Production of J/Ψ Meson as a Function of Event Activity: A Study with the PYTHIA 8 Event Generator

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Abstract

Experiments at the Large Hadron Collider (LHC) have recently begun to explore the production of heavy quarkonium as a function of activity in the underlying event. The ALICE collaboraiton has measured an increase in the production of the J/Ψ with increasing event activity. The data was compared to calculations using the PYTHIA 6.4 event generator, which shows the opposite trend. The purpose of this paper is to study the production of J/Ψ as a function of event activity using a new and improved version of PYTHIA: PYTHIA8. This version includes a physics model of Multi Parton Interactions. We present a study of PYTHIA8 via Monte Carlo simulations where we look at the production of the J/Ψ meson as a function of event activity. We find that PYTHIA8 has a better qualitative description of the observed data, but we also observe quantitative discrepancies for those events with the highest activity.

1 Introduction

The J/Ψ particle is a type of meson consisting of a charmed quark and a charmed anti quark. It has a mass of about 3.096916 GeV/c^2, the proton's mass is about 0.938272081 GeV/c^2 which makes the J/ψ three times more massive. It was independently discover by two separate American groups in 1974. Samuel C.C. Ting was credited for finding what he called the J particle. The same particle named Ψ was found at the same time at the Stanford Linear Accelerator Center by a group led by Burton Richter. The particle is now known as the J/Ψ. In 1976, the discovery led to a shared Nobel Prize in physics by both teams for confirming the existence of such particle [3]. Today, this discovery remains of immense importance in the realm of high energy physics.

The motivation behind studying high-energy nuclear physics is to confirm the predictions of quantum chromodynamics (QCD): which says that in a volume of hot and dense matter the quarks and gluon will become deconfined. Deconfinement occurs during a high energy collision that causes the melting of a nucleus into its constituent quarks and gluons. This phase transition from confined matter to deconfined matter is also called the formation of quark gluon plasma (QGP). It is predicted that the early universe was in a state of deconfinement prior to the Big Bang; this makes the study of QGP important in the understanding of our infant universe.

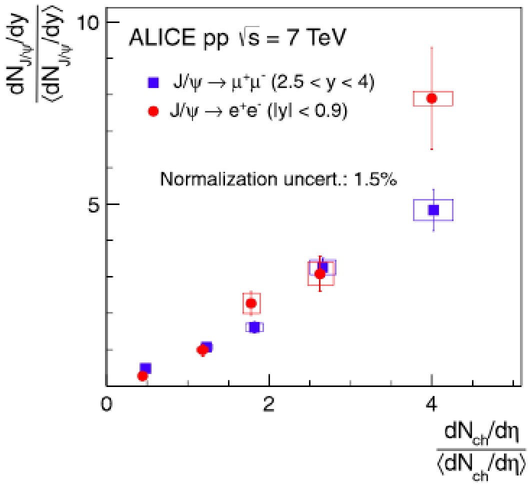
The most promising environment for the formation of QGP is a nucleus collision. In order to reach the high energy domain that is necessary and sufficient for the formation of QGP we need to collide heavy ions. For the sake of simplicity one can think of a heavy ion as a big chunk of matter made out of protons and neutrons, like gold (Au) and lead (Pb). The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator. The LHC consists of a 27-kilometer ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way [1]. The environment for the formation of QGP is set up perfectly by smashing heavy ions at tremendous amounts of high energy. In order to fully understand the formation of QGP one needs to have a more profound and solid understanding of how a proton-proton (pp) collision works. Why are pp collisions important? as opposed to n-n or p-n?

A big advantage in studying a proton-proton collision is that we can treat a heavy ion as a superposition of protons and neutrons. In actual collisions the main actors are the individual protons that collide with one another. However, we know that protons are not elementary particles, but they are made up of even smaller particles: quarks and gluons. A proton or a neutron is made up of three quarks, which are glued together by the strong nuclear force. Thus protons and neutrons are examples of hadrons, particles that are made from quarks, anti-quarks and gluons.Due to the composite nature of hadrons, it is possible to have multiple parton interactions, in events in which two or more distinct hard parton interactions occur simultaneously in a single hadron-hadron collision [2]. As a result of Multi-Parton Interactions (MPI), we can draw a correlation between the events in a collision and the number of particles formed. The underlying idea behind this project is to understand how MPI lead to an increase in the production of the J/Ψ meson. This was predicted by the ALICE collaboration and will be tested by the PYTHIA 8 event generator.

