Measurement of jets in Pb-Pb collisions with ALICE

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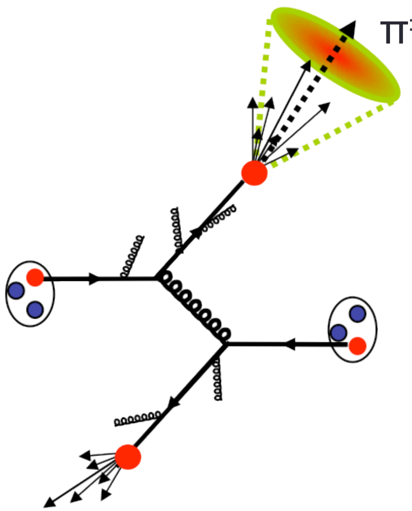
XXIV QUARK MATTER DARMSTADT 2014

Jets in heavy-ion collisions

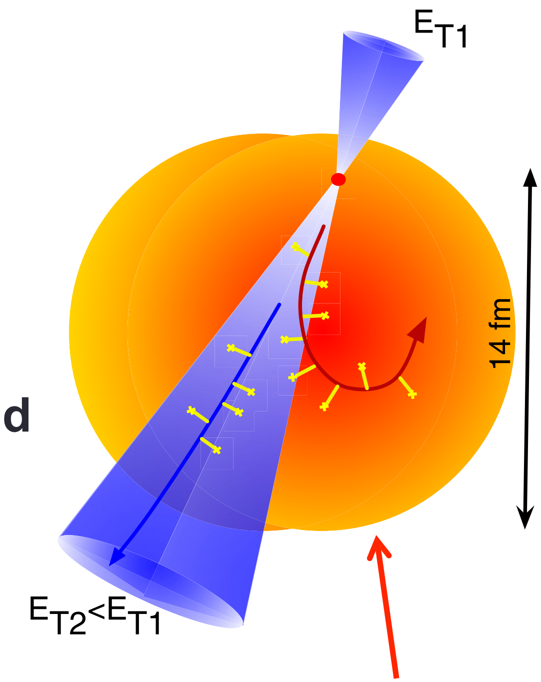


Parton hard scattering
$Q^2 >> 1\ GeV^2$

Radiation of soft gluons and quarks

Hadronization into a colorless spray of particles

In **heavy-ion collisions** scattered partons interact with the **hot dense medium**



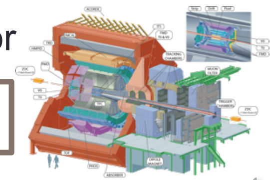
Jet quenching

- ✓ **suppression of jet yield**
- ✓ broadening of jet shape
- ✓ di-jet energy imbalance
- ✓ etc.

Challenge: large, fluctuating background!

Analysis overview

Tracking: |η| < 0.9, 0° < φ < 360°
TPC: gas detector
ITS: silicon detector

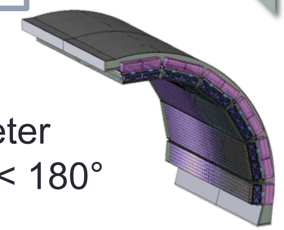


Start

Charged tracks

EMCal clusters

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

$$\mathbf{f^{det}(p_T^{det}) = RM_{comb}(p_T^{det}, p_T^{part}) \times \varepsilon(p_T^{part}) \times f^{part}(p_T^{part})}$$

Unfolding

Particle level jet spectrum

Centrality in Pb-Pb collisions determined using the **V0** detector: scintillator counters at forward rapidity

RM_{bkg} = Background fluctuations response matrix
RM_{det} = Detector effects response matrix

$$\mathbf{RM_{comb} = RM_{bkg} \times RM_{det}}$$

Jet reconstruction

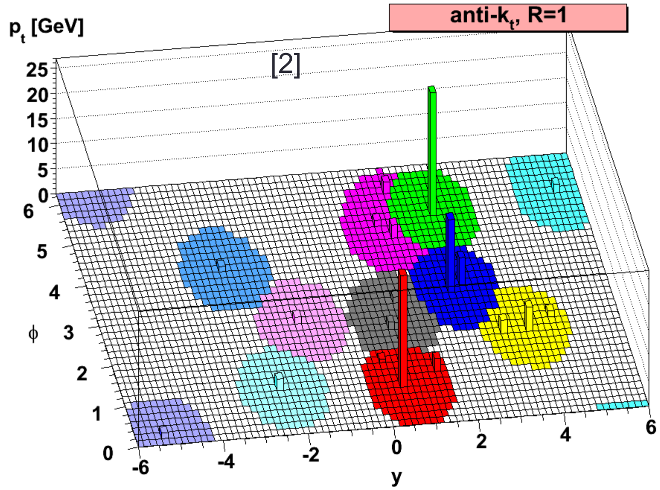
- Input to the jet finder
  - p_T recombination scheme: constituents assumed to be massless
  - **Charged tracks** with p_T > 150 MeV/c
  - **EMCal clusters** with E_T > 300 MeV after charged particle correction:

$$E_{\text{cluster}}^{\text{corr}} = E_{\text{cluster}}^{\text{orig}} - f \sum p^{\text{matched}}, \quad E_{\text{cluster}}^{\text{corr}} \geq 0$$

f = fraction of subtracted momentum = 100%

- Fiducial cut requires jet fully contained in the EMCal acceptance

Jet finding algorithm ➔ working definition of jet which must be used consistently in phenomenological models and experiments



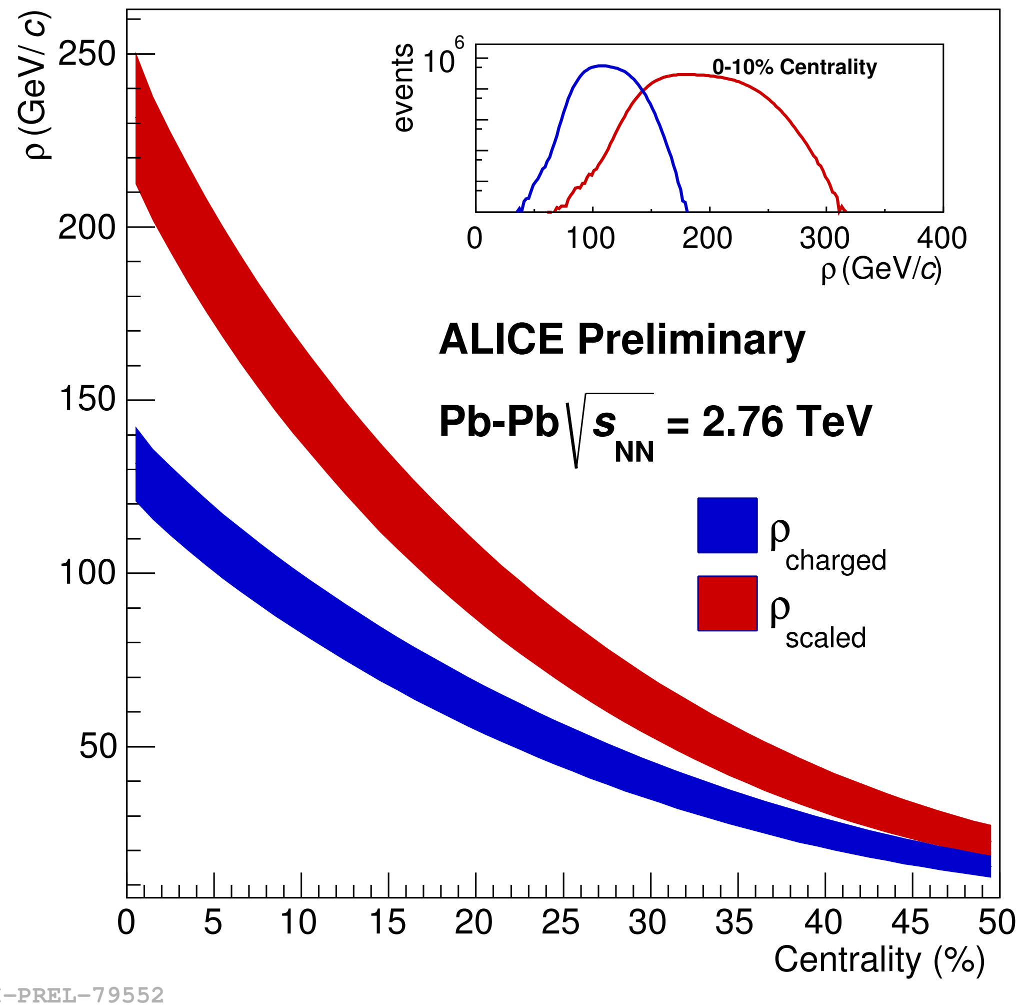
Sequential recombination algorithms

- anti-k_T (stable area, signal jets)
- k_T (background)
- **Infrared-** and **Collinear-Safe**
- FastJet[1] implementation

[1]M. Cacciari, G.P. Salam and G. Soyez Eur.Phys.J. C72 (2012) 1896 [arXiv:1111.6097]

[2]M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804 (2008) 063 [arXiv:0802.1189]

Average background density



- Event-by-event **charged background density**:

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

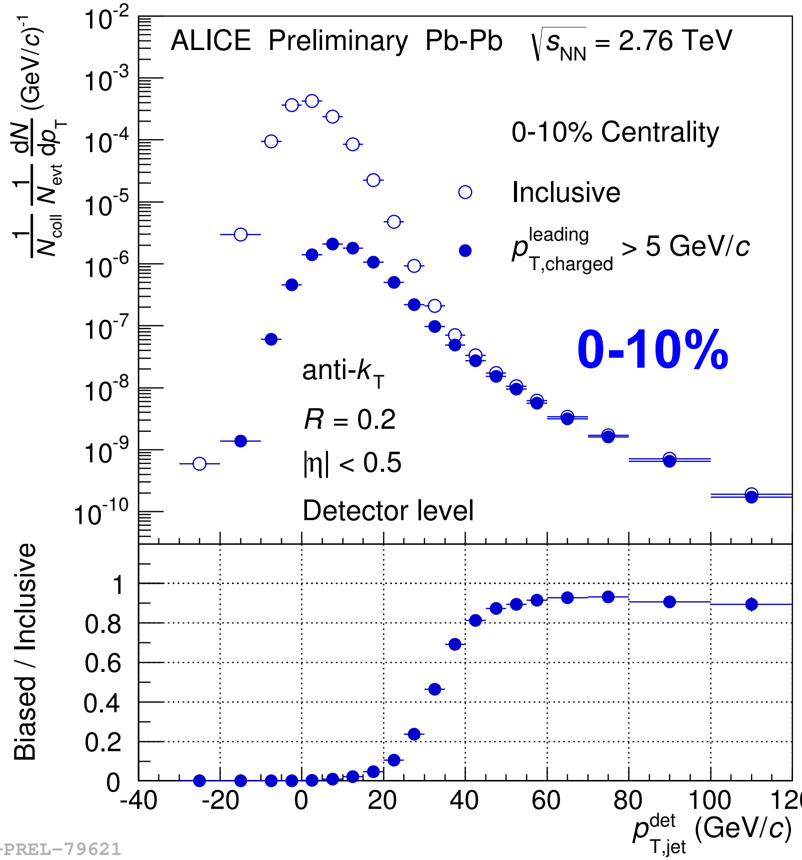
- Median approach reduces bias from signal jets
- **Scaled** to account for neutral energy:

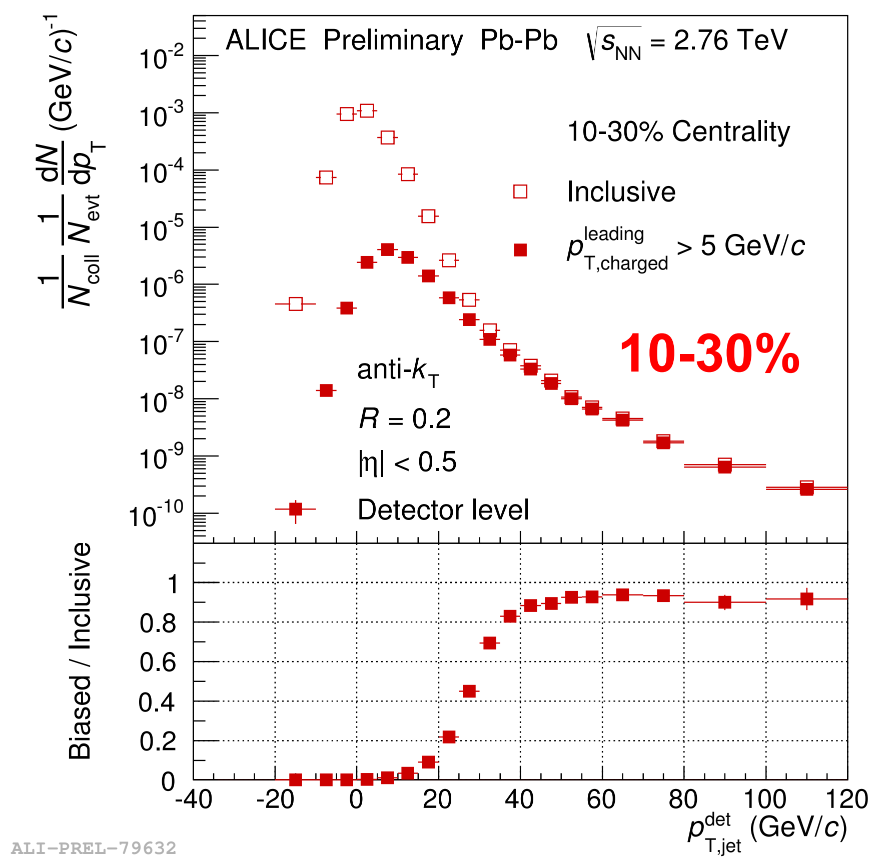
$$\boxed{\rho_{\mathrm{scaled}}} = \boxed{s_{\mathrm{EMC}}} \cdot \boxed{\rho_{\mathrm{charged}}}$$

- Background density in most central events:
  - ~ 200 GeV/*c* per unit area
  - ~ 25 GeV/*c* for an *R* = 0.2 jet!

Detector level jet spectra

Average background subtracted



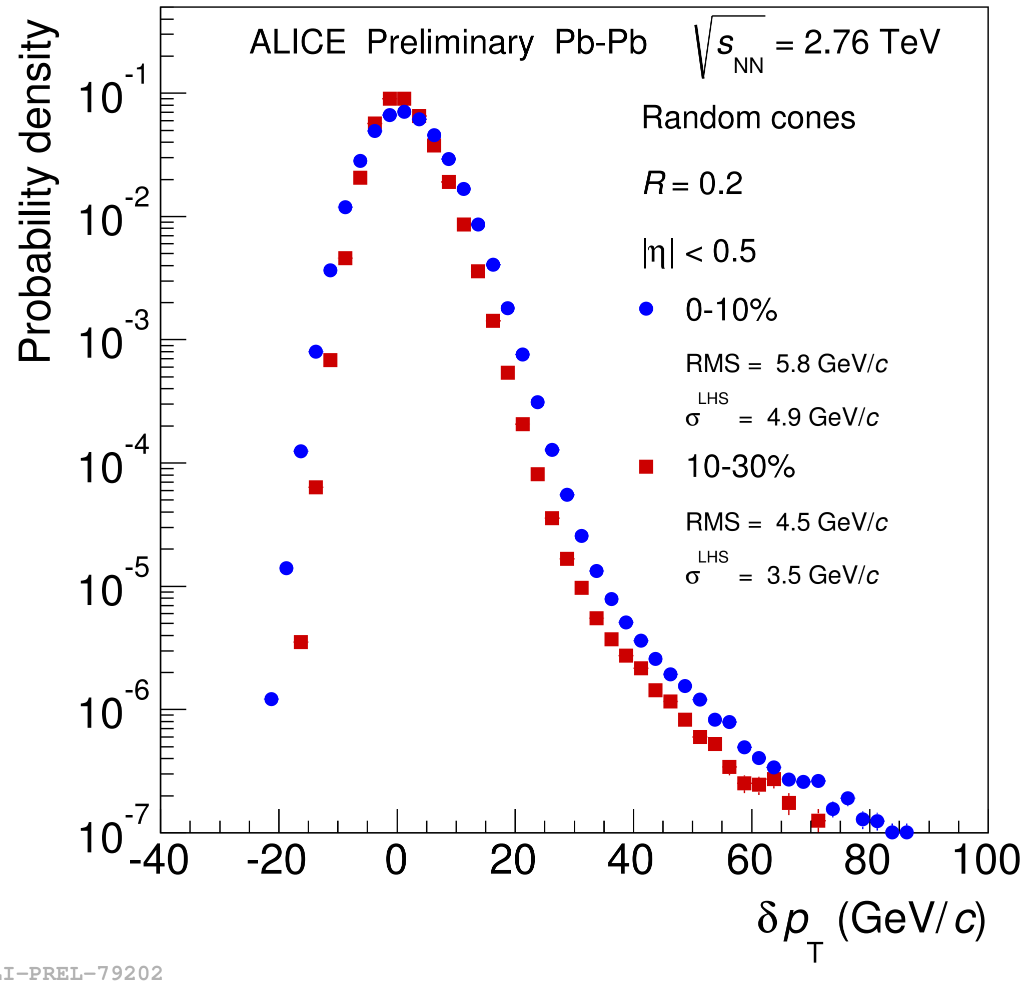


Charged leading hadron p_T > 5 GeV/c (full symbols)

- Suppress combinatorial background
- Bias towards harder fragmentation

Comparison with inclusive jet sample (open symbols)

Background fluctuations

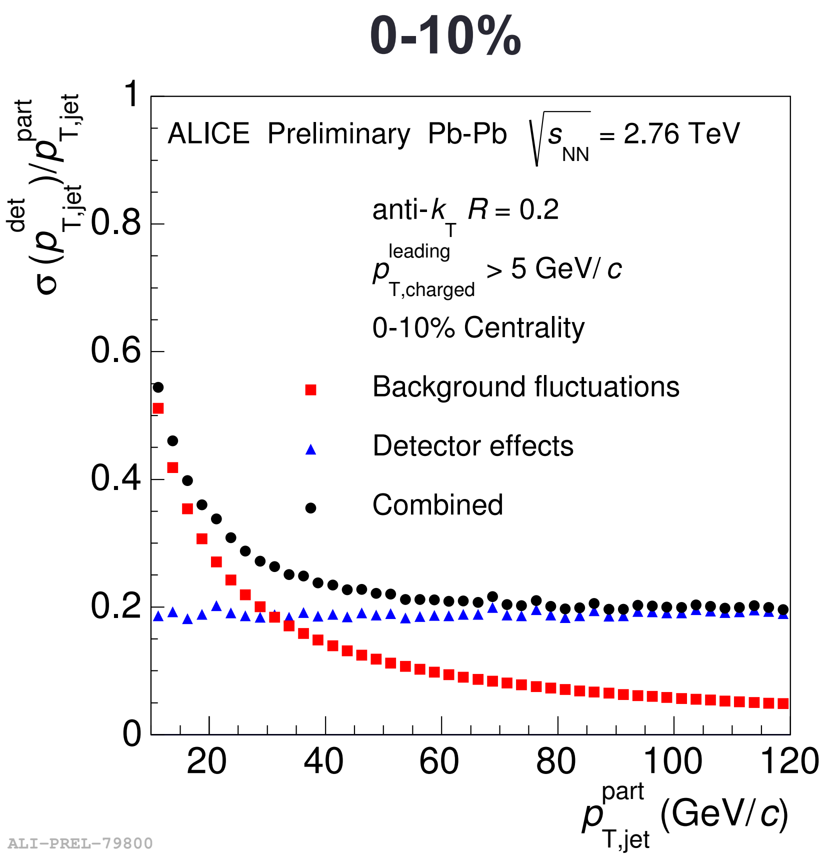


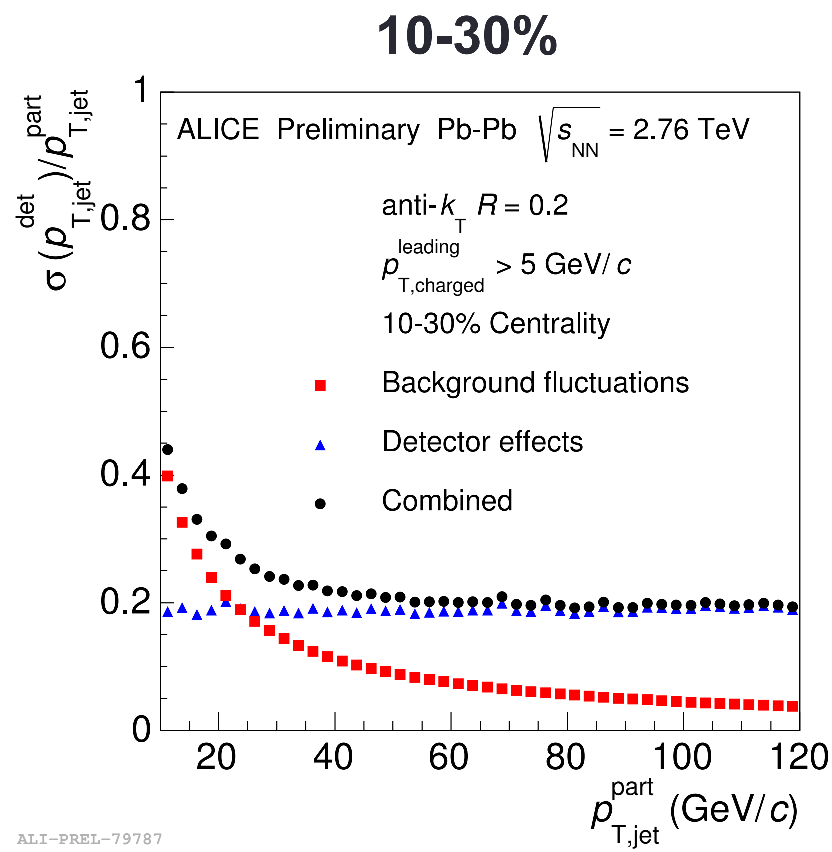
- Background density fluctuates within event
  - Smears jet momentum
- Fluctuation size characterized by δp_T

$$\delta p_T = \sum p_{T,\,part} - \rho_{scaled} \pi R^2$$

- Asymmetric distribution
  - LHS: Gaussian-like dominated by soft particle production
  - RHS: tail due to hard particles (jets overlap!)

