Jet production and structure in pp, p-Pb and Pb-Pb collisions measured by ALICE

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on behalf of the ALICE collaboration

Strangeness in Quark Matter
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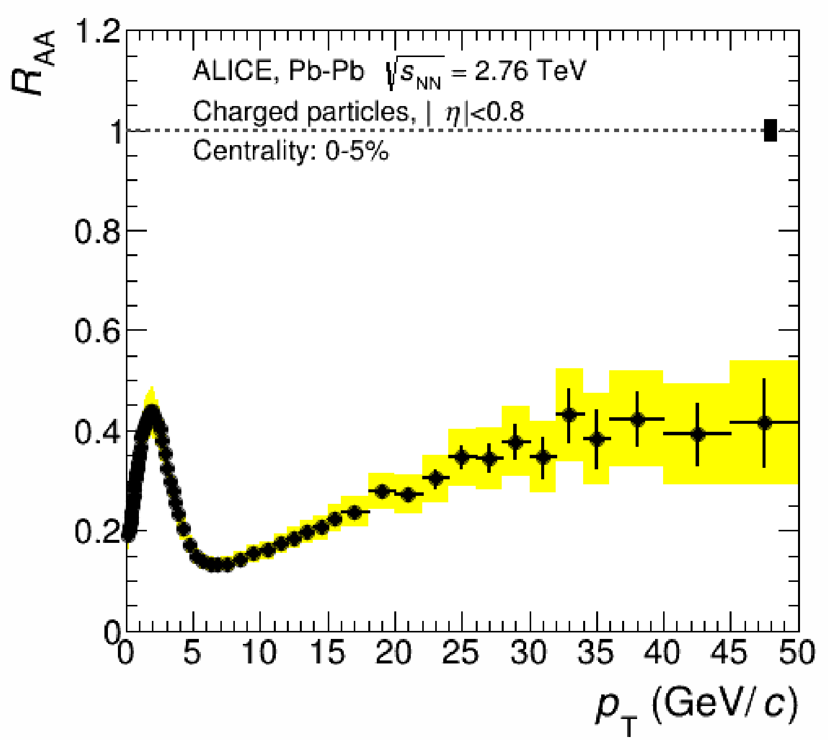
Hard Probes in QGP

Hard scatterings produce high energy partons

- Initial state production known from pQCD
- Parton loses energy due to interaction with medium
  → Jet Quenching
- Jet Quenching observed via suppression in single and away side di-hadron production



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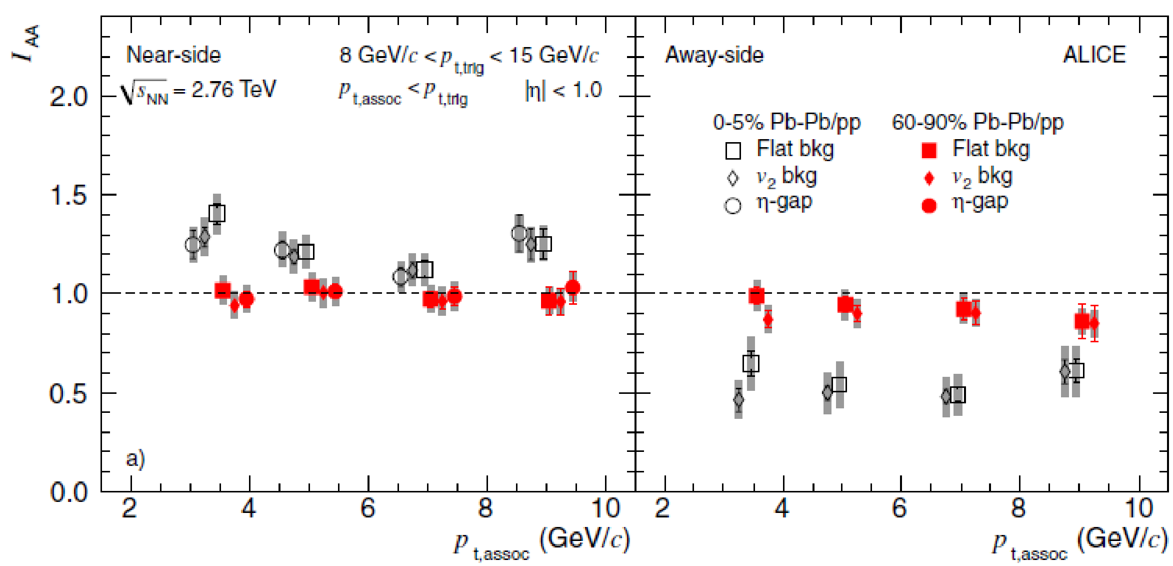
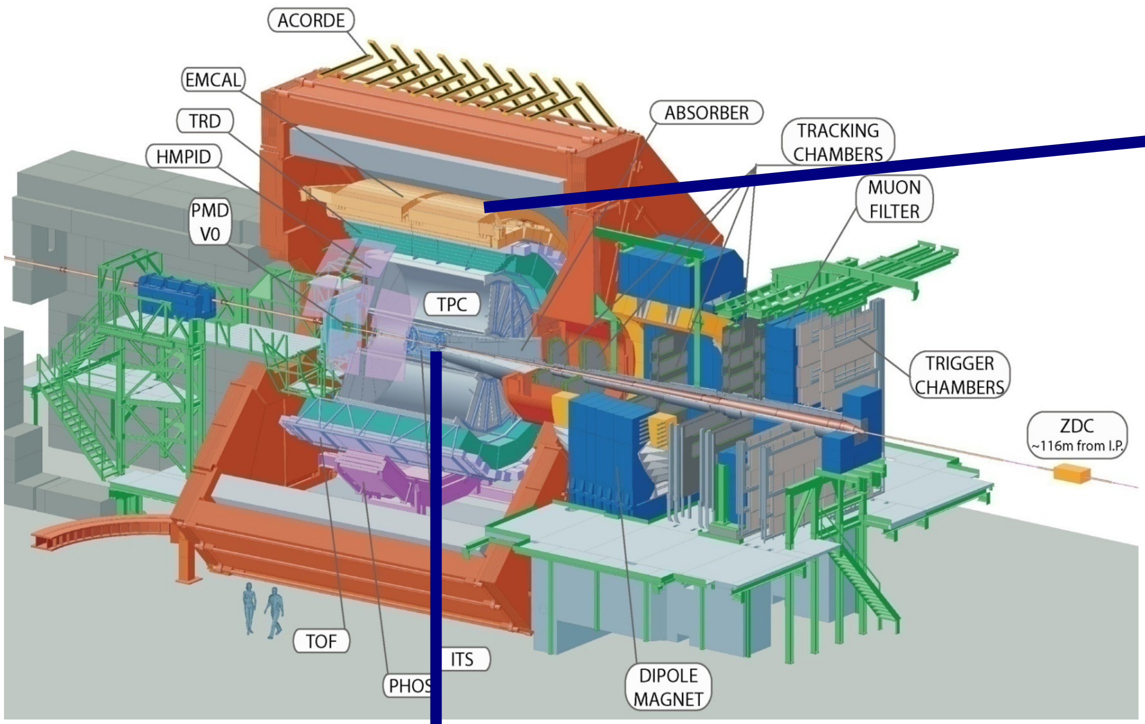
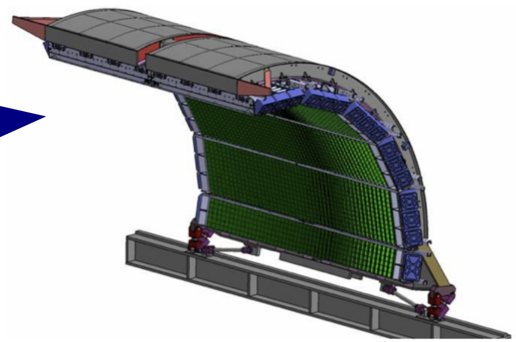
Use jet reconstruction to constrain parton kinematics better



PRL 108 092301 (2012)

Jets in ALICE





- EMCal is a Pb-scintillator sampling calorimeter which covers:

  $|\eta| < 0.7$, $1.4 < \varphi < \pi$

  tower $\Delta\eta \sim 0.014$, $\Delta\varphi \sim 0.014$

Charged hadronic correction prevents double counting

Tracking: $|\eta|<0.9$, $0<\varphi<2\pi$
TPC: gas detector
ITS: silicon detector

→ ***Charged constituents*** → **JET** ← ***Neutral constituents***

Jets in ALICE

- Jet reconstruction with charged tracks reconstructed in tracking detectors (ITS + TPC) + neutral energy in EMCal:
  - High precision at particle level
  - Uniform η-φ acceptance:

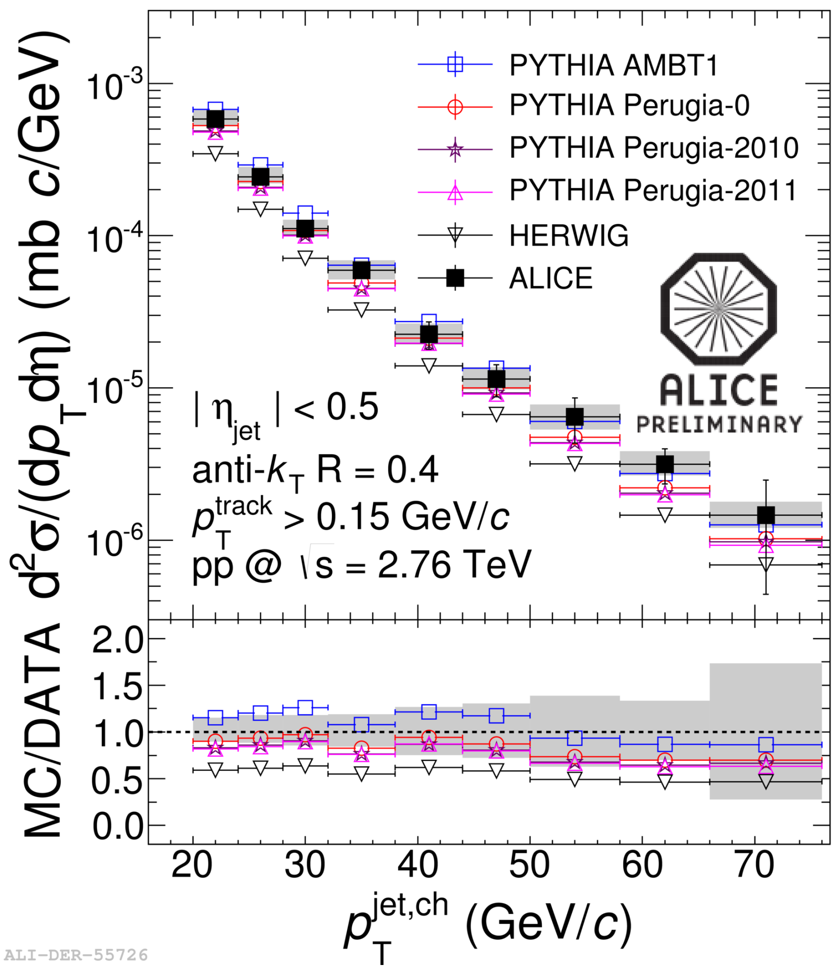
- Jet reconstruction with FastJet:
  - Charged particles: **p_T > 150 MeV/c;** EMCal clusters: E_T>300 MeV
  - anti-k_T for signal (stable area)
  - k_T to estimate background density
  - Boost invariant p_T recombination scheme

Jet spectra in pp

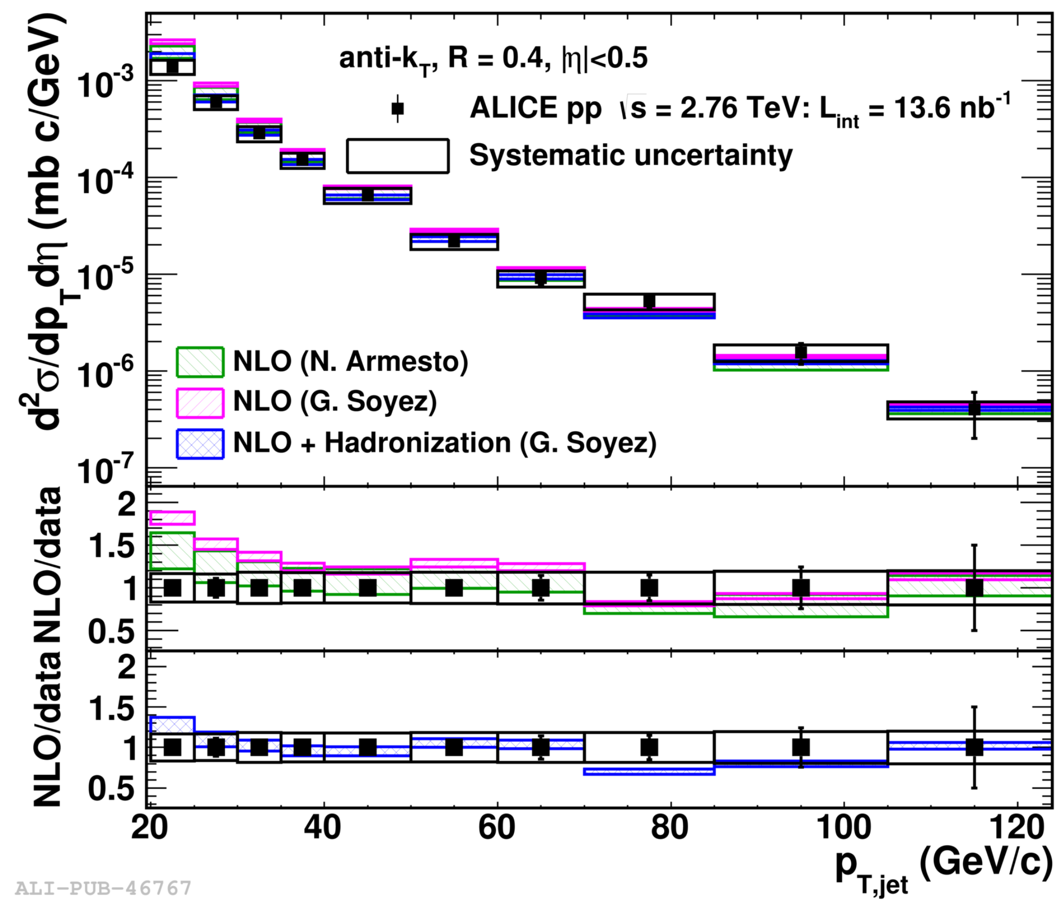
Inclusive jet spectra in pp collisions.
Baseline for Pb-Pb and p-Pb analysis.
NLO pQCD with hadronization reproduces data.

