Analysis of Υ-hadron Correlations in pp Collisions with PYTHIA

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Abstract

Measurements of the Υ meson in both heavy-ion (AA) and proton-proton (pp) collisions at CMS allow for study of the correlation between Υ production and activity in the rest of the collision event. One correlation to study is the angular location of the other particles in the collision relative to the produced Υ. More specifically, the azimuthal correlation between all the hadrons and the produced Υ in a collision. Studying such a correlation can help in understanding the production mechanism of the Υ more precisely. In this study, we will simulate pp collisions using the PYTHIA event generator, and find the angular correlation produced by the simulation. We will then compare these results to those measured in pp collisions at CMS (beam energy of 7 TeV in 2011). Also, this analysis will be done using the new heavy ion data set recently taken at CMS (5 TeV in November 2015). This will require the use of CMS analysis software in order to find the angular correlation directly from the data (results from 2011 had already been produced). Comparing the PYTHIA results to these data at two different energies will gauge the accuracy of the current model in describing the behavior of the Υ meson in pp collisions.

Additionally, data for Υ(1S) production in $\sqrt{s}$ = 2.76 TeV pp collisions from CMS [1] are compared to simulations using PYTHIA. This comparison is performed for both charged-particle multiplicity at mid-rapidity (in the pseudorapidity interval $|\eta| < 2.4$) and the sum of forward transverse energy ($4.0 < |\eta| < 5.2$). For each of these measurements the Υ cross sections–normalized by their event activity integrated values ($\Upsilon(nS)/ < \Upsilon(nS) >$)– are compared to the "activity" measured ($N_{Ch}/ < N_{Ch} >$ for charged-particle multiplicity, ΣE_T/<ΣE_T> for transverse energy). The cross sectional ratio for the Υ is found to increase with larger activity values. There is a stronger correlation found in the measurements of charged-particle multiplicity than transverse energy, most likely due to the detector regions these values are measured in. In order to check for this effect, results are also reported of activity in both track multiplicity and sum of transverse energy measured at mid-rapidity.

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1. Introduction

Studies of collision data taken at the Large Hadron Collider (LHC) have provided the field of particle physics with a much greater understanding of some of the fundamental forces of nature. More specifically, the LHC allows the study of the strong nuclear force. The LHC has several different detectors which collect various types of data on different collision systems. The Compact Muon Solenoid (CMS) is one of these detectors, and is used to study a wide range of particles. One of the particles analyzed at CMS is the Upsilon meson (Υ), which is a bound state between a bottom and anti-bottom quark. When it is produced in a collision, it can decay into two muons (μ^+ and μ^-), which are then measured by the detector. The properties of these muons can then be used to study the properties of the Υ that produced them.

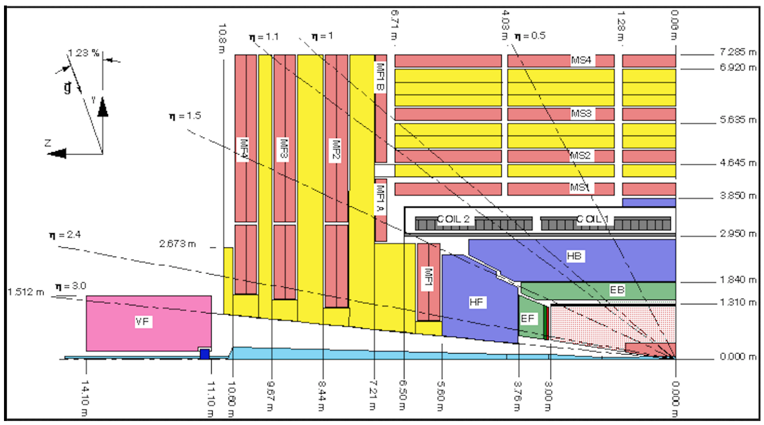

Figure 1: Vertical cross-section of CMS showing one quadrant of the detector. The muon detection system is composed of the barrel detector (MS1-4) and the endcap (MF1-4). These systems provide a pseudorapidity coverage of $|\eta| < 2.4$.

1.1 The CMS Detector

Both of the analyses presented in this thesis involve the coordinate values of pseudorapidity (henceforth written as η). The definition of this variable is relatively straightforward, however, it has interesting properties. Defining the beam pipe as the z axis, and θ as the angle off of this axis (just as in spherical coordinates), then η is defined as:

$$\eta = -\ln(\tan(\theta/2)). \tag{1}$$

Unlike rapidity, η describes the region of the detector in which a particle was measured, rather than it's longitudinal momentum. It is interesting to note, however, that for high energy particles (as $\beta \to 1$), the values of η and rapidity converge. Figure 1 shows the CMS detector regions corresponding to several values of η.

