



**Prompt  $D^{*+}$  production in proton-proton  
and lead-lead collisions, measured with the ALICE experiment  
at the CERN Large Hadron Collider**

**Directe  $D^{*+}$  productie in proton-proton  
en lood-lood botsingen, gemeten met het ALICE experiment  
aan de CERN Large Hadron Collider**

(met een samenvatting in het Nederlands)

Proefschrift

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*If first you don't succeed, use a bigger gun.*





## Outline

In this thesis the results are presented of the world's first measurements of the  $D^{*+}$  meson nuclear modification factor  $R_{AA}$  in heavy ion collisions at the Large Hadron Collider (LHC) using the ALICE (A Large Ion Collider Experiment) detector at CERN, using data accumulated over 2010 and 2011 for both lead-lead and proton-proton collisions.

Chapter 1 gives an qualitative overview of the history and theoretical background relevant to this thesis, as well as the results from previous experiments. It also contains a summary of various theoretical models used to describe the data. The second chapter focusses on the design and construction of the ALICE detector, and also includes a description of the analysis framework used for data analysis. The analysis strategy used for  $D^{*+}$  reconstruction via the  $D^{*+} \rightarrow D^0 \pi_{\text{soft}}^+ \rightarrow K^- \pi^+ \pi_{\text{soft}}^+$  decay channel is discussed in detail in chapter three. Here an important aspect is the application of selection cuts and their optimisation to improve signal significance. The importance of the proton-proton results as a reference is further highlighted. In chapter four the  $p_T$ -differential inclusive production cross section of prompt  $D^{*+}$  mesons, in the rapidity range  $|y| < 0.5$ , in  $\sqrt{s} = 7$  TeV proton-proton collisions is presented. In chapter five the  $p_T$ -differential inclusive production yield of prompt  $D^{*+}$  mesons, in the rapidity range  $|y| < 0.5$  and the  $p_T$  range 2-36 GeV/c, in  $\sqrt{s_{NN}} = 2.76$  TeV lead-lead collisions is shown. The nuclear modification factor, with respect to the proton-proton reference obtained and scaled down to a centre-of-mass energy of 2.76 TeV, is then determined and compared with several model based theoretical predictions. The conclusions of this work will be discussed in chapter six.

The results have been published in various papers [72, 73, 74] and presented at international conferences (e.g. [115]). A colour version of this thesis will become available online.



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# Chapter 1

## Heavy ion physics

An important aspect of man's culture and history has been his need to contemplate his place in the universe. One of those many enigmas that has interested mankind is the question of 'what is matter'? Throughout the ages many great thinkers have pondered this question. As a tribute to the efforts of these men and women, the first section of this chapter contains a brief summary of humanity's voyage of discovery to understand the fundamentals of matter, up to the present day.

The next two sections describe Quantum Chromodynamics and its role in the Standard Model. Then the principle of heavy ion collisions is discussed as well as the Quark Gluon Plasma (QGP). The signatures for the existence of the QGP are detailed, as well as the actual measurements performed by the Relativistic Heavy Ion Collider at Brookhaven National Laboratory (USA). The physical properties of azimuthal anisotropy and jet quenching in the QGP are discussed. Finally, aspects of the main topic of this work will be introduced; the study of D meson production in proton-proton and lead-lead collisions, which can be used to probe the properties in the Quark Gluon Plasma.

### 1.1 Towards Elementary Particle Physics, a brief history

For centuries mankind has wondered about the nature of matter. This has led to inspired, yet flawed interpretations like the classical elements of fire, water, earth and air during the Greek classical period, that stayed popular well into the Renaissance. Yet even in the Classical period the philosophers Leucippus, Democritus and Epicurus argued that the properties of a material could be traced back to their smallest undividable components.

The lack of empirical evidence one way or the other ensured that for two millennia the question of the structure of matter was purely philosophical.<sup>1</sup> Even the works of Descartes, Gassendi, and Newton in the the 17th century focussed on the interpretation of the resurgent theory of small indivisible components, or atoms. Fortunately,

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<sup>1</sup>Of course, up until the nineteenth century all scientific thinking was considered to be philosophy. The current segregation of science and philosophy is a rather modern development.

mankind became interested and experienced in chemistry in the 18th century. Using measurements and experiments those early chemists catalogued the properties of a great many materials and processes, paving the way for the works of Dalton and Avogadro who would start of humanity's current understanding of atoms and molecules.

As the knowledge of atoms and molecules grew, so too grew the realisation that atoms are not the smallest possible components and even smaller elements existed. The study of these 'elementary particles' began when Thomson discovered the electron in 1897 with its negative electric charge and its extremely small mass, for which he correctly surmised that these particles were part of the atom. Though Thomson was proven incorrect about the origin of the positive charge to compensate for the electrons' negative mass in the neutral atom, Rutherford proved decisively that atoms have internal structure with his famous scattering experiment where he discovered the presence of the atomic nucleus. This led to the discovery of the positively charged and heavy proton and the heavy but neutral neutron. With these three particles in place and a satisfactory model to describe them the period sometimes known as the 'classical period' of elementary particle physics was concluded [1].

However, starting with the 1930s the 'middle period' began, drawing knowledge not only from the discoveries of the 'classical period' of particle physics, but also on the revolutionary changes wrought by the discoveries of quantum mechanics and general relativity. The discovery of the photoelectric effect brought turmoil to the age-old question whether light was a wave or particle phenomena, introducing the photon and the concept of energy quanta. The study of black-body radiation showed conclusively that the 'classical' picture of electrons orbiting nuclei was flawed and quantisation of classical systems was required.

Naturally, the realisation that an atomic nucleus consist largely of positive particles gave rise to the question what 'strong force' was keeping the nuclei together, which apparently only interacted at very short distances. It was Yukawa who linked this 'strong force' with a mediating particle which he called the meson, which was more-or-less confirmed by Powell et al. in 1947 when his collaboration discovered both the pion and muon particles [2, 3, 4, 5].

The original version of quantum mechanics was based on a formalism of classical time and space, but evolving it into a relativistic version gave rise to some far-reaching realisations. This started when Dirac discovered the existence of negative energy states and his 'fix' of proposing the Dirac sea, where every negative energy state is already filled by a particle. This of course led to the idea that an electron could be excited from this 'sea' creating a 'hole' with similar properties but opposite charge of the electron. This idea in turn was mitigated by the interpretation of Feynman and Stueckelberg of the existence of an actual antiparticle. At any rate, the discovery of the positron in 1931 can be regarded as a triumph of elementary particle physics.

The third pillar that defined the 'middle period of elementary particle physics' is the realisation (and discovery) of the existence of another particle, which would account for the missing kinematic energy of the electron in beta decays. Fermi incorporated this particle proposed by Pauli and named it the neutrino. This very light particle could also be used to explain the awkward 'kink' visible in the bubble chambers when a pion or muon decayed. Despite this indirect evidence, one had to wait until the mid-1950s when Cowan and Reines confirmed the neutrino's existence. This did not answer yet whether the neutrino and its anti-neutrino were different particles or one

and the same. Davis and Harmer confirmed the former hypothesis in the late 1950s when they tried to repeat that experiment with anti-neutrinos and failed to produce an analogue reaction. This was not unexpected though, as already in 1953 Konopinski and Mahmoud had introduced the lepton number and the law of conservation of lepton number, which was thought to be different for neutrinos and anti-neutrinos.

Nevertheless, the absence of certain muon decays could not be explained without assigning separate lepton numbers to muons and electrons, which also suggested the existence of even more types of neutrinos. In 1962 the experiments of Lederman, Schwartz and Steinberger confirmed that the electron neutrino and muon neutrino were indeed fundamentally different particles. As 1962 came to a close, the lepton family had grown to 8 particles: the electron and muon, their extremely light neutrinos and all of their antiparticles.

With these three pillars in place around 1960, the middle period came to a conclusion. However, new developments were already unfolding, starting with developments on the strongly interacting particles collectively called the hadrons.

With the discovery of the meson, antiparticles and the widely accepted postulation of the neutrino, the structure of elementary particle physics was essentially though to be done already in 1947. Only the muon was somewhat of an enigma, being the odd-one-out in elementary particle physics to which Rabi famously asked: 'Who ordered *that*?'. However, this situation was overturned at the end of the year by Rochester and Butler when they discovered a new neutral particle called the kaon. Despite being at least twice as heavy, it had similarities with the pion. As such, it was included in the meson family.

In 1950 at CalTech Anderson's group discovered the  $\Lambda$  hyperon, which was later classified as a baryon. This latter fact can be attributed to Stükelberg as early as 1938 when he proposed the law of conservation of baryon number to hypothesise why protons did not seem to decay. Since  $\Lambda$ 's decay products determined at CalTech included a proton and a pion, the law demanded the  $\Lambda$  itself to be a baryon.

These heralded the discovery of enough new mesons and baryons to fill much of the Greek alphabet,<sup>2</sup> increasing dramatically when the Brookhaven Cosmotron (the first true modern particle accelerator) reached its full design energy of 3.3 GeV in January 1953. Following this Lamb told the following jest in his Noble prize acceptance speech in 1955: "the finder of a new elementary particle used to be rewarded by a Noble Prize, but such a discovery now ought to be punished by a \$ 10,000 fine."<sup>3</sup> [6]

Aside from the fact that they even existed, these new particles were considered quite strange due to the fact that they were very easy to produce (which suggested a very quick creation process), but decayed very slowly. Pias proposed that their production mechanism was radically different from their decay process, which today would be described as strange particles are produced by the strong force, and decay via the weak force. In 1953, Gell-Mann and Nishijima implemented this idea into the existence of a new quantum number called 'strangeness', which is conserved in strong interactions but not conserved in weak interactions.

Though strangeness did explain why certain processes occur for some particles and not for others, in 1960 there was no clear underlying system to organise this new

<sup>2</sup>This author has always been puzzled by modern science's tendency to denote most particles with a Greek letter. Not to mention most constants as well.

<sup>3</sup>Though he was quoting someone else.



'particle zoo'. It would take another year before all these exotic particles could be organised in their own version of the periodic table.

It was Gell-Mann who introduced the so-called Eightfold Way, which arranged the baryons and mesons into geometrical patterns depending on their charge and strangeness called supermultiplets. One of these patterns seemed to lack a particle, which Gell-Mann predicted would be found as well as calculating several properties. And indeed, the  $\Omega^-$  particle would be discovered in 1964. Newer hadrons would find their place in the supermultiplets as well. Since the Eightfold way opened the way for the Quark Model, it can be considered the start of the modern area in particle physics.

Understanding of the underlying physics of the Eightfold Way came in 1964, when Gell-Mann and Zweig independently hypothesised that hadrons are composed of smaller particles which Gell-Mann called Quarks.<sup>4</sup> It was supposed that there were three quarks or flavours; up, down and strange. Each carried partial charge and the latter nonzero strangeness. Also, each quark had a corresponding anti-quark with opposite charge and strangeness. Now the fundamental difference between mesons and baryons became clear, as the former consist of a quark and an anti-quark, while the latter consist of three quarks or three anti-quarks. All particles in the Eightfold Way could easily be linked to a combination of quarks and/or anti-quarks and it was even discovered that the  $\eta'$  was placed in the wrong supermultiplet when no particle was readily identified as the strange-antistrange meson. Also many particles in the supermultiplets consisted of the same combination of quarks and/or anti-quarks, so it was quickly recognised that several particles were actually excited states of another.

Despite of the many successes of the model, the fact that not a single quark had actually been detected was a huge problem, leading to widespread scepticism in the late 1960's and early 1970's. This problem gave rise to the notion of quark confinement, where the existence of quarks was supposed to be restricted within hadrons. The underlying mechanics were a mystery however.

Nevertheless, the Stanford Linear Accelerator Center (SLAC) conducted deep-inelastic scattering experiments in the late 1960's to probe the internal structure of the proton with high-energy electrons. These were repeated at CERN using neutrino beams and protons. The results were remarkably similar to those of Rutherford's experiment, again showing the concentration of mass at a certain location, albeit in the case of the proton the mass was centralised in three locations. Strong support for the quark model, but not yet conclusive.

Aside from the experimental problems, there was a major theoretical problem too. Being of half-integer spin, the quarks are subject to the Pauli exclusion principle. Baryons which consisted of three quarks of the same flavour in the same quantum state seemed to violate the principle. Greenberg found a solution to this problem in 1964 by supposing that quarks also come in three colours (and their anticolours in case of antiparticles); "red", "blue" and "green". This not only solved the problem with the three quarks in the same state in a baryon, since they obviously differed in colour, it also provided a straightforward explanation for the quark content of mesons and baryons, requiring that hadrons be colourless.

Moreover, the work of Frank Wilczek, David Gross, and David Politzer on asymp-

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<sup>4</sup>Contrary to popular belief, the name did not come from the line "Three quarks for Muster Mark" from James Joyce's *Finnegan's Wake*, only the spelling. He came up with the sound first [7]. This author could not discover why he (or indeed anyone) wanted to name this new particle 'kwork'...

otic freedom in 1973 [8] was another important contribution to the quark model, for which they would be rewarded with the Nobel Prize in physics in 2004. Before 1973, many theorists suspected that the quark model was fundamentally inconsistent because quark interactions should become infinitely strong at short distances. However, their work showed that asymptotically free theories like the quark model would become weak at short distances, so they would be completely consistent down to any length scale.

Nevertheless, the principles of quark confinement and colour charge were regarded as somewhat of a quick fix and a desperate attempt to rescue the problematic quark model. Unsurprisingly, the mass concentrations in the proton discovered by SLAC and CERN were for the time being called partons (since it was later discovered that gluons were also present, being the mediators between quarks, the name stuck). Full acceptance of the quark model only came following the discovery of a new particle during the "November Revolution" of 1974.

In this month both Ting's research group at Brookhaven and Burton's group at SLAC published their results of the discovery of a new meson with an unusual long lifetime, called  $J$  by Ting and  $\psi$  by Burton and was henceforth known as the  $J/\psi$ . The answer to the nature of this particle was provided by the quark model, which suggested that the  $J/\psi$  was a bound state of a new quark and its anti-quark, now known as the "charm".

The existence of the charm quark opened up a new range of undiscovered particles, and new ones were soon discovered. The confirmation of the charm hypothesis itself came not with the discovery of the  $J/\psi$  however, which has a quantum number called charm equal to zero due to the charm and anti-charm quarks in the meson and therefore has 'hidden charm'. Instead, it came with the discovery of 'open charm' particles, like the  $\Lambda_c^+$  for baryons in 1975, and  $D^0$  and  $D^+$  for open charm mesons in 1976.

The discovery of the charm quark was not fully unexpected, as Glashow, Iliopoulos and Maiani already postulated the existence of a fourth quark. However, their proposed symmetry of four leptons and four quarks was broken by the discovery of the tau lepton in 1975 and the implied existence of its corresponding tau neutrino (itself only discovered in 2000). Fortunately, two years later the  $Y$  particle was identified as a carrier of a new quark, called "bottom" or "beauty". The first particles with nonzero bottom quantum number, called 'bare bottom' or 'naked beauty' were confirmed to exist for baryons in 1980, and in 1983 for mesons when the first  $\bar{B}^0$  and  $B^-$  were detected.

Search for a sixth quark designated as "top" took much longer, its high mass making it difficult to produce for electron-positron colliders, and a very short lifetime unabling it to form the required bound states to produce hadrons. The final discovery of the top was not made until 1995 at the Tevatron at Fermilab when investigating the top decay modes.

However, not all discoveries were unexpected, as 1983 was also the year the  $W$  boson was discovered, the first of the sought after vector bosons. Fermi's model of electrons in beta decay, which is governed by the weak interaction, was suspected to be incomplete as it assumed to occur at a single point. In order to make it work at higher energies, a mediating particle was required, named the intermediate vector boson. Like Yukawa did before with the strong interaction, a mass prediction of this particle could be made if the range of the force could be determined. Unfortunately

the weak force was not strong enough to form bound states between particles and give a range estimate.

However the work of Glashow, Weinberg and Salam on the electroweak theory laid the theoretical groundwork for a prediction of not only the  $W^\pm$ , but also the  $Z^0$  intermediate vector boson masses. Such was the confidence of these predictions that at the end of the 1970s CERN started the construction of the Super Proton Synchrotron (SPS) proton-antiproton collider. The research group led by Rubbia confirmed the much anticipated existence of the  $W$  boson in January 1983, followed soon after by the  $Z$  boson.

At this point the elementary particle physics community was heavily committed to the Standard Model, of which the global aspects will be further discussed in section 1.2. It combined all the previous discoveries on the fields of the electroweak theory and quark model, effectively forming an overarching theorem of elementary particles.

It organises the six known leptons into three generations and does the same for the six quarks. Naturally, it also recognises their antiparticles and in the case of quarks their colour variants.<sup>5</sup> The electromagnetic, weak and strong interactions correspond to vector bosons. The first is the photon and the weak force corresponds to the  $W$  and  $Z$  bosons. In this picture the Yukawa's proposition of the pion as the mediator of the strong force could no longer be retained, itself merely a composite particle. Instead the strong force between baryons was the *residual* strong force, analogous to the Van der Waals force which is related to the fundamental electromagnetic force. The actual Strong Force was between the quarks of the nucleon themselves, where the mediator was called the "gluon", though there are actually 8 gluons, each distinct from one another due to the colour charge it carries. Since the gluon carries colour it too is confined within the hadron and cannot be observed directly. However, there is indirect evidence of the gluon, like jet structures occurring after particle collisions in deep inelastic scattering experiments following the hadronisation of scattered quarks and gluons.

Now for over three decades the Standard Model has stood unchallenged as the central theory of elementary particle physics. However, many questions remain. Many of the constants of the theory have been determined phenomenologically and their origins are uncertain. Or the accuracy of certain models that describe particle interactions, which is particularly relevant in regards to this thesis. Other questions include the discovery of neutrino oscillations and charge-parity (CP) violation.

Still, one question seems to be resolved. The Standard Model describes how every particle is associated with a field, as well as the existence of a field which interaction with other particles cause them to gain mass. This field itself is connected with the Higgs boson and for a long time this particle remained elusive. But with the successful startup of the Large Hadron Collider (LHC) in 2009 a new and exciting era of elementary particle physics has started. With its maximum centre-of-mass energy of 14 TeV and luminosity of  $10^{33} \text{cm}^{-2}\text{s}^{-1}$  a new range of experimental results has been opened. It was hoped it would enable confirmation of the existence of the Higgs particle, the

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<sup>5</sup>Experiments at SLAC and CERN seem to have confirmed that there are no more than three generations of particles, using the decay of the  $Z$  boson. This boson is able to decay into every particle-antiparticle pair possible, energy permitting. Since the decay rate depends on the number of decay modes, even if one just were to include the mode of decay into two fourth generation neutrinos would cause the  $Z$  boson to decay more rapidly than is currently being observed. However this experiment does not take into account that the neutrino pair might be heavier than the  $Z$  boson, but that possibility is considered to be remote.

keystone of the standard model. And as of the 4th of July 2012, a particle with the right characteristics has been found with 99.99997133% confidence level by the CMS collaboration [9] and an even higher confidence level by the ATLAS experiment [10], even though it may still take years to exclude every other possibility

But it does not stop here. Already the search is on for physics beyond the bounds of the Standard Model. These include Grand Unified Theories that link the strong, electromagnetic and weak interactions. Another is supersymmetry, which associates every boson with a new fermion and vice-versa. Or String Theory, which may one day unite General Relativity with Quantum Mechanics.

## 1.2 Quantum Chromodynamics and the Standard Model

The Standard Model (SM) forms the backbone of our current understanding in elementary particle physics. Since its development following the discoveries on electroweak theory and the quark model, it has stood the test of time well as a description of the known particles and the forces governing them.

It recognises six different spin-1/2 fermions called quarks into three generations (or families), with the strong force as their primary interaction. The three quarks with partial (two-thirds) positive charge are, in order of increasing mass, the up ( $u$ ), charm ( $c$ ) and top ( $t$ ). This corresponds to the three generations. The three quarks with partial (one-third) negative charge are the down ( $d$ ), strange ( $s$ ) and bottom/beauty ( $b$ ), again corresponding to the three families. The type of each quark is more commonly known as its flavour. Subject to the strong interaction, the most powerful force in the Standard Model, the massless spin-1 mediating vector boson is called the gluon.

The leptons are also divided into three families. The first family contains the electron, while the second and third contain the muon and tau, progressively heavier particles themselves and all carrying spin-1/2 and negative charge. The strongest force acting on these particles is the electromagnetic force due to the fact that they carry electric charge (which also means quarks experience this force too) and as such their mediating particle is the massless chargeless spin-1 photon.

The three leptons are each associated with a very light, neutral charged spin-1/2 particle called the neutrino, giving us the electron neutrino, muon neutrino and tau neutrino. Since they carry no electric charge, the only force they experience is the one that all particles are subjected to: the weak interaction, which is mediated by the massive charged  $W$  and  $Z^0$  gauge bosons.

A summary of the particles in the Standard model are represented in fig. 1.1. Take note that aside from the particles already mentioned, every particle also has its antiparticle, like the electron has the positive charged positron (though the bosons are actually their own antiparticle). Moreover, every quark flavour actually consists of three different quarks, which will be explained below.

However, the Standard Model also requires another massive spin-0 boson called the Higgs boson, responsible for adding mass to other particles via the Higgs mechanism due to symmetry breaking. Higgs interaction and the electroweak interactions fall outside the scope of this thesis however, regardless of their importance in modern particle physics.

A peculiar quality of quarks rests in the fact that none have actually been observed

| Three Generations<br>of Matter (Fermions) |                                                                                    |                                                                                    |                                                                                    |                                                       |
|-------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------|
|                                           | I                                                                                  | II                                                                                 | III                                                                                |                                                       |
| mass→                                     | 2.4 MeV                                                                            | 1.27 GeV                                                                           | 171.2 GeV                                                                          | 0                                                     |
| charge→                                   | $\frac{2}{3}$                                                                      | $\frac{2}{3}$                                                                      | $\frac{2}{3}$                                                                      | 0                                                     |
| spin→                                     | $\frac{1}{2}$                                                                      | $\frac{1}{2}$                                                                      | $\frac{1}{2}$                                                                      | 1                                                     |
| name→                                     | <b>u</b><br>up                                                                     | <b>c</b><br>charm                                                                  | <b>t</b><br>top                                                                    | <b>Y</b><br>photon                                    |
| Quarks                                    | 4.8 MeV<br>$-\frac{1}{3}$<br>$\frac{1}{2}$<br><b>d</b><br>down                     | 104 MeV<br>$-\frac{1}{3}$<br>$\frac{1}{2}$<br><b>s</b><br>strange                  | 4.2 GeV<br>$-\frac{1}{3}$<br>$\frac{1}{2}$<br><b>b</b><br>bottom                   | 0<br>0<br>1<br><b>g</b><br>gluon                      |
|                                           | <2.2 eV<br>0<br>$\frac{1}{2}$<br><b><math>\nu_e</math></b><br>electron<br>neutrino | <0.17 MeV<br>0<br>$\frac{1}{2}$<br><b><math>\nu_\mu</math></b><br>muon<br>neutrino | <15.5 MeV<br>0<br>$\frac{1}{2}$<br><b><math>\nu_\tau</math></b><br>tau<br>neutrino | 91.2 GeV<br>0<br>1<br><b>Z</b><br>weak<br>force       |
|                                           | 0.511 MeV<br>-1<br>$\frac{1}{2}$<br><b>e</b><br>electron                           | 105.7 MeV<br>-1<br>$\frac{1}{2}$<br><b><math>\mu</math></b><br>muon                | 1.777 GeV<br>-1<br>$\frac{1}{2}$<br><b><math>\tau</math></b><br>tau                | 80.4 GeV<br>$\pm 1$<br>1<br><b>W</b><br>weak<br>force |
| Leptons                                   |                                                                                    |                                                                                    |                                                                                    | Bosons (Forces)                                       |

Figure 1.1: The elementary particles known by the Standard Model (excluding the Higgs boson). Organised by generation and class of particle [11].

directly. Instead, they are bound together into particles collectively known as hadrons, which form the vast majority of visible matter in the universe. Hadrons are subdivided into baryons and mesons. Baryons consist of bound states of three quarks, for which the proton ( $uud$ ) and neutron ( $udd$ ) are the most prominent members. Mesons are particles formed by bound states of a quark and an antiquark, which includes particles like the  $\pi^+$  ( $u\bar{d}$ ) or the  $\pi^-$  ( $d\bar{u}$ ).

Most hadronic matter consist of quarks from the first generation. This is due to the fact that matter from the second and third families is much heavier and unstable, causing heavy quarks to decay into lighter components. Since decays across generations are not forbidden (though comparatively slow) hadron matter will eventually decay into particles constructed from the first generation. Since all quarks are fermions, so too are all baryons. Mesons carry integer spin due to their quark-antiquark pair and are therefore bosons (at least on a macroscopic scale).

It is important to note that the idea that hadrons are built up from quarks is not the whole picture. As a matter of fact, experiments as the Stanford Linear Accelerator Center (SLAC) showed that on average only about half of the momentum carried by a proton is carried by its constituent quarks. Gluons that mediate the strong force between the quarks are responsible for the rest. Since gluons interact with quarks, the Standard Model proposes that gluons produce quark-antiquark pairs. Though this at first glance seems to violate the principles of conservation of energy, the Heisenberg exclusion principle states that for short times there is an uncertain amount of energy available for the creation of these quarks, albeit their existence is very temporary. These are the 'sea quarks', which contrast to the 'valence quarks' permanently

attached to the hadron. The part of the standard model that defines the mechanics of quarks and their interactions is named Quantum Chromo Dynamics (QCD).

Every flavour of quark actually consists of three quarks. This is because quarks carry another quantum number that can separate them, which in this case is called 'colour' and which gives the name to Quantum *Chromo* Dynamics. There are three colours, defined as red ( $r$ ), blue ( $b$ ) and green ( $g$ ). Antiparticles carry an anticolour. Because of this, baryons formed by three quarks of the same flavour do not violate the Pauli exclusion principle since the three quarks are not in the same quantum state as their colour charge differs. This offers also a subtle explanation to why hadrons consist only of baryons and mesons. It is required by the standard model that all hadrons are colourless,<sup>6</sup> achievable by pairing a colour-anticolour like in a meson, or by combining all three colours as is achieved in a baryon. Gluons carry colour charge too, which enable gluons to interact with other gluons. This has far-reaching consequences.

When separating charged particles, the electromagnetic force between the particles will decrease. Schematically, when two charged particles are being separated, the field lines of the electric field that crosses a random surface between the two will grow less dense. On the other hand, when quarks are separated, the interaction of the gluons themselves will cause the strong force field lines to bunch together between the particles, causing the strength of the force between the two to increase, requiring an infinite amount of energy to separate. Figure 1.2 depicts a visual representation. This is the origin of the principle of 'confinement' where quarks cannot be separated from one another and viewed individually. Separating quarks will merely cause a new quark-antiquark pair to form when the energy threshold is reached.

Though this was an intuitive description of quark interaction, the more formal description is given by the classical string model which defines the interaction between quarks as a confined colour flux tube, also known as a string. On the outside of this flux tube there is no field whatsoever, but inside a colour-charge field is present. When quarks are separated more than the diameter of the hadron ( $\approx 10^{-15}$  m) asymptotic freedom no longer applies and the potential will rise enough for new quark pairs to form. As quarks fly away from one another new quark pairs are formed which can similarly fly away, forming a growing cascade of hadronised particles moving into the direction of the original quark, designated as a jet.

Though the string model is a good description of particle production in quark processes, theoretical calculations will have to resort to using the formalism of QCD itself. A massive problem when performing calculations on quark interactions is its coupling constant, which is a measure of the strength of an interaction. In a theory like quantum electrodynamics, which governs interactions of charged particles, the coupling constant is the fine structure constant given by  $\alpha = 1/137$ . Since this number is smaller than 1, only the simpler types of possible interactions are significant and perturbation theory can be employed to perform calculations.

But for quarks the structure constant is variable, given by

$$\alpha_s(|Q^2|) = \frac{12\pi}{(11n - 2f)\ln(|Q^2|/\Lambda_{\text{QCD}}^2)} \quad (1.1)$$

---

<sup>6</sup>More correctly, every hadron is a colour singlet.

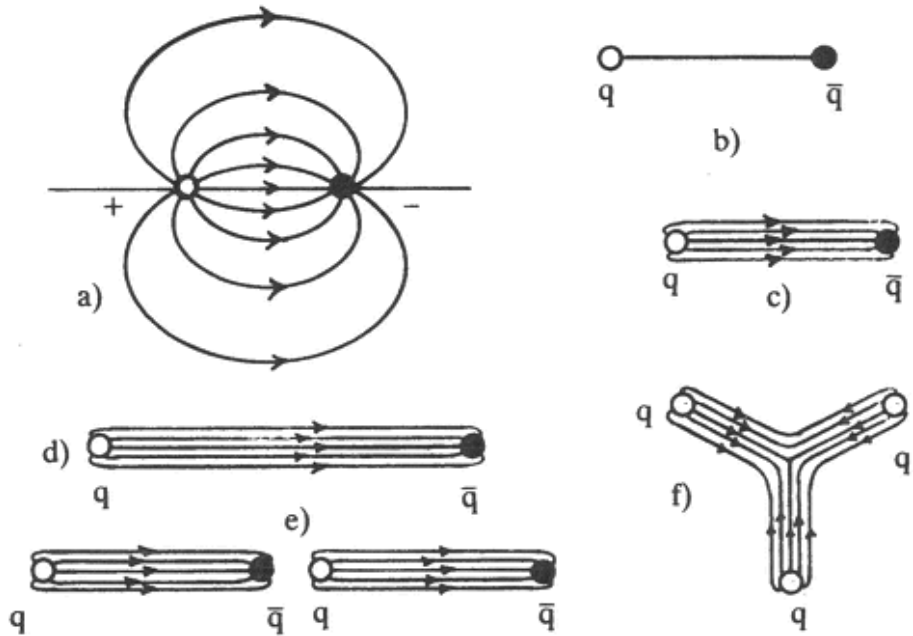


Figure 1.2: Comparison of field lines in QED and QCD. a) Electromagnetic field lines between two charges according to Maxwell's theory. b) Description of quark-antiquark pair in a string model. c) Gluon field between quark-antiquark pair. d) Separating quark-antiquark pair strengthens field between the two. e) Separating quarks increases potential until a new quark-antiquark pair is created. f) QCD field lines in a baryon [12].

where  $|Q^2|$  is the square of the exchanged four momentum,  $n$  the number of colours available for each quark flavour in QCD, which is set to three.  $f$  is set to six as it defines the number of quark flavours.  $\Lambda_{\text{QCD}}$  is a experimentally determined constant of about 300 MeV/c.

For larger distances, corresponding to a smaller  $|Q^2|$ ,  $\alpha_s$  is large and thus the possible contributions to an interaction become more important as they grow more complex. Perturbation theory can not be performed and calculations are not renormalisable.

Fortunately, eq. 1.1 also implies that at very short distances (due to the term  $11n - 2f > 0$ ), typically the size of a hadron, the coupling constant is very small. Effectively quarks behave like free particles within the confines of the hadron. This is called 'asymptotic freedom'. Furthermore, perturbation theory can be performed on this system.

Since perturbation theory can only be performed when  $\alpha_s \ll 1$ , lattice QCD has been developed. Here the equations are solved numerically on lattice space-time points. These calculations predict that a phase transition from hadronic matter to a plasma like state of deconfined quarks and gluons can take place when the temperature and/or pressure of the baryonic system is extremely high. This new state of matter is called the Quark Gluon Plasma (QGP).

The results from lattice QCD calculations are shown in fig. 1.3. Here one can

see the energy density  $\varepsilon$ , normalised to the temperature  $T$  to the fourth power, as a function of  $T$  normalised to the critical temperature  $T_c$  where phase transition is expected to occur according to lattice QCD calculations. The three curves represent three combinations of flavours and heavy or light quark masses. All three curves show a rapid increase of the energy density as the critical temperature is reached signifying a phase transition where more degrees of freedom become available. The critical temperature is about 175 MeV, equivalent to about  $2 \cdot 10^{12}$  K.

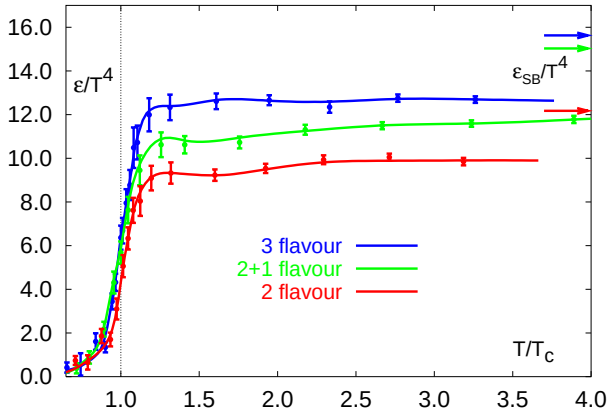


Figure 1.3: Scaled energy density (i.e. the number of degrees of freedom) vs. the temperature of the system scaled with the critical temperature where a phase transition to the QGP is thought to occur. The three graphs are calculated using lattice QCD where 2 light quarks (red), 3 light quarks (blue) and 2 light and 1 heavy quark (green) is included in the calculations. Notice the rapid increase of the energy density as the critical temperature is reached. The arrows correspond to the values the graphs should get when the system becomes an ideal gas [13].

This new state of matter is explained in more detail in section 1.3, but it is expected to have a definite impact on another physical process intrinsic QCD, the so-called *chiral symmetry restoration*. The standard model predicts that inside hadrons the quark masses are determined by both their coupling to the Higgs-field (the bare masses), as well as spontaneous chiral symmetry breaking in QCD. Figure 1.4 shows the Higgs component of the quark mass vs. the QCD quark mass. Here the heavier quarks clearly draw their mass almost exclusively from the coupling to the Higgs field. Light quarks however, have a significant contribution from chiral symmetry breaking. In a very high density medium however, like the QGP, it is expected that chiral symmetry is restored and the quark masses reduce to their bare Higgs masses.

### 1.3 Heavy ion collisions and the Quark Gluon Plasma

Figure 1.5 shows the phase diagram for strongly interacting matter. Here the vertical axis is defined by the temperature, and the horizontal axis by the net baryon density



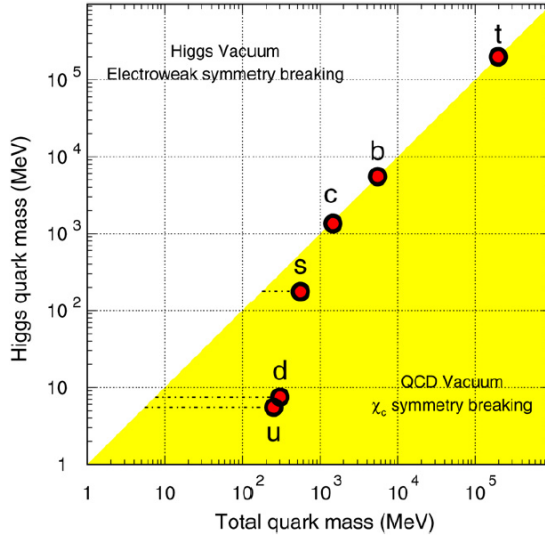


Figure 1.4: Higgs mass (i.e. the 'bare' mass) of the six quark flavours vs. their total mass (which is a sum of their bare mass and the contribution of chiral symmetry breaking). Heavy quarks contain almost exclusively Higgs mass, but the light quarks contain significant contributions due to the symmetry breaking. It is expected that the QGP the chiral symmetry is restored and light quarks masses reduce to their bare values [14].

(i.e. the number of baryons over antibaryons). Normal nuclear matter has a low temperature and low net baryon density.

By increasing the net baryon number density with equal temperature, equivalent to compressing the nuclear matter, a phase transition is expected to occur when the density reaches about four times that of normal nuclear matter. It should be noted though that before final phase transition occurs first a state is created consisting of a hadron gas in which the quarks are still confined. This situation is expected to exist in neutron stars. Conversely, when keeping the density the same while increasing the temperature, the phase transition will occur immediately at its critical temperature.

This second route of creating the QGP is both very interesting and very practical. First and foremost, it was created using heavy ion collisions. The Super Proton Synchrotron (SPS) at CERN pioneered this field of research, while the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory set a new benchmark in centre-of-mass energy, itself now overtaken by the Large Hadron Collider (LHC) at CERN when using lead-lead collisions. Secondly, the situation of low net baryon density and very high temperature very much resembles the state of the early universe about 10 microseconds after the big bang, see fig. 1.6. It is believed that the universe itself underwent a phase transition after it cooled enough as a result of its expansion to bind quarks into regular nuclear matter that forms most of the visible universe today.

The phase transition itself is first-order phase transition (i.e. non-continuous) up to about 1.5 times the net baryon density of regular nuclear matter. The point at which abrupt phase transition stops and a continuous crossover of a second order phase tran-

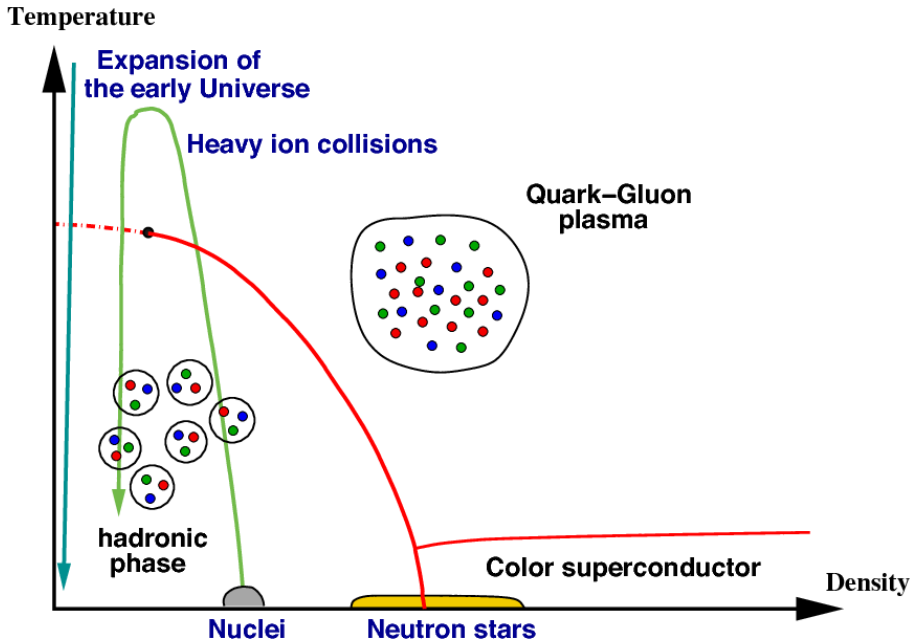


Figure 1.5: Phase diagram of strongly interacting matter with respect to the temperature of the system (vertical axis) and the net baryon density (i.e the compression of the system). At high enough temperature and/or compression a deconfinement of quarks and gluons occurs and the QGP is created. At low temperature but high net baryon density a continuous intermediate phase is reached first, where the quarks are still confined but the hadrons form an ideal gas. The point where the dashed line becomes a solid line is the tricritical point, which indicates where the phase transition becomes continuous instead of abrupt [15].

sition occurs (like in the case for low temperature, high density phase transitions) is called the tricritical point, whose location is dependent on the light quark masses (including the strange quark). The discontinuity of first-order phase transitions take place due to the latent heat involved in the transition. It also depends on the temperature and how many degrees of freedom become available during phase transition. Heavier quarks can participate if the temperature is high enough. In the case of collider experiments, where the nuclei collided consist almost exclusively of up and down valence quarks, this is of little importance.

Since 2010 the Large Hadron Collider has provided collisions of lead ions with a centre-of-mass energy per nucleon-nucleon pair of 2.76 TeV, and in the near future will produce collisions at 5.5 TeV. By studying these collisions the emergence of collective phenomena and macroscopic properties from the individual particle interactions and degrees of freedom.

At these energies the created QGP has a lifetime of about 10 fm/c. However, this is not the only process taking place during collision. Figure 1.7 shows a sketch of the four stages of a typical heavy-ion collision event. The first frame shows the approach of two Lorentz-contracted heavy ions. Note the appearance of heavy sea-quarks in the

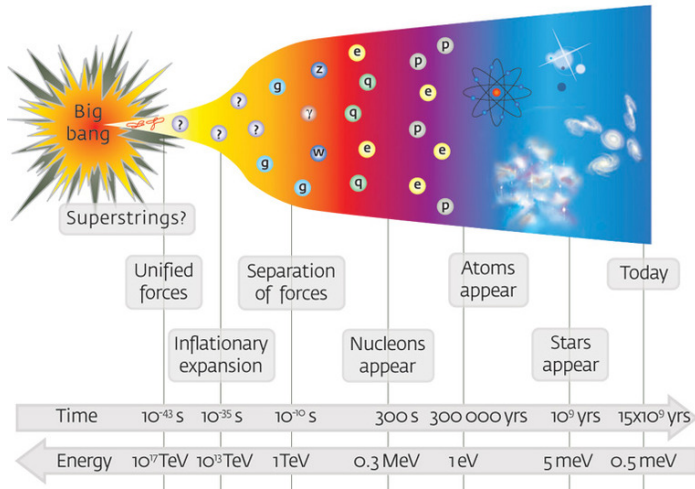


Figure 1.6: Sketch of the evolution of the early universe. It is believed that about 10 microseconds after the big bang the universe was filled with matter which was in a state similar to the Quark Gluon Plasma [16].

nuclei given by the purple colour. The second frame shows the initial impact. In this phase heavy quarks are scattered. The third phase is the formation of the QGP. The fourth and final frame the components of the QGP hadronises into hadronic matter.

Heavy quarks are scattered in the early stages of the collisions. In particular, they experience primary partonic interactions with large virtuality  $Q$ . This is equivalent with small time scales, since  $\Delta t \approx 1/Q$ . As the minimum value of  $Q$  for the production of a heavy quark-antiquark pair with mass  $m_q$  suggest a timescale of about  $1/(2m_q)$ , this is about 0.1 fm/c for charm quarks and 0.02 fm/c for beauty. These values are much lower than the QGP expected lifetime. As such, these heavy quarks have the ability to cross the medium and experience interactions with it, forming an effective probe of the medium. Therefore, they probe the entire lifetime of the QGP. This makes these heavy quarks valuable tools to study the QGP.

If one were to disregard the notion of the QGP (and cold nuclear effects), the evolution of the system in many particle collisions (like in heavy ion collisions) is very similar to that of proton-proton collisions, also performed at the LHC. To describe the former, the so-called Glauber model of a heavy ion collision regards the system as a superposition of many independent inelastic nucleon-nucleon collisions, called binary collisions. This means that the cross section (the interaction probability) for hard processes in heavy ion collisions can be extrapolated from proton-proton collisions by scaling the number of binary collisions of the two processes [18].

The presence of the QGP will result in radically different behaviour compared to a system of independent single hadron-hadron collisions, as the created medium will interact with the partons involved in the collision, resulting in medium effects. Heavy quarks which were created in the early stages of the collisions will experience

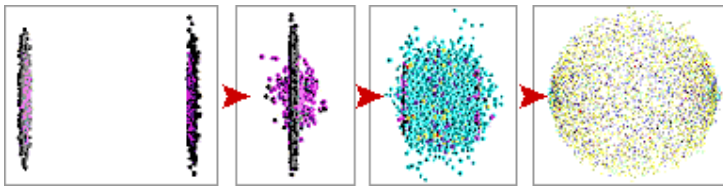


Figure 1.7: Sketch of the four phases of a typical heavy ion collision. From left to right, initial approach of two Lorentz contracted nuclei. Note the presence of sea quarks denoted in purple. Next, first impact of the two nuclei. Here hard scattering takes place, also for the heavy quarks. Then comes the creation of the QGP as deconfinement occurs. Finally, hadronisation takes place when the quarks become confined in hadrons once again [17].

the entire evolution of the system and interact with it, resulting in changes to their observables. this was first predicted by Matsui and Satz for the  $J/\psi$  meson [19]. As such, any measurable difference from a superposition of binary collisions will provide information about the medium. It is important to note that the medium of the QGP is not the only nuclear effect which influences the properties of the particles. There are also effects which are a result of the imbedding of partons in a nucleus, which are different from the physics of the hot and dense QGP medium. These are called cold nuclear effects.