$\sqrt{s}$ = 2.76 TeV
Anti-k_T; R=0.4; $|\eta_{jet}|$<0.5

Charged Jets



Full Jets



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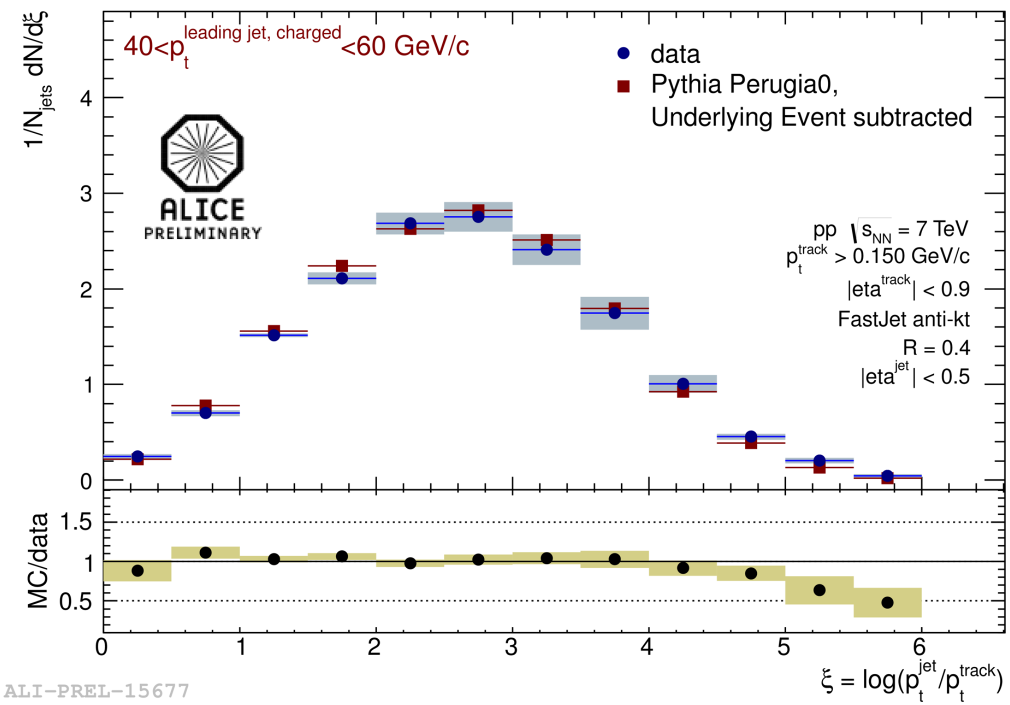
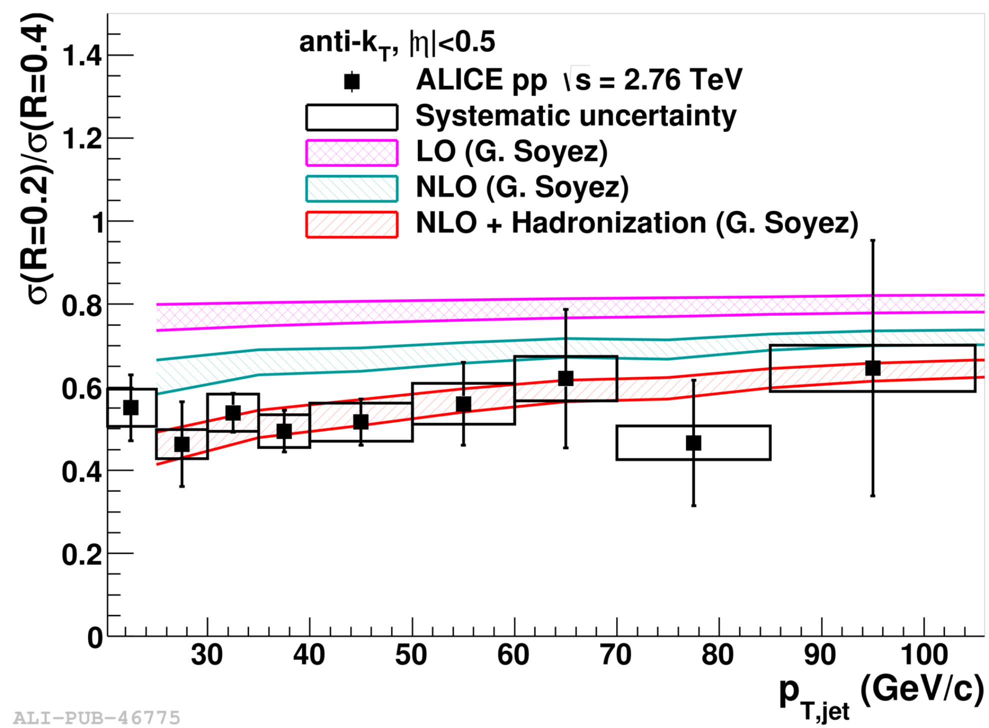
Jet structure in pp

Momentum distribution of jet constituents



Cross section ratio $\sigma(R=0.2)/\sigma(R=0.4)$



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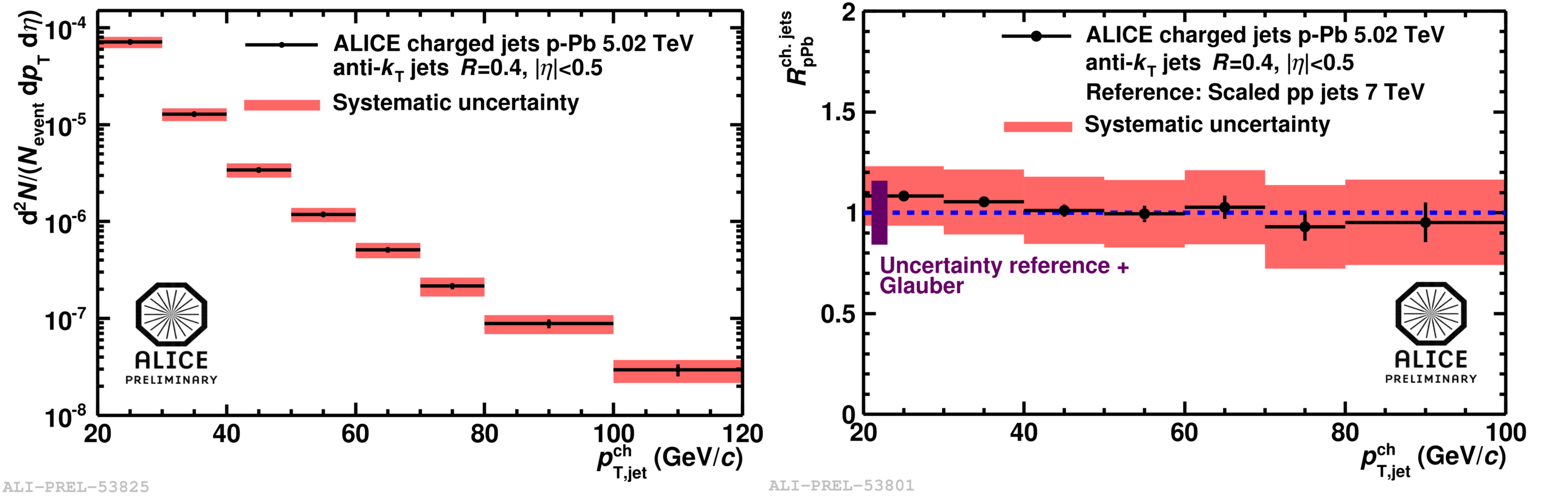
Scaled momentum $\xi = ln\,(p_T^{\text{jet,ch}}/p_T^{\text{particle}})$

→ hump-backed plateau

Jet transverse structure. Consistent with rising trend: jet collimation.

Jet spectrum in p-Pb

Minimum bias p-Pb events at √s = 5.02 TeV



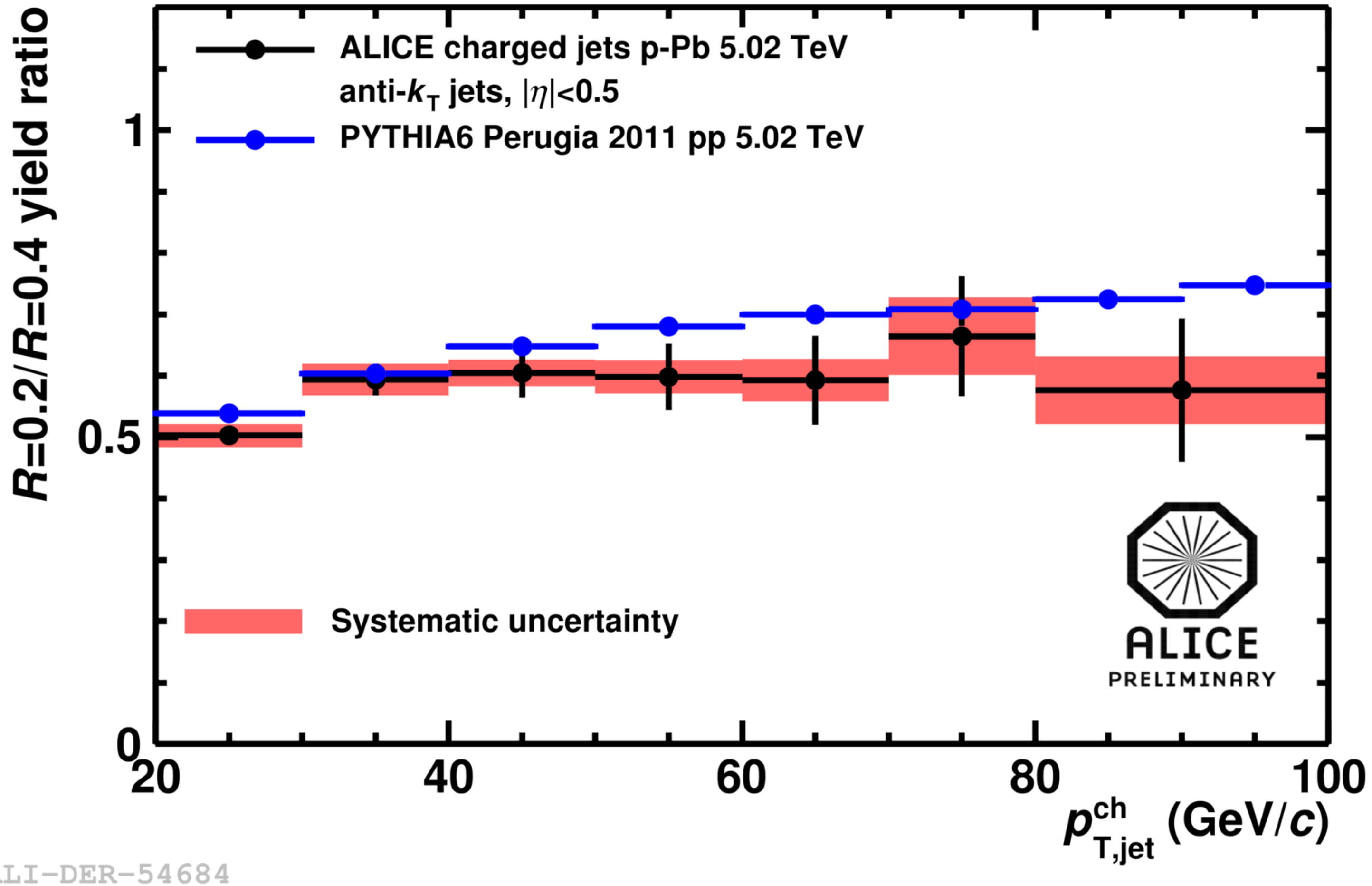
Jet spectrum corrected for background from underlying event and detector effects.

