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**The ALICE experiment: D^+ -meson production in
heavy-ion collisions and silicon low noise sensors
characterization for the ITS Upgrade**

Cristina Bedda

Relatore:
Michelangelo Agnello

Co-relatore:
Elena Bruna



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Introduction

This thesis collects my work on two aspects of the ALICE experiment at the Large Hadron Collider: the measurement of D^+ -meson production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and the characterization of silicon low noise sensors for the Inner Tracking System Upgrade. I worked within the INFN group of Torino that it is involved in the ALICE experiment both in the physics program related to the study of heavy-flavour production and in the project of the ITS Upgrade.

ALICE is one of the main experiment of the LHC and it is the only one optimized to study ultra-relativistic heavy-ion collisions. The main goal is to study the properties of the Quark Gluon Plasma (QGP), a phase of matter where quarks and gluons are deconfined. Heavy quarks are a powerful tool to study such properties because they can be created only in hard scattering processes at the initial stage of the collision and, subsequently, they interact with the QGP. The measurement of charmed meson production in Pb-Pb collisions allows to assess final state effects due to the formation of the QGP. One of the physical observable studied is the nuclear modification factor (R_{AA}). It quantifies the modification of the D-meson momentum distribution in nucleus-nucleus collisions with respect to the one in proton-proton collisions. The results of the D^+ -meson R_{AA} , obtained with the Pb-Pb data sample collected in 2011 by ALICE, will be presented in this thesis.

However, a more precise measurement, in term of both statistical and systematic uncertainties, would be fundamental for a complete understanding of the properties of the medium and its components.

For this reason, an upgrade of the ALICE apparatus and, in particular of the ITS, is planned to be installed during the second long shutdown of LHC in 2019. The goal is to enhance the ALICE physics capabilities and, especially, the tracking performance for heavy-flavour detection. To overcome the limitations of the present ITS, a different technology has been chosen for the layers of the upgraded detector: Monolithic Active Pixels Sensors. They can offer the granularity and the material budget needed to fulfil the requirements of the new ITS.

Several prototypes have been developed to find the best solution, hence an intensive characterization campaign has taken place. I contributed in the characterization of small-scale prototypes of MIMOSA sensors, developed at IPHC (Strasbourg), and in the characterization of a full-scale prototype of pALPIDE-v2, developed by a collaboration formed by CCNU (China), CERN, INFN (Italy) and Yonsei (South Korea). The first sensors have been characterized in the framework of the development of a testbeam telescope at the LNF (Frascati, Italy).

In the first Chapter of this thesis, an introduction to the physics of heavy-ion collisions will be given. The last section of this chapter will concentrate on the heavy-flavour measurements in high-energy experiments. The second Chapter will be dedicated to the description of the ALICE apparatus, focusing on the sub-systems directly involved in the D^+ -meson analysis. In the third Chapter, first the procedure used to extract the D^+ -meson yield in Pb-Pb collisions will be described and, then, the measurement of the D^+ -meson nuclear modification factor will be presented. The result of the R_{AA} as a function of the D^+ -meson transverse momentum in the most central Pb-Pb collisions are published in [1], while the result as a function of the centrality of the collisions in [2]. The fourth Chapter will be dedicated to the limitations of the current apparatus, the physics motivations for the ITS upgrade and its main specifications. The last section of this chapter will focus on the features of the Monolithic Active Pixels Sensors, that have been chosen as the baseline for the ITS upgrade. In the fifth Chapter the characterization

of small-scale prototypes of MIMOSA sensors at the DAΦNE Beam Test Facility (BTF) will be presented. The sixth Chapter will be dedicated to the characterization of a full-scale prototypes of pALPIDE-v2 in laboratory and at the PS beam test facility at CERN.

Chapter 1

Heavy-ion physics

1.1 Exploring a new state of matter

Heavy-ion collisions are used to obtain a state of matter at extreme conditions of energy density and temperature. Quantum-Chromo-Dynamics (QCD) theory predicts that nuclear matter at those conditions undergoes a phase transition to a state where quarks and gluons are deconfined: the Quark Gluon Plasma (QGP) [3]. The first indications of the QGP existence were found at the Super Proton Synchrotron (SPS) at CERN colliding Pb nuclei at $\sqrt{s_{\text{NN}}} = 17.2$ GeV and then confirmed at the Relativistic Heavy-Ion Collider (RHIC) through gold and copper collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. A further step in the study of the QGP was done with the first lead collisions in 2010 at the Large Hadron Collider (LHC) at the highest center-of-mass energy $\sqrt{s_{\text{NN}}} = 2.76$ TeV. In this chapter, the QCD theory will be briefly presented to introduce the physics motivation behind the ALICE experiment and some of the most relevant heavy-ion collisions measurements will be shown. A section will be dedicated to one of the most powerful tools for the study of the QGP: the open charm physics.

1.1.1 Quantum-Chromo-Dynamics

The Quantum-Chromo-Dynamics is the Gauge field theory that describes the strong interaction between quarks and gluons in the Standard Model [4]. It is described by the QCD Lagrangian of the non abelian $\text{SU}(3)_{\text{colour}}$ gauge symmetry group:

$$L_{\text{QCD}} = -\frac{1}{4}F_{\mu\nu}^{(a)}F_{(a)}^{\mu\nu} + \sum_{flav} i\bar{\psi}\gamma^\mu(\partial_\mu - ig_s\frac{\lambda^{(a)}}{2}A_{(a)}^\mu)\psi - \sum_{flav} m\bar{\psi}\psi \quad (1.1)$$

where $F_{\mu\nu}^{(a)}$ is the non-abelian gluon field strength tensor and has the form

$$F_{\mu\nu}^{(a)} = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f_{abc} A_\mu^b A_\nu^c; \quad (1.2)$$

ψ is the fermionic field, A_ν^a are the eight gluonic fields, λ_a are the eight $\text{SU}(3)$ group generators, f_{abc} are the structure constants and g_s is the gauge coupling constant. The latter is proportional to the coupling constant α_s that decreases with the momentum transferred in the process Q^2 following this formula [5]:

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2N_f)\ln\frac{Q^2}{\lambda_{\text{QCD}}^2}} \quad (1.3)$$

where λ_{QCD} (~ 200 MeV) represents the limit of the perturbative approach. Indeed, when the momentum transfer is equal to λ_{QCD} the coupling constant diverges. The α_s as a function of the energy is shown in the left panel of Figure 1.1. We can divide the energetic range in two parts:

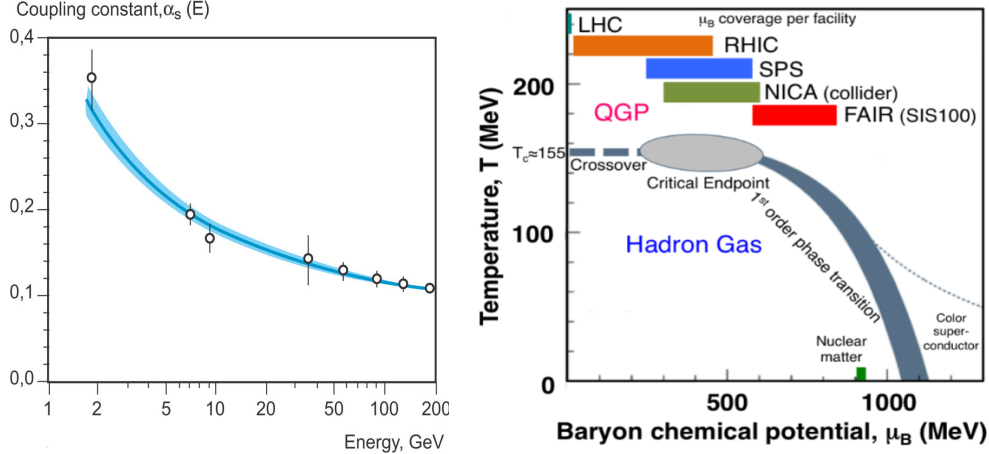


Figure 1.1: Left: Coupling constant α_s as a function of energy. The lines shows the $\pm 1\sigma$ limits of the theoretical calculation while the empty points are the values measured by different experiments [6]. Right: Schematic representation of the phase diagram of strongly-interacting matter, with the approximate coverage of the various experimental facilities in terms of a range in baryon chemical potential μ_B .

- asymptotic freedom: when the momentum transfer $Q^2 \rightarrow \infty$ the process can be defined hard and $\alpha_s(Q^2) \rightarrow 0$. In this case quarks and gluons can be considered free and QCD can be studied with a perturbative approach.
- confinement: when the momentum transfer $Q^2 \rightarrow 0$ the process can be defined soft and $\alpha_s(Q^2) \rightarrow \infty$. In this case quarks and gluons are confined in hadrons that are colour singlets and QCD can not be studied with a perturbative approach but with phenomenological models, like MIT Bag Model [7], or lattice QCD [8].

1.1.2 QCD Phase diagram

This division in two different kinematic ranges leads to the hypothesis that there could be a phase transition between the hadronic matter, where partons are confined, and the Quark Gluon Plasma state, where partons are free [9]. This is expressed by the QCD phase diagram shown in the right panel of Figure 1.1. There, the nuclear matter behaviour is described in terms of its temperature T on the y axis and baryon-chemical potential μ_B on the x axis. The latter is defined as the energy needed to increase by one unity the total number of baryons and anti-baryon and it is directly related to the baryonic density. At low temperature and for $\mu_B \sim 1$ GeV, corresponding to the nuclear density, the matter is confined in hadrons and nuclei. An intermediate state of hadronic gas can be obtained increasing the temperature or compressing the nuclear matter. At these conditions hadron resonances are excited and interact inelastically, such as an hadron resonance gas can be formed. For sufficiently high values of T or μ_B , a transition between hadronic matter and QGP is predicted. In the formation of neutron stars, the transition takes place at temperature close to zero and very high baryonic density caused by the gravitational collapse. On the contrary, the early Universe evolved from the deconfined state to the hadronic matter at high temperatures and vanishing baryon-chemical potential. In heavy-ion collisions at the LHC we try to recreate the conditions at the early Universe. In this case the transition from hadronic matter to QGP is expected to take place at $\mu_B \sim 0$.

Lattice QCD predicts that the deconfinement transition from hadron resonance gas to QGP at $T > T_{cr}$ and $\mu_B < \mu_{B,cr}$ is not a first order transition but a rapid crossover that occur in a well defined temperature interval and in a critical energy density. Recent calculations predict a critical point at $\varepsilon_{cr} \sim 1$ GeV/fm³ and $T_{cr} \sim 155$ MeV [10].

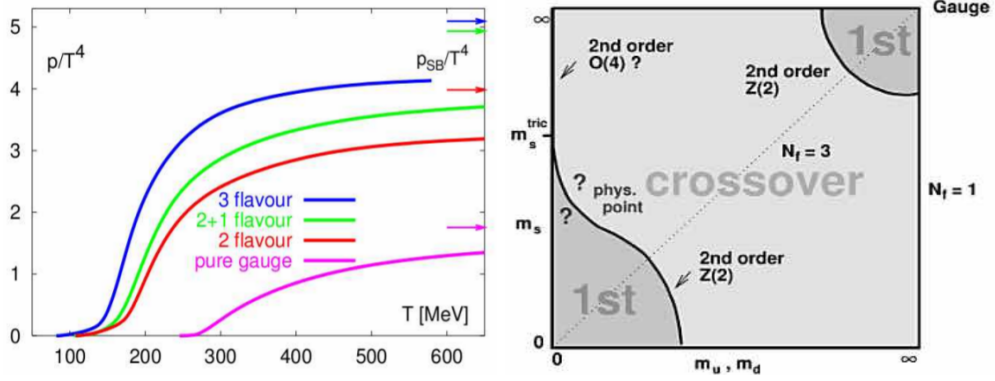


Figure 1.2: Left: pressure vs temperature from lattice QCD predictions. Predictions are shown in the pure-gauge scenario, in a 2 and 3 light quarks scenery and in the (2+1) scenario, that considers two lighter and one heavier quark. The arrows on the right indicate the Stephan-Boltzmann value for each scenario. Right: order of the phase transition as a function of quark masses [11].

1.1.3 Lattice QCD

Lattice QCD is a method to calculate equilibrium properties of strongly interacting systems from the QCD Lagrangian. The system created in a heavy-ion collision is studied as a statistical system in a gran canonical approach. In thermal quantum field theory, the grand canonical partition function at a given temperature T can be written as:

$$Z = Tr(e^{\frac{1}{T}(H - \mu_i N_{ix})}) = \int dx \langle x | e^{-\frac{1}{T}(H - \mu_i N_{ix})} | x \rangle \quad (1.4)$$

where H is the hamiltonian of the system and the integral $\int dx$ is a formal sum over a complete set of eigenstates $|x\rangle$. The path integrals are then evaluated by introducing a four-dimensional space-time lattice of size $N_\sigma^3 \times N_\tau$.

This is a non perturbative treatment of QCD, but it is formulated on a discrete space-time lattice, which allows to study quark and gluon interactions over a large distance scale. Phisycal results would be obtained in a continuum limit $a \rightarrow 0$, $N_\tau \rightarrow \infty$. Unfortunately, there are some limitations of this method on the lattice spacing and on its size, mainly due to limited computing power. Typical lattice spacing are larger than 1 fm and with 32^3 lattice sites in three dimensional space and 16 points on the time axis. Nevertheless, some significant results can be obtained.

The precise value of the transition temperature depends on the treatment of the fermion fields with two or three different flavours (u,d,s) and masses. Transition has been studied in the limit of 2-flavour QCD (quark up and down with zero masses) and of 3-flavour QCD (quark up, down and strange with zero masses). The last one is the most realistic approach. A different T_{cr} has been obtained at $\mu_B = 0$ depending on the fermions treatment:

1. $T_{cr} = 271 \pm 2$ MeV for a Pure Gauge field;
2. $T_{cr} = 173 \pm 4$ MeV for 2 light flavours;
3. $T_{cr} = 154 \pm 8$ MeV for 3 light flavours.

In the left panel of Figure 1.2, the pressure as a function of the temperature for the different fermions treatment is presented. The arrows on the right indicate the Stephan-Boltzmann value for each scenario. The values are not reached even at the highest temperature, indicating that no ideal gas behaviour occurs and strong interactions among the constituents are still present [11].

Lattice QCD also predicts the order of the phase transition: a first order transition would lead

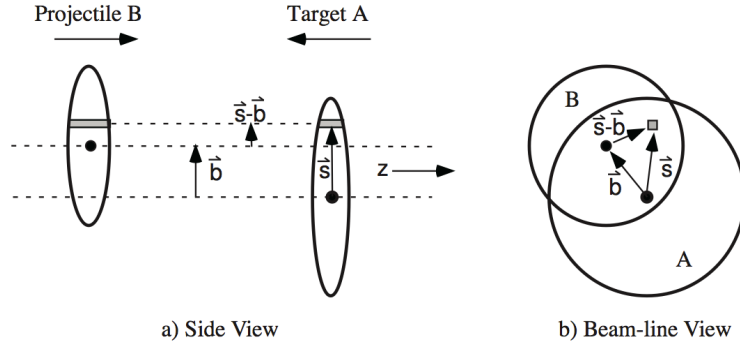


Figure 1.3: Schematic view of a nucleus-nucleus collision described in terms of the impact parameter b in the longitudinal (left) and transverse (right) plane.

to a discontinuity in the energy density between the plasma phase and the hadron gas, while a second order transition would lead to a rapid change in the thermodynamical variables as the critical temperature is approached. In the right panel of Figure 1.2 it is possible to notice that in the pure gauge theory the transition is of the first order. In the case of 2 (u,d) or 3 (u,d,s) massless (or light) quarks the transition is also of the first order, while for intermediate values of the quark masses lattice QCD predicts the existence of a crossover between the 2 phases. QCD predictions suggest that the crossover takes place above a critical temperature, below which the transition is of the first order [12].

Another phenomenon studied by the lattice QCD is the chiral symmetry restoration. The QCD lagrangian chiral symmetry is spontaneously broken by the mass term $m\bar{\psi}\psi$ and this is reflected in the mass values of hadrons. For example, if the chiral symmetry were valid, all states with the same quantum number and opposite parity should have the same mass but this is not observed in experimental data. For example ρ ($J^P = 1^-$) and a^1 ($J^P = 1^+$) mesons have masses of $770 \text{ MeV}/c^2$ and $1260 \text{ MeV}/c^2$. The lattice QCD predicts a restoration of the chiral symmetry at the critical temperature.

Besides lattice QCD, there are other possible approaches to study non-perturbative phenomena in QCD. For example the Anti-de-Sitter/Conformal Field Theory correspondence (AdS/CFT), based on a string theoretical construction, is used to study non-perturbative phenomena of non-Abelian gauge theories, like those involved in QGP phenomenology [13].

1.1.4 Ultra-relativistic heavy-ion collisions

Heavy-ion collisions are used to create a strongly interacting system with high energy density and temperature where the QGP could be formed. In order to obtain the QGP, the system should consist of many particles and be sufficiently long-lived that a high number of collisions between the constituents could occur, leading to thermal equilibrium. In high-energy heavy-ion collisions the presence of multiple collisions between nucleons in the colliding nuclei allows a large energy deposit in the collision region, creating the conditions needed for the formation of QGP. The system created in a Pb-Pb collision, already at SPS energies, can reach a volume of the order of 1000 fm^3 , consisting of ~ 1000 hadrons and an energy density ~ 200 times larger than in a nucleus ($0.15 \text{ GeV}/\text{fm}^3$).

The Glauber Model

The process of a nucleus-nucleus collision could be described with a phenomenological description starting from the geometrical configuration of the nuclei, the *Glauber model* [14]. In this approach, a superposition of independent nucleon-nucleon collisions is used to describe a

nucleus-nucleus collision. The main parameter considered is the impact parameter b , i.e. the distance between the centres of the nuclei in the transverse plane of the collision, as shown in Figure 1.3. Lower values of b correspond to a higher overlap of the incoming nuclei in the transverse plane, while larger values of b to a smaller overlap. The probability of interaction of two incoming nucleons inside two nuclei with mass number A and B , respectively, and with impact parameter b can be written in the Glauber model as $T_{AB}(b)\sigma_{\text{in}}$. Where σ_{in} is the nucleon-nucleon inelastic cross section and $T_{AB}(b)$ is the normalized overlap function that depends on the impact parameter of the collision and on the nuclear density functions of the two nuclei. $T_{AB}(b)$ is defined as:

$$T_{AB}(b) = \int d^2s T_A(s) T_B(b-s) \quad (1.5)$$

where $T_A(s) = \int dz \rho_A(z, s)$ is the nuclear profile function that depends on the coordinate s from the center of the nucleus A in the transverse plane. In the hypothesis of independent nucleon-nucleon collisions, the probability for the occurrence of n inelastic collisions for an impact parameter b is then given by:

$$P_{AB}(n, b) = \binom{AB}{n} [T_{AB}(b)\sigma_{\text{in}}]^n [1 - T_{AB}(b)\sigma_{\text{in}}]^{AB-n} \quad (1.6)$$

The total probability of an inelastic event in the collision of A and B is the sum of equation 1.6 from $n=1$ to $n=AB$:

$$\frac{d\sigma_{\text{in}}^{AB}}{db} = \sum_{n=1}^{AB} P_{AB}(n, b) = 1 - [1 - T_{AB}(b)\sigma_{\text{in}}]^{AB} \quad (1.7)$$

From this equations it is possible to estimate the average number of binary nucleon-nucleon collisions $\langle N_{\text{coll}} \rangle$ as a function of the impact parameter. $\langle N_{\text{coll}} \rangle$ can be calculated as the mean value of the the binomial distribution $P(n, b)$:

$$\langle N_{\text{coll}} \rangle = AB\sigma_{\text{in}} T_{AB}(b) \quad (1.8)$$

The number of nucleons involved in the collision (participant nucleons) and the number of nucleons which do not participate (spectator nucleons) can be also estimated with similar calculations. The Glauber model is used in the centrality determination, as described in Section 2.5.3.

In the case of hard processes, with small cross section, the Glauber model predicts that the production yield in heavy-ion collisions can be obtained as the production yield in pp collisions multiplied by the average number of binary collisions $\langle N_{\text{coll}} \rangle$ (binary scaling). The nuclear modification factor R_{AA} , defined in the following equation 1.9, is used to validate the binary scaling hypothesis that predicts a R_{AA} equal to unity for hard processes, mainly at high transverse momentum.

$$R_{AA}(p_T) = \frac{d^2 N_{AA}^{\text{hard}} / dp_T dy}{\langle N_{\text{coll}} \rangle d^2 N_{pp}^{\text{hard}} / dp_T dy} \quad (1.9)$$

A $R_{AA} \neq 1$ at high p_T indicates that there are some effects that affect the binary scaling, as the presence of the QGP.

Time evolution of the collision

The space-time evolution of a central heavy-ion collision is shown in Figure 1.4. Before the collision the two incoming nuclei can be represented by two thin disks because of the Lorentz contraction in the longitudinal direction [15]. Then, the system undergoes these phases:

- **Pre-equilibrium:** it is the first stage where parton scatterings with high momentum exchange occur. In this phase the so called “high- p_T probes” (jets, heavy quarks, etc.) are produced and a large amount of energy is released.

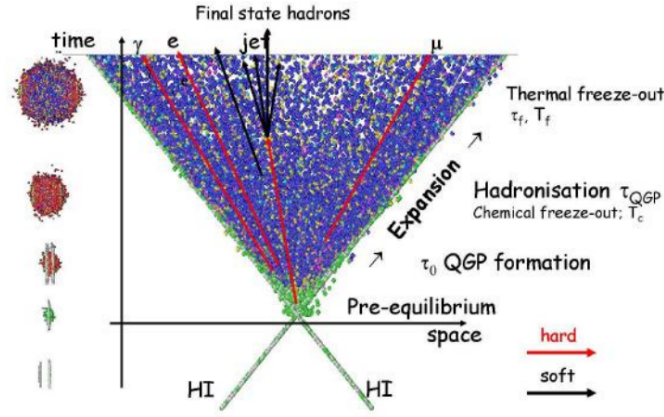


Figure 1.4: Space-time evolution of a central collision.

- **Thermalization, QGP phase:** in this phase the system reaches thermal equilibrium through multiple scatterings between the constituents and, if the energy density is $\varepsilon > 1 \text{ GeV}/\text{fm}^3$, a thermalized QGP fluid is expected to be formed. After around $\tau_0 \sim 1 \text{ fm}/c$ the system expands hydrodynamically and cools down approximately adiabatically.
- **Hadronization:** when the temperature of the expanding system drops below T_{cr} quarks and gluons can be confined into hadrons.
- **Chemical freeze-out:** the system continues to expand and cools down until inelastic processes stopped and the relative abundances of hadron species are fixed.
- **Thermal freeze-out:** in this last phase the elastic collisions, that occurs during the continuous expansion and cooling down of the system, cease when the distance between hadrons becomes larger than the range of strong interaction.

1.2 Experimental observables

Since it is not possible to measure the phase transition directly, indirect observables are measured to probe the formation of the QGP and its properties at different stages of the collision evolution. Some of the observables considered in high-energy nuclear physics, in particular in ALICE, are listed in this section. Another important observable to study partonic energy-loss in the medium is the open charm production. A separated section is dedicated to its description, since it is one of the main topics of this thesis.

1.2.1 Thermal photons

Photons produced in heavy-ion collisions can be divided in three groups:

- **decay photons** come from decays of other particles and, hence, from secondary vertices, like $\pi^0 \rightarrow \gamma\gamma$;
- **prompt photons** come from initial partonic processes with large Q^2 and they have large momenta (above $3 \text{ GeV}/c$);
- **thermal photons** come from thermal radiation of the QGP and they have lower momenta (below $2 \text{ GeV}/c$).

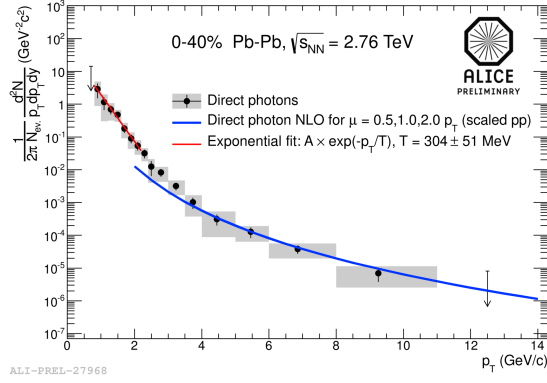


Figure 1.5: Direct photons p_T spectrum in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured with ALICE [16].

The spectrum of direct photons, prompt and thermal, could provide an information on the temperature of the fireball. The fireball can be considered as a source at constant temperature that emits photons following a Maxwell-Boltzmann exponential rate $\sim e^{-p_T/T}$. Since the final spectrum is the convolution of all photons emitted during the temperature history of the fireball, it provides a sort of temporal mean of the temperature from the very initial stages of the collision to hadronization. Figure 1.5 shows the direct photons spectrum measured by ALICE in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ [16]. The exponential fit is superimposed to the low p_T points, a temperature of $T = 304 \pm 51$ MeV is obtained, well above the critical temperature T_{cr} predicted for the QGP formation by lattice QCD calculations.

1.2.2 Particle multiplicity

The particle multiplicity can be used to estimate the energy density of the QGP. This approach was proposed by Bjorken in the '70s [17] and suggests that the energy density of the medium can be estimated from the transverse energy density in rapidity¹, dE_T/dy , as follows:

$$\varepsilon_{Bj} = \frac{1}{\tau_0 A} \left. \frac{dE_T}{dy} \right|_{y=0} \quad (1.12)$$

where A is the transverse overlapping area in the collision of the nuclei and τ_0 is the formation time for the QGP. At mid-rapidity ($y = 0$) it is possible to approximate the transverse energy density as:

$$\left. \frac{dE_T}{dy} \right|_{y=0} \sim \langle E_T \rangle \left. \frac{dN}{dy} \right|_{y=0} \sim \langle E_T \rangle \left. \frac{dN}{d\eta} \right|_{y=0} \quad (1.13)$$

where dN/dy and $dN/d\eta$ are the particle rapidity and pseudo-rapidity density, respectively and E_T is the average hadron transverse energy which can be obtained experimentally.

In the left panel of Figure 1.6 the charged-particle pseudorapidity at mid-rapidity is shown as a function of $\langle N_{part} \rangle$ measured with ALICE [18] and RHIC [19]. The charged-particle density per participant pair increases with centrality from 4.4 ± 0.4 to 8.3 ± 0.3 in the most central collisions in ALICE. A similar centrality dependence is observed also at RHIC. From this data

¹ The rapidity for a given particle is usually defined as:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad (1.10)$$

while the pseudo-rapidity η is defined as:

$$\eta = \frac{1}{2} \ln \frac{|p| + p_z}{|p| - p_z} = -\ln[\tan(\theta/2)] \quad (1.11)$$

in the high energy limit η could be approximate with y .

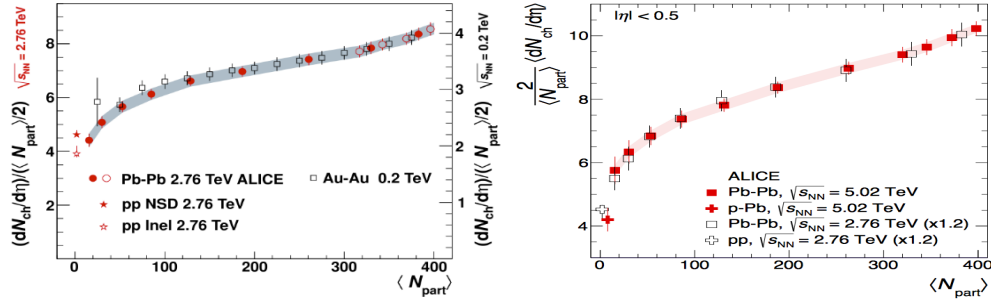


Figure 1.6: Left: centrality dependence of $dN_{\text{ch}}/d\eta/(0.5\langle N_{\text{part}}\rangle)$ in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV measured with ALICE [18] and in Au-Au collisions at $\sqrt{s_{\text{NN}}} = 0.2$ TeV obtained with an average of RHIC results [19]. The latter is scaled by a factor 2.1. Right: comparison between $dN_{\text{ch}}/d\eta/(0.5\langle N_{\text{part}}\rangle)$ in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV (scaled by a factor 1.2) and $\sqrt{s_{\text{NN}}} = 5.02$ TeV measured with ALICE [20].

and the above equation, the Bjorken energy-density is evaluated as $\varepsilon_{\text{Bj}} \sim 16 \text{ GeV}/\text{fm}^3$ in ALICE and around a factor 3 lower at RHIC in the centrality range 0 – 5%. The energy density in both experiments is well above the critical value predicted by the lattice QCD calculation for the medium formation, suggesting that the conditions for the QGP formations are reached at RHIC and LHC.

The right panel of Figure 1.6 shows the comparison between $dN_{\text{ch}}/d\eta/(0.5\langle N_{\text{part}}\rangle)$ in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV (scaled by a factor 1.2) and $\sqrt{s_{\text{NN}}} = 5.02$ TeV measured with ALICE [20]. The trend of the centrality dependence does not vary increasing the center-of-mass energy of the collisions.

1.2.3 Particle spectra and radial flow

The study of particle spectra can give us insight on the system after the kinetic freeze-out. At this stage the distance between the particles is so large that both elastic and inelastic collisions cease. Therefore, the transverse momentum spectra of the produced particles is fixed and the system could be considered in equilibrium at the temperature of the kinetic freeze-out T_{kin} . The shape of the spectrum for a given particle species i could be described in a simplified approach as a Maxwell-Boltzmann exponential slope $\sim e^{-p_{\text{T}}/T_{\text{slope}}}$ where T_{slope} is:

$$T_{\text{slope}} = T_{\text{kin}} + \frac{1}{2}mv_{\perp} \quad (1.14)$$

The temperature extracted from the fit of particle spectra is the sum of two contributions: the random thermal motion and the radial flow, a collective expansion of the system with mean velocity $\langle v_{\perp} \rangle$ which is caused by the high pressure gradients created in the collision.

Figure 1.7 shows the p_{T} spectra of pions, kaons and protons in central Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV measured by ALICE [21] and in central Au-Au collisions at $\sqrt{s_{\text{NN}}} = 0.2$ TeV measured by PHENIX [22] and STAR [23]. The results show a change in the particle spectra from RHIC to LHC energies, indicating a stronger radial flow at higher energies. The data are fitted with a blast-wave function [24] that takes into account both hadron yields from resonances decay and radial flow to extract T_{kin} and $\beta_{\perp} = v_{\perp}/c$. The parameters extracted are $\langle \beta_{\perp} \rangle = 0.65 \pm 0.02$ and $T_{\text{kin}} = 95 \pm 10$ MeV from ALICE data and $\sim 10\%$ lower values from RHIC data.

1.2.4 Elliptic flow

Another important observable to study the properties of the system in heavy-ion collisions is the elliptic flow. In non-central collisions, the higher pressure gradients along the direction of the collisions lead to an anisotropic momentum distribution of particles on the transverse

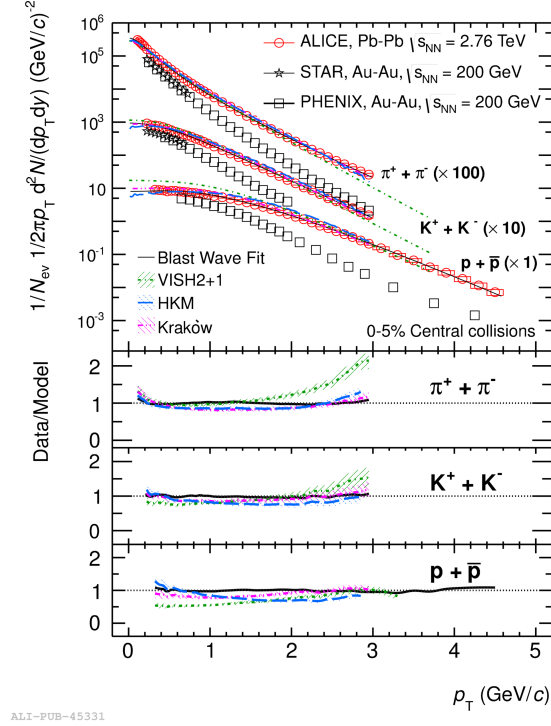


Figure 1.7: Pion, proton and kaons p_T spectra in central AA collisions in ALICE [21], PHENIX [22] and STAR [23]. The data are fitted with a blast-wave function [24] and compared to hydrodynamical calculations [25, 26, 27].

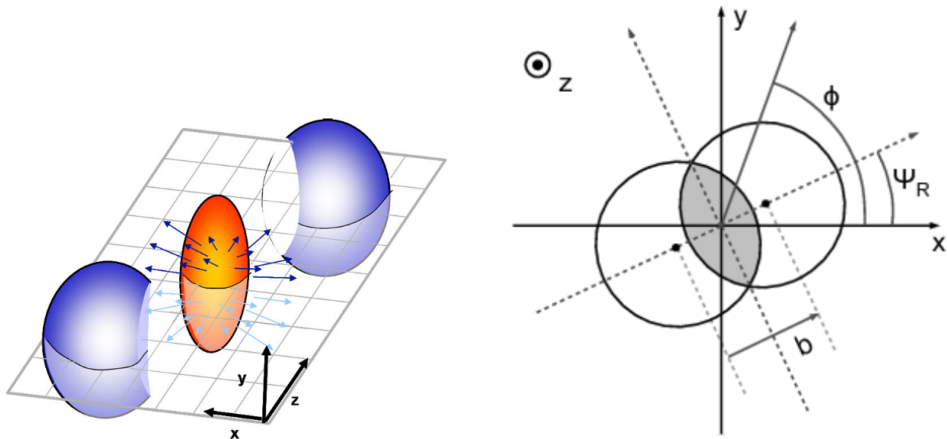


Figure 1.8: Schematic view of a non-central nucleus-nucleus collision and the reaction plane.

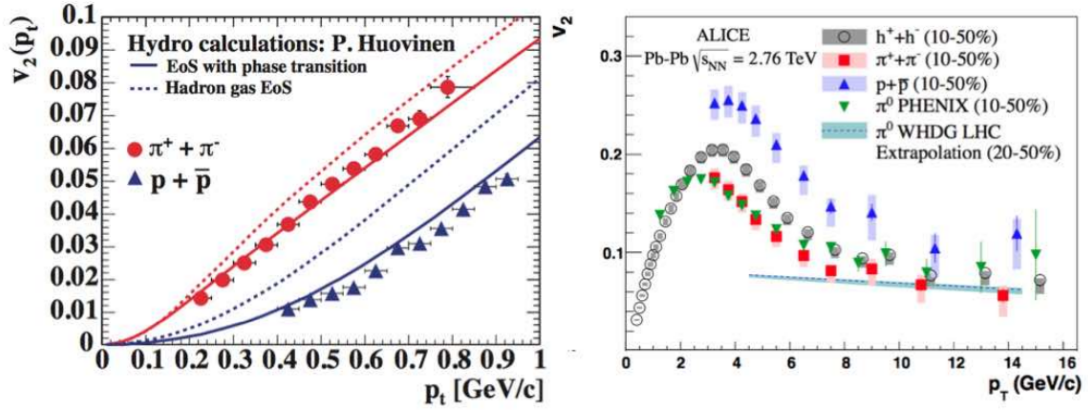


Figure 1.9: Left: PHENIX low p_T measurements of pions and protons v_2 compared to hydrodynamical calculations [29]. Right: ALICE results for proton and pion v_2 from semicentral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [30].

plane. The anisotropy could be quantified by the coefficients of the Fourier expansion of the final state particle distribution in the azimuthal angles relative to the reaction plane Ψ_{RP} [28]. The reaction plane is defined by the impact parameter of the collision and the longitudinal axis of the collision, as schematically shown in 1.8. The Fourier expansion of the final state particle distribution is described by this formula:

$$\frac{dN}{d(\phi - \Psi_{RP})} = \frac{N_0}{2\pi} (1 + 2v_1 \cos(\phi - \Psi_{RP}) + 2v_2 \cos(2(\phi - \Psi_{RP})) + \dots) \quad (1.15)$$

The first coefficient v_1 is called directed flow, while the second v_2 is called *elliptic flow* and represents an elliptic distribution of particles in the transverse plane. The effect is visible in semi-central/semi-peripheral collisions where the eccentricity of the overlap region of the colliding nuclei is significative. On the other hand, the eccentricity is negligible in central collisions and in most peripheral collisions where the number of rescatterings occurred between particles is not enough to translate the initial spatial anisotropy into a momentum anisotropy. The elliptic flow gives an important indication of the level of thermalization of the system but, since interactions among the constituents occur also in the hadronic phase of the fireball evolution, a fraction of the elliptic flow could also be built up after hadronization.

The left panel of Figure 1.9 shows the v_2 measured by PHENIX for pions and protons as a function of p_T (for $p_T < 1$ GeV/c) [29], indicating a lower v_2 for protons with respect to pions at low p_T . The results are also superimposed to two hydrodynamic predictions: one that takes into account a deconfined state that undergoes a phase transition to hadron gas and another one with a hadron gas system only. The first prediction is in a better agreement with the data. In the right panel of Figure 1.9 the v_2 of identified hadrons measured by ALICE is reported [30]. The results for pions and protons are presented in a higher p_T region with respect to the PHENIX results and, there, it can be noticed that the v_2 of protons is higher than that of pions. This behaviour can be interpreted as an effect of recombination [31] and/or of the different radial flow at the different energies.

Several studies are also ongoing on higher order armonics, like v_3 , v_4 and v_5 , that are interesting to study event-by-event fluctuations of the initial geometric configuration and deviations of the medium from an ideal fluid behaviour.

1.2.5 Quarkonia

Quarkonia states are a powerful probes to test the creation of a deconfined state of matter in heavy-ion collisions [32]. Indeed, the presence of free colour charges in the QGP could affects the binding potential between quark-antiquark pairs in quarkonia states (as schematically shown

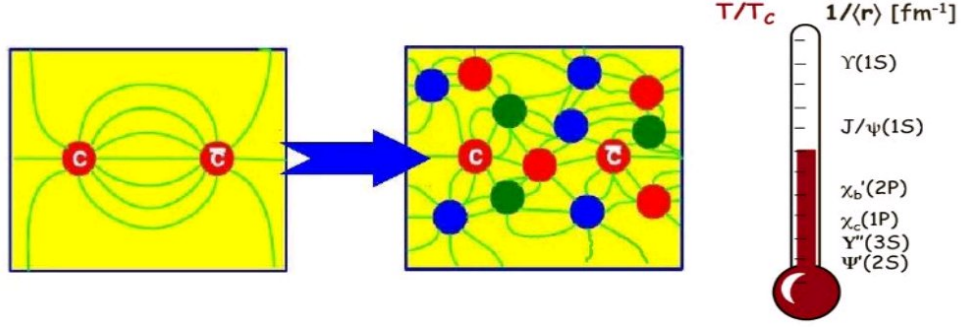


Figure 1.10: Left panel: Representation of the quarkonia states with and without the presence of deconfined quarks and gluons. Right panel: Melting temperature of binding states.

in the left panel of Figure 1.10). Heavy $q\bar{q}$ states are particularly interesting because heavy quarks are produced only in the hard partonic scatterings in the initial stage of the collision and, therefore, they undergoes all stages of the system evolution. In presence of a deconfined state, the color attraction between q and $\bar{q}$ gets screened by the presence of deconfined quarks and gluons. The Yukawa potential describes the q and $\bar{q}$ bound as follows:

$$V(r) = -\frac{\alpha}{r} e^{-\frac{r}{\lambda_D}} \quad (1.16)$$

where λ_D is the Debye screening length, related to the maximum distance between two quarks convenient to form a bound state. The λ_D depends on the temperature of the plasma created in the collision, such as quarkonia states with different binding energies are expected to melt at different temperatures. Therefore, the measurement of the suppression of these states could provide an estimate of the temperature of the system (as shown in the right panel of Figure 1.10). For this reason, quarkonia states, in particular the most stable charmonia states ($c\bar{c}$) J/Ψ , are studied intensively starting from SPS. The J/Ψ binding state is expected to dissociate at temperature larger than $T/T_{cr} \sim 1.1$. Indeed, a suppression in the J/Ψ production is observed in heavy-ion collisions at SPS and RHIC energies. The latter result is shown in the left panel of Figure 1.11 where the R_{AA} as a function of transverse momentum p_T of inclusive J/Ψ is measured by PHENIX in central Au-Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV [33]. A strong suppression of a factor ~ 5 is observed for $p_T < 4$ GeV/c. The data are compared with the inclusive J/Ψ R_{AA} measured by ALICE in the same centrality class in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. At LHC energies the $c\bar{c}$ pair production is much higher, therefore the J/Ψ production via recombination of charm quarks in the medium can explain the lower suppression measured by ALICE and reported in Figure 1.11 as a function of N_{part} (left) and p_T (right) [34]. An extensive study is also carried out on bottomonium states in order to study the role of dissociation and recombination [35].

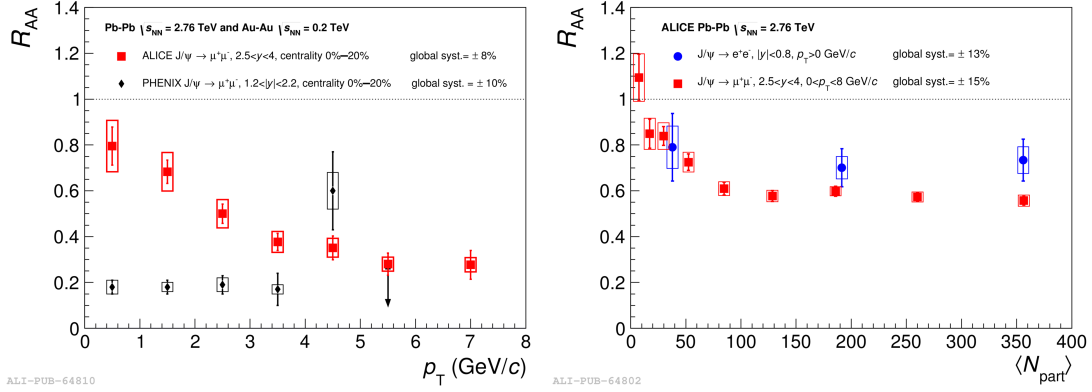


Figure 1.11: Left: R_{AA} of inclusive J/Ψ as a function of p_T measured with ALICE in central Pb-Pb collisions (0 – 20%) at $\sqrt{s_{NN}} = 2.76$ TeV and with PHENIX in Au-Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV [33] in the same centrality range. Right: R_{AA} of inclusive J/Ψ as a function of the collision centrality measured with ALICE in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at mid- and forward-rapidity [34].

1.3 Open charm physics

In this section, the basic features of open charm production in heavy-ion collisions are presented. The theoretical models based on different calculations of the heavy-quark dynamics are discussed and a selection of the results on heavy-flavour production in high-energy experiments is reported.

1.3.1 Heavy quarks in heavy-ion collisions

Heavy quarks are a powerful probe to study the properties of the system created in heavy-ion collisions. Because of their large mass, they can be created only in hard scattering processes at the initial stages of the collision. Therefore, they pass through all the phases of the system evolution, interacting with the medium produced in heavy-ion collisions. There, they lose energy via elastic collisions with other medium constituents and inelastic processes, i.e. gluon radiation. Other processes that can affect heavy-quark production are cold nuclear matter effects that are not a consequence of the interaction with the QGP and are present also in proton-nucleus collisions. In this section, the hot and cold nuclear matter effects that could affect heavy-flavour production are presented.

Hot nuclear matter effects

Hot nuclear matter effects can be observed experimentally as a modification of the transverse momentum spectrum of charmed and beauty hadrons in heavy-ion collisions, as shown in Figure 1.12. The effect can be studied looking at the nuclear modification factor of heavy-flavoured mesons. It results in a reduction of the R_{AA} at high p_T due to *radiative* and *collisional* energy loss processes affecting heavy quarks.

- **Radiative energy loss**

The radiative energy loss, also called *gluonsstrahlung*, is a phenomenon that consists in the emission of gluons from high- p_T partons due to the QCD interactions with the particles of the deconfined medium. Gluonsstrahlung processes are expected to dominate for high p_T partons at LHC energies. This phenomenon depends on the properties of the medium, in particular on the in-medium path length L of the parton, the mean free path for elastic collisions λ_{mfp} and the transport coefficient $\hat{q}$. The latter is defined as:

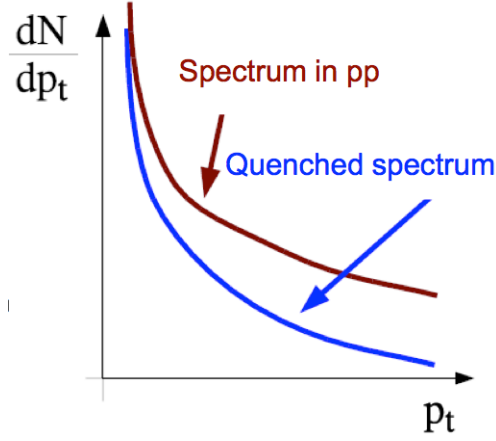


Figure 1.12: Effect of the in-medium energy loss of charm quarks on the p_T spectrum of heavy flavoured mesons.

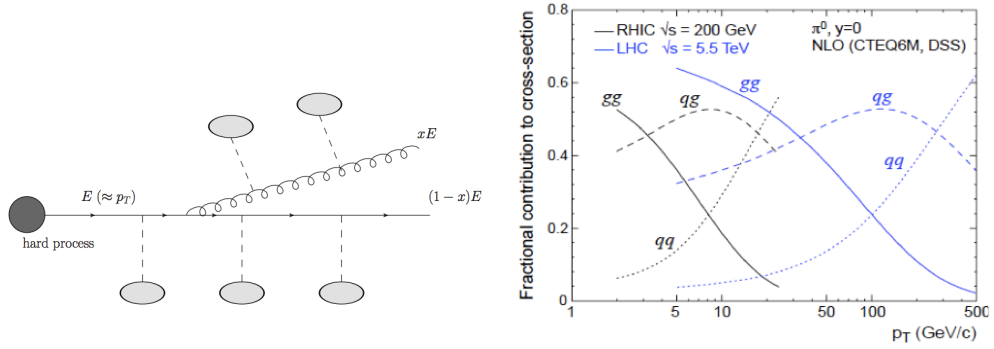


Figure 1.13: Left: schematic view of the medium-induced gluon radiation off a hard parton due to its interaction with the scattering centres in the medium. Right: fractional contribution to π^0 production cross-section as a function of p_T from different initial hard partonic processes for RHIC and LHC energies [37].

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda_{\text{mfp}}} \quad (1.17)$$

where k_T is the transverse momentum transferred in the parton interaction with the medium. Radiative energy loss calculations can be performed with different approaches. For example, in the BDMPS model [36] the QCD medium is considered as a collection of static scattering centres at a discrete set of points, giving rise to a colour potential $A_\mu(x)$. A schematic view of the induced gluon radiation off a hard parton due to the scattering centres in the medium is shown in the left panel of Figure 1.13. Following this approach, the average energy loss due to the gluon radiation in the high-energy fully coherent regime can be described by this formula:

$$\langle \delta E \rangle \sim \alpha_s C_r \hat{q} L^2 \quad (1.18)$$

where C_r is the Casimir factor of the parent high-energy parton and L is the in-medium path length. In first approximation, the average energy loss does not depend on the initial energy of the parton but, since it depends on C_r , it is expected to be larger for gluons than for quarks ($C_r = 4/3$ for quarks, $C_r = 3$ for gluons). Another effect has to be considered

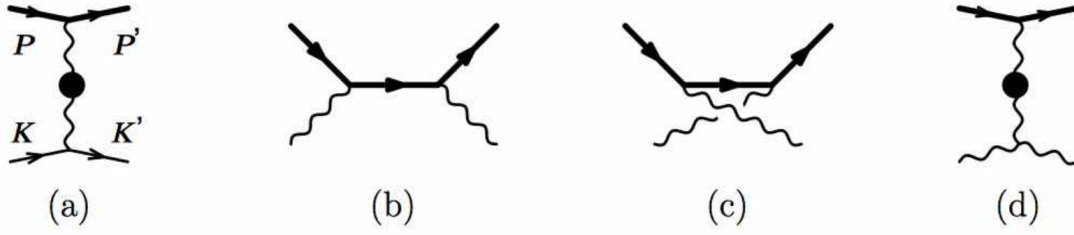


Figure 1.14: Feynman diagrams of heavy quark elastic scattering in a QGP, the curly line represents a gluon.

in the energy loss valuation, i.e. the *dead cone* effect [38]. For massive quarks, it causes a suppression of gluon emission at small angles with respect to the emitting parton direction because of the presence of the mass term in the heavy-quark propagator, modifying the gluonsstrahlung spectrum also in the vacuum. Because of the effects listed above, a mass hierarchy is expected for quarks and gluons:

$$\langle \delta E_{\text{gluons}} \rangle > \langle \delta E_{\text{light}} \rangle > \langle \delta E_{\text{charm}} \rangle > \langle \delta E_{\text{beauty}} \rangle \quad (1.19)$$

This could reflect in a hierarchy in the nuclear modification factor of different particles at high p_T which we want to test experimentally:

$$R_{AA}^B > R_{AA}^D > R_{AA}^{\text{light}} \quad (1.20)$$

This relation can be naively justified with the fact that a large fraction of light-flavoured hadrons are produced in the hadronization of light quarks and gluons, whose abundances depends on p_T and on the collision energy. An example of the fractional contribution as a function of p_T of quarks and gluons pairs to a light hadron production cross-section can be observed in the right panel of Figure 1.13 for RHIC and LHC energies [37]. Instead, all heavy-flavoured hadrons, due to their large masses, originate from the hadronization of heavy quarks. Nevertheless, other mechanisms have to be considered in order to obtain a reliable prediction for the R_{AA} , like the different p_T -shapes of the initial heavy and light parton spectra and the differences in the fragmentation functions of gluons, light and heavy quarks.

• Collisional energy loss

The second phenomenon that plays a role in parton energy loss is the elastic collisions with the medium constituents. It has a non negligible effect for heavy quarks at RHIC and LHC energies in the low transverse momentum region.

The two partonic processes that have to be considered are the Coloumb scattering and the Compton scattering with thermal gluons. The scattering amplitude is given by the Feynman diagram shown in Figure 1.14, where elastic scattering occurs with gluons and up, down and strange quarks. In the limit of $M^2 \ll E_T$ (where M and E_T are the mass and the transverse energy of the quark, respectively), it can be found that the energy loss due to elastic collisions depends linearly on the in-medium path length and logarithmically on the initial parton energy [39].

In Figure 1.15 a theoretical calculation of the energy loss as a function of p_T is shown for RHIC energy ($\sqrt{s_{NN}}=200$ GeV) for charm quarks. The radiative contribution starts to dominate for charm quark with transverse momentum $p_T \sim 10$ GeV/ c .

