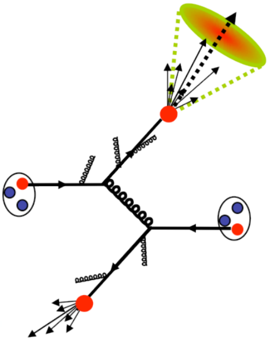
Jet results in the ALICE experiment

Redmer Alexander Bertens - University of Tennessee, Knoxville
on behalf of the ALICE Collaboration

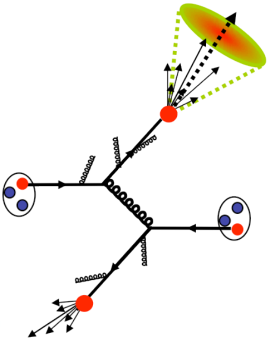
Jets in ALICE



Hard scattering ($Q^2 > 1$ $(\text{GeV}/c)^2$)

- **Radiation** of quarks and gluons
- **Hadronization** into colorless spray of particles: **jets**

Jets in ALICE



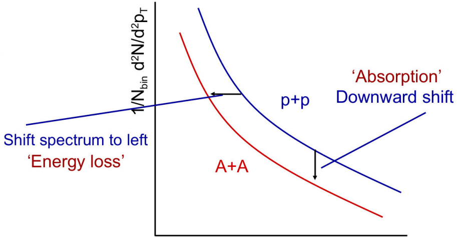
Hard scattering ($Q^2 > 1$ (GeV/c)^2)

- **Radiation** of quarks and gluons
- **Hadronization** into colorless spray of particles: **jets**

The ALICE physics program is aimed primarily on studying the **strong** interaction via **heavy-ion** collisions

Pb–Pb collisions: scattered partons **interact** with **medium**
→ **jet quenching**

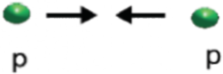
Large fluctuating **background**
→ **analyses are challenging**



Jets in various systems

proton proton (pp)

- test of **pQCD** (constrain models)
- reference for **p–Pb Pb–Pb**



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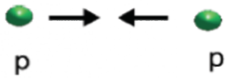
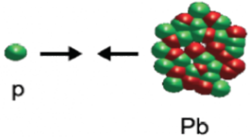


proton lead (p–Pb)

- **cold** nuclear matter effects (nPDFs, CGC)
- **jet quenching** in small systems?



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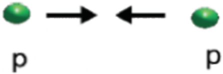

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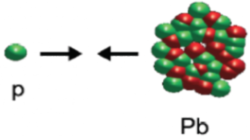
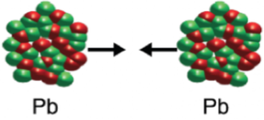


lead lead (Pb–Pb)

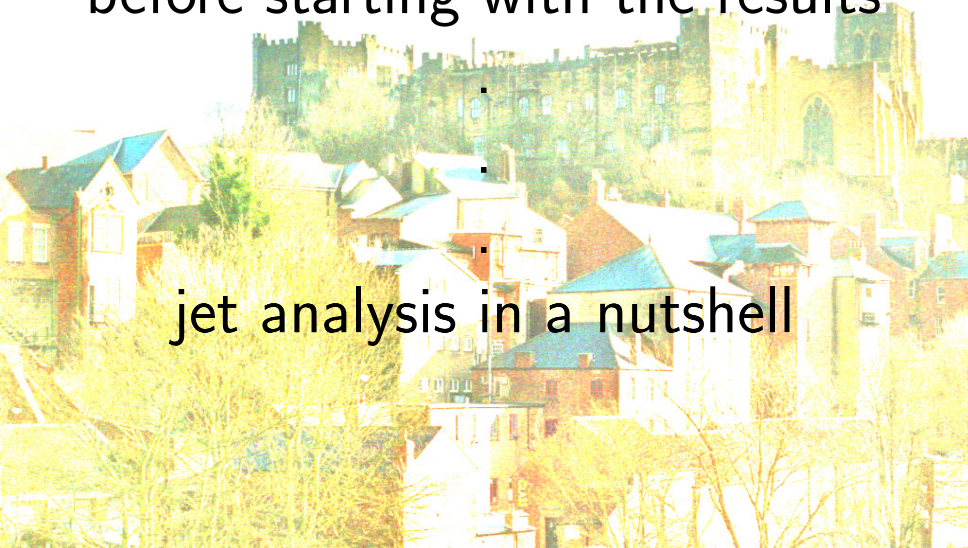
- medium-induced **parton energy loss** (scattering, gluon radiation)
- jets as **perturbative** probe of **QGP**