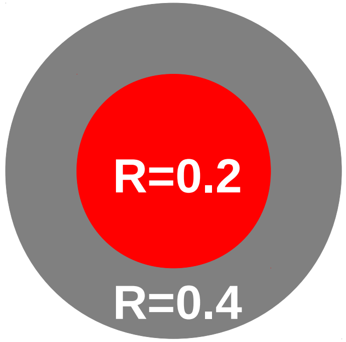
No jet suppression in p-Pb collisions within uncertainties

no cold nuclear matter effects → pp good reference for Pb-Pb

Jet transverse structure p-Pb

Cross section ratio



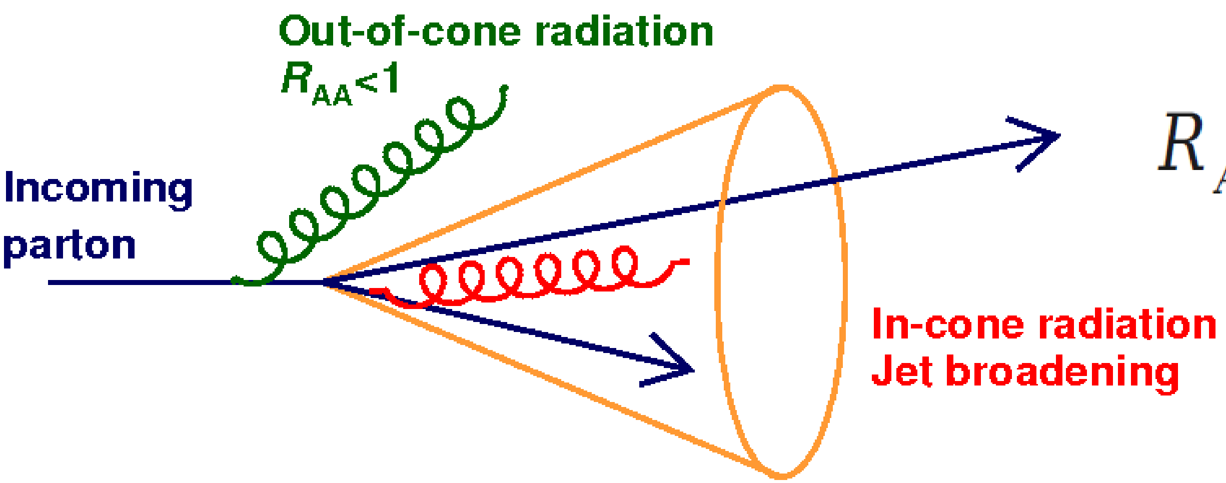


Jet cross section ratio compatible with PYTHIA in p-Pb collisions

→ no modification of jet core within uncertainties

Jets in Heavy-Ion Collisions

- Due to interactions of the hard parton with the medium, the jet is modified relative to pp: Jet Quenching

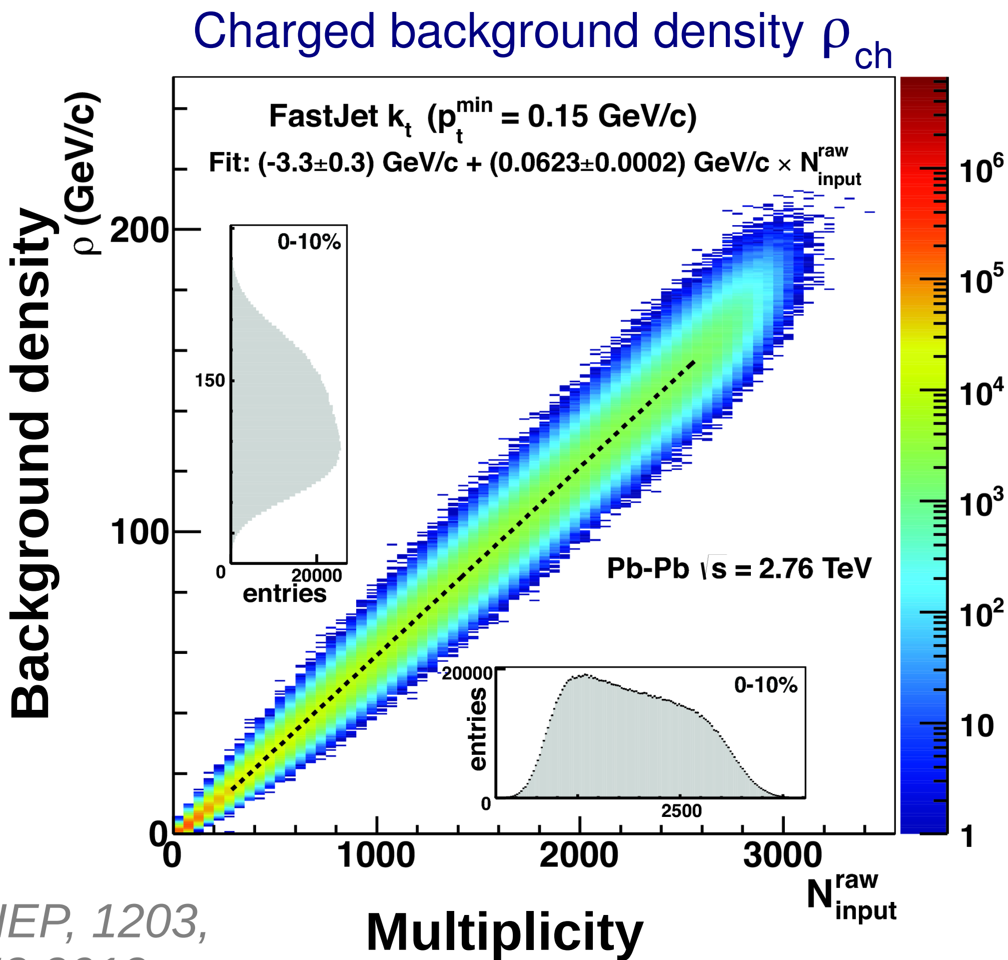


$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dp_T d\eta}{d^2 \sigma_{pp} / dp_T d\eta}$$

Experimental challenge in HI collisions:

Separate jet signal from large soft background

Event Background



JHEP, 1203, 053 2012

- Event-by-event background substraction
- ρ: p_T density per unit area
- Background density scales with event multiplicity: $\rho \sim N\langle p_T \rangle$
- Correction for background fluctuations and detector effects via unfolding

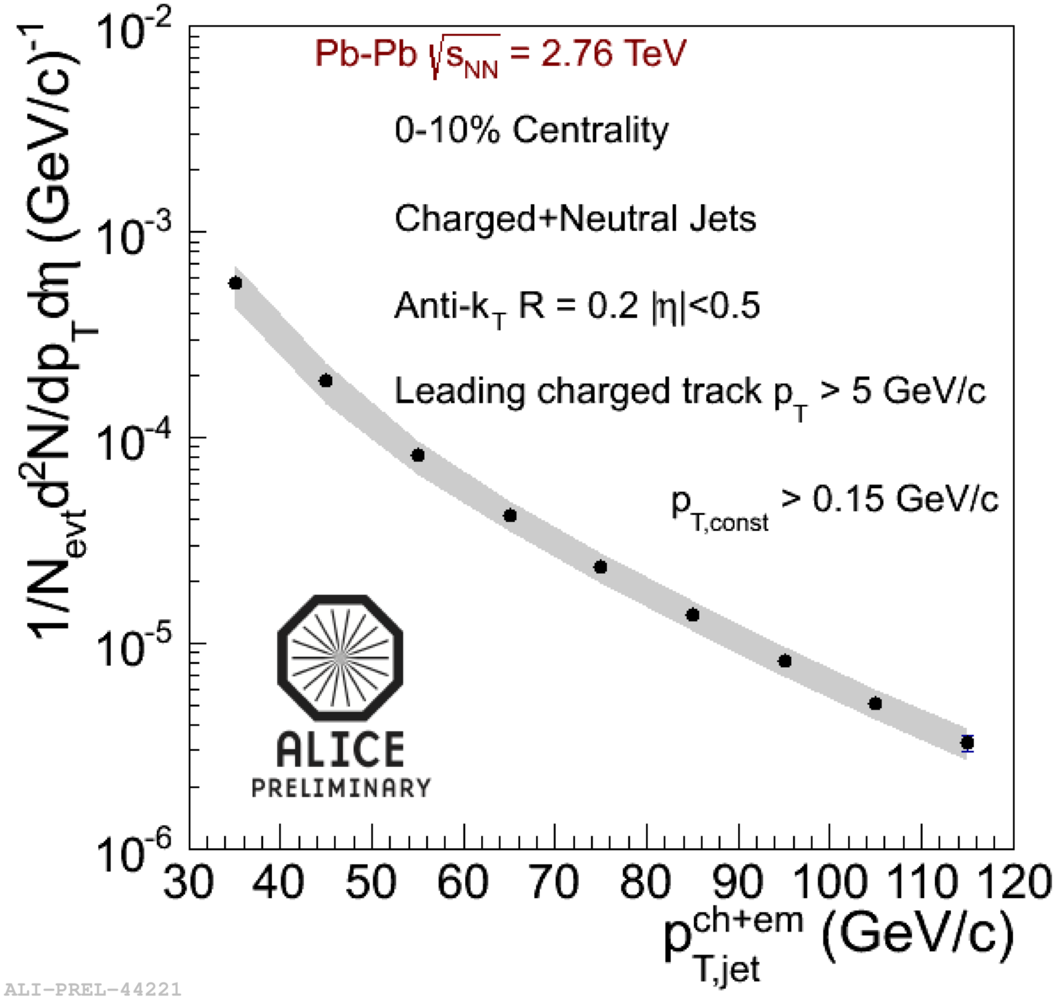
Subtract average background from each jet event-by-event

