Dimuon results in PbPb and pp collisions in CMS

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Abstract

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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 $J/\psi$ and $\Upsilon$ 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, \( J/\psi \)s can be classified into prompt \( J/\psi \) (primary vertex) and non-prompt \( J/\psi \) (secondary vertex) [4, 5]. Prompt \( J/\psi \)s are composed of \( J/\psi \) from direct production and feed-down from higher order state such as \( \psi' \) and \( \chi_c \). Non-prompt \( J/\psi \)s are dominantly originating from B-hadron decays. Because of the longer life time of B-hadrons, the identification of non-prompt \( J/\psi \) 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

\[
L_{x,y} = \frac{\hat{u}^T \sigma^{-1} \vec{x}}{\hat{u}^T \sigma^{-1} \hat{u}}
\]  

(1)

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

Theoretical calculations compared to prompt and non-prompt \( J/\psi \) 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 \( p_T \).

3 \( \Upsilon \) 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 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 \( \mu b^{-1} \), 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 \( R_{AA} \).

\[
R_{AA} = \frac{L_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}(Q\bar{Q})}{N_{pp}(Q\bar{Q})} \frac{\epsilon_{pp}}{\epsilon_{PbPb}}
\]  

(2)
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 $J/\psi$ and non-prompt $J/\psi$ have been separated in PbPb collisions for the first time (Fig.3).

The central value of $R_{AA}$ for non-prompt $J/\psi$ with $6.5 < p_T < 30$ GeV/$c$ and $|y| < 2.4$ is $0.36 \pm 0.08_{\text{(stat)}} \pm 0.03_{\text{(syst)}}$ 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 $J/\psi$ positioned at the average $J/\psi$ $p_T$ 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 $J/\psi$ 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
dense medium [7, 8].

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

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

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

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

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 2.4 $\sigma$ 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.

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

**REFERENCES**