Unveiling the jet angular broadening with photon-tagged jets in high-energy nuclear collisions

Authors: Dr. Sa Wang, Li, Dr. Yao, Kang, Dr. Jin-Wen, Zhang, Dr. Ben-Wei, Wang, Dr. Sa

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Abstract

The medium modification of jet substructure in hot and dense nuclear matter has garnered significant interest from the heavy-ion physics community in recent years. Measurements of inclusive jets show an angular narrowing in nucleus-nucleus collisions, while recent CMS results for photon-tagged jets (γ+jets) suggest evidence of broadening. In this study, we conduct a theoretical analysis of the angular structure of inclusive jets and γ+jets using a transport approach that accounts for jet energy loss and the medium response in the quark-gluon plasma. We examine the girth modification of γ+jets in $0-30\%$ PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, achieving satisfactory agreement with recent CMS measurements. We explore the relationship between selection bias and jet kinematics by varying the threshold for $x_{j\gamma} = p_T^{\text{jet}}/p_T^{\gamma}$. Notably, we quantitatively demonstrate that γ+jets significantly reduce selection bias and can effectively select jets that have been sufficiently quenched in PbPb collisions, which is crucial for capture the jet angular broadening. Additionally, we estimate the contributions of medium-induced gluon radiation and the medium response to the broadening of the jet angular substructure. Lastly, we analyze the modification patterns of jet R_g and ΔR_{axis} in PbPb collisions, which indicate slight broadening for γ+jets and noticeable narrowing for inclusive jets compared to pp collisions.

Full Text

Preamble

Affiliations: 1. College of Science, China Three Gorges University, Yichang 443002, China 2. Center for Astronomy and Space Sciences and Institute of Modern Physics, China Three Gorges University, Yichang 443002, China 3. Key

Laboratory of Quark & Lepton Physics (MOE) and Institute of Particle Physics,
Central China Normal University, Wuhan 430079, China

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Medium modification of jet substructure in hot and dense nuclear matter has garnered significant interest from the heavy-ion physics community in recent years. Measurements of inclusive jets show an angular narrowing in nucleus-nucleus collisions, while recent CMS results for photon-tagged jets (γ+jets) suggest evidence of broadening. In this study, we conduct a theoretical analysis of the angular structure of inclusive jets and γ+jets using a transport approach that accounts for jet energy loss and medium response in quark-gluon plasma. We examine the girth modification of jets at $\sqrt{s_{NN}} = 5.02$ TeV, achieving good agreement with recent CMS γ+jet measurements in 0-30% PbPb collisions. We explore the relationship between selection bias and jet kinematics by varying the threshold for $x_{j\gamma} = p_T^{\text{jet}}/p_T^{\gamma}$. Notably, we quantitatively demonstrate that γ+jets significantly reduce selection bias and can effectively select jets that have been sufficiently quenched in PbPb collisions, which is crucial for capturing the jet angular broadening. Additionally, we estimate the contributions of medium-induced gluon radiation and medium response to the broadening of the jet angular substructure. Finally, we analyze the modification patterns of jet R_g and ΔR_{axis} in PbPb collisions, which indicate slight broadening for γ+jets and noticeable narrowing for inclusive jets compared to pp collisions.

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INTRODUCTION

High-energy collisions of heavy nuclei at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) provide an experimental avenue to unravel the mysteries of quark-gluon plasma (QGP), a short-lived state of deconfined nuclear matter created at extremely high temperature and density. The jet quenching phenomenon—energy dissipation of an energetic parton traversing hot and dense nuclear matter—stands as one of the most important signatures of QGP formation [1-10]. Investigations of jet quenching reveal the phase structure of strongly-coupled nuclear matter and advance our understanding of quantum chromodynamics (QCD) under extreme conditions [11-25].

Jet substructures serve as valuable tools for gaining insight into the details of jet-medium interactions in QGP, including medium-induced gluon radiation [26,27], medium response [28-33], medium resolution length [34-36], and "Molière scattering" [37,38]. Recent reviews on this topic can be found in references [14,15,39-41]. A significant focus of recent research has been the modification of jet angular structure in nucleus-nucleus collisions—specifically, whether jets narrow or broaden—a question that has garnered considerable attention [35,40-54]. Measurements of the angular structure of inclusive jets indicate that jets become narrower in PbPb collisions at both RHIC [55] and the LHC [56-63], contrary to theoretical expectations of intra-jet broadening [40,42,49].

In experimental analyses, medium modifications are typically extracted by comparing jet samples in PbPb and pp collisions selected within identical pT bins. However, quenched jets that traverse longer path lengths and experience greater energy loss in the QGP are less likely to survive the pT selection threshold in AA collisions, while jets with minimal quenching may still be retained. This phenomenon is referred to as "selection bias" [14,64-68]. Such biases can complicate jet-by-jet comparisons and obscure the connection between experimental measurements and the underlying jet quenching mechanism [66,67,69,70].

