Jet Physics with ALICE at the LHC

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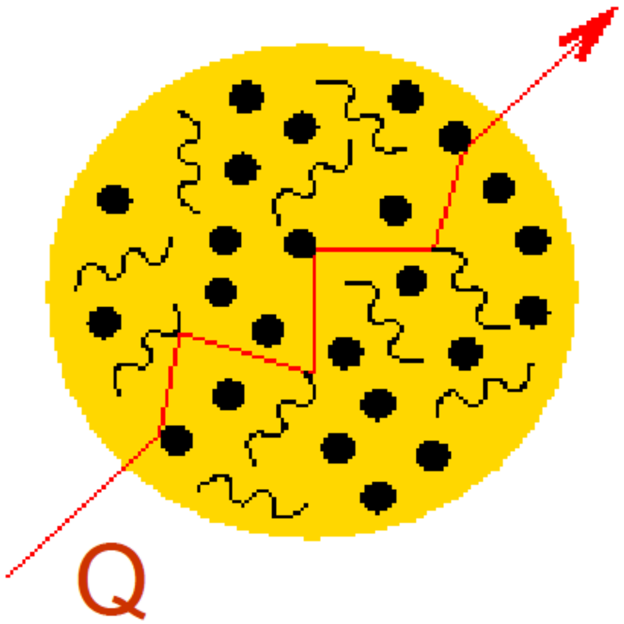
for the ALICE Collaboration

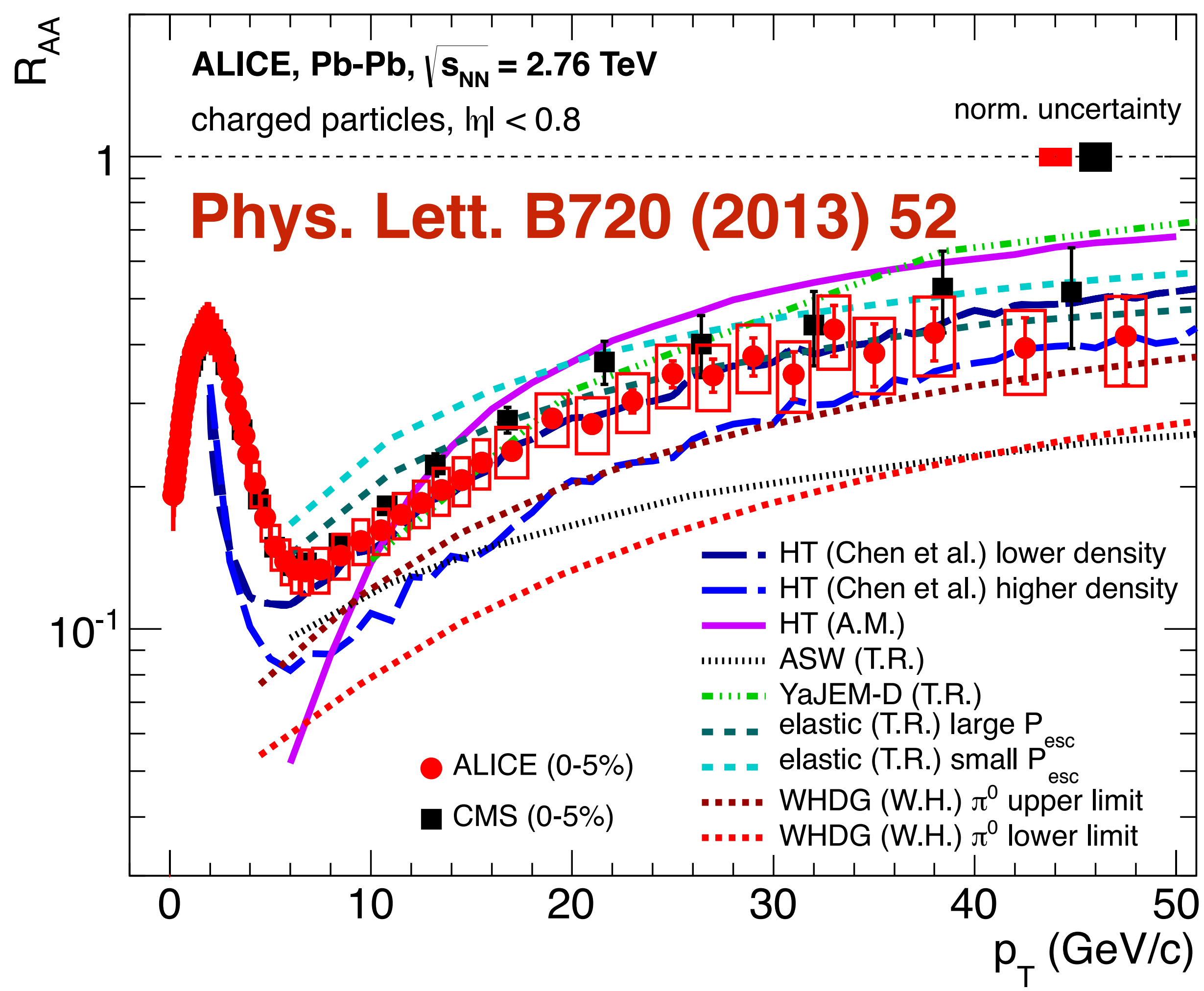
The 5th ATHIC, August 5–8, 2014, Osaka, Japan

Introduction

Jet Quenching

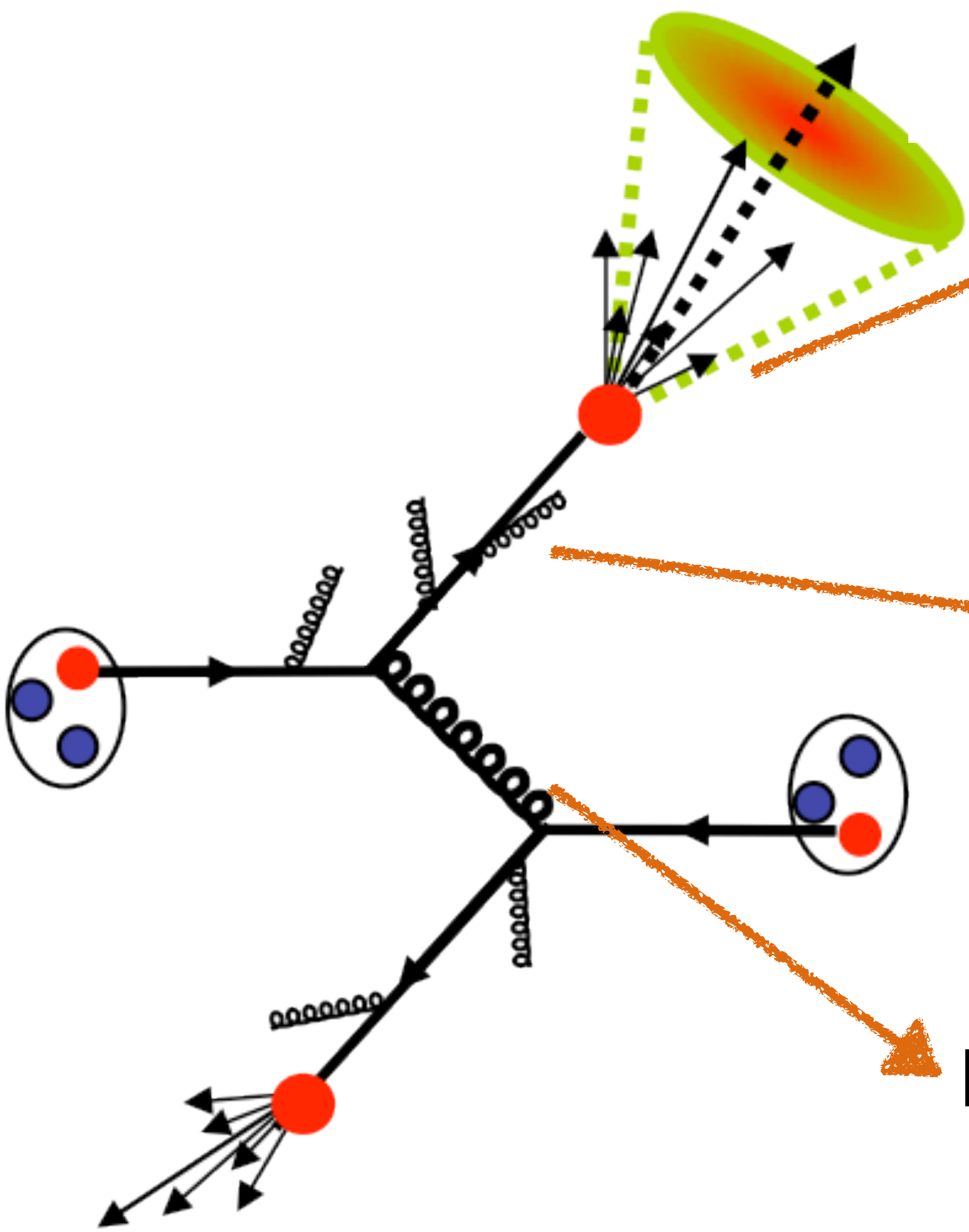


- Jet quenching: parton in-medium energy loss
  ➡ observed charged hadron suppression in heavy-ion collisions



- Time to quantify the jet quenching mechanisms via the reconstructed jets
  ✓ avoiding surface bias
  ✓ better connection to theory
  ✓ assessing jet quenching at partonic level

Jets in Proton–Proton Collisions



Hadronization into a spray of colorless particles — **Jet**

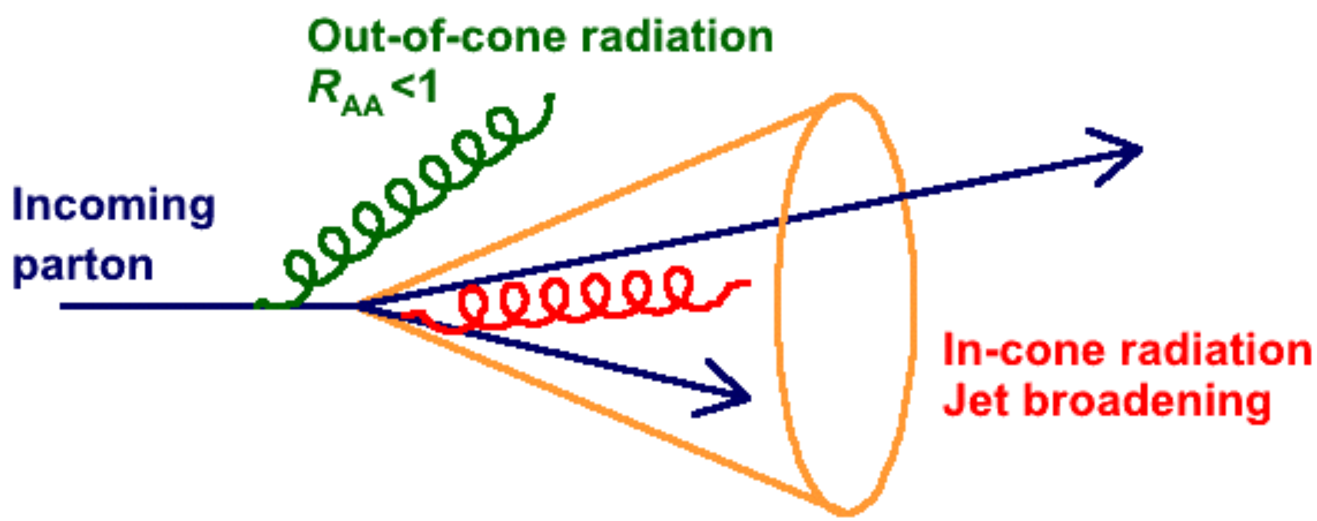
Radiation of (soft) gluons and quarks

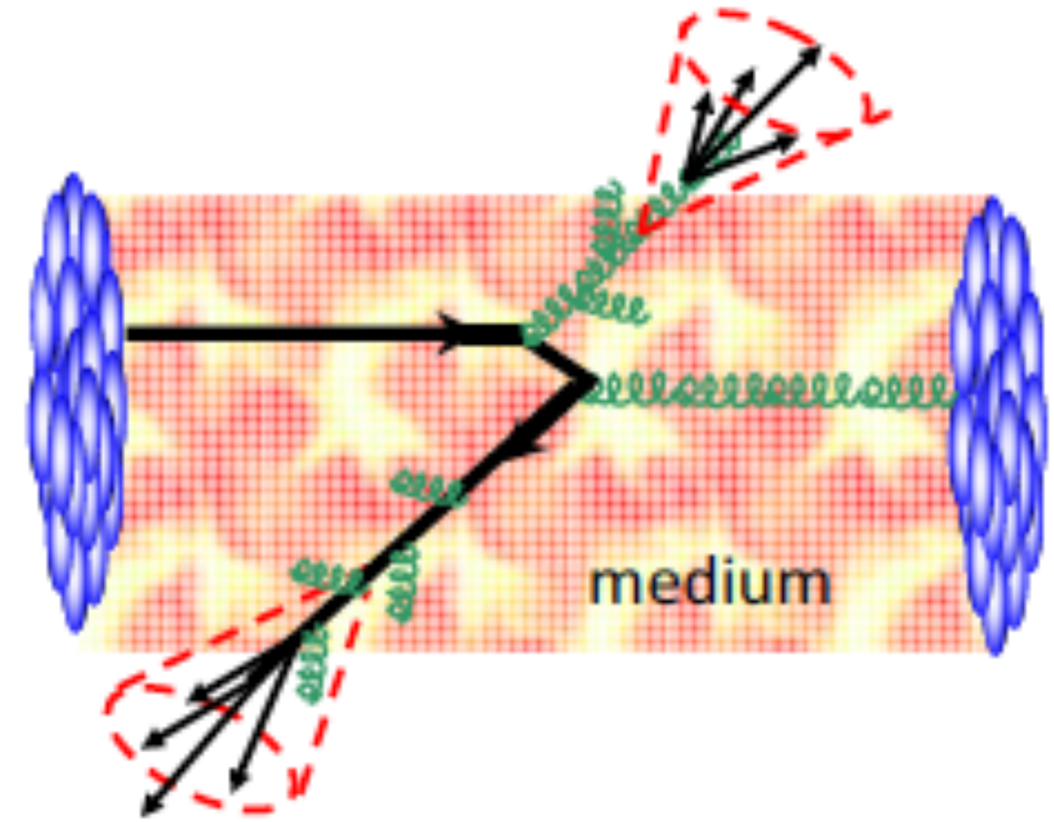
Initial parton hard scattering ($Q^2 >> \Lambda_{QCD}$)

Jets are attractive both experimentally and theoretically

Jets in Heavy-Ion Collisions

- Hard partons produced before the QCD medium forms
- Interact with the hot dense medium





$$R_{\mathrm{AA}} = \frac{1/T_{\mathrm{AA}}\, 1/N_{\mathrm{ev}}\, \mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

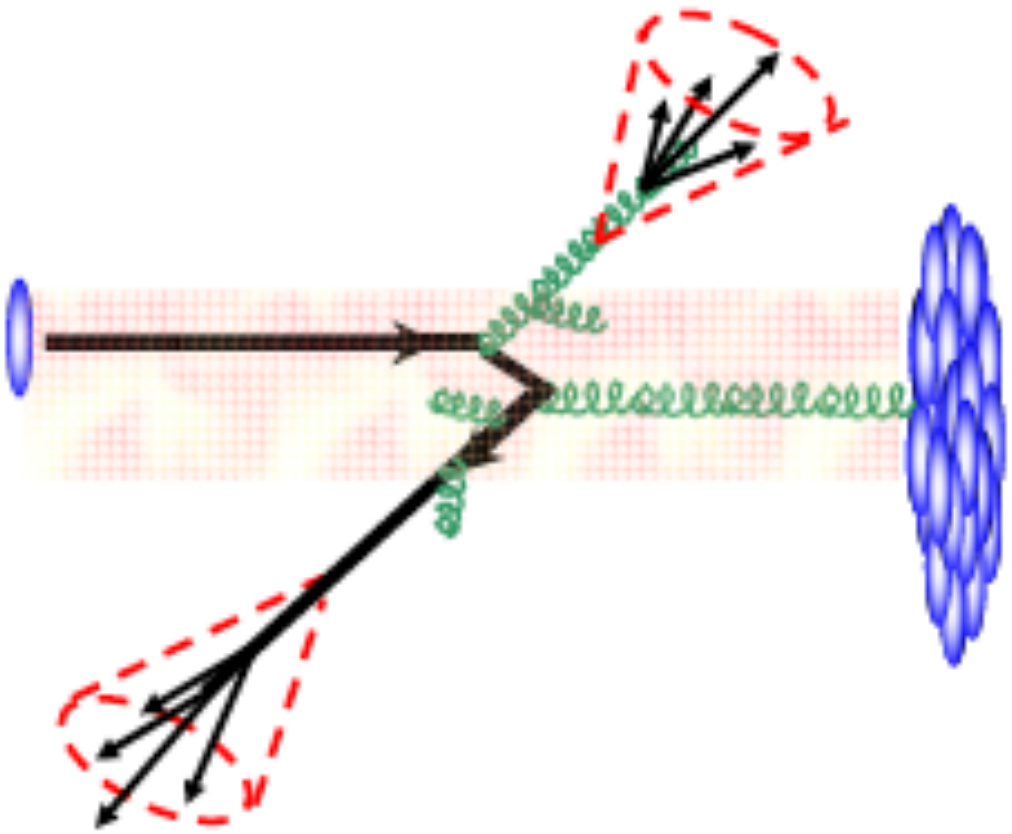
- Out-of-cone radiation: energy loss in jet cone

➡ jet yield suppression, dijet or hadron jet acoplanarity…

- In-cone radiation: medium modified fragmentation function

➡ jet shape broadening, modification of transverse energy profile…

Jets in Proton–Nucleus Collisions



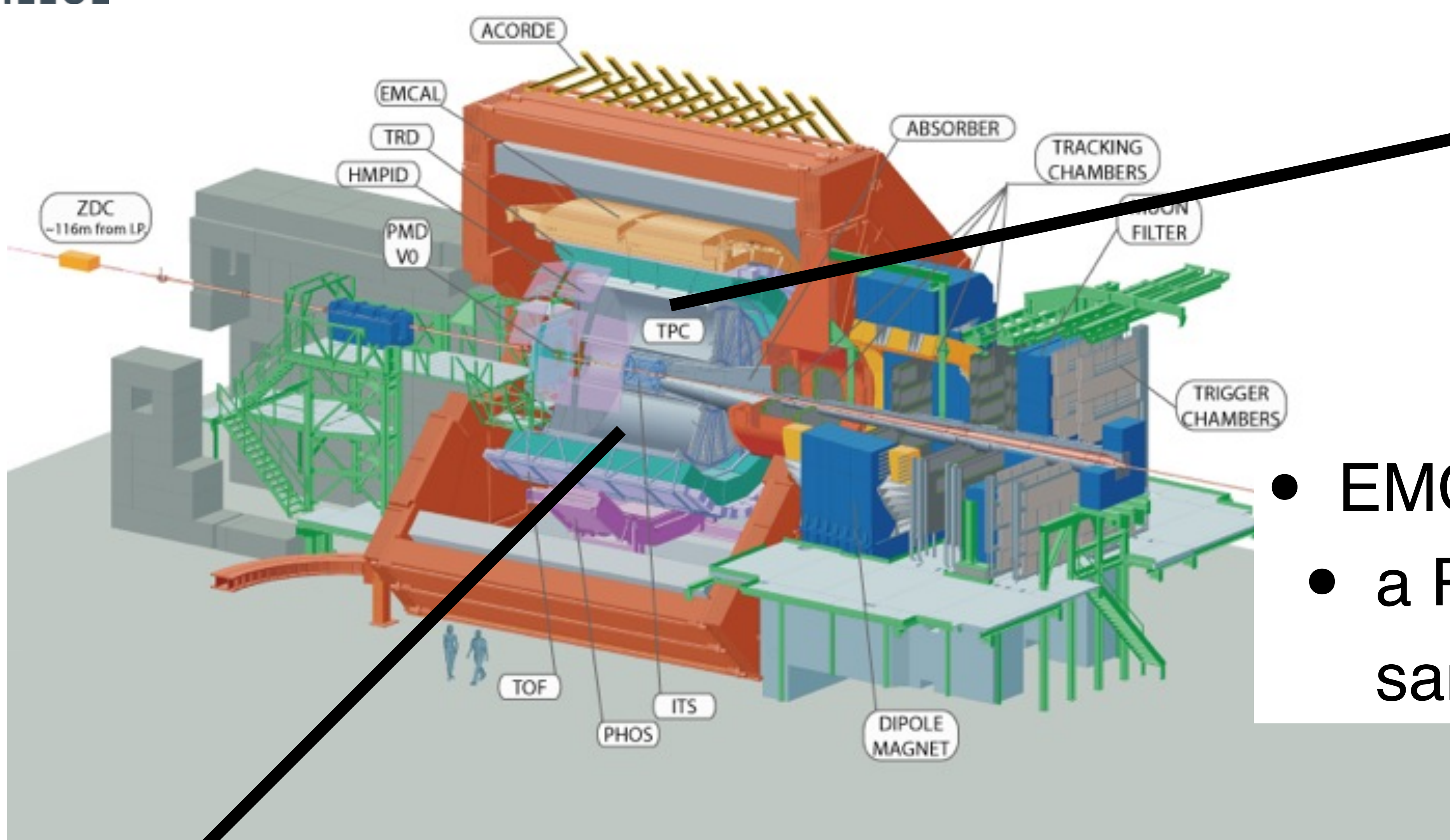
Study of cold nuclear matter

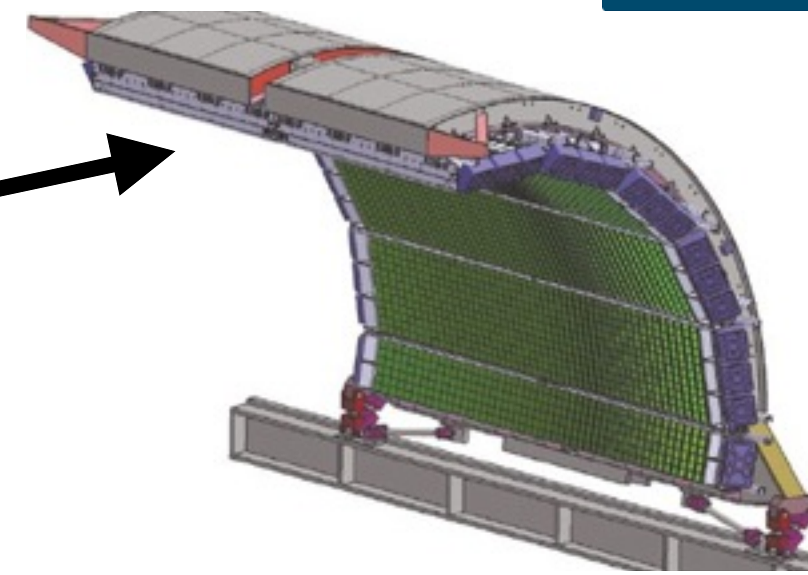
- Initial state effects:
  - ➡ Color Glass Condensate (CGC)?
  - ➡ nuclear modified Parton Distribution Function (nPDF)…
- Final state effects:
  - ➡ parton scattering in cold nuclear matter…

Baseline for heavy-ion collisions:

➡ disentangle the initial state effects from the hot and dense medium produced in the final state of the heavy-ion collisions

Jet Measurement with ALICE





- EMCal: |η|<0.7, 1.4<ϕ<π
  - a Pb-scintillator sampling calorimeter

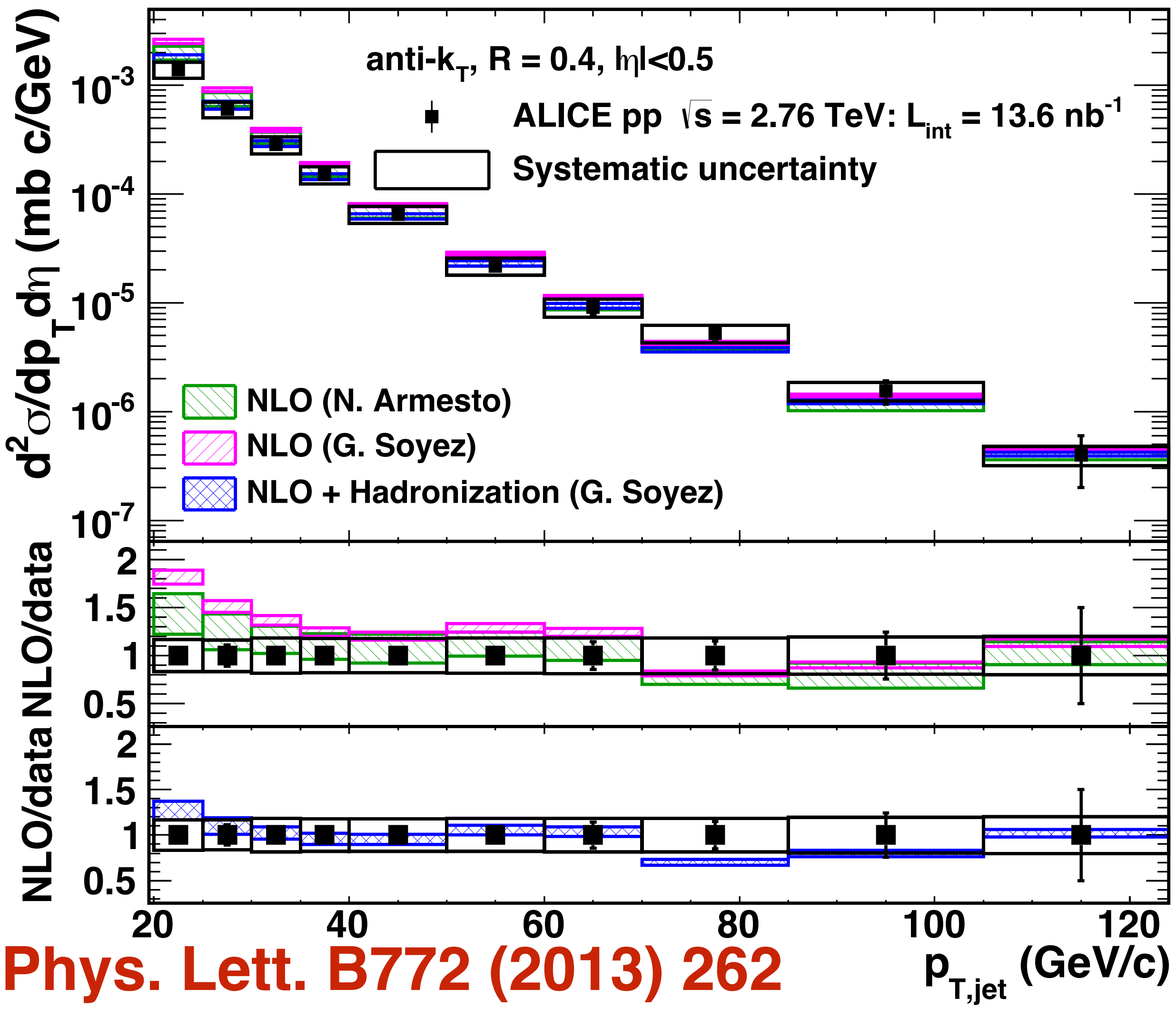
Charged particle correction: prevents energy double counting

