High-p_{T} hadron+jet correlations in ALICE

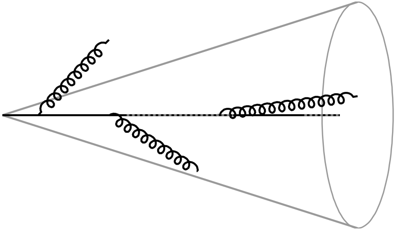
Filip Krizek
on behalf of the ALICE collaboration

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

March 2019

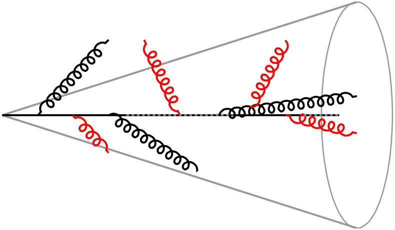
In-medium modification of QCD shower

Jet shower in vacuum



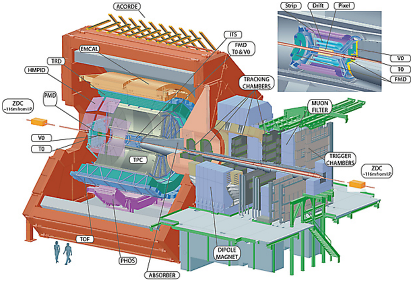
- Highly virtual parton radiates gluons
- Angular ordering due to quantum interference
- Precise understanding in pQCD
- Accurately calculable with QCD-based Monte Carlo models

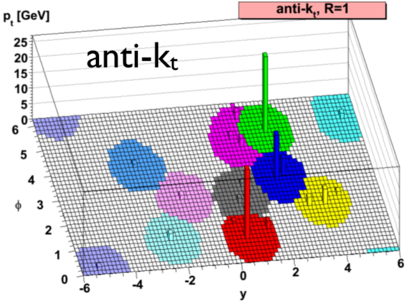
Jet shower in medium



- Superposition and interference of vacuum shower and medium-induced gluon emission
- Angular ordering is modified or destroyed
- Color coherence phenomena: medium resolves color dipole as independent charges only when the charges are separated enough

Jets in ALICE



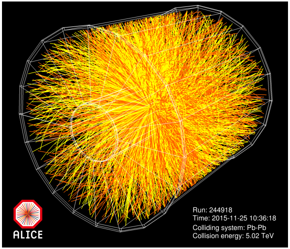


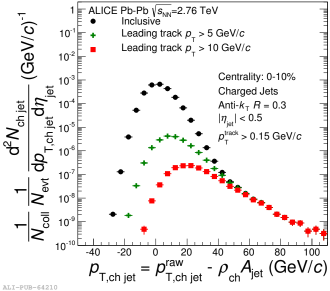
- **Charged jets:** tracks $|\eta| < 0.9$, $0^\circ < \varphi < 360^\circ$, $p_{\mathrm{T}}^{\mathrm{const}} > 150$ MeV/c
- **Jet reconstruction:** anti-k_{T} algorithm (FastJet package [1])

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

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

Selection of jets using fragmentation bias





[2]

- Hard scattering, rare process embedded in large background
- Correction of jet transverse momentum for mean background energy density [1]

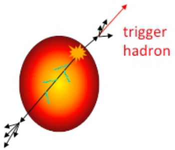
  $p_{T,jet}^{reco,ch} = p_{T,jet}^{ch,raw} - \rho \times A_{jet}$ where A_{jet} is jet area and

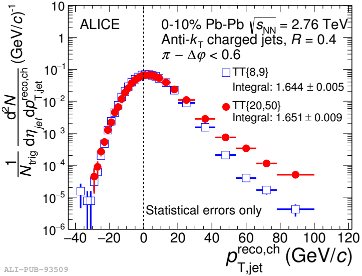
  $\rho = \text{median}_{k_T \text{ jets}} \{p_{T,jet}/A_{jet}\}$
- Spectrum of reconstructed jets at low p_T is dominated by combinatorial jets
- Suppression of combinatorial jets by high-p_T jet constituent requirement results in fragmentation bias on jets

