FONLL calculations for heavy quark production in nuclear collisions



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Abstract

The ALICE detector at the LHC has been designed to study the collisions of heavy nuclei at energies much higher then the previous dedicated experiments at the Relativistic Heavy-Ion Collider (RHIC) of the Brookhaven National Laboratory. Colliding heavy nuclei allows to reproduce the hot and dense plasma of quarks and gluons (QGP) existing right after the Big Bang and hence study the very first instants of universe's existence. In heavy ions collisions, heavy flavours, such as beauty and charm quark, are fundamental probes for the quark gluon plasma properties. That is because they experience the entire evolution of the system since they are produced at the very beginning. They are indeed a very powerful tool to test field theories such as Quantum Chromodynamics (QCD). Theoretical models predict that a fast parton(quark or gluon) looses energy while traversing a medium composed of colour charges. This phenomenon is called "jet quenching", it can be used to describe the QGP. It was first observed at RHIC by measuring the yields of hadrons. These particles are produced via the hadronization of the scattered energetic partons. In this project some theoretical predictions on the behaviour of heavy flavoured(charm and beauty) partons and hadrons produced in heavy ions collisions(p-Pb and Pb-Pb) are studied using QCD calculations. The initial production of heavy flavoured quarks is implemented using the fixed-to-next-to-the-leading order (fonll) approximation model. The calculation should also take into account the nuclear effects present in the heavy nuclei before the collision due to the high number of nucleons. The nuclear parton distribution functions(nPDF) are introduced for this purpose. The predictions are then use to scale the experimental data and get information about the effects due only to the QGP. The project has been done in the contest of the Summer Student School of CERN.

Acknowledgements

I would like to warmly thanks Giuseppe for guiding me through this project. Thanks for the support and useful conversations about physics and life. I will always remember this summer school as the turning point of my educational career. For that I would like as well to thanks CERN and all the stuff of this Summer School for the great opportunity they gave to us. Thanks for providing an ideal environment for developing our skills and growing from an academical and human point of view. Working in this contest has been delightful for me, and I've certainly learnt more than what I would have never learnt in any other place. The lecture program was so intense and interesting that I would benefits of that for the rest of my studies. I would like to thanks also all the amazing colleagues I met, with our passion and dedication to works and life we manage to make this summer unforgettable. The network of relationships we built along with the experienced we made will follow us for the rest of our life.

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1 Introduction

Heavy ions collision is a field which developed in the last thirty years and which gave a huge contribution to the understanding of the very first instant of life of our universe. Few millionths of second after the Big Bang, the universe was filled with a hot soup of quarks and gluons forming the so cold quark gluon plasma (QGP). At this stage quark and gluons, which are usually confined due to the strong interaction, were bounded only weakly and so they were free to move. Today's powerful accelerator make collision between ions, such as gold and lead, to recreate conditions similar to those of the very early universe. After the collision, the fireball formed instantly cools down and the quarks and gluons recombine into ordinary matter, going back to their confined state. The theory describing this strong interactions is Quantum ChromoDynamics (QCD) and it predicts that at sufficiently high energy density there will be a transition from ordinary hadronic matter to free plasma ("deconfined"), a phase comparable to the QGP of the early universe. The transition temperature is about $160MeV$. In the contest of heavy ions collision, heavy quarks are a very good probes of QCD and QGP since due to their heavy mass they are produced at the very first instants of the collision and thus they experience the full evolution of the system. They lose energy while traversing the medium via radiative and collisional mechanisms. In this project some QCD predictions about heavy quark production, such as $c\bar{c}$ and $b\bar{b}$ pairs, are implemented and applied to the physics analysis done at the ALICE experiment of CERN.

2 The European Center for Nuclear Research

CERN, European Center for Nuclear Research, is an organization bringing together thousand of scientists from all over the world. Built in 1954, in the center of Europe, it was one of the first European's joint organization and it has today 22 member states. The purpose of this joint venture is to probe an investigate the fundamental structure of matter and though of the entire universe. From the W and Z to the Higgs bosons, CERN didn't only contribute to build our knowledge in particle physics, but also to change the world we leave in. Indeed in 1990 the World Wide Web was invented as well as the touch screen in 1973.

2.1 The Large Hadron Collider

At the heart of CERN there is The Large Hadron Collider (LHC),the biggest circular accelerator of the word. This collider lies in a tunnel of 27km in circumference and 173

meters under the ground. It is made of 1232 dipole magnets (operating at 8.3 T and 11.8 kA) keeping the beam on his trajectory and 392 quadrupole magnets used to focus the beam. Around 10 000 super conducting magnets are used. To keep them at the operational temperature of $1.9K$ one of the largest cryogenic facility in the world has been build, using superfluid Helium-4. Inside the collider there are two parallel beamlines (beam pipes) each containing a beam travelling in the opposite direction around the ring. There are 4 interaction points with 4 different main detectors: ATLAS, CMS, LHCb, ALICE.

2.2 A Large Ion Collider Experiment - ALICE

ALICE, A Large Ion Collider Experiment, is a heavy-ions detector whose aim is to study strongly interacting matter at extreme energy where a new phase of matter appears, the quark gluon plasma (QGP). As explained in the introduction, this phase of matter is formed under extreme condition similar to those just after the Big Bang. The properties of the QGP are fundamental to understand color confinement and chiral symmetry restoration in quantum chromodynamics.

