NPAC

PRE-THESIS INTERNSHIP

Measurement of the quarkonium production in p-Pb collisions at the LHC with ALICE

Student:
Mohamad TARHINI

Supervisors:
Bruno ESPAGNON
Christophe SUIRE
Zaida CONESA DEL VALLE

May 12, 2014

Abstract

I present here an overview of my ongoing internship in the ALICE IPN team. A presentation of the ALICE experiment, its goals and a brief description of its muon spectrometer are the contents of the introduction. It is followed by a short presentation of the IPN ALICE team and its responsibilities. In the next section, more details on the heavy-ion physics plus a discussion of a few articles related to the subject of my internship are presented. The conclusion presents the current state of heavy-ion physics in ALICE.

1 Introduction and experiment overview

During two months I will do my internship with the ALICE (A Large Ions Collider Experiment) team in IPN (Institut de Physique Nucleaire). This internship will be about the determination of the J/ψ production cross section in p-Pb collisions at the LHC (Large Hadrons Collider) using ALICE detector. IPN is one of 130 labs and institutes from 30 different countries working in ALICE, one of the four large experiments (ATLAS, CMS, LHCb) at the LHC. ALICE is dedicated to study heavy-ion physics, rather than particle physics. For that reason it has its own features that help in this domain like the ability to detect and identify particles down to zero transverse momentum (p_{T}).

1.1 Apparatus

ALICE has put big efforts to make a muon spectrometer which is able to study quarkonia ($Q\bar{Q}$) via dimuon channel down to zero transverse momentum. For my internship subject, it is the most important part. I will not go to the details of this spectrometer which can be found in [1], but I will briefly describe its different parts:

- The tracking system: ten cathode pad chambers arranged two by two in five tracking stations providing a spatial resolution of 100 μm and covering an area of about 100 m^2.
- The trigger system: two trigger stations, each one consists of two planes of 18 resistive plates chambers. It provides a triggering based on single and dimuon tracks above a given p_{T}.
- The absorbers system consists of three absorbers. The front absorber (before the first tracking station) aims to stop kaons and pions in order to reduce the muon background from their decays. The iron wall (between the tracking and the trigger systems) to absorb the low-momentum muons. In addition a small-angle dense matter shield surrounds the beam tube.
- The warm dipole magnet which is placed between the 2^{nd} and the 4^{th} tracking stations (embedding the 3^{rd} one) provides an integral magnetic field of 3 T.m .

The ALICE detector is then formed by this spectrometer and an onion shaped ordinary particle physics detector (central barrel). A total of 17 different detection systems.

ALICE analysis are performed with the offline framework AliRoot, which takes ROOT as a base, and GEANT as a transport code.

1.2 Goals

The main goal of ALICE is to well understand the confinement mechanism. This mechanism is responsible for the quarks' binding inside a nucleon. A key in the understanding of this mechanism is the existence of a phase of matter, the quark-gluon plasma (QGP). Quantum chromo dynamics

(QCD) predicts that QGP exists at very high temperature and energy density, these conditions were available short time after the Big-Bang.
Heavy-ion collisions can be understood as a process of multiple nucleon-nucleon collision. These collisions would provide a large amount of energy in a small volume and thus QGP can be created.
As we will see in section 3 with more details, ALICE probes this new phase of matter by studying the heavy quarkonia (charm and bottom resonances), and the heavy hadrons (contain charm or bottom quarks). In the charm sector J/ψ resonance and D mesons with their excited states are the main probes. The reason why heavy flavors are chosen rather than the light ones is because heavy flavors are produced at an earlier time after the collision, so they can probe all the QGP phase.
To achieve this goal, tracks reconstruction for a huge number of particles and measurement of their momenta in a broad range (100 MeV/c - 100 GeV/c), as well as the localisation of the decay vertices, are the ALICE detector requirements.

