Jet Measurements in pp and PbPb Collisions

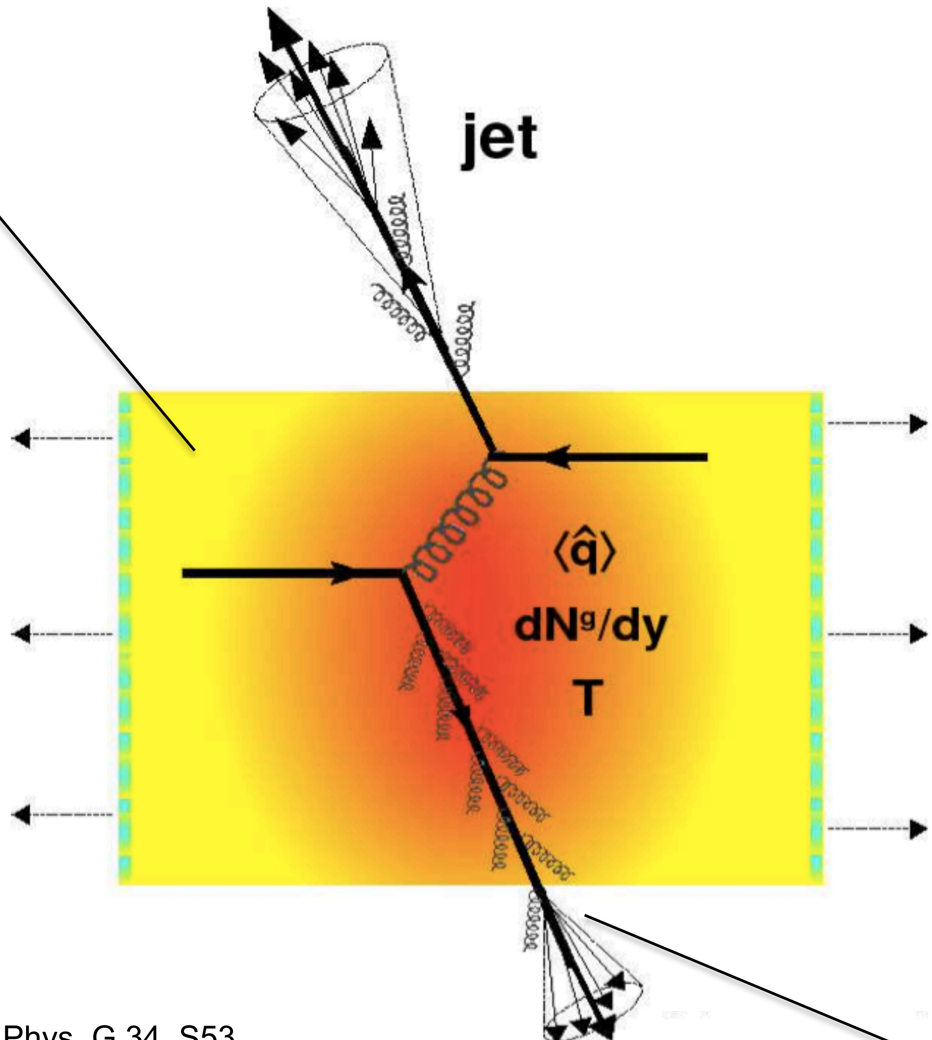
Frank Ma

Massachusetts Institute of Technology

for the CMS Collaboration

Jet Physics in Heavy ion Collisions

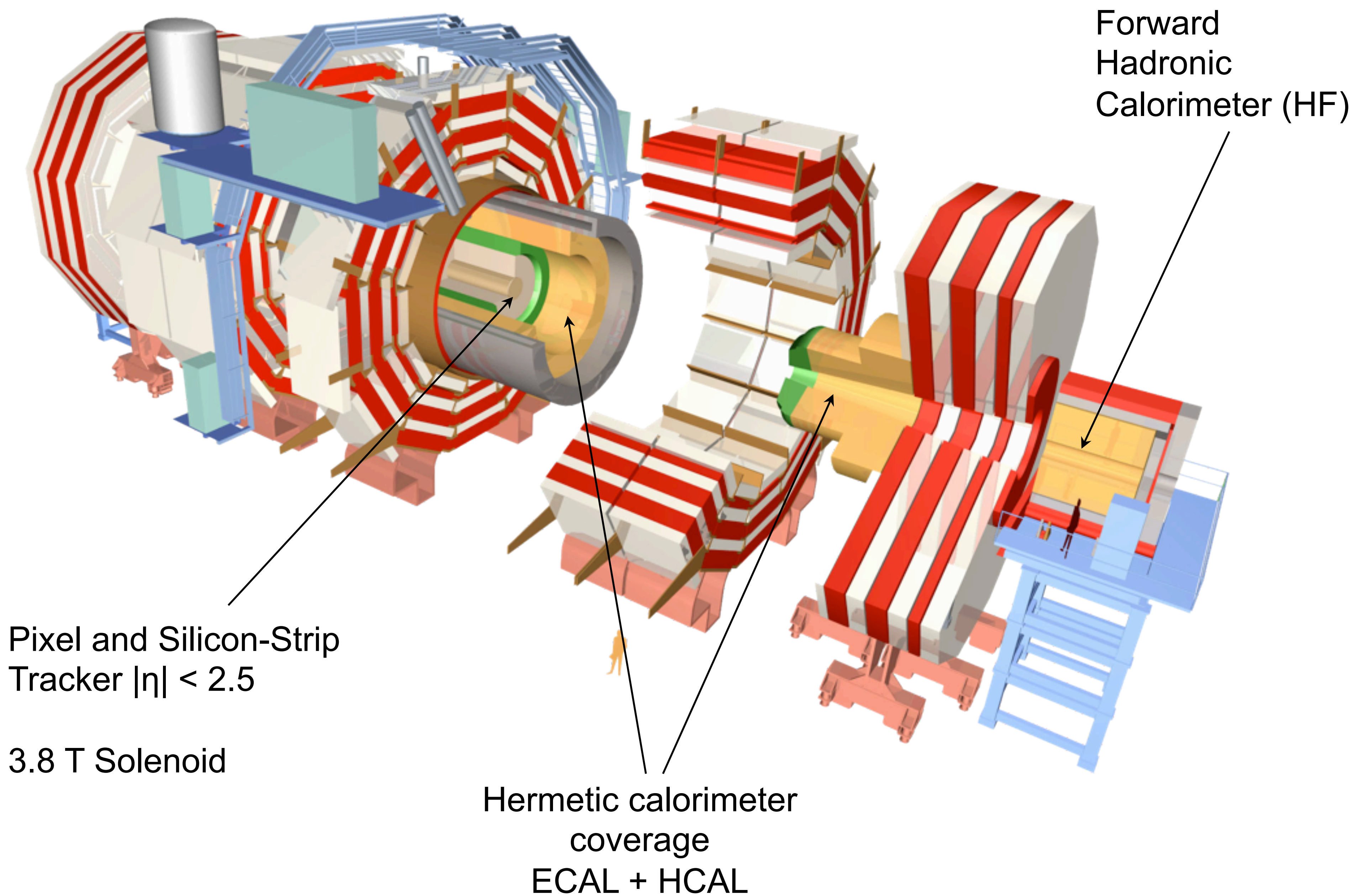
Hot and dense QCD medium created in heavy ion collisions



