Event activity-dependence of jet production in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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
  - ◇ $\Delta E \propto \hat{q} L^2$

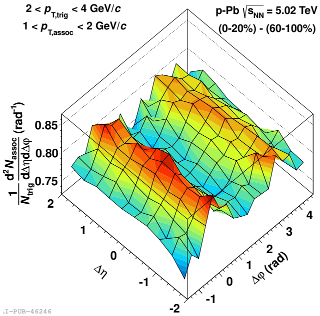
    BDMPS, Nucl. Phys. B483 (1997) 291
  - ◇ $\hat{q}|_{\text{pPb}} = \frac{1}{7}\hat{q}|_{\text{PbPb}}$

    K.Tywoniuk, Nucl.Phys. A 926 (2014) 85–91
  - ◇ $\hat{q}|_{\text{PbPb}} = (1.9 \pm 0.7)\ \text{GeV}^2/\text{fm}$

    JET Collaboration, Phys.Rev. C 90, 014909 (2014)
  - ◇ $\hat{q}|_{\text{Cold Nuclear Matter}} \approx 0.02\ \text{GeV}^2/\text{fm}$

    W.T.Deng, X.N.Wang, Phys.Rev. C 81, 024902 (2010)
  - ◇ $\Delta E = (8 \pm 2_{\text{stat}})\ \text{GeV}/c$ medium-induced E transport to $R > 0.5$ in Pb–Pb

    ALICE, JHEP 09 (2015) 170



ALICE, Phys.Lett. B 719 (2013) 29–41

PHENIX jet R_{dAu} in d+Au at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$

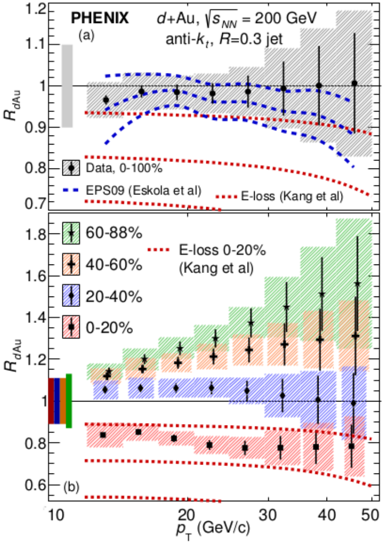
$$R_{\mathrm{dAu}} = \frac{\mathrm{d}N^{\mathrm{cent}}_{\mathrm{jets}}/\mathrm{d}p_{\mathrm{T}}}{T_{\mathrm{dAu}} \cdot \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

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

EA from BBC in Au-going direction

$3 < |\eta| < 3.9$

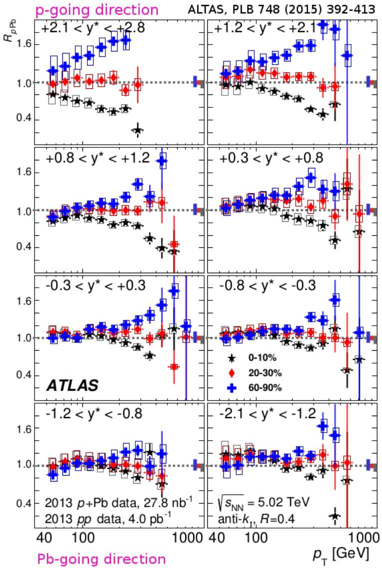
PHENIX, Phys. Rev. C94, 064901 (2016)



Event activity biased jet measurements in p–Pb at LHC

ATLAS jet R_{pPb} in
p–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

EA from E_{T} in Pb-going direction $-4.9 < \eta < -3.2$

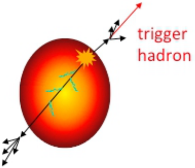


- T_{pPb}, T_{dAu} assume EA correlated with geometry (Glauber modeling)
- Conservation laws and fluctuations