1.3 Colliding systems and center of mass energy

The LHC is dedicated to particle physics, and beam time consists mostly of pp collisions. Moreover for $\sim$ 4 weeks/year the LHC is dedicated to heavy ion collisions. Aside with Pb-Pb collisions ALICE also study pp and p-Pb collisions, as a reference to compare to the Pb-Pb results.
Note that pp collisions are also studied in ALICE to give complementary information on QCD topics studied at the three others LHC experiments.
Compared to other heavy-ion colliders (SPS at CERN, AGS and RHIC at Brookhaven) which have respectively 20 GeV, 5 GeV and 200 GeV as a center of mass energy, The probed region is larger and smaller values of Bjorken-x become accessible at LHC energy.
Table 1 shows the different data taking periods at ALICE, and information about the energy and the colliding systems. In general the center of mass energy per nucleons pair in nucleus-nucleus collision $\sqrt{s_{\mathrm{NN}}}$ is obtained by multiplying the pp center of mass energy $\sqrt{s}$ by the proton to nucleon ratio in this nucleus. For Pb this ratio is about 0.4.

	2009	2010	2011	2012	2013
pp	0.9; 2.36	0.9; 7	2.76; 7	8	2.76
p-Pb				5.02	5.02
Pb-Pb		2.76	2.76		

Table 1: Center of mass energy (TeV) of the colliding systems studied in ALICE for the recent years.

The next data taking will be in 2015 (the first year of the thesis). About 13 TeV and 5 TeV are respectively the expected center of mass energies in pp and Pb-Pb collisions.

2 The IPN ALICE team

Four permanents, one post-doc, and one PHD student are the members of the IPN ALICE team [2]. They work with ALICE on different subjects, focusing mainly on J/ψ production.
In addition to the data analysis which is the main task of this team, they participated in the muon spectrometer building, particularly in the readout electronic for the tracking system.
In the last two years, two PHD thesis [3, 4] have been achieved in the team. The first one was about the J/ψ polarisation and the second one was about the measurement of the J/ψ production in Pb-Pb collisions. Before these two, five thesis were also achieved in this team from 1996 to 2011. Some of them were before the LHC started data taking and they were about modelling and simulation of the muon spectrometer.
In the last four years two post-doc did also worked with the IPN team. They focused on the study of

the open-bottom hadrons in the three muons decay channel, and the data analysis for the coherent J/ψ production.

The IPN team major contributions in the ALICE publications are [5–10]. They are all related to the J/ψ production in different processes except [6] which was on the D mesons.

3 The internship related physics

As it is mentioned in the introduction, QGP is probed using heavy quarkonia and heavy flavours hadrons, now we are going to explain this process in more details:

3.1 The QGP physics

The QGP is the state of the deconfined partons (quarks or gluons). Quarkonium is a bound state of these partons. When a quarkonium is present in a QGP medium, dissociation mechanism is expected to take place and break this binding.
Indeed the free partons of the QGP make a screening between the quark and the anti-quark of the given quarkonium. This screening changes the Coulombian long range interactions into short ones. These short range interactions decrease in strength with the temperature increasing. Above a temperature T_d which characterizes this mechanism, dissociation take place in the medium. Once we have a dissociation, the number of quarkonia would be reduced. So an observation of this reduction (suppression) is nothing but a signature of the QGP formation [11].
The challenge arises from the fact that not only the QGP is responsible for this suppression. Other effects can also contribute, as we will see later in section 3.4 . Another thing that must be taken into account is that the studied quarkonia and open hadrons can be classified into two categories. The prompt ones which are either direct collisions products, or come from the decay of their excited states. The non-prompt ones which come from the decay of other types. For example the J/ψ which is the charmonium fundamental state, could be a direct product or from the decay of the charmonium excited states (ψ(2S), χ_c) or from the decay of a B hadron.

3.2 Main processes

In the charm sector the J/ψ and the D mesons are the main QGP probes. They decay through different hadronic and leptonic channels and accordingly different detectors are used:

- The hadronic decays for the open charm hadrons: $D_s^+ \to K^-K^+\pi^+$; $D^{*+} \to D^0\pi^+$; $D^+ \to K^-\pi^+\pi^+$; $D^0 \to K^-\pi^+$.
- The leptonic decays for the charmonium:
J/$\psi \to e^+e^-$; J/$\psi \to \mu^+\mu^-$.

