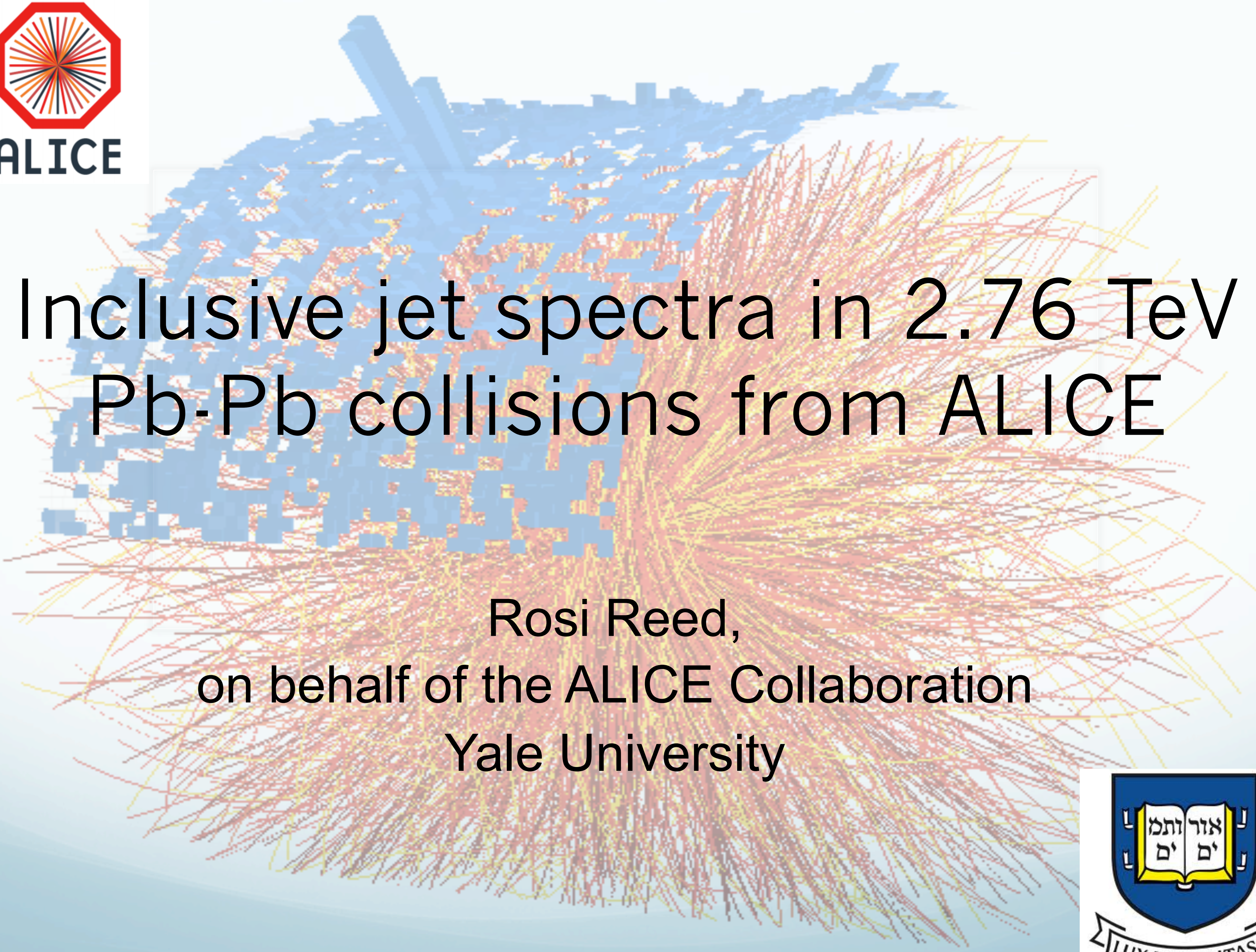
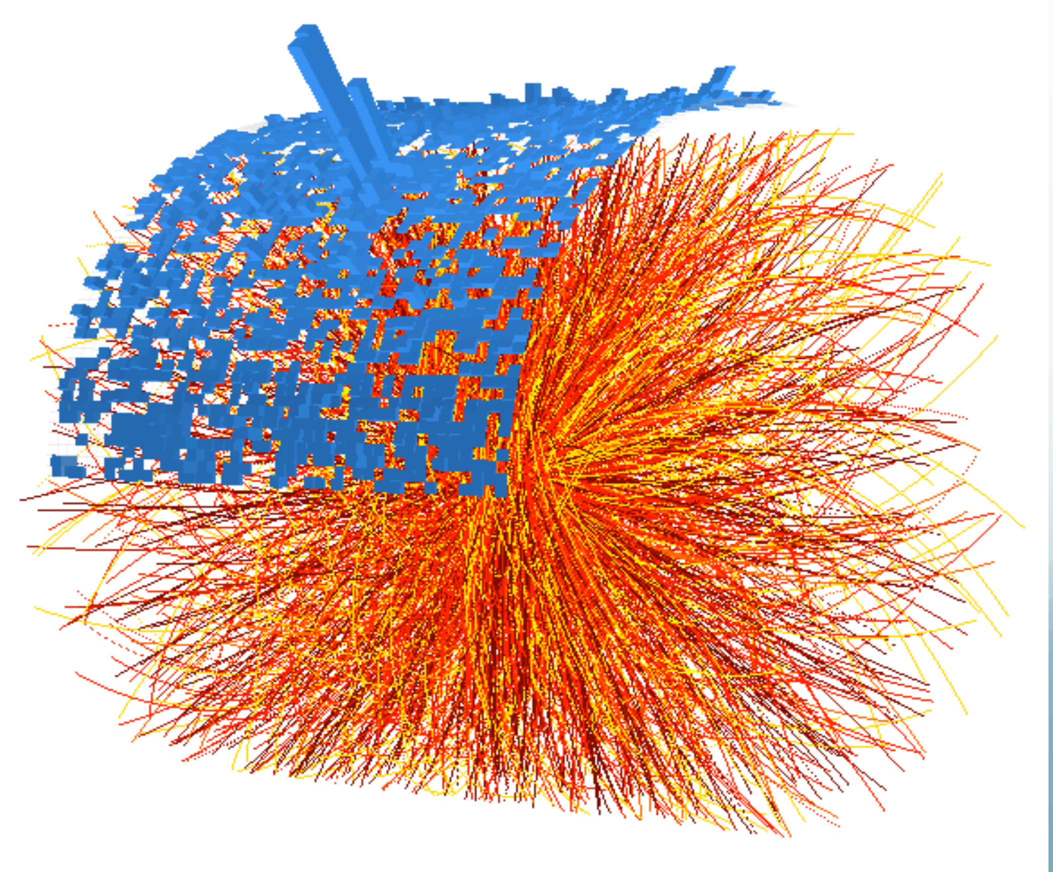


Inclusive jet spectra in 2.76 TeV Pb-Pb collisions from ALICE

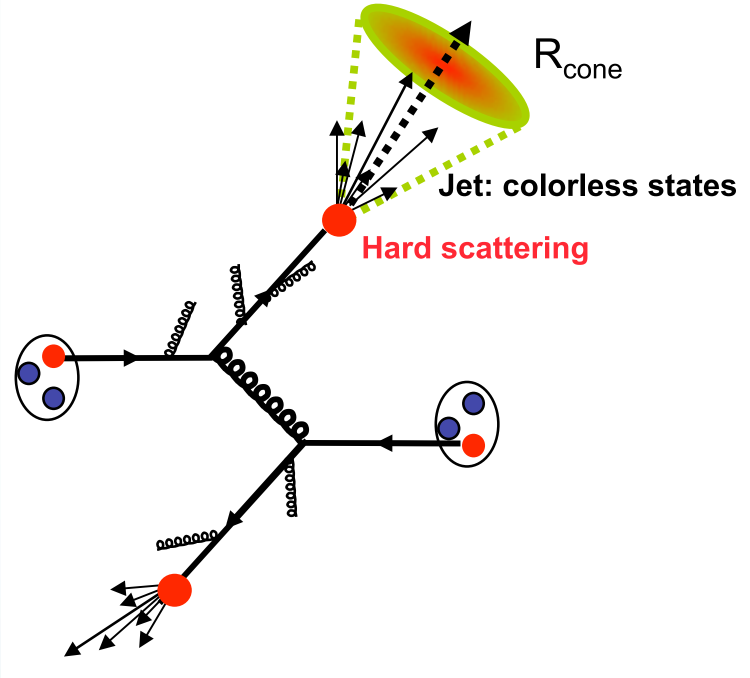
Rosi Reed,
on behalf of the ALICE Collaboration
Yale University

Outline

- Introduction
- Fully reconstructed jets in ALICE
- Hadronic Correction
- pp Jet Spectra
- Pb-Pb Jet Spectra
- R_{AA}
- Conclusions



What is a Jet?



- Colored partons undergo a hard scatter and hadronize into a spray of particles
- Expected to reflect the kinematics and topology of the hard scattered partons
- Jets are defined by algorithm used to find them

There is no unambiguous definition of what a jet is!

