Jet Measurements at STAR

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Jets in p+p:
  test of pQCD
  baseline for Au+Au measurements

Jets in Au+Au:
  access to medium properties
  • Inclusive Charged Jets
  • Semi-inclusive Recoil Charged Jets
  • Di-jet Asymmetry $A_j$
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**: probe of hot and dense nuclear matter

\[ R_{AA} \times <N_{\text{bin}} > \]

\[ \frac{d\sigma_{\text{Jet}}}{dE_T} \]

Energy shift?  
Suppression?  

\[ E_T \]
Central Au+Au collisions: suppression of away side jet - "jet quenching"

d+Au: no suppression -> medium effect

Better understanding of jet quenching => full jet reconstruction

Intermediate trigger momentum:

Central Au+Au: away-side "jet" suppression of the order of charged hadrons suppression
Inclusive jets, hadron+jet:
- TPC tracks only
- Run 11 Au+Au $\sqrt{s_{NN}} = 200$ GeV

Di-jet asymmetry $A_J$:
- TPC tracks + BEMC towers
- Run 7 Au+Au $\sqrt{s_{NN}} = 200$ GeV

full azimuthal coverage
pseudo-rapidity coverage: $-1 < \eta < 1$
TPC: low-momentum tracking (0.1 GeV/c)
First measurement (2006):
- midpoint-cone algorithm
- good agreement with pQCD

new measurement using high statistics Run9 data on the way
Jet Reconstruction in Heavy Ion Collisions

- extremely challenging task – due to high multiplicity environment with **large and fluctuating background**
- discrimination between hard jets and “combinatorial” fake jets: **not strictly possible on event-by-event basis**
- jet quenching over a wide kinematic region can only be studied on an **ensemble-averaged 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
  
  density $\rho = med\left\{ \frac{p_{T,i}}{A_i} \right\} \quad A_i \ldots$jet area

  $p_{T,corr} = p_T - A_{jet} \times \rho$
• STAR: first experiment to perform full jet reconstruction in HI collisions


• Run 7 data
• Baseline: Run 6 p+p data
• $R_{AA}$ inconclusive: large systematic uncertainties

Higher statistics recorded, new techniques developed since then
Inclusive Jet Measurement

- combinatorial background reduced by a cut on leading hadron $p_T$

- induces bias (however jet can still contain many soft constituents)
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
Inclusive Charged Jet Spectra

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Semi-inclusive Recoil Jets

**Observable:**
Recoil jets per trigger

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

**Measured**

**Calculated in NLO pQCD**

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

**Recoil jet:** no further cuts => unbiased
Semi-inclusive Recoil Jets

Analysis in STAR:

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

- **BKG subtraction:**
  - Mixed event technique

ALICE:

- **BKG subtraction:**
  - two different trigger $p_T$ ranges

arXiv:1210.7610
Sample number of tracks from real event distribution in each centrality bin, $\Psi_{EP}$ bin and z-vertex bin.

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

Run jet-finder on mixed events ...
Mixed Event describes combinatorial background well

Signal = (SE-ME) distribution
Semi-inclusive Recoil Jets: Signal (SE-ME)

$R=0.3, p_T^{\text{trig}}>9 \text{ GeV/c}$

- PYTHIA smeared by simulation of detector effects and BKG fluctuations
- Central collisions show strong suppression with respect to peripheral collisions
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:

- $\sqrt{s_{NN}} = 2.76$ TeV
- $L_{int} = 1.7 \mu b^{-1}$

Phys. Rev. Lett. 105 252303
Calculate $A_J$ with constituent:

**HIGH $p_{T,cut} > 2$ GeV/c**

\[
A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} , \quad p_T = p_{T,rec} - \rho \times A
\]
Rerun jet-finding algorithm anti-\( k_T \) on these events ... 

