Studies of Heavy Flavored Jets with CMS

Kurt Eduard Jung for the CMS Collaboration

Abstract

The energy loss of jets in heavy-ion collisions is expected to depend on the mass and flavor of the initiating parton. Thus, measurements of jet quenching with identified partons place powerful constraints on the thermodynamic and transport properties of the hot and dense medium. We present recent results of heavy flavor jet spectra and nuclear modification factors of jets associated to charm and bottom quarks in both pPb and PbPb collisions. New measurements to be presented include the dijet asymmetry of pairs of b-jets in PbPb collisions and a finalized c-jet measurement in pPb collisions based on new data collected during the 2015 heavy-ion run period at the LHC.

Presented at QM2017 Quark Matter 2017, XXVI international conference on ultrarelativistic heavy-ion collisions
Studies of Heavy Flavored Jets with CMS

Kurt Jung
for the CMS Collaboration

Dept. of Physics, University of Illinois at Chicago
845 W. Taylor St., Chicago, IL 60607

Abstract
The energy loss of jets in heavy-ion collisions is expected to depend on the mass and flavor of the initiating parton. Thus, measurements of jet quenching with identified partons place powerful constraints on the thermodynamic and transport properties of the hot and dense medium. We present recent results of heavy flavor jet spectra and nuclear modification factors of jets associated to charm and bottom quarks in both pPb and PbPb collisions. New measurements to be presented include the dijet asymmetry of pairs of b-jets in PbPb collisions and a finalized c-jet measurement in pPb collisions based on new data collected during the 2015 heavy-ion run period at the LHC.

Keywords: heavy-ion, jet, heavy flavor, energy loss, quenching

1. Introduction
The energy loss of highly energetic partons in large collision systems (e.g. PbPb or AuAu) is thought to be due to a process known as “jet quenching.” This effect stems from interactions of the jet with the hot and dense medium known as Quark Gluon Plasma, thought to be created in such collisions. Furthermore, measurements of jet quenching are expected to depend on the flavor of the parton through two primary mechanisms. First, since partons are expected to lose energy primarily through radiative and collisional means [1, 2] and these processes are thought to include mass-dependent effects, it is likely that the interactions of the partons with the medium are modified differently with respect to light partons [3, 4]. Second, variations in the quark and gluon components of a particular jet sample can dramatically influence the amount of quenching that a typical jet in the sample might see. An inclusive-jet measurement typically contains a large fraction of jets seeded by high-\(p_T\) gluons, while a measurement of tagged b-jets, for example, will contain significantly fewer gluon-seeded jets. Under the assumption that radiative energy loss is a dominant component of jet quenching, gluon jets are expected to quench more strongly than quark jets, due to the larger color factor for gluon emission from gluons than from quarks [5].

Email address: kurtjung@uic.edu (Kurt Jung for the CMS Collaboration)
New measurements in the heavy flavor jet sector for this conference are finalized measurements of charm-tagged jets [6], as well as measurements of di-b-jets [7]. Charm-tagged jets are identified in proton-lead (pPb) collisions, primarily to test effects of initial-state “cold nuclear matter” processes on jet production. This first ever measurement of an inclusive cross-section of jets from charm quarks will shed light on the nature of the charm jet process and open the door to further exploration of the charm-tagged sector at high energies. Measurements of di-b-jets are performed in PbPb collisions and aim to separate the quenching strength of various b-jet production mechanisms. At LHC energies, it is thought that next-to-leading order production mechanisms should dominate the overall b-jet production [8], so processes like gluon splitting, where a highly energetic gluon splits into a b̅b pair, ought to contribute significantly to an inclusive b-jet measurement. While gluon splitting events may not suffer quenching effects in the same way as leading order processes, these high-$p_T$ gluons are still highly virtual and may experience the great majority of the medium evolution. Nevertheless, by requiring back-to-back di-b-jet production, leading order processes are preferentially selected in order to directly test b-jet quenching instead of convoluting the measurement with gluon splitting events.

Here the CMS Collaboration [9] presents measurements of inclusive b-jet cross-sections of 2.76 TeV PbPb collisions [10] and 5.02 TeV pPb collisions [11], as well as inclusive charm-jet cross-sections of 5.02 TeV pPb collisions [6]. These measurements are compared to pp collisions at the corresponding center-of-mass energies in order to extract the magnitude of jet quenching effects. Finally, di-b-jets are measured in 5.02 TeV PbPb collisions and are compared to inclusive dijet measurements at the same center-of-mass energy [7].