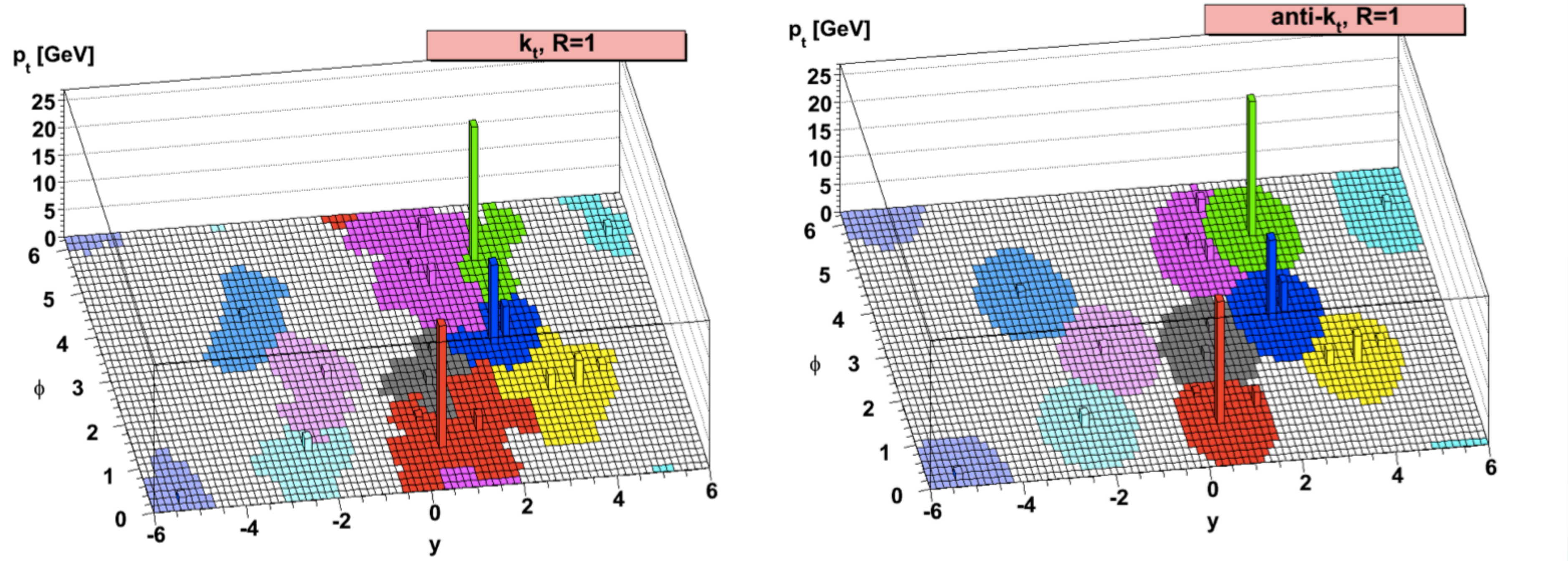
S.D Drell, D.J.Levy and T.M. Yan, Phys. Rev. **187**, 2159 (1969)
N. Cabibbo, G. Parisi and M. Testa, Lett. Nuovo Cimento **4**,35 (1970)
J.D. Bjorken and S.D. Brodsky, Phys. Rev. D 1, 1416 (1970)
Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977) … and many more

Jets in Heavy-Ion Collisions

- Jets make an ideal probe of the medium
  - Partons from hard scattering are produced early
  - Propagating parton is modified by the QCD medium
  - Observation of jet quenching indicates modification
- Experimental challenges
  - Need to remove underlying event contribution
  - Jet $p_{\mathrm{T}} = p_{\mathrm{T}}^{rec} - \rho A$
    - A = Jet area
    - ρ = Underlying event momentum density
    - p_{T}^{rec} = Jet p_{T} from jet finder

Jet Finding Algorithms

Matteo Cacciari, Gavin P. Salam, Gregory Soyez, arXiv:0802.1189v2



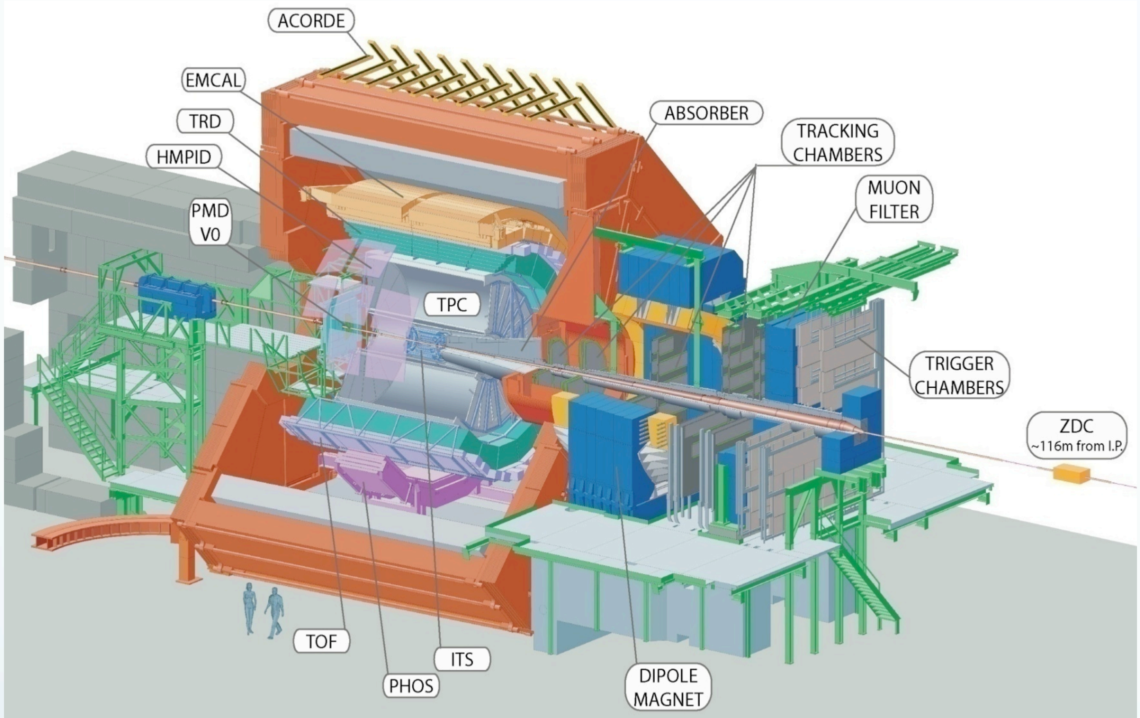
Background

Not dependent on hardest particles – samples backgound

Signal

Creates round jets around the hardest particles!

Jets at ALICE

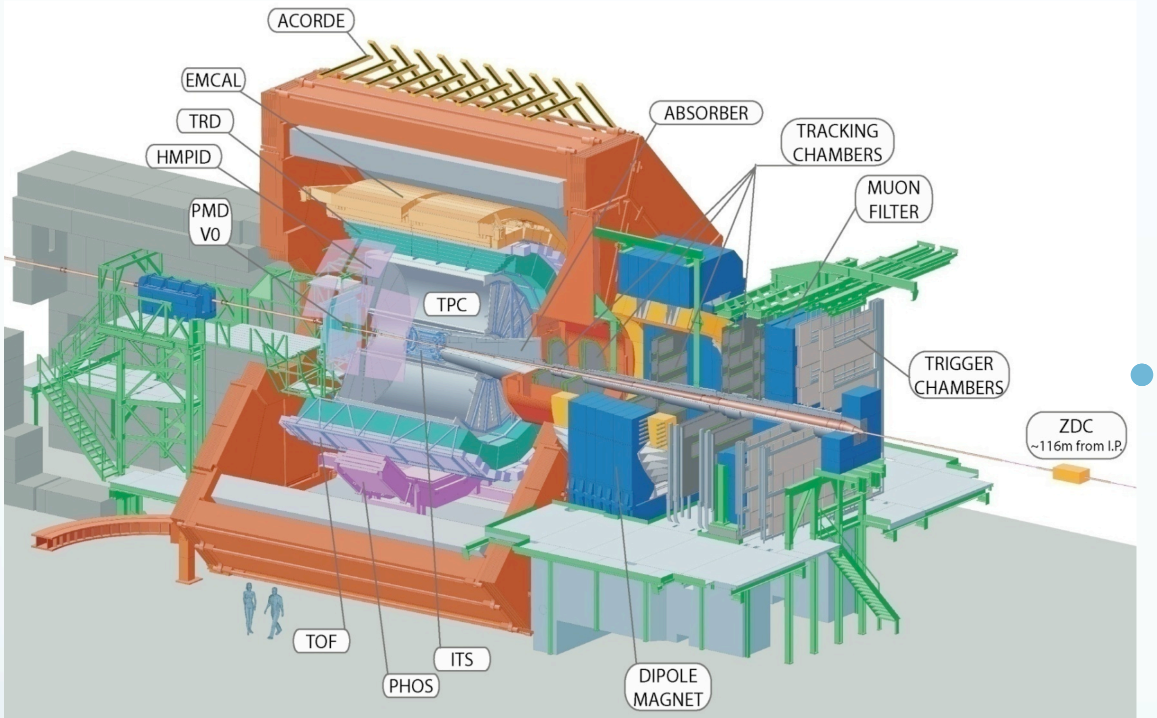


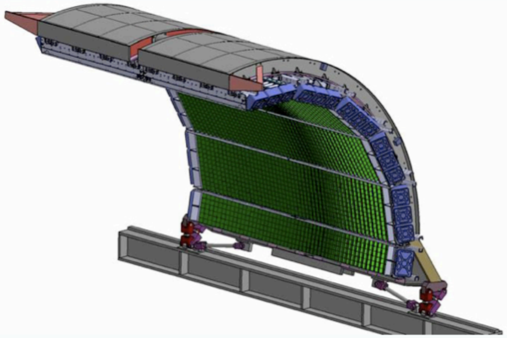
Tracking: $|\eta| < 0.9$, $0<\varphi<2\pi$

