Semi-Inclusive Jet Measurements in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV at STAR

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Motivation for Jet Studies

**Jets**: collimated sprays of hadrons created by fragmentation and hadronization of hard-scattered partons

**Elementary collisions**: fundamental test of pQCD

**Heavy-ion collisions**: energy loss mechanism in Quark Gluon Plasma (QGP)

\[
\frac{d\sigma_{Jet}}{dE_T} \quad p+p \times <N_{bin}> \quad \text{Suppression?} \quad \text{Energy shift?}
\]

\[
E_T \quad R_{AA} \quad \text{Au+Au}
\]
Central Au+Au collisions: suppression of away side jet - "jet quenching"

Better understanding of jet quenching => fully reconstructed jets

intermediate trigger momentum:

Central Au+Au collisions: suppression of away side jet - "jet quenching"
d+Au: no suppression -> medium effect

high trigger momentum:

Central Au+Au: away-side "jet" suppression of the order of charged hadrons suppression
Relativistic Heavy Ion Collider (RHIC) 

Unique machine: polarized $p+p$ collisions, wide range of species, $\sqrt{s_{NN}}$ from 5.5 to 510 GeV, asymmetric collision...

Data-set:
- TPC tracks only
- Year 2011 Au+Au $\sqrt{s_{NN}} = 200$GeV

Solenoidal Tracker at RHIC (STAR)

Time Projection Chamber
Barrel ElectroMagnetic Calorimeter

full azimuthal coverage
pseudo-rapidity coverage: $-1<\eta<1$
TPC: low-momentum tracking (0.1 GeV/c)
Jet Reconstruction in Heavy Ion Collisions

LHC:
- Jets dominate over the background
  → Clear jet identification (at high $p_T$)

RHIC:
- Background fluctuations comparable to signal → Jet identification is extremely challenging task
- Signal identification on statistical basis
Jet Reconstruction Algorithms

- infrared and collinear safe reconstruction algorithms

- clustering algorithms:
  - $k_T$ - starts clustering from low-$p_T$ particles; irregular jet shapes
  - anti-$k_T$ - starts clustering from high-$p_T$ particles; cone-like jet shapes

key steps:
- jet reconstruction: different resolution parameters $R$
- correction for background energy
  
  \[
  \rho = \text{med} \left\{ \frac{p_{T,i}}{A_i} \right\} \quad A_i \ldots \text{jet area}
  \]

  \[
  p_{T,\text{reco}} = p_T - A_{\text{jet}} \times \rho
  \]
Background Fluctuations

Simulated jets embed into real events to determine effect of background fluctuations on jet momentum.

\[ \delta p_T = p_{T,\text{reco}} - p_{T,\text{emb}} = p_T - A_{\text{jet}} \times \rho - p_{T,\text{emb}} \]

- \( \delta p_T \) depends little on embedded particle momentum.
- \( \delta p_T \) used to unfold the spectrum.
Semi-inclusive Recoil Jets

Observable: Recoil jets per trigger

\[
\frac{1}{N_{\text{trig}}^h} \frac{dN_{\text{jet}}}{dp_{T,jet}} = \frac{1}{d\sigma^{AA\to h+jet+X}} \frac{d\sigma^{AA\to h+jet+X}}{dp_{T,jet}}
\]

Measured: Calculable in NLO pQCD

**Trigger:** high-\(p_T\) hadron \(\rightarrow\) selects hard event

**Recoil side:** use all jet candidates within \(+/- 45^\circ\)

\(\rightarrow\) no fragmentation bias
Analysis in STAR:

- Recoil jet azimuth: $|\Delta \phi - \pi| < \pi/4$
- No rejection of jet candidates on jet-by-jet basis
- Jet measurement is collinear-safe with low infrared cutoff (0.2 GeV/c)
- **Background subtraction:**
  
  Mixed event technique

ALICE:

- **Background subtraction:**
  
  two different trigger track (TT) $p_T$ ranges

\[
\Delta_{\text{recoil}} = \Delta_{\text{TT signal}} - \Delta_{\text{TT reference}}
\]

arXiv:1506.03984
Mixed Event Generation for Jets

Pick one random track per real event → add to mixed event

Mix only similar centrality, $\Psi_{EP}$, z-vertex position
Raw Charged Recoil Jet Spectrum: Central

- Excellent description of low $p_T$ SE spectrum with ME
- Normalization region varied systematically
- Significant jet signal at $p_{T\text{reco}} = p_T - \rho A > 10$ GeV/c

Combinatorial jet background statistically described by mixed event technique
Raw Charged Recoil Jet Spectrum: Reference

- Reference spectrum: peripheral collisions
- Much less combinatorial background compared to most central data
- Excellent signal/background ratio down to 3 GeV/c
Peripheral Preliminary Reference vs. PYTHIA

- Background-subtracted spectrum in 60%-80% Au+Au in comparison with smeared PYTHIA
- PYTHIA shape in good agreement with 60%-80% data
- small suppression in yield (data/PYTHIA)
Recoil Jet Energy Loss

Central

- Significant suppression (central/smeared PYTHIA) over whole $p_T$ range → energy loss
- Very similar shape over 4 orders of magnitude
Unfolding Examples

Central (Levy prior example)

- \( SVD \) and Bayesian unfolding used
- Systematic variation of: Prior \( \rightarrow \) \{Levy function \((T, n)\), PYTHIA\}, regularization parameter, +/-5% efficiency variation, ME normalization, \( \delta p_T \) distribution (single particle embedding, PYTHIA jet embedding)
- Check based on backfolding \( \chi^2 \)

Peripheral (PYTHIA prior example)

- \( Au+Au, 0\%-10\% \)
- \( \sqrt{s_{NN}}=200\text{GeV} \)
- \( 9.0<p_{T\text{, trig}}<30.0\text{GeV/c} \)
- \( R=0.3, \text{anti-}kT \)

\[ \text{STAR Preliminary} \]
Comparison Central-Peripheral: $I_{\text{CP}}$

- Significant suppression (~0.2) at $p_T > 10$ GeV/c
- $I_{\text{CP}}$ close to 1 at low $p_T$
- Larger suppression wrt LHC energies
  - but: different trigger range, background subtraction, $\Delta \phi$ cut,...
- Similar shift in $\Delta p_T$ (-8+/−2 GeV/c for ALICE)

Errors show combined systematics of unfolding and track reconstruction
Summary

- First measurement of hadron triggered recoil jet spectra at RHIC
- New mixed event technique can reproduce combinatorial jet background
- Low $p_T$ jets accessible, and no bias on recoil jet side
- Direct comparison to pQCD calculations possible
- Suppression (~0.2) is larger compared to LHC energies

Outlook

- Full jet reconstruction @ 200 GeV+ more statistics soon
- Low energy (Au+Au @ 62.4 GeV) jet reconstruction
Large Angle Scattering off the QGP?

Discrete scattering centers or effectively continuous medium?

Scattering probability can give us important information about coupling:
- strongly/weakly coupled QGP
- quasiparticles?

"Weak"  "Strong"
No additional broadening observed in Pb+Pb compared to p+p so far.
\[ \Delta \phi, \ 60\% - 80\%, \ R = 0.3 \]

- \[ \Delta \phi = \phi_{\text{trig}} - \phi_{\text{jet}} \]
- Projections for different recoil jet \( p_T \)
- Gaussian + 0\(^{th}\) order polynomial
- Fit results do not depend on ME normalization
- Almost no pedestal for 60\%-80%
$\Delta \Phi, \, 0\%-10\%, \, R = 0.3$

- $\Delta \phi = \phi_{\text{trig}} - \phi_{\text{jet}}$
- Projections for different recoil jet $p_T$
- Gaussian + $0^{\text{th}}$ order polynomial
- Fit results do not depend on ME normalization
- Some pedestal for 0%-10%
ΔΦ, at low $p_T$

