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Evidence of b-jet quenching in PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$

The CMS Collaboration*

Abstract

The production of jets associated to bottom quarks is measured for the first time in PbPb collisions at a center-of-mass energy of 2.76 TeV per nucleon pair. Jet spectra are reported in the transverse momentum (p_{T}) range of 80–250 GeV/c, and within pseudorapidity $|\eta| < 2$. The nuclear modification factor (R_{AA}) calculated from these spectra shows a strong suppression in the b-jet yield in PbPb collisions relative to the yield observed in pp collisions at the same energy. The suppression persists to the largest values of p_{T} studied, and is centrality dependent. The R_{AA} is about 0.4 in the most central events, similar to previous observations for inclusive jets. This implies that jet quenching does not have a strong dependence on parton mass and flavor in the jet p_{T} range studied.

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By colliding heavy nuclei at the Large Hadron Collider (LHC), one expects to reach sufficiently large energy densities to form a quark-gluon plasma (QGP), a state which is characterized by effective deconfinement of the color degrees of freedom [1, 2]. Hard-scattered partons are expected to suffer energy loss as they traverse the QGP via elastic and inelastic interactions [3]. This is commonly thought to be the mechanism responsible for the observed suppression of high transverse momentum (p_{T}) hadrons and jets, or "jet quenching", in nuclear collisions [4–14]. Measurements of parton energy loss are expected to reveal the fundamental thermodynamic and transport properties of this phase of matter (see Refs. [15, 16] for recent reviews).

The quenching of jets in heavy-ion collisions is expected to depend upon the flavor of the fragmenting parton [17]. For example, under the assumption that radiative energy loss is the dominant mechanism, gluon jets are expected to quench more strongly than quark jets, owing to the larger color factor for gluon emission from gluons than from quarks. Moreover, jets from heavy quarks may radiate less strongly than those from light flavor due to the so-called "dead-cone" effect [18], particularly when the parton p_{T} is comparable to its mass. The relevance of this mechanism in heavy-ion collisions, however, is debated [19].

Until now, identification of reconstructed b jets has not been performed in heavy-ion collisions. Recent data on single-particle production of B mesons (via non-prompt J/ψ) [20] suggest a mass dependence of the suppression, compared to D mesons [21] and non-identified charged particles [22, 23]. Compared to B mesons, b jets provide a more direct connection to the b-quark energy loss, albeit typically in a different range of p_{T}. Through comparisons with the existing measurements of inclusive jet production [24], b-quark jet (b jet) measurements can be used to study the flavor dependence of jet quenching, which in turn provides insight on the dynamics of parton energy loss.

The Compact Muon Solenoid (CMS) detector has excellent capabilities to perform b-jet identification (b tagging) measurements as demonstrated in Ref. [25]. Measurements of the b-jet cross section [26] and b-jet angular correlations [27] have been performed in pp collisions at 7 TeV. This Letter presents the first measurements of b-jet production in heavy-ion collisions using a dataset corresponding to an integrated luminosity of 150 $\mu\mathrm{b}^{-1}$ of PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV delivered by the LHC in 2011. The comparison measurements are performed with a dataset consisting of pp data recorded in 2013 and corresponding to an integrated luminosity of 5.3 pb^{-1} at $\sqrt{s} = 2.76$ TeV.

The central feature of the CMS apparatus is a superconducting solenoid providing a magnetic field of 3.8 T. Charged particle trajectories are measured with the silicon tracker, which provides an impact parameter resolution of $\sim$15 μm and a p_{T} resolution of $\sim$1.5% for 100 GeV/c particles. A $\mathrm{PbWO_4}$ crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL) surround the tracking volume. The forward regions ($2.9 < |\eta| < 5.2$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle measured with respect to the counterclockwise beam direction) are instrumented with iron/quartz-fiber hadron forward calorimeters (HF). Collision centrality, defined as a percentile of the total inelastic nucleus-nucleus cross section (with 0% denoting collisions with zero impact parameter), is calculated using the sum of the HF transverse energy [28]. A set of scintillator tiles, used for triggering and beam-halo rejection, is mounted on the inner side of the HF calorimeters. A more detailed description of the CMS detector can be found in Ref. [29].