TPC: gas detector → *Charged constituents* → **JET**

ITS: silicon detector

Jets at ALICE





- EMCal is a Pb-scintillator sampling calorimeter which covers:
  - $|\eta| < 0.7$, $1.4 < \varphi < \pi$
  - tower $\Delta\eta \sim 0.014$, $\Delta\varphi \sim 0.014$

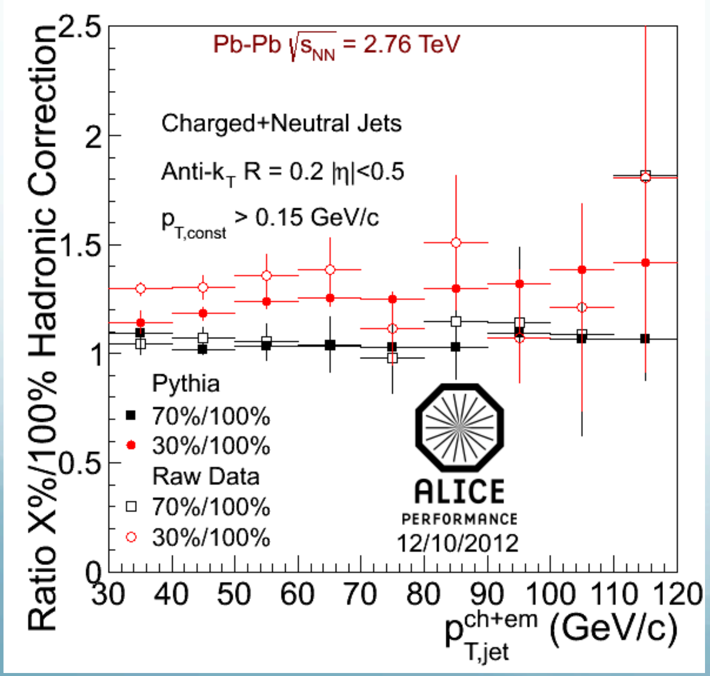
Charged hadronic correction prevents double counting

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

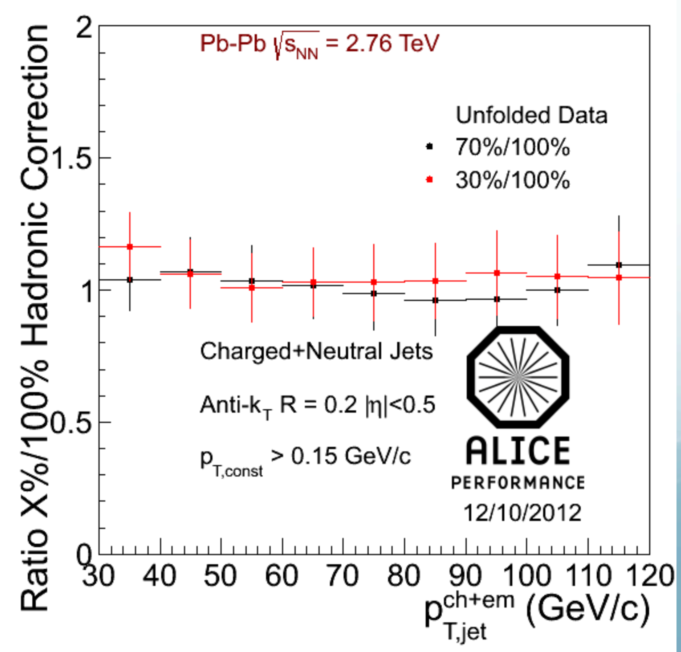
Charged constituents → **JET** ← *Neutral constituents*

Hadronic Correction

- We need to correct the double counting of charged energy deposited in EMCal
  - Energy deposition is a statistical process
  - Corrected in unfolding
- Charged tracks matched to clusters and clusters are corrected by: $E^{cor}_{cluster} = E^{orig}_{cluster} - f\sum p^{matched}, \quad E^{cor}_{cluster} \geq 0$



Unfolding



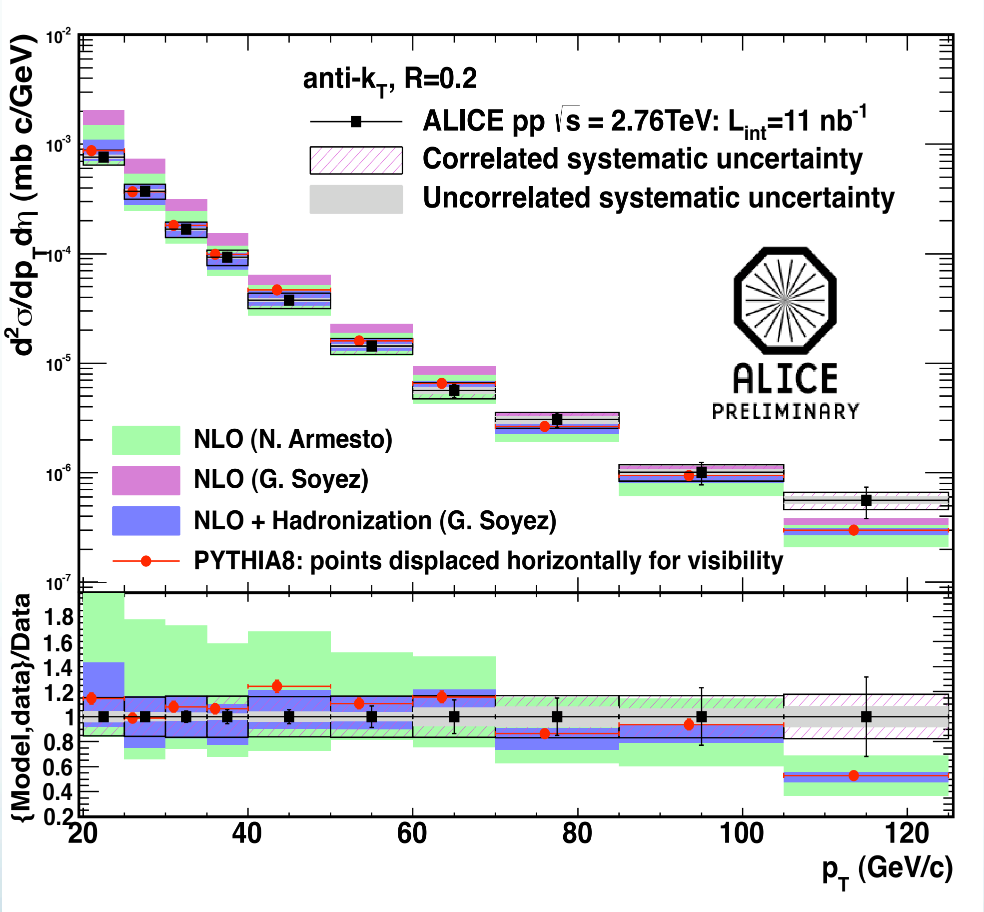
Jet Reconstruction

- Input to the Jet Finder
  - Assumed to be massless
  - Charged tracks with p_T > 150 MeV/c (pp, Pb-Pb)
  - EMCal clusters with E_T > 300 MeV after hadronic correction: (pp, Pb-Pb)
    - $E^{cor}_{cluster} = E^{orig}_{cluster} - f\sum p^{matched}, \quad E^{cor}_{cluster} \geq 0$
    - For pp analysis f = 100%
- Jets reconstructed using FastJet package
  - R = 0.2 (pp, Pb-Pb)
  - Anti-k_T for signal jets (pp, Pb-Pb)
  - k_T for ρ calculation (Pb-Pb)
  - EMCal jets: Fiducial cut requires jet fully contained in the EMCal acceptance (pp, Pb-Pb)

