Overview of jet physics results from ALICE

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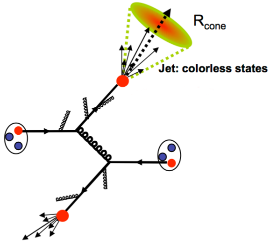
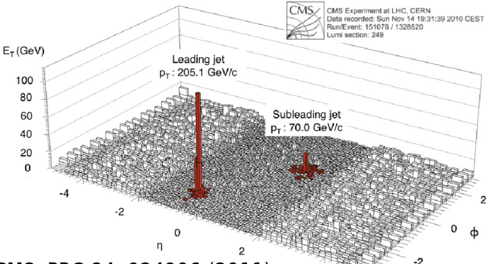
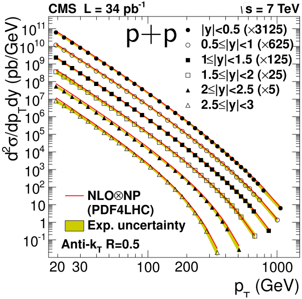
Jets in heavy-ion collisions

- Hard scattered partons produce collimated sprays of particles
- Jet is a phenomenological object defined by an algorithm
- Well understood theoretically in pQCD in elementary reactions
- Jet quenching in presence of Quark-Gluon plasma



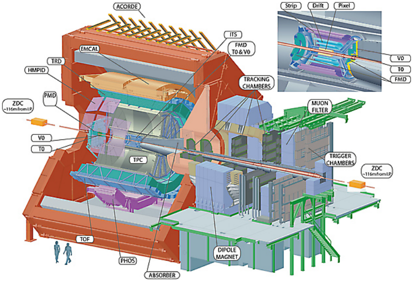


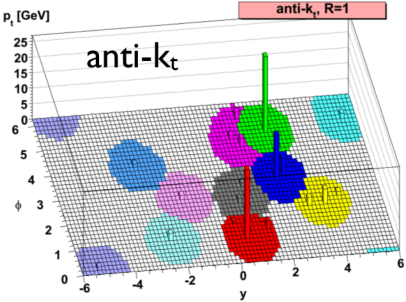
CMS, PRC 84, 024906 (2011)



CMS, Phys. Rev. Lett. 107 (2011) 132001

Jets in ALICE





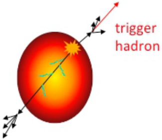
- Charged jets: tracks $|\eta| < 0.9$, $0^\circ < \varphi < 360^\circ$, $p_{\mathrm{T}}^{\mathrm{const}} > 150$ MeV/c
- Jet reconstruction: anti-k_{T} algorithm (FastJet package [1])

  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.

Quantification of medium-induced jet modification

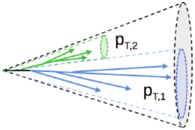
- Inclusive observables (p_{T} spectra, high-p_{T} hadron-jet correlations)



- Quantification of jet shapes by functions which depend on 4-momenta of constituents (angularity, $p_{\mathrm{T}}D$, jet mass,. . .)

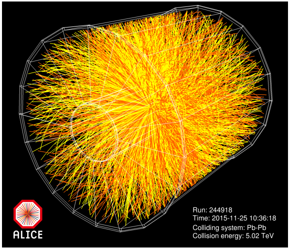
$$\lambda_\beta^\kappa = \sum_{i \in \text{constituents}} \left(\frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \right)^\kappa \left(\frac{\Delta R_{\mathrm{jet},i}}{R} \right)^\beta \quad [1]$$

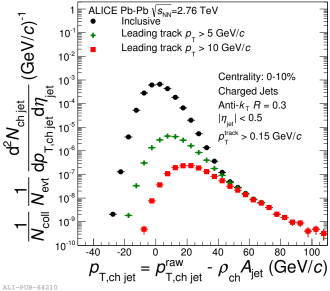
- Clustering history (grooming, N-subjettiness)



[1] A. J. Larkoski, J. Thaler, and W. J. Waalewijn, JHEP 11 (2014) 129

Selection of jets using fragmentation bias

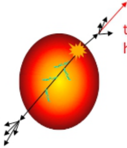


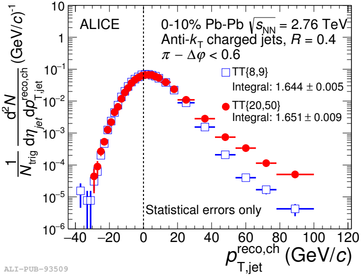


- Hard scattering, rare process embedded in large background
- Correction of jet transverse momentum for mean background energy density [1]
  $p_{T,jet}^{reco,ch} = p_{T,jet}^{ch,raw} - \rho \times A_{jet}$ where A_{jet} is jet area and
  $\rho = \text{median}_{k_T \text{ jets}} \{p_{T,jet}/A_{jet}\}$
- 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
$X < p_{T,trig} < Y$ 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]

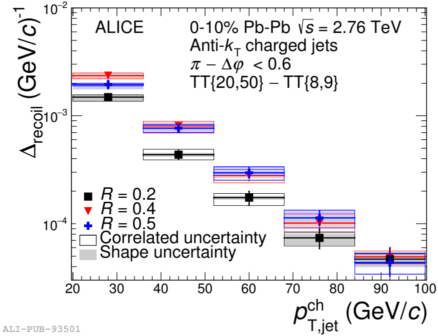
$$|\varphi_{trig} - \varphi_{jet} - \pi| < 0.6 \text{ rad}$$

- Assuming uncorrelated jets are independent of trigger p_T

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

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

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



- Δ_{recoil} corrected for background smearing of jet p_{T} + detector effects
- Medium effects

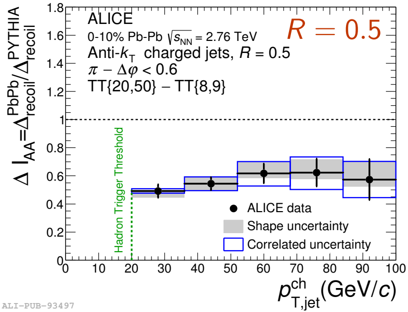
$$\Delta I_{\mathrm{AA}} = \Delta^{\mathrm{Pb\text{-}Pb}}_{\mathrm{recoil}} / \Delta^{\mathrm{pp}}_{\mathrm{recoil}}$$

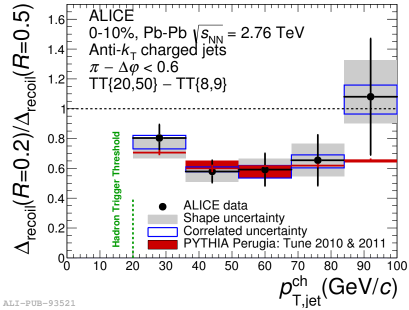
Need pp reference at the same $\sqrt{s}$

ALICE, JHEP 09 (2015) 170

ΔI_{AA} and Δ_{recoil} ratio in Pb–Pb

ALICE





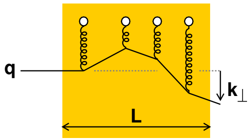
- Left: ΔI_{AA} with Reference Δ_{recoil}^{PYTHIA} from PYTHIA Perugia 10
  Suppression of the recoil jet yield
- Right: Observable sensitive to lateral energy distribution in jets
  Red band: variation in the observable calculated using PYTHIA tunes
  No evidence for significant energy redistribution w.r.t. PYTHIA

ALICE, JHEP 09 (2015), 170

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

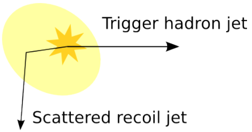
$$\hat{q} \equiv \frac{\langle k_\perp^2 \rangle}{L} = \frac{1}{L} \int \frac{\mathrm{d}^2 k_\perp}{(2\pi)^2} k_\perp^2 P(k_\perp)$$

