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

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Introduction

Jets in PHENIX
  Gaussian Filter
  Analysis Techniques

p+p
  Fragmentation

d+Au
  $k_T$ Broadening

Cu+Cu
  $\Delta \phi$ broadening

Outlook
  Jets at RHIC

Acknowledgements
Jet reconstruction is being done in heavy ion collisions at RHIC and the LHC:

- Reconstruct full fragmenting parton kinematics at LO.
- Sensitive probe of suppression/quenching effects.
Why Jets at RHIC?

- Complementary set of measurements from two high statistics colliders!

- Can measure jet modification at:
  - lower energies due to smaller underlying event
  - different $x$ and $Q^2$ (different mixture of quark and gluon jets)

- Versatility of collision species provides:
  - ability to vary system size, energy density, geometry
  - control against cold nuclear matter effects

$\Rightarrow$ Cu+Au, U+U collisions in the next 1-2 months!
Drift Chamber (DC), Pad Chambers (PC) and Ring Imaging Čerenkov Detector (RICH) measure charged hadrons and electrons

Electromagnetic Calorimeter (EMCal) clusters photons, $\pi^0$'s, (some) neutral hadrons

EMCal/RICH Trigger (ERT) and the high PHENIX DAQ rate allow complementary Minimum Bias and high-$p_T$ triggered datasets
Gaussian Filter algorithm

1. Seedless, cone-like algorithm with a Gaussian angular weighting (nucl-ex/0806.1499)

\[ p_{T}^{\text{jet}} \equiv \max \left\{ \int \int d\eta' d\phi' p_{T} (\eta', \phi') e^{-(\Delta \eta^2 + \Delta \phi^2)/2\sigma^2} \right\} \]

2. Focuses on the energetic core of the jet, optimizing \( S/B \)

3. Stabilizes the jet axis in the presence of background
Fake jet rejection

- Technique to separate low-$p_T$ jets from underlying event fluctuations in HI collisions on a jet by jet basis.
- $g$-discriminant (with $\sigma_{\text{dis}} < \text{typical distance between underlying event particles}$):

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

- Similar to “angularly-weighted” $p_T$ which rewards jets with a tight core of energy and punishes diffuse jets.
Fake jet rejection

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

- Require \( g_{\sigma_{\text{dis}}} > g_{\text{min}} \):
  - \( \Rightarrow \) efficient saturation with reconstructed \( p_T \)
  - \( \Rightarrow \) trade reconstruction efficiency for sample purity
- Data-driven approaches used to set fake jet rejection threshold \( g_{\text{min}} \).
In PHENIX, energy “resolution” driven by tracking inefficiency, loss of $n, K_L^0$ neutral energy, edge of acceptance effects.

- **PYTHIA** Tune A 2 $\rightarrow$ 2 QCD events from $Q^2 = 0.5$ to 64 GeV.
  - Cross-checks with HERWIG, other PYTHIA tunes
  - Embedding into real heavy ion background.

- NLO calculation + hadronization correction in progress that will allow proper comparison to data.
Demonstration of PHENIX jet reconstruction capability.

Comparison with NLO pQCD across ten orders of magnitude.

- residual differences from jet definition

Analysis being finalized, moving towards publication.
Proof of principle measurement of fragmentation function

\( z = \frac{p_{_{\text{particle}}}}{p_{_{\text{jet}}}} \)

\( n \)-dimensional generalization to GURU SVD unfolding implementation:

\[
\left( p_{_{\text{particle}}}^{_{\text{rec}}}, p_{_{T}}^{_{\text{rec}}} \right) \rightarrow \left( p_{_{\text{particle}}}^{_{\text{truth}}}, p_{_{T}}^{_{\text{truth}}} \right)
\]
Jets in $d+Au$ at $\sqrt{s} = 200$ GeV

