Reconstructed Jet Results in p+p, d+Au and Cu+Cu collisions at 200 GeV from PHENIX

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Abstract. Jet reconstruction in heavy ion collisions at RHIC and the LHC is becoming a popular tool for exploring medium effects including the energy loss and modified fragmentation of hard-scattered partons. In p+A and d+A collisions, reconstructed jets are important for evaluating cold nuclear matter effects such as the impact parameter dependence of nuclear parton distribution functions and initial state energy loss. We present current PHENIX results from p+p, d+Au, and Cu+Cu collisions at 200 GeV using the Gaussian filter and anti-$k_T$ algorithms. The systematic study of direct jet reconstruction across a variety of collisions systems at PHENIX will help to tell a coherent story of jet physics at RHIC.

1. Introduction

Jet reconstruction in heavy ion collisions at RHIC and the LHC is evolving into a sophisticated method to probe suppression, quenching and other hot and cold nuclear medium effects on fragmenting hard-scattered partons. Because reconstructed jets can better determine the full kinematics of a fragmenting parton at leading order (LO), they may be more sensitive to medium effects than inclusive measurements of leading hadrons from parton fragmentation. Together, jet measurements at RHIC and the LHC can provide a complementary set of high-statistics heavy ion results to investigate energy loss mechanics at two different temperatures.

The flexibility of colliding species in the RHIC facility in particular allows experimental control over the system size, energy density and geometry of heavy ion collisions, all of which can be exploited with a developing jet physics program.

An important signature of cold and hot nuclear medium effects on reconstructed jets is the deviation of jet yields from a naive geometry-dependent scaling of jets in $p+p$ collisions. The nuclear modification factor $R_{AA}$ is defined as the ratio of jet yields in Cu+Cu collisions of a given centrality to the scaled $p+p$ reference,

$$R_{AA}^{cent} = \frac{\langle 1/N_{cent} \rangle (dN_{cent}/dp_T)}{<T_{cent}^{AB}> (d\sigma_{p+p}/dp_T)},$$

where $<T_{cent}^{AB}>$ is the nuclear overlap function derived from a Glauber simulation of Cu+Cu collisions. The $R_{AA}$ is sensitive to effects from the hot medium formed in heavy ion collisions, such as partonic energy loss or jet quenching.
In lieu of a $p+p$ reference, peripheral collisions, where the medium effects are expected to be small, can be used instead. The nuclear modification factor $R_{\text{CP}}$ is defined as the ratio of jet yields relative to that in peripheral collisions,

$$R_{\text{CP}}^{\text{cent}} = \frac{(1/N_{\text{cent}}^{\text{coll}})(1/N_{\text{cent}}^{\text{evt}})(dN_{\text{cent}}^{\text{jet}}/dp_T)}{(1/N_{60-88\%}^{\text{coll}})(1/N_{60-88\%}^{\text{evt}})(dN_{60-88\%}^{\text{jet}}/dp_T)},$$  \hspace{1cm} (2)

where $N_{\text{coll}}^{\text{cent}}$ is the mean number of binary collisions. In $d+Au$ collisions, the $R_{\text{CP}}$ measures the scale of the differences in jet production between the centralities that arise from cold nuclear matter effects (CNM) such as initial and final state energy loss or modification of nuclear parton distribution functions (nPDF’s). It does not, however, measure the absolute scale of the nuclear effect relative to $p+p$ collisions, which is necessary for a full understanding of CNM effects and their implications for suppression/quenching in $A+A$ (ion-ion) collisions.

In these proceedings, we present the latest jet reconstruction results in $p+p$ and Cu+Cu[1] and in $d+Au$ collisions[2] at PHENIX.

2. Experimental setup

2.1. PHENIX Detector
This analysis uses the two PHENIX central arm spectrometers, which cover a pseudorapidity range of $-0.35 < \eta < +0.35$ and have a azimuthal acceptance of $\Delta \phi = \pi/2$ in each arm.

