Semi-inclusive charged jet measurements in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Observable: semi-inclusive \( h+\text{jet} \) correlation

Trigger-normalized yield of jets recoiling from a high \( p_T \) hadron trigger

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

**Measured**  
**Calculable in pQCD**

Semi-inclusive: event selection only requires trigger hadron
- experimentally clean; trigger bias theoretically calculable

Count all recoil jet candidates:
- uncorrelated background corrected at level of ensemble-averaged distributions
- jet selection does not impose fragmentation bias

Expected geometric bias: surface, not tangential
- Large path length for recoil
- Model studies: T. Renk, PRC74, 024903; H. Zhang et al., PRL98 212301;…
Analysis details

Dataset
Year 2011 data: Au+Au, $\sqrt{s_{NN}}=200$ GeV
Minbias trigger; 500M events after cuts
  • Offline centrality selection 0-10%, 60-80% (mid-rapidity raw multiplicity)

Charged jet reconstruction
Charged tracks: $0.2<p_T^{\text{track}}<30$ GeV/c
Algorithm: anti-$k_T$, R=0.2, 0.3, 0.4, 0.5
  • Jet centroid: $|\eta^{\text{jet}}|<1.0 - R$
  • Recoil jet centroid acceptance: $[\pi-\pi/4, \pi+\pi/4]$

Hadron trigger
Charged particle, $9<p_T<30$ GeV/c
  • Inclusive selection: choose one trigger particle without regard to rest of event $\Rightarrow$ trigger may not be highest $p_T$ track

Uncorrelated background measured via mixed events (new method)

Correction for background fluctuations and instrumental effects
  • Event-wise pedestal shift $\rho*A$ (Fastjet prescription)
  • Unfolding of ensemble averaged distribution

Corrected $p_T^{\text{jet}}>0$
Recoil jet spectrum

\[ \rho_{\text{reco, ch}} = \rho_{\text{raw, ch}} - \rho \cdot A \]

\( \rho = \) estimated background energy density

Central Au+Au

Peripheral Au+Au

Mixed event distribution is good description of combinatorial jet background
Recoil jet spectrum: RHIC vs LHC

Central Au+Au, $\sqrt{s}_{NN}=200$ GeV

Closely related ALICE measurement  
*arXiv:1506.03984*

Central Pb+Pb, $\sqrt{s}_{NN}=2.76$ TeV
Correlation of $p_T$-scale via unfolding

Unfolding algorithms: SVD, Bayesian
Systematic variations: prior, regularization, tracking efficiency, ME normalization, bkgd fluctuation distribution

Consistency check: $\chi^2$ of backfolding

Unfolding generates large off-diagonal covariance $\Rightarrow$ corrected distribution is unbinned
Recoil yield suppression

Calculate spectrum shift

- requires distributions ~ exponential, ratio ~ flat

<table>
<thead>
<tr>
<th>Spectrum Shift Periph/pp ➔ Central</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_{\text{T_{jet}}}^\text{ch} range [GeV]</td>
</tr>
<tr>
<td>Au+Au @ 200 GeV</td>
</tr>
<tr>
<td>Pb+Pb @ 2.76 TeV ALICE arXiv:1506.03984</td>
</tr>
</tbody>
</table>

RHIC: smaller shift for larger R

R=0.5: smaller shift at RHIC than LHC

Out-of-cone energy transport?

- comparison requires similar trigger bias ➔ theory calculation
Intra-jet broadening: recoil yield vs. $R$

Redistribution of jet energy transverse to jet axis

**Au+Au peripheral**

**Au+Au central**
Intra-jet broadening: recoil yield vs. R

Redistribution of jet energy transverse to jet axis

Au+Au peripheral

Ratios for peripheral and central are consistent within uncertainties
- compatible with some broadening within R<0.5
- future measurement (higher stats): reduce uncert.

LHC: similar picture in overlapping p_T range

arXiv:1506.03984
Inter-jet broadening: secondary scattering off the QGP

Discrete scattering centers or effectively continuous medium?

d’Eramo et al, arXiv:1211.1922

Distribution of momentum transfer $k_T$

Weak coupling:

\[ \text{hard tail } \sim \frac{1}{k_T^4} \]

Strong coupling:

Gaussian distribution

Conjecture for weak coupling: $\Delta \phi$

- distribution dominated by single hard Molière scattering at “sufficiently large” $\Delta \phi$
- vacuum QCD effects fall off more rapidly
- “sufficiently large” not yet known
Inter-jet broadening: data

Quantitative search requires absolute normalization

→ semi-inclusive distribution

\[ Au+Au \sqrt{s_{NN}} = 200 \text{ GeV} \]
\[ p_T^{\text{trig}} > 9 \text{ GeV/c} \]

Consistent with zero at current precision

Low energies: hint of finite yield at large \( \Delta \phi \) yield at but not fully corrected for uncorrelated background

QCD calculation in progress (d’Eramo): will indicate integrated luminosity needed for significant measurement

**QM15**

Semi-inclusive h+Jet in Au+Au collisions

11
Summary and Outlook

Semi-inclusive h+jet correlations:
• jet measurements with large R over full \( p_T \) range at RHIC
• comparable to similar ALICE measurement

Recoil yield is suppressed
Suggests less out-of-cone energy transport for
• large R
• central A+A collisions
• central AA @ RHIC vs. LHC

Intra-jet broadening:
• compatible with some broadening within R<0.5

Large-angle scattering: probe quasi-particle degrees of freedom in QGP
• proof of principle; low energy jets are crucial
• QCD calculation in progress \( \rightarrow \) future measurements at RHIC and LHC

Next step: extend to fully measured jets with BEMC (higher int lumi in Year 14 data)
• reduced systematic uncertainties for all observables

Theory calculations needed to assess biases, compare RHIC/LHC
Backup slides
Uncorrelated Background: Mixed Events

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

Mixed event

Mix only similar centrality, $\Psi_{EP}$, z-vertex position

Ev. 1

Ev. 2

Ev. 3

Real events

Ev. 765
Comparison of recoil jet spectra: 
STAR Au+Au 60-80 and PYTHIA pp

Peripheral 60-80%

Smeared PYTHIA: convolute recoil jet spectrum from p+p@200 GeV with distribution of background fluctuations

Compare Au+Au 60-80% with smeared PYTHIA

Both shape and yield in good agreement
Jets in STAR: inclusive jet cross section in p+p collisions at $\sqrt{s}=200$ GeV

- Good and improvable systematic uncertainties over broad kinematic range
- Good agreement with NLO pQCD

Jets in heavy ion collisions: instrument is in place, need the right algorithms
Intra-jet structure: (semi-)inclusive ratios at different $R$

Inclusive jets, $pp \sqrt{s} = 2.76, 7$ TeV

Jets with different $R$ sensitive to different components of shower

Calculable perturbatively:
- require (N)NLO + non-pert. corrections
- MC models ~OK

Semi-inclusive $h+\text{jet}$, $pp \sqrt{s} = 7$ TeV

Ratios in vacuum
- sensitive to transverse jet structure
- rigorous data/theory comparison

⇒ Now use to measure intra-jet broadening due to quenching
Secondary scattering off the QGP: low $p_T^{\text{jet}}$

**Peripheral**

- Significant difference at $5 < p_T - pA < 8 \text{ GeV/c}$
  - $\rightarrow$ Flow?
  - $\rightarrow$ $\Phi$ dependent normalization needed?
  - $\rightarrow$ Background from multiple interactions?
  - $\rightarrow$ More studies needed!

**Central**