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

[2] ALICE JHEP 03 (2014) 013

Hadron-jet coincidence measurement





[1] ALICE, JHEP 09 (2015) 170

TT = trigger track

TT{X,Y} means

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

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

- Hadron-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]

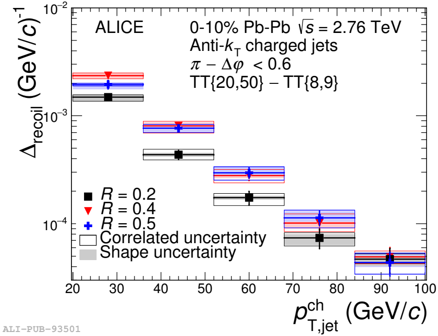
$$|\varphi_{trig} - \varphi_{jet} - \pi| < 0.6 \text{ rad}$$

- The fraction of jets uncorrelated with TT is the same in both samples

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



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

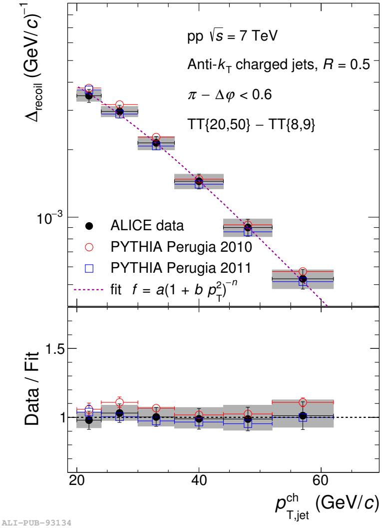
$$\Delta I_{\rm AA} = \Delta^{\rm Pb\text{-}Pb}_{\rm recoil} / \Delta^{\rm pp}_{\rm recoil}$$

Need pp reference at the same $\sqrt{s}$

ALICE, JHEP 09 (2015) 170

Δ_{recoil} spectra in pp at $\sqrt{s} = 7$ TeV

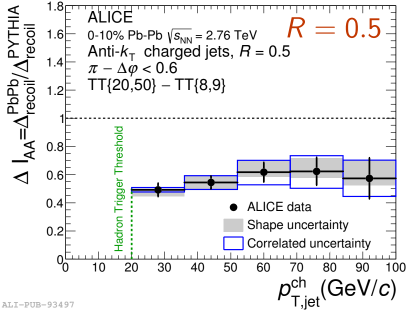
ALICE

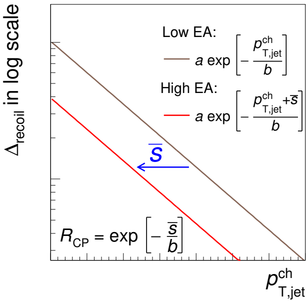


- pp analysis similar to Pb–Pb
- Gray boxes - syst. uncert. resulting from detector effects and unfolding
- PYTHIA comparison
  - Perugia 10 and 11 are compatible with the data
  - Supports the use Perugia 10 calculation as a reference for Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV
- Bottom panel shows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

ALICE, JHEP 09 (2015) 170

ΔI_{AA} in Pb–Pb





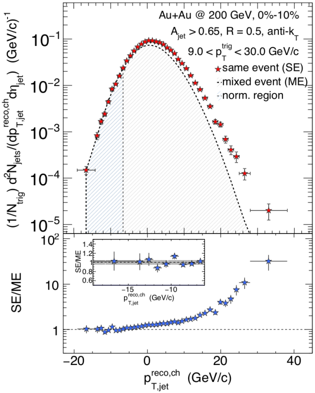
- Left: ΔI_{AA} with Reference Δ_{recoil}^{PYTHIA} from PYTHIA Perugia 10
  Suppression of the recoil jet yield
- Right: Cartoon ilustrating spectrum shift due to energy loss
  Medium-induced charged energy transport out of $R = 0.5$ cone is $\bar{s} = (8 \pm 2_{stat})$ GeV/c

