Measurement of the Azimuthal Angle Dependence of Inclusive Jet Yields in Pb + Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector

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Measurements of the variation of inclusive jet suppression as a function of relative azimuthal angle, $\Delta\phi$, with respect to the elliptic event plane provide insight into the path-length dependence of jet quenching. ATLAS has measured the $\Delta\phi$ dependence of jet yields in 0.14 nb^{-1} of $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb collisions at the LHC for jet transverse momenta $p_T > 45$ GeV in different collision centrality bins using an underlying event subtraction procedure that accounts for elliptic flow. The variation of the jet yield with $\Delta\phi$ was characterized by the parameter, $v_2^{\rm jet}$, and the ratio of out-of-plane ($\Delta\phi \sim \pi/2$) to in-plane ($\Delta\phi \sim 0$) yields. Nonzero $v_2^{\rm jet}$ values were measured in all centrality bins for $p_T < 160$ GeV. The jet yields are observed to vary by as much as 20% between in-plane and out-of-plane directions.

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Studies of jet production in Pb + Pb collisions at the LHC [1,2] show behavior consistent with "jet quenching," a general term for the modification of parton showers in the hot dense medium created in ultrarelativistic nuclear collisions. For example, the inclusive yield of jets was observed to be suppressed by a factor of approximately 2 in central Pb + Pb collisions relative to peripheral collisions [3], consistent with a medium-induced reduction in the jet energies. Perturbative or weak-coupling calculations model jet energy loss, dE/dx, through a combination of collisional and radiative energy loss of the partons traversing the medium. The radiative contributions are subject to coherence effects [4] that explicitly depend on the in-medium path length of the parton. Strong-coupling calculations also have an explicit path-length dependence that differs from that predicted by weak-coupling calculations [5,6]. Measurements of the jet yield as a function of quantities providing indirect control over the jet path lengths may provide insight into the physical mechanisms responsible for jet quenching [7,8]. Such quantities include the Pb + Pb collision centrality and the azimuthal angle of the jet with respect to the elliptic event plane.

Elliptic flow refers to a $\cos 2\phi$ modulation of the azimuthal angle (ϕ) distribution of particles produced in ultrarelativistic nuclear collisions [9]. This modulation is understood to arise from an approximately elliptic anisotropy of the initial-state transverse energy density profile that is imprinted on the azimuthal angle distribution of final-state particles [10] by the strong collective evolution of the medium. The resulting azimuthal angle distribution is often parametrized by the form

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2), \tag{1}$$

where the elliptic event plane angle, Ψ_2, specifies the orientation of the initial density profile in the transverse plane, and the parameter v_2 quantifies the magnitude of the modulation. Jets measured at different azimuthal angles relative to the event plane, $\Delta\phi \equiv \phi_{\rm jet} - \Psi_2$, result from partons that traverse, on average, different path lengths and density profiles in the medium. Thus, a measurement of the variation of the jet yield as a function of $\Delta\phi$ should provide a direct constraint on theoretical models of the path-length dependence of the energy loss. This measurement is not directly sensitive to potential variations in the jet yield with respect to higher-order event plane angles. Such variations may result from fluctuations in the initial geometry that also give rise to higher-order flow harmonics [11–13].

Variations in jet yield as a function of $\Delta\phi$ have been observed indirectly through measurements of single hadrons with large transverse momentum (p_T) at the RHIC [14–16] and the LHC [17–19]. The utility of such measurements is limited by the weak relationship between hadron p_T and the transverse momentum of the parent parton shower. This Letter presents the results of measurements using fully reconstructed jets, which have kinematic properties that are more closely related to those of the parent partons. The $\Delta\phi$ dependence of the inclusive jet yield was measured in $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb collisions as a function of jet $p_{\rm T}$ and Pb + Pb collision centrality. The measurement was performed with the anti-k_t algorithm [20] with distance parameter $R = 0.2$, chosen to limit the contribution of the underlying event (UE) to the measurement. The $\Delta\phi$ dependence was characterized by the jet v_2, $v_2^{\rm jet}$, and the ratio of out-of-plane ($3\pi/8 \leq \Delta\phi \leq \pi/2$) to in-plane ($0 \leq \Delta\phi < \pi/8$) jet yields at

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fixed p_T and centrality. Such dependence is expected to be small in either the most central or most peripheral collisions, due to the lack of initial-state anisotropy and the lack of quenching, respectively. For intermediate centralities, measurement of the $\Delta\phi$ dependence of the jet yields probes the interplay between dependence of quenching on the overall system size and energy density, as well as on the initial-state anisotropy.