- Tracking: |η|<0.9, 0<ϕ<2π
  - TPC: gas drift detector
  - ITS: silicon detector

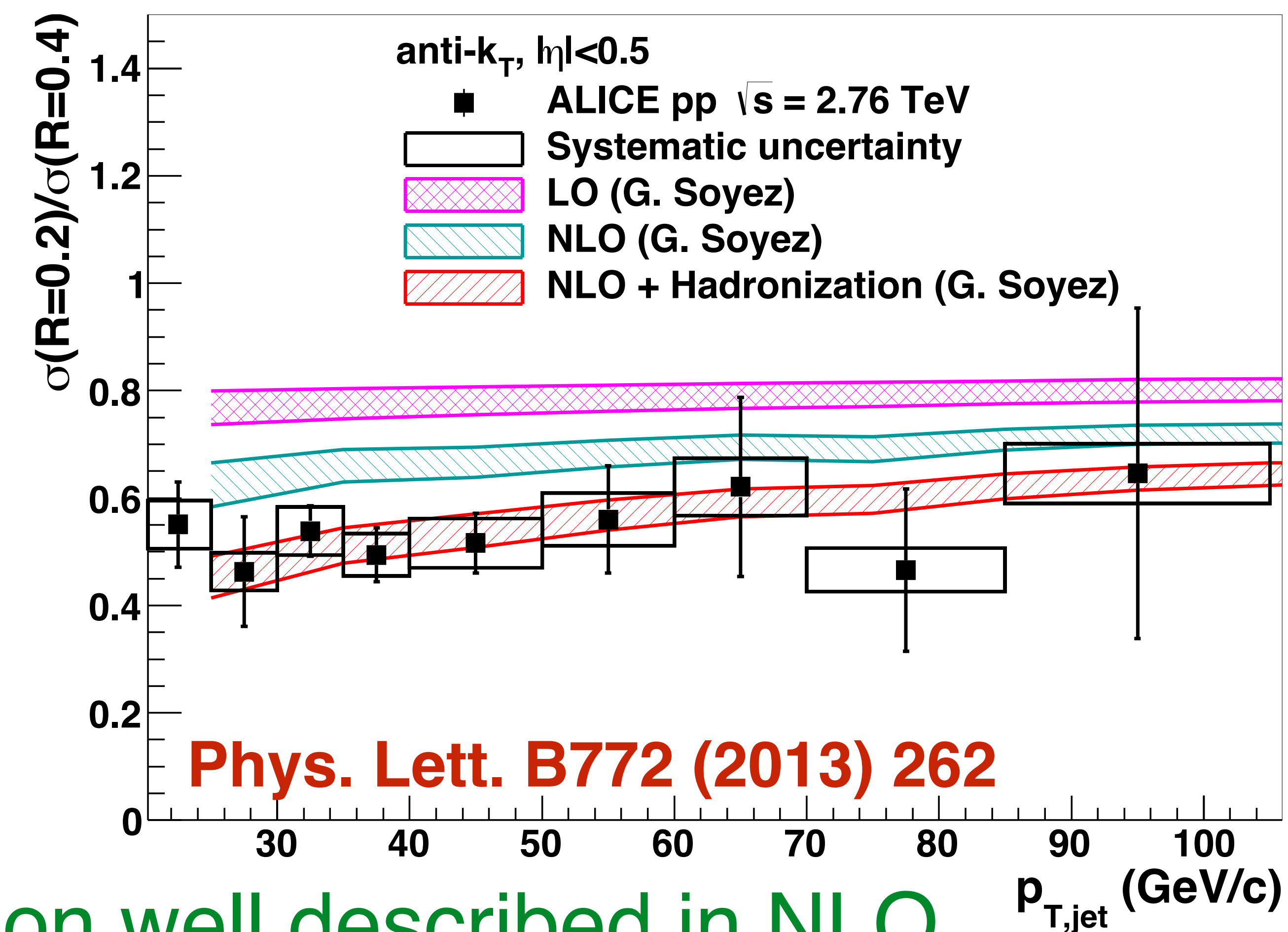
Charged constituents →  ← Neutral constituents

Results in pp Collisions

Jet p_T Spectra



- Agree with NLO pQCD calculations within errors
- Reference for jet measurements in p–Pb and Pb–Pb collisions

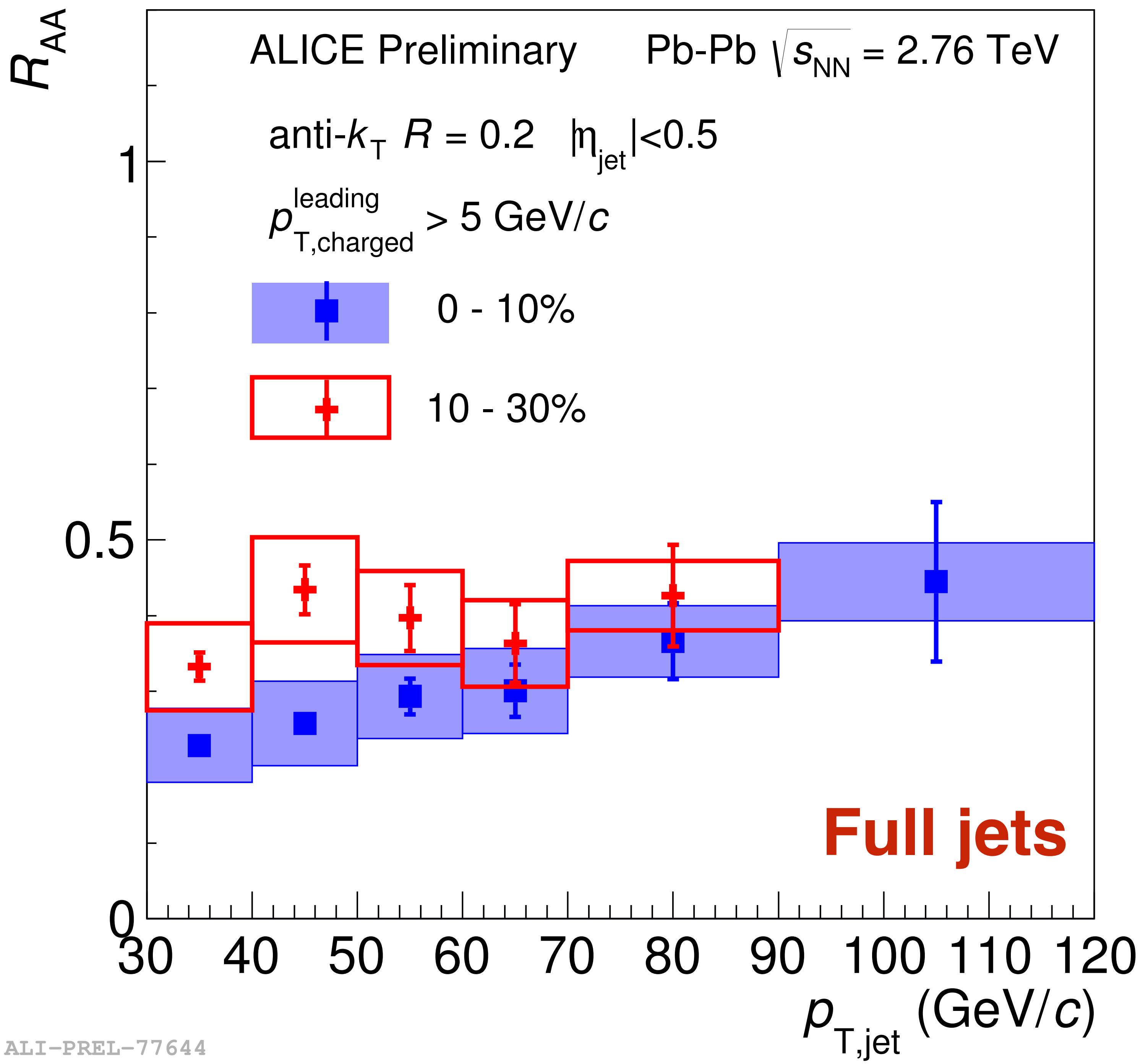


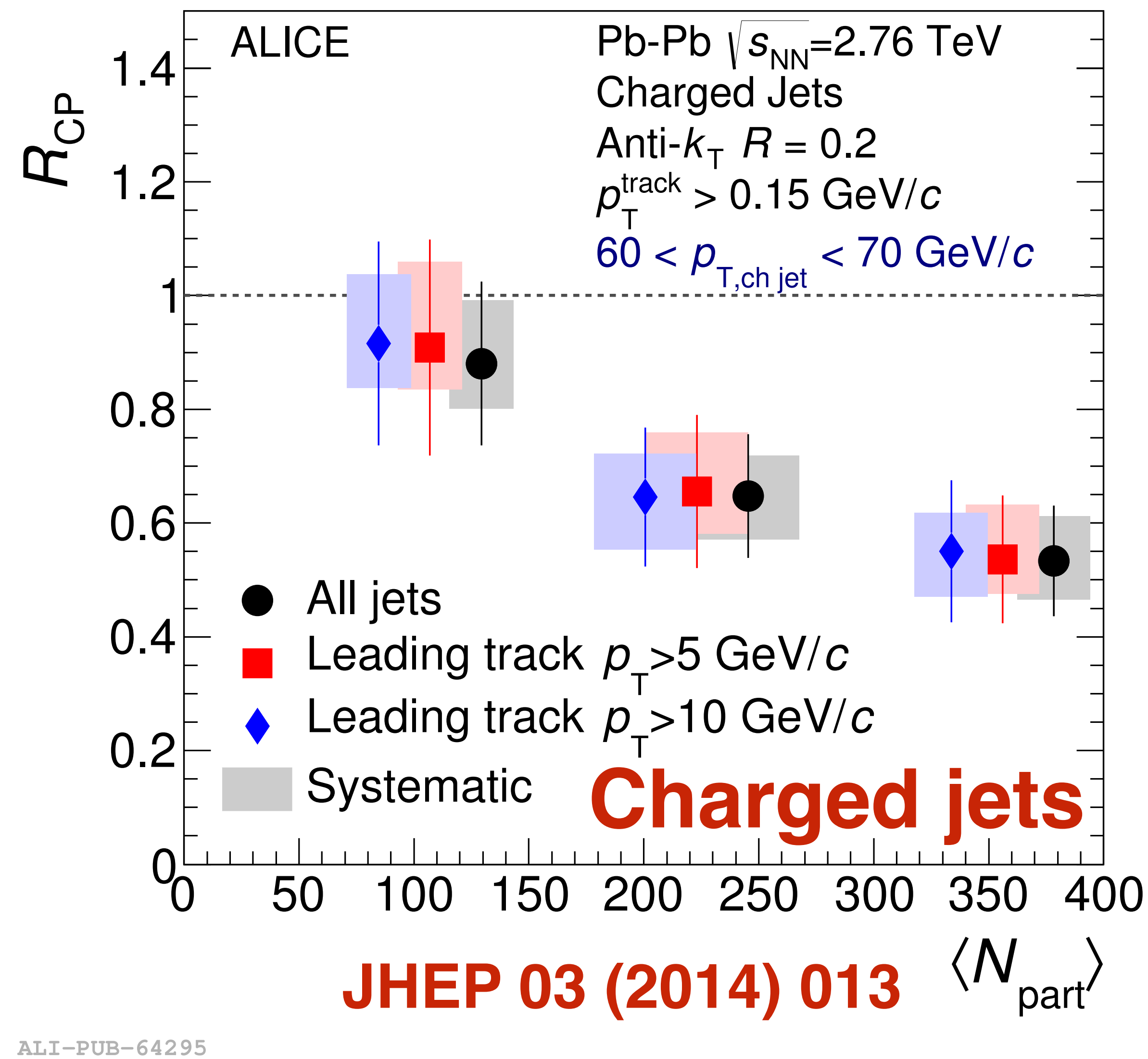
- Cross section ratio: provides the measurement of jet transverse structure

➡ hint: intra-jet radiation distribution well described in NLO calculations with hadronization

Results in Pb–Pb Collisions

Nuclear Modification Factor



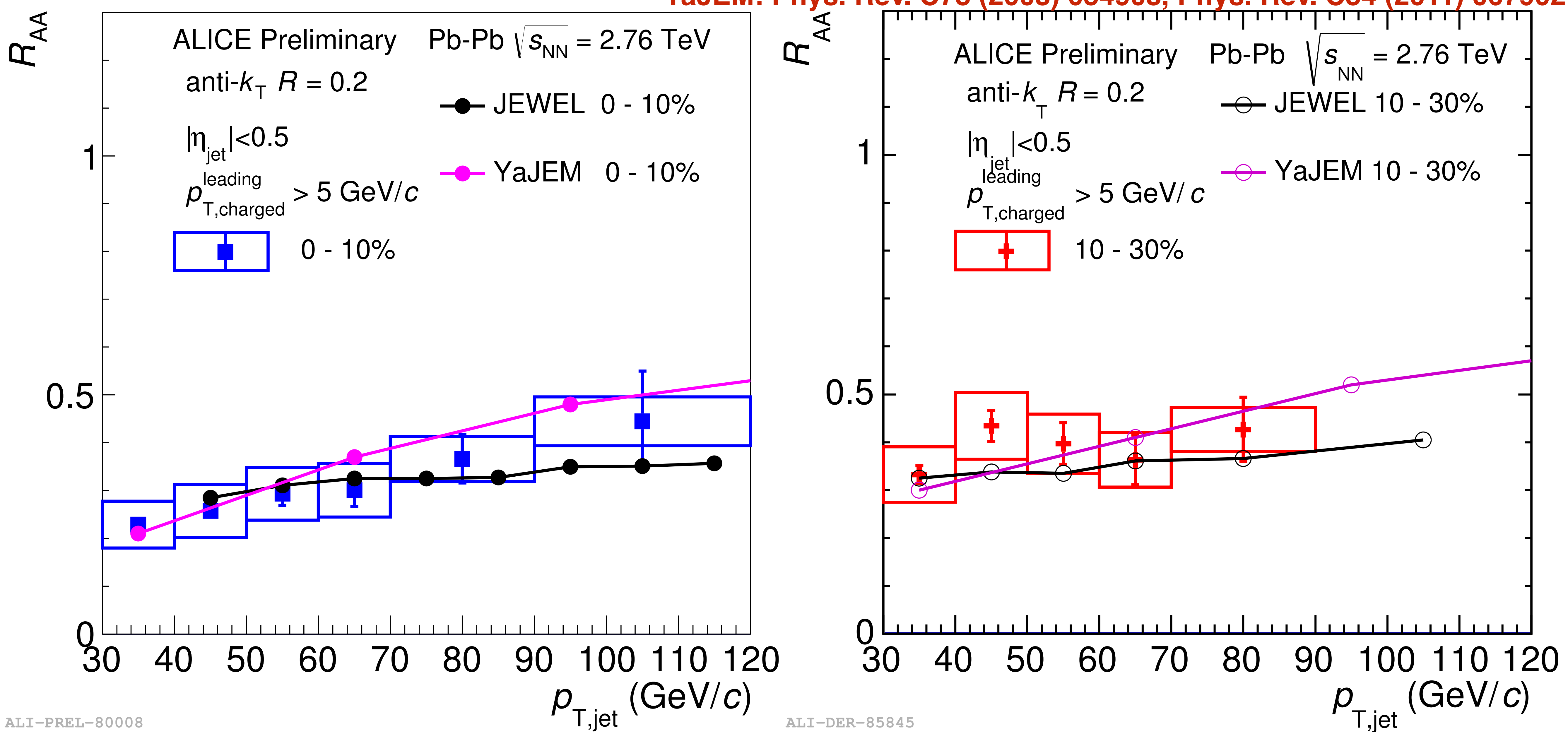


- Consistent with ALICE published results on charged jet R_{CP}
- Observed strong, centrality dependent jet suppression

Comparison with Theoretical Models

JEWEL: JHEP 1303 (2013) 080, Eur. Phys. J. C74 (2014) 2762

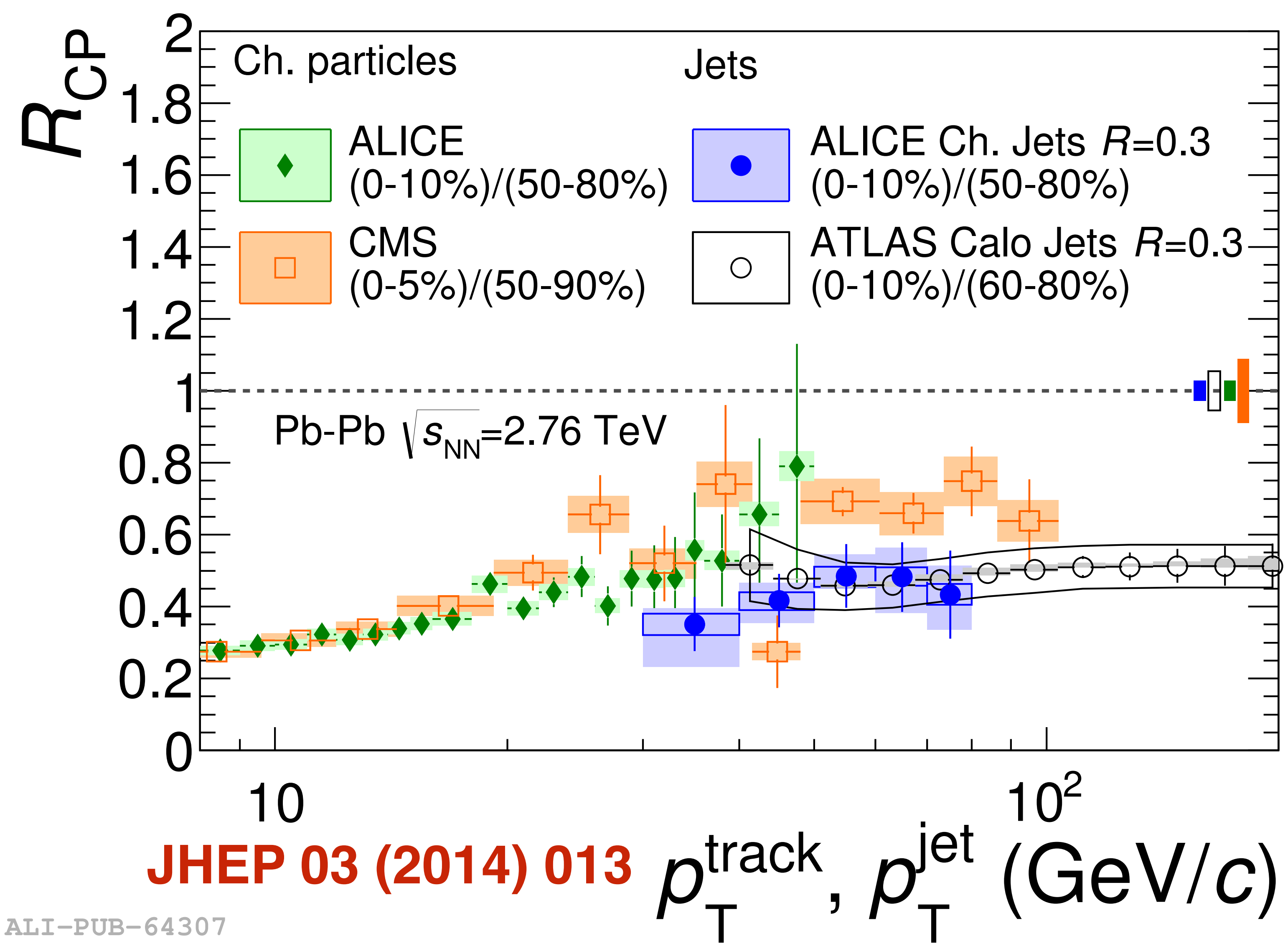
YaJEM: Phys. Rev. C78 (2008) 034908, Phys. Rev. C84 (2011) 067902



- Good agreement between data and models within errors

➡ both models fitted to the single particle R_{AA}

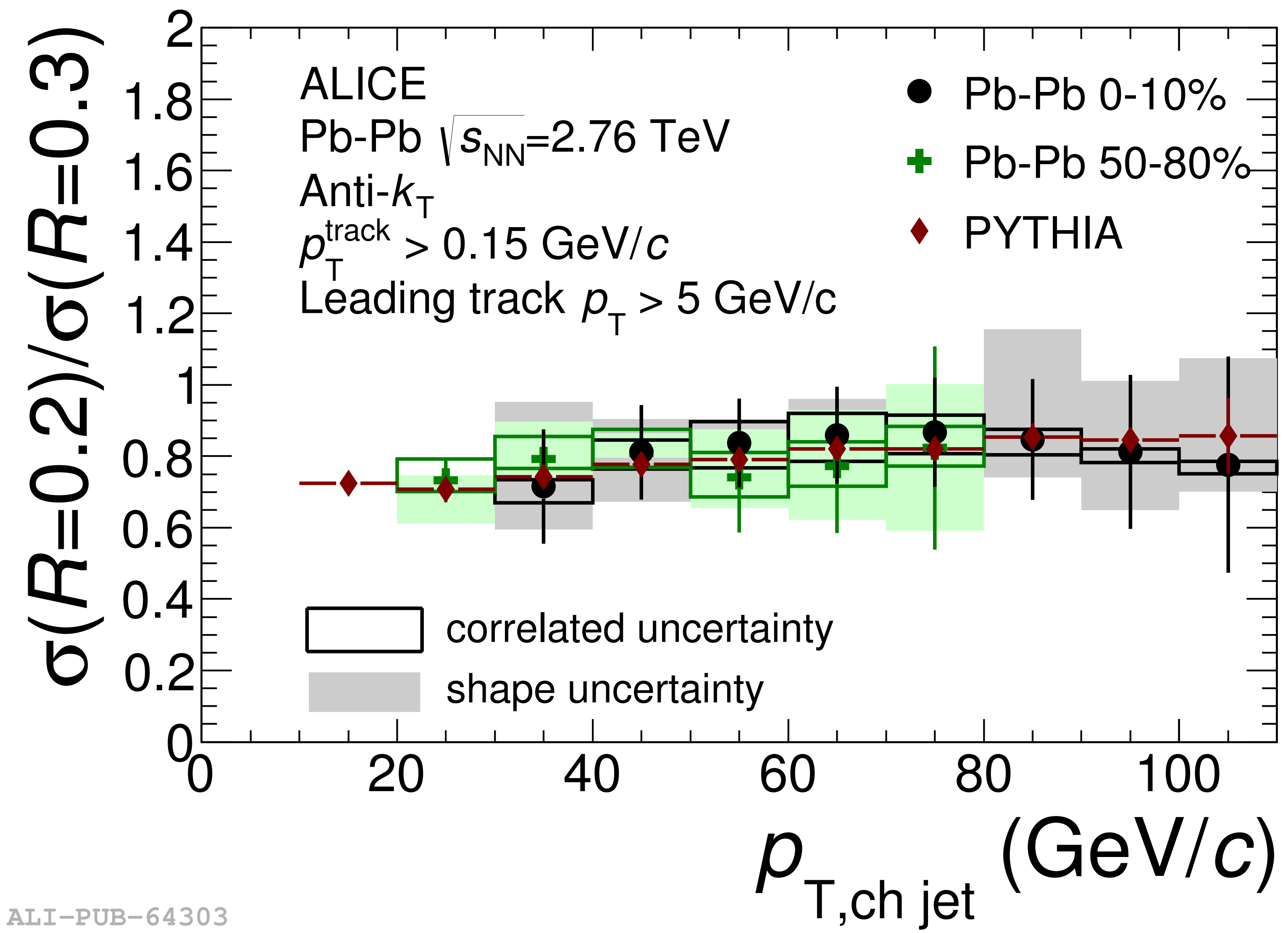
Comparison with ATLAS and CMS



- ATLAS: calorimetric jets
- ALICE: charged particle jets — more sensitive to the low-momentum fragments

- Agreement between ALICE and ATLAS:
  ➡ contribution of low momentum jet fragments to jet energy is small
- R_{CP} for jets and single hadrons are similar:
  ➡ indicates the momentum is redistributed to larger angles

