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Heavy flavours in heavy-ion collisions in the CMS experiment at the LHC

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Abstract

The CMS detector at the LHC is well suited for the study of quarkonium states J/ψ , ψ' , Υ , Υ' and Υ'' , as well as Z boson production in heavy ion collisions through their dimuon decays. The CMS detector has a large muon system with a trigger acceptance of $\approx 20\%$ for Υ and $\approx 1\%$ for J/ψ . The precise tracker enables dimuon reconstruction with efficiencies above 90% in the barrel for dimuons from quarkonia decays, a dimuon mass resolution of 0.5% at the Υ mass, and background rejection. Results of quarkonium simulations are presented for several ion species with high and low background hypotheses. The expected dimuon invariant mass distributions are shown and the signal-to-background ratios, significance and the estimated statistics are also given. The CMS capability for detecting high-mass $\mu^+\mu^-$ pairs from semileptonic $B\bar{B}$ decays and secondary J/ψ 's from single B decays (useful channels for studying medium-induced bottom-quark energy loss) is also discussed.

1 Introduction

Heavy quarkonium resonances are an important tool to study the hot, dense matter produced in heavy ion collisions. The relative suppression within J/ψ and Υ families, and J/ψ and Υ themselves has been suggested as one of the best signatures of quark-gluon plasma formation [1]. The strong anomalous suppression of J/ψ in Pb + Pb collisions was observed at $\sqrt{s} = 17$ A GeV at CERN SPS [2]. The J/ψ production is studied at RHIC at $\sqrt{s} = 200$ A GeV. The Υ suppression, however, can be observable with large statistics only at LHC, where energy per nucleon is as high as $\sqrt{s} = 5.5 - 7$ A TeV. The CMS detector is particularly well suited to study both J/ψ and Υ production [3]. Open flavour production is important to study the behaviour of massive colour charges in a dense medium at the LHC. The charm and bottom cross sections are much larger than at RHIC. In-medium gluon radiation and collisional energy loss of heavy quarks can result in suppression and modification of high-mass dilepton [4, 5, 6] and secondary J/ψ spectra from $B \rightarrow J/\psi$ [5, 6]. The systematic studies of heavy-quark production and decay into dilepton can be performed with CMS [7].

2 The CMS Detector

Figure 1: The CMS detector [9].

The CMS detector, shown in Fig. 1, is designed to identify and measure muons, electrons, photons and jets over large pseudorapidity and energy domains [8]–[11]. The central element of CMS is a 13 m long, 6 m diameter, high-field (4 T) solenoid with an internal radius of ≈ 3 m. The tracker and muon chambers cover the pseudorapidity region $|\eta| < 2.4$ while the electromagnetic (ECAL) and hadron (HCAL) calorimeters reach $\eta = \pm 3$ and $\eta = \pm 5.2$ respectively. A pair of quartz-fibre very-forward (HF) calorimeters, located at ± 11 m from the interaction point, cover the region $3 < |\eta| < 5.2$. In addition, the quartz-fibre calorimeter CASTOR covers the region $5.3 < |\eta| < 6.4$. The high precision tracker is composed of silicon pixel and strip counters and allows track momenta to be determined with a resolution better than 1% for tracks with p_T between 0.5 GeV/c and a few tens of GeV/c. The large acceptance of the muon system and the tracker allow muon measurements over wide transverse momentum and pseudorapidity ranges, and therefore the study of quarkonia and heavy-quark decays to muons.

3 Track reconstruction

The goal of the track-finding algorithm is to select pairs of muon tracks coming from the interaction point [12]. The vertex is obtained from the combination of clusters in the pixel layers, under the assumption that the interaction occurs at the geometrical centre in the transverse plane of the detector. The resolution of the longitudinal coordinate is $\sigma_z = 190 \mu\text{m}$. The track finding starts in the muon chambers because they are the least populated planes. The tracks are backward propagated within roads in transverse ($R/z, \varphi$) and longitudinal (R, z) planes with the simple parametrizations: $\Delta\varphi = k\Delta r/p_T$ for the barrel, $\Delta\varphi = k\Delta z/p_L$ for the endcaps, and as a straight line in the (R, z) plane. The track candidates are then fitted and, after the vertex constraints, the best quality dimuon vertex is selected. Several dimuon types have been studied: homogenous dimuons from Υ and π/K decay, as well as mixed pairs originating from $\pi/K/b$ decays where the muons in a pair can have different origins, e.g. one muon from a π or K and the other from b or Υ . The mass resolution for the Υ when both muons are in the range $|\eta| < 0.8$ is $50 \text{ MeV}/c^2$.

4 Low mass dimuon production

For simulation of J/ψ and Υ background the muons from π , K and $Q\bar{Q}$ pairs decays are used. After applying the muon transverse momentum cuts ($p_T > 3.5$ GeV/c), 0.03% of the J/ψ 's and 16% of the Υ 's are kept. The invariant mass is calculated for each pair and the distribution is fitted to Gaussian of width equal to the expected mass resolution. Cross sections for the different processes are taken from [13]. The opposite sign (OS) dimuon mass distributions obtained in Pb + Pb, Sn + Sn, Kr + Kr and Ar + Ar are shown in Fig. 2 for the J/ψ and in Fig. 3 for the Υ . The results are presented for a one month run assuming a 50% operation efficiency, i.e. 1.3×10^6 seconds. Two multiplicity assumptions, corresponding to expected upper and lower limits of the charged particle multiplicity at midrapidity in the 5% most central events at the LHC, $dN^\pm/d\eta$, are considered. The assumed multiplicity are shown in the figures. The number of quarkonia detected in a one month run are shown in Figs. 2 and 3 (left).