The main feature of the CMS detector is a superconducting solenoid which provides a magnetic field of 3.8 T. Within this solenoid are the silicon pixel and silicon tracker, which measure the trajectories of charged particles within the range $|\eta| < 2.5$. Outside the solenoid field are the muon detectors. The muon detection system can be separated into two parts, the barrel detectors and the endcaps (shown in Fig 1). Around the barrel region of CMS with $|\eta| < 1.2$ there are a series of drift tube chambers and resistive plate chambers. The endcap muon system covering $0.9 < |\eta| < 1.2$ consists of resistive plate chambers as well as cathode strip chambers. With these systems, CMS is able to detect muons within $|\eta| < 2.4$.

1.2 Proton Collisions

Measurements of the Υ in both heavy-ion (AA) and proton-proton (pp) collisions at CMS allow for the study of correlations between Υ production and event variables. One area of particular interest is the correlations between the produced Υ and the other tracks measured in the event. It is important to not only examine the number of tracks, but also their distribution relative to the Υ in the event. Understanding this relationship in elementary pp collisions is important to the understanding of certain phenomena found in collisions involving heavy ions (such as the suppression of Υ(nS) yields relative to pp collision [2]). The pp collisions system offers the ability of study such correlations in a much more direct way, without having to take into account the effects present in larger systems.

1.3 Heavy-Ion Collisions

The heavy-ion collision system behaves quite differently from the proton-proton system. Due to the much larger number of nucleons—208 in the case of Pb—the system begins to exhibit emergent properties. One of these properties can be seen when examining the number of Υ s produced in Pb-Pb collisions as a function of centrality (i.e. how "head-on" the Pb nuclei collided). In this system, it was expected that the Υ yield would scale linearly with the number of nucleon-nucleon collisions. In other words, with no additional effects present, the system would behave like a superposition of many pp collisions. However, it was found that for more central events, the Υs produced relative to pp collisions (scaled by number of binary collisions) was below unity [2]. In fact, this suppressive effect was found to be more pronounced for the higher energy Υ states.

The observation of suppression occurring in heavy-ion collisions supported the existence of a deconfined medium known as the Quark-Gluon Plasma (QGP). In this medium, the quark-antiquark strong force potential responsible for confinement is expected to be screened by partons in the surrounding medium, as predicted by Quantum Chromodynamics [8]. This screening effect would also cause the suppressive effects to be sequential, leading to more decreased yields for higher energy states. The behavior predicted by the QGP model is consistent with that measured in high-centrality heavy-ion collisions.

1.4 PYTHIA Event Generator

In high-energy physics, event generators are an indispensible tool in analyzing collision systems. These computational models are designed to use Monte-Carlo methods, as well as theoretical models, to simulate particle collisions. They allow for the fine-tuning of event parameters to allow the most direct comparison to experimental data to various models. They also give the user the ability to store both event-level and particle-level data from each collision.

The simulation results presented in this thesis were produced using the PYTHIA event generator—specifically, PYTHIA 8.2 [3]. PYTHIA generate the various aspects of collisions with three main classes: ProcessLevel, PartonLevel, and HadronLevel. The user may interact with event generation in three phases: initialization, event-loop generation, and finishing. PYTHIA 8 is useful for the study of the Υ in particular due to its inclusion of color-singlet and -octet charmonium and bottomonium production mechanisms, as well as the addition of Multi-Parton Interactions (MPI) since PYTHIA 6. Though PYTHIA can model several elementary particle collisions, only proton-proton events were generated for this analysis.

2. Research Objectives

2.1 Upsilon Activity Analysis

In a recent paper published by CMS [1], there was a positive correlation found between the event-normalized cross sections of the Υ and both track multiplicity and transverse energy (Fig 2). The track multiplicity was measured in the detector region $|\eta| < 2.4$, the same region in which the Υ was reconstructed. The

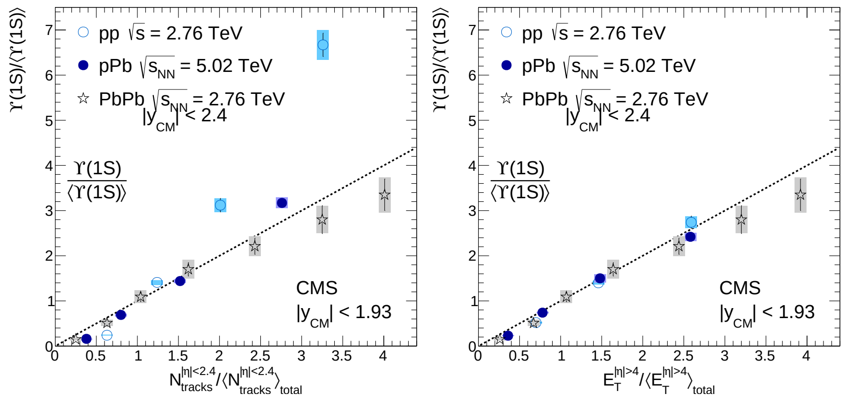

Figure 2: Event data posted by CMS [1] with normalized Υ cross sections vs normalized track multiplicity (left) and forward transverse energy (right). In both of these cases there is an approximately linear correlations between the measured quantities and Υ yield. The line represents a linear function with slope equal to unity.