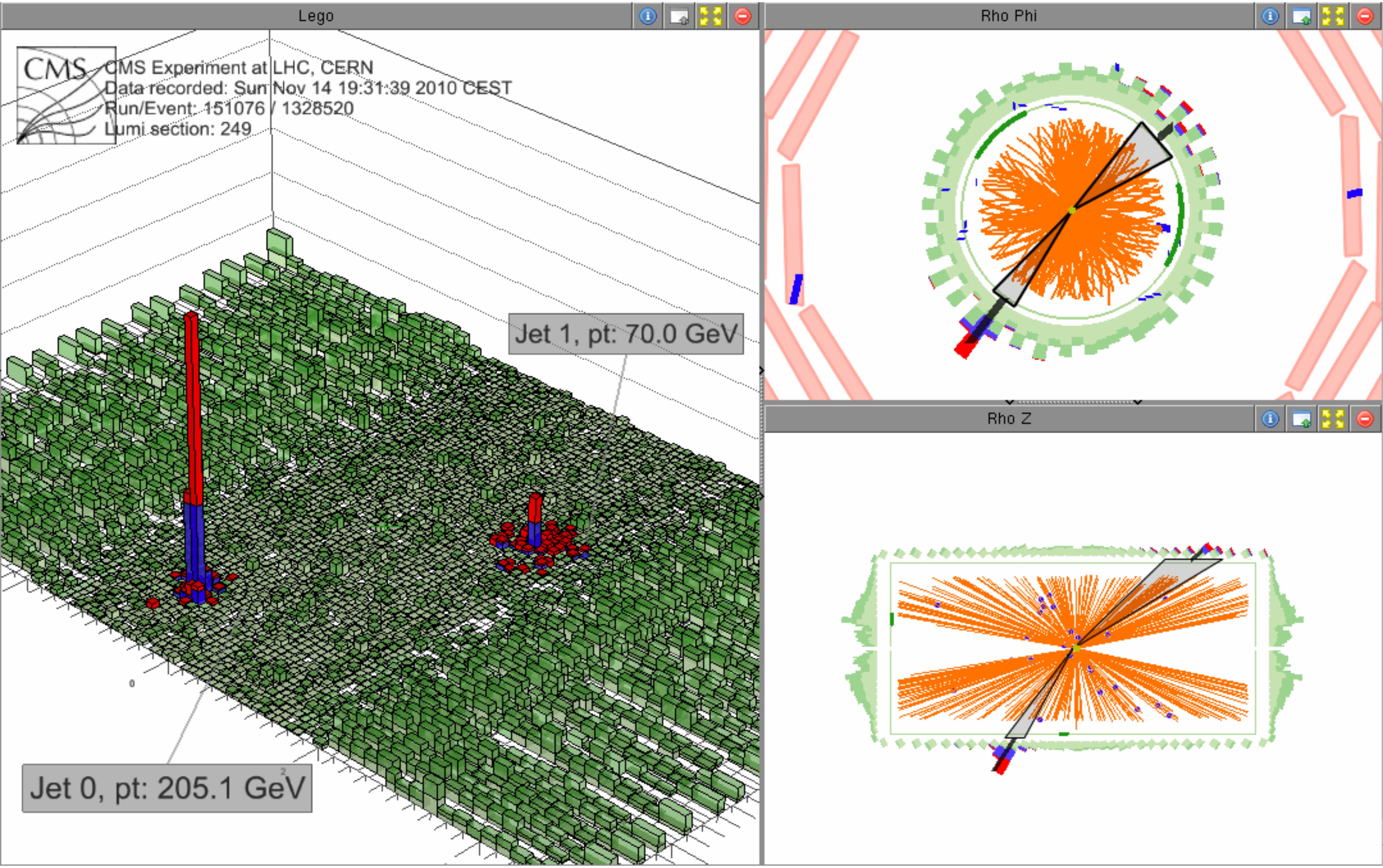
D. d'Enterria, J. Phys. G 34, S53

Scattered parton probes the QCD medium

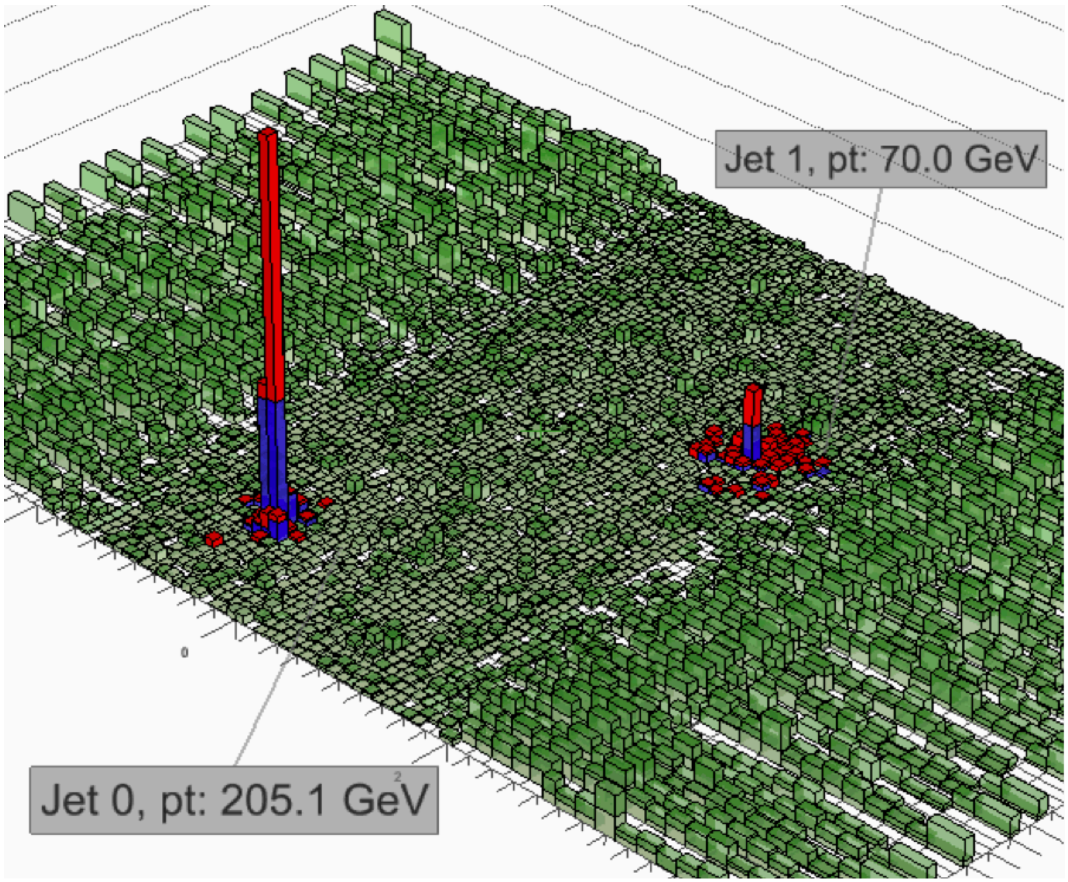
CMS Detector



Jets in CMS Detector



Jet Reconstruction



Calorimeter Jet Finder

- Iterative Cone Algorithm
- R = 0.5

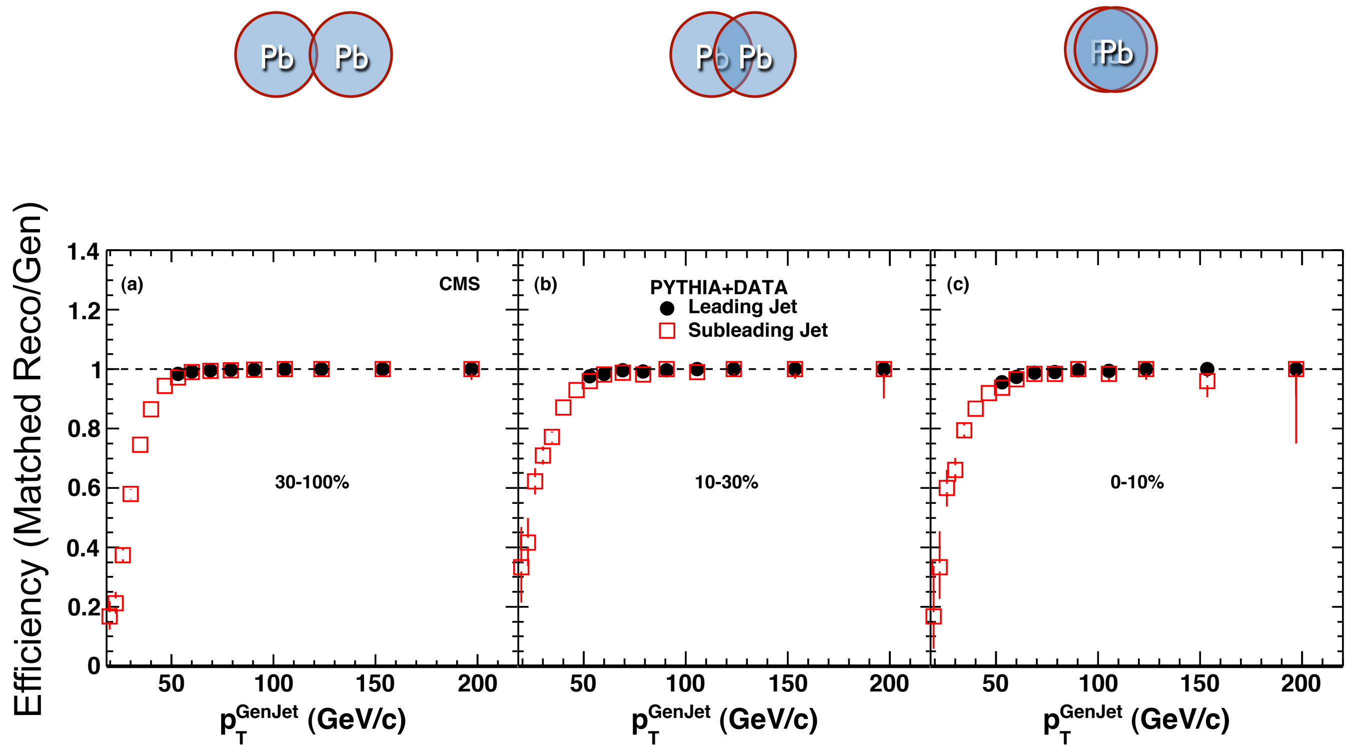
Underlying event subtraction

- Iterative PileUp subtraction*

Particle flow jet finder with Anti-k_T algorithm (later in talk)

* O. Kodolova, I. Vardanian, A. Nikitenko et al., Eur. Phys. J. C50 (2007) 117

Jet Reconstruction



Calorimeter Jet Finder

- Iterative Cone Algorithm
- R = 0.5

Underlying event subtraction

- Iterative PileUp subtraction

arXiv:1102.1957 (Accepted by PRC)