Jet momentum resolution





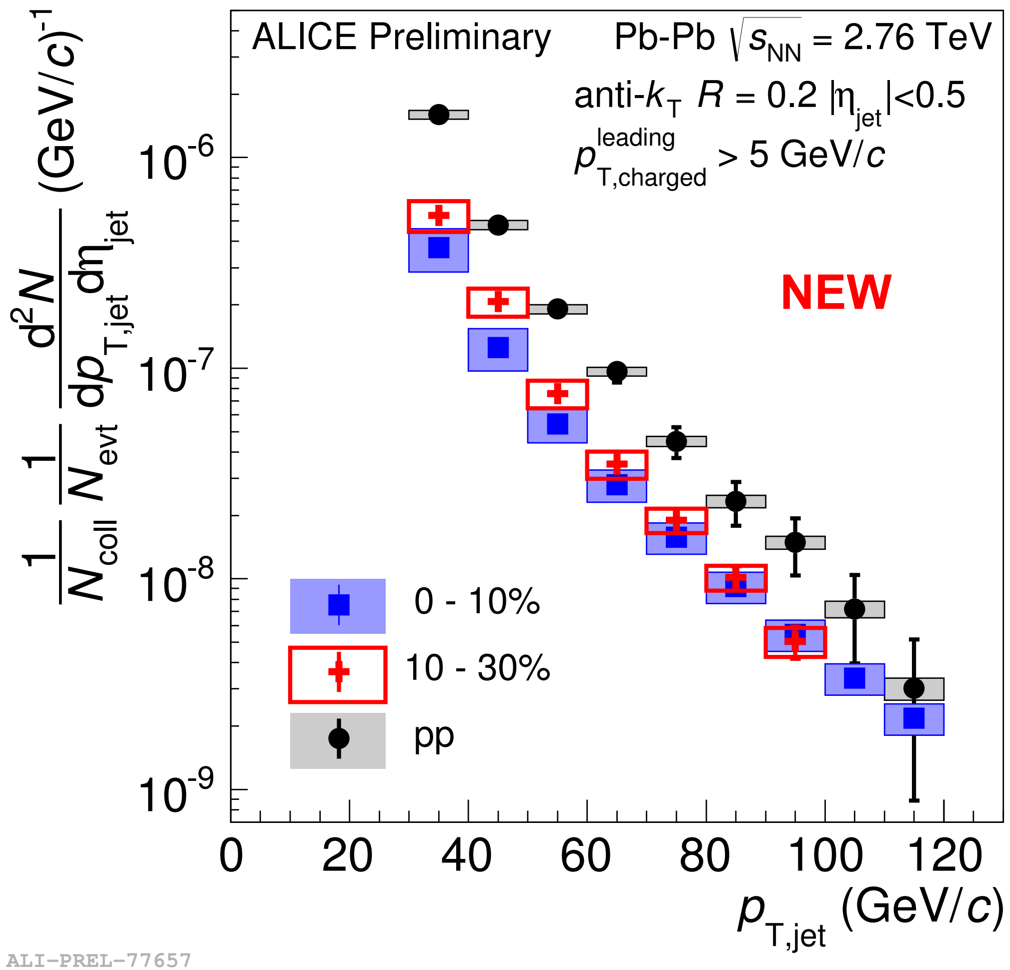
Background fluctuations

- smaller for 10-30% centrality
- dominate for p_T < 30 GeV/c

Detector effects

- ~ independent of centrality and p_T
- dominate for p_T > 30 GeV/c

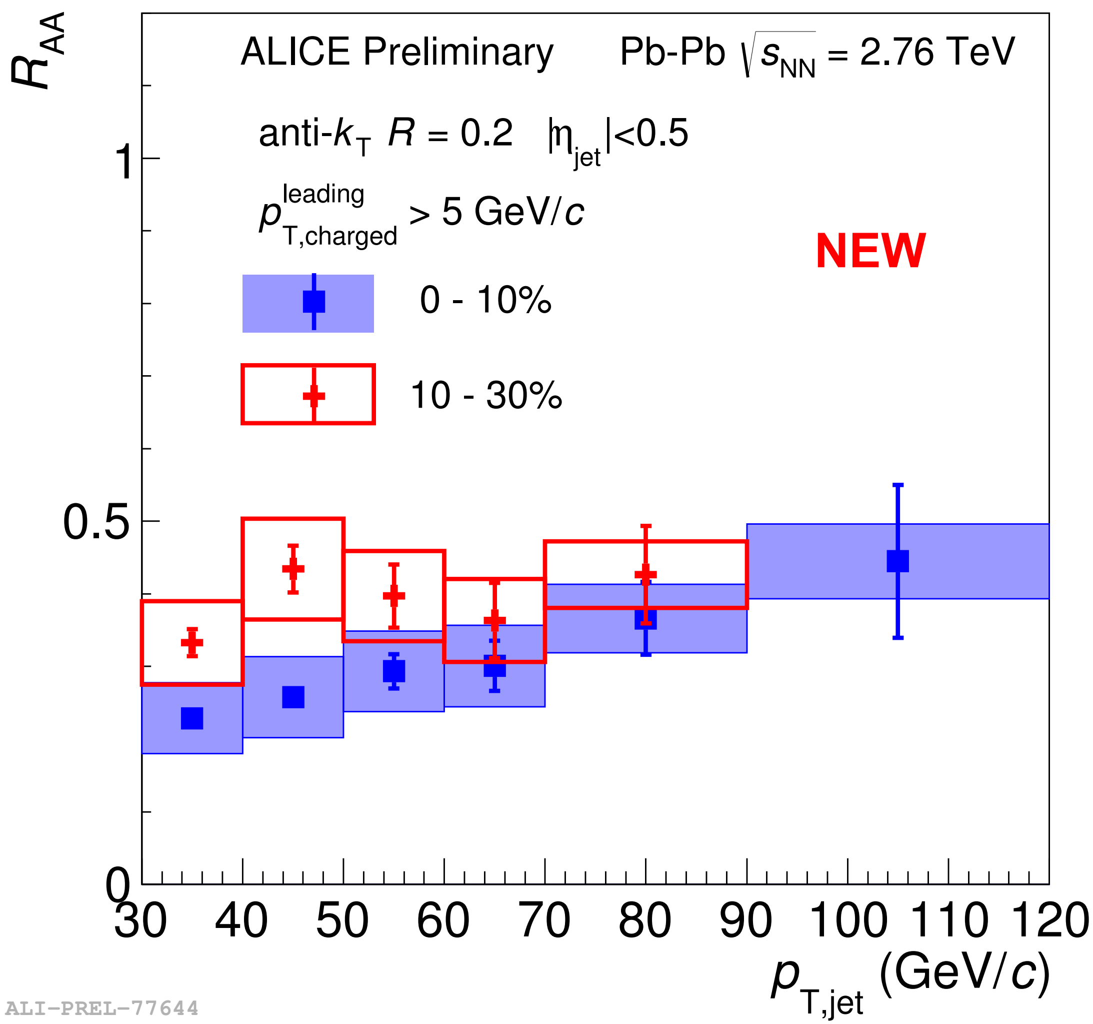
Jet p_T spectra in Pb-Pb collisions



- Two centrality classes
  - 0-10% and 10-30%
- **pp** measurement[1]
- Background subtracted
- Corrections applied for both detector effects and background fluctuations through unfolding
- Unfolding methods
  - Pb-Pb: SVD, Bayesian, χ^2
  - pp: bin-by-bin correction, Bayesian

[1] The ALICE Collaboration, Physics Letters B, 722 (2013) 262 (link)

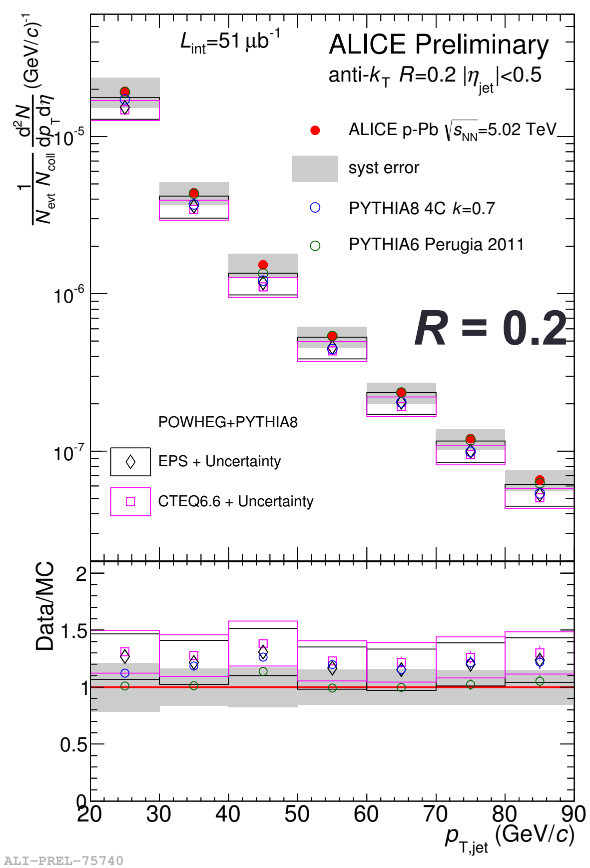
Nuclear modification factor in Pb-Pb collisions

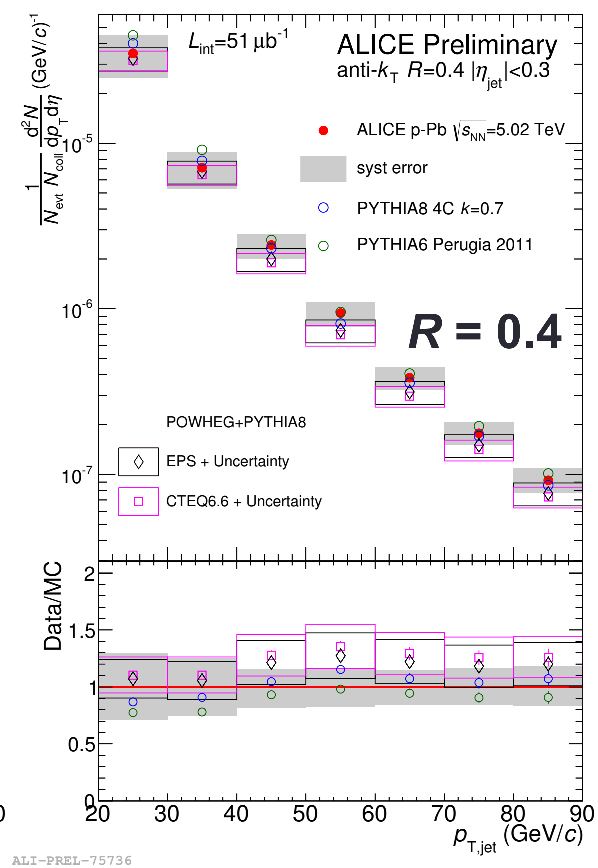


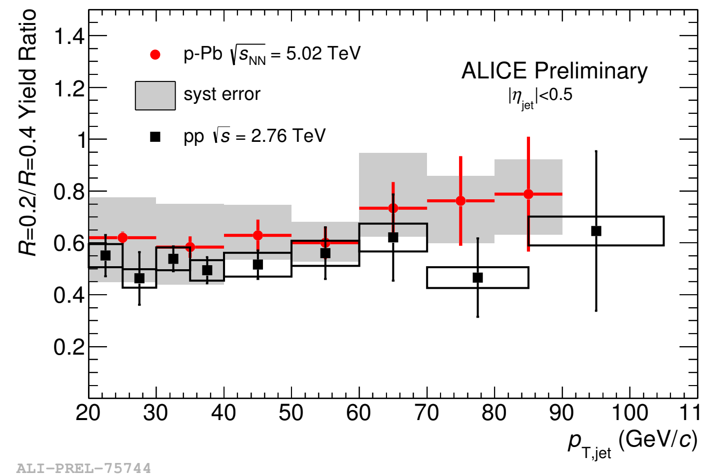
- Strong **jet suppression** observed
- **Dependence on centrality class**
- Systematic uncertainties are mainly driven by unfolding and tracking efficiency
  - Partially correlated between centralities
- Consistent with ALICE published results on **charged jet** R_{CP}
  - The ALICE Collaboration, JHEP 1403 (2014) 013 [arXiv:1311.0633]