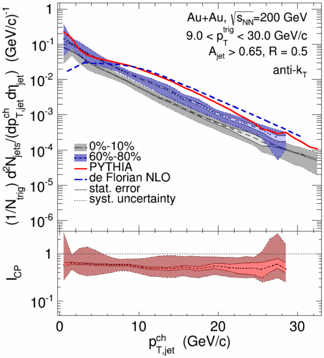
ALICE, JHEP 09 (2015), 170

Hadron-jet correlations in STAR at RHIC

ALICE

Background estimated using event mixing technique (multiplicity, z_{vtx}, event plane azimuth bins)





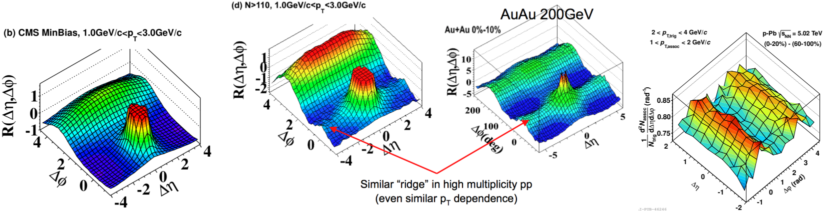
Medium-induced charged energy transport out of jet cone:

STAR, Phys. Rev. C 96, 024905 (2017)

System		Au+Au $\sqrt{s_{NN}} = 200$ GeV	Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV
$p^{ch}_{T,jet}$ range (GeV/c)		[10,20]	[60,100]
		p_T-shift of $Y\left(p^{ch}_{T,jet}\right)$ (GeV/c)	
		peripheral→central	p+p→central
R	0.2	$-4.4 \pm 0.2 \pm 1.2$	
	0.3	$-5.0 \pm 0.5 \pm 1.2$	
	0.4	$-5.1 \pm 0.5 \pm 1.2$	
	0.5	$-2.8 \pm 0.2 \pm 1.5$	-8 ± 2

QGP signatures in small systems

- Indication of collective effects in pp and p–Pb



CMS, JHEP 09 (2010) 091

ALICE, Phys.Lett. B 719 (2013) 29–41

- Is there jet quenching in p–Pb?
  - ◇ $\Delta E \propto \hat{q} L^2$

    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
  - ◇ $\Delta E = (8 \pm 2_{\text{stat}})$ GeV$/c$ medium-induced E transport to $R > 0.5$ in Pb–Pb

    ALICE, JHEP 09 (2015) 170

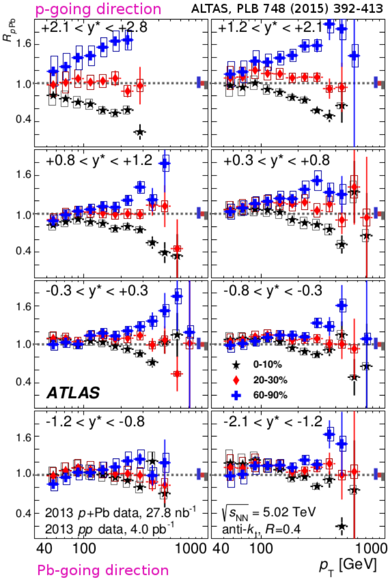
Event Activity biased jet measurements in p–Pb at LHC

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

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

$$R_{\mathrm{pPb}} = \frac{\mathrm{d}N_{\mathrm{jets}}^{\mathrm{cent}}/\mathrm{d}p_{\mathrm{T}}}{T_{\mathrm{pPb}} \cdot \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- R_{pPb} depends on rapidity range



Caveats:

- T_{pPb} assume Event Activity correlated with geometry (Glauber modeling)
- Conservation laws and fluctuations

