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Open charm measurements via hadronic decay channels in the ALICE experiment

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Introduction

ALICE (A Large Ion Collider Experiment) is one of the four experiments at the Large Hadron Collider (LHC). The main objective of ALICE is the study of nucleus-nucleus collisions at a center-of-mass energy (for Pb^{208} nuclei) of 5.5 TeV per nucleon. ALICE will carry on the experimental heavy-ion program started twenty years ago at the CERN SPS and continued at the Brookhaven Relativistic Heavy Ion Collider (RHIC). The aim of heavy-ion physics is to study the properties of the hadronic matter at the extremely high energy densities which were reached in the Big-Bang.

Presently no real data are available, therefore it is important to evaluate the detector physics performances by means of an accurate Monte Carlo simulation of the apparatus. For this purpose, reconstruction algorithms and analysis packages are developed, including for example feasibility studies of interesting exclusive decay channels.

The main goal of this thesis is the detection of $D^\pm$ mesons through their three-body decay channel $D^+ \rightarrow K^- \pi^+ \pi^+$. Heavy quarks, like charm and bottom, are produced in hard scatterings in the early stages of high energy nucleus-nucleus collisions and are expected to be a powerful tool to investigate nuclear effects on charm production. The measurement of charm and beauty production in proton-proton and proton-nucleus collisions is also of great interest, since it provides a baseline to compare the results obtained with nucleus-nucleus collisions.

The expected multiplicity in Pb-Pb collisions at the LHC energies is about 2000 particles per rapidity unit. In 10 central Pb-Pb collisions, only one $D^\pm$ meson is expected to be reconstructed with its three decay products in the detector. Such numbers indicate the difficulty in the setting up of a selection strategy, having in mind also that the full simulation of a Pb-Pb collision requires a large computing power. Therefore, a separate generation of signal and background events is necessary. This was done using the distributed computing resource offered by the Grid on national scale.

The background rejection is largely based on the capability of the apparatus to discriminate the production point of the particles: the three particles coming from a D meson decay come from a secondary vertex close to the primary vertex, where most of the particles are produced. The distance between the primary and the secondary vertices is of the order of the decay length of the D meson, namely $c\tau = 311 \mu\text{m}$.

The main points of this work are summarized in the following:

1. Simulation of a proper number of events, both for Pb-Pb and pp collisions.

2. Development of an algorithm for the secondary vertex finding.
3. Setting up of the selection criteria for the signal selection, in order to maximize the significance in one year of data taking.
4. Setting up of an optimization procedure, consisting in the maximization of the significance in a n-dimensional set of selection variables.

The points 1 and 2 are treated in Chapter 4, devoted to the description of the simulation tools for heavy flavour analyses.

The points 3 and 4 are discussed in Chapter 5, where the analysis strategy is presented, and in Chapter 6, where the obtained results are reported.

Once the feasibility study of the hadronic decay $D^+ \rightarrow K^- \pi^+ \pi^+$ has been established, we evaluate the expected statistical and systematic errors in the measurement of the nuclear modification factor, defined as the ratio of the D meson yield in Pb-Pb over the D meson yield in pp properly scaled to Pb-Pb with geometrical models. Such an observable provides information on the quenching mechanisms of the particles in the nuclear medium.

Finally, we evaluate the feasibility of charm *flow* measurements and we show that, in order to have a good accuracy, a semi-peripheral selection at trigger level is necessary. The feasibility studies reported above are discussed in Chapter 7.

The remaining chapters are organized as follows. A general introduction on the heavy-ion physics is given in Chapter 1. The physical observables useful for such kinds of analyses and the most significant results from SPS and RHIC are presented.

Chapter 2 is devoted to open charm physics and to the production of open charm in heavy-ion collisions. An overview of the most recent results on open charm measurements is also given.

A description of the ALICE apparatus, of the ALICE experimental program and of the LHC experimental conditions is presented in Chapter 3.

Introduzione

ALICE (A Large Ion Collider Experiment) è uno dei quattro esperimenti previsti al Large Hadron Collider (LHC) del CERN ed il suo obiettivo principale consiste nello studio di collisioni tra nuclei atomici completamente ionizzati ad un'energia che, nel caso di nuclei Pb^{208} , sarà di 5.5 TeV per nucleone. Questo esperimento si propone di proseguire, all'energia dell'LHC, il programma scientifico iniziato venti anni fa da diversi esperimenti all'SPS del CERN e successivamente al Relativistic Heavy Ion Collider (RHIC) di Brookhaven, volto essenzialmente a studiare le proprietà della materia adronica a densità di energia raggiunte in natura nei primi istanti di vita dell'Universo ed eventualmente nel nucleo delle stelle a neutroni.

Allo stato attuale, non essendo ancora disponibili i dati reali, vengono valutate le potenzialità di indagine fisica ("Physics Performances") dell'esperimento attraverso l'accurata simulazione Monte Carlo dell'apparato nella sua versione definitiva. Questo richiede lo sviluppo di algoritmi di ricostruzione e la messa a punto di protocolli di elaborazione ed analisi volti a stabilire la fattibilità dello studio di alcuni canali esclusivi particolarmente interessanti.

L'argomento centrale di questa tesi è la rivelazione del mesone dotato di charm $D^\pm$ nel suo canale di decadimento adronico a tre corpi ($D^+ \rightarrow K^- \pi^+ \pi^+$). Lo studio dei quark charm e beauty in collisioni nucleari ad alta energia è particolarmente interessante perché questi vengono prodotti nei primi istanti della collisione in urti tra partoni ad alto momento trasferito e consentono, attraverso il confronto con i dati di interazioni protone-protone e protone-nucleo, di valutare gli effetti della materia nucleare che si forma a seguito della collisione. In una collisione Pb-Pb all'LHC verranno ricostruite in ALICE circa 2000 particelle per unità di rapidità secondo le stime correnti. Si stima che in circa una collisione centrale su 10, tre delle particelle ricostruite nell'apparato centrale di ALICE siano i prodotti di decadimento di un mesone D carico. Da questi numeri si evince quanto sia difficile la messa a punto di criteri di reiezione del fondo combinatoriale e quanto non sia scontata a priori la fattibilità di una misura di questo genere. Le difficoltà sono aumentate dalle risorse di calcolo necessarie per simulare una collisione Pb-Pb completa. Si rende pertanto necessaria una simulazione separata del segnale da studiare e del fondo. Per queste simulazioni sono state utilizzate le risorse di calcolo distribuite su scala nazionale afferenti alla Grid.

La reiezione del fondo è basata in buona parte sulla capacità dell'apparato di discriminare il punto di origine delle particelle, il cosiddetto vertice di produzione: le tre particelle che derivano dal decadimento di un mesone D provengono da un vertice secondario prossimo a quello primario da cui proviene gran parte del fondo.

La distanza scala tra il vertice primario e quello secondario è definita dalla vita media del mesone, $c\tau = 311 \mu\text{m}$.

I punti essenziali di questo lavoro di tesi si possono sintetizzare nel seguito:

1. Simulazione di un adeguato numero di eventi sia per collisioni Pb-Pb che pp.
2. Sviluppo di un algoritmo per la ricerca di vertici secondari prossimi al primario.
3. Messa a punto di criteri per la selezione del segnale in modo da rendere massima la significatività statistica della misura in un anno di presa dati. I tagli sviluppati sono stati applicati a vari livelli: traccia singola, aggregazione di più tracce, vertici secondari.
4. Messa a punto di una tecnica di ottimizzazione del punto di lavoro consistente in una massimizzazione della significatività in funzione di un set n-dimensionale di variabili di taglio.

I punti 1 e 2 sono trattati nel Capitolo 4, dedicato alla descrizione degli strumenti di simulazione indispensabili per analisi di open charm ed open beauty.

I punti 3 e 4 sono discussi nel Capitolo 5, in cui viene presentata la strategia di analisi, e nel Capitolo 6, in cui sono riportati i risultati ottenuti.

Una volta stabilita la fattibilità di una misura di open charm nel canale $D^+ \rightarrow K^- \pi^+ \pi^+$ sia con fascio di ioni che di protoni, sono stati valutati gli errori statistici e sistematici attesi nella determinazione del fattore di modificazione nucleare. Questa osservabile è definita come il rapporto tra il numero di mesoni D prodotti in Pb-Pb, rispetto a quello atteso nel caso di assenza di effetti nucleari, che si ottiene a partire dal numero di mesoni D prodotti in pp opportunamente riscalo alle collisioni Pb-Pb con modelli geometrici.

Infine, è stata stimata la fattibilità di misure di *flow* del quark charm, analisi interessante alla luce dei recenti risultati di RHIC, trovando che per avere dei risultati conclusivi su questo tema sarà opportuno utilizzare una selezione di semi-centralità degli eventi a livello di trigger. Gli studi di fattibilità sopra descritti sono discussi nel Capitolo 7.

I restanti capitoli sono così strutturati. Nel Capitolo 1 è data un'introduzione generale sulla fisica degli ioni pesanti, con l'intento di focalizzare l'attenzione sulle osservabili fisiche che possano provare l'esistenza di uno stato deconfinato di materia nucleare. Sono inoltre riportati i risultati più significativi ottenuti all'SPS e al RHIC.

Il Capitolo 2 è dedicato alla fisica del quark charm prodotto in collisioni nucleari di alta energia e comprende una panoramica dei risultati sperimentali più recenti riguardanti misure di open charm.

Nel Capitolo 3 sono presentati i rivelatori che compongono l'apparato sperimentale di ALICE, ponendo particolare attenzione ai rivelatori che vengono impiegati per la rivelazione di particelle dotate di charm. Viene inoltre data una descrizione del programma dell'esperimento ALICE, nel contesto delle condizioni sperimentali offerte da LHC.

Chapter 1

Heavy Ion physics

The Standard Model is the theory of the elementary particles and their fundamental interactions which has been developed and validated in the second half of the twentieth century and it is currently well established. The aim of ultra-relativistic heavy-ion physics is to apply the Standard Model to complex and dynamically evolving systems of finite size and under extreme conditions of density and temperature. Even prior to the identification of quantum chromodynamics (QCD) as the underlying theory of strong interactions, it was suggested that new phases of nuclear matter could arise in high density and/or temperature domains. When QCD became the correct theory of strong interactions, it was argued that quarks and gluons would be deconfined under such conditions and moreover that QCD implies a phase transition that is accessible to experimental evidence.

There were soon indications that the dense nuclear matter at the center of neutron stars, in the high density and low temperature regime of QCD, could consist of deconfined quarks and gluons. Similar arguments were also applied to the evolution of the universe: according to the Big-Bang cosmology, the universe evolved from an initial state of extreme energy density, consisting of deconfined quarks and gluons, to its present state through rapid expansion and cooling, thereby traversing the series of phase transitions predicted by the Standard Model. Global features of our universe like baryon asymmetry or the large scale structure (galaxy distribution) are believed to be linked to characteristic properties of these phase transitions.

The new deconfined matter was called “Quark Gluon Plasma” (QGP) [1] and was described as the state of matter formed when the energy density exceeds the typical hadronic value of $\sim 1 \text{ GeV/fm}^3$: in these conditions matter no longer consists of separate hadrons (protons, neutrons) but it is made of their fundamental constituents, quarks and gluons, which behave as free over longer distances. Because of the apparent analogy with similar phenomena in atomic physics, this phase of matter is called quark-gluon plasma.

Old conceptions of the QGP considered quarks and gluons to be non-interacting; recent calculations suggest that such an ideal state may be reached only at temperatures much higher than that required for the deconfinement transition. Furthermore, the attainment of thermalization on the very short timescale of a collision must rely on frequent interactions among the constituents during the earliest stages of the collision: considerations such as these led some authors to denote quark gluon plasma as “sQGP” for “strongly interacting QGP”.

The main objective of heavy-ion physics is to explore the system created at high energy density, where the deconfinement phase transition is expected to occur, and to study the properties of the Quark Gluon Plasma state.

The description of microscopic processes involving quarks and gluons can be done stemming from the fundamental lagrangian of QCD by means of three categories of theoretical tools:

1. perturbative QCD (pQCD): in order to use a perturbative expansion in series of the strong coupling constant α_s , the requirement is $\alpha_s \ll 1$. Therefore, pQCD can be used only to describe those processes which guarantee such condition, for example heavy flavour production in hadron collisions, as discussed in Chapter 2. See for example Ref. [2] for a review of the QCD.
2. Lattice QCD: it is a formulation of the QCD on a discrete lattice of space-time coordinates. Lattice QCD calculations can reproduce some of the pQCD results and, in addition, provide a description of non-perturbative processes. The main results obtained by lattice QCD calculations are reported in Section 1.2. Nevertheless, such calculations show uncertainties related to limitations of the lattice spacing and on the size of the lattice. It is difficult to reduce the lattice spacing, in order to approach the continuum, and to extend its size due to the limited computing power. Therefore, due to the approximations used in lattice calculations, some results might not always be “exact”. For a review of lattice QCD see [3] and references therein.
3. Effective models: these models are based on the QCD and provide a phenomenological description of the physical processes. Obviously such models are not able to reproduce at the same time all the QCD properties, like symmetries, confinement, ... The MIT bag model [4], the Nambu-Jona-Lasinio (NJL) model [5] and the parton model are among the effective models largely used for practical calculations.

1.1 The QCD phase diagram

The formulation of QCD and the observation that QCD is an asymptotically free theory, led to the hypothesis that there could be a phase transition between the hadronic matter where partons are confined and a plasma where partons are essentially free. Depending upon the temperature T and on the chemical potential μ_B ¹, the strongly interacting matter is expected to exhibit different states. This is shown in the QCD phase diagram in Fig. 1.1. At low temperatures and for $\mu_B \sim 1$ GeV (corresponding to the nuclear density) there is the ordinary hadronic matter.

The hadron gas is made of nucleons which interact and form pions or excited states of protons and neutrons (Δ resonances). It can be reached either by compression of the nuclear matter (i.e. increasing μ_B) or by heating (i.e. increasing T).

For sufficiently high values of the baryo-chemical potential, the system exhibits a first-order phase transition² between hadronic matter and the QGP. Calculations at non-zero chemical potential suggest the existence of a critical point $(\mu_{B,c}, T_c)$, such that the transition is no longer first-order for $\mu_B < \mu_{B,c}$ and $T > T_c$. However, such a critical point is foreseen to be at baryon densities well above those obtained in heavy-ion collisions at the Relativistic Heavy Ion Collider RHIC.

The nature of the transition for low values of the baryon chemical potential

¹In statistical mechanics, the chemical potential is the minimal energy necessary to add (or extract) a particle to a system, $\mu = dE/dN$. The baryon chemical potential is directly related to the baryon-number density, for example in a non-interacting gas of nucleons at zero temperature $\mu_B = \varepsilon_F \equiv p_F^2/2m \propto \rho_B^{2/3}$ (ε_F is the Fermi level).

²A phase transition is classified according to the discontinuity of the free energy F as a function of the temperature T . The free energy is defined as follows:

$$F = U - TS$$

where U is the internal energy and S is the entropy of the thermodynamical system. A first-order phase transition is characterized by a discontinuity of $\partial F/\partial T$ and a continuous F . The free energy is related to the energy density ϵ by the following relation:

$$\epsilon = \frac{E}{V} = \frac{F + T\partial F/\partial T}{V}$$

where E and V are the total energy and the volume of the system respectively. Therefore, a first-order phase transition implies a discontinuous energy density as a function of the temperature. The variation of the energy density at the discontinuity represents the latent heat. A second-order phase transition is characterized by a discontinuity of $\partial^2 F/\partial T^2$, while both F and $\partial F/\partial T$ are continuous. Since the specific heat is defined by $\partial E/\partial T$, it is discontinuous in a second-order phase transition. If there are no discontinuities in thermodynamical observables, as opposed to first or second order phase transitions, the transition is called crossover and there is no clear separation between the phases.

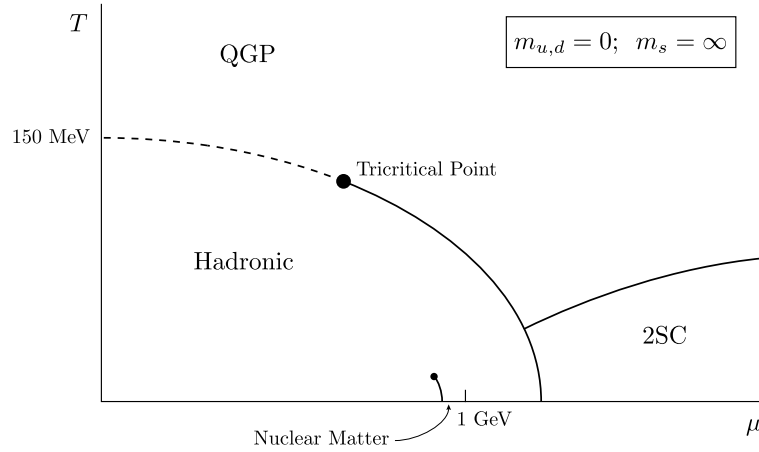


Figure 1.1: The phase diagram of QCD with two massless flavours: the solid lines indicate first-order transitions. The dashed line indicates a possible region of a continuous but rapid crossover transition.

depends dramatically on the number of quark flavours and on the light quark masses, especially on the strange-quark mass: indeed, it is still unclear whether the transition shows discontinuities for realistic values of the light quark masses, or whether it is a crossover. Recent calculations [6, 7] indicate that the transition is a crossover for values of $\mu_B \lesssim 400$ MeV.

At low temperatures and high values of the chemical potential, nuclear matter consists of an interacting and degenerate Fermi gas of quarks at high density. The interaction among the quarks can be attractive in specific combinations of colour states, leading to the formation of quark-quark pairs which determine a colour superconducting phase [8–10].

In the early universe, the transition from QGP to hadrons occurred at vanishing chemical potential and high temperatures during the rapid expansion and cooling; on the other hand, in the neutron stars the QGP state is supposed to be formed for high values of the baryo-chemical potential and temperature close to zero, due to gravitational collapse. In both cases the deconfined phase of hadronic matter appears to play a crucial role. Nowadays the region of high T and low μ_B is being investigated with the relativistic heavy-ion collisions, while the high μ_B and $T \sim 0$ regime is indirectly investigated in the context of astrophysical studies.

1.2 Lattice QCD results

Developing a quantitative understanding of the deconfining phase transition has proven to be a challenging task.

Simple models such as the MIT Bag Model provide qualitative arguments to identify both the critical temperature $T_C \sim 170$ MeV and the critical energy density $\epsilon_C \sim 1$ GeV/fm³ (such densities are nearly one order of magnitude larger than that of nuclear matter). Nevertheless, as QCD is generally considered the correct theory for interactions of quarks and gluons, it is necessary to study the phases of quark matter using full QCD. Furthermore, equilibrium and phase transitions involve quarks and gluons interacting over a large distance scale, indicating the importance of non-perturbative physics: it is for this purpose that QCD calculations on a space-time lattice were developed [11]. Despite numerical difficulties and constraints of computing limitations (even in the presence of specifically devised and dedicated machines), progress has been made in recent years and the main results are summarized in the following:

- The predicted transition between hadronic matter and a QGP phase occurs at a temperature of $T_c = 175 \pm 15$ MeV for zero chemical potential. The precise value of the transition temperature depends on the treatment of quarks in the calculation. The influence of a non-zero chemical potential has also been studied and it has been found that the effect is small for the values of μ_B observed at RHIC ($\mu_B \simeq 50$ MeV) and will be even smaller at the LHC energies.
- Although the transition is of second order in the limit of 2-flavour QCD (two quarks with zero masses) and of first order for 3-flavour QCD (three quarks with zero masses), the most realistic calculations, incorporating the s quark mass, indicate that the transition is most likely of the crossover type at zero chemical potential.

This is reflected for example in the behaviour of the energy density ϵ as a function of the temperature T shown in Fig. 1.2 (b): it can be seen that the transition is not of first order because this would indicate a discontinuity of ϵ at the critical temperature T_c .

Nevertheless, it must be kept in mind that lattice calculations have intrinsic systematic errors due to the use of a finite lattice cutoff and to the use of quark masses which are eventually infinite (“quenched QCD”). The crossover occurs in a small range of temperatures, thus the “phase transition” is still well localized. This is reflected in a rapid rise of the energy density ϵ in the vicinity of the crossover temperature: indeed, ϵ changes by $\Delta\epsilon/T_c^4 \simeq 8$ in a temperature interval of only about 20 MeV (see Fig. 1.2 (b)).

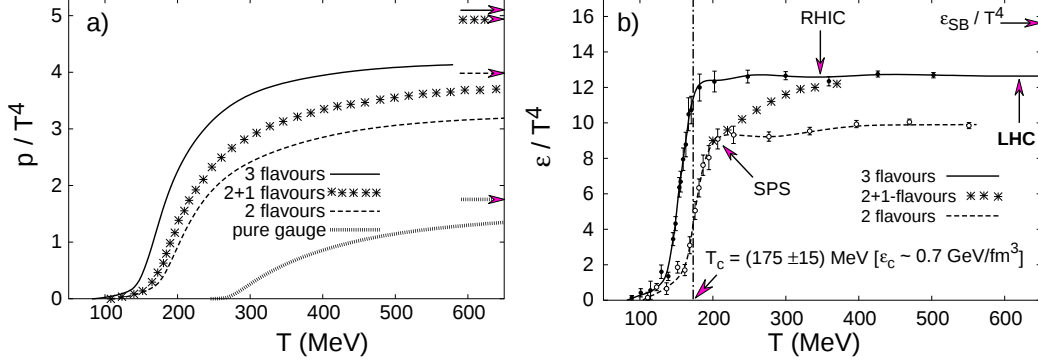


Figure 1.2: Lattice results for the pressure (a) and energy density (b), in QCD with 0, 2 and 3 degenerate quark flavours as well as with two light and a heavier (strange) quark. The arrows on the right-side ordinates show the value of the Stefan–Boltzmann limit for an ideal quark–gluon gas.

The current estimate of the critical energy density, given by the 2-flavour QCD, is $\epsilon_c \simeq 0.3 - 1.3 \text{ GeV/fm}^3$.

In the limit of massless non-interacting particles, each bosonic degree of freedom contributes $\frac{\pi^2}{30}T^4$ to the energy density; each fermionic degree of freedom contributes $\frac{7}{8}$ this value. The corresponding Stefan–Boltzmann limit of the energy density ϵ_{SB} for the case of 2-flavour QGP is then:

$$\epsilon_{SB} = \left[2_f \cdot 2_s \cdot 2_q \cdot 3_c \cdot \frac{7}{8} + 2_s \cdot 8_c \right] \frac{\pi^2}{30} T^4 = \frac{37\pi^2}{30} T^4 \quad (1.1)$$

where the flavour, spin, quark/antiquark and colour contributions for quarks have been considered. In case of gluons, only spin and colour factors enter into play. The rapid rise of the energy density ϵ in a restricted temperature interval is also interpreted as the latent heat of the transition necessary to change the number of degrees of freedom from 3, in the pion gas, to 37 of the deconfined phase with two flavours.

In Fig. 1.2 (b) it is also visible that the saturated values of energy density at high temperatures are still below the expected value given by the Stefan–Boltzmann limit: this deviation from the SB limit indicates residual interactions among the quarks and gluons in the QGP phase.

Also the pressure p_{SB} of a gas of non-interacting quarks and gluons can be determined in the Stefan–Boltzmann limit at $\mu_b \simeq 0$:

$$\frac{p_{SB}}{T^4} = \left[2(N_c^2 - 1) + \frac{7}{2} N_c N_f \right] \frac{\pi^2}{90} \quad (1.2)$$

where N_c is the number of colours and N_f the number of flavours; the two terms on the right are related to gluon and quark contributions respectively. The pressure divided by T^4 rises above the critical temperature T_c , then begins to saturate by $2T_c$, but at values substantially below the Stefan–Boltzmann limit (see Fig. 1.2 (a)), suggesting a more complex structure even at $T \simeq 5T_c$.

The pressure rises more slowly than the energy density: this has consequences on the sound velocity $c_s^2 = dp/d\epsilon$ in the plasma phase.

In the phase diagram of Fig. 1.2 (b) the thermodynamical quantities which characterize the system created in the early stages of heavy-ion collisions at the SPS, RHIC and LHC are indicated.

- In most calculations, the deconfinement transition is also accompanied by a chiral symmetry restoration.

In absence of quark masses, the QCD Lagrangian splits into two independent sectors:

$$L_{QCD} = -\frac{1}{4}G_a^{\mu\nu}G_{\mu\nu}^a + i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{q}_R\gamma^\mu D_\mu q_R$$

where $G^{\mu\nu}$ is the gluonic tensor, built up in terms of the gluon fields, q denotes the quark field with the different flavours and L, R stand for the left- and right-handed components of the quarks. The QCD Lagrangian is symmetric under chirality transformation ($q \rightarrow e^{i\theta\gamma_5}q$) only if the quark masses can be neglected, as it is the case for the u and d quarks, the main constituents of ordinary hadronic matter.

By defining the vector ($V_\mu = \bar{q}\gamma_\mu q$) and axial vector ($A_\mu = \bar{q}\gamma_\mu\gamma_5 q$) currents, it turns out that, for $m_q = 0$, the associated charges both commute with the QCD Hamiltonian, hence being conserved.

The symmetry of the QCD Lagrangian under the transformation ($q \rightarrow e^{i\theta}q$) implies that the vector charge is conserved; such a symmetry is realized in nature in the existence of isospin multiplets. On the contrary, in nature hadrons do not possess chiral partners (identical particles with opposite parity). Indeed, while $Q_V|0\rangle \equiv V_0|0\rangle = 0$, $Q_A|0\rangle \equiv A_0|0\rangle \neq 0$, namely the vacuum does not possess the symmetry of the Lagrangian and the chiral symmetry is spontaneously broken. This implies the existence of soft (massless) modes: the pion, on the basis of the Goldstone theorem.

The spontaneous chiral symmetry breaking is related to the chiral condensate, defined as:

$$\langle\bar{q}(x)q(x)\rangle = \lim_{\epsilon\rightarrow 0^+} \langle\bar{q}(x^0 + \epsilon, \vec{x})q(x^0, \vec{x})\rangle = - \lim_{\epsilon\rightarrow 0^+} \langle Tq(x^0, \vec{x})\bar{q}(x^0 + \epsilon, \vec{x})\rangle = -G(x, x^+)$$

where $q(x)$ is the quark field, x is the four-vector associated to the quark $(x^0, \vec{x})$, T is the time-order product and G is the quark propagator from $(x^0, \vec{x})$ to $(x^0 + \epsilon, \vec{x})$, thus representing a quark loop (in the vacuum).

The connection between spontaneous chiral symmetry breaking and non-vanishing chiral condensate can be established by introducing a pseudoscalar operator $P(x) = \bar{q}(x)\gamma_5 q(x)$ and deriving the commutator relation $[Q_A, P] = -\bar{q}(x)q(x)$ [12]. Taking the ground state

expectation value, it can be found that $Q_A|0\rangle \neq 0$ implies $\langle\bar{q}q\rangle \neq 0$. On the contrary, if the symmetry were conserved, we would have $Q_A|0\rangle = 0$ and $\langle\bar{q}q\rangle = 0$.

The pseudoscalar operator P applied to the vacuum gives the pion, which is indeed a pseudoscalar meson, i.e. $P|0\rangle = |\pi\rangle$.

One can then write the relation:

$$\langle 0|A_\mu(x)|\pi(p)\rangle = -if_\pi p_\mu e^{-ip\cdot x}$$

where $f_\pi = 94$ MeV is the pion decay constant, $|\pi(p)\rangle$ is the pion state and p_μ is the four-momentum of the pion.

The above relation implies the GOR (Gell-Mann, Oakes and Renner) relation:

$$m_\pi^2 f_\pi^2 = -2m\langle\bar{q}q\rangle$$

where m is the quark mass ($m_u \simeq m_d$) and m_π is the pion mass. From the latter relation, one obtains the ground state expectation value $\langle 0|\bar{q}q|0\rangle \equiv \langle\bar{q}q\rangle \simeq -(240\text{MeV})^3$.

This condensate is a measure of spontaneous chiral symmetry breaking. The non-zero pion mass reflects the explicit symmetry breaking by the small quark masses.

The chiral symmetry is broken at low temperature (for the ordinary hadronic matter) but is expected to be restored in the high temperature regime created in heavy-ion collisions. The chiral condensate is calculated as a function of temperature T and baryon density ρ , obtaining (for example in the limit of low T and low ρ):

$$\frac{\langle\bar{q}q\rangle_{T,\rho}}{\langle\bar{q}q\rangle_0} \approx 1 - aT^2 - b\rho$$

where $\langle\bar{q}q\rangle_0$ is the vacuum condensate at $T = 0$ and $\rho = 0$; a and b are two positive constants. From the latter relation we see, in a qualitative way, that in high temperature and/or density regime, the chiral condensate goes to zero, suggesting a possible restoration of the chiral symmetry.

Lattice calculations found that in the Quark Gluon Plasma phase, where the particles are deconfined, the chiral condensate goes to zero (see left panel of Fig. 1.3) and that the two transitions (deconfinement and chiral symmetry restoration) occur at approximately the same temperature.

- Another important result of lattice QCD is the calculation of the potential between two quarks as a function of the temperature. In the Quark Gluon Plasma, it goes to a constant at long distances, confirming the deconfinement. With increasing temperature the potential flattens towards smaller values and the confinement is lost; indeed, the quark-antiquark separation decreases as the temperature increases (see right panel of Fig. 1.3 in case of heavy quarks).

Lattice calculations show that for temperature above few hundreds MeV, QCD enters a deconfined phase where quarks and gluons are free.

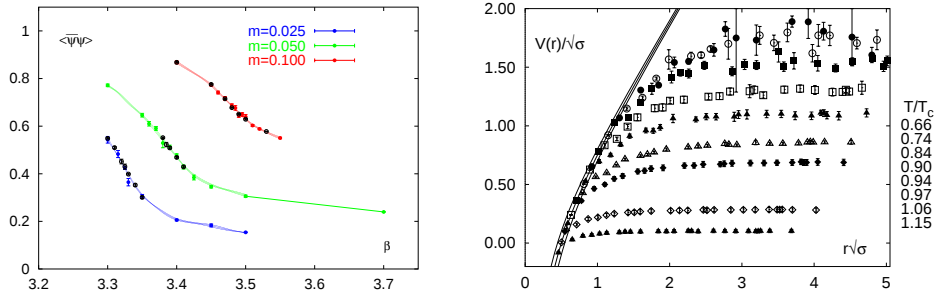


Figure 1.3: Left panel: chiral condensate (in units of its value in the vacuum) as a function of β for different values of the quark bare mass. Increasing β corresponds to decreasing lattice spacing and to increasing temperature. β should not be confused with the inverse temperature $1/T$. Taken from [13]. Right panel: heavy-quark potential for 3-flavour QCD versus the quark-antiquark separation. The different points correspond to lattice calculations with different temperatures. σ is the string tension. Taken from [14].

This consideration would suggest to consider the QGP as a weakly coupled medium, characterized by the coupling constant $\alpha_s(T) \propto 1/\log(2\pi T/\Lambda_{QCD})$. For $T > 300$ MeV, i.e. well above the critical temperature, the coupling is reasonably small, i.e. $\alpha_s < 0.3$, to allow in principle a perturbative approach. However, recent observations at RHIC and recent theoretical arguments seem to favour a description of the QGP as a strongly interacting fluid rather than a perfect gas (where interactions between particles are absent and pQCD could be applied).

1.3 Experimental heavy-ion observables

In order to characterize the system produced in heavy-ion collisions as a state of matter, it is necessary to establish if concepts such as temperature, chemical potential and flow velocity can be defined and the system can be described by an experimentally determined equation of state. Additionally, the experiments should be able to provide information on the physical characteristics of the transition, such as the critical temperature, the order of the phase transition and the sound velocity.

While at very high temperature ($T \gg T_c$, currently experimentally unobtainable) the QGP may behave as made of weakly interacting particles, in the transition region near T_c the degrees of freedom of the system may be more complex. Therefore the properties of the QGP depend on the temperature.

The experimental results from the AGS, SPS and RHIC have contributed to the theoretical understanding of the thermodynamic and hydrodynamic properties

of the hot strongly interacting matter and of the propagation of partons through such matter. However, the complexity of heavy-ion collisions still lead to a patchwork of theories and models to treat the collision evolution.

The aim of the experimentalists is to identify the predictions of the theory and to look for various observables that would confirm such predictions.

There are two basic classes of experimental probes in heavy-ion collisions. On one side, the study of electroweak products of the collision (essentially dileptons and photons) allows to exploit the absence of final state interactions with the evolving strongly interacting matter. Since these probes are not strongly interacting, they allow to study particles produced in the first stages of the collision bearing the imprints of the bulk properties of these stages. The drawback of this kind of study is that such products are not copious and must compete with those originating from hadron decays and interactions from the later stages of the collisions.

On the other side, one may focus on the more abundant hadrons, which are affected by final state interactions. It becomes then crucial to distinguish between partonic and hadronic final state interactions and to distinguish both from initial state interactions.

In this section the main heavy-ion observables that will be measured by the ALICE experiment will be discussed, as well as the most significative results obtained by the heavy-ion programs at SPS and RHIC.

1.3.1 Observables in ALICE

1.3.1.1 Particle multiplicity

The average charged-particle multiplicity per rapidity unit (rapidity density dN_{ch}/dy) is the most fundamental ‘day-one’ observable: it is directly related to the energy of the collision and to the properties of the medium produced in the collision, like the degree of transparency, the number gluons in the initial state, ... Another important observable is the transverse energy per rapidity unit, which determines how much of the total initial energy is converted in particles produced in the transverse direction.

A prior estimation of the particle multiplicity expected in the experiment is fundamental in the design of the detector, because it can be used to define the granularity of the detectors. Both charged-particle multiplicity and transverse energy cannot be easily extracted from QCD calculation (i.e. starting from the QCD lagrangian) because they include soft processes which are dominant at large distance scale where perturbative QCD fails. As a consequence, there is not a safe estimate of the multiplicity which will be measured at the LHC, even after RHIC

data. Before RHIC, extrapolations from SPS at $\sqrt{s} = 20$ to 200 GeV mostly overestimated the result. Now that RHIC data are available, extrapolations from 200 to 5500 GeV are still difficult.

Since the aim of studying heavy-ion collisions is to discover new effects which are not present in proton-proton collision, it is then appropriate to compare the multiplicities achieved in proton-proton and nucleus-nucleus collisions. This can be quantitatively done introducing the number of participants N_{part} in the collision which is 2 in pp, about $2A$ for central AA collisions and varies with the centrality. Dividing the multiplicity by N_{part} gives a measure of how efficient are AA collisions for each subcollision: Fig. 1.4 shows the extrapolation of $N_{ch}/(0.5N_{part})$ in proton-proton and nucleus-nucleus collisions from SPS and RHIC. An approximate prediction for the LHC taken directly from the plot is $dN_{ch}/dy \sim 13 \times A_{eff} = 13 \times 170 \sim 2200$ (A_{eff} is the atomic number effectively considered taking into account centrality cuts): this value is currently an upper limit of the most believed estimations, which are of the order of 1000-2000 particles per rapidity unit. It should be noticed that this value is much lower than the first predictions available at the time when ALICE was designed (between 2000 and 8000 charged particles per rapidity unit).

1.3.1.2 Particle spectra

Most of the particles produced in heavy-ion collisions ($\approx 99\%$) are soft hadrons originated in the late stage of the collision evolution during the hadronic freeze-out. Particle spectra are relevant because they carry indirect information about the early stages of the collision.

At the hadronization, also called chemical freeze-out³, the particles decouple from the collision region, move outward and are detected.

Spectral shapes can be modified after the chemical freeze-out because rescattering processes among hadrons are expected to occur.

Chemical and kinetic freeze-out stages can be studied through short-lived resonances such as the ρ , K^* , Δ . These resonances are produced in the chemical freeze-out and decay before the kinetic freeze-out is reached: the ρ meson for example has a width $\Gamma \sim 150$ MeV corresponding to a decay length of $c\tau \sim 1.3$ fm, smaller than the expected time interval between chemical and kinetic freeze-out

³The chemical freeze-out occurs during the hadronization, when mesons and baryons are produced from the expanding medium. The chemical freeze-out in AA collisions is reached when the average energy per average number of hadrons drops below 1 GeV at all collision energies [16]. The total particle yields reflect the chemical abundances of the fireball and remain almost fixed after the chemical freeze-out. After the hadronization phase, the system further cools via elastic interactions among the hadrons until the kinetic or thermal freeze-out is reached and the system becomes non-interacting. The particles coming out from this stage are detected by the experiment.

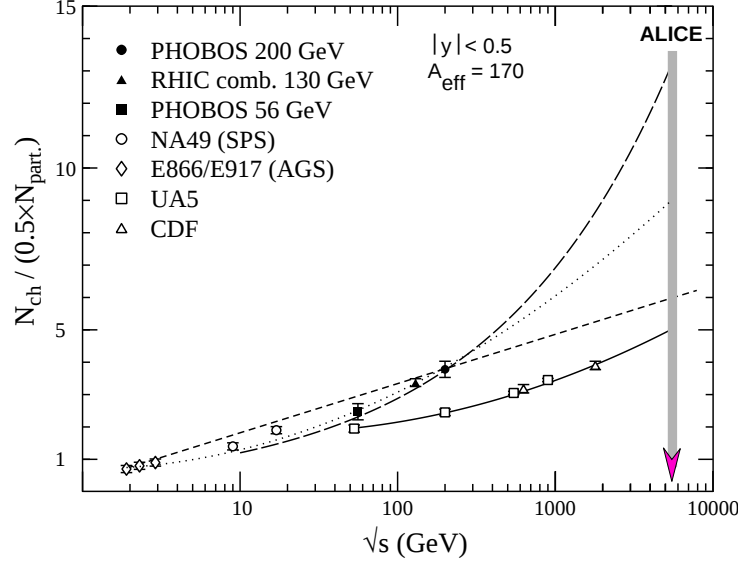


Figure 1.4: Charged-particle rapidity density per participant pair as a function of centre-of-mass energy for A–A and pp collisions. Experimental data for pp collisions are overlaid by the solid line. The dashed line is a fit $0.68 \ln(\sqrt{s}/0.68)$ to all the nuclear data. The dotted curve is $0.7 + 0.028 \ln^2 s$. It provides a good fit to data below and including RHIC, and predicts $dN_{\text{ch}}/dy \sim 9 \times 170 = 1500$ at the LHC. The long dashed line is an extrapolation to the LHC energies using the saturation model [15], which gives $dN_{\text{ch}}/dy \sim 2200$ reported in the text.

(such time scale depends upon the models and is of the order of tens of fm). The hadronic decay products of the resonances suffer rescattering processes inside the medium. The invariant-mass distribution of the resonances measured from their hadronic decays is then broadened compared to the same distribution measured from leptonic decays. It is hence important to compare hadronic and leptonic decays of resonances to understand better the hadronic rescattering stage.

The particle spectra at a given beam energy can be reproduced by a model based on a superposition of local thermal motion and global collective expansion [17], [18]; the model is characterized by an initial state defined by the initial energy density and the initial baryon density. The shape of the spectrum is described by three parameters: the particle mass, the freeze-out temperature T and the surface velocity at freeze-out $v_{\perp}$. Thermal radiation produces a transverse momentum spectrum [19]:

$$dN/m_T dm_T dy \propto e^{-m_T/T} \quad (1.3)$$

where T is the freeze-out temperature and m_T is the transverse mass ($m_T = \sqrt{m^2 + p_T^2}$). The spectrum in Eq. 1.3, if plotted logarithmically versus m_T , is

a straight line, whose inverse slope is simply T . Therefore, it is convenient to use the transverse mass instead of the transverse momentum p_T .

At relativistic transverse momenta, the inverse slope of all hadrons is the same:

$$T_{\text{slope}} = T \sqrt{\frac{1 + \langle v_{\perp} \rangle}{1 - \langle v_{\perp} \rangle}}. \quad (1.4)$$

For non-relativistic transverse momenta, there is a contribution of the collective flow on top of the thermal motion depending on the rest mass of the hadron:

$$T_{\text{slope},i} = T + \frac{1}{2} m_i \langle v_{\perp} \rangle^2. \quad (1.5)$$

where m_i is the hadron mass. Eq. 1.4 and 1.5 show that the spectra are steeper at high p_T and become flatter at low p_T .

In order to measure such a change in slope, an experiment must cover the entire low- p_T range, from the smallest p_T which can be measured to about 3 GeV/c. At larger p_T the slope is no longer described by the collective flow picture.

Some results on particle spectra from the SPS and RHIC experiments are reported in Sections 1.3.3 and 1.3.4.

1.3.1.3 Flow

Flow is a collective phenomenon which affects almost all particles produced in a given collision. At low energy it is mainly due to the nucleons in the incoming nuclei and the theoretical interpretations involve the compressibility of nuclear matter or mean field effects. At higher energies, nucleon contributions are negligible at mid-rapidity, where parton effects are expected to be dominant; in this regime, the collective pattern is explained from a theoretical point of view with hydrodynamic models, which are based on the equation of state of the flowing medium provided that the mean free path of particles is much smaller than the system size (see for example [18], [20], [21] for a review of the hydrodynamical description of heavy-ion collisions).

In the following subsections the different patterns of collective flow (radial and anisotropic) are introduced, as well as the main methods developed in order to do such measurements in heavy-ion collisions.

Radial flow

In central collisions the overlap region of two spherical nuclei is symmetric in azimuth. This implies an isotropic production of the outgoing particles on the transverse plane. Under such conditions, pressure gradients may intervene resulting in an azimuthally symmetric collective flow of the final state particles, which

is called radial flow. This effect is superimposed onto the random thermal motion, thus is observable by studying the transverse momentum distributions of the various particle species (see Section 1.3.1.2).

Anisotropic flow

In non-central heavy-ion collisions, an initially asymmetric overlap region is created. Due to pressure gradients, this almond shaped region tends to assume a more symmetric shape as the system expands; if the initially produced particles scatter enough in the overlap region, then the spatial anisotropy is converted into a momentum anisotropy which can be detected even in the later stages of the collision evolution. This will not happen if the particles are not subject to rescattering or if the rescattering is too weak to equilibrate the system before the anisotropy is lost in the expansion of the medium.

The momentum anisotropies are described with respect to the reaction plane, which is the plane given by the beam axis and the line connecting the centres of the two colliding nuclei or equivalently is the plane parallel to the beam axis oriented in the direction of the impact parameter of the collision.

Hence, the particle azimuthal distribution is parametrized by a Fourier expansion [22] (the azimuthal angle is taken on the transverse plane with respect to the beam axis), which for convenience is usually written as:

$$dN/d\varphi = N_0 \left\{ 1 + \sum_i 2v_i \cos(i(\varphi - \Psi_{RP})) \right\}, \quad (1.6)$$

where N_0 is a normalization constant, φ and Ψ_{RP} are the azimuthal angles of the outgoing particles and of the reaction plane respectively. The Fourier coefficients are given by:

$$v_n = \langle \cos(n(\varphi - \Psi_{RP})) \rangle \quad (1.7)$$

The first coefficient of the series, v_1 , is called directed flow, while the second coefficient, v_2 , is called elliptic flow.

Directed flow, $v_1 = \langle \cos((\varphi - \Psi_{RP})) \rangle$, which quantifies a preferential emission direction along the reaction plane and it is thought to be due to pressure which builds up between the two nuclei. The $\varphi - \Psi_{RP}$ distribution is plotted in Fig. 1.5 for different values of the parameter v_1 .

According to Fig. 1.5, a non-zero v_1 ($v_1 > 0$) implies a favoured emission along the reaction plane ($\varphi \sim \Psi_{RP}$). On the other hand, there is a depletion around $\Delta\varphi \sim \pi$. By definition, $v_1 > 0$ (< 0) implies that the particles are bounced off in the reaction plane with a favoured emission angle $\Delta\varphi = \varphi - \Psi_{RP} \sim 0$ ($\sim \pi$). Furthermore, the flow of the particles originating from one of the nuclei is opposite to and equal as the flow of the particles coming from the other nucleus.

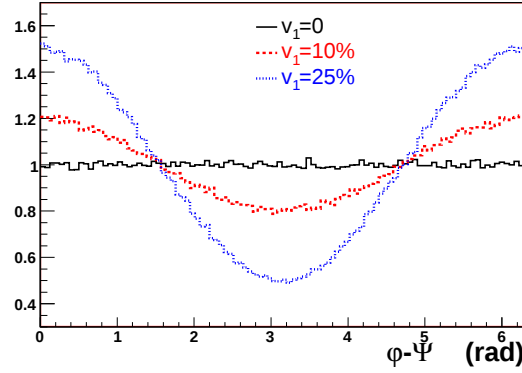


Figure 1.5: $\varphi - \Psi_{RP}$ distribution for $v_1 = 0$ (black line), $v_1 = 10\%$ (red, dashed line), $v_1 = 25\%$ (blue, dotted line).

This effect cannot be seen at mid-rapidity for symmetric collisions, where there is no reason why pressure should favour one direction rather than the opposite one.

At colliders with ultrarelativistic energies, at the early stages of non-central collision, the spectator neutrons which do not take part to the interaction may be bounced off each other in the transverse plane by the pressure established at mid-rapidity. Since they do not take part to the interaction, they go on towards the forward-rapidity zones where v_1 of the spectator neutrons can be measured.

On the other hand, the *elliptic flow* $v_2 = \langle \cos(2(\varphi - \Psi_{RP})) \rangle$ has maxima either in the reaction plane in both directions $\Delta\varphi = 0, \pi$ (in-plane flow, $v_2 > 0$), or the perpendicular to the reaction plane in both directions $\Delta\varphi = \pi/2, 3\pi/2$ (out-of-plane flow, $v_2 < 0$). This pattern reflects the geometrical anisotropy of the interaction region created in symmetric collisions, thus v_2 can be observed at mid-rapidity.

The $\varphi - \Psi_{RP}$ distribution is shown in Fig. 1.6 (left panel) for different values of the parameter v_2 . For $v_2 = 0$ there is not elliptic flow and the azimuthal distribution is flat as expected. The azimuthal distribution gets more and more peaked at $\Delta\varphi = 0, \pi$ as v_2 increases. The azimuthal anisotropy with non-zero v_2 is visualized in Fig. 1.6 (right panel), where the curves represent the profile of the expansion on the transverse plane. The x axis in the figure is the direction given by the reaction plane. As expected, the emission is isotropic for $v_2 = 0$, while for $v_2 > 0$ the particles are preferentially emitted along the reaction plane.

As the matter expands faster in the shorter axis of the overlap region, the spatial asymmetry decreases and thus also the buildup of flow anisotropies ceases

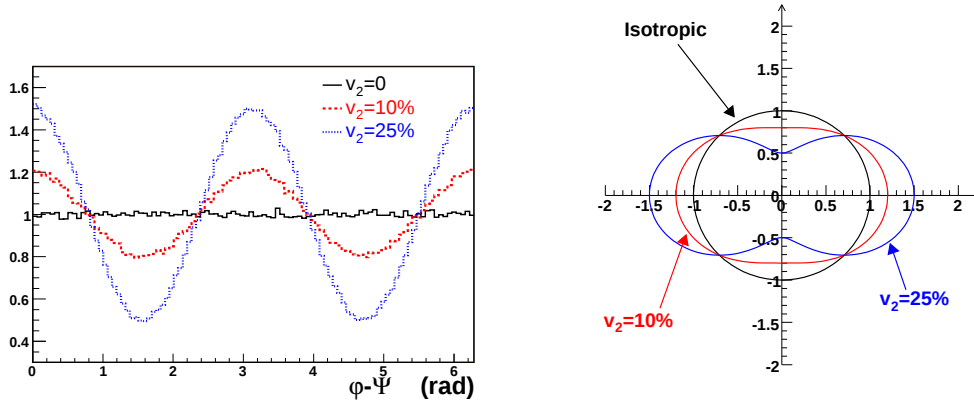


Figure 1.6: Left panel: $\varphi - \Psi_{RP}$ distribution for $v_2 = 0$ (black line), $v_2 = 10\%$ (red, dashed line), $v_2 = 25\%$ (blue, dotted line). Right panel: profile of the emitted particles on the transverse plane. The x axis in the figure is the direction of the reaction plane.

and the elliptic flow saturates: thus, elliptic flow is inevitably a self-limiting phenomenon. Saturation may be reached if the time required for the particles to scatter among themselves and transfer the anisotropy to momentum space is shorter than the kinetic freeze-out time. If the initial energy density is sufficiently high, elliptic flow saturates before chemical freeze-out starts.

Also the hexadecupole coefficient v_4 can be used as a probe of ideal fluid behaviour. It has been argued that $v_4(p_T, y) = 1/2 v_2(p_T, y)^2$ [23] for fast particles within ideal fluid dynamics predictions. The experimental value for $\frac{v_4}{2v_2^2}$ found by the STAR experiment [24] at RHIC is a factor of 2 to 3 higher than the predicted 0.5. A possible explanation is that the equilibrium is not reached at RHIC, and therefore higher values of v_4 are related to the expected deviations from ideal fluid behaviour [25].

Methods of anisotropic flow measurements

In order to perform accurate measurements of anisotropic flow, various procedures were developed, starting from the determination of the estimate of the reaction plane with its error, to the measurement of v_n with its experimental error.

- *Determination of the event plane.* The first step is to calculate for each event an estimator of the reaction plane. This estimator is called event plane, and its azimuthal angle is denoted by Φ_R . The difference $\Psi_{RP} - \Phi_R$ depends on the angular resolution of the apparatus, on the magnitude of flow and on the number of particles used for its calculation.

The event flow vector Q_n can be introduced for each harmonic n of the anisotropic flow [26]:

$$Q_x = \sum_i w_i \cos(n\varphi_i) = Q_n \cos(n\Phi_R) \quad (1.8)$$

$$Q_y = \sum_i w_i \sin(n\varphi_i) = Q_n \sin(n\Phi_R) \quad (1.9)$$

where the sum runs over all the particles, φ_i is the azimuthal angle of each particle and w_i is a weight selected in order to maximize the resolution. The event plane angle Φ_R can be derived from the equations above, measuring the two components of the flow vector.

Repeating this procedure for all the events, one should find that the reconstructed event plane has an isotropic azimuthal distribution after proper corrections for instrumental and acceptance effects. This is also a useful check for the analysis.

- *Resolution on the event plane.* The measurement of the event plane is not enough to determine the harmonic v_n ; the flow estimate is indeed computed in the following way:

$$v_p\{EP_n\} = \frac{\langle \cos[p(\varphi - \Phi_R)] \rangle}{\langle \cos[p(\Phi_R - \Psi_{RP})] \rangle} \quad (1.10)$$

where p is a multiple of the harmonic n . The numerator is nothing but the flow calculated respect to the reconstructed event plane instead of the reaction plane. The denominator is the event-plane resolution.

The above notation for $v_p\{EP_n\}$ means that, once the event plane has been calculated (for example with the first harmonic $n = 1$), it can be used to obtain not only $v_1\{EP_1\}$ but also higher harmonics for the elliptic flow, such as $v_2\{EP_1\}$, $v_3\{EP_1\}$, $v_4\{EP_1\}$, $\dots$

The most common procedure to derive the event-plane resolution is to divide each event in two subevents, each of which are assumed to maintain the same flow properties as the whole event.

The event plane may vary within a given event because it can be calculated rejecting those particles whose flow one wants to measure, in order to avoid autocorrelations.

Other methods to determine the coefficients v_n are not based on the event plane measurement, but rather on azimuthal correlations between pairs of particles [27] or on multi-particle correlations [28]. The latter is also called cumulant method

and is less sensitive to contaminations due to non-flow effects which remain hidden in the standard methods. Non-flow effects are azimuthal anisotropies mainly originating from two- or four-particle correlations; these effects are superimposed to the effective flow pattern, which is thus biased.

Anisotropic flow measurements will be important at the LHC because the initial energy densities will be so high that elliptic flow is expected to saturate well before hadronization: this could be an indication that the QGP thermalized early and can be described as an ideal fluid with an equilibrium equation of state. It is possible to derive properties, such as pressure and energy density, of the matter at the time the anisotropy developed, by comparing the v_2 for different types of hadrons. Theoretical calculations [29, 30] as well as extrapolation from lower energies predict v_2 values of about 5%–10% at the LHC for semi-peripheral events. If they are indeed that large, flow measurement should be feasible; nevertheless, non-flow effects such as correlations due to mini-jets are expected to be much larger at the LHC than RHIC and to bias the flow signal.

ALICE is well suited for such measurements, since with its barrel detectors and its forward zero degree calorimeter it is able to measure both v_1 and v_2 .

1.3.1.4 Particle correlations

Since the system created in heavy-ion collisions exhibits a collective behaviour, the properties of the fireball immediately before the thermal freeze-out, such as the size or the phase space density, can be assessed through interferometric measurements.

The studied quantity is for example the two-particle correlation function:

$$C(p_1, p_2) = \frac{d^6 N}{dp_1^3 dp_2^3} \bigg/ \frac{d^3 N}{dp_1^3} \frac{d^3 N}{dp_2^3}. \quad (1.11)$$

It represents the probability of measuring two particles with four-momenta p_1 and p_2 in the intervals $p_1 + \Delta p_1$ and $p_2 + \Delta p_2$ respectively.

The correlation function depends on the emitting source, as it appears in the following definition for spin-0 particles:

$$C(K, q) = 1 + \frac{\left| \int d^4 x S(x, K) \exp(ix \cdot q) \right|^2}{\int d^4 x S(x, K + q/2) \int d^4 y S(y, K - q/2)}, \quad (1.12)$$

where $K = (p_1 + p_2)/2$, $q = p_1 - p_2$ and x is the space-time four-vector. Here $S(x, K)$ is the emission function, i.e. the probability to emit a particle of momentum K from the position x . The aim of particle interferometry is to learn as much as possible about this emission function: this is not an easy task, first of all because the correlation function depends on the square of Fourier transform of

$S(x, K)$, therefore the phase of $S(x, K)$ remains inaccessible. In addition, since the detected identical particles are on their mass shell, the condition $q \cdot K = 0$ must be verified. This implies that only three of the four components of the four-momentum q can be determined independently. Usually three spatial components in the so-called *out-side-long* coordinate frame are adopted: *longitudinal* (z -axis) direction parallel to the beams, *outward* (x -axis) given by the direction of transverse pair momentum, and *sideward* perpendicular to the above two (in the direction of the y -axis).

$C(K, q)$ can be then parametrized in terms of the radius parameters R_o , R_s and R_l , also called HBT (Hanbury–Brown–Twiss) radii. They are related to the dimension of the fireball. Such a kind of measurements requires good statistics, thus pions and kaons are often used due to their abundance.

It is unclear how large the fireball, and thus the HBT radii, will be at the LHC. If the system volume at freeze-out is proportional to the particle multiplicity, then the product $R_o R_s R_l$ or $R_s^2 R_l$ should increase linearly with dN/dy . With the expected multiplicities at the LHC $(dN_{\text{ch}}/dy)_{\text{LHC}} \sim 1400\text{--}3000$ and with the measured value from RHIC $(dN_{\text{ch}}/dy)_{\text{RHIC}} \sim 650$, one would obtain an increase of the correlation radii by a factor $[(dN_{\text{ch}}/dy)_{\text{LHC}}/(dN_{\text{ch}}/dy)_{\text{RHIC}}]^{1/3} \approx 1.3\text{--}1.7$. This would result in radii of the order of 8 to 12 fm. However, larger radii (e.g. $R_l \simeq 15$ fm) cannot be firmly ruled out at present. RHIC data suggest an increase in phase-space density at freeze-out, meaning that correlation radii may increase by less than the factor derived above.

Measuring the HBT radii it is possible to access the total lifetime of the system: a large value of $R_o^2 - R_s^2$ was indeed proposed as a signal for QGP formation [31], but so far SPS and RHIC data do not show such a signal.

The current situation for HBT interferometry is that measurements are not yet well understood and theoretical expectations for the LHC are currently still open.

1.3.1.5 Fluctuations

Fluctuations characterize any physical quantity which can be measured in an experiment. In heavy-ion collisions fluctuations are usually studied on an event-by-event basis, meaning that a given observable is measured event-by-event and the fluctuations of this observable are then studied over a big ensemble of events. Fluctuations are supposed to reveal information about the system; as the system expands, fluctuations may be frozen early, providing understanding also on the stage of the collision evolution prior the thermal freeze-out.

Such a kind of analysis is largely employed in physics, for example fluctuations were observed in the cosmic micro-wave background radiation [32]. The traditional approach employed to look at fluctuations is based on measures of the

excess variance of some observable, which is normally zero with only statistical fluctuations.

So far fluctuation analyses have been focused on transverse momentum and charge fluctuations. The former should be sensitive to temperature-energy fluctuations [33] and are predicted to increase in the vicinity of the critical point. The latter are sensitive to the fractional charges carried by the quarks [34] and are expected to be smaller than in a hadronic scenario if a quark gluon plasma has been created in the collisions. The electric charge is of course a conserved quantity over all the phase space: this implies that the numbers of positive and negative charges produced in the full phase space are equal, $N_+ = N_-$, and that the net charge $Q = N_+ - N_-$ is identically zero so that there are no net-charge fluctuations and the variance $V(Q) = \langle Q^2 \rangle - \langle Q \rangle^2 = 0$. In a smaller region of phase space the variance is no longer identically zero and fluctuations of the net charge can be studied. This is an example to show that in order to perform fluctuation analyses, a detector must have large acceptance and complete event-by-event reconstruction capabilities: these requirements are very well satisfied in ALICE.

1.3.1.6 Jets

In hadronic collisions, hard scatterings with high momentum transfer occur between some partons involved in the collision; those which instead are not taking part in the hard scattering give origin to the so called ‘underlying event’. The energetic partons just created undergo a cascade of branching processes which degrade their energies and momenta. This stage lasts until the partons, together with the remnants of the incoming projectiles, fragment into colourless hadrons giving rise to the hadronization phase. This final state is characterized by the presence of clusters of hadrons close in the phase space with high transverse energy and generated by the hard processes at the parton level.

QCD calculations predict at the LHC energies for Pb-Pb collisions ~ 30 hard partons per event with transverse energy $E_T > 10$ GeV and still 3×10^{-3} hard partons per event with transverse energy $E_T > 100$ GeV. Besides, the production cross-section for minijets with $E_T > 5$ GeV is pretty high ($\sim 30\%$ of the total inelastic cross-section), thus hard processes will be more important at the LHC than at RHIC in understanding the dynamics of the evolution of the system. The estimated number of jets with $E_T > 100$ GeV produced in the ALICE central barrel in one month of data taking at average luminosity $\mathcal{L} = 5 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$ is $\sim 10^6$.

Jets are interesting not only because they are connected to hard scatterings occurring in the initial stage of a nucleus-nucleus collision, but also because the high E_T partons initially produced in such scatterings travel along the nuclear medium before fragmenting into ordinary hadrons. Thus, jets bring information

about the possible in-medium effects involving hard partons.

The main nuclear effect which produces the usually called ‘jet quenching’ effect is the energy loss of high p_T quarks and gluons. At first a collisional energy loss mechanism was conjectured [35]; more recent calculations suggest that the dominant energy-loss mechanism is radiative rather than collisional [36, 37]. According to these studies, partons radiate gluons and the parton energy loss grows quadratically with the in-medium path length.

Some of the expected consequences for the ‘jet quenching’ effect are the following:

- Reduction of the high- p_T particle yield.
- Reduction in the ratio $\bar{p}/p$ due to the different energy loss of quarks and gluons and to the different contributions of gluons in hadron species.
- Dependence on the impact parameter of the collision: jet quenching should be larger in central collisions.
- Two back-to-back jets with high momentum are not likely to be reconstructed because, due to parton energy loss, jets with a longer path in the nuclear medium become softer and are thus rejected from the jet algorithm.
- The p_T spectra of jets made of charm and beauty reveal possible medium-modifications of the heavy quark fragmentation functions.

1.3.1.7 Photons

Photons are produced at various stages of a heavy-ion collision:

1. In the first stage of the collisions ‘prompt’ photons mainly originate from parton-parton scatterings. This stage is common for both nucleon-nucleon and nucleus-nucleus collisions. The photon production decreases as an inverse power of p_T but increases with the center-of-mass energy. Photons with p_T up to several hundreds GeV/c are expected to be detected at the LHC.
2. During the quark gluon plasma phase (expected to be reached at a temperature of ~ 1 GeV at the LHC) photons are emitted from quarks which undergo collisions with other quarks and gluons of the medium. These photons have an exponentially suppressed spectrum extending up to several GeV.

3. The system then expands and cools. At the hadronization (reached at a temperature of $\sim 150 - 200$ MeV), photons are produced either in the scatterings of π 's, ρ 's, ω 's and so on, or in resonance and π^0 decays. This mechanism survives until the resonances cease to interact. The energy of these photons ranges from a few hundred MeV to several GeV.
4. Once the kinetic freeze-out is also reached, the photon production is mainly due to resonance decays and the spectrum extends up to few hundred MeV.

The main task of photon analyses is to distinguish thermal photons emitted during phases (2) and (3) from the background because one is interested in understanding the properties of the QGP phase and to see whether the system has thermalized or not.

One of the difficulties is to extract the background. Photons produced by π^0 decay can be subtracted from the data provided a dedicated detector is available (a good calorimetry is needed in order to reconstruct the $\pi^0 \rightarrow \gamma\gamma$ decay channel). On the other hand, photons emitted in phase (1) are not easily subtracted and a precise comparison with the proton-proton benchmark is needed.

Thermal effects can be studied at low energies where the photon production rate is expected to show an excess if the system is thermalized. Higher energy photons, above 20 GeV, are usually produced in association with a recoil jet: in this kinematic regime thermal effects can be studied analysing photon-hadron correlations and the shape of the correlation functions. Reliable tests of the thermal-photon production are obtained only comparing proton-proton collisions (no thermal effects), proton-nucleus collisions (nuclear effects but no thermal effects) and nucleus-nucleus collisions (both nuclear and thermal effects).

1.3.1.8 Dileptons

As well as photons, dileptons are an interesting tool to determine the properties of the matter produced in heavy-ion collisions because they do not have strong interactions with the medium. The production stages for dileptons are similar to those of photons, i.e. there are prompt dileptons coming from initial hard scatterings, then thermal dileptons are radiated from the QGP and in the final part of the collision evolution dileptons are produced in meson decays after the chemical freeze-out.

The study of dileptons can be divided in three kinematic domains:

- *Low mass region*: in the dilepton mass range below pair mass ~ 1.5 GeV, thermal dilepton spectra are dominated by decays of resonances like ρ , ω and ϕ . Medium effects are predicted to occur and to modify the shapes of these resonances. The ρ meson plays an active role in such analyses: with

its large width of ~ 150 MeV, its lifetime is comparable to the lifetime of the collision fireball. Several medium effects which are expected to affect the production of ρ mesons produced in initial hard scatterings, namely mass reduction [38] and shape broadening [39].

- *Intermediate mass region:* at masses $\sim 1.5 - 2$ GeV there is a prompt contribution to the continuum dominated by semileptonic decays of heavy-flavour mesons and by Drell-Yan processes ($q\bar{q} \rightarrow l^+l^-$). It is therefore possible to study heavy quark properties, such as their energy loss, through their semileptonic channel, as already done at RHIC. Thermal dileptons are expected to be in this region.
- *High mass region:* the high mass of the lepton pair spectrum is dominated by J/Ψ , Ψ' , Υ , Υ' and Z^0 decays. The capability to measure the Z^0 is useful in studies of jet quenching effect in Pb-Pb collisions where a jet is produced opposite to a Z^0 .

1.3.1.9 Heavy quarks and quarkonia

Heavy quarks are produced early after the collision in hard parton scatterings, typically in the following processes:

- $q\bar{q} \rightarrow Q\bar{Q}$, where $q(\bar{q})$ is a light (anti-)quark belonging to the incoming nucleus and $Q(\bar{Q})$ is the heavy (anti-)quark.
- $gg \rightarrow Q\bar{Q}$, which is a gluon-gluon fusion process and gluons are distributed in the incoming nuclei.

The momentum transfer for such processes has to be larger than $2m_Q$, thus heavy quarks are produced on short timescale of the order of $\sim 1/m_Q$; on the other hand, their relatively long lifetime allows them to survive during the QGP phase and to be affected by its presence.

In addition, the high temperature reached in the plasma phase may give rise to thermal production of heavy-quark pairs. Both open heavy-quark and quarkonia studies are then necessary in order to have an independent probe of the medium.

The inclusive cross section for heavy quark production is another quantity which ALICE is able to measure down to very low p_T .

So far, no data are available on a wide transverse momentum range for charm and beauty cross sections; trigger selections and detector configurations indeed prevent Tevatron to perform such measurement at low p_T .

ALICE is probably the only experiment at the LHC able to access the low p_T region.

The heavy quark production will be treated in a dedicated chapter on open charm physics (see Chapter 2).

As far as quarkonium production in heavy-ion collision is concerned, there are two basic approaches: the Colour Evaporation Model (CEM) [40] and the Non-Relativistic QCD (NRQCD) [41].

Once the quark gluon plasma is formed, the presence of free colour charge is expected to screen the binding colour potential, leading to the breakup of quarkonium states because the binding energies are of the order of few MeV and are comparable in size to the mean energies ($\sim 3T_c$) of the plasma.

The first states to be suppressed are the less bound, namely the ψ' and the χ_c followed by the J/ψ . Also the Υ family should follow a similar suppression pattern.

The quarkonium production rates at the LHC will be pretty high: $\simeq 10^8$ J/ψ and $\simeq 5 \times 10^5$ Υ resonances in a one-month run with the integrated Pb-Pb luminosity, $\mathcal{L}_{\text{int}}^{\text{PbPb}} = 10^3 \mu\text{b}^{-1}$. Therefore, both charmonium and bottomonium suppression should be measurable at the LHC with fairly high accuracy.

Other mechanisms which are supposed to occur in addition to colour screening are the nuclear absorption, which should be rather small if the J/ψ is formed away from the nucleons, and the regeneration of quarkonia, either in the plasma phase or in the hadron phase. At the LHC there will be room to study these different contributions, provided a solid reference given by proton-proton collisions will be available.

1.3.2 Proton-proton physics

With its excellent tracking and particle identification over a broad momentum range (100 MeV/c - 100 GeV/c), its good secondary vertex determination capability, its low magnetic field and low material budget, ALICE will be a competitive experiment also in proton-proton physics, especially in the low p_T domain.

The interest in pp physics is not only motivated by the requirement that a benchmark for heavy-ion collisions is mandatory, but also by the curiosity to explore pp collisions in a new energy domain.

1.3.2.1 Proton-proton collisions as baseline for heavy-ion collisions

There are several reasons why proton-proton measurements are needed as a reference for nucleus-nucleus collisions. The observables to be studied for such purposes are presented below in a non-exhaustive list:

- Particle multiplicities: differences in particle multiplicities in pp and A-A are related to different parton distributions in the nucleon with respect to the

nuclear case (shadowing effect) in part due to saturation of parton densities at small- x .

- Jets: models predict that the presence of in-medium parton energy loss affects jets produced in A-A with respect to those in pp.
- Slopes of transverse mass: transverse mass slopes in A-A and pp are expected to be different because in the nuclear case collective effects like transverse flow should take place.
- Particle yields and ratios: in A-A they give information on the chemical equilibrium and have to be compared to the same yields and ratios in pp. Different ratios of momentum spectra at high p_T in A-A and pp may indicate that in the nuclear case different contributions of quarks and gluons to the energy loss occur.
- Strangeness enhancement: this effect has been seen in heavy-ion collisions with respect to pp at energies between 2 GeV and 10 GeV. It was also observed that the ratio K^+/π^+ decreases towards RHIC energies. This ratio at the LHC energies will reveal new mechanisms governing strangeness production.
- Heavy quark and quarkonia production cross sections: in order to understand clearly the quarkonia suppression and heavy quark energy loss in A-A, their yields must be compared to the ones in pp collisions.
- Dileptons: nuclear effects occurring in A-A are expected to affect the dileptons coming from resonance decays; these effects can be revealed only comparing the same dilepton spectra in the pp case.
- Photons: photon energy spectra in pp are needed to estimate the background to thermal photons in A-A.

It must be said that pp and Pb-Pb data will be collected at different beam energies, therefore the extrapolation from pp to nucleus-nucleus collisions will not be a straightforward task.

1.3.2.2 ALICE contribution to proton-proton physics

With ALICE it will be possible to have a genuine pp program that is not only devoted to the comparison with A-A data. Different aspects will be addressed, like particle multiplicities, particle spectra, baryon production, strangeness production, jets, photon production and diffractive physics. Although all these topics are largely studied because pp will be the first data collected by ALICE, here we

focus only on the heavy-flavour production in pp collisions, which is more related to this thesis work. The heavy-quark production cross section in pp at the CERN SPS and Tevatron does not completely agree with theoretical pQCD calculations. Recent pp data from RHIC seem to be well above the FONLL (Fixed-Order-Next-To-Leading-Log) calculations, as discussed in Chapter 2. Thus, pp data from the LHC will be helpful to clarify this issue. Comparing to the other LHC experiments, ALICE can measure heavy-quark production down to $p_T \sim 1$ GeV/c, either by reconstructing exclusive charmed meson decays, or through the semileptonic decays of heavy flavoured mesons. The capability to go to low p_T will require a smaller extrapolation, resulting in an improved precision in the measurement of heavy-quark cross section.

1.3.3 Results from the SPS

The experimental program based on heavy-ion collisions started in 1986 at the CERN SPS. The experiments dedicated to Pb-Pb collisions were NA44, NA45/CERES, NA49, NA50, NA52/NEWMASS, WA97/NA57 and WA98. The experiments dedicated to the physics of S nuclei were NA34, NA35, NA80 and NA38. Finally, the most recent experiment, NA60, studied In-In collisions. NA60 is a second generation experiment designed to answer specific questions still open after the previous programs. The NA60 experimental apparatus consists of the muon spectrometer inherited from NA50 and a new tracker system in the target region.

This section is dedicated to reviewing the most relevant results obtained during the CERN SPS heavy-ion program.

1.3.3.1 J/ψ suppression

The suppression of the J/ψ yield in heavy-ion collisions, predicted by Matsui and Satz [45], is one of the most interesting signals of the formation of a deconfined state of quarks and gluons in relativistic heavy-ion collisions.

J/ψ and ψ' mesons are detected by NA50 and NA60 through the leptonic decays to a pair of muons: this technique has the advantage that leptons do not have strong interactions with particles produced at hadronization. In order to study quantitatively the suppression pattern of the J/ψ , the J/ψ production yield is usually measured with respect to the production of Drell-Yan muons ($B_{\mu\mu}\sigma(J/\psi)/\sigma(DY)$). This ratio is insensitive to experimental efficiencies and furthermore the Drell-Yan process scales linearly with the number of binary nucleon-nucleon collisions. The J/ψ suppression has been studied as a function of the centrality of the collision using three centrality estimators directly measurable, namely transverse energy, forward energy and particle multiplicity. The results were also expressed as a function of three calculated variables which better de-

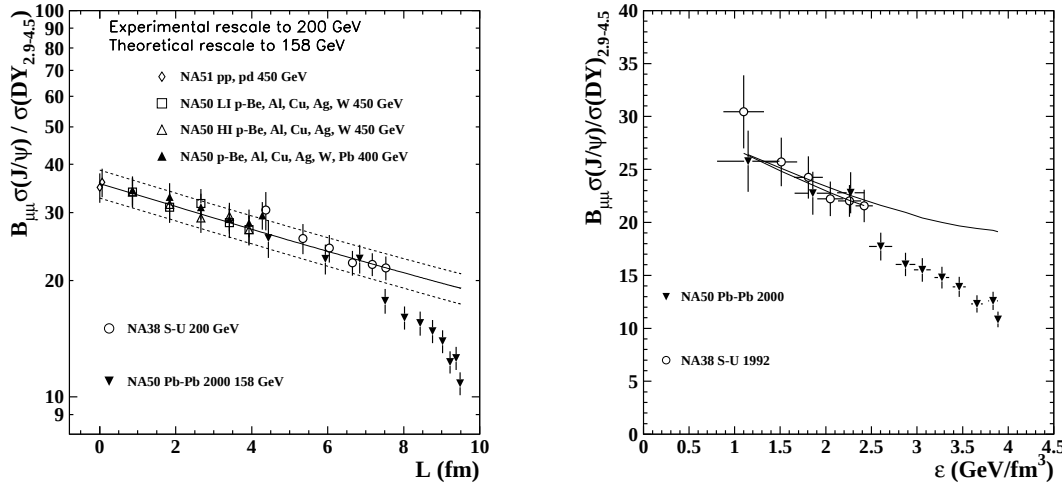


Figure 1.7: The J/ψ /Drell-Yan cross-sections ratio vs L (left panel) and vs ϵ (right panel), for several collision systems, compared to the normal nuclear absorption pattern. Taken from [42].

scribe the system created in the collision: the average length L of nuclear matter traversed by the $c\bar{c}$ state, the energy density ϵ averaged over the whole transverse area of the collision and the number of participants N_{part} . They are calculated starting from measured centrality estimators using the Glauber model [46].

Fig. 1.7 (left panel) shows the J/ψ production yield over Drell-Yan as a function of L for different collision systems. The same J/ψ yield is plotted in the right panel of Fig. 1.7 as a function of the energy density ϵ for S-U and Pb-Pb.

These plots clearly show that Pb-Pb peripheral collisions with $L < 7$ fm and $\epsilon < 2.3$ GeV/fm³ exhibit a J/ψ production yield in agreement with the behaviour observed in p-A reactions and presently understood as due to J/ψ absorption in ordinary nuclear matter. For more central collisions, a departure from the normal nuclear absorption curve was observed (“anomalous suppression”) without saturation even in the most central Pb-Pb collisions. S-U data and other lighter systems closely match the absorption curve determined by p-A points.

A second analysis technique introduced by NA60 overcomes the problem of the low Drell-Yan statistics by studying the measured J/ψ without any normalization to the production of Drell-Yan muons. In this approach, the observed J/ψ centrality distribution is directly compared to the theoretical distribution expected in case normal nuclear absorption is the only suppression mechanism. This analysis is feasible in NA60 thanks to the vertex detector which allows the selection of the J/ψ coming from the primary interaction; the achieved invariant mass resolution on the J/ψ is ~ 70 MeV/c², smaller than the one achieved by NA50 without

vertex detector, $\sim 100 \text{ MeV}/c^2$. NA50 was based on multiplicity measurements and did not allow the detection of direct J/ψ , especially for peripheral events. Hence, the normalization to Drell-Yan processes was needed.

The result is shown in Fig. 1.8, where the ratio between the measured and the expected J/ψ yield is plotted as a function of the number of participants. The observed pattern indicates that an anomalous suppression is already present in In-In collisions, setting in at $N_{part} \sim 80$ with a saturation for more central events.

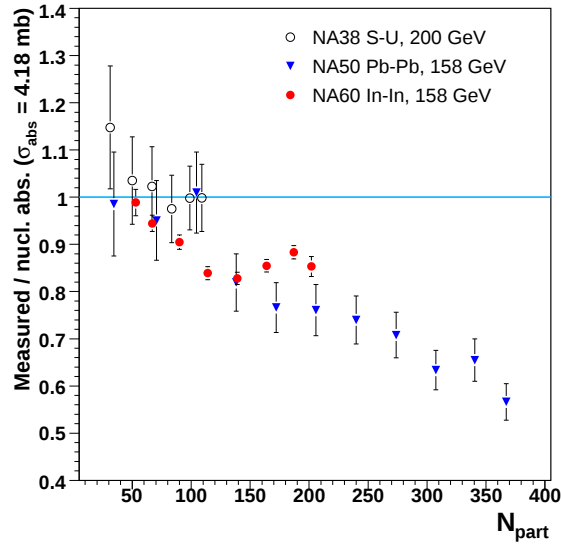


Figure 1.8: Ratio between measured J/ψ yield and the absorption curve as a function of N_{part} for S-U, Pb-Pb and In-In collisions. Taken from [43].

The data from the previous experiments NA38 and NA50 also reported in Fig. 1.8 are obtained with the standard analysis based on the normalization to Drell-Yan production, differently from NA60 which measures direct J/ψ .

1.3.3.2 Intermediate dimuon masses

The intermediate-mass spectra were studied in p-A collisions at the SPS and well explained with contributions of both dileptons from both Drell-Yan processes and charmed meson decays. The NA50 experiment studied this mass region in Pb-Pb collisions and observed an excess of dimuons with respect to the binary scaling from p-A collisions. This excess was compatible with both a thermal production and an origin from open charm decays.

NA60 performed more precise measurements in In-In collisions, thanks to its tracker detector which allows the reconstruction of dimuons from displaced secondary vertices of semi-leptonic decays of charmed mesons. The present results are compatible with an excess due a thermal origin of dimuons. As shown in Fig. 1.9, the offset distributions⁴ can be reasonably well fitted assuming a fixed open charm yield and using the prompt muon yield as a free parameter of the fit. On the contrary, an enhancement of open charm seems not to agree with the data. Therefore, the open charm cross section preserves its scaling with hard processes, i.e. with the number of binary collisions.

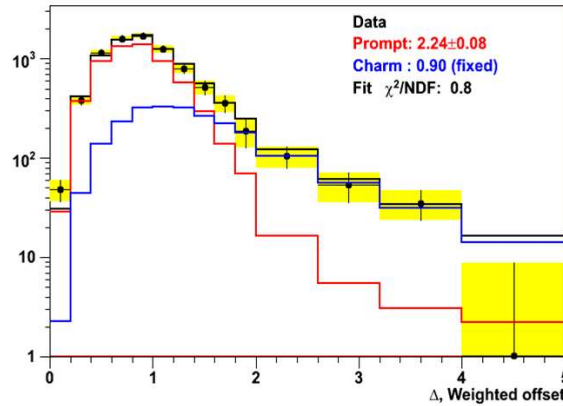


Figure 1.9: Offset muon distributions. The parameters of the fit function are the charm yield (fixed) and the prompt muons (variable).