All of these processes are detected using the barrel central detector, except the last one (dimuonic decay of J/ψ) which is detected in the muon spectrometer.
The same is for the bottomonium and the B hadrons in the bottom sector, but they will not be addressed in this report.

3.3 Production of $c\bar{c}$ in pp collisions

Thanks to the factorization theorem in QCD we can express the $c\bar{c}$ production cross section into the product of two terms. These terms refer to the hard and soft processes. At the LHC the hard process is dominated by the gluon fusion $gg \to c\bar{c}$. The soft process is the confinement of the c and $\bar{c}$ inside a hadron. The hard process is studied using perturbative QCD while the soft process does not.

3.4 Quarkonium suppression in p-Pb collisions

In the proton-nucleus collisions the production process is physically the same. But the number of the produced charmonium is reduced with respect to the p-p collisions case. This reduction is the consequence of several effects related to the presence of the cold-nuclear matter (CNM). One can classify these effects into two parts:

- Initial state effects:
  A parton inside a nucleus is not the same as a one inside the proton from the partons kinematic distribution point of view. In other words the gluon Parton Distribution Function (PDF) inside a nucleon is different than this PDF inside the nucleus. The hard process $gg \to c\bar{c}$ is the dominant one at the LHC, so the modification in the gluons PDF as it is shown in the Figure 1 will influence the production of J/ψ. This effect is known as "the shadowing effect".
  Another initial state effect can contribute in the quarkonia suppression is the decreasing of the partons energy due to the partons energy loss inside the nucleus.

- Final state effects:
  After the formation of the J/ψ bound state, there is a probability of its breaking through an interaction with the nuclear matter.
  Also energy loss may occur on the charmonium final-state level.

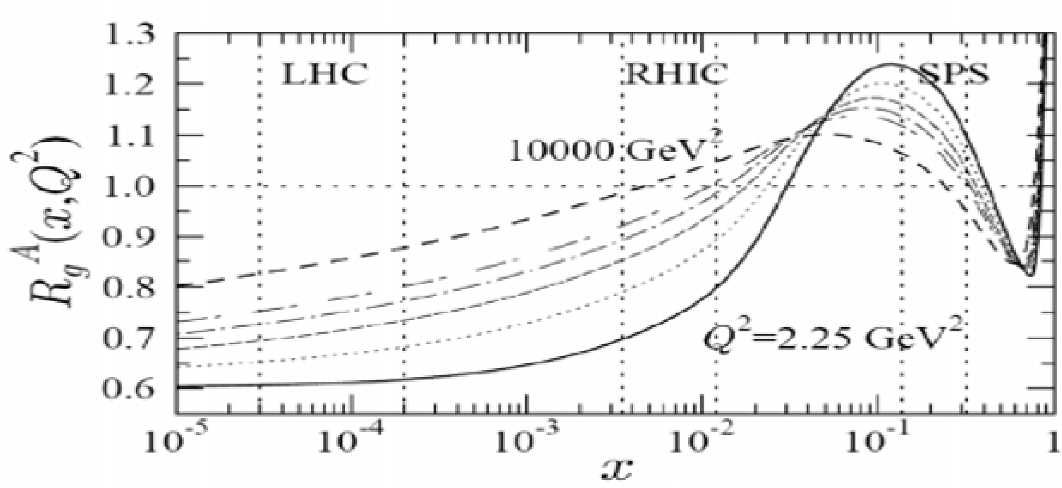

Figure 1: The variation of the ratio between the gluon PDF inside nucleus and proton with the Bjorken-x.

3.5 Important variables

centrality

Nucleus is an extended object, so the volume of the interacting region when two nuclei collide depends on the impact parameter b. In heavy-ion physics this impact parameter is studied by the so called centrality. A collision is said to be central when $b = 0$ and peripheral when b is maximum. Usually the centrality is studied class by class, and not with single values.
In the same context we can define the overlap function $< T_{NN} >$ by the area for which the two nuclei can interact.

