The Compact Muon Solenoid Experiment

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Dimuon results in PbPb and pp collisions in CMS

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Abstract

The unprecedented center-of-mass energy available at the LHC offers unique opportunities for studying the properties of the strongly-interacting QCD matter created in PbPb collisions at extreme temperatures and very low parton momentum fractions. With its high precision, large acceptance for tracking and calorimetry, and a trigger scheme that allows analysis of each minimum bias PbPb event in the high-level trigger, CMS is fully equipped to study dimuon production in the high multiplicity environment of nucleus-nucleus collisions. Such probes are especially relevant for these studies since they are produced at early times and propagate through the medium, mapping its evolution. The capabilities of the CMS experiment to study dimuon production in pp and PbPb collisions based on LHC runs in 2010 and 2011 will be reviewed. In particular, CMS is able to measure primary and secondary J/ψ s, but also the first 3 Υ states, differentially in p_T and rapidity. In heavy ions, the observation of quarkonia at $\sqrt{s_{NN}} = 2.76$ TeV will be presented, and the Z boson inclusive and differential measurement as probe of the initial state will be detailed.

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Dimuon Results in PbPb and pp Collisions in CMS

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INTRODUCTION

The suppression of quarkonium states in the quark-gluon plasma (QGP) [1] and the propagation of heavy quarks in the medium [2] are promising probes for studying the properties of the QGP. Quarkonia and heavy quarks are not part of the thermalized system, thus carrying information about the early stages of the evolution of the QGP.

The Z boson production can be affected by various initial-state effects, but do not undergo strong final-state interactions. Therefore they are the standard candle of the initial state in PbPb collisions.

A detailed description of the CMS detector can be found in [3]. Within a superconducting solenoid providing a magnetic field of 3.8 T, silicon pixel and strip tracker, crystal electromagnetic calorimeter, and brass/scintillator hadron calorimeter are installed. Muons are measured with gaseous detectors made of three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers.

QUARKONIUM PRODUCTION

The reconstructions of the J/ψ and Υ in the dimuon channel are started by selecting events with an opposite-sign muon pair. In the offline analysis, the muon identification starts with tracks which are reconstructed in the muon system. They are combined with silicon tracker tracks to form global muons.

Depending on their origin, J/ψ s can be classified into prompt J/ψ (primary vertex) and non-prompt J/ψ (secondary vertex) [4, 5]. Prompt J/ψ s are composed of J/ψ from direct production and feed-down from higher order state such as ψ' and χ_c . Non-prompt J/ψ s are dominantly originating from B-hadron decays. Because of the longer life time of B-hadrons, the identification of non-prompt J/ψ is made possible by the measurement of a secondary dimuon vertex displaced from the primary collision vertex. Based on the measured displacement $\vec{x}$, the most probable transverse decay length can be estimated by

$$L_{xy} = \frac{\hat{u}^T \sigma^{-1} \vec{x}}{\hat{u}^T \sigma^{-1} \hat{u}} \quad (1)$$

where $\hat{u}$ is the unit vector of the J/ψ $\vec{p}_T$ and σ is the sum of the primary and secondary vertex covariance matrices. From this quantity, the pseudo-proper decay length $\ell_{J/\psi} = L_{xy} m_{J/\psi} / p_T$ is computed as an estimate of the B-hadron decay length.

Theoretical calculations compared to prompt and non-prompt J/ψ measurements at $\sqrt{s} = 7$ TeV [5] are shown in Fig.1. Prompt and non-prompt cross section results have been compared with NRQCD and FONLL predictions. A reasonable agreement is found, except for non-prompt cross sections at high p_T .

FIGURE 1. cross section as a function of p_T for the different rapidity bins. (Left) Prompt J/ψ and (Right) Non-prompt J/ψ compared to theoretical predictions. The lines are added only for illustrative purposes.

