

High- p_T hadron+jet correlations in ALICE

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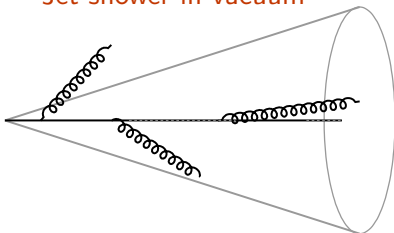
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May 2019



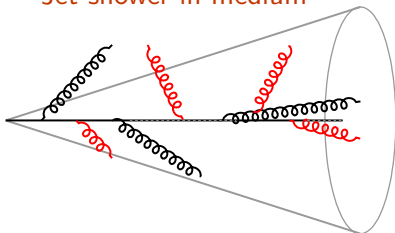
In-medium modification of QCD shower

Jet shower in vacuum

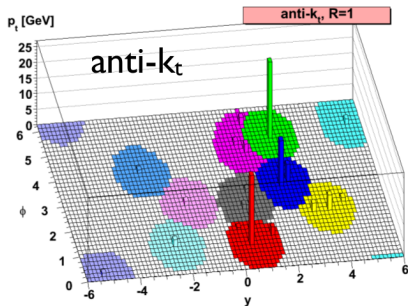
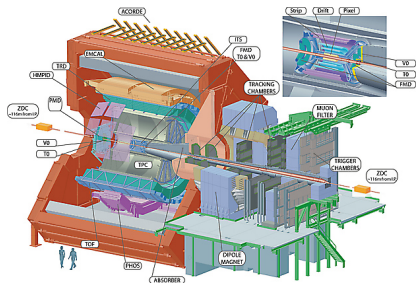


- ▶ Highly virtual parton radiates gluons
- ▶ Angular ordering due to quantum interference
- ▶ Precise understanding in pQCD
- ▶ Accurately calculable with QCD-based Monte Carlo models

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



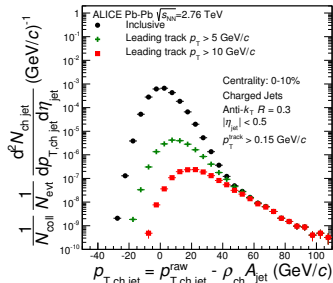
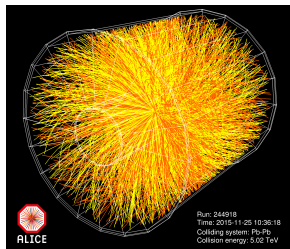
▶ **Charged jets:** tracks $|\eta| < 0.9$, $0^\circ < \varphi < 360^\circ$, $p_T^{\text{const}} > 150 \text{ MeV}/c$

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

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

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

Selection of jets using fragmentation bias



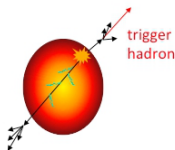
- ▶ Hard scattering, rare process embedded in large background
- ▶ Correction of jet transverse momentum for mean background energy density [1]

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

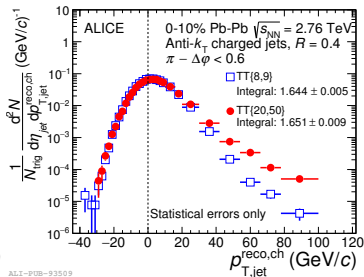
$$\rho = \text{median}_{k_T \text{ jets}} \{ p_{T,jet} / A_{jet} \}$$
- ▶ Spectrum of reconstructed jets at low p_T is dominated by combinatorial jets
- ▶ Suppression of combinatorial jets by high- p_T jet constituent requirement results in fragmentation bias on jets

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

Hadron-jet coincidence measurement



[1] ALICE, JHEP 09 (2015) 170



TT = trigger track

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

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

- ▶ 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]

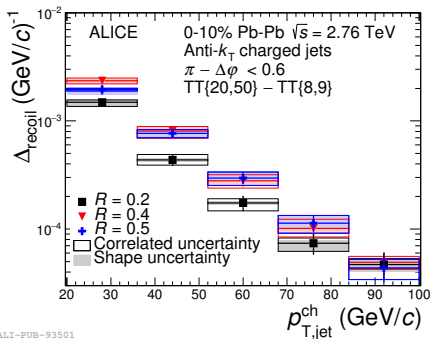
$$|\varphi_{\text{trig}} - \varphi_{\text{jet}} - \pi| < 0.6 \text{ rad}$$