Detector Effects - pp

- Bin-by-bin technique
  - Compare the simulated cross sections before and after Detector response
  - Use uncorrected spectrum in data as weighting function
- *Shift of jet energy scale ~ 20-25%*
  - Unmeasured neutrons and K^0_L's: compare proton and kaon spectra to data; PYTHIA vs HERWIG
  - Tracking inefficiency: track quality in data vs simulation
  - Residual hadronic correction for EMCal: data-driven check
  - *JES uncertainty ~ 4%*
- *Jet energy resolution ~ 18%*
  - Detector resolution: data-driven check + test beam
  - Fluctuations (e-by-e) in correction of jet energy scale

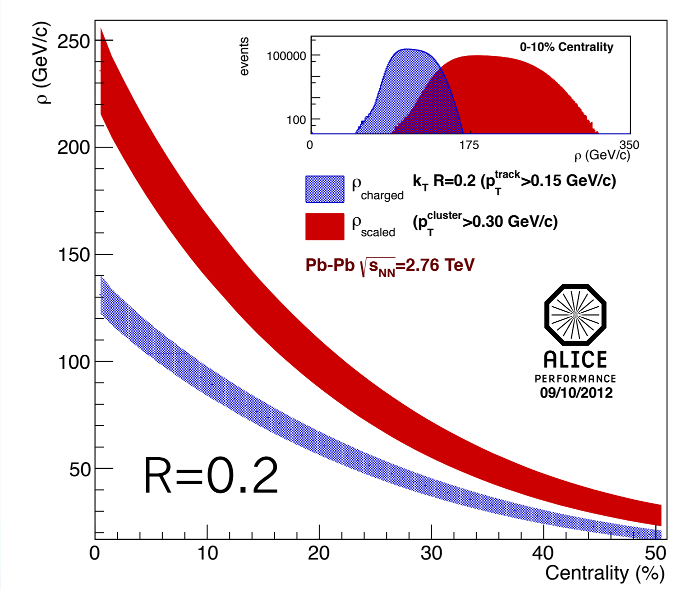
pp Baseline Result



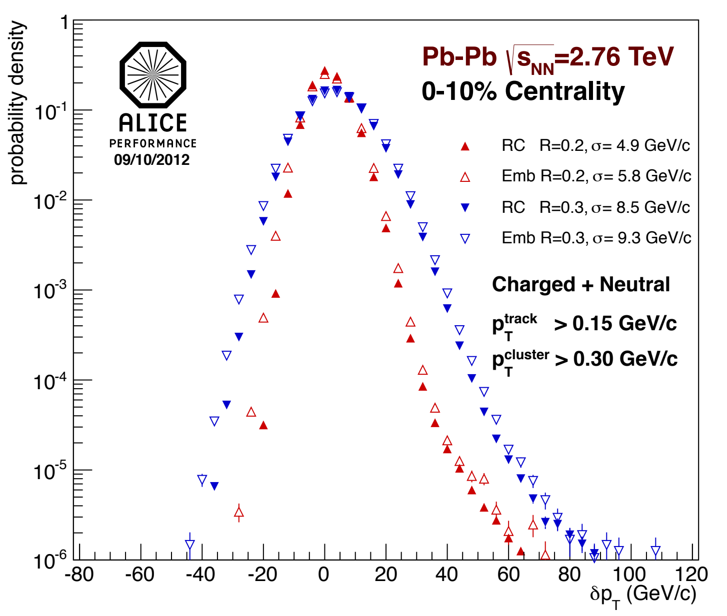
- Green and magenta bands: NLO on Parton level
- Blue band: NLO + hadronization
- Red points: Pythia8. Shifted horizontally for visibility
- f_{hadcor} = 100%, R = 0.2, p_T > 150 MeV/c
  E_T > 300 MeV

Good agreement between data and NLO calculations as well as Pythia8 prediction within both experimental and theoretical uncertainties

Charged+Neutral Background Determination



R=0.2
R=0.3



$$\rho_{ch+em} = s_{EMC}\rho_{ch} = s_{EMC}\cdot\mathrm{median}\left(\frac{p_T^{k_T\,jet}}{A^{k_T\,jet}}\right)$$

s_{EMC} = (TPC+EMCAL density)/(TPC density)

- $\sigma_{ch+em}(\delta p_T) > \sigma_{ch}(\delta p_T)$
  - 4.9 vs 4.5 GeV/c

- Fluctuation size characterized by δp_T
  - Embedded particle

$$\delta_{p_T} = p_T^{rec} - \rho_{ch+em}A^{\text{Anti-k}_T} - p_T^{emb}$$

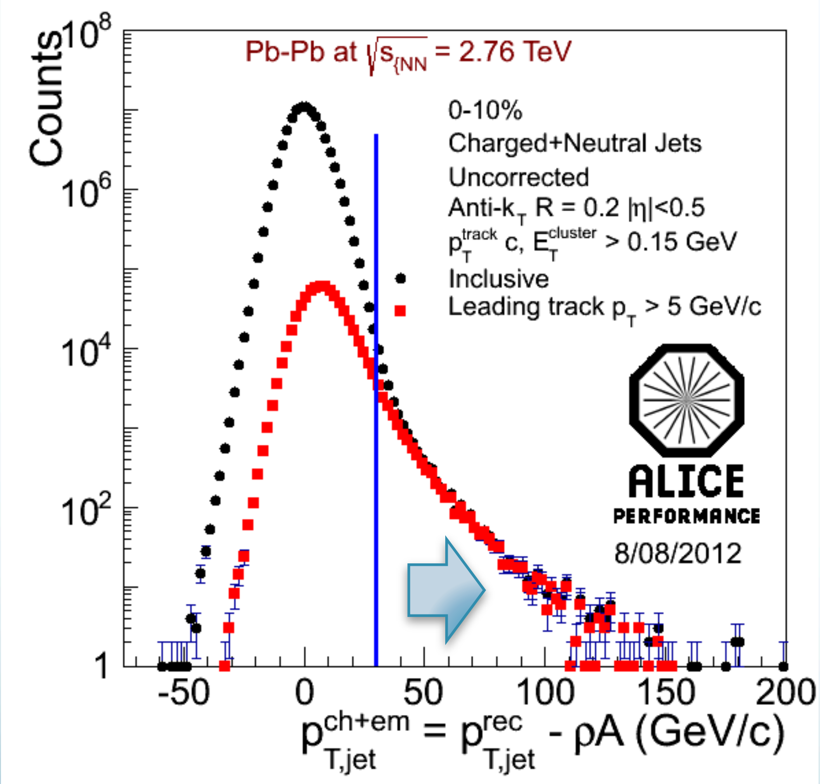
  - Random Cones

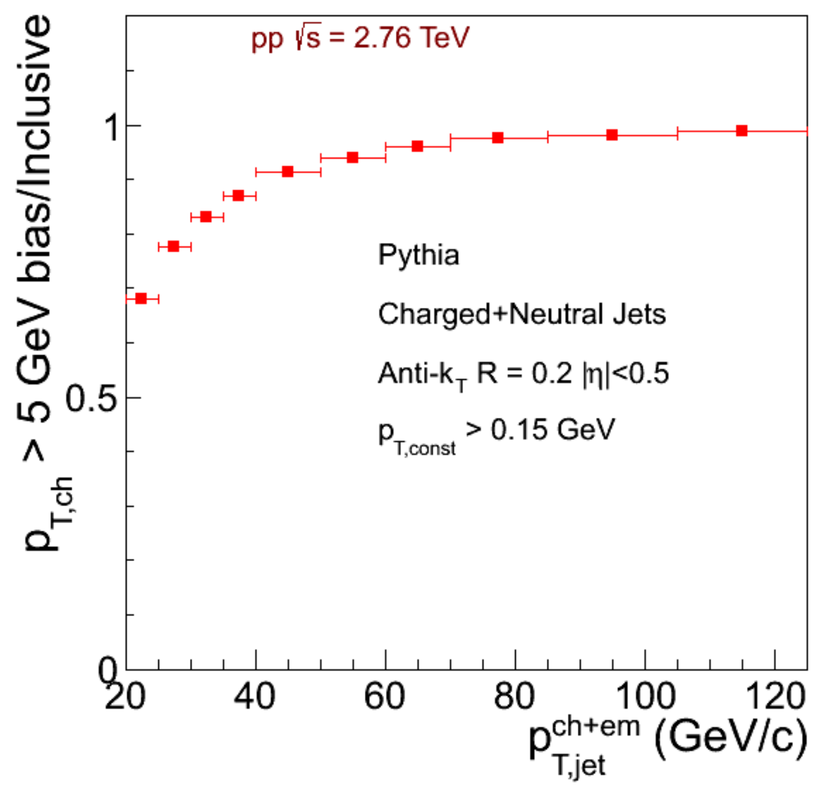
$$\delta_{pT} = p_T^{rec} - \rho_{ch+em}\pi R^2$$