Cold nuclear matter effects

The cold nuclear matter effects are those mechanisms that affect the simple binary scaling of the hard particles spectra in nucleus-nucleus collisions, they are not due to the interaction with

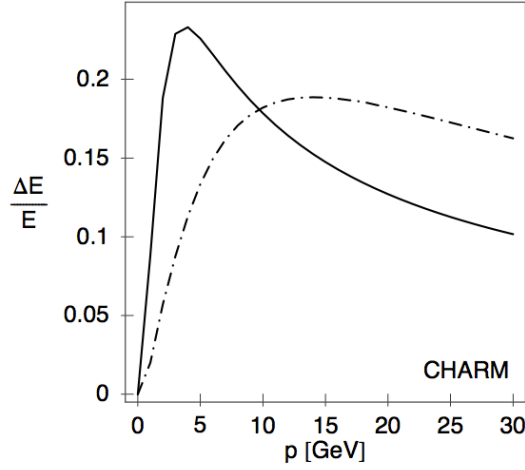


Figure 1.15: Comparison between collisional and radiative fractional energy loss as a function of the momentum for charm quarks for $\sqrt{s_{NN}}=200$ GeV. Radiative energy loss is shown with a dashed curve while the full curve shows the collisional energy loss contribution [40].

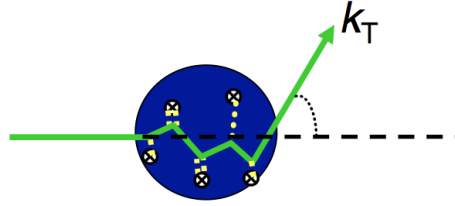


Figure 1.16: Schematic view of the effect of multiple scattering that affect a parton before the hard interaction occurs.

a hot deconfined medium but to the fact that the colliding particles are nuclei. They are expected to affect both proton-nucleus and nucleus-nucleus collisions.

These phenomena have an impact on the colliding partons before the hard process takes place, as the k_T -broadening. The latter is a consequence of the multiple elastic scatterings that a parton in a nucleus undergoes with the partons of the other nucleus before the hard scattering process occurs (as shown in Figure 1.16). In this way an average transverse square-momentum is acquired by the incoming partons crossing the other nucleus, causing a modification at low-intermediate p_T of the p_T -spectra of the heavy partons produced in the hard scattering processes. The k_T -broadening could explain the Cronin effect, an enhancement of the R_{AA} observed for the first time in the intermediate p_T region at Fermilab [41].

The modification of the parton distribution functions (PDFs) in nuclei with respect to a nucleon is another phenomenon considered as an initial state effect [42]. Different regions can be distinguished in the modification of the nuclear PDFs depending on the value of the Bjorken scaling variable x . To evaluate the modification we use the variable $R_{F_2}^A(x, Q^2)$ defined as:

$$R_{F_2}^A(x, Q^2) = \frac{F_2^A(x, Q^2)}{AF_2^{nucleon}(x, Q^2)} \quad (1.21)$$

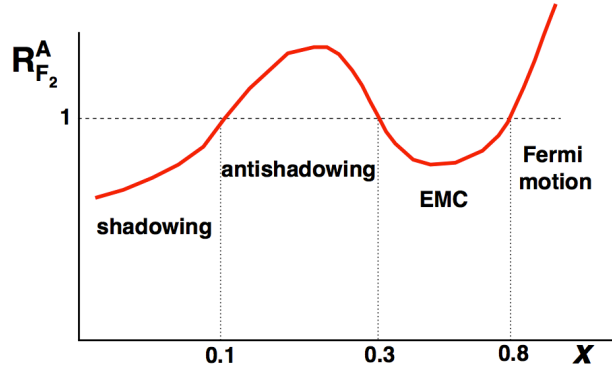


Figure 1.17: $R_{F_2}^A(x, Q^2)$ as a function of the scaling variable x [42].

where $F_2^A(x, Q^2)$ and $F_2^{\text{nucleon}}(x, Q^2)$ are the nuclear structure functions of a nucleus with mass number A and of a free nucleon, respectively. The behaviour of $R_{F_2}^A(x, Q^2)$ as a function of the scaling variable x for a given Q^2 is shown in Figure 1.17. It can be divided in:

- *shadowing region*: $R_{F_2} < 1$ for $x < 0.1$;
- *anti-shadowing region*: $R_{F_2} > 1$ for $0.1 < x < 0.3$;
- *EMC region*: $R_{F_2} < 1$ for $0.3 < x < 0.8$;
- *Fermi motion region*: $R_{F_2} > 1$ for $x > 0.8$.

The heavy-flavour production in heavy-ion collisions at the LHC energies is expected to take place in the shadowing region (in central collisions the $c\bar{c}$ pairs produced have an average x values below 10^{-4}) [43]. Different approaches have been considered to describe the shadowing region. For example, in the Color Glass Condensate Model (CGC) it is described as an effect of the overlap of gluons at small x [44, 45]. This results in processes of gluon fusion, limiting the achievable gluon density up to gluon saturation.

Hadronization

In heavy-ion collisions partons could hadronize in two different ways: *fragmentation* and *recombination*. In Figure 1.18 a schematic view of the effect of the two mechanisms on the hadron transverse momentum spectrum is shown. In the fragmentation case, a quark Q with momentum p_Q hadronizes into a hadron h that carries a fraction $z = p_h/p_Q$ of the momentum of the initial quark with a probability given by the fragmentation function $D(z, \mu_F^2)$. In the approach of recombination a low-momentum quark can hadronize through a process of coalescence with a light quark of the medium to form a heavy flavoured hadron with a momentum p_h , which is the sum of the momenta of the two quarks $p_h = p_{q,1} + p_{q,2}$. The coalescence between two quarks is possible only if they are sufficiently close in phase space in order to allow the overlap of their density functions. In central heavy-ion collisions, where the phase space is densely populated, the recombination is expected to be relevant for low- p_T partons and, mainly, for mesons (made of two quarks).

1.3.2 Phenomenological models

Several theoretical calculations aim to describe heavy-flavour production in nucleus-nucleus collisions implementing the phenomena described above. In this Section a briefly description of the main models that will be compared to data is provided.

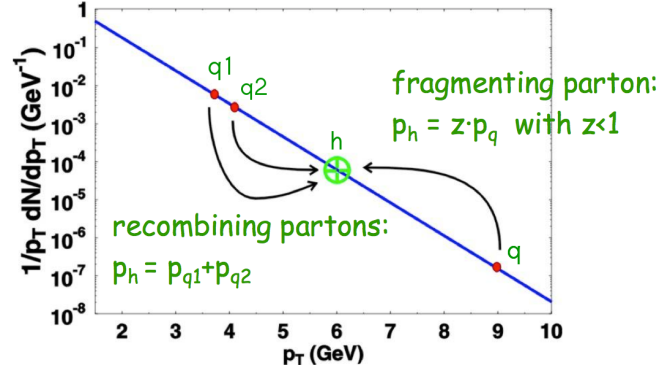


Figure 1.18: Schematic view of the effects of fragmentation and recombination on the transverse momentum spectrum of heavy-flavoured hadrons.

- **TAMU** [46, 47] is a heavy-flavour transport code based on the Langevin equation. It takes into account elastic scatterings with medium constituents and a hydrodynamic medium evolution as an (2+1)D ideal fluid. The transport coefficients are calculated with a non perturbative T-matrix approach, which includes resonances that transfer momentum from the heavy quark to the medium constituents. The diffusion is simulated using relativistic Fokker-Plank dynamics and the evolution is constrained by light-flavour hadron spectra and elliptic flow data. Hadronization is described via recombination and fragmentation which dominate at low and high p_T , respectively.
- **Djordjevic** [48, 49] predictions include energy loss due to both radiative and collisional processes in a finite size dynamical QCD medium. In this model the final heavy-flavour hadrons spectra are obtained convoluting the initial heavy quark spectrum, $\frac{E_i d\sigma(Q)}{dp_i^3}$ with the energy loss probability, $P(E_i \rightarrow E_f)$, and the fragmentation function, $D(Q \rightarrow H_Q)$:

$$\frac{E_f d\sigma(H_Q)}{dp_f^3} = \frac{E_i d\sigma(Q)}{dp_i^3} \otimes P(E_i \rightarrow E_f) \otimes D(Q \rightarrow H_Q) \quad (1.22)$$

The initial heavy-quark spectrum is provided by FONLL calculations, while the energy-loss probability takes into account also path-length fluctuations and magnetic mass of QGP constituents. The model does not include neither a hydrodynamic evolution of the medium nor heavy-quark hadronization via recombination. The medium temperature is fixed separately at RHIC and LHC energies.

- **Cao, Qinn, Bass** [50] is a model based on a modified version of the Langevin equation. It includes both elastic scatterings and radiative energy-loss, the latter implemented considering gluon radiation as an additional friction term. A viscous hydrodynamical evolution of the medium is considered and the model includes also charm recombination with light thermal partons.
- **WHDG** [51, 52, 53] predictions are computed using the same approach of Djordjevic to evaluate the final heavy-flavour hadron spectra, following the equation 1.22. The Glauber model is used to implement a realistic collision geometry. No hydrodynamical expansion is considered, while path length and energy-loss fluctuations are taken into account in the energy loss probability term. The collisional energy loss in an ideal ultra-relativistic QGP with n_f active flavours and temperature T is evaluated as:

$$\frac{dE^{el}}{dx} = C_r \pi \alpha_s^2 T^2 (1 + n_f/6) \ln B_c \quad (1.23)$$

where the parameter B_c takes into account the minimum and maximum momentum transfers. The radiative energy loss is given by the DGLV formula [51]. Unlike the Djordjevic

model, the tuning of medium parameters is done at RHIC energies and then scaled with $dN_{\text{ch}}/d\eta$.

- **MC@sHQ+EPOS** [54] is based on Monte-Carlo propagation of heavy quarks in the medium, which expands dynamically according to the EPOS model. It includes initial conditions obtained from a flux tube [55] approach and treats plasma as a (3+1)D ideal fluid, imposing the local energy-momentum, baryon number, strangeness and electric charge conservation. The elastic cross sections are obtained from pQCD matrix elements in Born approximation. The incoherent emission of bremsstrahlung gluons is included via matrix elements from scalar QCD, while the coherent one is implemented via an effective reduction of the spectrum. Both recombination and fragmentation hadronization mechanisms (for low and high p_T , respectively) are implemented and took place at the transition temperature T_c . The QGP transport coefficient is fixed at LHC energy and slightly adapted to RHIC energy.
- **Vitev** [56, 57] gives a QCD description of heavy-flavour dynamics in the thermal medium that links D and B meson in-medium formation and dissociation to parton-level charm and beauty quark radiative energy loss. Heavy-quark initial distributions are taken from FONLL predictions and the formation of heavy-quark bound states above the deconfinement temperature T_{cr} is taken into account. The medium is modelled as a longitudinal ideal fluid following Bjorken expansion. As in the WDHG model, the tuning of the medium parameters is done at RHIC energies and then scaled with $dN_{\text{ch}}/d\eta$. Only hadronization via fragmentation is implemented.
- **POWLANG** [58, 59, 60] implements collisional energy loss using the relativistic Langevin equation. The model includes a viscous hydrodynamic expansion of the medium and the hadronization is implemented via vacuum fragmentation functions and, in the latest version, via recombination with light thermal partons and subsequent strong fragmentations. From an initial time τ_0 up to hadronization, an iterative procedure is used to follow the stochastic evolution of the heavy quarks in the plasma. The Langevin transport coefficients are evaluated at each step according to local temperature of the medium.
- **BAMPS** [61, 62, 63] is a partonic transport model based on the Boltzmann equation. The medium follows a (3+1)D expansion. The model includes collisional energy loss via binary scatterings, while the lack of radiative energy loss and of NLO correction is accounted for by a phenomenological factor $K=3.5$ in order to describe well the elliptic flow and nuclear modification factor at RHIC. Only hadronization via fragmentation is implemented.

More details on the various models can be found in a recent review [64].

1.3.3 Open-charm measurements

In this section a selection of the open-charm measurements at RHIC and LHC is presented in different colliding systems: pp, pA and AA collisions.

Results in pp collisions

Figure 1.19 shows the invariant cross section of electrons from decays of charm and beauty hadrons measured by PHENIX in pp collisions at $\sqrt{s} = 200$ GeV [65]. A black line, representing FONLL calculation [66] for inclusive electrons from heavy-flavour decays, is superimposed to the data. In red and green the beauty and charm contributions are plotted, respectively. According to FONLL, the beauty contribution dominates for transverse momenta above 4 GeV/c. It can be observed that the central values of FONLL predictions underestimate charm and beauty production at RHIC energies in almost all the p_T range. In Figure 1.20 the p_T -differential cross sections are shown for prompt D mesons from fully reconstructed hadronic decays, $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^+ \rightarrow D^0 \pi^+$ measured with ALICE in pp collisions at $\sqrt{s} = 7$ TeV [67]. As it will be discussed in more details in Chapter 3, the contribution of D mesons coming from B

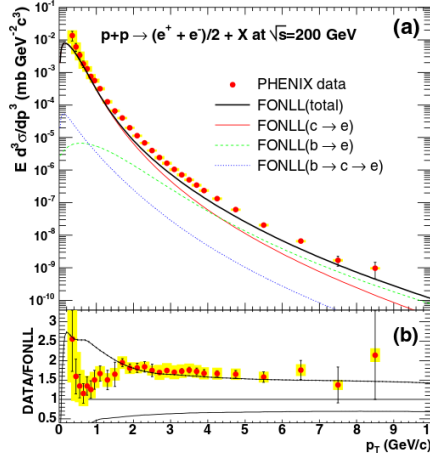


Figure 1.19: Invariant differential cross sections of electrons from heavy-flavour decays measured by PHENIX in pp collisions at $\sqrt{s} = 200$ GeV [65]. The data are compared to FONLL calculations.

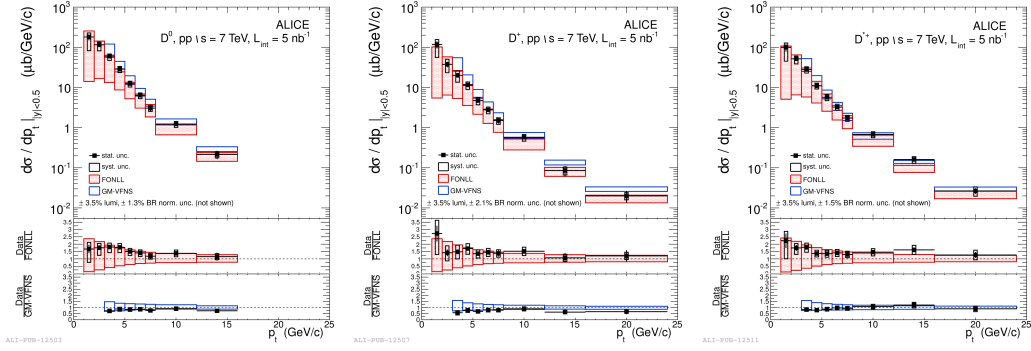


Figure 1.20: p_T -differential cross sections of $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^+ \rightarrow D^0 \pi^+$ measured by ALICE in pp collisions at $\sqrt{s} = 7$ TeV [67] compared to FONLL [68] and GM-VFNS [69] predictions.

meson decays is evaluated using FONLL calculations and subtracted. The results are compared to FONLL [68] and GM-VFNS [69] calculations. Both the predictions are compatible with the data within the uncertainties. The central values of GM-VFNS are systematically above the measurements, while the ones of FONLL are below as already observed at RHIC.

Results in pA collisions

The left panel of Figure 1.21 shows the nuclear modification factor R_{dAu} for electrons from open heavy flavour decays measured with PHENIX in minimum-bias d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [70]. The nuclear modification factor in pA collisions is defined as follows²:

$$R_{pA}(p_T) = \frac{dN^{pA}/dp_T}{\langle N_{coll} \rangle dN^{pp}/dp_T} = \frac{d\sigma^{pA}/dp_T}{A d\sigma^{pp}/dp_T} \quad (1.24)$$

where A is the mass number of the colliding nucleus. The R_{dAu} measured by the PHENIX Collaboration shows an enhancement above unity up to $p_T = 5$ GeV/c. In the right panel of

² For minimum-bias p-Pb collisions at this energies $\langle N_{coll} \rangle = A \frac{\sigma_{tot}^{pp}}{\sigma_{pA}^{pp}}$, where $\sigma_{tot}^{pp} = \frac{N_{pp}}{L_{int}}$.

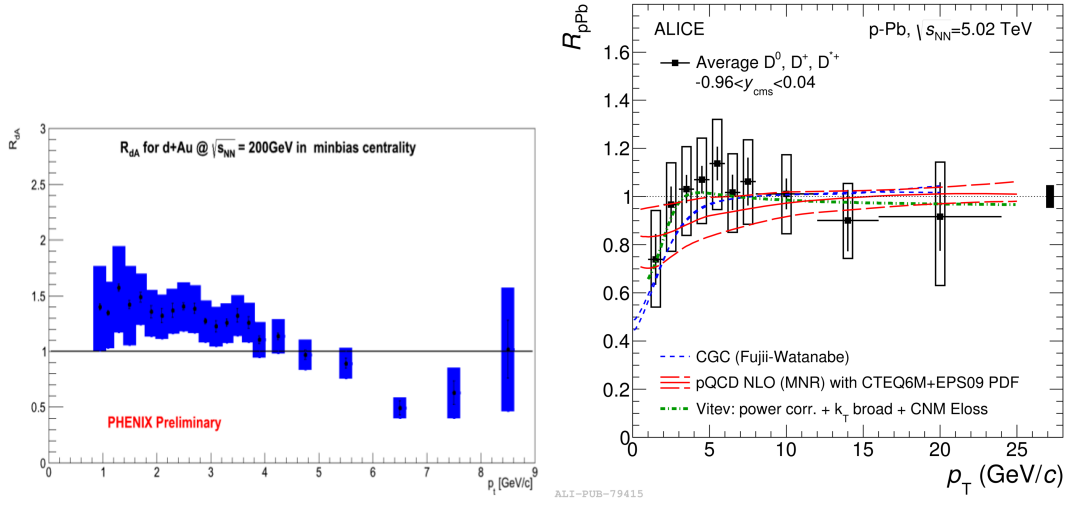


Figure 1.21: Left: nuclear modification factor, R_{dA} , for electrons from open heavy flavour decays measured with PHENIX in minimum-bias d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [70]. Right: D-meson R_{pPb} , averaged for the three mesons, measured with ALICE in minimum-bias p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of the transverse momentum [71]. The result is compared to theoretical calculations [72, 73, 74, 57].

Figure 1.21 the R_{pPb} of D mesons from the hadronic decay channels measured with ALICE in minimum-bias p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of the transverse momentum is shown [71]. The result is a weighted average of the D^0 , D^+ and D^{*+} R_{pPb} and is compatible with unity in all the p_T interval studied. Data are compatible with theoretical calculations [72, 73, 74, 57] that include initial state effects within the uncertainties.

Results in AA collisions

In nucleus-nucleus collisions, the D-meson nuclear modification factor is measured with PHENIX and STAR from semileptonic and hadronic decays. In Figure 1.22 the measurements performed at RHIC are shown. In the left panel the R_{AA} of electrons from open heavy flavour decays measured with PHENIX in 0 – 10% centrality class in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV is shown [75]. In this case, both charm and beauty hadrons decays electrons are included. A R_{AA} compatible with 1 can be observed for $p_T < 1.5$ GeV/c, while a clear suppression is seen for $p_T > 3$ GeV/c. In the right panel the D^0 -meson R_{AA} measured with STAR from hadronic decays is presented in different centrality classes (0 – 10% (c), 10 – 40% (b) and 40 – 80% (a)) [76]. In the 0 – 10% centrality class a suppression of D^0 -meson yield is observed for $p_T > 2.5$ GeV/c. The result is compared with different theoretical calculation, named as explained in the caption [58, 50, 54, 56]. The POWLANG model [58] (named Torino in the figure), that do not include a coalescence type hadronization mechanism for charm quark at low and intermediate p_T , can not describe very well the enhancement observed for $p_T < 3$ GeV/c.

The R_{AA} of electrons and muons [77] from heavy-flavour hadron decays measured by ALICE in 0 – 10% centrality class in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is shown in Figure 1.23. Heavy-flavour decay electron R_{AA} at mid-rapidity ($|y| < 0.6$) is compatible with that of heavy-flavour decay muons at forward rapidity ($2.5 < y < 4$). A clear suppression is observed for the whole p_T interval studied, for $3 < p_T < 20$ GeV/c.

Another observable measured in nucleus-nucleus collisions in both RHIC and LHC is the elliptic flow of open heavy flavour hadrons. In the left panel of Figure 1.24 the elliptic flow of electrons from open heavy flavour decays measured with PHENIX in minimum-bias Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV is shown [75]. A positive v_2 is measured in the low transverse

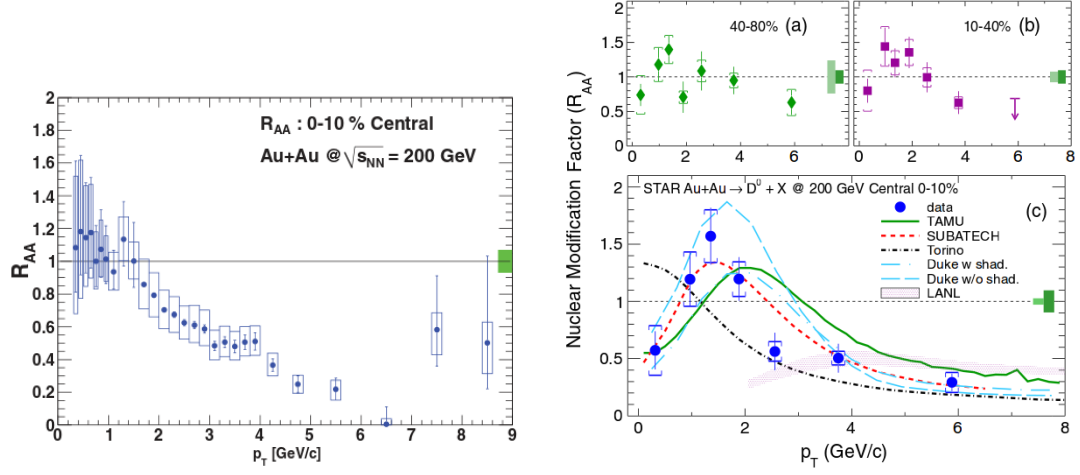


Figure 1.22: Left: R_{AA} of electrons from open heavy flavour decays as a function of p_T measured with PHENIX in 0 – 10% centrality class in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [75]. Right: D^0 R_{AA} measured by STAR in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of the transverse momentum in different centrality classes (0 – 10% (c), 10 – 40% (b) and 40 – 80% (a)) [76]. For the most central events the results are compared to theoretical calculations: the SUBATECH curve correspond to the MC@shQ+EPOS model [54]. The TORINO curve corresponds to POWLANG [58]. The DUKE curve corresponds to Cao, Qinn, Bass [50]. The LANL curve corresponds to Vitev [56].

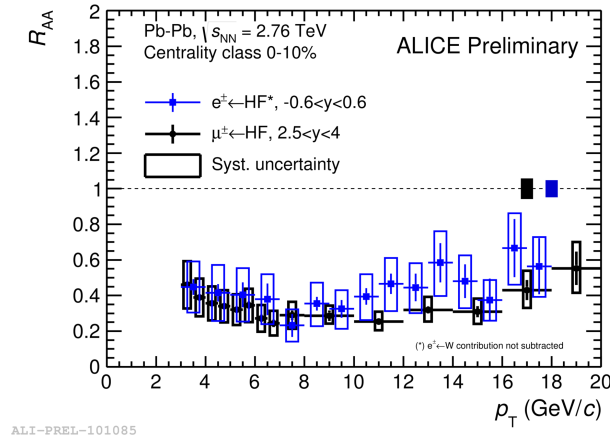


Figure 1.23: R_{AA} of electrons (in blue) and muons (in black) [77] from heavy flavour decays as a function of p_T measured by ALICE in 0 – 10% centrality class in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

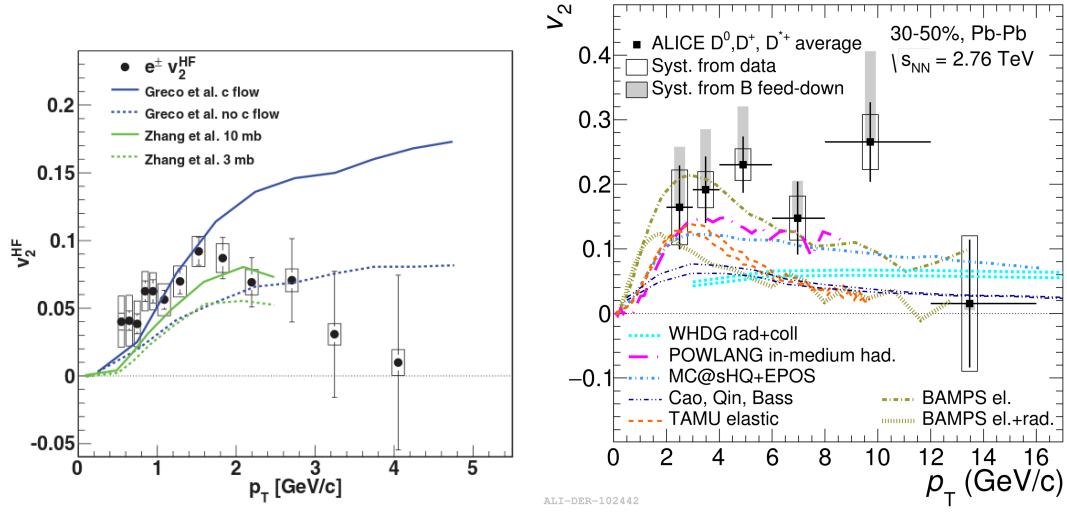


Figure 1.24: Left: v_2 of electrons from open heavy-flavour decays as a function of p_T measured with PHENIX in minimum-bias Au-Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV [75] compared with theoretical calculations [79, 80]. Right: D-meson v_2 , averaged for the three mesons, measured by ALICE in semi-peripheral Pb-Pb collisions (30-50%) at $\sqrt{s_{\text{NN}}} = 2.76$ TeV as a function of the transverse momentum [81]. The result is compared to theoretical calculations [58, 50, 54, 56].

momentum region and this gives a first indication that heavy quarks can be sensitive to the collective expansion of the medium created in heavy-ion collisions. This is also confirmed by ALICE measurement of leptons v_2 from heavy-flavour decays in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [78].

A further indication in the same direction is provided by the measurement of D-meson v_2 by ALICE in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV in the centrality class 30 – 50% [81], shown in the right panel of Figure 1.24. A positive v_2 (with a mean value ~ 0.2) is observed in $2 < p_T < 6$ GeV/c for the weighted average of D^0 , D^+ and D^{*+} . The result is similar to that observed for light-flavour hadrons v_2 , shown in the right panel of Figure 1.9, suggesting that even quark charm is affected by collective motions, despite its large mass. The D-meson v_2 is also compared with theoretical calculations, using the same models as the right panel of Figure 1.22. Data are qualitatively described by models that include both charm quark energy loss in a geometrically anisotropic medium and mechanisms that transfer to charm quarks the elliptic flow induced during the system expansion. Models that do not include a collective expansion of the medium or the hadronization of charm quarks from recombination with light quarks in the medium predict in general a smaller anisotropy than observed in the data. The simultaneous description of R_{AA} and v_2 at both RHIC and LHC energies is still challenging. It will be pointed out also by the D-meson R_{AA} measured by ALICE that is the subject of this thesis and will be presented in Chapter 3. A reduction of systematic and statistical uncertainties on these observables is fundamental to provide further constraints to heavy quarks energy-loss models.

Chapter 2

The ALICE experiment

ALICE (A Large Ion Collider Experiment) is one of the four main experiments at the LHC, the only one optimized for the study of heavy-ion collisions.

2.1 Overview on the LHC Collider

The LHC is the larger collider ever built so far, it consists of a 26.7 km long circular tunnel ~ 100 m underground at the frontier between France and Switzerland. It was designed to accelerate protons at 7 TeV and Pb ions at 2.76 TeV, in order to allow pp collisions at $\sqrt{s} = 14$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. Until today LHC has been providing data in pp collisions at center-of mass energy $\sqrt{s} = 900$ GeV, 2.76 TeV, 7 TeV and 13 TeV, in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and also in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

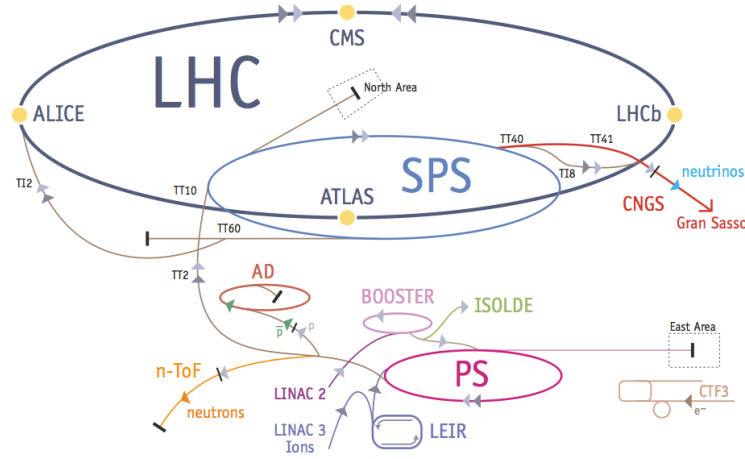


Figure 2.1: Overview of the various accelerating lines at the LHC.

A schematic view of the LHC can be seen in Figure 2.1. The previous accelerator lines that were built in the last decades at CERN and are now used by LHC are also shown. The processes to accelerate protons and ions consist in different steps that mainly differ in the initial stages. Protons are extracted from a hydrogen tank and injected in a linear accelerator (Linac2) in which they reach an energy of 50 MeV. After that, they are accelerated up to 1.4 GeV in the Proton Synchrotron Booster (PSB) and injected in the Proton Synchrotron (PS), which leads to the the Super Proton Synchrotron (SPS). After the SPS, protons at 450 GeV can be injected in the LHC accelerator ring.

The process of ion acceleration (summarized in Figure 2.2) starts from the source of the

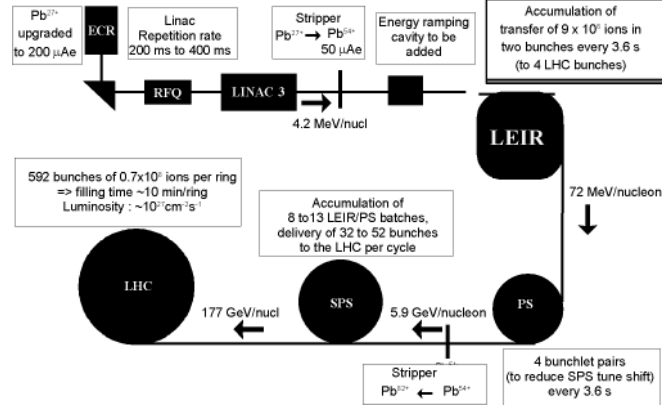


Figure 2.2: Overview of the various accelerating lines at the LHC. The various step to accelerate Pb ion at 2.76 TeV are also indicated.

Pb beam, i.e the ECR (electron-cyclotron resonance), where it is possible to create a gas of Pb atoms. This has to be ionized to obtain a plasma confined with solenoids and hexapoles. The plasma is irradiated with microwaves at high frequency (14.5 GHz) and the extracted electrons pass through a magnetic field of 0.52 T. Then, ions pass through a spectrometer with a 0.3% resolution that selects only ions with a momentum $p=2.5$ KeV/c. Afterwards, they pass through some quadrupoles to ripristinate transversal beam symmetry and through a radiofrequency quadrupole. The latter allows an increase in the momentum up to 250 KeV/c. To accelerate the beam of Pb ions at 4.2 MeV/c a linear accelerator LINAC3 is used. Then, the beam pass through a stripper and 4 synchrotrons that accelerate 10 bunches, each at 95.4 MeV/c. At this point the bunches are ready to go through the PS. There are some difficulties to maintain the heavy-ion beam stable for a long time (the beamlife is 10 hours) because of the electron capture by the pair production process, the intra-beam scattering (Coulombian scattering of particles within the bunch) and spatial charge effect (every particle feels the effect of the spatial charge of the other bunch particles). Up to now these effects limit the luminosity that the accelerator can reach with the Pb beams at the value of $L \sim 1 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ for heavy-ions collisions.

2.2 The ALICE detector

The ALICE detector [82] is built by a collaboration including over 1000 physicists and engineers from 105 institutes in 30 countries. Its overall dimensions are $16 \times 16 \times 26 \text{ m}^3$ with a total weight of approximately 10000 t. The ALICE detector was designed for a predicted multiplicity of charged particles produced in a central Pb-Pb collisions of $dN_{\text{ch}}/dy \sim 8000$ at midrapidity. The granularity of the detectors and their distances from the beam pipe were optimized to cope with such high multiplicities. This turned out to be an overestimation, since the pseudorapidity density measured in central Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ is $1584 \pm 4(\text{stat}) \pm 76(\text{sys})$ [83]. ALICE was designed to investigate the majority of the experimental observables relevant for the QGP characterization. In particular, it can track particles down to 100 MeV/c up to 100 GeV/c and identify them in a wide momentum range using information from different detectors.

A schematic view of the ALICE detector can be found in Figure 2.3. It consists of a central barrel, embedded in a large solenoidal magnet, and a muon arm with a separate dipole magnet. The acceptance of the central detector system covers the pseudorapidity interval $|\eta| < 0.9$ over the full azimuth, while the muon arm covers the pseudorapidity interval $-4 < \eta < -2.4$. The global reference frame consists of the z axis parallel to the beam and pointing to the opposite direction of the muon arm, while the x and y axes lay in the plane transverse to the beam direction. The ALICE magnet (constructed for the L3 experiment at LEP) provides a

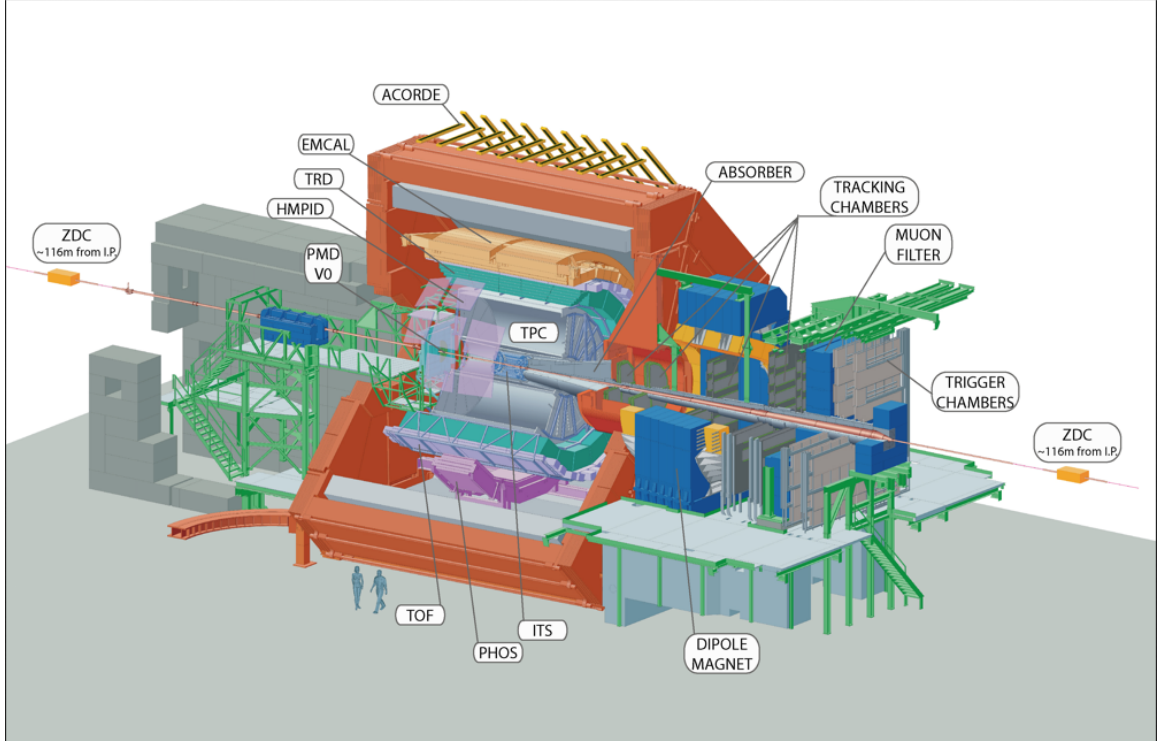


Figure 2.3: Longitudinal view of the ALICE detector.

magnetic field of 0.5 T, parallel to the beam axis. This field has been chosen to have both a good acceptance for low- p_T tracks and a good resolution for high- p_T tracks.

The beam pipe is made of beryllium, a low atomic number element, to minimize multiple scattering in the material. It has an outer radius of 3 cm and a thickness of 0.8 mm.

The central barrel includes the Inner Tracking System (ITS) which consists of 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 (TOF) for charged particle identification.

In addition, other three detectors with smaller acceptances are located at mid rapidity: the High-Momentum Particle Identification Detector (HMPID), which consists of an array of Cherenkov detectors designed to identify high-momentum particles and two electromagnetic calorimeters, the Photon Spectrometer (PHOS) and the Electromagnetic Calorimeters (EMCaL and DCal). The PHOS is dedicated to the measurement of photons and neutral mesons, while the EMCaL and DCal are meant to enhance ALICE capabilities in jet studies, besides from measure neutral mesons and electrons from heavy-flavour decays. The Forward Muon Spectrometer (FMS), which is designed to detect muons, is situated in the pseudo-rapidity range $-4 < \eta < -2.5$. In the same rapidity region there are also a Photon-Multiplicity Detector (PMD) and the Forward Multiplicity Detector (FMD), which is a silicon strip detector built to measure particle multiplicity. In addition, two sets of neutron and proton calorimeters, the Zero Degree Calorimeters (ZDCs) are located about 116 m far from the interaction point at almost zero degrees in order to measure the event centrality in Pb-Pb and p-Pb collisions. Two arrays of scintillator counters, the V0 detectors, are located on each side of the interaction point. They are used in ALICE to provide trigger and centrality information and to allow the rejection of beam-gas interactions. Other two Cherenkov counters, the T0 detectors, are installed to measure the interaction time of the collisions.

In the following paragraphs, a more accurate description of the ALICE detectors used in the analysis presented in this thesis will be provided. For more details on the ALICE apparatus see [84].

Parameter	SPD	SDD	SSD
Spatial resolution $r\phi$ [μm]	12	38	20
Spatial resolution z [μm]	100	28	830
Two tracks resolution $r\phi$ [μm]	100	200	300
Two tracks resolution z [μm]	850	600	2400
Cell size [μm^2]	50×425	150×300	95×40000
Readout channel per module	40960	2×256	2×768
Total number of modules	240	260	1698

Table 2.1: Main specifications of the ALICE ITS.

2.2.1 The Inner Tracking System

The ITS consists in six cylindrical layers of silicon pixel (SPD), drift (SDD) and strip (SSD) detectors. One of the main purpose of the ITS is the precise reconstruction of primary and secondary vertices, originated from the decays of charmed and beauty hadrons. In addition, it is fundamental to reach a high resolution on the momentum resolution of the track and its impact parameter, defined as the distance of closest approach to the primary vertex. The capabilities of the ITS allow the reconstruction and identification of low-momentum tracks with $p_T < 200$ MeV/ c , which are bent too strongly by the magnetic field to be reconstructed by the TPC.

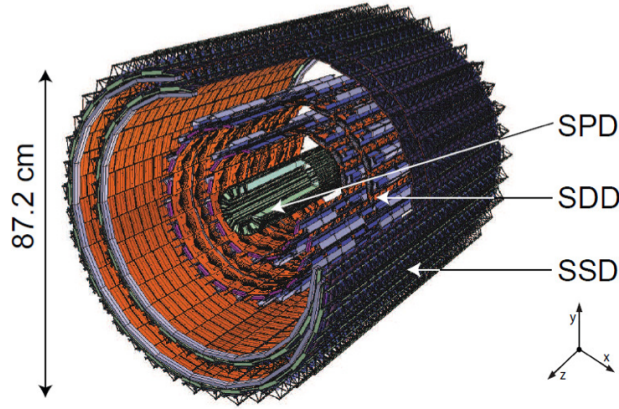


Figure 2.4: The ALICE Inner Tracking System.

The layout of the ITS is shown in Figure 2.4. The ITS is designed to have large acceptance ($|\eta| < 9$), very low material budget to minimize the effect of the multiple scattering and high spatial precision and granularity to guarantee very low occupancy also in central nucleus-nucleus collisions. The first two layers are located at 4 and 7.2 cm from the interaction point. The high particle density in this region requires an excellent position resolution which is achieved with a silicon pixel detector (SPD) with cell size of $50(r\psi) \times 425(z)$ μm^2 . Two layers of silicon drift detectors (SDD) are situated at $r = 15$ and 23.9 cm, while two layers of silicon strip detectors (SSD) are at $r = 38.5$ and 43.6 cm. The SDD is capable of delivering good 2-dimensional space-point resolution together with high two-tracks separation capability and energy loss measurements. At larger distances from the interaction point (where the particle density can be lower than one track per cm^2) the double-sided microstrip detectors still allow for dE/dx measurements and deliver important information for the connection of tracks from the TPC and ITS.

The main parameters for each of the three detector types are summarized in Table 2.1.

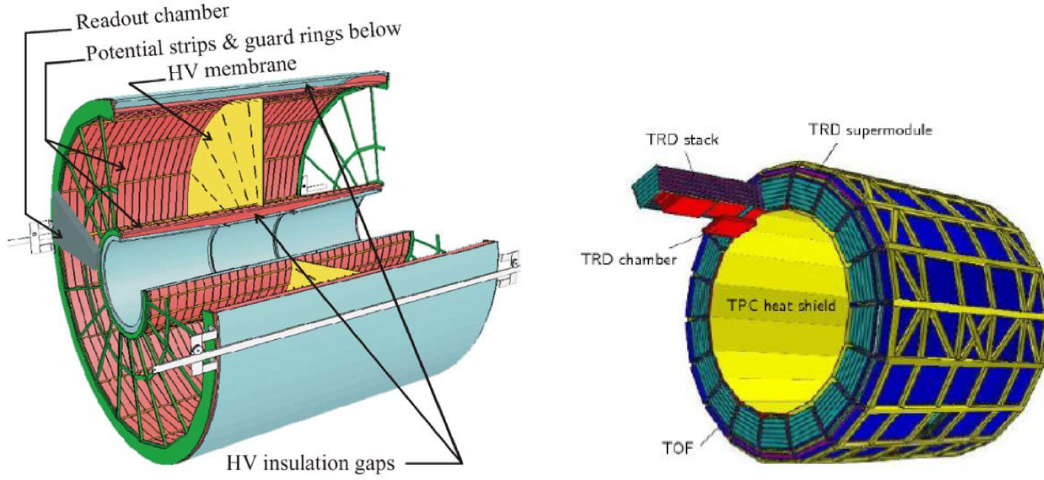


Figure 2.5: A view of the Time Projection Chamber (left) and of the Transition Radiation Detector (right)

2.2.2 Time Projection Chamber

The TPC (shown in the left panel of Figure 2.5) is the main tracking detector in the central barrel and it is optimised to measure the momentum of charged particles with good two-track separation. It also provides excellent particle identification and vertex determination. The global acceptance is $|\eta| < 0.9$ for tracks that pass through all the TPC and 2π azimuthal coverage. For tracks with reduced track length and, hence, reduced momentum resolution it can be extended up to $|\eta| \sim 1.5$.

The inner radius of TPC is 80 cm, determined by the maximum acceptable hit density. The outer radius is 2.5 m and it is determined by the length required to achieve a dE/dx resolution better than 5-7%.

The TPC can be used also as a detector for particle identification in the region of the relativistic rise, up to momenta of order 20 GeV/c.

Inside the TPC there is a drift gas mixture Ne/CO₂/N₂ (90%/10%/5%), optimised for drift velocity and to ensure multiple scattering and secondary particle production. Typical drift velocities of electrons are about 2.7 cm/ μ s which leads to maximum drift time of about 90 μ s. Due to the TPC large drift times, ALICE can not afford high interaction rates and therefore the luminosity in proton-proton collisions has to be reduced by displacing the proton beams or using main- satellite collisions.

2.2.3 Transition Radiation Detector

The main purpose of the TRD (shown in the right panel of Figure 2.5) is to identify electrons above 1 GeV/c (below this value electrons can be identified via specific energy loss measurements in the TPC). It consists of 540 modules, each composed of a wire chamber placed after a composite foam and fibre radiator and a distributed tracklet processor in the front-end electronics for triggering purposes. Charged particles emit x-rays when traversing the interface between two media with different dielectric constant that are detected in the multi-wire proportional readout chamber. This detector is useful for particle with Lorentz factor γ larger than 1000, which corresponds to good electron/pion separation for momenta $1 \leq p \leq 100$ GeV/c. The TRD covers the same rapidity window and the full azimuthal angle of the TPC.

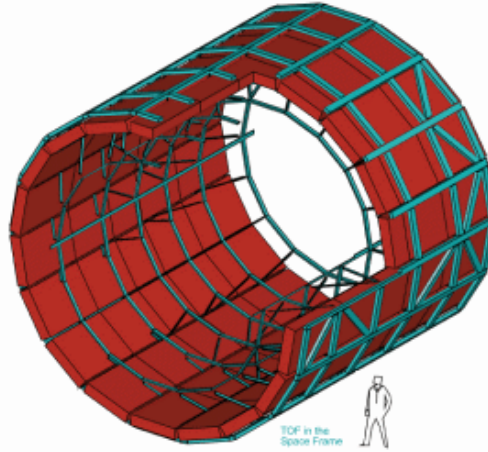


Figure 2.6: Schematic drawing of the Time-Of-Flight detector.

2.2.4 Time-Of-Flight Detector

The TOF (Figure 2.6) detector provides identification of charged particles in the intermediate momentum range (from 0.2 to 2.5 GeV/c) via the measurement of the time of flight. It allows K/ π and K/p separation up to a track momentum $p_T \sim 2.5$ GeV/c and $p_T \sim 4$ GeV/c respectively. The TOF covers the central barrel over an area of 140 m^2 with 160000 individual cells at a radius close to 4 m for an overall longitudinal length of 7.45 m. It covers the central pseudorapidity region ($|\eta| < 0.9$) and the complete azimuthal angle. To cover such a large area and have an intrinsic time resolution below 60 ps, multi-gap resistive-plate chamber (MWPC) detectors are used. They allow to identify particles with different masses measuring their time of flight, knowing their momenta from others detectors. The start time for measurement can be determined with several methods, e.g. using the time-zero given by the T0 detectors. In pp collisions, the total resolution is about 85 ps, while in Pb-Pb collisions is significantly larger (~ 100 ps) due to the larger uncertainty on the start time.

2.2.5 V0

The V0 detector is made of two arrays of scintillator counters located on both sides of the ALICE detector. The V0C is located at 90 cm from the interaction point on the Muon Spectrometer side while the V0A detector is located at 340 cm on the opposite side. The detectors are segmented into 64 elementary counters and distributed in 8 rings which cover the pseudo-rapidity ranges $-3.8 < \eta < -1.7$ (V0C) and $2.8 < \eta < 5.1$ (V0A). The detectors are used to:

- define minimum bias trigger selection, together with the SPD;
- reject beam-gas interactions through the measurement of the time difference between signals in V0A and V0C;
- define the centrality classes in nucleus-nucleus collisions, since the signal amplitude measured in V0 detectors is proportional to the particle multiplicity (see Section 2.5.3).

2.2.6 T0

The T0 detector consists of two arrays of Cherenkov counters placed at -72.7 cm and 375 cm from the nominal interaction point. It is used to generate a start time (T0) for the TOF detector, to measure the vertex position (with a precision ± 1.5 cm) for each interaction and to provide a L0 trigger when the position is within the preset values.

2.2.7 Zero Degree Calorimeters

The ZDC detector consists of two pairs of hadronic calorimeters for neutrons (ZN) and protons (ZP) placed at 116 m from the interaction point on both sides at zero degree angle with respect to the beam direction. The ZDCs are made of heavy materials, tungsten for ZN, brass for ZP and quartz fibres. The latter are used to detect the Cherenkov light produced by charged particles in the hadronic showers. In addition, the ZDC system includes two small electromagnetic calorimeters (ZEM), which are located at 7 m from the collision point. The ZDC detectors provide centrality estimation in Pb-Pb collisions by measuring the energy carried in the forward region by spectators nucleons. A detailed description of the methods of centrality estimation in ALICE in Pb-Pb collisions is provided in Section 2.5.3. ZDCs are also used to reject background events (e.g. machine-induced background due to parasitic collisions from debunched ions).

2.3 Trigger System and Data Acquisition

The hardware trigger in ALICE combines the input from detectors with fast response. It is handled by the Central Trigger Processor (CTP) and operates at three levels to satisfy the individual timing requirements of the different detectors.

Fast trigger detectors, like SPD, V0 and T0, send L0 input trigger to the CTP 1.2 μ s after the collision time-zero. The CTP verifies if the L0 trigger conditions are satisfied and, in the positive case, sends it to the Local Trigger Units (LTUs) of the readout detectors, which start registering the event. A L1 trigger input is sent after 6.5 μ s from the trigger class to the CTP, including slower trigger detectors, otherwise readout detectors stop registering the event. A final trigger (L2 at about 100 μ s) is issued after the end of the maximum drift time of electrons in the TPC. The L2 trigger can also include additional requirements in order to avoid, for example, the presence of two sequential central lead-lead collisions, which would cause a too high occupancy in the TPC. If the L2 requirements are fulfilled, the event can be sent to the Data Acquisition System (DAQ).

The main functions of the DAQ are the transfer of data from the front-end electronics, the event building, performed by the GDC (Global Data Collectors), and the archive of data in the Permanent Data Storage. Once the CTP decides to register a specific event, raw data are sent to the Local Data Concentrators (LDCs) via the optical Detector Data Links (DDLs). LDCs perform sub-event reconstruction, processing the raw data. In this step basic calibrations and reconstruction of hit and cluster are performed. Then, GDCs build the events and an additional event selection and compression is done through the High-Level Trigger (HLT) in order to decrease the data rate from about 25 to 1.25 GB/s.

Events passing those selections are finally transferred to the Permanent Data Storage and registered on tape.