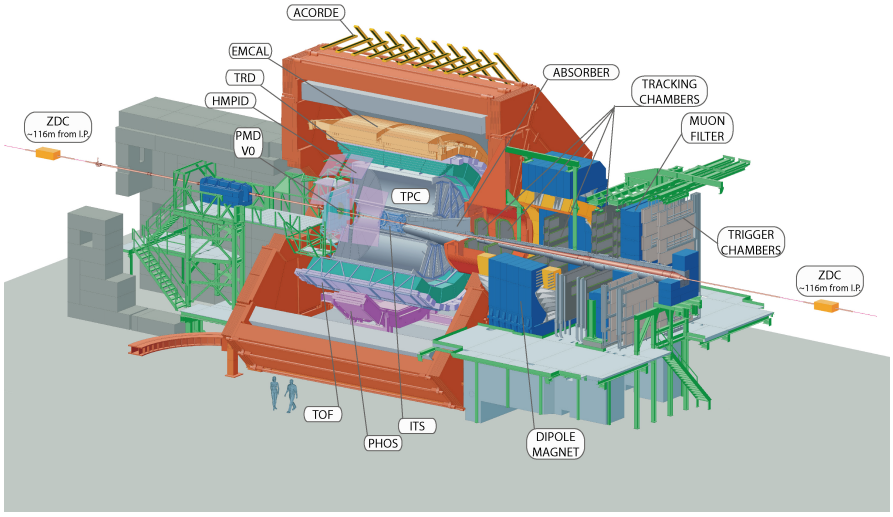


Figure 2 – Alice Detector [6]

2.3 ALICE detector

The ALICE detector is shown in Fig. 2. It is placed 50m underground and it is 16 m high, 16 m wide and 26 m long. Its design had been guided by the experimental conditions

necessary for Pb-Pb collisions. The central barrel detectors cover a pseudorapidity region $|\eta| < 0.9$ and it identifies mostly hadrons, electrons and photons. A huge magnet surrounds the detector: the magnetic field his used to bend charged particles to determine their electric sign and momentum. Here a short description of the main components is given, more details can be found in [6] and all the information are taken from [9].

Inner Tracking System (ITS) The Inner Track System (ITS) stands at the center of the main-barrel. It is made of six layers of cylindrical silicon detector: two Silicon Pixel Detectors (SPD), two Silicon Drift Deetectors (SDD) and two Silicon Strip Detectors(SSD). The main role of the inner tracker is to identify the low-p_T particles which don't reach the Time Projection Chamber, improve moment resolution for high-p_T particles and participate in primary and secondary vertex reconstruction.

Time Projection Chamber (TPC) The next detector is the Time Projection Chamber (TPC) and it is the main tracking system of ALICE. A gas mixture of Ne and CO_2 fills it. Particles are identified thanks to electrons produced via the ionization of this gas. The TPC can also identify individual particles by measuring the specific energy loss $(-dE/dx)$ in its gas.

VZERO detector system (V0) The VZERO detector is made of two layers of scintillators asymmetrically located on each side of the interaction point. It provides a trigger source rejecting beam-induced backgrounds and also contributes to measurements of luminosity, particle multiplicity, centrality and event plane direction.

Electromagnetic Calorimeter (EMCal) This is a Pb-scintillator calorimeter which has high energy resolution and low granularity. It is capable of triggering on jets and it mainly measures photons and electrons from the decay of short-lived particles. The detection is made using electromagnetic showers of photons, electrons and positrons. Although sometime particles hit the nuclei in an atom inside the calorimeter and deposit energy creating a contamination.

Photon Spectrometer (PHOS) It is an high resolution electromagnetic calorimeter. Made of lead tungstate crystals it is so dense that it can stop high energy photons. Thus it measures the temperature of the collision. To measure the light emitted by the tungsten it uses APDs (Avalanche Photo-Diodes).

3 Overview on the physics involved

3.1 The Standard Model in a nutshell

The Standard Model (SM) is the most complete physical theory describing particles and interactions between them. It explains how the building blocks of nature interact and it has been elaborated thanks to the common effort of thousands of physicists since the 1930s. Although it explains in a very precise way a wide range of phenomena, it has some open questions which can't find an answer in the SM and which motivate scientists to work in high energy physics. The general picture of the world given by the SM is based on two basic types of particles: the quarks and the leptons. Each of those is divided into three generations, from the lightest to the heavier particles. Quarks are paired in the three generations as up and down, charm and strange, top and bottom (or beauty). They can appear in three different colours and only mix in such a way that the combination is colourless. There are six leptons with their respective neutrinos: the electron and his electron neutrino, the muon and his muon neutrino, the tau and his tau neutrino. All these particles interacts via four fundamental forces: the strong force, the weak force, the electromagnetic force and the gravitational force. Each of those has a different strength and a different range, which leads them to act on different types of particles and have different features. The weak and the strong forces act on a very short range, but they have the strongest coupling. Gravity and electromagnetic forces have an infinite range. ALICE experiment deals mostly with the strong force since it investigates quark and gluon behaviour. All those forces are transmitted by some others particles, the bosons, which allow the exchange of energy between particles and thus the interaction. The carrier bosons are the gluons for the strong force, the W and Z for the weak and the photon for the electromagnetic force. For gravity the "graviton" has been theorised but not yet found. This is another of the holes of the SM, it does not include gravity, but luckily at the scale of particle physics the effect of gravity is negligible. Finally, the Higgs bosons, discovered by ATLAS and CMS on 4 July 2012, it's a the heart of the mechanism explaining the origin of mass of subatomic particles. In conclusion, the SM it is still incomplete; it does not explain what is dark matter and the asymmetry matter-antimatter. New physics or just a bigger picture has to be discovered in order to include all the missing phenomena.