The measurements presented here were performed with the ATLAS detector [21] using its calorimeter, inner detector, trigger, and data acquisition systems. The calorimeter system consists of a liquid-argon electromagnetic (EM) calorimeter covering $|\eta| < 3.2$, a steel-scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, a liquid-argon hadronic calorimeter covering $1.5 < |\eta| < 3.2$, and a forward calorimeter (FCal) covering $3.2 < |\eta| < 4.9$. Charged-particle tracks were measured over the range $|\eta| < 2.5$ using the inner detector [22], which is composed of silicon pixel detectors in the innermost layers, followed by silicon microstrip detectors and a straw-tube transition-radiation tracker ($|\eta| < 2.0$), all immersed in a 2 T axial magnetic field. The zero-degree calorimeters (ZDCs) are located symmetrically at $z = \pm 140$ m and cover $|\eta| > 8.3$. In Pb + Pb collisions the ZDCs primarily measure noninteracting "spectator" neutrons from the incident nuclei. A ZDC coincidence trigger was defined by requiring a signal consistent with one or more neutrons in each of the calorimeters.

Pb + Pb collisions corresponding to a total integrated luminosity of 0.14 nb^{-1} were analyzed. The events were recorded using either a minimum-bias trigger, formed from the logical OR of triggers based on a ZDC coincidence or total transverse energy in the event, or a jet trigger implemented using the Pb + Pb jet reconstruction algorithm. The jet trigger selected events having at least one jet with transverse energy $E_T > 20$ GeV. Event selection and background rejection criteria were applied [17] yielding 52×10^6 and 14×10^6 events in the minimum-bias and jet-triggered samples, respectively. For each event, Ψ_2 was computed from the azimuthal distribution of the transverse energy measured in the FCal [17,23], and angles with respect to Ψ_2 were defined over $0 \leq \Delta\phi \leq \pi/2$. The centrality of Pb + Pb collisions was characterized by $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$, the total transverse energy measured in the FCal [17]. The results reported here were obtained using the following centrality intervals defined according to successive percentiles of the $\Sigma E_T^{\mathrm{FCal}}$ distribution ordered from the most central (highest $\Sigma E_T^{\mathrm{FCal}}$) to the most peripheral collisions: 5%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, and 50%–60%. The centrality interval 5%–60% coincides to the range over which the Ψ_2 resolution is adequate for the measurement. A Glauber model analysis [24,25] of the $\Sigma E_T^{\mathrm{FCal}}$ distribution [17] was used to evaluate the average number of nucleons participating in the collision, $\langle N_{\mathrm{part}} \rangle$, in each centrality interval.

The jet reconstruction and underlying event subtraction procedures are the same as those used in Ref. [3], which is summarized in the following. The anti-k_t algorithm was applied to calorimeter towers with segmentation $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. A two-step iterative procedure was used to obtain an event-by-event estimate of the average η-dependent UE energy density while excluding actual jets from that estimate. The jet kinematics were obtained by subtracting the UE energy from the towers within the jet. This subtraction accounts for elliptic flow by modulating the average background density by the magnitude of the elliptic flow measured by the calorimeter, v_2^{calo}, over the interval $|\eta| < 3.2$ and excluding η regions containing jets. Following reconstruction, the jet energies were corrected to account for the calorimeter energy response using an η- and E_T-dependent multiplicative factor that was derived from Monte Carlo (MC) simulations [26].

Separate from the calorimeter jets, "track jets" were reconstructed by applying the anti-k_t algorithm with $R = 0.4$ to charged particles having $p_T > 4$ GeV. The p_T of the track jets, p_T^{trkjet}, is largely unaffected by the UE due to the $p_T > 4$ GeV requirement. To exclude the contribution to the jet yield from UE fluctuations of soft particles falsely identified as calorimeter jets, the jets used in this analysis were required to be within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.2$ of a track jet with $p_T^{\mathrm{trkjet}} > 10$ GeV or an EM cluster [27] with $p_T > 9$ GeV.