2.4 ALICE Offline framework

The framework adopted by the ALICE Offline project is Aliroot [85], an object-oriented code based on Root [86], a software specifically designed to analyze the huge amount of data coming from high-energy experiments. Aliroot and Root provide the instruments to analyze both simulated and real collisions, including the geometry of the detectors and their response to the passage of the particles. To simulate the particle interactions with the detectors, Aliroot uses different Monte Carlo transport programs, like Geant3 [87], Geant4 [88] and Fluka [89]. Monte Carlo event generators are used to simulate events, for example to evaluate efficiencies. The main event generators used are based on PYTHIA [90] and HERWING [91] for pp collisions, while for proton-nucleus and nucleus-nucleus collisions HIJING [92] and DPMJET [93] are mainly considered. In addition, AliRoot provides the tools for the local reconstruction, vertex reconstruction, tracking and analysis for the whole apparatus. Figure 2.7 schematically shows all the functionalities of the Aliroot framework. The left part of the parabola summarizes the steps from the event simulation from the Monte Carlo generators to the raw data, while the

right part, that is common for real data and Monte Carlo events, describes the process of event reconstruction.

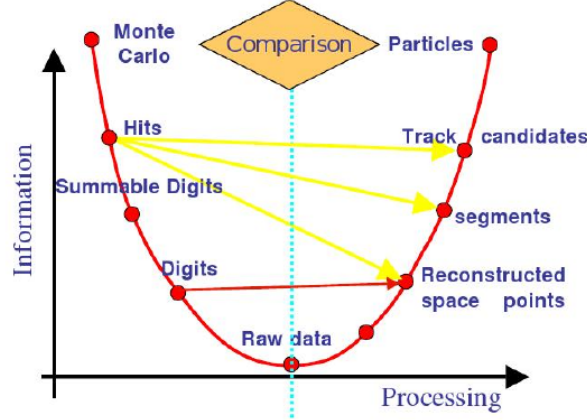


Figure 2.7: The AliRoot data processing framework.

2.4.1 Alien and the Grid

In order to deal with the huge amount of data to be stored by the LHC, a distributed computing project was started in 2000: the Grid [94]. The Grid is an infrastructure that allows to distribute computer resources across institutes and universities which take part in the project. The Grid is based on the MONARC model (Models of Networks Analysis at Regional Centres for the LHC Experiment) and it is organised in different levels or Tiers.

- Tier 0 is located at CERN, where the raw data directly coming from the experiments are stored;
- a second copy is 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 contribute to perform Monte Carlo simulations and to produce manageable files for the analysis by single users.

The interface to the Grid middleware is guaranteed in ALICE by the AliEn environment [94]. The AliEn User Interface, in particular, is used by ALICE users to access the data, send and monitor analysis tasks and simulations.

2.5 ALICE performance

2.5.1 Track and vertex reconstruction

A precise reconstruction of the particle trajectories and the position of the primary and secondary vertices is fundamental for all the physics analyses. The track reconstruction procedure in ALICE is based on a Kalman filter algorithm [95], following those steps:

- the clusters in the two layers of SPD are used to reconstruct tracklets that are considered for the primary vertex determination. The primary vertex is defined as the space point to which the maximum number of tracklets converge. When a 3D reconstruction of the primary vertex is not feasible (essentially in very low-multiplicity events) the algorithm performs a minimization using information from the distance of closest approach (DCA) of tracklets to the beam axis. This method only gives access to the z coordinate of the vertex;

- track seeds are built, starting from the TPC outer layer, first with two TPC clusters and the vertex point, then with three clusters and without the vertex constraint. The seeds are propagated inward and, at each step, updated with the nearest cluster found by the Kalman filter algorithm until the inner radius of the TPC is reached;
- tracks are then propagated to the outermost ITS layer and become the seeds for track finding in the ITS. Each TPC track produces a tree of track hypotheses in the ITS and the candidates are selected according to their reduced χ^2 . The matching efficiency of this step, defined as the ratio of the fraction of TPC tracks that have a prolongation in the ITS, is shown in left panel of Figure 2.8 for data and simulations, different requirements on the ITS hits attached to the track are considered;
- the ITS clusters not used in the TPC-ITS reconstruction are used to perform an ITS stand-alone reconstruction. In fact, the TPC track finding efficiency drops at low p_T (right panel of Figure 2.8), whereas the ITS still has a good performance in this p_T region. This ITS stand-alone reconstruction also allows to reconstruct tracks traversing dead regions of the TPC or decaying before the inner TPC radius;
- once the reconstruction in the ITS is complete, all tracks are extrapolated to their point of closest approach to the interaction vertex, and the outward propagation starts. Once the track reaches the TRD an attempt is made to match it with a TRD tracklet (track segment within a TRD layer) in each of the six TRD layers. Tracks reaching the TOF detector are matched to TOF clusters. The tracks are then propagated further to match with signals in EMCal, DCal, PHOS, and HMPID;
- at the final stage of the track reconstruction, all tracks are propagated inward starting from the outer radius of the TPC. In each detector (TPC and ITS), the tracks are refitted with the previously found clusters. The track position, direction, inverse curvature and its associated covariance matrix are determined. The vertex position is recomputed using these tracks.

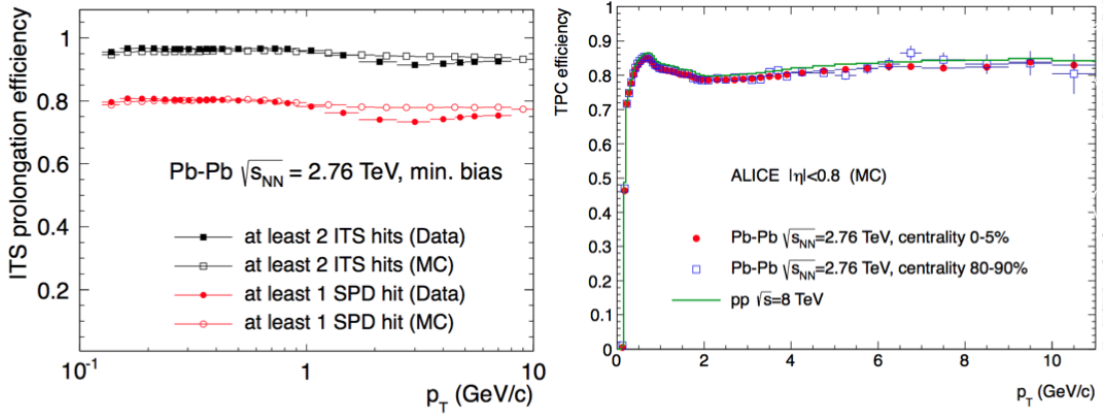


Figure 2.8: Left: ITS-to-TPC matching efficiency as a function of p_T for data and MC in minimum bias Pb-Pb collisions. Tracks used in the evaluation of the matching efficiency are required to have at least 2 ITS hits or at least 1 SPD hit. Right: TPC track finding efficiency from MC simulations for pp collisions at $\sqrt{s} = 8$ TeV, central and peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [96].

The left panel of Figure 2.9 shows the resolution on the transverse distance of closest approach of the track to the primary vertex (impact parameter) for all charged tracks in pp, Pb-Pb and p-Pb collisions. One can notice an improvement of the resolution in p-Pb and Pb-Pb collisions thanks to the more precise determination of the primary vertex for higher multiplicities.

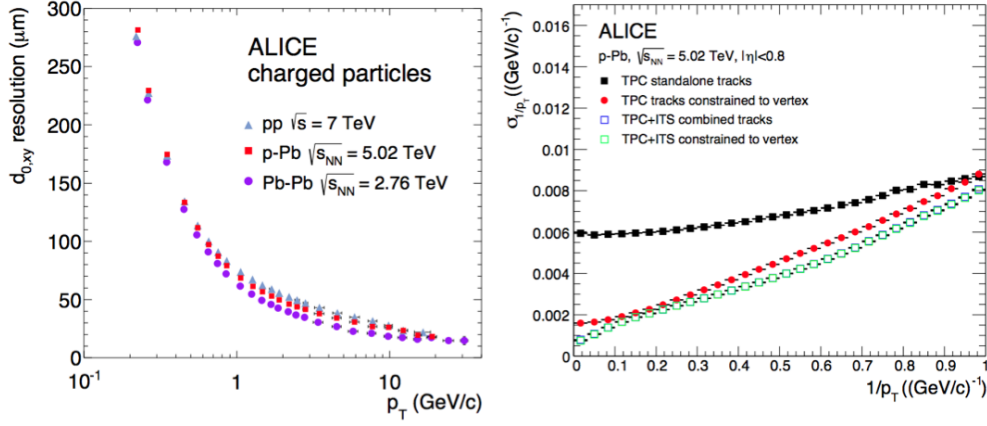


Figure 2.9: Left: resolution on the projection of the impact parameter in the transverse plane for charged particles in pp, p-Pb and Pb-Pb collisions as a function of p_T . Right: inverse- p_T resolution $1/p_T$ as a function of p_T in p-Pb collisions, for TPC and ITS-TPC tracks without and with vertex constrain [96].

The absolute resolution on $1/p_T$ for TPC standalone tracks and ITS-TPC combined tracks is shown in the right panel of Figure 2.9 for the case of p-Pb collisions. The effect of constraining the tracks to the primary vertex is shown as well. The absolute inverse- p_T resolution $1/p_T$, plotted in this figure, is connected to the relative transverse momentum resolution via $\sigma_{p_T}/p_T = p_T \sigma_{1/p_T}$.

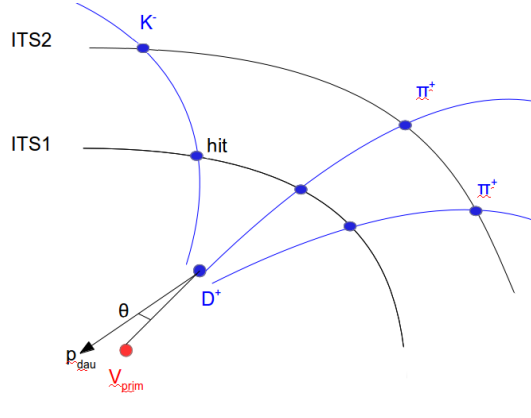


Figure 2.10: Example of a D^+ secondary vertex reconstruction. The blue lines represent the reconstructed charged particle tracks, extrapolated to the secondary vertex candidates. The radii of the ITS planes, in black, are not to scale.

During the event reconstruction, tracks with a distance of closest approach to the interaction vertex exceeding a certain minimum value (0.5 mm in pp and 1 mm in Pb-Pb) are selected in order to calculate secondary decays vertices. As shown in Figure 2.10 for the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay, tracks with the correct combination of signs are grouped together and passed to the vertexing algorithm in the analysis stage. The algorithm is based on the same method used to find the primary vertex in pp collisions: it finds the point of minimum distance in space to the three decay tracks approximated as straight lines.

Figure 2.11 shows the expected resolution on the position of the D^+ secondary vertex. [43]. A resolution below $100 \mu\text{m}$ is achievable in the transverse plane, around a factor 3 below the D^+

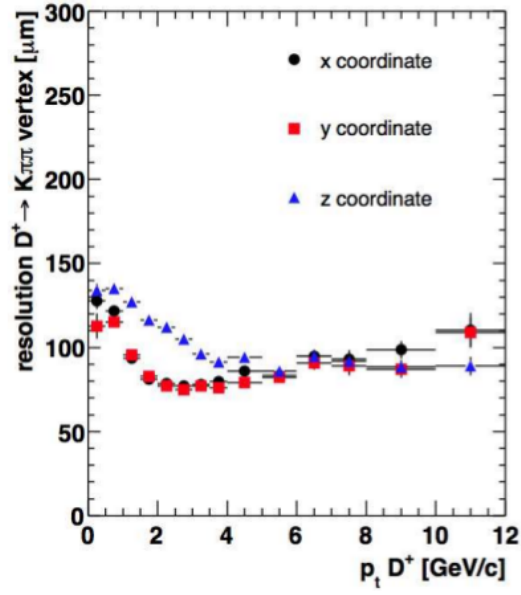


Figure 2.11: Resolution on the three coordinates (x, y, z) of the position of the D^+ decay vertex, as a function of the transverse momentum of the D^+ [43].

decay length. A poorer resolution is achievable at low p_T , where the daughter particles have low momentum and are more affected by multiple scattering, and at high p_T , where the tracks are more collinear with the direction of the parent D^+ momentum.

Tracks and candidate vertices have to pass a second selection: a set of topological cuts that will be discussed in more details in the next Chapter.

2.5.2 Particle identification

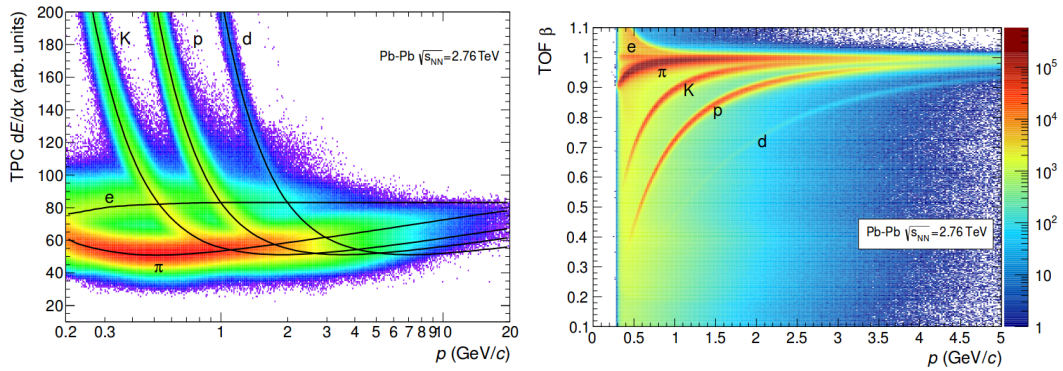


Figure 2.12: Left: Specific energy loss (dE/dx) in the TPC vs. particle momentum in Pb-Pb collisions. The lines show Bethe-Block curves of the expected mean energy loss for electrons, pions, kaons and protons. Right: TOF measured velocity distribution as a function of momentum in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [96].

The particle identification is performed in ALICE combining the information from different detectors.

In the case of the analysis performed in this thesis, the TPC and TOF signals are used to

identify pions and kaons. In the TPC, as discussed in Section 2.2.2, the charge is deposited on up to 159 pad rows and a truncated mean dE/dx (40% highest-charge clusters are discarded) is calculated and used for a wide range of momenta. The mean energy-loss per path length dE/dx as a function of the velocity of the particle β is described by the Bethe-Bloch formula. Therefore, one can obtain the identity of a particle by comparing the specific energy loss in the TPC with the one expected for the different mass hypothesis at a given particle momentum. The relative dE/dx resolution is measured to be about 6% for tracks that cross the entire detector. Instead, the TOF measures the arrival time of particles with a resolution of ~ 100 ps, providing complementary particle identification capabilities in the intermediate momentum range. In both detectors tracks are identified on the basis of the difference, expressed in units of resolution (σ), between the measured signal and that expected for the considered particle species.

In the Figure 2.12 the PID performance of the TPC (left) and TOF (right) are presented. The separation of hadron species can be improved by combining information from TOF and TPC, thus allowing a further extension of the momentum range for identified particle measurements.

2.5.3 Centrality determination in Pb-Pb collisions

The Glauber model, introduced in Section 1.1.4, is adopted to determine the centrality class in Pb-Pb collisions [97]. The impact parameter is not directly measurable in the experiment, so it is necessary to find a connection between the impact parameter and an experimental observable. In this section, the procedure to express the centrality of nuclear collisions not in terms of the impact parameter b but via a percentage of the total hadronic interaction cross section σ_{AA} is described.

The centrality percentage c of an AA collision with $0 < b < b_{\max}$ is defined integrating the impact parameter distribution $d\sigma/db$ as:

$$c = \frac{1}{\sigma_{AA}} \int_0^{b_{\max}} \frac{d\sigma}{db} db \quad (2.1)$$

The Glauber model can be used to generate the number of binary nucleon collisions, N_{coll} , and the number of participant nucleons that experience at least one collision, N_{part} , for each event in Pb-Pb collisions giving the value of the impact parameter b . The particle multiplicity per nucleon-nucleon collision is parametrized with a Negative Binomial Distribution (NBD):

$$P_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \cdot \frac{(\mu/k)^n}{(\mu/k + 1)^{n+k}} \quad (2.2)$$

where k is a parameter related to the width of the distribution and μ is the mean multiplicity per *ancestor*, i.e. an emitting source of particles. The number of ancestors is defined as $N_{\text{ancestors}} = fN_{\text{part}} + (1-f)N_{\text{coll}}$, with f as a free parameter. This definition accounts for the soft and hard components of a particle production which are expected to scale with N_{part} and N_{coll} , respectively.

The global multiplicity is then obtained summing the multiplicities generated by all the ancestors of the event. Using this model, the experimental multiplicity distribution (proportional to the amplitudes of the V0 scintillators) can be fitted with respect to the free parameters k , μ and f , that appears in the definition of $N_{\text{ancestors}}$, via a χ^2 -minimization procedure in the multiplicity range. In the left panel of Figure 2.13 the distribution of the sum of the amplitudes of the V0 scintillators is fitted with the Glauber-NBD distribution and the parameters extracted are shown. After that, the 100% of the hadronic cross section is determined by the fit, the centrality classes are obtained by slicing the multiplicity distribution from most central to peripheral events. For each centrality class, one can obtain the average number of binary collisions, $\langle N_{\text{coll}} \rangle$, and of participant nucleons, $\langle N_{\text{part}} \rangle$, and the average nuclear overlap function T_{AA} , which are needed for this analysis. A discrepancy between the fit and the data distribution is visible for peripheral events (above 90% of the total hadronic cross section) where trigger effects and electromagnetic process are not negligible.

The method described above is used also to fit other observables: the number of clusters in the

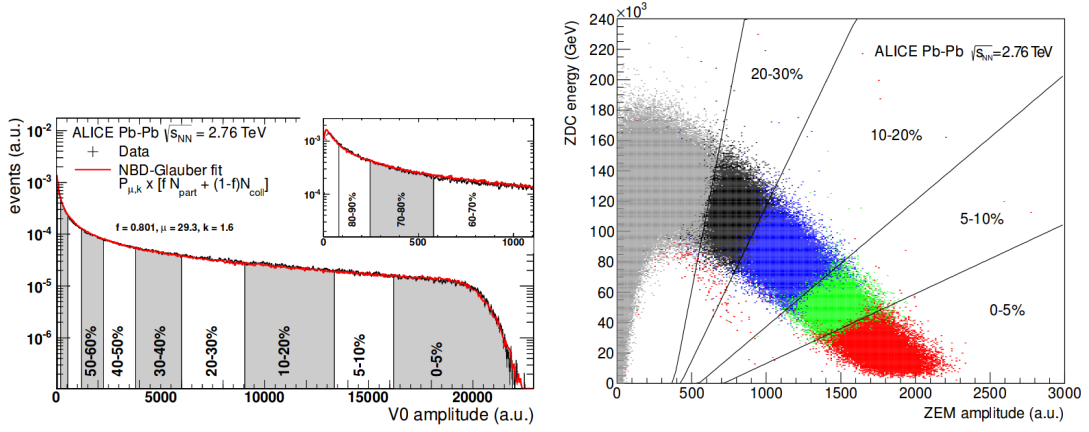


Figure 2.13: Left: Distribution of V0 amplitude in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The distribution is fitted with the NBD-Glauber distribution plotted as a red line. Right: Spectator energy deposited in the ZDC calorimeters as a function of ZEM amplitude. [97]

second layer of SPD and the number of tracks reconstructed in the TPC.

Another way to determine the centrality classes is to measure the energy deposited by the spectator nucleons in the ZDC. In the ideal case, the number of participant nucleons N_{part} and the energy deposited in the ZDC, E_{ZDC} , are related by this simple equation:

$$N_{part} = 2A - E_{ZDC}/E_A \quad (2.3)$$

where $A=208$ is the mass number of Pb and E_A is the beam energy per nucleon.

In practice this monotonic relation between N_{part} and E_{ZDC} does not hold for peripheral events because spectator nucleons can bound into light nuclear fragments with a charge over mass ratio similar to the ion beam. Therefore, they remain in the beam pipe and becoming undetectable by the ZDC. A quantity that has a monotonic increasing behaviour with N_{part} is the energy deposited in the ZEM detectors. The additional information provided by the ZEM can be used to define centrality classes. In the right panel of Figure 2.13 the correlation between ZDC and ZEM amplitudes is shown. Centrality classes can be defined cutting the plane into regions by straight lines. This method is reliable only in 0-30% centrality region, above which the monotonic relation is not trustable any more and, therefore, the correlation between ZDC and ZEM is lost. The centrality classes defined according to the V0 selection are in agreement with the ones obtained with the ZDCs and ZEM information. Usually these information are used to assess the systematic uncertainties on the centrality determination.

Chapter 3

D⁺ meson production in Pb-Pb collisions

The analysis of D⁺-meson production in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV on data collected in 2011 at LHC is presented in this Chapter.

ALICE has already published a paper in 2012 on the suppression of high transverse momentum D mesons in central Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV from data collected in 2010 at LHC [98]. In that analysis D⁺ mesons were studied in the 0 – 20% centrality class, the most central collisions, as a function of transverse momentum in three p_{T} intervals: 6-8, 8-12 and 12-16 GeV/c and as a function of the centrality class in $6 < p_{\text{T}} < 12$ GeV/c (0-10%, 10-20%, 20-40%, 40-60% and 60-80% centrality classes).

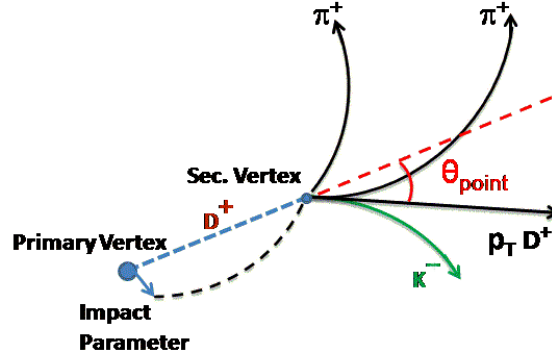
The aim of this thesis is to extend the p_{T} interval considered both in the study as a function of p_{T} to $3 < p_{\text{T}} < 36$ GeV/c and in the study as a function of the centrality of the collision to $3 < p_{\text{T}} < 16$ GeV/c (0-10%, 10-20%, 20-30%, 30-40%, 40-50% and 50-80% centrality classes). Moreover, the study as a function of p_{T} will be made in a narrower centrality class of 0 – 10% Pb-Pb collisions. This is possible thanks to the centrality trigger applied to the data collected in 2011 that allows an integrated luminosity in central collisions larger by a factor of about 10 with respect to the previously published results.

The strategy adopted to reconstruct the D⁺-meson raw-yield is described in the first section, while the results are presented in the second section. Then, all the corrections applied to the measured yields to obtain the p_{T} -differential cross-section are outlined in the third section. A detailed description of all the contributions to the systematics uncertainties is provided in the fourth section. In the last section the results of the D⁺ corrected yields and nuclear modification factor are presented and discussed in comparison to other D mesons, other particles and models.

3.1 Reconstruction of D⁺-meson hadronic decays

D⁺ mesons and their charge conjugates (D⁻ mesons) are measured in the central rapidity region $|y| < 0.8$ via the exclusive reconstruction of their hadronic decay channel $\text{D}^+ \rightarrow \text{K}^- \pi^+ \pi^+$ ($\text{D}^- \rightarrow \text{K}^+ \pi^- \pi^-$). The branching ratio of this decay is $9.13 \pm 0.19\%$ [6]. A schematic view of the $\text{D}^+ \rightarrow \text{K}^- \pi^+ \pi^+$ decay is shown in Figure 3.1. The D⁺ mean proper decay length is $c\tau = 312 \mu\text{m}$.

Thanks to ALICE detectors capabilities it is possible to separate D⁺ secondary vertices from the main interaction vertex. The analysis strategy is based on selection of decay topologies with secondary vertices sufficiently displaced from the primary vertices. Furthermore, a selection on the displacement of the decay tracks from the secondary vertex is applied and the particle identification is used to reduce the large combinatorial background. For this analysis ITS, TPC and TOF are used as described in Section 2.5.

Figure 3.1: Schematic view of the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay channel.

Centrality	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$	$\langle T_{\text{AA}} \rangle \text{ (mb)}^{-1}$
0-10%	356 ± 4	1501 ± 142	23.44 ± 0.76
10-20%	260 ± 4	921 ± 96	14.39 ± 0.45
20-30%	172 ± 3	557 ± 55	8.70 ± 0.28
30-40%	129 ± 3	320 ± 31	5.00 ± 0.19
40-50%	85 ± 3	171 ± 16	2.68 ± 0.13
50-80%	33 ± 1	46 ± 4	0.72 ± 0.07

Table 3.1: Average of the nuclear overlap function, number of participants and number of collisions for the centrality classes analyzed [97].

3.1.1 Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$

The analysis is performed on a data sample of Pb-Pb collisions collected in November-December 2011 at a center-of-mass energy $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$. A minimum-bias interaction trigger based on information from the V0 detector is used. The events are selected if a coincidence of signal on both V0A and V0C is registered. Beam-gas events are removed using the time information provided by the T0 and by the neutron ZDC detectors. Only events with a vertex position on the z-direction (along the beam line) within 10 cm from the nominal interaction point were considered. An online selection based on the information from V0 detectors is used to divide the events in centrality classes, as described in Section 2.5.3. Two separate trigger classes are used to select central and semi-central collisions. The analysis is performed on ~ 16.4 Million events in the most central collisions 0 – 10% and ~ 4.5 Million events in each centrality class: 10 – 20%, 20 – 30%, 30 – 40% and 40 – 50%. In the 50-80%, where the 2010 data are used, the analyzed event sample corresponds to ~ 5.1 Million events. The average of the nuclear overlap function, the average number of participants and of collisions for the centrality classes analyzed [97] are listed in Table 3.1.

In Figure 3.2 the centrality percentile distribution is shown for the most central collisions 0 – 10%. An offline selection (*flattening*) is used to flat the sample to overcome the bias due to inefficiency of the trigger. The trigger bias is evident in the range 7.5 – 12%, hence the flattening procedure is adopted in the 0-10% and 10-20% centrality classes to avoid further statistical fluctuations.

3.1.2 Candidate selection

D^+ candidates are defined from triplets of tracks with the proper charge sign combination. Tracks are considered only if they have these characteristics: a fiducial acceptance of $\eta < 0.8$ and a transverse momentum $p_{\text{T}} > 0.4 \text{ GeV}/c$. Furthermore, they should have at least 70 associated space points (out of a maximum of 159) and a fit quality $\chi^2/ndf < 2$ in the TPC

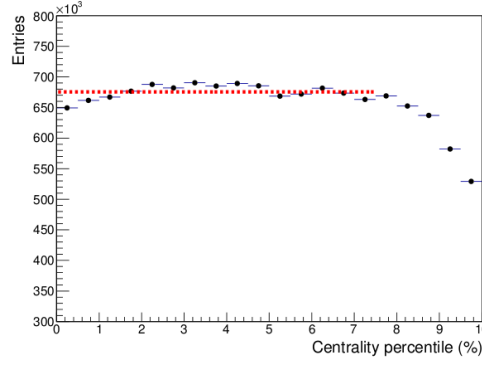


Figure 3.2: Centrality percentile distribution in the range 0 – 10% in bins of 0.5%.

and at least two hits (out of six) in the ITS, out of which at least one in either of the two SPD layers. As a consequence of the track selection, a p_T -dependent fiducial acceptance cut y_{fid} is applied to D^+ -meson rapidity. This is done to avoid border effects for the steeply decrease down to zero of the D^+ acceptance in rapidity at $|y| \sim 0.5$ at low p_T and at $|y| \sim 0.8$ at $p_T > 5$ GeV/c. The $y_{fid}(p_T)$ follows this function: $y_{fid}(p_T) = -0.2/15 \times p_T^2 + 1.9/15 \times p_T + 0.5$. Since the candidates are built from combinations of tracks, a huge combinatorial background covers the D^+ signal. Therefore, selection criteria based on the kinematical and topological characteristics of the reconstructed decay are applied to reduce the background and select the D^+ signal. In the left panel of Figure 3.3 an example of the D^+ invariant mass distribution without any topological selection is shown and no peak is visible in the D^+ mass region. On the other hand, a clear peak is visible in the right panel of Figure 3.3 where the topological selection is applied.

The topological and kinematic variables used to select the signal are:

- **Decay length:** distance between primary and secondary vertices, the selection cut varies from 0.09 to 0.174 cm. Another selection is made on the projection of the decay length in the transverse plane divided by its uncertainty (L_{XY}) and multiplied by the factor p/p_T : $L_{XY} = \frac{(\text{decay length})_{XY}}{\delta(\text{decay length})_{XY}} \frac{p}{p_T}$. L_{XY} varies from 6 to 13.
- **Pointing angle θ_{pointing} :** the angle between the D^+ -meson flight line (the line that joins the primary and secondary vertices) and the direction of the reconstructed D-meson momentum. The variables used are the cosine of the pointing angle ($\cos(\theta_{\text{pointing}})$) and its projection on the transverse plane ($\cos(\theta_{\text{pointing}}^{XY})$). The latter is used because of the better secondary vertex resolution in that plane. The cut on $\cos(\theta_{\text{pointing}})$ and $\cos(\theta_{\text{pointing}}^{XY})$ varied from 0.95 to 0.999, since the signal distributions of the D^+ candidate are peaked at $\cos(\theta_{\text{pointing}})$ and $\cos(\theta_{\text{pointing}}^{XY})$ equal to 1.
- **σ_{vertex} :** selection on the distance of closest approach of the daughter tracks, approximate to straight line, to the secondary vertex d_1 . σ_{vertex} is defined as follows: $\sigma_{\text{vertex}} = d_{1,pi}^2 + d_{1,\pi}^2 + d_{1,k}^2$. Only candidates with a σ_{vertex} lower than the cut are considered. The selection cut varies from 0.015 to 0.023 cm.
- **Daughter tracks p_T :** only daughter tracks with a p_T above a cut that varies from 0.4 to 0.9 GeV/c are kept.
- **PID:** pions and kaons were identified using TPC and TOF detectors, as described in Section 2.5.2. A 3σ compatibility cut is applied to the difference between the measured and expected signals (for pions and kaons) for the TPC dE/dx and TOF time-of-flight. In the case that a matched hit is not found in the TOF detector, only the TPC information is used to identify the particle species. The particle identification is used for $p_T < 16$ GeV/c.

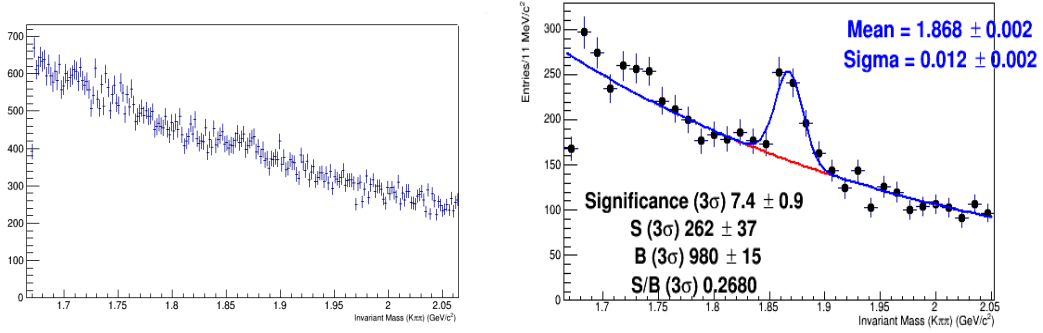


Figure 3.3: Example of the D^+ invariant mass distribution without (left) and with (right) applying the topological selections in $4 < p_T < 5$ GeV/c in 0 – 10% Pb-Pb collisions.

3.1.3 Signal extraction

The D-meson raw yield is extracted from a fit of the invariant mass distribution $M(k\pi\pi)$ of D^+ candidates in each p_T interval. The function used to fit the distribution is composed of a Gaussian for the signal and an exponential term for the background. Different background functions are then considered for the systematic uncertainty evaluation of the raw yield extraction, as will be described in Section 3.4.2.

The fitting procedure is based on a χ^2 minimization approach in two steps:

1. A preliminary estimation of the background shape is obtained by fitting the invariant mass regions outside the signal peak (*side bands*).
2. The total fit is performed using as a starting point the parameters evaluated in the first step for the background.

In the right panel of Figure 3.3 an example of a fitted invariant mass distribution is shown for $4 < p_T < 5$ GeV/c in 0 – 10% Pb-Pb collisions. The blue line represents the final fit with the Gaussian and exponential functions, while the red line indicates the background component. The signal S and the background B are evaluated by integrating the Gaussian and the exponential function, respectively, around $\pm 3\sigma$ from the Gaussian mean. Different criteria are used to optimize the yield extraction. First of all, the maximisation of the statistical significance (*Significance*), which is defined in Equation 3.1, has to be considered.

$$Significance = \frac{S}{\sqrt{S+B}} \quad (3.1)$$

A Significance higher than 5 indicates that the probability for the peak being a fluctuation of the exponential background is lower than 2.87×10^{-7} . The Significance can also be used to estimate the statistical uncertainty on the extracted signal ($\sigma_S/S \sim 1/Signif$). Then, the maximisation of the signal over background ratio (S/B) is also taken into account. Furthermore, the position and the width of the Gaussian function are required to be compatible with the values evaluated through a Monte Carlo simulation (MC). The position of the peak is also compared with the PDG mass value of the D^+ meson: 1.869 GeV/c² [6].

3.2 Signal extraction results in Pb-Pb collisions

The signal extraction method, described above, is applied to the 2011 Pb-Pb data sample to extract D^+ signals in different transverse momentum intervals and in different centrality classes. The analysis is performed in the 0 – 10% centrality class in 8 p_T intervals in the range $3 < p_T < 36$ GeV/c (**study as function of p_T**) and in centrality classes from 0 to 50% (in bins of 10%) in 3 p_T intervals [3,5], [5,8] and [8,16] GeV/c (**study as function of the**

p_T (GeV/c)	[3,4]	[4,5]	[5,6]	[6,8]	[8,12]	[12,16]	[16,24]	[24,36]
$ \Delta M_{D^+} $ MeV/ c^2	200	200	200	200	200	200	200	200
σ_{vertex} (cm)	0.02	0.02	0.023	0.02	0.015	0.015	0.015	0.018
$p_T(K)$ GeV/ c	0.6	0.87	0.9	0.6	0.6	0.6	0.6	0.6
$p_T(\pi)$ GeV/ c	0.6	0.73	0.8	0.7	0.6	0.6	0.6	0.6
Decay Length (cm)	0.14	0.16	0.17	0.17	0.096	0.122	0.174	0.12
$\text{Cos}(\theta_{\text{pointing}})$	0.994	0.9984	0.9984	0.998	0.994	0.976	0.97	0.98
$\text{Cos}(\theta_{\text{pointing}}^{XY})$	0.9984	0.9984	0.9985	0.994	0.994	0.994	0.95	0.975
L_{XY}	13	13	13	10	10	9	6	10

Table 3.2: List of the topological selections applied for the D^+ analysis in the 0–10% centrality class.

centrality class). The topological cuts adopted in the 0 – 10% centrality class are summarized in Table 3.2. They depend on the p_T of the D^+ meson. but giving the combination of several selection variables, it is not easy to identify a trend. A similar selection is used in the analysis as a function of the centrality class, in this case the cut values become tighter from peripheral to central collisions where the amount of background to be subtracted is higher. The particle identification is used in each p_T interval, except for the [16,24] and [24,36] GeV/ c in the 0 – 10% centrality class, where the particle identification of daughter tracks is not reliable any more (see Figure 2.12).

The invariant mass distributions of the D^+ candidates are shown in Figure 3.4 in 0 – 10% centrality class for the study as a function of p_T and in Figure 3.5 for the study as a function of centrality classes. The fit described above is applied to extract signal, significance and signal over background ratio. A Significance above 4 can be obtained in each transverse-momentum interval studied.

The stability of the fit parameters (mean and sigma of the Gaussian fit) is also checked comparing the results with Monte Carlo in Figure 3.6 and 3.7. The results are shown in the 0 – 10% centrality class as a function of p_T (Figure 3.6) and in $5 < p_T < 8$ GeV/ c as a function of the centrality classes (Figure 3.7). Similar results are obtained in the other cases. A good agreement is observed in almost all the p_T intervals studied. In some cases a difference of the order of 1 or 2σ is visible in the sigma and the possible effect of this difference is considered in the systematic uncertainty evaluation (see Section 3.4.2).

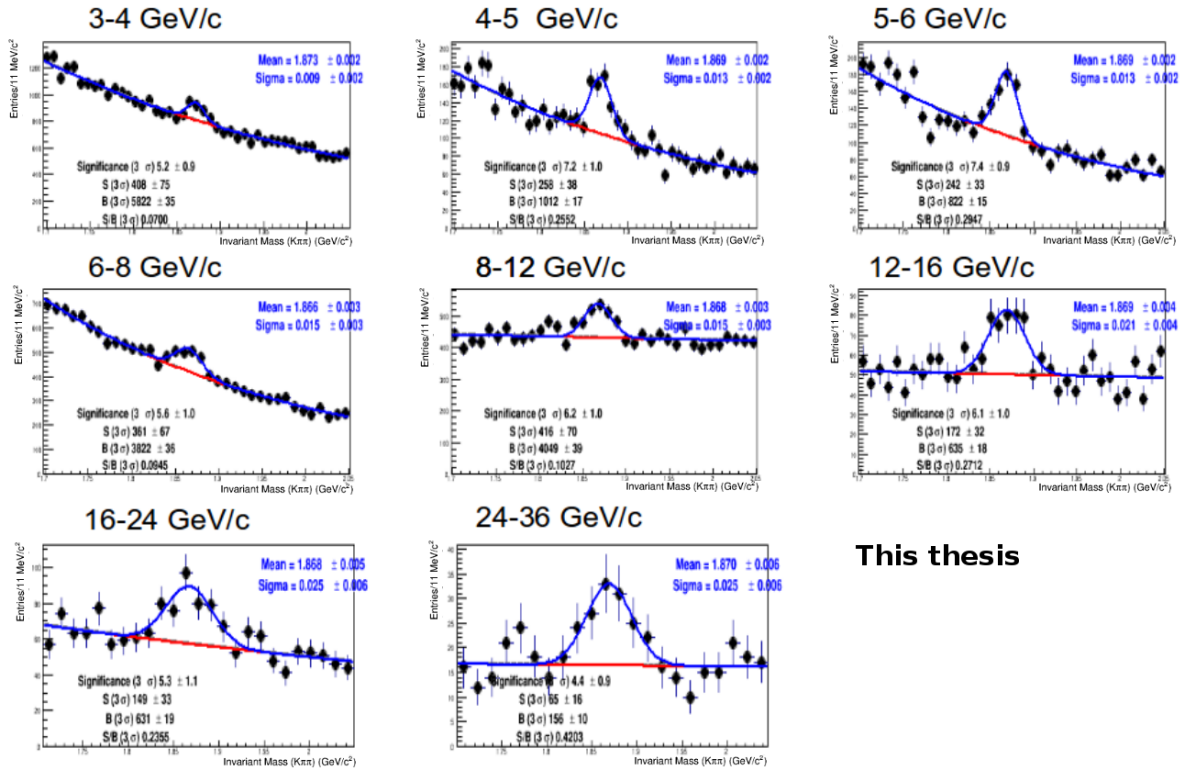


Figure 3.4: Invariant mass distributions of D^+ candidates in 8 p_T bins in the range $3 < p_T < 36$ GeV/c in the 0–10% centrality class.

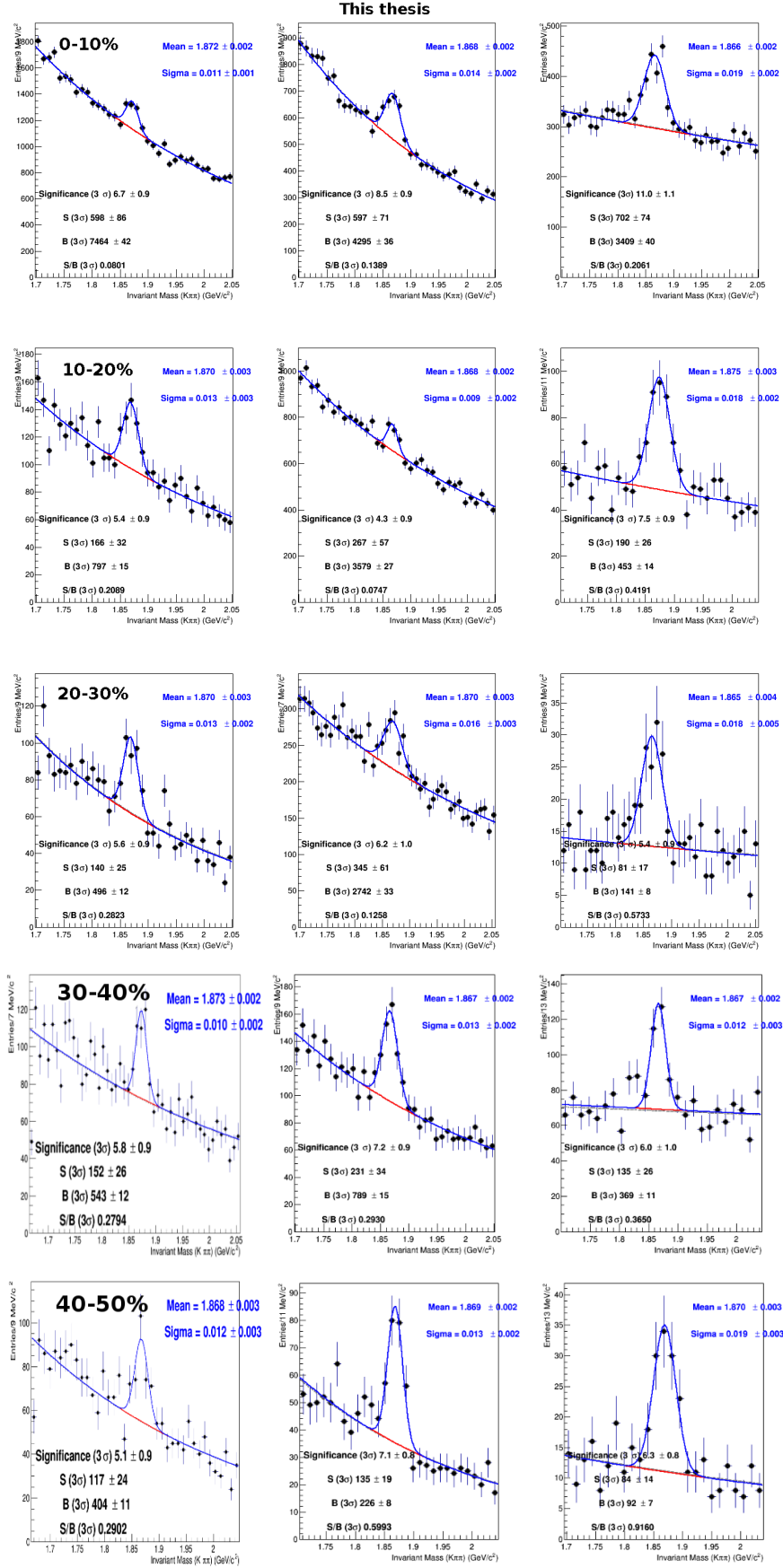


Figure 3.5: Invariant mass distributions of D^+ candidates in the p_T intervals [3,5] (left), [5,8] (center) and [8,16] (right) GeV/c in centrality classes from 0 to 50% (from top to bottom 0-10%, 10-20%, 20-30%, 30-40% and 40-50%).

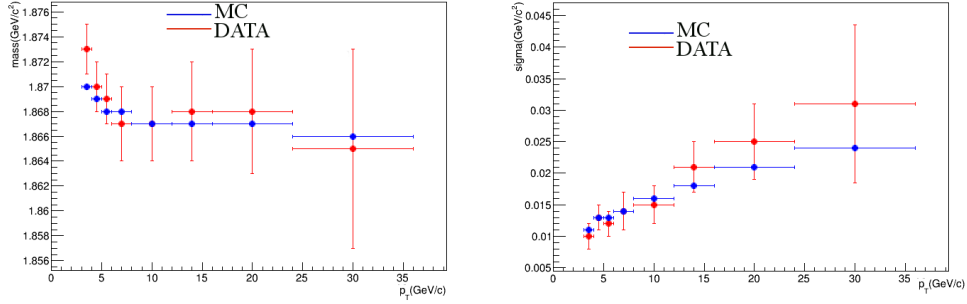


Figure 3.6: Comparison of the mass (left) and sigma (right) from the fit to the D^+ invariant mass distribution in data (red) and MC (blue) in the centrality class 0 – 10% as a function of p_T .

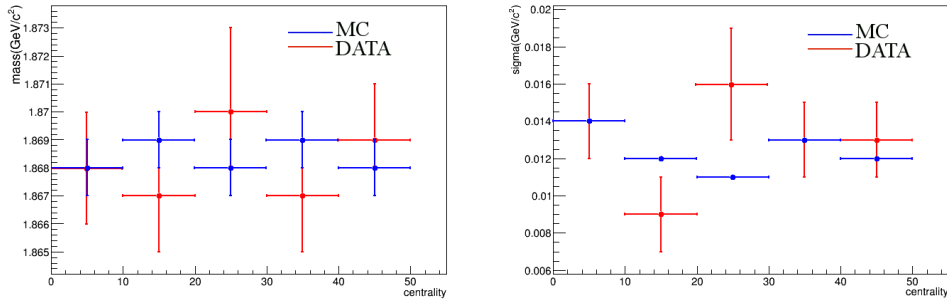


Figure 3.7: Comparison of the mass (left) and sigma (right) from the fit to the D^+ invariant mass distributions in data (red) and MC (blue) in $5 < p_T < 8 \text{ GeV}/c$ as a function of the centrality class.

3.3 D⁺-meson corrected yield

Once the raw yield $N^{\text{D}^+ \text{raw}}$ is extracted, the D⁺ corrected yield can be evaluated using the following equation:

$$\left. \frac{dN^{\text{D}^+}}{dp_T} \right|_{|y| < 0.5} = \frac{1}{2} \frac{1}{\Delta y \Delta p_T} \frac{f_{\text{prompt}} \cdot N^{\text{D}^+ \text{raw}} \Big|_{|y| < y_{fid}}}{(Acc \times \varepsilon)_{\text{prompt}} \cdot BR \cdot N_{ev}} \quad (3.2)$$

where:

- the factor $1/2$ takes into account that the corrected yield is defined for D⁺ while the measured raw yields include the contributions of D⁺ and D⁻ mesons;
- $\Delta y = 2 \times y_{fid}$; is the D⁺-meson rapidity interval;
- Δp_T is the width of transverse momentum range;
- f_{prompt} is the D⁺ mesons prompt fraction (i.e. D⁺ mesons not coming from B decays);
- $(Acc \times \varepsilon)$ is the acceptance-times-efficiency correction factor for prompt D⁺ mesons;
- BR is the decay branching ratio;
- N_{ev} is the number of events analyzed.

The factors $(Acc \times \varepsilon)$ and f_{prompt} are described in details in the following sections.

3.3.1 Efficiency and acceptance corrections

The acceptance-times-efficiency correction factor is evaluated as follows:

$$(Acc \times \varepsilon)_{\text{prompt}} = Acc_{\text{prompt}} \times \varepsilon_{\text{prompt}} \quad (3.3)$$

The factor Acc_{prompt} is defined as the number of prompt D⁺ candidates with the three prongs in the geometrical acceptance of the central barrel detector ($|\eta| < 0.8$), normalized by the total number of prompt D⁺ candidates with rapidity ($|y| < y_{fid}$).

The factor $\varepsilon_{\text{prompt}}$ is defined as the number of reconstructed D⁺ mesons that pass the kinematical and topological cuts and the PID selection normalized by the number of D⁺ candidates with the three prongs in the geometrical acceptance of the central barrel detector.

Acceptance and efficiencies are extracted from Monte Carlo simulations. The Monte Carlo sample in pp collisions is made of pp events generated with PYTHIA v6.421 [90]. Since charm production has low cross section, a charm-enriched Monte Carlo data sample is generated to evaluate D⁺-meson efficiencies with low statistical uncertainties and computation costs. Therefore, only events satisfying one of these conditions are kept:

- an event which contains a $c\bar{c}$ pair with at least one of the quarks having $|y| < 1.5$.
- an event which contains a $b\bar{b}$ pair with at least one of the quarks having $|y| < 1.5$.
- an event which contains a $c\bar{c}$ pair and one heavy-flavour decay electron with $|y| < 1.2$.
- an event which contains a $b\bar{b}$ pair and one heavy-flavour decay electron with $|y| < 1.2$.

In the first two cases, D mesons from the hadronization of charm quarks or that are produced by the decay of a B meson are forced to decay in hadronic decays.

In order to obtain a data sample to simulate Pb-Pb collisions, for each event N_{coll} is extracted from a Glauber Monte Carlo simulation of Pb-Pb events. Then, if $N_{\text{coll}} > 1$, a Pb-Pb event generated with HIJING (Heavy Ion Jet Interaction Generator) [92] Monte Carlo generator is added as underlying event to the PYTHIA pp collision. The underlying events are fundamental to reproduce the multiplicity distribution in the Monte Carlo. Subsequently, the GEANT3

particle transport package is used to reconstruct the generated particles, taking into account a detailed description of the geometry of the apparatus and of the detector response. The simulation is also configured to reproduce the luminosity conditions and the active electronic channels, calibration level, and time evolution of all the ALICE subsystems during the 2011 Pb-Pb data taking period.

The efficiency is also evaluated for feed-down D^+ mesons, i.e. D^+ mesons coming from B decays. The factor $(Acc \times \varepsilon)_{feed-down}$ is used to subtract the feed-down contribution from the extracted D^+ -meson raw-yield.

Since a discrepancy on D mesons momentum distribution has been observed between data and simulation, the D^+ -meson spectrum in Monte Carlo simulations is re-weighted to reproduce the shape given by D^0 data or BAMPS [61] calculations. This is done to avoid a bias in the efficiency evaluation that depends on the width of the p_T interval and on the variation of the efficiencies within them. The weights applied depend on the centrality class and their variation is considered in the systematic uncertainty evaluation, a more detailed description could be found in Section 3.4.5.

In the left panel of Figure 3.8 and in Figure 3.9 the $(Acc \times \varepsilon)$ are shown, respectively, as a function of the D^+ transverse momentum for the 0 – 10% centrality class and for all the centrality classes studied. In both figures the values of prompt and feed-down $(Acc \times \varepsilon)$ are superimposed, they increase with p_T starting from few per mil at low p_T up to 10-20% in the highest p_T interval. The feed-down efficiencies are larger by a p_T -dependent factor because of the larger $c\tau$ of B mesons. Hence, they are preferentially selected by the cut based on vertex displacements.