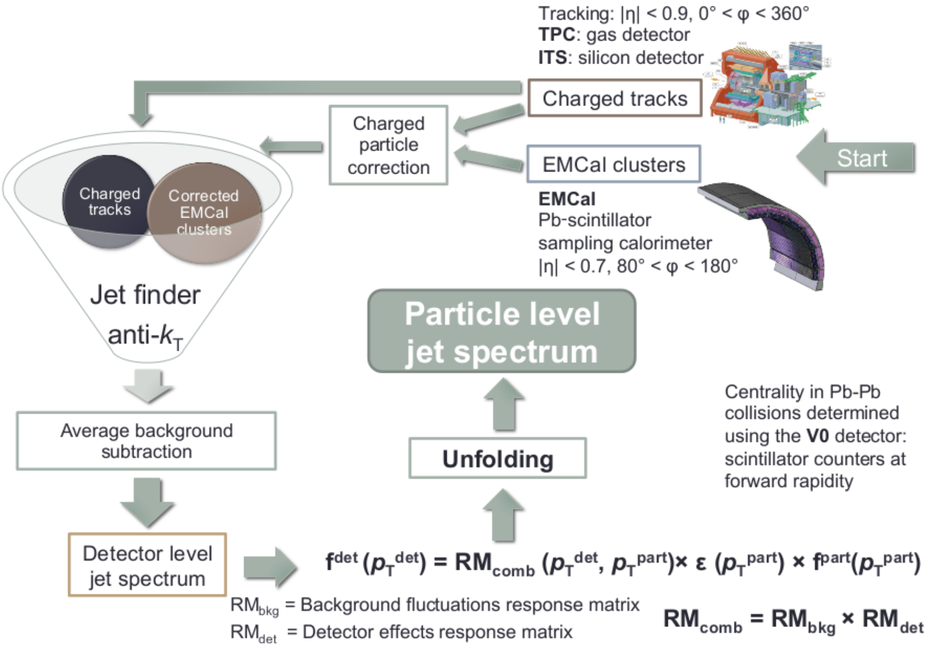


before starting with the results

⋮

jet analysis in a nutshell



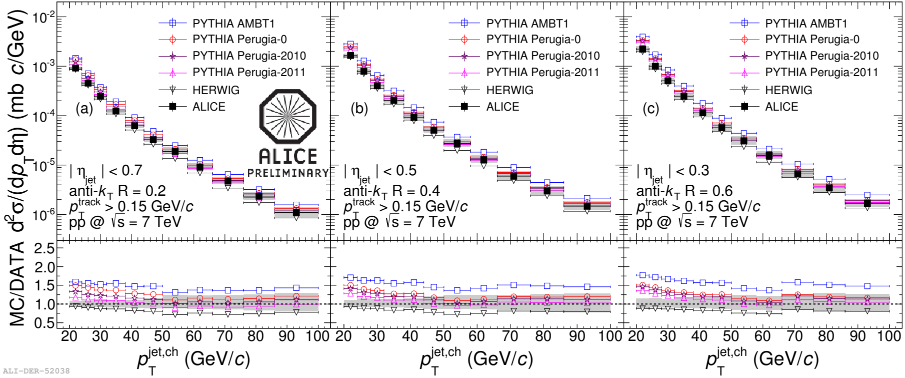


Tracking: |η| < 0.9, 0° < φ < 360°
TPC: gas detector
ITS: silicon detector
Charged tracks
EMCal clusters
Start
EMCal
Pb-scintillator
sampling calorimeter
|η| < 0.7, 80° < φ < 180°
Charged particle correction
Charged tracks
Corrected EMCal clusters
Jet finder
anti-k_T
Average background subtraction
Detector level jet spectrum
Particle level jet spectrum
Unfolding
Centrality in Pb-Pb collisions determined using the V0 detector: scintillator counters at forward rapidity
$f^{det}(p_T^{det}) = RM_{comb}(p_T^{det}, p_T^{part}) \times \varepsilon(p_T^{part}) \times f^{part}(p_T^{part})$
RM_{bkg} = Background fluctuations response matrix
RM_{det} = Detector effects response matrix
$RM_{comb} = RM_{bkg} \times RM_{det}$

proton proton collisions

jet spectra and shapes

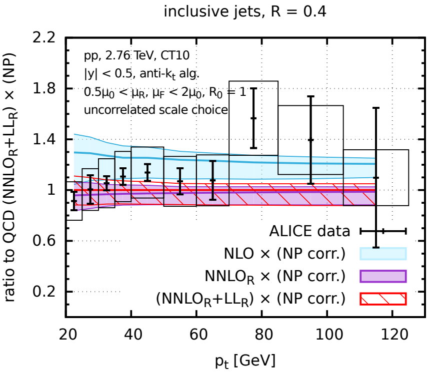
Charged jet cross sections at $\sqrt{s} = 7$ TeV



Good agreement with **PYTHIA** and **HERWIG** for different cone **radii**

Full jets at $\sqrt{s} = 2.76$ and (N)NLO QCD

Full jet cross section at measured up to **low** $p_{T,\text{ full}}^{\text{jet}}$, ratio to (N)NLO



Phys. Lett. B 722 (2013) 262-272

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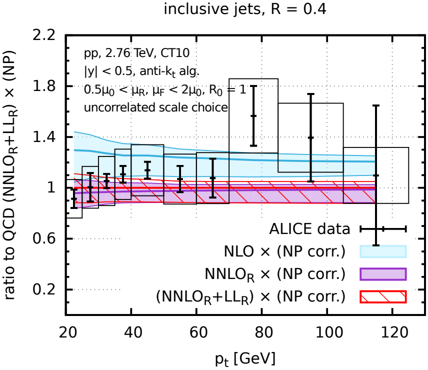

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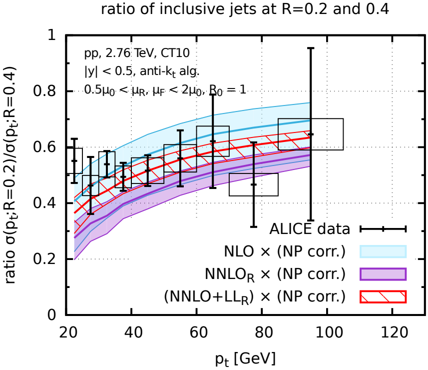

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Important to constrain **NNLO** calculations especially at **low** jet energies

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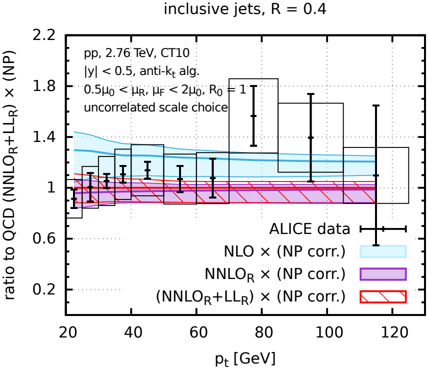

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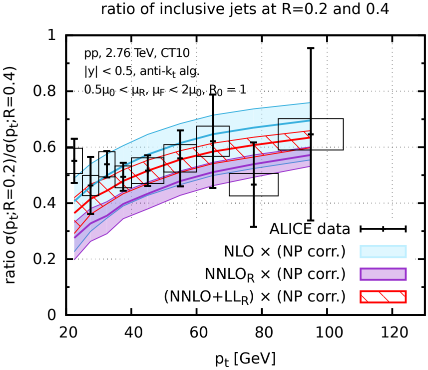

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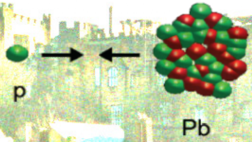
Important to constrain **NNLO** calculations especially at **low** jet energies

