Z^0-Tagged Jet Event Asymmetry in Heavy-Ion Collisions at the CERN Large Hadron Collider

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Tagged jet measurements provide a promising experimental channel to quantify the similarities and differences in the mechanisms of jet production in proton-proton and nucleus-nucleus collisions. We present the first calculation of the transverse momentum asymmetry of Z^0/γ^*-tagged jet events in $\sqrt{s} = 2.76$ TeV reactions at the LHC. Our results combine the $\mathcal{O}(G_F\alpha_s^2)$ perturbative cross sections with the radiative and collisional processes that modify parton showers in the presence of dense strongly interacting matter. We find that a strong asymmetry is generated in central lead-lead reactions that has little sensitivity to the fluctuations of the underlying soft hadronic background. We present theoretical model predictions for its shape and magnitude.

Jet production in energetic particle collisions is one of the most powerful channels through which to test and advance perturbative quantum chromodynamics (QCD) [1]. This is particularly true at the CERN LHC, where the available large center-of-mass energies guarantee an abundant yield of high transverse momentum hadrons and jets [2]. In relativistic heavy-ion collisions at the LHC, parton-shower formation and evolution are modified by the hot and dense deconfined matter, or quark-gluon plasma (QGP), created during the early stages of the interaction [3]. Consequently, the related jet observables can help quantify the properties of the QGP and differentiate between competing paradigms of jet production and modification in ultrarelativistic nuclear collisions.

In light of the above motivation, it is not surprising that quantitative theoretical description and experimental measurement of jet observables in heavy-ion collisions have become an important priority, both at the Relativistic Heavy Ion Collider and the LHC [4]. Recently, the ATLAS and CMS Collaborations reported a significant enhancement in the transverse momentum imbalance of dijets produced in central lead-lead (Pb + Pb) collisions at the LHC relative to the ones produced in proton-proton ($p + p$) collisions [5]. The broader distribution of the asymmetry variable, denoted A_J and defined as

$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}, \qquad (1)$$

where p_{T1} and p_{T2} are the transverse momenta of the leading and subleading jets, is reflective of the jet in-medium modification. Attempts to explain the observed asymmetry based on Monte Carlo simulations with a PYTHIA-generated $p + p$ baseline have been presented [6]. Fixed order $\mathcal{O}(\alpha_s^3)$ perturbative QCD calculations that include nuclear matter effects describe well both single and dijet production in nucleus-nucleus ($A + A$) reactions at the LHC [7]. The importance of potentially large

background fluctuations in heavy-ion collisions on the A_J asymmetry distribution has been argued for in Ref. [8].

Jets tagged with electroweak bosons offer a complementary channel to dijet measurements and have the potential to circumvent some of the problems inherent in multijet observables. Because the tagging boson does not interact strongly, this channel has been proposed as an experimental avenue through which to constrain the initial energy of the associated jet [9]. In both $p + p$ and $A + A$ reactions, however, next-to-leading accuracy is necessary for quantitatively and even qualitatively accurate description of tagged jet production [10]. In what follows, we provide first theoretical predictions to $\mathcal{O}(G_F\alpha_s^2)$ for the asymmetry and nuclear modification factor of Z^0/γ^*-tagged jets in heavy-ion collisions at LHC energies. Our calculation includes both the radiative and collisional processes important for parton-shower modification in a nuclear medium. The heavy-ion program at the LHC has now enabled the first experimental measurements of Z^0 boson production [11]. Although differential tagged jet measurements in this channel require significantly more statistics to become quantitatively rigorous, there is ongoing effort on this front. Our predictions are complementary to this experimental program and will provide timely guidance to the qualitative expectations for all electroweak boson-tagged jet measurements.

In $p + p$ reactions, we evaluate the Z^0/γ^*-tagged jet production using the Monte Carlo for femtobarn processes (MCFM) code [12]. MCFM provides one-loop results for many QCD processes of interest to the hadron collider physics community. A principal channel used to measure Z^0's is their decay to dileptons. All cross sections presented in this Letter are for the $Z^0/\gamma^* \rightarrow \mu^+\mu^-$. We implement the following acceptance cuts: $|y| < 2.5$ for both jets and final-state muons. We constrain the invariant mass of the muon pair in an interval around $M_z = 91.2$ GeV to fully contain the Z^0 peak. Jets are reconstructed using MCFM's

