The Compact Muon Solenoid Experiment
Conference Report

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Open Heavy Flavor Measurement in heavy ion collisions with CMS

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Abstract

The study of heavy quark production may reveal critical features of the medium produced in heavy ion collisions as heavy quarks are sensitive to the transport properties of the medium and may interact differently from light quarks. Non-prompt J/ψ and b jet produced in both 5.02 TeV pPb as well as 2.76 TeV PbPb collision data have been measured with the CMS detector as a function of both rapidity and transverse momentum. Fully reconstructed B mesons in pPb data were also analyzed and along with these measurements, the nuclear modification factors constructed using either a theoretically calculated pp reference or CMS pp collision data will be presented for each analysis and collision systems.

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Abstract

The study of heavy quark production may reveal critical features of the medium produced in heavy ion collisions as heavy quarks are sensitive to the transport properties of the medium and may interact differently from light quarks. Non-prompt J/ψ and b jet produced in both 5.02 TeV pPb as well as 2.76 TeV PbPb collision data have been measured with the CMS detector as a function of both rapidity and transverse momentum. Fully reconstructed B mesons in pPb data were also analyzed and along with these measurements, the nuclear modification factors constructed using either a theoretically calculated pp reference or CMS pp collision data will be presented for each analysis and collision systems.

Keywords: heavy-flavor, quark-gluon-plasma, B-meson, b-jet, quarkonium

1. Introduction

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 evident 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 conference talk, various measurements regarding bottom quark in heavy ion collision performed by the Compact Muon Solenoid (CMS) experiment are presented. Unlike its lighter siblings, b quark can be measured within detector by different means. When a b quark is produced, b hadrons and other collinear hadrons are quickly produced and together form a jet. Because of the relative longer life time of b hadron, it's decay position will be distant away from the primary interaction point and forms a secondary vertex. Base on this picture, three different strategies to probe b quark were employed.

- An inclusive reconstruction of b jets (jets resulting from b quarks).
- Measurements of decay products such as the non-prompt J/ψ particles from b hadrons decay.
- Fully reconstructed B mesons (B^+ , B_0 , B_s).

In the following sections, the three approaches will be introduced and presented separately.

2. b jets

The b jet measurements were performed in both PbPb [2] and pPb [3] collision data with a common workflow as the following. The very first step is jet

Figure 1: b jet R_{AA} binned in two p_T range as a function of number of collision participant.

reconstruction and identification of b jets. The identification of b jets in CMS made use of the so called "Secondary Vertex" (SV) tagger which clusters charged tracks with $p_T > 1$ GeV/c within a 0.3 jet cone to form a (secondary) vertex. Base on this tagger, one can then distinguish b jets from other jets by selecting on the significance of the 3D distance between this displaced vertex and the primary vertex. With b tagged jets at hand, one then need to determine the purity of this tagged jet collection, i.e., b tagged jets coming from genuine b quarks, or equivalently the mis-tagged rate that comes from other types of quark, especially the c quark. Since b jet SV mass is higher than c jet, the determination can be done via a template fit on the SV mass spectrum with templates obtained from simulation. The final step is to calculate the efficiency associated with all the selection criteria being used including the SV tagger as well as corrections for the detector resolution.

Using the pp data at the same collision energy as reference, the nuclear modification factor of b jet in PbPb collision (R_{AA}) can be calculated as shown in Figure 1. A clear suppression, i.e., $R_{AA} < 1$, of b jet production is observed. Furthermore, the suppression is larger in more central collision events which have higher number of collision participants (N_{part}).

Similar quantity (R_{pA}^{PYTHIA}) can be computed in pPb collision. Spectra from PYTHIA[4], tune Z2, simulation was used as pp collision reference. The results are shown in Figure 2. In the pPb case, R_{pA} is consistent with unity throughout the measured range which suggests that the suppression observed in PbPb might not be coming from the cold nuclear matter effect.

Figure 2: b jet R_{pA}^{PYTHIA} as a function of b jet p_T .

3. Non-prompt J/ψ

As mentioned previously, one can also measure the decay products of b hadrons to indirectly probe the b quark properties. Non-prompt J/ψ , i.e., J/ψ produced at a displaced vertex, is the ideal candidate for this study as its production is dominantly coming from b hadrons decay. In addition, profit from the outstanding performance of CMS muon chamber and tracking system, J/ψ can be well reconstructed as dimuon resonance. The analysis [5, 6] proceeds as the following. Muon pairs selected and passed to a vertex fitter which calculates the compatibility for the input tracks to form a secondary vertex. Selections are made based on the compatibility. On top of the selected pairs, invariant mass (Figure 3) and proper decay length spectra can be created. Non-prompt J/ψ are then extracted by a simultaneous fitting on both spectra in order to separate the prompt and combinatorial background components. Extracted yields are then subjected to corrections regarding detector acceptance and selection efficiency which are obtained from simulation. Potential differences in correction factors between simulation and data are cross checked by the "tag and probe" data-driven technique.

