Inclusive distribution of fully reconstructed jets in heavy ion collisions at RHIC: status report

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Jet quenching and full jet reconstruction

Jet quenching is a \textit{partonic} process: can we study it at the partonic level?

Jet reconstruction: capture the entire spray of hadrons to reconstruct the kinematics of the parent quark or gluon
Jets Reconstruction in STAR

Jet energy measurement
- Charged particle tracking
- Barrel EM Calorimeter

Jet reconstruction: FASTJET
- Anti-kT algorithm (jet signal)
- kT algorithm (background estimation)
- $R = 0.4$
- Energy scheme recombination

Jet quenching corresponds to softening of the fragmentation
- Cuts on particle $p_T$ suppress background
- But cuts on particle $p_T$ also induce biases in quenched jet population

Goal: unbiased reconstruction of quenched jets $\Rightarrow$ minimum possible cuts ($p_T > 200$ MeV)
Large backgrounds $\Rightarrow$ very challenging measurement
Inclusive jet production: previous heavy ion results

Compare inclusive production for R=0.2 and R=0.4 in p+p and Au+Au

- Evidence for jet broadening due to quenching

Analysis based on
- PYTHIA embedded in real events
- Background via randomized events
- Thresholds imposed on reconstructed jet energy

We have been seeking fully data-driven and model-free corrections to assess the systematic uncertainties

- This talk reports further progress in that direction
Directly measured jet spectrum

Jet defined operationally: output of algorithm (need not be interpretable perturbatively)

FastJet: collect all jets in acceptance \(i=1,\ldots,N\)

Event-wise estimate of background density:

\[
\rho = \text{median} \left\{ \frac{p_T^{\text{jet, } i}}{A_{\text{jet, } i}} \right\}
\]

\[
p_{T}^{\text{direct}} = p_{T}^{\text{reco}} - \rho \cdot A_{\text{reco, jet}}
\]

Hard jets bias towards \(p_{T}^{\text{direct}}>0\)

“Combinatorial jets”: soft background

- Local fluctuations relative to event-wise density estimate \(\rho\)
- \(~50\%\) of population are “negative energy jets”

\(\Rightarrow\) carry vital information about fluctuation structure of events!

Cutting away soft jets via threshold on \(p_{T}^{\text{direct}}\) introduces complex biases, not well-justified
Anti-$k_T$ response: sensitivity to fragmentation

- Embed object of known $p_T$
- Reconstruct event
- Match jet containing embedded object and remove its $p_T$

Resolution function:
$$\delta p_T = p_{\text{reco}} - \rho \cdot A_{\text{reco jet}} - p_{\text{emb}}$$

Event-wise comparison:
PYTHIA jet $p_T>30$ GeV
Single pion with same $p_T$, $\eta$, $\phi$

Calculate event-wise
$$\Delta \delta p_T = \delta p_\pi - \delta p_{\text{jet}}$$

Embed single $p_T=30$ GeV pion in to 8M central STAR events

Similar results for wide range of $p_T$, fragmentation patterns (incl QPYTHIA)
$\Rightarrow$ anti-$k_T$ response is geometric (acts like rigid cone)
Anti-$k_T$ response: jet area

Jet area vs $\delta p_T$ for different embedded $p_T$

$\Rightarrow A>0.4$: Unbiased for hard embedded jets

Direct jet spectrum ($A>0.4$) for different event centralities

- Average charged part. multiplicity changes by $\sim 12\%$
- Jet multiplicity consistent within $\sim 0.3\%$

Density of jets ($A>0.4$) is invariant with multiplicity
$\Rightarrow$ anti-$k_T$ response is geometric (acts like rigid cone)
Inclusive jet distribution: analysis strategy

Goal: measure hard jet distribution in heavy ion collisions

Elementary collisions ($e^+e^-, pp$):
- Modest underlying event
- Hard production (large $Q^2$) strongly correlated with large measured jet $p_T$