built-in midpoint cone algorithm with a separation parameter $R = \sqrt{\delta\phi^2 + \delta\eta^2}$. Standard $\mu_r = \mu_f = \sqrt{M_Z^2 + p_{TZ}^2}$ renormalization and factorization scales and MSTW parton distribution functions are used [13]. For presentation purposes, we define the dimensionless double differential cross section

$$\tilde{\sigma} = \left[\frac{\text{GeV}^2}{fb}\right]\frac{d\sigma^{Z\text{-jet}}}{dp_{TZ}dp_{T\text{Jet}}} \quad (2)$$

and show $\log_{10}\tilde{\sigma}$ in Fig. 1 for $\sqrt{s} = 2.76$ TeV $p + p$ collisions at the LHC. We have chosen a typical jet reconstruction parameter $R = 0.4$. The calculation was performed in $\Delta p_{TZ} = 20$ GeV and $\Delta p_{T\text{Jet}} = 5$ GeV bins. The most important feature of this cross section is how broad it is in the $(p_{TZ}, p_{T\text{Jet}})$ plane [10], defined by the transverse momentum of the Z^0 boson and the transverse momentum of the jet. Its precise shape is determined by the parton level processes and the $Z^0 \rightarrow \mu^+\mu^-$ Dalitz decay kinematics.

In reactions with heavy nuclei, the inclusive and tagged jet production cross sections are modified by effects induced by the passage of the hard-scattering partons and the resulting parton showers through the strongly interacting medium created in these reactions. Initial-state cold nuclear matter effects for Z^0 production at $\sqrt{s} = 2.76$ TeV were shown to be small both experimentally and theoretically [11]. Furthermore, initial-state effects described in [14] do not affect the asymmetry of dijet or tagged jet events [7].

Final-state quark-gluon plasma effects include medium-induced parton splitting and the dissipation of the energy of the parton shower through collisional interactions in the strongly interacting matter. Medium-induced parton splitting factorizes from the hard-scattering cross section and enters observables as a standard integral convolution [15]. In the limit when the subleading parton carries on average a small fraction $x \ll 1$ of the parent parton's large light-cone momentum ($p^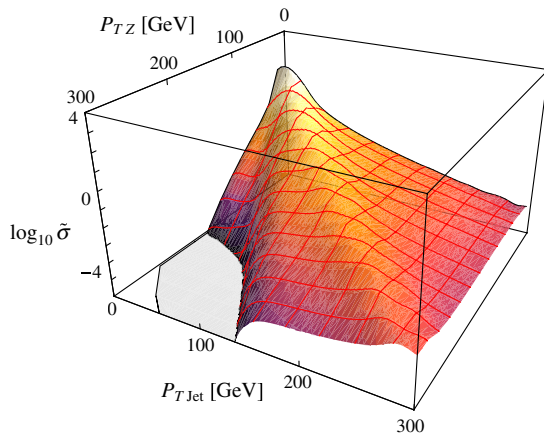+ = p^z + p^0$ for a parton traveling in the z direction), these processes have a transparent energy loss interpretation. The magnitude and angular distribution of radiative energy losses are here described by the reaction operator formalism [16]. Specifically, we use the fully differential bremsstrahlung spectra for hard quarks and gluons, averaged over the collision geometry in central Pb + Pb reactions at the LHC, that have been previously employed to discuss jet and particle production in heavy-ion collisions [7,14]. The probability density that the hard-scattered quark or gluon will lose a fraction of its light-cone momentum $\epsilon = \sum_i x_i$ due to multiple gluon emission (the summation is over emitted gluons), or a medium-induced parton shower, is also evaluated and denoted $P_{q,g}(\epsilon)$, respectively.

The collisional energy losses are here motivated by the work done in Ref. [17]. The energy transferred from the induced parton shower to the nuclear medium is evaluated in the hard thermal loop approximation to leading logarithmic accuracy. We are careful to keep track of the color correlations between the constituents within the shower and find that rate of energy loss is suppressed at time scales $\delta t \sim 1/m_D\theta$ relative to the naive superposition of two independent partons. Here, $m_D = g_{\text{med}}T$ is the Debye screening mass for a gluon-dominated plasma, g_{med} is the strong coupling constant that sets the rate of parton energy loss, and θ is the parton splitting angle. For large-angle radiation, which is characteristic of medium-induced showers [3,4], this effect is small. Our simulations suggest that the shower generated by the propagation of a 75 GeV gluon through medium can transfer as much as 20 GeV of its energy to the medium.