Charged tracks from charged hadrons and electrons are reconstructed using the drift chamber (DC), pad chamber (PC) and ring-imaging Čerenkov detector (RICH). Electromagnetic energy from photons, $\pi^0$’s and other neutral hadrons is clustered by the electromagnetic calorimeter (EMCal). Clusters are required to have a time of flight within a $\pm 5\sigma_{\text{tof}}$ window of a light-speed particle, where $\sigma_{\text{tof}}$ is the timing resolution in calorimeter towers.

Reconstructed tracks and clusters with $p_T > 400$ MeV/c are used as the inputs to the jet reconstruction algorithms. For the case when charged tracks are associated with a cluster in the EMCal, only the track (which better captures the momentum of charged hadrons) is ultimately used.

2.2. Dataset
The measurements presented here are based on data taken by the PHENIX detector in $p+p$ and Cu+Cu collisions in 2005 and $d+Au$ collisions in 2008, all at a center of mass energy per nucleon of $\sqrt{s_{\text{NN}}} = 200$ GeV.

The high rate of the PHENIX data acquisition system ($> 6$ kHz in $p+p$ collisions) allows the complementary recording of a triggered dataset for high-statistics high-$p_T$ results as well as a large minimum bias dataset to understand the trigger efficiency in a data-driven way. Data from minimum bias collisions is used to evaluate and extrapolate the performance of the high-$p_T$ Electromagnetic/RICH Trigger (ERT), which requires $> 2.1(1.6)$ GeV within a $4 \times 4$ calorimeter tower window in the PbSc (PbGl) sectors of the EMCal. Efficiency-corrected, trigger-selected data is used to construct the jet yields used in the final result.

3. Methodology

3.1. Jet Reconstruction
In $p+p$ and Cu+Cu collisions, jets are reconstructed with the Gaussian filter algorithm (parameter $\sigma = 0.3$), a seedless, cone-like, infrared- and collinear-safe algorithm with a continuous angular weighing of energy deposits[3]. The Gaussian filter jet axis ($\eta', \phi'$) is defined by the position at which the convolution of the event energy density $p_T(\eta', \phi')$ with a gaussian kernel is a local maximum:
Figure 1. Left: $\Delta \phi$ distributions for jets in Cu+Cu 0-20% collisions that pass successively harder fake jet rejection cuts. Right: transfer matrix $P(p_{T,rec}^T|p_{T,true}^T)$ for reconstructed jets in $p+p$ collisions at PHENIX.

$$p_{T,jet}^T \equiv \max \left\{ \int \int d\eta' d\phi' p_T(\eta', \phi') e^{-((\Delta \eta^2 + \Delta \phi^2)/2\sigma_{dis}^2)} \right\},$$

where $\Delta \eta = \eta - \eta'$, $\Delta \phi = \phi - \phi'$ and $p_{T,jet}^T$ is the local maximum value which is taken to be the transverse momentum of the jet. The continuous angular weighing stabilizes the jet axis in the presence of background and optimizes the signal to background ratio (S/B) by focusing on the energetic core of the jet.

In $d+Au$ collisions, the anti-$k_T$ jet algorithm[4] with a cone size of $R = 0.3$ is used. This is the first time anti-$k_T$, a sequential recombination algorithm which is popular in other heavy ion jet analyses, was tested for use in the PHENIX experiment.

Reconstructed jets are required to have three of more constituents within a $30^\circ$ solid angle of the jet axis. Additionally, jets must pass a fiducial cut requiring that they lie $\Delta \eta, \Delta \phi > 0.05$ units away from any edge of the PHENIX central arm acceptance. Finally, a cut on the charged fraction of the jet momentum is applied to eliminate residual background from mis-identified charged tracks.

3.1.1. Fake jet rejection Two different methods are used to handle the influence of fake jets (jets reconstructed from a combinatorial collection of nearby underlying heavy ion event particles). In $d+Au$ collisions, we only consider the jet yields $> 15$ GeV/c, where the fake rate is determined from data to be negligible.

In Cu+Cu collisions, PHENIX has developed a technique to separate real low-$p_T$ jets from UE fluctuations on a jet by jet basis, which is implemented by forming the $g$-discriminant for each jet:

$$g \equiv \sum_{i \in \text{fragment}} (p_T)^2_i \exp \left( -((\Delta \eta^2 + \Delta \phi^2)/2\sigma_{dis}^2) \right),$$

where $\Delta \eta$ and $\Delta \phi$ are the distances in $\eta/\phi$ space between the jet axis and fragment, and $\sigma_{dis} = 0.1$ is chosen to provide a tighter angular weighing than the Gaussian filter jet reconstruction. Requiring a minimum value of $g$ is similar to an angularly weighted $p_T$ cut which is efficient for collimated jets with a harder fragmentation pattern, and inefficient for jets consistent with underlying event fluctuations.
A data-driven method examining the angular correlation of reconstructed jets is used to determine the point at which point successively harder cuts on the $g$-discriminant saturate. In Figure 1, the combinatorial component in the $\Delta \phi$ distribution for reconstructed di-jets (indicative of fake jets) decreases for harder cuts on $g$, until the effect of the cut saturates and only a back-to-back peak (indicative of angularly correlated QCD dijets) remains. A fake jet rejection cut of $g > 17.8$ GeV$^2$ is used for the Cu+Cu results here.

3.2. Performance and Spectrum Corrections

The detector response to partonic jets in $p+p$ collisions is evaluated with a Monte Carlo (MC) simulation. $14 \times 10^6$ total PYTHIA events were generated with values of the minimum transverse momentum transfer in the QCD hard scattering ranging from $p_T = 0.5$ to 64 GeV/c, and Gaussian jet reconstruction is run on final state particles with $p_T^{\text{true}} > 400$ MeV/c. Other PYTHIA tunes, as well as the HERWIG generator, are used as a cross-check. Then, the jet reconstruction performance is determined with a GEANT3 simulation of the PHENIX detector geometry. The transfer matrix $P(p_T^{\text{rec}}|p_T^{\text{true}})$, which relates jets reconstructed at the detector scale to the truth jets is shown in Figure 1. In PHENIX, the energy scale is driven mainly by the loss of neutral energy (primarily $n$ and $K^0$'s), tracking inefficiency and edge of acceptance effects rather than fluctuations of the underlying event or the intrinsic DC and EMCal resolutions.

Using the transfer matrix and jet reconstruction efficiency, the $p+p$ reconstructed jet spectrum is unfolded to the truth spectrum using a singular value decomposition (SVD) unfolding method[5]. Future work in this part of the analysis now includes an additional hadronization correction that associates the hadronic and partonic energy scales, allowing for a better comparison to NLO theory calculations.

In $d+Au$ collisions, the effects of the mild underlying event on the jet $p_T$ are evaluated with an embedding analysis in which jet reconstruction is run on MC jet events embedded into minimum bias data. From this, the reconstructed jet yields are corrected to an equivalent yield in $p+p$ collisions though a bin by bin unfolding correction.

In Cu+Cu collisions, we subtract an event-averaged underlying event background which is parameterized in centrality and $z$-vertex position. The effects of the underlying event fluctuations on the jet $p_T$ are determined through an embedding procedure similar to $d+Au$, and the reconstructed jet yields are corrected to the equivalent $p+p$ yield through a bin by bin unfolding.

4. Results

The invariant cross section for inclusive jet production in $p+p$ collisions is shown in Figure 2. Comparisons to Gaussian filter reconstruction run on PYTHIA final-state hadrons, an NLO calculation, and a jet measurement by the STAR Collaboration[6] are shown as well. The fragmentation function for charged particles $(1/N_{\text{jet}})(dN/dz)$ is shown for different selections of jet $p_T$, where $z = p_T^{\text{charged}}/p_T^{\text{jet}}$ is the longitudinal fraction of the jet energy in the fragment.

