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Generalized angularities and differential jet shapes measurements from STAR at $\sqrt{s}$ = 200 GeV

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Jets from early stages of heavy-ion collisions undergo modified showering in quark-gluon plasma (QGP) relative to vacuum due to jet-medium interactions, which can be measured using observables like differential jet shape and generalized angularities. Differential jet shape ($\rho(\mathbf{r})$) encodes radially differential information about jet broadening and has shown an average migration of charged energy away from the axes of quenched jets from Pb+Pb collisions at the LHC. Measurements of generalized angularities in presence of the medium from Pb+Pb collisions at the LHC show harder, or more quark-like jet fragmentation relative to vacuum. Measuring these distributions in heavy-ion collisions at RHIC will help us further characterize jet-medium interactions in a phase-space region complementary to that of the LHC.

In these proceedings, we present the first fully corrected measurements of $\rho(\mathbf{r})$, jet girth (g), momentum dispersion ($\mathrm{p_T^D}$) and momentum difference of leading and subleading constituent particles (LeSub) observables, using hard-core jets in $p+p$ collisions at $\sqrt{s}$ = 200 GeV, collected by the STAR experiment. Finally, the data are compared with model calculations and the physics implications are discussed.

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1. Introduction

Hard scattered partons from early stages of high-energy hadron collisions undergo successive, small-angle fragmentations, and eventually appear in the final state as collimated sprays of hadrons called *jets*. In heavy-ion collisions, jets traverse the quark-gluon plasma (QGP) medium and are modified relative to a $p + p$ baseline. This is known as *jet quenching* [1]. Therefore, jets are used as probes of QGP, containing information of interaction between hard partons and QGP medium. One way to access the quenching information is by studying intra-jet angular distribution of energy relative to the jet-axis through generalized jet angularities, calculated as:

$$\lambda_\beta^\kappa = \sum_{\text{const}\in\text{jet}} \left(\frac{p_{\text{T,const}}}{p_{\text{T,jet}}}\right)^\kappa r(\text{const},\text{jet})^\beta, \tag{1}$$

where $p_{\text{T,jet}}$ is the jet's total momentum, and $r(\text{const},\text{jet}) = \sqrt{(\eta_{\text{jet}} - \eta_{\text{const}})^2 + (\phi_{\text{jet}} - \phi_{\text{const}})^2}$ is the (η, ϕ) distance of a constituent from the jet-axis. Parameters κ and β tune experimental sensitivity to hard and wide-angle radiation, respectively. λ_β^1's are infra-red and collinear (IRC) safe angularites [2], which probe the average angular spread of energy around the jet-axis. They are radial moments of the jet's momentum profile, also known as differential jet-shape ($\rho(\mathbf{r})$), given by,

$$\rho(\mathbf{r}) = \lim_{\delta r\to 0} \left\langle \frac{1}{\delta r} \frac{\sum_{|\mathbf{r}_{\text{const}}-\mathbf{r}|<\delta r/2} p_{\text{T,const}}}{p_{\text{T,jet}}} \right\rangle_{\text{jets}}, \tag{2}$$

where $\mathbf{r}_{\text{const}} = (\eta_{\text{const}} - \eta_{\text{jet}})\hat{\eta} + (\phi_{\text{const}} - \phi_{\text{jet}})\hat{\phi}$, and it follows that,

$$\lambda_\beta^1 = \int_{\text{jet}} r^\beta \rho(\mathbf{r}) d\mathbf{r}. \tag{3}$$

The jet angularity based observables like jet-substructure measurements in Pb+Pb collisions at $\sqrt{s_{\text{NN}}}$ = 2.76 TeV at the LHC, have shown quenched jets, on average, have migration of charged energy away from their axis relative to a $p + p$ baseline [3] and possibly a survivor bias toward harder, quark-like fragmentation [4]. Similar measurements using jets with lower $p_{\text{T,jet}}$ at RHIC, will help understand jet-medium interactions in a complementary phase-space region to LHC.

In this proceeding, jet girth ($g = \lambda_1^1$), momentum dispersion ($\text{p}_\text{T}^\text{D} = \sqrt{\lambda_0^2}$) and the differential jet-shape ($\rho(\mathbf{r})$) are measured in $p + p$ collisions $\sqrt{s}$ = 200 GeV to set a baseline for heavy-ion collisions at RHIC. We also calculate a non-angularity based jet observable LeSub which gives a measure of the hardest splitting of the jet:

$$LeSub = p_{\text{T,constituent}}^{\text{leading}} - p_{\text{T,constituent}}^{\text{subleading}}. \tag{4}$$

2. Dataset and Analysis Method

The analysis uses data from $p + p$ collisions at $\sqrt{s}$ = 200 GeV collected in 2012 using the Solenoidal Tracker At RHIC (STAR) detector system. Charged-particle tracks and neutral energy depositions (towers) are measured using STAR's Time Projection Chamber (TPC) [5] and Barrel Electromagnetic Calorimeter (BEMC) [6] detectors respectively. Together, they provide full azimuthal coverage with a pseudorapidity acceptance of $|\eta| \leq 1$. The tracks and towers are clustered into jets using the anti-k_T algorithm with a jet resolution parameter $R = 0.4$, implemented using the FastJet library [7]. To suppress contributions of fake tracks and combinatorial background (especially in the context of the larger heavy-ion background), a "hard-core" constituent selection as was done in previous STAR analyses [8] is applied, which only allows tracks (towers) with $cp_{T,\text{track}}(E_{T,\text{tower}}) \geq 2$ GeV to be clustered into jets. To enhance jet signal, only High-Tower (HT) triggered events, with at least one tower with $E_{T,\text{tower}} \geq 4$ GeV are considered. After clustering, only jets completely falling within acceptance ($|\eta_{\text{jet}}| \leq 0.6$) are kept. Jets with area, $A_{\text{jet}} < 0.3$ are rejected to further reduce the fake jet contribution.

The distributions of g, p_T^D and LeSub are fully corrected for detector effects by using iterative bayesian unfolding, implemented using the RooUnfold library [9]. The unfolding requires a response matrix between particle-level and detector-level. This is constructed using an embedding simulation which involves PYTHIA-6 STAR tune [10] events processed into detector hits using GEANT3 [11] and added to real zero-bias events from $p + p$ collision environment. To calculate $\rho(\mathbf{r})$, additional associated tracks not clustered into jets, but inside the jet cones are also used. This was done to look at the complete jet, around its hard core. Given a jet, tracks with $p_{T,\text{assoc}} \geq 1$ GeV/c and $r(\text{assoc, jet}) \leq 0.4$ are used. The $\rho(\mathbf{r})$ is corrected using bin-by-bin factors obtained from the aforementioned embedding simulation[1].

3. Result and Discussion

Differential jet-shape as a function of $r = r(\text{assoc, jet})$ from the jet axis is shown in Fig. 1. Girth (g), p_T^D and LeSub distributions are shown in Fig. 2. Systematic uncertainties are shown as shaded grey bands. On average, lower energy jets with $15 \leq p_{T,\text{jet}} < 20$ GeV/c have higher g, lower *LeSub* and more energy away from jet-axis than jets with $p_{T,\text{jet}} \geq 20$ GeV/c.

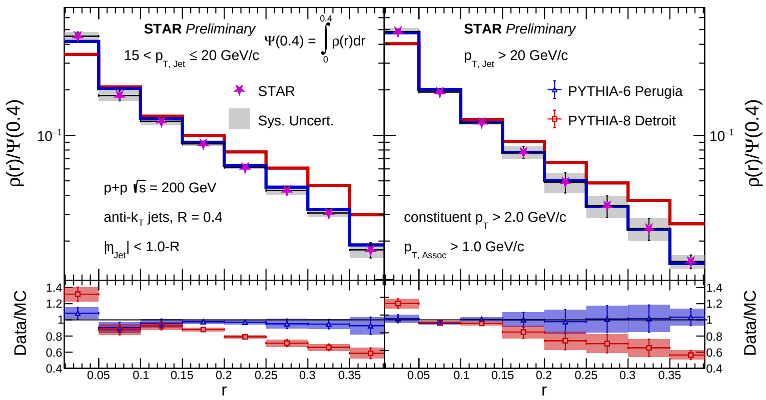

Figure 1: $\rho(\mathbf{r})$ vs r (magenta stars, normalized to unity) for jets with $15 \leq p_{T,\text{jet}} < 20$ GeV/c (left) and $p_{T,\text{jet}} \geq 20$ GeV/c (right). The results are compared to PYTHIA-6 (STAR) (blue) and PYTHIA-8 (Detroit) (red). The lower panels show the ratio of the data calculation to the PYTHIA-6 (STAR) (blue) and PYTHIA-8 (Detroit) (red).

[1]Details of closure associated with the unfolding can be found in slides 25-33 in the talk associated with this proceeding, https://wwuindico.uni-muenster.de/event/1409/contributions/2038/attachments/859/1764/HP2023.pdf

The results are compared to PYTHIA-6 (STAR) [10] and PYTHIA-8 Detroit underlying event tune [12]. All measurements show a good agreement with PYTHIA-6, while PYTHIA-8 is shown to underestimate jets with higher $LeSub$ and lower g values. $\rho(\mathbf{r})$ from PYTHIA-8 underestimates the fraction of jet momentum closer to the jet axis. Figures 3 and 4 show STAR data compared to PYTHIA-8 (Detroit) with (a) all hard scatterings, (b) only $qq \rightarrow qq$ hard scatterings (quark jets), and (c) only $gg \rightarrow gg$ hard scatterings (gluon jets).