transverse energy, on the other hand, was measured in the detector range $4 < |\eta| < 5.2$. It would be expected for there to be a stronger correlation for the "activity" measured in the region where the Υ is produced, which is what is seen in the p-p case. The data also shows that, for p-Pb and Pb-Pb collisions, the correlation is not nearly as large as in the p-p case, indicating that nuclear effects are suppressing the Υ(1S) yield. For track multiplicity, both the p-Pb and Pb-Pb systems show an approximate linear increase, while the p-p system deviates from this in the high multiplicity region. In the forward transverse energy data, all three systems show a linear relationship (with slope equal to unity) between the Υ yield and sum of transverse energy.

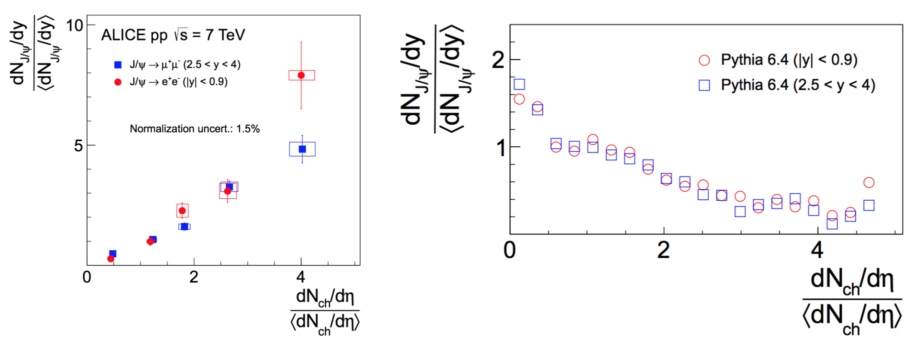

Figure 3: ALICE results for p-p collisions at $\sqrt{s} = 7$ TeV [6]. Data shows a positive correlation between event activity (binned with reference multiplicity) and J/ψ yield through dimuon and electron-positron decay (left). In the study, a PYTHIA 6.4 model was made, and the model shows a negative correlation between event activity and J/ψ yield (right).

Comparisons of simulation results to data on the dependence of quarkonia production on event activity were also done by ALICE [6] for J/ψ production (Fig 3). It was found that PYTHIA 6.4 predicted a negative correlation between event activity (measured in track multiplicity at mid-rapidity) and J/ψ production. This result was contrary to that which was seen in the ALICE data, where a positive correlation between event activity and J/ψ production was measured. This positive correlation between quarkonia production and multiplicity, seen in both CMS [1] (for the Υ) and ALICE (J/ψ) data, suggests that MPIs have a substantial effect on processes involving heavy flavor production for pp collisions.

This thesis will provide the results which PYTHIA 8 produces for these measurements. Both track multiplicity (mid-rapidity) and sum of transverse energy (forward rapidity) results from the simulations will be analyzed, and compared to the corresponding data from CMS. Also, sum of transverse energy will be recorded at mid-rapidity in order to check if the correlations in event activity are due to the quantities being measured or the rapidity region in which they are measured. Though the analysis published by CMS [1] was done for Υ(1S), Υ(2S), and Υ(3S), the results reported here will only be for the 1S state, due to the lack of differences in PYTHIA between the various states. Υ-Hadron Angular Correlations

2.2 Υ-Hadron Angular Correlations

Dihadron correlations have been used to study jets in many collision systems. Jets are formed in high energy collisions when a high-p_T parton is produced–usually through hard scattering. As this parton travels away from the interaction point, it undergoes *hadronization*–the process of quark-antiquark creation from the vacuum. This results in a highly collimated beam of high p_T particles, which will be measured in the detector. Due to conservation of momentum, jets typically are produced in pairs with $\Delta\phi \approx \pi$. Analysis of dihadron correlations can give insight to the properties of the jets in an event.

The method used to study dihadron correlations in jets typically involves selecting high-p_T particles (*trigger particles*) and measuring the $\Delta\phi$ and $\Delta\eta$ for the remaining particles in the event. For this analysis, rather than using p_T, trigger particles will be constructed using opposite-sign dimuons in an event, specifically targeting dimuons within the Υ mass range. With these reconstructed dimuons, the angular correlation between the produced Υ and tracks in an event can be studied.

3. Methods of Analysis

3.1 Upsilon Activity Analysis

3.1.1 Matching of Event Selection Criteria

The CMS data, which the results posted here are compared to, were from two separate regions of the CMS detector. The multiplicity measurements were made at mid-rapidity ($|\eta| < 2.4$), while the transverse energies were measure by the hadron forward calorimeters at forward rapidity ($4 < |\eta| < 5.2$). The pp data corresponds to an integrated luminosity of 5.4 pb^{-1}, with a center of mass energy $\sqrt{s}$ = 2.76 TeV. These datasets were collected in 2013 by the CMS experiment at the LHC.