Jet reconstruction fully efficient above 50 GeV/c

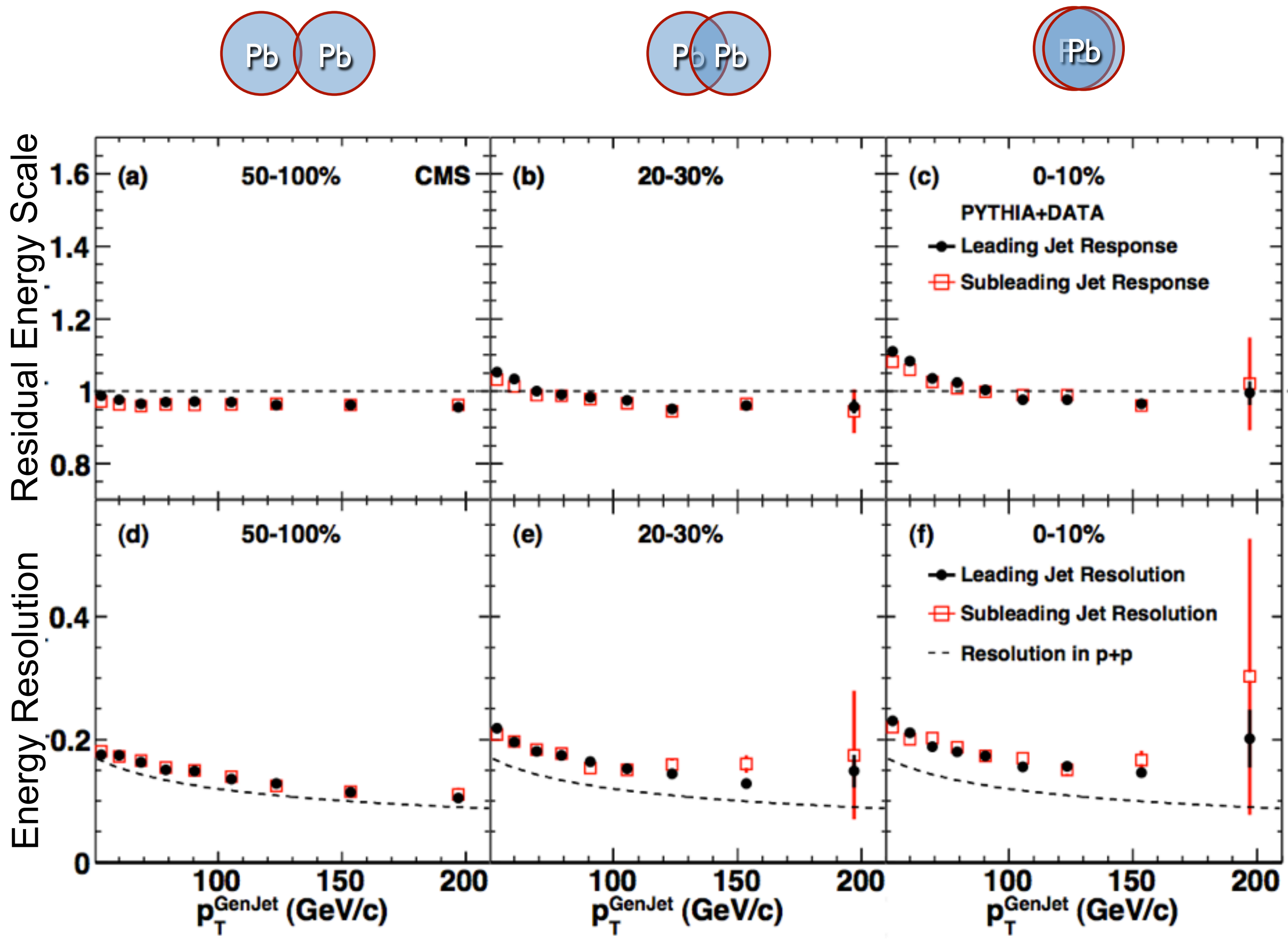
Jet Energy Correction

Calorimeter Jet Finder

- Iterative Cone Algorithm
- R = 0.5

Underlying event subtraction

- Iterative PileUp subtraction



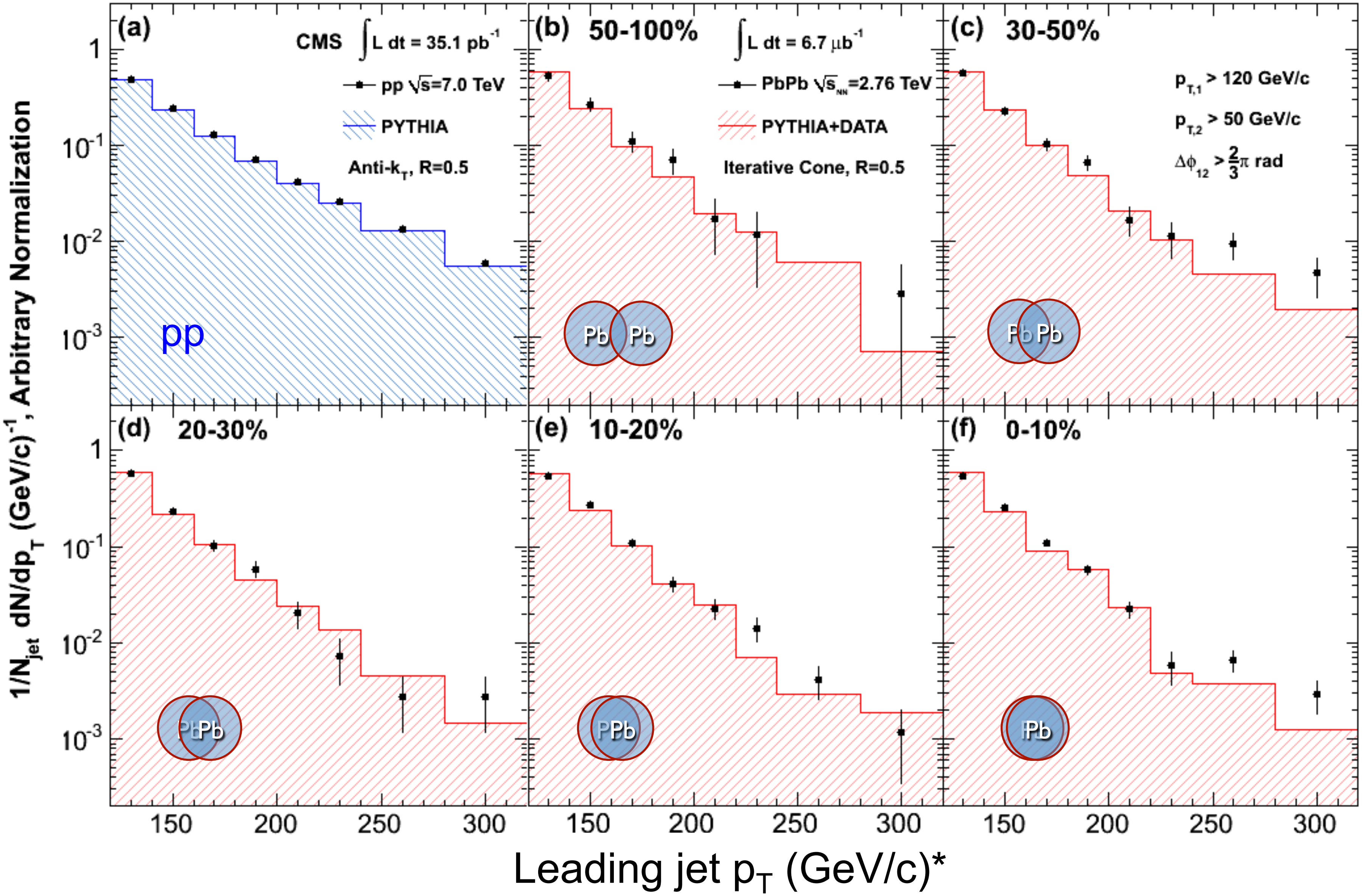
arXiv:1102.1957 (Accepted by PRC)

Jet p_T corrected to **generator final state particle level**

- Correction derived from PYTHIA
- Closure checked with dijets embedded into PbPb data

Jets in Data

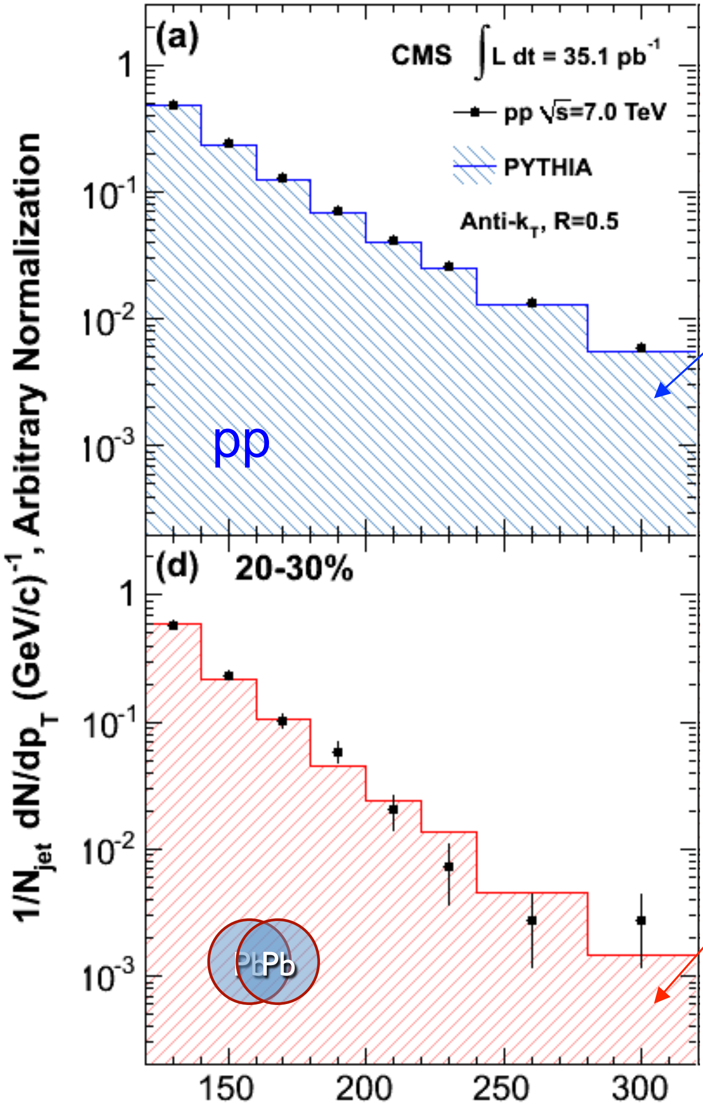
arXiv:1102.1957 (Accepted by PRC)