3 Υ states have been clearly separated in the invariant mass distribution of $\mu^+ \mu^-$ pairs as shown in Fig.2 (left). The cross sections of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ have been measured as a function of p_T [6]. Fig.2 (right) shows the measured $\Upsilon(1S)$ cross section, which shows good agreement with PYTHIA prediction in shape after applying an extra normalization factor of $\tilde{2}$.

CMS recorded data samples of pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV which correspond to integrated luminosities of 225 nb^{-1} and $7.28 \mu\text{b}^{-1}$, respectively. These datasets are analyzed following similar conditions to the pp collisions at $\sqrt{s} = 7$ TeV. The yields measured in PbPb collisions are compared to expectations from independent binary collisions [7]. This idea is formulated with the nuclear modification factor R_{AA} .

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{\text{PbPb}}(Q\bar{Q})}{N_{pp}(Q\bar{Q})} \cdot \frac{\epsilon_{pp}}{\epsilon_{\text{PbPb}}} \quad (2)$$

FIGURE 2. (Left) $Y(nS)$ invariant mass distribution in the range $2 < p_T < 5$ GeV/c for $|\eta| < 1$. (Right) $Y(1S)$ cross section as a function of p_T for $|y| < 2$ compared to the PYTHIA predictions normalized to the measured p_T -integrated cross sections.

Here T_{AA} is the nuclear overlap function, $\mathcal{L}_{pp}$ is the pp luminosity, N_{MB} is the measured number of equivalent minimum bias events in PbPb, $N_{pp}(Q\bar{Q})$ and $N_{PbPb}(Q\bar{Q})$ are the raw yields measured in pp and PbPb, respectively, and $\varepsilon_{pp}/\varepsilon_{PbPb}$ is the multiplicity dependent fraction of the efficiency. The signal extraction has been performed by an unbinned 2-dimensional maximum-likelihood fit to the mass and pseudo-proper decay length distributions. Thanks to the excellent performance of the tracker system, prompt J/ψ and non-prompt J/ψ have been separated in PbPb collisions for the first time (Fig.3).

FIGURE 3. (left) Invariant mass and (right) the pseudo-proper decay length distributions for $\mu^+\mu^-$ pairs.

The central value of R_{AA} for non-prompt J/ψ with $6.5 < p_T < 30$ GeV/c and $|y| < 2.4$ is $0.36 \pm 0.08(stat) \pm 0.03(syst)$ for the 20% most central collisions, and no centrality dependence is found within uncertainties when compared to the 20-100% centrality bin.

In the right panel of Fig.4, the result of R_{AA} for non-prompt J/ψ positioned at the average J/ψ p_T for the centrality bin 0-20% is compared to the R_{AA} for charged hadrons, photons and Z-bosons for the 10% most central collisions. In spite of a small difference in the choice of the centrality bin, this comparison shows that the suppression factor of non-prompt J/ψ is qualitatively similar to that of light charged hadrons at $\sqrt{s_{NN}} = 2.76$ TeV. This could be a first indication of high p_T b -quark quenching in a hot and

FIGURE 4. (Left) R_{AA} of non-prompt J/ψ as a function of N_{part} . (Right) R_{AA} vs. m_T for Z in squares, isolated photons in closed circles and charged hadrons in open circles and b -quark measurement with corresponding p_T .

dense medium [7, 8].

The R_{AA} of prompt J/ψ with $6.5 < p_T < 30$ GeV/ c and $|y| < 2.4$ is shown in Fig.5. A centrality dependent prompt J/ψ suppression is observed. Despite the fact that the center-of-mass energy is lower and J/ψ p_T is much smaller, the PHENIX results [10] show similar suppression patterns. In contrast to the centrality dependence, the rapidity dependence of the J/ψ suppression measured by CMS at high p_T differs from the one measured by PHENIX at low p_T : J/ψ are less suppressed at forward rapidity than at mid-rapidity. There is no strong p_T dependence on the prompt J/ψ R_{AA} and the tendency of high p_T J/ψ 's to survive at RHIC is not seen.