The performance of the jet reconstruction was evaluated using the GEANT4-simulated detector response [28,29] in a MC sample of pp hard scattering events at $\sqrt{s_{NN}} = 2.76$ TeV. The events were produced with the PYTHIA event generator [30] version 6.423 using the AUET2B tune [31] and overlaid on minimum-bias Pb + Pb collisions recorded by ATLAS. Through this embedding procedure, the MC sample contains a UE contribution that is identical in all respects to the data, including azimuthal modulation of the UE due to harmonic flow. Jets reconstructed in the MC events using the same algorithms as applied to data were compared to generator-level jets reconstructed from final-state PYTHIA hadrons. Potential variations in the jet energy resolution (JER) and jet energy scale (JES) with $\Delta\phi$ due to elliptic and higher-order modulation [11–13] of the UE were investigated in the MC sample; no significant variation was found.

The dependence of the JES on $\Delta\phi$ was further constrained by comparing the calorimeter jets to matched track jets in the data. For different values of $\Delta\phi$, the mean p_T of calorimeter jets was evaluated as a function of the p_T of the matched track jet, and no significant variation with $\Delta\phi$ was observed. This study provides an upper limit on the variation in the JES between jets at $\Delta\phi = 0$ and $\Delta\phi = \pi/2$ of 0.1% for $p_T > 45$ GeV.

Double differential jet yields, $d^2N_{\mathrm{jet}}/dp_T d\Delta\phi$, were measured over $|\eta| < 2.1$ for each of the centrality ranges described above and in five p_T intervals: 45–60 GeV, 60–80 GeV, 80–110 GeV, 110–160 GeV, and 160–210 GeV. The measurement in each p_T range was performed using events selected by the jet trigger except for the 45–60 GeV p_T range, in which minimum-bias events were used. The $\Delta\phi$ dependence of the jet yields in the 60–80 GeV p_T interval is shown for each centrality range in Fig. 1. A significant $\Delta\phi$ variation that is consistent with a $\cos 2\Delta\phi$ modulation is seen for all centrality intervals.

The measured yields and the resulting $v_2^{\rm jet}|_{\rm meas}$ values are distorted by the finite resolutions in Ψ_2 and the jet p_T. The Ψ_2 resolution was evaluated using a subevent technique [17,23] in which Ψ_2 was measured separately in the positive and negative η halves of the FCal yielding values Ψ_2^+ and Ψ_2^-, respectively. The width of the $\Psi_2^+ - \Psi_2^-$ distribution was used [23] to estimate a factor, κ, that was used to correct each measured v_2 value for the finite Ψ_2 resolution according to

$$v_2 = v_2|_{\rm meas}/\kappa. \tag{2}$$

This factor was evaluated for events containing jets to account for the relevant distribution of events within each centrality interval.

The p_T dependence, and possibly also the $\Delta\phi$ dependence, of the measured yields are affected by the JER, which arises from both fluctuations in the UE and the