The $(Acc \times \varepsilon)_{prompt}$ is also evaluated without applying the PID selection (superimposed in Figures 3.8 and 3.9). The ratio between $(Acc \times \varepsilon)_{prompt}$ with and without PID is shown in the right panel of Figure 3.8 in the 0 – 10% centrality class, the vertical bars represent the binomial errors. The difference between $(Acc \times \varepsilon)$ with and without PID depends on the p_T interval and it will be considered in the evaluation of the PID systematic uncertainty discussed in Section 3.4.4.

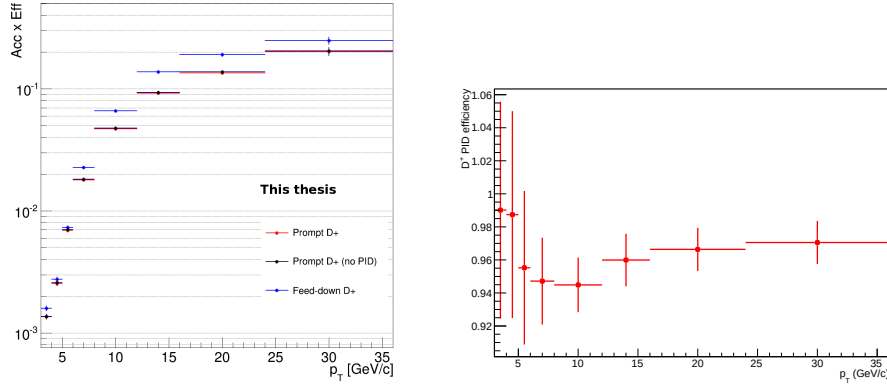


Figure 3.8: Left: transverse momentum dependence of $(Acc \times \varepsilon)$ for prompt (red) and feed-down (blue) in Pb-Pb collisions in the centrality class 0 – 10%. The $(Acc \times \varepsilon)$ without PID is also shown in black. Right: ratio between $(Acc \times \varepsilon)_{prompt}$ with and without PID.

Evaluation of the D^+ selection efficiencies at low p_T in peripheral events.

A special attention is dedicated to study the efficiencies in $3 < p_T < 5$ GeV/c because an instability is observed in the corrected yield when changing the input D-meson spectrum. In that p_T interval the Monte Carlo input spectrum is steeply falling and, hence, the p_T shape could lead to a significant alteration of the efficiencies. This is observed in particular in the peripheral collisions (30-40% and 40-50% centrality classes).

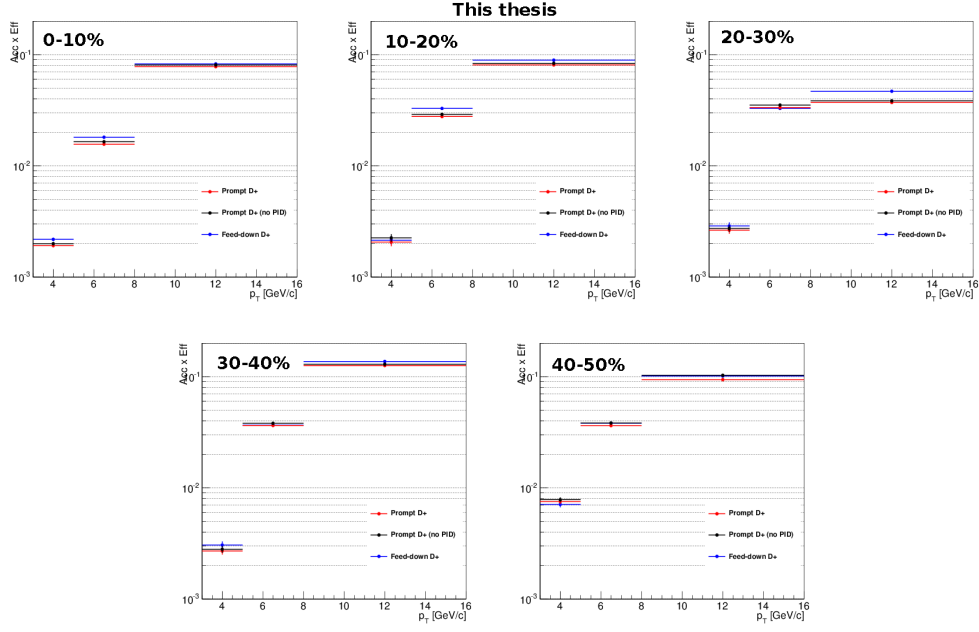


Figure 3.9: $(Acc \times \varepsilon)$ for prompt, feed-down and prompt without PID as a function of p_T in different centrality classes: (starting from top left) 0-10%, 10-20%, 20-30%, 30-40% and 40-50%.

In Figure 3.10, the efficiencies from two different sets of cuts are shown in steps of 200 MeV/c in $3 < p_T < 5$ GeV/c in the centrality class 40-50%, as an example. The efficiencies shown in the left panel manifest a more steeply rising momentum distribution with respect to those from the second set of cuts shown in the right panel. A steeply rising efficiency could be biased by the choice of the D^+ -meson spectrum shape, indeed in the left panel a significant variation of the efficiency considering the whole p_T interval could be observed with (solid line) and without (dashed line) applying the weights. In the right panel the efficiencies with and without weights are superimposed, validating the stability of the efficiency evaluation on the variation of the D-meson spectrum shape.

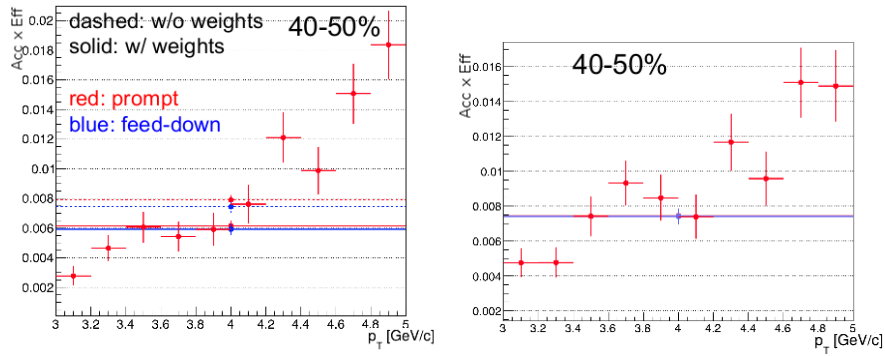


Figure 3.10: D^+ efficiencies evaluated in steps of 200 MeV/c in $3 < p_T < 5$ GeV/c with two different set of cuts in the left and right panels to check the efficiency stability in the centrality class 40-50%. Efficiencies of prompt D^+ mesons in the whole p_T interval are in red, while feed-down in blue. In the right panel the dashed line represents efficiencies evaluated without applying weights, while solid line efficiencies evaluated with weights.

Hence, the set of cuts corresponding to the flatter efficiencies in the right panel, that selects a different sample of D^+ mesons in the p_T interval $3 < p_T < 5$ GeV/c, is chosen as the central cut.

3.3.2 Beauty feed-down subtraction

The prompt fraction of D^+ mesons, f_{prompt} , is evaluated as:

$$\begin{aligned} f_{prompt} &= 1 - (N^{D^+ \text{ feed-down}} / N^{D^+ \text{ raw}}) = \\ &= 1 - \langle T_{AA} \rangle \cdot \left(\frac{d^2\sigma}{dy dp_T} \right)_{feed-down}^{FONLL} \cdot R_{AA}^{feed-down} \cdot \frac{(Acc \times \varepsilon)_{feed-down} \cdot \Delta y \Delta p_T \cdot BR \cdot N_{ev}}{N^{D^+ \text{ raw}} / 2} \end{aligned} \quad (3.4)$$

where $\left(\frac{d^2\sigma}{dy dp_T} \right)_{feed-down}^{FONLL}$ is the B-meson production cross section from FONLL pQCD calculations [99]. The $B \rightarrow D^+$ decay kinematic is simulated with the EvtGen package [100]. The $R_{AA}^{feed-down}$ is currently unknown, so an hypothesis has to be made. On the basis of the comparison between the J/Ψ from B-meson decay measured by the CMS experiment [101], the value $R_{AA}^{feed-down} = 2 \cdot R_{AA}^{prompt}$ is chosen in all the p_T intervals and a variation of $1 < R_{AA}^{feed-down} / R_{AA}^{prompt} < 3$ is considered in the systematic uncertainty evaluation, to take also into account possible centrality and p_T dependences. The factor of prompt D^+ mesons obtained from this approach (Nb method) varies from 0.85-0.97 in the measured p_T range, shown in Figure 3.11.

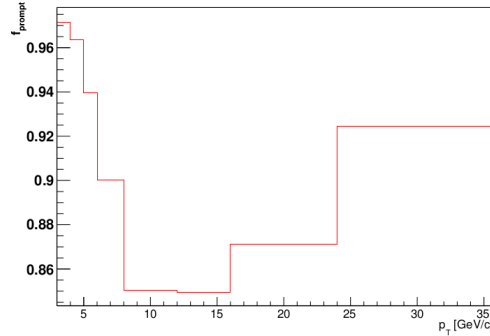


Figure 3.11: D^+ -meson f_{prompt} as a function of p_T in Pb-Pb collisions in the centrality class 0 – 10%.

3.4 Systematic uncertainties on the D^+ -meson corrected yield

In this section the various sources of systematic uncertainties that affect the measurement of D^+ -meson corrected yield in Pb-Pb collisions are presented. The resulting systematic uncertainties are summarized in Table 3.3.

3.4.1 Tracking efficiency

The systematic uncertainty on the tracking efficiency is estimated by comparing the probability to match the TPC track to the ITS hits in data and simulation and by varying the track quality selection criteria, such as the minimum number of associated hits in the TPC and in the ITS

and the maximum χ^2/ndf of the tracks.

The resulting systematic uncertainties is estimated to be 5% for each track, that results in a 15 % systematic uncertainty for the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay.

3.4.2 Yield extraction

The yield extraction, as discussed in Section 3.1.3, depends on the parameter of the fit function considered in the procedure. A systematic uncertainty is evaluated by repeating the fit of the invariant mass distributions while varying the fit configurations. This study provides a test to check the stability of the yield extraction procedure. The following tests are considered:

- using a different bin width for the invariant mass distribution (from around 5 to 13 MeV/c^2 bin width);
- varying the invariant mass range used in the fit (either all the bins are included in the fit, or either the first or the first two bins are excluded from the fit);
- fixing the Gaussian sigma to the value extracted from Monte Carlo simulations;
- using a different fit function for the background, a second order polynomial (if possible), instead of an exponential;
- using a bin counting method based on the sum of the entries of the invariant mass histogram within $\pm 3\sigma$ from the peak center after subtracting the background in each bin. The latter is estimated with the exponential fit. A further check is made by varying the interval where the entries are counted.

For each of these tests this quantity is evaluated:

$$unc. = \frac{S_{\text{best}} - S_{\text{var}}}{S_{\text{best}}} \quad (3.5)$$

where S_{best} is the signal extracted in the default configuration and S_{var} is the signal obtained from one of the tests listed above. In the most cases, all the bins of the invariant mass distribution from 1.69 to 2.05 GeV/c^2 are included in the default configuration with a bin width of $\sim 10 \text{ MeV}/c^2$.

The final systematic uncertainty is assigned as the maximum of these values removing the cases in which the fit is not reliable. The statistical uncertainties on the raw yields extracted with different configurations are not considered because the raw yields, that are extracted from the same data sample, are completely correlated.

The *unc.* values are shown in the Figures 3.12 and 3.13 for the study as function of p_T and of

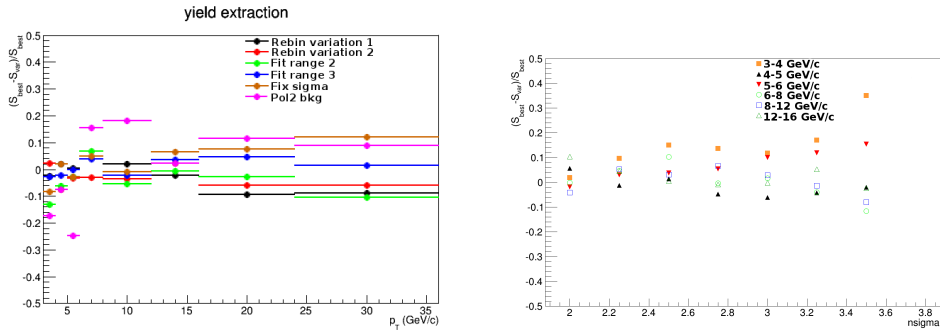


Figure 3.12: Left: D^+ -meson signal residuals in the analysis as a function of p_T from the variation of fit range, bin width and background fit and fix of the Gaussian sigma. Right: systematic uncertainty from bin counting method varying the interval, in terms of number of σ from the peak center, in which the entries are counted.

the centrality class, respectively. For the latter the results are reported for $5 < p_T < 8$ GeV/ c and $8 < p_T < 16$ GeV/ c . In the left panel the uncertainties obtained varying the fit parameters are presented, while the ones from the bin counting approach are shown in the right panel. There, the interval in which the entries are counted is varied in terms of number of σ from the peak center.

A complementary approach is also applied to study the systematic uncertainty on the yield extraction based on multi trials. This approach consisted in exploiting all the combinations of the tests described above. For each trial the raw yield is extracted. Then, a selection on the Gaussian sigma of the invariant mass distribution is applied to reject fit with sigma not compatible to MC: $1/2 \cdot \sigma_{MC} < \sigma < 3/2 \cdot \sigma_{MC}$. Figure 3.14 shows an example of the multi-trial approach applied to $3 < p_T < 4$ GeV/ c in the most central collisions, ~ 60 trials are used. The raw yields and sigma extracted from the invariant mass distributions of each trial are shown in the top panels. The fit χ^2 of the invariant mass distributions is also shown in the bottom left panel and, as it can be noticed, the χ^2 is ~ 1 for all the trials considered. The distribution of the raw yields obtained from all the trials is shown in the bottom right panel. The raw yield extracted in the default configuration ($S=408$, for $3 < p_T < 4$ GeV/ c in 0-10% centrality class) is included between the minimum and the maximum values of the distribution. The spread of the values is in line with the systematic uncertainties evaluated from the single trial approach.

The final uncertainty assigned on the yield extraction varies from 8 to 15% depending on p_T .

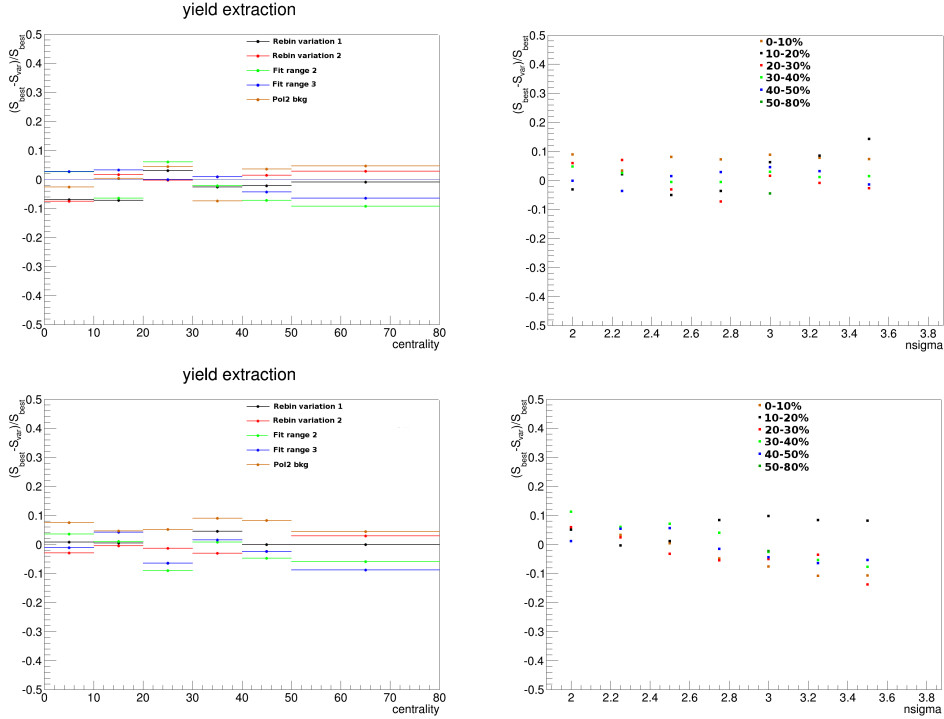


Figure 3.13: D^+ -meson signal residuals as a function of centrality obtained with different fit parameters with respect to the central value in the p_T bins: $5 < p_T < 8$ GeV/ c (top plots, with bin counting variations on the right) and $8 < p_T < 16$ GeV/ c (bottom plots, with bin counting variations on the right).

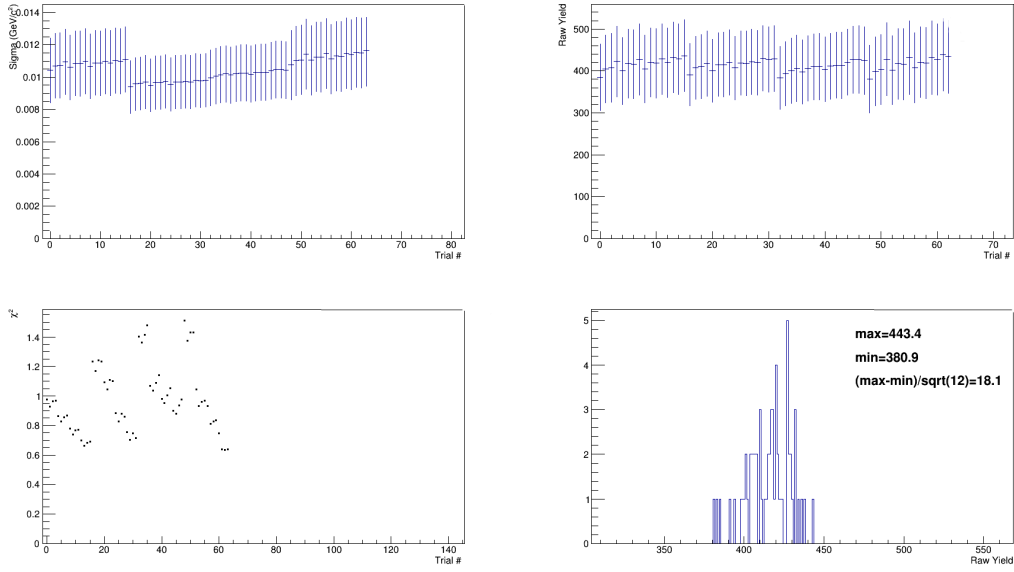


Figure 3.14: Multi-trial approach applied to $3 < p_T < 4$ GeV/ c in the most central collisions. Top left: sigma of the invariant mass distributions as a function of the trial. Top right: raw yield extracted from the fit as a function of the trial. Bottom left: fit χ^2 as a function of the trial. Bottom right: raw yield distribution.

3.4.3 Topological selection efficiency

Another source of systematic uncertainty depends on possible imperfections on the description of the D-meson kinematic properties and of the detector description in the Monte Carlo simulations. To quantify this systematic effect, the corrected yields are calculated for different topological selections. The variation of the corrected yields with respect to the one obtained with the cuts in Table 3.2 gives the systematic uncertainty in each p_T interval. The statistical uncertainty is not considered because is strongly correlated, since the same D^+ candidates are selected by more than one cut configuration. The topological cuts are varied in order to ensure a stable extraction of the signal. In general, two of the exploited sets of cuts are looser, i.e. with higher selection efficiencies with respect to those reported in Table 3.2, while other two are tighter, i.e. with lower selection efficiencies.

In Figures 3.15 and 3.16, the ratio between the corrected yields with different topological selections and the default one is shown for both the studies as a function of p_T and as a function of the centrality class. The yields are corrected for $Acc \times \varepsilon$ and feed-down contribution factors. The final systematic uncertainty assigned for this source is 10% in each p_T interval, except for the $3 < p_T < 5$ GeV/ c where it is 20% in peripheral and semi-peripheral collisions.

3.4.4 PID selection

The systematic uncertainty on PID selection is obtained comparing the corrected yield with and without applying the particle identification criteria.

The difference between the efficiency with and without the particle identification is shown in the right panel of Figure 3.8. The ratio between the corrected yields with and without PID is shown in Figure 3.17 as a function of p_T in the centrality class 0 – 10%. As already mentioned, no particle identification is applied in $16 < p_T < 36$ GeV/ c . The statistical errors on the extracted corrected spectra are treated as correlated in the ratio. Comparing the result with what obtained for the others D mesons, a final systematic uncertainty of 5% is assigned for the PID selection in each p_T interval and in each centrality class.

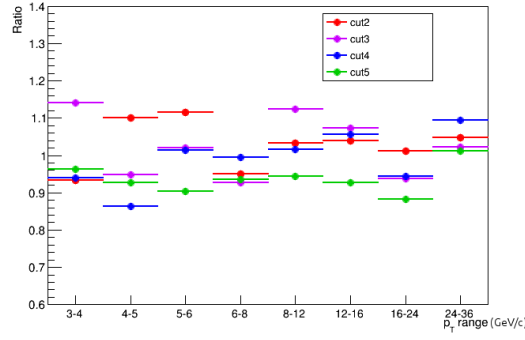


Figure 3.15: D^+ cut variation as a function of p_T in the 0-10% centrality class. The y axis represents the ratio between the corrected yields obtained with the central cut and with one of the different topological selections.

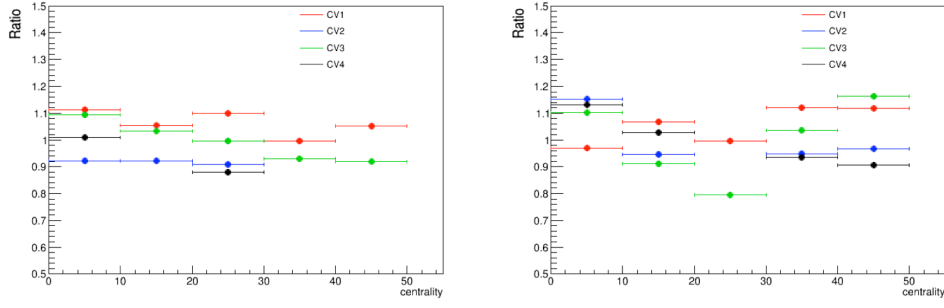


Figure 3.16: D^+ cut variation as a function of centrality for $5 < p_T < 8$ GeV/ c (left) and $8 < p_T < 16$ GeV/ c (right). The y axis represents the ratio between the corrected yields obtained with the central cut and with one of the different topological selections.

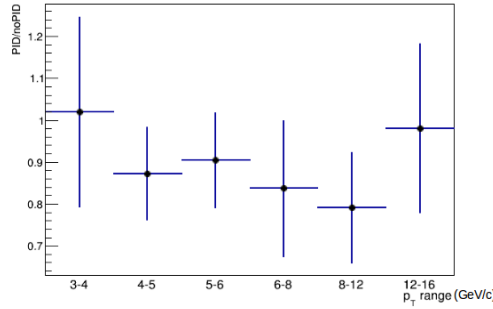


Figure 3.17: Ratio between corrected yields with and without PID as a function of p_T for the 0-10% centrality class.

3.4.5 Monte Carlo p_T -shape

As mentioned above, efficiencies depend on the shape of the p_T distribution in the Monte Carlo sample used to extract the selection efficiencies. A systematic uncertainty is evaluated comparing the efficiencies obtained with the default p_T shape (shown in Section 3.3.1) and implementing a different set of weights. For 0 – 10% and 10 – 20% centrality classes, the weights are obtained using a D^0 p_T shape from data as a parametrization, while for 20 – 50%

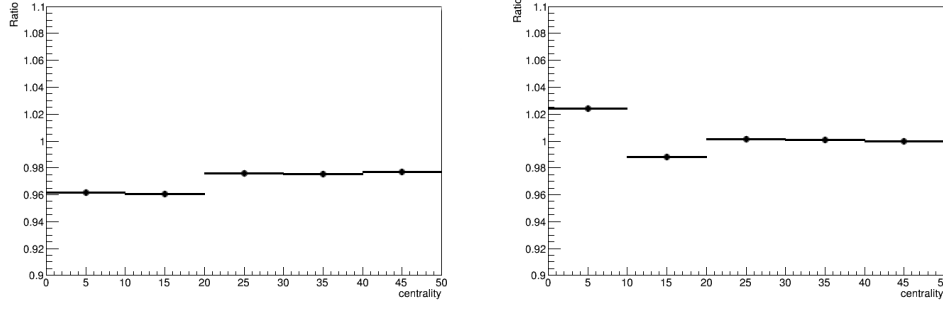


Figure 3.18: D^+ -meson systematic uncertainty on Monte Carlo p_T -shape for $5 < p_T < 8$ GeV/ c (left) $8 < p_T < 16$ GeV/ c (right) as a function of centrality classes.

centrality classes the p_T shape comes from BAMPS [66] calculations. Among the D mesons, D^0 -meson is considered to evaluate weights because it is possible to extract its signal at lower p_T (above 1 GeV/ c) and in narrower p_T intervals, thanks to the higher statistics. The D^0 signal in central collisions is then corrected by the $Acc \times \varepsilon$ factor in these narrow p_T intervals, where the effect of weights is negligible, to obtain the D^0 p_T spectrum. The BAMPS p_T shape used for 20-50% centrality class, instead, comes from the FONLL pp spectrum multiplied by the D-meson R_{AA} in semi-central Pb-Pb events evaluated with BAMPS that closely describe the central value of the previous measurements.

The systematic uncertainty is evaluated from the variation of Monte Carlo efficiencies obtained applying the weights from D^0 p_T shape and BAMPS and applying the weights considering a p_T distribution calculated with FONLL in all the centrality classes. The difference between the slope of the p_T distributions applying different weights is more significant at low p_T , resulting in a p_T -dependent uncertainty. In Figure 3.18 the systematic uncertainty is shown as a function of the centrality class for $5 < p_T < 8$ GeV/ c and $8 < p_T < 16$ GeV/ c . The final systematic uncertainties vary from 6% at low p_T to be negligible at high p_T in peripheral collisions.

3.4.6 Beauty feed-down systematic uncertainty

The systematic uncertainty on the subtraction of D^+ mesons coming from B decays (feed-down) is estimated by:

- varying the p_T -differential feed-down D^+ -meson cross section from the FONLL calculation within the theoretical uncertainties;
- varying the hypothesis on the ratio of the prompt and feed-down D^+ meson R_{AA} in the range $1 < R_{AA}^{feed-down}/R_{AA}^{prompt} < 3$;
- applying an alternative method to compute f_{prompt} (fc method).

The left panel of Figure 3.19 shows the relative variation of the prompt D^+ yield as function of the hypothesis on the ratio of the prompt and feed-down D^+ -meson R_{AA} in the range $1 < R_{AA}^{feed-down}/R_{AA}^{prompt} < 3$. The systematic uncertainty is shown for four p_T intervals in the most central collisions and it increases increasing the p_T .

The alternative method is based on the ratio of charm and beauty FONLL cross sections in pp collisions, instead of extracting the fraction of B mesons from data. In this approach f_{prompt} is evaluated as:

$$f_{prompt} = \left(1 + \frac{(Acc \times \varepsilon)_{feed-down}}{(Acc \times \varepsilon)_{prompt}} \frac{\left. \frac{d\sigma_{FONLL}^{D^+ from B}}{dp_T} \right|_{|y| < 0.5}}{\left. \frac{d\sigma_{FONLL}^{D^+}}{dp_T} \right|_{|y| < 0.5}} \frac{R_{AA}^{feed-down}}{R_{AA}^{prompt}} \right)^{-1} \quad (3.6)$$

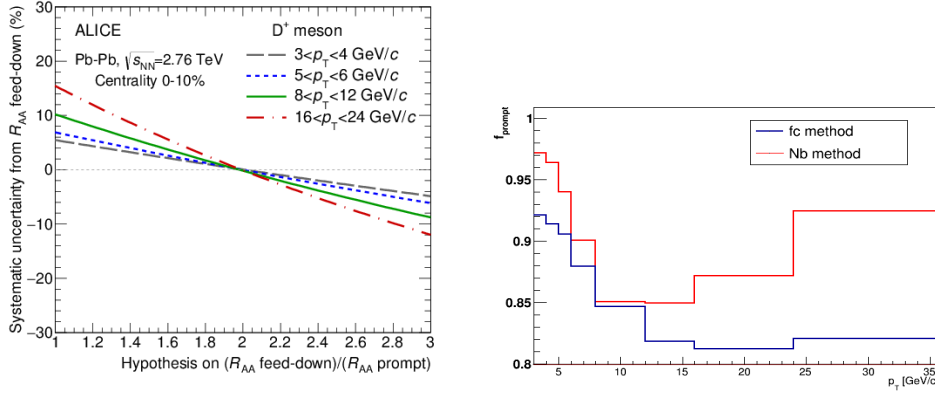


Figure 3.19: Left: relative variation of the prompt D^+ yield as a function of the hypothesis on $R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}}$ for the B feed-down subtraction. Right: feed-down subtraction factor as a function of p_T in Pb-Pb collisions in the centrality class 0 – 10% with Nb and fc methods.

The resulting f_{prompt} is shown in the right panel of Figure 3.19, together with the f_{prompt} obtained from the Nb method.

The total systematic uncertainty on feed-down depends on p_T and on the centrality class. It varies from -21% to +16%, considering the envelope of the uncertainties from all the variations and methods.

The precision on the measurement of D-meson corrected yield can be considerably improved by a deeper understanding of the B-meson production. A data-driven method is already used to extract the f_{prompt} fraction in pp collisions [67], while further efforts are ongoing to apply the same method also in p-Pb and Pb-Pb collisions.

3.4.7 Summary of systematic uncertainties on the D^+ -meson corrected yield

A summary of the systematic uncertainties on the D^+ -meson corrected yield is shown in Table 3.3 for three selected p_T intervals in the most central collisions. The uncertainties are approximately independent on centrality.

The uncertainty on the branching ratio from PDG (0.24%) [6] as well as the uncertainty on the determination of the centrality class from the Glauber model ($< 1\%$) are also considered. The latter is evaluated by shifting the limits of centrality classes by $\pm 1.1\%$ and taking the variation of the D-meson dN/dp_T .

The systematic uncertainties on the D-meson corrected yields are obtained considering the different contributions described above as uncorrelated and, hence, summed in quadrature.

centrality class	0–10%		
p_T interval (GeV/ c)	3–4	6–8	24–36
Yield extraction	10%	8%	8%
Tracking efficiency	15%	15%	15%
Topological selection efficiency	10%	10%	10%
PID efficiency	5%	5%	5%
MC p_T shape	6%	1%	1%
FONLL feed-down corr.	+4% –12%	+6% –11%	+8% –14%
$R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}}$ (Nb)	+6% –5%	+9% –7%	+14% –11%
BR	2.1%		
Centrality class definition	< 1%		

Table 3.3: Relative systematic uncertainties on the prompt D^+ -meson production yields in Pb–Pb collisions for three p_T intervals in 0-10% centrality class.

3.5 Nuclear modification factor of D^+ in Pb-Pb collisions

The nuclear modification factor R_{AA} of prompt D^+ in Pb-Pb collisions is defined as:

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}^{D^+}/dp_T}{d\sigma_{pp}^{D^+}/dp_T} \quad (3.7)$$

where dN_{AA}/dp_T is the corrected p_T -spectrum, $\langle T_{AA} \rangle$ the average nuclear overlap function and $d\sigma_{pp}/dp_T$ the proton-proton reference at $\sqrt{s} = 7$ TeV scaled at $\sqrt{s} = 2.76$ TeV.

3.5.1 pp reference

The pp reference is obtained by scaling the p_T -differential cross section of prompt D^+ mesons measured at $\sqrt{s} = 7$ TeV (shown in Figure 1.20) to $\sqrt{s} = 2.76$ TeV using FONLL calculations. The procedure is applied separately to each p_T interval, as explained in detail in [67]. The ratio of the theoretical predictions of the cross sections at the two energies in the same rapidity region is used to obtain a scaling factor. The central value of the scaling factor is determined using the standard FONLL parameters, while the systematic uncertainty is evaluated varying coherently the parameters in the same ranges at the two energies.

A second source of systematic uncertainty is the systematic uncertainty of the measured p_T -differential D^+ -meson cross-section at $\sqrt{s} = 7$ TeV.

The p_T -differential cross section is measured by ALICE also at $\sqrt{s} = 2.76$ TeV [102] but the scaling procedure is chosen because of the limited statistics available in the $\sqrt{s} = 2.76$ TeV sample. Figure 3.20 shows the comparison between the p_T -differential cross section measured by ALICE at $\sqrt{s} = 2.76$ TeV and the cross section scaled from $\sqrt{s} = 7$ TeV to $\sqrt{s} = 2.76$ TeV in $2 < p_T < 12$ GeV/ c . The central values are compatible within the systematic uncertainties.

The p_T -differential cross section in pp collisions at $\sqrt{s} = 7$ TeV is measured only up to p_T 24 GeV/ c . Therefore, an extension of the pp reference is needed to cover the full p_T interval considered in this analysis in Pb-Pb collisions up to 36 GeV/ c . The value of the D^+ -meson cross section at $\sqrt{s} = 7$ TeV in $24 < p_T < 36$ GeV/ c is extrapolated using FONLL predictions as a baseline for the p_T shape dependence. Then, the same scaling procedure is used to obtain the D^+ cross section at $\sqrt{s} = 2.76$ TeV. The systematic uncertainties on the pp reference in $24 < p_T < 36$ GeV/ c is $^{+37\%}_{-56\%}$.

The $\sqrt{s}$ -scaled pp reference in the p_T intervals considered in the study as a function of p_T in the 0-10% Pb-Pb centrality class is shown in the left panel of Figure 3.21 multiplied by the nuclear overlap function corresponding to the 0-10% centrality class. The extrapolated reference in $24 < p_T < 36$ GeV/ c is also shown with an empty marker.

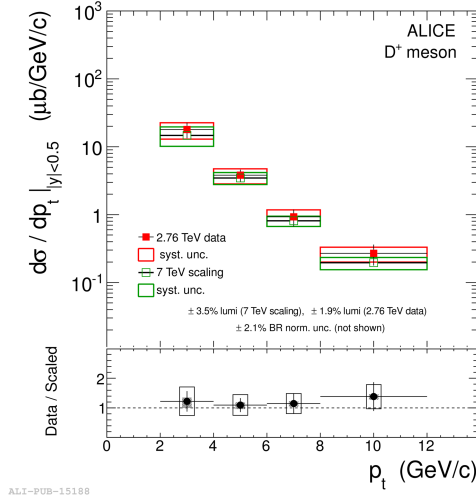


Figure 3.20: p_T -differential cross section for prompt D^+ mesons in pp collisions at $\sqrt{s} = 2.76$ TeV [102] compared with the cross section at $\sqrt{s} = 7$ TeV scaled at $\sqrt{s} = 2.76$ TeV [67], both measured by ALICE. The empty boxes represent the systematic uncertainties.

3.5.2 Systematic uncertainties on R_{AA}

The systematic uncertainties on the D-meson corrected yields, on the proton-proton cross section reference and on the normalization have to be considered in the evaluation of the systematic uncertainty affecting the R_{AA} measurement. The systematic uncertainties on the D-meson corrected yields are described in Section 3.4 and the uncertainties on the pp reference in Section 3.5.1. These two sources of uncertainties are summed in quadrature to evaluate the uncertainty on R_{AA} , except for the systematic on the feed-down subtraction. The latter derives from the variation of the parameters of the FONLL calculation and from the usage of the alternative method to compute f_{prompt} . These variations are considered correlated in the Pb-Pb and pp measurements and they are carried out simultaneously for the numerator and denominator of R_{AA} . Only the residual effect is attributed as a systematic uncertainty. Therefore, the variation of the hypothesis $1 < R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}} < 3$, that is not considered correlated, becomes the main contribution to the feed-down uncertainty on R_{AA} .

The uncertainties on R_{AA} are reported in Table 3.4. The uncertainties on the $\sqrt{s}$ -scaling of the pp reference, its extrapolation at high p_T and the FONLL feed-down correction are the same for all the centrality classes. The other uncertainties are approximately independent on centrality. The uncertainty on the normalisation is the quadratic sum of the pp normalisation uncertainty (3.5%) [67] and the uncertainty on the average nuclear overlap function $\langle T_{AA} \rangle$, which is 4.0% in the 0-10% centrality classes.

	0-10%		
p_T interval (GeV/c)	3-4	6-8	24-36
dN_{Pb-Pb}/dp_T (excl. feed-down)	22%	20%	22%
dN_{pp}/dp_T (excl. feed-down)	20%	19%	20%
$\sqrt{s}$ - scaling of the pp ref.	+ 8% - 19%	+ 6% - 10%	—
High- p_T extrapolation	—	—	+37% -56%
FONLL feed-down corr.	+ 2% - 1%	+ 1% - 2%	+ 8% - 14%
$R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}}$ (Nb)	+ 8% - 7%	+12% - 9%	+16% - 12%
Normalisation	4.8%		

Table 3.4: Relative systematic uncertainties on the prompt D^+ -meson R_{AA} for three p_T intervals in the most central collisions. The uncertainty in the high- p_T extrapolation of the pp reference is evaluated only in $24 < p_T < 36$ GeV/c, where the $\sqrt{s}$ -scaling procedure is not possible.

3.6 Results of D^+ corrected yield and R_{AA} in Pb-Pb collisions

The left panel of Figure 3.21 shows the D^+ corrected yield as a function of p_T in the 0-10% centrality class in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The corrected yield is superimposed to the pp reference multiplied by the average nuclear overlap function corresponding to the 0-10% centrality class. In both distributions the vertical bars represent the statistical uncertainties, the open boxes the systematic uncertainties from the data analysis and the shaded boxes the systematic uncertainty due to the subtraction of the feed-down contribution. The uncertainties on the pp cross section normalisation and on the branching ratios are also quoted on the figure. A clear suppression of the D^+ -meson yield is observed in the whole p_T interval with respect to the scaled pp reference.

The ratio between the two distributions is shown in the right panel of Figure 3.21, which represents the D^+ -meson nuclear modification factor. The vertical bars represent the statistical uncertainties and the open boxes the total systematic uncertainties, while the normalisation uncertainty is presented as a filled box at $R_{AA} = 1$.

The R_{AA} measured in the most central Pb-Pb collisions presents a minimum for $p_T \sim 10$ GeV/c with a suppression of the yield by a factor of 5-6 with respect to the scaled pp reference. The suppression decreases with decreasing p_T for $p_T < 10$ GeV/c up to a factor ~ 2.5 for $3 < p_T < 4$ GeV/c. The suppression seems to decrease also for $p_T > 10$ but the large uncertainties in the highest p_T interval do not allow to conclude on the R_{AA} trend.

The D^+ -meson corrected yield and R_{AA} as a function of p_T in 0-10% centrality class in Pb-Pb collision are published in [1] together with D^0 and D^{*+} R_{AA} .

In Figure 3.22 the R_{AA} as a function of the average number of participants $\langle N_{\text{part}} \rangle$ is reported in 3 p_T intervals: [3-5], [5-8] and [8-16] GeV/c. The quantity N_{part} is related to the centrality of the collision through the Glauber model, as explained in 2.5.3, and the corresponding values are listed in Table 3.1. The centrality classes considered are 0-10%, 10-20%, 20-30%, 30-40%, 40-50% and 50-80%, going from higher to lower values of $\langle N_{\text{part}} \rangle$.

The suppression of the D^+ -meson yield measured in Pb-Pb collisions with respect to the scaled pp reference increases increasing the centrality of the collision in each p_T interval. In $3 < p_T < 5$ GeV/c and $5 < p_T < 8$ GeV/c the R_{AA} is compatible with unity in the most peripheral centrality class, while in the highest p_T interval $8 < p_T < 16$ GeV/c a suppression can be observed in each centrality class considered. A suppression up to a factor 5-6 for $p_T > 5$ GeV/c is observed in the most central collisions, consistently with what has been already pointed out in the study as a function of p_T .

The D^+ R_{AA} in $5 < p_T < 8$ GeV/c and $8 < p_T < 16$ GeV/c are published in [2] together with D^0 and D^{*+} R_{AA} .

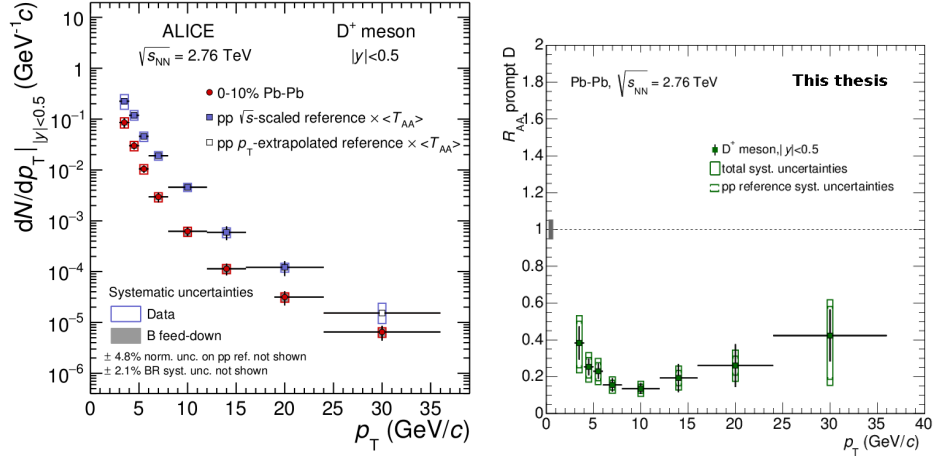


Figure 3.21: Left panel: D^+ -meson corrected yield in the transverse momentum range $3 < p_T < 36$ GeV/c in the 0-10% centrality class, the corrected yield is compared to the pp reference scaled by the nuclear overlap function corresponding to the 0-10% centrality class. Right panel: D^+ -meson R_{AA} in the most central collisions.

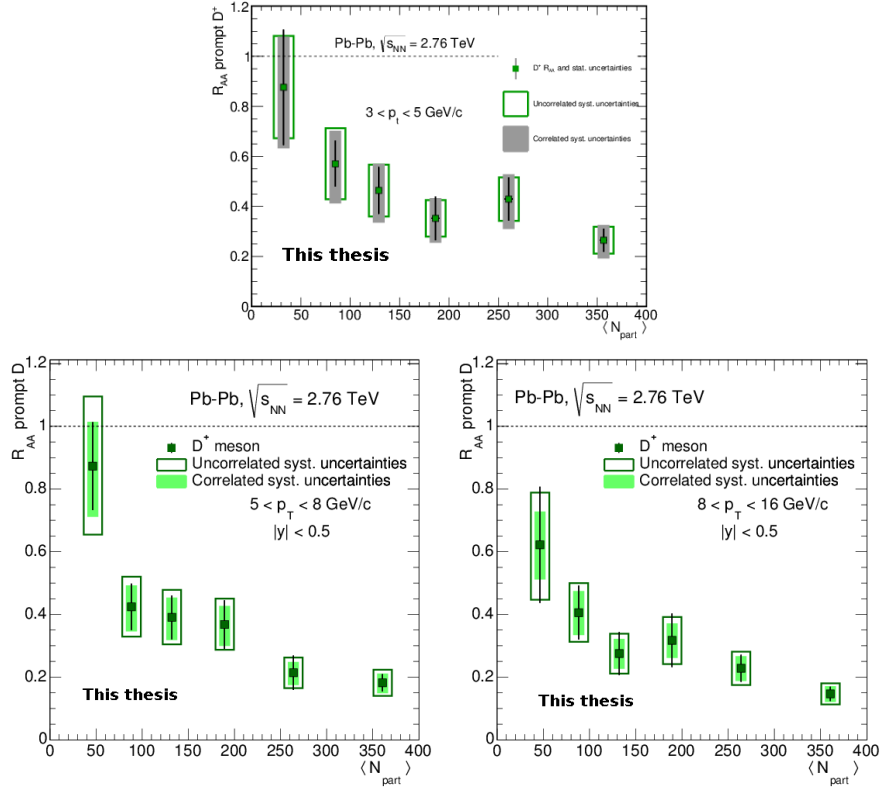


Figure 3.22: D^+ R_{AA} as a function of N_{part} in 3 p_T intervals: 3-5 (up), 5-8 (bottom left), 8-16 (bottom right) GeV/c.

3.7 Discussion

In this Section the results of the D^+ -meson nuclear modification obtained in this thesis are compared with the R_{AA} of the other D mesons: D^0 , D^{*+} and D_s^+ . Then, the average of non-strange D-meson R_{AA} is compared with the results obtained in other colliding systems, with the R_{AA} of other particles and with theoretical models.

3.7.1 Comparison with other D mesons

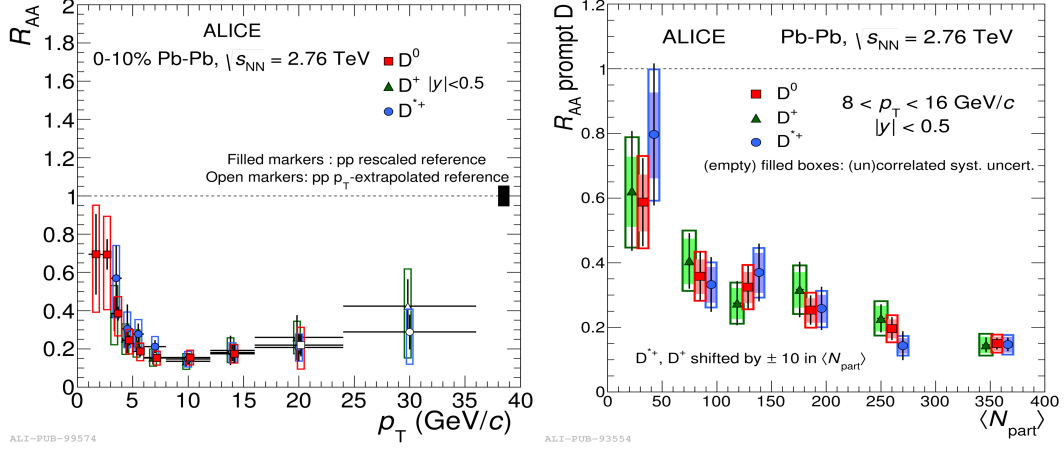


Figure 3.23: Comparison between R_{AA} of prompt D^+ , D^0 and D^{*+} mesons as a function of p_T in the 0 – 10% centrality class [1] (left) and as a function of N_{part} in $8 < p_T < 16$ GeV/c [2] (right).

In Figure 3.23 the comparison between R_{AA} of prompt D^+ , D^0 and D^{*+} mesons is shown as a function of p_T in the 0 – 10% centrality class in the left panel and as a function of N_{part} in $8 < p_T < 16$ GeV/c in the right panel. In both cases the R_{AA} of prompt D^+ is compatible with the R_{AA} of prompt D^0 and D^{*+} mesons within statistical uncertainties.

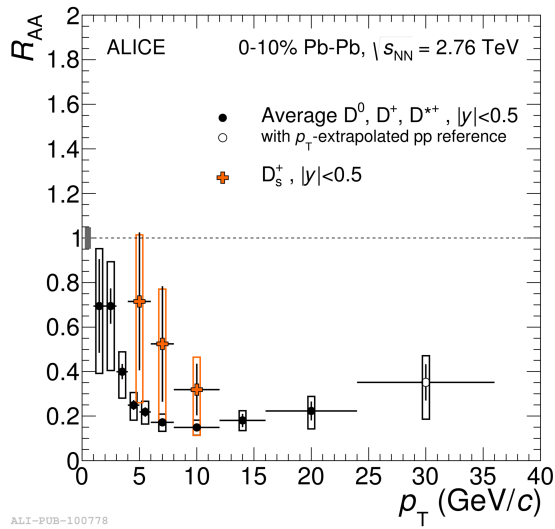


Figure 3.24: Comparison between average R_{AA} of non-strange D mesons [1] and D_s^+ meson as a function of p_T for the 0 – 10% centrality class [103].

In order to study the properties of charmed mesons, the average of D^+ , D^0 and D^{*+} mesons R_{AA} is computed using the inverse of the squared relative statistical uncertainties as weights. In Figure 3.24 the average of D^+ , D^0 and D^{*+} mesons R_{AA} is compared with the R_{AA} of D_s^+ meson measured by ALICE in the same centrality class (0-10% most central Pb-Pb collisions). The systematic uncertainties are propagated through the averaging procedure, considering the contributions from the tracking efficiency, the B-meson feed-down subtraction and the FONLL-based $\sqrt{s}$ -scaling factor of the pp cross section as fully correlated among the three D-meson species.

The comparison between strange and non-strange D mesons is meant to study the hadronization via recombination of light quarks with strange quarks in the QGP, favoured by the expected strangeness enhancement. The comparison of the central values could suggest an enhancement of the D_s^+ -meson yield relative to that of non-strange D mesons, although the values are compatible within uncertainties. Unfortunately, the current uncertainties do not allow a conclusive statement on the role of recombination in the partonic medium.

3.7.2 Comparison with other colliding systems

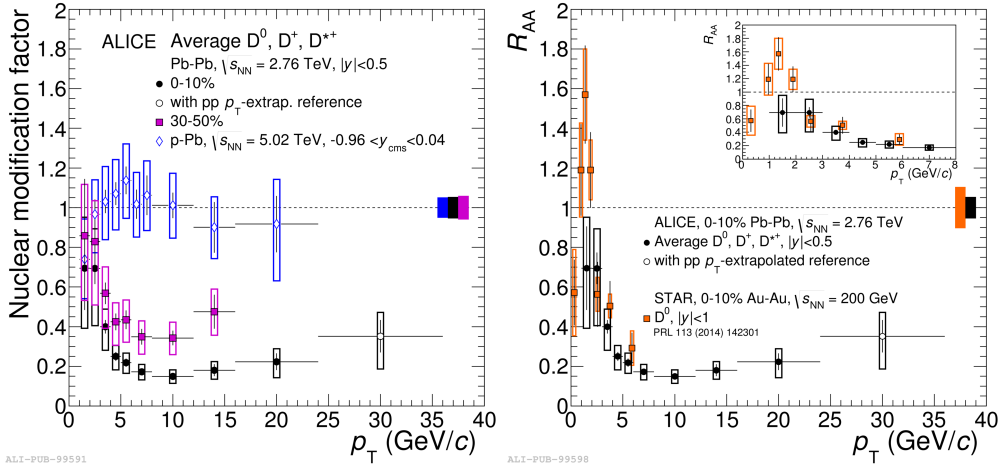


Figure 3.25: Left panel: Comparison between the average nuclear modification factor of prompt D mesons as a function of p_T in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in 0 – 10% and 30 – 50% centrality classes [1] and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by ALICE [71]. Right panel: Comparison between the average R_{AA} of prompt D mesons as a function of p_T in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured by ALICE [1] and the R_{AA} of D^0 mesons in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by STAR in the 0 – 10% centrality class [76].