  PHENIX, Phys.Rev. C90 (2014) 034902

  Kordell, Majumder, arXiv:1601.02595v1

Semi-inclusive hadron+jet correlations in ALICE



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

- Charged jets (tracks: $|\eta| < 0.9$, $0^\circ < \varphi < 360^\circ$, $p_{\mathrm{T}} > 150$ MeV/c)
- Jet reconstruction: anti-k_{t} algorithm (FastJet package [3])
Given jet R, charged jet acceptance is $|\eta_{\mathrm{jet}}| < 0.9 - R$
- Background energy density ρ estimated by area-based method [4]
$$\rho = \mathrm{median}_{k_{\mathrm{t}}\,\mathrm{jets}}\{p_{\mathrm{T,jet}}/A_{\mathrm{jet}}\}$$

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

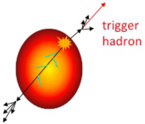
[1] de Barros et al., arXiv:1208.1518

[2] ALICE, JHEP 09 (2015) 170

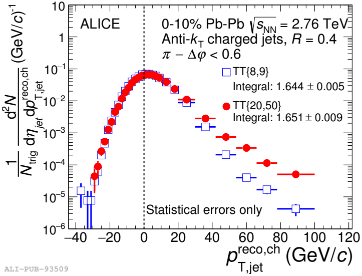
[3] Cacciari et al., Eur. Phys. J. C 72 (2012) 1896

[4] Cacciari et al., Phys. Lett. B 659 (2008) 119

Hadron-jet coincidence measurement



ALICE,JHEP 09 (2015) 170



TT = 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

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

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

Semi-inclusive hadron + jet observables and T_{AA}

Calculable at NLO pQCD [1]

$$\underbrace{\frac{1}{N_{\rm trig}^{\rm AA}} \frac{{\rm d}^2 N_{\rm jet}^{\rm AA}}{{\rm d}p_{\rm T,jet}^{\rm ch}{\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT}}}_{\text{measured}} = \underbrace{\left(\frac{1}{\sigma^{\rm AA\to h+X}} \cdot \frac{{\rm d}^2\sigma^{\rm AA\to h+jet+X}}{{\rm d}p_{\rm T,jet}^{\rm ch}{\rm d}\eta_{\rm jet}}\right)\Bigg|_{p_{\rm T,h}\in {\rm TT}}}_{\text{from theory}}$$

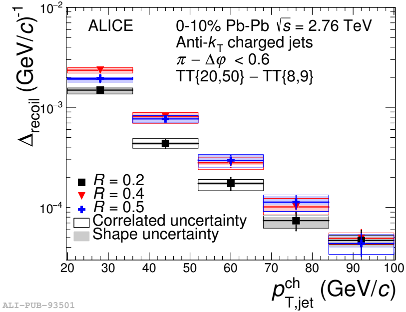
In case of no nuclear effects

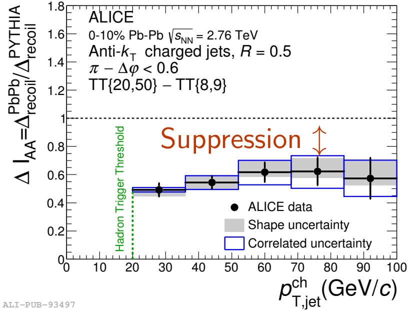
$$\frac{1}{N_{\rm trig}^{\rm AA}} \frac{{\rm d}^2 N_{\rm jet}^{\rm AA}}{{\rm d}p_{\rm T,jet}^{\rm ch}{\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT}} = \left(\frac{1}{\sigma^{\rm pp\to h+X}} \cdot \frac{{\rm d}^2\sigma^{\rm pp\to h+jet+X}}{{\rm d}p_{\rm T,jet}^{\rm ch}{\rm d}\eta_{\rm jet}}\right)\Bigg|_{p_{\rm T,h}\in {\rm TT}} \times \cancel{\frac{T_{\rm AA}}{T_{\rm AA}}}$$

- 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

[1] D. de Florian, Phys.Rev. D79 (2009) 114014

Δ_{recoil} *in Pb–Pb at* $\sqrt{s_{NN}} = 2.76$ *TeV*





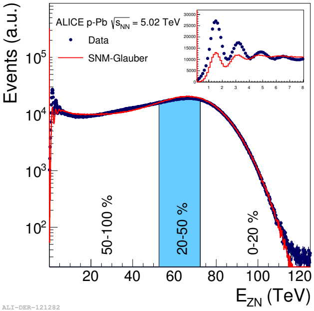
Fully corrected Δ_{recoil} for different jet R