1.3.3.3 The ρ spectral function

In the low mass sector ($m < m_\phi$) the CERES experiment has studied the production of dielectron pairs in nucleus-nucleus collisions [47]. An excess has been observed and well established in the dielectron mass distribution in the low mass region but the lack of statistics and a poor mass resolution did not allow a clear discrimination between the various theoretical explanations. The left part of Fig. 1.10 shows the opposite-sign, background and signal dimuon mass spectra as measured by NA60, integrated over all collision centralities. The excess is isolated using a novel procedure [48] and the result is plotted in Fig. 1.10 (right) for semi-central In-In collisions. The comparison with theoretical models indicates that the excess shape is consistent with a broadening of the ρ meson [49] rather than a mass shift of the ρ [38, 50].

⁴The offset is the distance of closest approach of the track from the primary vertex.

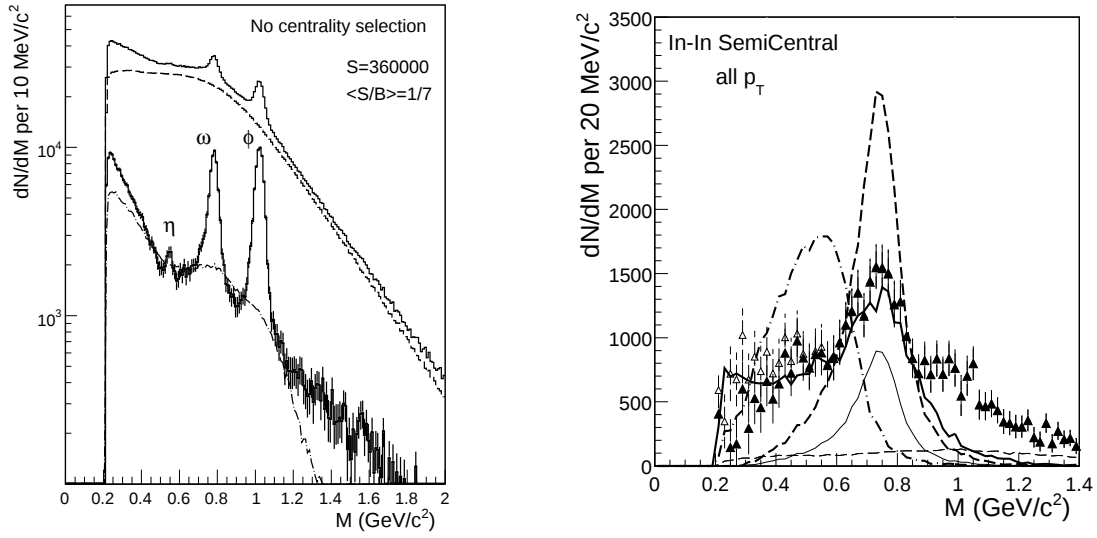


Figure 1.10: Left: mass distribution of opposite-sign dimuons (upper histogram), combinatorial background (dashed), signal fake matches (dashed-dotted) and resulting signal (lower histogram with error bars). Right: comparison of the excess mass spectrum for the semi-central bin to model predictions, such unmodified ρ (dashed), in-medium broadening ρ (thick solid), in-medium moving ρ (dashed-dotted). Taken from [44, 48].

1.3.3.4 Particle spectra

As already mentioned in Section 1.3.1.2, the particle yields as a function of the transverse momentum reveal the dynamics of the collision, characterized by the temperature and the transverse flow velocity of the system at the kinetic freeze-out.

Fig. 1.11 shows the transverse mass distributions for positively and negatively charged hadrons produced in central Pb-Pb collisions at 40, 80 and 160 GeV per nucleon, measured by the NA49 Collaboration [51]; the lines are a fit based on the hydrodynamically inspired model introduced in Section 1.3.1.2.

The m_T -spectra are compatible with radial flow, with similar temperature $T \approx 130$ MeV and transverse flow velocity $v_\perp \approx 0.45$ at the different energies. The spectra for Ξ and Ω , which are measured only at 158 GeV, do not show indications of early freeze-out.

1.3.4 Recent results and open issues from RHIC

All the four experiments at RHIC have been successful in providing information on the dynamics of heavy-ion collisions in a new regime of very high energy den-

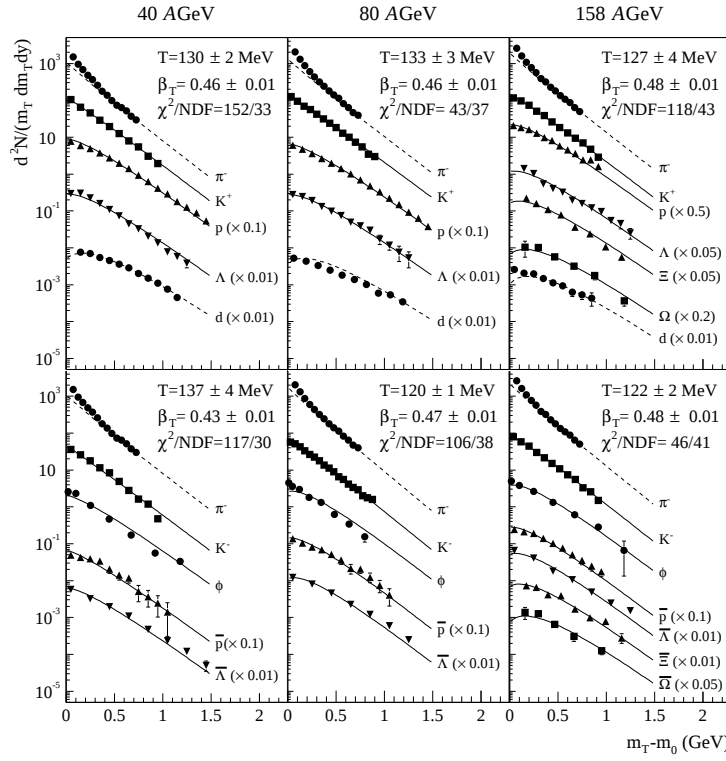


Figure 1.11: Positively and negatively charged hadron spectra from central Pb-Pb collisions at 40, 80 and 160 GeV per nucleon (left to right), measured by the NA49 Collaboration. The results of the fits based on the hydrodynamic model [17], [18] are reported in the figure.

sities. The theory-experiment comparison indicates that central Au-Au collisions at RHIC produce a unique form of strongly interacting matter.

In order not to go too far from the main subject of this thesis, only the main results obtained by the PHENIX, STAR, PHOBOS and BRAHMS experiments at RHIC will be presented in this section.

1.3.4.1 Energy density and multiplicity measurements

The energy density achieved at RHIC is $\sim 15 \text{ GeV/fm}^3$ and is most likely an underestimate (see detailed discussion in [52]). This is well in excess with respect to the $\sim 1 \text{ GeV/fm}^3$ required, according to lattice QCD predictions, for the transition to QGP.

Most of bulk properties measured appear to show only very modest increases

with centrality and beam energies: these experimental results contrast with theoretical predictions made before RHIC start-up, which often suggested a big contribution of factorized perturbative QCD processes and thus a strong energy dependence accompanying the hadron-to-QGP transition. This is shown for example in Fig. 1.12, where it is clear that the measured multiplicities per participant as a function of the center-of-mass-energy are not reproduced by the sharp curve predicted by factorized pQCD: hence, some mechanisms must be present at RHIC energy to reduce the particle production. One possible explanation is given by the Color Glass Condensate (CGC) picture [53], which describes the initial state at small- x of hadrons as well as heavy nuclei. In this model the small- x gluon density begins to saturate because of the competition of gluon fusion ($g + g \rightarrow g$) and gluon splitting ($g \rightarrow g + g$) processes. There is a critical momentum scale Q_s ($\gg \Lambda_{QCD}$ and also called CGC saturation scale), depending on both the longitudinal parton momentum fraction x and the atomic number A , which controls the occupation number of gluons inside a nucleon. For transverse momenta $p_T < Q_s$ the transverse gluon phase space density is saturated. It has been conjectured that saturation in nuclei occurs at higher Q_s , or equivalently at higher x (at fixed Q^2) compared to single protons, and that the Color Glass Condensate may explain the so called nuclear shadowing effect. Fig. 1.13 confirms that the CGC reasonably reproduces the experimental data and could be considered as the initial state of a nucleus-nucleus system, from which the subsequent QGP evolves.

1.3.4.2 Thermalization

The measured yields and spectra of different hadron species are consistent with thermal emission from a strongly expanding source.

The transverse momentum spectra for identified particles from the STAR experiment are reported in Fig. 1.14; a fit to the spectra shows that the system seems to freeze-out with a temperature and expansion velocity similar to that observed at the SPS energies.

The obtained fit parameters for the 0-5% Au-Au events are $T = 89 \pm 10$ MeV and $\beta_s = 0.84 \pm 0.07$.

The strangeness production is consistent with predictions based on a complete chemical equilibrium reached at a chemical freezeout temperature of 163 ± 5 MeV and a baryo-chemical potential ~ 25 MeV [58]. This result is compatible with the QGP transition temperature predicted by lattice QCD calculations.

The scaling of the elliptic flow v_2 with eccentricity (see Fig. 1.15) for low p_T ($p_T < 1$ GeV/c) shows that v_2 is strongly connected with the spatial asymmetry of non-central collisions and therefore indicates that a high degree of collectivity is built up at a very early stage of the collision. Hydrodynamic models, based on an ideal fluid, on a early thermalization ($\tau_{Therm} \leq 1$ fm/c) and on a high initial

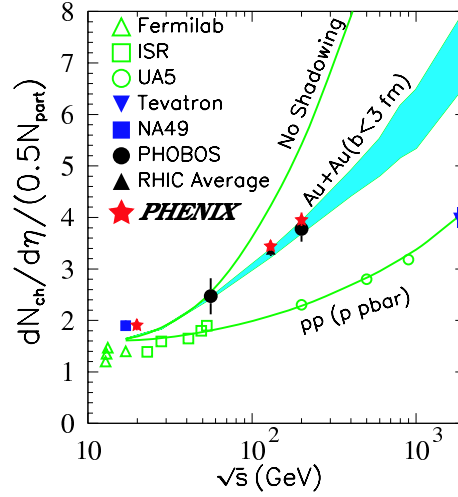


Figure 1.12: Measured mid-rapidity charged particle densities, scaled by the calculated number of participant nucleons, for central collisions at SPS and RHIC, plotted as a function of the center of mass energy. Results from $p(\bar{p}) + p$ collisions are shown for comparison. Taken from [52]. The curves are a theoretical model [54] which reproduces well the multiplicity from elementary collisions at RHIC energies. The same model extended to nucleus-nucleus collisions overpredicts the multiplicities in central RHIC collisions. The data can be matched if nuclear shadowing is included in the model.

energy density ($\epsilon \geq 10 \text{ GeV/fm}^3$), reproduce reasonably well the measured $v_2(p_T)$ of pions, kaons and protons. This is an evidence for the formation of a strongly interacting matter that thermalizes very rapidly. Nevertheless, the hydrodynamic calculations have not succeeded yet in explaining the emitting hadron source from measured HBT correlations. Hence, currently there is not a consistent picture of the space-time dynamics of reactions at RHIC.

1.3.4.3 Binary scaling and high p_T suppression

One of the tasks of RHIC experiments is to understand if the particle yield in d-Au and Au-Au can be considered as the result of independent collisions between the point-like constituents of the nucleons. If this happens, the production should scale with pp yield with a coefficient, N_{coll} , which is the average number of binary nucleon-nucleon inelastic collisions. This is the reason why the scaling law for point-like processes is also called binary-collision (or N_{coll}) scaling.

In order to establish whether the binary scaling has occurred or not, d-Au data must be used at first, since they do not have final state effects due to the

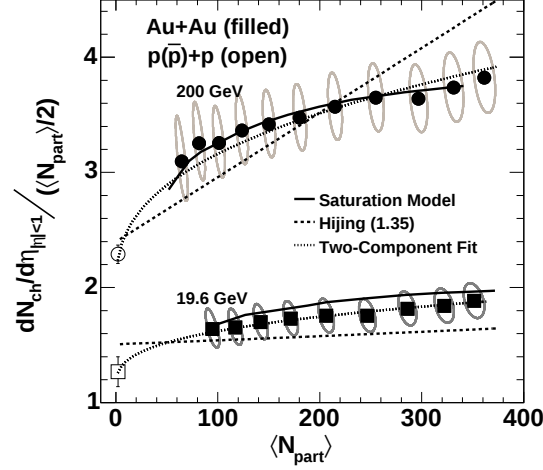


Figure 1.13: Pseudorapidity density of charged particles at midrapidity divided by the number of participant pairs as a function of the number of participants. Data are shown for Au-Au at 19.6 GeV and 200 GeV center of mass energies. $p(\bar{p}) + p$ data measured at 200 GeV and interpolated to 19.6 GeV are also shown. The ellipses represent the 90% C.L. systematic errors. Taken from [55].

medium.

Nuclear medium effects, either in the initial or final state scaling, can modify the expected scaling: these modifications can be quantitatively estimated by measuring the *nuclear modification factor*, R_{AA} , defined as follows:

$$R_{AA} = \frac{dN_{AA}^P}{\langle N_{coll} \rangle \times dN_{NN}^P}$$

where dN_{AA}^P is the yield of a point-like process P in a nucleus-nucleus collision and dN_{NN}^P is the same yield in nucleon-nucleon collision.

Alternatively, the central to peripheral ratio R_{CP} is used:

$$R_{CP} = \frac{dN^{centr} / \langle N_{coll}^{centr} \rangle}{dN^{per} / \langle N_{coll}^{per} \rangle}$$

where dN^{centr} and dN^{per} are the differential yields of the studied process for central and peripheral collisions respectively. The two quantities R_{AA} and R_{CP} can be measured also in d-Au collisions.

If the yield of the process scales with the number of collisions ($N_{coll} \sim A^{4/3}$), we expect $R_{AA} = 1$ and $R_{CP} = 1$.

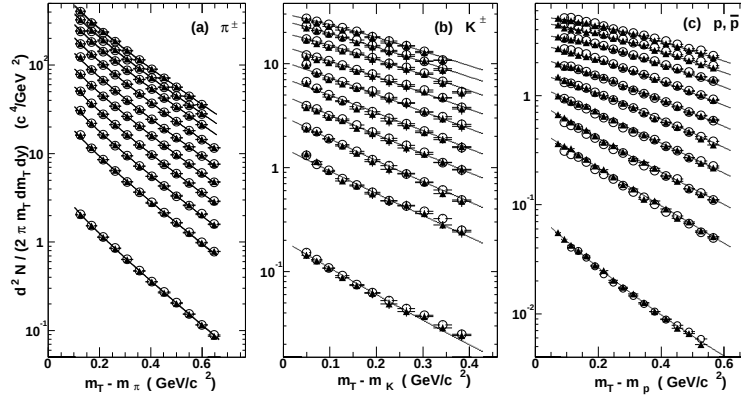


Figure 1.14: Invariant yield as function of transverse mass for $\pi^\pm$, $K^\pm$, and inclusive p and $\bar{p}$ at mid-rapidity ($|y| < 0.1$) for pp (bottom) and Au-Au events at $\sqrt{s_{NN}} = 200$ GeV from 70-80% (second bottom) to the 0-5% centrality bin (top). The curves shown are Bose-Einstein fits for π^- and hydrodynamic-based (blast-wave) model [18] fits for K^- and $\bar{p}$. Taken from [56].

The above definitions are valid only for hard point-like scatterings, which guarantee the validity of the factorization theorem in the calculation of the cross section. Therefore, the cross sections in pp , pA or AA collisions are proportional to the number of possible point-like encounters and the cross sections in pA or AA , compared to pp , scale with the number of binary nucleon-nucleon collisions. On the other hand, the soft regime is characterized by a scaling of the cross sections in pA or AA , compared to pp , with the number of participants ($N_{part} \sim (2)A$ in case of (AA) pA collisions). In this case, we expect for Au-Au collisions:

$$R_{AA} = \frac{\langle N_{part} \rangle \times dN_{NN}^P}{\langle N_{coll} \rangle \times dN_{NN}^P} \sim \frac{2 \times 197}{1600} \sim 0.25 \quad (1.13)$$

which is compatible with the plots on R_{AA} measured at RHIC reported in the following (Fig 1.18).

Hard scattering is considered the dominant process for particle production with $p_T \geq 2$ GeV/c at mid-rapidity in pp collisions at RHIC. Indeed, as can be observed in Fig. 1.16, the spectra for pp collisions exhibit an asymptotic power law, due to hard scattering processes, with increasing x_T ($x_T = 2p_T/\sqrt{s}$). The transition region from hard to soft physics at RHIC lies in the p_T region of about 2 GeV/c.

The binary scaling does not hold in the soft physics regime, due to additional scattering processes, and $R_{AA} < 1$. Therefore, in order to look for a possible breaking of the binary scaling, only the hard momentum region has to be consid-

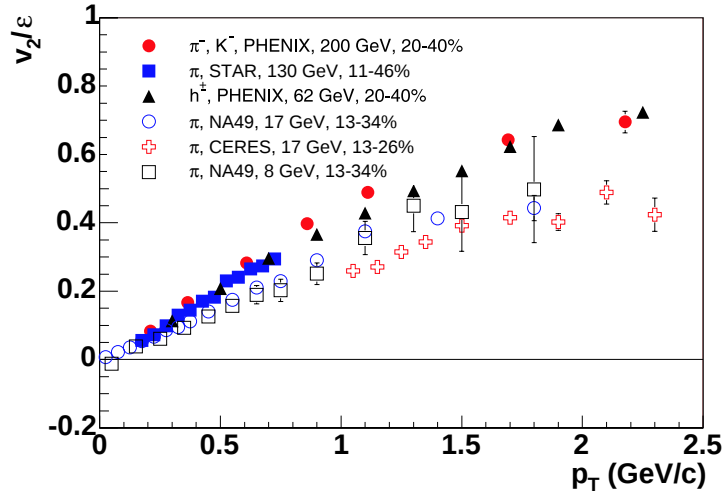


Figure 1.15: $v_2(p_T)$ normalized by the eccentricity ϵ as a function of p_T , for mid-central collisions at RHIC (filled symbols) and SPS (open symbols). Dividing by ϵ makes a uniform comparison between different nuclei and different centrality selections. Taken from [52].

ered, as shown in Fig 1.17.

Fig 1.18 shows the R_{dA} of particles produced at mid-rapidity in d-Au collisions as a function of the transverse momentum p_T (left panel for STAR and right panel for PHENIX): it is clear that the binary scaling is not respected in d-Au collisions, indeed an enhancement is observed at intermediate p_T . This behaviour, known as Cronin effect [57], is generally attributed to the influence of multiple scattering before the hard collisions.

At large rapidities in the deuteron direction, a suppression of high- p_T hadrons has been observed by the BRAHMS collaboration [59]: this pattern suggests a depletion of small- x gluons in the colliding Au nucleus and is in qualitative agreement with the predictions of gluon saturation models.

The R_{AA} of π^0 (Fig. 1.18, right panel) for central Au-Au collisions at RHIC is well below 1 over the entire measured p_T range, revealing that the π^0 yields are strongly suppressed relative to the expected yields given by the binary scaling. In contrast, the peripheral yields show little or no suppression. The observed suppression of hadron yields in central collisions can be efficiently described by perturbative QCD calculations incorporating parton energy loss in a thin and dense medium. The magnitude of such suppression needs to assume that the initial gluon density when the collective expansion begins is more than a order of magnitude greater than that in the ordinary nuclear matter [60] ($dn_g/dy \sim$

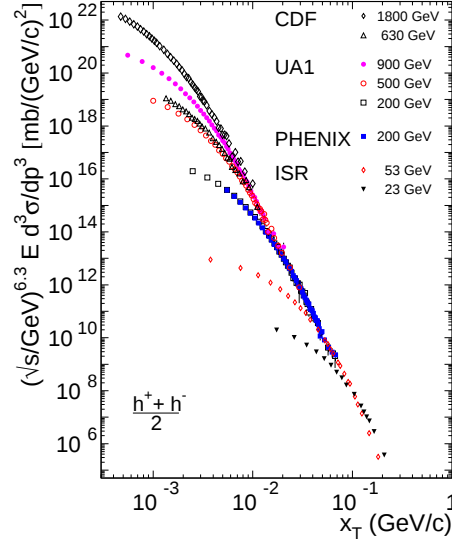


Figure 1.16: $\sqrt{s}(\text{GeV})^{6.3} \times E d^3\sigma/d^3p$ vs. $x_T = 2p_T/\sqrt{s}$ at mid-rapidity in pp collisions for different center-of-mass energies.

1000). Also the initial energy density is required to be above the one present in nuclear matter ($\epsilon_0 \sim 15 \text{ GeV/fm}^3$ compared to $\epsilon_{nucl} \sim 0.17 \text{ GeV/fm}^3$). These values are consistent with those obtained with $dE_T/d\eta$ measurements and with the predictions from hydro models. The magnitude of the suppression at high p_T reported for Au-Au collisions in Fig. 1.18 ($R_{AA} \sim 0.25$) is in qualitative agreement with a simple argument based on the assumption that only the jets emitted on the surface of the fireball and directed outward can be triggered, while those emitted inside the fireball and directed inward are lost due to medium effects. Therefore, the number of triggered jets should be proportional to the surface of the medium rather than to its volume. We should then expect for Au-Au collisions:

$$R_{AA} \sim \frac{R^2}{R^3} \sim \frac{A^{2/3}}{A} \sim 0.2 \quad (1.14)$$

where $R \propto A^{1/3}$ is the nucleus radius.

Another important result is the confirmation that high- p_T hadrons result from hard scatterings followed by jet fragmentation. Since a hard-scattered parton fragments into multiple particles within a restricted angular region (jet), one would expect to observe angular correlations between hadrons in the jets: this is visible in Fig. 1.19 (left panel), where the peak at $\Delta\Phi = 0$ (near side) represents the correlation between hadrons in the same jet, while the broader peak at $\Delta\Phi = \pi$ (away side) reflects the correlation between hadrons in one jet and hadrons produced in

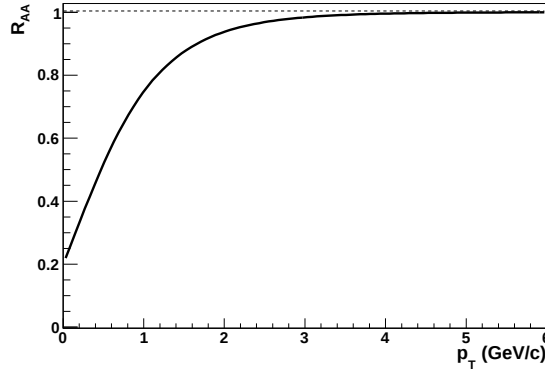


Figure 1.17: Schematic representation of the R_{AA} as a function of the transverse momentum in case of no medium effects occur. For $p_T \geq 2$ GeV/c the binary scaling holds.

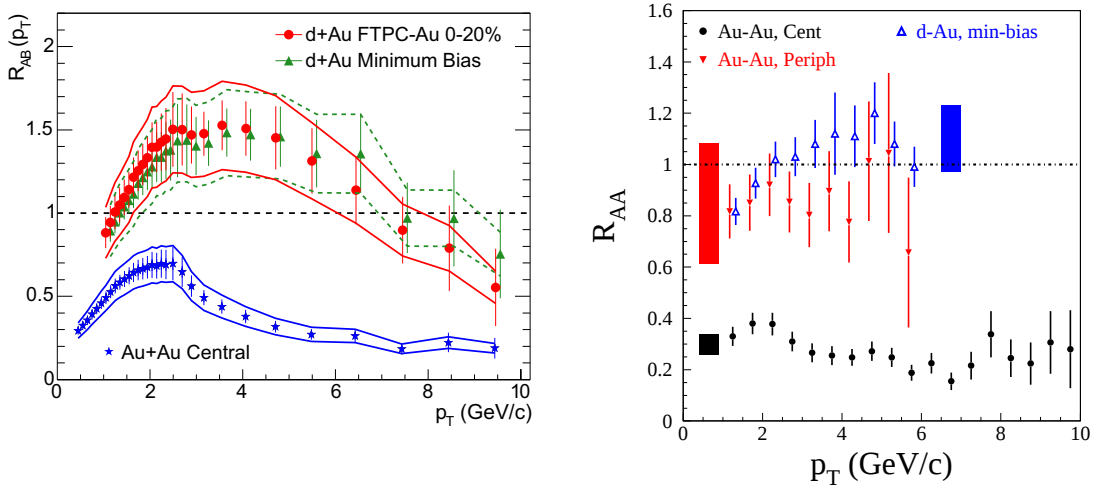


Figure 1.18: Left: binary-scaled ratio $R_{AB}(p_T)$ of charged hadron yields from 200 GeV Au-Au and d +Au relative to pp collisions from STAR. Taken from [58]. Right: the same ratio for π^0 for central (0-10%) and peripheral (80-92%) Au-Au and d -Au minimum bias collisions from PHENIX. Taken from [52].

the opposite jet. The away side correlation peak is absent in case of central Au-Au collisions; on the contrary, peripheral Au-Au, d -Au and pp collisions exhibit the same shape of the back-to-back peak. This leads to the suggestion that, if the correlation is the result of jet fragmentation, the suppression in Au-Au collisions is due to final state interactions of hard-scattered partons or of their fragmenta-

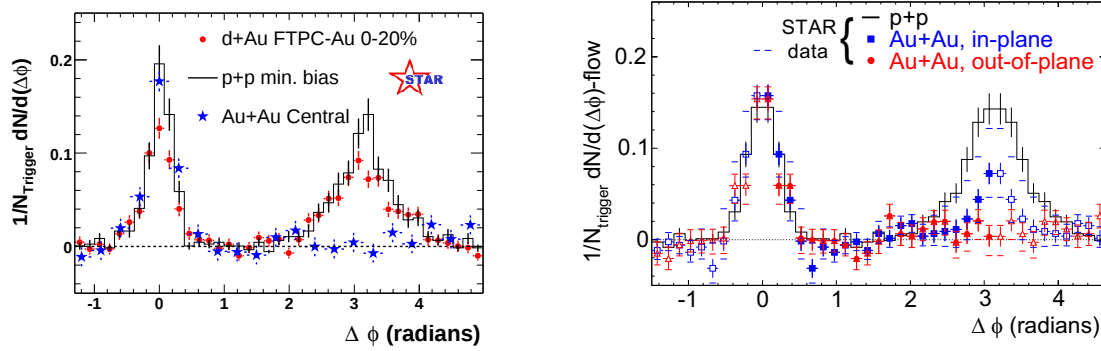


Figure 1.19: Dihadron azimuthal correlations at high p_T . Left panel shows correlations for pp, central d-Au and central Au-Au collisions (background subtracted) from STAR. Right panel shows the background-subtracted high p_T dihadron correlation for different orientations of the trigger hadron relative to the Au-Au reaction plane. Taken from [58].

tion products in the dense medium. In this scenario, the hard hadrons (and thus the near-side peak) are the ones produced in hard parton scatterings occurring on the surface of the collision region and outward. On the contrary, partons exiting inward lose part of their energy crossing the dense matter and do not form the away-side peak. Another confirmation of the parton energy loss mechanism is the plot in the right panel of Fig. 1.19, where the dihadron correlation is shown with two different orientations of the trigger hadron with respect to the reaction plane (direction of the impact parameter of the collision): parallel to it (in-plane) or orthogonal to it (out-of-plane). The suppression of the away-side peak depends strongly on the relative angle between the trigger hadron and the reaction plane: for an out-of-plane trigger hadron, the correlated opposite jet must cross a longer path than in the reaction plane, leading to correspondingly larger energy loss.

1.3.4.4 Hadron production

The process of hadronization, to date not well understood, includes the dressing of the quarks from their bare masses and the confinement of the quarks into colorless hadrons.

The hadron production in the soft region ($p_T \lesssim 2$ GeV/c) is reasonably described by hydrodynamics, while in the hard region ($p_T \gtrsim 5$ GeV/c) hydrodynamics should fail and fragmentation should dominate. The intermediate- p_T regime ($p_T \sim 2 - 5$ GeV/c) is particularly interesting since it represents the transition between soft and hard production mechanisms. The jet fragmentation dominates in the high- p_T range, but it is still not clear the intermediate- p_T region, where also the coalescence mechanism is supposed to occur. The quark recombination or co-

alescence models assume that quarks in a densely populated phase space combine together to form the final-state hadrons (see Chapter 2 for more details).

It is indeed in the intermediate- p_T regime that it was observed at RHIC a large enhancement of baryons and antibaryons relative to pions. Although there are several models based on the quark recombination or coalescence [61] which try to describe the ratio $p(\bar{p})/\pi$, the anomalous enhancement remains a puzzle. According to such models, baryons at moderate p_T would be enhanced relative to mesons because their transverse momentum is the sum of 3 quarks rather than 2.

Furthermore, recombination predicts that the collective flow of final-state hadrons should follow the collective flow of their constituent quarks, which is somewhat observed in RHIC data at intermediate p_T , as discussed in the following.

At present, no theoretical framework provides a complete understanding of hadron formation in the intermediate- p_T regime: on one side, baryons have a large v_2 (typically 20%) indicative of strong collective motion, on the other side the near-angle correlation between particles is characteristic of jet fragmentation.

One possible measurement which could set light on this unclear situation is v_2/n_q as a function of p_T/n_q , where n_q is the number of valence quarks in a hadron. Fig. 1.20 shows that for $p_T/n_q > 1$ GeV/c, v_2 seems to be related to the constituent quarks rather than to the hadrons⁵. If this scaling will be confirmed by improved statistics, it will provide more information on the hadronization at intermediate p_T , where two processes may be competing: the coalescence of n_q quarks (which would explain the v_2 at the level of quarks and the baryon excess) plus fragmentation of hard-scattered partons (which would account for the hadron near-side jet shape). Several models based on both these two mechanisms are currently trying to reproduce the experimental data with quite good results (Oregon [62], TAMU [63]). An experimental measurement supporting the recombination models is also the R_{CP} of ϕ meson [64]: present data show that ϕ follows the suppression pattern of K_s^0 as well as pions, although its mass is more similar to that of proton or Λ . Also the first measurement of ϕ elliptic flow v_2 from STAR shows that at intermediate p_T v_2 favours the number of constituent quark scaling.

1.3.4.5 Open issues and needs from future experiments

The interesting results obtained so far by RHIC still reveal that a complete theoretical framework able to describe the fundamental properties of the matter produced is not achieved. In order to reach such a goal, also on the experimental side

⁵Recent results reported at the Quark Matter 2006 conference show that the curve of v_2/n_q is universal for different particle species as a function of the kinetic energy. Thus, a more promising scaling variable is the kinetic energy instead of the transverse momentum.

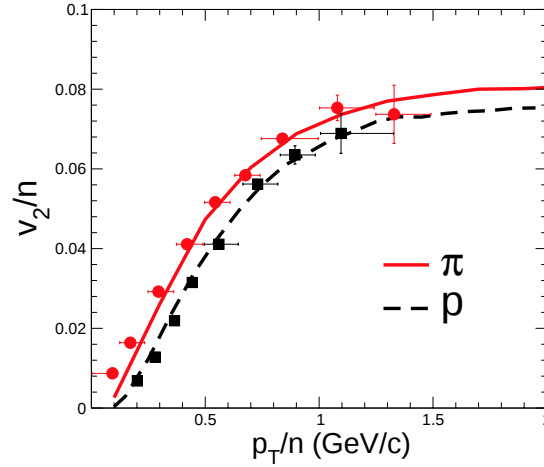


Figure 1.20: v_2/n as a function of p_T/n , where n is the number of constituent quarks, for pions and protons measured by PHENIX in minimum bias Au-Au reactions at $\sqrt{s_{NN}} = 200$ GeV. Results from the TAMU model are also shown (dashed line for pions and dotted line for protons).

several measurements which can quantitatively test the theoretical predictions are needed.

The main prospects for the short term RHIC measurements and for a longer time scale (LHC, RHIC upgrade) are briefly summarized in the following:

- Establish whether or not the v_2 scaling is really existing.
- Measure open charm yields and flow to understand the collective properties of the matter including heavier quarks and to study the relative contributions of coalescence and fragmentation in the charmed hadron production.
- Find probes which can be used as thermometers for the early stages of the collisions, well before the chemical freezeout.
- Measure yields and spectra of various heavy quarkonium species, including the Υ states.
- Test the fundamental QCD symmetries (chiral, CP, ...) in the strongly interacting matter.
- Extend at the LHC and GSI the models which work at RHIC and quantitatively compare the predictions with the experimental measurements.

Chapter 2

Open charm physics

Heavy quarks, like charm and bottom, are produced in the early stages of high energy nucleus-nucleus collisions and their lifetime is longer than the expected lifetime of the Quark Gluon Plasma. This makes open charmed mesons a powerful tool to investigate nuclear effects on charm production, propagation and hadronization in the medium produced in heavy-ion collisions at high energy. In addition, measurements of mesons with open charm and beauty provide a natural normalization for charmonia and bottomonia production at the LHC. The reference signal used for charmonia normalization at the SPS was the Drell-Yan process ($q\bar{q} \rightarrow \mu^+\mu^-$) because it scales with the number of binary collisions and it is independent on nuclear effects. In addition, the high mass dilepton spectrum ($4 \leq m \leq 7 \text{ GeV}/c^2$) at the SPS in Pb-Pb collisions originates exclusively from the Drell-Yan process. Such a normalization is not adequate at the LHC energies, because the Drell-Yan signal is expected to be completely drowned into dileptons from semi-leptonic decays of open charm and open beauty, even when the energy loss of heavy quarks is assumed. At RHIC, the leptons coming from decays of mesons with charm and beauty dominate over the Drell-Yan up to $\sim 20 \text{ GeV}/c$ [65]. The Drell-Yan process might anyway be not well adapted for charmonia normalization at the LHC, where heavy quarks are mostly produced in the initial fusion of gluons ($gg \rightarrow Q\bar{Q}$) rather than in interactions like $q\bar{q} \rightarrow Q\bar{Q}$ and different shadowing effects may intervene [66]. The measurement of charm and beauty production in proton-proton and proton-nucleus collisions is also of great interest, not only because it provides a baseline to compare the results obtained with nucleus-nucleus collisions, but also because it provides important tests for QCD in a new energy domain.

2.1 Heavy-quark production in pp collisions

The main contribution to heavy-quark production in pp collisions is thought to come from partonic hard scatterings. Since the heavy-quarks have a large mass ($m_Q > \Lambda_{QCD}$), their production can be described by perturbative QCD (pQCD).

The single-inclusive differential cross section for the production of a heavy-flavoured hadron H_Q can be expressed as follows [67], using the factorization theorem:

$$\frac{d\sigma}{dp_T}^{NN \rightarrow H_Q X}(\sqrt{s_{NN}}, m_Q, \mu_F^2, \mu_R^2) = \sum_{i,j=q,\bar{q},g} f_i(x_1, \mu_F^2) \otimes f_j(x_2, \mu_F^2) \otimes \quad (2.1)$$

$$\frac{d\hat{\sigma}}{d\hat{p}_T}^{ij \rightarrow Q(\bar{Q})\{k\}}(\alpha_s(\mu_R^2), \mu_R^2, \mu_F^2, m_Q, x_1 x_2 s_{NN}, \hat{p}_T) \otimes D_Q^{H_Q}(z, \mu_F^2),$$

In the above formula, Q refers to heavy quarks, charm and bottom, m_Q is the quark mass, $\hat{p}_T$ is transverse momentum of the heavy quark and the hadrons with heavy quarks, like D or B mesons, are called H_Q . Corrections to the formula 2.1 which would break the factorization, are of the order of $O\left(\frac{\Lambda_{QCD}}{Max(m_Q, p_T)}\right)$, where p_T is the transverse momentum of the heavy hadron. Such corrections are suppressed for large quark masses, i.e. for heavy quarks, and/or for large p_T .

The sum in Eq. 2.1 runs over all subprocesses leading to the production of a heavy-flavoured hadron.

The different ingredients taking part in Eq. 2.1 are the following:

- $f_i(x_i, \mu_F^2)$ is the parton distribution function (PDF): it gives the probability of finding a quark or a gluon of type i carrying a momentum fraction x_i of the nucleon. μ_F is the factorization scale. The parton distribution functions are evolved with the virtuality $(Q^2)^1$ up to the factorization scale μ_F through the DGLAP equations [68–70]. At high factorization scale μ_F there is an increase of quarks at lower values of x and a disappearance of these quarks at higher x because they lose momentum by radiating gluons. The evolution of parton distributions in QCD is governed by the parameter α_s/π . Once the initial conditions of the nucleon structure are experimentally determined through the measurement of deep inelastic cross-section at a given Q^2 , the PDFs can be predicted by perturbative QCD at higher Q^2 .

The PDFs are well measured and represent a precision test of QCD because the experimental data can be reasonably well reproduced by DGLAP equations. For more details refer to [71].

¹The PDFs are measured in deep inelastic scatterings like $ep \rightarrow eX$, where the quarks in the hadron are struck by the virtual photon with four-momentum squared Q^2 which has been exchanged in the scattering process.

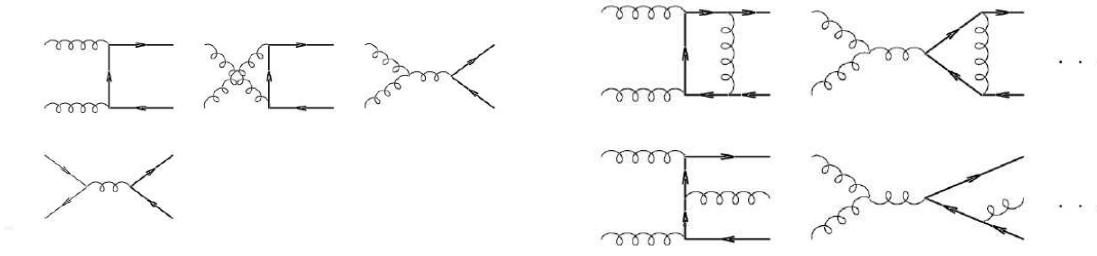


Figure 2.1: Left panel: Leading Order (LO) Feynman diagrams for heavy-quark production. Right panel: some of the Next-To-Leading (NLO) Feynman diagrams for heavy-quark production.

Present event generators, like PYTHIA [72], make use of the parametrizations of the PDFs obtained by different collaborations (refer to [73] for CTEQ4, [74] for CTEQ5 and [75] for CTEQ6). The results presented in this thesis are obtained with events generated using the set of parton distribution functions CTEQ4L.

- $d\hat{\sigma}^{ij \rightarrow Q(\bar{Q})\{k\}}/d\hat{p}_T$ is the partonic cross section; it can be described by pQCD since it is related to interactions of partons at high Q^2 . It is a function of the heavy-quark mass m_Q , of the parton-parton center-of-mass energy squared $x_1 x_2 s$ and on the quark transverse momentum $\hat{p}_T$. The partonic cross section is calculable as a power expansion in α_s ; the coupling constant α_s depends on μ_R , which is the renormalization scale for QCD. The heavy-quark cross section was calculated to next-to-leading order (NLO, see for example [76] for NLO implementations), corresponding to $O(\alpha_s^3)$. Some of the Leading and Next-To-Leading order diagrams relevant for the heavy-quark production are shown in Fig. 2.1.

In the calculation of the heavy quark cross section, the possible gluon emission from both light and heavy quarks has to be taken into account.

Collinear gluon emission from light quarks² is taken care off by the factorization and the evolution of the PDFs.

The gluon emission from heavy quarks has to be treated in a different way from the light quarks.

First of all, the hard scale given by the heavy-quark mass m_Q prevents from collinear singularities even when $\hat{p}_T \rightarrow 0$, hence the introduction of a factorization scale μ_F is no longer useful in case of heavy quarks. The gluon

²A gluon is collinearly emitted when it is radiated along the direction of the quark, i.e. its relative transverse momentum is close to zero.

emission from heavy quarks contributes with a factor $\alpha_s(\hat{p}_T^2) \log \frac{\hat{p}_T}{m_Q}$: this term is not dangerous, even at high $\hat{p}_T$, due to the presence of m_Q . Perturbative expansions in terms of α_s can then be done; however, reasonably large values of $\log \frac{\hat{p}_T}{m_Q}$ can bias the calculation of the cross section. For example, NLO calculations are not much reliable at high $\hat{p}_T$. To avoid these possible inconsistencies, Next-To-Leading-Log calculations (refer to [77, 78] and [79] for NLL calculations in e^+e^- collisions and hadronic collisions respectively) have been performed with the aim to “resum”³ at all the orders in α_s the terms like $\alpha_s(\hat{p}_T^2)^n \log^n(\frac{\hat{p}_T}{m_Q})$ (LL) and $\alpha_s(\hat{p}_T^2)^n \log^{n-1}(\frac{\hat{p}_T}{m_Q})$ (NLL).

An additional improvement is given by the matching of the two calculations: NLO, in the low- p_T region, and NLL, in the high- p_T region. This procedure is called FONLL (Fixed Order Next-To-Leading-Log) [80] and can be applied to obtain the p_T spectrum of heavy-flavour production.

- $D_Q^{H_Q}(z, \mu_F^2)$ is the fragmentation function which represents the probability for the scattered heavy quark Q to materialize as a hadron H_Q with momentum fraction $z = p_{H_Q}/p_Q$. It contains a resummation of the collinear terms due to gluon emission, plus a non-perturbative contribution related to the hadronization process which can be described only with models, such as the Lund string model [81], used for example in PYTHIA, and the cluster hadronization model [82], used in HERWIG [83]. The fragmentation functions can be experimentally determined by measuring jets in e^+e^- collisions.

A precise measurement of the heavy-quark cross section cannot be done directly from the measurement of the total cross section for heavy-flavoured hadrons, because there are several experimental constraints, like the restricted detector acceptance, which do not allow the measurement of total cross sections. Nevertheless, since both the parton distribution functions and the fragmentation functions are well measured, they can be used to determine the heavy-quark cross section starting from the measured heavy-flavoured hadrons: it must be kept in mind that in this case theoretical uncertainties may intervene in the deconvolution from the cross section of heavy-flavoured hadrons to that of heavy quarks (see Eq. 2.1).

³Resummation in QCD is a procedure to sum all the orders in a series rather than truncating it. In the case of heavy quarks, the series $\sum \alpha_s(\hat{p}_T^2)^n \log^n \frac{\hat{p}_T}{m_Q}$ is not divergent because of the hard scale m_Q , nevertheless it is appropriate to resum anyway in order to have more reliable results.

2.2 Heavy-quark production in nucleus-nucleus collisions

Heavy-quarks are produced on a time scale of $\sim \hbar/(2m_Q c^2) \simeq 0.2/2.4 \simeq 0.08$ fm/c (for $c\bar{c}$ production) from hard partonic scatterings during the early stages of the nucleus-nucleus collision and also possibly in the QGP, if the initial temperature is high enough. There is no production at later times in the QGP, whose expected τ is ~ 10 fm/c, and none in the hadronic matter. Thus, the total number of charm quarks gets frozen very early in the history of the collision, making them good candidates for a probe of the QGP.

In this section the pure geometrical extrapolation of the heavy-flavoured hadron cross section from pp to nucleus-nucleus collisions is firstly presented; then, some of the nuclear effects which can break the geometrical scaling in the heavy-quark production are described.

2.2.1 Extrapolation to nucleus-nucleus collisions

The simplest way to proceed when extrapolating to heavy-ion collisions is to consider such collisions as superpositions of independent nucleon-nucleon interactions. This is true under certain assumptions, like high beam energies, big nuclei, ... The charm (and beauty) differential yield in nucleus-nucleus interactions can be obtained from the yield in nucleon-nucleon with an appropriate normalization factor N_{coll} :

$$d^2 N_{AA}^{H_Q}/dp_T dy = N_{coll} \times d^2 N_{NN}^{H_Q}/dp_T dy \quad (2.2)$$

N_{coll} represents the number of binary collisions occurring between two nucleons. In the following we derive the expression for the average number of binary collisions and the inelastic cross sections as a function of the impact parameter which can be estimated on a geometrical basis with the Glauber model [46].

In a collision of two nuclei with atomic numbers A and B respectively, the probability that n collisions between two incoming nucleons occurs is given by the binomial distribution:

$$P_{m,n} = \binom{m}{n} p^n (1-p)^{m-n} \quad (2.3)$$

where m is the number of trials (in our case it corresponds to the total number of possible nucleon-nucleon collisions, $m = AB$), n is the number of successes and p is the probability for a binary collision to occur. This last term takes into account the interaction cross section between two nucleons, σ_{NN} , and the so called thickness function $T_{AB}(b)$, related to the overlapping volume of the two nuclei at

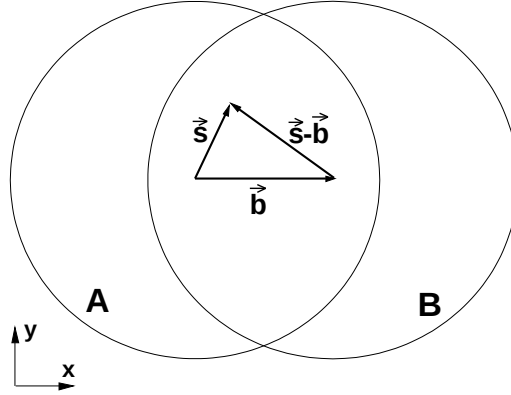


Figure 2.2: Collision geometry in the transverse plane.

a given collision impact parameter b :

$$T_{AB}(b) = \int d^2s T_A(\vec{s}) T_B(\vec{s} - \vec{b}) \quad (2.4)$$

In the above formula, $T_i(\vec{s}) = \int dz \rho_i(\vec{s}, z)$ is the thickness function of the nucleus i ($i = A, B$) calculated integrating over the longitudinal direction z the nuclear density ρ_i described by the Woods-Saxon profile⁴. The thickness function is normalized to unity when integrated over the all transverse nucleus area: $\int d^2s T_i(\vec{s}) = 1$. A sketch of the collision geometry is reported in Fig. 2.2.

The probability of one interaction of two incoming nucleons inside two colliding nuclei with impact parameter b is then $p(b) = \sigma_{NN} \cdot T_{AB}(b)$.

The binomial probability for n binary interactions is obtained from Eq. 2.3:

$$P_{AB,n}(b) = \binom{AB}{n} (\sigma_{NN} T_{AB}(b))^n (1 - \sigma_{NN} T_{AB}(b))^{AB-n} \quad (2.5)$$

⁴The density of nucleons is distributed according to the Woods-Saxon formula, which is defined for the spherical case by:

$$\rho(r) = \frac{\rho_0}{1 + \exp(\frac{r-R}{a})}$$

where r is the distance of the nucleons from the centre of the nucleus, ρ_0 is a constant, R is the radius of the nucleus and a is the surface thickness.

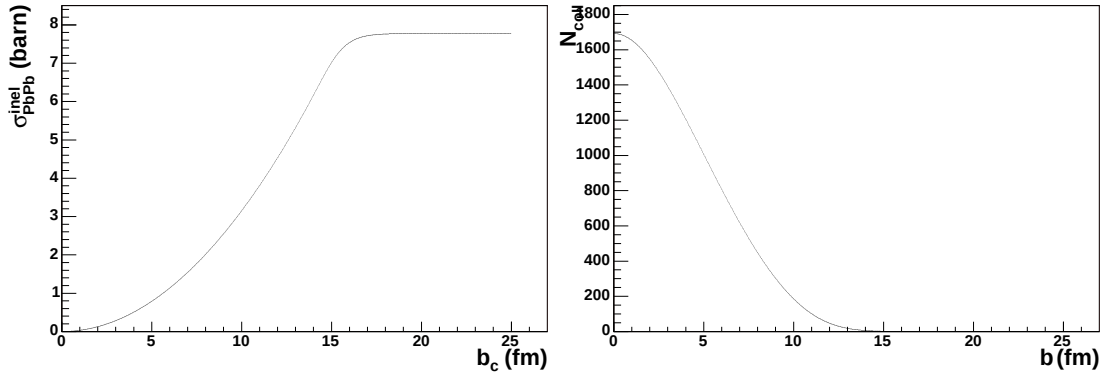


Figure 2.3: Left panel: inelastic Pb-Pb cross section for $b < b_c$. Right panel: average number of nucleon-nucleon collisions in Pb-Pb as a function of the impact parameter.

The probability for at least one binary collision to occur at a given impact parameter b is:

$$\frac{d\sigma_{AB}}{db} = 1 - P_{AB,0}(b) = 1 - (1 - \sigma_{NN}T_{AB}(b))^{AB} \quad (2.6)$$

The inelastic cross section corresponding to a given centrality interval ($0 < b < b_c$) is obtained integrating the differential cross section up to the value b_c :

$$\sigma_{AB}^{inel}(b_c) = \int_0^{b_c} 2\pi b db \frac{d\sigma_{AB}}{db} = \int_0^{b_c} 2\pi b db [1 - (1 - \sigma_{NN}T_{AB}(b))^{AB}] \quad (2.7)$$

The cross section calculated in Eq. 2.7 is reported in the left panel of Fig. 2.3 as a function of the impact parameter b_c ; the value $\sigma_{NN} = 55.6$ mb [84] has been used for the nucleon-nucleon cross section at $\sqrt{s_{NN}} = 5.5$ TeV. The plot shows that the inelastic cross section for minimum bias (i.e. $0 < b < \infty$) Pb-Pb collisions at the LHC is ~ 8 b.

The centrality class $0 < b < b_c$ is usually defined in terms of the corresponding fraction of the minimum bias cross section: for example, an impact parameter selection given by $b < 2$ fm corresponds to a centrality cut in Pb-Pb of 1.6% of the total inelastic cross section.

The average number of collisions at a given impact parameter b is simply the mean value of the binomial distribution ($\langle n \rangle = m \cdot p$):

$$\langle N_{coll} \rangle = AB \cdot \sigma_{NN}T_{AB}(b) \quad (2.8)$$

The right panel of Fig. 2.3 shows the average number of nucleon-nucleon collisions as a function of the impact parameter.

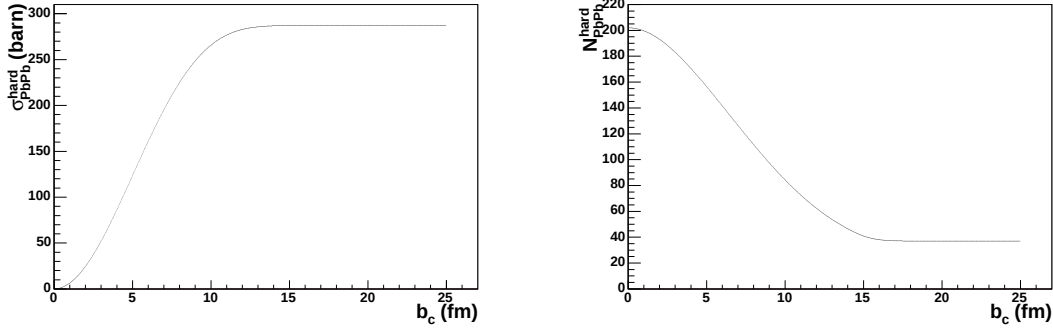


Figure 2.4: Left panel: $c\bar{c}$ cross section in Pb-Pb for $b < b_c$. Right panel: number of $c\bar{c}$ processes in different centrality classes $b < b_c$ for Pb-Pb collisions.

It is now possible to find the average number of collisions that produces a hard process, by replacing the inelastic nucleon-nucleon cross section in the formula 2.8 with the cross section for a given hard process, σ_{NN}^{hard} :

$$\langle N_{coll} \rangle^{hard} = AB \cdot \sigma_{NN}^{hard} T_{AB}(b) \quad (2.9)$$

From Eq. 2.7 we derive the cross section for a hard process in the centrality class $0 < b < b_c$:

$$\sigma_{AB}^{hard}(b_c) = \int_0^{b_c} 2\pi b db [1 - (1 - \sigma_{NN}^{hard} T_{AB}(b))^{AB}] \approx \int_0^{b_c} 2\pi b db \cdot AB \sigma_{NN}^{hard} T_{AB}(b) \quad (2.10)$$

where in the second passage the approximation of small σ_{NN}^{hard} has been considered.

For minimum bias collisions the above cross section becomes:

$$\sigma_{AB}^{hard} = \sigma_{NN}^{hard} AB \quad (2.11)$$

The cross section for charm production is reported in Fig. 2.4 (left panel) in the centrality interval $0 < b < b_c$. We assumed $\sigma_{NN}^{c\bar{c}} = 6.64$ mb [85].

The number of hard processes per triggered event is the ratio of the cross section for the hard process to that of the inelastic collision (as reported in the right panel of Fig. 2.4):

$$N_{AB}^{hard}(b_c) = \frac{\sigma_{AB}^{hard}}{\sigma_{AB}^{inel}} = R(b_c) \cdot \sigma_{NN}^{hard} \quad (2.12)$$

where (see Fig. 2.5):

$$R(b_c) = \frac{\int_0^{b_c} b \, db \, A_B T_{AB}(b)}{\int_0^{b_c} b \, db \, \{1 - [1 - \sigma_{NN} T_{AB}(b)]^{AB}\}}. \quad (2.13)$$

It is important to know the error on $R(b_c)$ in the evaluation of the systematic error on σ_{NN}^{hard} . The particular case of the $D^\pm$ production cross section is treated in Chapter 6.

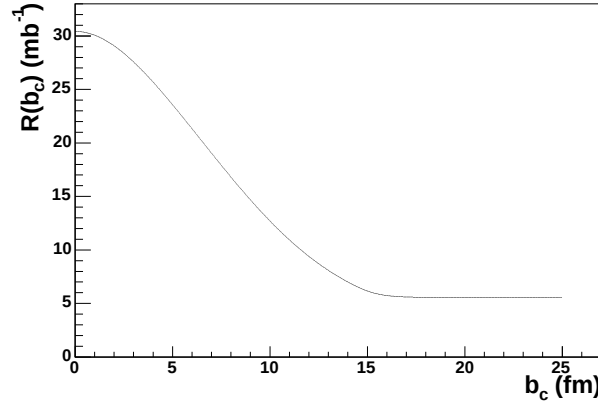


Figure 2.5: $R(b_c)$ for $b < b_c$ as a function of b_c .

2.2.2 Nuclear effects on heavy-quark production

Several effects can possibly break the binary scaling. They are usually divided into two classes:

- Initial-state effects, such as nuclear shadowing, which affect the heavy-quark production by modifying the parton distribution functions in the nucleus. There are predictions that initial-state effects may occur already in pp collisions at the LHC energies.
- Final-state effects, due to the interactions of the initially produced partons in the nuclear medium. They affect the heavy-flavoured meson production by modifying the fragmentation function. Energy loss of the partons and development of anisotropic flow patterns are among such processes.

2.2.2.1 Initial-state effects

In this paragraph the recent theoretical calculations concerning the initial-state effects on heavy-quark production are summarized.

Nuclear shadowing

There are various theoretical models [86] to describe the nuclear effects whose experimental evidence dates back to 1982. It is believed that different mechanisms are responsible for the different initial-state effects in the different regions of x : indeed, these nuclear effects are often grouped according to the behaviour of the experimentally observed ratio of the PDFs of the nucleon in the nucleus, $f_i^A(x, Q^2)$, with respect to those of the free nucleon, $f_i^N(x, Q^2)$:

$$R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{f_i^N(x, Q^2)} \quad (2.14)$$

where i is the parton species (valence quark, sea quark, gluon). At small x ($x < 0.05 - 0.1$), a reduction of the hard cross section producing a suppression of low transverse momentum particles at mid-rapidity ($R_i^A(x, Q^2) < 1$) is observed [86]. This is called nuclear shadowing (see also Section 1.3.4.1). On the contrary, at intermediate x ($x \sim 0.1 - 0.2$) an anti-shadowing effect is expected to be dominant ($R_i^A(x, Q^2) > 1$).

Fig. 2.6 shows, as obtained in different models, the ratio of the gluon distribution functions for Pb to the one for proton as a function of x for $Q^2 = 5 \text{ GeV}^2$, corresponding to the threshold for the $c\bar{c}$ production, $Q^2 = (2m_c)^2 \simeq 5 \text{ GeV}^2$. The bands represent the ranges of x for the $c\bar{c}$ production with $|y| \leq 0.5$, at RHIC ($\sqrt{s} = 200 \text{ GeV}$) and LHC ($\sqrt{s} = 5.5 \text{ TeV}$).

The nuclear shadowing can be taken into account by recalculating the hard nucleon-nucleon cross section in a nucleus-nucleus collision with nuclear-modified PDFs. Most models of shadowing predict that the PDF modifications should be correlated with the local nuclear density; calculations reported in [88] include also a parametrization with a centrality dependence.

The cross section for $c\bar{c}$ production (Eq. 2.10) and the number of $c\bar{c}$ processes per triggered event (Eq. 2.12) can now be calculated taking into account the shadowing effect, using the centrality dependence [88]:

$$\sigma_{NN}^{hard} = \sigma_{NoShad}^{hard} \left[C_0 + (1 - C_0) \left(\frac{b}{16} \right)^4 \right] \quad (2.15)$$

where σ_{NoShad}^{hard} is the nucleon-nucleon cross section for a hard process without the shadowing effect, which is assumed to be $\sigma_{NN}^{c\bar{c}} = 6.64 \text{ mb}$ [85] for charm production. C_0 is a parameter, which is taken to be 0.65 in case of charm production according to EKS98 parametrization [89]; b is the impact parameter measured in fm. The behaviour of this parametrization is shown in Fig. 2.7. The cross section for $c\bar{c}$ production in Pb-Pb and the number of $c\bar{c}$ processes are plotted in Fig. 2.8.

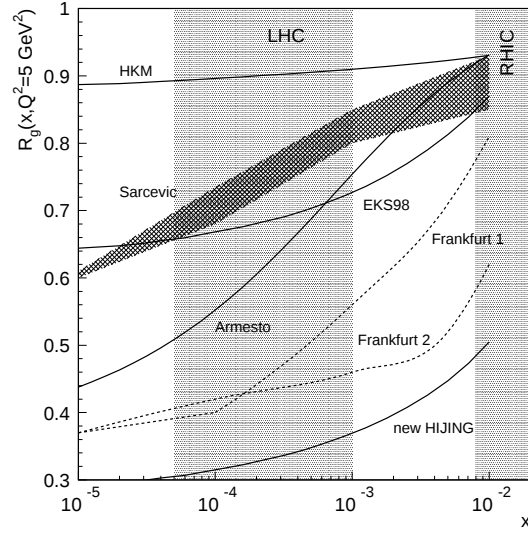


Figure 2.6: Ratios of gluon distribution functions from different models at $Q^2 = 5 \text{ GeV}^2$. Taken from [87].

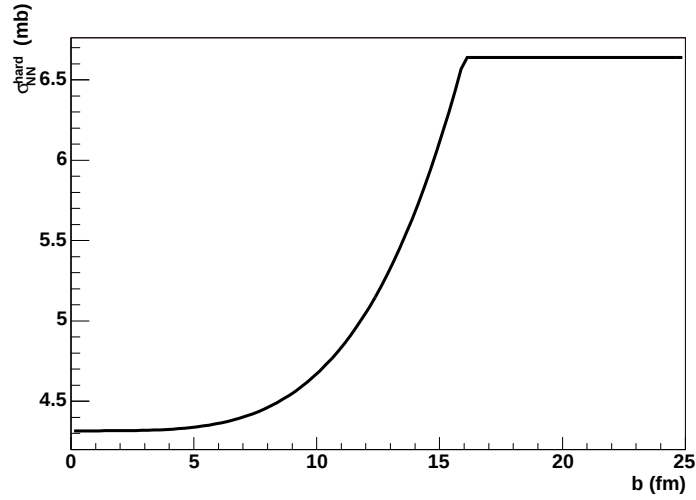


Figure 2.7: Parametrization of the shadowing effect in the $c\bar{c}$ nucleon-nucleon cross section as a function of the impact parameter. The parametrization is applied for $b \leq 16 \text{ fm}$; for $b > 16 \text{ fm}$ the constant value $\sigma_{NN}^{c\bar{c}} = 6.64 \text{ mb}$ [85] is considered.

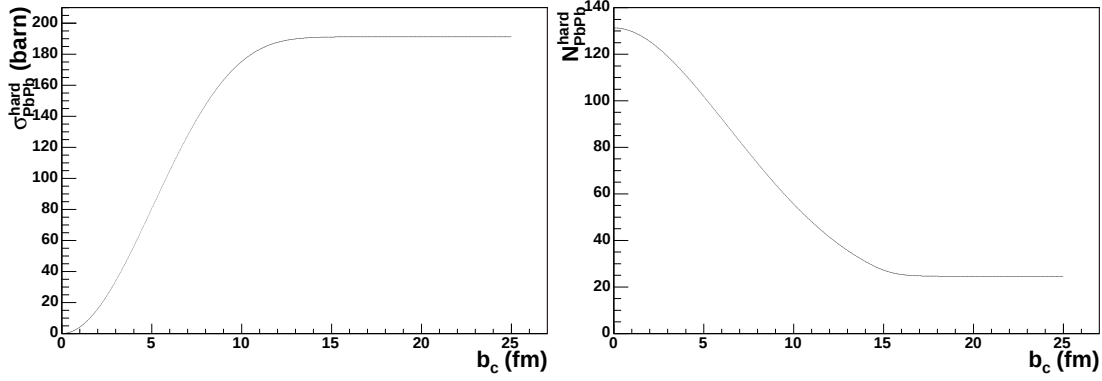


Figure 2.8: Left panel: $c\bar{c}$ cross section in Pb-Pb for $b < b_c$. Right panel: number of $c\bar{c}$ processes in different centrality classes $b < b_c$ for Pb-Pb collisions. In both the plots the shadowing parametrization [88] is included.

PDF modification in pp collisions

A modification of the parton distribution functions is expected to occur even in case of pp collisions at the LHC energies, where the density of low- x gluon is close to the saturation of the phase space, leading to gluon recombination effects like $gg \rightarrow g$, as described in the Color Glass Condensate picture. These effects are taken into account by adding a non-linear term in the DGLAP evolution equations due to gluon-gluon interactions [90]:

$$\partial f_g(x, Q^2) / \partial \log Q^2 = \left[\text{DGLAP}, \mathcal{O}(f_g) \right] - \left[\mathcal{O}(f_g^2) \right]. \quad (2.16)$$

This term slows down the Q^2 evolution at given x and, as a consequence, allows a higher gluon density at small Q^2 in order to maintain a good fit of the experimental distribution functions [90]. A higher gluon PDF at low Q^2 ($Q^2 \lesssim 10 \text{ GeV}^2$) implies a possible enhancement, compared to DGLAP calculations, of $c\bar{c}$ (whose production threshold is $Q^2 = 5 \text{ GeV}^2$) at low p_T at the LHC [91], as shown in Fig. 2.9.

CGC predictions for open charm

The production of open charm has been studied in the framework of the Color Glass Condensate (CGC), which describes the initial state of incoming hadrons and nuclei before the collision. As mentioned in Chapter 1, the CGC picture predicts a saturation scale Q_s determined by the parton density.

Within this approach, it has been argued [93] that at energies higher than RHIC, or forward rapidities at RHIC, where smaller x values are probed by charm

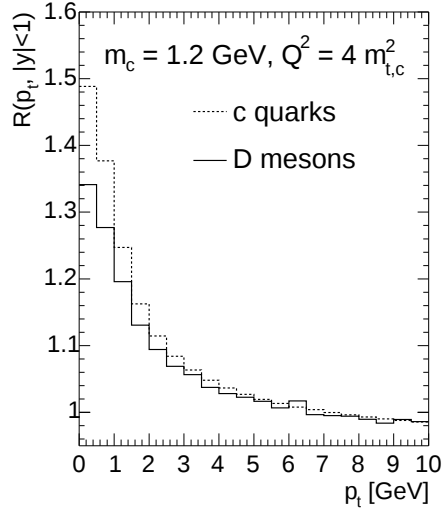


Figure 2.9: Enhancement due to non-linear gluon evolution for c quarks and D mesons in pp collisions at $\sqrt{s} = 14$ TeV. Taken from [92].

processes, the saturation scale exceeds the charm quark mass⁵, leading to a N_{part} ($\sqrt{N_{part}}$) scaling in AA (pA) collisions instead of the N_{coll} scaling typical of the collinear factorization. In such conditions, the production mechanism of heavy quarks is expected to be similar to that of light quarks: heavy partons at small x are not independent and act coherently, making the factorization theorem no longer valid.

In addition, in the CGC at high energy, the transverse momentum k_T associated to the partons in the incoming hadrons is of the order of Q_s ($Q_s \gg \Lambda_{QCD}$), rather than Λ_{QCD} , suggesting that the charmed-meson spectrum should be much harder than that predicted by calculations based on collinear factorization.

Multipartonic interactions

Heavy-flavour production in proton-nucleus collisions is expected to be a promising tool for studying multipartonic interaction events, characterized by more than one hard process occurring within the same hadronic collision [94, 95].

Multipartonic events can be measured by reconstructing jets: for example, the cross section for final states with four jets made of charmed particles is calculated to be significantly high at the LHC energy, suggesting that the observation of DD or $\overline{D}\overline{D}$ pairs in the same event would be a clear signal for $c\bar{c}c\bar{c}$ production

⁵The saturation scale $Q - s$ is expected to be $Q_s^2 \simeq 2 - 3 \text{ GeV}^2$ at $x \sim 10^{-4} - 10^{-5}$ for a Pb nucleus at the LHC energy.

in a double-parton collision. From an experimental point of view, it would be interesting to measure in one event a fully reconstructed D ($\bar{D}$) meson and a high- p_T ℓ^+ (ℓ^-) lepton, or a high- p_T lepton pair with the same sign.

2.2.2.2 Final-state effects: energy loss

The experimental observable used to investigate the energy loss mechanism is the nuclear modification factor, defined as follows:

$$R_{AA}(p_T) = \frac{d^2 N_{AA}/dp_T dy}{N_{coll} \times d^2 N_{pp}/dp_T dy} \quad (2.17)$$

which is the ratio of the particle yield in nucleus-nucleus collisions to the expected yield in case of superposition of binary nucleon-nucleon collisions without any nuclear effect. This observable is useful to make a comparison between experimental measurements and models predicting the in-medium energy loss.

An intense activity has been developed around the parton energy loss, and to date the situation is still controversial. There are two main contributions to the energy loss of a parton in the QGP: one is caused by elastic collisions among the partons in the QGP and the other by radiation of the decelerated colour charge, which originates a bremsstrahlung of gluons, sometimes referred to as “gluon-strahlung”.

Radiative energy loss

The “BDMPS” model [96] assumes that when an energetic parton crosses the medium and experiences multiple scattering, the gluons in its wave function may acquire a transverse momentum k_T with respect to the parton direction and may eventually be radiated. In this scenario, the average energy loss $\langle \Delta E \rangle$ depends on several quantities:

$$\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$$

Namely, it is proportional to:

- $\alpha_s C_R$, where C_R is the Casimir factor⁶, and thus is larger by a factor of 9/4 for gluons than for quarks;
- transport coefficient $\hat{q}$. It is related to the average squared transverse momentum transferred to the parton and is proportional to the density of scattering centers in the medium;

⁶The colour Casimir factors are different for quarks and gluons, namely they are 4/3 and 3 respectively.

- length L traveled in the medium. It can be noticed that the energy loss is proportional to L^2 and not only to L .

The average energy loss does not depend on the initial energy of the projectile parton. The parton energy loss involves both light and heavy quarks but it is expected to be stronger for light partons and gluons than for the massive charm and bottom quarks [97], due to the so called “dead-cone effect”, which predicts a suppression of the gluon radiation at angles Θ smaller than $\Theta_0 = m/E$: since Θ_0 is larger for heavy quarks than for light quarks, the cone where gluon radiation is forbidden is bigger for heavy quarks.

It has been suggested that a comparative study of the quenching effects on the light and heavy quarks can assess the influence of the heavy-quark mass and of the colour-charge on the parton energy loss. It has been proven in calculations based on the BDMPS formalism that for D meson spectra at high but experimentally accessible transverse momentum ($10 \lesssim p_T \lesssim 20$ GeV/c) in Pb-Pb at the LHC, the charm mass dependence of the parton energy loss becomes negligible since $m_c/p_T \rightarrow 0$ [98] and consequently $\Theta_0 = m/E \simeq 0$ for both light and heavy quarks.

A colour charge effect is expected to play an important role at the LHC energies affecting the light-flavoured hadrons more than the charmed hadrons. Indeed, a large fraction of light-flavoured hadrons are produced in the late stages of the collision evolution from gluons which lose more energy in the medium than the quarks due to their larger Casimir factor [98]. On the contrary, charmed and beauty mesons mainly originate from the fragmentation of heavy quarks directly produced in the early stages of the collision. Heavy-flavoured hadrons cannot be produced from gluon fusion in the late stages of the collision because the gluon lose energy in the medium and their energy is under threshold for heavy-quark production.

The comparison between energy loss effects on light and heavy quarks can be experimentally achieved by measuring the heavy-to-light ratio, namely the ratio of the nuclear modification factor of the heavy-flavoured mesons to that of light-flavoured hadrons:

$$R_{D/h}(p_T) = \frac{R_{AA}^D(p_T)}{R_{AA}^h(p_T)} \quad (2.18)$$

The heavy-to-light ratio is plotted in Fig. 2.10 as a function of the transverse momentum of D and B mesons: it can be seen that the effect of the mass is small for charm, while it is strong for the bottom quark.

Other studies on the influence of bottom jet quenching in the radiative energy loss were done by Djordjevic et al. [99].

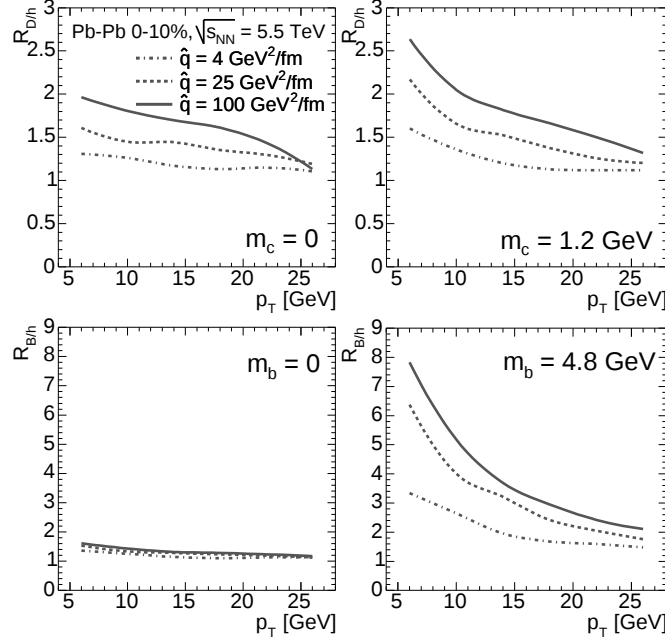


Figure 2.10: Heavy-to-light ratios at the LHC energies, Eq. (2.18), for D mesons (upper plots) and B mesons (lower plots) for a realistic heavy quark mass (plots on the right) and for zero masses of the quarks (plots on the left). The different curves refer to different choices of the transport coefficient in the BDMPS formalism. From Ref. [98].

Collisional energy loss

The suppression pattern of high- p_T hadrons in high-energy heavy-ion collisions, called jet quenching, was considered for long time to be one of the consequences of the medium-induced radiative energy of high-energy partons. However, recent data from RHIC on charmed mesons showed large disagreement with the radiative energy loss predictions, leaving the question open.

Recent studies [100] stated that, for a set of parameters relevant for RHIC, among them the transport coefficient $\hat{q}$, radiative and collisional energy losses for heavy quarks are comparable, and therefore collisional energy loss cannot be neglected in the computation of the jet quenching: in fact, the heavy quarks are possibly not ultra-relativistic for much of the measured momentum range, and in this case it is not clear that the radiative energy loss dominates over the elastic one. Very similar arguments apply to the energy loss of electrons in a medium, where ionization energy loss is dominant at low electron energies, photon bremsstrahlung mainly contributes at higher energies and at intermediate energies

the two phenomena are comparable.

Starting from Wicks et al. [101], several studies tried to reproduce the RHIC data on non-photonic electrons (which should come mainly from semi-leptonic charm decays) with the two contributions of radiative and collisional energy loss. Subsequent calculations [102] suggested that collisional energy loss is large in case of an infinite medium, while the finite size medium effects lead to significant reduction of the collisional energy loss; however the authors did not completely separate collisional from radiative contributions.

A more accurate determination of the relative contribution to jet quenching of elastic and radiative energy loss in a finite medium was then necessary to explain the large set of data from RHIC available: recent results show in two independent ways [103,104], consistently with the claims in [100] and the estimates in [101], that elastic energy loss is important and has to be included in the computation of the jet quenching.

Fig. 2.11 shows the comparison between elastic (solid line) and radiative (dash-dotted line) fractional energy loss as a function of the jet momentum (left panel) and of the thickness of the medium (right panel). It can be noticed that in the lower momentum range ($p < 10$ GeV) the collisional energy loss dominates the radiative one. Since at RHIC jet suppression is most measured in this momentum range, according to Fig. 2.11, the dominant contribution to the energy loss should be due to the collisional energy loss.

The heavy-to-light ratio, namely D/π , has been also estimated within the model presented in [100] with both collisional and radiative energy loss: even if the results are not definitive and are waiting for experimental data, they provide information on the medium energy loss in the momentum range $5 < p_T < 10$ GeV/c.

Also in the framework of the collisional energy loss the heavy-to-light ratio is found to be larger than one (as reported in Fig. 2.10 for the radiative energy loss), the reason being no longer based on the dead cone effect typical of the radiative energy loss, but rather on the assumption that, because of the large mass of the charm quark, D mesons are produced in a shorter distance with respect to light mesons and hence charm quarks have less time to propagate in the medium before transforming into D mesons. On the contrary, light quarks travel in the medium over a longer distance and suffer more energy loss than heavy quarks.

Other studies of heavy-quark energy loss based on elastic scatterings predict a thermalization of the charm in the medium and calculate the diffusion coefficient [105], which depends on the plasma temperature T through the relation $D \propto 1/T$. The diffusion coefficient is related to elastic $2 \rightarrow 2$ scattering processes like $qH \rightarrow qH$ (H is the heavy quark) and $gH \rightarrow gH$.

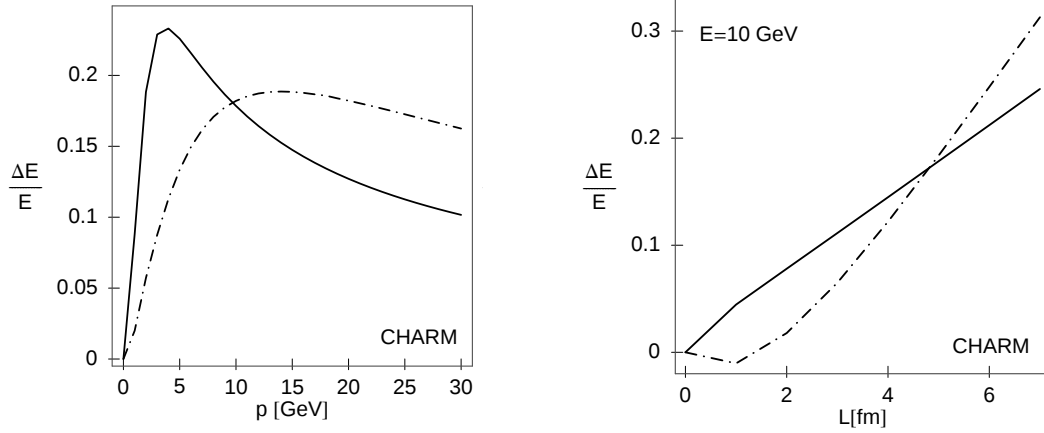


Figure 2.11: Left panel: comparison between collisional and radiative fractional energy loss is shown as a function of momentum for charm quark jets. Full curve shows the collisional energy loss, while dot-dashed curve shows the net radiative energy loss. Assumed thickness of the medium is $L = 5$ fm and mean free path $\lambda = 1.2$ fm. Right panel: fractional energy loss of the charm quark as a function of the thickness of the medium. Full curve shows the collisional energy loss, while dot-dashed curve shows the net radiative energy loss. Assumed initial energy of the jet $E=10$ GeV, $\lambda = 1.2$ fm. From [104].

The R_{AA} ⁷ for charm quarks calculated within this model is plotted in Fig. 2.12 as a function of the quark transverse momentum. Hadronization effects are ignored in this work, therefore a direct comparison with the data is not useful. However, from the comparison with the simulations done by [106], the most realistic values for the diffusion coefficient was found to be $D \sim 3/(2\pi T)$, corresponding to central collisions with $dN/dy=2000$ and total gluon-gluon cross section $\sigma_0 = 10$ mb.

Finally, recent studies tried to account for the strong nuclear suppression of non-photonic electrons observed at RHIC by evaluating the heavy-quark rescattering in the expanding fireball via D and B meson resonances above the critical temperature. The existence of such resonances is assumed in this model [107]. Their main conclusion is that the introduction of resonances in the QGP leads to a substantial reduction of the equilibration-time scales, making the resonance rescattering a promising candidate for an explanation of the large energy loss and v_2 (see next paragraph) of charm quarks measured at RHIC.