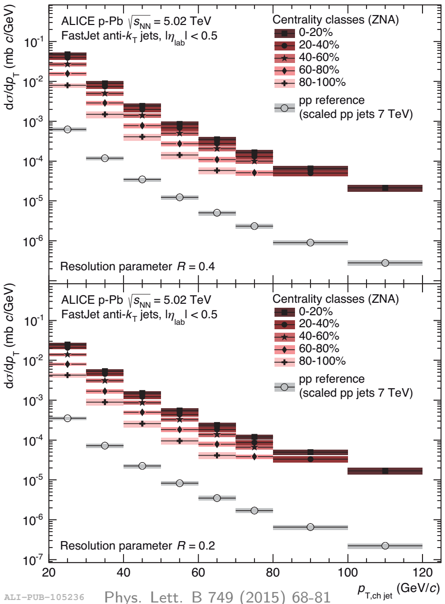
agreement between **theory** and **experiment** validates pQCD and justifies using pp spectra as **reference** for p–Pb and Pb–Pb

proton lead



spectra and centrality
nuclear modification factor
di-jet imbalance

p–Pb charged jet spectra at $\sqrt{s_{NN}} = 5.02$ TeV



Phys. Lett. B 749 (2015) 68-81

p–Pb spectra measured in various **centrality** classes

- clear **scaling** with centrality

p–Pb charged jet spectra at $\sqrt{s_{NN}} = 5.02$ TeV

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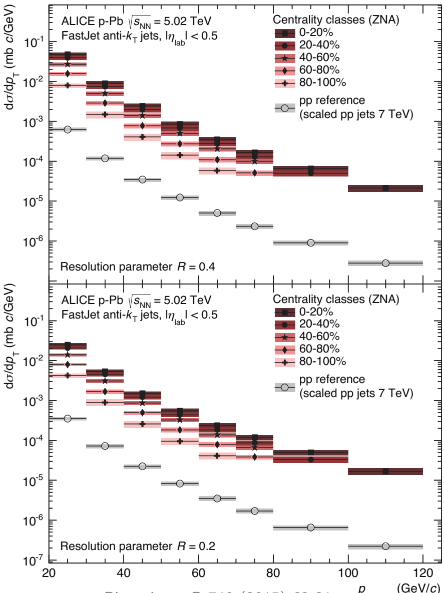
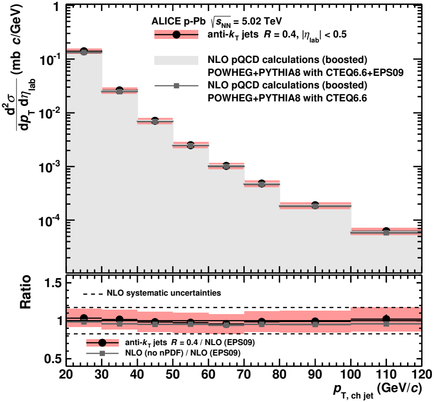


ALI-PUB-105236 Phys. Lett. B 749 (2015) 68-81

p–Pb spectra measured in various **centrality** classes

- clear **scaling** with centrality
- spectra well-described by **NLO pQCD**



Jet quenching in small systems?

Nuclear modification factor

$$Q_{pPb}(p_T, \text{cent}) = \frac{dN^{pPb}_{cent}/dp_T}{\langle N^{coll}_{cent}\rangle \cdot dN^{pp}/dp_T}$$

$$\approx \frac{\text{medium}}{\text{no medium}}$$

Possible scenarios

- $Q_{pPb} > 1$ (enhancement)
- $Q_{pPb} = 1$ (no medium effect)
- $Q_{pPb} < 1$ (suppression)

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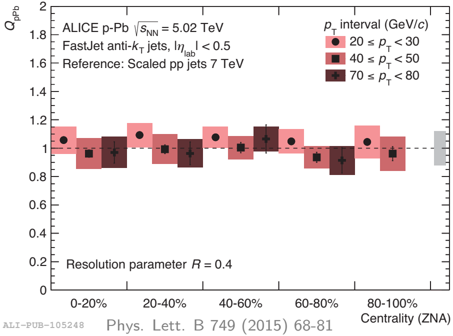

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Q_{pPb} consistent **with unity** for all centrality classes

- **no final state** effect on jet spectra

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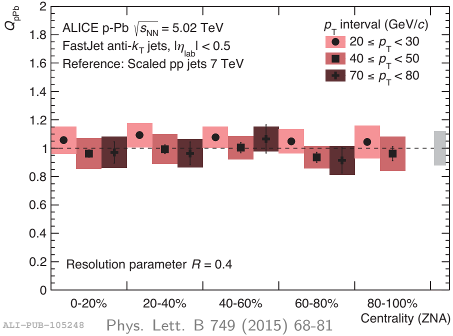

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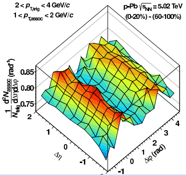
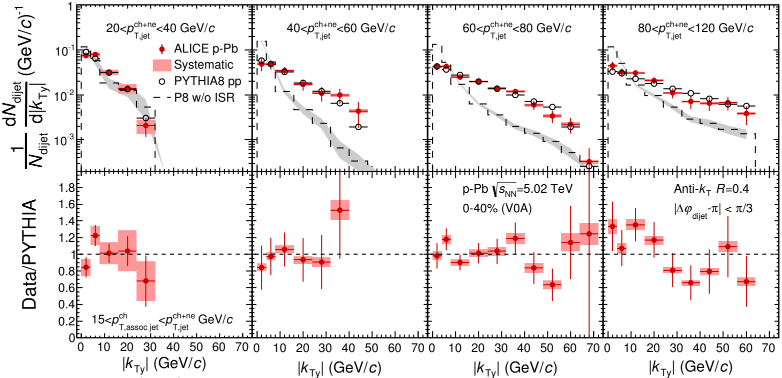
Q_{pPb} consistent **with unity** for all centrality classes

- **no final state** effect on jet spectra
- in **contrast** to **collective behavior** at **low** p_T



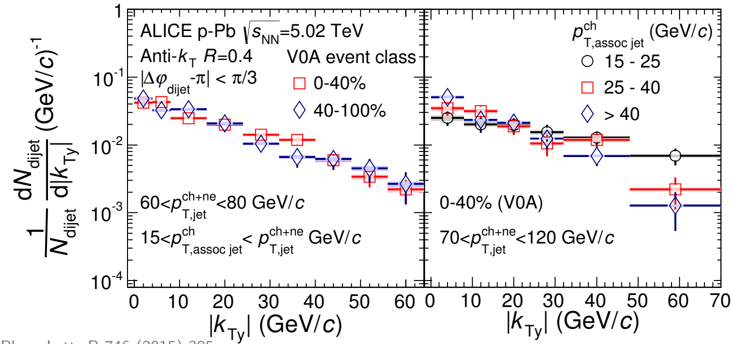
Di-jet imbalance **in Pb–Pb** strong evidence of parton energy loss



