The Compact Muon Solenoid Experiment
Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

15 December 2016 (v2)

B meson nuclear modification factor in PbPb at 5.02 TeV with CMS

Ta-Wei Wang for the CMS Collaboration

Abstract

The study of beauty production in heavy-ion collisions is considered one of the key measurement to address the flavour-dependence of in-medium energy loss in PbPb collisions. In pPb collisions, studies of b-quark production can also provide insights into the relevance of cold nuclear matter effects in the heavy-flavour sector. The CMS experiment has excellent capabilities for measuring b-quark production thanks to the excellent performances of its muon and tracker system. In this talk, we will present the measurement of nuclear modification factors for fully reconstructed B mesons in pPb, and for the first time, pp and PbPb collisions at 5.02 TeV, as a function of transverse momentum.

Presented at *HardProbes2016 The 8th International Conference on Hard and Electromagnetic Probes of High-energy Nuclear Collisions*

Ta-Wei Wang on behalf of the CMS collaboration

Abstract

The study of beauty production in heavy-ion collisions is considered to be one of the key measurement to address the flavour-dependence of in-medium energy loss in PbPb collisions. The Compact Muon Solenoid (CMS) experiment has excellent capabilities for measuring b-quark production thanks to the excellent performances of its muon and tracker system. In this talk, the measurement of nuclear modification factor of fully reconstructed B mesons for the first time in pp and PbPb collisions at 5.02 TeV as a function of transverse momentum will be presented.

Keywords: Compact Muon Solenoid, Quark Gluon Plasma, Heavy-ion Collisions, B mesons

1. Introduction

Relativistic heavy ion collisions allow the study of quantum chromodynamics (QCD) at very high temperature and density. Under such extreme conditions, a strongly interacting state consisting of deconfined quarks and gluons, the quark-gluon plasma (QGP), is predicted by lattice QCD calculations. Hard-scattered partons are expected to lose energy as they traverse the QGP via elastic collisions and medium-induced gluon radiation. Medium induced energy loss can basically be classified into two categories, collisional and radiative. In spite of the color charge difference which leads to different energy loss behavior between gluons and quarks, quarks themselves also differ from each other. From kinematic consideration, gluon radiation for heavier quarks are expected to be suppressed at small angle comparing to lighter quarks, often referred to as dead cone effect [1].

$$dP \equiv \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_{\perp}^2 dk_{\perp}^2}{(k_{\perp}^2 + \omega^2 \theta_0^2)^2}, \quad \theta_0 \equiv \frac{M}{E} \quad (1)$$

Consequently, the ratio between the two types of energy loss mechanisms changes with quark mass. This effect is expected to be more pronounced as one goes to lower p_T regime. In turns of experimental observables, this suggests that the nuclear modification factors

$$R_{AA} = \frac{dN^{AA}/dp_T}{\langle T_{AA} \rangle d\sigma^{pp}/dp_T} \quad (2)$$

might have a hierarchy pattern: $R_{AA}^b > R_{AA}^c > R_{AA}^{\text{light}}$.

As a result, heavy flavor production measurements could be one of the most direct way to disentangle this energy loss pattern and provides important knowledge about the quark gluon plasma (QGP) such as its transport properties. In this talk, we will present the fully reconstructed B meson R_{AA}^b measurement via $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$ decay channel in heavy ion collision performed by the CMS experiment.

2. B meson reconstruction

The B mesons are measured in a region $|y_{\text{lab}}| < 2.4$ via the full reconstruction the of decay channel: $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$. This analysis does not separate B^+ from B^- for the purposes of reconstruction. Accordingly, for the final cross section values, the results are divided by two to obtain an average. The pp and PbPb data samples used in this analysis correspond to an integrated luminosities of 25.80 pb^{-1} and $350.68 \mu\text{b}^{-1}$, respectively.

A detailed description of the CMS experiment and coordinate system can be found in Ref. [2]. Only the detector subsystems most relevant for this analysis are

described here. Charged particles (tracks) are reconstructed within the range $|\eta_{\text{lab}}| < 2.5$ by using the silicon tracker detector, located in the 3.8 T magnetic field of a superconducting solenoid. Muons are identified in the interval $|\eta_{\text{lab}}| < 2.4$ with gas-ionization detectors made of three technologies: drift tubes, cathode strip chambers, and resistive plate chambers, embedded in the steel flux-return yoke of the magnet. The CMS apparatus also has extensive forward calorimetry, including two steel and quartz-fiber Cherenkov hadron forward (HF) calorimeters, which cover the range $2.9 < |\eta_{\text{lab}}| < 5.2$.