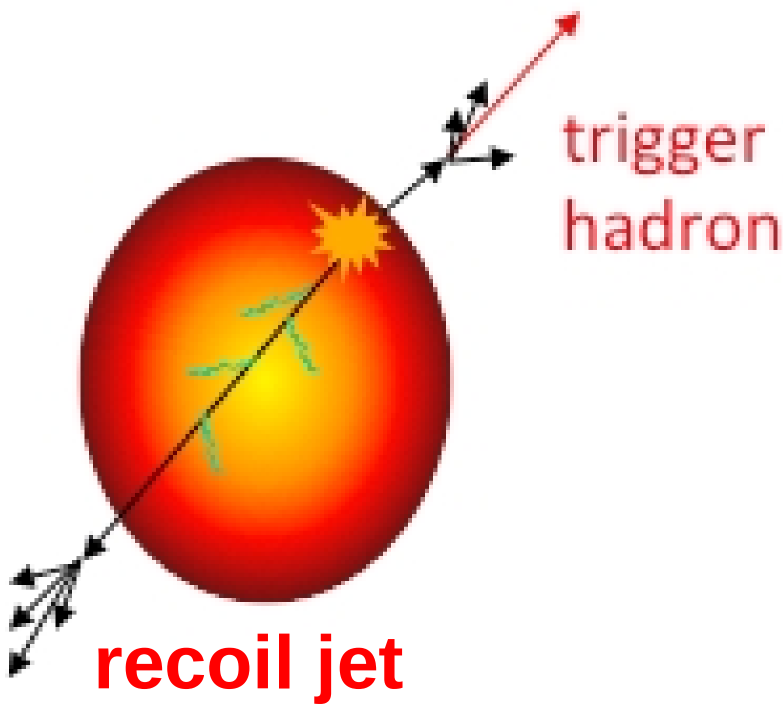
Ratio of Jet Spectra



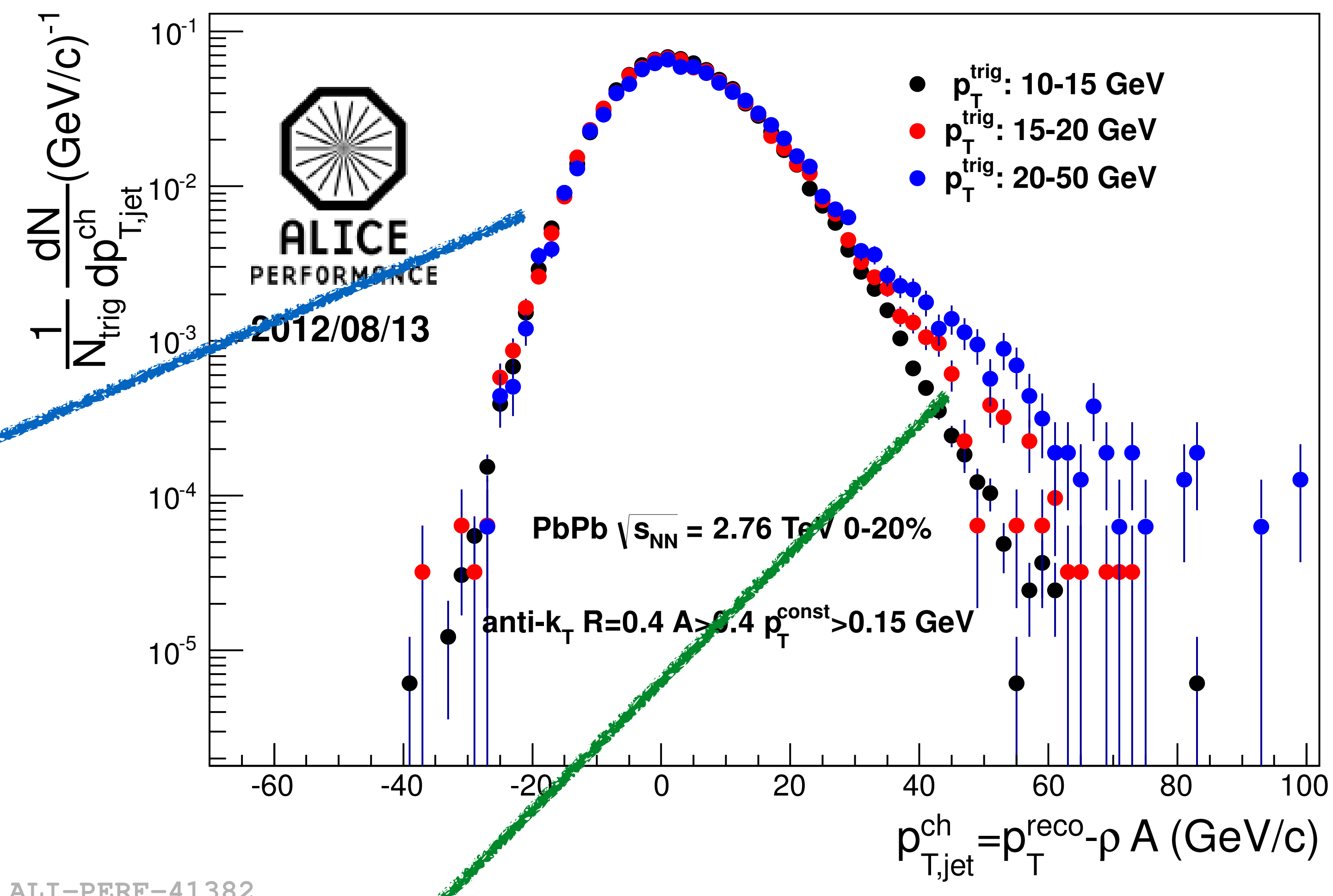
- Charged jet ratio consistent with vacuum jets (PYTHIA) and no centrality dependence

➡ no evidence of jet structure modification in cone

Semi-inclusive Recoil Jet Distribution



- Hadron triggered recoil jet spectrum: minimal surface and fragmentation bias down to low p_T



- Dominated by combinatorial jets — uncorrelated with trigger hadron p_T

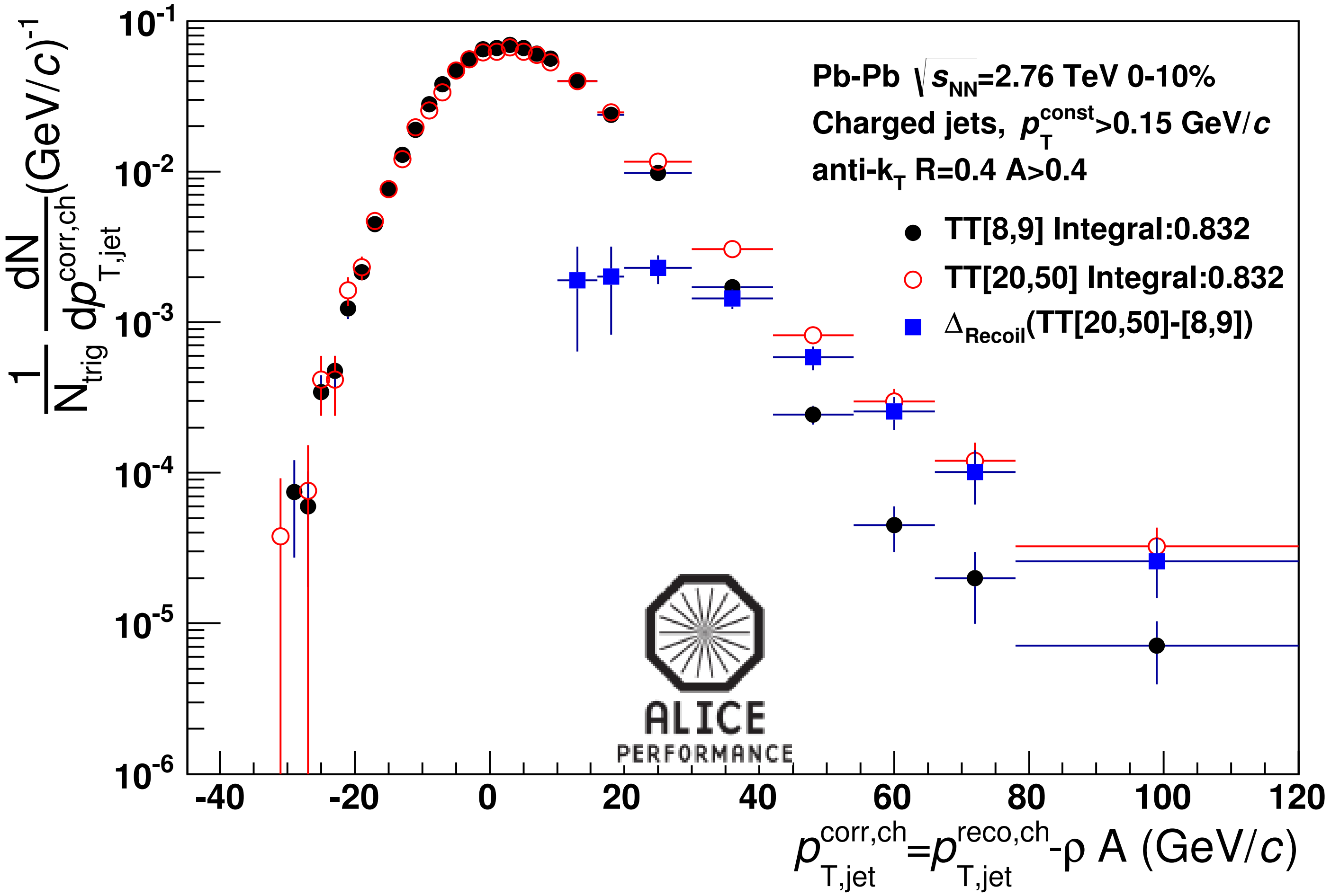
Only charged jets are used for the recoil jet analysis in ALICE

- Recoil jet spectrum — evolves with trigger hadron p_T

Δ_{recoil} Distribution

- Opportunity: remove combinatorial background by considering the difference of the recoil jet spectra for two exclusive hadron trigger intervals

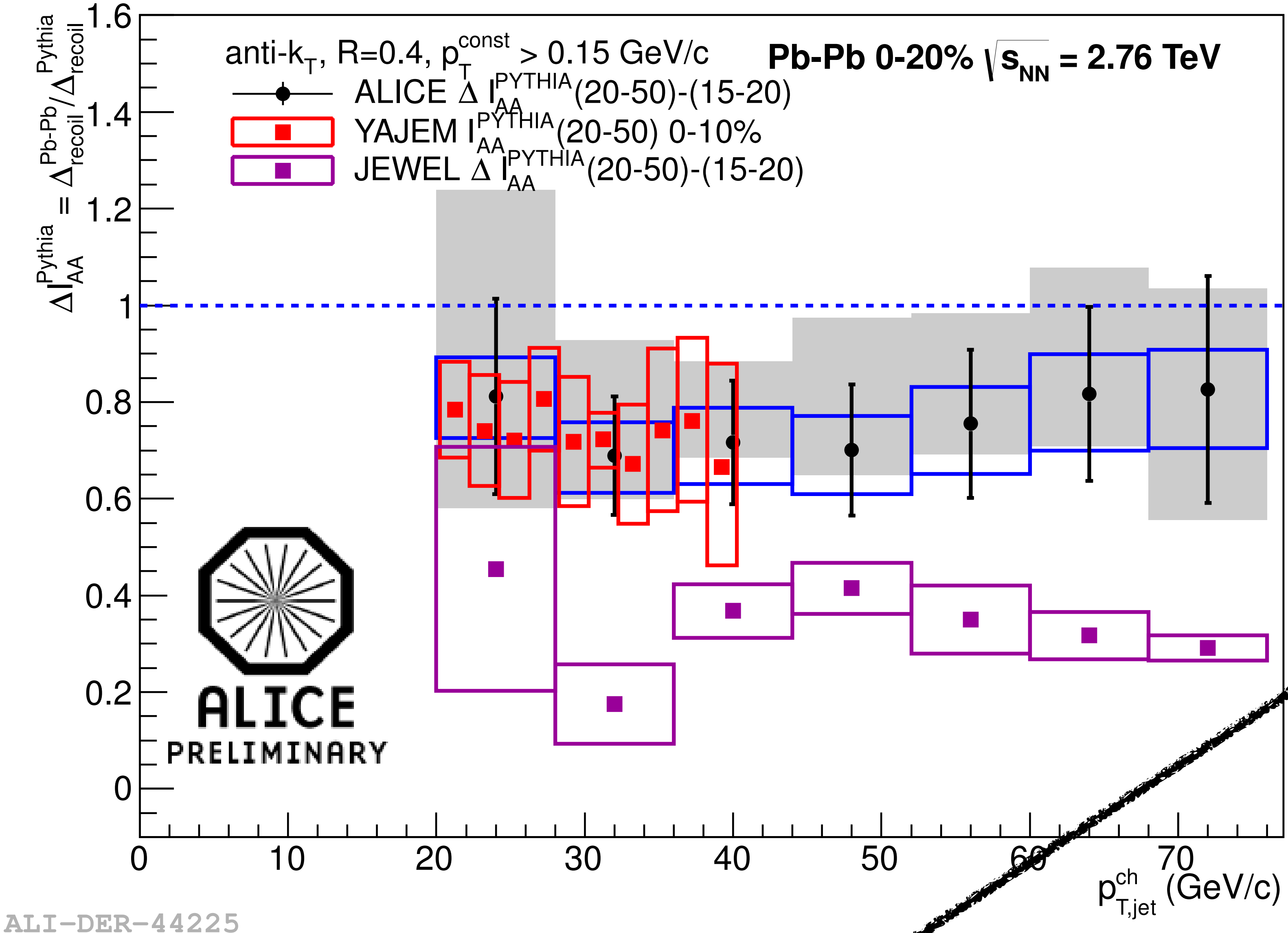
$$\Delta_{\mathrm{recoil}} = [1/N_{\mathrm{trg}} \mathrm{d}N/\mathrm{d}p_{\mathrm{T,jet}}]_{\mathrm{trg}} - [1/N_{\mathrm{ref}} \mathrm{d}N/\mathrm{d}p_{\mathrm{T,jet}}]_{\mathrm{ref}}$$



ALI-PERF-64032

- Δ_{recoil} is free of the combinatorial background
- Still has to be corrected for background smearing of jet energy and detector effects

Recoil Jet ΔI_{AA}

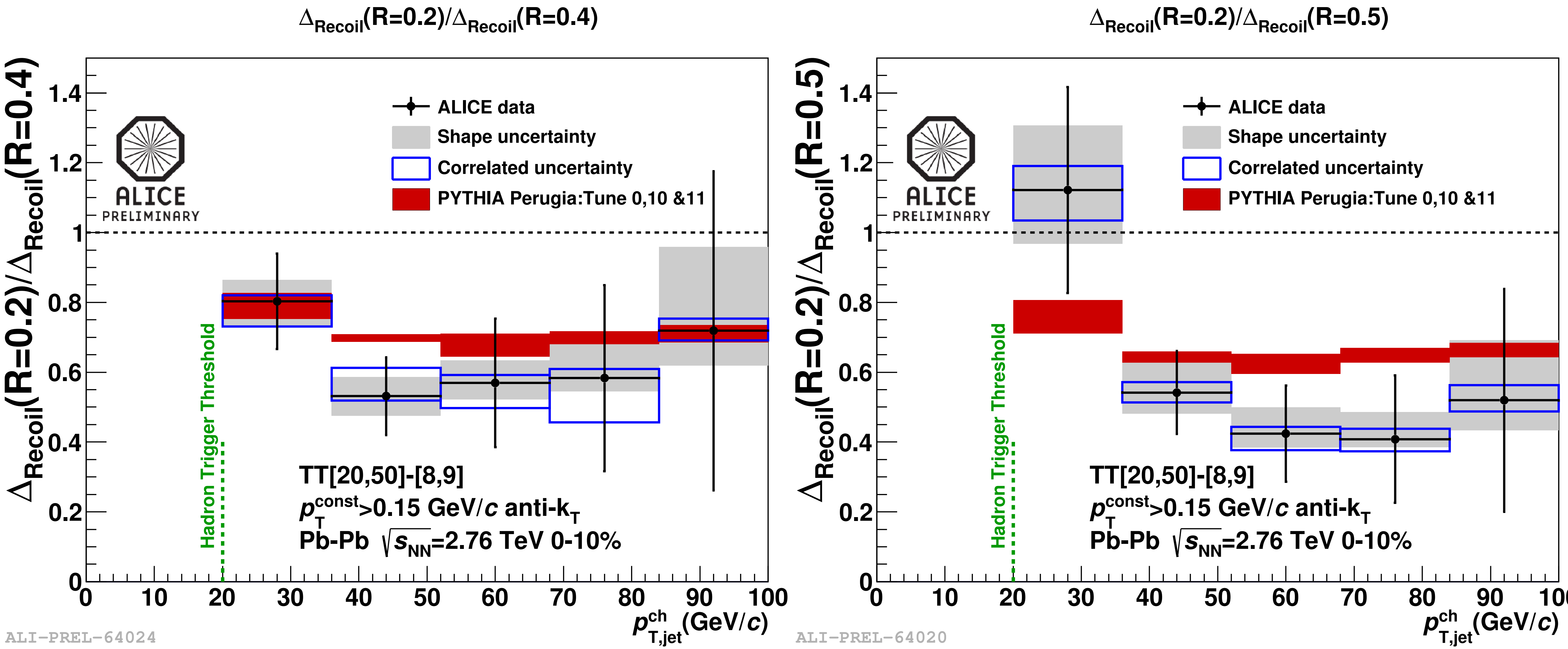


$$\Delta I_{AA}^{\rm Pythia} = \Delta_{\rm recoil}^{\rm Pb-Pb} / \Delta_{\rm recoil}^{\rm Pythia}$$

- YAJEM: agrees with data
- JEWEL: $\Delta I_{AA} \sim 0.4$ underestimates the measurement

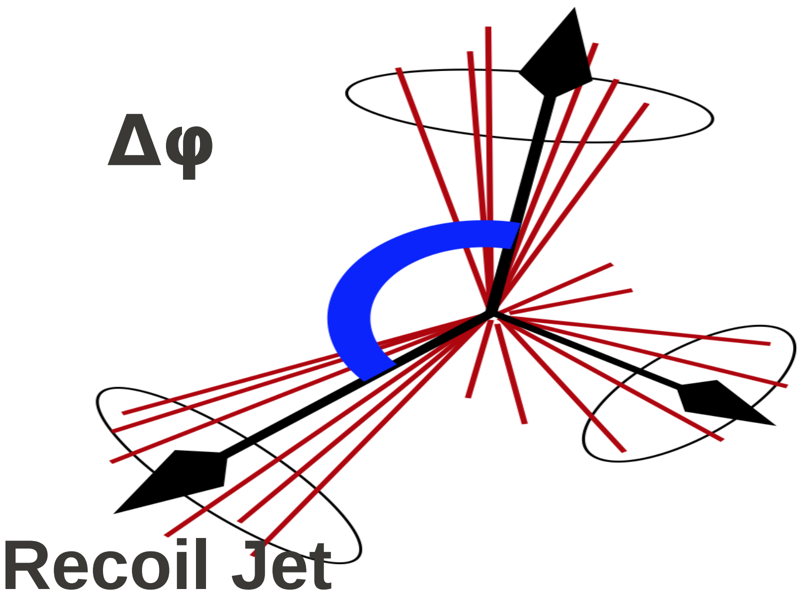
- Difference in energy loss mechanism or modeling collision/medium?

Ratio of Recoil Jet Yield

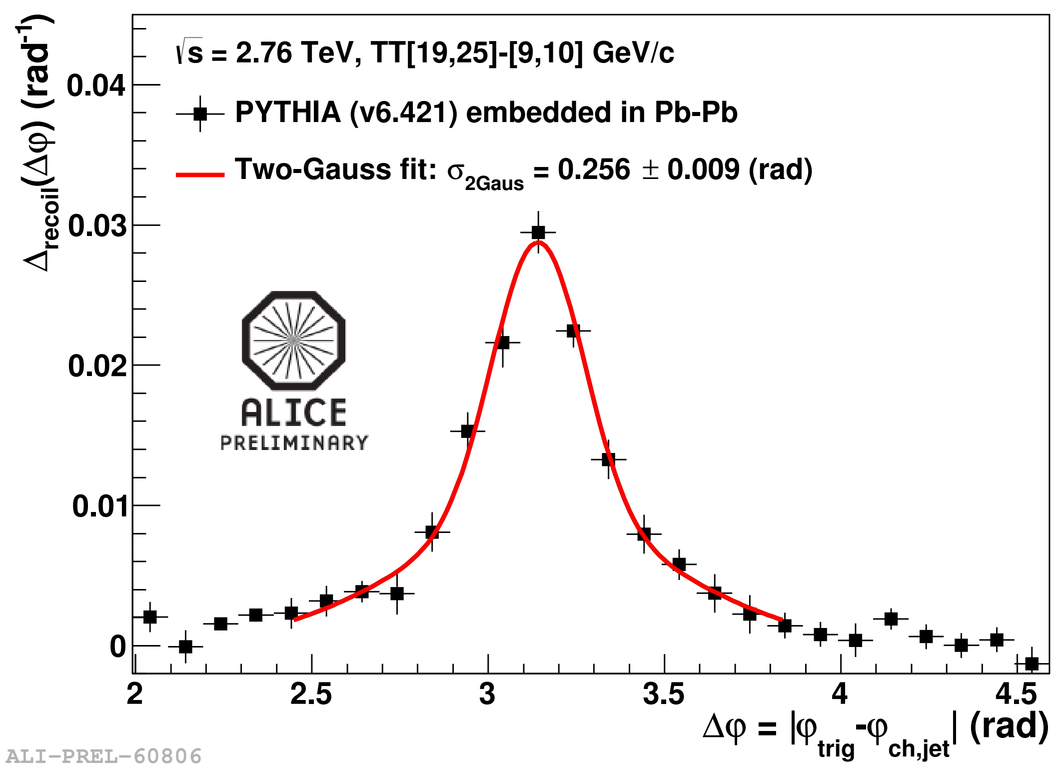


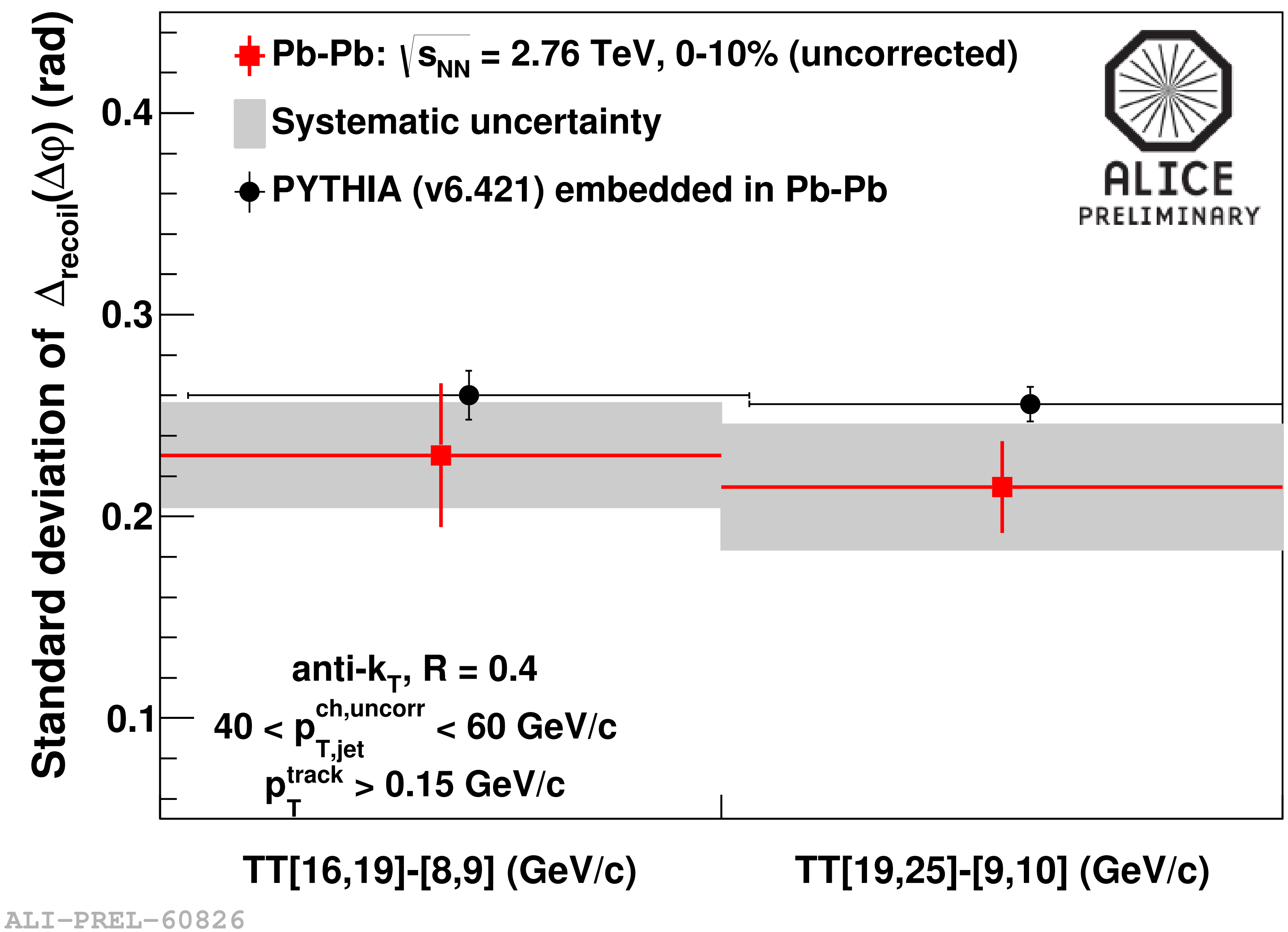
- $\Delta_{recoil}(R=0.2)/\Delta_{recoil}(R=0.4)$: no evidence for significant energy redistribution within R=0.4
- $\Delta_{recoil}(R=0.2)/\Delta_{recoil}(R=0.5)$: data systematically below PYTHIA (in jet p_T>36 GeV/c) — hint of energy redistribution?

Hadron–Jet Azimuthal Correlation



- Can medium-induced radiation emitted out-of-cone change the jet direction?

