ICHEP2018 SEOUL

XXXIX INTERNATIONAL CONFERENCE ON high energy PHYSICS

JULY 4 - 11, 2018 COEX, SEOUL

ALICE

Investigating jet modification in heavy-ion collisions at $\sqrt{s_{NN}}$ = 5.02 and 2.76 TeV with ALICE

Hiroki Yokoyama for the ALICE Collaboration

University of Tsukuba, Japan

ICHEP 2018, Seoul, South Korea

7 July 2018

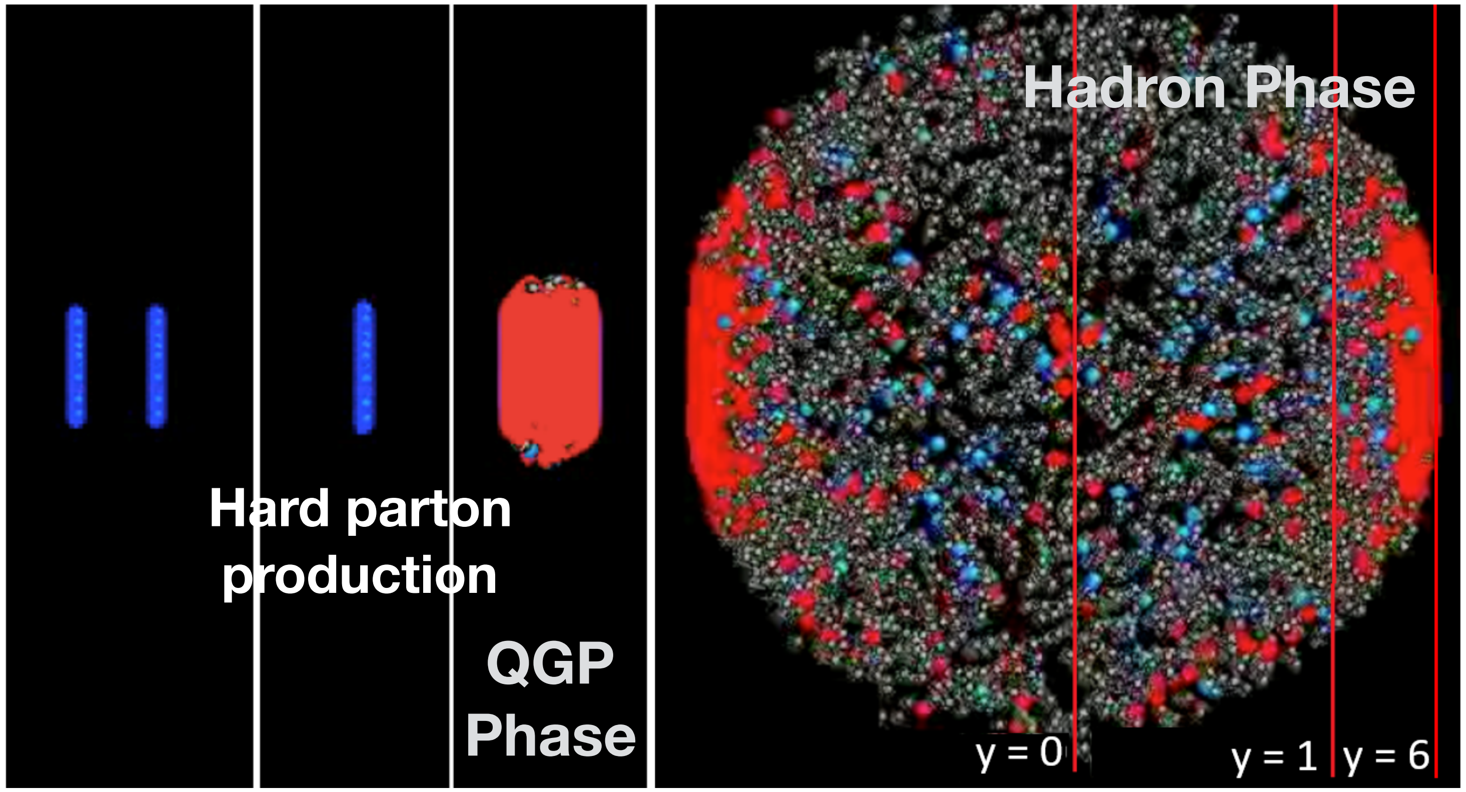
筑波大学
University of Tsukuba

Quark-Gluon Plasma

- **Quark-Gluon Plasma (QGP)**
  - Hot & dense QCD matter
    - Similar to early Universe ~1μs old
  - Deconfined state of quarks and gluons
  - Theoretically inferred through lattice gauge simulations of QCD
- **Ultra-Relativistic Heavy Ion Collision**
  - High-energy nucleus-nucleus collisions at particle accelerators (RHIC, LHC)

Hard Probes
- Produced by high-p_T QCD process
- Initial hard parton scattering

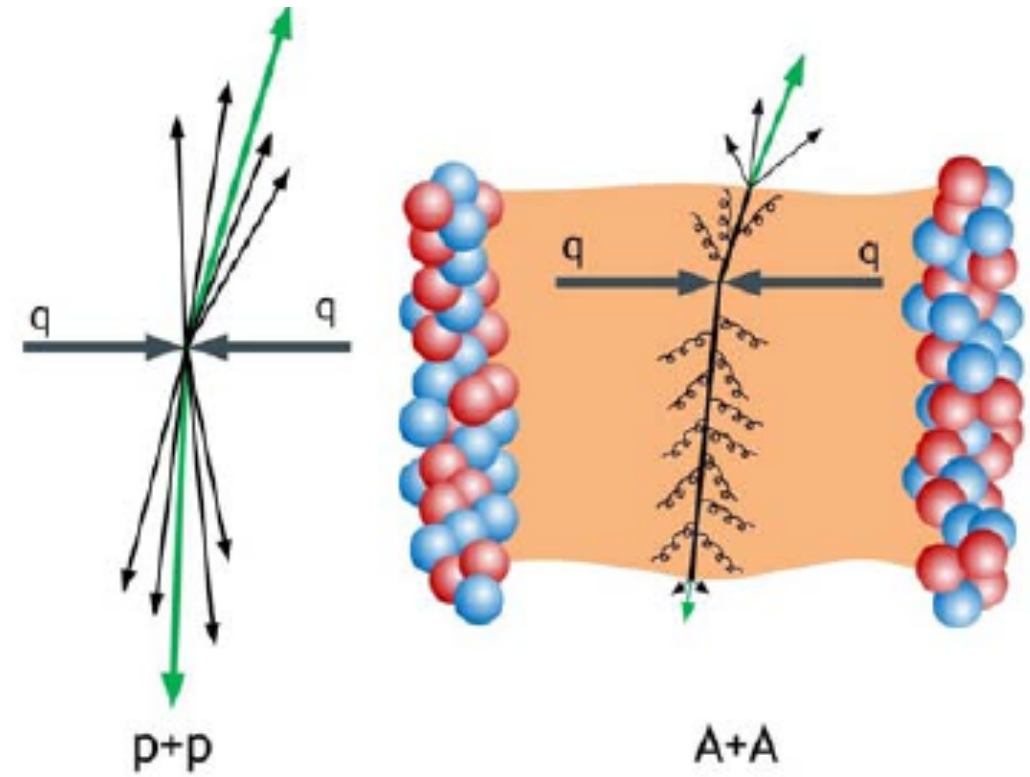
Soft Probes
- Bulk of created particles
- Dominant at low-p_T



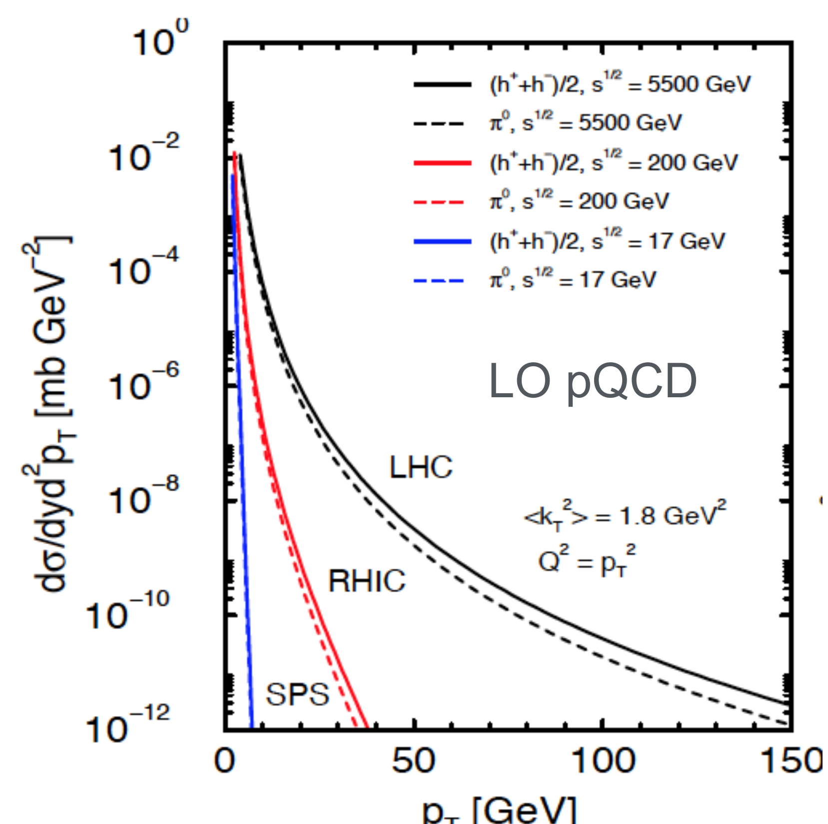
Jet as Hard Probes of the QGP

Jet Quenching

- ☑ Partons' energy loss in the QGP
  - Energy attenuation/disappearance or shape modification of observed Jets
  - **Evaluation of these modifications allows to assess QGP properties**