Figure 2: The opposite sign dimuon invariant mass distributions in the J/ψ mass region for the high (left) and low (right) multiplicity sets.

Figure 3: The opposite sign dimuon invariant mass distributions in the Υ mass region for the high (left) and low (right) multiplicity sets.

Figure 4 (left) shows the most important contributions to the background expected in the opposite sign dimuon spectrum. For hh, both muons come from π and K decays; for hb and hc, one muon arises from π or K while the second is from b or c decay; for bb, both muons come from $B\bar{B}$ decays. The background is typically dominated by uncorrelated π and K decays and can be subtracted from the OS spectrum using the like-sign dimuon spectrum as done by NA50 [2]. Fig. 4 (right) shows the mass distributions after subtraction. The signal-to-background ratios and significance are given in Table 1.

Figure 4: Left: The opposite sign dimuon invariant mass distributions in Pb + Pb collisions in the Υ mass region for the high multiplicity set. The largest background contributions are shown. Right: The signal invariant mass distributions after background subtraction for J/ψ (left) and the Υ family (right).

Table 1: The signal-to-background ratio S/B and the ratio of the signal to the statistical error $S/\sqrt{S+B}$ in the 5% most central collisions for the two multiplicity sets. The smaller numbers correspond to the high multiplicity set.

		Pb + Pb	Sn + Sn	Kr + Kr	Ar + Ar
S/B	J/ψ	0.2–0.5	0.4–1.1	0.7–1.8	2.0–6.8
	Υ	0.4–0.9	0.7–1.9	1.5–4.3	5.3–15.6
$S/\sqrt{S+B}$	Υ	69–93	220–276	396–460	925–978
	Υ'	24–38	84–123	165–218	447–512
	Υ''	16–26	55–86	113–157	325–391

5 J/ψ and Υ triggering

Figures 5 and 6 show the inclusive pseudorapidity η and transverse momentum p_T spectra of J/ψ and Υ produced in central Pb + Pb collisions [13]. These spectra are used as input for the detector simulation [14] and reconstruction [15] programs. The J/ψ 's and Υ 's were generated without underlying events. The overall trigger efficiency changes from 0.4% (default pp trigger) [16] to 0.97% (optimized AA trigger) for J/ψ and from 16% (default pp trigger) to 21% (optimized AA trigger). Figs. 7 and 8 show the η and p_T spectra of J/ψ and Υ for default pp and optimized AA triggers.

6 High dimuon mass production

In the high invariant mass region ($M(\mu^+\mu^-) > 20 \text{ GeV}/c^2$) Drell–Yan, Z boson and semileptonic decays of heavy flavours ($c\bar{c}$, $b\bar{b}$) are the main dimuon sources. A cut on the muon transverse momentum $p_T > 5 \text{ GeV}/c$ makes the contribution from uncorrelated decays of soft particles negligible. A clear signal for $Z \rightarrow \mu^+\mu^-$ is seen in Fig. 9 (left) [17]. Totals of ~ 11000 decays and ~ 900 Z+jet events with $E_T^{\text{jet}} > 50 \text{ GeV}$ are expected in a one month Pb + Pb run assuming 50% operation efficiency. The b-quark energy loss affects the B-jet fragmentation and modifies the dimuon spectrum depending on the mechanism of heavy-quark production for $B\bar{B} \rightarrow \mu^+\mu^- + X$ and the intensity of jet quenching [18]. The $B\bar{B} \rightarrow \mu^+\mu^- + X$ and $B \rightarrow J/\psi \rightarrow \mu^+\mu^-$ decays can be separated from Drell–Yan dimuons using the secondary vertex position, or the distance between two muon trajectory points closest to the beam axis δr , shown on in Fig. 9 (right).

Figure 5: The J/ψ η (left) and p_T (right) distributions in central Pb + Pb collisions at $\sqrt{s} = 5.5$ A TeV.

Figure 6: The Υ η (left) and p_T (right) distributions in central Pb + Pb collisions at $\sqrt{s} = 5.5$ A TeV.

Figure 7: The J/ψ η (left) and p_T (right) distributions in central Pb + Pb collisions at $\sqrt{s} = 5.5$ A TeV when both muons are triggered by the default pp (solid histograms) and the optimized AA (shaded histograms) triggers.

Figure 8: The Υ η (left) and p_T (right) distributions in central Pb + Pb collisions at $\sqrt{s} = 5.5$ A TeV when both muons are triggered by the default pp (solid histograms) and the optimized AA (shaded histograms) triggers.

Figure 9: Left: Dimuon invariant mass distribution for muons with $p_T > 5 \text{ GeV}/c$ in a one month Pb + Pb run. Right: The distribution of $\mu^+\mu^-$ pairs from $B\bar{B}$ decays (solid histogram) and Drell–Yan production (dashed histogram) as a function of δr .

7 Summary

The CMS detector is well suited for detection of quarkonia and heavy-quark decays into muons. The resonance states are well separated in mass and the expected number of events in a one month run is large enough to carry out correlation studies such as the dependence of dimuon production on transverse momentum and event centrality. The significance for Υ are between 70 for Pb + Pb and 1000 for Ar + Ar.

The dimuon spectrum from $B\bar{B}$ decays can be separated from that of Drell–Yan production with secondary vertex reconstruction. The Z-boson can be measured in the muon and muon+tracker systems. A study of the Z+jet imbalance could provide a unique tool to investigate jet quenching.

Recent studies indicate that the trigger efficiency can be improved by using an optimized combination of hardware and the on-line muon trigger. The High-Level Trigger also increases the acceptance for low p_T J/ψ , important for heavy ion physics.

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