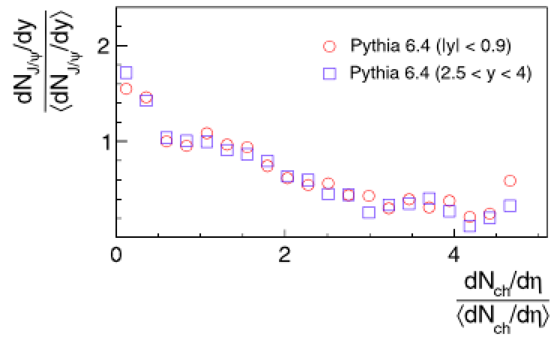
2 Background

Event activity refers to the number of particles and energy produced in a given region in the detector. A detected charge particle in a region in the detector is referred to as a track. Higher activity gives us more charmonium , which in our case raises the probability of the J/Ψ to be measured. The J/Ψ is detected via electron/positron and muon/antimuon decay.

ALICE (A large Ion Collider Experiment) is the detector part of the LHC ring that is primarily used to study the formation of the quark gluon plasma. In 2012 the ALICE collaboration published an article reporting the production of the J/Ψ as a function of charged particle multiplicity in a pp collision at 7 TeV. The J/Ψ particles are detected for a transverse momentum (pT) > 0 in the y < 0.9 rapidity interval via e^+e^- decay and in the $2.5 < y < 4.0$ via $\mu^+\mu^-$ decay. The collaboration did confirm a linear increase in the production of the J/Ψ as a function of event activity (figure 1).



(a) J/ψ production at ALICE in two channels, as a function of event activity



(b) J/ψ production reported by PYTHIA 6, as a function of event activity

Figure 1: ALICE AND PYTHIA 6 reports on J/ψ

The PYTHIA program is a standard tool for the generation of high-energy collisions. Versions of PYTHIA include: PYTHIA 6.4 written in Fortran and the most current version is PYTHIA 8, which is written in C++. The experiment conducted at ALICE was evaluated using the PYTHIA 6.4 event generator (figure 3). The conclusion drawn by PYTHIA 6.4 is that as a function of event activity there is no correlation in the expectation of finding a J/Ψ (figure 1)." It exhibits a decrease of the J/Ψ multiplicity with respect to the event multiplicity, which indicates that hard J/Ψ production, as modeled by PYTHIA 6.4.25, is not accompanied by an increase of the total hadronic activity.Further studies with other models such as PYTHIA 8 and Cascade are needed ". A great emphasis is placed in the validity of the PYTHIA 8.

However, the ALICE collaboration argues that the increase in the production of the J/Ψ as a function of event multiplicity, is due to MPI." If the effect of MPI extends into the regime of hard processes, also the J/Ψ yield should scale with the number of partonic collisions and the observed correlation will result".My goal for this project is to model the production of the J/Ψ with a newer and "improved" version of PYTHIA and to compare it with the ALICE results.

3 Methodology

The backbone of understanding this project is knowing how the J/Ψ yields were extracted using the PYTHIA 8 event generator. I intend in this section to provide the reader with two basic concepts used in high energy collisions and hopefully this will facilitate the understanding behind the kinematic cuts applied by ALICE. I will not however, give an intensive explanation behind the algorithms used for this simulation for reasons that will become clearer and fully addressed in the analysis section.