  Kordell, Majumder, arXiv:1601.02595v1

Alternative: Hadron-jet conditional yields

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

Calculable at NLO pQCD [1]

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

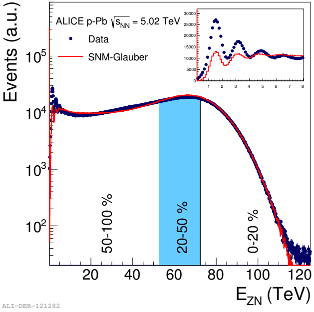
In case of no nuclear effects

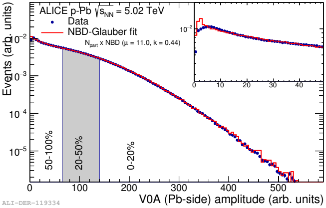
$$\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}}\frac{\mathrm{d}^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\mathrm{d}\eta_{\mathrm{jet}}}\bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}} = \left(\frac{1}{\sigma^{\mathrm{pp}\to\mathrm{h+X}}}\cdot\frac{\mathrm{d}^2\sigma^{\mathrm{pp}\to\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{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

- This coincidence observable is self-normalized, no requirement of T_{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



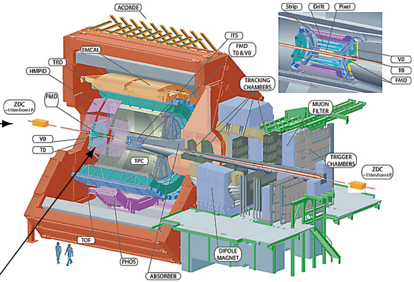


Pb-going direction

ZNA

V0A

$\eta \in (2.8, 5.1)$



Charged track reconstruction

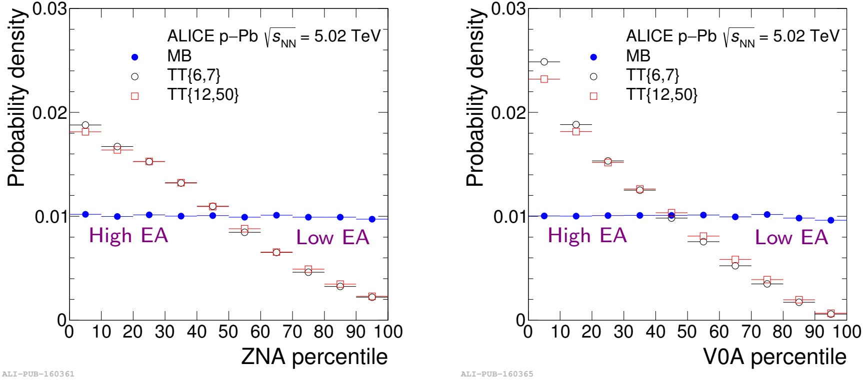
$|\eta| < 0.9,\ p_{T} > 150\ \mathrm{MeV}/c$

ITS 6-layered silicon tracker

TPC time projection chamber

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

Event Activity assignment in p–Pb

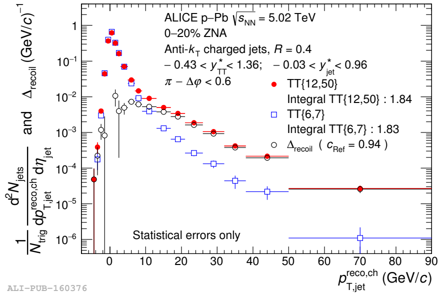


- High-p_T track requirement (TT) biases event to large Event Activity
- Similar Event Activity bias for TT 6–7 GeV/c and 12–50 GeV/c

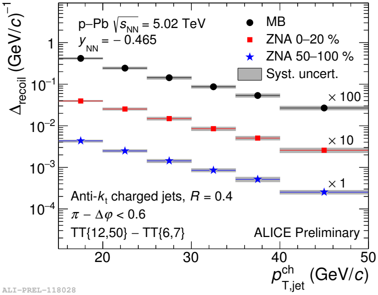
ALICE, PLB 783 (2018) 95–113.