Jet p_T spectra in p-Pb collisions

NEW



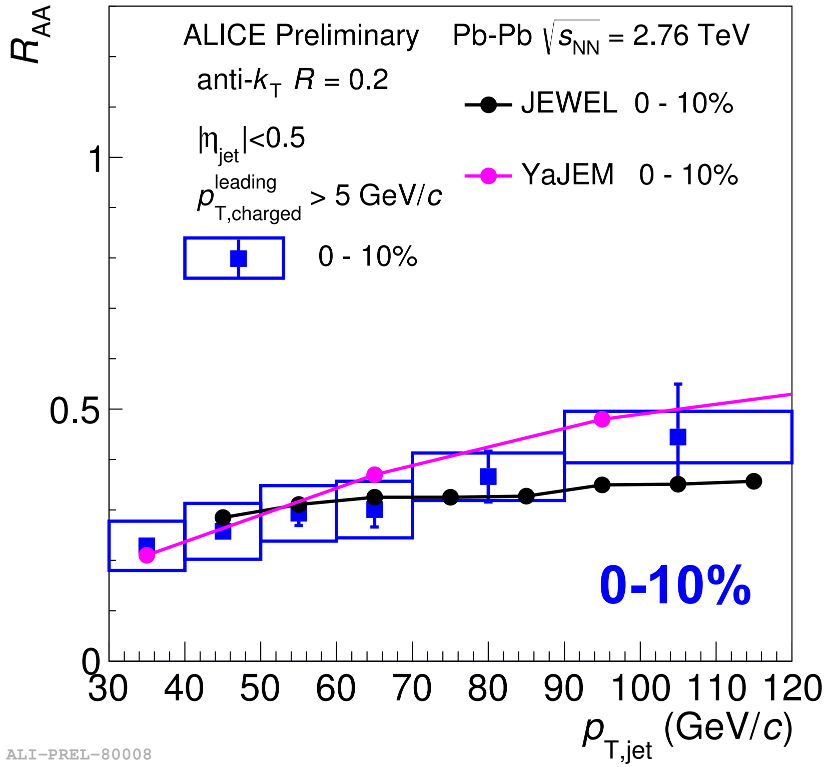


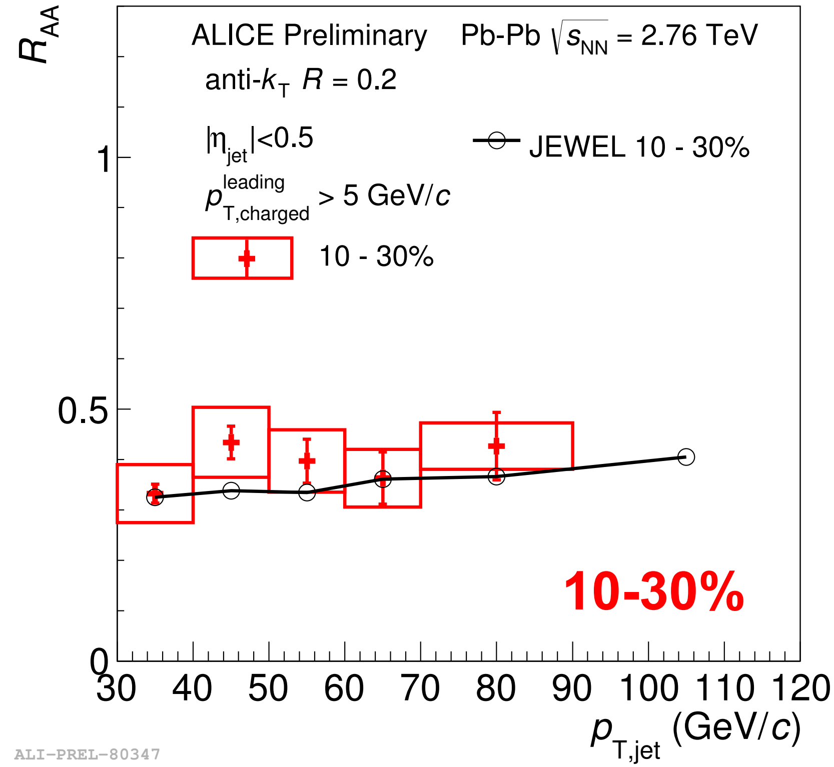


- Results consistent with **no CNM effects** on jets
- Posters: M. Connors (**E-06**), C. Yaldo (**E-39**)
- Similar conclusions from **charged jet** analysis: R. Haake (**E-09**)
- j_T spectra of charged jet constituents: J. Kral (**E-16**)

- Jets measured by ALICE in **p-Pb collisions** at 5.02 TeV using similar techniques
- Crucial test of **Cold Nuclear Matter** (CNM) effects
- Compared with different MC pp references

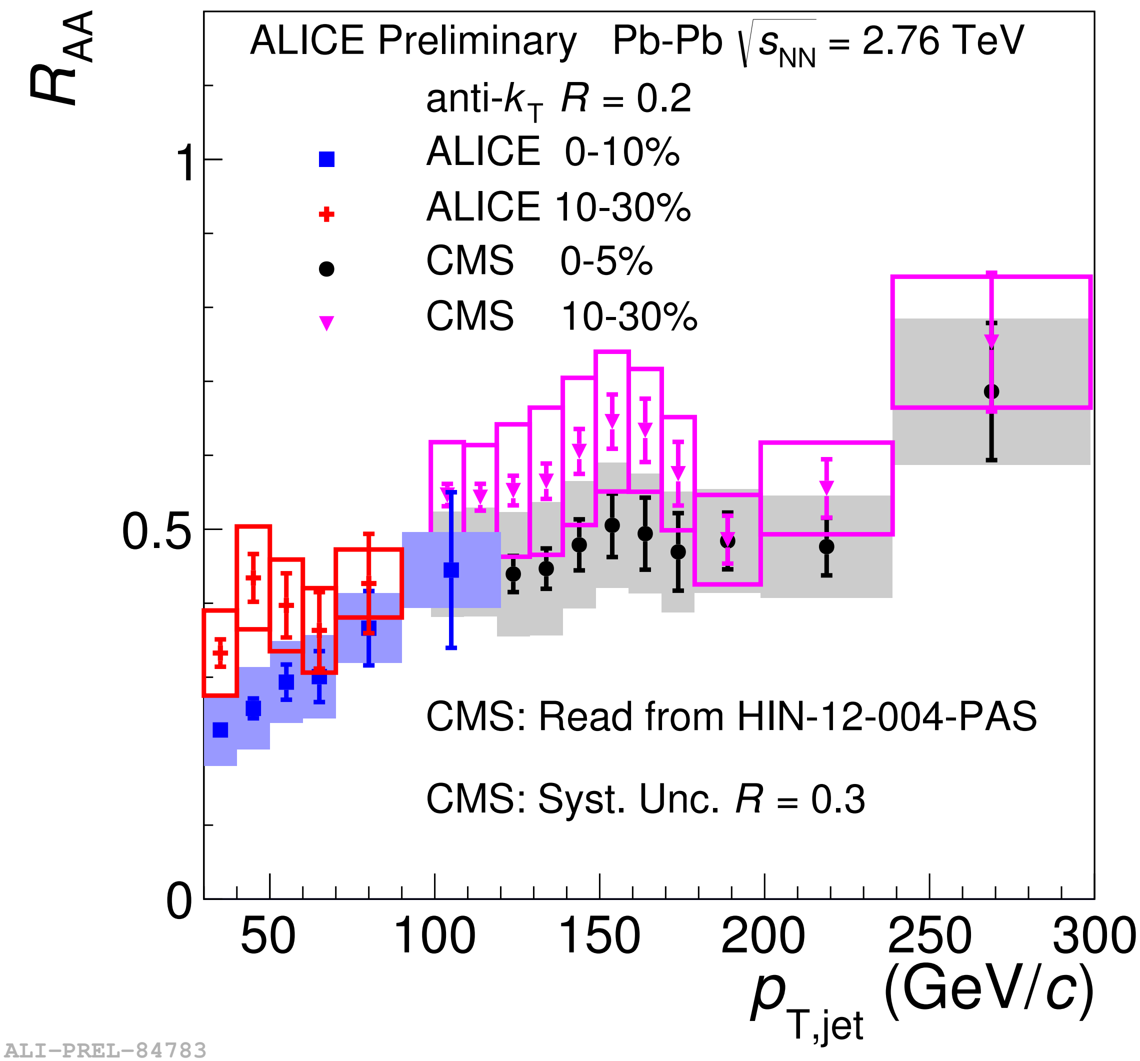
Comparison with theoretical models





- Well-established models: realistic geometry, initial state conditions, hadronization
  - **JEWEL**: arXiv:1212.1599, arXiv:1311.0048
  - **YaJEM**: T. Renk, Phys. Rev. C 78 (2008) 034908, Phys. Rev. C 84 (2011) 067902
  - Both models fitted to single particle R_{AA}

Comparison with CMS

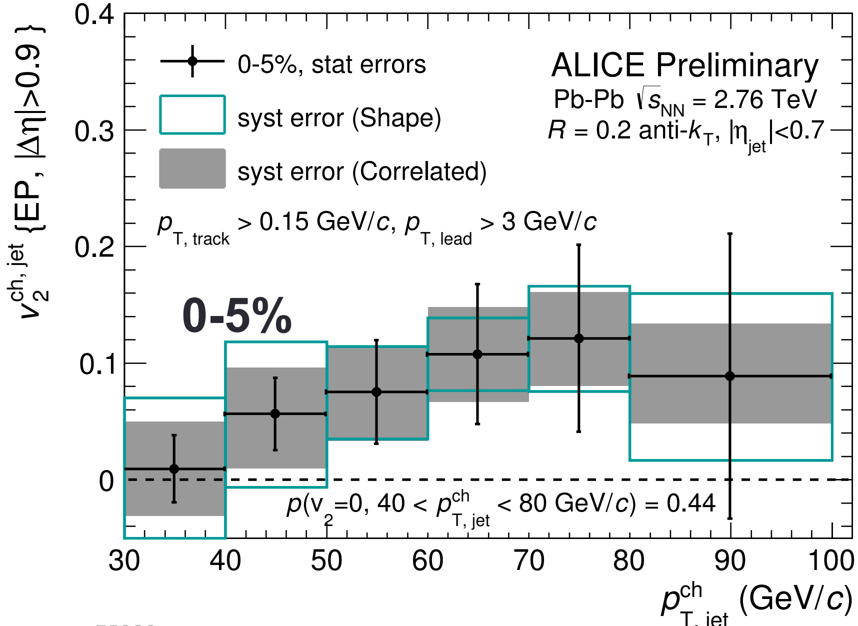


- Agreement with CMS in the narrow region of overlap (only 0-10%)
- It would be interesting to extend the p_T ranges of both analyses to have a more significant comparison
  - Calorimeter triggered data being used by ALICE to extend to higher p_T
    - ➢ Poster: R. Reed (**E-27**)

Event plane dependence of jets

NEW

Charged-only jets



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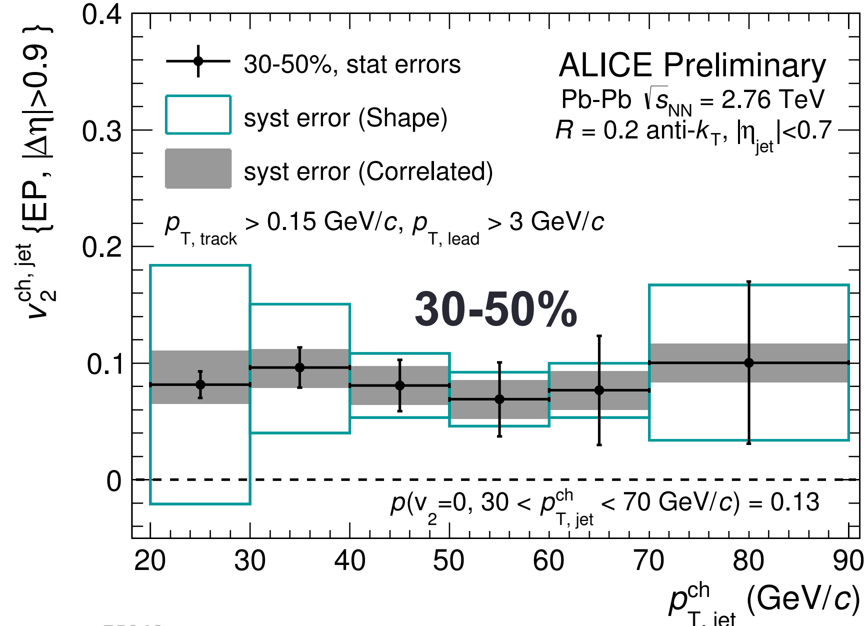