⁷The R_{AA} is experimentally the ratio of the hadron yield in AA collisions over the hadron yield in pp collision scaled to AA by the number of collisions. In this particular case, the authors use a different definition of R_{AA} because they are considering only quarks and not hadrons. See the reference [105] for more details.

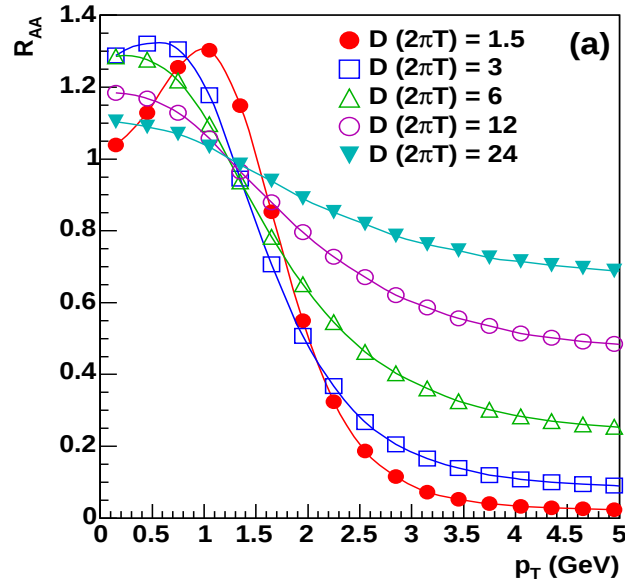


Figure 2.12: The nuclear modification factor R_{AA} for charm quarks for representative values of the diffusion coefficient. Taken from [105].

Fig. 2.13 illustrates the heavy-quark nuclear suppression factor in central Au-Au collisions at RHIC using both the more traditional LO pQCD scattering and the resonance interactions: as expected, resonance rescatterings have much larger effect on the R_{AA} of charm than pQCD interactions. As the previous case [105], the R_{AA} is defined as a nuclear suppression factor for heavy quarks and not for hadrons.

Collisional dissociation of heavy mesons

Other effects may contribute to the observation of the jet suppression at RHIC. Recent calculations [111] predict that heavy quarks fragment inside the medium and the heavy-flavoured mesons are then suppressed by collisional dissociation inside the QGP. The dissociation emulates energy loss by shifting the quarks/hadrons to lower transverse momenta.

QGP-induced dissociation predicts B meson suppression comparable to or larger than that of D mesons at transverse momenta as low as $p_T \sim 10$ GeV/c. This is not predicted by the other mechanisms for energy loss.

The reason for such suppression of B mesons is due to the significantly smaller formation times for hadrons with bottom quarks relative to those with charm quarks. Thus, each fragmentation/dissociation cycle proceeds at a much faster rate for b quarks/B mesons. According to the simulations described in [111], this

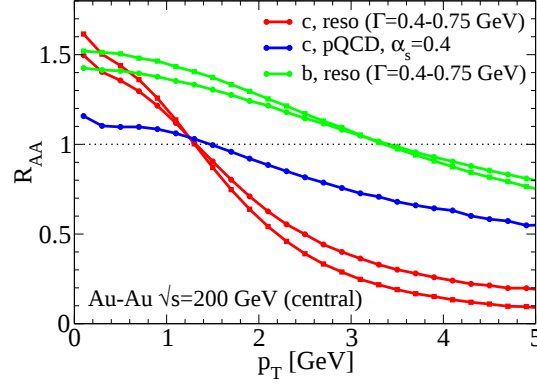


Figure 2.13: Heavy-quark nuclear suppression factor; red (green) lines: c (b) quarks using resonance+pQCD interactions; blue lines: c quarks with LO pQCD scattering only. Taken from [110].

faster rate might be responsible for a large suppression of B mesons.

2.2.2.3 Final-state effects: elliptic flow

Elliptic flow, $v_2 = \langle \cos(2\phi) \rangle$, is the second Fourier moment of the azimuthal momentum distribution (as described in Chapter 1) and is thought to be an important experimental probe that provides information about the thermalization of the medium created in non-central heavy-ion collisions. It results from the geometrical anisotropy in the transverse plane in non-central collisions, which is largest at early times. Therefore, v_2 is sensitive to the properties of the dense matter, such as its equation of state or the scattering cross section of the partons produced in the collision. In addition, measurements of elliptic flow at high momentum provide information on the density and energy loss of partons.

Heavy-flavour flow is especially interesting because, since it is related to the scattering of heavy quarks in the medium, it describes the degree of thermalization of the heavy quarks. In fact, due to the large mass of heavy quarks compared to light ones, it is expected that heavy-quark momenta are more difficult to randomize, at least at RHIC energies, and thus more collisions are needed for the heavy quarks to thermalize.

As soon as data from RHIC on electrons coming from open heavy-flavour decays were available, several theoretical models and predictions on collective motion of charm quarks started to develop.

The first proposal of measuring charm v_2 comes from the work of Gyulassy et al. [112], where RHIC data are shown to be consistent with two opposite scenarios. First, data on non-photonic electrons are well described by conventional factorized

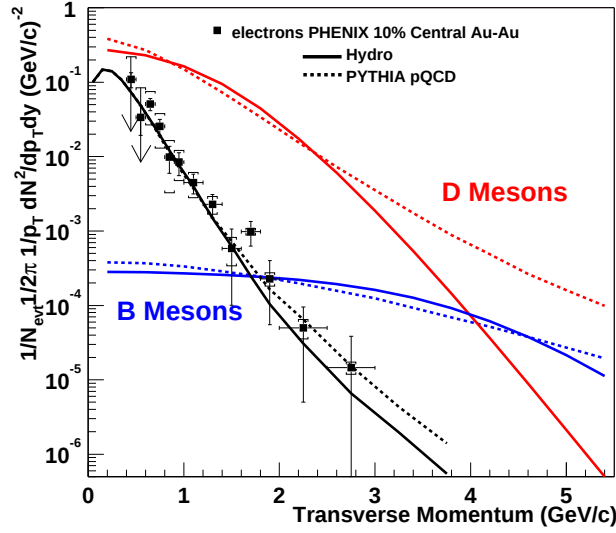


Figure 2.14: The PHENIX 10% central Au-Au at $\sqrt{s} = 130$ AGeV non-photonic electron spectra as a function of transverse momentum. The dashed curves are the PYTHIA evaluations for D mesons, B mesons and their combined resulting decay electrons. The solid curves are the results from the thermal hydrodynamic model. Taken from [112].

pQCD; this would indicate the validity of the factorization theorem (Eq. 2.1) and hence that heavy quarks have large mean free paths. Second, the same spectra are reproduced by an ideal hydrodynamic model with zero mean free path; this would suggest that a local equilibrium of charm quark is achieved. Surprisingly, data are compatible with both the predictions within the rather large errors, as can be seen in Fig. 2.14. As stated by the authors, higher statistics of single electron data at higher p_T could differentiate such models because pQCD is power suppressed while hydrodynamics is exponentially suppressed.

However, the measurement of non-zero charm v_2 would be a “smoking gun” for hydro behaviour.

The elliptic flow of charmed hadrons, like D mesons, will provide a more decisive experimental test at RHIC.

Hydrodynamics seems to be successful in describing the spectra of charged particles at RHIC and in reproducing the elliptic flow parameter v_2 at low p_T , as shown in Fig. 2.15. It is also observed that hydrodynamics fails to reproduce v_2 at high p_T , where the assumptions of zero mean free path and local thermal equilibrium are no longer satisfied.

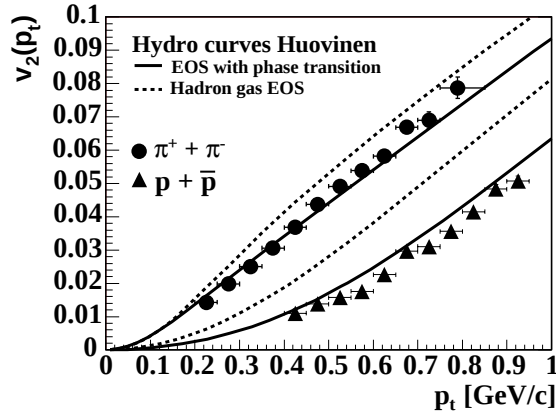


Figure 2.15: Elliptic flow for pions and protons + antiprotons versus transverse momentum. The lines are hydro model calculations. Taken from [113].

The use of parton covariant transport theory (see for example [114, 115]), in which parton phase space densities evolve with elastic $2 \rightarrow 2$ and inelastic $2 \rightarrow 2$ scatterings, overcomes this problem by using a finite mean free path: the theory naturally interpolates between free streaming ($\lambda = \infty$) and ideal hydrodynamics ($\lambda = 0$). To compare to the experiments, the parton transport model incorporates the hadronization process: the two main hadronization processes are fragmentation and coalescence.

Fragmentation is the process where each outgoing parton picks up sea quarks from the medium and independently fragments to hadrons. In this picture, hadron momenta depend on the parton momenta via $p_{T,H} = z p_{T,q}$ where z is distributed according to the fragmentation function $D(z)$. The hadrons carry only a fraction of the initial quark momenta; in case of heavy-flavour, $z \approx 1$ [116], the elliptic flow of charmed hadrons is essentially the same as the charm quark [106]. The independent parton fragmentation process is expected to prevail at very high transverse momentum [117].

In the coalescence process, mesons originate from a constituent quark and antiquark, while (anti)baryons from three (anti)quarks; comoving constituents are favoured in this formalism. Coalescence model has recently been considered as a mechanism for light hadron production at intermediate $p_T \simeq 2 - 6$ GeV/c at RHIC. Both the anomalous ratios baryons/mesons and the constituent scaling of the hadron v_2 found at RHIC are naturally accounted for within this framework. In addition, as it will be underlined in the following, coalescence can describe the rather high charged particle elliptic flow at RHIC with moderate initial gluon densities, giving a possible solution to the so called “opacity problem” [117].

In the coalescence model, the constituent momentum fractions $z_i = p_{T,i}/p_T$ for

mesons and baryons are then [118]:

$$z_i = \frac{m_i}{m_\alpha + m_\beta}, \quad z_i = \frac{m_i}{m_\alpha + m_\beta + m_\gamma} \quad (2.19)$$

where m_i are the effective masses of the constituent quarks and the indices α, β and γ refer to the quarks inside the hadrons. If the masses are similar, as in the case of pions, $p_{T\alpha} = p_{T\beta} = p_T/2$; on the contrary, for D mesons we have $m_\alpha \gg m_\beta$, hence most of the D momentum is carried by the heaviest quark. The asymmetric momentum configuration arises because coalescence requires the constituents to have similar velocities, not momenta.

Meson and baryon elliptic flow in the coalescence framework are given by that of partons via [118]:

$$v_{2,M}(p_T) \approx \sum_{i=\alpha,\beta} v_{2,i}(z_i p_T), \quad v_{2,B}(p_T) \approx \sum_{i=\alpha,\beta,\gamma} v_{2,i}(z_i p_T) \quad (2.20)$$

The hadron momentum is shared roughly in proportion to the quark masses, for example $m_{u,d} : m_c = 1 : 5$ and $m_s : m_c = 1 : 3$. In case of the D^+ meson, we have:

$$v_{2,D}(p_T) \approx v_{2,u}\left(\frac{p_T}{6}\right) + v_{2,c}\left(\frac{5p_T}{6}\right) \quad (2.21)$$

In the left panel of Fig. 2.16 the quark v_2 as calculated with the transport model described in [106] is shown as a function of the quark transverse momentum. At low p_T the charm elliptic flow is suppressed relatively to the v_2 of the light partons, confirming the expectations that heaviest quarks are more difficult to thermalize. At high p_T charm v_2 is very similar to that of the light partons.

The elliptic flow of D mesons is plotted in the right panel of Fig. 2.16 using the transport model plus the hadronization given only by coalescence. The results are compared with two extreme scenarios: zero charm v_2 , meaning no rescattering, and $v_{2,c} = v_{2,light}$. Neither of the two extremes is valid in general.

Additional improvements are obtained in another work [119], where D mesons are formed from charm quark coalescence with thermal light quarks which also carry the collective expansion characteristics (radial and elliptic flow): this is a more realistic scenario than that presented above [106]. The results on the p_T spectrum and v_2 of D mesons are shown in Fig. 2.17.

The expectations for the quark v_2 at the LHC energies calculated within the parton transport model [108] are reported in Fig. 2.18.

Finally, Fig. 2.19 illustrates the charm v_2 as a function of the transverse momentum, as obtained with the model based on resonance rescatterings described in the previous paragraph.

From this non-comprehensive review of the current situation of the theoretical studies on charm flow we can draw the following conclusions:

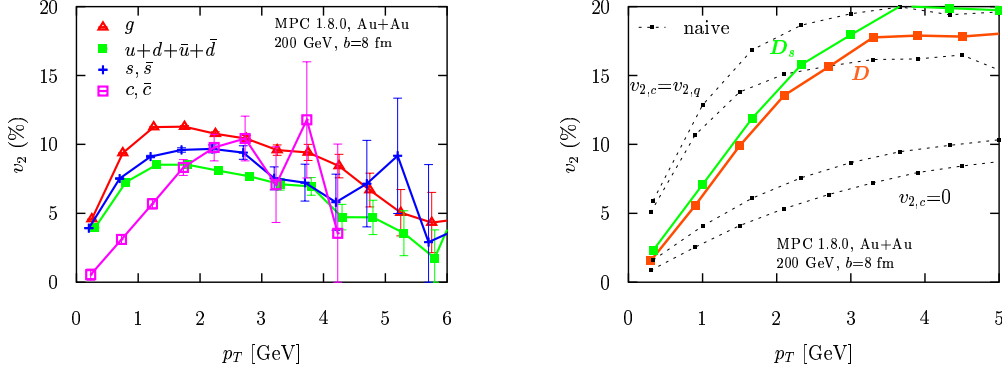


Figure 2.16: Parton elliptic flows (left panel) and D meson elliptic flow (right panel) as a function of p_T in semi-central Au-Au at $\sqrt{s_{NN}} = 200$ GeV, computed using the parton transport model. The D meson v_2 was obtained from the parton flows via the quark coalescence formula. The dashed lines correspond to the two extreme scenarios in [118] (see text). For hadronization via independent fragmentation, charm hadron v_2 is approximately the same as the charm quark v_2 . Taken from [106].

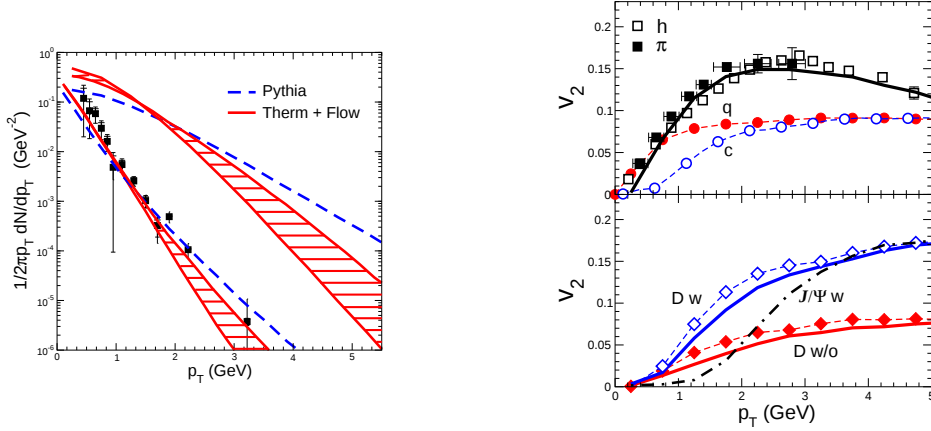


Figure 2.17: Left panel: Coalescence results for transverse-momentum spectra of all D-mesons (upper curves) and pertinent electron decays (lower curves) in central 200 AGeV Au-Au collisions at midrapidity. Dashed lines are obtained from pQCD c -quark distributions. Right panel: elliptic flow in minimum bias Au-Au collisions at $\sqrt{s} = 200$ AGeV. Upper: v_2 for light (solid circles) and charm quarks (open circles) together with the v_2 for pions (solid line) from coalescence plus fragmentation, as well as experimental data from PHENIX for π^+ (filled squares) and charged particles (open squares). Lower: v_2 for D mesons (solid line), lower: using pQCD charm-quark distributions, upper: for thermal+flow c -quark spectra at T_c and respective decay electrons (diamonds), as well as J/ψ mesons (dash-dotted line). Taken from [119].

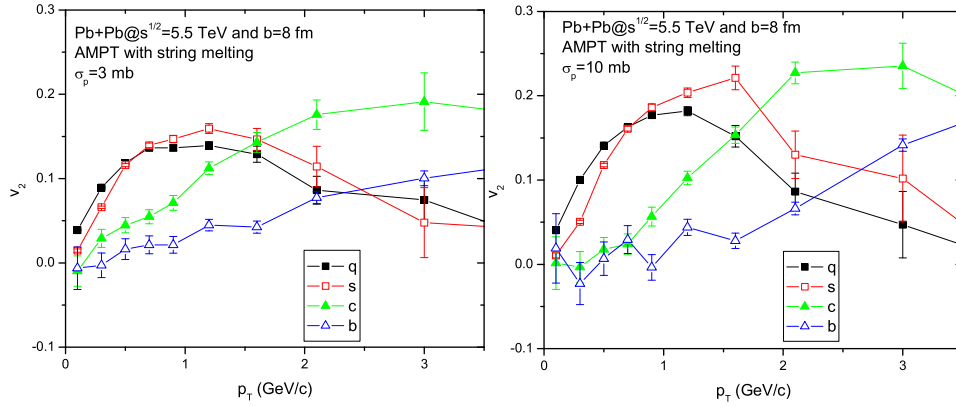


Figure 2.18: v_2 as a function of the transverse momentum for light and heavy quarks for semi-central Pb-Pb collisions at the LHC energies. The two plots refer to two different choices of the parameter σ_p representing the parton transport cross section. From Ref. [109].

- D meson spectrum calculated with pQCD, i.e. no rescattering, cannot be really distinguished from a thermalized one ([112] and [119]); therefore, no conclusion on charm thermalization can be drawn from p_T spectra;
- on the contrary, the elliptic flow pattern of D mesons exhibits a more pronounced difference between the two extreme cases of no rescattering of the charm and complete thermalization ([106] and [119]). This difference makes the charmed meson elliptic flow a promising observable to address the strength of charm rescattering;
- data on both D meson and J/ψ elliptic flow will provide information whether the charm quarks really flow or not.

2.3 Experimental results on charm production

In this section the most important results on charm production recently obtained in electron-proton collisions at the HERA accelerator, in $p\bar{p}$ collisions at the Tevatron and in pp and Au-Au collisions at RHIC are presented.

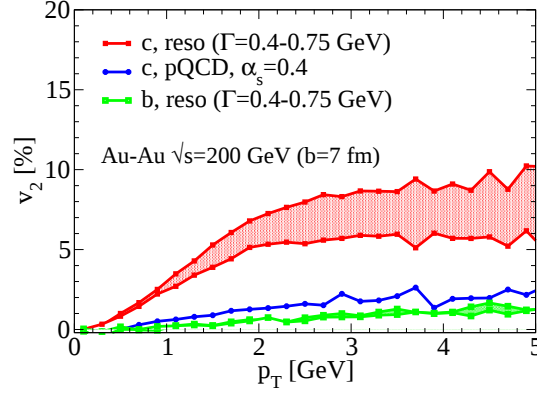


Figure 2.19: Heavy-quark v_2 ; red (green) lines: c (b) quarks using resonance+pQCD interactions; blue lines: c quarks with LO pQCD scattering only. Taken from [110].

2.3.1 Results from HERA

Charm production has been extensively studied in ep collisions at HERA ($E_e = 27.5$ GeV and $E_p = 920$ GeV) in order to test the universality of the charm fragmentation.

The measurements of open-charm fragmentation fractions [120] are consistent with previous results in e^+e^- collisions from LEP [121] and generally support the hypothesis that fragmentation proceeds independently of the hard sub-process, i.e. ep or e^+e^- . A relevant result is the ratio of neutral to charged D meson production rates [120]:

$$R_{u/d} = \frac{\sigma(D^{*0}) + \sigma^{dir}(D^0)}{\sigma(D^{*+}) + \sigma^{dir}(D^+)} \quad (2.22)$$

where $\sigma^{dir}(D^0)$ and $\sigma^{dir}(D^+)$ are those parts of the D mesons cross section which do not originate from D^* decays. The measured $R_{u/d}$ value agrees with unity, hence it is consistent with isospin invariance, which implies that u and d quarks are produced equally in charm fragmentation.

The measured $D^0/D^+ \sim 2.4$ ratio ([120]) is consistent with MC expectations, which were tuned on previous data. It can also be noticed that, as also stated by the authors, naive spin counting does not work in practice. According to this prediction, charm quarks are assumed to fragment to D (spin singlets: $J = 0$) and D^* (spin triplets: $J = 1$) mesons according to the number of available spin states;

therefore, $N(D^0) : N(D^+) : N(D^{*0}) : N(D^{*+}) = 1 : 1 : 3 : 3$ and:

$$\begin{aligned}
 \frac{N(D^0)}{N(D^+)} &= \frac{N(D_{\text{primary}}^0) + N(D^{*+}) \times BR(D^{*+} \rightarrow D^0) + N(D^{*0}) \times BR(D^{*0} \rightarrow D^0)}{N(D_{\text{primary}}^+) + N(D^{*+}) \times BR(D^{*+} \rightarrow D^+) + N(D^{*0}) \times BR(D^{*0} \rightarrow D^+)} \\
 &= \frac{1 + 3 \times 0.68 + 3 \times 1}{1 + 3 \times 0.32 + 3 \times 0} \\
 &= 3.08.
 \end{aligned} \tag{2.23}$$

2.3.2 Results from Tevatron

Extensive studies on open charmed mesons were carried out by the experiments at the Tevatron, as can be observed in Fig. 2.20, where the invariant mass distributions for reconstructed D mesons in the CDF experiment at the Tevatron in $p\bar{p}$ collisions with $\sqrt{s} = 1.96$ TeV are reported.

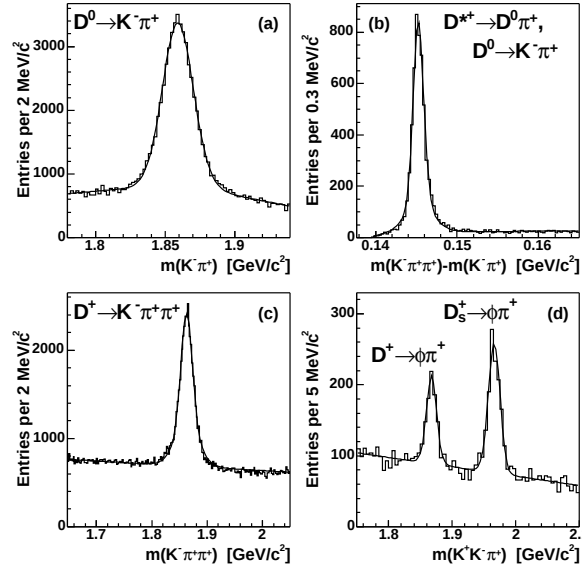


Figure 2.20: Charm signals summed over all p_T bins: (a) invariant mass distribution of $D^0 \rightarrow K^- \pi^+$ candidates; (b) mass difference distribution of $D^{*+} \rightarrow D^0 \pi^+$ candidates; (c) invariant mass distribution of $D^+ \rightarrow K^- \pi^+ \pi^+$ candidates; (d) invariant mass distribution of $D^+ \rightarrow \phi \pi^+$ and $D_s^+ \rightarrow \phi \pi^+$ candidates. Taken from [122].

Charm production is slightly underpredicted by the theory, as shown in Fig. 2.21, where the measured differential cross section for open charmed mesons is compared to FONLL calculations [80]. Such a behaviour appears also for RHIC data in pp collisions, as discussed in the next paragraph.

It must be said that FONLL calculations well reproduce data on beauty at Tevatron.

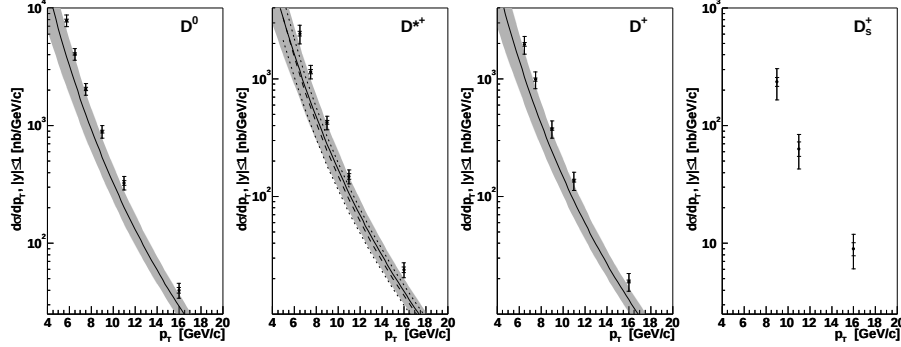


Figure 2.21: The measured differential cross section measurements for $|y| \leq 1$, shown by the points. The solid curves are the theoretical FONLL predictions. Taken from [122].

2.3.3 Results from RHIC

Open charm analyses are done at RHIC experiments by reconstructing D mesons either through their semi-leptonic decays or via hadronic channels. The latter is the cleanest signal, nevertheless it is more difficult to reconstruct without dedicated vertex detectors. STAR has performed such measurements (i.e. so far the $D^0 \rightarrow K^- \pi^+$ channel has been studied) with its TPC. However, both STAR and PHENIX experiments plan to upgrade their detectors by adding silicon vertex detectors close to the interaction point.

2.3.3.1 pp collisions

Measurements of heavy-flavour production in pp collisions provide a baseline for studying hot and dense matter effects in heavy-ion reactions. In Figure 2.22 (a) it is reported the invariant differential cross section of electrons from heavy-flavour decays measured by the PHENIX experiment [123]. All background sources, such as Dalitz decays and photon conversions, were subtracted. The data are compared with FONLL pQCD calculation. The top curve in Fig. 2.22 shows the central values of the FONLL calculation. The contributions of charm and beauty are also shown. For $p_T > 4$ GeV/c, the beauty contribution becomes dominant. In Fig. 2.22 (b), the ratio of the data to the FONLL calculation is shown. The ratio is nearly p_T independent over the entire p_T range. Similar ratios are observed in charm production at high p_T at the Tevatron [122].

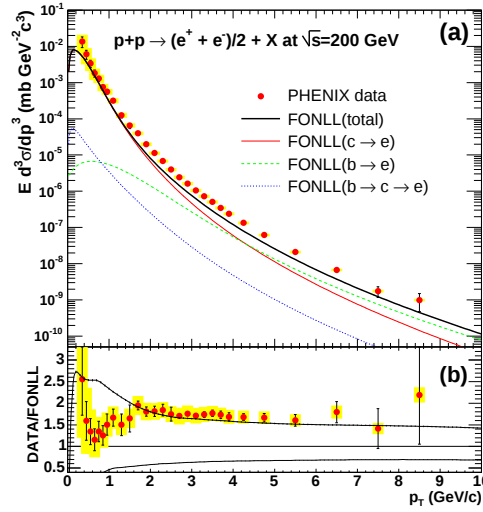


Figure 2.22: (a) Invariant differential cross section of electrons from heavy-flavor decays in pp collisions at RHIC. The curves are the FONLL calculations (see text). (b) Ratio of the data and the FONLL calculation. The upper (lower) curve shows the theoretical upper (lower) limit of the FONLL calculation. The error bars (bands) represent the statistical (systematic) errors. Taken from [123].

Recently STAR reported [124] (see Fig. 2.23) that non-photonic electron production in pp at $\sqrt{s} = 200$ GeV is about 4 times larger than the one predicted by the same FONLL calculation (see also Fig. 2.24). In spite of this, the shape is well reproduced by FONLL predictions. PHENIX does not observe such a large discrepancy, nevertheless STAR performs the only exclusive measurement of D mesons through the $K\pi$ decay and of 95% of the total charm cross section.

Since the results of the two experiments are not in agreement, it was argued that a possible reason is the difference of material budget; hence, a low material run at STAR and more precise D meson measurements in the two experiments were suggested.

2.3.3.2 Au-Au collisions

Charm cross section and yield

The STAR and PHENIX experiments measured the charm cross section in Au-Au collisions. In Fig. 2.23, the results from STAR are shown: the charm spectrum can be measured down to $p_T \sim 0.2$ GeV by means of muon and direct D meson measurements, thus covering the 95% of the total charm cross section.

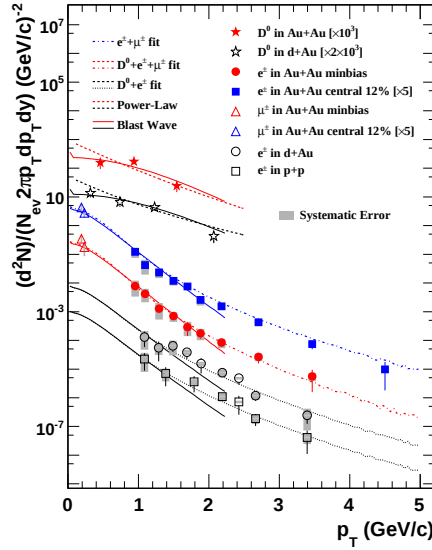


Figure 2.23: Open charm reconstruction summary from STAR: p_T distributions for D^0 mesons, for charm-decayed muons, and for non-photonic electrons. The overall magnitude of the cross-section in d-Au and Au-Au is about 5 times larger than NLO calculations. Taken from [125] (see also [126]).

A comparison of the charm cross sections measured by STAR and PHENIX in different collision configurations is illustrated in Fig. 2.24, where the discrepancy between the two experiments is evident. Nevertheless, both the experiments indicate a scaling of the charm yield with the number of nucleon-nucleon collisions, as shown in Fig. 2.25 for PHENIX (left panel) and STAR (right panel) data. Medium effects, such as energy loss, can only influence the momentum distribution of charm and have little effect on its total yield; initial-state effects, such as shadowing, are believed to be very small at RHIC. Therefore, the observation of binary scaling of the total charm yield may be a verification of the binary scaling of a point-like pQCD process, leaving no room for thermal production in the QGP at RHIC.

Charm energy loss

As shown in the upper panel of Fig. 2.26 [124], the nuclear modification factor R_{dA} for d-Au collisions is consistent with a moderate Cronin enhancement.

Since no suppression of the nuclear modification factor R_{AA} was observed in d-Au collisions, it was argued that the observed suppression in Au-Au at high p_T could be related to final-state effects, like the jet quenching in the medium created in heavy-ion collisions.

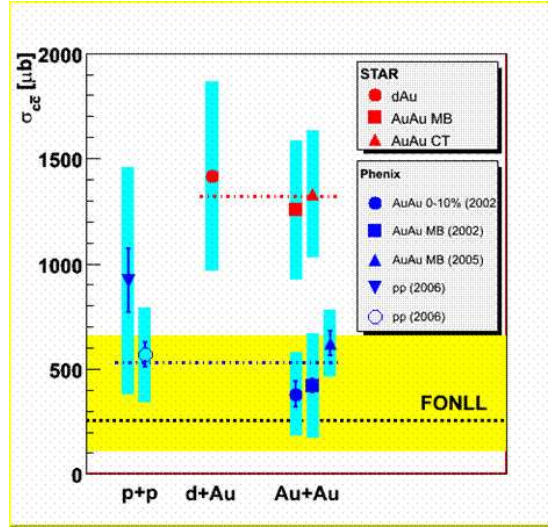


Figure 2.24: $c\bar{c}$ cross section as measured by STAR and PHENIX for different collision systems. Taken from [127].

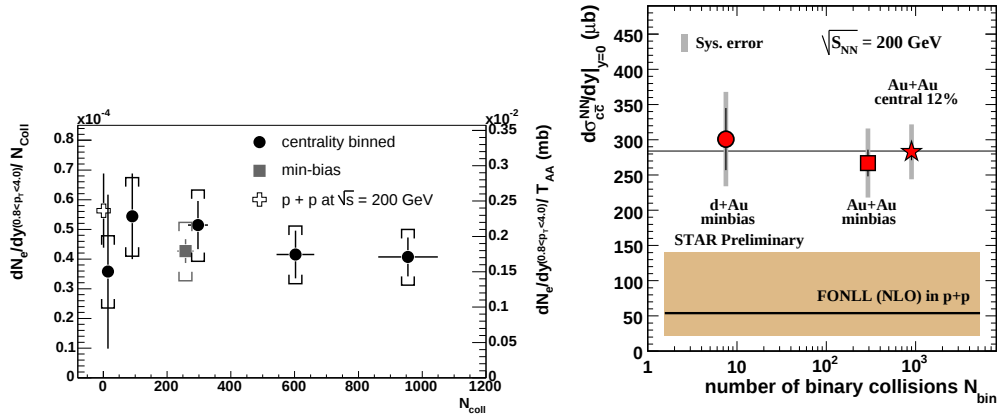


Figure 2.25: Left panel: non-photonic electron yield ($0.8 < p_T < 4.0$ GeV/c), dominated by semi-leptonic charm decays, measured by PHENIX in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV scaled by N_{coll} as a function of N_{coll} . The right-hand scale shows the corresponding electron cross section per NN collision in the above p_T range. The yield in pp collision at 200 GeV is also shown. Taken from [52]. Right panel: charm cross section at mid-rapidity as a function of the number of binary collisions, in d-Au and Au-Au. Taken from [126].

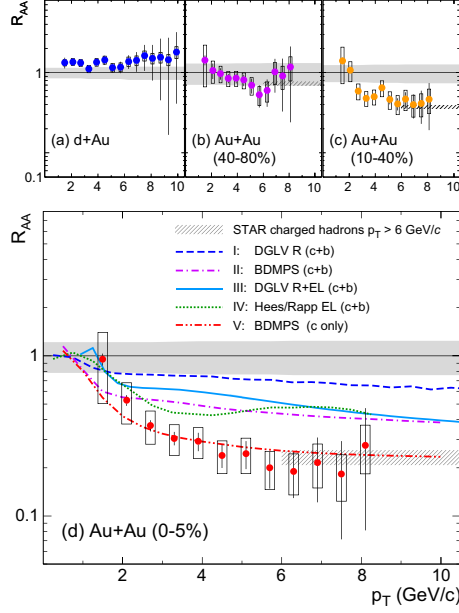


Figure 2.26: Upper panel: the nuclear modification factor, R_{AA} , for d-Au and semi-peripheral Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Bottom panel: R_{AA} for central Au-Au collision. The superimposed theoretical curves are described in the text. Taken from [124].

R_{AA} is then used as the observable related to the charm energy loss, already discussed in Section 2.2.2.2.

The R_{AA} of non-photonic electrons measured by STAR and PHENIX respectively in central Au-Au collisions is shown in Fig. 2.26 and 2.27 as a function of the transverse momentum; the data are compared to some of the theoretical predictions on parton energy loss described in Section 2.2.2.2.

STAR data reported in Fig. 2.26 are compared to five calculations. Calculation I uses the radiative energy loss with few hard scatterings, including bottom quark and assuming an initial gluon density $dN_g/dy=1000$. Calculation II uses the BDMPS radiative energy loss via multiple soft collisions [65] with transport coefficient $\hat{q} = 14$ GeV²/fm. Both calculations overpredict the observed R_{AA} . This discrepancy may indicate significant collisional energy loss for heavy quarks. Calculation III is a prediction which includes both radiative and collisional energy losses of charm and bottom quarks [101]. In Curve IV, the heavy-quark energy loss is due to elastic scatterings mediated by resonance excitations of D and B mesons ([110]): the quality of these predictions is still marginal at high- p_T . Calculation V, which is the same calculation of Curve II but for D-meson decay only, agrees better with the data. The authors also state that the scale factor 5.5 between

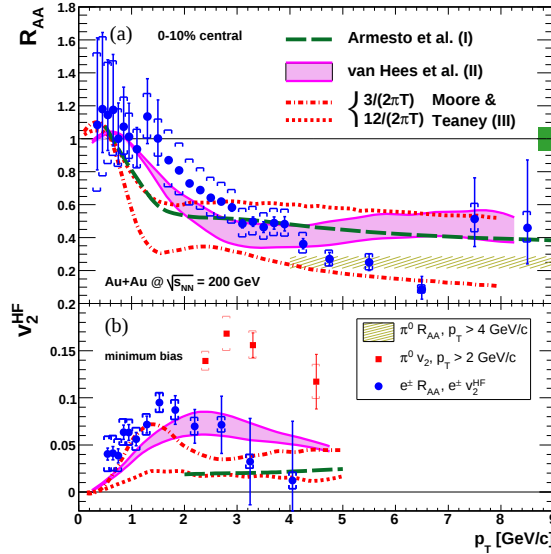


Figure 2.27: (a) R_{AA} of heavy-flavour electrons in 0-10% central collisions compared with π^0 data and model calculations. (b) v_2^{HF} of heavy-flavour electrons in minimum bias collisions compared with π^0 data and the same models. See the text for the description of the models. Taken from [128].

measured and calculated electron yield in pp collisions (see previous paragraph in this section) may overestimate in model calculations the B-decay contribution, and thus D-meson decay may in fact dominate the electron yield in the p_T range up to ~ 8 GeV/c.

PHENIX data on R_{AA} of single electrons reported in Fig. 2.27 (top panel) are compared with the Calculations IV and V described above. A model based on the diffusion coefficient D [105], also compared to the data, suggests that a small diffusion coefficient is required by the data and that the ratio viscosity to entropy (η/s) is small, i.e. the matter formed at RHIC is a near-perfect fluid.

Another effect which may contribute to the observed suppression is the collisional dissociation of particles created by fragmentation of heavy quarks inside the medium [111]. The predictions of this model are shown in Fig. 2.28.

Charm azimuthal anisotropy

From the study of non-photonic single electrons [128] and from the comparison with theoretical models, there are indications of charm elliptic flow v_2 for $p_T < 2$ GeV, compatible with v_2 of light quarks. In addition, as shown in Fig. 2.27 (bottom panel) for PHENIX data, v_2 seems to decrease at high p_T . The model [110] based on elastic collisions and resonance rescatterings (shaded area in the figure) is in good agreement with the data. Other calculations based on radiative energy

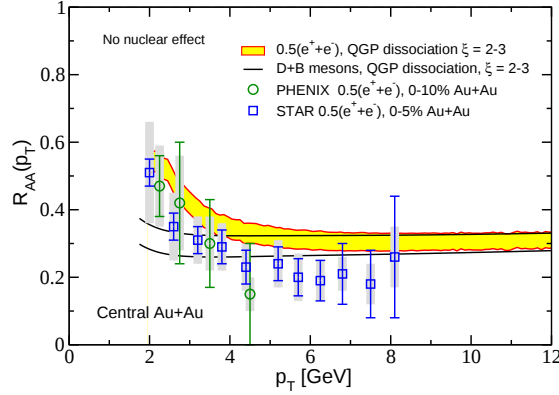


Figure 2.28: Suppression of inclusive non-photonic electrons from D- and B-meson spectra softened by collisional dissociation in central Au-Au collisions. Data on non-photonic electron quenching from PHENIX and STAR are also shown. Taken from [111].

loss [65] (dashed line) or on the transport properties of the medium [105] (dotted and dashed-dotted lines) fail in describing the v_2 .

Summary of the RHIC results on charm

We give in the following a short summary of the main conclusions that can be drawn from the results obtained by the RHIC experiments:

- Charm cross section has been measured in both pp and Au-Au collisions. In both the cases there are discrepancies between STAR and PHENIX; nevertheless, both experiments found that the charm yield in Au-Au collisions scales with the number of binary collisions.
- Charm suppression in Au-Au is very large when compared to the expectation from radiative energy loss that seems to work well for light quark hadrons. Other possible mechanisms were considered, such as collisional energy loss, resonances and in-medium fragmentation.
- Non-photonic electron v_2 supports the hypothesis that charm quarks, in spite of their large mass, suffer enough scatterings inside the medium to be possibly thermalized.
- The above results are not final, in particular larger statistics are necessary to study the v_2 at high p_T and, very important, it is mandatory to disentangle charm from bottom in order to separate the different contributions to R_{AA} and v_2 .

2.4 Expected charm production at the LHC

In this section the expected yields of charm quark and D mesons at the LHC are presented for both proton-proton and Pb-Pb collisions.

The charm production cross section obtained from NLO calculations [85] in proton-proton collisions for different energies and for two choices of the parton distribution functions (MRSTHO [129] and CTEQ5M1 [74]) are reported in Table 2.1.

Table 2.1: NLO calculation ([85], see Section 3.3) for the total $c\bar{c}$ cross section in pp collisions at 5.5, 8.8 and 14 TeV, using the MRSTHO and CTEQ5M1 parton distribution functions. Taken from [92].

	$\sigma_{pp}^{c\bar{c}} [\text{mb}]$		
$\sqrt{s}$	5.5 TeV	8.8 TeV	14 TeV
MRSTHO	5.9	8.2	10.3
CTEQ5M1	7.4	9.4	12.1
Average	6.6	8.8	11.2

Using the pp inelastic cross section $\sigma_{pp}^{\text{inel}} = 70 \text{ mb}$ [130, 131] at 14 TeV and the average charm cross section in the last row of Table 2.1, the yield per event for the production of $c\bar{c}$ is:

$$N_{pp}^{c\bar{c}} = \sigma_{pp}^{c\bar{c}} / \sigma_{pp}^{\text{inel}} = 0.16 \quad (2.24)$$

The differential $c\bar{c}$ cross section in pp collisions at $\sqrt{s} = 14 \text{ TeV}$ is shown in the left panel of Fig. 2.29. The ratio between the cross sections at $\sqrt{s} = 14$ and $\sqrt{s} = 5.5 \text{ TeV}$ is shown in Fig. 2.29 (right panel) with the theoretical uncertainties.

Table 2.2 reports the charm total cross section and yield for NN collisions (with and without shadowing [89]) at $\sqrt{s_{NN}} = 5.5 \text{ TeV}$, as calculated with the HVQMNR program [85], and the extrapolated values for Pb-Pb collisions (see Section 2.2.1).

The p_T and rapidity distributions of charm quarks generated with PYTHIA in Pb-Pb at $\sqrt{s_{NN}} = 5.5 \text{ TeV}$ and in pp at $\sqrt{s} = 14 \text{ TeV}$ are shown in Fig. 2.30 and 2.31. PYTHIA was tuned in order to reproduce NLO calculations [85]. The CTEQ4 parametrization of the PDFs [73] was used. In the simulation for Pb-Pb collisions the PDFs are modified for nuclear shadowing using EKS98 [89].

The LHC will allow the study of charm production down to unprecedented low values of the momentum fraction (Bjorken x). The x range actually probed depends on the value of the centre-of-mass (c.m.s.) energy per nucleon pair $\sqrt{s_{NN}}$,

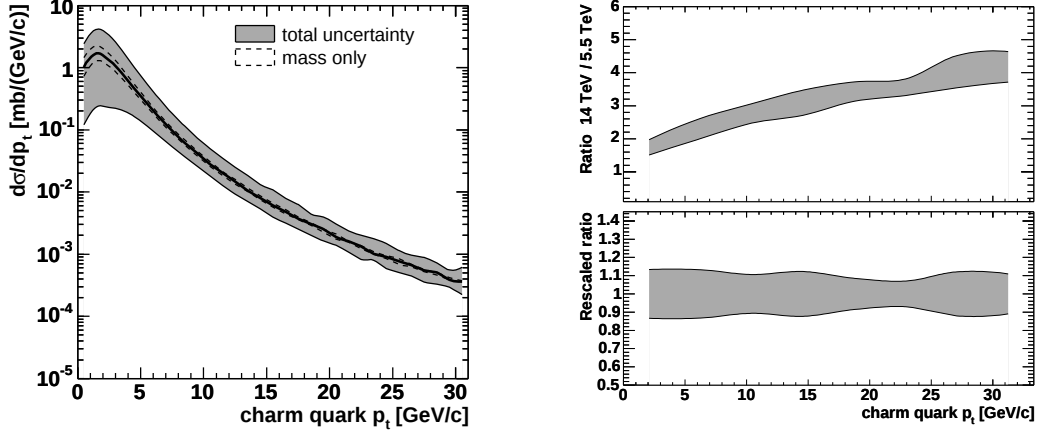


Figure 2.29: Left panel: evaluation of the theoretical uncertainty on the single-inclusive c quark p_T -differential cross section at $\sqrt{s} = 14$ TeV. Right panel: theoretical uncertainty on the ratio of single-inclusive heavy-quark p_T -differential cross sections at $\sqrt{s} = 14$ and at $\sqrt{s} = 5.5$ TeV (upper panel); in the lower panel, the same band is normalized to unity, i.e. divided by its central value, in order to quantify its relative width. Taken from [92].

Table 2.2: Total cross section and yield for charm production in NN and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. The effect of shadowing is shown as the ratio C_{shad} of the cross section calculated with and without the modification of the parton distribution functions. For the Pb–Pb three centrality ranges are also reported: 1.6%, 5% and 10% of the total inelastic cross section. Taken from [92].

		Charm
$\sigma_{NN}^{Q\bar{Q}}$ [mb]	w/o shadowing	6.64
	w/ shadowing	4.32
C_{shad}		0.65
$\sigma_{\text{Pb-Pb}}^{Q\bar{Q}}$ [b]	1.6% σ^{inel} ($b < 2$ fm)	16.0
	5% σ^{inel} ($b < 3.5$ fm)	45.0
	10% σ^{inel} ($b < 5$ fm)	81.0
$N_{\text{Pb-Pb}}^{Q\bar{Q}}$	1.6% σ^{inel} ($b < 2$ fm)	125
	5% σ^{inel} ($b < 3.5$ fm)	115
	10% σ^{inel} ($b < 5$ fm)	102

on the invariant mass $M_{Q\bar{Q}}$ of the heavy-quark pair produced in the hard scattering

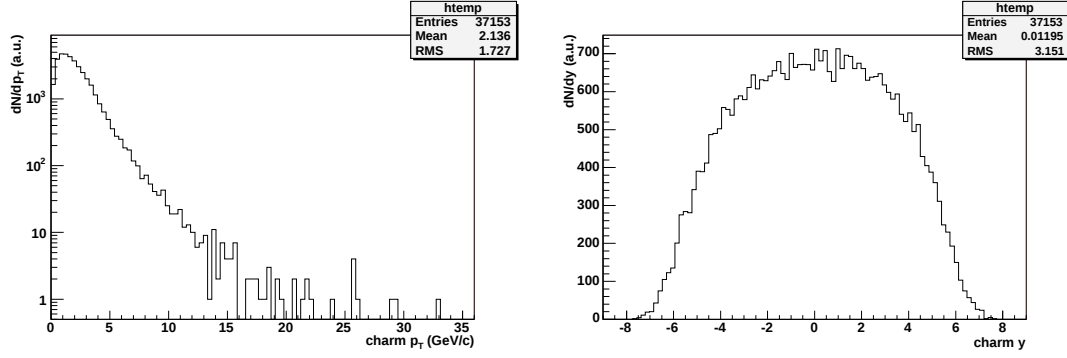


Figure 2.30: Transverse momentum (left panel) and rapidity (right panel) distributions for charm quarks in Pb-Pb collisions at the LHC.

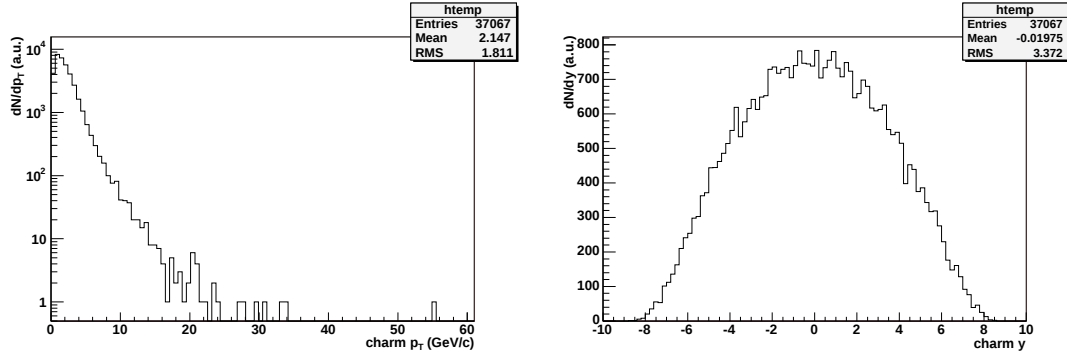


Figure 2.31: Transverse momentum (left panel) and rapidity (right panel) distributions for charm quarks in proton-proton collisions at the LHC.

and on its rapidity $y_{Q\bar{Q}}$.

Considering the process $gg \rightarrow c\bar{c}$ in the collision of two nuclei (A_1, Z_1) and (A_2, Z_2) , the two incoming gluons are characterized by four-momenta $(x_1, 0, 0, x_1) \cdot (Z_1/A_1) \sqrt{s_{pp}}/2$ and $(x_2, 0, 0, -x_2) \cdot (Z_2/A_2) \sqrt{s_{pp}}/2$, where x_1 and x_2 are the momentum fractions carried by the gluons, and $\sqrt{s_{pp}}$ is the c.m.s. energy for pp collisions (14 TeV at the LHC). The square of the invariant mass of the $Q\bar{Q}$ pair is given by⁸:

$$M_{Q\bar{Q}}^2 = \hat{s} = x_1 x_2 s_{NN} = x_1 \frac{Z_1}{A_1} x_2 \frac{Z_2}{A_2} s_{pp}; \quad (2.25)$$

and its longitudinal rapidity in the laboratory is:

$$y_{Q\bar{Q}} = \frac{1}{2} \ln \left[\frac{E + p_z}{E - p_z} \right] = \frac{1}{2} \ln \left[\frac{x_1}{x_2} \cdot \frac{Z_1 A_2}{Z_2 A_1} \right]. \quad (2.26)$$

From Eq. 2.25 and 2.26 we can extract x_1 and x_2 :

$$x_1 = \frac{A_1}{Z_1} \cdot \frac{M_{Q\bar{Q}}}{\sqrt{s_{pp}}} \exp(+y_{Q\bar{Q}}) \quad x_2 = \frac{A_2}{Z_2} \cdot \frac{M_{Q\bar{Q}}}{\sqrt{s_{pp}}} \exp(-y_{Q\bar{Q}}); \quad (2.27)$$

which simplifies to

$$x_1 = \frac{M_{Q\bar{Q}}}{\sqrt{s_{NN}}} \exp(+y_{Q\bar{Q}}) \quad x_2 = \frac{M_{Q\bar{Q}}}{\sqrt{s_{NN}}} \exp(-y_{Q\bar{Q}}) \quad (2.28)$$

for a symmetric colliding system ($A_1 = A_2$, $Z_1 = Z_2$). At central rapidities we have $x_1 \simeq x_2$.

The x values corresponding to charm production at threshold, $M_{c\bar{c}} = 2m_c \simeq 2.4$ GeV, can be computed from Eq. 2.28 at central rapidity and for different energies, as reported in Table 2.3. At the LHC it will be possible to reach values of x relevant for charm production about 2 orders of magnitude lower than at RHIC and 3 orders of magnitude lower than at the SPS.

The total yield and the rapidity density dN/dy in the central region for hadrons with open charm in Pb-Pb at 5.5 TeV (1.6% σ^{inel} and 5% σ^{inel} centrality selections) and pp at 14 TeV are summarized in Tables 2.4 and 2.5 respectively.

It can be noticed the large ratio of the neutral-to-charged D meson yields: $N(D^0)/N(D^+) \simeq 3.1$. In PYTHIA, charm quarks are assumed to fragment to D (spin singlets: $J = 0$) and D^* (spin triplets: $J = 1$) mesons according to the number of available spin states (see Section 2.3.1). Then, the resonances D^* are decayed to D mesons according to the branching ratios and, owing to the slightly larger (≈ 4 MeV) mass of the D^+ , the D^{*+} decays preferably to D^0 and the D^{*0} decays exclusively to D^0 .

⁸See Section 3.4 for the derivation of the nucleon-nucleon cross section $\sqrt{s_{NN}}$.

Table 2.3: Bjorken x values corresponding to charm production at central rapidity and $p_T \rightarrow 0$ at SPS, RHIC and LHC energies.

Machine System	SPS Pb-Pb $\sqrt{s_{NN}}$	RHIC Au-Au 200 GeV	LHC Pb-Pb 5.5 TeV	LHC pp 14 TeV
$c\bar{c}$	$x \simeq 10^{-1}$	$x \simeq 10^{-2}$	$x \simeq 4 \times 10^{-4}$	$x \simeq 2 \times 10^{-4}$

Table 2.4: Total yield, average rapidity density for $|y| < 1$, and relative abundance, for hadrons with charm in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. The values reported correspond to two centrality selections of 1.6% σ^{inel} and 5% σ^{inel} .

	Particle	Yield	$\langle dN/dy \rangle_{ y_{\text{lab}} < 1}$	Rel. Abund.
1.6% σ^{inel}	$D^0 + \bar{D}^0$	152.5	14.8	61%
	$D^+ + D^-$	47.5	4.4	19%
	$D_s^+ + D_s^-$	30	2.82	12%
	$\Lambda_c^+ + \bar{\Lambda}_c^-$	20	2.3	8%
5% σ^{inel}	$D^0 + \bar{D}^0$	140.8	13.7	61%
	$D^+ + D^-$	44.6	4.12	19%
	$D_s^+ + D_s^-$	26.8	2.52	12%
	$\Lambda_c^+ + \bar{\Lambda}_c^-$	17.9	2.03	8%

Table 2.5: Total yield, average rapidity density for $|y| < 1$, and relative abundance, for hadrons with charm in pp collisions at $\sqrt{s} = 14$ TeV. Taken from [92].

Particle	Yield	$\langle dN/dy \rangle_{ y_{\text{lab}} < 1}$	Rel. Abund.
$D^0 + \bar{D}^0$	0.1908	0.0196	61%
$D^+ + D^-$	0.0587	0.0058	19%
$D_s^+ + D_s^-$	0.0362	0.0038	12%
$\Lambda_c^+ + \bar{\Lambda}_c^-$	0.0223	0.0026	8%

A non-exhaustive summary of the measurements on heavy flavoured mesons which will be carried out by the ALICE experiment at the LHC is listed in the following:

- small- x physics: at the LHC it will be possible to reach unprecedented low values of the Bjorken x for charm and bottom quarks. This will allow

the study of the parton distribution functions with pp collisions and their modifications in the nucleus with pA and AA collisions;

- test of pQCD predictions: the measurement of charm and beauty cross sections at the high energies allowed by the LHC will be an important test for pQCD, especially because the current measurements in pp collisions seem not to agree well with FONLL calculations;
- jet quenching: the charmed hadrons suppression, clearly observed at RHIC, is expected to be even stronger at the LHC where a more dense medium will be created. The heavy-to-light ratios are promising observables to test the several partonic mechanisms of the energy loss;
- azimuthal anisotropy: there are predictions of an increase of the elliptic flow parameter of charged particles v_2 at the LHC energies [25]. Also the v_2 of charm quarks is expected to enhance [109]. the measurement of D-meson elliptic flow at the LHC will provide information on the possible thermalization of charm in the dense medium;
- beauty mesons: ALICE will be able to measure the $b\bar{b}$ cross section through semi-electronic decays of B mesons into electrons and muons. The expected number of beauty hadrons in a central Pb-Pb at the LHC with $\sqrt{s_{NN}} = 5.5$ TeV is about 9 [92].

Chapter 3

The ALICE experiment

Early investigations of the matter created in relativistic heavy-ion collisions date back to the experimental programs of the Berkeley Bevalac (1975-1985), the BNL AGS (1987-1995) and the CERN SPS (1987-2004).

Then, the BNL Relativistic Heavy Ion Collider (RHIC) was commissioned with four experiments: it became operational in 2000 and is currently running. Its published results concern Au-Au collisions at center-of-mass energies per nucleon pairs of $\sqrt{s_{NN}} = 130$ GeV and $\sqrt{s_{NN}} = 200$ GeV, pp collisions at $\sqrt{s} = 200$ GeV and d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

Another decisive step on the way of heavy-ion physics will be carried out by the LHC at CERN, starting from 2007.

LHC will accelerate Pb nuclei at $\sqrt{s_{NN}} = 5.5$ TeV, ~ 27 times larger than that achieved at RHIC. The ALICE detector at LHC is the new frontier of the experiments dedicated to heavy-ion physics at ultra-relativistic energies. Nevertheless, experimental programs with pp and pA collisions are foreseen as a reference for the Pb-Pb data, in order to well establish the QGP observables.

3.1 The experimental design

Since the predictions for the multiplicity in central Pb-Pb collisions at the LHC at the time of ALICE design were defined in a wide range from 2000 to 6000 charged particles per rapidity unit at mid-rapidity (see Chapter 1), the ALICE detector was designed to be able to cope with a very high multiplicity of 8000 charged particles per rapidity unit, which guarantees a safety margin.

The interaction rate for Pb-Pb collisions at the nominal luminosity of $\mathcal{L} \sim 10^{27}$ cm⁻²s⁻¹ is $R = \mathcal{L} \times \sigma \sim 8000$ s⁻¹, where the cross section for minimum bias collisions is $\sigma \sim 8$ b (see Section 2.2.1). Such a rate allows the use of slow but high-granularity detectors, like the time projection chamber and the silicon drift

detectors.

The main requirements for a heavy-ion experiment are an efficient tracking system within a large acceptance and a good particle identification in a wide momentum region. An efficient online trigger system is also required for specific analyses, for example those involving high- p_T electrons and rare processes.

Tracking is performed in ALICE with detectors mostly using three-dimensional hit information in a moderate magnetic field. The choice of a low magnetic field allows the reconstruction of low-momentum particles. This is desirable for several reasons: the study of collective effects related to the presence of the QGP, the measurement of rare process cross sections (like heavy quark production) down to low p_T , the reconstruction of the decay products of low- p_T hyperons and the rejection of the soft conversions and Dalitz decays, like $\pi^0 \rightarrow e^+e^-\gamma$, in the lepton-pair spectrum. The best choice for the field strength corresponds to the maximum field the magnet can produce, $B=0.5$ T, because it guarantees a good momentum resolution even at high momenta. Thus, ALICE will run at the highest field for the majority of the time. Nevertheless, a program at lower magnetic field, $B=0.2$ T, is foreseen since this value corresponds to the maximum reconstruction efficiency at low momentum.

A good particle identification system is needed to identify hyperons, vector mesons (i.e. $\phi \rightarrow K^-K^+$), heavy-flavour mesons through their hadronic decays (i.e. $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D_s^+ \rightarrow K^-K^+\pi^+$) and to carry out analyses with identified particles, like the measurements of azimuthal anisotropies v_2 , particle spectra and ratios, HBT correlations. Hadron identification is performed in the full acceptance of the ALICE central barrel ($|\eta| < 0.9$) for momenta up to $p \leq 4$ GeV/c; at higher momenta the particle identification is provided in a restricted acceptance (both in η and ϕ) and possibly with reduced momentum resolution.

3.2 ALICE setup

The ALICE layout is shown in Fig. 3.1. It consists of a central barrel covering the full azimuthal angle in $|\eta| \leq 0.9$ and several forward systems. The central system is embedded in a magnetic field $B \leq 0.5$ T. The central detectors are, in the order from the interaction vertex to the outside, the Inner Tracking System (ITS) with six layers of silicon detectors, the Time Projection Chamber (TPC) which is the main tracking detector, the Transition Radiation Detector (TRD) for electron identification and the Time Of Flight detector (TOF) for the identification of high-momentum particles. Two other detectors with smaller acceptance (both in η and ϕ) complement the central barrel: the High-Momentum Particle Identification Detector (HMPID) consisting of an array of ring-imaging Cherenkov counters

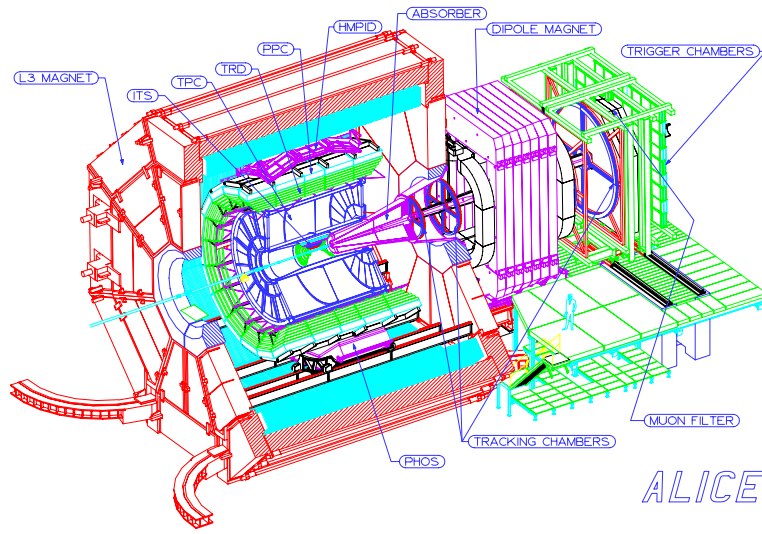


Figure 3.1: View of the ALICE detector.

and the Photon Spectrometer (PHOS) which is an electromagnetic calorimeter. The last commissioned detector (not shown in Fig. 3.1) is the Electromagnetic Calorimeter (EMCal): it will be put in the central barrel and will be dedicated to the physics of high- p_T photon jets.

The Muon Spectrometer is a forward detector located at $-4 < \eta < -2.4$ made of an absorber with small atomic number Z , followed by a spectrometer with a dipole magnet, five tracking stations and an iron absorber.

Additional forward detectors are the Forward Multiplicity Detector (FMD) made of silicon strips, the Photon Multiplicity Detector (PMD) made of layers of lead converter and the Zero Degree Calorimeter (ZDC) consisting of two hadronic calorimeters, one for protons and one for neutrons, plus one electromagnetic calorimeter: these detectors provide information on the centrality of the collisions. They are not shown in Fig. 3.1 because they are located too far from the interaction point.

Two trigger detectors are located on each side of the interaction point: the V0, made of scintillator material, and the T0, consisting of two arrays of Cherenkov counters.

The ALICE experimental program includes also a contribution to cosmic-ray physics with the aim of studying high-energy cosmic air showers in the energy range $10^{15} - 10^{17}$ eV and to determine the nature of primary cosmic rays. This goal can be reached with the dedicated Cosmic Ray Detector (ACORDE) based on the ALICE tracking detectors plus an additional Cosmic Ray Trigger (CRT)

made of scintillators located on top of the ALICE magnet.

3.2.1 Magnet

The central apparatus is embedded in the magnet constructed for the L3 experiment at LEP, which produces a weak solenoidal magnetic field ($B \leq 0.5$ T). The choice of the magnetic field is driven by the important constraint that it has to be intense enough to bend the tracks, but still able to allow the reconstruction of low-momentum particles in the TPC.

The lower momentum cut-off which allows the reconstruction of the tracks in the whole TPC is given by $p_{cut-off} = 0.3BR \sim 0.2$ GeV/c, where B is the magnetic field, $R=2.5\text{m}/2$ is the minimum radius for a particle to traverse the TPC, whose external radius is $R_{ext}=2.5$ m.

The diameter of the holes in the lateral doors of the magnet has been reduced to improve the magnetic field homogeneity in the volume of the TPC.

3.2.2 Inner Tracking System

The Inner Tracking System (ITS) [132] consists of six cylindrical layers of silicon detectors located in the central barrel at radii, $r \approx 4, 7, 15, 24, 39$ and 44 cm. The innermost radius is the minimum allowed by the presence of the beam pipe, whose radius is 3 cm. The outermost radius is determined by the requirement to match tracks from the ITS to the TPC and viceversa.

The tasks of the ITS are:

- primary and secondary vertex reconstruction with the high resolution required for the detection of hyperons and particles with open charm and open beauty;
- reconstruction and identification of low momentum tracks with $p < 100\text{--}200$ MeV/c, which are too bent by the magnetic field to be reconstructed by the TPC;
- reconstruction and identification of those particles which traverse the dead regions of the TPC;
- improvement of the momentum resolution for the high momentum particles which also traverse the TPC.

With its improvement to the global tracking, momentum and impact parameter¹ resolutions, the ITS significantly contributes to the study of several physics

¹The track impact parameter is defined as the distance of closest approach of the track to the interaction point. See also Chapter 4.

topics, such as multiplicity distributions, particle spectra, resonances (ρ , ω , ϕ), heavy-flavour particles with short lifetime, jet production and jet quenching. Also the particle identification (PID) in the non-relativistic region is necessary because, including in the PID system low-momentum particles with $p < 100 - 200$ MeV/c, the momentum range where particle spectra are measured is wider and this is important to study collective effects which are usually associated to long distance scale length.

The following factors were considered in the design of the ITS:

- **Acceptance:** in order to study particle spectra and correlations down to the lower momenta, the acceptance has to be as large as possible. The ITS covers the same acceptance as the TPC, which is $|\eta| < 0.9$ for collisions with vertex located within the length of the interaction diamond, $-5.3 < z < 5.3$ cm. Besides, the full azimuthal coverage ensures an efficient rejection of the low-mass Dalitz decays. The inner pixel layers cover a larger pseudorapidity range ($|\eta| < 1.98$ for particles emitted at $z = 0$) to extend the coverage of multiplicity measurements.
- **dE/dx measurements:** the ITS provides PID information through the ionization energy loss in the four outermost layers. In order to identify particles at very low momenta where the specific energy loss is high, the dynamic range of the analog readout system has to be large enough.
- **Material budget:** one of the main tasks of the ITS is to improve the tracking performance and thus the momentum and impact parameter resolutions. This can be achieved only if processes like multiple scattering are minimized. Therefore, the amount of material in the active volume must be reduced to a minimum: the thickness of the four outermost layers (silicon drift and strips) used for the particle identification is approximately $300 \mu\text{m}$ and is even smaller for the two inner silicon pixel layers. In addition, the detectors must overlap in order to cover the entire solid angle. The total effective thickness of the detectors amounts to 6% of X_0 .
- **Spatial precision and granularity:** the ITS, together with all the ALICE detectors, was designed to cope with a high multiplicity environment, corresponding to about 15 000 tracks in its active area. Thus, the granularity is high enough to guarantee a low occupancy in the detector, at the level of few percent, with the drawback that several millions of effective cells are needed in each layer of the ITS. The granularity in the innermost layers is achieved with silicon micro-pattern detectors with two-dimensional readout: Silicon Pixel Detectors (SPD) and Silicon Drift Detectors (SDD). At larger radii, the requirements in terms of granularity are less stringent, therefore

double-sided Silicon Strip Detectors (SSD) with a small stereo angle are used. With such granularities the spatial precision is sufficiently high (few tens of μm) to guarantee a good resolution on the track impact parameter (better than $100\ \mu\text{m}$ in the $r\varphi$ plane), necessary to detect charmed mesons which have decay lengths of the order of hundreds μm . In addition, the spatial precision is an essential ingredient needed to keep the momentum resolution as high as possible even at larger momenta ($p > 3\ \text{GeV}/c$), where the decay products of charmed mesons can be detected.

- **Radiation level:** the expected total radiation dose received by the ITS in the lifetime of the experiment, ranges from a tens of Gy^2 (few krad) for the outer parts of the ITS to about $2.2\ \text{kGy}$ ($220\ \text{krad}$) for the inner parts. Each subdetector is designed to withstand the ionising radiation doses expected during ten years of operation. The fluency is approximately $5 \times 10^{11}\text{cm}^{-2}$ equivalent neutrons throughout the ITS, which does not cause significant damage to the detectors or the associated electronics.
- **Readout rate:** two main readout chains with two different triggers will be used during the data acquisition. The centrality trigger activates all the ALICE detectors, in particular all the layers of the ITS, while the trigger of the muon arm activates the readout of a subset of fast readout detectors, including the two inner layers of the ITS, whose readout time is set at less than $400\ \mu\text{s}$.

The layout of the ITS is shown in Fig. 3.2. Each layer is made of longitudinal supports, the ladders, which host the detectors. The geometrical dimensions, the technology used and the number of channels needed in the various layers of the ITS are summarised in Table 3.1.

Some parameters of the three detector types are reported in Table 3.2.

Further details on the ITS are discussed in the ITS Technical Design Report [133].

²The gray (Gy) is the unit for the absorbed radiation and depends on the energy deposited in a matter of mass $1\ \text{kg}$, through the following relation:

$$1\text{Gy} = 1\text{joule kg}^{-1} = 6.24 \times 10^{12}\text{MeV kg}^{-1}$$

Alternatively, the rad is used:

$$1\text{rad} = 0.01\text{Gy}$$

Table 3.1: Dimensions of the ITS detectors (active areas).

Layer	Type	r (cm)	$\pm z$ (cm)	Area (m ²)	Ladders	Det./ladder	Channels
1	pixel	3.9	14.1	0.07	80	1	3 276 800
2	pixel	7.6	14.1	0.14	160	1	6 553 600
3	drift	15.0	22.2	0.42	14	6	43 008
4	drift	23.9	29.7	0.89	22	8	90 112
5	strip	37.8/38.4	43.1	2.09	34	22	1 148 928
6	strip	42.8/43.4	48.9	2.68	38	25	1 459 200
Total area				6.28			

Table 3.2: Parameters of the various detector types. A module represents a single sensor element.

Parameter		Silicon Pixel	Silicon Drift	Silicon Strip
Spatial precision $r\varphi$	(μm)	12	38	20
Spatial precision z	(μm)	100	28	830
Two track resolution $r\varphi$	(μm)	100	200	300
Two track resolution z	(μm)	850	600	2400
Cell size	(μm^2)	50×425	150×300	95×40000
Active area per module	(mm ²)	12.8×69.6	72.5×75.3	73×40
Readout channels per module		40 960	2×256	2×768
Total number of modules		240	260	1698
Total number of readout channels	(k)	9 835	133	2608
Total number of cells	(M)	9.84	23	2.6
Average occupancy (inner layer)	(%)	2.1	2.5	4
Average occupancy (outer layer)	(%)	0.6	1.0	3.3

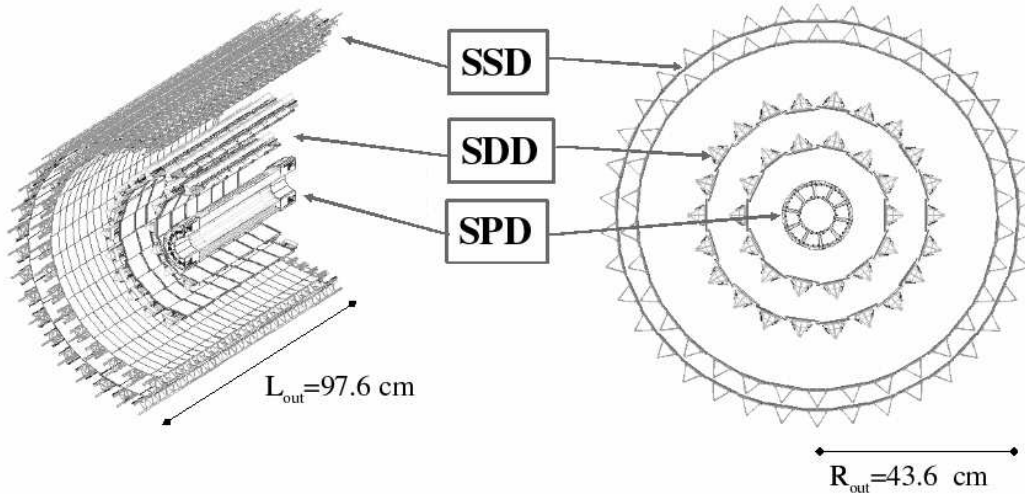


Figure 3.2: Layout of the ITS.

3.2.3 Time Projection Chamber

The Time Projection Chamber (TPC) [132] is the main tracking detector in ALICE: it provides charged-particle track reconstruction, identification, momentum measurements, primary and secondary vertex determination. All these requirements have to be fulfilled at the Pb-Pb nominal luminosity, corresponding to an interaction rate of 8 kHz, of which about 10% are central collisions with impact parameter $b < 5$ fm. For these we assume the extreme multiplicity of $dN_{\text{ch}}/d\eta = 8000$, resulting in an unprecedented track density for a TPC.

The TPC allows the study of hadronic and leptonic observables with transverse momenta up to ~ 100 GeV/c in the pseudorapidity window $|\eta| < 0.9$ (up to $|\eta| \sim 1.5$ for tracks with reduced track length and momentum resolution).

3.2.3.1 Hadronic observables

The TPC will reconstruct hadrons produced both in Pb-Pb and pp collisions. Hadronic observables provide information on the QGP phase, like its flavour composition, its space-time evolution before the freeze-out and its event-by-event fluctuations. The main hadronic observables are particle spectra, particle correlations and hard probes such as particles with charm or bottom quarks, heavy quarkonia and high- p_T jets. All these topics require a large acceptance and very good momentum resolution and particle identification, which can be obtained also with the help of other detectors.

The study of low cross section processes, like hard processes, is also favoured by a large acceptance.

The specific needs to perform measurements of hadronic observables with the TPC are the following:

- **Momentum and two-track resolution:** the TPC ensures a momentum resolution for low and intermediate momenta between 1% and 2% depending on the magnetic field setting. At higher momenta, a resolution of $\sim 3.5\%$ for $p_T \sim 100$ GeV/c with $B=0.5$ T is attainable with the help of the ITS and TRD. Also the two-track resolution has to be as high as possible especially in case of analyses like two-particle correlations based on the HBT interferometry.
- **dE/dx resolution:** dE/dx measurements are necessary in the TPC in order to identify particles through their ionization energy loss. Particle identification in the TPC extends from low momenta ($p \sim 200$ MeV/c) up to ~ 1 GeV/c, corresponding to the momentum range where specific ionizations for different types of particles are well separated. The dE/dx resolution depends on the particle multiplicities³ and it is approximately 7% for the extreme multiplicities. Such a resolution is sufficient to separate, at least on a statistical basis, different hadron species even at higher momenta where the energy losses are the same for the different particle species.
- **Track matching:** the matching of the tracks reconstructed in the TPC with the track segments found in the ITS is necessary to have a better determination of the track impact parameter at the interaction point as well as the measurement of secondary vertices which can be located either in the beam pipe or in the ITS. The matching with other detectors (ITS, TRD) also improves the momentum resolution with respect to the TPC stand-alone. In order to increase the matching efficiency, the thickness of the material between the detectors has to be kept to a minimum.
- **Azimuthal coverage:** an azimuthal coverage is necessary in flow analyses which require the event-plane reconstruction. Also processes limited by statistics are favoured from a large azimuthal acceptance.

3.2.3.2 Leptonic observables

There are in ALICE two detectors, the TRD and the Muon Spectrometer, dedicated to the leptonic observables. The TPC is able to track with a good momentum resolution high-mass and high- p_T electron pairs, but in order to distinguish

³In a high multiplicity environment the density of clusters created by the passage of particles in the detector is high. Therefore, the measurement of the energy deposition obtained by the clusters is less accurate because clusters belonging to different particles may overlap.

electrons from pions the TRD is needed. Thanks to the matching of the tracks reconstructed in the TPC with those reconstructed in the ITS, the impact parameter can be determined and thus the production of charmed and beauty particles through their semileptonic decays can be measured. Moreover, impact-parameter measurement can be used to separate directly produced J/ψ mesons from those produced in B-decays.

Even though the needs to perform measurements of leptonic observables are almost the same as the ones listed above for hadronic observables, there are some requirements which are specific for electron physics:

- **Tracking:** the tracking efficiency for tracks with $p_T > 1$ GeV/c that enter the TRD must be as large as possible. According to simulation results, the efficiency at high momenta obtained with the combined tracking (ITS+TPC+TRD) is well above 90%. As far as the momentum resolution is concerned, it should be better than 1.5% in order to keep the electron-pair invariant mass below 1% and resolve the Υ family. Such a resolution can be reached in ALICE with the combined tracking in the magnetic field $B=0.5$ T.
- **High-Level Trigger (HLT):** rare processes like J/ψ and Υ production need a trigger to achieve useful statistics because, as described in the next paragraph, the TPC is a slow detector with limited rate capabilities. The HLT is intended for this task: it finds high-momentum electron tracks in the TRD and matches them to the TPC tracks. The recorded data volume can be then reduced using the ‘region-of-interest’ option of the trigger, i.e. only the sectors of the TPC containing the data about the high- p_T tracks are read out.

3.2.3.3 TPC design considerations

The layout of the TPC is shown in Fig. 3.3 and a synopsis of its main parameters is presented in Table 3.3.

It has a cylindrical shape with an inner radius of about 85 cm, an outer radius of about 250 cm and an overall length of 500 cm.

It is filled with 88 m³ of a mixture of Ne/CO₂ (90%/10%), where the particles ionize; the field cage is made of a material with small radiation length because the material budget is kept as low as possible to ensure minimal multiple scattering and secondary particle production. The TPC material corresponds to about 3.5% of a radiation length.