Abundant hight p_T jets from jet triggered dataset ($6.7\mu b^{-1}$)

*Uncorrected for p_T resolution

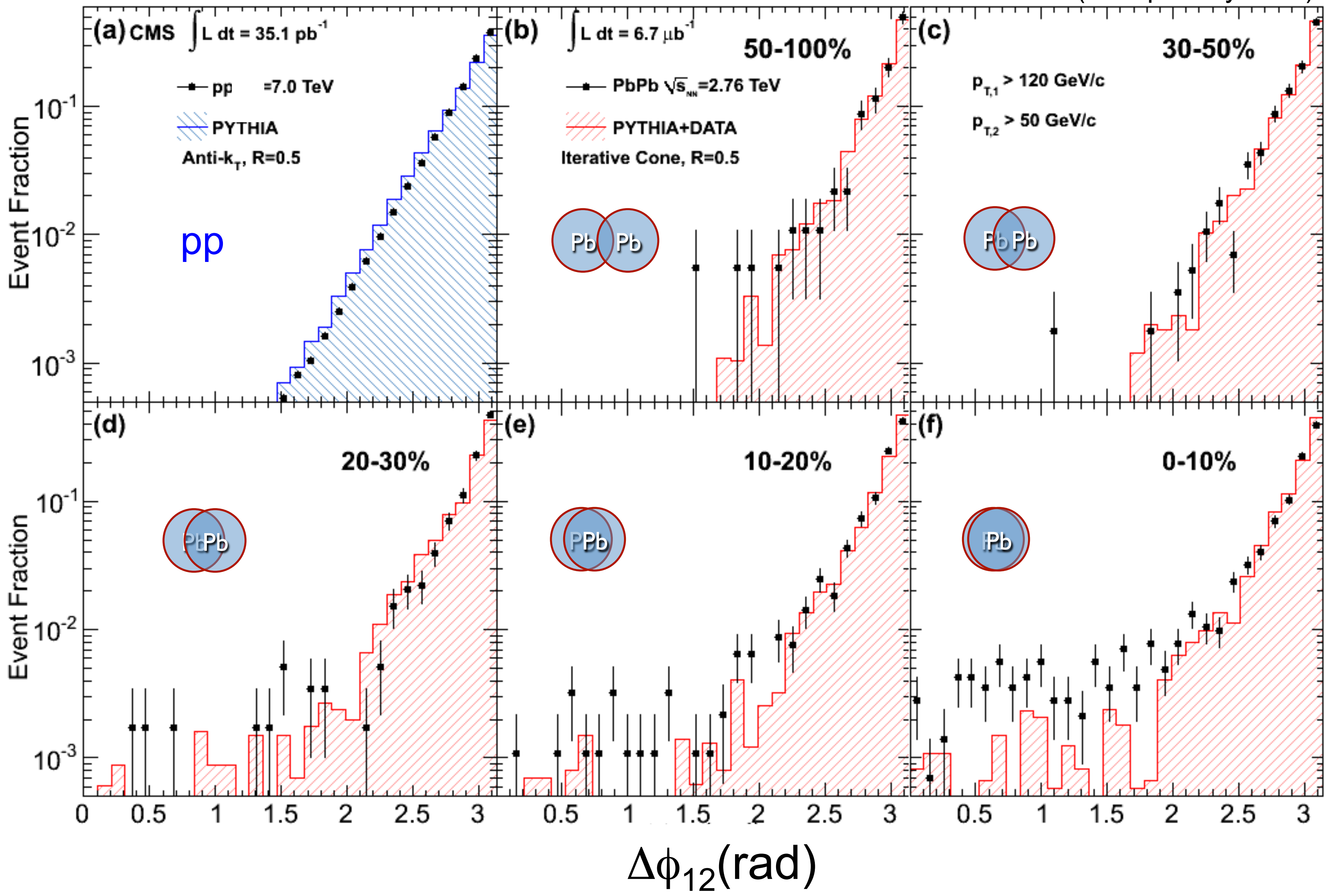
Reference Distributions



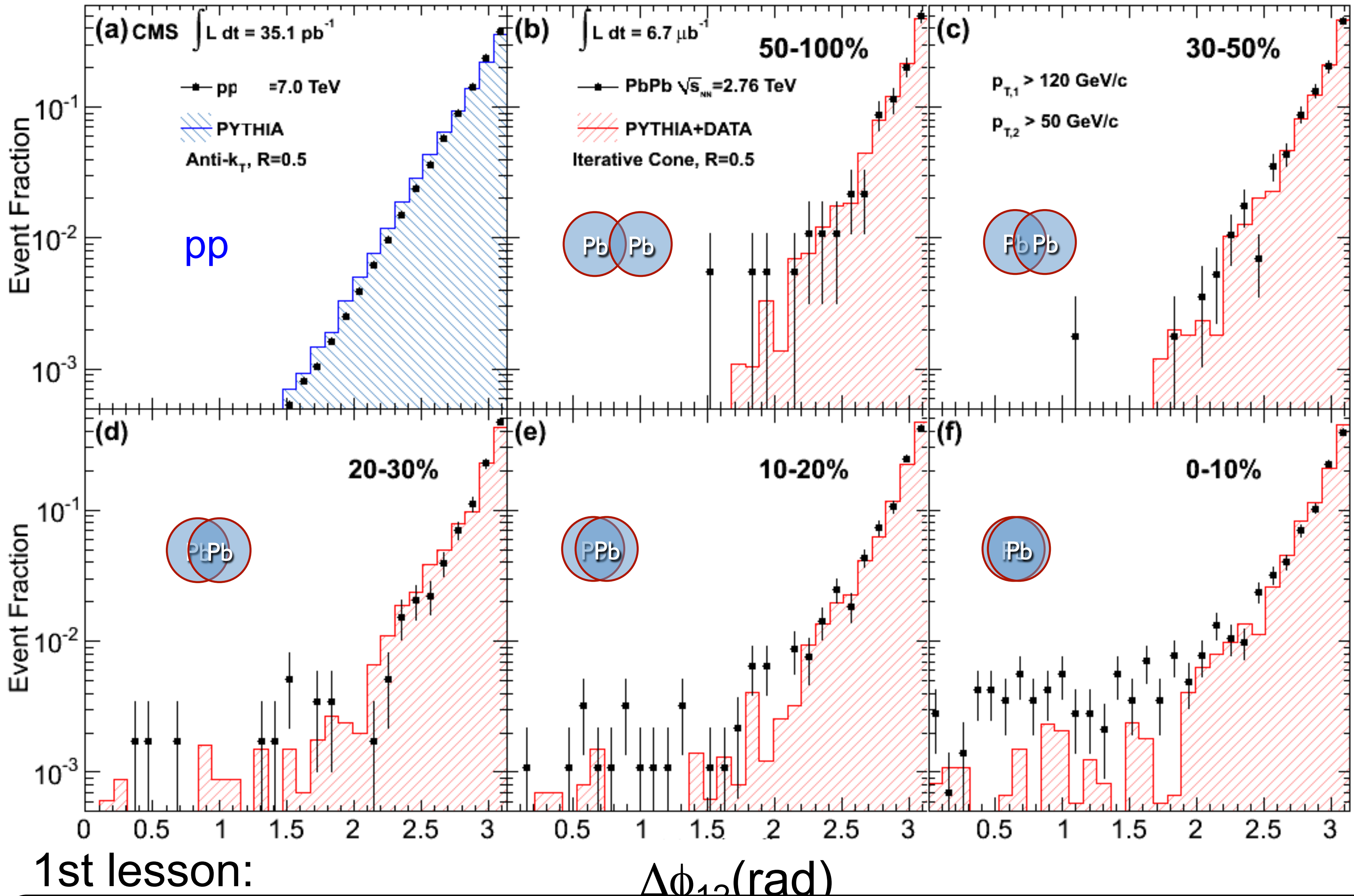
- PYTHIA 6:
- PYTHIA + DATA:
  - PYTHIA dijet events embedded into real data background
  - modified isospin ($^{208}_{82}$Pb)

Jet Angular Correlation

arXiv:1102.1957 (Accepted by PRC)