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



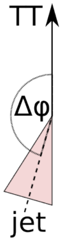
$\mathcal{W}_{\mathcal{R}}(x_\perp) \equiv$ expectation value of the Wilson loop

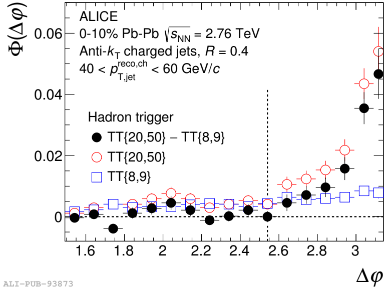
- Strongly coupled plasma (AdS CFT) : $P(k_\perp)$ is Gaussian
- Weakly coupled plasma (perturbative thermal field theory) : $P(k_\perp)$ is a Gaussian with a power-law $P(k_\perp) \propto 1/k_\perp^4$ tail emerging from single hard Molière scatterings off QGP quasi-particles $\Rightarrow$ Use recoil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

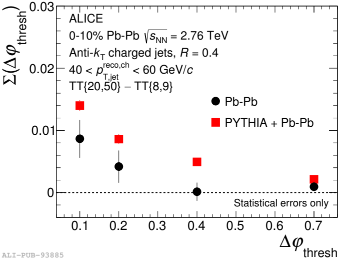
For recoil jets in $40 < p_{T,jet}^{ch} < 60$ GeV/c define

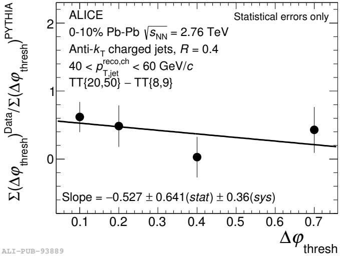
$$\Phi(\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp_{T,jet}^{ch} d\Delta\varphi}\bigg|_{TT\{20,50\}} - \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp_{T,jet}^{ch} d\Delta\varphi}\bigg|_{TT\{8,9\}}$$

Quantify the rate of large angle scatterings

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

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





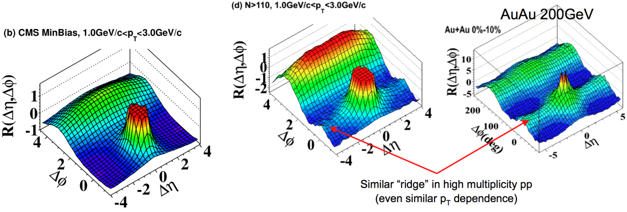
- Raw data are compared with PYTHIA smeared with detector response and embedded into real events
- Ratio < 1 corresponds to the suppression of recoil jet yield
- Shape of the ratio depends on underlying processes
- Fit of the ratio by a linear function gives a slope consistent with zero $\Rightarrow$

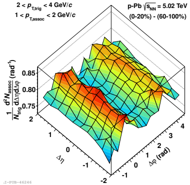
  No evidence for medium-induced Molière scattering
- To be further studied in Run3 with more statistics and for lower jet p_Ts

ALICE, JHEP 09 (2015), 170

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

    K.Tywoniuk, Nucl.Phys. A 926 (2014) 85–91
  - ◇ $\Delta E = (8 \pm 2_{\mathrm{stat}})\,\mathrm{GeV}/c$ medium-induced E transport to $R > 0.5$ in Pb–Pb

    ALICE, JHEP 09 (2015) 170

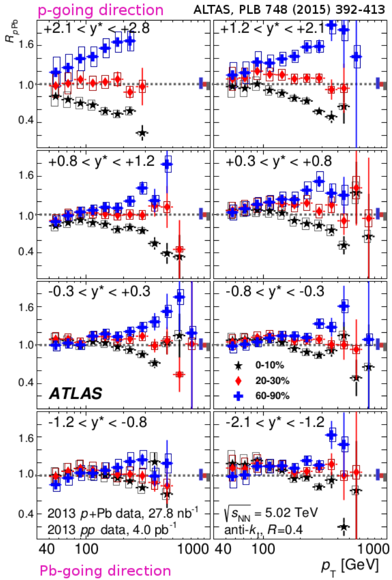
Event Activity biased jet measurements in p–Pb at LHC