FIGURE 5. (Left) R_{AA} of prompt J/ψ in red squares as measured by CMS as a function of N_{part} . PHENIX data at mid-rapidity in open black squares and at forward rapidity in open blue squares are superimposed. (Center) R_{AA} as a function of η , compared to PHENIX data. (Right) R_{AA} as a function of p_T is compared to PHENIX data and STAR data in green stars.

CMS is able to disentangle $\Upsilon(1S)$ from the higher Υ states in PbPb as well as in pp collisions [7, 9]. The dimuon invariant mass distributions in the Υ mass range are presented in Fig.6 for pp (left) and PbPb (right) collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Single muons are required to have $p_T^\mu > 4$ GeV/ c .

In PbPb collisions, strikingly smaller relative yields of the excited Υ states are observed when compared to pp . In order to quantify this suppression, a simultaneous, ex-

FIGURE 6. The dimuon invariant mass distributions in pp (left) and PbPb (right) collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

tended unbinned maximum likelihood fit to the pp and PbPb mass spectra is performed, following the method described in [9]. The ratio of the $\Upsilon(2S+3S)/\Upsilon(1S)$ ratios in PbPb and pp benefits from an almost complete cancellation of possible acceptance and/or efficiency differences among the reconstructed resonances. The double ratio obtained is

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{\text{PbPb}}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} (\text{stat.}) \pm 0.03 (\text{syst.}). \quad (3)$$

The probability to obtain the measured value, or lower, if the true double ratio is unity, has been calculated to be less than 1%. This corresponds to 2.4σ in a one-tailed integral of a Gaussian distribution.

The $\Upsilon(1S)$ suppression has been studied as a function of p_T , y and centrality as shown on Fig.7. A suppression by a factor of 2.3 has been measured at low p_T which disappears for $p_T > 6.5$ GeV/c. The rapidity dependence indicates a slightly smaller suppression at forward rapidity. Within uncertainties, no centrality dependence is observed. In all cases however, the statistical uncertainties are too large for any strong conclusions.

FIGURE 7. R_{AA} of $\Upsilon(1S)$ as a function of (left) centrality, (center) y and (right) p_T .

Z BOSON PRODUCTION

The Z to $\mu^+\mu^-$ measurement in heavy ion collisions by CMS is described in [11]. Fig.8 shows the differential yields as a function of N_{part} , y and p_T . Within uncertainties,

no modification is observed with respect to theoretical next-to-leading order perturbative quantum chromodynamics proton-proton cross sections scaled by the number of elementary nucleon-nucleon collisions. This measurement confirms the validity of the Glauber scaling for perturbative cross sections in nucleus-nucleus collisions at the LHC and establishes the feasibility of carrying out detailed Z physics studies in heavy ion collisions with the CMS detector.

FIGURE 8. The yields of $Z \rightarrow \mu\mu$ per event: a) dN/dy divided by the T_{AB} and as a function of event centrality parametrized as the N_{part} , b) dN/dy versus the Z boson y , c) $d^2N/dydp_T$ versus the Z boson p_T . Data points are located horizontally at average values measured within a given bin. Vertical lines (bands) correspond to statistical (systematic) uncertainties.

SUMMARY

This paper presented highlights of CMS quarkonia and Z boson measurement in pp and PbPb collisions. The first observation of the suppression of non-prompt J/ψ gives a hint of b -quark energy loss in the medium. Strong suppression of prompt J/ψ is found. The comparison of the ratios of $\Upsilon(1S)$ and $\Upsilon(2S+3S)$ shows smaller relative yields of excited states with respect to the ground state in PbPb collisions than in pp collisions. Furthermore, Υ are suppressed. This is consistent with the partial disappearance of the higher states with respect to the ground state in the PbPb collisions. Reasonable agreement between the Z measurement and theoretical calculations in PbPb collisions indicates that Z is unmodified by the medium.

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