High-$p_T$ hadron+jet correlations in ALICE

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Hard scattering in heavy-ion collisions

- Hard scattered partons produce collimated sprays of particles (back-to-back, $p_T$ balanced)

- Jet is a phenomenological object defined via algorithm

- Well understood theoretically in pQCD in elementary reactions

- Hard scattering occurs in early stages of heavy-ion collision

- Jet quenching

CMS, PRC 84, 024906 (2011)
Hard scattering, rare process embedded in large background

Spectrum of reconstructed jets at low $p_T$ dominated by combinatorial jets

Suppression of combinatorial jets by high-$p_T$ jet constituent requirement results in fragmentation bias on jets
**Hadron-jet coincidence measurement**

\[ TT = \text{trigger track} \]

\[ TT\{X,Y\} \text{ means } X < p_{T,\text{trig}} < Y \text{ GeV/c} \]

- h-jet correlation allows to suppress combinatorial jets including multi parton interaction without imposing fragmentation bias
- Data driven approach allows to measure jets with large \( R \) and low \( p_T \)
- In events with a high-\( p_T \) trigger hadron analyze recoiling away side jets [1]
  \[ |\phi_{\text{trig}} - \phi_{\text{jet}} - \pi| < 0.6 \text{ rad} \]
- Assuming combinatorial jets are independent of trigger \( p_T \)
\[ \Delta_{\text{recoil}} \text{ in Pb–Pb at } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \]

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

Link to theory

\[ \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^2 N_{\text{jet}}^{\text{AA}}}{dp_{T,\text{jet}}^\text{ch} d\eta_{\text{jet}}} \bigg|_{p_{T,\text{trig}} \in \text{TT}} = \left( \frac{1}{\sigma^{\text{AA} \rightarrow h+\text{jet}+X}} \cdot \frac{d^2 \sigma^{\text{AA} \rightarrow h+\text{jet}+X}}{dp_{T,\text{jet}}^\text{ch} d\eta_{\text{jet}}} \right) \bigg|_{p_{T,h} \in \text{TT}} \]

- \( \Delta_{\text{recoil}} \) corrected for background smearing of jet \( p_T \) + detector effects
- Medium effects

\[ \Delta I_{\text{AA}} = \Delta_{\text{recoil}}^{\text{Pb–Pb}} / \Delta_{\text{recoil}}^{\text{pp}} \]

Need pp reference at the same \( \sqrt{s} \)
\[ \Delta I_{AA} = \Delta^{\text{Pb-Pb}}_{\text{recoil}} / \Delta^{\text{PYTHIA}}_{\text{recoil}} \] in Pb–Pb at \( \sqrt{s_{NN}} = 2.76 \) TeV

- Reference \( \Delta^{\text{PYTHIA}}_{\text{recoil}} \) from PYTHIA Perugia 10
- Suppression of the recoil jet yield
- Magnitude of the suppression similar for different \( R \)

More details in ALICE collab., JHEP 09 (2015), 170
Ratios of recoil jet yields obtained with different $R$

**ALICE**

- 0-10%, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
- Anti-$k_T$ charged jets
- $\pi - \Delta \varphi < 0.6$
- TT{20,50} – TT{8,9}

**Red band:** variation in observable calculated using PYTHIA tunes

- No evidence for significant energy redistribution w.r.t. PYTHIA up to jets with $R = 0.5$
Search for medium-induced large angle Molière scatterings

Multiple Coulomb scattering of charged particle in matter

- Small deflections - Gaussian due to multiple Coulomb scattering
- Large deflections - power-law tail due to single hard scatterings
Search for medium-induced large angle Molière scatterings

- Small deflections - Gaussian due to multiple Coulomb scattering
- Large deflections - power-law tail due to single hard scatterings
- Use recoil jets to search for QGP quasi-particles [1] by looking at enhancement in large angle deflections w.r.t. reference pp

$\Phi(\Delta \varphi)$ in Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV

For recoil jets in $40 < p_{T,jet}^{ch} < 60$ GeV/c define

$$\Phi(\Delta \varphi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{jet}}}{dp_{T,jet}^{ch} d\Delta \varphi} \bigg|_{TT\{20,50\}} - \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{jet}}}{dp_{T,jet}^{ch} d\Delta \varphi} \bigg|_{TT\{8,9\}}$$
\( \Phi (\Delta \varphi) \) in Pb–Pb at \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \) and PYTHIA

Compare raw data with PYTHIA pp folded with ALICE accept. & res.