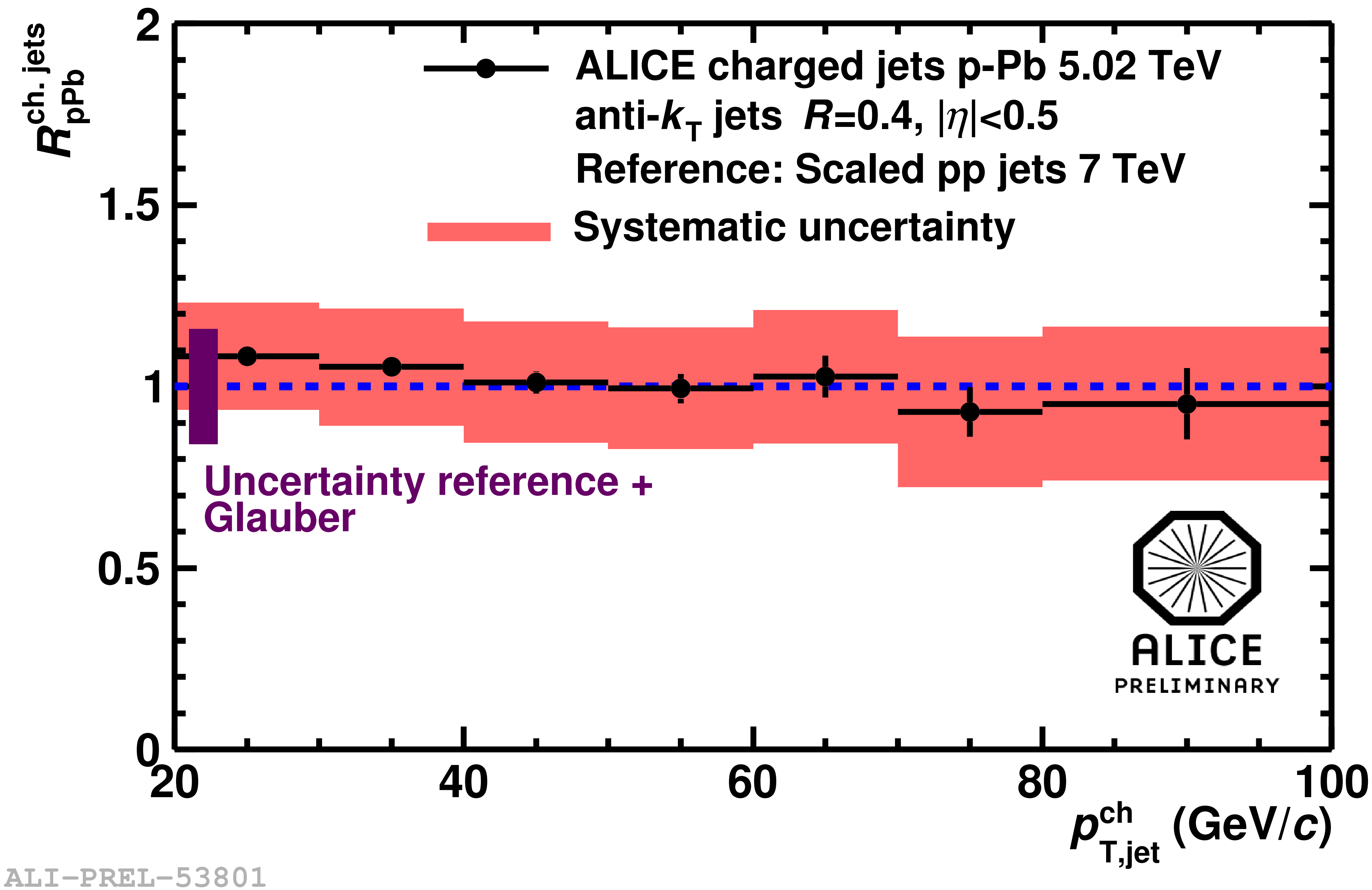




- PYTHIA consistent with data within errors — no evident medium-induced acoplanarity observed for selected kinematics

Results in p–Pb Collisions

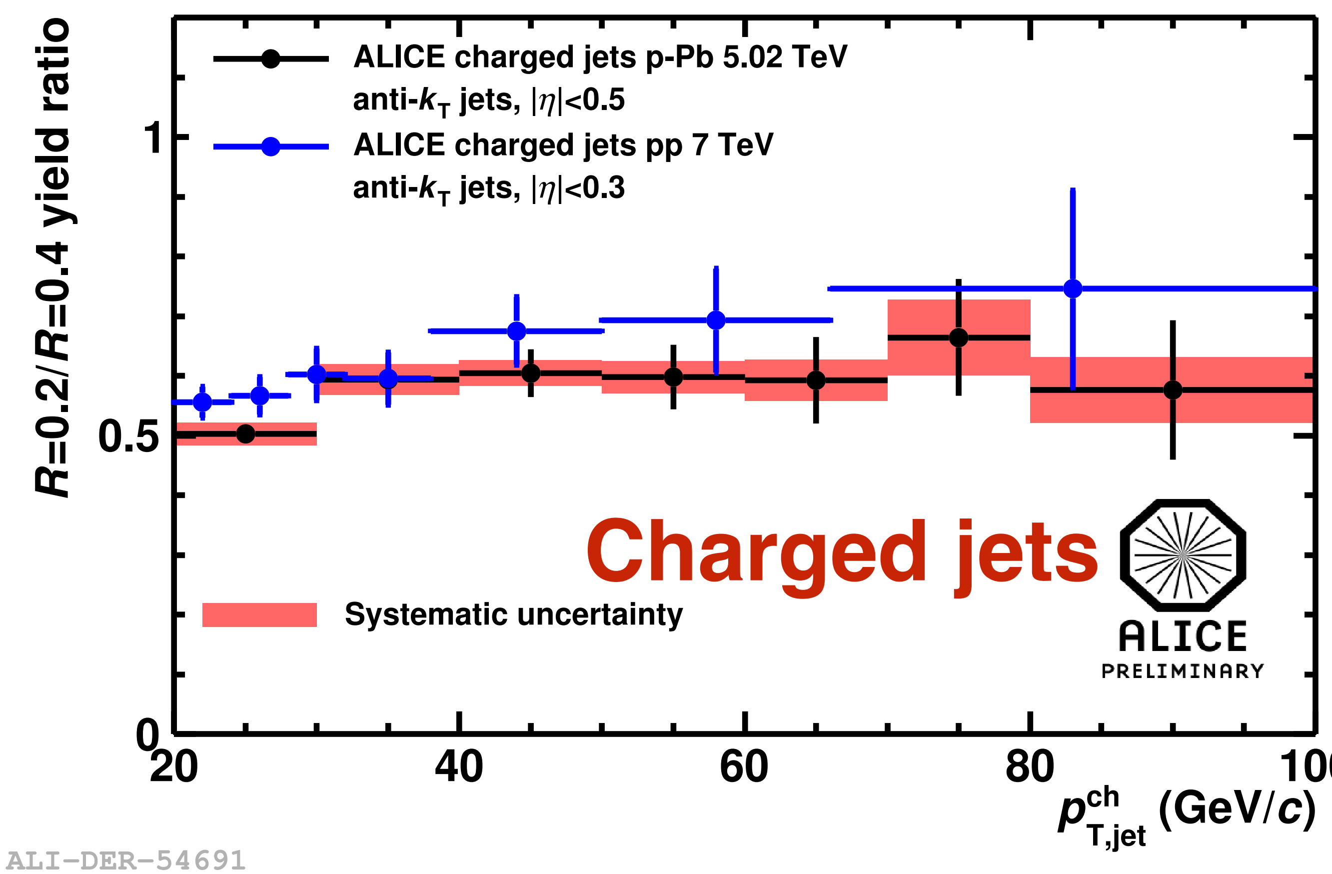
Charged Jet R_{pA}

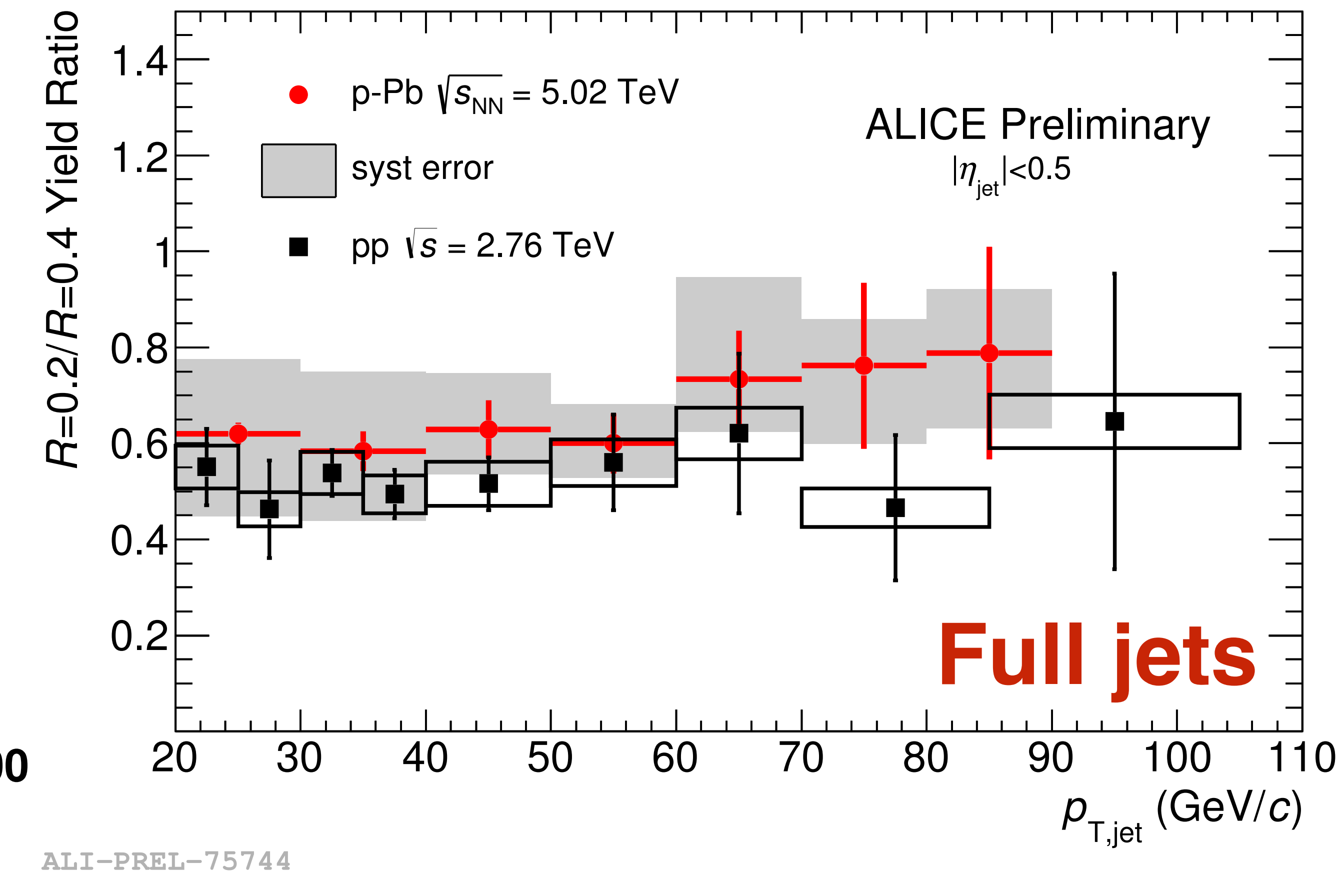


- No significant cold nuclear effect has been observed on jet production in p–Pb collisions

➡ jet suppression in Pb–Pb is final state effect

Ratio of Jet Spectra





- Results consistent with no significant cold nuclear effect on jet transverse structure in $R<0.4$ in p–Pb collisions

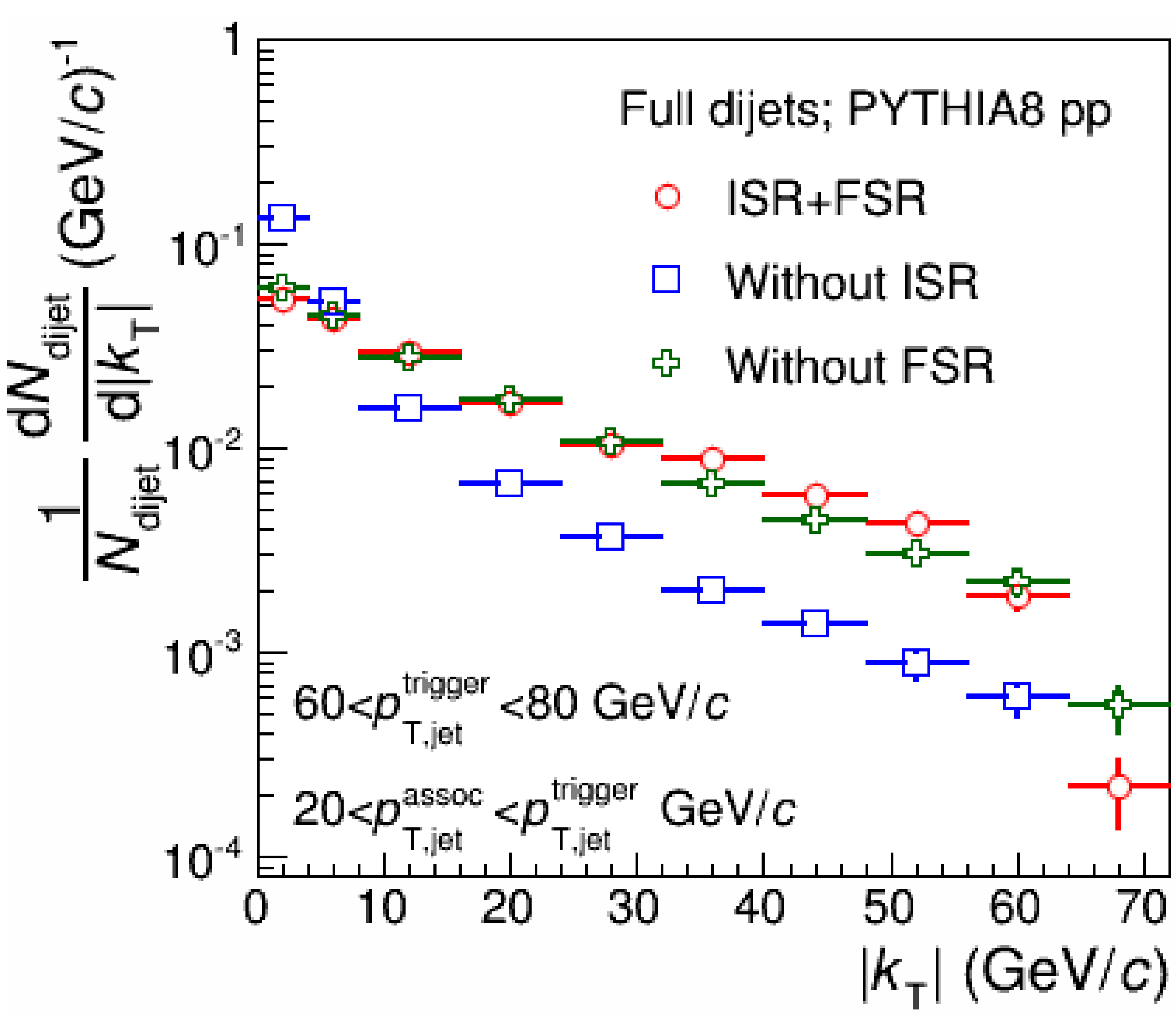
- The same conclusion for both full jets and charged jets

Dijet k_T in p–Pb Collisions

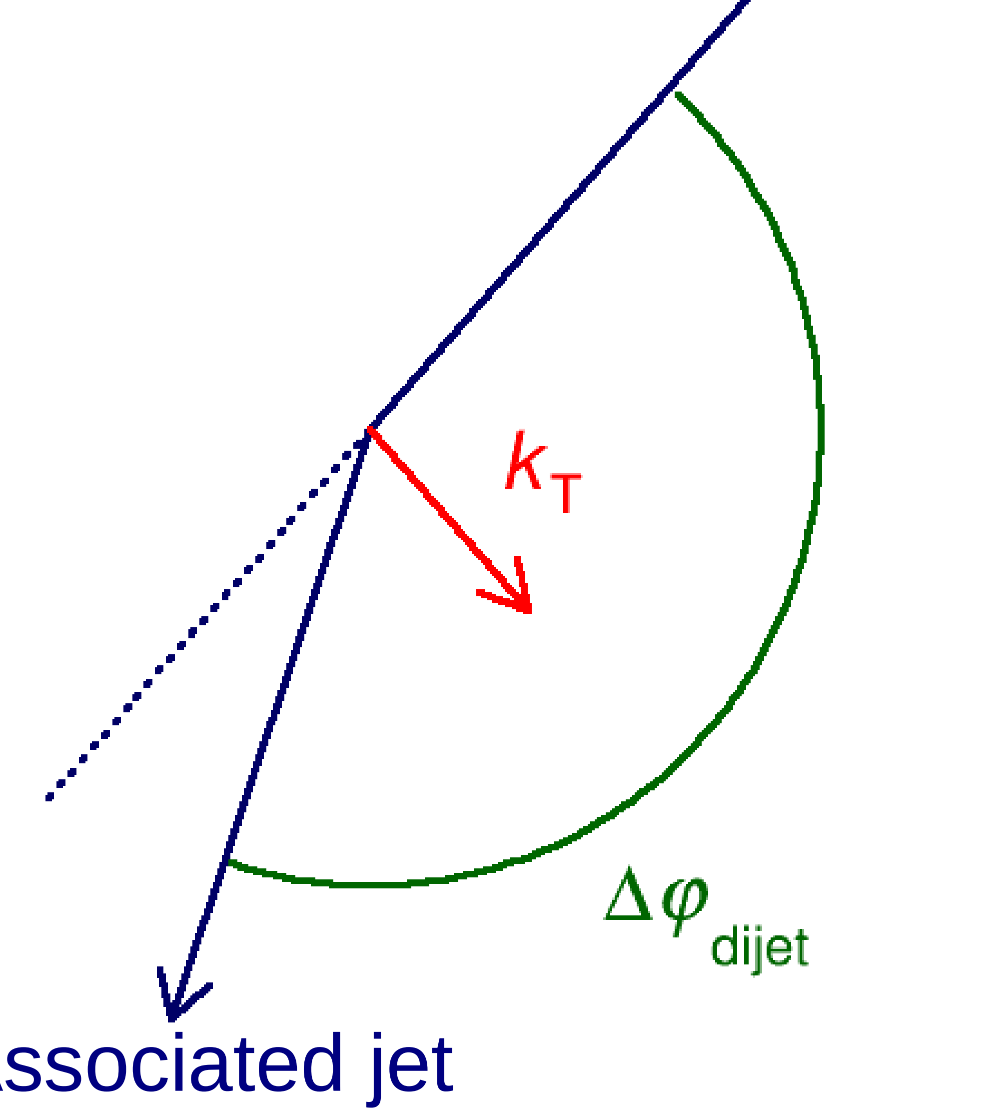
- Dijet k_T in p–Pb collisions

➡ intrinsic k_T + initial and final state radiations

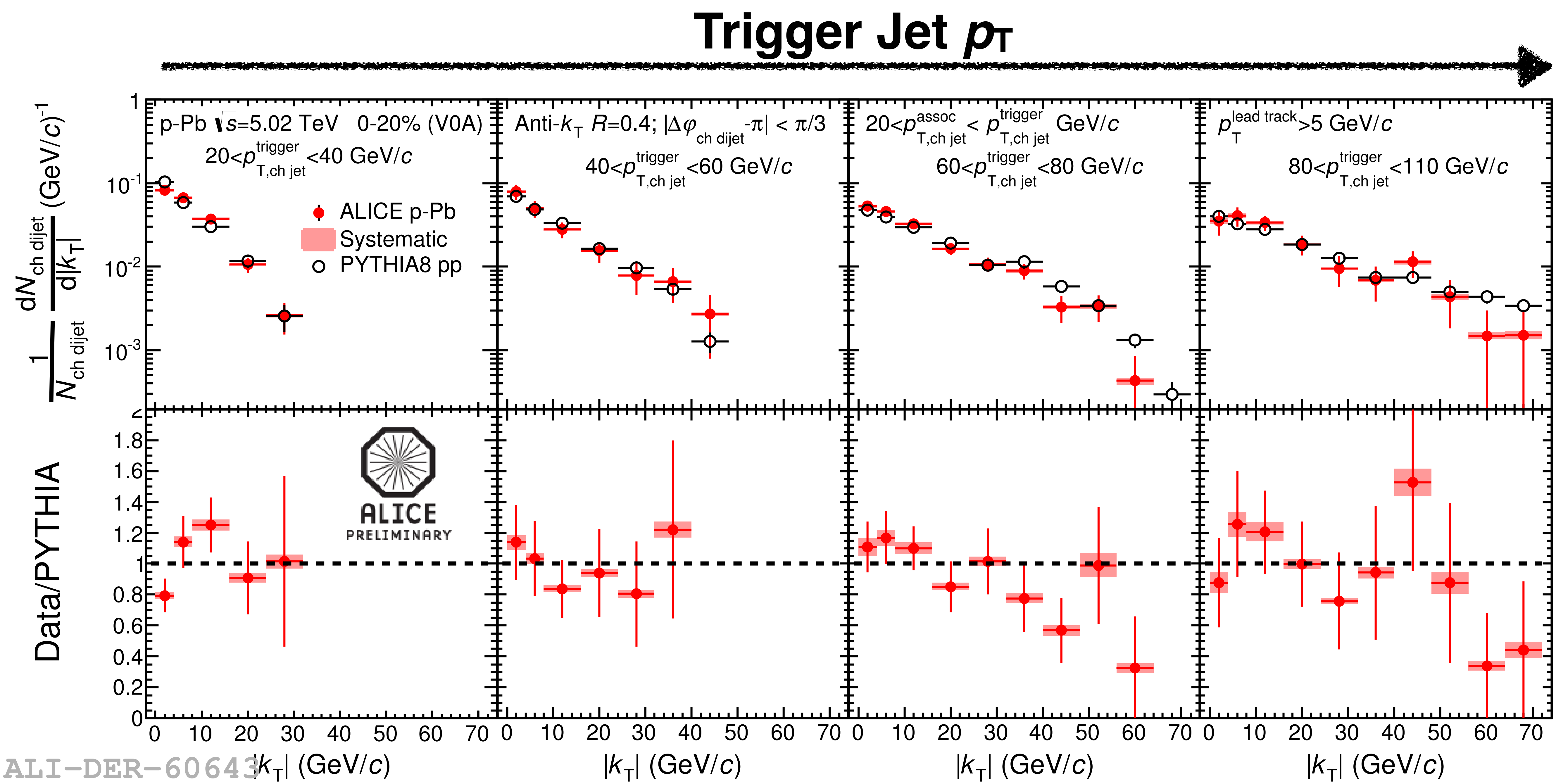
➡ + scattering of parton in cold nuclear matter