Even though the material budget is low, the TPC is able to maintain its integrity against gravitational and thermal loads, with a mechanical stability and precision guaranteed to be of about 250 μ m. The drawback of Ne/CO₂ mixture is

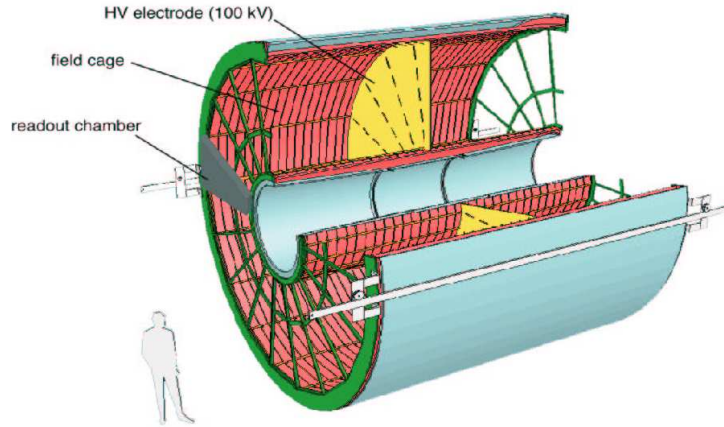


Figure 3.3: Schematic view of the TPC.

that it has a steep dependence of drift velocity on temperature. For this reason, the TPC is aiming for a thermal stability with $\Delta T \leq 0.1$ K in the drift volume over the running period.

The potential needed to drift particles is established between a central electrode and the two end caps: the voltage gradients are very high, 400 V/cm, with a high voltage of 100 kV at the central electrode which results in a maximum drift time of about 90 μ s.

The two end-plates consist of 18 trapezoidal sectors with multi-wire proportional chambers with cathode pad readout: three different sizes of the pads were chosen to keep the occupancy low and to ensure a good spatial and dE/dx resolution. Usually the readout chambers are closed by a gating grid which prevents ionization electrons coming from the drift region to be collected; they are opened only by the L1 trigger (6.5 μ s after the collision) for the duration of one drift-time interval, i.e. of about 90 μ s.

The TPC readout chain has been designed to be able to transfer 200 central or 400 minimum-bias Pb-Pb events per second for the extreme multiplicity case. The recorded data volume can be reduced with the ‘region-of-interest’ option of the trigger, reading out only a few sectors of the TPC. Moreover, the High Level Trigger will help to increase the statistics for rare signals like dielectron pairs selecting only those particles identified as electrons by the TRD.

Further details on the TPC are discussed in the TPC Technical Design Report [134].

Table 3.3: Synopsis of TPC parameters.

Pseudo-rapidity coverage	$-0.9 < \eta < 0.9$ for full radial track length $-1.5 < \eta < 1.5$ for 1/3 radial track length
Azimuthal coverage	2π
Radial position (active volume)	$845 < r < 2466$ mm
Radial size of vessel	$780 < r < 2780$ mm
Length (active volume)	5000 mm
Segmentation in φ	18 sectors
Segmentation in r	2 chambers per sector
Segmentation in z	central membrane, readout on 2 end-plates
Total number of readout chambers	$2 \times 2 \times 18 = 72$
Inner readout chamber geometry	trapezoidal, $848 < r < 1320$ mm active area
pad size	4×7.5 mm ($\varphi \times r$)
pad rows	63
total pads	5504
Outer readout chamber geometry	trapezoidal, $1346 < r < 2466$ mm active area
pad size	6×10 and 6×15 mm ($\varphi \times r$)
pad rows	$64 + 32 = 96$ (small and large pads)
total pads	$4864 + 5120 = 9984$ (small and large pads)
Detector gas	Ne/CO ₂ 90/10
Gas volume	88 m ³
Drift length	2×2500 mm
Drift field	400 V/cm
Drift velocity	2.84 cm/ μ s
Maximum drift time	88 μ s
Total HV	100 kV
Diffusion	$D_L = D_T = 220 \mu\text{m}/\sqrt{\text{cm}}$
Material budget	$X/X_0 = 3.5$ to 5% for $0 < \eta < 0.9$
Pad occupancy (for $dN/dy = 8000$)	40 to 15% inner / outer radius
Pad occupancy (for pp)	5 to 2×10^{-4} inner / outer radius
Event size (for $dN/dy = 8000$)	~ 60 MB
Event size (for pp)	$\sim 1\text{--}2$ MB depending on pile-up
Data rate limit	400 Hz Pb–Pb minimum bias events
Trigger rate limits	200 Hz Pb–Pb central events 1000 Hz proton–proton events
Position resolution (σ) in $r\varphi$	1100 to 800 μm inner / outer radii
in z	1250 to 1100 μm
dE/dx resolution, isolated tracks	5.5%
$dN/dy = 8000$	6.9%

3.2.4 Particle identification system

Particle identification is one of the key points in the ALICE experiment. Besides the TPC and the ITS, there are detectors specifically built to this purpose: the TOF provides identification of charged particles in the intermediate momentum range, the TRD identifies electrons with momenta above 1 GeV/c and the HMPID is able to separate hadrons of higher momenta, up to ~ 5 GeV/c.

3.2.4.1 Transition-Radiation Detector (TRD)

The TRD [132, 135] provides electron identification in the momentum region above 1 GeV/c where the identification through ionization energy loss made by the TPC is no more efficient. This is necessary to measure the production of J/ψ and Υ in their dielectron channel rejecting the background given by Dalitz decays. Furthermore, using the information of the TRD together with the impact-parameter determination in the ITS, it is possible to study mesons with open charm and open beauty via their semi-leptonic decays.

The TRD is composed of several modules, each consisting of a radiator where x-rays are emitted by charged particles per boundary crossing, and a multi-wire proportional readout chamber which detects the x-rays. This detector is useful for particles with Lorentz factor γ larger than 1000, which in practice corresponds to good electron/pion separation for momenta $1 \lesssim p \lesssim 100$ GeV/c.

3.2.4.2 Time-Of-Flight Detector (TOF)

The TOF detector [132, 136] of ALICE covers the central pseudorapidity region ($|\eta| < 0.9$) and plays an important role in the identification of pions, kaons and protons in the intermediate momentum range. This detector is inscribed in a cylindrical shell with an internal radius of 370 cm and an external one of 390 cm for an overall longitudinal length of 7.45 m. Since a large area has to be covered, multi-gap resistive-plate chamber detectors (MRPC) were chosen. When a charged particle traverses the detector, it ionizes the gas producing an avalanche which is driven at the electrodes by the electric field. One feature of the MRPC is that the magnetic field is high and uniform over the whole gaseous volume.

A view of a TOF sector is shown in Fig. 3.4.

The TOF measures the time of flight, defined as the interval between the production of a particle and its detection in the MRPC. Particles with different masses can be separated once that the time of flight and momentum are known. The difference of times of flight of two particles with equal momenta $p_1 = p_2 = p$ is indeed given by:

$$\Delta t = \frac{Lc}{2p^2}(m_1^2 - m_2^2)$$

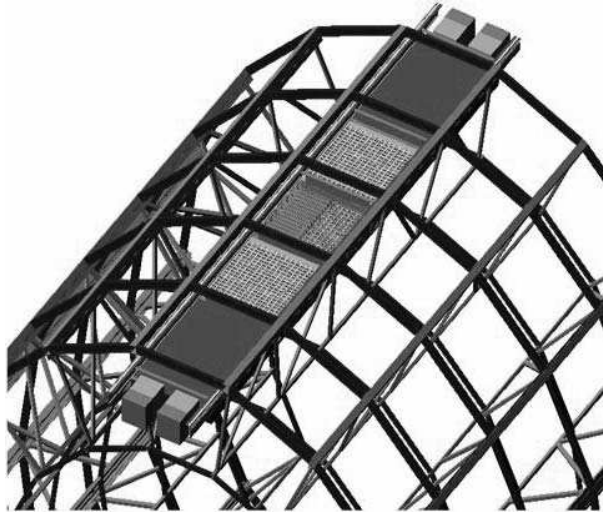


Figure 3.4: TOF sector, consisting of 5 modules inside the space frame.

where L is the track length, p is the momentum and m_1 and m_2 the two masses. In the above formula, the assumption $L_1 = L_2 = L$ was done for simplicity.

The detector has been designed to cope with the highest expected multiplicity ($dN/d\eta = 8000$) with an occupancy not exceeding the 10-15% level; this implies more than 10^5 readout channels.

The time resolution is of the order of 60-80 ps. With a time resolution of 80 ps, the TOF is expected to provide π/K and K/p separation up to a track momentum $p \simeq 2.5$ GeV/c and $p \simeq 4$ GeV/c respectively.

3.2.4.3 High-Momentum Particle Identification (HMPID)

The HMPID [132, 137] identifies hadrons with momenta larger than 1 GeV/c and thus enhances the PID capabilities of ALICE by extending the limited momentum region where particles can be identified through energy loss (in ITS and TPC) and time-of-flight measurements (in TOF).

It allows a good separation π/K and K/p on a track-by-track basis up to 3 GeV/c and 5 GeV/c respectively.

The technology chosen for such purposes is that of Ring-Imaging Cherenkov counters (RICH); the HMPID consists of seven modules of about 1.5×1.5 m² each, mounted on a cradle which will be fixed to the space frame in the two o'clock position at distance of ~ 4.5 m from the beam direction: the acceptance is only 5% of the central barrel detectors (see left panel of Fig. 3.5).

The radiator is a thick layer of C₆F₁₄ (perfluorohexane) with an index of

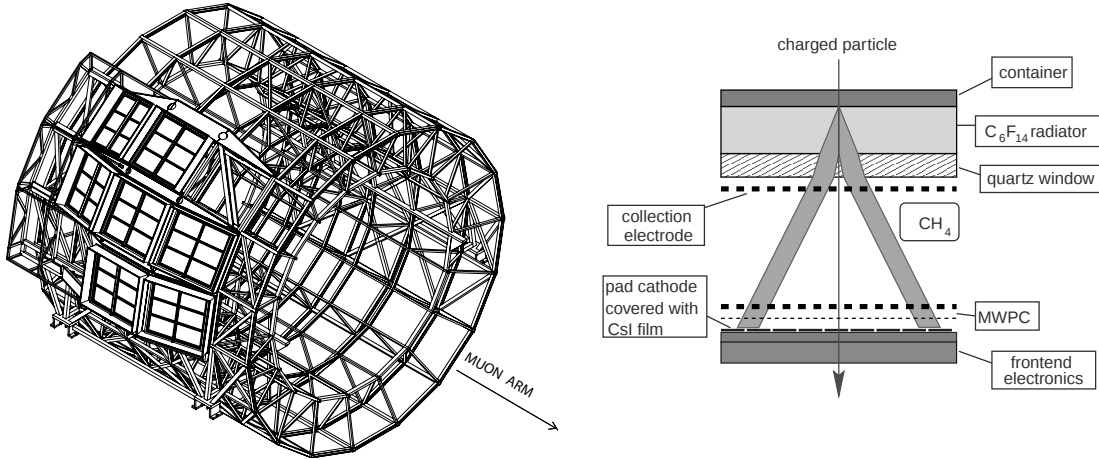


Figure 3.5: Left panel: view of the HMPID with cradle and space frame. Right panel: working principle of a RICH detector.

refraction $n = 1.2989$ at $\lambda = 175$ nm, corresponding to a momentum threshold of $p_{th} = 1.21 \times m$ where m is the particle mass. When a particle crosses the radiator with a velocity larger than the light velocity in the same medium, it emits Cherenkov photons which are detected by a photon counter made of CsI located on the pad cathode of a Multi-Wire Pad Chamber (MWPC). The working principle of the RICH detector is shown in the right panel of Fig. 3.5.

With its surface of about 10 m^2 , the HMPID represents the largest scale application of this technique.

3.2.5 Photon Spectrometer (PHOS)

The PHOS [132, 138] is a high resolution electromagnetic calorimeter dedicated to the detection of photons directly coming from the interaction point and neutral mesons like π^0 and η through their decay in two photons. Since the main task of the detector is to distinguish between direct photons and photons coming from particle decays, it has to be characterized by a high granularity and good spatial and energetic resolution. The segmentation must be below the Molière radius⁴ of the material. The calorimeter is made of lead tungstate crystals, PWO, grouped

⁴The Molière radius is a constant describing the electromagnetic characteristics of the material:

$$R_M = 0.0026 X_0 (Z + 1.2),$$

where X_0 is the radiation length and Z is the atomic number. R_M is related to the transverse dimension of the electromagnetic shower in the calorimeter, thus the smaller is R_M , the better is the capacity of the calorimeter to contain the shower.

in five modules; this material has a Molière radius equal to 2 cm.

The PHOS is located at 460 cm from the interaction point and covers approximately a quarter of a unity in pseudorapidity, $-0.12 \leq \eta \leq 0.12$, and 100° in azimuthal angle. Its total area is $\sim 8 \text{ m}^2$.

3.2.6 Electromagnetic Calorimeter (EMCal)

The main physics motivation for the EMCal [139] is to improve the ALICE performances for an extensive study of jet quenching: in fact the EMCal extends the ALICE p_T capabilities for jets, direct photons and electrons from heavy-flavour decays.

The detector contains several modules each consisting of sampling calorimeters made of alternating layers of 1.44 mm Pb and 1.76 mm polystyrene, which is the scintillating material. The EMCal covers the pseudorapidity range $-0.7 \leq \eta \leq 0.7$.

Due to the installation of the PHOS and the HMPID respectively below and above the TPC, the EMCal is limited to a region of about 110° in azimuth above the TPC and adjacent to the HMPID. It is positioned to provide partial back-to-back coverage with the PHOS. Its nominal acceptance is about 25% of the TPC acceptance.

3.2.7 Forward Muon Spectrometer

With the forward muon spectrometer [140] it will be possible to study resonances like J/ψ , ψ' , Υ , Υ' and Υ'' through their decay into $\mu^+\mu^-$ pairs, and to disentangle them from the continuum given by Drell-Yan processes and semi-leptonic decays of D and B mesons. It will also be interesting the study of open heavy flavour production in the muon spectrometer, accessible through measurements of $e - \mu$ coincidences, where the muon is detected by the muon spectrometer and the electron by the TRD.

A resolution of $70 \text{ MeV}/c^2$ in the $3 \text{ GeV}/c^2$ region is needed to resolve J/ψ and ψ' peaks and of $100 \text{ MeV}/c^2$ in the $10 \text{ GeV}/c^2$ region to separate Υ , Υ' and Υ'' .

This detector is located around the beam pipe and corresponds to the pseudorapidity range $-4.0 \leq \eta \leq -2.5$. It consists of a passive front absorber to absorb hadrons and photons from the interaction vertex. The material must have a small

interaction length⁵ in order to absorb hadrons and a large radiation length, and thus small Z ($X_0 \propto 1/Z$ [84]), in order to reduce multiple scattering.

muon tracks are then reconstructed by tracking chambers consisting of multi-wire proportional chambers with cathode pad readout. They are embedded in a magnetic field generated by a dipole magnet located outside the L3 magnet. The trigger on dimuon signals is done by four layers of RPC operating in streamer mode located behind a second absorber.

3.2.8 Forward rapidity detectors

To complete the experimental apparatus there are detectors located at small angles with respect to the beam axis.

The Zero-Degree Calorimeter (ZDC) [141] measures the energy of the spectator nucleons and thus provides information on the centrality of the collision: in fact, the zero degree forward energy decreases with increasing centrality. Furthermore, the ZDC allows to perform flow analyses because it can estimate the reaction plane through the directed anisotropy (see Chapter 1).

The ZDC consists of two calorimeters, one for neutrons and one for protons. Two ZDCs will be symmetrically installed with respect to the interaction point, at a distance of 116 m from the interaction point. The adopted technique for this detector is to alternate a dense absorber (passive material), where incident particles originate showers, and quartz fibres (active material), where the showers produce Cherenkov radiation in boundary crossings. Because of the incomplete fragmentation of the spectator nucleons, the correlation between the ZP (proton calorimeter) and the ZN (neutron calorimeter) is not enough to determine the centrality of the collision. Thus, ZDC project includes also an electromagnetic calorimeter (ZEM) to solve the ambiguity due to fragment production. The ZEM is designed to measure, event by event, the energy of photons emitted at forward rapidities coming from π^0 decays.

The Photon Multiplicity Detector (PMD) [142] measures the multiplicity and the spatial distribution of photons on an event-by-event basis in the forward region of ALICE. It consists of two planes of multi-wire proportional counters having honeycomb structure with a thick lead converter in between them.

The PMD will be placed at 360 cm from the interaction point, on the opposite side of the forward muon spectrometer, covering the region $2.3 \leq \eta \leq 3.5$.

The Forward Multiplicity Detector (FMD) [143] provides information on the

⁵The nuclear interaction length is given roughly by [84]:

$$\lambda_I \approx 35 \text{ g cm}^{-2} A^{1/3}$$

The smaller is λ_I , the smaller is the hadronic shower inside the material.

charged-particle multiplicity in the pseudorapidity ranges $-3.4 \leq \eta \leq -1.7$ and $1.7 \leq \eta \leq 5.1$. With this detector it will be possible to extend the pseudorapidity coverage of multiplicity measurements, to study multiplicity fluctuations on an event-by-event basis and to perform flow analyses. The FMD consists of five rings of silicon strip detectors, two of which are installed on the muon absorber side where the available space is most restrained; the remaining three are located on the opposite side of the interaction point.

The T0 [143] detector, made of 24 Cherenkov radiators, generates the T0 signal for the TOF detector with a precision of ~ 50 ps, measures a rough vertex position, provides a first level trigger and helps to discriminate against beam-gas interactions.

The V0 [143] detector, consisting of scintillators, provides a minimum bias trigger for the central barrel detectors and can be used as a centrality indicator.

Both the T0 and V0 consist of two modules installed on each side of the interaction point.

3.3 Trigger and Data acquisition

3.3.1 Trigger system

The trigger system [144] in ALICE is studied to be able to select events with different features depending on the physical interests and must be optimized to work both in nucleus-nucleus and pp collisions.

The trigger includes three levels (L0, L1 and L2) and the so called High Level Trigger (HLT). The trigger system is monitored by the Central Trigger Processor (CTP) which receives inputs from the trigger detectors and sends decisions to the other detectors for the data acquisition. The first trigger input is the ‘TRD pre-trigger’ consisting of signals from T0 and V0 detectors which are sent to the TRD in less than 100 ns after the collision, where they wake-up the TRD electronics, which otherwise would be in a standby state. The Level 0 (L0) trigger is sent to the detectors at $1.2 \mu\text{s}$: the latency of this fast signal is due both to the time required by the electronics to elaborate the signal (order of ns) and to the time needed to propagate through the cables (order of μs). The latency is fixed in order to know the time of the collision. The L0 signal is too fast to be able to receive all the trigger inputs, therefore a Level 1 (L1) signal is sent at $6.5 \mu\text{s}$ to pick up all remaining fast inputs. If the L1 decision reaches the fast detectors, they start the data conversion and bufferization on a temporary ring memory. The latency of L1 ($\sim 5.5 \mu\text{s}$) has been chosen to allow the bufferization of the SDD of the ITS, whose drift time is of the order of $5 \mu\text{s}$. The expected trigger inputs for L0 and L1 are listed in Table 3.4.

Table 3.4: List of trigger inputs for Pb–Pb and pp interactions.

L0 (Pb–Pb)	L0 (pp)	L1 (Pb–Pb)
V0 minimum bias	V0 minimum bias	TRD unlike e pair high p_T
V0 semi-central	V0 high multiplicity	TRD like e pair high p_T
V0 central	V0 beam gas	TRD jet low p_T
V0 beam gas	T0 right	TRD jet high p_T
T0 vertex	T0 left	TRD electron
PHOS MB	T0 vertex	TRD hadron low p_T
PHOS jet low p_T	PHOS MB	TRD hadron high p_T
PHOS jet high p_T	PHOS jet low p_T	ZDC 1
EMCAL MB	PHOS jet high p_T	ZDC 2
1EMCAL jet high p_T	EMCAL MB	ZDC 3
EMCAL jet med p_T	EMCAL jet high p_T	ZDC special
EMCAL jet low p_T	EMCAL jet med p_T	EMCal e, γ, π^0
Cosmic Telescope	EMCAL jet low p_T	EMCal jet
DM like high p_T	Cosmic Telescope	Topological 1
DM unlike high p_T	DM like high p_T	Topological 2
DM like low p_T	DM unlike high p_T	
DM unlike low p_T	DM like low p_T	
DM single	DM unlike low p_T	
TRD pre-trigger	DM single	
TRD pre-trigger		

The third trigger level (L2) fulfils the request to avoid piled-up events. The event pile-up will be frequent and in some cases unavoidable in ALICE, because of the slow detectors in ALICE and the high luminosity reached with LHC. The TPC is the slowest detector with a drift time of $88\mu\text{s}$ and thus it will be affected by pile-up: it may indeed happen either that in the TPC there are still the drift charges of the previous event when the interesting event is coming, or that a subsequent event is triggered before the interesting one has been registered. In order to avoid such a problem, the Central Trigger Processor makes use of the ‘past-future protection’, which rejects any other event occurring within a specified time window. The time window is set equal to the sensitive window for the TPC, $\pm 88\mu\text{s}$ centered on the event under consideration: if two events are separated by less than $88\mu\text{s}$, their pile-up is unavoidable.

In Pb-Pb collisions, the past-future protection accepts no more than 4 additional peripheral events and no additional semi-central events to take place in an interval of $176\mu\text{s}$ centered on the interesting event. In case of proton-proton

collisions, given the increased luminosity, the pile-up becomes a certainty; nevertheless, if it is possible to distinguish multiple event vertices, the pile-up is more tolerable because the multiplicities are much lower than in nucleus-nucleus interactions. The approach adopted in this case is to control with the past-future protection not only the TPC but also the other detectors: for example, pile-up in the ITS is serious for the reconstruction of primary vertex. Therefore, the past-future protection checks two different time windows ($\pm 10 \mu\text{s}$ for the ITS, whose drift detectors have a drift time of $\sim 5 \mu\text{s}$, and $\pm 88 \mu\text{s}$ for the TPC), to ensure that pile-up is not excessive. The L2 trigger waits for the end of the past-future protection interval to verify that the event can be registered. When the CPT sends the L2 decision the event is ready to be transferred to the Data Acquisition system (DAQ).

The L0 and L1 trigger levels may also include signals coming from detectors specific for certain analyses, like the Muon Spectrometer, the TRD, the PHOS and the EMCal. The trigger given by Muon Spectrometer is used to select only those events containing a pair of muons with p_T above than a given threshold. The trigger given by the TRD allows the selection of events containing high- p_T electron pairs or jets. Finally, with the PHOS and the EMCal it is possible to trigger events with photon jets, with photons plus jets, and with very high- p_T jets.

At the nominal luminosity of $10^{27} \text{ cm}^{-2}\text{s}^{-1}$ the interaction rate will be 8000 Hz for Pb-Pb: with such conditions, the maximum total rates of the different trigger levels will be of 1300 Hz and 1100 Hz for L0 and L1 respectively. These numbers are reduced in case of additional selections on centrality or dimuon event candidates are required. The L2 rate using the TPC for triggering on minimum bias events will be 40 Hz. The rates can be reduced applying downscaling factors.

3.3.2 Data Acquisition (DAQ) System

The main functions of the DAQ system [144] are the following:

- data transfer from the front-end electronics to the control room; this is done in parallel for all the sub-detectors. The transfer is initiated by the L2 trigger;
- event building, performed by the Global Data Collectors (GDC);
- archive data to mass storage Permanent Data Storage (PDS).

The estimated bandwidth to mass storage is 1.25 GB/s, even though the maximum real amount of readout data is $\sim 25 \text{ GB/s}$.

According to simulation results, the event size of Pb-Pb collisions is rather big: $\sim 86.5 \text{ MB}$ for central events, 50% and 25% of that size for semi-central and

minimum bias events respectively. ALICE DAQ is designed to cope with the event sizes resulting from heavy-ion collisions by using a combination of increased trigger selections and data compression.

3.3.3 High-Level Trigger (HLT)

As a multi-purpose experiment, ALICE searches for a large number of probes such as open charm and beauty, quarkonia, direct photons, jets, correlations. Since most of the probes are rare signals, it is necessary to exploit all the data collected with a collision rate of 8 kHz for Pb-Pb. It may happen that the remaining data rate after the three trigger levels are still high to be transferred to the permanent storage system. The HLT [144] works online to reduce such data rate by improving particle identification and momentum resolution, or by selecting regions of interest like jet regions, or by filtering out low momentum tracks in the TPC.

The HLT system is located in the data flow between the front-end electronics and the event building of the DAQ system.

Ongoing studies suggest the feasibility of an open charm trigger for the ALICE HLT. The cut variables used for the online selection of $D^0 \rightarrow K^- \pi^+$ candidates are the same as those used for the offline analysis: track transverse momentum and impact parameter, product of the impact parameters, distance of closest approach between the two tracks, pointing of the reconstructed charmed particle to the primary vertex, ... The HLT efficiency is reasonably good although smaller than the offline one, with the advantage that the data-rate is considerably reduced.

As far as a HLT for D^+ mesons is concerned, a dedicated study is required, also because pions and kaons coming from D^+ hadronic decays ($D^+ \rightarrow K^- \pi^+ \pi^+$) are softer than those coming from D^0 , making more difficult a cut on high transverse momentum.

In addition, in order for the HLT system to work, an online knowledge of the alignment of the subdetectors is mandatory, and this is a difficult task especially for the first runnings.

On the other hand, the hardware trigger on high- p_T leptons given by the TRD (for electrons) and the muon spectrometer (for muons) could be used for open charm semi-leptonic decays ($D^0 \rightarrow K^- l^+ \nu_l$ for example is the most promising decay channel): nevertheless it must be said that such analyses are less clean than the hadronic ones, which can be studied in ALICE because the ITS allows the reconstruction of secondary vertices.

3.4 LHC experimental conditions

Whether ALICE will reach its physics goals will depend not only on the performance of the detectors, but also on the statistics available. The number of collected events depend on the nature of the beam, on the luminosity and on the running time.

Like the SPS and RHIC programs, the heavy-ion program at LHC will be based on colliding both the largest available nuclei at the highest energy, and different collision systems (pp, pA, AA) with various energies.

The LHC yearly program will consist of several months of pp running followed at the end of each year by several weeks of heavy-ion collisions. The effective running time per year is foreseen to be 10^7 s for pp and 10^6 s for heavy ions.

ALICE will start its data taking with pp collisions because the LHC will accelerate proton beams at first. At the end of the first pp run, a Pb-Pb run is foreseen, even though of short duration and with low luminosity. Nevertheless, it will allow studies on global event properties and on large cross section observables; in order to study low cross section signals, in particular hard processes such as those containing charm and beauty, further 1-2 years of Pb-Pb will be required in order to collect enough statistics.

The ALICE program is related to the LHC one and is summarized below:

- regular pp collisions at center-of-mass energy of $\sqrt{s} = 14$ TeV;
- first Pb-Pb short run (pilot run);
- 1-2 years of Pb-Pb at $\sqrt{s_{NN}} = 5.5$ TeV per nucleon pair;
- 1 year of pA-like collisions (pPb, dPb, α Pb);
- 1-2 years of Ar-Ar.

The program includes pA runs because pA collisions allow to determine nuclear modifications on the parton distribution functions (nuclear shadowing). The study of Ar-Ar collisions has been proposed to study how the energy density varies with the mass of the collision systems. Additional Pb-Pb runs at lower energies are also foreseen in order to connect LHC results with those from RHIC.

The LHC will accelerate protons at the maximum energy of $\sqrt{s} = 14$ TeV; this puts a constraint on the maximum center-of-mass energy for heavy-ion collisions. Since only charged particles are effectively accelerated, the Z protons inside a nucleus will drag the $A - Z$ neutrons, resulting in an average momentum of the nucleons of $\frac{Z}{A}p$, where p is the momentum of the protons in case they are not bound into the nucleus.

Considering two colliding nuclei, the center-of-mass energy per nucleon pair s_{NN} is therefore given by:

$$s_{NN} = \left(\frac{Z_1}{A_1} \tilde{p}_1 + \frac{Z_2}{A_2} \tilde{p}_1 \right)^2 = 2 \frac{Z_1}{A_1} \frac{Z_2}{A_2} \tilde{p}_1 \cdot \tilde{p}_1 \quad (3.1)$$

where $Z_{1(2)}$ and $A_{1(2)}$ are the atomic and mass numbers for the two ions. $\tilde{p}_1 = (p, \vec{p})$ and $\tilde{p}_2 = (p, -\vec{p})$ are the four-momenta of the two incoming protons. In the second passage, the approximation $E \gg m$ has been taken into account. We also considered $\hbar = c = 1$.

Since in the above approximation the center-of-mass energy for the proton pair is $s_{pp} = 2\tilde{p}_1 \cdot \tilde{p}_2$, we have:

$$s_{NN} = \frac{Z_1 Z_2}{A_1 A_2} s_{pp} \quad (3.2)$$

Considering Pb ions with $Z_1 = Z_2 = 82$ and $A_1 = A_2 = 207$, we find $\sqrt{s_{NN}} = 5.5$ TeV.

Comparing different systems (pp, pA, AA), also the rapidity $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$ behaves differently: in case of pp or symmetric heavy-ion collisions, the rapidity of the system made of two colliding nucleons is identically zero in the laboratory frame because the total longitudinal momentum of the pair of incoming hadrons is zero. On the contrary, for asymmetric systems the four momenta of two incoming nucleons are not the same in the laboratory frame:

$$\tilde{p}_1 = (p, 0, 0, p) \frac{Z_1}{A_1}, \quad \tilde{p}_2 = (p, 0, 0, -p) \frac{Z_2}{A_2} \quad (3.3)$$

where $(p, 0, 0, \pm p)$ are the proton four-momenta above defined and the transverse momenta have been neglected.

The rapidity of the nucleon pair in the laboratory system undergoes a shift:

$$y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z} = \frac{1}{2} \ln \frac{(p \frac{Z_1}{A_1} + p \frac{Z_2}{A_2}) + (p \frac{Z_1}{A_1} - p \frac{Z_2}{A_2})}{(p \frac{Z_1}{A_1} + p \frac{Z_2}{A_2}) - (p \frac{Z_1}{A_1} - p \frac{Z_2}{A_2})} = \frac{1}{2} \ln \frac{Z_1 A_2}{Z_2 A_1} \quad (3.4)$$

3.4.1 Luminosity determination

The luminosity $\mathcal{L}$ is a parameter of the accelerating machine relating the process rate R to its cross section σ :

$$R = \mathcal{L} \sigma$$

In case of two colliding beams (for example at LHC), the luminosity is given by the following relation:

$$\mathcal{L} = f N_b \frac{N^2}{4\pi \sigma_x \sigma_y} F \quad , \quad (3.5)$$

where f is the revolution frequency, N_b the number of bunches, N the number of particles per bunch. The quantity $4\pi\sigma_x\sigma_y$ indicates the transverse area of the two bunches in the interaction point; it is calculated assuming a Gaussian distribution of the transverse spot of the two beams with horizontal and vertical standard deviations σ_x and σ_y respectively. The factor F is related to the finite crossing angle of the beams and depends on the ratio between longitudinal and transverse beam sizes.

The TOTEM experiment [145] will measure the total pp cross section at LHC. In ALICE only a fraction of the rate of inelastic pp cross section is measured ($R = a \cdot R_{tot}$, where a is the detector acceptance); the luminosity is then given by:

$$\mathcal{L} = \frac{R}{a \cdot \sigma_{inel}} \quad (3.6)$$

The total pp cross section ($\sigma \sim 100$ mb) is the sum of the elastic ($\sigma_{el} \sim 28$ mb) and inelastic events ($\sigma_{inel} \sim 72$ mb). The inelastic interactions include non-diffractive ($pp \rightarrow XY$, $\sigma_{nd} \sim 60$ mb) and diffractive processes (like $pp \rightarrow pX$, $\sigma_{sd} \sim 12$ mb) [130, 131]. The V0 scintillator array is able to trigger on both non-diffractive and diffractive collisions.

One possible way to monitor the luminosity in Pb-Pb runs with ALICE is to measure the total hadronic cross section, mainly given by the geometry of the collision and known with an accuracy better than 10%. Measuring the hadronic interaction rate, the luminosity is then $\mathcal{L} = \mathcal{R}_{had}/\sigma_{had}$.

3.4.1.1 Pb-Pb collisions

The luminosity for Pb-Pb collisions is given by the accelerating machine. The maximum rate is limited by the ALICE detectors, mainly by the TPC and the Forward Muon Spectrometer. The TPC limits the sustainable rate because of event pile-up during the 90 μ s drift time; another constraint comes from the RPC of the muon spectrometer, which has a maximum acceptable illumination of 50-100 Hz/cm².

The maximum expected value for the luminosity in Pb-Pb is 10^{27} cm⁻²s⁻¹; the total hadronic cross section is 8 b, thus the expected rate is ~ 8000 Hz, 10% of which are central. Of course, as discussed in Section 3.3.1, the trigger rate is less than 8000 Hz.

3.4.1.2 pp collisions

In order to keep the event pile-up at an acceptable level in the TPC and in the drift detectors of the ITS, the luminosity has to be limited to $\simeq 5 \times 10^{30}$ cm⁻²s⁻¹, corresponding to an interaction rate of $\simeq 200$ kHz. Thus, the luminosity has to

be reduced comparing to the dedicated high-luminosity LHC experiments where $\mathcal{L} \simeq 10^{34} \text{ cm}^{-2}\text{s}^{-1}$: this is done by de-focusing the beams in an appropriate way.

3.4.1.3 pA collisions

ALICE program includes also pA collisions in order to investigate nuclear effects in particle production.

With the same collision rate of 200 kHz as for pp collisions, the expected luminosities are $1.1 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ and $3 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ for pPb and pAr collisions, respectively.

Since pA collisions are asymmetric systems, the center-of-mass energy per nucleon pair is higher in pA collisions ($\sqrt{s_{pA}} = 14 \text{ TeV} \times \sqrt{Z/A}$) compared to AA ones ($\sqrt{s_{AA}} = 14 \text{ TeV} \times \sqrt{Z/A}$). The $\sqrt{s_{pA}}$ can be possibly changed to match the $\sqrt{s_{AA}}$.

Collisions of very low mass ions, such as d or α , are also foreseen at $\sqrt{s_{NN}} = 7 \text{ TeV}$. The required luminosities are $1.1 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ and $6.2 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ for dd and $\alpha\alpha$, respectively. These collisions have the additional advantage of contributing to the cross section with factors 4 (dd) and 16 ($\alpha\alpha$) respect to pp collisions, thus compensating for the shorter running period.

3.5 Radiation damage

The radiation dose on the various detectors of ALICE depends on the beam type, on the luminosity and on the running time. The main sources of radiation in ALICE are the following:

- particles produced at the interaction point;
- beam losses due to mis-injection: ALICE will receive such radiation because it is placed near the injection point in the beam pipe;
- beam-gas interactions.

The major contribution comes from the second point; beam losses and beam-gas interactions contribute 10% and 1% respectively to the radiation fluency. In Table 3.5 a typical scenario for ten years of LHC operation is presented. The last line, showing the total number of charged particles, suggests that 80% of the radiation dose is from pp and Ar-Ar interactions.

Another possible source of radiation is due to thermal neutrons. They come from scatterings of highly energetic neutrons largely produced through hadronic

Table 3.5: Operation scenario for a ten-year run period, where $\langle \mathcal{L} \rangle$ is the mean luminosity, and σ_{inel} is the inelastic cross section. One year of pp run corresponds to 10^7 s and one year of heavy-ion run corresponds to 10^6 s.

	pp	Ar–Ar	Ar–Ar	Pb–Pb	dPb
$\langle \mathcal{L} \rangle$ ($\text{cm}^{-2}\text{s}^{-1}$)	3×10^{30}	3×10^{27}	10^{29}	10^{27}	8×10^{28}
σ_{inel} (mb)	70	3000	3000	8000	2600
Rate (s^{-1})	2×10^5	9×10^3	3×10^5	8×10^3	2×10^5
Runtime (s)	10^8	1.0×10^6	2.0×10^6	5×10^6	2×10^6
Events	2×10^{13}	9×10^9	6×10^{11}	4×10^{10}	4×10^{11}
Particles per event	100	2400	2400	14 200	500
N_{tot}	2.1×10^{15}	2.2×10^{13}	1.4×10^{15}	5.7×10^{14}	2×10^{14}

cascades in the ALICE absorbers. According to the present estimates, each minimum bias event produces approximately 50 thermal neutrons per m^2 at a distance of 5 m from the interaction point.

Since the average time between two Pb-Pb collisions, $\sim 100\mu\text{s}$, is much larger than the decay time of the neutron signal, the thermal neutron contribution to the radiation dose is expected to be negligible.

Chapter 4

Simulation tools for heavy flavour analyses

This chapter describes the software environment which was used and developed to produce the results presented in this work. A brief description of the ALICE offline framework, AliRoot, is given, including a section dedicated to the event generators used for heavy-ion and pp collisions and specific for charm analyses. Then, the Grid project used to generate the events needed for the analysis is presented. Finally, a description of the ALICE performance required for open charm studies is given.

4.1 ALICE offline framework

The main task of the offline project of the ALICE experiment is to reconstruct and analyse data coming from simulated or real collisions. This is done by means of programs based on Object-Oriented techniques. The software environment specifically introduced in 1998 for the ALICE offline is called AliRoot and is based on the ROOT framework.

ROOT [146] is an Object Oriented framework written in C++ language; its architecture consists of about 650 classes, most of which inherit from common base classes.

The ROOT structure is well suited to manage with enormous amounts of data coming from high energy physics (HEP) experiments, in fact it provides the packages for event generation, detector simulation, event reconstruction, data acquisition and data analysis, as schematically shown in Fig. 4.1.

AliRoot was developed as an extension of ROOT to include the geometry of the detectors, their typology and their response to the passage of particles. The basic principles taken into account in the design of AliRoot are modularity and

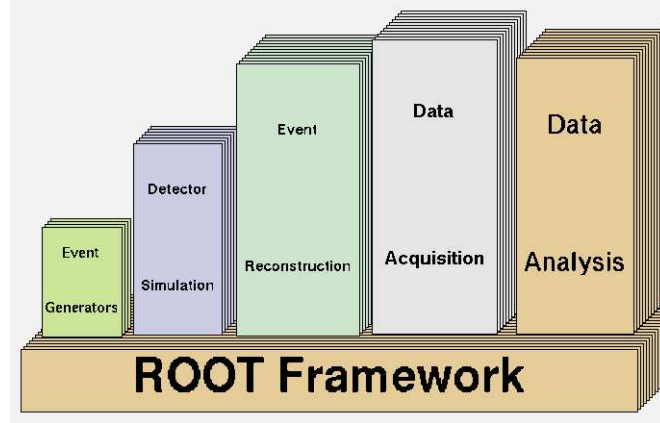


Figure 4.1: The ROOT framework and its application to HEP. Taken from [147, 148].

re-usability. Modularity allows the user to choose different parts of the code (i.e. different event generators, different reconstruction algorithms,...) without changing the structure of the system. Re-usability means to maximize the possibility of using the code even if the system is evolving.

The scheme of the AliRoot framework is shown in Fig. 4.2. The central module, called STEER, coordinates all the system providing an interface to detector specific code, to event generators, to Monte Carlo simulators and to steering classes for reconstruction. The event generators are grouped in the EVGEN module. They include generators based on microscopic models, which were developed outside the ALICE Collaboration (see Section 4.3); they are mostly written in FORTRAN language and are interfaced via wrapping classes. In addition, other generators were developed on purpose by the ALICE Collaboration with the aim of testing the detector performance: they include parametrizations of microscopic models, generators of specific particles with defined momentum and cocktails of different generator types.

AliRoot allows the use of three different Monte Carlo transport programs: GEANT3 [149] and FLUKA [151] are written in FORTRAN; GEANT4 [150] is written C++. GEANT3 is the one so far used, FLUKA is thought to be the one ALICE will use in the future.

The sub-detectors provide independent modules with specific code for simulation and local reconstruction. The information coming from the local reconstruction in each sub-detector is grouped in a global event reconstruction, which provides track reconstruction, primary and secondary vertices, particle identification,...

The output of the global reconstruction is detector independent and is contained in the ESD (Event Summary Data) structure, not shown in Fig. 4.2. The ESD module is well established and is used as a starting point for the analysis.

Another module not shown in the figure and still under development is the analysis package AOD (Analysis Object Data Set): it will contain all the classes needed for the various analyses, like reconstruction of open charmed mesons with two or three prongs, hyperon reconstruction, . . . In the current project, the AOD object is divided in different sub-groups, about one for each analysis, so that the user can retrieve only the object concerning the analysis of interest. The AOD module is also detector independent.

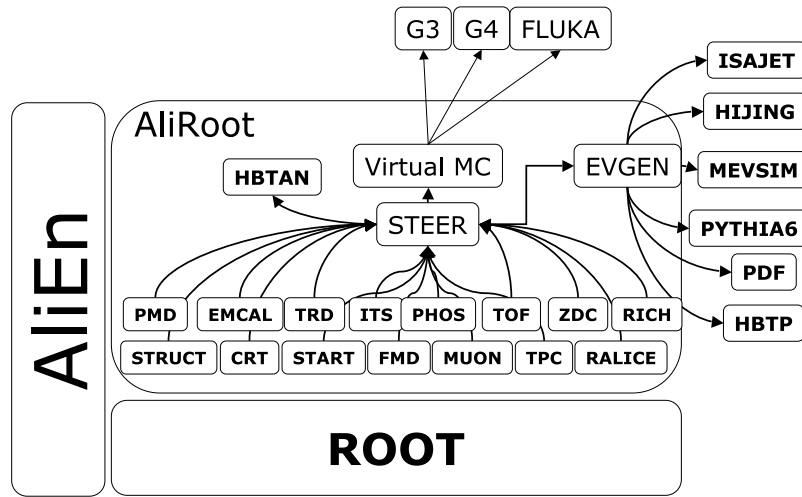


Figure 4.2: The AliRoot framework. Taken from [147,148].

Fig. 4.2 shows also that AliRoot is interfaced to a module AliEn, which allows productions on large scale using the distributed resources and the Grid project. A more detailed description of the distributed computing is given in Section 4.2.

4.2 Distributed computing and the Grid

All the LHC experiments will make use of unprecedented computing resources, in fact for ALICE a data acquisition rate of 1.25 GB/s in heavy-ion mode and

about 5 PB of data stored on tape each year are foreseen. As a consequence, it is unlikely to have enough data processing and storage resources located in a single computing centre; it is indeed more natural to distribute these resources across the institutes and universities participating in the experiments. This is done according to the MONARC model (Models of Networks Analysis at Regional Centres for LHC Experiments) [156] schematically shown in Fig. 4.3.

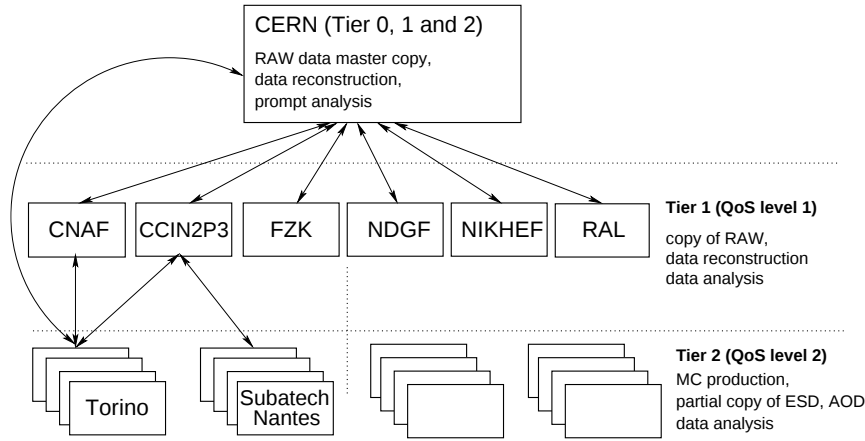


Figure 4.3: Schematic view of the ALICE computing tasks in the framework of the MONARC model. Taken from [148].

In this framework, the available computing resources are arranged in different tiers: Tier 0 is located at CERN, where the raw data directly coming from the experiments will be stored; a second copy will be distributed among the external Tier 1 centres, which are the biggest computing centres, whose additional task will be also the reconstruction of the events. Regional Tier 2 centres will contribute to perform Monte Carlo simulations and to produce files ready to be taken by the single users for the analyses.

This model can be realized with the use of the Grid. The Grid is a project currently under development which allows the sharing of computing resources over large scale. The activity of the Grid is controlled by a “middleware” which manages the distributed computing among a dynamical ensemble of institutions called “virtual organizations”. A “resource broker” has the task of sending the jobs in selected centres: in this sense the Grid has a “push” architecture where a central service assigns the jobs to remote queues. The main Grid functions are summarized in the following:

- authentication: before submitting a job on the Grid, the user must be authenticated and authorized by the Grid services;

- job management: once the user sends a job to the Grid via a local User Interface (UI), the resource broker assigns the job to a Computing Element (CE), monitors the job while it is running and stores the output files on a Storage Element (SE);
- file catalogue: output files are also registered in a virtual catalogue, which keeps the association between a unique Logical File Name (LFN) and the one or more Physical File Names (PFN) that describe physical replicas of the file located on the Storage Elements.

The ALICE experiment has developed a software based on the Grid technology and specifically prototyped to satisfy the ALICE demands: AliEn (ALICE production Environment) [157]. It maintains interoperability with EDG-LCG¹ Grid projects but, as opposed to the “push” architecture, AliEn system is based on a “pull” approach: according to this model, the submitted jobs are sent to a central queue and the local centres which satisfy the specific requirements of the job pull down the job from the queue and execute it locally, whenever they have available resources.

The events needed for this thesis work were produced using the LCG Grid project, with middleware and broker developed by EDG and its successors EGEE (Enabling Grid for E-science) and EGEE-II. The file catalogue used was LFC (LCG File Catalogue). We chose not to use AliEn because at the time of our production the software was still in a development and improving phase, and consequently it was not stable. The files were then moved from the LFC catalogue to the AliEn one.

4.3 Event generators

Since ALICE will study both pp, pA and heavy-ion collisions, the simulation tools must include generators for all the interaction typologies.

As discussed in Chapter 1, theoretical models give different predictions for the expected multiplicity in nucleus-nucleus collisions at LHC energies. Thus, different generators with different predictions for the multiplicity, p_T and rapidity distributions were developed in the 80s and 90s.

It must be taken into account that the results from RHIC on particle multiplicities in Au-Au collisions are not reproduced by any of the available generators.

Furthermore, the existing generators do not exactly reproduce several physics signals, like exclusive channels. Finally, the existing generators do not simulate

¹EDG is the European Data Grid; LCG (LHC Computing Grid) was developed on purpose for the LHC.

correctly some features like particle correlations, flow and quark energy loss in nuclear medium, also because the theory behind these phenomena is still not completely clear.

The main generators used for hadron-hadron collisions are PYTHIA [72] and HERWIG [83]. The available generators for heavy-ion interactions are: HIJING [152], DPMJET (Dual Parton Model Jet) [153] and SFM (String Fusion Model) [154]. The charged particle density predicted by these generators ranges widely at the LHC energy, from $dN/dy \simeq 2000$ (SFM) to $dN/dy \simeq 6000$ (HIJING).

The generators used for the work presented here are HIJING and PYTHIA for Pb-Pb and pp collisions respectively. These generators are also the ones chosen by the ALICE collaboration for the official productions of the Physics Data Challenges (PDC).

HIJING (Heavy Ion Jet Interaction Generator) is the generator specific for the simulation of nucleus-nucleus collisions. Such a Monte Carlo model was developed in the 90s with the important task of serving as theoretical laboratory to test the probes of the ultradense matter created in nuclear collisions at ultrarelativistic energies of $\sqrt{s_{NN}} \geq 200$ GeV/c.

The model includes multiple minijet production and some processes typical of dense matter created in nuclear collision, like nuclear shadowing of parton distribution functions and a schematic mechanism of jet interactions in the medium. The multiple jet interaction is incorporated in HIJING according to the pQCD approach of PYTHIA. This is relevant because the hard processes, like jet production, play a crucial role at RHIC and are expected to be important also at the LHC.

The PYTHIA program generates sets of outgoing particles produced in pp interactions. The objective is to reproduce the real high-energy physics event as much accurately as possible. Since the physics processes are not fully calculable because of non-perturbative contributions, the generator includes both analytical results and QCD-based models. PYTHIA is a leading order generator, i.e. in case of charm production only processes like $q\bar{q} \rightarrow Q\bar{Q}$ and $gg \rightarrow Q\bar{Q}$ are considered. Nevertheless, higher order contributions [155], though not exactly at next-to-leading order, are included in the generator, allowing flavour excitation processes like $qQ \rightarrow qQ$ and $gQ \rightarrow gQ$, and the gluon splitting $g \rightarrow Q\bar{Q}$. However, these processes are calculated with massless matrix elements and their cross section diverges as p_T^{hard} goes to zero. The divergencies can be controlled using a lower cut-off on p_T^{hard} ; the value of p_T^{hard} has a large influence in the heavy-flavour production in the low p_T region, which is of prime interest for ALICE.

PYTHIA parameters (and in particular the lower p_T^{hard} limit) were tuned in

² p_T^{hard} is the transverse momentum of the outgoing quarks in the rest frame of the hard interaction.

order to reproduce as much as possible the NLO predictions for charm production [92] obtained with the HVQMNR program [85].

4.4 Event simulation and reconstruction

The complete chain of the event simulation and reconstruction is visualized in Fig. 4.4: the left part of the parabola is the simulation, down to the raw data; the right part is the reconstruction procedure which will be used also for the real data.

The different steps of a simulation and reconstruction process are reported in the following; items 1-4 are referred to the first part of the parabola, items 5-7 to the second:

1. Generation: the particles produced in the collision are created with a generator code.
2. Transport: the final-state particles are transported through the detector via simulation packages which take into account all the processes occurring to the particles in the detector system and generate the energy depositions in the detector, usually called ‘hits’. Hits represent the ideal response of the detector to the passage of particles.
3. Digitization: hits are then transformed into digits (ADC counts), which represent the real detector response and take into account instrumental effects, such as the noise due to the front-end electronics.
4. “Raw-data” format: digits are subsequently transformed into the ‘raw’ format, identical to the one that will directly come from the data acquisition system during the data taking. From here on the processing of real or simulated data is the same.
5. Cluster reconstruction: at this point the reconstruction of the signal starts. First, digits are extracted from the raw data; physical and electronic contributions are still convoluted in a single signal. Then, several digits are grouped together (clusterization procedure) in order to find a cluster which represents the signal given by a particle in the detector.
6. Local reconstruction: in this process the reconstructed point (rec point) is found, by calculating the center of gravity of the cluster. The rec point is an estimation of the position where a particle crossed the sensitive area of the detector. In the TPC the reconstructed point contains both spatial and energy deposition information.

7. Global reconstruction: the rec points are associated into tracks, which contain information on the kinematic variables, the identity and the energy loss of the particles. This step is detector independent. A description of the tracking and particle identification algorithms used in ALICE is given in Section 4.5.

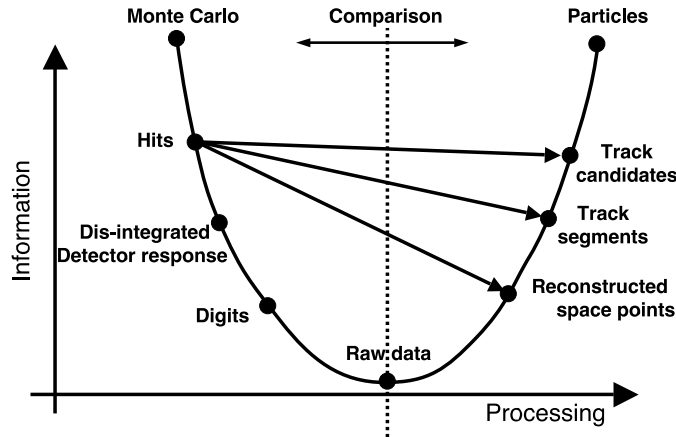


Figure 4.4: Simulation process framework. Taken from [147, 148].

In order to evaluate the efficiencies of reconstruction programs and the detector performance, the generated events are processed through the whole simulation chain and the final reconstructed events are compared to the initial Monte Carlo ones.

As shown by the arrows in Fig. 4.4, the complete chain of simulation and reconstruction can be parametrized in order to be faster. This fast simulation does not cover all the steps of the parabola, at the expense of a loss of detail in the final result. On the other hand, the full simulation chain is called the slow simulation.

The Pb-Pb events analysed in this work were processed with the slow simulation. For the pp case a fast simulation was chosen in order to speed up the production and have the data quickly available for the analysis: the simulation does not perform the full particle transport in the TPC, but rather makes use of a

parametrized response of the TPC tracking [92]; as shown in Section 4.5.1.1, the use of a quite old parametrized tracking implies a loss of efficiency with respect to the performance which can be obtained using the most up-to-date full tracking procedure.

4.5 ALICE performance

The tools necessary for the event reconstruction and analysis, like tracking, vertex reconstruction and particle identification (PID) algorithms, are fully integrated within the ALICE software.

Since the design requirement for ALICE is to have good track-finding and PID down to very low momenta (~ 100 MeV/c) in the maximum multiplicity scenario ($dN/dy=8000$), the code is continuously under development and optimization. The development is done for the Pb-Pb case, where the track density will be the highest and thus the situation is more problematic than for pp collisions. However, in some cases, such as the primary vertex determination, the high track multiplicity helps to reduce the statistical error.

4.5.1 Tracking

Track reconstruction is one of the most challenging tasks in this experiment.

A precise reconstruction of both momentum and origin of the particles produced in nucleus-nucleus collisions is mandatory for several practical cases.

The tracking system starts from the reconstructed points given by the local reconstruction in each detector. The general tracking strategy is to start from the best tracker device, i.e. the TPC, to extrapolate the candidate tracks in the ITS and to backpropagate the tracks to the outer detectors, namely the TRD, TOF, HMPID and PHOS. Three steps enter the tracking procedure: track seeding, track finding and track fitting. The track seeding consists in the combination of pairs of rec points belonging to two pad rows located in the external part of the TPC, where the density of the particles is lower. These track segments are called ‘seeds’. Due to the small number of clusters assigned to a seed, the low precision of its parameters does not allow the extrapolation of the seed in the outward direction. Instead, the track candidate is propagated towards the primary vertex³, associating whenever possible new rec points to the track. This

³A big uncertainty of the order of few centimeters is assigned to the primary vertex in order not to lose tracks displaced from the primary vertex. A first information on the z coordinate of the primary vertex is given by the silicon pixel detectors in the ITS. Its transverse position is defined by the transverse bunch size (approximately $15\ \mu\text{m}$).

is performed using the Kalman filter method [158], where track finding and track fitting procedures are combined.

When the seeds are extrapolated to the inner radius of the TPC, the tracks are prolonged from the TPC to the ITS. In this step, a strict vertex constraint with a resolution of $\sim 100 \mu\text{m}$ is imposed; then, another pass is done without the vertex constraint in order to reconstruct also the tracks coming from secondary vertices. The extrapolation to the ITS is a difficult procedure because the distance between the TPC and the most external layer of the ITS is not negligible (about 45 cm) and the track density is very high. In fact, since multiple scattering effects have to be taken into account, more than one cluster in the ITS may be compatible with the track segment found in the TPC. Therefore, for each TPC track, a track hypothesis tree is built in the ITS and the most probable path along the tree is chosen taking into account some information, like the χ^2 of the track and the possibility that a cluster is shared by several track candidates. The track is then propagated to the point on the track of minimum distance from the interaction point and all the track parameters are defined in this point.

A special ITS stand-alone tracking procedure is applied to those clusters which are not assigned to the tracks propagated from the TPC; the aim of this reconstruction algorithm is to recover the tracks that were not found in the TPC because of the low transverse momentum cut-off, dead zones between the TPC sectors or decays.

At this point, the Kalman filter is applied from the vertex to the outward direction. In this way the track is propagated towards the TRD, TOF, HMPID, PHOS and EMCal. The space points with large- χ^2 contributions are eliminated.

Finally, all the tracks are refitted backwards to the primary vertex. The tracks which passed the final refit are used for the secondary vertex reconstruction.

The tracks found with the Kalman filter are locally defined by the parameters of a helix. A helix is generally described by six parameters as follows:

$$\begin{cases} x = R \cos \varphi + x_0 \\ y = R \sin \varphi + y_0 \\ z = K \varphi + z_0 \end{cases} \quad (4.1)$$

where $C=(x_0, y_0)$ is the centre of the circumference in the bending plane, R is the radius, φ is the azimuthal angle, z_0 is the starting point along the z axis and K is a coefficient giving the proportionality between the z coordinate and φ . An alternative way is to replace R , φ and K by the three components of the momentum, p_x , p_y and p_z .

In our case, the parameters are defined in the so called reference plane (x_r, y_r) , which is the plane, defined track by track, parallel to the bending plane (x, y) and rotated in such a way that the x_r axis is oriented along the TPC sector which

includes the track. The tracks are always defined locally, i.e. at a given position X along x_r . Therefore, only five parameters (and consequently a 5×5 covariance matrix) are needed to locally describe the track, simply because one parameter (X) is already known.

The five parameters are:

1. y coordinate of the track in the local reference system, corresponding to the position X along x_r ;
2. z coordinate of the track;
3. $\sin \varphi$, where φ is the track azimuthal angle defined in the reference system;
4. $\tan \lambda$, where $\lambda = \frac{\pi}{2} - \theta$ and θ is the polar angle;
5. curvature $C = 1/R$, where R is the radius of the circumference.

For more details on the tracking algorithm, refer to [159].

In the following, the performance of the tracking algorithm which is especially interesting from the point of view of open charm analyses is reported.

4.5.1.1 Performance of the tracking algorithm

In order to evaluate the tracking efficiency within the ALICE simulation, tracks are grouped in the following classes:

1. “Generated track”: is a particle generated within the beam pipe and emitted within the TPC acceptance.
2. “Good generated track”: is a particle which crosses at least 50% of all the pad rows.
3. “Found good track”: is a reconstructed track which is effectively associated to a particle. Such track must satisfy several requirements: its number of clusters has to be larger than half of the number of crossed pad rows, more than 90% of assigned clusters must belong to the same particle and at least half of the innermost 10% of clusters must be assigned correctly to the particle.
4. “Found fake track”: for this track the requirements presented in the above point are not satisfied.

The tracking efficiency of the algorithm (also known as software efficiency) is defined by the ratio between the numbers “Found good track” and “Good

generated track”. The probability to find a fake track is given by the ratio between “Found fake track” and “Generated good track”.

Fig. 4.5 shows the efficiency of the track reconstruction in TPC+ITS and the probability of finding a fake track as a function of the momentum for different multiplicities. Even for the highest multiplicity scenario, the efficiency is well above 80%.

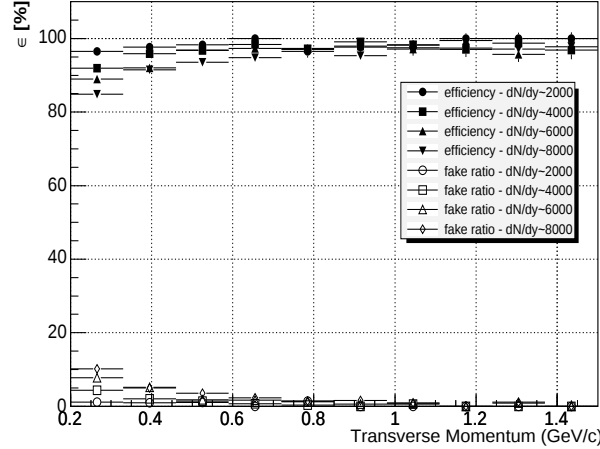


Figure 4.5: Track reconstruction efficiency (closed symbols) and probability of obtaining a fake track (open symbols) as a function of the momentum for different multiplicities. Taken from [148].

The “physical” track finding efficiency includes also effects like dead zones in the detectors, particle decays and interactions with the material. It is defined as the ratio of the number of “Found good track” and “Generated track” and is shown in Fig. 4.6. The “physical” efficiency is the quantity relevant for the analysis but includes the effect of several factors. The software efficiency measures the performance of the tracker in a better way.

The quality of a track improves with the number of detectors which contribute to the tracking, even though the requirement of being reconstructed in as many detectors as possible reduces the statistics of such tracks. For example, adding the TRD implies a loss of track-finding efficiency (see Fig. 4.6); however, the detector is needed for electron identification and furthermore improves the momentum resolution especially at high momenta (see Fig. 4.7).

As far as the angular resolution is concerned, Fig. 4.8 shows the angular resolutions given by different combinations of the tracking detectors. At low momenta, it is dominated by the multiple scattering in the material; at high momenta multiple scattering effects are negligible and the main influence on the angular resolution is the space point precision of the contributing detectors.

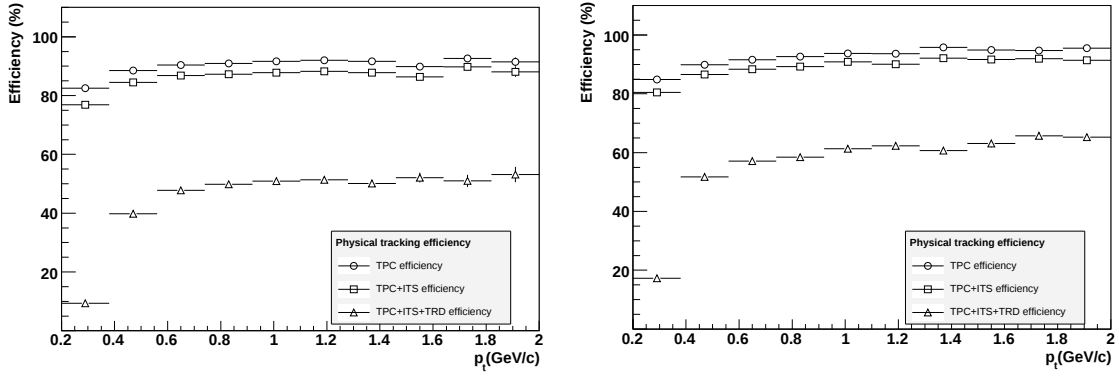


Figure 4.6: Physical track-finding efficiency for different combinations of the tracking detectors. Left: Central Pb-Pb collisions ($dN/dy = 6000$). Right: pp collisions. Taken from [159].

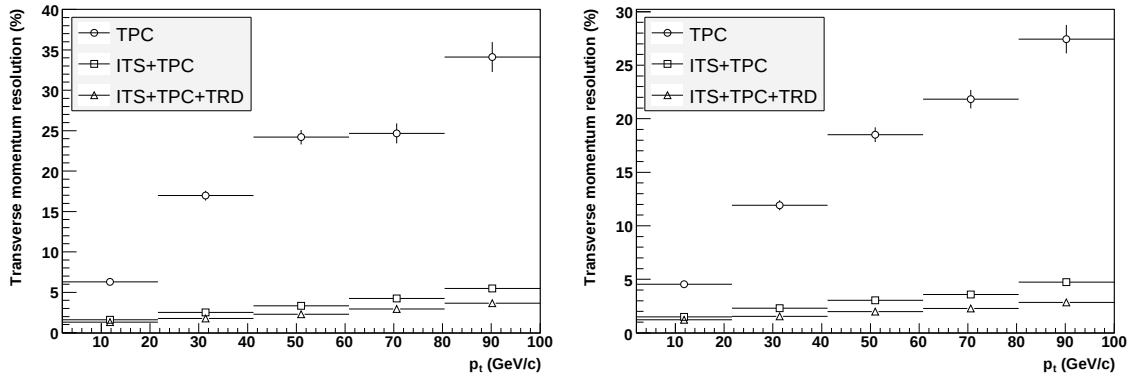


Figure 4.7: Transverse-momentum resolution for different combinations of the tracking detectors. Left: Central Pb-Pb collisions ($dN/dy = 6000$). Right: pp collisions. Taken from [159].

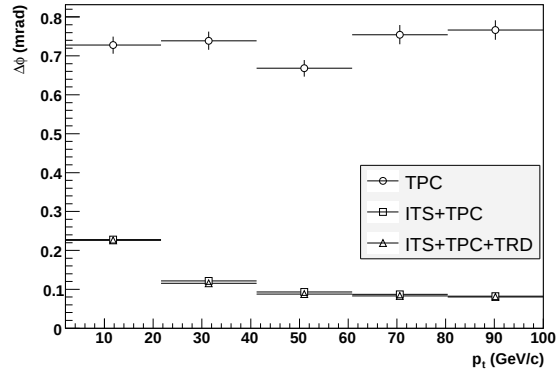


Figure 4.8: Azimuthal-angle resolution ($\Delta\phi$) for different combinations of the tracking detectors (central collisions, $dN/dy = 6000$). Taken from [159].

The p_T resolution of tracks reconstructed in ITS+TPC and belonging to our sample of signal events (see Section 4.6 for a discussion of the events generated for this thesis work) generated with $B=0.5$ T is shown in Fig. 4.9, for the range $0 < p_T < 10$ GeV/c.

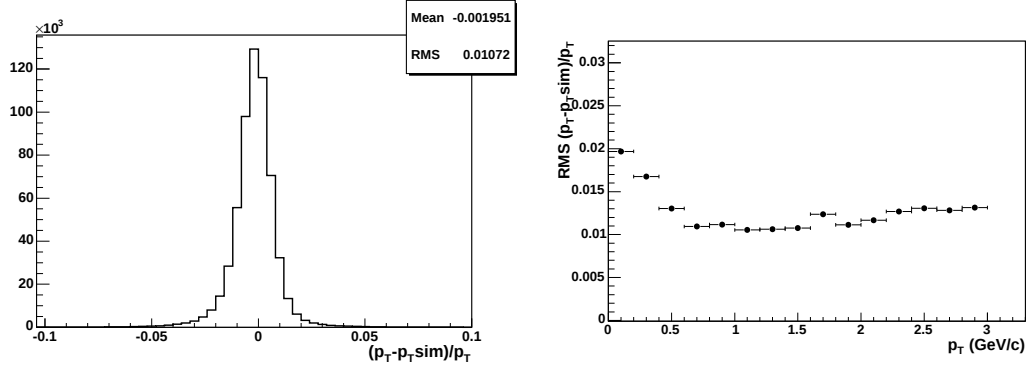


Figure 4.9: Left panel: p_T resolution in central Pb-Pb collisions for tracks reconstructed in ITS+TPC. Right panel: p_T resolution as a function of the transverse momentum.

It can be observed from the left plot of Fig. 4.9 that the p_T resolution in the range $0 < p_T < 10$ GeV/c is $\sim 1\%$, in agreement with Fig. 4.7. At very low reconstructed p_T , i.e. $p_T \leq 0.2$ GeV/c, the resolution is dominated by the multiple scattering (Fig. 4.9, right panel). The transverse momentum range where $D^\pm$ mesons are likely to be produced in Pb-Pb collisions at the LHC is $0 < p_T < 10$ GeV/c (see also Section 5.3): hence, the p_T resolution of their decay products is of the order of 1%. Of course, the p_T resolution worsens with increasing p_T , as can be noticed in Fig. 4.9 and, on a larger scale, in Fig. 4.7.

In open charm analyses, where the challenge is to reconstruct decay topologies displaced few hundreds μm from the interaction point, a good precision on the measurement of track impact parameters is of great importance. The impact parameter of a track is defined as the distance of closest approach of the track to the interaction point. It can be defined separately in the transverse plane and along the beam axis:

$$d_0(r\varphi) = \rho - \sqrt{(x_v - x_0)^2 + (y_v - y_0)^2} \quad \text{and} \quad d_0(z) = z_{\text{track}} - z_v, \quad (4.2)$$

where ρ and (x_0, y_0) are the radius and the centre of the track projection in the transverse plane, (x_v, y_v, z_v) is the position of the primary vertex, and z_{track} is the z position of the track after it has been propagated to the distance of closest approach in the transverse plane. Clearly, the d_0 resolutions strongly depend on both the track position resolution and the primary vertex position resolution.

In ALICE, the measurement of the impact parameter is mainly provided by the Inner Tracking System, and, in particular, by the two layers of silicon pixels, which have fine granularity and are positioned close to the interaction point.

In Fig. 4.10 the resolution on the impact parameter (both on the bending plane and along the z coordinate) is reported as a function of the transverse momentum for different particle types.

It can be noticed that the impact parameter resolution is better in the bending plane than along the z axis. This is due to the bad spatial precision of the pixel detectors along the beam axis. The main contribution to the impact parameter resolution along the z axis is given by the drift detectors, whose spatial precision is of the order of $30 \mu\text{m}$ (see Chapter 3).

Pions and kaons coming from decays of open charmed mesons have an average $p_T \sim 0.7 - 1 \text{ GeV}/c$, thus the precision on the measurement of their impact parameters in the bending plane in Pb-Pb is $\sim 50 - 100 \mu\text{m}$. Such value is smaller than the decay length of charmed mesons ($\sim 100 - 300 \mu\text{m}$), allowing selection cuts on the projection of the impact parameter in the bending plane. The resolution worsens in the case of pp collisions, where it is dominated by the large uncertainty on the primary vertex determination (see subsection 4.5.2).

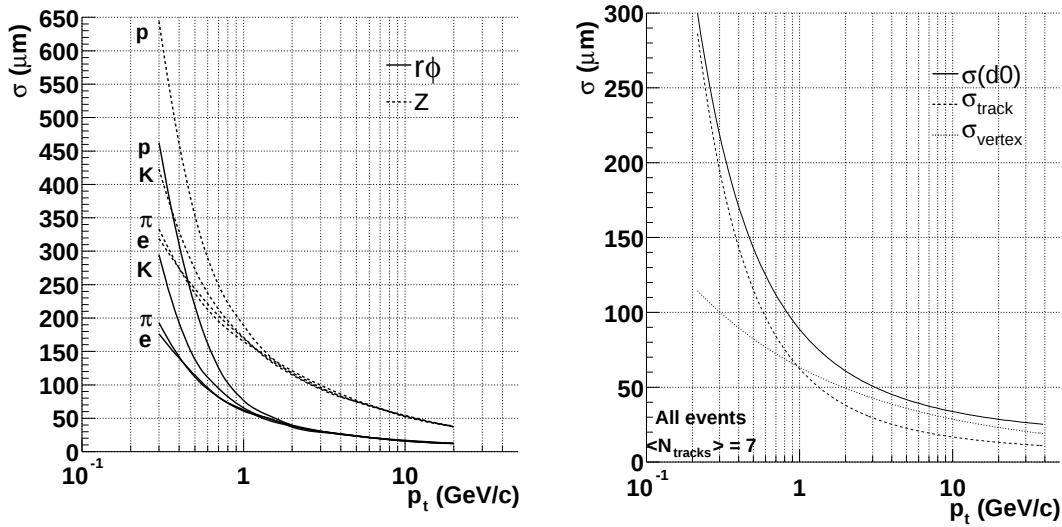


Figure 4.10: Left panel: impact parameter resolution in central Pb-Pb collisions for electrons, pions, kaons and protons as a function of the transverse momentum. Right panel: impact parameter resolution in the transverse plane as a function of the transverse momentum for pp collisions. Taken from [159].

The quality of the measured impact parameters can also be characterized by the so called “pulls”, defined as follows:

$$pull = \frac{(d_{0sim} - d_{0rec})}{err(d_{0rec})} \Big|_{r\phi} \quad (4.3)$$

where d_{0sim} is the impact parameter in the transverse plane given by the simulation, d_{0rec} is the same quantity obtained with the reconstructed tracks and $err(d_{0rec})$ is the error on the measurement of d_{0rec} . If the impact parameter is correctly reconstructed and the error determination is done in a proper way, the pulls are distributed normally with mean value equal to zero and width equal to 1. We checked this by calculating the pull in different momentum windows: as shown in Fig. 4.11, the σ of a Gaussian fit to the pull distributions in different p_T ranges is close to 1, confirming the good performance of the tracking algorithm.

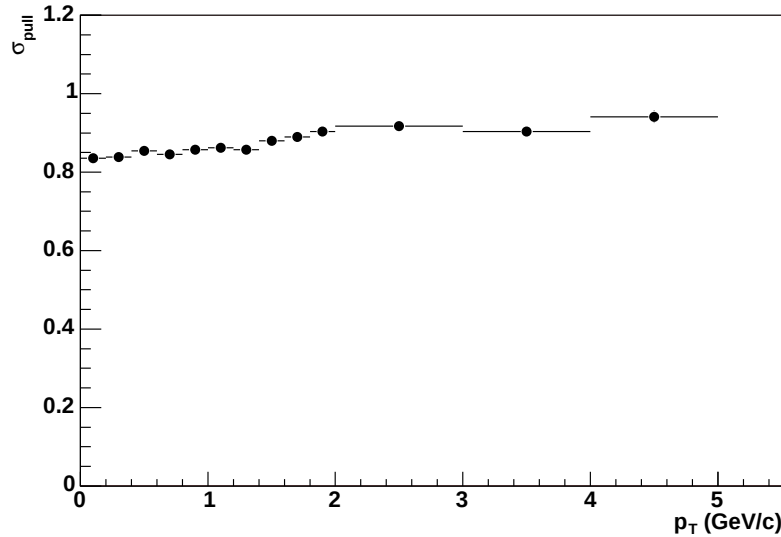


Figure 4.11: σ of the Gaussian fit to the d_0 pull distributions as a function of the transverse momentum.

4.5.2 Primary-vertex reconstruction

The reconstruction of primary vertices is provided in ALICE by the two innermost layers of the ITS, made of silicon pixels.

The primary vertex will be located in the diamond given by interaction of two bunches. Along the z -axis the interaction region is spread over a length of 5.3

cm, while the width of the diamond in the transverse plane depends on the LHC parameters: it can vary between $15\ \mu\text{m}$ and $75\ \mu\text{m}$ in case of Pb-Pb collisions and it can be even larger than $150\ \mu\text{m}$ for pp collisions in case of beam defocusing to reduce the luminosity. Such considerations are extremely important in the development of the algorithms for the primary-vertex determination.

A first reconstruction of the primary vertex is done before the tracking reconstruction step using the information of the pixel detectors. The vertex found with the pixels is used to constrain the tracking. After the tracking, a more precise reconstruction of the interaction vertex (with rejection of secondary tracks and proper error determination) can be done using the tracks.

The algorithm for the first estimation of the primary vertex consists in the correlation of reconstructed points coming from the modules of the two layers of pixels within a small azimuthal window (by default set to $0.01\ \text{rad}$). In this way, only high momentum tracks, i.e. straight lines in the bending plane, are selected, the combinatorial background is reduced, and only the tracks less affected by the multiple scattering are considered. The choice of the azimuthal angle must be optimized because too strict windows would considerably reduce the statistics. The selected pairs of points are called tracklets.

Fig. 4.12 shows the resolution of the z coordinate of the reconstructed primary vertex as a function of the track multiplicity for $B = 0.2\ \text{T}$. Even in the lowest multiplicity scenario for Pb-Pb collisions, $dN_{ch}/dy \simeq 1500$, the precision is better than $10\ \mu\text{m}$. With the increase of the magnetic field the resolution is expected to worsen because there is a higher occupancy⁴, with a consequent increase of the combinatorial background. Nevertheless, the resolution does not significantly change with the increase of the magnetic field, from $0.2\ \text{T}$ to $0.5\ \text{T}$, for example it ranges from $5\ \mu\text{m}$ to about $8\ \mu\text{m}$ going from $0.2\ \text{T}$ to $0.5\ \text{T}$.

The above algorithm was extended in order to reconstruct the three-dimensional vertex position starting from the tracklets.

A comparison of the two algorithms, i.e. the one which reconstructs only the z coordinate and the one giving the three-dimensional vertex position, is shown in Fig. 4.13 in case of pp events. It can be observed that in pp events with lower track multiplicities the resolution on the vertex position is worse than in Pb-Pb collisions.

Even though such a precision in pp is enough for the reconstruction, it becomes insufficient for specific physics analyses. This is the case for the detection of

⁴According to the Lorentz formula, the higher is the magnetic field, the more curved are the charged particles. This effect is expected to worsen the reconstruction performance because of the presence of low- p_T particles, namely electrons, whose curvature radius is smaller than the ITS radius. For example, electrons with $p_T \sim 50\ \text{MeV}/c$ have a curvature radius $R = p_T/(0.3 \times B) \sim 30\ \text{cm}$ with $B=0.5\ \text{T}$. Softer electrons are even more curved and increase the occupancy in the ITS layers.

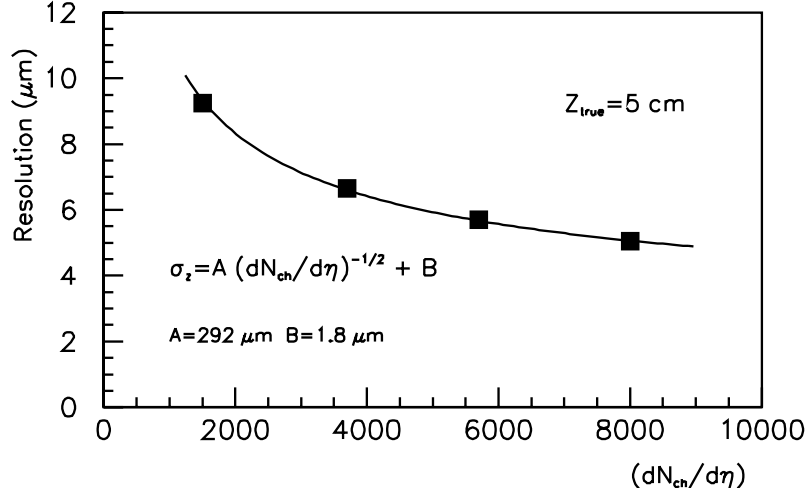


Figure 4.12: Resolution of the reconstructed z vertex position as a function of the particle density for $B = 0.2$ T. The solid line is a fit through the parametrization given in the figure.

particles with open charm and open beauty, namely D^0 ($c\tau \simeq 123 \mu m$), $D^\pm$ ($c\tau \simeq 315 \mu m$), $D_s^\pm$ ($c\tau \simeq 147 \mu m$) and B mesons ($c\tau \simeq 500 \mu m$). For such analyses a precision of $50 - 100 \mu m$ for the primary vertex positions in the bending plane is demanded: this result is obtained in pp collisions using tracks instead of tracklets, as described in [160]. Tracks are propagated to the beam axis and then approximated as straight lines. The coordinates of the primary vertex are given by finding the point of minimum distance among the tracks (the algorithm, also called “vertex finder”, is based on the one developed for the reconstruction of secondary vertices. See Section 4.5.3 for more details).

