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Reconstructed Jet Measurements in p+p, d+Au and Cu+Au collisions using PHENIX

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Nuclear modification factor measurements of jets in d+Au and Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity have been performed in PHENIX. Jets are reconstructed from charged particle tracks and electromagnetic calorimeter clusters with the anti-k_T algorithm. The measurements are unfolded for detector response. While the nuclear modification factor for centrality integrated data in d+Au collisions is found to be consistent with unity, the centrality-selected modification factor shows substantial deviations from unity. New measurements in p+Au collisions will provide crucial information for understanding the anomalous relationship between hard and soft processes in p/d+A systems. Meanwhile the Cu+Au collision system offers an intermediate testing ground for heavy ion jet reconstruction between small systems and those with the largest heavy ions. The underlying event in Cu+Au events is smaller when compared to that in the largest heavy ion systems, simplifying the extraction of the jet signals, but still achieving the large energy densities needed to drive substantial in-medium energy loss. To further explore the modification of the jets in Cu+Au collisions, jet fragmentation functions and jet grooming studies accessing the jet substructure have been performed. This talk presented the latest results from the reconstruction jet studies in PHENIX and their implications for energy loss in the quark gluon plasma.

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[*] Speaker

1. Introduction

Nuclear modification provides insight into the behaviour of the quark-gluon plasma (QGP) medium. The products of hard scattering in heavy ion collision systems traverse and interact with the QGP medium, leading to fewer reconstructed jets. RHIC provides different collision geometries, system sizes, and energy densities to study the QGP medium. PHENIX has measured nuclear modification for single particles, which carry only a fraction of the energy of the hard-scattered parton, in d+Au[2] and Cu+Au[3]. To leading order, jet measurements are probes of the hard scattered quark or gluon and can help quantify the energy loss of hard-scattered partons in the medium.

2. Jets at PHENIX

Jet reconstruction is a procedure to combine the products of the original scattered parton. In PHENIX, this means using the neutral clusters found in the electromagnetic calorimeter and the charged tracks in the drift chambers (DC) and pad chambers (PC). The PHENIX central arms each cover pseudo-rapidity range $|\eta| < 0.35$ and azimuth of (Φ) 90°. The tracks and clusters are combined using the anti-k_T algorithm[1], where the jet radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is a parameter set for a given analysis.

3. Jet Reconstruction in d+Au collisions with PHENIX

Jet production in d+Au $\sqrt{s} = 200$ GeV is sensitive to cold nuclear matter effects and provides an intermediary comparison between p+Au and Cu+Au systems. Jets were reconstructed using the anti-k$_T$ algorithm with input parameter R = 0.3 combining tracks and clusters reconstructed from the PHENIX electromagnetic calorimeter, drift chamber (DC), and pad chambers (PC). The cuts made in jet reconstruction are:

- Track $p_T > 0.4$ GeV/c
- Cluster energy > 0.4 GeV/c
- Jet particle multiplicity ≥ 3
- Jet axis to edge: $\Delta\eta > 0.05, \Delta\phi > \pi/64$
- CF = $\frac{\sum_{ChargedParticles} p_T}{jet_{p_T}} < 0.75$

The charged fraction (CF) is the momentum fraction carried by the charged particles in the reconstructed jet. This cut helps reduce the number of jets reconstructed from fake high p_T tracks due to conversions. The jet edge cut ensures most of the jet energy and constituents are reconstructed within the detector. The minimum jet multiplicity, along with the minimum cluster and track energy cuts, helps reduce background from fake jets.

The jet distribution is unfolded using Singular Value Decomposition (SVD) unfolding procedure. Simulations using PYTHIA embedded in $d + Au$ data are used to correct for contributions from the underlying event. A response matrix is generated from simulations, which correlates the true jet energy to the reconstructed jet energy, to unfold the reconstructed jet distribution in data. Many systematic errors are common to $p + p$ and $d + Au$ and will cancel in the R_{dAu}[1] ratio.

$$R_{AB} = \frac{\frac{1}{N_{Evt}}\frac{dN}{dp_T}}{T_{AB}\frac{d\sigma}{dp_T}} \tag{1}$$

The jet nuclear modification factor for all centralities in $d + Au$[4] is shown in Figure 1 (left), with the data points shown with grey systematic uncertainty bands. The data points are consistent with EPS09 nPDF calculations, which are shown as blue dashed lines[5]. The red dashed lines are cold nuclear matter energy-loss calculations[6]. The data favors the small momentum transfer curve. The centrality dependent R_{dAu} is also shown in Figure 1 (right), with the different centralities in their respective colors. The central $(0-20\%)$ $d+Au$ shows suppression which is consistent with modest cold nuclear matter energy-loss (red dashed lines). The peripheral events are consistent with unity with large overall normalization uncertainty.

