Jets and high-$p_T$ probes measured in the STAR experiment

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Jets and high-\(p_T\) measurements in Heavy-Ion Collisions

Jets and high-\(p_T\) particles:

- Tomography to probe the hot and dense QCD medium (\(p_T > Q_0 >> \Lambda_{QCD}\))
- Directly coupled to QCD degrees of freedom
- Produced on very short time scales (\(\tau \sim 0.1\) fm/c)

To understand the medium properties:
Parton energy loss in QCD medium depends on
  - Initial energy of parton, color factor, path length, gluon density, transport coefficient, etc.

Jets and high-\(p_T\) physics help to understand the properties of hot and dense QCD medium (QGP)
• 2π azimuthal acceptance
• Extended mid rapidity |η| < 1
• Excellent PID capability (using TPC and ToF)
• BEMC and TPC: Neutral and charged particles

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Some of the interesting observations in STAR exp.

**Central AuAu collisions**

Disappearance of away side jet

Di-Jet: Disappearance at low $p_T$ and survival at high-$p_T$

Jet-h correlations: High-$p_T$ balanced by Low $p_T$ enhancement

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Jet quenching effect: signatures of hot and dense medium (QGP)

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PRL 112, 122301 (2014)

PRL 97, 162301 (2006)
Recent measurements in STAR experiment

• γ-hadrons and π⁰-hadrons correlations
  (jet-like correlations)

• Di-jets $p_T$ imbalance
  (Full jet reconstruction using anti-$k_T$ algo.)

• Semi-inclusive recoil charged jets
  (charged jet reconstruction using anti-$k_T$ algo.)
Direct photon-hadrons and $\pi^0$-hadrons correlations

Direct photon+jet coincidence is a good tomographic probe to study the QGP in HIC

- Doesn’t interact with QCD medium
- Transverse energy approximates that of initial parton $p_T$ in $\gamma$-jet events
- Volume emission dominates for $\gamma$-trigger events

H. Zhang et al., PRL 103, 032302 (2009).

An interesting comparison with $\pi^0$-hadron (jet)
- $\gamma$-triggered parton (jet) loses less energy than that of $\pi^0$-trigger
  - dominant $\gamma$ production: $qg \rightarrow q\gamma$
  - due to color factor ($C_A/C_F = 9/4$)
- on ave. $\gamma$-triggered parton (jet) loses less energy than that of $\pi^0$-trigger
  - due to path length (surface biased of $\pi^0$-trigger)
Direct photon-hadrons and $\pi^0$-hadrons correlations

Nuclear modification factor of $\Upsilon_{\text{dir}}$ and $\pi^0$

- **Within large uncertainties**, $I_{AA}^{\pi^0-h}$ and $I_{AA}^{\Upsilon_{\text{dir}}-h}$ show
  - similar suppression: No clear path length and color factor effect observed
  - strong suppression: particularly for $z_T > 0.2$

- **Indication of less suppression at low $z_T$, but not significant**
- Models show a difference between $\gamma$ and $\pi^0$ trigger but uncertainties in data are too large to prove it
Nuclear modification factor: \( I_{AA}^{\gamma_{\text{dir}}}(p_{T}^{\text{assoc}}, p_{T}^{\text{trig}}) \)

- Soft associated particles are less suppressed compared with high \( p_T \)

- Energy loss is insensitive to the energy of triggered direct photon at high \( p_T \) (8-20 GeV/c)

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Energy loss in azimuthal windows

12 < $p_T^{\text{trig}}$ < 20 GeV/c  [±35° vs ±80°]

- High trigger $p_T$, no recovery of energy loss even at wider azimuthal angle
  [12 < $p_T^{\text{trig}}$ < 20 GeV/c  ⇒  0.1 < $z_T$ < 0.4  ⇒  1.2 < $p_T^{\text{asso}}$ < 8 GeV/c]
- Low trigger $p_T$, recovery at smaller $z_T$
  [5 < $p_T^{\text{trig}}$ < 9 GeV/c  ⇒  0.1 < $z_T$ < 0.4  ⇒  0.5 < $p_T^{\text{asso}}$ < 3.6 GeV/c]

Soft particles coming out at wider azimuthal window!