2. Identification of Flavored Jets

2.1. Inclusive flavored-jets

Jets containing heavy quarks are identified via quantities that exploit the relatively long lifetimes of b quarks and c quarks. Reconstructed secondary vertices are used to identify both b- and c-jets, though different kinematic requirements are imposed on the vertices when tagging b- or c-jets. While b-jets are tagged via the presence of a secondary vertex with a flight distance significance greater than 2 standard deviations away from the primary vertex, c-jets are tagged using secondary vertices with a flight distance significance at least 1.68 standard deviations away from the primary vertex. Once the jets are tagged, the tagging purity is calculated using template fits to distributions of the secondary vertex mass (b-jets) and an analog of secondary vertex mass with an additional correction factor to account for non-reconstructed particles associated to the vertex (c-jets). The correction for missing particles is required in order to provide enough discrimination power between b- and c-jets such that the template fits accurately calculate all three flavor contributions (light, c, and b) simultaneously in a sample. The maximum b-tagging purity achieved is roughly 60%, while the maximum c-tagging purity is roughly 30%. For further details, see the b-jet [11] and c-jet [6] publications.

2.2. Flavored dijets

The dijet analysis uses a more advanced b-jet identification strategy which makes use of machine learning algorithms that effectively combine information from secondary vertices, leptons, and single-tracks associated to jets. A boosted decision tree is used to combine more than 60 different parameters such that a b-jet purity on the order of 90% is achieved. After tagging jets with the boosted decision tree, combinatorial background is removed by calculating the yield of dijet pairs close together in azimuthal angle ($\Delta \phi < \pi/3$) and subtracting that yield over the entire azimuthal range, exploiting the fact that random combinatorial jet pairs should have a flat $\Delta \phi$ distribution. In addition, correction factors are derived to account for the cases where a random uncorrelated jet is selected as the “subleading” jet instead of the true partner jet to a leading jet. This correction factor is highly $p_T$ and centrality-dependent, ranging from about 50% at 40 GeV to a negligible value at 100 GeV. Finally, the sample is corrected for mistagging a light jet as a b-jet by inverting the b-tagging selection and subtracting away the yields of the inverted selection, taking into account the tagging purity as derived from simulation. More details can be seen in the di-b-jet preliminary document [7].
3. Results

One of the primary tools used to investigate dijets is the quantity \( x_j \), which is the ratio of the subleading jet \( p_T \) divided by the leading jet \( p_T \). By construction, this quantity will range up to a value of one and will depend on the kinematic cuts used for the jet selection. The di-b-jet measurement uses a leading jet \( p_T \) selection of 100 GeV and a subleading jet \( p_T \) selection of 40 GeV, where the two jets are required to be larger than \( \Delta \theta > 2 \pi / 3 \). This selection leads to an average \( \langle x_j \rangle = 0.7 \) for b-jets in pp and between 0.6 and 0.7 for b-jets in PbPb, depending on collision centrality. When these values are compared to those for inclusive-jets, we observe similar \( \langle x_j \rangle \) values in all centrality bins, indicating a lack of significant quenching effects for b-jets as compared to inclusive-jets. The differences between the average \( x_j \) values for dijets in PbPb and pp collisions are shown in Fig. 1 (left). While both the inclusive jets and the b-jets show a significant trend as a function of centrality, which indicates the presence of jet quenching, the trend is similar for both jet species. Figure 1 (right) shows the ratios of the \( x_j \) values for b-jets and inclusive jets. The ratios do not deviate from unity by more than \( \approx 1 \) standard deviation. The similarity of both these distributions suggests that (at least at high-\( p_T \)), leading-order b-jets behave like light jets. This strengthens the conclusions of previous inclusive b-jet measurements [10, 11], which show similar quenching behavior between inclusive and b-jets.