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

Raw spectrum



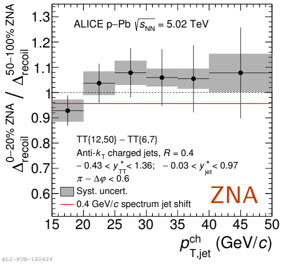
Fully corrected

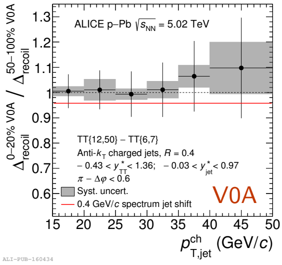


$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{jet}}}{dp^{\text{ch}}_{\text{T,jet}} d\eta}\bigg|_{p_{\text{T,trig}} \in \text{TT}\{12,50\}} - \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{jet}}}{dp^{\text{ch}}_{\text{T,jet}} d\eta}\bigg|_{p_{\text{T,trig}} \in \text{TT}\{6,7\}}$$

ALICE, Phys. Lett. B 783 (2018) 95–113.

Ratios of Event Activity biased Δ_{recoil} distributions



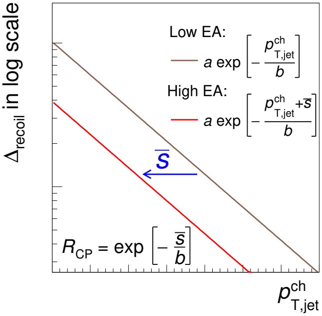


Ratio

$$R_{CP} = \frac{\Delta_{recoil}|_{0-20\,\%}}{\Delta_{recoil}|_{50-100\,\%}}$$

compatible with unity

ALICE, PLB 783 (2018) 95–113.



- Medium-induced spectrum shift $\bar{s}$ for high relative to low Event Activity p–Pb

  $\bar{s} = (-0.06 \pm 0.34_{stat} \pm 0.02_{syst})$ GeV/c for V0A

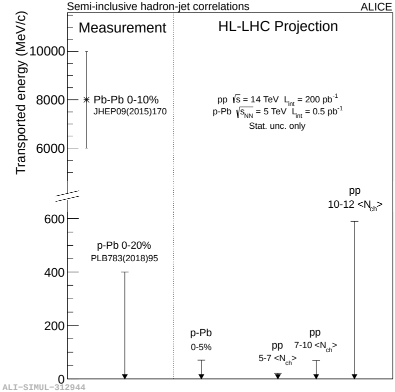
  $\bar{s} = (-0.12 \pm 0.35_{stat} \pm 0.03_{syst})$ GeV/c for ZNA

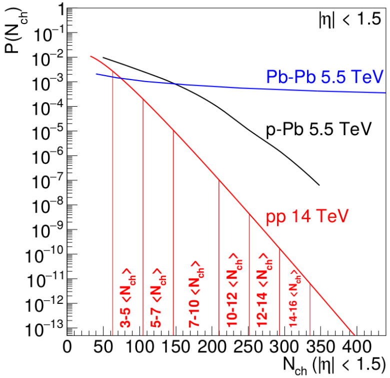
  $\bar{s} = (8 \pm 2_{stat})$ GeV/c in Pb–Pb

  ALICE, JHEP 09 (2015) 170

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

Prospects of energy loss measurements in Run 3+4





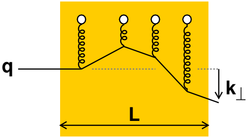
- pp $\sqrt{s} = 14\,\text{TeV}$ ($L_{\text{int}} = 200\,\text{pb}^{-1}$)
- p–Pb $\sqrt{s_{\text{NN}}} = 5\,\text{TeV}$ ($L_{\text{int}} = 0.5\,\text{pb}^{-1}$)
- Statistics will allow to improve constraints on energy loss by an order of magnitude