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

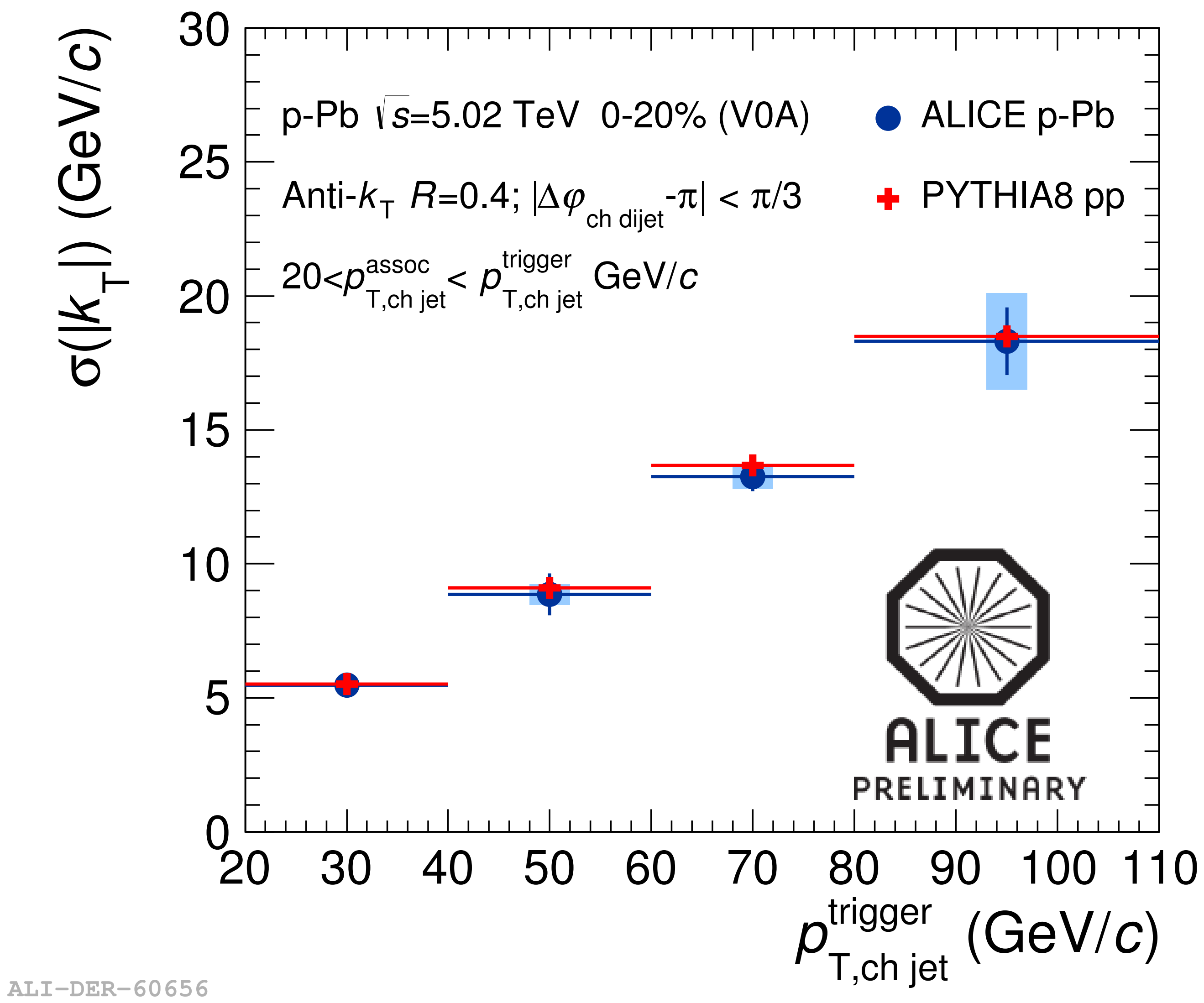


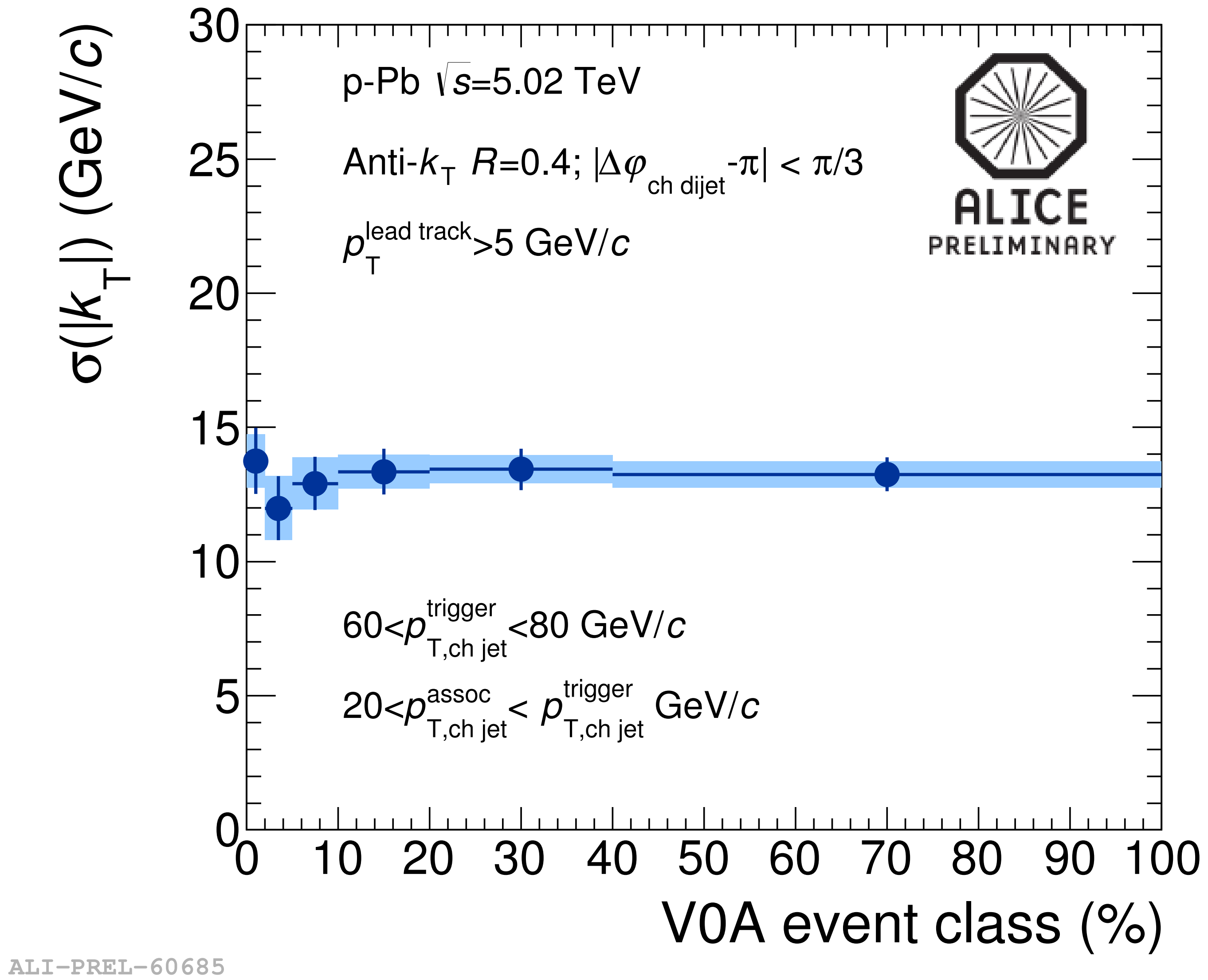
k_T vs. Trigger p_T



- No Significant deviation in data compared to PYTHIA

Dijet k_T Width





- k_T width increases with trigger jet p_T

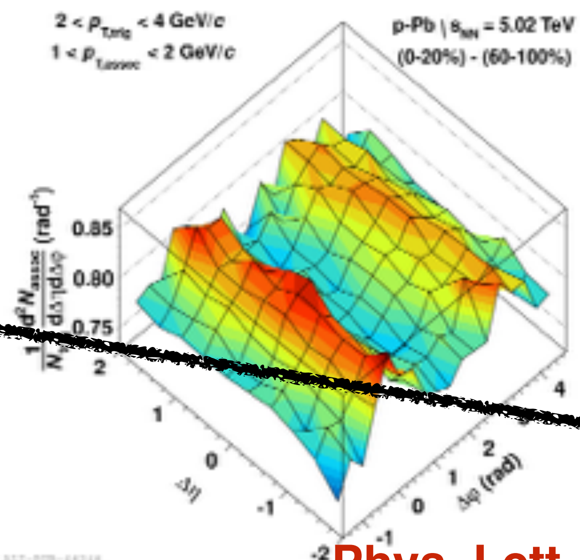
  ➡ compatible in data and PYTHIA simulations

- No modification of k_T width observed also in high multiplicity events

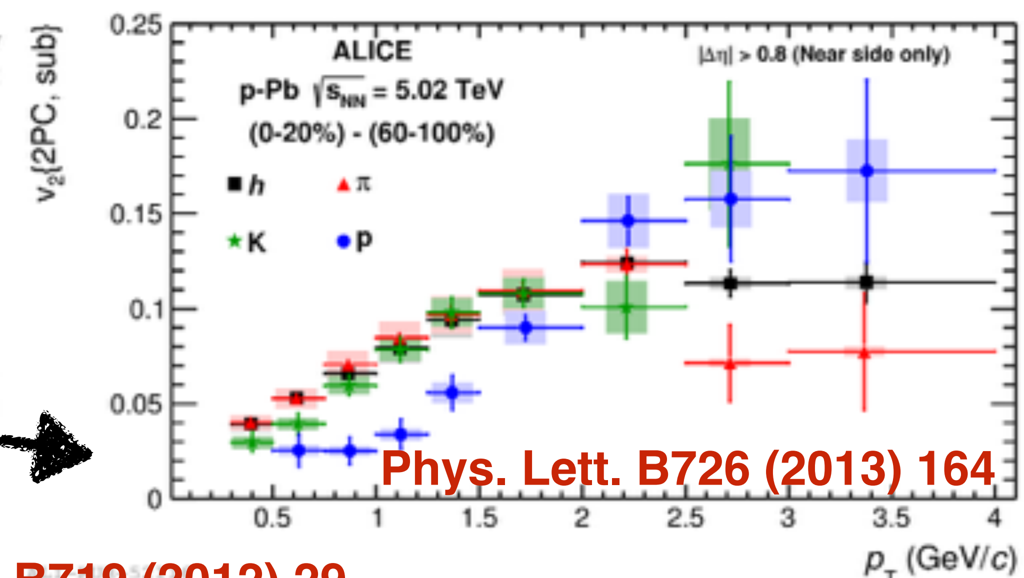
Particle Production in p–Pb Collisions

High multiplicity p–Pb and Pb–Pb collisions - similarities

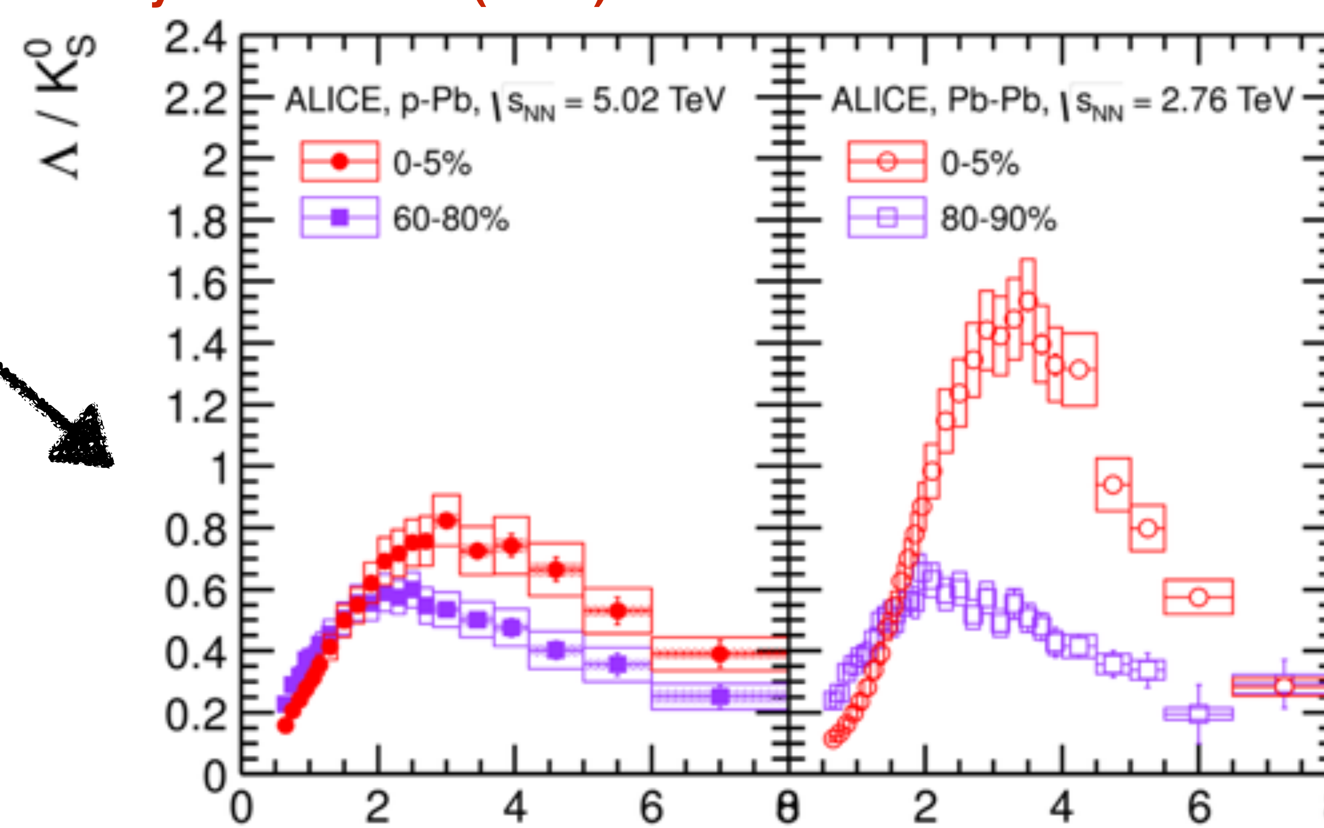
- Double ridge structure
- $v_2 > 0$ and PID dependent
- Enhanced Λ/K_S^0 ratio
  - ➡ involving several phenomena:
    - ➡ radial flow
    - ➡ coalescence/recombination
    - ➡ jet fragmentation…



Phys. Lett. B719 (2012) 29



Phys. Lett. B726 (2013) 164



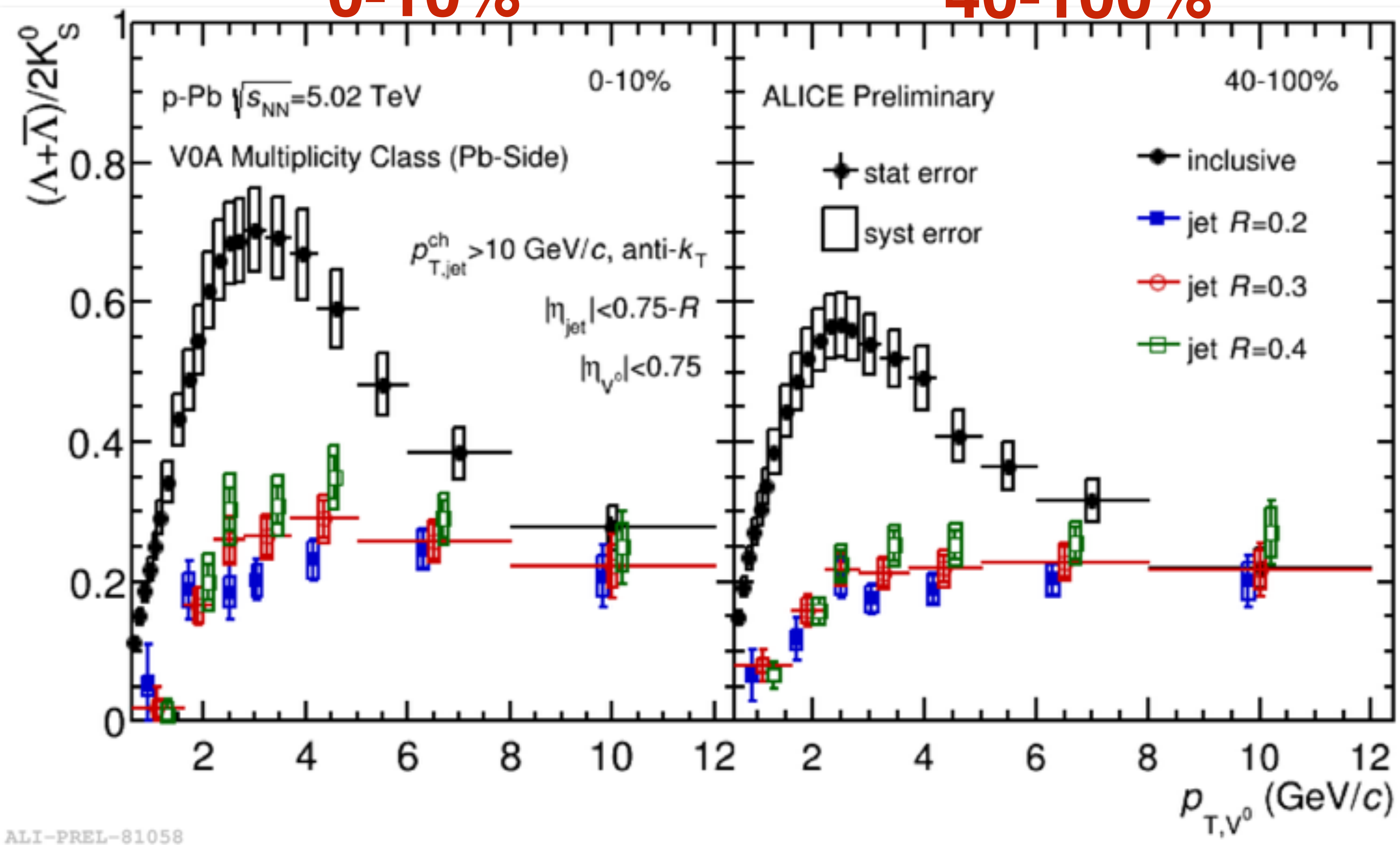
Phys. Lett. B728 (2014) 25

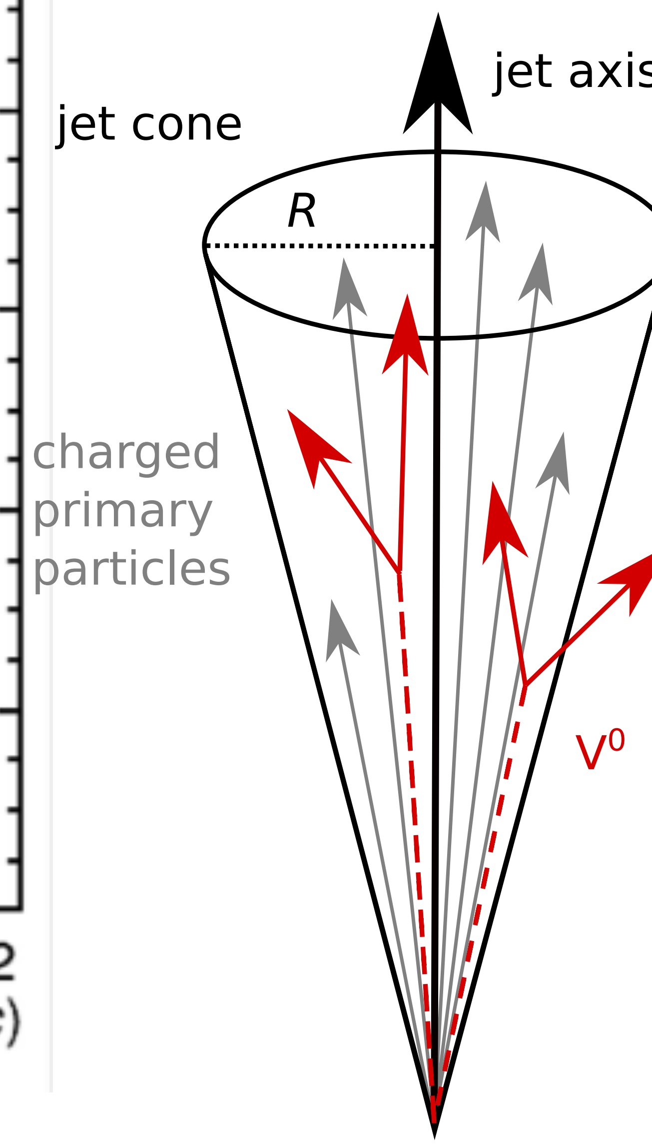
Study Λ/K_S^0 ratio in jets in p–Pb

➡ separation of soft and hard processes

Λ/K_S^0 Ratio in Jets in p–Pb Collisions

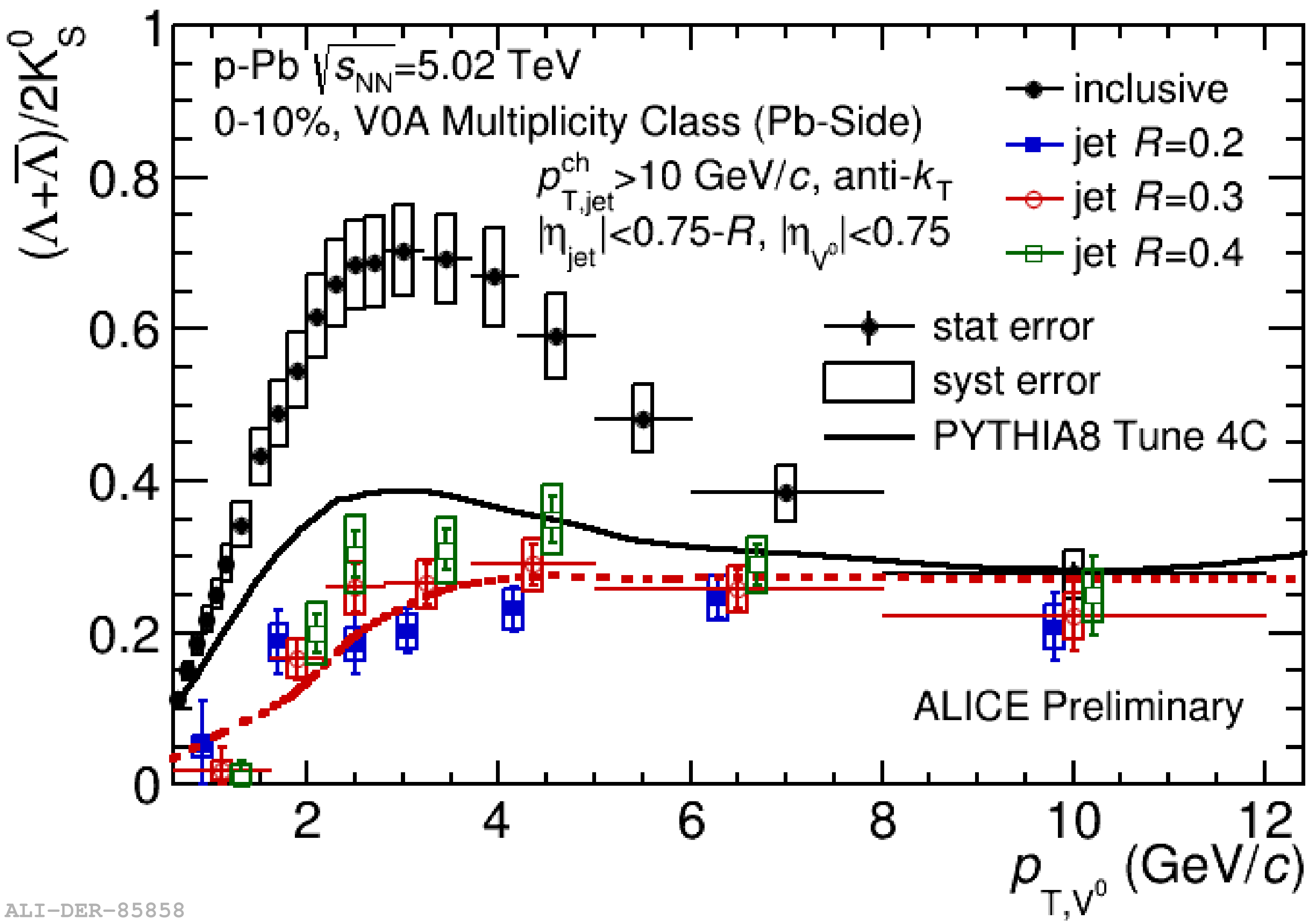
0-10% **40-100%**





- Λ/K_S^0 ratio significantly lower in jets than inclusive
- Ratio for different radii is the same within uncertainties
- Similar observation within errors for high and low multiplicity events

Comparison with PYTHIA



- Λ/K_S^0 ratio in jets in p–Pb consistent with PYTHIA simulations
- underlying event dominated by soft particle production
  - ➡ an interplay of radial flow and recombination
  - ➡ next step: proton/ϕ ratio inside and outside jets — study mass dependence — radial flow

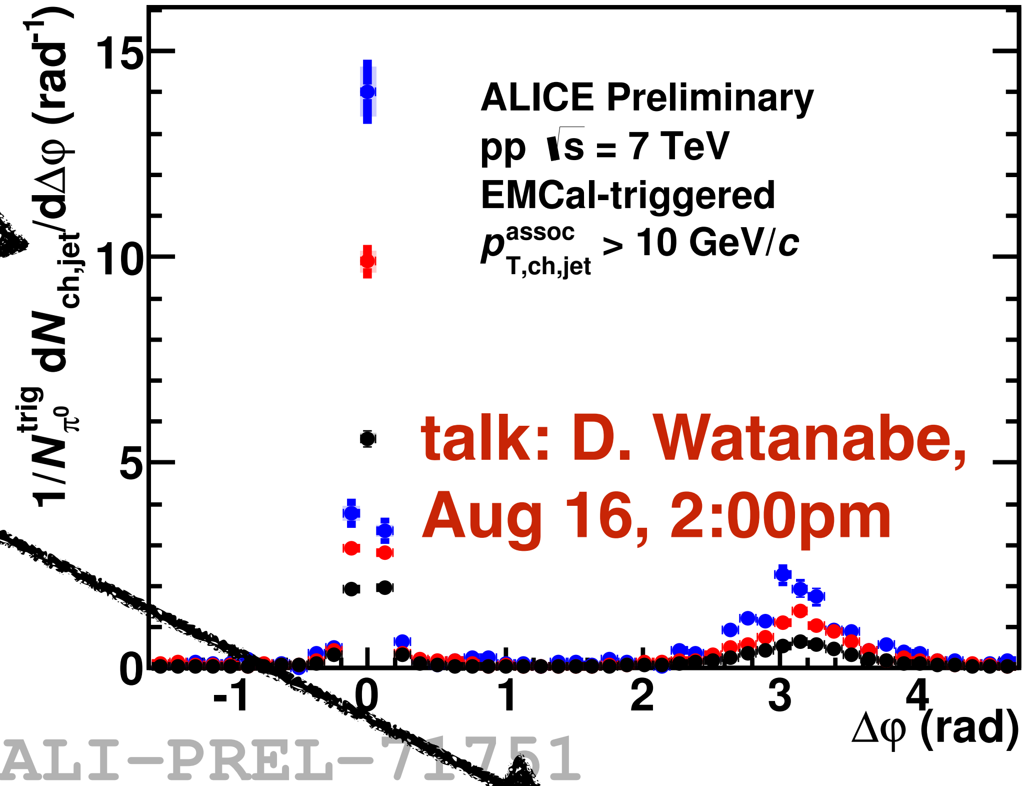
Conclusion

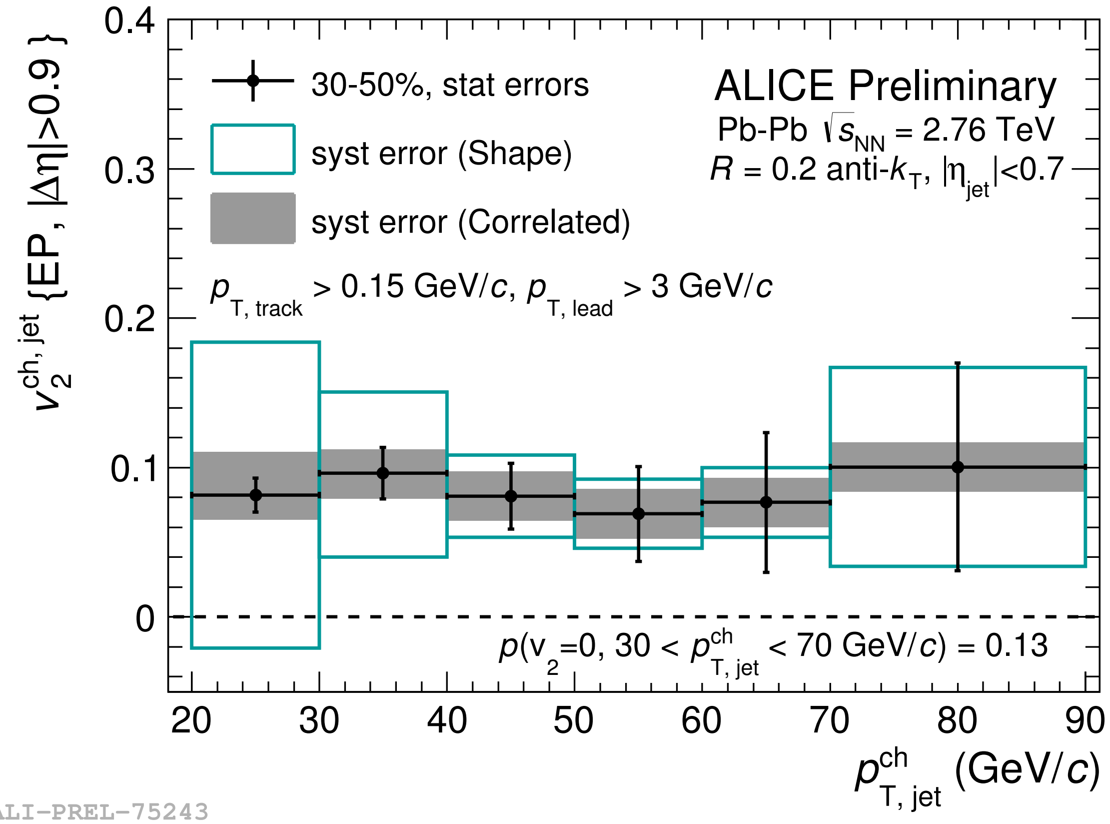
- **Pb—Pb collisions**
  - Large jet yield suppression — $R_{AA}, R_{CP} < 1$
  - No significant energy redistribution within $R < 0.4$
    ➡ ratio of jet and Δ_{recoil} spectra consistent with vacuum jets
  - No evident medium-induced acoplanarity
    ➡ $\Delta_{recoil}(\Delta\phi)$ distribution reproduced by PYTHIA