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

\[ p_T = p_T^{\text{rec}} - \rho \times A \]

Calculate \( A_J \) with constituent \( \text{HIGH } p_T^{\text{cut}} > 2 \text{ GeV/c} \)
$A_J$ Calculation in STAR

$p_{T,\text{Lead}}>20$ GeV/c
$p_{T,\text{SubLead}}>10$ GeV/c
$\Delta\Phi_{\text{Lead,SubLead}}>2/3\pi$

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

Calculate “matched” $A_J$ with constituent LOW $p_{T,\text{cut}}>0.2$ GeV/c

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

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

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

Au+Au 0-20%

Anti-$K_T$ $R=0.2$

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

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

$|A_j|$ $R=0.2$: Matched Au+Au $\neq$ matched $p+p$
A_{J} : R=0.4

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

- pp HT $\otimes$ AuAu MB $p_{T}^{\text{cut}}>2 \text{ GeV/c}$
- pp HT $\otimes$ AuAu MB Matched $p_{T}^{\text{cut}}>0.2 \text{ GeV/c}$
- AuAu HT $p_{T}^{\text{cut}}>2 \text{ GeV/c}$
- AuAu HT Matched $p_{T}^{\text{cut}}>0.2 \text{ GeV/c}$

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

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

$\Rightarrow$ Energy recovered for R=0.4 with low $p_{T}$ particles
• Inclusive charged jet spectrum extracted

• Semi-inclusive recoil charged jets:
  • Background estimated with the new mixed event technique
  • Suppression in HI collisions with respect to PYTHIA for $R=0.3$ jets

• Di-jet asymmetry $A_J$:
  • no significant difference between Au+Au and p+p
    for low $p_T$ constituent cut for $R=0.4$

OUTLOOK:
• utilize Run 14 statistics + BEMC
BACKUP
Heavy Ion Jet Reconstruction

- take all jets in acceptance
- Jet candidates: reconstructed using anti-\(kT\) algorithm
- jet area \(A\): Fastjet definition
- bckd. energy density – calculated event-wise (\(kT\)):
  \[ \rho = \text{med}\left\{ \frac{p_{T,i}}{A_i} \right\} \]
  (hard jets not discarded for the calculation)
- distribution corrected for bckd. energy density:

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

\(~\text{half of the jet candidates have negative } p_{T,corr}\)

\(\text{we don't discard them (for now)}\)

\(\text{contain crucial information about background}\)
Influence of bckg fluctuations: $\delta p_T$ Distribution

Effect of background on jet finding:

- embedding of a known jet into an event $\rightarrow$ jet reconstruction $\rightarrow\delta p_T$

$$\delta p_T = p_{T,\text{corr}} - p_{T,\text{emb}} = p_T - A_{\text{jet}} \times \rho - p_{T,\text{emb}}$$

- ensemble-averaged $\delta p_T$ distribution $\rightarrow$ measurement of the response matrix

\[\delta p_T\] distributions, SP

Response matrix
Unfolding of Measured Spectra

- Undo the effects of smearing on hard jet spectrum
- In order to compare measured data directly with theory
- Correction for BG fluctuations
- Correction for detector effects

“Inversion” of response matrix => unfolding matrix

- We use iterative method based on Bayes' theorem [G. D'Agostini, arXiv:1010.0632]
- Singular Value Decomposition (SVD) unfolding used to validate Bayesian for background fluctuations. Full unfolding with SVD in progress [Nucl.Inst.Meth.A372:469-481, 1996]
first attempt - we use an iterative procedure based on Bayes' theorem

it relates the conditional probability for a Cause to generate given Effect

\( P(C_i|E_j) \) to its inverse \( P(E_j|C_i) \)

\[
P(C_i|E_j) = \frac{P(E_j|C_i) \cdot P_0(C_i)}{\sum_{l=1}^{n_c} P(E_j|C_l) \cdot P_0(C_l)}
\]

the Effect distribution can be then “unfolded” to the cause distribution:

\[
n(C_i) = \frac{P(E_j|C_i) \cdot P_0(C_i)}{\sum_{l=1}^{n_c} P(E_j|C_l) \cdot P_0(C_l)} \cdot n(E_j)
\]

next iteration: \( n(C_i) \Rightarrow P_0(C_i) \)

Including Detector Effects

Detector effects: parametrized tracking efficiency

Overall response matrix: