# *Hadron+jet correlations in ALICE*

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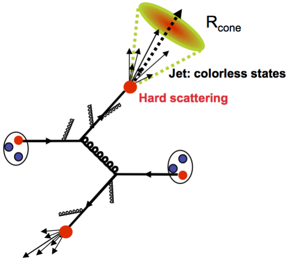
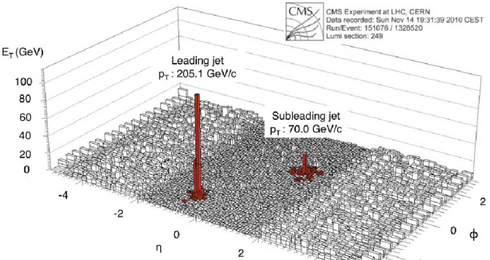
# *Hard scattering in heavy-ion collisions*

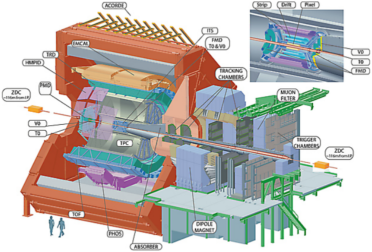
- Hard scattered partons produce collimated sprays of particles (back-to-back, $p_T$ balanced)
- Jet is a phenomenological object defined via algorithm
- Well understood theoretically in pQCD in elementary reactions
- Hard scattering occurs in early stages of heavy-ion collision
- Jet quenching




CMS, PRC 84, 024906 (2011)

# *Jets in ALICE*



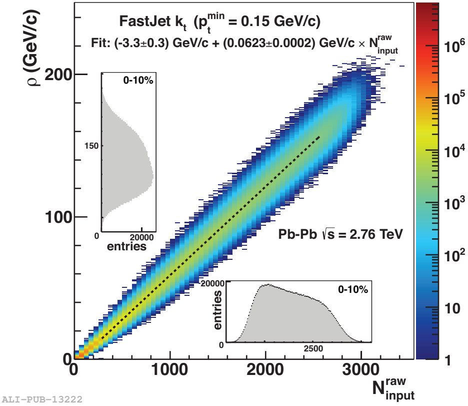

- **Charged jets:** tracks $|\eta| < 0.9$, $0^\circ < \varphi < 360^\circ$, $p_{\mathrm{T}}^{\mathrm{const}} > 150$ MeV/$c$
- **Full jets:** tracks + EMCAL/DCAL clusters, $|\eta| < 0.7$,
  EMCAL: $80^\circ < \varphi < 180^\circ$, DCAL: $260^\circ < \varphi < 327^\circ$
- **Jet reconstruction:** anti-$k_{\mathrm{T}}$ algorithm (FastJet package [1])

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

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

# *Mean background density correction*

ALICE, JHEP03 (2012) 053




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

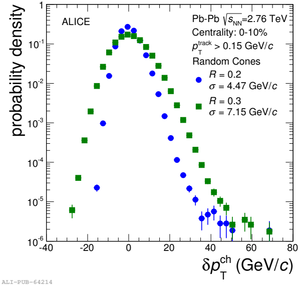
  $$\rho = \text{median}_{k_T \text{ jets}} \{p_{T,\text{jet}}/A_{\text{jet}}\}$$

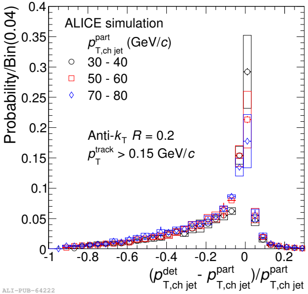
  event by event $$p_{T,\text{jet}}^{\text{corr}} = p_{T,\text{jet}} - \rho \times A_{\text{jet}}$$


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

# Corrections of raw jet spectra

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

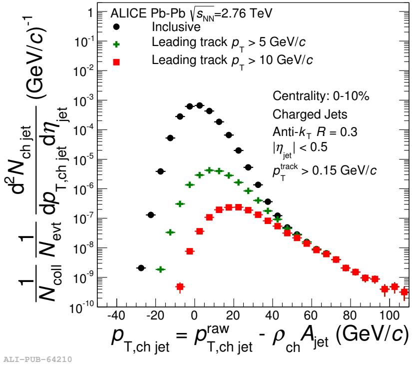




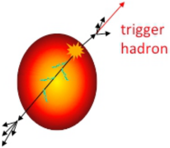
[1] ALICE collab., JHEP 1203 (2012) 053
[2] D'Agostini, Nucl.Instrum.Meth.A362 (1995) 487
[3] Höcker and Kartvelishvili, Nucl.Instrum.Meth.A372 (1996) 469
[4] http://hepunx.rl.ac.uk/~adye/software/unfold/RooUnfold.html

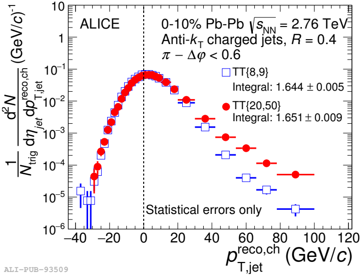
# *Selection of jets using fragmentation bias*




- 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*




[1] ALICE, JHEP 09 (2015) 170

TT = trigger track

TT{X,Y} means $X < p_{T,trig} < Y$ 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]

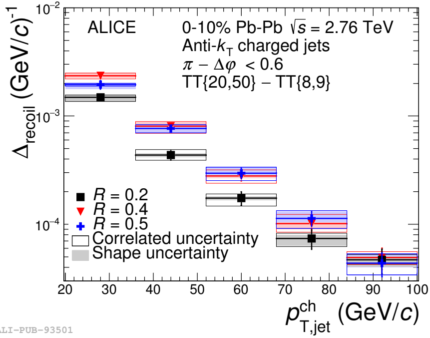
$$|\varphi_{trig} - \varphi_{jet} - \pi| < 0.6 \text{ rad}$$

- ◇ Assuming combinatorial jets are independent of trigger $p_T$

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

$$\Delta_{\rm recoil} = \frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}{\rm d}\eta}\Bigg|_{p_{\rm T,trig}\in {\rm TT}\{20,50\}} - \frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}{\rm d}\eta}\Bigg|_{p_{\rm T,trig}\in {\rm TT}\{8,9\}}$$

◇ Link to theory $$\frac{1}{N^{\rm AA}_{\rm trig}} \frac{{\rm d}^2 N^{\rm AA}_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}{\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT}} = \left( \frac{1}{\sigma^{\rm AA\to h+X}} \cdot \frac{{\rm d}^2\sigma^{\rm AA\to h+jet+X}}{{\rm d}p^{\rm ch}_{\rm T,jet}{\rm d}\eta_{\rm jet}} \right)\Bigg|_{p_{\rm T,h}\in {\rm TT}}$$



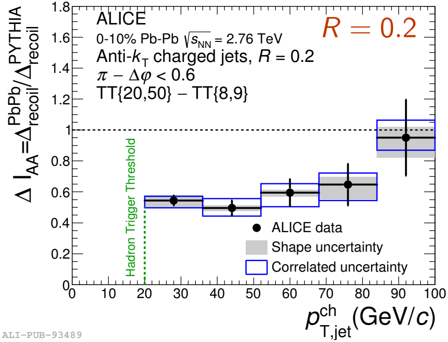

ALI-PUB-93501

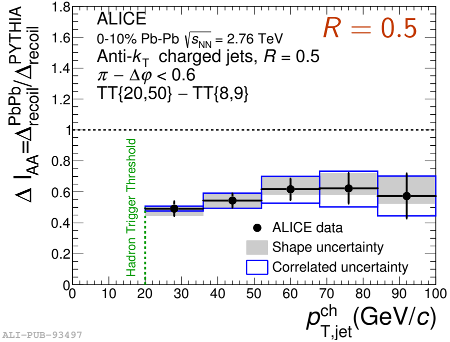
- $\Delta_{\rm recoil}$ corrected for backgroung smearing of jet $p_{\rm T}$ + detector effects
- Medium effects

$$\Delta I_{\rm AA} = \Delta^{\rm Pb\text{-}Pb}_{\rm recoil} / \Delta^{\rm pp}_{\rm recoil}$$

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*

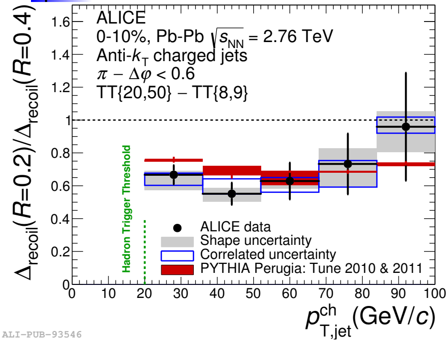


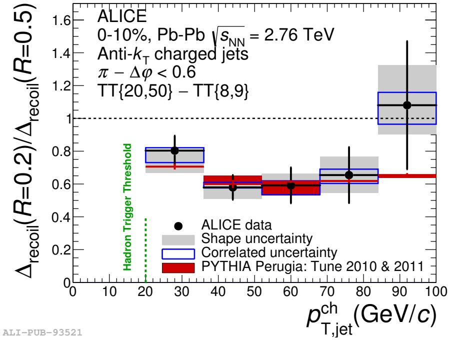




- Reference $\Delta^{\text{PYTHIA}}_{\text{recoil}}$ from PYTHIA Perugia 10
- Suppression of the recoil jet yield
- Magnitude of the suppression similar for different $R$

More details in ALICE collab., JHEP 09 (2015), 170

# Ratios of recoil jet yields obtained with different $R$




- Red band: variation in observable calculated using PYTHIA tunes
- No evidence for significant energy redistribution w.r.t. PYTHIA up to jets with $R = 0.5$

# QGP signatures in small systems

- Indication of collective effects in p–Pb
- Is there jet quenching in p–Pb?
- Considerations
  - $\Delta E \propto \hat{q} L^2$

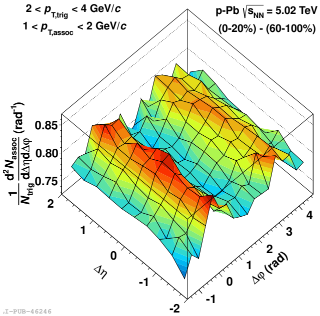
    BDMPS, Nucl. Phys. B483 (1997) 291
  - $\hat{q}|_{\mathrm{pPb}} = \frac{1}{7}\hat{q}|_{\mathrm{PbPb}}$

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

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

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

    ALICE, JHEP 09 (2015) 170




ALICE, Phys.Lett. B 719 (2013) 29–41

# Event Activity biased jet measurements in d+Au at RHIC

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

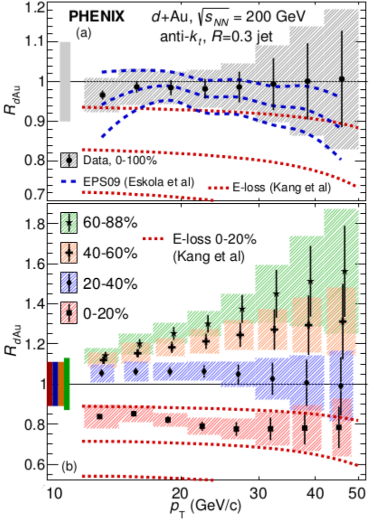
$$R_{dAu} = \frac{dN^{cent}_{jets}/dp_T}{T_{dAu} \cdot d\sigma_{pp}/dp_T}$$

- $R_{dAu}$ 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

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



# Event Activity biased jet measurements in p–Pb at LHC

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

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

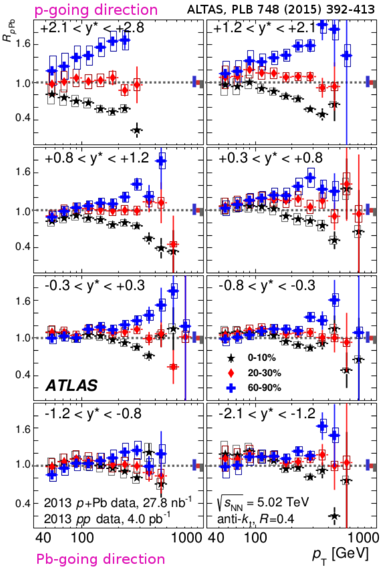
## Caveats:

- $T_{\mathrm{pPb}}$, $T_{\mathrm{dAu}}$ 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 $T_{\mathrm{AA}}$

Calculable at NLO pQCD [1]

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

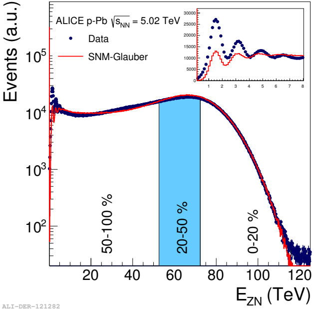
In case of no nuclear effects

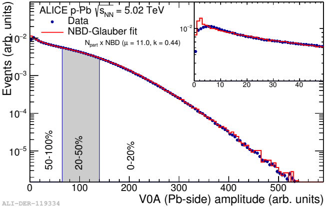
$$\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}}\frac{\mathrm{d}^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}} = \left(\frac{1}{\sigma^{\mathrm{pp}\to\mathrm{h+X}}}\cdot\frac{\mathrm{d}^2\sigma^{\mathrm{pp}\to\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{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

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

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

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



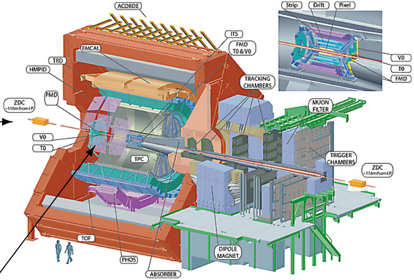




Pb-going direction

ZNA

V0A

$\eta \in (2.8, 5.1)$




Charged track reconstruction

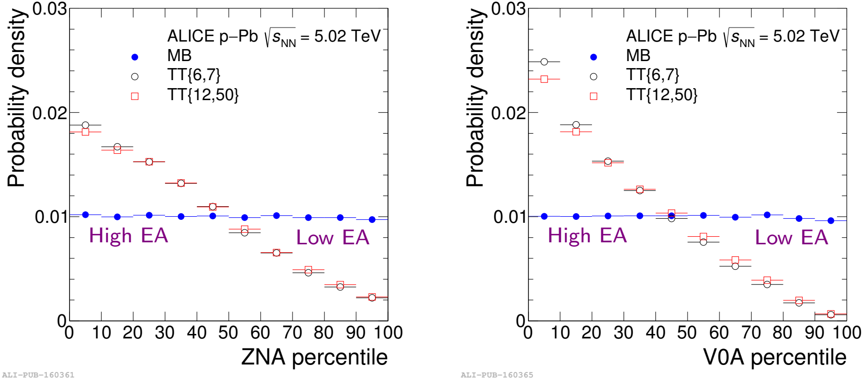
$|\eta| < 0.9, \ p_T > 150$ MeV/$c$

ITS 6-layered silicon tracker

TPC time projection chamber

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

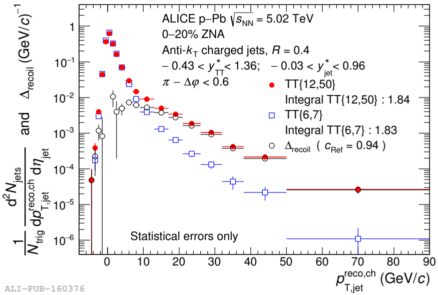
# Event Activity assignment in p–Pb



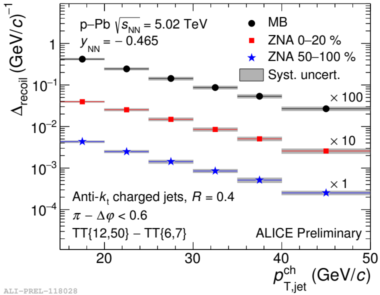

- High-$p_T$ track requirement (TT) biases event to large EA
- Similar EA bias for TT 6–7 GeV/$c$ and 12–50 GeV/$c$