- Quantify the width \( \sigma \) by the fit in range \( 2\pi/3 < \Delta \varphi < \pi \)

\[
f (\Delta \varphi) = a \times \exp \left( \frac{\Delta \varphi - \pi}{\sigma} \right) + b
\]

- Similar \( \sigma \) no evidence for medium-induced acoplanarity of

40 < \( p_{T,\text{jet}}^{\text{ch}} < 60 \) GeV/c recoil jets

- Quantify the rate of large angle scatterings

\[
\Sigma (\Delta \varphi_{\text{thresh}}) = \int_{\pi/2}^{\pi - \Delta \varphi_{\text{thresh}}} d \Delta \varphi \left[ \Phi (\Delta \varphi) \right]
\]
$\Sigma (\Delta \varphi_{\text{thresh}})$ in Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV and PYTHIA

- Ratio $< 1$ corresponds to the suppression of recoil jet yield
- Shape of the ratio depends on underlying processes
- Fit of the ratio by a linear function gives slope consistent with zero
  $\Rightarrow$ No evidence for medium-induced Molière scattering
QGP signatures in small systems

- Indication of collective effects in p–Pb
- Is there jet quenching in p–Pb?

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
Event Activity biased jet measurements in d+Au at RHIC

Jet $R_{dAu}$ in d+Au at $\sqrt{s_{NN}} = 200$ GeV

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

- $R_{dAu}$ for MB compatible with unity
- Event Activity strongly affects $R_{dAu}$

EA from BBC in Au-going direction $3 < |\eta| < 3.9$

EA = Event Activity
Jet $R_{pPb}$ in p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

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

Caveats:

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

Kordell, Majumder, arXiv:1601.02595v1

Alternative:

h-jet correlations conditional yields
Semi-inclusive hadron + jet observables and $T_{AA}$

Calculable at NLO pQCD [1]

$$\frac{1}{N_{trig}^{AA}} \left. \frac{d^2 N_{jet}^{AA}}{d p_{T, jet}^{ch} d \eta_{jet}} \right|_{p_{T, trig} \in TT} \left. \frac{1}{\sigma_{AA \rightarrow h+X}} \cdot \frac{d^2 \sigma_{AA \rightarrow h+jet+X}}{d p_{T, jet}^{ch} d \eta_{jet}} \right|_{p_{T, h} \in TT}$$

In case of no nuclear effects

$$\frac{1}{N_{trig}^{AA}} \left. \frac{d^2 N_{jet}^{AA}}{d p_{T, jet}^{ch} d \eta_{jet}} \right|_{p_{T, trig} \in TT} = \left. \frac{1}{\sigma_{pp \rightarrow h+X}} \cdot \frac{d^2 \sigma_{pp \rightarrow h+jet+X}}{d p_{T, jet}^{ch} d \eta_{jet}} \right|_{p_{T, h} \in TT} \times \frac{T_{AA}}{T_{AA}}$$

- 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

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 large EA
- Similar EA bias for TT 6–7 GeV/$c$ and 12–50 GeV/$c$
$\Delta_{\text{recoil}}$ in p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

**Raw spectrum**

- ALICE p–Pb $\sqrt{s_{NN}} = 5.02$ TeV
- 0–20% ZNA
- Anti-$k_T$ charged jets, $R = 0.4$
  - $-0.43 < y_T^* < 1.36$; $-0.03 < y_{jet}^* < 0.96$
  - $\pi - \Delta \phi < 0.6$
- $\text{TT}(12,50)$
  - Integral $\text{TT}(12,50) = 1.84$
- $\text{TT}(6,7)$
  - Integral $\text{TT}(6,7) = 1.83$
- $\Delta_{\text{recoil}} (c_{\text{Ref}} = 0.94)$

Statistical errors only

**Fully corrected**

- p–Pb $\sqrt{s_{NN}} = 5.02$ TeV
- $y_{NN} = -0.465$
- $\text{MB} 20\% - \text{ZNA} 0$
- $\text{Syst. uncert.} \text{ALICE Preliminary}$