The yield

In fact to quantify the suppression of a given quarkonium state $Q\bar{Q}$ we do not use directly their number $N_{Q\bar{Q}}$. Instead we use its yield because it is corrected for the detector biases, in order to compare fairly between suppressions. The yield is defined by:

$$Y^i_{Q\bar{Q}} = \frac{N_{Q\bar{Q}}}{BR_{Q\bar{Q}\to l^+l^-} N^i_{event} A \times \epsilon^i} \tag{1}$$

where the index i refers to the centrality class. $BR_{Q\to l^+l^-}$ is the branching ratio for a given leptonic channel ($\mu^+\mu^-$ or e^+e^-), N^i_{event} is the total number of events in this centrality class, and $A \times \epsilon^i$ is the product of the detector acceptance and its efficiency in this centrality class. The last product is obtained from a Monte-Carlo simulation.

The nuclear modification factor

The suppression for a given quarkonium state $Q\bar{Q}$ is quantitatively studied by this factor. This factor combines information from the Pb-Pb or the p-Pb collisions where suppression is expected to take place, and pp collisions. In other words, it expresses the suppression in the (Pb-Pb or p-Pb) collisions with respect to the pp ones. This factor is given by:

$$R^i_{AB}(\Delta_{p_T}, \Delta_y) = \frac{Y^i_{Q\bar{Q}}(\Delta_{p_T}, \Delta_y)}{< T^i_{AB} > \sigma^{pp}(\Delta_{p_T}, \Delta_y)} \tag{2}$$

where σ^{pp} is the pp cross section, it must be determined in the same transverse momentum and rapidity ranges as Y^i_Q. A and B can be p or Pb.

4 My internship

In this internship we will focus on the J/ψ production. The goal is to determine its cross section in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Reconstruction of the J/ψ invariant mass spectrum in the dimuon channel and extraction of the number of the J/ψ with the evaluation of its systematic uncertainty will be the main part of this internship.
From the calculation of this cross section, we will try to evaluate the production cross section of double J/ψ and search for the signal in data. Production of double J/ψ is a new topic in the sense that nobody in ALICE has studied it.
The first two weeks of my internship were important to build a base in heavy-ion physics from various relevant articles, before starting the work with the data analysis using the AliRoot framework. Being familiar with such analysis and adapting with the work in large international collaboration are the main goals of this internship.

The first part in the discussion bellow will center on the content of an article [10] which is very close to my internship subject. This article is entitled by "J/ψ production and nuclear effects in p-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV". The determination of the J/ψ production cross section at $\sqrt{s_{NN}} = 5.02$ TeV, and the corresponding nuclear modification factor $R_{\text{p-Pb}}$ using the ALICE detector are presented.
J/ψ are studied through the dimuon channel which is covered by the forward rapidity ranges $2.03 < y_{cm} < 3.53$ and $-4.46 < y_{cm} < -2.96$, where y_{cm} is the center of mass rapidity.
In order to discuss the results of this article and understand some ideas in it, other papers are presented.

4.1 The interest of p-Pb collisions study

Pb-Pb collisions can achieve the conditions to create the QGP phase. This phase of matter is associated with the suppression of the quarkonium yields. In Pb-Pb collisions the quarkonium production can be influenced by the presence of the nuclear cold matter. These effects are the same as in p-Pb collisions. So studying both p-Pb and Pb-Pb collisions gives us access to disentangle between the effects of the QGP and the presence of the nuclear cold matter on the quarkonium suppression.
In ALICE Pb-Pb collisions were studied before the p-Pb ones. The results concerning the cross section and the nuclear modification factor have been published in [9] (where IPN team played an important role).
In Pb-Pb collisions, the center of mass energy was $\sqrt{s_{\rm NN}} = 2.76\,\mathrm{TeV}$, and also the rapidity range was different than the one studied in p-Pb. But the fact that the Bjorken-x regions probed by the two processes are only shifted by 10% allow us to compare the p-Pb and the Pb-Pb results.

