Jet Measurements with PHENIX

Arbin Timilsina (Iowa State University)
for the PHENIX Collaboration

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Jets at RHIC

- Versatility of RHIC provides ability to study jet modification in different collision geometries, system sizes, and energy densities.

- Jets at RHIC interact with the QGP:
  - for a larger time fraction
  - at larger length scales in medium
  - at temperatures closer to $T_c$
- Central arm: $|\eta| < 0.35$ and $\Delta \phi = \pi$

- Charged particle tracks are reconstructed using the Drift Chamber (DC), the Pad Chamber (PC), and the collision point

- Neutral clusters are measured in the Electromagnetic Calorimeter (EMCal)

- Beam Beam Counters (BBCs) provide vertex and centrality classification
Jets in PHENIX

- Jets reconstructed using the anti-$k_t$ algorithm
  - **EMCal cluster energy** + **charged particle tracks**

- Jet-level requirements
  - number of constituents $\geq 3$
  - restriction on contribution of charged constituents
  - jet axis required to be away from detector edge

- Centrality-dependent response matrices generated by embedding PYTHIA $p+p$ jets into real heavy ion events
  - Due to missing **neutral hadronic energy** and tracking inefficiency, on average, PHENIX gets $\approx 70\%$ of the true jet energy
  - Spectra corrected for detector effects and underlying event fluctuations with unfolding procedure
Jet results from PHENIX

Two new results shown first at Quark Matter 2015

$d+Au$ and $p+p$ jet spectra (2008 data)
- $R=0.3$ anti-$k_t$ algorithm
- Phys.Rev.Lett. 116 (2016) no.12, 122301
- Establish pQCD baseline

Cu+Au and $p+p$ jet spectra (2012 data)
- Preliminary measurement, manuscript being written
- $R=0.2$ anti-$k_t$ algorithm; choice of smaller cone size due to demands of HI environment
- First look at inclusive suppression of jet spectra by the QGP from PHENIX!
$p+p$ collisions
Jet spectra in $p+p$ collisions

$p+p$ spectra: compare well with NLO pQCD calculation

- validates jet reconstruction and correction procedure in PHENIX
$d+\text{Au collisions}$
Centrality in $d+Au$ collisions

- Selection of centrality categories in $d+Au$ collisions based on total charge in Au-going beam-beam counter (-3.9 < $\eta$ < -3.0)
- Glauber Monte Carlo simulation to map from the measured charge to geometric quantities
  - estimate nuclear overlap factor $T_{dAu}$ for classes of $d+Au$ collisions
  - previously successful with hard and soft observables
Jet yields in $d+$Au Collisions

$d+$Au per-event yields: first publication of jet production in asymmetric systems at RHIC
Incentrality-integrated collisions, $R_{dAu} = 1$
Minimum bias jet rate

- In centrality-integrated collisions, $R_{dAu} = 1$
  - compares favorably to global nuclear PDF analyses (EPS09) within uncertainties
Minimum bias jet rate

- In centrality-integrated collisions, $R_{dAu} = 1$
  - compares favorably to global nuclear PDF analyzes (EPS09) within uncertainties
  - within initial state E-loss calculations, favors only small momentum transfers between parton and nuclear material
Centrality-selected jet rate

- **Suppression of jet rate in central 0-20% (large $N_{\text{coll}}$) events**
- **Enhancement in 40-60% and 60-88% (small $N_{\text{coll}}$) events**
Centrality-selected jet rate

- Suppression of jet rate in central 0-20\% (large $N_{\text{coll}}$) events
  - comparable with initial state E-loss calculation
- Enhancement in 40-60\% and 60-88\% (small $N_{\text{coll}}$) events
  - very challenging to explain within existing frameworks
Analogous LHC results

Same modification pattern

Similar hadron physics at RHIC and LHC?
Reconciling the puzzle

One possibility: “Shrinking proton” picture

- nucleon configuration with a high-x parton (>0.1) are different that “typical” configurations
- interact more weakly than average

Geometric interpretation: as these compact configurations traverse the large nucleus, they strike fewer nucleons

- relative decrease in the $N_{\text{coll}}$ distribution
- so peripheral $R_{d\text{Au}} > 1$, central $R_{d\text{Au}} < 1$
Cu+Au collisions
Cu+Au collisions

Cu+Au comes with challenges

- Stronger underlying event contribution
  -> choice of smaller cone size
- Fake jet contribution
  -> fake jet subtraction
Data driven method of estimating and statistically subtracting fake jet contribution

- For events in which jet is not reconstructed, position ($\eta, \phi$) of tracks and position ($\eta, \phi$) of clusters are randomly shuffled
- Jet reconstruction performed in these shuffled tracks and clusters
  - returns estimated fake jet
Data driven method of estimating and statistically subtracting fake jet contribution

- For events in which jet is not reconstructed, position \((\eta, \phi)\) of tracks and position \((\eta, \phi)\) of clusters are randomly shuffled
- Jet reconstruction performed in these shuffled tracks and clusters
  - returns \textit{estimated fake jet}
- Estimated fake jet yield is statistically subtracted from the raw jet yield
  - returns \textit{estimated signal jet}
Fake jet

- Fake jet contribution is both $p_T$ and centrality dependent; the contribution being largest for central collisions and at low $p_T$
- for 0-20%, purity is 70% (93%) at 15 GeV/c (23 GeV/c)
Fake jet HIJING simulation study

- **Matched jet**: Reco jet which is within $\Delta R < 0.2$ of true jet
- **Fake jet**: Reco jet which is not matched

Fake jet estimation procedure gives comparable result!