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

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

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

- 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]

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

In case of no nuclear effects

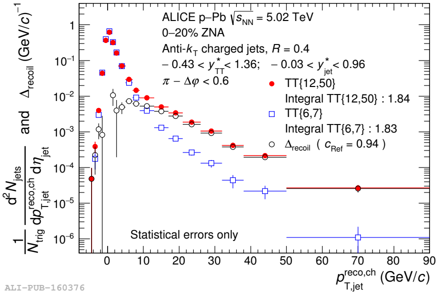
$$\frac{1}{N_{\rm trig}^{\rm AA}} \frac{{\rm d}^2 N_{\rm jet}^{\rm AA}}{{\rm d}p_{\rm T,jet}^{\rm ch}{\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT}} = \left(\frac{1}{\sigma^{\rm pp\to h+X}} \cdot \frac{{\rm d}^2\sigma^{\rm pp\to h+jet+X}}{{\rm d}p_{\rm T,jet}^{\rm ch}{\rm d}\eta_{\rm jet}}\right)\Bigg|_{p_{\rm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

- 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

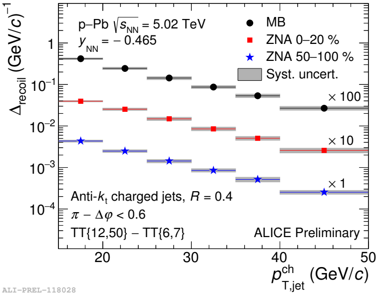
[1] D. de Florian, Phys.Rev. D79 (2009) 114014

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

Raw spectrum



Fully corrected

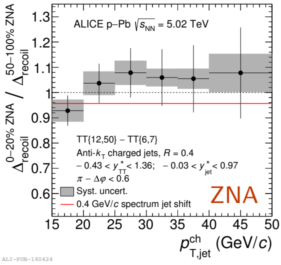


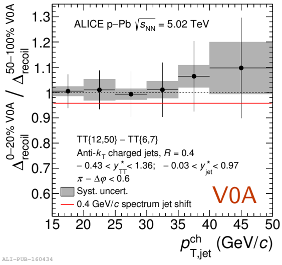
Event Activity selected by - ZNA zero degree neutron calorimeter $\eta \approx 10$
- V0A scintillator array $\eta \in (2.8, 5.1)$
both detectors are located in Pb-going direction

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

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

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



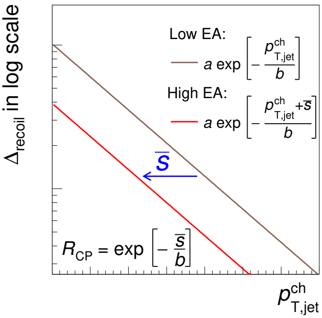


Ratio

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

compatible with unity

ALICE, PLB 783 (2018) 95–113.



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

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

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

  $\bar{s} = (8 \pm 2_{\rm stat})$ 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)

Jet shapes in pp and central Pb–Pb collisions

ALICE, *Medium modification of the shape of small-radius jets in central Pb–Pb collisions at* $\sqrt{s_{\rm NN}} = 2.76$ *TeV* JHEP 10 (2018) 139

- Angularity

$$g = \sum_{i \in \rm jet} \frac{p_{\rm T,\it i}}{p_{\rm T,jet}} |\Delta R_{{\rm jet},i}|$$

$\Delta R_{{\rm jet},i}$ = angle between jet constituent and jet axis; $p_{\rm T,\it i}$ = jet constituent transverse momentum