4.2 The results

In addition to the muon spectrometer described above. The two innermost layers of the inner tracking system (SPD), which is responsible to the interaction vertex determination, and two arrays of 32 scintillator (VZERO-A and VZERO-C) are used in this analysis.
The detection of the J/ψ has been done in the dimuon channel, choosing as candidates muons pairs with opposite sign having $p_{\rm T} > 0.5\,\mathrm{GeV}/c$ per muon. Because the energy asymmetry for the p and Pb, they have studied two possible configurations. The first one was symbolized by p-Pb, it covers the rapidity range $2.03 < y_{cm} < 3.53$ and represents the cases when the proton travels towards the spectrometer. The opposite case which is symbolized by Pb-p and covers the rapidity domain $-4.46 < y_{cm} < -2.96$.
Figure 2 shows the dimuon invariant mass distributions. From these plots the number of J/ψ is extracted thanks to the following fit functions:
For the background (the blue continuum) a variable width Gaussian

$$f(x) = N.exp(\frac{-(x-\alpha)^2}{2\sigma^2}), \text{where } \sigma = \beta + \gamma(\frac{x-\alpha}{\alpha}) \quad (3)$$

has been chosen. For the resonance, an extended Crystal Ball function was used for fit. This function is defined [4] as:

$$f(x;\bar{x},\sigma,\alpha,n,\alpha',n') = \begin{cases} N.\exp\left(\frac{-(x-\bar{x})^2}{2\sigma^2}\right) & \text{for } \alpha' > \frac{x-\bar{x}}{\sigma} > -\alpha \\ N.A.(B - \frac{x-\bar{x}}{\sigma})^{-n} & \text{for } \frac{x-\bar{x}}{\sigma} \leq -\alpha \\ N.C.(D + \frac{x-\bar{x}}{\sigma})^{-n'} & \text{for } \frac{x-\bar{x}}{\sigma} \geq \alpha' \end{cases}$$

where (A,B) and (C,D) depend respectively on (n,α) and (n',α').

This procedure results in a J/ψ mass mean value which coincides with the PDG value within 0.1%, and the following J/ψ numbers:

$$N^{J/\psi}_{\text{p-Pb}} = (6.69 \pm 0.05(stat) \pm 0.08(sys)).10^4 \quad (4)$$

$$N^{J/\psi}_{\text{Pb-p}} = (5.67 \pm 0.05(stat) \pm 0.07(sys)).10^4 \quad (5)$$

These numbers were corrected by the corresponding $A \times \epsilon$ which are determined by a Monte-Carlo simulation to be (25.4± 1.3)% and (17.1± 1.2)% for $(A \times \epsilon)_{\text{p-Pb}}$ and $(A \times \epsilon)_{\text{Pb-p}}$ respectively. Then $N^{cor}_{J/\psi} = \frac{N_{J/\psi}}{A\times\epsilon}$. Finally the inclusive J/ψ production cross section is given by:

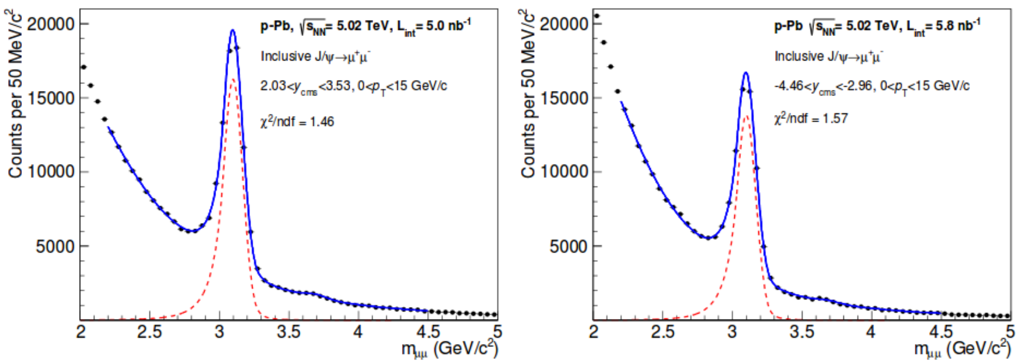

Figure 2: The dimuon invariant mass for the two configurations

$$\sigma^{J/\psi}_{\text{p-Pb}} = \frac{N^{cor}_{J/\psi}}{BR_{J/\psi\rightarrow\mu^+\mu^-}} \frac{\sigma^{MB}_{\text{p-Pb}}}{N_{MB}} \tag{6}$$

The MB index in the last ratio refers to (Minimum Bias event). Such an event is selected if signals are simultaneously detected in VZERO-A and VZERO-C. The ratio itself represents the integrated luminosity.
In the internship we will access to the data used in this article and try to determine the cross sections.