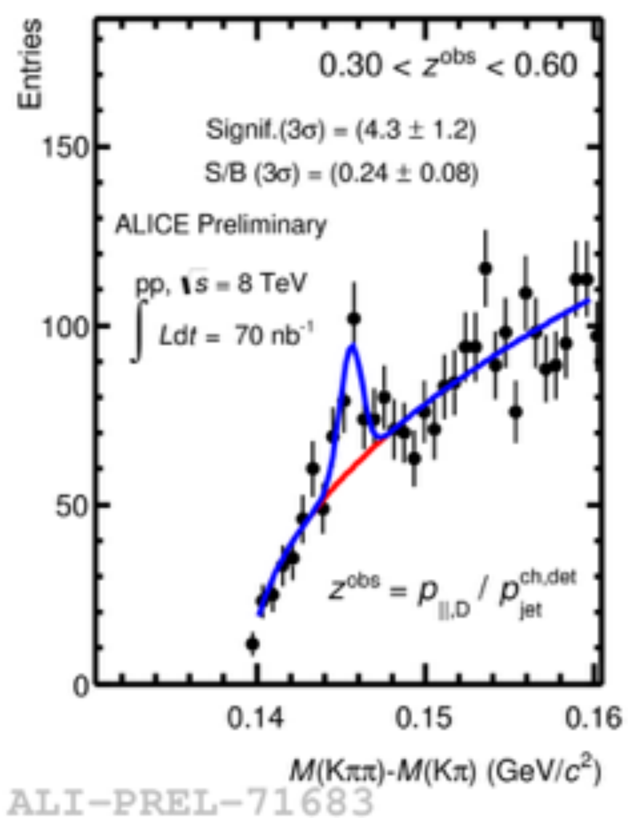
- **p–Pb collisions**
  - No indication of cold nuclear effects for jet observables
    ➡ jet $R_{pPb} = 1$, energy redistribution and dijet k_T in agreement with vacuum case
  - Underlying event dominated by soft particle production
    ➡ the enhanced ratio of Λ/K_S^0 is not present within the jet region

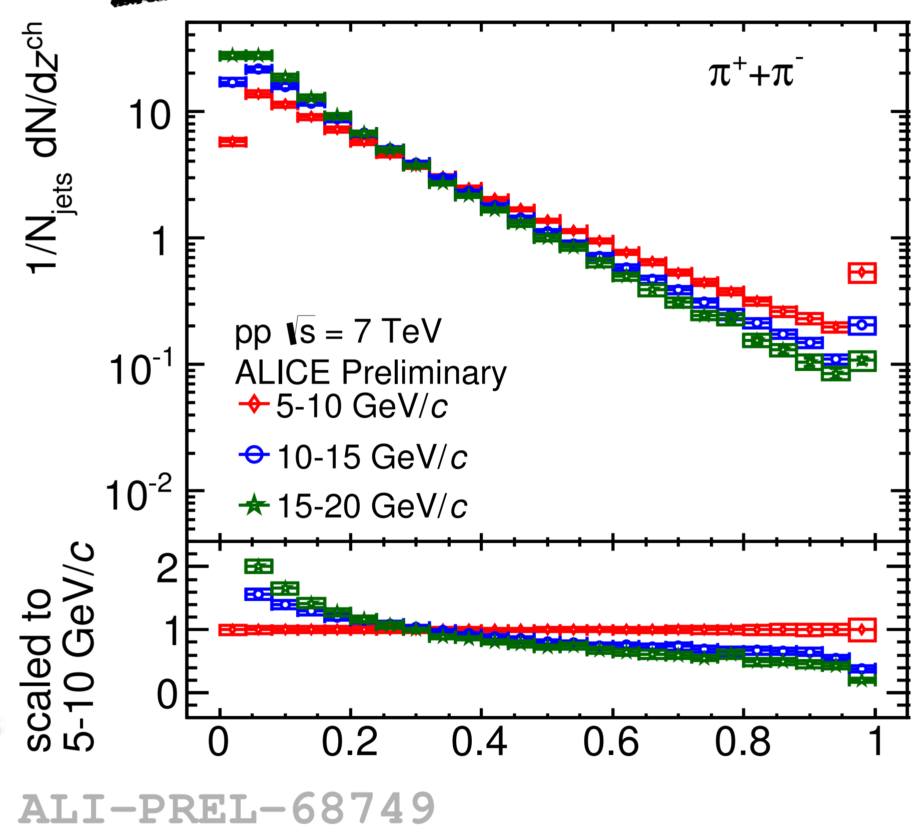
Outlook

- Hadron–jet correlations
- Jet fragmentation function
- Heavy flavor in jets
- Jet v_2



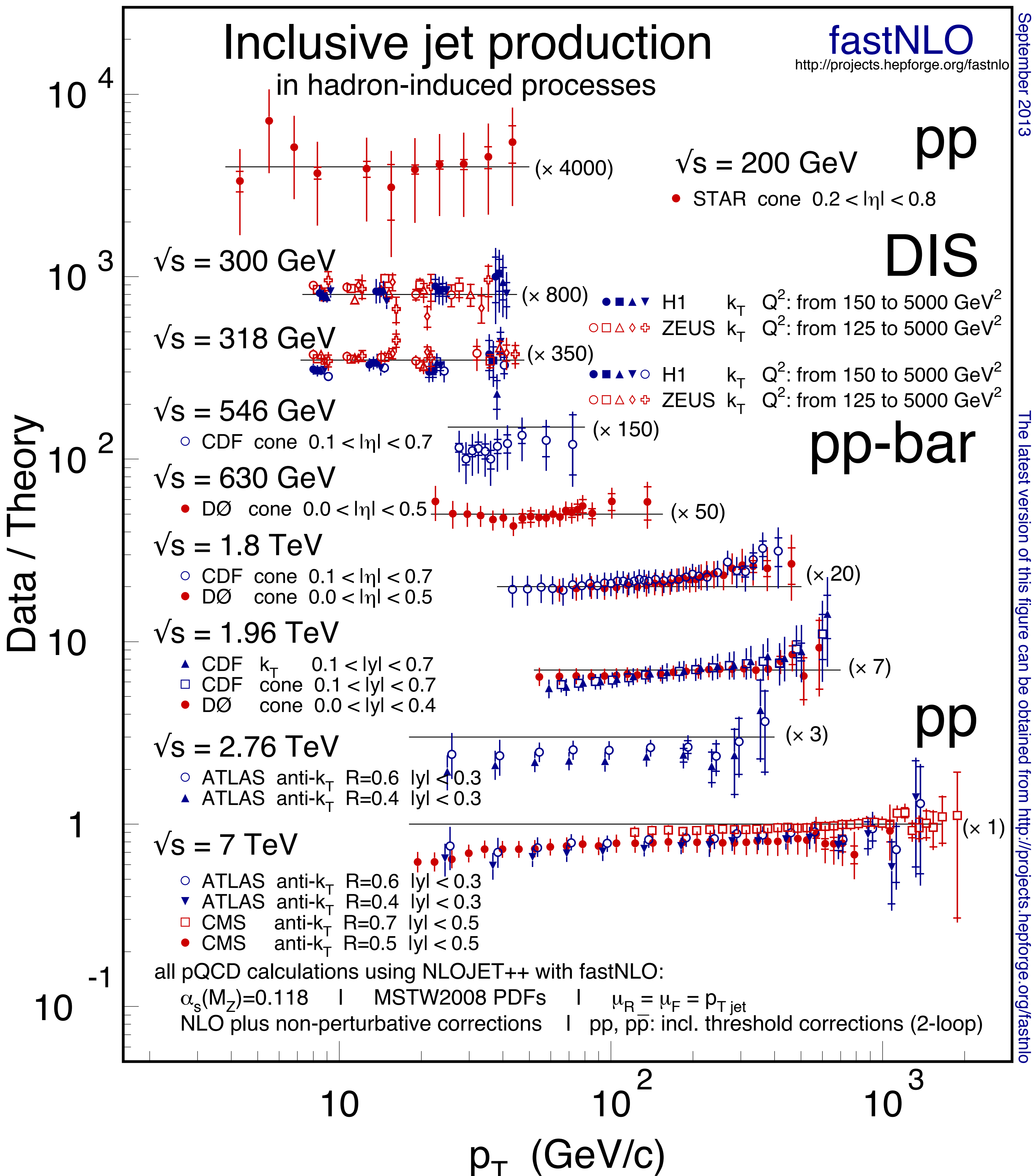






Backup

Motivation


Inclusive jet production
in hadron-induced processes
fastNLO
http://projects.hepforge.org/fastnlo
September 2013
pp
√s = 200 GeV
STAR cone 0.2 < |η| < 0.8
(× 4000)
DIS
√s = 300 GeV
(× 800)
H1 k_T Q²: from 150 to 5000 GeV²
ZEUS k_T Q²: from 125 to 5000 GeV²
√s = 318 GeV
(× 350)
H1 k_T Q²: from 150 to 5000 GeV²
ZEUS k_T Q²: from 125 to 5000 GeV²
pp-bar
√s = 546 GeV
CDF cone 0.1 < |η| < 0.7
(× 150)
√s = 630 GeV
DØ cone 0.0 < |η| < 0.5
(× 50)
√s = 1.8 TeV
CDF cone 0.1 < |η| < 0.7
DØ cone 0.0 < |η| < 0.5
(× 20)
√s = 1.96 TeV
CDF k_T 0.1 < |y| < 0.7
CDF cone 0.1 < |y| < 0.7
DØ cone 0.0 < |y| < 0.4
(× 7)
pp
√s = 2.76 TeV
ATLAS anti-k_T R=0.6 |y| < 0.3
ATLAS anti-k_T R=0.4 |y| < 0.3
(× 3)
√s = 7 TeV
ATLAS anti-k_T R=0.6 |y| < 0.3
ATLAS anti-k_T R=0.4 |y| < 0.3
CMS anti-k_T R=0.7 |y| < 0.5
CMS anti-k_T R=0.5 |y| < 0.5
(× 1)
all pQCD calculations using NLOJET++ with fastNLO:
α_s(M_Z)=0.118 | MSTW2008 PDFs | μ_R = μ_F = p_T jet
NLO plus non-perturbative corrections | pp, pp̄: incl. threshold corrections (2-loop)
The latest version of this figure can be obtained from http://projects.hepforge.org/fastnlo
Data / Theory
10^4
10^3
10^2
10
1
10^-1
10
10^2
10^3
p_T (GeV/c)

Jet Finder

- Experiment does not know about initial partons and the evolution just about the final detected particles
- Jet finder algorithm: assemble particles to obtain the physical observable
  - infrared and collinear safe: soft emission and collinear splitting should NOT change jets
  - identical defined at parton and hadron level: calculations can be compared to experiments
- Two main jet algorithm classes
  - cone-type algorithms: identify energy flow in cones — infrared and collinear safe must be carefully studied
  - sequential clustering algorithms: pair-wise successive recombinations — simple definition, infrared and collinear safe

Sequential Clustering Algorithms

1. For each pair of particles, i and j, calculate:

$$d_{ij} = \min\{p_{\mathrm{T},i}^{2n}, p_{\mathrm{T},j}^{2n}\}\frac{(\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2}{R}, \begin{cases} n = 1 & k_\mathrm{T} \text{ algorithm} \\ n = 0 & \text{C/A algorithm} \\ n = -1 & \text{anti-}k_\mathrm{T} \text{ algorithm} \end{cases}$$

   R is resolution parameter which is one of the inputs of the jet finder

2. if $d_{ij} = \min\{d_{ij}, p_{\mathrm{T},i}^{2n}, p_{\mathrm{T},j}^{2n}\}$, merge particles i and j into a single particle:

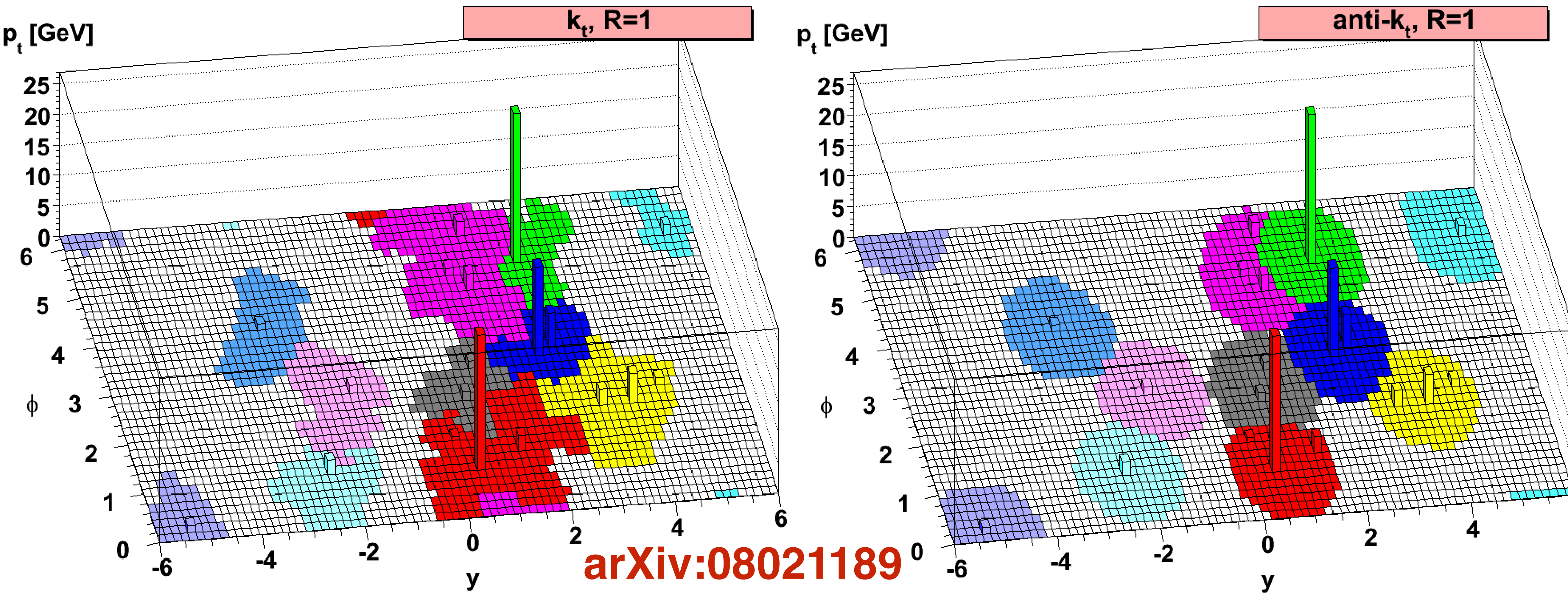
$$\begin{aligned} p_{\mathrm{T},r} &= p_{\mathrm{T},i} + p_{\mathrm{T},j} \\ \varphi_r &= (w_i\varphi_i + w_j\varphi_j)/(w_i + w_j) \\ \eta_r &= (w_i\eta_i + w_j\eta_j)/(w_i + w_j) \end{aligned}$$

   $w_i = 1, p_{\mathrm{T},i}, p_{\mathrm{T},i}^2$ for different recombination schemes

3. repeat from step 1 until no particle is left

Jet Area: k_T vs. anti-k_T

- The jet area can be used to access jet susceptibility to contaminations: underlying background, pileup…



- k_T: the detailed jet shapes are in part determined
- anti-k_T: more like the circles — insensitive to soft radiation

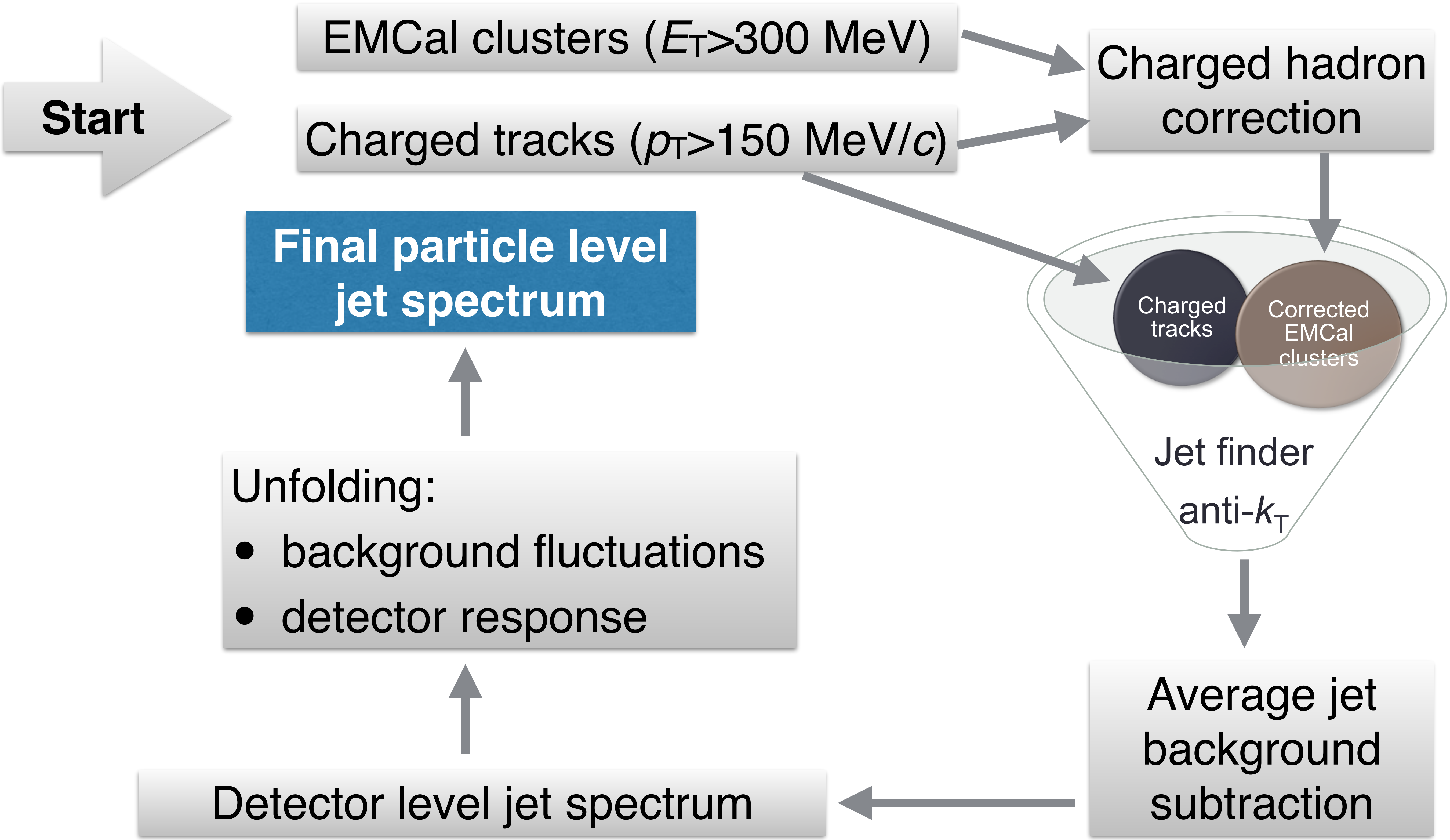
Measured Jets in Experiment

- Reporting a jet with p_T = 100 GeV/c in data is meaningless

- A correct way to define a measured jet is:
  - a full (or charged) jet at p_T = 100 GeV/c
  - with resolution parameter (jet cone size) $R = 0.2$
  - reconstructed by anti-k_T algorithm with p_T/E_T-scheme

- But one has to keep in mind that the measured jet p_T may be contaminated by:
  - energy redistribution, detector effects and underlying background and background fluctuations…

Analysis Workflow



Average Background Density

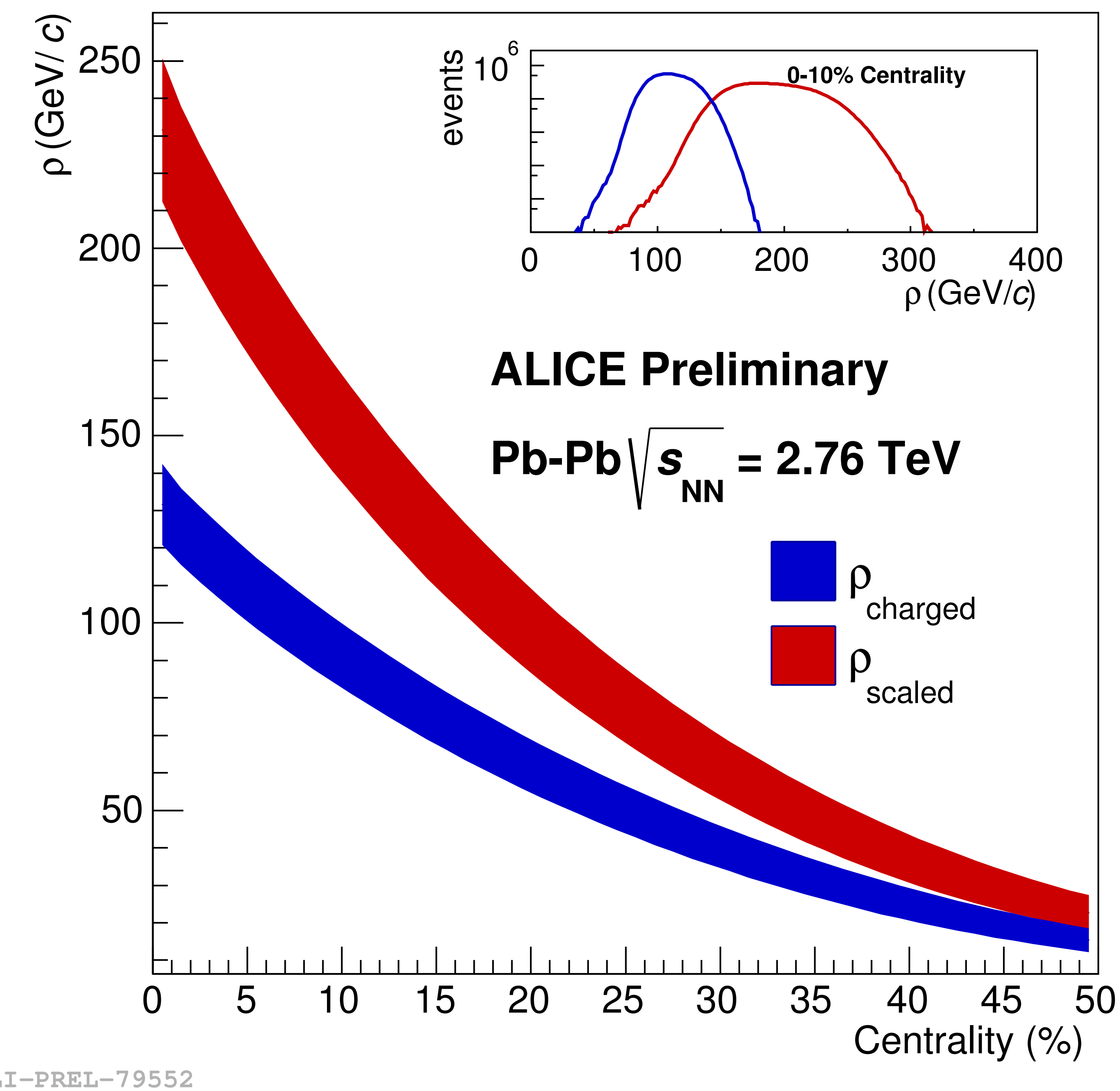
- Event-by-event background is obtained using the charged particle jets reconstructed by k_T algorithm

$$\rho_{\mathrm{charged}} = \mathrm{median}\left(\frac{p^{\mathrm{ch}}_{\mathrm{T},k_{\mathrm{T}}\mathrm{jet}}}{A^{\mathrm{ch}}_{k_{\mathrm{T}}\mathrm{jet}}}\right)$$

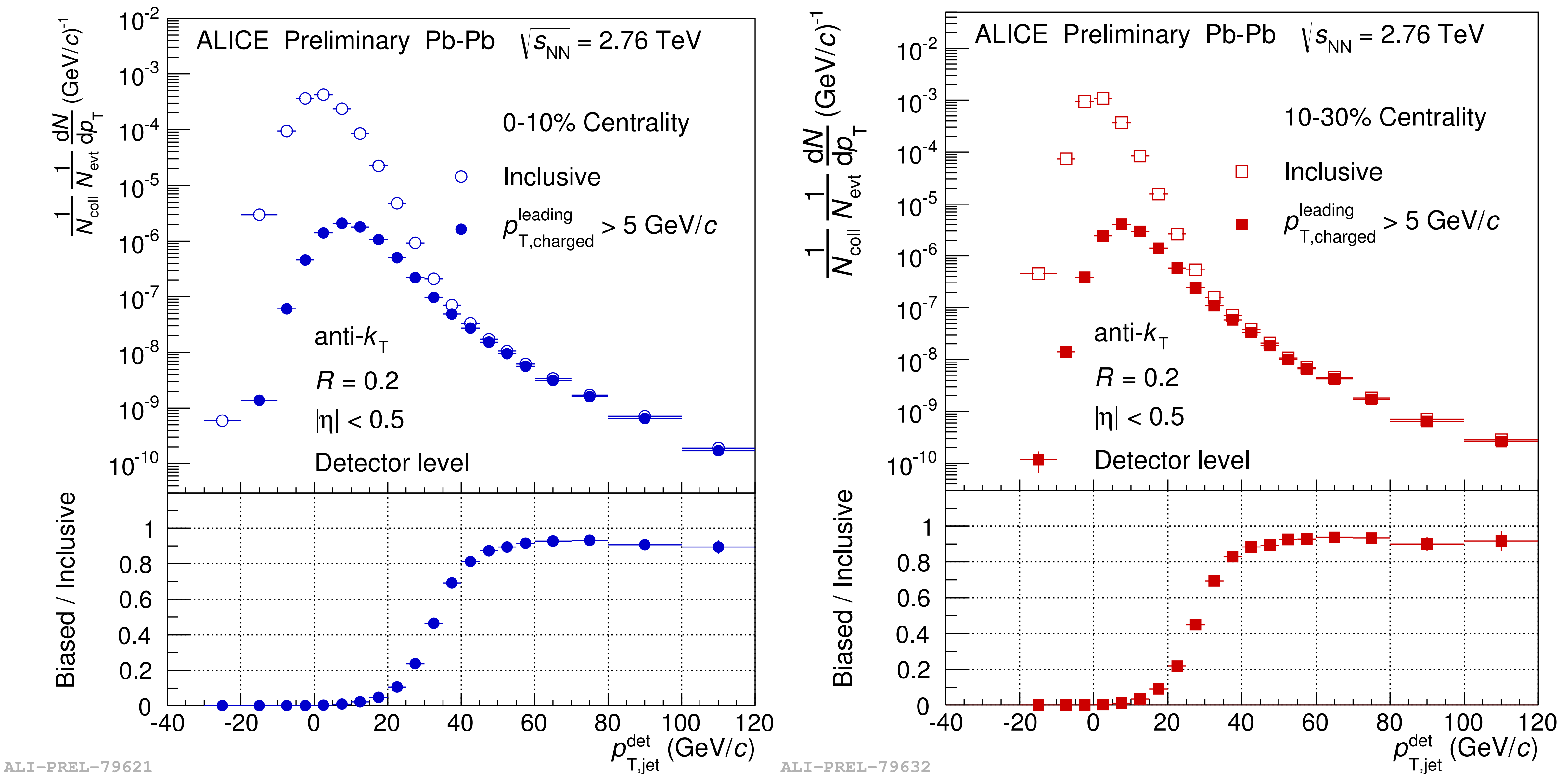
- Scaled to account for neutral energy

$$\rho_{\mathrm{scaled}} = \rho_{\mathrm{charged}} \frac{\sum E_{\mathrm{T}}^{\mathrm{cluster}} + \sum p_{\mathrm{T}}^{\mathrm{track}}}{\sum p_{\mathrm{T}}^{\mathrm{track}}}$$