Cold nuclear effects include phenomena like the Cronin effect, which causes an enhancement to the nuclear modification factor for intermediate- $p_T$  partons due to multiple interactions within the colliding nuclei causing broadening of the parton's transverse momenta [20, 21]. Initial state multiple collisions also give rise to cold nuclear matter energy loss, via radiative energy loss that is sensitive to the quark and gluon mass [22]. Also important is nuclear shadowing, where the nuclear modification factor is suppressed due to the fact that nuclear structure functions in nuclei are different from the superposition of those of their constituents nucleons [23].

One observable that can be investigated in order to gain information on the QGP is its influence on open heavy flavour and quarkonium production. Here open heavy flavour consist of mesons which carry one heavy flavour quark (charm and bottom) and one lighter quark (up, down and strange). Mesons of these types include the  $D^0$  ( $\bar{u}c$ ),  $D^{*+}$  ( $\bar{d}c$  in an excited state) and  $B^0$  ( $\bar{d}b$ ), where open charm mesons carry nonzero charm and bare bottom/naked beauty carry nonzero bottom. On the other hand, quarkonium consist of mesons consisting of a quark and its exact antiquark. Examples include  $J/\psi$  ( $c\bar{c}$ ) for charmonium and  $b\bar{b}$  for bottomium.

In order to quantify the medium effects caused by the QGP, and thus getting a handle on the mechanisms involved in ion-ion collisions, first a baseline on the observables in the case of absence of any medium effects is essential. For this detailed investigations of proton-proton collisions are required. In this thesis the heavy flavour cross sections in proton-proton events, in particular for the  $D^{*+}$  meson, are investigated. Another field of study are nucleon-nucleus (pA) collisions. In this collision system one can study cold nuclear effects like rescattering and nucleon energy loss.

The presence of the QGP in heavy ion collisions will result in a change of the observed kinematic distribution of heavy flavour quarks and even their total cross sec-

tion as a whole. Energy loss processes and flow (see subsection 1.4) can significantly alter the transverse momentum ( $p_T$ ) distribution of heavy flavour quarks, but are not expected to alter their total yields. The slope of the transverse momentum distribution will steepen, since the heavy quark  $p_T$  is reduced due to the energy loss.

In a detector with a limited acceptance range this has some profound effects on the detected yield (i.e. the number of detected heavy quarks). Depending on the detector's acceptance range, the yield may appear to be suppressed or enhanced.

If the quarks have a particular small transverse momentum ( $p_T < m_Q$ , where  $m_Q$  is the quark mass) and the medium has a collective motion (as is the case with flow), the quarks may pick up the velocity of the medium.

There are several sources for energy loss. First, elastic collisions with light partons may occur. This is designated as collisional energy loss. Secondly, gluon radiation may occur. This process is similar to Bremsstrahlung for electromagnetic processes and is also known as radiative energy loss. An interesting side effect for the process is the so-called 'dead cone' effect. According to Dokshitzer and Kharseev, soft gluon radiation is suppressed for heavy quarks at angles  $\theta_0 < m_Q/E_Q$ , effectively creating a cone along the quarks direction of travel inside the medium where no gluons are radiated, hence the name [24]. Since the dead cone effect scales with the quark mass, heavy quarks will loose less energy and will be able to probe deeper inside the medium. In particular, the suppression of the radiative energy loss at an angle  $\theta$  is given by the equation  $(1 + \theta_0^2/\theta^2)^{-2}$ .

## 1.4 Signatures of the Quark Gluon Plasma

It is impossible to observe the QGP directly, since its medium has a lifetime of about 10 fm/c and hadronises well before it can be measured by the detector. In addition, many of the particles the QGP hadronises into are also unstable, decaying long before they can be observed themselves. Nevertheless, the particles that do reach the detector can be reconstructed in order to get information of the medium from which they originated, including the formation and evolution of the QGP.

Unfortunately, there is no single observable that unambiguously proves the existence of the QGP and its characterisation. There are however several signatures that indicate its presence, some of which have been measured at the RHIC accelerator at Brookhaven National Laboratory (USA). One of these processes mentioned involves collective flow, as well as jet suppression and its quantisation called the nuclear modification factor. Both will be discussed in more detail below.

### Azimuthal anisotropy

The properties of the medium can be studied by evaluating the azimuthal momentum distribution of the emitted hadronised particles. Since ions are not point-like particles but have definite size, not every collisions will be head-on, but may only glance one another, with only a few nucleons involved in the creation of the QGP. The quantity that defines this measure is centrality, which ranges from 0 to 100%, where head-on collisions have a low centrality value and are called central events. Peripheral collisions have a high centrality value.

For central events the system can be considered in thermal equilibrium, most importantly because the mean free path of the particles involved is much smaller than the size of the system even though it is clearly not a static system, but also since there is no preferred azimuthal direction (the overlap between the two colliding nuclei is perfectly spherical). The resulting pressure in the medium creates a common velocity in the outgoing particles.

The collective flow of the medium includes a common radial expansion component affecting the thermal spectra of outgoing particles and is called radial flow. It also includes an anisotropic component, which influences the spatial orientation of particle momenta. This is called anisotropic flow, or azimuthal anisotropy. The most important contribution to anisotropic flow is elliptic flow. This is caused by semi-peripheral collisions as seen in fig. 1.8, where the overlap between the two nuclei is almond-shaped and the system is not in thermal equilibrium due to higher pressure near the centre than in the extremities, causing differences in resulting particle velocities. A prime observable associated with elliptic flow is the so-called  $v_2$  harmonic [25], which quantises the inhomogeneous expansion rate of the medium.

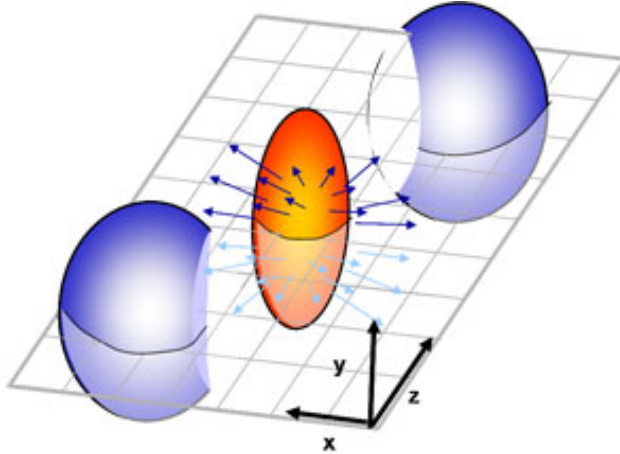


Figure 1.8: Drawing of two heavy ions just after a semi-peripheral heavy ion collision. Note how the medium is not homogeneous in the transverse plane. Pressure gradients in the medium mean that the medium will not expand at the same rate in every direction (as denoted by the arrows). This is the cause of the elliptic flow phenomena [27].

## Jet quenching

In QCD one defines a jet as a cascade of consecutive emissions of partons, started by a hard scattering of a quark or gluon. Since confinement does not allow these particles to exist separately, scattering them will result in the creation of new particles as the original pair becomes separated. This process is repeated until one observes a cone of particles with typically high momentum and high total energy, making these jets easily distinguishable in a charged particle tracking detector due to their highly lo-

calised high density of charged particle tracks, and the energy deposited in a hadronic calorimeter. Since hard scattering tends to produce quarks in pairs, it is a common feature to observe two back-to-back jets after a collision, as can be seen in fig. 1.9, where a schematical representation of so-called 'dijets' are shown, both as a result of a proton-proton collision and a heavy ion collision. It is even possible to observe three-jet events, depending on the number of quarks and gluons scattered.

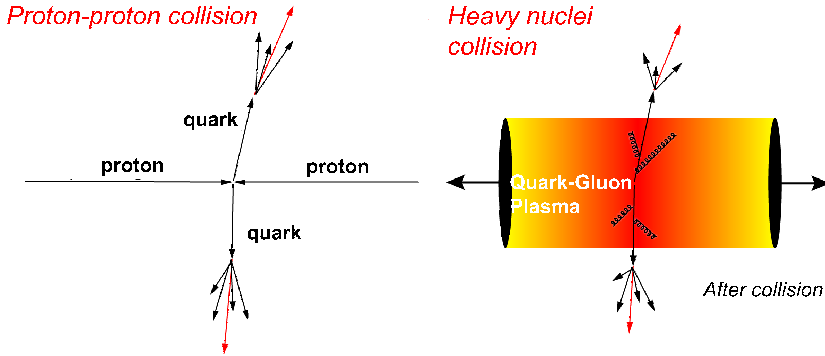


Figure 1.9: Dijets just after a proton-proton collision (left) and heavy ion collision (right). The presence of the medium will cause interaction between the jet particles and the QGP and thus energy loss for the former [28].

In the case of heavy ion collisions, the presence of the QGP will cause high- $p_T$  partons to undergo multiple interactions inside the medium before hadronisation, through the process of collisional energy loss and medium induced gluon radiation [29]. Here the latter process is dominant in the QGP. Since the two jets originate roughly in the same point inside the medium and rarely travel the same distance through it (especially if the dijet origin is close to the edge of the medium), this has the profound effect that one of the two jets carries remarkably less energy than the other one or even fully absorbed in the expanding medium. This effect has been named 'jet quenching' [26]. Since the QGP is expected to have significant influence on jet quenching, above and beyond any cold nuclear effects, it is used as a probe of the QGP.

The presence of the QGP will make itself known in a very distinct way when plotting the azimuthal distribution of the dijet. In the case of proton-proton collisions, a jet can be identified by triggering on the highest momentum particle, around which a cone is defined where all particles are attributed to that jet. If this high momentum triggering particle is set to the angle  $\phi = 0$ , this will result in a peak of the number of jets around this value (keep in mind that the angle of the trigger particle momentum can deviate somewhat from the average momentum of the jet as a whole), which is called the 'near-side peak'. Using similar methods another jet can be identified roughly at the opposite side, as the original particles are produced back-to-back in their centre-of-mass frame (but not necessarily the laboratory frame), which is repre-

sented in another peak in the histogram at  $\phi = \pi$ , the 'away-side peak'. This second peak will be wider, but should contain the same number of entries in proton-proton collisions.

In heavy ion collisions the scattered partons interact with the QGP. For the jet that has to travel the longest way through the medium, its constituents will lose more of their energy, possibly even enough to be absorbed into the expanding medium itself, obscuring the whole jet. This can lead to a much reduced away-side peak.

Closely related to jet quenching is the suppression of particle yields in the presence of the QGP. A hard scattered quark, even if it does not create a jet, is just as eligible to interact with the medium and lose energy, potentially becoming absorbed in the medium or will at the very least lose momentum. So by counting the yield of hard scattered partons one can also get a measure of the interaction with the QGP. Two things are important to realise: firstly, not all quarks behave equally in this respect. Heavy quarks tend to lose less energy due to the dead-cone effect and are only created during the initial scattering [29]. Lighter quarks can be produced in later phases of the collision when fragmentation occurs, courtesy of their lesser mass and the high temperature of the medium to cause pair creation.

Secondly, since there is no "near-side particle" to compare an "away-side particle" with, the particle yield of the quark under investigation will have to be compared with a baseline measurement using proton-proton collisions. Because of the different number of nucleons involved, the yields will have to be scaled to their number of binary collisions. The observable that describes this difference is the nuclear modification factor  $R_{AA}$ , which is the ratio between the yield in heavy ion collisions and the yield in proton-proton interactions, normalised using binary scaling. Formally:

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T}, \quad (1.2)$$

where  $dN_{AA}/dp_T$  is the normalised yield measured in heavy-ion collisions,  $\langle T_{AA} \rangle$  is the average nuclear overlap function (defined as the convolution of the nuclear density profiles of the colliding ions in the Glauber model) in the considered centrality range, and  $\sigma_{pp}$  is the production cross-section in proton-proton collisions. Since  $T_{AA} = N_{AA}/\sigma_{nn}$  (here  $\sigma_{nn}$  is the nucleon-nucleon cross section), this can be written as

$$R_{AA}(p_T) = \frac{Y_{AA}(p_T)}{\langle N_{AA} \rangle Y_{pp}(p_T)}, \quad (1.3)$$

where  $Y_{AA}$  and  $Y_{pp}$  represent the particle yield in nuclei-nuclei and proton-proton collisions, respectively. If the ion-ion collisions is simply a superposition of many independent nucleon-nucleon collisions, the  $R_{AA}$  is defined to be equal to 1. Cold nuclear effects and the hot medium are expected to change this value, with the contribution of the cold nuclear effects generally increasing this value, while the presence of the QGP will lower this value below 1.

## Results from the Relativistic Heavy Ion Collider (RHIC)

The RHIC accelerator at Brookhaven National Laboratory is the oldest operational heavy ion collider in the world. It has the ability to collide (among other particles) gold nuclei with a typical centre-of-mass energy of 200 GeV per nucleon-nucleon pair.



Two of its experiments are still operational, the Solenoidal Tracker At RHIC (STAR) and the Pioneering High Energy Nuclear Interaction eXperiment (PHENIX). Their technical details will not be discussed, but suffice to say both detectors performed investigations of the QGP phenomena and found evidence of flow and jet quenching.

In figure 1.10 the  $v_2$  harmonic is shown for several particles for both STAR and PHENIX at different particle momenta, as well as a comparison with several hydrodynamical models. The nonzero  $v_2$  values are a clear indication of collective behaviour and indicative of flow.

Results on the jet quenching are represented in fig. 1.11. The bottom plot shows that for central collisions the away-side jets are completely quenched. The top plot shows the nuclear modification factor for the  $\pi^0$  and  $\eta$  mesons as well as direct photons. Here the two hadrons have an  $R_{AA} < 1$ , the two detectors and compared with certain models. Conversely, the direct photons have an  $R_{AA} \approx 1$ . This is since they do not experience the strong interaction, which dominates the QGP.

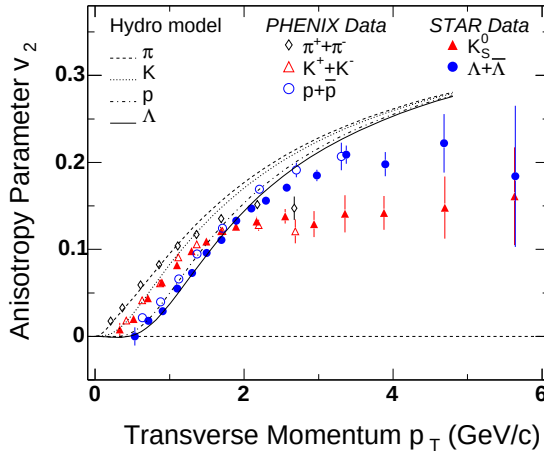


Figure 1.10: Graphs of the  $v_2$  of several particle species produced in 200 GeV collisions at RHIC versus their transverse momenta, both for PHENIX and STAR results. The nonzero value of  $v_2$  is a clear indication of collective behaviour of the particles in the medium due to an anisotropic reaction volume, suggesting the presence of elliptic flow [30].

## 1.5 Heavy flavour production

As mentioned in section 1.3, charm and beauty quarks are good probes of the QGP due to their short formation time compared to the lifetime of the medium, coupled with their reduced energy loss caused by their high mass, which means they experience the full development history of the medium. Moreover, heavy quark production by thermal processes in the QGP is smaller than the energy required to produce a quark-antiquark pair (compare  $\sim 0.7$  GeV thermal energy in the medium with about 2.55

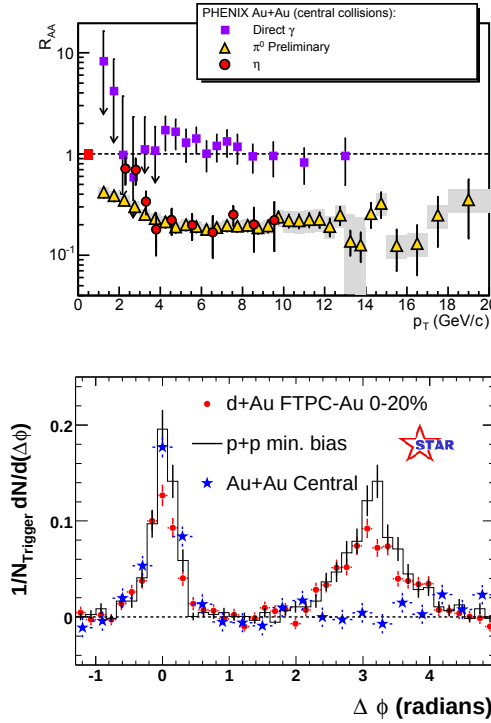


Figure 1.11: (top)  $R_{AA}$  of  $\gamma$ ,  $\pi^0$  and  $\eta$  at a function of the transverse momentum, measured by the PHENIX experiment [31]. The photons have an  $R_{AA}$  close to 1 while the hadronic particles have  $R_{AA} < 1$ . (bottom) Two-particle azimuthal correlation function from STAR [32]. In central gold-gold collisions the away side peak is suppressed.

GeV for charm-pair production). At any rate, these probes are reliable enough to get information on physical parameters describing the medium. It is possible to use perturbative QCD (pQCD) to determine heavy flavour production in nucleon-nucleon collisions, due to their high mass (specifically,  $m_Q > \Lambda_{QCD}$ , where  $m_c = 1.275 \text{ GeV}/c^2$  and  $m_b = 4.2 \text{ GeV}/c^2$ ).

From an experimental standpoint however, the non-perturbative contribution to heavy flavour production will have a noticeable effect. It is for this reason that proton-proton collisions are not only an essential baseline for nuclei-nuclei collisions for comparing heavy flavour yields, they can also be used to compare models on nonperturbative calculations. These calculations are performed by matching the resummation of logarithms of the transverse momentum over the mass of the quark at the next-to-leading-logarithm (NLL) accuracy, with the fixed-order exact next-to-leading-order (NLO) calculations for massive quarks (as a whole this is called first order next-to-leading log, or FONLL) [29].

PYTHIA is an event generator that uses pQCD calculations, which are exact only at leading order (LO). LO includes processes like pair creation ( $q\bar{q} \rightarrow Q\bar{Q}$  and  $gg \rightarrow Q\bar{Q}$ ). Some NLO processes are also included. Figure 1.12 shows some of the processes used in PYTHIA, like pair creation, flavour excitation ( $qQ \rightarrow qQ$  and  $gQ \rightarrow gQ$ ) and gluon splitting ( $g \rightarrow Q\bar{Q}$ ).

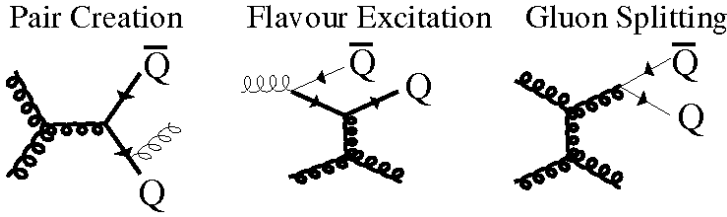


Figure 1.12: Feynmann diagrams of the leading order and next-to-leading order heavy-flavour creation processes as used by PYTHIA. The thick lines are associated with hard scattering processes. Thin lines represent initial state partons or final state jets [29]

Some of the more recent experiments measuring the heavy flavour production rate have been performed at Tevatron and RHIC. Figure 1.13 shows these results. These include the D meson production cross section measured at STAR and the  $D^0$  as well as beauty production at the CDF experiment at Tevatron. Both at RHIC and Tevatron (proton-proton collisions at  $\sqrt{s} = 1.96$  TeV) the best description of the differential cross section was obtained using the FONLL theoretical framework, which coincided with the fixed order (NLO) HVQMNR calculation in the low transverse momentum region, while being more accurate at high  $p_T$  where terms beyond NLO are partially accounted for in NLL resummation [29]. Both at CDF and STAR the theoretical prediction of the charm production fall slightly short. On the other hand, results at CDF do describe the beauty production fairly well [29].

Figure 1.14 shows the total charm production cross section for various experiments as a function of centre-of-mass energy, compared to PYTHIA and NLO pQCD calculations. Note that these values have been extrapolated from measurements from acceptors with a finite acceptance range. The PHENIX and STAR experiments have measured the charm production cross section only in a mid-rapidity range.

At any rate, experimental results showed that theoretical predictions did not fully describe the underlying mechanics of heavy flavour production, so proton-proton collisions at a centre-of-mass energy at 7 and finally 14 TeV at the LHC would further test perturbative and non-perturbative QCD in a new energy domain.

## 1.6 Open charm and D meson production

Charm is one of the heavy flavour quarks that can be used to probe the medium. Due to confinement, observing them is a matter of detecting the mesons that contain them after hadronisation. Charm quarks can typically be found in hidden charm configurations, where the charmness quantum number is equal to zero, like for the  $J/\psi$  particle (which has  $c\bar{c}$  as its constituents).

Another possibility are open charm configurations, where a charm quark is bound into a meson with a light antiquark. These mesons are the D mesons. In particular, they include the  $D^0$  ( $c\bar{u}$ ),  $D^+$  ( $c\bar{d}$ ),  $D^{*+}$  (an excited  $c\bar{d}$  state) and the  $D_s^+$  ( $c\bar{s}$ ). Note that the D mesons marked with an asterisk are in a spin triplet state (since  $J=1$ ), otherwise they are spin singlets ( $J=0$ ).

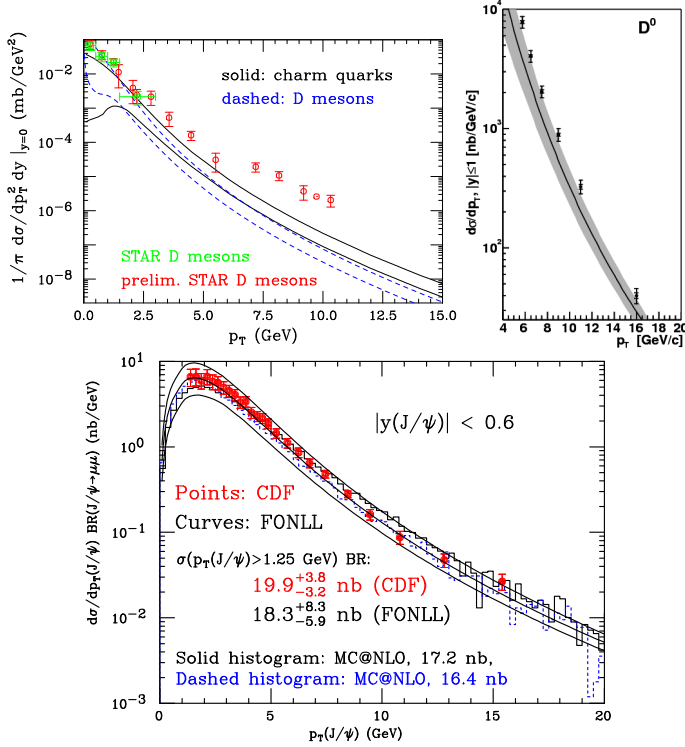


Figure 1.13: (top left) Comparison of the D meson production cross section versus  $p_T$  at the STAR experiment and the production rate expected according to FONLL calculations [29]. (top right)  $D^0$  differential cross section measured at the CDF experiment compared to FONLL [29]. (bottom) Beauty production measured at CDF compared to FONLL and MC@NLO calculations [29] [36].

Relevant decay channels within the scope of this thesis are [62]

$$\begin{aligned}
 c &\rightarrow D^0 + X & \text{BR} &= 0.565 \\
 c &\rightarrow D^{*+} + X & \text{BR} &= 0.224 \\
 b &\rightarrow B \rightarrow D^0 + X \\
 b &\rightarrow B \rightarrow D^{*+} + X
 \end{aligned} \tag{1.4}$$

The D mesons that come directly from a hadronised charm quark are called 'prompt' or 'direct' D mesons. When coming from the decay of a beauty quark, it is called B feed-down.

As mentioned in sect. 1.4, one observable to study the QGP is the nuclear modification factor  $R_{AA}$ , given by eq. (1.3), which would be smaller than one when experiencing in-medium energy loss. In the range of D meson  $p_T \leq 10$  GeV/c a smaller suppression is expected for D and B mesons compared to mostly gluon-originated light flavour hadron (like pions), due to the latter's mass being non-negligible and since the

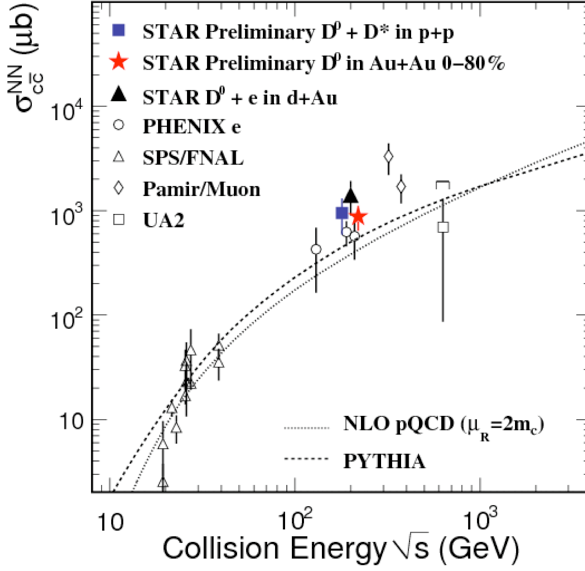


Figure 1.14: Total charm production cross section for various experiments as a function of centre-of-mass energy, compared to PYTHIA and NLO pQCD calculation [33].

scattered gluons interact more strongly with the medium compared to hard-scattered quarks. As such one expects  $R_{AA}^{\pi} < R_{AA}^D < R_{AA}^B$  [37] [38].

Figure 1.15 shows STAR and PHENIX results on the D meson  $R_{AA}$  as a function of its transverse momentum [34, 35]. The top figure shows the  $D^0$   $R_{AA}$  measured at STAR. At higher  $p_T$  the nuclear modification factor is indeed lower than 1. At low momentum the  $R_{AA}$  is actually larger, which can be attributed to the fact that charm quarks with high momentum will lose energy and end up with less momentum, causing them to be relatively abundant. Conversely, very low momentum charm will become largely absorbed by the medium and have low  $R_{AA}$  again.

Figure 1.15 also shows the single electron  $R_{AA}$ , where the single electrons come from D and B meson decays (red shows STAR results, blue for PHENIX).

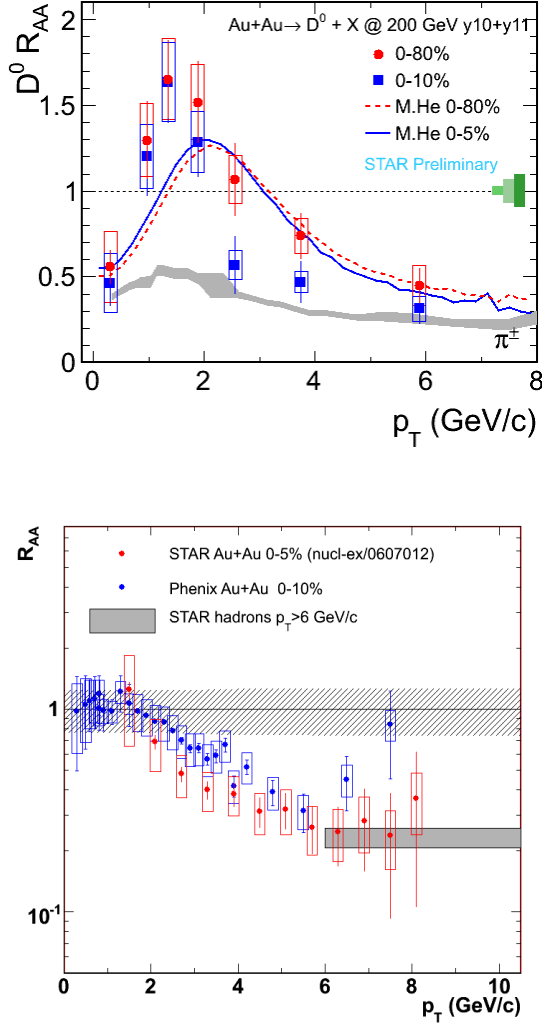


Figure 1.15: (Top)  $D^0 R_{AA}$  measured at STAR, for peripheral (red) and central (blue) collisions, compared to light hadron  $R_{AA}$  and corresponding models [34]. (Bottom) Single electron  $R_{AA}$  coming from D and B meson decays, measured by the STAR (red) and PHENIX experiments (blue) [35].

## 1.7 Theoretical models for parton energy loss in the Quark Gluon Plasma

The nuclear modification factor of heavy quarks in lead-lead collisions is calculated by several theoretical models, based on parton energy loss in the Quark-Gluon Plasma (QGP). This chapter will give a brief description of several models available that have been used to compare with the results of this work. While for this thesis these models are used to describe the average D meson nuclear modification factor, most can also be used to compute the charged-hadron and/or heavy flavour decay electron  $R_{AA}$ . Moreover, many these models can also be used to estimate the parameter  $v_2$  of the elliptic flow.

One of the goals of performing heavy ion collisions is the determination whether the medium produced is a weakly coupled gas of the quarks and gluons of the Quantum Chromodynamics (QCD) Lagrangian, or perhaps a strongly coupled fluid made up of emergent collective degrees of freedom. This also raises the question how does its description change with the centre-of-mass energy, momentum transfer and centrality.

Most of the models described are based on weakly coupled perturbative QCD calculations and include various energy loss mechanisms. In this case the calculations are focussed on parton energy loss via collisional or radiative processes, though earlier models often did not yet include radiative energy loss. On the other hand it was found that models considering medium induced gluon radiation as the dominant energy loss mechanism have difficulties reproducing large suppressions in heavy-flavour electron spectra [39, 40], which led to further work on collisional energy loss in models [41, 42]. Nevertheless, there are models based on strong-coupling non-perturbative QCD (non-pQCD), of which two will also be described.

### General considerations

Generally speaking, energy loss calculations for intermediate  $p_T$  partons requires a convolution of a hard production spectrum, followed by the energy loss in the medium and a fragmentation function. Though the details vary per model, the first stage usually consists of pQCD calculations to describe the hard processes where charm and beauty are produced. Most models vary at the second stage, where they describe parton energy loss in a medium that may or may not expand, have a running coupling constant, be weakly coupled parton gas or a strongly coupled fluid. The final stage describes the formation of hadron and/or hadronic electrons from the heavy and/or light quarks. Depending on the model certain parameters may be particular important. For example, pQCD energy loss calculations appear to have a strong dependence on the initial thermalisation time and pre-thermalisation conditions [43].

An interesting question is whether which parton energy loss mechanism dominates in heavy ion collisions, pQCD or non-pQCD, and to what extent. It will be shown in the final chapters that the statistical significances of the determined results are too large to definitely exclude most models. However, there may be a means of separating the two in the near future.

It is suggested that the ratio of charm suppression divided by the beauty suppression will provide decent evidence of the dominant energy loss process. In particular,

perturbative QCD calculation predicts a rapid rise of the ratio as a function of the  $p_T$  to one, since the pQCD calculation will become insensitive to the mass of the parent parton [44, 45]. On the other hand a fully non-pQCD treatment (like the AdS/CFT drag model) suggests a nearly  $p_T$  independent ratio significantly lower than 1 at about the ratio of the two quark masses [44, 45].

## WHDG energy loss model

The Wicks-Horowitz-Djordjevic-Gyulassy Opacity Expansion (WHDG) model is based on perturbative QCD, which includes both collisional and radiative energy loss [44, 45]. Specifically it is computed in a realistically described 1D Bjorken-expanding medium. The radiative energy loss equations were found via the use of standard Feynman diagram techniques, where the fact that the high- $p_T$  parton is created at a finite time was taken into account. Thermal field theory is used to correlate the medium density to the temperature, while temperature is related to the Debye mass and mean free path in a QGP. This means that in the WHDG model the only free parameter becomes the medium gluon density, where the strong coupling constant  $\alpha_s = 0.3$  is fixed and the geometry set by the colliding nuclei. It is assumed that the QGP density scales with the measured charged particle multiplicity via a proportionality constant found via a rigorous statistical analysis of the central RHIC  $\pi_0$  suppression data. This model has been developed to predict results gathered at the RHIC facility, but can be extrapolated to LHC energies, where the all parameters have been constrained by RHIC data. This model predicts that even at top LHC energies the elastic (i.e. collisional) energy loss provides a sizable  $\sim 25\%$  fraction of the total energy loss.

However, care must be taken when comparing the WHDG model with data as a large number of theoretical uncertainties have not been taken into account. This includes higher order effects in opacity, coupling, heavy quark mass (divided by parton energy), collinearity, initial conditions and energy loss in confined matter.

## Langevin HTL2

This model is based on a relativistic Langevin stochastic equation [47] [48], which itself is based on a picture of modifications to heavy quark spectrum, caused by the cumulative effect of multiple uncorrelated random collisions within the medium. Heavy-quark transport coefficients are evaluated by a pQCD approach, with a Hard Thermal Loop (HTL) resummation of medium effects for soft scattering.

The Langevin equation is part of an approach to model heavy flavour observable in proton-proton and heavy ion collisions, which uses next-to-leading order (NLO) pQCD calculations for the initial heavy-quark yields (generated using POWHEG [50], with CTEQ6M parton distribution functions as input and EPS09 nuclear corrections to the distribution functions for heavy ion collisions) complemented by the cold nuclear effects of shadowing, the Cronin effect and nuclear geometry effects.

For heavy ion collisions the Langevin equation is then solved numerically via a iterative procedure at a given proper-time to follow the stochastic evolution of the heavy quarks in the plasma up to hadronisation, taking place in a background medium described by relativistic hydrodynamics. Finally the propagated heavy quarks are made to hadronise and decay into electrons, according to the charm and beauty branching



fractions, while their momenta are sampled from a Petersen fragmentation function and finally decay into final state particles with PYTHIA.

In this approach the relativistic Langevin equation is used to describe the time evolution of the heavy-quark momentum, which involves a deterministic friction term and a stochastic noise term. The latter term involves the transverse and longitudinal transport coefficients, which are evaluated according to [49]. An intermediate cutoff is introduced to separate hard and soft scattering, where the hard collisions are evaluated via pQCD calculations.

For soft collisions a resummation of medium effects is provided by the Hard Thermal Loop (HTL) approximation. According to the scale  $\mu$  at which the strong coupling constant  $\alpha_s(\mu)$  to calculate the soft contribution is evaluated, the approximation is referred to as HTL1 (when  $\mu \propto T$ , where  $T$  is the temperature of the medium) and HTL2 (for  $\mu = |t|$ , with  $t$  the time). In this thesis only the second scale is employed.

### **Collisional energy loss and radiative energy loss via the Landau Pomeranchuk Migdal effect**

This model is based on pQCD collisional energy of heavy quarks in an expanding medium, to which radiative energy loss is included [51, 52]. The expanding plasma is described by a hydrodynamical approach, but neglecting an eventually hard component created by jets. Here the boost invariant model of Heinz and Kolb is used. It allows the calculation of two separate cases of the expansion; either a sudden transition from the QGP to the hadronic phase or a system that traverses a mixed phase. The latter is used for this thesis. Temperature and velocity are parameters required in this calculation to determine the interaction of heavy quarks with the medium. Also, for the LHC it is assumed that the soft thermalised component contains between 1600 and 2200 charged particles per unit of rapidity.

The collisional energy loss part of the model is based on a running coupling constant, determined from electron-positron annihilation and non-leptonic decay of  $\tau$  leptons. Furthermore, it uses an infrared (IR) regulator in the momentum-transfer channel, which is adjusted to give the same energy loss as calculated in a HTL approach. In particular, the energy loss calculated via pQCD matrix elements only agrees with those calculated in the hard thermal loop approach if a screening mass  $m \approx 0.2g_s^2 T^2$  is used, where  $g_s^2 = 4\pi\alpha_s$  with  $\alpha_s$  the strong coupling constant and  $T$  the temperature, making this the set parameter for this part.

The radiative contribution makes use of the "scalar QCD" approximation (sQCD) [53] (as well as a running strong coupling constant), which is appropriate at small or moderate gluon fractional momentum. The light-cone gauge is then taken and only the leading term in the centre-of-mass energy is kept. It can be shown that in this case gluon emissions from the light quarks do not contribute. By assuming massless quarks (i.e.  $\sqrt{s} \gg m_q$ ) it is possible to recover the model's matrix elements in factorised form from which an expression for the radiative differential sQCD cross section can be found. This has been used numerically in a framework called MC@<sub>s</sub>HQ [54], together with a specific radiative factor that partly cures IR-divergence of the elastic cross section, a collisional cross section described in [54] as well as a rigorous implementation of the phase-space constrain.

In the QGP environment the radiated gluons polarise the medium, which can be

incorporated into the model by imposing a thermal gluon mass  $m_g$  in the order of the Debye mass. This model also incorporated the Landau Pomeranchuk Migdal (LPM) effect, which are important to describe radiation from light partons in the medium as it encompasses multiple scattering.

### The Boltzmann Approach to Multi-Parton Scattering

The Boltzmann Approach to Multi-Parton Scattering (BAMPS) is a pQCD-based partonic transport model, which features inelastic  $2 \rightarrow 3$  processes (i.e. radiative and annihilation processes) based on the Gunion-Bertsch matrix element and includes light quarks and gluons [55]. Binary interactions involving light quarks and gluons are computed from leading order pQCD cross sections in a small angle approximation. The model incorporates a fixed strong coupling constant and freeze-out energy density. The LPM effect is modelled via the introduction of a cutoff that effectively discards coherent contributions from multiple induced gluon radiation. However a complex interplay of the Gunion-Bertsch matrix element and the effective implementation of the LPM effect, which causes a strong energy loss, is not included. This is also true for the  $q \rightarrow g$  conversions in jets.

Heavy quark elastic interactions with the gluon part of the medium are added using a running coupling constant and a Debye screening coming from HTL calculations. Radiative contributions are in this case accounted for by multiplying the cross section by a factor of four.

### The CUJET 1.0 Monte-Carlo model

CUJET 1.0 is a Monte-Carlo pQCD model of jet quenching in nuclear collisions [56]. It extends the development of models like the WHDG by including several dynamical features, requiring extra computational power, most easily accessible via Monte Carlo techniques. This is done to reduce large theoretical and numerical uncertainties in previous models, making it easier to distinguish between pQCD and non-pQCD models when limited experimental data is available.

The CUJET code features dynamical jet interaction potentials, the ability to calculate high order opacity corrections, full jet path proper time integration over expanding and diffuse QGP geometries, the ability to evaluate systematic theoretical uncertainties out of reach of analytical approximations, fluctuating elastic and radiative energy loss distributions, convolution of centre-of-mass and flavour dependent pQCD invariant jet spectral density and final fragmentation decay distributions.

The code uses Monte-Carlo techniques to compute finite order opacity contributions to the jet-medium induced gluon radiative spectrum. Here in the multiple collision gluon radiation part the effective (Debye screened) potential is replaced with a normalised but path dependent effective dynamical transverse momentum exchange distribution, generalised from the pure HTL dynamically magnetically screened model. Also included are fluctuations of radiative energy loss and the probability distribution of radiating a fraction of energy. Elastic energy loss is included as in for the WHDG model.

Where in WHDG the expansion of the medium is taken into account by a mean proper time expansion, the CUJET Monte Carlo integrates numerically arbitrary proper

time evolution, allowing the study of several uncertainties. The results used in this thesis assume a sudden thermal freeze-out of the medium. The pQCD initial jet flavour invariant proton-proton cross sections were computed with the Leading Order (LO) pQCD CTEQ5 code, with NLO and First Order Next-to-Leading Logarithm (FONLL) charm and bottom quark invariant cross sections for LHC energies. Also, a charge-particle pseudo-rapidity density of 1600 was assumed, with further parameters constrained by data from the RHIC facility, like the opacity, the multiplicity per unit of rapidity and the strong coupling constant.

### **BDMPS-ASW radiative model**

In the model by Baier, Dokshitzer, Mueller, Peigné, Schiff and Armesto, Salgado, Wiedemann the pQCD factorised formalism for leading hadron production is used with the addition of radiative parton energy loss [57]. In order to get the baseline without parton energy loss the PYTHIA event generator was used, using CTEQ 4L parton distribution functions with EKS98 nuclear corrections. The event generator contains all the relevant partonic subprocesses and gluon splitting. It also accounts for the possibility that a quark-antiquark pair is created by (vacuum) gluon radiation from the primary partons created in the hard collision, an effect negligible at RHIC but significant at the LHC. The parameterisation of fragmentation functions is based on the string model implemented in PYTHIA, in particular it generates proton-proton events which contain charm or beauty quarks, while corresponding heavy flavour mesons are forced into semi-electronic decay. For LHC energies a tuning of PYTHIA is used that reproduces the shape of the transverse momentum distributions for charm and beauty quarks given by pQCD calculations at NLO with CTEQ 4M parton distribution functions.

Medium-induced parton energy loss depends on medium density and the in-medium path length, which can be characterised in terms of the time-dependent BDMPS transport coefficient that denotes the average squared transverse momentum transferred from the medium to the hard parton per unit length. Here the effects of a time-dependent density of the medium on parton energy loss can be accounted for by an equivalent static medium. The quenching weights for light quarks and gluons are available as a FORTRAN routine. This has been extended to include massive quarks. Partons that lose their entire energy due to medium effects are redistributed according to a thermal distribution, for which a temperature of 300 MeV has been assumed.

### **Dissociative and radiative models**

The radiative model developed by Vitev et al. is based on perturbative QCD, which focusses on parton energy loss via radiative and collisional processes [58]. However, a newer version includes the contribution of effective energy loss via meson dissociation in the QGP. For heavy ion collisions the geometry of the interaction is based on the Glauber model, so contributions from cold nuclear effect are included.

It is possible to use the light-cone description of hadrons and the operator definitions of distributions and decay probabilities from perturbative QCD to calculate the charm and beauty distribution and fragmentation functions in a co-moving plasma. Determination of the D meson suppression was done using an instant wave approx-

imation, relevant to an out-of-equilibrium jet propagation through the medium when the timescale of the onset of thermal effects exceeds the formation time.

### Method based on lattice QCD

This method, developed by Rapp et al. employs a framework that implements a strongly coupled QGP in both micro- and macroscopic components of the calculation [59]. It includes a hydrodynamic medium evolution, quantitatively tuned to hadron observables, as well as being combined with non-perturbative T-matrix interactions for both heavy quark diffusion (compatible with lattice QCD) and hadronisation in the QGP. In particular, heavy quark kinetics in the medium can be described by Brownian motion, which are implemented via relativistic Langevin simulations. Here the medium evolves is approximated by ideal hydrodynamics, which is employed by the AZHYDRO code [60, 61]. It also utilises a lattice QCD equation of state with pseudo-critical deconfinement temperature of 170 MeV and a subsequent hadron-resonance-gas phase with chemical freeze-out at 160 MeV to account for the observed hadron ratios.

### AdS/CFT drag model

The Anti de Sitter/Conformal Field Theory (AdS/CFT) drag model is based on a fully non-perturbative QCD treatment for heavy quark energy loss in a medium as found by the RHIC experiment [44, 45]. Here the Feynman diagrammatic approach in four-dimensional space-time is replaced by a classical string derivation in five dimensions. Again it assumes that the medium density scales with the observed charged particle multiplicity, while keeping all other parameters the same.

Note that the calculations on the AdS/CFT drag model were performed in  $\mathcal{N}=4$ SYM [46], not QCD, and in the limit where the number of charm quarks goes to infinity and that the path length is large. Moreover, the drag calculations assume that the quark mass is very large compared to the temperature of the plasma, which may not hold particularly well for charm quarks. Finally there is upper bound to the velocity of the heavy quark for which the AdS/CFT derivations are applicable. This upper limit depends on the mass, path length and temperature.

This model has many theoretical uncertainties, starting with the fact that calculations are done in  $\mathcal{N}=4$ SYM instead of QCD. Also higher order corrections from e.g. loops and quark mass to plasma temperature have not been taken into account.



## Chapter 2

# The ALICE detector and analysis environment

### 2.1 General overview

The experimental setup used for this thesis is the ALICE detector, which stands for A Large Collider Experiment. It was built and is operated by a collaboration of over a thousand physicists, engineers and technicians worldwide, with 105 institutes from 30 countries contributing. It is one of the four main experiments associated with the Large Hadron Collider (LHC) and constructed at interaction point 2 (IP2), the same location the L3 experiment was located when the Large Electron-Positron Collider (LEP) was operational and from which ALICE inherited its solenoid magnet.