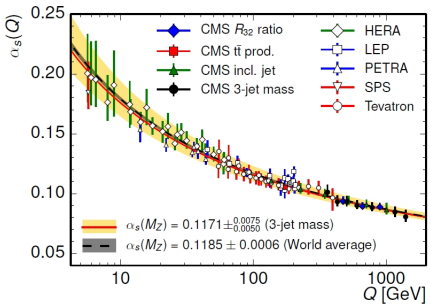


Figure 3 – "Alpha strong QCD behaviour, experimentally measured by CMS collaboration. From [12]"

3.2 Heavy Ions: a probe to QCD predictions

Quantum Chromodynamics(QCD) is the theory used to describe the strong interaction which affects quarks and gluons. The main features of QCD are confinement and asymptotic freedom. Heavy-Ion physics is a way to study Quantum Chromodynamics(QCD) without confinement, with quarks at their bare masses. It is also a way to study matter how it was a few microseconds after the Big Bang, at temperatures of 10^5 times sun's temperature. Confinement is the phenomenon responsible for the absence of free color charges. Quarks and gluons are only observed within hadrons which can be of two types: mesons, formed by a quark and an antiquark and baryons, made by three quarks. Confinement is not fully understood and it can be described by a linearly rising potential for color charge: $V(r) = A + B/r + \sigma r$. The origin of the linear part it is the self-interaction of the gluons. The partons, quarks and gluons, are confined at low energy but behave as free at high energy, this is the phenomenon called asymptotic freedom. It is mainly due to the coupling constant α_S behaviour shown in Fig.3; at high energy α_S strongly decreases. At low energy the coupling constant is small hence the interaction strength can be computed in a perturbative way.

Whereas perturbative QCD (pQCD) can't explain confinement because his basic assumption is a small coupling constant, it's a very powerful tool at high energy and it is the direct consequence of the phenomenon of asymptotic freedom. In the regime of soft QCD interactions the perturbative calculations don't applied, hence other approach should be elaborated. Lattice QCD is the most solid theoretical approach. Important prediction of lattice QCD, as depicted in the introduction, is the indication of a new phase of nuclear matter at very high energy densities. At low temperature, solid matter is formed by protons and neutrons bound inside of nuclei. At very high temperature (predicted to be around $T_c \approx 170 MeV$) it becomes a liquid called a Quark Gluon Plasma

(QGP) in which quarks and gluons are deconfined. In Fig. 4 the phase diagram of nuclear matter is shown.

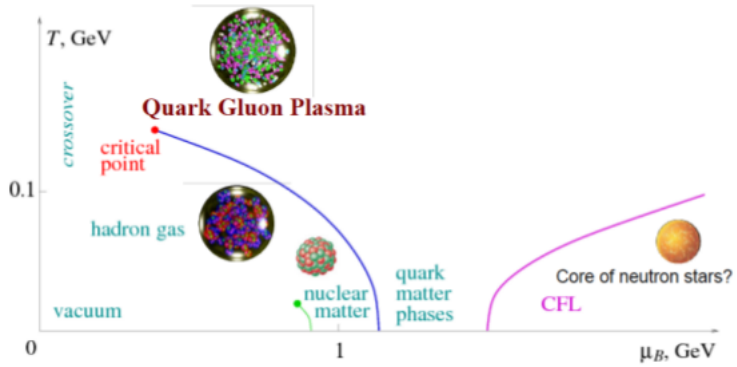


Figure 4 – Phase diagram for the QGP.[15]

On the y-axis there is the temperature T and on the x-axis the chemical potential μ_b, which is related to the net baryon number of the system. The QGP state appears for low μ_b and high T whereas normal matter occurs at low temperature and at μ_b close to $1GeV$. The nuclear collision at LHC can bring the system at temperatures of 2-4 times higher then the critical temperature. Using lead-lead collision the system would reach the needed temperature to study the QGP transition.

3.2.1 Evolution of a heavy ions collision

There are essentially two ways to access the QGP region of the diagram: by increasing the baryon density with a compression of the nuclear matter, or by increasing the temperature. The first approach cannot be reach in a laboratory while the second one can be achieved at the LHC. The threshold to reach is of the order of $1GeV/fm^3$ [1].The evolution of such a collision is shown in Fig.5.

Due to the high speed of the nuclei before the collision,they are contracted due to relativistic effects. At the very first stage of the collision, heavy flavoured quarks(charm and beauty) and high-p_T partons(gluons and other quarks) are produced in rare hard scattering processes. When the nuclei overlap they produce the energy density needed to produce a QGP. A this stage the nuclei melt and quark and gluons start acting as free. The initially produced heavy flavoured particles interact with the medium while the system expands and cools down until it reaches the critical temperature where a phase transition and hence the hadronic phase takes place. The system will continue to evolve an reach a chemical freezout temperature where the inelastic collision and then

the hadronic ones will stop. At this point the properties of the outgoing product of the collision can be defined. In the case of pp collision there is no formation of such a QGP and the hard scattered partons hadronize in the vacuum(with a mechanism described by string fragmentation). For that reason it is interesting to compare the yield of ions collisions and pp collisions, in order to extract information about the QGP.

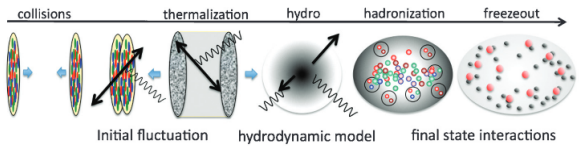


Figure 5 – Evolution of a Heavy Ions collision from [4]

3.3 Heavy quark production

Heavy quark, such as charm and beauty, are useful to study the QGP properties since they are produced at the very beginning of the collision (charm $\approx 0.1 fm/c$, beauty $\approx 0.01 fm/c$ vs. QGP $\approx 0.3 fm/c$) and thus they experience the whole evolution of the system. While traversing the medium they interact with the hot and dense QCD matter therefore they are sensitive to the medium properties. Because of this interaction they loose energy via radiative and collisional mechanisms. They are mainly produced in hard gluon scattering processes, after which they undergo a fragmentation. The heavy hadron produced will further decay into leptons, the observable particles from which we can reconstruct all the process. The main ingredients to describe this process are the elementary parton-parton interaction, which can be described with perturbative QCD, the non-perturbative fragmentation function and the parton distribution functions, explained in the following paragraphs.