Heavy ions:
- Huge underlying event
- Hard production (large $Q^2$) poorly correlated with large measured jet $p_T$
  - Thresholds on $p_T^{\text{direct}}$ induce complex biases that are difficult to disentangle
  - Need a different approach

Utilize measured anti-kT property:
  - Acts like rigid cone: jet multiplicity is invariant with particle multiplicity

Utilize heavy ion phenomenology + Glauber theory:
  - Production rate of hard processes scales as equivalent number of binary collisions
    - $N_{\text{bin}}(0-5\%) \sim 1050$
    - $N_{\text{bin}}(5-10\%) \sim 850$
    - highly correlated uncertainties

Hard jet signal lies in redistribution of $p_T^{\text{direct}}$ with change in centrality!
Evolution of Direct jet spectrum with centrality

Difference between centrality bins: 200 binary collisions with additional underlying event

Qualitative features of difference spectrum are as expected:
- Jet number is conserved $\Rightarrow p_T^{\text{direct}}$ redistributed
- $p_T^{\text{direct}} < 0$: incremental underlying event
- $p_T^{\text{direct}} > 0$: incremental underlying event plus hard jets

Still need to model additional underlying event, but relative contribution is strongly reduced
Background estimate I: statistical model


- Fit to $p_T^{\text{direct}} < 0$ (background-dominated)
- Extrapolation to $p_T^{\text{direct}} > 0$

- good description over 3 orders of magnitude.

- Difference of fit fns:
  - Background model undershoots data where hard jets expected to dominate, i.e. difference of spectra is more than just difference in underlying event – good

- Background model exceeds data at moderate $p_T^{\text{direct}} > 0$
  ➔ as expected: hard jets displace soft jets + total jet number conserved

Qualitatively: model OK
To do: explore systematics

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Background estimate II: data-driven

Classify Direct jet population:

Background jet: all constituents (tracks and calorimeter towers) have $p_T<2.0$ GeV/c

Signal jet: everything else

In other words: signal jets are those with at least one constituent having $p_T>2.0$ GeV/c

- mild bias on quenched jets (can still be dominated by softer constituents)
- vary $p_T$ cut to explore systematics

Compare:
- full Direct spectrum
- “Background-only” event ($p_T^{\text{constituent}}<2\text{GeV}$)

LHS ($p_T^{\text{direct}}<0$): should be dominated by backgd
- shape of distributions identical over 3 decades
- small shift in normalization ➔ conservation of jet number in acceptance
Data-driven background: hard jet distribution

“Hard jet” definition: at least one constituent with pT > 2.0 GeV/c

Expect mild bias on fragmentation:
- Simulations in progress to assess bias in p+p
- Bias will be less for quenched jets

Compare centralities
- 0-5%
- 5-10%
Difference is due to
- Addition of ~200 binary collisions
- Additional soft background
Summary and Outlook

Inclusive jet distribution in heavy ion collisions: challenging measurement
- Jet quenching: need unbiased analysis methods
  ➔ minimize cuts on jet constituents
- Large underlying event
  ➔ spectrum of “negative energy jets” measures structure of fluctuations

Anti-$k_T$: measured properties in presence of background
- behaves like rigid cone ($A > 0.4$)
- jet multiplicity is independent of particle multiplicity

Opportunity for new approach to extract hard jet component:
- compare centralities ➔ add known number of binary collisions
- Jet signal lies in redistribution of jet energy distribution

Background estimation (combinatorial jets):
- Statistical model
- Data driven ($p_T^{\text{constituent}} < \sim 1-2$ GeV)

To do: systematic exploration of background estimates

Promising approach to fully data-driven inclusive jet measurement over large kinematic range
Backup slides
Anti-\( k_T \) response: sensitivity to fragmentation

Resolution function:
\[
\delta p_T = p_T^{\text{reco}} - p \cdot A_{\text{reco jet}} - p_T^{\text{emb}}
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