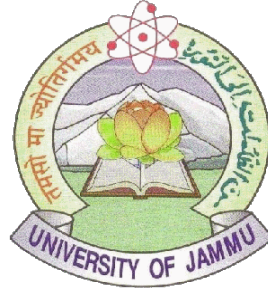


Open charm studies as function of event shape variable with ALICE detector at the LHC



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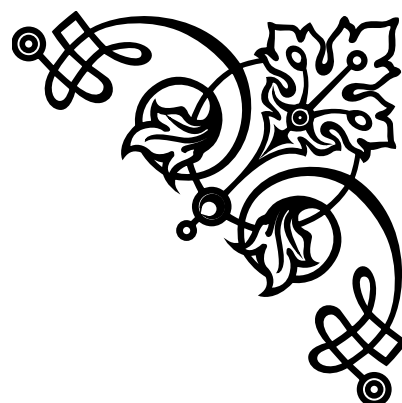
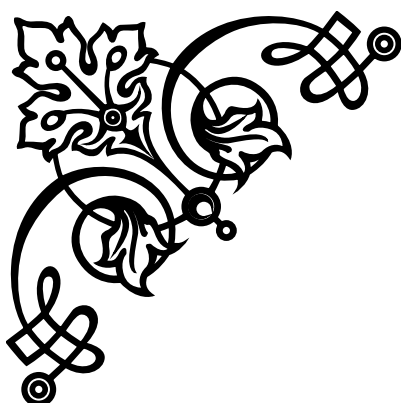
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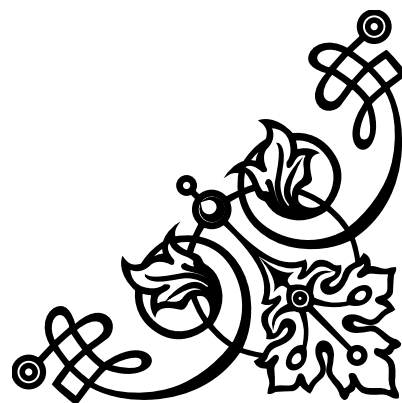
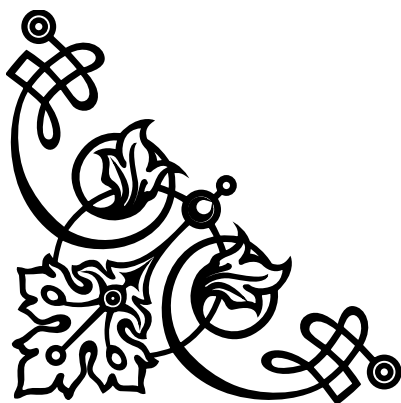
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(July 2022)





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DECLARATION

I, hereby, declare that the thesis entitled “**Open charm studies as function of event shape variable with ALICE detector at the LHC**” submitted for the award of degree of Doctor of Philosophy is a record of the research work carried out by me in the Department of Physics, University of Jammu, under the guidance of **Prof. Sanjeev Singh Sambyal**. I also ascertain that no part of this thesis is presented elsewhere for the award of any degree or diploma of any University or Institution. Moreover this thesis is having 2% degree of plagiarism as per the Urkund analysis report.

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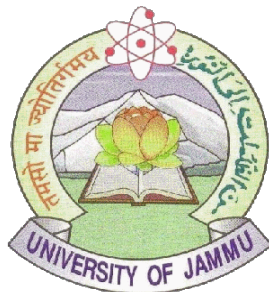
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CERTIFICATE

It is certified that Mr. Randhir Singh, worked under my supervision and the work is worthy of consideration for the award of Ph.D. degree in Physics. It is further certified that:

1. the thesis embodies the work of the candidate himself,
2. the candidate worked under my supervision for the period required under Statutes,
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4. the candidate fulfils all the requirements of thr UGC-MSP-2016 regulations,
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ACKNOWLEDGMENT

All praises belong to Almighty, the most merciful, the most beneficent and the most kind for giving me the opportunity, courage and enough energy to carry out and complete the entire thesis work. I am grateful and deeply indebted to my Research Guide Prof. Sanjeev Singh Sambyal, Department of Physics, University of Jammu. I have the great privilege and honour to express my whole hearted indebtedness to him for kindly placing at my disposal all the facilities available in the department for his guidance, supervision, inspiring encouragement, constructive criticism and help in carrying out this thesis work.

I would like to give my deepest respect to Prof. Anju Bhasin (Group Incharge, HEP Group) for her valuable support and encouragement. I would also like to thank Er. Anik Gupta for his time to time help for the accomplishment of this work. My sincere thanks to Dr. Ramni Gupta for all the encouragement and advice. I am also thankful to Er. Sanjay Mahajan and Dr. Saroj Nayak for their help and good wishes. I would also extend my thanks to all the teachers of the department for their academic support and encouragement.

My Sincere thanks to Prof. Arun Bharti, Head of the Department of Physics for providing the necessary infrastructure for this work.

My special thanks to Dr. Renu Bala for her constant support, valuable guidance, timely help and for assisting me to carry out this analysis work from the beginning up to its completion. She has always been a driving force behind this work.

My sincere thanks to all my seniors Dr. Ranbir Singh (Scientific Officer, NISER Bhubaneswar), Mr. Inayat Rasool Bhat, Ankita Sharma and Sonia Sharma for their valuable suggestions and help throughout this journey.

Thanks are also due to my fellow research colleagues Mrs. Binti, Ms. Meenakshi, Mr. Salman, Mr. Vikash, Ms. Sheetal, Mr. Rizwan, Ms. Pratibha, Mr. Nassir, Ms. Zarina, Mrs. Upasna, Ms. Mahima, Mr. Ashish, Mr. Haider and Mr. Balwan for helping me to create a stimulating and enjoyable atmosphere of research. I would

also thank my parents, Mr. Avtar Singh and Mrs. Surjeet Kour, my brother Mr. Karandeep Singh and bhabhi Mrs. Rupinder Kour without whom this work would have been quite literally impossible and to my cute little niece "Harjas Kour" whose smile is always a refreshing and cheering.

I would like to thank all the people associated with the ALICE Collaboration, especially Cristina Terevolli, Andrea Festanti and Fabrizio Grosa for their help, and valuable suggestions. I am equally thankful to all the Physics Working Group Members and Conveners from Heavy Flavour for their useful suggestions and healthy discussions. I am also thankful to Indian ALICE Collaborators for providing me an opportunity to work with them.

My sincere thanks also goes to Marco Giacalone (INFN, Italy) and Yoshini Bailung (IIT Indore, India) with whom I have worked as a team to get this analysis done and carrying on future work.

A special mention of thanks to my friends, Sujeet Chalotra, Ramandeep Singh, Har-simranjeet Singh, Bhramvir Singh, Gurminder Singh and Hargun Singh for their constant support, motivation and cooperation during this period. Thanks for always listening to me, supporting me, and encouraging me.

Last but not the least, a very special piece of thanks to my co-scholar and a very good friend Mr. Hans Raj Sharma for his moral support and help.

Abstract

Our diverse universe consists of a handful of 'elementary' or 'fundamental' particles. These elementary particles can be classified as (i) matter particles, the fermions and (ii) mediator particles, the bosons. There are only four distinct ways for fundamental particles to interact, (i) strong interaction (ii) electromagnetic interaction (iii) weak interaction and (iv) gravitational interaction.

At present, Quantum Chromodynamics (QCD) is the best theory that we have to understand the strong force. It describes interaction between quarks and gluons (together called partons) inside a nucleon. QCD involves two very important phenomena related to strong interaction: *asymptotic freedom and confinement*. At high energy density or high temperature, the coupling strength of the QCD decreases and almost vanishes. Thus at high temperature, the quarks and gluons essentially behave as interaction free. This property is referred to as asymptotic freedom. On the other hand Quarks and Gluons are never observed freely or isolated but are always found in confined colourless composite particles, the confinement is an additional property required for QCD. QCD also suggests that u and d quarks must have the same mass. This symmetry is called chiral symmetry and in observed phenomenon the chiral symmetry must be broken spontaneously.

To answer such questions the ideal approach would be to directly solve QCD equations, which result from the QCD Lagrangian but it is a very challenging task. But an alternative approach is to create some physical conditions in which the QCD equations are most simple. One such system is achieved when QCD matter is subjected to high temperature via heavy-ion collision. At this high temperature, Quarks and Gluons move freely in the matter and this state is referred as Quark Gluon Plasma (QGP) state. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and the Large Hadron Collider (LHC) at CERN are both designed for heavy ion collision experiments. A Large Ion Collider Experiment (ALICE) at CERN is a special set of detectors designed to study QGP.

Direct observation of QGP is very difficult because of its very short lifetime ($\sim 10 fm/c$). It then quickly thermalises and expands to form hadron gas. Therefore an indirect method is required to look for the formation of the QGP. QCD theory provides a large number of such observables which can be used as an evidence not only to qualify but also to quantify the QGP produced and hence also a test to QCD theory. One such probe is the study of heavy flavour hadrons which are made up of at least a charm or beauty quark. The large masses of heavy flavors have several implications: (i) Heavy flavours are produced in initial hard scattering processes. Due to their small formation time ($\Delta t \sim 0.1 fm/c$) as compared to the formation time of QGP ($\Delta t \sim 0.3 fm/c$) at the LHC, they go through all the stages that occur as the hot and dense medium created in heavy-ion collisions evolves over time. As a result, heavy quarks can investigate the qualities of dense matter formed early in a collision. (ii) Heavy quark thermalization is “delayed” in comparison to light quark thermalization. Heavy quarks might “thermalize” to some extent, but not totally, on a time scale comparable to the QGP lifetime. Therefore, their spectra should be significantly modified, but still retain memory about their interaction history, and, hence, represent an “optimal” probe. (iii) RHIC and, in particular, LHC experiments enable extremely low parton momentum fractions x , when gluon saturation effects become significant. Since they have enormous masses, heavy quarks are useful tools for studying gluon saturation because charm productions can be calculated using perturbative QCD and their yield is sensitive to the initial gluon density.

As a result, measuring open charm and beauty creation allows researchers to investigate QGP features and the colour charge and mass dependency of parton in-medium energy loss. The study of open charm mesons (mesons made up of one light quark and one charm quark) is a useful tool for probing pQCD theoretical models to reproduce data.

In the present work, the study of open heavy flavour (D^+ -meson) yield in pp collisions at 13 TeV as a function of charged-particle multiplicity and transverse sphericity gives insight into the mechanism influencing their production in hadronic collisions

at these energies and is a tool to test the influence of Multiple Parton Interactions (MPI). Moreover, analyzing the charm production processes using pp data could help in learning the basic differences between hard and soft processes of particle production. Along with that, they also serve as a reference for the similar measurements in p-Pb and Pb-Pb collisions.

This thesis is organised as follows:

Chapter 1: This chapter gives a brief introduction about the field of high energy physics. The goal of high-energy physics is to study matter that interacts strongly at extremely high energy densities. Moreover, a discussion of the Standard Model of particle physics is given, which is currently the best description about the elementary particles and interactions we have. In addition to that a general introduction to the Quantum Chromodynamics (QCD) is given. QCD is a quantum field theory of the strong force. Similar to QED, quantum chromodynamics predicts the existence of force-carrying particles called gluons, which transmit strong forces between matter particles that carry "color", a strong form of "charge". A brief presentation about Quark Gluon Plasma (QGP) is also made and its phase diagram is discussed. QGP is composed of asymptotic free quarks and gluons and proof of its discovery has been published in heavy ion collision analysis experiments. A brief introduction about the Ultrarelativistic heavy-ion collisions and stages involved in its evolution will also be discussed. Relativistic collisions of heavy ions provide a unique opportunity to study the most interesting aspects of strong interactions in the laboratory. In these collisions, the energy density is so high that a transition from hadronic state to QGP state occurs. The analysis of collision involves the study of different quantities and parameters which are related to the properties of the different particles produced in the collision. These parameters and quantities are also described in this chapter. Besides that, this chapter also discusses about the experimental signatures related to the formation of QGP medium in relativistic collisions.

Chapter 2: In this chapter, the ALICE Experimental setup and its main characteristics is discussed. ALICE is one of the four main detector setup at the LHC at

CERN. It is designed to handle very large particle production rate occurring in most central Pb-Pb collisions. Due to its very good tracking, vertexing and PID capabilities ALICE is very well suited for the open-charm studies. The main detectors used for the present analysis are the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Time Of Flight (TOF). All these detectors and their performances will be described in detail in this chapter.

Chapter 3: This chapter introduces ALICE data taking and computing framework. In ALICE the collection and processing of data is controlled by five central online systems which are (i) Data Acquisition system (DAQ) (ii) Central Trigger Processor (CTP) (iii) the High-Level Trigger (HLT) system (iv) the Detector Control System (DCS) and (v) the Experiment Control System (ECS). During the data taking period, the configuration of different detectors is controlled by the DAQ which work in collaboration with the CTP and the HLT system to select interesting physics events, provide an efficient access to these events and finally to store this data for later analysis. The DCS allows for the monitoring of the detector hardware from a central interface whereas ECS controls all these operations. The software package required for the data analysis in this work will also be discussed. The software used for this is called "AliRoot" which is an extension of "Root" and is based on the C++ language. Further, a detailed description of the simulations and reconstruction techniques of data, primary and secondary vertex reconstruction will be discussed.

Chapter 4: This chapter emphasizes the importance of heavy flavour study in understanding the QCD as well as QGP. The heavy flavour have large masses as compared to the transition temperature which is around $T \sim 160$ MeV. Due to this, heavy flavour is produced in the hard scattering processes which occur at the very early stages of the collision. The heavy flavour, therefore, observes the production of the QGP medium and evolution of QGP medium in spacetime in a heavy-ion collision. This chapter is, therefore, dedicated to the discussion of different kinds of processes involved in the production of heavy flavour in pp, pA and AA collisions. The different observables like nuclear modification factor (R_{AA}) and elliptic

flow variable (v_2) which play a significant role for understanding the production and behaviour of heavy flavour are also discussed. It also describes different effects like Cold Nuclear Matter (CNM) effects and Hot Nuclear Matter (HNM) effects that occur due the differences in the collision systems such pp, pA and AA. A summary of the results from the study of open heavy flavours in pp, pA, and AA collisions performed in different experiments like RHIC and LHC is also presented.

Chapter 5: This chapter presents the analysis strategy for the D^+ meson self-normalized yield as a function of charged-particle multiplicity. The data used in this work has been collected by the ALICE Experiment during the Run-II of the LHC at CERN. This data is collected with pp collisions at $\sqrt{s} = 13$ TeV in the year 2016, 2017 and 2018. For the analysis, two different event triggers namely Minimum Bias and High-Multiplicity triggers are used. For the Minimum Bias trigger, we have around 1600 million events and the High-Multiplicity trigger gives us around 332 million events. Before the extraction of the raw yield of D^+ meson, the z-vertex correction has been applied. This z-vertex correction is needed because the efficiency of the detector varies along z-axis (beam-axis or longitudinal axis) and also changes over time. The z-vertex correction removes this inefficiency. After this, the D^+ meson candidates are reconstructed in the central pseudorapidity ($|\eta| < 1$) region from their charged hadronic decay channel $D^+ \rightarrow K^- \pi^+ \pi^+$. Daughter particles are identified using PID information from TPC and TOF to reduce background at low p_T . Different selection criteria are applied on the angle between the reconstructed momentum and the line joining the primary and the secondary vertex. D-meson candidates were then filtered by applying kinematical and topological cuts and the D^+ candidates decay vertex was calculated. This gives us the invariant mass spectra. This invariant mass spectra contains both the signal as well as background. To get the raw spectra, the invariant mass spectra is fitted with gaussian function for the signal and exponential function for the background. The raw spectra has been corrected for the detector efficiency and acceptance. For this, the Monte Carlo datasets (which is anchored to the pp collision data) are used. The raw spectra is then corrected to

get the corrected spectra in different intervals of event multiplicity and p_T . To get the self-normalized yield, the ratio of the corrected spectra in different multiplicity and p_T intervals is taken with respect to the corrected spectra in the Minimum Bias sample. After the calculation of self-normalized yields, the systematic errors from different sources are calculated. These include systematics from raw yield extraction, kinematical and topological variations, Monte Carlo p_T shape and feed-down subtraction. The systematics related to the raw yield extraction are calculated by multitrial approach. In this approach, we vary the different parameters like background fitting functions, lower and upper range of invariant mass spectra, fixing and non-fixing of sigma values. The ratio between the production of the mesons in a multiplicity and p_T interval class over the multiplicity integrated class is calculated. The assigned systematic was estimated considering the r.m.s of the distribution of the plotted ratios. For the systematics related topological and kinematical variations, five different sets of loose and five different sets of tight cuts with respect to the standard cuts are used. The ratio of the self-normalized yields for different varied sets are calculated with respect to the self-normalized values for the standard cuts. The r.m.s of these values are assigned as the systematics. For the MC p_T shape systematics, the efficiency is further calculated using p_T weights. The ratio of efficiency with and without p_T weights is the assigned systematic. To calculate the contribution from the beauty production, we used the N_b method in which the b quark mass and the factorization and renormalization scales in the FONLL calculations were varied. The envelope of these variations was taken and assigned directly as systematic. The final results of the D^+ -meson self-normalized yield including systematics is presented. In addition to that the results for the average D mesons (D^0 , D^+ , and D^{*+}) self-normalized yields are also calculated and these results are compared to theoretical models and other heavy flavour measurements.

Chapter 6: In this chapter the analysis strategy for the D^+ - meson self-normalized yield as a function of transverse sphericity is discussed. The data sample used for this analysis is the same Minimum Bias data that has been used for the analysis

in previous chapter. In this case, additional sets of cuts related the sphericity calculations are used. Here the strategy of D^+ meson reconstruction in pp collisions and the details of cut selection strategy, signal extraction, particle identification and data quality selections will be discussed. The spectra is plotted in different classes of multiplicity, transverse sphericity and p_T . The detailed discussion will be made on the self-normalized yield measurements and the description of systematic uncertainties affecting our results. The sources of systematics and their calculations are same as in the case of analysis of D^+ meson as a function of charged-particle multiplicity. The final results for the self-normalized yields including the systematics values are presented as a function of transverse sphericity in different intervals of tracklet multiplicity and p_T .

Chapter 7: In this chapter, the results presented in chapter 5 and 6 are summarized. The physics conclusion for the whole work done pertaining to the thesis will be given.

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1 Introduction: Physics at High Energy

Quarks and gluons, collectively referred to as partons, are the basic building blocks of nuclear matter. Strong force between quarks is mediated by gluons. Quarks and gluons are contained within hadrons as colourless objects because the strong interaction between quarks grows with their separation [1, 2]. There has never been evidence of free quarks or gluons. However, the fundamental theory governing strong interactions known as *Quantum Chromodynamics*(QCD) [3, 4, 5, 6] predicts that quarks and gluons can exist in a deconfined state known as *Quark Gluon Plasma* (QGP) [7, 8]. In the QGP state, quarks and gluons can move freely throughout a large space without being restricted by the size of hadrons. In the laboratory, relativistic heavy-ion collisions are employed to construct and investigate such a QGP state. At great distances, the attractive attraction between a quark-antiquark pair is essentially constant. Quark and antiquark's gluon binding potential is consequently proportional to their separation. Given that the energy required to split quarks increases linearly with their distance, the linear potential confines them to the hadron size at absolute zero [9]. The gluon binding potential between quarks must be taken into account when trying to detach a single quark from a hadron since it can become potent enough to produce the quark-antiquark pair and split the gluon field into two distinct regions. Each area will eventually become a hadron, which once more restricts quarks. An isolated, unbound quark cannot be produced by this technique. High nuclear concentrations, however, can lead to deconfinement. The hadrons are forced against one another when the density of nuclear matter is high enough. Because there are so many other quarks in their former hadron radius, the

quarks cannot recognise their former hadron partners (see Figure 1.1). The attractive forces on quarks become minimal when the separations between them and their new neighbours are tiny enough. As a result, the quarks can migrate across a large volume. Deconfinement is the term for such a shift in quark motion. Deconfinement can happen at high temperatures as well as being compressed into a high nuclear density. High temperatures can effectively shorten the distances between quarks and eliminate the hadron borders by producing new quark-antiquark couples. Due to its resemblance to the Debye screening effect in electric plasmas, the transition from confinement to deconfinement can also be viewed in this way. Each ion in a concentrated plasma is surrounded by other ions and electrons. The surrounding ion and electron cloud with vanishing net charge screens the effective Coulomb potential between an ion and its electron at a specific distance. With an increase in charge density, the effective potential falls. When the effective potential is low enough, the ion and electron's bound state dissolves. In QCD, the binding energy is proportional to r due to gluon self-interactions, whereas at very long distances, the Coulomb potential is proportional to $1/r$.

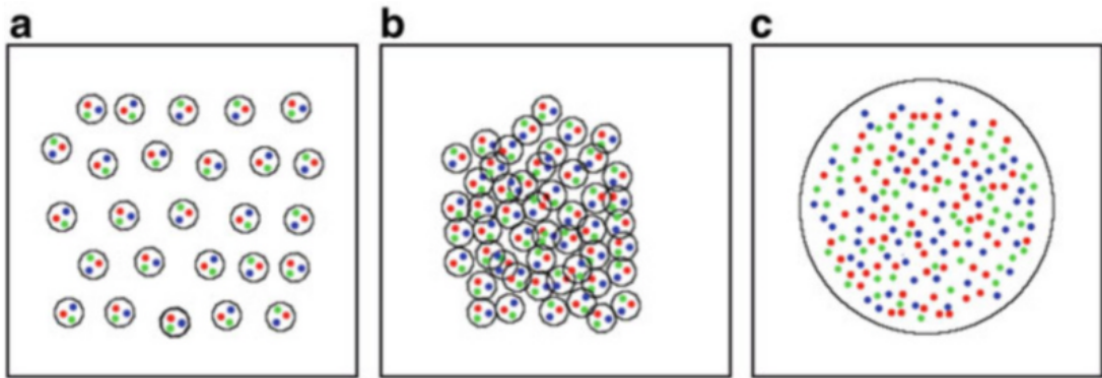


Figure 1.1: With increasing nuclear matter density, matter changes from nuclear to quark matter. When nuclear matter density is low as shown in (a), quarks are confined inside their hadrons. As nuclear matter density increases, the hadrons are compressed and become close to each other as shown in (b). Eventually when the density is high enough, the hadron boundaries disappears and quarks are deconfined as shown in (c).

1.1 The Standard Model of Particle Physics

Particle physics is central to our knowledge of natural laws. It is the area of research that examines the fundamental interactions that take place between these *particles* and *forces*, which is what matter is made up of at its core. At the present, four types of interactions are sufficient to explain all phenomena in physics. The gravitational force governs the interactions between massive bodies separated by large distances. However, the gravitational force between particles, where a typical mass is 10^{-27} kg, is so small that it does not appear to have a significant effect on elementary particle interactions. Thus, for particles the electromagnetic force dominates for distances down to 10^{-13} cm, where the nuclear forces begin to become important. The strong nuclear force is responsible for the binding of particles into nuclei, while the weak nuclear force is responsible for processes such as nuclear beta decay. The electromagnetic interactions between particles can be studied under the domain of the theory of quantum electrodynamics (QED). This is probably the most successful theory in all of physics and is capable of making extremely precise predictions.

Hundreds of new particles have been discovered in the study of high energy interactions. Many ways have been devised to group them into different categories. The type of interactions in which particles participate is one method to classify them. The leptons are particles that are not affected by the strong interaction. The electron, muon, and neutrino are examples of leptons. Leptons appear to be true elementary particles at the moment. They have no measured internal structure and are sometimes referred to as pointlike particles. Particles that are affected by the strong interaction are known as hadrons. There are two main classes of hadrons. The baryons are hadrons with a half-integral value for the spin quantum number. The mesons, on the other hand, are hadrons with integral values of the spin quantum number. The pions are examples of mesons. Unlike the leptons, the hadrons are believed to have an internal structure. In the currently favoured model of strong interaction (quantum chromodynamics, or QCD) hadrons are built up from pointlike spin $1/2$ objects known as quarks. Free quarks have never been seen in scattering

studies, and their charge is equivalent to one-third or two-thirds of the charge on an electron. A quark trying to escape a hadron's interior would result in the formation of additional quark-antiquark pairs under the QCD model. In order to create new hadrons, the quarks and antiquarks would then join once more. Quarks with high energy would create a jet, which is a narrow spray of hadrons. .

Another way to classify the particles is according to their spin value. The particles with a half-integer spin are called fermions while the particles with an integer spin are the bosons. Fermions are categorized as leptons (l) and quarks (q) depending on their colour charge properties. Quarks interact via the colour force through the strong interaction. There are six flavours of quarks and each flavour possesses a mass and a fractional electric charge. The up (u), charm (c) and top (t) quarks have a positive charge of $+2/3$ while the down (d), strange (s) and bottom (b) quarks have a negative charge of $-1/3$. The most massive quark is the top quark and the lightest one is the up quark. Besides, for each quark, it exists an antiquark ($\bar{q}$) with an opposite electric charge but the same mass. They are the antiup ($\bar{u}$), anticharm ($\bar{c}$), antitop ($\bar{t}$), antidown ($\bar{d}$), antistrange ($\bar{s}$) and antibottom ($\bar{b}$). On the other hand, the leptons do not interact with other particles through strong interactions since they do not carry any colour charge. Instead they interact via electroweak interaction. There are six flavours of leptons, three of them have an integer electric charge but the other three do not. The best-known lepton is the electron (e). The other two are the muon (μ) and tau (τ). The leptons without electrical charges are the three types of neutrinos (ν_e , ν_μ and ν_τ) and they have a small mass, according to the observation of neutrino flavour oscillations. Likewise, for each lepton, there is a corresponding antilepton with an opposite electrical charge but the same mass. They are the positron (e^+), the antimuon (μ^+)[10], the antitau (τ^+), the electron antineutrino (ν_{e^+}), the muon antineutrino (ν_{μ^+}), and the tau antineutrino (ν_{τ^+}). Bosons include the gauge bosons (photons, gluons, $W^\pm$ and Z bosons) and the scalar boson (Higgs boson). They are the force-carrier particles. Photons are the force carriers of the electromagnetic interaction. Particles with electrical charges interact

with other charged particles by exchanging photons. The quantum electrodynamics (QED) is the fundamental theory describing the electromagnetic forces based on the relativistic quantum field framework. The weak interaction, which causes hefty quarks and leptons to decay into lighter quarks and leptons, is carried out by the $W^\pm$ and Z bosons. $W^\pm$ and Z bosons have large masses but their interaction strength is very weak compared to the electromagnetic and strong interactions. For this reason, this interaction is named the weak interaction. The electromagnetic and weak interactions are unified into the electroweak interaction. Gluons are the mediators of the strong interaction. Particles carrying colour charges can interact via the strong interaction [11]. The strong interaction strength is around 100 times stronger than the electromagnetic interaction strength at short distance. The strong interaction between quarks and gluons and how they combine to form hadrons like the proton are both covered by the quantum chromodynamics (QCD) theory. $W^\pm$ and Z bosons, among other particles, receive their mass from the Higgs boson through the Higgs field.

According to the present theory, leptons, quarks, and mediators are the three types of basic particles that make up all matter. According to their charge (Q), electron number (L_e), muon number (L_μ), and tau number (L_τ), the six leptons are categorised. Naturally, they are divided into three families (or generations). Additionally, there exist six antileptons with all of the signs switched. For instance, the positron has an electron number of -1 and a charge of +1. In actuality, there are 12 leptons. Similar to this, there are six different quark "flavours" that are categorised based on charge, strangeness (S), charm (C), beauty (B), and truth (T). The quarks are divided into three generations as well.

Finally, each interaction has a mediator: the graviton (supposedly) for gravity, two $W^\pm$ s and a Z for the weak force, and a photon for the electromagnetic force. Yukawa proposed a theory for strong interaction in 1934, according to which the pion served as the strong force's mediator. However, with the discovery of heavy mesons, this straightforward model could no longer hold up because protons and neutrons could now exchange heavier mesons like the ρ -meson, ϕ -meson, and other heavy mesons.

talks about how coloured particles known as partons interact strongly (quarks and gluons together are called partons). Partons carry a colour charge (red, blue, green or their respective anticolours). QCD is based on the gauge invariance of these colour charged particles. The gluon self-interaction gives rise to a strong confinement force between partons. It is therefore that quarks always appear in bound states, called hadrons. It is not possible to measure an individual parton directly. On the other hand, hadrons can be measured in colliders like the LHC. Baryons, which are made up of three (anti)quarks, and mesons, which are made up of a quark and an anti-quark, are the two different forms of hadrons. At very vast distances, a potential that increases linearly with the distance between the partons can mimic the confinement force that holds these quarks together. Instead of a free quark existing, this increase ensures that a new quark-antiquark pair will be produced. The strong coupling constant controls the magnitude of the chromodynamic force as defined by the equation:

$$g = \sqrt{4\pi\alpha_s} \quad (1.1)$$

which may be thought of as the fundamental unit of color. Despite the name, this coupling is not constant. It reaches very large scales in interactions between partons of small momentum scales. In a first-order approximation, this momentum dependence is given by

$$\alpha_s \propto 1/\ln \frac{Q^2}{\Lambda_{QCD}^2} \quad (1.2)$$

Experimental measurements of the coupling constant are shown in Figure 1.3 [12]. Both in theoretical and experimental results one observes that as $Q \rightarrow \infty$ then $\alpha_s \rightarrow 0$. Due to the fact that the coupling constant of the strong interaction gets stronger when two or more partons are pulled away one has two effects: on one side when partons are very close to each other i.e. when the energy and the density of the system is very high they act freely and do not feel the presence of the others. On

the other side it is impossible to separate partons because once the distance starts to increase the colour force becomes stronger and the energy needed to separate the partons increases. This behaviour leads to the phenomena of the asymptotic freedom and of confinement. The former is the fact that at high energies or densities partons behave like free particles that suffer no interactions. The latter is the fact that single parton can never be observed but they are always confined into hadrons. If one can create a system where the energy or the density of the partons are extremely high then the confinement can not be maintained and a state of matter of strongly interacting deconfined partons is created: this medium is what we call *Quark-Gluon Plasma* (QGP). In the case of QGP the colour charge is screened by the quarks and gluons that are free to move over volumes much larger than the hadron size so that we effectively obtain a plasma of QCD matter strongly interacting. It is predicted that QGP can occur when the temperature of the system goes above the critical temperature $T_c \approx 170$ MeV or when the baryonic density is higher than $\rho_c \approx 0.72$ fm⁻³ (more than 5 times larger than nuclear density of 0.14fm⁻³). At present, such conditions are expected to exist in the core of neutron stars that are extremely dense stars or to be created surviving for a few instants in the heavy ion collisions at the big accelerator facilities on planet Earth. The cosmological models assume that the QGP was the state of all the matter in the universe in the very first moments. For this reason the study of QGP properties allows us to obtain a better understanding of the history of our universe and it can help in building a theory to link quantum mechanics and cosmological models. QGP was originally expected to be a perfect gas but the first measurements of QGP properties made at the Relativistic Heavy Ion Collider (RHIC) in 2005 . [13] showed that QGP is better described as almost a perfect liquid i.e. a strongly interacting fluid with extremely low viscosity.

1.3 QCD Phase Diagram

After the Big Bang, the universe is believed to exist, for a millionth of a second, in the QGP state. In this state the quarks and gluons exist freely, in the deconfined

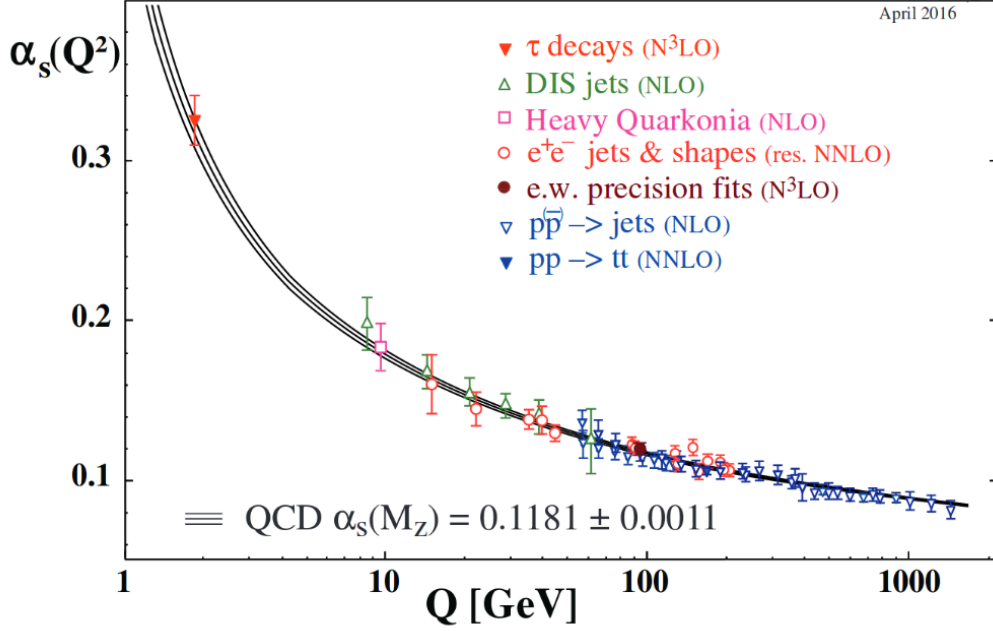


Figure 1.3: Theoretical predictions and experimental measurements of the strong running coupling constant α_s as a function of the momentum transfer Q .

state. After few microseconds, the system started to cool down and confined state of hadrons were formed. The different states of QCD are characterized in the (T, μ_B) space, where T is the temperature of the system and μ_B is the baryo-chemical potential which measures the baryon density of the system. Figure 1.4 represents the QCD phase space diagram.

As seen, there are two ways to create QGP. Either this can be done by increasing the temperature (similar to the conditions as there were during the Big Bang). In another way, we can create QGP by increasing the baryon density by compressing the nuclear matter. This situation occurs naturally in the core of neutron stars [14]. BM@N at NICA and CBM at FAIR are going to study this type of regime. In the former regime, a QGP is expected to have existed during the first 10^{-5} s after Big Bang. This region is being probed by heavy-ion collisions at the RHIC and LHC experiments (particularly by ALICE). The goal is to obtain a better knowledge of both QCD and the conditions in the early Universe in this way.

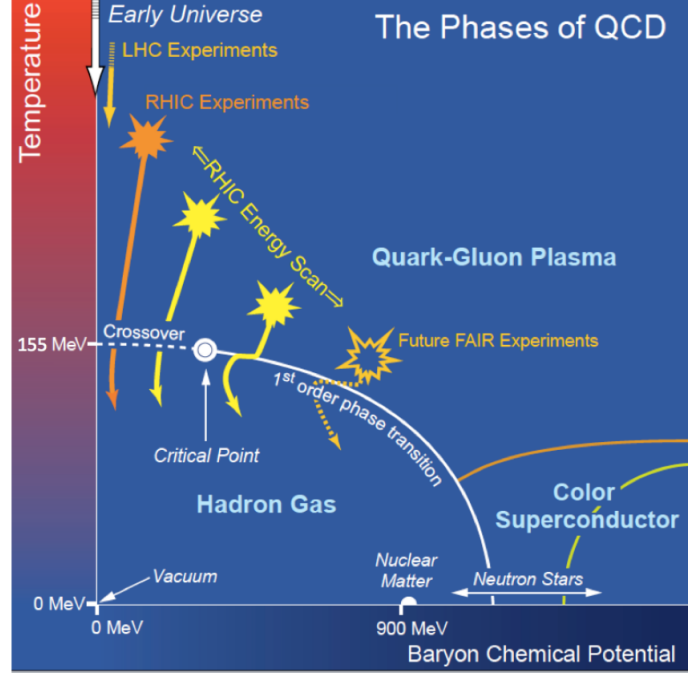


Figure 1.4: Current understanding of the QCD phase diagram as a function of temperature and baryon chemical potential (= net baryon density). Conditions for normal nuclear matter, neutron stars, and hypothesised conditions just after Big Bang are indicated in the figure, along with a few trajectories mapped by a selection of experiments.

There is an important basic difference between the high-temperature phase transition and the one at high baryon density. In the phase transition occurring at high temperature, there is a 2nd order phase transition or a smooth cross-over, meaning that there is a gradual transition from one phase to the other. While in case of high baryon density phase transition, there is expected to be a 1st order phase transition, i.e. a sharp transition. A critical point of second order separates those two regions. Theoretical calculation based on lattice QCD predicts the critical temperature to be about 160 MeV at zero μ_B when the phase transition takes place between the QGP and the hadronic matter[15]. At large values of μ_B but low values of T , the QCD phase of matter becomes a colour superconductor[16]. In the universe, neutron stars are expected to be the only known place in this QCD phase region where μ_B is likely high enough to produce quark matter and T is low enough for color superconductivity to occur.

1.4 Heavy-Ion Physics

Experimental study of QGP is a challenging task. To directly detect the deconfined partons is not possible, it is therefore necessary to use macroscopic thermodynamical quantities to study the QGP properties. For this the system must reach some kind of thermodynamical equilibrium so that those quantities to be properly defined. Also there must be an extended system so that the rescattering among the partons can maintain the equilibrium and it should have sufficiently large lifetime. The size of the system must be much larger than the mean free path of the parton in the medium so that it can undergo enough scatterings. When nuclei collide at relativistic speeds in large accelerator facilities like the *Relativistic Heavy Ion Collider* (RHIC) at Brookhaven and the *Large Hadron Collider* at CERN, all of these conditions are satisfied (LHC). The significant amount of energy involved is one of the most significant properties of high-energy nucleus-nucleus collisions. When a significant portion of this energy is concentrated in a small location for a brief period of time, the energy density can be rather high [17]. For instance, RHIC is built to accelerate atoms to an energy of approximately 100 GeV per nucleon. In such a collider, the energy carried by each nucleus in a collision between a gold nucleus and another gold nucleus is approximately 100×197 GeV, or 19.7 TeV, and the center-of-mass energy $\sqrt{s}$ is approximately 2×19.7 TeV, or 39.4 TeV. Nucleus-nucleus collisions release a tremendous amount of energy. Pb-Pb ions smash in the Large Hadron Collider (LHC) at an energy of $\sqrt{s_{NN}} = 2.76$ TeV per nucleon. As a result, the system developed at the LHC has a relatively high energy density when compared to RHIC. [18, 19].

Inelastic nuclear collisions are thought to have enormous cross sections and to be substantially inelastic, according to experimental findings. The inelastic nucleon-nucleon cross section predominates in the total nucleon-nucleon cross section, and the two colliding nucleons often lose a significant portion of their energy during collisions (roughly half). The energy lost by the nucleons is deposited close to the centre of mass, where it is then picked up by pions and other mesons and released. The most

frequent occurrence in low energy nuclear physics is an elastic collision, in which the projectile and target both retain their structural integrity and even their internal quantum states. One or both of the escaping particles may be in an excited state in low energy inelastic processes, and even some extra particles are produced. However, in the end, the multiplicity is just a little bit. The multiplicities are high, however, in relativistic heavy ion collisions.

Whether massive ions meet head-on or just barely brush one other, the outcome of the collision might be substantially different. Since neither the projectile nor the target can be seen before they collide, a classification of the events must be made based on the ultimate state. It is a widely held belief that a collision will be more violent and produce more departing particles the more central it is. It is difficult to measure this component of the collision, though. It is presumable that multiplicity increases as effective parameter decreases on average. As a result, the collisions with the largest multiplicity are those that are most central (and hence, the most fascinating). A core nucleus-nucleus collision involves several inelastic nucleon-nucleon collisions. In terms of the energy deposition around the centre of mass, the effect of the numerous inelastic nucleon-nucleon collisions in a nucleus-nucleus reaction is roughly additive in nature. The quantity of energy deposited close to the centre of mass increases as the number of inelastic nucleon-nucleon collisions increases. Furthermore, the two colliding nuclei first look as two narrow discs due to Lorentz contraction. The two nuclei collide nearly instantaneously and in close proximity. As a result, a significant quantity of energy is quickly deposited in a very tiny area of space as the colliding baryon matter moves away from one another following the collision. As a result, there is an extremely high energy density in this area. It is possible to achieve an energy density of the order of a few GeV/fm^3 . This energy density, which is an order of magnitude higher than the energy density of nuclear matter in equilibrium, may contribute in the creation of the QGP.

1.4.1 Relativistic Kinematic Variables

It is practical to use kinematic variables with straightforward properties under a shift in frame of reference in relativistic heavy-ion collisions and many other high-energy reaction processes. Natural units are used; $c = \hbar = 1$. A contravariant vector with components x^μ is used to represent the space-time coordinates of a point x .

$$x^\mu = (x^0, x^1, x^2, x^3) = (t, x, y, z) \quad (1.3)$$

The momentum vector p is similarly defined by a contravariant vector with components p^μ :

$$p^\mu = (p^0, p^1, p^2, p^3) = (E, p_x, p_y, p_z) \quad (1.4)$$

The space-time metric tensor $g_{\mu\nu}$ is given by the matrix

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \quad (1.5)$$

The covariant vector x_μ is related to the contravariant vector x^μ through the metric tensor $g_{\mu\nu}$ by

$$x_\mu \equiv g_{\mu\nu} x^\nu \quad (1.6)$$

Conversely, the contravariant vector x^μ is related to the corresponding covariant vector x_μ by

$$x^\mu \equiv g^{\mu\nu} x_\nu \quad (1.7)$$

the metric tensor $g^{\mu\nu}$ is given by

$$g^{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \quad (1.8)$$

The *scalar product* between two vectors in four dimensional space-time is defined as:

$$a.b \equiv a^\mu b_\mu = g_{\mu\nu} a^\mu b^\nu = a^0 b^0 - a^1 b^1 - a^2 b^2 - a^3 b^3 \equiv a^0 b^0 - \mathbf{a}.\mathbf{b} \quad (1.9)$$

(a) Light Cone Variables: A detected particle in high-energy reaction processes can be identified as coming from one of the colliding particles. For instance, in the reaction indicated by the equation. It is possible to think of refraction c as fragmenting from either the target particle a or the incident beam particle b.

$$a + b \longrightarrow c + X \quad (1.10)$$

Projectile fragmentation reactions are those in which the observed particle c is thought to have originated from the beam particle b. The term projectile fragmentation region refers to the area of the momentum of c where this particular sort of reaction predominates. In relation to the beam axis, it is located forward. On the other hand, a target fragmentation reaction is one where the observed particle c can be assumed to have come from the target particle a. The kinematic region where this type of response is most common is the target fragmentation zone, which is close to the momentum region where the target particle is initially at rest. In a reaction, the properties of kinematic values along the longitudinal axis of the incident beam, which we will refer to as the longitudinal axis, are very different from those along transverse directions perpendicular to the beam axis. The z-axis will be designated as the longitudinal axis. For the produced particle in the equation.1.10 particle with its four-momentum given as (c_0, c_x, c_y, c_z) the quantity

$$c_+ = c_0 + c_z \quad (1.11)$$

is called as forward light cone momentum of the particle while the quantity

$$c_- = c_0 - c_z \quad (1.12)$$

is called as backward light cone momentum of the particle. A forward-moving energetic particle has a large forward light-cone momentum (c_+) and a small backward light-cone momentum (c_-) as it moves along the beam direction. The forward light-cone momentum is negligible, while the backward light-cone momentum of a particle moving in the opposite direction of the beam is large.

If a daughter particle, c , breaks off from a parent particle, b , the ratio of c 's forward light-cone momentum to that of b is independent of the Lorentz frame. It is easy to introduce the forward light-cone variable x_+ of c relative to b , which is defined as the difference between the forward light-cone momentum of the parent particle b and that of the daughter particle c as given below:

$$x_+ = \frac{c_0 + c_z}{b_0 + b_z} \quad (1.13)$$

The variable x_+ for the forward light cone is always positive. The forward light-cone variable x_+ has an upper limit of 1, since a daughter particle cannot have a forward light-cone momentum greater than that of its parent particle. It does not depend on the Lorentz frame; it is a Lorentz-invariant quantity. Similarly, if one assumes that a target particle a 's daughter particle c 's fragmentation, it is convenient to introduce the backward light-cone variable x_- defined as

$$x_- = \frac{c_0 - c_z}{a_0 - a_z} \quad (1.14)$$

which is a Lorentz-invariant quantity, independent of the Lorentz frame of reference. It is a positive quantity and its upper limit is 1.

(b) Rapidity Variable: The speed variable y is an additional helpful variable that is frequently used to characterise the kinematic state of a particle. A particle's energy-momentum components p_0 and p_z are used to characterise its speed as follows:

$$y = \frac{1}{2} \ln \left(\frac{p_0 + p_z}{p_0 - p_z} \right) \quad (1.15)$$

It is an irrational number with no dimensions that measures the percentage of forward to backward light-cone momentum. It could be favourable or unfavourable. The speed of a particle moving in a longitudinal direction in the nonrelativistic limit is equal to the particle's velocity expressed in units of the speed of light. Although the speed variable is dependent on the frame of reference, the relationship is relatively straightforward. A constant additive relationship exists between the particle's speed in one Lorentz frame of reference and its speed in another. The transverse mass of the particle is defined as:

$$m_T^2 = m^2 + p_x^2 + p_y^2 = m^2 + p_T^2 \quad (1.16)$$

where $p_x^2 + p_y^2 = p_T^2$ is the square of the transverse momentum p_T of the particle. In terms of rapidity of the particle, the energy and longitudinal momentum of the particle is defined as

$$p_0 = m_T \cosh y \quad (1.17)$$

$$p_z = m_T \sinh y \quad (1.18)$$

The speed of the projectile particles and the rapidity of the target particles can be easily measured for a given incident energy. The distance between the projectile's speed and the target's rapidity increases with incident energy. The central rapidity region is the area of rapidity that lies roughly halfway between the projectile rapidity and the target rapidity. The majority of the generated particles' rapidities are located in this area.

(b) Pseudorapidity Variable: To determine a particle's speed, two properties of the particle must be measured, such as its energy and longitudinal momentum. In many experiments, the only variable that can be measured is the angle of the detected particle with respect to the beam axis. In that situation, it is practical to make use of this knowledge by describing the discovered particle using the pseudorapidity variable

eta. A particle c 's pseudorapidity variable is defined as:

$$\eta = -\ln [(\tan (\theta / 2))] \quad (1.19)$$

where θ is the angle between the particle momentum $\mathbf{p}$ and the beam axis. In terms of the momentum, the pseudorapidity variable can be written as

$$\eta = \frac{1}{2} \ln \left(\frac{|\mathbf{p}| + p_z}{|\mathbf{p}| - p_z} \right) \quad (1.20)$$

comparing equations 1.15 and 1.20 we can see that for large momentum values pseudorapidity variable coincides with the rapidity variable, that is, when $|\mathbf{p}| \approx p_0$. When the discovered particles are not identifiable and their masses are unknown, the pseudorapidity is typically a more helpful experimental metric. It is typically more convenient to use rapidity for phenomenological calculations because the desired particle's mass is known. Rapidity cannot be defined as in equation 1.15 if the detected particles are unidentifiable. Pseudorapidity is a natural variable to utilise because a typical detector or detector component often spans some well-defined θ region with respect to the beam axis.

1.4.2 Invariants

Position and momentum of a particle depend on the frame. However, a lot of the physical quantities measured in experiments, such cross sections and speeds, ought to be unaffected by the measurement frame. As a result, cross sections are typically expressed simply in terms of invariants. These four-momenta based invariants, which are used to explain particle interactions, can be seen in computations of scattering cross sections. Figure 1.5 displays a typical two-body scattering diagram. The squares of four-momenta sums or differences are the invariants. There are three invariants that characterize Figure 1.5,

$$S = (p_1 + p_2)^2 = (p_3 + p_4)^2 \quad (1.21)$$

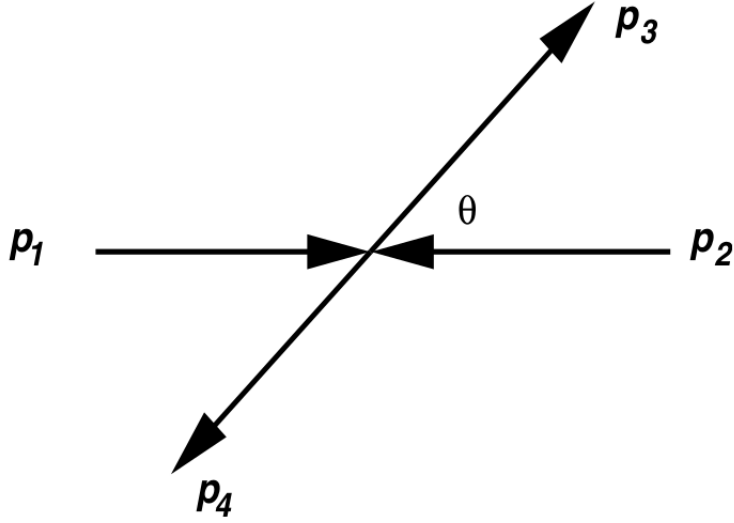


Figure 1.5: A typical $2 \rightarrow 2$ scattering diagram with particles 1 and 2 incoming while 3 and 4 are outgoing.

$$T = (p_1 - p_3)^2 = (p_2 - p_4)^2 \quad (1.22)$$

$$U = (p_1 - p_4)^2 = (p_2 - p_3)^2 \quad (1.23)$$

Mandelstam invariants are another name for these variables. While the other two combine the initial and final states, the first, S , only depends on either the initial or final state. As a result, the total energy present in a collision is typically defined as the square root of the first, or $\sqrt{S}$. T , also known as the momentum transfer between the initial and final states, involves both an initial and final state four-momentum. An additional invariant is the sum of Mandelstam invariants:

$$\begin{aligned} S + T + U &= (\mathbf{p}_1 + \mathbf{p}_2)^2 + (\mathbf{p}_2 - \mathbf{p}_4)^2 + (\mathbf{p}_2 - \mathbf{p}_3)^2 \\ &= 3m_1^2 + m_2^2 + m_3^2 + m_4^2 + 2\mathbf{p}_1(\mathbf{p}_2 - \mathbf{p}_3 - \mathbf{p}_4) \\ &= \Sigma_i m_i^2 \end{aligned} \quad (1.24)$$

1.4.3 Luminosity

The luminosity is an important parameter in collision experiments which defines the reaction rate. The reaction rate in a collider is given by

$$R = \sigma L \quad (1.25)$$

where,

$\sigma \equiv$ interaction cross-section

$L \equiv$ luminosity (in cm^{-2}, s^{-1})

$$L = f n \frac{N_1 N_2}{A} \quad (1.26)$$

where,

$f \equiv$ revolution frequency

$N_1, N_2 \equiv$ number of particles in each bunch

$n \equiv$ number of bunches in one beam in the storage ring

$A \equiv$ cross-sectional area of the beams

L is larger if the beams have small cross-sectional area.

1.4.4 Little Bangs: QGP in the lab

The energy domains of heavy ion physics involves a wide range of beam energies from 100 MeV/nucleon to 10 TeV/nucleon. These ranges involve very different collision processes and physical phenomena. The energy region can be divided into three basic regions from a physical standpoint:

- Intermediate energy heavy ion reactions,
- Relativistic energy heavy ion reactions,

- Ultra-relativistic heavy ion reactions.

1.4.4.1 Intermediate Energy Reactions

Around the usual nuclear density, n_0 , it is possible to study the properties of hot nuclear matter in this energy range. The matching beams have energies that vary from 10 to 100 MeV per nucleon. The nuclear liquid-gas phase transition is an intriguing event that occurs in this area of thermodynamic variable space. Due to the attractive nuclear interaction, the nuclear matter is constrained at low excitations. We may initially compress the nuclear matter and heat it to 10–20 MeV in an intermediate heavy ion collision energy. The substance then expands practically adiabatically to densities below n_0 and to a lower temperature, between 5 and 10 MeV. In this last state, the attractive interaction causes the nuclear vapour to condense into droplets of nuclear liquid, which results in the formation of smaller nuclear fragments. The nuclear multi-fragmentation is this. The effects of the phase transition, such as critical phenomena, can be explored if the collision energy is low enough. Among the accelerators engaged in this effort are the NSCL at Michigan State University, UNILAC and SIS at GSI in Darmstadt, Germany, GANIL in Caen, France, and CELSIUS in Uppsala, Sweden.

1.4.4.2 Relativistic Energy Heavy Ion Reactions

Nuclear matter is squeezed and heated more intensely in this energy range (100 MeV/nucleon to 10 GeV/nucleon) than it is at lower beam energies. Here, nuclear interactions as well as the nuclear EOS's compressibility and other key characteristics can be examined. The findings in this energy range have application to neutron stars and supernova explosions in astrophysics. Real quantitative questions about nuclear incompressibility, transport coefficients, medium cross sections, momentum dependence of the nucleon-nucleon interaction, etc., are explored in this field where research is most advanced. For instance, numerous experimental and conceptual

demonstrations of various collective flow patterns have been made. The reaction plane's collective sideways flow is by far the most important because it may be employed to both move nuclear matter and extract its EOS. This energy range is being studied by some of the accelerators described above, as well as others like SATURN in Saclay, France, the heavy ion accelerator in Dubna, and BEVALAC at LBL in Berkeley.

1.4.4.3 Ultra-Relativistic Heavy Ion Reactions

The most intriguing physics question in this energy zone, which begins at 10 A.GeV beam energy, is the search for quark-gluon plasma. Even at 10 A.GeV, QGP creation is possible according to the most optimistic theoretical predictions. The ultra-relativistic domain can be divided into two regimes with essentially different physics: *the stopping region*, where baryons from the projectile and the target are partially or fully stopped by each other, forming a fairly baryon-rich matter in the middle of the reaction zone, and *the transparent region*, where initial target and projectile baryons are so far apart in the phase space that the heavy ion collision cannot completely slow them down. The boundary between these two zones is not particularly clear and is not yet understood empirically.

(i) Stopping Region: Up to 60 A.GeV, reactions with S and Si projectiles nearly completely cease, as shown by the earliest findings of the SPS at CERN and the AGS at BNL. According to some theoretical estimates using lead beams, even 200 or 800 A.GeV collisions will cause the baryons to cease in the reaction zone and phase space [20]. These reactions thus offer a means of investigating extremely highly excited baryon rich matter, or even even baryon rich quark gluon plasma. Additionally, this region has astrophysical significance in relation to potential hybrid stars, or neutron stars with dense quark matter cores.

(ii) Transparent Region: The initial baryon charge from the bullet and target won't be completely slowed down if we increase the energy more, according

to theory.

The reaction's centre zone will be free of baryons, and the baryon-carrying quanta will mainly preserve their starting velocities. Of course, energy will also be deposited here. A baryon free quark gluon plasma, which is of great theoretical interest, may arise from the centre region's high energy density matter. Theoretically, this kind of high energy density and low baryon density matter is easier to calculate than baryon dense quark gluon plasma. It is also the form of matter that predated the production of hadrons in the early cosmos. It is possible to offer the Fermilab TEVATRON proton antiproton collider as a proton antiproton collider relevant to this topic, where some preliminary experience can be acquired prior to the accessibility of the heavy ion colliders.

1.4.5 Heavy-Ion Collisions

In general, there are two methods for forming QGP at high energy densities. One technique is to increase temperature in order to produce particle-antiparticle pairs without increasing net baryon number. The second option is to compress a system with lots of nucleons in order to boost baryon number density. QGP is principally produced by the first-increasing temperature in ultra-relativistic heavy-ion collisions. Two nuclei are driven almost to the speed of light (99.995 percent of the speed of light) in ultra-relativistic heavy-ion collisions, which causes them to be Lorentz contracted. The nuclei slow down as a result of numerous inelastic nucleon-nucleon collisions, depositing energy into the collision zone. QGP will emerge if the energy density reaches the threshold required for the phase transition ($\sim 1 \text{ GeV}=\text{fm}^3$ according to the QCD prediction). High energy nucleons (baryonic matter) continue to have significant forward/backward velocity after a collision, allowing them to fly far from the collision zone. As a result, there are not many baryons in the impact zone. The generated stuff, however, has a very high temperature.

A potential approach of creating high temperature or high density materials in the lab involves very high energy nucleus-nucleus collisions. They can be used to

investigate the quark-gluon plasma's potential existence. Nucleus-nucleus collisions may form matter at high temperatures and densities for a variety of causes, one of which being the occurrence of multiple collisions [21, 22]. A nucleon from one nucleus may collide with several nucleons from the other nucleus through repeated collisions, depositing a significant amount of energy in the collision zone. Experimental studies have provided a large portion of the evidence for the occurrence of numerous collisions. One nucleon from a projectile colliding directly with a target nucleus comes to mind as an illustration. The longitudinal inter-nucleon spacings between target nucleons in the nucleon-nucleon center-of-mass system are decreased by Lorentz contraction and can sometimes be as low as 1 fm in high-energy collisions. On the other hand, in the nucleon-nucleon center-of-mass system, particle creation only happens when the leading quark and antiquark are separated by a minimum of around 1 fm. As a result, when a projectile nucleon collides with a large number of target nucleons, particle production from the initial nucleon-nucleon collision does not end until the projectile collides with a new target nucleon. Experimental evidence suggests that once the projectile nucleon collides, the projectile-like particle that results from the initial collision appears to continue colliding with other nucleons in the target nucleus as it travels through the target nucleus.

The object (or objects) that emerge in the projectile nucleon direction have a net baryon number of unity in each collision due to the conservation of baryon number. The multiple collision process can be explained by the projectile nucleon colliding with the target nucleons numerous times, losing energy and momentum in the process, and then emerging from the other side of the target nucleus with significantly less energy and momentum. This object is sometimes referred to as the projectile or baryon-like object. Depending on how dense the target nucleus is, there will be a certain amount of collisions. As a result, the projectile nucleon will experience a higher loss of energy and momentum the wider the target nucleus's radius is. Therefore, a substantial quantity of energy is lost during the collision process of the nuclear materials. High-energy nucleus-nucleus collisions are a good instrument for producing regions of very high energy densities because the energy lost by colliding nuclear

matter is deposited in the neighbourhood of the centre of mass with the generation of hadrons. The energy density can be so high that these reactions might be utilized to explore the existence of the quark-gluon plasma. [17]. The loss of the incident nuclear matter kinetic energy is accompanied by the production of a large number of particles (mostly pions). As a result, in high-energy nucleus-nucleus central collisions, a significant portion of the longitudinal energy is converted into the energy of hadronic matter created around the colliding system's centre of mass. If a phase change and the formation of a quark-gluon plasma are possible, it will depend on how much halting has occurred.

The distance between the beam rapidity and the target rapidity for a collision in a centre of mass system at a few GeV per nucleon is roughly 3–4 units. The Lorentz contraction also brings the baryon matter closer together longitudinally before the collisions happen in this center-of-mass system where the baryons may be stopped. As a result, the matter produced may have a baryon density that is so high that the deconfined quark-gluon plasma phase rather than the hadron phase may be the ground state of the baryon matter with this baryon density. A quark-gluon plasma with a high baryon content might arise as a result of the high-energy heavy-ion collisions in the "stopping" area.

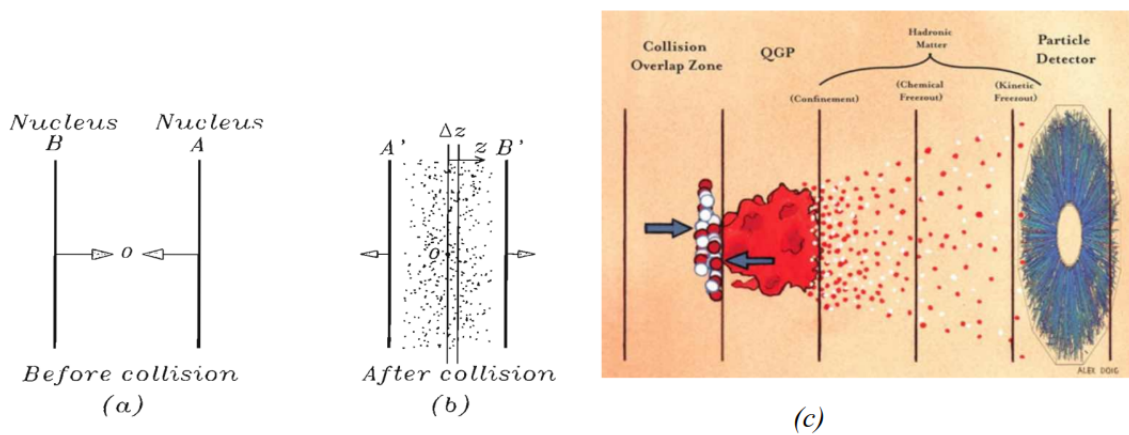


Figure 1.6: (a) The configuration of two colliding nuclei A and B before collision. (b) The configuration after collision with energy deposited in the region around $z \sim 0$ (c) Full evolution picture of heavy-ion collision

In the central high-energy nucleus-nucleus collisions (Figure 1.6) involving heavy nuclei, the baryon matter will be slowed and lose a few units of speed. After a central collision, the rapidities of the beam and target baryons will remain relatively remote from the central rapidity area if the separation between the beam and target rapidities is significantly more than a few units as a result of the collision. The net baryon content of the central rapidity region will thereafter be extremely low.

The difference between the projectile rapidity and the target rapidity in the centre of mass system for nucleus-nucleus collisions with an energy of 100 GeV per nucleon is 10.7 units. However, in a central collision of Au on Au, the baryons typically experience a velocity loss of 2 to 4 units. As a result, there may be a core rapidity area with a low baryon content if the gap between the starting beam and target rapidities is sufficiently wide. The "baryon-free quark-gluon plasma" or "pure quark-gluon plasma" area can be studied using reactions at these energy.

The plasma might not be in thermal equilibrium at first, but further equilibration could bring it to local equilibrium at the right time τ_0 , and the plasma might then proceed to evolve in accordance with the laws of hydrodynamics from that very point. The plasma's temperature decreases as it expands, delaying the plasma's hadronization until a later, more appropriate period. Hadrons will stream out of the collision zone when the temperature drops below the freeze-out temperature (Figure 1.7). The various stages of evolution involved during these processes are as follows:

- (a) After the collision of two heavy ions, the partons of the nuclei involved the experience of multiple scatterings in the high density nuclear matter, and as a consequence many new particles are produced.
- (b) The plasma initially may not be in thermal equilibrium, the produced particles and multiple scatterings cause a rapid increase of the entropy of the system. The system thermalizes and its temperature becomes high.
- (c) The system begins to grow in the meantime, but subsequent equilibration may allow it to reach local equilibrium at the right period τ_0 , after which the plasma may continue to evolve in accordance with the rules of hydrodynamics.

(d) In this stage, the system reaches a deconfined phase where the quarks and gluons are deconfined. The system is expanding and its temperature cools down.

(e) The system becomes a hot hadron gas when its temperature is less than the critical temperature T_c , at which the phase transition happens. In this stage, quarks and gluons are not de-confined anymore: they hadronize into hadrons.

(f) This hadron gas continues to expand with its temperature decreasing. The system is at the chemical freeze-out stage when the quantity of produced hadrons does not vary since no more inelastic scatterings occur. Then the system cools down further. Hadron momenta are fixed and the system enters the kinetic freeze-out stage when the density of the system is too low to allow for elastic scatterings between hadrons. At this point, the particles stream freely and are recorded in detectors. Charge, momentum, or energy of final state particles that have been reconstructed in detectors could constitute the experimental observables. Final state particles carry information on QGP and the different stages of evolution. The production of deconfined QGP and the research of its characteristics, including critical temperature and order of phase transition, equation of state, and transport parameters, are the primary goals of the high-energy heavy-ion collision programme.

1.4.6 Geometry of the Collision

As a nucleus consists of protons and neutrons, they are composite objects and have some finite extension in space; for a Pb nucleus the radius is about 6.6 fm. Not all nucleons will participate in the collision and contribute to QGP formation. Nucleons (or partons) that take part in the collision are called participants, whereas the non-participating nucleons are called spectators. The number of participants depend on the impact parameter b , which is a measure of the distance between the centres of the nuclei during collision. Figure 1.8 shows two nuclei approaching each other along the z axis. The impact parameter value is used to classify the collisions.

- $b \approx 0$, it refers to a head-on collision in which the nuclei's centres approach along

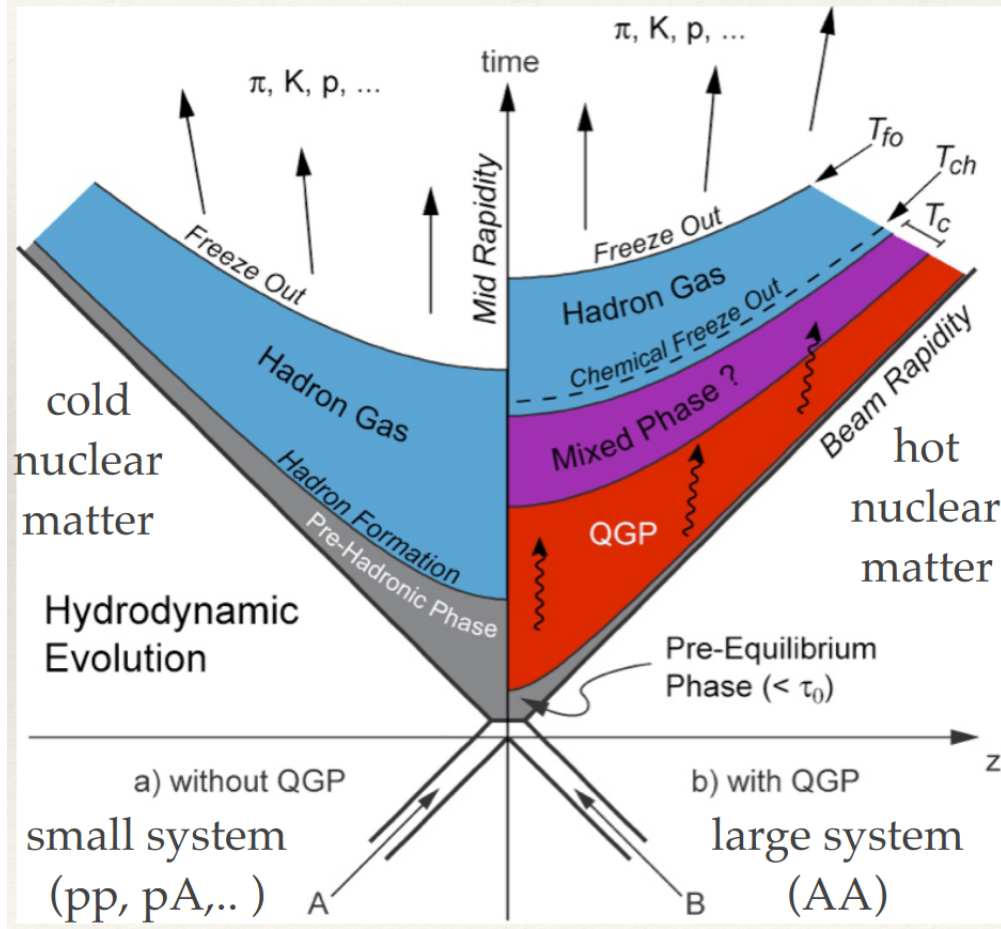


Figure 1.7: Evolution of a central heavy ion collision in a Minkowski-like plane. The two scenarios with and without QGP are pointed out. The critical temperature is indicated by T_c , while the freeze-out and chemical freeze-out temperatures, are pointed out with T_{fo} , and T_{ch} , respectively.

the same trajectory. This form of collision is known as a central collision.

- b is about equal to the sum of the two ion radii. During the interaction, the two nuclei are separated by a large distance. This form of collision is called as Peripheral collision.

In heavy-ion collisions, the Glauber model [23] is commonly used to characterise the collisions. This model considers that nucleus-nucleus collision is basically a superposition of independent nucleon-nucleon collisions. It provides several quantities such as the number of participating nucleons (N_{part}), the number of binary nucleon-nucleon collisions N_{coll} , and the number of spectators (N_{spec}). The spectators are

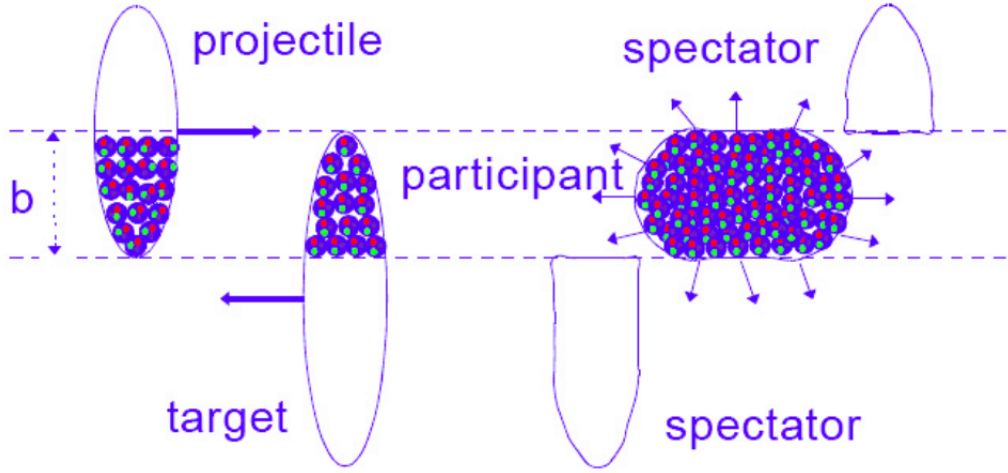


Figure 1.8: Definitions of impact parameter b , spectators, and participants in a nuclear collision.

the nucleons which do not participate in the collision. The Glauber model can be used to calculate these variables, and their values indicate the sort of collision.

1.4.7 Signatures of QGP

When matter is in the quark-gluon plasma phase, particles that result from interactions between the plasma's components can be used to learn more about the plasma's current state. A helpful plasma diagnostic tool will be the identification of the byproducts of their interactions. It is well acknowledged that there isn't a single distinct signal that can be used to pinpoint the quark-gluon plasma phase. So, in this section, we'll talk about the many signatures that have been utilised to look for quark-gluon plasma.

1.4.7.1 Dilepton Production in the QGP

In the quark-gluon plasma, a quark and an antiquark can combine to produce a virtual photon called γ^* , which then decays into the leptons l^- and l^+ . Figure 1.9 depicts the diagram that explains the reaction $q + \bar{q} \longrightarrow l^+ + l^-$. A dilepton is the

name for the system that contains the created lepton-antilepton pair. It is sometimes referred to as a lepton pair or a l^+l^- pair. A dilepton's properties include its invariant mass squared ($M^2 = (l^+ + l^-)$), four-momentum ($P = (l^+ + l^-)$), and transverse momentum ($P_T = (l_T^+ + l_T^-)$).

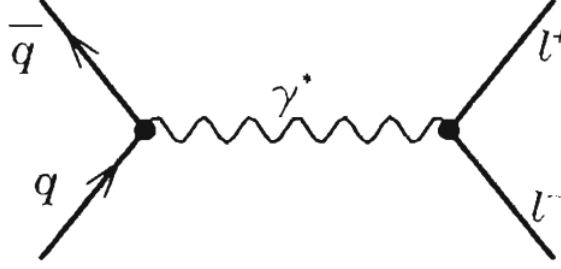


Figure 1.9: The diagram for the reaction $q + \bar{q} \longrightarrow l^+ + l^-$

In order to be seen, the lepton l^- and its antiparticle companion l^+ must travel across the collision area to reach the detectors. Since the leptons only interact with the particles in the collision region through electromagnetic interaction, the interaction between them and the leptons in the collision region is not strong enough. The fine structure constant $\alpha = 1/137$ and the lepton-(charge particle) center-of-mass energy $\sqrt{s}$ are used to calculate the lepton-(charge particle) cross section, which is of the order $(\alpha/\sqrt{s})^2$. As a result, it is anticipated that the mean-free route of the leptons will be quite large and that they won't experience any more collisions once they are created. The rate of production and the momentum distribution of the created $l^+ + l^-$ pairs, on the other hand, are influenced by the momentum distributions of quarks and antiquarks in the plasma, which are controlled by the plasma's thermodynamic properties. As a result, pairs $l^+ + l^-$ contain details about the thermodynamical state of the medium at the moment of production [24, 25, 26, 27].

Mathematically, it can be demonstrated that the dilepton distribution is generally dependent on the quark distribution $f(E)$ and its integral $F(E)$. The properties of the quark distribution in the quark-gluon plasma can be ascertained if we can

extract the dilepton distribution from the quark-gluon plasma through experimental observations. The dilepton invariant mass distribution actually varies roughly in line with the original quark distribution. It is possible to figure out the plasma's starting state temperature if the dilepton spectrum from the quark-gluon plasma can be recovered.

1.4.7.2 J/Ψ Suppression

Quarks and gluons are released from their confinement in a quark-gluon plasma, and the string tension between c and $\bar{c}$ disappears. The colour charge of a quark is veiled by the quarks, antiquarks, and gluons in the plasma. In reference to the well-known Debye screening of an electric charge in QED, this phenomena is referred to as the Debye screening. The presence of quark matter causes the densities of quarks, antiquarks, and gluons to be rearranged around charm quarks c and $\overline{c}$ when a J/Ψ particle, which is the bound state of these particles, is introduced into the plasma. The colour charge of c from $\bar{c}$ is screened as a result of the rearrangement, and vice versa. The long-range Coulomb-type colour interaction between c and $\bar{c}$ is changed by the Debye screening into a short-range Yukawa-type interaction, whose range is determined by the Debye screening length λ_D . At this distance λ_D , the attractive interaction between the elements c and $\bar{c}$ is successful, but it is not very successful beyond this range since the size of the interaction shrinks exponentially with distance.

The temperature has an inverse relationship with the Debye screening length, λ_D . High temperatures cause the attractive interaction's range to contract to the point where the pair $c\bar{c}$ cannot form a bound state. When this occurs, the $c\bar{c}$ system splits apart in the plasma into a distinct c quark and a $\bar{c}$ antiquark. Later, the c quark and $\bar{c}$ antiquark hadronize by mixing with light quarks or light antiquarks to form "open charm" mesons like $D(c\bar{u}, \text{ and } c\bar{d})$, $\bar{D}(\bar{c}u, \text{ and } \bar{c}d)$, $D_s(c\bar{c})$.

In the first stages of nucleus-nucleus collisions, J/Ψ particles are created, for instance, by hard-scattering processes (Figure 1.10). The effect of the plasma will

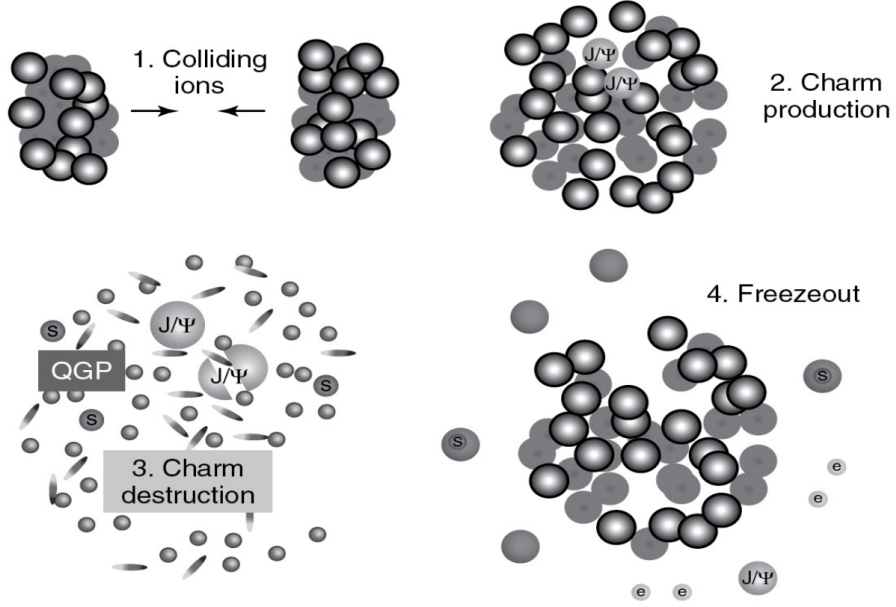


Figure 1.10: Formation and evolution of J/Ψ particles in relativistic heavy ion collisions. After the formation, the J/Ψ s are dissociated in the plasma due to color screening. The end effect is a smaller number J/Ψ s of than expected from pure hadron-hadron multiple collisions.

be to make the J/Ψ particle unbound, and the final yield of J/Ψ particles will be suppressed as compared to the scenario where there is no quark-gluon plasma [28]. This will happen if a quark-gluon plasma forms in the region of J/Ψ production. In order to identify the presence of the quark-gluon plasma, the generation of J/Ψ may be suppressed.

1.4.7.3 Photon Production in the QGP

In the quark-gluon plasma, a quark and an antiquark interact with each other to produce a photon and a gluon,

$$q + \bar{q} \longrightarrow \gamma + g \quad (1.27)$$

This process is called the annihilation process represented by the Feynman diagrams displayed in Figure 1.11. The analogous electromagnetic process $q\bar{q} \longrightarrow \gamma\gamma$

is allowed but the probability for its occurrence is smaller than the probability for $q\bar{q} \rightarrow g\gamma$ by a factor of the order of (α_e/α_s) , or about 0.02. So the only processes of interest to study the photon production by $q\bar{q}$ annihilation is $q\bar{q} \rightarrow g\gamma$.

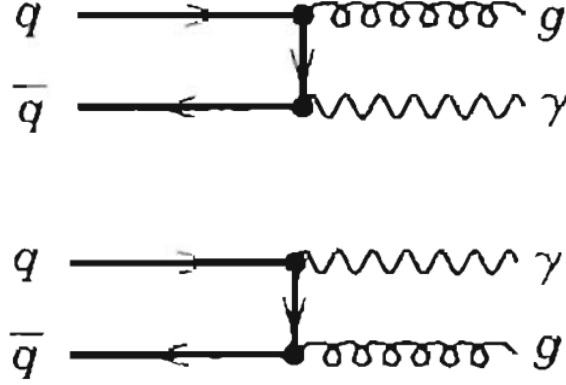


Figure 1.11: Annihilation processes

A gluon can interact with a quark to produce a photon by the reaction

$$g + q \rightarrow \gamma + q \quad (1.28)$$

or with an antiquark to produce a photon by the reaction

$$g + \bar{q} \rightarrow \gamma + \bar{q} \quad (1.29)$$

These reactions are represented by the Feynman diagrams as displayed in Figure 1.12. They are analogous to the scattering of a photon off a charged particle, which is called the Compton scattering. The incident gluon in eq.1.28 and eq.1.29 plays the role analogous to the incident photon in the Compton scattering of the photon. Hence, the processes eq.1.28 and eq.1.29 are called Compton processes.

The Feynman diagrams shown in Figure 1.12 serve as a representation of these reactions. They are comparable to the Compton scattering, which occurs when a photon collides with a charged particle. In the Compton scattering of the photon,

the incident gluon in equation 1.28 and 1.282 performs a similar function to the incident photon. The processes equation 1.28 and equation 1.29 are referred to as Compton processes as a result.

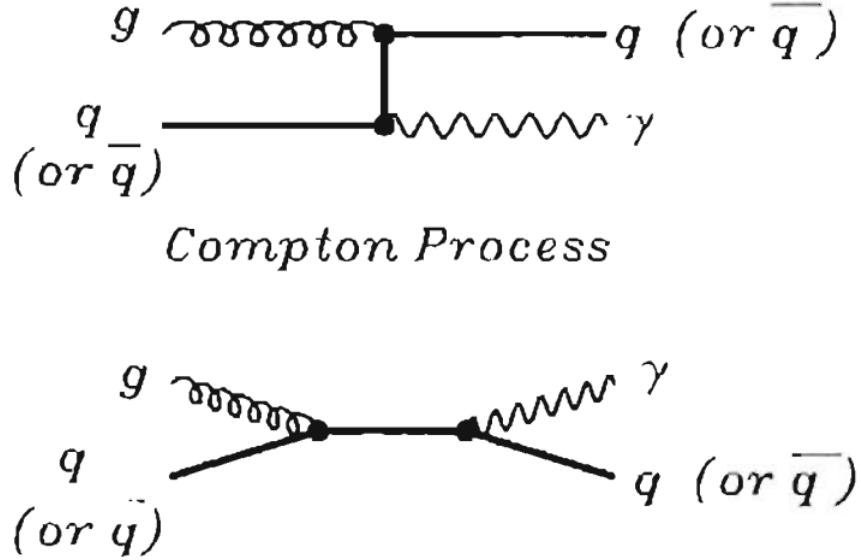


Figure 1.12: Compton processes

A photon must leave the collision region after it is created in order to be detected. The photon's only method of communication with the collision region's particles is electromagnetic, hence the interaction is weak. As a result, it is anticipated that the photon's mean-free journey will be quite long and that it may not collide after being created. On the other hand, the pace of photon production and the distribution of photon momentum are governed by the momentum distributions of quarks, antiquarks, and gluons in the plasma, which are governed by the thermodynamical state of the plasma. As a result, photons created in a quark-gluon plasma contain information about the medium's thermodynamical state at the time of generation [29, 30, 31, 32].

1.4.7.4 Strangeness Enhancement

The amplification of strange hadrons has long been predicted as a marker of QGP production. In hadronic reactions, the generation of strange hadrons is suppressed in comparison to nonstrange hadrons. The suppression grows along with the hadron's strangeness content. The *soverlines* pair synthesis in gluon-gluon collisions quickly saturates the strange quark concentration in a QGP, increasing the generation of strange hadrons. As a result, it is projected that when a QGP forms, multi-strange baryons and strange antibaryons will be greatly amplified.

The transition towards a deconfined state is associated to a partial restoration of the chiral symmetry. Due to this fact, the mass of the strange quark is expected to decrease from its constituent value to the current value of $\approx 150 \text{ MeV}/c^2$. Therefore an abundant production of strange quark-antiquark pairs in gluon-fusion processes ($gg \rightarrow s\bar{s}$) is expected also because of the large gluon density of the system. As a consequence of the large strange content of the fireball, an enhancement of the yields of particles containing strange quarks and antiquarks is expected. The magnitude of the strangeness enhancement is usually estimated in experiments by measuring the enhancement factor E , defined as the ratio of the yields of a given particle per participant nucleons in nucleus-nucleus collisions over the same ratio measured in smaller systems (pp, pBe or pA). The enhancement factor is also predicted to depend on the strangeness content of the particles. The first evidence of strangeness enhancement was measured by the NA57 and WA97 collaborations in fixed-target Pb-Pb collisions at $\sqrt{S_{NN}} = 17.2 \text{ GeV}$ [33, 34]. In Figure 1.13 the enhancement factor measured by NA57 for Λ, Ξ^- (left) and their anti-particles (right) are shown for p-Pb, p-Be and Pb-Pb collisions. At the LHC, ALICE measured the strangeness enhancement factor for Λ, Ξ and Ω in Pb-Pb collisions at $\sqrt{S_{NN}}=2.76 \text{ TeV}$ in four centrality bins [35]. The expected hierarchy is observed in nucleus-nucleus collisions as well as a strong increase of enhancement for central with respect to peripheral collisions. In p-Be and p-Pb collisions, there is no evidence of strangeness enhancement.

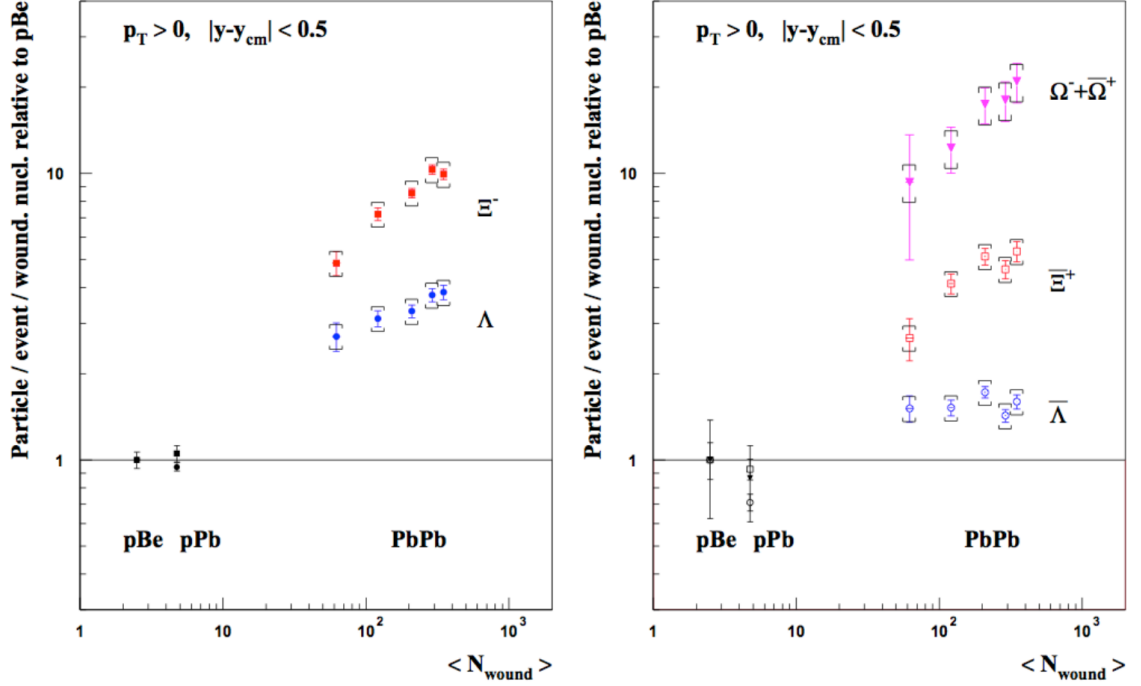


Figure 1.13: Strangeness enhancement factor measured at the SPS by the NA57 experiment for Λ , Ξ^- (left) and their anti-particles (right) for p-Be, p-Pb and Pb-Pb collisions as a function of the number of participants.

1.4.7.5 Jet Quenching

A jet can be defined as a collimated spray of hadrons, which originate from the fragmentation of a high- p_T parton. Due to the development of the QGP in heavy-ion collisions, extremely energetic partons interact with the deconfined medium's hot and dense coloured charge plasma and lose energy primarily through radiative mechanisms (it begins to disintegrate). As a consequence, the energy spectrum of the reconstructed jets is expected to be modified, resulting in a suppression of the jet yield in the large transverse momentum region. This is known as *jet quenching*. Apart from providing a direct indication for a new phase of matter, this quick quenching of hard particles is the mechanism of parton thermalization. It should be pointed out that this phase happens well before hadronisation, so it is the parton(s) and the colour field itself, which later gives rise to a jet, that are dissolving. Jets originate from hard (i.e. high-energy) processes where scattering occurs between two quarks

or gluons with large momenta, which results in the build-up of a colour string. Along this string, energy will be radiated in the form of gluons, resulting in formation of a collimated hadron shower. If the string is passing through a strongly-interacting medium, however, it will absorb these gluons and hence the jet loses energy i.e. it gets quenched. Therefore, jets going back-to-back, which would have been of similar energy in a pp collisions, have a strong momentum imbalance, as shown in Figure 1.14

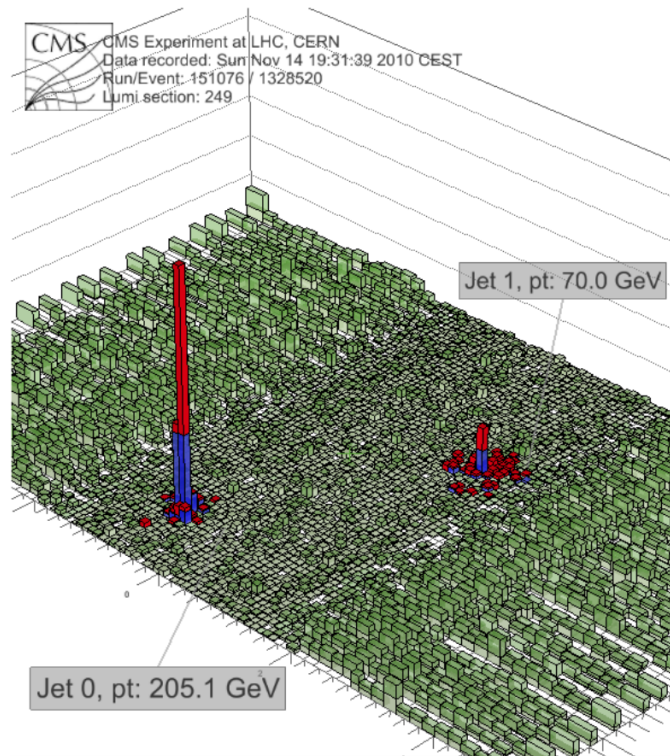


Figure 1.14: CMS event display of a Pb-Pb dijet event with a collision energy of $\sqrt{s_{NN}} = 2.76$ TeV, draw as a Lego plot with collected energy on the z axis, pseudorapidity going from top left to bottom right, and azimuthal angle in the other direction. Due to jet quenching, there is a large momentum imbalance between the jets.

If really there is a QGP medium we expect high p_T hadrons to be produced near the fireball border, because partons produced in the centre of the fireball will lose too much energy before escaping the fireball, as shown in Figure 1.15. This means that in pp collisions jets are produced back to back, whereas in heavy ions collisions

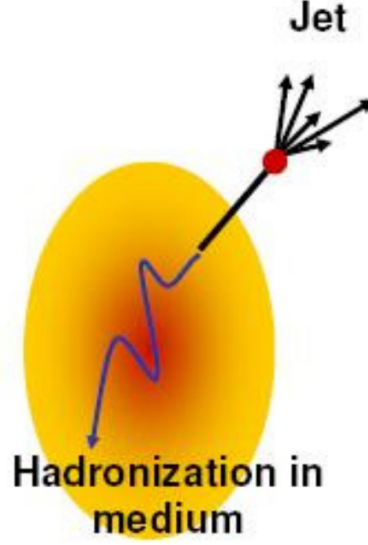


Figure 1.15: Jet creation in the medium.

we expect the away side jet to be likely absorbed in the medium. Due to the partons energy loss in the medium we expect the p_T distribution of produced particles to be softer when there is a medium and being harder when no medium is created, like in p-p collisions. This effect can be quantified using the nuclear modification factor R_{AA} , defined by the ratio between the particle transverse momentum distribution in nucleus-nucleus and proton-proton collisions divided by the average number of binary collisions in a nucleus-nucleus collision N_{coll} (in a given centrality class). The nuclear modification factor R_{AA} is defined as

$$R_{AA} = \frac{d^2 N_{AA}/dp_T d\eta}{N_{coll} d^2 N_{pp}/dp_T d\eta} \quad (1.30)$$

where N_{AA} and N_{pp} are the number of produced particles of interest measured in A-A and pp collisions, respectively, and η is the pseudorapidity. This is a measure of how much the spectra are changed in a heavy-ion collision compared to the pp reference, i.e. it measures the impact of the QGP medium. From this definition, if a nucleus-nucleus is only the superposition of proton-proton collisions, then $R_{AA} = 1$. The number of particles produced in a nucleus-nucleus collision is expected to

be proportional to the number of participants at low p_T (according to the wounded nucleon model) and to the number of nucleon-nucleon collisions at high p_T . If no QGP is created we would expect the value of R_{AA} to have a value close to 1. In this case the A-A collision is assumed to be a superposition of binary nucleon-nucleon collision. While Eq.1.30 could be modified to quantify the impact of many different parameters, measuring the spectra is useful since most of the energy from the fragmenting parton goes into the leading hadron (i.e. the one with the highest p_T). The reverse also holds, i.e. most high- p_T hadrons come from the leading jet, so jet quenching will manifest itself as a drop in the high- p_T part of the inclusive hadron spectrum. The first measurement of the nuclear modification factor of fully reconstructed inclusive jets was performed by the STAR collaboration in central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV [36]. The R_{AA} is expected to be consistent with the unity in case the medium-induced energy loss of the parton is radiated inside the jet cone, with possible small deviations due to initial state effects. Values of R_{AA} smaller than one indicate that a fraction of the radiation was emitted outside the jet cone. In Figure 1.16, the R_{AA} measured by STAR with two values of the jet radius ($R=0.2$ and $R=0.4$) is displayed. The measured R_{AA}^{jet} with $R=0.4$ is significantly larger than single hadron R_{AA} for $p_t > 20$ GeV/ c and a stronger suppression is clearly observed for $R=0.2$. The STAR results seem to indicate of a strong jet quenching in the medium which eventually leads to a substantial broadening of the jet shapes. At the LHC, a significant jet suppression was also observed. A measurement of R_{AA} for inclusive charged hadrons, as well as separated into pions, kaons, and protons, in Pb-Pb collisions is shown in Figure 1.17. The jet quenching impact is strongest in central collisions and fades as one moves to more peripheral collisions, as one would predict as the QGP size shrinks.

1.5 Organisation of thesis

It is possible to examine QGP features and the parton in-medium energy loss's dependency on colour charge and mass by measuring the generation of heavy quarks.

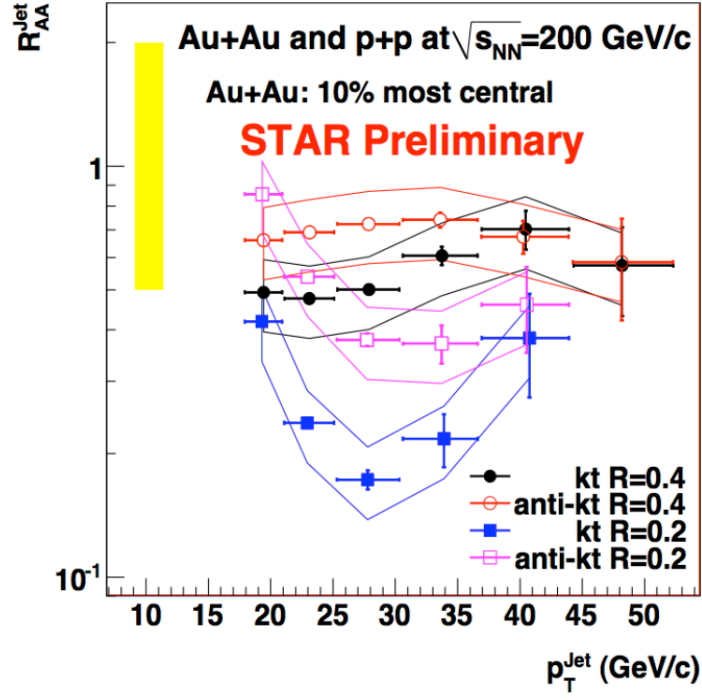


Figure 1.16: Nuclear modification factor of fully reconstructed jets measured with the STAR collaboration in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

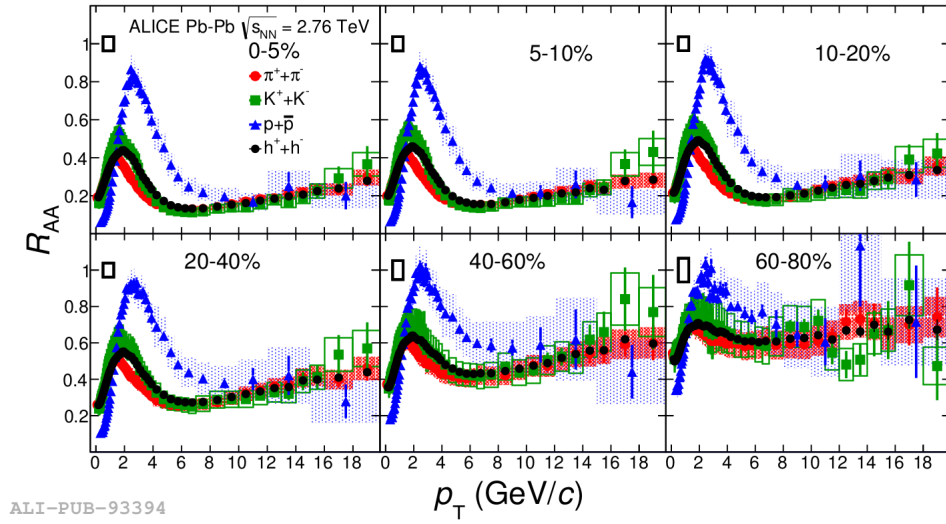


Figure 1.17: Nuclear modification factor of inclusive charged hadrons as well as pions, kaons, and protons, measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for different centrality classes.

Additionally, because of their enormous masses, their pp production cross sections may be calculated using perturbative QCD, making them a great way to validate pQCD calculations. .

In Chapter 1 a brief discussion about the standard model is given. Along with that, Quantum Chromodynamics (QCD) is briefly overviewed which is followed by the discussion on heavy-ion collision and different experimental parameters related to it. Further, Quark Gluon plasma and its various signatures are briefly covered.

Chapter 2 describes the ALICE experiment along with different sub-detectors.

In Chapter 3, the ALICE framework will be discussed. This includes the procedure involved in data taking, its storage and its distribution. Also a brief discussion about the software used to perform the analysis on the ALICE data will be given.

Chapter 4 discusses the role played by the heavy flavour measurements in understanding the QGP and its evolution in heavy-ion collisions. In addition, some details about the earlier results regarding the heavy flavour measurements done with different detectors and at different energies will be given.

The analysis conducted for the self-normalized yield of the D^+ -meson as a function of charged-particle multiplicity will be discussed in detail in chapter 5. This description includes a number of phases, beginning with the rawyield extraction in various multiplicity and p_T intervals, its efficiency correction, and acceptance to the many sources of systematics in the analysis.

Chapter 6 discusses about the analysis of D^+ -meson performed for the self-normalized yield as a function of tranverse sphericity. This analysis plays a crucial role in differentiating the hard and soft events.

In chapter 6, summary and conclusion of the present analysis will be given.

2 ALICE Experimental Setup

One of the four primary experiments at the CERN LHC, ALICE (A Large Ion Collider Experiment) is a heavy-ion detector with a general-purpose focus on QCD, the strong-interaction region of the Standard Model. In nucleus-nucleus collisions at extremely high energy densities and temperatures, it aims to study the physics of strongly interacting matter and the quark-gluon plasma. Up to the greatest multiplicities anticipated for the LHC, it will allow for a thorough investigation of the hadrons, electrons, muons, and photons produced in heavy nuclei (Pb-Pb) collisions. The physics programme also incorporates collisions with lighter ions and at lower energies, as well as specialised proton-nucleus runs, in order to modify energy density and interaction volume. Data gathered from proton-proton runs at the highest LHC energy will be utilised to provide reference data for the heavy-ion programme and will address a variety of specialised strong-interaction issues for which ALICE will be helpful in conjunction with the other LHC detectors. In this chapter, a detector named ALICE will be briefly introduced.

2.1 LHC Collider: An Overview

The LHC is the largest and most powerful collider ever built so far [37]. It was built beneath the France-Switzerland border near Geneva from 1998 and accomplished in 2008 and consists of a 26.7 km long circular tunnel ~ 100 m underground. The main beams can be of two types: protons and ions (Pb, Xe). It can 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. The first run took place in 2010 at an energy of 3.5 TeV per proton beam. The LHC had a long shut-down in 2013 for an upgrade lasting two years. The LHC started to run again in 2015 up to 2018. This second period defines the Run 2 period. The second upgrade is currently ongoing. In 2015, the energy per proton beam was increased to 6.5 TeV, which is the highest proton beam energy until now.

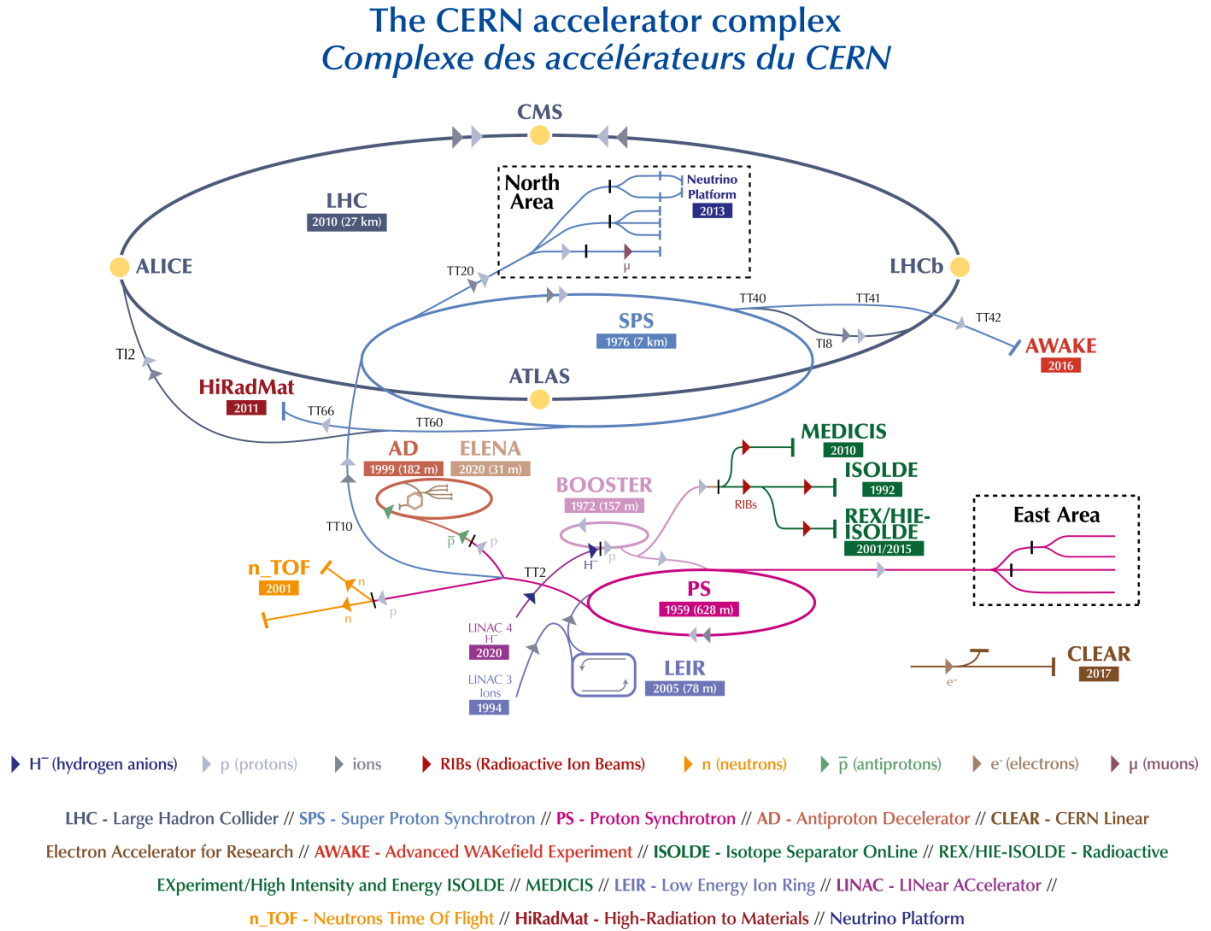


Figure 2.1: The CERN accelerator complex.

A schematic view of the LHC can be seen in Figure 2.1. Each accelerator, shown in Figure 2.1, boosts the energy of a beam to reach the required energy and then injects the beam into the next machine. The hydrogen gas is fed into a machine called a duoplasmatron to produce proton beam [38]. This machine removes the electrons from hydrogen gas, resulting in a plasma of protons, electrons, and ions.

The plasma expands towards the extraction electrodes, forming a proton beam that is pumped into a LINear ACcelerator (LINAC2) [39], where it reaches a 50 MeV energy. It is then transferred to the Proton Synchrotron Booster (PSB) [40], which accelerates the proton beam to the energy of 1.4 GeV. Then the Proton Synchrotron (PS) [41] and the Super Proton Synchrotron (SPS) [42] consequently accelerate the beam to 450 GeV. The proton beam is then delivered from the SPS to the LHC's two beam pipes, where it is accelerated to an energy of 6.5 TeV. In one pipe, one beam travels clockwise while the other travels counterclockwise. The two beams are brought to collide inside four interaction points where lie the four experiments: ALICE, ATLAS, CMS and LHCb.

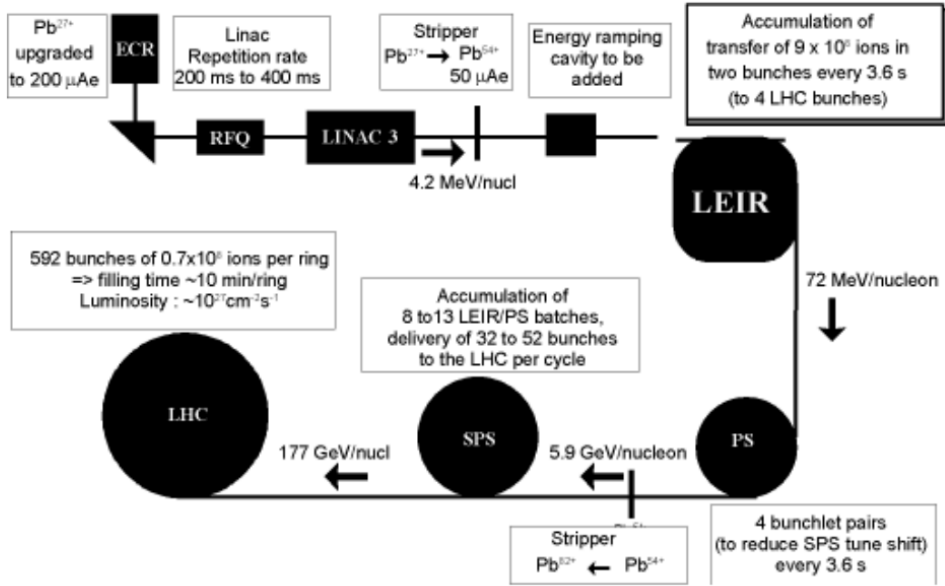


Figure 2.2: Overview of the various accelerating lines at the LHC. The various step to accelerate Pb ion at 2.76 TeV are also indicated.

The process of ion acceleration (summarized in Figure 2.2) starts from the source of the 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 radiofrequency quadrupole that allows an increase in the momentum up to 250 KeV/c. The Pb beam is delivered into LINear ACcelerator 3 (LINAC 3) [43]. The Pb beam strips off its electrons through Linac 3. When all of the electrons have been removed from the Pb beams, they have become bare nuclei, Linac 3 injects the Pb beams to the Low Energy Ion Ring (LEIR) to accelerate it up to an energy of the Pb beam per nucleon of 72 MeV. Then the Pb beam travels the same route of accelerators as the proton beam until the two beam pipes of the LHC. Finally, the energy of the Pb beam per nucleon is 2.76 TeV at the LHC.

2.2 The ALICE detector

ALICE (A Large Ion Collider Experiment) [44] is the only LHC experiment which is dedicated to study heavy-ion physics. It was designed to study the QGP in heavy-ion collisions. It was first proposed in 1993 with the central detector and then the supplementary forward muon spectrometer was designed in 1997. ALICE recorded the first Pb-Pb collisions in 2010. Nowadays, along with the physics of heavy-ion collisions the subjects of pp and p-Pb collisions are also studied in ALICE with a collaboration consisting of 2000 Physicists, Engineers from over 174 Physics Institutes in 39 countries. The ALICE detector was designed for a predicted multiplicity of charged particles produced in a central Pb-Pb collisions of $dN_{ch}/dy \sim 8000$ at mid-rapidity. The granularity of the detectors and their distances from the beam pipe were optimized in such a way so that it can cope with very high multiplicities. This turned out to be an over estimation, since the pseudorapidity density measured in central Pb-Pb collisions at $\sqrt{s_{NN}}= 2.76$ TeV is $1584 \pm 4(\text{stat}) \pm 76(\text{sys})$ [45]. ALICE was designed to investigate the majority of the experimental observables which are relevant for the characterization of the QGP. 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. Ideally, one wants to identify every single

particle in the detector acceptance and measure its position and momentum, and in this way characterise the QGP. This is not possible yet, but nevertheless ALICE has the best particle identification (PID) capabilities for charged hadrons of the LHC experiments, and particularly at low p_T where the bulk of the particles are produced, which is particularly relevant when studying the QGP. The heavy-ion data is collected during a few weeks at the end of each operational year. During the rest of the year, data from pp collisions is collected. Besides that proton collisions are now also an important part of the ALICE physics programme. Here, the collision multiplicities are much lower than for a Pb-Pb collision.

An overview of the ALICE detector is given in Figure 2.3. Its total dimensions are $16 \times 16 \times 26 \text{ m}^3$. It is made up of a muon arm with a built-in dipole magnet and a centre barrel that is submerged in a massive solenoidal magnet. The pseudorapidity interval $|\eta| < 0.9$ along the entire azimuth is covered by the central detector system's acceptance. The Inner Tracking System (ITS), which is made up of six layers of silicon detectors, the Time Projection Chamber (TPC), which serves as the primary tracking detector, the Transition Radiation Detector (TRD), which identifies electrons, and the Time-of-Flight (TOF), which identifies charged particles are all included in the central barrel. The High-Momentum Particle Identification Detector (HMPID), which comprises of an array of Cherenkov detectors designed to identify high-momentum particles and two electromagnetic calorimeters, the Photon Spectrometer, and another detector with a smaller acceptance are also situated at mid speed (PHOS) and the Electromagnetic Calorimeters (EMCaL and DCal). While the EMCaL and DCal are intended to improve ALICE's capabilities in jet research in addition to measuring neutral mesons and electrons from heavy-flavour decays, the PHOS is focused to the measurement of photons and neutral mesons. The pseudo-rapidity range $-4 < \eta < -2.4$ is where the Forward Muon Spectrometer (FMS), which is made to detect muons, is located. An absorber, Muon Tracker, Muon Wall, a trigger mechanism, and a dipole magnet ($B = 0.67 \text{ T}$) are all included in this component. The Forward Multiplicity Detector (FMD), a silicon strip detector designed to measure particle multiplicity, and the Photon-Multiplicity Detector

(PMD) are likewise located in the same rapidity zone. In order to quantify the event centrality in Pb-Pb and p-Pb collisions, two sets of neutron and proton calorimeters, known as Zero Degree Calorimeters (ZDCs), are placed around 116 m apart from the interaction centre at virtually zero degrees. On either side of the contact point are two scintillator counter arrays known as V0 detectors. To enable the rejection of beam-gas interactions and to provide trigger and centrality information, they are used in ALICE. The collision contact time is determined using the T0 detectors, the other two Cherenkov counters (interaction time).

The muon spectrometer extends only in the forward region i.e C-side (The A and C sides are used to define ALICE geometry. The A-side is the side closer to ATLAS detector and corresponds to positive values of the z coordinate, while C-side is closer to CMS detector and corresponds to negative z . 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 DETECTOR

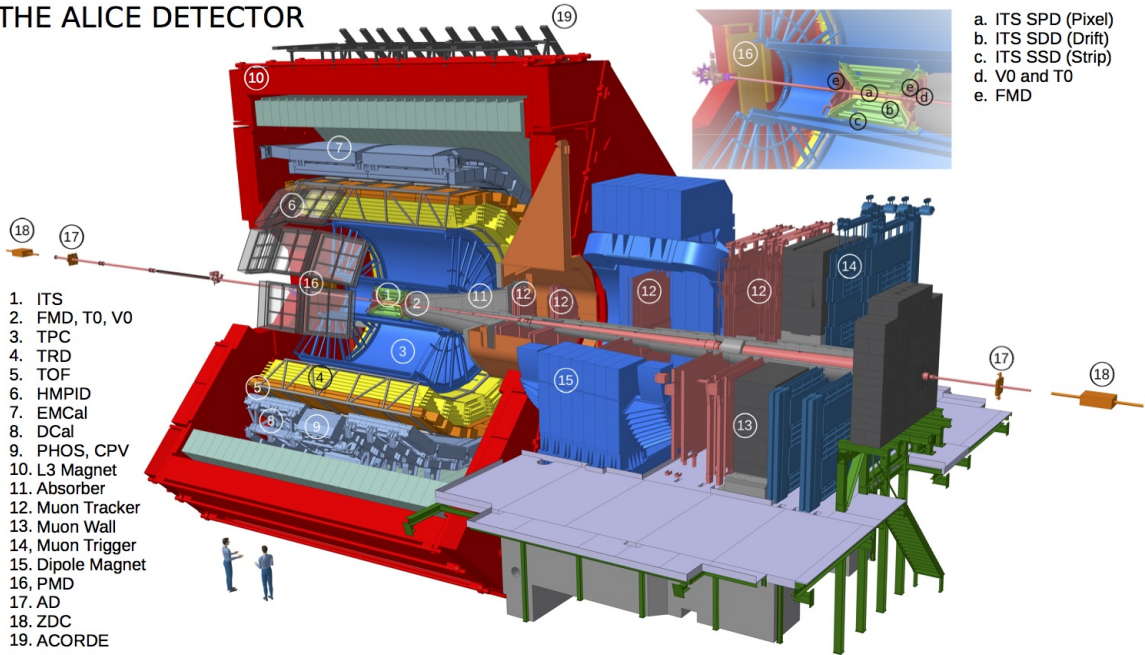


Figure 2.3: Schematics of the ALICE detector.

The ALICE detectors were primarily created to identify the particles produced in these types of collisions since the ALICE experiment focuses on exploring the QGP

in heavy-ion collisions. The L3 magnet, which generates a magnetic field of 0.5 T to deflect charged particles, surrounds the central-barrel detectors. A good acceptance for low- p_T tracks as well as a decent resolution for high- p_T tracks are why this field was selected. They measure particle properties, such as velocities and momenta in the mid-rapidity region. The forward detectors are used for event multiplicity studies, event centrality estimation and triggering. The muon spectrometer is placed in the forward region to measure muon particles. The acceptance of each sub-detectors is given by η (the pseudorapidity) and by the angular coverage, ϕ .

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

2.2.1 Central Barrel Detectors

2.2.1.1 Inner Tracking System

As shown in Figure 2.4[46], the Inner Tracking System (ITS) is situated in the middle of ALICE and is closest to the Interaction Point (IP). Silicon Pixel Detectors (SPD), Silicon Drift Detectors (SDD), and Silicon Strip Detectors each make up two levels of the six concentric layers of silicon detectors that encircle the beam pipe in the ITS (SSD). The SPD's pseudorapidity is $|\eta| < 2$. The principal vertex of a collision, as well as the vertices of decays with heavy flavours and unusual particle types, are to be reconstructed by the SPD (in particular strange hadrons and B and D mesons, which have typical decay lengths of a couple of cms). The SDD and the SSD measure the energy loss along the trajectories to identify the low-momentum particles. The pseudorapidity of the SDD and the SSD are for $|\eta| < 0.9$ and $|\eta| < 0.97$, respectively. This detector system has a very fine granularity and provides a high tracking and vertexing resolution also at extremely high multiplicity. The capabilities of the ITS allow the reconstruction and identification of low-momentum tracks with $p_T < 200$ MeV/c, which are curved too strongly under the effect of the magnetic field to be reconstructed by the TPC.

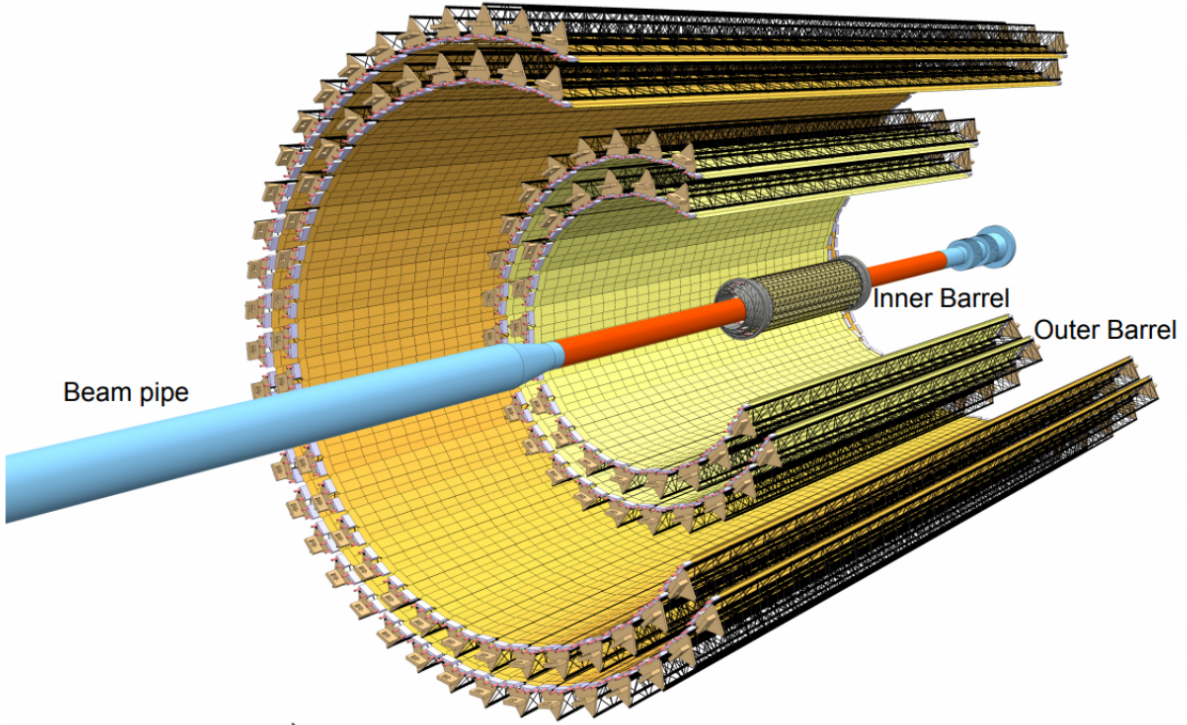


Figure 2.4: Layout of the ITS detector.

The first two layers are located at 4 and 7.2 cm from the interaction point. Because of the high particle density in this area, great position resolution is required, which is attained via a silicon pixel detector (SPD) with cell size of $50(r\psi) \times 425(z) \mu\text{m}^2$. 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. When connecting tracks from the TPC and ITS over longer distances from the point of contact (where the particle density can be lower than one track per cm^2), the double-sided microstrip detectors provide crucial information and still permit dE/dx measurements. The main parameters for each of the three detector types are summarized in Table 2.1

Throughout the ITS, silicon based detector modules are used (which is a semiconductor). The advantages of using a semiconductor are that this creates a fast signal, which makes it possible to determine the interaction time at high accuracy,

Table 2.1: Main specifications of the ALICE ITS.

Parameter	SPD	SDD	SSD
Spatial resolution $r\text{-}\phi$ [μm]	12	38	20
Spatial resolution z [μm]	100	28	830
Two Tracks Resolution $r\text{-}\phi$ [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

and that makes it possible to achieve a very high tracking resolution, since the electron diffusion length is only a few μm .

Each subdetector of the ITS uses a different technology. The *Silicon Pixel Detector* (SPD) is built of pixels of silicon diodes, each measuring $50 \times 425 \mu\text{m}^2$. These are read out by 1200 chips per layer, each covering 8192 cells, totalling 9.8×10^6 cells per layer. The fine granularity makes it possible to detect the position of a charged track traversing the detector to a very high precision. The layers are located 3.9 and 7.6 cm from the beam axis, respectively, and extend 282 mm in the longitudinal direction. The SPD detector provides a binary information for each pixel. The spatial resolution of the SPD is determined by the cells size, by the track angle with respect to the cell orientation and by the detector thresholds applied in the readout. The spatial resolution measured during beam tests was found to be 12 μm in the $r\text{-}\phi$ direction and 100 μm along the z axis. The SPD is also one of the ALICE trigger detectors, and its response was used to trigger minimum-bias events both in the proton-proton and Pb-Pb data taking. Each SPD front-end chip give a fast trigger signal when fired (Fast-OR).

The *Silicon Drift Detector* (SDD) equips the two intermediate layers of the ITS. The inner layer is placed at an average radius of 15.03 cm while the outer layer at a radius of 23.91 cm. Both layers cover a pseudorapidity range of $|\eta| < 0.9$. The basic building block of the ALICE SDD is a module that covers an active region of

$7.017 \times 7.526 \text{ cm}^2$. Each module is divided into two drift regions by a central cathode strip. Both drift regions have 256 anodes with $294 \text{ }\mu\text{m}$ pitch and 291 cathode strips with $120 \text{ }\mu\text{m}$ pitch on both sides of the detector. When a charged particle crosses one SDD module active region it creates electron-holes pairs. The electrons, driven by a 1800 V potential that generates an electric field of $\sim 500 \text{ V/cm}$, drift from the generation point to the collecting anodes. The measure of the time necessary to collect all the electrons produced by the crossing particle allows to determine one coordinate (along $r\phi$ in the ALICE coordinate system) of the point where the particle crossed the detector, while the other coordinate (along the beam direction z) is given by the centroid of the collected charge distribution. The amount of collected charge is proportional to the energy deposit of the particle (more specifically dE/dx) in the silicon, and this information can be used for particle identification. The SDD read out time is $1023 \text{ }\mu\text{s}$. The drift velocity and time-zero, which is the measured drift time for particles with zero drift distance, must be known with high precision in order to reconstruct the ϕ coordinate optimally.

The two outermost layers of the ITS are composed of *Silicon Strip Detectors* (SSD). SSD, being the closest detector to the TPC, plays a crucial role in the prolongation of tracks from the TPC to the ITS. The SSDs are built of double layers of silicon strips, which are put at an angle of 35 mrad ($\approx 2^\circ$) relative to each other. The resolution along z is $\sim 800 \mu\text{m}$. Therefore, a particle crossing one of the SSDs will give rise to a signal in both strip layers, which gives a detection at the crossing point. The SSD working mechanism is based on the collection on each strip side, the electron/holes pairs created by a charged particle crossing the detector. Similar to the SDD, the SSD also measures the particle specific energy loss (dE/dx) to perform particle identification. In total, 1.15×10^6 strips are used in the inner layer and 1.46×10^6 in the outer one, distributed on chips with 768×2 strips each. The inner and outer SSDs are located at 38cm and 43 cm from the beam axis, respectively, and extend 86cm and 98 cm in the z direction.

2.2.1.2 Time Projection Chamber

The TPC is the main tracking device of the ALICE detector. This is a gas detector and can identify particles from their measured energy loss in the TPC volume by using ionisation of the gas from where the charged particles pass.

When charged particles pass through the gas, the gas will be ionised which lead to the production of electron-ion pairs. In a gas detector, an electric field is applied. This field causes the electrons to drift towards the anode and ions towards the cathode. In most detector setups which includes a TPC, thin wires are used as anodes. In the vicinity of the anode, the electric field is inversely proportional to the distance from the anode. Due to this a very strong electric field is created near the wire. Consequently, electrons accelerated in the field will gain enough energy to cause secondary ionisation, giving rise to a chain reaction. This is known as *avalanche multiplication* and is shown in Figure 2.5. Therefore, a few initial electrons can give rise to a substantial voltage pulse induced at the cathode readout plane, which is detected by the system. The voltage pulse will however not stop until the ions are collected at the cathode. Since these have a much lower drift velocity than the electrons, gas detectors are quite slow.

If the voltage is not high, the deposited energy at the electrodes is proportional to the number of initial ionisations, which in turn is proportional to the energy deposit in the gas, giving dE/dx information of the ionising particle. This is the TPC's operational mode, also called as proportional mode. The voltage should not be too high, though, since then the gas atoms may get excited during avalanches. The photons released in the de-excitation process may then trigger additional avalanches. Another issue is that during recombination at the electrodes, the gas atoms may again enter an excited state, which in a similar process may cause secondary ionisations or at least prolong the avalanche. To prevent this, a molecule (typically CO_2) or an organic molecule is added to the gas as a quencher. Due to vibration and rotation modes, this component has more excitation levels than the noble gas, and thus these

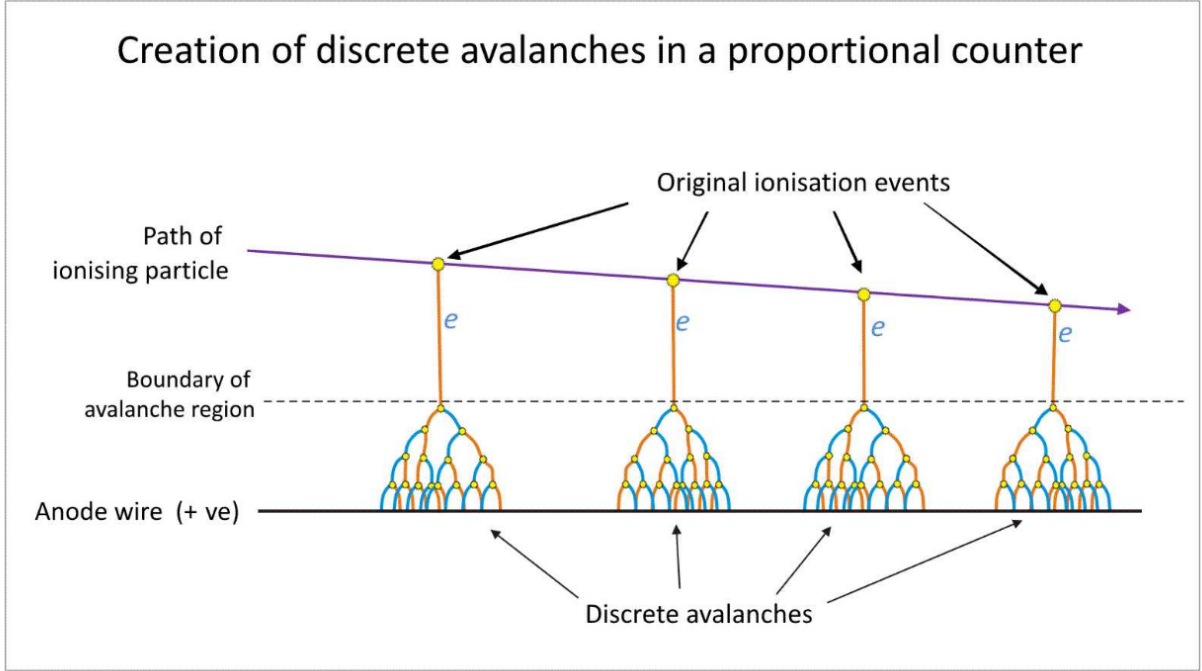


Figure 2.5: Principle of avalanche multiplication in a gas detector. Electrons released during ionisation by an energetic particle will start a chain reaction of ionisations -avalanches near the anode wire. In reality, avalanches may overlap however, which is not indicated by the figure.

will dissipate absorbed energy without liberating further electron-ion pairs. The ALICE TPC has a cylindrical geometry surrounding the ITS, as shown in Figure 2.6 and Figure 3.10. It is designed to track charged particles up to $p_T = 100 \text{ GeV}/c$. Over the entire azimuthal coverage, it covers a rapidity range of $|\eta| < 0.9$. It has an overall length of 500 cm, an outer radius of 250 cm, an inner radius of 85 cm, and an approximate active volume of 88 m^3 . A combination consisting of 85.7% of Ne, 9.5% of CO_2 and 4.8% of N_2 (which act as quencher) is used to fill the volume. The TPC cage is divided in two sections by a high voltage electrode which act as cathode where the ions released during the initial ionisation are collected. At the endcaps are Multi-Wire Proportional Chambers (MWPCs), which are arrays of anode wires operating in proportional mode. When a charged particle from the collision traverses the gas, electron-ion pairs will be created along its trajectory. Since the field is longitudinal, the electrons will be projected onto the endcaps, giving precise information about

the (r, φ) coordinates of the trajectory. Since the drift velocity is being monitored, the z coordinate is obtained by measuring the arrival time of the electrons.

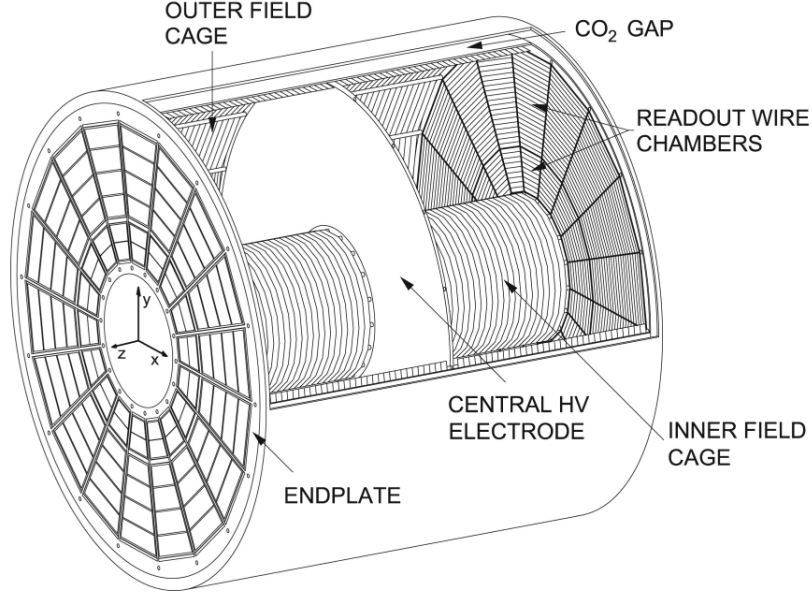


Figure 2.6: Sketch of the TPC field cage. The electrons are collected at the readout chambers at the endcaps, whereas the ions released in the initial ionisation events are collected at the central high-voltage electrode.

With a voltage of 100 kV between the centre and endcaps, the resulting field strength within the detector volume is 400 V/cm. This results in an average drift velocity of 2.65 cm/ μ s for the electrons, or an overall drift time of 94 μ s for the longest drift distances. The PID is based on comparing the crossing particle energy loss in the TPC volume dE/dx with a Bethe-Bloch function, with parameters tuned on data, under the mass assumption for a given particle to determine whether the particle is compatible with that specie or not. An example of the particles dE/dx in the TPC as a function of particle momentum for pp collisions at $\sqrt{s}=13$ TeV is shown in Figure 2.8, where the separation among different species is clearly visible.



Figure 2.7: Photograph of the TPC, when it had been taken out from the ALICE cavern for the upgrade.

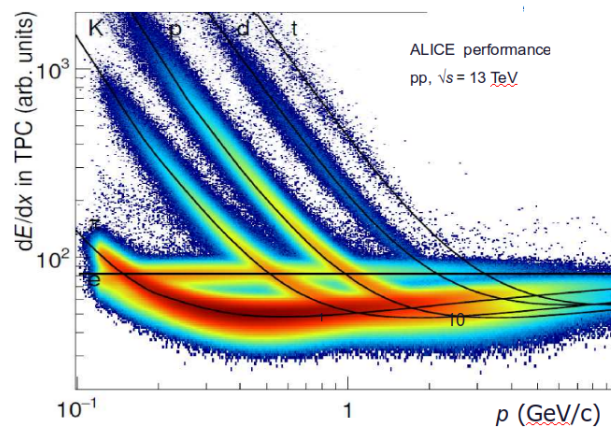


Figure 2.8: dE/dx in the TPC as a function of particle momentum for pp collisions at $\sqrt{s} = 13$ TeV. Black lines are Bethe-Bloch lines for different species.

TPC Upgrade

The TPC is currently being upgraded, with the installation taking place during Long Shutdown 2, just as for the ITS upgrade. In this upgrade the MWPCs are being replaced by Gas Electron Multipliers (GEMs), which allow for continuous operations [47]. Including a major upgrade in the DAQ and readout system, this makes it possible to record tracks piled up from several events simultaneously, significantly increasing the detection rate. During Run 3, the design detection frequency for Pb-Pb collisions is 50 kHz, and for pp collisions it is 500 kHz, with the latter possibly increasing to 1 MHz. A GEM is made up of a thin ($\sim 50 \mu\text{m}$) insulator foil made of ALICE polyimide, with even thinner conducting layers (copper) on the top and bottom. This is perforated by small holes, which replace the wires in the MWPCs. The layer facing the detector volume has a lower potential than the surrounding volume, whereas the other layer has a higher potential. With a potential difference of 200 - 400 V, the electric field strength within the hole is large enough for avalanche multiplication. Following this, the released electrons will then drift towards the outer surface, whereas the ions will be collected at the inner surface, as can be seen in Figure 2.9. One important aspect which is ensured by this design is that less than 1% of the ions flow back into the detector, which is a rough limit for tolerable field distortions. In order to stabilise the operations, e.g. by reducing the risk of discharges, and to increase the gain, the GEM foils are stacked into four layers, with varying spacing between the holes in the foil, in order to ensure that they are not aligned.

2.2.1.3 Transition Radiation Detector

The electron identification in the central barrel is provided by the *Transition Radiation Detector* (TRD) [48], which identifies electrons and positrons with $p_t > 1 \text{ GeV}/c$, where the separation between electrons and pions with the TPC becomes too small. Below this value electrons can be identified via specific energy loss measurements in the TPC. This is done by measuring the transition radiation of the charged

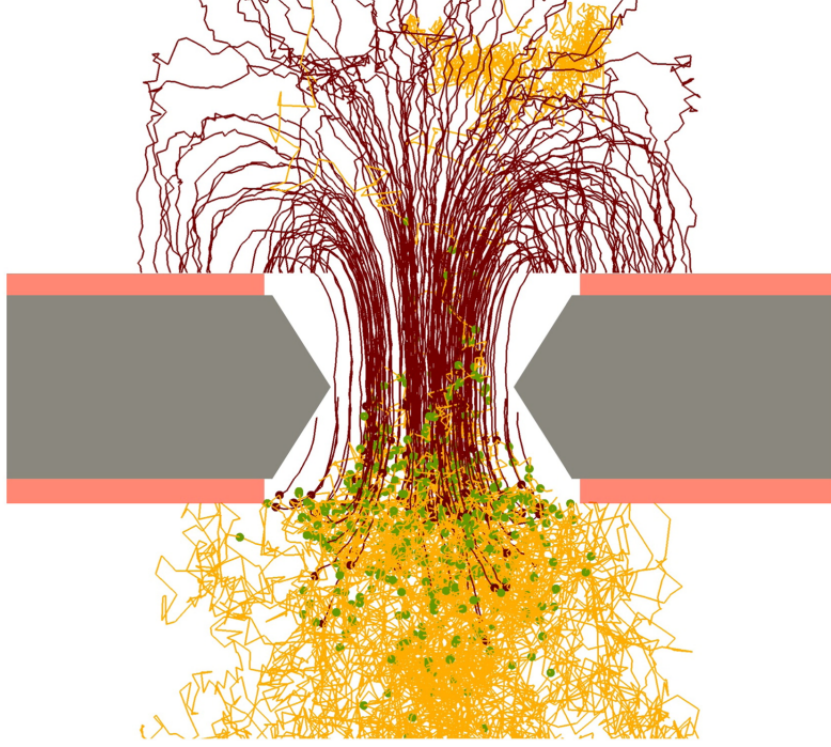


Figure 2.9: Simulation of an avalanche in a hole in a GEM foil, originating from two electrons, projected onto the cross section plane. The green dots mark places where ionisation takes place. The dark lines mark the drift of ions and the fair lines the drift of electrons.

particles crossing the detector. The TRD, having $e^\pm$ identification capabilities can improve the reconstruction of light and heavy vector meson. As it reconstructs a set of space points with good spatial resolution ($\sim 600\mu\text{m}$) the TRD allows to prolong tracks outside the TPC, therefore improving the resolution on the track momentum. Figure 2.10 shows the geometry of the TRD in the ALICE central barrel. The TRD detector has an inner and outer diameter w.r.t the beam axis of 290 cm and 368 cm respectively, enclosing the TPC. The TRD is composed of 540 modules organized in 18 sectors (or super-modules), each module consisting of a 4.8 cm thick radiator and a multi-wire proportional chamber. It covers the full azimuth in the mid rapidity region ($-0.84 < \eta < 0.84$) and with a fast response time it can provide a trigger for charged particles. This detector is useful for particle with Lorentz factor γ larger than 1000, which corresponds to good electron/pion separation for momenta $1 \leq p_T$

$\leq 100 \text{ GeV}/c$.

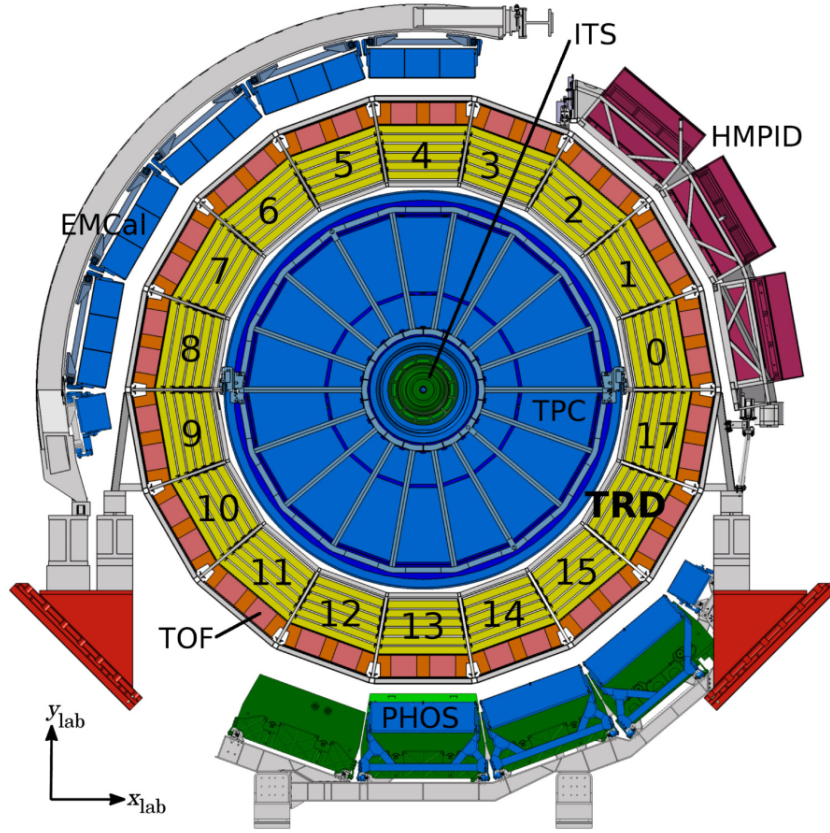


Figure 2.10: Schematic cross-section of the ALICE central barrel detector perpendicular to the LHC beam direction.

2.2.1.4 Time-Of-Flight detector

The Time-Of-Flight detector (TOF) determines charged particle velocities, and its major duty is to identify charged particles with low and intermediate momentum (from 0.2 to 2.5 GeV/c) by measuring the time of flight from the particle's contact point (collision point). The time measurement, in conjunction with the momentum and track length measured by the tracking detectors is used to calculate the particle mass. It allows K/π and K/p separation up to a track momentum $p_T \sim 2.5 \text{ GeV}/c$ and $p_T \sim 4 \text{ GeV}/c$ respectively.

The TOF shape is cylindrical and is shown in the left panel of Figure 2.11 with the

inner and outer radius of 370 and 399 cm, respectively. The TOF pseudorapidity range covers $|\eta| < 0.9$. The TOF consists of 1593 Multigap Resistive Plate Chambers (MRPC) distributed in 18 azimuthal sectors. The detector covers an area of 150 m^2 filled with a mixture composed of 90% of $\text{C}_2\text{H}_2\text{F}_4$, 5% of C_4H_{10} and 5% of SF_6 . Each MRPC is made by a ten layer double-stack detector with a time resolution of about 40 ps. The MRPCs are organized in 18 sectors placed in a cylindrical shell with an inner radius of 3.7 m.

If a charged particle passes through the MRPC, it causes an electron avalanche in the gas. The pickup electrodes stop the avalanche and send the signal that gives the time of traveling. The TOF works together with the Time0 (T0) detector which gives the start time. With the time information specified above and the track length measured by the tracking detectors, the velocity of a charged particle is then determined. The particles created by collisions can be identified using the momentum information obtained by the ITS and TPC. The overall TOF resolution is around 85 ps in Pb-Pb events and 100 ps in proton-proton collisions. TOF is able to disentangle pions from kaons up to $3 \text{ GeV}/c$ and kaon from protons up to $5 \text{ GeV}/c$. The right panel of Figure.2.11 shows the TOF velocity as a function of momentum. The electrons, pions, kaons, proton and deuterium particles are visible in the plot. Assuming that the distance L travelled by a particle to reach the TOF is known with good precision (assumption that needs a good precision on the primary vertex), then the velocity of the particle will be $v = L/t$ where t is the time needed by the particle to reach the TOF. From this, and knowing the particle momentum p , the mass of the particle can be determined by the equation:

$$m = p \sqrt{\frac{1}{v^2} - \frac{1}{c^2}} = \frac{p}{c} \sqrt{\frac{c^2 t^2}{l^2} - 1} \quad (2.1)$$

2.2.1.5 High-Momentum Particle Identification Detector

The High-Momentum Particle Identification Detector (HMPID) uses Ring Imaging Cherenkov (RICH) technology to identify charged particles with enormous momenta,

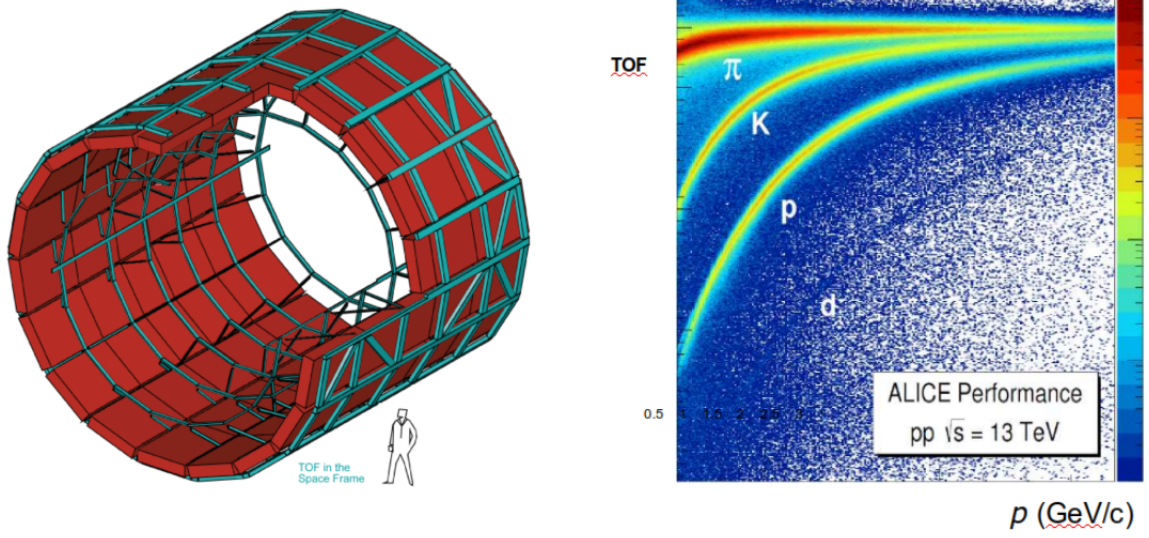


Figure 2.11: Left: illustration of the TOF detector. Right: the TOF velocity β as a function of the particle momentum in pp collisions at $\sqrt{s} = 13$ TeV

such as pions, kaons, and protons. It extends the ALICE PID capability for charged hadrons at high p_T increasing the useful range for the π/K separation up to 3 GeV/ c and the K/proton separation up to 5 GeV/ c . Seven RICH counters are installed on the support cradle inside the ALICE solenoid at 5 m from the beam line. The HMPID consists of an array of proximity-focusing Ring Imaging counters (RICH) and covers a pseudorapidity range of $|\eta| < 0.6$ and the angular coverage of the HMPID is $1.2 < \varphi < 58.8^\circ$. The HMPID has two main parts: a radiator medium and a photon detector. The charged particles that move faster than the speed of light (in the medium of the detector) emit the Cherenkov radiations. The Cherenkov radiations are emitted in the form of a cone along the trajectory of charged particles. The angle between the trajectory of a charged particle and the edge of the cone is the Cherenkov ring angle. From the Cherenkov ring angles and the momenta measured by the ITS and the TPC, the identification of the charged particles can be determined. Figure 2.12 shows the Cherenkov angle of charged particles as a function of their momenta. The pions, kaons and protons are visible in the plot. For

the π/K and K/p discrimination, the HMPID extends the p_T range of the particle identification up to 3 and 5 GeV/ c on a track-by-track basis, respectively.

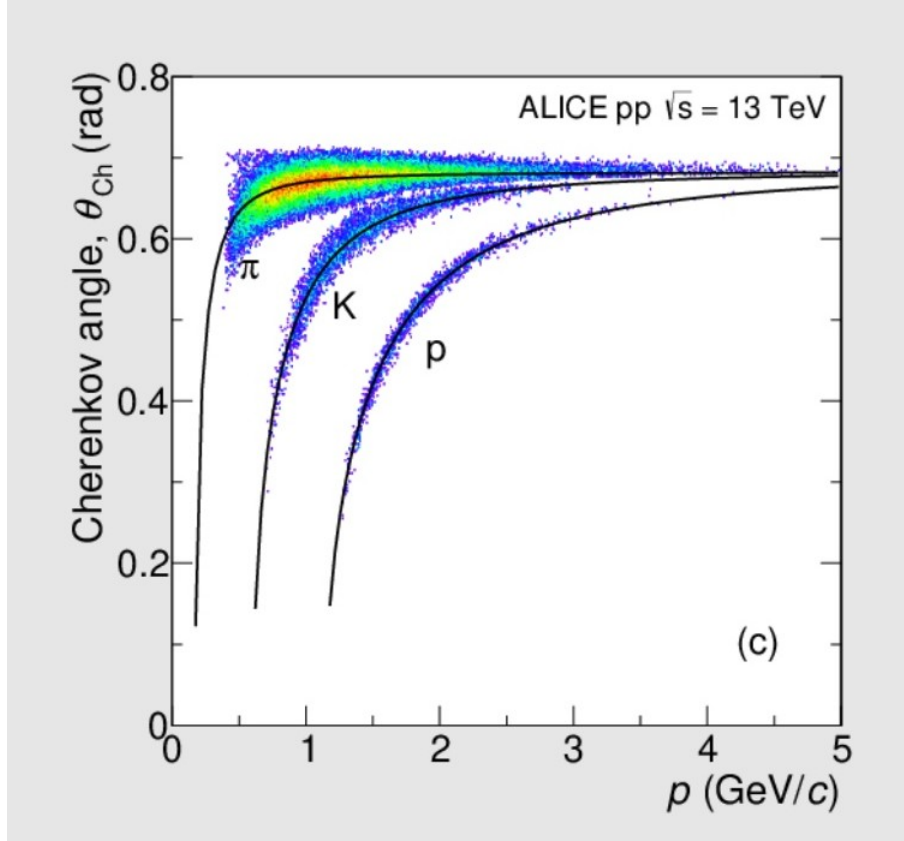


Figure 2.12: The Cherenkov angle θ_{ch} as a function of the particle momentum in in pp collisions at $\sqrt{s}=13$ TeV.

2.2.1.6 Electromagnetic Calorimeter

The EMCAL is a lead scintillator sampling calorimeter that covers an azimuthal angle range of 107° in the rapidity interval $|\eta| < 0.7$ at a radial distance of about 4.5 metres from the vacuum tube. Its length in the longitudinal direction is 700 cm. The EMCAL is designed to measure the energy of charged particles, photons and the photonic decays of neutral mesons to study jet quenching and can provide trigger signals for hard jets, photons and electrons. There is another calorimeter installed, which is called Di-jet Calorimeter (DCal). This complement the EMCAL.

The azimuthal coverage of the DCal is 70 degrees and the DCal is placed in front of the EMCal. This configuration allows back-to-back jet measurements.

2.2.1.7 Photon Spectrometer

The Photon Spectrometer (PHOS) is an electromagnetic calorimeter, made of lead-tungstate (PbWO_4) crystal. It is a high resolution electromagnetic calorimeter which provides photon and neutral meson identification, the latter being reconstructed through their decay in two photons. The direct photons which come directly from the medium produced in the heavy ion collisions are an extremely interesting probe as they (almost) do not interact with the medium once produced and thus can provide direct insight in the medium properties. The PHOS covers 60 degrees in azimuth and the pseudorapidity range $|\eta| < 0.12$.

2.2.2 Forward Detectors

2.2.2.1 Muon Spectrometer

The ALICE muon spectrometer is designed to detect muons in the rapidity range $-4 < |\eta| < -2.5$. It allows to perform a rich physics program covering quarkonia, heavy quarks and low masses vector mesons (J/ψ , Υ , ϕ , . . .) studied through their dimuon decays and semi-leptonic decays of charmed and beauty particles. The muon spectrometer is composed of a high granularity system of 5 stations each made of two tracking planes, 4 planes of trigger chambers, each one placed after a muon filter wall, a large dipole magnet producing a strong magnetic field perpendicular to the beam axis and an hadron absorber placed inside the L3 magnet to reduce contamination from large rapidity hadrons coming from the interaction vertex.