The comparison between the average nuclear modification factor of prompt D mesons as a function of p_T in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in 0 – 10% centrality class and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in the left panel of Figure 3.25.

The R_{pPb} is compatible with unity in the whole p_T interval considered and this is consistent within uncertainties with models taking into account cold nuclear matter effects only. Therefore, the strong suppression observed at high p_T in central Pb-Pb collisions could not be explained in terms of cold nuclear matter effects but it is due to final-state effects that comes from the interaction of the charm quarks with the hot and dense medium.

In the same figure the D-meson R_{AA} is also shown for Pb-Pb collisions in the 30 – 50% centrality class. As already discussed in Section 3.6, a higher R_{AA} is observed decreasing the collision centrality for $p_T > 5$ GeV/c. In semi-peripheral collisions a maximum suppression by a factor of about 2.5 is evident for $p_T \sim 10$ GeV/c and it decreases at lower p_T , as observed in the most central collisions.

The comparison between the average R_{AA} of prompt D mesons as a function of p_T in Pb-Pb collisions $\sqrt{s_{NN}} = 2.76$ TeV measured by ALICE and the R_{AA} of D^0 mesons in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by STAR in the 0 – 10% centrality class is shown in the right panel of Figure 3.25.

The results at the different energies are compatible for $p_T > 2$ GeV/c. When comparing the suppression of the D-meson production at two energies, despite a possible different effect of in-medium parton energy loss, other effects have to be taken into account. For example, the different slopes of the p_T spectra in pp collisions at RHIC and LHC energies can compensate the different energy loss and, hence, contribute in obtaining a similar D-meson R_{AA} . At lower p_T the R_{AA} measured by STAR shows a maximum that is not present in ALICE results. The maximum can be described by model including parton energy loss, collective radial flow and the contribution of recombination [54, 50]. The absence of a peak in the ALICE results can be explained by the different role of initial-state effects and/or of radial flow at the different collision energies. In particular, the modification of the parton distribution functions in the nuclei is predicted to lead a stronger suppression of the heavy quark production yields at low p_T with increasing $\sqrt{s_{NN}}$ [104] and the k_T -broadening effect is expected to be more significative at lower $\sqrt{s_{NN}}$ [105, 106]. The interactions with the medium constituents are expected to transfer momentum to low- p_T charm quarks, which could take part in the collective radial flow of the medium. From the momentum distribution of identified light-flavour hadrons the radial flow is about 10% higher at LHC than at RHIC. Unfortunately, the current uncertainties can not allow to draw a conclusion on the observed difference. A reduction of statistical and systematical uncertainties and the possibility to extend the p_T range of the measurements at LHC energies below 1 GeV/c is fundamental for this comparison.

3.7.3 Comparison with other particles

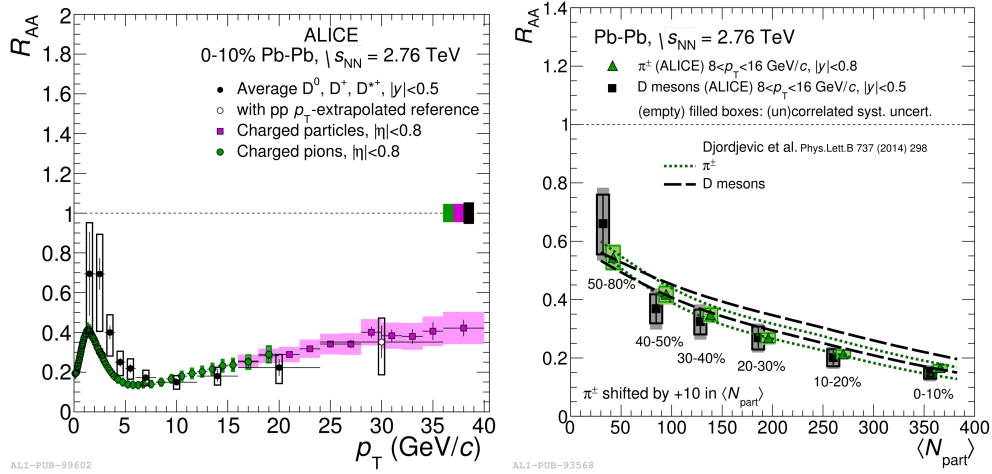


Figure 3.26: Left panel: Comparison between the R_{AA} of D mesons [1], charged pions [107] and charged hadrons [97] in 0 – 10% centrality class in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of p_T . Right panel: Comparison between the R_{AA} of D mesons and charged pions in $8 < p_T < 16$ GeV/c as a function of N_{part} in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. A theoretical calculation by Djordjevic *et al.* is also superimposed to D-meson and pion R_{AA} [49].

As described in Section 1.3.1, a mass hierarchy is expected in the quark energy loss and it could be tested by comparing the nuclear modification factor of different particles.

In the left panel of Figure 3.26 the comparison between the R_{AA} of D mesons, charged pions and charged hadrons in the 0 – 10% centrality class in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is shown as a function of p_T . The R_{AA} of D mesons is compared to that of charged pions in the interval $1 < p_T < 20$ GeV/c, while the comparison with charged particles is shown in

$16 < p_T < 40$ GeV/ c (for $p_T > 20$ GeV/ c the contribution of charged pions is about the 65% of charged particles). In the right panel of Figure 3.26 the R_{AA} of D mesons is compared to that of charged pions for $8 < p_T < 16$ GeV/ c in different centrality classes, from 0 to 80%.

In both figures we can conclude that at high p_T the R_{AA} of D mesons and charged hadrons are compatible. The compatibility within the uncertainties can be observed both for $p_T > 6$ GeV/ c in the 0 – 10% centrality class and for $8 < p_T < 16$ GeV/ c in all the centrality classes. For $p_T < 6$ GeV/ c , a $R_{AA}^D > R_{AA}^\pi$ is observed with a significance of about 1σ in the most central events.

Besides the quark energy loss, other effects have to be considered to interpret these results. For example, the harder p_T distribution and the harder fragmentation function of charm quarks with respect to light quarks and gluons could lead to a similar value of D-meson and pion R_{AA} . In addition, soft production processes contribute to the pion production up to p_T of about 2-3 GeV/ c due to the strong radial flow at LHC energies. This contribution does not scale with the number of binary nucleon-nucleon collisions, but with the number of participants.

To validate these statements, a theoretical calculation by Djordjevic *et al.* [49] is also superimposed to the R_{AA} of D mesons and pions. This calculation is in a good agreement with the D-meson nuclear modification factor and predicts a very similar R_{AA} for D mesons and pions, as observed in the data. This model considers the colour-charge dependence of energy loss including both radiative (DGLV formalism) and collisional processes in a finite-size dynamical QCD medium. The heavy-quark p_T -differential cross sections are obtained from FONLL calculations and the hadronization assumes fragmentation outside the medium. Furthermore, the production and fragmentation function are mostly up to date. Several effects related to the heavy- and light-quark productions can be studied with this model, some of the main predictions that can help to interpret the data are summarized in Figure 3.27 [108].

In the left panel of Figure 3.27, the suppression predictions of bare charm quark and D meson

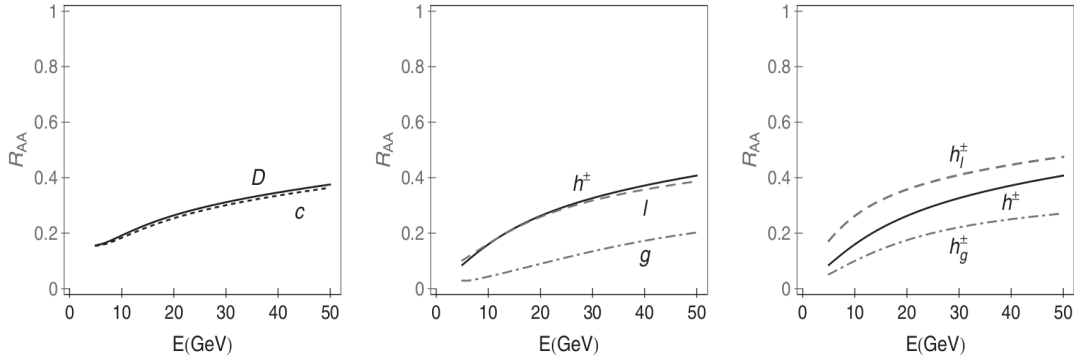


Figure 3.27: Comparison of suppression predictions as a function of momentum. Left panel: comparison of the charm quark suppression predictions (dotted curve) with the D meson suppression predictions (full curve). Center panel: comparison of charged hadron suppression predictions (full curve) with light quark (dashed curve) and gluon (dot-dashed curve) suppression predictions. Right panel: the dashed curve shows what would be the charged hadron suppression if only light quarks contributed to charged hadrons, the dot-dashed curve shows what would it be if only gluons contributed to charged hadrons, whereas the full curve shows the actual hadron suppression predictions. [108].

as a function of the momentum is shown. A negligible difference between the two suppression patterns is observed, therefore, the D meson suppression is indeed a genuine probe of the charm quark suppression in the QCD medium. In the center panel of Figure 3.27, the charged hadron suppression are compared with the bare light quark and gluon suppressions. It can be noticed that the charged hadron suppression is very similar to the bare light quark suppression. The right panel of Figure 3.27 shows the charged hadron suppression if hadrons were composed of only light quark jets (the dashed curve) or only gluon jets (the dot-dashed curve). The actual

charged hadron suppression is clearly in between the two suppression alternatives, indicating the contribution to charged hadrons of both light quarks and gluons. By comparing the central and the right panels, it is possible to notice that charged hadron fragmentation functions influence the bare light quark and gluon suppressions in such a way that the corresponding charged hadron suppression becomes significantly milder than the suppression of its parton constituent. Therefore, the similarity between the D-meson and charged hadron suppression is a consequence of a specific combination of the suppression and fragmentation patterns for light partons and it does not require invoking an assumption of the same energy loss for light and charm partons.

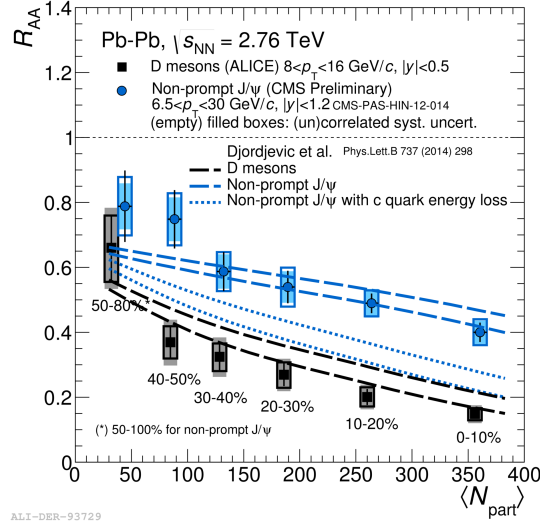


Figure 3.28: Comparison between R_{AA} of D mesons in $8 < p_T < 16$ GeV/c measured by ALICE [2] and R_{AA} of non-prompt J/ψ in $6.5 < p_T < 30$ GeV/c measured by CMS in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of the collision centrality (Preliminary results) [101]. A theoretical calculation by Djordjevic *et al.* is superimposed to the distributions [49].

Figure 3.28 shows the R_{AA} of prompt D mesons in $8 < p_T < 16$ GeV/c measured by ALICE [2] compared to non-prompt J/ψ from B decays measured in $6.5 < p_T < 30$ GeV/c by the CMS Collaboration (Preliminary results) [101]. The D-meson p_T range is chosen in order to cover a similar kinematic region with an average p_T of prompt D and B mesons of about 10-11 GeV/c. A larger suppression of D mesons with respect to non-prompt J/ψ is observed in all the centrality classes, except for the most peripheral collisions (50 – 80%).

A theoretical calculation by Djordjevic *et al.* [49] is also superimposed to the R_{AA} of D mesons and non-prompt J/ψ for $8 < p_T < 16$ GeV/c as a function of the centrality. The calculation is consistent with both D-meson and non-prompt J/ψ R_{AA} . The same calculation was carried out using the c-quark mass for the b-quark energy loss to extract the R_{AA} of non-prompt J/ψ . The result is closer to the D-meson R_{AA} , indicating that the large difference between the D-meson and non-prompt J/ψ R_{AA} in central collisions derives predominantly from the different energy loss of c and b quark, due to their masses.

3.7.4 Comparison with theoretical models

Several theoretical calculations are available to describe the D-meson R_{AA} as a function of p_T in the 0 – 10% centrality class. In Figure 3.29 some of these models are superimposed to the R_{AA} of prompt D mesons as a function of p_T in the 0 – 10% centrality class in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In the left panel only pQCD-based models are considered: Djordjevic [49], WHDG [51, 52, 53], Vitev [57] and CUJET3.0 [109]; while in the right panel the models that have also a prediction for the D-meson v_2 (right panel of Figure 1.24) are superimposed: TAMU

[47], Cao, Qin, Bass [50], WHDG [51, 52, 53], MC@sHQ+EPOS [54], POWLANG [59, 60] and BAMPS [61, 62, 63]. The description of the models can be found in Section 1.3.2. Some of them describe reasonably well the R_{AA} of prompt D mesons in a wide p_T interval. The models that do not include a hydrodynamical expansion of the medium and hadronization via recombination, namely Djordjevic, Vitev and WHDG, can reproduce the R_{AA} above 5 GeV/c if both radiative and collisional energy loss are included. The BAMPS model provides a better description of the data at low p_T when only collisional energy loss is considered, as in the D-meson v_2 , while the inclusion of radiative energy loss improves the agreement at high p_T . The Cao, Qin, Bass model describes the R_{AA} of D-meson in the whole p_T range, but it underestimates the D-meson v_2 . The TAMU elastic model overestimates the R_{AA} in central collisions in the $6 < p_T < 30$ GeV/c, while the POWLANG model underestimates it for $p_T > 5$ GeV/c. The last two models can provide a reasonable description of v_2 at low p_T .

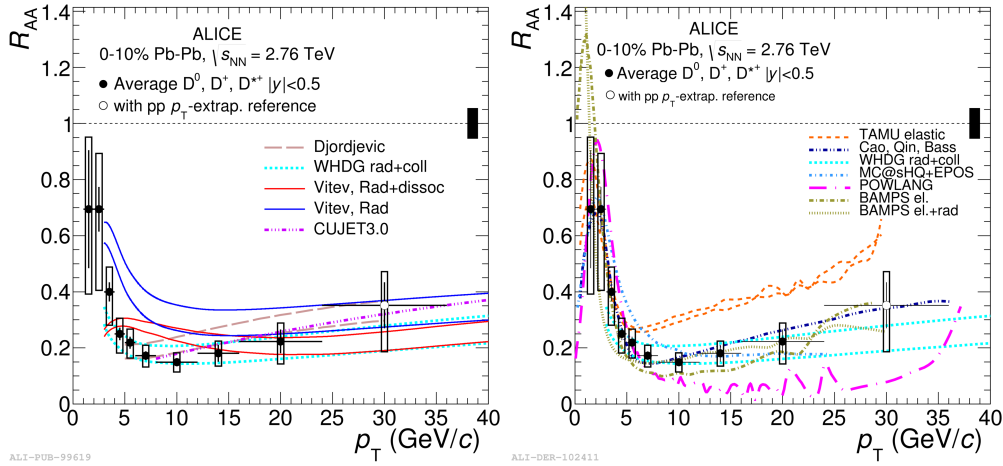


Figure 3.29: Comparison between R_{AA} of D mesons as a function of p_T in the 0–10% centrality class in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [1] and several theoretical calculations: Djordjevic [49], WHDG [51, 52, 53], Vitev [57] and CUJET3.0 [109] (left) and TAMU [47], Cao, Qin, Bass [50], WHDG [51, 52, 53], MC@sHQ+EPOS [54], POWLANG [59, 60] and BAMPS [61, 62, 63] (right).

In order to study the role of shadowing at low p_T , Figure 3.30 shows the TAMU elastic and MC@sHQ+EPOS models compared to the D-meson R_{AA} for $p_T < 16$ GeV/c in the 0–10% centrality class with and without including the EPS09 shadowing parameterization. For both models the inclusion of shadowing provides a better agreement with the data at $p_T < 5$ GeV/c.

Giving the considerations above, some steps forward have been done in the understanding of the D-meson production, but the simultaneous description of D-meson R_{AA} at LHC and other variables, like v_2 or R_{AA} at RHIC energies, is still challenging for theoretical calculations. A reduction of statistical and systematic uncertainties is fundamental to provide further constraints to energy-loss models. This will be possible in the LHC Run 3 and 4 with the higher luminosity reachable after the LHC upgrade and with the improvement of the ALICE capabilities after the upgrade of several detectors during LHC long shutdown in 2019. A simulation study to show the expected improvement with the higher statistics and the better performances of the upgraded detectors, in particular of the ITS, is reported in 4.1.3.

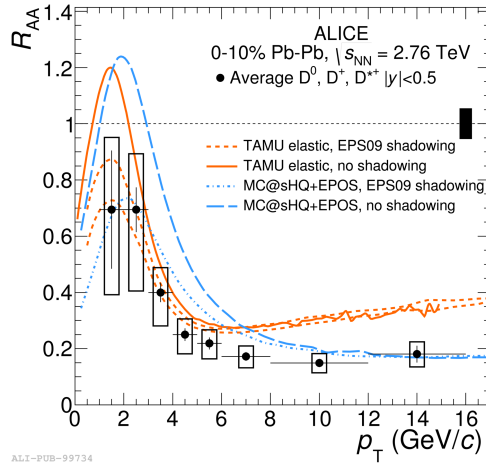


Figure 3.30: Comparison between R_{AA} of D mesons as a function of p_T in the 0–10% centrality class in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [1] and TAMU elastic [47] and MC@sHQ+EPOS [54] with and without including EPS09 shadowing parametrizations [104].

Chapter 4

The upgrade of the Inner Tracking System

As introduced in the previous chapter, a reduction of systematics and statistical uncertainties is needed to improve our understanding of heavy-ion physics. For this reason a project to upgrade several ALICE detectors started in 2008, in order to be ready for installation in the second long LHC shutdown in 2019. The upgrade strategy is based on the assumption that the LHC will progressively increase its luminosity up to $L = 6 \cdot 10^{27} \text{cm}^{-2}\text{s}^{-1}$ with an interaction rate of about 50 kHz.

The upgrade plans include:

- a new beampipe with smaller radius (from 29.8 to 19.8 mm);
- a new ITS;
- the upgrade of the TPC, that consists on the replacement of the wire chambers with Gas Electron Multiplier (GEM) detectors and new pipelined read-out electronics;
- the upgrade of the read-out electronics of TRD, TOF and Muon Spectrometer for high rate operation;
- the upgrade of the forward trigger detectors;
- the upgrade of the online systems, offline reconstruction and analysis framework;
- the introduction of a new detector, the Muon Forward Tracker (MFT), in order to add vertexing capabilities to the current Muon Spectrometer (a full description of this new detector and its physics program can be found in [110])

The ALICE long-term physics goals, its experimental strategy and the general upgrade plans are discussed in the ALICE Upgrade Letter of Intent [111]. The rest of this chapter is focused on the upgrade of the ITS [112].

4.1 Motivation for the ITS Upgrade

4.1.1 Physics motivations

The study of the properties of the Quark Gluon Plasma requires very high precision measurements of all the physics channels. The analyses have to be pushed to their limits and those of very rare physics channels have to become possible, in particular in heavy-flavour measurements. The two main open questions concerning heavy-flavour interactions with the QGP medium are:

- Thermalisation and hadronisation of heavy quarks in the medium, which can be studied by measuring the heavy-flavour baryon/meson ratio, the strange/non-strange ratio for charm, the azimuthal anisotropy v_2 for charm and beauty mesons and the possible in-medium thermal production of charm quarks.

Observable	Current, 0.1 nb ⁻¹		Upgrade, 10 nb ⁻¹	
	$p_{\text{T}}^{\text{min}}$	statistical	$p_{\text{T}}^{\text{min}}$	statistical
	[GeV/c]	uncertainty	[GeV/c]	uncertainty
Heavy Flavour				
D Mesons R_{AA}	1	10%	0	0.3%
D _s Mesons R_{AA}	4	15%	< 2	3%
D Meson from B R_{AA}	3	30%	2	1%
J/Ψ Meson from B R_{AA}	1.5	15%	1	5%
B ⁺ yield	not accessible		3	10%
Λ _c R_{AA}	not accessible		2	15%
Λ _c /D ⁰ ratio	not accessible		2	15%
Λ _b yield	not accessible		7	20%
D Meson v_2 ($v_2 = 0.2$)	1	10%	0	0.2%
D _s Meson v_2 ($v_2 = 0.2$)	not accessible		< 2	8%
D Meson from B v_2 ($v_2 = 0.05$)	not accessible		2	8%
J/Ψ Meson from B v_2 ($v_2 = 0.05$)	not accessible		1	60%
Λ _c v_2 ($v_2 = 0.15$)	not accessible		3	20%
Dielectron				
Temperature (intermediate mass)	not accessible			10%
Elliptic flow ($v_2 = 0.1$)	not accessible			10%
Low mass spectral function	not accessible		0.3	20%
Hypernuclei				
$^3_{\Lambda}H$ yield	2	18%	2	1.7%

Table 4.1: Summary of the physics reach foreseen after the ITS upgrade: minimum accessible p_{T} and relative statistical uncertainty in Pb-Pb collisions for an integrated luminosity of 10 nb^{-1} . For heavy flavour, the statistical uncertainties are given at the maximum between $p_{\text{T}} = 2 \text{ GeV}/c$ and $p_{\text{T}}^{\text{min}}$. For elliptic flow measurements, the value of v_2 used to calculate the relative statistical uncertainty σ_{v_2}/v_2 is given in parenthesis. The case of the program up to Long Shutdown 2, with a luminosity of 0.1 nb^{-1} collected with minimum-bias trigger, is shown for comparison.

- Heavy-quark in-medium energy loss and its mass dependence, which can be addressed by measuring the nuclear modification factors R_{AA} of the p_{T} distributions of D and B mesons separately in a wide momentum range, as well as heavy flavour production associated with jets.

The measurements that will be positively affected by the ITS upgrade and the higher luminosity are summarized in the Table 4.1. The current p_{T} interval and statistical uncertainties are also listed for comparison. The possible improvements will not concern only heavy flavour. In general, a larger p_{T} interval will be accessible with a reduction of the related uncertainties.

4.1.2 Limitations of the current ITS

The current ITS, described in Section 2.2.1, presents some limitations in the study of heavy-flavours. For example, the precision in the determination of the track distance of closest approach is not adequate to study the production of charm mesons for p_{T} below $1 \text{ GeV}/c$. Moreover, the current impact parameter resolution (in the left panel of Figure 2.9) is larger than the decay length of Λ_c ($c\tau = 60 \mu\text{m}$), making the measurement inaccessible in Pb-Pb collisions.

Another limitation of the present ITS is its limited read-out rate capabilities of 1 kHz , irrespective of the detector occupancy. This prevents ALICE to exploit the full Pb-Pb collision rate of 8 kHz , restricting the data to a small factor of the LHC capabilities.

Finally, the present ITS is inaccessible for maintenance and repair interventions during the LHC yearly shutdowns, compromising the preserve of high data quality. For all these reasons the present ITS is clearly inadequate to fulfil the required performance and rate capabilities of LHC Run 3 and 4.

4.1.3 Simulation studies: D-meson analysis with the upgraded ITS

Several simulations has been carried out in order to study the possible improvement after the ITS upgrade. In this section an example of performance studies for D-meson reconstruction

with the upgraded ITS is presented. In Figure 4.1 the resolution on the $D^0 \rightarrow K^- \pi^+$ decay vertex is shown for three cases: the current ITS, the upgraded ITS with full simulation of the new detector and the Hybrid method that consists in applying the detector performance of the upgraded ITS to full simulations of the current ITS. An improvement of a factor of about 3 for x and y coordinates and about 6 for z coordinate is observed in the case of the upgraded ITS with full simulation. The improvement on the secondary vertex reconstruction is fundamental

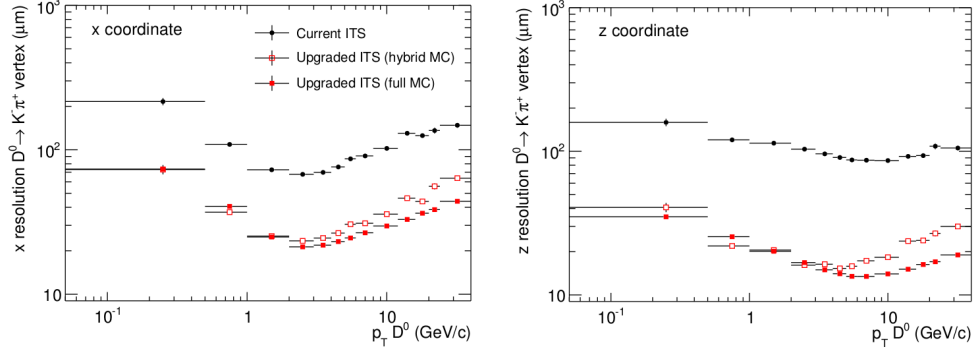


Figure 4.1: $D^0 \rightarrow K^- \pi^+$ secondary vertex position resolutions for current and upgrade scenarios: x (left panel) and z (right panel) coordinates [111].

to increase the statistical significance of the current measurements and to extend the p_T interval studied.

In left panel of Figure 4.2 the invariant mass distribution of D^0 candidates with $2 < p_T < 4$ GeV/c obtained from the analysis of $\sim 3 \times 10^4$ central (0 – 20%) Pb-Pb simulated events at $\sqrt{s_{NN}} = 2.76$ TeV is shown for both current and upgrade scenarios. An improvement in statistical significance and signal over background ratio could be observed with the upgraded ITS, even if the same selections were applied in both cases. In the right panel of Figure 4.2 the invariant mass distribution of D^0 candidates with $0 < p_T < 2$ GeV/c is shown in the same centrality class. A significance of 8.9 could be obtained in the upgraded scenario, while the extent to $p_T = 0$ GeV/c is not possible with the current ITS. The events used for this analysis are taken from a HIJING production enriched with charm signals.

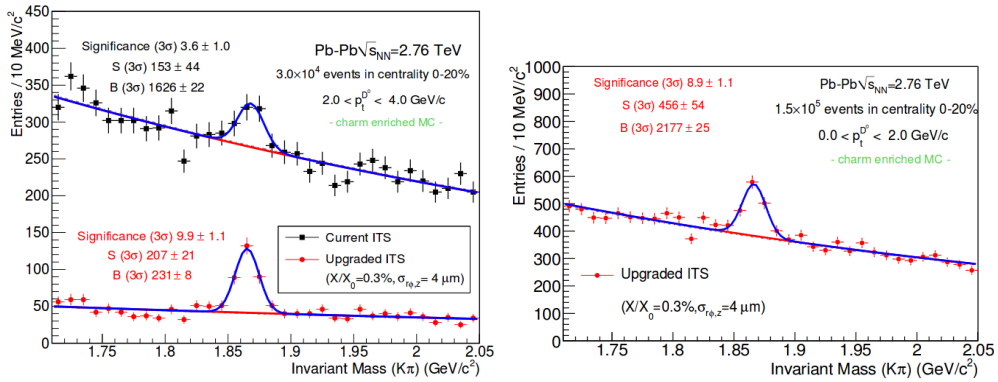


Figure 4.2: Left panel: Comparison between the invariant mass distributions of D^0 candidates with $2 < p_T < 4$ GeV/c obtained from the analysis of $\sim 3 \times 10^4$ central (0 – 20%) Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV (HIJING events enriched with charm signals) with the current and upgrade scenarios. Right panel: Invariant mass distribution in $0 < p_T < 2$ GeV/c obtained from the analysis of $\sim 1.5 \times 10^5$ central (0 – 20%) Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV with the upgrade scenario [113].

A simulation of the D^0 -meson R_{AA} is presented in the Figure 4.3 in (0 – 10%) Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV. Both statistical and systematic uncertainties are plotted in this figure. The difference with respect to the current measured uncertainties shown in Figure 3.23 is evident. Among all, the systematic uncertainties on the B feed-down correction, the signal yield extraction and the tracking efficiency will more profit from the better performances of the ITS upgrade. In the same figure the D_s^+ R_{AA} is also presented. Only statistical uncertainties are considered in this case. Also for the D_s^+ the extension of the p_T interval will be possible with a narrower binning.

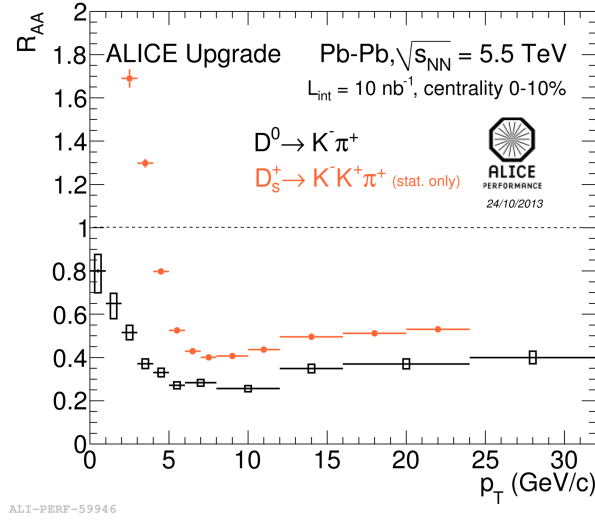


Figure 4.3: D^0 and D_s^+ R_{AA} as a function of the transverse momentum simulated in (0 – 10%) Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV with the upgrade scenario for the case of $L_{int} = 10 \text{ nb}^{-1}$.

In addition, the knowledge on D mesons will profit by the possibility to measure beauty mesons and hadrons that are not accessible with the current ITS.

4.2 ITS Upgrade overview

In order to satisfy the requirements and overcome the limitations described in the previous section, various measures will be taken in the ITS upgrade:

- **First detection layer closer to the beam line:** a reduction of the beampipe diameter is fundamental to improve the impact parameter resolution. The current beryllium beampipe has an inner radius of 29 mm but a value of 17.2 mm could be reached. In the upgrade project a conservative value of 19.2 mm is assumed for the inner radius and of 0.8 mm for the wall thickness. A smaller thickness values is not feasible due to possible issues with gas tightness and mechanical stability.
- **Reduction of material budget:** another basic requirement to improve the impact parameter resolution is the reduction of material budget of the first detection layer. In general, a reduction of the overall material budget will improve the tracking performance and momentum resolution. Monolithic Active Pixel Sensors (MAPS) are useful to achieve this goal, they will allow to reduce the silicon material budget from 350 μm to 50 μm per layer. Combining also the lower power consumption and a highly optimised scheme for the distribution of the electrical power and signals, it will be possible to achieve a radiation length of at least 0.3% X_0 per layer in the upgraded ITS.
- **No measurement of energy loss:** the new ITS will not measure the energy loss in its silicon layers. Studies have been carried out in order to assess the benefit of the ITS PID

	Inner Barrel Inner Layers			Outer Barrel Middle Layers Outer Layers			
	L. 0	L. 1	L. 2	L. 3	L. 4	L. 5	L. 6
Radial position (min.) [mm]	22.4	30.1	37.8	194.4	243.9	342.3	391.8
Radial position (max.) [mm]	26.7	34.6	42.1	197.7	247.0	345.4	394.9
Length (sensitive area) [mm]	271	271	271	843	843	1475	1475
Pseudo-rapidity coverage	± 2.5	± 2.3	± 2.0	± 1.5	± 1.4	± 1.4	± 1.3
Active area [cm ²]	421	562	702	10483	13104	32105	36691
Nr. Pixel Chips	108	144	180	2688	3360	8232	9408
Nr. Staves	12	16	20	24	30	42	48
Staves overlap in $r\phi$ [mm]	2.23	2.22	2.30	4.3	4.3	4.3	4.3
Pixel size [μm^2]	$(20 - 30) \times (20 - 30)$			$(20 - 50) \times (20 - 50)$			

Table 4.2: Geometrical parameters of the upgraded ITS.

capabilities, in particular on low-mass di-electron analysis and $\Lambda_c \rightarrow pK\pi$ reconstruction that are more sensitive to low-momentum PID. These studies confirm that the benefit of implementing an energy-loss measurement would be marginal. For this reason, the new ITS will have a binary read-out, instead of an analogue one.

- **Lower read-out time:** the new detector is designed to reach a maximum read-out rate of 100 kHz for Pb-Pb collisions and 400 kHz for pp collisions, increasing the currently maximum readout rate of 1kHz by a factor 100 in Pb-Pb collisions.
- **Radiation hardness:** the radiation doses and hadron fluences has been computed for the upgraded ITS for the integrated luminosities needed to the proposed physics studies (4×10^{11} for pp collisions and 8×10^{10} for Pb-Pb collisions). The expected NIEL radiation levels ranges from 9.2×10^{12} 1MeVn_{eq}/cm² for the first layer to 4.6×10^{11} 1MeVn_{eq}/cm² for the last layer. Instead, the expected TID radiation levels ranges from 646 kRad for the first layer to 6 kRad for the last layer. A conservative factor of ten were applied to take into account uncertainties on the beam background, possible beam losses inefficiency in data taking and data quality requirements. The new ITS chips have to show no degradation to those radiation level, even when operated at room temperature.
- **Increasing of number of detection layers and segmentation:** in the new ITS the number of concentric silicon layers will increase from 6 to 7, covering a radial extension from 22 to 392 mm with respect to the beamline. Several studies have been carried out assuming or that all layers are segmented in pixels with dimensions of $20 \times 20 \mu\text{m}^2$ or that the cell size of the three inner layers and of the four outer layer increase to $30 \times 30 \mu\text{m}^2$ and $50 \times 50 \mu\text{m}^2$, respectively. No significant deterioration in terms of parameter resolution and standalone momentum were observed in the lower granularity scenario.
- **Insertion/removal for yearly maintenance:** the design of the entire apparatus has been planned carefully in order to allow the substitution of the damaged detector modules during the yearly shutdown.

4.2.1 Layout overview

A summary of the geometrical parameters of each layer of the upgraded ITS could be found in Table 4.2.

The layers are grouped into two separate barrels: the Inner Barrel, containing the three innermost layers, and the Outer Barrel, containing the four outermost layers. Figure 4.4 shows the layout of the upgraded detector, while Figure 4.5 shows the schematic view of the cross section of Inner (left panel) and Outer (right panel) Barrels. The ITS layers are azimuthally segmented in units named **Staves**, which are mechanically independent. Staves (Figure 4.6) are fixed to a support structure, half-wheel shaped, to form the **Half-Layers**. The term Stave will be used to refer to the complete detector element. It consists of the following main components:

- **Space Frame:** a carbon fiber support structure for a single stave.
- **Cold Plate:** carbon ply to embed the cooling pipes.
- **Hybrid Integrated Circuit:** hosts the Flexible Printed Circuit (FPC) on which the pixel chips are bonded
- **Half-Stave:** further azimuthal segmentation for the Outer Barrel Stave.

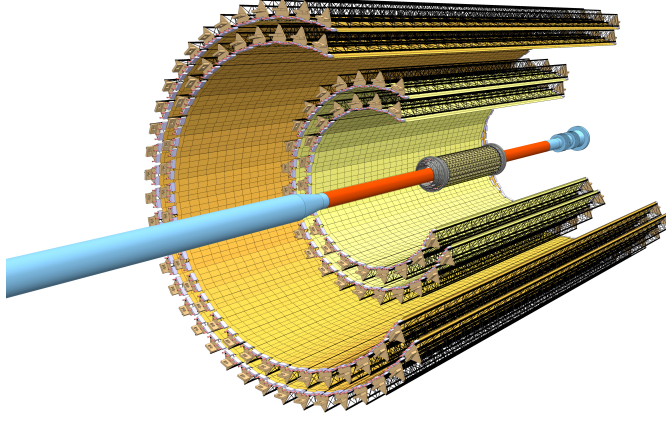


Figure 4.4: Layout of the new ITS detector.

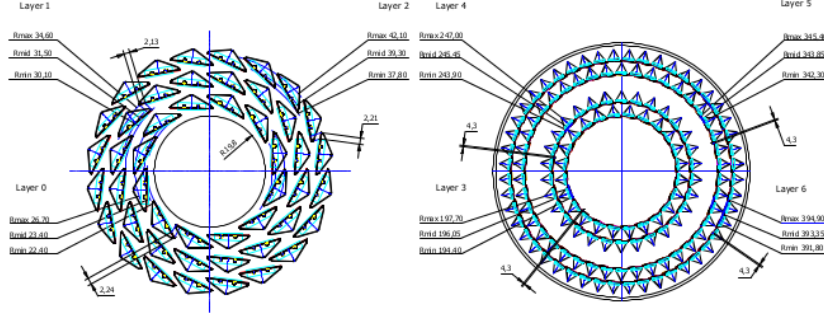


Figure 4.5: Schematic view of the cross section of the Inner Barrel (left) and Outer Barrel (right).

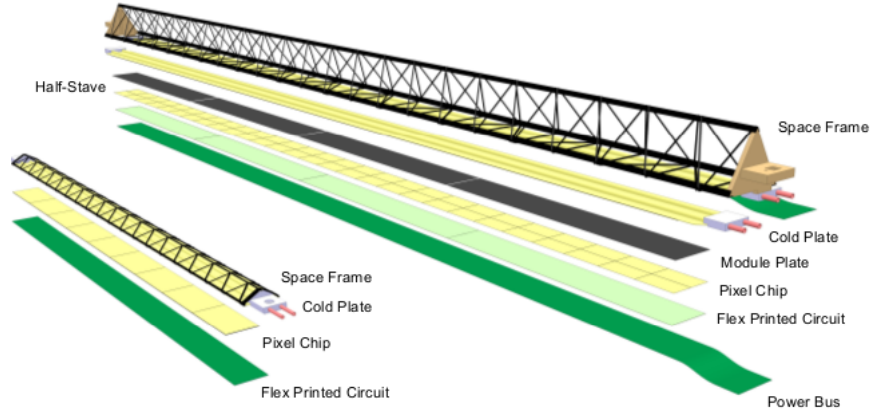


Figure 4.6: Schematic drawing of the Inner Barrel (left) and Outer Barrel (right) Staves.

4.3 Monolithic Active Pixel Sensors

On the basis of the above considerations, the baseline solution for the layout of the ITS upgrade is to replace the existing ITS detector with seven concentric layers of pixel detectors. Monolithic Active Pixel Sensors (MAPS) implemented using the $0.18\ \mu\text{m}$ CMOS technology of TowerJazz have been selected as the technology for all layers.

The development of sensors based on silicon (Si) semiconductor technology and of readout electronics based on CMOS technology (application-specific integrated circuits, ASICs) started in the 1980s, revolutionising the implementation of detection systems. Nowadays silicon micro strip and pixel sensors are used in the majority of particle tracking systems in particle physics experiments. For example, the present Si pixel detectors, where the sensor and the read out electronics are separate components bump-bonded, are used in the innermost layers of the LHC experiments. This technology presents some technical limitations, that are being reached, due to the interface between the sensor and the read-out electronics. The development of a new technology is required to go beyond these limitations on granularity and material thickness. One possible approach considered is to merge both sensor and read-out electronics in a single detection device, such as in MAPS.

Before explaining the characteristics of MAPS in details, a brief introduction of the detection principle of semiconductors will be given in this section.

4.3.1 Particle detection in semiconductors

In semiconductor detectors the detection principle is based on the detection of charged particle generated by the interaction of radiation or charged particles with the material. The interaction process depends on the type, charge or energy of the particles traversing the sensor material. The charge collection mechanism depends, instead, on the material properties, like resistivity and doping level, its geometry, like thickness of sensitive material and pixel pitch, and the electric field of the sensor.

Interaction of particle with silicon sensors

- **Interaction of charged particle.** The charged particles traversing the sensor undergo scattering processes with the electrons of the interacting medium. These processes are dominant for particles heavier than electrons and the energy that they loose can be obtained by the Bethe-Block formula [114]. In the case of electrons and positrons a correction has to be applied to the Bethe-Block formula since they interact with identical particles and additional energy loss mechanism, like *bremsstrahlung*, have to be considered. For a particle with $\beta\gamma \sim 3$ the energy loss reach a minimum and the particle is called *Minimum*

ionizing particle (MIP). The number of charge carriers (electrons and holes) generated in a semiconductor by the traversing particle is determined by dividing the deposited energy by the mean energy required for ionization (3.6 eV for silicon). The ionization process is subjected to statistical fluctuations that depends on the thickness of the absorber, in the case of a thin absorber the energy loss distribution is asymmetric. Instead, it has a Gaussian shape for thick absorber. For silicon sensors, the energy loss distribution was calculated by Landau [115] and Vavilov [116].

A part from energy loss, charged particles traversing a detector suffer from *Multiple Coulomb Scattering*. This causes a small deviations of the track due to successive small angle deflections from the incident direction. The scattering angle follows roughly a Gaussian distribution [117] with a root mean square of:

$$\sqrt{\langle\theta^2\rangle} = \frac{13.6z}{\beta pc} \frac{X}{X_0} \left[1 + 0.038 \log \frac{X}{X_0} \right] \quad (4.1)$$

where β , p and z are the velocity, momentum and charge of the particle, respectively and the ratio X/X_0 gives the thickness of the absorption medium in units of radiation length.

- **Interaction of electromagnetic radiation.** The interaction of photons with semiconductor detectors occurs through three processes: the Compton effect, where the incident radiation is scattered and photoelectric effect and pair production, where the radiation is completely absorbed in the sensor material.

The photons that pass through the sensor are those that have not suffered any interaction. Consequently, a monochromatic photon beam traversing the sensor do not change its energy but its intensity is attenuated by:

$$I(x) = I_0 e^{-x/\mu} \quad (4.2)$$

where I_0 is the incident beam intensity, x is the thickness of the traversed material and μ is attenuation length (characteristic of the medium and depending on the photon energy). More details on the use of silicon for photon detection can be found in [118].

Detection principle

Semiconductor detectors are usually based on a reverse bias junction. The particles interacting with the semiconductor produce electron-hole pairs along their path through the material. In order to be collected by the electrodes associated to the front end readout electronics, the produced charge carriers could be moved by drift applying a reverse bias and/or by diffusion thanks to a variation of the concentration.

In Figure 4.7 a simulation of the electric field on a semiconductor device is shown for different values of reverse bias and epitaxial layer doping. The diode is made of a $3\mu\text{m} \times 3\mu\text{m}$ square n-well, which has a $0.5\mu\text{m}$ spacing to the surrounding p-well. As it could be observed from the white lines indicating the boundaries of the depletion region, a larger reverse bias produces a larger depletion region and, hence, facilitates the collection of charges.

Nevertheless, a leakage current of some nA/cm^2 due to the thermal diffusion of minority charge carriers across the junction has to be considered. This leakage current depends on the intrinsic carrier concentration of the silicon, the diffusion constant of both electrons and holes, the diffusion length of the charge carriers and the diode section.

Another contribution is given by the carriers that are thermally generated in the depletion region because of the trap densities and that are separated by the electric field. This results in a parasitic current of some $\mu\text{mA}/\text{cm}^2$. This contribution can be reduced using a high purity silicon wafer.

Radiation damage

The performance of particle detectors could be affected by a high radiation environment, for this reason the radiation hardness of the sensors has to be guarantee.

There are two types of radiation damage [119]:

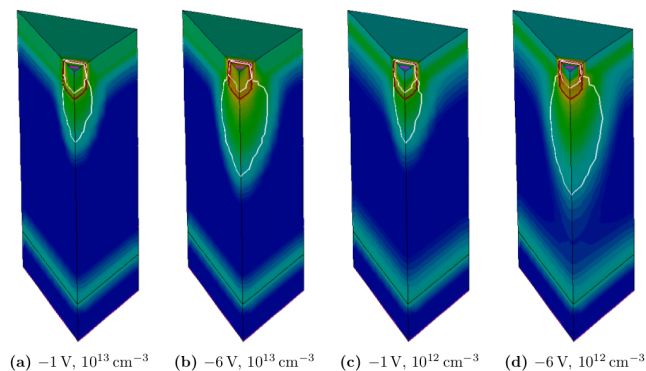


Figure 4.7: Semiconductor device simulations for different settings of total diode reverse bias and epitaxial layer doping. The color code shows logarithmically the absolute value of the electrical field, and the white line indicates boundaries of the depletion region.

- **Single Event Effects (SEE)** that have an influence on the detectors electronics and can be produced by a single traversing particle. They depend on circuit complexity, deposited charge and the volume in which the charge has been deposited. They could be destructive or not and, because of their stochastic nature, they could not be foreseen. However, it is possible to equip the circuit of some ancillary blocks to reconfigure it in the case of a non-destructive SEE.
- **Cumulative effects** that invest both the sensor and the electronics. They depend on the flux and the type of radiation that pass through the detector. They can cause a displacement damage or a ionization damage. The displacement damage is a non-ionizing damage which take place in the silicon bulk and consists on the kick out of a silicon atom from its natural position, changing the doping characteristics. It depends on the mass and the energy of the incident particle and generates defects that modify the electrical characteristics of the crystal as well as its band gaps. It manifests in mid-band gap between the valence and the conduction bands that can increase the leakage current in the depletion region because of generation mechanisms and reduce the direct current because of recombination mechanisms. This effect could also vary with the temperature and it could be attenuated by adding oxygen to the silicon that prevents the formation of electrical active sites in the sensor bulk. The ionization damage allows the formation of free charge carriers altering the electrical field in the proximity of charge collection point. It could affect the SiO_2 gate surface of the transistor and the insulator layers and depends on the energy released from the radiation in the material. The major effect consists in increasing the threshold voltage of MOS transistors. Hence, the voltage gate has to be lowered to create a channel in the transistor. Specific layout techniques have been developed to limit the ionization damage. Furthermore, since the holes trapping probability increases roughly linearly with the oxide thickness, a thinner oxide could help to reduce the threshold voltage shift.

4.3.2 MAPS

As already mentioned above, the majority of the innermost vertexing and tracking detectors in the LHC experiments uses hybrid pixel detectors. In these detectors the silicon sensor and the front-end readout electronics are separated components electrically connected by bump bonding. This technology has the advantage that the two components can be optimized separately but there are technical limitations due to the bump bonding technics and the power density.

A schematic view of a hybrid pixel is shown in the left panel of Figure 4.8, while on the right panel a monolithic pixel is shown.

The monolithic pixel technology allows for the sensor and the front end to be on the same

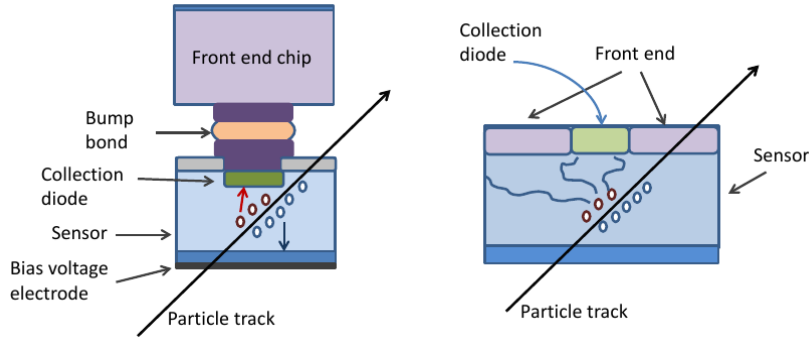


Figure 4.8: Left: Hybrid pixel. The sensor and the front end chip are two separate components attached by a bump bond. Right: Monolithic pixel. The sensor and the frontend are developed on the same silicon substrate.

substrate. MAPS present some limitations with respect to radiation hardness and readout speed that do not allow their use in experiments like ATLAS, CMS or LHCb. On the contrary, they can be used in heavy-ion experiments like ALICE where the radiation tolerance and readout requirements are less stringent. A MAPS sensor, the ULTIMATE, is already in use in the Heavy Flavour Tracker at RHIC from 2014.

The ULTIMATE sensor has been developed exploiting AMS 0.35 μm technology that does not satisfy the ALICE ITS upgrade requirements in terms of radiation hardness and readout time. For this reason a different technology, TowerJazz 0.18 μm , has been selected for the project.

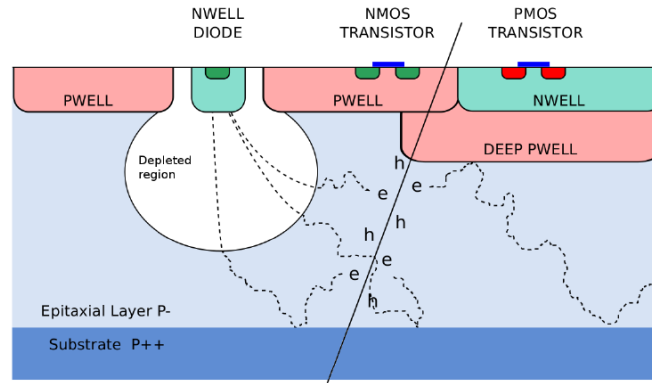


Figure 4.9: Schematic cross section of a MAPS pixel in the TowerJazz 0.18 μm imaging CMOS with the deep p-well feature.

The main components of MAPS in a standard CMOS process are shown in Figure 4.9 and are listed below:

- **Substrate** is the lowest layer made of highly doped (p type) crystalline silicon with low resistivity.
- **Epitaxial layer** is grown on top of the substrate. It is lightly doped (p type), high resistive and forms the active volume of the detector where charges are generated. The active devices are embedded in this layer.
- **Well implantations** are the bulk for the Field Effect Transistors. The n-well and p-well implantations are used to integrate PMOS and NMOS transistors, respectively.

- **Diffusion implantations** form the source and drain of the transistors. They have higher doping than the wells in which they are embedded into. The p-type and n-type implantations are done for PMOS and NMOS respectively.
- **Collection diode** collects the charge generated in the epitaxial layer. The depletion region is formed at the junction between the diode n-well and the p-epitaxial layer.
- **Metal lines** connect the different silicon structures. They are generally made of aluminum or copper and embedded into silicon oxide, which serves as an insulator.

The particular characteristics of MAPS in the TowerJazz 0.18 μm technology allow to fulfil the requirements of the ITS Upgrade:

- Epitaxial layer resistivity from 1 $\text{k}\Omega\text{cm}$ to 6 $\text{k}\Omega\text{cm}$ are possible, obtaining a depletion area in the epitaxial layer that would improve the signal to noise ratio of the sensor, reducing its power consumption, and its resistance to non-ionizing radiation. A further gain is also guaranteed by the possibility of applying a back-bias voltage.
- Implementation of high density and low power circuit is allowed thanks to the 6 metal layer available in the technology and the small feature size. This would reduce the area of the digital circuit located at the periphery of the pixel matrix, decreasing the insensitive area of the pixel chip.
- Availability of a deep p-well (heavily doped) in the region where the front-end electronics is situated, circumventing the problem of the parasitic charge collection by the n-well that accommodate the PMOS transistor.