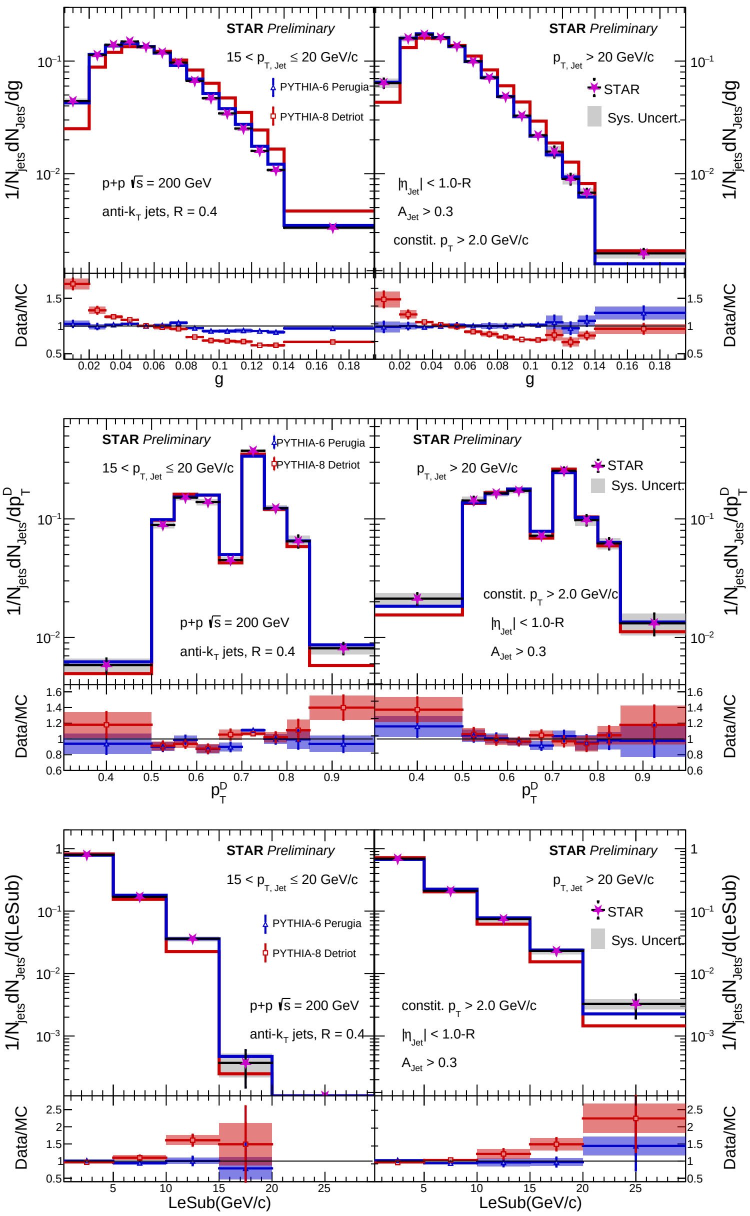

Figure 2: g (top), $\mathrm{p_T^D}$(middle) and $LeSub$ (bottom) distributions (magenta stars, normalized to unity) for jets with $15 \leq p_{\mathrm{T,jet}} < 20$ GeV/c (left) and $p_{\mathrm{T,jet}} \geq 20$ GeV/c (right). The results are compared to PYTHIA-6 (STAR) (blue) and PYTHIA-8 (Detroit) (red). The lower panels show the ratio of the data calculation to the PYTHIA-6 (STAR) (blue) and PYTHIA-8 (Detroit) (red).