- Background density in most central Pb–Pb event:
  - ~200 GeV/*c* per unit area
  - ~25 GeV/*c* for *R*=0.2 jets



Jet Spectra at Detector Level



- With charged leading hadron p_T>5 GeV/c
  - suppress combinatory background
  - bias towards harder fragmentation

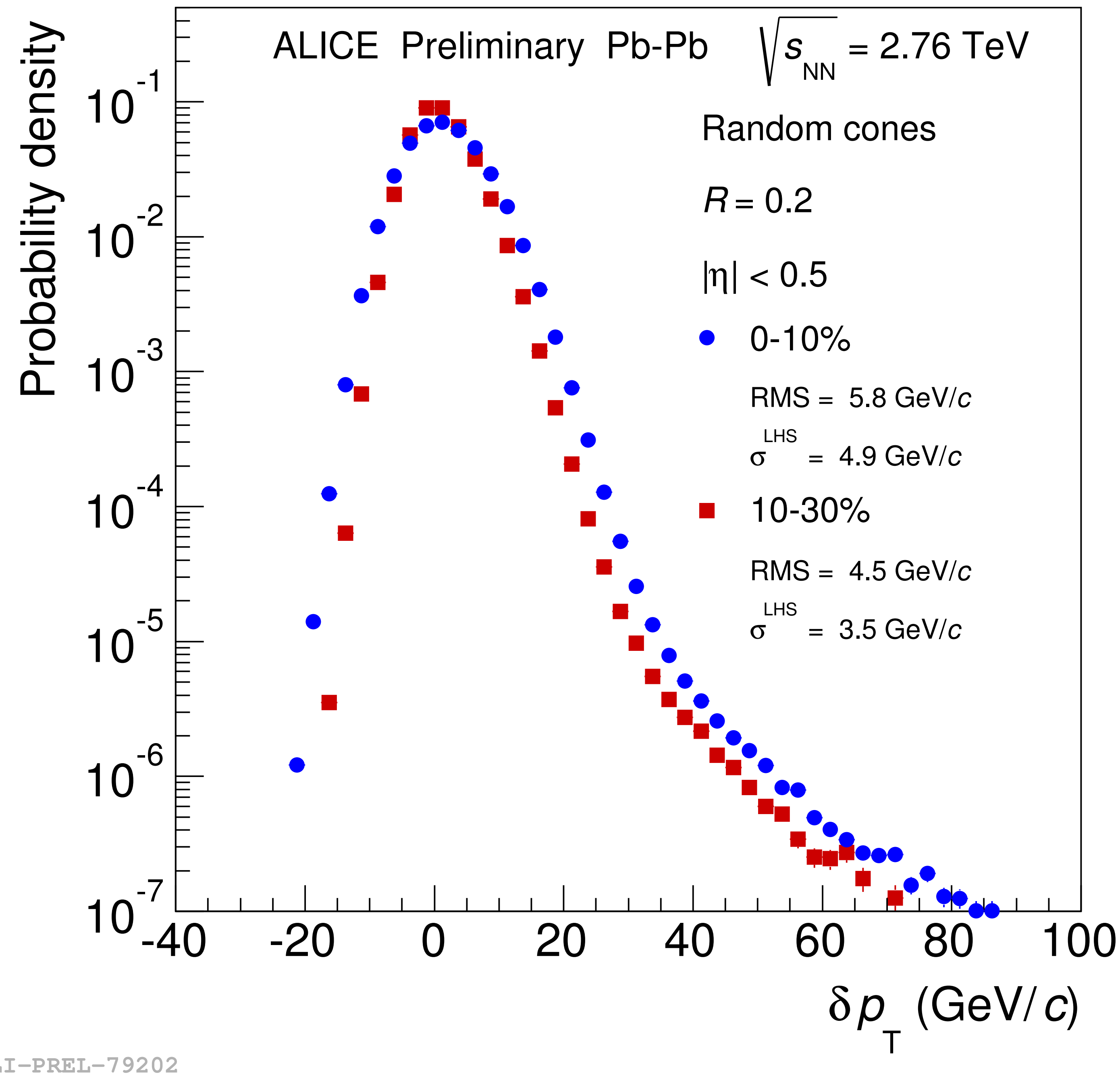
$$p_{T,jet}^{det} = p_{T,jet}^{meas} - \rho A_{jet}$$

Background Fluctuations: Random Cone

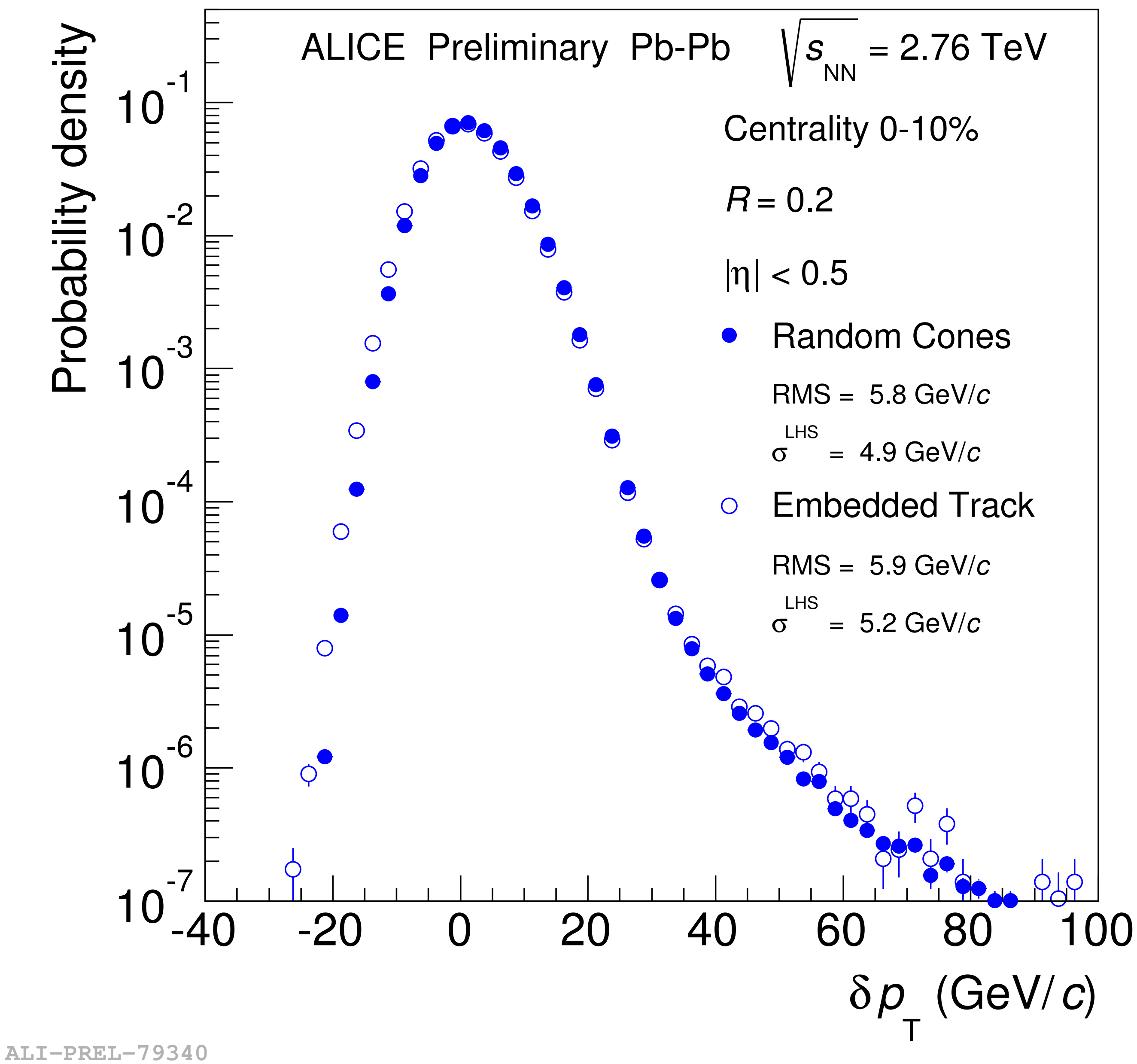
- The size of background fluctuations is characterized by δp_T

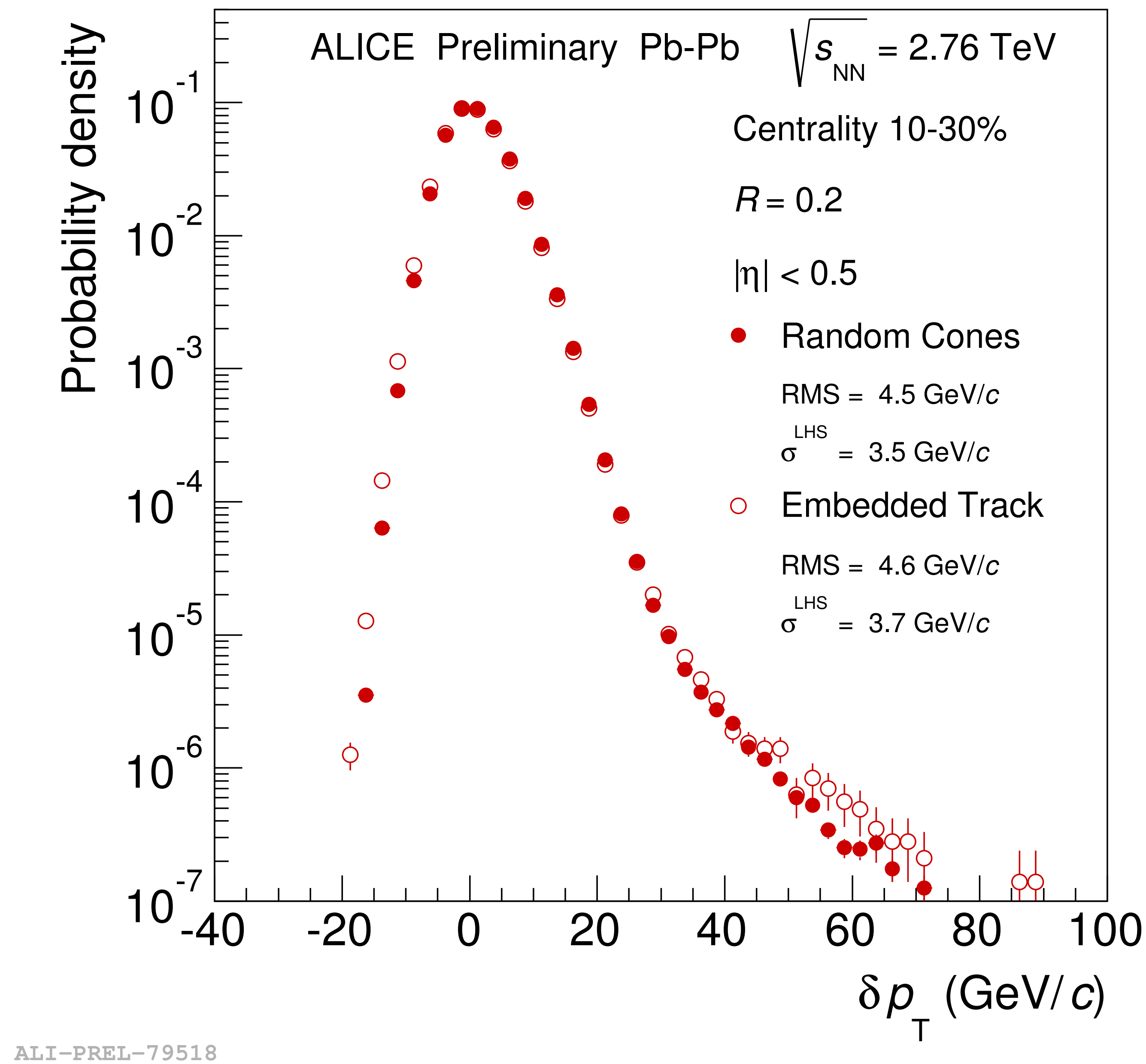
$$\delta p_T = \sum_{RC} p_{T,\text{part}} - \rho_{\text{scaled}} \times \pi R^2$$

- Asymmetry distribution
  - LHS: Gaussian-like — dominated by soft particle production
  - RHS: tail due to hard particles — jets overlap



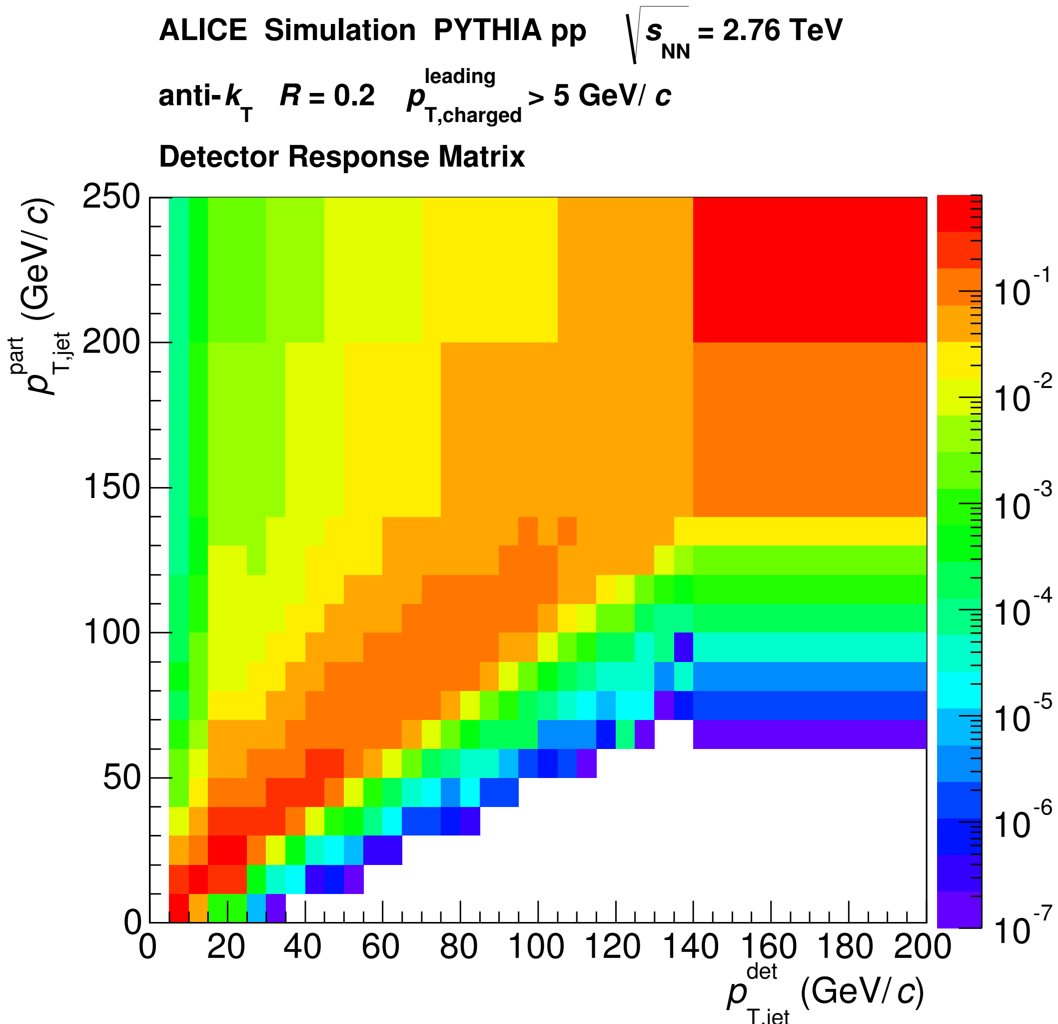
Background Fluctuations: Embedding



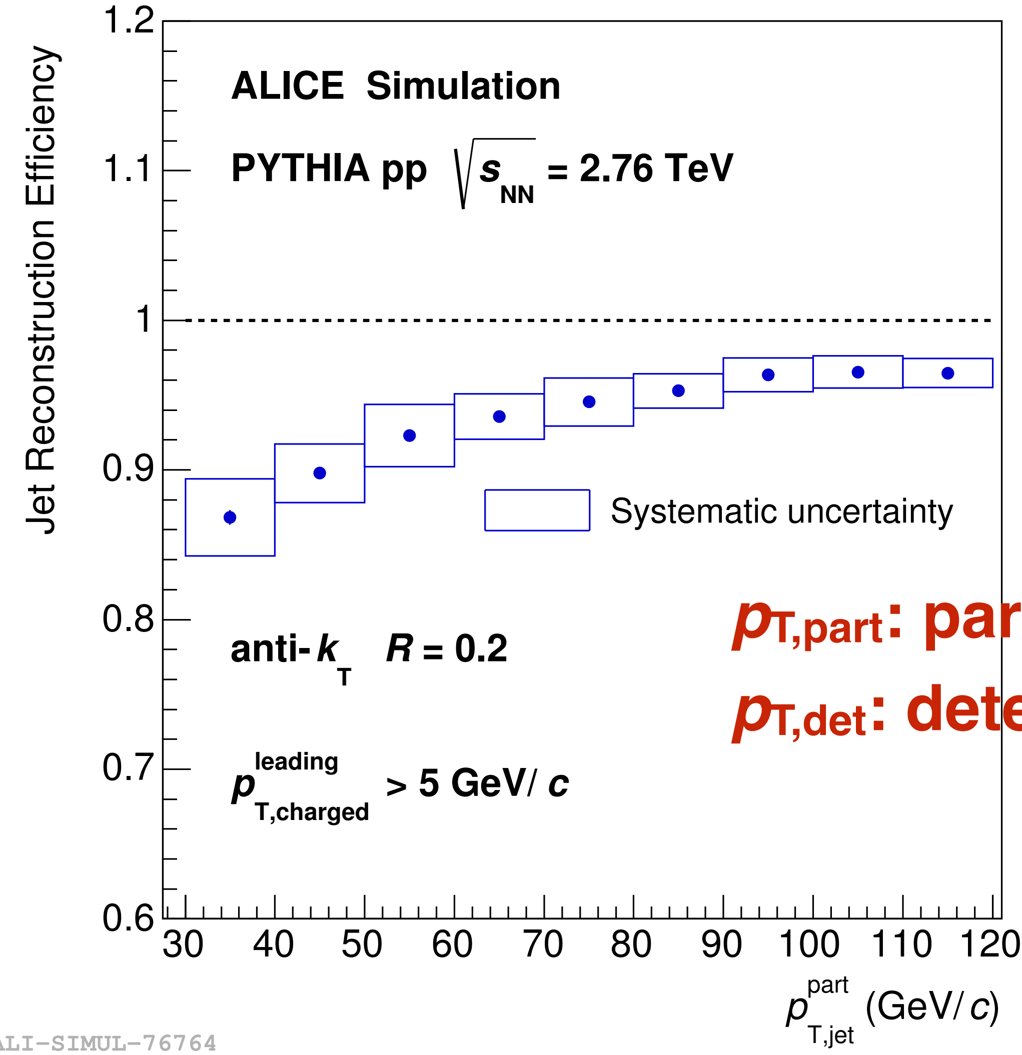


- Single particle embedding δp_T is compared with random cones
  - difference gives the the uncertainty on background fluctuations

Detector Effect



ALI-SIMUL-76830



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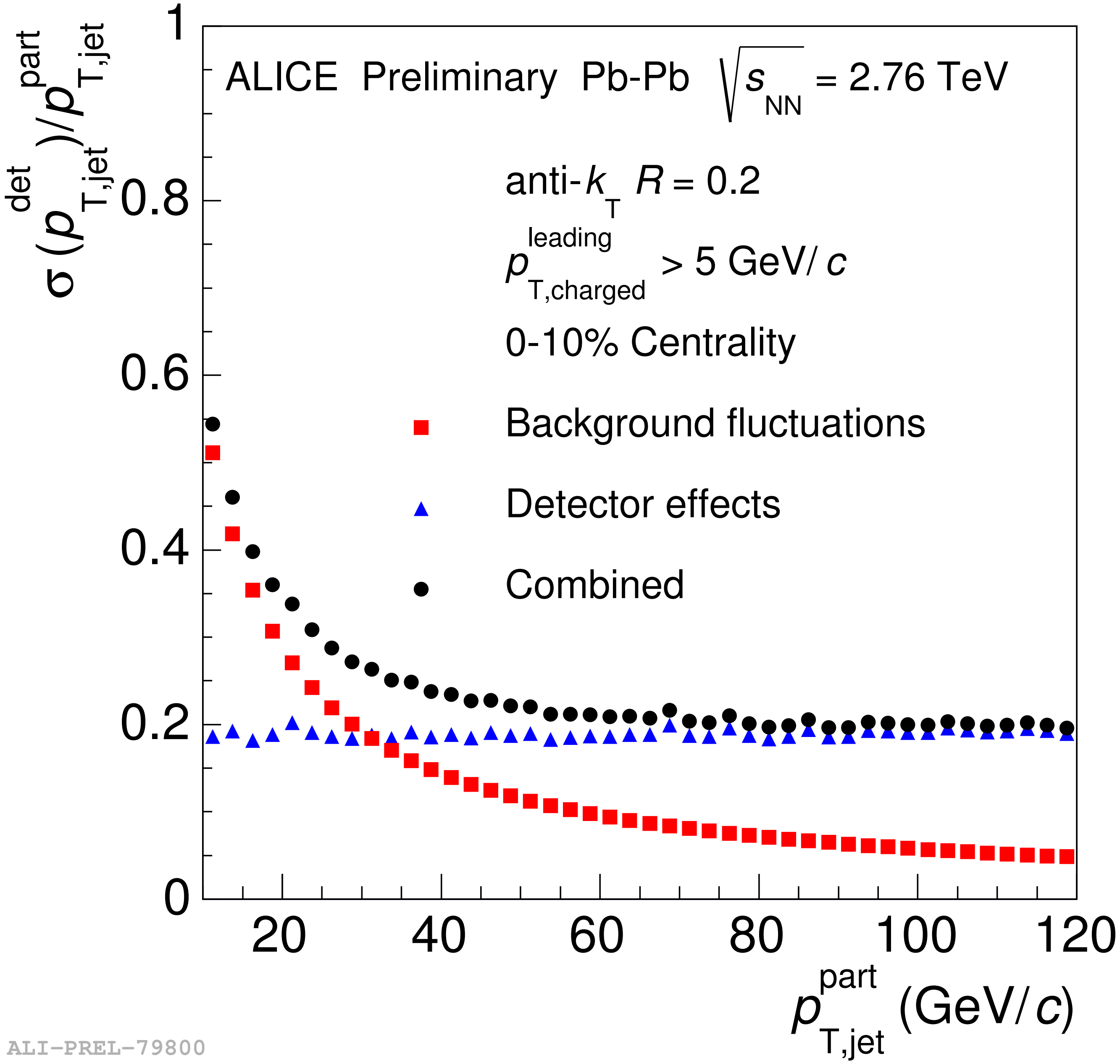
$p_{T,part}$: particle level jet p_T