The latter is one of the most important features offered by this technology since the charge collection is based on diffusion. Indeed, the charge collection is facilitated by the different doping concentrations in different layers of MAPS. The charged carriers (electron-hole pairs) are generated in the epitaxial layer by the impinging particles. The electrons generated are deflected by the substrate due to a potential barrier formed between the lightly doped p-type epitaxial layer and the heavily doped p-type substrate. Similarly, a potential barrier exists between the lightly doped epitaxial layer and the heavily doped p-wells of the NMOS transistors. This results in the containment of the majority of the electrons within the epitaxial layer which diffuse randomly. Diffusing electrons are then collected as a signal when they reach the built-in electric field at the junction formed by the n-well of the sensing diode and the p-type epitaxial layer.

The possibility of integrating the PMOS transistors inside the pixel, that is impossible without the deep p-well, allows the construction of more complex read-out architectures. For example, the discriminator could be placed inside the pixel and the chip could work in a continuous or self-triggered mode.

Another important aspect of the detection circuit is its noise.

There are two main sources of noise: the input capacitance, that generates the kTC noise, and the small input transistor, that generates the random telegraph signal noise (RTS noise). The first is created by resetting the collection electrode, i.e. by recharging the diode capacitance. One way to mitigate this noise contribution is to measure the voltage signal on the diode twice and subtract the value of the first measurement from the second one (correlated double sampling, CDS).

On the contrary, the RTS noise depends on the transistor geometries and type (NMOS or PMOS). For this reason different layouts have been studied in order to minimize it. RTS noise typically diminishes when increasing the size of the input transistors, which however also increases the capacitance; some trade-off between gain and noise needs to be made.

Additional so-called “shot noise” is caused by the leakage of the collection node. Its magnitude is proportional to the square root of the number of leaked electrons and, hence, does not only depend on the electrode geometry but also on the integration time.

Parameter	Inner Barrel	Outer Barrel
Max. silicon thickness	5 μm	50 μm
Intrinsic spatial resolution		10 μm
Chip size	15 mm x 30 mm ($r\phi$ x z)	
Max. dead area on chip	2 mm ($r\phi$), 25 μm (z)	
Max. power density	300 mW/cm ²	100 mW/cm ²
Max. integration time		30 μs
Max. dead time		10% at 50 kHz Pb-Pb
Min. detection efficiency		99%
Max. fake-hit rate		10^{-5}
TID radiation hardness ^a	2700 krad	100 krad
NIEL radiation hardness ^a	1.7×10^{13} 1 MeV n _{eq} /cm ²	1.7×10^{12} 1 MeV n _{eq} /cm ²

^a includes a safety factor of ten.

Table 4.3: Pixel detector general requirements.

4.3.3 Prototype circuits

The physics objectives and the design goals described in Section 4.1 led to the requirements for the pixel chip listed in Table 4.3.

Four different design streams are followed to explore the TowerJazz technology capabilities in order to fulfill these requirements: MISTRAL, ASTRAL, CHERWELL and ALPIDE. The main features are summarised in Table 4.4.

A series of prototypes have been developed for each design stream. I have contributed to the characterization of a subsample of these prototypes. In this thesis, I will focus on the characterization of small-scale prototypes from the MISTRAL stream (MIMOSA22-ThrB and MIMOSA22-ThrB6/7 designed for the ITS outer layers) and one full-scale prototype from the ALPIDE stream (pALPIDE-v2). MISTRAL (Mimosa Sensor Tracker ALice) prototypes are developed at IPHC (Strasbourg) and they derive from the ULTIMATE chip, designed for the STAR-PXL detector at RHIC. In the new prototypes hit rate capability, pixel dimension and integrated circuit are improved.

ALPIDE (ALICE Pixel DEtector) is developed by a collaboration formed by CCNU (Wuhan, China), CERN, INFN (Italy), and Yonsei (South Korea).

The main difference between the two architecture is the read-out circuit that is schematized in Figure 4.10.

The MISTRAL prototypes use a rolling-shutter architecture, shown in the right panel of Figure 4.10. A comparator is placed at the end of column to discriminate the signals that are also compressed by a zero-suppression algorithm (SUZE). Thanks to the small feature size, two rows are read at once, speeding up the read-out time and decreasing the integration time (30 μs). Another approach is followed by the ALPIDE development: an Adress-Encoder-Reset-Decoder (AERD) circuit [120] is used, shown in the left panel of Figure 4.10. In this case a comparator is placed in each pixel, allowing to get the digital information faster and, hence, to increase the read-out speed. ALPIDE uses a data-driven read-out in which the digital outputs of the pixels are fed into an encoder circuit that generates directly the address of a hit pixel. In this way it become possible to reset the pixel and go to the next one untill all the pixels are read out. This approach allow a lower power consumption (~ 35 mW/cm²) with a faster read-out time (< 10 μs). Reduce as much as possible the read-out time would be useful for the LHC Run 3 and 4 because signals from all events within the read-out time are integrated, leading to pile-up in case of large interaction rate.

Architecture (discriminator, read-out)	Pitch ($r\phi \times z$)(μm^2)	Integration time (μs)	Power consumption (mWcm ⁻²)
MISTRAL (end-of-column, rolling shutter)	22 x 33.3	40	200
ASTRAL (in-pixel, rolling shutter)	24 x 31	20	75
CHERWELL (in-strixel ^a , rolling shutter)	36 x 31	60	60
ALPIDE (in-strixel ^a , rolling shutter)	20 x 20	30	90
ALPIDE (in-pixel, rolling shutter)	28 x 28	< 10	~ 35

^a A strixel is a 128-pixel column over which the electronics are distributed.

Table 4.4: Chip design options.

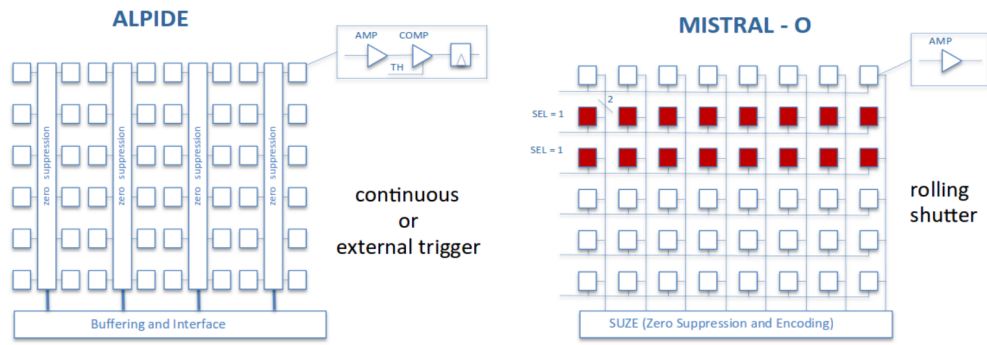


Figure 4.10: Read-out scheme of ALPIDE (left) and MISTRAL (right) architectures.

Chapter 5

Characterization of small-scale MISTRAL prototypes

All the prototypes developed for the ALICE ITS Upgrade pass through an intensive characterization campaign. The characterization takes place both in laboratories and at beam test facilities in order to calibrate the sensors and study their response to different particles.

In this Chapter, I will focus on the characterization of MISTRAL small-scale prototypes (MIMOSA22ThrB, MIMOSA22ThrB6 and MIMOSA22ThrB7) at the DAΦNE Beam Test Facility (BTF)[121] at the INFN Laboratori Nazionali di Frascati (LNF). The BTF provides an electron or positron beam with a maximum energy of ~ 500 MeV with a selectable particle rate from 10 to 50 Hz and spill duration from 1.5 to 40 ns. The prototypes have been characterized in the framework of the development of a telescope based on MIMOSA sensors (monolithic pixel sensors developed at IPHC). The project has been carried out by a collaboration formed by the INFN groups of Turin, Padova, Catania, Frascati and by the PICSEL group from IPHC. I took part in the preparation of the software required to decode the raw data from the sensors and in the analysis of the data collected during the testbeams, in which I participated.

In the first section the telescope setup will be described. Then, the analysis procedure will be explained and, in the last section, the analysis results are presented.

5.1 The telescope setup

Three testbeam campaigns have been carried out in June and September 2014 and in March 2015. In each campaign MIMOSA28 and MIMOSA18 prototypes have been used to build the telescope. The number and the position of the sensors in the telescope has been changed in each campaign in order to optimize the performance of the telescope. A picture of the telescope from the September campaign can be seen in Figure 5.1.

One of the main difficulties in building the telescope setup has been to synchronize and read three different sensors with integration times that vary by one order of magnitude, as reported below in the sensors description.

5.1.1 MIMOSA28

The MIMOSA28 sensor (M28, ULTIMATE) [122], shown in the left panel of Figure 5.2, is the final sensor developed for the upgrade of the inner layer of the vertex detector of the STAR experiment at RHIC. This chip has been fabricated in the $0.35\ \mu\text{m}$ AMS opto process. It is composed by a matrix of 928 (rows) $\times$ 960 (columns) pixels of $20.7\ \mu\text{m}$ pitch, for a total chip size of $19.21 \times 19.87\ \text{mm}^2$. The sensor has an epitaxial layer thickness of $15\ \mu\text{m}$ on a High Resistivity substrate ($400\ \Omega\text{cm}$) and has been thinned down to $50\ \mu\text{m}$ to reduce the material budget. Pixel columns are readout in parallel, row by row; the readout time is $185.6\ \mu\text{s}$. Each pixel includes an amplification and Correlated Double Sampling (CDS) and each end of

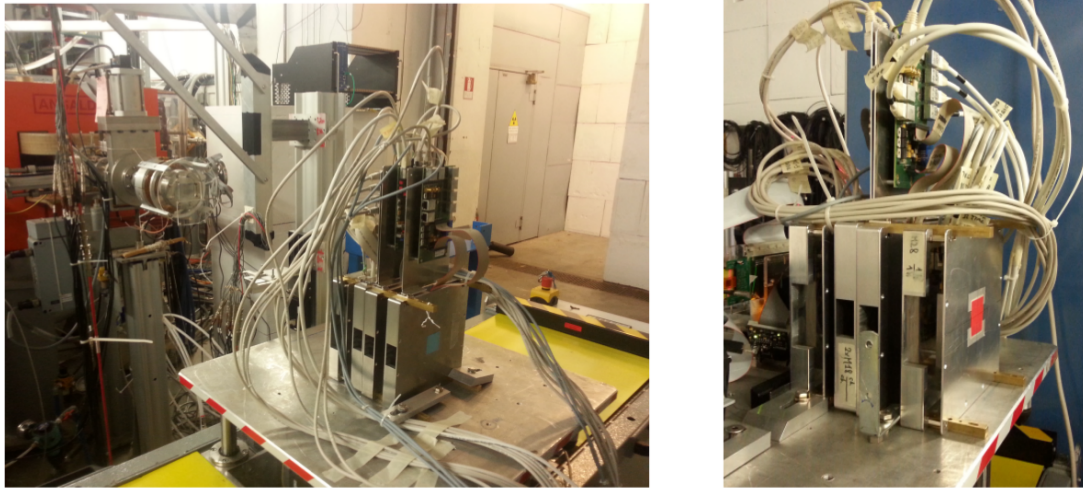


Figure 5.1: Left: setup of the telescope at the BTF. Right: close up of the layers composing the telescope.

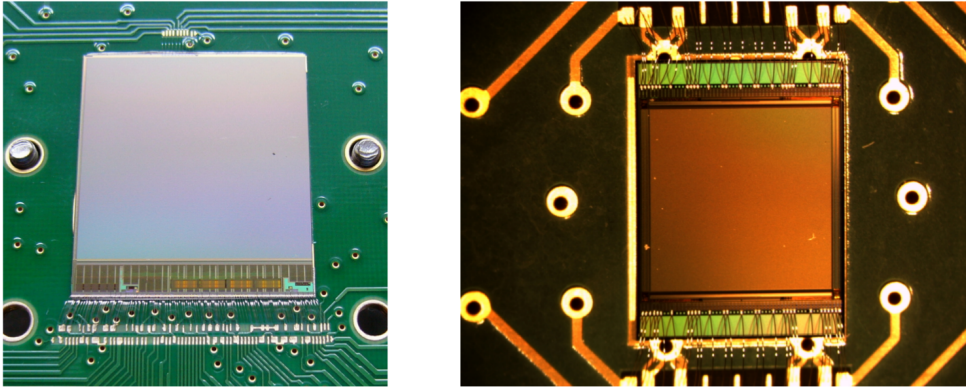


Figure 5.2: MIMOSA28 (left) and MIMOSA18 (right) MAPS sensors composing the telescope.

columns is equipped with a discriminator. The threshold of the discriminator is programmable by JTAG slow control. After analog to digital conversion, the digital signals pass through the zero suppression block: digital signals are processed in parallel on 15 banks, then arranged and stored in a memory row by row.

5.1.2 MIMOSA18

The MIMOSA18 sensor (M18) [123], shown in the right panel of Figure 5.2, has been fabricated in the $0.35\ \mu\text{m}$ AMS opto process and is composed of 4 matrices of 256×256 analog pixels with a pitch of $10\ \mu\text{m}$. Therefore, a single sensor consists of an array of 512×512 pixels, providing a total area of $5 \times 5\ \text{mm}^2$. The sensor is fabricated using a standard $14\ \mu\text{m}$ thick epitaxial layer and has been thinned down to $50\ \mu\text{m}$. A simple read out architecture is used: it consists of a 2-transistor pixel cell (half of a source follower plus a readout selection switch) connected to the charge collecting n-well diode, continuously biased by another diode (forward biased) implemented inside sensing n-well. The size of the sensing n-well diode is of $4.4 \times 3.4\ \mu\text{m}^2$. The signal information from each pixel is serialized by a circuit (one per sub-array), which can withstand up to a 25 MHz readout clock frequency. However, all the results presented in this work are obtained with a 20 MHz clock, which provides a full frame readout time of $\sim 3\ \text{ms}$. In

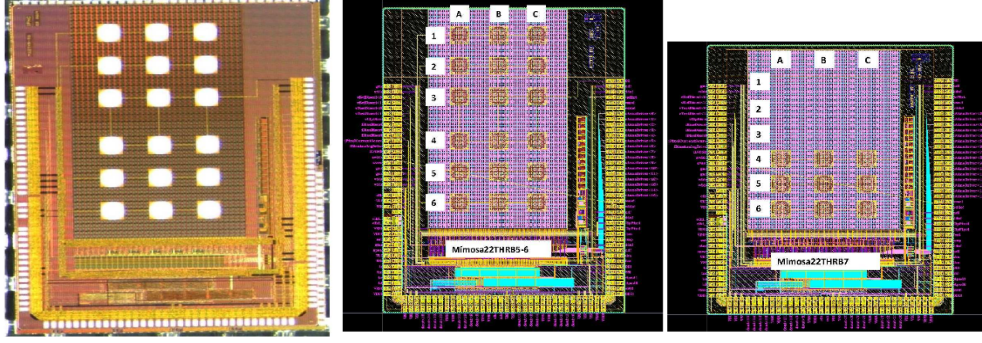


Figure 5.3: MIMOSA22ThrB (left), MIMOSA22ThrB6 (middle) and MIMOSA22ThrB7 (right) sensors used as device under test in the telescope.

this architecture, the frame readout time is equal to the signal integration window. Information from two consecutive frames is read out, one frame before and one frame after each trigger. Correlated double sampling (CDS) method is used for hit reconstruction.

5.1.3 Devices under test

MIMOSA22ThrB

The MIMOSA22ThrB (M22ThrB), shown in the left panel of Figure 5.3, has been designed for the ALICE ITS Upgrade in TowerJazz 0.18 μm process on a high resistivity epitaxial layer. The sensor is composed of a matrix of 64×64 elongated pixels, with a pixel size of $33 \times 22 \mu\text{m}^2$. Its architecture is based on the MIMOSA22 [124] which is a fast binary readout MAPS, with an integration time of $6.4 \mu\text{s}$. At the bottom of the matrix there are 56 columns ended with two discriminators for double row readout and 8 columns formed of 2 output buffers for double row readout. Only the 56 columns with a digital output are read out in the analysis. The matrix is controlled by internal fully programmable digital sequencer and integrates each one output multiplexers for 16 binary outputs. The chip is driven by a 100 MHz clock. The setup with programmable registers is accessed via an embedded slow control JTAG interface. The M22ThrB has been used as a device under test (DUT) in the telescope in June and September 2014.

MIMOSA22ThrB6/7

The MIMOSA22ThrB6 and MIMOSA22ThrB7, respectively shown in the middle and left panel of Figure 5.3, have been designed to validate larger pixel performances for the outer layers (3-7) of the new ITS. Those layers have looser requirements in terms of radiation hardness and spatial resolution (see Table 4.3). The sensors are composed of 64×64 elongated pixels, with a pixel size of $36 \times 62.5 \mu\text{m}^2$ (M22ThrB6) and of $39 \times 50.8 \mu\text{m}^2$ (M22ThrB7). As for the M22ThrB, 56 columns ended with a discriminator and are considered in the analysis, while the others 8 columns have an analog output. The sensors are divided into two parts: the upper part with a large diode of $14.8 \mu\text{m}^2$ for both M22ThrB6 and M22ThrB7 and the lower part with a small diode of $7.4 \mu\text{m}^2$ for the M22ThrB6 and $4.8 \mu\text{m}^2$ for the M22ThrB7. The two prototypes differ for the pre-amplifier input transistor and coupling capacitor variants. The readout time of the chips is $5 \mu\text{s}$, driven by the 100 MHz clock. The two sensors M22ThrB6 and M22ThrB7 have been both used as a DUT in March 2015.

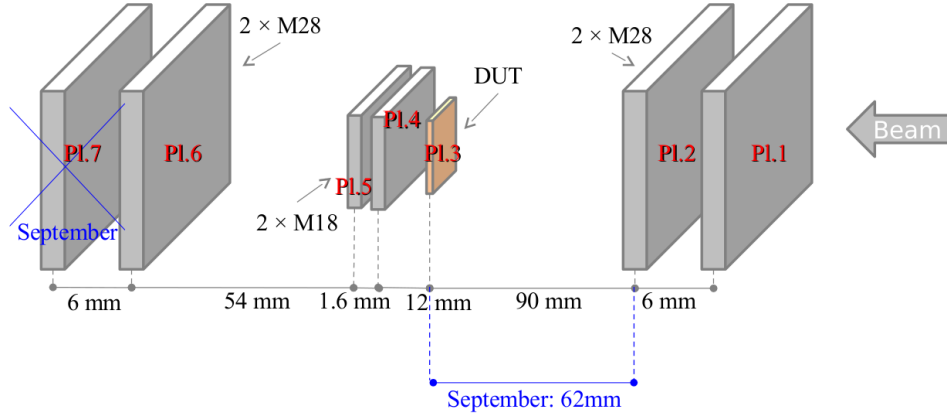


Figure 5.4: Telescope geometry (not to scale) during June and September testbeams. In black the configuration used in June 2014 is schematized, while in blue the modifications made to the setup in September 2014 are shown. The identification number of each plane is indicated in red.

5.2 Telescope geometry

5.2.1 June 2014 Setup

Figure 5.4 schematically shows the telescope setup during the June and September 2014 testbeams. The distances between the planes used in June are written in black. Starting from the beam injector there were two planes of M28 placed at 6 mm from each other and one DUT of M22ThrB at a distance of 90 mm from the second plane of M28. Then, there were two planes of M18 at 12 mm from the DUT that were bonded on the opposite sides of the same board, enabling a distance of 1.6 mm from each other. Last, a second pair of M28 was placed at 54 mm from the second plane of M18. Moreover, between the first couple of M28 and the DUT a plane of MIMOSA22-ThrA was placed. It was planned to be used as a further DUT but it was never connected with the DAQ. Anyway, its presence must be taken into account for the multiple scattering effect.

The figure is not to scale but it is important to notice the differences in the area covered by each plane that have to be considered carefully during the telescope construction: $\sim 382 \text{ mm}^2$ for M28, $\sim 26 \text{ mm}^2$ for M18 and $\sim 3 \text{ mm}^2$ for M22ThrB.

During the June testbeam there were some constraints because we were not main users of the area, so the beam was not centered on the telescope and the particle rate was limited to a few particles/cm² per frame. As a consequence, the number of runs with very high statistics was limited. In the left panel of Figure 5.5 the non-centered beam profile on the map of the hits in one of the M28 planes is clearly visible.

5.2.2 September 2014 setup

During the September testbeam the unused plane of MIMOSA22-ThrA was removed and the first pair of M18 were moved closer to the DUT at a distance of 62 mm (instead of 90 mm) in order to reduce the effect of the multiple scattering. The modifications to the telescope setup with respect to the June data taking are indicated in blue in Figure 5.4. Due to technical issues, the last M28 in the telescope was not included in the data acquisition. This modification did not have any effect on the data. Being main user of the area, it was possible to better center the telescope with respect to the beam and to increase the particle rate up to $\sim 100 \text{ particle/cm}^2$ per bunch. In the right panel of Figure 5.5 it can be observed that the beam profile is centered on one of the M28 planes.

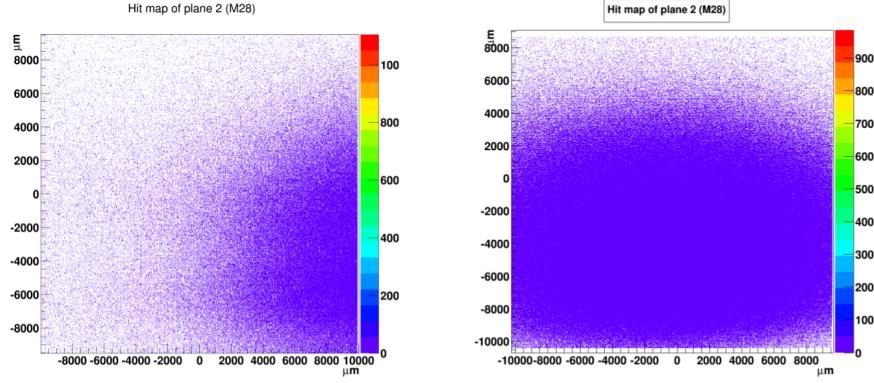


Figure 5.5: Map of the hits of one of the M28 planes in June (left) and September (right) testbeams, the beam profile is visible in both cases.

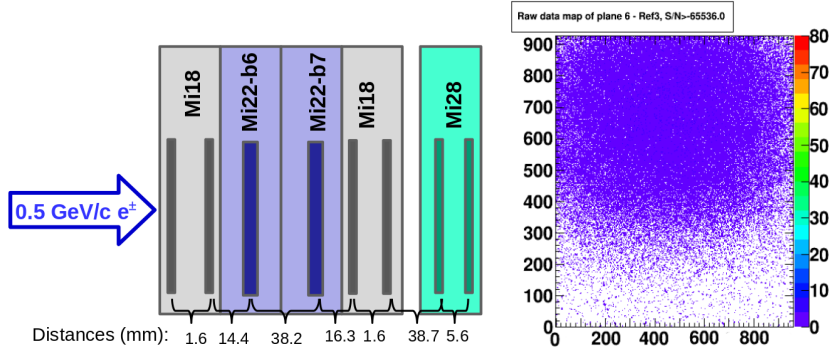


Figure 5.6: Left: telescope geometry (not in scale) during March 2015 testbeam. Right: map of the hits of one of the M28 planes.

5.2.3 March 2015 setup

The left panel of Figure 5.6 shows the telescope setup during March 2015 testbeam. Following the beam direction, we had a pair of M18 and, then, a M22ThrB6 and a M22ThrB7 at 14.4 and 52.6 mm, respectively. After the DUTs, there was another pair of M18 at 16.3 mm and a pair of M28 at a distance of 38.7 mm to the second M18. This setup was more compact with respect to the June and September ones and the distances between the DUT and the closest planes were reduced in order to decrease the effect of multiple scattering. As in the September campaign, we were main user of the area and the beam is well centered on one of the M28 planes (see the right panel of Figure 5.6).

5.2.4 DAQ

The Data Acquisition system (DAQ) is based on the VME bus standard. In June and September, the whole system consists of four Caen V1495 modules (General Purpose VME board, equipped with a EP1C20 Altera Cyclone FPGA), one ADC SIS3300 and one ADC SIS3301 Struck boards, one Caen V895 module (16 channel leading edge discriminator) and one Caen V2718 VME controller optical bridge. The 8 analog signals from the M18 are sampled by the 8 differential inputs of the SIS3301 module. The SIS3300 has 8 single-ended analog inputs, which are used to acquire the data from the beamline calorimeter and the beam signal from the BTF. The BTF signal has a repetition rate of 25 Hz (the pulse duration is a few ns) and is used as trigger for the whole system. The trigger signal is sent to one input of the V895 board (low threshold discriminator), which in its turn sends its output pattern to one of the V1495, which also acts as Trigger Supervisor. The Trigger Supervisor sends the trigger signals to all

the other V1495 modules and manages the BUSY signal: at each trigger, the Trigger Supervisor waits to be reset by the acquisition software. The Trigger Supervisor also produces a common clock at 80 MHz which is distributed to all the four V1495. One of the four V1495 is then used to generate the control signals for the SIS3300 and SIS3301, which are working at a clock frequency of 20 MHz (the same frequency as the M18). The other V1495 modules are used to generate all the digital control signals for all the chips, to readout and store the digital outputs from the M28 and the M18 planes in some FIFOs internal to the FPGA. The initialization procedures for the M28 and the M18 planes are managed by a software which reads out their respective ASCII Configuration Files and sends the proper signals to the sensors through the V1495, which acts as a parallel port. In the March setup the only difference is that two different DAQ are used for the two pairs of M18, while only one pair of M28 is present.

5.3 Analysis procedure

The analysis has been carried out using TAF (TAPI analysis Framework) [125], a package created and managed by the PICSEL group at IPHC (Strasbourg, France) to analyze data from CMOS sensors characterization measurements both in laboratories and test beam facilities. During this analysis work I contributed to improve some features already presented in TAF and new methods have also been implemented.

The analysis follows this steps:

1. data decoding
2. cluster reconstruction
3. alignment
4. tracking
5. final analysis

In the runs registered without the beam to evaluate the noise only the first two steps and, then, a different analysis step is performed.

The data decoding is a set of methods to decode raw data files from different acquisition systems into a list of pixels that can be used in the subsequent analysis in a common format. In the case of this telescope, three different decoding methods have been implemented to read the analog output of M18 sensors, the sparsified binary output of M28 sensors and the binary output of M22ThrB sensors. A further decoding method has been implemented by the Catania group to read the output of a GEANT-based simulation.

In the second step, clusters are reconstructed selecting the seed pixel and gathering the neighbouring hit pixels. The seed pixel is identified as the hit pixel with the highest signal in analog output sensors and as the first hit found in the case of a binary output sensor. The hit finder algorithm starts from the seed and search for neighbouring hit pixels in a window of 5×5 pixels. The cluster position is then reconstructed as the center of gravity of the pixels belonging to the cluster and it is called hit.

The left panel of Figure 5.7 shows a map of the hits reconstructed in the M22ThrB in a run with 150000 events during the June testbeam, the first 8 empty columns are the part of the sensor with an analog output that are excluded from the analysis. In the right panel of Figure 5.7 the distribution of the number of pixels associated to a cluster (*cluster multiplicity*) is also reported. The mean cluster multiplicity is 2.5 pixels in this run.

The alignment and tracking steps are explained in the following sections, while the final analysis is described when presenting the results for the characterization of the DUTs.

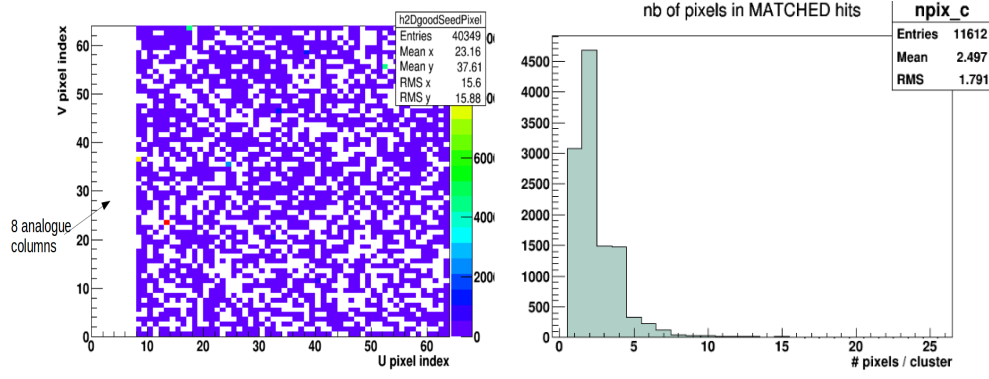


Figure 5.7: Map of the hits (left) and distribution of the number of pixels associated to a cluster (right) in the M22ThrB from the June testbeam.

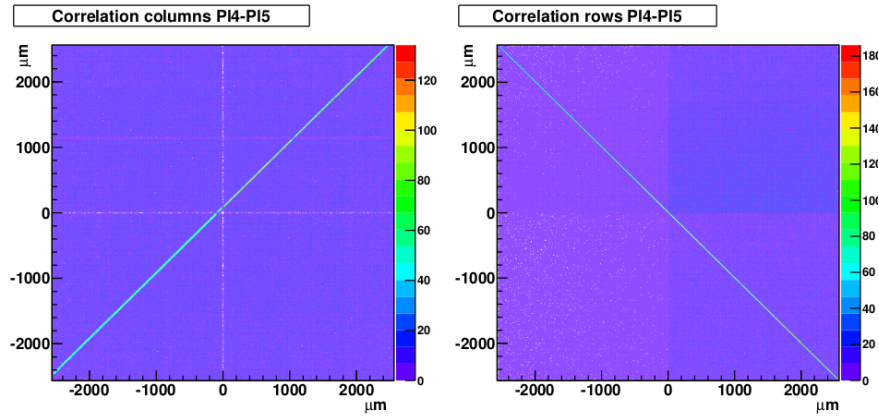


Figure 5.8: Correlation plots between hits on plane 4 and 5 of the telescope from the September setup: correlation of hits along column direction on the left and along row direction on the right.

5.3.1 Alignment procedure

One of the fundamental step for the correct analysis of the data is the alignment of the telescope planes. To study the mutual position of the planes, correlation plots are built plotting the horizontal (or vertical) hit position on one plane as a function of all the other horizontal (or vertical) hit positions of the same event on another plane. An example of a correlation plot is shown in Figure 5.8 between two planes of M28 in the September setup. The diagonal line in the figures represents the hits correlated in the two planes. The different direction of the diagonal in the horizontal and vertical direction depends on the fact the two M18 sensors are mounted on the two sides of the same board rotated of 180° one respect to the other.

The correlation between hits of different planes indicates that the particle crossed the telescope but, to properly track through all the planes, it is necessary to apply some corrections to the measured plane positions in order to reproduce their real mutual position. The alignment procedure consists in the determination of 5 parameters for each plane, 2 for translations and 3 for rotations. These parameters define the position and orientation of a plane in the laboratory or telescope frame. The position in the beam direction is fixed and the frame is defined by one or two fixed reference planes.

For each beam test a common alignment procedure is followed. It consists in aligning plane by plane with respect to the tracks built from fixed planes with an iterative semi-automatic procedure. The track starts with a single hit in the seed and with zero slope. Then, the track

is extrapolated to a hit (if any) in the next plane within a circular search area with a given radius. If more than one hit is found within the areas, the closest one is associated to the track. Then, the track parameters are recomputed and the iteration goes to the next plane. The program continues to build tracks until it reaches a predefined number of hit-track association. Then, a minimization procedure is applied to the squared hit-to-track distances, to evaluate the translations and rotations parameters of the considered plane. The minimization procedure is not applied to the position in the beam axis that is fixed by default. The parameters evaluated are propagated in the next iteration, until all the planes are aligned. In addition to the cut on the searching distance, another cut on the maximum χ^2 value is applied to select the tracks.

Due to the different statistics and telescope conditions during the testbeams, the alignment procedure has been performed in a different way for each of them.

In June 2014, the alignment strategy started with the definition of plane 6 (M28) as the reference plane. Then, plane 7 (M28) was aligned with respect to plane 6. Using tracks passing through plane 6 and 7, plane 4 and 5 (M18) were then aligned. Finally, the alignment has been performed on plane 1 and 2 tracking with plane 4, 5, 6 and 7. DUT was then aligned with respect to the telescope.

In September 2014, it was not possible to use the same procedure since plane 7 was not included in the DAQ. Thus in the alignment procedure plane 2 was considered as the reference plane, profiting of the smaller distance to the DUT. Plane 1 was then aligned with respect to it. Thanks to the high statistics, the DUT was included in the procedure and aligned with respect to plane 1 and 2. Then, planes 4 and 5 were aligned using as a reference the first three planes and, eventually, plane 6 was aligned with respect to the other five planes.

In March 2015, the alignment procedure profits by the presence of two pairs of M18. It started from the second M18 (counting from the beam injector). The first M18 was immediately aligned to the second one, thanks to their close mutual distance. Then, the second pair of M18 were aligned with respect to the first one and, finally, the DUTs were aligned with respect to all the other planes, after the alignment of the M28 pair. A tighter cut on the hit-track distance could be applied during this analysis of 200 μm , instead of 400 μm in June and September.

5.3.2 Tracking procedure

Once all the planes are correctly aligned, the tracks reconstruction can be performed. Some requirements are considered to define a track:

- a distance lower than a maximum value is required for a hit-track association;
- a hit is associated in 4 out of 6 planes in June data (4 out of 5 in September data).

The track fitting model is a straight line where the parameters are obtained by a least square fit. Thus, this strategy does not take into account multiple scattering. Tracks are extrapolated on a plane after another as explained in the alignment procedure, except for the DUT that is excluded from the tracking procedure.

Figure 5.9 shows the statistics on the tracking results in June and September testbeams. It represents the distribution of the fraction of times each plane gives a contribution to a track. The values are normalized to the total number of reconstructed tracks. In June, almost all the tracks are obtained with 4 planes (the minimum number required) and using the planes 1, 2, 6 and 7, i.e. the four planes of M28. This means that the M18 planes, with a sensitive area ~ 16 times smaller than the M28, are usually excluded from the tracking algorithm. In September, most of the tracks is built with 5 hits, hence all the telescope planes are available. In this case requiring 4 hits to make a track implies including one of the M18 planes in the fitting procedure and, since the M18 pairs are very close one to each other, it is almost always possible to find a hit associated to the track within the searching region in the other M18 plane.

Figure 5.10 shows the hit-track distance (residual) distribution in the vertical coordinate after the alignment procedure normalized to the number of reconstructed tracks. Similar results are obtained in the other coordinate. The residual distribution should have a gaussian shape, centered at 0. As it can be observed, this is not the case for some of the distributions,

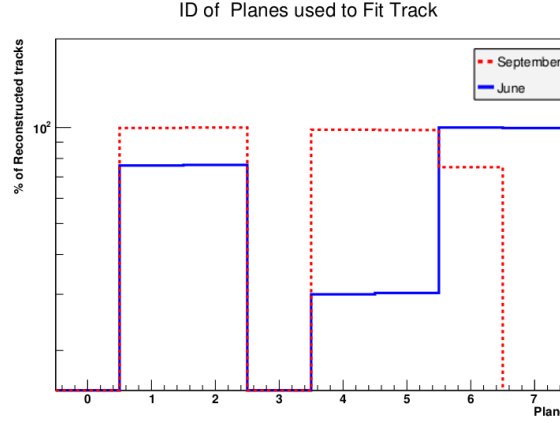


Figure 5.9: Left: distribution of the fraction of times each plane is used to fit a track. Right: distribution of the number of hits that composed a track. In both panel June and September statistics are plotted in blue and red, respectively.

in particular in June. This could point out both an incorrect alignment and/or a better (more careful) mechanical assembly of the telescope. Indeed, the width of the distributions depends on the sensor resolution (which is different between M18 and M28), the global resolution of the telescope and on the multiple scattering effect.

The different alignment strategies and setup conditions are evident in the comparison of June (in blue) and September (in red) distributions. In June the alignment strategy started from plane 6 and the first couple of planes that were aligned was 6 and 7, while the last was 1 and 2. For this reason, the residuals distributions of the last two planes of the telescope show a narrow peak ~ 0 -centred (with a sigma of $\sim 7 \mu\text{m}$), while the residuals of the first two planes have a broad distribution which is not centred at 0 but rather at $\sim 12 \mu\text{m}$ for plane 1 and at $\sim -12 \mu\text{m}$ for plane 2. This means that they are not perfectly aligned with respect to the other planes and that the multiple scattering effect has an important effect on the tracking precision.

The different strategy applied in September led to an opposite situation in the residuals distribution. Indeed, in this case the narrow distributions are on plane 1 and 2 while, although centred at ~ 0 , plane 6 presents a broad peak. This means that the higher statistics and the better position with respect to the beam in this occasion improved the alignment capability of the telescope but the multiple scattering still has an important effect. In planes 4 and 5, the small pitch of the pixels, the analogue readout and their close mutual position allow to have a distance of the tracks associated to a hit distribution whose width is comparable for the two testbeams.

The effect of the hot pixels (noisy pixels hit a number of times above a certain threshold) in the tracking planes has also been studied during the September data analysis. However, it seems that the requirement of having at least 4 hits in each track is already enough to exclude their contribution.

In September and March the tracking procedure took profit by the implementation in TAF of the possibility to consider a different resolution for each plane. An intrinsic resolution of $3.5 \mu\text{m}$ is set for each M28 plane and $1.5 \mu\text{m}$ for each M18 plane. The plane resolutions provide the uncertainties of the least square fit used to construct the track.

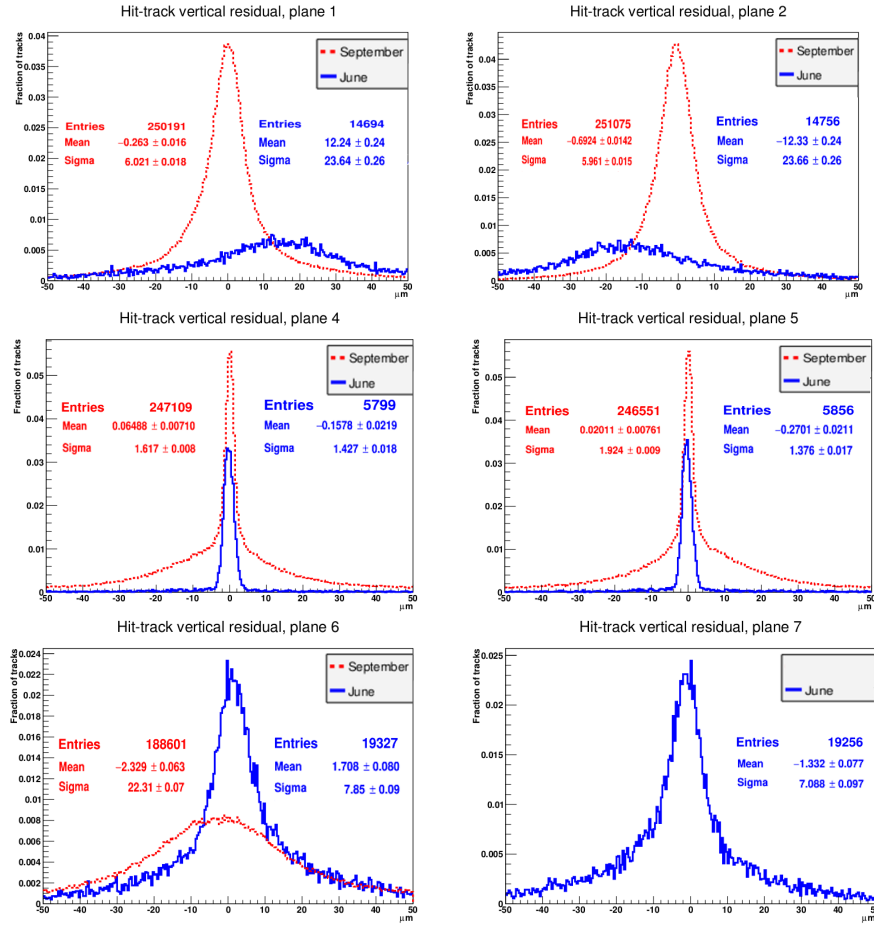


Figure 5.10: Telescope planes residual (hit-track distance) distributions in vertical direction after alignment procedure. Distributions are normalized to the total number of reconstructed tracks. Blue solid distributions refer to June data, while red dotted ones refer to September data.

5.4 Analysis results

In this section, the analysis results of M22ThrB and M22ThrB6/7 are presented. Data were collected in each testbeam for different values of the discriminators threshold applied to the DUT, expressed in terms of units of noise (noted as Signal to Noise ratio, SNR, in terms of number of σ). The aim is to study the dependence of the DUT performances on the SNR applied. Previous measurements were carried out in laboratories by IPHC to evaluate the noise. The quantities measured during the analysis of the data from the testbeams are: detection efficiency, spatial resolution and fake-hit rate.

As already mentioned, the M22ThrB has been characterized during June and September testbeam in 2014, while M22ThrB6/7 during March testbeam in 2015.

5.4.1 MIMOSA22ThrB

Detection efficiency

The detection efficiency of the DUT is evaluated as follows:

$$\varepsilon = \frac{\text{Number of tracks associated to a hit in the DUT}}{\text{Number of tracks crossing the DUT}} \quad (5.1)$$

The hits in the DUT are associated to a track if their distance is within a certain value and a further selection is applied to the χ^2 of the tracks. Several studies have been carried out to check the effect of the selection criteria applied to the DUT performances and they are reported in this Section.

Figure 5.11 shows the maps of hits in the M22ThrB associated to a track crossing the DUT within the searching area of $500 \mu\text{m}$ and the maps of track impact positions which could not be associated to a hit in the DUT. The latter could happen either because there are no hits in the DUT in that event either because the hits are outside the maximum allowed distance. The tracks with a $\chi^2 > 45$ are excluded from the analysis. The results are presented for two runs with the same SNR threshold applied on the DUT (9σ) for June and September testbeams in top and bottom panels, respectively. The different statistics available in the two runs is evident, however, no inhomogeneity in the tracks rejection is present in the whole sensitive area.

The distribution of the track-hit distance of hits associated to a track in the DUT and the distribution of the associated tracks χ^2 are shown in Figure 5.12 for the same run from September testbeam. A maximum distance allowed to associate a track is set in the final analysis to $500 \mu\text{m}$ to take into account the possible great effect of the multiple scattering for electron of 500 MeV but it has been verified that the majority of the hits presented a distance to the associated tracks below $100 \mu\text{m}$. Furthermore, with a fake-hit rate $\sim 3 \times 10^{-4}$ at this SNR threshold, as will be described in Section 5.4.1, the possible contribution from noisy pixels within the searching region is negligible.

The distribution of the associated tracks χ^2 , shown in the right panel of Figure 5.12, is presented for two values of the hit-track distance in the DUT at $100 \mu\text{m}$ and $500 \mu\text{m}$. The position of the peak in the two distribution is slightly different: ~ 0.8 in the case of hit-track distance in the DUT $100 \mu\text{m}$ and ~ 2 in the case of hit-track distance in the DUT $500 \mu\text{m}$. The χ^2 maximum value of the tracks is usually chosen as 45 that, in the case of the September testbeam, cut only the extreme tail of the distribution. The performances of the DUT both in terms of detection efficiencies and spatial resolution have been studied for different values of hit-track maximum distance in the DUT and maximum track χ^2 .

Figure 5.13 shows the detection efficiencies of the M22ThrB as a function of SNR threshold applied to the DUT. In June testbeam, the SNR threshold considered are from 7 to 11σ , while in September the range studied has been extended to 6 - 16σ .

In the left panel of Figure 5.13, results from June testbeam are presented, both with and without excluding the two pixels external crown of the DUT matrix. The detection efficiencies are compatible within the statistical error in the two cases. For this reason, the 2-pixel external

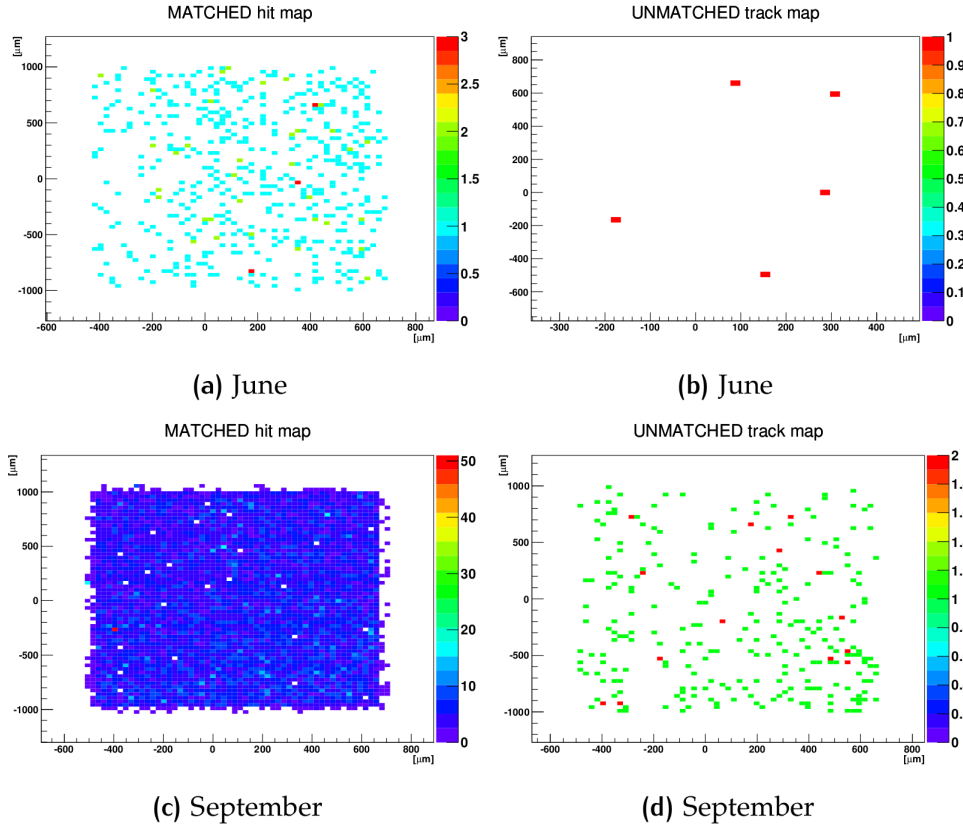


Figure 5.11: Left panels: maps of hits in the DUT matched to a track crossing the DUT. Right panels: maps of track impact positions in the DUT which could not be associated to any tracks in the DUT. Top plots refer to June data (a and b), bottom to September ones (c and d). Both in June and September the SNR threshold on the DUT is 9σ and the maximum distance to associate hit to tracks is $500 \mu\text{m}$.

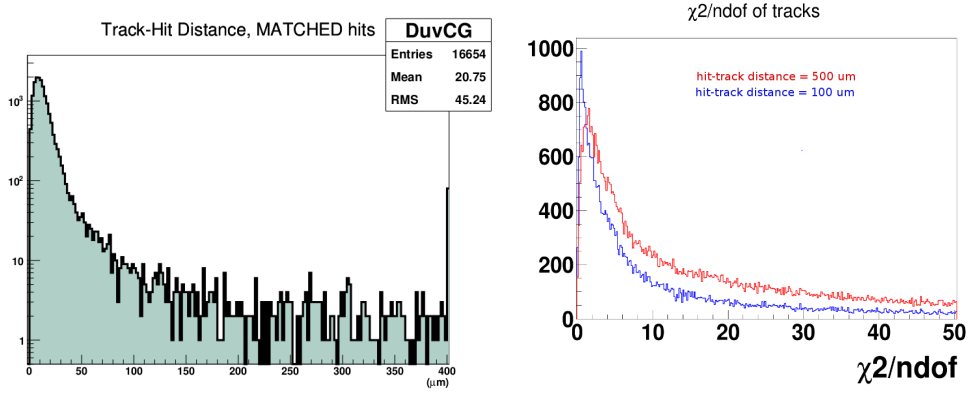


Figure 5.12: Left: distribution of the track-hit distance of hits matched to a track on the DUT with a SNR threshold of 9σ . Right: distribution of the associated tracks χ^2 in the same run with a maximum hit-track distance of 100 μm in blue and 500 μm in red.

crown is excluded in the final analysis in order to not consider uncomplete clusters.

In the right panel of Figure 5.13, the detection efficiencies are shown for the September testbeam data for two different cuts applied to the hit-track distance in the DUT: 400 μm and 500 μm . Errors on the detection efficiency are evaluated as the variance of a binomial distribution, depending on the statistics. In June, the number of associated tracks varied from few hundreds to few thousands depending on the run considered, while in September it varied from ~ 10 thousands to ~ 170 thousands in the case of a 500 μm track-hit distance.

The detection efficiencies evaluated in June and September are compatible within the errors for runs with the same threshold. An efficiency close to 99% is reachable up to SNR threshold of 9σ , while the signal started to be lost for higher SNR thresholds, as it can be noticed from the drop of the efficiencies. In order to allow a better comparison, the statistics and the efficiencies are reported in Table 5.1 for June and September testbeams for a hit-track distance of 500 μm .

The difference in the maximum distance allowed to associate hit to a track from 400 μm to 500 μm is not negligible only for high values of SNR threshold.

A study varying the selection on the χ^2 parameter has also been done on September data, an increase of $\sim 0.5\%$ on the detection efficiencies is observed decreasing the χ^2 maximum value to 4 and the hit-track distance at 100 μm . A tighter χ^2 cut can be reasonably applied to the September data but it is not feasible for the June data without a strong cut on the statistics.