The PYTHIA events with Υ production are only analyzed if the dimuon decay occurs in the correct detector region. The cuts used were adapted from the CMS paper in which the initial data were posted [1]. Cuts were made in both rapidity ($\mid y_{CM}^{\mu+\mu-} \mid < 1.93$) and transverse momentum ($p_T^{\mu+\mu-} > 4$ GeV). Only events in which these cuts were satisfied were analyzed, in order to keep the results consistent with those that were measured at CMS.

For the track multiplicity measurements, cuts were made in both pseudorapidity ($\mid \eta \mid < 2.4$) and transverse momentum ($p_T > .10$ GeV), as well as requiring the particles to be charged. For each event, all final state particles that satisfied these criteria were counted, and the total number was stored in an ntuple for further analysis. For the events with Υ production, the dimuon pair was not counted in the multiplicity measurement to avoid measuring an autocorrelation. For the calculation of sum of transverse energy, cuts were also made in both in both pseudorapidity ($4 < \mid \eta \mid < 5.2$) and transverse momentum ($p_T > .10$ GeV). The sum of the transverse energy of all of the final state particles that satisfied these criteria was then stored in an ntuple.

Another point of analysis was conducted in order to distinguish the effects of the differing detector regions in which the multiplicity and transverse energy counts were made. Though the CMS detector does not currently have any calorimeters situated at mid-rapidity, transverse energy was also summed in the region $\mid \eta \mid < 2.4$. This was done to see if the correlations found were due to the values being measured (multiplicity and energy), or due to the detector region these values are studied in (mid-rapidity versus forward/backward rapidity). The same cuts that were used in the measures of sum of transverse energy at forward/backward were also used for the mid-rapidity transverse energy sum. Also, for Υ events, the transverse energy of the produced muons was not included in the sum. The resulting points were then compared to those using track multiplicity at mid-rapidity.

3.1.2 Computational Methods

The events from which this analysis is based were generated using PYTHIA 8 [3]. For some of the events, alternate parton distribution functions (PDFs) were used, and were taken from LHAPDF[5] (MRSTMCal Library). Also, the STAR Heavy Flavor Tune was used for some of the events generated. The statistics from these events were then analyzed and plotted with ROOT [4].

In the PYTHIA simulations, minimum bias events were run in order to obtain the activity ranges in both ΣE_T and track multiplicity. These events were ran using the nonDiffractive option under the soft QCD library, and were not confined to any particular particle production. For the Υ(1S) analysis, events were required to produce an Υ through one of four possible mechanisms. The produced Υ's were then confined to decay only into a dimuon pair. Relevant kinematic quantities for the final Υ in the event record–as well as each for the muons that were produced–were stored in an Ntuple for the analysis with ROOT.

In order to obtain a range of uncertainty from the PYTHIA simulation events, the code was run with and without tuning parameters. Events were run using both the default settings and the STAR heavy flavor tune. The main difference between the two settings is the use of alternate parton distribution functions (PDFs) in the heavy flavor tune. The alternated PDF used was from the MRSTMCal library from LHAPDF.

3.1.3 Uncertainty Calculations

The ranges in results from PYTHIA simulation presented here were attained by running the simulation with and without the STAR heavy flavor tune, as well as calculating the statistical uncertainty for these results. For the calculation of the statistical uncertainty of the PYTHIA model, detector efficiencies had to be taken into account. Though poisson and binomial distribution uncertainties are usually used for such calculations, an alternate probability density function (PDF) presented in Ref [12] was used. This PDF was derived using a Bayesian approach which uses the uniform prior that the efficiency must be between zero and one to calculate the efficiency of a measure given that k out of n events were detected (where k is a subset of n total events). The resulting PDF is found to be (for the full derivation, see Ref [12]):

$$P(\varepsilon; k, n) = \frac{(n+1)!}{k!(n-k)!}\varepsilon^k(1-\varepsilon)^{n-k} \tag{2}$$

Further calculation from this result yields the variance in this measurement to be:

$$V(\varepsilon) = \frac{(k+1)}{(n+2)}\frac{(k+2)}{(n+3)} - \frac{(k+1)^2}{(n+2)^2} \tag{3}$$

Given the large number of events run in the PYTHIA simulation (millions), this statistical uncertainty becomes negligible when used to calculate uncertainties in multiplicity and transverse energy measurements.

3.2 Υ-Hadron Angular Correlations

3.2.1 Computational Methods

As with the previous analysis, the simulated events were generated using PYTHIA 8 [3]. Unlike the previous analysis, however, the Υ-Hadron analysis simulations were generated using only default PYTHIA, and did not utilize any alternate parton distribution functions. As before, the data produced by these simulations were analyzed and plotted using ROOT [4].