1. **<u>Auto-generated probes</u>**
   - short QGP lifetime (~10^{-23} s)
2. **<u>Probe the entire medium evolution</u>**
   - occur at early stage : τ ~ 1/Q
3. **<u>Well calibrated probes</u>**
   - production rate calculable within pQCD
4. **<u>Copious production at the LHC</u>**
5. **<u>Access to initial parton kinematics</u>**
   - via jet reconstruction



hep-ph/0212109

Jet Measurement in LHC-ALICE

Charged Particles : |η| < 0.9, 0<ϕ<2π

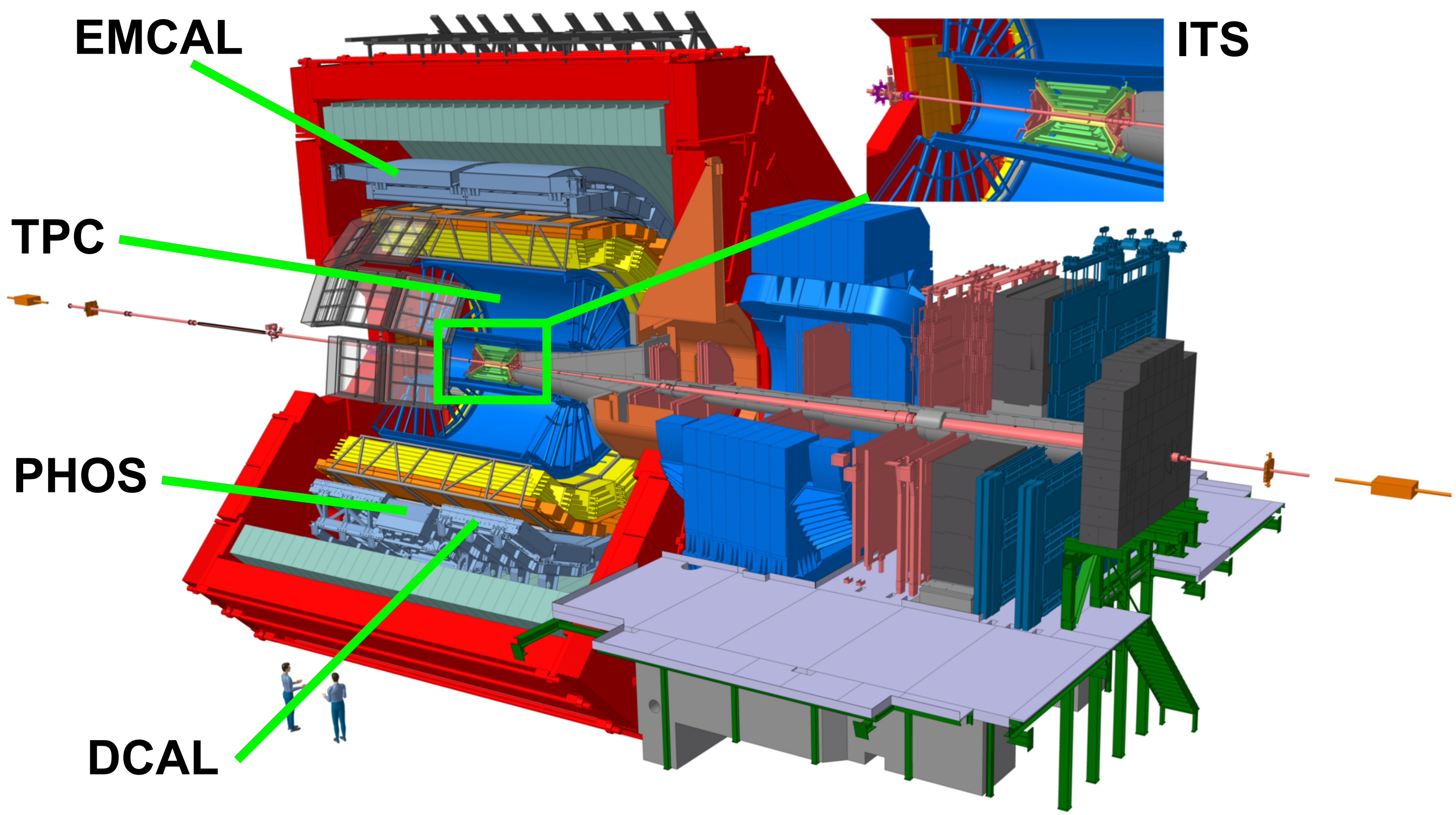
- ☑ **ITS** : Silicon tracking detector
- ☑ **TPC** : Time projection chamber

⇒ "Charged" Jet

Electromagnetic particles : |η| < 0.7

- ☑ **EMCAL, (DCAL : Run 2 from 2015-)**
  - Pb-Scintillator sampling calorimeter
- ☑ **PHOS**
  - Lead-tungsten crystal (PWO) based calorimeter

⇒ Charged+EM = "Full" Jet



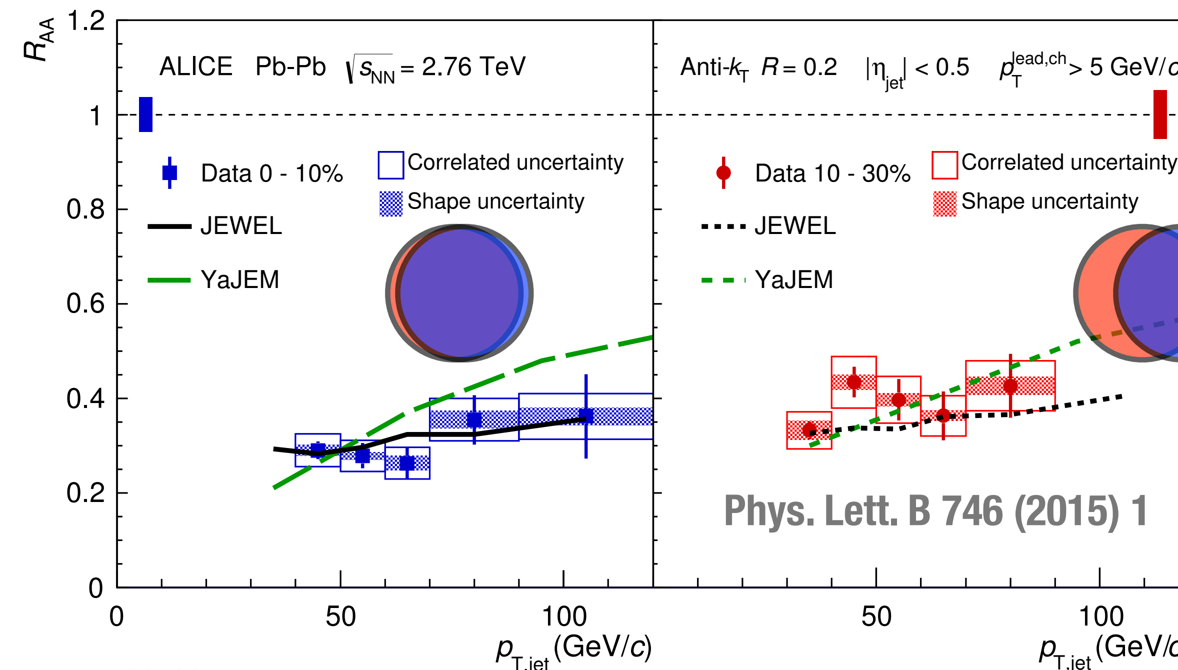
Main Physics Observables

Nuclear Modification Factor : R_{AA}

- Evaluate the jet suppression as compared to *pp*
- $R_{AA} < 1$
  - Jet (parton) energy loss due to parton interaction with the medium
  - Out-of-cone energy radiation

$$R_{AA} = \frac{dN^{AA}/dp_T}{\langle N_{coll} \rangle \, dN^{pp}/dp_T} = \frac{dN^{AA}/dp_T}{\langle T_{AA} \rangle \, d\sigma^{pp}/dp_T}$$

Full Jet

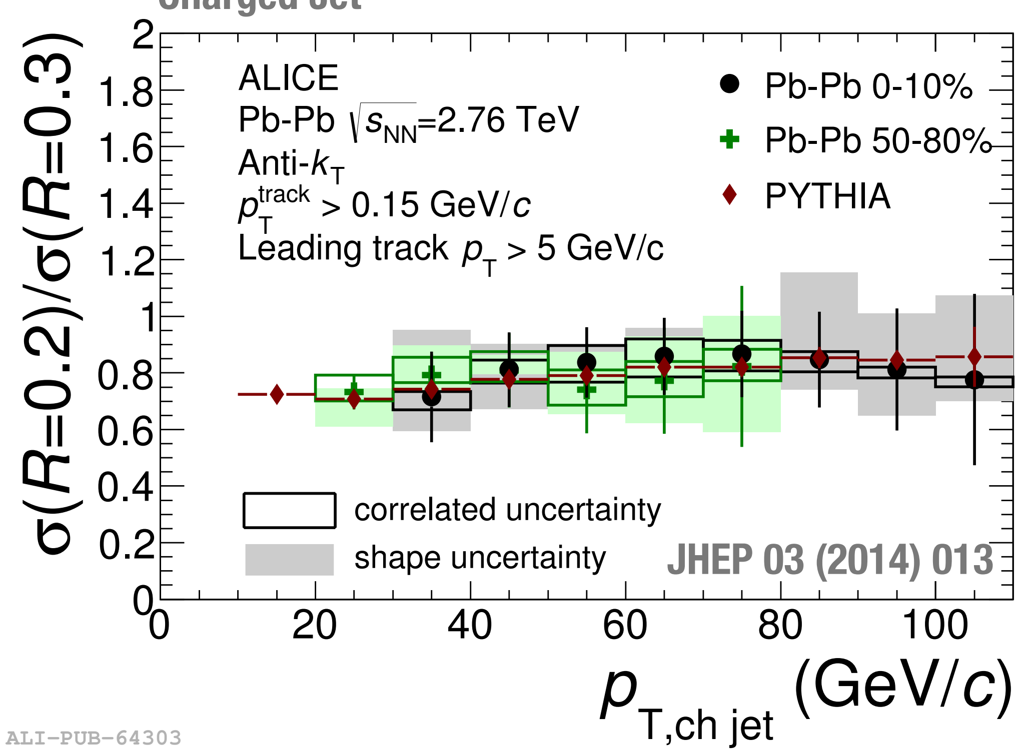


ALI-PUB-92182

Cross Section Ratio

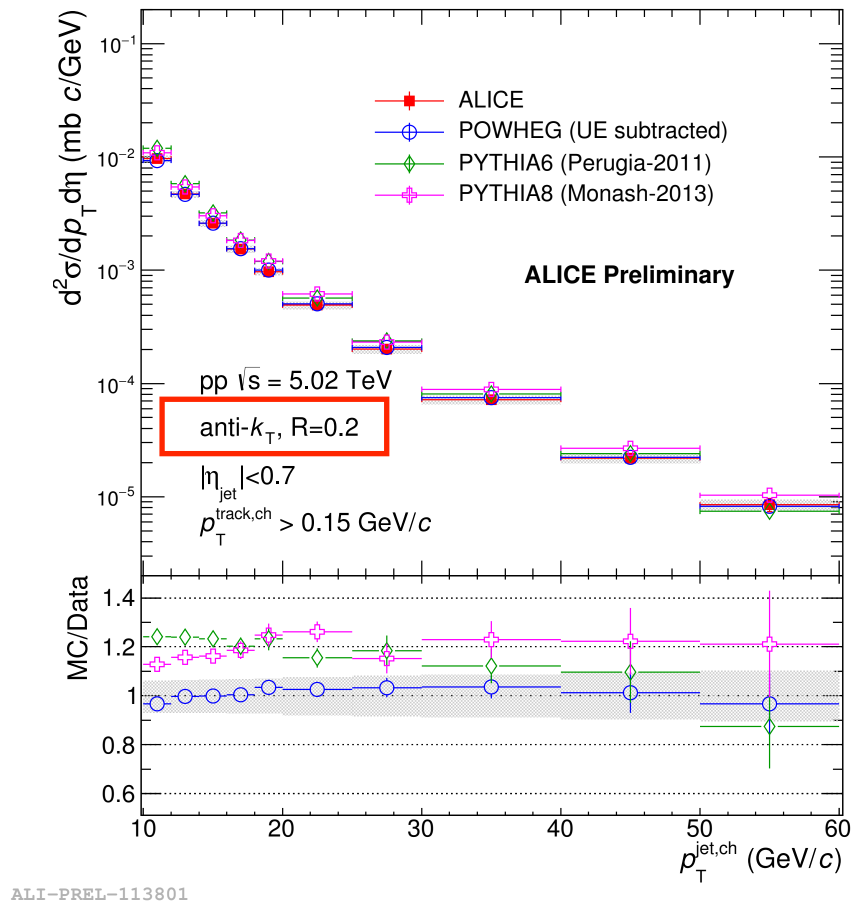
- Sensitive to structure of jets
- Jet broadening/collimation