- Momentum dispersion

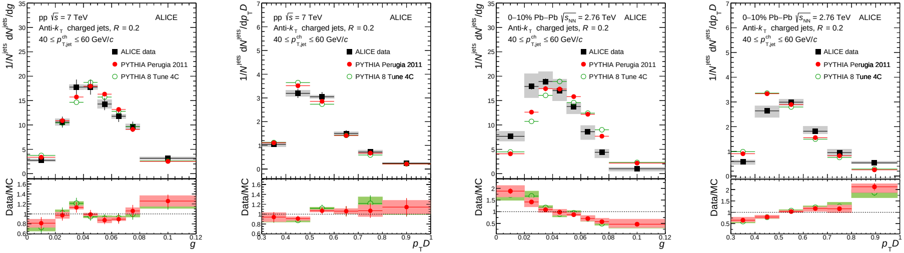
$$p_{\rm T} D = \frac{\sqrt{\sum_{i \in \rm jet} p^2_{\rm T,\it i}}}{\sum_{i \in \rm jet} p_{\rm T,\it i}}$$

$p_{\rm T,\it i}$ denotes jet constituent transverse momentum

Underlying event corrected for by area-derivatives method [1]

[1] G.Soyez et al., Phys.Rev.Lett. 110 (2013) 162001

Jet shapes in pp and Pb–Pb (0–10% centrality)



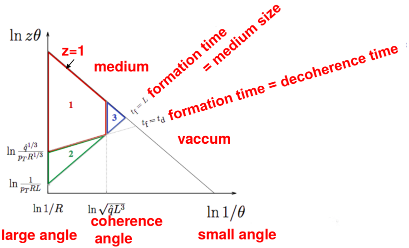
pp collisions at $\sqrt{s}$=7 TeV

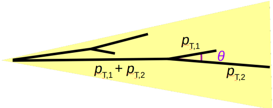
Pb–Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

- Anti-k_T track-based jets with $R = 0.2$ and $40 < p_{T,jet}^{ch} < 60$ GeV/c
- Fully corrected on detector effects and underlying event
- pp: jet shapes well reproduced by PYTHIA
- Pb–Pb: decrease in mean angularity $\Rightarrow$ jets are more collimated
  increase in mean $p_T D$ $\Rightarrow$ jets are more hard
  qualitatively consistent with more quark-like fragmentation

ALICE, JHEP 10 (2018) 139

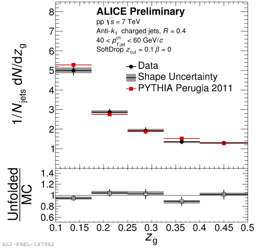
Jet substructure from iterative declustering

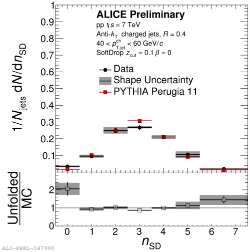




Lund plot maps jet shower splittings in plane opening angle θ and p_T fraction

$$z = \frac{\min(p_{T,1},\ p_{T,2})}{p_{T,1} + p_{T,2}}$$



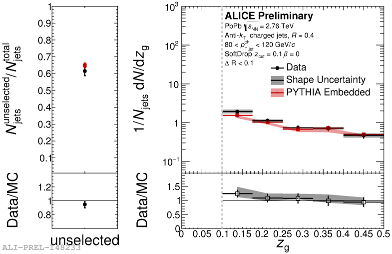


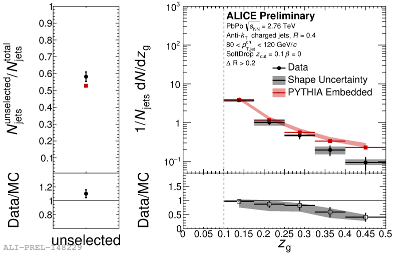
pp collisions at $\sqrt{s}$=7 TeV

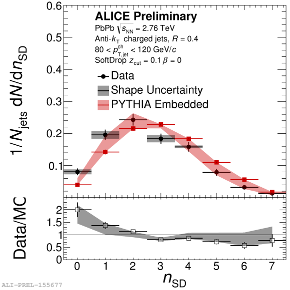
- Grooming aims to select hard splittings within jet shower Soft Drop: $z > z_{cut}$
- z_g filled with z of the first splitting where $z > 0.1$
- n_{SD} the number of splittings that fulfill $z > 0.1$ when we follow the hardest branch
- pp reproduced by PYTHIA