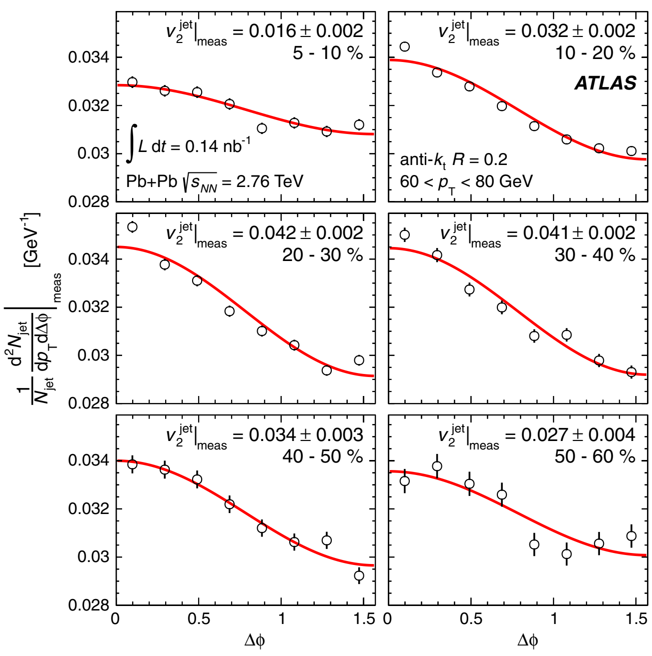

FIG. 1 (color online). $\Delta\phi$ dependence of measured $d^2N_{\rm jet}/dp_T d\Delta\phi$ in the $60 < p_T < 80$ GeV interval for six ranges of collision centrality. The yields are normalized by the total number of jets in the p_T interval. The solid curves indicate the results of fitting the data to the functional form of Eq. (1), with the resulting v_2 values, $v_2^{\rm jet}|_{\rm meas}$, listed in each panel. The error bars and errors on $v_2^{\rm jet}|_{\rm meas}$ indicate statistical uncertainties.

detector response. The MC study shows that for the $R = 0.2$ jets used in this analysis, the JER-induced migration between jet p_T intervals is sufficiently small that a "bin-by-bin" unfolding method, utilizing multiplicative corrections to the jet yields, is appropriate. The bin-by-bin correction factors are defined to be the number of generator-level jets divided by the number of reconstructed jets in each p_T, $\Delta\phi$, and centrality interval. The MC studies show no significant $\Delta\phi$ variation of the JER, JES, and the correction factors, and so these correction factors were taken to be $\Delta\phi$ independent. Since the measurements presented here depend only on the ratios of jet yields between different $\Delta\phi$ intervals for the same p_T range, the correction factors do not affect any of the final results; the potential for a $\Delta\phi$ dependence of the correction factors is included in the estimates of the systematic uncertainty.

Systematic uncertainties on the corrected v_2 values arise due to uncertainties on the two correction procedures described above. Uncertainties on κ were estimated by using the values obtained in previous studies [17]. The uncertainties were found to vary between 1% and 4% from central to peripheral collisions. Potential distortions in the measurement of Ψ_2 due to the production of jets in the FCal pseudorapidity range were studied in the MC sample and found to be negligible for the centrality intervals included in this analysis.

Uncertainties on the measurements arising from $\Delta\phi$-dependent systematic uncertainties on the bin-by-bin correction factors were estimated by determining the sensitivity of these correction factors to each systematic variation and then parametrizing that sensitivity with a $\cos 2\Delta\phi$ dependence. The sensitivity to the $\Delta\phi$ dependence of the spectrum was evaluated by varying the p_T spectrum of the generator-level jets in each $\Delta\phi$ interval within a range consistent with the measured $v_2^{\rm jet}$ values. The JES and JER contributions to the uncertainty were obtained by varying the relationship between generator-level and reconstructed jet p_T in the determination of the correction factors. These procedures utilized the JES constraints obtained from track jets and direct measurements of the UE contribution to the JER [3]. Parametrizations of the measured $v_2^{\rm calo}$ and the average background E_T underlying a typical jet measured in the data were used to provide the dependence of variations on centrality.

The azimuthal dependence of jet suppression can be characterized by $v_2^{\rm jet}$, which was obtained by correcting the $v_2^{\rm jet}|_{\rm meas}$ values using Eq. (2). Figure 2 shows the resulting $v_2^{\rm jet}$ values as a function of jet p_T for all centrality intervals. Significant, nonzero values are observed over the range $45 < p_T < 160$ GeV for all centrality intervals. A direct comparison between the v_2 of single high-p_T charged particles and $v_2^{\rm jet}$ is generally not possible; however, the fact that both quantities exhibit only a weak p_T dependence leads to the expectation that they should be of similar magnitude. In the charged-particle measurements,