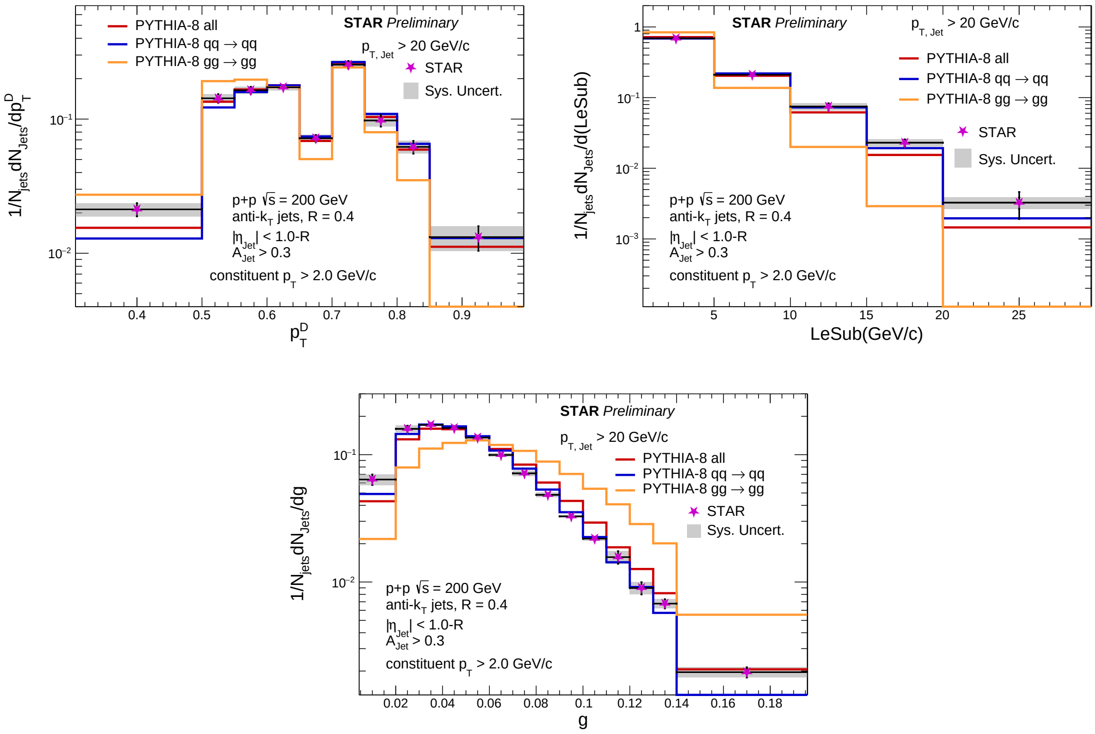

Figure 3: $p_T^D = \sqrt{\lambda_0^2}$ (top-left), LeSub(top-right) and g (bottom) distributions for jets with $p_{T,\mathrm{jet}} \geq 20$ GeV$/c$. The results are compared to PYTHIA 8 (Detroit) with all hard processes (red), with only $qq \to qq$ processes (blue) and $gg \to gg$ processes (orange).

Since gluon jets have softer, more spread-out radiation pattern on average than quark jets [13], they are likely to have lower p_T^D, lower LeSub, higher g with more momentum ($\rho(\mathbf{r})$) away from the jet-axis. As even quark-jets from PYTHIA-8 (Detroit) show softer fragmentation on average than the STAR data, it is likely that PYTHIA-8 (Detroit) underestimates hard fragmentation of partons.

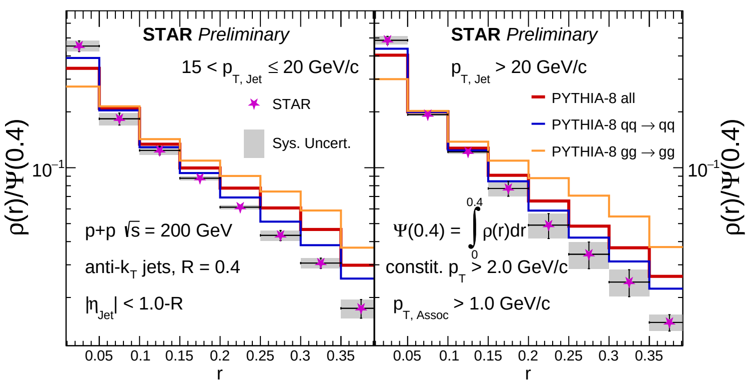

Figure 4: $\rho(\mathbf{r})$ vs r (magenta) for $15 \leq p_{T,\mathrm{jet}} < 20$ GeV$/c$ (left) and $p_{T,\mathrm{jet}} \geq 20$ GeV$/c$ (right). The results are compared to PYTHIA 8 (Detroit) with all hard processes (red), with only $qq \to qq$ processes (blue) and $gg \to gg$ processes (orange).

4. Conclusions

First measurements of jet-shape observables g, p_T^D, LeSub and $\rho(\mathbf{r})$ from STAR using hard-core jets $p+p$ collisions at $\sqrt{s}$ = 200 GeV are presented, setting the baseline for heavy-ion collisions to measure the medium-modification at RHIC. With the hard-core jet definition and HT trigger requirement, the sample of jets used here is biased towards hard-fragmented jets. The results show good agreement with PYTHIA-6 (STAR). PYTHIA-8 (Detroit) is shown to underestimate harder-fragmented jets, and needs further tuning of PYTHIA-8's parton shower/hadronization parameters to explain STAR hard-core jets.

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