Recent High-\(p_T\) and Jet Results from STAR

Li Yi
Yale University
High \(p_T\) Workshop 2017
Outline

• high $p_T$ hadron @BES
• $pp$ jets vs pQCD
• $h$-jet energy loss
• $\gamma$-hadron energy ‘calibrated’
• Dijets energy imbalance
• $z_g$ substructure
Single Hadron High $p_T$ Suppression

High $p_T$ hadron suppression at RHIC and LHC energies
Single Hadron High $p_T$ Suppression @ BES

feed-down subtracted

Meson and Baryon: different $R_{cp}$ trends
At high $p_T$, pion suppressed for $\sqrt{s_{NN}} > 27$ GeV
proton enhanced at all BES energies
Jets in Vacuum: pp@200 GeV

Jets: reduce complexity of many hadrons to single objects

Inclusive Jet

Dijet

Jets: reduce complexity of many hadrons to single objects

Well described by NLO pQCD → Jets as high precision tool

STAR Preliminary

jet cross section

jet cross section

ratio: color band for various sys. err.

STAR, PRD. 95, 071103(R) 2017

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Background Activity in pp

Beam View

Transverse

Away

Toward

leading jet angle

60°

p+p@200 GeV

Particle-level Leading jet $p_T$ (GeV/c)

Particle-level $\langle N_{di}/d\eta d\phi \rangle$

- Toward
- Away
- Transverse

$|\eta|<1$

jet R = 0.6

STAR Preliminary

Underlying event only weakly depends on jet energy
Background Activity in A+A

STAR, Au+Au@200 GeV

Challenges: large fluctuating background
-> modified JES + smeared JER + **combinatorial jets**

Experiment methods:
-> constituent cuts, high $p_T$ particle match,.. **mixed event**
Semi-inclusive Jet Measurements

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

Measurable \quad \text{Calculable in pQCD (in vacuum)}

charged jet \quad R = 0.3
Semi-inclusive Jet Measurements

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

Measurable

Calculable in pQCD (in vacuum)

No significant evidence for large-angle scattering in central Au+Au

Energy Shift Out of Cone

R=0.5

$\Delta p_T$

R=0.5: smaller shift at RHIC than LHC → lower energy loss at RHIC but larger $\Delta p_T/p_T^{jet}$ at RHIC

Spectrum shift → energy transport out-of-cone

<table>
<thead>
<tr>
<th>System</th>
<th>Au+Au $\sqrt{s_{NN}} = 200$ GeV</th>
<th>Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{ch}_{Tjet}$ range (GeV/c)</td>
<td>[10,20]</td>
<td>[60,100]</td>
</tr>
<tr>
<td>$p_T$-shift of $Y (p_T^{ch}_{Tjet})$ (GeV/c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>peripheral→central</td>
<td>p+p→central</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>$-4.4 \pm 0.2 \pm 1.2$</td>
<td>$-8 \pm 2$</td>
</tr>
<tr>
<td>$0.2$</td>
<td>$-5.0 \pm 0.5 \pm 1.2$</td>
<td></td>
</tr>
<tr>
<td>$0.3$</td>
<td>$-5.1 \pm 0.5 \pm 1.2$</td>
<td></td>
</tr>
<tr>
<td>$0.4$</td>
<td>$-2.8 \pm 0.2 \pm 1.5$</td>
<td></td>
</tr>
</tbody>
</table>

ALICE, JHEP 09 (2015) 170

STAR, PRC 96, 024905 (2017)
Energy Shift Out of Cone

\( R = 0.5 \)

\[ \Delta p_T \]

\( R = 0.5 \): smaller shift at RHIC than LHC

\( \rightarrow \) lower energy loss at RHIC

but larger \( \frac{\Delta p_T}{p_T^{jet}} \) at RHIC

Not a cross section measurement per trigger instead of per event
Trigger Particle Normalization

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

In the case of no nuclear effect

\[
\rightarrow \left( \frac{1}{\sigma_{pp\rightarrow h+X}} \cdot \frac{d\sigma_{pp\rightarrow h+jet+X}}{dp_{T,jet}^{pp}} \right) \times \frac{N_{coll}}{N_{coll}^{AA}}
\]

\(N_{coll}\): number of binary nucleon-nucleon collisions

\(N_{coll}\) no longer needed for comparison to pp

In p(d)A, various centrality biases depending on phase space selection
Bias could also be in peripheral AA

ALICE, arXiv:1706.07612
ALICE, PRC 91, 064905
Loizides, Morsch, PLB 773 (2017) 408
RHIC Jet in p/d+Au?