- anti-$k_T$ jet reconstruction with $R = 0.3, 0.5$
- Reconstructed jet $R_{CP}$ at the $p+p$ reconstructed scale.
  - $p_T$-feeding from modest underlying event evaluated with embedding procedure and unfolded
- Suppression effect consistent with single-particle $\pi^0$ measurement.
  - Cold nuclear matter energy loss?
  - Centrality dependent nPDF modification?
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Systematic change in $R_{CP}$ with centrality selection

Consistency between cone sizes

Ongoing improvements to analysis will produce:

$R_{dA}$

lower $p_T$ behavior

results at $p_T^{\text{truth}}$ scale

⇒ critical for refining our understanding of Au+Au results!
Reconstructed di-jets can be used to examine multiple scattering effects in the cold nuclear medium.

Search for possible broadening by examining:

\[ p_{\text{out}} \left( = \langle k_T \rangle \right) \equiv (p_T)_{\text{low}} \cdot \sin \Delta \phi \]

Kinematic requirements on away-side jet removes combinatorial contribution.

\[ \Rightarrow \text{constraint on centrality-dependent broadening.} \]
Jets in \( Cu+Cu \) at \( \sqrt{s} = 200 \) GeV

- \( p_T \)-feeding from underlying event:
  - subtraction of centrality- and \( z \)-vertex parameterized average background

- \( p_T \)-smearing from UE fluctuations:
  - evaluated through embedding \( p+p \) jets into \( Cu+Cu \) minimum bias events
  - results shown here unfolded to \( p+p \) reconstructed scale
Suppression of reconstructed jet $R_{AA}$:

$\Rightarrow$ over a wide $p_T$ range

$\Rightarrow$ systematic with centrality

$\Rightarrow$ comparable to single-particle suppression

Potential out-of-cone radiation or other jet modification?
Changes in the width of $\Delta \phi$ distribution would be a possible signal of cold nuclear matter effects.

⇒ No centrality-dependent broadening observed within sensitivity.
Outlook

- Jet reconstruction efforts are ongoing.
  - Current set of measurements being finalized!

- PHENIX capability for jet measurements improving:
  - VTX (silicon vertex tracker) and FVTX (forward silicon vertex tracker) to provide superior tracking and b/c separation

- “sPHENIX” upgrade plan:
  - dedicated jet detector with acceptance, hermiticity, hadronic calorimetry
  - see A. Hanks talk, Tuesday 6:30pm
Jets at RHIC Study

- In support of the sPHENIX program:
  - “Jet - Underlying Event Separation Method for Heavy Ion Collisions at the Relativistic Heavy Ion Collider” (nucl-ex/1203.1353)
    - Test ability to associate truth jets with reconstructed jets at RHIC energies.
    - Proof of principle that reconstructed jets produced at RHIC rates can be separated from fake jets.
  - \(0.75 \times 10^9\) Au+Au HIJING events at \(\sqrt{s_{NN}} = 200\) GeV
  - \(\Delta \eta \times \Delta \phi = 0.1 \times 0.1\) segmented “ideal” calorimeter with \(\phi \in (0, 2\pi), \eta \in (-1, +1)\)
Iterative background subtraction evolved from ATLAS procedure:

- exclusion of jet energy from background determination
- proper $v_2$ modulation
High purity of reconstructed jets:

- Appropriate regime for well-controlled unfolding to $E_{T,true}$

- Before any fake jet rejection scheme!
Jet Results

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Jets at RHIC Study

- Jets from hard scatterings dominate above $E_T^{\text{reco}} > 20, 30, 40 \text{ GeV}$ for $R = 0.2, 0.3, 0.4$ anti-$k_T$, respectively.
- RHIC luminosity upgrade: $10^{10}$ central $Au+Au$ collisions / year
  - capitalize on high PHENIX data rate
  - high statistics inclusive jet, di-jet, $\gamma$-jet measurements!
- see A. Hanks talk, Tuesday 6:30pm
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