The nuclear modification factor $R_{\text{CP}}$ for anti-$k_T$ jets in $d+Au$ collisions is shown in Figure 3. Different centrality selections (relative to the most peripheral collisions) are plotted in different colors. We observe an $R_{\text{CP}}$ flat in $p_T$ that is suppressed in the most central collisions ($R_{\text{CP}} \sim 0.75$-0.80) and is close to unity ($R_{\text{CP}} \sim 0.95$-1.00) in the mid-peripheral collisions. The 0-20%/60-88% $R_{\text{CP}}$ is also compared to that of single $\pi^0$'s from PHENIX 2003 data[7]. This comparison emphasizes the increased kinematic reach of reconstructed jets compared to using leading single hadrons. The $R_{\text{CP}}$ for $\pi^0$'s suggests a suppression at high-$p_T$ but has growing statistical errors after $> 10$ GeV/c. The $R_{\text{CP}}$ for reconstructed jets confirms this behavior out to 35 GeV/c.

The $p_{\text{out}} \equiv (p_T)_{\text{low}} \cdot \sin \Delta \phi$ for reconstructed dijets can be used to search for possible $k_T$-broadening from cold nuclear matter effects. Figure 4 shows the $p_{\text{out}}$ in different centralities,
Figure 2. Left: Jet production cross section in $p+p$ collisions, corrected to the $p_T^{true}$ hadron energy scale. Shown compared with theory. Right: Fragmentation function for charged particles in $p+p$ jets. Curves for different trigger jets are shown.

Figure 3. Left: Nuclear modification factor $R_{CP}$ for jets in $d+Au$ collisions as a function of the $p+p$-reconstructed energy scale $p_T^{rec}$ for three different centrality bins (0-20%/60-88%, 20-40%/60-88%, and 40-60%/60-88%). Right: The 0-20%/60-88% $R_{CP}$ for reconstructed jets compared to that of $\pi^0$s[7].

with kinematic and away-side peak cuts to select real QCD dijets. The distribution are very nearly centrality-independent.

The nuclear modification factor $R_{AA}$ for Gaussian filter jets in Cu+Cu collisions, as well as the $\Delta\phi$ distributions for reconstructed dijets, are shown in Figure 5. At high-$p_T$, the nuclear modification for peripheral collisions shows no effect ($R_{AA} \sim 1.0$) while for central collisions it indicates a strong suppression ($R_{AA} \sim 0.45 - 0.50$). As the $\Delta\phi$ distributions shows, the suppressed jets do not become angularly de-correlated in central events.

5. Jets at RHIC Study
Recently, the PHENIX Collaboration has proposed a re-imagining of the PHENIX experiment as “sPHENIX”[11], a dedicated jet detector with the acceptance, hermiticity and hadronic
calorimetry needed to support a robust jet physics program at RHIC. To this end, a proof of principle study[10] was undertaken to demonstrate the feasibility of separating real high-pT reconstructed jets from fakes in Au+Au collisions at √sNN = 200 GeV, without any fake jet rejection or subtraction scheme. The anti-kT algorithm is used exclusively throughout, with cone sizes R = 0.2, 0.3, 0.4.

The total Monte Carlo dataset was 0.75 × 109 minimum bias HIJING events. The study assumes an “ideal” calorimetric detector spanning |η| < 1 by φ ∈ [0, 2π) with a segmentation of Δη × Δφ = 0.1 × 0.1 towers. The HIJING code was modified to run jet reconstruction at every call of the HIJING fragmentation subroutine, and the fragmentation jets with E_{T}^{true} > 5 are defined as the truth jets used to evaluate the reconstruction performance.

Figure 6 outlines the underlying event subtraction procedure, which builds upon the one described by the ATLAS Collaboration[12]. In the first pass of the procedure, “seed jets” (R = 0.2 jets containing an energetic tower with > 3 times the mean tower energy) are excluded.

Figure 4. Left: Acceptance-corrected ∆φ distribution for d+Au 0-20% jets, different pT selections. Right: Self-normalized p_{out} distributions for different d+Au centrality selections.

Figure 5. Left: Nuclear modification factor R_{AA} for jets in Cu+Cu collisions as a function of the p+p-reconstructed energy scale p_{T}^{rec} for four different centrality bins (0-20%, 20-40%, 40-60% and 60-80%). Right: Reconstructed dijet away-side ∆φ distributions for the different Cu+Cu centrality bins (each distribution has been given unit normalization).
Figure 6. Left: Flowchart of underlying event subtraction procedure.

from the determination of the background, which is corrected for \( v_2 \) flow modulation in the event and done separately in \( \Delta \eta = 0.1 \) strips. This zeroth-order estimate of the background is subtracted from the towers in seed jets. The background determination procedure is repeated, this time only excluding seed jets with \( E_T > 20 \) from the background determination. In the second iteration, the \( v_2 \)-modulated, \( \eta \)-dependent background is subtracted from all towers in the event.