The reconstruction of the B^+ meson candidates are done via the aid of a vertex fitter which calculates the likelihood of a set of trajectories to be originated from a common vertex. The workflow is summarized as the following. 1). Starting with muon and track objects, quality selections are applied. This includes basic cuts such as the p_T , η or impact parameter of the object. 2). Within the selected muon collection, muon pairs are formed with all possible combinations. A common vertex fitting is done to reconstruct a J/ψ candidate for each pair. 3). J/ψ Candidates is then paired with tracks where all the tracks are assumed to have the mass of a K^+ . Common vertex fitting of the J/ψ and K^+ is done to form a B^+ candidate. 4). A multi-variate analysis (MVA) was conducted in order to reach a high signal to background significance. The variables used in MVA are listed below.

To maximally utilize the long decay length feature of the B meson. A MVA cut value optimization procedure is done. This also include cuts on basic kinematic variables to further suppress background contribution. The five variables trained by the MVA are listed as the following:

- track p_T : the transverse momentum of the track
- $|\text{track } \eta|$: the pseudorapidity of the track
- normalized B^+ displacement: the distance between primary and reconstructed B^+ decay vertex normalized by its uncertainty
- χ^2 probability: the χ^2 probability of the common vertex fitting
- $\cos\theta$: cosine value of the angle between B^+ meson displacement and B^+ meson momentum in the transverse plane

The optimal cut values are selected base on maximizing a figure of merit defined as $S / \sqrt{S + B}$.

- S is the number of signal which is derived from theory calculation and simulation.

- B is the number of background contribution which is directly obtained from the side band region of real data.

Once the B^+ candidates are at hand, the invariant mass spectrum can be plotted. To extract the B^+ mesons signal from background, a fitting on the mass spectrum is performed. The fitting function consist of three components.

- A double Gaussian with same mean but different widths to model the signal component.
- A 1st-order polynomial to describe the combinatorial background. This background component is produced by the random combination of a J/ψ with tracks that are not coming from a B^+ decay.
- An error function + a double Gaussian to model the non-prompt J/ψ background component. This component is due to 4-prong B meson decay, e.g., $B^+ \rightarrow J/\psi K^*(892)^+$, that are partially reconstructed as $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$ and can form peaking structures around invariant mass $\approx 5.3 \text{ GeV}/c^2$ and below. These background sources are studied with Monte Carlo samples which simulate all possible B meson decays with a final states J/ψ and found to be well described by a superposition of an asymmetric Gaussian and an error function.

Raw yields can then be extracted in each B meson p_T -interval via the above fitting procedure. Examples of the resulting mass spectrum fitting for B^+ in p_T 10 to 15 GeV/c interval from pp and PbPb data can be seen in Fig 1.

3. Cross section and nuclear modification factor

With the raw yields of B^+ extracted via fitting and the selection efficiency obtained from simulated Monte Carlo samples. The p_T -differential production cross section can be computed in each p_T interval. In Fig. 2, the p_T -differential production cross sections in pp collisions measured in $|\eta_{\text{lab}}| < 2.4$ are presented, with data points placed at the center of each bin. Also shown in the same figure is the predicted cross section obtained from fixed-order plus next-to-leading-logarithm (FONLL) calculations [3, 4]. The obtained B^+ FONLL reference is consistent with the measured pp spectra, similar to what was observed in the measurement conducted in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ [5].

With the corrected yields from pp and PbPb data, the nuclear modification factor R_{AA} can then be computed

Figure 1: Invariant mass distributions of $B^+ + B^-$ candidates in pp (up) and PbPb (down) collisions in the transverse momentum regions 10–15 GeV/c.

as:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{dN_{PbPb}^{B^+}}{dp_T} / \frac{d\sigma_{pp}^{B^+}}{dp_T}. \quad (3)$$

Where $\frac{1}{T_{AA}} \frac{dN_{PbPb}^{B^+}}{dp_T}$ is defined as.

$$\frac{1}{T_{AA}} \frac{dN}{dp_T} \Big|_{|y|<2.4} = \frac{1}{T_{AA}} \frac{1}{2} \frac{1}{\Delta p_T} \frac{N^{B^+} \Big|_{|y|<2.4}}{(\text{Acc } \epsilon) \cdot \text{BR} \cdot N_{events}}. \quad (4)$$

where T_{AA} is the nuclear overlap function. $N(p_T)_{|y|<2.4}$ is the raw signal yield extracted in each p_T interval of width Δp_T , $(\text{Acc } \epsilon)$ represents the corresponding acceptance times efficiency. BR is the branching fraction of the decay chain. N_{events} represents the corre-

Figure 2: The p_T -differential production cross section of B^+ in pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty, listed in the legend, comprises the uncertainties in the integrated luminosity measurement and the B meson branching fractions. Results are compared to FONLL calculations represented by the orange boxes with its width indicating the theory uncertainty.

sponding number of minimum bias events investigated in this analysis. The factor 1/2 accounts for the fact that the yields were measured for particles and antiparticles added together as mentioned above.