$$p_{T,j}^{sub} = p_{T,j} - \rho A_j$$

Jet Spectra in Pb-Pb

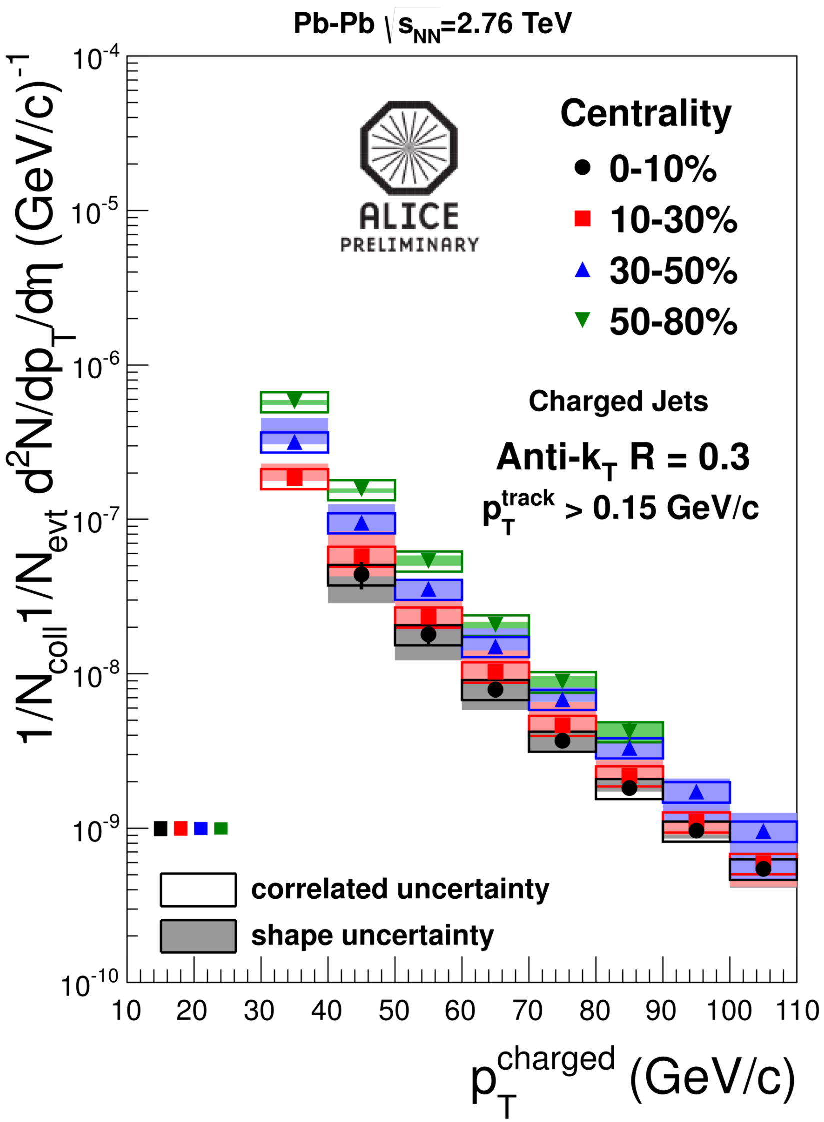
Full Jets

- R = 0.2; Central events



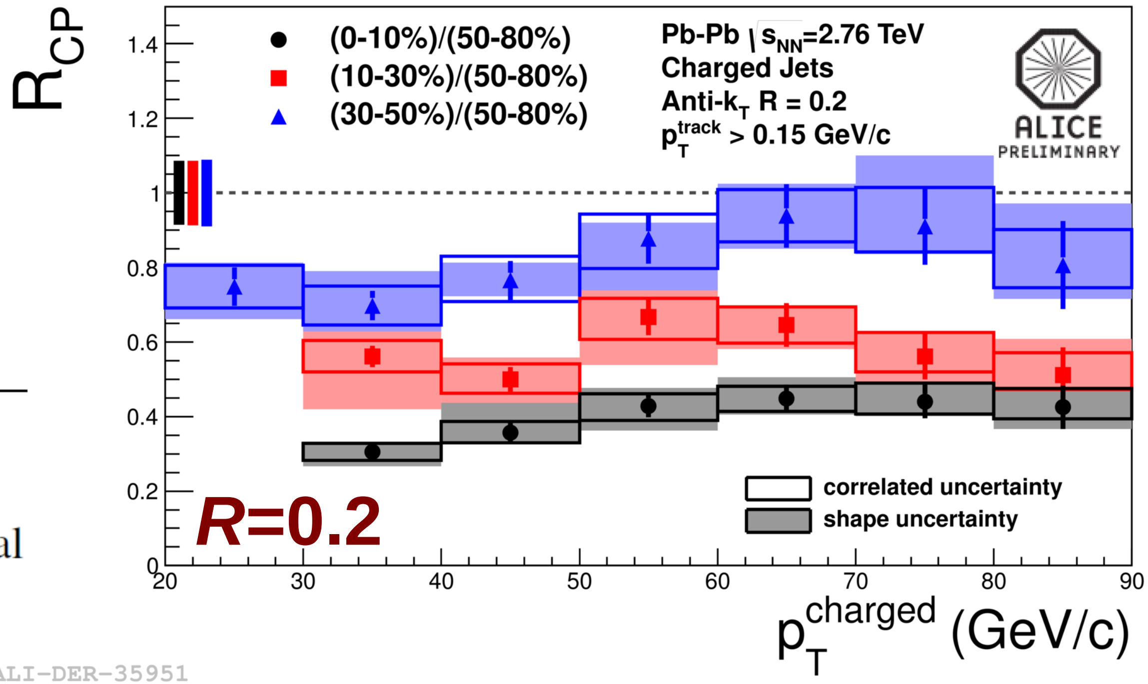
Charged Jets

- R = 0.3; 4 centrality intervals



Jet R_{CP}

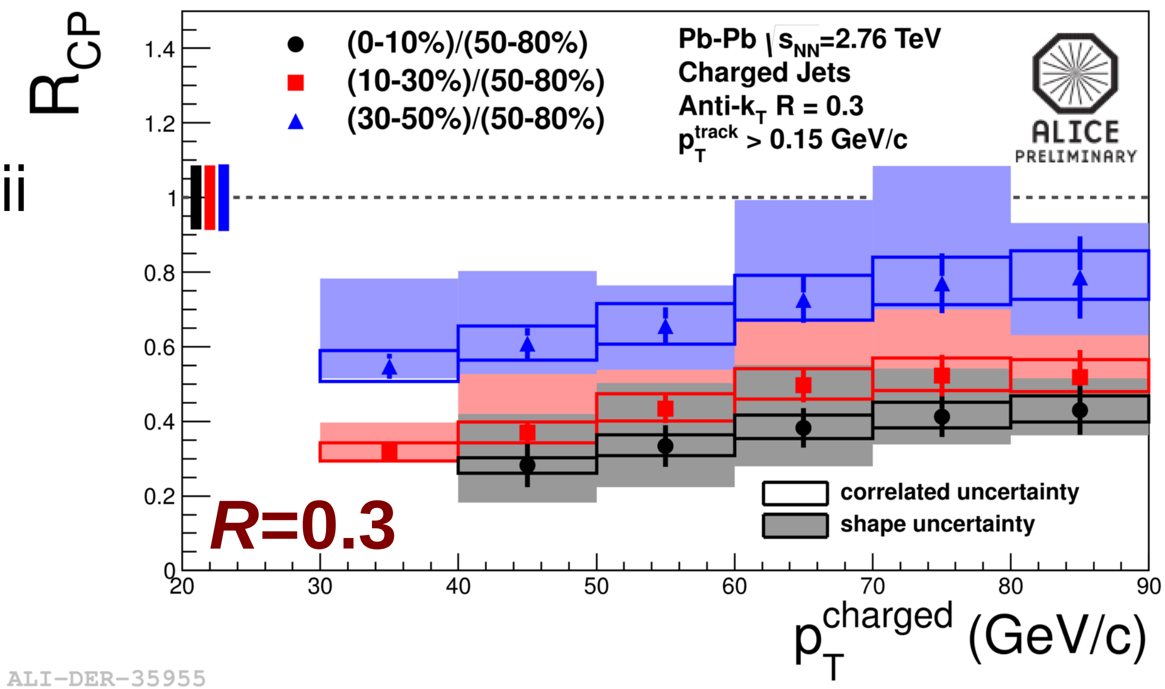
$$R_{CP} = \frac{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{evt}} \frac{d^2 N_{ch\,jet}}{dp_{T,jet} d\eta}\Big|_{central}}{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{evt}} \frac{d^2 N_{ch\,jet}}{dp_{T,jet} d\eta}\Big|_{peripheral}}$$



ALI-DER-35951

- Strong suppression for jets
- No strong p_T dependence
- Similar suppression for jet radii *R*=0.2 and *R*=0.3

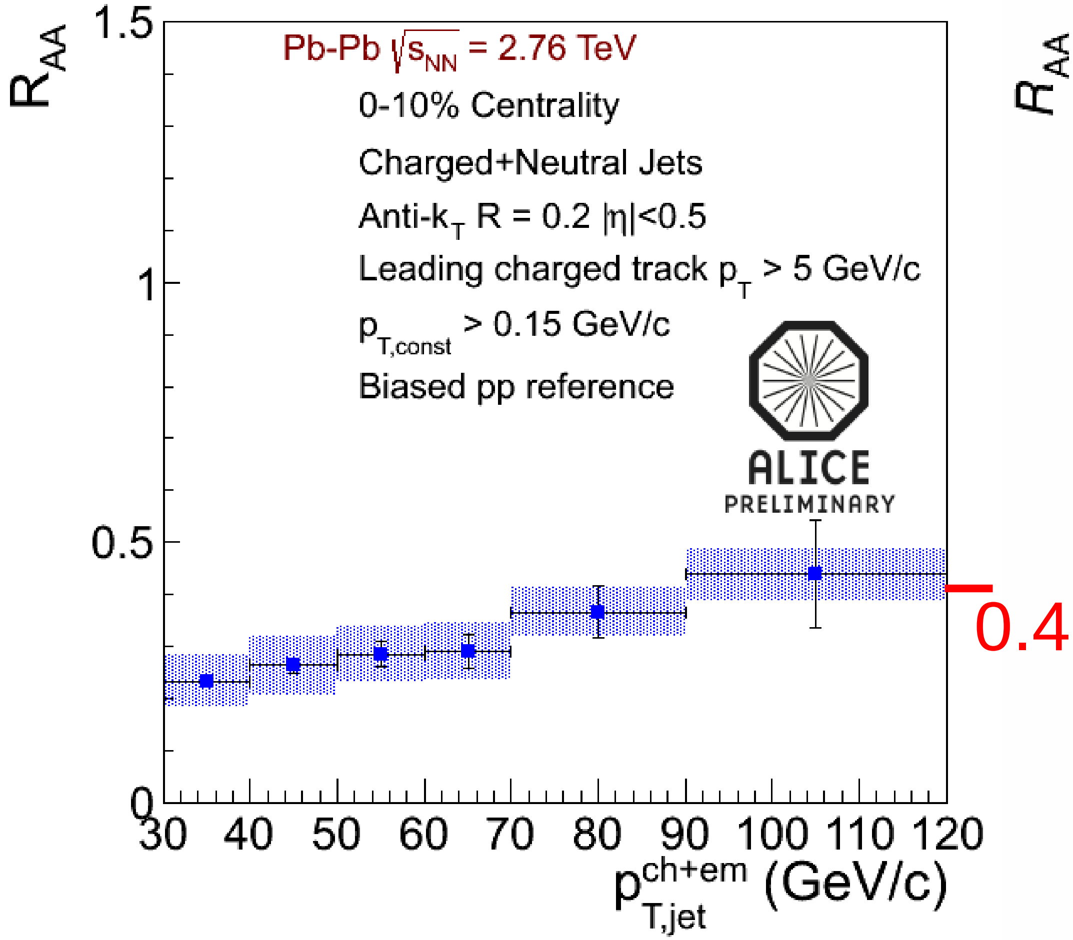
- Central events jet R_{CP} ~ 0.4
- Peripheral closer to unity



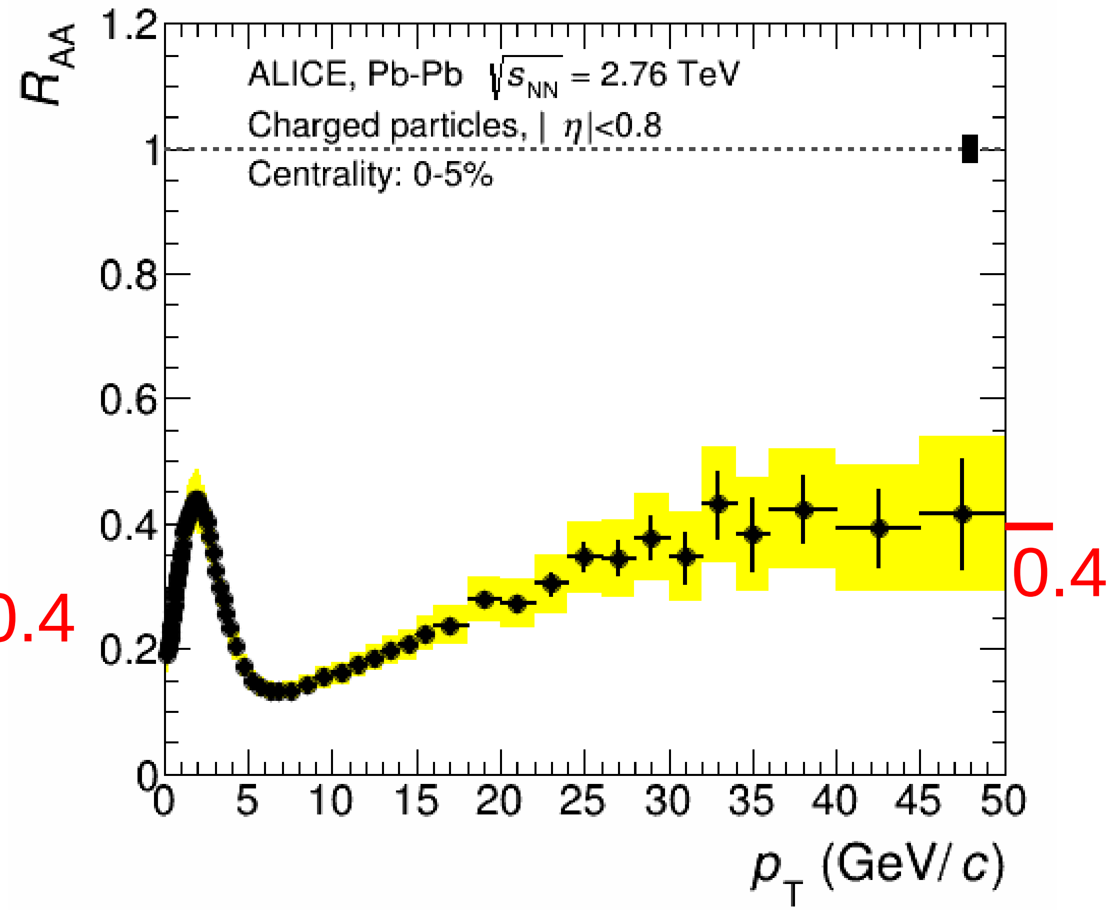
ALI-DER-35955

Jet R_{AA} vs Hadron R_{AA}

Jets



Hadrons



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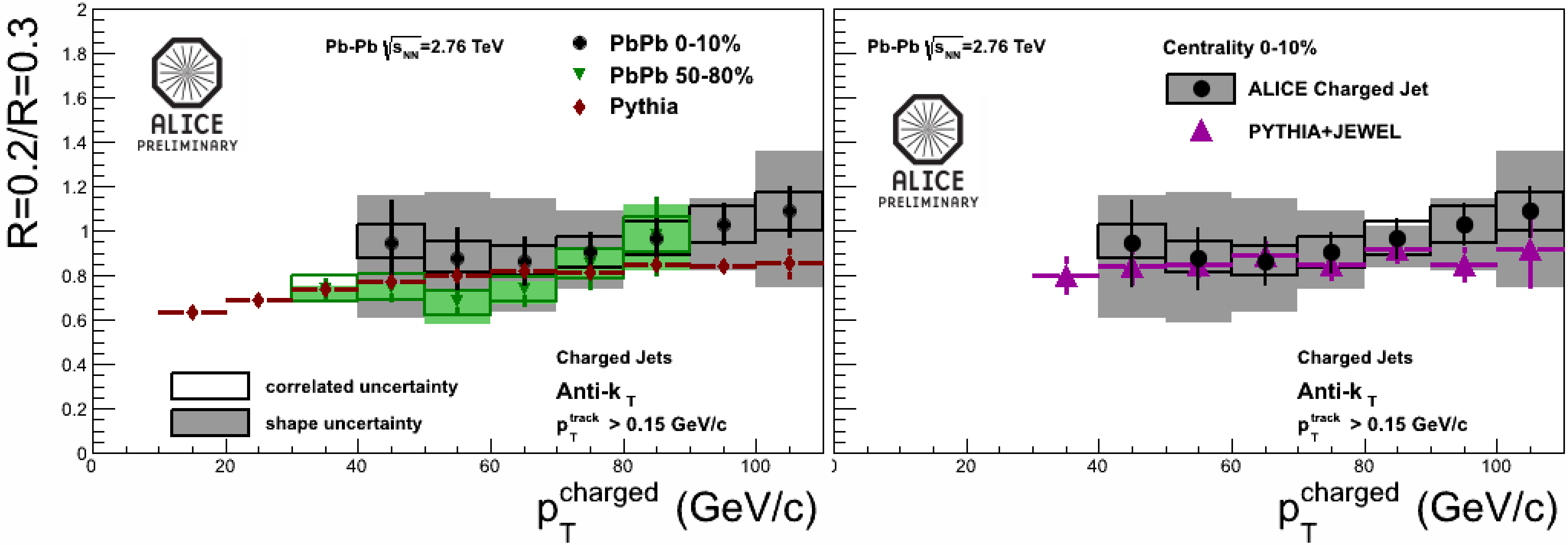
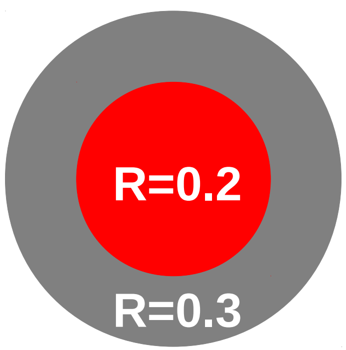
Jet R_{AA} ~ Hadron R_{AA}

Ratio of jet cross sections

$\sigma(R=0.2)/\sigma(R=0.3)$





σ$(R=0.2)/$***σ***$(R=0.3)$ consistent with vacuum jets for peripheral and central collisions

→ no sign of jet broadening within uncertainties

Good agreement with energy loss MC JEWEL.