A more accurate determination of the vertex position is given by a fitting procedure. The fitter is applied starting from the positions obtained with the finder algorithm. The efficiency and the resolution as a function of the track multiplicity are shown in Fig. 4.14.

4.5.3 Secondary-vertex reconstruction

In this subsection the ALICE capabilities to reconstruct special decay topologies are presented, with an emphasis on the performance of the secondary vertex finder algorithm especially studied for n -prong decays of charmed mesons, with $n \geq 2$.

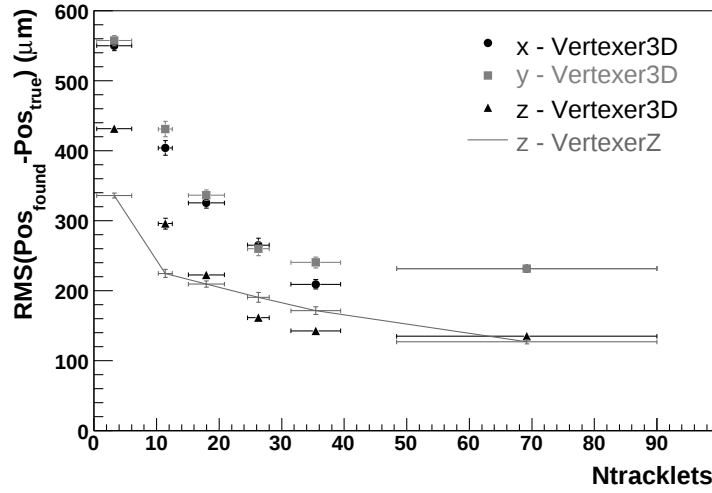


Figure 4.13: Resolution of the reconstructed primary vertex positions (using the three-dimensional algorithm based on tracklets) as a function of the number of tracklets in pp collisions with $B=0.5$ T. Also the resolution of the z coordinate obtained with the tracklet method (the one which finds only the z coordinate) is shown for comparison.

4.5.3.1 V^0 and cascade finding

The V^0 vertices are made of two opposite-sign tracks typically originating from decays of hyperons, like $\Lambda^0 \rightarrow \pi^- p$, including also cascades like $\Xi^- \rightarrow \pi^- \Lambda^0 \rightarrow \pi^- \pi^- p$ and $\Omega^- \rightarrow K^- \Lambda^0 \rightarrow K^- \pi^- p$. Also the $K_s^0 \rightarrow \pi^+ \pi^-$ is a V^0 topology. The main steps of the V^0 finding procedure are:

- selection on the impact parameters of the tracks with respect to the primary vertex in order to keep only the secondary tracks;
- determination of the distance of closest approach (DCA) between the two tracks (parametrized as helices) and rejection of pairs with large DCA;
- determination of the V^0 position on the DCA segment taking into account the errors on the track parameters;
- rejection of V^0 candidates whose reconstructed momentum does not point to the primary vertex;
- selection on the invariant mass of the V^0 candidates.

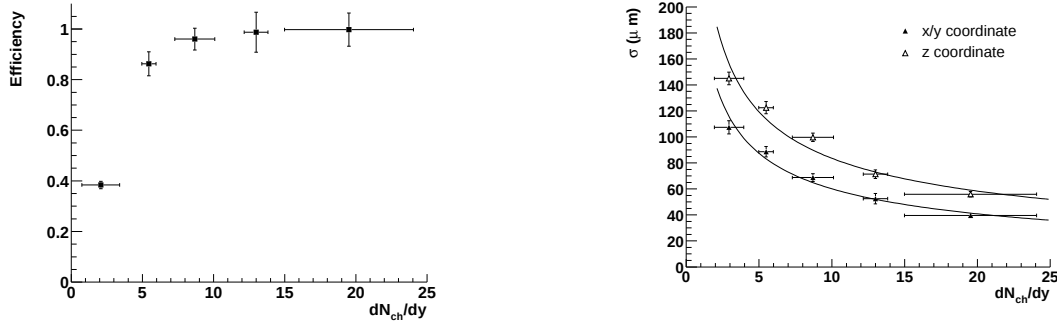


Figure 4.14: Efficiency and resolutions for the primary vertex reconstructed in 3D from tracks as a function of dN/dy for the case of pp events.

This procedure is also extended to cascades.

A similar approach was followed for the reconstruction of the secondary vertex of the D^0 meson in the two-body decay channel $D^0 \rightarrow K^- \pi^+$ [163].

4.5.3.2 Kinks

Kinks are topologies defined by 1-prong vertices. Typical kinks are those originated by the muonic decays of charged π and K mesons: $\pi \rightarrow \mu\nu$, $K \rightarrow \mu\nu$. The strategy adopted for the kink-finding procedure is divided into two steps: first, large-decay-angle kinks are reconstructed; second, the algorithm searches for kinks produced at small decay angles.

Large-decay-angle kinks are reconstructed by associating pairs of tracks with the same charge and intersecting within a fiducial spatial zone. For each track pair the DCA in the transverse plane is found, and the pair is rejected if this does not occur inside a fiducial region. The decay vertex is reconstructed by a numerical minimization of the distance in space of the two tracks, in a way similar to that used for the V^0 .

In order to find small-decay-angle kinks, the task is to search for a change in the track direction: this is done performing, for each rec point of the track, a fit to the part of the track upstream, a fit to the part of the track downstream, and a fit to the whole track. The kink is located at the track breakpoint, defined as the point corresponding to the biggest change in the track direction. Once the kink is defined, additional selection criteria (i.e. number of clusters associated to the two track segments, DCA between the two track segments, p_T of the mother track, etc.) are applied.

More details on V^0 and kink studies can be found in Ref. [159].

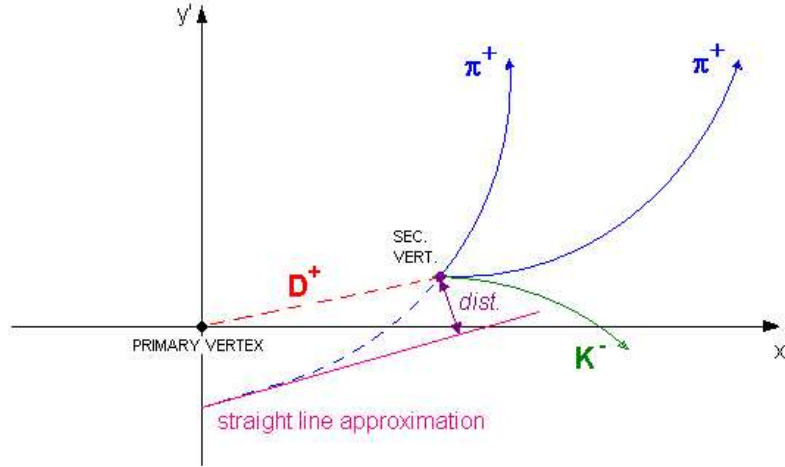


Figure 4.15: Sketch of the three-body decay of the D^+ meson with the illustration of the straight line approximation for one of the decay products. d is the distance between the secondary vertex and the tangent line. The reference system (x', y') represents the local coordinates of the tracking algorithm.

4.5.3.3 Reconstruction of the secondary vertex for $D^+ \rightarrow K^- \pi^+ \pi^+$

Since the goal of this thesis is the detection of the three body decay of $D^\pm$ mesons, we studied and optimized different methods for the reconstruction of secondary vertices originated by 3-prong decays (see also Appendix A). The best one is based on the straight line approximation of the tracks, i.e. the track (which is a helix) is prolonged to the point of closest distance from the primary vertex and in this point the tangent line is calculated. A sketch of the linear approximation is shown in Fig. 4.15. A check on whether or not the straight line approximation of the track near the primary vertex produces a significant worsening in our measurement of the secondary vertex has been done. For this purpose, we consider the distance d between the secondary vertex and the straight line (reported in 4.15) as a geometrical measurement of the discrepancy between the helix and the tangent line.

In Fig. 4.16 the distance d defined above is plotted as a function of the transverse momentum of the particle originating from the D^+ decay, for two different choices of the D^+ decay length: $300 \mu\text{m}$, of the order of $c\tau$ of $D^\pm$ mesons, and $3000 \mu\text{m}$, less probable since it corresponds to $\sim 10 c\tau$.

As expected, d decreases with p_T because high-momentum tracks are less bent; in addition, as it appears from the comparison of the two plots, d is larger as the secondary vertices are more displaced from the interaction point, confirming that

the farther the origin of the particle from the primary vertex, the less precise is the approximation of the helix with the tangent line calculated in proximity of the interaction point. However, even in the worst case of a distance between primary and secondary vertices of the order of 3 mm, the discrepancy between the helix and the tangent line is less than $1 \mu\text{m}$ for $B = 0.5 \text{ T}$ and $p_T \sim 0.5 \text{ GeV}/c$, and thus much smaller than the detector spatial resolutions.

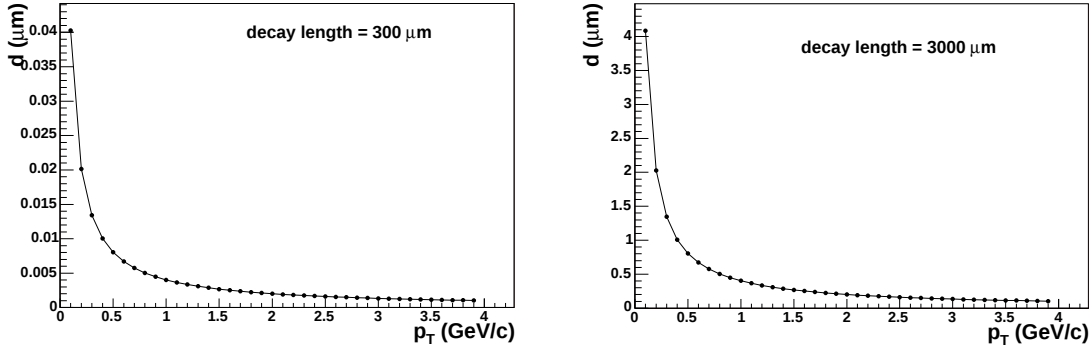


Figure 4.16: Distance between secondary vertex and the tangent line as a function of the transverse momentum of the particle, for decay lengths of $300 \mu\text{m}$ (left panel) and $3000 \mu\text{m}$ (right panel) and for $B = 0.5 \text{ T}$. See text for more details.

Similar results are shown in Fig. 4.17, where d is plotted as a function of the distance between primary and secondary vertices for two choices of the transverse momentum of the particle originating from the D^+ decay.

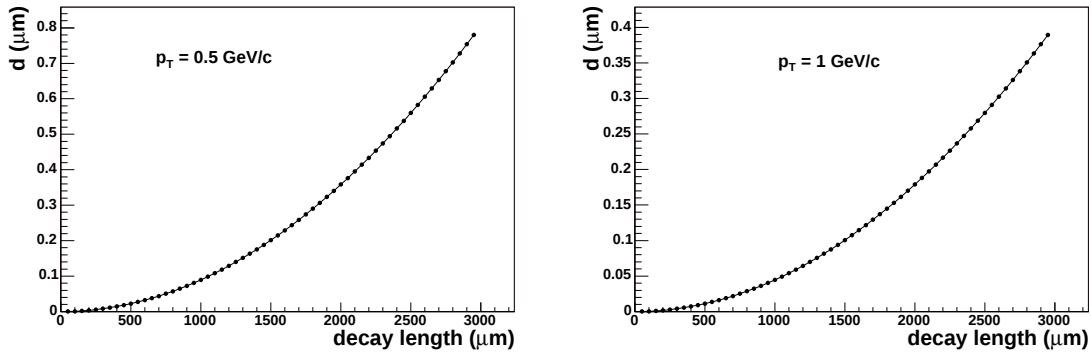


Figure 4.17: Distance between secondary vertex and the tangent line as a function of the decay length of the $D^\pm$, for $p_T = 0.5 \text{ GeV}/c$ (left panel) and $p_T = 1 \text{ GeV}/c$ (right panel) and for $B = 0.5 \text{ T}$.

Since we are interested in a three body decay, the algorithm finds the point of minimum distance between three tracks (approximated as straight lines) by

minimizing the quantity:

$$D^2 = d_1^2 + d_2^2 + d_3^2 \quad (4.4)$$

where d_i ($i = 1, 2, 3$) is the distance between the track i and the secondary vertex (x_0, y_0, z_0) , weighted with the errors on the track:

$$d_i^2 = \left(\frac{x_i - x_0}{\sigma_{xi}} \right)^2 + \left(\frac{y_i - y_0}{\sigma_{yi}} \right)^2 + \left(\frac{z_i - z_0}{\sigma_{zi}} \right)^2 \quad (4.5)$$

The errors on the track parameters (σ_{xi} , σ_{yi} and σ_{zi}) are obtained from the 5×5 covariance matrix of the track.

The results of the secondary vertex finder algorithm applied to events containing only $D^+ \rightarrow K^- \pi^+ \pi^+$ decays are reported in the following.

The residual distributions of the secondary vertex finder are shown in Fig. 4.18 for the three coordinates: the RMS of the histograms is of the order of $\sim 120 \mu\text{m}$. The slightly larger RMS for the residual distribution along the z coordinate may be due to the lower track precision of the Inner Tracking System in the z axis compared to the bending plane (see Table 3.2 for a list of the spatial resolutions of the ITS).

We can now plot the RMS of the residual distribution as a function of the p_T of the D^+ : at low p_T the daughter tracks are softer and therefore they suffer multiple scattering, thus we expect that the RMS of the residual distribution is almost the same for all the three coordinates. This is indeed what can be seen in the plot in Fig. 4.19.

As the p_T of the D^+ increases one would expect a decreasing of the RMS since the decay tracks have larger momentum and, thus, are less affected by multiple scattering. Instead, we observe that in the bending plane the RMS increases at high p_T of the D^+ . This can be understood taking into account the fact that as the D^+ transverse momentum increases, its decay products get more and more collinear with a direction given by the transverse momentum of the D^+ . Hence, along this direction a worsening of the resolution of the secondary vertex finder should be observed. This behaviour is illustrated in Fig. 4.20, where the RMS is now calculated in a rotated reference system in the bending plane: x' is the direction of the p_T of the D^+ . Along the x' coordinate the RMS increases at high p_T , while in the y' coordinate the RMS goes down to $\sim 40 \mu\text{m}$.

At high transverse momentum we would expect to obtain a resolution comparable with the expected resolution given by the silicon pixels located in the two innermost layers of the ITS, $\sim 12 - 14 \mu\text{m}^5$. The observed resolution, $\sim 40 \mu\text{m}$, is

⁵The size of a cell of pixel detector is: $50 (r\varphi) \times 425 (z) \mu\text{m}^2$. Therefore, a resolution of $\sigma = \frac{50 \mu\text{m}}{\sqrt{12}} \simeq 14 \mu\text{m}$ in the bending plane is the highest resolution which can be attained by a vertexer algorithm. See also Table 3.2.

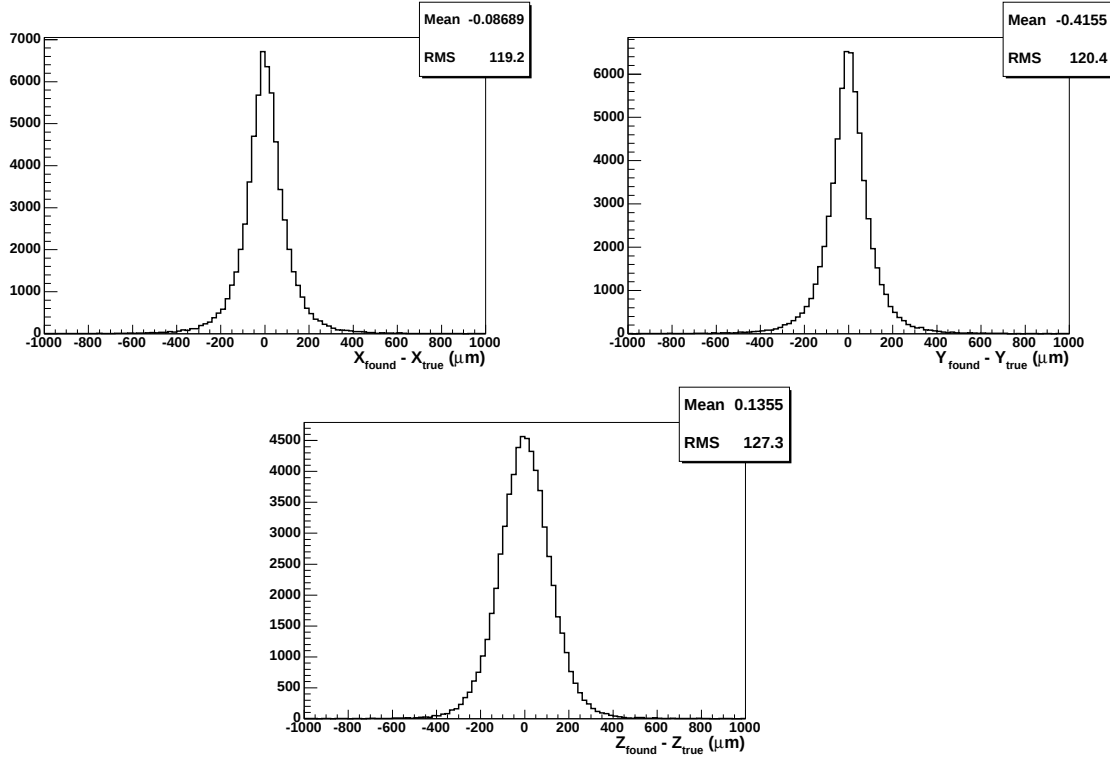


Figure 4.18: Residual distributions, i.e. difference between the true coordinate of the secondary vertex $D^+ \rightarrow K^- \pi^+ \pi^+$ and the found coordinate, for x, y and z coordinates.

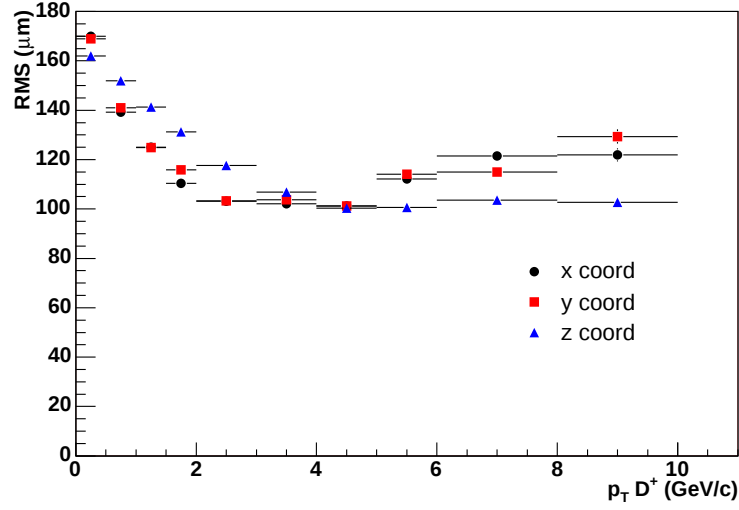


Figure 4.19: RMS of the residual distribution for x, y and z coordinates as a function of the p_T of the D^+ .

higher than the expected, but is not in contrast with the limit given by the pixel

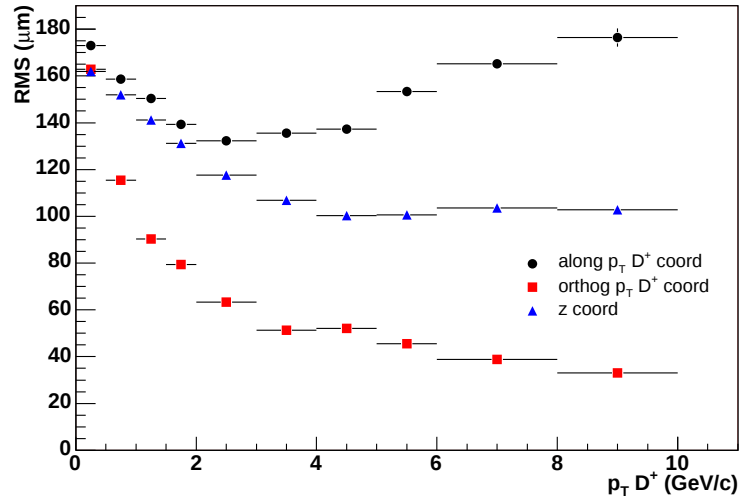


Figure 4.20: RMS of the residual distribution for the x', y' (rotated bending plane) and z coordinates as a function of the p_T of the D^+ .

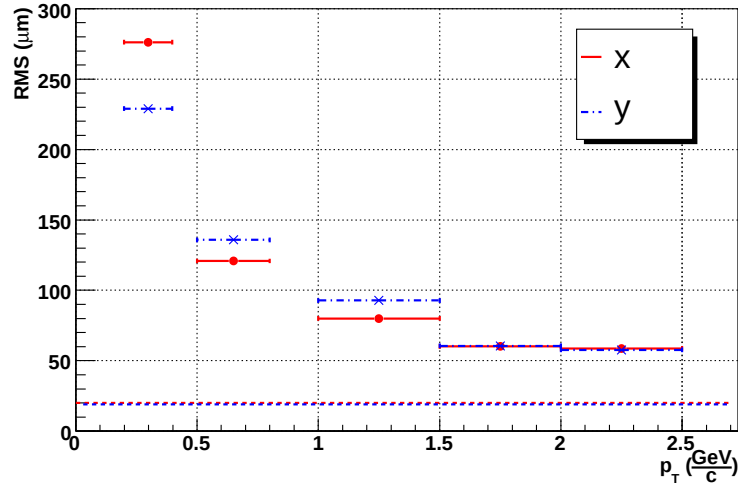


Figure 4.21: RMS of the residual distribution of the secondary vertex for x and y coordinates as a function of the p_T interval of the three tracks. The dotted line at $20 \mu\text{m}$ is the asymptotic limit obtained when all three tracks have $p_T = 100 \text{ GeV}/c$.

resolution.

Indeed, we see from Fig. 4.21 that the RMS of the residual distribution decreases with p_T ⁶ and reaches the value of $\sim 20 \mu\text{m}$, compatible with the pixel resolution, only if the three tracks have a transverse momentum larger than $100 \text{ GeV}/c$ (as indicated by the dotted line in the figure which shows the asymptotic limit at $100 \text{ GeV}/c$).

The algorithm described above is now a part of the framework of the ALICE offline software and can be applied to n -prong vertices, where $n \geq 2$, both for Pb-Pb and pp collisions.

The study of a vertex fitting step after the vertex finder is presently under study.

4.5.4 Particle Identification

Particle Identification (PID) in ALICE is performed by means of several detectors (ITS, TPC, TRD, TOF, HMPID) in different kinematical regions.

⁶In this case, each secondary vertex was found using three tracks generated with the same p_T . The plot is similar to the one shown in Fig. 4.19, but in that case the p_T of the D^+ was used.

For the reconstruction of open charmed mesons a particle identification system is necessary in order to identify the products (pions and kaons) of their hadronic decays. The detectors employed for such purposes are mainly the TPC, the ITS and the TOF because they provide efficient PID in the momentum range typical of the decay products of D mesons produced in ALICE (0 - 5 GeV/c): the TPC and ITS identify particles in the low momentum region ($p < 1 - 2$ GeV/c), while the TOF is used for the identification of particles of higher momentum

An important additional contribution of the ITS is to reconstruct and identify those tracks at low momentum which are out of the acceptance of the TPC (for a detailed description of the ITS stand-alone tracking refer to [159]).

The reconstruction of a track in the central ALICE detectors ITS, TPC, TRD, TOF and HMPID is needed in order to apply the combined PID [159] which returns the Bayesian probability for the track identity combining the information of the different detectors.

The following information can be easily obtained track by track using the PID system in each detector:

- $f_i(s) = f(s|i, p)$, where f is the conditional probability density function for a particle of type i , to give a signal s in the momentum window $[p, p+\Delta p]$. Given the conditional probability density function we can get the conditional probability, which is the probability, for a track of type i in a given momentum window, to observe a signal s in the interval $[s, s+ds]$:

$$dP(s|i) = f_i(s)ds$$

- $P(i|s, p)$, where P is the probability (calculated using Bayes' theorem) for a track, with a measured signal s in a given momentum window $[p, p+\Delta p]$, to be of type i .

The probability $P(i|s, p)$ also makes sense from the point of view of classical statistics, since it is the fraction of times a track of momentum p with a measured s will be of type i . In a Bayesian framework [161], $P(i|s, p)$ gives the degree of belief that a particle with a measured s in the momentum bin $[p, p+\Delta p]$ is of type i .

For each particle, the conditional probability density function for a vector of signals from the various detectors

$$S \equiv \{s_{ITS}, s_{TPC}, s_{TOF}, \dots\}$$

is simply the product of the corresponding normalized response functions:

$$R(S|i) = \prod_{ITS, TPC, \dots} f_{Ni}(s|i)$$

The conditional probability is then:

$$dP(S|i) = R(S|i) ds_{ITS} \cdots ds_{TPC} \cdots ds_{TOF} \cdots$$

It is important to stress that the conditional probability does not depend (at least as a first approximation) on the Monte Carlo model used to generate the event, but only on the response function of the detector.

Finally, the combined PID makes use of the Bayesian probability in order to get the probability for a track with a set of signals S of being of type i :

$$P(i|S) = \frac{R(S|i)P(i)}{\sum_{t=p,K,\pi,e,\mu} R(S|t)P(t)}$$

In this formula $P(i)$ is the prior probability for a particle of type i , i.e. is the concentration of the different particle species in one set of events. It can be defined as a function of the momentum p :

$$P(i; p) = \lim_{N \rightarrow \infty} \frac{N_i}{N} \Big|_p \quad (4.6)$$

where N is the total number of particles in the sample and N_i is the number of particles of type i .

Prior probabilities depend upon the collision type and on the event selection. In this study we used PID only for Pb-Pb collisions where the track multiplicity is too high to perform the analysis without the use of PID information; therefore we decided to set the prior probabilities equal to the particle concentrations given by HIJING and integrated on the momentum: $P(p) = 0.055$, $P(K) = 0.072$, $P(\pi) = 0.864$, $P(e) = 0.006$, $P(\mu) = 0.003$.

In practice the prior probabilities can be estimated starting from the reconstructed tracks. One possible way to work out these particle concentrations is to use the PID algorithm assuming equal prior probabilities and to count the tracks tagged as type i (p, K, π) in the momentum range $[p, p+\Delta p]$. Since each track is characterized by five Bayesian probabilities for the set of five hypotheses p, K, π, e, μ , the identity of the track is assigned taking the highest Bayesian probability among the three.

The estimation of the priors can be improved using the number of particles identified as type i in the momentum range $[p, p+\Delta p]$, $N_{ID}(t; p)$:

$$P(i; p) = \frac{N_{ID}(i; p)}{\sum_{t=p,K,\pi,e,\mu} N_{ID}(t; p)}$$

After a few iterations of this procedure, the priors $P(i; p)$ get close to the true ones.

The PID algorithm assigns to each reconstructed track a set of “Bayesian” probabilities of being a proton, a kaon and a pion. The highest probability determines the identity of the track.

For each momentum bin $[p, p+\Delta p]$, the efficiency $\epsilon(i; p)$ and the contamination $K(i; p)$ for the particle of type i (protons, kaons, pions) are defined respectively as:

$$\epsilon(i; p) = \frac{N_{GOOD}(i; p)}{N_{TRUE}(i; p)}$$

$$K(i; p) = \frac{N_{FAKE}(i; p)}{N_{ID}(i; p)}$$

where:

$N_{TRUE}(i; p)$ is the number of particles of type i in the momentum range previously defined.

$N_{GOOD}(i; p)$ is the number of particles of type i correctly tagged as i .

$N_{ID}(i; p)$ is the number of particles identified as i .

$N_{FAKE}(i; p)$ is the number of particles tagged as i without being of type i ($N_{ID}(i; p) = N_{GOOD}(i; p) + N_{FAKE}(i; p)$).

From these definitions, it follows that the purity Π is $\Pi(i; p) = 1 - K(i; p)$.

In the ITS, only the silicon drifts and strips can measure the energy loss and are employed for PID purposes. The energy deposition per unit length of a charged particle is determined starting from the reconstructed points (rec points) in each layer of the ITS. The rec points are subjected to fluctuations of the energy loss depending on the thickness of the material: in the case of the SDD and SSD, made of thin layers of $\sim 300\mu\text{m}$, the dE/dx follows the Landau asymmetric distribution with the most probable value given by the Bethe-Bloch formula. Because of the long tail extending to high values of dE/dx , the mean and higher moments of the Landau distribution do not exist, i.e. the integral $\int_0^{+\infty} s^n f(s) ds$ ($dE/dx = s$) diverges for $n \geq 1$.

One way to reduce the effects of the fluctuations is to apply the truncated mean method, discarding the two higher energy signals and averaging the remaining two.

As we showed in [162], the dE/dx (truncated mean) distributions in the ITS cannot be correctly described neither with Gaussian nor Landau functions, because only few measurements for each track are taken. Instead of using the truncated mean, all the clusters signals are taken for each track and consequently four signal distributions (2 clusters SDD and 2 clusters SSD) instead of one are fitted with a convolution of a Gaussian and a Landau function [162]. Thus, the dE/dx variable is considered to be the sum of two random quantities: the first is

the ionization energy loss, which is distributed according to a Landau curve, and the second one is a Gaussian which represents the smearing of the signal due to the detector response. The convolutions of Landau and Gaussian functions give reasonable results in the fits of the response functions in the four ITS subdetectors. An interpolation of these fit parameters as a function of the momentum is performed, in order to reduce the amount of information required at the level of reconstruction. This method for the PID in the ITS is implemented in the AliRoot framework in the context of the combined PID and can be used at the level of the reconstruction.

Fig. 4.22 shows the efficiencies and the contaminations as a function of the momentum, for protons, kaons and pions, which are the only species that can be separated by the ITS. The prior probabilities for the three particle species used to make this plot are assumed to be equal to 1/3. The same efficiencies and contaminations are plotted in Fig. 4.23, but the default PID in the ITS (based on the truncated mean of the energy depositions) was used. By the comparison of the two plots, it can be seen that the new algorithm developed for PID in the ITS slightly improves the efficiencies and considerably reduces the contaminations at low momenta.

In this work (Pb-Pb case), we decided to use the combined PID with the method presented above for the ITS.

The global efficiencies and contaminations obtained with the combined PID given by ITS, TPC and TOF are shown for protons, kaons and pions in Fig. 4.24. We used the prior probabilities above reported given by the particle concentrations in HIJING central events.

4.6 Simulation strategy for open charm analyses

The feasibility study of the reconstruction of heavy-flavoured meson decays presented in this work has been performed both in Pb-Pb and in pp collisions at the LHC energies of $\sqrt{s_{NN}} = 5.5$ TeV and $\sqrt{s} = 14$ TeV respectively.

The different strategies followed to generate events for the two collision types (Pb-Pb and pp) are presented in the following.

4.6.0.1 Open charm in Pb-Pb collisions

Since heavy-quark observables are rare signals, as discussed in Chapter 2, the simulation of such processes would demand a huge amount of central Pb-Pb events in order to have enough statistics to study the charmed meson decays.

Following the same strategy as for the D^0 study [163,164], a separate generation of signal and background is done. The background events are central Pb-Pb events

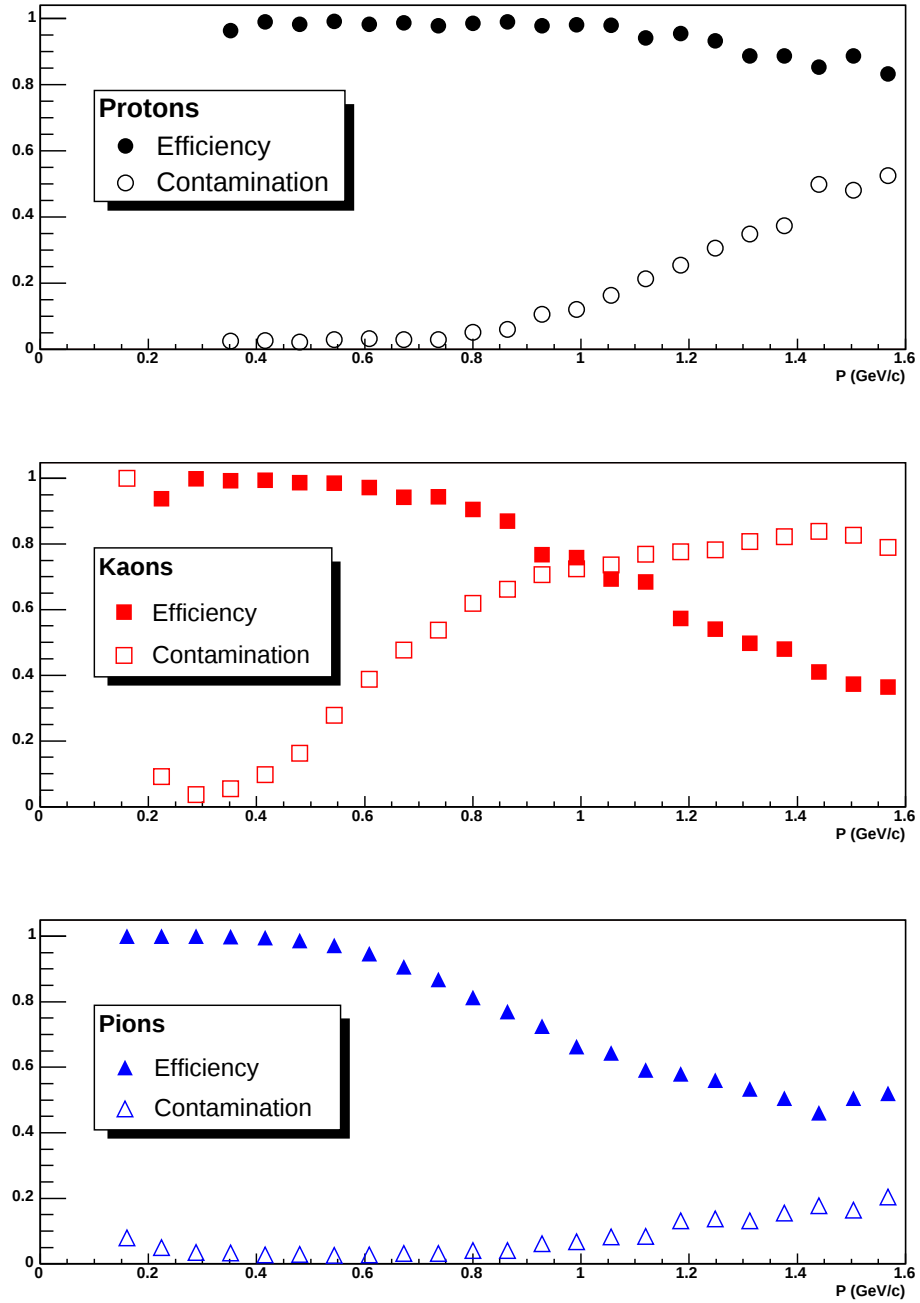


Figure 4.22: Efficiencies and contaminations in the ITS for the different particle species as a function of the momentum. Response functions in the four layers were obtained with a convolution of Gaussian and Landau functions.

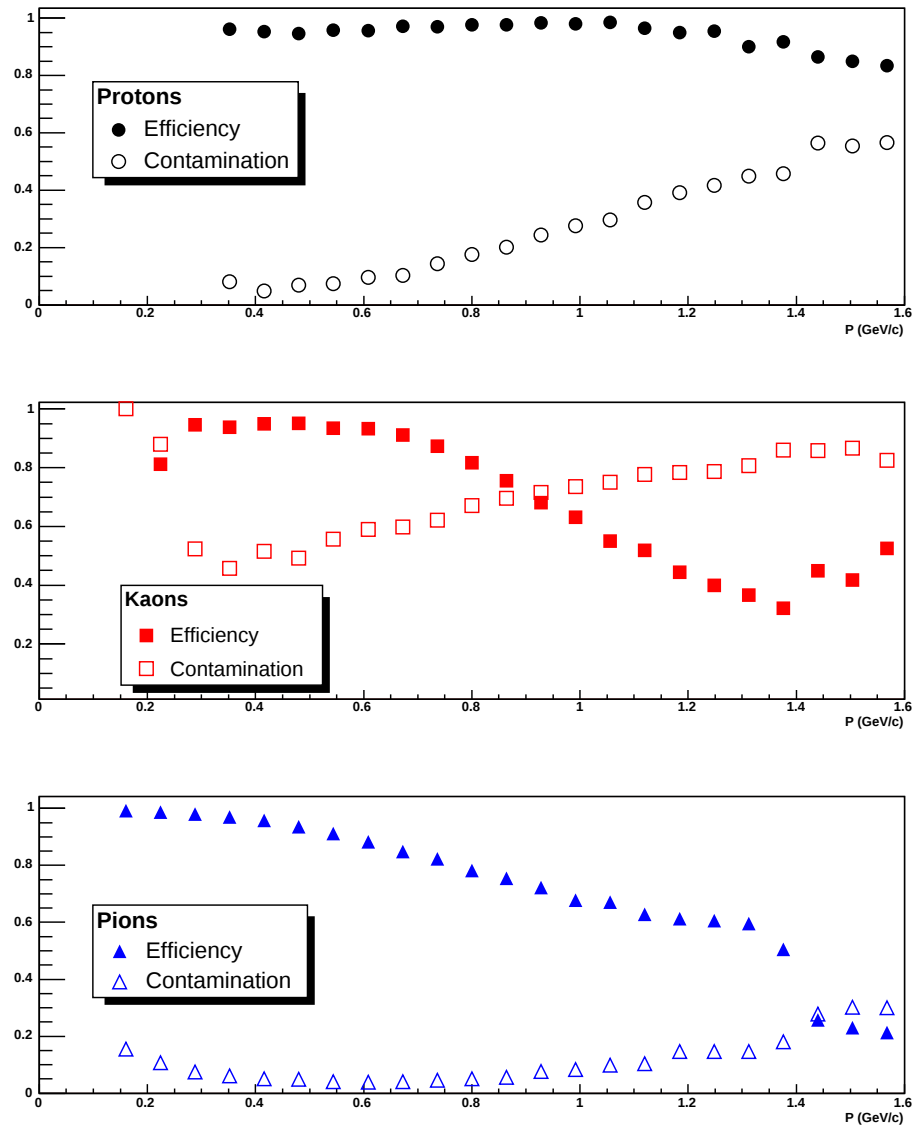


Figure 4.23: Efficiencies and contaminations in the ITS for the different particle species as a function of the momentum. Here the standard PID is applied, i.e. a Gaussian fit to the truncated mean of the four signals.

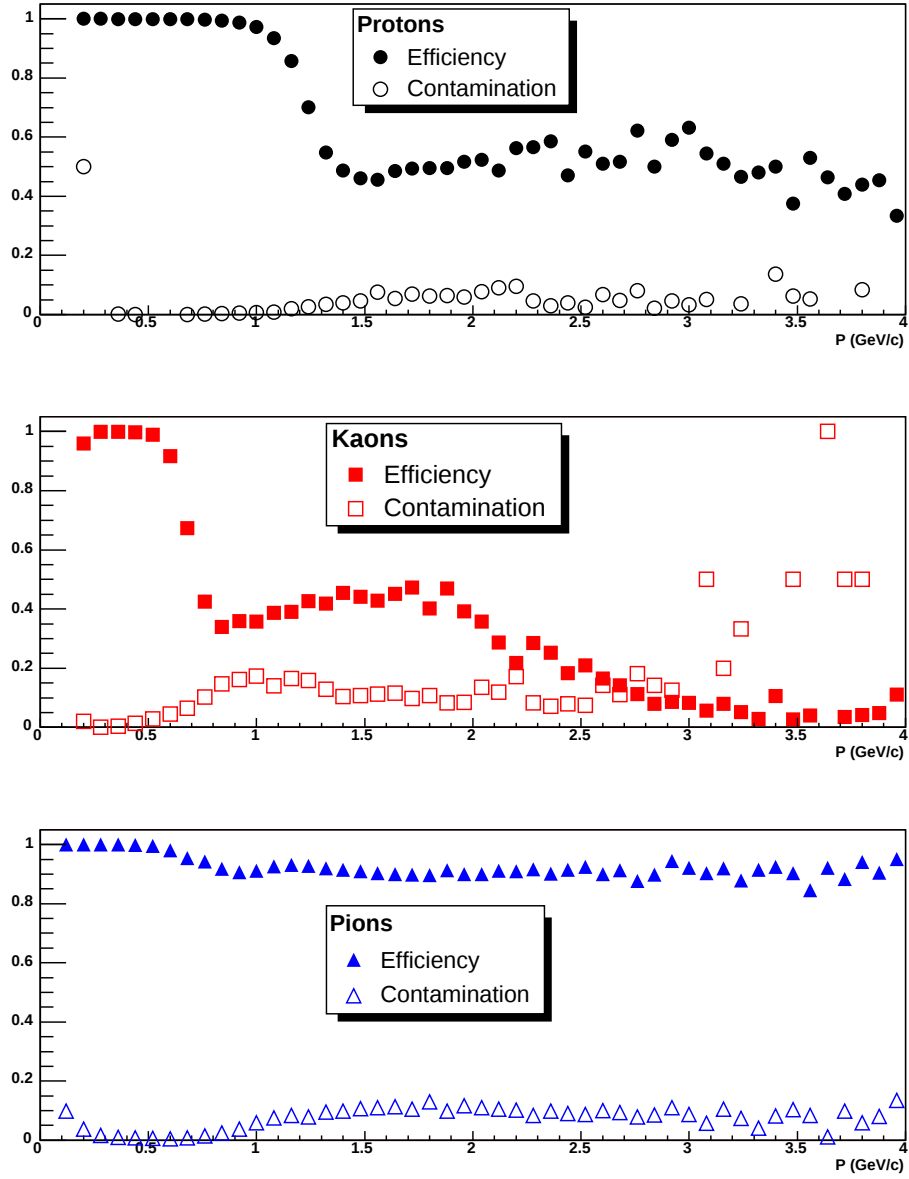


Figure 4.24: Efficiencies and contaminations with the combined PID for the different particle species as a function of the momentum.

Table 4.1: Summary of the event production for Pb-Pb collisions.

	Generator	Simulation	AliRoot version	Events
Signal ev.	PYTHIA	Full transport	v4-02-Rev-00	5000
Background ev.	HIJING	Full transport	v4-02-Rev-00	20000

generated with HIJING: we considered for this study the most central events with impact parameter of the collision $0 < b < 2$ fm. The corresponding multiplicity is $dN/dy = 6000$.

Since HIJING does not reproduce well the amount of charm expected from NLO calculations, the charm processes are switched off in HIJING; the proper number of $c\bar{c}$ pairs, as obtained from Glauber calculations (see Section 2.2.1), is then generated by PYTHIA⁷ in the p_T^{hard} range $p_T^{hard} > 2.1$ GeV/c. The Pb-Pb event is then a cocktail of the two generators with the settings described above.

The signal events are generated by PYTHIA; the number of $D^+ \rightarrow K^- \pi^+ \pi^+$ decays per event ($\simeq 9100$) was tuned in order to reproduce the HIJING multiplicity of a central Pb-Pb event. This is done in order to have similar reconstruction performance as for background events.

The events were generated on the Italian Grid, and the statistics obtained for signal and background events, as well as the AliRoot version used⁸, are summarized in Table 4.1.

4.6.0.2 Open charm in pp collisions

Since the CPU time needed to simulate and reconstruct a pp collision is largely smaller than that requested to simulate a Pb-Pb interaction (approximately 5 minutes compared to 8 hours), the adopted strategy was no longer to perform a separate production of signal and background events, but rather to generate an amount of pp events corresponding to a physics run of 10^7 events with the exact proportions of events with charm and beauty. There is also another reason why a separate production of signal and background was not done, namely that the reconstruction of the primary vertex depends on the track multiplicity and therefore it is important to have realistic pp events.

The main goal of this production was to have a large set of pp events available earlier than the PDC06⁹ production in order to test the software for the PDC06

⁷It is possible to use the PYTHIA program to generate only $c\bar{c}$ pairs without the underlying pp event. In this case the multiple interactions are switched off.

⁸The AliRoot version has been modified in order to force in PYTHIA the 3-charged body decay of the $D^\pm$ mesons.

⁹PDC06 (Particle Data Challenge) is the production of pp events planned by the ALICE Collaboration in 2006.

analysis, to develop the D^+ and D_s^+ selection strategies for pp collisions and to test the performance of the primary vertex algorithms.

The production consists of 10^7 pp events¹⁰, $\sim 85\%$ of which are minimum bias events without charm and beauty, including also diffractive events. The rest is made of events with charm and beauty. The percentage of events with $c\bar{c}$, $f_c \sim 14\%$ ¹¹, and $b\bar{b}$, $f_b \sim 1\%$, can be easily extracted from the charm and beauty cross section in pp collisions at $\sqrt{s} = 14$ TeV: $f_c = \sigma_{pp}^{c\bar{c}}/\sigma_{pp}^{inel}$ and $f_b = \sigma_{pp}^{b\bar{b}}/\sigma_{pp}^{inel}$, where $\sigma_{pp}^{c\bar{c}} = 11.2$ mb, $\sigma_{pp}^{b\bar{b}} = 0.51$ mb (see Table 2.1 and [92]) and the minimum bias pp cross section given by PYTHIA is $\sigma_{pp}^{inel} = 79$ mb.

Since this production was needed to be fast, the tracks were reconstructed only in the ITS and TPC, with parametrized TPC tracking response.

Each of the two samples with charm and beauty was appropriately subdivided in subsamples generated in different p_T^{hard} intervals. The p_T^{hard} intervals were tuned in such a way to obtain a p_T distribution of the heavy quarks in agreement with NLO calculations. A summary of the composition of the production (10^7 pp events) is reported below:

- 8'498'000 ($\sim 85\%$) events with $Q\bar{Q}$ production switched off
- 1'414'000 ($\sim 14\%$) events with $c\bar{c}$ in 4 subsamples of p_T^{hard} :
 - $2.76 < p_T^{hard} < 3$ GeV/c: 25%
 - $3 < p_T^{hard} < 4$ GeV/c: 40%
 - $4 < p_T^{hard} < 8$ GeV/c: 29%
 - $p_T^{hard} > 8$ GeV/c: 6%
- 73'000 ($\sim 1\%$) events with $b\bar{b}$ in 4 subsamples of p_T^{hard} :
 - $2.76 < p_T^{hard} < 4$ GeV/c: 5%
 - $4 < p_T^{hard} < 6$ GeV/c: 31%
 - $6 < p_T^{hard} < 8$ GeV/c: 28%
 - $p_T^{hard} > 8$ GeV/c: 36%

¹⁰This is roughly the number of events which was expected to be collected by ALICE in the first low-luminosity pp run during the first month (November 2007) of operation at the LHC. Recent revisions of the LHC schedule moved the start-up of the LHC by few months, thus the above scenario is unlikely to be reliable.

¹¹Using the inelastic cross section given by PYTHIA, $\sigma_{pp}^{inel} = 79$ mb, we obtain $N_{pp}^{c\bar{c}} = \sigma_{pp}^{c\bar{c}}/\sigma_{pp}^{inel} = 0.14$, which is different from the number obtained in Eq. 2.24 in Chapter 2, where the inelastic cross section taken from Ref. [130, 131] was used.

Our sample of events includes also a production consisting of $\sim 10^6$ pp events in which $c\bar{c}$ pairs are produced and the D^0 , $D^\pm$ and $D_s^\pm$ mesons are forced to decay into their “golden” hadronic channels $D^0 \rightarrow K\pi$, $D^\pm \rightarrow K\pi\pi$ and $D_s^\pm \rightarrow KK\pi$. These events were generated in order to have larger statistics for the ongoing analysis on the selection of open charmed mesons through hadronic decays. For such purpose, the AliRoot version used has been modified in order to force in PYTHIA the 3-charged body decay of the $D^\pm$ and $D_s^\pm$ mesons, including also the resonant decays.

The events of the two productions were generated on the Italian Grid.

In order to increase the signal statistics, we generated additional 5×10^4 pp events with at least one $D^\pm$ forced to decay in the hadronic channel $K\pi\pi$.

Chapter 5

Exclusive reconstruction of $D^\pm$ mesons in ALICE

This chapter is devoted to the feasibility study of the reconstruction of the $D^\pm$ mesons in both Pb-Pb and pp collisions via their hadronic decay channel $K\pi\pi$. This study has been the main part of this thesis work.

5.1 Experimental requirements for open charm analyses

As can be seen in Table 5.1, the weakly decaying charm and beauty states have decay lengths of the order of hundreds μm . Therefore, the distance between the production point (primary vertex) and the decay point (secondary vertex) is measurable, provided that a good tracking detector is available.

As explained in detail in Chapter 4, the main requirements to reconstruct hadrons with open charm and open beauty can be summarized as follows:

- p_T resolution of the order of $\sim 1\%$.
- $r\varphi$ track impact parameter resolution of the order of $\sim 60 \mu\text{m}$ for $p_T \sim 1 \text{ GeV}/c$. This is mandatory, together with the p_T resolution, in order to reconstruct secondary vertices.
- Particle identification from momenta of about $0.2 \text{ GeV}/c$ and up to a few GeV/c .

The performances mentioned above can be achieved in ALICE by the combined use of all the barrel detectors, namely ITS, TPC, TRD and TOF.

The study of rare signals in Pb-Pb collisions, for example particles with open charm, requires a separate simulation and reconstruction of signal and background

Table 5.1: Weakly decaying charm and beauty states.

Particle	mass (GeV/c ²)	$c\tau$ (μm)
$D^+(cd)$	1869	312
$D^0(c\bar{u})$	1865	123
$D_s^+(c\bar{s})$	1968	147
$\Lambda_c^+(udc)$	2285	60
$\Xi_c^+(usc)$	2466	132
$\Xi_c^0(dsc)$	2472	34
$\Omega_c^0(ssc)$	2698	21
$B^+(ub)$	5279	501
$B^0(db)$	5279	460
$B_s^+(sb)$	5370	438
$B_c^+(cb)$	6400	100 – 200
$\Lambda_b^+(udb)$	5624	368

events (see Chapter 4): in fact, taking into account that ~ 8 hours of computing time are needed for each Pb-Pb event, the statistics of events ($\sim 10^7$ - 10^8) required to study the signal with enough accuracy would be too large and beyond the capacity of the computing resources currently available.

As far as pp collisions are concerned, a separate generation of signal and background events was not carried out for two main reasons:

- pp events are characterized by a lower resolution in the reconstruction of the primary vertex with respect to Pb-Pb collisions (as discussed in Chapter 4). A generation of only signal events, would not be affected by such bias;
- a separate generation of signal events should have the advantage of achieving the required signal statistics with a smaller number of events than that needed with the physical event, i.e. Pb-Pb or pp. In case of pp collisions the track multiplicity is very low, namely ~ 4 reconstructed tracks per event per rapidity unit, and thus a huge number of signal events with the same multiplicity as pp events should be required, making the choice of a production of signal events no longer convenient. The goal of increasing the signal statistics has been reached by generating two additional sets of pp events: the first sample contains pp events with charm forced to decay hadronically (this could be useful also for other analyses like D^0 , $D_s^\pm, \dots$); the second contains pp events with at least one $D^\pm$ forced to decay in the hadronic channel $K\pi\pi$ (this has been carried out on purpose for this thesis work).

5.2 $D^0 \rightarrow K^- \pi^+$: benchmark study

The first study in ALICE on open charmed mesons was performed on D^0 mesons through their two-body hadronic channel $K^- \pi^+$, which is the simpler decay topology.

Hence, the studies on the reconstruction of $D^0 \rightarrow K^- \pi^+$ (see [163] for central Pb-Pb and pp collisions and [164] for pPb collisions) are a benchmark for the analysis of n -prong decays ($n > 2$) of open charmed mesons.

A sketch of the $D^0 \rightarrow K^- \pi^+$ decay is shown in Fig. 5.1.

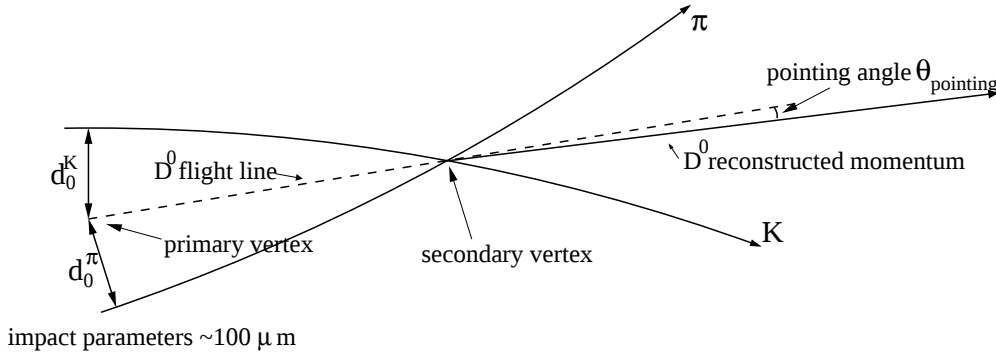


Figure 5.1: Schematic representation of the $D^0 \rightarrow K^- \pi^+$ decay with the track impact parameters (d_0) and the pointing angle (θ_{pointing}).

The selection strategy for this decay topology in Pb-Pb collisions is based on some cuts on the maximum distance of closest approach between two opposite sign tracks ($300 \mu\text{m}$) and on the minimum p_T ($800 \text{ MeV}/c$) for K and π which can be possibly identified by the TOF. Then, since the two decay tracks coming from the D^0 should have large and opposite sign impact parameters, an appropriate cut is performed on the product $d_0^K \times d_0^\pi$. Furthermore, the condition for the D^0 to point back to the primary vertex is imposed by a cut on the angle defined by the momentum vector of the D^0 candidate and the line connecting the primary and the secondary vertex (pointing angle θ_{pointing}). The cosine of θ_{pointing} peaks at +1 for the signal, and is almost uniformly distributed for the background. Combining these two cuts is even more efficient, as can be seen in the comparison between signal and background scenarios shown in Fig. 5.2.

Fig. 5.3 illustrates the invariant mass distributions of the $K\pi$ candidates after all the cuts, corresponding to 10^7 central Pb-Pb events. The final values for signal over background ratio (S/B) and significance ($S/\sqrt{S+B}$) for pp, pPb and Pb-Pb are reported in Table 5.2.

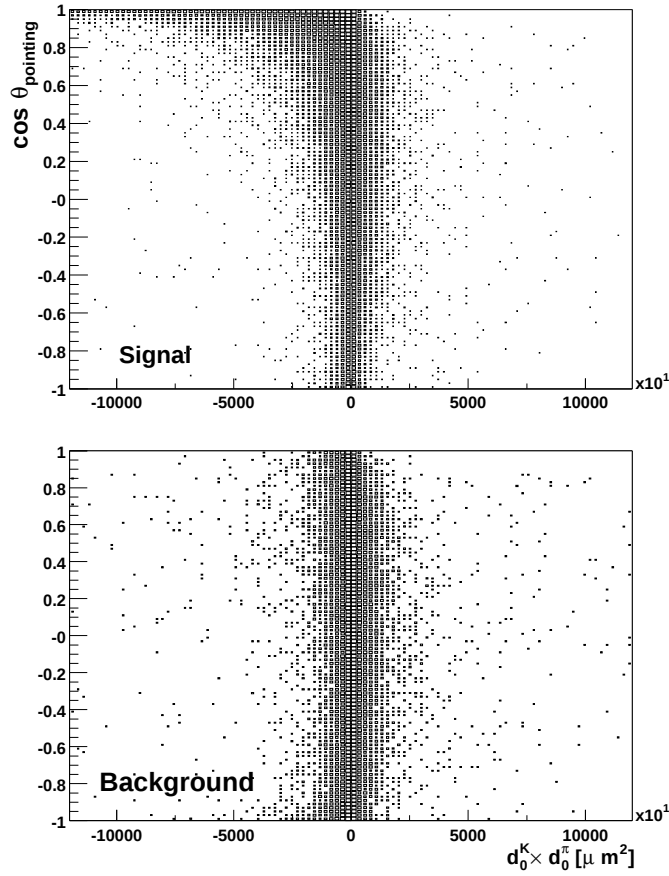


Figure 5.2: Cosine of the pointing angle versus product of the impact parameters for signal and background track pair combinations.

Table 5.2: Final values of S/B and significance for pp, pPb and Pb–Pb.

System	S/event	B/event	S/B	S/ $\sqrt{S+B}$
pp (10^9 events)	1.5×10^{-5}	12.4×10^{-5}	12%	39
pPb (10^8 events)	2.4×10^{-4}	5.4×10^{-3}	4%	32
Pb–Pb (10^7 events)	1.3×10^{-3}	1.16×10^{-2}	11%	37

5.3 $D^+ \rightarrow K^- \pi^+ \pi^+$ vs $D^0 \rightarrow K^- \pi^+$

The longer decay length of the D^+ meson ($c\tau \simeq 311 \mu\text{m}$) compared to that of the D^0 meson ($123 \mu\text{m}$) can be regarded as an advantage for the D^+ reconstruction,

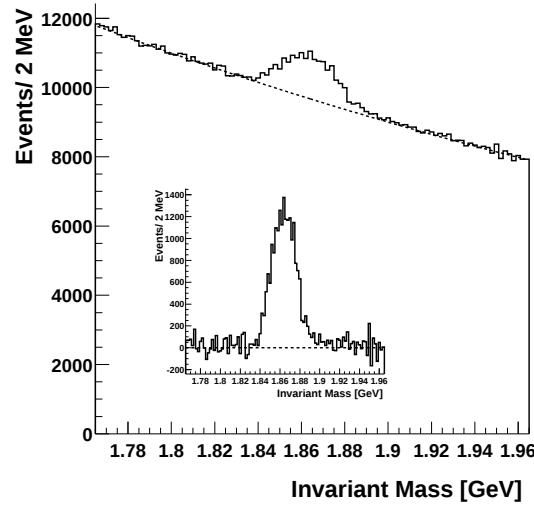


Figure 5.3: $K\pi$ invariant mass distribution for 10^7 events. The same distribution after background subtraction is shown in the inset.

since a more displaced secondary vertex should help in the separation of the signal from the background.

An easy check is to extract the $c\tau$ of D^+ mesons from our generated signal events. The probability that a particle travels a distance x greater than x_0 is [84]:

$$P(x > x_0) = e^{-\frac{x_0 M}{c\tau p}} \quad (5.1)$$

where M and p are the mass and the momentum of the particle.

The plot in Fig. 5.4 reports on the x axis the variable $x_0 M/p$ where x_0 is the decay length in the laboratory reference system, M and p are the mass and the momentum of D^+ mesons. For each bin of the histogram, the number of entries corresponds to the D^+ mesons with $x_0 M/p$ greater than the centroid of the bin. Both the mean value of the histogram and the inverse slope of the exponential fit superimposed are in perfect agreement with the $c\tau \simeq 311 \mu\text{m}$: indeed, the inverse slope is $1/31.5\text{cm} \sim 315 \mu\text{m}$.

In addition, the decay channel $D^+ \rightarrow K^- \pi^+ \pi^+$, which is the most promising from an experimental point of view because all its decay products can be reconstructed in the detectors, has a larger branching ratio with respect to $D^0 \rightarrow K^- \pi^+$ ($BR = 9.2\%$ compared to 3.8%).

On the other hand, the main drawback comes from the combinatorial background, which is $B_3 = \frac{N(N-1)(N-2)}{3!}$ for a three body decay, where N is the track multiplicity per event, and $B_2 = \frac{N(N-1)}{2!}$ in case of two body.

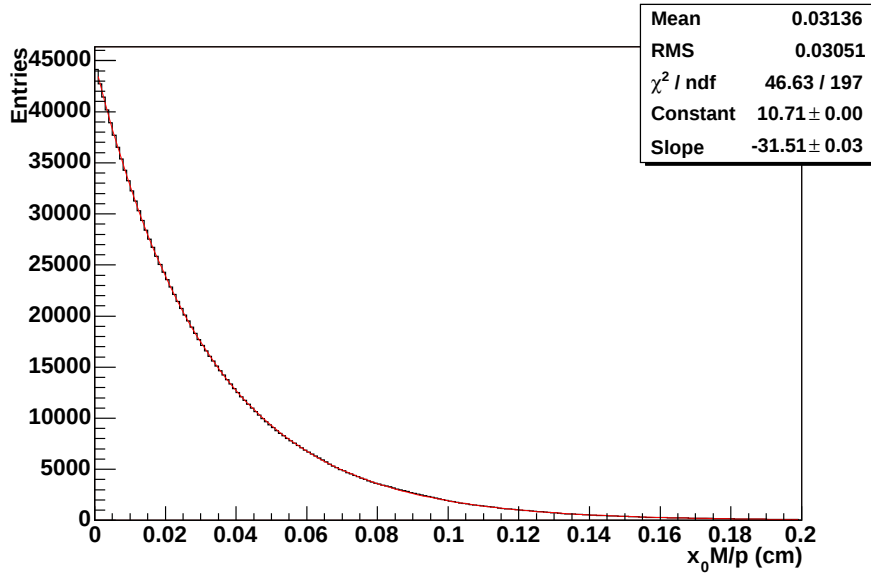


Figure 5.4: Number of D^+ mesons with x_0M/p or greater (see text for details) as a function of x_0M/p . An exponential fit is superimposed to the histogram. The slope of the fit corresponds to $\Gamma = 1/c\tau$ in Eq. 5.1.

It is easy to find that for $N > 5$ the total number of possible combinations of triplets B_3 is larger than the total number of pairs B_2 : in particular, as N becomes large, like in Pb-Pb collision, we have $B_3 \gg B_2$. For example, the track multiplicity per event in ALICE for Pb-Pb collisions given by HIJING (with particle multiplicity $dN_{ch}/dy=6000$) is $N \sim 7000$, leading to $B_3 \sim 6 \times 10^{10}$ and $B_2 \sim 2 \times 10^7$ without particle identification.

Another disadvantage is that the average transverse momentum of the decay products is softer for $D^\pm$ mesons compared to D^0 , making a selection based on cuts on the p_T of the tracks less powerful. The left panels of Fig. 5.5 report the transverse momentum distributions given by the generator, i.e. without any reconstruction effect, for $D^\pm$ mesons and their decay products, kaons and pions. The mean p_T are 1.66 GeV/c, 0.86 GeV/c and 0.66 GeV/c for $D^\pm$, kaons and pions respectively. The decay products of $D^\pm$ mesons are softer with respect to the particles coming from D^0 decays, whose p_T is of the order of 1 GeV/c.

The right panels of Fig. 5.5 contain the same plots as the left panels but using the reconstructed tracks instead of the generated particles. The plot (b) showing the p_T distribution of reconstructed $D^\pm$ mesons was done by grouping the $K\pi\pi$ triplets coming from $D^\pm$ decays by means of information stored at generation time. The spectra of the reconstructed particles are harder compared to the ones

of the generated particles because low- p_T particles are lost in the tracking.

The spectra of particles from open charm decays are slightly harder than those of the bulk of pions and kaons produced in Pb-Pb collisions, as can be seen in Fig. 5.6 for reconstructed particles: hence, the rejection of low- p_T particles in order to reduce background is a reasonable choice.

From the above considerations it comes out that a different selection strategy for the $D^+ \rightarrow K^- \pi^+ \pi^+$ reconstruction has to be exploited. In addition, a selection based on the product $d_0^K \times d_0^\pi$ as done for the D^0 is no longer useful for a three-body decay.

The three charged body channel $K\pi\pi$ (with a total branching ratio $BR = 9.2\%$) can be studied with the two following channels:

- via the non-resonant decay $D^+ \rightarrow K^- \pi^+ \pi^+$, with $BR = 8.8\%$;
- via the resonant decay through the K^{*0} with its three mass states:
 - $D^+ \rightarrow \overline{K^{*0}}(892) \pi^+ \rightarrow K^- \pi^+ \pi^+$ with $BR = 1.3\%$;
 - $D^+ \rightarrow \overline{K^{*0}}(1430) \pi^+ \rightarrow K^- \pi^+ \pi^+$ with $BR = 2.3\%$;
 - $D^+ \rightarrow \overline{K^{*0}}(1680) \pi^+ \rightarrow K^- \pi^+ \pi^+$ with $BR = 3.8 \cdot 10^{-3}\%$.

The difference between the non-resonant and resonant decays is clear in the Dalitz plots¹ shown in Fig. 5.7, where the left panel corresponds to non-resonant $D^+ \rightarrow K^- \pi^+ \pi^+$ decays and the right panel refers to the resonant channel through the $K^{*0}(892)$.

Although a dedicated work on the possibility to exploit the resonant decays of the K^{*0} has not yet been concluded due to the low branching ratios, a possible selection based on the K^{*0} mass may be helpful in the background rejection.

5.4 Selection strategy for the $D^+ \rightarrow K^- \pi^+ \pi^+$ channel in Pb-Pb collisions.

Before tuning the cuts needed to select the signal from the background, it is important to know what is the invariant mass resolution, in the $D^\pm$ mass region, which can be attained in the ALICE barrel. To this purpose, we use a sample of our Monte Carlo signal events and group the reconstructed $K\pi\pi$ triplets coming from $D^\pm$ decays by means of information stored at generation time: this is an

¹The Dalitz plot is a largely used representation of a three body decay $a \rightarrow b + c + d$: on the x axis the invariant mass square M_{bc}^2 is reported, while the quantity M_{bd}^2 is on the y axis. The edges of the area define the kinematical constraints of the decay. Any deviation from uniformity of the area is due to resonant decays.

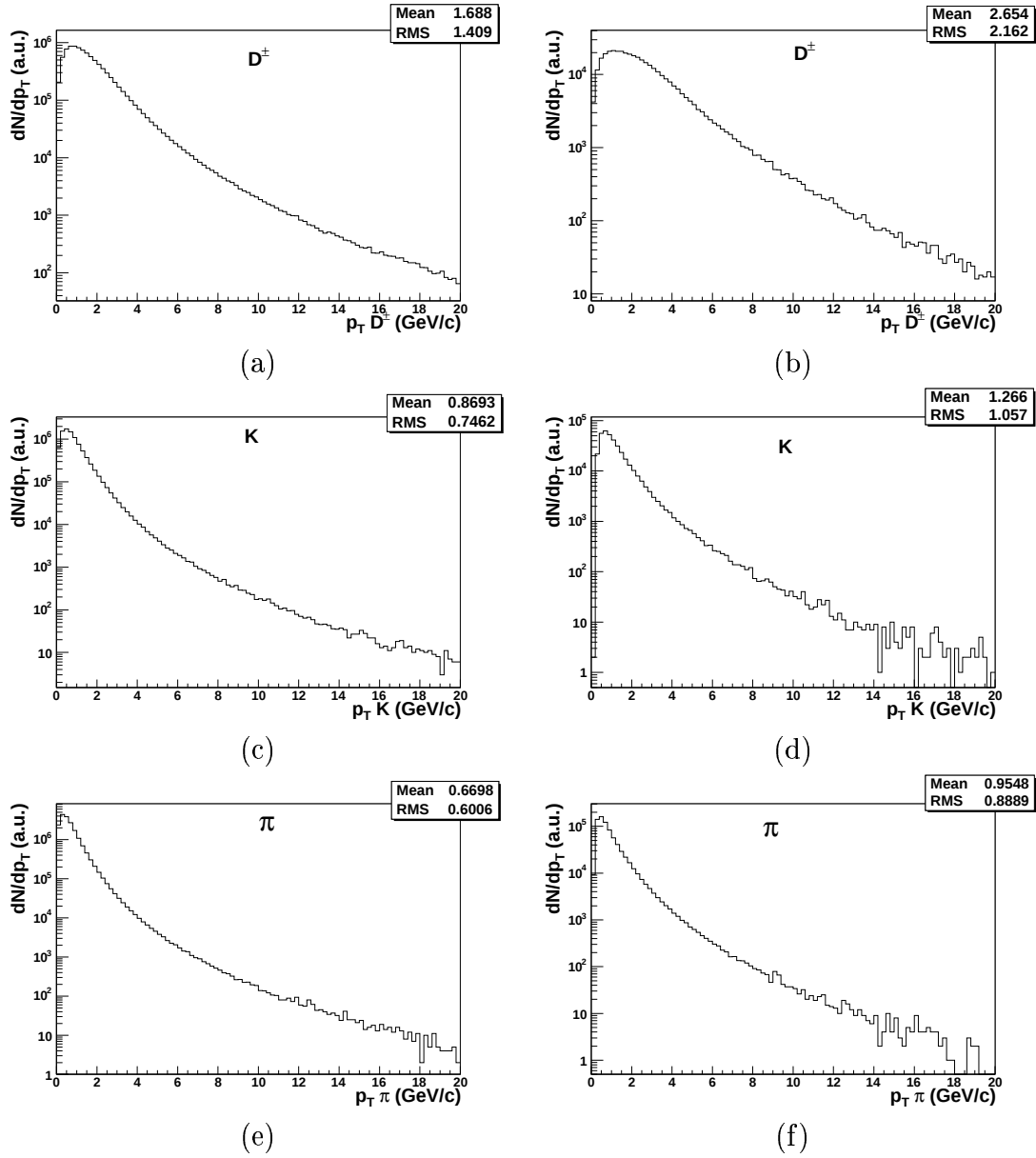


Figure 5.5: p_T distribution of the generated (a) and reconstructed (b) $D^\pm$ mesons. p_T distribution of generated (c) and reconstructed (d) kaons coming from $D^\pm$ decays. p_T distribution of generated (e) and reconstructed (f) pions coming from $D^\pm$ decays.

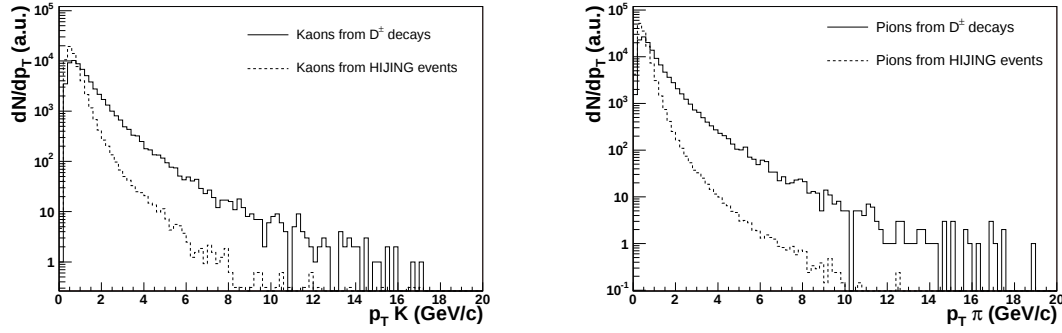


Figure 5.6: Left (right) panel: p_T distribution of reconstructed kaons (pions) coming from $D^\pm$ decays superimposed to that of kaons (pions) produced in Pb-Pb collisions. The histograms are normalized to the same area.

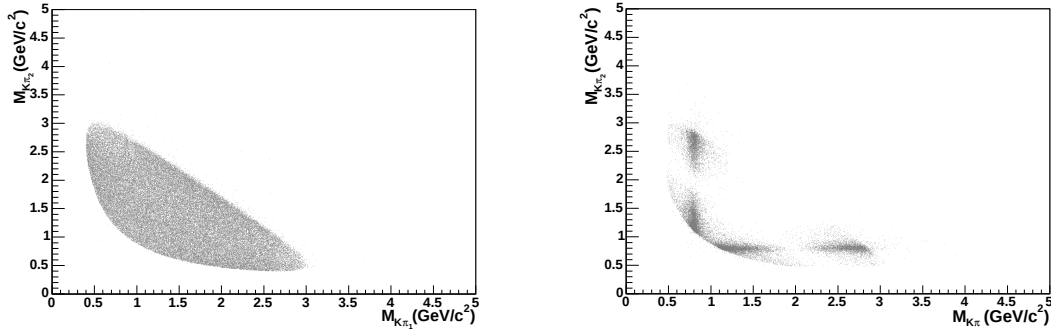


Figure 5.7: Left panel: Dalitz plot for the non-resonant decay $D^+ \rightarrow K^- \pi^+ \pi^+$. Right panel: Dalitz plot for the resonant decay $D^+ \rightarrow \bar{K}^{*0} \pi^+ \rightarrow K^- \pi^+ \pi^+$. The two plots are produced from the reconstructed momenta using the information stored at the generation level.

evaluation of the detector performance, thus the knowledge of the Monte Carlo information is mandatory.

The D^+ invariant mass distribution integrated over p_T is shown in Fig. 5.8 (a): as expected, the peak corresponds to the mass of the D^+ meson ($M = 1.867$ GeV/c²), smeared by the experimental resolution of ~ 11 MeV/c². The peak position does not depend on the D^+ transverse momentum, as can be seen in Fig. 5.8 (b).

The resolution on the measurement of the invariant mass depends on p_T as it is clear from Fig. 5.8 (c). The width σ reported in Fig. 5.8 (d) is obtained with a Gaussian fit to the histograms in each p_T bin. In the following, when we will tune the cuts in the invariant mass range $|M_{inv(K\pi\pi)} - M_{D^+}| < 1\sigma$, we refer to a safe choice of $\sigma = 12$ MeV/c².

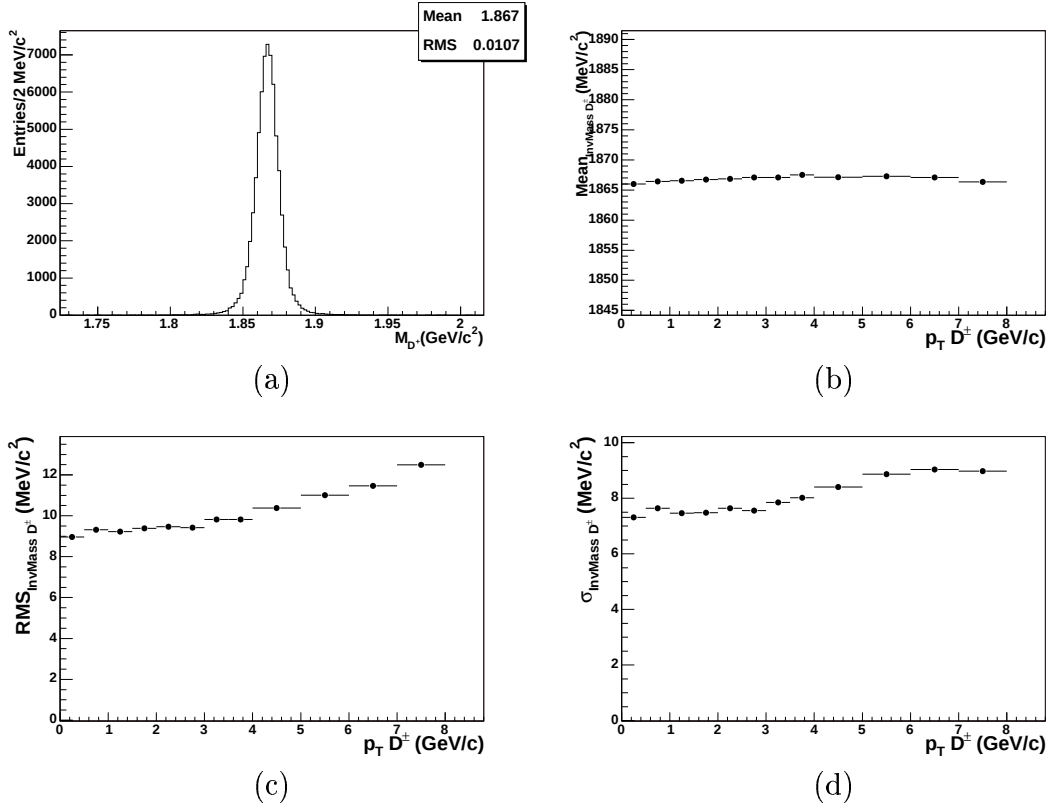


Figure 5.8: (a) D^+ invariant mass distribution integrated over p_T . (b) Mean value of the D^+ invariant mass distribution as a function of p_T of the D^+ . (c) RMS of the D^+ invariant mass distribution as a function of p_T . (d) Width of the Gaussian fit to the D^+ invariant mass distribution as a function of p_T . The horizontal error bars represent the momentum ranges where the invariant mass distributions are considered.

After the above preliminary remarks, it is possible to start by choosing the cut variables and to optimize the cuts on both signal and background events in order to achieve the best signal over background ratio (S/B) and Significance ($S/\sqrt{S+B}$).

The strategy is to perform three different kinds of selections:

1. Cuts applied on the single reconstructed tracks: this first selection is based on particle identification, transverse momentum p_T and track impact parameter d_0 . It is done on the tracks before they are combined into triplets and passed to the secondary vertex finding algorithm (from now on “vertexer”). The goal is to reduce the number of the possible combinatorial triplets in a central Pb-Pb collision. Since this number is $\sim 10^{10}$ without any initial cut, it must be cut by 3-4 orders of magnitude before using the vertexer.
2. Cuts applied on combined tracks (pairs and triplets): this selection takes place before the triplets are passed to the vertexer. The triplets are made of tracks with the right combination of charge signs and are formed starting from those pairs of opposite sign tracks which are appropriately displaced from the primary vertex. In addition, only the triplets satisfying specific requirements on combinations of track impact parameters are accepted.
3. Cuts applied on the secondary vertices: once the secondary vertices are found, selections based on the quality of the vertices and on the distance between primary and secondary vertices can be performed. Furthermore, an efficient selection is the request of a good pointing of the reconstructed D momentum to the primary vertex.