Jet Angular Correlation

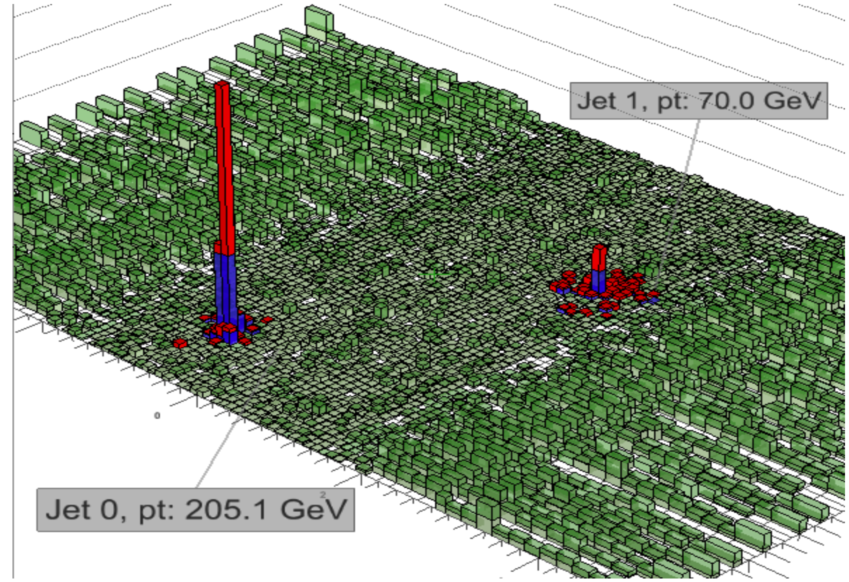


1st lesson:

The propagation of high p_T partons in a dense nuclear medium does not lead to a visible angular decorrelation

DiJet Energy Asymmetry

- Dijet selection:
  - $|\eta^{Jet}| < 2$
  - Leading jet $p_{T,1} > 120$ GeV/c
  - Subleading jet $p_{T,2} > 50$ GeV/c
  - $\Delta\phi_{1,2} > 2\pi/3$



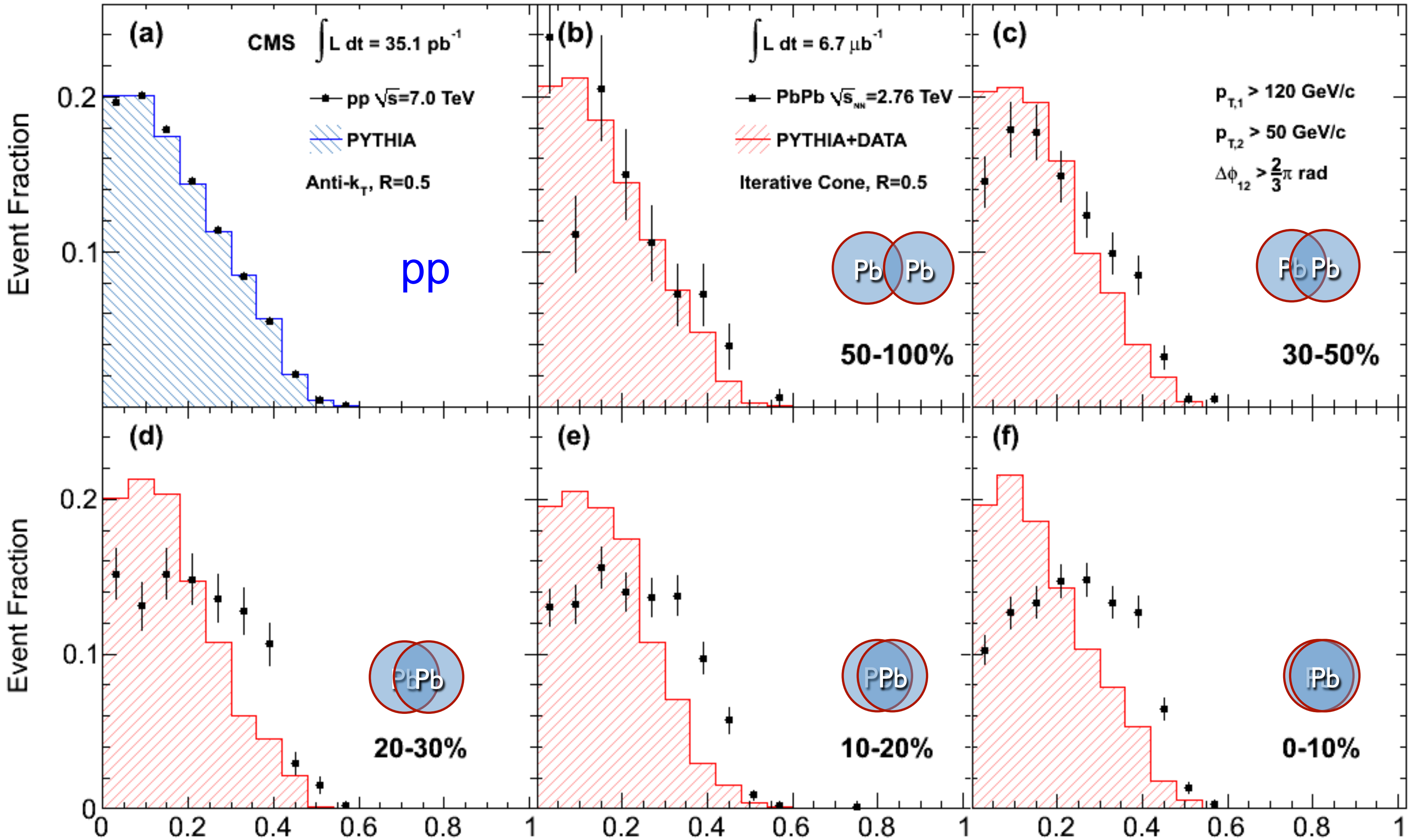
- Quantify dijet energy imbalance by asymmetry ratio:

$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- Removes uncertainties in overall jet energy scale

DiJet Energy Asymmetry

arXiv:1102.1957 (Accepted by PRC)



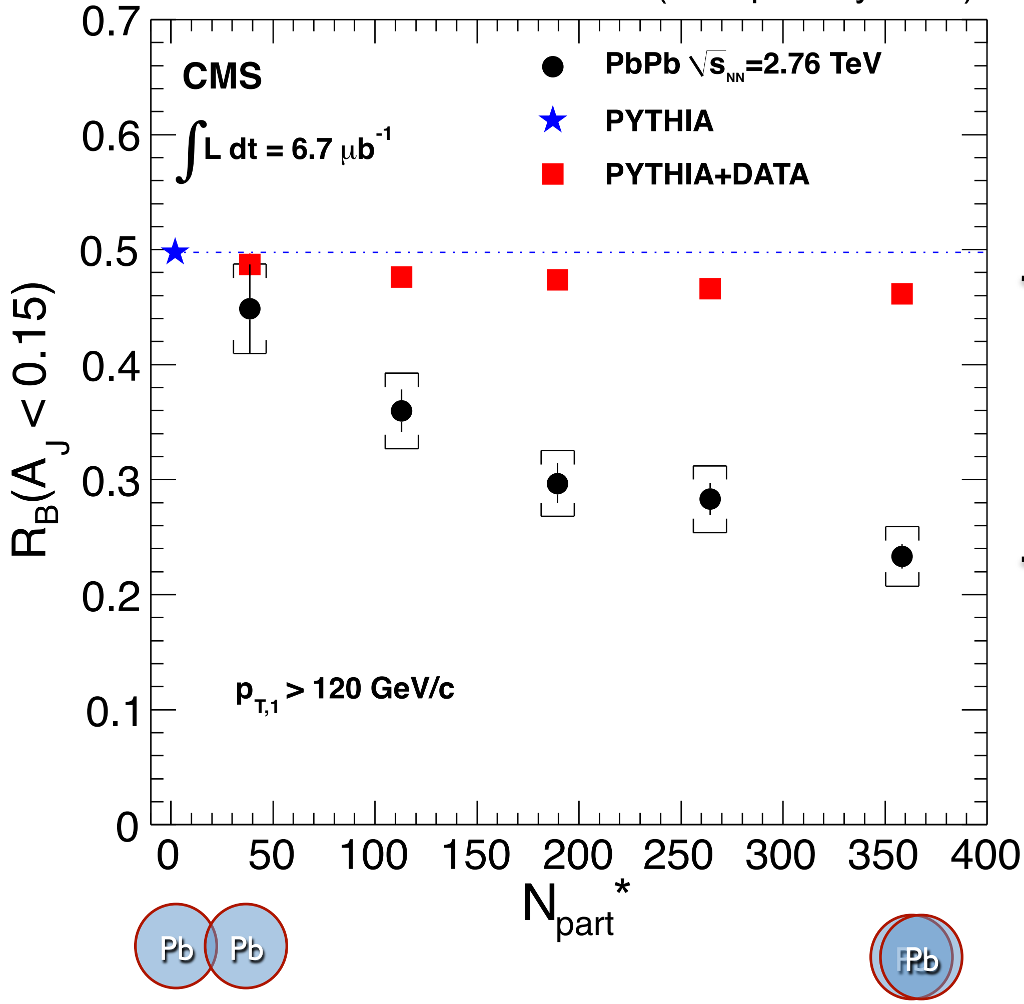
$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