ALICE is designed as a general-purpose heavy-ion detector, but with a definite focus on QCD related effects and the only dedicated heavy-ion experiment at CERN [63]. It enables the investigation of hadrons, electron, muons and photons that are produced directly and indirectly in heavy ion collisions up to the highest particle multiplicities expected to occur at maximum LHC centre-of-mass energies of 5.5 TeV per nucleon-nucleon pair for heavy ion collisions. ALICE also operates during proton-proton runs, as this data provides the required baseline to compare the heavy-ion results with, but also to complement other detectors with regards to other strong-interaction studies.

Though the second smallest of the four experiments related to the LHC, it is still a massive piece of hardware, measuring  $16 \times 16 \times 26 \text{ m}^3$  and weighing about ten thousand tons. It consists roughly of two parts: the central barrel which houses inside the L3 solenoid magnet (which creates a  $B = 0.5\text{T}$  magnetic field) a variety of detectors for particle reconstruction within 45 to 135 degrees from the beamline, and a forward muon spectrometer. A sketch of the ALICE detector is depicted in figure 2.1.

From the inside-out, the central barrel consists of the Inner Tracking System (ITS) at the centre and a Time Projection Chamber (TPC) for tracking and vertexing and in the case of the TPC also particle identification. The former is subdivided into two planes each of high-resolution silicon pixel, drift and strip detectors (SPD, SDD and SSD, respectively). Next is the Transition Radiation Detector (TRD), Time-of-

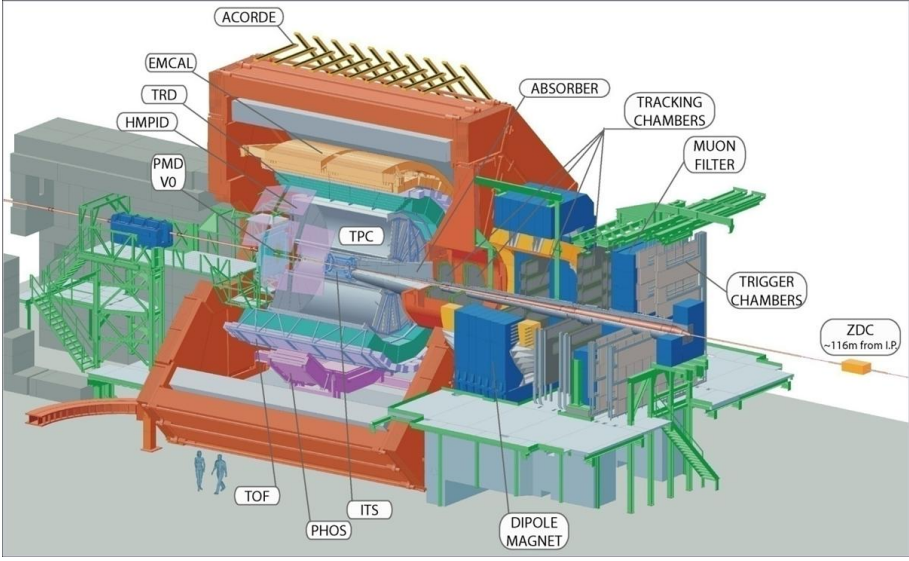


Figure 2.1: The central barrel consists of the Inner Tracking System (ITS), a Time Projection Chamber (TPC), the Transition Radiation Detector (TRD), Time-of-Flight (TOF), the High Momentum Particle Identification Detector (HMPID), a Photon Spectrometer (PHOS), Electromagnetic Calorimeter (EMCAL), the Photon Multiplicity Detector (PMD), Forward Multiplicity Detector (FMD), the T0 and V0 detectors. The forward muon arm consists of layers of absorbers, a dipole magnet and fourteen planes of tracking and triggering chambers. At  $\sim 114$  meters on both sides from the interaction point there are Zero-Degree Calorimeters. The top of the solenoid magnet is covered by the ACORDE.

Flight (TOF) and a Ring Imaging Cherenkov detector called the High Momentum Particle Identification Detector (HMPID), which are used for particle identification. The Photon Spectrometer (PHOS) and Electromagnetic Calorimeter (EMCAL) are two electromagnetic calorimeters. Except for the HMPID, the PHOS and EMCAL all these detectors cover the full azimuthal range. Close to the beam pipe are also the Photon Multiplicity Detector (PMD), Forward Multiplicity Detector (FMD) and T0 and V0 detectors used for event characterisation and triggering.

The forward muon arm, which has an acceptance at an angle of two to nine degrees to the beamline, consists of layers of absorbers, a dipole magnet and fourteen planes of tracking and triggering chambers. Also, at about 114 meters on both sides from the interaction point there are Zero-Degree Calorimeters for further event characterisation and the top of the solenoid magnet is covered by an array of scintillators of the ACORDE to trigger on cosmic rays.

It should be noted that not all components of ALICE have been fully installed. As of the writing of this thesis only 10 of the 18 TRD modules are installed, as well as three of the four PHOS modules.

Though this thesis will only cover the subdetectors related with  $D^{*+}$  reconstruction, it is worth mentioning that ALICE was designed with a broad range of physical

observables in mind, which were previously covered by AGS (Alternating Gradient Synchrotron), SPS and RHIC in more specialised experiments. Aside from the physics requirements, the design of the ALICE was largely driven by the expected experimental conditions, primarily the extreme particle multiplicity in lead-lead events. This was expected to have been up to three orders of magnitude more than in proton-proton collisions at the same centre-of-mass per nucleon pair and up to five times larger than particle multiplicities measured at RHIC. As such, the ALICE design was optimised for a particle multiplicity density of  $dN/d\eta = 4000$  (where  $\eta$  is its pseudorapidity), but its operation was also tested for multiplicity densities up to twice that number using simulations. The ALICE uses three dimensional hit information with up to 159 space points, allowing for robust tracking even in a cluttered environment.

In order to study various physical processes, ALICE allows for a broad momentum range, spanning over three orders of magnitude starting from particle momenta of several tens of MeV/c (useful for studying collective events at large length scales and resonance decays) up to over 100 GeV/c (important when investigating jet physics). This achieved by a low material budget of 7.7%  $X_0$  for the ITS to reduce multiple scattering for low  $p_T$  particles. A tracking lever arm of up to 3.5 m and a 0.5 T magnetic field ensure good resolution at high  $p_T$ . Also, by employing subdetectors (such as the TPC, TOF, TRD and HMPID), ALICE employs several particle identification techniques. The ALICE detector central barrel allows measurements midrapidity, where the baryon density is lowest but the energy density is expected to be at a maximum.

The detector acceptance should enable reconstruction of particle decays even at low momentum, but also jet fragmentation and separation of individual events where several thousand reconstructed particles per event can be expected. Therefore the subdetectors cover a rapidity range of roughly two around midrapidity for the central barrel. For the forward muon-arm it is approximately 1.5 units of rapidity. The interaction rate of the ALICE with nuclear beams at the LHC is about 10 kHz for lead-lead collisions and the resulting radiation doses are less than 3000 Gy [63]. These comparatively low numbers allow employment of the TPC and SDD detectors, which have rather slow readout but high granularity. Selective triggers at operating level are used to enrich certain rare signals.

However, some rare signals are very difficult to select at trigger level. These include heavy flavour decays. In order to reconstruct these signals a very large sample of events is required (which can be selected on their centrality), permanently stored using a high bandwidth data acquisition system of 1.3 GB/s.

Within the scope of this thesis three of the ALICE subdetectors were the most employed. The ITS was primarily used for vertexing and tracking. The TPC was the primary tracker and used for particle identification. The TOF was used for particle identification as well. Next subsections will go into greater detail on these subdetectors.

### 2.1.1 Inner Tracking System

Six concentric cylindrical layers of silicon detectors make up the ITS, which are located at radial distances of about 4, 7, 15, 24, 39 and 44 cm from the beamline (which in the following is defined as the z-axis). As a whole the ITS covers the pseudorapidity range of  $|\eta| < 0.9$  (though inner layer covers up to 1.98), valid for all vertices



located within 5.3 cm before or after the expected interaction point along the z-axis. It has a material budget of about 7.7 % radiation length in the transverse plane over its pseudorapidity range and full coverage over the azimuth. The design of the ITS is optimised for efficient track finding and displaced vertex reconstruction with a transverse impact parameter resolution smaller than  $65 \mu\text{m}$  for transverse momenta larger than  $1 \text{ GeV}/c$ , effective for determining secondary decay vertices. Figure 2.2 shows a schematic representation of the six layers of the ITS.

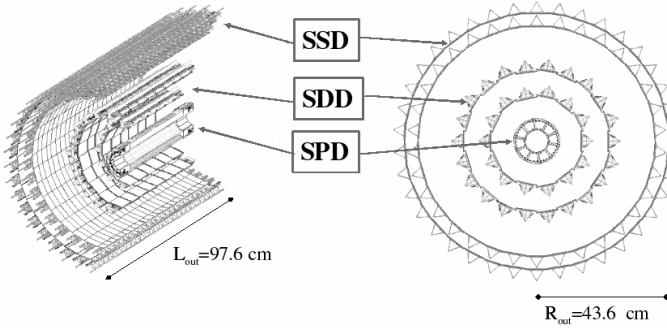


Figure 2.2: Schematic representation of the design of the ITS [29]. Six layers of silicon detectors are used for vertexing and charged particle tracking. The inner two layers form the Silicon Pixel Detector (SPD). The two middle layers form the Silicon Drift Detector (SDD) and the outer layers are the Silicon Strip Detector (SSD). The active detector surfaces are attached to modules that appear triangular when viewed from the side.

The inner two layers form the Silicon Pixel Detector (SPD), the two middle detectors encompass the Silicon Drift Detector (SDD). The outer two layers are the Silicon Strip Detector, built with strong involvement of Utrecht University (UU) in Utrecht (the Netherlands), whose outer radius is governed by the fact that the ITS is required to fit inside and match tracks with those from the TPC. Conversely, the inner radius was limited by the radius of the beam pipe (3 cm).<sup>1</sup> The first layer has a more extended coverage ( $|\eta| < 1.98$ ), due to the simple fact that it's closer to the beamline, which provides together with the FMD a broad rapidity coverage range for charged-particles multiplicity measurements of  $-3.4 < \eta < 5.1$ . Other details about the ITS layers can be found in table 2.1.

The choice of detector for the three layers was determined by the requirements on the impact parameter resolution, which is presented in fig. 2.3. Due to the high particle density (which could reach up to  $80 \text{ particles cm}^{-2}$ ), pixel detectors have been chosen for the innermost two layers to provide the necessary granularity. The smaller particle density in the middle two layers ensured silicon drift detectors would suffice. Double-sided silicon micro-strip were used for the outer two layers since there the densities were expected to be less than one particle per  $\text{cm}^2$ .

<sup>1</sup>Now that the LHC has been running for some time, and the behaviour of the beam is well under control, it has been suggested that for a future upgrade of the ALICE detector another pixel layer could be introduced inside the beampipe [67].

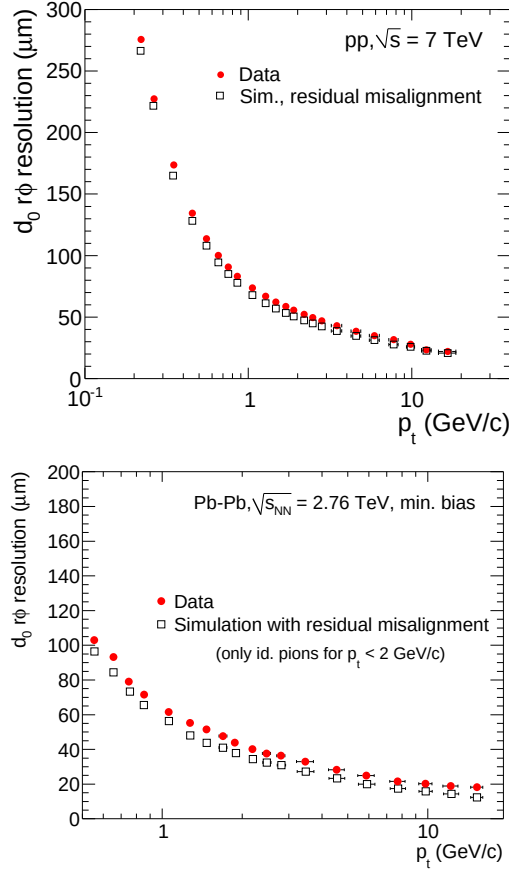


Figure 2.3: Impact parameter resolution of ITS+TPC tracks for proton-proton [72] (top) and lead-lead collisions [74](bottom). Data (red) has been compared with Monte-Carlo simulations (boxes) with residual masalignment has been introduced.

Except for those of the SPD, all layers are able to perform particle identification via  $dE/dx$  measurement for non-relativistic particles, enabling the ITS to operate as a stand-alone low- $p_T$  particle spectrometer. Furthermore, the ITS provides a functionality for tracking low momenta charged particles that have tracks that have a too curved and therefore too short of a track inside the TPC for the latter to reconstruct the track. This is called the ITS stand-alone method and is effective in the momentum range  $p_T \sim 70 - 200 \text{ MeV}/c$ . Naturally, when working in conjunction with the TPC the increased tracking arm length the ITS will also increase the momentum resolution for high  $p_T$  particles.

Using survey information, cosmic particle tracks and data from proton-proton collisions it was possible to perform alignment on the ITS sensor modules in order to improve the space point resolution. Following this, the residual misalignment in the detectors'  $r\phi$  plane is about  $8 \mu\text{m}$  for the SPD and  $15 \mu\text{m}$  for the SSD [66]. For the SDD this number was determined to be about  $60 \mu\text{m}$  even for those modules that did

not suffer from significant drift field non-uniformities [66]. At any rate, these numbers are used to emulate the misalignment effects in detector simulations.

Table 2.1: General information on the six silicon detector layers of the ITS [63, 66].

| Layer     | Radius (cm) | $\pm z$ (cm) | $ \eta $ | $\sigma_{r\phi}$ ( $\mu m$ ) | $\sigma_z$ ( $\mu m$ ) |
|-----------|-------------|--------------|----------|------------------------------|------------------------|
| 1 (SPD 1) | 3.9         | 14.1         | 1.98     | 12                           | 100                    |
| 2 (SPD 2) | 7.6         | 14.1         | 0.9      |                              |                        |
| 3 (SDD 1) | 15.0        | 22.1         | 0.9      | 35                           | 25                     |
| 4 (SDD 2) | 23.9        | 29.7         | 0.9      |                              |                        |
| 5 (SSD 1) | 38.0        | 43.1         | 0.9      | 20                           | 830                    |
| 6 (SSD 2) | 43.0        | 48.9         | 0.98     |                              |                        |

### 2.1.2 Time Projection Chamber

The TPC is a gas detector, shown in fig. 2.4, and operates as the main tracking device, chosen for its robust tracking capabilities. Despite that the TPC design has disadvantages with regards to its slow speed when handling the data volume (requiring the LHC to have a reduced interaction rate with nuclear beams at the ALICE interaction point of about 8 kHz to prevent data stacking), its the only design conservative enough to have the redundancy to guarantee reliable performance when tracking in the excess of over ten thousand charged particles. As such the TPC principle has already been successfully used in previous experiments like STAR, ALEPH and NA49.

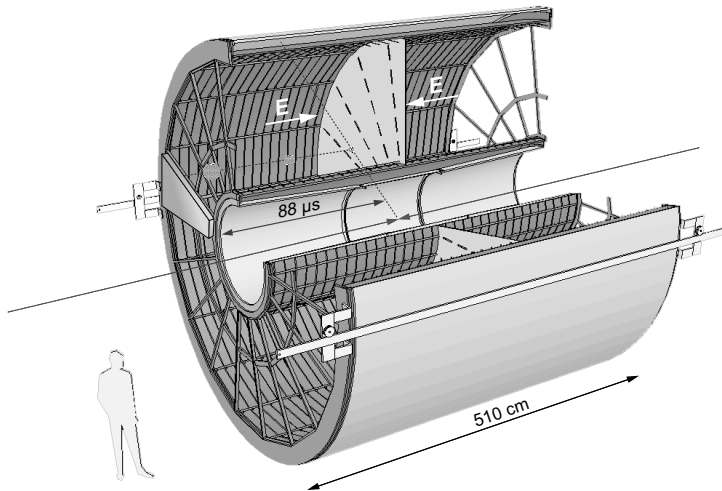


Figure 2.4: Drawing of the TPC. The active volume (filled with a Ne/CO<sub>2</sub>/N<sub>2</sub> gas mixture) is divided into two halves by a cathode, creating two opposite electric fields. Readout electronics are attached to the cathode and anodes of the TPC.

The ALICE TPC is designed to enable charged particle tracking and particle identification. It is required to handle the LHC design luminosity for lead-lead collisions. It was expected that 10 percent of these interactions would be central collisions, conservatively overestimated to correspond with a particle multiplicity of eight thousand particles per unit of rapidity and 20,000 primary and secondary charged particle tracks in acceptance.<sup>2</sup> An amount that surpasses every other TPC design so far.

The TPC covers  $2\pi$  in azimuth and  $|\eta| < 0.9$  in pseudo-rapidity. With an inner radius of 85 cm, an outer radius of 247 cm for the active volume and 500 cm of active length in the z-direction it has 90 m<sup>3</sup> of worth of 85.7% Ne, 9.5% CO<sub>2</sub> and 4.8% N<sub>2</sub> gas mixture. Its large volume enables tracking with up to 159 three-dimensional space points with a position resolution of 1100-1250  $\mu\text{m}$  in the  $r\phi$  plane and 800-1100  $\mu\text{m}$  in the z-direction. Furthermore, for low momenta particles (up to 1 GeV/c) the momentum resolution is 1-2% (depending on the magnetic field), while for the high  $p_T$  region up to 100 GeV the resolution is 10% when used in conjunction with the ITS and TRD, which obviously requires good track matching. More details can be found in table 2.2.

Table 2.2: Technical details on several aspects of the TPC. [71]

|                        |                                                      |
|------------------------|------------------------------------------------------|
| $\eta$ range           | [-0.9,0.9] for full radial track length              |
| $\eta$ range           | [-1.5,1.5] for 1/3 radial track length               |
| Material budget        | $X/X_0 \in [2.5, 5]\%$ for $ \eta  < 0.9$            |
| Drift length           | $2 \times 2.500\text{mm}$                            |
| Drift field            | 400 V/cm                                             |
| Drift velocity         | 2.84 cm/ $\mu\text{m}$                               |
| Maximum Drift time     | 88 $\mu\text{s}$                                     |
| Event size (for dN/dy) | $\pm 60$ MB                                          |
| Event size (for pp)    | $\pm 1\text{-}2$ MB (depends on pile-up)             |
| Data rate limit        | 400 Hz (Pb-Pb minimum bias)                          |
| Trigger rate limits    | 200 Hz (Pb-Pb central events)<br>1000 Hz (pp events) |

The TPC is also capable of particle identification by measuring the specific ionisation energy loss ( $dE/dx$ ). It has a  $dE/dx$  resolution of 5.5% for isolated tracks, determined using cosmic ray muons and proton-proton data [68], which increases to 6.8% when the particle multiplicity density as a function of the rapidity reaches 8000 [63].

### 2.1.3 Time-Of-Flight detector

Further particle identification is performed by the Time-Of-Flight detector, an array of Multi-gap Resistive Plate Chambers (MRPCs) placed in a cylindrical configuration at a radius of 370 to 399 cm from the beamline. It consists of 152,928 sensitive pads

<sup>2</sup>For comparison, the charged particle multiplicity at ALICE for  $|\eta| < 0.5$  is measured to be  $dN_{\text{charged}}/d\eta = 1601 \pm 60$  in the 5% most central PbPb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV [64], about 2.1 times higher than at RHIC operating at top heavy ion collision energy [65].

for readout, each 2.5 by 3.5 cm<sup>2</sup> large for a total of about 140 m<sup>2</sup> of active surface. It covers the full azimuth and has a pseudorapidity range of  $|\eta| < 0.9$ . Figure 2.5 shows one of the supermodules that form the TOF.

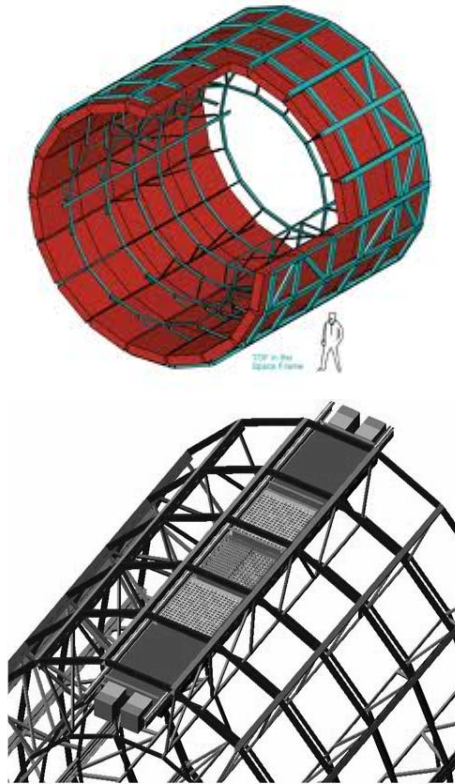


Figure 2.5: Technical design of the TOF. (top) The TOF is constructed using various supermodules that cover the whole azimuth and absolute pseudorapidity range  $< 0.9$ . Part of several TOF modules have been removed in this picture to improve visibility. (bottom) Detailed view of a TOF supermodule.

The TOF operates in conjunction with the T0 detector, two arrays of Cherenkov counters located at +350 cm and -70 cm from the centre of the TPC along the beamline and covering  $\eta \in [4.61, 4.92]$  and  $\eta \in [-3.28, -2.97]$ , respectively. The particle identification is based on the difference between the expected time-of-flight for a particular particle and its measured value, where the T0 detector is used to determine the start time. The expected value depends on the particles mass hypothesis computed from its track length and momentum. When no T0 signal is present, the time-of-flight is estimated using particle arrival times at the TOF.

The TOF is able to achieve a time resolution better than 100 ps. For Pb-Pb collisions in the centrality range of 0-70% the resolution is even 90 ps for pions with a momentum of 1 GeV/c. For the centrality range 70-80% the TOF resolution worsens slightly because of an increasing uncertainty on the start time measurement, but is still below 100 ps. For these Pb-Pb events this includes the uncertainties on the detector

intrinsic resolution, the contribution of the electronics and calibration, the tracking and momentum resolution and the start time of the event. For proton-proton events this last contribution has not been accounted for yet, so the combined time resolution between TOF and T0 will be about 160 ps. Effectively this means that time-of-flight measurement enables separation of kaons and pions up to a momentum of about 1.5 GeV/c for proton-proton collisions. For heavy ion collisions the separation of protons, kaons and pions is possible up to about 2 GeV/c. Figure 2.6 shows the TOF particle identification separation when using the kaon hypothesis for lead-lead collisions.

The TOF was used in correspondence with the TPC. Here the latter provided a compatibility cut on the particle identification response in order to decrease the contamination from tracks with wrong hit association in the TOF.

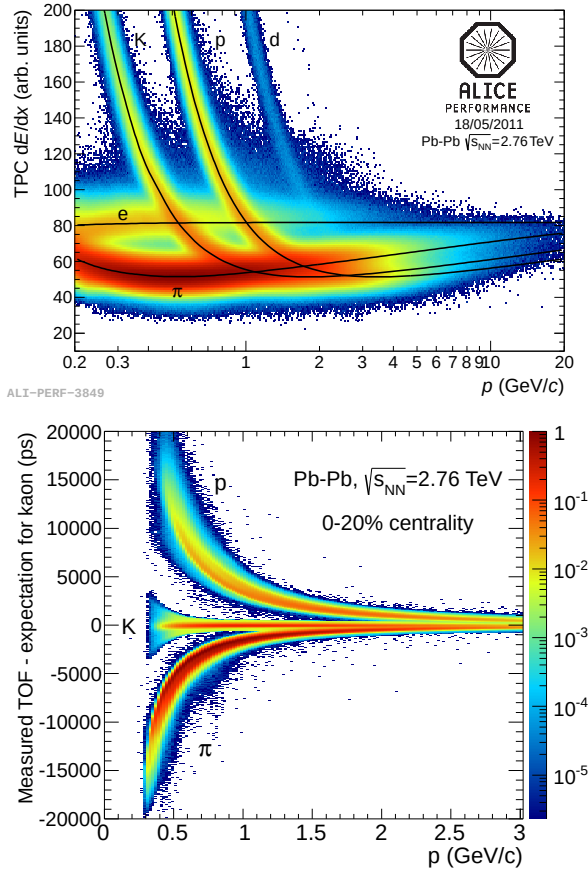


Figure 2.6: (top) Specific ionisation energy loss for charged particles in the TPC as a function of the particle momentum. This figure shows the energy loss for five common particles in the case of proton-proton collisions with a centre-of-mass energy of 7 TeV. (bottom) Difference between the measured time-of-flight and the expected value assuming the measured particle is a kaon as a function of the track momentum. These results are for the lead-lead collisions in the centrality range 0-20% [74].

### 2.1.4 Triggering

Event triggering was performed using the SPD and V0 detectors. The V0 consists of two arrays of 32 scintillators tiles which cover the full azimuth for the centrality ranges  $\eta \in [2.8, 5.1]$  (V0-A) and  $\eta \in [-3.7, -1.7]$  (V0-C). For proton-proton events the minimum bias collisions were triggered by demanding at least one hit in either V0 detector or the SPD, coinciding with the arrival of two proton bunches at the interaction point. It has been estimated that this trigger would be sensitive to 87% of the proton-proton inelastic cross section. Moreover, it has been verified using Monte-Carlo simulations (using the PYTHIA 6.4.21 event generator using Perugia-0 tuning) that this trigger is 100% efficient for D mesons with a transverse momentum higher than 1 GeV/c and absolute rapidity smaller than 0.5. Beam-induced background contamination was rejected offline using the timing information from the V0 detector as well as the correlation between the number of hits and tracklets in the SPD.

In the ALICE experiment the instantaneous luminosity was limited by the TPC refresh rate, and as such was reduced to  $[0.6, 1.2] \times 10^{29} \text{cm}^{-2} \text{s}^{-1}$  by displacing the proton beams in the transverse plane by about 3.8 times their root mean square of their transverse profile to decrease the interaction probability per bunch crossing to 4-8%, with a collision-pile up probability less than four percent per triggered event.

For heavy ion collisions two different interaction trigger configurations were employed. During one data-taking period there was the requirement of signals from two out of the three triggering detectors. Another period demanded a coincidence between the two V0 detectors. Event selection was continued further offline to remove background parasitic beam interactions using timing information coming from the V0 and neutron ZDC detectors. It has been confirmed that in all the hadronic interactions that were triggered on had timing information from the ZDCs available.

It is possible to categorise a collision with respect to its centrality. Here the centrality is defined as the percentile of the total hadronic lead-lead events and was determined using the distribution of the summed amplitudes in the V0 scintillators. A Glauber model function for the geometrical description of the nuclear collision (complemented by a two-component model for particle production) was then fitted to the distribution [69] [70]. This has been done in fig. 2.7. The fit has been applied to a centrality range where the trigger reaches 100% efficiency for hadronic interactions and contamination from electromagnetic process were negligible.

## 2.2 The analysis framework

The basis of the offline analysis framework for both simulations and analysis is centred around the ROOT software. This software application was started in 1994 for the NA49 heavy ion experiment. It has been written fully in the C++ programming language and makes full use of the latter's object oriented programming capabilities. Using the opportunities granted by object oriented programming, it is possible to extend its capabilities to both remote and distributed analysis, dynamical extensions, addition of user-constructed macros and libraries and more. It offers users various way of interacting with the software, namely via command line, batch scripts and even graphical interfaces.

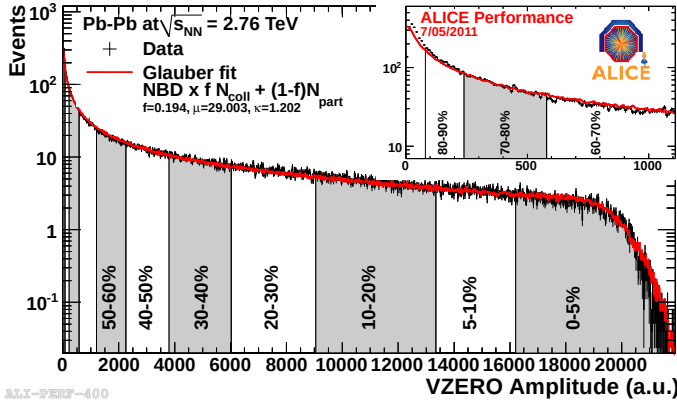


Figure 2.7: Multiplicity distribution for Pb-Pb events as measured by the V0 detector, with the corresponding centrality class included in the histogram and a Glauber model fit applied.

The actual ALICE offline framework is named AliRoot. It is designed to reconstruct and analyse data from both actual collision data as well as Monte-Carlo simulations. In the latter case it is capable to generate the simulated data as well, performing the necessary calculations to simulate the particle interactions at the interaction point, the interaction of particles with the detector hardware and the generated signal in a detector's active surface or volume. The software is designed in layers, where each layer corresponds with a specific phase of data generation, reconstruction and analysis, analogue to the real life steps of particle collisions, track reconstructing and data analysis in an operational detector.

The first layer is associated with real-life particle collisions. Here the Monte-Carlo event generators designated as PYTHIA and HIJING simulate the production of a list of final-state particles, with corresponding momenta and rapidity distributions as they propagate from the interaction point. As these propagating particles cross the detector's hardware their interactions are simulated by the GEANT3 transport code. At this second layer the various particle decays, ionisations, multiple scattering, pair creations, energy depositions and other physical processes that the propagating particles can undergo are taken into account. New particles that are a result of these interactions will also be included. Each original and new particle is traced up till the moment it leaves the full ALICE detector volume or its energy drops below a predesignated threshold. These two simulation layers are done via two external libraries, since they are not ALICE specific.

The third layer quantises the ALICE detectors' responses to the particle interactions and makes use of the ALICE specific code. Simulated particle interactions are translated into specific detector responses, or hits. Any (residual) detector misalignments are taken into account for these responses. This corresponds to the phase of real particles generating hits in the actual detector.

From this point the digitisation software formats the results from the detector responses to an output according to the specifications of the detector's front-end electronics and data acquisition system. For simulations the software is again ALICE



specific and thus part of the internal AliRoot libraries and subroutines. Hardware noise can be emulated by introducing smearing. The simulated output is very close to the actual output generated by the detector when operational.

Up to this point simulations and real data are very separate, the former generating simulated data using the AliRoot framework (which can be done virtually), the latter having the actual ALICE detector register output data. However, both sets of data will end up in the same format and are handled identically by the last layer of the AliRoot analysis chain, which is the event reconstruction. Here offline algorithms reconstruct space points, which are in turn used to create track candidates and gain additional track information on parameters like energy loss, momenta and particle identification. Furthermore, global event characteristics like multiplicity, centrality and the primary vertex are registered. All this information is then stored in a specific file format called the Event Summary Data (ESD). It is worth noting that simulated data does contain information of the simulated particles that the framework uses to reconstruct tracks, something actual data obviously lacks.

Though the ESD contains all the information stored and can be readily used to evaluate physical phenomena, the size of these datafiles make them slow and cumbersome to use. As such, the information is usually distilled into files called Analysis Object Data (AOD). Here the information contained in the ESDs is filtered according to the requirements of a user (usually one of the physical working groups in the ALICE collaboration) who is interested in specific physical phenomena. If quantities are unimportant for a specific analysis, or if required parameters fall outside the physical relevant range, the information is removed from inclusion in the AOD. Furthermore, information that remains can be translated into other forms more suitable for the follow-up analysis and stored in AODs. For example, information on tracks can be combined to create data on possible particle candidates.

At this point user-designed macros can be used to evaluate the data in the AODs to gain information on the relevant physical processes. These macros can be custom-built for certain analyses, but for mainstream physical parameters the framework contains extensive libraries to perform standardised analyses. Most of the results in chapter 5 are made using these standard macros.

However, even using AODs the amount of data that needs to be analysed remains massive, often far too large for what a single consumer-grade computer can realistically handle. Fortunately, the framework can also be executed on a single remote computing farms like the CERN Analysis Farm (CAF) or spread over several using the GRID, the latter also functioning as a catalogue of available remote storage elements. At any rate, the computing time required for a specific analysis generally depends on the complexity of the collisions, where the analysis of proton-proton data can take as little as a few minutes when using the GRID, up to days for lead-lead data.

## 2.3 Charged particle tracking and vertexing

The process of track reconstruction and vertexing could fill a thesis in its own right, especially considering the high particle multiplicity that was expected at the ALICE detector. However, the translation of detector hits to particle tracks and vertices forms the basis of all physical parameters stored in AODs. As such it will briefly be ex-

plained in this section.

The track finding procedure employed within the central barrel is based on a technique commonly employed in high-energy physics experiments, namely the Kalman filter. It enables both track recognition and reconstruction by providing the optimal estimate of the track geometrical patterns at any point along the track. It implements energy loss and multiple scattering and enables track matching between different sub-detectors like TPC and ITS.

The reconstruction employs an algorithm where the Kalman filter is employed iteratively. It starts at the outside of the TPC, where track density is the lowest. Here track candidates (or seeds) are identified which are then extended iteratively towards the inner edge of the TPC. When all seeds from the TPC are extrapolated in this way the tracking is continued in the ITS, prolonging the tracks from the TPC up to as close to the primary vertex as possible. Next an ITS stand alone procedure is executed, where it is attempted to reconstruct tracks through unassigned ITS clusters, which correspond to particle tracks not found in the TPC due to a  $p_T$  cut-off, dead zones between TPC sectors or decays.

Next the tracking procedure is started again, beginning at the vertex and continued to the outer rim of the TPC, the tracks are extrapolated further into TRD, TOF, HMPID and PHOS detectors. However, within the scope of this thesis this was limited to the TPC and ITS. Finally, the tracks are refitted backwards to the primary vertex (or as close to the centre as possible for secondary tracks). If a track passes this final refit, it will be used further for secondary vertex reconstruction. Track information is then stored in ESDs.

Track information is stored by approximating particle trajectories by helices that can be fully described by five parameters. Two govern the track geometry in the  $z$  direction, and three describe the geometry in the transverse plane. Also a 5 by 5 covariance matrix is added which contains at any given point the best estimate on the errors on the parameters and their correlations.

Primary vertex reconstruction is performed using the two layers of the SPD. The algorithm evaluates the  $z$  coordinate distribution of the reconstructed hits in the first pixel layer. When the distribution is symmetric the primary vertex is very close to  $z=0$ . If however the primary vertex is displaced along the  $z$ -axis the distribution is no longer symmetric, and the centre of the distribution no longer corresponds with the primary vertex. However, for small displacements (no more than  $\pm 12$  cm) the correlation between the distribution centres of both pixel layers is considered.

For the reconstruction of the primary vertex in the transverse plane, one can take advantage of the small radii of the pixel layers at only 4 and 7 cm distance. As such, the deviation from a straight line is small, especially for high momentum particles and a reasonable result can be achieved with a linear approximation. Moreover, when a good result of the vertex  $z$ -coordinate has been found the combinatorial background can almost be reduced to zero. The distribution of intersections of all straight lines connecting the points on the two pixel layers with randomly displaced  $x$  and  $y$  axes has its minimum width if the origin of the displaced axis is at the true vertex coordinate, which can be found via an iterative procedure.



## Chapter 3

# $D^{*+}$ reconstruction and analysis strategy

Making use of the track reconstruction and vertexing procedure described previously, this chapter introduces the strategy for the  $D^{*+}$  reconstruction via the  $D^{*+} \rightarrow D^0 \pi_{\text{soft}}^+ \rightarrow K^- \pi^+ \pi_{\text{soft}}^+$  hadronic decay channel. Furthermore, the decay topology defines a multitude of observables on which can be cut in order to increase the statistical significance of the  $D^{*+}$  signal compared to the combinatorial background which arises from uncorrelated pairs of tracks. These 'cuts', their kinematical properties and the procedure to optimise them are explained in more detail in this chapter.

The D meson reconstruction strategy in general is based on the reconstruction and selection of secondary vertex topologies that are significantly separated from the primary vertex. Since the  $D^{*+}$  decays via the strong interaction, its secondary vertex and the primary vertex are practically inseparable. As such, the cuts will have to be applied to a daughter particle decay topology. For this thesis the  $D^0$  is evaluated.

In order to decrease the combinatorial background the  $D^{*+}$  reconstruction makes use of the particle identification capabilities supplied by the TPC and TOF. Some details on their selection parameters will also be mentioned.

Following this procedure it becomes possible to obtain the  $D^{*+}$  yield in both proton-proton collisions as well as in heavy ion collisions of various centralities by extracting the signal from the reconstructed  $D^{*+}$  invariant mass spectrum. This can then be used for the determination of the relevant  $D^{*+}$  nuclear modification factor, which will be elaborated upon in the following chapters.

This chapter will not show the cuts used in this thesis, since the values of these cut parameters differed for proton-proton and lead-lead collisions. As such, they will be presented in chapter 4 for proton-proton interactions and chapter 5 for heavy ion collisions.

### 3.1 $D^{*+}$ reconstruction

The reconstruction of the  $D^{*+}$  mesons is done via its hadronic decay channel, given by  $D^{*+} \rightarrow D^0 \pi_{\text{soft}}^+$  (as well as its charge conjugate), a strong decay with a branching ratio

(BR) of  $67.7 \pm 0.5\%$  [62]. Given that it is a strong decay, the  $D^{*+}$  has a decay length of  $c\tau = 0.1\mu\text{m}$ , its decay vertex can not be distinguished from the primary vertex. Topological selection cuts are applied on the  $D^0$  to obtain a distinctive signal in the invariant mass difference between the  $D^{*+}$  and the  $D^0$ . The difference is about  $145.5\text{ MeV}/c^2$ , only slightly above the pion mass, so the decay pion has a low momentum for low  $D^{*+}$  momentum and is called the "soft pion" ( $\pi_{\text{soft}}^+$ ).

Before finalising the reconstruction strategy of the  $D^{*+}$ , first the reconstruction of its  $D^0$  decay daughter needs to be discussed in detail.

### 3.1.1 $D^0$ reconstruction

The  $D^0$  hadronic decay channel is given by  $D^0 \rightarrow K^- \pi^+$  with  $\text{BR} = 3.87 \pm 0.05\%$  [62]. The  $D^0$  has a  $c\tau = 123\mu\text{m}$ , which results in a significantly displaced secondary decay vertex. For a typical two-prong decay of one neutral mother into two charged daughter particles, the determined decay vertex is the secondary vertex and starting point of the daughter particles. This secondary vertex can be reconstructed using particle tracks by finding the minimum spatial distance of the two helices representing the two daughter tracks of opposite charge. Figure 3.1 shows a sketch of the reconstructed secondary vertex in a typical  $D^0$  to  $K^- \pi^+$  decay using two track helices.

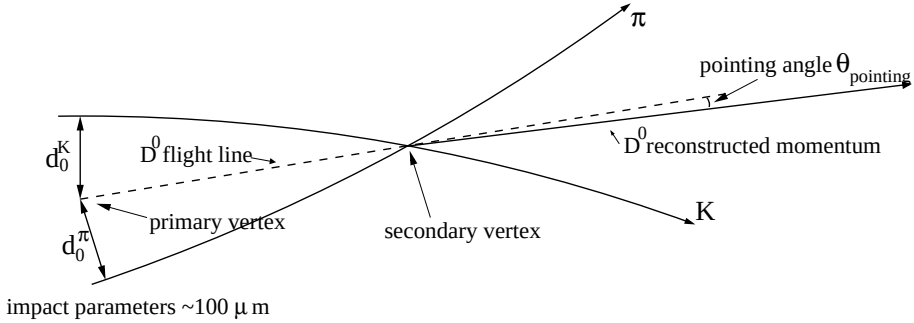


Figure 3.1: Topology and some kinematical variables of a  $D^0$  meson decay, for which a primary and secondary vertex have been reconstructed as well as two tracks with opposite charge. Tracks can be prolonged to the primary vertex. Visible are the definition of the impact parameters, the distance of closest approach and the  $D^0$  flight line.

It is impossible to determine directly which tracks correspond to a  $D^0$  decay, so it is necessary to evaluate all tracks and reconstruct the  $D^0$  candidates. Here  $D^0$  candidates were defined using pairs of tracks which have the correct charge sign combination and at least 70 associated space point in the TPC with  $\chi^2/\text{ndf} < 2$ . There was also a requirement of several hits in the ITS, one of which had to come from the SPD. These tracks were also selected on their pseudorapidity and momentum as to fall well inside acceptance region of the central barrel ( $|\eta| < 0.9$ ) to decrease the combinatorial background.

Since most of these  $D^0$  candidates will not correspond with an actual  $D^0$  decay, the cuts are used to remove candidates that have physical parameters which will not

be compatible with those expected for a real  $D^0$  decay. This is why the reconstruction exploits the displacement of the secondary vertex from the primary vertex, since a certain displacement can be attributed to the lifetime of the  $D^0$  meson and is a good selection parameter. Moreover, the difference between the primary and secondary vertex should correspond to the  $D^0$  flight line, which needs to correspond to the candidate's momentum reconstructed from the daughter tracks. These selections and several more will be discussed in more detail in the next section.

## 3.2 Selection cuts

The cut parameters are applied at several levels. The first level is the collision event itself, where only those events are accepted that correspond to the physical situation under investigation. An important selection is whether a primary vertex can be reconstructed at all for a certain collision event. Other selections like the centrality of the collision for heavy ion events also fall in this classification.

The selections are also applied at the track reconstruction level. Here tracks are selected if they meet certain detector requirements. The aforementioned requirements on the TPC space points and ITS layers are part of this. The results of the TOF and TPC particle identification fall under this header as well.

As important as previous cuts are, they are nevertheless mostly selections on event and track quality. In order to properly separate signal from background for the  $D^0$  candidates, it is necessary to evaluate the decay topology corresponding to a candidate. For this multiple selections on single and two-track properties are applied, mostly benefitting from the secondary vertex displacement associated with the  $D^0$  decay.

The cuts are applied in order to optimally separate the signal from the combinatorial background. Without proper selections the  $D^0$  signal would be comparable with statistical fluctuations and be impossible to extract. To properly separate the signal, it has to be greater than the background fluctuations. For this the statistical significance has been defined, given by

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

where  $S$  and  $B$  are the number of entries in the signal and background around the signal range (i.e. three times the  $D^0$  signal peak width around the mean signal value), respectively. Since the statistical fluctuations are the square root of the total number of entries (i.e.  $\sqrt{S+B}$ ), the significance is a good comparison of the signal and the error. A significance value of at least three was demanded to consider a signal distinguishable from the combinatorial background.

In order to maximise the significance it is necessary to optimise these cuts. This is an essential but involved operation and varies depending on the analysis performed. It is discussed in more detail in section 3.3. However, it will also be explained that a set of selections that maximised the statistical significance was not necessarily the 'best' set of cuts.

Furthermore, there is the risk that background fluctuations would cause distortions on the shape of the signal peak, resulting in anomalous quantities of the signal peak position and width, requiring them to be checked against PDG values and simulation results.

Most importantly though, the topological cut values depend on the D meson transverse momentum and the centrality of the event in the case of heavy ion collisions. Higher transverse momentum leads to a greater displacement of the secondary vertex and less tight cuts to separate the real D mesons from the combinatorial background. More central events have higher multiplicity and require stronger cuts to distinguish signal from background. A summary of the various cuts discussed in the following sections is given in table 3.1.

