Event activity-dependence of jet production in $p$–$Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured with semi-inclusive hadron+jet correlations by ALICE

Filip Krizek
on behalf of the ALICE collaboration

Nuclear Physics Institute of CAS
krizek@ujf.cas.cz

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QGP signatures in small systems

- Indication of collective effects in p–Pb
- What about jet quenching?
- Considerations
  - $\Delta E \propto \hat{q}L^2$
  - $\hat{q}|_{pPb} = \frac{1}{7}\hat{q}|_{PbPb}$
  - $\hat{q}|_{PbPb} = (1.9 \pm 0.7)\text{ GeV}^2/\text{fm}$
  - $\hat{q}|_{\text{Cold Nuclear Matter}} \approx 0.02\text{ GeV}^2/\text{fm}$
  - $\Delta E = (8 \pm 2_{\text{stat}})\text{ GeV}/c$ medium-induced $E$ transport to $R > 0.5$ in Pb–Pb
    - ALICE, JHEP 09 (2015) 170
PHENIX jet $R_{dAu}$ in $d+Au$ at $\sqrt{s_{NN}} = 200$ GeV

$$R_{dAu} = \frac{dN_{jets}^{\text{cent}}/d\rho_T}{T_{dAu} \cdot d\sigma_{pp}/d\rho_T}$$

- $R_{dAu}$ for MB compatible with unity
- Strong effects on $R_{dAu}$ with event activity (EA)

EA from BBC in Au-going direction

$3 < |\eta| < 3.9$
ATLAS jet $R_{pPb}$ in p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

EA from $E_T$ in Pb-going direction $-4.9 < \eta < -3.2$

- $T_{pPb}, T_{dAu}$ assume EA correlated with geometry (Glauber modeling)

- Conservation laws and fluctuations

PHENIX, Phys.Rev. C90 (2014) 034902
Kordell, Majumder, arXiv:1601.02595v1
Hadron trigger ($|\eta| < 0.9$) selected as single inclusive

In events with a high-$p_T$ trigger hadron analyze recoiling away side jets $[1,2]$

$$|\varphi_{\text{trig}} - \varphi_{\text{jet}} - \pi| < 0.6 \text{ rad}$$

Charged jets (tracks: $|\eta| < 0.9$, $0^\circ < \varphi < 360^\circ$, $p_T > 150$ MeV/$c$)


Given jet $R$, charged jet acceptance is $|\eta_{\text{jet}}| < 0.9 - R$

Background energy density $\rho$ estimated by area-based method $[4]$

$$\rho = \text{median}_{k_t\text{jets}} \{p_{T,\text{jet}}/A_{\text{jet}}\}$$

event by event

$$p_{T,\text{jet}}^{\text{reco,ch}} = p_{T,\text{jet}} - \rho \times A_{\text{jet}}$$


Hadron-jet coincidence measurement

$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{jet}}}{dp_{T,jet}^\text{ch} d\eta} \bigg|_{p_{T,trig} \in \text{TT}\{20,50\}} - c_{\text{Ref}} \cdot \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{jet}}}{dp_{T,jet}^\text{ch} d\eta} \bigg|_{p_{T,trig} \in \text{TT}\{8,9\}}$

c_{\text{Ref}} accounts for invariance of the jet density with TT-class, ($c_{\text{Ref}} \approx 0.94$)

$TT = \text{trigger track}$

$TT\{X,Y\}$ means $X < p_{T,trig} < Y$ GeV/c

- Uncorrelated jet yield is independent of $p_{T,trig}$ by definition
- Uncorrelated yield removed at the level of ensemble-averaged distributions
- Data driven approach allows to measure jets with a large $R$ and low $p_T$
Semi-inclusive hadron + jet observables and $T_{AA}$

Calculable at NLO pQCD \cite{1}

\[
\frac{1}{N_{trig}^{AA}} \frac{d^2 N_{jet}^{AA}}{dp_{T,jet}^{ch} d\eta_{jet}} \bigg|_{p_{T,trig} \in TT} = \frac{1}{\sigma_{AA \to h+X}} \cdot \frac{d^2 \sigma_{AA \to h+jet+X}}{dp_{T,jet}^{ch} d\eta_{jet}} \bigg|_{p_{T,h} \in TT}
\]