The system of absorbers suppress hadrons, mainly pions and kaons, to decrease the background for single muon and dimuon measurements. The first component of the absorbers is the front absorber which has a conical structure with a length of 4.13 m and located at 90 cm from the interaction point on the C-side. The carbon and

concrete are adopted to lower down the effect of multiple scatterings and energy loss by traversing muons. The rear attenuate low energy photons, neutrons and secondary particles produced in the front absorber.

The dipole magnet provides an integral field of 3 Tm to deflect charged particles. Associated to the particle trajectory reconstructed by the tracking chambers, the magnetic field allows one to determine the particle momentum and electric charge. The magnetic field from the dipole is perpendicular to the beam pipe in the horizontal plane. The charged particle is therefore deviated in the vertical plane. The plane perpendicular to the magnetic field is referred to as "bending plane", while the one parallel to the magnetic field is referred as "non-bending plane". The volume of the magnet is of $5 \times 6.6 \times 8.6 \text{ m}^3$ and is placed at 7 m from the interaction point.

The tracking system was designed to record the three-dimensional information of muon particles. They are designed in such a way so that a spatial resolution of $100 \mu\text{m}$ is achieved. The system consists of five tracking stations. A tracking station has two planes of Multi-Wire Proportional Chambers (MWPC) with two cathode planes readout. The first two tracking stations, called Station 1 and 2 are located right after the front absorber. The third tracking station, called Station 3 is inside the dipole magnet. The last two tracking stations, called Station 4 and 5 are placed between the dipole magnet and the muon filter.

The muon trigger system is made of four Resistive Plate Chambers (RPC) placed in two different stations 1 metre from each other at about 16 metres from the interaction point. Each station consists of two planes of 18 single-gap RPCs, placed behind an iron absorber (muon filter). The muon filters are 120 cm thick and combined with the front absorber they prevent efficiently pions from reaching the trigger chambers. Also muons with momentum $p_T < \text{GeV}/c$ are stopped by the muon filters.

2.2.2.2 V0 Detector

The V0 detector is made up of two scintillator counter arrays. One is placed at 340 cm from the interaction point in the A-side of the ALICE detectors. It is called V0-A

. Its pseudorapidity range is for $2.8 < |\eta| < 5.1$. Another one is located at 90 cm from the IP in the C-side, and is known as V0-C. It covers the pseudorapidity range of $-3.7 < |\eta| < -1.7$.

2.2.2.3 T0 Detector

The T0 detector is made of two arrays (T0-A and T0-C) of Cherenkov counters connected to fast photomultipliers. The T0-A is located at 3.6 m from the IP in the A-side and its pseudorapidity range is $4.61 < |\eta| < 4.92$. In the opposite direction, the T0-C is located at 70 cm from the IP and it covers the pseudorapidity range $-3.28 < |\eta| < -2.97$. The T0 detector, with its time resolution of 25 ps, is able to provide a precise start-up time of a collision. It measures the vertex position online and determines the multiplicity of charged particles produced in hadron collisions. Furthermore, it serves as an alternative Minimum Bias trigger detector.

2.2.2.4 Zero Degree Calorimeter

The Zero Degree Calorimeter measures the energy carried by the spectator nucleons. The ZDC can also give an estimate of the reaction plane in nucleus-nucleus collisions and it is very important to reject parasitic collisions both in pp and Pb-Pb. The ZDC consists of two pairs of calorimeters, each one is placed about 116 m from the interaction point on the two sides of the vacuum tube. Each pair is made of one neutron calorimeter (ZN) and one proton calorimeter (ZP) to measure the deflected spectator protons. They are placed on different sides of the vacuum tube in order to use the nucleons deflection driven by the beam magnetic fields. ZN and ZP cover the pseudorapidity range of $|\eta| < 8.8$ and $6.5 < |\eta| < 7.5$, respectively. The ZDC is used in heavy-ion collisions to estimate the centrality of the event. It also serves to remove debunched heavy-ion collisions and to reject electromagnetic Pb-Pb interactions.

3 The ALICE Framework

The ALICE Detector has eighteen different sub-detectors which can be operated either in a standalone mode (independent of other sub-detectors) or in global partitions (set of sub-detectors). The ALICE Experiment make use of online and offline service to manage its operations right from collisions of particles to analysis of the collected data.

3.1 ALICE online operations

Five central web systems are in charge of managing the data collection activities [49, 50, 51, 52, 53]: The *Data Acquisition system* (DAQ), which interfaces with *The Central Trigger Processor* (CTP) and *The High-Level Trigger* (HLT) system, is in charge of configuring the various detectors during data collection. *The Detector Control System* (DCS) provide an overall supervision for the experimental equipment, and ensure safe operations during beam conditions. The Experiment Control System oversees and coordinates all of these procedures (ECS). The detectors are capable of operating independently in "standalone" mode for calibration, commissioning, and debugging tasks. During the collection of physics data (using cosmic rays or just a beam), detectors are organised into "partitions" that can operate concurrently and independently after receiving trigger inputs. The ECS keeps track of the DCS's condition, communicates with the DAQ and HLT operations, and connects the partition to either the Local Trigger Unit (LTU) in standalone mode or the Central Trigger Processor (CTP), depending on whether it is a global partition.

3.1.1 The Data Acquisition System

ALICE uses several beam configurations to investigate a range of (physics) observables. The events are chosen and described using a wide variety of trigger classes. Depending on how common or uncommon they are, these trigger classes fall into one of two major categories.

The performance of the data collection system is the limiting factor for a few triggers (central, semi-central, and lowest bias). The bandwidth used by these triggers will account for a significant portion of the total data gathering bandwidth. Rare triggers, such as dielectron or dimuon events, consume less bandwidth and are constrained by the luminosity and detector live time. By collecting data for multiple observables concurrently while simulating various scenarios, the experiment will make the best use of the data-taking intervals. Therefore, the job of the ALICE Trigger, Data Acquisition (DAQ), and High-Level Trigger (HLT) systems is to choose interesting physics events, to provide an efficient access to these events for the execution of high-level trigger algorithms, and finally to archive the data to permanent data storage for later analysis.

With regard to DAQ bandwidth for frequent triggers and detector life time for rare triggers, the trigger and DAQ systems were created to offer various observables a fair part of the trigger and DAQ resources. The ability to record huge events caused by centre collisions and the capacity to compile the greatest percentage of rare events must be balanced by the trigger and DAQ systems. The ALICE DAQ system must work under highly difficult circumstances, such as the tremendous proton-proton contact rate with a small event size on the one hand, and the lesser Pb-Pb collision rate but enormous data volume on the other. Its design has also been influenced by the need to share resources among various detector clusters; these clusters are arranged to examine various observables with various cross sections and, consequently, various trigger rates. Figure 3.1 schematically depicts the ALICE DAQ system flow. For every bunch crossing in the LHC machine during data collection, the Central

Trigger Processor (CTP) decides in less than one *mus* whether to collect data arising from a collision. The Local Trigger Unit (LTU), which is interfaced with an optical broadcast system, the Trigger and Timing Control (TTC) system, transmits the trigger decision to the front-end electronics (FEE) of each detector. Following the receipt of a favourable judgement, the information gathered by each detector is transmitted over 400 optical Detector Data Links to the DAQ Readout Receiver Card (D-RORC) (DDL). The Local Data Concentrator (LDC) and Front-End Processors are connected by the D-RORD via 300 separate computers (FEP). The information is delivered from DDLs to LCDs in several hundred fragments (each of which corresponds to the details of a single event), where it is examined, processed, and put together into sub-events. The 40 Global Data Collector (GDC) computers receive these sub events and construct the whole events in ROOT file format. These events are initially saved locally in the Transient Data Storage (TDS), before being exported to the CERN Computer Center and recorded in the Permanent Data Storage (PDS), where they are then made accessible for offline analysis.

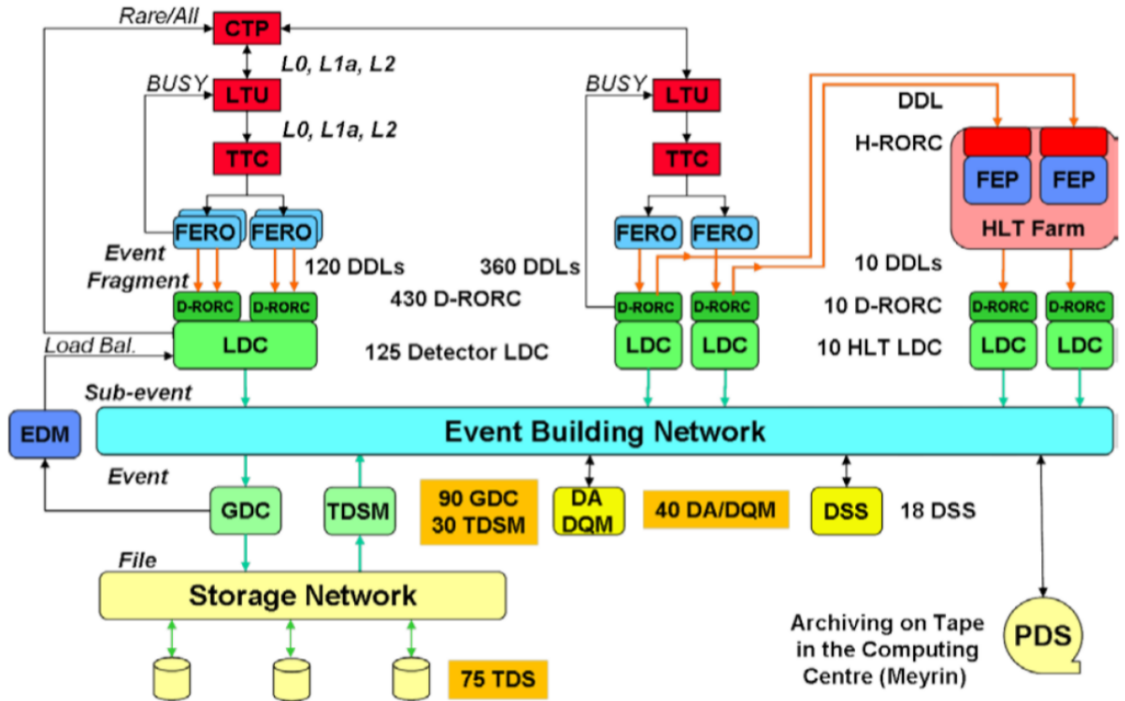


Figure 3.1: The ALICE DAQ architecture.

3.1.2 The Central Trigger Processor

The ALICE Central Trigger Processor (CTP) [54] is intended to select events with a variety of different features at rates that can be scaled down to meet physics requirements and bandwidth constraints imposed by the Data Acquisition System (DAQ) and the High-Level Trigger (HLT). The CTP determines the trigger decision during data collection based on detector signals and knowledge of the LHC bunch filling process. To meet the needs of the detector, the trigger system must have a quick initial response.

In order to achieve this, the trigger's "fast" component is divided into two levels: Level0 (L0), which arrives to detectors in $1.2 \mu\text{s}$ but is too quick to pick up all of the trigger inputs, and Level1, which does so in $6.5 \mu\text{s}$ and picks up all of the remaining fast inputs. CTP judgments are made in 100 ns, as you may have noticed. The propagation and computation times (TRD and EMCal) are to blame for this delay (ZDC, located at 112.5 m from IP2). The event data is buffered in the detector front-end electronics as a result of the L0 and L1 decisions. Information on whether there are bunches arriving from both A-side and C-side, one of them, or neither, with a resolution of 25 ns, is included to the trigger decisions.

ALICE uses minimum-bias (MB) triggers, which are mostly based on V0 and SPD, as well as uncommon triggers that are optimised to choose specific types of events, such as jets or muons, or high-multiplicity events. The V0 information has been used to initiate central and semicentral events in Pb-Pb collisions.

3.1.3 The High Level Trigger

In a single central nucleus-nucleus collision, the quantity of data generated in the TPC alone equals to around 75 MB, assuming $dN_{ch}/d\eta = 8000$ at mid-rapidity, according to simulation studies. While the physical content of many events may be low and the DAQ archiving rate is only about 1 GB/s, the data rate for all detectors that results from a trigger selection can easily reach 25 GB/s. Thus, it is recommended to

use online processing to choose pertinent events or sub-events and to compress the data without losing its physical substance. The High Level Trigger (HLT) system is designed for the acceptance or rejection of an event on the basis of an online analysis and, in case of positive decision, compress the amount of collected data (without any loss of physical information) using specific algorithms in order to reduce the data rate to a value acceptable by the DAQ and by the storage elements. The High Level Trigger gathers raw data from the LDCs, executes a local fast tracking and pattern recognition operation, locates the principal vertex, and builds the global event. Once the trigger decision has been made, the event's summary data and compressed data are transmitted back to the DAQ via the HLT DDL output. The HLT utilises a cluster of 1000 multi-processor computers in order to complete all these calculations quickly. In Figure 3.2," the HLT system is depicted. The High-Level Trigger [55] general physics needs can be divided into the following categories: • **Trigger** Accept or reject events using extensive online analysis as a trigger.

- **Select** A physics region is selected which is of interest within the event by performing only a partial readout.
- **Compress** Apply compression algorithms to the approved and selected data to reduce the event size without sacrificing physical information.

3.1.4 The Detector Control System

The main responsibility of the ALICE Control System is to guarantee the ALICE experiment's correct and safe operation. With the use of a special set of operator panels, it enables remote control and monitoring of all experimental equipment, enabling the ALICE experiment to be managed and controlled from the ALICE Control Room (ACR) at LHC point 2. The system offers the best circumstances for operation so that the experiment's data collection yields the best results. The ALICE control system was developed to reduce downtime for the experiment and hence increase running effectiveness. Additionally, It also maximises the number of

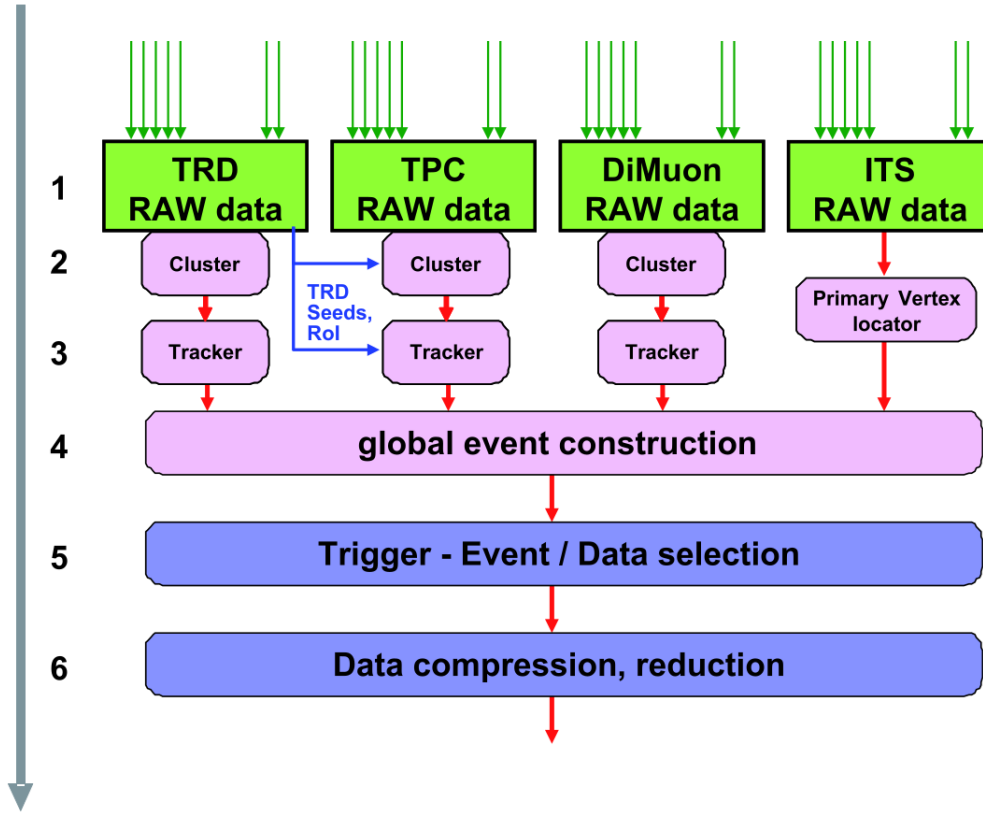


Figure 3.2: The six architectural layers of the HLT.

channels operational at any time, and measures and stores all parameters necessary for efficient analysis of the physics data.

The DCS facilitates simple component integration because it is a coherent and homogeneous system. To adapt to changes made by the experiment during the course of its existence, the DCS is adaptable and expandable. The control system can handle a variety of operating modes and permits every sub-detector, or any piece of it, to work independently and concurrently because it is intended to be operational throughout all operational stages of the experiment (data gathering, shutdown, etc.). The ALICE control system is in charge of setting up, watching over, and managing the experiment's equipment.

3.1.5 The Experiment Control System

The "online systems" enable partitioning, are independent, and may interact with all particle detectors. The ability to run groups of ALICE detectors simultaneously is referred to as partitioning. In the final configuration, the detectors will mostly work together to gather physics data. The Experiment Control System (ECS) is in charge of coordinating the operations of the 'online systems'. It allows different operators to work on different parts of the experiment at the same time and coordinates the functions of the "online systems" for all detectors and within each partition. The ECS components receive status information from the 'online systems' and give commands to them via Finite-State Machine interfaces (FSM). Access control methods are present in the interfaces between the ECS and the "online systems," which govern the permissions granted to the ECS. The "online systems" may be managed by the ECS or may function independently. The 'online systems' in the second example send status information to the ECS but do not receive directives from it.

The Detector Control Agent (DCA), Partition Control Agent (PCA), Detector Control Agent Human Interface (DCAHI), and Partition Control Agent Human Interface are the four main parts of the ECS that are explained below (PCAHI).

3.2 ALICE offline operations

3.2.1 ALICE Grid

Because of the enormous and unprecedented volume of data being gathered at LHC, processing and storage resources must be distributed across multiple computing facilities. The distribution of these resources across the facilities of all the institutes and universities taking part in the experiment is more natural and effective. To do this, a worldwide distributed computing project was started in 2000: the Grid [56]. In order to provide ALICE users with transparent access to global distributed computing resources via the Grid, the ALICE Environment (AliEn) architecture was created. The Grid enables the project's participating institutions and universities to

spread their computing resources. The Grid is organised into many tiers or Tiers and is based on the MONARC model (Models of Networks Analysis at Regional Centers for the LHC Experiment).

- The raw data immediately originating from the experiments is preserved in Tier 0 at CERN.
- The largest external Tier 1 centres are given access to a second copy, and one of their new tasks will be to recreate the event.
- Regional Tier 2 centres participate in Monte Carlo simulations and help create digestible files for solitary users to analyse.

The AliEn environment ensures the access to the Grid middleware in ALICE. Users of ALICE access data, send analytical jobs and simulations, and monitor them using the AliEn User Interface in particular. The AliCE Environment (AliEn) architecture was created with the intention of giving ALICE users transparent access to the world's distributed computing resources via the Grid. .

3.2.2 AliRoot framework

Figure 3.3 presents a schematic representation of the ALICE offline framework, AliRoot [57]. The AliEn system provides access to the computational Grid, and its implementation is based on Object-Oriented programming techniques and the ROOT system as a supporting framework. These essential technical decisions lead to the creation of a single framework that is entirely written in C++, with some external (but user-hidden) FORTRAN applications. For simulation, reconstruction, and analysis, AliRoot is employed. The framework and all applications are constructed using the ROOT [58] system, which is supplemented with the AliEn interface, which provides access to the Grid. This framework was created in C++ and is nearly entirely based on the Object-Oriented programming paradigm. It is a software specifically designed to analyze the huge amount of data coming from high-energy experiments. The tools to examine simulated and actual collisions, including the shape of the detectors and their reaction to the passage of the particles, are provided by Aliroot and Root. Ali-

root employs a variety of Monte Carlo transport programmes, including Geant3 [59], Geant4 [60], and Fluka [61], to model particle interactions with detectors. Monte Carlo event generators are used to simulate occurrences in order to calculate efficiency, for example. The main event generators used are based on PYTHIA [62] and HERWING [63] for pp collisions, while for proton-nucleus and nucleus-nucleus collisions HIJING [64] and DPMJET [65] are mainly considered. In addition, AliRoot provides the tools for the local reconstruction, vertex reconstruction, tracking and analysis for the whole apparatus. Figure 3.4 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.

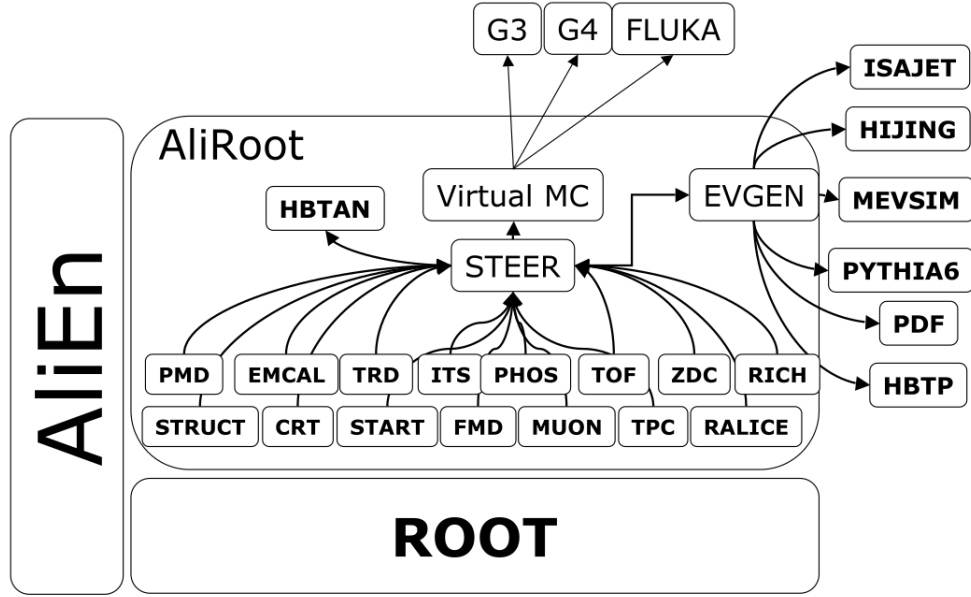


Figure 3.3: The AliRoot data processing framework.

Event generators produce the kinematic tree, which contains the physics operations at the particle level and the fragmentation products (primary particles). The information about the generated particles, including their type, momentum, charge, and mother-daughter relationship, is fully contained in the data supplied by the event

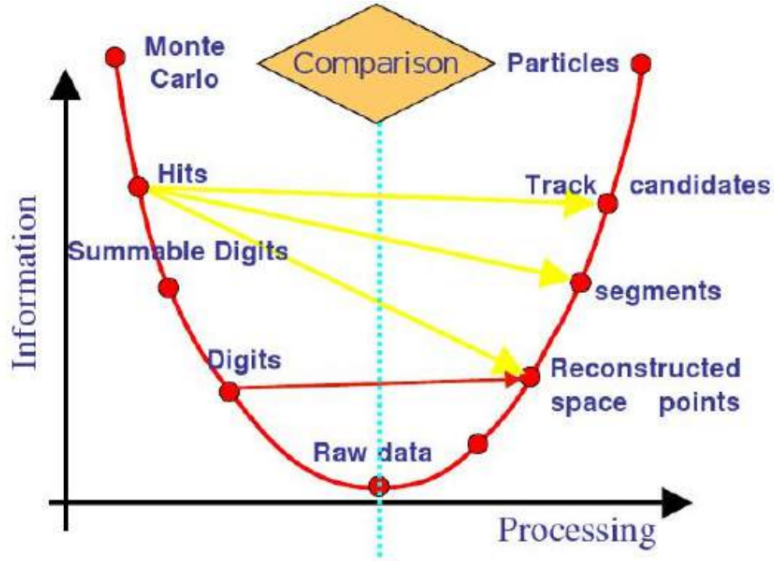


Figure 3.4: The functionalities of the Aliroot framework.

generators. The reaction of the detectors to each crossing particle is simulated during the journey. For each detector, the hits (energy deposition at a specific point and time) are saved. "Trail references," or the sites where the particles cross user-defined reference planes, are added to the data as a supplement. The detector and related electronics response function are taken into account when converting the hits into digits. The raw data is then saved in the hardware format relevant to each detector. The reconstruction chain is now turned on at this stage. Typically, the detectors do local reconstruction, such as clustering, and then begin a Kalman filter tracking process [66] using a seeding procedure. To test the software and detector performance, simulated events are processed through the full cycle. The reconstructed particles are then compared to the Monte Carlo created ones.

3.3 ALICE Performance

A precise reconstruction of the particle trajectories and the position of the primary and secondary vertices is fundamental for all the physics analyses. In this section we discuss the basic performance of the ALICE detector for track and vertex finding,

reconstruction and particle identification.

3.3.1 Reconstruction

When a particle crosses the sensitive area of a detector, a signal is released in it, which is recorded as a digit. This *digit* is then associated to the information on the physical location of the digit in the detector: these informations pertaining to the raw data of the detector. The raw data are the starting point for the event reconstruction both in real data and MonteCarlo simulations. Clustering is the first step in the reconstruction process. A *cluster* is loosely defined as a collection of points that are close together. Digits are extracted from raw data and adjacent digits are grouped together to identify clusters, which describe the signals produced by the passage of a particle in a sensitive part of the detector. The reconstructed points are then defined via the calculation of centres of gravity of clusters which give an estimate of the positions where particles have crossed a sensitive area of the detector. In the global event reconstruction, reconstructed points from each sub-detector are associated into tracks, which contain the kinematical information related to the trajectory of the particles and their identity (if available). The output of the global reconstruction is stored in a tree object called Event Summary Data (ESD). But currently, the analyses are being performed on smaller Aliroot objects (Analysis Object Data or AODs), which include only the information needed for physics analyses.

3.3.1.1 Reconstruction in ALICE

The track reconstruction procedure in ALICE is based on a Kalman filter algorithm [95]. The Kalman filter is used to perform track finding and fitting simultaneously and being a local method allows to extract the optimal estimate of the geometrical parameters of each track point-by-point. For this reason it is an ideal method when it is needed to prolong tracks from one detector to another, the typical situation we have in the central barrel. Multiple scattering and energy loss are also taken into

account by this approach. The track reconstruction is a sequential procedure and includes the following steps:

- **SPD primary vertex** A first estimation on the position of the interaction vertex is performed by using the information from the SPD. The clusters in the two layers of SPD are used to reconstruct tracklets that are considered for the determination of the primary vertex. 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 (mainly in very low-multiplicity events) the algorithm uses information from the distance of closest approach (DCA) of tracklets to the beam axis to accomplish a minimization, allowing access to the vertex's z position.

- **Track reconstruction in the TPC.** Track seeds are created, using the information from starting point on the TPC outer layer and the position of the SPD vertex. 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. A copy of the tracks from the TPC reconstruction is propagated to the primary vertex position and used to perform TPC-only analyses (TPC-only tracks).

- **Track reconstruction in the ITS.** Tracks are then propagated to the outermost ITS layer and become the seeds for track finding in the ITS which are then propagated down to the SPD. Track finding is performed in two passes. In the first iteration the position of the primary vertex estimated using the SPD pixels is used to guide the track finding and maximize the efficiency for primary tracks. In the second pass, the vertex constraint is not used in order to allow the reconstruction of tracks with large displacements with respect to the primary vertex. The ITS clusters which are not used in the TPC-ITS reconstruction are then used to perform an ITS stand-alone reconstruction. In fact, the TPC track finding efficiency drops at low p_T , whereas the ITS still shows good performance in this p_T region. This ITS stand-alone reconstruction also enables for the rebuilding of tracks that pass through TPC dead zones or deterioration before reaching the inner TPC radius.

- **Track back propagation.** When the ITS reconstruction is finished, all tracks

are extrapolated to their closest approach to the interaction vertex, and outward propagation begins. Tracks are then back-propagated to the outermost ITS layers, to the TPC and to the TRD. The extrapolation of the tracks to the TOF, HMPID is then performed to allow Particle Identification and eventually to PHOS and EMCal.

- **Inward fitting and vertex reconstruction with tracks.** All tracks are propagated inward starting from the TPC's outer radius at the end of the track reconstruction. The tracks are refitted with the previously discovered clusters in each detector (TPC and ITS). 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 position of the interaction point is then recalculated with the reconstructed tracks in order to improve its resolution using the Vertexer-Tracks algorithm. With the same method, the vertex position using TPC-only tracks is also determined. The Inner Tracking System used as a standalone tracker enables the reconstruction of particles that do reach the TPC down to very low transverse momentum (e.g. $p_T^{min}(\pi) \approx 100 \text{ MeV}/c$). The ITS standalone tracking system also allows to identify particles with very low momenta by using dE/dx measurements in the drift and strip detectors.

For Pb-Pb and pp collisions, the track-finding efficiency at various phases are shown as a function of transverse momentum in Figure 3.5 and Figure 3.6. At very high momenta, the TPC and TPC-ITS track finding efficiency reaches 90%; this number is largely influenced by the size of the TPC dead zones, which occupy 10% of the azimuthal angle. The significant decrease following the TRD's insertion is the result of interactions within the material, decays, and more dead zones. As a result, the TRD is only used in tracking when it increases precision, which is only occasionally.

Figure 3.7 and Figure 3.8 show the momentum precision obtained with different detector combinations, again for two different values of the charged-particle density. The significant improvement at high transverse momenta when we combine the measurements from the TPC and ITS is basically due to the increase in track-

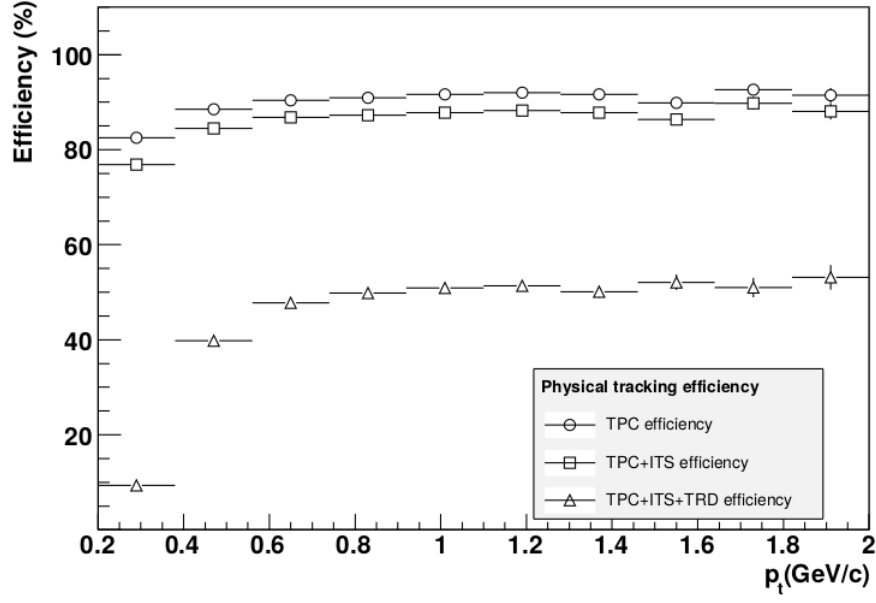


Figure 3.5: Physical track-finding efficiency for different combinations of the tracking detectors for Pb-Pb collisions

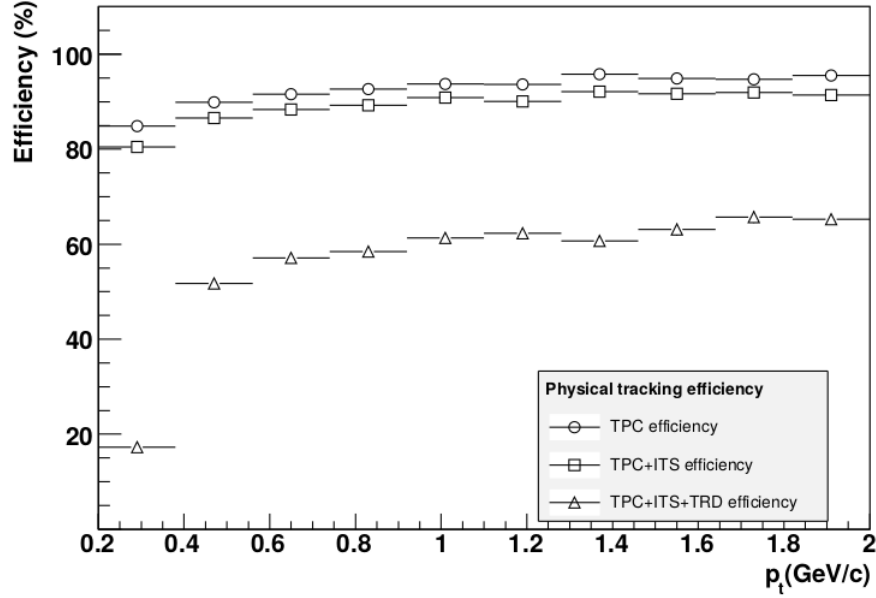


Figure 3.6: Physical track-finding efficiency for different combinations of the tracking detectors for pp collisions

ing length. When moves from low to high charged-particle density, there is only a minor loss in track-finding efficiency and momentum precision. The momentum precision achieved with various detector combinations, again for two distinct values

of the charged-particle density, is shown in Figures 3.7 and 3.8. When we combine the values from the TPC and ITS, we notice a large improvement at high transverse momenta, which is primarily attributable to the longer tracking distance. Only a slight reduction in track-finding effectiveness and momentum accuracy occurs when switching from low to high charged-particle densities.

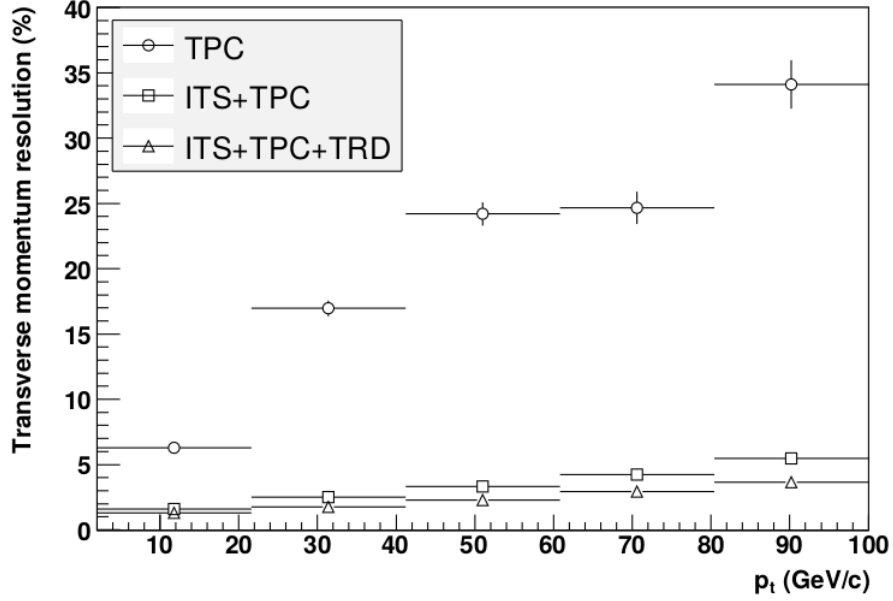


Figure 3.7: Transverse-momentum resolution for different combinations of the tracking detectors for Central Pb-Pb collisions

In order to determine the vertices of secondary decays, the tracks with the closest approach distance to the interaction vertex surpassing a particular minimum value are chosen during the reconstruction of an event. For instance, vertices from odd particle decays are searched at the reconstruction level. Due to this, only secondary tracks those with an impact parameter large enough are used. We integrate opposite-sign secondary tracks and determine their separation. If the distance is smaller than a certain threshold (0.5 mm in pp and 1 mm in Pb-Pb), and the point of closest approach is located before the first recorded points on both tracks, we keep the pair as a candidate for a secondary decay vertex. Some more cuts are then imposed in the subsequent analysis phase. In case of the D^+ decay vertices, a precise determination of the D^+ decay vertex is of high importance for the $D^+ \rightarrow K^- + \pi^+ + \pi^+$ analysis,

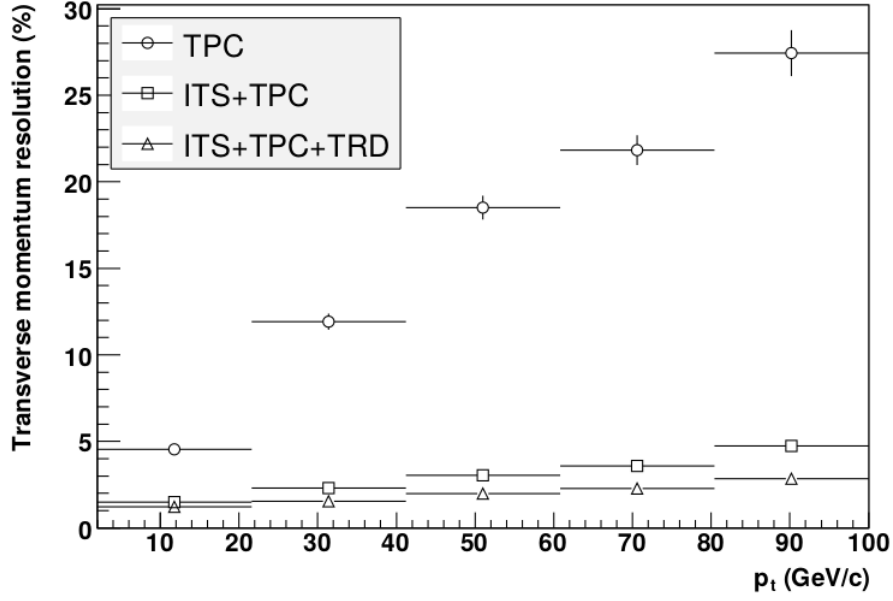


Figure 3.8: Transverse-momentum resolution for different combinations of the tracking detectors for pp collisions.

as many topological cuts we applied to select our candidates depend on it. As shown in Figure 3.9 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

3.3.2 Particle Identification

In ALICE, a number of sub-detectors, including the ITS, TPC, TRD, TOF, and HMPID, take part in the charged-Particle IDentification (PID). Each detector performs differently depending on momentum. Combining the data from the several detectors they each provide independently yields the best results. The process of identifying particles involves two parts. In the first, each track is given a set of probabilities, one for each type of particle, based on the information from each detector. These probabilities are added up and adjusted to one. For instance, a detector will assign equal probability to all particle kinds if it has no identifying power for a particular track. On the other hand, if the detector determines without a doubt that the track belongs to a specific type, it gives that type probability 1 and 0 to all

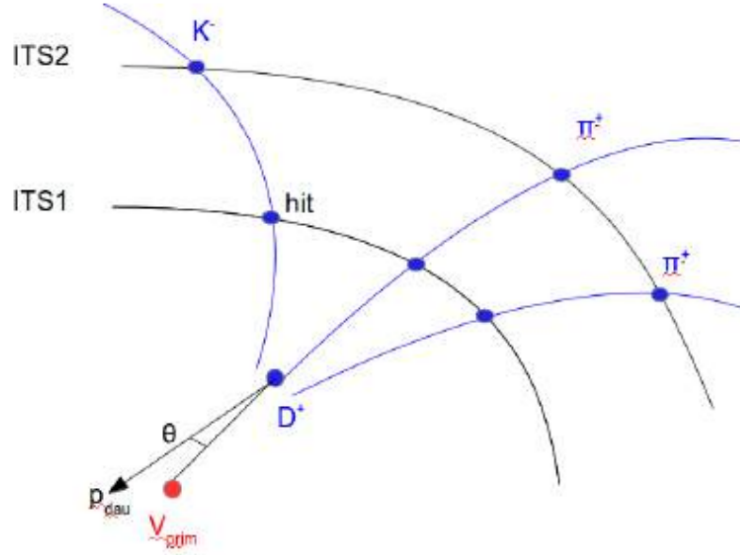


Figure 3.9: Example of a D^+ secondary vertex reconstruction. The blue lines represent the reconstructed charged particle tracks, extrapolated to the secondary vertex candidates.

other types. The combined PID process must ensure that in the first of these two extreme scenarios—where there is no identification power—the detector in question has no bearing on the outcome and that in the second—where there is an unambiguous identification—the detector in question has made a final decision that cannot be changed by data from other detectors.

- **ITS.** The signal-amplitude information from the ITS's four layers—two silicon-drift and two silicon-strip detector layers—can be used for PID in the low-momentum range by monitoring the ionisation energy loss dE/dx . The ITS dE/dx measurement has a resolution of around 11%, enabling good pi/K separation up to 450 MeV/textitc and good p/K separation up to about 1 GeV/ c .
- **TPC.** The charge deposited on up to 159 pad rows is measured by TPC. The charged-particle density has a small impact on the predicted resolution of the dE/dx measurement; it changes from 5.5% for pp events to 6.5% for centre Pb-Pb collisions.
- **TRD.** In the same momentum range as for the TPC, the measurement of dE/dx in the TRD contributes to charged-particle Particle Identification (PID). Due to the short TRD track length (the resolution scales as $\sqrt{L}$), even if the ionisation in the

TRD gas (based on xenon) is greater than that in the TPC gas (based on neon), the TRD dE/dx measurement is just a supplement to the TPC measurement. According to estimates, the TRD's dE/dx measuring precision is 18 to 20%.

- **TOF.** In the ALICE experiment the higher range (more than 4 GeV/ c) is covered by the TOF detector, that is able to measure a particle's arrival time with a precision of about 80 ps. The TOF detector allows us to extend, on a track-by-track basis, the kaon/pion separation out to 2.5-3 GeV/ c and the proton/kaon separation out to 3.5-4 GeV/ c .

- **HMPID.** The HMPID is used to broaden the momentum range for charged-particle identification, but only to a certain extent. The HMPID can detect protons with energies of up to 5 GeV/ c .

- **EMCal.** By measuring the energy deposition of electrons and comparing it to the measured track momentum (E/p), the Electromagnetic Calorimeter (EMCal) can identify specific electrons.

- **PHOS.** A high-granularity electromagnetic calorimeter that can also distinguish between electrons using the E/p approach is called the Photon Spectrometer (PHOS). In the analysis done in this thesis, particle identification is exploited to identify the pions and kaons coming from D⁺ mesons decay. To do this, PID information from TPC and TOF is used.

In the TPC particle identification is performed by simultaneously measuring the specific energy loss (dE/dx), the charge, and the momentum of each particle traversing the detector gas. The energy loss is measured by the Bethe-Bloch formula which is given by the equation:

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \cdot \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right] \quad (3.1)$$

Figure 3.10 shows the measured dE/dx variation for different particle species as a function of particle momentum in the TPC, where we can see a clear separation between the different particle species.

The TOF works together with the Time0 (T0) detector in order to provide the

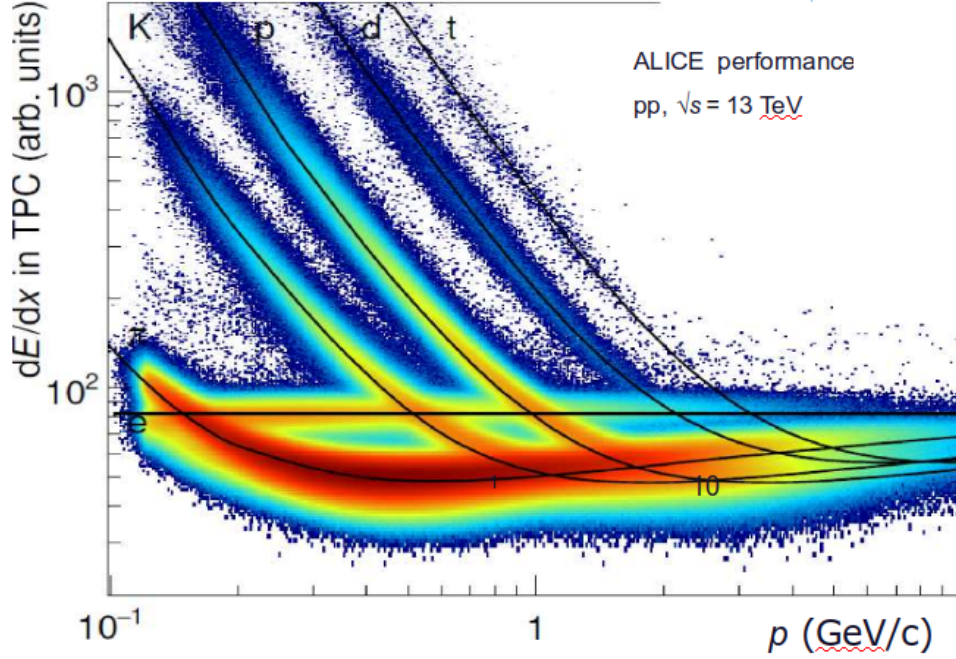


Figure 3.10: Specific energy loss (dE/dx) in the TPC vs. particle momentum in pp collisions.

time of flight of the particles reaching the detector. The interaction point (IP) is located at $-3.28 < \eta < -2.97$ and $-4.61 < \eta < -4.92$, respectively. The T0 detector is made up of two arrays of Cherenkov counters, T0C and T0A. Pb-Pb events have a TOF resolution of about 85 picosecond, while proton-proton events have a resolution of 100 picosecond. TOF can distinguish between pions from kaons up to 3 GeV/ c and kaon from protons up to 5 GeV/ c . An alternate approach was devised where the TOF information itself is used to establish the event time when at least three tracks contain a related TOF signal because the detector acceptance (especially in pp collisions) causes T0 to not see any signal are for a fraction of the events. Using a combinatorial method, this is accomplished by comparing the measured TOF times to the anticipated times of the tracks under the assumption of a shared event time t_0 . A χ^2 minimization method is employed to generate this latter amount. The recorded velocity β distribution as a function of track momentum is displayed in Figure 3.11 to demonstrate how well the TOF detector performs.

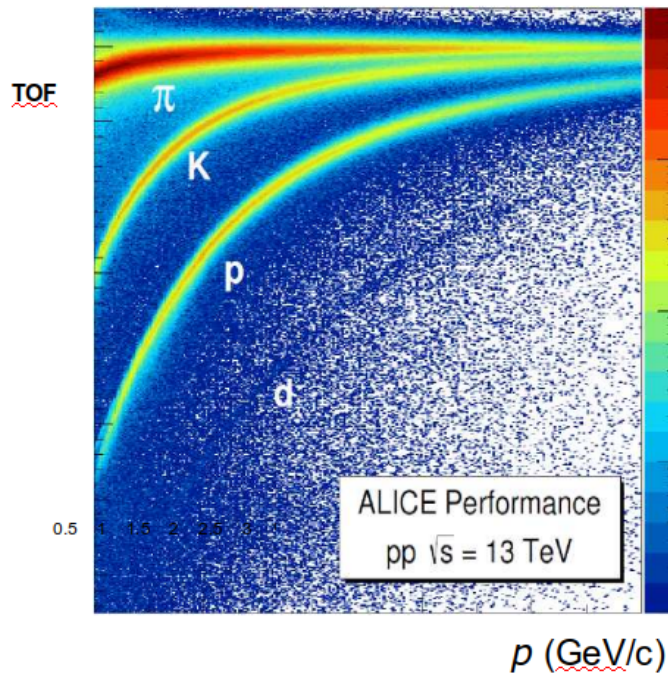


Figure 3.11: Specific energy loss (dE/dx) in the TOF vs. particle momentum in pp collisions.

4 Charmness in QGP

The heavy quarks charm and beauty have masses of $1.28 \text{ GeV}/c^2$ and $4.18 \text{ GeV}/c^2$, respectively. Their production cross-sections are calculable under the domain of perturbative QCD due to their enormous masses ($m_c, m_b \gg \Lambda_{QCD}$), providing a great test of pQCD computations. Therefore heavy quarks are valuable tools to study gluon saturation and their yield is also sensitive to the initial gluon density. Furthermore, any dynamical influence of the QGP medium on the development of heavy quarks is sensitive to the comparison of observables associated to the c-quark in pp and AA collisions.

Observables related to heavy quark production can be divided in two categories, hidden and open heavy flavour:

- **Hidden heavy flavour:** Hidden charm [charmonia= $(c\bar{c})$] and hidden beauty [bottomonia= $(b\bar{b})$] mesons (called collectively heavy quarkonia) are the bound states of the charm quark-antiquark pair, or bottom quark-antiquark pair, respectively. The dissociation owing to colour in heavy quarkonia could make it sensitive to the system's initial temperature. Hidden charm states are easily reconstructed through their decay into lepton pairs (e^+e^- or $\mu^+\mu^-$).

- **Open heavy flavour:** Open charm $D = (c\bar{q})$ and open beauty $B = (b\bar{q})$ mesons composed of a heavy quark $Q = (c, b)$ and a light antiquark $\bar{q} = (\bar{u}, \bar{d})$. Due to the mechanism of in-medium energy loss, these mesons could be very much sensitive to the energy density of the medium. They are experimentally detected by reconstructing their decay products:

- (a) hadronic decay modes: These allow a full reconstruction of the charm hadron

kinematics, i.e. the value of the open heavy-flavour hadron transverse momentum, azimuthal angle, etc. are measured.

(b) semileptonic decay modes: a high- p_T lepton coming from the open heavy-flavour hadron decay is detected. To separate leptons from charm and beauty hadron decays different analysis strategy are available (impact parameter studies, e-h correlations). This allows an inclusive measurement of open heavy-flavour hadron properties and theoretical models can be compared to the measured leptonic transverse momentum distributions.

4.1 Charm flavour production in pp collisions

The interaction between two protons is depicted in Figure .4.1, where two protons clash with a high center-of-mass energy and collide inelastically (several hundreds GeV). The two particles are interacting inelastically which leads to large momentum transfer(Q^2) among two constituent partons. In this example two valence quark interact, but at this energy regime sea quarks and gluons can also contribute.

Before the collision the valence quarks of the protons are constantly held together by the exchange of virtual gluons. These are mostly soft gluons, like a and b, and are responsible for the QCD confinement. The inelastic scattering in the red box (Figure .4.1) is characterized by large momentum transfer and this happens on a time scale which is very short. This means that the interactions mediated by soft-gluons with the rest of the proton can be neglected, since they happen on a longer time scale. The impacted quark just does not have enough time to communicate with the proton that it is being kicked away. The proton fragments excluded from the hard scattering will continue their evolution interacting on a low momentum scale and hadronizing into colorless states, constituting the *Underlying Event* (UE-yellow box).

In the hard scattering, a $q\bar{q}$ pair is generated , which could be a $c\bar{c}$ pair. These two quarks will emit gluons, which in turn generate quark pairs and so on (parton shower). The evolution depicted above can be expressed by the factorization theorem:

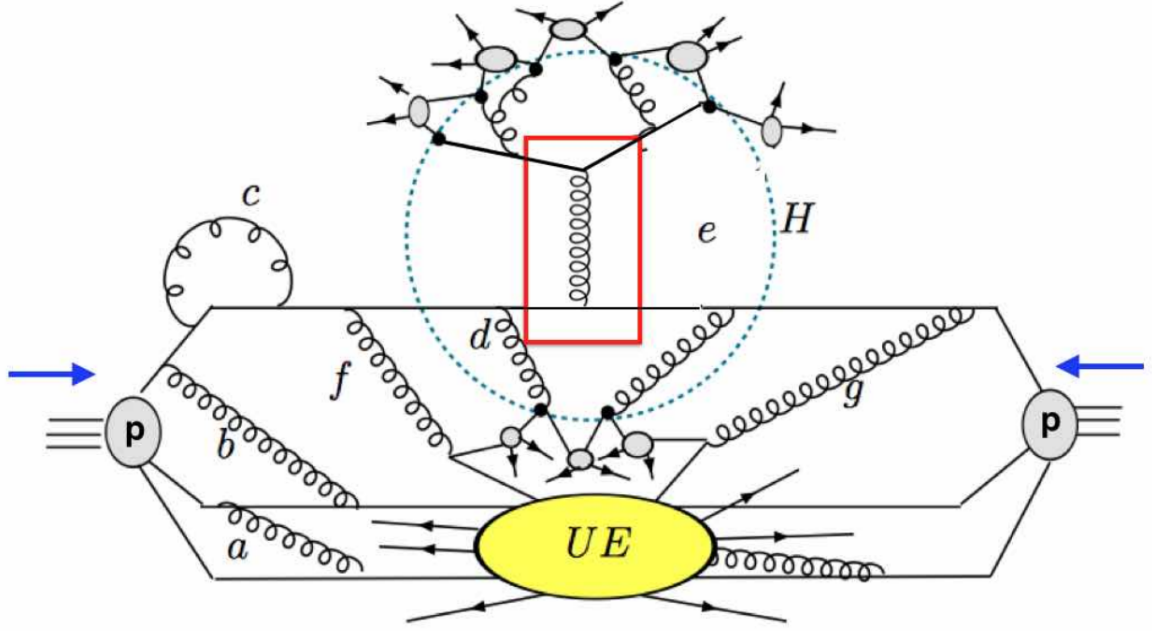


Figure 4.1: Schematic view of a pp interaction in which a hard scattering between two valence quarks (red box) takes place.

$$\sigma_{pp \rightarrow Hx} = \sum_{a,b} PDF(x_a, Q^2) PDF(x_b, Q^2) \sigma_{ab \rightarrow q\bar{q}} D_{q \rightarrow H}(z_q, Q^2) \quad (4.1)$$

where $\sigma_{pp \rightarrow Hx}$ is the inclusive cross-section for the production of a given hadron H in pp collisions and:

- the sum runs over all the possible combinations of parton pairs participating to the hard scattering, including sea quarks and gluons.
- $\sigma_{ab \rightarrow q\bar{q}}$ represents the partonic cross section for the production of a $q\bar{q}$ quark pair. For a given hard interaction (which is due to large momentum transfer), this cross section is calculable with perturbative QCD.
- $PDF(x_a, Q^2)$ and $PDF(x_b, Q^2)$ represents the Parton Distribution Functions of the two partons involved in the interaction inside the protons. They are the probabilities of the fraction of proton momentum carried by the interacting parton.
- $D_{q \rightarrow H}(z_q, Q^2)$ is the quark fragmentation function and represents the probability that the quark q produces a hadron H carrying a fraction z of its momentum.

The production of light quarks and gluons, which have low (or zero) mass, is also possible via soft processes. This means that in order to present a theoretical account of light flavour hadron generation, non-perturbative components of QCD must be considered. If the $q\bar{q}$ produced in the hard scattering are $c\bar{c}$ (or $b\bar{b}$) pairs, their mass $m_c \gg \Lambda_{QCD}$ will set a scale for the momentum transfer of the binary partonic interaction, assuring that its cross section will be calculable by perturbative QCD. This means that the study of charmed hadrons allows to better separate the non-perturbative and perturbative factors of Equation 4.1 when observing a hadronic cross-section.

4.2 Charm flavour production in heavy-ion collisions

Heavy $Q = c, b$ quarks play a unique role as probes of the heavy-ion collision (HIC) medium since their masses are far greater than normally obtained ambient temperatures or other nonperturbative scales. They are produced in the initial phases of hard scattering. They have a shorter formation time ($\Delta t \sim 0.1$ fm/c) than QGP ($\Delta t \sim 0.3$ fm/c) at the LHC and hence are better probes of hot QCD medium since they go through all the stages of the evolution of the hot and dense medium created in heavy-ion collisions. After the formation of the QGP, the inelastic scattering among partons occur in the QGP fireball, the characteristic temperature in this phase are too low for thermal heavy-flavour production, whose contribution is small even at RHIC and LHC energies. Figure 4.2 displays the space-time evolution of heavy-ion collision in which the different stages of heavy quark journey right from its production to hadronization into heavy-flavour hadrons.

The heavy quarks production in AA collisions is proportional to the total number of binary collisions N_{coll} that took place in the nuclear interaction. But how can we extract information from heavy-flavour probes in heavy-ion collisions? From equation 4.1 we need to take care of the fact that the Parton Distribution Functions (PDF) are modified in a nuclear environment. Furthermore, in the case of heavy ion

state occurs. They include the interaction of the heavy-quark with the medium and the way it hadronizes.

If these effects influence heavy-quark production and dynamics, we cannot consider ultrarelativistic heavy-ion collisions as a superposition of incoherent nucleon-nucleon interactions.

When a measurement is made of the yield of some observable in AA collisions, we define the nuclear modification factor as the ratio of the observables yield in AA collisions and the one in pp collisions scaled by the average number of binary collisions $\langle N_{coll} \rangle$ obtained from Glauber calculation for the AA centrality class considered

$$R_{AA} = \frac{Yield^{AA}}{\langle N_{coll} \rangle Yield^{pp}} \quad (4.2)$$

In the case where the modification of the p_T distributions occurs, R_{AA} can be expressed as:

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll} \rangle dN^{pp}/dp_T} \quad (4.3)$$

If there is no modification (due to either cold or hot nuclear matter effect), we expect R_{AA} to be equal to 1, and AA collisions can be treated as a superposition of N_{coll} nucleon-nucleon collisions. On the contrary any modification in the production rate and the momenta distributions of the considered observables in nuclear collisions leads to an R_{AA} different than 1.

The same observable can be computed in pA collisions as:

$$R_{pA}(p_T) = \frac{dN^{pA}/dp_T}{\langle N_{coll} \rangle dN^{pp}/dp_T} = \frac{d\sigma^{pA}/dp_T}{A \cdot d\sigma^{pp}/dp_T} \quad (4.4)$$

4.2.1 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 a hot deconfined medium but to the fact that the colliding

particles are nuclei. The presence of a nucleus in the initial state induces modifications in the heavy quarks production mechanism with respect to what happens in pp interactions. They are expected to affect both proton-nucleus and nucleus-nucleus collisions. Cold nuclear matter effects can be divided in initial state and final state effects.

Initial state effects: These effects mainly include:

- nuclear modification of the PDFs
- k_T broadening and Cronin enhancement

The modification of the *parton distribution functions (PDFs)* in nuclei with respect to a nucleon is considered as an initial state effect [67]. Different regions can be distinguished in the modification of the nuclear PDFs depending on the value of the Bjorken scaling variable x . We utilise the variable $R_{F_2}^A(x, Q^2)$ to assess the change which is defined as:

$$R_{F_2}^A(x, Q^2) = \frac{F_2^A(x, Q^2)}{A \cdot F_2^{nucleon}(x, Q^2)} \quad (4.5)$$

where $F_2^A(x, Q^2)$ and $F_2^{nucleon}(x, Q^2)$ 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 is shown in Figure 4.3. The following regions can be defined as:

- shadowing region: $R_{F_2}^A(x, Q^2) < 1$ for $x < 0.1$;
- anti-shadowing region: $R_{F_2}^A(x, Q^2) > 1$ for $0.1 < x < 0.3$;
- EMC region: $R_{F_2}^A(x, Q^2) < 1$ for $0.3 < x < 0.8$;
- Fermi motion region: $R_{F_2}^A(x, Q^2) > 1$ 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}).

The Initial state effects also have an impact on the colliding partons before the

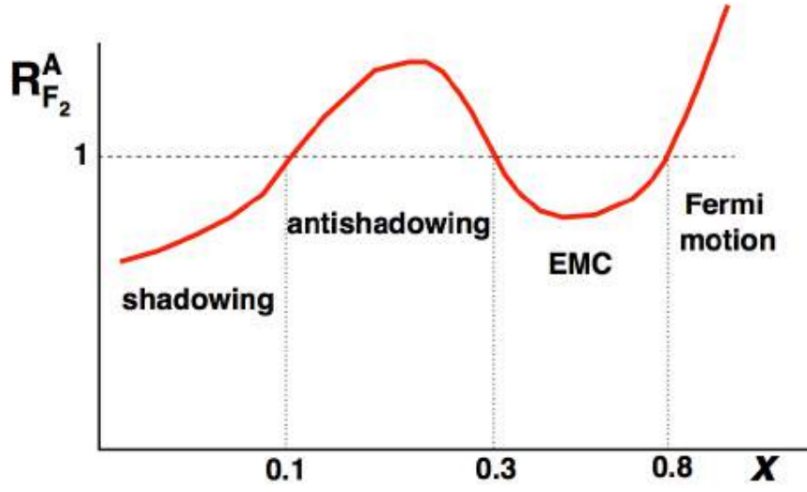


Figure 4.3: $R_{F_2}^A(x, Q^2)$ as a function of the scaling variable x .

hard process takes place, as the k_T -broadening. It can be interpreted as a consequence of multiple elastic scatterings of the projectile parton with the partons of the other nucleus in the nucleus prior to the hard scattering (Figure 4.4). These elastic interactions provide to the projectile parton an initial extra quantity of transverse momentum before the hard scattering occurs, leading to a broadening of the momentum distributions for the produced heavy quarks. In this way an average transverse square-momentum is acquired by the incoming partons crossing the other nucleus, which causes 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. The so-called Cronin enhancement was first observed in fixed-target experiments at Fermilab [68]. This effect consists in an enhancement above unity of the nuclear modification factor of produced particles at intermediate p_T (2-6 GeV/c).

Final state effects: These effects are the phenomena due to the interaction between the produced heavy quarks with the cold nuclear matter. In addition to this, they also include processes in which the heavy flavoured hadron (produced in the heavy quark hadronization) interacts with the hadronic matter. There have been several indications which suggest the creation of a dense medium in pA collisions

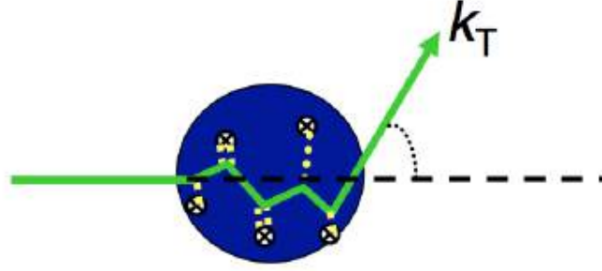


Figure 4.4: Schematic view of the effect of multiple scattering that affect a parton before the hard interaction occurs.

that exhibits some kind of collective behaviour. For example, in d-Au collisions at RHIC, the nuclear modification factor of protons as a function of p_T showed a faster rise with respect to the R_{dAu} of pions and kaons [69]. The observed mass hierarchy could be described by the presence of a collective expansion of the system. At the LHC, the presence of final state interactions in proton-nucleus collisions fits with the observation of a ridge-like structure in the correlation between pairs of particles formed in high-multiplicity collisions. The measurements were performed by the CMS [70, 71] and the ALICE collaborations for charged particles and identified particle respectively.

Studying of cold nuclear matter effects is not straightforward when one looks at A-A results, since the modification of transverse momentum spectra with respect to pp collisions could also be due to the creation of the QGP which affect the particle production. However cold nuclear matter effects can be studied in p-A collisions, under the assumption that energy densities and temperature achieved in this kind of collisions are not high enough for an extended QGP phase to form.

4.2.2 Hot nuclear matter effects

The $c\bar{c}$ (or $b\bar{b}$) pairs are produced in the very early stages of a AA collision which provide a very good probes of the high-density medium created in the interaction.

The interactions of these heavy quarks with the medium constituents modify their dynamical properties. Hot nuclear matter effects can be observed experimentally as a result of the modification of the transverse momentum spectrum of charmed and beauty hadrons in heavy-ion collision as shown in Figure 4.5. In particular, this 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.

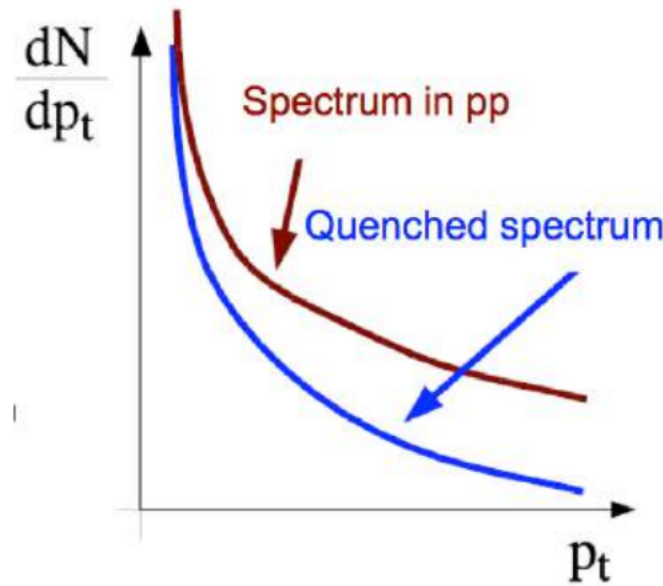


Figure 4.5: Effect of the in-medium energy loss of charm quarks on the p_T spectrum of heavy flavoured mesons.

• Radiative energy loss

The radiative energy loss, also called as *gluonsstrahlung*, is a phenomenon which causes the emission of gluons from high- p_T partons due to the QCD interactions of the particles with the deconfined medium. This process is analogous to the QED brehmstrahlung of high-energy electrons traversing ordinary matter. Gluon-sstrahlung 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:

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda_{mfp}} \quad (4.6)$$

where k_T is the transverse momentum which is transferred in the parton interaction with the medium. A schematic view of the induced gluon radiation off a hard parton due to the scattering centres in the medium is shown in the Figure 4.6. This formula can be used to describe the average energy loss owing to gluon radiation in the high-energy completely coherent regime:

$$\langle \delta E \rangle \propto \frac{1}{4} \alpha_s C_r \hat{q} L^2 \quad (4.7)$$

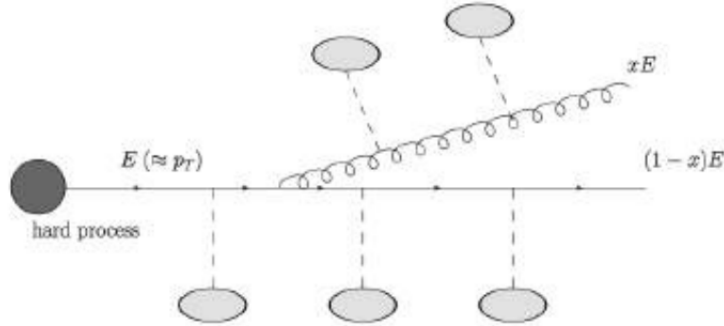


Figure 4.6: Schematic view of the medium-induced gluon radiation off a hard parton due to its interaction with the scattering centres in the medium.

where C_r is the Casimir factor of the parent high-energy parton and L is the in-medium path length. In the first approximation, the average energy loss is independent of the parton's initial energy, 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 in the energy loss valuation, i.e. the *dead cone effect* [72]. In gauge theories, the dead cone is a well-known effect in which radiation

from a charged particle with mass m and energy E is inhibited within an angular radius of m/E . For massive quarks, this effect causes a suppression of gluon emission at small angles with respect to the emitting parton direction, modifying the gluonsstrahlung spectrum. This effect is relevant up to an energy of the heavy quark $E_{HQ} = M\sqrt{\hat{q}L^3} \sim 100\text{GeV}$ at LHC energies [73]. The inclusion of the dead cone effect clearly reduces the energy loss of heavy quarks and a mass hierarchy is expected for quarks and gluons:

$$\Delta E_{gluons} > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \quad (4.8)$$

and one can expect:

$$R_{AA}(b) > R_{AA}(c) > R_{AA}(g, u, d, s) \quad (4.9)$$

However this relation has to be interpreted keeping in mind that the initial transverse momentum spectrum of quarks produced in the collisions plays a role in the final R_{AA} of hadrons that one observes. In 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. Instead, all heavy-flavoured hadrons, due to their large masses, originate from the hadronization of heavy quarks. For a given value of ΔE , the steeper the transverse momentum distribution of the quark, the lower the resulting nuclear modification factor will be. 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.

• **Collision energy loss:** The second phenomenon that plays a role in parton energy loss is the elastic collisions with the medium constituents. Ionization energy loss of charged particles in ordinary matter via electromagnetic interactions is ex-

tremely similar in structure to this mechanism. It has a non negligible effect for heavy quarks at RHIC and LHC energies in the low transverse momentum region. The Coloumb scattering and the Compton scattering with thermal gluons are the two partonic processes that have to be considered. The scattering amplitude is given by the Feynman diagram shown in Figure 4.7, 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 [74].

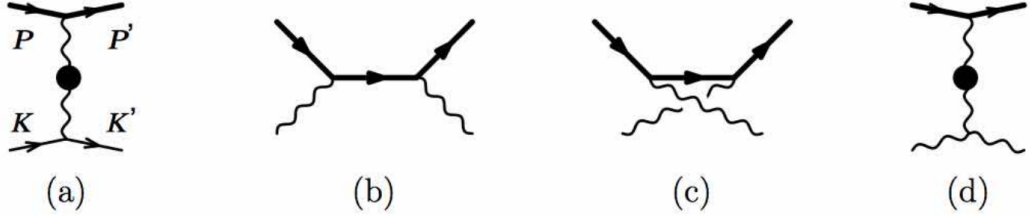


Figure 4.7: Amplitudes for heavy quark elastic scattering in a QGP. A curly line denotes a gluon.

In Figure 4.8 a theoretical calculation of the energy loss as a function of p_T is shown for RHIC energy ($\sqrt{s_{NN}} = 200$ GeV, left [75]) and as a function of their initial energies (right [76]) for charm quarks. The radiative contribution starts to dominate for charm quark with transverse momentum $p_T \sim 10$ GeV/ c . The first quantitative calculations of this effect was performed by Bjorken [77] and a similar formalism was carried out by Peigne' in [78] for heavy and light quarks with initial energy $E \gg T, m_q$, where m_q is the mass of the light constituents of the medium.

4.3 Hadronization

In heavy-ion collisions hadronization of partons could occur in two different ways: fragmentation and recombination. Figure 4.9 shows a schematic view of the effect of the two mechanisms on the hadron transverse momentum spectrum. In the case

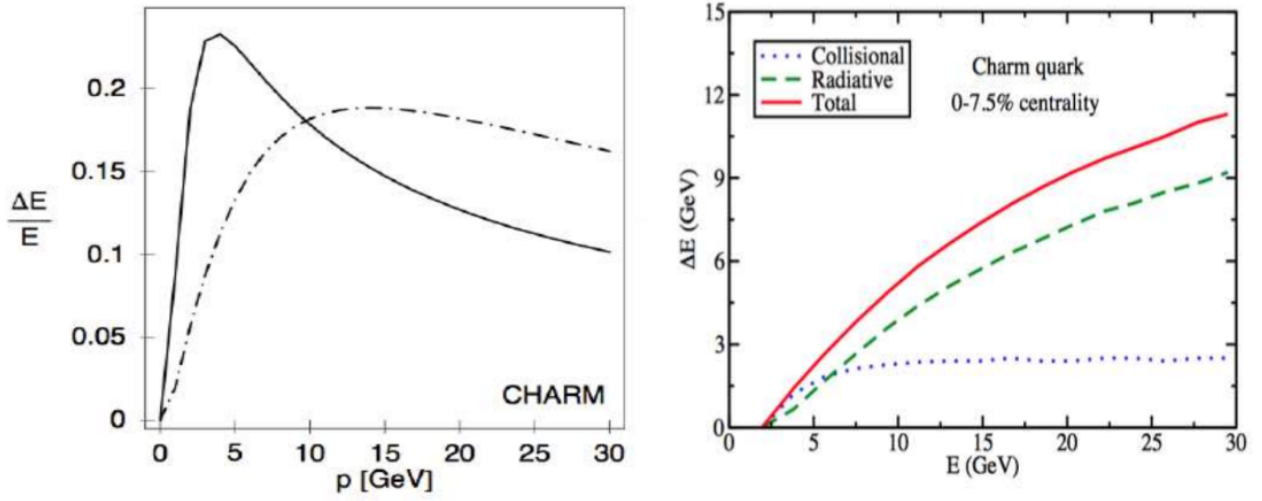


Figure 4.8: Left: Comparison between collisional and radiative fractional energy loss as a function of the momentum for charm quarks for $\sqrt{s_{NN}} = 200$ GeV. Radiative energy loss is shown with a dashed curve while the full curve shows the collisional energy loss contribution. Right: energy loss of charm quarks as a function of their initial energies

of fragmentation, 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 combining quarks 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).

4.4 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. D-mesons are the

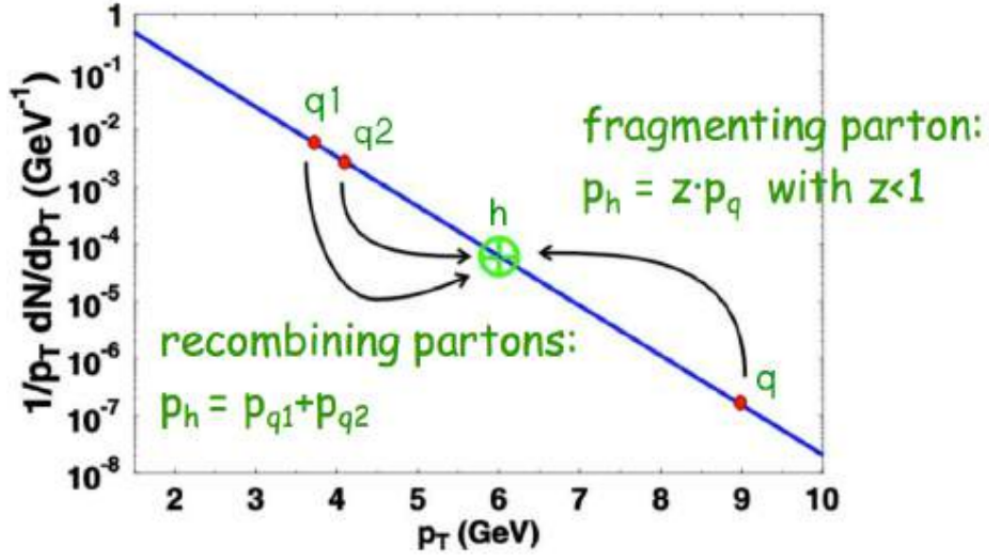


Figure 4.9: Schematic view of the effects of fragmentation and recombination on the transverse momentum spectrum of heavy-flavoured hadrons.

lightest particle containing charm quarks. The decay of charm quark takes place via weak interaction.

