Reconstructed jet probes of small and large systems with the PHENIX detector

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Jets in **small** and **large** systems

- Benchmark of jet production in nuclear environment
- Given collective signatures, search for “QGP”-like energy loss?
  - see talk by J. Orjuela-Koop

\[
R_g(x, Q^2 = 100 \text{ GeV}^2)
\]

- Parton shower develops **in evolving QGP medium**
  - internally-generated, multi-scale probe of QGP properties

Salgado et al., hep-ph/1105.3919 comparing nuclear PDF sets

\[
\begin{align*}
\log x & \quad 10^{-5} & 10^{-4} & 10^{-3} & 10^{-2} & 10^{-1} & 1 \\
R_g & \quad 0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 & 1.2 & 1.4 \\
\end{align*}
\]
- **Drift & pad chambers** for measuring charged-particle tracks
  - both subsystems cover $|\eta| < 0.35$, with two $\Delta \phi = \pi/2$ arms
- **Electromagnetic calorimeters** with $\approx 18\lambda$ (PbSc) or $\approx 14\lambda$ (PbGl)
- **Beam-beam counters** $(2.1 < |\eta| < 3.8)$ provide MB event definition and centrality classification
- Online hardware-based trigger on energy deposit in EMCal
Analysis overview

- Cluster EMCal **energy deposits** + charged-particle **tracks**
  - jet core required to be away from detector edge
  - strict run-level, particle-level, jet-level QA to ensure *good measurement of jet energy*

- GEANT simulation of detector response & embedding into minimum-bias HI data events

- Capture $\approx 0.65-0.70$ of jet momentum on average
  - 25% “resolution” from fluctuations in (mostly unmeasured) **neutral hadronic** component
  - correct spectra for detector effects with unfolding
Jet results from PHENIX

- **d+Au** and **p+p** jet spectra (2008 data)
  - $R=0.3$ anti-$k_t$ algorithm, *establish pQCD and cold nuclear matter baseline*

- **Cu+Au** and **p+p** jet spectra (2012 data)
  - Preliminary measurement, $R=0.2$ anti-$k_t$ algorithm due to demands of HI environment
  - *first look at inclusive suppression of full jets*
Jet spectra in $p+p$ collisions

- $p+p$ spectra: compare favorably with NLO pQCD calculation
  - validates jet reconstruction & correction procedure

Jet spectra in $p+p$ collisions

$\sqrt{s} = 200$ GeV

anti-$k_t$, $R=0.3$ jet

PHENIX

NLOJET++ w/ NNPDF2.3 and hadronization corrections from Pythia

• $p+p$ spectra: compare favorably with NLO pQCD calculation
  - validates jet reconstruction & correction procedure
Jet yields in $d+Au$

- First measurement of jet production in asymmetric systems at RHIC

- Centrality from with Au-going beam-beam counter ($-3.8 < \eta < -2.1$) signal

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

Anti-$k_t$, $R=0.3$ jet

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$N_{coll}$ values in the different centrality selections according to the Glauber model, from [242].

The mean number of binary collisions in each centrality category are given by

- $N_{coll} = 15.061 \pm 1.013$ for 0-20% collisions
- $N_{coll} = 10.248 \pm 0.704$ for 20-40% collisions
- $N_{coll} = 6.579 \pm 0.444$ for 40-60% collisions
- $N_{coll} = 3.199 \pm 0.193$ for 60-88% collisions

BBC fires on this fraction of the inelastic $d+Au$ cross-section. Thus, the data is partitioned into four centrality categories consisting of the highest-20/88ths of the data, called "0-20%", and all the way down to the lowest-28/88ths of the data, called "60-88%". Then, the mean $N_{coll}$ and $N_{part}$ are taken from the corresponding selection in the Glauber distribution. The distribution of $N_{coll}$ values in each centrality bin is shown in Figure 6.15.

The final systematic uncertainties on the mean $N_{coll}$ (and other geometric quantities) are derived from a number of sources, including variations in the Glauber MC parameters as well as repeating the fit procedure with the mean BBC Charge parameterized in terms of $N_{part}$ instead of $N_{coll}$.

$d+Au @ 200$ GeV Results

Minimum Bias 0-100\% $<N_{coll}> = 7.590$

- Centrality 00-20\% $<N_{coll}> = 15.061$
- Centrality 20-40\% $<N_{coll}> = 10.249$
- Centrality 40-60\% $<N_{coll}> = 6.590$
- Centrality 60-88\% $<N_{coll}> = 3.199$

NLO pQCD

p+p

(a)

(b)

0-20\%, $\times 10^4$

20-40\%, $\times 10^3$

40-60\%, $\times 10^2$

60-88\%, $\times 10$

\(p+p/\text{fit}\ d^2N/dp_T^2dh/dN_{coll} = T_{dA}\) (mb / GeV)

\(p+p/\text{fit}\ d^2N/dp_T^2dh/dN_{coll} = T_{dA}\) (mb / GeV)

Chapter 6. Direct Jet Reconstruction in $D+Au$ Collisions

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successful with previous hard and soft observables
Minimum bias jet rate

\[ R_{dAu} = \frac{dN^{d+Au}/dp_T}{T_{dA} \times d\sigma^{p+p}/dp_T} \]

- In centrality-integrated collisions, \( R_{dAu} = 1 \)
  - consistent with global nuclear PDF analyses (EPS09)
  - within an initial state E-loss calculation, favors only small parton ↔ nuclear material momentum transfer
Centrality-selected jet rate