Table 3.1: Summary of the various cuts used within the scope of this thesis.

| Cut class               | Name of cut                                                                                                                                                                                                                                                                                                                                                                                                                                         | unit/parameter                                                                                                                                                                                                                              |
|-------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Event selection         | Event trigger<br>Collision centrality<br>Primary vertex I<br>Primary vertex II<br>Magnetic field<br>Presence of $D^{*+}$ (AOD only)                                                                                                                                                                                                                                                                                                                 | Hits SPD & V0<br>Track multiplicity<br>Reconstructed?<br>Nr. outgoing tracks<br>Present?<br>Present?                                                                                                                                        |
| Track quality           | Clusters in ITS<br>Clusters in TPC<br>ITSrefit<br>TPCrefit<br>TPC Track quality (reduced $\chi^2$ )<br>Kink candidate tracks<br>$p_{TK;\pi}$<br>$p_{T\pi_{\text{soft}}}$<br>fiducial acceptance cut                                                                                                                                                                                                                                                 | nr. of clusters<br>nr. of clusters<br>refitted?<br>refitted?<br><br>included?<br>(GeV/c)<br>(GeV/c)<br>pseudorapidity                                                                                                                       |
| Topological cuts        | $D^0 m_{\text{inv}}$<br>Distance of Closest Approach (dca)<br>$\cos \theta^*$<br>$p_{TK}$<br>$p_{T\pi}$<br>$d_{0;K}$<br>$d_{0;\pi}$<br>$d_{0;K} \times d_{0;\pi}$<br>$\cos \theta_{\text{pointing}}$<br>$m_{\text{inv};D^{*+}} \frac{1}{2} \text{width}$<br>$\frac{1}{2} \text{width} \Delta M$<br>min. $p_{T\pi_{\text{soft}}}$<br>max. $p_{T\pi_{\text{soft}}}$<br>$\theta$<br>$\cos \theta_{\text{pointing}XY}$<br>Normalised Decay Length (NDL) | (GeV/c <sup>2</sup> )<br>(cm)<br><br>(GeV/c)<br>(GeV/c)<br>(cm)<br>(cm)<br>(cm <sup>2</sup> )<br><br>(GeV/c <sup>2</sup> )<br>(GeV/c <sup>2</sup> )<br>(GeV/c)<br>(GeV/c)<br><br>$\cos \theta_{\text{pointing}XY}$<br>(GeV/c <sup>2</sup> ) |
| Particle identification | TPC particle id. selection<br>TOF particle id. selection                                                                                                                                                                                                                                                                                                                                                                                            | distribution width<br>distribution width                                                                                                                                                                                                    |

### 3.2.1 Event selection

The event selection starts at detector level with the trigger. The trigger is based on hits in the SPD or V0 detectors that coincide with the arrival of particle bunches at the interaction point. The minimum-bias triggers varied in details depending on whether it involved proton-proton collisions or heavy-ion collisions (for example, for proton-proton events one hit in the SPD or V0 sufficed, while lead-lead events demanded at least two hits in the SPD and/or hits in at least two out of the three triggering detectors), which will be summarised in their respective chapters. Further offline beam-induced background events were rejected using timing information of the V0 and also the hit-tracklet correlation information in the SPD (for proton-proton events) or timing information of the ZDC (heavy-ion collisions). For Pb-Pb collisions it was also possible to select on the collision centrality using information on the track multiplicity.

Aside from the triggering selection, further cuts were required on the event at analysis level. This was primarily to ensure no events were selected that lacked quantities that were required for proper vertexing and tracking. Therefore, events for which no primary vertex could be reconstructed were rejected, as well as those without magnetic field. As an additional insurance of quality, no events were accepted that had primary vertices that were determined with less than one contributing track. This thesis will focus on  $D^{*+}$  reconstruction, so any AOD events that did not contain information on D meson candidates were rejected too.

### 3.2.2 Track selection

In order to further decrease the combinatorial background it is imperative to limit the evaluation of  $D^{*+}$  candidates to those whose associated daughter tracks pass certain quality checks. These checks come in the form of cuts to the quantities of the track. These include the number of clusters in the TPC and ITS, and whether or not these reconstructed tracks have been refitted in said detectors and if these tracks had kinks. The goodness of the track through the detector hits in the TPC is ensured by a reduced  $\chi^2 < 2$ . Hits in specific ITS layers is also required, typically by demanding clusters in the SPD). A minimum track transverse momentum of 300 MeV/c is also set, as tracking accuracy at lower value decreases significantly. A fiducial acceptance cut was also applied, where the selection on the pseudorapidity depended on the particle  $p_T$ .

For tracks that are designated as possible soft pion tracks the same cuts are applied, though with different values. Since this particle has the possibility to have very low momentum the minimum momentum is set down to zero (depending on the candidate's momentum), and since its track can be significantly curved the TPC requirements are typically released. These tracks are usually reconstructed via the ITS stand-alone method of the detector.

### 3.2.3 Topological cuts

The selection of  $D^0$  mesons makes use of the separation of the primary vertex and secondary vertex and several parameters which are expected to have distinctive values for the decay topology of an actual  $D^0$  decay. These can be for single daughter tracks



or for combinations of tracks. Some are already visually sketched in fig. 3.1. These parameters depend on the reconstructed  $D^{*+}$  momentum.

The transverse momentum of the daughter particles (which are defined as the transverse momentum of the kaon and pion for a  $D^0$  decay, or  $p_{T_{K,\pi}}$ ) are already discussed as part of the reconstruction selection cuts. However, since the daughter particles of a  $D^0$  decay are created back-to-back in the rest frame of the  $D^0$ , their momentum in the lab frame depends largely on the  $D^0$  momentum and thus even the momentum of the original  $D^{*+}$ , which makes them viable parameters to use for cuts optimisation.

The decay angle selection parameter makes full use of the fact that the daughter kaon and pion are produced back-to-back in a rest frame of a  $D^0$  decay, or more specifically, the cosine of the decay angle given by  $\cos \theta^*$ . This is defined as the angle between the kaon and the  $D^0$  flight line in the  $D^0$  rest frame. More formally this can be written as  $\cos \theta^* = (p'_{\parallel} - \gamma_f |\beta_f| E) / (\gamma_f p)$ , where  $p'_{\parallel}$  denotes the kaon momentum measured along the  $D^0$  flight line. The total energy and momentum of the decay products in the  $D^0$  rest frame is given by  $E$  and  $p$  respectively. Here  $\beta_f$  is the velocity of the  $D^0$  rest frame with respect to the laboratory frame (where speed of light  $c = 1$  for convenience). Finally the Lorentz factor is given by  $\gamma_f = (1 - \beta_f^2)^{-1/2}$ .

Since in the  $D^0$  reference frame the kaon is not expected to have a preferred emission, the corresponding  $\cos \theta^*$  is expected to be uniform. The equation is only valid for actual  $D^0$  decay daughters and not the random track combinations of the combinatorial background. It was thought that the decay angle tends to accumulate at  $|\cos \theta^*| = 1$ . So by applying a cut on the cosine of the decay angle below this value should have the potential to remove a significant portion of the background while retaining most of the signal.

Since the information of a particle track is stored as the information of a helix with corresponding covariance matrix, it is possible to prolong a track back towards the primary interaction point (even if it comes from a secondary interaction). This allows for the definition of a signed impact parameter  $d_0$  of the prolonged track of the primary vertex. This was limited to only the transverse plane as it gives the best accuracy.

Previous studies [29] [71] have shown that the dominant contribution to the background at  $|d_0|$  larger than about  $500 \mu\text{m}$  comes from decays of kaons and hyperons, while there is almost no signal. So this cut can be applied to reduce the combinatorial background. However, care must be taken since this selection parameter is not independent from other cuts which can alter the background and signal distributions. As such, this cut parameter is not fixed and can also be optimised for the different  $D^0$   $p_T$  bins.

Another parameter that distinguishes the  $D^0$  from the background is the product of impact parameters  $d_{0,K} \times d_{0,\pi}$ . This parameter is particularly important since it is associated to the  $D^0$  decay length of  $123 \mu\text{m}$  [62]. Since the distance between secondary and primary vertex is so small and the secondary vertex has worse resolution, it is preferred to work with the product of impact parameters which only is dependant on the resolution of the primary vertex.

For practical considerations however, it suffices to know that the signal and background distributions of this parameter are distinctively different. For  $D^0$  decay daughters coming from decays displaced from the primary vertex it is expected that the

prolongated tracks should be on opposite sides of the  $D^0$  flight line and have comparatively large absolute impact parameter values. As such, the product of impact parameters will (most likely) give a large absolute value with negative sign. The background on the other hand, which consist of randomly matched tracks, will be symmetric around zero. This gives another potential value to cut on.

Another very important selection parameter is the cosine of the pointing angle  $\cos \theta_p$ . This variable is defined as the angle between the  $D^0$  flight line (the displacement between the primary and secondary vertex) and the  $D^0$  momentum reconstructed from its decay particles. Figure 3.1 gives a graphical example. For tracks coming from actual  $D^0$  decays the angle will be close to zero and it is expected that the distribution of  $\cos \theta_p$  will peak at 1.

Unfortunately, Monte-Carlo simulations have shown the existence of a smaller signal peak at  $\cos \theta_p = -1$ , caused by situations where the secondary vertex is reconstructed on one side of the primary vertex while the total kaon plus pion momentum points in the other direction. This result of the secondary vertex resolution also causes entries for any value in between, though not peaking at any intermediate value. However, a cut on the kaon and pion transverse momentum can reduce the peak at the negative value while the one at  $\cos \theta_p = 1$  is not affected.

More importantly though, the background is proven to be much more symmetric around zero, even though it also peaks at  $\cos \theta_p \pm 1$ . Moreover, the transverse momentum cut on kaons and pions can potentially significantly reduce the background on the cosine of the pointing angle while the signal is much less affected (especially at  $\cos \theta_p = 1$ ).

A very closely related cut is the cosine of the pointing angle in the XY plane, or  $\cos \theta_{p,XY}$ , where only the transverse components are evaluated. This cut allows a further refinement on the results of the pointing angle for  $D^0$  at midrapidity, where  $|\eta| < 0.9$ .

Since particle tracks are stored as helices, even tracks coming from the same secondary vertex will rarely intersect, instead approaching each other most closely at the secondary vertex. The smallest value to which track approach one another is the so-called distance of closest approach (*dca*). Since signal tracks are expected to come from the same secondary vertex their *dca* is generally expected to be smaller than random combinations of background tracks, which gives the opportunity to select upon.

The normalised decay length (*NDL*) is another selection. This is the candidate's decay length divided by the error on the decay length. The  $D^0$  decay length is well known, and any candidates with decay length much shorter or longer than this value are not expected to be proper  $D^0$  decays. Since the decay length depends on the secondary vertex resolution, which in turn depends on the particle momentum, the decay length is normalised to its uncertainty.

Despite the fact that most important cuts are on the  $D^0$ , there are a few more specifically for  $D^{*+}$  analysis. Since the soft pion momentum in the  $D^{*+}$  decay rest frame is only 39 MeV/c, most of its momentum in the laboratory frame comes from the  $D^{*+}$  momentum. The soft pion carries about 7% of the  $D^{*+}$  transverse momentum. Therefore a cut on the soft pion transverse momentum  $p_T^{\pi_{\text{soft}}^+}$  can be effective.

The selection on the angle  $\theta$  between the soft pion momentum and the plane defined by the kaon and pion momenta is used. Since the soft pion momentum and  $D^{*+}$  momentum are expected to have very similar direction, the former's momentum will

lie on or close to plane spanned by the  $D^0$  decay daughter's momenta, so that it is expected that  $\theta \approx 0$  for the  $D^{*+}$  momentum range that is discussed in this thesis.

A selection cut is applied on the  $D^0$  invariant mass. This is discussed in sect. 3.4.1.

### 3.2.4 Particle identification

The particle identification relies on the techniques already discussed in the sections on the TPC and TOF, but here the strategy will be discussed in more detail. Both for proton-proton and lead-lead collisions the strategy was based on cuts applied around the expected mean of the energy deposit  $dE/dx$  for the TPC and the expected flight time determined by the TOF. As can be deduced from figure 2.6, they can be described by a Gaussian distribution of the measured mean energy deposit and time-of-flight around their expected values as a function of the particle momentum. The selections were based on the width  $\sigma$  of the distributions, where ideally a 3 and 2 sigma cut would be 99.7% and 95% efficient for the signal respectively for the two particle identification procedures, though it will be shown that this is not exactly the case.

Nevertheless, the particle identification does provide additional background rejection in the low-momentum region, up to a factor of three. The particle identification strategy employed (i.e. the values of the cuts) does try to keep a high efficiency of the  $D^{*+}$  signal. Furthermore tracks which lacked either TOF or TPC particle identification would be identified with the remaining identification method or not identified at all (though they would still be used in the analysis as in this case they were compatible with both pions and kaons). Soft pion candidates were not subjected to particle identification.

## 3.3 Cut optimisation

In order to get the best set of selection cuts, where the maximum of combinatorial background is rejected while retaining the maximum amount of signal, cuts have to be optimised. There are several techniques available that have been used in the scope of this thesis.

The most straightforward method is the iterative procedure, where each cut is optimised one after the other (keeping the selection of those that are optimised before), varying the selection parameter until a maximum significance is reached. After all cuts have been optimised, a maximum of the significance should have been reached.

However, the selections are not independent from one another. Changing one cut parameter will change the optimal value for another. As such the significance maximum is merely a local maximum in the selection parameter phase space. A different order of iterative optimisation will lead to a different set of optimised cuts and significance. Ideally one should optimise all cuts simultaneously. For this the multidimensional method has been used, which will be discussed in section 3.3.1. The iterative procedure provided an important contribution to optimisations, before the multidimensional method was fully developed.

Optimisations could generally be performed on both Monte-Carlo simulation and data. Monte-Carlo data have the distinct advantage that signal and background entries were properly labeled and were clearly distinguishable in the final result. This made the process of optimisation very transparent and straightforward. This was the primary

procedure in the earlier stages of optimisation when not even an ansatz of selection parameters that could extract a signal in data was available.

Optimisation was continued with actual data when preliminary cut sets provided an extractable signal. Since in actual data signal and background are not labelled, it was necessary to resort to fitting a function to the combinatorial background, which could be used to subtract the background to get the signal. For this a clear signal with decent significance is required.

### 3.3.1 The multidimensional method

The set of cuts in table 4.5, was acquired using multidimensional optimisation in order to maximise the significance in the various  $D^{*+}$  momentum bins. This method allows multiple selection parameters to be optimised simultaneously. This property is especially beneficial since the selection parameters are not independent from one another, which means that iterative optimisation is dependent of the order in which parameters are optimised.

The optimisation method is available in the Aliroot framework as the *AliAnalysis-TaskSESignificance* class. It functions by accepting a lower and upper bound on the various cut parameters, as well as a number of bins (which are like steps) in which the cut values are incrementally changed from its looser to its tighter value. What results is a multidimensional array in which each entry corresponds to a particular combination of the selection parameters that are to be optimised, which has a corresponding invariant mass distribution as an output.

Though theoretically all topological cuts can be optimised simultaneously in this manner, a limiting factor is computing memory as the number of entries in the array increases exponentially. For the results obtained in this thesis no more than 4 variables were optimised simultaneously, with an incremental tightening of the cuts divided in 6 steps, for 15 momentum bins of the  $D^{*+}$ , resulting in an array with  $15 \times 6^4 = 19440$  entries. For four variables, 6 steps proved to be the limit.

The multitude of invariant mass histograms can be further analysed en masse, where the *charmCutsOptimisation.C* macro determines the signal and background for each individual histogram, by bin counting or a function fit as per user request. It automatically gives the combination of selection parameter values which supply the highest significance in each individual  $p_T$  bin. Closer inspection of the results is possible by plotting the significance as a function of two parameters in a two-dimensional plot, for which one example is shown in fig. 3.2. This can also be used to investigate the cut stability.

However, selections that give the highest significance might not actually be the best cut set. For cuts like on the product of impact parameters the signal and background can significantly increase with only minor changes to the cut value, both for data and Monte-Carlo. Since Monte-Carlo results play an important role in determining the total yield within a limited acceptance detector, any residual difference between data and Monte-Carlo could potentially give significantly different total yields for relatively small changes to the cut, making these cuts unstable (i.e. significance changes greatly with minor changes to the cut value). Furthermore, the multidimensional optimisation method gives discrete results, which means that better cut values can lie in between two determined cut values. In order to correct for this possibility,

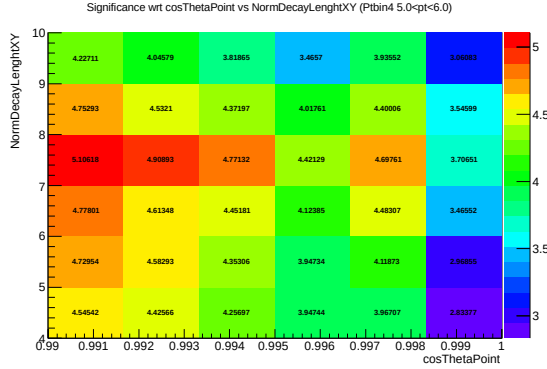


Figure 3.2: Typical (preliminary) result of the optimisation of the  $D^{*+}$  significance using the multidimensional optimisation method, 92.6 million Pb-Pb events analysed, with 13.7 million events selected and about 976 thousand  $D^{*+}$  candidates included. Here the significance is shown as a function of the cosine of the pointing angle and the normalised decay length. Each bin corresponds to one particular set of cuts.

the selections are "smoothened". This means that cuts sets for a certain  $p_T$  bin are compared with those of neighbouring bins and if a value varies much from the global trend, it will be changed to be more in line with this trend. As a rule-of-thumb, selections tend to be looser for increasing  $D^{*+}$   $p_T$  due to decreasing  $D^{*+}$  production rates at higher transverse momenta and decreasing background. Furthermore, very tight cuts would result in a relative increase of the number of  $D^{*+}$  coming from B feed-down compared to prompt  $D^{*+}$  mesons, due to the fact that the former have a more removed secondary vertex and are thus easier to reconstruct. So the requirement to keep the reconstruction efficiency as high as possible was added as well.

A convenient advantage of multidimensional optimisation is that the procedure as a whole is fast. One optimisation is effectively equivalent to  $n^r$  individual optimisation actions, where  $n$  is the number of optimisation steps and  $r$  the number of variables. As a matter of fact, for the 2011 lead-lead dataset the Monte-Carlo data was not used for optimisation, as the data itself could be used for optimisation since the selections for the 2010 data provided an adequate ansatz as a starting point.

### 3.4 $D^{*+}$ yield extraction

The techniques employed for vertexing, reconstruction and selection are used to extract the  $D^{*+}$  yield from the particle collisions under study. Vertexing and reconstruction allows for the definition of  $D^{*+}$  candidates (via the intermediate step of  $D^0$  candidates), while the selections attempt to separate the real  $D^{*+}$  decays from the combinatorial background by rejecting false candidates.

The yield extraction itself however, will be performed using an invariant mass analysis (where the masses of the  $D^{*+}$  and  $D^0$  are well defined), which should give a significant signal in a invariant mass distribution, from which a background fitting

method is employed to separate the supposed signal from the background.

### 3.4.1 Invariant mass analysis

The determination of the  $D^0$  invariant mass occurs simultaneously when the  $D^0$  candidates are created, and are stored as such in the AOD. Using the two tracks an algorithm calculates the invariant mass of the two particles using the following formula

$$M_{K\pi} = \sqrt{(E_- + E_+)^2 - (\vec{p}_- + \vec{p}_+)^2} \quad (3.2)$$

where  $\vec{p}_-$  and  $\vec{p}_+$  are the negative and positive particle track momenta. When the kaon is assigned to negative track and the positive associated track with a pion, the particle energy is calculated as

$$E_- = \sqrt{m_K^2 + \vec{p}_-^2}, \quad (3.3)$$

$$E_+ = \sqrt{m_\pi^2 + \vec{p}_+^2}. \quad (3.4)$$

For the  $\overline{D}^0$  the kaon and pion mass are assigned to the positive and negative tracks, respectively.

Whether its a real  $D^0$  or a fake candidate that passes the cuts, the calculated invariant mass will be an entry in an invariant mass spectrum. Assuming one has good selection, real  $D^0$  will stand out from the background as a significant peak with a mean at the known  $D^0$  mass and peak width  $\sigma_M^{D^0}$ . Since any candidates that fall outside the peak region cannot be real  $D^0$ , these entries are cut away. This mass resolution depends on the whether the analysis involves proton-proton or Pb-Pb collisions, as well as the original  $D^{*+}$  momentum, this value varies for the individual  $p_T$  bins. For Pb-Pb data however it is at least 32 MeV/c<sup>2</sup>.

When a  $D^0$  candidate is reconstructed and passes the selection cuts, they are used to find  $D^{*+}$  candidates. Here an algorithm will loop over the positive tracks (or negative ones for  $\overline{D}^{*+}$ ) and uses the negative-positive-positive triplet of tracks to determine the invariant mass of the  $D^{*+}$  candidate, where the two original tracks are designated to be the negative kaon and positive pion, and the third positive track the soft pion. This gives

$$M_{K\pi\pi} = \sqrt{(E_- + E_+ + E'_+)^2 - (\vec{p}_- + \vec{p}_+ + \vec{p}'_+)^2} \quad (3.5)$$

where  $E'_+$  and  $\vec{p}'_+$  are the third positive track's energy and momentum, for to which the soft pion is assigned, so that

$$E'_+ = \sqrt{m_\pi^2 + \vec{p}'_+^2}. \quad (3.6)$$

Though the mass of the  $D^{*+}$  is 2010 MeV/c<sup>2</sup> [62], it is actually more advantageous to determine the spectrum of the invariant mass difference  $\Delta M = M_{K\pi\pi} - M_{K\pi}$ . This will result in a value slightly above the pion rest mass, with a sharp peak at 145.42 MeV/c<sup>2</sup>. This way the uncertainties in the kaon and pion momenta cancel out which will lead to a better resolution. Effectively, the peak width is now only governed by the soft pion momentum resolution.

### 3.4.2 Signal extraction via background fitting

To finalise the  $D^{*+}$  yield extraction, the signal and combinatorial background in the invariant mass spectrum have to be separated. This was done using a fit function that was the sum of a Gaussian distribution that would describe the signal and a function describing the combinatorial background.

The background function was given by

$$f(\Delta M) = a\sqrt{\Delta M - m_\pi}e^{b(\Delta M - m_\pi)} \quad (3.7)$$

and an alternative description by

$$f_{\text{alt}}(\Delta M) = a(\Delta M - m_\pi)^b. \quad (3.8)$$

Here  $a$  and  $b$  are free parameters, which together with the three parameters of a Gaussian distribution resulted in a fit with 5 degrees of freedom.

For a good fit the mean of the Gaussian should match the difference of the  $D^{*+}$  and PDG mass values within errors. The fitting procedure was handled by the algorithm available in the *AliHFMassFitter* class. This class had the possibility to use different background fit functions, where equation (3.8) was used as an alternative to equation (3.7) for systematic studies. Combined with the Gaussian distribution this function only has 4 degrees of freedom, since one of the parameters could be fixed using the integral over the background.

Though the above method sufficed to extract the  $D^{*+}$  yields, it was very uncertain in the early stages of this work whether the combinatorial background would be too high at LHC energies. Therefore, work has been done on advanced methods to reconstruct the background using collision data itself. Two of these methods, the like-sign reconstruction and multiple rotations methods are described in detail in appendix A.

## 3.5 Corrections on $D^{*+}$ reconstruction and systematic on B feed-down

The extracted  $D^{*+}$  yield also includes contributions from the B meson decay feed-down, which is predicted using the method described in this section to be about 15% of the  $D^{*+}$  yield in lead-lead collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV [74]. It is necessary to subtract this from the total  $D^{*+}$  yield to get the contribution of the 'prompt'  $D^{*+}$ , those containing charm quarks produced in the initial stages of the heavy ion collision. The B feed-down contribution ( $f_{\text{prompt}}$ ) has not been measured directly, but was determined using perturbative QCD (pQCD) to predict B meson production, as well Monte-Carlo simulations. This will result in a systematic uncertainty on the prompt  $D^{*+}$  cross section.

The  $D^{*+}$  raw yield (defined as  $N_{D^{*+}}^{\text{raw}}$ ) also depends on quantities like the limited detector acceptance (Acc) and reconstruction efficiency  $\epsilon$  for prompt  $D^{*+}$ . To get the total production prompt  $D^{*+}$  production at the interaction point, the raw yield is normalised to the  $D^{*+}$  decay channel branching ratio (BR), the  $D^{*+}$   $p_T$  bin width  $\Delta p_T$ , the number of analysed events  $N_{\text{evt}}$  and a factor 1/2 since the calculations are do not include anti-particles. It is normalised to the rapidity coverage  $\Delta y$ , since the fiducial acceptance selection depends on the  $D^{*+}$  transverse momentum which needs to be

scaled as well. This correction factor assumes a uniform rapidity distribution for the  $D^{*+}$  in the relevant  $y$  range, so that  $\Delta y = 2y_{\text{fid}}$ . This assumption has been checked to within 1% [75] with PYTHIA 6.4.21 event generator for proton-proton simulations [76] using the Perugia-0 tuning [77] and the FONLL pQCD calculation [78] [79].

Taking all this into account, the  $D^{*+}$  differential yield with respect to the  $D^{*+}$  transverse momentum is given by

$$\left. \frac{dN^{D^{*+}}}{dp_T} \right|_{|y|<0.5} = \frac{1}{2\Delta y \Delta p_T} \frac{f_{\text{prompt}}(p_T) N_{D^{*+}}^{\text{raw}}|_{|y|<y_{\text{fid}}}}{(\text{Acc} \times \epsilon)_{\text{prompt}}(p_T) \cdot \text{BR} \cdot N_{\text{evt}}} \quad (3.9)$$

The  $D^{*+}$   $p_T$ -dependent differential cross section (at the central rapidity range)  $\left. \frac{d\sigma_{\text{pp}}^{D^{*+}}}{dp_T} \right|_{|y|<0.5}$  for proton-proton interactions can also be determined, where the integrated luminosity  $L_{\text{int}}$  can be expressed as  $L_{\text{int}} = N_{\text{pp}}^{D^{*+}} / \sigma_{\text{pp}}^{D^{*+}}$ , so that

$$\left. \frac{d\sigma_{\text{pp}}^{D^{*+}}}{dp_T} \right|_{|y|<0.5} = \frac{1}{2\Delta y \Delta p_T} \frac{f_{\text{prompt}}(p_T) N_{D^{*+}}^{\text{raw}}|_{|y|<y_{\text{fid}}}}{(\text{Acc} \times \epsilon)_{\text{prompt}}(p_T) \cdot \text{BR} \cdot L_{\text{int}}} \quad (3.10)$$

Monte-Carlo simulations were used to correct for the detector acceptance and  $D^{*+}$  reconstruction efficiency  $(\text{Acc} \times \epsilon)_{\text{prompt}}$ . For proton-proton interactions this was based on the settings of the GEANT3 transport code [80], which included the luminous region distribution and conditions of all ALICE subdetectors, specifically the active electronic channels, gain, noise level, calibration level, alignment and any changes in the course of the 2010 LHC proton-proton run. The proton-proton collisions themselves were simulated with again the PYTHIA 6.4.21 event generator for proton-proton simulations using the Perugia-0 tuning [76] [77]. For these simulations only the events containing  $D$  mesons were transported through the detector and reconstructed. The efficiency was also determined separately for the prompt  $D^{*+}$  and those coming from  $B$ .

The prompt fraction  $f_{\text{prompt}}$ , the fraction of  $D^{*+}$  coming from  $c$  quark hadronisation (instead of  $B$  decay), was evaluated using the  $B$  production cross section from pQCD calculations using FONLL. These calculations had been used previously at Tevatron to successfully describe beauty production [82] and at the LHC [83] [84]. Furthermore, the  $B \rightarrow D$  decay kinematics were described using the EvtGen package [85]. As such, the computed cross section of the  $B$  feed-down  $D^{*+}$  was used in conjunction with the Monte-Carlo acceptance-times-efficiency  $(\text{Acc} \times \epsilon)_{\text{feeddown}}$  for  $D^{*+}$ s coming from  $B$  decays. This is the so-called  $n_b$  method, for which one would get

$$f_{\text{prompt}} = 1 - (N_{\text{feeddown}D^{*+}}^{\text{raw}} / N^{\text{raw}}), \quad (3.11)$$

which can be rewritten for proton-proton collisions as

$$f_{\text{prompt}} = 1 - 2 \left. \frac{d\sigma_{\text{FONLL}}^{\text{feeddown}D^{*+}}}{dp_T} \right|_{|y|<0.5} \cdot \Delta y \Delta p_T \cdot (\text{Acc} \times \epsilon)_{\text{feeddown}} \cdot \text{BR} \cdot \frac{L_{\text{int}}}{N^{\text{raw}}}. \quad (3.12)$$

The final value of  $f_{\text{prompt}}$  depends on a lot of factors: whether it involves proton or heavy ion collisions, the transverse momentum interval, the applied cuts, the



parameters of the FONLL B prediction and the hypothesis in the  $R_{AA}^{\text{feeddown}}$ . For the proton-proton results presented in this thesis  $f_{\text{prompt}}$  was about  $> 0.9$ , depending on the transverse momentum interval.

To study the systematic uncertainty, two methods were employed. The first one involved the perturbative uncertainty on the FONLL beauty production cross section. For this the heavy quark masses as well as the factorisation and normalisation scales were varied over certain ranges, as proposed by [89].

The second method consisted of using an alternative method to evaluate the prompt fraction, which is called the  $f_c$  method. Here the ratio of the FONLL feed-down and prompt production cross sections and the ratio of their respective Monte-Carlo acceptance-times-efficiency results are used. This gives for proton-proton collisions

$$f_{\text{prompt}} = \left( 1 + \frac{(\text{Acc} \times \varepsilon)_{\text{feeddown}}}{(\text{Acc} \times \varepsilon)_{\text{prompt}}} \cdot \frac{\left. \frac{d\sigma_{\text{FONLL}}^{\text{feeddown}D^{*+}}}{dp_T} \right|_{|y| < 0.5}}{\left. \frac{d\sigma_{\text{FONLL}}^{\text{prompt}D^{*+}}}{dp_T} \right|_{|y| < 0.5}} \right)^{-1} \quad (3.13)$$

The systematic uncertainty would then be determined by varying the FONLL parameters for the two methods.

In the case of Pb-Pb collisions, the minimum bias collisions at a centre-of-mass energy of 2.76 TeV per nucleon-nucleon pair were simulated using the HIJING v1.36 event generator [81]. To this prompt and feed-down  $D^{*+}$  were added via simulated proton-proton events again using the PYTHIA 6.4.21 event generator with Perugia-0 tuning. Like for the proton-proton events, the GEANT3 transport code was used with a detailed description of the detector's geometry, responses and its evolution over the data taking periods. Due to the detector occupancy, the efficiencies were evaluated in centrality classes corresponding to those used in the analysis of the data in terms of charged-particle multiplicity.

The method to determine the systematic on the B feed-down in Pb-Pb collisions is very similar to the one used for proton-proton collisions. However, here the  $p_T$ -dependent prompt differential  $D^{*+}$  yield is examined, not the differential cross section, so that the  $n_b$  methods is expressed as

$$f_{\text{prompt}} = 1 - 2\langle T_{AA} \rangle \left( \frac{d^2 \sigma_{\text{FONLL}}^{\text{feeddown}D^{*+}}}{dp_T} \right) \cdot R_{AA}^{\text{feeddown}} \cdot \Delta y \Delta p_T \cdot (\text{Acc} \times \varepsilon)_{\text{feeddown}} \cdot \text{BR} \cdot \frac{N_{\text{evt}}}{N_{\text{raw}}} \quad (3.14)$$

where  $\langle T_{AA} \rangle$  is the average nuclear overlap function of the interacting nuclei, defined as the convolution of the nuclear density profiles of the colliding ions in the Glauber model [69] and used to scale the FONLL feed-down cross section in proton-proton interactions at  $\sqrt{s_{NN}} = 2.76$  TeV.

In the case of heavy ion collisions it was found that  $f_{\text{prompt}} \approx 0.95$  at very low  $p_T$ , while it dropped to 0.85 at high transverse momentum.

Likewise one can use the  $f_c$  method to study the systematics, for which one has for heavy-ion collisions

$$f_{\text{prompt}} = \left( 1 + \frac{(\text{Acc} \times \varepsilon)_{\text{feeddown}}}{(\text{Acc} \times \varepsilon)_{\text{prompt}}} \cdot \frac{\left( \frac{d^2 \sigma_{\text{FONLL}}^{\text{feeddown} D^{*+}}}{dp_T dy} \right)}{\left( \frac{d^2 \sigma_{\text{FONLL}}^{\text{prompt} D^{*+}}}{dp_T dy} \right)} \cdot \frac{R_{AA}^{\text{feeddown}}}{R_{AA}^{\text{prompt}}} \right)^{-1} \quad (3.15)$$

The nuclear modification factor for the feed-down  $D^{*+}$   $R_{AA}^{\text{feeddown}}$  is related to the nuclear modification factor of beauty production in lead-lead collisions. Unfortunately, this quantity is currently unknown, so it is assumed that at least for the systematic that the nuclear modification factors for feed-down and prompt  $D^{*+}$  is equal, so that  $R_{AA}^{\text{feeddown}} = R_{AA}^{\text{prompt}}$ . This hypothesis has merit since it corresponds to a range of model predictions for the charm and beauty  $R_{AA}$  [86] [87] as well as experimental results of the CMS collaboration on non-prompt  $J/\psi$   $R_{AA}$  [88]. The hypothesis was varied in the range of  $R_{AA}^{\text{feeddown}}/R_{AA}^{\text{prompt}} \in [1/3, 3]$  in order to determine the systematic uncertainty.

### 3.6 Reference proton-proton cross section at $\sqrt{s} = 2.76$ TeV

For the determination of the  $D^{*+}$  prompt nuclear modification factor  $R_{AA}$  it was necessary to apply a scaling to the  $D^{*+}$  cross section measured at  $\sqrt{s} = 7$  TeV in proton-proton collisions to correspond to heavy ion collisions where the centre-of-mass per nucleon-nucleon pair is 2.76 TeV. This scaling factor was defined as the ratio of the cross sections determined by using FONLL calculations for pQCD at both 2.76 and 7 TeV. For this the same charm quark mass  $m_c$ , renormalisation scale  $\mu_R$  and pQCD factorisation scale  $\mu_F$  were used, where  $\mu_R = \mu_F = m_T$  when  $m_T = \sqrt{p_T^2 + m_c^2}$  with  $m_c = 1.5 \text{ GeV}/c^2$ .

This scaling procedure has been used before to scale ALICE proton-proton data to Tevatron energies, where  $\sqrt{s} = 1.96$  TeV, which was verified to correspond to CDF data. Furthermore, it has been found that the scaling factor and its uncertainty are similar if instead of FONLL calculations the GM-VFNS method is employed.

In order to determine the theoretical uncertainty in the scaling factor it was necessary to consider the envelope of scaling factors, which resulted from varying the scales independently in the ranges  $\mu_R/m_T \in (0.5, 2)$ ,  $\mu_F/m_T \in (0.5, 2)$ ,  $\mu_R/\mu_F \in [0.5, 2]$  and  $m_c \in (1.3, 1.7) \text{ GeV}/c^2$  [89]. It was found that the uncertainty ranged from -10% to 30% at  $p_T = 2 \text{ GeV}/c$  to about  $\pm 5\%$  at transverse momenta larger than  $10 \text{ GeV}/c$  [90].

It remains to be seen whether the real values for the  $p_T$ -dependent  $D^{*+}$  differential cross section with a centre-of-mass energy of 2.76 TeV can be properly approximated by the scaled down  $\sqrt{s} = 7$  TeV results. This can be checked, as about  $6 \cdot 10^7$  minimum bias events were collected for proton-proton collisions at a centre-of-mass energy of 2.76 TeV during a short run, though with limited  $p_T$  coverage and precision. Too small a sample to be used as a reference itself, it did provide a cross-check with the scaled  $\sqrt{s} = 7$  TeV results. In section 4.5 it will be shown to be within agreement with one-another, within 20-40% statistical uncertainty depending on the transverse momentum.

As chapter 4 will show, it was possible to extend the  $D^{*+}$  transverse momentum range of the reference up to 24 GeV/c. In chapter 5 it will be shown that a  $D^{*+}$  signal has been found in a transverse momentum range that exceeds the range for the reference, namely in the  $p_T$  range of 24-36 GeV/c. This requires the extension on the range of the reference up to a value where no actual data is available. This extension is based on theoretical predictions as a baseline for the  $p_T$  shape dependence, so the cross section in the 'extended' bin can be predicted at  $\sqrt{s} = 7$  TeV. This value is then scaled down to  $\sqrt{s} = 2.96$  TeV in a similar fashion as described above. The procedure can be summarised as follows

$$\frac{d\sigma}{p_T}(2.76\text{TeV}, p_T^1, p_T^2) = \frac{Fit_{\text{integral}}(data/FONLL, 7\text{TeV}, p_T^3, p_T^4)}{p_T^4 - p_T^3} \times \left( \frac{d\sigma}{p_T}(2.76\text{TeV}, p_T^1, p_T^2) \right)^{FONLL} \quad (3.16)$$

where  $[p_T^1, p_T^2]$  is the transverse momentum which needs to be extrapolated and  $[p_T^3, p_T^4]$  is the range where data is available. It depends on the evaluation of the ratio data-theory where the measurement's statistical uncertainties are considered. To determine the procedure's systematic it is repeated with different FONLL parameters, as well as varying the data points by an amount equal to their systematic uncertainty.

At this point the ratio is fitted with a constant  $Fit_{\text{integral}}$  from which the next value can be extrapolated. For this extrapolated point the uncertainties are given by the envelope of the systematic checks mentioned before. Checks using data indicate that this method gives stable results.

## Chapter 4

# Proton-proton collisions at 7 TeV centre-of-mass energy

In this chapter the results of the  $D^{*+}$  analysis for proton-proton collisions at  $\sqrt{s} = 7$  TeV will be presented. The first section will show both the  $p_T$  integrated  $D^{*+}$  raw yield as well as the selection cuts used to obtain these results. The  $D^{*+}$  reconstruction efficiency will be presented in the second section. In section three the  $D^{*+}$  production cross section is presented. The final section will show comparisons of the results with the 2.76 TeV proton-proton collisions when scaled to that centre-of-mass energy.

The results in this chapter are based on AOD data samples from the LHC proton-proton collision periods *b*, *c*, *d* and *e* collected during over the course of 2010, which would correspond to run numbers given in table 4.1.

This constitutes a total of  $\sim 368$ M proton-proton minimum bias interactions and corresponds to an integrated luminosity of  $5.2 \text{ nb}^{-1}$ . Here only  $5 \text{ nb}^{-1}$  is used for normalisation purposes, where events also pass a selection on the coordinate of the interaction point along the beamline ( $|z| < 10 \text{ cm}$ ). The number of events collected with respect to the period is shown in table 4.2.

The data used for this analysis consists of Analysis Object Data (AOD), filtered from Event Summary Data (ESD). This filtering step includes several cuts to decrease the amount of data not necessary for D meson analysis. It introduces some basic selection criteria on the single track quality and decay topology (i.e. the cuts are much looser compared to the cuts applied in the analysis of the AODs). Number of  $D^{*+}$  candidates per event after AOD filtering is shown in fig. 4.1. Table 4.3 summarises the filtering cuts applied on the kaon, pion and soft pion candidates that are expected to come from  $D^{*+}$  decay.

Loose topological selections are also applied on the candidate  $D^0$  decay topology in order to further reject combinatorial background in the AODs, further saving CPU time and disk space during the actual analysis using the AODs. Theoretical calculations for proton-proton collisions at  $\sqrt{s} = 7$  TeV, which take into account the branching ratios of the  $D^{*+}$  production and decay channels, as well as the detector acceptance, predict in the order of  $0.0005 D^{*+}$  per event from the channels used in this thesis. The signal to background ratio in the AODs is expected to be about  $1/14000$  when an average number of seven  $D^{*+}$  candidates per event is created, see figure 4.1.

Table 4.1: Runs of the proton-proton collision periods  $b$ ,  $c$ ,  $d$  and  $e$  in 2010.

| Run number |        |        |        |        |        |        |        |        |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|
| 117222     | 117220 | 117116 | 117112 | 117109 | 117099 | 117092 | 117086 | 117077 |
| 117065     | 117063 | 117060 | 117059 | 117054 | 117053 | 117052 | 117050 | 117048 |
| 116645     | 116643 | 116574 | 116571 | 116562 | 116403 | 116288 | 116102 | 115401 |
| 115393     | 115193 | 115186 | 114931 | 120829 | 120825 | 120824 | 120823 | 120822 |
| 120821     | 120820 | 120758 | 120750 | 120741 | 120671 | 120617 | 120616 | 120505 |
| 120504     | 120503 | 120244 | 120079 | 120076 | 120073 | 120072 | 120069 | 120067 |
| 119862     | 119859 | 119856 | 119853 | 119849 | 119846 | 119845 | 119844 | 119842 |
| 119841     | 119163 | 119161 | 119159 | 126437 | 126432 | 126425 | 126424 | 126422 |
| 126409     | 126408 | 126407 | 126406 | 126405 | 126404 | 126403 | 126359 | 126352 |
| 126351     | 126350 | 126285 | 126284 | 126283 | 126168 | 126167 | 126160 | 126158 |
| 126097     | 126090 | 126088 | 126082 | 126081 | 126078 | 126073 | 126008 | 126007 |
| 126004     | 125855 | 125851 | 125850 | 125849 | 125848 | 125847 | 125844 | 125843 |
| 125842     | 125633 | 125632 | 125630 | 125296 | 125134 | 125101 | 125100 | 125097 |
| 125085     | 125023 | 124751 | 122375 | 122374 | 130840 | 130834 | 130799 | 130798 |
| 130795     | 130793 | 130696 | 130628 | 130623 | 130620 | 130609 | 130519 | 130480 |
| 130360     | 130358 | 130356 | 130354 | 130343 | 130178 | 130158 | 129961 | 129960 |
| 129959     | 129744 | 129742 | 129738 | 129736 | 129735 | 129729 | 129726 | 129725 |
| 129723     | 129667 | 129666 | 129659 | 129654 | 129653 | 129652 | 129650 | 129647 |
| 129641     | 129639 | 129599 | 129586 | 129540 | 129528 | 129527 | 129523 | 129520 |
| 129513     | 129512 | 128913 | 128855 | 128853 | 128843 | 128836 | 128835 | 128824 |
| 128823     | 128820 | 128778 | 128777 | 128678 | 128677 | 128615 | 128611 | 128609 |
| 128605     | 128582 | 128507 | 128504 | 128503 | 128495 | 128494 | 128486 | 128483 |
| 128452     | 128366 | 128260 | 128192 | 128191 | 128186 | 128185 | 127942 | 127941 |
| 127940     | 127937 | 127936 | 127935 | 127933 | 127822 | 127718 | 127714 | 127712 |

Table 4.2: The amount of events available in the various 2010 LHC run periods of proton-proton collision at 7 TeV centre-of-mass energy. Only the events that pass a cut on the  $z$ -coordinate of the primary vertex are used for normalisation purposes.

| LHC period<br>(2010 data) | Nr. of events<br>analysed ( $\times 10^6$ ) | Nr. of events used<br>for normalisation ( $\times 10^6$ ) |
|---------------------------|---------------------------------------------|-----------------------------------------------------------|
| b                         | 24.5                                        | 23.8                                                      |
| c                         | 67.9                                        | 67.4                                                      |
| d                         | 146.1                                       | 132.7                                                     |
| e                         | 104.7                                       | 91.0                                                      |

Table 4.3: Summary of the filtering cuts when producing AODs from ESDs when D meson physics in proton-proton collisions at 7 TeV centre-of-mass is involved.

|                                                      |                                                                           |
|------------------------------------------------------|---------------------------------------------------------------------------|
| K, $\pi$ candidates<br>from $D^0$ decay              | ITS refit<br>TPC refit<br>$\geq 1$ cluster in SPD<br>$p_T \geq 300$ MeV/c |
| $\pi_{\text{soft}}$ candidate<br>from $D^{*+}$ decay | $\geq 1$ cluster in SPD<br>$p_T \geq 60$ MeV/c                            |

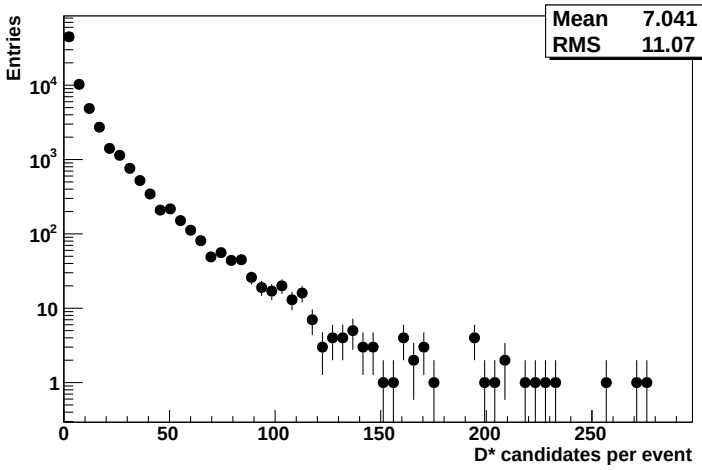


Figure 4.1: Number of  $D^{*+}$  candidates per event after AOD filtering. The average number of  $D^{*+}$  candidates per event is seven [Courtesy of A. Grelli].