$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{jet}}}{d p^{ch}_{T,\text{jet}} d \eta} \bigg|_{p_{T,\text{trig}} \in \text{TT}\{12,50\}} \quad - c_{\text{Ref}} \cdot \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{jet}}}{d p^{ch}_{T,\text{jet}} d \eta} \bigg|_{p_{T,\text{trig}} \in \text{TT}\{6,7\}}$

- 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**

\[
\text{ALICE p-Pb } \sqrt{s_{NN}} = 5.02 \text{ TeV}
\]

- $\Delta_{\text{recoil}}$ distributions
- $p_{T,jet}^{ch}$ (GeV/c)
- 100% ZNA - 50-100% ZNA
- $\Delta_{\text{recoil}}$
- $R = 0.4$
- $0.43 < y^* < 1.36$; $-0.03 < y_{jet}^* < 0.97$
- $\pi - \Delta \phi < 0.6$
- Syst. uncert. $\pm 0.4$ GeV/c spectrum jet shift

**V0A**

\[
\text{ALICE p-Pb } \sqrt{s_{NN}} = 5.02 \text{ TeV}
\]

- $\Delta_{\text{recoil}}$ distributions
- $p_{T,jet}^{ch}$ (GeV/c)
- 100% V0A - 50-100% V0A
- $\Delta_{\text{recoil}}$
- $R = 0.2$
- $0.43 < y^* < 1.36$; $-0.23 < y_{jet}^* < 1.17$
- $\pi - \Delta \phi < 0.6$
- Syst. uncert. $\pm 0.4$ GeV/c spectrum jet shift

**Ratio**

\[
\frac{\Delta_{\text{recoil}}|_{0-20 \%}}{\Delta_{\text{recoil}}|_{50-100 \%}}
\]

compatible with unity

Systematic uncertainties:
- unfolding $3-8\%$
- other sources $<4\%$

Correlated syst. uncert. in numerator and denominator cancel
Out-of-cone energy transport

- Low infra-red cutoff ⇒ suppression results from spectrum shift due to out-of-cone energy transport
- Express the suppression in terms of energy shift $\bar{s}$
  
  ![Graph](image.png)

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

  Assume parton energy loss causes average shift of $\Delta_{\text{recoil}}$ by $\bar{s}$ independent of $p_{T,\text{jet}}^{\text{ch}}$
  $$\Delta_{\text{recoil}}|_{0-20\%} = a \exp \left( -\frac{p_{T,\text{jet}}^{\text{ch}} + \bar{s}}{b} \right)$$

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

  \[
  \frac{\Delta_{\text{recoil}}|_{0-20\%}}{\Delta_{\text{recoil}}|_{50-100\%}} = \exp \left( -\frac{\bar{s}}{b} \right)
  \]
Shift for high EA (0–20 %) relative to low EA (50–100 %) p–Pb
\[ \bar{s} = (-0.06 \pm 0.34_{\text{stat}} \pm 0.02_{\text{syst}}) \text{ GeV/c for V0A} \]
\[ \bar{s} = (-0.12 \pm 0.35_{\text{stat}} \pm 0.03_{\text{syst}}) \text{ GeV/c for ZNA} \]
\[ \bar{s} = (8 \pm 2_{\text{stat}}) \text{ GeV/c in Pb–Pb} \]

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

- h+jet technique allows to measure jet quenching in heavy-ion collisions and 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

- Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV: suppression of recoil jet yield, but no evidence of intra-jet broadening of energy profile out to $R = 0.5$

- p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV: no significant quenching effects are observed when comparing recoil jet yield 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 0.4 GeV/c
Backup slides
Corrections of raw jet spectra

- **Background fluctuations:**
  embedding MC jets or random cones \[ \delta p_t = \sum_i p_{t,i} - A \cdot \rho \]

- **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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Charged jets: tracks $|\eta| < 0.9, 0^\circ < \varphi < 360^\circ, p_T^{\text{const}} > 150$ MeV/c

Full jets: tracks + EMCAL/DCAL clusters, $|\eta| < 0.7$, EMCAL: $80^\circ < \varphi < 180^\circ$, DCAL: $260^\circ < \varphi < 327^\circ$

Jet reconstruction: anti-$k_T$ algorithm (FastJet package [1])

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

Mean background density correction

Background energy density $\rho$ estimated by area-based method [1]

$$\rho = \text{median}_{kT \text{ jets}} \left\{ \frac{p_{T,\text{jet}}}{A_{\text{jet}}} \right\}$$

event by event

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