To relate the generation of medium-induced parton showers and the dissipation of part of their energy in the QGP to experimental observables, we need to implement the effects of the jet reconstruction kinematics. Let us define by $f(\omega_{\min}, R)$ the fraction of the energy that is simply redistributed inside the jet of radius R [3]. Here, $\omega_{\min}$ is a parameter that simulates the effects of collisional energy loss discussed above [7]. A hard parton contributing a fraction ϵ of its transverse momentum p_T to a medium-induced shower will produce a jet of $p_{T\text{Jet}} = \{1 - [1 - f(\omega_{\min}, R)]\epsilon\}p_T$. The resulting cross section per binary collision (of $\langle N_{\text{bin}}\rangle$ total) reads [10]

$$\frac{1}{\langle N_{\text{bin}}\rangle}\frac{d\sigma_{AA}}{dp_{TZ}dp_{T\text{Jet}}} = \sum_{q,g}\int_0^1 d\epsilon \frac{P_{q,g}(\epsilon)}{1 - [1 - f(\omega_{\min}, R)]\epsilon}$$
$$\times \frac{d\sigma^{q,g}\left(\frac{p_{T\text{Jet}}}{1 - [1 - f(\omega_{\min}, R)]\epsilon}\right)}{dp_{TZ}dp_T}. \quad (3)$$

The physical meaning of Eq. (3) is that the observed tagged jet cross section in nucleus-nucleus reactions is a probabilistic superposition of cross sections for jets of higher initial transverse energy. This excess energy is then redistributed outside of the jet due to strong final-state interactions.

FIG. 1 (color online). The $\mathcal{O}(G_F\alpha_s^2)$ cross section for Z^0/γ^*-tagged jets, where $Z^0/\gamma^* \rightarrow \mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 2.76$ GeV ($R = 0.4$).
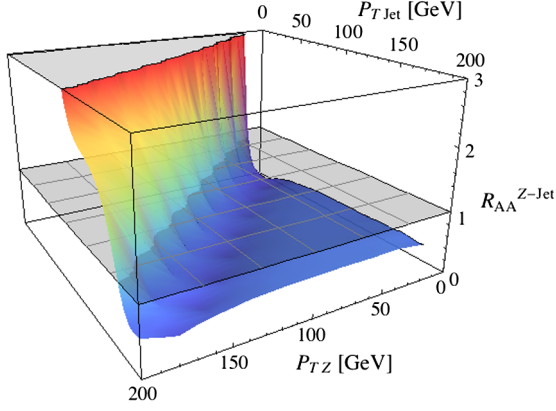
FIG. 2 (color online). The tagged jet nuclear modification factor, $R_{AA}^{Z\text{-jet}}$, defined in Eq. (4), including both collisional and radiative energy loss effects. Our result is for $R = 0.4$ and coupling between the jet and the medium given by $g_{\mathrm{med}} = 2$.

We first consider the generalized jet nuclear modification factor, $R_{AA}^{Z\text{-jet}}$, given by

$$R_{AA}^{Z\text{-jet}}(p_{TZ}, p_{T\mathrm{Jet}}; R, \omega_{\min}) = \frac{\frac{d\sigma_{AA}}{dp_{TZ}dp_{T\mathrm{Jet}}}}{\langle N_{\mathrm{bin}}\rangle \frac{d\sigma_{pp}}{dp_{TZ}dp_{T\mathrm{Jet}}}}. \quad (4)$$

The nuclear modification factor provides a compact way through which to quantify the effects of the nuclear medium. Our predictions for $R_{AA}^{Z\text{-jet}}(R = 0.4, \omega_{\min} = 20$ GeV$)$ are presented in Fig. 2, where we plot the result that includes both collisional and radiative energy loss effects. Since part of the parton-shower energy is redistributed outside of the jet cone radius, the jets are pushed to lower values of $p_{T\mathrm{Jet}}$. This redistribution results in an enhancement in $R_{AA}^{Z\text{-jet}}$ in the region of $p_{T\mathrm{Jet}} < p_{TZ}$ and suppression in $R_{AA}^{Z\text{-jet}}$ in the region of $p_{T\mathrm{Jet}} > p_{TZ}$, which is characteristic of in-medium tagged jet dynamics [10].