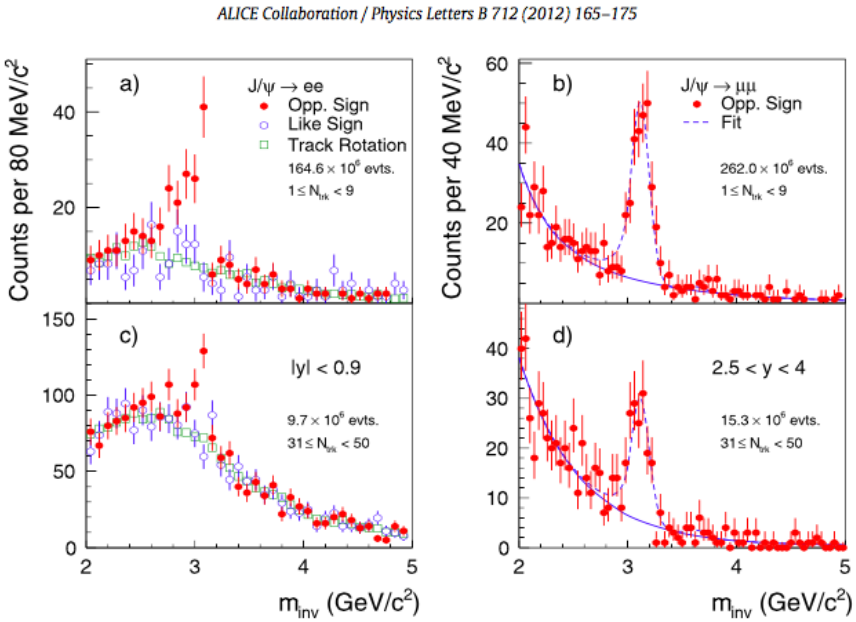


Figure 2: Invariant Mass Plot as reported by ALICE ,a clear peak at about $3.1GeV/c^2$ is observed which indicates the presence of a J/Ψ

3.1 Kinematics

All the PYTHIA simulations were made by generating millions of proton-proton collisions at 7 TeV. The requirements were that each collision would reproduce a J/Ψ decaying exclusively into electrons/positrons and muons in each of their appropriate rapidity regions. One can think of rapidity as a generalization of velocity that is invariant under a Lorentz Transformation.

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

The problem with rapidity is that, it is incredibly hard to measure given that you need both the energy and total momentum. Instead,we use a simpler version of rapidity label as (η), called the pseudo-rapidity which is the same as rapidity for relativistic particles.

$$\eta = -\ln[\tan(\frac{\theta}{2})] \tag{2}$$

From now on I will refer to rapidity and pseudo rapidity interchangeably and use them to give some insight into the detection of the J/Ψ. The ALICE collaboration reported that the J/Ψ is detected via electron decay at mid-rapidity y < 0.9 in the di-electron chamber (which can thought of as a certain region in the detector). The muons are detected for rapidity $2.5 < y < 4.0$ which is a different region of the detector. The J/Ψ trajectory can be reconstructed by the invariant mass plot formed by the decaying daughters in each of their appropriate rapidity regions (figure 2)

3.2 Minimum Biased

Using the PYTHIA environment enabled me to write my code by first running millions pp collision at 7 TeV by accepting all the charged particles produced. Counting all the particles allowed me to get a mean average of all the charged particles that were generated; I used this to determine the event activity which I will be referring to as a Minimum Biased. The next part consisted of running the same pp collision at 7 TeV, but this time forcing the production of a J/Ψ via electron and muon decay, which are the daughters of the J/Ψ. The J/Ψ yield was then reconstructed by applying the appropriate kinematics cuts on the daughters. Since all charged particles were previously accounted for, I simply isolated the daughters by removing them from the counter. This was accomplished by applying the appropriate kinematics cut: y $<$ .9 for electrons/positrons and $2.5 < y < 4.0$ for muon/dimuons. By mutually excluding the daughters,I constructed an average J/Ψ in the rapidity range, which will serve as my y-axis.

4 Data and Analysis

All the analysis done in this experiment was constructed using PYTHIA with all the plots generated in ROOT [8]. In this section I present all my plots and my full analysis using the newer and improved version (PYTHIA 8) with all the computational details as stated in section 3.

4.1 PYTHIA 6.4 Results

The conclusions drawn by PYTHIA 6.4, based on the ALICE experiment, showed an anti correlation between activity and the production of the J/Ψ. It promulgated that overall production of the J/Ψ seems to not be influenced by MPI and are independent of the overall event multiplicity (figure 1). The ALICE collaboration measured an opposite trend, showing a positive correlation between the production of J/Ψ at mid rapidity and forward rapidity (figure 2) with respect to track multiplicity.