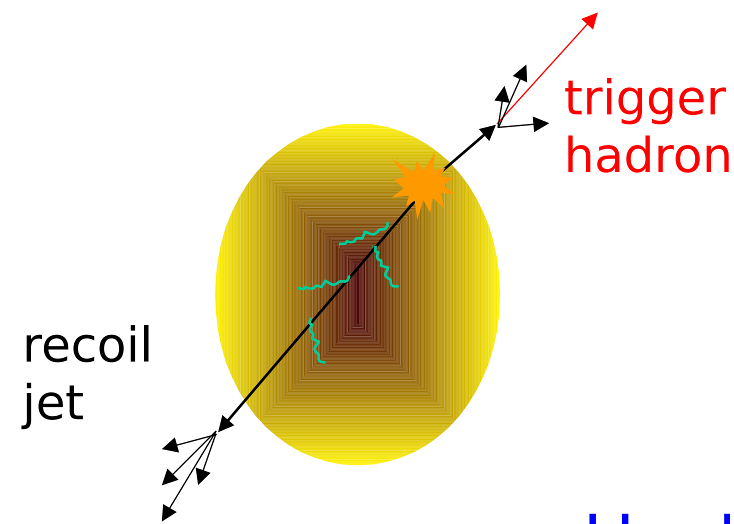
JEWEL: Zapp, Krauss, Wiedemann arXiv:1111.6838

Recoil Jets

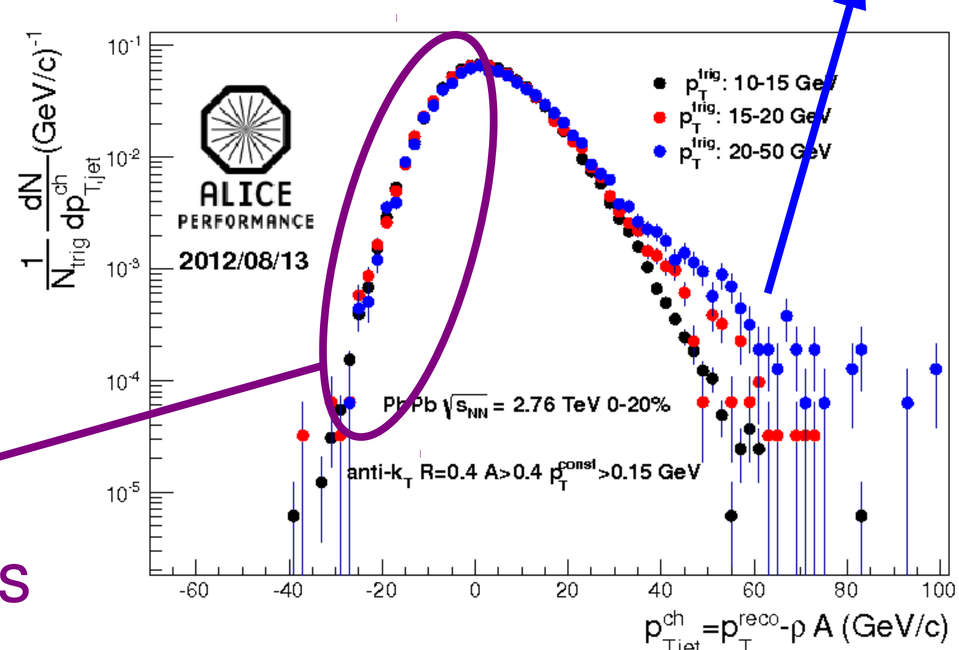
- Hadron-triggered semi-inclusive recoil jet distribution

  Δ_{recoil} = Signal – Background

- No fake jets in Δ_{recoil} and minimal fragmentation bias
- Can go to larger R and lower p_T (w.r.t. Inclusive spectrum)
- Unfolding for background fluctuations and detector effects



Hard jets

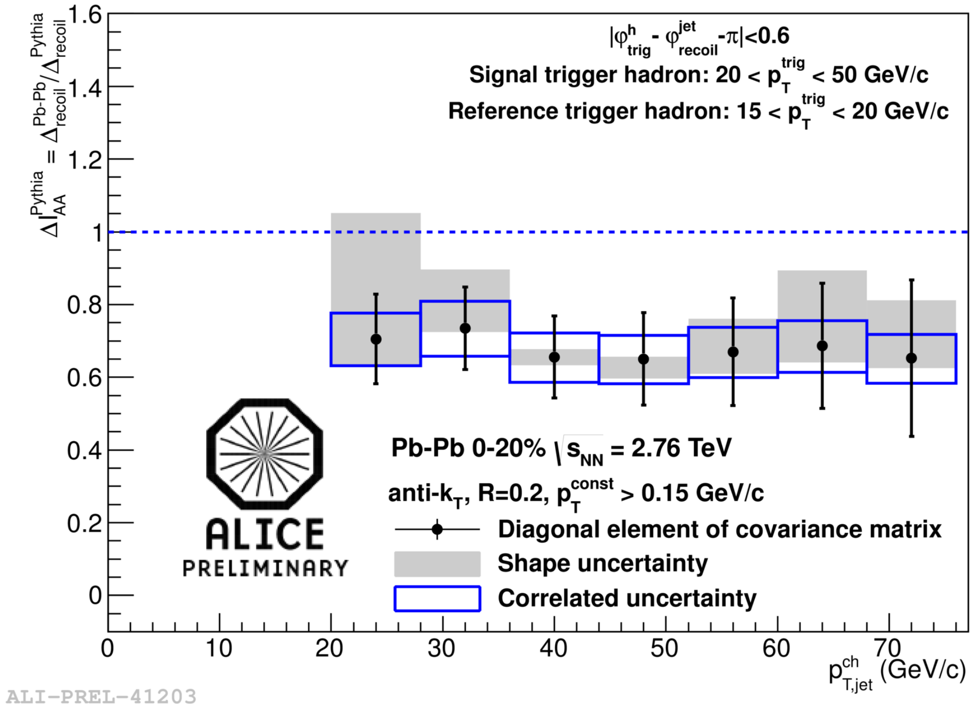


Combinatorial jets (background)

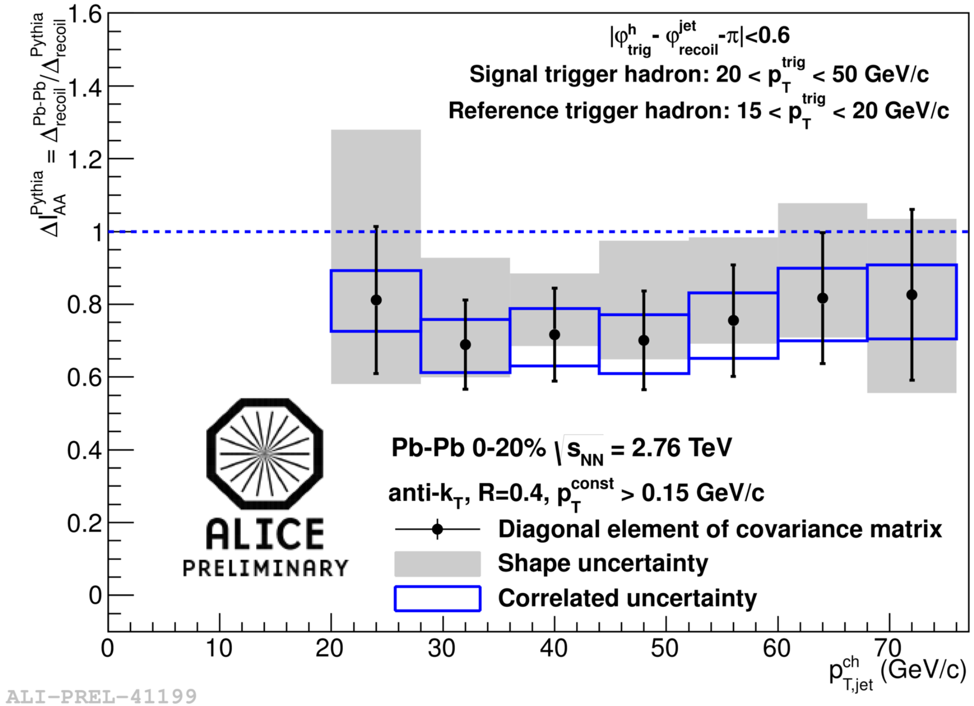
Recoil jet ΔI_{AA}^{PYTHIA}

$$\Delta I_{\mathrm{AA}}^{\mathrm{PYTHIA}} = \frac{\Delta_{\mathrm{recoil}}^{\mathrm{Pb-Pb}}}{\Delta_{\mathrm{recoil}}^{\mathrm{PYTHIA}}}$$

R=0.2



R=0.4



ΔI_{AA}^{PYTHIA} ~ 0.75, approximately constant with p_T

No indication of modification to jet core

Summary

- Jets strongly suppressed in central heavy-ion collisions
  - similar to charged hadron suppression
  - Jets less suppressed in peripheral collisions
  - No signs of modified jet structure observed in ratio of jet cross section $\sigma(R=0.2)/\sigma(R=0.3)$
- Recoil jets: little room for modification of jet core in Pb-Pb
- No cold nuclear matter effects observed in p-Pb jet spectra: R_{pPb}~1 and jet cross section ratio consistent with PYTHIA

backup

Detector Effects

Particle level jets

Anti-k_T jets reconstructed from particles produced by PYTHIA (charged or charged+neutral)

Detector level jets

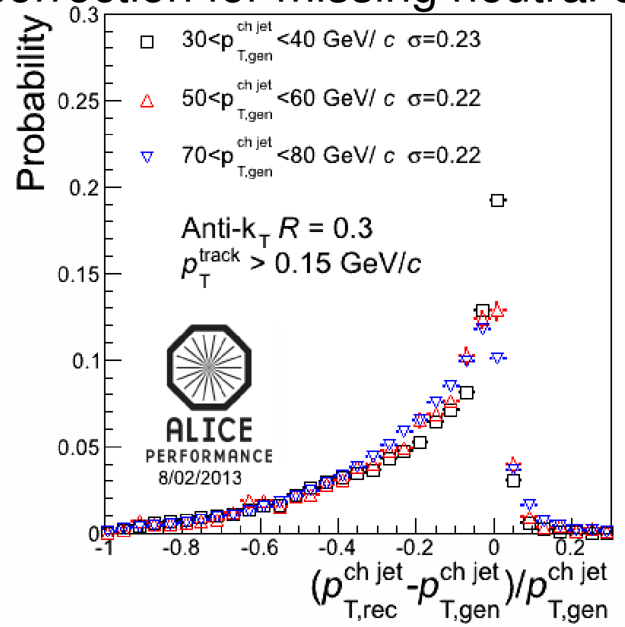
Anti-k_T jets reconstructed from tracks after detector simulation PYTHIA

Detector level jets affected by: tracking efficiency and momentum resolution

Geometrical Matching between **particle** level and **detector** level jets gives detector response

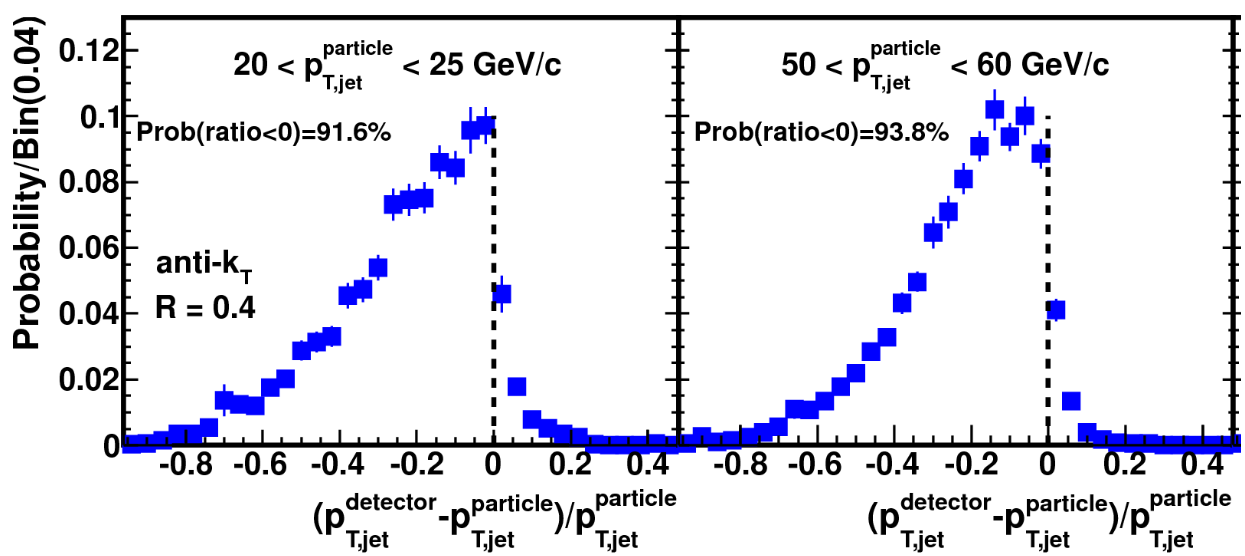
Charged Jets

No correction for missing neutral energy



Full Jets

arXiv:1301.3475



Background Fluctuations

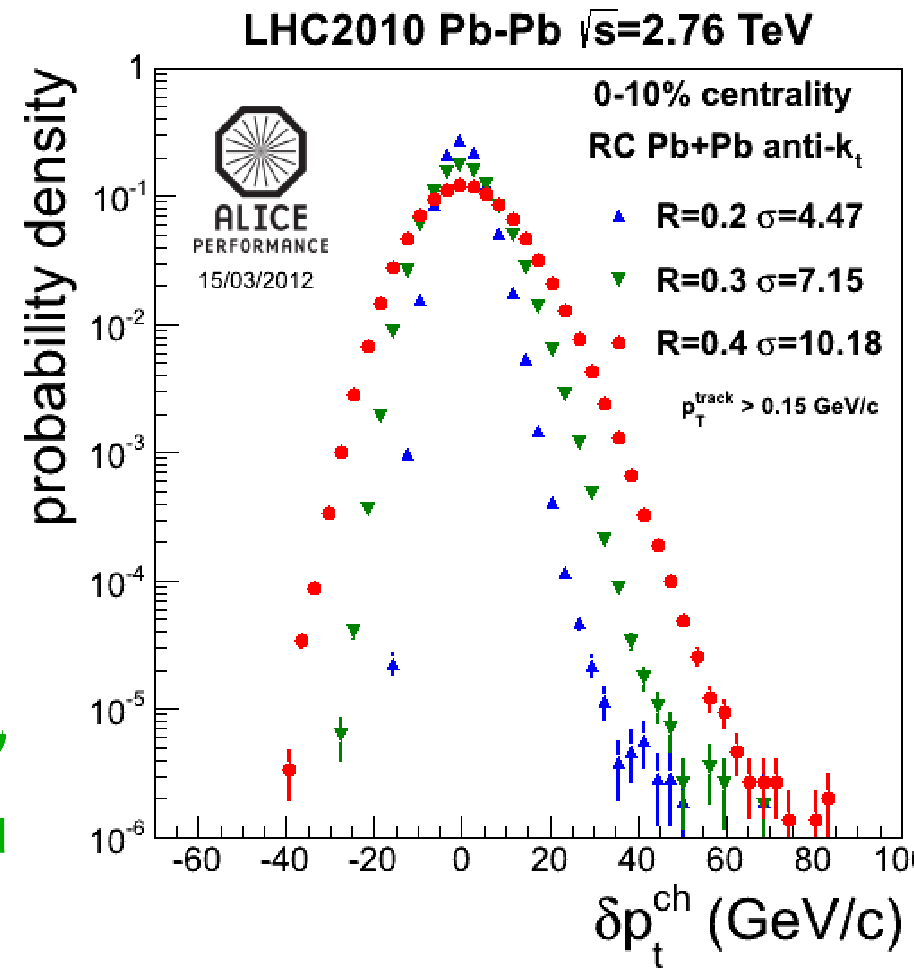
ALICE

Background varies from region-to-region:
- statistical fluctuations
- collective effects