Resulting R_{AA} are shown in Figure 4 where R_{AA} of J/ψ in $1.6 < |\eta| < 2.4$ region binned in two p_T range are plotted as a function of N_{part} . Slow increase of suppression in more central collisions is again observed. A potential hint that low p_T is less suppressed in the forward region can also be seen.

Due to the lack of pp data at the same collision energy as pPb collision and a reliable theoretical calculation to serve as pp reference, R_{pA} was not calculated in the pPb analysis. Instead, forward backward asymmetry, R_{FB} , which is the ratio between the number of forward moving J/ψ to backward moving one is calculated. Because of the nuclear shadowing effect which

Figure 3: J/ψ invariant mass spectrum, the three components correspond to prompt (black), non-prompt (red) J/ψ and background (blue).

Figure 4: R_{AA} of Non-prompt J/ψ in $1.6 < |\eta| < 2.4$ region binned in two p_T range as a function of number of collision participants in the event.

predicts a depletion of low x partons inside a nucleus, proton side and Pb side will have different production cross sections. For a forward moving proton colliding with a backward moving lead ion, this means that the outgoing forward moving low p_T J/ψ which is produced by sampling the low x part of the lead ion will be more suppressed. The pPb analysis had confirm this to be truly the case as shown in Figure 5 where a smaller than unity R_{FB} is presented for low p_T while no dependence to rapidity is observed.

4. B mesons

Although lower statistics available due to smaller reconstruction efficiency comparing to other methods, measurement of fully reconstructed B meson decay in

Figure 5: The forward backward asymmetry R_{FB} of Non-prompt J/ψ in three different η range.

principal is a more direct probe to the b quark kinematics compared to non-prompt j/ψ . In pPb collisions, three different B meson decay channels, $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- \pi^-$, $B^0 \rightarrow J/\psi K^* \rightarrow \mu^+ \mu^- K^+ \pi^-$, $B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$, were analyzed [7]. Similar to the J/ψ analysis, J/ψ candidates are first reconstructed from muon pairs via a vertex fitter. Charged tracks are selected and attached to the J/ψ vertex to form B candidates. The same vertex fitter is then utilized again to calculate the vertex compatibility of the B candidates. By fitting the B meson invariant mass spectra, yields are extracted and corrected for various efficiency and acceptance factors. Shown in Figure 6 are the R_{pA}^{FONLL} of various B mesons measured in pPb data. FONLL theoretical calculation [8] is used here as pp reference. Similar to what is observed in b jet analysis, no suppression of B meson production in pPb collision is observed.

For the PbPb case, current CMS collision data were not enough for a precise measurement of R_{AA} yet. However, a preliminary detector performance plot of B^+ mass spectrum using current CMS PbPb collision data is shown in Figure 7 which demonstrates the ability of CMS detector for full reconstruction of B meson in the high multiplicity PbPb collision environment. It is worthy to note that this is also the first ever fully reconstructed B mesons in nucleus nucleus collision. In the coming Run 2 of CMS heavy ion collision with an increased luminosity and higher collision energy, a factor of 20 or more increase in B meson statistic is therefore expected. Therefore accurate measurements of different types of B mesons (B^+ , B^0 and B_s) R_{AA} will be a very promising and important topic which makes accurate B meson nuclear modification factor measurements possible.

Figure 6: R_{pA} of three different B mesons, B^+ , B^0 and B_s^0 from left to right, as a function of B meson p_T

Figure 7: Invariant mass spectrum of B^+ reconstructed from CMS PbPb collision data.

5. Summary

The measurements of b quark energy loss and cold nuclear effects from CMS are summarized. Three different analysis strategies complemented to each other had merged to a consistent result. Clear evidence of suppression had been observed in both b jet and non-prompt J/ψ analysis in PbPb data. In addition, both of them show a trend of decreasing R_{AA} in more central collision events. On the other hand, no suppression was observed in pPb collision in either b jet or B meson production measurements.

With the scheduled Run 2 of LHC, a much larger dataset will be accumulated and enable CMS to explore more possibilities in the heavy flavor field. The aforementioned B meson PbPb analysis will certainly be one

of the most important aim. For c quark related physics, the reconstruction of c jets which is challenging because of its smaller multiplicity and softer vertices as well as the measurement of fully reconstructed D mesons are both part of the plan. A revamped version of current analysis will also be very crucial to provide a more precise result. Hopefully, all these interesting physics results together will shed more light on the transport properties of the Quark Gluon Plasma.

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