4.2 PYTHIA 8 Result

These new plots presented above were constructed using PYTHIA 8. The X-axis() represents the normalized track multiplicity obtained from the minimum biased. The Y-axis() references the yield of the J/Ψ obtained from extracting the mean average of the J/Ψ produced. Our main interest is whether or not the yield of the J/Ψ better matches the data given by ALICE. As you can see, both plots (figures 4 and 5) do exhibit some sort of improvement and are in better agreement with ALICE, contrast to what the older version (PYTHIA 6.4) reported. However, as the number of tracks increases,the correlation becomes less pronounced.

These quantitative discrepancies brought into question the validity of the code written and motivated me to seek additional help. As a check on my code, a colleague working on an identical project used an independently written simulation with the same kinematic cuts. The two codes gave the same results (see figure 5).

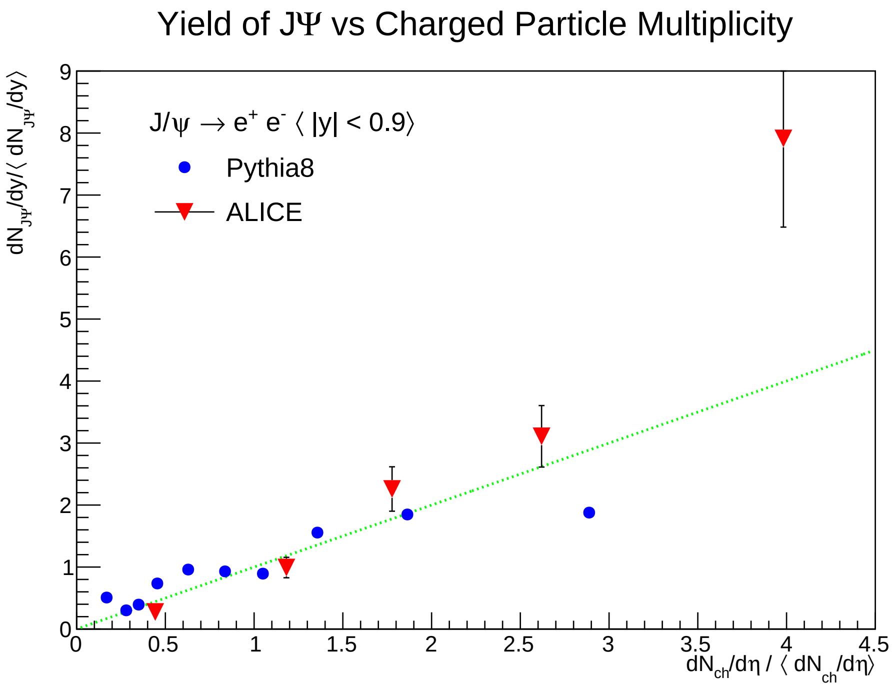


Figure 3: J/Ψ yield as a function of charged particle multiplicity measured via ($J/\Psi \rightarrow$ e+,e- for y $<$ 0.9) at mid rapidity. The X-axis is the normalized reference multiplicity (with respect to the minimum bias pp collisions). The Y-axis is the normalized J/Ψ yield