In case of no nuclear effects

\[
\frac{1}{N_{trig}^{AA}} \frac{d^2 N_{jet}^{AA}}{dp_{T,jet}^{ch} d\eta_{jet}} \bigg|_{p_{T,trig} \in TT} = \frac{1}{\sigma_{pp \to h+X}} \cdot \frac{d^2 \sigma_{pp \to h+jet+X}}{dp_{T,jet}^{ch} d\eta_{jet}} \bigg|_{p_{T,h} \in TT} \times \frac{T_{AA}}{T_{AA}}
\]

- This coincidence observable is self-normalized, no requirement of $T_{AA}$ scaling
- No requirement to assume correlation between Event Activity and collision geometry, no Glauber modeling

\cite{1} D. de Florian, Phys.Rev. D79 (2009) 114014
\[ \Delta_{\text{recoil}} \text{ in } Pb-Pb \text{ at } \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

Fully corrected \( \Delta_{\text{recoil}} \) for different jet \( R \)

Suppression in recoil jet yield corresponds to a spectrum shift (energy transfer out of a jet cone) of \( 8 \pm 2_{\text{stat}} \) GeV/c \[^{[1]}\].

[^{[1]}]: ALICE, JHEP 09 (2015) 170
Event activity in $p$–$Pb$ at $\sqrt{s_{NN}} = 5.02$ TeV

Pb-going direction

ZNA

Charged track reconstruction

$|\eta| < 0.9$, $p_T > 150$ MeV/$c$

ITS 6-layered silicon tracker

TPC time projection chamber

Event activity assignment in $p$–$Pb$

- High-$p_T$ track requirement (TT) biases event to larger EA
- Similar EA bias for TT 6–7 GeV/$c$ and 12–50 GeV/$c$
$\Delta_{\text{recoil}}$ in $p-Pb$ at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

### Raw spectrum

- $\Delta_{\text{recoil}}$ in $p-Pb$ at $\sqrt{s_{\text{NN}}} = 5.02$ TeV
- ZNA 0–20%
- Anti-$k$, charged jets, $R = 0.4$
- $\pi - \Delta \varphi < 0.6$
- Integrated $TT\{12,50\}$: 1.83
- Integrated $TT\{6,7\}$: 1.82
- $\Delta_{\text{recoil}}$ ($c_{\text{Ref}} = 0.94$)

### Fully corrected

- $\Delta_{\text{recoil}}$ in $p-Pb$ at $\sqrt{s_{\text{NN}}} = 5.02$ TeV
- $y_{\text{NN}} = -0.465$
- $\Delta_{\text{recoil}}$ ($c_{\text{Ref}} = 0.94$)

**Correction via unfolding for local bkgd. fluct. and instrumental effects**

**Systematic uncertainties on $\Delta_{\text{recoil}}$**
- tracking efficiency: 4–10%
- other sources: < 4%
**Ratios of event activity biased $\Delta_{\text{recoil}}$ distributions**

**ZNA**

![Graph showing the ratio of event activity biased $\Delta_{\text{recoil}}$ distributions for ZNA. The graph indicates $R = 0.4$ for $p^\text{ch}_{T,jet}$ (GeV/c) ranging from 15 to 50.](ALICE-Preliminary)

**V0A**

![Graph showing the ratio of event activity biased $\Delta_{\text{recoil}}$ distributions for V0A. The graph indicates $R = 0.4$ for $p^\text{ch}_{T,jet}$ (GeV/c) ranging from 15 to 50.](ALICE-Preliminary)

| Ratio | $\Delta_{\text{recoil}}|0-20\%|$ | $\Delta_{\text{recoil}}|50-100\%|$ |
|-------|-----------------|-----------------|
|       | compatible with unity |

**Systematic uncertainties:**
- Unfolding: 3–8%
- Other sources: < 4%
- Correlated systematics in numerator and denominator cancel
Out-of-cone energy transport