← Balanced | UnBalanced →

Fraction of Balanced Jets vs Centrality

Fraction of found balanced dijets out of all selected leading jets

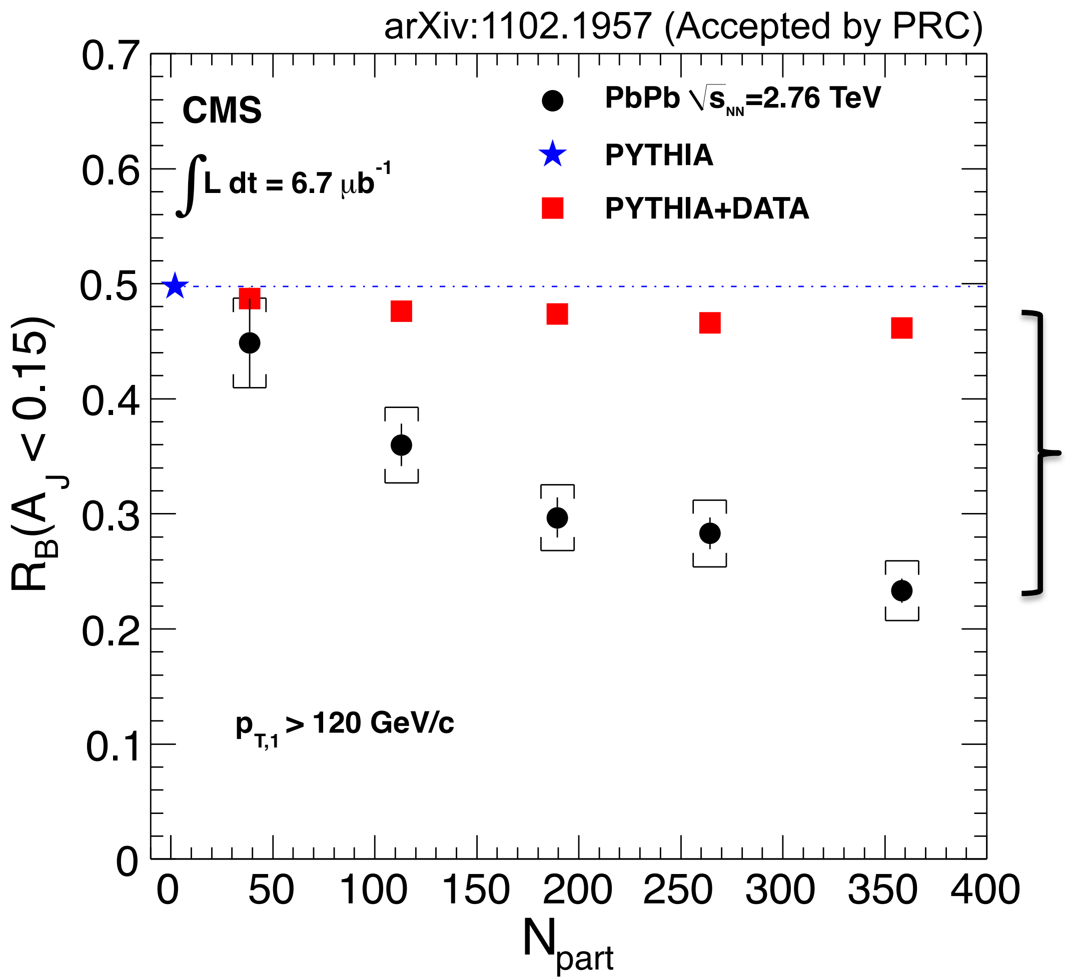
arXiv:1102.1957 (Accepted by PRC)



~ x2 suppression of balanced dijets in central events

*N_{part}: Number of nucleon participating in collisions

Fraction of Balanced Jets vs Centrality



~ x2 suppression of balanced dijets in central events

2nd Lesson:

Parton energy loss is observed as a pronounced suppression of balance dijets in central PbPb

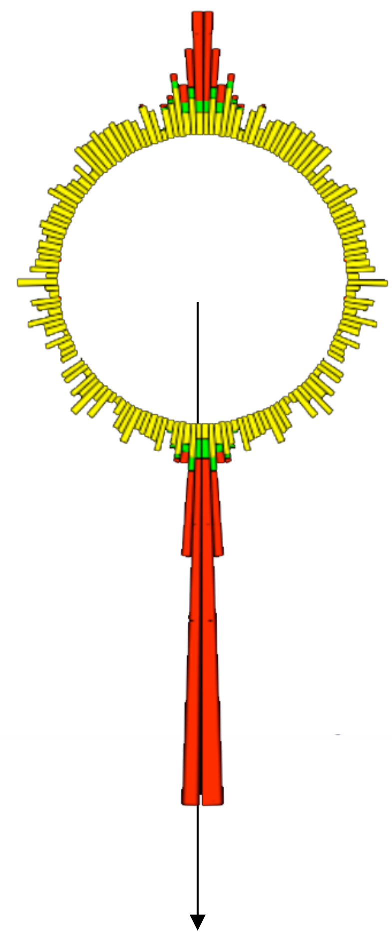
Missing-$p_T^{||}$

Missing $p_T^{||}$: $\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$

Calculate projection of p_T on leading jet axis and average over selected tracks with

$p_T > 0.5$ GeV/c and

$|\eta| < 2.4$

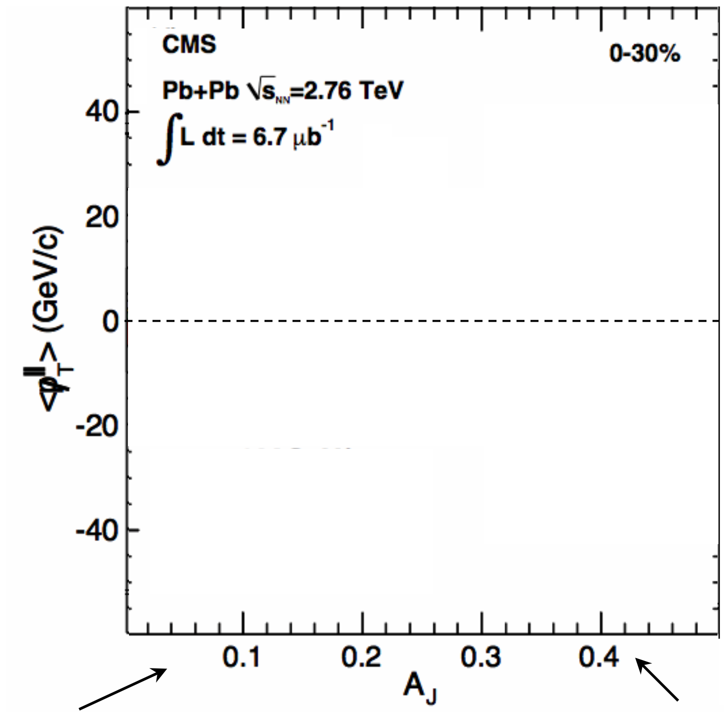


Vector sum of all track p_T in the event
Study projection to leading jet direction

Missing-$p_T^{\parallel}$

Missing $p_T^{\parallel}$: $\not{p}_{T}^{\parallel} = \sum_{\mathrm{Tracks}} -p_{T}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$

0-30% Central PbPb

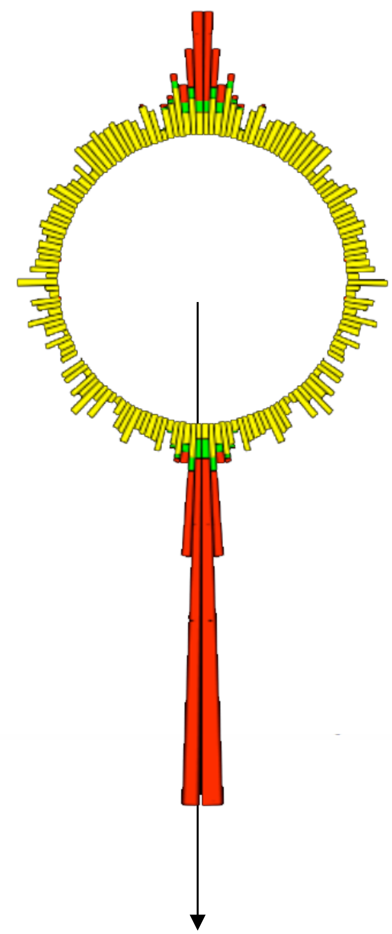


balanced jets

unbalanced jets

excess away from leading jet

excess towards leading jet

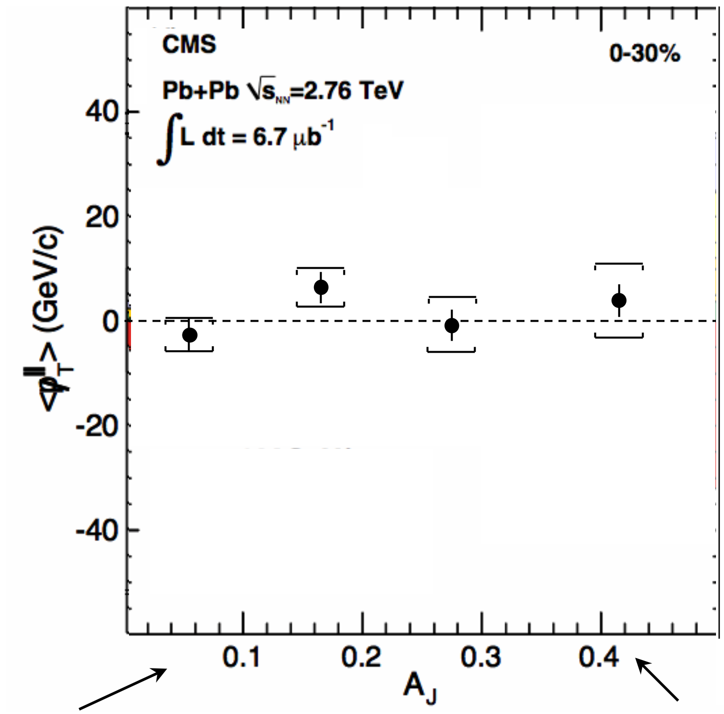


Missing-$p_T^{||}$

arXiv:1102.1957 (Accepted by PRC)