Leading Track Bias

Leading Track $p_T > 5$ GeV/c

- Reduces combinatorial background, improves unfolding stability

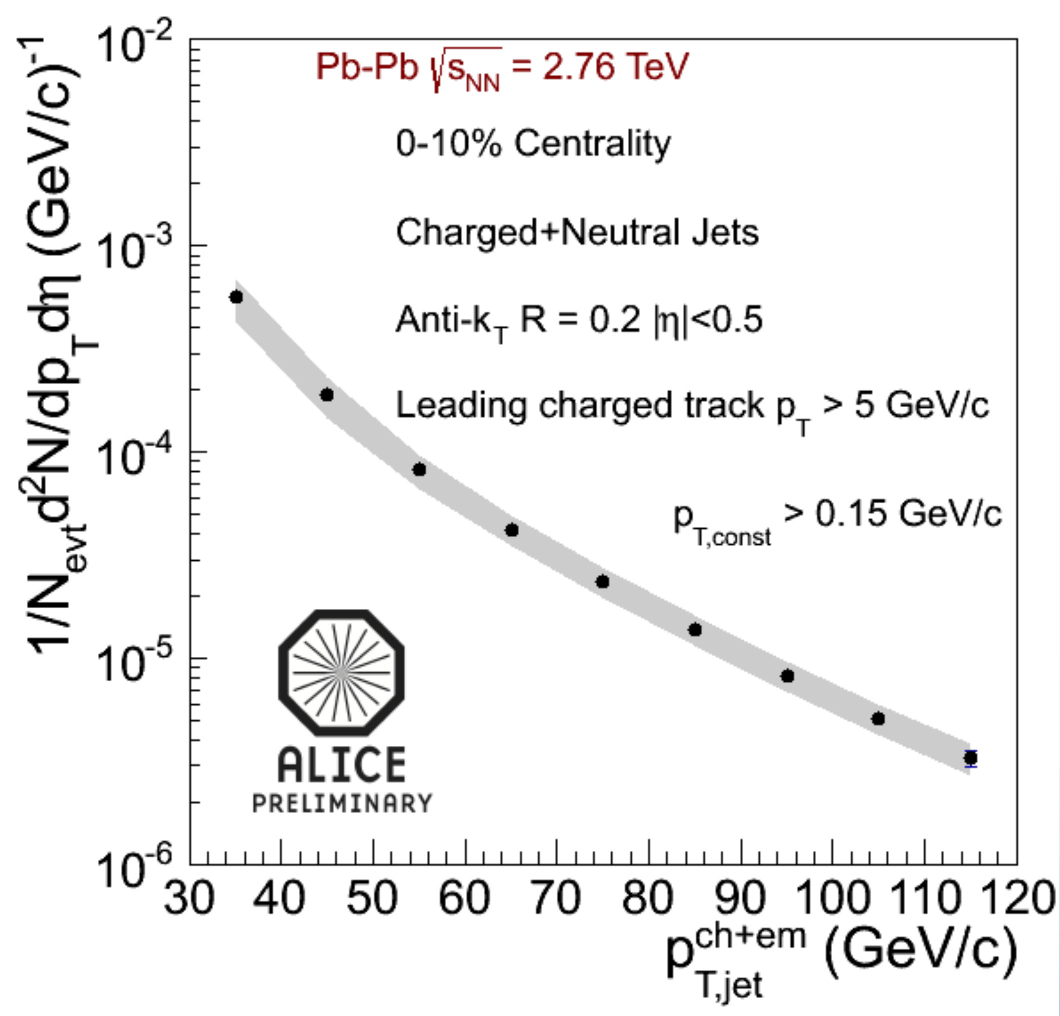




Fully Reconstructed Jet Spectrum

See Salvatore's talk

0-10% Centrality



- Jets are corrected for background fluctuations and detector effects in unfolding
- Systematics:
  - ~19% (p_T dependent)
  - EMCal effects (Resolution, scale, clusterizer, non-linearity)
  - Unfolding
  - Tracking efficiency
  - Background

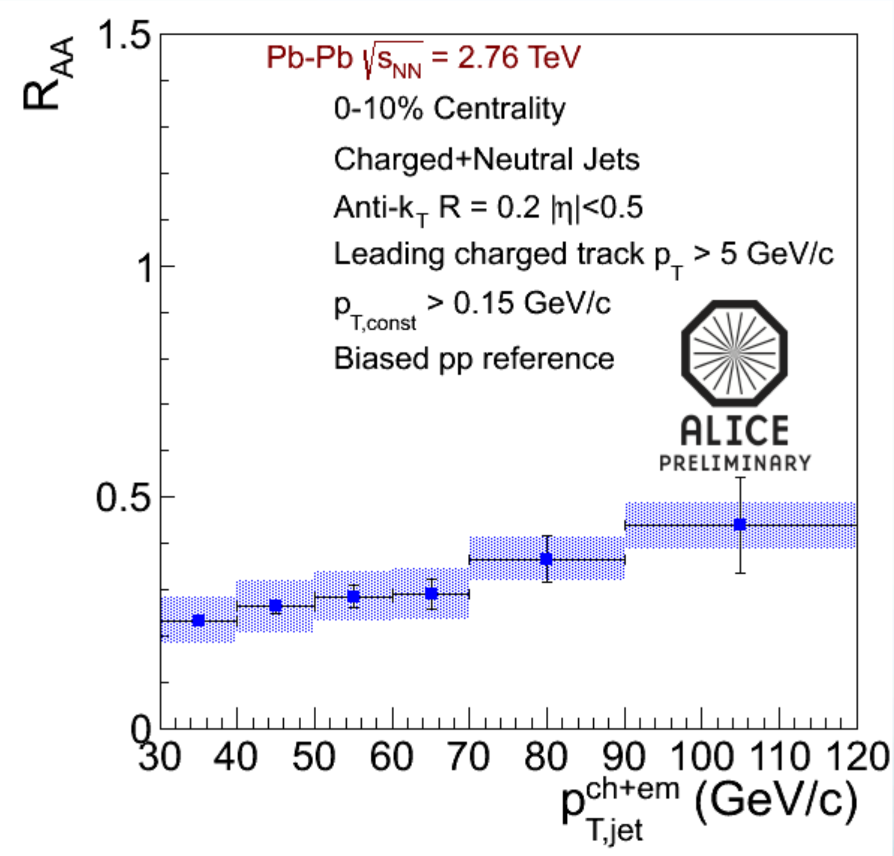
Fully Reconstructed Jet R_{AA} 0-10% Centrality

- We want to understand how partons lose energy in the medium and where that lost energy goes
- Nuclear modification factor (R_{AA}) can help quantify jet suppression
  - Which reference pp spectrum should be used?
    - Biased?
      - Same as Pb-Pb
    - Unbiased?
      - Calculable
      - IR and colinear safe

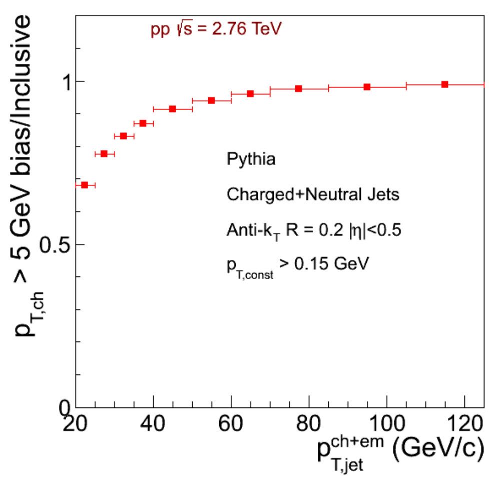
$$T_{AA} = \frac{\#\,\text{Binary Collisions}}{\sigma_{pp}}$$

$$R_{AA} = \frac{\dfrac{1}{N_{events}} \dfrac{d^2 N_{jets}}{dp_T d\eta}}{T_{AA} \dfrac{d^2\sigma}{dp_T d\eta}}$$

