PROCEEDINGS OF SCIENCE

Heavy flavor production in heavy ions with the CMS detector

Matthew Nguyen for the CMS Collaboration[*†]
Laboratoire Leprince-Ringuet / Ecole Polytechnique
E-mail: Matthew.Nguyen@cern.ch

We review recent results relating to beauty production in heavy-ion collisions, in both the closed and open heavy flavor sectors, from the CMS experiment at the LHC. The sequential suppression of the Υ states in PbPb collisions is thought to be evidence of the dissociation of quarkonia bound states in deconfined matter. Data from pPb collisions demonstrate that while cold nuclear effects appear to be subdominant in minimum bias collisions, there exists a non-trivial dependence on collision multiplicity that remains to be understood. The suppression of high p_{T} particles in heavy-ion collisions, relative to the expectation from pp collisions, is typically interpreted in terms of energy loss of hard scattered parton in the dense nuclear medium. The flavor dependence of the energy loss may be accessed via measurements of b hadrons and b-tagged jets. Measurement of B mesons, via non-prompt J/ψ, at relatively low p_{T} indicate a smaller suppression factor than D meson or inclusive charged hadrons. Data on b jets at larger values of p_{T} show no significant difference between the suppression factors of b jets and inclusive jets. In both cases a number of other potential effects need to be precisely understood before the flavor dependence of parton energy loss can be understood in detail.

The 15th International Conference on B-Physics at Frontier Machines at the University of Edinburgh, 14 -18 July, 2014
University of Edinburgh, UK

[*]Speaker.
[†]On behalf of the CMS collaboration

PoS(Beauty2014)017

1. Introduction

Heavy flavor has long been a topic of interest in collisions of heavy ions. Such collisions are known to access a region of the QCD phase diagram in which novel features emerge, most notably the creation of a quark-gluon plasma (QGP), which is characterized by an effective deconfinement, such that the degrees of freedom in the equation of state correspond to those of the partons. One of the early proposed signatures of the QGP was the screening of the potential binding quarkonia [1], which was indeed observed as a suppression in the J/ψ yield compared to expectation at the CERN SPS [2]. The anomalous dissociation due to QGP formation must be disentangled from so-called cold nuclear matter effects, which may be studied in proton-nucleus collisions. Such effects are expected from the initial state, via modification of the nuclear parton distributions, as studied in Ref. [3]. Final state effects, particularly nuclear absorption, were studied in detail at the SPS, for example in Ref. [4]. Even interference effects in the form of energy loss may be important [5]. In addition to such cold nuclear matters effects, quarkonia may also be regenerated [6], which is thought to explain the smaller suppression observed in central PbPb collisions at forward rapidity ($2.5 < y < 4$) at the LHC compared to AuAu at RHIC ($1.2 < y < 2.2$) [7].

Another signature of QGP formation is the quenching of high p_{T} jets as the result of energy loss as the parton traverses the hot dense matter [8]. The phenomenon provides a means to study the interaction of hard scattered partons with the QGP, and ultimately to use these partons as tomographic probes of this medium's properties. One of the outstanding issues in the field is the flavor dependence of parton energy loss. Gluons are expected to lose more energy than quarks, due to the larger color factor for gluon radiation from a gluon than from a quark. Moreover, gluon radiation from heavy quarks is expected to be suppressed in the direction of propagation, for parton energies comparable to the quark mass. By comparing measurements of b hadrons and b jets to their light counterparts, we may test our fundamental understanding of this phenomenon.

Due to the large cross section of bottom quarks at TeV energies, the heavy-ion program at the LHC brings with it the possibility to cleanly study bottom quark observables, both in the open and closed heavy flavor sectors. The CMS detector is very well suited for this purpose. The large magnetic field and high precision silicon tracker allows for the separation of the three upsilon states. The impact parameter resolution of the tracker is sufficient to separate decays of b hadrons from the primary collision vertex, which enables topological reconstruction of B meson decays and – combined with its jet reconstruction capabilities – permits b-jet tagging.