Spatial resolution

The spatial resolution of the M22ThrB has been evaluated with June and September testbeam data from the residual distributions of the hits associated to a track. These distributions are obtained as the difference between the impact position of the particle extrapolated from the track direction and the position of the hit on the DUT. The width of the residual distribution (σ_{res}), obtained as the standard deviation of a gaussian fit, is a convolution of the DUT resolution (res_{DUT}) and the resolution of the telescope (res_{tel}). The latter takes into account also the multiple scattering effect. It can be expressed as:

$$\sigma_{\text{res}} = \sqrt{res_{\text{tel}}^2 + res_{\text{DUT}}^2} \quad (5.2)$$

In Figure 5.14 the residual distributions of the M22ThrB in both vertical and horizontal directions are shown, as an example, for the run with 9σ SNR threshold from the September testbeam. The selections applied are: a χ^2 cut of 45 and a hit-track distance of 400 μm . The distributions have a gaussian shape and are centered at 0. The standard deviation of the gaussian fit is 8.65 ± 0.02 μm in the horizontal direction, where the pixel width is 22 μm , while

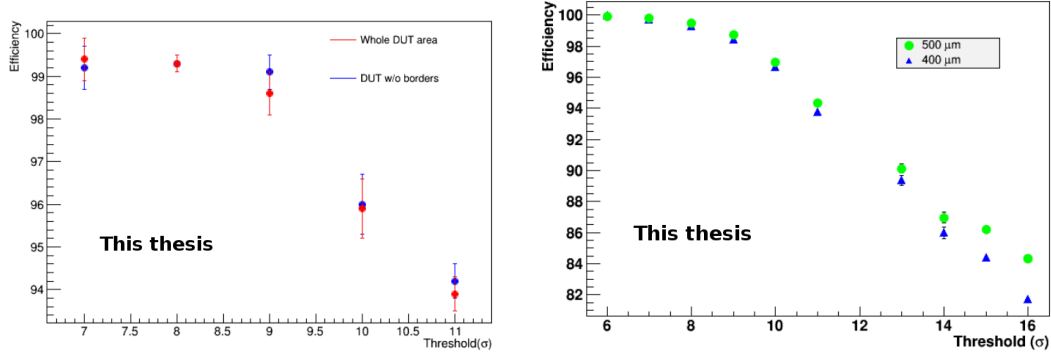


Figure 5.13: Left: detection efficiency as a function of SNR threshold in terms of σ for the June testbeam data, the blue points are obtained excluding the two external pixels crown of the DUT matrix and the red ones considering the whole DUT area. The maximum distance to associate hit to tracks is 500 μm . Right: detection efficiency as a function of SNR threshold in terms of σ for the September testbeam data, green circles are obtained considering as maximum distance to associate hits to tracks on the DUT 500 μm , blue triangles using 400 μm . In both cases the external two pixels crown of the DUT has been excluded from the searching region.

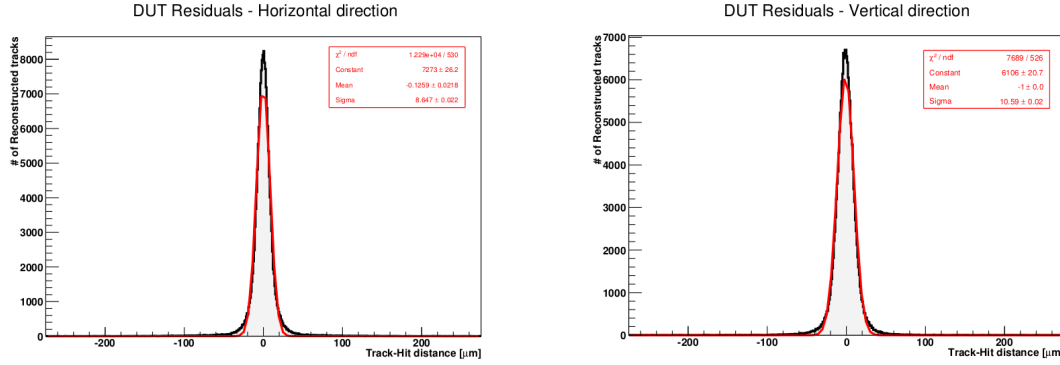


Figure 5.14: DUT residuals distributions along columns (left) and rows (right) directions in a run with a SNR cut of 9σ from September testbeam with a cut on χ^2 tracks of 45. The distributions are fitted to a Gaussian.

it is $10.59 \pm 0.02 \mu\text{m}$ in the vertical direction, where the pixel dimension is 33 μm .

As for the detection efficiencies, the spatial resolution is studied varying the hit-track distance on the DUT and the tracks χ^2 cut. No significant effect is observed on the resolution with a different maximum hit-track distance allowed. The study as a function of the cut on the tracks χ^2 is shown in the left panel of Figure 5.15 for hit-track distance of 100 μm . The σ_{res} increases increasing the cut on the tracks χ^2 in both directions and seems to saturate at χ^2 above 30. In the right panel of Figure 5.15, the resolution is evaluated for clusters with different multiplicity, considering clusters composed from 1 to 6 pixels separately. For higher values of cluster multiplicity the statistics is very low, as it can be noticed from the Figure 5.7 from the same run, hence, the fit of the residual distribution is not feasible any more. The blue and red lines at 7.1 μm and 8.6 μm represent the values of σ_{res} evaluated with all the clusters, respectively, in horizontal and vertical directions. These values are within the maximum and the minimum σ_{res} obtained fitting the residual distributions of hits with a specific selection on the cluster multiplicity.

	June			September		
	$d_{hit-track} < 500 \mu m$			$d_{hit-track} < 500 \mu m$		
σ	Associated tracks	Tot. tracks through DUT	Efficiency [%]	Associated tracks	Tot. tracks through DUT	Efficiency [%]
6				$42247 \pm 0.5\%$	$47257 \pm 0.5\%$	99.900 ± 0.008
7	$309 \pm 5\%$	$311 \pm 5\%$	99.2 ± 0.5	$159939 \pm 0.3\%$	$160223 \pm 0.2\%$	99.82 ± 0.01
8	$1778 \pm 2\%$	$1790 \pm 2\%$	99.3 ± 0.2	$78910 \pm 0.4\%$	$79332 \pm 0.4\%$	99.47 ± 0.03
9	$631 \pm 4\%$	$640 \pm 4\%$	99.1 ± 0.4	$170405 \pm 0.2\%$	$172601 \pm 0.2\%$	98.72 ± 0.03
10	$829 \pm 3\%$	$864 \pm 3\%$	96.0 ± 0.7	$99848 \pm 0.3\%$	$102962 \pm 0.3\%$	96.97 ± 0.05
11	$3677 \pm 1\%$	$3917 \pm 1\%$	93.9 ± 0.4	$11771 \pm 0.4\%$	$12485 \pm 0.3\%$	94.32 ± 0.08
13				$8164 \pm 1\%$	$9059 \pm 1\%$	90.1 ± 0.3
14				$7810 \pm 1\%$	$8982 \pm 1\%$	86.9 ± 0.3
15				$21595 \pm 0.7\%$	$25058 \pm 0.6\%$	86.2 ± 0.2
16				$79699 \pm 0.5\%$	$84491 \pm 0.3\%$	84.3 ± 0.2

Table 5.1: Summary of the efficiency values found for different SNR used to acquire the DUT data (σ) and number of tracks used to evaluate the efficiencies. In bold font values obtained in the same conditions in June and September.

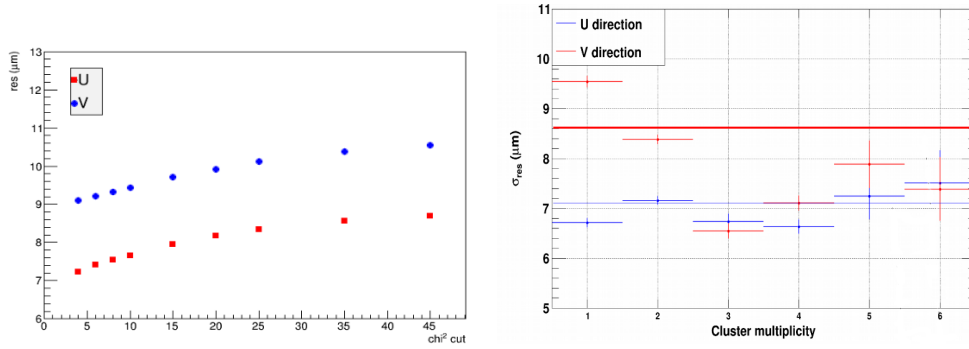


Figure 5.15: DUT residual distribution width as a function of cut on the χ^2 of the tracks with a hit associated in the DUT (left) and as a function of the cluster multiplicity (right). In the right panel the lines at $7.1 \mu m$ and $8.6 \mu m$ represent the values of σ_{res} evaluated with all the clusters in horizontal and vertical directions.

Figure 5.16 shows the residual distribution widths as a function of the DUT SNR threshold obtained from September testbeam data. The cuts applied to the hit-track distance and to the χ^2 cut were $150 \mu m$ and 4, respectively. The σ_{res} in the horizontal direction (in red) reaches a minimum at 10 SNR threshold and varies from ~ 7.7 to $\sim 7.0 \mu m$, while in vertical direction (in blue) it increases increasing the SNR threshold from ~ 8.3 to $\sim 9.3 \mu m$.

A comparison between the residual distribution width obtained in June and September in a run with SNR threshold equal to 9σ is presented in Figure 5.16. The results are evaluated using the same parameters in both analysis, a hit-track distance $400 \mu m$ and a χ^2 cut of 45, in order to not have a strong reduction of the statistics in the June data. The results from June and September are compatible within the uncertainties in both horizontal and vertical directions. The difference in the uncertainties depends on the higher statistics available for the September data.

An estimate of the DUT spatial resolution is obtained using this values. The resolution of the telescope is evaluated with a Toy Monte-Carlo included in the TAF software package and validated by a GEANT simulation made by the INFN group in Catania. In both cases the geometry of June and September setup is implemented and the result gives a resolution of $8.0 \pm 0.5 \mu m$. The telescope resolution uncertainty comes from the error on the single planes resolution and position.

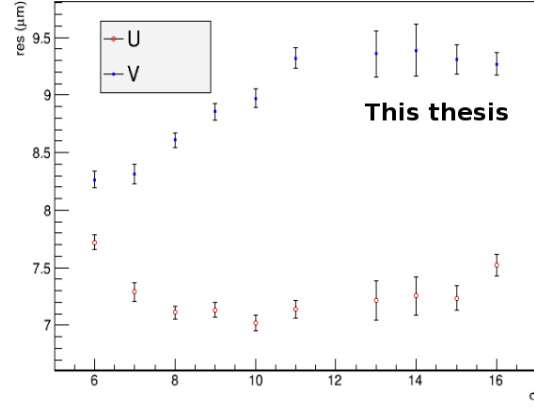


Figure 5.16: Residual distribution width as a function of DUT SNR threshold (expressed in terms of noise unity σ) for the September testbeam.

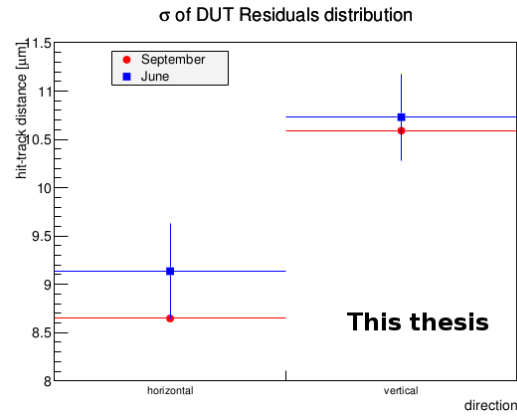


Figure 5.17: Comparison of the residual distribution width obtained in June and in September in a run with 9σ SNR threshold.

	DUT resolution (μm)	
	Horizontal	Vertical
June	4.3 ± 0.7	7.1 ± 0.6
September	3.3 ± 0.5	6.9 ± 0.5

Table 5.2: DUT Resolution estimation with a SNR threshold set on DUT discriminators of 9σ . Only statistical uncertainty are quoted.

Following the equation 5.2, the estimated M22ThrB spatial resolution are noted in Table 5.2 for the horizontal and vertical direction, that correspond to a pitch of $22 \mu\text{m}$ and $33 \mu\text{m}$ respectively. There were some limitations on the accuracy of the telescope resolution obtained from the Monte-Carlo simulation because it was not possible to implement in the June description of the setup the MIMOSA22ThrA passive layer and the quoted uncertainties do not take into account possible inefficiencies in the alignment procedure. Indeed, the latter has been developed for a much higher energy of the incoming beam where multiple scattering had a smaller effect. The GEANT simulation aim was to evaluate the contribution of the multiple scattering, transporting particle through the telescope and using directly TAF to reconstruct the tracks. The role of the multiple scattering has also been studied as a function of the parameters applied to the analysis.

Fake-hit rate

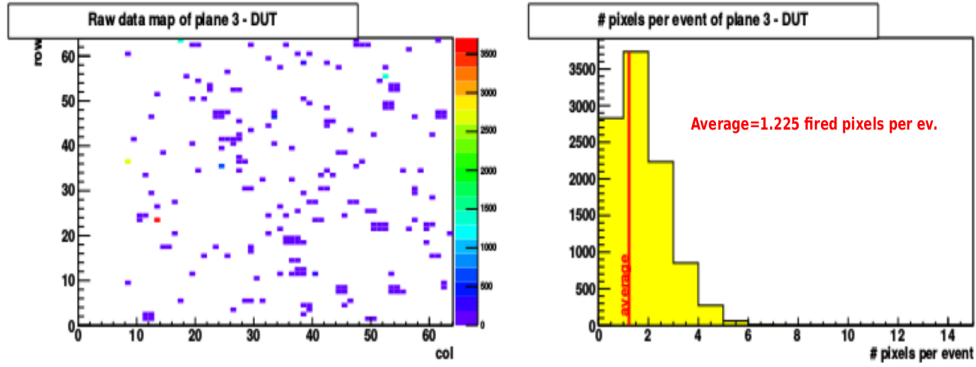


Figure 5.18: Left: M22ThrB hit map in a run of 1000 events without beam with a SNR threshold of 9σ . Right: distribution of the number of hit pixels per event during the same run.

The fake-hit rate is defined as the number of fired pixels per events divided by the total number of pixels and the number of events. It is evaluated in events with no beam and it could also be studied in laboratory. The M22ThrB fake-hit rate has been measured during the June testbeam with 1000 events for each run. Figure 5.18 shows the DUT hit map integrated over 1000 events (left panel) and the distribution of the number of hit pixels per event (right panel) in a run with a SNR threshold of 9σ . The average of the number of pixels hit in each event is indicated with a red line in the plot and corresponds to 1.225.

This value has been measured for different SNR threshold applied to the DUT discriminators and divided by the total number of pixels and the number of events in order to obtain the fake-hit rate. The result is presented in Figure 5.19. It is possible to notice that the fake-hit rate decreases up to SNR of 13σ and then remains constant to a value of about 10^{-5} . It has to be mentioned that the prototype used as DUT has a small number of pixels with respect to the final version of the chip and it has not been designed to minimize the known effect of Random Telegraph Signal noise (RTS). The RTS noise originates from the presence of defects in the oxide layer of a MOS transistor. It depends on different variables including temperature, gate voltage of the transistor and the oxide thickness. The amplitude of the RTS

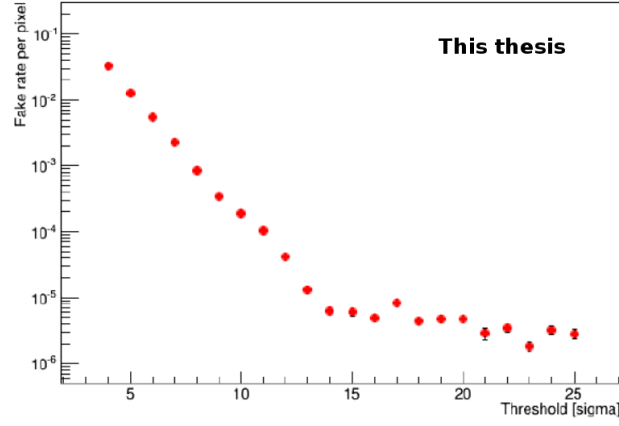


Figure 5.19: Fake-hit rate on the DUT as a function of the SNR threshold applied on the DUT data taking.

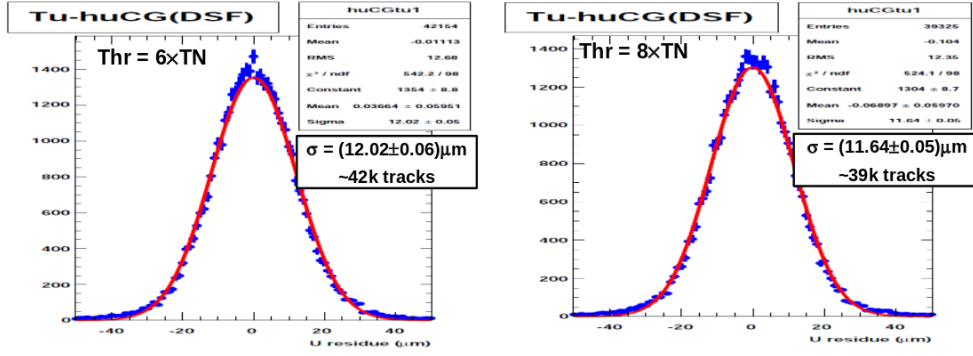


Figure 5.20: Residual distributions of the bottom part of M22ThrB6 in the horizontal direction for SNR threshold = 6σ (left) and SNR threshold = 8σ (right).

is sufficient to exceed the pre-set threshold of the detector and may therefore generate fake hits. Hence, possible improvement on the fake-hit rate could be obtained in future prototypes.

The results on the MIMOSA22ThrB characterization obtained from the June testbeam are published in [126].

5.4.2 MIMOSA22ThrB6/7

The same strategy is followed during the analysis of the M22ThrB6 and M22ThrB7 in March. The upper and the bottom parts have been analysed separately, in this section only the bottom part of the two sensors, with a smaller diode, is presented.

In Figure 5.20 the horizontal residual distributions of the bottom part of M22ThrB6 are shown, as an example, for SNR threshold = 6σ (left) and SNR threshold = 8σ (right). The standard deviations of the gaussian fit in the two cases are $12.02 \pm 0.06 \mu\text{m}$ and $11.64 \pm 0.05 \mu\text{m}$ with a statistics of $\sim 4 \cdot 10^4$ tracks. In order to obtain the spatial resolution of the DUT, the telescope resolution has been estimated as (5.8 ± 0.2) for the M22ThrB6 and (6.3 ± 0.2) for the M22ThrB7, as explained for June and September setup. The difference between the two estimates depends on the position of the M22ThrB6 and M22ThrB7 in the telescope.

The analysis results of the M22ThrB6 are presented in Figure 5.21 where detection efficiencies (in black), spatial resolution (in red) and fake-hit rate (in blue) are summarized. The main

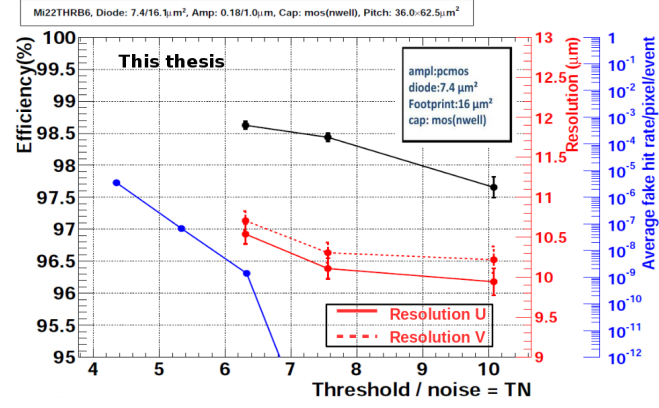


Figure 5.21: Analysis results of the M22ThrB6 bottom part. The efficiency is reported in black, the spatial resolution in red and the fake-hit rate in blue. The relative y axis of each measurement is in the same color.

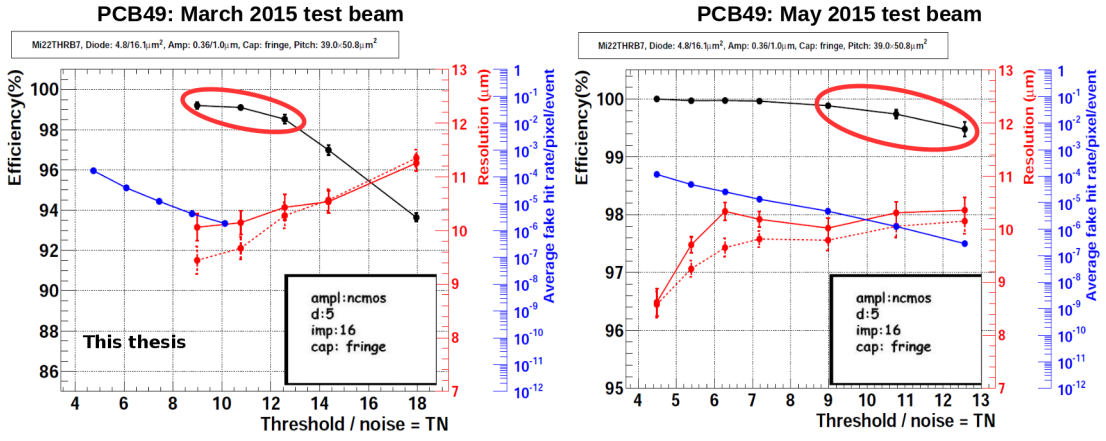


Figure 5.22: Analysis results of the M22ThrB7 bottom part obtained from the data collected in March (left) and in May (right) [127]. The same legend as 5.21 has been used.

characteristics of the sensor are listed in the figure. The fake-hit rate has not been measured during the testbeam but in laboratory by the PICSEL group.

A detection efficiency below 99% is measured with a SNR threshold from 6.5 to 10 σ and it could be mainly due to the instability of the pre-amplifier PMOS transistor, which is one of the characteristics of the bottom part of the sensor. A measured spatial resolution of $\sim 10 \mu\text{m}$ in both horizontal and vertical direction allows to validate the large pixel size for the outer layer of the ITS upgrade. A spatial resolution slightly higher in the vertical direction is measured and it can be explained by the different pitch in the two directions: 36 and 62.5 μm . The fake-hit rate is below the requirement of 10^{-5} already for a SNR threshold of 4 σ and decreases below 10^{-12} for a SNR threshold above 7 σ .

The left panel of Figure 5.22 shows the results for the M22ThrB7 bottom part obtained from the data collected during March testbeam. Because of a problem in the threshold setting, only relatively high SNR thresholds from 9 to 18 are applied. A detection efficiency $\sim 99.2\%$ is measured for the lower SNR threshold applied to the DUT discriminator and then it decreases increasing the threshold, as expected. The detection efficiencies measured for M22ThrB6 and M22ThrB7 seem a bit lower than expected and an additional testbeam in May 2015 confirmed the suspect of a possible inefficiencies related to the DAQ system.

	MIMOSA22ThrB	MIMOSA22ThrB6 (small diode)	MIMOSA22ThrB7 (small diode)
Detection efficiency	$\sim 99.0\%$	$\sim 99.0\%$	$\sim 99.8\%$
Spatial resolution	$3\text{-}7\ \mu\text{m}$	$\sim 10\ \mu\text{m}$	$\sim 10\ \mu\text{m}$
Fake-hit rate	$\sim 10^{-4}$	$< 10^{-9}$	$\sim 10^{-5}$

Table 5.3: Results of MIMOSA22ThrB, MIMOSA22ThrB6 (small diode) and MIMOSA22ThrB7 (small diode) prototypes characterization at the LNF testbeam facility in Frascati for SNR threshold equal to 9σ .

In the right panel of Figure 5.22 the final results of the M22ThrB7 bottom part from the data collected in May with the same telescope setup are reported for completeness. The data for the three points circled with a red line in the figure have been taken in both testbeams, they corresponds to a SNR threshold of 9, 10.5 and 12.5σ . Lower values of SNR threshold have also been applied, up to 4σ in May. An efficiency $\sim 99.8\%$ has been measured for a SNR threshold of 9σ , hence $\sim 0.6\%$ higher with respect to the March result. A spatial resolution around $\sim 10\mu\text{m}$ or below is obtained for all the SNR threshold considered. The fake-hit rate is $\sim 10^{-4}$ for the lowest SNR threshold (4σ) and decreases below $\sim 10^{-6}$ for the highest SNR threshold (13σ). In conclusion, it is possible to find a working point for the M22ThrB7 with a diode of $\sim 5\ \mu\text{m}^2$ that fulfil the requirements for the outer layers of the upgraded ITS.

5.4.3 Final considerations

A telescope based on different types of MIMOSA sensors with integration times varying by orders of magnitude has been developed. It has been used to characterize three MISTRAL prototypes, developed by the PIXEL group of IPHC (Strasbourg) at the LNF testbeam facility in Frascati, Italy, with a 500 MeV e^- beam. The MIMOSA22ThrB chip has been characterized during June and September 2014 testbeams and the final results are summarized in Table 5.3, together with the results of MIMOSA22ThrB6 and MIMOSA22ThrB7 chips.

The testbeam campaign in March 2015 allows to validate the use of large pixel in terms of spatial resolution for the full scale prototype MISTRAL-O developed by IPHC for the outer layers of the upgraded ITS. The MISTRAL-O with 16×10^4 pixels of $36 \times 65\ \mu\text{m}^2$ has been submitted at the end of 2015 and the first tests will be performed at the beginning of 2016.

Chapter 6

Characterization of full-scale pALPIDE-v2 prototype

This Chapter will focus on the characterization of a full-scale prototype developed for the new ITS in the TowerJazz $0.18\ \mu\text{m}$ imaging sensor technology, the pALPIDE-v2. As mentioned in Chapter 4, this prototype has been developed by a collaboration formed by CCNU (China), CERN, INFN (Italy) and Yonsei (South Korea). Its innovative read-out approach allows to reduce the power density and integration time with respect to the MISTRAL prototypes. The pALPIDE-v2 is the second full-scale prototype developed by the collaboration to address system aspects related to the integration of a large scale ($3 \times 1.5\ \text{cm}^2$) MAPS chip. In addition it addresses the physical and electrical interconnection of such a chip on flex printed circuits. With respect to its immediate predecessor (pALPIDEfs), the pALPIDE-v2 enables the construction of complete prototypes of Hybrid Integrated Circuits for the ALICE ITS Upgrade.

In this Chapter, first a general description of pALPIDE-v2 prototype will be given, then the measurements in laboratory and at the PS testbeam facility at CERN will be presented.

6.1 Generalities

The chip is composed by a matrix of 512×1024 pixels, $28 \times 28\ \mu\text{m}^2$ each and by a periphery region containing the digital part of the readout electronics. In total, the chip measures $15.3 \times 30\ \text{mm}^2$. The matrix is divided in four sectors of 512×256 pixels. A general block diagram of the pALPIDE-v2 chip is shown in Figure 6.1.

The sectors differ by the size of the collection diode, shown in Figure 6.2, and by the way the diode reset is implemented. The features of each sector are listed in Table 6.1. The pALPIDE-v2 collection diode is obtained by implementing a n-well in the lightly p-doped epitaxial layer. From the tests on small scale prototypes, an octagonal shape of the n-well and a square shape of the deep p-well has been chosen in order to minimise couplings between the two and to maximise the ratio between the collected charge and the input capacitance (Q/C). Two reset mechanisms are implemented in the pALPIDE-v2 and they are schematically shown in Figure 6.3. In both cases (reset via PMOS transistor and reset via Diode) the collection diode is continuously reset. In the first case the time constant associated to the reset mechanisms can be varied by setting

Sector	Spacing	Input transistor	Reset
0	$2\ \mu\text{m}$	$0.22\ \mu\text{m}$	PMOS
1	$2\ \mu\text{m}$	$0.88\ \mu\text{m}$	PMOS
2	$4\ \mu\text{m}$	$0.22\ \mu\text{m}$	PMOS
3	$4\ \mu\text{m}$	$0.22\ \mu\text{m}$	Diode

Table 6.1: Charge collection electrode parameters for each sector of the pixel chip.

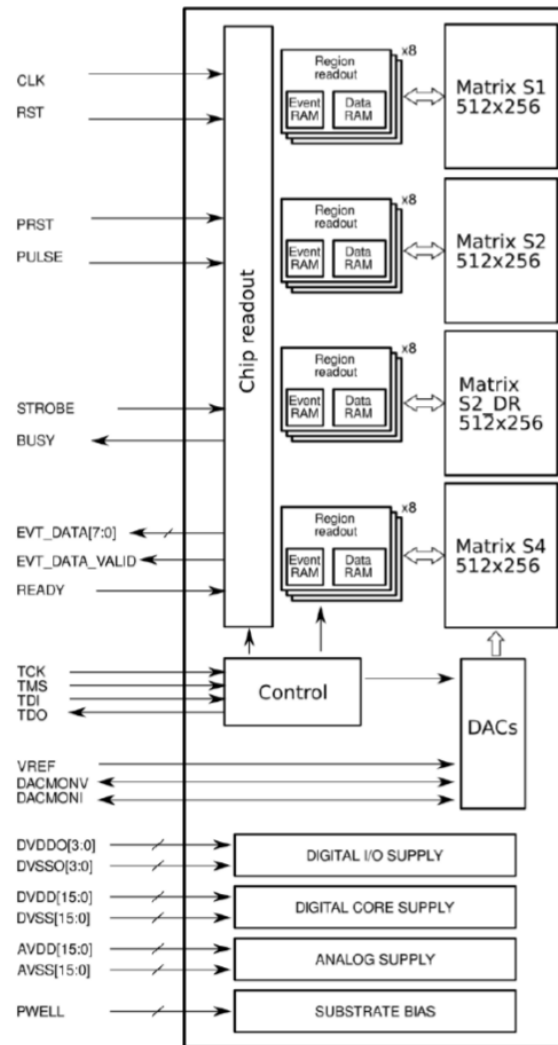


Figure 6.1: General block diagram of the pALPIDE chip.

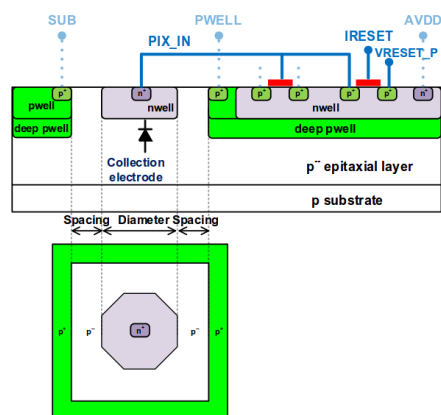


Figure 6.2: Schematic view of pALPIDE collection diode with PMOS reset mechanism.

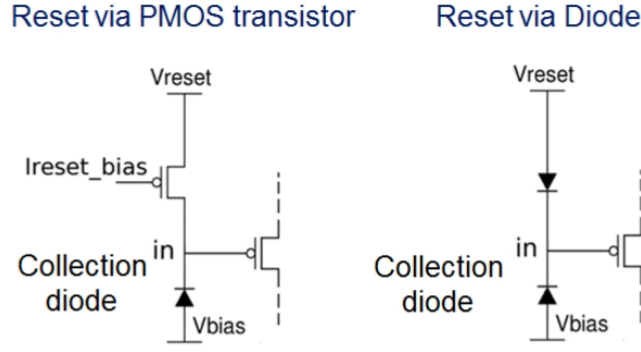


Figure 6.3: pALPIDEfs-v2 reset mechanisms: reset via PMOS transistor (left) and reset via Diode (right).

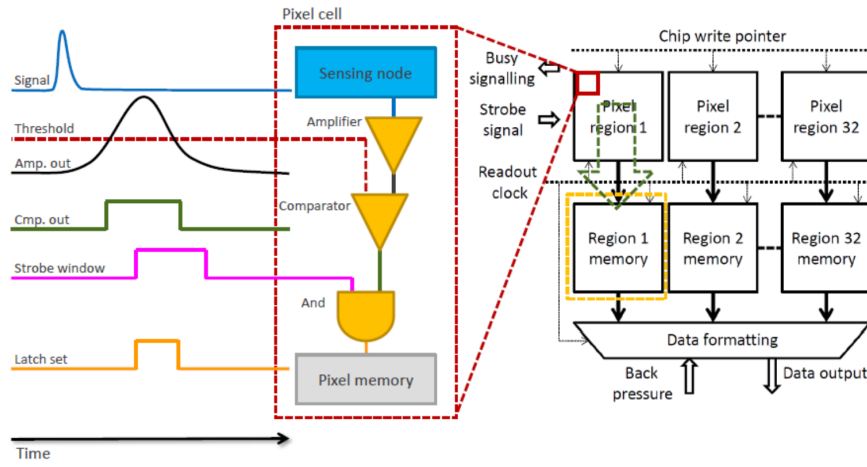


Figure 6.4: Readout organization of the chip with details on the pixel cell.

the gate potential of the reset transistor, while in the second case the diode resets the collection diode with a fixed time constant of the order of 10^{-3} s.

Each pixel features a low-power front-end with binary (discriminated) output. The front-end is non-linear with a raising time of around $2 \mu\text{s}$. After an event of charge release in the pixel, the assertion of a STROBE signal causes the latching of the discriminated output into an in-pixel storage cell during the response interval. The STROBE signal is related to an external trigger but the circuit can operate also in continuous mode. The readout organization is schematized in Figure 6.4. The pixels feature also a built-in test pulse injection circuit triggered by an external signal (PULSE).

The hits stored in the pixels are read out by means of Priority Encoder circuits [120]. They provide the address of a pixel with a hit based on a topological priority. In consecutive read cycles, the selected pixels are reset and the addresses of subsequent hit pixels are generated. This continues until all hits at the inputs of the Priority Encoders are read out. The readout of the sensitive matrix to the periphery is zero-suppressed and digital power is consumed only to transfer hit information to the periphery.

The matrix is organized in 32 regions (512×32 pixels), each of them with 16 double columns being read out by 16 priority encoder circuits (there is one priority encoder logic for each double column). The hits inside one region are read out sequentially in consecutive readout cycles. The readout of regions is executed in parallel and it is driven by state machines in the region readout blocks. The region readout units also contain multi-event storage SRAM memories and

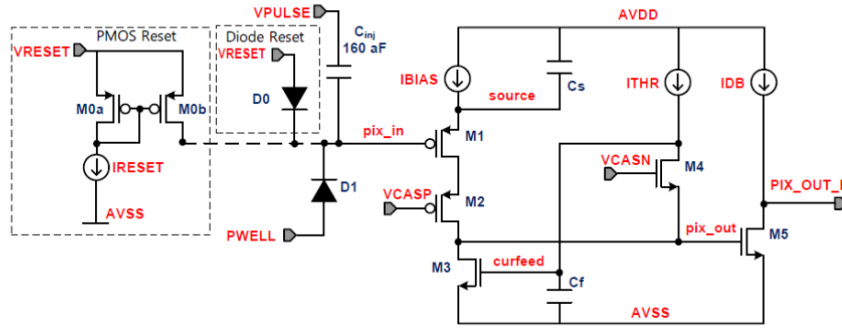


Figure 6.5: Schematic of the pixel analog front-end(s) of pALPIDEfs, very similar to the pALPIDE-v2

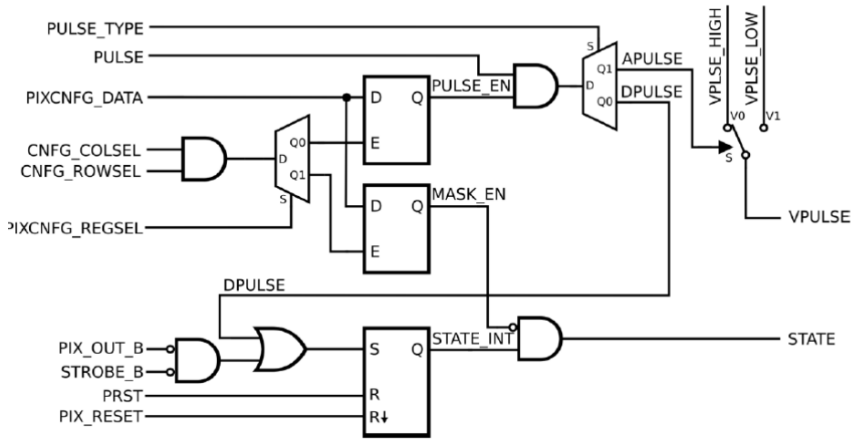


Figure 6.6: Functional diagram of the pixel digital front-end of pALPIDEfs, very similar to the pALPIDE-v2.

data compression functionality based on clustering by adjacency. The data from the 32 region readout blocks are combined and transmitted off-chip by a top level Chip Readout Unit. Hit data are transmitted on a parallel 8-bit output data port using CMOS signaling.

Analog and digital front-ends

The front-end is composed of two part: analog and digital.

The analog front-end sections (shown in Figure 6.5) presents two implementations depending on the reset of the collecting diode. The functionality of the chip depends on the voltages and currents applied to its elements, namely V_{RESET} , I_{THR} , V_{CASN} and I_{DB} . During the characterization measurements the values of these quantities are varied to find the best configuration in terms of detection efficiency, spatial resolution and fake-hit rate of the chip. The charge threshold of the pixel is defined by I_{THR} , V_{CASN} and I_{DB} . The effective charge threshold increases by increasing I_{THR} or I_{DB} and decreases by increasing V_{CASN} . V_{RESET} establishes the reset voltage of the charge collecting node and I_{RESET} defines the maximum reset current, the latter is implemented only in the PMOS reset scheme. It is possible to inject a test charge in the input node for test purposes.

The rest of the front-end circuitry is digital and full custom. Figure 6.6 shows a schematic view of this part. Three registers are implemented: a register (D-latch), a pulse register state register (SR-latch) and a mask (D-latch). Few combinatorial gates allow for these registers to be addressed and set by the digital periphery.

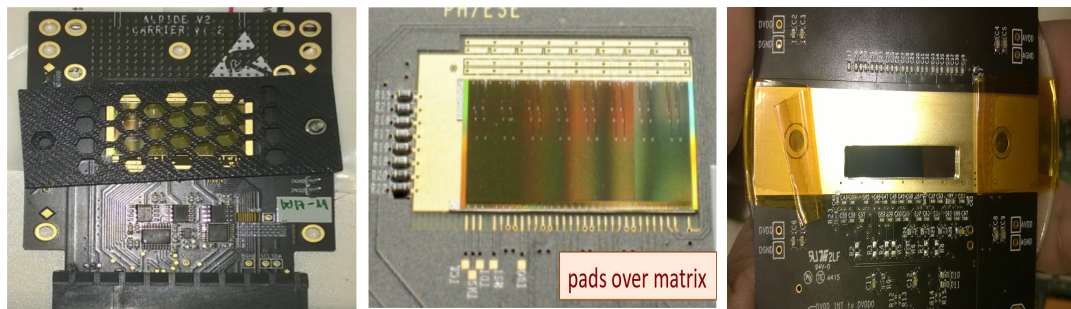


Figure 6.7: Left: Carrier board with the chip pALPIDEs-v2 soldered, the chip is under the black protection for the wire bonds. Center: back view of the carrier board. Center: close up of the wire bonded chip. Right: back view of the carrier board.

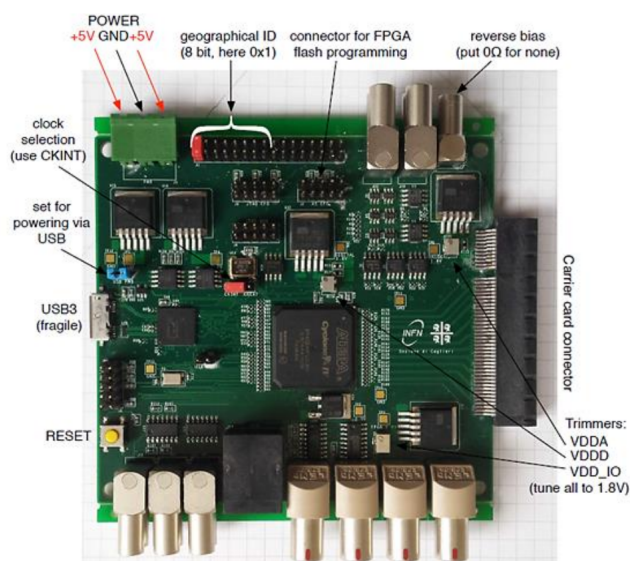


Figure 6.8: DAQ board.

6.1.1 Readout System

The readout system used to test the pALPIDE-v2 consists on a carrier board, show in Figure 6.7, and a DAQ board, show in Figure 6.8, developed in Cagliari (Italy). Both boards have been designed to test the pALPIDEs but they are also compatible with the pALPIDE-v2 with small modifications. The carrier board holds the pALPIDE-v2 chip that is electrically connected to it with wire bonds. A hole is made in the back of the carrier board (shown in the right panel of Figure 6.7) to allow the measurement of the chip spatial resolution without the carrier board material budget. The size of the hole is shown in the center panel of Figure 6.7 The carrier board is connected to the DAQ board through the connector in the bottom of the figure. The various electronic elements of the DAQ board are described in Figure 6.8. The board is powered with a voltage of 5V and it is connected to the PC through a USB connector for configuration and raw data transmission.

The test system for laboratory measurements is composed of a single DAQ card whose main clock is provided by an on-board 40 MHz oscillator.

The configuration used in beam tests is different and consists in several DAQ cards each connected to a carrier board. In this case the main clock is generated internally and provided to each card via a LEMO connector to ensure proper synchronization of the system. Each card receives also a trigger signal from an external TLU and has to provide its BUSY status.

Epitaxial layer thickness	non-irradiated	1×10^{13} 1MeV n_{eq}/cm^2 irradiation level	1.7×10^{13} 1MeV n_{eq}/cm^2 irradiation level
18 μm	5	1	3
25 μm	5	1	2
30 μm	6	3	3

Table 6.2: List of the number of available chips

V_{AUX}	V_{RESET}	V_{CASN}	I_{RESET}	I_{BIAS}	I_{DB}	I_{THR}
117 DAC	117 DAC	57 DAC	50 DAC	64 DAC	64 DAC	51 DAC

Table 6.3: Default settings.

6.2 Laboratory measurements

The readout system described above is used to perform several measurements in laboratory. After a quick test to check the JTAG communication with the chip and the characteristics of the eleven DACs, these measurements have been performed during this thesis:

- threshold and temporal noise;
- fake-hit rate.

Each test is performed on pALPIDE-v2 chips with 18, 25 and 30 μm high resistivity epitaxial thickness, thinned to 50 μm . Both non-irradiated and irradiated chips are used. The irradiation levels considered are 1×10^{13} 1MeV n_{eq}/cm^2 and 1.7×10^{13} 1MeV n_{eq}/cm^2 . The latter is the NIEL radiation hardness needed to fulfill the new ITS requirements. The number of working chips available in the laboratory is listed in Table 6.2.

One important feature of the pALPIDE is that the chip can be back-biased, i.e. the substrate potential can be brought below the ground of the system modifying the shape and the volume of the depletion region, as shown in Figure 4.7. Therefore, all the chips are also tested to work with different values of back-bias (V_{BB}): 0, -3 and -6 V.

The following sections will describe the main results from those tests. All measurements are performed shielding the sensor from sunlight. The noise, charge and threshold values are measured in DAC units and then converted to electrons. The conversion factor that gives the correspondence between DAC units and electrons is not obtained with a calibration of the system, but exploiting the pulse mechanism offered by the sensor. Since the pulsing capacitor is 160 aF and the reference voltage to the eleven 256-step DACs is 1.8V, the conversion factor is 1 DAC $\sim 7e^-$.

The settings that will be referred to as the default configuration are listed in Table 6.3 in DAC units.

6.2.1 Threshold and temporal noise

The threshold and temporal noise of a selected pixels is studied injecting N times a given test charge. The injected charge varies from 20 to 49 DACs and for each charge value it is injected 50 times. The test is usually performed on 1% of the pixels (chosen uniformly in the sensor) and, for each of them, the number of times a hit has been registered is saved. The number of hits as a function of the charge injected is shown in Figure 6.9 for one pixel, as an example. The points are fitted with an error function from which the threshold and temporal noise could be evaluated:

- the noise of the pixel is the RMS value of the derivative of the fit function;
- the threshold of the pixel is the value of the injected charge for which the number of hits is equal to half of the injecting times.

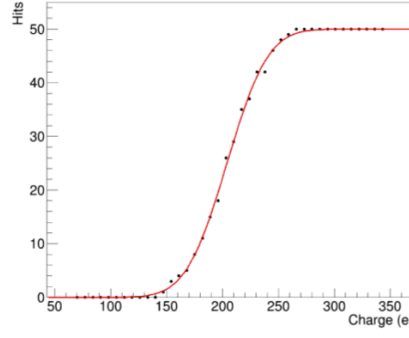


Figure 6.9: Hits as a function of the injected charge fitted with the error function (red).

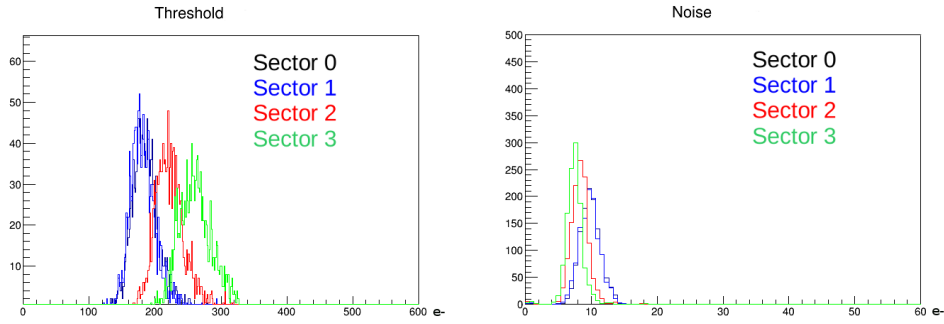


Figure 6.10: Threshold (left) and noise (right) distributions for an irradiated chip, 1.7×10^{13} 1MeV $n_e q/cm^2$ irradiation level, with epitaxial layer thickness of $18 \mu m$ and default settings applied.

Due to pixel to pixel variations, the threshold and noise values are different for each pixel. Therefore, the procedure is repeated on 1% of the pixels and the distribution of threshold and noise values are constructed for each sector. The means of these distributions provide the values of threshold and noise of the sector.

Figure 6.10 shows an example of the threshold (left) and the noise (right) distributions obtained for all the sectors of an irradiated chip, 1.7×10^{13} 1MeV $n_e q/cm^2$ irradiation level. The chip has an epitaxial layer thickness of $18 \mu m$ and the default settings are applied.

It can be noticed that sectors 0 and 1, with the same spacing, have a very similar behaviour and present the lower values of threshold and the higher values of noise. Sector 3, with the Diode reset mechanism, has the higher value of threshold and the lower value of noise.

The test is repeated for all the available irradiated chips, listed in Table 6.2, and the threshold and noise values are summarized in Figure 6.11. In both plots, the chips are grouped depending on the epitaxial layer thickness indicated under the x axis. The results for chips with both 1.7×10^{13} 1MeV $n_e q/cm^2$ and 1×10^{13} 1MeV $n_e q/cm^2$ irradiation levels are reported. The vertical bars in the upper plot represent the RMS of the threshold distributions.

Chip-to-chip fluctuations can be observed but no indication of a dependence from epitaxial layer thickness or irradiation level is evident. The threshold values vary from 140 to 300 e^- , while the noise values from 7 to 13 e^- depending on the sectors. Therefore, the threshold is, at least, around a factor 10 higher than the noise and a factor 7 smaller than the most-probable energy loss signal of a MIP in $18 \mu m$ of silicon.

In all the chips similar values of threshold and noise are measured for sector 0 and 1, while higher values of threshold (lower values of noise) are measured for sector 2 and even more for sector 3, as described in the previous example. In general, the same behaviour is observed also in non-irradiated chip.

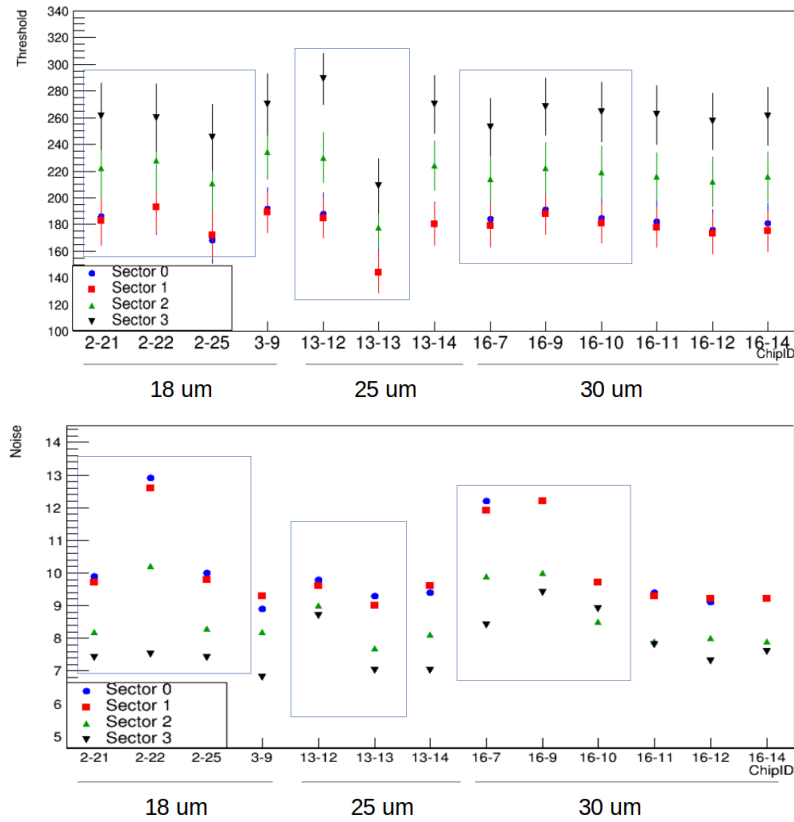


Figure 6.11: Threshold (top) and noise (bottom) values for all the sectors of different irradiated chips. In both plots, the chips are grouped depending on the epitaxial layer thickness indicated under the x axis. The values inside the rectangular boxes correspond to chips with an irradiation level of 1.7×10^{13} 1MeVn_{eq}/cm², the remaining values to 1×10^{13} 1MeVn_{eq}/cm² irradiation level chips.

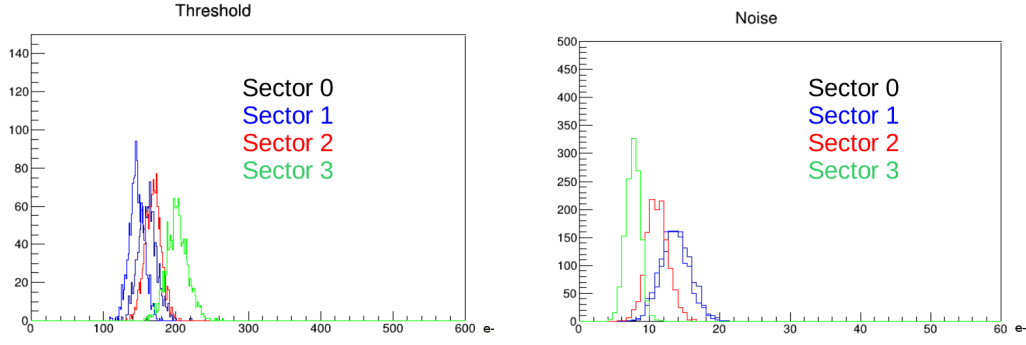


Figure 6.12: Threshold (left) and noise (right) distributions for an irradiated chip, 1×10^{13} $1\text{MeVn}_e\text{q}/\text{cm}^2$ irradiation level, with epitaxial layer thickness of $25\text{ }\mu\text{m}$ and $V_{\text{BB}} = -3\text{ V}$.