Nuclear modification factor

In the expression of the nuclear modification factor (equation 2), the p-Pb yield and the pp cross section must be taken in the same (p_T,y) domain, as well as at the same center of mass energy. But pp data are not available at $\sqrt{s} = 5.02$ TeV as it is shown in Table 1. The method to solve this problem is the so called interpolation procedure.
The interpolation procedure corresponding to this case is explained in details in [12] as a common work of ALICE and LHCb. The goal of this procedure is to find if possible, a mathematical relation between the pp cross section σ_{pp} and $\sqrt{s}$. Then extract σ_{pp}(5.02 TeV) knowing σ_{pp}(7 TeV) and σ_{pp}(2.76 TeV) which are available. For that three shapes were proposed:

$$\sigma(\sqrt{s}) = \begin{cases} P_0 + P_1\sqrt{s} & \text{linear} \\ (\sqrt{s}/P_0)^{P_1} & \text{power law} \\ P_0(1 - exp(-\sqrt{s}/P_1)) & \text{exponential} \end{cases}$$

First of all, values for σ_{pp} at the three center of mass energies are determined using theoretical models based on NLO calculations. These results are then normalized in such a way that for all the predictions σ_{pp}(5.02 TeV) take the same value. This fixed value is then compared to the interpolated one using the above shapes.
The closest interpolated cross section was the one corresponds to the power law parametrization, however the variance for the three shapes is determined.
After checking the validity of using these parameterizations, the interpolated cross section at $\sqrt{s} = 5.02$ TeV is given by the average of the results obtained using the three parameterizations. This average is weighted to the inverse of the obtained variance for each model.

Results to model matching

Matching between the results of $R_{\text{p-Pb}}$ and the possible theoretical models is the last part of this article. To reduce the uncertainty it is better to work with the ratio between forward and backward nuclear modification factors $R_{FB} = R_{\text{p-Pb}}/R_{\text{Pb-p}}$ to get rid of σ_{pp}.
There are four proposed models:

- A model based on NLO calculation taking into account only the shadowing effects.
- A model include shadowing effects aside with a contribution from coherent parton energy loss.
- A model which is only taking coherent parton energy loss into account.
- A model based on a calculation in the CGC (Color-Glass condensate: an effective theory that describes the nucleus as a dense partonic system) framework.

Figure.3 compares various predicted R_{FB} to the measured one. Prediction using the last model is not included since it is not predictive for backward rapidity. By the way it overestimates $RpPb$.
Once we find some models that well describe the results, we can use them in Pb-Pb collisions to get rid of the non QGP suppression effects.
In [9] the Pb-Pb nuclear modification factor is determined to be $R_{\text{Pb-Pb}} = 0.57 \pm 0.01(stat) \pm 0.09(sys)$. Assuming that shadowing is the only nuclear effect (which is not a wrong hypothesis referring to Figure.3), we can write as a first approximation:

$$R^{CNM}_{\text{Pb-Pb}} = R_{\text{p-Pb}}.R_{\text{Pb-p}} \tag{7}$$

This relation arises from the factorizability of the shadowing effect, and give $R^{CNM}_{\text{Pb-Pb}} = 0.75 \pm 0.10 \pm 0.12$. The difference between this value and the measured one tell us that nuclear effect cannot be considered alone.