Table 4.4: Parameters used for the single track selection cuts on the candidates for the  $D^0$  decay daughter.

| Track selection              | threshold value       |
|------------------------------|-----------------------|
| Kink candidate tracks        | excluded              |
| Track status $D^0$ daughters | ITSrefit and TPCrefit |
| Track status $\pi_s$         | ITSrefit              |
| Clusters in ITS              | $\geq 1$ SPD          |
| $p_T$ (GeV/c)                | $> 0.5$               |

## 4.1 $D^{*+}$ raw yield in proton-proton collisions

In order to properly extract the  $D^{*+}$  raw yield, single-track selection cuts have been applied to the  $D^0$  decay candidates and topological selections to the  $D^0$  decay topology, shown in tables 4.4 and 4.5, respectively.

Using these track cuts, the acceptance in rapidity for  $D^{*+}$  will decrease for  $|y| < 0.5$  at low transverse momentum as well as for  $|y| < 0.8$  at  $p_T > 5$  GeV/c. To account for this a cut at  $|y| < y_{acc}(p_T)$  was included, where  $y_{acc}$  smoothly increases from 0.5 to 0.8 in the transverse momentum region  $p_T \in \langle 0, 5 \rangle$  GeV/c.

Figure 4.2 represents the  $p_T$  integrated  $\Delta M = M(K\pi\pi) - M(K\pi)$  invariant mass distribution for the  $D^{*+}$  (to be exact  $p_T \in [1, 24]$  GeV/c) for the rapidity range  $|y| < 0.8$ , using the LHC proton-proton collision run periods *b*, *c*, *d* and *e*. From this a total raw yield of  $2560 \pm 79$   $D^{*+}$  in 368 million minimum bias events have been obtained (314 million after cuts), resulting in a signal with a significance of  $33.0 \pm 0.8$ .

Figure 4.3 depicts the invariant mass  $\Delta M$  distribution for the same total number of events. For this analysis the  $p_T$  range was divided into ten  $D^{*+}$  transverse momentum

Table 4.5: Topological selection cuts used for maximising the  $D^{*+}$  signal significance in the various transverse momentum bins. Other cuts were employed, but not for optimisation.

| $p_T$ (GeV/c)                                      | [1,2] | [2,3] | [3,4]  | [4,5] | [5,6] | [6,7] | [7,8] | [8,12] | [12,16] | [16,24] |
|----------------------------------------------------|-------|-------|--------|-------|-------|-------|-------|--------|---------|---------|
| dca (cm)                                           | 0.022 | 0.025 | 0.04   | 0.07  | 0.1   | 0.1   | 0.1   | 0.2    | 0.2     | 0.3     |
| $\cos \theta^*$                                    | 0.8   | 0.8   | 0.8    | 0.8   | 0.9   | 1.0   | 1.0   | 1.0    | 1.0     | 1.0     |
| $p_{T,K^-, \pi^+}$ (GeV/c)                         | 0.5   | 0.7   | 1.0    | 1.0   | 1.0   | 0.8   | 0.8   | 0.5    | 0.5     | 0.5     |
| $d_{0,K^-, \pi^+}$ (cm)                            | 0.08  | 0.08  | 0.06   | 0.07  | 0.08  | 0.1   | 0.1   | 0.1    | 0.15    | 0.25    |
| $d_0 \times d_0$ ( $\times 10^{-3} \text{ cm}^2$ ) | -0.26 | -0.16 | -0.065 | 0.1   | 1.0   | 10.   | 10    | 10     | 60      | 60      |
| $\cos \theta_{\text{pointing}}$                    | 0.8   | 0.9   | 0.9    | 0.9   | 0.9   | 0.6   | 0.6   | 0.7    | 0.5     | 0.5     |

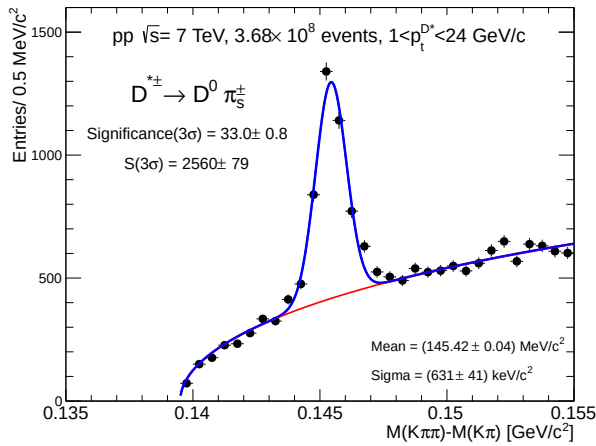


Figure 4.2:  $D^{*+}$  candidate  $p_T$  integrated  $\Delta M$  invariant mass spectrum for minimum bias proton-proton collisions at  $\sqrt{s} = 7$  TeV, where it is integrated over the momentum range  $p_T \in [1, 24]$  GeV/c. This results corresponds to 314 million events after the event selection cuts and  $D^{*+}$  reconstruction cuts.

bins, ranging from 1 to 24 GeV/c. The signal extraction process is discussed in the previous chapter. A Gaussian distribution is used for the signal and a threshold function convoluted with an exponential to reproduce the background shape. The signal is represented as a sharp peak of width  $\sigma \approx 0.63$  MeV/c<sup>2</sup> on top of the combinatorial background, centred at a mean invariant mass of  $(145.42 \pm 0.04)$  MeV/c<sup>2</sup>. The peak position as a function of the  $D^{*+}$   $p_T$  is plotted on the left of fig. 4.4. These values are in good agreement with the expected literature value [62]. Table 4.6 gives the raw yields for the individual  $D^{*+}$   $p_T$  bins as well as the corresponding significance.

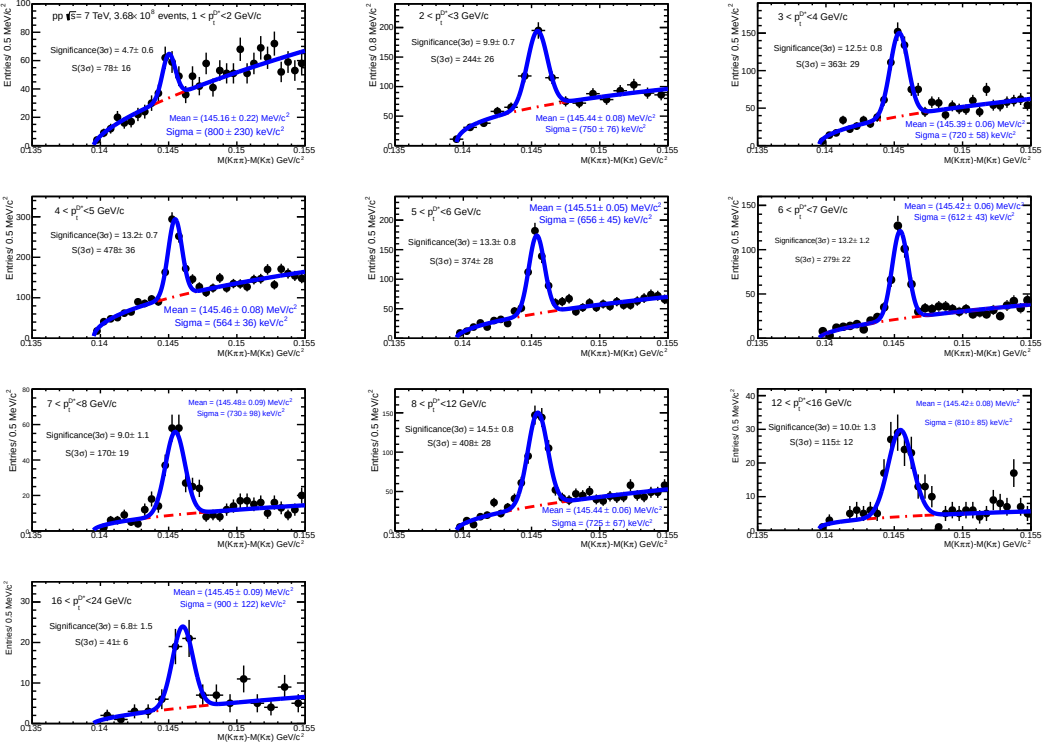


Figure 4.3: Invariant mass spectrum  $\Delta M = M(K\pi\pi) - M(K\pi)$  for minimum bias proton-proton interactions at  $\sqrt{s} = 7$  TeV for the various  $D^{*+}$  transverse momentum bins. This corresponds to 314 million events after the event selection cut and  $D^{*+}$  reconstruction cuts.

By evaluating  $\Delta M = M(K\pi\pi) - M(K\pi)$  instead of  $\Delta M = M(K\pi\pi)$  itself, the width of the peak is dominated by the soft pion momentum resolution instead of all three daughter particles combined, which accounts for the sharpness of the peak. At very low momentum this resolution grows worse as a result of multiple scattering of the soft pion in the detector. Conversely, at large momentum the resolution degrades due to the finite spatial resolution of the detector. This can be seen in the right panel of figure 4.4. As such the peak width reaches a minimum around 500 MeV/c, which corresponds to a  $D^{*+}$  transverse momentum of about 5 GeV/c. Also, by taking the



Table 4.6: Numerical summary of the determined  $D^{*+}$  raw yields and corresponding significances. The value of raw yield are given with its statistical and systematic uncertainty.

| $p_T$ bin [GeV/c] | raw yield ( $\frac{dN}{p_T dy} \pm \text{stat.} \pm \text{syst.}$ ) | significance   |
|-------------------|---------------------------------------------------------------------|----------------|
| [1,2]             | $78 \pm 16 \pm 8$                                                   | $4.7 \pm 0.6$  |
| [2,3]             | $244 \pm 26 \pm 10$                                                 | $9.9 \pm 0.7$  |
| [3,4]             | $363 \pm 29 \pm 7$                                                  | $12.5 \pm 0.6$ |
| [4,5]             | $478 \pm 36 \pm 14$                                                 | $13.2 \pm 0.7$ |
| [5,6]             | $374 \pm 28 \pm 22$                                                 | $13.3 \pm 0.8$ |
| [6,7]             | $279 \pm 22 \pm 11$                                                 | $13.2 \pm 1.2$ |
| [7,8]             | $170 \pm 19 \pm 19$                                                 | $9.0 \pm 1.1$  |
| [8,12]            | $408 \pm 28 \pm 8$                                                  | $14.5 \pm 0.8$ |
| [12,16]           | $115 \pm 11 \pm 10$                                                 | $10.0 \pm 1.3$ |
| [16,24]           | $41 \pm 6 \pm 10$                                                   | $6.8 \pm 1.5$  |

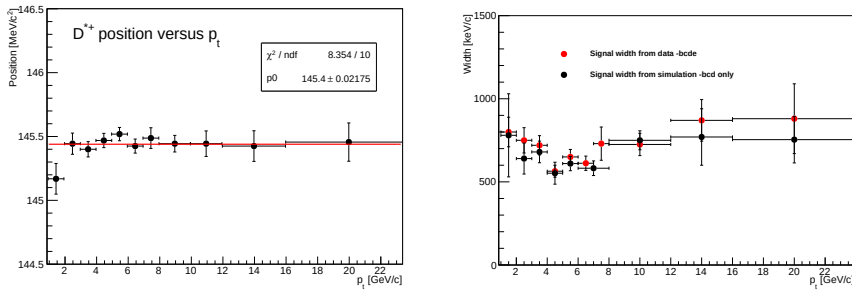


Figure 4.4: (Left) Mass peak position as a function of transverse momentum. Depending on the  $p_T$  bin, the position is shifted to a maximum of 0.23% in the bin [1,2] GeV/c, with respect the average value (red line). (Right) Signal width versus the  $D^{*+}$   $p_T$ .

mass difference the invariant mass spectrum has a threshold at the pion rest mass of  $m_{\pi^+} = 139.57 \text{ MeV}/c^2$ .

The background gradually increases with increasing invariant mass. It also decreases rapidly when the  $D^{*+}$  candidates transverse momentum increases, such that at high momenta the distribution is almost free of combinatorial background. This is due to particle multiplicity decreasing rapidly with increasing transverse momentum, so that the number of false possible  $D^0$  daughter kaon and pion candidates decreases as well. As such increasing the momentum will result in less combinatorial background.

As part of the analysis strategy, particle identification has been applied to the daughter candidate tracks in order to decrease the combinatorial background. Here the pion and kaon candidates were selected from a  $3\sigma$  band from the specific energy loss in the TPC, as well as a  $3\sigma$  selection cut on the particle flight-time. This decreases the background drastically. Nevertheless,  $\sim 99\%$  of the reconstructed signal survives this selection cut.

## 4.2 $D^{*+}$ reconstruction efficiency

Using Monte-Carlo simulations the  $D^{*+}$  reconstruction efficiency has been determined to account for the losses caused by vertex and track reconstruction and the various selections cuts on single tracks, secondary decay topologies and particle identification. These proton-proton interactions were simulated using PYTHIA using Perugia-0 tuning [76, 77]. The  $D^{*+}$  reconstruction efficiency as a function of the  $D^{*+}$  transverse momentum is shown in fig. 4.5.

This figure represents, as a function of the  $D^{*+}$  transverse momentum, the efficiencies for the  $D^{*+}$  originating directly from charm production (i.e. prompt  $D^{*+}$ ) meson decaying via the  $K\pi\pi$  decay channel and with all the decay tracks in the acceptance  $|\eta| < 0.8$ . The selection cuts are tighter at low  $D^{*+}$  transverse momentum, causing an efficiency in the order of one percent. At higher  $p_T$  the efficiency increases (due to the more relaxed cuts) and top of at about 45 percent for transverse momenta larger than 12 GeV/c.

Figure 4.5 also contains the efficiency when no particle identification selection is applied. The results are very close to those with particle identification. This indicates a particle identification selection with close to 100% efficiency on the  $D^{*+}$  signal. However, the combinatorial background is reduced up to a factor 2 at low transverse momentum.

The figure furthermore summarises the efficiency of the B feed-down component of the  $D^{*+}$  signal (i.e. the  $D^{*+}$  mesons that are produced via B meson decay) for the various momentum bins, required for the correction of the prompt  $D^{*+}$  cross section calculation. At low transverse momenta it exceeds the prompt efficiency almost by a factor of about two. This can be attributed to the fact that this feed-down component is more displaced from the primary vertex due to the relatively large B lifetime (the B meson decays via weak interaction to the  $D^{*+}$ ). Above a  $D^{*+}$  transverse momentum of 5 GeV/c the prompt and B feed-down contributions have the same similar efficiencies.

The reconstruction efficiency is evaluated using nine steps, starting with  $D^{*+}$  mesons produced in a limited acceptance region ( $|y| < 0.5$ ), up to the mesons passing the topological cuts and particle identifications. At each step, which corresponds to passing a certain selection cut, it is possible to perform efficiency calculations. This is since all main variables of the  $D^{*+}$  mesons as well as its decay particles are stored separately. Table 4.7 contains a summary of the selection steps with the relevant variables involved. Figure 4.6 depicts a comparison of the efficiencies for the different LHC periods.

For this Monte-Carlo efficiency study only events which contained at least one produced  $D^{*+}$  were transported through the virtual detector and used for reconstruction. The efficiency could be evaluated for both prompt  $D^{*+}$  from charm quark fragmentation as well as B feeddown  $D^{*+}$ , since the Monte-Carlo information retained information on the mother particle of the  $D^{*+}$ .

Monte-Carlo data was also used to study the performance of the particle identification strategy, and then tested in actual data, to assure its results are as expected. Since one of the steps in the Monte-Carlo efficiency study is the application of particle identification cuts, the correction framework enables the opportunity to check the simulated particle identification efficiencies.

When applying particle identification, a selection cut of  $3(2) \sigma$  around the ex-

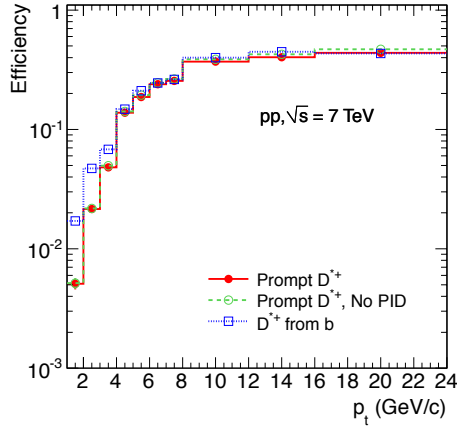


Figure 4.5:  $D^{*+}$  reconstruction efficiency as a function of  $D^{*+}$  transverse momentum. Red symbols represent prompt  $D^{*+}$ ; prompt  $D^{*+}$  with no particle identification applied are given with green symbols; B feed-down  $D^{*+}$  are represented with blue. For these efficiencies the Monte-Carlo simulations have all been used that employ the detector configuration of the LHC run periods  $b$ ,  $c$ ,  $d$  and  $e$ .

Table 4.7: List of the various selection steps used in the correction framework and the main variables stored at each step. The generated steps contain pure Monte-Carlo generated particle information, while the reconstructed step represents the detector response.

| Selection step                                   | Particle                     | Variables                                                                              |
|--------------------------------------------------|------------------------------|----------------------------------------------------------------------------------------|
| Generated Limited Acceptance                     | $D^{*+}, K,$<br>$\pi, \pi_s$ | $p_{T D^{*+}}, y_{D^{*+}},$<br>$\phi_{D^{*+}}, p_{TK},$<br>$p_{T\pi}, p_{T\pi_s}, dca$ |
| Generated Acceptance (I)                         |                              |                                                                                        |
| Generated I and Vertex selection (II)            |                              |                                                                                        |
| Generated II and refit                           |                              |                                                                                        |
| Reconstructed (I)                                |                              |                                                                                        |
| Reconstructed I and in Acceptance (II)           |                              |                                                                                        |
| Reconstructed II with ITS clusters request (III) |                              |                                                                                        |
| Reconstructed III with topological cuts (IV)     |                              |                                                                                        |
| Reconstructed IV with particle identification    |                              |                                                                                        |

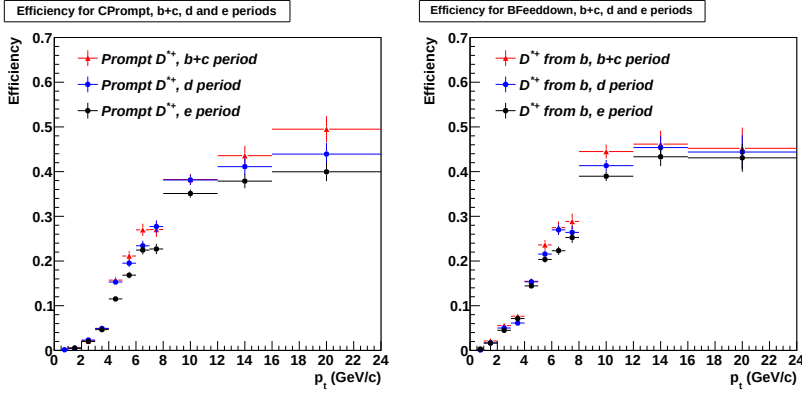


Figure 4.6: Reconstruction efficiency of prompt  $D^{*+}$  (left) and  $D^{*+}$  from B decays (right) of the LHC periods  $b+c$ ,  $d$  and  $e$ .

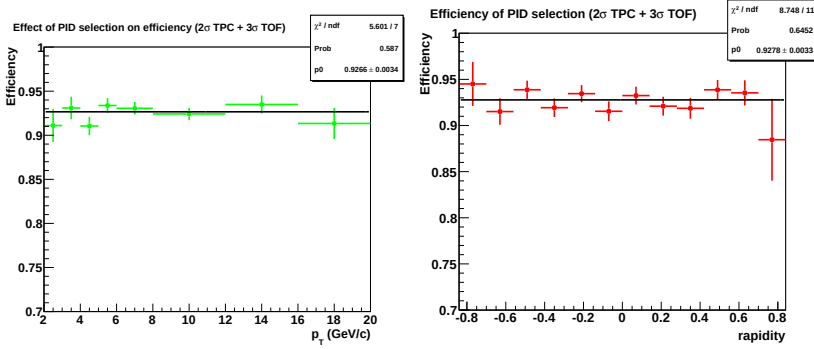


Figure 4.7:  $D^{*+}$  reconstruction efficiency as a function of  $p_T$  (left) and rapidity (right). Here only particle identification selection cuts for  $2\sigma$  TPC and  $3\sigma$  TOF are applied.

pected energy loss in TPC is applied for both kaons and pions. For the particle identification supplied by the TOF there was a further kaon rejection cut added which corresponded with a  $3\sigma$  selection over the TOF response for a kaon transverse momentum up to  $p_T \sim 1.5$  GeV/c. When applying a  $3\sigma$  selection cut both on the TPC and TOF responses it is expected that the  $D^{*+}$  signal would reduce by  $(1 - 0.997 \times 0.997) - (1 - 0.997) \sim 1\%$ . If a  $2\sigma$  selection cut is set for the TPC response instead, the signal reduction should be about 9%.

In figures 4.7 and 4.8 the stability of the particle identification cuts are shown, as a function of transverse momentum and rapidity. In this case a  $2\sigma$  particle identification cut in the TPC was applied. This selection reduces the signal by about 8% over the whole  $p_T$  and rapidity range considered here. Within errors, these results are in agreement with the expectations. A  $3\sigma$  cut on the TPC particle identification gives a signal reduction of about 3%, again in good agreement with the expected value.

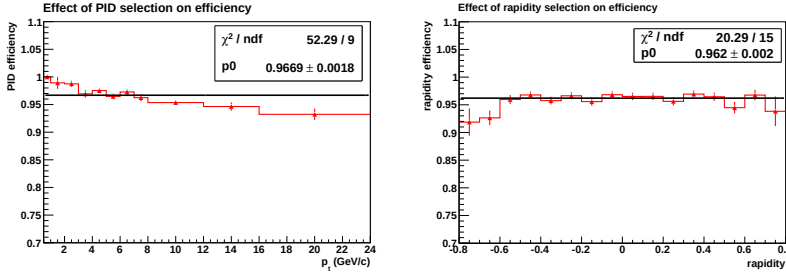


Figure 4.8: Efficiency with particle identification as a function of signal  $p_T$  (left) and rapidity (right). Here only particle identification selection cuts for  $3\sigma$  TPC and  $3\sigma$  TOF are used. Here a small dependence of the efficiency versus the  $D^{*+}$  transverse momentum is noticeable, attaining a difference of 3.5% in the  $[16, 24]$  GeV/c  $p_T$  bin. This effect is caused by the parameterization of the energy loss in the TPC for the region of relativistic rise in the  $dE/dx$  energy loss spectrum.

Table 4.8: List of the systematic errors determined for yield extraction, the particle identification strategy, tracking efficiency and Monte-Carlo  $p_T$  shape.

| $p_T$ bin [GeV/c] | yield ext. [%] | part. id. [%] | tracking [%] | $p_T$ shape [%] |
|-------------------|----------------|---------------|--------------|-----------------|
| [1, 2]            | 10             | 4             | 13           | 3               |
| [2, 3]            | 4              | 4             | 5            | 1               |
| [3, 4]            | 3              | 4             | 3.2          | 1               |
| [4, 5]            | 3              | 4             | 3            | 1               |
| [5, 6]            | 5              | 4             | 3            | 1               |
| [6, 7]            | 5              | 4             | 3            | 1               |
| [7, 8]            | 5              | 3             | 3            | 1               |
| [8, 12]           | 4              | 3             | 3            | 1               |
| [12, 16]          | 9              | 3             | 3            | 1               |
| [16, 24]          | 20             | 3             | 3            | 1               |

## 4.3 Systematics

This study considered several sources of systematics, which influenced not only the results of the signal extraction from the  $D^{*+}$  invariant mass spectra, but also the correction factors applied to obtain the  $D^{*+}$   $p_T$ -differential cross section. The estimated relative systematic errors are summarised in table 4.8.

In order to determine the systematic uncertainty on the yield extraction, the fitting procedure for the invariant mass spectra was determined by repeating it, using different invariant mass intervals and background fit functions in each  $D^{*+}$   $p_T$  bin. A complementary check consisted of the implementation of a side-band background simulation, from which the yield was extracted. The difference with respect to the fit method was about 2-3%. Furthermore, a bin counting method was also used as a check. Here the total number of entries in the invariant mass distribution for the background, estimated with a side-band background fit, was subtracted.

Since there can be differences between simulated and actual data for the parameters used to select the  $D^{*+}$  signal candidates, another systematic is introduced. For

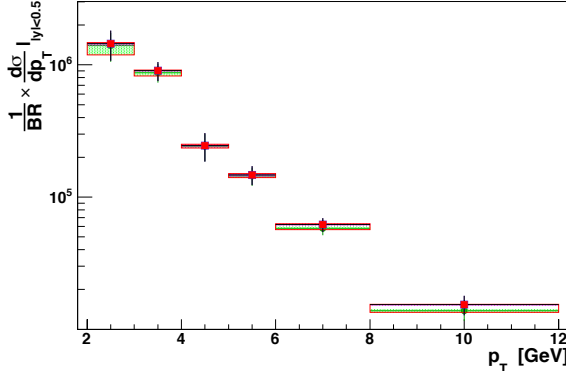


Figure 4.9: Estimation B feed-down systematic for the  $D^{*+}$   $p_T$  range [2,12] GeV/c, obtained with partial statistic. Here the systematic (represented by the red box) is determined by the envelope of the  $n_b$  (shaded red) and  $f_c$  (shaded green) methods. See text for details.

$D^{*+}$  candidates passing relaxed topological cuts the distributions of these variables for actual data and Monte-Carlo has been compared, which was dominated by background candidates due to the selections. It was determined that simulation and actual data matched well.

The systematic on cut stability was determined by repeating the analysis with different sets of selection cuts. This meant that cut values were varied by about 20–40%, provided they produced a reasonable statistical significance. This produced a systematic error of about 10% as a function of the  $D^{*+}$  transverse momentum. The systematic error caused by the selection of the particle identification cut was determined by repeating the analysis by either without this selection or with tighter cuts (in particular,  $2\sigma$  compatibility instead of  $3\sigma$ ).

In order to determine the evolution of the experimental conditions as time progressed, separate sub-samples of collected data were analysed, acquired with different detector configurations and magnetic field orientations. This proved to be compatible within statistical errors.

A possible source of systematic is the shape of the  $D^{*+}$   $p_T$  distribution in simulated events, for which the slope is significantly different between PYTHIA [76] (with the Perugia-0 tune) and FONLL pQCD calculations at high transverse momenta. The systematic on the  $D^{*+}$  selection efficiency that this caused remained below three percent however.

In figure 4.9 the systematic error caused by subtracting B feed-down  $D^{*+}$  is shown. It has been estimated on one hand by using the limits of the FONLL prediction. This has already been used to describe beauty production at Tevatron [82] and the LHC [83, 84] and has proven its merit. The average theoretical  $p_T$ -differential cross section for B feed-down  $D^{*+}$  was multiplied with the efficiency ratio of feed-down and prompt  $D^{*+}$  in each transverse momentum bin. This was then subtracted from the total cross section. The resulting systematic on this correction could then be estimated to range between  $^{+5\%}_{-45\%}$  at low transverse momentum (1-2 GeV/c) to  $^{+8\%}_{-10\%}$  for  $p_T > 12$

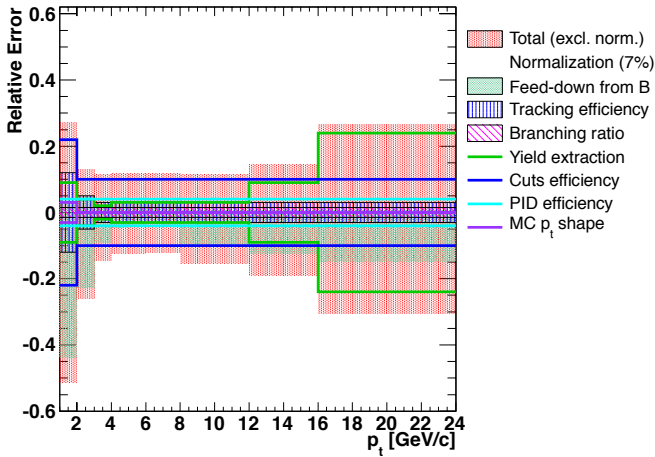


Figure 4.10: Summary of the various systematic uncertainties evaluated for the analysis for the different transverse momentum intervals.

GeV/c. These numbers were determined from the range of results gained with the minimum and maximum predictions for B feed-down  $D^{*+}$  production, which could be gathered by varying the renormalisation and factorisation scales and the  $b$  quark mass. On the other hand, the estimation is also based on the theoretical prediction of the beauty to charm production ratio, called the  $f_c$  method, discussed in section 3.5. The uncertainties on this efficiency ratio had a negligible contribution.

The other systematic errors considered in this study were on the branching ratios, for which literature set an uncertainty of 1.5%, and a 4% systematic on the normalisation of the minimum-bias proton-proton cross section. Figure 4.10 summarises all the systematic sources investigated.

#### 4.4 Prompt $D^{*+}$ $p_T$ -differential production cross section in proton-proton collisions at $\sqrt{s} = 7$ TeV

The differential production cross-section, using the full 2010 minimum bias proton-proton  $\sqrt{s} = 7$  TeV collision data sample, is shown in figure 4.11. The results are compared in each  $D^{*+}$  transverse momentum bin with two theoretical models FONLL and GM-VFNS [78, 79, 105, 106]. The experimental data points correspond within errors with both theories. Here the theoretical predictions were integrated over the whole range of the individual  $p_T$  bins to correspond with the datapoints that themselves are the integrand over the  $p_T$  bin widths. The numerical values of the cross section for the various  $D^{*+} p_T$  bins, together with their statistical and systematic uncertainties is summarised in table 4.9.

In figure 4.11 the average transverse momentum over the  $p_T$  bin used for each datapoint. Since the  $D^{*+}$  transverse momentum distribution has an exponential shape,

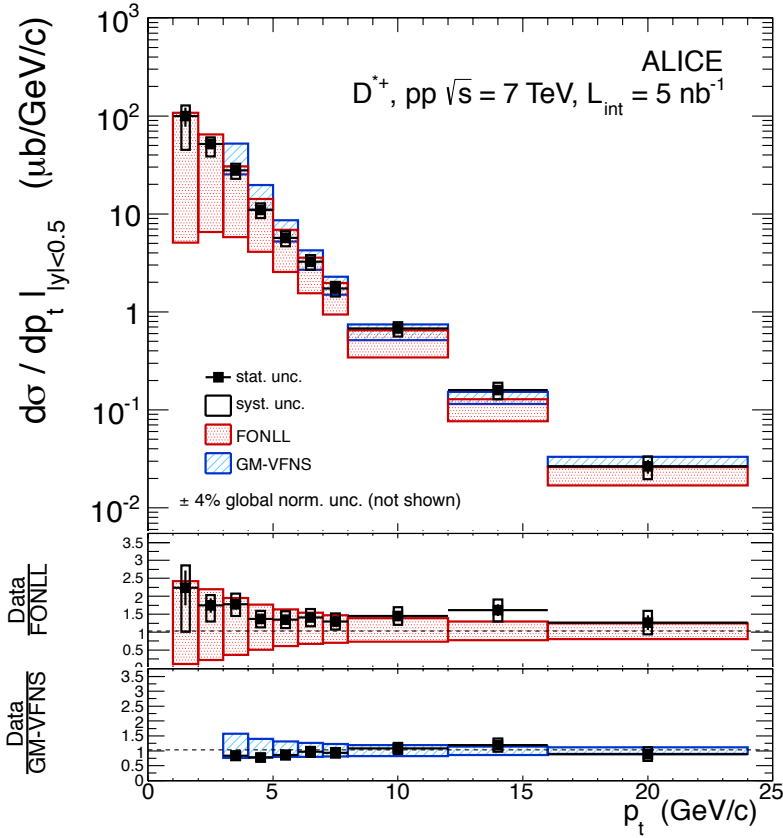


Figure 4.11: Prompt  $D^{*+} \rightarrow K^- \pi^+ \pi_{\text{soft}}^+$  inclusive  $p_T$ -differential production cross section for the transverse momentum range  $p_T \in [1, 24]$  GeV/c. The plot in the middle shows the ratio of the data with the central value of the FONLL prediction [78, 79, 104]. Likewise, the bottom plot shows the same for the GM-VFNS calculation [105, 106].



Table 4.9: Numerical values of the prompt  $D^{*+}$  production cross section in  $|y| < 0.5$  for proton-proton collisions at  $\sqrt{s} = 7$  TeV, divided over 10 transverse momentum intervals. Here the reported systematic error does not include the normalisation uncertainty of 4%.

| $p_T$ interval [GeV/c] | $\langle p_T \rangle$ [GeV/c] | $\frac{d\sigma}{dp_T} _{ y <0.5} \pm \text{stat.} \pm \text{syst.}$<br>( $\mu\text{b/GeV/c}$ ) |
|------------------------|-------------------------------|------------------------------------------------------------------------------------------------|
| [1, 2]                 | $1.5 \pm 0.3$                 | $99 \pm 22^{+28}_{-54}$                                                                        |
| [2, 3]                 | $2.5 \pm 0.2$                 | $51.6 \pm 5.9^{+8.7}_{-13.1}$                                                                  |
| [3, 4]                 | $3.5 \pm 0.1$                 | $27.9 \pm 2.3^{+4.6}_{-5.2}$                                                                   |
| [4, 5]                 | $4.5 \pm 0.1$                 | $10.97 \pm 0.87^{+1.81}_{-1.88}$                                                               |
| [5, 6]                 | $5.5 \pm 0.1$                 | $5.68 \pm 0.45^{+0.97}_{-0.99}$                                                                |
| [6, 7]                 | $6.5 \pm 0.1$                 | $3.25 \pm 0.27^{+0.55}_{-0.56}$                                                                |
| [7, 8]                 | $7.4 \pm 0.1$                 | $1.73 \pm 0.21^{+0.29}_{-0.30}$                                                                |
| [8, 12]                | $9.4 \pm 0.3$                 | $0.674 \pm 0.050^{+0.113}_{-0.116}$                                                            |
| [12, 16]               | $13.8 \pm 0.9$                | $0.160 \pm 0.016^{+0.030}_{-0.031}$                                                            |
| [16, 24]               | $17.0^{+2.0}_{-1.0}$          | $0.027 \pm 0.004^{+0.007}_{-0.007}$                                                            |

this demands a correction to account for the fact that relatively more  $D^{*+}$  will have a momentum lower than the bin average. This correction, included in table 4.9 mostly affects the high  $p_T$  bins due to their comparatively large width. However, since the theoretical predictions used in this work are not continuous but normalised over the  $p_T$  range of the respective  $D^{*+}$   $p_T$  bins, the exact  $p_T$  value of the datapoint is trivial.

With the results shown in this work, as well as those for other charmed mesons studied at the ALICE collaboration, it has become possible to extend the investigated range of the total cross section of charm-anticharm production versus the proton-proton centre-of-mass energy to 7 TeV. This is a very significant increase (of about a factor 70) compared to the results of STAR and PHENIX found at the RHIC complex. This is shown in figure 4.12.

## 4.5 Comparison scaled 7 TeV and 2.76 TeV proton-proton data

The  $D^{*+}$  nuclear modification factor ( $R_{AA}$ ) is calculated using the 2010 Pb-Pb data sample, with at  $\sqrt{s_{NN}} = 2.76$  TeV, while the reference used is based on proton-proton collision with a centre-of-mass energy of 7 TeV, even though a proton-proton run of  $\sqrt{s} = 2.76$  TeV is available. This is done because the  $\sqrt{s} = 7$  TeV proton-proton data contains much more statistics compared to those of the 2.76 TeV proton-proton run. Specifically, the former consists of about 314 million events collected with a minimum-bias trigger, while the latter only had about 58 million events. As such the former has much more statistical significance and will be used as reference for the  $D^{*+}$   $R_{AA}$  measurement, albeit via a theoretical scaling of the 7 TeV cross section to get it down to 2.76 TeV. This assumes that the pQCD scales and quark masses do not change with centre-of-mass energy.

Since the proton-proton run at  $\sqrt{s} = 2.76$  TeV has comparatively low statistics,

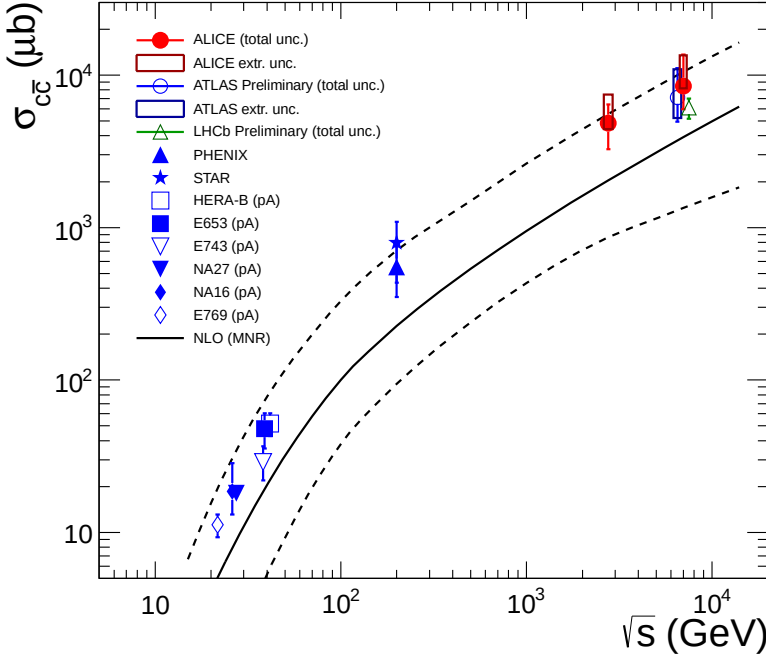


Figure 4.12: Total charm production cross section for various experiments as a function of centre-of-mass energy, compared to PYTHIA and NLO pQCD calculation [107, 108, 109, 110, 111, 112]. This figure includes the results of the ALICE collaboration (as well as ATLAS, CMS and LHCb) up to a centre-of-mass energy of 7 TeV for proton-proton interactions. For proton-nucleus (pA) and deuteron-nucleus (dA) collisions the cross sections measured have been scaled down according to the number of binary nucleon-nucleon collisions, calculated in a Glauber model of the proton-nucleus or deuteron-nucleus collision geometry. The NLO MNR calculation [113] is represented by the solid black line, while its uncertainties are given by the dashed lines.

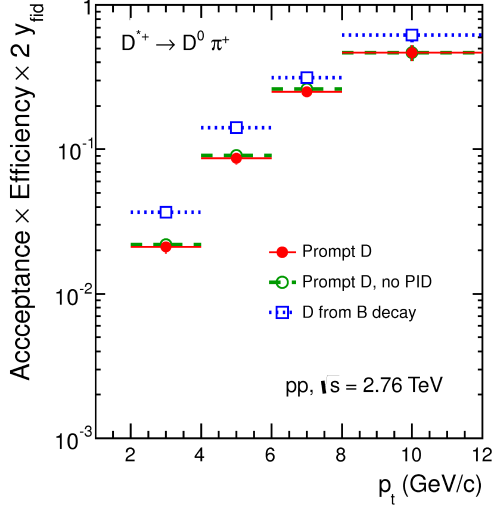


Figure 4.13: Reconstruction efficiencies for the  $D^{*+}$  meson. The red point indicate the efficiencies for D mesons from prompt charm production. Blue points are for reconstructed D mesons from B decay. Green points are for D mesons from prompt charm production when particle identification is included in the reconstruction.

it will have large statistical uncertainties and a limited  $D^{*+}$  transverse momentum reach for which a clear signal can be separated from the background. Nevertheless, its results for the cross section can still be used as a cross check of the scaling procedure and of the systematics arising from the scaling itself.

In order to determine the cross section for the proton-proton run at  $\sqrt{s} = 2.76$  TeV the same methods have been used as for the 7 TeV analysis. This includes determining the reconstruction efficiencies for  $D^{*+}$  mesons using Monte-Carlo reconstruction, which is presented for the  $D^0$  meson in fig. 4.13. The result for the cross section itself is shown in fig. 4.14.

In figure 4.15 the comparison is shown of the measured  $D^{*+}$  cross section (as well as two other D mesons) at  $\sqrt{s} = 2.76$  TeV with the theoretical scaling of the 2010 run proton-proton data at 7 TeV result on  $D^{*+}$  cross section scaled down to the former's centre-of-mass energy. Within the statistical and systematic uncertainty the two results are in good agreement.

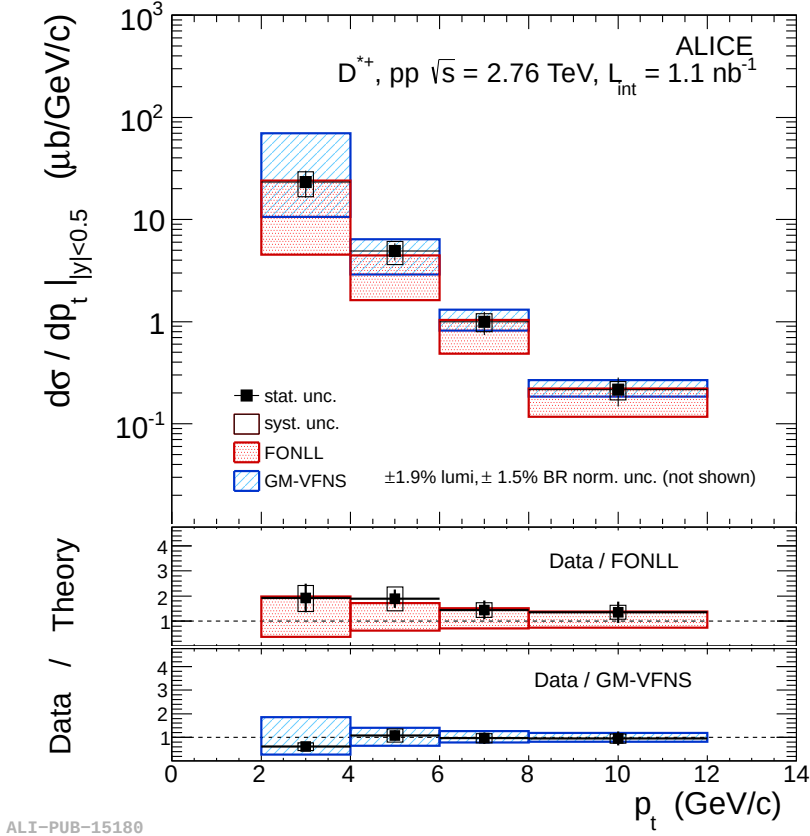
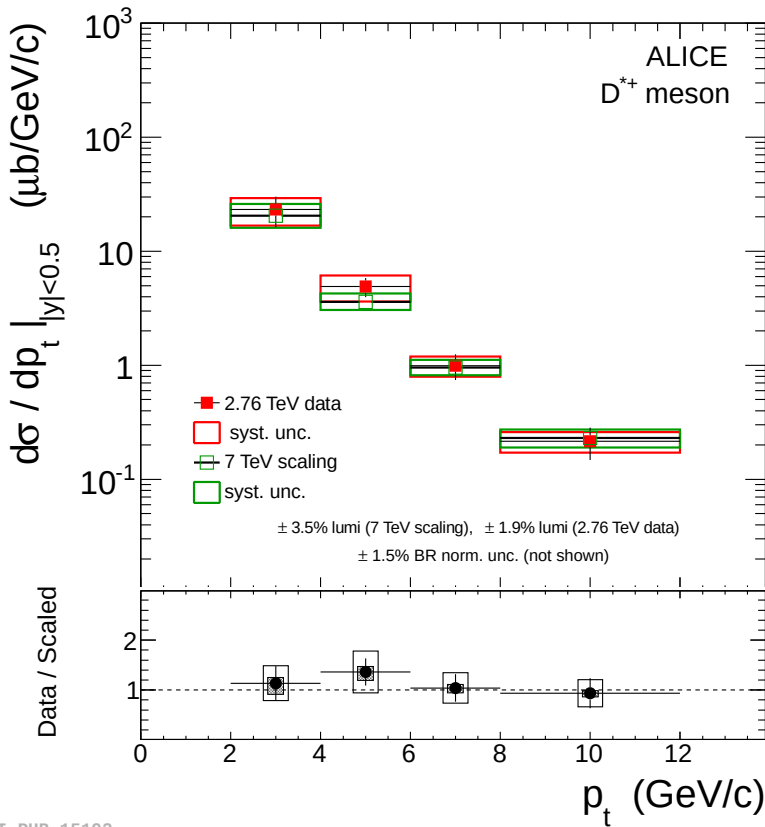


Figure 4.14: Prompt  $D^{*+}$  meson cross sections (top) as a function of the transverse momentum for proton-proton interactions at  $\sqrt{s} = 2.76$  TeV. The datapoints are compared to the theoretical predictions from the FONLL (red box) and GM-VFMS (blue box) models. The ratio between the cross section determined from the data and the FONLL calculation (centre) and GM-VFMS calculation (bottom) are also shown.