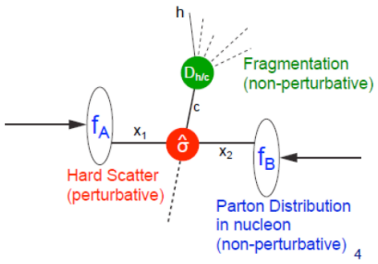


Figure 6 – Heavy quark production process

3.3.1 Fragmentation

The gluons of QCD have color charge and whereas for instance the electric field decreases with distance, the gluon field between colour charged particles forms a flux tube or string between them. Therefore at some point it becomes energetically favourable to separate the two quarks and forms a new pair of quark-antiquark rather then expand the string as shown in Fig. 7. This phenomenon is known as hadronization or string breaking. After the hadronization process new mesons are formed with a fraction of the momentum of the original pair of quark and anti-quark. Fragmentations Functions (FFs) describes the

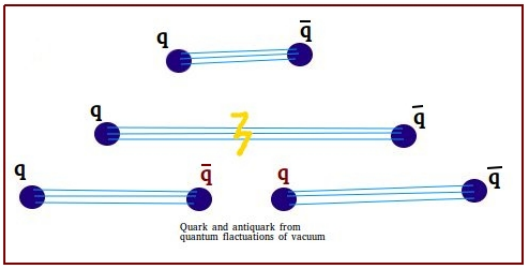


Figure 7 – Cartoon representing the hadronization process.

final state of an hard-scattering process giving the probability for a quark to fragment into a specific hadron with a momentum fraction z. For simplicity the hadron produced after the fragmentation is considered having a parallel momentum with respect to the heavy quark that produced it. The integral of the fragmentation function gives the fragmentation fraction, that is the fraction of hadrons produced after the fragmentation of the string.

3.3.2 Parton Distribution Functions

Within the nucleons quark and gluons carry a fraction x of the total longitudinal momentum of the nucleon. During a high energy collision it is possible to consider the partons as almost collinear with the nucleon momentum. From experimental data it is possible to extract the parton distribution functions (PDFs), which describes the momentum distribution of the partons within the proton. They represent the probability densities for a parton to carry a momentum fraction x at a squared energy scale $Q^2 = -q^2$. In the case of more complex nucleus with several nucleons the distribution of the momentum within the partons is modified, to take this phenomenon in account another set of PDFs is used, called nuclear PDFs (nPDFs). The nPDFs take into account that nuclei are composed by several nucleons and during a collision an effect of shadowing

(or anti-shadowing in some cases) will take place on the latter nucleons from the further ones. Several sets of nPDFs have been elaborated during the years by different groups, using data and theoretical models. One of the most popular was the EPS09, but in May 2017 a new set has been released by the same group and started to be used, the EPPS16. It is part of the goal of this project to test this new set and the resulting predictions. The EPPS16 have been fitted with more precise data, e.g. those coming from the dijets analysis of CMS [10]. Furthermore one more gluon parameter is left free. Here is a plot, Fig.8, to compare the two sets. As one can notice, the EPS09 set

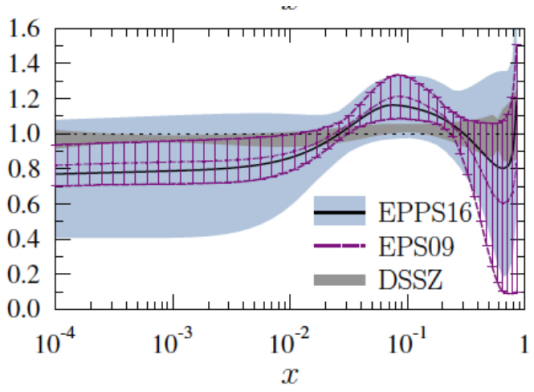


Figure 8 – Comparison between nPDFs sets, [10]

has smaller uncertainties. This could seem not logical since the data precision has been improved passing from one set to the other. The reason for that is explained in [11] and it is also due to a previous wrong treatment of a data set with EPS09.

4 Useful physical quantities

4.1 Rapidity, pseudorapidity and transverse momentum

It is a variable commonly used in accelerators physics. If p_L as the longitudinal component along the beam axis and E the energy, one can define the rapidity as :

$$y = \frac{1}{2} ln(\frac{E + P_L}{E - P_L}) \tag{1}$$

It is a good variable because is invariant with respect to Lorentz boosts along the z-axis. It is also useful to define the *pseudorapidity* ,a spatial coordinate describing the

angle between the particle and the beam axis. It is define as follows:

$$\eta = -ln(\tan\left(\frac{\theta}{2}\right)) \tag{2}$$

For highly relativistic particles rapidity and pseudorapidity are the same. Pseudo rapidity is useful in accelerators a the LHC where the interactions rarely have their centre of mass frame coincident with the detector rest frame. The last important variable is the transverse momentum p_T. It is the momentum component of the particle in the plane perpendicular to the axis. If the beam is on the z-axis then

$$p_T = \sqrt{p_x^2 + p_y^2} \tag{3}$$

4.2 Centrality of a collision

When dealing with nuclei of heavy atoms, the geometry of the collisional system becomes more complex. The nuclei of lead atoms are bigger compare to protons. In order to describe the geometry one needs to take int account the impact parameter, usually called b, which is the distance between the centers of the two colliding Pb nuclei in the transverse direction a depicted in Fig. 9. A collision is central if the impact parameter b is small and peripheral if it is big (it can be as large as twice the radius of colliding nuclei). It is important to notice that the energy density achieved in peripheral collision is smaller than in central ones. A quantity related to the centrality and used to determine it is the number of particles produced in a collisions. In a collision it is possible to distinguish between protons and neutrons which really collide, the so-called participants, and others which don't pass in the collision zone and don't collide, the so-called spectators. It is clear that in a central collision the number of participants will be bigger then in a peripheral one. In conclusion, the number of produced particles is a good measure of the centrality of a collision.