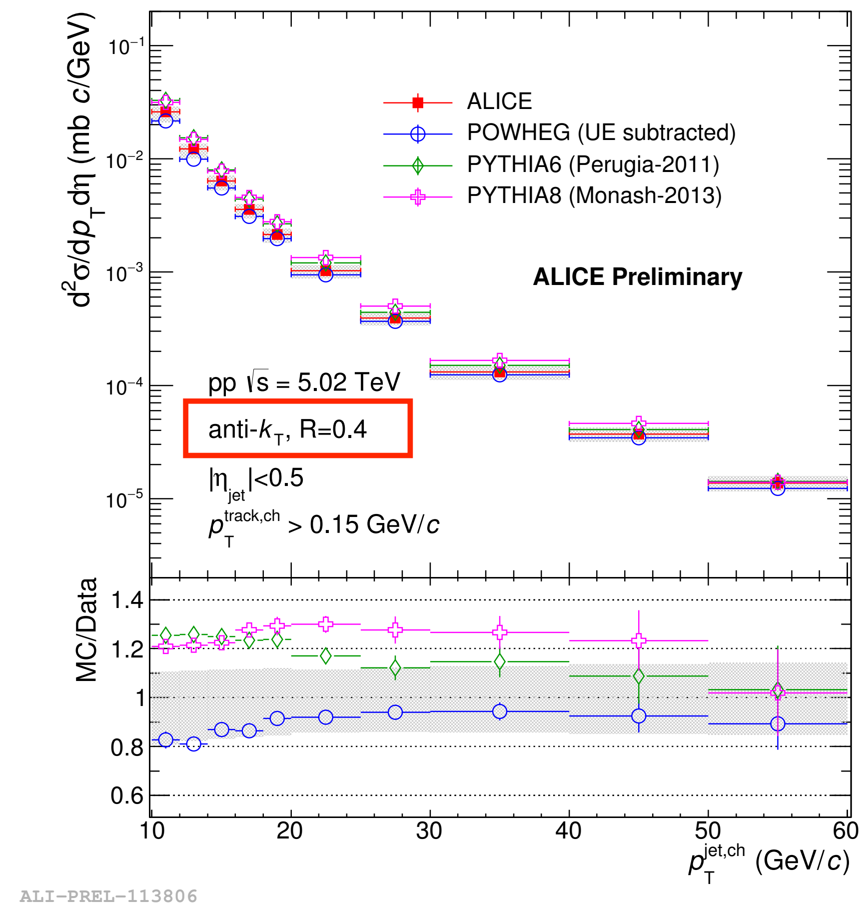
Charged Jet



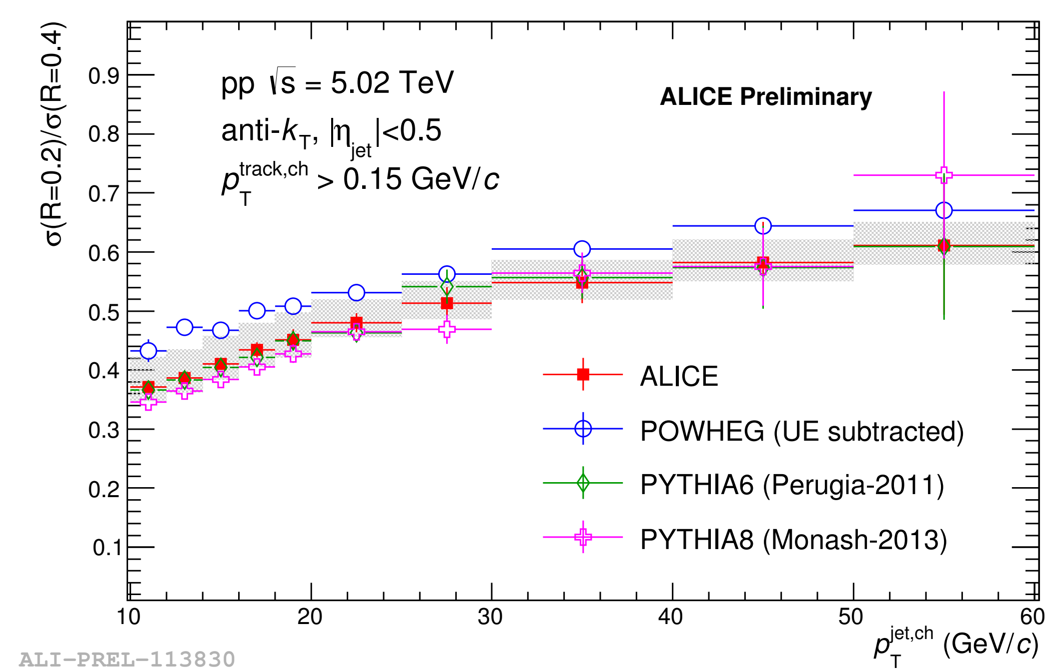
ALI-PUB-64303

Jet Production in *pp* 5.02 TeV



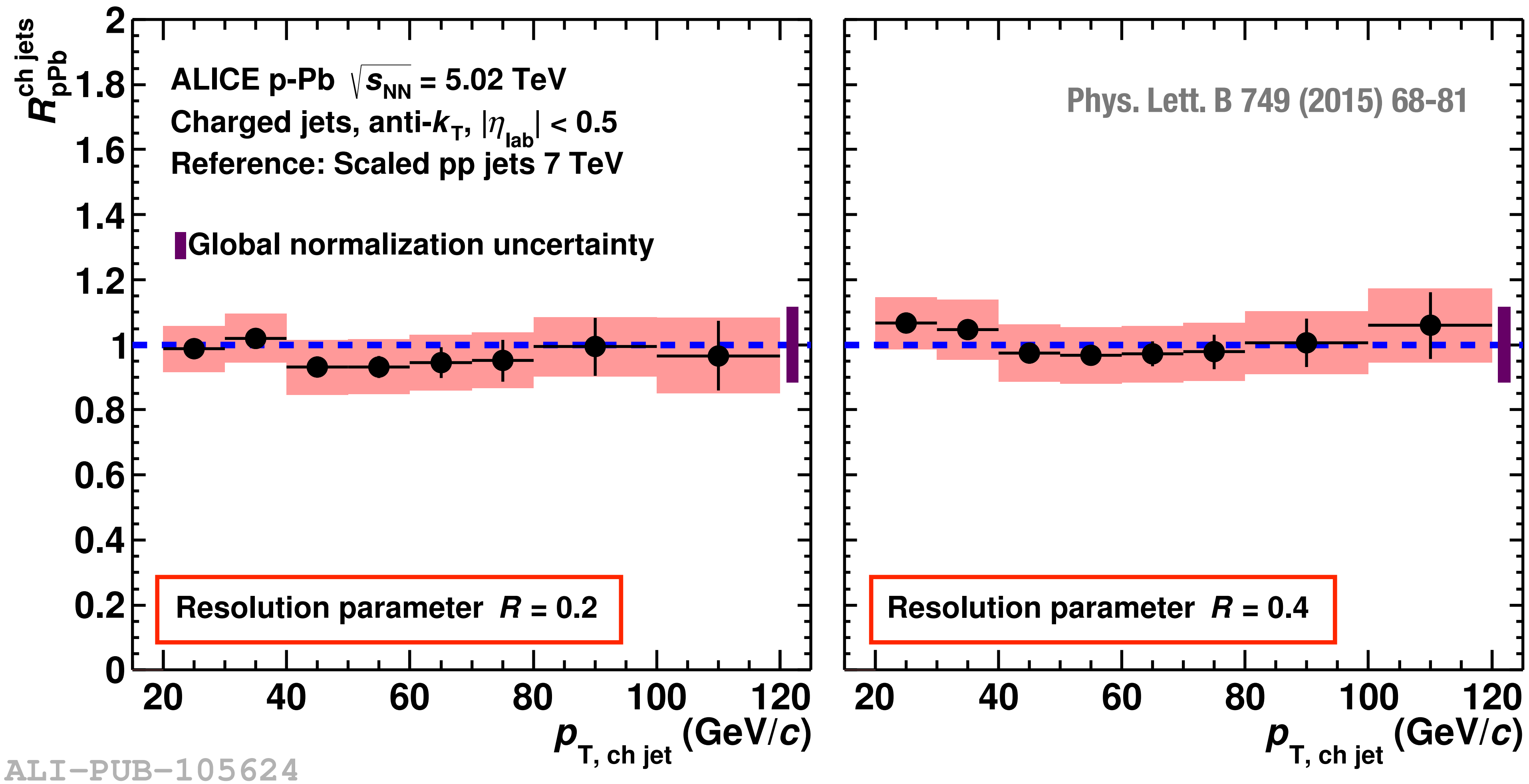


- ☑ Measured charged jet cross sections are well described by POWHEG+Pythia8 (NLO pQCD + parton shower, hadronization)
  - for cross section and cross section ratio
- ☑ POWHEG+Pythia8 viable reference for Pb-Pb measurements where lack of *pp* data