To be consistent with the data being analyzed, pp events were generated at a center of mass energy of 5.02 TeV. As before, events were required to generate an Υ through one of four possible mechanisms. This Υ was then confined to decay to dimuon pair. The kinematic quantities for the produced Υ–as well as the dimuon pair it decayed to—were collected for later analysis. This study also required kinematic data from all final-state charged particle in the event record. To reduce run time and data storage, track cuts were applied within the event loop. These cuts required charged final-state particles to have $|\eta < 2.4|$, as well as p_T > .10 GeV.

3.2.2 CMS Data Analysis

Both the pp and PbPb data used in this analysis were collected by the CMS detector. The pp data were taken at $\sqrt{s}$ = 7 TeV in 2011, and corresponds to an integrated luminosity of 5.55 fb^{-1}. The PbPb data were taken during the LHC heavy ion run at $\sqrt{s_{NN}}$ = 5.02 TeV in 2015. These peripheral events range in centrality from 30-100%, and correspond to an integrated luminosity of 467.1 μb^{-1}.

Before being analyzed, preliminary cuts were made to the PbPb data set, specifically to the dimuons. Each muon was required to be reconstructed as both a global muon and a tracker muon. Additionally, cuts were made on the number of hits for each muon—requiring at least 6 inner tracker hits and 1 or more pixel hits. Finally, cuts were made on the transverse and longitudinal distance w.r.t the primary vertex—requiring D_{xy}< 3 mm and D_z < 200 mm.

Further cuts were imposed in the analysis of the data. For each event, a high-level trigger was applied, which required the event to have a centrality between 30-100%, as well as two measured muons with a non-zero transverse momentum. The dimuon pairs were required to be composed of opposite-signed muons, each with a p_T > 4 GeV/c and $|\eta|$ < 2.4. The reconstructed dimuons were then correlated with the tracks in that event. These tracks were required to be charged and have a p_T > .10 GeV/c. Also, like the muons, only tracks within the region $|\eta|$ < 2.4 were considered for this analysis.

3.2.3 Determination of Background

The procedure for background reduction was adopted from the dihadron-correlation method, outlined in Ref [11]. For this analysis, opposite sign dimuons within a specified p_T^{Υ} range that have $|\eta|$ < 1.2 are defined as *trigger particles*. Υ-hadron pairs are then formed by associating these dimuons with charged tracks with $|\eta|$ < 2.4 and p_T^{trk} > .10 GeV. The per-trigger-particle associated yield distribution is given by:

$$\frac{1}{N_{trig}} \frac{d^2 N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)} \tag{4}$$

where N_{trig} is the number of trigger particles in each event (primarily equal to one for this analysis), N^{pair} is the total number of Υ-hadron pairs in the event, and $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ of the pair, respectively. The signal distribution, $S(\Delta\eta, \Delta\phi)$, is the measured per-trigger-particle distribution composed from same event pairs,

$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \times \frac{d^2 N^{same}}{d\Delta\eta d\Delta\phi}. \tag{5}$$

The background distribution, $B(\Delta\eta, \Delta\phi)$, is the measured per-trigger-particle distribution of mixed-event pairs defined by:

$$B(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \times \frac{d^2 N^{mix}}{d\Delta\eta d\Delta\phi}, \tag{6}$$

where N^{mix} is the number of Υ-hadron pairs formed from the mixed event. This is constructed by forming Υ-hadron pairs between the dimuon trigger and tracks from different events. This is done by pairing dimuon trigger particles with tracks associated with twenty random events–excluding the original–that also had a dimuon trigger particle associated with them. The value B(0, 0) represents the mixed-event associated yield where both particles of the Υ-hadron pair are going in approximately the same direction ($\Delta\eta \approx 0$ and $\Delta\phi \approx 0$, where the bin widths are 0.3 and $\pi/16$, respectively), which means it has the maximum possible geometric pair acceptance. Thus, the ratio $B(0,0)/B(\Delta\eta, \Delta\phi)$ is the pair-acceptance correction factor that is applied to the signal distribution, Eq. 5, to give the corrected per-trigger-particle associated yield distribution.

4. Results

4.1 Upsilon Activity Analysis

For the track multiplicity plot (Fig. 4 Left), alternate activity binning was used in order to achieve a more direct comparison with the CMS data. Initially, the multiplicity was divided into 10 % activity bins, however, this was only able to reach the first 3 data points. In order to get a better comparison, activity was divided into smaller bins for the higher activity events, and the lower bins were not changed. This allowed for the study of Υ production at the highest event activity.

Though the PYTHIA model does not reach the high level of Υ production for high activity found in the CMS data, it does show a strong correlation. It also shows a relative production far above a slope 1 line for the highest activity events, which agrees with the CMS data.

The green line in the activity plots is present as a visual in order to see if the relative Υ production scales with relative activity for track multiplicity and transverse energy. In the mid-rapidity track multiplicity case, the model follows an approximately linear relationship for low activity events, but begins to diverge for the higher activity events. For the forward transverse energy, on the other hand, this linear relationship is maintained throughout the range of event activity.

For the sum of transverse energy at forward rapidity (Fig. 4 Right), alternate binning was not necessary, as

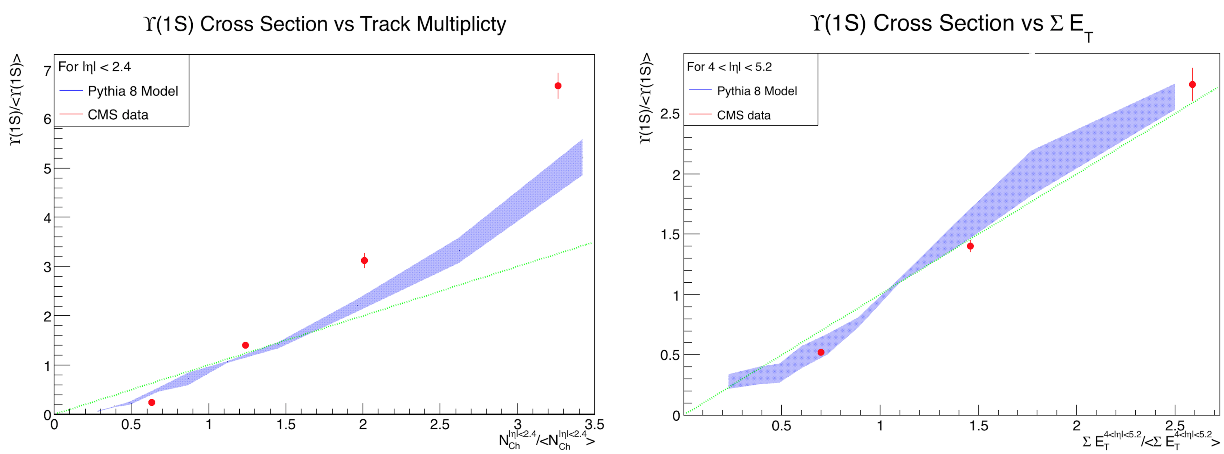

Figure 4: (Left): The Υ(1S) cross section versus the track multiplicity measured at mid-rapidity ($|\eta| < 2.4$). Both the cross section and multiplicity are normalized by their corresponding activity-integrated values. (Right): The Υ (1S) cross section versus the sum of transverse energies in the HF calorimeters ($4 < |\eta| < 5.2$). Both the cross section and sum of transverse energy are normalized by their corresponding activity-integrated values. The line represents a linear function with slope equal to unity.

the 10 % activity bins initially used were able to reach all the CMS data points. The correlation in forward transverse energy is much lower than that found in the mid-rapidity track multiplicity, which is consistent with the CMS data. The PYTHIA model shows the relative Υ production to have a linear relationship with forward transverse energy (with slope equal to unity).

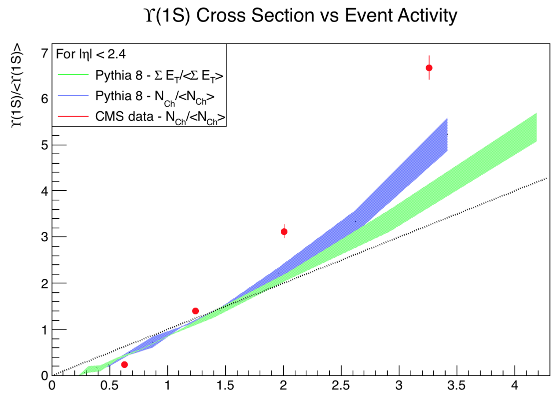

Figure 5: The Υ(1S) cross section versus mid-rapidity activity ($|\eta| < 2.4$), calculated using both track multiplicity and the sum of transverse energy. All of these values were normalized by the activity-integrated values. Though there is no CMS data corresponding to transverse energy measurements at mid-rapidity, this measurement was included to more directly compare the effect of binning activity with different event variables.

For the mid-rapidity analysis, it was found that the sum of transverse energy measurement maintains the approximately linear relationship that was seen in the forward rapidity region. This result demonstrates that in the PYTHIA 8 model, heavy flavor production has a stronger correlation with track multiplicity than with sum of transverse energy.

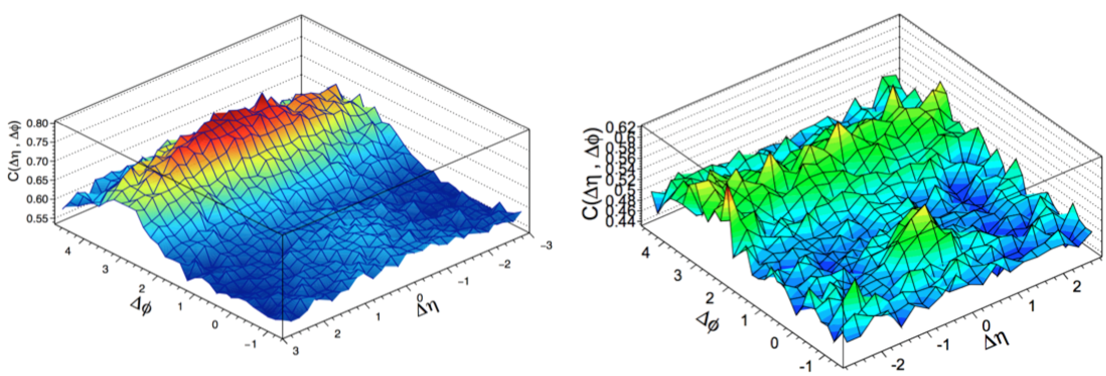

Figure 6: Comparison between PYTHIA 8 simulation results (left) and CMS pp collision data (right). Though the simulations were run at a slightly lower center of mass energy (5.02 TeV compared to the 7 TeV dataset), both systems exhibit similar Υ-hadron correlations characterized by a small near-side bump ($\Delta\phi \approx \Delta\eta \approx 0$) with broad far-side ridge ($\Delta\phi \approx \pi$).

4.2 Υ-Hadron Angular Correlations

The first analysis was conducted using the results generated by PYTHIA 8 at 5.02 TeV. The cuts applied to the simulation data were adopted from those used in the CMS analysis [10]. The resulting kinematic distributions for the dimuons and tracks are shown in Figures 8 and 9, respectively. Additionally, an

Υ-hadron correlation distribution was produced. The comparison to CMS data taken at 7 TeV is shown in Figure 6. Though the PYTHIA simulations were run at a different energy, the two distributions share key characteristics. Namely, the broad far-side ridge occurring at $\Delta\phi = \pi$.

For the PbPb data set, a invariant mass plot was made for the dimuon pairs passing the cuts. Using this distribution, it was determined that the optimal dimuon mass range was 9.31 GeV/c^2 < $m_{\mu+\mu-}$ < 9.61 GeV/c^2 for maximum signal to background ratio. The p_T, η, and ϕ dimuon distributions for the whole mass range (7 GeV/c^2 < $m_{\mu+\mu-}$ < 14 GeV/c^2) are shown in Figure 8, as well as the corresponding PYTHIA distributions for pp collisions at the same energy. This comparison is also done for tracks in Figure 9.

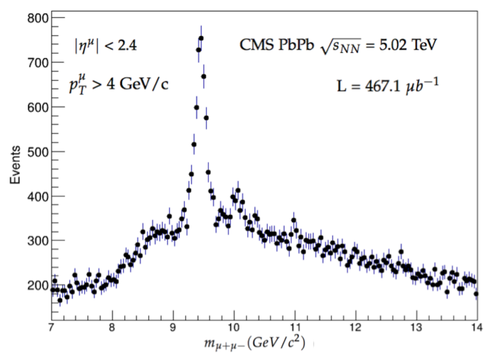

Figure 7: Invariant mass spectrum in PbPb collisions of dimuon pairs with single muons with $p_T^\mu > 4$ GeV/c and $|\eta^\mu| < 2.4$. The peak centered at m_Υ = 9.46 GeV/c^2 was used to determine the appropriate mass range of dimuons to include in the analysis.

Currently, the PbPb data set is continuing to be analyzed. A preliminary correlation result is shown in Figure 10. Due to the lack of published data on Υ-hadron correlations, it is currently unknown what correlation is expected in the PbPb collision system. Further analysis will be done on this data set to further calibrate the cuts and background calculation in order to extract a signal. Once calibration is complete, other factors can be analyzed, such as the effect of imposing p_T ranges on both the dimuons as well as the tracks. Additionally, the effect of centrality on angular correlations can be examined.

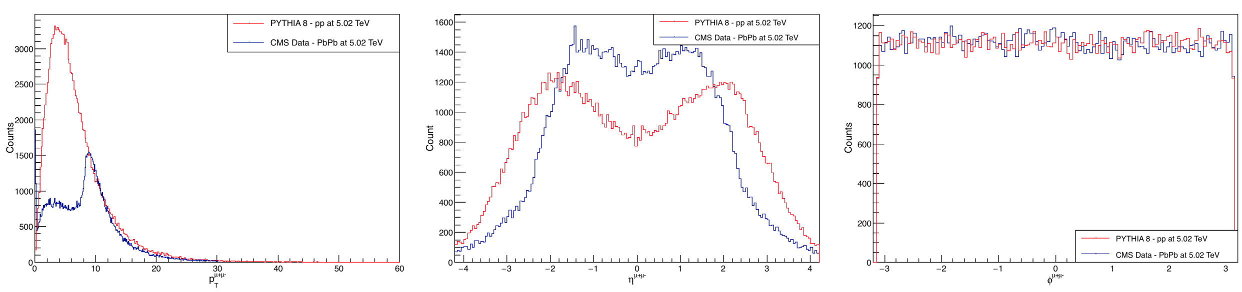

Figure 8: Tranvserve momentum, η, and ϕ distributions for dimuon pairs in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and PYTHIA pp simulations at the same energy. These distributions only include opposite signed dimuon pairs with each muon having $|\eta| < 2.4$ and $p_T > 4$ GeV/c.