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

Δ_{recoil} in Pb-Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

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

◊ Link to theory $\frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^2 N_{\text{jet}}^{\text{AA}}}{d p_{\text{T,jet}}^{\text{ch}} d \eta_{\text{jet}}} \Big|_{p_{\text{T,trig}} \in \text{TT}} = \left(\frac{1}{\sigma^{\text{AA} \rightarrow \text{h}+\text{X}}} \cdot \frac{d^2 \sigma^{\text{AA} \rightarrow \text{h}+\text{jet}+\text{X}}}{d p_{\text{T,jet}}^{\text{ch}} d \eta_{\text{jet}}} \right) \Big|_{p_{\text{T,h}} \in \text{TT}}$



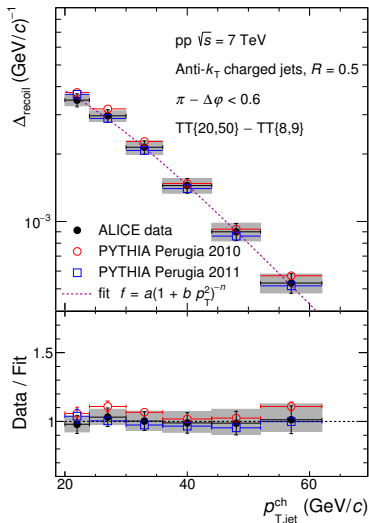
- ▶ Δ_{recoil} corrected for background smearing of jet p_T + detector effects
- ▶ Medium effects

$$\Delta_{\text{AA}} = \Delta_{\text{recoil}}^{\text{Pb-Pb}} / \Delta_{\text{recoil}}^{\text{pp}}$$

Need pp reference at the same \sqrt{s}

ALICE, JHEP 09 (2015) 170

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

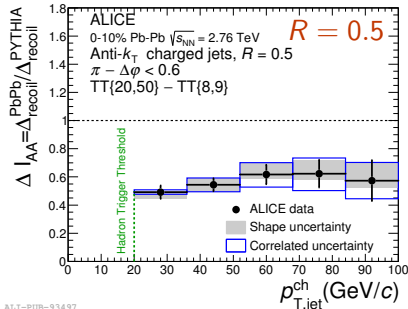


- ▶ pp analysis similar to Pb–Pb
- ▶ Gray boxes - syst. uncert. resulting from detector effects and unfolding
- ▶ PYTHIA comparison
 - ▶ Perugia 10 and 11 are compatible with the data
 - ▶ Supports the use Perugia 10 calculation as a reference for Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV
- ▶ Bottom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

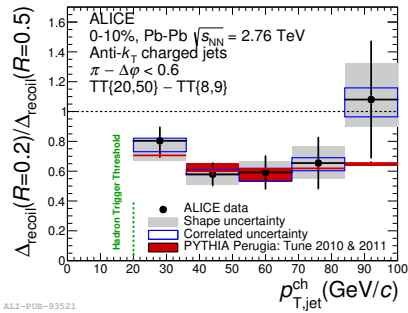
ALICE, JHEP 09 (2015) 170

ALICE-PUB-93134

ΔI_{AA} and Δ_{recoil} ratio in Pb-Pb



ALI-PUB-93497



ALI-PUB-93521

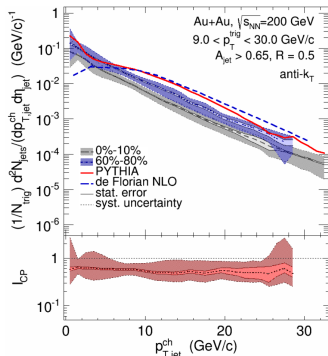
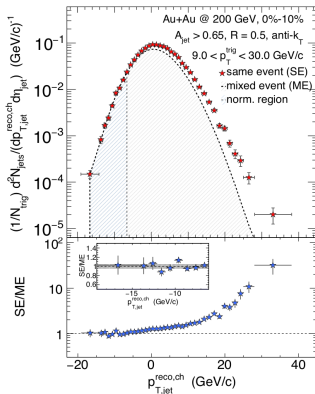
- ▶ Left: ΔI_{AA} with Reference Δ_{recoil}^{PYTHIA} from PYTHIA Perugia 10
Suppression of the recoil jet yield \Rightarrow Medium-induced charged energy transport out of $R = 0.5$ cone is $\bar{s} = (8 \pm 2_{stat})$ GeV/c
- ▶ Right: Observable sensitive to lateral energy distribution in jets
 Red band: variation in the observable calculated using PYTHIA tunes
No evidence for significant energy redistribution w.r.t. PYTHIA