Consequently, V+jet production (where a jet is tagged by a vector boson such as Z0/W± or γ) provides a golden channel for exploring jet quenching in high-energy heavy-ion collisions [71-78]. Since vector bosons do not interact strongly with hot nuclear matter, they effectively tag the initial momentum of the recoiling jet. Furthermore, V+jet processes are dominated by quark-jet production, reducing potential uncertainties from variations in the quark-to-gluon fraction during AA collisions [59]. Additionally, constraining the pT of the vector boson was expected to minimize the impact of selection biases on jet measurements in AA collisions [66,67,80,81].

II. THEORETICAL FRAMEWORK

To investigate the angular structure of inclusive jets and γ+jets, we employ PYTHIA8 [85] with the Monash Tune [86] to generate pp events as a baseline for nucleus-nucleus collision calculations. Furthermore, we utilize a transport approach that incorporates both radiative and collisional energy loss to simulate massive and massless jet evolution in QGP. This hybrid transport approach has been extensively applied in studies of light- and heavy-ion collisions [55-90].

Since medium-induced gluon radiation constitutes the dominant energy loss mechanism for high-energy partons, we use the higher-twist formalism [92-95] to simulate in-medium jet showers in hot/dense QCD matter. In this work, we adopt the extracted value q0 = 1.2 GeV^2/fm, determined through ^{2} fitting to identified hadron production in PbPb collisions at the LHC [103].

To incorporate the effects of medium-induced gluon radiation, we assume that the number of radiated gluons during a time step (Δt = 0.1 fm) follows a Poisson distribution f(n) = λ^ne^(-λ)/n!, where the parameter λ denotes the mean number of radiated gluons calculated by integrating Eq. (1). Once the radiation number n is determined, the corresponding energy-momentum distribution is sampled using Eq. (1) iteratively. Due to the LPM effect, a radiated gluon can only interact independently with the medium after a formation time τf, after which it may undergo further energy loss (including additional medium-induced gluon radiation).

III. RESULTS AND DISCUSSIONS

Recently, CMS measured the medium modifications of γ+jet girth in 0-30% PbPb collisions relative to pp at sNN = 5.02 TeV [84]. The girth variable quantifies the pT distribution of particles within a jet, weighted by their angular distance from the jet axis, as defined in Eq. (6).

Figure 1 [Figure 1: see original paper] presents the normalized girth distributions of γ+jets in pp and 0-30% PbPb collisions at sNN = 5.02 TeV, calculated with xjγ > 0.4 (upper panel) and xjγ > 0.8 (middle panel), compared to recent CMS data [84]. The PbPb/pp ratios of the girth distributions are shown in the lower panel. The theoretical calculations provide a satisfactory description of CMS data for both xjγ selections. For xjγ > 0.4, the girth distribution shows a modest enhancement in the region 0.08 < g < 0.14. Since girth quantifies the angular-weighted pT distribution within a jet, an increased PbPb/pp ratio at larger g indicates jet broadening in heavy-ion collisions. In contrast, for xjγ > 0.8, the distribution exhibits clear suppression at g > 0.02 and enhancement at g < 0.02, suggesting jet narrowing for more tightly balanced γ+jet events.

Figure 2 [Figure 2: see original paper] displays the normalized xjγ distribution of γ+jets before and after quenching (labeled "unquenched" and "quenched") in 0-30% PbPb collisions at sNN = 5.02 TeV, using different xjγ cuts through the Jet-by-Jet matching procedure: xjγ > 0.4 (upper panel) and xjγ > 0.8 (lower panel). The solid lines represent the initially selected (unquenched) jets, while dashed lines show jets after quenching and application of the same xjγ cuts. The difference between solid and dashed lines illustrates how quenching modifies the xjγ distribution. For xjγ > 0.4, the quenched distribution shows depletion at high xjγ and enhancement at low xjγ, indicating that energy loss shifts events toward lower xjγ values. For xjγ > 0.8, this effect is more pronounced, with significant reduction of events in the high xjγ region.

Therefore, it is natural to inquire how jet-medium interactions affect the angular structure of jets before and after quenching in nucleus-nucleus collisions. In this work, we have studied medium modifications of γ+jet girth in PbPb collisions at sNN = 5.02 TeV using a hybrid transport approach. Our theoretical calculations provide a satisfactory description of recent CMS data. We find that the girth distribution is sensitive to the xjγ selection, exhibiting different modifications for loose (xjγ > 0.4) and tight (xjγ > 0.8) cuts. The Jet-by-Jet matching procedure is essential for correctly accounting for selection biases in theoretical calculations. Medium-induced gluon radiation and the resulting energy loss lead to jet narrowing for tightly balanced γ+jet events, while modest broadening is observed for loosely balanced events. These results provide new insights into the angular structure of jets in heavy-ion collisions and the underlying jet quenching mechanism.