Phys. Lett. B 746 (2015) 385

$$k_T = p_{T,\ full}^{jet} \sin(\Delta\varphi_{dijet})$$

Imbalance in p–Pb is **consistent** with PYTHIA predictions



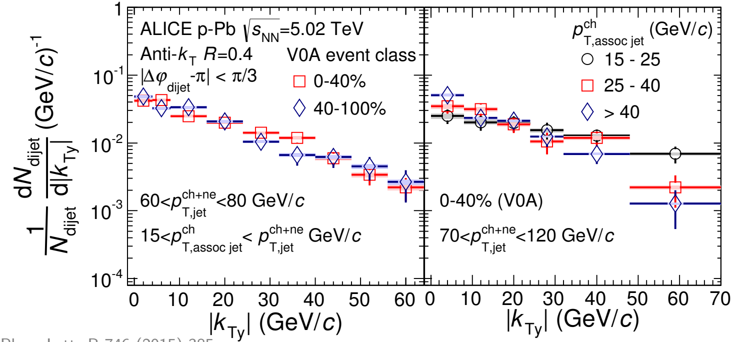
Phys. Lett. B 746 (2015) 385

$$k_T = p^{jet}_{T,\ full} \sin(\Delta\varphi_{dijet})$$

no centrality dependence of di-jet k_T

consistent with $\mathbf{Q}_{pPb}$ observation of **no modification** of jet spectra

Centrality dependence of di-jet k_T in p–Pb



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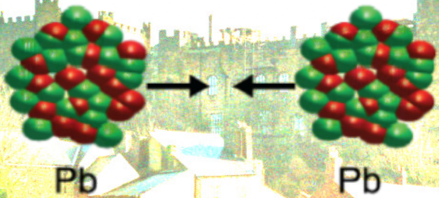
$$k_T = p_{T,\ full}^{jet} \sin(\Delta\varphi_{dijet})$$

no centrality dependence of di-jet k_T

consistent with $\mathbf{Q}_{pPb}$ observation of **no modification** of jet spectra

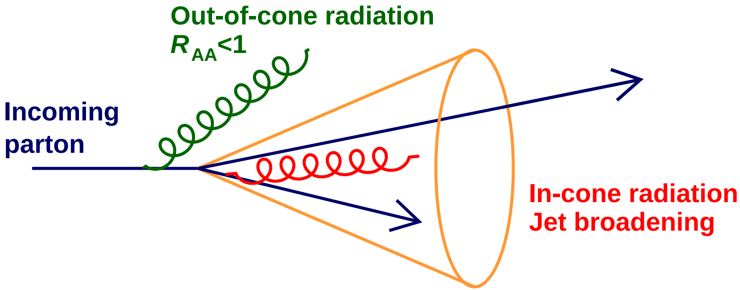
no evidence of **jet quenching** in p–Pb collisions

lead lead



jet quenching ($R_{\mathbf{AA}}$, $v_2^{\text{ch jet}}$)
jet shapes

Jets in Pb–Pb collisions are used to study the QGP via medium-induced energy loss



Two **qualitative** scenarios

1) **Out-of-cone** radiation: $R_{\mathrm{AA}} < 1$, modification of jet spectra

2) **In-cone** radiation: $R_{\mathrm{AA}} = 1$, changes in jet shapes

Out-of-cone radiation: R_{AA} of jets

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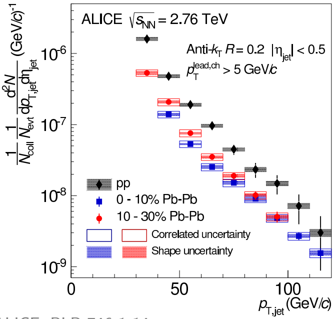
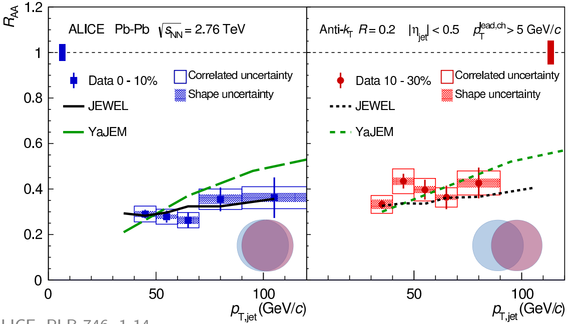


ALICE, PLB 746 1-14



ALICE, PLB 746, 1-14

$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle \cdot d^2\sigma_{pp}/dp_T d\eta} \approx \frac{\text{QCD in medium}}{\text{QCD in vacuum}}$$

- **Strong** suppression in central and semi-central colisions
- Resonable model agreement (JEWEL[1], YaJEM[2])

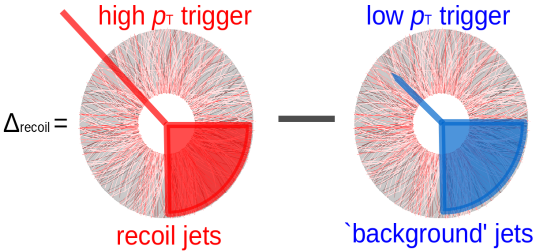
Indication of **out-of-cone** radiation

[1] K.C.Zapp *et al.* JHEP 1303 080

[2] T.Renk, PRC 78 034908

ALICE

Semi-inclusive hadron-jet distributions



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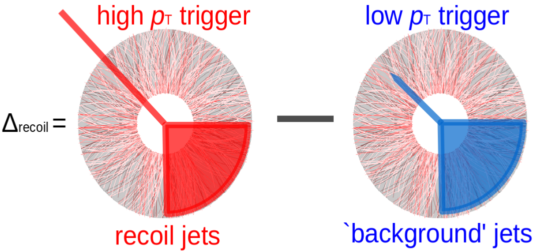

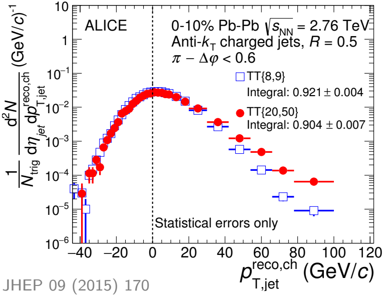

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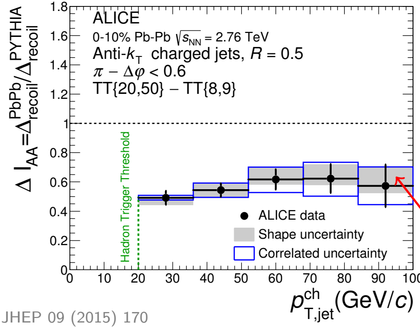
$$\Delta_{recoil} = \frac{1}{N_{trig}^{AA}} \frac{d^2 N_{jet}^{AA}}{d p_{T,jet}^{ch}\, d\eta_{jet}} \Bigg|_{p_{T,trig} \in TT_{Sig}} - \underbrace{c_{Ref}}_{\approx 1} \cdot \frac{1}{N_{trig}^{AA}} \frac{d^2 N_{jet}^{AA}}{d p_{T,jet}^{ch}\, d\eta_{jet}} \Bigg|_{p_{T,trig} \in TT_{Ref}}$$

difference between semi-inclusive **recoil jet** yields in two intervals of **hadron trigger** p_T - powerful **background jet** subtraction

$$\Delta_{\mathrm{recoil}} = \frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{d^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{d p_{\mathrm{T,jet}}^{\mathrm{ch}} d\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}_{\mathrm{Sig}}} - \underbrace{c_{\mathrm{Ref}}}_{\approx 1} \cdot \frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{d^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{d p_{\mathrm{T,jet}}^{\mathrm{ch}} d\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}_{\mathrm{Ref}}}$$



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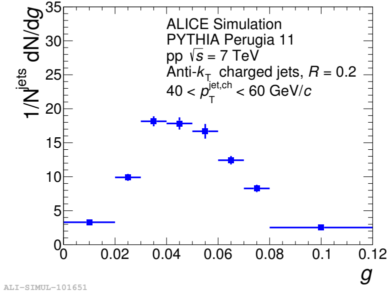
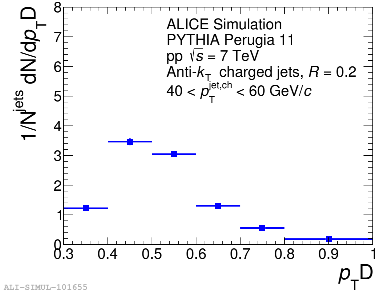
ΔI_{AA}: **ratio** of Δ_{recoil} measured in **Pb–Pb** collisions to Δ_{recoil} measured in **PYTHIA** events

- measurement to **very low** p_{T}, where energy loss is expected to be **large** (relative increase with decreasing p_{T})

$\Delta I_{\mathrm{AA}} < 1$ indicates **jet quenching**





Radial moment g

$\longrightarrow$ 'jet **width**'

Dispersion $p_{\mathrm{T}}\mathrm{D}$

$\longrightarrow$ 'constituent **dispersion**'

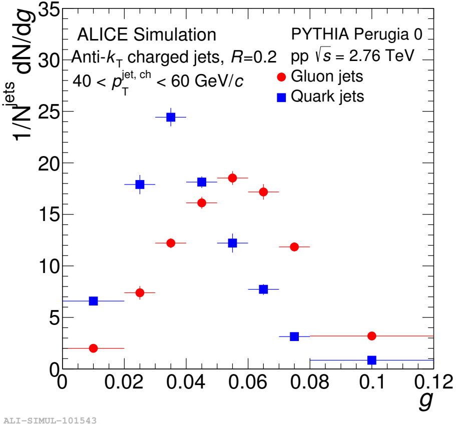
$$g = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T}\,i}}{p_{\mathrm{T,\,ch}}^{\mathrm{jet}}} |r_i|$$

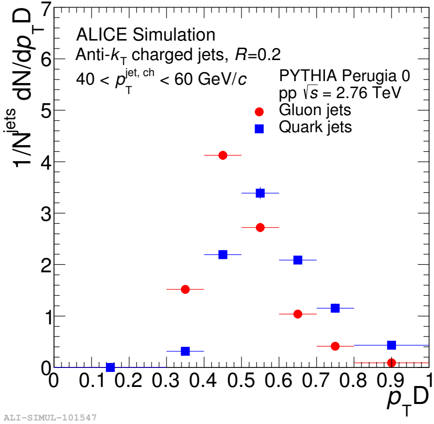
$$p_{\mathrm{T}}\mathrm{D} = \frac{\sqrt{\sum_i p_{\mathrm{T}\,,i}^2}}{\sum_i p_{\mathrm{T}\,,i}}$$

fully corrected (particle level) probes of jet **fragmentation**

Jet shapes illustrated - pp simulations

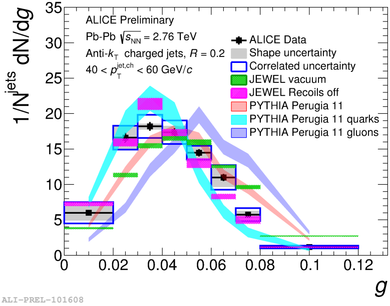
collimated jets have lower **g** ↔ **less** constituents gives **higher** p_TD

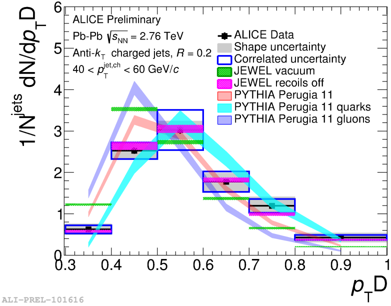




g and p_TD are sensitive to **differences in fragmentation** between **quark** and **gluon** jets

Jet shapes in Pb–Pb collisions





g in Pb–Pb

- **small** R (=0.2)
- Jets **more collimated**
- Soft particles emitted at **larger angles**

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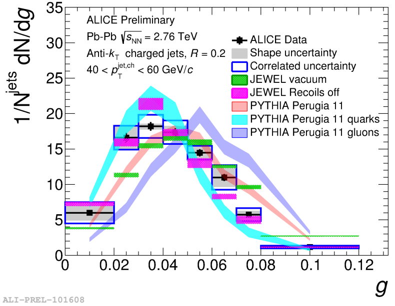

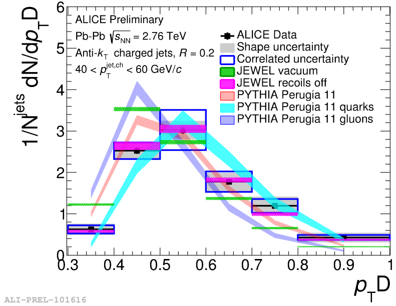

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p_TD in Pb–Pb

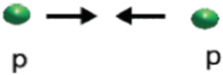
- **small** R (=0.2)
- p_TD is **larger** than PYTHIA
- indicative of larger p_T **dispersion in Pb–Pb**

qualitative agreement with JEWEL (QCD in medium)

Conclusion

proton proton (pp)

- test of **pQCD** (constrain models)
- reference for **p–Pb Pb–Pb**
- **consistent with pQCD**



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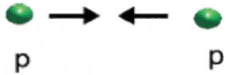
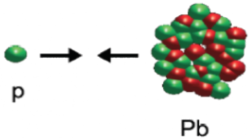


proton lead (p–Pb)

- **CNM** effects (nPDFs, CGC)
- **jet quenching** in small systems?
- **no jet quenching**