Yellow Report, arXiv:1812.06772 [hep-ph]

Jet broadening and the transport coefficient $\hat{q}$

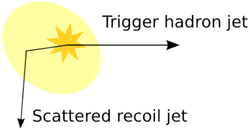
$$\hat{q} \equiv \frac{\langle k_\perp^2 \rangle}{L} = \frac{1}{L} \int \frac{\mathrm{d}^2 k_\perp}{(2\pi)^2} k_\perp^2 P(k_\perp)$$

$$P(k_\perp) = \int \mathrm{d}^2 x_\perp e^{-\mathrm{i} k_\perp x_\perp} \mathcal{W}_\mathcal{R}(x_\perp)$$



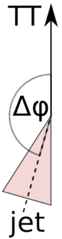
$\mathcal{W}_\mathcal{R}(x_\perp) \equiv$ expectation value of the Wilson loop

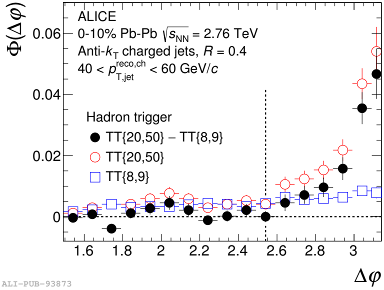
- Strongly coupled plasma (AdS CFT) : $P(k_\perp)$ is Gaussian
- Weakly coupled plasma (perturbative thermal field theory) : $P(k_\perp)$ is a Gaussian with a power-law $P(k_\perp) \propto 1/k_\perp^4$ tail emerging from single hard Molière scatterings off QGP quasi-particles $\Rightarrow$ Use recoil jets to search for QGP quasi-particles [1] by looking at enhancement in large angle deflections w.r.t. reference pp



[1] D'Eramo et al., JHEP 05 (2013) 031.

Search for large-angle single hard Molière scatterings





ALICE, JHEP 09 (2015), 170

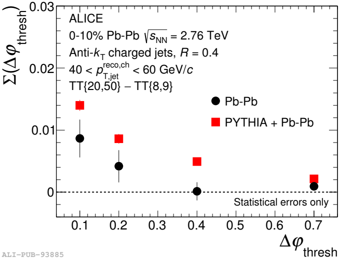
For recoil jets in $40 < p_{T,jet}^{ch} < 60$ GeV/c define

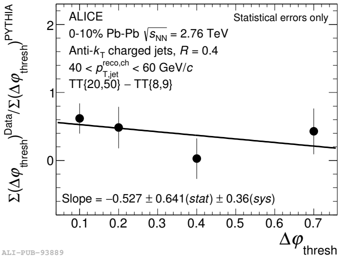
$$\Phi\left(\Delta\varphi\right) = \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp_{T,jet}^{ch} d\Delta\varphi}\Bigg|_{TT\{20,50\}} - \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp_{T,jet}^{ch} d\Delta\varphi}\Bigg|_{TT\{8,9\}}$$

Quantify the rate of large angle scatterings

$$\Sigma\left(\Delta\varphi_{thresh}\right) = \int_{\pi/2}^{\pi - \Delta\varphi_{thresh}} \Phi\left(\Delta\varphi\right) d\Delta\varphi$$