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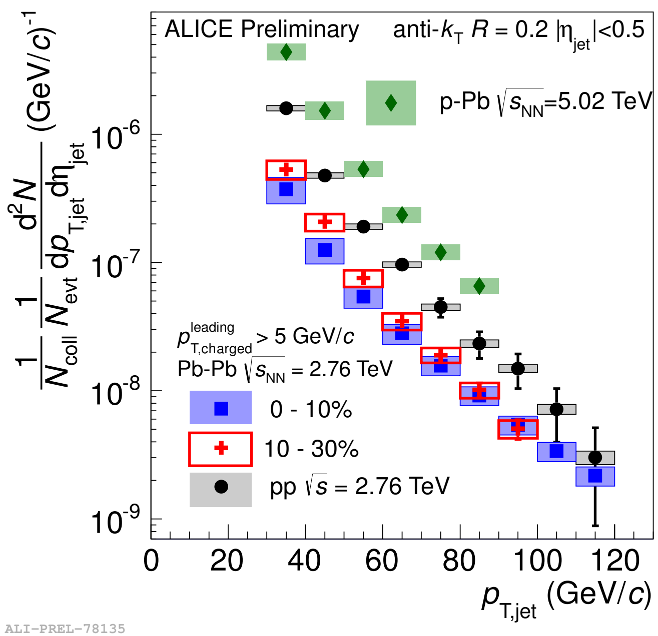
- Path length dependence of jet energy loss can be investigated by measuring jet v_2:

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

- In central events (0-5%) zero $v_2^{ch,jet}$ hypothesis can't be excluded
- Indication of $v_2^{ch,jet} \neq 0$ in the 30-50% centrality class (2 sigma significance)
- Poster: R. Bertens (**E-02**)

Conclusions and outlook

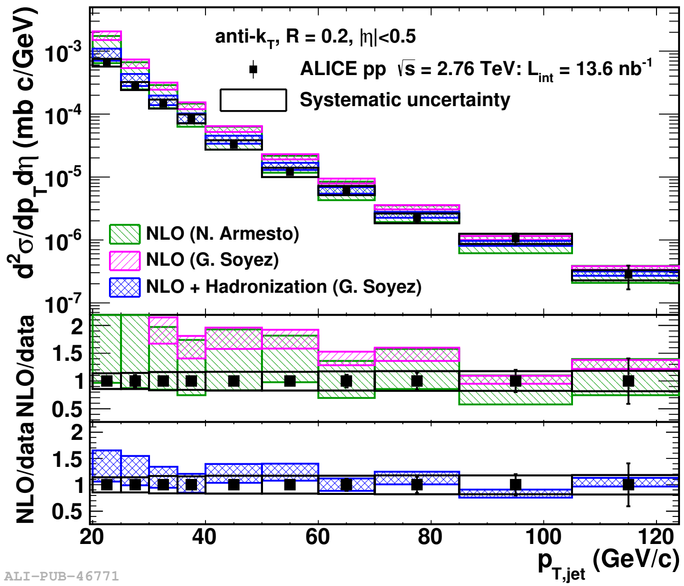
- ALICE has measured jets in **various collision systems**
  - **pp**: test of pQCD at LHC energies, **baseline measurement** for heavy-ion collisions
  - **p-Pb**: crucial test of **CNM effects**, also baseline for future Pb-Pb measurements at 5 TeV
  - **Pb-Pb**: strong centrality dependent **jet suppression** observed relative to pp (binary scaling assumed)

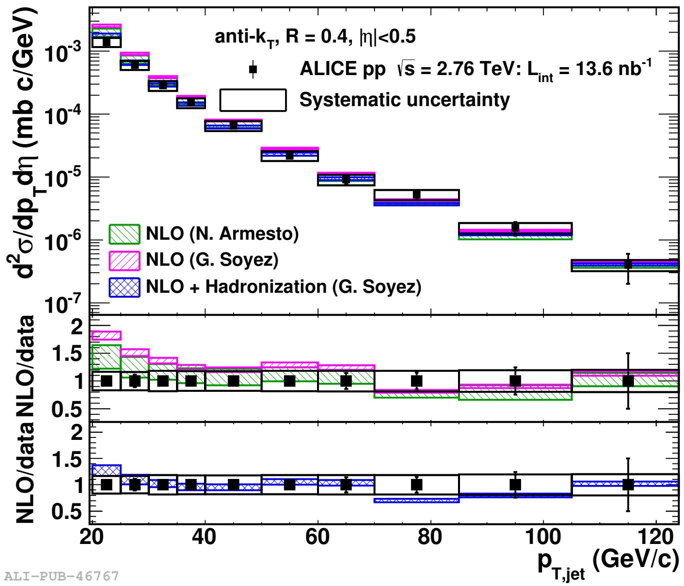


- CNM effects cannot account for the **observed jet quenching**
  - ➢Strong indication of **hot nuclear matter effects**

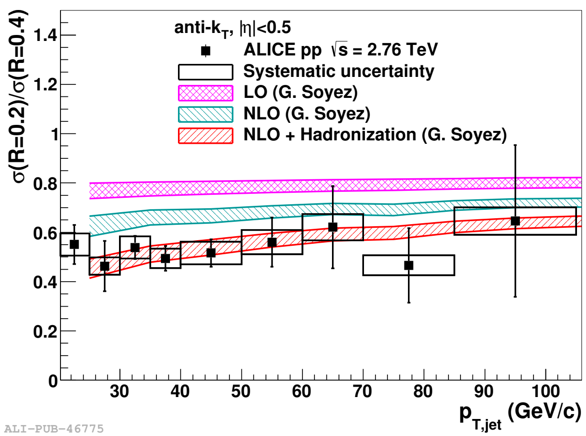
Backup slides

Jet cross section in pp collisions





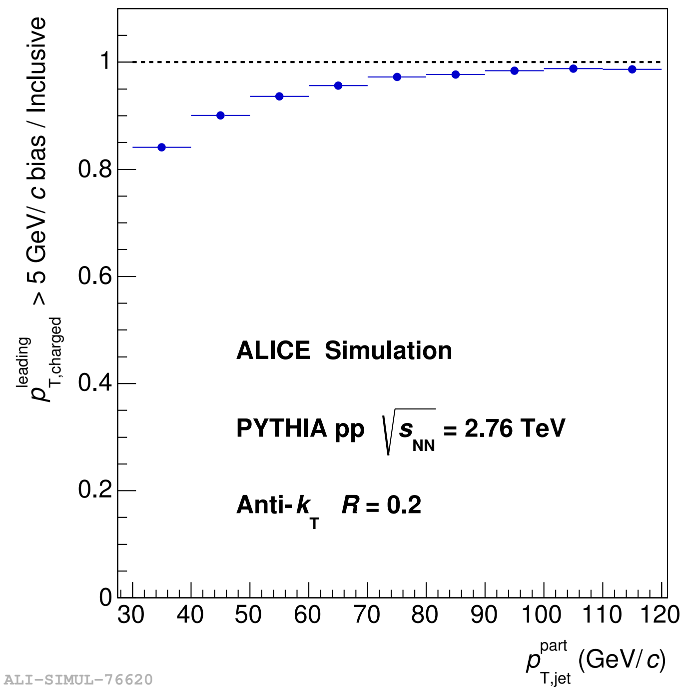
Jet cross sections in pp collisions have been measured by ALICE[1]

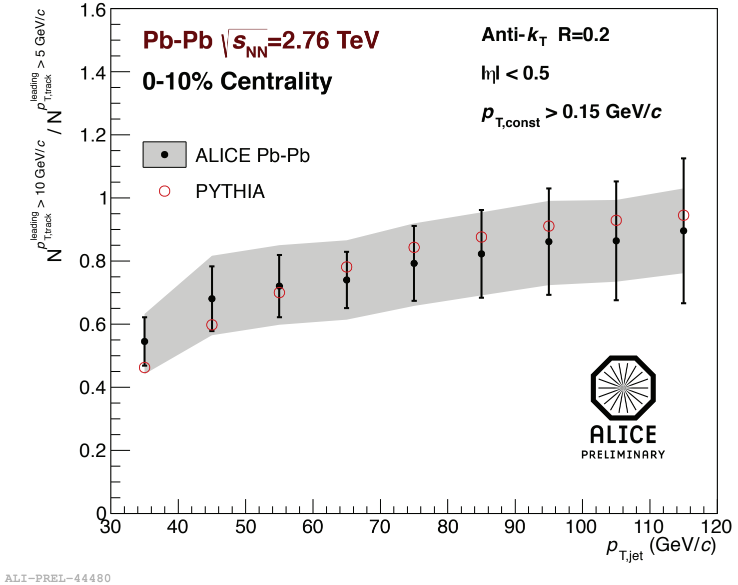


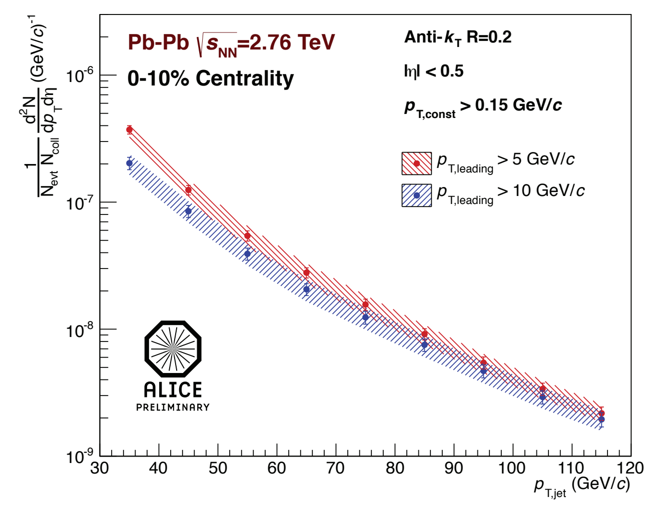
- Anti-k_T, R = 0.2 and R = 0.4
- Excellent agreement with **pQCD NLO** with hadronization effects
- Ratio R = 0.2 / R = 0.4 gives information on the jet structure

[1] The ALICE Collaboration, Physics Letters B, 722 (2013) 262 (link)