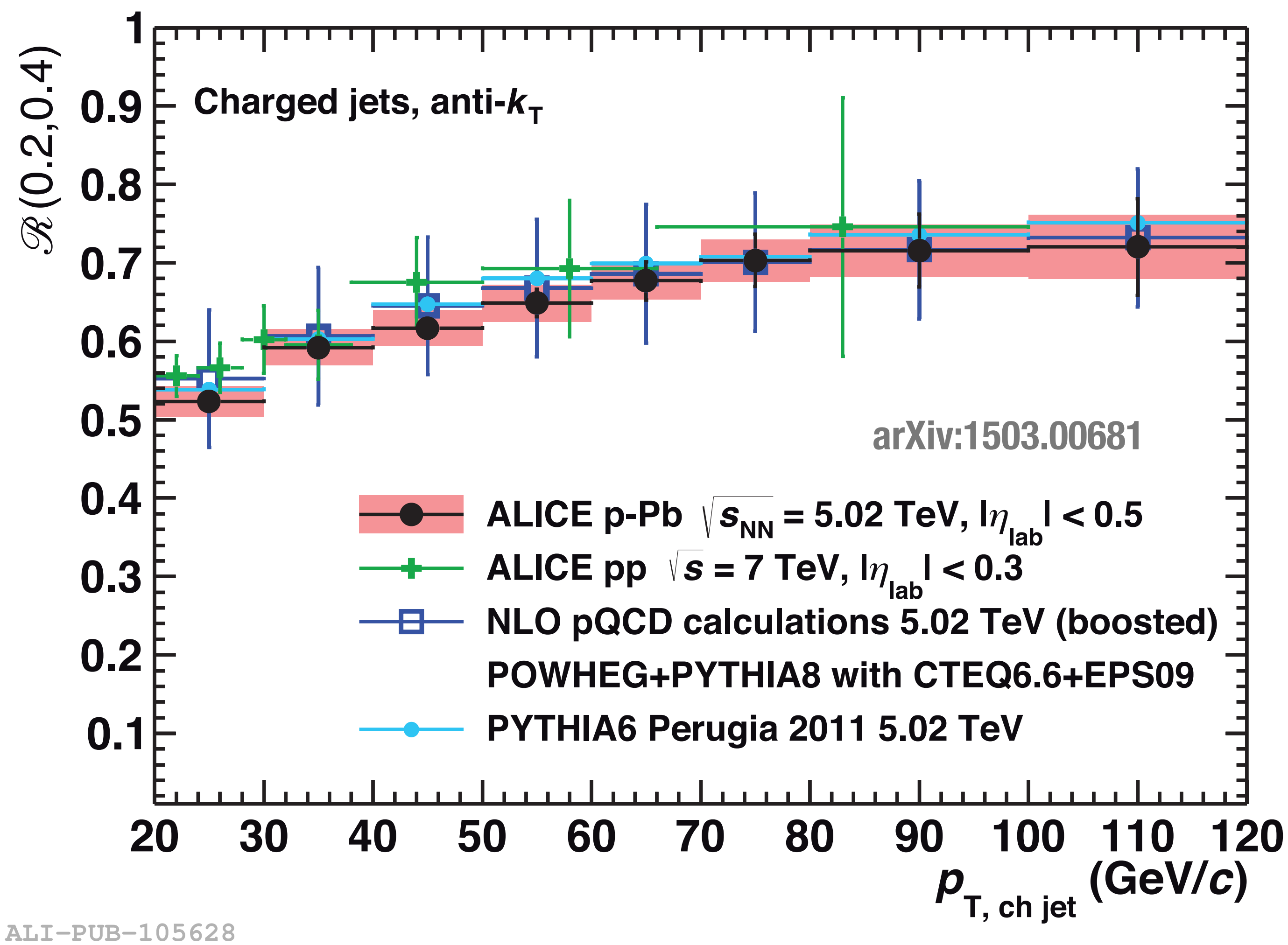
Inclusive Jet R_{pA} at 5.02 TeV

- ☑ Is there jet quenching in p-Pb?
- ☑ Charged jet R_{pA} in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- ☑ R_{pA} is consistent with unity.
  - Jet production in *p*-Pb is well described by binary scaling of *pp*
  - No modification within uncertainties



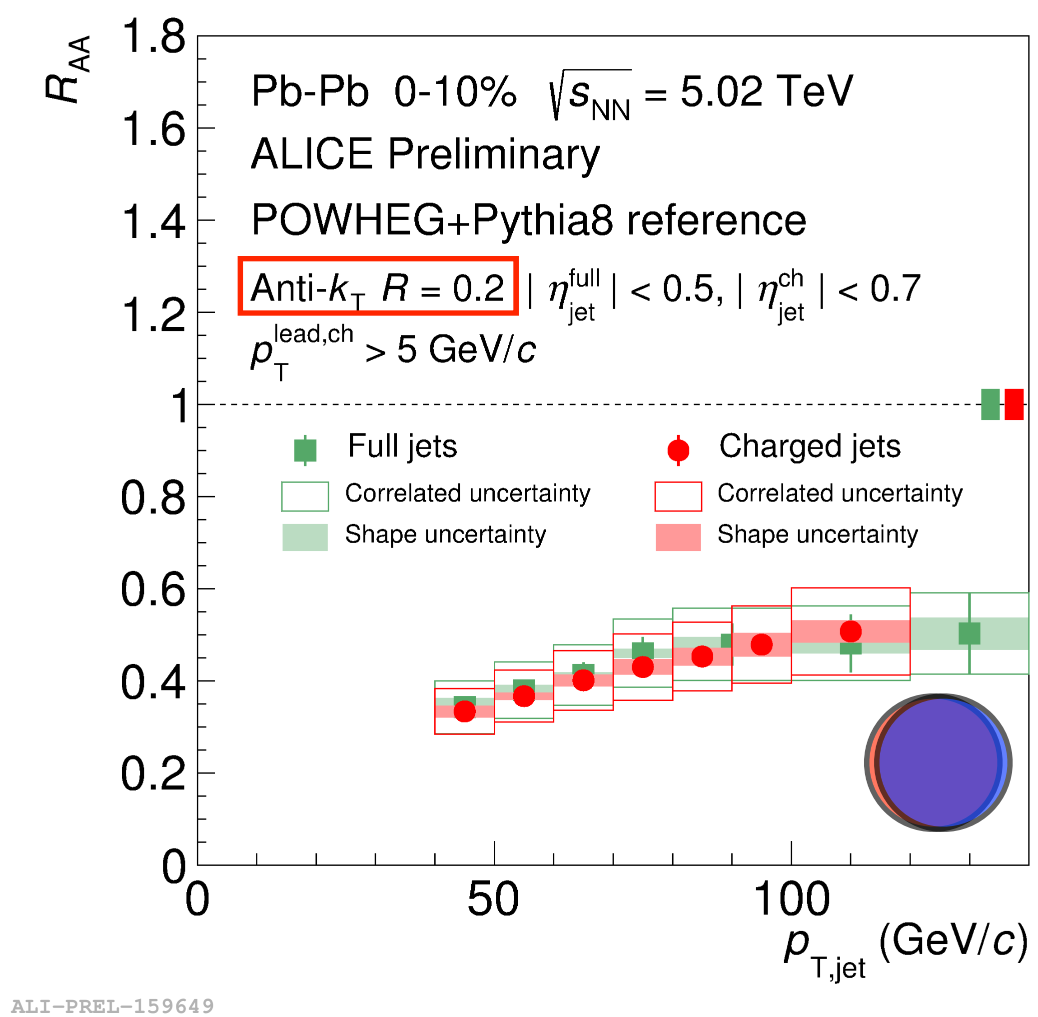
Jet Radial Structure in *p*-Pb 5.02 TeV

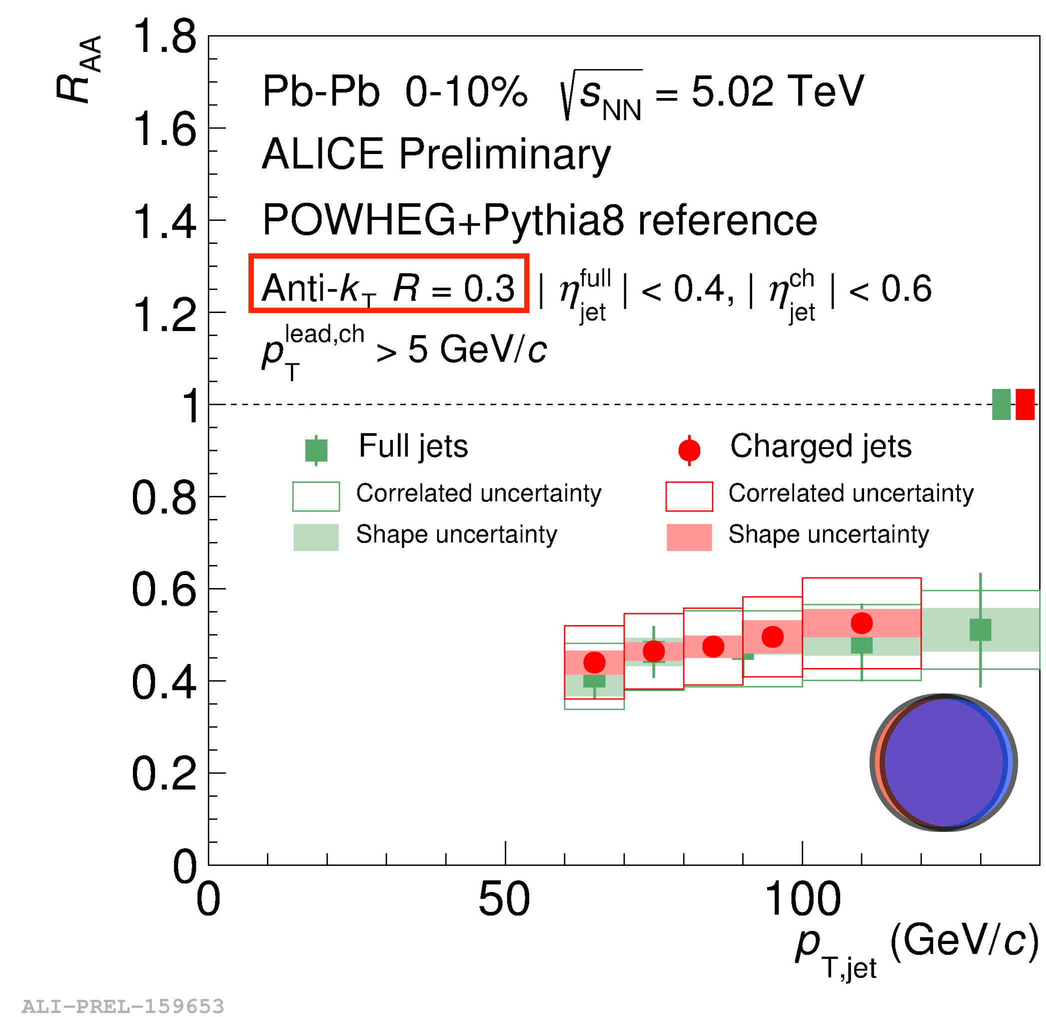
- ☑ Jet cross section ratio between different resolution parameters
  - σ(R=0.2) / σ(R=0.4)
- ☑ No indication of nuclear modification in jet radial profile
- ☑ ΔE < 0.4 GeV/c medium-induced energy transport out of R = 0.4 cone. (arXiv:1712.05603)



Inclusive Jet R_{AA} at 5.02 TeV

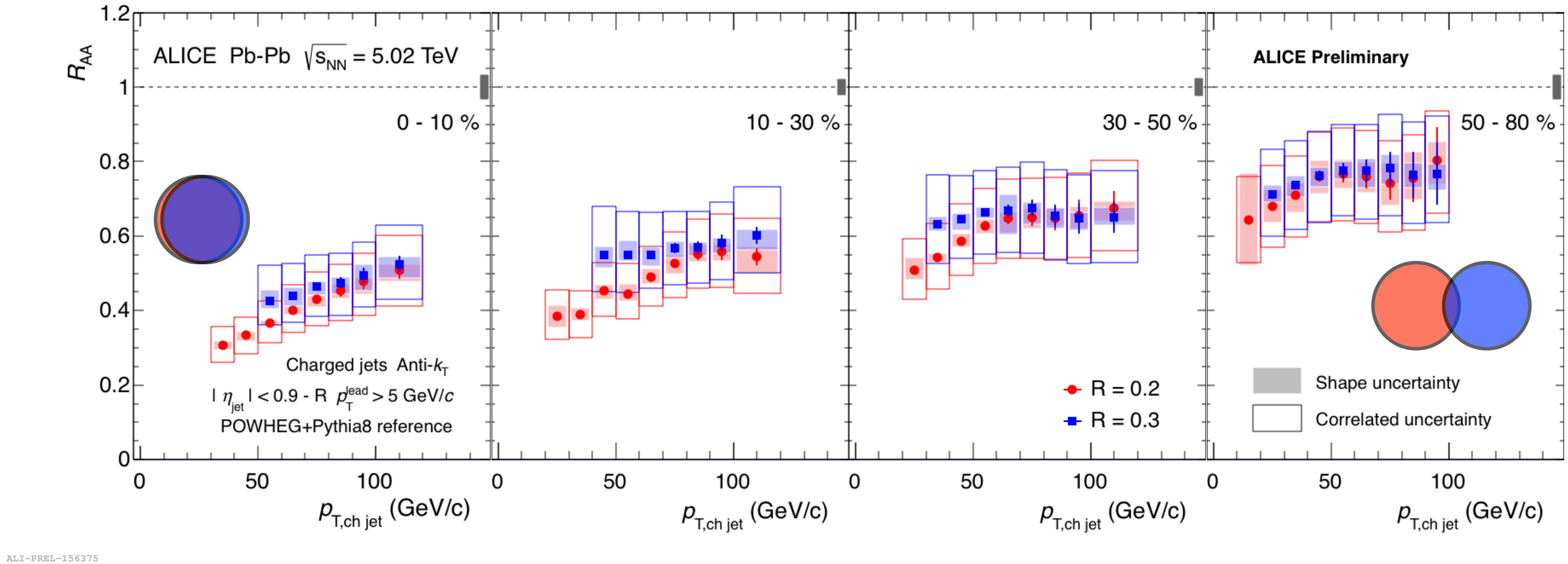
- ☑ Charged and Full Jet R_{AA} in the most central Pb-Pb collisions
- ☑ R_{AA} is smaller than unity
  - Strong jet suppression
  - Increase gently in low-p_T and reach a constant value
- ☑ No significant difference between Full and Charged jet R_{AA}