Fully Reconstructed Jet R_{AA} 0-10% Centrality

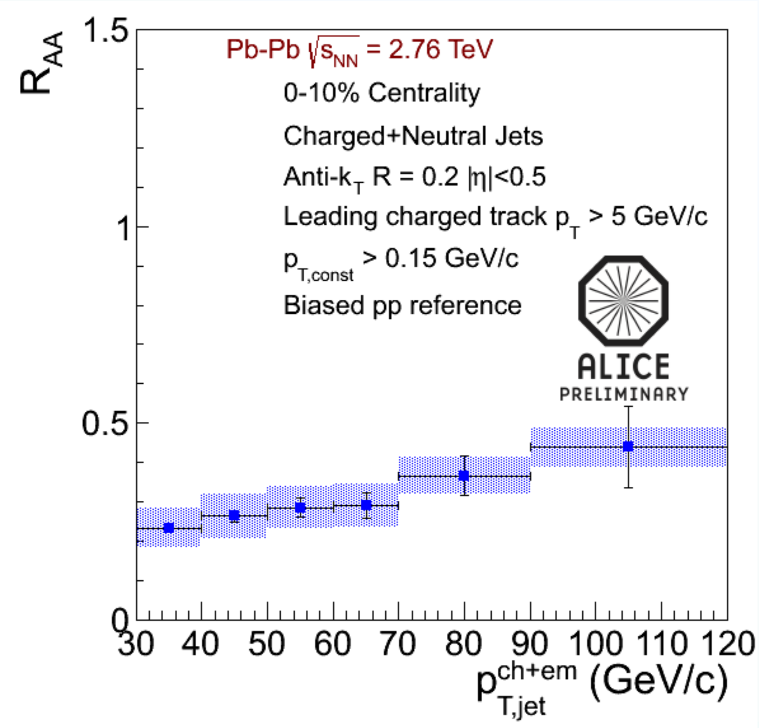


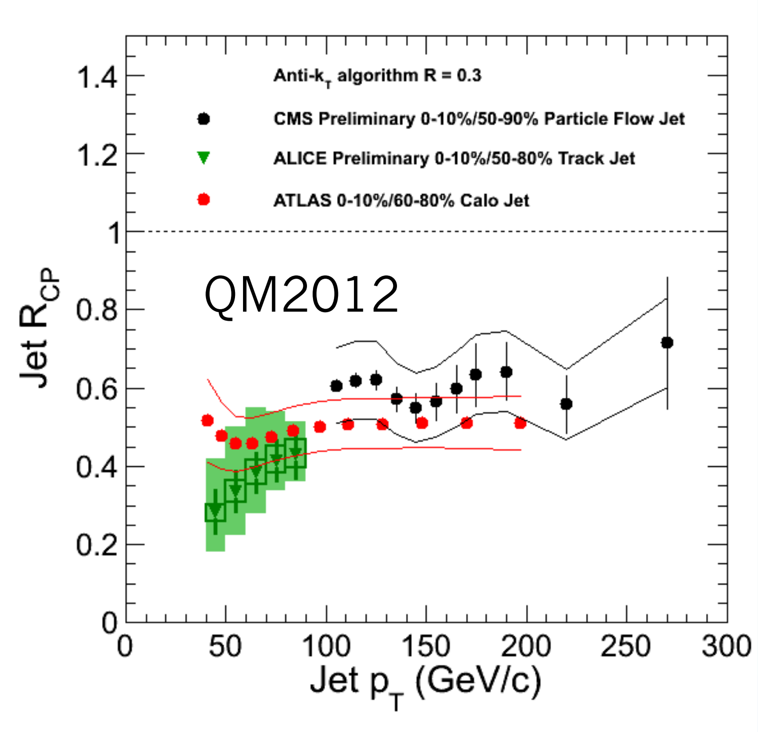
- Biased pp reference
- Biased Pb-Pb
- Jets are suppressed in a p_T dependent manner



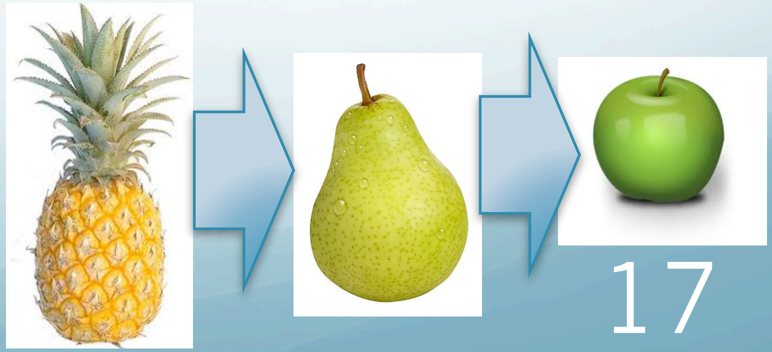
Bias/Unbiased pp in Pythia ~0.85 for 30-40 GeV/*c*

LHC Jet R_{AA} (R_{CP}) Comparison

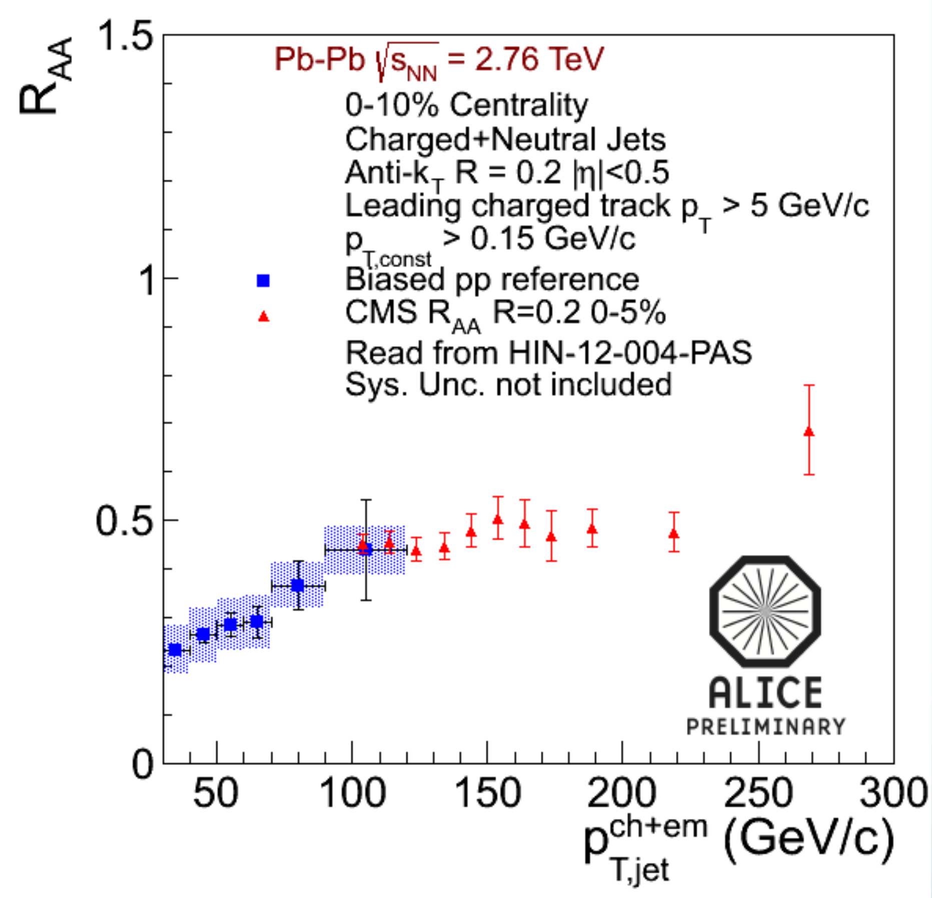




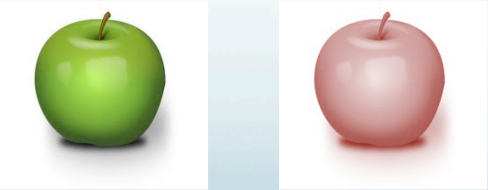
- All experiments see Jet suppression in central Pb-Pb collisions at 2.76TeV
  - Comparison is complicated
    - R, η, p_T constituent, Background
  - Need apples-to-apples



CMS and ALICE



- ALICE and CMS are consistent within overlap region
  - Same R
  - Different constituent cuts
- Complementary results

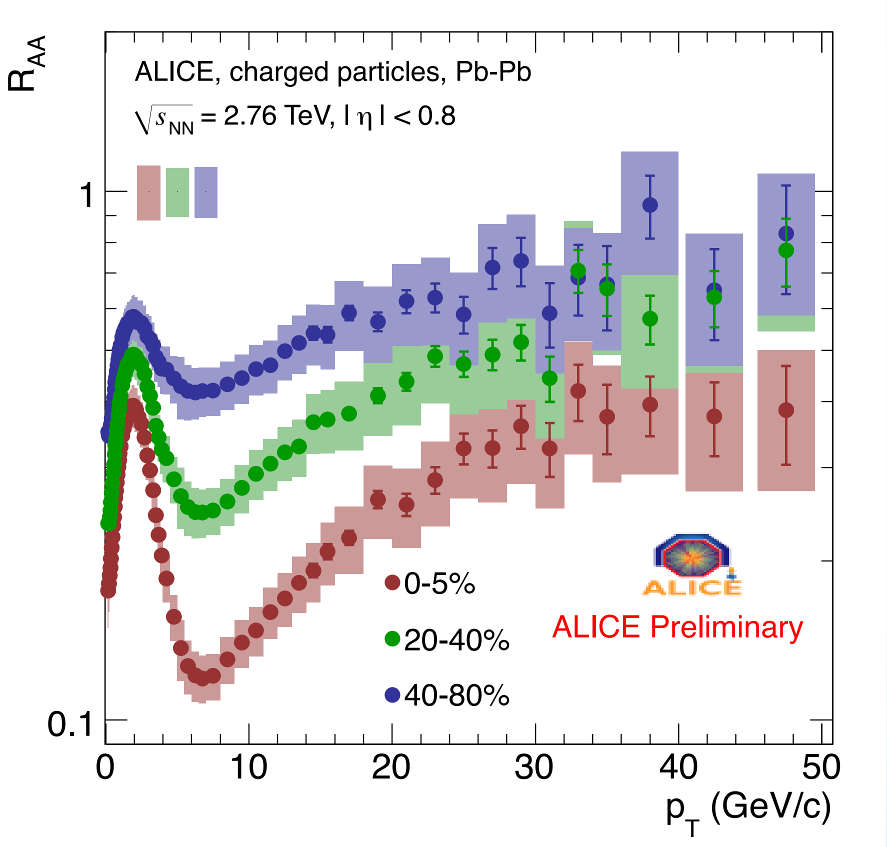


Conclusions

- Reporting on a corrected fully reconstructed jet spectrum from 2011 Pb-Pb data in 0-10% in ALICE
- First full jet R_{AA} with $p_{T,jet} < 100$ GeV/c at the LHC
- **R = 0.2 jets are suppressed in 0-10%**
  - Further study needed
  - Variations on jet radius
  - Event plane dependence
- R = 0.3 measurement coming soon!
- All experiments should work towards an Apples-to-Apples comparison!