Fake jet contribution analyzed alternately by re-running the analysis with cluster and track selections of $> 2$ GeV
Jet spectra in $p+p$ and Cu+Au

- Spectra unfolded using SVD method (cross-checked using iterative Bayesian method)
  - detector effects
  - centrality dependent underlying event fluctuations
Jet suppression: $R_{AA}$ vs. $p_T$

- At high $p_T$, consistent with 1 within the uncertainties
Jet suppression: $R_{AA}$ vs. $p_T$

- Suppression shows centrality dependence
Jet suppression: $R_{AA}$ vs. $p_T$

- Suppression shows centrality dependence
- No $p_T$ dependence
For central collisions, jets are suppressed by approximately a factor of two.
Jet suppression: $R_{AA}$ vs. $N_{\text{part}}$

- Another look at the $N_{\text{part}}$ dependence of suppression
- No $p_T$ dependence within sensitivity over this kinematic range

$\sqrt{s_{NN}} = 200$ GeV

Cu+Au R=0.2 jet, 17-20 GeV/c
Cu+Au R=0.2 jet, 29-35 GeV/c

(gl. sys. 12%)
Comparisons to theory

- **Left**: 0-20%; **right**: 40-60%
- SCET\(_G\) calculations done for 2 different couplings between the jet and the medium (\(g=2.0\) and \(g=2.2\))
- Quantitatively in line with state-of-the-art jet quenching calculations

Calculations done by Vitev/Chien

**PH\(\)ENIX preliminary**

Cu+Au, \(\sqrt{s_{NN}} = 200\) GeV, anti-\(k_T\), \(R = 0.2\) jet

Hep-ph/1509.07257
Hep-ph/1509.02936
Summary

- Progress on jet measurements in small and large systems with PHENIX detector
  - good guidance for future heavy ion jet program at RHIC

- Surprising, unexpected centrality dependence in $d+Au$ jet rate
  - one possibility: are we sensitive to the fact that high-$x$ nucleons are “smaller” than average?

- Preliminary measurement of a centrality-dependent suppression of jet in Cu+Au collisions
  - jets found to be suppressed by approximately a factor of two in central collisions
  - suppression shows no $p_T$ dependence
Backup
Evaluation of systematic uncertainty

- Variation is made in unfolding procedure. The default data is unfolded with modification in unfolding procedure.
  - Shape of input spectrum: The input spectrum is obtained by modifying the power of the truth spectrum by ±0.5.
  - Unfolding is performed with Bayes method (default is SVD method).

- Variation is made in simulation. The default data is unfolded with modified response matrix.
  - Energy scale
    - EMCal energy scale: The energy of EMCal clusters is varied by ±3%
    - DC $p_T$ scale: The $p_T$ of tracks is varied by $p_T$ dependent way: 2% for $p_T < 10$ GeV/c and increased linearly such that it is 4% at 30 GeV/c.

- Same variation is made in both data and simulation. The modified data is unfolded with modified response matrix.
  - Jet-level cuts:
    - Default: $nc >= 3$ && $cf > 0.2$ && $cf < 0.7$. Variation: $nc >= 5$ && $cf > 0.2$ && $cf < 0.6$
  - Acceptance
    - Fiducial cut: The reconstructed jets are required to lie within tighter phase space.
    - East/West arm: East arm yield is unfolded with response matrix for east arm and west arm yield is unfolded with response matrix for west arm.
  - Fake jet
    - Default: Cluster energy > 0.5 GeV, track $p_T > 0.5$ GeV/c. Variation: Cluster energy > 2.0 GeV, track $p_T > 2.0$ GeV/c.
Jet suppression: $R_{CP}$ vs. $p_T$

$R_{CP}^{\text{cent}} = \left( \frac{N_{\text{cent}}}{N_{\text{coll}}} \right) \left( \frac{dN_{\text{cent}}}{dp_T} \right)_{\text{CuAu}} \left( \frac{N_{\text{60-90\%}}}{N_{\text{80-90\%}}} \right) \left( \frac{dN_{60-90\%}}{dp_T} \right)_{\text{CuAu}}$

- $R_{CP}$ probes relative central vs. peripheral (60-90%) jet production
- Relatively reduced systematics

Cu+Au, $\sqrt{s_{NN}} = 200$ GeV, anti-$k_t$, R = 0.2 jet

PHENIX preliminary
Comparisons to theory

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- Calculations done for 2 different couplings between the jet and the medium ($g=2.0$ and $g=2.2$).
Jets in PHENIX: Jet Energy Scale

• For each $p_{T,\text{True}}$ bin, $p_{T,\text{Reco}}/p_{T,\text{True}}$ distribution is examined

• Due to missing neutral hadronic energy and tracking inefficiency, on average, PHENIX gets $\approx 70\%$ of the true jet energy
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- Due to missing neutral hadronic energy and tracking inefficiency, on average, PHENIX gets $\approx 70\%$ of the true jet energy.

- For 0-20%, the UE increases the $p_{T,\text{Reco}}$ up to 3.2% (1.7%) at 15 GeV/c (26 GeV/c) relative to that in $p+p$ events.
Jets in PHENIX: Jet Energy Resolution

- The width of $p_{T,\text{Reco}}/p_{T,\text{True}}$ distribution is $\approx 16\text{-}24\%$

- In PHENIX, the resolution is not driven by EMCal & DC resolution but by jet-by-jet fluctuations
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- In PHENIX, the resolution is not driven by EMCal & DC resolution but by jet-by-jet fluctuations.

- For 0-20%, the UE increases the $p_{T, \text{Reco}}$ resolution up to 2.7% (1.3%) at 15 GeV/c (26 GeV/c) relative to that in $p+p$ events.