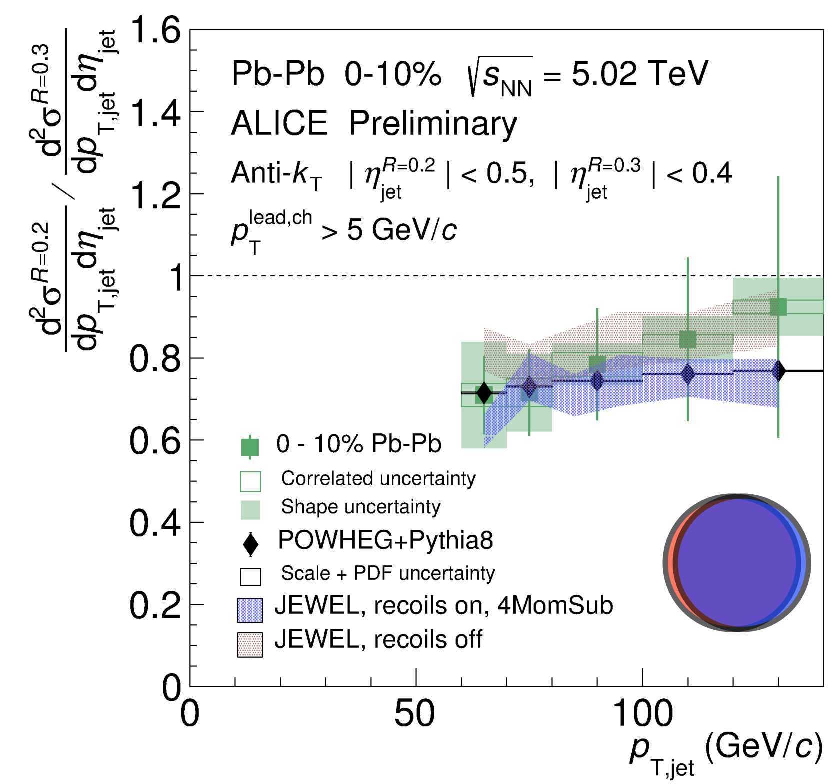
Inclusive Jet R_{AA} at 5.02 TeV

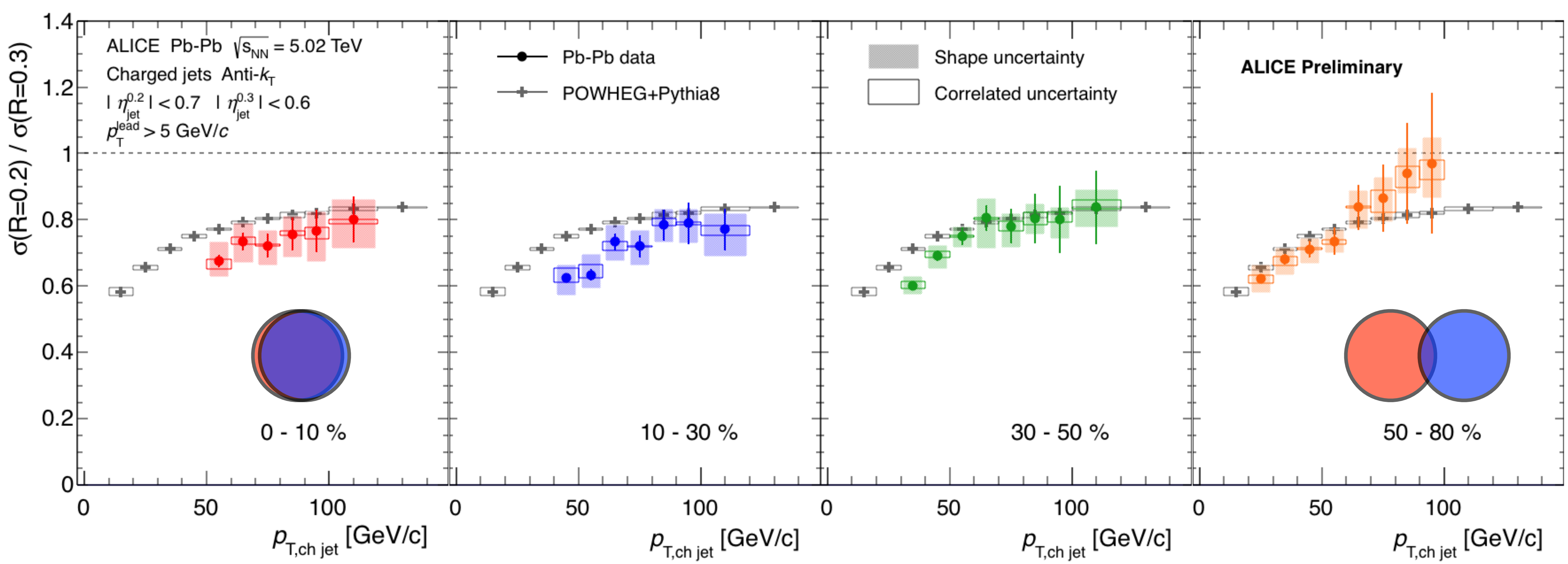
- ☑ Charged jet R_{AA} in four centrality classes
- ☑ Larger R_{AA} (smaller suppression) in the peripheral collisions, due to smaller system size.
- ☑ Jet R_{AA} for different resolution parameter are consistent within systematic errors
  - Jet radial structure is similar to *pp*?



Jet Radial Structure in Pb-Pb 5.02 TeV

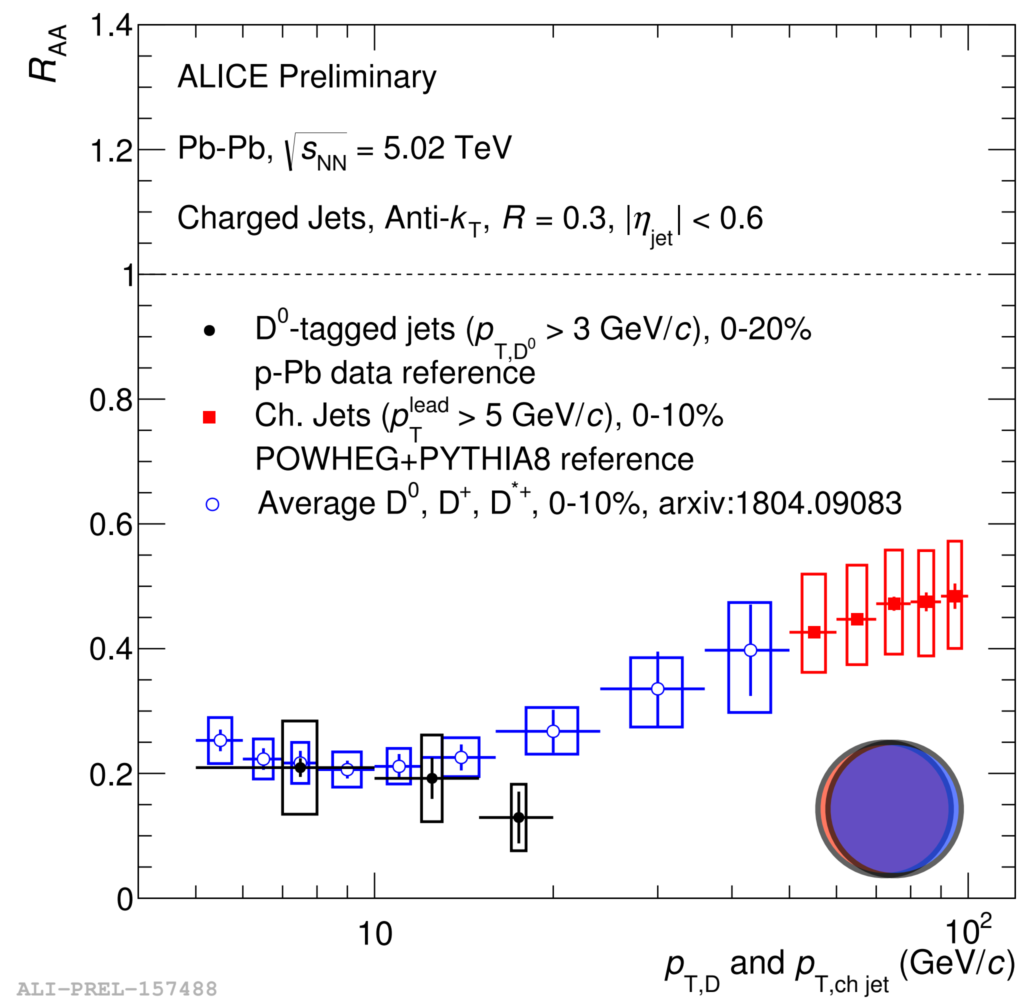
- ☑ Jet cross section ratio between different resolution parameters
  - σ(R=0.2) / σ(R=0.3)
- ☑ Consistent to POWHEG+Pythia8 and JEWEL expectation within uncertainties
  - The angular structure of jet core is unmodified in AA as compared to *pp.*
  - **More precision needed to conclude**





Introduction of Another Angle : Heavy-Flavor in Jets

- Charged Jet containing D^0 in its constituent
  - Suppression of charm quarks
  - Robust against combinatorial background
    - Enable to extend jet p_T down to few GeV/c
- Strong D-tagged jet suppression in the most central Pb-Pb collisions
- Investigation of type/mass dependent parton energy loss mechanism is expected
  - Charm and beauty jets
  - Motivation for upcoming Run 3, 4 with more data/precision



see A.Rossi talk
(Heavy Ion 1, Jul. 5th)

Summary and Prospects

- ☑ ALICE successfully measured charged and full jet in *pp*, *p*-Pb and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV for jet resolution parameters of R=0.2 and 0.3

- ☑ Nuclear modification factor (R_{pA}, R_{AA})
  - No jet suppression in *p*-Pb collisions
  - Strong jet suppression in the most central Pb-Pb collisions
    - Support significant jet energy loss via parton-medium interactions

- ☑ Jet cross section ratio between different R
  - Jet angular structure is consistent to *pp* within uncertainties at the moment
  - More precision needed
    - Extend the range: larger R and/or jet-p_T reach

- ☑ Study of parton type dependent jet modification is starting
  - Strong suppression of D-tagged jet
  - Detail and/or extended study of heavy-flavor jets expected at Run3, 4

Thank you for your attention!