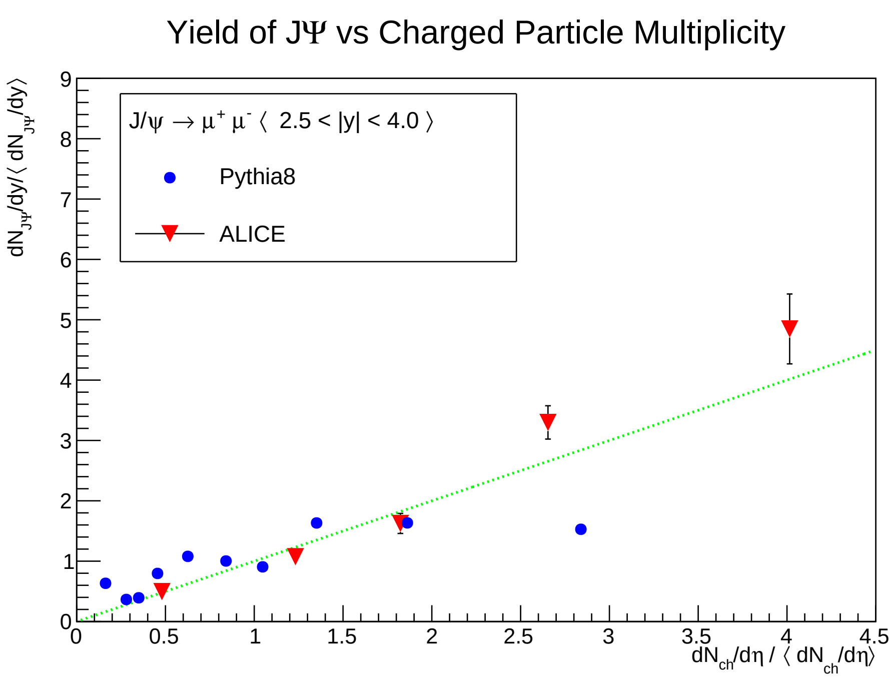


Figure 4: J/Ψ yield as a function of charged particle multiplicity measured via ($J/\Psi \rightarrow$ u+, u- for 2.5 $<$ 4.0) at forward rapidity. The X-axis is the normalized reference multiplicity (with respect to the minimum bias pp collisions).The Y-axis is the normalized J/Ψ yield

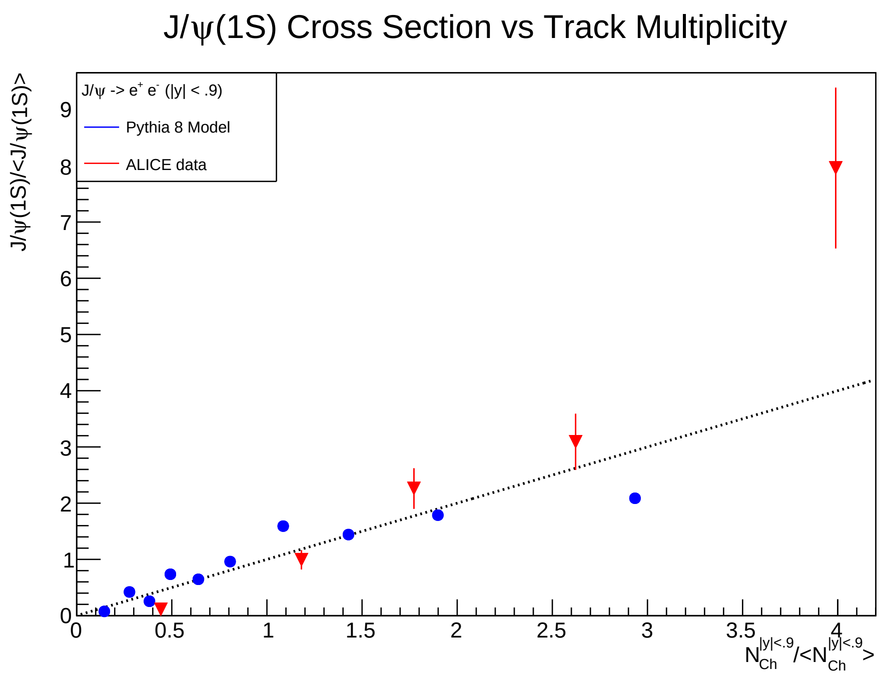


Figure 5: Plot by Alex Dorsett which looks identical to the ones from figure (6 and 7). The Y-axis() is the normalized J/ψ yield and the X-axis() corresponds to the normalized event track multiplicity. Both plots exhibit a much stronger correlation with ALICE data at more central activity bins.

4.3 Yield of $\Upsilon(1S)$ at CMS

In the following section I plan to diverge from the ALICE collaboration and the J/Ψ, to an experiment conducted at CMS (COMPACT MUON SOLENOID) in looking at the production of Υ as a function of event activity. The drive behind studying the Υ is to further confirm the validity of the PYTHIA 8 event generator. The different excited states of the $\Upsilon(nS)$ seem to become suppressed and melt at sufficiently high temperatures. As a result, the study of the Υ can potentially gives us more insight on the formation of QGP [8].