Measurements of flavor-tagged jets in pPb collisions are expected to probe initial-state nuclear effects, like nuclear parton distribution functions, rather than quenching, as a medium ought not to be produced in these smaller collisions. Measurements of a quantity known as \( R_{pA} \) are used to measure the modification of jets in a nuclear collision relative to a proton-proton collision. The \( R_{pA} \) value is defined as:

\[
R_{pA} = \frac{1}{A} \frac{d\sigma_{pPb}}{dp_T} / d\sigma_{pp}/dp_T.
\]

where \( A \) is the nuclear mass number (Pb = 208), included in order to account for the purely geometrical enhancement of jet production based on the additional number of hard scatterings in pPb collisions relative to pp collisions. When the \( R_{pA} \) is measured for b-jets in Fig. 2 (left) and for c-jets in Fig. 2 (right, lower panel), we observe consistency with unity, indicating no modification of flavored jet production in pPb relative to pp collisions. The conclusion is complicated somewhat by the use of a Pythia 6 simulation [12] as a stand-in for 5 TeV pp data in the b-jet \( R_{pA} \) measurement, as no 5 TeV pp data existed at the time of the measurement. To account for this, a 22% uncertainty was assigned to the pp reference to account for residual differences.
in the b-jet cross-section between simulation and data, derived from 7 TeV pp measurements. Within these uncertainties, we conclude that both the b-jet and c-jet $R_{pA}$ values are consistent with unity and with each other. The theme of a lack of heavy-flavor suppression relative to inclusive-jet suppression continues when these measurements are compared to the CMS measurement of inclusive-jet $R_{pA}$ [13]. While some tension between the measurements might be claimed at first glance, it must be noted that all three measurements use different pp references, some of which carry large uncertainties that immediately alleviate any tension that one might claim.

Fig. 2. The $R_{pA}$ values for b-jets (left [11]) and c-jets (right, lower panel [6]) are shown as a function of jet $p_T$. The b-jet measurements are compared to a prediction including only energy-loss effects from Vitev., et. al. [3]. The upper panel of the right figure shows the c-jet cross-sections in pp and pPb, where the pPb spectrum is scaled by the mass number of Pb. Also shown are uncertainties from luminosity on both figures, as well as a pp reference uncertainty on the b-jet measurement.

References
[1] H. van Hees, R. Rapp, Thermalization of heavy quarks in the quark-gluon plasma, Phys. Rev. C 71 (2005) 034907. arXiv:nucl-th/0412015, doi:10.1103/PhysRevC.71.034907.
[2] G.D. Moore, D. Teaney, How much do heavy quarks thermalize in a heavy ion collision?, Phys. Rev. C 71 (2005) 064904. arXiv:hep-ph/0412346, doi:10.1103/PhysRevC.71.064904.
[3] J. Huang, Z. B. Kang, I. Vitev, Inclusive b-jet production in heavy ion collisions at the LHC, Phys. Lett. B 726 (2013) 251. arXiv:1306.0909, doi:10.1016/j.physletb.2013.08.009.
[4] D. K. Yu.L. Dokshitzer, Heavy quark calorimetry of QCD matter, Phys. Lett. B 519 (2001) 199. arXiv:hep-ph/0010553, doi:10.1016/S0370-2693(01)00530-9.
[5] D. d’Enterria, Jet quenching, Vol. 23, Springer Materials, 2010, Ch. 6.4. arXiv:0902.2011, doi:10.1007/978-3-642-01539-7.
[6] V. Khachatryan, et al., Measurements of the charm jet cross section and nuclear modification factor in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Lett. B to appear. arXiv:1612.08972.
[7] CMS Collaboration, Transverse momentum balance of b-jet pairs in pPb collisions at 5 TeV (2016). URL http://cds.cern.ch/record/2202805
[8] A. Banfi, G. P. Salam, G. Zanderighi, Accurate QCD predictions for heavy-quark jets at the Tevatron and LHC, JHEP 07 (2007) 026. arXiv:0704.2999, doi:10.1088/1126-6708/2007/07/026.
[9] S. Chatrchyan, et al., The CMS experiment at the CERN LHC, JINST 3 (2008) S08004.
[10] S. Chatrchyan, et al., Evidence of b-jet quenching in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. Lett. 113 (2014) 132301. doi:10.1103/PhysRevLett.113.132301.
[11] V. Khachatryan, et al., Transverse momentum spectra of b jets in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Lett. B 754 (2016) 59. arXiv:1510.03373, doi:10.1016/j.physletb.2016.10.010.
[12] R. Field, Min-bias and the underlying event at the LHC, Acta Phys. Polon. B 42 (2011) 2631. arXiv:1110.5530, doi:10.5506/APhysPolB.42.2631.
[13] V. Khachatryan, et al., Measurement of inclusive jet nuclear modification factor in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Eur. Phys. J. C 76 (2016) 372. arXiv:1601.02001, doi:10.1140/epjc/s10052-016-4205-7.