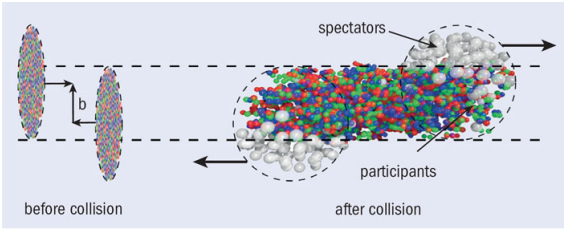


Figure 9 – Illustration of two colliding heavy nuclei taken from [5]

5 QCD framework and FONLL

In high energy collisions hard and soft processes can occur, for high and low Q^2 respectively. The hard processes can be treated using pQCD while the hard ones can't. Factorization consist in treating those two processes separately.

FONLL (Fixed Order + Next-to-Leading Logarithms) is a model for calculating the single inclusive heavy quark production cross section. A prediction for the cross section of the observed particles is obtained as a numerical convolution of a perturbative cross section $d\sigma_Q^{FONLL}$, a non-perturbative fragmentation function $D_{Q\to H_Q}^{NP}$ and a decay function $g_{H_Q\to l}^{weak}$ describing the hadron decay into a lepton. Hence the differential cross section is given by:

$$d\sigma_l^{FONLL} = d\sigma_Q^{FONLL} \circledast D_{Q\to H_Q}^{NP} \circledast g_{H_Q\to l}^{weak} \tag{4}$$

The fragmentation fraction $f(Q \to H_Q)$ is given by the integral of the fragmentation functions $D_{Q\to H_Q}^{NP}$. Some of the result of FONLL predictions can be accessed by a public webpage [2]. The authors also provide the code for running these calculations but without fragmentation functions. A part of this project consists in implementing the part concerning the fragmentation functions in order to get the cross section of the hadron production.

5.1 Non-perturbative fragmentation functions

A summary of the parameters and functions used for the analysis is given here. The hadronization is studied for charm and bottom quark. For bottom production the fragmentation function used is the Kartvelishvili et al. distribution [16]:

$$D_{b\to H_b}^{NP} = (\alpha+1)(\alpha+2)x^{\alpha}(1-x) \tag{5}$$

Where we followed the choices of [14] and choose $m_b = 4.75GeV$ as central value for the bottom quark mass and the values of the fragmentation parameter α obtained in ref. [13], that is $\alpha = 24.2$. There are no available data for single mesons so only a prediction for a mixture of B-hadrons is given.

For the charm quark instead, experimental data are available for individual mesons (D^*, $D^{\pm}$ and D^0) but the theoretical understanding of the different but quite similar fragmentation functions is only partial. The details fragmentation functions are given in [3] and reproduced here. Building block of all the fragmentation functions are the

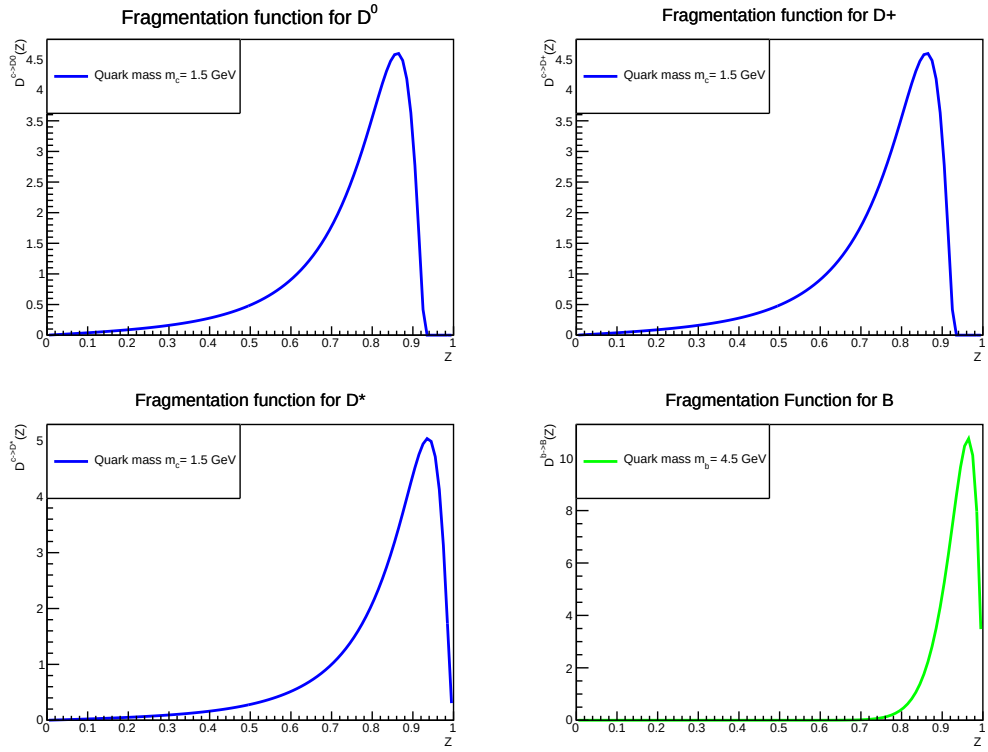


Figure 10 – Fragmentation functions used.