Iterative declustering in Pb–Pb (0–10% centrality)

splittings with $\theta < 0.1$ | splittings with $\theta > 0.2$







- Raw spectra compared to PYTHIA smeared by detector effects and embedded to raw Pb–Pb events
- Anti-k_T jets $R = 0.4$ and $80 < p^{ch}_{T,jet} < 120$ GeV/c
- Normalization includes jets with $n_{SD} = 0$
- Small enhancement of small angle asymmetric splittings + suppression of large angle symmetric splittings: qualitatively expected from color coherence
- Shift towards lower number of splittings passing Soft Drop w.r.t. PYTHIA:
  harder, more quark-like fragmentation (cf. g and $p_T D$)

Summary

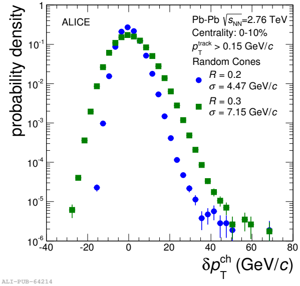
- Hadron-jet technique allows to measure jet quenching in heavy-ion collisions and small systems
  - does not require the assumption that Event Activity is correlated with collision geometry
  - provides systematically well-controlled comparison of jet quenching as a function of Event Activity
  - Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV: suppression of recoil jet yield, but no evidence of intra-jet broadening of energy profile out to $R = 0.5$
  - p–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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 GeV/c
- Jets in Pb–Pb are more hard and collimated w.r.t. pp
- Suppression of large angle symmetric splittings

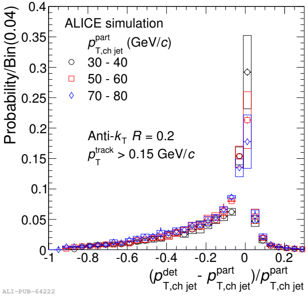
Backup slides

Corrections of raw jet spectra

- Background fluctuations:
  embedding MC jets or random cones [1]
  $\delta p_{\rm t} = \sum_i p_{t,i} - A \cdot \rho$
- Detector response:
  based on GEANT + PYTHIA
- Response matrix:
  two effects are assumed to factorize
  $$R_{\rm full}\left(p_{\rm T,jet}^{\rm rec}, p_{\rm T,jet}^{\rm part}\right) = \delta p_{\rm t}\left(p_{\rm T,jet}^{\rm rec}, p_{\rm T,jet}^{\rm det}\right) \otimes R_{\rm instr}\left(p_{\rm T,jet}^{\rm det}, p_{\rm T,jet}^{\rm part}\right)$$
- $R_{\rm full}^{-1}$ 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





QGP signatures in small systems

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

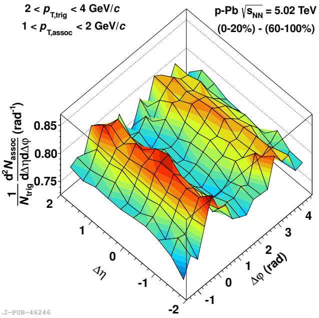
    BDMPS, Nucl. Phys. B483 (1997) 291
  - ◇ $\hat{q}|_{\mathrm{pPb}} = \frac{1}{7}\hat{q}|_{\mathrm{PbPb}}$