Effect of the leading hadron bias

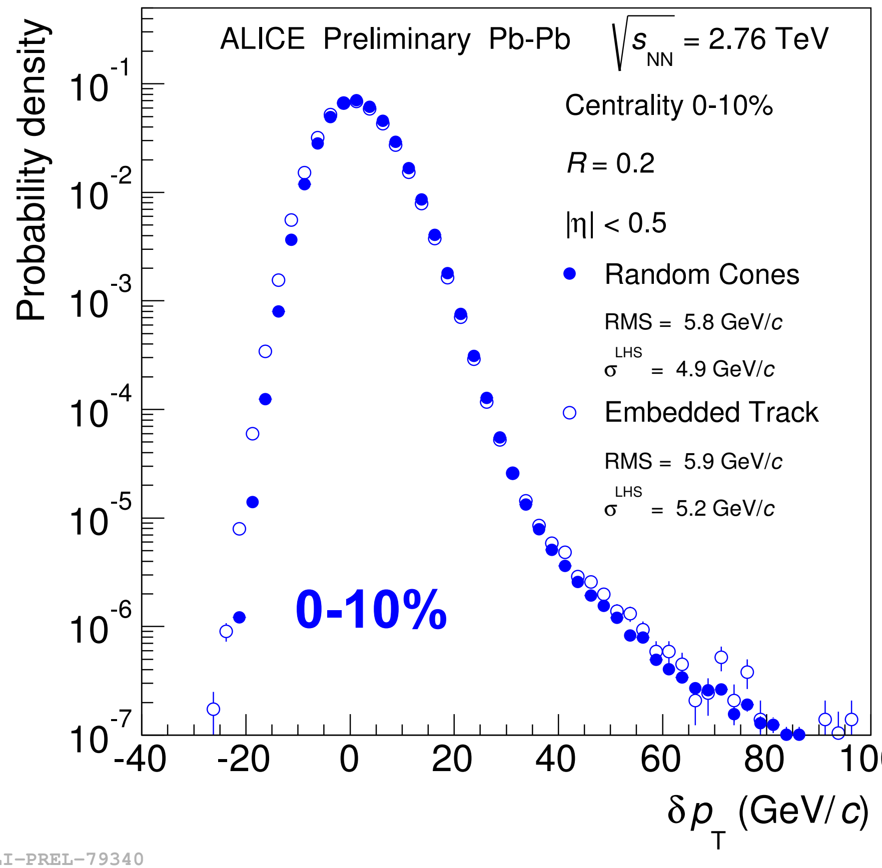


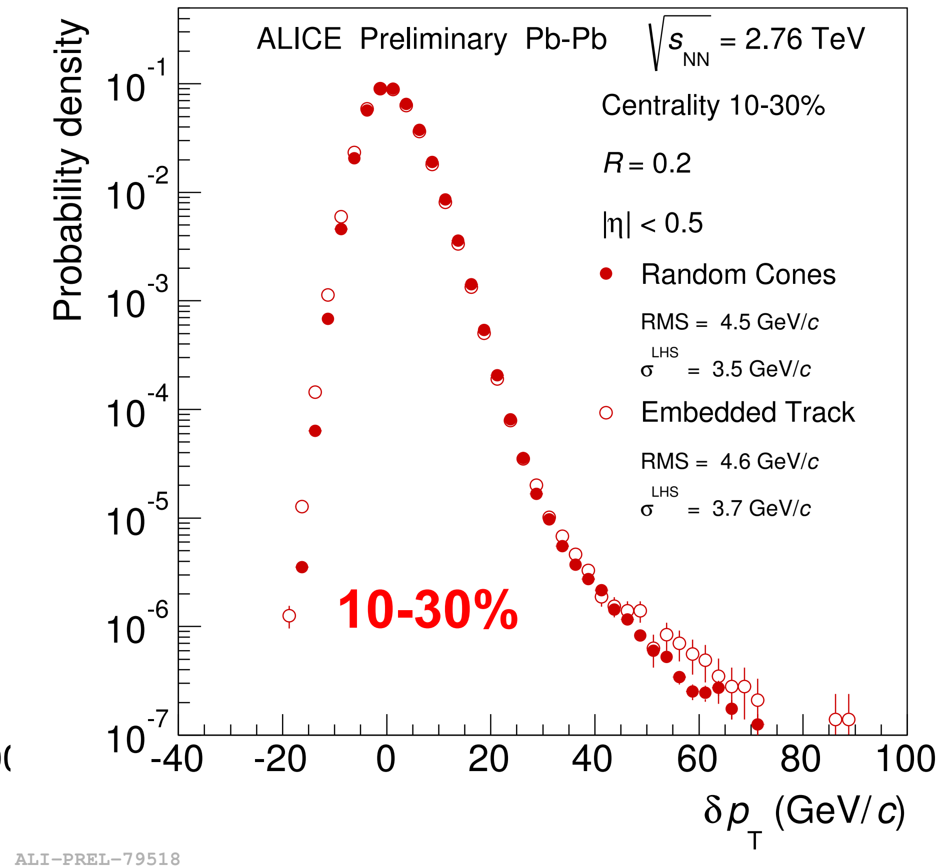




- PYTHIA pp
  - 5 GeV/c over inclusive
- Pb-Pb collisions
  - 10 GeV/c over 5 GeV/c
  - Compatible with PYTHIA pp

Background fluctuations - Embedding

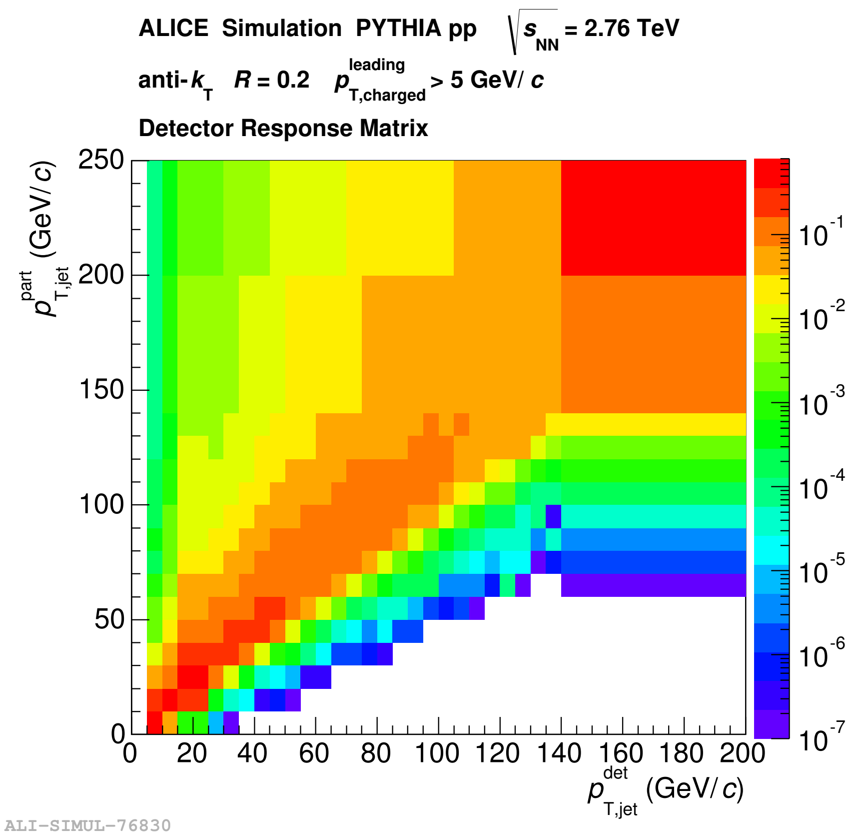


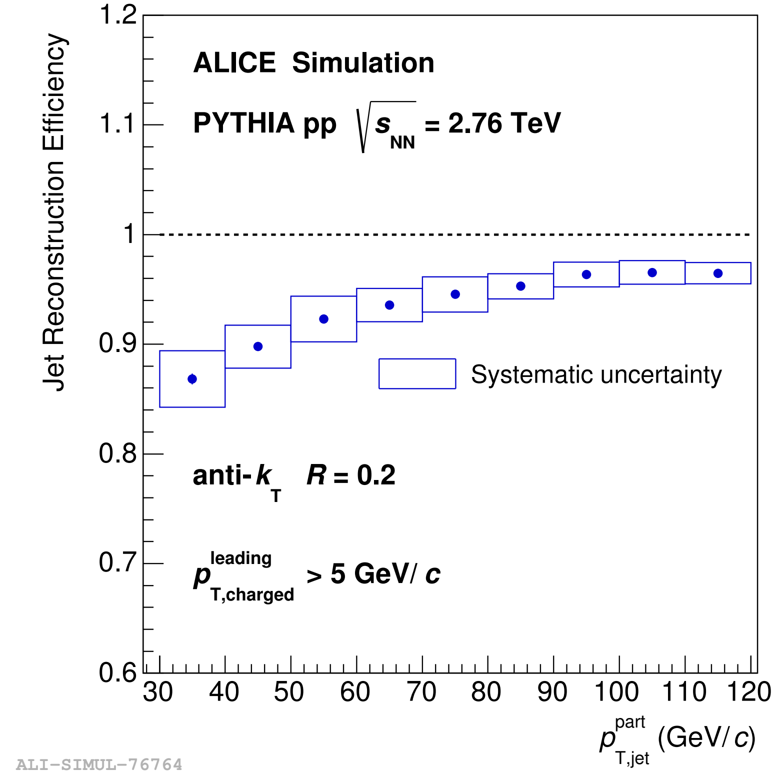


Single particle embedding δp_T (open symbols) is compared with random cones (full symbols)

p_T^{part} = particle level jet p_T
p_T^{det} = detector level jet p_T

Detector effects

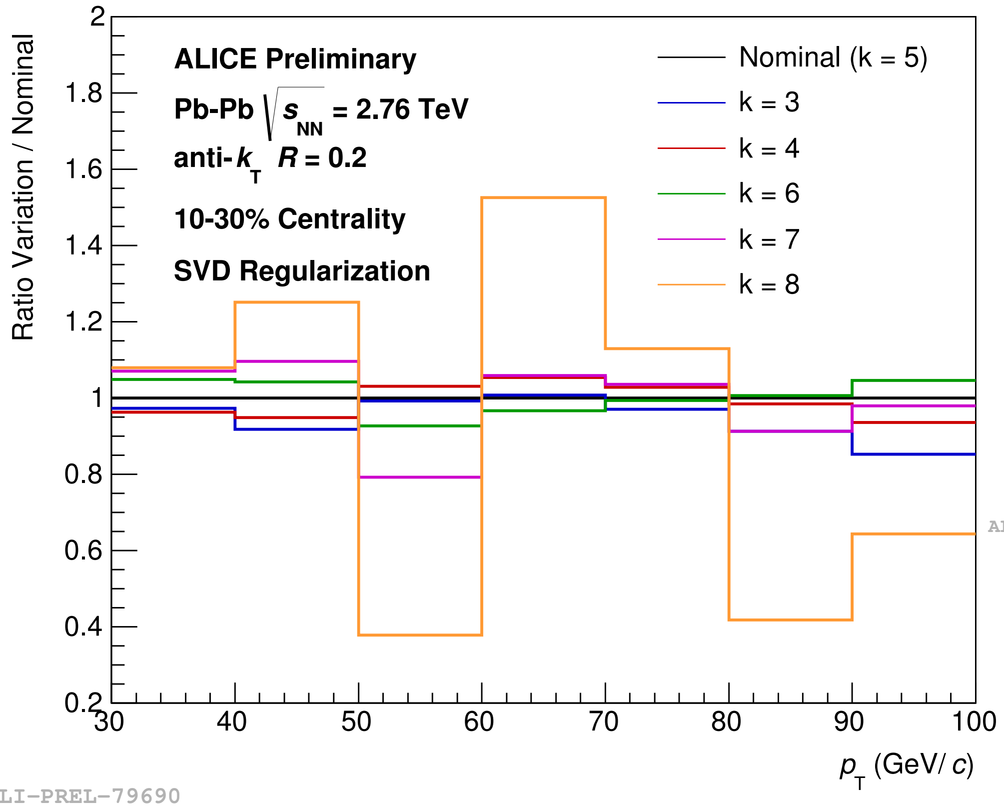


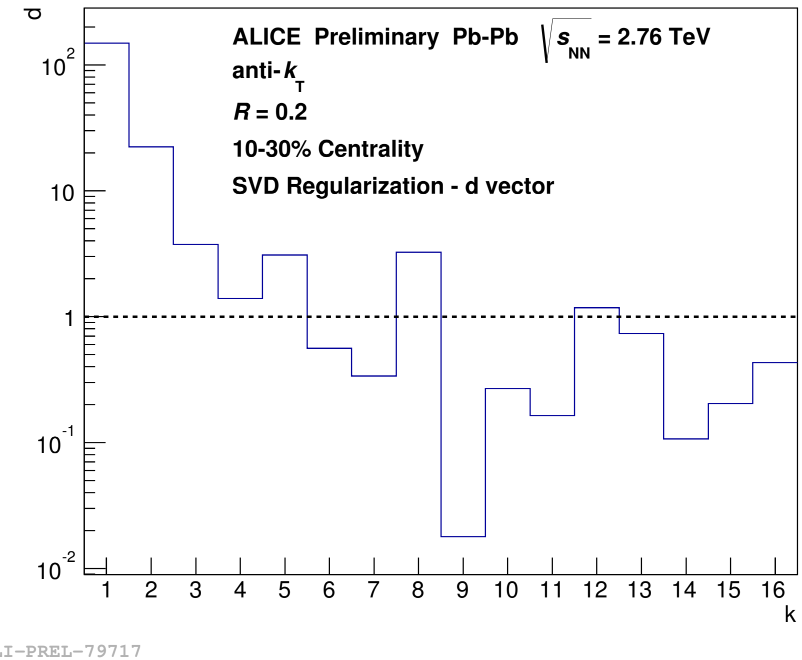


Jet efficiency dominated by single track efficiency of the leading hadron

- **Detector effects** extracted from a **PYTHIA+GEANT** simulation
- Response assumed to be the same as for pp collisions, except tracking efficiency
  - HIJING simulation used to determine multiplicity effects in Pb-Pb collisions