"pseudo" end "vectorial" quark fragmentation functions derived in Ref.[7] and the

$$D_{Q\to P}(z) = N\frac{rz(1-z)^2}{(1-(1-r)z)^6}[6-18(1-2r)z+(21-74r+68r^2)z^2- \\ 2(1-r)(6-19+18r^2)z^3+3(1-r)^2(1-2r+2r^2)z^4 \tag{6}$$

$$D_{Q\to V}(z) = 3N\frac{rz(1-z)^2}{(1-(1-r)z)^6}[2-2(3-2r)z+3(3-2r+4r^2)z^2- \\ 2(1-r)(4-r+2r^2)z^3+(1-r)^2(3-2r+2r^2)z^4] \tag{7}$$

The D^* further decay into a D^0 and this could be calculated explicitly. However since the channel $D^* \to \pi D^0$ is dominant, the effect of this further decay is taken into account by a rescaling factor of the longitudinal momentum by $\frac{m_D}{m_{D^*}}$ for the D^* production:

$$\tilde{D}^{(V)}_{BCFY}(z;r) = \Theta(\frac{m_D}{m_{D^*}}-z)D^{(V)}_{BCFY}(\frac{m_D}{m_{D^*}}z;r)\frac{m_D}{m_{D^*}} \tag{8}$$

where $\Theta(z)$ is the Heaviside step function. The r parameter can be interpreted as

the ratio of the constituent mass of the light quark to the mass of the meson. N is a normalization parameter independent of m_Q and r taken equal to 5. Finally, one can then define the proper fragmentation functions for each one of the D-mesons as follows. For the D^* meson, the fragmentation function used is given by:

$$D^{c\to D^*}(z;r) = BR(c- > D^*)D^{(V)}_{BCFY}(z;r) = 0.233D^{(V)}_{BCFY}(z;r) \tag{9}$$

For D^0 and D^+:

$$D^{c\to D^0}(z;r) = 0.168D^{(P)}_{BCFY}(z;r) + 0.39\tilde{D}^{(V)}_{BCFY}(z;r) \tag{10}$$

$$D^{c\to D^+}(z;r) = 0.162D^{(P)}_{BCFY}(z;r) + 0.07153\tilde{D}^{(V)}_{BCFY}(z;r) \tag{11}$$

The differences between the three functions are minimal, when doing an average of D mesons it is sufficient to take the fragmentation function of D^*.

5.2 Nuclear Shadowing and R_{AA}

As explained in section 3.2 at very high temperature strongly-interacting matter behaves as a deconfined Plasma of Quarks and Gluons(QGP). The conditions to create this state are expected to be attained in high energy collisions of heavy nuclei. This state lasts for a short time, then the system expands and cools down, the hadronisation then starts. A the initial stage of the collision heavy quarks are produced in quark-antiquark pairs and they move towards the hot and dense medium losing energy due to gluon radiation and collisional processes. An evidence of this loss of energy is the modification of the transverse momentum distribution in Au-Au and Pb-Pb collisions with respect to pp scaled collisions. This modification is usually quantified by the nuclear modification factor R_{AA}, which is defined as the ratio between the measure in nucleus-nucleus and the cross sections expected in proton-proton (pp) collisions divided by the average overlap function. In absence of nuclear effects this ratio is expected to be equal to one. Whereas in nuclear collisions a suppression of the yield products is observed and $R_{AA} < 1$. One should take into account that initial effects, like the nuclear modification to PDF, can also modify the R_{AA}. Indeed one can calculate with the FONLL approach the expected R_{AA} as due to only the effects of the nuclear modifications of the parton distributions function. As said, these effects are present before the collision and therefore they are independent of the QGP medium and the collision. It is interesting to predict to what extend are this effect affecting the production of quark in order to understand if the strong suppression

observed at low p_T is due to nuclear modifications or to a QCD medium effect. The experimental R_{AA} is computing using the following standard formula:

$$R_{AA} = \frac{1}{N_{coll}} \frac{\sigma_{AA}}{\sigma_{pp}} = \frac{1}{N_{coll}} \frac{dN/dp_T\Big|_{AA}}{dN/dp_T\Big|_{pp}} \tag{12}$$

where N_{coll} is the umber of collisions, σ_{AA} and σ_{pp} are th invariant cross sections and dN/dp_T are the p_T distributions for a given process in AA and pp collisions [8].

6 Method

6.1 Starting point and fragmentation

A fortran code with FONLL calculations made by M.Cacciari is available online [2]. First step of the project consisted in making this code available to everyone in ALICE in an easy and user friendly way. The code has been rearranged and updated to be interfaced also with the last version of nPDFs EPPS16. It is now build in AliPhysics software, version FONLL 3.1.3, with PDF library of CERN LHAPDF. This is very useful since under this format it is easy to run the code on grid[1] or condor[2]. The output of this code is a differential cross section for $c\bar{c}$ or $b\bar{b}$ production, $d^2\sigma/dydp_T^2$ given for a certain value of transverse momentum p_T and rapidity y, with the associated error. With a straightforward script it is possible to create a grid of points where for each point in rapidity ones get the differential cross section in p_T. Unfortunately the output of this code doesn't include the fragmentation of the quark, which has been implemented in this project following the fragmentation functions described in Sec.5.1. Once the output is created, the files are read and the convolution with the fragmentation is done to get the inclusive cross section. An other useful tool made available by M. Cacciari is the web page [2] where the result with the fragmentation are made available. Unless the result with fragmentation are available online it is not possible to use them to make large predictions sine the interface can't produce a large number of files with a large number of parameters. However one can use it to check if the fragmentation was implemented correctly. Once the code has been check it is possible to safely predict the behaviour of experimental observables as explained in the next section. As a general remark, the code has been implemented in c++ using ROOT, the software for analysis used and developed

[1]The grid is a distributed system of networked computers performing large tasks

[2]Condor is a software allowing to work in a system of High Throughput Computing (HTC)

at CERN.