Data driven method to quantify background fluctuations:
Random cone and high p_T probe embedding in Pb-Pb events

$$\delta p_{\mathrm{T}} = p_{\mathrm{T,jet}}^{\mathrm{rec}} - \rho A - p_{\mathrm{T}}^{\mathrm{probe}}$$

Reconstructed jet p_T | **Background subtraction** | **Embedded probe p_T**



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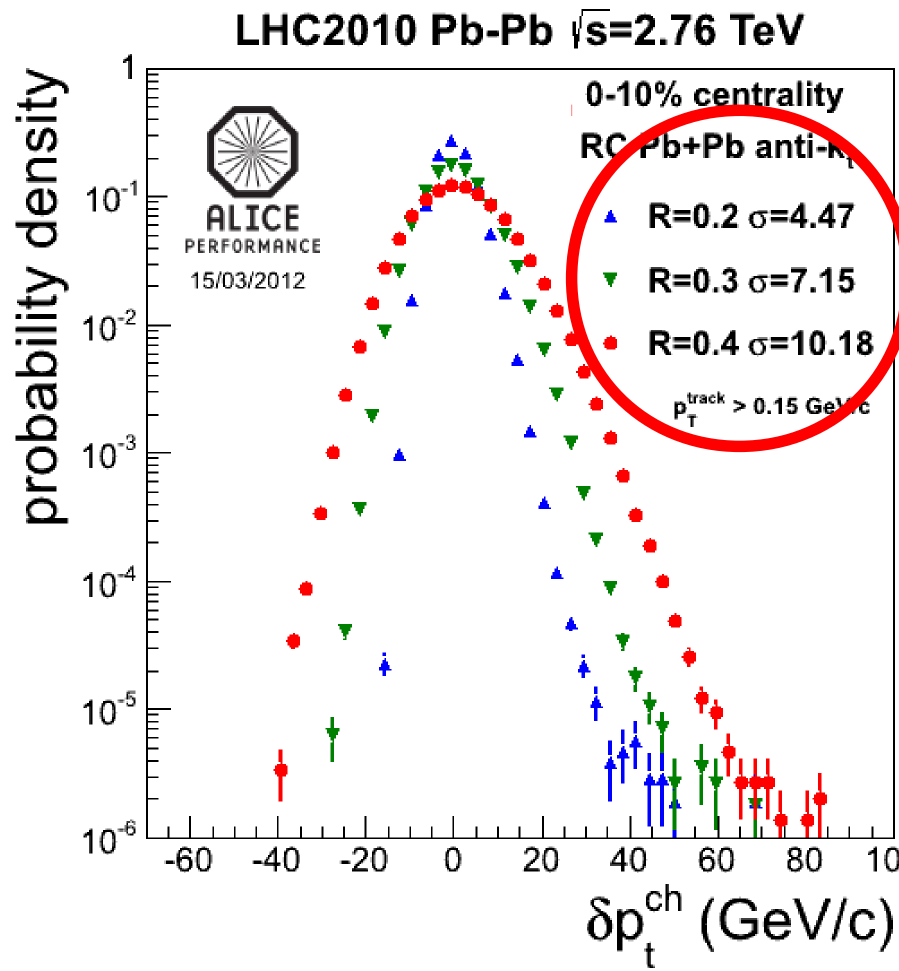
Reconstructed jet p_T — **Background subtraction** — **Embedded probe p_T**

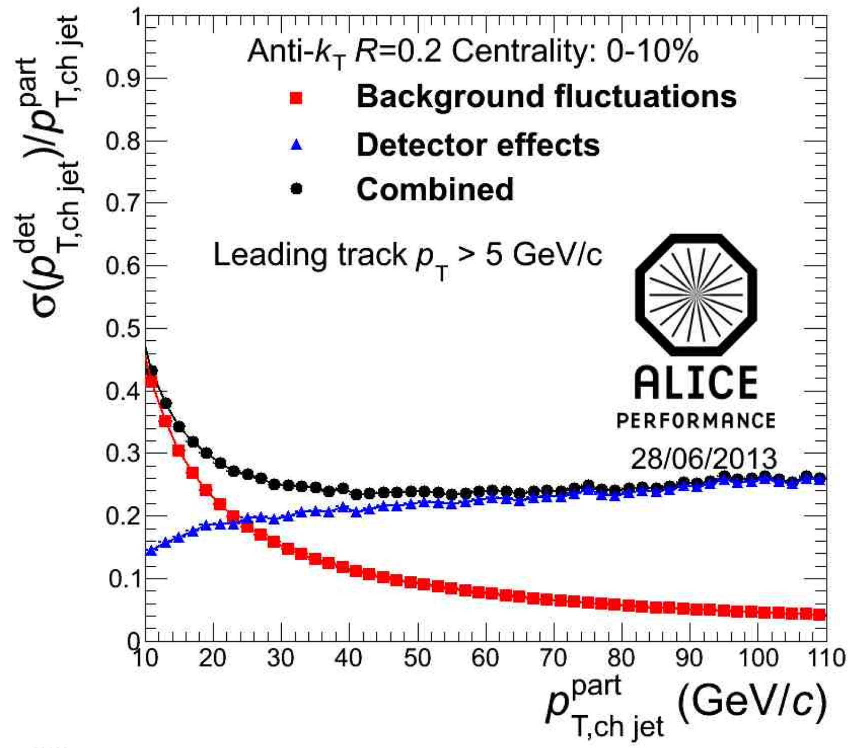


Size of fluctuation depends on particle multiplicity in jet cone:
$\sigma(\delta p_T, R=0.3) > \sigma(\delta p_T, R=0.2)$ and **$\sigma(\delta p_T, \mathit{central}) > \sigma(\delta p_T, \mathit{peripheral})$**

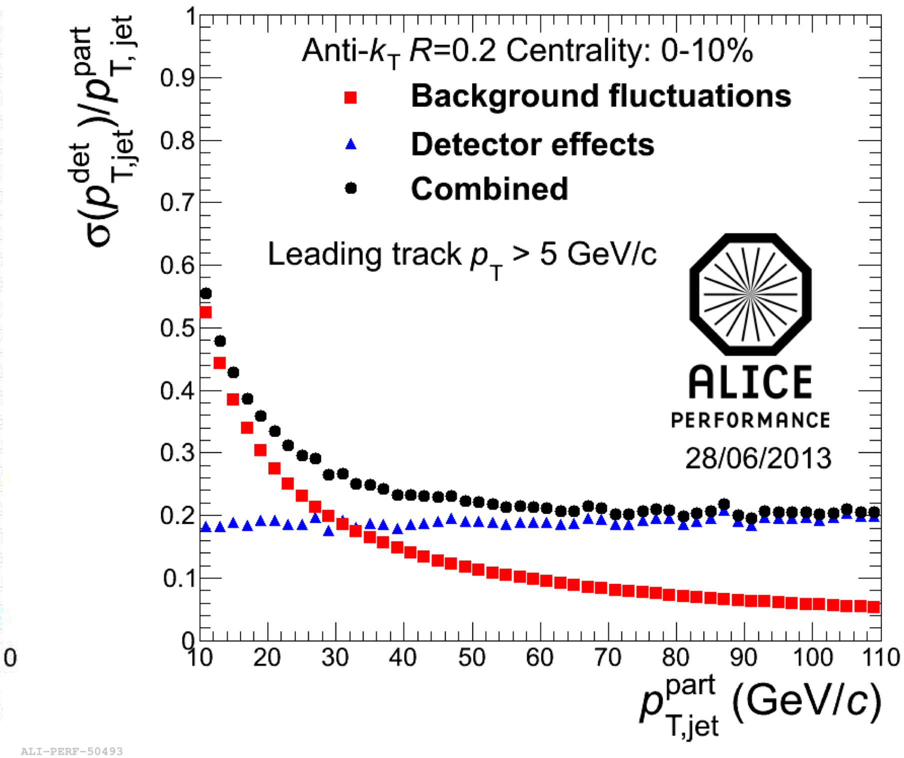
Jet p_T resolution

- Detector effects and Background Fluctuations: Partially compensating effects
  - At low p_T background fluctuations dominate
  - At high p_T detector effects dominate

Charged Jet Response



Full Jet Response



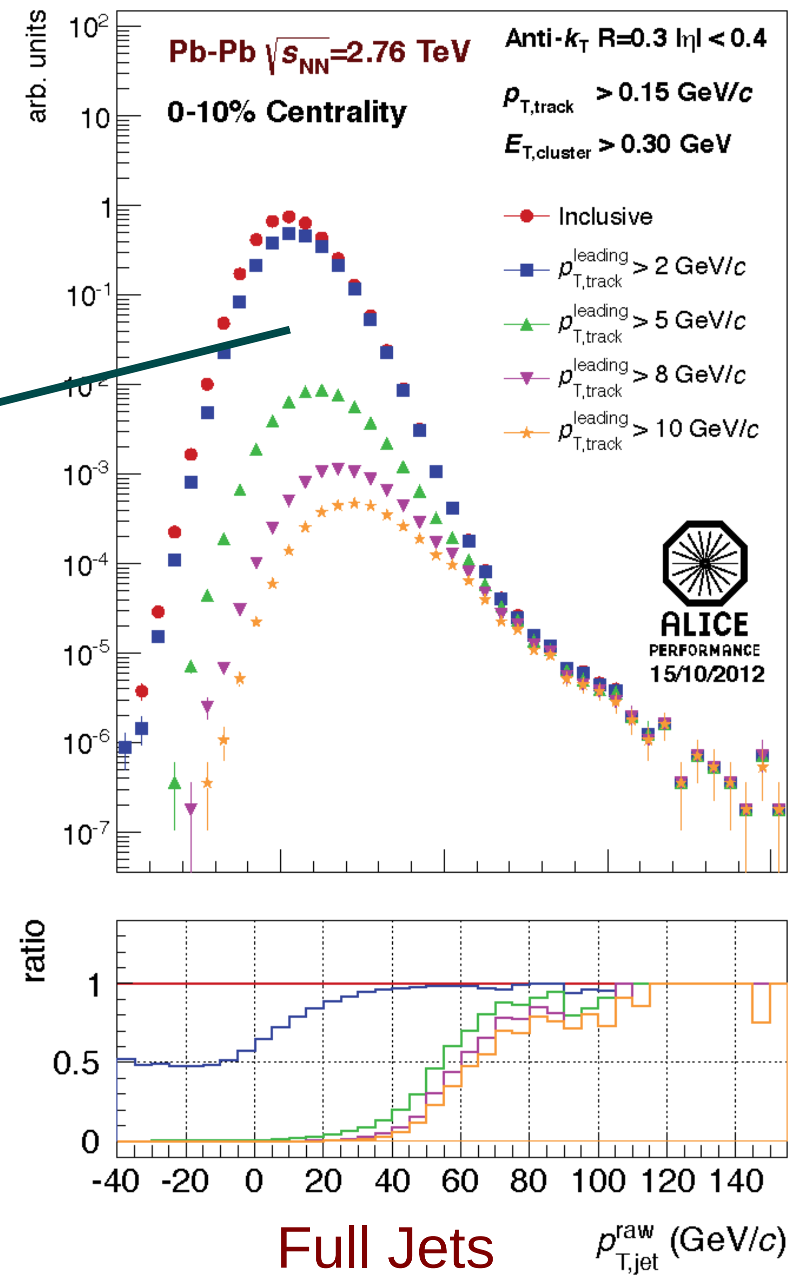
Combinatorial Jets

- Combinatorial jets: clusters which do not originate from a hard process.