Model estimates smaller bias in d+Au@200 GeV than p+Pb@5.02 TeV

\[ R_{dAu} = \frac{dN_{dAu}^{jet}}{N_{dAu}^{jet} d^3p_{T}} / (N_{coll} \times \frac{dN_{pp}^{jet}}{N_{pp}^{jet} d^3p_{T}}) \]

\( N_{coll} \) needed in \( R_{dAu} \) calculation

STAR’s plan with 2B p+Au events from year 2015

Semi-inclusive jet in p+Au to remove \( N_{coll} \) complication
Photon Triggered Recoil Jet

Select more quark recoil jets
Avoid surface bias
Calibrate initial parton energy for study of energy loss, substructure modification
γ - hadron

Absolute $p_T$ rather than particle $p_T$ fraction ($z_T$) more relevant

$z_T = \frac{p_T^{\text{assoc}}}{p_T^\gamma}$

$5 < p_T^\gamma < 7 \text{ GeV/c}$

$7 < p_T < 9 \text{ GeV/c}$

$9 < p_T < 2 \text{ GeV/c}$
γ - jet

Background techniques: Mixed event; Off-axis cone

Uncorrelated vs correlated background
‘Hard Core’ Dijets

Au+Au w/o soft particles

Au+Au w/soft particles

locate hard core dijets
reconstruct matched dijets

p_T, cut = 2 GeV/c
p_T, Lead > 20 GeV/c
p_T, SubLead > 10 GeV/c
|Δφ-π| < 0.4
Dijets Restore Balance with Low $p_T$

for **hard core** matched dijets

\[ A_J = \frac{p_{T_{\text{Lead}}} - p_{T_{\text{SubLead}}}}{p_{T_{\text{Lead}}} + p_{T_{\text{SubLead}}}} \]

Momentum balance restored to pp baseline for $R = 0.4$, after adding particle $< 2\text{GeV/c}$
Dijet-Hadron Correlations

for **hard core** matched dijets

Background subtracted with Gaussian+constant fit

No significant difference for jet constituent multiplicity
But jet energy changed — $A_J$ different
→ Extend $p_T$ coverage, study $A_J$ dependence

HT: $E_T > 4.5$ GeV
Jet Substructure: Soft Drop $z_g$

Large-angle soft radiation + background are removed
Goal: to search for modification of hardest jet splitting

Larkoski, et al, JHEP05(2014)146

Credit: Marta Verweij

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \theta^\beta$$
Dijet Substructure $z_g$

$z_g$ in hard core matched dijets with $p_{T,cut} > 0.2$ GeV/c

No significant splitting modification on near- or away-side
Probing the jet modification at RHIC

- High $p_T$ hadron suppression at BES (arXiv:1707.01988)
- pp in very good agreement with theory (Di-jets, *PRD* 95 (2017) 71103 (R))
- Unbiased recoil jets highly suppressed due to medium induced broadening
- Total $E_{loss}$ less than at LHC (Hadron-jet correlations, *PRC* 96 (2017) 24905)
- Lost energy re-emerges at low $p_T$ not $z_T$ ($\gamma$-hadron correlations, *PLB* 760 (2016) 689)
- Di-jet energy imbalance largely recovered within $R=0.4$ when low $p_T$ hadrons included (Di-jet $A_J$, *PRL* 119 (2017) 062301 - Editor’s suggestion)
- $z_g$ unmodified for hard core jets (preliminary release)
- $\gamma$-jet, jet in small systems, flavor jet … (stay tuned)

Significantly enhanced understanding of jet modifications at RHIC
Jets in Vacuum: pp@200 GeV

Jets: reduce complexity of many hadrons to single objects

Inclusive Jet

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Dijet

II described by NLO pQCD → Jets as high precision tool

STAR, PRD. 95, 071103(R) 2017
STAR, PRL 97, 152301 (2006)
Transverse Max Vs. Transverse Min

$p+p@2.76\text{TeV, 13TeV}$

$p+p@200\text{GeV, 500GeV}$

Hints of less Initial/Final State Radiation at RHIC energies

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z_g for Hard Core Dijets in p+p at Detector Level

- Hard-core selection p_T^{Cut} > 2 GeV/c shifts jet p_T and may bias toward different splitting pattern
  —> However, observe rather mild effect!

- Stat. uncertainty only, no unfolding

stat. errors only