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Observation of quarkonia with the CMS detector at LHC

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Abstract

The production of quarkonia is one of the most promising signals at the LHC for the study of the production properties of Quark Gluon Plasma. In addition to the J/ψ , the extent to which Υ is suppressed should give much insight into the new state of matter. The large muon acceptance and the high precision tracker make the CMS detector ideal for studies of this physics. The performance of the CMS detector for quarkonia measurements in heavy-ion collisions in the dimuon channel is presented. Dimuon reconstruction efficiencies and mass resolution are calculated using detailed detector simulation. Mass spectra and signal to background ratios are estimated with a fast Monte Carlo program. Results obtained with the fast Monte Carlo are compared with more detailed simulations.

1 Introduction

The interest in quarkonium production at the LHC emerged from the CERN SPS results [1] which showed a strong anomalous suppression of J/ψ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. RHIC is studying the J/ψ production in detail at $\sqrt{s_{NN}} = 200$ GeV. However recent theoretical analysis [2] suggests that the direct J/ψ could survive for temperature as high as 1.5 Tc (The critical temperature for the phase transition is about 200 MeV) which could be out of the range of the RHIC. Although the Υ production cross section is large enough to be observed at RHIC, albeit with limited statistics, its suppression is not expected until the high initial temperatures foreseen at LHC are reached.

Thanks to its large muon detector and to the high precision tracker, CMS is particularly well suited to study the quarkonia state production in the dimuon channel.

2 Event simulation

Due-to huge difference between Pb-Pb inelastic cross section and production cross sections of the Υ and J/ψ the fast Monte Carlo method is unavoidable.

2.1 Quarkonia production rates

The quarkonium cross sections per nucleon in Pb-Pb interactions are calculated in the color evaporation model [6]. These are NLO calculations which include nuclear shadowing. The additional effect like the absorption is not taken into account. The inclusive quarkonia production cross section values averaging over impact parameter in the case of Pb-Pb collisions are 48930 μb for J/ψ and 304 μb for Υ . The kinematical distributions in p_T and η of the quarkonia are simulated within the same model.

2.2 Muon background rates

The choice of the impact parameter, b , governs the overall charged particles multiplicity, N_{ch} , as well as the number of open heavy quark pairs, $N_{Q\bar{Q}}$ produced in the collision. Charged particles and open charm and bottom production give the essential contributions to the dimuon background.

2.2.1 From pions and kaons

Two hypotheses with higher multiplicity values are used: $\frac{dN^\pm}{d\eta} = 5000$ and $\frac{dN^\pm}{d\eta} = 2500$ for the 5% most central collisions. In the fast Monte Carlo, only pions and kaons, which all together represent about 90% of all charged particles emitted in the collision, are considered. Neither neutral hadrons nor gammas are taken into account. Kaons and pions are distributed according a ratio $K/\pi = 11\%$ given by HIJING [3]. The transverse momentum and the pseudorapidity of the particle are chosen randomly from distributions extracted from HIJING.

2.2.2 From open heavy quark pair production

The number of pairs produced in Pb-Pb collisions as a function of impact parameter b is directly proportional to the nuclear overlap $T_{AA}(b)$ where $T_{PbPb}(0) = 30.4/\text{mb}$. The NLO $Q\bar{Q}$ production cross sections in 5.5 TeV pp interactions are $\sigma(c\bar{c}) = 7.5$ mb and $\sigma(b\bar{b}) = 0.2$ mb. These cross sections do not include the shadowing effect, the reducing factor of which is taken to be 35% and 15% respectively [5]. The muon p_T and η distributions are extracted from [6].

3 Fast Monte Carlo Method

3.1 Detector response

The response of CMS Muon stations to the incident pions, kaons and muons is given under the form of the 2-dimensional tables in P, η space with binning of 0.1 GeV/c in P and 0.05 in η . Incident particles generated with a given set of P, η values are tracked and reconstructed using CMS simulation and reconstruction code [4]. Finally, the particle is accepted or rejected according to criteria specific to the heavy ion dimuon trigger.

The track reconstruction [8] efficiency is parametrized in four momentum and four pseudorapidity bins depending on particle type and multiplicity. The dependence of the purity of the track reconstruction and dimuon mass

resolution on track multiplicity is determined in two pseudorapidity regions (both tracks are in $|\eta| < 0.8$; at least one track is in $|\eta| > 1.2$).

3.2 Event simulation with fast Monte Carlo

In each Pb-Pb collision characterized by its impact parameter, all 5 resonances J/ψ , J/ψ' and the 3 states of the Υ family, generated according to [6], are superimposed to the background made of π 's, K 's and muons coming from open heavy quark pair production.

The muon pairs are weighted according to:

$$W_{pair} = W_1^{orig} \times W_1^{rec} \times W_2^{orig} \times W_2^{rec} \times W_{tr}$$

where $W_{1,2}^{orig}$ is equal to 1 for the background muons or to $\sigma(\text{quarkonium})/\sigma(\text{PbPb})$ for the muons from quarkonia decay with $\sigma(\text{PbPb}) = 8$ barns and W_{tr} is the combination of the trigger efficiencies of Level 1 and Level 2 of both muons. The track reconstruction efficiency ($W_{1,2}^{rec}$) is parametrized depending on the multiplicity, momentum, pseudorapidity and purity.