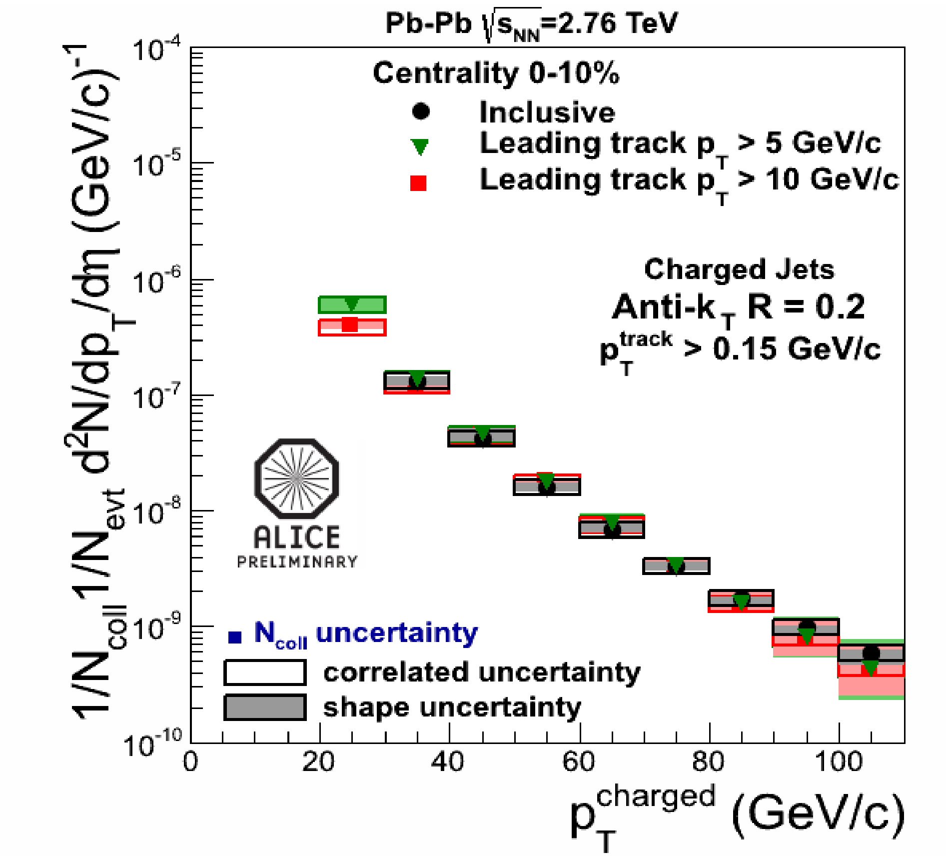
- Bump at zero: combinatorial jets
  Transition to 'real' is grey area

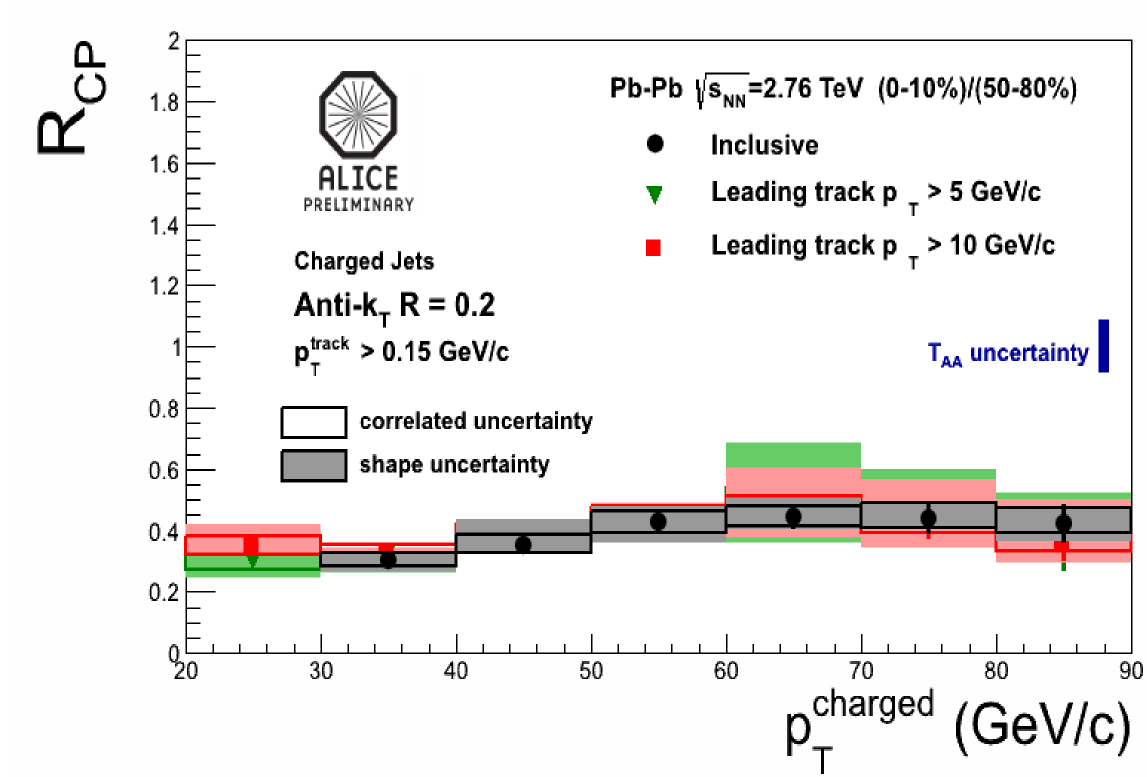
- Combinatorials reduced by selecting jets with a leading track of p_T > 5, 8, 10 GeV/*c*. Selection after jet finding.
  However, fragmentation bias

- ~60-80 GeV: hard jets start to dominate



Jet Suppression in Pb-Pb





- Leading track requirement → fragmentation bias at low p_T → potentially modified by jet quenching

Fragmentation bias the same for central and peripheral events.

Raw vs corrected jet

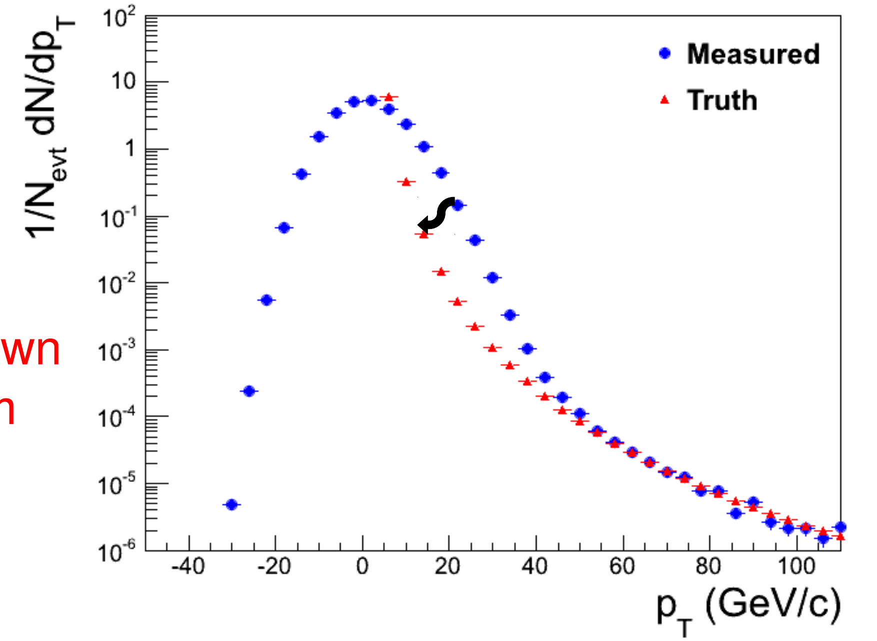
- What we measure:
  - p_T of a jet which is clustered by a jet algorithm (anti-k_T)
  - hard jets + fakes on top of a soft fluctuating background
    p_T resolution of jets affected by detector effects
- What we want to measure:
  - jets which originate from the shower of a highly energetic parton
  - Independent of detector effects and background fluctuations
- Corrections:
  - Average background ⟶ jet-by-jet
  - Background fluctuations & Fake jets } Unfolding
  - Detector Effects } Unfolding

Unfolding

- Problem to solve:

$$\mathbf{M_m} = \mathbf{G_{m,t}} \cdot \mathbf{T'_t}$$

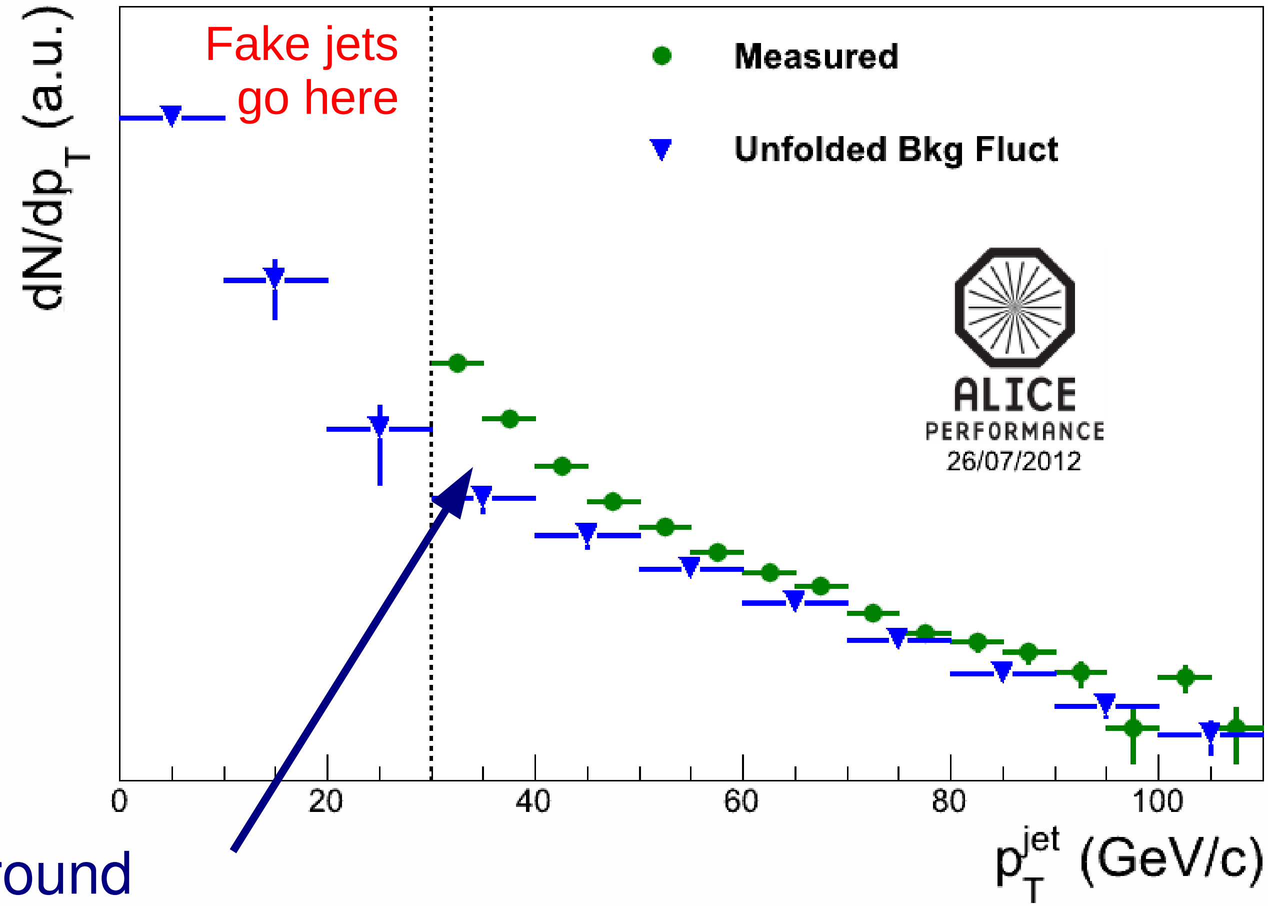
Measured jet spectrum — Response matrix — 'true' unknown jet spectrum



- Response matrix encodes effect of detector and background
- ill-posed problem, cannot invert response matrix
- Regularized unfolding
- Used unfolding methods:
  - χ^2 minimization of refolded and measured spectrum
  - SVD
  - Bayesian

Unfolding Strategy

Raw jet spectra need to be corrected for background fluctuations



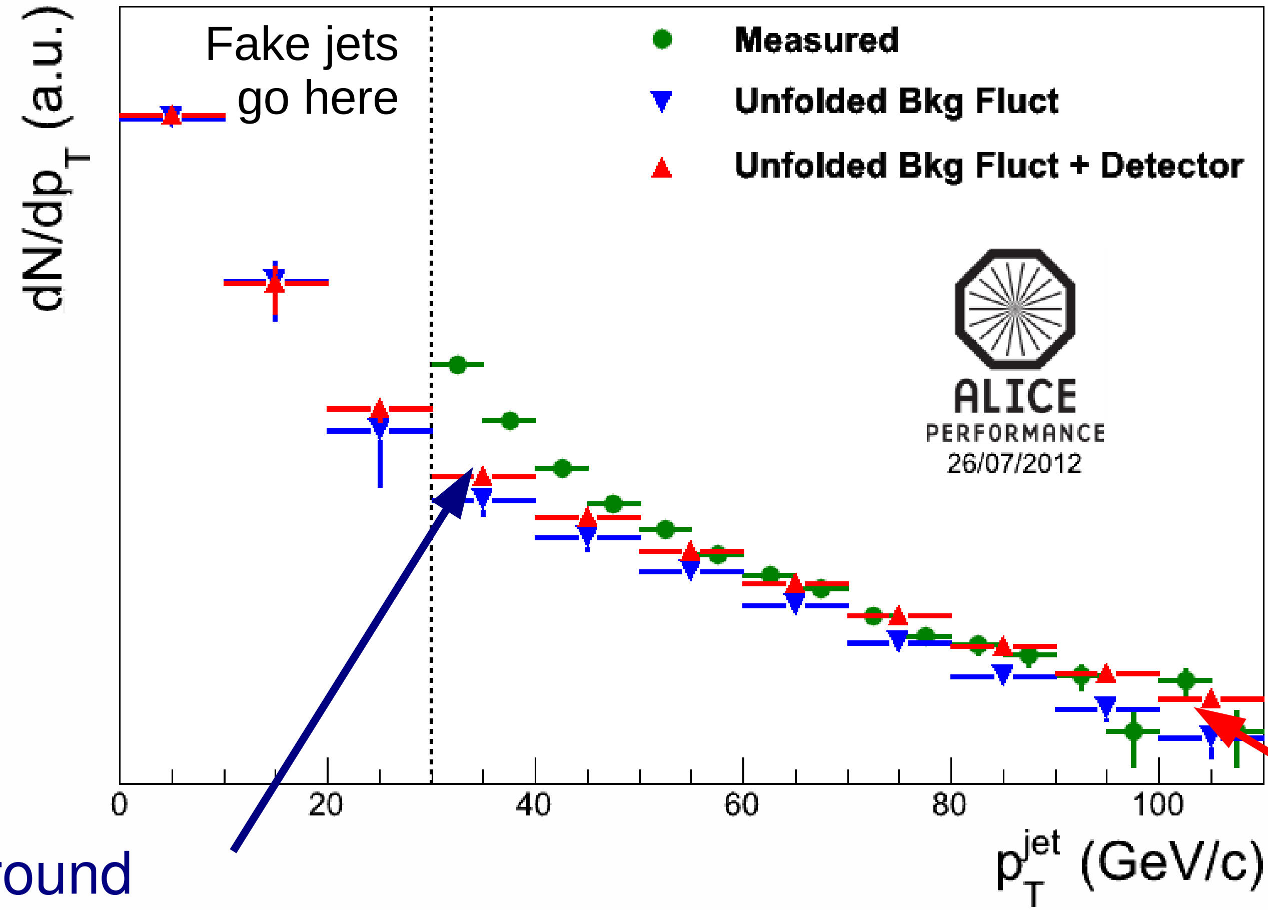
Combinatorial jets suppressed with minimum p_T cut on measured spectrum