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Figure 4.15: Comparison of the prompt D<sup>\*+</sup> meson cross sections for proton-proton interactions at  $\sqrt{s} = 7$  TeV (scaled down to 2.76 TeV) with ones measured at  $\sqrt{s} = 2.76$  TeV. Statistical and systematic errors are included. The bottom figures give the ratio between these cross sections.

## Chapter 5

# $D^{*+}$ production in lead-lead collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

This chapter describes the measurement of the nuclear modification factor for  $D^{*+}$  mesons in Pb-Pb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV. It is divided into two parts. The first part shows the results from the 2010 lead-lead run. This physics run accumulated about 17 million Pb-Pb collisions that were used in the  $D^{*+}$  analysis and passed the selection criteria and 13 million events in a centrality range of 0 to 80 percent. This corresponded to a integrated luminosity of  $L_{\text{int}} = 2.12 \pm 0.07 \mu\text{b}^{-1}$ .

Following another Pb-Pb run in the fall of 2011, more data became available for analysis. In the scope of this thesis, it meant an accumulation of 126 million lead-lead collisions over those collected in 2010, of which about 30 million passed the central trigger criteria. This significant increase in statistics enabled the investigation of the  $D^{*+}$  nuclear modification factor  $R_{\text{AA}}$  (defined in chapter 4) over both a larger  $p_{\text{T}}$  range and a narrower centrality selection. This analysis will be discussed in the second part of the chapter.

### 5.1 $D^{*+}$ analysis using 2010 data sample

The main focus for the 2010 dataset was the determination of the  $D^{*+}$   $R_{\text{AA}}$  as a function of the transverse momentum for the centrality ranges [0, 20]% and [40, 80]%, which are within the scope of this chapter informally called the central and peripheral centrality classes. This dataset corresponds to the run numbers given in table 5.1.

In order to study the  $R_{\text{AA}}$  dependency on the centrality more closely, the nuclear modification factor has also been studied for the 0-10%, 10-20%, 20-40%, 40-60% and 60-80% centrality classes, though with wide  $D^{*+}$   $p_{\text{T}}$  intervals. For these centrality ranges, the average number of participating nucleons  $\langle N_{\text{part}} \rangle$  and nuclear overlap function  $\langle T_{\text{AA}} \rangle$  (both defined in sect. 3.5) in the Pb-Pb collision are summarised in table 5.2. There the numbers are determined using a Monte-Carlo simulation of the Glauber model, where an inelastic nucleon-nucleon cross section of 64 mb is assumed [114].

Several single track and topological selection cuts have been used to maximise the

Table 5.1: List of the lead-lead collision runs taken over 2010.

| Run<br>number |        |        |        |        |        |        |        |        |
|---------------|--------|--------|--------|--------|--------|--------|--------|--------|
| 139514        | 139513 | 139511 | 139510 | 139507 | 139505 | 139503 | 139470 | 139467 |
| 139466        | 139465 | 139438 | 139437 | 139360 | 139329 | 139328 | 139314 | 139310 |
| 139309        | 139173 | 139107 | 139105 | 139038 | 139037 | 139036 | 139029 | 139028 |
| 138872        | 138871 | 138870 | 138837 | 138796 | 138732 | 138730 | 138666 | 138662 |
| 138653        | 138652 | 138638 | 138624 | 138621 | 138583 | 138582 | 138579 | 138578 |
| 138534        | 138469 | 138442 | 138439 | 138438 | 138396 | 138364 | 138225 | 138201 |
| 138197        | 138192 | 138190 | 138154 | 138153 | 138151 | 138150 | 138126 | 138125 |
| 137848        | 137843 | 137752 | 137751 | 137724 | 137722 | 137718 | 137704 | 137693 |
| 137692        | 137691 | 137686 | 137685 | 137639 | 137638 | 137608 | 137595 | 137549 |
| 137546        | 137544 | 137541 | 137539 | 137531 | 137530 | 137443 | 137441 | 137440 |
| 137439        | 137434 | 137432 | 137431 | 137430 | 137366 | 137243 | 137236 | 137235 |
| 137232        | 137231 | 137165 | 137162 | 137161 |        |        |        |        |

Table 5.2: Average number of participating nucleons and the nuclear overlap function for various Pb-Pb collision centrality ranges, obtained from the Glauber calculations [114].

| Centrality range (%) | $\langle N_{\text{part}} \rangle$ | $\langle T_{\text{AA}} \rangle (\text{mb})^{-1}$ |
|----------------------|-----------------------------------|--------------------------------------------------|
| 0-20                 | $308 \pm 3$                       | $18.93 \pm 0.74$                                 |
| 40-80                | $46 \pm 2$                        | $1.20 \pm 0.07$                                  |
| 0-10                 | $357 \pm 4$                       | $23.48 \pm 0.97$                                 |
| 10-20                | $261 \pm 4$                       | $14.43 \pm 0.57$                                 |
| 20-40                | $157 \pm 3$                       | $6.85 \pm 0.28$                                  |
| 40-60                | $69 \pm 2$                        | $2.00 \pm 0.11$                                  |
| 60-80                | $23 \pm 1$                        | $0.42 \pm 0.03$                                  |

Table 5.3: Parameters used for the  $D^0$  decay daughter candidates single track selection.

| Track selection                  | threshold value                             |
|----------------------------------|---------------------------------------------|
| Kink candidate tracks            | excluded                                    |
| Track status $D^0$ daughters     | ITSrefit and TPCrefit                       |
| Track status $\pi_s$             | ITSrefit                                    |
| Clusters in ITS                  | $\geq 4$ , for which $\geq 1$ SPD           |
| Clusters in TPC                  | $\geq 70$                                   |
| $p_{TK;\pi}$ (GeV/c)             | $> 0.3$                                     |
| $p_{T\pi_{\text{soft}}}$ (GeV/c) | $> 0.0$                                     |
| TPC, TOF particle id. selection  | $2, 3\sigma$ (0-20%); $3, 3\sigma$ (40-80%) |

Table 5.4: List of the various topological selection cuts for the centrality class 0-20% in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV.

| $D^{*+} p_T$ (GeV/c)                                            | [4,5] | [5,6] | [6,7] | [7,8] | [8, 10] | [10,12] | [12,16] |
|-----------------------------------------------------------------|-------|-------|-------|-------|---------|---------|---------|
| $D^0 m_{\text{inv}}$ (GeV/c <sup>2</sup> )                      | 0.032 | 0.036 | 0.036 | 0.036 | 0.055   | 0.055   | 0.074   |
| dca (cm)                                                        | 0.025 | 0.027 | 0.027 | 0.027 | 0.03    | 0.03    | 0.07    |
| $\cos \theta^*$                                                 | 0.7   | 0.8   | 0.8   | 1.    | 1.0     | 1.0     | 1.0     |
| $p_{TK}$ (GeV/c)                                                | 1.1   | 1.    | 1.    | 1.    | 1.      | 1.0     | 0.3     |
| $p_{T\pi}$ (GeV/c)                                              | 1.1   | 1.    | 1.    | 1.    | 1.      | 1.0     | 0.3     |
| $d_{0;K}$ (cm)                                                  | 0.08  | 0.1   | 0.1   | 0.1   | 0.15    | 0.15    | 0.15    |
| $d_{0;\pi}$ (cm)                                                | 0.08  | 0.1   | 0.1   | 0.1   | 0.15    | 0.15    | 0.15    |
| $d_{0;K} \times d_{0;\pi}$ ( $\times 10^{-3}$ cm <sup>2</sup> ) | -0.3  | -0.25 | -0.14 | -0.14 | -0.08   | -0.04   | 0.1     |
| $\cos \theta_{\text{pointing}}$                                 | 0.99  | 0.99  | 0.99  | 0.98  | 0.98    | 0.98    | 0.99    |
| $\frac{1}{2}$ width $m_{D^{*+}}$ (GeV/c <sup>2</sup> )          | 0.3   | 0.3   | 0.3   | 0.3   | 0.3     | 0.3     | 0.3     |
| $\frac{1}{2}$ width $\Delta M$ (GeV/c <sup>2</sup> )            | 0.15  | 0.15  | 0.1   | 0.15  | 0.15    | 0.15    | 0.1     |
| min. $p_{T\pi_{\text{soft}}}$ (GeV/c)                           | 0.2   | 0.2   | 0.2   | 0.2   | 0.34    | 0.35    | 0.45    |
| max. $p_{T\pi_{\text{soft}}}$ (GeV/c)                           | 1.8   | 1.    | 100   | 100   | 100     | 100     | 100     |
| $\theta$                                                        | 0.5   | 0.5   | 0.5   | 0.5   | 0.5     | 0.5     | 1.      |
| $\cos \theta_{\text{pointingXY}}$                               | 0.998 | 0.998 | 0.998 | 0.998 | 0.998   | 0.994   | 0.992   |
| NDL                                                             | 6     | 5     | 5.    | 5.    | 5.      | 4.5     | 3.      |

significance of the  $D^{*+}$  signal in the various transverse momentum bins. The single track selection cuts are given in table 5.3. Table 5.4 contains the topological cuts used for the analysis of the central events within the 0-20% centrality range, while table 5.5 has the same for the peripheral events of the 40-80% centrality class.

### 5.1.1 Raw yield extraction

Three examples of the  $\Delta M$  invariant mass distributions of the central event class is shown in fig. 5.1. All results (including their statistical and systematic errors) are summarised in table 5.6.



Table 5.5: List of the various topological selection cuts for the centrality class 40-80% in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV.

| $D^{*+} p_T$ (GeV/c)                                            | [2,3] | [3,4] | [4,5] | [5,6] | [6,7] | [7,8] | [8, 10] | [10,12] | [12,16] |
|-----------------------------------------------------------------|-------|-------|-------|-------|-------|-------|---------|---------|---------|
| $D^0 m_{inv}$ (GeV/c <sup>2</sup> )                             | 0.024 | 0.032 | 0.032 | 0.036 | 0.036 | 0.036 | 0.074   | 0.076   | 0.074   |
| dca (cm)                                                        | 0.025 | 0.03  | 0.03  | 0.1   | 0.1   | 0.1   | 0.2     | 0.3     | 0.1     |
| $\cos \theta^*$                                                 | 0.8   | 0.7   | 0.8   | 1.    | 1.    | 1.    | 1.0     | 1.0     | 1.0     |
| $p_{TK}$ (GeV/c)                                                | 0.7   | 0.8   | 1.    | 1.    | 1.    | 0.3   | 0.3     | 0.3     | 1.0     |
| $p_{T\pi}$ (GeV/c)                                              | 0.7   | 0.8   | 1.    | 1.    | 1.    | 0.3   | 0.3     | 0.3     | 1.0     |
| $d_{0;K}$ (cm)                                                  | 0.08  | 0.1   | 0.1   | 0.1   | 0.1   | 0.1   | 0.15    | 0.15    | 0.15    |
| $d_{0;\pi}$ (cm)                                                | 0.08  | 0.1   | 0.1   | 0.1   | 0.1   | 0.1   | 0.15    | 0.15    | 0.15    |
| $d_{0;K} \times d_{0;\pi}$ ( $\times 10^{-3}$ cm <sup>2</sup> ) | -0.16 | -0.14 | -0.14 | -0.05 | 0.1   | 0.5   | 40      | 40      | 60      |
| $\cos \theta_{pointing}$                                        | 0.9   | 0.96  | 0.96  | 0.94  | 0.9   | 0.7   | 0.5     | 0.5     | 0.7     |
| $\frac{1}{2}$ width $m_{D^{*+}}$ (GeV/c <sup>2</sup> )          | 0.3   | 0.3   | 0.3   | 0.3   | 0.3   | 0.3   | 0.3     | 0.3     | 0.3     |
| $\frac{1}{2}$ width $\Delta M$ (GeV/c <sup>2</sup> )            | 0.1   | 0.1   | 0.1   | 0.1   | 0.1   | 0.1   | 0.1     | 0.1     | 0.1     |
| min. $p_{T\pi_{soft}}$ (GeV/c)                                  | 0.05  | 0.15  | 0.05  | 0.3   | 0.4   | 0.45  | 0.5     | 0.05    | 0.05    |
| max. $p_{T\pi_{soft}}$ (GeV/c)                                  | 100   | 100   | 100   | 100   | 100   | 100   | 100     | 100     | 100     |
| $\theta$                                                        | 0.5   | 0.5   | 0.5   | 0.5   | 0.5   | 0.5   | 0.5     | 0.5     | 1.      |
| $\cos \theta_{pointing XY}$                                     | 0.998 | 0.996 | 0.996 | 0.993 | 0.993 | 0.993 | 0.96    | 0.96    | 0.9     |
| NDL                                                             | 5.    | 4.5   | 4.5   | 4.5   | 2.5   | 2.5   | 0.      | 0.      | 0.      |

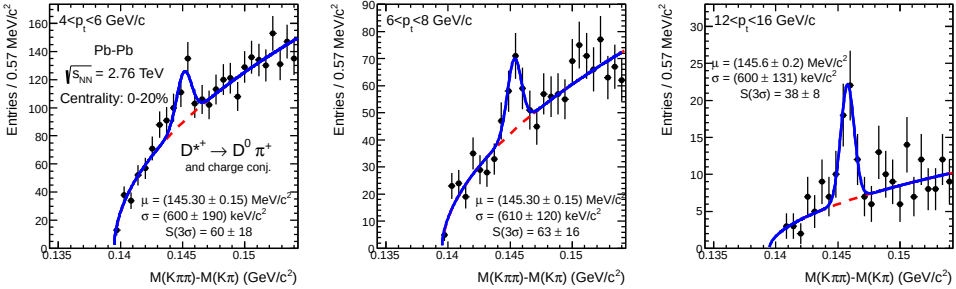


Figure 5.1:  $\Delta M$  invariant mass spectra for  $D^{*+}$  candidates in selected transverse momentum intervals for  $3.2 \times 10^6$  20% most central Pb-Pb events at  $\sqrt{s_{NN}} = 2.76$  TeV.

## 5.1.2 Efficiencies

In order to account for the B feed-down contribution to the  $D^{*+}$  raw yield, which requires the determination of the acceptance-times-efficiency corrections, the  $D^{*+}$  prompt and feed-down efficiencies have been determined using Monte-Carlo simulations that generated minimum bias Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV using the HIJING v1.36 event generator. Here the  $D^{*+}$  signals were added using proton-proton events of the PYTHIA v6.4.21 event generator with Perugia-0 tuning. The efficiencies for the  $D^{*+}$  meson in central events, when subjected to the previously mentioned selection cuts, is shown in figure 5.2

Table 5.6:  $D^{*+}$  raw yield per transverse momentum bin (some bins are merged due to limited statistics) for both central and peripheral collisions. Statistical and systematic uncertainties are given.

| $p_T$ interval<br>(GeV/c) | $N_{\text{raw}} \pm \text{stat.} \pm \text{syst.}$ |                    |
|---------------------------|----------------------------------------------------|--------------------|
|                           | 0-20% centrality                                   | 40-80% centrality  |
| 2-3                       | -                                                  | $82 \pm 21 \pm 12$ |
| 3-4                       | -                                                  |                    |
| 4-5                       | $60 \pm 18 \pm 12$                                 | $36 \pm 7 \pm 5$   |
| 5-6                       |                                                    | $29 \pm 9 \pm 3$   |
| 6-8                       | $63 \pm 16 \pm 6$                                  | $47 \pm 13 \pm 5$  |
| 8-12                      | $55 \pm 12 \pm 6$                                  | $57 \pm 11 \pm 6$  |
| 12-16                     | $38 \pm 8 \pm 4$                                   | $23 \pm 6 \pm 2$   |

### 5.1.3 Systematic uncertainties

The systematic uncertainties on the  $D^{*+}$  are given in table 5.7 for the lowest and highest  $D^{*+}$  transverse momentum intervals for both the central and peripheral centrality classes. These were obtained using the same methods as for the proton-proton cross-section results, but several are not present in the proton-proton systematics.

As such, the systematic contribution coming from the different  $R_{AA}$  for prompt and B feed-down  $D^{*+}$  was determined by varying the hypothesis on the  $R_{AA}^{\text{feeddown}}/R_{AA}^{\text{prompt}}$  ratio in the range  $[1/3, 3]$  for both feed-down subtraction methods (which in the case for the  $D^0$  is no more than 30%). Given the results for the prompt  $R_{AA}$  that are presented above, the systematic can be calculated to give the values presented in table 5.7.

The systematics on the reference cross section of the proton-proton collisions, the lead-lead  $D^{*+}$  yields and the average nuclear overlap function drive the systematic uncertainties on the  $R_{AA}$  measurement. In case of the proton-proton reference the  $D^{*+}$  cross section measurement at  $\sqrt{s} = 2.76$  TeV has uncertainties that are explained in more detail in [75]. The scaling to 2.76 TeV introduces another uncertainty of 10 to

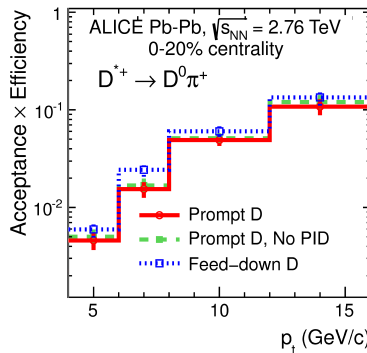


Figure 5.2: Acceptance-times-efficiency for  $D^{*+}$  mesons in central (0-20%) Pb-Pb collisions. Here the efficiencies as shown for prompt  $D^{*+}$ , B feed-down and prompt  $D^{*+}$  when no particle identification is applied.

Table 5.7: Relative systematic uncertainties on the yield for prompt  $D^{*+}$  mesons in Pb-Pb at  $\sqrt{s_{NN}} = 2.76$  TeV, specifically the lowest and highest transverse momentum bin.

| Centrality class                                  | 0-20%             |                   | 40-80%            |                  |
|---------------------------------------------------|-------------------|-------------------|-------------------|------------------|
| $p_T$ interval (GeV/c)                            | 4-6               | 12-16             | 2-4               | 12-16            |
| Yield extraction                                  | 20%               | 10%               | 15%               | 8%               |
| Tracking efficiency                               | 15%               | 15%               | 15%               | 15%              |
| Cut efficiency                                    | 10%               | 10%               | 10%               | 10%              |
| PID efficiency                                    | $+15\%$<br>$-5\%$ | 5%                | $+10\%$<br>$-5\%$ | 5%               |
| Monte-Carlo $p_T$ shape                           | 3%                | 3%                | 5%                | 4%               |
| FONLL B feed-down corr.                           | $+2\%$<br>$-5\%$  | $+2\%$<br>$-7\%$  | $+1\%$<br>$-8\%$  | $+1\%$<br>$-4\%$ |
| $R_{AA}^{\text{feeddown}}/R_{AA}^{\text{prompt}}$ | $+4\%$<br>$-9\%$  | $+5\%$<br>$-12\%$ | $+2\%$<br>$-6\%$  | $+3\%$<br>$-8\%$ |
| Branching ratio                                   | 1.5%              |                   | 1.5%              |                  |

30 percent. The previously explained uncertainties on the  $D^{*+}$  yield also contribute.

When determining the systematic on the  $D^{*+} R_{AA}$ , the systematics of the proton-proton reference and the lead-lead yield were added in quadrature. However, this was not the case for the systematic on the B feed-down contribution due to the FONLL uncertainties, which are partially cancelled in the ratio. This is because this systematic has been determined by comparing the  $R_{AA}$  values gathered from the two previously described feed-down correction methods as well different heavy quark masses, factorisation and renormalisation scales used in FONLL. Since this analysis used the same sets of FONLL parameters and methods for the determination of the proton-proton reference cross-section and the heavy-ion  $D^{*+}$  yield, the numerator and denominator of the calculation of the  $R_{AA}$  contains the same terms that cancel.

The final systematic is on the normalisation, which is obtained by taking the quadratic sum of the proton-proton normalisation uncertainty and the uncertainty on the nuclear overlap function. All these values are summarised in table 5.8.

Table 5.8: Relative systematic uncertainties on the  $D^{*+} R_{AA}$ , for the lowest and highest transverse momentum bin.

| Centrality class                                  | 0-20%              |                    | 40-80%             |                    |
|---------------------------------------------------|--------------------|--------------------|--------------------|--------------------|
| $p_T$ interval (GeV/c)                            | 4-6                | 12-16              | 2-4                | 12-16              |
| Data syst. pp and Pb-Pb                           | $+42\%$<br>$-41\%$ | $+34\%$<br>$-35\%$ | $+33\%$<br>$-39\%$ | $+29\%$<br>$-30\%$ |
| Data syst. in Pb-Pb                               | $+39\%$<br>$-36\%$ | $+29\%$<br>$-29\%$ | $+28\%$<br>$-27\%$ | $+22\%$<br>$-22\%$ |
| Data syst. in pp                                  | 15%                | 18%                | 15%                | 18%                |
| $\sqrt{s}$ -scaling of pp ref                     | $+7\%$<br>$-14\%$  | $+5\%$<br>$-6\%$   | $+10\%$<br>$-24\%$ | $+5\%$<br>$-6\%$   |
| Feed-down subtraction                             | $+5\%$<br>$-12\%$  | $+8\%$<br>$-16\%$  | $+3\%$<br>$-13\%$  | $+3\%$<br>$-14\%$  |
| FONLL B feed-down corr.                           | $+1\%$<br>$-1\%$   | $+2\%$<br>$-1\%$   | $+1\%$<br>$-5\%$   | $+1\%$<br>$-3\%$   |
| $R_{AA}^{\text{feeddown}}/R_{AA}^{\text{prompt}}$ | $+4\%$<br>$-9\%$   | $+5\%$<br>$-12\%$  | $+2\%$<br>$-6\%$   | $+3\%$<br>$-8\%$   |
| Normalisation                                     | 5.3%               |                    | 6.9%               |                    |

### 5.1.4 Prompt $D^{*+}$ yield distribution

The prompt  $D^{*+}$  yield  $dN/dp_T$  as a function of the transverse momentum in lead-lead collisions is given in figure 5.3 for both central and peripheral events. In this plot the spectra are compared to proton-proton collision reference spectra, the latter which are defined by the nuclear overlap function (see table 5.2) and the 7 TeV centre-of-mass energy proton-proton collision results when scaled down to 2.76 TeV per interacting nucleon-nucleon pair. For heavy ion collisions a suppression of the yield is visible, which is stronger for the more central collisions.

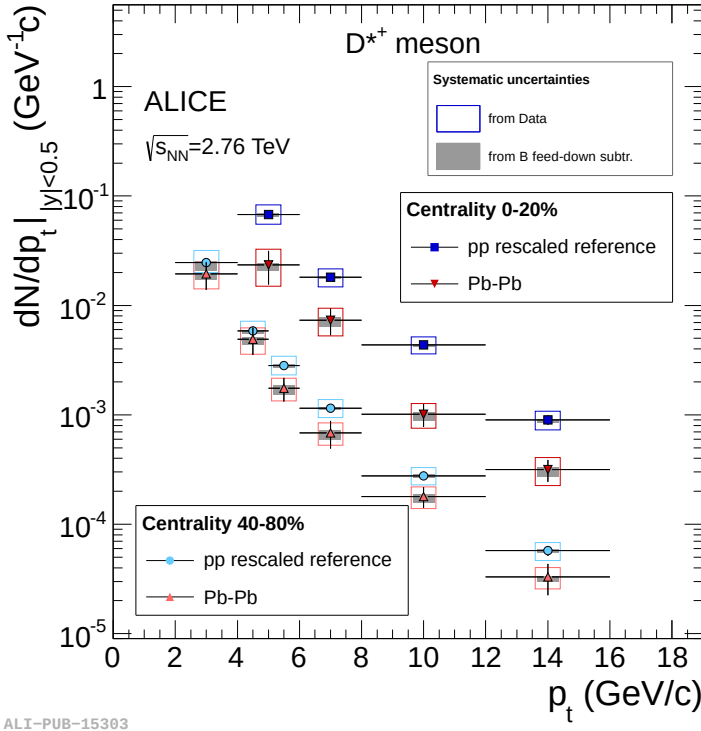


Figure 5.3: Prompt  $D^{*+}$  yield distribution as a function of transverse momentum, for both the 0-20% and 40-80% centrality classes in lead-lead collisions as  $\sqrt{s_{NN}} = 2.76$  TeV. The corresponding reference proton-proton cross-section distributions  $\langle T_{AA} \rangle d\sigma/dp_T$  are also shown for comparison. Statistical uncertainties are displayed as bars, systematic uncertainties from data analysis are given as empty boxes and systematics from B feed-down subtraction are shown as filled boxes. The uncertainties on the FONLL feed-down correction and variation of the  $R_{AA}^{\text{feeddown}}/R_{AA}^{\text{prompt}}$  hypothesis have been included in the full boxes.

### 5.1.5 Nuclear modification factor of the $D^{*+}$ meson

The  $D^{*+} R_{AA}$  can be determined from the ratio between the  $D^{*+}$  yield spectrum in lead-lead collisions and that of the proton-proton reference. Figure 5.4 shows the  $R_{AA}$  of  $D^{*+}$  (and  $D^0$  and  $D^+$ ) mesons as a function of transverse momentum, both for central and peripheral collisions. The statistical errors (given by the black error bars) for the  $D^{*+}$  are about 30 to 40 percent in central collisions. The boxes around the determined values give the systematic errors (though not the normalisation uncertainty, given by the filled box at  $R_{AA} = 1$ ). At any rate, the  $D^{*+}$  shows a suppression of a factor 3 to 4 for central collisions and  $p_T > 5$  GeV/c. Furthermore, these results are in agreement with the other two D mesons, within statistical uncertainties.

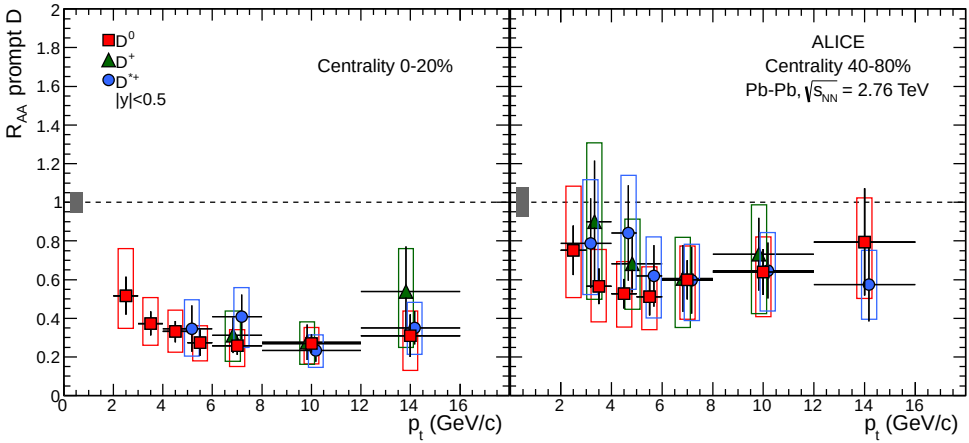


Figure 5.4:  $R_{AA}$  for D mesons using the 2010 dataset of  $\sqrt{s_{NN}} = 2.76$  TeV Pb-Pb collisions, for the 0-20% (left) and 40-80% (right) centrality classes. Solid black bars represent statistical errors, while empty boxes give the systematics. Normalisation uncertainties are given by the full boxes. The  $D^{*+}$  and  $D^+$  data points are slightly displaced to increase visibility.

The results for the investigation of the  $R_{AA}$  dependence on the centrality are given in figure 5.5, where the nuclear modification factor is given as a function of the average number of participants in a collision. Here the prompt  $D^{*+}$  yield was integrated over the momentum range  $p_T \in 6 - 12$  GeV/c, within the five previously mentioned centrality classes, ranging from [0, 10]% up to [60, 80]%. Here the systematic uncertainties are similar to the  $p_T$ -dependent spectra, but also includes a systematic for the Monte-Carlo simulated  $p_T$  shape for the meson, which tend to be larger in wide  $p_T$  intervals. In this plot the systematic uncertainty is split into two contributions; those that are fully correlated between centrality classes (like the normalisation and proton-proton cross-section) and those remaining uncorrelated systematics, respectively given by filled and empty boxes in the graph. The contribution to the systematics of the B feed-down correction was categorised as a source of uncorrelated systematics, since the variation of the ratio  $R_{AA}^{\text{feeddown}}/R_{AA}^{\text{prompt}}$  dominates this contribution, which in itself may depend on the centrality.

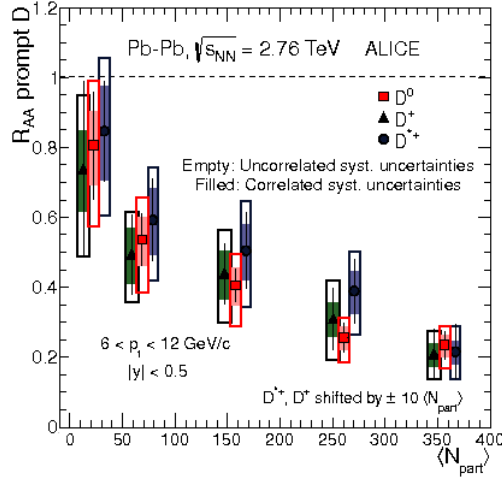


Figure 5.5: Prompt D meson  $R_{AA}$  as a function of centrality (represented by the number of participants). The figure gives the  $R_{AA}$  for three D mesons for  $p_T \in 6 - 12$  GeV/c.  $D^{*+}$  and  $D^+$  points are slightly displaced to increase visibility.

## 5.2 $D^{*+}$ analysis using 2011 data sample

The data sample was collected during the 2011 LHC lead-lead run at  $\sqrt{s_{NN}} = 2.76$  TeV, for which the following runs were selected for D meson analysis following quality assurance checks as given in table 5.9.

These runs were in the format of Analysis Object Data (AOD), following a filtering of ESD event using the *ConfigVertexingHF.C* to produce AOD095, the AOD used in this analysis.

This chapter will focus on the results of events that lie in the centrality range 0-7.5%. In this case a minimum bias and central trigger were employed which (together with the cut at 7.5%) reduced the number of events analysed down to 16 million events. Minimum bias events were triggered by requiring at least one hit in the SPD or V0 detectors. The central trigger in turn was based on a geometrical Glauber-model fit on the V0 amplitude spectrum.

### 5.2.1 Topological cuts

In order to maximise the significance in the various  $D^{*+}$  transfer momentum bins, topological selection cuts have been applied. These are summarised in table 5.10.

Furthermore, selection cuts are applied on the single decay-candidate tracks. These are summarised in table 5.11. Note that to decrease computation time, invariant mass cuts have been applied around the  $M_{D^0}$ ,  $M_{D^{*+}}$  and  $\Delta M = M_{K\pi\pi} - M_{K\pi}$  peaks, with values well over their  $3\sigma$  widths.

Identification of the charged kaons in the TPC and TOF detectors provides additional background rejection in the low momentum region. In order to assign kaon and/or pion masses to decay tracks, cut are applied to the difference in expected and

Table 5.9: List of the lead-lead collision runs taken over 2011.

| Run<br>number |        |        |        |        |        |        |        |        |
|---------------|--------|--------|--------|--------|--------|--------|--------|--------|
| 167902        | 167903 | 167909 | 167915 | 167920 | 167985 | 167986 | 167987 | 167988 |
| 168066        | 168068 | 168069 | 168076 | 168103 | 168104 | 168105 | 168107 | 168108 |
| 168115        | 168212 | 168310 | 168311 | 168322 | 168325 | 168341 | 168342 | 168361 |
| 168362        | 168458 | 168460 | 168461 | 168464 | 168467 | 168511 | 168512 | 168514 |
| 168777        | 168826 | 168984 | 168988 | 168992 | 169035 | 169040 | 169044 | 169045 |
| 169091        | 169094 | 169099 | 169138 | 169143 | 169144 | 169145 | 169148 | 169156 |
| 169160        | 169167 | 169238 | 169411 | 169415 | 169417 | 169418 | 169419 | 169420 |
| 169475        | 169498 | 169504 | 169506 | 169512 | 169515 | 169550 | 169553 | 169554 |
| 169555        | 169557 | 169584 | 169586 | 169587 | 169588 | 169590 | 169591 | 169835 |
| 169837        | 169838 | 169846 | 169855 | 169858 | 169859 | 169922 | 169923 | 169956 |
| 169965        | 169975 | 169981 | 170027 | 170036 | 170038 | 170040 | 170081 | 170083 |
| 170084        | 170085 | 170088 | 170089 | 170091 | 170152 | 170155 | 170159 | 170163 |
| 170193        | 170195 | 170203 | 170204 | 170207 | 170208 | 170228 | 170230 | 170268 |
| 170269        | 170270 | 170306 | 170308 | 170309 | 170311 | 170312 | 170313 | 170315 |
| 170387        | 170388 | 170556 | 170572 | 170593 |        |        |        |        |

Table 5.10: List of the various topological selection cuts used for the extraction of the  $D^{*+}$  signal from Pb-Pb events of the 0-7.5% centrality class.

| $p_T$ (GeV/c)                                                   | [1,2] | [2,3] | [3,4] | [4,5] | [5,6] | [6,8] | [8,12] | [12,16] | [16,24] | [24,35] |
|-----------------------------------------------------------------|-------|-------|-------|-------|-------|-------|--------|---------|---------|---------|
| $D^0 m_{inv}$ (GeV/c <sup>2</sup> )                             | 0.020 | 0.029 | 0.032 | 0.032 | 0.036 | 0.036 | 0.055  | 0.074   | 0.074   | 0.074   |
| dca (cm)                                                        | 0.025 | 0.02  | 0.04  | 0.025 | 0.022 | 0.023 | 0.023  | 0.018   | 0.018   | 0.1     |
| $\cos \theta^*$                                                 | 0.8   | 0.8   | 0.8   | 0.8   | 1.    | 1.    | 1.0    | 0.8     | 1.0     | 1.      |
| $p_{T,K}$ (GeV/c)                                               | 0.6   | 1.0   | 0.8   | 1.    | 1.    | 1.    | 0.9    | 0.3     | 0.3     | 0.3     |
| $p_{T,\pi}$ (GeV/c)                                             | 0.6   | 1.0   | 0.8   | 1.    | 1.    | 1.    | 0.9    | 0.3     | 0.3     | 0.3     |
| $d_{0,K}$ (cm)                                                  | 0.08  | 0.07  | 0.08  | 0.1   | 0.075 | 0.12  | 0.15   | 0.2     | 0.5     | 0.5     |
| $d_{0,\pi}$ (cm)                                                | 0.08  | 0.07  | 0.08  | 0.1   | 0.075 | 0.12  | 0.15   | 0.2     | 0.5     | 0.5     |
| $d_{0,K} \times d_{0,\pi}$ ( $\times 10^{-3}$ cm <sup>2</sup> ) | -0.3  | -0.35 | -0.35 | -0.3  | -0.23 | -0.13 | -0.033 | 0.05    | 3.0     | 3.55    |
| $\cos \theta_{pointing}$                                        | 0.99  | 0.99  | 0.992 | 0.992 | 0.99  | 0.98  | 0.985  | 0.97    | 0.95    | 0.7     |
| $\frac{1}{2}$ width $m_{D^{*+}}$ (GeV/c <sup>2</sup> )          | 0.05  | 0.08  | 0.3   | 0.1   | 0.11  | 0.3   | 0.3    | 0.3     | 0.3     | 0.3     |
| $\frac{1}{2}$ width $\Delta M$ (GeV/c <sup>2</sup> )            | 0.15  | 0.15  | 0.15  | 0.15  | 0.15  | 0.15  | 0.15   | 0.15    | 0.15    | 0.15    |
| min. $p_{T,\pi_{soft}}$ (GeV/c)                                 | 0.05  | 0.05  | 0.05  | 0.05  | 0.2   | 0.2   | 0.35   | 0.45    | 0.05    | 0.05    |
| max. $p_{T,\pi_{soft}}$ (GeV/c)                                 | 0.5   | 0.5   | 0.5   | 10    | 10    | 100   | 100    | 100     | 100     | 100     |
| $\theta$                                                        | 1.0   | 0.8   | 1.    | 0.5   | 0.5   | 0.5   | 0.5    | 1.      | 1.      | 1.      |
| $\cos \theta_{pointing,xy}$                                     | 0.998 | 0.998 | 0.998 | 0.998 | 0.998 | 0.998 | 0.998  | 0.998   | 0.996   | 0.9     |
| NDL                                                             | 7.    | 7.0   | 6.7   | 6.    | 7.    | 7.    | 4.     | 3.5     | 3.      | 0.7     |

Table 5.11: List of the various single track selection cuts applied for the  $D^{*+}$  analysis of the 2011 lead-lead data set.

| Track selection                   | threshold value         |
|-----------------------------------|-------------------------|
| Kink candidate tracks             | excluded                |
| Track status $D^0$ daughters      | ITS refit and TPC refit |
| Track status $\pi_{\text{soft}}$  | ITS refit               |
| Clusters in ITS                   | $\geq 1$ SPD            |
| Transverse momentum $p_T$ (GeV/c) | $> 0.3$                 |

measured signals, which are the specific energy deposited in the TPC, and the particle flight-time for the TOF. In the former case a  $2\sigma$  compatibility cut is applied, while the latter is subjected to a  $3\sigma$  cut. When tracks of particle have no TOF signal, only the TPC particle identification was used. Tracks with contradicting particle identification were considered to be non-identified. At any rate, only two-prong candidates that are compatible with an actual  $D^{*+}$  were accepted. No particle identification was used for the soft pion.

### 5.2.2 Raw yield extraction

Using aforementioned procedures, the raw signal yields were extracted for the  $D^{*+}$  by fitting the  $M_{K\pi\pi} - M_{K\pi}$ . For central events the results are visible in fig. 5.6 for the  $p_T$  integrated results, and 5.7 for the various  $p_T$  bins. The signal mean and width are shown in fig. 5.8, but appear stable. Note that there are less bins available than expected from the optimised cut set, since the transverse momentum bins 1-2 and 2-3 GeV/c used in the selection optimisation had a significance too low to be considered having a significant signal, i.e. a significance lower than three. The values of the yield extraction are summarised in table 5.12.

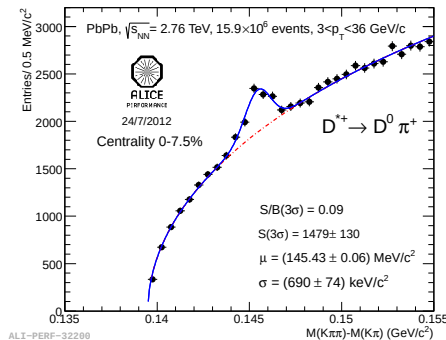


Figure 5.6:  $p_T$  integrated  $\Delta M$  invariant mass distribution for 0-7.5% central Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. A fit is applied using a convolution of a Gaussian and a threshold  $\times$  exponential function to describe the signal and background, respectively.



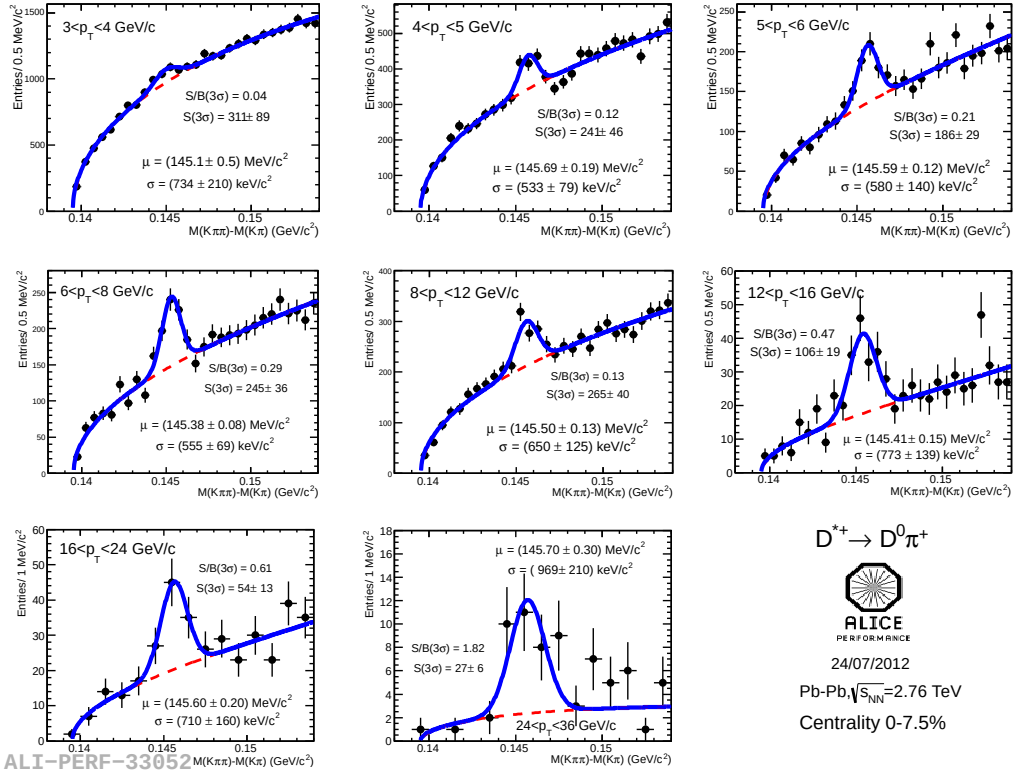


Figure 5.7: Invariant mass distributions for the various  $p_T$  bins together with a Gaussian plus background fit to the data, for the 7.5% most central lead-lead collisions at  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ .

Table 5.12:  $D^{*+}$  raw yield and peak significance versus the transverse momentum for 0-7.5% central Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ .

| $p_T$ bin [GeV/c] | raw yield    | significance    |
|-------------------|--------------|-----------------|
| 3-4               | $311 \pm 98$ | $3.17 \pm 0.49$ |
| 4-5               | $241 \pm 46$ | $5.24 \pm 0.48$ |
| 5-6               | $186 \pm 29$ | $6.41 \pm 0.44$ |
| 6-8               | $245 \pm 36$ | $6.81 \pm 0.55$ |
| 8-12              | $265 \pm 40$ | $6.63 \pm 0.42$ |
| 12-16             | $106 \pm 19$ | $5.58 \pm 0.52$ |
| 16-24             | $54 \pm 13$  | $4.15 \pm 0.54$ |
| 24-35             | $27 \pm 6$   | $4.50 \pm 0.46$ |

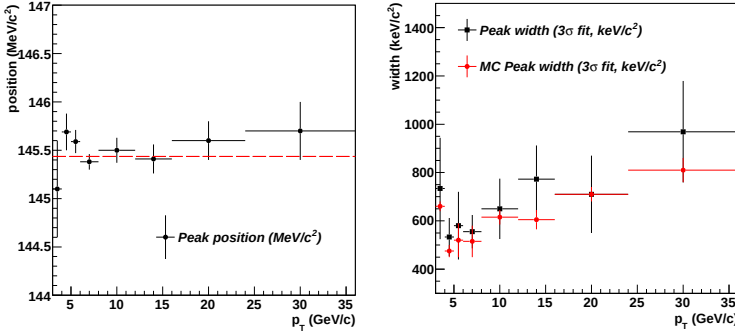


Figure 5.8:  $D^{*+}$  signal position (left) and width (right) as a function of  $D^{*+}$  transverse momentum bin. The Particle Data Group (PDG) value of  $M(K\pi\pi) - M(K\pi)$  is represented by a dashed red line.