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Transverse momentum imbalance for back-to-back di-jet pairs

Di-jet Selection:
- Jet $p_T^{\text{Lead}} > 20$ GeV/c
- Jet $p_T^{\text{SubLead}} > 10$ GeV/c
- $|\Delta \phi - \pi| < 0.4$

Constituent $p_T^{\text{Cut}} > 2$ GeV/c
Reduce BG and combinatorial jets compared with including constituent $p_T^{\text{Cut}} > 0.2$ GeV/c

$A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}}$

How to understand the background effect and compare that with AuAu?
Background fluctuations and underlying event study

- \( p_T^{\text{Cut}} = 2 \text{ GeV/c} \)
- \( p_T^{\text{Lead}} > 20 \text{ GeV/c} \)
- \( p_T^{\text{SubLead}} > 10 \text{ GeV/c} \)
- \( |\Delta \phi - \pi| < 0.4 \)

Rerun jet-finding algorithm anti-\( k_T \) on these events

\[ p_T^{\text{Jet}} = p_T^{\text{rec}} \]

\( \rho = 0 \)

pp HT

\( p_T^{\text{Cut}} = 0.2 \text{ GeV/c} \)

\( p_T^{\text{Lead}} > 20 \text{ GeV/c} \) (\( p_T^{\text{Cut}} = 2 \text{ GeV/c} \))

\( p_T^{\text{SubLead}} > 10 \text{ GeV/c} \) (\( p_T^{\text{Cut}} = 2 \text{ GeV/c} \))

pp HT \( \otimes \) AuAu MB

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

HT: \( E_T > 5.4 \text{ GeV} \) at least one BEMC tower energy per event

Calculate “matched” \( |A_J| \) with constituent \( p_{T,\text{cut}} > 0.2 \text{ GeV/c} \) and with geometrical matching condition \( \Delta R < 0.4 \)

Competition between soft ( \( p_{T,\text{cut}} > 0.2 \text{ GeV/c} \)) and hard (\( p_{T,\text{cut}} > 2.0 \text{ GeV/c} \)) contributions?
Di-Jet imbalance in transverse momentum

- Central AuAu collisions are significantly more imbalanced than the corresponding pp for constituent $p_T > 2$ GeV/c
- Balance is restored for $R=0.4$ when including jet constituents $p_T < 0.2$ GeV/c

Indication of energy loss of di-jet interacting with the medium and lost energy reappears as soft particles

$p$-value $< 10^{-4}$

$(pp$ HT $\otimes$ AuAu MB and AuAu HT not drawn from same $A_j$ distribution

STAR preliminary
Semi-inclusive yield of (charged) jets recoiling from a high-$p_T$ hadron trigger

\[
\frac{1}{N_{trig}} \frac{dN_{jet}}{dp_{T, jet}} = \frac{1}{\sigma_{pp\rightarrow h+X}} \frac{d\sigma_{pp\rightarrow h+jet+X}}{dp_{T, jet}}
\]

Experimental observable

pQCD calculation

(Semi-inclusive charged recoil jet dist., since selection of triggered hadrons not inclusive)

- Trigger on high $p_T$ hadron \(\Rightarrow\) Selection of a high $p_T$ process
- Use all jet candidates on the other azimuthal hemisphere within +/- 45 degrees \(\Rightarrow\) no fragmentation bias on recoil side!
- Combinatorial background determined via mixed events
Semi-inclusive recoil charged jets: *high $p_T$ suppression*

- Significant suppression (~80%) of $I_{CP}$ for $R=0.3$ compared with $R=0.5$ ($p_{T,Jet} > 10$ GeV/c)
- Horizontal shift for $R=0.3$:
  -- Indication of Energy transported out of the cone: *Jet-quenching effect* (Partonic energy loss)

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Semi-inclusive recoil charged jets: \textit{Large scattering angle}

Peripheral \hspace{1cm} Central

\begin{align*}
\Delta\phi &= \phi_{\text{trig}} - \phi_{\text{jet}} \\
&= \phi_{\text{trig}} - \phi_{\text{jet}}
\end{align*}

-\rightarrow \text{medium induced acoplanarity?} \\
-\rightarrow \text{No significant large angle scattering}

Scattering probability can give us important information about coupling
\begin{itemize}
    \item strongly/weakly coupled QGP
    \item quasiparticles?
\end{itemize}

QM2015 \hspace{1cm} arXiv:1512.08784

( jet energy not corrected for instrumental effects and background fluctuations )
Summary

Recent measurements in STAR experiment

γ-hadrons and π⁰-hadrons correlations

• no clear path length and color factor effect observed in π⁰ vs. γ triggers I_{AA}! (Within uncertainties)
• Less suppression at low p_{T}^{assoc}
• Energy loss is insensitive to the energy of triggered γ at high p_{T} (8-20 GeV/c) at RHIC

Di-jets p_{T} imbalance

• Central AuAu collisions are significantly more imbalanced than the corresponding pp for constituent p_{T} > 2 GeV/c
• Balance restored when including soft particles

Semi-inclusive recoil charged jets

• New mixed event technique can reproduce combinatorial jet background
• Suppression (~80%)
• No large angle scattering is observed so far

Thank you!

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