2. Bottomonium

The invariant mass distribution of dimuons in the vicinity of the Υ states in 2.76 TeV PbPb collisions is shown in Fig. 1 (left) [9]. Using a selection of muon p_{T} >4 GeV/c, the $1S$ and $2s$ states are clearly visible, while the statistical precision is insufficient to see a clear $3s$ peak. The PbPb data are compared to the lineshape extracted from pp data at the same center of mass energy. The pp lineshape has been scaled by the mean number of individual nucleon-nucleon collisions, in order to give the expectation for PbPb collisions in the absence of nuclear effects. The data show a clear suppression in the yield of all three Υ states, although the excited states are more suppressed. This is quantified on the left panel, which shows the nuclear modification factor (R_{AA}), which is the ratio of the PbPb to the scaled pp data. R_{AA} is plotted vs. the number of participating nucleons, a quantity correlated to the geometrical overlap of the nuclei, i.e., their centrality. In the most central collisions,the $1S$ state shows an R_{AA} approaching about 0.4, while the $2S$ state clearly shows a larger suppression, with a value of around 0.1. The $1S$ is known to have a feed-down contribution of $50.8 \pm 8.2 \pm 9.0\%$ [10, 11]. As the $1S$ is the most tightly bound state, the simplest explanation for the data is that QGP is hot enough to dissociate the excited states while ground state survives.

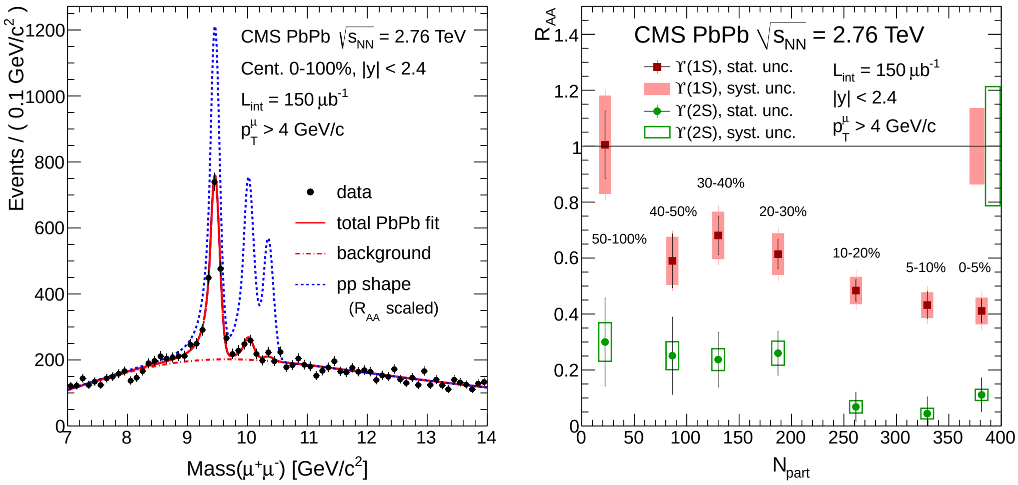

Figure 1: Left: Dimuon invariant mass spectrum in PbPb collisions showing the fits used to extract the yields of the Υ states as well as the corresponding line shape from pp collisions. Right: R_{AA} as a function of the number of participating nucleons for the $1S$ and $2S$ states.

A quantitative description of Υ dissociation in a QGP relies on a detailed understanding of cold nuclear matter effects, which may be explored more readily in pPb collisions. CMS has measured the excited to ground state ratio in pp, pPb and PbPb collisions for both the $2S$ and $3S$, as shown in Fig. 2 (left) [12]. The data show a modest modification in this ratio of around 20% is already present comparing pPb to pp collisions, but that this modification is small compared to that of PbPb collisions. One may try to study the effect more differentially, to observe the turn-on of effects in a particular class of events. Whereas in PbPb collisions, quantities related to global event activity (multiplicity, sum E_T, etc.), are strongly correlated to the underlying event geometry, this is not the case in pPb collisions, where fluctuations in particle production play a larger role. As a consequence, the ratio of excited to ground states are independent of the sum E_T in the forward calorimeters, the quantity mostly used by CMS to define collision centrality. One may also explore the dependence on the track multiplicity $|y| < 2.4$, as shown on the right panel of Fig. 2. A clear decrease in the ratio $2S/1S$ is observed with increasing multiplicity in pPb collisions. A similar effect, with at least as strong of a dependence is observed in pp, while the statistical precision in PbPb precludes an observation of such an effect. The effect may be an indication of final state effects which are related to the local particle density. Alternatively, they may be related to differences in associated particle production between the ground and excited states, which then biases the overall multiplicity measurement. These observations call for studies of Υ-hadron correlations in to clarify the role of final state cold nuclear matter effects.

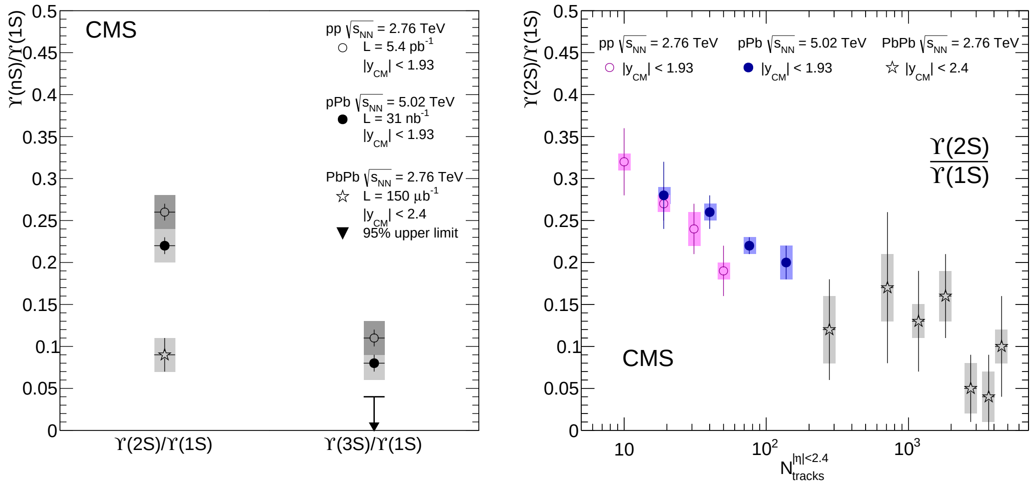

Figure 2: Left: Excited to ground-state ratios for Υ in pPb collisions. Right: The ratio $\Upsilon(2S)/\Upsilon(1S)$ vs the number of reconstructed tracks in pp, pPb and PbPb collisions. Figures from Ref. [12].

3. Open beauty

With the CMS tracking system, the non-prompt component of J/ψ production, i.e., the part from feed-down from b hadrons, can be clearly identified by measuring the apparent lifetime from the dimuon vertex. The measured R_{AA} of non-prompt J/ψ, shown in Fig. 3, is found to show significantly less suppression than is found for inclusive charged particles or for D mesons [13, 14]. This observation is consistent with a decreased suppression for bottom quarks, compared to lighter flavors, although the different production spectrum and fragmentation of b quarks should also contributes to an increased value of R_{AA} at these values of p_T. The right panel of Fig 3, shows the R_{pA} of $B^{\pm}$ mesons, reconstructed from the decay $B^{\pm} \to J/\psi + K^{\pm}$ [15]. A FONLL baseline [16] is used to construct R_{pA}, as pp data at the same center of mass energy were not available. The data verify that no strong nuclear effects are present in pPb collisions, within a precision of about 20%.

At larger values of p_{T} one may attempt to move beyond level of single hadron measurements, and reconstruct jets associated to bottom quark fragmentation. This is achieved by searching for the secondary vertices from b-hadron decays using charged particle tracks within the jet. The mass distribution of secondary vertices in PbPb collisions, after a selection on the secondary vertex flight distance significance, is shown in Fig. 4 (left) [17]. The shapes of the mass distributions in simulation are used to perform a template fit to extract the b-jet contribution. The b-tagging efficiency is derived from simulation and cross-checked using an alternative tagging strategy. The right panel of Fig. 4 shows the resulting R_{AA} for b jets. The results are compared to theoretical calculations from [18] and are found to agree within uncertainties with the R_{AA} of inclusive jets. It should be noted, however, that a sizable fraction of identified b jets are not primary, but come from the final state splitting of gluons into b-quark pairs, such that their progenitor partons may traverse the plasma as gluons. Future measurements at increased luminosity should focus on tagging pairs of b jets in the back-to-back configuration where this gluon splitting contribution is much reduced.

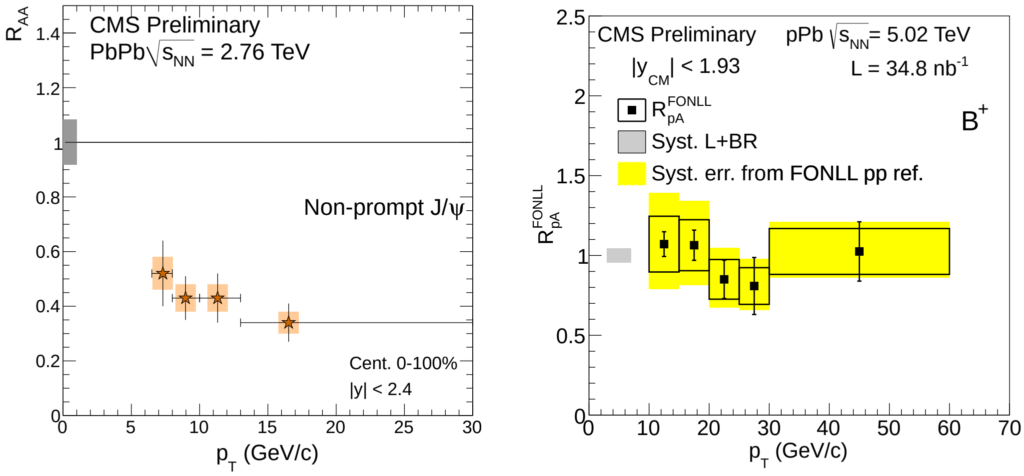

Figure 3: Left: R_{AA} of non-prompt J/ψ vs. p_{T} [13]. Right: R_{pA} of $B^{\pm}$ mesons vs p_{T} [15].

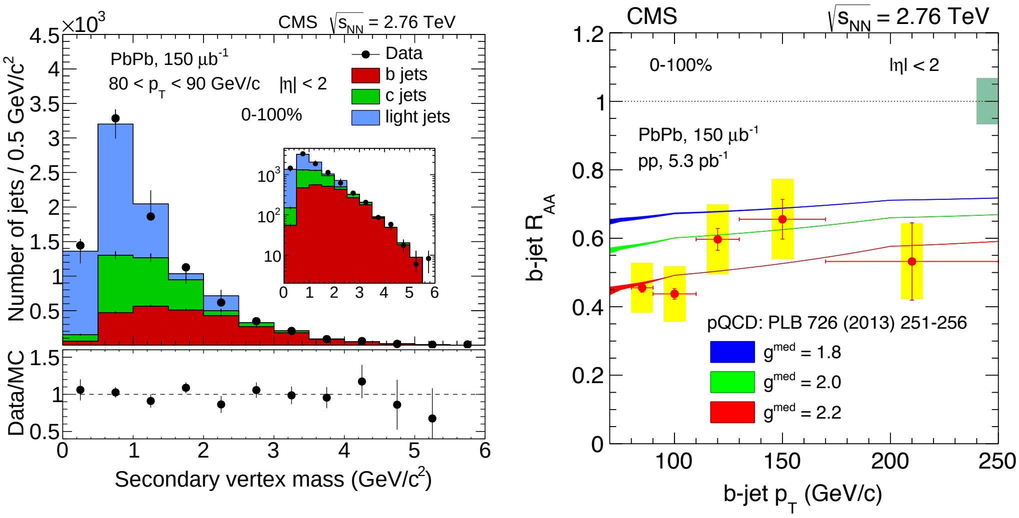

Figure 4: Left: Mass distribution of secondary vertices associated to jets. Right: R_{AA} of b jets vs. p_{T}, compared to theoretical calculations from Ref [18]. Figures are from Ref. [17].