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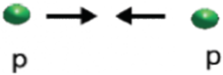
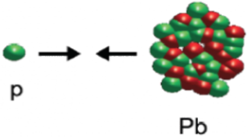
- reference for **p–Pb Pb–Pb**
- **consistent with pQCD**



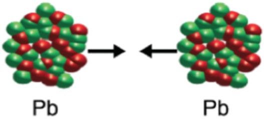
proton lead (p–Pb)

- **CNM** effects (nPDFs, CGC)
- **jet quenching** in small systems?
- **no jet quenching**

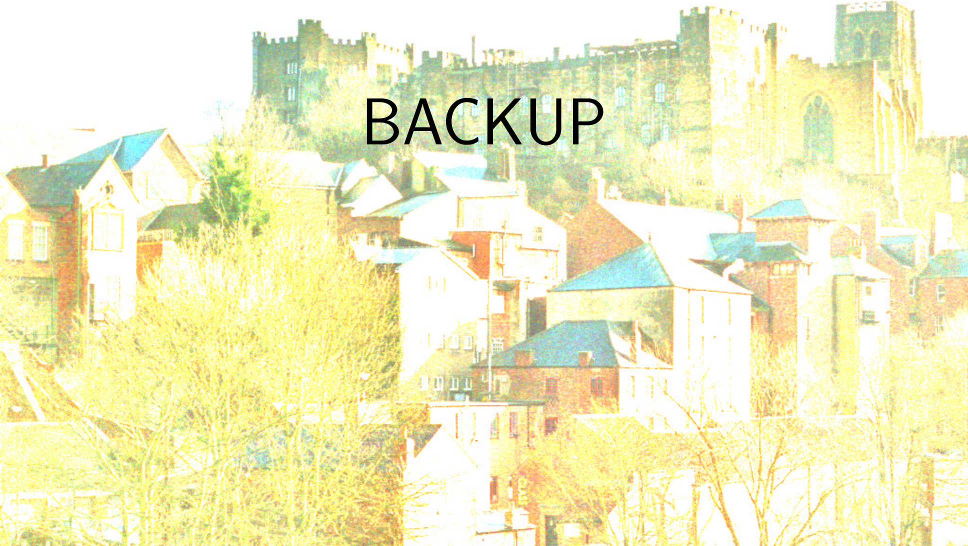


lead lead (Pb–Pb)

- medium-induced **parton energy loss** (scattering, gluon radiation)
- jets as **perturbative** QGP probe
- **significant changes in jet energy and fragmentation**



BACKUP



Energy loss and medium geometry - $v_2^{\text{ch jet}}$

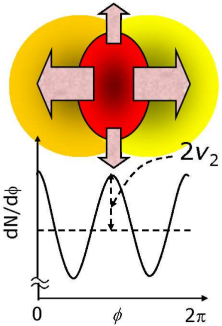
Different theoretical predictions on **path-length** (L) dependence of parton energy loss (ΔE)[3,4,5]

$$\underbrace{\Delta E \propto L}_{\text{collisional}} \leftrightarrow \underbrace{\Delta E \propto L^2}_{\text{radiative}} \leftrightarrow \underbrace{\Delta E \propto L^3}_{\text{AdS/CFT}}?$$

$v_2^{\text{ch jet}}$: direct connection between **in-medium** path-length and **jet suppression**

$v_2^{\text{ch jet}} \approx 0$?

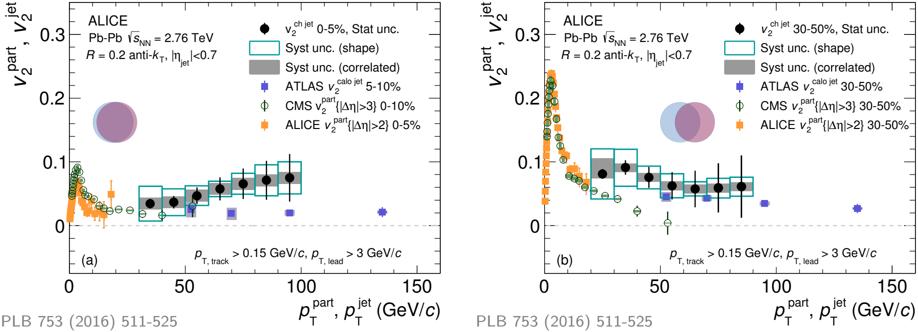
$v_2^{\text{ch jet}} > 0$?



Hydrodynamic flow is suppressed on an event-by-event basis

[3] R.Baier *et al.* NPB484 265-282 ($\propto L$)
[4] R.Baier *et al.* NPB483 291-320 ($\propto L^2$)
[5] C. Marquet, T. Renk, PLB685 270-276 ($\propto L^3$)

Different energy scales for v_2^{part}, $v_2^{\text{ch jet}}$ and $v_2^{\text{ch+emjet}}$, qualitative comparison only



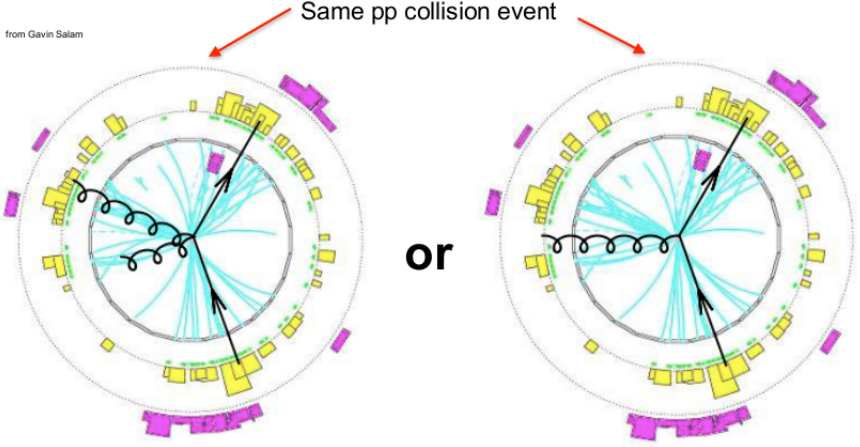
PLB 753 (2016) 511-525 PLB 753 (2016) 511-525

Non-zero $v_2^{(\dots)}$ indicative of dependence on (effective) **path-length**
what role do initial state **fluctuations** play?