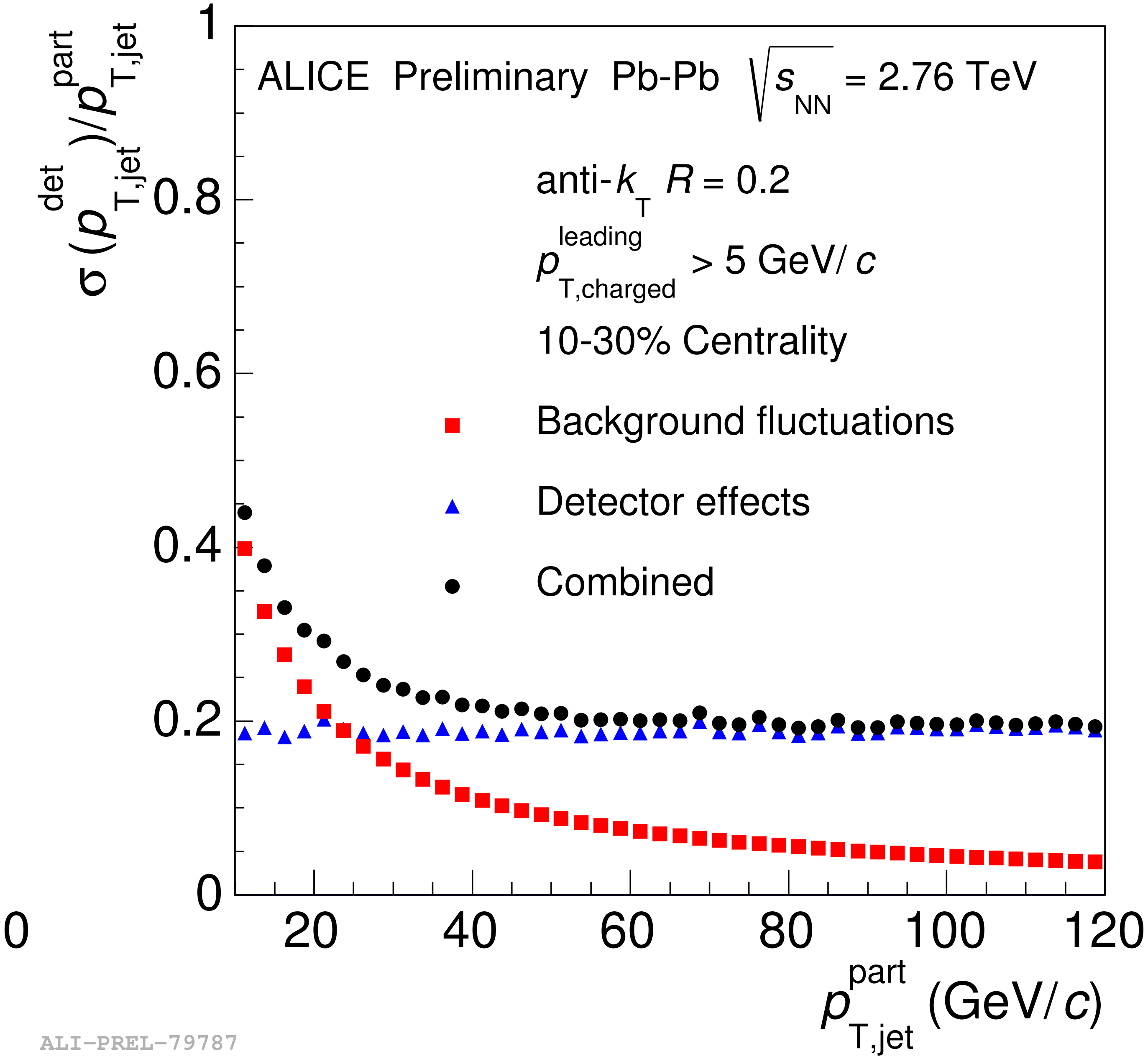
$p_{T,det}$: detector level jet p_T

- Detector effect: obtained by PYTHIA+realistic detector simulations
  - detector resolution — response matrix
  - jet reconstruction efficiency — dominated by the single track efficiency of the leading hadron

➡ multiplicity dependence is determined by Hijing simulations

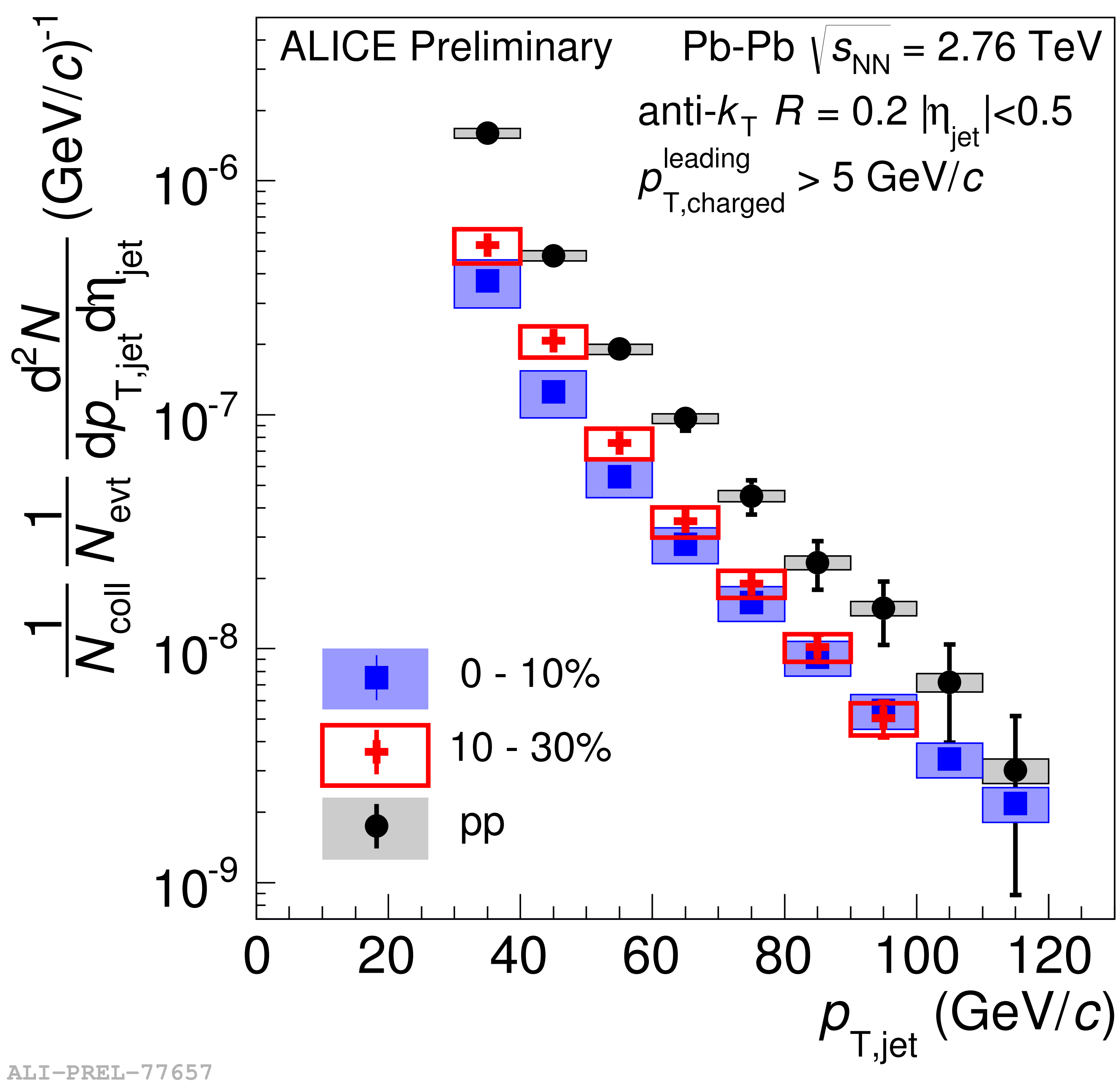
Jet Momentum Resolution





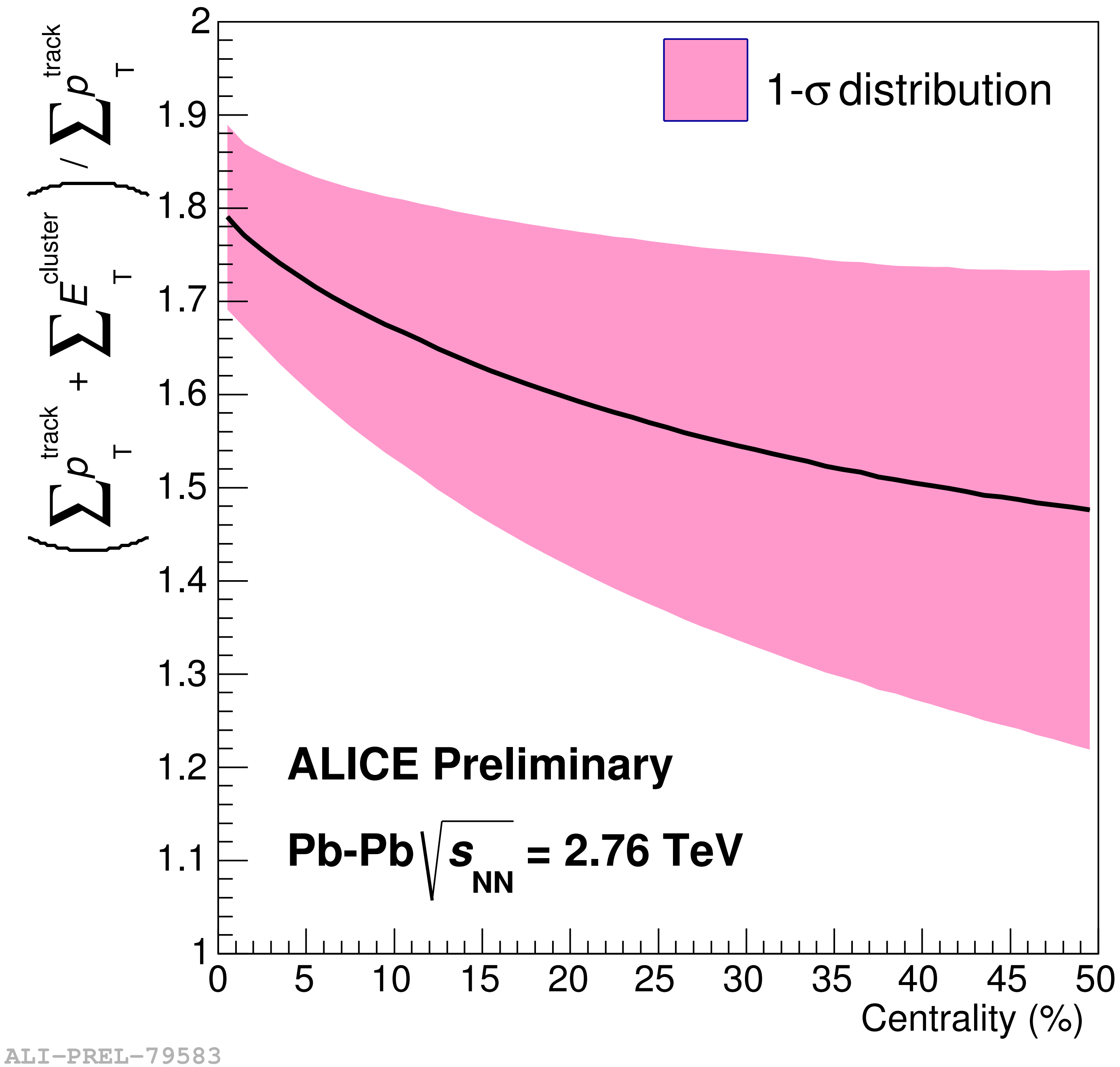
- Background fluctuations: smaller in semi-central collisions (10-30%) than in central collisions (0-10%), dominate in p_T<30 GeV/c
- Detector effects: independent of centrality and p_T, dominate in p_T>30 GeV/c

Jet p_T Spectra at Particle Level

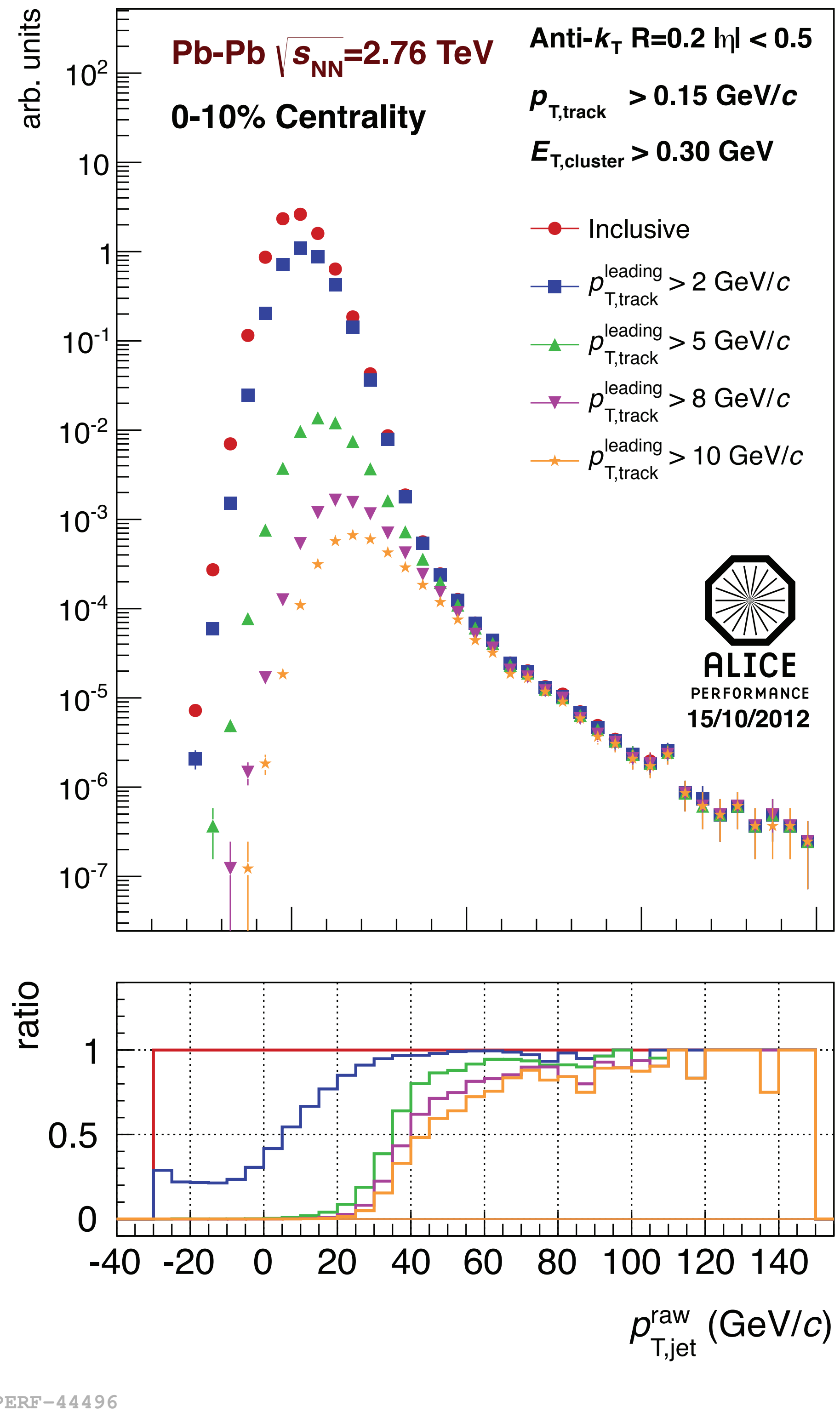


- Corrections applied for both detector effects and background fluctuations through unfolding
- Unfolding methods
  - Pb–Pb: SVD, Bayesian, χ^2
  - pp: Bayesian, bin-by-bin

Background Scale Factor

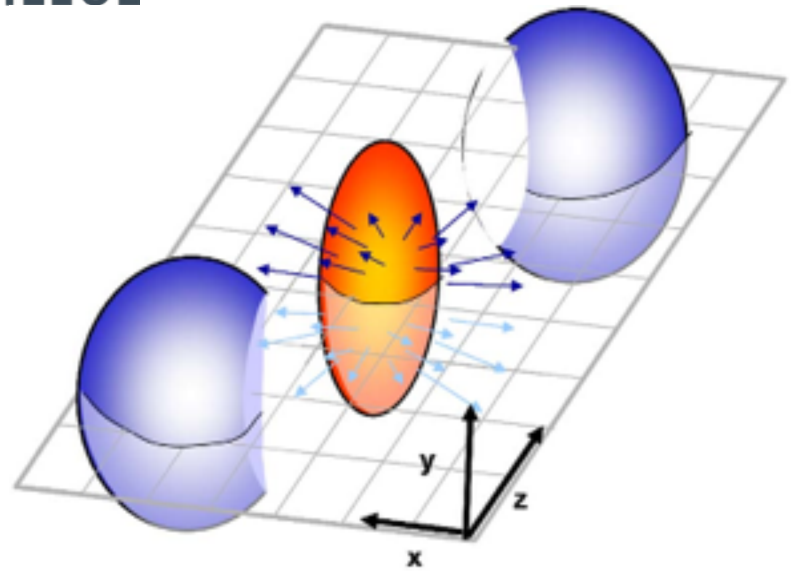


Again: Background

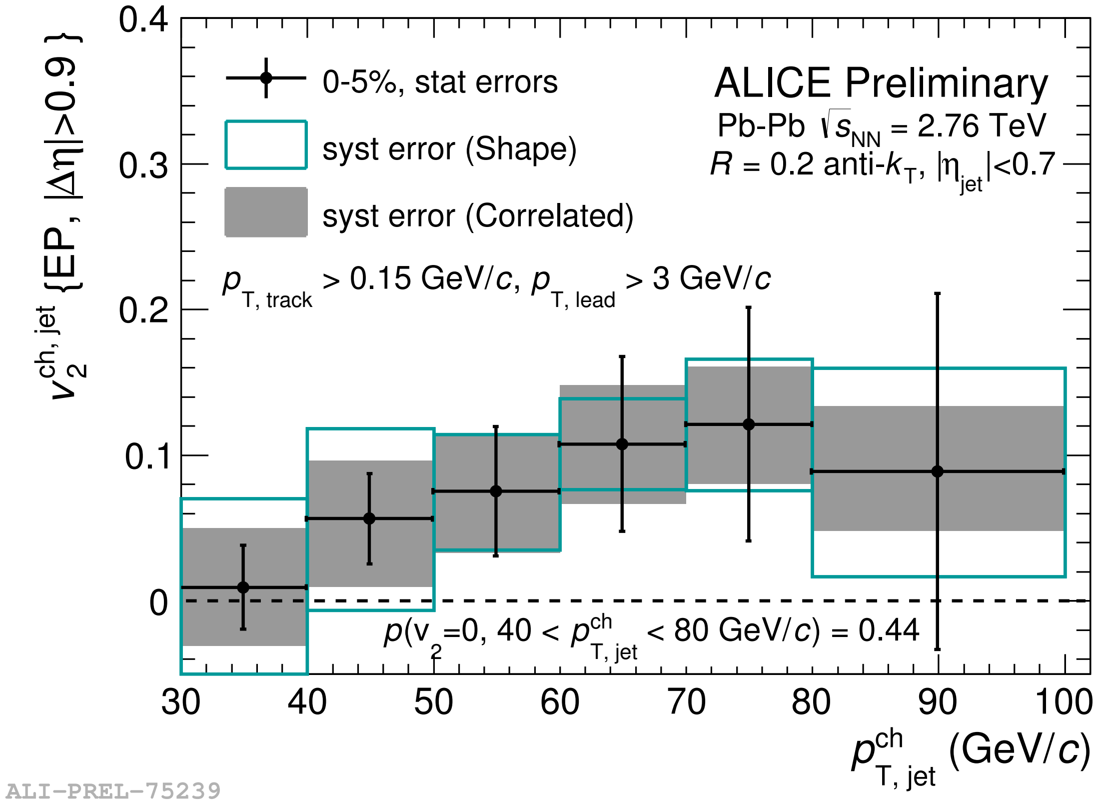


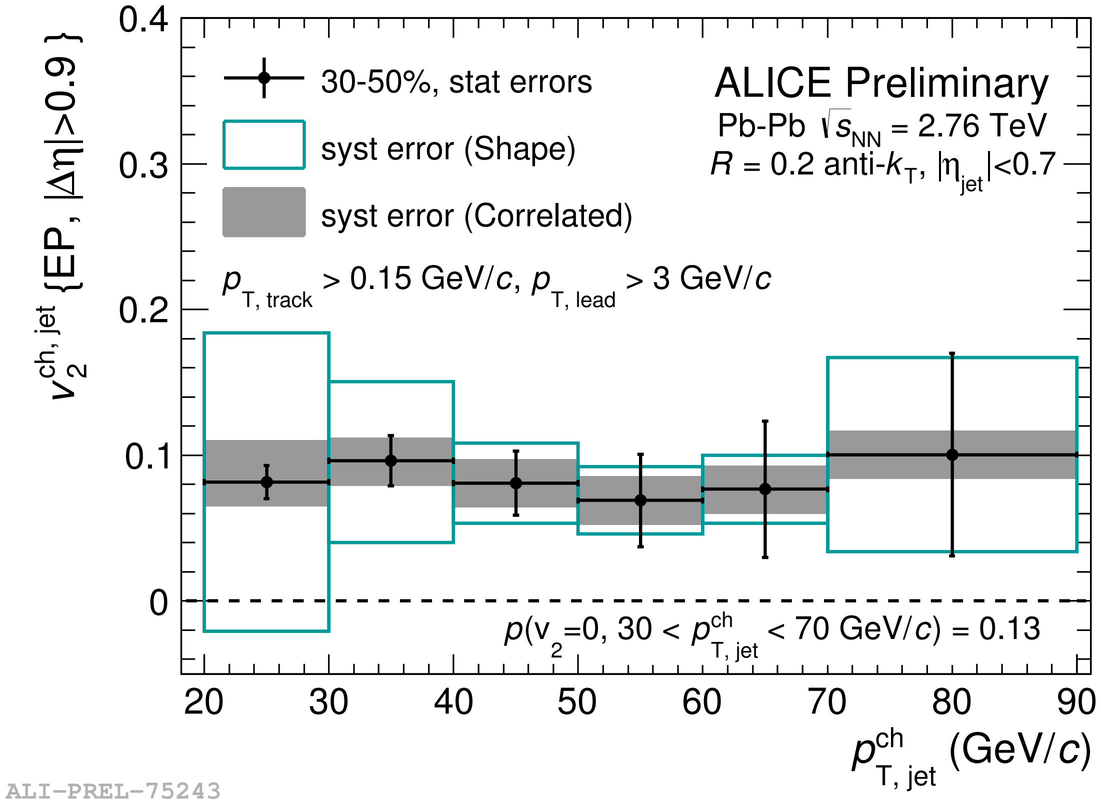
- Challenge in heavy-ion collisions
  - large combinatorial background and background fluctuations
  - leading track cut: suppress combinatorial jets — surface bias
  - small jet radius: decrease the background fluctuations — missing redistributed energy

Event Plane Dependence of Jets



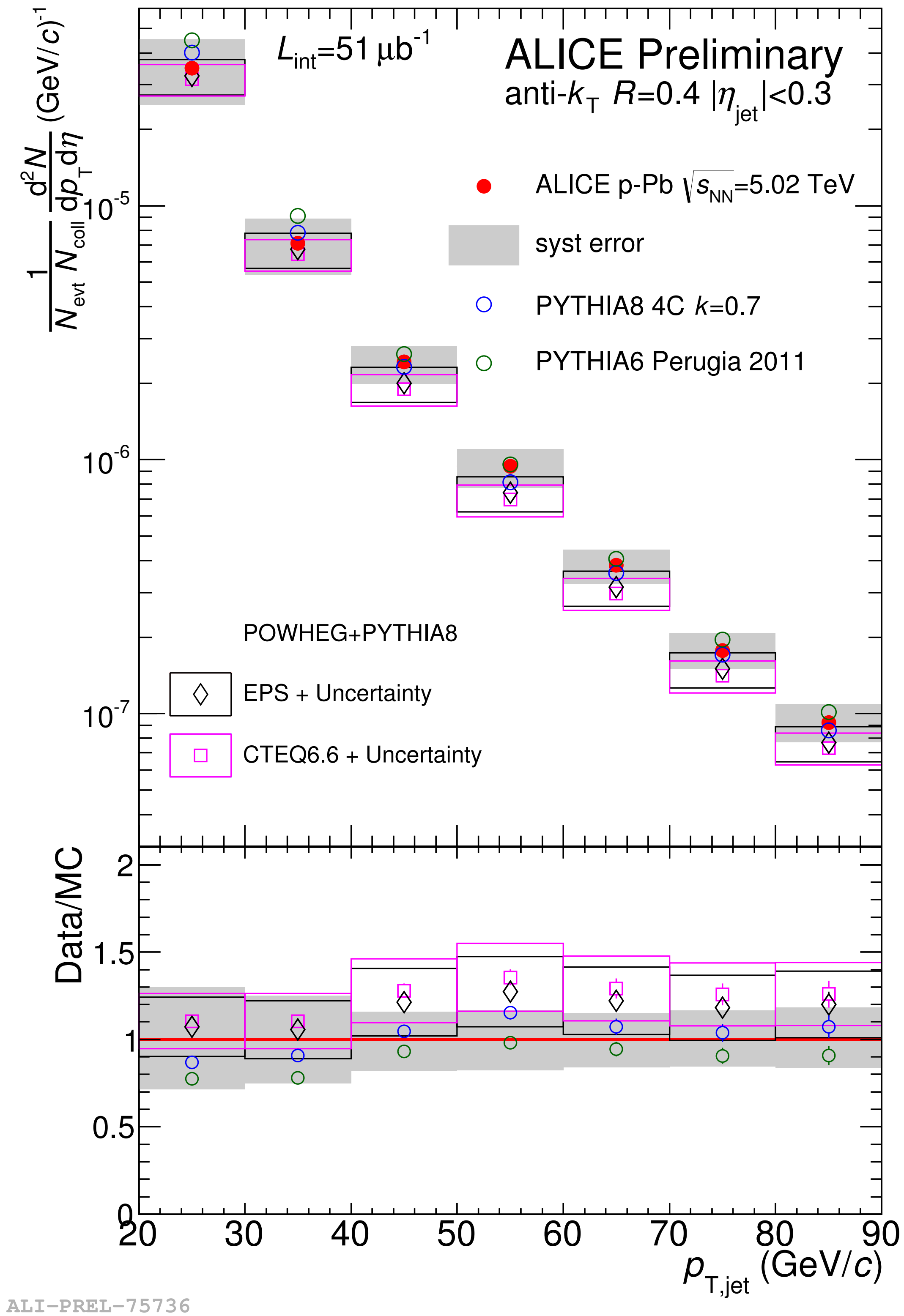
$$v_2^{\mathrm{jet}} = \frac{1}{R_{\mathrm{EP}}} \frac{1}{4\pi} \frac{N_{\mathrm{in}} - N_{\mathrm{out}}}{N_{\mathrm{in}} + N_{\mathrm{out}}}$$





- Used to investigate the path length dependence of jet energy loss
- non-vanished v_2 in semi-central collisions (30-50%) with 2σ effect

Corrected Jet Spectrum



- Jet measurements in p–Pb collisions
  - crucial test of the cold nuclear effects
  - using the similar techniques as in Pb–Pb collisions
  - background density is corrected by the event occupancy to since the large local fluctuations of the event multiplicity

K/π and P/π ratios in Jets in pp Collisions

- K/π ratio increases with z/p_T
- Proton/π ratio suppression at high z/p_T
- No scaling with particle p_T observed
- scaling in $z > 0.2$