A more detailed description of the above selection criteria is presented in the following subsections, together with the cut values obtained as a result of an optimization procedure.

5.4.1 Single track cuts

The variables which appear more promising to separate tracks which are decay products of $D^\pm$ mesons and tracks coming from the primary vertex are the transverse momentum p_T and the track impact parameter in the bending plane (d_0). Since the cut on the track p_T may be different for kaons and pions, we started by assuming a perfect particle identification, i.e. the identity of the particle given by the generation is used. Therefore, the cut variables are $p_{Tcut,K}$, $p_{Tcut,\pi}$ (different for kaons and pions) and d_{0cut} (a single cut for the two species) and a candidate triplet is accepted when:

$$p_{T,K} > p_{Tcut,K}, \quad p_{T,\pi_j} > p_{Tcut,\pi}, \quad d_{0,K} > d_{0cut}, \quad d_{0,\pi_j} > d_{0cut} \quad (5.2)$$

where $j = 1, 2$ refers to the two pions in the triplets, and $p_{T,i}$ and $d_{0,i}$ ($i = K, \pi_1, \pi_2$) are the reconstructed kinematical variables associated to the three particles in the triplet.

The cuts are tuned by applying them in parallel on both signal and background events.

The number of background triplets per event B , and for all the possible single track cut combinations, is extracted from the background events in the following way:

$$B = N_{K^+} \frac{N_{\pi^-}(N_{\pi^-} - 1)}{2!} + N_{K^-} \frac{N_{\pi^+}(N_{\pi^+} - 1)}{2!} \quad (5.3)$$

where $N_{K^\pm}$ and $N_{\pi^\pm}$ are the numbers of kaons and pions in one background event which are accepted in the cuts defined in Eq. 5.2.

As far as the signal events are concerned, we have to define a procedure to obtain the expected signal yield in real Pb-Pb collisions from the number of D^+ accepted within the cuts in the signal events.

Hence, we start from the ratio of accepted signal triplets within a given cut to the number of reconstructed $D^+ \rightarrow K^- \pi^+ \pi^+$ topologies in our sample of signal events, R_D^{acc} :

$$R_D^{acc} = \frac{N_D^{acc}}{N_D^{rec}} \quad (5.4)$$

Then, we define the number of reconstructed $D^+ \rightarrow K^- \pi^+ \pi^+$ topologies per Pb-Pb event, M_D^{rec} (which represents the yield in a realistic event):

$$M_{D^+}^{rec} = M_{D^+}^{gen} \times K \sim 0.105 \quad (5.5)$$

where M_D^{gen} is the number of generated $D^+ \rightarrow K^- \pi^+ \pi^+$ topologies per Pb-Pb event (obtained from Table 2.4 in Section 2.4 and taking into account the branching ratio $BR = 9.2\%$) and K is a factor accounting for the detector acceptance and the track reconstruction efficiency. The factor K is estimated from the signal events and may vary with the $D^\pm$ transverse momentum: as can be seen in Fig. 5.9, the fraction of reconstructed $D^+ \rightarrow K^- \pi^+ \pi^+$ topologies over the produced $D^\pm$ in the solid angle is not constant but, as expected, changes from a minimum at low p_T to a maximum at high p_T . For simplicity, a p_T -integrated value of $K \sim 2\%$ has been considered in this work; however, it is a safe choice because it is underestimated at high p_T .

Therefore, the number of reconstructed signal triplets S per Pb-Pb event accepted within the cuts is given by $S = R_{D^+}^{acc} \times M_{D^+}^{rec}$.

Given the signal and background triplets per event, S and B , the Significance normalized to 10^7 central Pb-Pb events (expected to be collected in one year of data taking) is then $S/\sqrt{S+B} \times \sqrt{10^7}$.

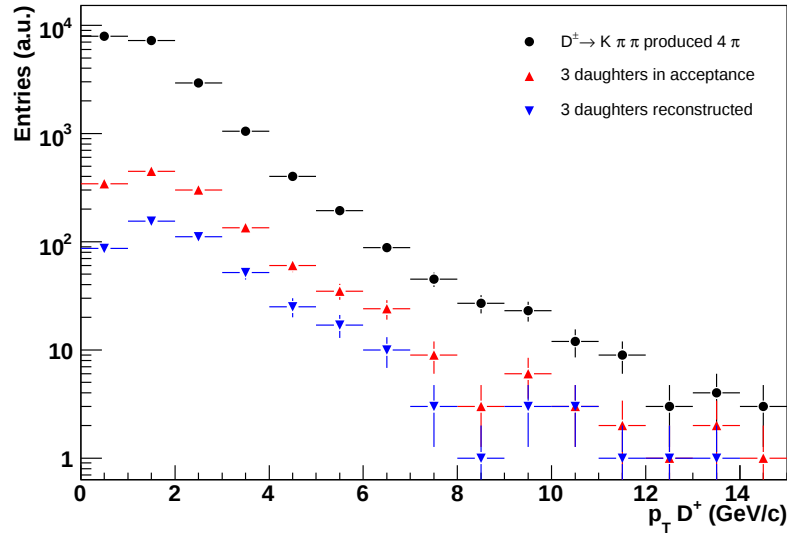


Figure 5.9: p_T distributions of $D^\pm$ mesons generated in the full solid angle (black circles), with the three decay products in the ALICE acceptance (red triangles-up) and with the three decay products reconstructed in the detector (blue triangles-down).

In Fig. 5.10 it is shown the number of accepted background triplets per event, B , as a function of the ratio R_D^{acc} of signal accepted within the cuts applied on single tracks. For simplicity only the numbers of background triplets for which the Significance is maximized are shown: in fact in a given interval of R_D^{acc} there are several choices of single track cuts which give different values of background triplets B . As shown in the figure, if no signal S is rejected by the cuts, i.e. 100% signal is accepted, the best choice of the single track cuts would lead to $B = 10^9$ background triplets per event (if the particle identification is assumed, otherwise $B \sim 10^{10}$). Similarly, applying very hard cuts ($p_{Tcut,K}, p_{Tcut,\pi} > 1.2$ GeV/c), B is significantly reduced at the expense of the fraction of accepted signal which is less than 1-2%.

The goal is to find a good compromise between the number of background triplets which has to be taken as low as possible and, on the other hand, the number of signals which has to be large enough.

The approach followed in this work is to tune the cuts in order to reduce the combinatorial background of about three orders of magnitude (from $B \sim 10^9$ to $B \sim 10^6$), because with $B \sim 10^6$ the secondary vertices of the background triplets can be computed in a reasonable time. An additional requirement is that the choice of the single track cuts must preserve the p_T distribution of $D^\pm$ mesons down to at least ~ 1 GeV/c, because one of the tasks of ALICE is to be able to measure the charm production cross section in the low- p_T region.

The choice of $B \sim 10^6$ can be given by the set of single track cuts which maximizes the Significance defined by $p_{Tcut,K} = p_{Tcut,\pi} = 0.95$ GeV/c and $d_{0,cut} = 0$; the corresponding ratio of accepted signal would be $\sim 10 - 15\%$ (see Fig. 5.10) and the Significance normalized to 10^7 central Pb-Pb events would be ~ 0.034 in the full invariant mass range. Unfortunately such cuts are too hard and do not satisfy the above requirement on the p_T distribution of $D^\pm$ mesons, as can be seen in Fig. 5.11, where the p_T distribution of $D^\pm$ mesons exhibits a cut-off of $p_T \sim 2$ GeV/c.

Therefore, different single track selections with $B \sim 10^6$ have been tried and the best combination of cuts which preserves the p_T spectrum down to ~ 1 GeV/c is defined by $p_{Tcut,K} = 0.7$ GeV/c, $p_{Tcut,\pi} = 0.5$ GeV/c and $d_{0,cut} = 95$ μ m. The Significance corresponding to such cuts is ~ 0.025 in the full invariant mass range.

As shown in Fig. 5.12 (left panel), this choice of cuts guarantees signal statistics well below 1 GeV/c. In addition, it can be seen from Fig. 5.12 (right panel) that the single track cuts distort the $D^\pm$ p_T spectrum, in fact the ratio of the p_T distribution of reconstructed $D^\pm$ mesons with single track cuts over the same spectrum without any preliminary selection is not constant for $p_T \leq 4$ GeV/c.

With the chosen selection on the single tracks the corresponding ratio of accepted signal (p_T integrated) is $\sim 7.5\%$.

Starting from this set of cuts on the single tracks, three different analyses have

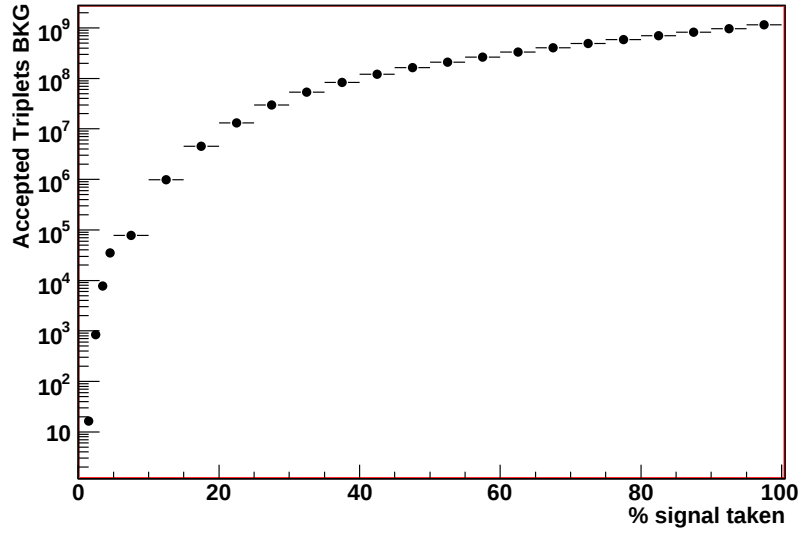


Figure 5.10: Accepted background triplets per event as a function of the ratio of signal (R_D^{acc}) accepted within the cuts applied on single tracks. Only the background triplets for which the Significance is maximized are shown.

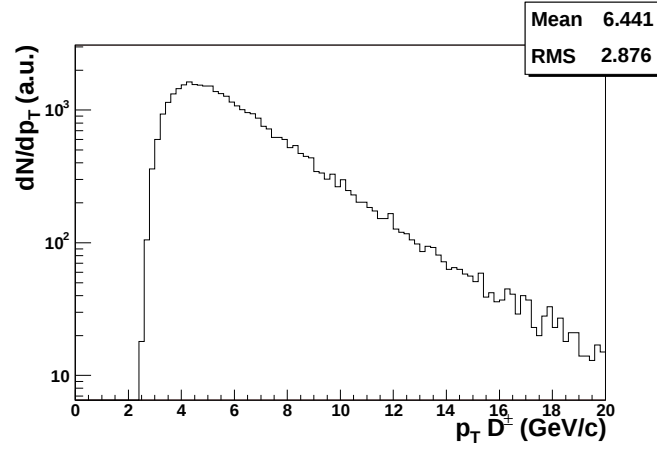


Figure 5.11: p_T distribution of reconstructed $D^\pm$ mesons with the set of tight single track cuts $p_{Tcut,K} = 0.95$ GeV/c, $p_{Tcut,\pi} = 0.95$ GeV/c and $d_{0,cut} = 0$ μm .

been performed with different treatment on PID information:

1. perfect particle identification (i.e. given by the generation);
2. real particle identification (i.e. combined PID given at reconstruction level);
3. no particle identification.

Different single track cuts on pions and kaons are applied also in the analysis without PID, thanks to the topology of the decay $D^+ \rightarrow K^- \pi^+ \pi^+$ which always allows to identify the kaon in a triplet by means of its charge sign.

5.4.2 Cuts on combined tracks: pairs and triplets

Once the cuts on the single tracks have been applied, the triplets are formed according to their sign.

The strategy is to start by combining pairs of tracks with opposite charge, which are by definition (in case of a signal triplet) one kaon and one pion. Before adding a third track and forming the triplet, the secondary vertex of the track pair is found using the algorithm implemented on purpose for open charm analyses and discussed in detail in Section 4.5.3.

This procedure is applied to the three analyses mentioned above: ideal PID, real PID and without PID. The following plots refer to the first case.

Fig. 5.13 shows a distribution of the distance between the primary vertex and the vertex of the track pair for both signal and background candidate triplets. It is evident that signal and background are well separated, suggesting that a possible cut on this distance may be helpful in the selection phase.

Another confirmation comes from Fig. 5.14 (left panel), where it is reported the ratio of $K\pi$ pairs (both signal and background) accepted in the selection $\delta > \delta_{cut}$, where δ is the distance between the primary vertex and the secondary vertex of the track pair $K\pi$.

The same procedure as for the single track cuts is followed in order to tune the cut variable indicated as δ_{cut} : for all the possible values of the cut variable δ_{cut} , the numbers of signal S and background B triplets per event with both $K\pi_1$ and $K\pi_2$ passing the selection $\delta > \delta_{cut}$ are counted. The best cut is the one which maximizes the Significance. Fig. 5.14 (right panel) shows the ratio of triplets (both signal and background) accepted within the cut.

The value of δ_{cut} which maximizes the Significance is $\delta_{cut} = 700 \mu\text{m}$.

The cut variable δ_{cut} has been optimized also for the case with real PID, obtaining $\delta_{cut} = 700 \mu\text{m}$, and for the case without any PID, obtaining $\delta_{cut} = 600 \mu\text{m}$. The values of the Significance obtained at each step of the selection procedure are summarized in Chapter 6.

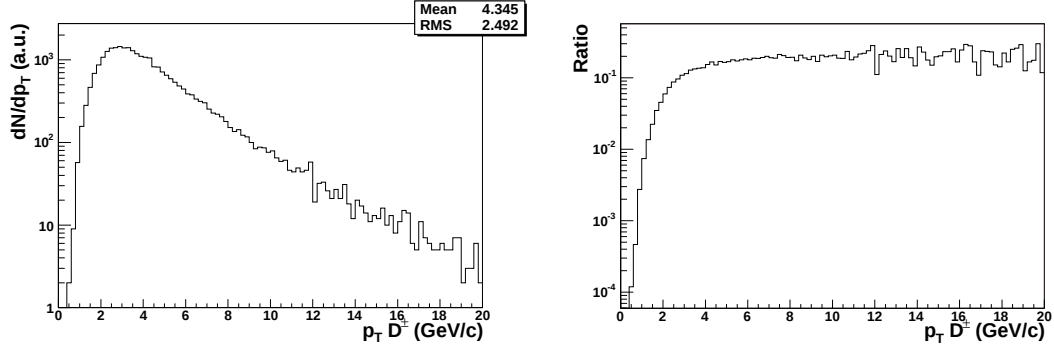


Figure 5.12: Left panel: p_T distribution of reconstructed $D^\pm$ mesons with the set of single track cuts $p_{Tcut,K} = 0.7$ GeV/c, $p_{Tcut,\pi} = 0.5$ GeV/c and $d_{0,cut} = 95$ μm . Right panel: ratio of the p_T distribution of reconstructed $D^\pm$ mesons with the single track cuts over the same spectrum without any preliminary selection.

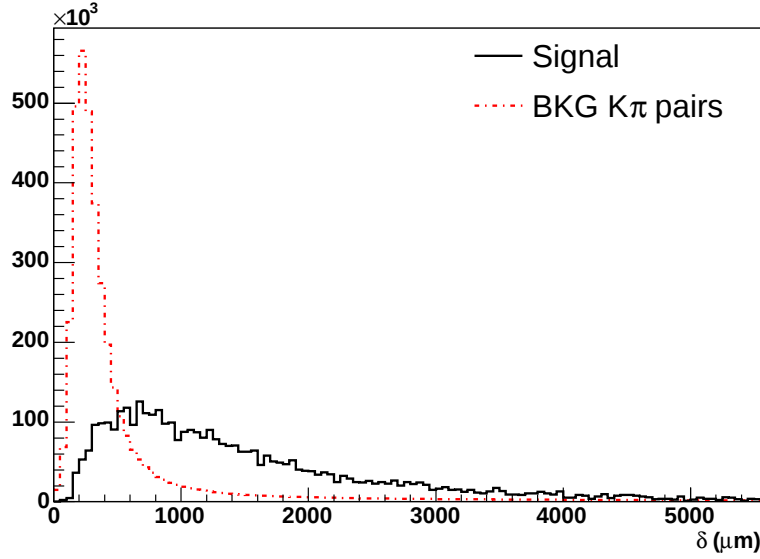


Figure 5.13: Distribution of the distance between primary vertex and the secondary vertex of the track pair $K\pi$, for both signal and background events. The histograms are normalized to the same area. The plot is obtained assuming an ideal particle identification.

At this point, only the pairs $K\pi_1$ and $K\pi_2$ satisfying the above requirement on the distance between primary and secondary vertex are grouped into triplets.

An additional constraint is that the tracks belonging to a candidate $D^\pm$ triplet must have: $d_{0,K} \times d_{0,\pi_1} > 0$ or $d_{0,K} \times d_{0,\pi_2} > 0$. The track impact parameter d_0 in the bending plane with respect to the primary vertex (already defined in Section 4.5.1) is given by the difference between the radius of the track circumference on the transverse plane and the distance of the centre of the circumference from the primary vertex. Therefore:

- $d_0 > 0$ if the primary vertex is inside the circumference defined by the track in the bending plane;
- $d_0 < 0$ if the primary vertex lies outside the circumference defined by the track in the bending plane.

Fig. 5.15 (left panel) shows a typical display of the generated particles coming from a $D^+ \rightarrow K^-\pi^+\pi^+$ decay. A zoom of the secondary vertex region is shown together with the signs of the impact parameters in Fig. 5.15 (right panel). In this case, $d_{0,K} \times d_{0,\pi_1} > 0$ and $d_{0,K} \times d_{0,\pi_2} > 0$.

This requirement on the signs of the products of the impact parameters comes from kinematical constraints of the $D^\pm$ decay: indeed, in order to conserve the $D^\pm$ momentum, the configuration with $d_{0,K} \times d_{0,\pi_1} < 0$ and $d_{0,K} \times d_{0,\pi_2} < 0$ is forbidden. An example of the impossibility of this configuration is shown in Fig. 5.16, where, it is clearer in the zoom reported in the right panel, the total momentum of the three particles is not conserved because it does not point to the primary vertex.

The result of applying such a selection on the product of the impact parameters is that $\sim 1/4$ of background triplets are rejected. This is shown in Fig. 5.17, where two bi-dimensional histograms, for both signal triplets (left panel) and background triplets (right panel), report $d_{0,K} \times d_{0,\pi_1}$ on the x axis and $d_{0,K} \times d_{0,\pi_2}$ on the y axis. The signal events exhibit a depleted region for $d_{0,K} \times d_{0,\pi_1} < 0$ and $d_{0,K} \times d_{0,\pi_2} < 0$. Few signal points actually enter in the forbidden area because of a bad reconstruction of the track impact parameters.

5.4.3 Cuts on the secondary vertices

Once the triplets are combined, they are passed to the algorithm which finds the coordinates of secondary vertices made of three tracks (see Section 4.5.3 for a complete description of the performance of the algorithm).

A very effective cut is given by the quality of the found secondary vertex, defined by the variable called σ , which measures the track dispersion around the calculated secondary vertex and it is expressed in the following way:

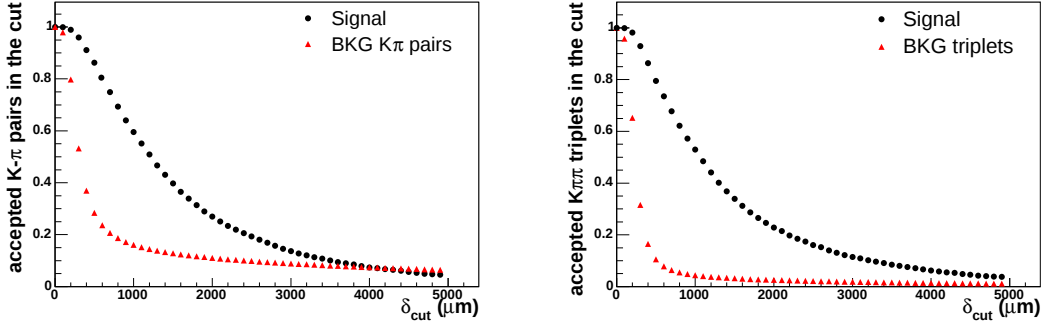


Figure 5.14: Left panel: ratio of pairs (both signal and background) selected by the cut $\delta > \delta_{cut}$. Right panel: ratio of triplets (both signal and background) selected by the cut $\delta > \delta_{cut}$. The plots are obtained assuming an ideal particle identification.

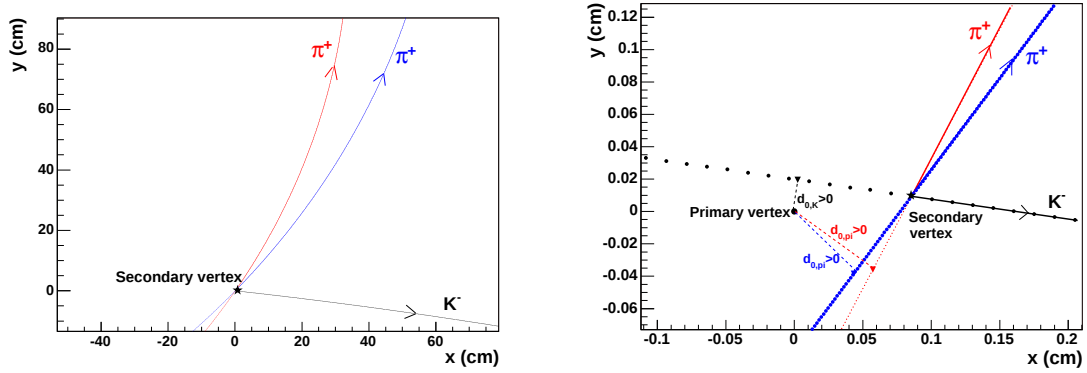


Figure 5.15: Left panel: display of a $D^+ \rightarrow K^- \pi^+ \pi^+$ decay obtained with the kinematical variables stored at generation time. Right panel: zoom of the same decay shown in the left panel. The impact parameters of the particle trajectories with their signs are also indicated in the figure.

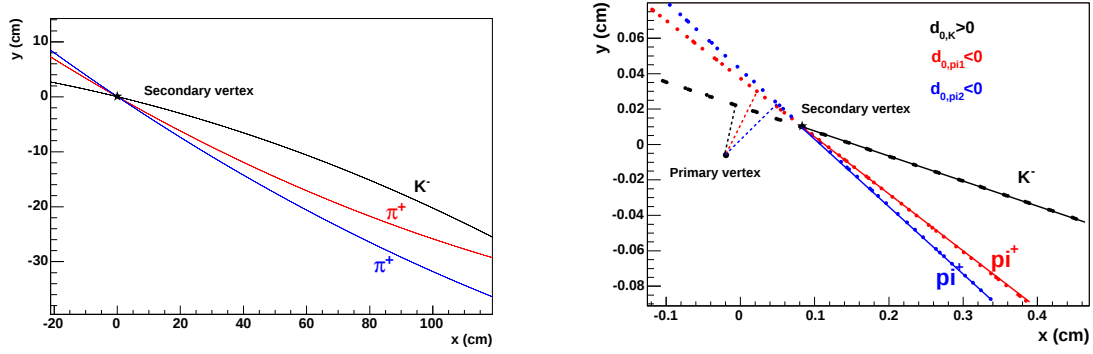


Figure 5.16: Left panel: display of a fake $D^+ \rightarrow K^- \pi^+ \pi^+$ decay where the momentum is not conserved. Right panel: zoom of the same decay shown in the left panel. The impact parameters of the particle trajectories with their signs are also indicated in the figure. It can be seen that the momentum resulting from the three decay products do not point to the primary vertex. This is an example of the kinematically forbidden case $d_{0,K} \times d_{0,\pi1} < 0$ and $d_{0,K} \times d_{0,\pi2} < 0$.

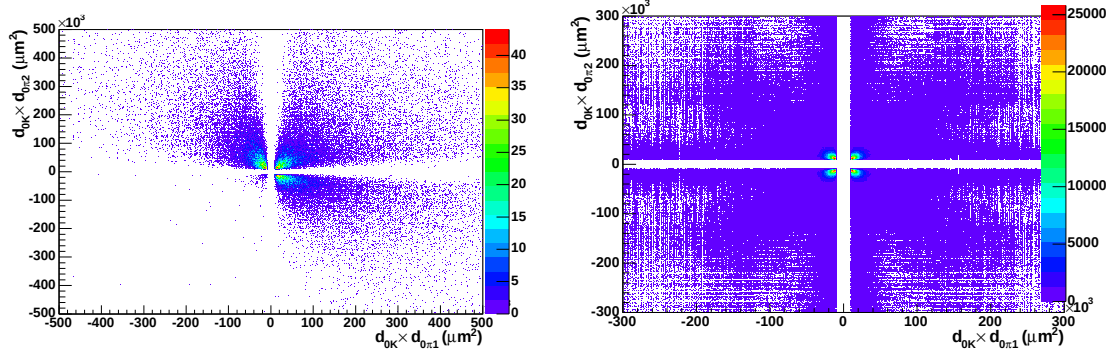


Figure 5.17: Left panel: bi-dimensional histogram for reconstructed signal triplets with $d_{0,K} \times d_{0,\pi1}$ on the x axis and $d_{0,K} \times d_{0,\pi2}$ on the y axis. The empty area corresponds to the forbidden case $d_{0,K} \times d_{0,\pi1} < 0$ and $d_{0,K} \times d_{0,\pi2} < 0$. Right panel: the same as left panel but for reconstructed background triplets. The empty strips centered on the x and y axes are a consequence of the single track cuts on the track impact parameters.

$$\sigma^2 = d_1^2 + d_2^2 + d_3^2 \quad (5.6)$$

where d_i is the distance between the track i ($i = 1, 2, 3$) and the secondary vertex (x_0, y_0, z_0) :

$$d_i^2 = (x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 \quad (5.7)$$

Differently from Eq. 4.4 in Section 4.5.3, here σ is not weighted by the errors on the track parameters, the reason being that in this way σ has dimension $[L]$ and it has the same meaning of a standard deviation. The distribution of the variable σ is shown in Fig. 5.18 for both signal and background triplets. The two histograms are well separated and, as expected, the σ distribution of the signal events, for which the found secondary vertex is the real decay vertex of the $D^\pm$ mesons, is almost contained within $\sigma < 0.1$ cm.

The tuning of this cut variable has been performed in the three hypotheses of ideal particle identification, real particle identification and no particle identification. The cut has been tuned in four different ranges of the $D^\pm$ transverse momentum p_T which can be reconstructed from the three tracks in a triplet: $p_T < 2$ GeV/c, $2 < p_T < 3$ GeV/c, $3 < p_T < 5$ GeV/c, $p_T > 5$ GeV/c.

Since the track parameters are defined by the reconstruction algorithms in the vicinity of the interaction point (see Section 4.5.1), the tracks of the same triplet need to be propagated to the common point of origin (secondary vertex) in order to reconstruct the $D^\pm$ transverse momentum in the secondary vertex position. However, it has been verified that the difference between the reconstructed track momenta p_x, p_y, p_z at the primary vertex and those calculated propagating the tracks to the secondary vertices, is at the level of the fourth decimal digit. Consequently, in case of decays of open charmed mesons, there are no appreciable differences in the distributions of $D^\pm$ p_T and $\cos \theta_{point}$ if the tracks are propagated to the secondary vertex or not.

The left plot in Fig. 5.19 reports the ratio of accepted triplets (both signal and background) as a function of the cut variable σ_{cut} , for $D^\pm$ transverse momentum $2 < p_T < 3$ GeV/c. The triplets are accepted when $\sigma < \sigma_{cut}$, meaning that the tracks belonging to a triplet are required not to be too separated in space in order to be candidates of a $D^\pm$ decay with the same secondary vertex. As can be seen in the left panel of Fig. 5.19, if the cut on σ is very loose no selection is actually applied and all the background triplets are accepted. On the other hand, as is more evident in the zoom shown in the right panel of Fig. 5.19, for $\sigma_{cut} < 0.02$ cm a drastic reduction of the background triplets without losing too much signal can be attained.

The best cut value is the one which maximizes the Significance $S/\sqrt{S+B}$ in the invariant mass range $|M_{inv} - M_{D^\pm}| < 1\sigma = 12$ MeV/c². Fig. 5.20 shows the

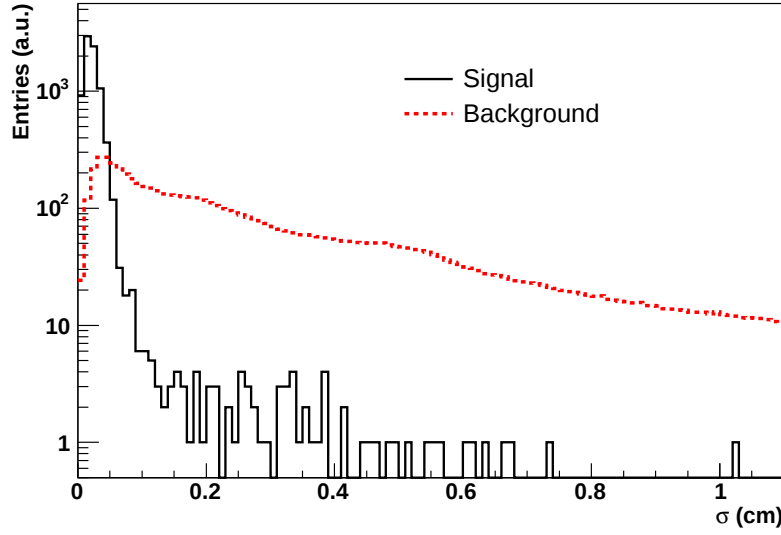


Figure 5.18: Distribution of the quality of the found secondary vertex, σ , for both signal and background events. The histograms are normalized to the same area. The plot is obtained assuming an ideal particle identification.

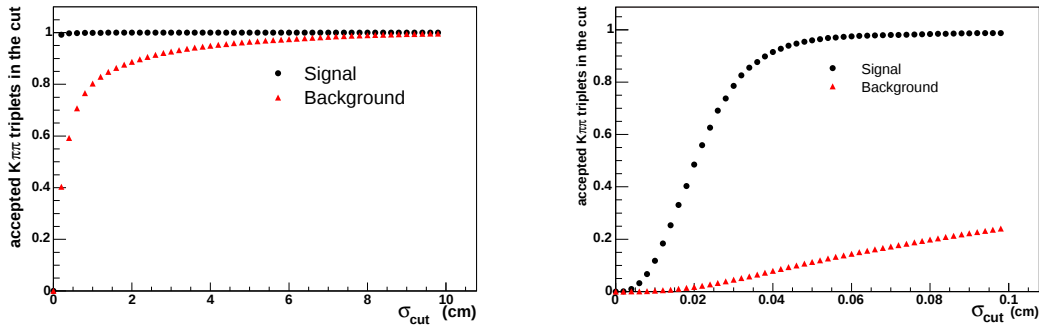


Figure 5.19: Left panel: ratio of triplets (both signal and background) selected by the cut $\sigma < \sigma_{cut}$, for $D^\pm$ transverse momentum $2 < p_T < 3$ GeV/c. Right panel: zoom of the left plot. The plots are obtained assuming an ideal particle identification.

Table 5.3: Values of σ_{cut} (expressed in cm) which optimize the Significance in the different p_T bins of $D^\pm$ mesons and for the three analyses: ideal PID, real PID and no PID.

	Ideal PID	Real PID	No PID
$p_T < 2$ GeV/c	0.024	0.026	0.024
$2 < p_T < 3$ GeV/c	0.026	0.016	0.022
$3 < p_T < 5$ GeV/c	0.012	0.022	0.022
$p_T > 5$ GeV/c	0.017	0.03	0.012

Significance, normalized to 10^7 minimum bias Pb-Pb events, as a function of the cut variable σ_{cut} in the $D^\pm$ transverse momentum interval $2 < p_T < 3$ GeV/c.

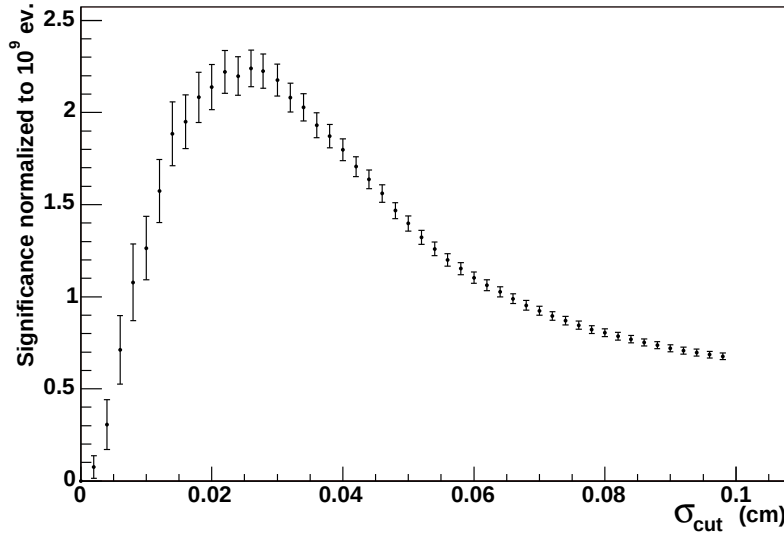


Figure 5.20: Significance $S/\sqrt{S+B}$ normalized to 10^7 central Pb-Pb events in the invariant mass range $|M_{inv} - M_{D^\pm}| < 1\sigma = 12$ MeV/c², as a function of the cut variable σ_{cut} , for $D^\pm$ transverse momentum $2 < p_T < 3$ GeV/c.

The Table 5.3 summarizes the chosen values of the cut variable σ_{cut} for the three analyses and in the different p_T bins.

Once the cut on the quality of the vertexer has been performed, the candidate triplets undergo additional selections. The cut variables which have been considered at this level of the selection strategy are described in the following:

1. *Distance between the primary and the secondary vertices.* Fig. 5.21 shows the

distribution, for both signal and background events in various $D^\pm$ transverse momentum ranges, of the distance d defined as follows:

$$d = \sqrt{(x_s - x_0)^2 + (y_s - y_0)^2 + (z_s - z_0)^2} \quad (5.8)$$

where (x_0, y_0, z_0) are the coordinates of the primary vertex and (x_s, y_s, z_s) are the coordinates of the secondary vertex.

As expected the signal triplets are characterized by larger values of d , according to the fact that they come from displaced decay vertices: in particular, it can be observed that the mean value of the signal distribution increases as the $D^\pm$ p_T increases because the harder the $D^\pm$ mesons, the longer the traveled distances.

It can be noticed that the mean value obtained for signal events is much larger than the decay length of $D^\pm$ mesons, the reason being that cuts on single tracks (see Section 5.4.1) and on the $K\pi$ vertices (see Section 5.4.2) have already been applied². A possible optimization of this cut is to use also the error on the vertex position given by the fitter.

2. *Maximum transverse momentum among the three tracks belonging to a triplet*, indicated as $\text{Max}\{p_{TK}, p_{T\pi1}, p_{T\pi2}\}$. This selection accounts for the slightly harder p_T of the decay products (pions and kaons) of $D^\pm$ mesons compared to all the pions and kaons produced in a Pb-Pb event.

Fig. 5.22 shows the distribution of $\text{Max}\{p_{TK}, p_{T\pi1}, p_{T\pi2}\}$ for signal and background triplets and for different ranges of the $D^\pm$ transverse momentum.

It can be observed that, for $D^\pm$ transverse momenta $2 \leq p_T \leq 3$ GeV/c, the peak of the background is well below that of the signal triplets, in agreement with the above arguments, by which the kaon coming from a $D^+ \rightarrow K^- \pi^+ \pi^+$ decay is likely to have a large transverse momentum compared to the pions coming from the same decay. For larger momenta, the variable $\text{Max}\{p_{TK}, p_{T\pi1}, p_{T\pi2}\}$ seems not to be not effective; however, there could be hints for a separation of signal and background histograms for $\text{Max}\{p_{TK}, p_{T\pi1}, p_{T\pi2}\} \leq 1.5$ GeV/c.

3. $\cos \theta_{point}$, where θ_{point} is the so called pointing angle between the direction of the reconstructed $D^\pm$ momentum on the bending plane and the line connecting the primary and the secondary vertices. If the found vertex really corresponds to a $D^\pm$ decay vertex, then $\theta_{point} \sim 0$ and $\cos \theta_{point} \sim 1$. Indeed, as can be seen in Fig. 5.23 (left panel), the $\cos \theta_{point}$ distribution of

²As will be discussed in Chapter 6, a tight cut on d can bias the measurements because it favours the selection of $D^\pm$ coming from beauty decays.

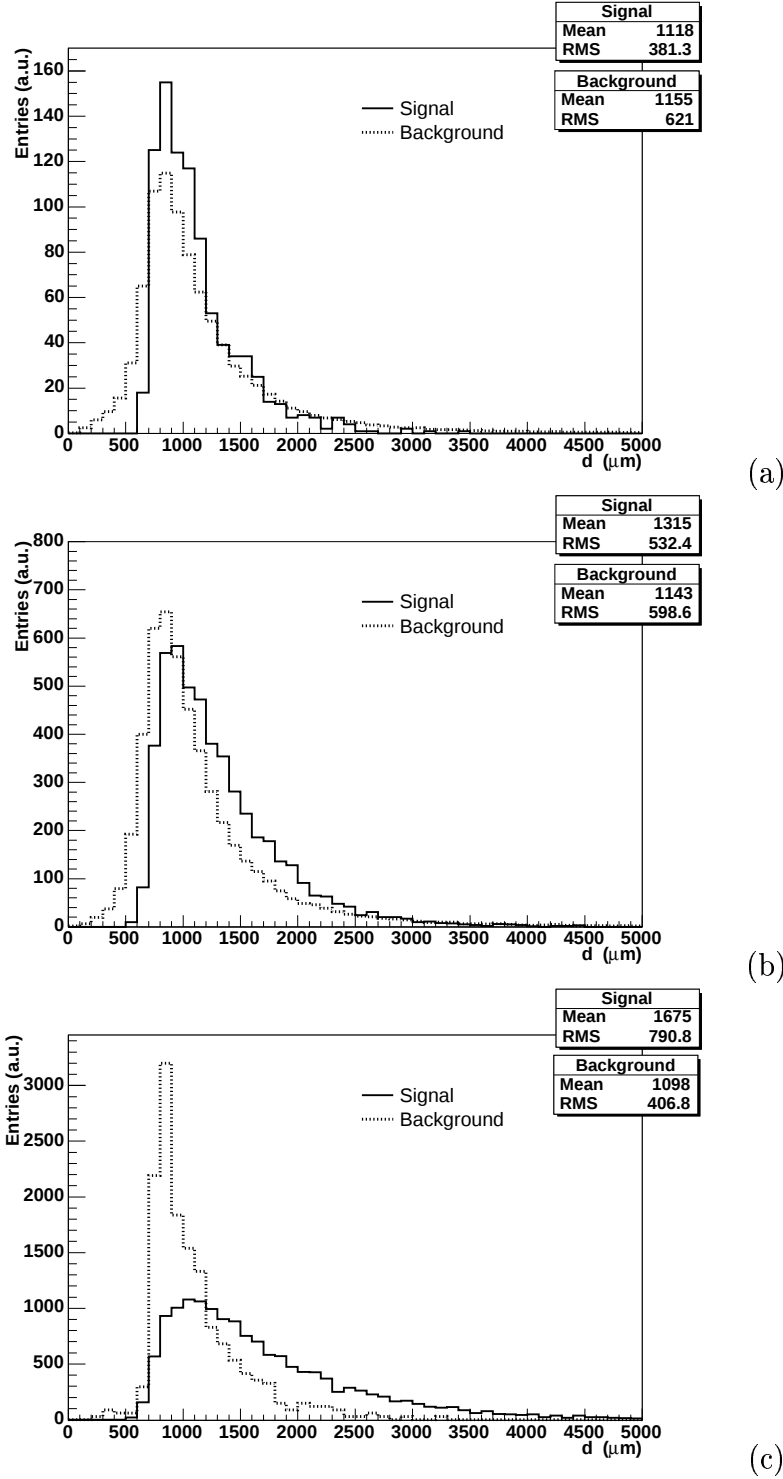


Figure 5.21: Distribution of the distance d between the primary and the secondary vertices for signal triplets (solid lines) and background triplets (dotted lines) in different bins of the $D^\pm$ transverse momentum: $0 < p_T < 2$ GeV/c (a), $2 < p_T < 3$ GeV/c (b), $3 < p_T < 5$ GeV/c (c). The histograms are normalized to the same area. The plots are obtained assuming an ideal particle identification.

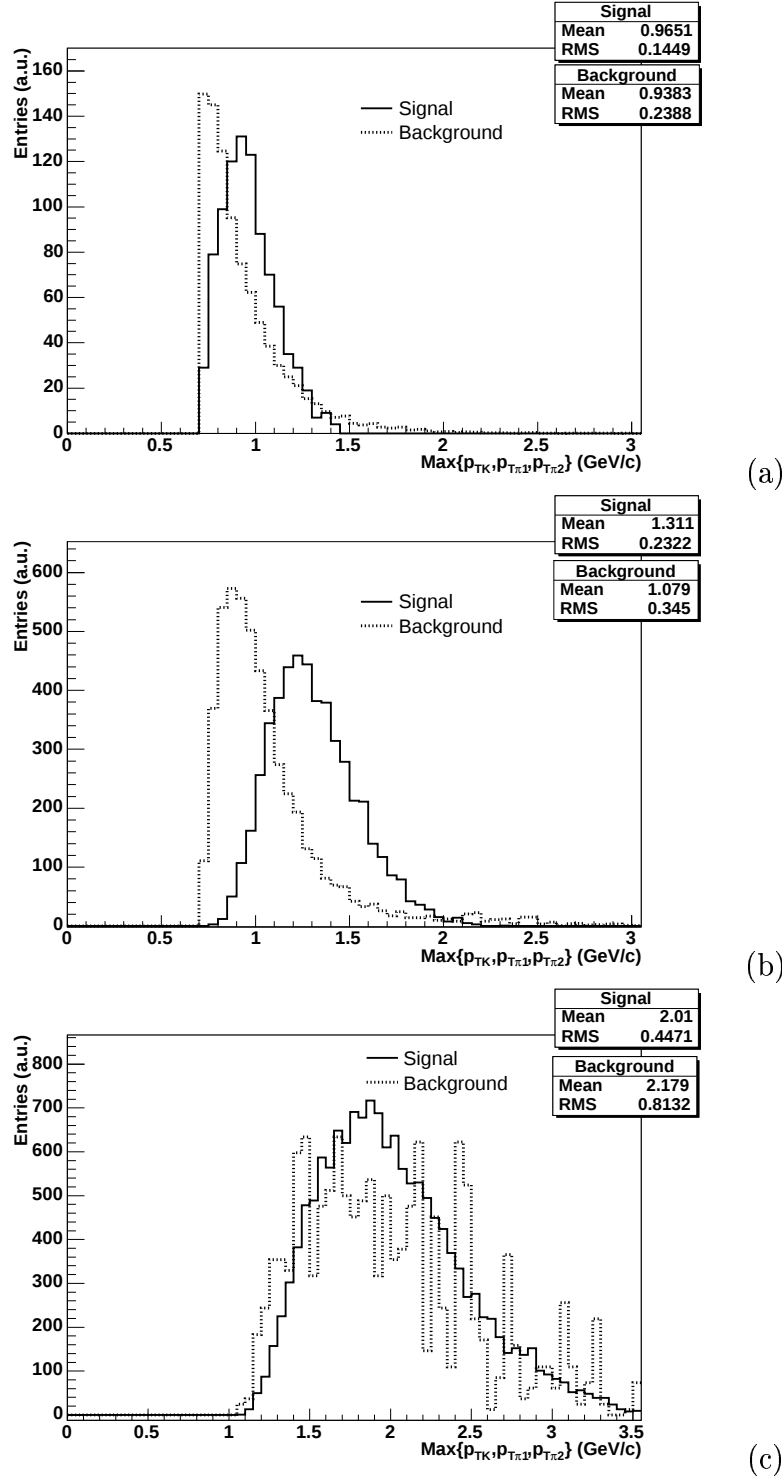


Figure 5.22: Distribution of the maximum transverse momentum among the three tracks in a triplet, $\text{Max}\{p_{TK}, p_{T\pi 1}, p_{T\pi 2}\}$, for signal triplets (solid lines) and background triplets (dotted lines) in different bins of the $D^\pm$ transverse momentum: $0 < p_T < 2$ GeV/c (a), $2 < p_T < 3$ GeV/c (b), $3 < p_T < 5$ GeV/c (c). The histograms are normalized to the same area. Ideal particle identification is assumed.

signal triplets is peaked at 1, differently from the background, which exhibits the typical shape of a flat distribution in θ_{point} . The right panel of the same figure is just a zoom in order to visualize better the peak of the signal events.

4. *Sum of the squares of the three track impact parameters with respect to the primary vertex.* Fig. 5.24 shows the distribution, for signal and background triplets, of the variable s defined as:

$$s = \sum_{i=1,2,3} d_{0,i}^2 = d_{0,K}^2 + d_{0,\pi_1}^2 + d_{0,\pi_2}^2 \quad (5.9)$$

As it appears from Fig. 5.24 (left panel), this cut is not tunable without applying in advance a cut on the quality of the vertex σ , indeed the mean value of the histogram filled with background triplets is much larger than the one filled with signal triplets. On the other hand, if a cut on σ is applied (see Fig. 5.24, right panel), for example $\sigma_{cut} = 0.024$ cm, the histogram representing the signal triplets has a larger mean value compared to that of the background, reflecting the fact that signal triplets come from vertices really displaced from the primary vertex, and thus their impact parameters are large by definition.

In order to optimize the cuts on the candidate $D^\pm$ which have passed the selection on the quality of the secondary vertices, a method which simultaneously tunes all the cut variables has been developed.

This method is based on multi-dimensional matrices for both signal and background events. The dimension of the matrix is equal to the chosen number of independent cuts: in case of four selection variables, which are the ones described above, the dimension of the matrix is four.

The four selection variables define a set of four cuts ($cut_i, cut_j, cut_k, cut_l$)³ which are properly binned; the number of bins for each selection variable can be different for each of the four dimensions ($i = 1 \cdots N_1, j = 1 \cdots N_2, \dots$).

Each cell of the matrix, associated to the indices $ijkl$, contains the number of triplets which pass the selection criteria defined by the set of cuts:

$$C_{ijkl} = \{cut_i \text{ AND } cut_j \text{ AND } cut_k \text{ AND } cut_l\} \quad (5.10)$$

Therefore, the cells of the two matrices, S_{ijkl} for signal and B_{ijkl} for background, will be defined as follows:

$$S_{ijkl} = N^{sig}(C_{ijkl}), \quad B_{ijkl} = N^{bkg}(C_{ijkl}) \quad (5.11)$$

³For instance, a cut on $\cos\theta_{point}$ is $\cos\theta_{point} > cut_i$.

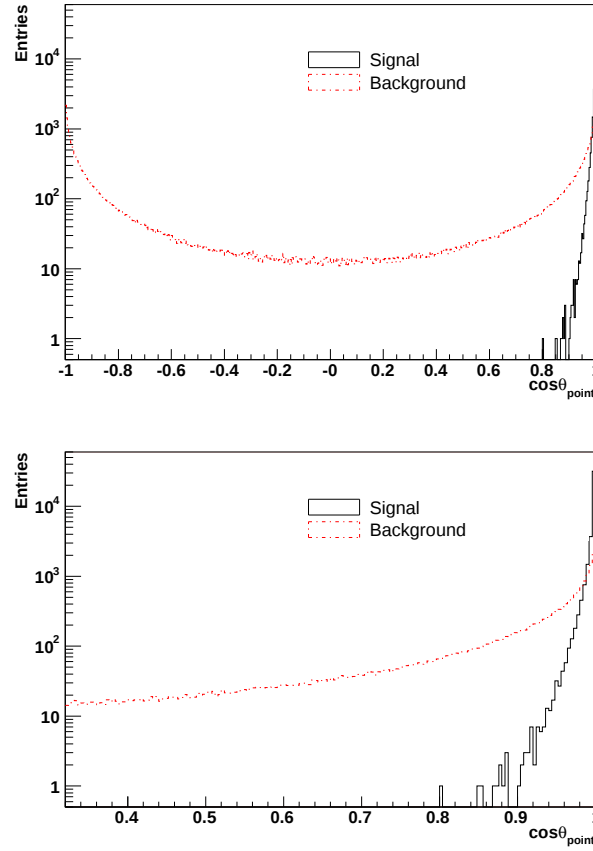


Figure 5.23: Upper panel: $\cos\theta_{point}$ distribution for signal and background triplets. The definition of θ_{point} is given in the text. Bottom panel: zoom of the upper plot. The histograms are normalized to the same area. The plots are obtained assuming an ideal particle identification.

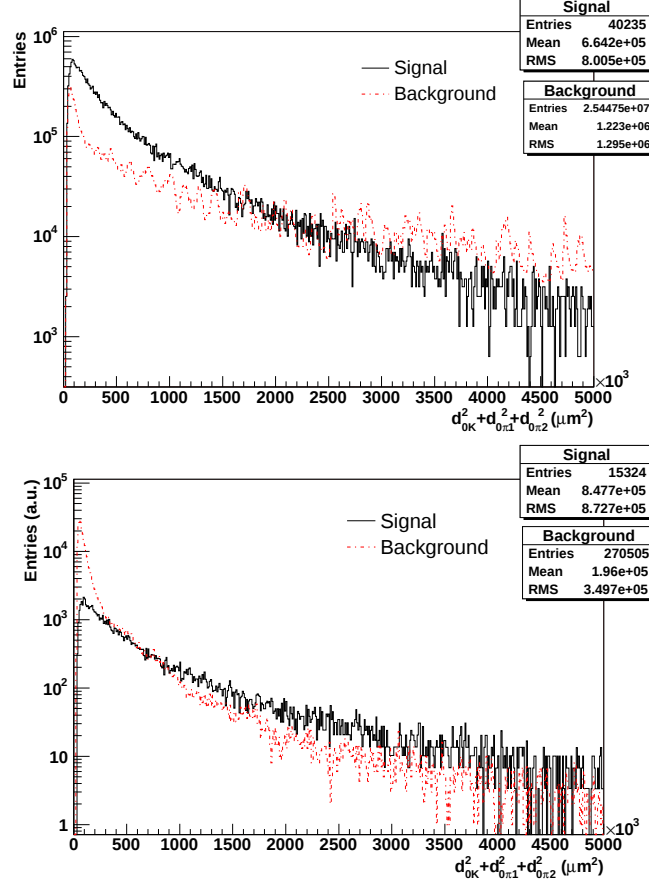


Figure 5.24: Upper panel: distribution of the variable s representing the sum of the squares of the three track impact parameters with respect to the primary vertex. The histograms are obtained before applying the cut on the quality of the vertex σ and are normalized to the same area. The plots are obtained assuming an ideal particle identification. Bottom panel: the same as for the upper plot, but in this case the histograms are obtained after a p_T independent cut on the quality of the vertex σ , $\sigma < 0.024$ cm.

where N^{sig} and N^{bkg} are the numbers of signal and background triplets which pass the corresponding cut C_{ijkl} .

Once signal and background triplets S_{ijkl} and B_{ijkl} are available, the Significance can then be easily calculated for each cut C_{ijkl} . This selection strategy has several advantages:

- it is a global maximization: the cut variables which maximize the Significance are found at the same time. This approach is more efficient than the method operating in cascade (previously studied), according to which the variables are tuned one at a time and each time a local maximization of the Significance is performed;
- it is fast for two main reasons: first and differently from the cascade method, it is sufficient to loop on the triplets once and fill the matrices, instead of looping n times (where n is the number of cut variables, for example $n = 4$), finding each time the cut variable which maximizes the Significance and using it in the procedure which tunes the subsequent variable. Second, the matrices can be filled once per event and then simply summed to increase statistics.
- it is easy to add new selection variables.

In this thesis work, four-dimensional matrices have been considered with the cut variables described above:

1. distance d between primary and secondary vertex;
2. maximum p_T of the three tracks, $\text{Max}\{p_{TK}, p_{T\pi 1}, p_{T\pi 2}\}$, from now on called p_M ;
3. $\cos \theta_{point}$;
4. sum of the squares of the three track impact parameters with respect to the primary vertex, s .

The optimization of the cuts has been performed in various transverse momentum bins of the reconstructed $D^\pm$ mesons.

The final results from the multi-dimensional matrix analysis for Pb-Pb collisions are presented in Chapter 6.

As a final remark it is important to underline that signal candidate triplets are characterized by a typical pattern in the Dalitz plot (see Fig. 5.7) and in the correlation of azimuthal angles of the decay products (see Fig. 5.25) directly connected to the Dalitz plot shape. Nevertheless, no selection based on the Dalitz plot has been applied in order to preserve the shape of the combinatorial background to be subtracted from the $D^\pm$ invariant mass peak. Only a very loose cut on the invariant mass of the triplets, i.e. $1 < M_{inv, D^\pm} < 3 \text{ GeV}/c^2$ has been adopted.

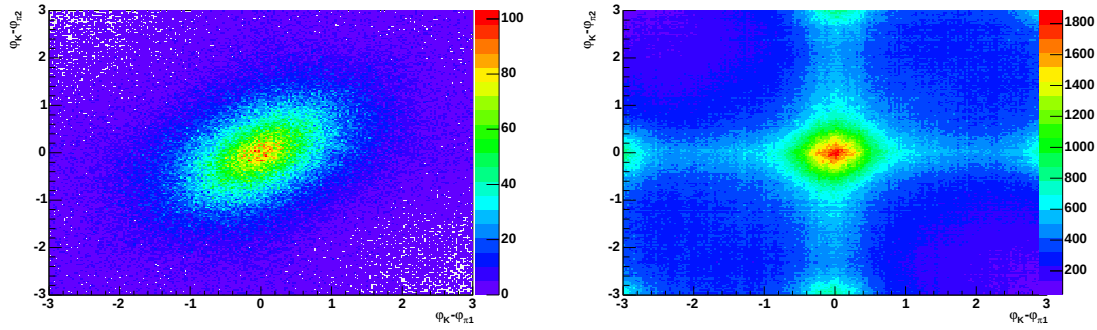


Figure 5.25: Left panel: two-dimensional histogram filled on the x axis with the difference of azimuthal angles of kaon and first pion coming from $D^+ \rightarrow K^- \pi^+ \pi^+$ decays and on the y axis with the difference of azimuthal angles of kaon and second pion. Right panel: the same as left panel, but for combinatorial background triplets. Differently from background, in the signal triplets, i.e. true $D^+ \rightarrow K^- \pi^+ \pi^+$ decays, the azimuthal angles are correlated, as a consequence of the kinematics of the decay.

5.5 Selection strategy for the $D^+ \rightarrow K^- \pi^+ \pi^+$ channel in pp collisions.

The approach followed to develop an analysis strategy in pp collisions is practically the same as the one discussed in the previous section. Of course, due to the lower combinatorial background in pp compared to Pb-Pb collisions, less tight cuts are needed.

A separate generation of signal and background events was not necessary in this case, hence combinatorial triplets (background triplets) and triplets actually coming from resonant and non-resonant $D^\pm$ decays (signal triplets) are formed in each of the minimum bias pp events.

The analyses presented here are done for the worst case of no particle identification, and the results suggest that with the low multiplicity expected in pp collisions, the reconstruction of the $D^+ \rightarrow K^- \pi^+ \pi^+$ channel is a very promising study even in the situation where a particle identification system is not yet well established, like in the first data taking period.

As already mentioned in Section 5.4, the first step in the selection strategy is given by the single track cuts. Even without particle identification, different cuts on kaons and pions can still be applied since the kaons have always opposite sign with respect to the pair of pions.

The plot reported in Fig. 5.26 shows the number of background triplets B per pp event as a function of the ratio of the accepted signal, for the single track cuts

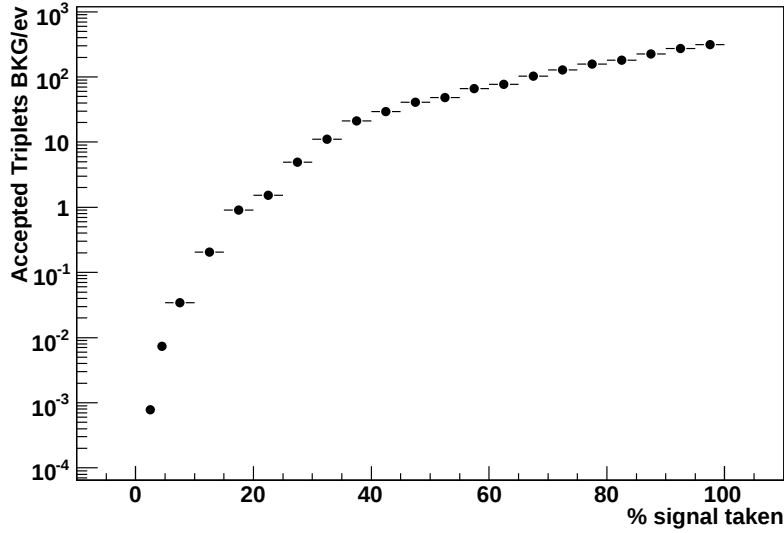


Figure 5.26: Accepted background triplets per pp event as a function of the ratio of signal accepted within the cuts. Only the background triplets for which the Significance is maximized are shown.

which maximize the Significance. In case all the signal is accepted, all the background triplets (only ~ 125) are accepted. The signal per event, S , is calculated in the same way as for the Pb-Pb case (see Section 5.4), $S = R_D^{acc} \times M_D^{rec}$, where R_D^{acc} is the ratio between the accepted triplets after a cut and all the signal triplets. M_D^{rec} is the number of reconstructed $D^+ \rightarrow K^- \pi^+ \pi^+$ topologies in pp, obtained from the generated $D^\pm$ per pp event (see Table 2.5 in Section 2.4) and taking into account the branching ratio $BR = 9.2\%$ and the acceptance and reconstruction efficiencies. Since the pp events of our production were reconstructed using a fast parametrization of the tracks, the number of reconstructed candidate triplets has to be corrected by a factor taking into account the loss of tracking efficiency caused by the use of the parametrized tracking instead of the full tracking. The tracking efficiency with the fast reconstruction, ϵ_{fast} , is $\sim 75\%$ of the tracking efficiency with the full reconstruction, i.e. $\epsilon_{fast} \sim 75\% \times \epsilon_{full}$. Therefore, the number of reconstructed triplets is less in case of parametrized tracking by a factor of $\sim 1/(0.75)^3 \simeq 2.37$. Fig. 5.27 shows the p_T distribution for the $D^\pm$ triplets which are reconstructed in the detector, corrected for the inefficiency of the fast reconstruction; the histogram is compared to the spectra of $D^\pm$ mesons produced in the full solid angle and $D^+ \rightarrow K^- \pi^+ \pi^+$ produced in the full solid angle and in the detector acceptance.

The value for the p_T independent ratio K of reconstructed $D^+ \rightarrow K^- \pi^+ \pi^+$ over generated $D^+ \rightarrow K^- \pi^+ \pi^+$ in the full solid angle is comparable to that for Pb-Pb, $K \sim 2\%$. The order of magnitude between the p_T distribution of $D^\pm$ mesons and of $D^+ \rightarrow K^- \pi^+ \pi^+$ produced in the full solid angle is due to the branching ratio 9.2%.

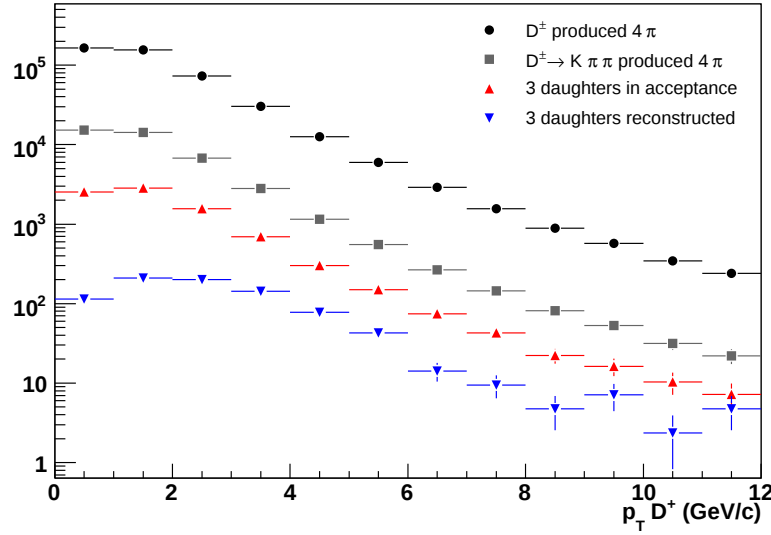


Figure 5.27: p_T distributions of $D^+ \rightarrow K^- \pi^+ \pi^+$ generated in the full solid angle in pp collisions (black circles), with the three decay products in the ALICE acceptance (red triangles-up) and with the three decay products reconstructed in the detector (blue triangles-down).

Here the Significance is normalized to one year of data taking of pp collisions, i.e. 10^9 pp events ($S/\sqrt{S+B} \times \sqrt{10^9}$). The working point chosen for the analysis in this first selection step is the one corresponding to 70% of selected signal. The cuts on the single tracks which maximize the Significance in this interval are $p_{Tcut,K} = 0.575$ GeV/c, $p_{Tcut,\pi} = 0.4$ GeV/c and $d_{0,cut} = 0$ μm and the corresponding number of background triplets per event is of the order of 100.

Then, before forming the triplets, a cut on the distance, indicated as δ , between the “intersection” of the two $K\pi$ tracks and the primary vertex is applied.

Differently from the Pb-Pb case where the track multiplicity is high, the measured primary vertex position in the low-track multiplicity environment of pp events is significantly affected by the presence of the tracks originating from secondary vertices. Therefore, the primary vertex is calculated each time rejecting the tracks of the triplet being examined. The primary vertex used for selection

Table 5.4: Values of σ_{cut} (expressed in cm) which optimize the Significance in the different p_T bins of $D^\pm$ mesons for pp collisions and for the case without PID.

	No PID
$p_T < 2$ GeV/c	0.03
$2 < p_T < 3$ GeV/c	0.044
$3 < p_T < 5$ GeV/c	0.044
$p_T > 5$ GeV/c	0.024

purposes is then different for each triplet.

Fig. 5.28 shows the number of accepted signal and background triplets as a function of the selection variable δ_{cut} .

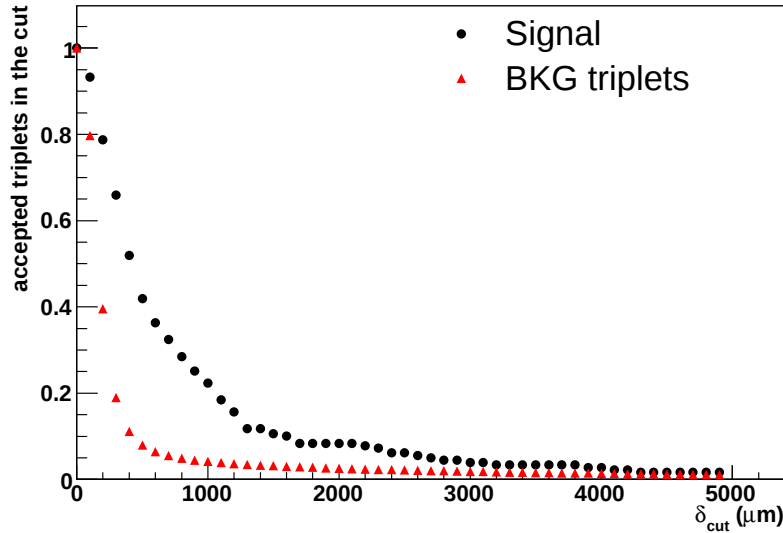


Figure 5.28: Ratio of triplets (both signal and background) selected by the cut $\delta > \delta_{cut}$.

The value which maximizes the Significance is $\delta = 400 \mu\text{m}$.

Once the triplets are combined, they are passed to the algorithm for the search of the secondary vertex position.

The ratio of signal and background triplets as a function of the cut on the quality of the secondary vertex, σ_{cut} , is shown in Fig. 5.29.

The value σ_{cut} has been optimized in different intervals of $D^\pm$ transverse momentum as can be seen in Table 5.4.

As expected, the values of the cut variable σ_{cut} are looser in pp than in Pb-Pb case.

The plot in Fig. 5.29 (left panel) is the ratio of accepted triplets (both signal and background) as a function of the cut variable σ_{cut} , for $D^\pm$ transverse momentum $2 < p_T < 3$ GeV/c. The triplets are accepted when $\sigma < \sigma_{cut}$. In Fig. 5.29 (right panel) the Significance normalized to 10^9 minimum bias pp events is shown as a function of σ_{cut} , for $D^\pm$ transverse momentum $2 < p_T < 3$ GeV/c. In this case the value of the cut maximizing the Significance is $\sigma_{cut} = 0.044$ cm.

Once the cuts on the quality of the vertex have been tuned, a n -dimensional matrix ($n = 4$) is filled, according to the same procedure described in the subsection 5.4.3. The variables are the same used in case of Pb-Pb:

1. distance d between primary and secondary vertex;
2. maximum p_T of the three tracks, $\text{Max}\{p_{TK}, p_{T\pi 1}, p_{T\pi 2}\}, p_M$;
3. $\cos \theta_{point}$;
4. sum of the squares of the three track impact parameters with respect to the primary vertex, s .

To have an idea of the importance of such cuts, Fig. 5.30 shows both signal (left panel) and background (right panel) two-dimensional histograms filled with $\cos \theta_{point}$ and the distance between the primary and the secondary vertices, d . Differently from the background, the histogram filled with signal triplets is populated only in the region $\cos \theta_{point} \geq 0.95$ and $d \geq 500 \mu\text{m}$, suggesting that the two variables are correlated. A selection based on these two combined cuts can be useful to reject a lot of combinatorial background, as is the case in the analysis of Pb-Pb events.

The final results for pp collisions are presented in Chapter 6.

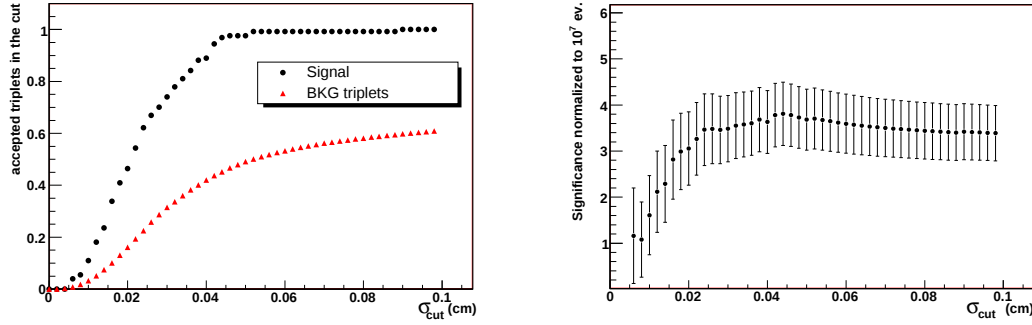


Figure 5.29: Left panel: ratio of triplets (both signal and background) selected by the cut $\sigma < \sigma_{cut}$. Right panel: Significance normalized to 10^9 events as a function of σ_{cut} , for $D^\pm$ transverse momentum $2 < p_T < 3$ GeV/c.

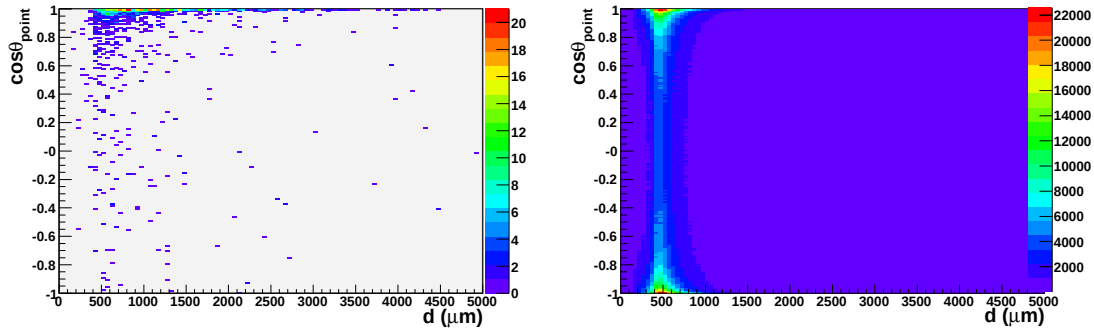


Figure 5.30: Left panel: two-dimensional histogram for signal triplets with $\cos\theta_{point}$ on the y axis and the distance between primary and secondary vertices on the x axis. Right panel: the same as left panel but for background triplets.

Chapter 6

$D^\pm$ meson reconstruction: results

The results on the performance of ALICE in the reconstruction of $D^\pm$ mesons through their hadronic decay $D^+ \rightarrow K^- \pi^+ \pi^+$ in both Pb-Pb and pp collisions are presented in this chapter.

6.1 Results for $D^\pm$ reconstruction in Pb-Pb collisions

This section is devoted to the results obtained in the different steps of the $D^\pm$ selection strategy in Pb-Pb collisions. First, the results with the set of cuts applied in sequence (i.e. single track cuts, cuts on the correlation of the impact parameters, on the distance of the $K\pi$ vertex from the primary vertex and on the quality of the secondary vertex) are reported. Then, the results obtained applying the multi-dimensional matrix procedure to the candidate triplets which pass the first selection are shown.

6.1.1 Results from the first set of cuts in sequence

The results of the first steps of the selection procedure described in Chapter 5, starting from the single track cuts up to the cut on the quality of the vertices, are reported in Tables 6.1, 6.2 and 6.3, for the analyses with ideal PID, real PID and no PID respectively. For each step of the selection sequence (i.e. single track cuts, cuts on the correlation of the impact parameters, on the distance of the $K\pi$ vertex from the primary vertex and on the quality of the secondary vertex) the signal (S) and background (B) per event, the ratio S/B and the Significance are indicated. The ratios of signal and background triplets which are accepted after each step are also indicated. The cuts are applied in sequence and the signal and background ratios are calculated for each cut with respect to the previous one.

Table 6.1: Results from the first set of cuts applied in sequence, in case of ideal PID. The Significance ($S/\sqrt{S+B}$) is normalized to 10^7 central Pb-Pb events.

cut	%kept S	S/ev	%kept B	B/ev	S/B	$S/\sqrt{S+B}$
No cut	100	0.09	100	2×10^7	4.5×10^{-9}	0.06
Single track cuts	7	0.006	0.08	1.7×10^4	3.5×10^{-7}	0.15
product $d_{0K} \times d_{0\pi}$	97	0.006	75	1.3×10^4	5×10^{-7}	0.17
K- π δ	67	0.004	5	690	6×10^{-6}	0.5
Secondary Vertex σ	50	0.002	0.9	6	3×10^{-4}	2.6

Table 6.2: Results from the first set of cuts applied in sequence, in case of real PID. The Significance ($S/\sqrt{S+B}$) is normalized to 10^7 central Pb-Pb events.

cut	%kept S	S/ev	%kept B	B/ev	S/B	$S/\sqrt{S+B}$
No cut	100	0.09	100	1.3×10^7	7×10^{-9}	0.08
Single track cuts	5	0.004	0.06	7.7×10^3	5×10^{-7}	0.14
product $d_{0K} \times d_{0\pi}$	97	0.004	75	5.8×10^3	7×10^{-7}	0.17
K- π δ	70	0.003	12	720	4×10^{-6}	0.4
Secondary Vertex σ	65	0.002	0.9	6	3×10^{-4}	2.6

Table 6.3: Results from the first set of cuts applied in sequence, in case of no PID. The Significance ($S/\sqrt{S+B}$) is normalized to 10^7 central Pb-Pb events.

cut	%kept S	S/ev	%kept B	B/ev	S/B	$S/\sqrt{S+B}$
No cut	100	0.09	100	3.6×10^8	2.2×10^{-10}	0.014
Single track cuts	7	0.006	0.08	2.7×10^5	2.4×10^{-8}	0.036
product $d_{0K} \times d_{0\pi}$	97	0.006	75	2×10^5	3×10^{-8}	0.04
K- π δ	70	0.0045	18	3.7×10^4	1.2×10^{-7}	0.07
Secondary Vertex σ	50	0.002	0.4	150	1.3×10^{-5}	0.52

The values of S and B , and thus S/B and the Significance, are calculated in the invariant mass range $|M_{inv} - M_{D^\pm}| < 1\sigma$.

The following conclusions can be drawn from the results obtained in Tables 6.1, 6.2 and 6.3 for the first set of cuts:

- Pretty severe cuts on single track cuts ($p_{Tcut,K} = 0.7$ GeV/c, $p_{Tcut,\pi} = 0.5$ GeV/c and $d_{0,cut} = 95 \mu\text{m}$) are needed in order to reduce the background of about three orders of magnitude, without losing too much low- p_T signal.
- The cut on the product of impact parameters (i.e. triplets are rejected when $d_{0,K} \times d_{0,\pi1} < 0$ and $d_{0,K} \times d_{0,\pi2} < 0$) reduces the background by a factor 3/4, keeping practically all the signal. This is in agreement with Fig. 5.17

in Chapter 5. A few percent of signal may be lost with this selection if the tracks are not well reconstructed.

- The values obtained with the cut on the distance between the primary vertex and the vertex of the track pair $K\pi$ confirm the results shown in Fig. 5.14, where the chosen $\delta_{cut} = 700 \mu\text{m}$ for the ideal PID case gives $\sim 65\%$ of accepted signal and $\sim 6\%$ of background.
- The results on the cut on the quality of the secondary vertex σ are in agreement with Fig. 5.19. Even if that plot refers to a particular $D^\pm p_T$ bin, nevertheless it can be qualitatively seen that with $\sigma_{cut} = 0.02 \text{ cm}$ (equal to the average of the chosen σ_{cut} values in the different p_T bins) the corresponding ratios of signal and background accepted are $\sim 50\%$ and $\sim 1\%$ respectively.
- The analysis with the real PID reports smaller numbers for S (especially after the cuts on single track, on the product $d_{0K} \times d_{0\pi}$ and on the variable δ) due to the inefficiency of the particle identification. The background triplets B are roughly the same as the ideal PID case. Indeed, in the momentum region where kaons are not well identified (namely for momenta larger than $1 \text{ GeV}/c$), the number of triplets can be estimated in a very simple picture taking into account that not all the produced N_π pions and N_K kaons are correctly identified. Hence, the number of $N_{ID,i}$ ($i = p, K, \pi, e$) particles identified as type i is affected by a contamination:

$$N_{ID}(i) = N_{GOOD}(i) + N_{FAKE}(i)$$

From Fig. 4.24, and neglecting for simplicity the contamination from and to protons, we have $N_{GOOD}(\pi) \sim 90\%N_\pi$, $N_{FAKE}(\pi) \sim 60\%N_K$, $N_{GOOD}(K) \sim 40\%N_K$ and $N_{FAKE}(K) \sim 10\%N_\pi$. Therefore, taking into account that $N_\pi \sim 10N_K$ (according to the abundances in HIJING Pb-Pb events), we find:

$$N_{ID}(\pi) \sim 90\%N_\pi + 60\%\frac{N_\pi}{10} \sim 0.96 \times N_\pi$$

and

$$N_{ID}(K) \sim 40\%N_K + 10\% \times 10 \times N_K \sim 1.4N_K$$

The number of identified triplets is then approximatively the same as the true number of $K\pi\pi$ triplets:

$$N_{ID}(tripl) \sim \frac{1}{4}N_K \times \frac{N_\pi(N_\pi - 1)}{2} \sim \frac{1}{4} \times \frac{0.96^2 N_\pi^2 \cdot 1.4N_K}{2} \sim N_{true}(tripl)$$

where the factor $1/4$ accounts for the correct combination of sign of kaons and pions in the triplets.

- In case of no PID, the number of background triplets increases as expected. From Table 6.3 we observe an increase of about one order of magnitude with respect to the ideal PID case, the reason being that the pions misinterpreted as kaons¹ contribute with a factor of ~ 10 to the number of triplets because $N_\pi \sim 10N_K$. As far as the signal triplets are concerned, they should be in principle the same as the ideal PID case because there are no inefficiencies which may cause a loss of signal. Actually, as can be seen from Tables 6.1 and 6.3, S is slightly higher in the case without PID compared to the case with ideal PID: this is due to the different choices of the cut variables which maximize the Significance in the two cases.

6.1.2 Results from the multi-dimensional matrix procedure

The remaining four cut variables discussed in Chapter 5 are:

1. distance d between primary and secondary vertex;
2. maximum p_T of the three tracks, $\text{Max}\{p_{TK}, p_{T\pi 1}, p_{T\pi 2}\}, p_M$;
3. $\cos \theta_{point}$;
4. sum of the squares of the three track impact parameters with respect to the primary vertex, s .