Back-up

Hadron RAA



R_{AA}
ALICE, charged particles, Pb-Pb
$\sqrt{s_{NN}}$ = 2.76 TeV, | η | < 0.8
1
0.1
0
10
20
30
40
50
p_T (GeV/c)
0-5%
20-40%
40-80%
ALICE
ALICE Preliminary

Anti-kT

Sequential Recombination Algorithm

$$d_{ij} = \min\left(\frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

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

$$d_{iB} = \frac{1}{p_{ti}^2}$$

Creates round jets around the hardest particles!

Procedure

- compute all d_{ij} and d_{iB}
- Find minimum of the d_{ij} and d_{iB}
- If it is a d_{ij}, recombine i and j into a new particle
- otherwise declare it to be a jet and remove it from the sample
- Repeat until all particles are used

kT

Sequential Recombination Algorithm

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

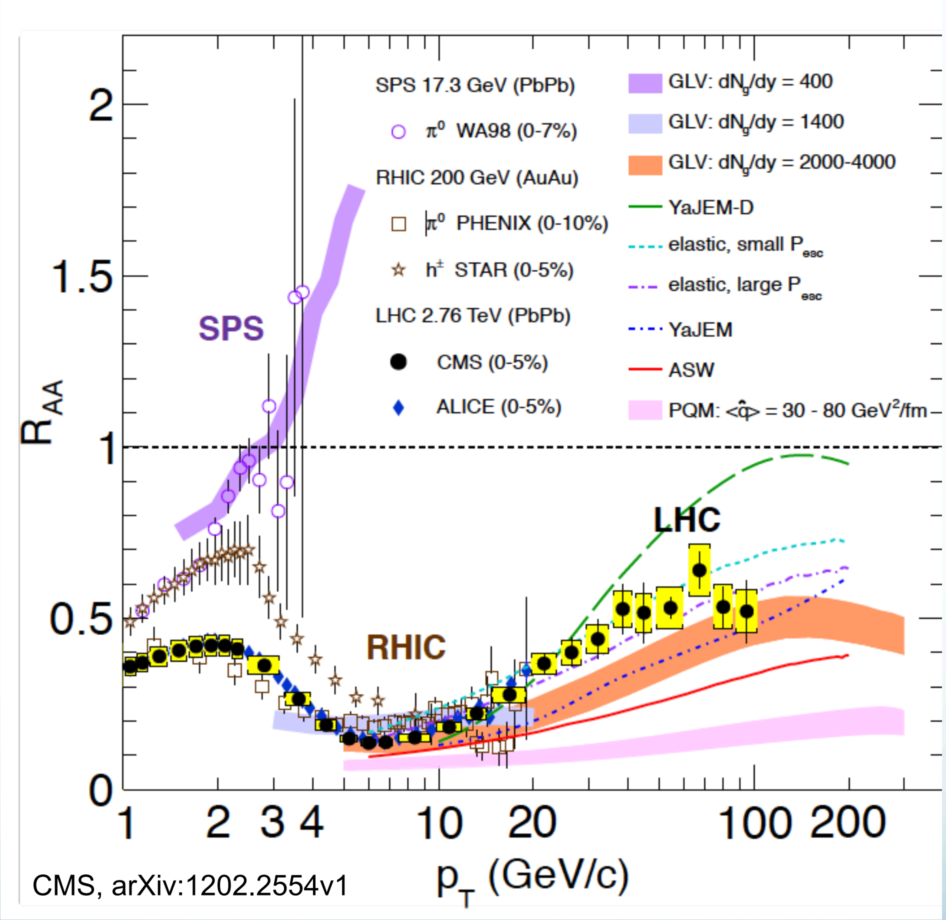
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

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

Procedure

- compute all d_{ij} and d_{iB}
- Find minimum of the d_{ij} and d_{iB}
- If it is a d_{ij}, recombine i and j into a new particle
- otherwise declare it to be a jet and remove it from the sample
- Repeat until all particles are used

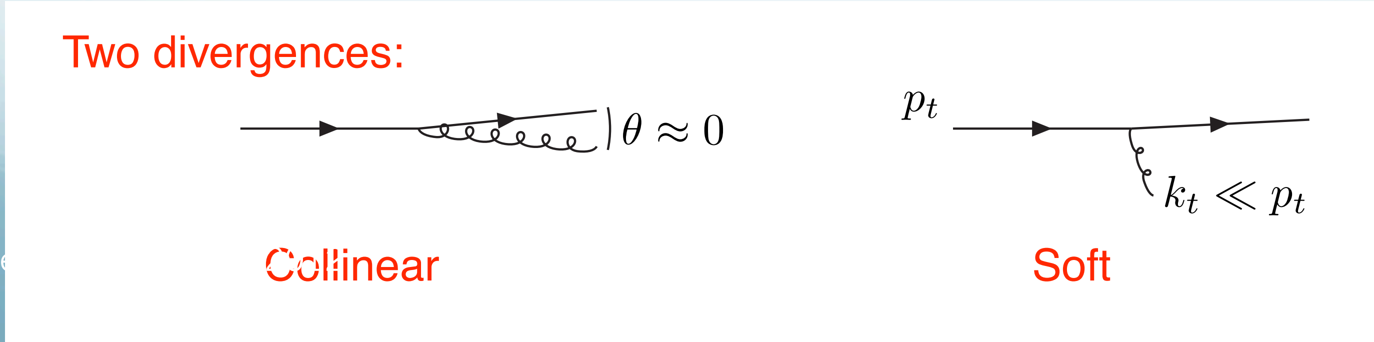
What are we trying to learn Jets in heavy ions?



CMS, arXiv:1202.2554v1

Good Jet Finding Algorithms

- Jets are defined by the algorithms that create them
- A good algorithm defines jets that are:
  - The same for
    - experimental analysis
    - Monte Carlo Simulations
    - analytical parton calculations
  - collinear safe
  - IR safe
  - not sensitive to the hadronization mechanism
- Collinear safe - emission of a collinear gluon does not change the jet
- IR safe - emission of a soft gluon does not change the jet