4.4.1 Results in pp collisions

The production of D meson was studied in pp collisions at RHIC and LHC. The different hadronic decay channels of D mesons are used to recreate them are:

- $D^0 \rightarrow K^- \pi^+$, $c\tau = 123\mu m$, $B.R = (3.95 \pm 0.031)\%$
- $D^+ \rightarrow K^- \pi^+ \pi^+$, $c\tau = 311.8\mu m$, $B.R = (9.38 \pm 0.16)\%$
- $D^{*+} \rightarrow D^0 \pi^+$, strong decay, $B.R = (67.7 \pm 0.05)\%$
- $D_s^+ \rightarrow \phi(\rightarrow K^- K^+) \pi^+$, $c\tau = 151.2\mu m$, $B.R = (2.24 \pm 0.08)\%$

In Figure 4.10, the invariant cross section of electrons from decays of charm and beauty hadrons measured by PHENIX in pp collisions at $\sqrt{s} = 200$ GeV [79]. A black line, representing FONLL calculations [80] for inclusive electrons from heavy-flavour decays, is superimposed to the data. In red and green the beauty and charm con-

tributions are plotted, respectively. According to FONLL, the beauty contribution dominates for transverse momenta above 4 GeV/c. Practically, all of the p_T range, the centre values of FONLL projections underestimate charm and beauty generation at RHIC energies.

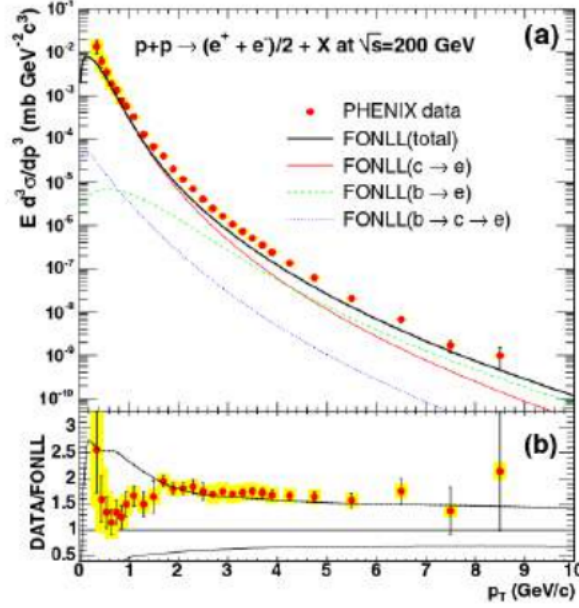


Figure 4.10: Invariant differential cross sections of electrons from heavy-flavour decays measured by PHENIX in pp collisions at $\sqrt{s} = 200$ GeV. The data is compared to FONLL calculations.

In Figure 4.11 to Figure 4.13 the p_T -differential cross sections are shown for prompt D mesons from fully reconstructed hadronic decays, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^{*+} \rightarrow D^0 \pi^+$ and $D_s^+ \rightarrow \phi(\rightarrow K^- K^+) \pi^+$ measured with ALICE in pp collisions at $\sqrt{s} = 7$ TeV [81]. The results are compared to FONLL [82] and GM-VFNS [83] 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.

Multiplicity dependence of D-meson yields: For various p_T ranges of the D-mesons, the self-normalized yields of D^0 , D^+ , and D^{*+} were assessed as a function of the charged-particle multiplicity normalized by their average in multiplicity-

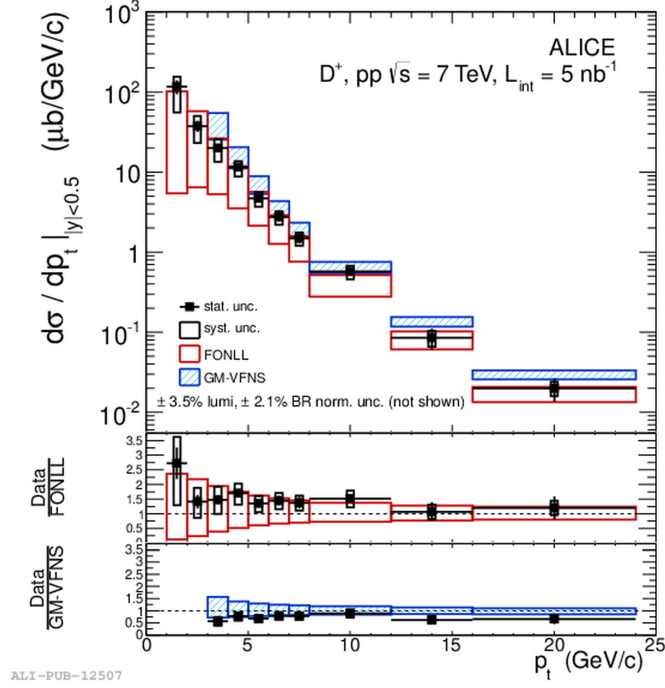


Figure 4.11: p_T -differential cross sections of $D^+ \rightarrow K^-\pi^+\pi^+$ measured by ALICE in pp collisions at $\sqrt{s} = 7$ TeV compared to FONLL and GM-VFNS predictions.

integrated events. [84, 85]. The self-normalized yields of average D-meson pp collisions are shown Figure 4.14 for different D-meson p_T ranges from 1 to 20 GeV/ c . Within uncertainties, a trend that is independent of the D-meson p_T with a faster-than-linear increase with multiplicity may be seen.

A comparison of the self-normalized yields derived using data and forecasts from the percolation models EPOS 3 and PYTHIA is shown in Figure 4.15." Each of these models accounts for the Multiple-Parton Interactions (MPI) contribution to particle generation. All of the models show a qualitative agreement with the data, but only at high multiplicities. The growing tendency with multiplicity as seen in the data appears to be underestimated by PYTHIA8 [86] and EPOS 3 [87] simulations without considering the collision's hydrodynamical history.

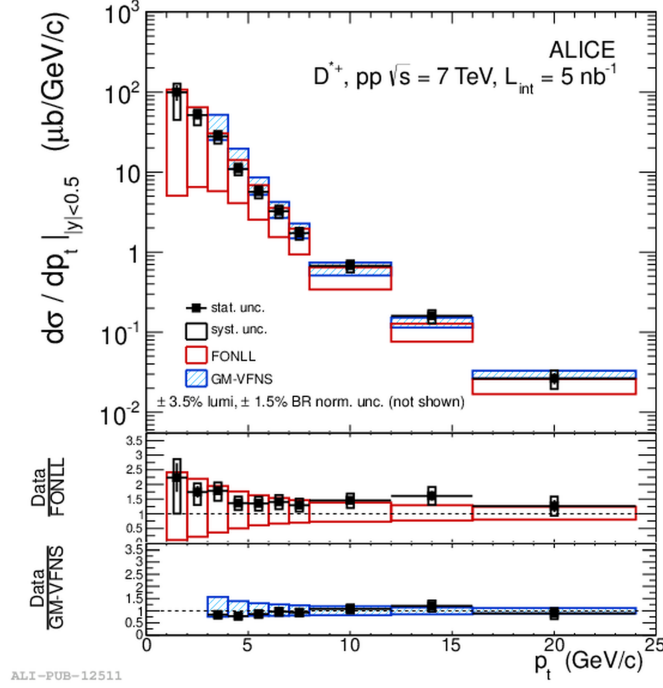


Figure 4.12: p_T -differential cross sections of $D^{*+} \rightarrow D^0 \pi^+$ measured by ALICE in pp collisions at $\sqrt{s} = 7$ TeV compared to FONLL and GM-VFNS predictions.

4.4.2 Results in pA collisions

Cold Nuclear Matter effects are visible and can be studied in p-A collisions. CNM effects are quantified by measuring the nuclear modification factor R_{pA} . R_{pA} is expected to be ~ 1 , which indicates that no medium is created in p-Pb collisions. The nuclear modification factor in pA collisions is defined by the equation 4.4. Figure 4.16 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 [88]. The R_{dAu} measured by the PHENIX Collaboration shows an enhancement above unity up to $p_T = 5$ GeV/c. Figure 4.17 displays the R_{pPb} of average D-mesons from the hadronic decay channels measured with ALICE in minimum-bias p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [89] as a function of the transverse momentum. The results are compatible with unity in almost all the p_T interval studied. Data are compatible with theoretical calculations [90, 91, 92] that include initial state effects within the uncertainties.

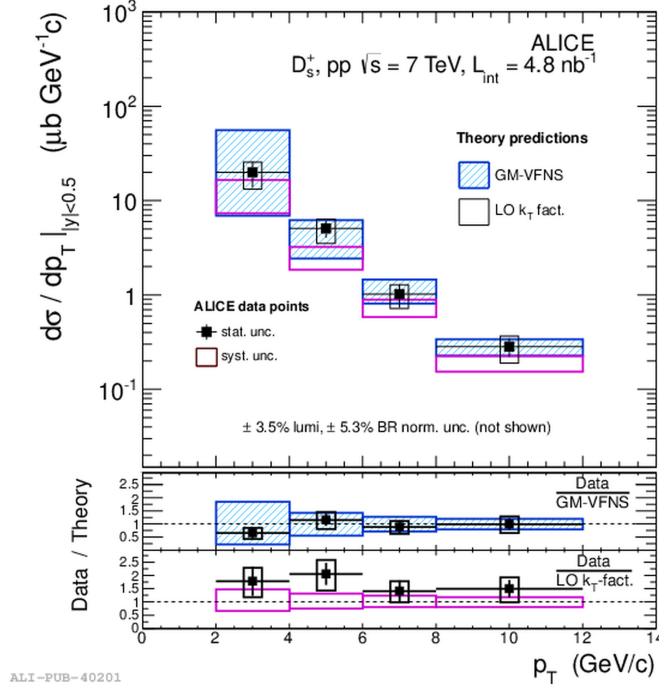


Figure 4.13: p_T -differential cross sections of $D_s^+ \rightarrow \phi(\rightarrow K^- K^+) \pi^+$ measured by ALICE in pp collisions at $\sqrt{s} = 7$ TeV compared to FONLL and GM-VFNS predictions.

In Figure 4.18, the data is compared with transport model calculations Duke [93] and POWLANG [94]. These models assume that QGP formation takes place in p-Pb collisions. With the current precision, it is very much difficult to discriminate between the two scenarios, with QGP formation or with only CNM effects. The data seem to disfavour a suppression larger than 15-20% in p_T interval $5 < p_T < 10$ GeV/ c .

D meson production in p-Pb collisions has also been studied as a function of the charged-particle multiplicity [84]. A similar enhancement of the average D-meson yields has been observed in pp collisions at $\sqrt{s} = 7$ TeV (as shown in Figure 4.19 and Figure 4.20). However, in p-Pb collisions in addition to the contribution by the MPI, the CNM effects and the multiple binary nucleon collisions also contributes and should be taken into account.

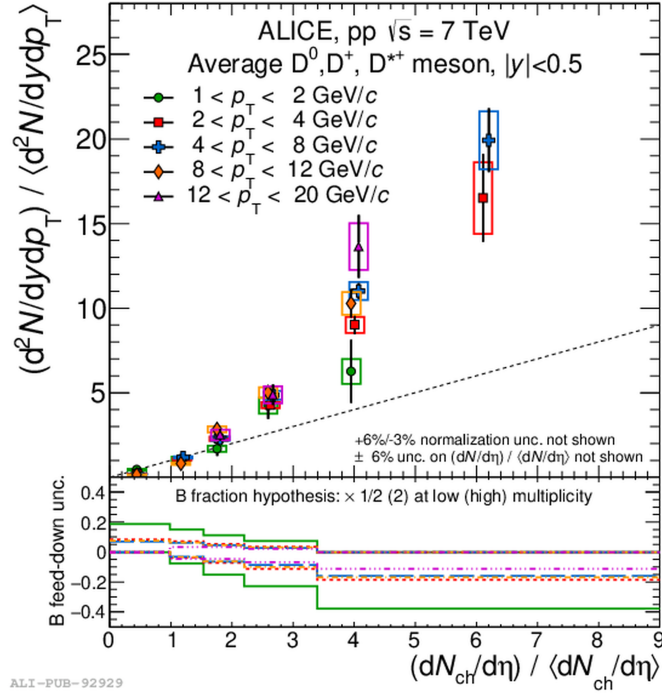


Figure 4.14: Average of D^0 , D^+ and D^{*+} relative yields in pp collisions at $\sqrt{s} = 7$ TeV, as a function of the relative charged-particle multiplicity at central rapidity in several p_T intervals. The results are presented with their statistical (vertical bars) and systematic (boxes) uncertainties, except for the feed-down fraction uncertainty that is drawn separately in the bottom panels.

4.4.3 Results in AA collisions

STAR and ALICE experiment determined the differential production cross section for open charm mesons. Figure 4.21 shows the measurement of R_{AA} for D^0 mesons in the most central Au-Au collisions by the STAR experiment [95]. It shows an enhancement at around 1.5 GeV/ c and shows a strong suppression at $p_T > 3$ GeV/ c . The ALICE experiment measured the production of D^0 , D^+ and D^{*+} in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [96]. The average value of R_{AA} for D mesons, for two centrality classes, is shown in Figure 4.22. For the most central events D-meson yield at high- p_T shows strong suppression, by a factor four at 10 GeV/ c . The Pb-Pb collisions allowed to extend the similar measurements to much higher momenta, at which a similar suppression pattern up to 30 GeV/ c is observed [97]. Another observable that is measured in nucleus-nucleus collisions in both RHIC and LHC is the elliptic

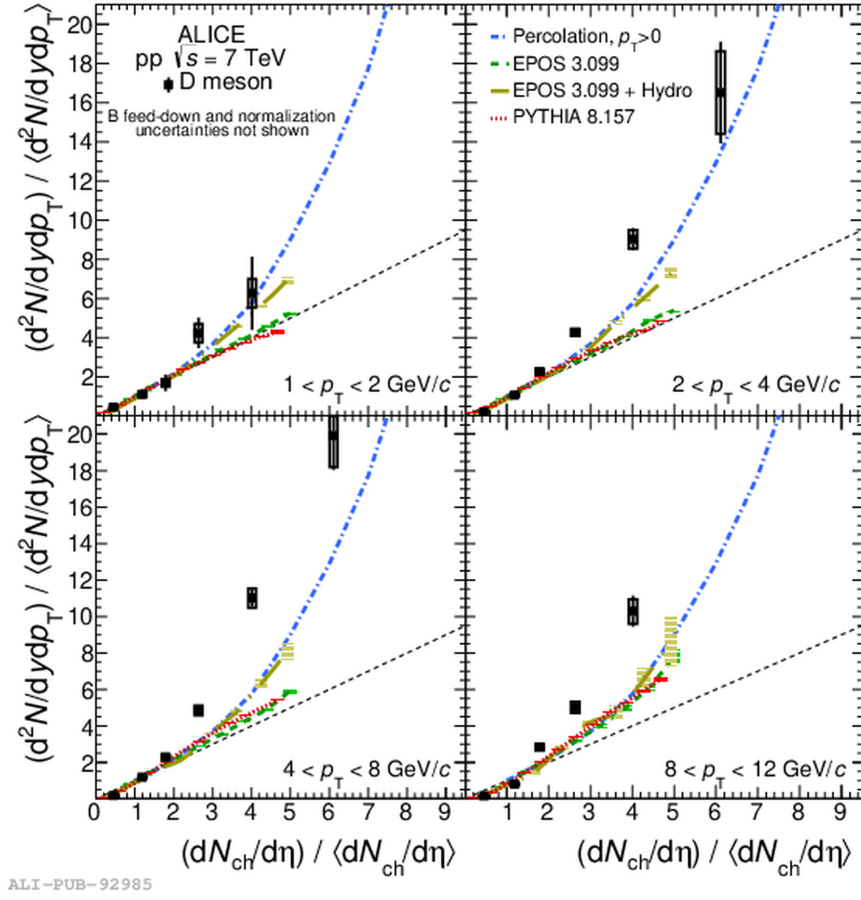


Figure 4.15: Results compared with calculations of several event generators with hard and soft components. The position of the points on the abscissa is the average value of $(dN_{ch}/d\eta)$.

flow of open heavy flavour hadrons. In the Figure 4.23 the elliptic flow of electrons from decays of open heavy flavour measured in minimum-bias Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV with PHENIX is shown [98]. At low transverse momentum region positive v_2 is measured which gives first indication of the sensitiveness of heavy quarks to the collective expansion of the medium created in heavy-ion collisions. This is also confirmed by ALICE measurement of D-mesons v_2 in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the centrality class 30-50% [99] as shown in the Figure 4.23. For the weighted average of D^0 , D^+ and D^{*+} a positive v_2 (with a mean value ~ 0.2) is observed in $2 < p_T < 6$ GeV/ c region. This observation is similar to the result observed for light-flavour hadrons v_2 . This suggests that even the charm quark is affected by collective motions, despite its large mass. The D-meson v_2 is also compared

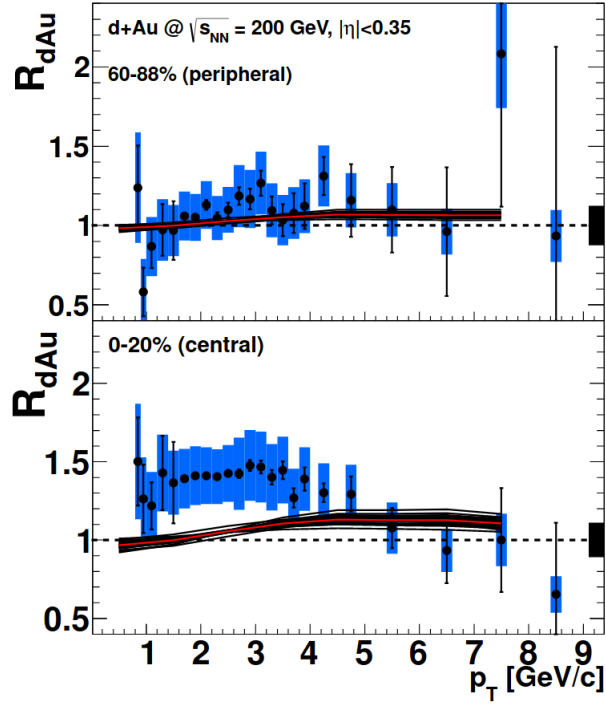


Figure 4.16: Nuclear modification factor, R_{dAu} , for electrons from open heavy flavour decays measured with PHENIX in minimum-bias d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

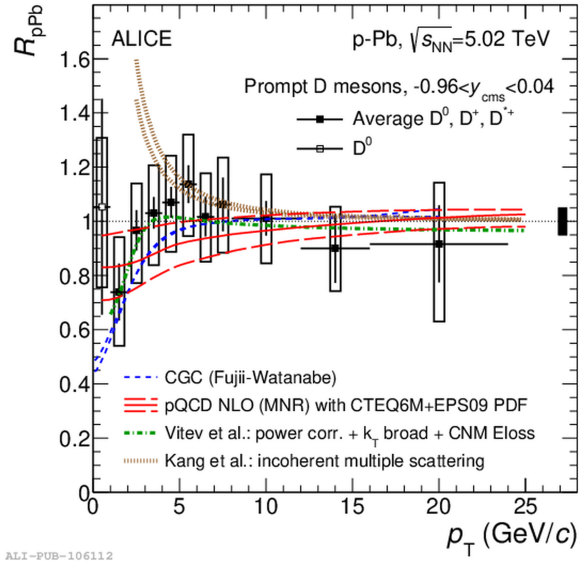


Figure 4.17: D-meson R_{pPb} , averaged for the three mesons, measured with ALICE in minimum-bias p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of the transverse momentum. The result is compared to theoretical calculations.

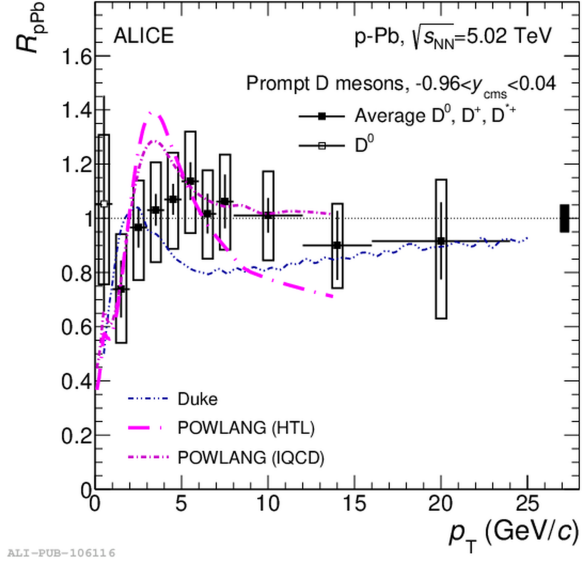


Figure 4.18: Same data as on Figure 4.17. Here the results are compared to the results of the Duke and POWLANG transport models

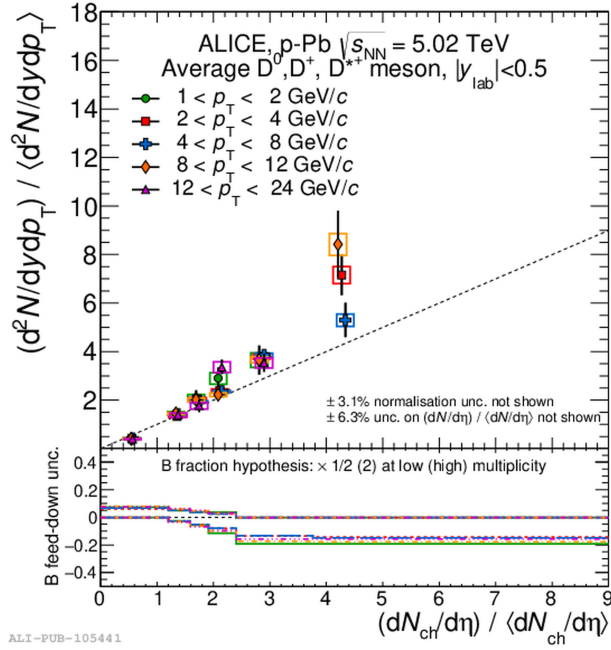


Figure 4.19: Average of D^0 , D^+ and D^{*+} relative yields in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as a function of the relative charged-particle multiplicity at central rapidity in several p_T intervals.

with theoretical models. Models that account for both charm quark energy loss in a geometrically anisotropic medium and mechanisms that transmit the induced elliptic

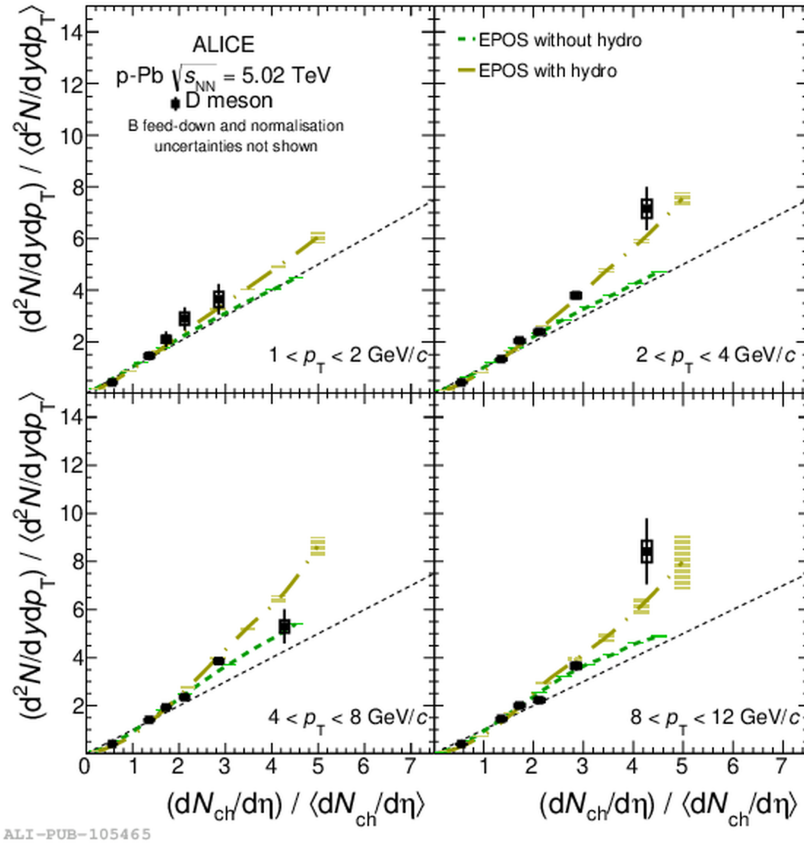


Figure 4.20: Results for the average D-meson yields vs relative charged-particle multiplicity at central rapidity, compared with EPOS 3

flow to charm quarks during system expansion are used to qualitatively describe the data. A lesser anisotropy than that reported in the data is generally predicted by models that do not account for the hadronization of charm quarks by recombination with light quarks in the medium or a collective expansion of the media. It is still difficult to simultaneously describe R_{AA} and v_2 at RHIC and LHC energies.

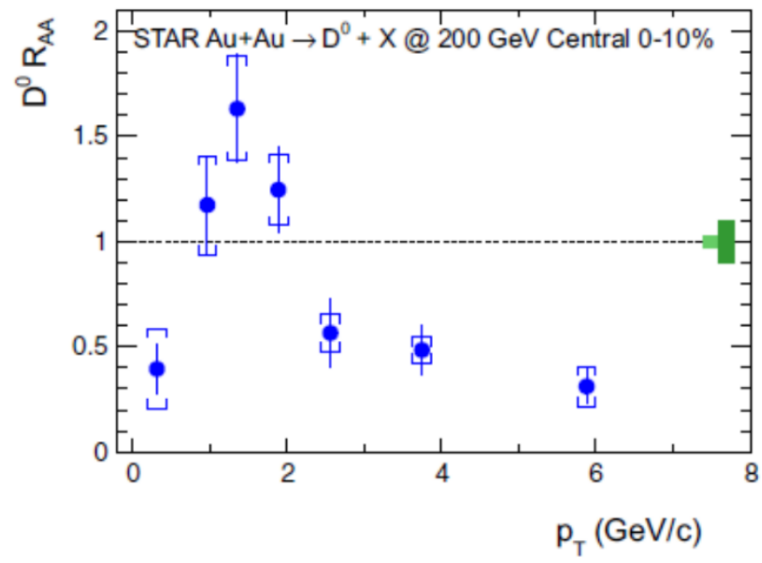


Figure 4.21: Transverse momentum dependence of the nuclear modification factor R_{AA} of D^0 mesons in the 10% most central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

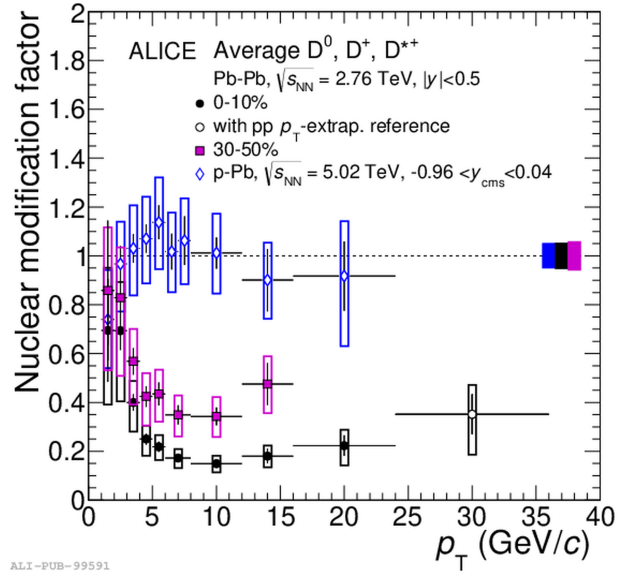


Figure 4.22: R_{AA} of prompt D mesons (average of D^0, D^+ and D^{*+}) versus p_T for 0-10% and 30-50% centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

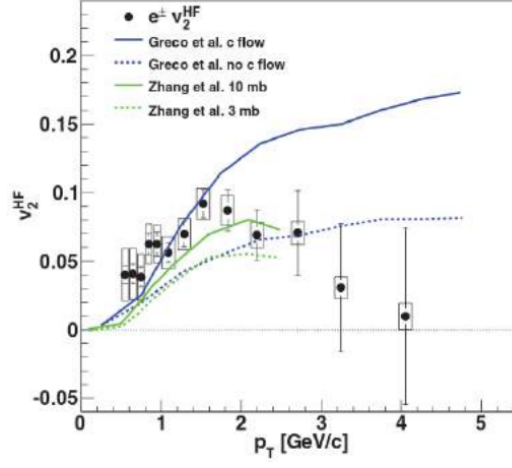


Figure 4.23: v_2 of electrons from open heavy-flavour decays as a function of p_T measured with PHENIX in minimum-bias Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV compared with theoretical calculations.

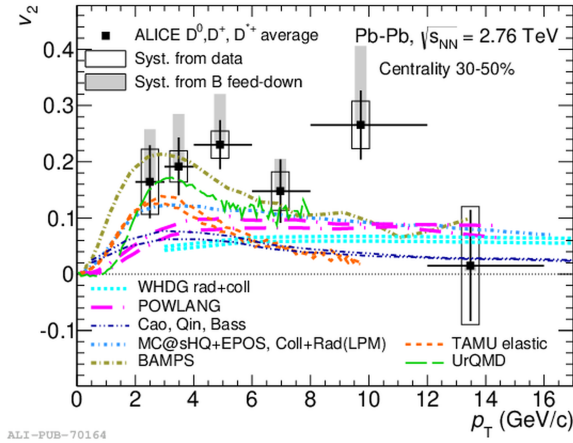


Figure 4.24: D-meson v_2 , averaged for the three mesons, measured by ALICE in semi-peripheral Pb-Pb collisions (30-50%) at $\sqrt{s_{NN}} = 2.76$ TeV as a function of the transverse momentum

5 Open Charm (D^+) vs multiplicity in pp collisions

Measurements in heavy flavor production in proton-proton (pp) collisions at the Large Hadron Collider (LHC) provides stringent test to perturbative Quantum Chromodynamics (pQCD) calculations. The study of heavy flavor production versus charged particle multiplicity provides information on the processes occurring at the microscopic level and the interplay between hard and soft processes in such collisions. The presence of charm with higher multiplicities led to believe the importance of multi parton interactions (MPI) and its role in heavy flavor production at higher energies. As the contribution of MPI at higher center of energies is expected to be large, it has the dependence on particle production. On a hard scale it is expected that MPI can have a significant contribution to introduce a correlation between D meson yields and charged particle production. A similar measurement was carried out for average D-meson (D^0 , D^+ , D^{*+} as displayed in Figure 5.1 [100]) production versus charged particle multiplicity at $\sqrt{s} = 7$ TeV where a stronger than linear correlation was observed. Similar measurements were also done for J/ψ at 7 TeV and 13 TeV ([101]). The study was performed in different intervals of multiplicity and transverse momentum (p_T). In this analysis, the data collected by the ALICE experiment during RUN-2 of the LHC is used. This data is collected for pp collisions at a higher center of mass energy at $\sqrt{s} = 13$ TeV. As a consequence, it will help to improve the precision of measurements and reach higher ranges in multiplicity and p_T .

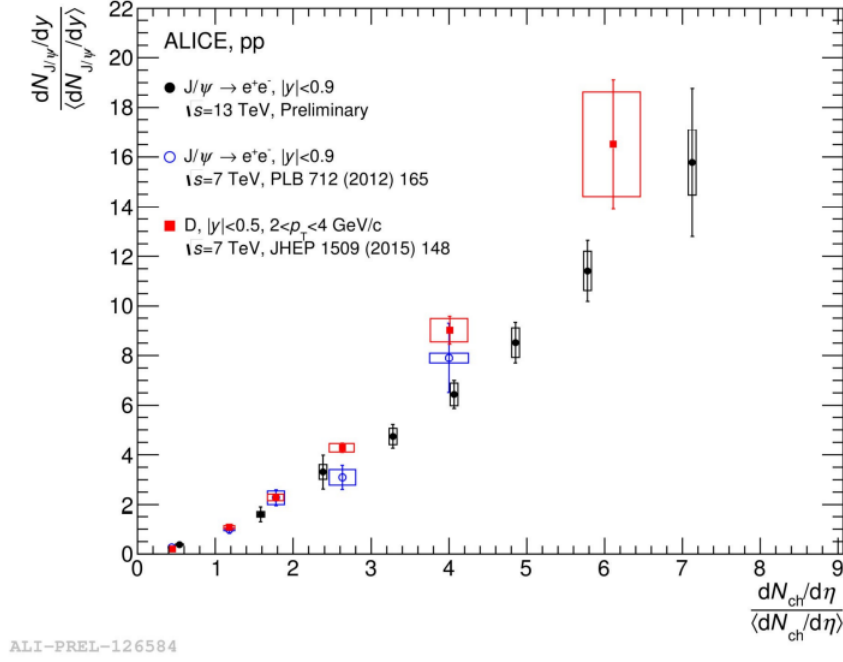


Figure 5.1: D^0, D^+, D^{*+} production vs charged-particle multiplicity at 7 TeV. Also shown the similar results for J/ψ at 7 TeV and 13 TeV.

In this analysis the self-normalized yield of D^+ meson is (ratio between yields in a given multiplicity interval normalized to the multiplicity integrated ones) shown as a function of SPD tracklet multiplicity as well as a function of relative charged-particle multiplicity in the full pp $\sqrt{s} = 13$ TeV data sample collected by ALICE in 2016, 2017, and 2018. In particular, the study for open charm mesons reported here is performed in different intervals of D^+ meson transverse momentum (p_T), with the aim of studying the hardness of the partonic interaction where the $c\bar{c}$ pair is created.

5.1 Data Samples

The analysis has been performed using Minimum Bias (MB kINT7) triggered data from 2016, 2017 and 2018 and High Multiplicity SPD (HMSPD) triggered data only from 2018. The data periods mentioned below are used for the analysis.

• LHC2016pp

1. Periods : LHC16d,e,g,h,j,o,p pass1 + k,l pass2

2. AOD production : 208
3. Number of events with MB trigger : 295+123 M
4. Available Triggers : kINT7

• **LHC2017pp**

1. Periods : LHC17e,f,h,i,j,k,l,m,o,r pass1
2. AOD production : 208
3. Number of events with MB trigger : 579 M
4. Available Triggers : kINT7

• **LHC2018pp**

1. Periods : LHC18b,d,e,f,g,h,i,j,k,l,m,n,o,p pass1
2. AOD production : 208
3. Number of events with MB(HM) trigger : 611 M (300M)
4. Available Triggers : kINT7, kHMSPD

• **Anchored Monte Carlo Productions** Anchored to these $\sqrt{s} = 13$ TeV pp collision data, several Monte Carlo productions have been produced. These simulations are heavy flavored enriched, meaning in each pp event a $c\bar{c}$ or $b\bar{b}$ pair is required. The Monte Carlo simulations were produced with event generator PYTHIA8. The datasets used or the efficiency calculations are described below.

LHC20f4a_2016_P8 $\approx$ 137 M events

LHC20f4a_2017_P8 $\approx$ 191 M events

LHC20f4a_2018_P8 $\approx$ 203 M events

LHC20k7a_HMSPD_P8_hmrunlist $\approx$ 43 M events (for HM triggered data)

while for the N_{trk} to N_{ch} conversion following general purpose samples are used

pp13_GenPurpose_2016

pp13_GenPurpose_2017

pp13_GenPurpose_2018

5.2 Analysis Details

5.2.1 Event Selection

The events are selected by applying both Minimum Bias (kINT7) as well as high Multiplicity Silicon Pixel Detector (KHighMultSPD) triggers. Events were selected by using standard event selection class with the following:

- 1) The minimum bias as well as the events with high multiplicity in the SPD were selected with physics selection task.
- 2) Only those events were selected for which the primary vertex lies within 10cm ($|Z_{vtx}| < 10\text{cm}$) from the centre of the detector. This centre point of the detector is assumed to be the origin of the coordinate system used in the ALICE detector or taken as the interaction point between the beams coming from the opposite directions.
- 3) There is another effect which needs to be taken care of while selecting events. The machine delivers high collision rates to maximise the potential of the measurements. As a consequence multiple pp collisions occurs when two beams cross each other. This effect is called Pile-up. The collision's final state is tainted by this consequence. It makes it more difficult to recreate the objects in their ultimate state, which raises the uncertainty. In this analysis the pileup rejection which is specific in heavy flavour measurements (AliRDHFCuts::kRejectMVPileupEvent) is applied.

5.2.2 Track Selection

The D^+ -meson is being studied in the three body decay channel in this analysis. Being a 3-body decay the channel the D^+ -meson yield is affected by a huge combinatorial background. This background needs to be reduced with a careful setting of the kinematic and topological selection cuts applied to the reconstructed D^+ -meson in order to have a visible peak in the invariant mass distribution. Some features of this decay channel can help improving the selection. The topological cuts applied to the D^+ candidates are summarised in Table.5.1.

p_T interval	1-2	2-3	3-4	4-8	8-24
p_T decay track (GeV/ c)	> 0.3	> 0.3	> 0.3	> 0.3	> 0.3
σ_{vertex} (cm)	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03
Decay length (μm)	> 700	> 700	> 1000	> 1000	> 1200
Norm Decay length XY ($n\sigma$)	> 6.0	> 5.0	> 5.0	> 5.0	> 5.0
Cosine pointing	> 0.97	> 0.97	> 0.97	> 0.97	> 0.96
Cosine pointing XY	> 0.985	> 0.985	> 0.980	-	-
$ d_0 - d_0^{exp} ^{prong}$ ($n\sigma$)	< 2.5	< 2.5	< 2.5	< 2.5	< 2.5

Table 5.1: D^+ topological cuts for used in the analysis.

A detailed description of the cut variables is as follows.

- p_T^K : This cut is applied on the minimum p_T of the track for daughter candidate which has opposite charge to the D^+ . In our case this daughter is always a kaon.
- p_T^π : This cut is applied on the minimum p_T of the two daughter tracks that have the same charge as that of the candidate. In case of our analysis this particle is π^+ .
- σ_{vertex} : This cut is applied on the spread of the tracks around the decay vertex. In principle, all the daughter tracks which are coming from the same decay vertex of a signal candidate should have this dispersion value close to 0. But in realistic conditions this value has a spread which is determined by the resolution of the tracking and vertexing. Thus the distribution of σ_{vertex} is close to 0 for signals visible in Figure.5.2, while for the background, this parameter has a broader distribution which is peaked at larger values.

• **Decay Length:** This is the cut which is applied on the decay length, which is defined as the distance between the primary vertex (interaction point) of the event and the decay vertex (secondary vertex) of the D^+ . For D^+ , average decay length has a value of around $c\tau \sim 311.8\mu\text{m}$. So this cut is one of the most important cut to separate background from signal. As particles at high p_T are also affected by a significant Lorentz boost, the value of this cut can reach values as high as 0.19 cm.

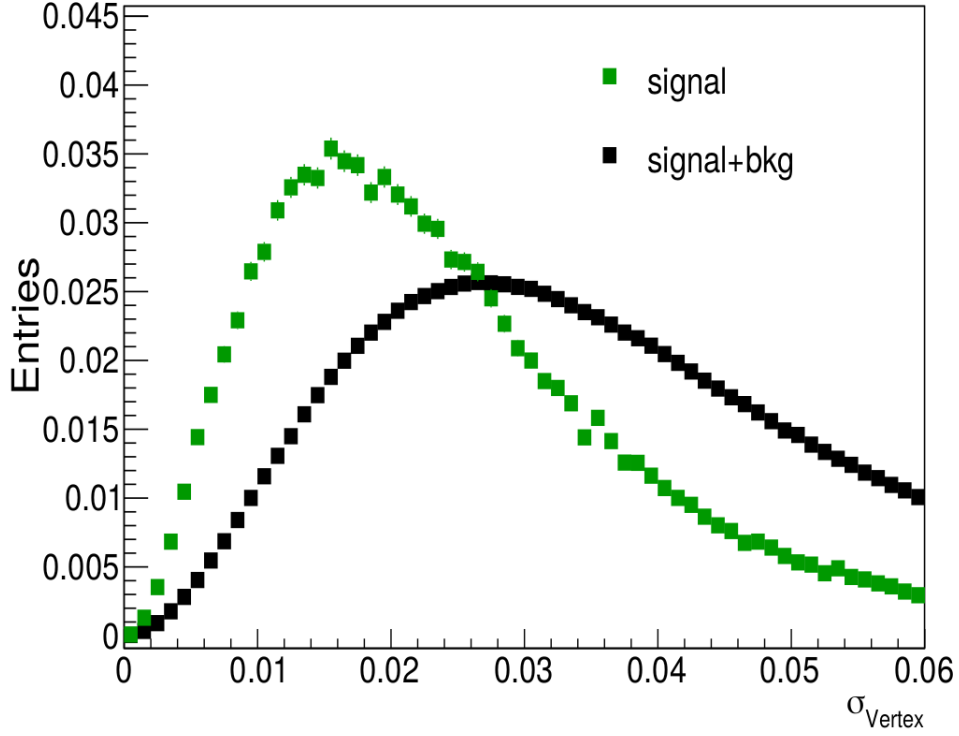


Figure 5.2: p_T integrated distribution of σ_{vertex} for signal and background candidates.

- $\text{Cos}\theta_{\text{pointing}}$: The straight line passing through the primary and secondary vertex towards the flight of D^+ candidates is called the line of flight. The angle formed between the line of flight and the line joining the primary vertex and the secondary vertex is called the pointing angle and is denoted as θ_{pointing} . Figure 5.3 shows schematic representation of the $D^+ \rightarrow K^- + \pi^+ + \pi^+$ decay channel in which the pointing angle is also shown. The cut on the pointing angle is based on the fact that for signal candidates the D^+ reconstructed momentum should point to the primary vertex of the event. The cut is done on the cosine of the angle θ_{pointing} between the D^+ meson flight line and the line passing through the primary and decay vertex. For signal candidates the distribution of $\text{Cos}\theta_{\text{pointing}}$ point is peaked at 1, while the distribution of background is flatter. A comparison among these two distributions is shown in Figure.5.4.

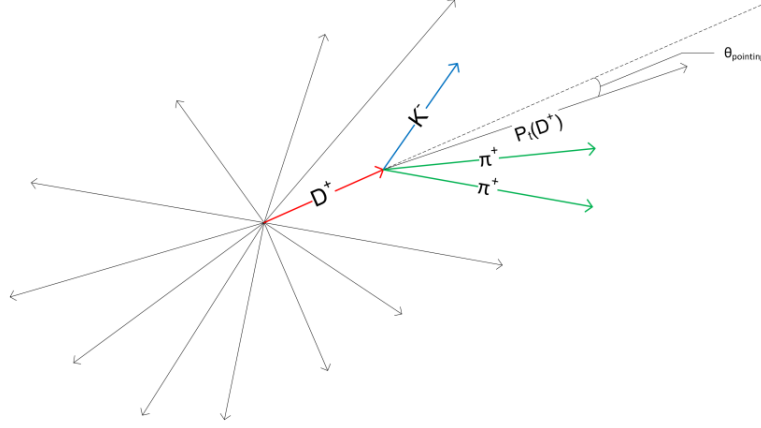


Figure 5.3: Schematic representation of the $D^+ \rightarrow K^- + \pi^+ + \pi^+$ decay channel. Pointing angle is also represented.

- $\text{Cos}\theta_{pointing}^{XY}$: This cut is applied on cosine of the pointing angle in the transverse plane.

5.2.3 Yield extraction

D^+ mesons and their anti-particles were reconstructed in the central rapidity region from its charged hadronic decay channel $D^+ \rightarrow K^- \pi^+ \pi^+$ decay channel (B.R. = $9.38 \pm 0.16\%$). D meson candidates were filtered by applying kinematical and topological cuts, and particle identification criteria. The D^+ signal was extracted in a p_T range of 1-24 GeV/ c , using a transverse momentum binning of [1-2], [2-4], [4-6], [6-8], [8-12], [12-24] GeV/ c , meaning a total of 6 intervals, in the SPD ntracklets ranges [1-8], [9-13], [14-19], [20-30], [31-59] and [60-99] (for the HMSPD data). For the multiplicity integrated analysis we considered an interval of [1,199] tracklets in order to account the condition $\text{INEL} > 0$.

The Inner Tracking System (ITS) offers the necessary resolution of a few tens of microns on the track location at the primary vertex to resolve the decay's vertex. Topological cuts are used to define and choose D meson candidates from displaced tracks. The actual cut values were adjusted to maximise the statistical significance

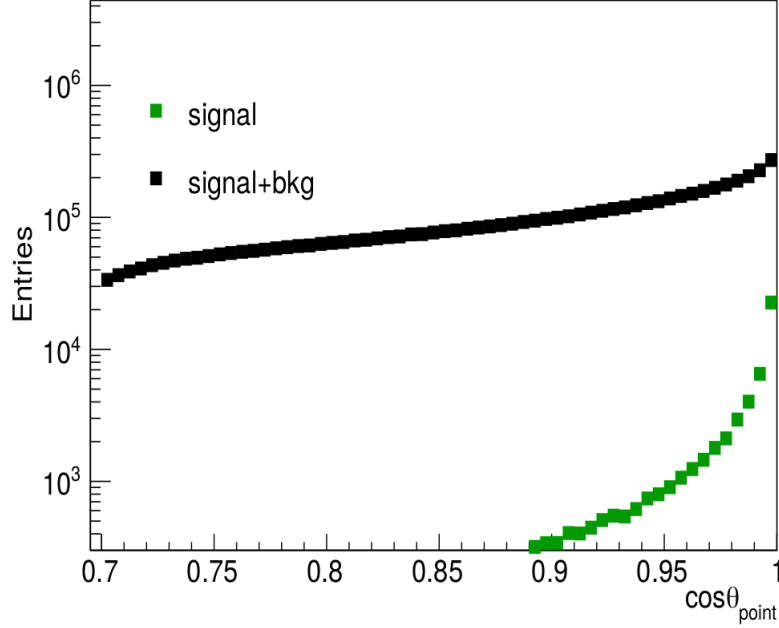


Figure 5.4: $\cos\theta_{point}$ distribution for signal (green) and background (black) candidates

of the signal and are p_T dependent, resulting in a selection efficiency that rises with p_T . Particle identification (PID) on the D meson decay tracks was used to further decrease the combinatorial background. When performing PID, data from the Time Projection Chamber's (TPC) Time of Flight (TOF) detector and the particular energy deposit (dE/dx) data are used. The TOF detector enables accurate kaon and pion identification over a broad momentum range up to 2 GeV/c. The particle in the D^+ meson decay with the opposite charge sign from the D meson is called a kaon. As a result, the triplets were disregarded if either the opposite sign track or at least one of the two identical sign tracks did not agree with the kaon hypothesis. The invariant mass distribution is fitted with a Gaussian function for the signal peak and an exponential shape for the background in order to obtain the signal yield. Additionally, using the cuts outlined in the preceding section, the reconstructed candidates are chosen topologically to lessen the combinatorial backdrop.

By fitting the invariant mass distributions with a function made up of an exponential term for the background shape and a Gaussian term for the signal, the D^+

yields were retrieved. The D^+ meson yields were extracted in different p_T ranges ([1,2], [2,4], [4,6], [6,8], [8,12] and [12,24] GeV/c) in the integrated multiplicity bin [1-199] for the minimum bias data. Figure 5.5 shows the fitting for the minimum bias data in p_T bin [2,4] GeV/c. Then the yield is extracted for a given p_T bin in different multiplicity ranges ([1-8], [9-13], [14-19], [20-30], [31-59] and [60-99]) by fixing the sigma values obtained from the invariant mass spectra in the integrated multiplicity bin. Figure 5.6 and Figure 5.7 show the invariant mass spectra in the multiplicity bin [1-8] and [60-99] respectively. Figure 5.8 shows the raw yield extracted after fitting in the different SPD tracklet multiplicity bins.

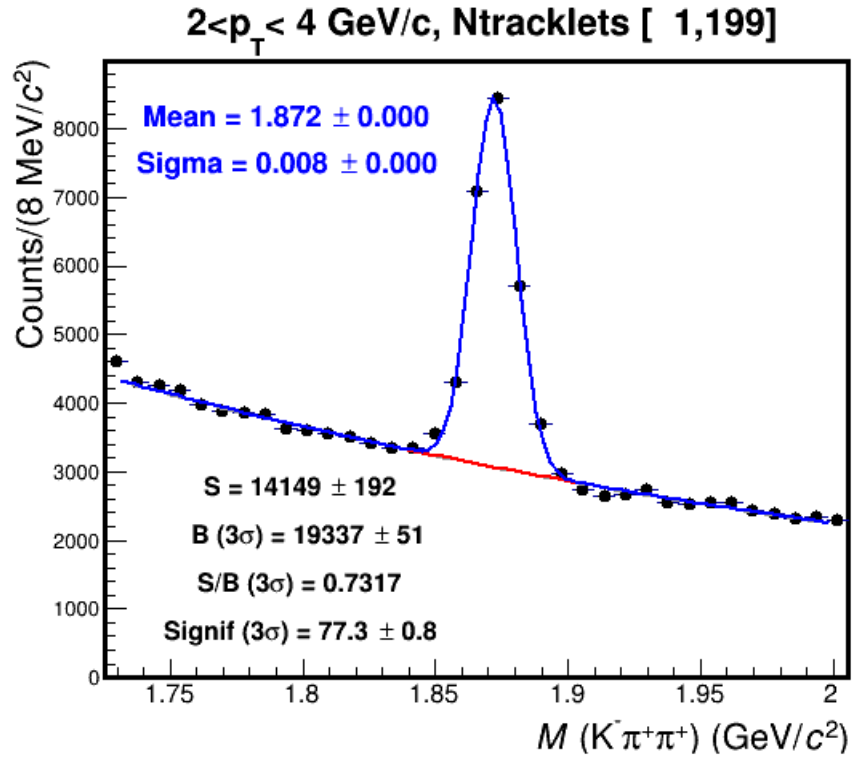


Figure 5.5: D^+ invariant mass plots in the p_T bin [2,4] GeV/c for the integrated multiplicity bin [1-199].

5.2.4 Efficiency and Acceptance

The raw counts of D^+ mesons retrieved from each p_T interval and multiplicity were adjusted for reconstruction, selection, and acceptance efficiency. Using Monte Carlo

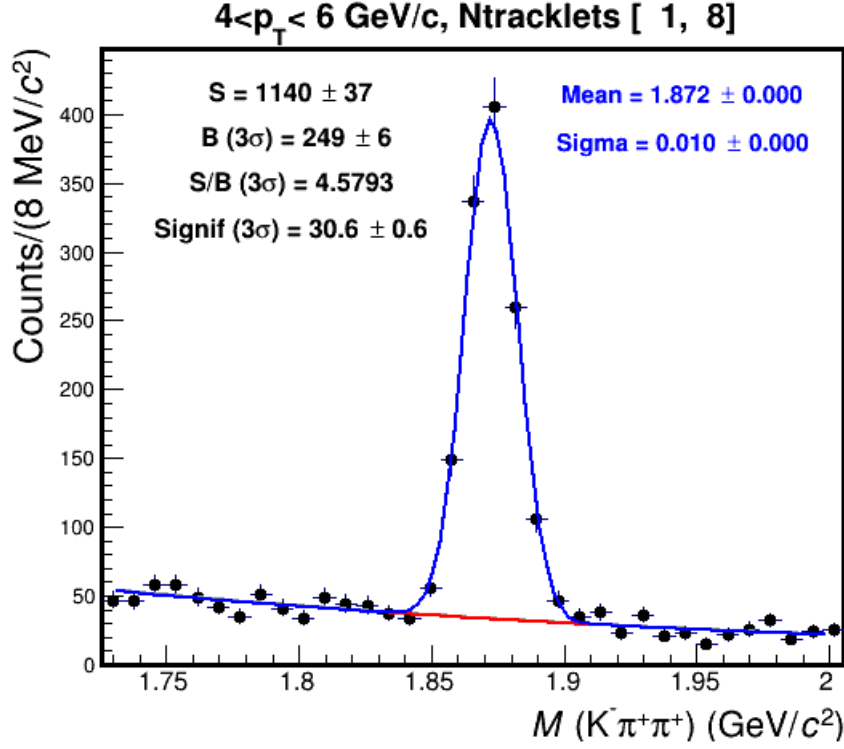


Figure 5.6: D^+ invariant mass plots in the p_T bin $[4,6]$ GeV/c for the tracklet multiplicity bin $[1-8]$.

simulations, the correction factor D^+ species was found. The primary vertex resolution and the resolution on the topological selection variables both improve at high charged particle multiplicity, hence the efficiency of the reconstruction and selection depends on this. As a result, the resolution of the selection variables (track impact parameter, particle decay length, and pointing angle) that depend on the primary vertex position likewise increases with increased multiplicity, generating a multiplicity dependence in the selection efficiency. .

The efficiencies in each multiplicity interval considered for this analysis were evaluated using a Monte Carlo sample that reproduces the multiplicity distribution observed in data. In particular, the simulated $N_{tracklets}$ distribution was weighted with the ratio of the $N_{tracklets}$ distribution observed in data over that of MCs, accordingly. The weights were computed selecting Monte Carlo and data events with at least one D^+ -meson candidate in the D^+ mass range.

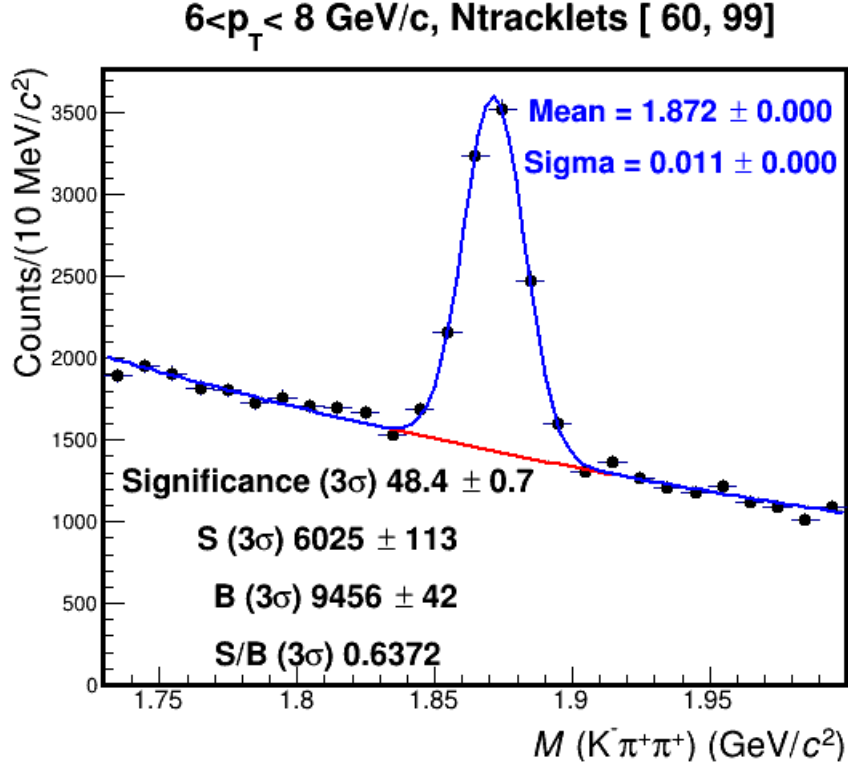


Figure 5.7: D^+ invariant mass plots in the p_T bin $[6,8] \text{ GeV}/c$ for the tracklet multiplicity bin $[60-99]$.

The weights have been computed separately for each year, and was ensured that they were compatible with each other. The data and MC tracklet distributions for the data collected in the year 2016 are shown in Figure 5.9 (left) and comparison between the weights computed for the three different years (2016, 2017, and 2018) are shown in Figure 5.9 (right).

Using Monte Carlo simulations of pp collisions produced using the PYTHIA 8 event generator with the Perugia-0 tune, the acceptance and efficiency correction factors, $(Acc \times \epsilon)$, are calculated for the D^+ -meson. GEANT3 transport algorithms were used to move the particles across the apparatus. The simulations took into account all of the ALICE detectors' luminous region distributions as well as their operational parameters (active channels, gain, noise level, and alignment), as well as how they changed over time across the LHC data collection periods in 2016, 2017, and 2018. The MC productions used to compute the $(Acc \times \epsilon)$ only events containing a

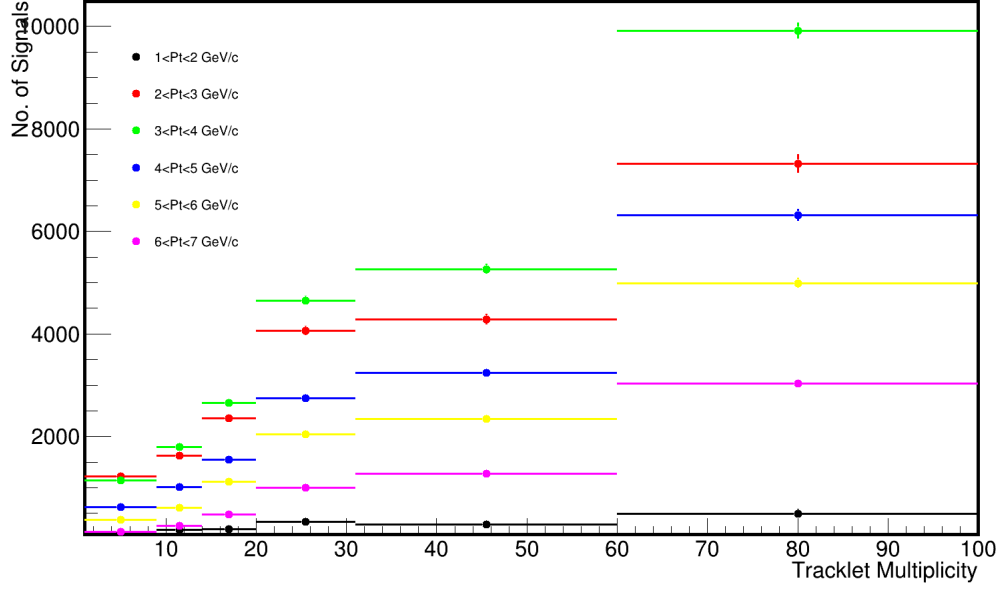


Figure 5.8: D^+ signals extracted after fitting Invariant mass spectra

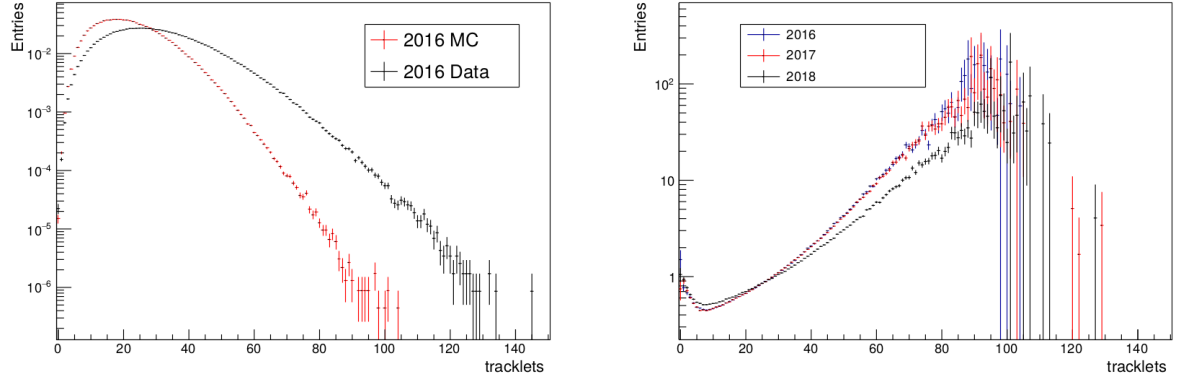


Figure 5.9: (left) $N_{tracklets}$ distribution comparison between data vs MC for the 2016 periods, (right) comparison of weights for all periods

$c\bar{c}$ or a $b\bar{b}$ pair were transported through the apparatus and reconstructed. Moreover, D^+ mesons were forced to decay in the hadronic channel considered in this analysis. The efficiency was extracted separately for prompt charmed particles and particles coming from B-meson decays (feed-down). The vertex selection efficiency is included in our calculation since at the denominator we have all the generated particles in events with $|Z_{vtx}| < 10$ cm, including those that do not have a reconstructed vertex.

Efficiency is defined as:

$$\epsilon = \frac{N_{\text{reco}}|_{|y| < y_{\text{fid}}}}{N_{\text{gen}}^{\text{dau in acc}}|_{|y| < y_{\text{fid}}}} \quad (5.1)$$

where, $N_{\text{reco}}|_{|y| < y_{\text{fid}}}$ is the number of reconstructed D^+ mesons after all the selections, $N_{\text{gen}}^{\text{dau in acc}}|_{|y| < y_{\text{fid}}}$ is the number of generated D^+ mesons which decayed to the decay channel of interest, having $|y| < y_{\text{fid}}$, with three daughters that fulfil the acceptance requirements of $|\eta| < 0.9$ and $p_T > 0.1$, belonging to the events with $|\text{vtx}_z^{\text{gen}}| < 10$ cm. Similarly acceptance is defined as

$$\text{Acc} = \frac{N_{\text{gen}}^{\text{dau in acc}}|_{|y| < y_{\text{fid}}}}{N_{\text{gen}}|_{|y| < 0.5}} \quad (5.2)$$

where, $N_{\text{gen}}|_{|y| < 0.5}$ is the number of generated D^+ mesons in events with $|\text{vtx}_z^{\text{gen}}| < 10$ cm decaying in the decay channel of interest with $|y| < 0.5$. The product of acceptance and efficiency is computed per p_T bin for each multiplicity ($N_{\text{tracklets}}$) bin and used for correction of the extracted D^+ raw-yields. For the HMSPD trigger data, a MC data anchored to the HM SPD trigger has been produced by simulating events with a threshold on the minimum multiplicity set at 65 generated charged particles in each event, in order to increase the statistics at the higher multiplicity events. The weights have been computed, as the ratio of Ntracklet distributions in HMSPD triggered data and Ntracklet distributions in the MB sample, and they are shown in Figure 5.10, in comparison with the weight computed for the MB sample. They have been used to correct the efficiency in the higher multiplicity interval. The efficiency for D^+ mesons are shown in Figure 5.11, for all the multiplicity bins. A slightly larger efficiency in the higher multiplicity interval is observed, and it is explained as the tendency to better reconstruction efficiency for primary vertex in a high multiplicity environment.

5.2.5 Feed-down subtraction

The prompt D^+ production yields normalized by the number of events in pp collisions are obtained by subtracting the contribution of D^+ from B decays. In detail, the D^+

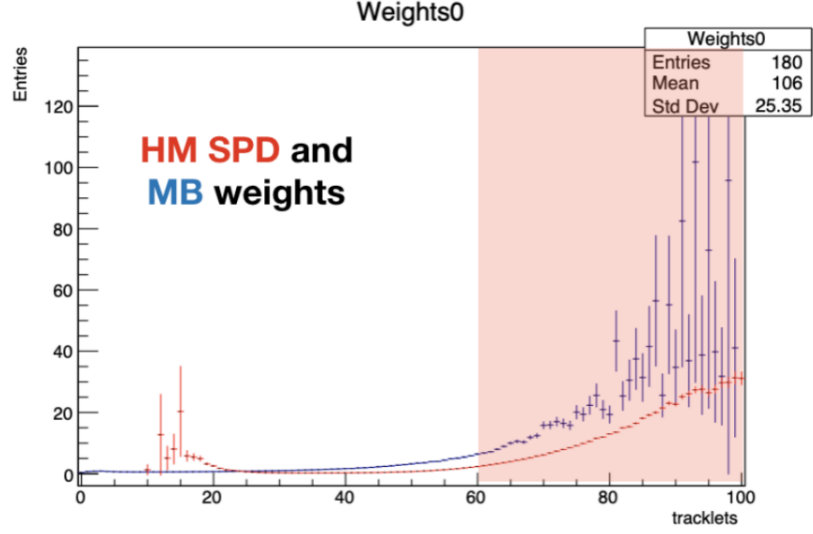


Figure 5.10: Multiplicity weights for data driven correction of HM MC, in comparison with those of the MB sample.

meson feed-down contribution is estimated using the beauty production cross section from the FONLL calculation, the $B \rightarrow D$ decay kinematics from the EvtGen package, and the Monte Carlo Efficiencies for Feed-down D^+ mesons. The fraction of prompt D^+ mesons can be understood as:

$$\begin{aligned}
 f_{\text{prompt}} &= 1 - (N^{\text{D feed-down raw}} / N^{\text{D raw}}) \\
 &= 1 - \left(\frac{d^2\sigma}{dydp_T} \right)_{\text{feed-down}}^{\text{FONLL}} \cdot \frac{(\text{Acc} \times \epsilon)_{\text{feed-down}} \cdot \Delta y \Delta p_T \cdot \text{BR} \cdot N_{\text{evt}}}{N^{\text{D raw}} / 2}
 \end{aligned} \tag{5.3}$$

where $(\text{Acc} \times \epsilon)_{\text{feed-down}}$ is the acceptance-times-efficiency for feed-down D^+ mesons and the factor 2 at the denominator comes for counting both particle and antiparticle. The variation of the parameters used for the FONLL B predictions is taken into account for the evaluation of part of the systematic uncertainties related to the feed-down subtraction, which will be discussed later separately because the FONLL calculations are multiplicity independent, this so-called N_b method does not converge for multiplicity bins.

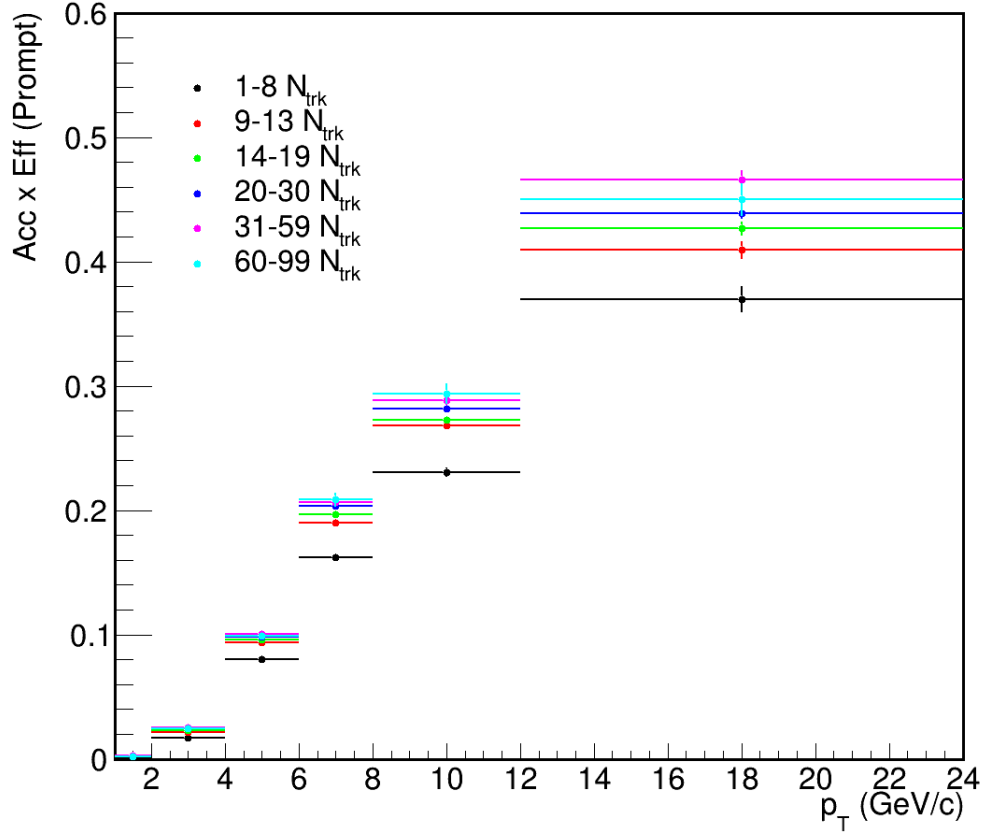


Figure 5.11: Prompt D^+ acceptance times efficiency vs p_T

5.2.6 Calculation of $dN_{ch}/d\eta$

The SPD multiplicity estimator, which in our case is the number of SPD tracklets, is not a physical primary observable. It is detector-dependent and can change over time when the SPD ages. Therefore, a conversion from used multiplicity classes to charged-particles (N_{ch}) which is a more “physical value”. A strategy to convert the $N_{tracklets}$ values after the Z_{vtx} correction, to a value of N_{ch} (physical primary) was developed. For this correction, the general-purpose MC’s anchored to the relevant periods are exploited. Runlists are the same as those used for data on the respective anchor period. The period-dependent Z_{vtx} correction of $N_{tracklets}$ are applied using same method and reference value as for data.

The conversion is performed with the two-dimensional plot of N_{ch} versus $N_{tracklets}$

within $|\eta| < 1$ for selected events as displayed in Figure 5.12. There is a linear correlation visible. As one can see, a sharp cut on the reconstructed multiplicity, does not correspond to a sharp cut on the true multiplicity estimator. Table 5.2 shows the mean, RMS, and values of the relative charged-particle density for each $N_{tracklets}$ interval.

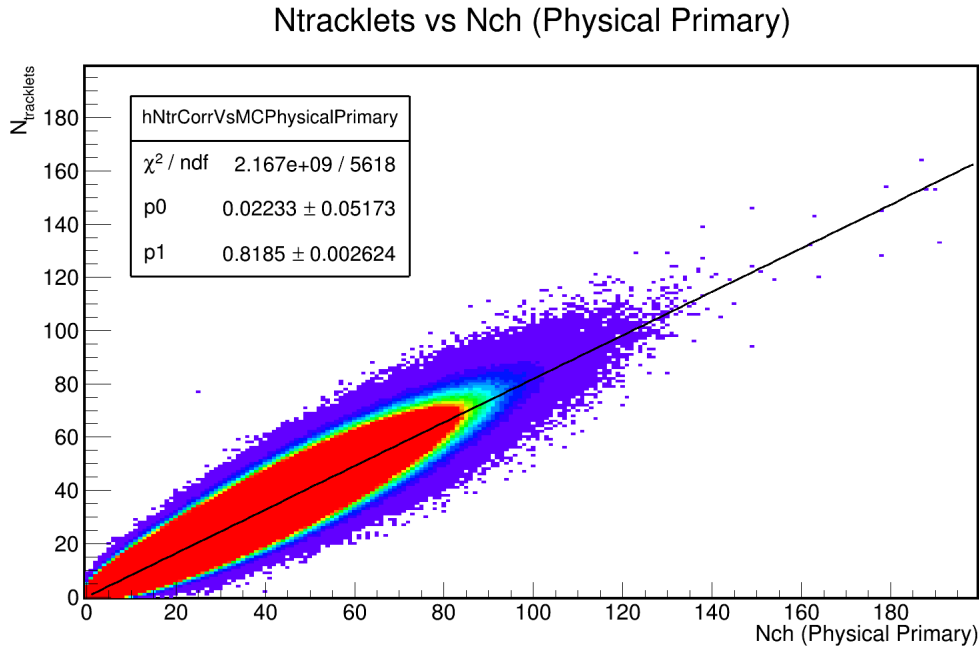


Figure 5.12: Two-dimensional plot of N_{ch} versus $N_{tracklets}$ within $|\eta| < 1$ for selected events

To estimate the mean and RMS, $N_{charged}$ distributions are used after applying the $N_{tracklets}$ selections and shown in Figure 5.13. This figure shows even better the clear overlap in true multiplicity for the different $N_{tracklets}$ bins. The mean and RMS are simply taken from these distributions, merging all analysed periods. To estimate the uncertainty on these values, this procedure is repeated for each period separately. The quoted uncertainty is the RMS of the distributions for each period as shown in Figure 5.14 for the $\langle dN_{ch}/d\eta \rangle$. The values are listed in the second column of the Table 5.2. For the integrated multiplicity bin [1-199], the value $7.42 \pm 0.002 \pm 0.001$ has been used.

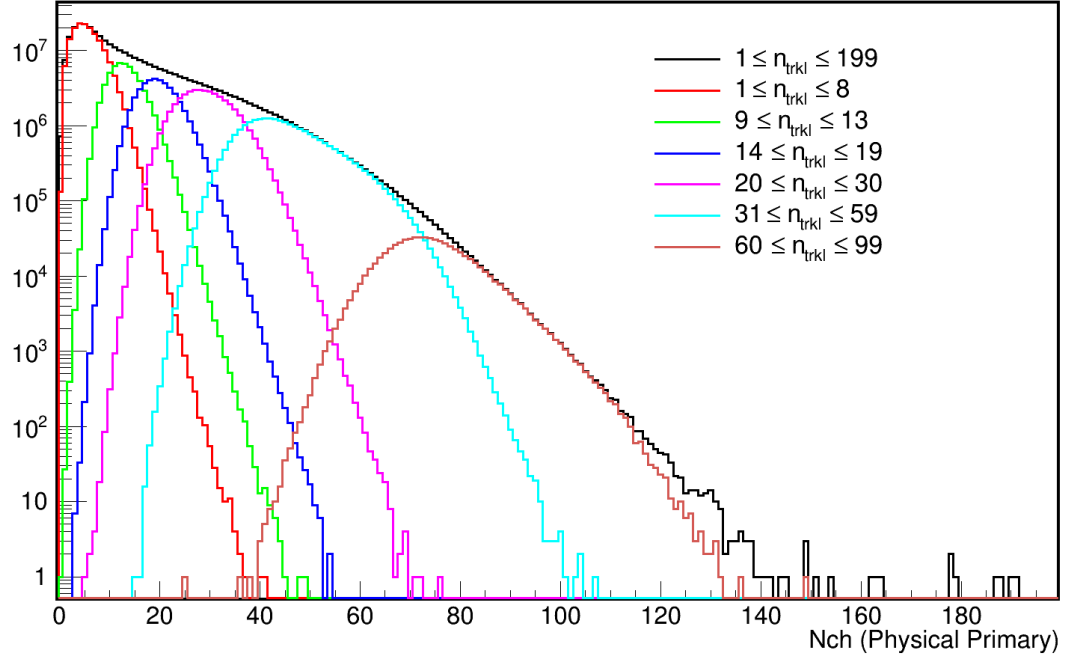


Figure 5.13: Distributions of charged particles in different Ntracklet multiplicity interval

$\langle dN_{ch}/d\eta \rangle$	Mean	RMS	$\langle dN_{ch}/d\eta \rangle / \langle dN_{ch}/d\eta \rangle_{MB}$
Overall	7.42 ± 0.10	6.49 ± 0.00	
[1-8]	2.87 ± 0.02	1.46 ± 0.02	0.39 ± 0.006
[9-13]	6.59 ± 0.04	1.68 ± 0.06	0.89 ± 0.02
[14-19]	9.88 ± 0.06	2.04 ± 0.07	1.33 ± 0.03
[20-30]	14.59 ± 0.10	2.78 ± 0.09	1.97 ± 0.05
[31-59]	22.64 ± 0.17	4.45 ± 0.06	3.05 ± 0.09
[60-99]	37.77 ± 0.47	4.55 ± 0.12	5.10 ± 0.14

Table 5.2: Mean, RMS and relative charged-particle density.