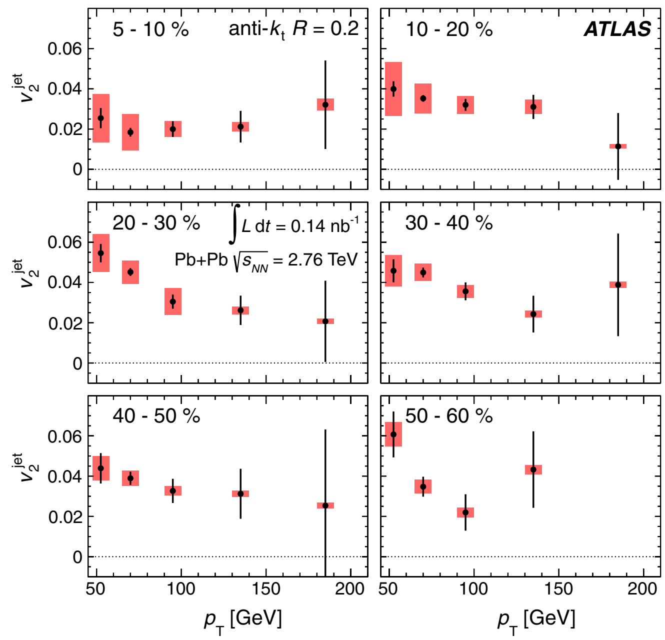

FIG. 2 (color online). $v_2^{\rm jet}$ as a function of jet p_T in each centrality interval. The error bars on the points indicate statistical uncertainties while the shaded boxes represent the systematic uncertainties (see text). The horizontal width of the systematic error band is chosen for presentation purposes only.

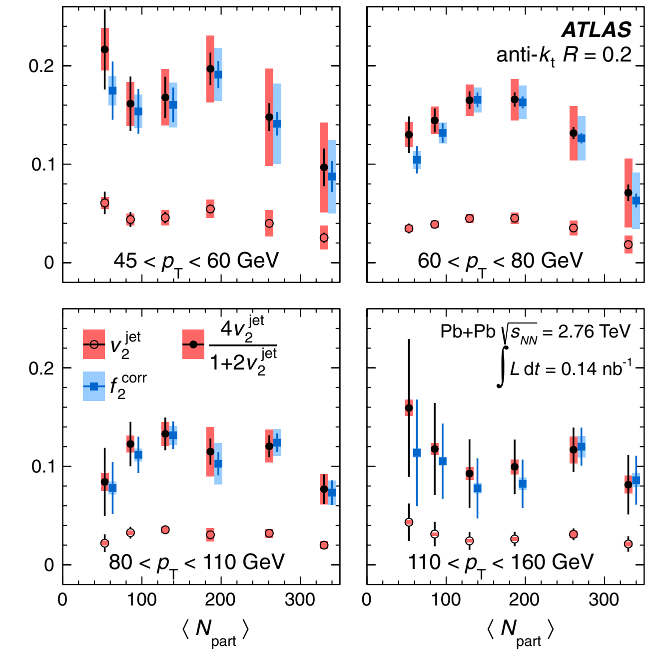

FIG. 3 (color online). The $\langle N_{\rm part}\rangle$ dependence of $v_2^{\rm jet}$ (○), $f_2^{\rm corr}$ (■), and $4v_2^{\rm jet}/(1+2v_2^{\rm jet})$ (●). All quantities have statistical and systematic uncertainties that are indicated by error bars and shaded bands, respectively. The uncertainties for all quantities are strongly correlated. The horizontal positions of the points have been offset slightly for presentation purposes and the width of the error bands indicates the uncertainty on $\langle N_{\rm part}\rangle$.

the v_2 values of charged particles with $28 < p_T < 48$ GeV were found to vary between 0.02 and 0.05 for the 10%–50% centrality range [18], which are generally in agreement with $v_2^{\rm jet}$ values reported here indicating no obvious inconsistencies between the two results.