The above variables enter the multi-dimensional matrix procedure which gives a result combining the four cut variables. Each cell $ijkl$ of the multi-dimensional matrices of signal and background contains the number of triplets which pass the selection criteria defined by the set of cuts:

$$C_{ijkl} = \{[d > d_{cut,i}] \text{ AND } [p_M > p_{Mcut,j}] \text{ AND } [\cos \theta_{point} > \cos \theta_{point,cut,k}] \text{ AND } [\sum d_{0,i}^2 > (\sum d_{0,i}^2)_{cut,l}]\} \quad (6.1)$$

The multi-dimensional matrix procedure is applied in several intervals of $D^\pm$ transverse momentum p_T , therefore the number of multi-dimensional matrices which are filled corresponds to the number of p_T intervals which have been considered. We decided to optimize the cuts in the following bins of the reconstructed transverse momentum of the candidate $D^\pm$ triplets: $0 < p_T < 2 \text{ GeV}/c$, $2 < p_T < 3 \text{ GeV}/c$, $3 < p_T < 5 \text{ GeV}/c$ and $p_T > 5 \text{ GeV}/c$.

¹Since no particle identification is applied on the tracks, the triplets can be formed by three pions.

Table 6.4: Results from the multi-dimensional matrix procedure applied in different p_T bins (expressed in GeV/c), in case of ideal PID. The Significance ($S/\sqrt{S+B}$) is normalized to 10^7 central Pb-Pb events.

	$0 < p_T < 2$	$2 < p_T < 3$	$3 < p_T < 5$	$p_T > 5$
d_{cut} (μm)	$0 \div 900$	1000	1300	1500
$p_{M,cut}$ (GeV/c)	0.8	0.9	$0.5 \div 1$	$0.5 \div 1.5$
$\cos\theta_{point,cut}$	0.9955	0.997	0.9895	0.997
$(\Sigma d_{0,i}^2)_{cut}$ ($\mu\text{m}^2 \times 10^3$)	1150	100	0	0
S/ev	1.8×10^{-5}	2.2×10^{-4}	2.7×10^{-4}	8.4×10^{-4}
B/ev	6.9×10^{-5}	2.7×10^{-4}	6.9×10^{-5}	2.7×10^{-4}
S/B	0.26	0.8	4	3
$S/\sqrt{S+B}$	6 ± 2	31 ± 4	47 ± 5	80 ± 5

The results are obtained with $\sim 1.5 \cdot 10^4$ Pb-Pb events (used for the background) and with ~ 5300 signal events corresponding to $\sim 1.94 \cdot 10^6$ $D^\pm$ with the three decay tracks reconstructed in the detector. The production of such a large number of Pb-Pb events was made possible by the use of the distributed computing resources offered by the Grid project.

The choice of the p_T intervals is constrained by the few background triplets available after the first set of cuts. In fact, as can be seen in the plot shown in the upper plot of Fig.6.1 (for the three scenarios obtained with the ideal particle identification, with the real particle identification and without particle identification), the number of background triplets of our sample of events which are passed to the multi-dimensional matrix procedure drastically decreases with p_T , suggesting that an optimization of the cuts in p_T bins of 1 GeV would not be appropriate for $p_T \geq 3$ GeV/c. As expected, a larger background statistics are obtained without particle identification, nevertheless also in this case the number of triplets begins to be small from $p_T \sim 5 - 6$ GeV/c.

As can be seen in Fig.6.1 (b), the initial signal statistics is problematic only in the momentum range $p_T < 1$ GeV/c.

We report in the following the three scenarios obtained with the ideal particle identification, with the real particle identification and without particle identification.

6.1.2.1 Ideal PID

The values of the cut variables included in the four-dimensional matrix which maximize the Significance in the different p_T bins are reported in Table 6.4 together with the values of signal and background triplets and the ratio S/B .

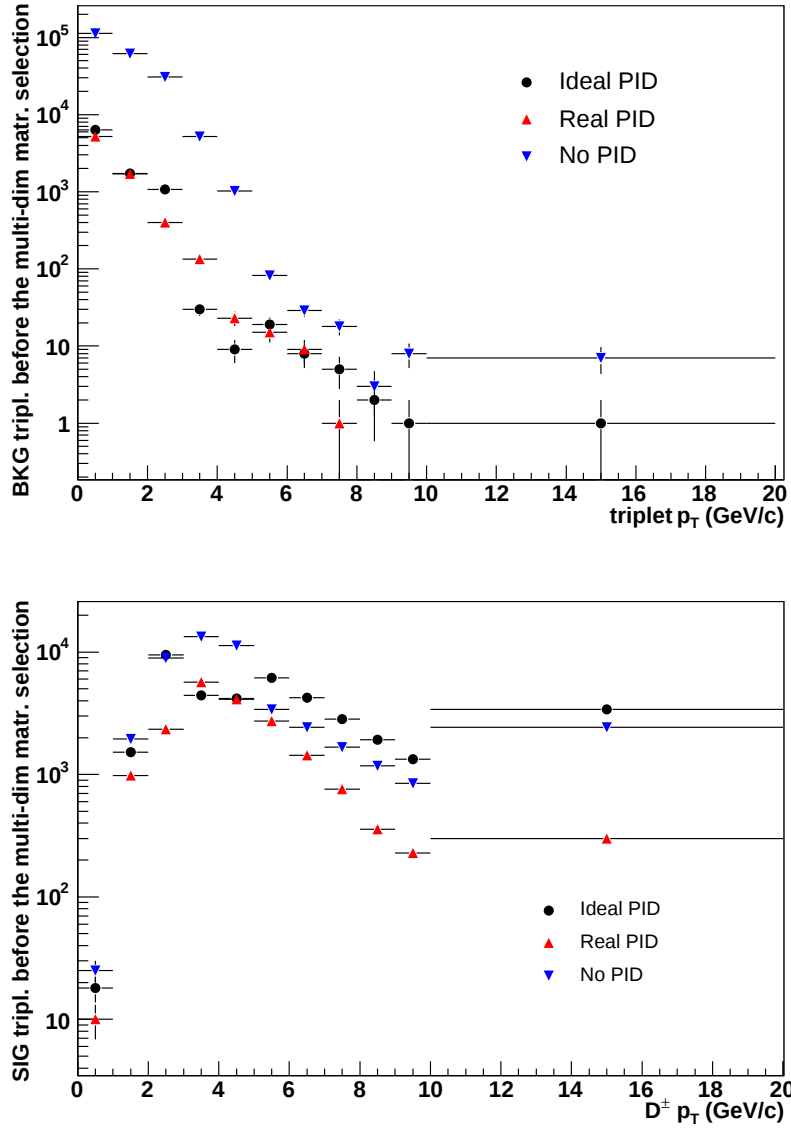


Figure 6.1: Upper panel: Number of background $K\pi\pi$ triplets of our sample of events ($\sim 1.5 \cdot 10^4$ Pb-Pb events), which have passed the first set of sequential cuts and are processed by the multi-dimensional matrix procedure, as a function of the reconstructed p_T of the triplet. The three cases of ideal PID, real PID and no PID are indicated. The last momentum bin is intended to be $p_T > 10$ GeV/c. Bottom panel: The same as the upper plot but with the signal triplets taken from our ~ 5300 signal events.

From a look at Table 6.4 we can comment on the following points:

- The cut on the distance between primary and secondary vertices is not powerful at low p_T , in fact several values of d are allowed for $0 < p_T < 2$ GeV/c: a possible explanation could be that at low p_T an important role is played by the cut on the distance of the $K\pi$ vertex from the primary vertex. In addition, the resolution on the position of the secondary vertex is worse at low p_T than at high p_T ; hence, the error on d is larger at low p_T and a selection based on d may be not effective. It can be also noticed that the value of the cut increases with the p_T of the reconstructed triplet, because the distance traveled by $D^\pm$ mesons increases as their p_T increases.
- The cut on p_M accepts those triplets where at least one of the three tracks has a p_T larger than the threshold $p_{M,cut}$. This cut could be appropriate to select $D^\pm$ decays, in which the kaon carries the largest part of the $D^\pm$ momentum. The cut starts to be effective from $p_{M,cut} = 0.7$ GeV/c, corresponding to the biggest single track cut on p_T . Such a cut is expected to be useful, according to Fig 5.22, especially in the low momentum bins. Indeed, it seems to be effective only for $p_T < 3$ GeV/c, while for $p_T > 3$ GeV/c several values of $p_{M,cut}$ give the best Significance, suggesting that this cut is not necessary.
- The cut on the $\cos\theta_{point}$ variable is almost independent of the p_T of the triplet.
- The cut on $\Sigma d_{0,i}^2$ is important for low-momentum triplets; on the other hand, it seems that it is not useful at high momentum where the variable d is more effective in the selection.
- The number of background triplets per event which remains after the selection procedure is of the order of 10^{-4} : this is the limit of the simulated statistics of $\sim 10^4$ Pb-Pb events. Even though the reported Significance is normalized to 10^7 Pb-Pb events, the corresponding cut values are obtained with a sample of $\sim 1.5 \times 10^4$ simulated events. The optimization of the cuts should ideally be evaluated with a number of simulated events greater than or at least equal to the statistics collected in one year of data taking. Unfortunately, such a number of events is really huge to be simulated with the present Grid resources, having in mind that our much smaller production of $\sim 1.5 \times 10^4$ Pb-Pb events was a challenging project for the Italian Grid². A possible alternative is the use of event mixing techniques. However, the aim of this thesis work is (1) to demonstrate that the reconstruction of $D^\pm$

²The production was limited to the Italian Grid because the ALICE production environment AliEn was in a setting-up phase for the PDC06. See also Section 4.

mesons in the ALICE barrel is feasible, (2) to find the most effective selection variables to be used in the analysis and (3) to show that the developed selection procedure is a powerful and handy tool to be applied to the detection of charmed mesons. These goals have been accomplished with the available data.

Further tests aimed at verifying the above points and the results of Table 6.4 have been performed in the framework of the multi-dimensional matrix. Few of such tests are reported in the following.

Fig. 6.2 shows a two-dimensional histogram where the Significance, in the triplet transverse momentum range $2 < p_T < 3$ GeV/c, is plotted as a function of the cut variables d_{cut} and $\cos\theta_{point,cut}$. The remaining two variables are fixed to the values reported in Table 6.4, namely $p_{M,cut} = 0.9$ GeV/c and $(\Sigma d_{0,i}^2)_{cut} = 100 \times 10^3 \mu\text{m}^2$.

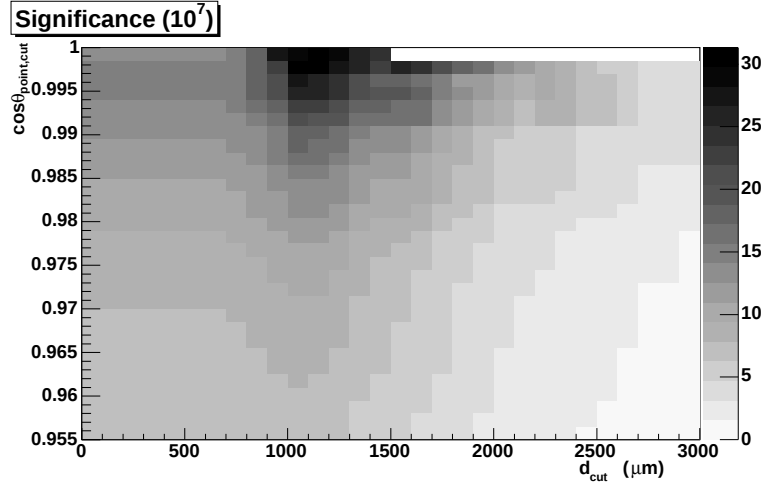


Figure 6.2: Significance (normalized to 10^7 Pb-Pb central events) as a function of the cut variables d_{cut} and $\cos\theta_{point,cut}$, for $p_{M,cut} = 0.9$ GeV/c and $(\Sigma d_{0,i}^2)_{cut} = 100 \times 10^3 \mu\text{m}^2$. The transverse momentum of the triplets is $2 < p_T < 3$ GeV/c. The ideal PID case is considered.

The histogram is simply the projection of the four-dimensional matrix on the plane $(d_{cut}, \cos\theta_{point,cut})$ and the Significance in each cell $ijkl$ is calculated from the signal and background triplets which pass the cut C_{ijkl} (see Section 5.4.3). In the example of Fig. 6.2 we have:

$$C_{ijkl} = \{[d > d_{cut,i}] \text{ AND } [\cos\theta_{point} > \cos\theta_{point,cut} \text{ } k] \text{ AND } [p_M > 0.9 \text{ GeV/c}] \text{ AND } [\Sigma d_{0,i}^2 > 100 \times 10^3 \mu\text{m}^2]\} \quad (6.2)$$

It can be noticed from Fig. 6.2 that the maximum is well localized, therefore we are confident in the method. The Significance is maximized for $d_{cut} \simeq 1000 \mu\text{m}$ and $\cos\theta_{point,cut} \simeq 0.997$, confirming the results reported in Table 6.4. The white area in the figure corresponds to cells where the number of selected background triplets is zero.

The same four-dimensional matrix of the Significance for $2 < p_T < 3 \text{ GeV}/c$ can be projected also on planes defined by other variables. For example, from the projection of the four-dimensional matrix on the plane $(\cos\theta_{point,cut}, (\Sigma d_{0,i}^2)_{cut})$, for $d_{cut} = 1000 \mu\text{m}$ and $p_{M,cut} = 0.9 \text{ GeV}/c$, shown in Fig. 6.3, we see that the highest values of the Significance are those with $\cos\theta_{point,cut}$ close to 1. We also notice that a cut on $(\Sigma d_{0,i}^2)_{cut}$ is not effective because the cut on $d_{cut} = 1000 \mu\text{m}$ is dominant.

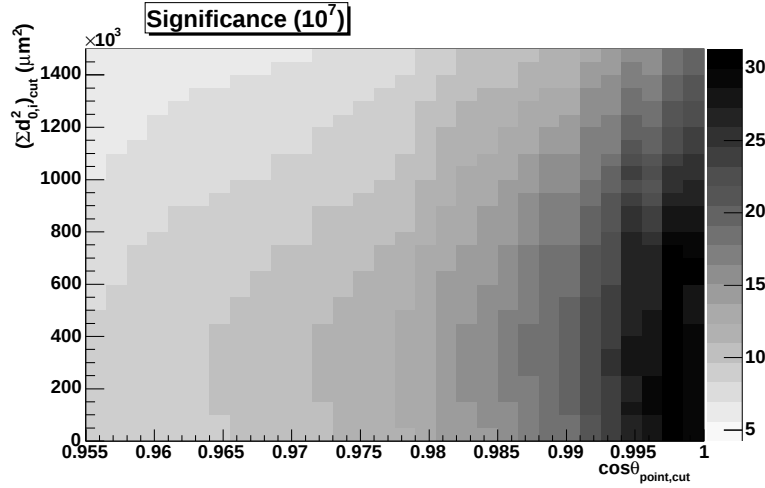


Figure 6.3: Significance (normalized to 10^7 Pb-Pb central events) as a function of the cut variables $\cos\theta_{point,cut}$ and $(\Sigma d_{0,i}^2)_{cut}$, for $p_{M,cut} = 0.9 \text{ GeV}/c$ and $d_{cut} = 1000 \mu\text{m}$. The transverse momentum of the triplets is $2 < p_T < 3 \text{ GeV}/c$. The ideal PID case is considered.

On the contrary, if we do not perform any cut either on d and on p_M , the cut on $\Sigma d_{0,i}^2$ becomes important at about $(\Sigma d_{0,i}^2)_{cut} \sim 600 \times 10^3 \mu\text{m}^2$ also with a good Significance, as can be observed in Fig. 6.4, where the maximum is more localized (at $(\Sigma d_{0,i}^2)_{cut} \sim 600 \times 10^3 \mu\text{m}^2$ and $\cos\theta_{point,cut} \simeq 1$) than in Fig. 6.3.

Fig. 6.2, 6.3 and 6.4 suggest that the cell with maximal Significance is not isolated but is inside a region with high Significance. Another way to verify such an internal coherence is to see the distributions of the cuts giving large Significance.

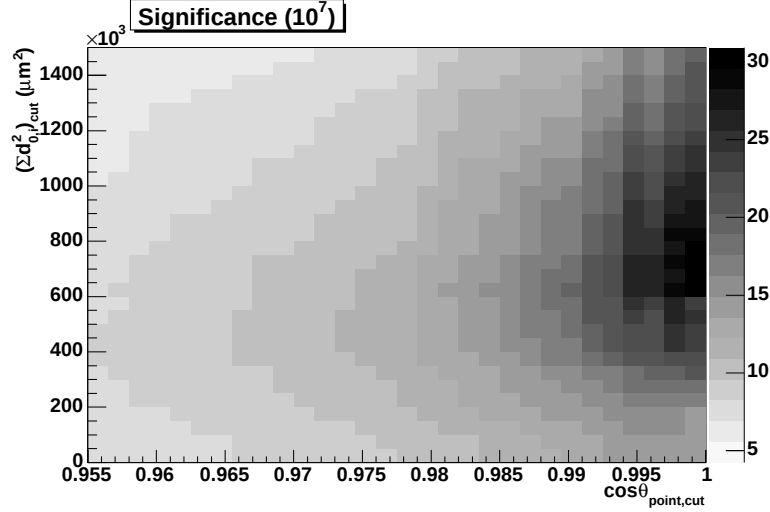


Figure 6.4: Significance (normalized to 10^7 Pb-Pb central events) as a function of the cut variables $\cos\theta_{point,cut}$ and $(\Sigma d_{0,i}^2)_{cut}$, for $p_{M,cut} = 0.5$ GeV/c and $d_{cut} = 0$ μm . The transverse momentum of the triplets is $2 < p_T < 3$ GeV/c. The ideal PID case is considered.

For example, considering the same transverse momentum bin $2 < p_T < 3$ GeV/c, it is interesting to plot the values of the cut variables leading to $S/\sqrt{S+B} > 27$ (corresponding to the maximum found value minus its error), but rejecting those cuts which reduce to zero the number of background triplets. The Significance is normalized to 10^7 central Pb-Pb events.

Fig. 6.5 (upper panel) shows a scatter plot of the variables $(\Sigma d_{0,i}^2)_{cut}$ vs. d_{cut} which give $S/\sqrt{S+B} > 27$ for $2 < p_T < 3$ GeV/c. Each square of the plot corresponds to the number of combinations of the four cut variables which give $S/\sqrt{S+B} > 27$. In the plot there is a well defined region of cut variables which give large values of Significance. In particular, it can be noticed that it is not necessary to impose tight cuts on both d and $(\Sigma d_{0,i}^2)$ in order to obtain high values of the Significance.

From Fig. 6.5 (bottom panel) we have the confirmation that high values of the Significance are reached with cuts on $\cos\theta_{point,cut} \geq 0.995$.

The results presented in Table 6.4 for $2 < p_T < 3$ GeV/c are consistent with the plots reported in Fig. 6.5, therefore we have crosschecked the validity of the procedure of optimization of the cuts. Similar arguments are valid also in the other p_T ranges.

As a final remark about Table 6.4, we comment on the value of d_{cut} which is not univocally determined in the optimization procedure for $0 < p_T < 2$ GeV/c

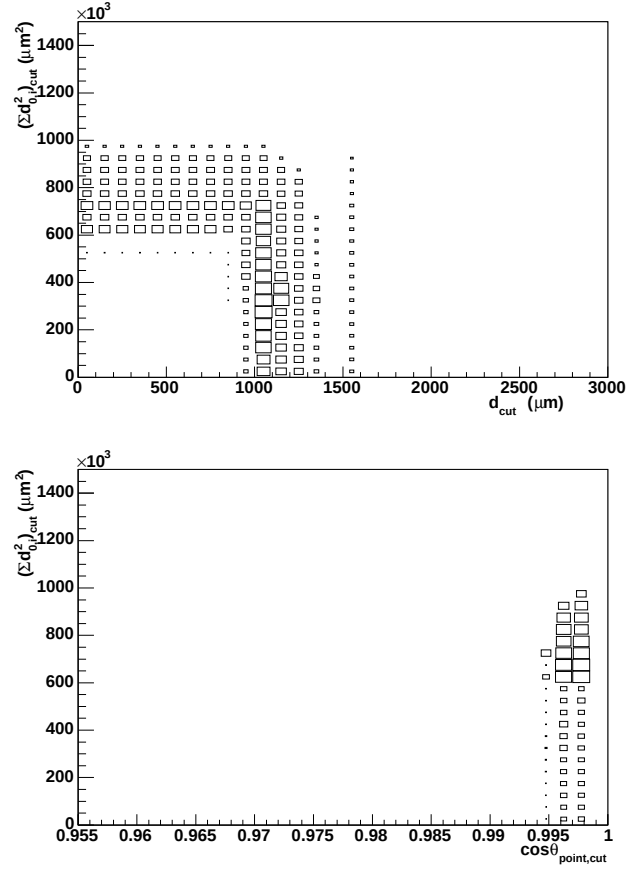


Figure 6.5: Upper panel: Number of combinations of cuts which give $S/\sqrt{S+B} > 27$ for $2 < p_T < 3$ GeV/c. The variables shown in the plot are $(\Sigma d_{0,i}^2)_{cut}$ vs. d_{cut} . Bottom panel: The same as the upper plot but for $(\Sigma d_{0,i}^2)_{cut}$ vs. $\cos\theta_{point, cut}$. The ideal PID case is considered.

and on the value of $p_{M,cut}$, which has the same behaviour but for $p_T > 3$ GeV/c. For the first case, it happens that other cuts are stronger and thus more powerful, hiding the smaller performance of the cut on d . This has been verified plotting the Significance as a function of d_{cut} when the cuts on p_M and $(\Sigma d_{0,i}^2)$ are not applied and $\cos\theta_{point,cut} = 0.955$ (see Fig. 6.6): it can be seen that there is a value of d_{cut} which indeed maximizes the Significance, nevertheless in the optimization procedure the other cuts are dominant.

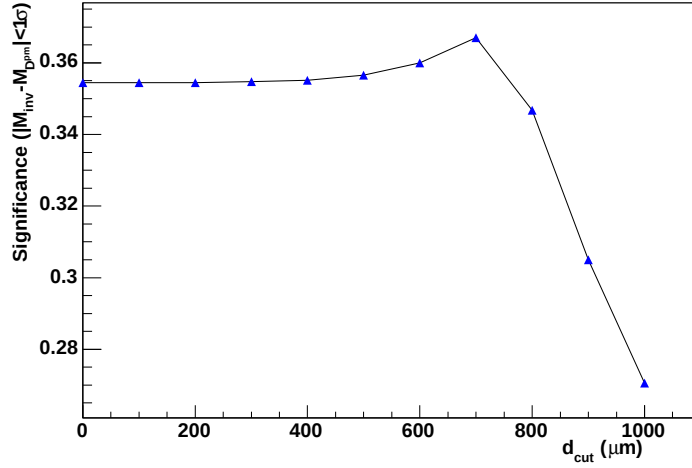


Figure 6.6: Significance (normalized to 10^7 and in the invariant mass range $|M_{inv} - M_{D^\pm}| < 1\sigma$) as a function of d_{cut} for no cut on p_M and $(\Sigma d_{0,i}^2)$ and for $\cos\theta_{point,cut} = 0.955$ (minimum allowed in the optimization with the multi-dimensional matrices). The transverse momentum of the triplets is $0 < p_T < 2$ GeV/c. The ideal PID case is considered.

As far as the cut on p_M is concerned, the behaviour indicated in Table 6.4 is in agreement with the plot (c) of Fig. 5.22, where the distributions of the variable $p_M = \text{Max}\{p_{TK}, p_{T\pi 1}, p_{T\pi 2}\}$ for signal and background are not well separated for the triplet transverse momentum $p_T > 3$ GeV/c.

Actually, it has been checked that, in case of optimization in the full invariant mass range (see Fig. 6.7 upper plot), the Significance shows a peak around $p_{M,cut} \simeq 1.5$ GeV/c, suggesting that such selection could be useful; on the other hand, performing the optimization of the cuts in the invariant mass range $|M_{inv} - M_{D^\pm}| < 1\sigma$, the effect of this cut disappears (Fig. 6.7, bottom plot), indeed the maximum is reached already at $p_{M,cut} = 0.5$ GeV/c.

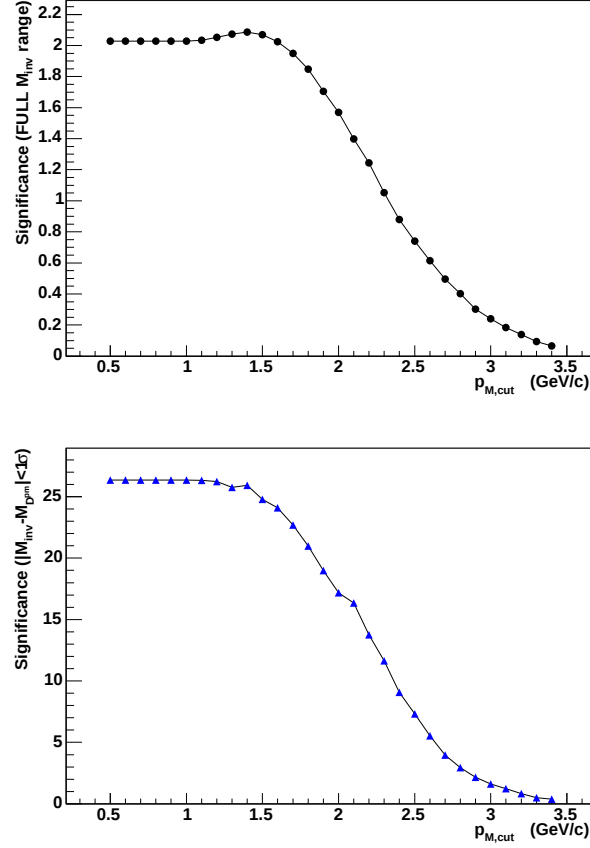


Figure 6.7: Significance (normalized to 10^7) as a function of $p_{M,cut}$ for no cut on d and $(\Sigma d_{0,i}^2)$ and for $\cos\theta_{point,cut} = 0.955$, in case of optimization in the full invariant mass range (upper panel) and in the invariant mass range $|M_{inv} - M_{D^\pm}| < 1\sigma$ (bottom panel). The transverse momentum of the triplets is $3 < p_T < 5$ GeV/c. The ideal PID case is considered.

Table 6.5: Results from the multi-dimensional matrix procedure applied in different p_T bins (expressed in GeV/c), in case of real PID. The Significance ($S/\sqrt{S+B}$) is normalized to 10^7 central Pb-Pb events.

	$0 < p_T < 2$	$2 < p_T < 3$	$3 < p_T < 5$	$p_T > 5$
d_{cut} (μm)	$0 \div 800$	900	800	1100
$p_{M,cut}$ (GeV/c)	$0.5 \div 0.7$	$0.5 \div 0.8$	$0.5 \div 1$	$0.5 \div 1.5$
$\cos\theta_{point,cut}$	0.997	0.9955	0.9985	0.994
$(\Sigma d_{0,i}^2)_{cut}$ ($\mu\text{m}^2 \times 10^3$)	950	0	0	100
S/ev	1×10^{-5}	6×10^{-5}	2.6×10^{-4}	2.6×10^{-4}
B/ev	6.9×10^{-5}	6.9×10^{-5}	6.9×10^{-5}	6.9×10^{-5}
S/B	0.14	0.9	4	4
$S/\sqrt{S+B}$	3.6 ± 1.6	17 ± 4	46 ± 5	46 ± 5

6.1.2.2 Real PID

Similarly to what has been done for the ideal PID case, the results for the multi-dimensional matrix analysis applied in the case of real particle identification are reported in Table 6.5.

The values of the cuts are consistent with those obtained in the ideal PID case; even in this case, the results in the highest p_T bin can be biased by the poor background statistics.

From the results on the Significance, it comes out that the analysis using the particle identification gives good Significances for $p_T \geq 2$ GeV/c. On the other hand, in the low- p_T region a higher statistics, i.e. larger than that acquired in one year of data taking, would be required in order to enhance the Significance.

Considering for example the low- p_T region, we see from Table 6.5 that the maximum Significance found is ~ 3.6 . As a crosscheck, we report in the scatter plot shown Fig. 6.8 (left) the numbers of combinations of cut variables which give Significance larger than 2 for $0 < p_T < 2$ GeV/c. As already discussed in the ideal PID case, the cut variables giving zero background triplets are not shown in the plots because the corresponding Significance would be large by definition.

The left plot in Fig. 6.8 identifies a region of $(\Sigma d_{0,i}^2)$ and d where high values of Significance, i.e. larger than the maximum minus its error, can be found. It seems clear from the plot that a cut on $(\Sigma d_{0,i}^2)$ is more useful than a cut on d . This is even more evident increasing the threshold on the Significance, i.e. larger than 3, as shown in the right plot in the same figure.

On the other hand, it can be noticed in the panels of Fig. 6.9 that in the larger p_T bins a cut on d is definitely more powerful than a cut on $(\Sigma d_{0,i}^2)$: the left plot defines a region of $(\Sigma d_{0,i}^2)$ and d with corresponding Significance larger than the

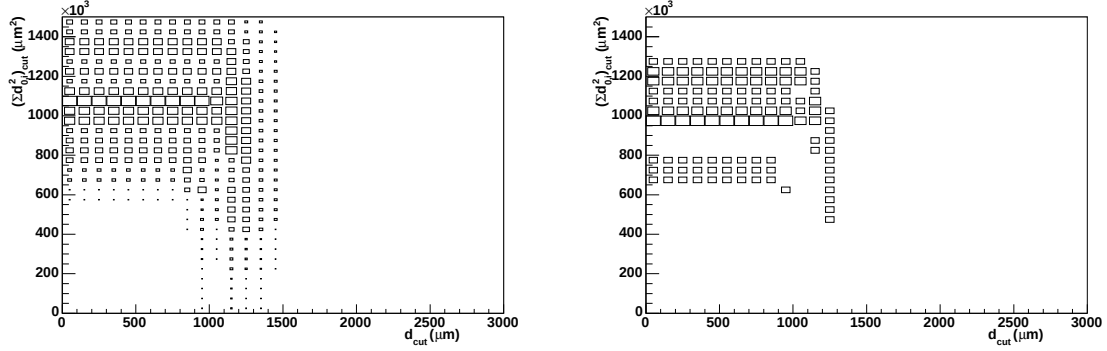


Figure 6.8: Left panel: distribution of the cut variables $(\Sigma d_{0,i}^2)_{cut}$ vs. d_{cut} which give $S/\sqrt{S+B} > 2$ for $0 < p_T < 2$ GeV/c. Right panel: the same as left but with higher threshold of the Significance, $S/\sqrt{S+B} > 3$. The real PID case is considered. The Significance is normalized to 10^7 central Pb-Pb events.

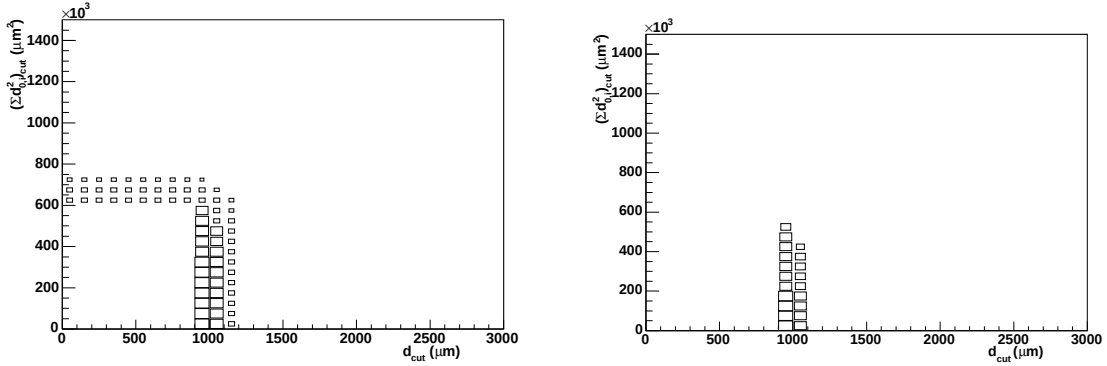


Figure 6.9: Left panel: distribution of the cut variables $(\Sigma d_{0,i}^2)_{cut}$ vs. d_{cut} which give $S/\sqrt{S+B} > 13$ for $2 < p_T < 3$ GeV/c. Right panel: the same as left but with higher threshold of the Significance, $S/\sqrt{S+B} > 15$. The real PID case is considered. The Significance is normalized to 10^7 central Pb-Pb events.

maximum minus its error, while the right plot refers to a higher threshold for the Significance, and thus the area $(\Sigma d_{0,i}^2)_{cut}$ vs. d_{cut} is smaller.

Finally, the result of the optimization of the cuts with the four-dimensional matrix procedure for $2 < p_T < 3$ GeV/c is reported in Fig. 6.10, where the Significance is projected on the plane $(\cos\theta_{point,cut}, d_{cut})$, for $(\Sigma d_{0,i}^2)_{cut} = 0 \mu\text{m}^2$ and $p_{M,cut} = 0.5$ GeV/c. It can be noticed that the maximum of the Significance is well localized. The white area in the figure corresponds to cells where the number of selected background triplets is zero: the cut variables defined by these cells are not considered in the optimization procedure.

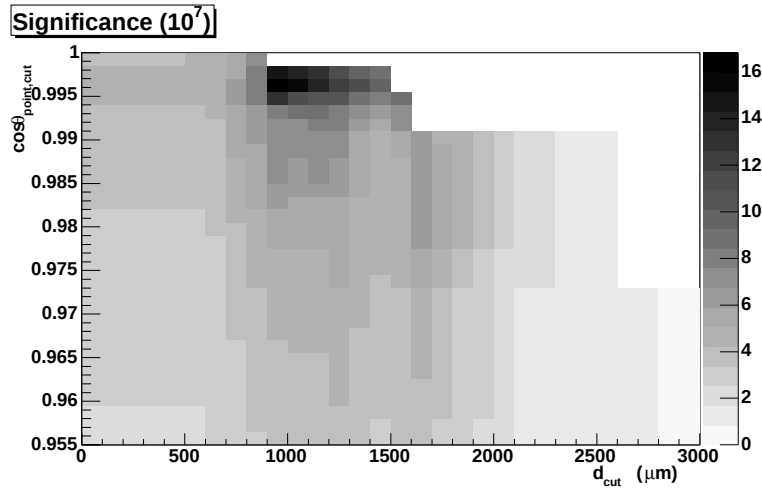


Figure 6.10: Significance (normalized to 10^7 Pb-Pb central events) as a function of the cut variables d_{cut} and $\cos\theta_{point,cut}$, for $p_{M,cut} = 0.5$ GeV/c and $(\Sigma d_{0,i}^2)_{cut} = 0 \mu\text{m}^2$. The transverse momentum of the triplets is $2 < p_T < 3$ GeV/c. The real PID case is considered.

6.1.2.3 No PID

The performance for the selection of $D^\pm$ mesons in ALICE has also been evaluated within the worst scenario where particle identification is assumed not to be working. The results reported in Table 6.6 suggest that for $p_T \geq 3$ GeV/c the analysis is feasible with a good Significance. On the contrary, this study gives a very low Significance for $p_T \leq 2$ GeV/c because the bulk of pions entering the combinatorial background is produced at low p_T . However, the drawback of such an analysis without particle identification is that it is more expensive from the point of view of the CPU time consumption, because no selection on the identity of the particles is done at the beginning.

Table 6.6: Results from the multi-dimensional matrix procedure applied in different p_T bins (expressed in GeV/c), in case of no PID. The Significance ($S/\sqrt{S+B}$) is normalized to 10^7 central Pb-Pb events.

	$0 < p_T < 2$	$2 < p_T < 3$	$3 < p_T < 5$	$p_T > 5$
d_{cut} (μm)	800	1700	1400	1900
$p_{M,cut}$ (GeV/c)	0.8	1.1	$0.5 \div 1$	2.4
$\cos\theta_{point,cut}$	0.997	0.9985	0.9985	0.997
$(\Sigma d_{0,i}^2)_{cut}$ ($\mu\text{m}^2 \times 10^3$)	800	0	250	50
S/ev	2.2×10^{-5}	4.6×10^{-5}	4.6×10^{-4}	4×10^{-4}
B/ev	8×10^{-3}	7×10^{-5}	4.8×10^{-4}	2×10^{-4}
S/B	0.003	0.66	0.97	2
$S/\sqrt{S+B}$	0.77 ± 0.05	13 ± 4	48 ± 5	52 ± 5

Similar to the previous cases of ideal and real particle identification, for high transverse momenta of the triplets the cut on d appears more effective, rather than a cut on $(\Sigma d_{0,i}^2)$.

The results of the multi-dimensional matrix method in the bins $3 < p_T < 5$ GeV/c and $p_T > 5$ GeV/c are reported in Fig. 6.11. Like in the examples shown in the previous paragraphs, even in this case the $\cos\theta_{point}$ is a powerful selection variable; in addition, it is evident that with increasing p_T the optimization of the cuts seems to favour higher values of d_{cut} .

6.2 Results for $D^\pm$ reconstruction in pp collisions

Our sample of $\sim 5 \times 10^6$ simulated pp events has limited signal statistics, in fact only ~ 700 $D^\pm$ with the three daughters are reconstructed in the detector. As already discussed in Chapter 4.6.0.2, two additional event typologies containing charm have been generated in order to increase the signal statistics. All the cuts have then been optimized considering the right proportions of minimum bias events without charm ($\sim 85\%$), events with $c\bar{c}$ ($\sim 14\%$) and events with $b\bar{b}$ ($\sim 1\%$).

In this section the results obtained in the different steps of the $D^\pm$ selection strategy in pp collisions are presented. First, the results with the set of cuts applied in sequence are reported. Then, the results obtained applying the multi-dimensional matrix procedure to the candidate triplets which pass the first selection are shown.

The $D^\pm$ reconstruction has been studied in pp collisions assuming no particle identification.

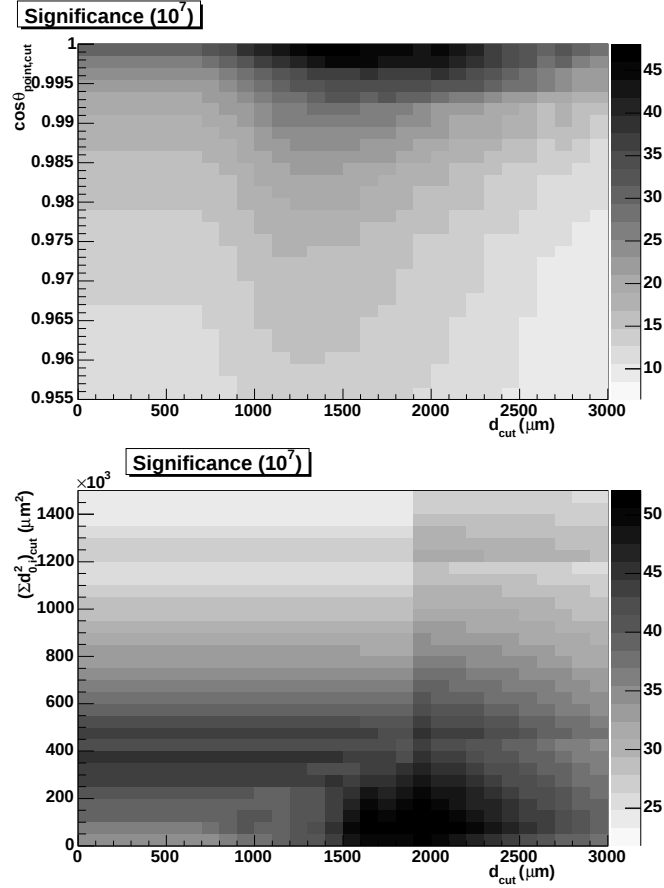


Figure 6.11: Upper panel: Significance (normalized to 10^7 Pb-Pb central events) as a function of the cut variables d_{cut} and $\cos\theta_{point,cut}$, for $p_{M,cut} = 0.5$ GeV/c and $(\Sigma d_{0,i}^2)_{cut} = 250 \times 10^3 \mu\text{m}^2$. The transverse momentum of the triplets is $3 < p_T < 5$ GeV/c. Bottom panel: The same as upper plot but with $(\Sigma d_{0,i}^2)_{cut}$ vs. d_{cut} , in the momentum range $p_T > 5$ GeV/c, and with $p_{M,cut} = 2.4$ GeV/c and $\cos\theta_{point,cut} = 0.997$. The no PID case is considered.

Table 6.7: Results of the set of cuts applied in sequence in the case of no PID in pp collisions. The Significance is normalized to 10^9 pp events.

cut	%kept S	S/ev	%kept B	B/ev	S/B	$S/\sqrt{S+B}$
No cut	100	0.000237	100	7	3.5×10^{-5}	2.8
Single track cuts	62	1.5×10^{-4}	23	1.64	9×10^{-5}	3.7
product $d_{0K} \times d_{0\pi}$	97	1.4×10^{-4}	75	1.23	10^{-4}	4
K- π δ	50	7×10^{-5}	12	0.15	5×10^{-4}	5.7
Secondary Vertex σ	87	6.2×10^{-5}	30	0.04	1.5×10^{-3}	9.8

6.2.1 Results from the first set of cuts in sequence

Table 6.7 reports the values of signal and background triplets after each step of the sequential cuts, up to that on the quality of the vertices. The ratios of signal and background triplets accepted after each selection are also indicated. The number of signal triplets per event, S/ev , and of background triplets per event, B/ev , as well as the ratio S/B and the Significance $S/\sqrt{S+B}$, are given in the invariant mass range $|M_{inv} - M_{D^\pm}| < 1\sigma$. The Significance is normalized to 10^9 minimum bias pp collisions expected to be collected in one year of data taking.

The main remarks from Table 6.7 are summarized below:

- As expected, the number of background triplets B is largely smaller in pp than in Pb-Pb. This allows for the use of less severe single track cuts ($p_{Tcut,K} = 0.575$ GeV/c, $p_{Tcut,\pi} = 0.4$ GeV/c and $d_{0,cut} = 0$ μm), which do not reject much of the signal which is very rare.
- The results from the cut on the products of impact parameters are consistent with what is found in the Pb-Pb case.
- The cut $\delta_{cut} = 400$ μm selects $\sim 50\%$ and $\sim 10\%$ of signal and background respectively. This is in agreement with the plot shown in Fig. 5.28.
- Using the same qualitative arguments as the Pb-Pb case, the results from the cut on the quality of the secondary vertex σ are consistent with Fig. 5.29.

6.2.2 Results from the multi-dimensional matrix procedure

The optimization of the cuts in the multi-dimensional matrix procedure has been studied in the same four bins of the transverse momentum of the reconstructed triplets as used in Pb-Pb (see Section 6.1.2): $0 < p_T < 2$ GeV/c, $2 < p_T < 3$ GeV/c, $3 < p_T < 5$ GeV/c and $p_T > 5$ GeV/c.

Table 6.8: Results from the multi-dimensional matrix procedure applied in different p_T bins (expressed in GeV/c), in case of no PID in pp collisions. The Significance ($S/\sqrt{S+B}$) is normalized to 10^9 minimum bias pp events.

	$0 < p_T < 2$	$2 < p_T < 3$	$3 < p_T < 5$	$p_T > 5$
d_{cut} (μm)	800	800	1100	1100
$p_{M,cut}$ (GeV/c)	1.1	$0.5 \div 0.8$	$0.5 \div 1.3$	2.2
$\cos\theta_{point,cut}$	0.979	0.991	0.9955	0.997
$(\Sigma d_{0,i}^2)_{cut}$ ($\mu\text{m}^2 \times 10^3$)	550	500	350	100
S/ev	3×10^{-7}	1.3×10^{-6}	1.7×10^{-6}	1.2×10^{-6}
B/ev	1.3×10^{-6}	9×10^{-7}	1.8×10^{-6}	4.4×10^{-7}
S/B	0.23	1.5	1	2.8
$S/\sqrt{S+B}$	7 ± 3	28 ± 5	29 ± 5	29 ± 5

The values of the cut variables included in the four-dimensional matrix which maximize the Significance in the different p_T bins are reported in Table 6.8 together with the values of signal and background triplets and the ratio S/B .

The background statistics after the selection procedure, namely $\sim 10^{-6}$ background triplets per pp event, suggests that the optimization of the cuts is limited by the statistics of $\sim 5 \times 10^6$ pp events available. Similar arguments are discussed in Section 6.1.2.1 for Pb-Pb collisions.

Fig. 6.12 shows the scatter plots for different cut variables used in the four-dimensional matrix procedure in the case of $2 < p_T < 3$ GeV/c. The plots are obtained keeping those cut variables which give a value of Significance larger than 23, i.e. the maximum minus its error. The cut variables which reject all the background triplets are not shown in the plots.

The plots of Fig. 6.12 confirm, as quoted in Table 6.8, that in order to get high values of the Significance in the range $2 < p_T < 3$ GeV/c, a cut $(\Sigma d_{0,i}^2)$ is more effective than a cut on d .

An example of projection of the four-dimensional matrix of the Significance on the plane $(d_{cut}, \cos\theta_{point,cut})$ after fixing the remaining two variables to the optimized values reported in Table 6.8, is shown in Fig. 6.13 for the case $3 < p_T < 5$ GeV/c. We see from Fig. 6.13 that the maximum of the Significance is well localized around $d_{cut} \sim 1000 \mu\text{m}$ and $\cos\theta_{point,cut} \sim 0.99$.

6.3 Summary of the results

The summary of the results on the performance of ALICE in the reconstruction of $D^\pm$ mesons through their hadronic decay $D^+ \rightarrow K^- \pi^+ \pi^+$ in both Pb-Pb and

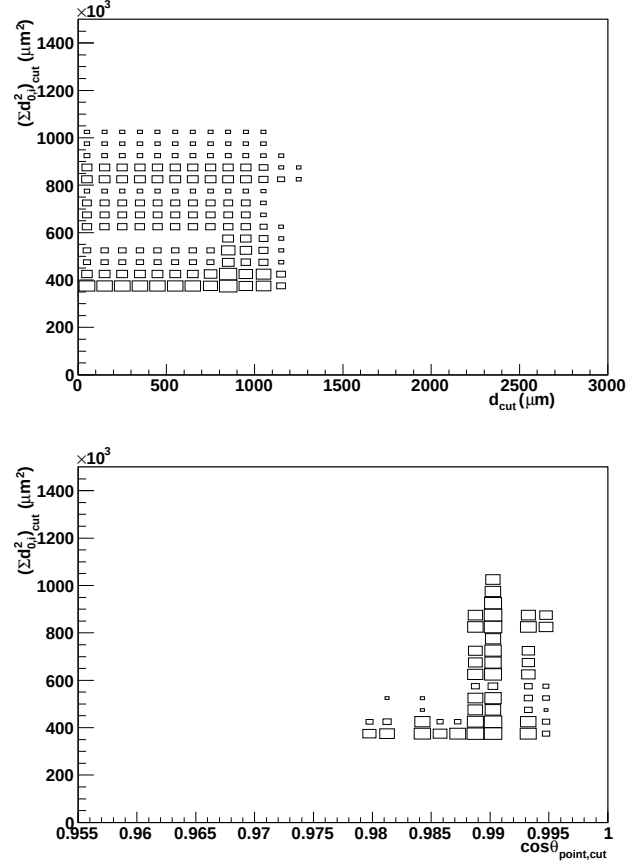


Figure 6.12: Upper panel: Number of combinations of cuts which give $S/\sqrt{S+B} > 23$ for $2 < p_T < 3$ GeV/c. The variables shown in the plot are $(\Sigma d_{0,i}^2)_{cut}$ vs. d_{cut} . Bottom panel: The same as upper panel but for $(\Sigma d_{0,i}^2)_{cut}$ vs. $\cos\theta_{point,cut}$.

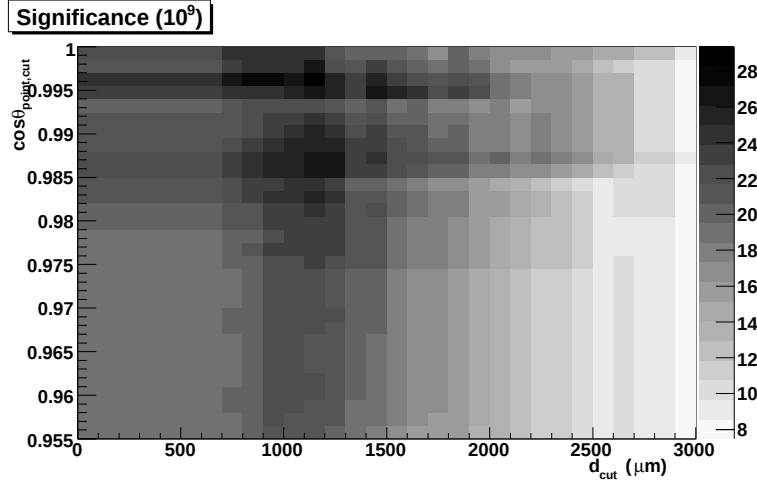


Figure 6.13: Significance (normalized to 10^9 pp events) as a function of the cut variables d_{cut} and $\cos\theta_{point,cut}$, for $p_{M,cut} = 0.5$ GeV/c and $(\Sigma d_{0,i}^2)_{cut} = 150 \times 10^3 \mu\text{m}^2$. The transverse momentum of the triplets is $3 < p_T < 5$ GeV/c. The no PID case is considered.

Table 6.9: Final values of S/B and $S/\sqrt{S+B}$ for both 10^7 Pb-Pb and 10^9 pp events.

	S/ev	B/ev	S/B	$S/\sqrt{S+B}$
Pb-Pb: ideal PID	1.3×10^{-3}	7×10^{-4}	1.8	92 ± 5
Pb-Pb: real PID	5.5×10^{-4}	3×10^{-4}	2	60 ± 5
Pb-Pb: no PID	9×10^{-4}	9×10^{-3}	0.1	30 ± 1
pp: no PID	5×10^{-6}	4.4×10^{-6}	1	50 ± 5

pp collisions is presented in this section.

The exclusive analysis of $D^\pm$ mesons in ALICE is a promising study, in spite of the difficulties in the reconstruction of a three-particle decay very close to the interaction point.

The final values of the p_T integrated S/B and Significance for both 10^7 Pb-Pb and 10^9 pp events are reported in Table 6.9.

6.3.1 Results for Pb-Pb collisions

The Significance $S/\sqrt{S+B}$ maximized in the $D^\pm$ transverse momentum bins $0 < p_T < 2$ GeV/c, $2 < p_T < 3$ GeV/c, $3 < p_T < 5$ GeV/c, $p_T > 5$ GeV/c is reported in Fig. 6.14 for the three cases of ideal PID, real PID and without PID.

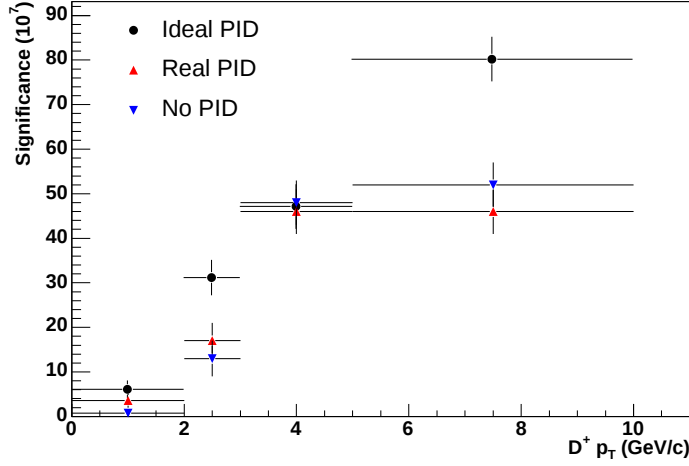


Figure 6.14: Significance $S/\sqrt{S+B}$ as a function of the $D^\pm$ transverse momentum for ideal PID (black circles), real PID (red triangles up) and no PID (blue triangles down).

It can be noticed from Fig. 6.14 that the values of Significance obtained with real particle identification and without particle identification are consistent within the error bars: this would suggest that also an analysis without PID could be feasible. However, the use of particle identification allows to reduce drastically the required computing time for the analysis.

The performance of the selection strategy based on the four-dimensional matrix can be evaluated by means of the selection efficiency, defined as follows:

$$\epsilon = \frac{N_{D^\pm}^{sel}}{N_{D^\pm}^{rec}} \quad (6.3)$$

where $N_{D^\pm}^{sel}$ is the number of $D^\pm$ mesons, in a given p_T bin, resulting after all the selection chain and $N_{D^\pm}^{rec}$ is the number of $D^\pm$ mesons in that p_T bin with all the three daughters reconstructed in the detector and thus a priori selectable.

Fig. 6.15 shows the selection efficiency for different momentum bins and for the three scenarios of ideal PID, real PID and without PID. The integrated- p_T selection efficiencies are 1.4%, 0.6% and 1% for ideal PID, real PID and no PID respectively. As expected, the selection efficiency is bigger for the ideal particle identification; in addition, it can be observed that the performance of the particle identification are reasonably good up to 4-5 GeV/c, while for larger momenta the decrease of the selection efficiency is related to the decrease of the performance of the TOF.

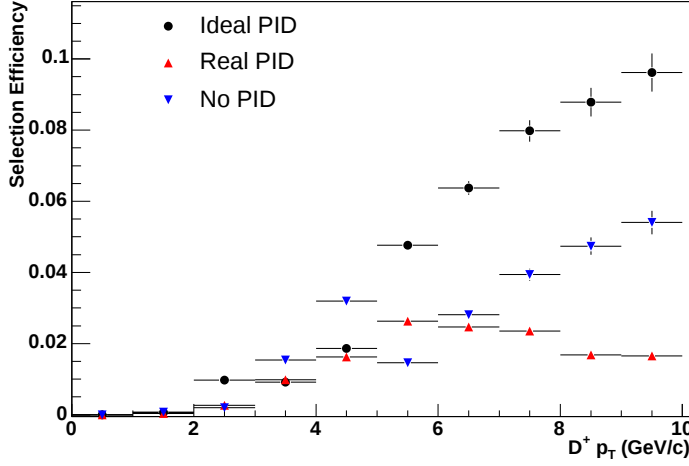


Figure 6.15: Selection efficiency as a function of the $D^\pm$ transverse momentum. The three cases of ideal PID, real PID and without PID are reported in the plot.

The relative error on the selected signal, $\sigma_S/S = 1/\sqrt{S}$ is calculated with the available signal statistics after all the steps in the selection chain. It has been evaluated in Fig. 6.16 with a sample of $\sim 1.9 \times 10^6$ signal triplets and normalized to 10^7 Pb-Pb collisions. Especially at high momentum, the limited signal statistics due to PID inefficiencies is responsible for large relative errors. Large errors can be seen also for $p_T \leq 2$ GeV/c, the reason being that the cut optimization selects only $\sim 0.1\%$ signal triplets among those in the same momentum bin (see Fig. 6.15). In the intermediate transverse momentum region, $2 \leq p_T \leq 6$ GeV/c, where the selection efficiency is of the order of 1.5-2%, the relative error on the selected signal reaches values of $\sigma_S/S \sim 2\%$.

The p_T distribution of the selected signal triplets is plotted in Fig. 6.17 for the three cases of ideal PID, real PID and without PID. For comparison, also the histograms with the signal triplets, i.e. $D^+ \rightarrow K^- \pi^+ \pi^+$, generated in the full solid angle and in the ALICE barrel acceptance, $-0.0 < \eta < 0.9$, are reported, as well as the signal triplets fully reconstructed in the detector. The histograms are normalized to the distribution of the generated $D^+ \rightarrow K^- \pi^+ \pi^+$. The ratio between the distributions of selected and reconstructed $D^\pm$ is nothing but the selection efficiency reported in Fig. 6.15.

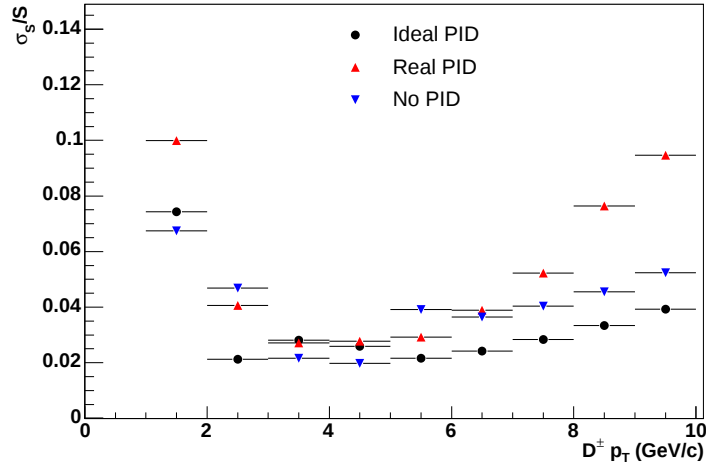


Figure 6.16: Relative error on the selected signal (normalized to 10^7 Pb-Pb events), $\sigma_S/S = 1/\sqrt{S}$, as a function of the $D^\pm$ transverse momentum. The three cases of ideal PID, real PID and without PID are reported in the plot.

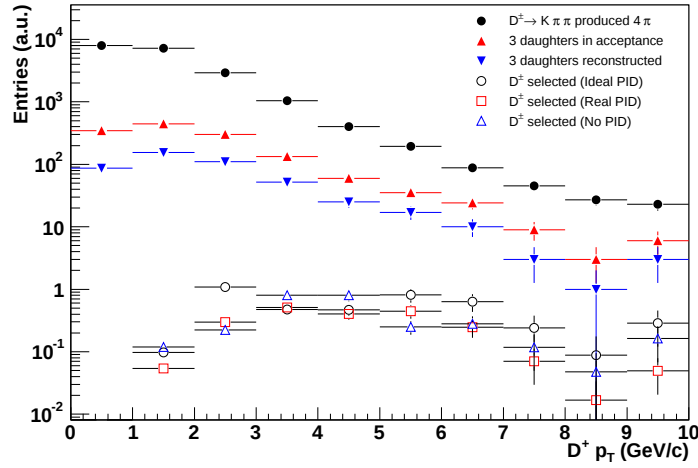


Figure 6.17: Transverse momentum distributions of signal triplets $D^\pm \rightarrow K\pi\pi$ generated in the full solid angle (black circles), in the ALICE acceptance (red triangles up), reconstructed in the detector (blue triangles down) and selected with ideal PID (black open circles), with real PID (blue open triangles) and without PID (red open squares).

6.3.2 Results for pp collisions

The Significance $S/\sqrt{S+B}$ maximized in the $D^\pm$ transverse momentum bins $0 < p_T < 2$ GeV/c, $2 < p_T < 3$ GeV/c, $3 < p_T < 5$ GeV/c, $p_T > 5$ GeV/c is reported in Fig. 6.18. The Significance is normalized to one year of data taking, corresponding to 10^9 minimum bias pp collisions.

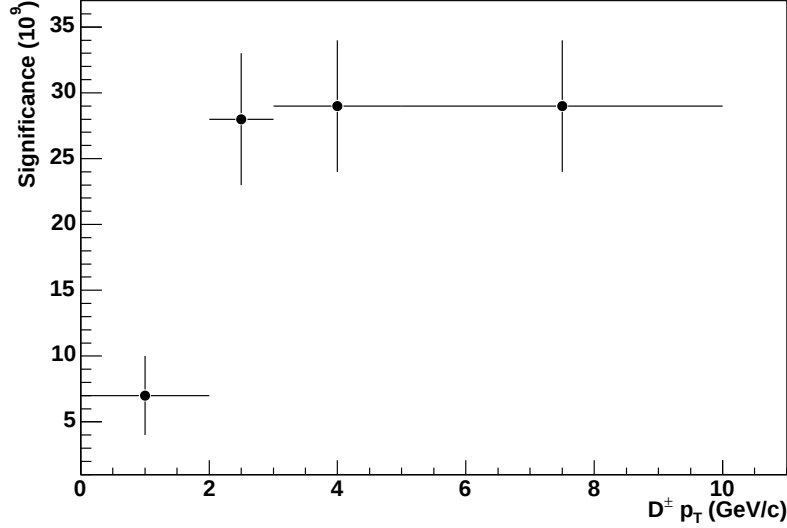


Figure 6.18: Significance $S/\sqrt{S+B}$ as a function of the $D^\pm$ transverse momentum for pp collisions without PID.

The plot confirms that the reconstruction of $D^\pm$ mesons in pp collisions is a promising analysis in the first year of the ALICE data taking, even in the worst scenario where particle identification is not used. The forthcoming start of the ALICE data taking, where not all the detectors will be ready for an efficient particle identification, will allow the test of the tools developed for the open charmed meson reconstruction in pp collisions.

The relative error on the detected $D^\pm$ triplets in the total sample of 5.4×10^6 pp collisions (normalized to 10^9 events) is shown in Fig. 6.19 as a function of the $D^\pm$ transverse momentum. It is important to notice that, in Pb-Pb as in pp collisions, the relative error has a minimum around 2-4 GeV/c, corresponding to the momentum region where the generated $D^\pm$ are copious and the selection chain is able to detect a large amount of signal compared to the low momentum bin $p_T \leq 2$ GeV/c where tight cuts are necessary to reject the bulk of background triplets.

Such behaviour is consistent with Fig. 6.20, where the p_T distribution of the selected signal triplets is plotted, together with the spectra of the signal triplets fully reconstructed in the detector. For comparison, the spectra of the generated $D^\pm$ mesons in the full solid angle and of the generated $D^+ \rightarrow K^- \pi^+ \pi^+$, in both the full solid angle and the ALICE barrel acceptance, are reported in the figure. The histograms are normalized to the distribution of the generated $D^\pm$ mesons. The ratio between the distributions of selected and reconstructed $D^\pm$ is the selection efficiency, which amounts to $\sim 4\%$ in the case that particle identification is not applied. It can be observed that the distribution of selected $D^\pm$ mesons is indeed peaked around 2-4 GeV/c, justifying the smaller relative errors on the signal with respect to low and high momentum bins.

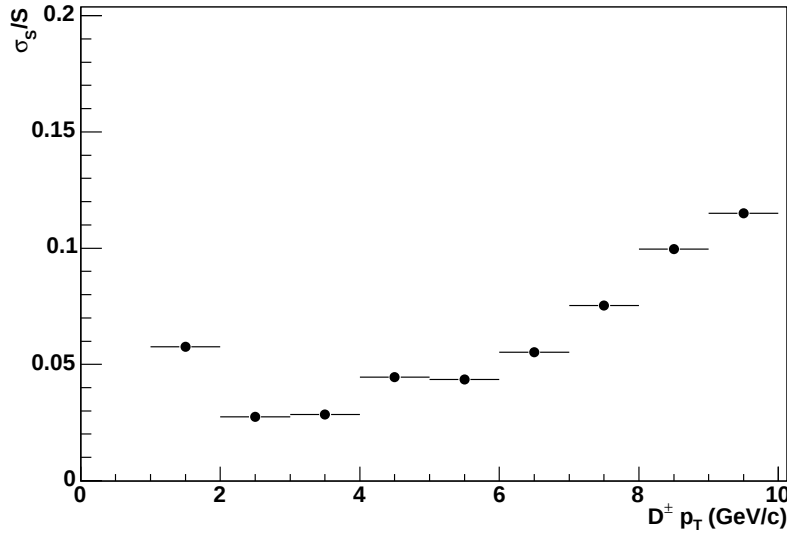


Figure 6.19: Relative error on the selected signal in pp collisions (normalized to 10^9 events), $\sigma_S/S = 1/\sqrt{S}$, as a function of the $D^\pm$ transverse momentum.

6.4 Results scaled to a lower multiplicity scenario for Pb-Pb collisions

A charged particle rapidity density $dN_{ch}/dy = 6000$ has been assumed for central Pb-Pb collisions in the present work. However, extrapolations from RHIC data to the LHC energy seem to favour a lower multiplicity scenario, $dN_{ch}/dy \sim 2000$ (see Section 1.3.1.1).

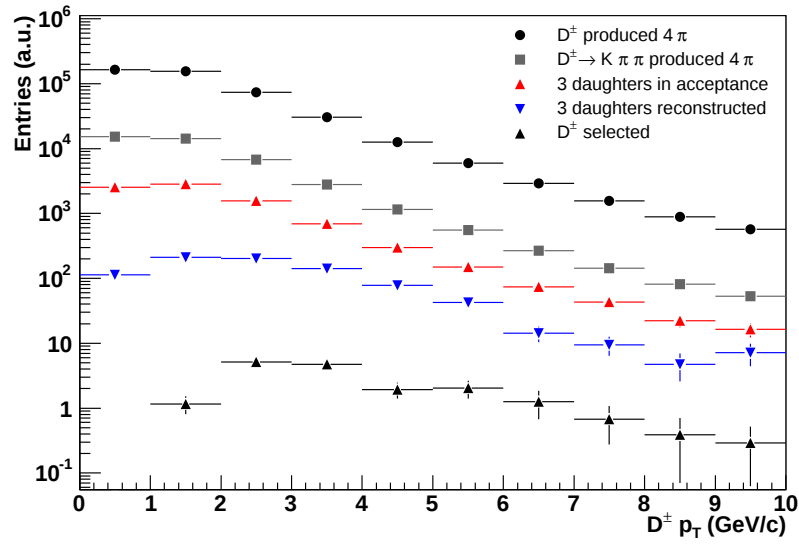


Figure 6.20: Transverse momentum distributions of signal triplets $D^\pm \rightarrow K\pi\pi$ generated in pp collisions in the full solid angle (black circles), in the ALICE acceptance (red triangles up), reconstructed in the detector (blue triangles down) and selected without PID (black triangles up).

It is then possible to estimate the performance of the reconstruction of $D^\pm$ mesons in Pb-Pb collisions in ALICE in case of a low multiplicity environment, i.e. $dN_{ch}/dy = 2000$. With lower dN_{ch}/dy , the number of background triplets is dramatically reduced, and thus the capabilities of the signal selection are expected to improve.

In case no particle identification is assumed, the number of background triplets B per event is roughly $B = N(N-1)(N-2)/3!$ (we are neglecting the charge sign combinations for simplicity), where N is the number of reconstructed tracks. In the most central Pb-Pb events studied in this work the track multiplicity in the ALICE acceptance is on average $N \sim 7000$, leading to $B \sim 6 \times 10^{10}$ background triplets. Neglecting as a first approximation the possible improvements in tracking efficiency in the lower multiplicity scenario, we roughly estimate a reduction of reconstructed tracks N of the order of 1/3 passing from $dN_{ch}/dy = 6000$ to $dN_{ch}/dy = 2000$. Hence, the number of background triplets before any selection decreases by a factor ~ 30 , $B = 2 \times 10^9$.

We can for example consider the $D^\pm$ transverse momentum bin $0 < p_T < 2$ GeV/c, where the results quoted above for the one-year data taking are not satisfactory, and estimate the S/B and the Significance in case of $dN_{ch}/dy = 2000$. The number of background triplets per event using the real PID, $B = 6.9 \times 10^{-5}$ (from Table 6.5), should be downscaled by a factor ~ 30 , leading to $B/ev \sim 2.3 \times 10^{-6}$. The signal per event, $S/ev \sim 10^{-5}$, is not rescaled because it is not clear whether or not the $c\bar{c}$ production cross section depends on the multiplicity: as we report in Chapter 2, the current calculations of $c\bar{c}$ cross sections depend on the center-of-mass energy but not on the number of particles produced in the Pb-Pb collision.

These assumptions lead to $S/B \simeq 4$ and Significance $S/\sqrt{S+B} \simeq 9$ normalized to one year of running at the LHC, thus suggesting that the increased signal statistics with respect to the fluctuations of $S+B$ could be sufficient to study the p_T spectra even in the low transverse-momentum region.

In case of no particle identification, the number of background triplets per event with $dN_{ch}/dy = 2000$ should be $B/ev \sim 3 \times 10^{-4}$ (see also Table 6.6). The signal per event, $S/ev = 2.2 \times 10^{-5}$, is not rescaled according to the same arguments reported above. These assumptions lead to $S/B \simeq 7\%$ and $S/\sqrt{S+B} \simeq 4$, suggesting that, even in the lower multiplicity scenario, the analysis without PID seems not to be feasible in only one year of data taking.

6.5 Statistical and systematic uncertainties on $D^\pm$ measurements

Two kinds of uncertainties enter $D^\pm$ cross section measurements: statistical and systematic relative errors, which are summed in quadrature to get the total error.

The relative statistical error on the selected signal, σ_S/S , is obtained by counting in each p_T bin the number of selected signal triplets in the invariant mass range $|M_{inv} - M_{D^\pm}| < 1\sigma$. Fig. 6.16 and 6.19 show the relative errors σ_S/S estimated for Pb-Pb and pp collisions and normalized to 10^7 and 10^9 Pb-Pb and pp events respectively.

In the present case of $D^+ \rightarrow K^- \pi^+ \pi^+$, the systematic errors which enter the $D^\pm$ production cross section are the same affecting the D^0 in the benchmark analysis of $D^0 \rightarrow K^- \pi^+$ [92, 163] and are listed in the following:

1. Acceptance, reconstruction and particle identification efficiencies. They are corrected with a Monte Carlo simulation of the detector geometry and response and are estimated to amount to $\sim 10\%$ [92]. However, as experienced by other experiments, this kind of systematic error can be reduced after a few years of running, as the detector responses are better understood.
2. Error on the centrality selection: the central Pb-Pb events of our production, corresponding to 1.6% of the total inelastic Pb-Pb collision, have an upper limit on the collision impact parameter, $b_c \sim 2$ fm. The error on the determination of b_c is given in ALICE by the Zero Degree Calorimeter, which provides a relative precision $\delta b/b \sim 30\%$ for $b \sim 2 - 3$ fm [165]. The upper limit is then $b_c = (2 \pm 1)$ fm: it determines the range for the factor $R(b_c)$ introduced in Section 2.2.1, $R(b_c) = (29 \pm 2) \text{ mb}^{-1}$. The error on $R(b_c)$ affects the $D^\pm$ production cross section per binary collision, which can be derived from Section 2.2.1 as:

$$\sigma_{NN}(D^\pm) = \frac{N_{AA}(D^\pm)/event}{R(b_c)} \quad (6.4)$$

Hence, the relative error is estimated as $2/29 \simeq 7\%$.

3. Uncertainties on the parameters of the Woods-Saxon profile of the nuclear density: they are of the order of 5% [166].
4. Error on the extrapolation of the pp results from 14 TeV to 5.5 TeV, of the order of 12% for charm production [92]. See also Section 2.4.
5. Error on the nucleon-nucleon inelastic cross section: the pp cross section will be measured at the LHC by the TOTEM experiment [167] with an expected precision of $\sim 5\%$.

6. Error on the branching ratio of the channel $D^+ \rightarrow K^- \pi^+ \pi^+$: it is small compared to the other sources. The relative error amounts to $\sim 3.6\%$ [84].
7. Error introduced by the feed-down from beauty. The cross section for the production of primary $D^\pm$ is calculated by subtracting from the selected $D^\pm$ ($N^{D^\pm}$), the number of $D^\pm$ coming from secondary decays of B mesons, i.e. $N^{c \rightarrow D^\pm} = N^{D^\pm} - N^{b \rightarrow B \rightarrow D^\pm}$. The relative error on $N^{b \rightarrow B \rightarrow D^\pm}$ is essentially given by the relative error on the beauty cross section, $\sigma^{b\bar{b}}$ at the LHC:

$$\frac{\delta N^{b \rightarrow B \rightarrow D^\pm}}{N^{b \rightarrow B \rightarrow D^\pm}} = \frac{\delta \sigma^{b\bar{b}}}{\sigma^{b\bar{b}}} \quad (6.5)$$

The relative error on $N^{c \rightarrow D^\pm}$ is then:

$$\frac{\delta N^{c \rightarrow D^\pm}}{N^{c \rightarrow D^\pm}} = \frac{\delta \sigma^{b\bar{b}}}{\sigma^{b\bar{b}}} \times \frac{N^{b \rightarrow B \rightarrow D^\pm}}{N^{c \rightarrow D^\pm}} \quad (6.6)$$

Presently, the uncertainty on $\sigma^{b\bar{b}}$ estimated with pQCD NLO calculations is quite large, $\sim 80\%$ [92]. The secondary-to-primary ratio estimated for the D^0 meson is of the order of 10%. Assuming such an error also for $D^\pm$ mesons, the relative error due to the correction for feed-down from beauty is about 8%.

In the following, we demonstrate with qualitative arguments that the secondary-to-primary ratio of $\sim 10\%$ estimated for the D^0 is reasonable also for the $D^\pm$ meson.

Given the number of $D^\pm$ and B mesons in a 5% central Pb-Pb event, respectively 44.6 and 7.3 [92] (see also Section 2.4), we can roughly estimate the contamination K of $D^\pm$ mesons from B meson decays:

$$K = \frac{N^{B \rightarrow D^\pm}}{N^{D^\pm}} \sim 4\% \quad (6.7)$$

The branching ratio for the channel $B \rightarrow D^\pm = 22.8\%$ [84] has been taken into account in the above equation.

The contamination K is expected to increase when a cut on the distance between the primary and the $D^\pm$ decay vertices is applied, because it is likely that the decay products of $D^\pm$ mesons originating from beauty decays are more displaced from the primary vertex compared to the decay products of prompt $D^\pm$ mesons. This is confirmed in Fig. 6.21 (left plot), where the distribution of the distance between the primary vertex and the $D^\pm$ decay point has larger mean value for $D^\pm$ from beauty feed-down, $\langle d \rangle \sim 1250 \mu\text{m}$, with respect to the one for primary $D^\pm$ mesons, $\langle d \rangle \sim 500 \mu\text{m}$. The plot

is obtained from events generated with PYTHIA without reconstruction in the detector. The same distribution as the left plot is shown in the right plot of Fig. 6.21, but in this case the histograms are normalized to the yields per event of prompt $D^\pm$ mesons, 44.6 in central Pb-Pb collisions, and of $D^\pm$ from beauty decays, $7.3 \times 22.8\% = 1.66$.

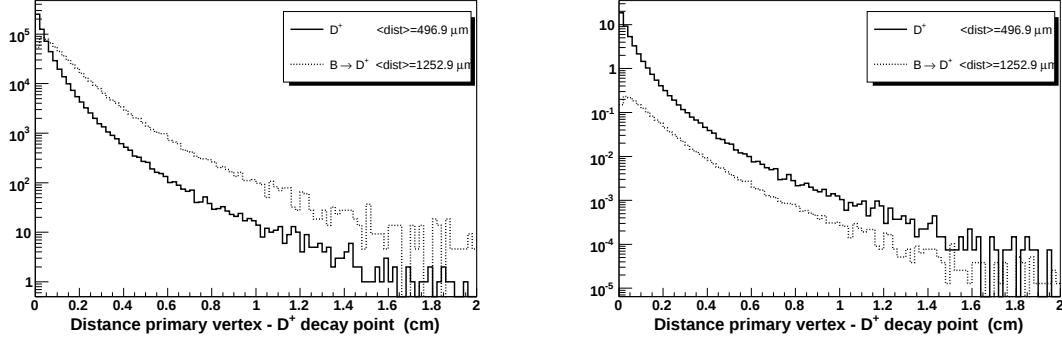


Figure 6.21: Left panel: distribution of the distance between the primary vertex and the $D^\pm$ decay point for primary $D^\pm$ meson (solid line) and for $D^\pm$ from beauty feed-down (dotted line). For comparison, the histograms are normalized to the same area. Right panel: the same distributions as left plot, but the histograms are normalized to the yields of D and B mesons reported in the text.

The ratio of the two histograms in the right panel of Fig. 6.21 gives the contamination $K = 4\%$. Furthermore, the contamination K can be calculated as a function of the cut on the distance between the primary vertex and the $D^\pm$ decay point, as shown in Fig. 6.22. For example, a cut of 1 cm or greater leads to a contamination of $\sim 20\%$.

The typical values of the cut variable d_{cut} representing the distance between the primary and the $D^\pm$ decay vertices are of the order of $\sim 1000 \mu\text{m}$, as discussed in Section 6.1.2. Therefore, we expect a contamination of the order of 10%. However, possible reconstruction and selection effects can alter this first estimate which has been obtained studying only generated quantities.

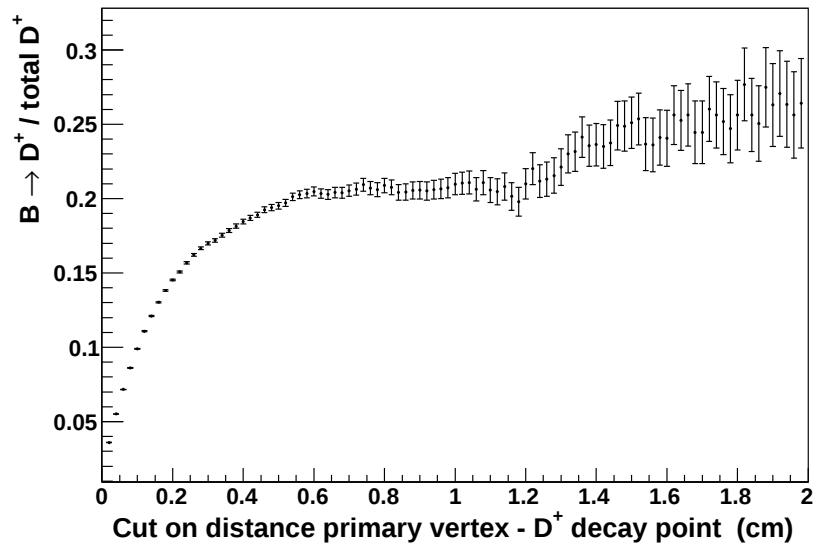


Figure 6.22: Contamination of $D^\pm$ from B decays as a function of the cut on the distance between the primary vertex and the $D^\pm$ decay point.