INTRODUCTION (continued)

In the upper panel, we also present results without considering medium-induced gluon radiation and medium response. In the lower panel, we compare the girth modification of inclusive jets and γ+jet events with the same pT cut, as well as results obtained using the Jet-by-Jet matching (JBJ) procedure.

Measurements of inclusive jets in PbPb collisions at sNN = 5.02 TeV indicate a narrow effect, consistent with CMS data [84]. The fraction of jets surviving the selection criteria demonstrates that medium-induced gluon radiation and medium response play a significant role in jet quenching for both inclusive jets and γ+jet events within the same collision system. In Fig. 3, we present the girth modification for γ+jet and inclusive jets in 0–30% PbPb collisions at sNN = 5.02 TeV, using the same pT cut (pT > 40 GeV and | jet| < 2.0) and photon tagging requirements (pγT > 100 GeV, xjγ > 0.4, | γ| < 1.44). The upper panel discusses the influence of medium-induced gluon radiation and medium response on γ+jet events, while the lower panel compares girth modifications between inclusive jets and γ+jet events, including JBJ results.

FIG. 5 [Figure 5: see original paper]: (Color online) Event-averaged transverse momentum loss ΔpT = pT^{init} - pT^{fin} _{evt} for γ+jet (solid line) and inclusive jets (dashed line) as a function of initial (left panel) and final jet pT (right panel) in 0–30% PbPb collisions at sNN = 5.02 TeV, obtained using the Jet-by-Jet matching procedure.

FIG. 4 [Figure 4: see original paper]: (Color online) Normalized pT distribution of unquenched and quenched jets for γ+jet and inclusive jet events in 0-30% PbPb collisions at sNN = 5.02 TeV, using the Jet-by-Jet matching procedure. The gluon-jet fractions in both samples are estimated in the lower panel.

We observe that medium-induced gluon radiation and medium response significantly enhance jet quenching in the region of large girth values. Compared to γ+jet events, inclusive jets exhibit stronger suppression at g > 0.05, indicating a narrowing effect consistent with previous ALICE measurements in PbPb collisions at sNN = 2.76 TeV [40]. This behavior suggests that medium-induced gluon radiation and medium response play a crucial role in the jet angular broadening observed in nucleus-nucleus collisions.

FIG. 7 [Figure 7: see original paper]: (Color online) Medium modification of the groomed radius distribution for γ+jet and inclusive jets in 0–30% PbPb collisions at sNN = 5.02 TeV, relative to pp. The results are compared with CMS γ+jet measurements [84]. JBJ results are shown for comparison in the lower panel.

To explore the sensitivity of jet quenching to xjγ and pγT cuts, we calculate the girth modification for γ+jet events in PbPb collisions at sNN = 5.02 TeV. Fig. 6 shows the medium modification of jet girth for various xjγ (0.2, 0.4, 0.6, 0.8) and pγT (80 GeV, 100 GeV, 120 GeV) thresholds. The upper panel presents results with varying xjγ cuts, while the lower panel displays results with different pγT requirements. We find that the girth modification shows moderate dependence on these selection criteria.

FIG. 6 [Figure 6: see original paper]: (Color online) Medium modification of jet girth for γ+jet events in 0-30% PbPb collisions at sNN = 5.02 TeV, relative to pp, for different xjγ (0.2, 0.4, 0.6, 0.8) and pγT (80 GeV, 100 GeV, 120 GeV) cuts.

The groomed radius Rg is defined using the Soft Drop algorithm [83, 84] with zcut = 0.5 and $\beta = 0$, representing the opening angle between the two hardest subjets after grooming. This quantifies the angular distance between substructures within the jet.

FIG. 8 [Figure 8: see original paper]: (Color online) Medium modification of the angle between jet axes for γ+jet and inclusive jets in 0–10% PbPb collisions at sNN = 5.02 TeV, relative to pp. The results are compared with ALICE inclusive jet measurements [61]. JBJ results are shown for comparison in the lower panel.

The angular difference between jet axes, ΔRaxis, is defined as the distance between the standard jet axis and the Winner-Take-All (WTA) axis [115]. This observable probes the medium response to jet propagation through the quark-gluon plasma.

SUMMARY

In summary, we present a theoretical study of γ+jet angular structure in heavy-ion collisions using the PYTHIA8 event generator. We quantify the medium modification of γ+jet events in PbPb collisions at sNN = 5.02 TeV and demonstrate that jet quenching leads to significant angular broadening. Our calculations show good agreement with recent CMS measurements [84], providing new insights into jet-medium interactions. The Jet-by-Jet matching method reveals that medium-induced gluon radiation and medium response are essential for reproducing the observed modifications in jet substructure. These results establish a foundation for future precision studies of jet quenching mechanisms and the properties of the quark-gluon plasma.

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