$\Sigma\left(\Delta\varphi_{\mathrm{thresh}}\right)$ in Pb–Pb and PYTHIA

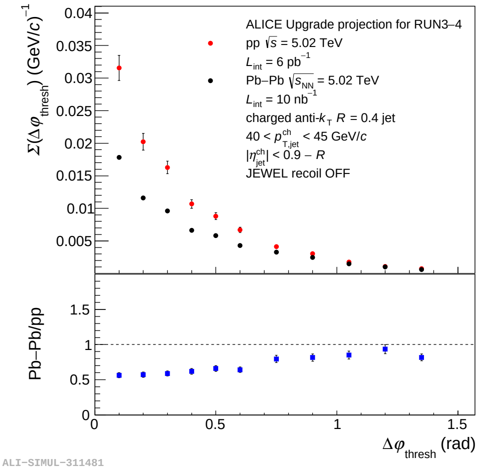




- Raw data are compared with PYTHIA smeared with detector response and embedded into real events
- Ratio < 1 corresponds to the suppression of recoil jet yield
- Shape of the ratio depends on underlying processes
- Fit of the ratio by a linear function gives a slope consistent with zero $\Rightarrow$
  No evidence for medium-induced Molière scattering

ALICE, JHEP 09 (2015), 170

Projection of $\Sigma(\Delta\varphi_{\text{thresh}})$ for Run 3 + 4



- ALICE expectations for Run 3+4:
  Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV:
  $L_{\text{int}} = 10\,\text{nb}^{-1}$ ($25\times$ w.r.t. Run2)
  pp at $\sqrt{s} = 5.02$ TeV:
  $L_{\text{int}} = 6\,\text{pb}^{-1}$
- JEWEL recoil OFF
- Statement on quasi-particle in QGP will be much more conclusive

[1] Yellow Report, arXiv:1812.06772 [hep-ph]

Summary

- Hadron-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 $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$: suppression of recoil jet yield, medium-induced charged energy transport out of $R = 0.5$ cone is $(8 \pm 2_{\mathrm{stat}})$ GeV/c
  - p–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$: no significant quenching effects are observed when comparing recoil jet yield for low and high Event Activity. At 90% CL, medium-induced charged energy transport out of $R = 0.4$ cone is less than $0.4\,\mathrm{GeV}/c$

Backup slides

Corrections of raw jet spectra

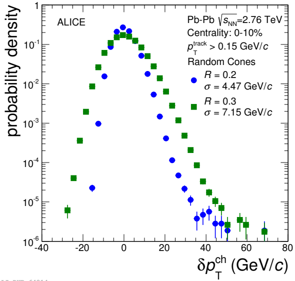
- Background fluctuations:
  embedding MC jets or random cones [1]
  $\delta p_{\mathrm{t}} = \sum_i p_{t,i} - A \cdot \rho$

- Detector response:
  based on GEANT + PYTHIA

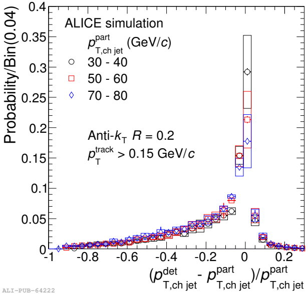
- Response matrix:
  two effects are assumed to factorize
  $$R_{\mathrm{full}}\left(p_{\mathrm{T,jet}}^{\mathrm{rec}}, p_{\mathrm{T,jet}}^{\mathrm{part}}\right) = \delta p_{\mathrm{t}}\left(p_{\mathrm{T,jet}}^{\mathrm{rec}}, p_{\mathrm{T,jet}}^{\mathrm{det}}\right) \otimes R_{\mathrm{instr}}\left(p_{\mathrm{T,jet}}^{\mathrm{det}}, p_{\mathrm{T,jet}}^{\mathrm{part}}\right)$$

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

[1] ALICE, 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



ALI-PUB-64214



ALI-PUB-64222

QGP signatures in small systems

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

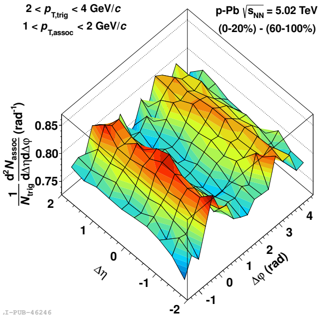
    BDMPS, Nucl. Phys. B483 (1997) 291
  - ◇ $\hat{q}|_{\mathrm{pPb}} = \frac{1}{7}\hat{q}|_{\mathrm{PbPb}}$