Experimentally, jets are tricky

from Gavin Salam

Same pp collision event



Need to ***define*** jet in experiment ***and*** theory

For a rainy afternoon: **(anti)-k_T jet finding**:
define for all **protojets** (tracks)

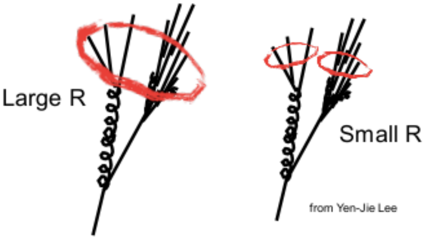
$$d_i = {p_\mathrm{T}}_{,i}^{2p}$$

$$d_{i,j} = \min\left({p_\mathrm{T}}_{,i}^{2p}, {p_\mathrm{T}}_{,j}^{2p}\right)\frac{\Delta^2_{i,j}}{R^2}$$

$$\Delta^2_{i,j} = (y_i - y_j)^2 + (\varphi_i - \varphi_j)^2$$

- smallest $d_x = d_{i,j} \longrightarrow$ merge tracks
- smallest $d_x = d_i \longrightarrow d_i$ is a jet

... go back to the beginning



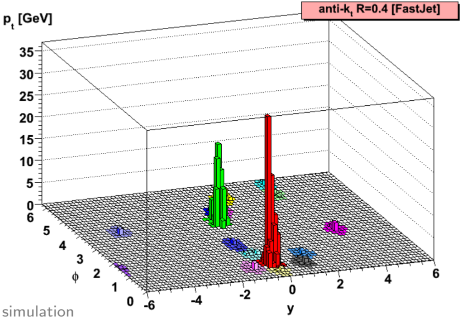
R: **resolution parameter** (maximum angular separation of tracks in η, φ)

Fast, infrared / collinear safe
... **but all tracks get clustered**

Jet reconstruction in Pb–Pb collisions

' ... **all** tracks get clustered '

- Generally **not** so problematic in pp collisions ...
- ... but in Pb–Pb this means including **overwhelming** energy from **uncorrelated emissions**



simulation

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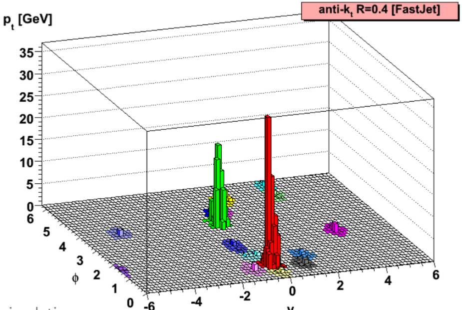
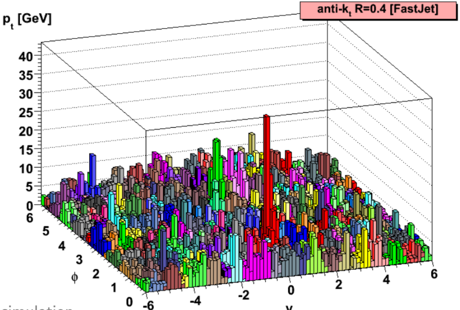


simulation

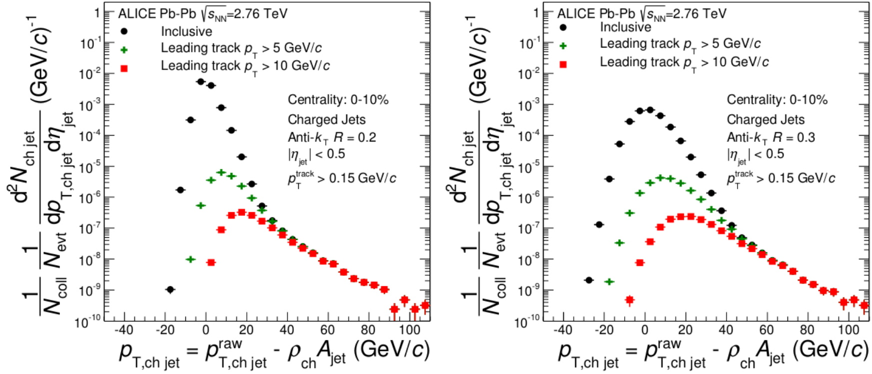


simulation

Challenge: inclusive measurement of jets while **removing** UE

- 'Background' (*Underlying Event*) **large** [1] compared to jet energy
- UE is **not unifotext** (e.g. flow [2]) and has large **statistical** fluctuations [3])

To get a feeling



Leading hadron cut removes **fake** jets

At low p_T contribution from fake clusters is **overwhelming**

[1] UE energy $\langle \rho_{ch} \rangle$

Event-by-event estimate of **energy density** of UE

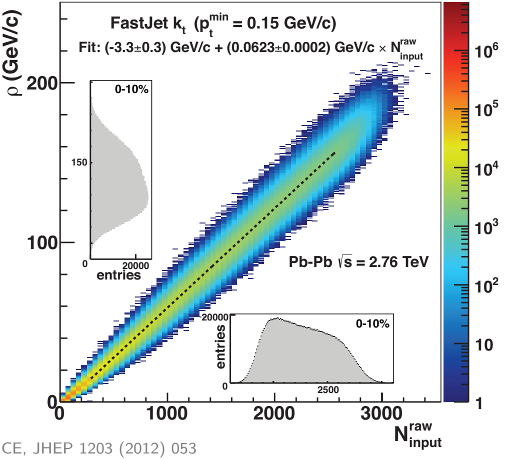
$$\langle \rho_{ch} \rangle = \text{median}\left(\frac{p_{T,\,ch}^{jet}}{A^{jet}}\right)$$

Linear dependence of $\langle \rho_{ch} \rangle$ on multiplicity

Quick example: 0–10% centrality

- $\langle \rho_{ch} \rangle \approx 140\ \mathrm{GeV}/c\ A^{-1}$
- $A \propto \pi R^2$