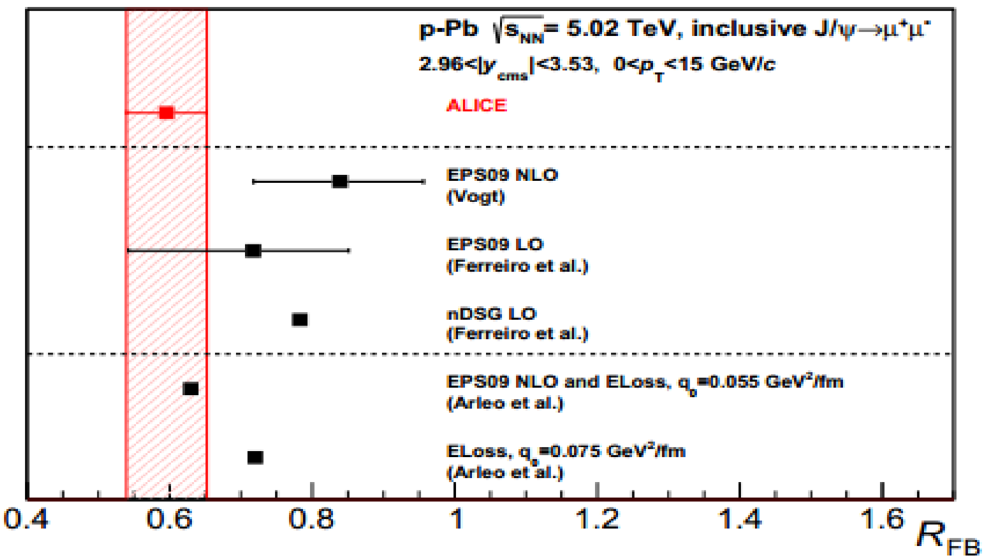

Figure 3: Measured R_{FB} in p-Pb collisions, compared to the predictions of various models.

4.3 J/ψ double production

Goals

The idea behind the search for a double production of a heavy quarkonium is to better understand the quarkonium production mechanism.
Indeed the hard process described above can be theoretically studied in non relativistic QCD by the contributions of two models, the color singlet (CS) and the color octet (CO) models. On the other hand the quarkonium double production process depends strongly on the production mechanism and experimental data of such productions would help in the modeling of this mechanism.

Double J/ψ production processes

In pp collisions J/ψ pairs can be produced:

- From a single parton scattering dominated at LHC by: $gg \rightarrow J/\psi J/\psi$.
- From a double partons scattering (DPS) which is the case when two J/ψ are produced independently by two hard processes. The cross section of the DPS is given [13] by:

$$\sigma^{DPS}_{J/\psi J/\psi} = \frac{1}{2}\frac{\sigma_{J/\psi}.\sigma_{J/\psi}}{\sigma_{eff,pp}} \tag{8}$$

  where $\sigma_{J/\psi}$ is the single J/ψ production cross section, and $\sigma_{eff,pp}$ is an effective quantity represents the two protons overlap function.

In the first case the two produced J/ψ are angularly correlated due to momentum conservation, while in the second case they are not.
In p-Pb and Pb-Pb collisions this formula for σ^{DPS} is the same, but with modifying σ_{eff} to take into account all the possibles overlap configurations. Due to these modifications, numerically [13] $\sigma_{eff,\mathrm{pp}}$ is expected to be larger than $\sigma_{eff,\mathrm{Pb\text{-}Pb}}$ by a factor of $9 \cdot 10^6$.

Double J/ψ observation

The first and the only observation before the LHC era of a double J/ψ production was by the NA3 collaboration, in pion-platinum and proton-platinum interactions. The pions and the protons momenta were respectively 280 GeV/c and 400 GeV/c. At this energy range the charmonium production is dominated by the quark-antiquark annihilation.
At the LHC, in 2010 LHCb observed double J/ψ production in pp collisions at the center of mass energy of 7 TeV with the cross section [14]

$$\sigma_{J/\psi J/\psi} = 5.1 \pm 1.0(stat) \pm 1.1(sys)nb. \tag{9}$$

Also in LHCb they have observed the different charm hadrons double production. The results are summarized in [15]. These observations at LHCb represent a motivation for ALICE to search for such productions, in Pb-Pb collisions.