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

Raw spectrum




Fully corrected




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

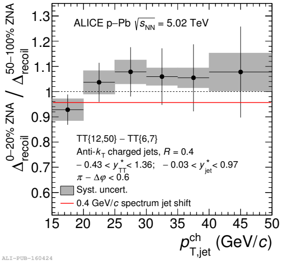
- Correction via unfolding for local bkgd. fluct. and instrumental effects
- Systematic uncertainties on $\Delta_{\mathrm{recoil}}$ : tracking efficiency 4–10 %; other sources $< 4\,\%$

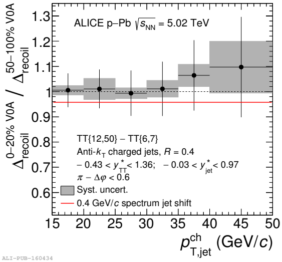
# Ratios of Event Activity biased $\Delta_{\text{recoil}}$ distributions

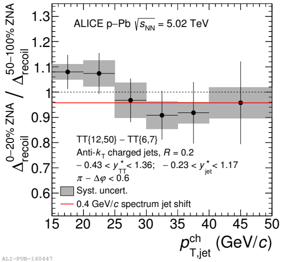
ALICE

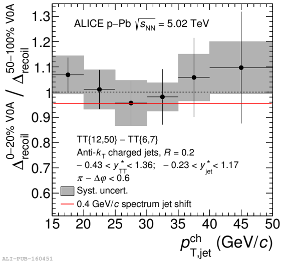
ZNA

V0A




Ratio

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

compatible with unity

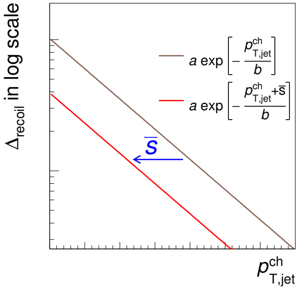
Systematic uncertainties:

| | |
|---|---|
| unfolding | 3–8 % |
| other sources | $< 4\,\%$ |

Correlated syst. uncert. in numerator and denominator cancel

# Out-of-cone energy transport

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




- Parameterize

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

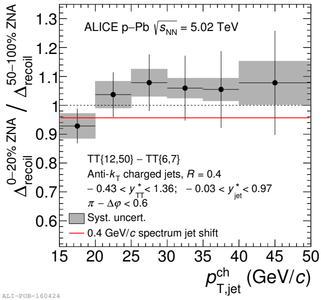
- Assume parton energy loss causes average shift of $\Delta_{\mathrm{recoil}}$ by $\bar{s}$ independent of $p^{\mathrm{ch}}_{\mathrm{T,jet}}$

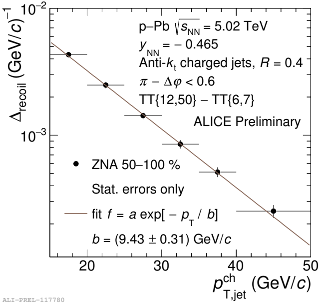
$$\Delta_{\mathrm{recoil}}\big|_{0-20\,\%} = a \exp\left(-\frac{p^{\mathrm{ch}}_{\mathrm{T,jet}}+\bar{s}}{b}\right)$$

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
  $\bar{s} = (-0.06 \pm 0.34_{\mathrm{stat}} \pm 0.02_{\mathrm{syst}})$ GeV/$c$ for V0A
  $\bar{s} = (-0.12 \pm 0.35_{\mathrm{stat}} \pm 0.03_{\mathrm{syst}})$ GeV/$c$ for ZNA
  $\bar{s} = (8 \pm 2_{\mathrm{stat}})$ GeV/$c$ in Pb–Pb ALICE, JHEP 09 (2015) 170
- Medium-induced charged energy transport out of $R = 0.4$ cone is less than 0.4 GeV/$c$ (one sided 90% CL)

## Summary

- h+jet technique alows 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 $\sqrt{s_{NN}} = 2.76\,\text{TeV}$: suppression of recoil jet yield, but no evidence of intra-jet broadening of energy profile out to $R = 0.5$
- p–Pb at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$: 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 $0.4\,\text{GeV}/c$