5.3 Systematics

In this section, studies are performed to evaluate the different sources of systematic uncertainties as given below:

- Raw yield extraction systematics;
- Selection efficiency;

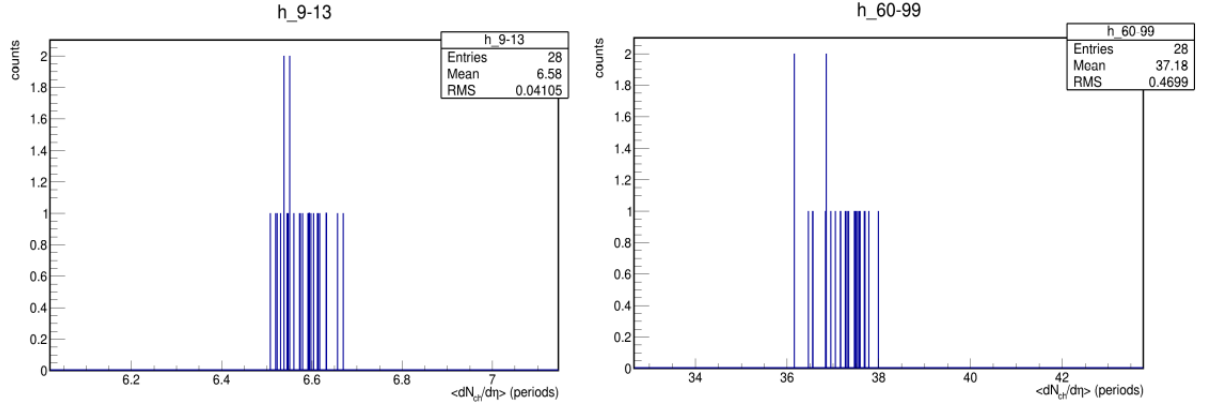


Figure 5.14: Distribution of the $\langle dN_{ch}/d\eta \rangle$ for different Ntracklet multiplicity interval

- Particle identification;
- MC p_T shape;
- Feed-down subtraction, including FONLL and multiplicity dependence;
- Efficiency, including multiplicity weights;
- Normalisation and Trigger correction.

5.3.1 Raw Yield extraction systematics

The yield extraction systematics is evaluated by extracting the yields varying the background fit function, the range of the invariant mass spectra, the binning using a MultiTrial approach. In this approach different fitting parameters like background functions, fit range, bin widths etc. are varied. Among the variations, two methods of bin counting are used: one in which the signal is extracted as the difference between the total histogram and the fit function of the background in the signal region and one in which the the same procedure is performed considering the entire invariant mass region. Only fits that have a reduced χ^2 below two, were considered as variation. The variations in the fit strategy are shown in the Table.5.3:

The main value plotted in the results is the ratio between the production of the mesons in the multiplicity class over the multiplicity integrated result in order to

account for the correlation between MB data and multiplicity. The results obtained using this procedure will be defined as systematics, while the MB yield extraction will be used summed in quadrature with HM systematic yield extraction uncertainties, since they're not correlated.

Lower bound Fit range (GeV/c^2)	(1.70, 1.72, 1.74, 1.76, 1.78)
Upper bound Fit range (GeV/c^2)	(1.97, 1.99, 2.01, 2.03, 2.03)
rebin values	1, 2, 3, 4
background functions	Linear, Pol2, expo.
Sigma	fixed sigma and free sigma

Table 5.3: Variations used for D^+ multitrial.

An example of the output of the MultiTrial fitter for the D^+ meson is shown in Figure 5.15, where the p_T bin is $[4-6] \text{ GeV}/c$ and the multiplicity bin is $[14-19]$. The figure shows the raw yield distributions extracted from the fit and using bin counting in green. The assigned systematic is estimated considering the RMS of the fit distribution.

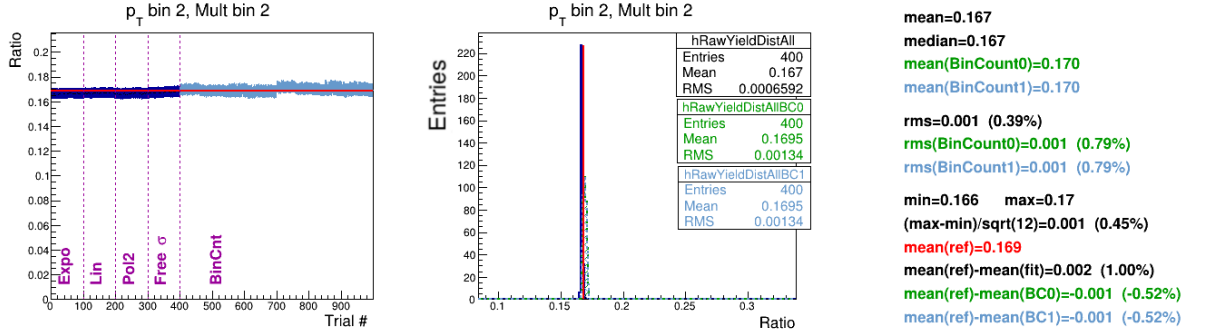


Figure 5.15: Output of the MultiTrial fitter for the D^+ meson for p_T bin $[4-6] \text{ GeV}/c$ for the multiplicity bin $[14-19]$.

5.3.2 Selection Efficiency

In order to obtain the measurement, the data has to be corrected for detector acceptances and efficiencies which are determined from Monte Carlo simulations. Differences between data and MC in the distribution of one (or more) of the variables used

in the candidates selection could introduce biases in the extraction of the corrected yields. To quantify the effect and estimate a corresponding systematic uncertainty, we compared the corrected yield obtained using different selection criteria i.e by comparing the corrected yield extracted by using different sets of topological cuts. Two sets looser and two sets of tighter cuts were checked, varying the efficiencies of around 5% and 10% respectively. Specifically the parameters that are varied are σ_{vertex} , $Cos\theta_{point}$, Decay length $_{XY}$. The systematics is assigned as the R.M.S of the difference of corrected yield from the central value.

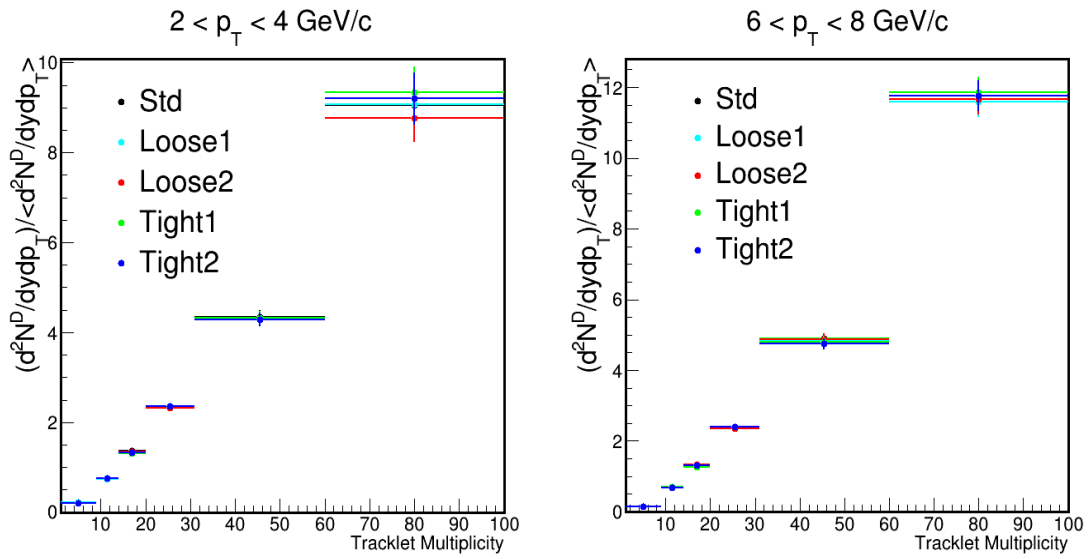


Figure 5.16: Comparison of D^+ corrected yield with respect to the central value.

Figure 5.16 shows the ratio of the corrected yield for all the loose and tight sets of cuts with respect to the standard cuts. In Figure 5.17, the ratio of the prompt D^+ MC efficiency for the varied cuts with respect to the efficiency for the standard cuts has been shown. Figure 5.18 shows the assigned systematics for the selection efficiency of the D^+ mesons.

5.3.3 PID efficiency

The particle identification (PID) strategy is used for three species by looking at the time of flight in the TOF and the specific energy deposit in the TPC. For all the

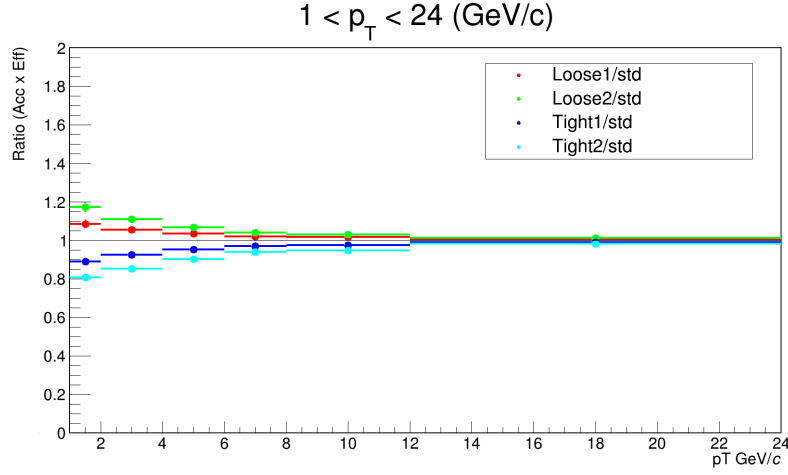


Figure 5.17: Ratio of prompt D^+ efficiencies for varied cuts with respect to the central value.

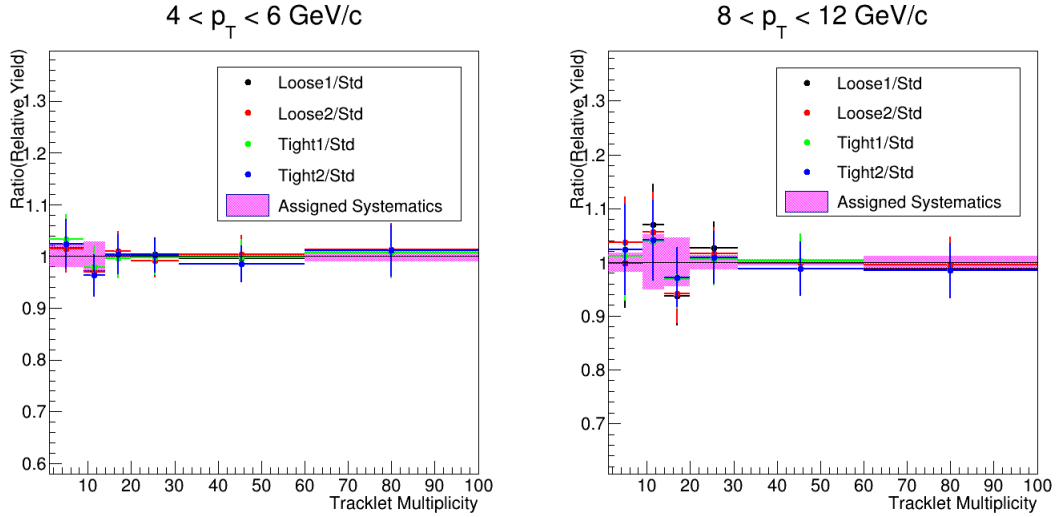


Figure 5.18: Assigned systematics for the selection efficiency of the D^+ mesons.

mesons the uncertainty due to the PID was studied by comparing the raw yields obtained with and without using PID. The yields were extracted imposing the peak position to the PDG one and its width to that obtained in the multiplicity integrated p_T bins with PID. The ratios of the yields without/with PID were corrected by their respective efficiencies (with/without PID). The result is shown in Figure 5.19. The ratios are compatible with unity in almost all p_T and multiplicity bins. These checks prove that there is no influence of the PID response in this analysis. As a consequence,

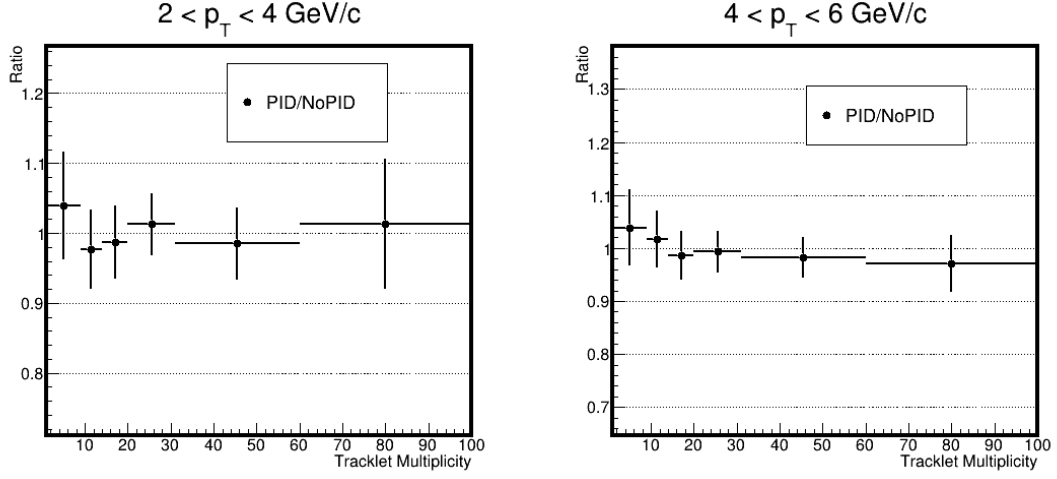


Figure 5.19: D^+ PID systematics.

no systematic uncertainty related to the PID response will be considered.

5.3.4 MC p_T shape

The systematic effect on the efficiency extracted from the simulations due to the generated p_T shape of D^+ mesons was tested by computing the efficiency with and without using p_T -dependent weights that allow us to correct for the difference between the p_T spectrum of generated D^+ mesons in the PYTHIA6 MC production used for these analyses and the prediction from FONLL. The p_T spectra and the actual weights are shown in Figure 5.20.

In Figure 5.21, the ratio of the efficiency computed using the FONLL and Pythia p_T shape for D^+ is shown. An uncertainty of 2% in the first p_T bin has been assigned whereas for p_T bin 12-24 GeV/c it is around 1%, while it is negligible for all other p_T bins.

5.3.5 Feed-Down correction and subtraction

The f_{prompt} factor is computed from FONLL predictions. In addition to this, we have made an assumption that the relative contribution of beauty hadron decays to the D^+ yields in the different multiplicity bins is constant and equal to that of

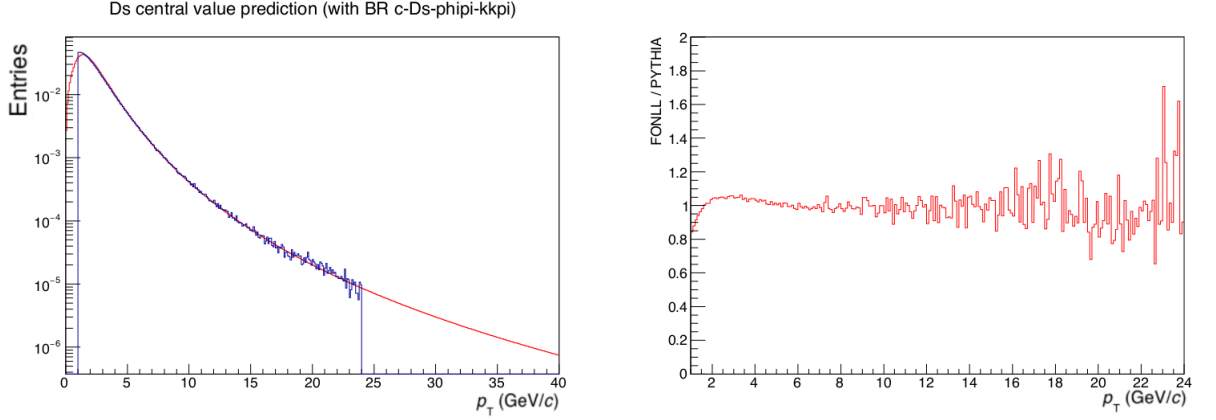


Figure 5.20: Left: Input p_T spectra from the used MC production (PYTHIA6 in blue) and from FONLL calculations (red curve). Right: Weights used to correct the MC p_T shape, by dividing the FONLL p_T spectra by the input PYTHIA one.

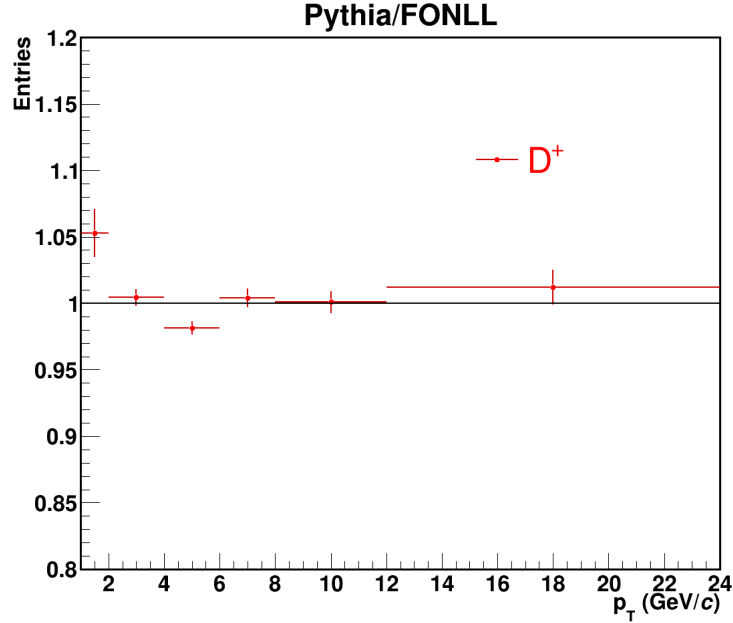


Figure 5.21: Efficiency ratios using FONLL p_T shape with respect to PYTHIA, for D^+ .

the multiplicity integrated sample. We therefore quote, in contrast to the usual HF studies, two different feed-down subtraction systematics. In this section we will discuss the strategy and estimation of both contributions to the systematics. The systematics was obtained by taking into account Pythia8 simulation run with

different models and tunes (Monash default, 4Cx, Monash CR mode 0/2/3) as shown in Figure 5.22.

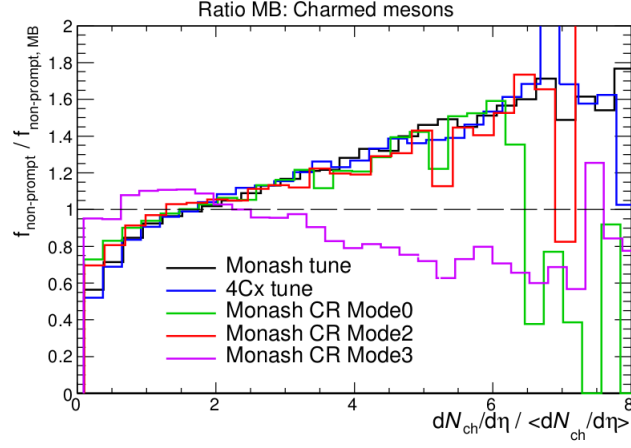


Figure 5.22: Ratio between $f_{\text{nonpromptmult}}$ and MB integrated as a function of charged particle density.

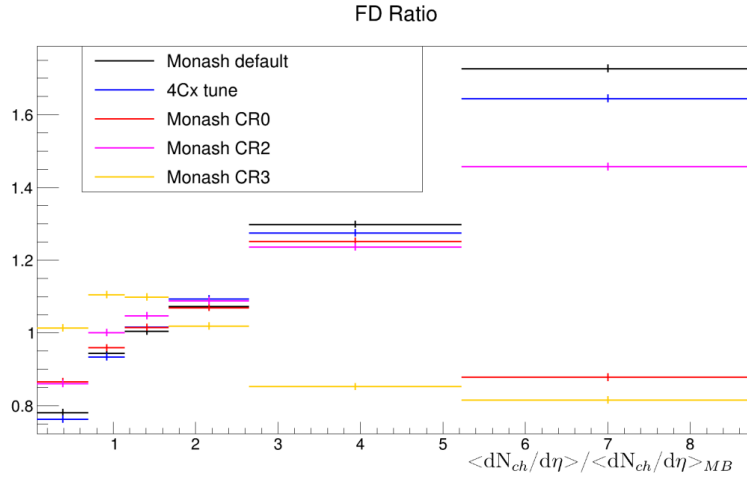


Figure 5.23: Adapted to our multiplicity intervals $f_{\text{nonprompt}}$ ratio.

Since the $f_{\text{nonprompt}}$ ratio is shown in the plot and we need the f_{prompt} uncertainty for our systematic, we used the following equation in order to obtain the sigma (obtain

from error propagation):

$$\sigma(f_{\text{prompt}})^{\text{REL}} = \frac{(1 - f_{\text{prompt}}) * \sigma(f_{\text{nonprompt}})^{\text{REL}}}{f_{\text{prompt}}}, \quad (5.4)$$

where $\sigma(f_{\text{nonprompt}})^{\text{REL}}$ was obtained from Figure 5.23 by looking at the minimum and maximum ratios for each multiplicity bin and then subtracting 1 to those values. In the end the chosen values are shown in Table 5.4. which led to the results in Table

Multiplicity interval	$\sigma(f_{\text{nonprompt}})^{\text{REL}}_{\text{LOW}}$	$\sigma(f_{\text{nonprompt}})^{\text{REL}}_{\text{HIGH}}$
[1-8]	0.24	0.02
[9-13]	0.07	0.10
[14-19]	0.00	0.10
[20-30]	0.00	0.09
[31-59]	0.15	0.30
[60-99]	0.18	0.73

Table 5.4: $\sigma(f_{\text{nonprompt}})^{\text{REL}}$.

5.5 for the systematic feeddown uncertainties of the D^+ meson.

5.3.5.1 FONLL theoretical uncertainties

The systematic on the feed-down estimation is performed by varying the parameters used for the FONLL B predictions using the N_b method, as given in equation 5.5 or equation 5.6. In particular, the b quark mass and the factorisation and renormalisation scales in the FONLL calculations are varied. For the D^+ mesons, the envelope of these variations is taken and assigned directly as systematic. The asymmetric error bars are shown in Figure 5.24.

$$f_{\text{prompt}} = 1 - (N^{\text{Dfeed-downraw}} / N^{\text{Draw}}) \quad (5.5)$$

$$f_{\text{prompt}} = 1 - \left(\frac{d^2\sigma}{dydp_T} \right)_{\text{feed-down}}^{\text{FONLL}} \cdot \frac{(Acc \times \epsilon)_{\text{feed-down}} \cdot \Delta y \cdot \Delta p_T \cdot BR \cdot N_{\text{evnt}}}{N^{\text{Draw}} / 2} \quad (5.6)$$

Mult.	p_T [GeV/ c]	$D^+ \sigma_{\text{LOW}}^{\text{REL}}$	$D^+ \sigma_{\text{HIGH}}^{\text{REL}}$
[1-8]	1-2	0.02	0.00
	2-4	0.02	0.00
	4-6	0.02	0.00
	6-8	0.02	0.00
	8-12	0.02	0.00
	12-24	0.02	0.00
[9-13]	1-2	0.01	0.01
	2-4	0.01	0.01
	4-6	0.01	0.01
	6-8	0.01	0.01
	8-12	0.01	0.01
	12-24	0.01	0.01
[14-19]	1-2	0.00	0.01
	2-4	0.00	0.01
	4-6	0.00	0.01
	6-8	0.00	0.01
	8-12	0.00	0.01
	12-24	0.00	0.01
[20-30]	1-2	0.00	0.01
	2-4	0.00	0.01
	4-6	0.00	0.01
	6-8	0.00	0.01
	8-12	0.00	0.01
	12-24	0.00	0.01
[31-59]	1-2	0.02	0.02
	2-4	0.01	0.02
	4-6	0.00	0.02
	6-8	0.00	0.02
	8-12	0.00	0.03
	12-24	0.01	0.03
[60-99]	1-2	0.01	0.06
	2-4	0.01	0.05
	4-6	0.01	0.05
	6-8	0.02	0.06
	8-12	0.02	0.06
	12-24	0.02	0.06

Table 5.5: $D^+ \sigma(f_{\text{prompt}})^{\text{REL}}$.

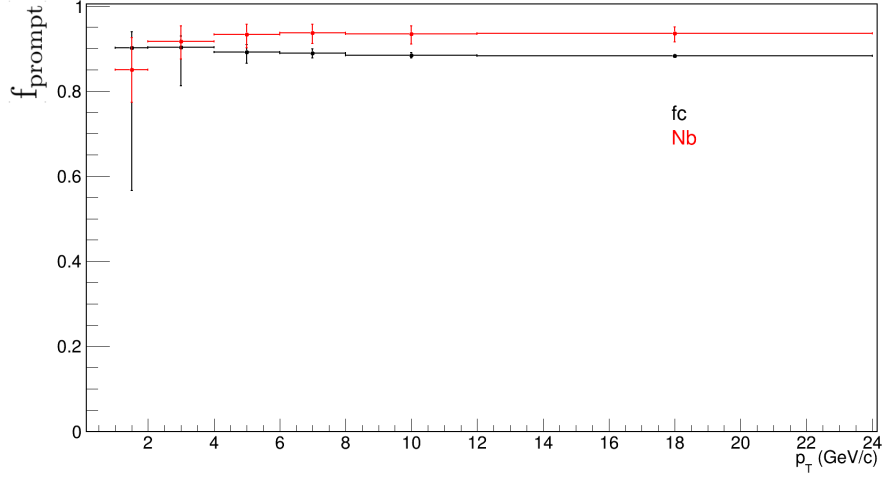


Figure 5.24: D^+ feed-down fraction as a function of p_T for the multiplicity integrated case, using the so-called N_b and f_c methods.

5.3.5.2 Multiplicity Dependence

In calculating the efficiencies we've weighted the shapes of the obtained tracklets using values computed from PYTHIA8 simulations, in particular considering at least one event with a D^+ meson. This procedure might be a source of systematic uncertainty so in order to evaluate it we compare the obtained efficiencies using those weights which are obtained by assuming there's at least one event, without a cut on the mass.

An example of the obtained results can be found in Figure 5.25, where the effect seems to be negligible.

5.3.5.3 Summary of the systematics

The final assigned systematic uncertainties for D^+ can be found in Table 5.6 to Table 5.12. Here we use the usual strategy of the D2H, where all systematic uncertainties are summed in quadrature.

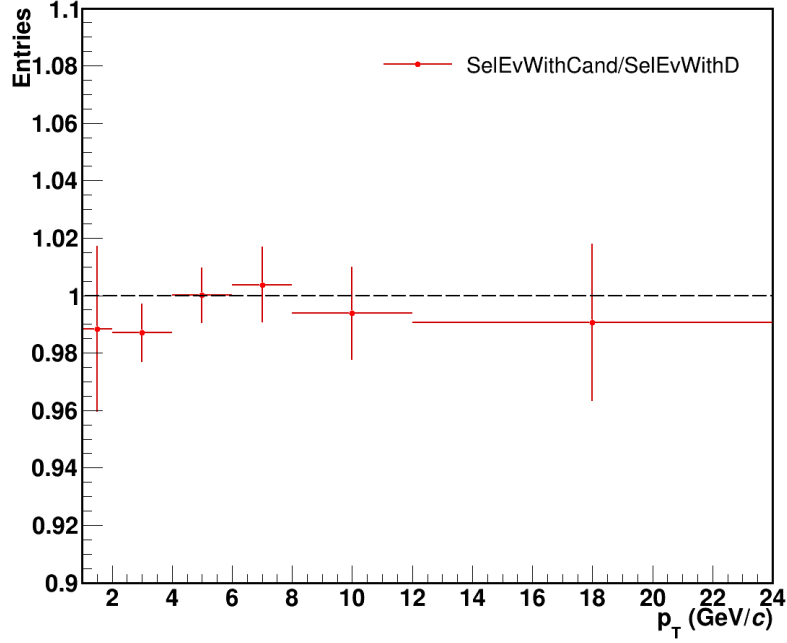


Figure 5.25: Multiplicity dependance systematic uncertainty for the D^+ meson.

p_T (GeV/c^2)	1-2	2-4	4-6	6-8	8-12	12-24
Raw Yield	3%	2%	2%	2%	3%	3%
Cut Variation	2%	2%	1%	0%	0%	0%
PID	0%	0%	0%	0%	0%	0%
MC p_T shape	2%	1%	0%	0%	0%	1%
FeedDown (lower)	2%	3%	2%	3%	3%	2%
FeedDown (upper)	2%	2%	3%	3%	2%	2%
Trigger	2%	2%	2%	2%	2%	2%

Table 5.6: Systematics for D^+ (except branching ratio and normalisation) for mult bin [1-199].

5.4 Results

The final results for the self-normalized yields for all D mesons are presented in this section. The observables to be shown in the following sections are:

1. Rawyield per event.
2. Self-normalized Yields vs multiplicity and charged particle density.
3. Average D-meson yield and comparison with J/ψ and heavy flavour electrons.

p_T (GeV/ c^2)	1-2	2-4	4-6	6-8	8-12	12-24
Raw Yield	3%	1%	1%	1%	2%	2%
Cut Variation	2%	1%	2%	3%	2%	1%
PID	0%	0%	0%	0%	0%	0%
MC p_T shape	2%	1%	0%	0%	0%	1%
FeedDown (lower)	2%	2%	2%	2%	2%	2%
FeedDown (upper)	0%	0%	0%	0%	0%	0%
Mult. Weights	1%	1%	1%	1%	1%	1%

Table 5.7: Systematics for D^+ (except branching ratio and normalisation) for mult bin [1-8].

p_T (GeV/ c^2)	1-2	2-4	4-6	6-8	8-12	12-24
Raw Yield	3%	1%	1%	1%	1%	1%
Cut Variation	3%	2%	3%	1%	3%	5%
PID	0%	0%	0%	0%	0%	0%
MC p_T shape	2%	1%	0%	0%	0%	1%
FeedDown (lower)	1%	1%	1%	1%	1%	1%
FeedDown (upper)	1%	1%	1%	1%	1%	1%
Mult. Weights	1%	1%	1%	1%	1%	1%

Table 5.8: Systematics for D^+ (except branching ratio and normalisation) for mult bin [9-13].

p_T (GeV/ c^2)	1-2	2-4	4-6	6-8	8-12	12-24
Raw Yield	1%	1%	1%	1%	1%	1%
Cut Variation	2%	3%	1%	1%	3%	2%
PID	0%	0%	0%	0%	0%	0%
MC p_T shape	2%	1%	0%	0%	0%	1%
FeedDown (lower)	0%	0%	0%	0%	0%	0%
FeedDown (upper)	1%	1%	1%	1%	1%	1%
Mult. Weights	1%	1%	1%	1%	1%	1%

Table 5.9: Systematics for D^+ (except branching ratio and normalisation) for mult bin [14-19].

4. Comparison with models.

5.4.1 Yield per Event

The Yield per event for the D^+ meson is shown in the Figure 5.26

p_T (GeV/ c^2)	1-2	2-4	4-6	6-8	8-12	12-24
Raw Yield	3%	1%	1%	1%	1%	1%
Cut Variation	2%	1%	1%	1%	1%	2%
PID	0%	0%	0%	0%	0%	0%
MC p_T shape	2%	1%	0%	0%	0%	1%
FeedDown (lower)	0%	0%	0%	0%	0%	0%
FeedDown (upper)	1%	1%	1%	1%	1%	1%
Mult. Weights	1%	1%	1%	1%	1%	1%

Table 5.10: Systematics for D^+ (except branching ratio and normalisation) for mult bin [20-30].

p_T (GeV/ c^2)	1-2	2-4	4-6	6-8	8-12	12-24
Raw Yield	5%	1%	1%	1%	3%	1%
Cut Variation	4%	1%	1%	2%	1%	1%
PID	0%	0%	0%	0%	0%	0%
MC p_T shape	2%	1%	0%	0%	0%	1%
FeedDown (lower)	1%	1%	1%	1%	1%	1%
FeedDown (upper)	2%	2%	2%	2%	3%	3%
Mult. Weights	1%	1%	1%	1%	1%	1%

Table 5.11: Systematics for D^+ (except branching ratio and normalisation) for mult bin [31-59].

p_T (GeV/ c^2)	1-2	2-4	4-6	6-8	8-12	12-24
Raw Yield	10%	3%	2%	1%	1%	2%
Cut Variation	5%	1%	1%	1%	2%	1%
PID	0%	0%	0%	0%	0%	0%
MC p_T shape	2%	1%	0%	0%	0%	1%
FeedDown (lower)	1%	1%	1%	1%	2%	2%
FeedDown (upper)	6%	5%	5%	6%	6%	6%
Mult. Weights	1%	1%	1%	1%	1%	1%

Table 5.12: Systematics for D^+ (except branching ratio and normalisation) for mult bin [60-99].

The D^+ yield-per-event shows an increasing trend as a function of tracklet multiplicity for all the p_T bins. But there is no clear trend with respect to the p_T bins. The yield -per-event is highest for the intermediate p_T bin [4-6 GeV/ c] in all multiplicity bins, whereas p_T bin [1-2 GeV/ c] has the lowest values.

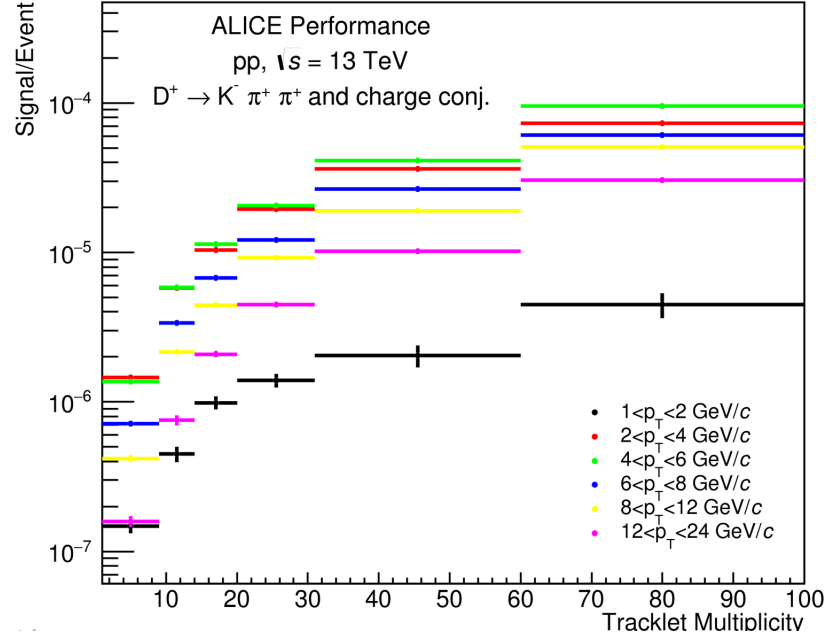


Figure 5.26: Raw yield per event as a function of tracklet multiplicity for D^+ mesons.

5.4.2 Self-normalized Yields vs multiplicity and charged particle density

The raw yields extracted from the fits to the invariant-mass distributions of D^+ -meson candidates were corrected to obtain the corrected yield per event of prompt D mesons. The D^+ meson raw yields, Y_{corr}^{mult} , were corrected by their reconstruction, topological and PID selection efficiencies, ϵ , to evaluate their multiplicity dependence. The results in the multiplicity bins, Y_{corr}^{mult} , will be given as relative to those in the multiplicity integrated sample, Y_{int}^{mult} . Therefore, the raw yields are normalized by the number of events analyzed in each sample, N_{event} . The corrected yield in each multiplicity bin was calculated as:

$$Y_{corr}^{mult} = \left(\frac{Y^{mult}}{((Acc \times \epsilon)_{prompt}^{mult} \times N_{event}^{mult})/\epsilon_{trigger}^{mult}} \right) \bigg/ \left(\frac{Y_{int}^{mult}}{((Acc \times \epsilon)_{prompt}^{mult \ int} \times N_{event}^{mult \ int})/\epsilon_{trigger}^{mult \ int}} \right) \quad (5.7)$$

where $Y^{mult}(p_T)$ are the values of the raw yields, which are corrected by the prompt fractions of $(Acc \times \epsilon)$ for each multiplicity bin times the number of events

N_{mult} in the $N_{\text{tracklets}}$ bin. This quantity is normalized by the value extracted from the integrated multiplicity bin. The normalized yields are also corrected for the effect of the trigger inefficiency $\epsilon_{\text{trigger}}$, that is 92% for INEL>0 events in the minimum bias sample, 87% for $N_{\text{tracklets}}$ interval 1-8, 98% for $N_{\text{tracklets}}$ interval 9-13, and 100% elsewhere. This is needed to account for those events which should have been selected by the trigger, but weren't. Figures 5.27 and 5.28 present the D^+ relative corrected yields as a function of the number of tracklets and the charged particle density in the measured p_T bins respectively. The error bars are showing statistical uncertainties whereas boxes are showing systematic uncertainties.

The self-normalized yields of D^+ meson increase with the relative charged-particle multiplicity faster than linearly at high multiplicities. A relative yield enhancement of about a factor of 15 with respect to the multiplicity integrated value is observed for events with five times the average charged-particle multiplicity.

5.4.3 Average D-meson yield and comparison with J/ψ and heavy flavour electrons

The results of the average D^0 , D^+ and D^{*+} mesons self-normalized yields as a function of the relative charged-particle multiplicity for each p_T interval are presented in Figure 5.29a. Except for the feed-down percent uncertainty, which is shown individually in the bottom panels in the form of relative uncertainties, the relative yields are shown in the top panels together with their statistical (vertical bars) and systematic (boxes) uncertainties. The average value of the relative charged-particle multiplicity, $\langle dN_{ch}/d\eta \rangle / \langle dN_{ch}/d\eta \rangle_{MB}$, is used to determine the positions of the points on the abscissa for each $N_{\text{tracklets}}$ interval. With an increase in charged-particle multiplicity, the average D-meson self-normalized yield rises. Similar to the self-normalized yield of the D^+ meson, the increase with the relative charged-particle multiplicity is quicker than linear at high multiplicities. The comparison of comparable observations made for the average D-mesons at 7 TeV is shown in Figure 5.29b. Due to high center-of-mass energy at 13 TeV the self-normalized yield of average

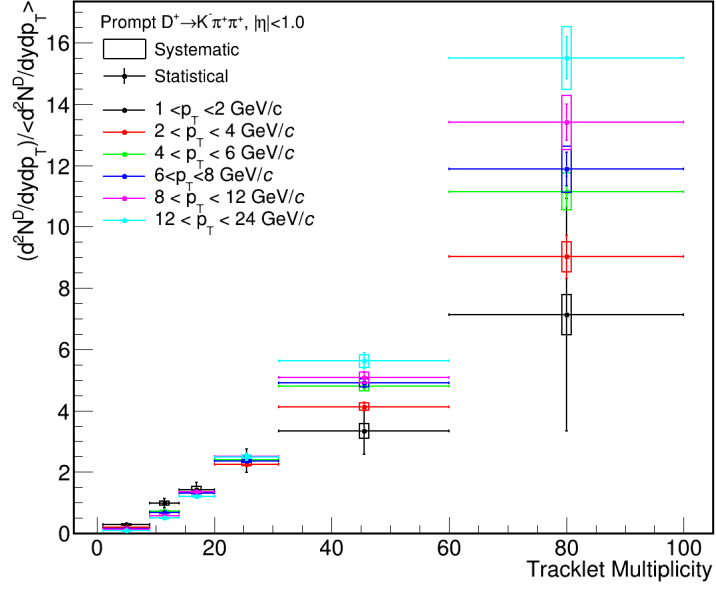


Figure 5.27: Self-normalized D⁺ yield as a function of p_T vs SPD number of tracklets as multiplicity including systematic uncertainties.

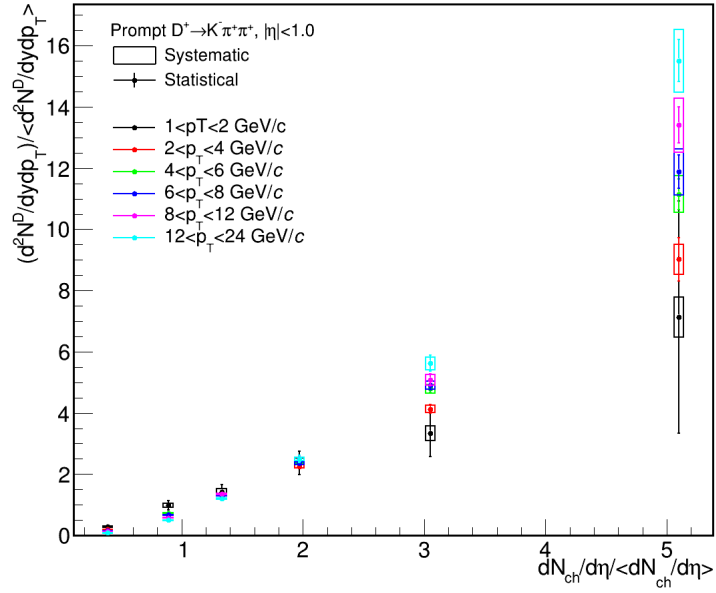


Figure 5.28: Self-normalized D⁺ yield as a function charged particle density for different p_T bins including systematic uncertainties

D-mesons have higher value at high p_T of [8-12] GeV/ c and [12-24] GeV/ c .

Figure 5.30 presents prompt D-meson and J/ψ results to compare open and hid-

den charm production. In the Figure 5.30a, the average prompt D-meson results are obtained in this analysis (along with D^0 , D^{*+} analysis) in the $2 < p_T < 4$ GeV/ c and $|y| < 0.5$ interval are compared with J/ψ measurement in $p_T < 4$ GeV/ c and $|y| < 0.9$ interval and the heavy-flavour electron measurements in $|y| < 0.7$ region in the $3 < p_T < 6$ GeV/ c range by the ALICE experiment. In the Figure 5.30b, the average prompt D-meson results are shown in the $8 < p_T < 12$ GeV/ c and $|y| < 0.5$ interval while J/ψ measurement in $4 < p_T < 8$ GeV/ c and $|y| < 0.9$ interval and heavy-flavour electron measurements in $|y| < 0.7$ region in the $6 < p_T < 12$ GeV/ c range are shown. From Figure 5.30 it is clearly visible that similar increase of the self-normalized yields with the charged-particle multiplicity is observed for open and hidden charm production at central rapidities.

5.4.4 Comparison with models

Figure 5.31 shows the comparison between D-meson (average of D^+ , D^0 , D^{*+}) production and theoretical calculations in three p_T intervals. The results of the EPOS 3 [102, 103] event generators, and of Color Glass Condensate models are represented.

EPOS 3 is an event generator for pp, p-A, and A-A systems that are colliding. In all of the systems, this event generator imposes the same theoretical framework, which assumes initial conditions followed by a hydrodynamic evolution. The "Parton based Gribov-Regge" formalism is used to establish initial conditions in the Gribov-Regge multiple scattering framework. Parton ladders are used to identify individual scatterings, or pomperons. A pQCD hard process with start and final state radiation makes up each parton ladder. A string fragmentation process is used to carry out the hadronization. A almost linear increase in the generation of D-mesons is predicted by EPOS 3 without the hydro component (**green line** in Figure 5.31). The Parton based Gribov-Regge technique in EPOS 3 has the effect of directly relating the multiplicity to the number of MPIs, i.e. $N_{hardprocess} \propto N_{ch} \propto N_{MPI}$. One notices a divergence from a linear multiplicity dependency when the hydrodynamic evolution is taken into account (**solid black line** in Figure 5.31).

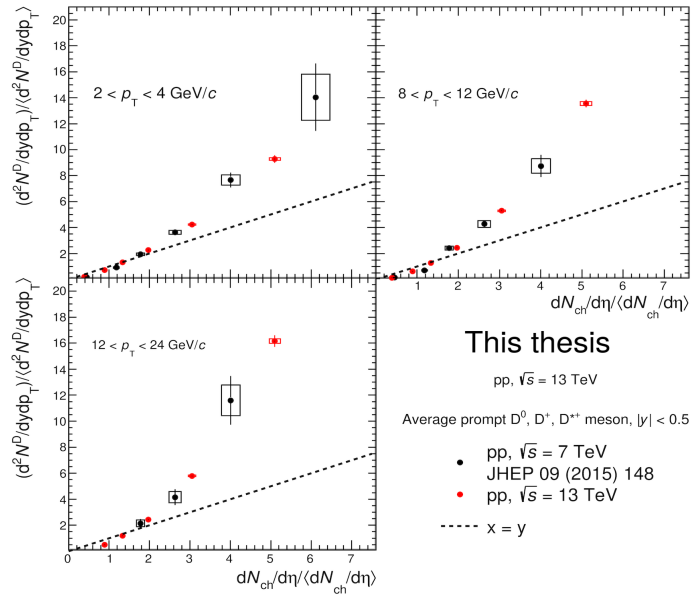
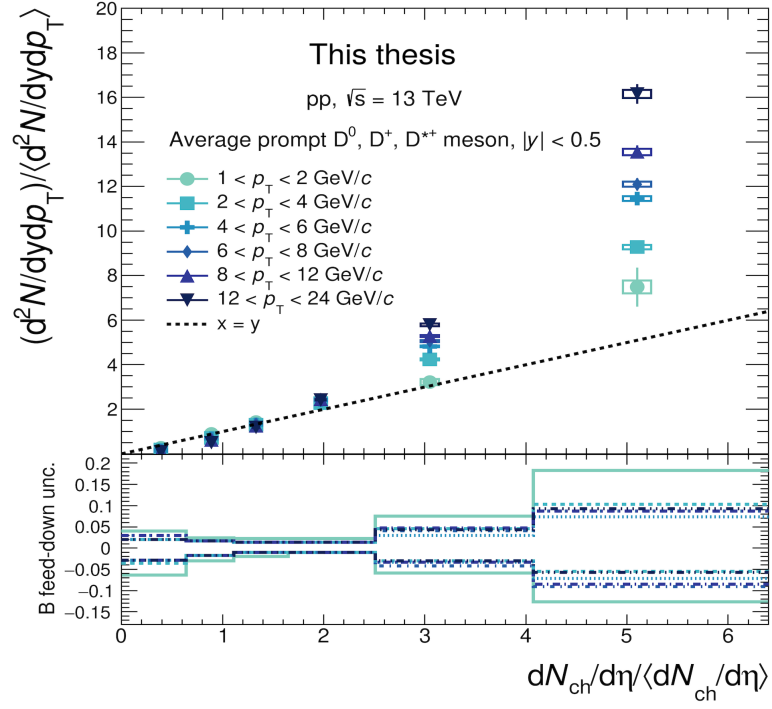
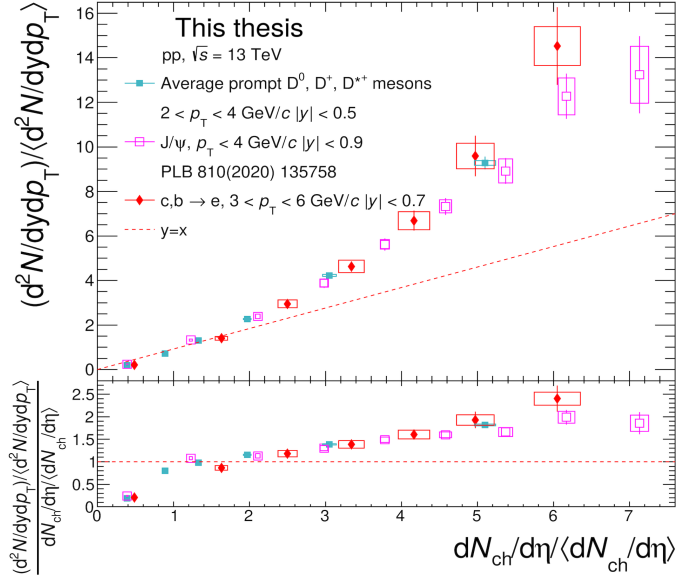
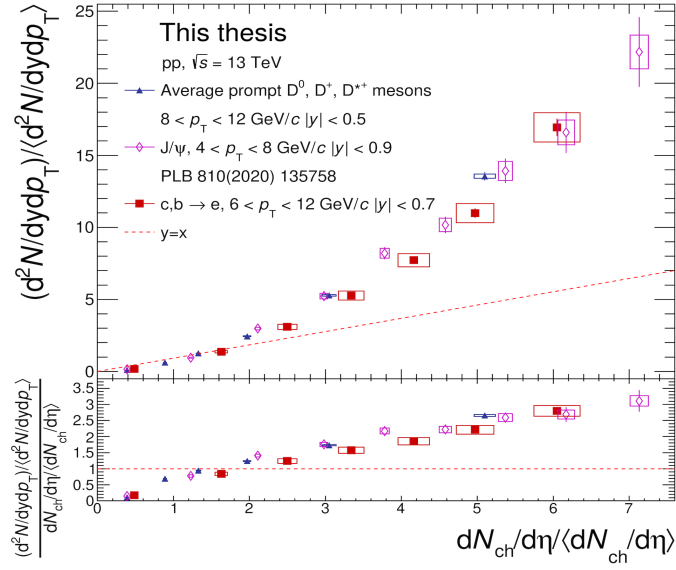


Figure 5.29: **(a)**: Average D-mesons (D^+ , D^0 , D^{*+}) self-normalized yields for each p_T interval as a function of charged-particle multiplicity at central rapidity. **(b)**: Average D-mesons self-normalized yields are compared with similar measurements at 7 TeV.



(a)



(b)

Figure 5.30: **(a):** Self-normalized yields of average D-mesons (D^+ , D^0 , D^{*+}) at $|y| < 0.5$, J/ψ at $|y| < 0.9$ and heavy-flavour electron measurements at $|y| < 0.7$ as a function of the relative charged-particle multiplicity at central rapidity are shown. D-meson yields are shown for $2 < p_T < 4$ GeV/c, while J/ψ yields are in $p_T < 4$ GeV/c and heavy-flavour electrons yields are in the $3 < p_T < 6$ GeV/c region. **(b):** D-meson yields are shown for $8 < p_T < 12$ GeV/c, while J/ψ yields are shown for $4 < p_T < 8$ GeV/c and heavy-flavour electrons yields in the interval $6 < p_T < 12$ GeV/c. Straight line is drawn to visualise non-linearity of the self-normalized yields.

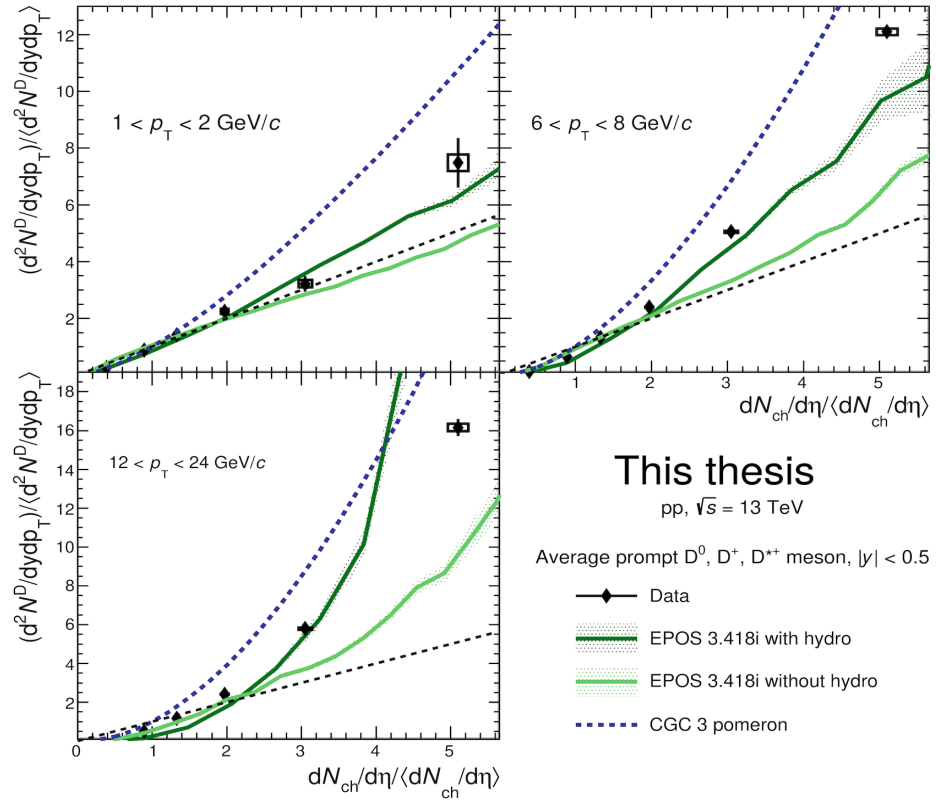


Figure 5.31: Different calculations are presented: EPOS 3 with and without hydro and CGC 3 with pomeron exchange.

6 Open Charm (D^+) vs Event Shape Variable in pp collisions

In pp collisions, the flow-like pattern is attributed to multiple parton interactions (MPI) and color reconnection (CR) mechanism. The event shape variables along with multiplicity allow isolating events according to their topologies, dominated by soft and hard processes. The soft processes are sensitive to CR and MPI, resulting in isotropic (partonic scattering with low Q^2) events whereas, jetty-like events do not show flow-like behaviour. The event shape variables are Infra Red and Collinear (IR&C) safe and provide a good tool to understand these soft-QCD processes. Their measurements allow the selection of the events for implementation of usual jet reconstruction algorithms to a better accuracy. ALICE has studied transverse sphericity, where sphericity shows rise with an increase in charge particles multiplicity. Another event shape variable, sphericity is advantageous as it depends on the total momentum of the jet, unlike sphericity which is sensitive to parcelling of jet momentum among the hadrons inside the jets.

The recent development in event shape variables provide an alternative way to characterise the high multiplicity events in small systems considering particle production, event multiplicity, and event shape variable together. Event shape observables provide information about the energy distribution in an event and could therefore create the possibility to study the perturbative as well as non-perturbative aspects of the QCD [104] in a cleaner environment. In hadronic collisions, final-state particle production can be described in two different approaches in the framework of

perturbative QCD, initial hard partonic scatterings and an underlying event [105]. The initial hard partonic processes give rise to the production of high p_T jets and can be explained by the pQCD approach. The underlying events attributed to final state particle production by soft-QCD [106] processes and perturbative mini-jets with low p_T need to be explained using phenomenological models. The event shape observables, calculated event-by-event allows one to isolate jetty-like (high p_T jets) and isotropic (partonic scattering with low Q^2) events[107]. For hadronic collisions, first measurements of event shapes for a study of jets was done at ISR [108] and SPS [109] at CERN. Experiments performed at Tevatron have reported the correlation of event shape observables with leading jet transverse energy and also with underlying events [110]. In deep-inelastic collision experiments using lepton collisions (e^+e^- , ep), event shape measurement was done to extract the strong coupling constant, α_S and test the predictions of pQCD [111, 112, 113]. The ALICE, CMS, and ATLAS experiments have done the studies based on event shape variable; transverse sphericity [114, 115] and/or thrust. These studies involved the understanding of event shape (as well jet production in case of CMS) as a function of charged particle multiplicity of the event. The results from these studies show that for high multiplicity, the events were more isotropic as compared to Pythia8 event generator. As transverse sphericity neglects the transverse-momentum spread within each jet, the transverse sphericity depends only on the total momentum of each jet and has a distinct advantage over sphericity, unlike sphericity which takes into account how jet momentum is distributed among the hadrons inside the jet[116]. This analysis is more about charm quark generation in pp collisions by examining the yield of D^+ mesons as a function of transverse sphericity at high multiplicity pp collisions at $\sqrt{s} = 13$ TeV data samples collected by ALICE. D^+ mesons are reconstructed via $D^+ \rightarrow K^- \pi^+ \pi^+$ decay channel (B.R. = $9.38 \pm 0.16\%$). The sphericity is defined using the transverse momentum of final state charged particles. The results suggest the higher production of high- p_T D^+ -mesons per event for the jetty-like events (low sphericity), whereas low- p_T D^+ -mesons production predominantly comes from isotropic events (high sphericity). These results suggest that events dominated by hard processes

produce the significant share of high- p_T D^+ mesons.

6.1 Event Shape Observables

In hadron collisions, event shape observables measure the deviation of an energy flow of events from a jetty-like to isotropic structure, defined in terms of geometrical distribution of the p_T 's of the charged hadrons in the final state [117]. The extensive list of the event shape observables and the different ways to formulate these observables are discussed in Reference [118]. The most widely used method to calculate the event shape is using the momenta of all particles in an event. These event shape observables are referred as ‘directly’ global event shapes considering the direct dependence on emission momenta of all particles. In hadron collider experiment, the event shape calculations considering only particles in phase space limited by pseudo-rapidity range which depends on detector acceptance, are termed as directly ‘central’ event shapes [104]. One of the most common event shape variables is thrust. The transverse thrust is defined as:

$$T_{\perp} = \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T_i} \times \hat{n}_T|}{\sum_i p_{T_i}} \quad (6.1)$$

where $\vec{p}_{T_i}$ represents the transverse momentum of i th particle, p_{T_i} is its modulus and $\hat{n}_T$ is the unit vector along the thrust axis. The summation runs over the all charged particle in the final state of the event and $\hat{n}_T$ maximizes the ratio in Eq.6.1. The measurement of event shapes in the transverse plane allows to eliminate the bias from the boost along the beam axis [104]. The use of complement of transverse thrust ($T_{\perp}$), $\tau_T = 1 - T_{\perp}$ provides compatibility with the definitions of other event shape variables and ranges from 0 for the perfectly pencil-like topology to $(1 - 2/\pi)$ for isotropic distribution. The transverse thrust axis $\hat{n}_T$ and the beam axis together form the event plane. The directly global **transverse thrust minor** can be defined

to measure the out-of-event-plane energy flow, and it is given by

$$T_m = \frac{\sum_i |\vec{p}_{T_i} \times \hat{n}_T|}{\sum_i p_{T_i}} \quad (6.2)$$

It can be reformulated to set a new variable; **the transverse sphericity** :

$$S_o^{(p_T=1)} = \frac{\pi^2}{4} \min_{\hat{n}=(n_x, n_y, n_z)} \left(\frac{\sum_i |\hat{p}_{T_i(p_T=1)} \times \hat{n}|}{N_{tracks}} \right)^2 \quad (6.3)$$

where $\hat{n}$ is used to minimise the ratio in Equation 6.3 and chosen from all possible unit transverse vectors. The factor, $\pi^2/4$ normalises the minimised value to 1 for isotropic case. As a result, the value of transverse sphericity run from 0 to 1, as the distribution of particles deviates from the jetty-like to an isotropic structure.

$$S_o = \begin{cases} 0 & \text{“pencil-like” limit (hard events)} \\ 1 & \text{“isotropic” limit (soft events)} \end{cases} \quad (6.4)$$

The transverse sphericity by construction is infra-red and collinear safe. Figure 6.1 shows the distribution of particles in both scenarios. Figure 6.2 shows the cross-

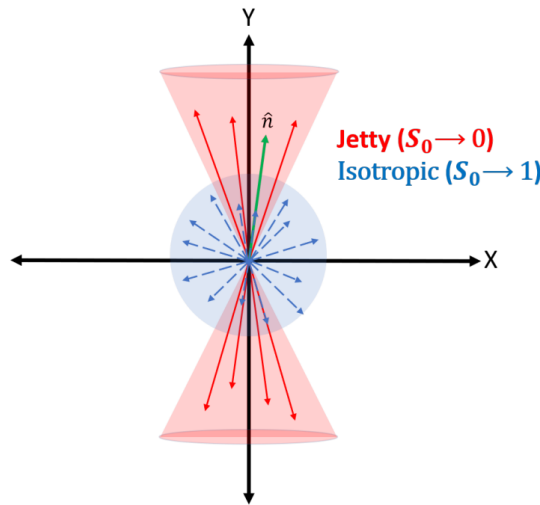


Figure 6.1: Jetty and isotropic events in the transverse plane.

sectional view for the distribution of particles in the XY-plane inside the detectors for both scenarios.

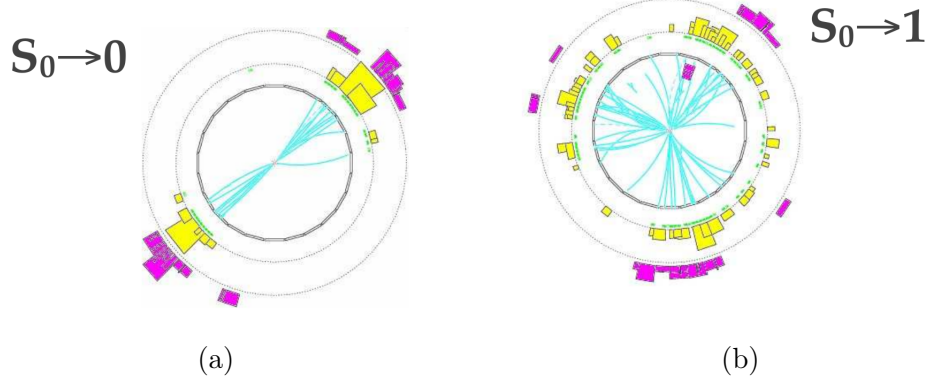


Figure 6.2: Cross-sectional of XY-plane inside the detector for **(a)**: Jetty events. **(b)**: Isotropic events

6.2 Analysis Details

6.2.1 Event Selection:

The analysis has been performed using same Minimum Bias (MB) triggered data from 2016, 2017 and 2018 that is used for D^+ meson vs multiplicity analysis. The events used in the analysis with a kINT7 trigger, passing the physics selections were required to have a primary vertex reconstructed from ITS+TPC tracks with at least one track with $|z_{vtx}| < 10$ cm. The minimum-bias trigger was based on the VZERO detector. Minimum-bias collisions were triggered by requiring a logic AND between the signal in VZEROA and VZEROC counters. The pile-up rejection similar to the "D⁺ vs multiplicity" analysis has been applied to reject the pile-up events. The event selection cuts are applied for this analysis are shown in the Table 6.1:

Aside from the events selection described above, the transverse sphericity were calculated only for those events which have at least three tracks with transverse momentum, $p_T > 0.15$ GeV/ c within $|\eta| < 0.8$. This selection is required to ensure that the calculated transverse sphericity has a good resolution.

Event cuts:	Values
Trigger Selection	kINT7
Primary Z vertex range	± 10 cm
Pile Up Rejection	AliRDHFCuts::kRejectMVPileupEvent

Table 6.1: Event Selection Cuts

6.2.2 Track Selection:

Once the events were selected, it was also important to ensure that the quality of the tracks was good for the reconstruction of D-mesons as well as for the measurement of event shape variable (sphericity). The track selection cuts were applied at two different stages of analysis: first, at the reconstruction of D-meson process and then, at the time of sphericity calculations. The two stages of track cuts described below are independent of each other.

• Track Selection for D-meson reconstructions

The D-meson candidates are reconstructed using the same track selection variables as used in the analysis of D^+ meson as a function of multiplicity and are summarized in Table 6.2.

Moreover, a track needs to have at least 70 associated space points out of the

p_T interval	1-2	2-3	3-4	4-8	8-24
p_T decay track (GeV/ c)	> 0.3	> 0.3	> 0.3	> 0.3	> 0.3
σ_{vertex} (cm)	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03
Decay length (μm)	> 700	> 700	> 1000	> 1000	> 1200
Norm Decay length XY ($n\sigma$)	> 6.0	> 5.0	> 5.0	> 5.0	> 5.0
Cosine pointing	> 0.97	> 0.97	> 0.97	> 0.97	> 0.96
Cosine pointing XY	> 0.985	> 0.985	> 0.980	-	-
$ d_0 - d_0^{exp} _{prong}$ ($n\sigma$)	< 2.5	< 2.5	< 2.5	< 2.5	< 2.5

Table 6.2: D^+ topological cuts used in the analysis.

maximum of 159 in TPC, and also tracks are required to have $\chi^2/ndf < 2$ in TPC, and at least one hit in either of the two layers of the SPD. The TPC and ITS refit are required to pass the selection of the track. Finally, the ratio of crossed rows over findable clusters in the TPC should be larger than 0.8 and implemented in the cutfile

as follows in the Table 6.3.

- – **Track Selection for Sphericity Measurements** These track selection

SetPtRange	0.3,1.e10
SetEtaRange	-0.8, 0.8
SetRequireTPCRefit	kTRUE
SetRequireITSRefit	kTRUE
SetMinNCrossedRowsTPC	70
SetClusterRequirementITS	AliESDtrackCuts::kSPD or kAny
SetMinRatioCrossedRowsOverFindableClustersTPC	0.8

Table 6.3: D^+ topological cuts used in the analysis.

cuts were applied at a time of measurement of sphericity. To achieve a better reconstruction of the event shape variable (sphericity), the two sets of track cuts namely, TPConly track cuts + TPCrefit and Hybrid track cuts were tried, which are listed below.

(a) TPConly Track Cuts+TPCrefit:

FILTER BIT 1: Standard cuts on primary tracks GetStandardTPCOnlyTrackCuts()+TPCrefit The tracks has to satisfy various cuts which includes number of TPC clusters > 70 , requires TPC refit, with no kink daughters, $DCA_{xy} < 2.4$ cm, $DCA_z < 3.2$ cm and constrained to SPD vertex. These track cuts provide uniform ϕ distribution, but p_T resolution is poor.

(i) Hybrid Track Cuts: These further include

FILTER BIT 256:

```
AliESDtrackCuts::GetStandardITSTPCTrackCuts2011(kFALSE)
SetMaxDCAToVertexXY(2.4)
SetMaxDCAToVertexZ(3.2)
SetDCAToVertex2D(kTRUE)
SetMaxChi2TPCConstrainedGlobal(36)
SetMaxFractionSharedTPCClusters(0.4)
SetHybridFilterMaskGlobalConstrainedGlobal(1<<8) // these normal global tracks
will be marked as hybrid
```

The tracks require to have p_T dependent cut on number of TPC clusters in 1st layer, requires TPC refit, fraction of shared TPC clusters < 0.4 , require ITS refit, χ^2 p/TPC cluster < 4 , χ^2 p/ITS cluster < 36 , with no kink daughters, $DCA_{xy} < 2.4$ cm, $DCA_z < 3.2$ cm, at least one hit on SPD and χ^2 between TPC constrained and global < 36 .

OR

FILTER BIT 512:

SetClusterRequirementITS(AliESDtrackCuts::kSPD, AliESDtrackCuts::kOff)

SetRequireITSRefit(kTRUE)

SetGlobalConstrainedFilterMask(1<<9) (these tracks are global constrained tracks)

SetWriteHybridGlobalConstrainedOnly(kTRUE)

The tracks cuts require a number of TPC crossed rows > 70 , the ratio of crossed rows to findable cluster > 0.8 . Also requires TPC refit, χ^2 p/TPC cluster < 4 , with no kink daughters, p_T dependent DCA_{xy} , $DCA_z < 2$ cm and constrained to primary vertex to improve p_T resolution. These track cuts provide a good track p_T resolution, uniform ϕ distribution.

6.2.3 Reconstruction and selection

D^+ mesons and their anti-particles were reconstructed in the central rapidity region from its charged hadronic decay channel $D^+ \rightarrow K^- \pi^+ \pi^+$ (B.R. = $9.38 \pm 0.16\%$ and $c\tau = 312 \mu\text{m}$). D mesons candidates were filtered by applying kinematical and topological cuts, and particle identification criteria. The D^+ signal was extracted in a p_T range of 1-24 GeV/ c , using a transverse momentum binning of [2-4], [4-6], [6-8], [8-12], [12-24] GeV/ c , meaning a total of 6 intervals, in the transverse sphericity intervals of [0-0.5], [0.5-0.65], [0.65-0.80], [0.80-1]. For the multiplicity integrated analysis we considered an interval of [20-81] tracklets. The Inner Tracking System (ITS) offers the necessary resolution of a few tens of microns on the track location at the primary vertex to resolve the decay's vertex. Topological cuts are

used to define and choose D meson candidates from displaced tracks. The actual cut values were adjusted to maximise the statistical significance of the signal and are p_T dependent, resulting in a selection efficiency that rises with p_T . Particle identification (PID) on the D meson decay tracks was used to further decrease the combinatorial background. PID is carried out using the Time Projection Chamber (TPC) specific energy data and the Time of Flight (TOF) detector time of flight measurements. The invariant mass distribution is fitted with a Gaussian function for the signal peak and an exponential shape for the background in order to obtain the signal yield. In order to lessen the combinatorial background, the reconstructed candidates are also chosen topologically.

6.2.3.1 Particle identification

Additional background rejection in the low momentum area is provided by the identification of the charged kaons in the TPC and TOF detectors. The Time Projection Chamber's (TPC) specific energy deposit data and the Time of Flight (TOF) detector's flight time measurements are both used in the PID selection technique. The TOF detector enables accurate kaon and pion identification over a broad momentum range up to 2 GeV/c. The particle in the D⁺ meson decay with the opposite charge sign from the D meson is called a kaon. As a result, the triplets were disregarded if either the opposite sign track or at least one of the two identical sign tracks did not agree with the kaon hypothesis.

6.2.4 RawYield Extraction

The D⁺ yields were extracted by fitting the invariant mass distributions with a function composed of a Gaussian for the signal and an exponential term that describes the background shape. The D⁺ meson yields were extracted in different p_T ranges ([2,4], [4,6], [6,8], [8,12] and [12,24] GeV/c) in the integrated multiplicity bin [20-81]. Figure 6.3 shows the fitting for the data in the p_T bin [2,4] GeV/c. Then the yield is extracted for a given p_T bin in different s_0 ranges ([0-0.5], [0.5-0.65], [0.65-0.8],

[0.8-1]) by fixing the sigma values obtained from the invariant mass spectra in the integrated sphericity bin[0-1.0]. Figures 6.4 and 6.5 show the invariant mass spectra in the different sphericity and p_T ranges.

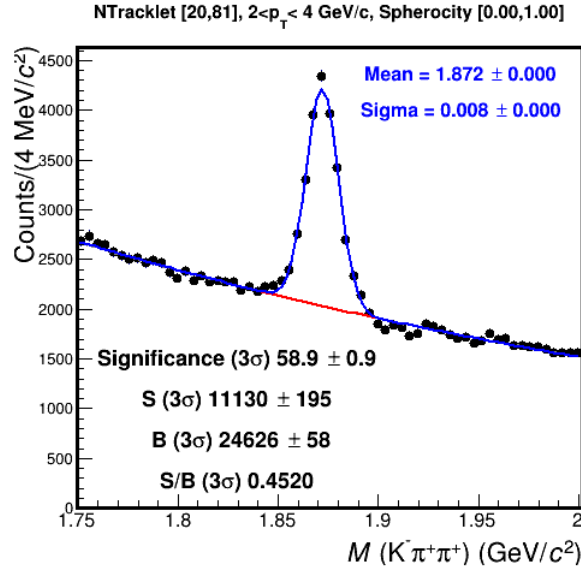


Figure 6.3: D^+ invariant mass plots for the transverse sphericity bin [0-1] and mult bin [20,81].

6.2.5 Efficiency and Acceptance

The raw counts of D^+ mesons extracted in each p_T and sphericity interval were corrected for the reconstruction and selection efficiency. The efficiency correction factors, were determined for the D^+ -meson hadronic decays considered in this analysis using Monte Carlo simulations of pp collisions generated with the PYTHIA8 event generator.

The efficiency is calculated by taking the ratio of D^+ candidates at reconstruction level (passing all selection cuts) to generator level. The efficiency was evaluated for prompt D^+ -mesons. The p_T dependence of efficiency is shown in Figure 6.6 for multiplicity bin [20, 81],[20,30] and [31,81] in different sphericity bins.

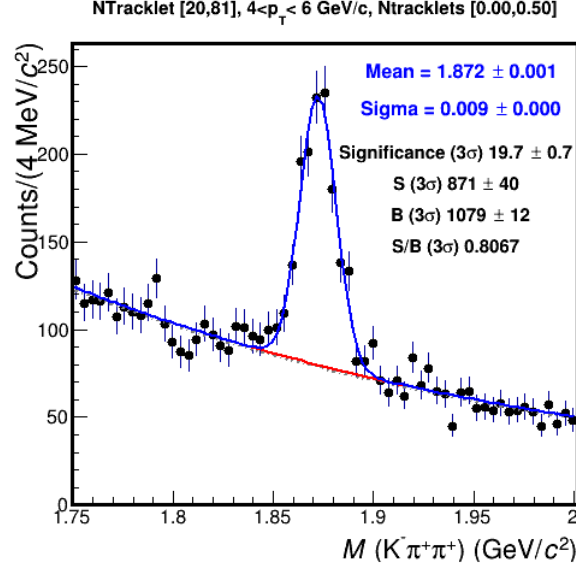


Figure 6.4: D^+ invariant mass plots for the transverse sphericity bin [0-0.5] and tracklet bin [20,81].