5. Conclusion

Relative Υ(1S) yields were measured in Pythia 8 and compared to data from CMS. The relative yields were plotted as a function of charged particle multiplicity at mid-rapidity ($|\eta| < 2.4$), as well as a function of the sum of forward transverse energy ($4 < |\eta| < 5.2$). An approximately linear increase in the relative

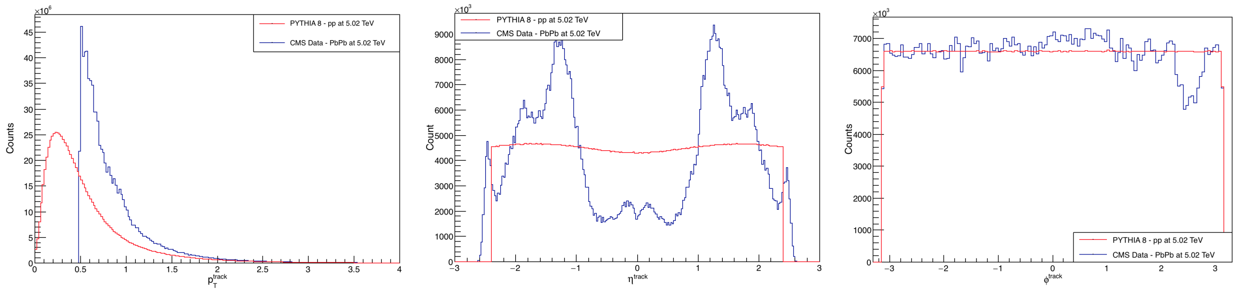

Figure 9: Tranvserve momentum, η, and ϕ distributions for tracks in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and PYTHIA pp simulations at the same energy. These distributions only include charged final-state particle. In the analysis, only tracks with p_T > .10 GeV/c and $|\eta|$ < 2.4 were used.

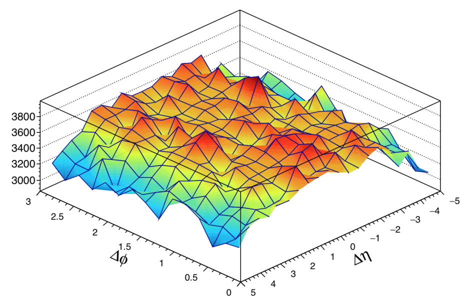

Figure 10: Preliminary correlation results for CMS PbPb data analysis.

yields of Υ is found in both these cases, with a stronger correlation found in track multiplicity ($|\eta|$ < 2.4). For the highest activity bin for track multiplicity measured (0-2%), the Υ yield is enhanced compared to minimum bias events by a factor of approximately 5. For the highest activity region for sum of transverse energy(0-10%), this factor is found to be approximately 2.5.

These results show a positive correlation between Υ yields and these event values, in contrast to results reported for Pythia 6. When compared to data, the PYTHIA 8 Υ model provides much more accurate results than those seen in the PYTHIA 6 J/ψ comparison [6]. This could be attributed to the inclusion of MPIs in heavy flavor production in PYTHIA 8.

Further analysis will need to be conducted on the CMS PbPb data set in order to determine if there are any angular correlations present between tracks and dimuons. From the PYTHIA simulation results, however, a clear correlation is observed. In the pp simulation system, this correlation is characterized by a broad far-side ridge at $\Delta\phi \approx \pi$ with a small bump at $\Delta\eta \approx \Delta\phi \approx 0$. This distribution resembles that found in the dihadron system with one key difference: the lack of the peak present at $\Delta\eta \approx \Delta\phi \approx 0$. In the dihadron system, the trigger particle is produced along with many others in the hadronization process which form a collimated stream. When measuring $\Delta\eta$ and $\Delta\phi$ values, this jet will result in a large peak at $\Delta\eta \approx \Delta\phi \approx 0$. In the Υ-hadron system, however, this peak will not be present, indicating the Υ was not produced through hadronization.

Understanding the behavior of particle production in pp collisions is important for understanding collisions where nuclear effects begin to have an influence (pA or AA). Behavior measured in pp collisions can be used as a baseline to more accurately probe effects that only occur in nuclear collisions (such as the formation of a quark-gluon plasma), and how they influence the particles produced. One example of such effects is the suppression of the $\Upsilon(nS)$ (n = 1, 2, or 3) states in Pb-Pb collisions measured by CMS [2]. The further study of production mechanisms that occur in pp collisions will allow nuclear effects present in heavy ion collisions to be more easily distinguished from those found in pp collisions.

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