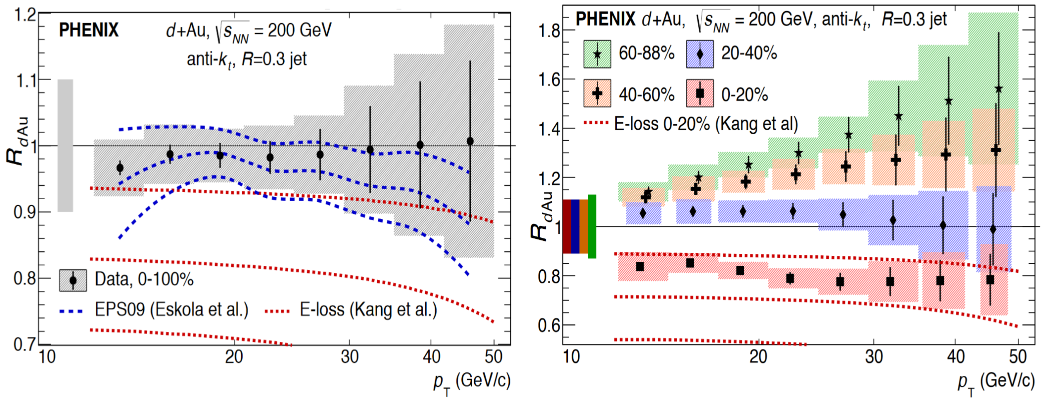

Figure 1: The R_{dAu} vs p_T for all centralities and theory curves for the EPS09 and E-loss are shown on the left. The Centrality dependent R_{dAu} and E-loss curves are shown on the right.

4. Jet Reconstruction in Cu+Au collisions with PHENIX

Measurements in $Cu + Au$ are more challenging because it has a stronger underlying event contribution. This leads to a larger fake jet contribution, which was mitigated by using a smaller jet radius and fake jet subtraction. $Cu + Au$ jets were reconstructed using anti-k_T radius $R = 0.2$. The cuts used were:

- Track $p_T > 0.5$ GeV
- Cluster energy > 0.5 GeV
- Jet particle multiplicity ≥ 3
- Jet axis to edge: $\Delta\eta > 0.05, \Delta\phi > 0.12$
- $0.2 < \mathrm{CF} = \frac{\sum_{ChargedParticles} p_T}{jet_{p_T}} < 0.7$

The cuts are similar to $d + Au$, except the minimum energy and p_T of track and clusters are higher and the charged fraction also has a minimum cutoff. The jet radius was chosen using PYTHIA+sHIJING simulation to study the effect of both $R = 0.2$ and $R = 0.3$ to limit the underlying event contribution to reconstructed jet energy. The jet energy scale and resolution were studied using PYTHiA $p + p$ embedded in $Cu + Au$ data. Figure 2 shows the jet energy scale and the jet energy resolution. The $p_{T,Reco}/p_{T,True}$ distribution is examined for each bin in $p_{T,True}$. The jet energy scale is the mean of that distribution plotted vs $p_{T,True}$, and PHENIX recovers 70% of the true jet energy. There is missing neutral hadronic energy and energy loss due to tracking inefficiency. In central collisions ($0-20\%$), the underlying event increases the $p_{T,Reco}$ relative to $p+p$ events. The jet energy resolution is the width of the $p_{T,Reco}/p_{T,True}$ distribution vs. $p_{T,True}$, and is $\approx 16-24\%$. The underlying event increases $p_{T,Reco}$ resolution of the central collisions ($0-20\%$) by 2.7% at 15 GeV relative to $p+p$ events.

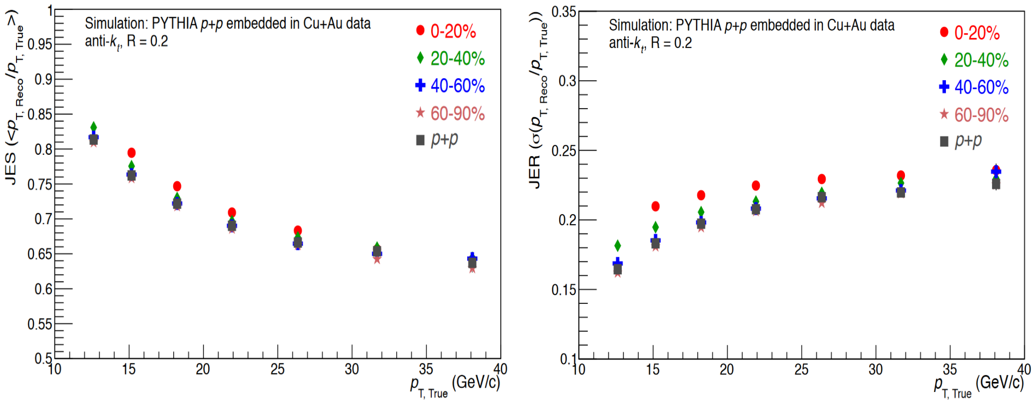

Figure 2: Left is the jet energy scale. Right is the jet energy resolution. The centrality bins and p+p are plotted.