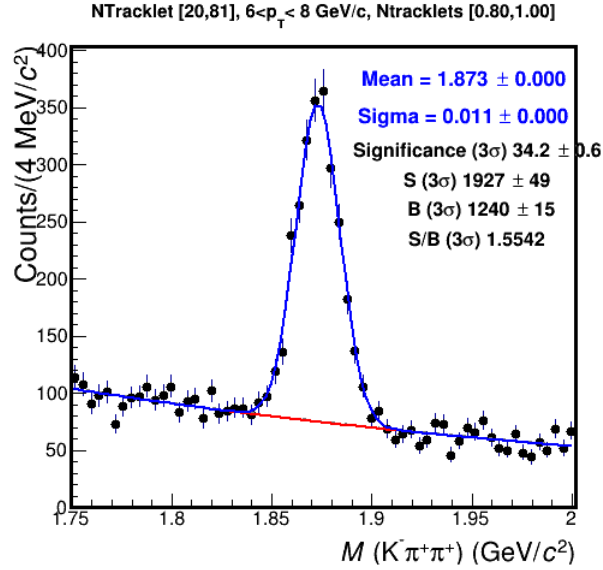


Figure 6.5: D^+ invariant mass plots for the transverse sphericity bin [0.8-1] and tracklet bin [20,81].

6.3 Systematics

In this section, we explore the possible systematic uncertainties on yield extraction, topological selections and feed-down contribution. The systematic uncertainties due

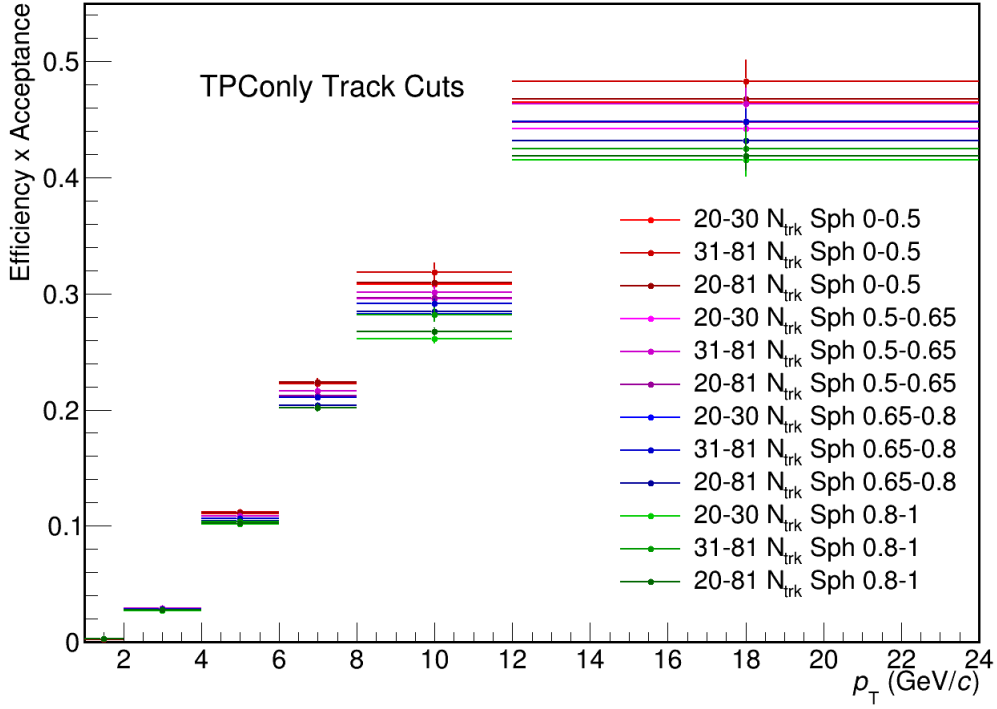


Figure 6.6: D^+ -meson efficiency times acceptance as a function of sphericity in tracklet intervals $[20,81]$, $[20,30]$ and $[31,81]$.

to PID efficiency, p_T shape, track reconstruction efficiency should cancel out while calculating the self-normalized values. We consider the following systematic uncertainties in these analyses:

- Raw yield extraction;
- Selection efficiency;
- Feed-down subtraction, including FONLL and multiplicity dependence;

The yield extraction systematics was evaluated by extracting the yields varying the background fit function, the range of the invariant mass spectra and the binning in the MultiTrial approach. The multiple trial approach is used to get raw yield distribution in different p_T and sphericity intervals for a multiplicity-integrated interval as described earlier and then it is divided by the raw yield distribution for p_T and integrated sphericity in the same multiplicity-integrated interval. In this approach different fitting parameters like background functions, fit range, bin widths etc. are

tried. Among the variations, we also considered two methods of bin counting: one in which the signal is extracted as the difference between the total histogram and the fit function of the background in the signal region and one in which the the same procedure is performed considering the entire invariant mass region. Only fits that have a reduced χ^2 below two, where considered as variation. The variations in the fit strategy are shown in the Table 6.4. The main value plotted in the results is the ratio between the production of the mesons in the sphericity class over the sphericity integrated results in order to account for the correlation between MB data and vs sphericity. The results obtained using this procedure will be defined as systematics.

An example of the output of the MultiTrial fitter for the D^+ meson is shown in

Lower bound Fit range (GeV/c^2)	(1.70, 1.72, 1.74, 1.76, 1.78)
Upper bound Fit range (GeV/c^2)	(1.97, 1.99, 2.01, 2.03, 2.03)
rebin values	1, 2, 3, 4
background functions	Linear, Pol2, expo.
Sigma	fixed sigma and free sigma

Table 6.4: Variations used in for rawyield extraction systematics for D^+ multi-trial.

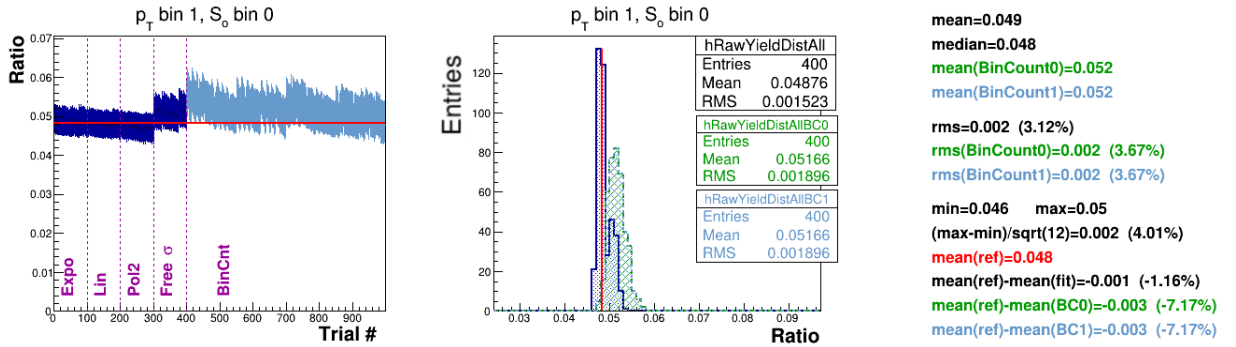


Figure 6.7: Output of the MultiTrial fitter for the D^+ meson for p_T bin [2-4] GeV/c for the multiplicity [20-81] and sphericity [0-0.5].

Figure 6.7, where the p_T bin is [2-4] GeV/c and the multiplicity bin is [20-81] and sphericity bin[0-0.5]. In the figure the raw yield distributions are shown. The assigned systematic was estimated considering the RMS of the fit distribution, together with the mean of the fit + bin counting distributions compared to the central value.

Similarly Figure 6.8 shows the results in p_T bin [4-6] GeV/ c for the sphericity bins [0.5-0.65] and [0.65-0.80] in the multiplicity range [20-81].

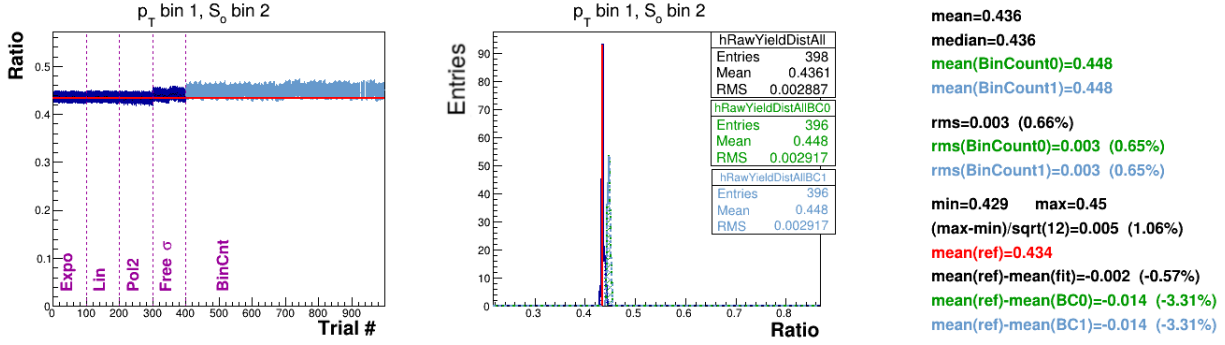


Figure 6.8: Output of the MultiTrial fitter for the D^+ meson for p_T bin [2-4] GeV/ c for the multiplicity [20-81] and sphericity [0.65-0.80].

6.3.1 Selection Efficiency

In order to obtain the measurement, the data has to be corrected for detector acceptances and efficiencies which are determined from Monte Carlo simulations. Differences between data and MC in the distribution of one (or more) of the variables used in the candidates selection could introduce biases in the extraction of the corrected yields. To quantify the effect and estimate a corresponding systematic uncertainty, we compared the corrected yield obtained using different selection criteria i.e by comparing the corrected yield extracted by using different sets of topological cuts. Four sets looser and four sets of tighter cuts with respect to the central value were checked. The systematics is assigned as the R.M.S of the difference of corrected yield from the central value. In Figure 6.9, the ratio of the prompt D^+ MC efficiency for the varied cuts with respect to the efficiency for the standard cuts has been shown. Figure 6.10 shows the ratio of the relative corrected yield for all the loose and tight sets of cuts with respect to the central cuts as well as the assigned systematics for the selection efficiency of the D^+ meson (pink patch).

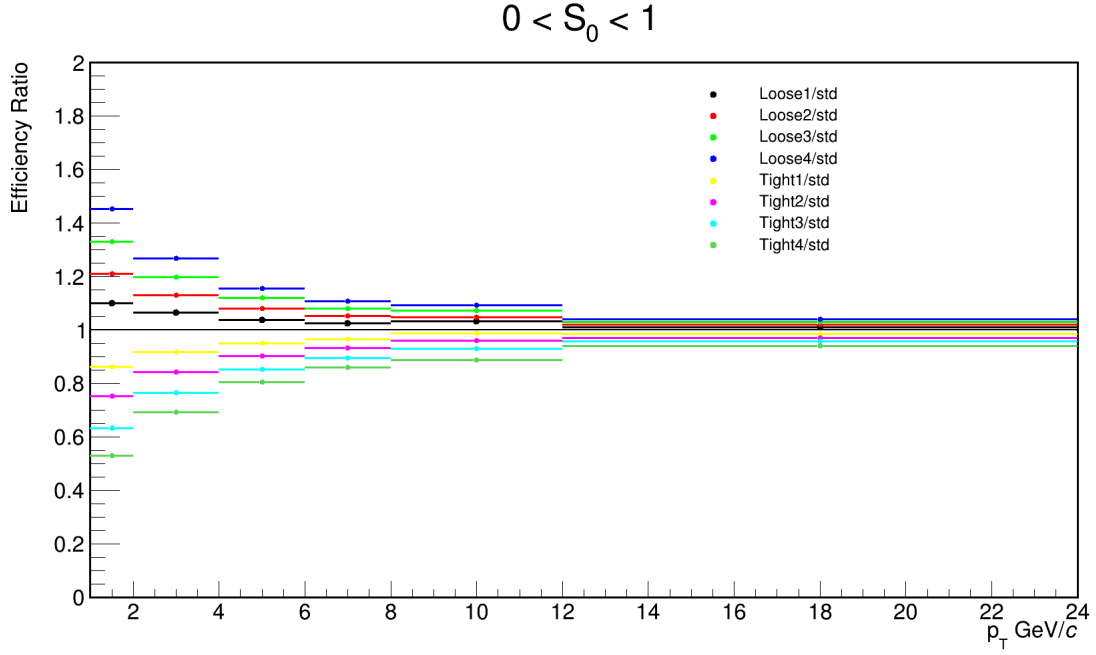


Figure 6.9: Ratio of prompt D^+ efficiencies for varied cuts with respect to the central value.

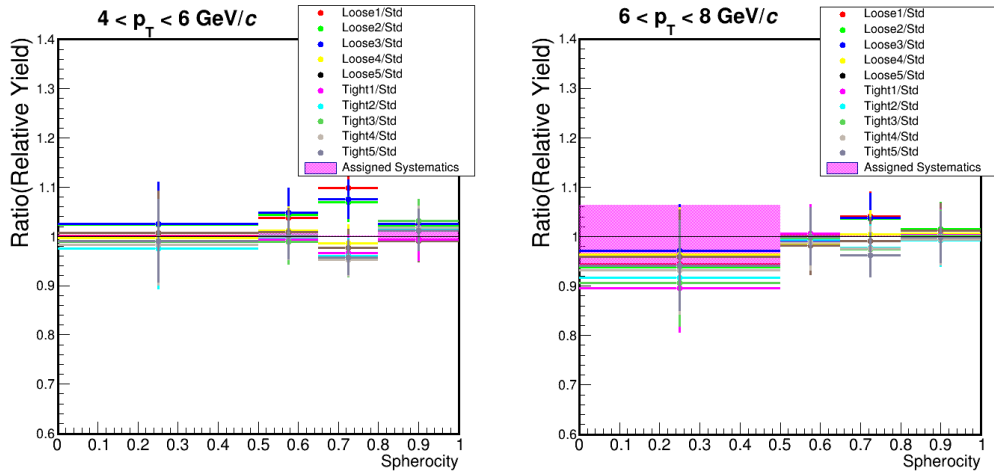


Figure 6.10: Ratio of D^+ relative corrected yields for varied cuts with respect to the central value. Pink region shows the assigned systematics.

6.3.2 Feed-down Systematics

The contribution from B-hadron decay (feed-down) to the fraction of prompt D^+ meson (fprompt (Figure 6.11), calculated from FONLL predictions) is expected to

cancel out in the ratio of the corrected yield in the different sphericity intervals to the integrated sphericity bin. For this it is assumed that the relative contribution from beauty decay product to the D^+ yield is a constant value in different sphericity intervals and in the integrated sphericity interval for a given p_T interval (using Pythia). In Figure 6.12, values of the ratio of prompt D^+ efficiencies to feed-down D^+ efficiencies are shown for sphericity integrated and sphericity intervals respectively.

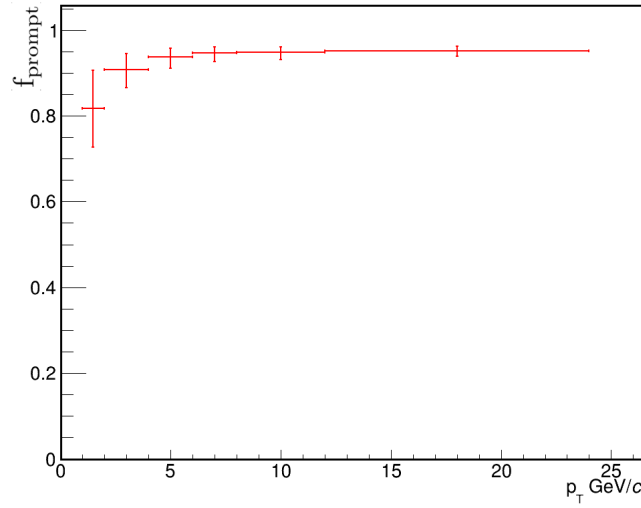


Figure 6.11: Fraction of prompt D^+ meson yield as a function of p_T .

The prompt and feed-down contributions were compared with Pythia Monte Carlo to get the distribution of prompt and feed-down to get the distribution of prompt and feed-down D^+ -mesons as a function of multiplicity and p_T in Pythia and are shown in Figure 6.13, Figure 6.14 and Figure 6.15 (for charm-enriched MC data sample, $N_{\text{tracklets}}$ [1, 80] and p_T [1, 24]). From Figure 6.15, it can be clearly seen that the ratio is compatible with unity. Therefore, the difference between prompt and feed-down fraction is negligible, suggesting that the systematic uncertainties coming from B-hadron decay (feed-down) were not needed to be assigned.

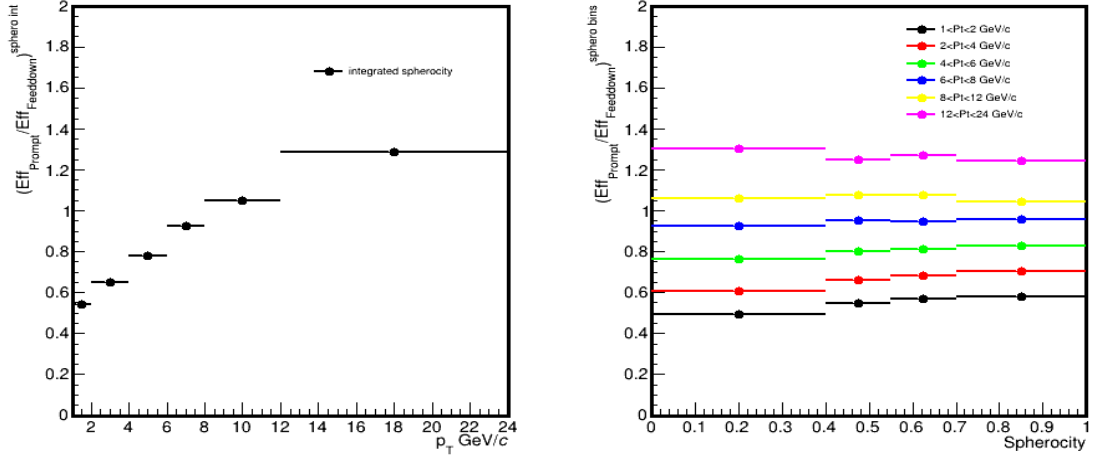


Figure 6.12: Comparison of B-hadron decay contribution in the D^+ mesons efficiencies for the study of relative yield using Pythia. (a) ratio between prompt to feeddown efficiency in integrated S_0 interval (b) ratio between prompt to feeddown efficiency in different p_T intervals.

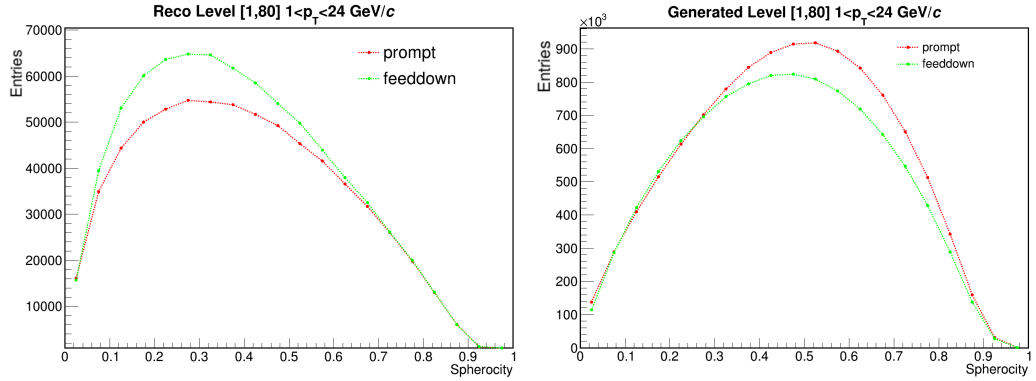


Figure 6.13: The comparison of prompt and feeddown D^+ at Reconstructed (left) and Generated (right) Level.

6.3.3 Systematic uncertainties in multiplicity sub-intervals

The systematics uncertainties were calculated for integrated multiplicity bin, $N_{\text{tracklets}}$ [20, 81] and these numbers are then used also for the multiple multiplicity bins since these are low statistics bins and may be affected by statistical fluctuations. The main source of uncertainty is from raw yield extraction, so to test if the uncertainties estimated from the wide multiplicity bin can be applied also to the sub-intervals, the

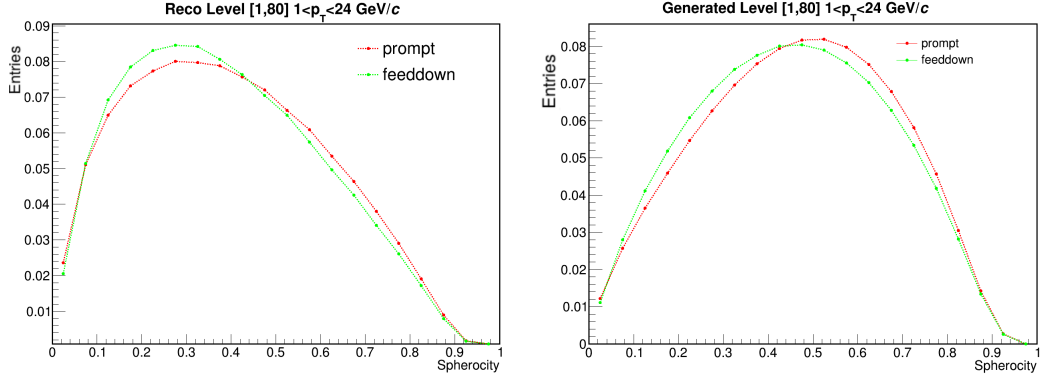


Figure 6.14: The comparison of normalized (to integral of same distribution) prompt and feeddown D^+ at Reconstructed (left) and Generated (right) Level.

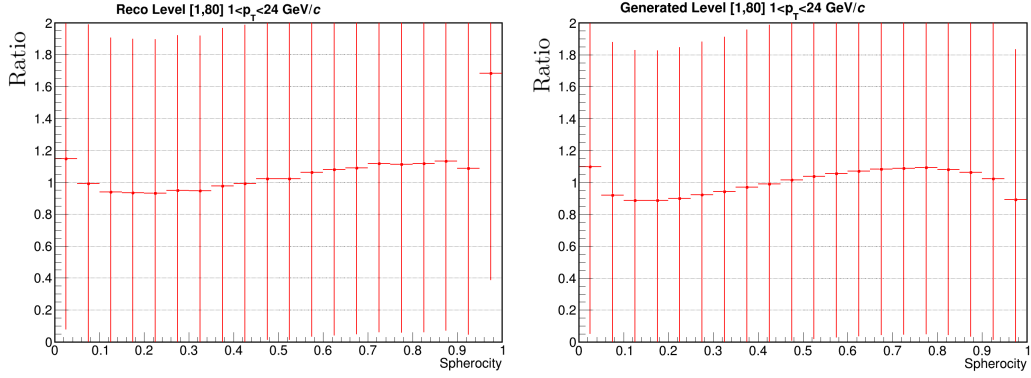


Figure 6.15: The Ratio of prompt and feeddown D^+ at Reconstruction level [left] and Generated level [right] for charm-enriched MC sample. (using Pythia in multiplicity interval, $N_{tracklets}$: [20,81] and p_T : [1, 24]).

line shape of signal and background in different intervals of multiplicity and sphericity is compared with that of sphericity intervals and integrated multiplicity in different p_T intervals. Figure 6.16 shows the ratio of invariant mass distribution of D^+ in different sphericity bins to integrated sphericity for integrated multiplicity interval for p_T interval between 2 to 4 GeV/ c . The flat distribution shows that the invariant mass distribution in different sphericity bins is similar to that of integrated sphericity. Similarly, the ratio of these distributions were checked for different multiplicity intervals with respect to integrated multiplicity (Figure 6.17 for a p_T (2, 4) GeV/ c).

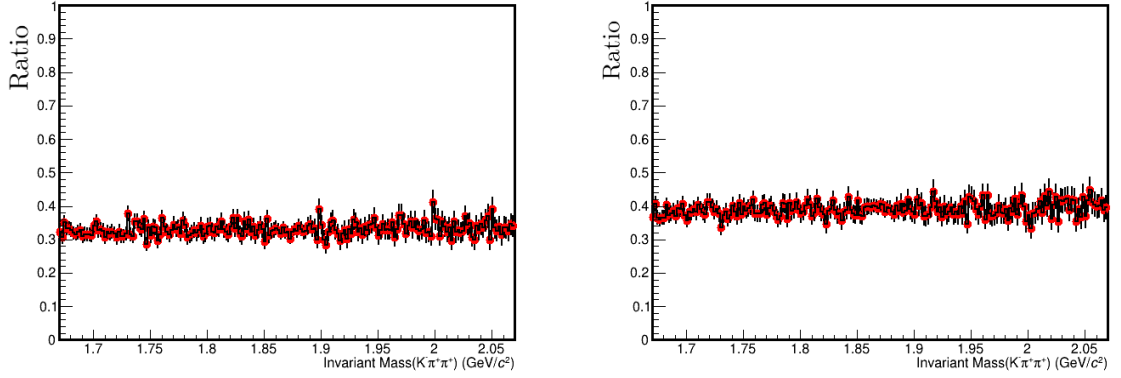
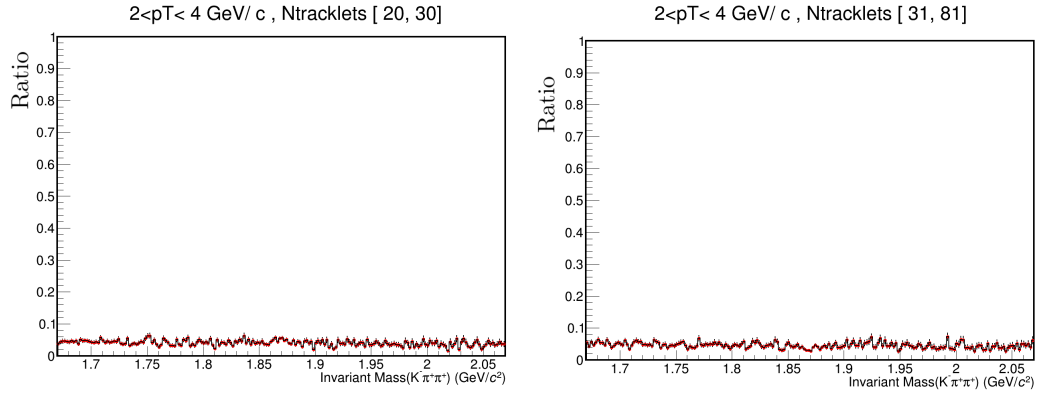


Figure 6.16: Mass distribution ratio in sphericity intervals to integrated sphericity interval for integrated multiplicity case in the p_T interval, (2,4) GeV/ c .



(a) The ratio of mass distribution in multiplicity interval [20,30] to the integrated multiplicity interval [20,81]. (b) The ratio of mass distribution in multiplicity interval [31,81] to the integrated multiplicity interval [20,81].

Figure 6.17: Mass distribution ratio in multiplicity intervals to integrated multiplicity interval in the p_T interval [2,4] GeV/ c

6.3.4 Summary of Systematics

All the other sources of uncertainties like PID efficiency, track reconstruction efficiency, p_T shape etc. are expected to cancel out in the ratio of corrected D^+ relative yields. The final systematic uncertainties are calculated by quadrature and are summarised in the Table 6.5

p_T intervals GeV/ c	Sphericity intervals, S_O			
	0.00-0.40	0.40-0.55	0.55-0.7	0.70-1.0
1-2	6%	3%	3%	4%
2-4	5%	4%	2%	3%
4-6	4%	4%	3%	4%
6-8	4%	3%	3%	3%
8-12	5%	3%	2%	3%
12-24	6%	4%	3%	6%

Table 6.5: Summary table of the systematics in p_T and transverse Sphericity bin for D^+ mesons in the multiplicity range [20-81].

p_T intervals GeV/ c	Sphericity intervals, S_O		
	0.00-0.40	0.40-0.55	0.55-1.0
1-2	6%	3%	4%
2-4	5%	4%	3%
4-6	4%	4%	4%
6-8	4%	3%	3%
8-12	5%	3%	3%
12-24	6%	4%	6%

Table 6.6: Summary table of the systematics in p_T and transverse Sphericity bin for D^+ mesons in the multiplicity range [20-30] and [31-81].

6.4 Results

The final results for the self-normalized yields for D^+ mesons as a function of sphericity for different p_T and tracklet intervals are presented in this section. The observables to be shown in the following sections are:

1. Self-normalized Yields vs transverse sphericity (S_O).
2. Average Self-normalized yields vs transverse sphericity (S_O).

6.4.1 Self-normalized Yields vs transverse sphericity

The extracted D^+ -meson raw yield is further corrected by the reconstruction, topological and PID selection efficiencies ($A \times \varepsilon_{promptD^+}$) evaluated using Monte Carlo

data sample enriched with charm. The final results are reported as the corrected relative yield (or Self-normalized yield) given by the ratio of reconstructed D^+ yield in each spherocity and p_T intervals ($d^2 N^{D^+}/dydp_T$) to the spherocity-integrated yield ($\langle d^2 N^{D^+}/dydp_T \rangle$), corrected for efficiency, for a given multiplicity interval. The raw yield reconstructed is normalized by total events analysed in that particular bin to get the D^+ raw yield per event. The corrected relative yield can be formulated as,

$$Y_{\text{corr}}^{\text{mult,sphero}} = \left(\frac{1}{N_{\text{events}}^{i,j}} \frac{N_{\text{rawD}^+}^{i,j}}{\epsilon_{\text{promptD}^+}^{i,j}} \right) / \left(\frac{1}{\langle N_{\text{events}}^j \rangle} \frac{\langle N_{\text{rawD}^+}^j \rangle}{\epsilon_{\text{promptD}^+}^j} \right) \quad (6.5)$$

where the indexes i, j defines the spherocity and multiplicity intervals respectively. The correction for acceptance, which accounts for a fraction of a mid-rapidity D^+ -mesons rejected due to limited detector coverage for a given p_T interval cancels out in the above ratio leaving behind the only correction due to reconstruction and selection efficiencies.

The results of the D^+ -meson relative corrected yields for each p_T interval at mid-rapidity are presented in Figures 6.18, 6.19 and 6.19 as a function of event spherocity, S_o for different event tracklet multiplicity, $N_{\text{tracklets}}$ ranges. The relative yields are reported with their statistical (vertical bars) and systematic (empty boxes) uncertainties. It has been observed that the production of D^+ meson can be isolated depending on the jetty-like (hard processes) and isotropic (soft processes) geometrical structure of the events. The results show that the jetty-like D^+ production is dominated at high p_T 12-24 GeV/ c whereas suppressed for low p_T production. On the other hand, at low p_T 1-6 GeV/ c D^+ production occurs more likely in isotropic events ($S_o \approx 1$). The analysis addresses different multiplicity intervals in high multiplicity region ($N_{\text{tracklets}} > 20$) to understand the D^+ production dependence versus spherocity in different multiplicity regions. The trend of D^+ production remains same for two different multiplicity regions. However at higher multiplicity the enhancement in the production of jetty-like D^+ -mesons is observed.

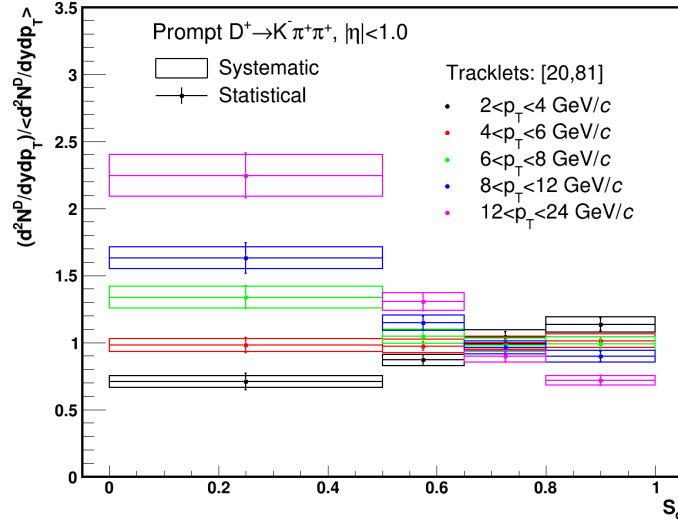


Figure 6.18: Final results of D^+ -meson corrected relative yield production as a function of sphericity, S_o in integrated multiplicity interval, $N_{tracklets}$ [20, 81].

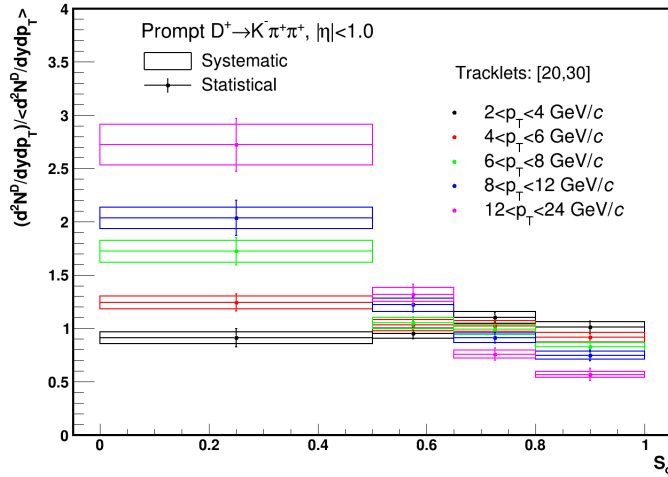


Figure 6.19: Final results of D^+ -meson corrected relative yield production as a function of sphericity, S_o in integrated multiplicity interval, $N_{tracklets}$ [20, 30].

6.4.2 Average Self-normalized yields vs transverse sphericity

In this section, the results of the average D mesons (D^0 , D^+ and D^{*+}) self-normalized yields as a function of transverse sphericity are presented in different intervals of transverse momentum and tracklet multiplicity. Figure 6.21 represents the average self-normalized yield as a function of transverse sphericity for D^0 , D^+ and D^{*+}

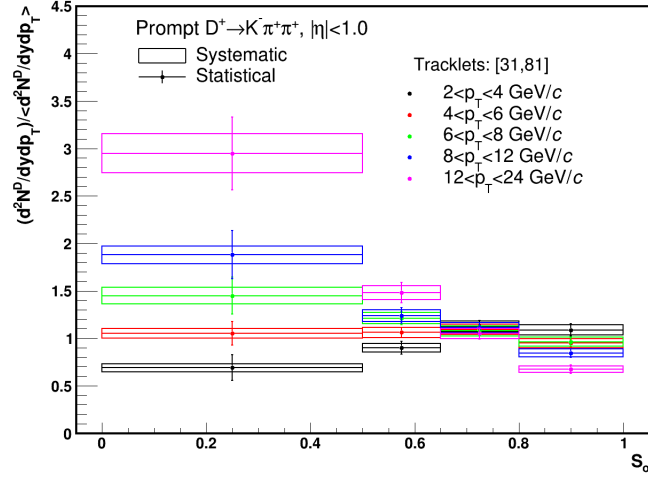


Figure 6.20: Final results of D^+ -meson corrected relative yield production as a function of sphericity, S_o in integrated multiplicity interval, $N_{tracklets}$ [31, 81].

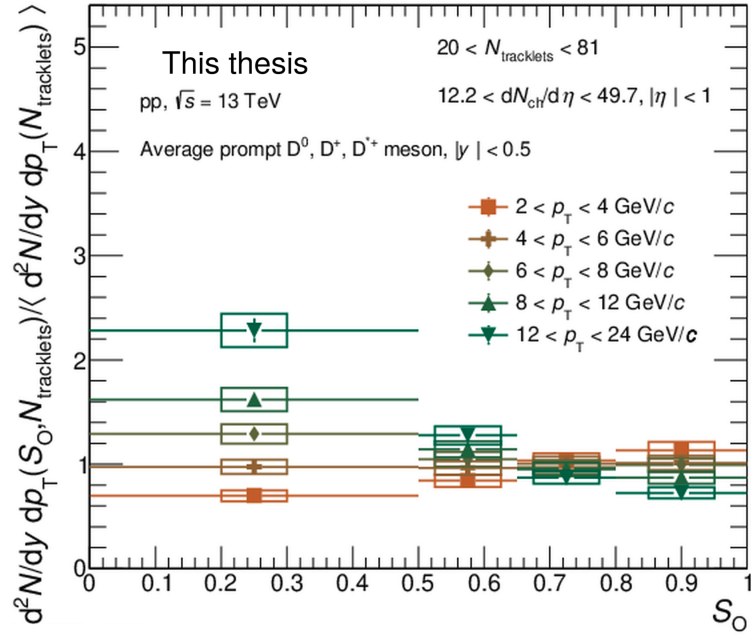


Figure 6.21: Average D-meson (D^0 , D^+ and D^{*+}) self-normalized yield production as a function of transverse sphericity, S_o in integrated multiplicity interval, $N_{tracklets}$ [20, 81].

mesons in the tracklet multiplicity interval [20,81]. Similarly Figure 6.22 shows the self-normalized yield of average D mesons in the two tracklet multiplicity sub-intervals [20,30] and [31,81]. From the results, it can be seen that the results isolate D-mesons production in hard and soft processes in different p_T and N_{trk} intervals.

The production of D-mesons at low p_T is more likely to be observed in isotropic events whereas high p_T D mesons production is favoured in jetty events. The comparison of results from the sub-intervals [20,30] and [31,81] shows that an enhancement of jetty-like D mesons production is observed at high multiplicity.

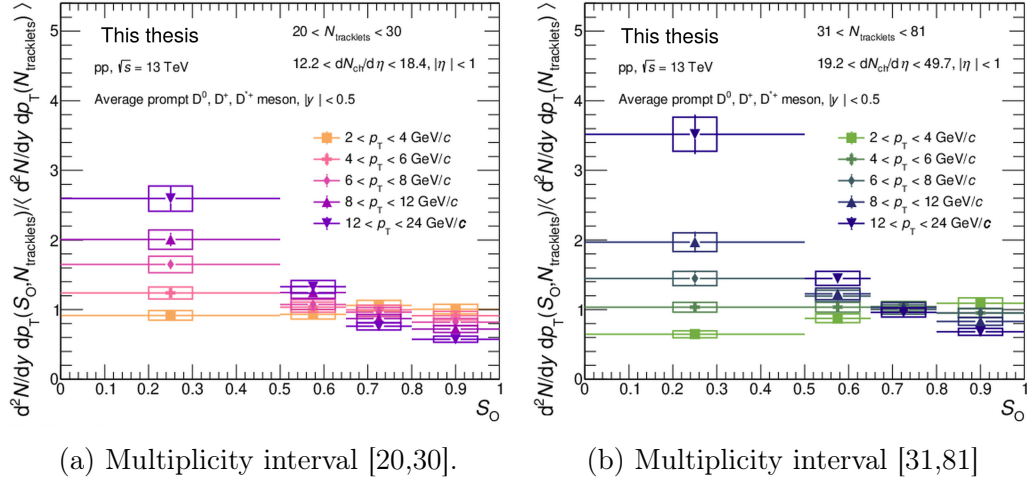


Figure 6.22: Average D-meson (D^0 , D^+ and D^{*+}) self-normalized yield as a function of transverse sphericity, S_o in the multiplicity intervals, $N_{tracklets}$ [20,30] and [31,81].

7 Summary and Conclusion

This thesis is aimed to measure the self-normalized yield of D^+ -meson as a function of multiplicity as well as the transverse sphericity (S_o) of the pp events at $\sqrt{s} = 13$ TeV. The yield of D^+ -mesons is extracted by reconstructing the invariant mass spectra in the hadronic decay channel $D^+ \rightarrow K^- \pi^+ \pi^+$ in the central rapidity region with the ALICE detector. The yield was extracted in six different p_T bins ([1,2],[2,4],[4,6],[6,8],[8,12],[12,24] GeV/ c). The optimized kinematical and topological cuts are applied to reduce the combinatorial background as well as to increase the statistical significance.

As a function of charged particle multiplicity, the Self-normalized yield of average D-mesons is calculated. For occurrences containing at least one charged particle in the range $|\eta| < 1.0$, the charged-particle multiplicity at central velocity was assessed. For events with high average charged-particle multiplicities, there is a relative yield improvement as compared to the multiplicity integrated value. The results were found to follow the same trend (non-linear increase) as that of average D-mesons measurement at 7 TeV as well as that of J/ψ at 7 TeV and 13 TeV. Similar increases in charged-particle multiplicity at centre speed are also shown in results relating to open beauty hadron yields. This shows that the augmentation of heavy-flavour relative yields is not considerably influenced by hadronization, but is instead more likely directly connected to the $c\bar{c}$ and $b\bar{b}$ production processes. The average D-meson relative yield enhancement is qualitatively characterised by (a) the CGC 3 pomeron model and (b) the EPOS 3 with hydro models as a function of the charged-particle multiplicity. .

In the centre rapidity area of the minimum bias pp events for different sphericity classes, an event shape investigation is conducted employing transverse sphericity in various tracklet multiplicity classes. It is evident that isotropic occurrences over the jetty dominate the bottom p_T region. As we approach larger p_T , this scenario, however, flips. In contrast to isotropic events, jetty events produce D^+ -mesons differently. While the latter is dominated by soft physics, the former involves high- p_T events. The self-normalized yield of D^+ -meson yield as a function of transverse sphericity (S_o) is highest for the jetty events ($S_o = 0.00-0.40$) and decreases as we go towards the isotropic events ($S_o \approx 1$).

In conclusion, it is discovered that relative yield rises with the multiplicity of charged particles and is higher for jetty events than isotropic ones. These findings imply that sphericity can be a useful tool for identifying events that are dominated by soft versus hard particle generation.

Bibliography

- [1] Murray Gell-Mann. A Schematic Model of Baryons and Mesons. *Phys. Lett.*, 8:214–215, 1964.
- [2] G. Zweig. *An $SU(3)$ model for strong interaction symmetry and its breaking. Version 2*, pages 22–101. 2 1964.
- [3] Yoichiro Nambu. A SYSTEMATICS OF HADRONS IN SUBNUCLEAR PHYSICS. pages 192–201, 1981.
- [4] M. Y. Han and Yoichiro Nambu. Three Triplet Model with Double $SU(3)$ Symmetry. *Phys. Rev.*, 139:B1006–B1010, 1965.
- [5] H. David Politzer. Reliable Perturbative Results for Strong Interactions? *Phys. Rev. Lett.*, 30:1346–1349, 1973.
- [6] David J. Gross and Frank Wilczek. Ultraviolet Behavior of Nonabelian Gauge Theories. *Phys. Rev. Lett.*, 30:1343–1346, 1973.
- [7] Edward V. Shuryak. Quark-Gluon Plasma and Hadronic Production of Leptons, Photons and Psions. *Sov. J. Nucl. Phys.*, 28:408, 1978.
- [8] J. F. Gunion and R. S. Willey. Hadronic spectroscopy for a linear quark confinement potential. *Phys. Rev. D*, 12:174–186, Jul 1975.
- [9] Xing-Min Wang, Xiao-Tong Song, and Peng-Cheng Yin. The Hadron Structure Functions in the Bag Model and Their Modifications. *Hadronic J.*, 6:985, 1983.

- [10] Susanne Mertens. Direct Neutrino Mass Experiments. *J. Phys. Conf. Ser.*, 718 (2):022013, 2016.
- [11] Shoichi Sakata, Hiroomi Umezawa, and Susumu Kamefuchi. On the Structure of the Interaction of the Elementary Particles, I: The Renormalizability of the Interactions*. *Progress of Theoretical Physics*, 7(4):377–390, 04 1952. ISSN 0033-068X.
- [12] C. Patrignani et al. Review of Particle Physics. *Chin. Phys. C*, 40(10):100001, 2016.
- [13] John Adams et al. Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration’s critical assessment of the evidence from RHIC collisions. *Nucl. Phys. A*, 757:102–183, 2005.
- [14] Eemeli Annala, Tyler Gorda, Aleksi Kurkela, Joonas Nättilä, and Aleksi Vuorinen. Evidence for quark-matter cores in massive neutron stars. *Nature Phys.*, 16(9):907–910, 2020.
- [15] A. Bazavov et al. Chiral crossover in QCD at zero and non-zero chemical potentials. *Phys. Lett. B*, 795:15–21, 2019.
- [16] Mark G. .et.al. Alford. Color superconductivity in dense quark matter. *Reviews of Modern Physics*, 80(4):1455–1515, Nov 2008. ISSN 1539-0756.
- [17] J. D. Bjorken. Highly relativistic nucleus-nucleus collisions: The central rapidity region. *Phys. Rev. D*, 27:140–151, Jan 1983.
- [18] Current bibliography of the history of science and its cultural influences, 2015. *Isis*, 106(S1):i–300, 2015. ISSN 00211753, 15456994. URL <https://www.jstor.org/stable/26455668>.
- [19] Edward Shuryak. Physics of ‘the first three fermis’ in high energy heavy ion collisions. *Nuclear Physics A*, 566:559–562, 1994. ISSN 0375-9474.

- [20] N. S. Amelin, L. P. Csernai, E. F. Staubo, and D. Strottman. Collectivity in ultrarelativistic heavy ion collisions. *Nucl. Phys. A*, 544:463–466, 1992.
- [21] Wit Busza and Alfred S. Goldhaber. Nuclear stopping power. *Physics Letters B*, 139(4):235–238, 1984. ISSN 0370-2693.
- [22] D. S. Barton and Brandenburg .et.al. Experimental study of the a dependence of inclusive hadron fragmentation. *Phys. Rev. D*, 27:2580–2599, Jun 1983.
- [23] Michael L. Miller, Klaus Reygers, Stephen J. Sanders, and Peter Steinberg. Glauber modeling in high energy nuclear collisions. *Ann. Rev. Nucl. Part. Sci.*, 57:205–243, 2007.
- [24] M. G. H. Mostafa, Cheuk-Yin Wong, and L. Chatterjee. Effect of q anti- q initial state interaction on dilepton emission rate from quark - gluon plasma. 3 1995.
- [25] K. Kajantie, J. Kapusta, L. McLerran, and A. Mekjian. Dilepton emission and the qcd phase transition in ultrarelativistic nuclear collisions. *Phys. Rev. D*, 34:2746–2754, Nov 1986.
- [26] E.V. Shuryak. Quark-gluon plasma and hadronic production of leptons, photons and psions. *Physics Letters B*, 78(1):150–153, 1978. ISSN 0370-2693.
- [27] Edmond L. Berger and D. Jones. Inelastic photoproduction of $\frac{J}{\psi}$ and Υ by gluons. *Phys. Rev. D*, 23:1521–1530, Apr 1981.
- [28] T. Matsui and H. Satz. J/ψ Suppression by Quark-Gluon Plasma Formation. *Phys. Lett. B*, 178:416–422, 1986.
- [29] S A Bass, M Gyulassy, H Stöcker, and W Greiner. Signatures of quark-gluon plasma formation in high energy heavy-ion collisions: a critical review. *Journal of Physics G: Nuclear and Particle Physics*, 25(3):R1–R57, Jan 1999. ISSN 1361-6471.

- [30] Edward V. Shuryak and Ismail Zahed. Towards a theory of binary bound states in the quark gluon plasma. *Phys. Rev. D*, 70:054507, 2004.
- [31] Rudolph C. Hwa and K. Kajantie. Diagnosing quark matter by measuring the total entropy and the photon or dilepton emission rates. *Phys. Rev. D*, 32:1109–1118, Sep 1985.
- [32] Joseph Kapusta, Peter Lichard, and David Seibert. High-energy photons from quark-gluon plasma versus hot hadronic gas. *Phys. Rev. D*, 44:2774–2788, Nov 1991.
- [33] E. Andersen et al. Strangeness enhancement at mid-rapidity in Pb Pb collisions at 158-A-GeV/c. *Phys. Lett. B*, 449:401–406, 1999.
- [34] F. Antinori et al. Hyperon yields in Pb Pb collisions from NA57 experiment. *Nucl. Phys. A*, 715:140–150, 2003.
- [35] Betty Bezverkhny Abelev et al. Multi-strange baryon production at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Lett. B*, 728:216–227, 2014. [Erratum: Phys.Lett.B 734, 409–410 (2014)].
- [36] Mateusz Ploskon. Inclusive cross section and correlations of fully reconstructed jets in $s(NN)^{1/2} = 200$ -GeV Au+Au and p+p collisions. *Nucl. Phys. A*, 830:255C–258C, 2009.
- [37] LHC Design Report Vol.1: The LHC Main Ring. 6 2004.
- [38] K. Schindl. The injector chain for the LHC. In *9th LEP Performance Workshop*, 3 1999.
- [39] E. Boltezar, H. Haseroth, W. Pirkel, G. Plass, T. Sherwood, U. Tallgren, P. Tetu, D. Warner, and M. Weiss. THE NEW CERN 50-MEV LINAC. In *10th International Linear Accelerator Conference*, 1979.
- [40] K. H. Reich. The CERN Proton Synchrotron Booster. *IEEE Trans. Nucl. Sci.*, 16:959–961, 1969.

- [41] Jean-Paul Burnet et al. Fifty years of the CERN Proton Synchrotron : Volume 2. 8 2013.
- [42] Niels Doble, Lau Gatignon, Kurt Hübner, and Edmund Wilson. The Super Proton Synchrotron (SPS): A Tale of Two Lives. *Adv. Ser. Direct. High Energy Phys.*, 27:135–177, 2017.
- [43] LHC Machine. *JINST*, 3:S08001, 2008.
- [44] K. Aamodt et al. The ALICE experiment at the CERN LHC. *JINST*, 3:S08002, 2008.
- [45] K Aamodt et al. Charged-particle multiplicity density at mid-rapidity in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Rev. Lett.*, 105:252301, 2010.
- [46] B Abelev et al. Technical Design Report for the Upgrade of the ALICE Inner Tracking System. *J. Phys. G*, 41:087002, 2014.
- [47] Fabio Sauli. The gas electron multiplier (gem): Operating principles and applications. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 805:2–24, 2016. ISSN 0168-9002. Special Issue in memory of Glenn F. Knoll.
- [48] A. Andronic and J.P. Wessels. Transition radiation detectors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 666:130–147, 2012. ISSN 0168-9002. Advanced Instrumentation.
- [49] Betty Bezverkhny Abelev et al. Performance of the ALICE Experiment at the CERN LHC. *Int. J. Mod. Phys. A*, 29:1430044, 2014.
- [50] Gerardo Herrera-Corral. A new detector array for diffractive physics in ALICE at the LHC. *AIP Conf. Proc.*, 1350(1):176–179, 2011.
- [51] J. Allen et al. ALICE DCal: An Addendum to the EMCal Technical Design Report Di-Jet and Hadron-Jet correlation measurements in ALICE. 6 2010.

- [52] E. Abbas et al. Performance of the ALICE VZERO system. *JINST*, 8:P10016, 2013.
- [53] C. Finck. The muon spectrometer of the ALICE. *J. Phys. Conf. Ser.*, 50: 397–401, 2006.
- [54] Upgrade of the ALICE Readout & Trigger System. 2013.
- [55] T Alt, G Grastveit, H Helstrup, V Lindenstruth, C Loizides, D Röhrich, B Skaali, T Steinbeck, R Stock, H Tilsner, K Ullaland, A Vestbø, T Vik, A Wiebalck, and (for the ALICE Collaboration). The ALICE high level trigger. *Journal of Physics G: Nuclear and Particle Physics*, 30(8):S1097–S1100, jul 2004.
- [56] S Bagnasco, L Betev, P Buncic, F Carminati, C Cirstoiu, C Grigoras, A Hayrapetyan, A Harutyunyan, A J Peters, and P Saiz. AliEn: ALICE environment on the GRID. *Journal of Physics: Conference Series*, 119(6): 062012, jul 2008.
- [57] A. Gheata. ALICE analysis framework. *PoS*, ACAT08:028, 2008.
- [58] R. Brun and F. Rademakers. ROOT: An object oriented data analysis framework. *Nucl. Instrum. Meth. A*, 389:81–86, 1997.
- [59] René Brun, F. Bruyant, Federico Carminati, Simone Giani, M. Maire, A. McPherson, G. Patrick, and L. Urban. GEANT Detector Description and Simulation Tool. 10 1994.
- [60] I. Huancco. Geant4 simulation of the dual phase time projection chamber tpc of argon to detect neutrinos. *Journal of Physics: Conference Series*, 1143: 012011, 12 2018.
- [61] A. Fasso et al. The FLUKA code: Present applications and future developments. *eConf*, C0303241:MOMT004, 2003.

- [62] Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands. PYTHIA 6.4 Physics and Manual. *JHEP*, 05:026, 2006.
- [63] Borut Paul Kersevan and Elzbieta Richter-Was. The Monte Carlo event generator AcerMC versions 2.0 to 3.8 with interfaces to PYTHIA 6.4, HERWIG 6.5 and ARIADNE 4.1. *Comput. Phys. Commun.*, 184:919–985, 2013.
- [64] Xin-Nian Wang and Miklos Gyulassy. HIJING: A Monte Carlo model for multiple jet production in p p, p A and A A collisions. *Phys. Rev. D*, 44: 3501–3516, 1991.
- [65] Stefan Roesler, Ralph Engel, and Johannes Ranft. The Monte Carlo event generator DPMJET-III. In *International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications (MC 2000)*, 12 2000.
- [66] Yan Pei, Swarnendu Biswas, Donald S. Fussell, and Keshav Pingali. An elementary introduction to kalman filtering. 2017.
- [67] Nestor Armesto. Nuclear shadowing. *J. Phys. G*, 32:R367–R394, 2006.
- [68] D. Antreasyan, J. W. Cronin, Henry J. Frisch, M. J. Shochet, L. Kluberg, P. A. Piroue, and Richard L. Sumner. Production of Hadrons at Large Transverse Momentum in 200-GeV, 300-GeV and 400-GeV p p and p n Collisions. *Phys. Rev. D*, 19:764–778, 1979.
- [69] Ming Shao. Cronin effect at rhic. *AIP Conference Proceedings*, 828(1):49–54, 2006.
- [70] Vardan Khachatryan et al. Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *JHEP*, 04:039, 2017.
- [71] Serguei Chatrchyan et al. Observation of Long-Range Near-Side Angular Correlations in Proton-Lead Collisions at the LHC. *Phys. Lett. B*, 718:795–814, 2013.

- [72] R. Thomas, Burkhard Kampfer, and G. Soff. Gluon emission of heavy quarks: Dead cone effect. *Acta Phys. Hung. A*, 22:83–91, 2005.
- [73] Yuri L. Dokshitzer and D. E. Kharzeev. Heavy quark colorimetry of QCD matter. *Phys. Lett. B*, 519:199–206, 2001.
- [74] S. Peigne and A. V. Smilga. Energy losses in a hot plasma revisited. *Phys. Usp.*, 52:659–685, 2009.
- [75] Magdalena Djordjevic. Collisional energy loss in a finite size QCD matter. *Phys. Rev. C*, 74:064907, 2006.
- [76] Shanshan Cao, Guang-You Qin, and Steffen A. Bass. Heavy-quark dynamics and hadronization in ultrarelativistic heavy-ion collisions: Collisional versus radiative energy loss. *Phys. Rev. C*, 88:044907, 2013.
- [77] J. D. Bjorken. Energy Loss of Energetic Partons in Quark - Gluon Plasma: Possible Extinction of High $p(t)$ Jets in Hadron - Hadron Collisions. 8 1982.
- [78] Stephane Peigne and Andre Peshier. Collisional energy loss of a fast heavy quark in a quark-gluon plasma. *Phys. Rev. D*, 77:114017, 2008.
- [79] A. Adare et al. Measurement of high- p_T single electrons from heavy-flavor decays in $p + p$ collisions at $\sqrt{s} = 200$ GeV. *Phys. Rev. Lett.*, 97:252002, 2006.
- [80] Matteo Cacciari, Paolo Nason, and Ramona Vogt. QCD predictions for charm and bottom production at RHIC. *Phys. Rev. Lett.*, 95:122001, 2005.
- [81] B. Abelev et al. Measurement of charm production at central rapidity in proton-proton collisions at $\sqrt{s} = 7$ TeV. *JHEP*, 01:128, 2012.
- [82] Matteo Cacciari, Stefano Frixione, Nicolas Houdeau, Michelangelo L. Mangano, Paolo Nason, and Giovanni Ridolfi. Theoretical predictions for charm and bottom production at the LHC. *JHEP*, 10:137, 2012.
- [83] B. A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger. Inclusive Charmed-Meson Production at the CERN LHC. *Eur. Phys. J. C*, 72:2082, 2012.

- [84] J. Adam et al. Measurement of D-meson production versus multiplicity in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *JHEP*, 08:078, 2016.
- [85] D. Adamová et al. J/ψ production as a function of charged-particle pseudo-rapidity density in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Lett. B*, 776: 91–104, 2018.
- [86] Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands. A Brief Introduction to PYTHIA 8.1. *Comput. Phys. Commun.*, 178:852–867, 2008.
- [87] T. Pierog, Iu. Karpenko, J. M. Katzy, E. Yatsenko, and K. Werner. EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider. *Phys. Rev. C*, 92(3):034906, 2015.
- [88] A. Adare et al. Cold-Nuclear-Matter Effects on Heavy-Quark Production at Forward and Backward Rapidity in d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev. Lett.*, 112(25):252301, 2014.
- [89] Betty Bezverkhny Abelev et al. Measurement of prompt D -meson production in $p - Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Rev. Lett.*, 113(23):232301, 2014.
- [90] Michelangelo L. Mangano, Paolo Nason, and Giovanni Ridolfi. Heavy quark correlations in hadron collisions at next-to-leading order. *Nucl. Phys. B*, 373: 295–345, 1992.
- [91] Daniel Stump, Joey Huston, Jon Pumplin, Wu-Ki Tung, H. L. Lai, Steve Kuhlmann, and J. F. Owens. Inclusive jet production, parton distributions, and the search for new physics. *JHEP*, 10:046, 2003.
- [92] Hirotugu Fujii and Kazuhiro Watanabe. Heavy quark pair production in high energy pA collisions: Open heavy flavors. *Nucl. Phys. A*, 920:78–93, 2013.
- [93] Jaroslav Adam et al. D -meson production in p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and in pp collisions at $\sqrt{s} = 7$ TeV. *Phys. Rev. C*, 94(5):054908, 2016.

- [94] Andrea Beraudo, Arturo De Pace, Marco Monteno, Marzia Nardi, and Francesco Prino. Heavy-flavour production in high-energy d-Au and p-Pb collisions. *JHEP*, 03:123, 2016.
- [95] L. Adamczyk et al. Observation of D^0 Meson Nuclear Modifications in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev. Lett.*, 113(14):142301, 2014. [Erratum: Phys.Rev.Lett. 121, 229901 (2018)].
- [96] Betty Abelev et al. Suppression of high transverse momentum D mesons in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *JHEP*, 09:112, 2012.
- [97] Andrea Rossi. D meson nuclear modification factors in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, measured with the ALICE detector. *J. Phys. G*, 38:124139, 2011.
- [98] A. Adare et al. Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ -GeV. *Phys. Rev. Lett.*, 98:172301, 2007.
- [99] Raphaele Bailhache. Heavy-flavour elliptic flow measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE. *Nucl. Phys. A*, 931:530–534, 2014.
- [100] Jaroslav Adam et al. Measurement of charm and beauty production at central rapidity versus charged-particle multiplicity in proton-proton collisions at $\sqrt{s} = 7$ TeV. *JHEP*, 09:148, 2015.
- [101] Anisa Khatun. Measurement of J/Ψ production as a function of multiplicity in pp and p-Pb collisions with ALICE. *EPJ Web Conf.*, 182:02064, 2018.
- [102] H.J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner. Parton-based gribov-regge theory. *Physics Reports*, 350(2):93–289, 2001. ISSN 0370-1573.
- [103] K. Werner, B. Guiot, Iu. Karpenko, and T. Pierog. Analyzing radial flow features in p-pb and p-p collisions at several tev by studying identified-particle production with the event generator epos3. *Phys. Rev. C*, 89:064903, Jun 2014.

- [104] Georges Aad et al. Measurement of charged-particle event shape variables in $\sqrt{s} = 7$ TeV proton-proton interactions with the ATLAS detector. *Phys. Rev. D*, 88(3):032004, 2013.
- [105] Jaroslav Adam et al. Measurement of charm and beauty production at central rapidity versus charged-particle multiplicity in proton-proton collisions at $\sqrt{s} = 7$ TeV. *JHEP*, 09:148, 2015.
- [106] Kenneth Wraight and Peter Skands. Forward-Backward Correlations and Event Shapes as probes of Minimum-Bias Event Properties. *Eur. Phys. J. C*, 71:1628, 2011.
- [107] Andreas Morsch. Multiple Parton Interactions with ALICE: from pp to p-Pb. *J. Phys. Conf. Ser.*, 535:012012, 2014.
- [108] T. Akesson et al. The Dominance of Jets at Large Transverse Energy in a Full Azimuth Hadron Calorimeter at ISR Energies. *Phys. Lett. B*, 128:354–360, 1983.
- [109] R. Ansari et al. Jet Measures and Hadronic Event Shapes at the CERN $\bar{p}p$ Collider. *Z. Phys. C*, 36:175, 1987.
- [110] T. Aaltonen et al. Measurement of Event Shapes in Proton-Antiproton Collisions at Center-of-Mass Energy 1.96 TeV. *Phys. Rev. D*, 83:112007, 2011.
- [111] S. Chekanov et al. Measurement of event shapes in deep inelastic scattering at HERA. *Eur. Phys. J. C*, 27:531–545, 2003.
- [112] P. Achard et al. Determination of α_s from hadronic event shapes in e^+e^- annihilation at $192\text{-GeV} \leq \sqrt{s} \leq 208\text{-GeV}$. *Phys. Lett. B*, 536:217–228, 2002.
- [113] J. Abdallah et al. The Measurement of α_s from event shapes with the DELPHI detector at the highest LEP energies. *Eur. Phys. J. C*, 37:1–23, 2004.

- [114] Serguei Chatrchyan et al. Jet and Underlying Event Properties as a Function of Charged-Particle Multiplicity in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV. *Eur. Phys. J. C*, 73(12):2674, 2013.
- [115] Betty Abelev et al. Transverse sphericity of primary charged particles in minimum bias proton-proton collisions at $\sqrt{s} = 0.9, 2.76$ and 7 TeV. *Eur. Phys. J. C*, 72:2124, 2012.
- [116] Howard Georgi and Marie Machacek. A Simple QCD Prediction of Jet Structure in $e^+ e^-$ Annihilation. *Phys. Rev. Lett.*, 39:1237, 1977.
- [117] Andrea Banfi, Gavin P. Salam, and Giulia Zanderighi. Phenomenology of event shapes at hadron colliders. *JHEP*, 06:038, 2010.
- [118] Andrea Banfi, Gavin P. Salam, and Giulia Zanderighi. Resummed event shapes at hadron - hadron colliders. *JHEP*, 08:062, 2004.

List of Presentations/participations in Conferences/Schools

1. Participated in XI SERC School on Experimental High-Energy Physics, at NISER Bhubaneswar, Odisha, November 07-27, 2017.
2. D⁺-meson production as a function of charged-particle multiplicity in pp collisions at $\sqrt{s}=13$ TeV with ALICE
Randhir Singh, (for the ALICE Collaboration), in Quark Matter 2019 - the XXVII-Ith International Conference on Ultra-relativistic Nucleus-Nucleus Collisions, Wuhan, China, November 4-9 2019.
3. Open charm studies as function of charged-particle multiplicity in pp collisions
Randhir Singh, Renu Bala and Sanjeev Singh Sambyal, in 14th JK Science Congress, at University of Jammu, Jammu, December, 20-22, 2019.
4. Open charm studies as function of charged-particle multiplicity in pp collisions
Randhir Singh (for the ALICE Collaboration), in XXIV DAE-BRNS HIGH ENERGY PHYSICS SYMPOSIUM, at NISER Bhubaneshwar, Odisha, December 14-18, 2020.
5. Open Charm production in proton-proton collisions at $\sqrt{s} = 13$ TeV using Pythia 8
Randhir Singh, in 65th DAE-BRNS Symposium on Nuclear Physics, 2021, at DAE Convention Centre, Anushaktinagar, Mumbai, Maharashtra, December 1-5, 2021.
6. D-meson production as a function of transverse sphericity in pp collisions at $\sqrt{s} = 13$ TeV with ALICE
Randhir Singh (for the ALICE Collaboration), in 29TH INTERNATIONAL CONFERENCE ON ULTRA RELATIVISTIC NUCLEUS - NUCLEUS COLLISIONS, at KRAKW, POLAND, APRIL 4-10, 2022.

List of papers Co-authored as ALICE Collaborator

- [1] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Multiplicity dependence of charged-particle jet production in pp collisions at $\sqrt{s} = 13$ TeV,” *Eur. Phys. J. C* **82** (2022) no.6, 514
- [2] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Forward rapidity J/ψ production as a function of charged-particle multiplicity in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV,” *JHEP* **06** (2022), 015
- [3] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Neutral to charged kaon yield fluctuations in Pb – Pb collisions at sNN=2.76 TeV,” *Phys. Lett. B* **832** (2022), 137242
- [4] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Production of light (anti)nuclei in pp collisions at $\sqrt{s} = 5.02$ TeV,” *Eur. Phys. J. C* **82** (2022) no.4, 289
- [5] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Observation of a multiplicity dependence in the p_T -differential charm baryon-to-meson ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV,” *Phys. Lett. B* **829** (2022), 137065
- [6] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Investigating charm production and fragmentation via azimuthal correlations of prompt D mesons with charged particles in pp collisions at $\sqrt{s} = 13$ TeV,” *Eur. Phys. J. C* **82** (2022) no.4, 335
- [7] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Measurement of prompt D_s^+ -meson production and azimuthal anisotropy in Pb–Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV,” *Phys. Lett. B* **827** (2022), 136986
- [8] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Prompt D^0 , D^+ , and D^{*+} production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *JHEP* **01** (2022), 174
- [9] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Measurement of inclusive charged-particle b-jet production in pp and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *JHEP* **01** (2022), 178
- [10] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Production of light (anti)nuclei in pp collisions at $\sqrt{s} = 13$ TeV,” *JHEP* **01** (2022), 106

- [11] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Prompt and non-prompt J/ψ production cross sections at midrapidity in proton-proton collisions at $\sqrt{s} = 5.02$ and 13 TeV,” JHEP **03** (2022), 190
- [12] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Inclusive J/ψ production at midrapidity in pp collisions at $\sqrt{s} = 13$ TeV,” Eur. Phys. J. C **81** (2021) no.12, 1121
- [13] S. Acharya,...,R.Singh,... *et al.* [A Large Ion Collider Experiment and ALICE], “Measurement of the groomed jet radius and momentum splitting fraction in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” Phys. Rev. Lett. **128** (2022) no.10, 102001
- [14] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Measurements of the groomed and ungroomed jet angularities in pp collisions at $\sqrt{s} = 5.02$ TeV,” JHEP **05** (2022), 061
- [15] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Polarization of Λ and $\bar{\Lambda}$ Hyperons along the Beam Direction in Pb-Pb Collisions at $\sqrt{s_{NN}}=5.02$ TeV,” Phys. Rev. Lett. **128** (2022) no.17, 172005
- [16] S. Acharya,...,R.Singh,... *et al.* [ALICE], “ K_S^0 - and (anti-) Λ -hadron correlations in pp collisions at $\sqrt{s} = 13$ TeV,” Eur. Phys. J. C **81** (2021) no.10, 945
- [17] S. Acharya,...,R.Singh,... *et al.* [A Large Ion Collider Experiment and ALICE], “Hypertriton Production in p-Pb Collisions at $\sqrt{s_{NN}}=5.02$ TeV,” Phys. Rev. Lett. **128** (2022) no.25, 252003
- [18] S. Acharya,...,R.Singh,... *et al.* [ALICE], “Anisotropic flow of identified hadrons in Xe-Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV,” JHEP **10** (2021), 152

Prompt D^0 , D^+ , and D^{*+} production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



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ABSTRACT: The production of prompt D^0 , D^+ , and D^{*+} mesons was measured at midrapidity ($|y| < 0.5$) in Pb–Pb collisions at the centre-of-mass energy per nucleon–nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector at the LHC. The D mesons were reconstructed via their hadronic decay channels and their production yields were measured in central (0–10%) and semicentral (30–50%) collisions. The measurement was performed up to a transverse momentum (p_T) of 36 or 50 GeV/c depending on the D meson species and the centrality interval. For the first time in Pb–Pb collisions at the LHC, the yield of D^0 mesons was measured down to $p_T = 0$, which allowed a model-independent determination of the p_T -integrated yield per unit of rapidity (dN/dy). A maximum suppression by a factor 5 and 2.5 was observed with the nuclear modification factor (R_{AA}) of prompt D mesons at $p_T = 6$ –8 GeV/c for the 0–10% and 30–50% centrality classes, respectively. The D-meson R_{AA} is compared with that of charged pions, charged hadrons, and J/ψ mesons as well as with theoretical predictions. The analysis of the agreement between the measured R_{AA} , elliptic (v_2) and triangular (v_3) flow, and the model predictions allowed us to constrain the charm spatial diffusion coefficient D_s . Furthermore the comparison of R_{AA} and v_2 with different implementations of the same models provides an important insight into the role of radiative energy loss as well as charm quark recombination in the hadronisation mechanisms.

KEYWORDS: Lepton-Nucleon Scattering (experiments)

ARXIV EPRINT: [2110.09420](https://arxiv.org/abs/2110.09420)

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1 Introduction

Ultra-relativistic heavy-ion collisions allow the study of quantum chromodynamics (QCD) at high energy density and temperature. According to lattice QCD (lQCD) calculations, these extreme conditions lead to a transition of hadronic matter into a strongly-interacting medium, called quark-gluon plasma (QGP), in which quarks and gluons are deconfined and chiral symmetry is partially restored [1–5]. A QGP is formed and studied in high-energy heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and at the CERN Large Hadron Collider (LHC). The existing measurements indicate that the QGP behaves as a strongly-coupled low-viscosity liquid-like system [6] and its lifetime at the energy densities reached at the LHC is of the order of 10 fm/c [7].

Heavy quarks, like charm and beauty, are mostly produced in primary hard scattering processes between the partons of the incoming nuclei, which occur in the early stages of the collisions. The time scales for heavy-quark production (≤ 0.07 fm/c for $c\bar{c}$ and ≤ 0.02 fm/c for $b\bar{b}$ pairs [8]) are shorter than the QGP formation time, which is about 0.3–1.5 fm/c at LHC energies [9]. Therefore, heavy quarks experience the full space-time evolution of the hot and dense QCD medium.

During their propagation in the QGP, heavy quarks interact with the medium constituents, by exchanging energy and momentum via elastic [10–12] and inelastic [13, 14] processes. Low-momentum heavy quarks (i.e. $\lesssim 3\text{--}4$ GeV/c) mainly interact via elastic

scatterings and are expected to acquire some collective behaviour of the system, like radial and anisotropic azimuthal flow, as a consequence of multiple interactions with the medium [15, 16]. The typical momentum exchange in the interactions of heavy quarks with the medium is small compared to the charm-quark mass. Therefore, heavy quarks undergo Brownian motion in the medium characterised by many small-momentum kicks. The degree of heavy-quark thermalisation provides unique insight into the thermalisation process of the system. Substantial theoretical efforts were made to describe the charm-quark transport in a hydrodynamically expanding medium [17]. The relevant transport parameter is the spatial diffusion coefficient D_s , which does not depend on the precise value of the heavy-quark mass and, hence, is a medium property. It can be estimated via the comparison of the measured differential yields as a function of transverse momentum (p_T) and azimuthal distributions of D mesons with model predictions.

For high- p_T quarks (i.e. $\gtrsim 8\text{--}10\text{ GeV}/c$) the main manifestation of the interactions with the medium is energy loss, which can occur via collisional processes and gluon radiation [18], with the latter expected to be the dominant mechanism. In particular, the amount of radiative energy loss is influenced by the colour charge of the parton interacting with the medium. According to QCD calculations, gluons are expected to lose more energy than quarks, due to their stronger coupling to the medium [13, 14]. At LHC energies, light-flavour particles in the momentum interval $5 < p_T < 20\text{ GeV}/c$ are expected to originate mostly from the fragmentation of gluons produced in hard scattering processes, while at higher p_T the contribution of light-quark jets becomes relevant [19]. On the other hand, charm mesons provide an experimental tag for a quark parent at all momenta. Thus, the comparison of heavy-flavour hadron production with that of light-flavour particles at high p_T can provide insight into this aspect. In addition, the energy loss of quarks can be affected by several mass-dependent effects like the dead-cone effect, which reduces the small-angle gluon radiation for quarks with moderate energy-over-mass values [20–23]. Similarly, collisional energy loss is predicted to depend on the quark mass and to be smaller for heavy quarks [24].

Heavy-flavour hadron yields and momentum distributions can be influenced by the modification of the parton distribution function (PDF) due to initial state effects, like nuclear shadowing [18]. It was also suggested that low-momentum heavy quarks could hadronise via recombination with other quarks from the medium, in addition to the fragmentation in the vacuum [16, 25].

The aforementioned effects can be investigated with the measurement of the nuclear modification factor R_{AA} of heavy-flavour hadrons. It is defined as the ratio of the p_T -differential production yield in nucleus-nucleus collisions (dN_{AA}/dp_T) and the production cross section in proton-proton collisions ($d\sigma_{pp}/dp_T$) scaled by the average nuclear overlap function $\langle T_{AA} \rangle$

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}, \quad (1.1)$$

where $\langle T_{AA} \rangle$ is defined as the average number of binary nucleon-nucleon collisions ($\langle N_{\text{coll}} \rangle$), which can be estimated via Glauber model calculations [26–28], divided by the inelastic nucleon-nucleon cross section.

Measurements of prompt D-meson production were performed by the ALICE collaboration in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [29] and 5.02 TeV [30] in the 0–10% and 30–50% centrality classes for both collision energies and in the 60–80% for the highest one. The D-meson yields show a suppression in central (0–10%) and semi-central (30–50%) collisions that reaches up to a factor of 5 and 2.5, respectively, at p_{T} of 6–10 GeV/ c . It then decreases with increasing p_{T} , while the suppression factor is of 1.25 without a pronounced p_{T} dependence in peripheral (60–80%) collisions. The prompt D^0 production was also measured by the CMS collaboration in the most central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [31] in the p_{T} range 2–100 GeV/ c and the result is in agreement with ALICE measurements. Furthermore, also the STAR collaboration measured the production of the prompt D^0 mesons in Au–Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV [32] and the comparison with this result can provide insight into the $\sqrt{s}$ dependence of energy-loss effects. Conversely, the D-meson nuclear modification factor measured by the ALICE collaboration in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [33], where an extended QGP is not expected to form, is compatible with unity for the whole measured p_{T} range.