ALICE, JHEP 09 (2015), 170

Hadron-jet correlations in STAR at RHIC



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



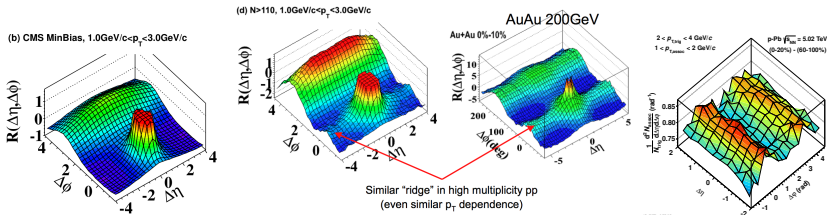
Medium-induced charged energy transport out of jet cone:

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

System		Au+Au $\sqrt{s_{NN}} = 200$ GeV	Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV
$p_{T,jet}^{ch}$ range (GeV/c)		[10,20]	[60,100]
		p_T -shift of $Y(p_{T,jet}^{ch})$ (GeV/c)	
		peripheral \rightarrow central	p+p \rightarrow 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

- ◇ $\hat{q}|_{pPb} = \frac{1}{7} \hat{q}|_{PbPb}$

K.Tywoniuk, Nucl.Phys. A 926 (2014) 85–91

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

ALICE, JHEP 09 (2015) 170

Event Activity biased jet measurements in p-Pb at LHC

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

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

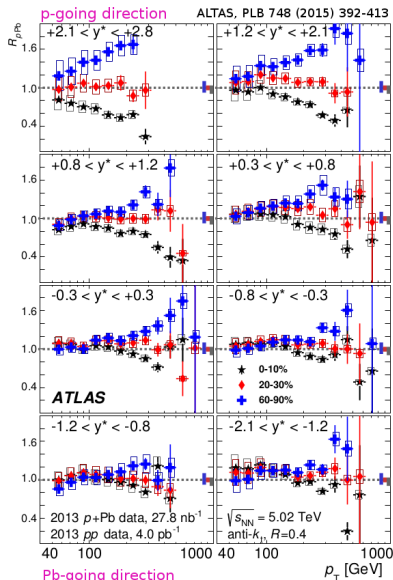
$$R_{pPb} = \frac{dN_{jets}^{cent}/dp_T}{T_{pPb} \cdot d\sigma_{pp}/dp_T}$$

- ▶ 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]

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

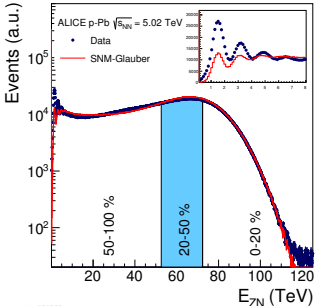
In case of no nuclear effects

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

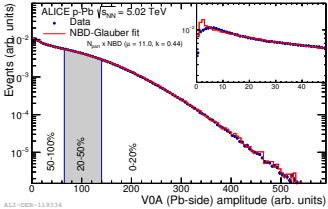
- ▶ This coincidence observable is self-normalized, no requirement of T_{AA} scaling
- ▶ No requirement to assume correlation between Event Activity and collision geometry, no Glauber modeling