Unfolding





SVD regularization[1] acts like a "high frequency filter" of a Fourier decomposition
Driven by an integer parameter **k**

[1] A. Hocker and V. Kartvelishvili, *Nucl. Instrum. Meth.* A 372 (1996) 469 [arXiv:hep-ph/9509307]

$$f^{det}(p_T^{det}) = RM_{comb}(p_T^{det}, p_T^{part}) \times \varepsilon(p_T^{part}) \times f^{part}(p_T^{part})$$

Unfolding

Mathematically ill-posed problem: **regularization** needed to suppress unphysical oscillations (see **k = 8**)

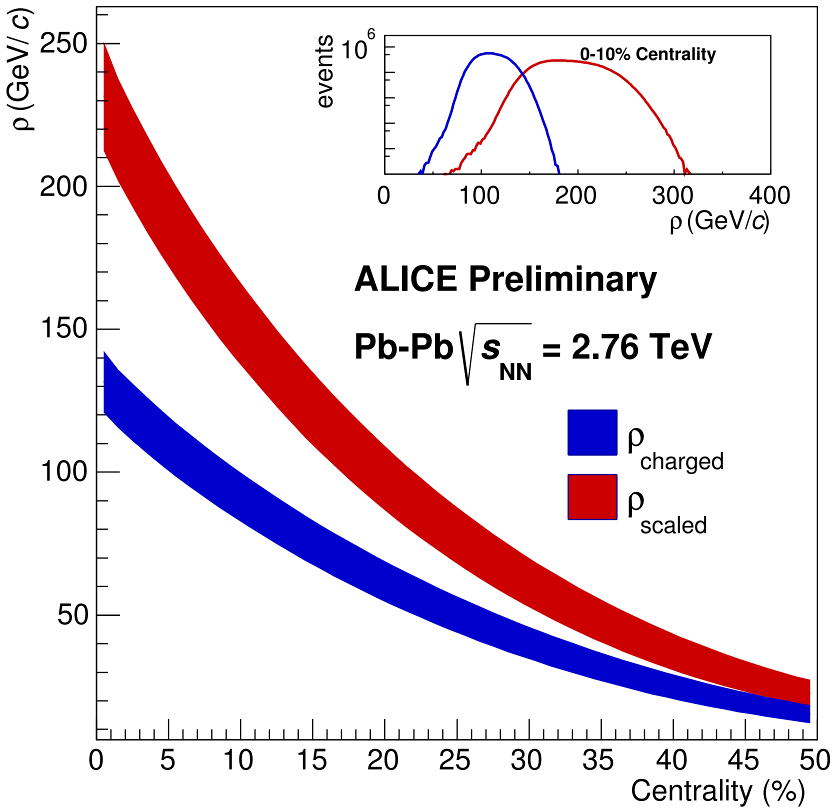
List of systematic uncertainties

	0-10%	10-30%
Unfolding: method, prior choice, regularization strength	10%	7%
Measured p_T range	5%	3%
Unfolded p_T range	1%	2%
Total unfolding	**11.2%**	**7.9%**
EMCal energy scale	3%	3%
Clusterizer	10%	6%
Resolution	1%	1%
Nonlinearity	3%	3%
Total EMCal	**10.9%**	**7.4%**
Scale factor	2%	2%
Tracking efficiency	10%	10%
Hadronic correction	7%	5%
Bkg. fluctuations (δp_T)	5%	2%
Flow	1%	2%
Total others	**13.4%**	**11.7**
Total	**~21%**	**~16%**

- Most of the uncertainties are p_T dependent
- The values shown in the table for each category correspond to the maximum uncertainty

Average background

$$\boxed{s_{\mathrm{EMC}}} = \frac{\left(\sum E_T^{\mathrm{cluster}} + \sum p_T^{\mathrm{track}}\right)}{\sum p_T^{\mathrm{track}}}$$



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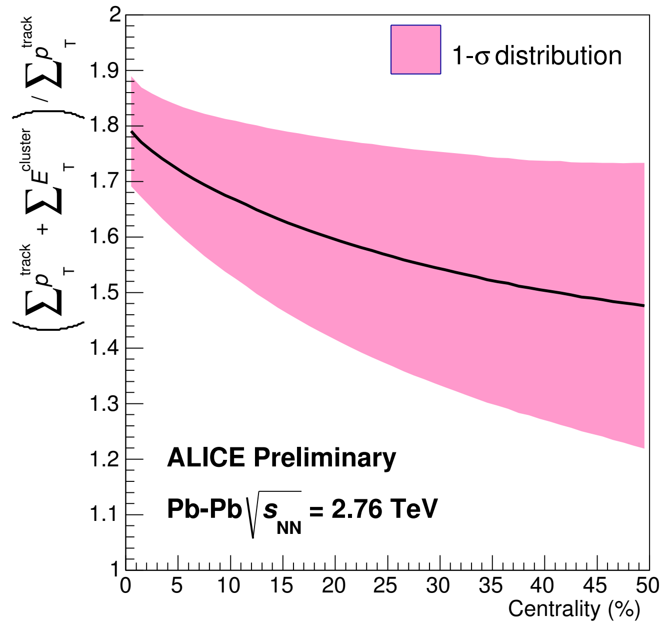

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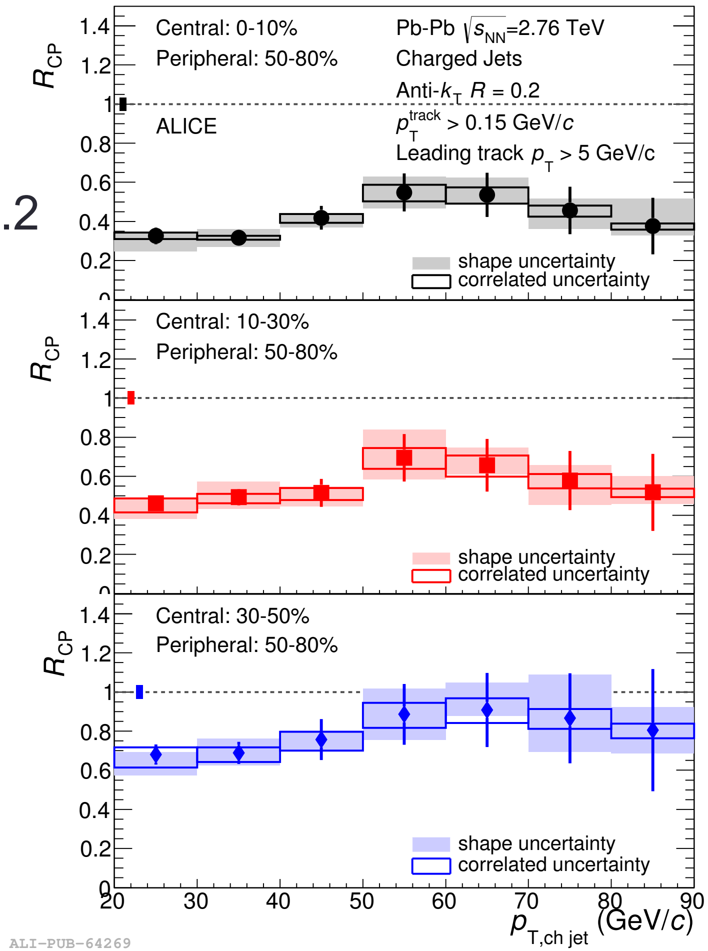
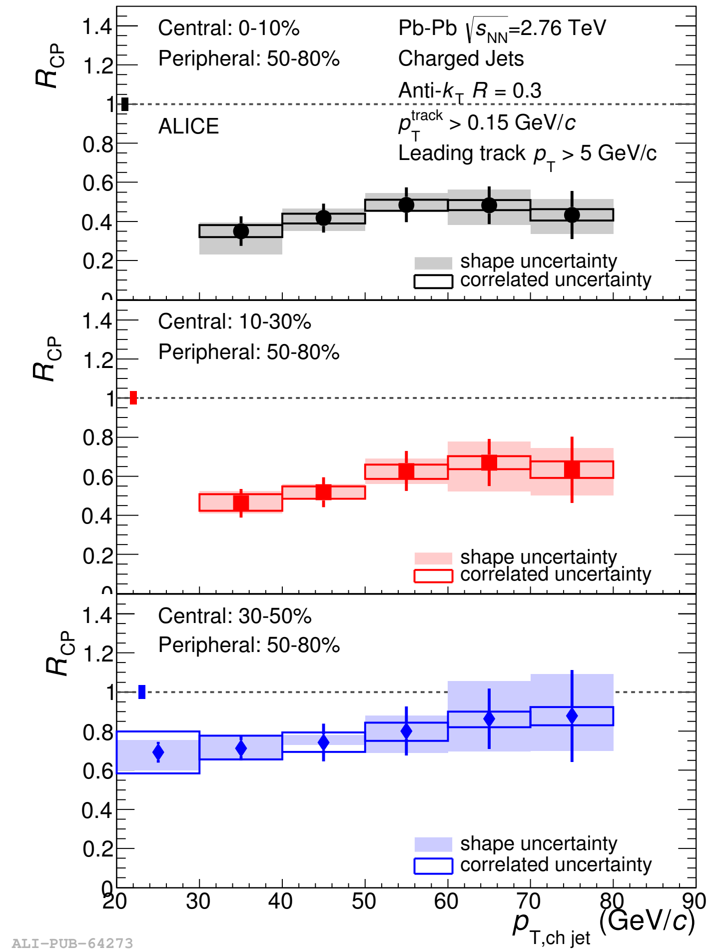
- Event-by-event **charged background density**: $\boxed{\rho_{\mathrm{charged}}} = \mathrm{median}\left(\frac{p_T^{k_T\,\mathrm{jet}}}{A^{k_T\,\mathrm{jet}}}\right)$
  Median approach reduces bias from signal jets
- **Scaled** to account for neutral energy: $\boxed{\rho_{\mathrm{scaled}}} = \boxed{s_{\mathrm{EMC}}} \cdot \boxed{\rho_{\mathrm{charged}}}$