	Threshold (e^-)		Threshold RMS (e^-)		Noise (e^-)	
	0 V	-3 V	0 V	-3 V	0 V	-3 V
Sector 0	179	160	19	10	9.4	13.8
Sector 1	180	145	19	10	9.7	13.5
Sector 2	221	165	16	11	8.0	11.0
Sector 3	271	204	21	15	7.0	7.5

Table 6.4: Summary table of threshold mean and RMS and noise for an irradiated pALPIDE-v2 chip, 1×10^{13} $1\text{MeVn}_e\text{q}/\text{cm}^2$ irradiation level and epitaxial layer thickness of $25\text{ }\mu\text{m}$.

The measurements of threshold and noise of each sector is also repeated applying a back-bias of $V_{\text{BB}} = -3\text{ V}$, when possible.

As it can be noticed in Figure 6.12 for an irradiated chip with epitaxial layer thickness of $25\text{ }\mu\text{m}$, a difference between the threshold values of sector 0 and sector 1 is observed for a back-bias $V_{\text{BB}} = -3\text{ V}$ and nominal I_{THR} . The values of threshold and noise are reported in Table 6.4. In general, higher values of noise and lower values of threshold are measured for all the sectors applying $V_{\text{BB}} = -3\text{ V}$ with respect to no back-bias applied.

The dependence of threshold, threshold RMS and noise on I_{THR} has also been studied. The results are reported in Figure 6.13 for each sector of a non-irradiated chip with epitaxial layer thickness of $18\text{ }\mu\text{m}$ in the I_{THR} range 20-90 DAC.

The threshold of each sector, shown in the top left panel of Figure 6.13, increases increasing the I_{THR} , as expected. Furthermore, the difference between the sectors threshold becomes more relevant for higher values of I_{THR} . For each I_{THR} value the sectors hierarchy observed in irradiated chips, shown in Figure 6.11, is respected but lower values of threshold are measured in the non-irradiated chip.

In the top right panel of Figure 6.13 the threshold RMS is also reported. A slight increase increasing I_{THR} can be observed for each sector.

On the other hand, a different dependence on I_{THR} is observed for the temporal noise distribution, shown in the bottom panel of Figure 6.13. The temporal noise slightly increase increasing I_{THR} in sector 3, while it decreases in the other sectors with the same reset mechanism. Also in this case the sectors hierarchy observed in irradiated chips is respected.

The correspondance between I_{THR} and the threshold and temporal noise has to be taken into account when comparing the performances of different sectors.

A special attention has been dedicated in this thesis work at the test of sector 3 when a back-bias is applied. The reason can be found in Figure 6.14. It shows a V_{RESET} scan for $V_{\text{BB}} = 0\text{ V}$ (left), $V_{\text{BB}} = -3\text{ V}$ (center) and $V_{\text{BB}} = -6\text{ V}$ (right) for all the sectors of a non-irradiated chip with $25\text{ }\mu\text{m}$ epitaxial layer thickness. The procedure of this test consists in injecting a fixed charge 50 times in a pixel varying the V_{RESET} and counting the number of

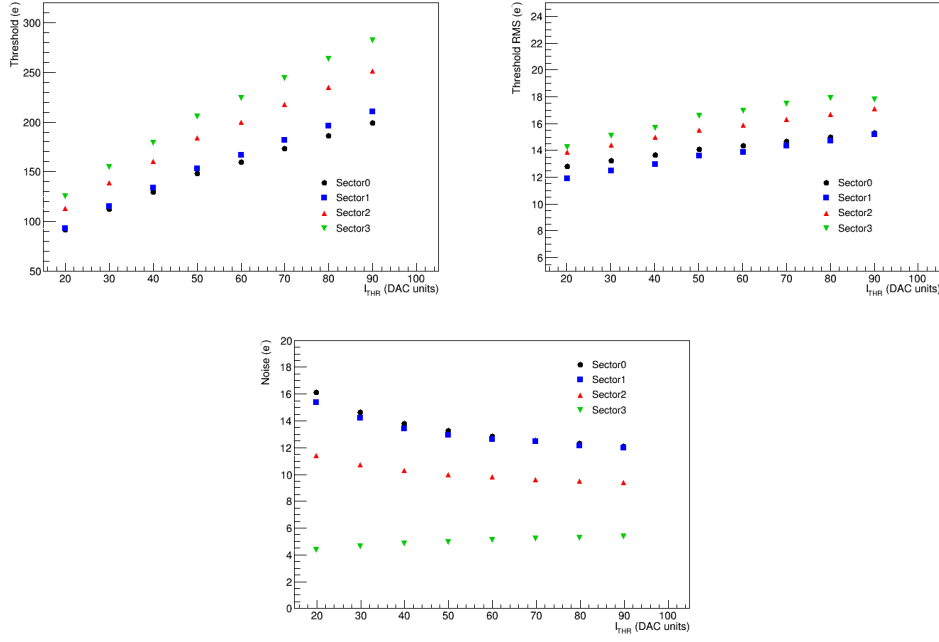


Figure 6.13: Threshold (top left), threshold RMS (top right) and noise (bottom) as a function of I_{THR} for each sector of a non-irradiated chip with epitaxial layer thickness of $18 \mu\text{m}$ without back-bias.

registered hits, that are reported on the y axis. The procedure is repeated for the 0.06% of the matrix (~ 310 pixels). A pixel is considered to work properly if 50 hits are registered. It is possible to notice a difference in the behaviour of sectors 0, 1 and 2 (PMOS reset mechanism) with respect to the behaviour of sector 3 (Diode reset mechanism). Regarding the first three sectors, the V_{RESET} has to be chosen in a window from ~ 50 and ~ 150 DAC without any back-bias and the window gets narrower applying a back-bias. Nevertheless, the default setting of $V_{RESET} = 117$ DAC can be applied for each back-bias value. For the sector 3, V_{RESET} has to be higher than a certain value. That value is above the default setting when a back-bias is applied. Therefore, $V_{RESET} = 140$ DAC and $V_{RESET} = 180$ DAC are chosen for $V_{BB} = -3$ V and $V_{BB} = -6$ V, respectively. It can be noticed that, for $V_{BB} = -6$ V, it is not possible to apply the same V_{RESET} value to all the sectors and, hence, to perform the test of the complete matrix in one time. The same behaviour is observed in non-irradiated and irradiated chips.

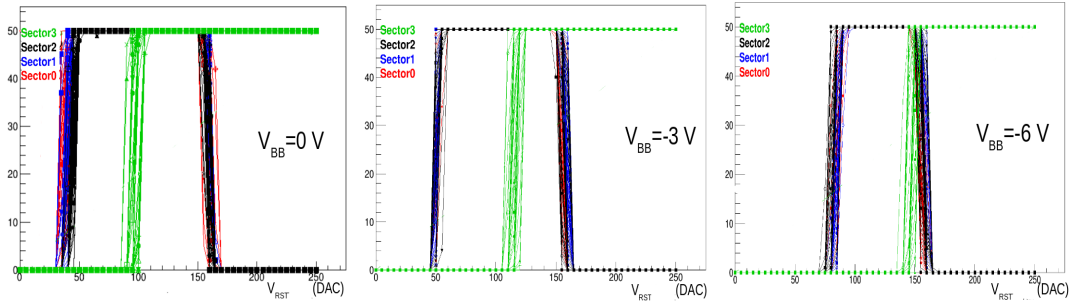


Figure 6.14: Number of hits as a function of V_{RESET} for $V_{BB} = 0$ V (left), $V_{BB} = -3$ V (center) and $V_{BB} = -6$ V (right) for all the sectors in a non-irradiated chip with $25 \mu\text{m}$ epitaxial layer thickness. Each line in the plot correspond to a pixel.

6.2.2 Fake-Hit Rate

The estimation of the fake-hit rate, already introduced in Chapter 5, is important to determine the tracking capability of the detector. A significant fake-hit rate could affect the efficiency of track fitting algorithms and the estimation of the impact parameter.

The following procedure is used in laboratory to estimate the rate at which noise produces a response which exceed the selected threshold in the pALPIDE-v2:

- the desired settings are applied;
- a given number of triggers (10^6) is sent to the chip in absence of any source;
- the total number of fake hits is counted in each of the four sectors of the chip;
- the fake-hit rate in each sector is obtained dividing the number of fake hits by the number of pixels in the sector and the number of triggers.

The test is performed for different chips with different characteristics and for different values of I_{THR} , in the range 20-100 DAC.

In Figure 6.15, the fake-hit rate is presented for three pALPIDE-v2 chips with different epitaxial layer thickness: 18, 25 and 30 μm . No back-bias is applied and the default settings are kept constant, except for the I_{THR} . For $I_{THR} > 30$ DAC, all the sectors exhibit fake-hit rates well below the new ITS requirement of 10^{-5} hits $\text{evt}^{-1} \text{pix}^{-1}$. A strong dependence on I_{THR} is observed in all the sector. In sector 0, 2 and 3, with the same input transistor size, the fake-hit rate decreases by 4 order of magnitude from the lowest to the highest value of I_{THR} explored. A more steep decrease is observed in sector 1 (with larger input transistor), in this case the fake-hit rate reaches values of the order of 10^{-10} hits $\text{evt}^{-1} \text{pix}^{-1}$ at $I_{THR} = 60$ DAC and remains more or less constant despite the further increase of I_{THR} . No clear dependence on the epitaxial layer thickness of the chip is observed, a systematic study on several chips with the same epitaxial layer thickness could be needed to draw a conclusion.

In general, the noise occupancy is strongly determined by few noisy pixels with very high fake-hit rates. Hence, it could be useful to mask a limited amount of noisy pixels: already masking the 0.01% of pixels a decrease of the fake-hit rate of 1-2 orders of magnitude is observed, depending on I_{THR} .

A reduction of the fake-hit rate is also evident when a back-bias is applied. Figure 6.16 shows the fake-hit rate of sector 3 as a function of I_{THR} comparing results for different back-bias: V_{BB} equal to 0, -3 and -6 V. The results are presented for a non-irradiated chip with 18 μm epitaxial layer thickness (left panel) and an irradiated chip, irradiation level of 1×10^{13} $1\text{MeVn}_e\text{q}/\text{cm}^2$, with 25 μm epitaxial layer thickness (right panel). In the non-irradiated chip, a lower fake-hit rate is already observed for $V_{BB} = -3$ V with respect to $V_{BB} = 0$ V, but a more significant drop is evident when the strongest back-bias is applied. The drop varies from 1 to 3 order of magnitude depending on I_{THR} , reaching a minimum of 10^{-11} hits $\text{evt}^{-1} \text{pix}^{-1}$. A fake-hit rate below the upgraded ITS requirement is also observed in the sector 3 of the irradiated chip for $I_{THR} \geq 30$ DAC. Similar results are obtained in the other sectors, proving the radiation hardness of the pAlpide-v2 prototype in terms of fake-hit rate.

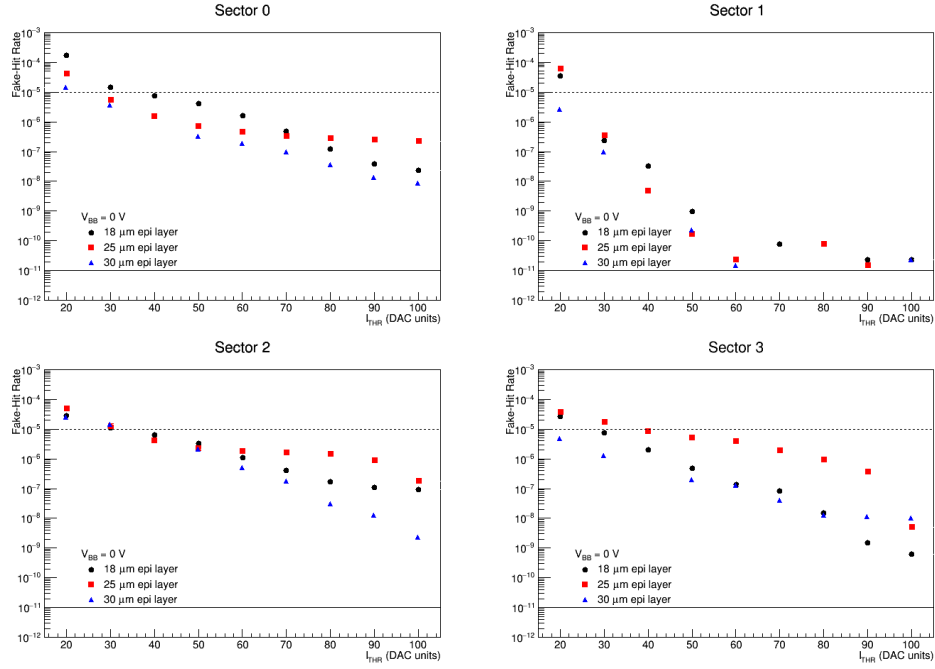


Figure 6.15: Fake-hit rate for three pALPIDE-v2 chips with different epitaxial layer thickness and no back-bias applied. Results on sector 0 (top left), sector 1 (top right), sector 2 (bottom left) and sector 3 (bottom right) are presented. In each plot the dashed line represents the ITS requirement limit, while the solid line the sensitivity limit of the test.

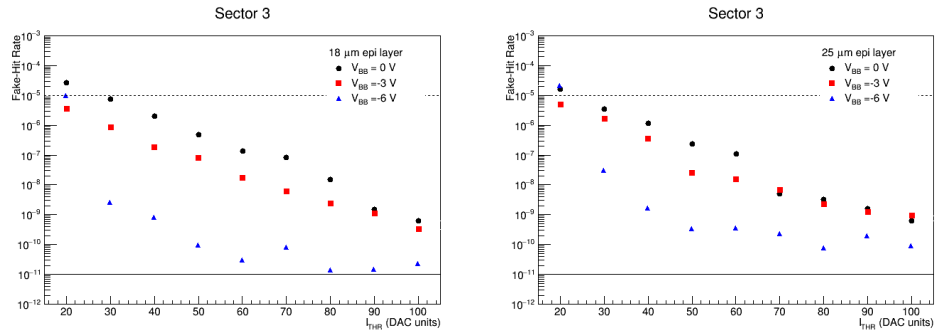


Figure 6.16: Fake-hit rate as a function of I_{THR} for different values of back-bias in the sector 3 of one non-irradiated chip (left) and one irradiated chip with irradiation level of 1×10^{13} $1\text{MeVn}_{eq}/\text{cm}^2$ (right).

6.3 Testbeam measurements

An intensive testbeam campaign has been carried out at CERN PS with a pion beam of 6 GeV/c from May to September 2015 to characterize pALPIDE-v2 chips. Detection efficiency, spatial resolution and clusters size are studied for chip with different high resistivity epitaxial thickness and irradiation levels. In each sector the behaviour of the chip performances varying V_{BB} , I_{THR} , V_{CASN} has been tested.

6.3.1 Telescope setup

During this campaign, a telescope composed of 6 planes of pALPIDEs has been used. The setup is shown in Figure 6.17. The chips are inserted in three boxes to shield them from the light (black boxes in the bottom of the picture), while the read-out electronics is visible in the figure. Two separated boxes on the left and on the right contain each 3 reference planes of pALPIDEs, which are at 18 mm distance from each other. The box in the center contains the DUT of pALPIDE-v2, which is at 36 mm distance from the closest reference planes. This setup allows to replace the DUT without moving the reference planes. To avoid too much material and, hence, multiple scattering between the DUT and the reference planes, the boxes have a hole in the area correspondent to the sensors that is covered with aluminum foils. A back-bias of -3 V is applied to the reference planes to improve their performances.

6.3.2 Analysis procedure

The data are analysed with EUTelescope [128], a generic pixel telescope data analysis framework developed in the context of the EUDET project. EUTelescope provides several processors implementing algorithms necessary for a full track reconstruction and data analysis of beam test experiments.

The analysis method is very similar to the one described for the analysis of MISTRAL prototypes in the previous chapter, the various analysis steps are summarized in the diagram in Figure 6.18. The raw data from each plane of the telescope are converted in the LCIO format, a Linear Collider I/O event-based data format. Then, the clusters are detected and their center of gravity (hits) are calculated. Subsequently, hits in the planes are written in the global reference system of the telescope using the information passed through the gear file, that contains the geometry description of the telescope. The reference planes are aligned all together in two steps: a first rough alignment step that allows only shifts in x and y directions and a second precise alignment step that includes also rotation around z . The alignment parameters are calculated from straight tracks. The aligned hits are then used to construct tracks, the fitting procedure in this case uses broken lines. Subsequently, the reconstructed tracks are associated to a hit in the DUT in order to perform the final analysis. In each of the previous steps, clusters, hits and

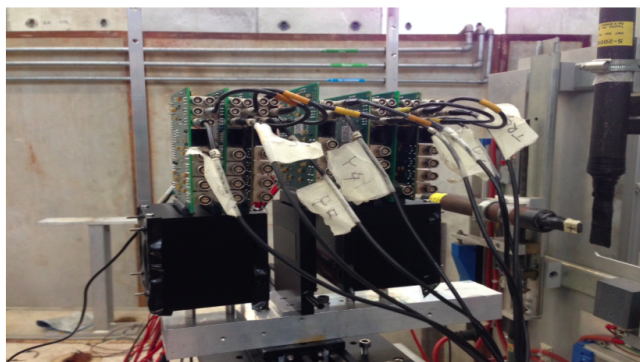


Figure 6.17: Telescope setup at CERN PS.

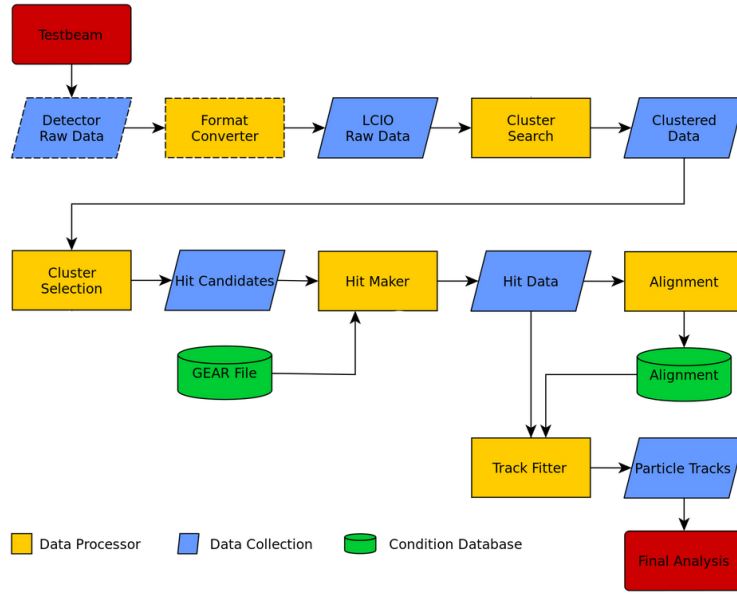


Figure 6.18: Diagram of the analysis steps in EUTelescope [128].

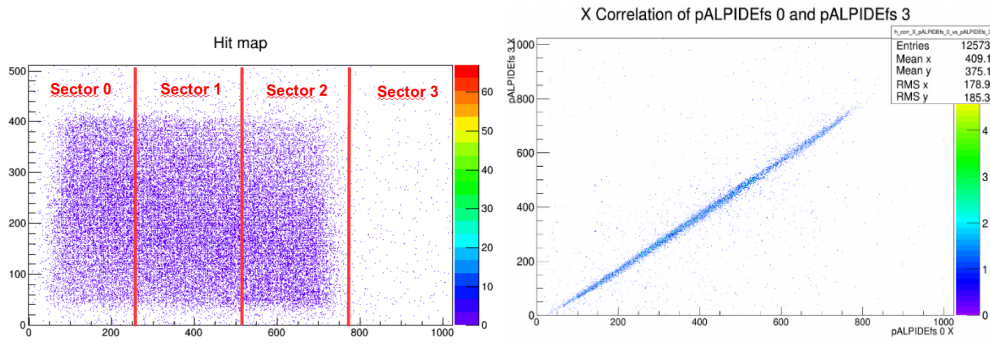


Figure 6.19: Left: hit map of a pALPIDE-v2 used as a DUT during the testbeam, the sectors are delimited by red lines. The rectangular beam spot is the shadow of the scintillator used for the trigger. Right: correlation between the x coordinate of hits in the first plane of pALPIDEs (plane 0) and the DUT (plane 3).

tracks had to pass different selection cuts depending on the step.

The left panel of Figure 6.19 shows the hit map of a pALPIDE-v2 used as DUT. The plot is obtained with 50000 events (all the runs analyzed contained that amount of events). The beam spot is clearly visible in the plot and it can be noticed that it did not cover the whole sensor active area. Therefore, it is not possible to test all the sectors at the same time but it is necessary to move the telescope in order to include the sector 0 or the sector 3 in the area covered by the beam. In the right panel of Figure 6.19 the correlation between the x coordinate of hits in the first plane of pALPIDEs (plane 0) and the DUT (plane 3) is shown. The correlation is clearly visible in the area covered by the beam, ensuring that particles are correctly crossing the telescope.

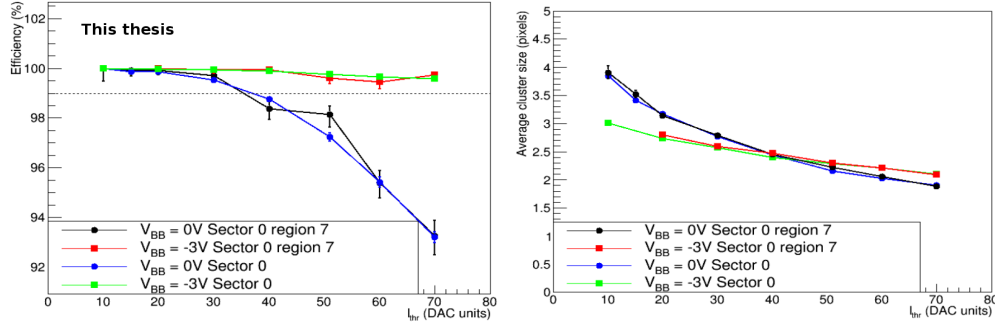


Figure 6.20: Comparison between detection efficiency (left) and average cluster size (right) of a pALPIDE-v2 with 18 μm epitaxial thickness in sector 0 and in the region 7 of the same sector with $V_{BB} = 0$ and $V_{BB} = -3$ V.

6.3.3 Analysis results

Sectors 0, 1 and 2

Detection efficiency, spatial resolution and cluster size are measured for each sector with PMOS reset mechanism as a function of I_{THR} , varied from 10 to 70 DAC (where $I_{THR}=51$ is the nominal value). The following results will focus on the characterization of one chip with 18 μm epitaxial layer thickness, thinned to 50 μm .

The left panel of Figure 6.20 shows the detection efficiency for sector 0 as a function of I_{THR} without back-bias and with $V_{BB} = -3$ V. In both cases, detection efficiency is $\sim 100\%$ at the lower value of I_{THR} and then it decreases increasing I_{THR} . Without back-bias the detection efficiency decreases to 93% for the higher value of I_{THR} , while for $V_{BB} = -3$ V a detection efficiency above 99% is measured in the whole I_{THR} range explored. In the same plot, the detection efficiency without back-bias and with $V_{BB} = -3$ V for region 7 of sector 0 is also shown. The region 7 has been measured separately to study the effect of the antenna protection diode implemented in this region. The antenna protection diode is expected to further reduce the noise but it could also produce a strong leakage current if it is applied to each pixel. Hence, its effect on the sensor performance has to be studied before implement it in the whole matrix. The detection efficiencies measured are compatible with those of the whole sector 0.

The average cluster size is presented for sector 0 and for the region 7 of the same sector in the right panel of Figure 6.20. Also in this case no difference is visible in the region 7. The average cluster size decreases increasing I_{THR} and varies from ~ 4 to ~ 2 pixels without back-bias and from ~ 3 to ~ 2.2 pixels with $V_{BB} = -3$ V. In the figure, the vertical bars represent the statistical errors. Obviously, the statistical error is higher when we consider only the region 7 because it is crossed by $\sim 1/7$ of the tracks crossing the sector 0. The total number of tracks crossing sector 0 is of the order of 10^4 tracks.

From laboratory and testbeam measurements, no difference between the region 7 and the other regions of sector 0 has been observed, validating the implementation of the antenna protection diode in the future prototypes.

Figure 6.21 shows the comparison between the detection efficiency of sector 0 and sector 1 of a pALPIDE-v2 as a function of I_{THR} without back-bias and with $V_{BB} = -3$ V. Sector 1, with a larger input transistor size (0.88 μm) with respect to sector 0 (0.22 μm), presents a detection efficiency very similar to sector 0 for both $V_{BB} = 0$ V and $V_{BB} = -3$ V. A slightly higher detection efficiency is observed for sector 1 with $V_{BB} = -3$ V for $I_{THR} > 20$ DAC but no systematic uncertainties due to chip-to-chip fluctuations are considered.

The detection efficiency of sector 1 of two pALPIDEs chips, obtained from previous testbeams, are also superimposed. The sector 1 of pALPIDEs has characteristics similar to sector 1 of pALPIDE-v2. Already without back-bias, a larger operational margin is gained with the pALPIDE-v2 chip with respect to the pALPIDEs: a detection efficiency above the requirement

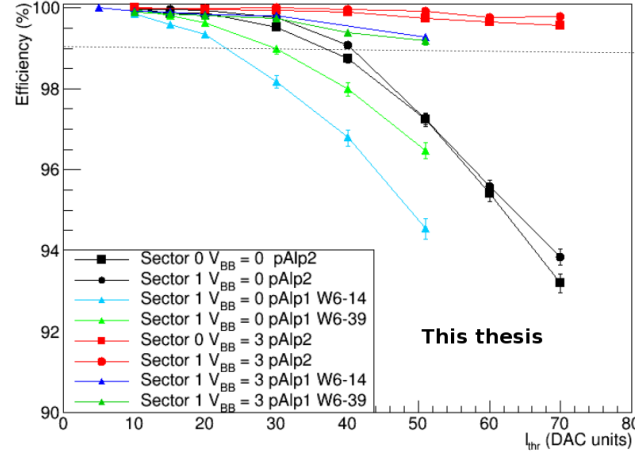


Figure 6.21: Comparison between detection efficiency measured in a pALPIDE-v2 with $18\ \mu\text{m}$ epitaxial thickness and two pALPIDEfs (W6-14 and W6-39) with $V_{\text{BB}} = 0$ and $-3\ \text{V}$.

of 99% can be obtained for a larger range of I_{THR} values (from 10 to 40 DACs). During this testbeam, a wider range of I_{THR} is explored with respect to the characterization of pALPIDEfs chips up to $I_{\text{THR}} = 51\ \text{DAC}$.

In order to evaluate the spatial resolution of the chip, the residual distributions are obtained for each sector in the x and y directions.

Residual distributions for sector 1 are shown in Figure 6.22. The distributions are obtained considering only hits in the area under the hole of the carrier board (shown in the right panel of Figure 6.7) in order to reduce, how much as possible, the material budget and hence multiple scattering effects. Although, this implies a reduction of statistics, around a factor 10 lower than the total number of tracks crossing the sector. The distributions are fitted to a Gaussian and the residual is calculated as the standard deviation of the fit. A residual of $6.0 \pm 0.1\ \mu\text{m}$ is obtained in both directions in the sector 1 of one chip with $18\ \mu\text{m}$ epitaxial layer thickness, $V_{\text{BB}} = -3\ \text{V}$ and $I_{\text{THR}} = 40\ \text{DAC}$.

As already explained in the previous Chapter, the residual measured is a convolution of the spatial resolution of the DUT and the tracking resolution of the telescope. The tracking resolution is evaluated through a simulation. For this telescope, the estimated tracking resolution is $\sim 2.8\ \mu\text{m}$. Hence, the spatial resolution obtained for the sector 3 of a chip with $18\ \mu\text{m}$ epitaxial layer thickness, applying a $V_{\text{BB}} = -3\ \text{V}$ and $I_{\text{THR}} = 40\ \text{DAC}$, is estimated as $5.3 \pm 0.1\ \mu\text{m}$.

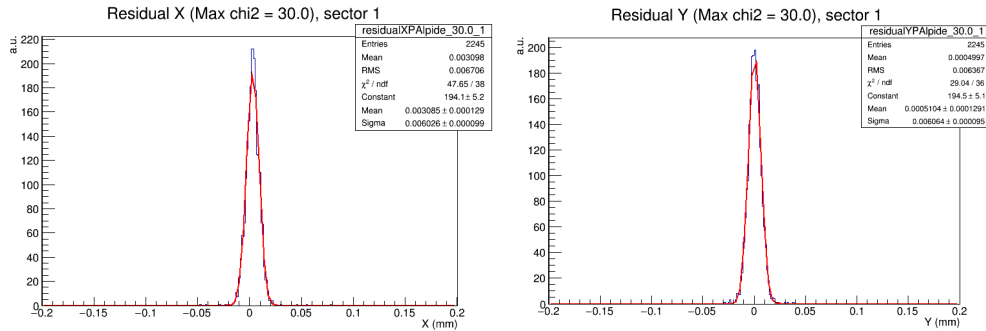


Figure 6.22: Residual distribution in the x (left) and y (right) directions in sector 1, obtained from the hits in the area under the hole.

The left panel of Figure 6.23 shows the residuals of sector 1 as a function of I_{THR} without back-bias and with $V_{\text{BB}} = -3\ \text{V}$. For almost all the I_{THR} values applied, a lower residual is

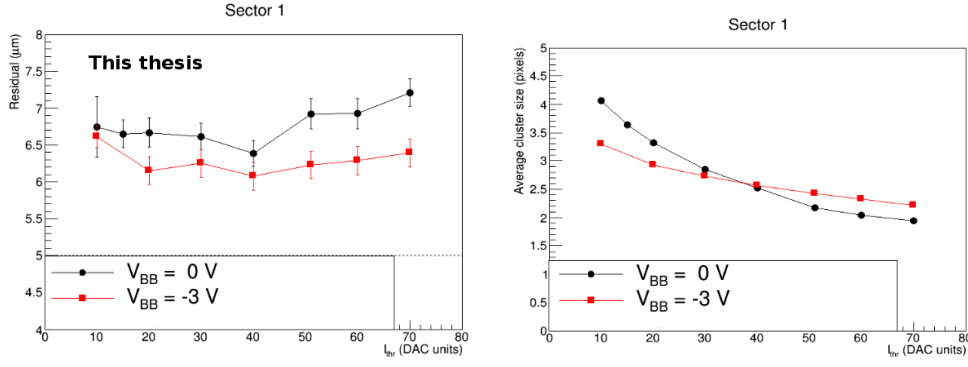


Figure 6.23: Residual (left) and average cluster size (right) as a function of I_{THR} in sector 1.

measured applying a back-bias.

In the right panel of Figure 6.23 the average cluster size of sector 1 is also shown for the same settings. The average cluster size of sector 1 follows the same behaviour of sector 0 as a function of I_{THR} and very similar values are measured.

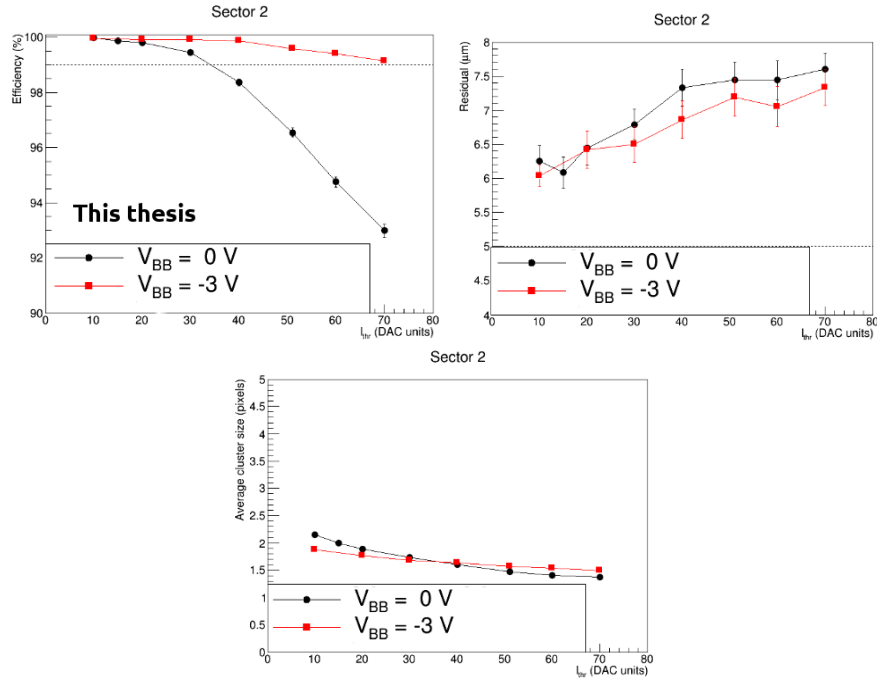


Figure 6.24: Detection efficiency (top left), residual (top right) and average cluster size (bottom) as a function of I_{THR} in sector 2 without back-bias and with $V_{\text{BB}} = -3 \text{ V}$.

Figure 6.24 shows the performances of sector 2 with a larger spacing ($4 \mu\text{m}$) with respect to sectors 0 and 1 ($2 \mu\text{m}$). Detection efficiency, residuals and average cluster size are presented in the figure. Also for this sector, a detection efficiency above 99% is measured for all the values of I_{THR} with $V_{\text{BB}} = -3$ and it increases decreasing I_{THR} up to 100%, even without back-bias. Residuals vary from 6 to $7.5 \mu\text{m}$ depending on I_{THR} and the values obtained with and without back-bias are compatible within the statistical uncertainties.

With respect to sector 0 and 1, lower values of average cluster size are measured (below 2.5 pixels for all the settings), indicating a lower spread of the signal between adjacent pixels.

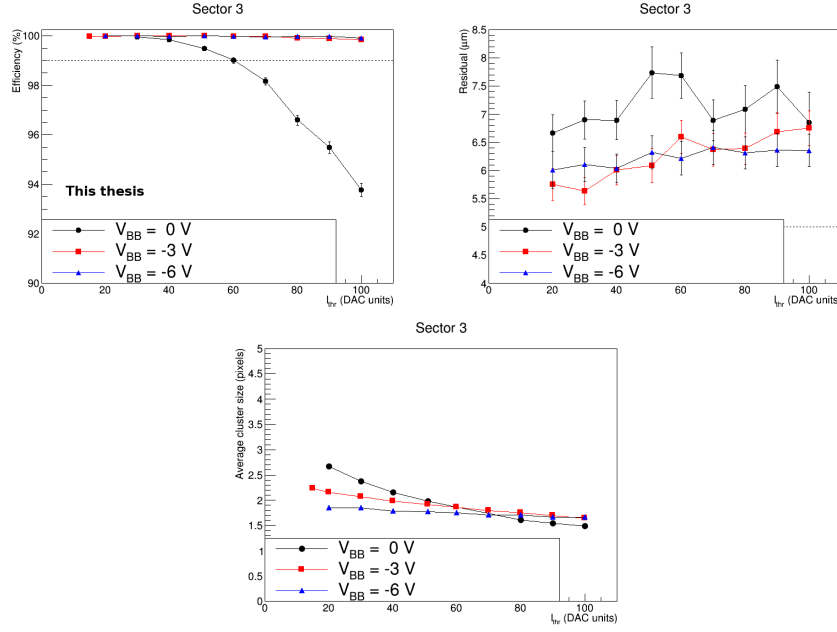


Figure 6.25: Detection efficiency (top left), residual (top right) and average cluster size (bottom) as a function of I_{THR} in sector 3 without back-bias, with $V_{BB} = -3$ V and $V_{BB} = -6$ V in one chip with epitaxial layer thickness of 25 μm .

Sector 3

The performances of the sector characterized by a Diode reset mechanism (sector 3) are shown in Figure 6.25. The settings are modified as described in Section 6.2.1.

At first the results are presented for a non-irradiated chip with epitaxial layer thickness of 25 μm and for 3 values of V_{BB} applied: 0, -3 and -6 V. A wider range of I_{THR} is covered: from 15 to 100 DAC.

In the top left panel of Figure 6.25, a detection efficiency decreasing increasing I_{THR} is evident for $V_{BB} = 0$ V, while results very close to 100% can be obtained with $V_{BB} = -3$ and -6 V in the whole I_{THR} range.

Also the residuals, shown in the top right panel of Figure 6.25, present an improvement when the back-bias is applied. Compatible results are obtained for $V_{BB} = -3$ and -6 V.

For lower values of I_{THR} the effect of the back-bias is evident also in the average cluster size results: smaller clusters are obtained with a stronger back-bias, as reported in the bottom panel of Figure 6.25.

It can be noticed that detection efficiency, residual and average cluster size do not show a dependence on I_{THR} when applying $V_{BB} = -6$ V, but the results remain more or less constant. Regarding the detection efficiency measurements at $V_{BB} = -6$ V, an offset of $\sim 0.4\%$ was measured during the first testbeam that was due to a not perfect optimization of the readout time. After further investigation, it was discovered that reducing the trigger delay to around a half of the default settings (trigger delay = 950 ns and strobe window = 500 ns) was sufficient to avoid losing signal, obtaining the results presented above. Unfortunately, it was not possible to repeat the measurements for other chips due to time constraints but this effect was observed only in the sector 3 with the Diode reset mechanism.

A comparison between non-irradiated chips with a different thickness of the high resistivity epitaxial layer is shown in Figure 6.26. The results are presented as a function of I_{THR} for $V_{BB} = -3$ V. For large values of I_{THR} , a higher detection efficiency is evident for epitaxial layer thickness of 25 and 30 μm . On the other hand, similar results are obtained in terms of residuals and average cluster size in chips with epitaxial layer thickness of 18 and 25 μm . The chip with 30 μm epitaxial layer thickness shows a lower residual and a higher average cluster

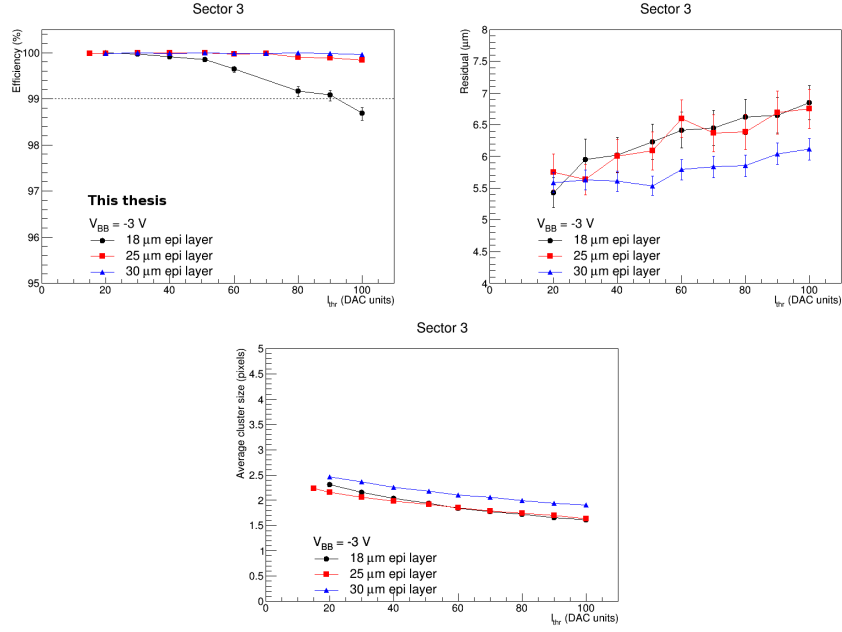


Figure 6.26: Detection efficiency (top left), residual (top right) and average cluster size (bottom) as a function of I_{THR} in sector 3 with $V_{BB} = -3$ V in three chips with epitaxial layer thickness of 18, 25 and 30 μ m .

size in the sector 3.

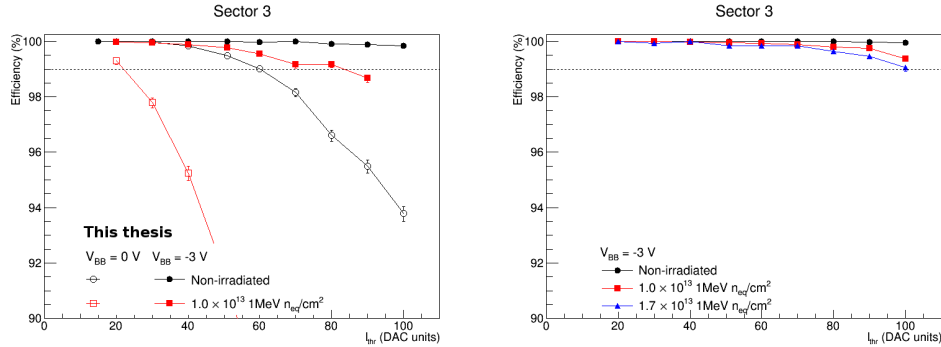


Figure 6.27: Left: comparison between efficiencies in one non-irradiated chip and one 1×10^{13} 1MeV n_{eq}/cm^2 irradiated chip with epitaxial layer thickness of 25 μ m for $V_{BB} = 0$ V and $V_{BB} = -3$ V. Right: comparison between efficiencies in one non-irradiated chip, one 1×10^{13} 1MeV n_{eq}/cm^2 irradiated chip and one 1.7×10^{13} 1MeV n_{eq}/cm^2 irradiated chip with epitaxial layer thickness of 30 μ m for $V_{BB} = -3$ V.

The radiation hardness of the pAlpide-v2 prototype is studied comparing the performances of non-irradiated and irradiated chips.

The left panel of Figure 6.27 shows the detection efficiencies of one non-irradiated chip compared to one irradiated chip with 1×10^{13} 1MeV n_{eq}/cm^2 irradiation level. Both chips have an epitaxial layer thickness of 25 μ m and the results are presented for $V_{BB} = 0$ and -3 V. A drop in the efficiency is visible in the case of the irradiated chip without a back-bias applied. But, an efficiency above 99% can be obtained in the irradiated chip for I_{THR} below 90 DAC when a back-bias of -3 V is applied.

In the right panel of Figure 6.27 different level of irradiation are also compared. In this case, one non-irradiated chip is compared with two irradiated chips with 1×10^{13} 1MeV n_{eq}/cm^2 and

1.7×10^{13} 1MeV n_{eq}/cm^2 irradiation levels. All the chips considered have a 30 μm epitaxial layer and a back-bias of $V_{BB} = -3$ V is applied. For lower values of I_{THR} no difference is observed between the detection efficiencies of the three chips. On the other hand, a dependence on the irradiation level is visible for high I_{THR} values: the non-irradiated chip has the higher detection efficiency and it decreases increasing the irradiation level. Nevertheless, the detection efficiencies are always above the ITS requirement of 99% for the chips with epitaxial layer thickness of 30 μm , demonstrating the radiation hardness of the sector 3 of pALPIDE-v2. The radiation hardness is also validated in terms of residuals and average cluster size.

6.3.4 Final results

The measurements presented in this thesis contributed to the full characterization of the pALPIDE-v2 sensor and the comparison between different design options.

A large margin over the ITS design requirements is observed in all the sectors. The design options that seem to be favoured are:

- a large spacing (4 μm), that guarantees the largest operational margin;
- a large input transistor size (0.88 μm), that allows an higher gain with respect to the smaller input transition size (0.22 μm);
- a PMOS reset mechanism that seems to be less sensitive to radiation damage.

Indeed, the best performances are obtained with sectors 1 (large input transistor and PMOS reset) and 2 (large spacing and PMOS reset), which final results are presented in Figure 6.28. The results are presented as a function of I_{THR} converted in pA (1 DAC= 9.8 pA).

In the left panel of Figure 6.28, detection efficiency and fake-hit rate are shown for three non-irradiated chips with epitaxial layer thickness of 18, 25 and 30 μm with $V_{BB} = -6$ V applied. A detection efficiency above 99% is measured for almost all the settings. For high values of I_{THR} , a detection efficiency of 100% is reachable in sector 2 in chips with 25 and 30 μm epitaxial layer thickness. A fake-hit rate well below the ITS requirements of 10^{-5} pixels is observed in all the measurements masking the 0.015% of pixels. The sensitivity limit of the test is reached for high I_{THR} .

In the right panel of Figure 6.28, spatial resolution and average cluster size are shown for one non-irradiated and one irradiated chip, 1.7×10^{13} 1MeV n_{eq}/cm^2 irradiation level. The results are presented for the sector 2 of two chips with 30 μm epitaxial layer thickness and $V_{BB} = -6$ V applied. Very similar spatial resolution and average cluster size are measured for the two chips, proving the radiation hardness of the sensor. The spatial resolution, obtained subtracting the telescope resolution to the residual, is below the upgraded ITS requirement of 5 μm .

Together with the low power density (~ 35 mW/cm $^{-2}$) and fast readout (< 10 μs), the results led to the choice of the ALPIDE implementation of TowerJazz 0.18 μm technology as the baseline for the pixel sensors that will compose the upgraded ITS. The characterization of a third version of the full-scale ALPIDE prototype (pALPIDE-v3) with the final interface is already started. The production of the chips will take place in 2016-2017, in order to be ready for the installation of the new ITS in ALICE in 2019.

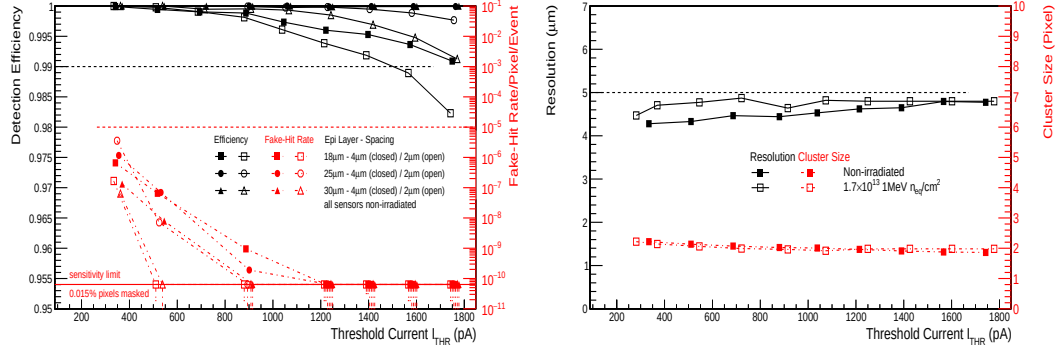


Figure 6.28: Left: detection efficiency and fake-hit-rate of sector 1 (open markers) and sector 2 (closed markers) for non-irradiated chips with different epitaxial layer thickness and $V_{BB} = -6$ V. Right: spatial resolution and average cluster size of sector 2 for a non-irradiated and an irradiated chip with 30 μm epitaxial layer thickness and $V_{BB} = -6$ V.

Chapter 7

Conclusions

In this thesis I described my work on two different aspects of the ALICE experiment: the study of D^+ -meson production in Pb-Pb collisions and the characterization of low-noise silicon pixel sensors developed for the upgrade of the ITS.

The D^+ -meson production was studied in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV collected in 2011 at the LHC.

The D^+ -meson analysis was performed via the exclusive reconstruction of the hadronic decay channel $D^+ \rightarrow K^- \pi^+ \pi^+$ in the central rapidity region with the ALICE detector. The D^+ -meson nuclear modification factor was measured in the transverse momentum interval $3 < p_T < 36$ GeV/ c in the 0-10% most central collisions. Furthermore, its dependence on the centrality of the collisions was studied in the transverse momentum interval $3 < p_T < 16$ GeV/ c .

The results indicates a suppression of the D^+ nuclear modification factor in the whole p_T interval in the most central collisions. In particular, a minimum suppression of a factor of about 5-6 was measured for $p_T \sim 10$ GeV/ c . Furthermore, a suppression increasing with the collision centrality was observed.

The measurement of D^+ -meson production is compatible with the results obtained for other non-strange charmed mesons, D^0 and D^{*+} . The strong suppression of the D-meson production observed at high p_T in the most central Pb-Pb collisions is interpreted to be due to the interaction of charm quarks with the Quark-Gluon-Plasma (final-state effects).

The D-meson R_{AA} as a function of the collision centrality was compared to non-prompt J/ψ R_{AA} measured by CMS, a lower suppression was observed for non-prompt J/ψ R_{AA} as expected from the mass hierarchy in energy-loss models.

Several theoretical calculations based on in-medium energy loss could reproduce quite well the D^+ -meson R_{AA} dependence on transverse momentum and collision centrality. Nevertheless, the simultaneous description of R_{AA} and other observables, like elliptic flow, is still challenging. A reduction of statistical and systematic uncertainties is fundamental to provide further constraints to energy loss models.

An upgrade program of the ALICE detectors is ongoing in order to provide high precision measurements. The upgrade program will allow ALICE to cope with the Pb-Pb collisions with an interaction rate of up to 50 kHz, corresponding to an instantaneous luminosity of $L = 6 \times 10^{27}$ cm $^{-2}$ s $^{-1}$ during the LHC Run 3 and 4.

One of the milestone of the ALICE upgrade is the new ITS that will provide an improvement in the vertices and tracks reconstruction and in the readout capabilities. The upgraded ITS will have a barrel geometry formed by seven layers of Monolithic Active Pixel Sensors (MAPS).

The TowerJazz 0.18 μ m technology was selected to design the pixels for the new ITS. Indeed, it provides the tools to fulfill the upgrade requirements in terms of material budget, readout and radiation hardness. Several prototypes using the TowerJazz 0.18 μ m technology were designed to investigate and validate the different components of the pixel sensor. Among my PhD thesis activities I took part in the intensive characterization campaign of these prototypes.

At first the results on the characterization of three small-scale MISTRAL prototypes, devel-

oped by the PICSEL group of IPHC (Strasbourg), were presented: MIMOSA22ThrB, MIMOSA22ThrB6 and MIMOSA22ThrB7. The characterization of those chips took place at the LNF testbeam facility in Frascati, Italy. In parallel, a telescope based on different types of MIMOSA sensors with integration times varying by orders of magnitude was developed. With this telescope, it was possible to estimate a detection efficiency above 99% and a spatial resolution below $10\text{ }\mu\text{m}$ of the devices under test.

Then, the results on the characterization of several chips of a full-scale pALPIDE-v2 prototype, developed by a collaboration formed by CCNU (China), CERN, INFN (Italy) and Yonsei (South Korea), were presented. Performances well above the new ITS requirements were observed in terms of detection efficiency ($> 99\%$), spatial resolution ($< 5\text{ }\mu\text{m}$), fake-hit rate ($< 10^{-5}$) and radiation hardness. For this reason and because of the low power density and fast readout, the ALPIDE implementation of the TowerJazz $0.18\text{ }\mu\text{m}$ technology was chosen as the baseline for the chips that will compose the upgraded ITS.

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