Complementary information on the interactions of heavy quarks with the medium constituents and their possible thermalisation can be obtained from the measurements of the anisotropies in the D-meson azimuthal distributions, which are characterised in terms of the Fourier coefficients [34, 35]. In particular, the second order coefficient v_2 , called elliptic flow, is defined as $v_2 = \langle \cos(2\varphi) \rangle$ where φ is the azimuthal angle. Recently, the ALICE collaboration reported the latest measurements of prompt D-meson azimuthal anisotropic flow [36] in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

In this paper, the measurements of the p_{T} -differential yields and nuclear modification factors of prompt D^0 , D^+ , and D^{*+} mesons (i.e. produced via the hadronisation of charm quarks or from the decays of excited charmed hadron states) and their charge conjugates, in central (0–10%) and semicentral (30–50%) Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are reported. The statistical and systematic uncertainties have been reduced due to the Pb–Pb data sample collected with the ALICE detector at the end of 2018, that is larger by a factor eight (four) for central (semicentral) collisions with respect to the data sample collected in 2015 used for the previous publication [30], and to the production cross section measured in pp collisions at the same centre-of-mass energy [37]. The larger data sample allowed the reduction of the statistical uncertainties and the extension of the p_{T} reach of the measurements down to $p_{\text{T}} = 0$ for D^0 mesons. Moreover, the previous measurements [30] were affected by the uncertainty on the $\sqrt{s}$ scaling of the pp production cross section. The new measurements do not include such uncertainty since they use the measured pp production cross section at the same collision energy [37].

The paper is structured as follows. The data sample and the experimental apparatus are briefly introduced in section 2. The D-meson reconstruction procedure and the corrections applied to the raw yields are presented in section 3, while the estimation of the systematic uncertainties is described in section 4. The results are presented in section 5, together with a comparison with the charged-pion, proton, and prompt and non-prompt J/ψ R_{AA} , along with model calculations. In addition, a simultaneous comparison of the measured R_{AA} and elliptic flow v_2 [36] at low and intermediate p_{T} with transport-model

calculations is discussed, together with an estimate of the spatial diffusion coefficient. This comparison will provide insights into the participation of the charm quark in the collective expansion of the medium [38], as well as on the role of the different hadronisation mechanisms. Conclusions and perspectives are drawn in section 6.

2 Detector and data sample

The ALICE experimental apparatus includes several detectors for particle tracking and identification as well as electromagnetic calorimeters at midrapidity ($|\eta| < 0.9$), a forward muon spectrometer ($-4 < \eta < -2.5$), and a set of forward and backward detectors used for triggering, background rejection, and event characterisation. A detailed description of the apparatus and its performance can be found in refs. [39, 40].

The main detectors used for the track reconstruction and particle identification in the analysis are the Inner Tracking System (ITS) [41], the Time Projection Chamber (TPC) [42], and the Time-Of-Flight (TOF) detector [43]. They are located inside a large solenoidal magnet, providing a uniform magnetic field of 0.5 T parallel to the LHC beam direction. Charged-particle trajectories are reconstructed from their hits in the ITS and the TPC. The ITS consists of a six-layer silicon detector, which is used for tracking and for the reconstruction of primary and secondary vertices. The TPC is used for track reconstruction and particle identification (PID) via the measurement of the specific energy loss dE/dx . The TOF detector extends at intermediate momenta the PID capabilities of the TPC via the measurement of the time-of-flight of charged particles from the interaction point to the detector.

Event selection and characterisation are performed with the V0 detector [44] and the Zero Degree Calorimeter (ZDC) [45]. The V0 detector consists of two scintillator arrays, which cover the full azimuth in the pseudorapidity intervals $-3.7 < \eta < -1.7$ (V0C) and $2.8 < \eta < 5.1$ (V0A), and is used for triggering, event selection, and centrality determination. A minimum-bias interaction trigger was provided by the coincidence of signals in the V0A and the V0C. Furthermore, two separate trigger classes, which consist of an online event selection based on the V0 signal amplitude, were used during the 2018 Pb–Pb data taking period in order to enrich the sample of central and semicentral collisions. Events due to the interaction of the beams with residual gas in the vacuum pipe were rejected offline using the V0 and the ZDC timing information. Only events with a primary vertex reconstructed within ± 10 cm from the centre of the detector along the beam axis were considered in the analysis.

Collisions were divided into centrality classes, defined in terms of percentiles of the hadronic Pb–Pb cross section, using the sum of the V0 signal amplitudes, as described in details in ref. [30]. The centrality classes used in the present analysis, together with the corresponding average nuclear overlap function $\langle T_{AA} \rangle$ [46, 47], the number of events (N_{events}), and the recorded integrated luminosity L_{int} [48] in each class, are summarised in table 1.

Centrality class	$\langle T_{AA} \rangle$ (mb $^{-1}$)	N_{events}	$L_{\text{int}}(\mu\text{b}^{-1})$
0–10%	23.26 ± 0.17	100×10^6	130.5 ± 0.5
30–50%	3.92 ± 0.06	85×10^6	55.5 ± 0.2

Table 1. Average nuclear overlap function, number of events, and recorded integrated luminosities for the two centrality classes used in the analysis.

3 Analysis techniques

3.1 D-meson raw yields

The D mesons and their charge conjugates were reconstructed via the following hadronic decay channels: $D^0 \rightarrow K^- \pi^+$ (with branching ratio, $\text{BR} = 3.950 \pm 0.031\%$), $D^+ \rightarrow K^- \pi^+ \pi^+$ ($\text{BR} = 9.38 \pm 0.16\%$), and $D^{*+} \rightarrow D^0 \pi^+$ ($\text{BR} = 67.7 \pm 0.5\%$) [49]. The analysis was based on the reconstruction of decay vertices displaced from the primary vertex, exploiting the separation of few hundreds μm due to the weak decays of D^0 and D^+ ($c\tau$ of ~ 123 and $\sim 312 \mu\text{m}$, respectively [49]). In the case of the strong decay of the D^{*+} meson, the decay topology of the produced D^0 was exploited. This method allowed the reconstruction of D^0 candidates for $p_T > 1 \text{ GeV}/c$ in both centrality classes and of D^+ (D^{*+}) candidates for $p_T > 2.5$ (3) GeV/c and for $p_T > 2$ (2) GeV/c in the 0–10% and 30–50% centrality classes, respectively.

D^0 and D^+ candidates were built using pairs and triplets of tracks with proper charge-sign combination, $|\eta| < 0.8$, $p_T > 0.4 \text{ GeV}/c$, a minimum number of two hits (out of six) in the ITS, with at least one in the two innermost layers, at least 70 out of 159 crossed TPC pad rows, and a fit quality $\chi^2/\text{ndf} < 1.25$ in the TPC (where ndf is the number of degrees of freedom involved in the track fit procedure). D^{*+} candidates were reconstructed by combining D^0 candidates with tracks, which were required to have $|\eta| < 0.8$, $p_T > 0.1 \text{ GeV}/c$, and at least three associated hits in the ITS.

These track selection criteria reduce the D-meson acceptance in rapidity, which, depending on p_T , varies from $|y| > 0.5$ at low p_T and $|y| > 0.8$ for $p_T > 5 \text{ GeV}/c$. Consequently, a p_T -dependent fiducial acceptance selection, $|y| < y_{\text{fid}}(p_T)$, was applied, with $y_{\text{fid}}(p_T)$ defined according to a second-order polynomial function increasing from 0.5 to 0.8 in the range $0 < p_T < 5 \text{ GeV}/c$, and fixed to 0.8 for $p_T > 5 \text{ GeV}/c$.

The D-meson selection strategy is similar to the one used in previous analyses and the variables used to distinguish between signal and background candidates are based on the impact parameters (i.e. the distance of closest approach between the track and the primary vertex in the plane transverse to the beam direction) of the decay particles, the separation of the primary and secondary vertices, and the pointing of the reconstructed D-meson momentum to the primary vertex, as described in refs. [30, 50]. These selection criteria tend to enhance reconstructed feed-down D mesons, originating from beauty-hadron decays, over those promptly produced. An additional selection was therefore applied on the normalised difference between the measured and expected impact parameters of each of the decay particles, which allows for a significant rejection of background candidates and

feed-down D mesons, while keeping a large fraction of prompt D mesons as reported in ref. [51]. Further reduction of the combinatorial background was obtained by applying PID for charged pions and kaons with the TPC and TOF detectors. A $\pm 3\sigma$ window around the expected mean values of dE/dx and time-of-flight was used for the identification, where σ is the resolution on these two quantities. A tighter PID selection criterion ($\pm 2\sigma$) was used for D^+ (for $p_T < 3 \text{ GeV}/c$) and D^{*+} candidate daughters in central collisions because of the large background of track triplets.

An alternative analysis method, not based on the reconstruction and selection of the displaced decay-vertex topology, was previously developed and applied for the two-body decay of D^0 mesons in pp and p-Pb collisions, in order to extend the measurement down to $p_T = 0$ [37, 52]. This technique, which is used for the first time in the analysis of Pb-Pb collisions, does not use geometrical selections on the displaced decay vertex (which are not effective at very low p_T), but relies mainly on particle identification and on the estimation and subtraction of the combinatorial background. The D^0 candidates were formed combining pairs of tracks with opposite charge sign (unlike sign, ULS), with $|\eta| < 0.8$ and $p_T > 0.4 \text{ GeV}/c$. Single-track and particle identification selections as well as the fiducial acceptance selection of the reconstructed candidates were performed using the same strategy adopted in the analysis with decay-vertex reconstruction previously described. The contribution to the invariant-mass distribution of ULS $K\pi$ pairs due to combinatorial background is estimated with the event-mixing technique. The events are grouped in pools, before the event-mixing, based on the primary vertex position along z and on the event multiplicity, quantified by the number of track segments reconstructed in the two innermost layers of the ITS. Then, the kaon tracks of a given event are mixed with the pion tracks of other events. The top left panel of figure 1 shows the invariant-mass distribution of ULS $K\pi$ pairs together with that of the background estimated with the event-mixing technique in the interval $0 < p_T < 1 \text{ GeV}/c$. The latter distribution was normalised to match the yield of ULS pairs at one edge of the invariant-mass interval considered for the extraction of the D^0 raw yield.

The D-meson raw yields, including particles and antiparticles, were obtained from binned maximum-likelihood fits to the D^0 and D^+ candidate invariant mass (M) distribution and to the mass difference $\Delta M = M(K\pi\pi) - M(K\pi)$ distribution for D^{*+} candidates. Figure 1 shows examples of fits for these distributions in the 0–10% centrality class and for four p_T intervals. In the analysis of the D^0 meson without decay-vertex reconstruction, the fit is performed after subtracting the estimated background from the ULS $K\pi$ invariant-mass distribution as shown in the top right panel.

The fit function was composed of a Gaussian term to describe the signal and an exponential function for the background for D^0 and D^+ candidates at intermediate and high p_T in the analysis with vertex reconstruction. At low p_T ($p_T < 3 \text{ GeV}/c$ for D^0 and $p_T < 5 \text{ GeV}/c$ for D^+), a second-order polynomial function is used to model the background invariant-mass shape in both centrality classes. In the D^0 analysis without vertex reconstruction, instead, the background was parametrised for $p_T < (>) 2 \text{ GeV}/c$ with a fourth-order (third-order) polynomial function. The ΔM distribution of D^{*+} candidates was fitted with a Gaussian function for the signal and the following function for

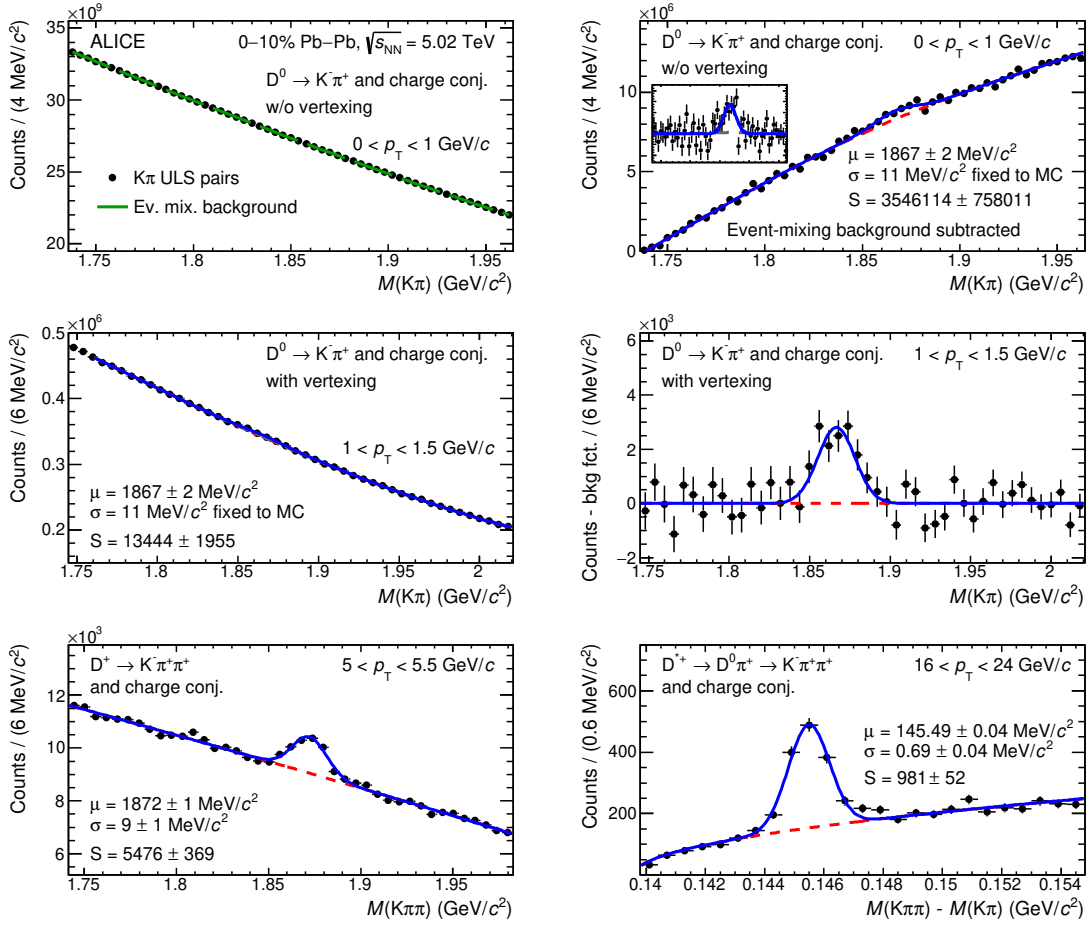


Figure 1. Invariant-mass (mass-difference) distribution of D^0 , D^+ , and D^{*+} meson candidates in different p_T intervals for the centrality class 0–10%. The fit functions are composed of a Gaussian function for the signal and an additional term for the background, as described in detail in the text. The values for the Gaussian mean μ , width σ , and raw yield S are also reported. Top row: D^0 -meson candidates with $0 < p_T < 1 \text{ GeV}/c$ without reconstructing the decay vertex. The invariant-mass distributions are shown before (left) and after (right) the subtraction of the combinatorial background estimated from event-mixing. Middle row: D^0 -meson candidates with $1 < p_T < 1.5 \text{ GeV}/c$ with reconstruction of the decay vertex before (left) and after (right) background subtraction. The width of the Gaussian in this and in the previous p_T interval is fixed to the value obtained from simulations. Bottom row: D^+ -meson candidates with $5 < p_T < 5.5 \text{ GeV}/c$ (left) and D^{*+} -meson candidates with $16 < p_T < 24 \text{ GeV}/c$ (right).

the background: $a\sqrt{\Delta M - m_\pi}e^{b(\Delta M - m_\pi)}$, where m_π is the pion mass and a and b are free parameters.

In some cases a D^0 -meson candidate can be also identified as a $\bar{D}^0$ meson when the two daughter tracks are compatible with both the kaon and pion hypothesis, leading to an irreducible correlated background. Hence, in the D^0 meson analyses, an additional term was included in the fit function to take into account this contribution to the invariant mass of signal candidates, which is called reflections. It was parametrised with a double-Gaussian distribution based on detailed Monte Carlo simulations. This contribution ranges between

2% and 3% of the raw signal depending on p_T [30]. Given the critical signal extraction for the D^0 meson at low p_T in the analysis with vertex reconstruction, due to the small signal-to-background ratio, the width of the Gaussian for the signal was fixed to the value obtained from the simulation for $p_T < 1.5 \text{ GeV}/c$. We verified that the widths from the simulation were consistent with those extracted from the data. For the same reason, in the analysis without vertexing the Gaussian width was fixed to the one from the simulation in the whole p_T range. The statistical significance of the signal, defined as $S/\sqrt{S+B}$ where S is the raw signal yield obtained by integrating the Gaussian function and B is the background under the peak (within 3σ), varies from 4 to 60, depending on the D-meson species, the p_T interval, and the centrality class. In the D^0 analysis without decay-vertex reconstruction, the S/B in the p_T range 0–1 GeV/ c is approximately $\sim 8.5 \times 10^{-6}$ before the mixed-event background subtraction.

3.2 Yield corrections and beauty feed-down subtraction

The D-meson raw yields were corrected to obtain the p_T -differential yields of prompt D-mesons according to:

$$\frac{d^2 N}{dy dp_T} = \frac{1}{2} \frac{1}{\Delta p_T \alpha_y(p_T) \times (\text{Acc} \times \epsilon)_{\text{prompt}}(p_T) \times \text{BR} \times N_{\text{events}}} f_{\text{prompt}}(p_T) \times N_{\text{raw}}^{D+\bar{D}}(p_T) \Big|_{|y| < y_{\text{fid}}} \quad (3.1)$$

The raw yield values $N^{D+\bar{D}, \text{raw}}$, which contain the contribution of feed-down from beauty-hadron decays, were multiplied by the fraction of promptly produced D mesons f_{prompt} and divided by a factor of two to obtain the charged-averaged yields. Furthermore, they were divided by the product of prompt D-meson acceptance and efficiency $(\text{Acc} \times \epsilon)_{\text{prompt}}$, the branching ratio BR of the decay channel, the width of the p_T interval (Δp_T), and by the number of events N_{events} . The factor $\alpha_y(p_T)$ normalises the corrected yields measured in $\Delta y = 2y_{\text{fid}}(p_T)$ to one unit of rapidity. It was computed as the ratio between the generated D-meson yield in $|y| < y_{\text{fid}}(p_T)$ and that in $|y| < 0.5$ using a data-driven p_T shape and a rapidity distribution from fixed order plus next-to-leading logarithms (FONLL) [53, 54] perturbative QCD calculations, after verifying that the D-meson rapidity distributions in FONLL are consistent with those from PYTHIA 8 [55].

The $(\text{Acc} \times \epsilon)$ correction was obtained separately for prompt and feed-down D mesons using simulations with the GEANT3 transport package [56], including a detailed description of the detector geometry and response as well as of the LHC beam conditions. The Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ were produced with the HIJING v1.36 [57] event generator and D-meson signals were added by injecting $c\bar{c}$ or $b\bar{b}$ pairs generated with the PYTHIA v8.2.43 event generator with Monash tune [58]. The D-meson p_T distributions from the simulations were reweighted in order to use realistic momentum distributions in the determination of the acceptance and the efficiency, which depend on p_T . The weights were defined with an iterative procedure to match the p_T dependence measured for D^0 mesons in the intervals used in the analysis, for both centrality classes and in the momentum interval $1 < p_T < 50 \text{ GeV}/c$.

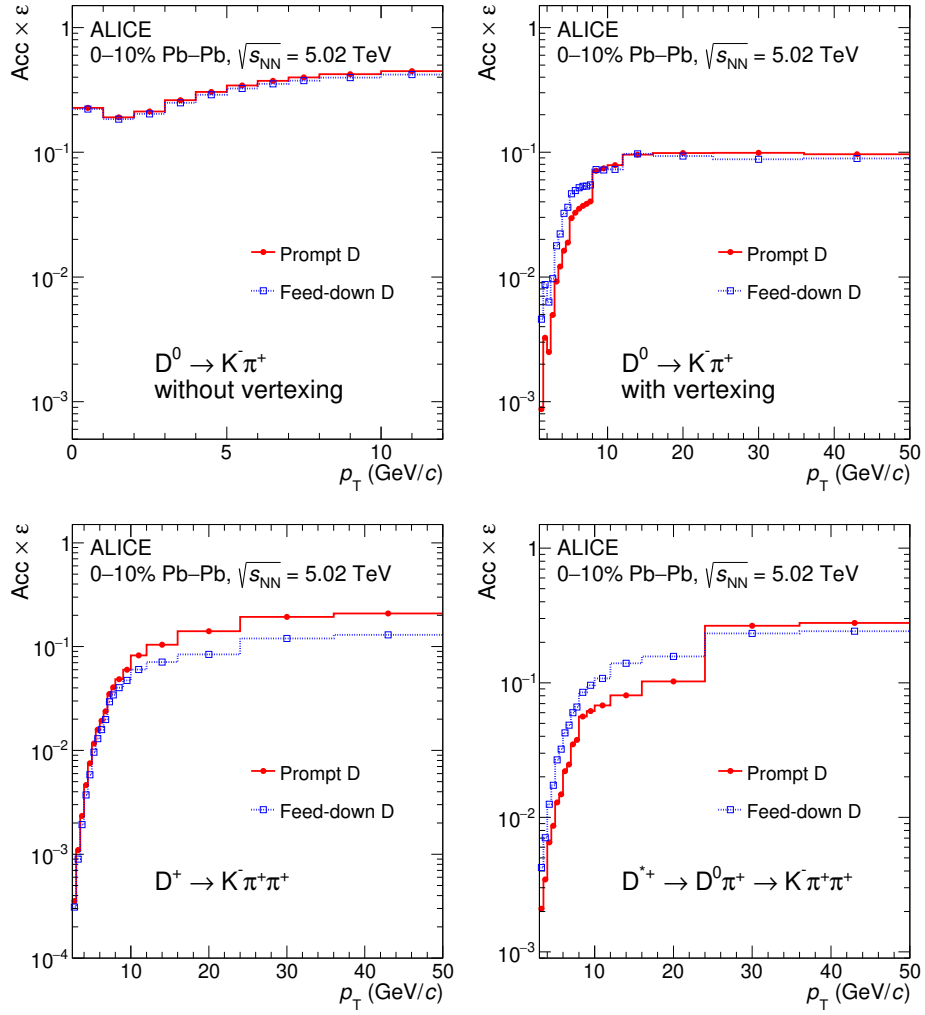


Figure 2. Product of acceptance and efficiency ($\text{Acc} \times \epsilon$) as a function of p_T for prompt (red circles) and feed-down (blue squares) D mesons in Pb–Pb collisions for the 0–10% centrality class.

Figure 2 shows the ($\text{Acc} \times \epsilon$) for prompt and feed-down D^0 (top panels), D^+ (bottom left panel), and D^{*+} (bottom right panel) mesons with $|y| < y_{\text{fid}}$ as a function of p_T in the 0–10% centrality class. For the analysis that does not exploit the selections on the D^0 -meson decay vertex (top left panel), the efficiency is higher by a factor of about 100 (5) at low (high) p_T as compared to the analysis with decay-vertex reconstruction (top right panel). The ($\text{Acc} \times \epsilon$) is almost independent of p_T (the mild increase with increasing p_T is mainly determined by the geometrical acceptance of the detector) and is the same for prompt and feed-down D^0 , as expected when no selection is made on the displacement of the D^0 -meson decay vertex from the interaction point.

The efficiencies for the analysis with geometrical selections on the displaced decay-vertex topology range from about 10^{-3} at low p_T to 0.1–0.3 at high p_T , depending on the D-meson species. The decreasing efficiency with decreasing p_T is due to the fact that more stringent selection criteria are needed at low p_T because of the larger background and the

smaller average displacement of the decay vertex from the interaction point. The trend of the efficiency with p_T is not completely smooth, especially for D^0 and D^{*+} , reflecting the p_T intervals in which the optimisation of the selection criteria was performed. The $(\text{Acc} \times \epsilon)$ is higher for semicentral collisions than for central collisions, since less stringent selections are applied because of the lower combinatorial background. The difference between the efficiencies for prompt and feed-down D mesons is due to the geometrical selections applied since the latter are more displaced from the primary vertex due to large B-meson lifetime ($\tau \approx 500 \mu\text{m}$) and are therefore more efficiently selected by the majority of the selection criteria applied in the analysis. However, the requirement on the difference between measured and expected decay track impact parameter rejects efficiently D mesons coming from beauty-hadron decays. This is particularly effective for D^+ mesons (figure 2 bottom left panel) whose feed-down efficiencies become lower than the prompt efficiencies after a selection on the aforementioned variable is applied.

The fraction of selected prompt D mesons f_{prompt} was obtained with the procedure introduced in refs. [30, 59] to account for the contribution of D mesons from beauty-hadron decays in the measured raw yield. The f_{prompt} factor was estimated in each p_T interval using perturbative QCD calculations for the cross section of feed-down D mesons, efficiencies from the simulations, and a hypothesis on the R_{AA} of feed-down D mesons. In detail, the expression for f_{prompt} is:

$$\begin{aligned}
 f_{\text{prompt}} &= 1 - \frac{N_{\text{raw}}^{\text{D}+\bar{\text{D}} \text{ feed-down}}}{N_{\text{raw}}^{\text{D}+\bar{\text{D}}}} \\
 &= 1 - R_{AA}^{\text{feed-down}} \times \langle T_{AA} \rangle \times \left(\frac{d\sigma}{dp_T} \right)_{\text{feed-down}, |y| < 0.5}^{\text{FONLL, PYTHIA 8}} \\
 &\quad \times \frac{2\Delta p_T \times \alpha_y \times (\text{Acc} \times \epsilon)_{\text{feed-down}} \times \text{BR} \times N_{\text{events}}}{N_{\text{raw}}^{\text{D}+\bar{\text{D}}}},
 \end{aligned} \tag{3.2}$$

where $N_{\text{raw}}^{\text{D}+\bar{\text{D}}}$ is the measured raw yield and $N_{\text{raw}}^{\text{D}+\bar{\text{D}} \text{ feed-down}}$ is the estimated raw yield of D mesons from beauty-hadron decays. The beauty-hadron production cross section in pp collisions at $\sqrt{s} = 5.02 \text{ TeV}$, estimated with FONLL calculations [60], was folded with the beauty-hadron $\rightarrow D + X$ decay kinematics from PYTHIA 8 and multiplied by the $(\text{Acc} \times \epsilon)$ of feed-down D mesons, by the $\langle T_{AA} \rangle$ of the corresponding centrality class, and by the other factors introduced in eq. (3.1). Finally, the nuclear modification factor of D mesons from beauty-hadron decays ($R_{AA}^{\text{feed-down}}$) was accounted for.

The comparison of the R_{AA} of prompt D mesons (R_{AA}^{prompt}) at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ [30] with that of J/ψ from B-meson decays at the same energy measured by the CMS [61] and the ATLAS [62] collaborations indicates that prompt charmed hadrons are more suppressed than non-prompt charmed hadrons. The difference between the R_{AA} values is about a factor two in central collisions at a p_T value of about $10 \text{ GeV}/c$ [30] and it is described by model calculations with parton-mass-dependent energy loss. Therefore, for the centrality classes 0–10% and 30–50%, the value $R_{AA}^{\text{feed-down}} = 2 \times R_{AA}^{\text{prompt}}$ was assumed to compute the f_{prompt} factor for D mesons with $3 < p_T < 24 \text{ GeV}/c$. To estimate a systematic uncertainty, this hypothesis was varied in the range $1 < R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}} < 3$ considering

the data uncertainties and model variations. For $p_T < 3 \text{ GeV}/c$ and $24 < p_T < 50 \text{ GeV}/c$, since model calculations predict a lower difference between R_{AA}^{prompt} and $R_{AA}^{\text{feed-down}}$ [63, 64], the hypothesis $R_{AA}^{\text{feed-down}} = 1.5 \times R_{AA}^{\text{prompt}}$ was used, with a variation in the range $1 < R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}} < 2$ for estimating the systematic uncertainty.

The resulting values of the f_{prompt} factor, for the central hypotheses on $R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}}$, range from about 0.80 to 0.95, depending on the D-meson species, centrality class, and p_T interval. The values of f_{prompt} for the D^0 analysis without decay-vertex reconstruction are larger compared to those from the analysis with geometrical selections since the feed-down component is not enhanced by the topological selection criteria. The systematic uncertainties obtained from the variation of the hypotheses are discussed in section 4.

4 Systematic uncertainties

The systematic uncertainties on the corrected yields of D^0 , D^+ , and D^{*+} mesons were estimated as a function of p_T for the 0–10% and 30–50% centrality classes considering the following sources: (i) extraction of the raw yield from the invariant-mass distributions; (ii) reconstruction efficiency of the decay-particle tracks; (iii) D-meson selection efficiency; (iv) PID efficiency; (v) generated D-meson p_T and rapidity shape; (vi) subtraction of the contribution originating from beauty-hadron decays. In addition, a global normalisation uncertainty due to the branching-ratio uncertainty and the centrality interval determination was considered. The estimated values of the systematic uncertainties are summarised in table 2 for the three D-meson species in representative p_T intervals.

The systematic uncertainty on the D-meson raw yield was estimated in each p_T interval by varying the invariant-mass interval considered in the fit and the functional form of the background fit function. The sensitivity to the line shape of the signal was tested by considering the raw yield values obtained by counting the candidates in the invariant-mass region of the signal peak after subtracting the background estimated from the side bands. In the case of the D^0 -meson analysis without decay-vertex reconstruction, an additional contribution related to the line shape of the signal was estimated by varying the width of the Gaussian function by $\pm 10\%$ with respect to the Monte Carlo expectation, based on the deviations between the Gaussian width values observed in data and simulations for the analysis with decay-vertex reconstruction. The systematic uncertainty was defined as the RMS of the distribution of the signal yields obtained from all these variations. In the case of D^0 mesons, an additional contribution due to the modelling of the reflection contribution in the fit was estimated by varying (by $\pm 20\%$) the ratio of the integral of the reflections to the integral of the signal and the shape of the templates used in the invariant-mass fits. The assigned uncertainty ranges from 2% to 11% depending on the D-meson species and p_T interval, being on average smaller in the 30–50% centrality class due to the larger signal-to-background ratio in this class as compared to central collisions.

The systematic uncertainty on the track reconstruction efficiency has two contributions. The first one was estimated by varying the track quality selection criteria. The second contribution originates from possible differences in the probability to match the

Particle		D ⁰			D ⁺		D ^{*+}	
p_{T} interval (GeV/ c)		0–1	1.5–2	7.5–8	3–3.5	7.5–8	3–3.5	7.5–8
0–10% centrality	Raw-yield extraction	9%	7%	2%	5%	5%	7%	3%
	Correction factor							
	Tracking efficiency	8%	9%	9%	14%	15.5%	13%	9%
	Selection efficiency	negl.	8%	2%	5%	5%	13%	4%
	PID efficiency	negl.	negl.	negl.	negl.	negl.	1%	1%
	MC p_{T} shape	negl.	0.5%	negl.	negl.	negl.	0.5%	negl.
	Feed-down from beauty	+2.7% –2.9%	+7.6% –8.3%	+11.6% –12%	+3.4% –3.2%	+7.1% –6.6%	+8.4% –8.1%	+10.3% –10.3%
	Branching ratio	0.8%			1.7%		1.1%	
Centrality limits	<0.1%							
30–50% centrality	Raw-yield extraction	11%	4%	2%	4%	3%	5%	4%
	Correction factor							
	Tracking efficiency	7%	7.5%	7%	11%	11%	10%	9%
	Selection efficiency	negl.	8%	2%	4%	3%	9%	4%
	PID efficiency	negl.	negl.	negl.	negl.	negl.	negl.	negl.
	MC p_{T} shape	negl.	1%	negl.	negl.	negl.	negl.	negl.
	Feed-down from beauty	+2.7% –2.9%	+9.6% –10.4%	+11.4% –11.7%	+3.4% –3.2%	+6.6% –6.3%	+8.5% –8.2%	+9.9% –9.9%
	Branching ratio	0.8%			1.7%		1.1%	
Centrality limits	2%							

Table 2. Relative systematic uncertainties on prompt D-meson yields in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for representative p_T intervals. The first p_T interval of the D⁰ corresponds to the analysis without decay vertex reconstruction. For the uncertainties on the correction factors, values below 0.5% are considered negligible.

TPC tracks to the ITS hits in data and in simulations. It was estimated by comparing the matching efficiency in data and simulations after weighting the relative abundances of primary and secondary particles in the simulation to match those observed in data. The uncertainty was estimated for the single track and propagated to the reconstructed D mesons using the decay kinematics. The estimated uncertainty is the quadratic sum of the two contributions and it depends on the D-meson species and p_T , ranging from 3% to 10.5% for the two-body decay of D⁰ mesons and from 5.5% to 15.5% for the three-body decays of D⁺ and D^{*+} mesons.

The uncertainty on the D-meson selection efficiency originates from imperfections in the description of the D-meson kinematic properties and of the detector resolution and alignment in the simulation. For the analyses with decay-vertex reconstruction, the systematic uncertainty was estimated by comparing the corrected yields obtained by repeating the analysis with different sets of selection criteria resulting in a significant modification of the raw yields, signal-to-background ratios, and efficiencies. The estimated uncertainty depends on the D-meson species and p_T interval, being larger at low p_T and for central collisions, where more stringent selections are used to obtain a good statistical significance

of the signal. The values obtained in these analyses range from 2% (3%) to 8% (13%) for the two-(three-) body decay channel. In the case of the D^0 -meson analysis without decay-vertex reconstruction, no geometrical selections on the displaced decay-vertex topology are applied, and the efficiencies are higher than those of the analysis with decay-vertex reconstruction and almost independent of p_T . The stability of the corrected yield was tested against variations of the single-track p_T selection and no systematic effect was observed.

The uncertainty on the PID selection efficiency was estimated by repeating the analyses with decay-vertex reconstruction without applying the PID selections. The resulting corrected yields were found to be compatible with those obtained with the PID selection and therefore no systematic uncertainty was assigned. For the D^0 -meson analysis without decay-vertex reconstruction, the analysis without applying PID selections could not be performed due to the insufficient statistical significance of the signal. More stringent PID criteria (at 2σ level on TPC, or TOF or both) were tested and compatible values for the corrected yields were obtained. Based on this result and on the fact that the PID selections are the same as used in the analysis with decay-vertex reconstruction, no uncertainty due to PID was assigned. In the case of the D^{*+} analysis, more stringent PID selection criteria were used in the 0–10% centrality class. A systematic uncertainty of 1% was estimated by comparing the pion and kaon PID selection efficiencies in the data and in the simulation and combining the observed differences using the D^{*+} -meson decay kinematics. For this study, pure pion samples were selected from strange-hadron decays, while pure kaon samples in the TPC (TOF) were obtained using a tight PID selection in the TOF (TPC).

An additional contribution to the systematic uncertainty on the efficiency originates from a possible difference between the real and simulated D-meson p_T and rapidity distributions. The effect of the p_T shape was estimated by calculating the efficiency using alternative D-meson transverse momentum shapes via a reweighting technique. In particular, the p_T distributions from FONLL calculations with and without hot-medium effects parametrised based on the R_{AA} in central collisions from different models were considered. For the analyses with decay-vertex reconstruction, the resulting uncertainty, which also includes the effect of the p_T dependence of the nuclear modification factor, was estimated to be negligible for $p_T > 5 \text{ GeV}/c$ and to increase to 1–1.5% in the lowest p_T intervals considered in the analysis, where the efficiency varies steeply with p_T . Instead, no sensitivity to the generated D^0 p_T shape was observed in the results of the D^0 -meson analysis without decay-vertex reconstruction. The simulated rapidity shape of D mesons affects the $\text{Acc} \times \epsilon$ and the α_y factors in the calculation of the cross section. It was verified that the D-meson rapidity distributions in the PYTHIA 8 simulations and FONLL calculations are similar, resulting in a negligible effect on the $\text{Acc} \times \epsilon$ and α_y correction factors. For the latter factor, an extreme assumption of a flat rapidity shape was tested and the difference with respect to the FONLL case was found to be smaller than 1% for $p_T < 10 \text{ GeV}/c$ and to be smaller than 2% at higher p_T . Considering that at high p_T the assumption of a flat rapidity shape is an extreme variation, the effect of the generated dN/dy shape was considered to be negligible and no systematic uncertainty was assigned.

The systematic uncertainty on the f_{prompt} correction factor was estimated by varying (i) the FONLL parameters (b-quark mass and factorisation and renormalisation scales,

according to the prescription in ref. [60]) in the calculation of the p_T -differential production cross section of feed-down D mesons, and (ii) the ratio between the feed-down and prompt D-meson R_{AA} , as described above. The resulting uncertainty ranges between 2% and 14%, depending on the D-meson species and p_T and centrality interval.

The normalisation uncertainty due to the centrality interval definition was estimated from the variation of raw yield observed when varying the limits of the centrality classes to account for the uncertainty on the fraction of the hadronic cross section used in the Glauber fit to determine the centrality percentiles (see ref. [29] for details).

In the calculation of the nuclear modification factor, the systematic uncertainties on the D-meson yield in Pb–Pb collisions and on the pp reference cross section were propagated as uncorrelated, except for the uncertainty on the BR, which cancels out in the ratio, and the contribution to the feed-down uncertainty originating from the variation of the parameters of the FONLL calculation, which was considered to be fully correlated between the Pb–Pb and pp measurements. In particular, the contributions of the uncertainties on (i) the normalisation of the pp cross section (due to the luminosity determination), (ii) the centrality limits of the Pb–Pb samples, and (iii) the $\langle T_{AA} \rangle$ estimated with the Glauber model are common to all the p_T intervals and therefore they constitute a normalisation uncertainty on the R_{AA} , which is shown separately from the other sources when displaying the results.

5 Results

5.1 Transverse-momentum-differential yields

In this section, the results on the p_T -differential ($d^2N/dydp_T$) and p_T -integrated (dN/dy) yields of prompt D^0 , D^+ , and D^{*+} mesons at midrapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the 0–10% and 30–50% centrality classes are presented. In the case of the D^0 mesons, two results for the $d^2N/dydp_T$ were obtained from the analyses with and without selections on the decay-vertex topology. They are compared in figure 3, with the inset showing their ratio in the common p_T range. In the calculation of the ratio, the results in the narrower p_T intervals of the analysis with decay-vertex reconstruction were merged together to match the binning of the analysis without vertexing, and the systematic uncertainties were propagated treating the raw yield extraction as uncorrelated between the two analyses, and all the other sources of uncertainty as correlated. The vertical error bars represent the statistical uncertainties and the systematic uncertainties are depicted as boxes except for the BR uncertainty, which is reported separately. The symbols, representing the data points, are positioned horizontally at the center of each interval and the horizontal bars represent the width of the p_T interval. This convention is adopted in all the figures shown in this section.

The two results for the p_T -differential yield of prompt D^0 mesons are found to be consistent within statistical uncertainties, which are independent between the two analysis techniques because of the largely different signal-to-background ratios and efficiencies. The usage of these two techniques allows the measurement of the D^0 p_T -differential yields in a wide transverse momentum range extending down to $p_T = 0$ for the first time in Pb–Pb

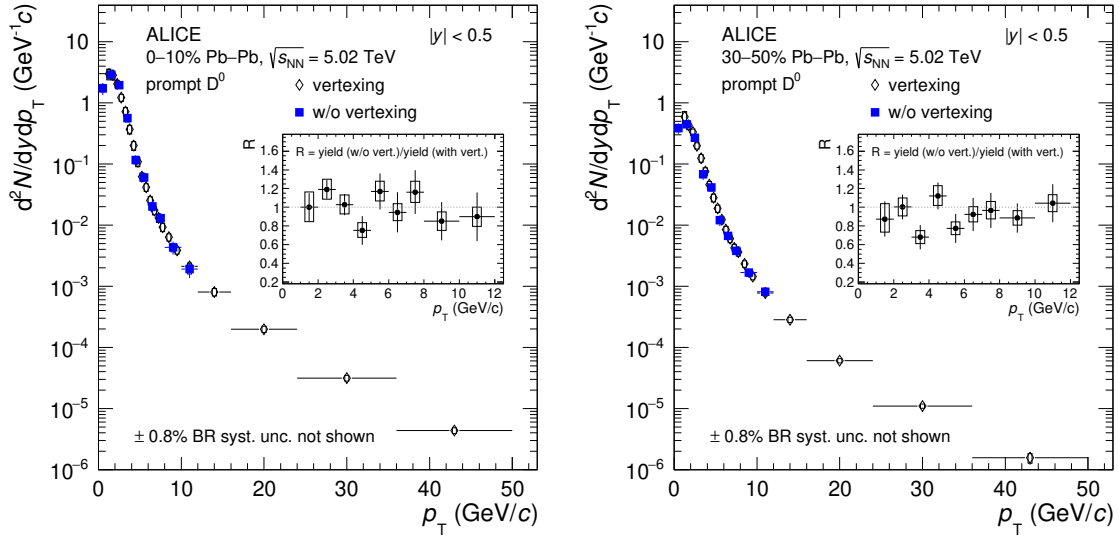


Figure 3. Transverse momentum distributions $d^2N/dydp_T$ of prompt D^0 mesons from the analysis with (open marker) and without (full marker) decay-vertex reconstruction in the 0–10% and 30–50% centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical uncertainties (bars) and systematic uncertainties (boxes) are shown.

collisions. The most precise measurement of the prompt D^0 -meson p_T spectrum, which will be shown and used for comparisons throughout the paper, is obtained by using the results of the analysis without decay-vertex reconstruction in the p_T interval $0 < p_T < 1$ GeV/ c and those from the analysis with decay-vertex reconstruction for $p_T > 1$ GeV/ c .

The p_T -differential yields $d^2N/dydp_T$ of prompt D^0 , D^+ , and D^{*+} mesons are shown in figure 4 for the 0–10% and 30–50% centrality classes. They are compared with the reference yields from pp collisions, which are computed as $\langle T_{AA} \rangle \times d\sigma_{pp}/dp_T$, where $d\sigma_{pp}/dp_T$ is the D-meson p_T -differential cross section measured in pp collisions at $\sqrt{s} = 5.02$ TeV [37, 65], and $\langle T_{AA} \rangle$ is the average nuclear overlap function [47]. The D-meson production cross sections in pp collisions are measured up to 36 GeV/ c and they are extrapolated with FONLL towards higher p_T , with the method described in refs. [29, 30]. The spectra in the 30–50% centrality class are scaled by the factor reported in the legend for visibility. A clear suppression of the production yield for $p_T > 3$ GeV/ c is visible in Pb–Pb collisions and it is stronger in central than in semicentral collisions.

Figure 5 shows the p_T -dependent ratios of the production yields of prompt D^+ and D^{*+} mesons relative to the D^0 ones, in the left panels, compared with the values measured in pp collisions at $\sqrt{s} = 5.02$ TeV [37]. The systematic uncertainties were propagated to the ratios, considering the contributions from the tracking efficiency and the beauty-hadron feed-down subtraction as fully correlated among the different D-meson species. The values obtained in Pb–Pb and pp collisions are compatible within uncertainties and this indicates there is no modification of the relative abundances of D^0 , D^+ , and D^{*+} mesons as a function of p_T and for different centrality classes. The D^+/D^0 and D^{*+}/D^0 ratios are described within uncertainties by the GSI-Heidelberg statistical hadronisation model

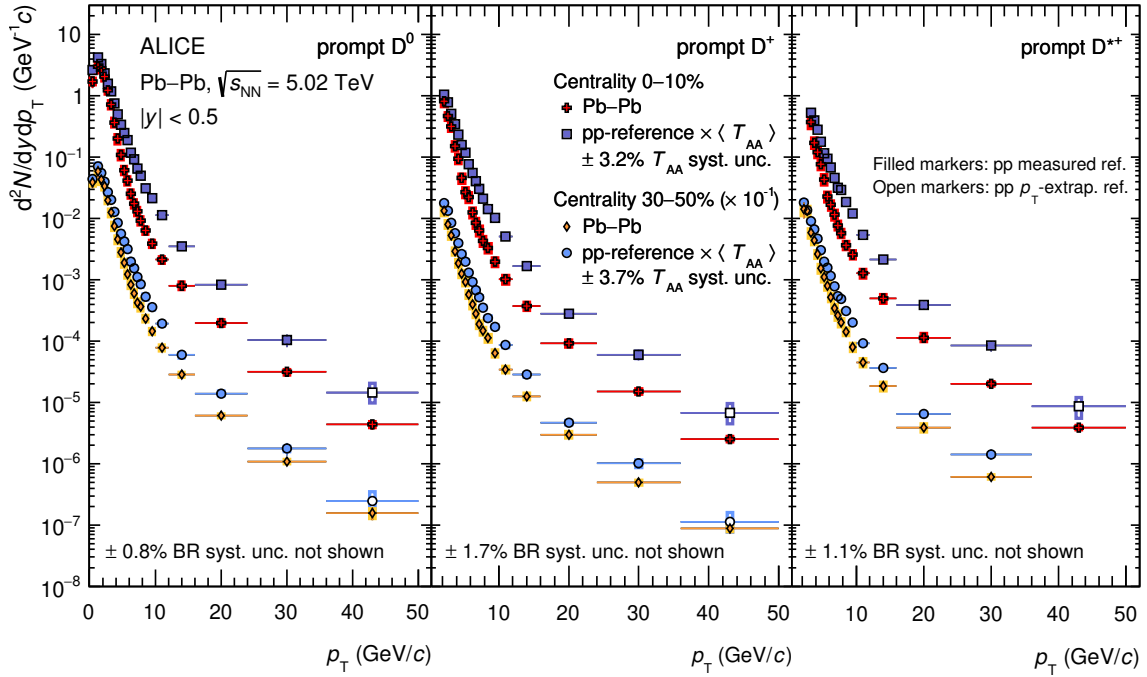


Figure 4. Transverse momentum distributions $d^2N/dydp_T$ of prompt D^0 (left), D^+ (middle), and D^{*+} (right) mesons in the 0–10% (cross) and 30–50% (diamond) centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The reference pp distributions multiplied by $\langle T_{AA} \rangle$ are shown as well. Statistical uncertainties (bars) and systematic uncertainties (boxes) are shown. The uncertainties on the BRs are quoted separately and the horizontal bars represent bin widths. The spectra in the 30–50% centrality class are scaled by the factor reported in the legend for visibility. Filled and empty markers of the pp reference indicate the measured [37, 65] and p_T -extrapolated values, respectively, of the p_T -spectrum.

(SHMc) [66, 67] (right panels of figure 5), which predicts the p_T spectra of charm hadrons with a core-corona approach. The low- p_T region is dominated by the core contribution described with a blast-wave function, while the corona contribution is more relevant at high p_T and is parametrised from pp measurements. The rise predicted by the model, especially for D^{*+}/D^0 , are due to the different D-meson masses and to the collective radial expansion of the system.

The visible production yields of prompt D^0 , D^+ , and D^{*+} mesons in the two centrality classes were evaluated by integrating the $d^2N/dydp_T$ over the p_T intervals of the measurements. The results are reported in table 3. For the yield integration, the systematic uncertainty was propagated assuming all sources of uncertainty as fully correlated among p_T intervals, except for the one on the raw-yield extraction, which was treated as uncorrelated because of the bin-to-bin variations of S/B and background invariant-mass shape.

The production yield of prompt D mesons per unit of rapidity, dN/dy , was obtained by extrapolating (where needed) the visible cross section to the full p_T range. Since the p_T -differential yields of D^0 mesons in the 0–10% and 30–50% centrality classes were measured

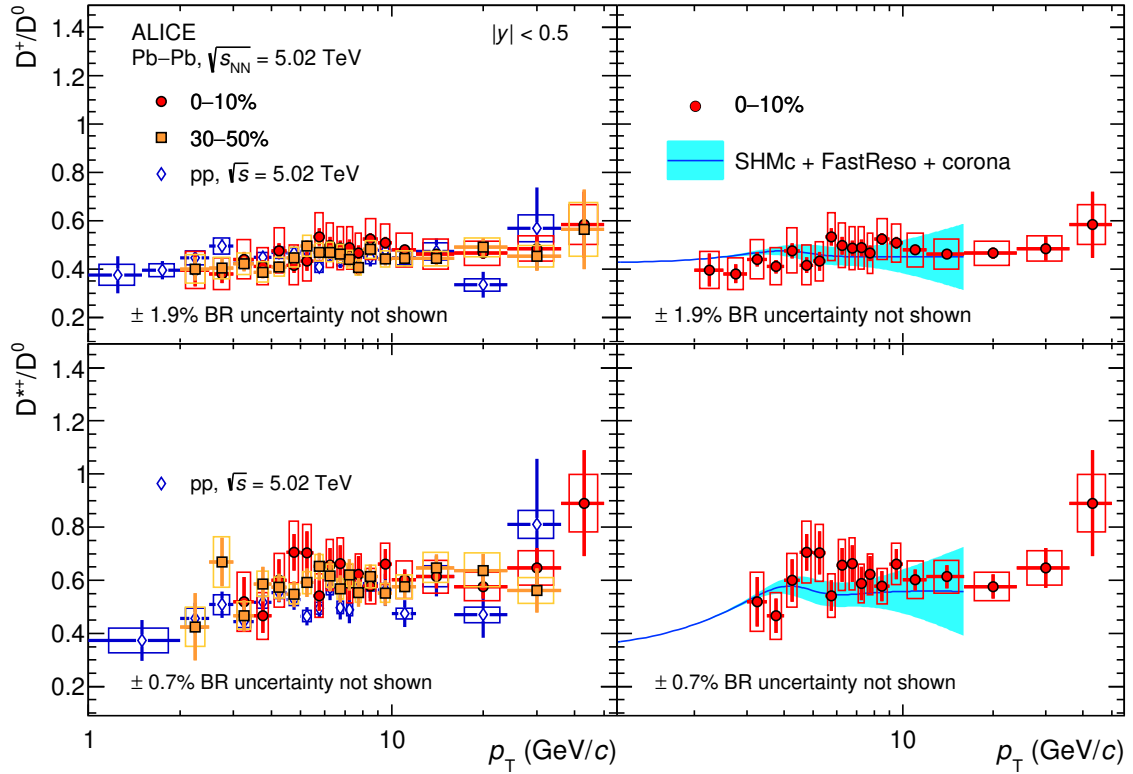


Figure 5. D^+/D^0 (top left panel) and D^{*+}/D^0 (bottom left panel) ratios as a function of p_T in central and semicentral Pb–Pb collisions compared to the results obtained from pp collisions [37]. The right panels show the ratios in central Pb–Pb collisions compared to the predictions from the statistical hadronisation model (SHMc) [66, 67] with a core-corona approach and the FastReso package [68] for resonance decays. Statistical (bars) and systematic (boxes) uncertainties are shown.

down to $p_T = 0$, it was possible to obtain the dN/dy at midrapidity for the first time in Pb–Pb collisions at the LHC without using models or assumptions to extrapolate the p_T -differential yield to unmeasured momentum range at low p_T . Conversely, the dN/dy of D^+ and D^{*+} mesons were obtained via an extrapolation procedure exploiting the measured p_T -differential ratios relative to the D^0 meson. The measured p_T -differential D^+/D^0 and D^{*+}/D^0 ratios, shown in figure 5, were fit with two different functions (a constant and a constant plus logarithmic function) in order to extrapolate the ratios in the interval $0 < p_T < 2$ GeV/c, where the yields could not be measured. The extrapolation in the high- p_T range is negligible because the fraction of D-meson yield in central (semicentral) collisions with $p_T > 50$ (36) GeV/c is negligible. The yields of D^+ and D^{*+} mesons in the interval $0 < p_T < 2$ GeV/c were obtained by multiplying the measured D^0 yield in this p_T interval by the extrapolated ratio from the fit function. For the D^+/D^0 ratios, which show a flat trend as a function of p_T , the fit to a constant was used in the determination of the central value of the D^+ yield, while for the D^{*+}/D^0 ratio the fit with a constant plus a logarithmic function was used. The systematic uncertainty due to the extrapolation was estimated by evaluating the yields using the other fit function and the shape of the SHMc predictions with normalisation parameter left free. The difference between the central

	Kinematic range	Visible production yield	
0–10% centrality			
D ⁰	0 < p _T < 50 GeV/c	6.819 ± 0.457 (stat.)	^{+0.912} _{−0.936} (syst.) ± 0.054 (BR)
D ⁺	2 < p _T < 50 GeV/c	0.992 ± 0.073 (stat.)	^{+0.154} _{−0.155} (syst.) ± 0.017 (BR)
D ^{*+}	3 < p _T < 50 GeV/c	0.438 ± 0.037 (stat.)	^{+0.084} _{−0.085} (syst.) ± 0.005 (BR)
30–50% centrality			
D ⁰	0 < p _T < 50 GeV/c	1.275 ± 0.099 (stat.)	^{+0.167} _{−0.173} (syst.) ± 0.010 (BR)
D ⁺	2 < p _T < 50 GeV/c	0.179 ± 0.008 (stat.)	^{+0.024} _{−0.024} (syst.) ± 0.003 (BR)
D ^{*+}	2 < p _T < 36 GeV/c	0.230 ± 0.023 (stat.)	^{+0.038} _{−0.039} (syst.) ± 0.002 (BR)

Table 3. Visible production yield of prompt D^0 , D^+ , and D^{*+} mesons in $|y| < 0.5$ in the 0–10% and 30–50% centrality classes of Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$.

	Measured dN/dy	SHMc dN/dy
0–10% centrality		
D^0	$6.819 \pm 0.457 \text{ (stat.)}$ $^{+0.912}_{-0.936} \text{ (syst.)} \pm 0.054 \text{ (BR)}$	6.42 ± 1.07
D^+	$3.041 \pm 0.073 \text{ (stat.)}$ $^{+0.154}_{-0.155} \text{ (syst.)} \pm 0.052 \text{ (BR)}$ $^{+0.352}_{-0.618} \text{ (extrap.)}$	2.84 ± 0.47
D^{*+}	$3.803 \pm 0.037 \text{ (stat.)}$ $^{+0.084}_{-0.085} \text{ (syst.)} \pm 0.041 \text{ (BR)}$ $^{+0.854}_{-1.175} \text{ (extrap.)}$	2.52 ± 0.42
30–50% centrality		
D^0	$1.275 \pm 0.099 \text{ (stat.)}$ $^{+0.167}_{-0.173} \text{ (syst.)} \pm 0.010 \text{ (BR)}$	1.06 ± 0.15
D^+	$0.552 \pm 0.008 \text{ (stat.)}$ $^{+0.024}_{-0.024} \text{ (syst.)} \pm 0.009 \text{ (BR)}$ $^{+0.068}_{-0.114} \text{ (extrap.)}$	0.471 ± 0.069
D^{*+}	$0.663 \pm 0.023 \text{ (stat.)}$ $^{+0.038}_{-0.039} \text{ (syst.)} \pm 0.007 \text{ (BR)}$ $^{+0.149}_{-0.165} \text{ (extrap.)}$	$0.419^{+0.065}_{-0.061}$

Table 4. Measured p_T -integrated yields of prompt D^0 , D^+ , and D^{*+} in $|y| < 0.5$ in the 0–10% and 30–50% centrality classes of Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$. The right column reports the dN/dy predicted by the GSI-Heidelberg statistical hadronisation model [66, 67].

value and the yields obtained with other functions for the extrapolation was assigned as systematic uncertainty and summed in quadrature to the uncertainty on the D^0 yield in the aforementioned p_T interval. The results for the prompt D-meson production yields per unit of rapidity dN/dy in $|y| < 0.5$ are reported in table 4. In the case of the D^0 meson, the result coincides with the visible yield because the measurement extends down to $p_T = 0$ and the contribution of D^0 mesons with $p_T > 50$ (36) GeV/c is negligible.

In the right column the dN/dy values predicted by the SHMc [66, 67] are reported. In the SHMc approach, the yield of hadrons containing charm quarks can be calculated utilising as input values (i) the temperature T_{chem} , (ii) the volume of the fireball at the chemical freeze-out estimated from a fit to light-flavour hadron yields, and (iii) the number of $c\bar{c}$ pairs produced in the Pb–Pb collision. The latter was calculated from the charm-

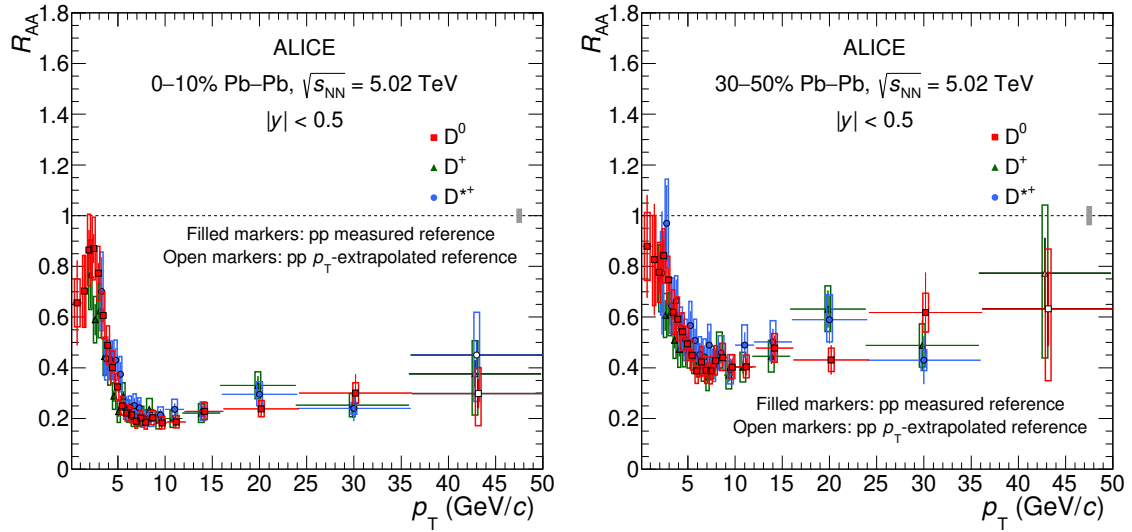


Figure 6. R_{AA} of prompt D^0 , D^+ , and D^{*+} mesons as a function of p_T for the 0–10% (left panel) and 30–50% (right panel) centrality classes. Statistical (bars), systematic (boxes), and normalisation (shaded box around unity) uncertainties are shown. Filled markers are obtained with the measured pp reference [37, 65], empty markers with the p_T -extrapolated reference.

quark production cross section estimated from measurements in pp and p–Pb collisions along with guidance from parameterisations of the nuclear modification of the PDFs [69]. The SHMc calculations agree with the measurements within uncertainties, even though the data lie on the upper edge of the uncertainty band of the theoretical predictions, which is related to the uncertainty on the total charm production cross section used in the calculation. It is useful to note that the charm production cross section in pp collisions, which was used to determine the charm content of the fireball in the SHMc calculations, is lower than the recent measurement reported in ref. [70] and therefore the yields from the SHMc would increase if the measured cross section were used as the input to the calculations. However, a firmer conclusion on the SHMc predictions for charm hadrons will be drawn when the measured dN/dy of D_s^+ , Λ_c^+ , and J/ψ will be available in Pb–Pb collisions and included in the comparison, since it is expected that the modifications of the hadronisation mechanisms in the presence of a QGP affect the relative abundances of different charm-hadron species [25, 71–76].

5.2 Nuclear modification factor

The R_{AA} of prompt D^0 , D^+ , and D^{*+} mesons was computed, as defined in eq. (1.1), using the $d^2N/dydp_T$ measured in Pb–Pb collisions and the pp reference at the same centre of mass energy reported in figure 4. The obtained results are shown in figure 6 for the two centrality classes. The nuclear modification factors of the three D-meson species are compatible among each other within statistical uncertainties.

The average R_{AA} of D^0 , D^+ , and D^{*+} mesons was computed as a weighted average using the inverse of the quadratic sum of the relative statistical and uncorrelated systematic uncertainties as weights, in the p_T intervals where more than one D-meson R_{AA} value

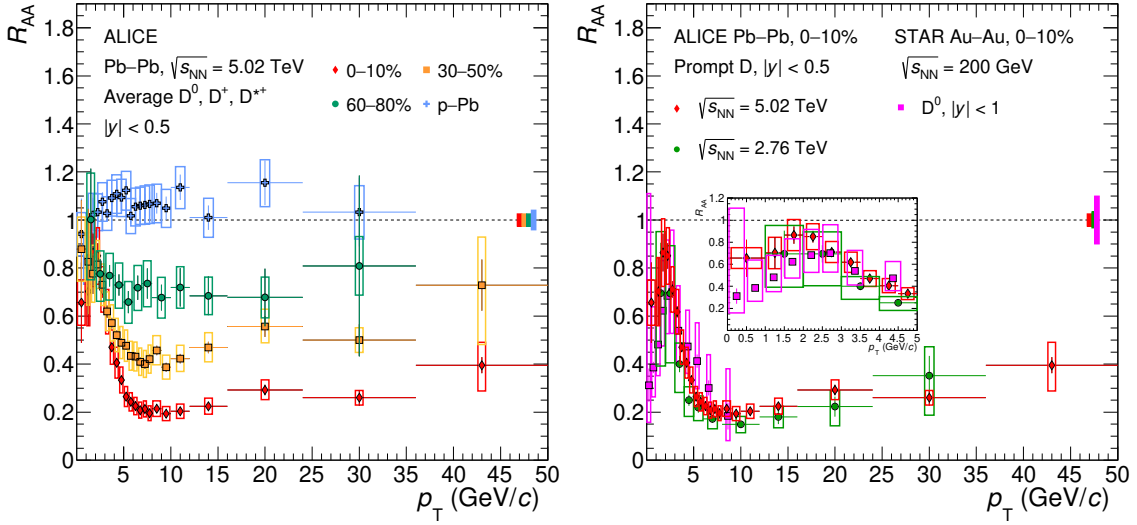


Figure 7. Left panel: prompt D-meson R_{AA} (average of D^0 , D^+ , and D^{*+}) as a function of p_T measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (2018 data sample) in the 0–10% and 30–50% centrality classes compared with published results in the 60–80% centrality class (2015 data sample) [30] and in p–Pb collisions at the same centre-of-mass energy [33]. Statistical (bars), systematic (boxes), and normalisation (shaded box around unity) uncertainties are shown. Right panel: prompt D-meson R_{AA} in the 10% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 2.76 TeV [29] compared to the D^0 R_{AA} measured by the STAR collaboration in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [32].

is available. The systematic uncertainties due to the raw-yield extraction and selection efficiency were considered as uncorrelated among different D-meson species and therefore they were used in the definition of the weights and propagated through the weighted average as uncorrelated, while the other sources of uncertainty (tracking efficiency, generated p_T shape, and beauty hadron feed-down) were treated as fully correlated.

The prompt D-meson average nuclear modification factors in the 0–10% and 30–50% centrality classes are shown in figure 7 together with the R_{AA} in the 60–80% centrality class taken from ref. [30], which was measured using the sample of Pb–Pb collisions collected in 2015. The suppression increases from peripheral to central collisions. The R_{AA} shows a minimum value at $p_T = 6$ –8 GeV/c, corresponding to a suppression of the yields by a factor 5 and 2.5 with respect to the binary-scaled pp reference in the 0–10% and 30–50% classes, respectively. The stronger suppression observed in central collisions is due to the increasing medium density, size, and lifetime of the fireball from peripheral to central collisions. Also shown in figure 7 is the nuclear modification factor R_{pPb} measured in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV taken from ref. [33], which is compatible with unity within uncertainties, confirming that the suppression observed in Pb–Pb collisions is due to final-state effects induced by the formation of a hot and dense QGP medium.

The right panel of figure 7 shows the R_{AA} of prompt D mesons measured by the ALICE collaboration in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 2.76 TeV [29] and of D^0 mesons measured at RHIC by the STAR collaboration in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [32].

The results from ALICE at the two different energies are compatible within uncertainties. This similarity originates from the interplay between the higher medium temperature and density at 5.02 TeV, which causes a larger energy loss and a lower R_{AA} , and the harder p_T distribution of charm quarks at 5.02 TeV, which would increase the R_{AA} if the medium temperature were the same at the two collision energies [63]. The nuclear modification factor of D^0 mesons at RHIC energies shows a trend with p_T similar to the one measured at the LHC, with a possible hint for a smaller R_{AA} at low p_T (< 2 GeV/ c) and a larger R_{AA} at high p_T (> 4 GeV/ c) in collisions at $\sqrt{s_{NN}} = 200$ GeV compared to LHC energies. This difference could be due to dependence with collision energy of the charm-quark p_T distributions, the initial-/final-state effects, and the medium properties. However, the rather large uncertainties prevent a firm conclusion on a $\sqrt{s_{NN}}$ dependence of the R_{AA} from being drawn.

In addition, the p_T -integrated R_{AA} of prompt D^0 mesons at midrapidity was calculated from the p_T -integrated yield in Pb–Pb collisions reported above and the D^0 production cross section measured in pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV [37]. The results in the 0–10% and 30–50% centrality classes are:

$$\begin{aligned} R_{AA}^{\text{prompt } D^0}(0\text{--}10\%) &= 0.689 \pm 0.054 \text{ (stat.)}_{-0.106}^{+0.104} \text{ (syst.)}, \\ R_{AA}^{\text{prompt } D^0}(30\text{--}50\%) &= 0.775 \pm 0.069 \text{ (stat.)}_{-0.120}^{+0.117} \text{ (syst.)}. \end{aligned} \quad (5.1)$$

Figure 8 shows the results obtained in Pb–Pb collisions compared with the nuclear modification factor R_{pPb} measured in p–Pb collisions at the same centre-of-mass energy [33]. The total charm cross section is expected to scale with the number of binary collisions N_{coll} , as introduced in section 1, and thus the R_{AA} should be equal to one. However, the nuclear shadowing effect reduces the charm production in Pb–Pb (and p–Pb) collisions with respect to pp interactions. In addition, the possible enhanced production of D_s^+ and Λ_c^+ due to the hadronisation via recombination is expected to further decrease the fraction of charm quarks that hadronise into D^0 mesons in Pb–Pb collisions compared to pp collisions [25, 71–76]. The measured p_T -integrated R_{AA} is significantly below unity and this confirms the suppression of the D^0 -meson yield in Pb–Pb collisions with respect to the binary-scaled pp reference due to shadowing and the possible modifications in the hadronisation mechanism. Conversely, the p_T -integrated D^0 R_{pPb} is closer to unity, as expected from the smaller shadowing effects in p–Pb compared to Pb–Pb collisions (where it affects the nucleons of both the projectile and the target nuclei). The integrated R_{AA} is also compared with perturbative QCD calculations of D^0 -meson production including only initial-state effects modeled using two different sets of nuclear PDFs, namely nCTEQ15 [77–81] and EPPS16 [82, 83]. The calculations with EPPS16 do not include the dependence of the shadowing on the impact parameter of the Pb–Pb collision and therefore they are the same in the central and semicentral event classes. The predictions with nCTEQ15 are obtained applying a Bayesian reweighting of the nuclear PDFs, which is constrained by measurements of heavy-flavour production in p–Pb collisions at the LHC [78], and are labelled as nCTEQ15_{rwHF} in figure 8. They include a modelling of the centrality dependence of the nuclear modification of the PDFs. The uncertainty bands represent a 90% confidence level

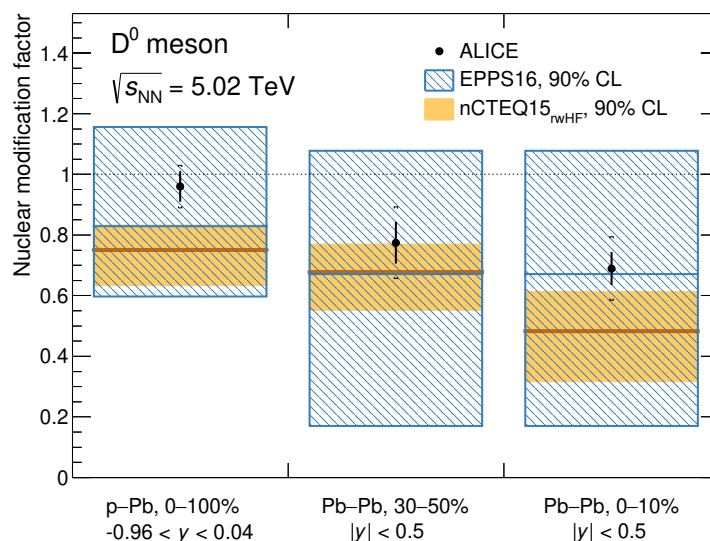


Figure 8. p_T -integrated nuclear modification factors of prompt D^0 mesons measured in p-Pb [33] and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical (bars) and systematic (brackets) uncertainties are shown. The results are compared with calculations at 90% of confidence level of theoretical models nCTEQ15 (with Bayesian reweighting, see text for details) [77–81] and EPPS16 [82, 83] that include only initial-state effects.

uncertainty. In the nCTEQ15 case they are determined by considering three different factorisation scales in addition to the PDF uncertainties, with the scale variation constituting the main source of uncertainty, as described in ref. [78]. Both model calculations include only the initial-state effects due to the nuclear PDFs, but not the possible modifications of the relative abundances of different charm hadron species due to hadronisation via recombination. The measured R_{AA} values lie on the upper edge of the theoretical predictions and this could be due to a smaller shadowing effect in the data with respect to the model expectations.

5.3 Discussion: energy loss regime

The comparison of the nuclear modification factor of prompt D mesons with that of pions and of particles originating from beauty-hadron decays can provide essential insights into the characteristics of the in-medium parton energy loss, in particular on its predicted dependence on the colour charge and the quark mass. To investigate possible differences with respect to light-flavour particles, the average R_{AA} of prompt D^0 , D^+ , and D^{*+} mesons in the 0–10% centrality class is compared in figure 9 with that of charged pions [84] and charged particles [85]. The charged-particle R_{AA} is shown for $p_T > 20$ GeV/ c in order to extend the comparison to light-flavour particles up to the highest p_T interval of the D-meson measurement. The R_{AA} of charged particles can be used in this comparison at high p_T in place of the pion one because for $p_T > 8$ –10 GeV/ c . In this range, the nuclear modification factors of different light-flavour hadron species are found to be consistent with

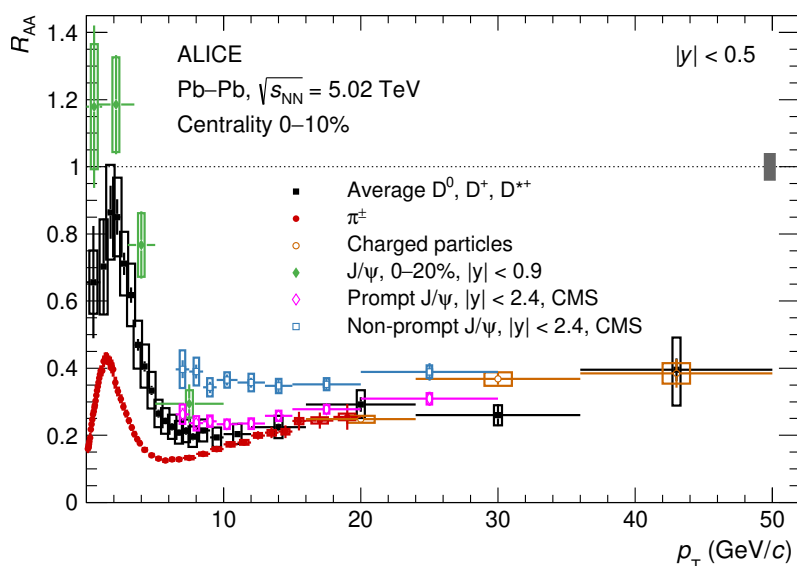


Figure 9. Average R_{AA} of prompt D^0 , D^+ , and D^{*+} mesons in the 0–10% centrality class compared to R_{AA} of charged pions [84], charged particles [85], inclusive J/ψ measured by ALICE [87], and of prompt and non-prompt J/ψ from CMS [61] in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

each other and the particle composition is compatible with that measured in pp collisions, that is dominated by pions [84, 86].

The R_{AA} of D mesons is larger than that of pions for $p_T < 8$ GeV/ c , providing a clear evidence for a different nuclear modification factor of D mesons and light-flavour particles at low and intermediate p_T . This difference originates from the interplay of several effects that concur in determining the magnitude and the p_T -dependence of the R_{AA} , so the interpretation in terms of different in-medium parton energy loss of charm quarks, light quarks, and gluons is not straightforward. As pointed out in ref. [19], also in the presence of a colour-charge and quark-mass dependent energy loss, similar values of D-meson and pion R_{AA} are expected at high p_T ($\gtrsim 8$ GeV/ c) due to the harder p_T distribution and the harder fragmentation function of charm quarks compared to those of light quarks and gluons. At low p_T , where a large difference is observed between the D-meson and pion R_{AA} 's, it should be considered that the pion yield can have a significant contribution from soft production up to transverse momenta of about 3–4 GeV/ c due to the strong radial flow at LHC energies. This soft component, which is not present in the D-meson production, does not scale with the number of binary nucleon-nucleon collisions. In addition, effects due to the radial flow and the hadronisation can affect D-meson and light-hadron yields differently at a given p_T , playing a role in the interpretation of their different R_{AA} at low and intermediate p_T . For instance, an enhanced production of D_s^+ mesons and charm baryons in Pb–Pb collisions due to recombination would imply a reduction of the fraction of charm quarks hadronising into non-strange meson species compared to pp collisions.