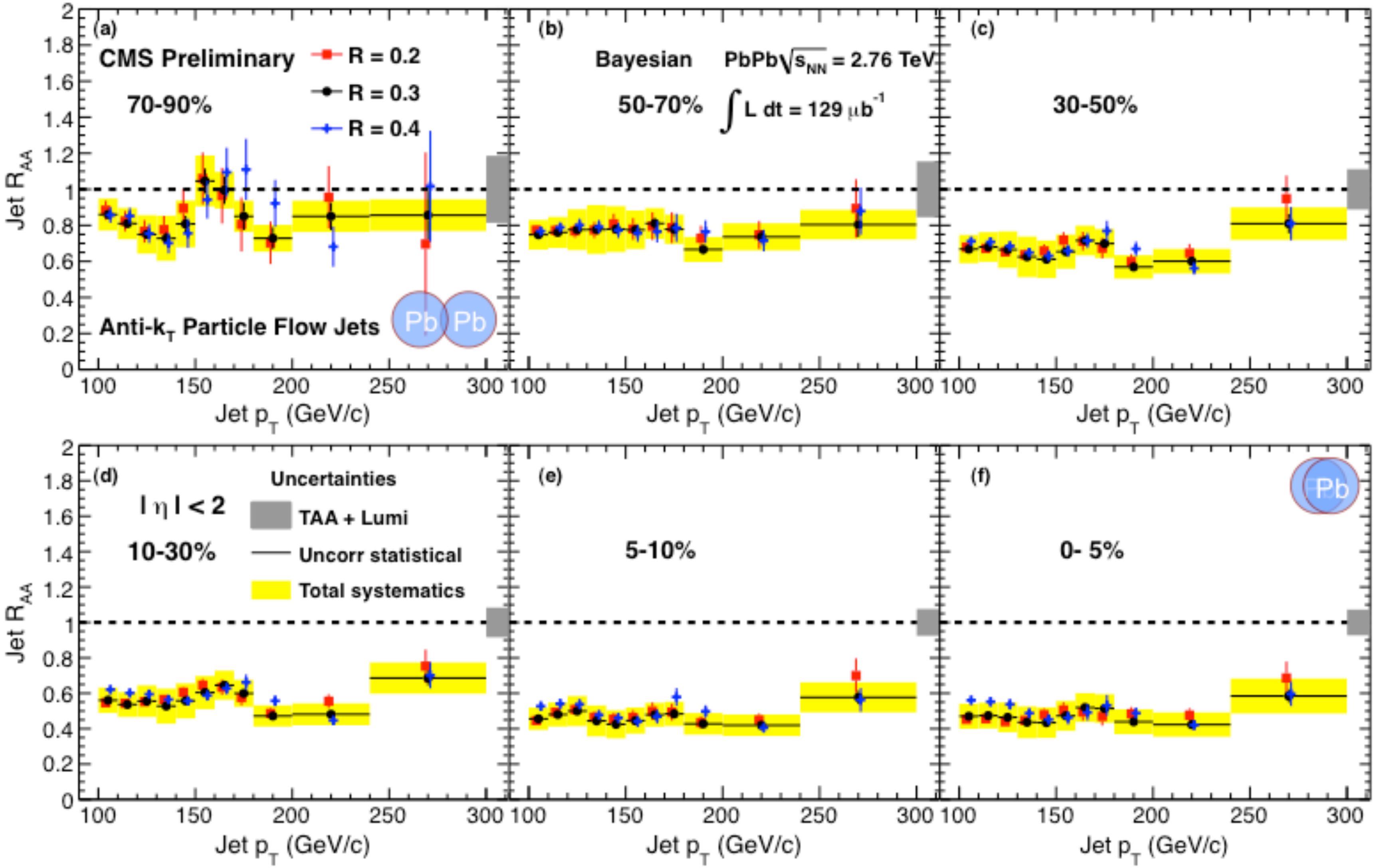


Two divergences:

Collinear

Soft

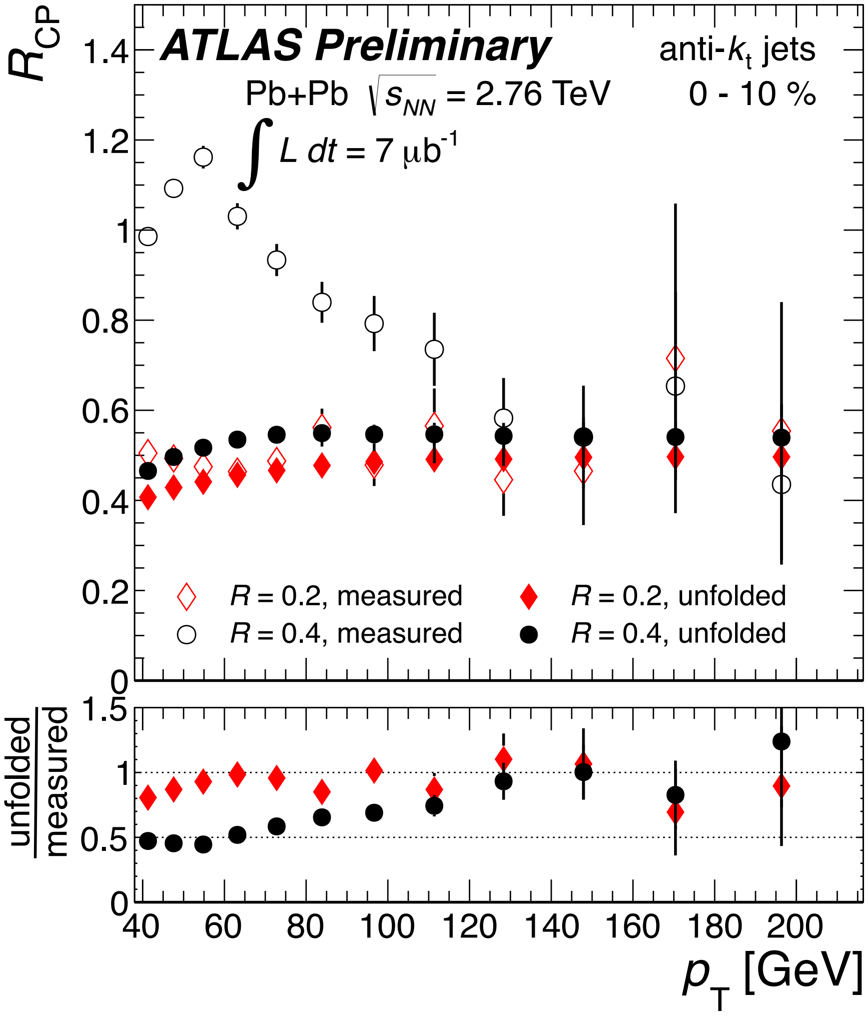
Different jet cone size



total systematic R=0.3

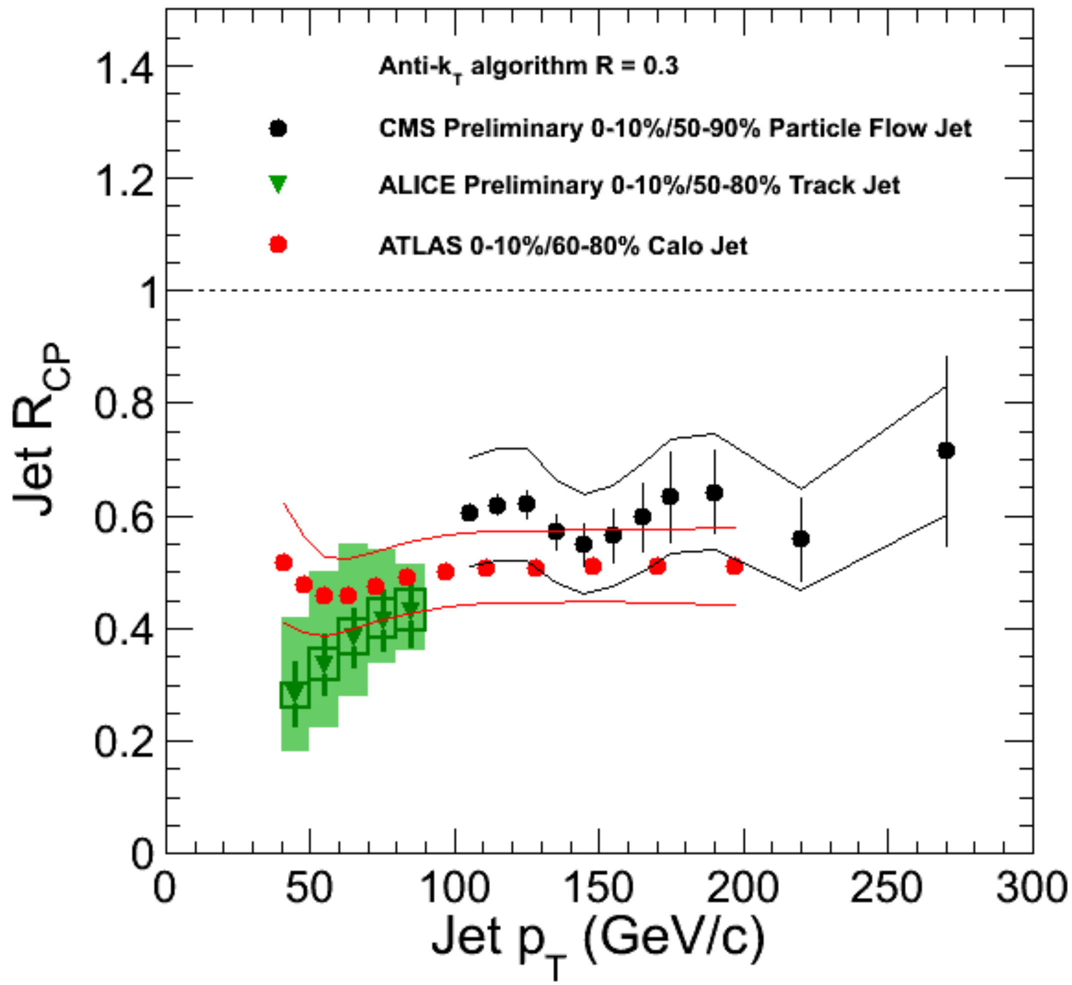
- No strong dependence on jet radius

Unfolding



- UE and detector effects result in finite JER
  - Jet spectrum is steeply falling
  - Result is significant bin migration
- Use MC to generate response matrix
  - Contains information about bin migration
- SVD unfolding
  - Invert response using curvature constraint on result to regularize unfolding
- Unfolding checks
  - Apply to MC, look for bias
  - "Refold" data, check refolded looks like input

`Hocker and Kartvelishvili: hep-ph/9509307`



Anti-k$_T$ algorithm R = 0.3
● CMS Preliminary 0-10%/50-90% Particle Flow Jet
▼ ALICE Preliminary 0-10%/50-80% Track Jet
● ATLAS 0-10%/60-80% Calo Jet
Jet R_{CP}
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
Jet p_T (GeV/c)