The fake jet contribution was estimated and subtracted from the total distribution. The fake jet distribution was found by shuffling the position (η, ϕ) of tracks and clusters, respectively, then using those shuffled tracks and clusters to reconstruct fake jets. The estimated fake jets are then subtracted from the raw jets to give the estimated signal jet distribution. The fake jet contribution is both p_T and centrality dependent. The most central bin ($0-20\%$) has largest fake jet contribution at low p_T where the purity (signal/raw jets) is 70% at 15 GeV. This fake jet estimation method was checked by comparing to HIJING Cu+Au simulations. Jets were reconstructed in the HIJING simulation and matched to truth jets with $\Delta R < 0.2$, which are the matched jets distribution. Then, the fake jets are the reconstructed jets which are not matched to the truth jets. The fake jet estimation method is used as well by shuffling the track and cluster locations in events with no jets found. Both methods yield comparable purity ratio and hence the data-driven estimation is used to subtract fake jets from the raw signal distribution.

The signal jet distribution is unfolded to correct for the centrality-dependent underlying event and detector effects using SVD unfolding method. The centrality-dependent response matrices are generated by embedding PYTHIA $p+p$ jets into real $Cu+Au$ events. The distributions are unfolded and the centrality-dependent R_{AB} is calculated.

Figure 3 shows the centrality-dependent nuclear modification factor R_{AB} in Cu+Au. The R_{AB} shows clear centrality dependence, with the most central ($0-20\%$) having a suppression of almost a factor of 2. The $20-40\%$ centrality shows a suppression of $\sim 20\%$, while the $40-60\%$ centrality is consistent with unity. The suppression shows no p_T dependence in any of the centrality bins. The dashed lines in the plot are the theory curve lines from SCET$_G$ calculations. The different g values determine the strength of interaction between parton and medium. Both the $0-20\%$ and

40 – 60% centralities have a preference for smaller g value SCET$_G$ predictions. A comparison of central (0 – 20%) π^0 R_{AB} in Cu+Au[7] shows it has similar R_{AB} to 0 – 20% centrality in jets. Note that the π^0 captures only a fraction of the total jet energy, and the measurement extends to lower p_T values and does not have seem to have a p_T dependence.

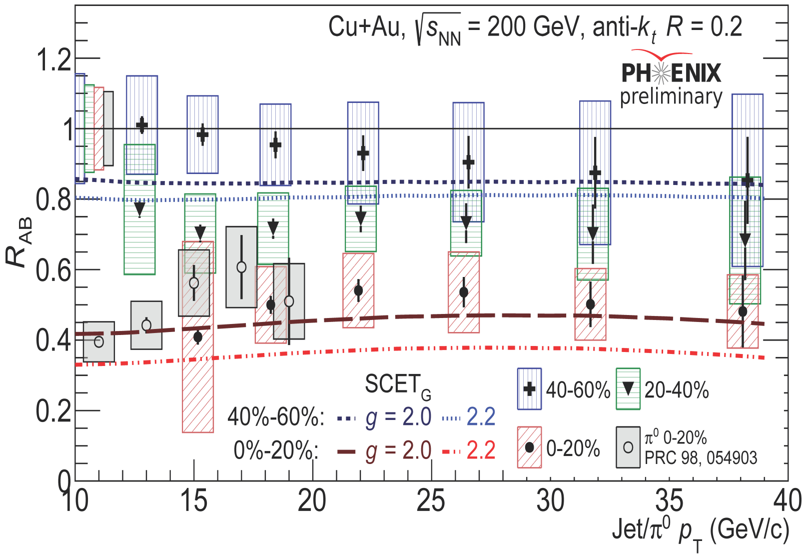

Figure 3: The centrality-dependent R_{AB} for Cu+Au. Jet data is plotted for different centrality bins; only the most central for π^0. The dashed lines show theory calculations for two centrality bins.

5. Conclusion

Jet modification studies in PHENIX d+Au and Cu+Au show centrality dependent jet modification. The d+Au measurement shows suppression in the most central collisions, but peripheral events are consistent with unity. The Cu+Au measurement shows jet suppression in both the 0 – 20% and 20 – 40% centrality bins. There is no p_T dependence to the jet suppression and the 0 – 20% is consistent with π^0 suppression. Future jet studies at PHENIX will study jet substructure in p+Au and Cu+Au.

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