A quantitative understanding of the parton in-medium energy-loss from the R_{AA} measurements needs therefore to be carried out via comparisons with model calculations. In

particular, in the high- p_T region, where effects due to radial flow and modifications in the hadronisation mechanisms are expected to be negligible, models based on perturbative QCD (pQCD) calculations of high- p_T parton energy loss are expected to describe the data. The R_{AA} and the elliptic flow v_2 of prompt D mesons (taken from ref. [36]) and pions (taken from refs. [84, 88]) in the 0–10% and 30–50% centrality classes are compared in figure 10 to three of these models, namely CUJET3.1 [89–91], DREENA-A [92–94], and SCET_{M,G} [95]. The DREENA-A is a numerical framework that calculates the medium-modified distribution of high- p_T hadrons based on a dynamical energy-loss formalism coupled with a modelling of initial parton momentum distributions, a full 3+1D hydrodynamic evolution of the medium, and fragmentation functions. The dynamical energy-loss formalism [96–98] is a model of jet-medium interactions incorporating collisional and radiative energy loss mechanisms in a QCD medium of finite size and temperature composed of dynamical scattering centers. It includes a colour-charge and quark-mass dependence as well as finite magnetic mass effects and running strong coupling constant. The CUJET3.1 framework provides a calculation of jet energy loss in a QCD medium described with relativistic viscous hydrodynamics. The jet-medium interactions are based on the DGLV opacity expansion model [22, 99, 100] including both inelastic and elastic scatterings with their colour-charge and quark-mass dependence, and taking into account interactions with both chromo-electric and magnetic charges of the medium. The SCET_{M,G} model implements medium-induced gluon radiation via modified splitting functions. It is based on a soft-collinear effective theory (SCET [101, 102]) describing the parton shower formed in the vacuum via soft and collinear splittings. This effective theory was extended to the case of massless [103, 104] and massive [95] quarks propagating in strongly-interacting matter by including additional splitting processes induced by the interactions of the incident parton with the QCD medium mediated by Glauber gluon exchange. These medium-induced splittings are calculated to first order in the opacity series expansion, thus limiting the applicability of these calculations to the high p_T region.

The considered models provide a fair description of both the R_{AA} and the v_2 of D mesons and pions for $p_T > 10$ GeV/c, where radiative energy loss is expected to be the dominant interaction mechanism. This suggests that the dependences of radiative energy loss on the colour charge and the quark mass of the hard-scattered parton, as well as on the path length in the hot and dense medium are reasonably well described in these calculations.

The comparison of the nuclear modification factors of particles originating from charm and beauty quarks is also reported in figure 9, to provide insight into the predicted quark-mass dependence of parton energy loss. In particular, the R_{AA} of inclusive J/ψ mesons measured by ALICE [87] at midrapidity in the 0–20% centrality class and those of prompt and non-prompt J/ψ from the CMS collaboration [61] are shown.

The R_{AA} of prompt D mesons in the 0–10% centrality class is lower than that of non-prompt J/ψ mesons from beauty hadron decays measured in the same centrality interval. This difference provides an indication for the predicted quark-mass dependence of in-medium energy loss, even though a proper interpretation of the different nuclear modification factors in terms of energy loss requires a full modelling of the initial momentum

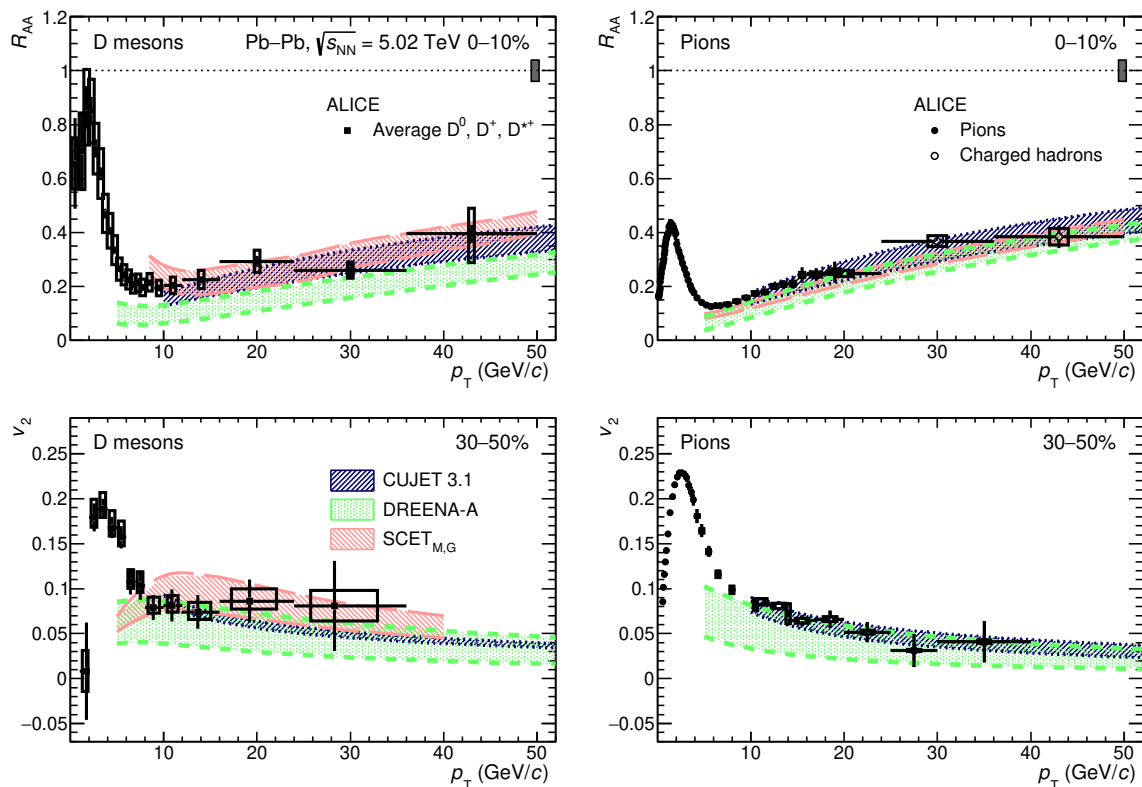


Figure 10. Average R_{AA} (top panels) and v_2 (bottom panels) of prompt D^0 , D^+ , and D^{*+} mesons [36] and pions (charged hadrons) [84, 85, 88] compared with predictions from models based on pQCD calculations, namely CUJET3.1 [89–91], DREENA-A [92], and SCET_{M,G} [95].

distributions of charm and beauty quarks, of the heavy-quark fragmentation, and of the beauty-hadron decay kinematics. The model from ref. [105], which includes all these effects, provides a good description of the measurements of prompt D and non-prompt J/ψ mesons. In this model, the large difference in the R_{AA} 's in the p_T interval around 10 GeV/c is mostly due to the different in-medium energy loss of c and b quarks, as the effects of initial distributions, quark fragmentation, and beauty-hadron decays are found to be small.

The comparison of the nuclear modification factors of prompt D mesons and prompt (inclusive) J/ψ mesons, also shown in figure 9, provides insight into the interplay of different QGP medium effects in the charm sector, where they are expected to affect differently the production of open charm and charmonium states. At high momentum ($p_T \gtrsim 10$ GeV/c), the R_{AA} of prompt D mesons is compatible within uncertainties with that of prompt J/ψ mesons, as well as with that of light-flavour hadrons. This may suggest that in this p_T region the yield of charmonia has a significant contribution from production within the parton shower originating from the splitting of a hard-scattered gluon [106, 107], which experiences in-medium energy loss before fragmenting [108, 109]. At lower p_T ($2 \lesssim p_T \lesssim 4$ GeV/c), the results for inclusive J/ψ , which are dominated by the prompt contribution, show a magnitude and a trend of the R_{AA} similar to that of D mesons. In this region, J/ψ production is likely dominated by recombination of c and $\bar{c}$ quarks in the medium either at the phase

boundary or during the QGP expansion [87, 110], similarly to the recombination of charm and light quarks forming D mesons. The similar R_{AA} of J/ψ and D mesons in this momentum region may signal the dominant contribution of hadronisation via recombination after the interactions of the charm quarks with the QGP medium constituents [111–114], with possible small differences arising from the different kinematics involved in the charm-quark coalescence with $\bar{c}$ and light antiquarks.

5.4 Discussion: transport models and an estimate of the spatial diffusion coefficient

As discussed in section 1, the charm-hadron yields and angular distributions at low and intermediate p_T are sensitive to the diffusion and the possible thermalisation of charm quarks in the medium. The comparison of the measured D-meson R_{AA} and v_2 to models implementing charm-quark transport in a hydrodynamically expanding QGP could therefore provide insight into the interactions of heavy quarks with the medium, constraining in particular the spatial diffusion coefficient, which is the relevant transport coefficient in the diffusion regime. In the left panels of figure 11 the measured nuclear modification factor of prompt D mesons for the 0–10% (top) and 30–50% (bottom) centrality class, respectively, is compared with various predictions from models implementing charm-quark transport in a hydrodynamically expanding medium [76, 115–125]. In particular, the TAMU [76], POWLANG-HTL [117, 118], PHSD [125], and Catania [122, 123] models describe the interactions of the charm quarks with the medium constituents solely via collisional processes, while the MC@sHQ+EPOS2 [115], DAB-MOD [116], LBT [119, 120], LGR [121], and LIDO [124] calculations include also radiative processes. All the models, except for DAB-MOD, include initial-state effects by using nuclear PDFs (nPDFs) in the calculation of the initial p_T distributions of charm quarks. A contribution of hadronisation via quark recombination, in addition to charm-quark fragmentation, is included in all theoretical predictions. The theoretical uncertainties, where available, are displayed with a coloured band.

Most of the models capture the measured p_T trend and magnitude of the nuclear modification factor and provide a good description of the data in the p_T interval $6 < p_T < 10$ GeV/ c where the minimum of the R_{AA} is observed, but many of them show significant deviations from the measurements at low p_T ($p_T \lesssim 4$ –5 GeV/ c). In particular, the LBT [119, 120], LIDO [124], MC@sHQ+EPOS2 [115], and Catania [122, 123] calculations tend to underestimate the results for $2 < p_T < 4$ GeV/ c in both centrality classes, while the PHSD [125] prediction is above the measured R_{AA} in semicentral collisions for the same p_T range. The POWLANG-HTL [117, 118] calculation, instead, predicts a narrower and more pronounced radial flow peak at low p_T as compared to the measured one for the 10% most central Pb–Pb collisions. Most of the models underestimate the measured R_{AA} in both centrality classes for $p_T < 1.5$ GeV/ c , with the exception of Catania [122, 123] calculations, which tend to overpredict the measured R_{AA} at low p_T in central and semicentral collisions and PHSD predictions, which overestimate the R_{AA} in the 30–50% centrality class. Nevertheless, it is important to remark that the R_{AA} at low p_T is sensitive not only to the modelling of the charm-quark interactions with the medium but also to the parametrisa-

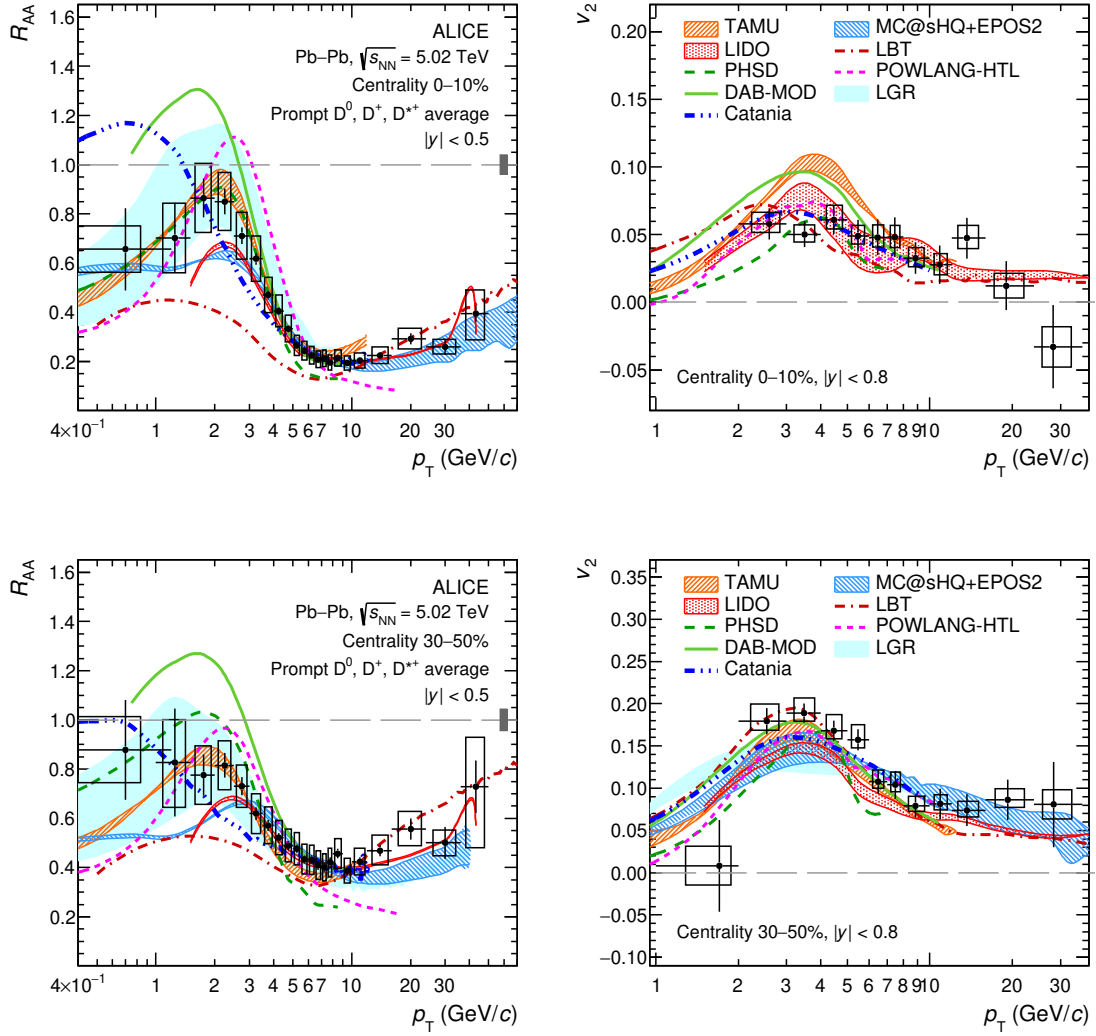


Figure 11. Average R_{AA} (left) and elliptic flow v_2 [36] (right) of prompt D^0 , D^+ , and D^{*+} mesons in the 0–10% (top) and 30–50% (bottom) centrality classes compared with predictions of models implementing the charm-quark transport in a hydrodynamically expanding medium [76, 115–125].

tion of the nPDFs used in the calculations and to the hydrodynamical description of the underlying medium.

More stringent constraints to the implementation of the heavy-quark interactions with the medium constituents can be provided by the simultaneous comparison of R_{AA} and v_2 measurements in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [36] with models, as reported in figure 11. All the models describe reasonably well the v_2 in the most central collisions, while they tend to underestimate the measured points in the $2 < p_T < 6$ GeV/c interval for the 30–50% centrality class, except for LBT which reproduces well the measured v_2 but misses completely the R_{AA} in the same p_T range. In this p_T region, the measured v_2 originates predominantly from the charm-quark interactions with the QGP constituents,

which impart the flow of the medium to the heavy quarks, and from the hadronisation via recombination, which enhances the charm-hadron v_2 with respect to the one of the charm quark because the D meson picks up the v_2 of the light quark. Similarly, the peak observed in the R_{AA} for $2 < p_T < 6 \text{ GeV}/c$ is also due to the interplay between the diffusion and recombination of the charm quarks with the medium constituents. Thus, the measurements of the R_{AA} and v_2 in this p_T region are particularly sensitive to quark diffusion and thermalisation with the medium, and to the hadronisation mechanisms.

The simultaneous description of R_{AA} and v_2 is challenging for the models and therefore the data have the potential to constrain the model ingredients and parameters. The global agreement between the measured R_{AA} and the theoretical models was evaluated by computing a χ^2/ndf , as done in refs. [36, 126]. The statistical and systematic uncertainties (treating separately the contributions correlated and uncorrelated among p_T intervals) were considered in the calculation together with the theoretical ones, when available. Since the upper p_T limit of the predictions is different for each model, the χ^2/ndf was computed in the $0 < p_T < 8 \text{ GeV}/c$ interval, which is common among all the models except for the LIDO predictions which start from $1.5 \text{ GeV}/c$. Therefore, the χ^2/ndf computation for LIDO was performed excluding the first two p_T intervals of the R_{AA} . This low- p_T range provides high sensitivity to charm-quark diffusion and hadronisation in the QGP. The χ^2/ndf values are reported in table 5. The large spread in the computed χ^2/ndf is not only due to the improved precision of the measurement, but also to the differences among the theoretical models. They do not only differ in terms of the interaction of charm quarks with the medium, as previously highlighted, but also in terms of the considered nuclear PDFs, the bulk evolution of the medium (i.e. ideal or viscous hydrodynamics), the charm hadronisation mechanism (i.e. fragmentation and/or recombination), and whether a hadronic phase is included or not. In particular, the charm-quark recombination mechanism is implemented with different approaches in the various models: most of the models use an instantaneous recombination based on the Wigner function formalism [127], while TAMU implements a resonance-recombination model [128], PHSD a dynamical coalescence via a Monte Carlo approach [125], and POWLANG an in-medium string formation approach [117]. The R_{AA} predictions are deeply influenced by these additional model ingredients, other than the transport properties of the medium. Therefore, a rather mild requirement on the data-to-model consistency, namely $\chi^2/\text{ndf} < 5$, was applied to select the models considered for the estimation of the heavy-quark spatial diffusion coefficient. With this criterion, the selected models are TAMU [76], MC@sHQ+EPOS2 [115], LIDO [124], LGR [121], and Catania [122, 123]. A similar analysis was performed for the elliptic and triangular flow [36]. In order to further constrain the description of heavy-quark transport in the medium and the spatial diffusion coefficient D_s , the results of the χ^2/ndf analysis for the R_{AA} model calculations were combined with those obtained for the elliptic and triangular flow in ref. [36]. Note that some theoretical predictions for the v_2 were updated after the publication of ref. [36], namely LBT [119, 120], LIDO [124], LGR [121], PHSD [125], and TAMU [76]. Therefore the χ^2/ndf of these predictions with respect to the measured v_2 and v_3 was re-computed. The outcome did not change significantly with respect to ref. [36], with the only exception of LIDO [124] for which the updated predictions provide a better

Model	χ^2/ndf		
	R_{AA}		global
	0–10%	30–50%	
Catania [122, 123]	94.9/15	48.9/15	143.8/30
DAB-MOD [116]	110.2/15	123.9/15	234.1/30
LBT [119, 120]	342.6/15	69.2/15	411.8/30
LIDO [124]	31.8/13	14.5/13	46.4/26
LGR [121]	4.7/15	4.5/15	9.2/30
MC@sHQ+EPOS2 [115]	31.8/15	24.8/15	56.6/30
PHSD [125]	103.2/15	191.4/15	294.7/30
POWLANG-HTL [117, 118]	331.0/15	137.6/15	468.6/30
TAMU [76]	16.7/15	13.5/15	30.2/30

Table 5. Summary of the χ^2/ndf values obtained in $0 < p_T < 8 \text{ GeV}/c$ for the different model predictions compared with the measured D-meson R_{AA} .

description of the data with respect to the old ones, resulting in a $\chi^2/\text{ndf} < 2$. Thus, the LIDO model is included among those providing a good description of v_2 and v_3 , while it was not considered in ref. [36]. The models that describe reasonably well both R_{AA} (with $\chi^2/\text{ndf} < 5$) and v_2 and v_3 (with $\chi^2/\text{ndf} < 2$) are TAMU [76], MC@sHQ+EPOS2 [115], LIDO [124], LGR [121], and Catania [122, 123]. These models use a value of heavy-quark spatial diffusion coefficient in the range $1.5 < 2\pi D_s T_c < 4.5$ at the pseudocritical temperature $T_{pc} = 155 \text{ MeV}$ [3]. According to lQCD calculations the $2\pi D_s T_c$ lies between 2 and 6 [129–131], and these results are also in agreement with the D_s range estimated from the v_2 measurements by ALICE (1.5–7 from ref. [36]), STAR (2–12 from ref. [132]), and PHENIX (value of ~ 3 from ref. [133]). The inclusion of the R_{AA} in the χ^2/ndf improved the constraint on the spatial diffusion coefficient with respect to the range reported in ref. [36]. It is however important to remark that this coefficient is not the only key parameter of the models describing the heavy-quark transport in an expanding medium, but there are other ingredients (such as the parameters of the underlying hydrodynamics, the modelling of the hadronisation, the description of the interactions in the hadronic phase, amongst others, see e.g. refs. [17, 134]) playing an important role.

A deeper insight on the impact of the different implementations of the charm-quark interaction and hadronisation in the QGP can be obtained from figures 12 and 13. In figure 12 the R_{AA} and the v_2 , measured in the 0–10% and 30–50% centrality classes, respectively, are compared with two different implementations of the LIDO [124] and LGR [121] models, in order to assess the role of elastic and radiative processes in the charm-quark interactions with medium constituents. In particular, the first implementation is the standard one including both elastic and radiative processes, while the second prediction was obtained by switching off the radiative processes. At low p_T (i.e. $\lesssim 3\text{--}4 \text{ GeV}/c$), the collisional processes

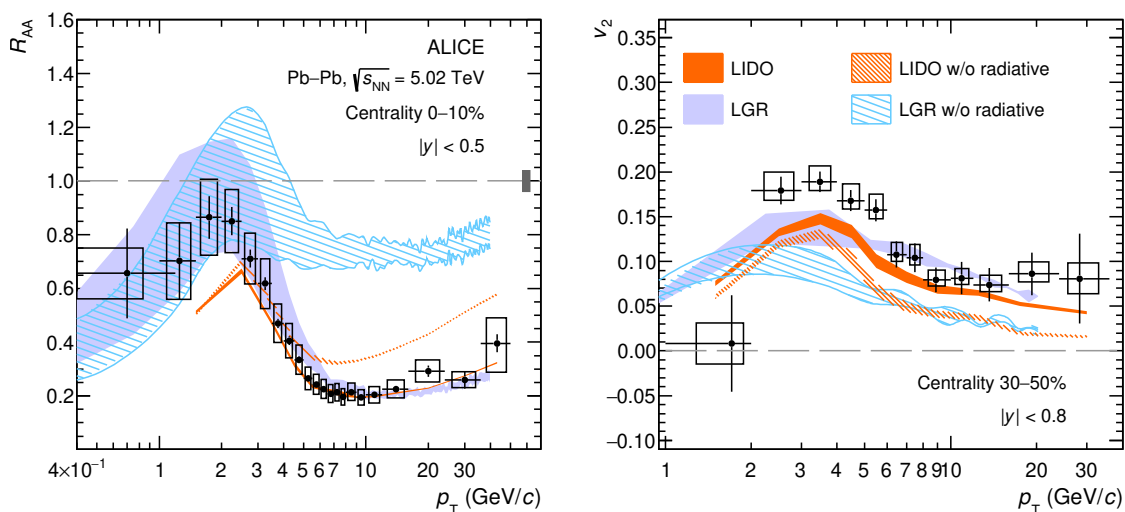


Figure 12. Prompt D-meson R_{AA} in the 0–10% centrality class (left panel) and v_2 in the 30–50% centrality class (right panel) compared with the LIDO [124] and LGR [121] predictions obtained with and without including radiative processes in the charm-quark interactions with the medium.

are expected to be the dominant interaction and this is confirmed by the similarity of the predictions for prompt D-meson R_{AA} and v_2 with (full band) and without (striped band) radiative processes. This is further supported by the agreement, in the same p_T range, between the experimental data and other theoretical models which implement only elastic processes, like TAMU [76], PHSD [125], and POWLANG-HTL [117, 118]. Radiative processes, instead, become dominant at intermediate and high p_T . This can be observed in figure 12 where the predictions without these processes overestimate (underestimate) the measured R_{AA} (v_2) for $p_T \gtrsim 5$ –6 GeV/c.

Similarly, figure 13 shows the comparison of the experimental data for R_{AA} and v_2 with two different versions of the PHSD [125], POWLANG-HTL [117, 118], and DABMOD [116] models, in order to investigate the effects of the hadronisation mechanism, and in particular the role of recombination. This plays a key role in the predictions for R_{AA} and v_2 , since the relation between the momentum of the charm hadron and that of the parent charm quark is different for the fragmentation process, where the hadron inherits a fraction of the initial quark momentum, and the recombination, where the D-meson p_T is larger than the one of the charm quark and the charm hadron inherits also the collective flow of the light quark. In figure 13, the predictions are provided with (solid line) and without (dashed line) the implementation of the recombination process in the hadronisation mechanism. The calculations performed including only the fragmentation process underestimate both the R_{AA} and v_2 , while the inclusion of the recombination of charm quarks with light quarks pushes the predictions closer to the experimental data. This indicates that recombination with light quarks from the medium plays a relevant role in the hadronisation of charm quarks at the QGP phase boundary.

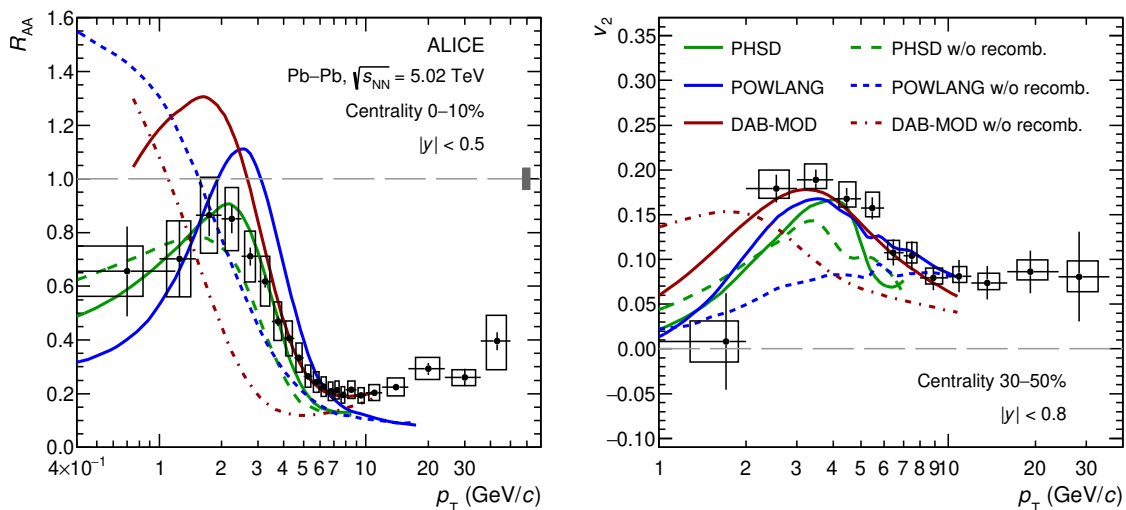


Figure 13. Prompt D-meson R_{AA} in the 0–10% centrality class (left panel) and v_2 in the 30–50% centrality class (right panel) compared with the PHSD [125], POWLANG [117, 118], and DAB-MOD [116] predictions obtained with and without including hadronisation via recombination.

6 Conclusions

We have reported the measurement of the p_T -differential production yields of prompt D^0 , D^+ , and D^{*+} mesons and charge conjugates at midrapidity ($|y| < 0.5$) in central and semicentral Pb–Pb collisions at a centre-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV. The results were obtained with the data sample collected at the end of 2018 with the ALICE detector. The p_T -spectra were measured in finer p_T intervals with respect to the previous measurements at the same centre-of-mass energy [30], providing a more precise description of the p_T distribution. The large data sample allowed for the first measurement of the D^0 -meson yield down to $p_T = 0$ in Pb–Pb collisions at the LHC. This enabled the determination of the p_T -integrated production yields of prompt D^0 , which is obtained in a model independent way, of prompt D^+ and D^{*+} , and the comparison with predictions from the statistical hadronisation model [66, 67]. The average R_{AA} of the D^0 , D^+ , and D^{*+} mesons reaches a maximum suppression value of 5.5 (i.e. $R_{AA} \sim 0.18$) and 2.7 (i.e. $R_{AA} \sim 0.4$) in the 0–10% and 30–50% centrality classes, respectively, at $p_T = 6$ –8 GeV/c. This suppression becomes less pronounced in peripheral collisions with a minimum value of 0.7–0.8, as observed in the 60–80% centrality class in ref. [30], and it is due to final-state effects, since it is not observed in minimum bias p–Pb collisions [33]. However, it was pointed out in refs. [135, 136] that event selection and geometry biases can cause an apparent suppression of R_{AA} , especially in peripheral collisions, even in the absence of nuclear effect. The R_{AA} of prompt D mesons at $p_T > 8$ GeV/c is well described by models which include both collisional and radiative energy loss processes. In addition, the p_T -integrated R_{AA} of prompt D^0 mesons was obtained and compared with the R_{pPb} measured in p–Pb collisions at the same centre-of-mass energy [33]. The results lie on the upper edge of the calculations which consider nuclear modification of the PDFs.

In central collisions, the p_T -differential R_{AA} of prompt D mesons is compatible within uncertainties with that of charged particles for $p_T \gtrsim 8 \text{ GeV}/c$ and prompt J/ψ mesons for $p_T \gtrsim 10 \text{ GeV}/c$, while an ordering in R_{AA} is observed at lower p_T . The latter is due to the interplay of different effects, such as the diffusion of charm quarks in the medium possibly leading to their thermalisation in the QGP and the hadronisation via recombination with light quarks from the medium, which along with energy loss contribute to the modification of the p_T -distribution of the hadrons. The comparison of the R_{AA} of prompt D mesons and non-prompt J/ψ for $p_T > 6 \text{ GeV}/c$ together with model calculations supports the predictions of quark-mass dependent energy loss. At low and intermediate p_T ($\lesssim 6\text{--}8 \text{ GeV}/c$), the R_{AA} is well described by different transport model calculations for the two centrality classes. However, most of them fail in describing simultaneously both R_{AA} and v_2 in central and semicentral Pb–Pb collisions. By considering the few models that are in fair agreement with both observables, the heavy-quark spatial diffusion coefficient was estimated to be in the range $1.5 < 2\pi D_s T_c < 4.5$ at the pseudocritical temperature $T_{pc} = 155 \text{ MeV}$, which is a narrower interval as compared to estimations based on previous D-meson measurements at LHC energies [36, 126]. Therefore, the simultaneous comparison of the data with the theoretical predictions for these observables allowed for more stringent constraints to the heavy-quark spatial diffusion coefficient and for significant progress in the understanding of the interaction processes and the hadronisation mechanisms of charm quarks in the high-density QCD medium.

Acknowledgments

The ALICE collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Ministry of Education of China (MOEC), Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the VILLUM FONDEN and Danish National Research Foun-

dation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l’Energie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; Indonesian Institute of Science, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan Society for the Promotion of Science (JSPS) KAKENHI and Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Applied Science (IIST), Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Académico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Education and Science, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics and Ministry of Research and Innovation and Institute of Atomic Physics, Romania; Joint Institute for Nuclear Research (JINR), Ministry of Education and Science of the Russian Federation, National Research Centre Kurchatov Institute, Russian Science Foundation and Russian Foundation for Basic Research, Russia; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSDTA) and Office of the Higher Education Commission under NRU project of Thailand, Thailand; Turkish Energy, Nuclear and Mineral Research Agency (TENMAK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), U.K.; National Science Foundation of the U.S.A. (NSF) and U.S. Department of Energy, Office of Nuclear Physics (DOE NP), U.S.A. .

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References

- [1] J.C. Collins and M.J. Perry, *Superdense Matter: Neutrons Or Asymptotically Free Quarks?*, *Phys. Rev. Lett.* **34** (1975) 1353 [[INSPIRE](#)].
- [2] F. Karsch, *Lattice simulations of the thermodynamics of strongly interacting elementary particles and the exploration of new phases of matter in relativistic heavy ion collisions*, *J. Phys. Conf. Ser.* **46** (2006) 122 [[hep-lat/0608003](#)] [[INSPIRE](#)].
- [3] WUPPERTAL-BUDAPEST collaboration, *Is there still any T_c mystery in lattice QCD? Results with physical masses in the continuum limit III*, *JHEP* **09** (2010) 073 [[arXiv:1005.3508](#)] [[INSPIRE](#)].
- [4] S. Borsányi, Z. Fodor, C. Höbbling, S.D. Katz, S. Krieg and K.K. Szabo, *Full result for the QCD equation of state with $2 + 1$ flavors*, *Phys. Lett. B* **730** (2014) 99 [[arXiv:1309.5258](#)] [[INSPIRE](#)].
- [5] A. Bazavov et al., *The chiral and deconfinement aspects of the QCD transition*, *Phys. Rev. D* **85** (2012) 054503 [[arXiv:1111.1710](#)] [[INSPIRE](#)].
- [6] W. Busza, K. Rajagopal and W. van der Schee, *Heavy Ion Collisions: The Big Picture, and the Big Questions*, *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 339 [[arXiv:1802.04801](#)] [[INSPIRE](#)].
- [7] ALICE collaboration, *Two-pion Bose-Einstein correlations in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *Phys. Lett. B* **696** (2011) 328 [[arXiv:1012.4035](#)] [[INSPIRE](#)].
- [8] A. Andronic et al., *Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions*, *Eur. Phys. J. C* **76** (2016) 107 [[arXiv:1506.03981](#)] [[INSPIRE](#)].
- [9] F.-M. Liu and S.-X. Liu, *Quark-gluon plasma formation time and direct photons from heavy ion collisions*, *Phys. Rev. C* **89** (2014) 034906 [[arXiv:1212.6587](#)] [[INSPIRE](#)].
- [10] M.H. Thoma and M. Gyulassy, *Quark Damping and Energy Loss in the High Temperature QCD*, *Nucl. Phys. B* **351** (1991) 491 [[INSPIRE](#)].
- [11] E. Braaten and M.H. Thoma, *Energy loss of a heavy fermion in a hot plasma*, *Phys. Rev. D* **44** (1991) 1298 [[INSPIRE](#)].
- [12] E. Braaten and M.H. Thoma, *Energy loss of a heavy quark in the quark-gluon plasma*, *Phys. Rev. D* **44** (1991) R2625(R) [[INSPIRE](#)].
- [13] R. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigne and D. Schiff, *Radiative energy loss and p_T broadening of high-energy partons in nuclei*, *Nucl. Phys. B* **484** (1997) 265 [[hep-ph/9608322](#)] [[INSPIRE](#)].
- [14] M. Gyulassy and M. Plumer, *Jet Quenching in Dense Matter*, *Phys. Lett. B* **243** (1990) 432 [[INSPIRE](#)].
- [15] S. Batsouli, S. Kelly, M. Gyulassy and J.L. Nagle, *Does the charm flow at RHIC?*, *Phys. Lett. B* **557** (2003) 26 [[nucl-th/0212068](#)] [[INSPIRE](#)].
- [16] V. Greco, C.M. Ko and R. Rapp, *Quark coalescence for charmed mesons in ultrarelativistic heavy ion collisions*, *Phys. Lett. B* **595** (2004) 202 [[nucl-th/0312100](#)] [[INSPIRE](#)].
- [17] A. Beraudo et al., *Extraction of Heavy-Flavor Transport Coefficients in QCD Matter*, *Nucl. Phys. A* **979** (2018) 21 [[arXiv:1803.03824](#)] [[INSPIRE](#)].

- [18] F. Prino and R. Rapp, *Open Heavy Flavor in QCD Matter and in Nuclear Collisions*, *J. Phys. G* **43** (2016) 093002 [[arXiv:1603.00529](#)] [[INSPIRE](#)].
- [19] M. Djordjevic, *Heavy flavor puzzle at LHC: a serendipitous interplay of jet suppression and fragmentation*, *Phys. Rev. Lett.* **112** (2014) 042302 [[arXiv:1307.4702](#)] [[INSPIRE](#)].
- [20] Y.L. Dokshitzer and D.E. Kharzeev, *Heavy quark colorimetry of QCD matter*, *Phys. Lett. B* **519** (2001) 199 [[hep-ph/0106202](#)] [[INSPIRE](#)].
- [21] N. Armesto, C.A. Salgado and U.A. Wiedemann, *Medium induced gluon radiation off massive quarks fills the dead cone*, *Phys. Rev. D* **69** (2004) 114003 [[hep-ph/0312106](#)] [[INSPIRE](#)].
- [22] M. Djordjevic and M. Gyulassy, *Heavy quark radiative energy loss in QCD matter*, *Nucl. Phys. A* **733** (2004) 265 [[nucl-th/0310076](#)] [[INSPIRE](#)].
- [23] B.-W. Zhang, E. Wang and X.-N. Wang, *Heavy quark energy loss in nuclear medium*, *Phys. Rev. Lett.* **93** (2004) 072301 [[nucl-th/0309040](#)] [[INSPIRE](#)].
- [24] H. van Hees, V. Greco and R. Rapp, *Heavy-quark probes of the quark-gluon plasma at RHIC*, *Phys. Rev. C* **73** (2006) 034913 [[nucl-th/0508055](#)] [[INSPIRE](#)].
- [25] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, *Statistical hadronization of charm in heavy ion collisions at SPS, RHIC and LHC*, *Phys. Lett. B* **571** (2003) 36 [[nucl-th/0303036](#)] [[INSPIRE](#)].
- [26] R.J. Glauber and G. Matthiae, *High-energy scattering of protons by nuclei*, *Nucl. Phys. B* **21** (1970) 135 [[INSPIRE](#)].
- [27] M.L. Miller, K. Reygers, S.J. Sanders and P. Steinberg, *Glauber modeling in high energy nuclear collisions*, *Ann. Rev. Nucl. Part. Sci.* **57** (2007) 205 [[nucl-ex/0701025](#)] [[INSPIRE](#)].
- [28] C. Loizides, J. Nagle and P. Steinberg, *Improved version of the PHOBOS Glauber Monte Carlo*, *SoftwareX* **1–2** (2015) 13 [[arXiv:1408.2549](#)] [[INSPIRE](#)].
- [29] ALICE collaboration, *Transverse momentum dependence of D-meson production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *JHEP* **03** (2016) 081 [[arXiv:1509.06888](#)] [[INSPIRE](#)].
- [30] ALICE collaboration, *Measurement of D^0 , D^+ , D^{*+} and D_s^+ production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *JHEP* **10** (2018) 174 [[arXiv:1804.09083](#)] [[INSPIRE](#)].
- [31] CMS collaboration, *Nuclear modification factor of D^0 mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Lett. B* **782** (2018) 474 [[arXiv:1708.04962](#)] [[INSPIRE](#)].
- [32] STAR collaboration, *Centrality and transverse momentum dependence of D^0 -meson production at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys. Rev. C* **99** (2019) 034908 [[arXiv:1812.10224](#)] [[INSPIRE](#)].
- [33] ALICE collaboration, *Measurement of prompt D^0 , D^+ , D^{*+} , and D_s^+ production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *JHEP* **12** (2019) 092 [[arXiv:1906.03425](#)] [[INSPIRE](#)].
- [34] S. Voloshin and Y. Zhang, *Flow study in relativistic nuclear collisions by Fourier expansion of Azimuthal particle distributions*, *Z. Phys. C* **70** (1996) 665 [[hep-ph/9407282](#)] [[INSPIRE](#)].
- [35] A.M. Poskanzer and S.A. Voloshin, *Methods for analyzing anisotropic flow in relativistic nuclear collisions*, *Phys. Rev. C* **58** (1998) 1671 [[nucl-ex/9805001](#)] [[INSPIRE](#)].
- [36] ALICE collaboration, *Transverse-momentum and event-shape dependence of D-meson flow harmonics in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Lett. B* **813** (2021) 136054 [[arXiv:2005.11131](#)] [[INSPIRE](#)].

- [37] ALICE collaboration, *Measurement of D^0 , D^+ , D^{*+} and D_s^+ production in pp collisions at $\sqrt{s} = 5.02$ TeV with ALICE*, *Eur. Phys. J. C* **79** (2019) 388 [[arXiv:1901.07979](#)] [[INSPIRE](#)].
- [38] G.D. Moore and D. Teaney, *How much do heavy quarks thermalize in a heavy ion collision?*, *Phys. Rev. C* **71** (2005) 064904 [[hep-ph/0412346](#)] [[INSPIRE](#)].
- [39] ALICE collaboration, *The ALICE experiment at the CERN LHC*, 2008 *JINST* **3** S08002 [[INSPIRE](#)].
- [40] ALICE collaboration, *Performance of the ALICE Experiment at the CERN LHC*, *Int. J. Mod. Phys. A* **29** (2014) 1430044 [[arXiv:1402.4476](#)] [[INSPIRE](#)].
- [41] ALICE collaboration, *Alignment of the ALICE Inner Tracking System with cosmic-ray tracks*, 2010 *JINST* **5** P03003 [[arXiv:1001.0502](#)] [[INSPIRE](#)].
- [42] J. Alme et al., *The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events*, *Nucl. Instrum. Meth. A* **622** (2010) 316 [[arXiv:1001.1950](#)] [[INSPIRE](#)].
- [43] A. Akindinov et al., *Performance of the ALICE Time-Of-Flight detector at the LHC*, *Eur. Phys. J. Plus* **128** (2013) 44 [[INSPIRE](#)].
- [44] ALICE collaboration, *Performance of the ALICE VZERO system*, 2013 *JINST* **8** P10016 [[arXiv:1306.3130](#)] [[INSPIRE](#)].
- [45] R. Arnaldi et al., *The Zero degree calorimeters for the ALICE experiment*, *Nucl. Instrum. Meth. A* **581** (2007) 397 [Erratum *ibid.* **604** (2009) 765] [[INSPIRE](#)].
- [46] ALICE collaboration, *Centrality dependence of the charged-particle multiplicity density at midrapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Rev. Lett.* **116** (2016) 222302 [[arXiv:1512.06104](#)] [[INSPIRE](#)].
- [47] ALICE collaboration, *Centrality determination in heavy ion collisions*, ALICE-PUBLIC-2018-011 (2018).
- [48] C. Loizides, J. Kamin and D. d’Enterria, *Improved Monte Carlo Glauber predictions at present and future nuclear colliders*, *Phys. Rev. C* **97** (2018) 054910 [Erratum *ibid.* **99** (2019) 019901] [[arXiv:1710.07098](#)] [[INSPIRE](#)].
- [49] PARTICLE DATA collaboration, *Review of Particle Physics*, *Prog. Theor. Exp. Phys.* **2020** (2020) 083C01 [[INSPIRE](#)].
- [50] ALICE collaboration, *Measurement of D_s^+ production and nuclear modification factor in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *JHEP* **03** (2016) 082 [[arXiv:1509.07287](#)] [[INSPIRE](#)].
- [51] ALICE collaboration, *Measurement of D -meson production at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV*, *Eur. Phys. J. C* **77** (2017) 550 [[arXiv:1702.00766](#)] [[INSPIRE](#)].
- [52] ALICE collaboration, *D -meson production in p –Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. C* **94** (2016) 054908 [[arXiv:1605.07569](#)] [[INSPIRE](#)].
- [53] M. Cacciari, M. Greco and P. Nason, *The p_T spectrum in heavy flavor hadroproduction*, *JHEP* **05** (1998) 007 [[hep-ph/9803400](#)] [[INSPIRE](#)].
- [54] M. Cacciari, S. Frixione and P. Nason, *The p_T spectrum in heavy flavor photoproduction*, *JHEP* **03** (2001) 006 [[hep-ph/0102134](#)] [[INSPIRE](#)].
- [55] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [[arXiv:1410.3012](#)] [[INSPIRE](#)].

- [56] R. Brun et al., *GEANT: Detector Description and Simulation Tool*, in *CERN Program Library W5013*, CERN, Geneva Switzerland (1993).
- [57] X.-N. Wang and M. Gyulassy, *HIJING: A Monte Carlo model for multiple jet production in pp, pA and AA collisions*, *Phys. Rev. D* **44** (1991) 3501 [[INSPIRE](#)].
- [58] P. Skands, S. Carrazza and J. Rojo, *Tuning PYTHIA 8.1: the Monash 2013 Tune*, *Eur. Phys. J. C* **74** (2014) 3024 [[arXiv:1404.5630](#)] [[INSPIRE](#)].
- [59] ALICE collaboration, *Suppression of high transverse momentum D mesons in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *JHEP* **09** (2012) 112 [[arXiv:1203.2160](#)] [[INSPIRE](#)].
- [60] M. Cacciari, S. Frixione, N. Houdeau, M.L. Mangano, P. Nason and G. Ridolfi, *Theoretical predictions for charm and bottom production at the LHC*, *JHEP* **10** (2012) 137 [[arXiv:1205.6344](#)] [[INSPIRE](#)].
- [61] CMS collaboration, *Measurement of prompt and nonprompt charmonium suppression in PbPb collisions at 5.02 TeV*, *Eur. Phys. J. C* **78** (2018) 509 [[arXiv:1712.08959](#)] [[INSPIRE](#)].
- [62] ATLAS collaboration, *Prompt and non-prompt J/ψ and $\psi(2S)$ suppression at high transverse momentum in 5.02 TeV Pb+Pb collisions with the ATLAS experiment*, *Eur. Phys. J. C* **78** (2018) 762 [[arXiv:1805.04077](#)] [[INSPIRE](#)].
- [63] M. Djordjevic and M. Djordjevic, *Predictions of heavy-flavor suppression at 5.1 TeV Pb+Pb collisions at the CERN Large Hadron Collider*, *Phys. Rev. C* **92** (2015) 024918 [[arXiv:1505.04316](#)] [[INSPIRE](#)].
- [64] M. He, R.J. Fries and R. Rapp, *Heavy Flavor at the Large Hadron Collider in a Strong Coupling Approach*, *Phys. Lett. B* **735** (2014) 445 [[arXiv:1401.3817](#)] [[INSPIRE](#)].
- [65] ALICE collaboration, *Measurement of beauty and charm production in pp collisions at $\sqrt{s} = 5.02$ TeV via non-prompt and prompt D mesons*, *JHEP* **05** (2021) 220 [[arXiv:2102.13601](#)] [[INSPIRE](#)].
- [66] A. Andronic, P. Braun-Munzinger, M.K. Köhler, K. Redlich and J. Stachel, *Transverse momentum distributions of charmonium states with the statistical hadronization model*, *Phys. Lett. B* **797** (2019) 134836 [[arXiv:1901.09200](#)] [[INSPIRE](#)].
- [67] A. Andronic et al., *The multiple-charm hierarchy in the statistical hadronization model*, *JHEP* **07** (2021) 035 [[arXiv:2104.12754](#)] [[INSPIRE](#)].
- [68] A. Mazeliauskas, S. Floerchinger, E. Grossi and D. Teaney, *Fast resonance decays in nuclear collisions*, *Eur. Phys. J. C* **79** (2019) 284 [[arXiv:1809.11049](#)] [[INSPIRE](#)].
- [69] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, *Decoding the phase structure of QCD via particle production at high energy*, *Nature* **561** (2018) 321 [[arXiv:1710.09425](#)] [[INSPIRE](#)].
- [70] ALICE collaboration, *Charm-quark fragmentation fractions and production cross section at midrapidity in pp collisions at the LHC*, *Phys. Rev. D* **105** (2022) L011103 [[arXiv:2105.06335](#)] [[INSPIRE](#)].
- [71] I. Kuznetsova and J. Rafelski, *Heavy flavor hadrons in statistical hadronization of strangeness-rich QGP*, *Eur. Phys. J. C* **51** (2007) 113 [[hep-ph/0607203](#)] [[INSPIRE](#)].
- [72] P.R. Sorensen and X. Dong, *Suppression of non-photonics electrons from enhancement of charm baryons in heavy ion collisions*, *Phys. Rev. C* **74** (2006) 024902 [[nucl-th/0512042](#)] [[INSPIRE](#)].

- [73] S.H. Lee, K. Ohnishi, S. Yasui, I.-K. Yoo and C.-M. Ko, Λ_c enhancement from strongly coupled quark-gluon plasma, *Phys. Rev. Lett.* **100** (2008) 222301 [[arXiv:0709.3637](#)] [[INSPIRE](#)].
- [74] Y. Oh, C.M. Ko, S.H. Lee and S. Yasui, Heavy baryon/meson ratios in relativistic heavy ion collisions, *Phys. Rev. C* **79** (2009) 044905 [[arXiv:0901.1382](#)] [[INSPIRE](#)].
- [75] M. He, R.J. Fries and R. Rapp, D_s -Meson as Quantitative Probe of Diffusion and Hadronization in Nuclear Collisions, *Phys. Rev. Lett.* **110** (2013) 112301 [[arXiv:1204.4442](#)] [[INSPIRE](#)].
- [76] M. He and R. Rapp, Hadronization and Charm-Hadron Ratios in Heavy-Ion Collisions, *Phys. Rev. Lett.* **124** (2020) 042301 [[arXiv:1905.09216](#)] [[INSPIRE](#)].
- [77] J.-P. Lansberg and H.-S. Shao, Towards an automated tool to evaluate the impact of the nuclear modification of the gluon density on quarkonium, D and B meson production in proton-nucleus collisions, *Eur. Phys. J. C* **77** (2017) 1 [[arXiv:1610.05382](#)] [[INSPIRE](#)].
- [78] A. Kusina, J.-P. Lansberg, I. Schienbein and H.-S. Shao, Gluon Shadowing in Heavy-Flavor Production at the LHC, *Phys. Rev. Lett.* **121** (2018) 052004 [[arXiv:1712.07024](#)] [[INSPIRE](#)].
- [79] A. Kusina, J.-P. Lansberg, I. Schienbein and H.-S. Shao, Reweighted nuclear PDFs using heavy-flavor production data at the LHC, *Phys. Rev. D* **104** (2021) 014010 [[arXiv:2012.11462](#)] [[INSPIRE](#)].
- [80] H.-S. Shao, HELAC-Onia: An automatic matrix element generator for heavy quarkonium physics, *Comput. Phys. Commun.* **184** (2013) 2562 [[arXiv:1212.5293](#)] [[INSPIRE](#)].
- [81] H.-S. Shao, HELAC-Onia 2.0: an upgraded matrix-element and event generator for heavy quarkonium physics, *Comput. Phys. Commun.* **198** (2016) 238 [[arXiv:1507.03435](#)] [[INSPIRE](#)].
- [82] K.J. Eskola, P. Paakkinen, H. Paukkunen and C.A. Salgado, EPPS16: Nuclear parton distributions with LHC data, *Eur. Phys. J. C* **77** (2017) 163 [[arXiv:1612.05741](#)] [[INSPIRE](#)].
- [83] I. Helenius and H. Paukkunen, Revisiting the D -meson hadroproduction in general-mass variable flavour number scheme, *JHEP* **05** (2018) 196 [[arXiv:1804.03557](#)] [[INSPIRE](#)].
- [84] ALICE collaboration, Production of charged pions, kaons, and (anti-)protons in Pb–Pb and inelastic pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Phys. Rev. C* **101** (2020) 044907 [[arXiv:1910.07678](#)] [[INSPIRE](#)].
- [85] ALICE collaboration, Transverse momentum spectra and nuclear modification factors of charged particles in pp , p –Pb and Pb–Pb collisions at the LHC, *JHEP* **11** (2018) 013 [[arXiv:1802.09145](#)] [[INSPIRE](#)].
- [86] ALICE collaboration, Production of charged pions, kaons and protons at large transverse momenta in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, *Phys. Lett. B* **736** (2014) 196 [[arXiv:1401.1250](#)] [[INSPIRE](#)].
- [87] ALICE collaboration, Centrality and transverse momentum dependence of inclusive J/ψ production at midrapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Phys. Lett. B* **805** (2020) 135434 [[arXiv:1910.14404](#)] [[INSPIRE](#)].
- [88] ALICE collaboration, Anisotropic flow of identified particles in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *JHEP* **09** (2018) 006 [[arXiv:1805.04390](#)] [[INSPIRE](#)].

- [89] J. Xu, J. Liao and M. Gyulassy, *Consistency of Perfect Fluidity and Jet Quenching in semi-Quark-Gluon Monopole Plasmas*, *Chin. Phys. Lett.* **32** (2015) 092501 [[arXiv:1411.3673](#)] [[INSPIRE](#)].
- [90] J. Xu, J. Liao and M. Gyulassy, *Bridging Soft-Hard Transport Properties of Quark-Gluon Plasmas with CUJET3.0*, *JHEP* **02** (2016) 169 [[arXiv:1508.00552](#)] [[INSPIRE](#)].
- [91] S. Shi, J. Liao and M. Gyulassy, *Global constraints from RHIC and LHC on transport properties of QCD fluids in CUJET/CIBJET framework*, *Chin. Phys. C* **43** (2019) 044101 [[arXiv:1808.05461](#)] [[INSPIRE](#)].
- [92] S. Stojku, B. Ilic, M. Djordjevic and M. Djordjevic, *Extracting the temperature dependence in high- $p_{\perp}$ particle energy loss*, *Phys. Rev. C* **103** (2021) 024908 [[arXiv:2007.07851](#)] [[INSPIRE](#)].
- [93] D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, *DREENA-B framework: first predictions of R_{AA} and v_2 within dynamical energy loss formalism in evolving QCD medium*, *Phys. Lett. B* **791** (2019) 236 [[arXiv:1805.04786](#)] [[INSPIRE](#)].
- [94] D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, *DREENA-C framework: joint R_{AA} and v_2 predictions and implications to QGP tomography*, *J. Phys. G* **46** (2019) 085101 [[arXiv:1805.03494](#)] [[INSPIRE](#)].
- [95] Z.-B. Kang, F. Ringer and I. Vitev, *Effective field theory approach to open heavy flavor production in heavy-ion collisions*, *JHEP* **03** (2017) 146 [[arXiv:1610.02043](#)] [[INSPIRE](#)].
- [96] M. Djordjevic, *Theoretical formalism of radiative jet energy loss in a finite size dynamical QCD medium*, *Phys. Rev. C* **80** (2009) 064909 [[arXiv:0903.4591](#)] [[INSPIRE](#)].
- [97] M. Djordjevic and U.W. Heinz, *Radiative energy loss in a finite dynamical QCD medium*, *Phys. Rev. Lett.* **101** (2008) 022302 [[arXiv:0802.1230](#)] [[INSPIRE](#)].
- [98] M. Djordjevic, *Collisional energy loss in a finite size QCD matter*, *Phys. Rev. C* **74** (2006) 064907 [[nucl-th/0603066](#)] [[INSPIRE](#)].
- [99] M. Gyulassy, P. Levai and I. Vitev, *NonAbelian energy loss at finite opacity*, *Phys. Rev. Lett.* **85** (2000) 5535 [[nucl-th/0005032](#)] [[INSPIRE](#)].
- [100] M. Gyulassy, P. Levai and I. Vitev, *Reaction operator approach to nonAbelian energy loss*, *Nucl. Phys. B* **594** (2001) 371 [[nucl-th/0006010](#)] [[INSPIRE](#)].
- [101] C.W. Bauer, S. Fleming, D. Pirjol and I.W. Stewart, *An Effective field theory for collinear and soft gluons: Heavy to light decays*, *Phys. Rev. D* **63** (2001) 114020 [[hep-ph/0011336](#)] [[INSPIRE](#)].
- [102] C.W. Bauer, D. Pirjol and I.W. Stewart, *Soft collinear factorization in effective field theory*, *Phys. Rev. D* **65** (2002) 054022 [[hep-ph/0109045](#)] [[INSPIRE](#)].
- [103] A. Idilbi and A. Majumder, *Extending Soft-Collinear-Effective-Theory to describe hard jets in dense QCD media*, *Phys. Rev. D* **80** (2009) 054022 [[arXiv:0808.1087](#)] [[INSPIRE](#)].
- [104] G. Ovanesyan and I. Vitev, *An effective theory for jet propagation in dense QCD matter: jet broadening and medium-induced bremsstrahlung*, *JHEP* **06** (2011) 080 [[arXiv:1103.1074](#)] [[INSPIRE](#)].
- [105] M. Djordjevic, B. Blagojevic and L. Zivkovic, *Mass tomography at different momentum ranges in quark-gluon plasma*, *Phys. Rev. C* **94** (2016) 044908 [[arXiv:1601.07852](#)] [[INSPIRE](#)].

- [106] LHCb collaboration, *Study of J/ψ Production in Jets*, *Phys. Rev. Lett.* **118** (2017) 192001 [[arXiv:1701.05116](#)] [[INSPIRE](#)].
- [107] R. Bain, L. Dai, A. Leibovich, Y. Makris and T. Mehen, *NRQCD Confronts LHCb Data on Quarkonium Production within Jets*, *Phys. Rev. Lett.* **119** (2017) 032002 [[arXiv:1702.05525](#)] [[INSPIRE](#)].
- [108] M. Spusta, *On similarity of jet quenching and charmonia suppression*, *Phys. Lett. B* **767** (2017) 10 [[arXiv:1606.00903](#)] [[INSPIRE](#)].
- [109] F. Arleo, *Quenching of Hadron Spectra in Heavy Ion Collisions at the LHC*, *Phys. Rev. Lett.* **119** (2017) 062302 [[arXiv:1703.10852](#)] [[INSPIRE](#)].
- [110] ALICE collaboration, *Differential studies of inclusive J/ψ and $\psi(2S)$ production at forward rapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *JHEP* **05** (2016) 179 [[arXiv:1506.08804](#)] [[INSPIRE](#)].
- [111] K. Zhou, N. Xu, Z. Xu and P. Zhuang, *Medium effects on charmonium production at ultrarelativistic energies available at the CERN Large Hadron Collider*, *Phys. Rev. C* **89** (2014) 054911 [[arXiv:1401.5845](#)] [[INSPIRE](#)].
- [112] X. Du and R. Rapp, *Sequential Regeneration of Charmonia in Heavy-Ion Collisions*, *Nucl. Phys. A* **943** (2015) 147 [[arXiv:1504.00670](#)] [[INSPIRE](#)].
- [113] M. He, R.J. Fries and R. Rapp, *Heavy-Quark Diffusion and Hadronization in Quark-Gluon Plasma*, *Phys. Rev. C* **86** (2012) 014903 [[arXiv:1106.6006](#)] [[INSPIRE](#)].
- [114] S. Cao et al., *Charmed hadron chemistry in relativistic heavy-ion collisions*, *Phys. Lett. B* **807** (2020) 135561 [[arXiv:1911.00456](#)] [[INSPIRE](#)].
- [115] M. Nahrgang, J. Aichelin, P.B. Gossiaux and K. Werner, *Influence of hadronic bound states above T_c on heavy-quark observables in Pb+Pb collisions at the CERN Large Hadron Collider*, *Phys. Rev. C* **89** (2014) 014905 [[arXiv:1305.6544](#)] [[INSPIRE](#)].
- [116] R. Katz, C.A.G. Prado, J. Noronha-Hostler, J. Noronha and A.A.P. Suaide, *Sensitivity study with a D and B mesons modular simulation code of heavy flavor RAA and azimuthal anisotropies based on beam energy, initial conditions, hadronization, and suppression mechanisms*, *Phys. Rev. C* **102** (2020) 024906 [[arXiv:1906.10768](#)] [[INSPIRE](#)].
- [117] A. Beraudo, A. De Pace, M. Monteno, M. Nardi and F. Prino, *Heavy flavors in heavy-ion collisions: quenching, flow and correlations*, *Eur. Phys. J. C* **75** (2015) 121 [[arXiv:1410.6082](#)] [[INSPIRE](#)].
- [118] A. Beraudo, A. De Pace, M. Monteno, M. Nardi and F. Prino, *Development of heavy-flavour flow-harmonics in high-energy nuclear collisions*, *JHEP* **02** (2018) 043 [[arXiv:1712.00588](#)] [[INSPIRE](#)].
- [119] S. Cao, T. Luo, G.-Y. Qin and X.-N. Wang, *Linearized Boltzmann transport model for jet propagation in the quark-gluon plasma: Heavy quark evolution*, *Phys. Rev. C* **94** (2016) 014909 [[arXiv:1605.06447](#)] [[INSPIRE](#)].
- [120] S. Cao, T. Luo, G.-Y. Qin and X.-N. Wang, *Heavy and light flavor jet quenching at RHIC and LHC energies*, *Phys. Lett. B* **777** (2018) 255 [[arXiv:1703.00822](#)] [[INSPIRE](#)].
- [121] S. Li and J. Liao, *Data-driven extraction of heavy quark diffusion in quark-gluon plasma*, *Eur. Phys. J. C* **80** (2020) 671 [[arXiv:1912.08965](#)] [[INSPIRE](#)].

- [122] F. Scardina, S.K. Das, V. Minissale, S. Plumari and V. Greco, *Estimating the charm quark diffusion coefficient and thermalization time from D meson spectra at energies available at the BNL Relativistic Heavy Ion Collider and the CERN Large Hadron Collider*, *Phys. Rev. C* **96** (2017) 044905 [[arXiv:1707.05452](#)] [[INSPIRE](#)].
- [123] S. Plumari, G. Coci, V. Minissale, S.K. Das, Y. Sun and V. Greco, *Heavy-light flavor correlations of anisotropic flows at LHC energies within event-by-event transport approach*, *Phys. Lett. B* **805** (2020) 135460 [[arXiv:1912.09350](#)] [[INSPIRE](#)].
- [124] W. Ke, Y. Xu and S.A. Bass, *Modified Boltzmann approach for modeling the splitting vertices induced by the hot QCD medium in the deep Landau-Pomeranchuk-Migdal region*, *Phys. Rev. C* **100** (2019) 064911 [[arXiv:1810.08177](#)] [[INSPIRE](#)].
- [125] T. Song et al., *Tomography of the Quark-Gluon-Plasma by Charm Quarks*, *Phys. Rev. C* **92** (2015) 014910 [[arXiv:1503.03039](#)] [[INSPIRE](#)].
- [126] ALICE collaboration, *D-meson azimuthal anisotropy in midcentral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Rev. Lett.* **120** (2018) 102301 [[arXiv:1707.01005](#)] [[INSPIRE](#)].
- [127] C.B. Dover, U.W. Heinz, E. Schnedermann and J. Zimányi, *Relativistic coalescence model for high-energy nuclear collisions*, *Phys. Rev. C* **44** (1991) 1636 [[INSPIRE](#)].
- [128] L. Ravagli and R. Rapp, *Quark Coalescence based on a Transport Equation*, *Phys. Lett. B* **655** (2007) 126 [[arXiv:0705.0021](#)] [[INSPIRE](#)].
- [129] O. Kaczmarek, *Continuum estimate of the heavy quark momentum diffusion coefficient κ* , *Nucl. Phys. A* **931** (2014) 633 [[arXiv:1409.3724](#)] [[INSPIRE](#)].
- [130] H.T. Ding, A. Francis, O. Kaczmarek, F. Karsch, H. Satz and W. Soeldner, *Charmonium properties in hot quenched lattice QCD*, *Phys. Rev. D* **86** (2012) 014509 [[arXiv:1204.4945](#)] [[INSPIRE](#)].
- [131] D. Banerjee, S. Datta, R. Gavai and P. Majumdar, *Heavy Quark Momentum Diffusion Coefficient from Lattice QCD*, *Phys. Rev. D* **85** (2012) 014510 [[arXiv:1109.5738](#)] [[INSPIRE](#)].
- [132] STAR collaboration, *Measurement of D^0 Azimuthal Anisotropy at Midrapidity in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys. Rev. Lett.* **118** (2017) 212301 [[arXiv:1701.06060](#)] [[INSPIRE](#)].
- [133] PHENIX collaboration, *Heavy Quark Production in p + p and Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys. Rev. C* **84** (2011) 044905 [[arXiv:1005.1627](#)] [[INSPIRE](#)].
- [134] S. Cao et al., *Toward the determination of heavy-quark transport coefficients in quark-gluon plasma*, *Phys. Rev. C* **99** (2019) 054907 [[arXiv:1809.07894](#)] [[INSPIRE](#)].
- [135] C. Loizides and A. Morsch, *Absence of jet quenching in peripheral nucleus-nucleus collisions*, *Phys. Lett. B* **773** (2017) 408 [[arXiv:1705.08856](#)] [[INSPIRE](#)].
- [136] ALICE collaboration, *Analysis of the apparent nuclear modification in peripheral Pb–Pb collisions at 5.02 TeV*, *Phys. Lett. B* **793** (2019) 420 [[arXiv:1805.05212](#)] [[INSPIRE](#)].

The ALICE collaboration

S. Acharya,¹⁴² D. Adamová,⁹⁷ A. Adler,⁷⁵ J. Adolfsson,⁸² G. Aglieri Rinella,³⁴ M. Agnello,³⁰ N. Agrawal,⁵⁴ Z. Ahammed,¹⁴² S. Ahmad,¹⁶ S.U. Ahn,⁷⁷ I. Ahuja,³⁸ Z. Akbar,⁵¹ A. Akindinov,⁹⁴ M. Al-Turany,¹⁰⁹ S.N. Alam,¹⁶ D. Aleksandrov,⁹⁰ B. Alessandro,⁶⁰ H.M. Alfanda,⁷ R. Alfaro Molina,⁷² B. Ali,¹⁶ Y. Ali,¹⁴ A. Alici,²⁵ N. Alizadehvandchali,¹²⁶ A. Alkin,³⁴ J. Alme,²¹ T. Alt,⁶⁹ I. Altsybeev,¹¹⁴ M.N. Anaam,⁷ C. Andrei,⁴⁸ D. Andreou,⁹² A. Andronic,¹⁴⁵ M. Angeletti,³⁴ V. Anguelov,¹⁰⁶ F. Antinori,⁵⁷ P. Antonioli,⁵⁴ C. Anuj,¹⁶ N. Apadula,⁸¹ L. Aphecetche,¹¹⁶ H. Appelshäuser,⁶⁹ S. Arcelli,²⁵ R. Arnaldi,⁶⁰ I.C. Arsene,²⁰ M. Arslanodok,¹⁴⁷ A. Augustinus,³⁴ R. Averbeck,¹⁰⁹ S. Aziz,⁷⁹ M.D. Azmi,¹⁶ A. Badalà,⁵⁶ Y.W. Baek,⁴¹ X. Bai,^{130,109} R. Bailhache,⁶⁹ Y. Bailung,⁵⁰ R. Bala,¹⁰³ A. Balbino,³⁰ A. Baldisseri,¹³⁹ B. Balis,² D. Banerjee,⁴ R. Barbera,²⁶ L. Barioglio,¹⁰⁷ M. Barlou,⁸⁶ G.G. Barnaföldi,¹⁴⁶ L.S. Barnby,⁹⁶ V. Barret,¹³⁶ C. Bartels,¹²⁹ K. Barth,³⁴ E. Bartsch,⁶⁹ F. Baruffaldi,²⁷ N. Bastid,¹³⁶ S. Basu,⁸² G. Batigne,¹¹⁶ B. Batyunya,⁷⁶ D. Bauri,⁴⁹ J.L. Bazo Alba,¹¹³ I.G. Bearden,⁹¹ C. Beattie,¹⁴⁷ P. Becht,¹⁰⁹ I. Belikov,¹³⁸ A.D.C. Bell Hechavarria,¹⁴⁵ F. Bellini,²⁵ R. Bellwied,¹²⁶ S. Belokurova,¹¹⁴ V. Belyaev,⁹⁵ G. Bencedi,^{146,70} S. Beole,²⁴ A. Bercuci,⁴⁸ Y. Berdnikov,¹⁰⁰ A. Berdnikova,¹⁰⁶ L. Bergmann,¹⁰⁶ M.G. Besoiu,⁶⁸ L. Betev,³⁴ P.P. Bhaduri,¹⁴² A. Bhasin,¹⁰³ I.R. Bhat,¹⁰³ M.A. Bhat,⁴ B. Bhattacharjee,⁴² P. Bhattacharya,²² L. Bianchi,²⁴ N. Bianchi,⁵² J. Bielčák,³⁷ J. Bielčíková,⁹⁷ J. Biernat,¹¹⁹ A. Bilandzic,¹⁰⁷ G. Biro,¹⁴⁶ S. Biswas,⁴ J.T. Blair,¹²⁰ D. Blau,^{90,83} M.B. Blidaru,¹⁰⁹ C. Blume,⁶⁹ G. Boca,^{28,58} F. Bock,⁹⁸ A. Bogdanov,⁹⁵ S. Boi,²² J. Bok,⁶² L. Boldizsár,¹⁴⁶ A. Bolozdynya,⁹⁵ M. Bombara,³⁸ P.M. Bond,³⁴ G. Bonomi,^{141,58} H. Borel,¹³⁹ A. Borissov,⁸³ H. Bossi,¹⁴⁷ E. Botta,²⁴ L. Bratrud,⁶⁹ P. Braun-Munzinger,¹⁰⁹ M. Bregant,¹²² M. Broz,³⁷ G.E. Bruno,^{108,33} M.D. Buckland,¹²⁹ D. Budnikov,¹¹⁰ H. Buesching,⁶⁹ S. Bufalino,³⁰ O. Bugnon,¹¹⁶ P. Buhler,¹¹⁵ Z. Buthelezi,^{73,133} J.B. Butt,¹⁴ A. Bylinkin,¹²⁸ S.A. Bysiak,¹¹⁹ M. Cai,^{27,7} H. Caines,¹⁴⁷ A. Caliva,¹⁰⁹ E. Calvo Villar,¹¹³ J.M.M. Camacho,¹²¹ R.S. Camacho,⁴⁵ P. Camerini,²³ F.D.M. Canedo,¹²² F. Carnesecchi,^{34,25} R. Caron,¹³⁹ J. Castillo Castellanos,¹³⁹ E.A.R. Casula,²² F. Catalano,³⁰ C. Ceballos Sanchez,⁷⁶ P. Chakraborty,⁴⁹ S. Chandra,¹⁴² S. Chapeland,³⁴ M. Chartier,¹²⁹ S. Chattopadhyay,¹⁴² S. Chattopadhyay,¹¹¹ A. Chauvin,²² T.G. Chavez,⁴⁵ T. Cheng,⁷ C. Cheshkov,¹³⁷ B. Cheynis,¹³⁷ V. Chibante Barroso,³⁴ D.D. Chinellato,¹²³ S. Cho,⁶² P. Chochula,³⁴ P. Christakoglou,⁹² C.H. Christensen,⁹¹ P. Christiansen,⁸² T. Chujo,¹³⁵ C. Cicalo,⁵⁵ L. Cifarelli,²⁵ F. Cindolo,⁵⁴ M.R. Ciupek,¹⁰⁹ G. Clai,^{II,54} J. Cleymans,^{I,125} F. Colamaria,⁵³ J.S. Colburn,¹¹² D. Colella,^{53,108,33} A. Collu,⁸¹ M. Colocci,³⁴ M. Concas,^{III,60} G. Conesa Balbastre,⁸⁰ Z. Conesa del Valle,⁷⁹ G. Contin,²³ J.G. Contreras,³⁷ M.L. Coquet,¹³⁹ T.M. Cormier,⁹⁸ P. Cortese,³¹ M.R. Cosentino,¹²⁴ F. Costa,³⁴ S. Costanza,^{28,58} P. Crochet,¹³⁶ R. Cruz-Torres,⁸¹ E. Cuautle,⁷⁰ P. Cui,⁷ L. Cunqueiro,⁹⁸ A. Dainese,⁵⁷ M.C. Danisch,¹⁰⁶ A. Danu,⁶⁸ P. Das,⁸⁸ P. Das,⁴ S. Das,⁴ S. Dash,⁴⁹ A. De Caro,²⁹ G. de Cataldo,⁵³ L. De Cilladi,²⁴ J. de Cuveland,³⁹ A. De Falco,²² D. De Gruttola,²⁹ N. De Marco,⁶⁰ C. De Martin,²³ S. De Pasquale,²⁹ S. Deb,⁵⁰ H.F. Degenhardt,¹²² K.R. Deja,¹⁴³ L. Dello Stritto,²⁹ W. Deng,⁷ P. Dhankher,¹⁹ D. Di Bari,³³ A. Di Mauro,³⁴ R.A. Diaz,⁸ T. Dietel,¹²⁵ Y. Ding,^{137,7} R. Divià,³⁴ D.U. Dixit,¹⁹ Ø. Djuvsland,²¹ U. Dmitrieva,⁶⁴ J. Do,⁶² A. Dobrin,⁶⁸ B. Dönigus,⁶⁹ A.K. Dubey,¹⁴² A. Dubla,^{109,92} S. Dudi,¹⁰² P. Dupieux,¹³⁶ N. Dzalaiova,¹³ T.M. Eder,¹⁴⁵ R.J. Ehlers,⁹⁸ V.N. Eikeland,²¹ F. Eisenhut,⁶⁹ D. Elia,⁵³ B. Erazmus,¹¹⁶ F. Ercolessi,²⁵ F. Erhardt,¹⁰¹ A. Erokhin,¹¹⁴ M.R. Ersdal,²¹ B. Espagnon,⁷⁹ G. Eulisse,³⁴ D. Evans,¹¹² S. Evdokimov,⁹³ L. Fabbietti,¹⁰⁷ M. Faggin,²⁷ J. Faivre,⁸⁰ F. Fan,⁷ A. Fantoni,⁵² M. Fasel,⁹⁸ P. Fecchio,³⁰ A. Feliciello,⁶⁰ G. Feofilov,¹¹⁴ A. Fernández Téllez,⁴⁵ A. Ferrero,¹³⁹ A. Ferretti,²⁴ V.J.G. Feuillard,¹⁰⁶ J. Figiel,¹¹⁹ S. Filchagin,¹¹⁰ D. Finogeev,⁶⁴ F.M. Fionda,^{55,21} G. Fiorenza,^{34,108} F. Flor,¹²⁶ A.N. Flores,¹²⁰ S. Foertsch,⁷³ S. Fokin,⁹⁰

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- 147 *Yale University, New Haven, Connecticut, United States*
- 148 *Yonsei University, Seoul, Republic of Korea*

Certificate

Randhir Singh

has successfully participated and presented a poster titled

Open charm studies as a function of charged-particle
multiplicity in pp collisions at $\sqrt{s} = 13$ TeV with ALICE

XXIV DAE-BRNS Symposium on High Energy Physics

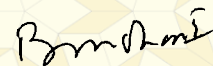
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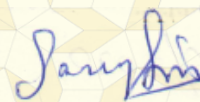
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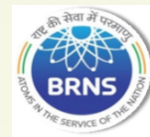




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BHABHA ATOMIC RESEARCH CENTRE

65th DAE-BRNS Symposium on Nuclear Physics, 2021

December 1-5, 2021, DAE Convention Centre,
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Certificate of Participation

This is to certify that **Randhir Singh** from Department of Physics, University of Jammu, Jammu, participated in the “65th DAE-BRNS Symposium on Nuclear Physics (SNP2021)”, during December 1-5, 2021 which was organized in a hybrid mode, where Mumbai participants joined physically and outside ones participated through online platform.

It is also certified that **Randhir Singh** has presented a paper with the title “Open Charm production in proton-proton collisions at $\sqrt{s} = 13$ TeV using Pythia 8”.

Dr. Y. K. Gupta
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SNP-2021

Dr. S. Santra
Convener
SNP-2021

Shri R. R. Sahu
Secretary
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