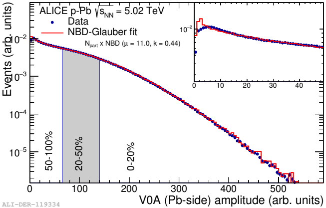
Ratio of Δ_{recoil} in Pb–Pb and pp (PYTHIA)

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

[1] ALICE, JHEP 09 (2015) 170

Event activity in p–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV



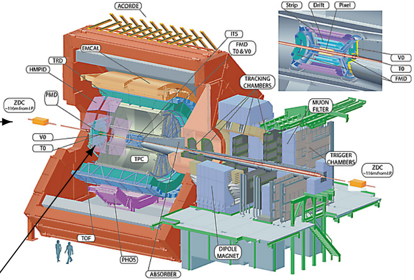


Pb-going direction

ZNA

V0A

$\eta \in (2.8, 5.1)$



Charged track reconstruction

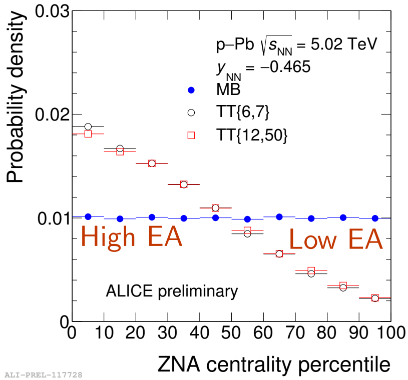
$|\eta| < 0.9,\ p_{\mathrm{T}} > 150\,\mathrm{MeV}/c$

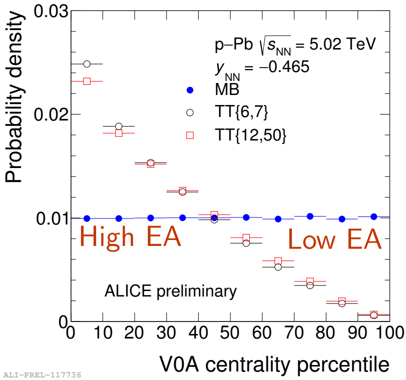
ITS 6-layered silicon tracker

TPC time projection chamber

ALICE, Phys. Rev. C 91 (2015) 064905

Event activity assignment in p–Pb

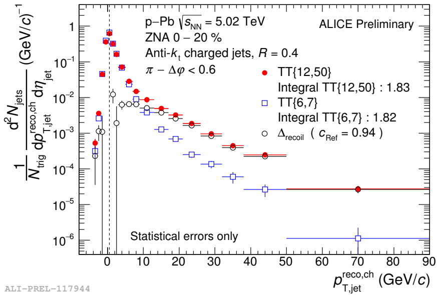




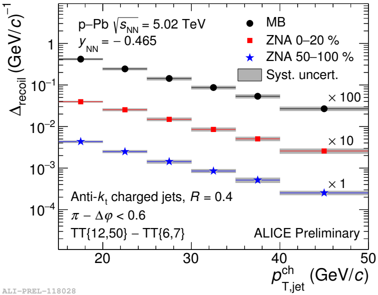
- High-p_T track requirement (TT) biases event to larger EA
- Similar EA bias for TT 6–7 GeV/c and 12–50 GeV/c

Δ_{recoil} *in p–Pb at* $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Raw spectrum



Fully corrected



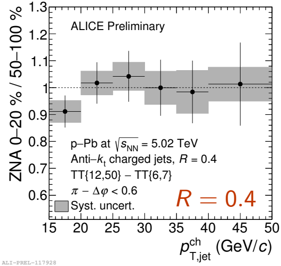
$$\Delta_{\mathrm{recoil}} = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\mathrm{d}\eta}\bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}\{12,50\}} - c_{\mathrm{Ref}} \cdot \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\mathrm{d}\eta}\bigg|_{p_{\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