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

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



ALICE-DEP-121282



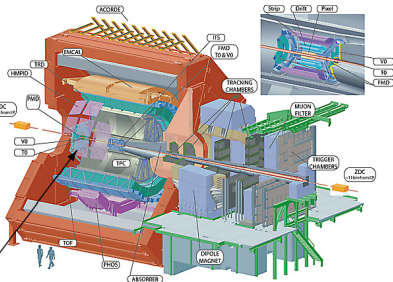
ALICE-DEP-119334

Pb-going direction

ZNA

V0A

$\eta \in (2.8, 5.1)$



Charged track reconstruction

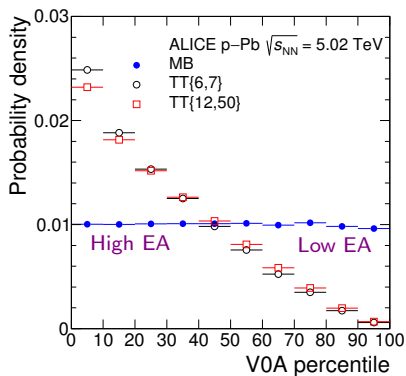
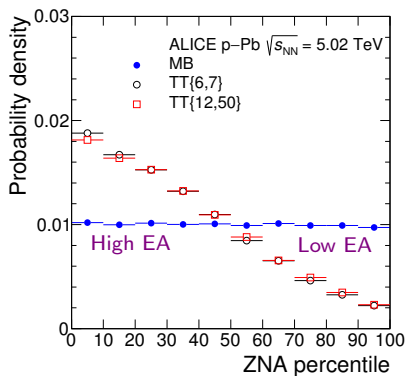
$|\eta| < 0.9, p_T > 150 \text{ MeV}/c$

ITS 6-layered silicon tracker

TPC time projection chamber

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

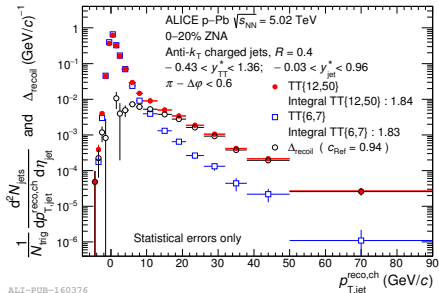
Event Activity assignment in p-Pb



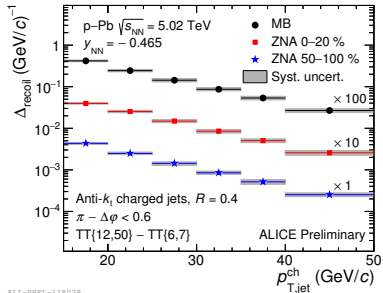
- ▶ High- p_T track requirement (TT) biases event to large Event Activity
- ▶ Similar Event Activity bias for TT 6–7 GeV/ c and 12–50 GeV/ c

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

Raw spectrum



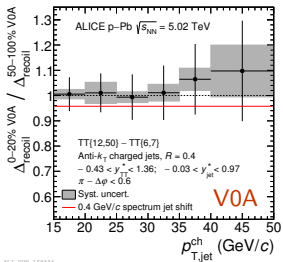
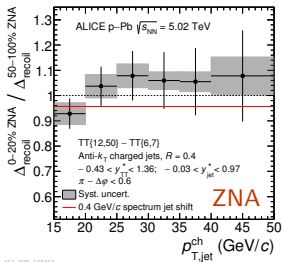
Fully corrected



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

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

Ratios of Event Activity biased Δ_{recoil} distributions

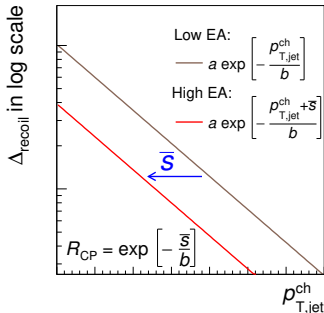


Ratio

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

compatible with unity

ALICE, PLB 783 (2018) 95–113.



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

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

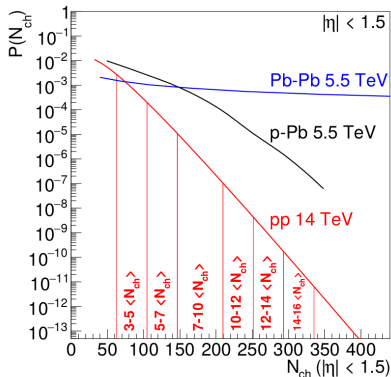
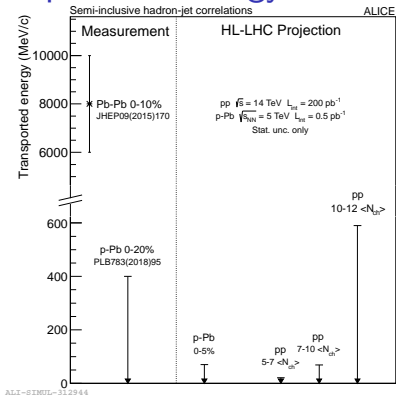
$$\bar{s} = (-0.12 \pm 0.35_{\text{stat}} \pm 0.03_{\text{syst}}) \text{ GeV/c for ZNA}$$