Chapter 7

$D^\pm$ elliptic flow and nuclear modification factor

7.1 Perspectives for the measurement of $D^\pm$ elliptic flow

The goal of this analysis is to obtain a simple estimation of the statistical error bars on measurements of the elliptic flow (v_2) of $D^\pm$ mesons reconstructed from their exclusive hadronic decays $K\pi\pi$. The results of v_2 as a function of the collision centrality and as function of the transverse momentum of $D^\pm$ mesons for different centrality classes will be presented.

7.1.1 Simulation strategy

The estimation of the reaction plane is done starting from the reconstructed tracks. The number of tracks per event and the v_2 of these particles (v_2^{ev}) determine the resolution of this reaction plane estimator (called event plane, see Section 1.3.1.3).

In addition, also the available $D^\pm$ statistics in one year of data taking has to be known to estimate the error bars of the $D^\pm$ v_2 (v_2^D).

As discussed in Section 2.2.1, a sample of Pb-Pb minimum bias events has a centrality distribution according to its differential cross section. Table 7.1 summarizes, for different centrality classes, the corresponding ratio of inelastic cross section $\sigma(\%)$, the number of events normalized to 2×10^7 (expected yield of minimum bias Pb-Pb collisions in one year of data taking), the number of $c\bar{c}$ pairs per event obtained from Glauber model calculations and the $D^\pm$ yield per event.

The yield of generated $D^\pm$ per event, reported in the last column of Table 7.1, has to be reduced by several factors, namely the branching ratio into the channel $K\pi\pi$, the detector acceptance, the reconstruction efficiency and finally the selec-

Table 7.1: Ratio of inelastic cross section $\sigma(\%)$, number of events, number of $c\bar{c}$ pairs per event and the $D^\pm$ yield per event for different centrality classes.

$b_{min}-b_{max}$ (fm)	$\sigma(\%)$	N_{ev} (10^6)	$N_{c\bar{c}}/ev$	$D^\pm$ yield/ev
0-3	3.6	0.72	118	45.8
3-6	11	2.2	82	31.8
6-9	18	3.6	42	16.3
9-12	25.4	5.1	12.5	4.85
12-18	42	8.4	1.2	0.47

tion efficiency. The first three points can be easily estimated from Monte Carlo simulations (see for example Fig 6.17); the last point (selection efficiency) depends on the analysis strategy for the reconstruction of the decay $D^+ \rightarrow K^- \pi^+ \pi^+$ which has been the main part of this thesis work.

The number of selected $D^\pm$ per event has been extracted (see Chapters 5 and 6) for the most central Pb-Pb events ($0 < b < 2$ fm), in different transverse momentum bins, $N_{D^\pm}(\Delta p_T)$. These numbers are then rescaled to the other centrality classes through the number of $c\bar{c}$ pairs reported in the fourth column of Table 7.1.

At this point, the strategy is to generate a number of $D^\pm$, which depends on p_T and on centrality, $N_{D^\pm}(\Delta p_T, \Delta b)$.

The number of $D^\pm$ is normalized to 2×10^7 minimum bias events, corresponding to one year of data taking at the LHC.

If $N(\Delta b)$ $D^\pm$ are expected to be reconstructed in a given centrality class in 2×10^7 minimum bias events, we generate not all the expected Pb-Pb events in that centrality, but only $N(\Delta b)$ Pb-Pb events with one $D^\pm$ per event.

The $D^\pm$ mesons are generated with an azimuthal angle distribution (see Section 1.3.1.3):

$$dN/d\varphi = N_0 \{1 + 2v_1^D \cos(\varphi - \Psi_{RP}) + 2v_2^D \cos(2(\varphi - \Psi_{RP}))\} \quad (7.1)$$

The generated $D^\pm$ azimuthal angle is smeared with its experimental resolution. The $D^\pm$ angular resolution is shown in Fig. 7.1 as a function of the $D^\pm$ transverse momentum.

Each of the generated $D^\pm$ is superimposed to an event made of tracks generated with a v_2^{ev} coefficient (different from v_2^D). The generation of the event is done with a fast simulation, i.e. neither typical event generator programs nor detector simulation programs are used. The simulation simply consists in the random generation of azimuthal angles, as many as the number of the reconstructed tracks per Pb-Pb event, according to the following azimuthal angle distribution:

$$dN/d\varphi = N_0 \{1 + 2v_1^{ev} \cos(\varphi - \Psi_{RP}) + 2v_2^{ev} \cos(2(\varphi - \Psi_{RP}))\} \quad (7.2)$$

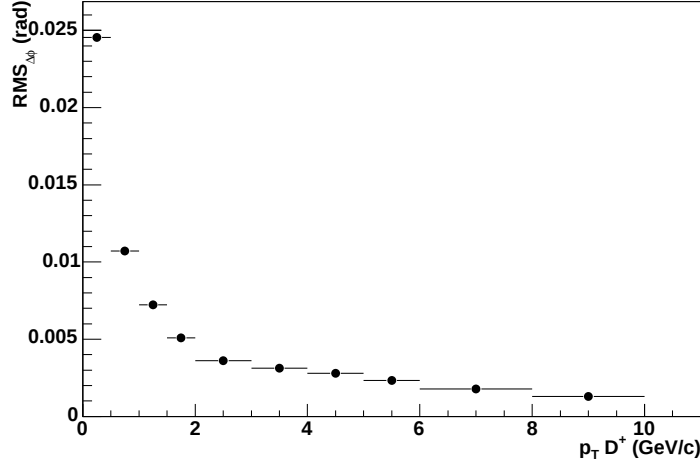


Figure 7.1: The y axis reports the standard deviation of the histogram filled with $(\phi_{D^+,sim} - \phi_{D^+,rec})$, where $\phi_{D^+,sim}$ and $\phi_{D^+,rec}$ are the azimuthal angles given by the simulation and the reconstruction respectively. The x axis reports various $D^\pm$ transverse momentum bins where the above histogram is considered.

The parameters of the simulation are then v_1^{ev} , v_2^{ev} , v_1^D , v_2^D and Ψ_{RP} , together with the track multiplicity and the number of selected $D^\pm$ above discussed. v_1 is set equal to zero both for the event and for $D^\pm$ because the study is performed in the midrapidity region where the coefficient v_1 is expected to be negligible (see Section 1.3.1.3). Also the reaction plane Ψ_{RP} can be set equal to zero because we do not take into account detector effects which may have an azimuthal dependence.

The choice of the input v_2^{ev} , v_2^D and track multiplicity, is taken from theoretical predictions for the LHC, as described in the following paragraphs. The last paragraph of this section describes the fast simulation of the event plane which requires the above ingredients; the results of the measurement of the $D^\pm$ v_2 will be presented in Section 7.1.1.2.

7.1.1.1 Charged multiplicity at the LHC

As already discussed in Section 1.3.1.1, the predictions for the multiplicity at the LHC are far from being well established. Even if the analysis for the selection of $D^+ \rightarrow K^- \pi^+ \pi^+$ signal has been done in a scenario of $dN/dy \sim 6000$, we do not use the too high multiplicity predictions of HIJING in this case, but rather a more recent scenario predicted by a model based on the geometrical scaling including saturation effects [168]. This model successfully reproduces the multiplicities mea-

sured in Au-Au collisions at RHIC. Fig. 7.2 shows the predictions of the model at the LHC as a function of the number of participants, which is related to the centrality of the collision.

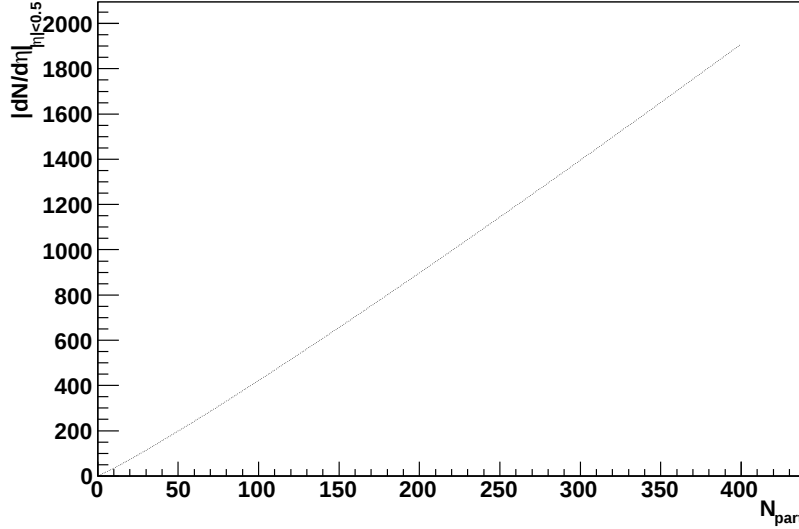


Figure 7.2: Charged particle multiplicity expected at the LHC in $|\eta| < 0.5$ as a function of the number of participants.

The curve in Fig. 7.2 has been obtained with the following parametrization of the charged multiplicity:

$$\frac{1}{N_{part}} \frac{dN_{ch}^{AA}}{d\eta} \Big|_{\eta \sim 0} = N_0 \sqrt{s} N_{part}^{\frac{1-\delta}{3\delta}} \quad (7.3)$$

where the parameters $N_0 = 0.235$, $\lambda = 0.288$ and $\delta = 0.79$ are taken from [168]. The center-of-mass energy is $\sqrt{s} = 5.5$ TeV.

In our simulation the number of reconstructed tracks is needed, rather than the charged particle multiplicity because the reaction plane is measured from the tracks. Nevertheless, since the value used for $dN_{ch}/d\eta$ is just an estimate, we decided to neglect the reconstruction efficiency of the detector. Therefore, the input of the simulation is simply $dN_{ch}/d\eta|_{|\eta|<1} = 2 \times dN_{ch}/d\eta|_{|\eta|<0.5}$, since the acceptance of the ALICE barrel is $|\eta| < 1$ ¹.

The number of participants and $dN_{ch}/d\eta|_{|\eta|<1}$ are listed in Table 7.2 for the five centrality classes used in this study. The five centrality classes are defined in ALICE by means of the ZDC [165].

¹ A flat $dN_{ch}/d\eta$ distribution at mid-rapidity is assumed.

Table 7.2: Number of participants in Pb-Pb collisions calculated with the Glauber model and charged particle multiplicity in the ALICE acceptance predicted by [168] for different centrality bins.

$b_{min}-b_{max}$ (fm)	N_{part}	$dN_{ch}/d\eta _{ \eta <1}$
0-3	381	3622
3-6	297	2762
6-9	177	1572
9-12	71	582
12-18	10	68

7.1.1.2 Prediction of v_2 value for charged hadrons at the LHC

Even though ideal hydrodynamic model calculations reproduce rather well the v_2 measurements at RHIC ([18], [20], [21]), they show a different behaviour for the v_2/ϵ as a function of the multiplicity, as can be seen in Fig. 7.3. ϵ is the eccentricity of the collision already introduced in Section 1.3.4.2.

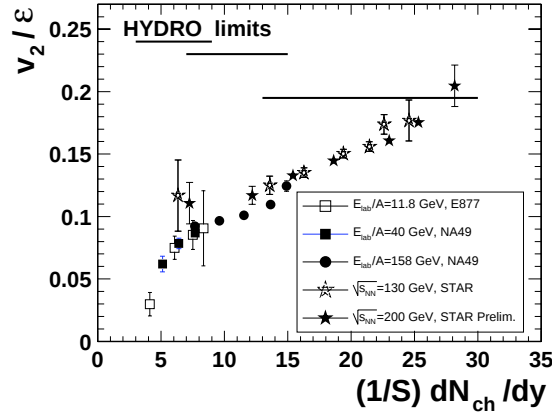


Figure 7.3: Elliptic flow divided by the initial eccentricity of the collision as a function of the multiplicity density. S is the transverse overlap area of the two nuclei. Taken from [58].

The lines in the figure represent the hydrodynamic limits of v_2/ϵ , including the highest RHIC energies. Other models based on hydrodynamics but assuming a non-zero mean free path, typically of the order of the size of the medium (also called low-density limit), show a monotonic dependence of v_2/ϵ which accounts for the trend in Fig. 7.3.

The values of v_2 at the LHC energies for Pb-Pb collisions as predicted by the ideal hydrodynamic calculations and by the hydrodynamic model with finite mean

Table 7.3: Predictions of v_2 at the LHC given by the ideal hydrodynamic model and by the more realistic hydrodynamic model with non-zero mean free path.

$b_{min}-b_{max}$ (fm)	v_2^{ev} (Hydro)	v_2^{ev} (low-density limit)
0-3	0.010	0.018
3-6	0.035	0.08
6-9	0.07	0.125
9-12	0.092	0.107
12-18	0.08	0.03

free path (based on the extrapolation of the trend observe at the SPS and RHIC) are shown in Fig. 7.4 as a function of the expected charged particle multiplicity at the LHC calculated with the multiplicity predictions of Ref. [168].

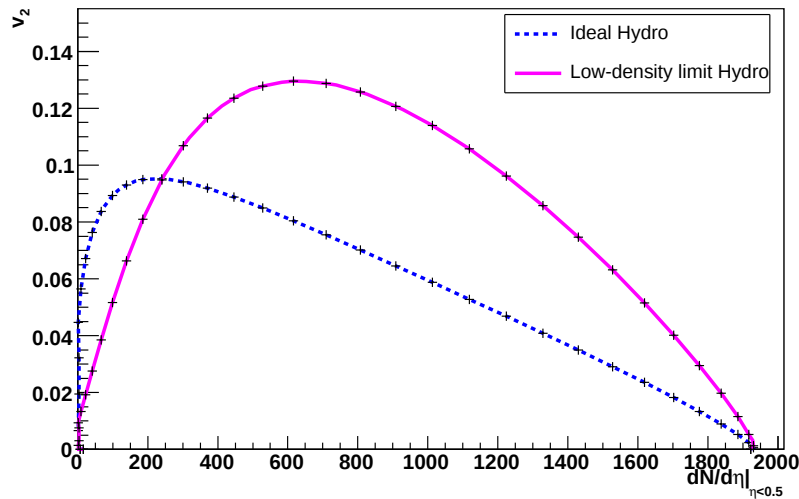


Figure 7.4: v_2 for charged hadrons at the LHC (v_2^{ev}) as a function of the charged particle multiplicity at mid-rapidity [169]. The two curves represent the predictions of the low-density-limit hydrodynamics (solid line) and of the ideal hydrodynamics (dashed line). The expected v_2/ϵ with ideal hydrodynamics is $v_2/\epsilon = 0.22$.

The values of v_2 taken from Fig. 7.4 are reported in Table 7.3 for the different centrality classes used in our study.

In our simulations, we use the prediction of the v_2 values from the framework of the low-density-limit model [25] reported in the third column of Table 7.3.

Table 7.4: Values for the charmed meson p_T -integrated v_2 in different centrality classes.

b_{min} - b_{max} (fm)	p_T -integrated $D^\pm$ v_2^D
0-3	0.01
3-6	0.02
6-9	0.03
9-12	0.04
12-18	0.05

7.1.1.3 D meson v_2 at the LHC

The values of v_2 of charm quark at the LHC have been calculated within the framework of the microscopic transport model [108], which describes the evolution of the system through elastic and inelastic scatterings between partons. The predictions (taken from [109]) are shown in Section 2.2.2.3 for collisions with an impact parameter $b = 8$ fm.

The v_2 of charmed mesons is calculated with the coalescence model. In the coalescence model, quarks with similar velocities coalesce and form mesons, i.e. $\alpha\beta \rightarrow M$, and baryons, i.e. $\alpha\beta\gamma \rightarrow B$. As already discussed in Section 2.2.2.3, in case of D^+ mesons, we have:

$$v_{2,D}(p_T) \approx v_{2,u}\left(\frac{p_T}{6}\right) + v_{2,c}\left(\frac{5p_T}{6}\right) \quad (7.4)$$

The values of D meson v_2 at the LHC for $b = 8$ fm, calculated in the coalescence model as a function of the transverse momentum of the D mesons, are shown in Fig. 7.5. The two plots refer to two different assumptions for the parton cross section in the transport model. Two extreme scenarios are treated: first, the charm flow is zero and therefore the flow of D mesons is only due to light quarks; second, the charm is supposed to flow as the light quarks.

The values for the charmed meson p_T -integrated v_2 in different centrality classes used in this analysis are reported in Table 7.4.

7.1.1.4 Event plane simulation and resolution

The event plane Φ_R is measured from the azimuthal distribution of particles generated according to the distribution of Eq. 7.2 by means of a fast simulation. This is an estimate of the reaction plane, which is the plane parallel to the beam axis and oriented along the line connecting the centres of the two colliding nuclei.

The event plane resolution calculated with the second harmonic can be visualized by the RMS of the distribution of $(\Phi_R - \Psi_R)$, where Ψ_R is the reaction plane

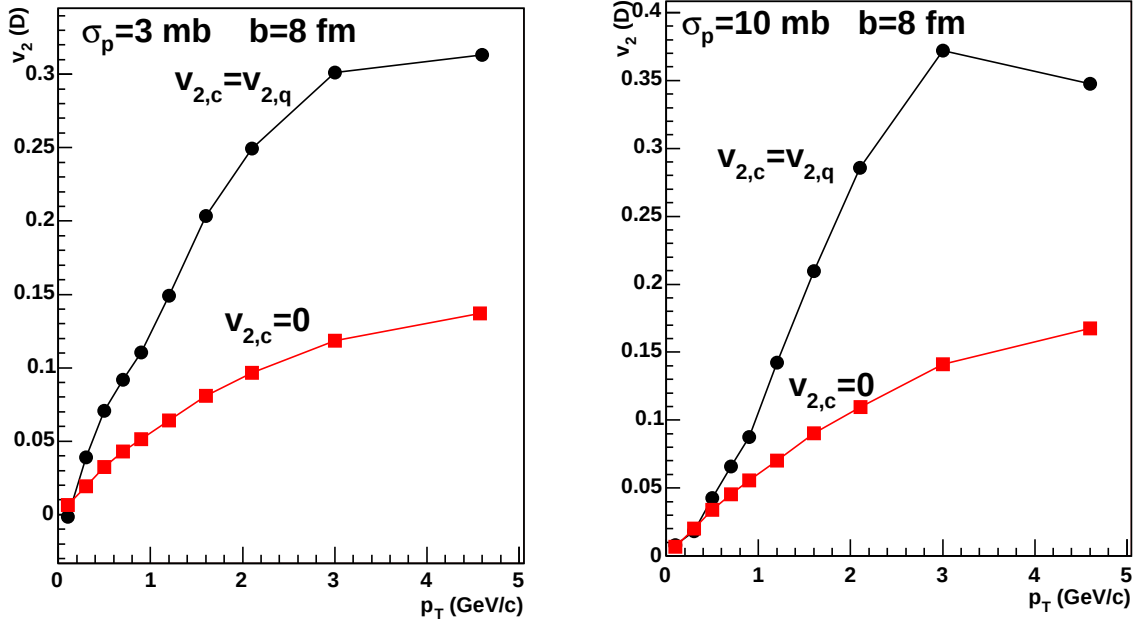


Figure 7.5: D meson v_2 at the LHC (v_2^D) as a function of p_T , for parton transport cross section $\sigma_p = 3$ mb (left panel) and $\sigma_p = 10$ mb (right panel). The black circles indicate the coalescence predictions in the case of charm v_2 equal to that of light quarks; the red squares indicate the opposite scenario where the charm quarks do not flow. The predictions on the flow of light and heavy quarks at the LHC are taken from [109].

and Φ_R is measured with the second harmonic:

$$\Phi_R = \frac{1}{2} \arctan \frac{\sum_i w_i \sin(2\phi_i)}{\sum_i w_i \cos(2\phi_i)} \quad (7.5)$$

As can be observed in Fig. 7.6, the event plane resolution depends on the number of tracks per event and on the value of the second harmonic coefficient v_2 .

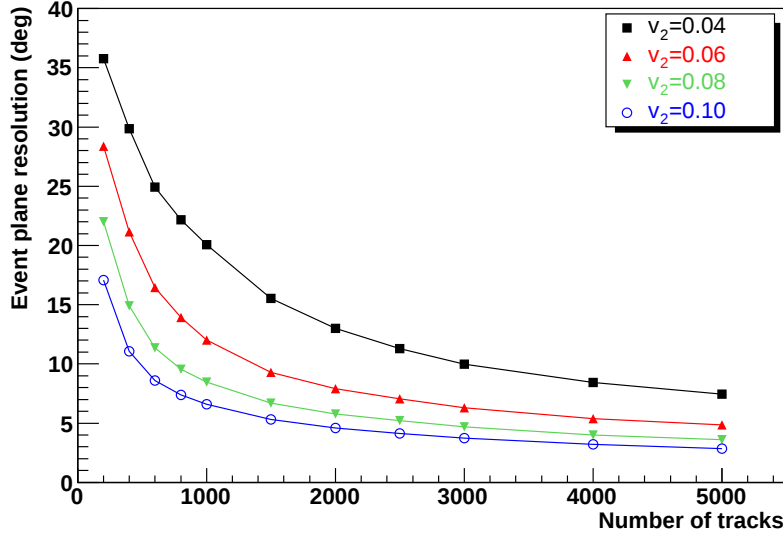
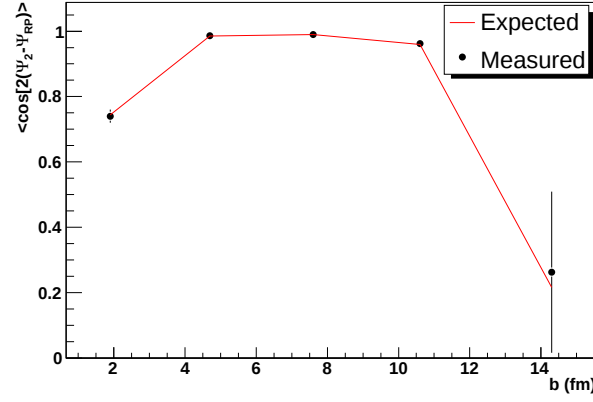


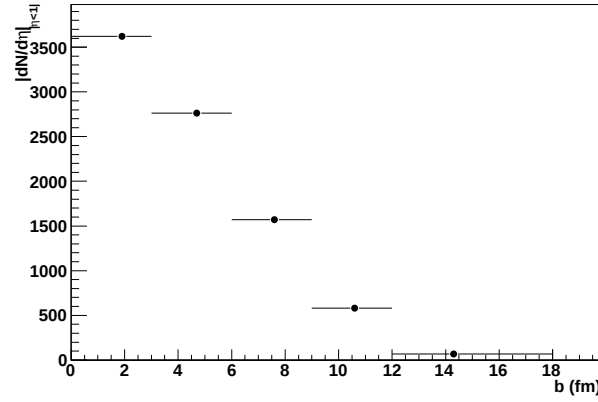
Figure 7.6: Event plane resolution, measured in degrees, as a function of the number of tracks per event for different values of the second harmonic coefficient v_2 .

As expected, the resolution improves as the number of tracks per event increases. Furthermore, the event plane is measured with higher accuracy in case of high values of v_2 : this is reasonable, since a large v_2 means that the particles are preferably emitted along the direction of the reaction plane.

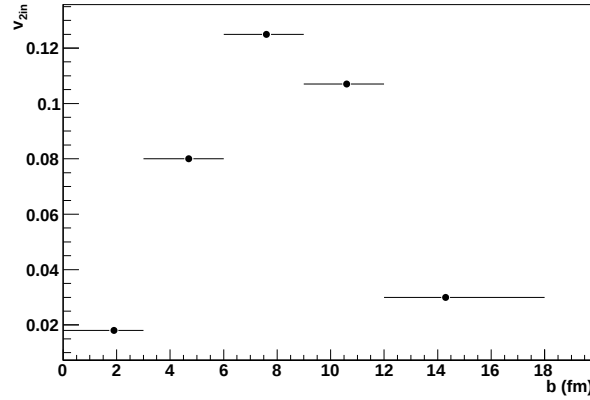
The event plane resolution, $\langle \cos[2(\Phi_R - \Psi_R)] \rangle$, which enters the v_2 calculation, is plotted for the different centrality selections used in the analysis in Fig. 7.7 (a); the superimposed line indicates the expected values based on the $\chi = v_2 \sqrt{N_{tracks}}$ variable defined in [22]. Also the number of tracks and the second harmonic coefficient v_2 used as input are shown as a reference for the different centrality classes (Fig. 7.7 (b) and (c)).



(a)



(b)



(c)

Figure 7.7: (a) Event plane resolution, $\langle \cos[2(\Phi_R - \Psi_R)] \rangle$, for the different centrality classes. (b) Charged particle multiplicity in the ALICE barrel for the different centrality classes. (c) v_2^{ch} value of charged hadrons for the different centrality classes.

Table 7.5: Number of p_T -integrated $D^\pm$ mesons which are expected to be selected in 2×10^7 minimum bias events for the different centrality classes.

$b_{min}-b_{max}$ (fm)	$N_{D^\pm}$ selected
0-3	980
3-6	2080
6-9	1750
9-12	730
12-18	115

7.1.2 $D^\pm$ elliptic flow at the LHC

The results of the $D^\pm$ elliptic flow as a function of centrality are reported in Fig. 7.8.

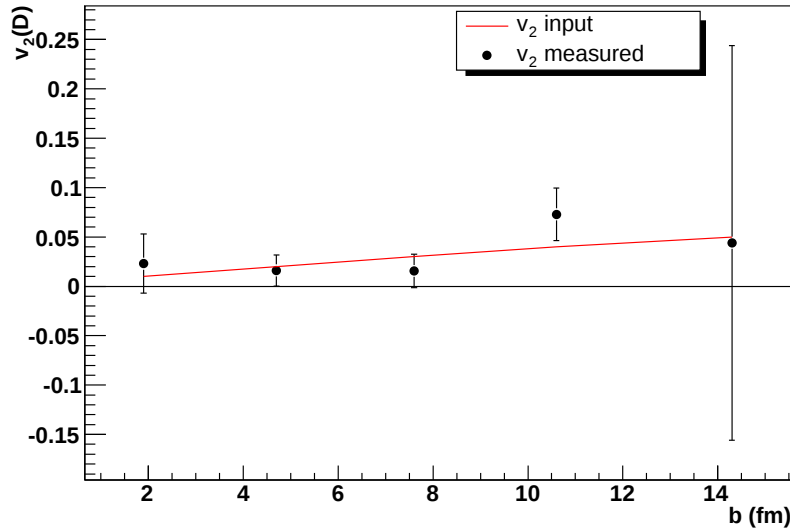


Figure 7.8: $D^\pm$ elliptic flow as a function of centrality. The points represent the measured v_2 with its error, the line indicates the $D^\pm$ v_2 used as input to the simulation taken from Table 7.4.

The number of events normalized to 2×10^7 minimum bias events is reported in Table 7.5 for the different centrality classes. As a remark, the number of events corresponds to the number of $D^\pm$ mesons expected to be selected through their three body decay $K\pi\pi$ in ALICE in 2×10^7 minimum bias Pb-Pb events.

It is clear from Fig. 7.8 that the error bars are quite large. Therefore, with

the statistics available in one year of data taking, the error bars may prevent significant conclusions in case of small anisotropy of D mesons.

Of course, the number of events reported in Table 7.5 could be enhanced by summing the $D^\pm$ -meson statistics collected in several years of data taking. It can be also possible to add the number of D^0 mesons selected through the channel $D^0 \rightarrow K^- \pi^+$, because they are made of one charm quark and one light quark as well as the $D^\pm$ mesons. As was discussed in Section 2.3.1, $N_{D^0} \sim 3N_{D^\pm}$; in addition, $BR_{D^0 \rightarrow K^- \pi^+} \sim 0.4 \times BR_{D^\pm \rightarrow K^- \pi^+ \pi^+}$. Therefore, assuming the same selection efficiency, we would roughly expect a similar number of selected D^0 and $D^\pm$, hence a gain of a factor ~ 2 in the D meson statistics which would reduce the error bars by $\sim \sqrt{2}$. According to this very naïve estimate, putting D^0 and $D^\pm$ together would be enough for the study of v_2 as a function of centrality, with the possible exclusion of the most peripheral case.

It is also possible to evaluate the performance of the measurement of v_2 of $D^\pm$ mesons as a function of p_T in a given centrality class. The semi-peripheral bin $6 < b < 9$ fm has been considered for this purpose.

We used as input the $v_2^D(p_T)$ values plotted in Fig. 7.5 considering the case $v_{2,c} = v_{2,q}$. The results are reported in Fig. 7.9 for two choices of the parton cross section in the transport model, $\sigma_p = 3$ mb (left panel) and $\sigma_p = 10$ mb (right panel). The lines represent the predictions for $D^\pm$ meson $v_2^D(p_T)$ in the case of charm flow and without charm flow.

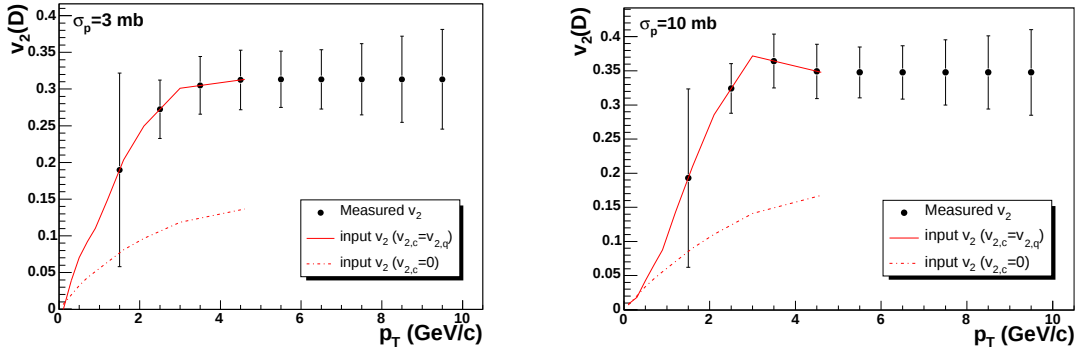


Figure 7.9: $D^\pm$ meson v_2^D as a function of p_T in the centrality class $6 < b < 9$ fm for two choices of the transport model parameter σ_p , $\sigma_p = 3$ mb (left panel) and $\sigma_p = 10$ mb (right panel). The number of $D^\pm$ mesons is normalized to 2×10^7 minimum bias events. The predictions from [109] are also shown in the case of charm flow (solid line) and without charm flow (dashed dotted line).

The statistical errors on v_2^D of $D^+ \rightarrow K^- \pi^+ \pi^+$ in 2×10^7 minimum bias events

are pretty large. As mentioned above, a possible way to increase the statistics would be to put D^0 and $D^\pm$ together. Unfortunately, a factor $\sim 1/\sqrt{2}$ in the error bars of Fig. 7.9 may be not enough to distinguish between the two scenarios ($v_{2,c} = 0$ and $v_{2,c} = v_{2,q}$) in the low p_T region.

Hence, the use of a semi-peripheral trigger would be appropriate to increase considerably the statistics. Collecting 2×10^7 semi-peripheral events with $6 < b < 9$ fm in one year of data taking², the results of $D^\pm$ meson v_2 as a function of p_T would significantly improve down to $p_T \sim 1$ GeV/c, as apparent from the plots shown in Fig. 7.10.

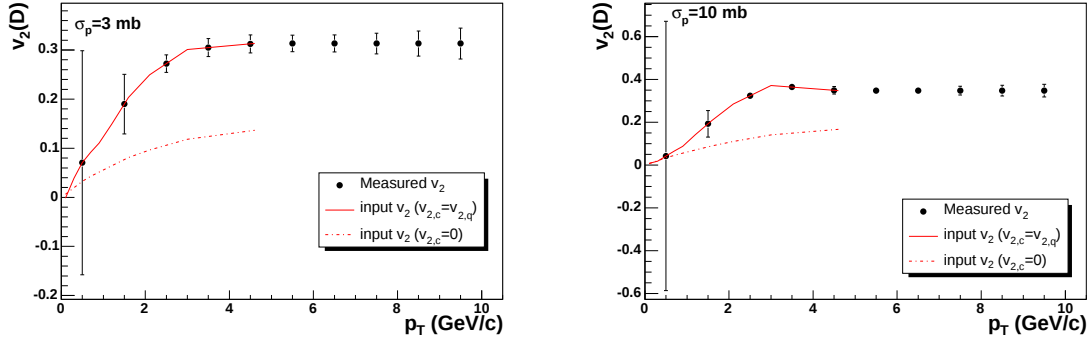


Figure 7.10: $D^\pm$ meson v_2^D as a function of p_T in the centrality class $6 < b < 9$ fm for two choices of the transport model parameter σ_p , $\sigma_p = 3$ mb (left panel) and $\sigma_p = 10$ mb (right panel). The number of $D^\pm$ mesons is normalized to 10^8 minimum bias events. The predictions from [109] are also shown in the case of charm flow (solid line) and without charm flow (dashed dotted line).

The results presented above are obtained calculating the $D^\pm$ meson v_2 through the formula $v_2 = \langle \cos(2(\varphi - \Psi_{RP})) \rangle$. This method could be somehow biased from the background triplets (or pairs in case of D^0) which are selected as $D^\pm$ or D^0 candidates, which in principle do not show the same azimuthal anisotropy as the true D mesons. Hence a background subtraction procedure will be necessary. A possible method for the background subtraction is to perform the analysis in bins $\Delta\phi^{EP}$ of the azimuthal angle relative to the calculated event plane: the number of reconstructed D mesons in each bin $\Delta\phi^{EP}$ is then given by a fit to the invariant mass distribution. The v_2 of D mesons can be found by fitting the obtained $\Delta\phi^{EP}$ distribution of D mesons with the usual Fourier parametrization of Eq. 7.1: in this way, the parameter v_2^D of the fit would measure the azimuthal anisotropy of

²From Table 7.1, we derive that 2×10^7 semi-peripheral events with $6 < b < 9$ fm ($\sim 20\%$ of the total Pb-Pb cross section) correspond to $2 \times 10^7 / 20\% \simeq 10^8$ minimum bias Pb-Pb events.

D mesons.

Other methods for the background subtraction could be based on the determination of the $\langle \cos(2(\varphi - \Psi_{RP})) \rangle$ distribution of the combinatorial $K\pi\pi$ triplets which are not under the peak of the $D^\pm$ meson in the invariant mass spectrum, but rather in the side bands. Alternatively, also the study of the $\langle \cos(2(\varphi - \Psi_{RP})) \rangle$ distribution of the combinatorial $K\pi\pi$ triplets with like sign, i.e. $K^+\pi^+\pi^+$ and $K^-\pi^-\pi^-$, could be useful.

Finally, another analysis method for the background subtraction is based on the calculation of v_2 as a function of the invariant mass, as proposed in [170].

7.2 Perspectives for the measurement of $D^\pm$ nuclear modification factor

This analysis is aimed to evaluate the statistical and systematics uncertainties related to the measurement of the nuclear modification factor (R_{AA}) for $D^\pm$ mesons. This factor is defined as follows:

$$R_{AA}(p_T) = \frac{dN_{AA}^{D^\pm}/dp_T}{\langle N_{coll} \rangle \times dN_{NN}^{D^\pm}/dp_T} \quad (7.6)$$

The evaluation of both statistical and systematic errors and the results are presented in the following subsections.

7.2.1 Statistical and systematic errors on R_{AA}

The statistical error is obtained in each p_T bin by adding in quadrature the relative errors σ_S/S on the selected $D^\pm$ estimated for 10^7 central Pb-Pb and 10^9 pp collisions. The relative statistical error affects the $D^\pm$ production cross section as well as the R_{AA} .

Not all the systematic errors entering the $D^\pm$ production cross section affect also the ratio R_{AA} . Indeed, many of the uncertainties listed in Section 6.5 are common to Pb-Pb and pp collisions and cancel out in the ratio: such errors are for example the error on the nucleon-nucleon inelastic cross section, on the branching ratio, on the correction for beauty feed-down and on the detector acceptance.

Some of the systematic errors, such as the error on the centrality selection and on the Woods-Saxon parameters, do not affect the shape of the p_T distribution and thus the shape of the nuclear modification factor.

The systematic uncertainties contributing to the R_{AA} are summarized below:

1. Monte Carlo corrections: they amount to $\sim 15\%$ by adding in quadrature the relative errors of Pb-Pb and pp, assumed to be both equal to $\sim 10\%$. This is an overestimate.

2. Extrapolation of the pp results from 14 TeV to 5.5 TeV, $\sim 12\%$.
3. Error on centrality selection and on the Woods-Saxon parameters: it amounts to $7\% \oplus 5\% = 8.6\%$. This kind of systematic error does not affect the p_T dependence of the R_{AA} .

7.2.2 $D^\pm$ nuclear modification factor at the LHC

The results are obtained using a reference theoretical curve based on the BDMPS model [96] with transport coefficient $\hat{q} = 25 \text{ GeV}^2/\text{fm}$ and dead cone effect taken into account. The R_{AA} calculated as a function of p_T in the case of no particle identification for both Pb-Pb and pp collisions is shown in Fig. 7.11.

Since the relative error on centrality selection and on the Woods-Saxon parameters is independent of p_T and does not affect the shape of the R_{AA} , its corresponding absolute error has been presented for convenience as centered on the line $R_{AA} = 1$. The R_{AA} with its errors is compared to two theoretical scenarios: without quenching of $D^\pm$, i.e. $\hat{q} = 0 \text{ GeV}^2/\text{fm}$, and with $\hat{q} = 100 \text{ GeV}^2/\text{fm}$ including the dead cone effect.

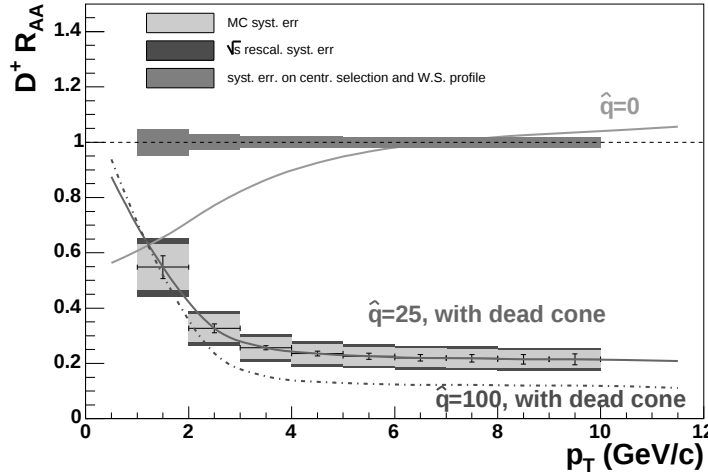


Figure 7.11: R_{AA} of $D^\pm$ mesons as a function of p_T , calculated with energy loss predicted by the BDMPS model [96] with the parameter $\hat{q} = 25 \text{ GeV}^2/\text{fm}$ (dark grey curve). The statistical and systematic errors are described in the legend. The results are compared to the scenario without quenching of $D^\pm$ ($\hat{q} = 0 \text{ GeV}^2/\text{fm}$, light grey curve) and with $\hat{q} = 100 \text{ GeV}^2/\text{fm}$ including the dead cone effect (dashed-dotted light grey line).

As shown in Fig. 7.12, the same R_{AA} with its experimental errors is also compared to a scenario without the dead cone effect, which could reduce the energy loss of heavy quarks with respect to the light quarks.

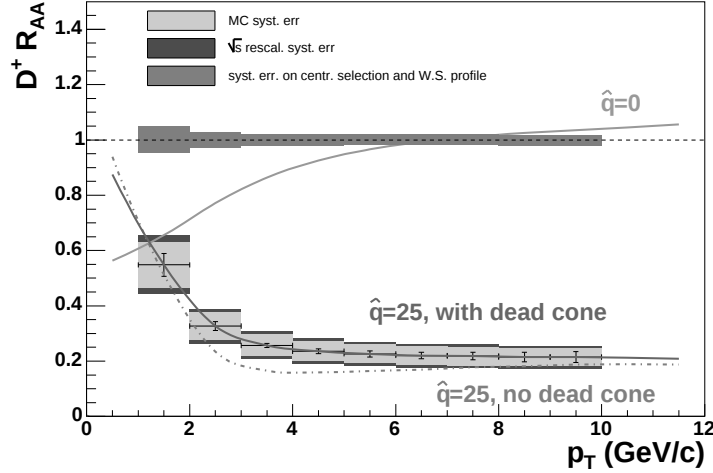


Figure 7.12: The R_{AA} of $D^\pm$ mesons as a function of p_T , calculated with energy loss predicted by the BDMPS model [96] with the parameter $\hat{q} = 25 \text{ GeV}^2/\text{fm}$ (dark grey curve). The statistical and systematic errors are described in the legend. The results are compared to the scenario without quenching of $D^\pm$ (light grey curve) and without the dead cone effect (dashed-dotted light grey line).

As can be observed from the figures, the measurement of the nuclear modification factor of $D^\pm$ mesons appears to be feasible in one year of data taking because the statistical error bars are well less than the systematic errors up to $\sim 10 \text{ GeV}/c$. On the other hand, a better control on the systematic errors is required to be sensitive to the different theoretical scenarios. This should be possible because, as already mentioned, some of the considered systematic uncertainties, like the Monte Carlo corrections, have been estimated with a large safety margin.

Appendix A

Algorithms for secondary vertices of open charmed mesons

This section is devoted to explain the different algorithms developed for the reconstruction of 3-prong secondary vertices. A comparison of the performance of the different vertexers is also shown, in order to motivate the choice of the algorithm described in Section 4.5.3.

The first method (I) is based on the algorithm previously used for the primary vertex reconstruction in pp collisions starting from the reconstructed tracks. According to this, the tracks are propagated in the vicinity of the primary vertex and then approximated as straight lines. For each pair of tracks, t_i and t_j , the segment of closest approach is found, with $P_i=(x_i, y_i, z_i)$ and $P_j=(x_j, y_j, z_j)$ which are the extreme points of the segment. Therefore, P_i belongs to t_i and P_j belongs to t_j .

The crossing point $C(i, j)$ is determined taking into account the errors on the track parameters. In this way, $C(i, j)$ is not in the centre of the segment of closest approach, but it is closer to the track which is better reconstructed. The coordinates of the crossing point $C(i, j)$ are determined as follows:

$$x_{ij} = \frac{\sigma_{xi}^{-2} x_i + \sigma_{xj}^{-2} x_j}{\sigma_{xi}^{-2} + \sigma_{xj}^{-2}} \quad , \quad y_{ij} = \frac{\sigma_{yi}^{-2} y_i + \sigma_{yj}^{-2} y_j}{\sigma_{yi}^{-2} + \sigma_{yj}^{-2}} \quad , \quad z_{ij} = \frac{\sigma_{zi}^{-2} z_i + \sigma_{zj}^{-2} z_j}{\sigma_{zi}^{-2} + \sigma_{zj}^{-2}} \quad (\text{A.1})$$

where σ_{xi} , σ_{yi} and σ_{zi} are the errors on the track parameters of the track t_i . The same applies for the track j .

The coordinates of the secondary vertex are then:

$$x_v = \frac{1}{N_{pairs}} \sum_{i,j} x_{ij} \quad , \quad y_v = \frac{1}{N_{pairs}} \sum_{i,j} y_{ij} \quad , \quad z_v = \frac{1}{N_{pairs}} \sum_{i,j} z_{ij} \quad (\text{A.2})$$

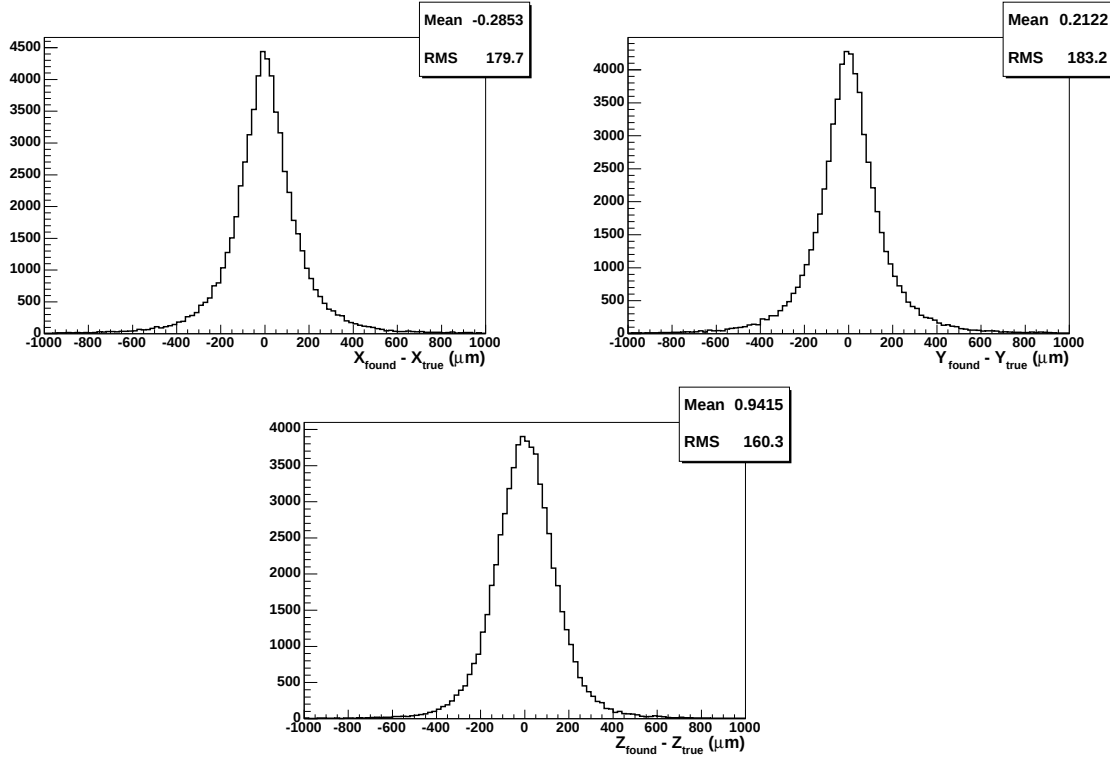


Figure A.1: Residual distributions, i.e. difference between the true coordinate of the secondary vertex $D^+ \rightarrow K^- \pi^+ \pi^+$ and the found coordinate, for x, y and z coordinates. The algorithm I is applied.

where N_{pairs} is the number of all the possible track pairs. In case of a 3-prong decay, $N_{pairs} = 3$.

The secondary vertex finder was applied to events containing only $D^+ \rightarrow K^- \pi^+ \pi^+$ decays: the resolutions are shown in Fig. A.1 for the three coordinates x, y and z : the RMS of the histograms is of the order of $\sim 160 - 170 \mu\text{m}$.

The second method (II) which was studied is based on the method I, but the complete parametrization of the track as helix is kept, instead of performing the straight line approximation.

The coordinates of the secondary vertex are calculated with the same formulas as the previous case. The drawback of this algorithm is that the distance of closest approach for each pair of tracks cannot be calculated in an analytic way but a minimization procedure (which does not always converge to a minimum) is required. The results obtained with this second method are shown in Fig. A.2: the RMS of the histograms is of the order of $\sim 150 - 170 \mu\text{m}$. The method II improves by $\sim 10 \mu\text{m}$ the results obtained with the algorithm I. This improvement is not

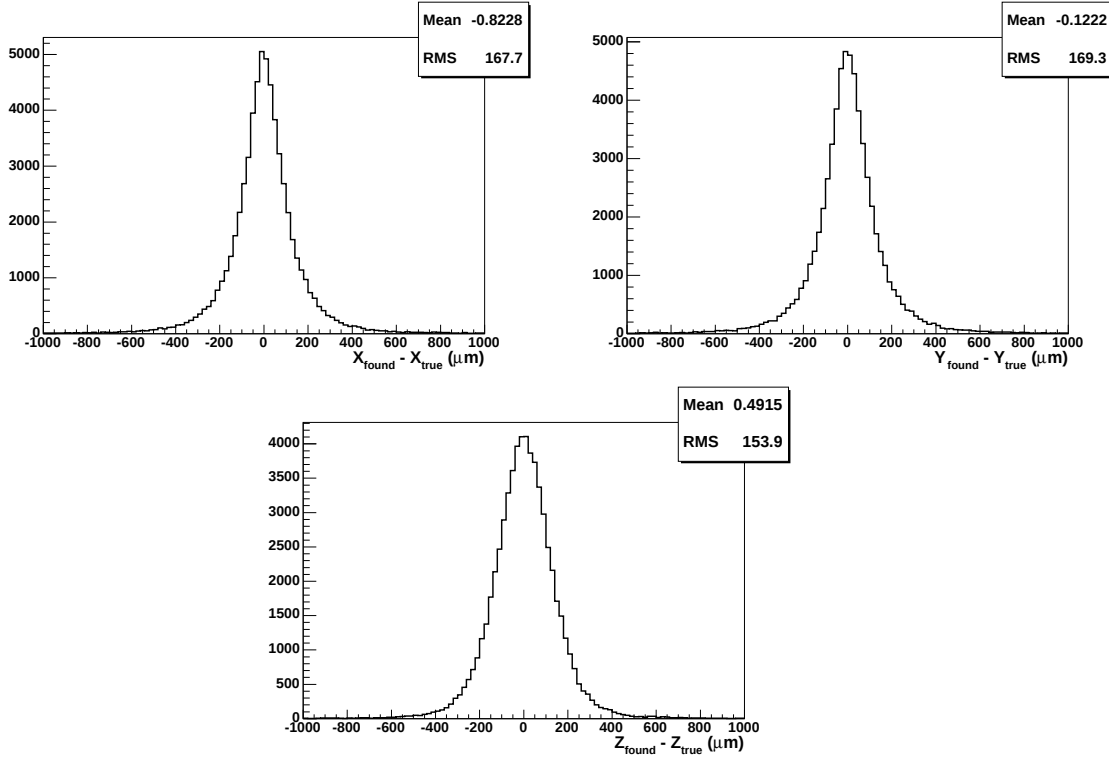


Figure A.2: Residual distributions, i.e. difference between the true coordinate of the secondary vertex $D^+ \rightarrow K^- \pi^+ \pi^+$ and the found coordinate, for x, y and z coordinates. The algorithm II is applied.

due to the use of the helix instead of the straight line (see also Section 4.5.3), but rather to the fact that in the method II the errors on the track parameters, after propagating the tracks to the segment of closest approach, are considered in the minimization.

We now compare the performance of the methods I and II described above with the third method (III) which was used for the analyses presented in this thesis work and described in Section 4.5.3.

The RMS of the residual distributions are plotted in Fig. A.3 as a function of the p_T of the D^+ for the three coordinates x, y and z .

It is clear from Fig. A.3 that the best algorithm for the secondary vertex finding is the one (III) based on the minimization of the distance of the three tracks from the secondary vertices.

The algorithm (III) was also tested on another 3-prong decay, namely the $D_s^+ \rightarrow K^- K^+ \pi^+$. The obtained RMS of the residual distributions are reported in Fig. A.4. The secondary vertex resolution for the $D^\pm$ and $D_s^\pm$ mesons are similar;

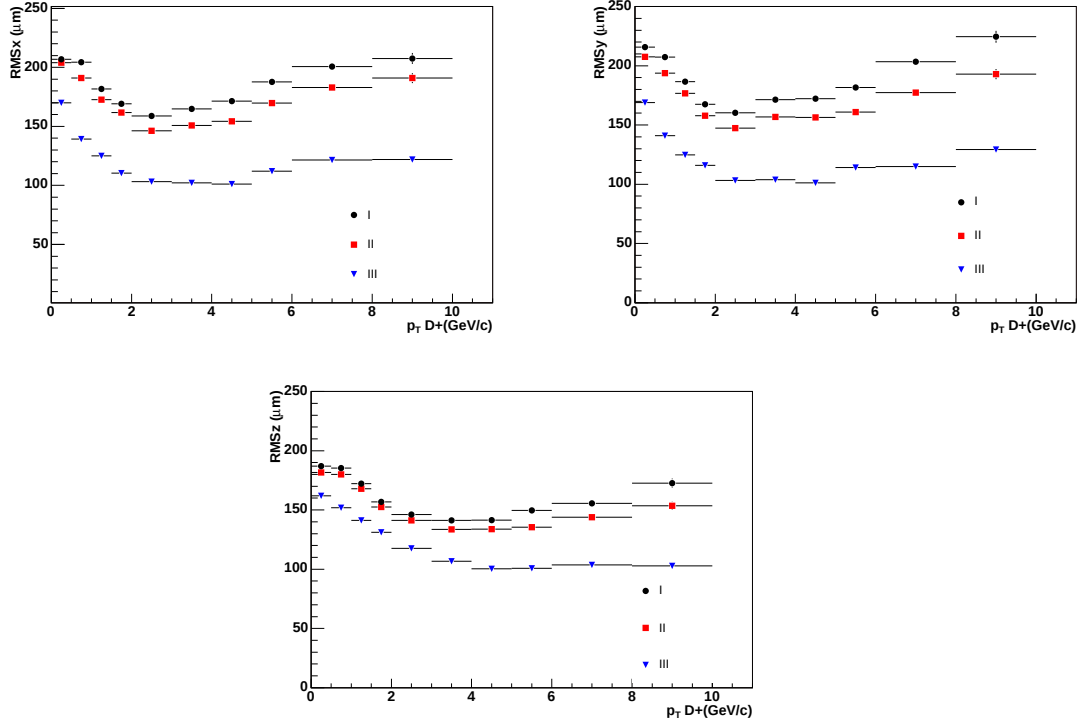


Figure A.3: RMS of the residual distributions for x (upper left), y (upper right) and z (bottom) coordinates. The results from the three algorithms I, II and III described in the text are shown.

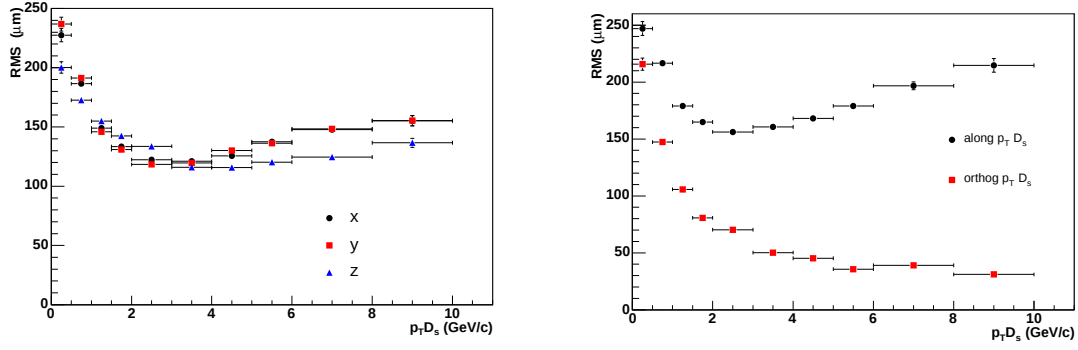


Figure A.4: Left panel: RMS of the residual distributions for x , y and z coordinates obtained with the algorithm III applied to the 3-body channel $D_s^+ \rightarrow K^- K^+ \pi^+$. Right panel: RMS of the residual distribution in coordinates along and orthogonal to the D_s transverse momentum (in the rotated bending plane, see Section 4.5.3).

the slight difference can be due to the fact that the decay products of $D_s^\pm$ mesons are softer than those of $D^\pm$ mesons.

This algorithm (III) is implemented in the software of the ALICE experiment and can be used for n -prong vertices, where $n \geq 2$, both for Pb-Pb and pp collisions.

Conclusions

Heavy quarks are an interesting tool to investigate the Quark Gluon Plasma formed in high energy nucleus-nucleus collisions. Thus, the reconstruction of charmed mesons and baryons is one of the challenges of heavy-ion experiments.

Recent results from the experiments running at RHIC show that D mesons provide information on the nuclear medium and on its effects on the produced particles.

In a near future Pb-Pb data at the LHC energies will allow to investigate a nuclear matter bigger and longer-lived than the one formed at RHIC. ALICE is the dedicated heavy-ion experiment at the LHC which will be able to analyze such data. Its unique design will allow the reconstruction of short-lived particles such as hyperons, D and B mesons in a high multiplicity environment.

The main goal of this thesis was the detection of $D^\pm$ mesons through their three-body decay channel $D^+ \rightarrow K^- \pi^+ \pi^+$ both in pp and in Pb-Pb collisions.

The secondary vertex reconstruction algorithm for the 3-prong decay of $D^\pm$ mesons in the ALICE barrel was studied and the algorithm is now implemented in the software of the ALICE experiment.

A dedicated trigger for $D^+ \rightarrow K^- \pi^+ \pi^+$ seems difficult in Pb-Pb because the decay products of the D^+ have momenta comparable with the ones of kaons and pions copiously produced in a central collision. The strategy is to perform different selection steps. A multi-dimensional optimization procedure of the selection variables was developed in order to maximize the significance in one year of data taking.

The results presented in this thesis show that the reconstruction of the channel $D^+ \rightarrow K^- \pi^+ \pi^+$ seems to be feasible with a good significance both in Pb-Pb and in pp collisions. In case of a lower multiplicity scenario in Pb-Pb the significance improves, allowing the reconstruction of $D^\pm$ mesons down to $p_T \sim 1$ GeV/c.

The analysis on the nuclear modification factor is feasible in one year of data taking, but a better control on the systematics is mandatory. The D meson elliptic flow has large error bars using the statistics collected in one year of data taking. The presented results prevent to draw conclusions in case of small elliptic flow of charm quarks. As shown, the error bars can be reduced by increasing the D meson statistics with semi-peripheral trigger.

Bibliography

- [1] E.V. Shuryak, Phys. Rep. 61 (1980) 71.
- [2] A. Pich, [arXiv:hep-ph/0001118].
- [3] F. Karsch, Nucl. Phys. A783 (2007) 13, [arXiv:hep-ph/0610024].
- [4] A. Chodos, R.L. Jaffe, K. Johnson, C.B. Thorn and V.F. Weisskopf, Phys. Rev. D9 (1974) 3471.
- [5] T. Hatsuda and T. Kunihiro, Phys. Rep. 247 (1994) 221.
- [6] Z. Fodorn, S.D. Katz, JHEP 0404 (2004) 050.
- [7] S. Ejiri et al., Prog. Theor. Phys. Suppl. 153 (2004) 118.
- [8] D. Bailin and A. Love, Phys. Rep. 107 (1984) 325.
- [9] M. Alford, K. Rajagopal and F. Wilczek, Phys. Lett. B422 (1998) 247.
- [10] R. Rapp, T. Schäfer, E.V. Shuryak and M. Velkovsky, Phys. Rev. Lett. 81 (1998) 53.
- [11] K.G. Wilson, Phys. Rev. D10 (1974) 2445.
- [12] W. Weise, [arXiv:nucl-th/0306036].
- [13] F. Karsch, E. Laermann, A. Peikert, B. Sturm, Nucl. Phys. Proc. Suppl. 73 (1999) 468, [arXiv:hep-lat/9901002].
- [14] F. Karsch, Nucl.Phys. A698 (2002) 199, [arXiv:hep-ph/0103314].
- [15] K.J. Eskola, K. Kajantie, P.V. Ruuskanen and K. Tuominen, Nucl. Phys. B570 (2000) 379.
- [16] J. Cleymans and K. Redlich, Phys. Rev. Lett. 81 (1998) 5284.
- [17] K.S. Lee, U. Heinz, E. Schnedermann, Z. Phys. C48 (1990) 525.

- [18] U. Heinz, [arXiv:hep-ph/0407360].
- [19] R. Hagedorn, Riv. Nuovo Cimento 6 (1983) 1.
- [20] P. Huovinen, [arXiv:nucl-th/0305064].
- [21] P. Kolb and U. Heinz, [arXiv:nucl-th/0305084].
- [22] S. Voloshin and Y. Zhang, Z. Phys. C70 (1996) 665.
- [23] N. Borghini, J.Y. Ollitrault, Phys. Lett. B642 (2006) 227, [arXiv:nucl-th/0506045].
- [24] J. Adams et al., STAR Collaboration, Phys. Rev. Lett. 92 (2004) 062301.
- [25] R. S. Bhalerao et al., Phys. Rev. Lett. B627 (2005) 49.
- [26] J.Y. Ollitrault, arXiv:nucl-ex/9711003.
- [27] S. Wang et al., Phys. Rev. C 44 (1991) 1091.
- [28] N. Borghini, P.M. Dinh and J.Y. Ollitrault, Phys. Rev. C 63(2001) 054906.
- [29] T. Hirano, U.W. Heinz, D. Kharzeev, R. Lacey and Y. Nara, arXiv:nucl-th/0511046.
- [30] P.F. Kolb, J. Sollfrank and U.W. Heinz, Phys. Rev. C 62 (2000) 054909.
- [31] D.H. Rischke and M. Gyulassy, Nucl. Phys. A608 (1996) 479.
- [32] COBE Collaboration, http://space.gsfc.nasa.gov/astro/cobe/cobe_home.html
- [33] L. Stodolsky, Phys. Rev. Lett. 75 (1995) 1044;
S. Mrówczyński, Phys. Lett. B430 (1998) 9;
E.V.Shuryak, Phys. Lett. B423 (1998) 9.
- [34] M. Asakawa, U. Heinz and B. Müller, Phys. Rev. Lett. 85 (2000) 2072.
- [35] J.D. Bjorken, preprint FERMILAB-PUB-82-59-THY.
- [36] X.-N. Wang, M. Gyulassy and M. Plümer, Phys. Rev. D51 (1995) 3436.
- [37] R. Baier, Y.L. Dokshitzer, S. Peigne and D. Schiff, Phys. Lett. B345 (1995) 277.
- [38] G.E. Brown and M. Rho, Phys. Rev. Lett. 66 (1991) 2720.
- [39] R. Rapp and J. Wambach, Adv. Nucl. Phys. 25 (2000) 1.

- [40] V. Barger, W.Y. Keung and R.N. Phillips, Z. Phys. C6 (1980) 169; Phys. Lett. B91 (1980) 253.
- [41] G.T. Bodwin, E. Braaten and G.P. Lepage, Phys. Rev. D51 (1995) 1125.
- [42] B. Alessandro et al., NA50 Collaboration, Eur. Phys. J C 39 (2005) 335.
- [43] R. Arnaldi for the NA60 Collaboration, to appear in the Proceedings of the “Hard Probes 2006” conference.
- [44] A. Förster for the NA60 Collaboration, Proceedings of the “Strangeness in Quark Matter 2006 (SQM2006)” conference, arXiv:nucl-ex/060939.
- [45] T. Matsui and H. Satz, Phys. Lett. B178 (1986) 416.
- [46] R.J. Glauber and G. Matthiae, Nucl. Phys. B21 (1970) 135.
- [47] G. Agakichiev et al., CERES Collaboration, Eur. Phys. J C 41 (2005) 475.
- [48] S. Damjanovic for the NA60 Collaboration, to appear in the Proceedings of the “Hot Quarks 2006” conference, arXiv:nucl-ex/060926.
- [49] H. van Hees and R. Rapp, Phys. Rev. Lett. 97 (2006) 102301.
- [50] G.Q. Li, C.M. Ko and G.E. Brown, Phys. Rev. Lett. 75 (1995) 4007.
- [51] M. van Leeuwen, for the NA49 collaboration, Nucl.Phys. A715 (2003) 161, [arXiv:nucl-ex/0208014].
- [52] K. Adcox et al., PHENIX Collaboration, Nucl. Phys. A757 (2005) 184, [arXiv:nucl-ex/0410003].
- [53] L. McLerran, arXiv:hep-ph/0311028. M. Gyulassy and L. McLerran, Nucl. Phys. A 750 (2005) 30.
- [54] S.Y. Li and X.N. Wang, Phys. Lett. B 527 (2002) 85.
- [55] B.B. Bach et al., PHOBOS Collaboration, Nucl. Phys. A757 (2005) 28-101.
- [56] J. Adams, et al., STAR Collaboration, Phys.Rev.Lett. 92 (2004) 112301, [arXiv:nucl-ex/0310004].
- [57] D. Antreasyan et al., Phys. Rev. D 19 (1979) 764.
- [58] J. Adams et al., STAR Collaboration, Nucl. Phys. A757 (2005) 102-183, [arXiv:nucl-ex/0501009].

- [59] I. Arsene et al., BRAHMS Collaboration, Phys. Rev. Lett. 93 (2004) 242303.
- [60] X.N. Wang, Phys. Lett. B 595 (2004) 165.
- [61] R.J. Fries, B. Muller, C. Nonata and S.A. Bass, Phys. Rev. Lett. 90 (2003) 202303.
- [62] R.C. Hwa, C.B. Yang, Phys. Rev. C 70 (2004) 024905.
- [63] V. Greco, C.M. Ko, P. Levai, Phys. Rev. Lett. 90 (2003) 202302.
- [64] Y.G. Ma, arXiv:nucl-ex/0609020.
- [65] N. Armesto, M. Cacciari, A. Dainese, C.A. Salgado, U.A. Wiedemann, Phys. Lett. B637 (2006) 362, [arXiv:hep-ph/0511257].
- [66] Physics Performance Report Vol II, Alice Collaboration, Chap. 6.7, J. Phys. G 32 (2006) 1295-2040.
- [67] J.C. Collins, D.E. Soper, G. Sterman, Nucl. Phys. B263 (1986) 37.
- [68] V.N. Gribov, L.N. Lipatov, Sov. J. Nucl. Phys. 15 (1972) 438.
- [69] G. Altarelli and G. Parisi, Nucl. Phys. B126 (1977) 298.
- [70] Yu.L. Dokshitzer, Sov. Phys. JETPS 46 (1977) 641.
- [71] M.E. Peskin and D.V. Schroeder, An Introduction to Quantum Field Theory, ABP.
- [72] T. Sjöstrand, L. Lonnblad, S. Mrenna and P. Skands, PYTHIA 6.301 manual, LU TP 03-38 [arXiv:hep-ph/0308153].
- [73] H.L. Lai, J. Huston, S. Kuhlmann, F. Olness, J. Owens, D.E. Soper, W.K. Tung, H. Weerts, Phys. Rev. D55 (1997) 1280.
- [74] H.L. Lai, J. Huston, S. Kuhlmann, J. Morfin, F. Olness, J.F. Owens, J. Pumplin, W.K. Tung, Eur. Phys. J. C12 (2000) 375, arXiv:hep-ph/9903282.
- [75] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P. Nadolsky, W.K. Tung [arXiv:hep-ph/0201195].
- [76] P. Nason, S. Dawson, R.K. Ellis, Nucl. Phys. B327 (1988) 697.
- [77] B. Mele, P. Nason, Nucl. Phys. B361 (1991) 626.

- [78] B. Mele, P. Nason, Phys. Lett. B245 (1990) 635.
- [79] M. Cacciari, M. Greco, Nucl. Phys. B421 (1994) 530 [arXiv:hep-ph/9311260].
- [80] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007 [arXiv:hep-ph/9803400].
- [81] B. Andersson, G. Gustafson, G. Ingelman, T. Sjostrand, Phys. Rep. 97 (1983) 31.
- [82] A. Kupco [arXiv:hep-ph/9906412].
- [83] G. Marchesini et al., Comput. Phys. Commun. 67 (1992) 465.
- [84] W.M. Yao et al., J. Phys. G 33, (2006) 1.
- [85] M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B373 (1992) 295.
- [86] M. Arneodo, Phys. Rep. 240 (1994) 301.
- [87] A. Accardi et al., HIP-2003-40/TH, [arXiv:hep-ph/0308248].
- [88] V. Emel'yanov, A. Khodinov, S.R. Klein and R. Vogt, Phys. Rev. C61 (2000) 044904.
- [89] K.J. Eskola, V.J. Kolhinen, C.A. Salgado, Eur. Phys. J. C9 (1999) 61 [arXiv:hep-ph/9807297].
- [90] K.J. Eskola, H. Honkanen, V.J. Kolhinen, J.w. Qiu and C.A. Salgado, Nucl. Phys. B660 (2003) 211 [arXiv:hep-ph/0211239].
- [91] K.J. Eskola, V.J. Kolhinen and R. Vogt, Phys. Lett. B582 (2004) 157 [arXiv:hep-ph/0310111].
- [92] Physics Performance Report Vol II, Alice Collaboration, Chap. 6.6, J. Phys. G 32 (2006) 1295-2040.
- [93] D. Kharzeev and K. Tuchin, Nucl. Phys. A735 (2004) 248 [arXiv:hep-ph/0310358].
- [94] N. Paver and D. Treleani, Nuovo Cim. A70 (1982) 215.
- [95] M. Strickman and D. Treleani, Phys. Rev. Lett. 88 (2002) 031801 [arXiv:hep-ph/0111468].
- [96] R. Baier, Yu.L. Dokshitzer, A.H. Mueller, S. Peigné and D. Schiff, Nucl. Phys. B483 (1997) 291, [arXiv:hep-ph/9607355].

- [97] Yu.L. Dokshitzer and D.E. Kharzeev, Phys. Lett. B519 (2001) 199, [arXiv:hep-ph/0106202].
- [98] N. Armesto, A. Dainese, C.A. Salgado and U.A. Wiedemann, Phys. Rev. D71 (2005) 054027, [arXiv:hep-ph/0501225].
- [99] M. Djordjevic, M. Gyulassy, R. Vogt, S. Wicks, Phys. Lett. B632 (2006) 81, [arXiv:nucl-th/0507019].
- [100] M.G. Mustafa, Phys. Rev. C72 (2005) 014905; M.G. Mustafa and M.H. Thoma, Acta Phys. Hung. A 22 (2005) 93.
- [101] S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, [arXiv:nucl-th/0512076].
- [102] S. Peigne, P.B. Gossiaux, T. Gousset, [arXiv:hep-ph/0509185].
- [103] A. Adil, M. Gyulassy, W. Horowitz, S. Wicks, [arXiv:nucl-th/0606010].
- [104] M. Djordjevic, Phys. Rev. C74 (2006) 064907, [arXiv:nucl-th/0603066].
- [105] G.D. Moore and D. Teaney, Phys. Rev. C71 (2005) 064904, [arXiv:hep-ph/0412346].
- [106] D. Molnar, J.Phys. G31 (2005) S421, [arXiv:nucl-th/0410041].
- [107] H.v. Hees and R. Rapp, Phys. Rev. C71 (2005) 034907, [arXiv:nucl-th/0412015].
- [108] Z.W. Lin, C.M. Ko, B.A. Li, B. Zhang, and S. Pal, Phys. Rev. C 72, (2005) 064901.
- [109] C.M. Ko, L.W. Chen, and B.W. Zhang, Braz. J. Phys., to be published.
- [110] H.v. Hees, V. Greco and R. Rapp, Phys. Rev. C73 (2006) 034913, [arXiv:nucl-th/0508055].
- [111] A. Adil, I. Vitev, [arXiv:hep-ph/0611109].
- [112] S. Batsouli, S. Kelly, M. Gyulassy, J.L. Nagle, Phys. Lett. B557 (2003) 26, [arXiv:nucl-th/0212068].
- [113] Physics Performance Report Vol II, Alice Collaboration, Chap. 6.4, J. Phys. G 32 (2006) 1295-2040.
- [114] B. Zhang, M. Gyulassy, C.M. Ko, Phys. Lett. B455 (1999) 45.

- [115] D. Molnar, M. Gyulassy, Phys. Rev. C62 (2000) 054907.
- [116] C. Peterson et al., Phys. Rev. D27 (1983) 105.
- [117] D. Molnar, S. Voloshin, [arXiv:nucl-th/0302014].
- [118] Z.W. Lin, D. Molnar, Phys. Rev. C68 (2003) 044901, [arXiv:nucl-th/0302045].
- [119] V. Greco, C.M. Ko, R. Rapp, Phys. Lett. B595 (2004) 202, [arXiv:nucl-th/0312100].
- [120] ZEUS Collaboration, Eur. Phys. J. C44 (2005) 351, [arXiv:hep-ex/0508019].
- [121] L. Gladlin, [arXiv:hep-ex/9912064].
- [122] D. Acosta et al., CDF Collaboration, Phys. Rev. Lett. 91 (2003) 241804, [arXiv:hep-ex/0307080].
- [123] A. Adare et al., PHENIX Collaboration, [arXiv:hep-ex/0609010].
- [124] B.I. Abelev et al., STAR Collaboration, [arXiv:hep-ex/0607012].
- [125] M. Calderon de la Barca Sanchez for the STAR Collaboration, [arXiv:nucl-ex/0608028].
- [126] C. Zhong, for the STAR Collaboration, [arXiv:nucl-ex/0702014].
- [127] A. Suaide, Proceeding for the Quark Matter 2006 Conference, to be published.
- [128] A. Adare et al., PHENIX Collaboration, [arXiv:nucl-ex/0611018].
- [129] A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, Eur. Phys. J. C4 (1998) 463.
- [130] Physics Performance Report Vol I, Alice Collaboration, Chap. 1, J. Phys. G30 (2004) 1517.
- [131] M. Mangano, G. Altarelli et al., 1999 CERN Workshop on Standard Model Physics at the LHC, CERN-2000-004.
- [132] Physics Performance Report Vol I, Alice Collaboration, Chap. 3, J. Phys. G30 (2004) 1517.
- [133] Technical Design Report of the Inner Tracking System, ALICE Collaboration, CERN/LHCC/1999-12.

- [134] Technical Design Report of the Time Projection Chamber, ALICE Collaboration, CERN/LHCC/2000-01.
- [135] ALICE Collaboration, Technical Design Report of the Transition-Radiation Detector, CERN/LHCC/2001-21.
- [136] ALICE Collaboration, Technical Design Report of the Time-Of-Flight Detector, CERN/LHCC/2000-12; Addendum CERN/LHCC/2002-16.
- [137] ALICE Collaboration, Technical Design Report of the High-Momentum Particle Identification Detector, CERN/LHCC/1998-19.
- [138] ALICE Collaboration, Technical Design Report of the Photon Spectrometer, CERN/LHCC/1999-04.
- [139] ALICE Collaboration, Technical Design Report of the Electromagnetic Calorimeter, CERN/LHCC/2006-14.
- [140] ALICE Collaboration, Technical Design Report of the Forward Muon Spectrometer, CERN/LHCC/1999-22; Addendum CERN/LHCC/2000-46.
- [141] ALICE Collaboration, Technical Design Report of the Zero-Degree Calorimeter, CERN/LHCC/1999-05.
- [142] ALICE Collaboration, Technical Design Report of the Photon Multiplicity Detector, CERN/LHCC/1999-32; Addendum CERN/LHCC 2003-038.
- [143] ALICE Collaboration, Technical Design Report of the Forward Detectors, in preparation.
- [144] ALICE Collaboration, Technical Design Report of the Trigger, Data Acquisition, High Level Trigger and Control System, CERN/LHCC/2003-062.
- [145] W. Kienzle et al., TOTEM Collaboration, TOTEM, Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC, Technical Proposal, CERN-LHCC-99-007, LHCC-P-5 (1999).
- [146] <http://www.root.cern.ch>
- [147] Physics Performance Report Vol I, Alice Collaboration, Chap. 4, J. Phys. G 30 (2004) 1517-1763.
- [148] Technical Design Report of the Computing, ALICE Collaboration, CERN-LHCC-2005-018.

- [149] GEANT, Detector Description and Simulation Tool, CERN Program Library Long Writeup W5013.
- [150] J. Allison et al., IEEE Transactions on Nuclear Science 53 No. 1 (2006) 270-278.
- [151] A. Fassò, A. Ferrari, J. Ranft, and P.R. Sala, CERN-2005-10 (2005).
- [152] X.N. Wang and M. Gyulassy, Phys. Rev. D44 (1991) 3501; <http://www-nsdth.lbl.gov/~xnwang/hijing/>
- [153] J. Ranft, Phys. Rev. D 51 (1995) 64.
- [154] N. S. Amelin, M. A. Braun and C. Pajares, Phys. Lett. B306 (1993) 312.
N. S. Amelin, M. A. Braun and C. Pajares, Z. Phys. C63 (1994) 507.
- [155] E. Norrbin and T. Sjöstrand, Eur. Phys. J. C17 (2000) 137.
- [156] <http://www.cern.ch/MONARC/>
- [157] P. Saiz et al., Nucl. Instrum. Methods A502 (2003) 437-440;
<http://alien.cern.ch/>
- [158] P. Billoir, NIM A225 (1984) 352;
P. Billoir et al., NIM A241 (1984) 115;
R. Fruhwirth, NIM A262 (1987) 444;
P. Billoir, Comput. Phys. Commun. 57 (1989) 390.
- [159] Physics Performance Report Vol II, Alice Collaboration, Chap. 5, J. Phys. G 32 (2006) 1295-2040.
- [160] A. Dainese and M. Masera, ALICE Internal Note 2003-27.
- [161] G. D'Agostini, Bayesian Reasoning in High Energy Physics: Principles and Applications, CERN 99-03.
- [162] E. Bruna, E. Crescio, M. Masera, ALICE Internal Note 2006-004.
- [163] A. Dainese, Ph.D. Thesis, Università degli Studi di Padova (2003) [arXiv:nucl-ex/0311004].
- [164] R. Grosso, Ph.D. Thesis, Università degli Studi di Trieste (2004).
- [165] Physics Performance Report Vol II, Alice Collaboration, Chap. 6.1, J. Phys. G32 (2006) 1295-2040.

- [166] C.W. de Jager, H. de Vries and C. de Vries, At. Data Nucl. Data Tables 14 (1974) 479.
- [167] TOTEM, Total cross section, elastic scattering and diffractive dissociation at the LHC: Technical Proposal, CERN/LHCC 99-007; LHCC-P-5 (1999).
- [168] N. Armesto, C. Salgado, U. Wiedeman, Phys.Rev.Lett. 94 (2005) 22002 [arXiv:hep-ph/0407018].
- [169] courtesy of E. Simili.
- [170] N. Borghini and J.Y. Ollitrault, Phys. Rev. C70 (2004) 064905.

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