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

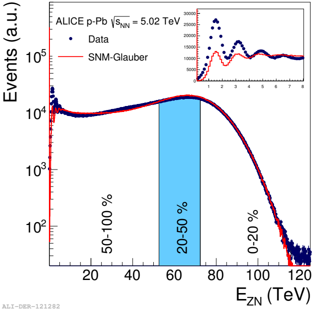
    W.T.Deng, X.N.Wang, Phys.Rev. C 81, 024902 (2010)
  - ◇ $\Delta E = (8 \pm 2_{\mathrm{stat}})\ \mathrm{GeV}/c$ medium-induced E transport to $R > 0.5$ in Pb–Pb

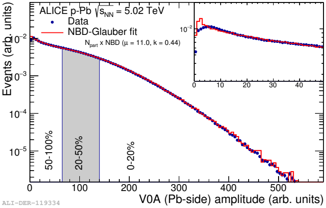
    ALICE, JHEP 09 (2015) 170



ALICE, Phys.Lett. B 719 (2013) 29–41

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



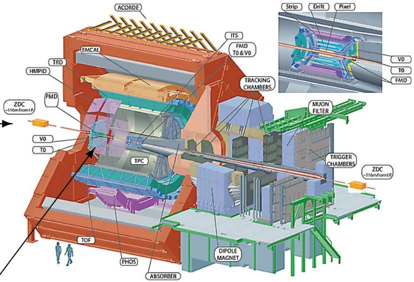


Pb-going direction

ZNA

V0A

$\eta \in (2.8, 5.1)$



Charged track reconstruction

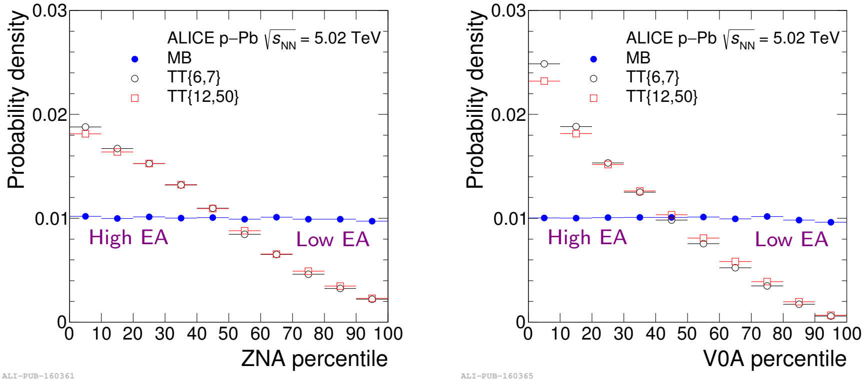
$|\eta| < 0.9$, $p_T > 150$ MeV/c

ITS 6-layered silicon tracker

TPC time projection chamber

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

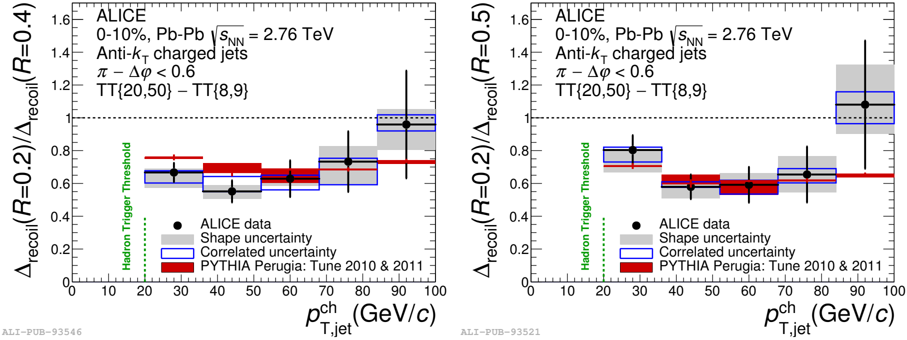
Event Activity assignment in p–Pb



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

ALICE, PLB 783 (2018) 95–113.

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