5 Conclusion

Heavy-ion physics is still an open field. A lot of work in the different subjects must be done. Of course ALICE is the leader in this domain. Find better theoretical models to describe the cold nuclear matter effects in the quarkonium suppression, improve the interpolation procedures, and compute the double J/ψ production are some of the next challenges for the ALICE collaboration in order to

achieve their goals in the understanding of the confinement mechanism and the quarkonia production.
However, ALICE like the other LHC experiments, is waiting for the next LHC run. With this run at higher energy, smaller Bjorken-x regions will be probed and so a better understanding for the different processes is expected.

Concerning the internship, achieving the above goals will be a good entrance to the LHC data analysis, and to heavy-ion physics. So far on the theoretical level I observe a significant progress. Even though it is only my second week, working with this team increases my motivation to obtain the thesis with them, which coincides with the LHC second run.

References

[1] K. Aamodt *et al.* (ALICE Collaboration), "The ALICE experiment at the CERN LHC," JINST **3**, S08002 (2008).

[2] "IPN ALICE web page," `http://ipnweb.in2p3.fr/~alice/`.

[3] L. Bianchi, *J/ψ polarization in pp collisions at $\sqrt{s}$ = 7 TeV with the ALICE muon spectrometer at the LHC*, Ph.D. thesis, Turin U. Torino / Paris, Universita' di Torino Universite Paris Sud-11 (2012), presented 06 Mar 2012.

[4] L. Valencia Palomo, *Inclusive J/ψ Production Measurement In Pb-Pb Collisions at $\sqrt{s}$ = 7 TeV With The ALICE Muon Spectrometer*, Ph.D. thesis, Paris,Universite Paris Sud-11 (2013), presented 06 Sep 2013.

[5] E. Abbas *et al.* (ALICE Collaboration), "J/Psi Elliptic Flow in Pb-Pb Collisions at sqrt(sNN) = 2.76 TeV," Phys.Rev.Lett. **111**, 162301 (2013), arXiv:1303.5880 [nucl-ex] .

[6] B. Abelev *et al.* (ALICE Collaboration), "D meson elliptic flow in non-central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$TeV," Phys.Rev.Lett. **111**, 102301 (2013), arXiv:1305.2707 [nucl-ex] .

[7] B. Abelev *et al.*, "Coherent photoproduction in ultra-peripheral pbpb collisions at," Physics Letters B **718**, 1273 (2013).

[8] K. Aamodt *et al.*, "Rapidity and transverse momentum dependence of inclusive production in pp collisions at," Physics Letters B **704**, 442 (2011).

[9] B. Abelev *et al.* (ALICE Collaboration), "J/ψ suppression at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV," Phys.Rev.Lett. **109**, 072301 (2012), arXiv:1202.1383 [hep-ex] .

[10] B. B. Abelev *et al.* (ALICE Collaboration), "J/ψ production and nuclear effects in p-Pb collisions at $\sqrt{S_{NN}}$ = 5.02 TeV," JHEP **1402**, 073 (2014), arXiv:1308.6726 [nucl-ex] .

[11] N. Brambilla, S. Eidelman, B. Heltsley, R. Vogt, G. Bodwin, *et al.*, "Heavy quarkonium: progress, puzzles, and opportunities," Eur.Phys.J. **C71**, 1534 (2011), arXiv:1010.5827 [hep-ph] .

[12] "Reference pp cross-sections for J/ψ studies in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV and comparisons between ALICE and LHCb results," (2013), cONF-2013-013.

[13] D. d'Enterria and A. M. Snigirev, "Double-parton scattering cross sections in proton-nucleus and nucleus-nucleus collisions at the LHC," (2014), arXiv:1403.2335 [hep-ph] .

[14] R. Aaij *et al.* (LHCb Collaboration), "Observation of J/ψ pair production in pp collisions at $\sqrt{s} = 7TeV$," Phys.Lett. **B707**, 52 (2012), arXiv:1109.0963 [hep-ex] .

[15] R. Aaij *et al.* (LHCb Collaboration), "Observation of double charm production involving open charm in pp collisions at $\sqrt{s}$ = 7 TeV," JHEP **1206**, 141 (2012), arXiv:1205.0975 [hep-ex] .