Charged jet R_{CP}

R = 0.2

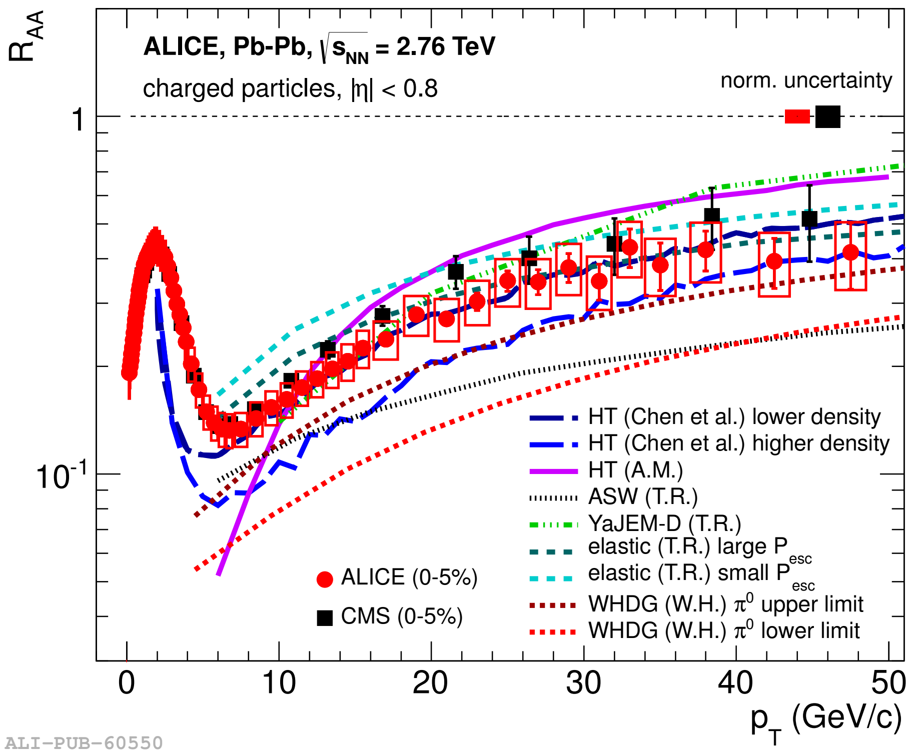


R = 0.3

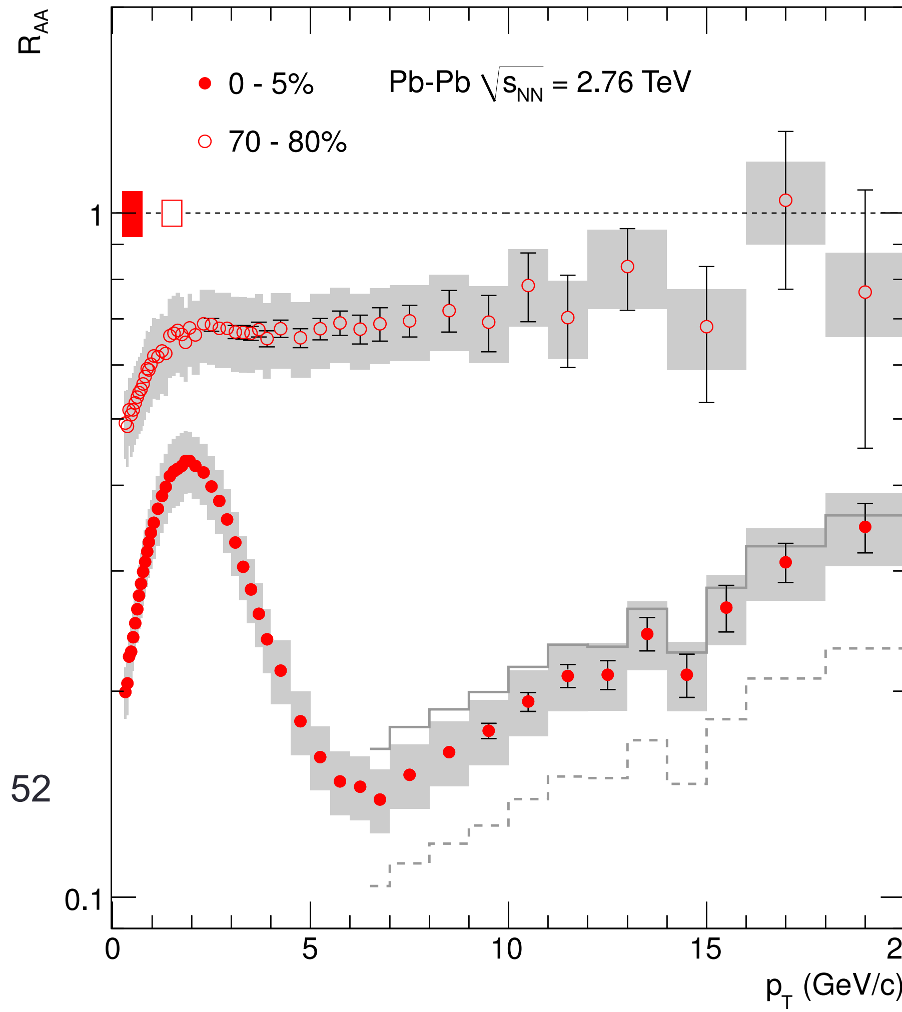


The ALICE Collaboration, JHEP 1403 (2014) 013

Charged particle R_{AA}

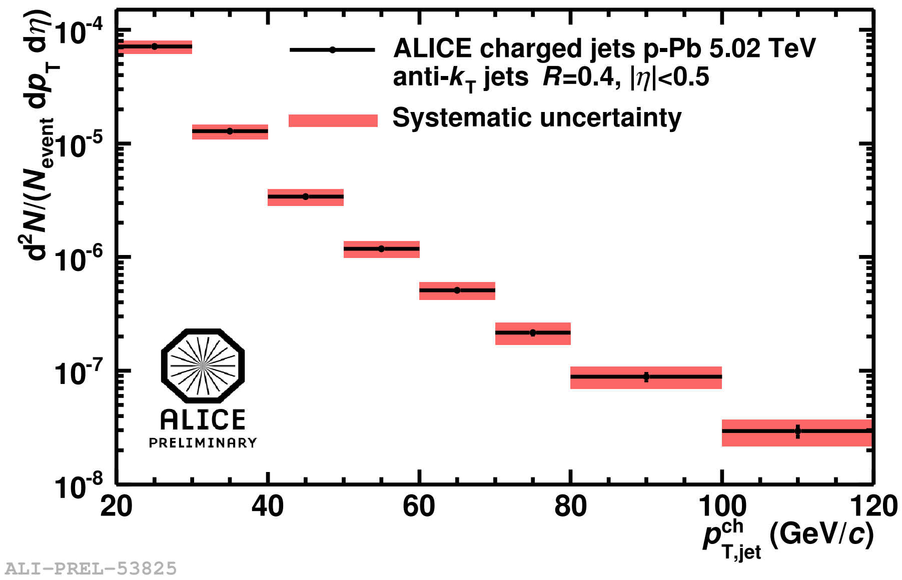


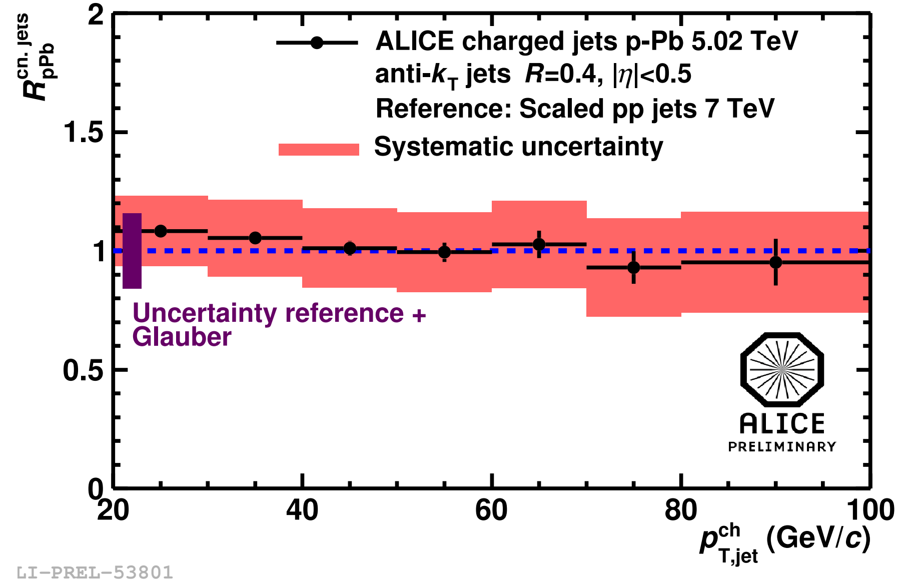
The ALICE Collaboration, Physics Letters B 720 (2013) 52
http://dx.doi.org/10.1016/j.physletb.2013.01.051.



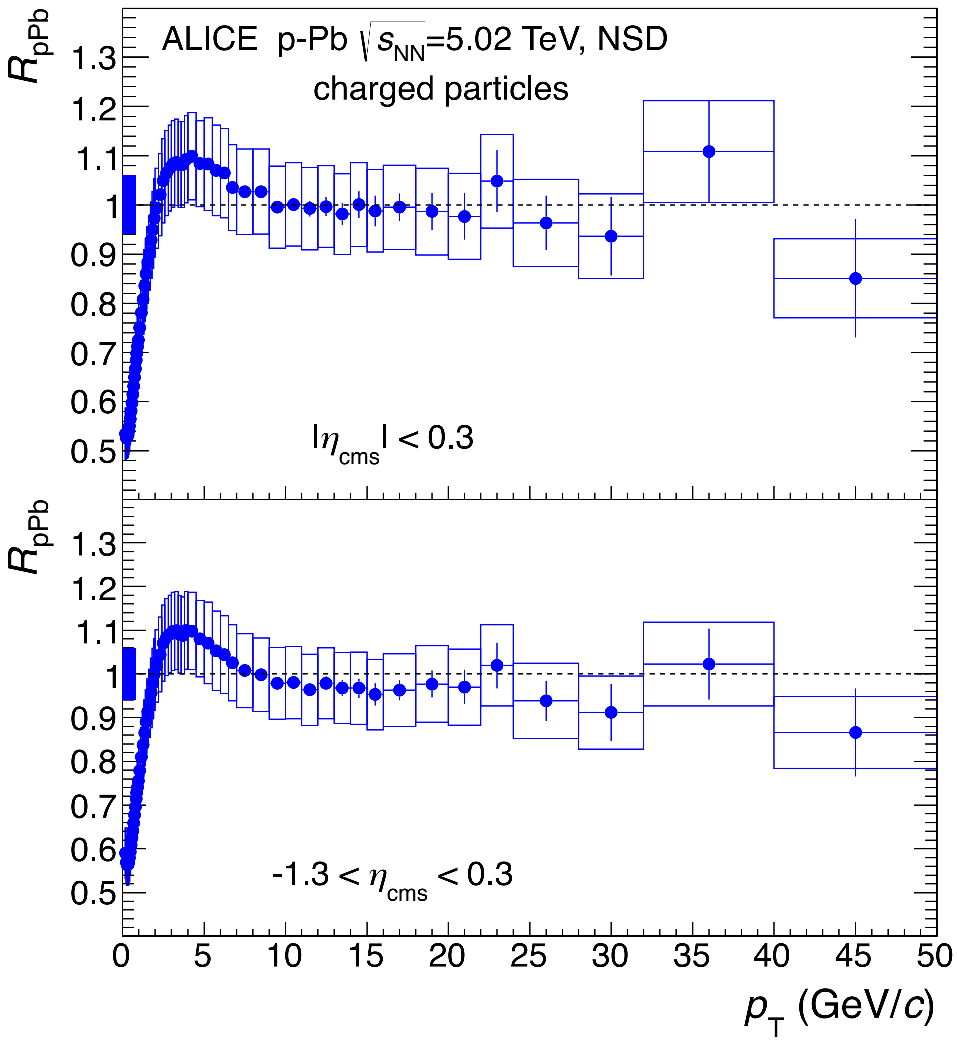
The ALICE Collaboration, Physics Letters B 696 (2011) 30
http://dx.doi.org/10.1016/j.physletb.2010.12.020.

Charged jet R_{pPb}





Charged particle R_{pPb}



[arXiv:1405.2737]