Jet reconstruction with the different \( R \) values is run on the background-subtracted towers. The reconstruction efficiency to have a reconstructed jet within \( \Delta R < 0.25 \) of a truth jets rises to 100\% above \( E_T^{\text{true}} > 15 \), \( > 20 \) and \( > 25 \) GeV for the \( R = 0.2, 0.3 \) and 0.4 cone sizes, respectively. The jet energy scale \( \langle E_T^{\text{reco}} - E_T^{\text{true}} \rangle / E_T^{\text{true}} \) is within 5\% of zero for jets above 20 GeV. The jet energy resolution \( \sigma(E_T^{\text{reco}} - E_T^{\text{true}})/E_T^{\text{true}} \) is < 25\% and < 15\% GeV for \( R = 0.2 \) and \( R = 0.4 \) jets above 20 GeV (and decreases with increasing truth jet energy).

Figure 7 shows the distribution of \( E_T^{\text{true}} \) for truth jets matched to a given \( R \) value and \( E_T^{\text{reco}} \) bin. We observe a dominant peak with \( E_T^{\text{reco}} \sim E_T^{\text{true}} \) with a \( \sim 5 \) GeV width well separated from the low-\( E_T^{\text{true}} \) exponential background. This is precisely the behavior necessary for a well-controlled unfolding from the reconstructed to true energy scales. Figure 7 also shows the distribution of \( E_T \) for \( R = 0.3 \) truth jets, and reconstructed jets matched and unmatched to truth jets. Reconstructed jets resulting from a hard scattering dominate above \( E_T^{\text{reco}} > 30 \) GeV (> 20 and > 40 GeV for \( R = 0.2 \) and \( R = 0.4 \) jets, respectively).

Taken together, the results from this study demonstrate a clear separation of jets resulting from a hard scattering from underlying event fluctuations at RHIC energies. As a reminder, this jet-background separation is achieved before any fake jet rejection or subtraction scheme is implemented, suggesting that it may be improved even further with additional work.

6. Conclusions
The direct jet cross section in \( p+p \) collisions at \( \sqrt{s} = 200 \) GeV, and its consistency with theory calculations over ten orders of magnitude, demonstrates the PHENIX capability for performing jet reconstruction measurements to \( p_T^{\text{true}} > 60 \) GeV/c and validates the Gaussian filter algorithm for general use.
Reconstructed jets have also been measured in $d+Au$ and $Cu+Cu$ collisions at $\sqrt{s_{NN}} = 200$ GeV for different centrality selections and over a wide $p_T$ range, and are starting to produce physics results. In $d+Au$ collisions, we observe a suppression of high-$p_T$ jets in central collisions relative to peripheral ones. Future work, such as the extracting the $R_{dA}$ (the nuclear modification factor relative to $p+p$ collisions) and controlling the fake rate to extend the kinematic reach to lower $p_T$, is needed to better understand the source of this effect. These results are important for the recent developments in modeling the impact parameter dependence of nPDFs[8]. Finally, we can derive a strong constraint on any centrality-dependent angular broadening in $d+Au$ collisions.

In $Cu+Cu$ collisions, we observe a strong suppression of jet production relative to the $p+p$ baseline, consistent with the level of suppression for high-$p_T$ $\pi^0$'s in Cu+Cu collisions also measured by PHENIX[9]. These preliminary results for reconstructed jets in different collision systems are currently being finalized.

The sPHENIX proposal, which re-envisions PHENIX as a dedicated jet detector, in tandem with the proposed RHIC luminosity upgrade would open the door to high-statistics inclusive jet, di-jet and $\gamma$-jet measurements. The study summarized here demonstrates that separation of reconstructed jets from background is feasible at RHIC energies with such an experimental setup.

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