Analysis Flow

1. Event/Track Selection

Event
- $\sqrt{s_{NN}}$ = 5.02 *TeV*, Pb-Pb
- Min. Bias trigger (61M events)
- $|v_Z| < 10$ cm

Charged Particle
- $|\eta| < 0.9$
- $p_T > 0.15$ *GeV/c*
- hybrid track selection

2. Jet Reconstruction

- anti-k_T algorithm
- R = 0.2, 0.3
- $|\eta^{jet}| < 0.9 - R$
- $p_T^{lead} > 5$ *GeV/c*

3. Soft BKG subtraction
- subtract average BKG event-by-event

Average Background Density
- k_T algorithm
- median calculation

4. Unfolding
- correct detector effects
- correct BKG fluctuation

- SVD unfolding method
- input response of detector effects and BKG fluctuation

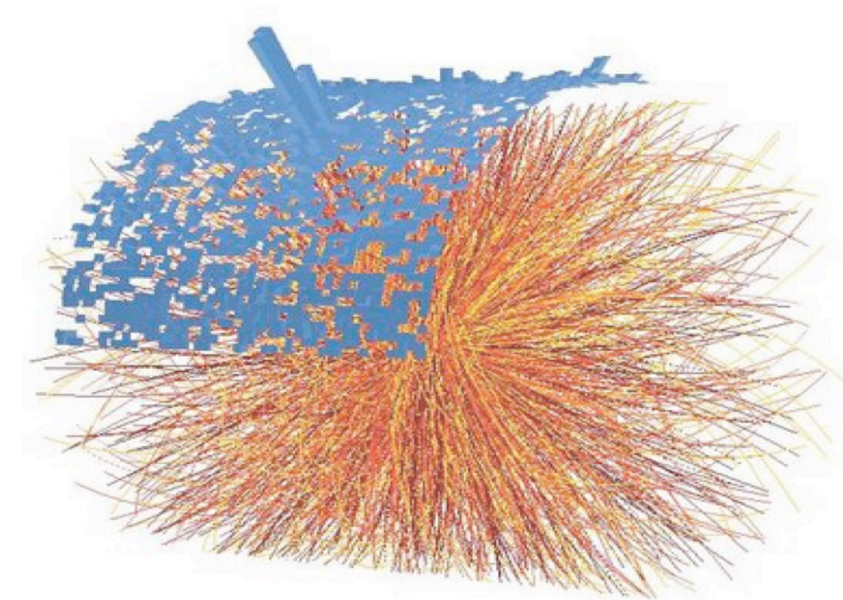
5. Inclusive Jet spectrum

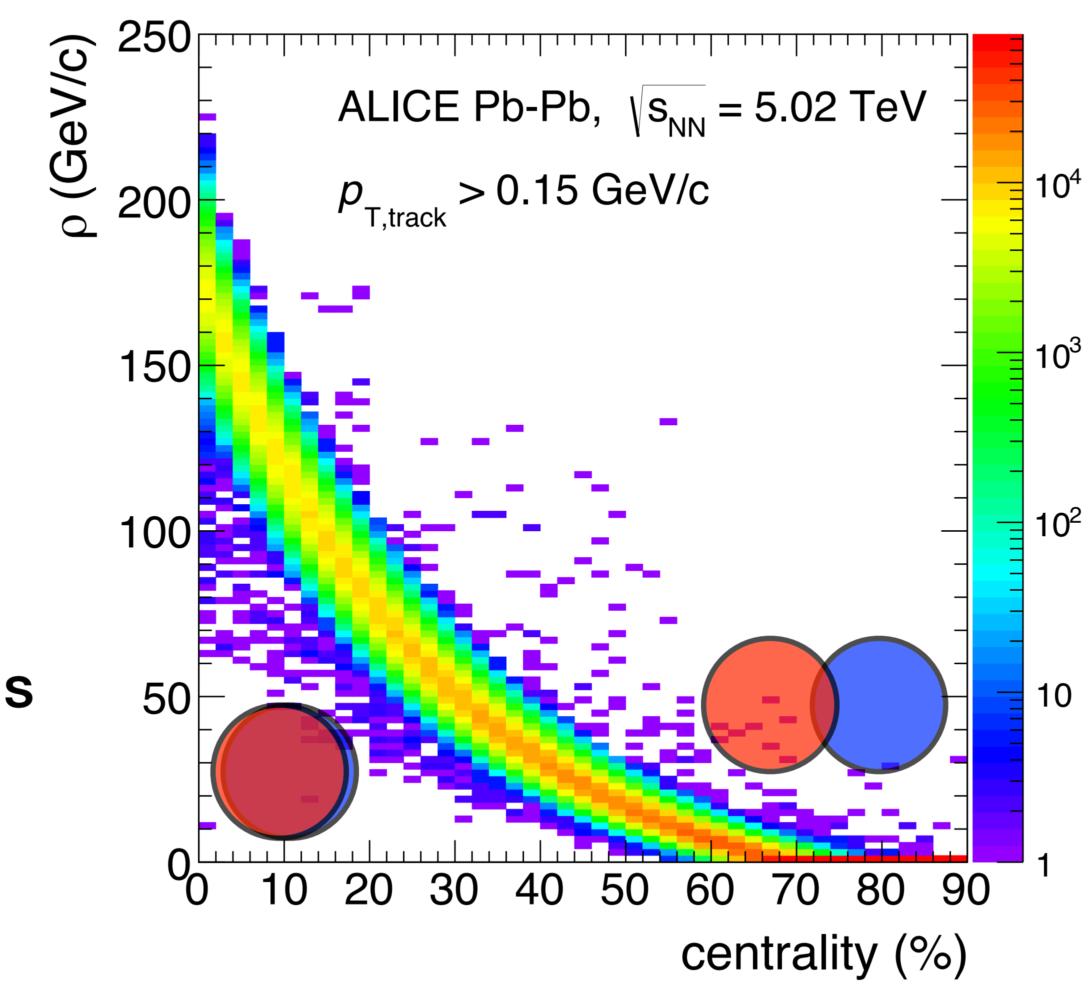
Challenge in Heavy-Ion Collisions

- Large background contribution to jet energy
  - $dN_{ch}/d\eta$ ~ 1300 (0-10% centrality)
- **Average Background Density : ρ**
  - k_T clusters excluding two leading clusters

$$\rho = \mathrm{median}\left(\frac{p_{\mathrm{T},i}}{A_i}\right)$$

  - event-by-event calculation
  - ρ ~ 145 *GeV/c* for 0-10%
  - (~18 *GeV/c* for R=0.2 jets)
- **Combinatorial Jets Removal**
  - random combination of BKG particles
  - minimum leading constituent p_T^{lead} > 5 *GeV/c* is required



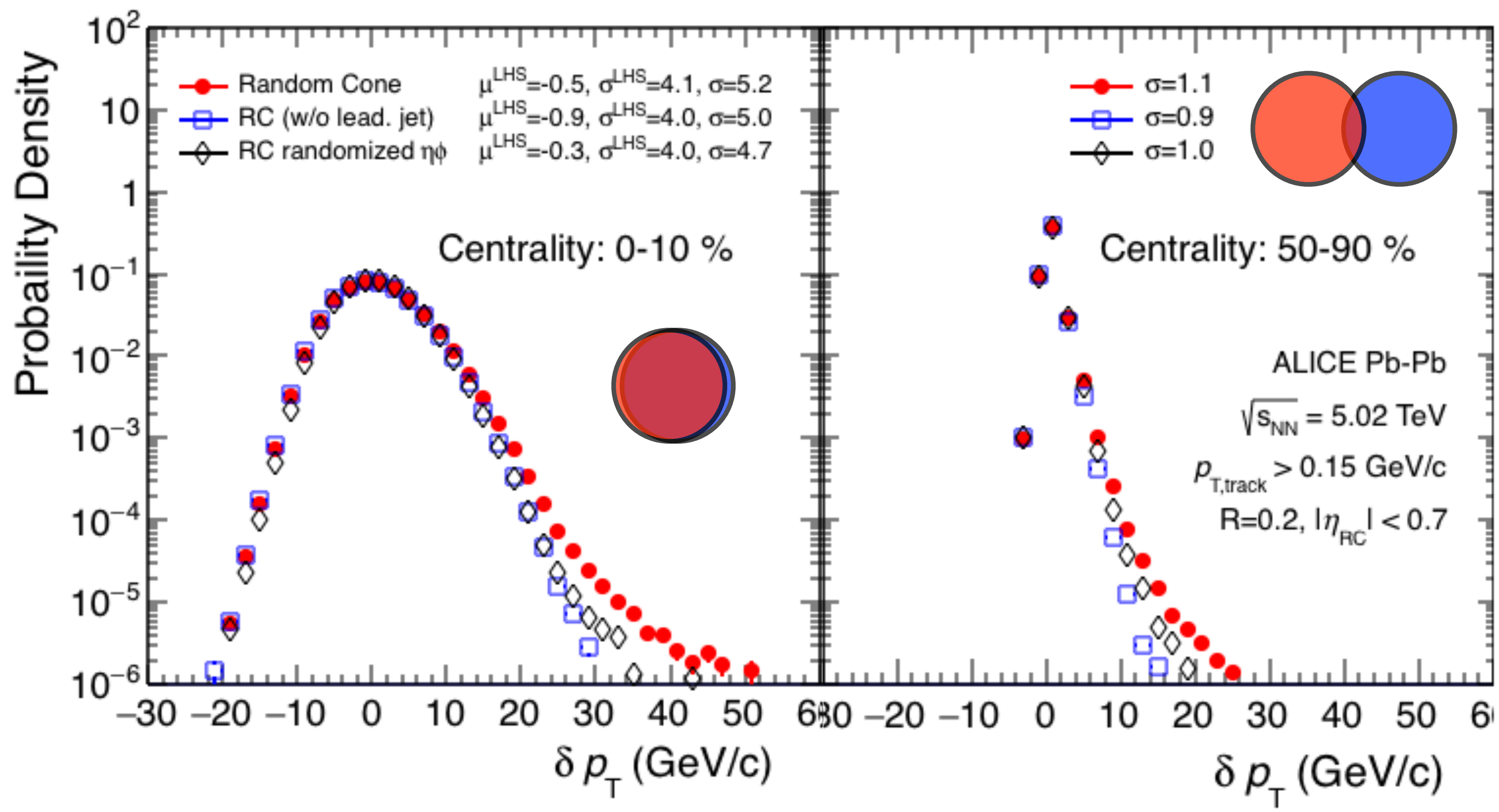


Underlying Event Fluctuation

- **Background fluctuation : δp_T**
  - from region to region around average background
  - **Random Cone method**
  - (exclude leading jet neighbour : $\Delta r > 1.0$)