Next, we consider the Z^0-tagged jet event asymmetry, which is obtained from Eq. (1) with $p_{T1} \to p_{TZ}$, $p_{T2} \to p_{T\mathrm{Jet}}$. Changing variables from $(p_{TZ}, p_{T\mathrm{Jet}})$ to $(A_J, p_{T\mathrm{Jet}})$ and then integrating over $p_{T\mathrm{Jet}}$, we can express the differential A_J distribution as follows:

$$\frac{d\sigma}{dA_J} = \int_{p_{T\mathrm{Jet}\,\min}}^{p_{T\mathrm{Jet}\,\max}} dp_{T\mathrm{Jet}} \frac{2 p_{T\mathrm{Jet}}}{(1 - A_J)^2} \frac{d\sigma}{dp_{TZ}dp_{T\mathrm{Jet}}}. \quad (5)$$

Here, $p_{TZ\,\min,\max}$ and $p_{T\mathrm{Jet}\,\min,\max}$ can be specified by the experiment and determine the range of the A_J distribution. In the examples that follow, $p_{TZ} \in (80, 100)$ GeV and $p_{T\mathrm{Jet}} > 20$ GeV. In $p + p$ collisions, the asymmetry is sensitive to the $\mathcal{O}(G_F \alpha_s^n)$, $n \geq 3$ multiparton QCD processes. To $\mathcal{O}(G_F \alpha_s)$, $d\sigma/dA_J = \sigma \delta(A_J)$. In $A + A$ collisions, the modified A_J distribution provides information on the medium modification to parton-shower evolution and jet propagation in the QGP.

The tagged jet asymmetry distribution for $p + p$ collisions at $\sqrt{s} = 2.76$ TeV for two different $R = 0.2, 0.4$ (dot-dashed and dot-dot-dashed curves) is shown in
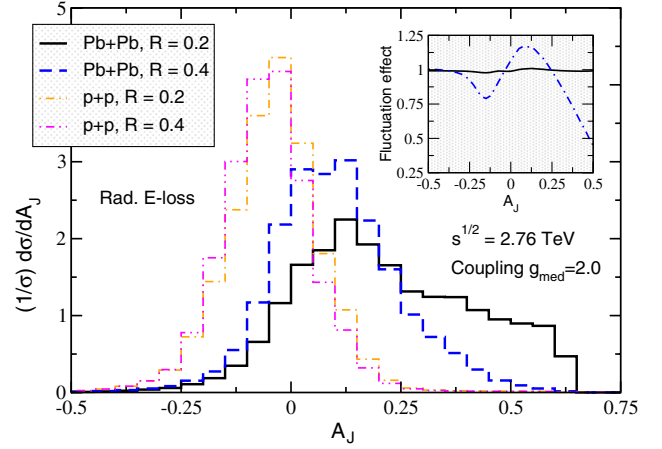

FIG. 3 (color online). The Z^0/γ^*-tagged jet event asymmetry for $p + p$ collisions at $\sqrt{s} = 2.76$ TeV for two different $R = 0.2, 0.4$. Predictions for central Pb + Pb collisions with radiative medium-induced energy loss are also presented. The inset shows the effect of fluctuations in the background subtraction.

Fig. 3. It peaks just below zero [10], and the mean values of A_J, defined as

$$\langle A_J \rangle = \int dA_J A_J \frac{1}{\sigma} \frac{d\sigma}{dA_J}, \quad (6)$$

are shown in Table I. The Pb + Pb curves (solid and dashed) are strongly shifted to $A_J > 0$ and considerably broader than the $p + p$ curves. This forward shift reflects the in-medium modification of the parton shower, which lowers the observed $p_{T\mathrm{Jet}}$ in Eq. (1). For medium-induced parton splitting [15], energy is lost due to large-angle radiation out of the jet reconstruction parameter R [3,4]. The dependence upon R shown in Fig. 3 further demonstrates this point, as the width and the average asymmetry of the curves with the smaller radii are larger.

In a heavy-ion collision, jet reconstruction is complicated by an enormous soft hadronic background [5]. When this background is subtracted on average, its fluctuations can affect the Z^0/γ^*-tagged cross section. The result can be expressed as follows:

TABLE I. Mean A_J with and without background fluctuations. Radius, jet-to-medium coupling, and type of energy loss dependencies are presented.