    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)
  - ◇ $\hat{q}|_{\text{Cold Nuclear Matter}} \approx 0.02\ \mathrm{GeV}^2/\mathrm{fm}$

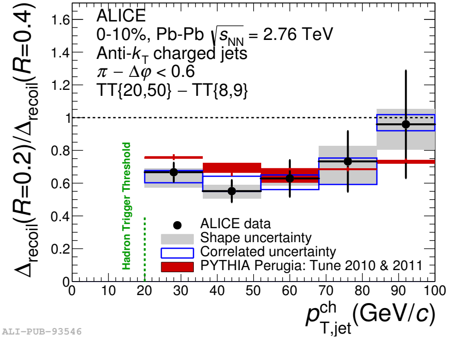
    W.T.Deng, X.N.Wang, Phys.Rev. C 81, 024902 (2010)
  - ◇ $\Delta E = (8 \pm 2_{\mathrm{stat}})\ \mathrm{GeV}/c$ medium-induced E transport to $R > 0.5$ in Pb–Pb

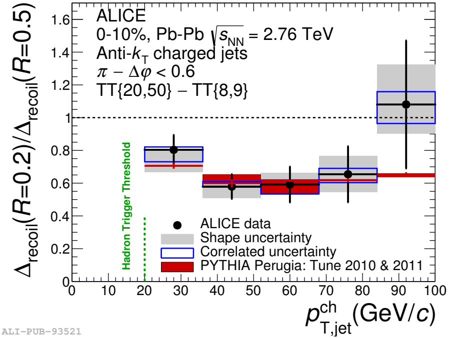
    ALICE, JHEP 09 (2015) 170



ALICE, Phys.Lett. B 719 (2013) 29–41

Ratios of recoil jet yields obtained with different R

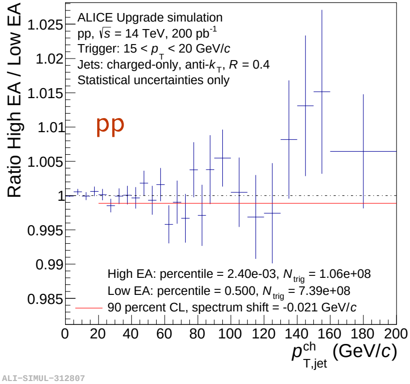


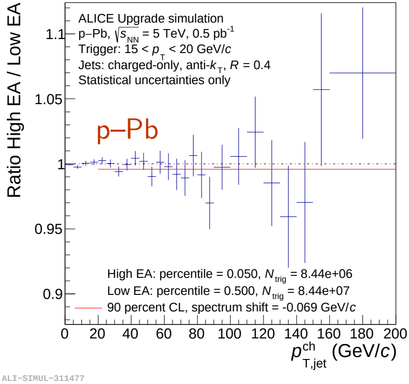


- Observable sensitive to lateral energy distribution in jets
- Red band: variation in observable calculated using PYTHIA tunes
- No evidence for significant energy redistribution w.r.t. PYTHIA up to jets with $R = 0.5$

ALICE JHEP 09 (2015), 170

Energy loss in small systems – projection for Run 3 + 4





- pp $\sqrt{s} = 14\,\text{TeV}$ ($L_{\text{int}} = 200\,\text{pb}^{-1}$)
  high-event activity bin: $5 - 7\,\langle N_{\text{ch}} \rangle$, low-event activity bin: 50–100 %
- p–Pb $\sqrt{s_{\text{NN}}} = 5\,\text{TeV}$ ($L_{\text{int}} = 0.5\,\text{pb}^{-1}$)
  high-event activity bin: 0–5 %, low-event activity bin: 50–100 %
- Projection represents the case where no energy loss occurs for high-event activity relative to low-event activity collisions, and demonstrates the statistically achievable limit.