4. Conclusions

The LHC heavy ion program has opened up the possibility to study the physics of the b quark in the QGP. Measurements of the Υ states in PbPb collisions indicate that the QGP temperature is such that the excited states dissociates, while the ground state survives. Measurements from pPb collisions show a dependence on charge particle multiplicity that remains to be understood and could have implications for the quantitative interpretation of the PbPb data. Measurements of open heavy flavor via b hadrons and b jets show hints of a flavor dependence of parton energy loss at low p_{T}, but not at large p_{T}. In addition to the necessary larger precision for these observables, the upcoming LHC Run 2 will enable new observables such as b-tagged dijets, which will allow to discriminate flavor dependent effects more precisely.

References

[1] T. Matsui and H. Satz. J/ψ suppression by quark-gluon plasma formation. *Phys.Lett.*, B178:416, 1986.

[2] M.C. Abreu et al. Evidence for deconfinement of quarks and gluons from the J/ψ suppression pattern measured in Pb + Pb collisions at the CERN SPS. *Phys.Lett.*, B477:28–36, 2000.

[3] K.J. Eskola, V.J. Kolhinen, and R. Vogt. Obtaining the nuclear gluon distribution from heavy quark decays to lepton pairs in pA collisions. *Nucl.Phys.*, A696:729–746, 2001.

[4] B. Alessandro et al. Charmonium production and nuclear absorption in pA interactions at 450-GeV. *Eur.Phys.J.*, C33:31–40, 2004.

[5] F. Arleo and S. Peigné. Quarkonium suppression in heavy-ion collisions from coherent energy loss in cold nuclear matter. 2014. arXiv:1407.5054.

[6] P. Braun-Munzinger and J. Stachel. (Non)thermal aspects of charmonium production and a new look at J/ψ suppression. *Phys.Lett.*, B490:196–202, 2000.

[7] A. Adare et al. J/ψ suppression at forward rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys.Rev.*, C84:054912, 2011.

[8] J. D. Bjorken. Energy loss of energetic patrons in quark-gluon plasma: Possible extinction of jets in hadron-hadron collisions, 1982. Fermilab-Pub-82/59-THY.

[9] Serguei Chatrchyan et al. Observation of sequential Upsilon suppression in PbPb collisions. *Phys.Rev.Lett.*, 109:222301, 2012.

[10] D. Acosta et al. Υ production and polarization in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$-TeV. *Phys.Rev.Lett.*, 88:161802, 2002.

[11] T. Affolder et al. Production of $\Upsilon(1S)$ mesons from χ_b decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. *Phys.Rev.Lett.*, 84:2094–2099, 2000.

[12] S. Chatrchyan et al. Event activity dependence of Υ(nS) production in $\sqrt{s_{NN}}$=5.02 TeV pPb and $\sqrt{s}$=2.76 TeV pp collisions. *JHEP*, 1404:103, 2014.

[13] CMS Collaboration. Prompt and non-prompt J/ψ R_{AA} with 150 μb^{-1} integrated PbPb luminosity at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV, 2012. CMS-PAS-HIN-12-014.

[14] Betty Abelev et al. Suppression of high transverse momentum D mesons in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *JHEP*, 1209:112, 2012.

[15] CMS Collaboration. Measurements of the B^+, B^0 and B^0_{s} production cross sections in pPb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, 2014. CMS-PAS-HIN-14-004.

[16] M. Cacciari et al. Theoretical predictions for charm and bottom production at the LHC. *JHEP*, 1210:137, 2012.

[17] S. Chatrchyan et al. Evidence of b-jet quenching in PbPb collisions at $\sqrt{s_{[NN}}$ = 2.76 TeV. *Phys.Rev.Lett.*, 113:132301, 2014.

[18] J. Huang, Z.-B. Kang, and I. Vitev. Inclusive b-jet production in heavy ion collisions at the LHC. *Phys.Lett.*, B726:251–256, 2013.