The CMS collaboration investigated the production of the $\Upsilon(nS)$ states in pPb (proton-lead) and pp collisions at the center of mass energies per nucleon of 5.02 and 2.76 TeV respectively. The Υ is measured via $\mu^+\mu^-$ decay at rapidity at ycm < 1.93. CMS measured the yield of the $\Upsilon(nS)$ as a function of event activity by measuring track particle multiplicity at pseudo-rapidity $\eta < 2.4$ and the sum of transverse energy deposited at forward rapidity $4.0 < \eta < 5.2$.

The $\Upsilon(1S)$ excited state was studied using the PYTHIA 8 event generator and by re-using the code already built in the J/Ψ project. Millions of events were generated in a pp collision at 2.76 TeV. The computational process was similar to that of the J/Ψ, first running a minimum biased and accounting for all charged particles for $\eta <$ 2.4. Tallying all charged particles allowed me to construct the mean number of tracks. The process was then repeated, this time by forcing PYTHIA to produce Υ via making

$\mu^+\mu^-$ decay and applying the rapidity cut (y < 1.93) on the muon pair. The $\Upsilon(1S)$ yield was then calculated by omitting the muons from the charge particle counter and normalizing it by the mean found in the minimum biased calculation (refer to section 3).

The result of this calculation can be summarized in (figure 8). The X-axis() represents the normalized event track multiplicity for $\eta < 2.4$. The Y-axis() is the normalized $\Upsilon(1S)$ yield. These data give us a much stronger agreement with what was expected and observed by CMS. This is additional evidence for the validity of the original J/ψ code since the computational process was almost identical to that used in the Upsilon calculation. Perfect agreement with data using PYTHIA 8 at this point has become a more elusive task.

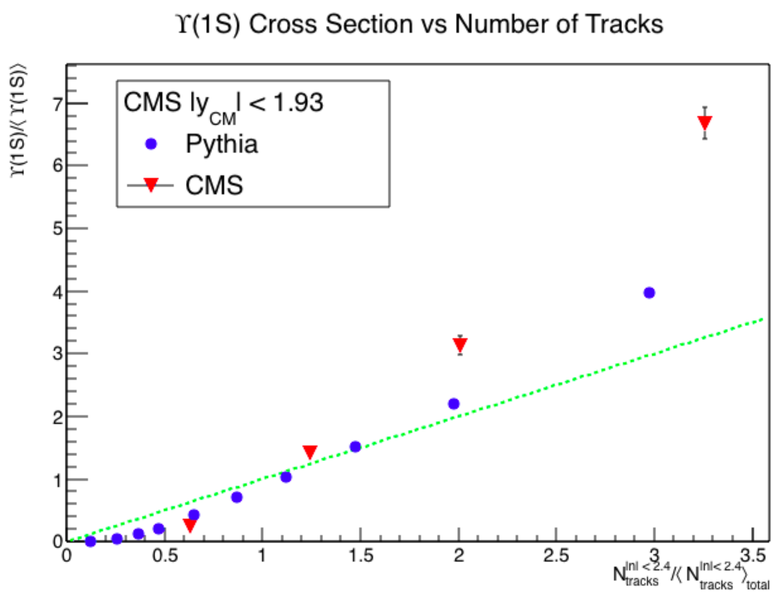


Figure 6: Upsilons

5 Conclusion

In summary the production of the J/Ψ meson was studied as a function of event activity using the PYTHIA 8 event generator. The ALICE collaboration measured a linear increase in the production of J/Ψ as a function of event activity (see figure 3). PYTHIA 6.4 showed an anti correlation to the results measured by ALICE (see figure 4). Kinematics cuts were applied and code was written to challenge the results reported by PYTHIA 6.4 (figures 6 and 7). Both data sets presumably agreed with ALICE. At events with highest activity, there seems to descrepancies which questioned the validity of the code written for the simulation. To address this issue, new code was written with the same kinematics cuts as the previous and both plots were compared (see figure 6). The conclusion drawn was that the code didn't seem to be problematic since both plots exhibit the same behavior. Rather, this gives rise to the fact that even though PYTHIA 8 seems to be in better agreement with both ALICE and CMS, it could still be improved.

6 Acknowledgments

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