### 5.2.3 Efficiencies

Due to limitations in the detector acceptance, branching ratios and other variables, the total  $D^{*+}$  production differs from the  $D^{*+}$  total yield. The measured raw yield  $Y^{D^{*+}}(p_T)$  for each  $p_T$  interval was corrected for acceptance (i.e. the factor  $2y_{acc}(p_T)$ ), reconstruction and efficiency selection  $\epsilon_{prompt}(p_T)$  for prompt  $D^{*+}$ , and for the prompt fraction  $f_{prompt}$  of the raw yield. Since the analysis involves both particles and antiparticles, the corrected yields had to be further divided by two, by the width  $\Delta p_T$  of each momentum bin interval and the decay branching ratio. This has been explained in greater detail in section 3.5.

The reconstruction efficiency takes into account signal loss due to primary vertex and track reconstruction, as well as loss of signal due to selection cuts on the single tracks, secondary vertex topology and particle identification. These results are shown in fig. 5.9.

These results were determined using Monte-Carlo simulations that used an accurate simulation of the real detector setup and response using the GEANT3 transport code. The acceptance and efficiency corrections were obtained with simulated minimum-bias Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$  using the HIJING v1.36 event generator [81]. Prompt and feed-down D meson signals were added using the proton-proton events from the PYTHIA 6 event generator with Perugia-0 tuning [76, 77]. Furthermore, D mesons were forced to decay via the hadronic decay channels relevant to D meson analyses. The number of proton-proton events added to each Pb-Pb event scaled with the event centrality of the latter. With the transport package GEANT3 [80] and with its detector geometry and detector response configured to closely match the actual detector setup, the simulation was used to generate the corresponding detector response. These results were used to produce the filtered AOD110 used in this analysis.

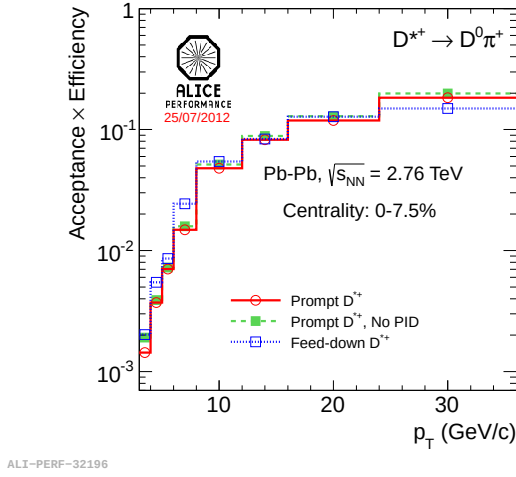


Figure 5.9:  $D^{*+}$  reconstruction efficiency as a function of  $p_T$  of the Monte-Carlo sample, for central lead-lead events. The red line signifies the reconstructed and selected prompt  $D^{*+}$ , while the green dashed line denotes the same but without particle identification applied. The blue symbols give the same for  $D^{*+}$  from B feed-down.

## 5.2.4 Systematic uncertainties

Several sources of systematic uncertainties were considered, including systematics on the yield extraction from the invariant mass distributions. The study of this systematic was performed by repeating the fitting procedure with a different mass range and/or different fitting function in the various momentum intervals. The functions compared were a power law convoluted with an exponential and a threshold function, which have been already been given in eq. (3.7) and (3.8).

A method based on bin counting was used as well. The standard fitting interval chosen was the mass range  $m_\pi$  to 155 MeV/c, which gives the best reduced  $\chi^2$  and assures the presence of enough background points within the fitting interval to give a reliable background estimation ( $\sim 10\sigma$  from the expected mass peak). The alternative fit range is  $m_\pi$  to 160 MeV/c, corresponding to a distance from the expected mass peak of  $\sim 15\sigma$ . The estimation on the systematic on yield extraction is shown in fig. 5.10. The numerical values determined bin by bin are shown in table 5.13.

Another uncertainty is due to differences in cut variable shapes in data and Monte-Carlo as well as residual misalignment. These were checked by repeating the analysis varying the selection cuts  $\sim 30\%$  tighter and looser from the standard set of cuts. Tightening or loosening all the main cuts together may introduce a bias due to the fact that all the cuts are changed in the same direction. Therefore a totally independent set of cuts was additionally used, which was based on a different approach than the standard set. The result of the cut variation procedure is shown in fig. 5.11. The numerical values of the cut variation systematic in each transverse momentum bin considered for  $D^{*+}$   $R_{AA}$  are reported in table 5.14.

The  $D^{*+}$  reconstruction method requires a  $n\sigma$  particle identification (PID) strategy, which for the centrality class 0 – 7.5% is a  $2\sigma$  cut applied to specific energy loss

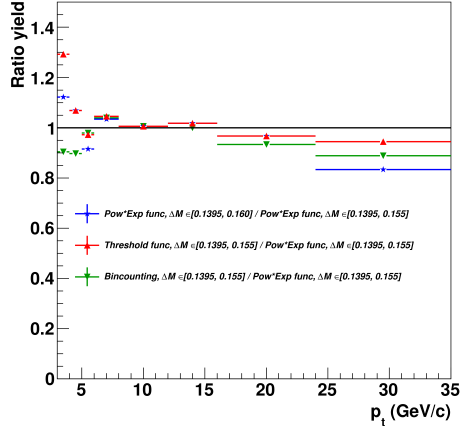


Figure 5.10: Contributions of the various fitting methods to the systematic uncertainty on yield extraction for centrality class 0-7.5%. From these results the systematics on the yield extraction are determined.

Table 5.13: Systematic on yield extraction is shown for all  $p_T$  bins considered for the centrality class 0 – 7.5%

| $p_T$ bin [GeV/c] | Systematic (%) |
|-------------------|----------------|
| 3-4               | 20             |
| 4-5               | 10             |
| 5-6               | 8              |
| 6-8               | 6              |
| 8-12              | 5              |
| 12-16             | 3              |
| 16-24             | 8              |
| 24-35             | 15             |

Table 5.14: Systematic for cut variation for all the  $p_T$  bins for the centrality class 0-7.5%

| $p_T$ bin [GeV/c] | Systematic (%) |
|-------------------|----------------|
| 3-4               | 10             |
| 4-5               | 10             |
| 5-6               | 10             |
| 6-8               | 10             |
| 8-12              | 10             |
| 12-16             | 15             |
| 16-24             | 10             |
| 24-35             | 5              |

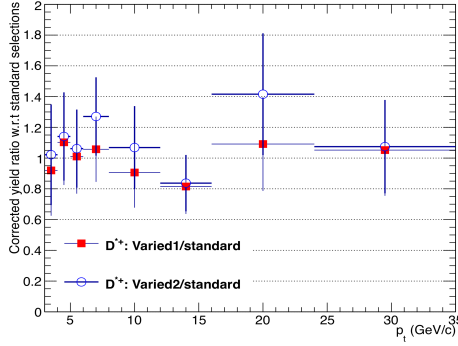


Figure 5.11: Ratio of standard cuts vs their variation for the centrality class 0-7.5%.

in the TPC. The request on the Time-of-Flight detector is a  $3\sigma$  cut. To check for a possible systematic on the PID strategy the analysis was repeated with and without particle identification when checking the extracted yield. The results are shown in fig. 5.12, where a data comparison of the  $D^0$  and  $D^{*+}$  results allow validation of the particle identification strategy in the full  $p_T$  range used for the  $R_{AA}$ .

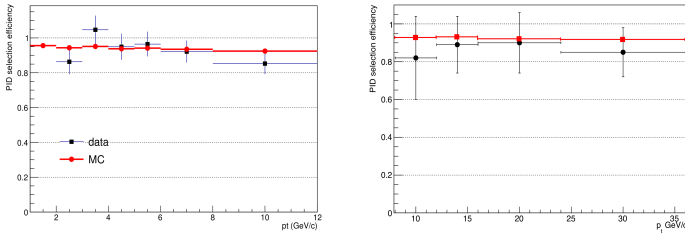


Figure 5.12: (Left) Ratio of the efficiency with particle identification applied, divided by the efficiency without particle identification for  $D^0$  using data and compared with Monte-Carlo simulations in the  $p_T$  range 1-12 GeV/c. (Right) Similar plot for  $D^{*+}$  in the  $p_T$  range 8-36 GeV/c.

During the 2011 data taking period the magnetic field polarity was switched once. A check was performed to confirm no large systematic effects arise from the switch due to a change in the negative to positive ratio. Here the sample of  $D^{*+}$  candidates was separated into several subsamples. For the different field polarities, the ratio of negative to positive candidates was evaluated, both for the  $p_T$  integrated case and versus the candidate transverse momentum. Furthermore, the check was repeated for different  $\eta$  regions to check the uniformity of the ratio versus  $\eta$ . Results are shown in fig. 5.13, where for positive pseudorapidity and polarity a small increasing trend is visible for increasing transverse momentum, though a similar trend is reproduced in Monte-Carlo simulations. On the other hand, the situation with integrated pseudora-

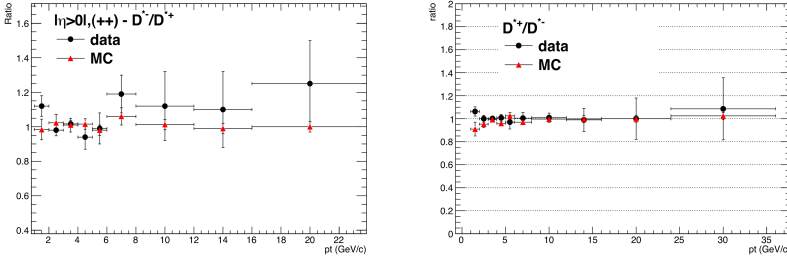


Figure 5.13: Systematic on particle anti-particle ratio. Left: the ratio  $N_{D^{*+}}/N_{D^{*-}}$  candidates is shown for positive field polarity and pseudorapidity as a function of the  $D^{*+}$  candidate transverse momentum. Right: Similar figure but for integrated pseudorapidity and averaged field polarity.

pidity and averaged polarity indicates that the systematic effect is negligible compared with other sources. From the comparison between data and Monte-Carlo it can be concluded that the systematic is smaller than the statistical error. As such, it is confined to less than 5%.

Another possible source of systematics is caused by the Monte-Carlo production, where the efficiency of reconstructed  $D^{*+}$  may vary depending on the underlying shape of  $p_T$  distribution of the generated  $D^{*+}$ . This is investigated by comparing the determined efficiency with those generated using different shapes of the underlying generated  $D^{*+}$  distributions. In particular, a flat shape and one determined by FONLL predictions. Results are displayed in fig. 5.14.

The summary of all the systematic sources entering in the analysis is shown in fig 5.15.

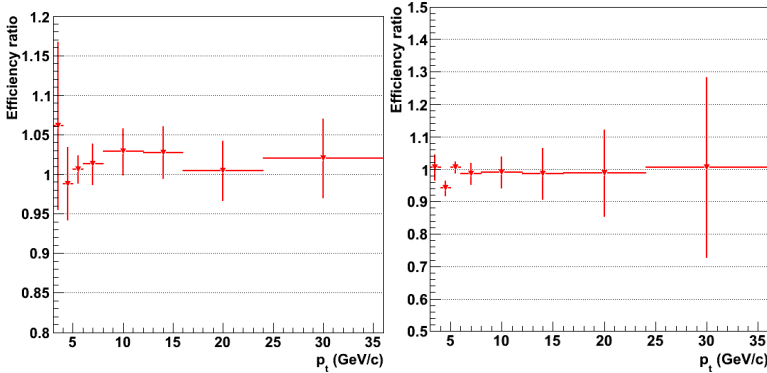


Figure 5.14: (Left) Ratio of efficiencies for a flat  $p_T$  distribution of generated  $D^{*+}$  in Monte-Carlo simulations, compared to the standard Monte-Carlo distribution for  $D^{*+}$  reconstructed in the centrality class 0–7.5%. (Right) Ratio for the case of FONLL generated  $D^{*+}$  distribution compared to standard distribution in the centrality class 0–7.5%.

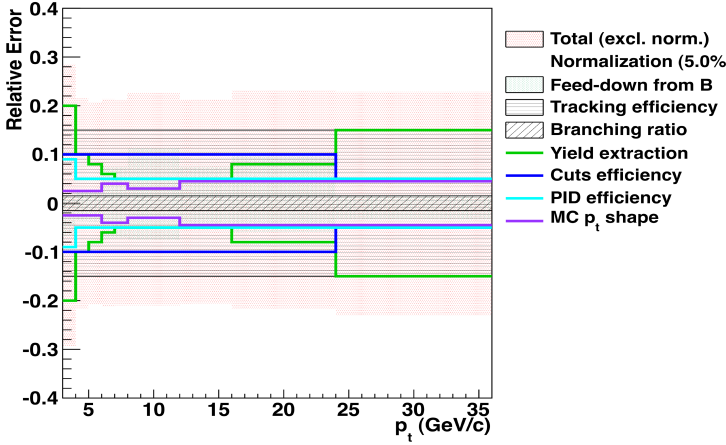


Figure 5.15: All systematics sources considered in the analysis.

### 5.2.5 Nuclear modification factor

The final result for the nuclear modification factor, when using the 2011 data, is shown in fig. 5.16. Here it is clear that for the  $D^{*+}$  there is a strong suppression of the  $D^{*+}$  production compared to the proton-proton reference, reaching up to a factor five in the 8-12 GeV/c transverse momentum bin. Also, it is visible that the suppression of the various D mesons correspond with one another within statistical errors (except for  $D_s$ ). Also visible is the estimated total systematic uncertainty, which takes into account the the uncertainties on the signal extraction procedure, the particle identification selection strategy, the efficiency on track reconstruction, the cut stability and the hypothesis on the B mesons  $R_{AA}$  (which itself takes into account all potential nuclear and medium effects which affect B meson production) varies from 70% to 12% depending on the  $p_T$  and the specific D meson species [115].

The combined results for the  $D^0$ ,  $D^+$  and  $D^{*+}$  mesons, as well as its comparison to lighter hadrons and models, are shown in fig. 5.17. Here the average nuclear modification factor for the three mesons are averaged, with the contributions of the three mesons weighted by their statistical uncertainties. Systematic errors have been calculated by propagating the uncertainties through the weighted average. Here contributions from tracking efficiency, the correction on the B feed-down and the scaling to the proton-proton reference were determined to be fully correlated among the three species of D meson.

The top of figure 5.17 contains a comparison of the combined D meson  $R_{AA}$  to the nuclear modification factor of lighter hadrons, in particular of charged pions and charged hadrons as measured by ALICE with the 2011 data sample in the 0-10% centrality class. The three results are compatible with one another (within uncertainties), though the D mesons seem to hint to a lower suppression at low transverse momentum.

In the bottom plot of figure 5.17 the average nuclear modification factor of the

three D mesons is compared with the results expected by various models. It is found that the radiative energy loss model (supplemented with in-medium D meson dissociation) and the WHDG implemented radiative plus collisional energy loss model, together with BDMPS-ASW and POWLANG models describe the data reasonably well. The heavy quark transport model with in-medium resonance scattering and coalescence seems to underestimate the observed suppression. The figure also contains an expected suppression in the absence of any in-medium effects, determined by perturbative QCD calculations based on the MNR [113] code with the addition of nuclear-modified particle distribution functions from the EPS09 parametrisation [116] to describe nuclear shadowing effects. This effect is indicated to be small for transverse momenta larger than 10 GeV/c, which indicated that the observed suppression is caused by significant energy loss of charm quarks in the hot and dense QCD medium created by heavy-ion collisions.

A comparison of 2010 and 2011 average D meson nuclear modification factor is given in fig. 5.18.

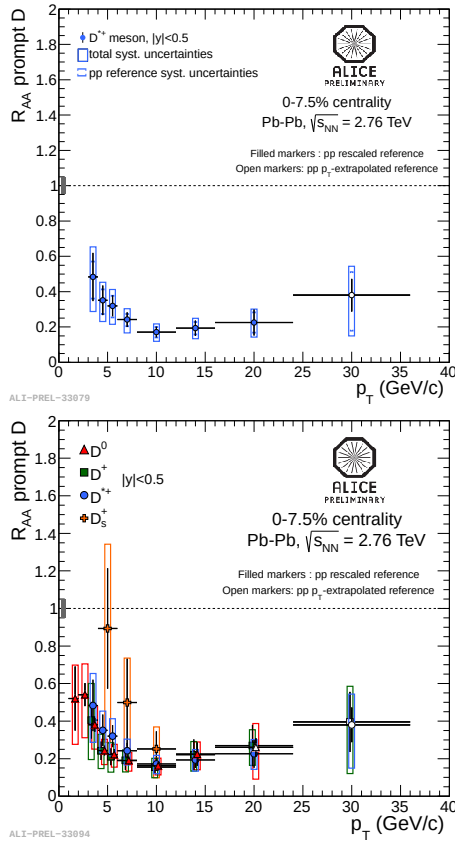


Figure 5.16: Nuclear modification factor of  $D^{*+}$  mesons for the 2011 Pb-Pb data (top) and its comparison with other D mesons (bottom).



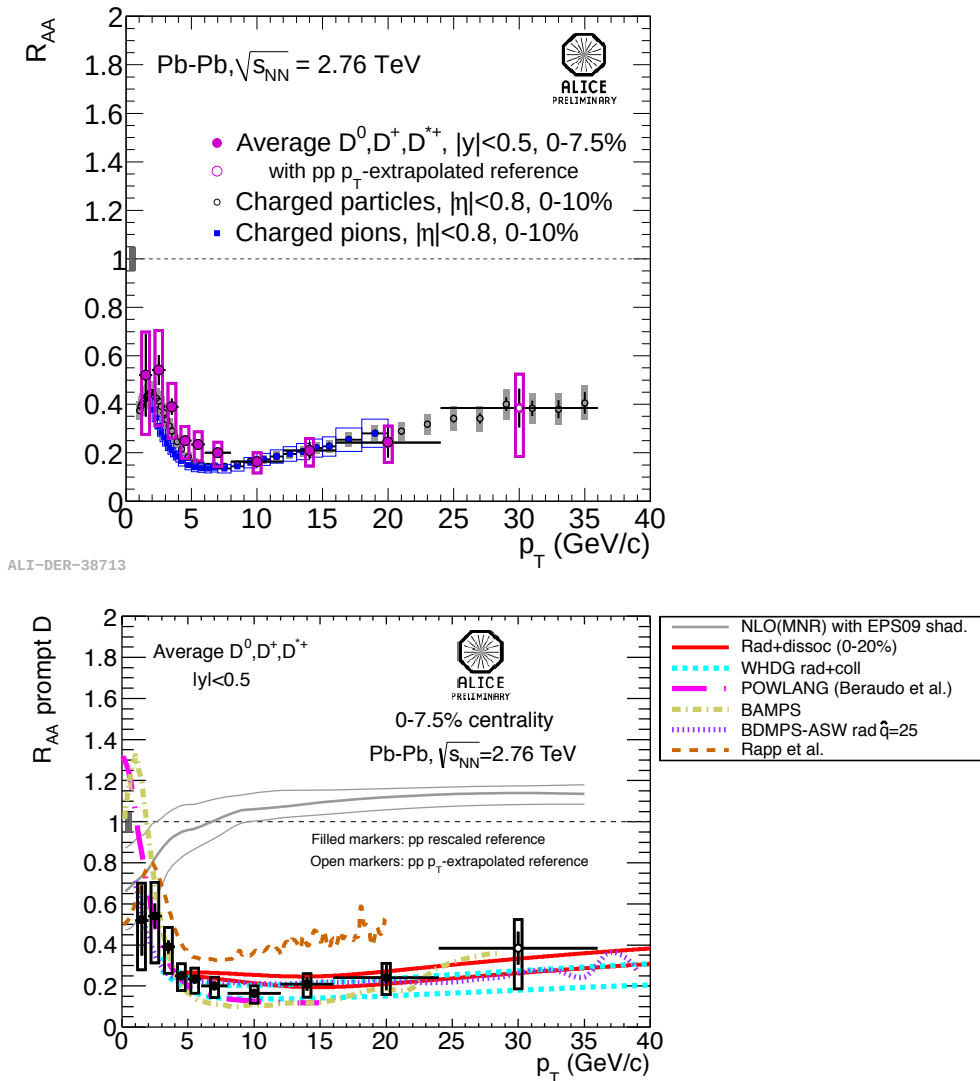


Figure 5.17: Combined D meson  $R_{AA}$  for the 2011 Pb-Pb data, compared with lighter hadrons (top) and models (bottom).

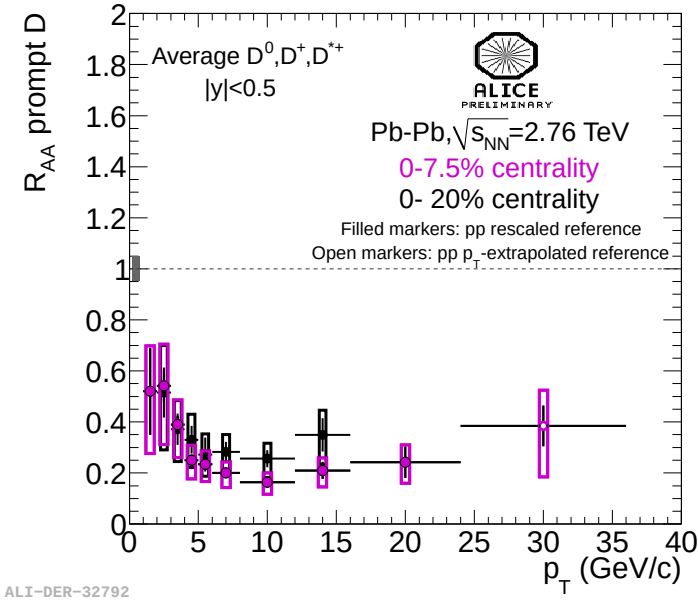


Figure 5.18: Comparison of the average D meson nuclear modification factor for the 2010 and 2011 Pb-Pb data.



# Chapter 6

## Conclusions

In this thesis the nuclear modification factor  $R_{AA}$  for  $D^{*+}$  mesons was measured with the ALICE detector at the CERN Large Hadron Collider (LHC) during the 2010 and 2011 run periods for lead-lead collisions at a centre-of-mass energy of 2.76 TeV per nucleon-nucleon pair. This was the worlds first measurement of the  $p_T$  dependence of the  $D^{*+}$  nuclear modification factor. Here the particle's transverse momentum has been measured up to 36 GeV/c. This value is about 5 times higher than analogue suppression measurements by the PHENIX and STAR experiments at the RHIC accelerator at the Brookhaven National Laboratory were capable of, even though they did not measure  $D^{*+}$  suppression. These results, as well those of the  $D^{*+}$  production cross section in proton-proton collisions at  $\sqrt{s} = 2.76$  and 7 TeV (required for baseline measurements and to test perturbative Quantum Chromodynamics), have been published in three papers [72, 73, 74] and will be published in a fourth [115].

With respect to the results of the differential production cross section of  $D^{*+}$  mesons coming from direct charm production (prompt  $D^{*+}$ ), when produced in proton-proton collisions with a centre-of mass energy of 7 TeV and studied at central rapidity, a good  $D^{*+}$  signal has been identified in the  $D^{*+}$  transverse momentum range 1-24 GeV/c. The  $D^{*+}$   $p_T$ -differential cross section agrees within uncertainties with theoretical predictions that are based on perturbative Quantum Chromodynamics (pQCD), particularly with FONLL and GM-VFNS model calculations. With regards to the FONLL central value the data tends to be higher, which corresponds to observations made with lower collision energies at RHIC and Tevatron. On the other hand, the GM-VFNS predictions generally seem to overestimate the data, which indicates that the energy dependence in this model is steeper than in data as it was not seen at the Tevatron.

The results of the measurement of the differential proton-proton production cross section of prompt  $D^{*+}$  mesons with a centre-of mass energy of 2.76 TeV have also been presented, again showing that the data are in agreement within uncertainties with FONLL and GM-VFNS model calculations and that the former seems to underestimate the data, while the latter overestimates it. These were not used as a baseline to determine the  $D^{*+}$   $R_{AA}$ , since the amount of statistics was very limited. However, a comparison was made with a rescaled reference computed from the cross section measured at  $\sqrt{s} = 7$  TeV with much higher statistics, that shows that the two results

are compatible and validates the rescaling procedure. As such, the  $D^{*+}$  differential production cross section in proton-proton collisions  $\sqrt{s} = 7$  TeV data could be used as the baseline for the determination of the nuclear modification factor ( $R_{AA}$ ) in lead-lead collisions at  $\sqrt{s_{NN}} = 2.76$  TeV.

From the various results for the lead-lead data of the 2011 period, when considering collisions with the centrality 0-7.5%, the  $D^{*+}$   $R_{AA}$  could be determined over a transverse momentum range of 3-36 GeV/c. Here the nuclear modification factor proved to be much smaller than one, with a suppression of about factor five at 10 GeV/c, much more than could be expected from cold nuclear effects. This is a clear indication of medium induced energy loss for charm quarks in the final state and can be attributed to the presence of the Quark-Gluon Plasma (QGP).

The results for the  $D^{*+}$  has been compared to the nuclear modification factor for other open charmed mesons. The results are in good agreement with the  $D^+$  and  $D^0$  mesons, even though the latter's results reached down to a transverse momentum of 1 GeV/c due to the fact that this particle is reconstructed via a decay mode with only two daughters, resulting in a lower combinatorial background. The results for  $D_s^+$  mesons seem to hint at a smaller suppression below 8 GeV/c, but future LHC runs will have to confirm or disprove this finding.

The averaged  $R_{AA}$  for  $D^{*+}$ ,  $D^0$  and  $D^+$  mesons has been compared to the nuclear modification factor predicted by several models, based on various calculations on either pQCD or on non-perturbative aspects. Both statistical uncertainties on the data and uncertainties on the models make it so far impossible to favour one model in particular. Nevertheless, it does seem that currently available models based on pQCD reproduce the  $p_T$  dependence of the nuclear modification factor better than the lattice QCD model, which based on non-perturbative calculations.

The suppression of D mesons, that contain heavy charm quarks, is almost as large as that observed for charged light-flavour hadrons. However, for the results based on the 2011 run period there is an indication that the suppression is less at transverse momenta smaller than 8 GeV/c, which is expected on the basis that heavier quarks should lose less energy in the medium. However, the uncertainties do overlap. Note that the suppression of the D mesons and light-flavoured charged particles was *not* done using the same centrality. The former was done in a centrality range of 0-7.5% while the latter at 0-10%. This would suggest that comparisons done at the same centrality range would yield a larger difference between the two nuclear modification factors, though this difference would probably be hardly noticeable since the two centrality ranges are very close to one another.

The D meson yield suppression (taken from the weighted average of the yield suppression of the  $D^{*+}$ ,  $D^0$  and  $D^+$  mesons) has been compared between data from the 2010 and 2011 run periods. Due to the fact that the 2010 period contained a lower number of events, the centrality range selected and D meson transverse momentum range evaluated was different compared to that of 2011. In particular, the centrality range was chosen to be 0-20% and the  $p_T$  range determined for 3-16 GeV/c. Within uncertainties the results agree, though there is a clear indication that above 4 GeV/c the yield in 2010 data is less suppressed, which is expected since its centrality selection includes more peripheral collisions.

## 6.1 Outlook

Despite the fact that these results have been obtained in an energy regime that far surpasses previous experiments, new steps are already planned to increase the understanding about the dynamics of heavy ion collisions and the Quark Gluon Plasma. As of 2015 the LHC is expected to perform heavy-ion collisions at the full design collision energy of 5.5 TeV. About three years later the Internal Tracking System is scheduled to be upgraded to increase this detector's performance further.

Also, the results of the  $D^{*+}$  yield suppression presented in this thesis are obtained via the  $D^{*+} \rightarrow D^0 \pi_{\text{soft}}^+$  decay channel. Already the nuclear modification factor has been determined with D mesons reconstructed via leptonic decay channels [118]. Also, the first results of proton-lead collisions have become available [117]. Moreover, as of March 2013 the first large proton-lead run at the LHC has been concluded, already gaining  $30\text{nb}^{-1}$  worth of collisions. The results of these collisions will shed new light on the interactions of the individual nucleon with the heavy ion and will give further insight into initial state cold nuclear effects. Further avenues of study involve charm content in jets and heavy flavour tagged jets.

Finally, when enough statistics has been gained by the ALICE experiment, one can study open beauty production via displaced  $D^{*+}$ , and it will even be possible to determine the nuclear modification factor of B mesons. Not only will that improve the systematic uncertainties on the  $D^{*+} R_{\text{AA}}$  (since the number of  $D^{*+}$  from B decays introduces a systematic into the  $D^{*+}$  nuclear modification factor), it will also give insight whether perturbative or non-perturbative QCD energy loss is dominant in the QGP. In the former case the ratio  $R_{\text{AA}}^D/R_{\text{AA}}^B$  will approach one with increasing  $p_{\text{T}}$ , while in the latter case it will approximate the charm and beauty mass ratio  $m_c/m_b$ .



## Appendix A

# Combinatorial background reconstruction methods

Aside from the application of selection cuts, more methods are available to distinguish the signal from background. In the earlier stages of this study, it was uncertain if selection cuts would suffice to distinguish the  $D^0$  signal from the combinatorial background, let alone the  $D^{*+}$  signal which was expected to be even smaller. As a preliminary investigation, techniques have been evaluated to extract signal from background after selections have been performed. These will be discussed in this appendix. This has been done for the  $D^0$  as baseline.

It has been shown in earlier analyses at the RHIC facility [93, 94, 95] that after applying selections as part of the analysis strategy, some residual background remains after background subtraction. The discrepancy of the shape between the invariant mass and the combinatorial background distribution, especially at lower masses ( $m < 1 \text{ GeV}/c^2$ ), are caused by the fact that the background does not fully take into account the correlation structure of the event. Important sources of particle correlations are misidentified resonances (e.g.,  $K^*(892)^0$ ), jet structure, collective flow (relevant in heavy-ion collisions) and non-conservation of energy and momentum (in the case of event-mixing).

To study the effect of these sources on the background shape, two different methods are used to evaluate the combinatorial background, namely like-sign pair combinations and multiple-rotations.

It has been shown for RHIC energies that in low multiplicity systems like proton-proton collisions the like-sign technique does not work due to the charge asymmetry [96]. In the case of  $D^0$  reconstruction this effect can be checked by the ratio of positive and negative pions and kaons. These particle ratios are found to be close to one at LHC energies. Thus, the like-sign pair method should provide a good description of the combinatorial background in the  $D^0$  reconstruction in proton-proton collisions.



Table A.1: Event statistics used for the different methods.

| Background evaluation technique | Event statistics |
|---------------------------------|------------------|
| Like-sign pairs                 | 33M              |
| Multiple rotations              | 33M              |
| Event mixing                    | 0.5M             |

### A.0.1 Dataset and analysis procedure

The data set used for this study is a sub-sample of the 2009 ALICE minimum bias production (*LHC09a4*). The *LHC09a4* is a large Monte Carlo production of 100M proton-proton collisions at  $\sqrt{s} = 10$  TeV. It includes realistic estimates of the expected detector efficiencies at the LHC startup. This study is based on four ALICE sub-detectors: the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). A minimum number of clusters is required in the ITS ( $\geq 5$ , no check for SPD clusters). To improve the quality of the tracks, we require for them to be refitted in TPC. The refitting procedure ensures a good estimation of the tracks parameters resulting in a better invariant mass resolution. An overview of the used event statistics are summarized in table A.1. The selection cuts for the  $D^0$  reconstruction are described elsewhere [97, 98, 99] (see also section A.2.2). No cuts are applied for particle identification.

## A.1 $D^0$ reconstruction

Although the two methods used to simulate the combinatorial background in this study vary significantly, all essentially make use of the fact that the  $D^0$  invariant mass is reconstructed by combining tracks of its decay particles (daughters), while all the others two track combinations result in a combinatorial background [100].

This invariant mass technique can be applied to any combination of two tracks independently for the charge of the particles involved. Only combining unlike-sign pairs could possibly recreate the  $D^0$  signal, but like-sign pairs can be used for background studies. Assigning to the tracks in the pair the mass of the known decay daughters of the  $D^0$  ( $\bar{D}^0$ ),  $K^-$  and  $\pi^+$  ( $K^+$  and  $\pi^-$ ), it is possible to determine the mass of the  $D^0$  ( $\bar{D}^0$ ) candidate using the formula 3.2, which can be written as

$$m_{inv}(K\pi) = \sqrt{m_-^2 + m_+^2 + 2(E_-E_+ - |p_-||p_+|\cos\theta)}. \quad (\text{A.1})$$

where  $\theta$  is the opening angle between the two tracks. Real  $D^0$  decays reveal as a peak around the known  $D^0$  mass ( $m_{D^0} = 1.86$  GeV/c<sup>2</sup> [101]) in the  $K\pi$  invariant mass distribution.

A key point in the  $D^0$  reconstruction is an optimal understanding of the combinatorial background, since subtracting it from the invariant mass distribution should result in the signal. Since the mass of the  $D^0$  is already known, it is mainly interesting to have the combinatorial background under control in a reasonably limited region around the nominal mass value.

The signal is compared to the background using the significance (see eq. 3.1), usually evaluated in a range  $\pm 3\sigma$  around the expected  $D^0$  mass, where  $\sigma$  is the peak

width from a Gaussian fit. In order to properly compare the  $K\pi$  invariant mass distribution with the one from the techniques used to "simulate" the combinatorial background have to be scaled properly to a similar number of events (especially for rotational background, which typically has several times the number of entries). Therefore, the distributions are normalised in a range where no resonances are expected ( $2.1 < m_{inv}(K\pi) < 2.5 \text{ GeV}/c^2$ ).

## A.2 Like-sign pair method

Of the two methods investigated in this thesis, the method of *like-sign pair combinations* is the most straightforward one. For the  $D^0$  reconstruction only combinations from unlike-sign pairs are of interest. Usually, particles with the same charge sign (like-sign pairs) do not correspond to the same mother particle (except the  $\Delta^{++}$  resonance). As a consequence, attempting to reconstruct the  $D^0$  assigning the  $K$  and  $\pi$  masses to like-sign, it will result in an invariant mass spectrum devoid of any signal or resonances.

The  $K\pi$  invariant mass distribution for positive and negative like-sign pairs can be used to mimic the combinatorial background by the application of the geometric mean of the positive and negative like-sign spectra. If there are  $N_{++}$  positive track pairs, and  $N_{--}$  negative ones, the geometric mean  $G$  is given by  $G = \sqrt{N_{++}N_{--}}$ . For the comparison with the unlike-sign pairs we multiply it with 2.

The number of possible unlike-sign pair combinations is invariably higher than for the individual like-sign (negative-negative and positive-positive) pairs. However, the geometric mean of the number of positive and negative like-sign pairs approximates the combinatorial background from the  $D^0$  reconstruction. If one event contains  $N_+$  positive and  $N_-$  negative tracks, it can be calculated that

$$G = 2\sqrt{N_{++}N_{--}} \quad (\text{A.2})$$

$$= 2\sqrt{\sum_{i=1}^{N_+} (N_+ - i) \sum_{j=1}^{N_-} (N_- - j)} \quad (\text{A.3})$$

$$= 2\sqrt{(N_+^2 - \frac{1}{2}N_+(N_+ + 1))(N_-^2 - \frac{1}{2}N_-(N_- + 1))} \quad (\text{A.4})$$

$$= \sqrt{(N_+^2 - N_+)(N_-^2 - N_-)} \approx N_+N_- = N_{+-}, \quad (\text{A.5})$$

where  $N_{+-}$  is the number of unlike-sign pairs. Another advantage is the fact that this method does not change the event topology. Contrary to other analysis methods (such as multiple rotations), this technique accepts the tracks as they have been detected without changing them.

This means that quantities like the location of the primary vertex, the number of jets, the detected pseudo-rapidity and  $\phi$  distribution of the tracks, as well as other variables are the same for the unlike-sign and like-sign pair combinations. As shown at RHIC the like-sign technique does not work in low multiplicity systems, like proton-proton collisions, due to the difference in the number of positive and negative pions

and kaons (charge asymmetry) [96]. However, at LHC energies this effect is expected to be small due to the higher centre-of-mass energy and due to the fact that the ratio between particles with positive and negative charge sign is close to one. For example, in the sample used for this work, these ratios are found to be  $N(\pi^-)/N(\pi^+) = 1.01$  and  $N(K^-)/N(K^+) = 0.95$ . Thus, the charge asymmetry relevant for the  $D^0$  analysis is small and might cause only negligible discrepancies at low invariant mass in the like-sign spectrum.

Another point to consider is that the intrinsic limitation of the like-sign method is the poor statistics available (only same-sign tracks in the same event) resulting in a poor control of the fluctuations in the  $K\pi$  invariant mass distribution. If we consider a sample of  $N$  events, the like-sign technique will use the same-sign tracks in each one of the events to simulate the background while the rotational technique investigated in the following sections will multiply the statistic to  $x \times N$ , where  $x$  is the number of rotations. This will result in a better control of the fluctuations and the signal extraction as discussed in section A.3.6.

### A.2.1 Results from the like-sign pair method

In this section results are shown using the like-sign method without applying  $D^0$  reconstruction cuts. Figure A.1 depicts the  $K\pi$  invariant mass distribution and the like-sign geometric mean. The ratio between these two distributions is shown in fig. A.2. As one can see there is a discrepancy between the two at lower invariant mass. Up to some extent a discrepancy is expected due to resonances. However, near the signal region, the background shape is stable, and the disagreement with the shape of the  $K\pi$  invariant mass distribution is less than 1%.

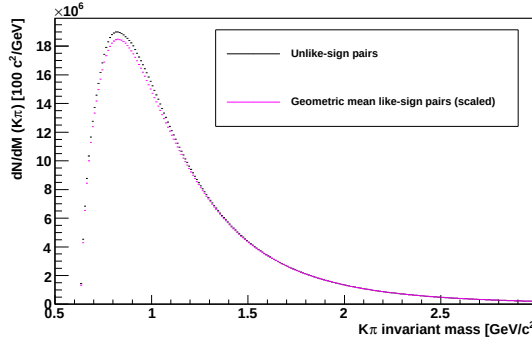


Figure A.1:  $K\pi$  invariant mass distribution compared to geometric mean of like-sign pairs (purple histogram). Note that the geometrical mean is normalised to the  $K\pi$  invariant mass distribution in the range  $2.1 < m_{inv}(K\pi) < 2.5 \text{ GeV}/c^2$ .

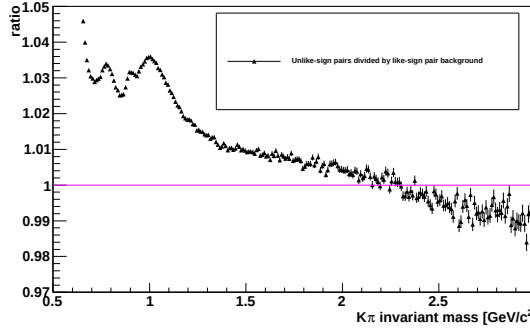


Figure A.2: Ratio between the  $K\pi$  invariant mass and like-sign pair distributions.

### A.2.2 Results from the like-sign pair method using $D^0$ selection cuts

The  $K\pi$  invariant mass distribution was also determined after application of the  $D^0$  selection cuts. The selection is applied dividing the  $D^0$  candidates  $p_T$  in bins. For each bin, cuts are applied to the distance of closest approach (dca) of the track pair, the cosine of the pointing angle ( $\theta_{pointing}$ ), the cosine of the decay angle in the  $D^0$  centre-of-mass frame ( $\theta^*$ ), the impact parameters of each single track ( $d_0^\pi$  and  $d_0^K$ ), the product of the impact parameters and the transverse momenta of the tracks. For details see [97, 98, 99].

Figures A.3 and A.4 show the shape of these variables in the cases of unlike-sign, positive like-sign, negative like-sign and multiple-rotations distributions (see next section) before and after the application of  $D^0$  reconstruct cuts. It is of considerable interest to see that the distribution of each single variable does not depend on the background method used.

Table A.2: Selection cuts for the  $D^0$  reconstruction as obtained from [99].

| $p_T^{D^0}$ (GeV/c)                         | 0–1   | 1–2    | 2–3    | 3–5    | 5–10   |
|---------------------------------------------|-------|--------|--------|--------|--------|
| Cut                                         |       |        |        |        |        |
| dca ( $\mu\text{m}$ )                       | < 400 | < 280  | < 320  | < 220  | < 200  |
| $\cos(\theta_{pointing})$                   | > 0.5 | > 0.92 | > 0.92 | > 0.96 | > 0.96 |
| $ \cos(\theta^*) $                          | < 0.8 | < 0.88 | < 0.56 | < 0.96 | < 0.72 |
| $d_0^\pi \times d_0^K (10^4 \mu\text{m}^2)$ | < -2  | < -4   | < -1.4 | < -1   | < -6   |
| $p_T^{\pi,K}$ (MeV/c)                       | > 500 | > 650  | > 800  | > 600  | > 1100 |
| $ d_0^{\pi,K} $ ( $\mu\text{m}$ )           | < 500 | < 720  | < 680  | < 600  | < 560  |

The  $D^0$  selection cuts that have been used are summarized in table A.2. For the  $D^0$  transverse momentum range larger than 1 GeV/c, the cuts from [99] have been used, where the cuts were optimized for the 2007 production of simulated proton-proton collisions at  $\sqrt{s} = 14$  TeV (PDC07). The optimisation was not carried out in

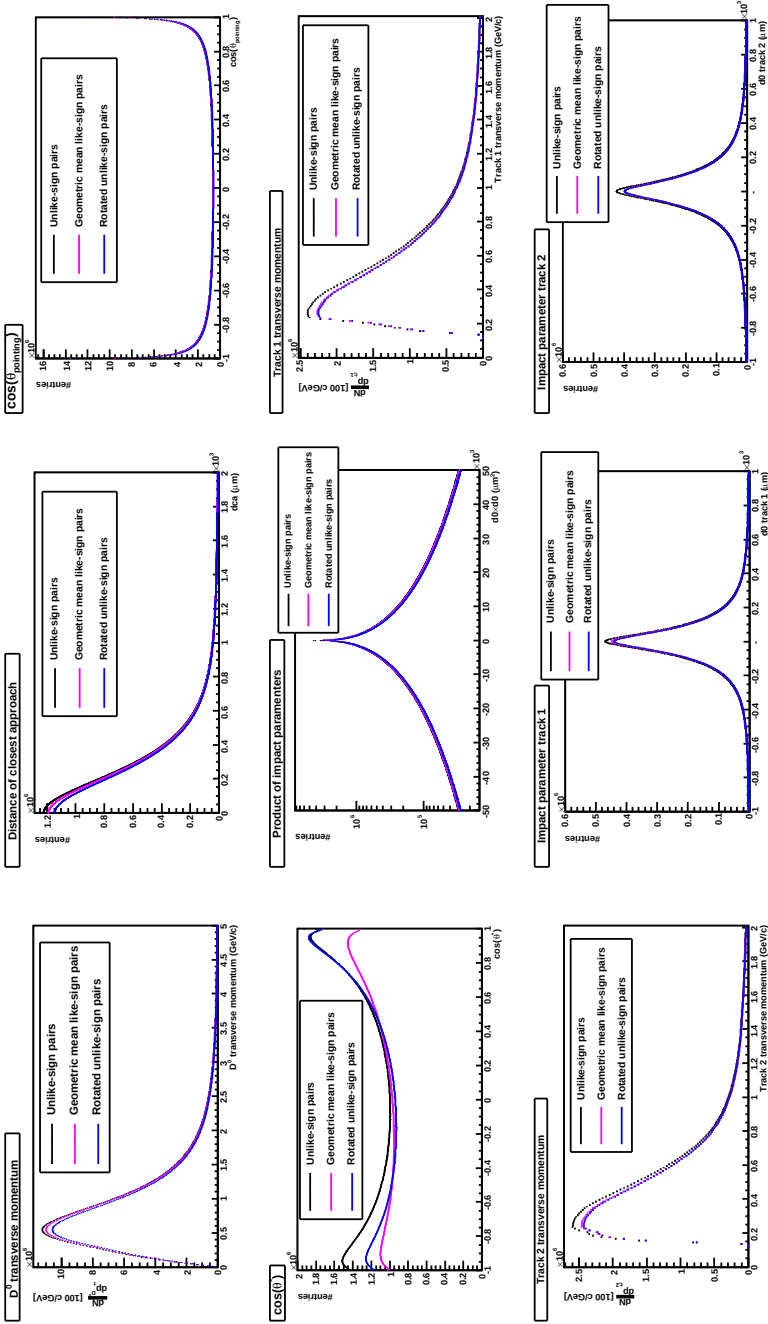
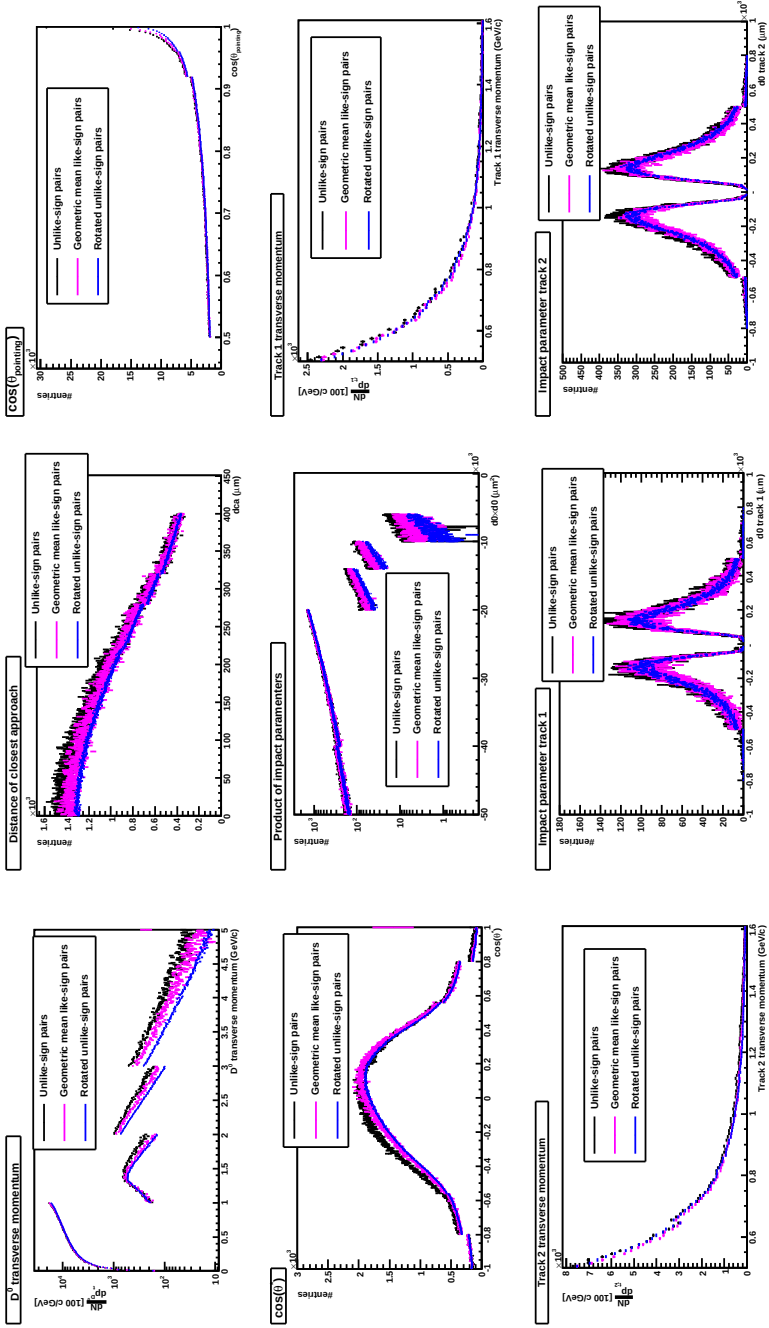


Figure A.3: Distribution of the  $D^0$  selection cut variables before application of all cuts. The curves are for the multiple rotations (blue), geometric mean like-sign (purple) and unlike-sign pairs combinations (black).