Jets are reconstructed from particle candidates obtained from a particle-flow algorithm [30]. The four-momentum of a charged hadron is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for zero-suppression effects, and calibrated for the nonlinear response of the calorimeters. This algorithm improves the resolution of jets, while reducing the parton flavor dependence of the detector response as compared to a purely calorimetric measurement. The anti-k_{T} clustering algorithm [31] is used, with a distance parameter of $R = 0.3$. Details of the jet reconstruction, resolution and energy corrections may be found in Refs. [12, 14, 32]. The underlying background of bulk particle production in PbPb collisions is subtracted using the same method described in Ref. [33]. Jet p_{T} resolution effects are unfolded using an iterative method [34], as implemented in the ROOUNFOLD package [35].

The Monte Carlo simulations are performed using PYTHIA 6.422 [36] with tune Z2 [37]. A parton flavor is assigned to reconstructed jets by matching them in $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ to generator-level partons (ϕ is the azimuthal angle measured in radians in the plane transverse to the beams). If a bottom quark is found within $\Delta R < 0.3$ then the jet is considered to be a b jet, irrespective of any other partons in the cone. This definition includes b quarks from gluon splitting ($\mathrm{g} \to \mathrm{b\overline{b}}$), even if the splitting occurs late in the parton shower (i.e., at low virtuality), consistent with the theoretical treatment of heavy-flavor production in Ref. [38]. We note that b jets from gluon splitting comprise about 60% of the total b-jet cross section (according to PYTHIA simulations) and are expected to interact differently with the QGP than those from primary b quarks [39]. To compare with PbPb data, PYTHIA events are embedded into PbPb events produced by the HYDJET generator (version 1.8) [40], which is tuned to reproduce event properties, such as charged-hadron multiplicity, p_{T} spectra, and elliptic flow.

Identification of b jets is based on kinematic variables related to the relatively long lifetime and large mass of b hadrons. Charged tracks of $p_{\mathrm{T}} > 1\,\mathrm{GeV}/c$ that are associated to jets are used to reconstruct secondary vertices (SV) from b hadrons and/or subsequent c-hadron decays from the $\mathrm{b} \to \mathrm{c}$ cascade. The contribution of b jets is enhanced by requiring that SVs are far enough from the primary vertex, using a selection on the significance of the three-dimensional flight distance. This selection is chosen to give a misidentification rate of roughly 1% for light jets and 10% on charm-quark jets (c jets), based on simulation. The corresponding b-tagging efficiency is about 65% for pp and 45% for PbPb collisions.

The SV invariant mass is calculated from the constituent tracks. An example SV mass distribution, for jets with $80 < p_{\mathrm{T}} < 90\,\mathrm{GeV}/c$, is shown in Fig. 1. For each jet p_{T} bin, the b-jet purity (f_{b}), i.e., the ratio of the number of b jets to that of inclusive jets in the tagged sample, is extracted by means of a template fit. The shapes of the light-quark, c and b contributions are determined from simulation, while their normalizations are allowed to float. After tagging, the three contributions are of comparable magnitude, as shown in the figure, but the b-quark contribution dominates above the c-quark mass threshold near $2\,\mathrm{GeV}/c^2$, which allows for an accurate determination of the b-jet contribution.

For the systematic studies described below, an alternative b-tagging strategy is employed, which uses the jet probability (JP) algorithm [25]. In contrast to direct reconstruction of SVs, the JP tagger is based on an estimate of the compatibility of tracks with the primary vertex, using their three-dimensional impact parameter significance. A probability density for this compatibility is obtained directly from data using tracks with negative impact parameter, i.e., tracks that appear to come from the side of the primary vertex opposite the jet direction. Such tracks are unlikely to be associated with heavy-flavor decays. The impact parameter (IP) has the same sign as the scalar product of the vector pointing from the primary vertex to the point of closest approach with the jet direction. Tracks originating from the decay of particles traveling along the jet axis will tend to have positive IP values.

The b-jet yield, in a given p_{T} bin, is obtained as $N_{\mathrm{b}} = N f_{\mathrm{b}}/\epsilon$, where N is the number of all b-

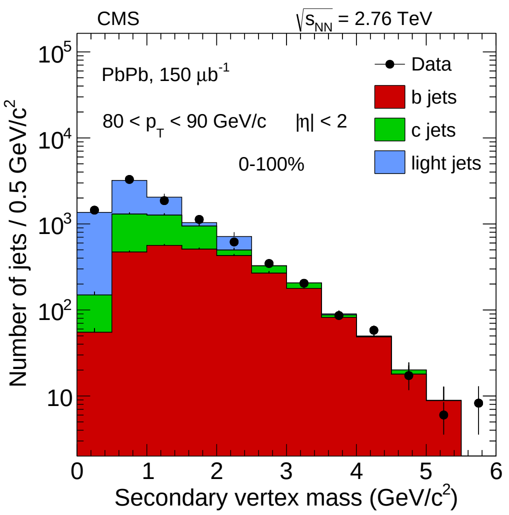

Figure 1: Template fit to the SV invariant mass distribution in centrality integrated (0–100%) PbPb collisions for jets of $80 < p_{\mathrm{T}} < 90\,\mathrm{GeV}/c$.

tagged jets and ϵ is the b-tagging efficiency. The efficiency ϵ is determined from simulation and cross-checked using the so-called reference lifetime tagger method, which uses the JP tagger to determine the efficiency of the SV tagger directly from data, taking advantage of the data-derived calibration of the JP tagger [25]. The simulation reproduces the estimate of ϵ from data to within 5%.

The unfolded b-jet p_{T} spectra in PbPb collisions are shown in Fig. 2 for several centrality selections. The PbPb data are divided by T_{AA}, computed from a Glauber model (for a review, see Ref. [41]), to scale to the expectation for pp collisions in the absence of nuclear effects. The value of the T_{AA} is the number of nucleon-nucleon (NN) collisions divided by the total inelastic NN cross section and may be interpreted as the NN equivalent luminosity per PbPb collision. Also shown is the measured b-jet cross section in pp collisions. The cross section is compared to PYTHIA simulations, which agree well with the data, as is the case at $\sqrt{s} = 7\,\mathrm{TeV}$ for the p_{T} range covered by the present study [26]. The points are placed along the abscissa at the centers of the bins.

The systematic uncertainties fall into two general categories: b tagging and jet reconstruction. The b-tagging uncertainty on b-jet yields varies from about 12 to 18%, depending on jet p_{T} and collision system. The uncertainty is evaluated via the following systematic variations of the tagging procedure, which influence the extracted b-tagging purity and efficiency values:

- varying the SV flight distance selection such that ϵ differs by about 10%,
- using ϵ from the reference lifetime tagger method [25], rather than from simulation,
- fixing the c jet to light-quark jet normalization, rather than allowing them to float independently in the template fits,
- using a non-b-jet template produced from jets with small JP in data,
- varying the gluon-splitting contribution in the b-jet and c-jet templates by 50%.

The uncertainty on the spectra due to the jet reconstruction is 10–12% for pp and 15–17% for PbPb, and is comprised of the following sources:

- a 10% uncertainty in the jet energy resolution [42],
- a 2% uncertainty in the jet energy scale (JES) [42],

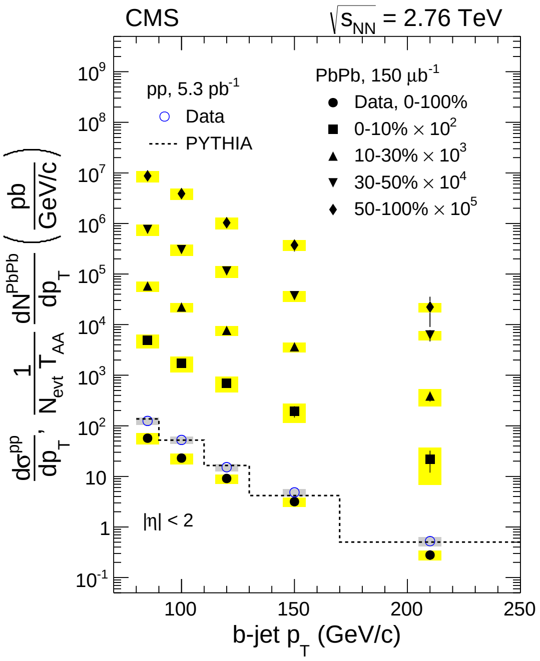

Figure 2: The b-jet yield as a function of p_T is shown for various centrality classes of PbPb collisions as indicated in the legend. The yields are scaled by the equivalent number of minimum bias events sampled and by T_{AA}. The spectra are also scaled by powers of 10 for visibility. The b-jet cross section in pp collisions is also shown, and compared to PYTHIA. Statistical uncertainties are represented by error bars, while systematics uncertainties are shown as filled boxes.

- an additional, centrality-dependent, 1–2% uncertainty in the JES in PbPb collisions due to the underlying event, evaluated from random-cone and embedding studies,
- an uncertainty in the unfolding procedure evaluated by varying the number of iterations and the presumed prior spectrum.

The pp luminosity has an uncertainty of 3.6%, while the uncertainty in T_{AA} varies from about 4% for centrality 0–10% to 15% for 50–100% [14].

Figure 3 shows the centrality-integrated b-jet nuclear modification factor (R_{AA}), which is the ratio of the T_{AA}-normalized PbPb yield and the measured pp cross section in Fig. 2, as a function of p_T. A significant suppression of the yield with respect to the pp expectation is observed in b jets, which is indicative of the parton energy loss in the hot medium. No strong trend is observed as a function of p_T, although the data hint a modest rise at higher p_T. The jet and b-tagging systematic uncertainties in R_{AA} are obtained by varying the pp and PbPb data simultaneously. This results in partial cancellation, giving a systematic uncertainty of 16–21%, which is dominated by the b-tagging uncertainty.

Figure 4 shows R_{AA} as a function of the number of participating nucleons (N_{part}), which is derived from the centrality (as measured by the energy in the forward calorimeters) through a Glauber calculation. Data for $80 < p_T < 90\,\mathrm{GeV}/c$ and $90 < p_T < 110\,\mathrm{GeV}/c$ are shown. For both jet selections R_{AA} shows a smooth decrease with increasing centrality from about 0.70–0.75 to about 0.35–0.40.

The data presented in this study demonstrate the jet quenching phenomenon in the b-quark sector using fully reconstructed b jets for the first time in heavy-ion collisions. Integrating over

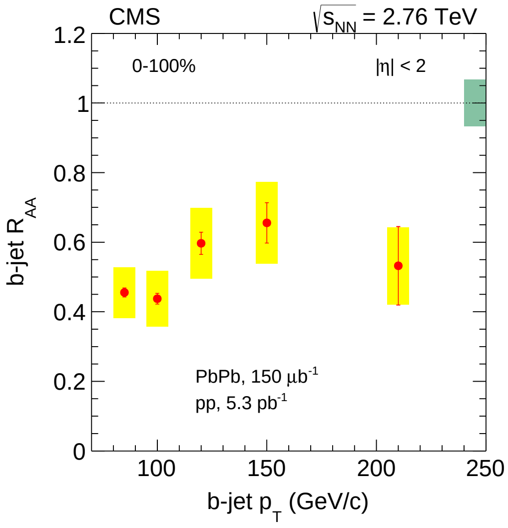

Figure 3: The centrality integrated (0–100%) b-jet R_{AA} as a function of p_T, integrated over collision centrality. Statistical uncertainties are shown as error bars, while filled boxes represent systematics uncertainties. The normalization uncertainty from the integrated luminosity in pp collisions and from T_{AA} is represented by the green band around unity.

all collision centralities, b jets are found to be suppressed over the 80–250 GeV/c p_T range explored in this study. For the 80–110 GeV/c p_T range, R_{AA} is found to decrease with collision centrality. At larger p_T, the trend is less evident due to the reduced statistical precision. The b-jet suppression is found to be qualitatively consistent with that of inclusive jets [24]. The absence of a strong dependence of the jet suppression on the mass of the fragmenting parton would favor a perturbative model in which mass effects are expected to be small at large p_T, as in Ref. [39], when compared against a model based on strong coupling (via the AdS/CFT correspondence) [17], in which mass effects could persist to large p_T. A weaker mass dependence, such as the one predicted in Ref. [43], cannot be ruled out with the present uncertainties.

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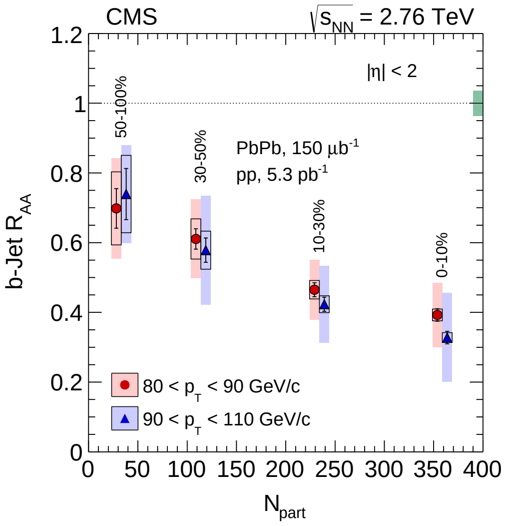

Figure 4: The b-jet R_{AA}, as a function of N_{part} for two jet p_T selections as indicated in the legend. Statistical uncertainties are shown as error bars. The filled boxes represent the systematics uncertainties, excluding the T_{AA} uncertainties, which are depicted as open boxes. The normalization uncertainty in the integrated luminosity in pp collisions is represented by the green band around unity.

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