$\propto$ **70 GeV/c charged background for** $R = 0.4$



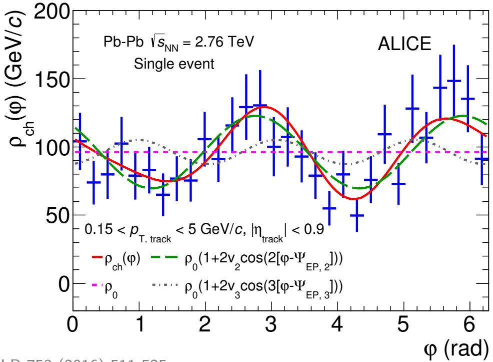
ALICE, JHEP 1203 (2012) 053

[2] Jet-by-jet UE subtraction

Adjust **jet-by-jet** for **UE** energy

$$p_{T,\,ch}^{jet} = p_{T,\,ch}^{raw} - \rho_{ch\ local} A$$

using jet **area A** and UE energy **density** $\rho_{ch\ local}$



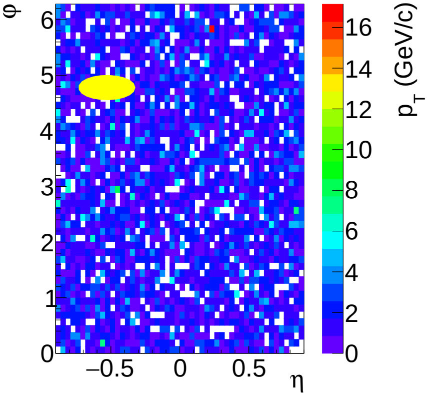
PLB 753 (2016) 511-525

UE **flow** (v_2 and v_3 and ...) can be **accounted for** in $\rho_{ch\ local}$ **event-by-event**

$$\rho_{ch}(\varphi) = \rho_0 \left(1 + 2\{v_2 \cos[2(\varphi - \Psi^{V0}_{EP,\,2})] + v_3 \cos[3(\varphi - \Psi^{V0}_{EP,\,3})] + \dots\}\right)$$

UE fluctuations in φ, η around $\langle \rho_{ch} \rangle$

- A jet of $p_T = x$ sitting on an upward fluctuation of magnitude a will be reconstructed at $p_T = x + a$ ...
- ... likewise a jet of $p_T = x$ sitting on a downward fluctuation of magnitude a will be reconstructed at $p_T = x - a$



Use e.g. **random cone** procedure to determine magnitude of fluctuations

$$\delta p_T = \underbrace{\sum p_T^{track}}_{\text{cone } p_T} - \underbrace{\rho \pi R^2}_{\text{expectation}}$$

δp_T distribution used to **unfold** jet spectra:

$$f_{meas}(x) = \int R(x|y) f_{true}(y) dy$$

[3] Fluctuations of UE

UE fluctuations in φ, η around $\langle \rho_{ch} \rangle$

- A jet of $p_T = x$ sitting on an upward fluctuation of magnitude a will be reconstructed at $p_T = x + a$ ...
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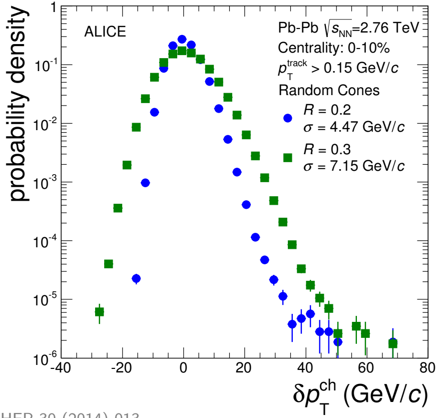

JHEP 30 (2014) 013

Use e.g. **random cone** procedure to determine magnitude of fluctuations

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$$f_{meas}(x) = \int R(x|y) f_{true}(y) dy$$

... and no jet talk without unfolding ...

$$f_{\text{meas}}(x) = \int R(x|y) f_{\text{true}}(y) dy$$

- $f_{\text{true}}(y)$: 'true' jet p_{T}
- $f_{\text{meas}}(x)$: 'measured' jet p_{T}
- $R(x|y)$: response function

... and no jet talk without unfolding ...

$$f_{\text{meas}}(x) = \int R(x|y) f_{\text{true}}(y) dy$$

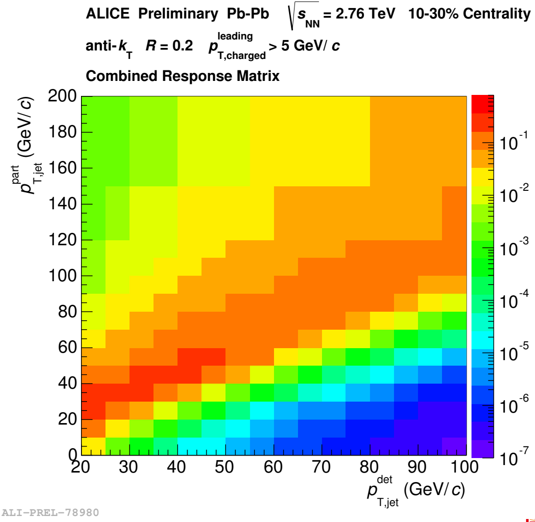
- $f_{\text{true}}(y)$: 'true' jet p_T
- $f_{\text{meas}}(x)$: 'measured' jet p_T
- $R(x|y)$: response function

A particle level jet at 200 GeV ....

- ... can end up between 20 and 100 GeV in the detector ... !

Unfolding spectra introduces a **systematic uncertainty**

- Unavoidable for meaningful comparison to **theory** and between **experiments**

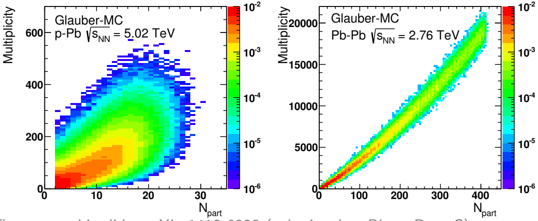


Q_{pPb} and centrality in p–Pb collisions

$\langle N_{coll} \rangle$ not easy to determine in p–Pb collisions

$$Q_{pPb}(p_T, \text{cent}) = \frac{dN^{pPb}_{\text{cent}}/dp_T}{\langle N^{\text{coll}}_{\text{cent}} \rangle \cdot dN^{pp}/dp_T}$$

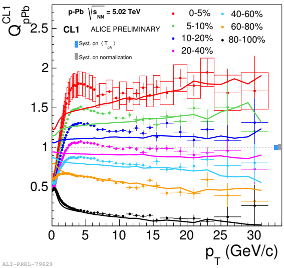
'Pb–Pb approach'(a) is biased



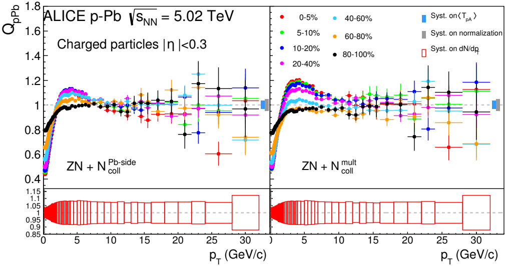
figures on this slide: arXiv 1412.6828 (submitted to Phys. Rev. C)

Hybrid centrality method (b):

- Estimate centrality from Zero Degree Calorimeter
- $\langle N^{\text{coll}}_{\text{cent}} \rangle$ scales with charged particle multiplicity in mid-rapidity or Pb-going side



a



b