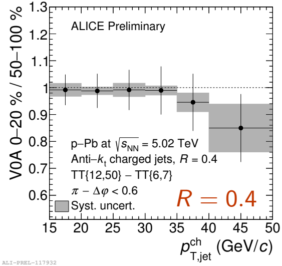
- Correction via unfolding for local bkgd. fluct. and instrumental effects
- Systematic uncertainties on Δ_{recoil} : tracking efficiency 4–10 %; other sources < 4 %

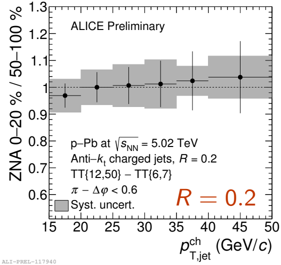
Ratios of event activity biased Δ_{recoil} distributions

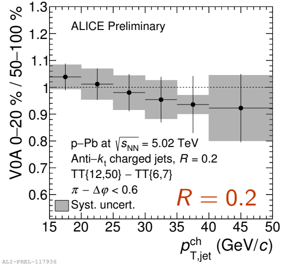
ZNA

V0A









Ratio

$$\frac{\Delta_{\mathrm{recoil}}\big|_{0-20\,\%}}{\Delta_{\mathrm{recoil}}\big|_{50-100\,\%}}$$

compatible with unity

Systematic uncertainties:

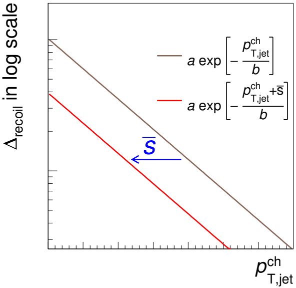
unfolding 3–8 %

other sources $< 4\,\%$

Correlated systematics in numerator and denominator cancel

Out-of-cone energy transport

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



- Parameterize

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

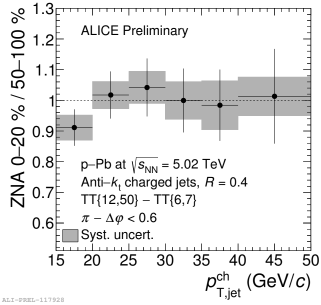
- Assume parton energy loss causes average shift of Δ_{recoil} by $\bar{s}$ independent of $p^{\mathrm{ch}}_{\mathrm{T,jet}}$

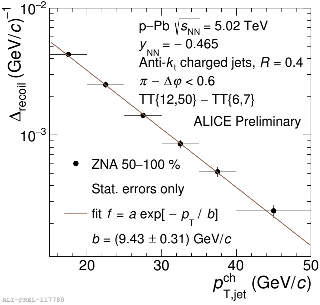
$$\Delta_{\mathrm{recoil}}\big|_{0-20\,\%} = a\exp\left(-\frac{p^{\mathrm{ch}}_{\mathrm{T,jet}}+\bar{s}}{b}\right)$$

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

$$\frac{\Delta_{\mathrm{recoil}}\big|_{0-20\,\%}}{\Delta_{\mathrm{recoil}}\big|_{50-100\,\%}} = \exp\left(-\frac{\bar{s}}{b}\right)$$

Limits on energy transport out of $R = 0.4$ cone in p–Pb





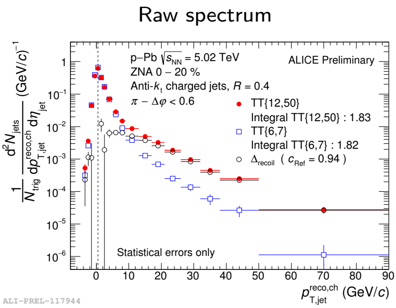
- Shift for high EA (0–20 %) relative to low EA (50–100 %) p–Pb
  $\bar{s} = (0.22 \pm 0.31_{stat} \pm 0.05_{syst})$ GeV/c for V0A
  $\bar{s} = (0.22 \pm 0.35_{stat} \pm 0.05_{syst})$ GeV/c for ZNA
  cf. $\bar{s} = (8 \pm 2_{stat})$ GeV/c in Pb–Pb ALICE, JHEP 09 (2015) 170
- Medium-induced charged energy transport out of $R = 0.4$ cone is less than 0.7 GeV/c (one sided 90% CL)