**PHENIX** $d+Au$, $\sqrt{s_{\text{NN}}} = 200$ GeV, anti-$k_t$, $R=0.3$ jet

- 60-88%
- 20-40%
- 40-60%
- 0-20%
- E-loss 0-20% (Kang et al)

### Key Observations

- **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...
- Occam’s razor: jet production unmodified, but multiplicity in Au-going direction is modified in jet events
  - e.g. jet events merely re-rearranged in centrality, so minimum-bias $R_{dAu} = 1$ by construction
Analogous LHC results

Same modification pattern, in the same Bjorken-x range

Modifications scale with proton-x and do not depend on nuclear-x...
Common “initial state” proton-x effect at RHIC and the LHC?
Proton spatial configurations

\[ |\psi_{proton}> = (3q) + (3q+g) + (3q+\pi) + \ldots \]

\[ |\psi_{proton;\ large\ x}> \approx (3q) \]

- **One idea:** this is a consequence of proton color fluctuations at collider energies
  - correlation between *spatial* and *momentum* structure
  - configurations with a high-\(x\) parton (\(\approx 0.1\)) are “small”: fewer other partons, smaller transverse size, etc.

See also Bzdak et al. hep-ph/1408.3156, Armesto et al. PLB 747 (2015) 441
Geometric interpretation

“typical” nucleon

“compact” nucleon

compact, large-x proton configurations *strike fewer nucleons*

$N_{\text{jet}}$ expectation

$N_{\text{coll}}$ data
Projectile-species dependence

- Explore these effects further this with a “projectile-species” scan at RHIC
- For QGP-induced E-loss:
  - \( R_{p\text{Au}} > R_{d\text{Au}} > R_{3\text{He+Au}} \) (central events)
- For a shrinking proton size, effect washed out by \( 1/A_{\text{projectile}} \):
  - \( R_{p\text{Au}} < R_{d\text{Au}} < R_{3\text{He+Au}} \) (central events)
- After tuning a simple model to \( d+\text{Au} \), predict \( p+\text{Au} \) and \( 3\text{He+Au} \)
  - DVP, J. Nagle, D. McGlinchey, nucl-th/1603.06607
Jet suppression in Cu+Au

Preliminary measurement of $R_{AA}$ in relatively novel system

➡ in 0-20% collisions, $R_{AA}$~0.5 and is $p_T$-independent
➡ differential suppression with increasing $N_{part}$

 пят А. Тимилсина

For more information, see QM15 talk & proceedings by A. Timilsina
Summary

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

• Jet rate in $p+p$ and minimum bias $d+Au$ collisions establish pQCD / nPDF baseline
  - limits on initial/final state energy loss over wide $p_T$

• Surprising, unexpected centrality dependence
  - one possibility: are we sensitive to the fact that large-$x$ nucleons are “smaller” than average?

• Preliminary measurement of jet suppression in Cu+Au
backup
Jets in heavy ion collisions

- Jets are most abundant final-state QCD object
- Full jet reconstruction difficult but rewarding in HI collisions

- In this talk, *progress in jets from PHENIX at RHIC*
Jet spectra in $p+p$ and Cu+Au

- For preliminary results, arbitrary normalization, but $p+p$-to-Cu+Au normalization is fixed.
- Expanded systematics for low-$p_T$ jets in most central events.
Could this be a bias or auto-correlation between the centrality signal and the presence of a hard scattering?

PHENIX published PRC 90 (2014) 034902 to address this point with p+p data and d+Au simulation.

Conclusion: there is a small bias which, when corrected for, magnifies the results, even for very high-$p_T$ processes.
is this just a feature of \( pp \) collisions?

\[ \Sigma E_T \] in target proton direction

\[ \Sigma E_T \] at large pseudorapidity vs. \( \mathbf{x} \) in the \textbf{projectile} proton (moving away)

\[ \mathbf{x} \] in the \textbf{target} proton (moving towards)

ATLAS, PLB 756 (2016)
ATLAS Preliminary

$pp, \sqrt{s} = 2.76$ TeV

$\langle \Sigma E_T \rangle^{\text{ref}} = \langle \Sigma E_T \rangle(\rho^{\text{avg}}_{T} \in 50-63$ GeV, $|\eta_{\text{dijet}}| < 0.3)$

MC / Data

$0 \leq x \leq 1$

$x$ in Pb “nucleon”

$x$ in “proton”

Data, 4.0 pb$^{-1}$

PYTHIA 6 AUET2B

PYTHIA 8 AU2

HERWIG++ UE-EE-3

ATLAS, PLB 756 (2016)
New angle on previous data?

- Strong **centrality dependence** in forward hadron and di-hadron production in $d+Au$
  - even though $<b>$ does not change so much
  - attributed by many to low nuclear-$x$ effects (CGC?), but kinematic region also associated with large deuteron-$x$

- My two cents: there's an overall suppression, but most of the centrality “dependence” is from large $x_d$, not small $x_{Au}$
Jet suppression in Cu+Au

\[ R_{AA} = \frac{dN/dp_T}{T_{AA} \times d\sigma/dp_T} \]

\( n_{p+p} \) overlap \( x\)-sect.

- Differential, centrality-dependent suppression of \( N_{\text{coll}} \)-scaled yield
  - \( \Rightarrow \text{peripheral events} \) just consistent with \( R_{AA} = 1 \)
  - \( \Rightarrow \) factor of 2 suppression in \textbf{central events}
- Interestingly, flat with \( p_T \)