- Significant difference at $5 < p_T \cdot pA < 8$ GeV/c
  → Flow?
  → Φ dependent normalization needed?
  → Background from multiple interactions?
  → More studies needed!
• combinatorial background reduced by a cut on leading hadron $p_T$

• induces bias (however jet can still contain many soft constituents)
• Measured spectra corrected via Bayesian unfolding

• Jet energy scale resolution: roughly 5% (mainly due to track. eff. uncertainty)

• $R_{AA}$: Work in progress: further systematic uncertainties, pp baseline improvement
Inclusive Charged Jet Spectra

- Measured spectra corrected via Bayesian unfolding
- Jet energy scale resolution: roughly 5% (mainly due to track. eff. uncertainty)
- \( R_{AA} \): Work in progress: further systematic uncertainties, pp baseline improvement
Jet Imbalance $A_J$ Measurements

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- di-jet momentum asymmetry
- signal of medium-induced jet modification

ATLAS: $p_{T,1}$, $p_{T,2}$

Phys. Rev. Lett. 105 252303
$A_J$ Calculation in STAR

Calculate $A_J$ with constituent HIGH $p_{T,\text{cut}} > 2$ GeV/c

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad p_T = p_{T,\text{rec}} - \rho \times A$$
Rerun jet-finding algorithm anti-k$_T$ on these events ...

\[ p_T^{\text{Lead}} > 20 \text{ GeV/c} \]
\[ p_T^{\text{SubLead}} > 10 \text{ GeV/c} \]
\[ \Delta\Phi_{\text{Lead,SubLead}} > 2/3 \pi \]

Calculate $A_J$ with constituent HIGH $p_T^{\text{cut}} > 2$ GeV/c

\[
A_J = \left( \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \right), \quad p_T = p_T^{\text{rec}} - \rho \times A
\]
$A_J$ Calculation in STAR

- $p_T^{\text{Lead}} > 20 \text{ GeV/c}$
- $p_T^{\text{SubLead}} > 10 \text{ GeV/c}$
- $\Delta \Phi_{\text{Lead,SubLead}} > 2/3 \pi$

Calculate $A_J$ with constituent HIGH $p_T^{\text{cut}} > 2 \text{ GeV/c}$

Calculate "matched" $A_J$ with constituent LOW $p_T^{\text{cut}} > 0.2 \text{ GeV/c}$

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad p_T = p_T^{\text{rec}} - \rho \times A$$
$A_J : R=0.2$

Anti-$k_T$ $R=0.2$, $p_{T,1}>16$ GeV & $p_{T,2}>8$ GeV

- $p_{T}^{cut}>2$ GeV/c
- $p_{T}^{cut}>0.2$ GeV/c
- Au+Au HT Matched $p_{T}^{cut}>0.2$ GeV/c
- Au+Au HT $p_{T}^{cut}>2$ GeV/c

**Au+Au 0-20%**

**Anti-$K_T$ $R=0.2$**

**STAR Preliminary**

$p$-value $<10^{-10}$ (stat. error only)

$p$-value $<10^{-4}$ (stat. error only)

$R=0.2$: Matched Au+Au ≠ matched p+p
$A_J : R=0.4$

Anti-$k_T$ $R=0.4$, $p_{T,1}>20$ GeV & $p_{T,2}>10$ GeV with $p_T^{\text{cut}}>2$ GeV/c

- pp HT ⊕ AuAu MB $p_T^{\text{cut}}>2$ GeV/c
- pp HT ⊕ AuAu MB Matched $p_T^{\text{cut}}>0.2$ GeV/c
- AuAu HT $p_T^{\text{cut}}>2$ GeV/c
- AuAu HT Matched $p_T^{\text{cut}}>0.2$ GeV/c

Au+Au 0-20%
Anti-$K_T$ $R=0.4$

p-value<10^{-5} (stat. error only)
p-value~0.8 (stat. error only)

STAR Preliminary

R=0.4: Matched Au+Au = matched p+p

=> Energy recovered for $R=0.4$ with low $p_T$ particles