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

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

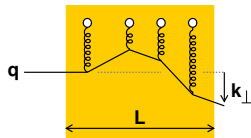
Yellow Report, arXiv:1812.06772 [hep-ph]

Jet broadening and the transport coefficient \hat{q}

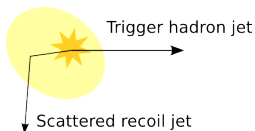
$$\hat{q} \equiv \frac{\langle k_{\perp}^2 \rangle}{L} = \frac{1}{L} \int \frac{d^2 k_{\perp}}{(2\pi)^2} k_{\perp}^2 P(k_{\perp})$$

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

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

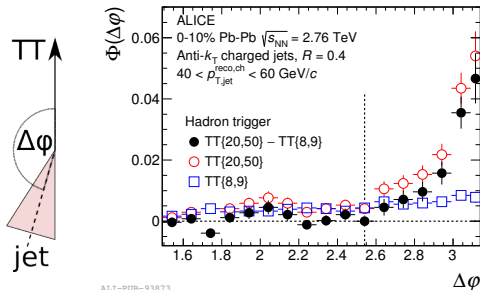


- ▶ Strongly coupled plasma (AdS CFT) : $P(k_{\perp})$ is Gaussian
- ▶ Weakly coupled plasma (perturbative thermal field theory) : $P(k_{\perp})$ is a Gaussian with a power-law $P(k_{\perp}) \propto 1/k_{\perp}^4$ tail emerging from single hard Molière scatterings off QGP quasi-particles \Rightarrow 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



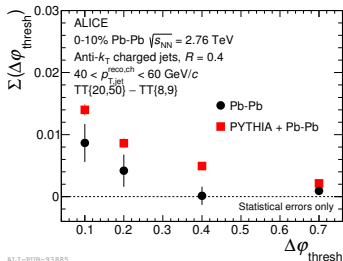
For recoil jets in $40 < p_{T,jet}^{ch} < 60$ GeV/c define

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

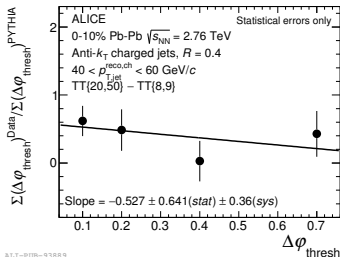
Quantify the rate of large angle scatterings

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

$\Sigma(\Delta\varphi_{\text{thresh}})$ in Pb–Pb and PYTHIA



ALI-PUB-93885

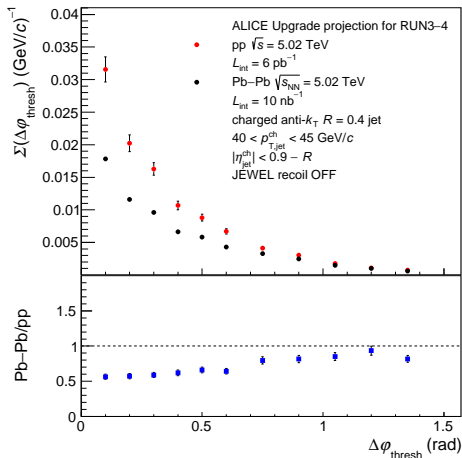


ALI-PUB-93889

- ▶ 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× 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]

- ▶ 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 $\sqrt{s_{NN}} = 2.76$ 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. At 90% CL, medium-induced charged energy transport out of $R = 0.4$ cone is less than $0.4 \text{ GeV}/c$

Backup slides

Corrections of raw jet spectra

- ▶ **Background fluctuations:**
embedding MC jets or random cones [1]

$$\delta p_t = \sum_i p_{t,i} - A \cdot \rho$$

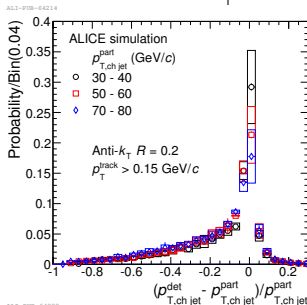
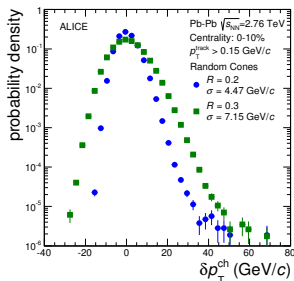
- ▶ **Detector response:**
based on GEANT + PYTHIA