6.2 Application of the results

Once the cross section is obtained, it is now possible to perform predictions on the cross section for heavy quarks such as charm and beauty. With an emphasis on the charm quark, the data obtained by ALICE in 2016 are compared with the predictions made by fonll. The comparison is done for $c\bar{c}$ production, for the D^0 , D^* and D^+. The second application is the computation of the nuclear modification factor R_{AA} (see 5.2). This has been done using the spectrum obtained for lead-lead collisions and the one of pp collisions. The R_{AA} is then obtained taking the ratio of them.

7 Results and discussion

7.1 Fragmentation

Here the result for the fragmentation part. For the fragmentation functions used see Fig. 11. Then it hi worth to compare the result obtained after the implementation of the fragmentation and the webpage of Cacciari. The fragmentation has been done well since the result match the one of the web interface.

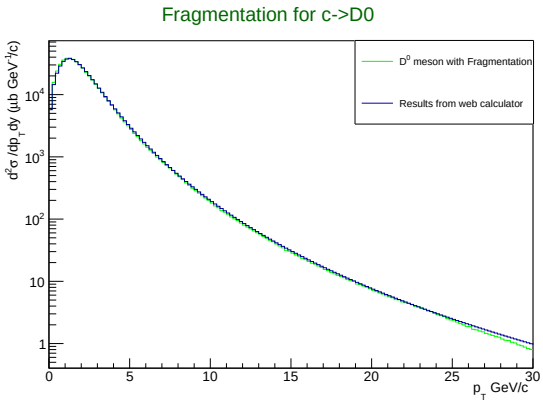


Figure 11 – Compare histograms after the fragmentation for D^0 and the results from the webpage.

7.2 Comparison DATA vs FONLL

Here the results obtained for the three mesons when comparing with data. Those are useful results since it is possible to compare QCD predictions with what have been

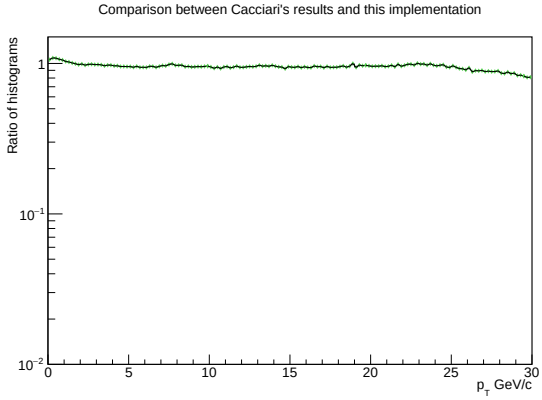


Figure 12 – Ratio of the two histograms.

experimentally measured. It allows to check either the theory and the experimental setup. Indeed the pp and p-Pb results published by ALICE experiment are presented with a comparison to the fonll predictions. The system study is p-Pb at a center of mass energy of $\sqrt{s_{NN}} = 5.02\,TeV$. The results shown here are for zero rapidity $y = 0$. For examples at other rapidities values see the appendices. The experimental results are expected to be higher then fonll predictions and this is confirmed by those plots.

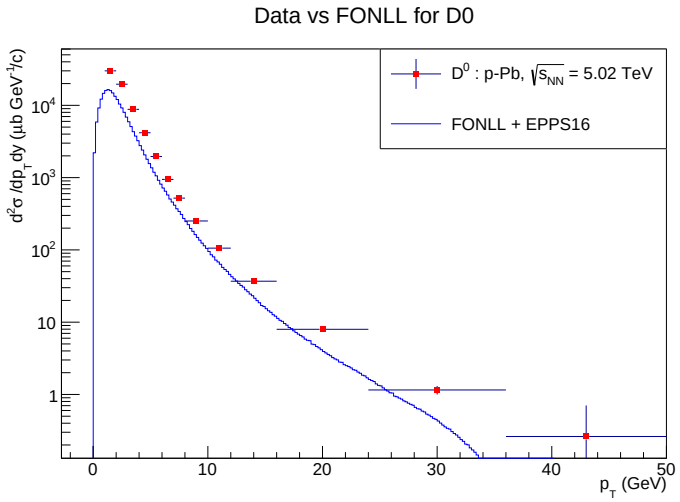


Figure 13 – Data vs FONLL predictions for D^0 meson.

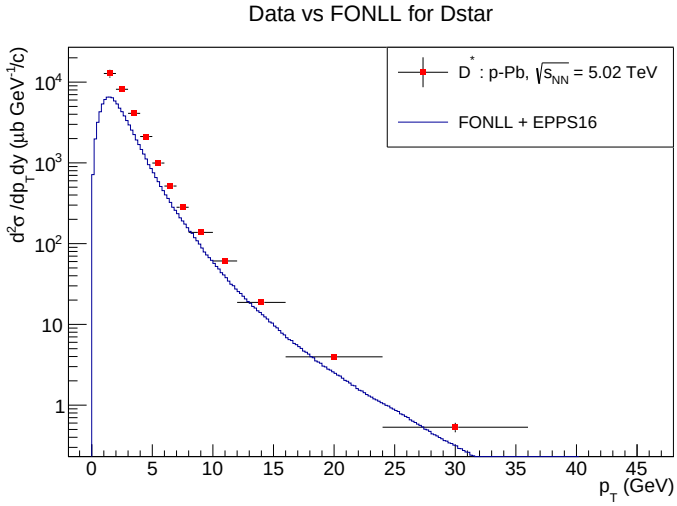


Figure 14 – Data vs FONLL predictions for D^* meson.