Feed in from low p_T: unfolded spectrum starts at p_T=0 GeV/*c*

Background fluctuations shift low p_T jets to high p_T

Unfolding Strategy

Raw jet spectra need to be corrected for background fluctuations and detector effects.



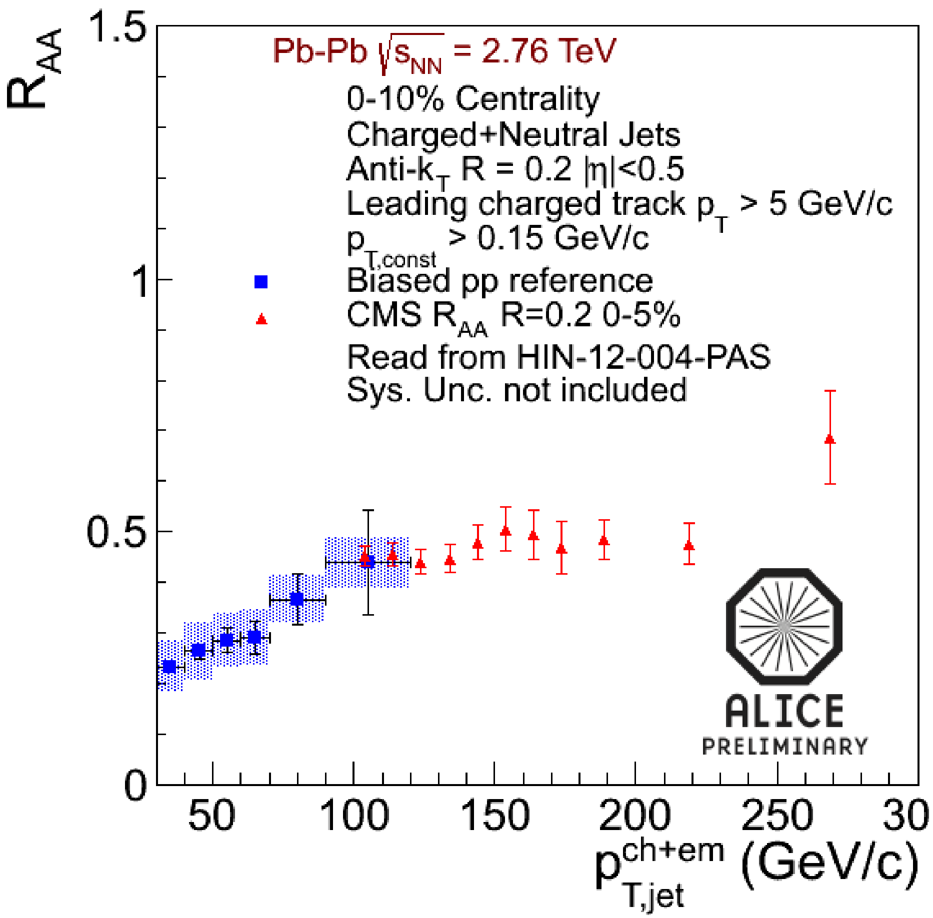
Combinatorial jets suppressed with minimum p_T cut on measured spectrum

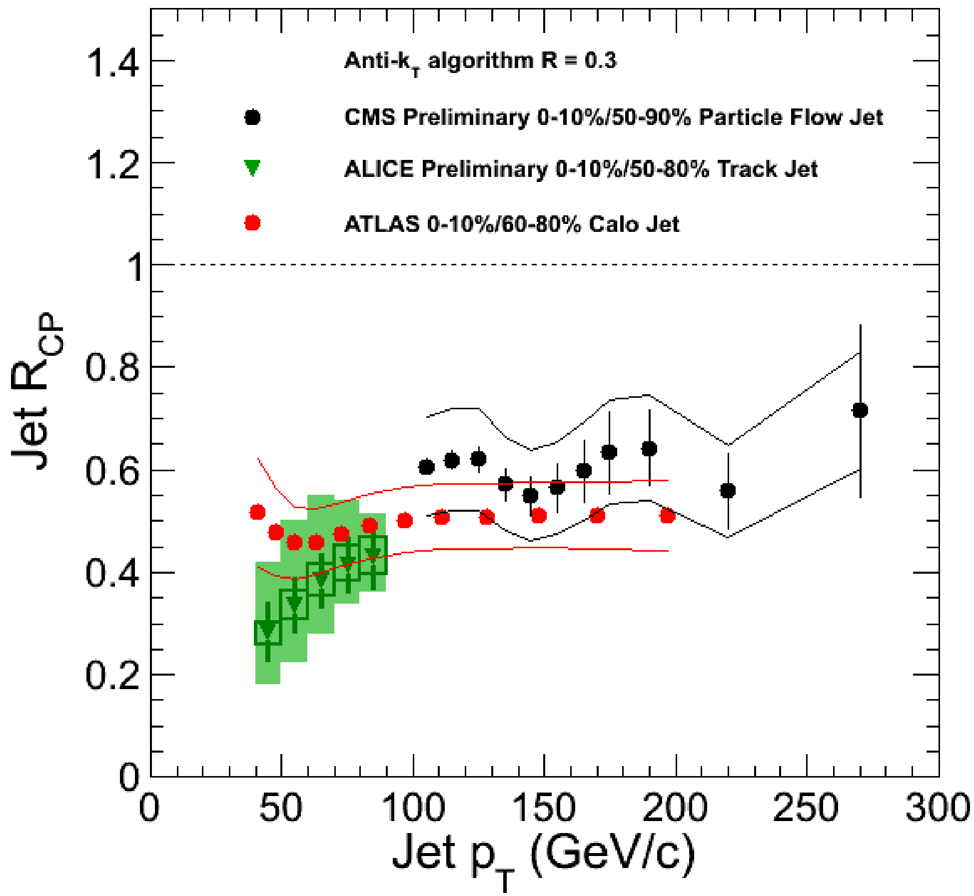
Feed in from low p_T: unfolded spectrum starts at p_T=0 GeV/c

Background fluctuations shift low p_T jets to high p_T

Detector effects shifts jets to lower p_T

ALICE vs ATLAS vs CMS



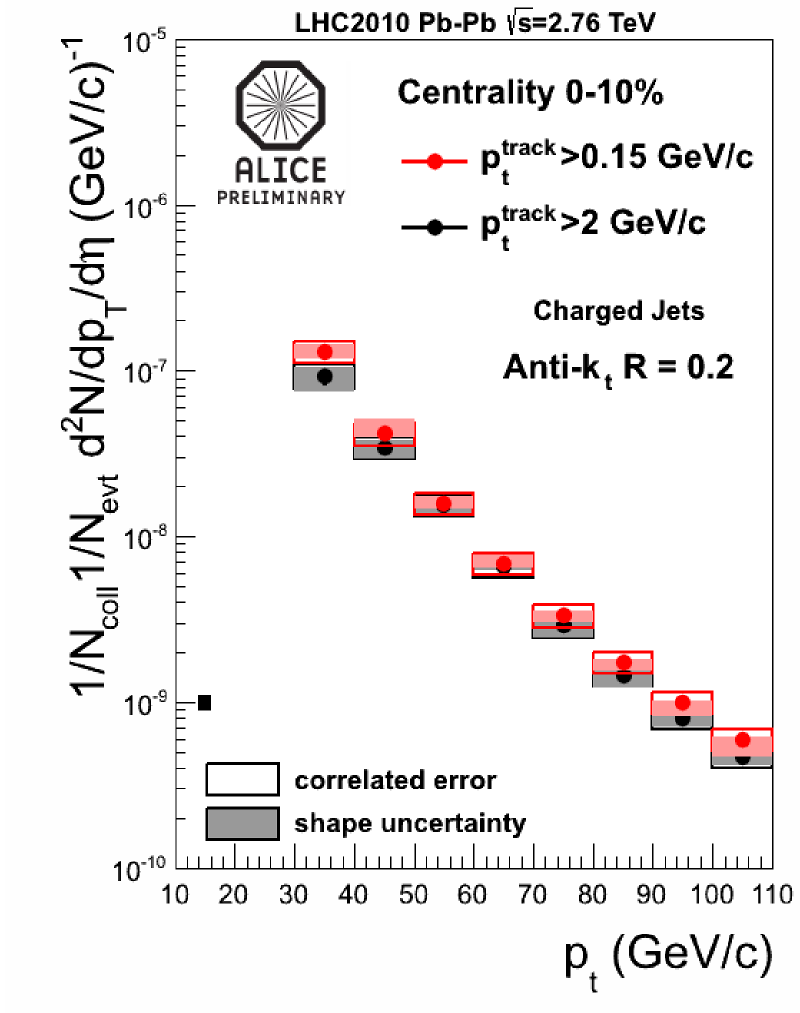


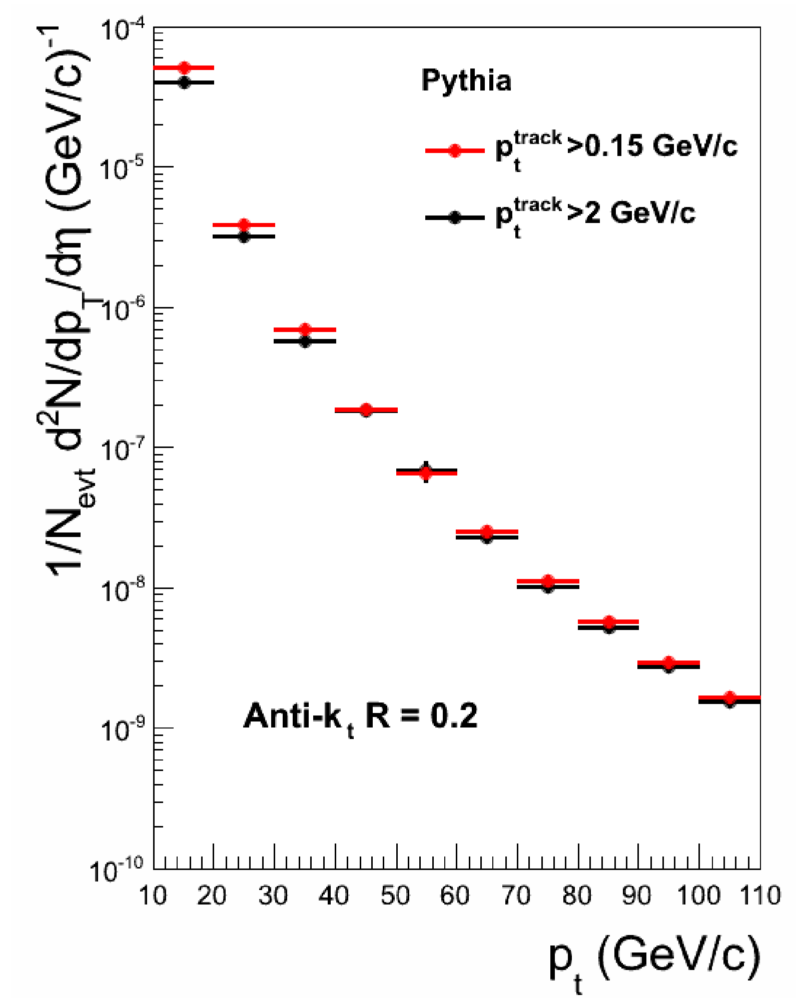
All experiments see jet suppression and are consistent in overlap region.

Jet Constituents

Spectra corrected for detector level effects for particles with $p_t > p_{t,min,track}$

R=0.2: PbPb very similar to Pythia → shift of spectrum in pt for PbPb and Pythia. Not many soft particles in small cone of R=0.2.





Recoil jets

- Difference distribution of recoil jets

$$\Delta_{\rm recoil} = \frac{1}{N_{trig}^{Sig}} \frac{\mathrm{dN_{jet}}}{\mathrm{d}p_{\rm T}}\Big|_{Sig} - c \cdot \frac{1}{N_{trig}^{Ref}} \frac{\mathrm{dN_{jet}}}{\mathrm{d}p_{\rm T}}\Big|_{Ref}$$