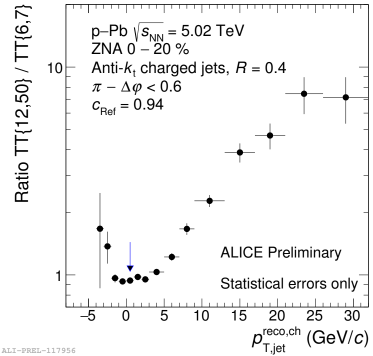
Summary

- 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 $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ 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 $0.7\,\text{GeV}/c$

Backup slides

$c_{\rm Ref}$ *in p–Pb*

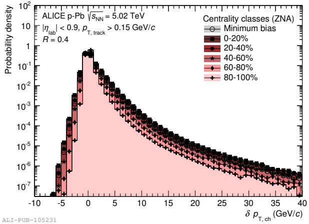


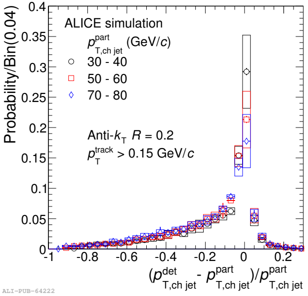


The Reference spectrum in $\Delta_{\rm recoil}$ is scaled by the factor $c_{\rm Ref}$ to account for invariance of the jet density with TT-class, and the larger yield of Signal spectrum at high $p_{\rm T,jet}^{\rm reco}$. The value of $c_{\rm Ref}$ in this analysis is the ratio of the Signal and Reference spectra in the bin $0 < p_{\rm T,jet}^{\rm reco} < 1\,{\rm GeV}/c$, indicated by the vertical arrow.

Corrections of raw jet spectra

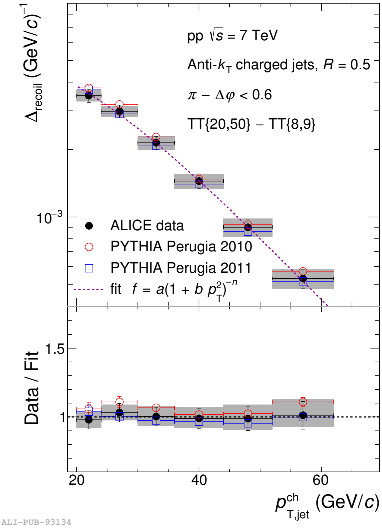
- Background fluctuations:
  embedding MC tracks [1]
  $\delta p_{\mathrm{T}} = \sum_i p_{\mathrm{T},i} - A \cdot \rho - p_{\mathrm{T}}^{\mathrm{emb.trk.}}$
- Detector response:
  based on GEANT + PYTHIA
- Response matrix:
  two effects are assumed to factorize
  $R_{\mathrm{full}}\left(p_{\mathrm{T,jet}}^{\mathrm{rec}}, p_{\mathrm{T,jet}}^{\mathrm{part}}\right) =$
  $\delta p_{\mathrm{t}}\left(p_{\mathrm{T,jet}}^{\mathrm{rec}}, p_{\mathrm{T,jet}}^{\mathrm{det}}\right) \otimes R_{\mathrm{instr}}\left(p_{\mathrm{T,jet}}^{\mathrm{det}}, p_{\mathrm{T,jet}}^{\mathrm{part}}\right)$
- R_{full}^{-1} obtained with Bayesian [2] and SVD [3] unfolding with RooUnfold [4]





[1] ALICE collab., JHEP 1203 (2012) 053
[2] D'Agostini, Nucl.Instrum.Meth.A362 (1995) 487
[3] Höcker and Kartvelishvili, Nucl.Instrum.Meth.A372 (1996) 469
[4] http://hepunx.rl.ac.uk/~adye/software/unfold/RooUnfold.html

Δ_{recoil} *spectra in* pp *at* $\sqrt{s} = 7$ *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 $\sqrt{s_{NN}} = 2.76$ TeV
- Bottom panel shows variation w.r.t. the smooth fit of ALICE data

More details in http://arxiv.org/abs/1506.03984