- ▶ **Response matrix:**
two effects are assumed to factorize

$$R_{\text{full}} \left(p_{T,\text{jet}}^{\text{rec}}, p_{T,\text{jet}}^{\text{part}} \right) = \delta p_t \left(p_{T,\text{jet}}^{\text{rec}}, p_{T,\text{jet}}^{\text{det}} \right) \otimes R_{\text{instr}} \left(p_{T,\text{jet}}^{\text{det}}, p_{T,\text{jet}}^{\text{part}} \right)$$

- ▶ R_{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://hepunix.rl.ac.uk/~adye/software/unfold/RooUnfold.html>



ALICE-PHB-64222

► 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

◇ $\hat{q}|_{pPb} = \frac{1}{7}\hat{q}|_{PbPb}$

K.Tywniuk, Nucl.Phys. A 926 (2014) 85–91

◇ $\hat{q}|_{PbPb} = (1.9 \pm 0.7) \text{ GeV}^2/\text{fm}$

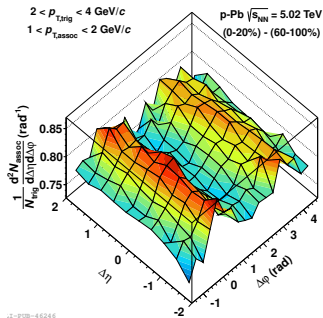
JET Collaboration, Phys.Rev. C 90, 014909 (2014)

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

W.T.Deng, X.N.Wang, Phys.Rev. C 81, 024902 (2010)

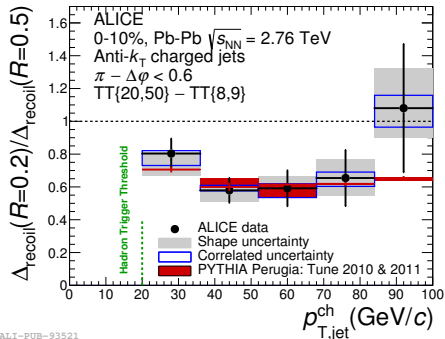
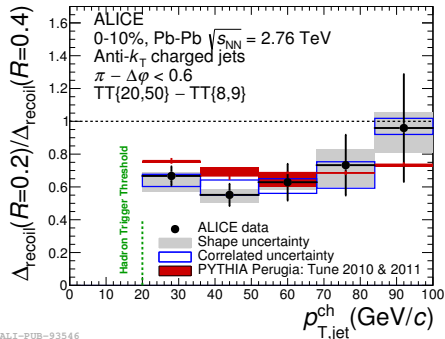
◇ $\Delta E = (8 \pm 2_{\text{stat}}) \text{ GeV}/c$ medium-induced E transport to $R > 0.5$ in Pb-Pb

ALICE, JHEP 09 (2015) 170



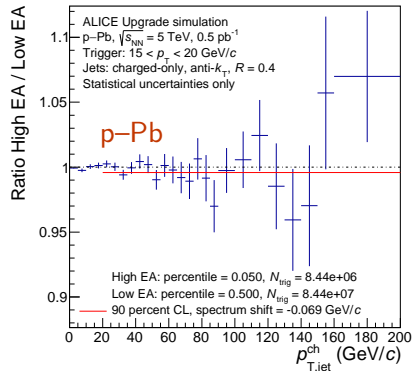
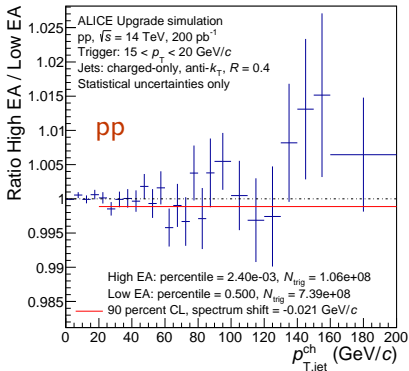
ALICE, Phys.Lett. B 719 (2013) 29–41

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 $R = 0.5$

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



ALICE-SIMUL-312807

ALICE-SIMUL-311477

- ▶ 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.