- Low IR cutoff ⇒ suppression results from spectrum shift due to out-of-cone energy transport
- Express suppression in terms of energy shift $\bar{s}$

Parameterize

$\Delta_{\text{recoil}}|_{50-100\%} = a \exp \left( -\frac{p_{T,\text{jet}}^{ch}}{b} \right)$

Assume parton energy loss causes average shift of $\Delta_{\text{recoil}}$ by $\bar{s}$ independent of $p_{T,\text{jet}}^{ch}$

$\Delta_{\text{recoil}}|_{0-20\%} = a \exp \left( -\frac{p_{T,\text{jet}}^{ch} + \bar{s}}{b} \right)$

the same $a$ and $b$ as for $\Delta_{\text{recoil}}|_{50-100\%}$

$$\frac{\Delta_{\text{recoil}}|_{0-20\%}}{\Delta_{\text{recoil}}|_{50-100\%}} = \exp \left( -\frac{\bar{s}}{b} \right)$$
Limits on energy transport out of \( R = 0.4 \) cone in p–Pb

Shift for high EA (0–20 %) relative to low EA (50–100 %) p–Pb
\[
\bar{s} = (0.22 \pm 0.31_{\text{stat}} \pm 0.05_{\text{syst}}) \text{ GeV/c for V0A}
\]
\[
\bar{s} = (0.22 \pm 0.35_{\text{stat}} \pm 0.05_{\text{syst}}) \text{ GeV/c for ZNA}
\]
cf. \( \bar{s} = (8 \pm 2_{\text{stat}}) \text{ GeV/c in Pb–Pb} \)

Medium-induced charged energy transport out of \( R = 0.4 \) cone is less than 0.7 GeV/c (one sided 90% CL)
Summary

- New technique for measuring jet quenching in small systems
  - does not require the assumption that Event Activity is correlated with collision geometry
  - provides systematically well-controlled comparison of jet quenching as a function of Event Activity

- Technique applied to p–Pb data at $\sqrt{s_{NN}} = 5.02$ TeV with both ZNA and V0A event selection.

- No significant quenching effects are observed when comparing recoil jet yields for low and high Event Activity for both EA metrics.

- At 90% CL, medium-induced charged energy transport out of $R = 0.4$ cone is less than 0.7 GeV/$c$.
Backup slides
The Reference spectrum in $\Delta_{\text{recoil}}$ is scaled by the factor $c_{\text{Ref}}$ to account for invariance of the jet density with TT-class, and the larger yield of Signal spectrum at high $p_{T,jet}^{\text{reco}}$. The value of $c_{\text{Ref}}$ in this analysis is the ratio of the Signal and Reference spectra in the bin $0 < p_{T,jet}^{\text{reco}} < 1$ GeV/c, indicated by the vertical arrow.
Corrections of raw jet spectra

- **Background fluctuations:**
  - embedding MC tracks [1]
  \[ \delta p_T = \sum_i p_{T,i} - A \cdot \rho - p_{T}^{\text{emb.trk.}} \]

- **Detector response:**
  - based on GEANT + PYTHIA

- **Response matrix:**
  - two effects are assumed to factorize
  \[ R_{\text{full}} \left( p_{T,\text{jet}}^{\text{rec}}, p_{T,\text{jet}}^{\text{part}} \right) = \delta p_t \left( p_{T,\text{jet}}^{\text{rec}}, p_{T,\text{jet}}^{\text{det}} \right) \otimes R_{\text{instr}} \left( p_{T,\text{jet}}^{\text{det}}, p_{T,\text{jet}}^{\text{part}} \right) \]

- \( R_{\text{full}}^{-1} \) obtained with Bayesian [2] and SVD [3] unfolding with RooUnfold [4]

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Δ_{recoil} spectra in pp at √s = 7 TeV

- pp analysis similar to Pb–Pb
- Gray boxes - syst. uncert. resulting from detector effects and unfolding
- PYTHIA comparison
  - Perugia 10 and 11 are compatible with the data
  - Supports the use Perugia 10 calculation as a reference for Pb–Pb at √s_{NN} = 2.76 TeV
- Bottom panel shows variation w.r.t. the smooth fit of ALICE data