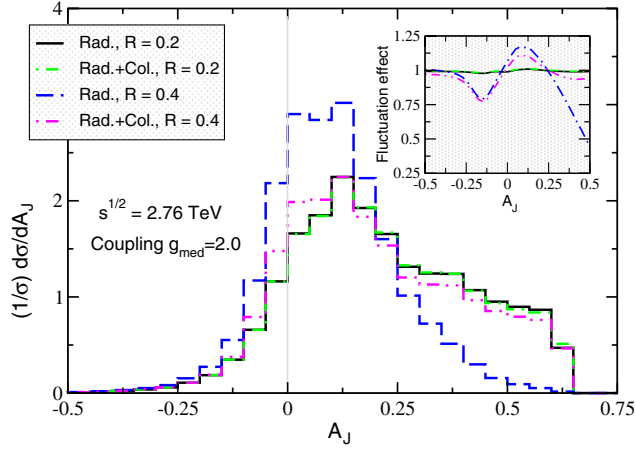| System	$\langle A_J\rangle_{\mathrm{nofluct.}}$	$\langle A_J\rangle_{\mathrm{fluct.}}$
$p + p$ with $R = 0.2$	-0.025	-0.025
$p + p$ with $R = 0.4$	-0.040	-0.040
Pb + Pb, rad, $R = 0.2$, $g_{\mathrm{med}} = 1.8$	0.190	0.189
Pb + Pb, rad, $R = 0.2$, $g_{\mathrm{med}} = 2.0$	0.229	0.228
Pb + Pb, rad, $R = 0.2$, $g_{\mathrm{med}} = 2.2$	0.274	0.272
Pb + Pb, rad, $R = 0.4$, $g_{\mathrm{med}} = 2.0$	0.115	0.132
Pb + Pb, rad + col, $R = 0.2$, $g_{\mathrm{med}} = 2.0$	0.229	0.229
Pb + Pb, rad + col, $R = 0.4$, $g_{\mathrm{med}} = 2.0$	0.211	0.214

FIG. 4 (color online). The asymmetry of Z^0/γ^*-tagged jet events ($R = 0.2, 0.4$) for Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV with radiative and radiative + collisional medium-induced energy losses. The collisional energy loss has a much more pronounced effect for a larger radius. $A_J = 0$ is shown to guide the eye. The inset shows the effect of fluctuations in background subtraction.

$$\frac{d\sigma_{AA}^{\text{fluc.}}}{dp_{TZ}dp_{T\text{Jet}}} = \int d\delta p_T \frac{d\sigma_{AA}(p_{T\text{Jet}} - \delta p_T)}{dp_{TZ}dp_{T\text{Jet}}} \mathcal{N}(\delta p_T; \Delta p_T^2).$$
(7)

In Eq. (7), $\mathcal{N}$ is a normal distribution. The ALICE experiment has measured the standard deviation, which scales with the jet area, as $\Delta p_T \approx 11$ GeV for jet $R = 0.4$ in central Pb + Pb collisions at the LHC [18]. The inset of Fig. 3 demonstrates the effect of these background fluctuations. Specifically, the curves show the ratio of the result without background fluctuations to that with background fluctuations. Even for large radii, the effect is <20% in the region where A_J is significant. For small radii, such as $R = 0.2$, the effect of fluctuations is completely negligible. This is demonstrated further quantitatively in Table I, where we present the average asymmetry, $\langle A_J \rangle$, for a wide range of parameters both with and without the fluctuations (effect <15%).

We present the Z^0/γ^*-tagged jet event asymmetry for central Pb + Pb collisions with radiative (solid and dashed curves) and radiative + collisional (dot-dashed and dot-dot-dashed curves) medium-induced energy losses in Fig. 4. The collisional energy loss has a more pronounced effect in the curve with the larger radius. This occurs because collisional energy loss from a parton shower comes primarily from the radiated gluons, as demonstrated in [17]. With the smaller radius, most of the gluons are already outside of the jet cone, making the extra energy loss redundant. We point out that background fluctuations again have minimal effect when the collisional energy loss is included, as can be checked from the inset in Fig. 4 and, more quantitatively, in Table I.

In summary, we presented the first study of the transverse momentum asymmetry of Z^0/γ^*-tagged jet events in $\sqrt{s} = 2.76$ TeV reactions at the LHC. Our results are also qualitatively representative of other electroweak boson-tagged jet final states. We found both considerable broadening of the event asymmetry distribution and a characteristic shift of its peak to $A_J > 0$ in central Pb + Pb collisions relative to $p + p$ collisions. Both features show very little sensitivity to the fluctuations of the underlying soft hadronic background and are related to the 2D nuclear modification factor $R_{AA}^{Z\text{-jet}}$. Largely unaffected by cold nuclear matter effects, they can be used to accurately characterize the parton-shower modification due to final-state interactions in the QGP.

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