The result is shown in Fig 3. A clear suppression of B meson production ($R_{AA} < 1$) in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is observed. The R_{AA} is around 0.3 to 0.6 for B meson p_T from 7 to 50 GeV/c. A few theory predictions are superimposed for comparison. Given the current statistical and systematic uncertainty, CMS measurement is compatible with these theory predictions. To disentangle the flavor dependence energy loss, a comparison with the nuclear modification factor results from CMS D meson [6] and charge hadron [7] analysis is shown in Figure 4. Given the current data statistic, no definite conclusion can be drawn yet.

Figure 3: The nuclear modification factor R_{AA} of B^+ measured in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The statistical and systematic uncertainties on the pp and PbPb data are shown as cross bars and boxes around the data points, respectively. The global systematic uncertainties are shown as full grey boxes at unity, and are not included in the data points. A few theory predictions are also plotted for comparison (M. Djordjevic et al.([8]), M. He et al.([9]), and CUJET3.0([10, 11, 12])).

4. Summary

This is the first measurement of the B^+ meson production cross section in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The B^+ mesons are measured in $|y_{lab}| < 2.4$ and $7 < p_T < 50$ GeV/c via the reconstruction of one of the exclusive hadronic decay channels. The nuclear modification factor of B^+ is measured as a function of the transverse momentum. The production cross section is found to be strongly suppressed in PbPb collisions when compared to the measured pp reference, scaled by the number of incoherent nucleon-nucleon collisions. These measurements provide strong constraints on the phenomenological models which aim to describe the flavor dependence of the in-medium parton energy loss.

References

- [1] Y. Dokshitzer, D. Kharzeev, Heavy-quark colorimetry of qcd matter, *Physics Letters B* 519 (34) (2001) 199 – 206. doi:[http://dx.doi.org/10.1016/S0370-2693\(01\)01130-3](http://dx.doi.org/10.1016/S0370-2693(01)01130-3).
- [2] S. Chatrchyan, et al., The CMS experiment at the CERN LHC, *JINST* 3 (2008) S08004. doi:[10.1088/1748-0221/3/08/S08004](https://doi.org/10.1088/1748-0221/3/08/S08004).
- [3] M. Cacciari, M. Greco, P. Nason, The p_t spectrum in heavy-flavour hadroproduction, *Journal of High Energy Physics* 1998 (05) (1998) 007.
- [4] M. Cacciari, S. Frixione, P. Nason, The p_t spectrum in heavy-flavour photoproduction, *Journal of High Energy Physics* 2001 (03) (2001) 006.

Figure 4: Nuclear modification factor R_{AA} as a function of p_T in the centrality range 0-100%, for B meson (blue), D meson (yellow) and charged particles (orange).

- [5] V. Khachatryan, et al., Measurement of the total and differential inclusive B^+ hadron cross sections in pp collisions at $\sqrt{s} = 13$ TeV arXiv:1609.00873.
- [6] D^0 meson nuclear modification factor in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Tech. Rep. CMS-PAS-HIN-16-001, CERN, Geneva (2016). URL <http://cds.cern.ch/record/2157844>
- [7] Measurement of the charged particle nuclear modification factor in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Tech. Rep. CMS-PAS-HIN-15-015, CERN, Geneva (2016). URL <https://cds.cern.ch/record/2155301>
- [8] M. Djordjevic, B. Blagojevic, L. Zivkovic, Lower vs. high momentum mass tomography in Quark-Gluon Plasmas arXiv:1601.07852.
- [9] M. He, R. J. Fries, R. Rapp, D_s meson as a quantitative probe of diffusion and hadronization in nuclear collisions, *Phys. Rev. Lett.* 110 (2013) 112301. doi:[10.1103/PhysRevLett.110.112301](https://doi.org/10.1103/PhysRevLett.110.112301).
- [10] J. Xu, J. Liao, M. Gyulassy, Bridging soft-hard transport properties of quark-gluon plasmas with cujet3.0, *Journal of High Energy Physics* 2016 (2) (2016) 1–50. doi:[10.1007/JHEP02\(2016\)169](https://doi.org/10.1007/JHEP02(2016)169). URL [http://dx.doi.org/10.1007/JHEP02\(2016\)169](http://dx.doi.org/10.1007/JHEP02(2016)169)
- [11] X. Jiechen, L. Jinfeng, M. Gyulassy, Consistency of perfect fluidity and jet quenching in semi-quark-gluon monopole plasmas, *Chinese Physics Letters* 32 (9) (2015) 092501.
- [12] J. Xu, A. Buzzatti, M. Gyulassy, Azimuthal jet flavor tomography with cujet2.0 of nuclear collisions at rhic and lhc, *Journal of High Energy Physics* 2014 (8) (2014) 1–90. doi:[10.1007/JHEP08\(2014\)063](https://doi.org/10.1007/JHEP08(2014)063). URL [http://dx.doi.org/10.1007/JHEP08\(2014\)063](http://dx.doi.org/10.1007/JHEP08(2014)063)