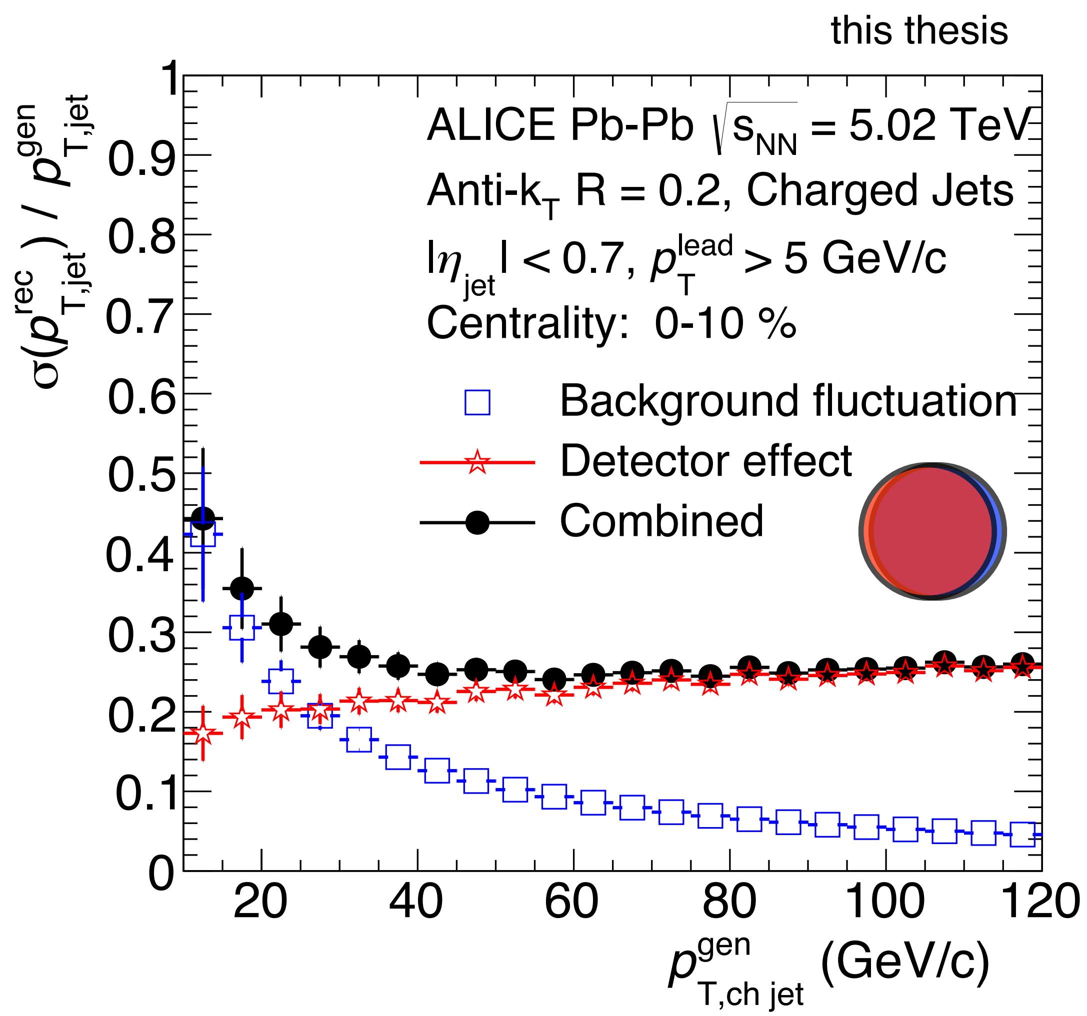
$$\delta p_{\mathrm{T}} = \sum_{i}^{RC} p_{\mathrm{T},i}^{\mathrm{track}} - \rho\,\pi R^2$$

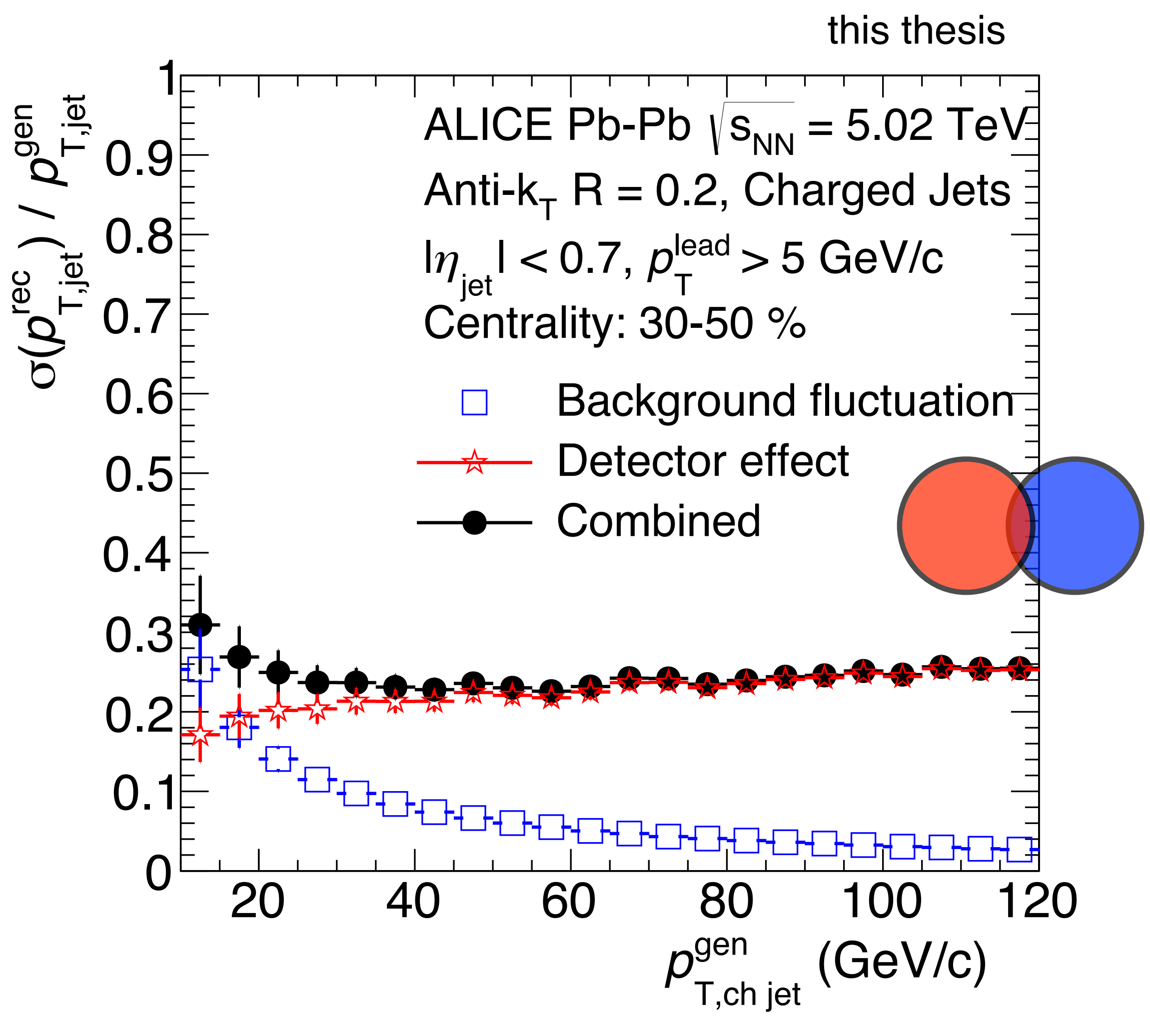
- **δp_T width (magnitude of fluctuation)**
  - ~ 5 GeV/c (0-10% , R=0.2)
  - smaller in peripheral



Jet Energy Resolution

- Jet energy resolution is derived by the Response Matrixes
- Effect from Underlying Event Fluctuation
  - dominant in lower jet pT
- Detector Effect
  - dominant at higher jet pT





Jet Reconstruction Algorithm

- FastJet anti-k_T algorithm (p=-1, p=1 for k_T algorithm)
  - calculate d_{ij} and d_{iB} by all particles combination
    - when minimum "d" among them is part of d_{ij}
      - merge particle "i" and "j"
    - when minimum "d" among them is part of d_{iB}
      - that cluster defined as jet
  - repeat until no particle are left

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} ,$$

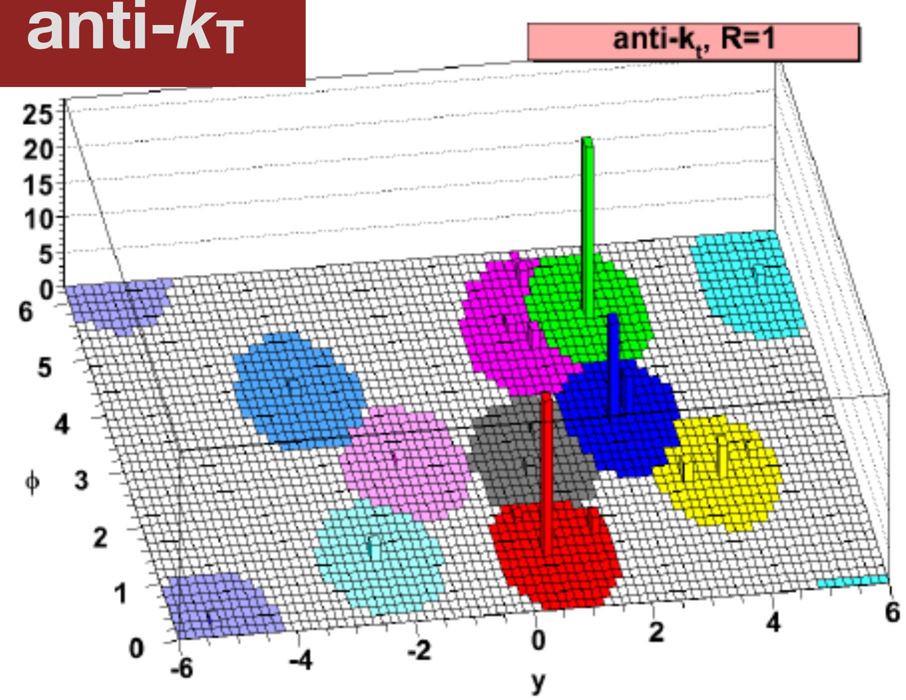
$$d_{iB} = k_{ti}^{2p} ,$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