The centrality dependence of $v_2^{\rm jet}$ is shown in Fig. 3 as a function of $\langle N_{\rm part}\rangle$ for different ranges in p_T. The variation of jet yields with $\Delta\phi$ can also be characterized by the ratio of jet yields between the most out-of-plane and most in-plane bins,

$$R_{\Delta\phi}^{\rm max} \equiv d^2N_{\rm jet}/dp_Td\Delta\phi|_{\rm out}/d^2N_{\rm jet}/dp_Td\Delta\phi|_{\rm in}. \quad (3)$$

This quantity is more general than $v_2^{\rm jet}$ as it does not assume a functional form for the $\Delta\phi$ dependence of the jet yields. The nuclear modification factor, $R_{\rm AA}$, is a measure of the effect of quenching on hard scattering rates, and $R_{\Delta\phi}^{\rm max}$ can be interpreted as the ratio of $\Delta\phi$-dependent $R_{\rm AA}$ factors, $R_{\Delta\phi}^{\rm max} = R_{\rm AA}|_{\rm out}/R_{\rm AA}|_{\rm in}$ [16]. The yields were corrected for Ψ_2 resolution assuming that the $\Delta\phi$ variation is dominated by the cos2$\Delta\phi$ modulation,

$$\frac{d^2N_{\rm jet}^{\rm corr}}{dp_Td\Delta\phi} = \frac{d^2N_{\rm jet}^{\rm meas}}{dp_Td\Delta\phi}\left(\frac{1+2v_2^{\rm jet}\cos 2\Delta\phi}{1+2v_2^{\rm jet}|_{\rm meas}\cos 2\Delta\phi}\right). \quad (4)$$

The results, expressed in terms of the quantity $f_2 \equiv 1 - R_{\Delta\phi}^{\rm max}$, show as much as a 20% variation between the out-of-plane and in-plane jet yields, but they are reduced slightly from the maximal difference, evaluated at $\Delta\phi = \pi/2$ and $\Delta\phi = 0$, by the finite bin size used in the measurement. That reduction was corrected by assuming a $1 + 2v_2^{\rm jet}\cos 2\Delta\phi$ variation of the jet yields *within* the $\Delta\phi$ bins containing $\Delta\phi = 0$ and $\pi/2$, and calculating the corresponding yields at those $\Delta\phi$ values. From these yields, $f_2^{\rm corr}$ was calculated analogously to f_2. The magnitude of the correction is typically a few percent. The $f_2^{\rm corr}$ values are shown in Fig. 3. For a pure cos2$\Delta\phi$ modulation of the jet yields, $f_2^{\rm corr}$ would be given by $4v_2^{\rm jet}/(1+2v_2^{\rm jet})$. To test for deviations of the $\Delta\phi$ dependence of the jet yields from a pure cos2$\Delta\phi$ variation, $4v_2^{\rm jet}/(1+2v_2^{\rm jet})$ was calculated using the measured $v_2^{\rm jet}$ values and is shown for each $p_{\rm T}$ and centrality interval in Fig. 3.

Similar variations of $v_2^{\rm jet}$, $f_2^{\rm corr}$, and $4v_2^{\rm jet}/(1+2v_2^{\rm jet})$ with $\langle N_{\rm part}\rangle$ are seen in the 60–80 GeV range, which has the best statistical precision. A reduction in $f_2^{\rm corr}$ and $v_2^{\rm jet}$ in both the most central and peripheral collisions is not surprising; for very central collisions, the anisotropy of the initial state is small and the possible $\Delta\phi$ variation of path lengths in the medium is limited. Although the anisotropy is greater in peripheral collisions, there is little suppression in the jet yields [3]. Therefore large variations in jet yield as a function of $\Delta\phi$ would be unexpected. The $f_2^{\rm corr}$ and $4v_2^{\rm jet}/(1+2v_2^{\rm jet})$ values are generally in agreement within uncertainties, indicating an azimuthal dependence of relative suppression when measured with respect to the elliptic event plane that is dominated by second-harmonic modulation.

This Letter has presented results of ATLAS measurements of the variation of $R = 0.2$ anti-k_t jet yields in $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb collisions as a function of $\Delta\phi$, the relative azimuthal angle of the jet with respect to the elliptic event plane. A significant $\Delta\phi$ variation in the jet yield is observed for all centrality intervals and in all p_T ranges except for the 160–210 GeV p_T interval where the statistical uncertainties are large. The observed azimuthal variation of jet yields amounts to a reduction of 10%–20% in the jet yields between in-plane and out-of-plane directions. These results establish a relationship between jet suppression and the initial nuclear geometry that should constrain models of the path-length dependence of the quenching mechanism.

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