The invariant dimuon mass is calculated and smeared according to a Gaussian law with $\sigma = 85 \text{ MeV}/c^2$ for masses above $5 \text{ GeV}/c^2$ and $\sigma = 37 \text{ MeV}$ for masses below $5 \text{ GeV}/c^2$.

3.2.1 Comparison of fast Monte Carlo with detailed simulations

The large number of PbPb events (500K) were generated with HIJING with quenching switched off. They are used as an input both for fast Monte Carlo program and detailed simulation and reconstruction program used by CMS. Figure 1 presents the comparison of the events simulated with fast monte-carlo method and events done with detailed simulation. The error bars shown for the fast Monte Carlo results include both statistical and systematic errors. The fast Monte Carlo spectrum is smoother then the detailed simulation spectrum due-to the simplification of the approach used in the fast Monte-Carlo.

3.3 Dimuon invariant mass

About 50×10^6 Pb-Pb collisions were simulated with the fast Monte-Carlo program depending on the impact parameter in each multiplicity set. The obtained mass spectrum is scaled to 0.5 nb^{-1} which corresponds to the integrated luminosity collected after one month of Pb beams with an average luminosity $\mathcal{L} = 4 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ and 0.5 machine efficiency.

Figures 2,3 shows the invariant mass distributions corresponding to 0.5 nb^{-1} and multiplicity $\frac{dN_{\pm}}{d\eta} = 5000$ in the J/ψ mass region and Υ mass region respectively. The different background contributions are also shown.

With the assumption of smaller multiplicity, $\frac{dN_{\pm}}{d\eta} = 2500$ the Υ mass region the three resonant states are well seen and well separated.

The track reconstruction in barrel ($|\eta| < 0.8$) gives a better track momentum resolution and as a consequence the best dimuon mass resolution of $54 \text{ MeV}/c^2$ in Υ mass range. Figure 4 show the mass distributions in Υ mass range for the dimuons with both particles in $|\eta| < 0.8$. Like sign dimuon mass spectra ($2\sqrt{N^{++} N^{--}}$) are presented in the same plots.

The uncorrelated background can be subtracted from the opposite sign dimuon mass distribution leaving the dimuons from quarkonia decay. In each bin of mass the signal is given by [7]:

$$N^{\text{Sig}} = N^{+-} - 2\sqrt{N^{++} N^{--}}$$

where N^{+-} , N^{++} and N^{--} are the combinations of opposite sign pairs and positive and negative like sign pairs respectively in a given mass interval. Figure 6 presents the J/ψ mass distribution resulting from the subtraction in full η range. Figure 5 presents the Υ mass distributions resulting from the subtraction with both muons in $|\eta| < 0.8$.

3.4 Signal/Background ratio and statistics

For low multiplicity assumption 180000 J/ψ 's and 25000 Υ 's with S/B ratio 1.2 and 0.12 correspondingly are expected in one month of data taking. For high multiplicity assumption 140000 J/ψ 's and 20000 Υ 's with S/B ratio 0.6 and 0.07 correspondingly will be collected.

3.5 Summary

With its $\approx 4\pi$ muon acceptance and full calorimetric coverage, CMS can make very significant and, in some respects, unique contribution to heavy ion physics. The large rapidity aperture of the muon detector, as well as the precise tracking, result in high statistics and a very good separation between the Υ states. The number of events (20000 or 25000 for Υ depending on the multiplicity set and 140 000 or 180 000 for J/ψ) for one month of data taking (0.5 nb^{-1}) is high enough to provide a comparison between the several impact parameter bins and to carry out the study of the more differential analysis (dN/dy , dN/dp_T).

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Figure 1: Comparison of the fast MC result (full squares) with a full HIJING simulation (empty circles). The mass resolution in the fast Monte Carlo is taken as $0.009 \times M$

Figure 2: Invariant mass of opposite sign muon pairs with $\frac{dN_{\pm}}{d\eta} = 5000$, in the J/ψ region. The main contributions of the background are shown. The sign h holds for π, K decay. Both muons have $|\eta| < 2.4$.

Figure 3: Invariant mass of opposite sign muon pairs with $\frac{dN_{\pm}}{d\eta} = 5000$, in the Υ region. The main contributions of the background are shown. The sign h holds for π, K decay. Both muons have $|\eta| < 2.4$.

Figure 4: Invariant mass of opposite sign muon pairs with $\frac{dN_{\pm}}{d\eta} = 5000$, in the Υ mass region. Both muons have $|\eta| < 0.8$

Figure 5: Signal after background subtraction in the Υ region with $\frac{dN_{\pm}}{d\eta} = 5000$. Both muons have $|\eta| < 0.8$.

Figure 6: Signal after background subtraction in the J/ψ region with $\frac{dN_{\pm}}{d\eta} = 5000$. Both muons have $|\eta| < 2.4$