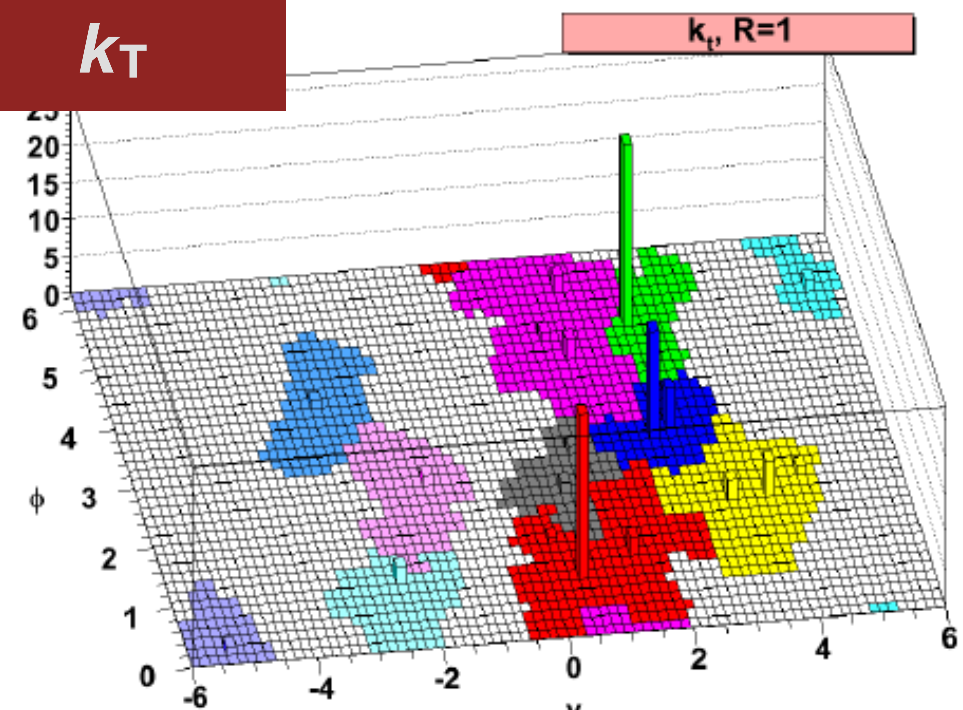
Jet Reconstruction

- ☑ **Combine/classify particles into clusters sequentially**
  - based on p_T weighted distance
  - (correspondence between parton level and detector level).
- ☑ **Anti-k_T algorithm**
  - start clustering from high-p_T particles ⇒ **Signal Jet** in Heavy Ion collisions
  - Circular and centred around harder energy deposit (with radius ~R)
- ☑ **k_T algorithm**
  - start clustering from low-p_T particles ⇒ **Estimation of Soft BKG**

anti-k_T



k_T

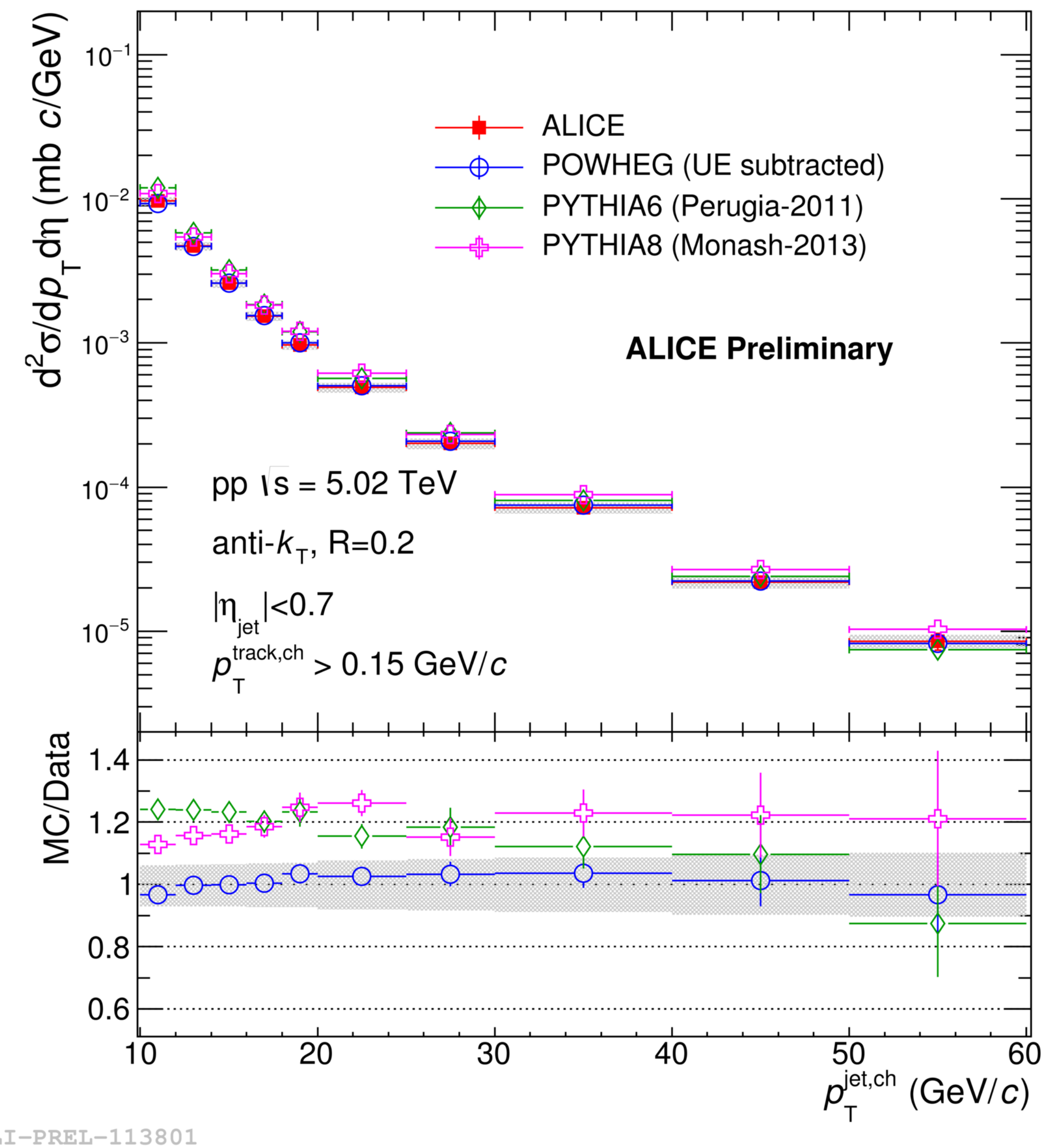


JHEP 04 (2008) 063

pp Inclusive Jet Cross Section

- **Jet cross section at $\sqrt{s}$ = 5.02 TeV pp collisions in 2015**
  - POWHEG NLO calculations well describes measured spectrum within systematic uncertainties

- **Dataset**
  - $\sqrt{s}$ = 5.02 TeV, pp collisions
  - MB triggered events (25.5M events)
- **Charged track selection**
  - $|\eta| < 0.9$, $p_T^{track} > 0.15$ GeV/c
- **Jet reconstruction**
  - anti-kt jet reconstruction algorithm
  - R = 0.2
  - $|\eta| < 0.7$, ($p_T^{lead} > 5$ GeV/c for R_{AA} ref.)
- **Unfolding**
  - to correct for detector effects



Pb-Pb Inclusive Charged Jet Cross Section

☑ **Jet cross section at √sNN = 5.02 TeV PbPb collisions in 2015**

☑ **Dataset**

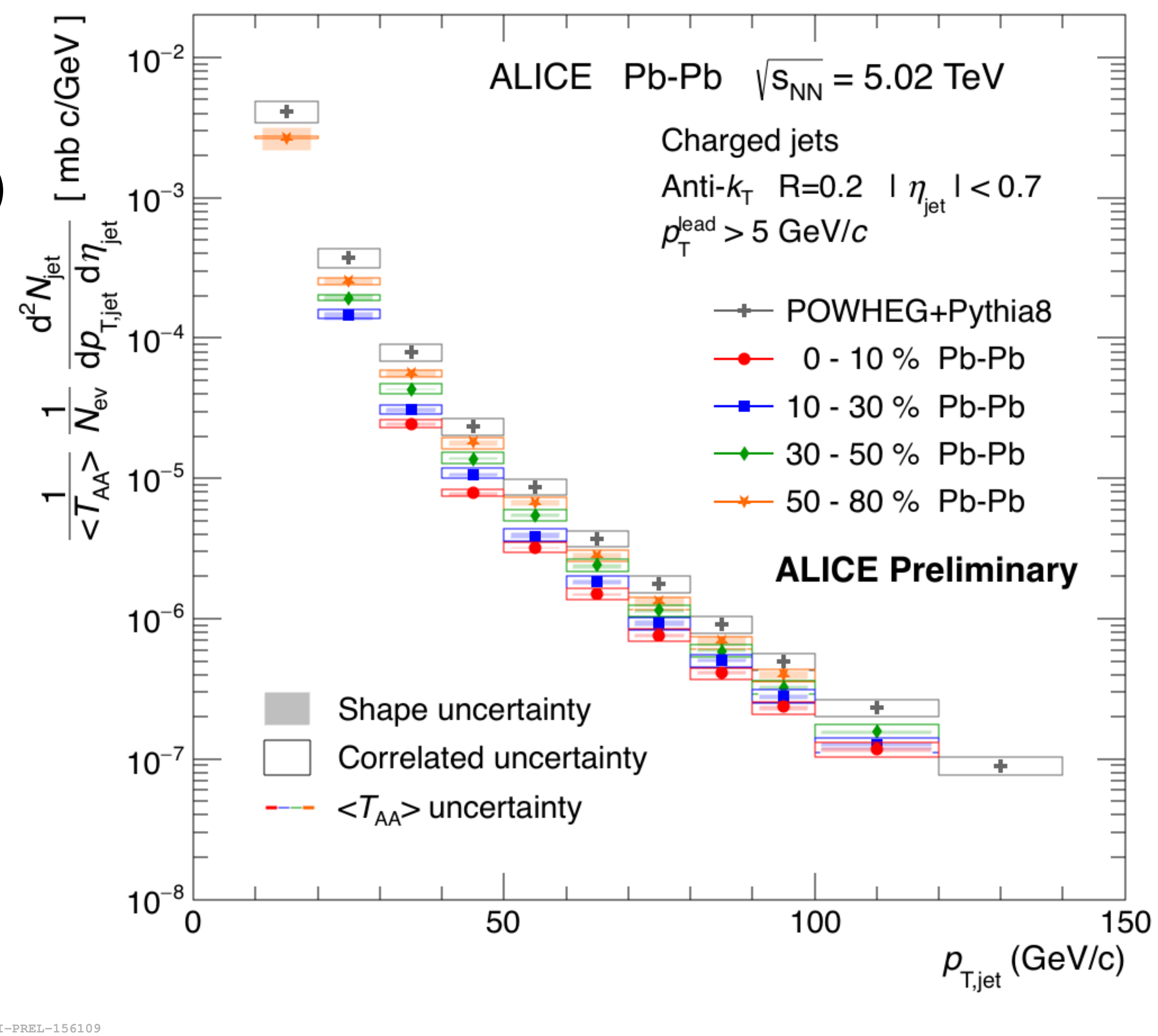
- √s = 5.02 TeV, PbPb collisions
  - MB triggered events (68M events)
  - 0-80% centrality

☑ **Charged track selection**

- | η | < 0.9, p_T^{track} > 0.15 GeV/c

☑ **Jet reconstruction**

- anti-kt jet reconstruction algorithm
- R = 0.2, 0.3
- | η | < 0.9-R, (p_T^{lead} > 5 GeV/c)



Pb-Pb Inclusive Full Jet Cross Section

- **Jet cross section at √sNN = 5.02 TeV PbPb collisions in 2015**

- **Dataset**
  - √s = 5.02 TeV, PbPb collisions
    - MB triggered events (4.5M events)
    - 0-10% centrality
- **Charged track selection**
  - | η | < 0.9, p_T^{track} > 0.15 GeV/c
- **EM cluster selection**
  - E_{clus} > 0.3 GeV
- **Jet reconstruction**
  - anti-kt jet reconstruction algorithm
  - R = 0.2, 0.3
  - | η | < 0.9-R, (p_T^{lead} > 5 GeV/c)