Figure A.4: Distribution of the  $D^0$  selection cut variables after application of all cuts.

the  $0 < p_t^{D^0} < 1$  GeV/c. Therefore, the so-called PPR cuts (the set of cuts published in the ALICE Physics Performance Report [29]) are used for this bin.

Figure A.5 shows the like-sign pair background after  $D^0$  selection cuts. The ratio between like-sign and unlike-sign pairs is illustrated in fig. A.6, which evidence a linear trend in the like-sign background in a large region around the expected signal. Unfortunately, the fluctuations do not allow to give a value with a small error, but we can safely assert that the disagreement is of the order of few percent. The resulting systematic uncertainty on the background shape is of the order of 2-3% around the  $D^0$  signal.

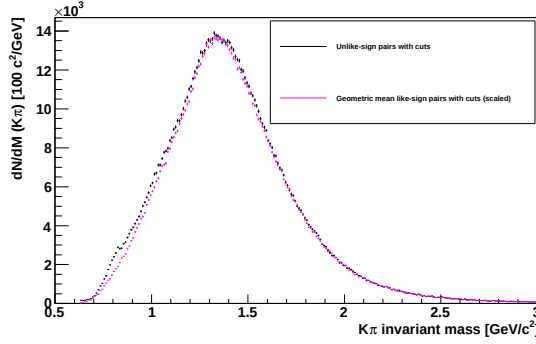


Figure A.5:  $K\pi$  invariant mass distribution compared to geometric mean like-sign pairs (purple histogram) after  $D^0$  selection cuts.

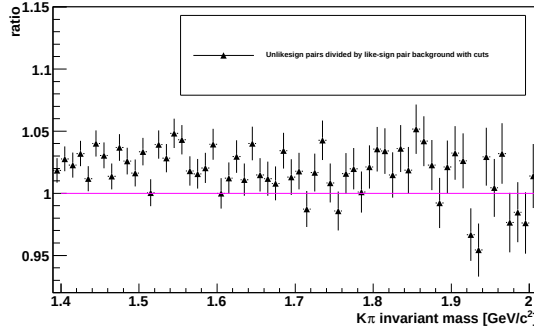


Figure A.6: Ratio between  $K\pi$  invariant mass and like-sign pairs distributions (geometric mean) after  $D^0$  selection cuts.

## A.3 Multiple-rotations method

Another technique that can be used to reproduce the background of the  $D^0$  invariant mass distribution is the so-called *multiple-rotations method*. This method breaks correlations between existing two-track pairs by rotating one of the tracks in the detector's X-Y plane (where the Z direction is parallel to the beam line). This redistribution of tracks will then be used to calculate the invariant mass spectrum that should mimic the combinatorial background of uncorrelated pairs.

### A.3.1 Description of the method

The method of multiple-rotations background is visually explained in fig. A.7. When combining two tracks in order to calculate the  $K\pi$  invariant mass, the track with negative charge sign is rotated around the Z-axis that is parallel to the beam direction and goes through the primary vertex. This rotation changes the track momentum and its location in the detector. By repeating this for all track pairs in the event, one effectively redistributes the tracks in the detector. This will break any correlations between tracks that are due to the signal, resulting in a pure combinatorial background.

The multiple-rotations method has the advantage that it can be used to significantly increase the statistics of the combinatorial background by rotating several times over different angles. This requires that individual rotations can be considered independent from one another. Therefore, certain parameters have to be chosen properly. These are the number of rotations  $N$ , the interval angle  $\alpha$  (the difference between two consecutive rotations) and the base rotation angle  $\alpha_B$  (defined as the average rotation angle). The following parameters have been used:  $N = 13$ ,  $\alpha = 5^\circ$  and

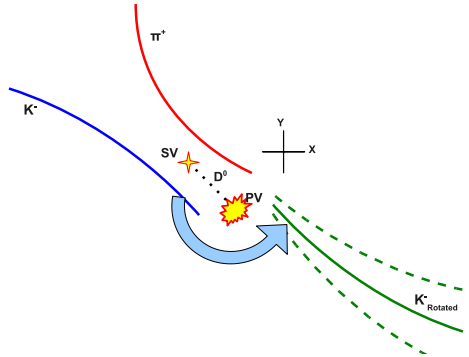


Figure A.7: Sketch to illustrate the multiple-rotations technique. The track with negative charge-sign (*solid blue line*) is rotated around the primary vertex over a certain base rotation angle (*solid green line*). To increase the statistics, this track can be rotated multiple times over different angles (*dashed green lines*).

$\alpha_B = \pi$ . Using these parameters, the combinatorial background has been determined for rotations over  $150^\circ, 155^\circ, 160^\circ, 165^\circ, 170^\circ, 175^\circ, 180^\circ$  (the base rotation angle),  $185^\circ, 190^\circ, 195^\circ, 200^\circ, 205^\circ$  and  $210^\circ$  around the Z-axis. The previously mentioned parameters have been chosen like this because they are reasonably close to their optimized values while keeping a margin for error.



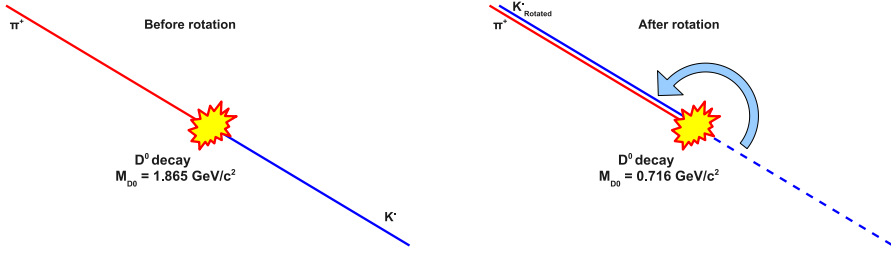


Figure A.8: Top: Drawing of a  $D^0$  decay. Bottom: The rotational background method applied to the same event. The  $K\pi$  invariant mass will be reconstructed improperly.

Even though this leaves some room for improvement when performing actual data analysis (i.e. gaining statistics on the rotated combinatorial background), for the purpose of testing the principle of rotational background itself the given values more than suffice.

### A.3.2 Detector inefficiencies and event topology bias

The multiple-rotations background method introduces a bias if the event topology is not homogeneous. As illustrated in fig. A.8, one can imagine an event consisting of a single  $D^0$  particle with zero momentum decaying into a  $K^-\pi^+$  pair with momenta in the X-Y plane. However, by rotating the tracks with negative charge sign over  $\pi$  will change the sign of the last term in equation (A.1), which in turn will cause a drop of the invariant mass. So even in this simple case where the event has a definite non-uniform topology, a bias is introduced.

The non-uniformity of the event topology can have two causes. First, the performance of the detector is not the same over all its acceptance. A certain percentage of modules and individual channels of the ALICE TPC and ITS are unresponsive or have low efficiency. The bottom panel of fig. A.9 depicts the  $\eta$ - $\phi$  distribution of the tracks having at least 5 clusters in ITS and 50% of the potential hits in TPC. For comparison the top panel of fig. A.9 shows the same distribution without applying these quality cuts, which looks mostly homogeneous (though with a preference in the direction of zero pseudo-rapidity). However, when preselection criteria are required the uniformity is lost, with whole sections partially inactive, corresponding to inactive ladders on the ITS. The problem of rotating tracks in this situation is twofold. Tracks can end up in inactive detector areas where there should be none (however, this can be compensated for by rejecting rotations that move tracks into these regions) and there are no tracks from the dead areas to compensate for those that rotate out of the active regions. The second cause is the event topology itself. As can be seen in the schematic representation of fig. A.10 the effect of rotating a two-jet event is to change the event topology. In fig. A.11 the distribution of the cosine of the opening angle between two tracks for multiple events is plotted in the absence of track quality cuts. This distribution should be flat for a uniform spread of the tracks.<sup>1</sup> Although it is mostly constant, there are

<sup>1</sup>Single events can have a non-uniform track spread, but for large statistic the distribution of the cosine of the opening angle averages out uniformly.

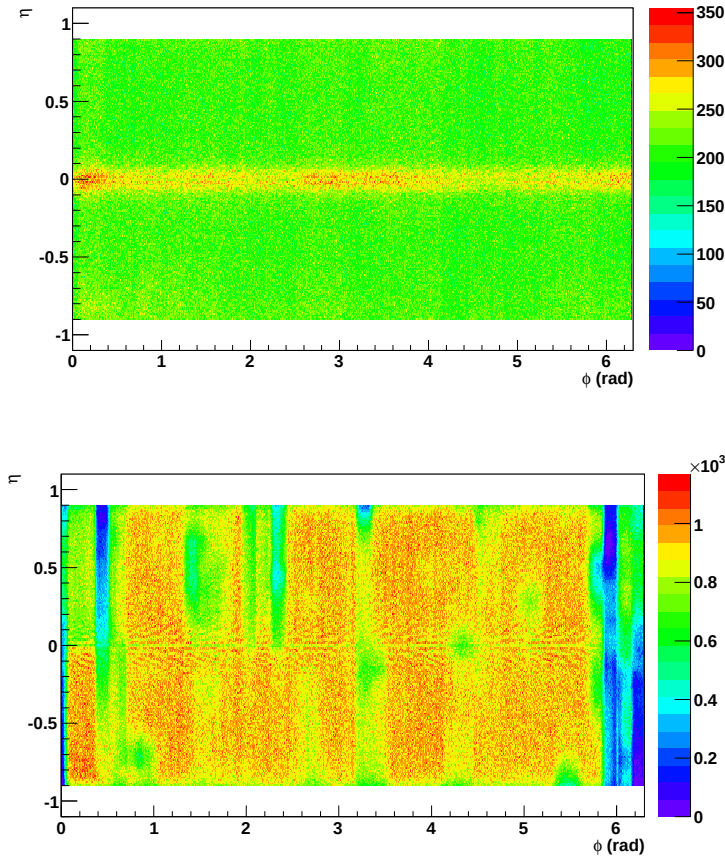


Figure A.9:  $\eta$ - $\phi$  distribution of the track of particles without (top) and with preselection criteria as defined in the text (bottom).

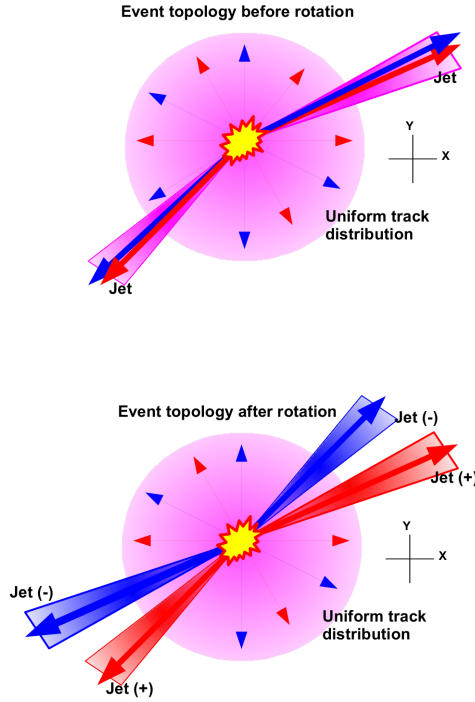


Figure A.10: Top: Sketch of an event with a uniform spread of positive (red line) and negative tracks (blue line) as well as two jets with approximately equal numbers of positive and negative tracks. Purple regions represent the underlying uniform distribution of positive and negative tracks. Bottom: The rotational background method applied to the same event. Though rotating most of the tracks will result in a similarly uniform spread of positive and negative tracks, the two mixed jets will be split in two negative and two positive jets.

still some preferred directions, primarily in the parallel and opposite directions (where at least a part of the contribution can be attributed to dijet events). Since there are more tracks that are parallel to one another, rotating will generally shift more  $K\pi$  invariant mass entries to higher mass than vice versa.

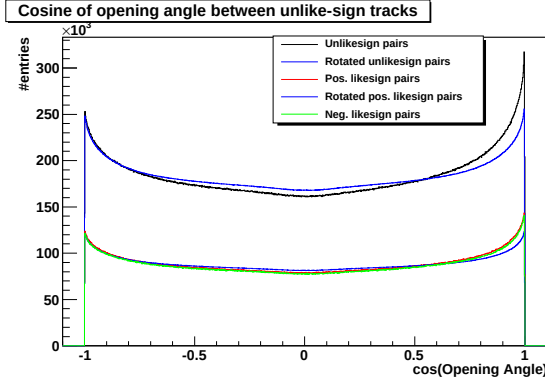


Figure A.11: Opening angle between two tracks for unlike-sign (black histogram), positive like-sign (red histogram), negative like-sign (green histogram) and their rotational counterparts (blue histogram).

### A.3.3 Considering detector inefficiencies for multiple-rotations background

The effect of detector dead areas on the multiple-rotations method implementation will be discussed briefly in this section. In the top panel of fig. A.12 the ratio of the  $K\pi$  invariant mass distribution versus multiple-rotations background before  $D^0$  selections is depicted in the case dead areas are masked. This has also been done for the like-sign pairs in the same panel and will be compared later in the text with their correspondents, where these detector inefficiencies are not included. In the right panel of fig. A.12 the relative difference between these two situations for the invariant mass is shown. For masses larger than  $1.5 \text{ GeV}/c^2$  the difference between the two distributions is negligible with an average of 0.1%. For low mass values the difference increases up to 4% at  $0.64 \text{ GeV}/c^2$ . The relative difference between these ratios including  $D^0$  selection cuts is shown in fig. A.13 and is found to be less than 2% in the signal region.

These results have demonstrated that the dead areas do not have a significant influence on the  $K\pi$  invariant mass distribution near the expected  $D^0$  mass peak. However, they need to be cross-checked with the actual geometries.

### A.3.4 Results from the multiple-rotations method

This subsection will present the results from the comparison between the  $K\pi$  invariant mass and multiple-rotations background distributions without the use of any  $D^0$  reconstruction cuts. Furthermore, as a check, the multiple-rotations method has been

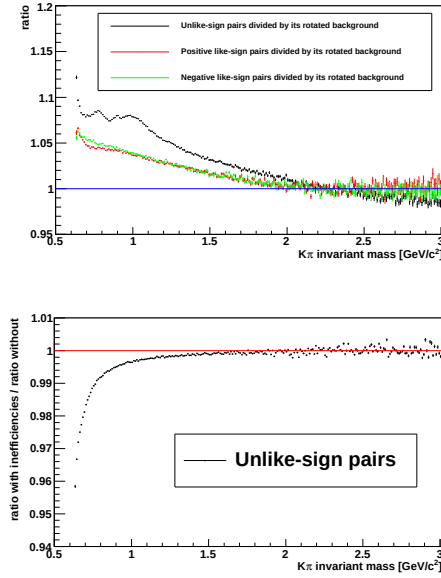


Figure A.12: Top panel: Ratio between the  $K\pi$  invariant mass (black histogram) and multiple-rotations distributions with masked detector inefficiencies, and the ratio between positive (red histogram) and negative (green histogram) like-sign pairs and their multiple-rotations distribution. Bottom panel: Relative difference between the ratios with masked detector inefficiencies and those without.

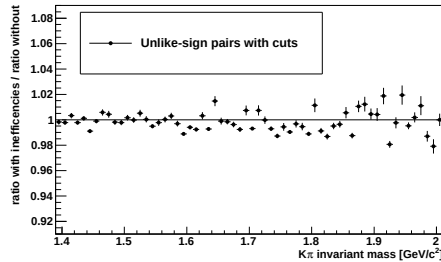


Figure A.13: Relative difference between the ratios with and without detector inefficiencies after  $D^0$  reconstruction cuts.

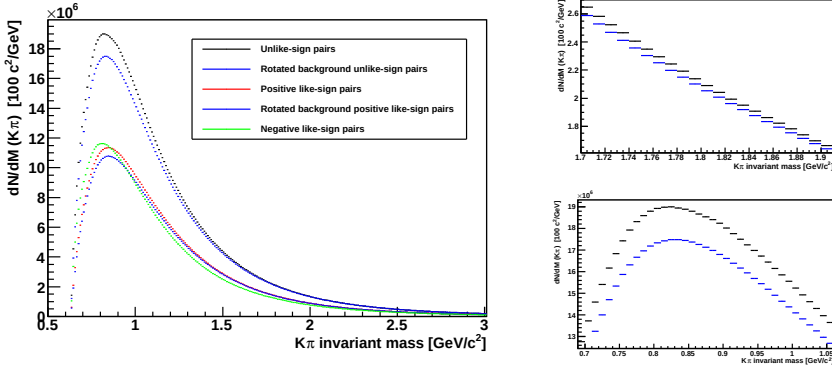


Figure A.14:  $K\pi$  invariant mass distribution normalised from 2.1 to 2.5  $\text{GeV}/c^2$ . Close-up of the distribution around the  $D^0$  signal region (upper right panel) and at low invariant mass (lower right panel).

applied to the like-sign pairs as well, as these are mostly background and should ideally match their rotated counterparts. The comparison between the multiple-rotations background and the  $K\pi$  invariant mass distribution is depicted in fig. A.14. The multiple-rotations background distribution follows the general shape of the combinatorial background. However, a difference is seen, especially at around  $0.8 \text{ GeV}/c^2$ . The non-uniformity of the track distribution causes a net shift of entries from low to higher mass. To quantify the difference between the combinatorial and multiple-rotations backgrounds the ratio of these distributions is plotted in fig. A.15. Clear peaks from the  $\rho(770)$  and  $K^*(892)^0$  mesons are observed.

The difference between the  $K\pi$  invariant mass and multiple-rotations background distributions in the mass range  $2.1 < m_{\text{inv}}(K\pi) < 2.5 \text{ GeV}/c^2$  is about 8% at  $1 \text{ GeV}/c^2$  and 1.2% at  $2 \text{ GeV}/c^2$ . A linear fit to the ratio in the mass range of  $\pm 5\sigma$  around the expected  $D^0$  mass peak results in a  $\sim 1.4\%$  disagreement. As concluded from fig. A.15, the relative difference between the multiple-rotations and the combinatorial background is approximately a linearly decreasing function, allowing a "simple" removal of residual background after background subtraction.

### A.3.5 Results from the multiple-rotations method after $D^0$ reconstruction cuts

In fig. A.16 the multiple-rotations background is superimposed to the unlike-sign pair distribution, where the  $D^0$  selection cuts are applied after the rotations. It is clear that in the mass range  $1 < m_{\text{inv}}(K\pi) < 1.5 \text{ GeV}/c^2$  the multiple rotations underestimate the background contribution. Nevertheless, in the region of interest for the  $D^0$  analysis the two shapes are in good agreement with each other. A more detailed analysis shows that the ratio between the two curves is almost flat in the region 1.6 to 2  $\text{GeV}/c^2$  (see fig. A.17) with an overall discrepancy of 2-3%.

The fact that the ratio is almost constant over a wide invariant mass range around the expected signal region allows to describe the residual background with a linear fit.

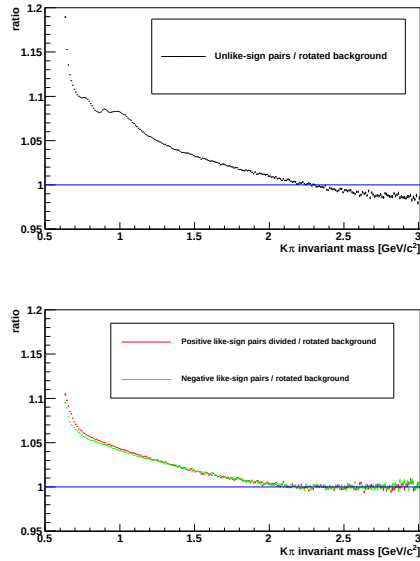


Figure A.15: Ratio between  $K\pi$  invariant mass and multiple-rotation distributions (top panel) and between positive (red histogram) and negative like-sign pairs (green histogram) and multiple-rotations background distributions (bottom panel).

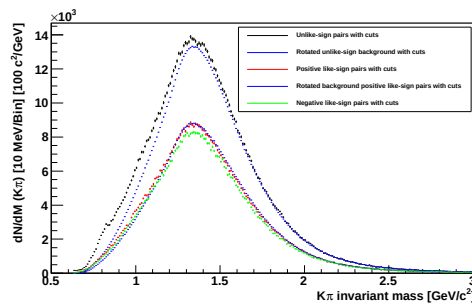


Figure A.16:  $K\pi$  invariant mass distribution after  $D^0$  selection cuts (black histogram). The multiple-rotations background is shown as a blue histogram. Like-sign pair and their rotated background distributions are added for comparison.

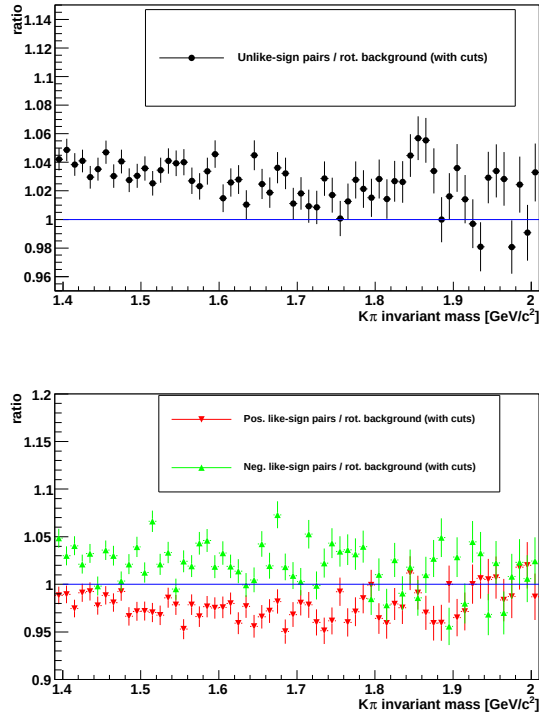


Figure A.17: Ratio between  $K\pi$  invariant mass and multiple-rotations distributions (top panel) after  $D^0$  selection cuts and between positive (red histogram) and negative like-sign pairs (green histogram) and multiple-rotations background distributions after  $D^0$  selection cuts (bottom panel).



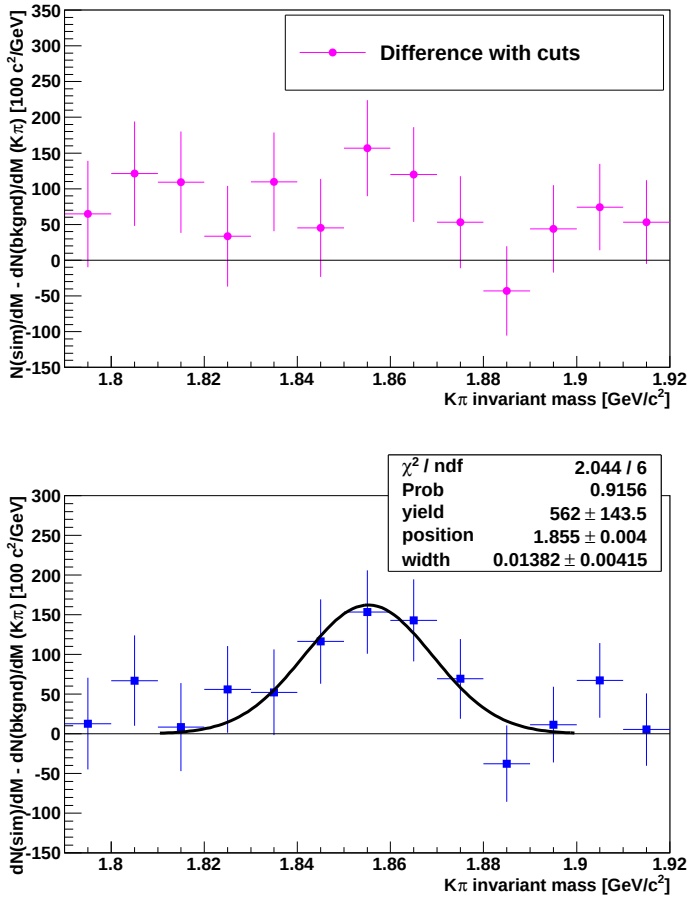


Figure A.18:  $K\pi$  invariant mass distribution after subtraction of the like-sign pairs (top panel) and multiple-rotations background (bottom panel).  $D^0$  selection cuts are applied in both cases. The solid line is a Gaussian fit to the data.

The difference between the invariant mass shape obtained with multiple rotations and combinatorial background after  $D^0$  selection cuts is about 25% at  $1 \text{ GeV}/c^2$ , 1-2% at  $1.75 \text{ GeV}/c^2$ , and about 1% at  $1.95 \text{ GeV}/c^2$ , considering a mass range of  $\pm 40 \text{ MeV}/c^2$  around the mean value.

### A.3.6 Comparison between multiple-rotations and like-sign pair methods

In this section a comparison between the like-sign pair method and multiple rotations is carried out in terms of signal extraction. The sample used is 33M minimum bias events. The top panel of fig. A.18 illustrates the  $K\pi$  invariant mass distribution after like-sign background subtraction. It is evident from that plot that, with the statistic available, it is not possible to extract a  $D^0$  signal using this method. However, the  $K\pi$  invariant mass distribution after the subtraction of the multiple-rotations background shows a tiny peak around the expected  $D^0$  mass (fig. A.18, right panel). The significance for this signal is about 2. The result, even if integrated over  $p_T$ , is impressive if considered the statistic available, corresponding to  $\sim 2$  days of data taking at nominal conditions. Thus, the multiple-rotations method is a promising technique to handle the combinatorial background.

### A.3.7 Results for different rotation parameters

In this section a study of the parameters for the multiple-rotations method is done. The standard values used up to now are the number of rotations ( $N = 13$ ) and the rotation interval ( $5^\circ$ ). In fig. A.19 the background fluctuations are shown as a function of the number of rotations. As one can see, up to about 37 rotations the background is decreasing as  $1/\sqrt{N}$ . This corresponds with expected reduction of noise for 37 times more statistics. Given the fact that the base (first) rotation is  $180^\circ$  and the rotation interval  $5^\circ$ , the rotated tracks are rotated in over a range from  $\pi/2$  to  $3/2\pi$ . The statistical fluctuations are fast decreasing up to  $\sim 12$  rotations and then almost saturating. Adding this consideration to the result for the relative computational time versus the number of rotations (cf. fig. A.20) it is clear that our choice of 13 rotations is justified by computing time consideration.

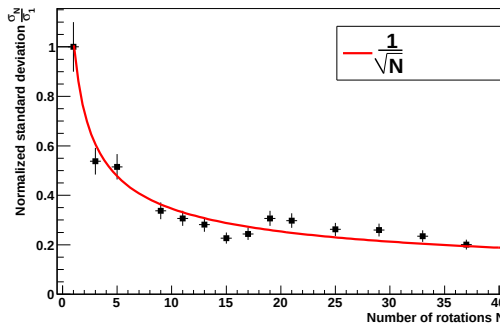


Figure A.19: Normalised standard deviation as a function of number of rotations.

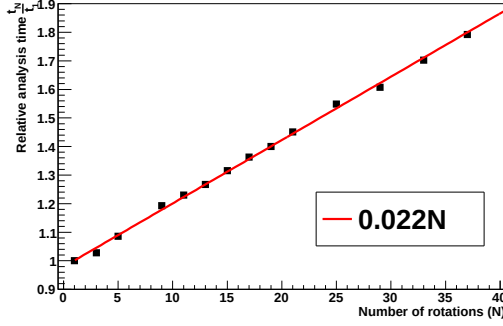


Figure A.20: Relative computing time versus number of rotations. The case of one rotation is taken as reference. The red line is a linear fit to the data.

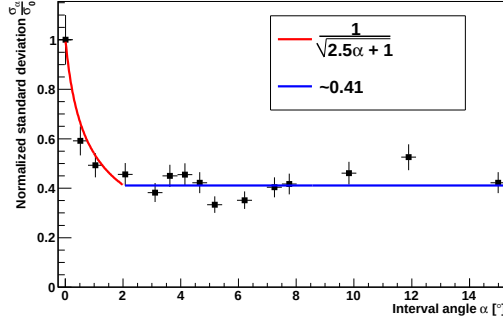


Figure A.21: Normalised standard deviation as a function of interval angle. The fit to the data (blue line) shows a saturation in the noise reduction at around 3 degrees.

The relative time  $t$  it takes for the analysis (for a fixed amount of computation power) is linearly increasing with the number of rotations, so up to 37 rotations (i.e. about 80% additional analysis time) the change in the normalised sample standard deviation versus the analysis time is given by  $\frac{\sigma_N}{\sigma_1} \approx \frac{0.148}{t_N/t_1}$ .

A second parameter that needs to be optimized is the angle that define the rotation interval. The optimisation of the rotation interval plays a crucial role for the multiple-rotations method, because on one side, the smaller the angle, the more rotations can be done in the interval  $\pi/2 < \alpha < 3/2\pi$ . On the other side, the angle cannot be too small because otherwise the result of the rotation of a correlated event is another correlated event. This has been plotted in fig. A.21.

As one can see for larger rotation intervals the noise becomes constant, as the individual rotations can be considered independent and there is nothing to gain from increasing this angle. Up to the threshold value of  $\sim 3$  degree the fluctuations decreases with a factor proportional to  $1/\sqrt{\alpha}$ . Note that the interval angle where the threshold occurs depends on the bin width of the  $D^0$  mass histogram. By making multiple rotations over varying angles, the value calculated will vary in accordance

to equation (A.1), as one gets different opening angles for different rotations. By reducing the rotation interval, the differences between the masses will reduce, and the probability that their masses lie in the same mass range will thus become greater. Increasing the bin width will allow this to occur sooner, resulting in a larger threshold value of the rotation angle. Repeating this process for different bin widths confirms this.

## A.4 Conclusions

This appendix contains the results of the study on two different techniques for the description of the combinatorial background from the reconstruction of  $D^0$  mesons, namely the like-sign pairs and multiple-rotations technique. Possible effects on the background shape, mainly arising from the underlying jet structure and detector inefficiencies, are discussed. The latter have played a role in the startup phase of the ALICE detector. The mass distribution from the three different methods are in agreement with the combinatorial background shape around the expected  $D^0$  signal within 3%.

The multiple-rotations technique seems to be the most promising one since it does not require the recalculation of the  $D^0$  selection cut parameters, as needed for the event mixing method, and it can provide sufficient statistics to decrease the fluctuations in the invariant mass distribution. A  $\sim 3\sigma$  signal was obtained with about 30M minimum bias proton-proton events. Even if the signal over background ratio and the significance are not large in absolute value, they are remarkable if compared with the result on like-sign pair background over the same statistics where no signal could be extracted.

Up to 4% of the residual background at low invariant mass ( $< 1 \text{ GeV}/c^2$ ) is due to detector inefficiencies (*dead areas*), especially in a small region  $\Delta\phi \sim 2\pi$ , and can be almost totally recovered by simply not allowing rotations over these dead regions. The remnant residual background is most likely due to the jet structure in the event and due to misidentified resonancies in the combinatorial background. Remarkably, the  $\rho(770)$  and  $K^*(892)^0$  signals are resolved after subtraction of the multiple-rotations background.



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## Abstract

In this thesis the results are presented of the first measurements of the  $D^{*+}$  meson nuclear modification factor  $R_{AA}$  in heavy ion collisions at the Large Hadron Collider (LHC) using the ALICE (A Large Ion Collider Experiment) detector at CERN. These open charmed mesons are a useful tool to investigate the properties of the Quark-Gluon Plasma (QGP) since their parent charm quarks are produced in the early stages of heavy ion collisions, so that they are sensitive to the full formation history of the QGP, and their high mass limits their energy loss in the medium. Baseline measurements of charm production in proton-proton collisions have also been performed, since they are required to form the understanding of charm production and suppression in the QGP.

Chapter 1 gives an overview of the theoretical background relevant to this thesis. Aside from a brief overview of the history of particle physics, it introduces the basics about the Standard Model, Quantum Chromodynamics (QCD), heavy ion collisions and the QGP. The experimental signature of the QGP and earlier results gained by experiments at the Relativistic Heavy-Ion Collider (RHIC) will be discussed. The motivation of using the charm quark as probe for the medium and measuring the  $D^{*+}$  yield will be addressed. This chapter ends with several models that are used to describe the energy loss mechanisms in the QGP.

The second chapter is focussed on the ALICE detector. A general overview is given, but only the subdetectors used in this thesis are described in more detail, namely the Time Projection Chamber (TPC) used for tracking and particle identification, the Inner Tracking System (ITS) designed for accurate vertexing and the Time-of-Flight (TOF) detector, used for particle identification. The analysis framework used for the analysis is discussed, including the method for charged particle vertexing and tracking.

The analysis strategy used for  $D^{*+}$  reconstruction via the  $D^{*+} \rightarrow D^0 \pi_{\text{soft}}^+ \rightarrow K^- \pi^+ \pi_{\text{soft}}^+$  decay channel is discussed in detail in chapter three. This includes aspects like the application of selection cuts and their optimisation to improve signal significance, the yield extraction procedure, the handling of corrections and systematics and the use of the  $D^{*+}$  cross section in proton-proton collisions as reference for heavy ion collisions.

In chapter four the  $p_T$ -differential inclusive production cross section of prompt  $D^{*+}$  mesons, in the rapidity range  $|y| < 0.5$ , in  $\sqrt{s} = 7$  TeV proton-proton collisions is presented. Reconstruction of their decays via the decay channel mentioned about 2600  $D^{*+}$  have been counted (after selection cuts) in the 1-24 GeV/c transverse momentum region, in a data sample of  $3.14 \times 10^8$  events collected with a minimum bias trigger (for an integrated luminosity of  $L_{\text{int}} = 5 \text{ nb}^{-1}$ ). The data agree, within uncertainties, with predictions on perturbative QCD. Moreover, when scaled down to a centre-of-mass energy of 2.76 TeV, the results correspond to results with limited statistics of the  $p_T$ -differential inclusive production cross section of prompt  $D^{*+}$  mesons in the rapidity range  $|y| < 0.5$  in  $\sqrt{s} = 2.76$  TeV proton-proton collisions.

In chapter five the  $p_T$ -differential inclusive production yield of prompt  $D^{*+}$  mesons, in the rapidity range  $|y| < 0.5$  and the  $p_T$  range 2-36 GeV/c, in  $\sqrt{s_{NN}} = 2.76$  TeV lead-lead collisions is shown. The nuclear modification factor ( $R_{AA}$ ), with respect to the proton-proton reference obtained and scaled down to a centre-of-mass energy of 2.76 TeV, is determined. This has been done for both the data accumulated over 2010

and 2011, but for different collision centrality ranges. For the dataset with the largest amount of data (2011) this was the 0-7.5% centrality class. For this the  $D^{*+}$  production yield is suppressed up to a factor five in the 8-12 GeV/c transverse momentum bin. This is in agreement with measurements of other charmed mesons measured in the ALICE experiment. Several models qualitatively describe the observed suppression, but the uncertainties from the measurements do not allow to identify one particular model as a preferred description, though the lattice QCD model can be excluded.

## Samenvatting

In dit proefschrift worden de resultaten gepresenteerd van de eerste metingen aan de  $D^{*+}$  meson nuclear modification factor  $R_{AA}$  in zware-ionenbotsingen in de Large Hadron Collider (LHC) met behulp van de ALICE (A Large Ion Collider Experiment) detector bij CERN. Deze 'open charm' mesons zijn een nuttig middel om de eigenschappen van het quark-gluonen plasma (QGP) te bestuderen, aangezien hun oorspronkelijke charm quarks in de vroege stadia van zware-ionenbotsingen worden geproduceerd, waardoor ze gevoelig zijn voor de volledige ontstaansgeschiedenis van de QGP en hun hoge massa beperkt hun energieverlies in het medium. Metingen aan de charm productie in proton-proton botsingen zijn ook uitgevoerd, aangezien die nodig zijn om charm productie en suppressie in het QGP begrijpelijk te maken.

Hoofdstuk 1 bevat een overzicht van de theoretische achtergrond relevant voor dit proefschrift. Naast een korte geschiedenis van de ontwikkeling van deeltjesfysica introduceert het de basis van het Standaardmodel (SM), Quantum Chromodynamica (QCD), zware-ionenbotsingen en het QGP. De experimentele kenmerken van de QGP en eerdere resultaten van de Relativistic Heavy-Ion Collider (RHIC) worden ook besproken. De motivatie om de charm quark als sonde van het medium te gebruiken en de meting van het aantal  $D^{*+}$  is belicht. Dit hoofdstuk eindigt met verschillende modellen die gebruikt worden om het energieverliesmechanisme in het QGP te beschrijven.

De focus van het tweede hoofdstuk is op de ALICE detector. Er wordt een algemeen overzicht gegeven, maar alleen de subdetectoren die gebruikt worden in dit proefschrift worden in meer detail beschreven; de Time Projection Chamber (TPC) wordt gebruikt voor het traceren en deeltjesidentificatie, de Inner Tracking System (ITS) is ontworpen voor accurate vertexing en de Time-of-Flight (TOF) detector die wordt gebruikt voor deeltjesidentificatie. Het systeem waarin de analyse plaatsvindt is ook behandeld, waaronder de methodes voor het vertexen en traceren van geladen deeltjes.

De analysestrategie die gebruikt wordt om de  $D^{*+}$  via het  $D^{*+} \rightarrow D^0 \pi_{\text{soft}}^+ \rightarrow K^- \pi^+ \pi_{\text{soft}}^+$  vervalskanaal te reconstrueren is besproken in hoofdstuk drie. Dit bevat aspecten als het toepassen van snedes en hun optimalisatie om de significantie van het signaal te verbeteren, de procedure om het aantal deeltjes te bepalen, het omgaan met correcties en systematische fouten en het gebruik van de  $D^{*+}$  botsingsdoorsnede in proton-proton botsingen als een referentie voor zware-ionenbotsingen.

In hoofdstuk vier wordt de  $p_T$  differentiele, inclusieve productie botsingsdoorsnede van directe  $D^{*+}$  mesonen gepresenteerd, in de rapiditeitsbereik  $|y| < 0.5$ , in  $\sqrt{s} = 7$  TeV proton-proton botsingen. Reconstructie van hun verval via het genoemde vervalskanaal leverden ongeveer 2600  $D^{*+}$  op (na het toepassen van snedes) in de 1-24 GeV/c transverse impuls bereik, in een dataset van  $3.14 \times 10^8$  botsingen verzameld met 'minimum bias trigger' (wat gelijk staat aan een geïntegreerde luminositeit van  $L_{\text{int}} = 5 \text{ nb}^{-1}$ ). Verder corresponderen de resultaten, indien naar beneden geschaald to een botsingsenergie van 2.76 TeV, met de resultaten met gelimiteerde statistiek van de  $p_T$  differentiele, inclusieve productie botsingsdoorsnede van directe  $D^{*+}$  mesonen, in de rapiditeitsbereik  $|y| < 0.5$ , in  $\sqrt{s} = 2.76$  TeV proton-proton botsingen.

In hoofdstuk vijf wordt de  $p_T$  differentiele, inclusieve productie aantal van directe  $D^{*+}$  mesonen gepresenteerd, in de rapiditeitsbereik  $|y| < 0.5$ , in  $\sqrt{s_{NN}} = 2.76$  TeV lood-lood botsingen. De nucleaire modificatie factor ( $R_{AA}$ ), afhankelijk van de verworven en tot een botsingsenergie van 2.76 TeV teruggeschaalde proton-proton referentie, is bepaald. Dit is gedaan voor zowel de data verkregen in 2010 en 2011, maar voor verschillende bereiken van de botsingscentraliteit. Voor de dataset met de grootste hoeveelheid gegevens (2011), dit was de 0-7.5% centraliteitsklasse. Hiervoor is de  $D^{*+}$  productie tot een factor vijf onderdrukt in de 8-12 GeV/c transverse impuls bereik. Dit komt overeen met metingen aan andere charm-mesonen in het ALICE experiment. Verschillende modellen beschrijven kwalitatief de geobserveerde suppressie, maar de onzekerheden van de metingen laten geen identificatie van een geprefereerd model toe, hoewel de lattice QCD model uitgesloten kan worden.

Graduated with 8 courses (7 being the norm). Finished with the second highest score of my year.





## Acknowledgements

What you are reading here is the culmination of over four years of dedicated labour and effort, and I am proud to say that working on this project took me to the very edge of human understanding and allowed me to help push the boundaries a little bit further. But of course, I did not do this alone, I worked with people whose effort was indispensable to my own. I think Newton said it best: *If I have seen a little further it is by standing on the shoulders of giants.*

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