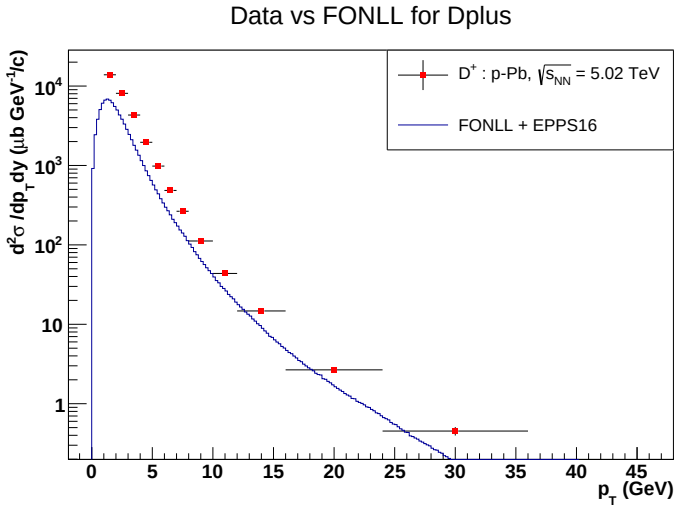


Figure 15 – Data vs FONLL predictions for D^+ meson.

7.3 R_{AA} for Pb-Pb at $\sqrt{s_{NN}} = 5.02\,TeV$

For the effect of the PDF when considering the nuclear modification factor R_{AA}in Pb-Pb collisions, the results are shown with error bars in Fig. 16. As explained in sec 3.3.2 the uncertainties for EPPS16 are bigger with respect to the results of EPS09 which leads to a huge error band. As a general observation,at low p_T the suppression goes down to 0.45 where at high p_T it get closer to one. This means that the effects of shadowing due to nuclear PDFs are important only at low p_T. This effects are present before the

collision since they depend on the distribution of the momentum between the partons. However a higher suppression has been observed in experimental data. In Fig 17 one can observe that at high p_T there is a suppression down to 0.7 and the minimum is reached around 6-7 GeV. This means that other QCD medium effects play a decisive role in the suppression of the R_{AA}. In data, at p_T close to zero, the ratio approaches one, this can be explained as follows. They $c\bar{c}$ pairs produced loose energy and momentum when traversing the medium but the total charm number has to be conserved.Looking at the spectra in Fig. 13, one can notice that the majority of the production takes place at low p_T (note that those results are presented in a logarithmic scale). Hence the particles produced accumulates at low p_T. Furthermore if one scales the data obtained with the simulations of the effects of nPDFs, the points would reach even higher values..

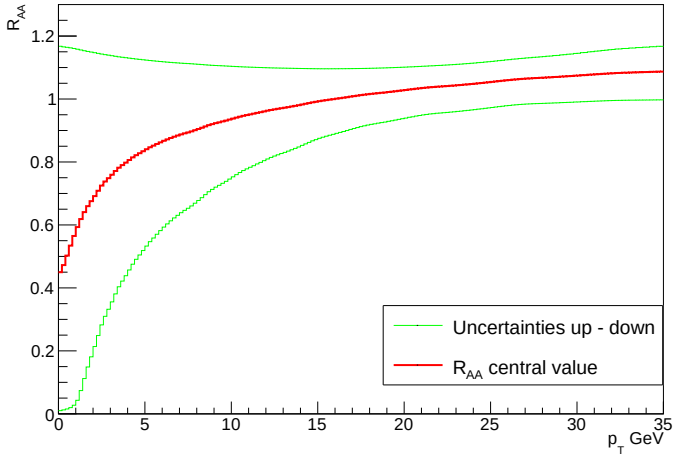


Figure 16 – Nuclear modification factor R_{AA} , theoretical prediction with fonll and EPPS16.

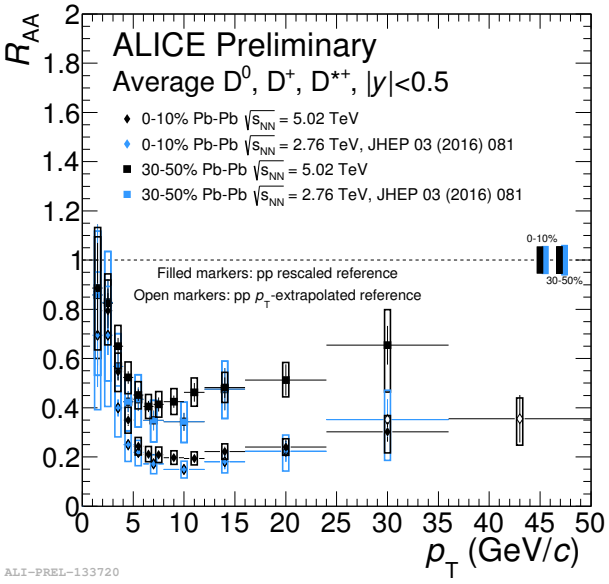


Figure 17 – Average nuclear modification factor R_{AA} of D^0,D^+, D^* mesons with $|y| < 0.5$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76TeV$ and $\sqrt{s_{NN}} = 5.02TeV$ in the $0 - 10\%$ and $30 - 50\%$ centrality classes.

8 Conclusions

In this project a new tool to easily make QCD calculations has been implemented. The fonll package has been made available on the ALICE software, using the more updated version of nuclear PFDs. More in general the results of this implementation are consistent with the previous one. The error bars due to the uncertainties on nPDFs have increased, but thanks to the very precise last data taken by ALICE it will be possible to reduce it by including them in the global fit to derive nPDF. Furthermore the R_{AA} predictions done with the EPPS16 sets can be used in future analysis in order to scale the data to the effects of cold nuclear matter. Further development could include doing the same analysis for the B meson,plot the error bar taking into all the uncertainties (from theoretical to experimental) and eventually reduce the error bars on the EPPS16 with new data.

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