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

0-30% Central PbPb

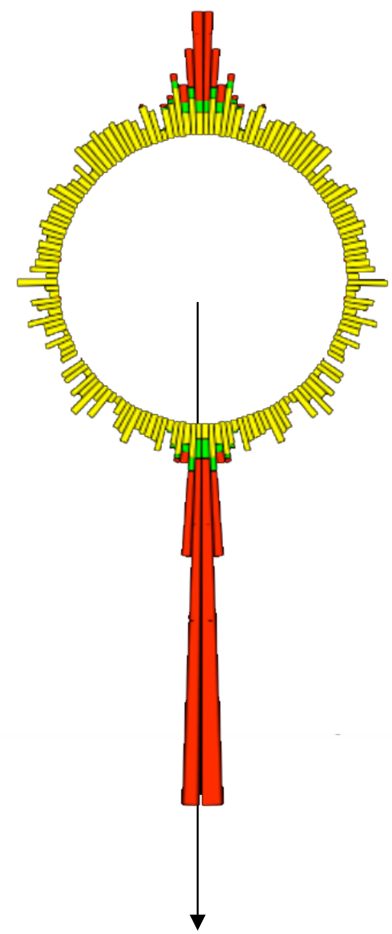


balanced jets

unbalanced jets

excess away from leading jet

excess towards leading jet



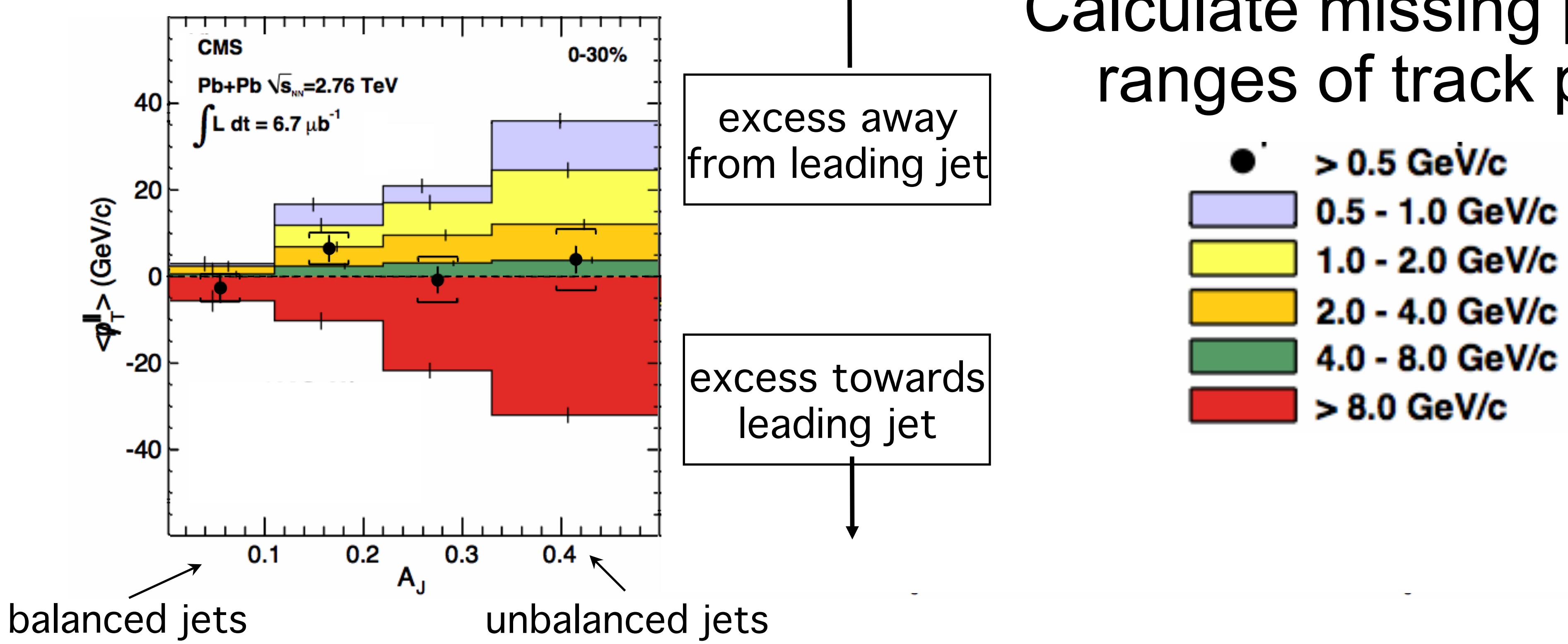
Intergrating over all tracks in the event, the momentum balance is found.

Missing-$p_T^{||}$

arXiv:1102.1957 (Accepted by PRC)

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

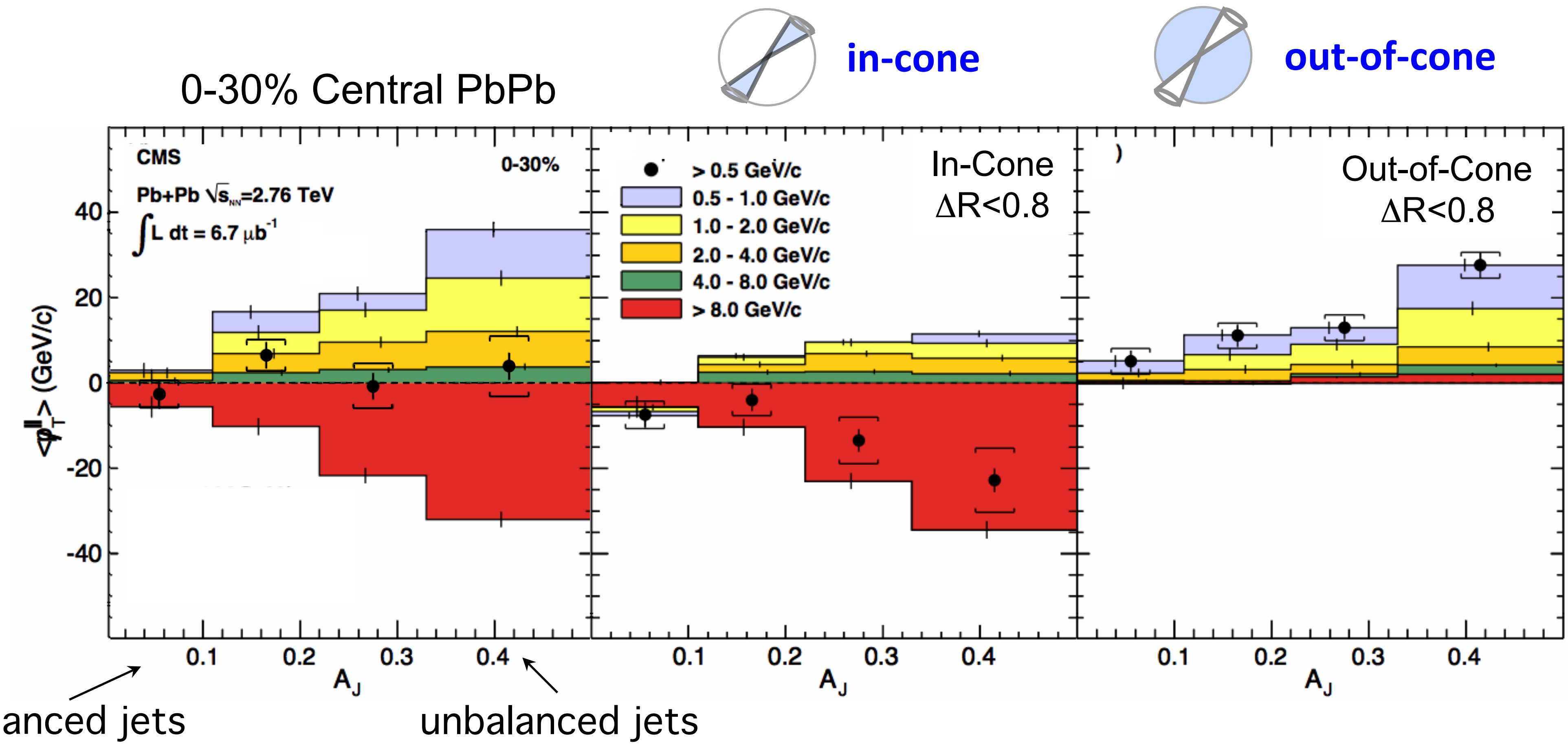
0-30% Central PbPb



Calculate missing p_T in ranges of track p_T:

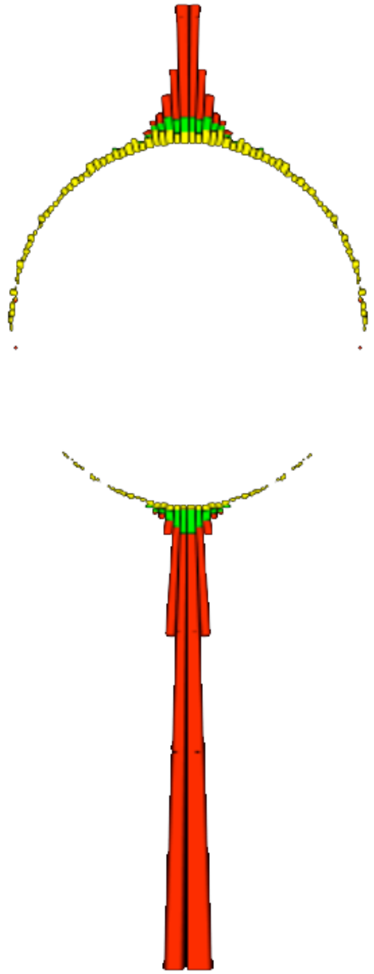
The momentum difference in the dijet is balanced by low p_T particles arXiv:1102.1957 (Accepted by PRC)

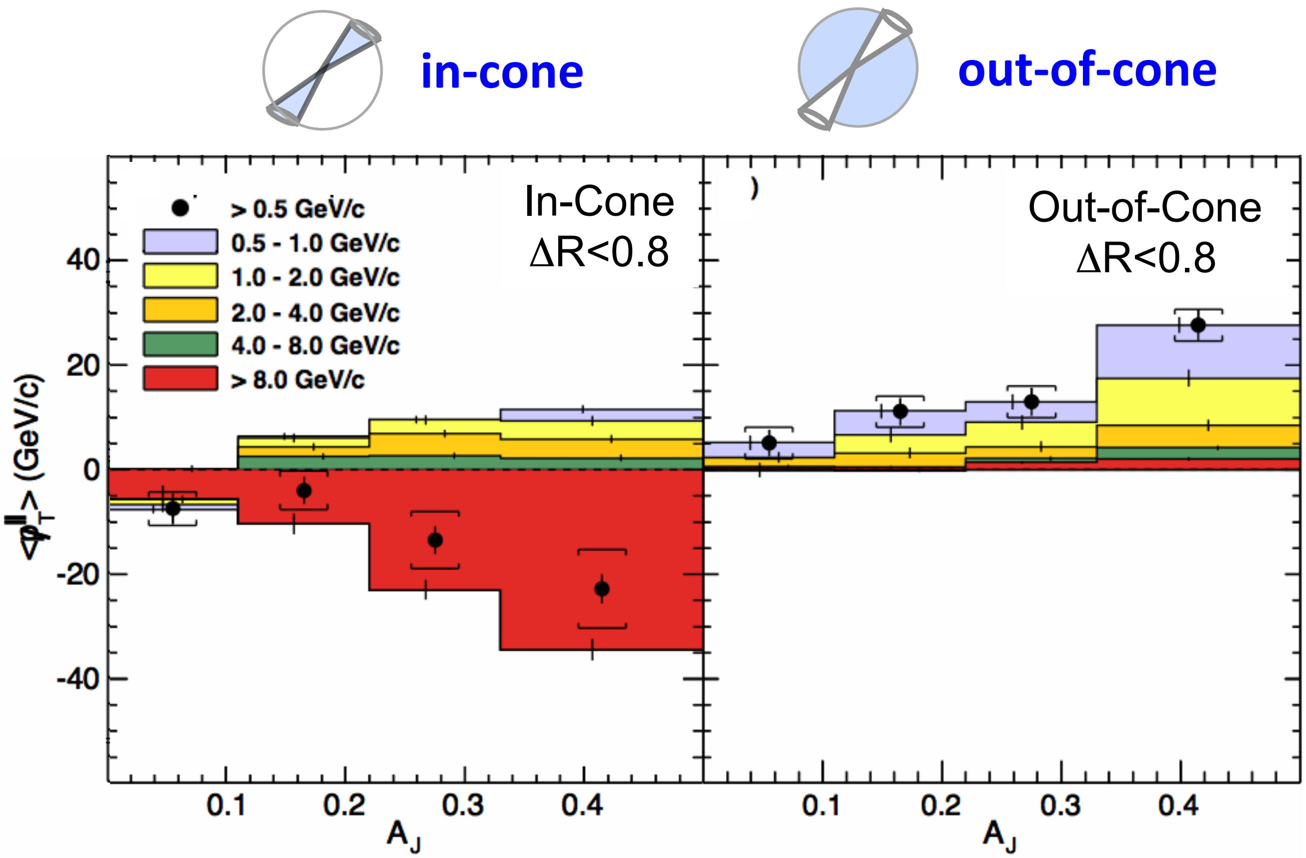
0-30% Central PbPb



Missing-$p_T^{||}$

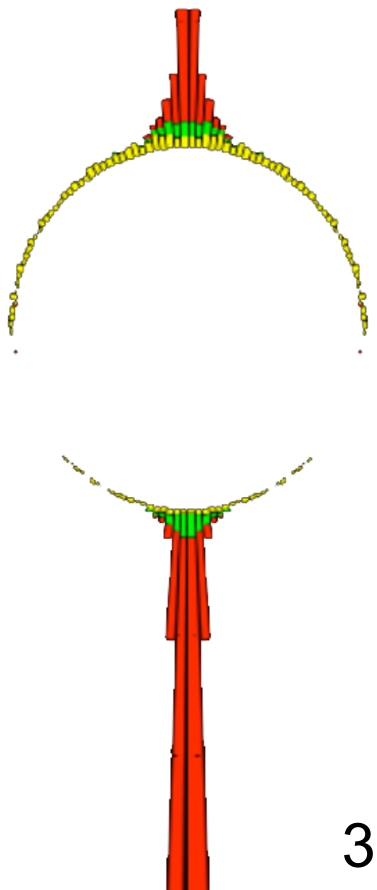
arXiv:1102.1957 (Accepted by PRC)

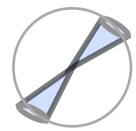




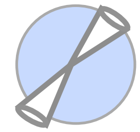
Missing-$p_T^{||}$

arXiv:1102.1957 (Accepted by PRC)

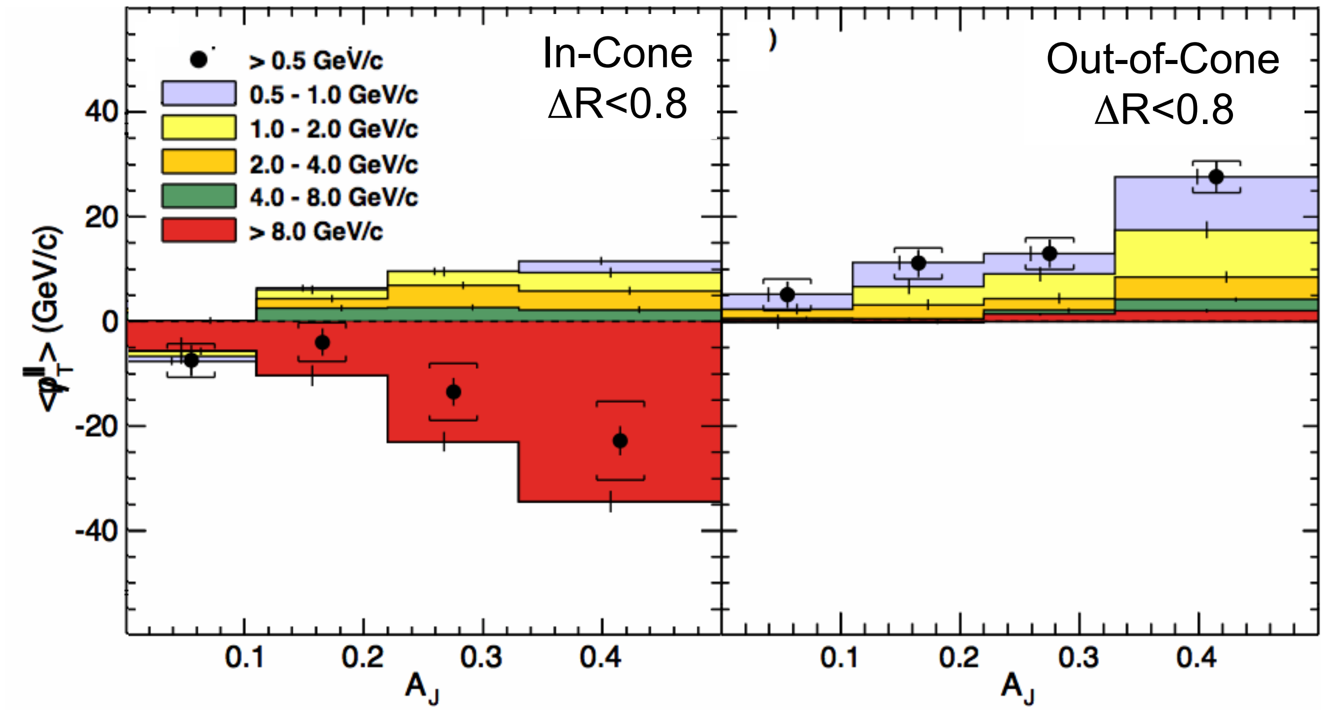




in-cone



out-of-cone

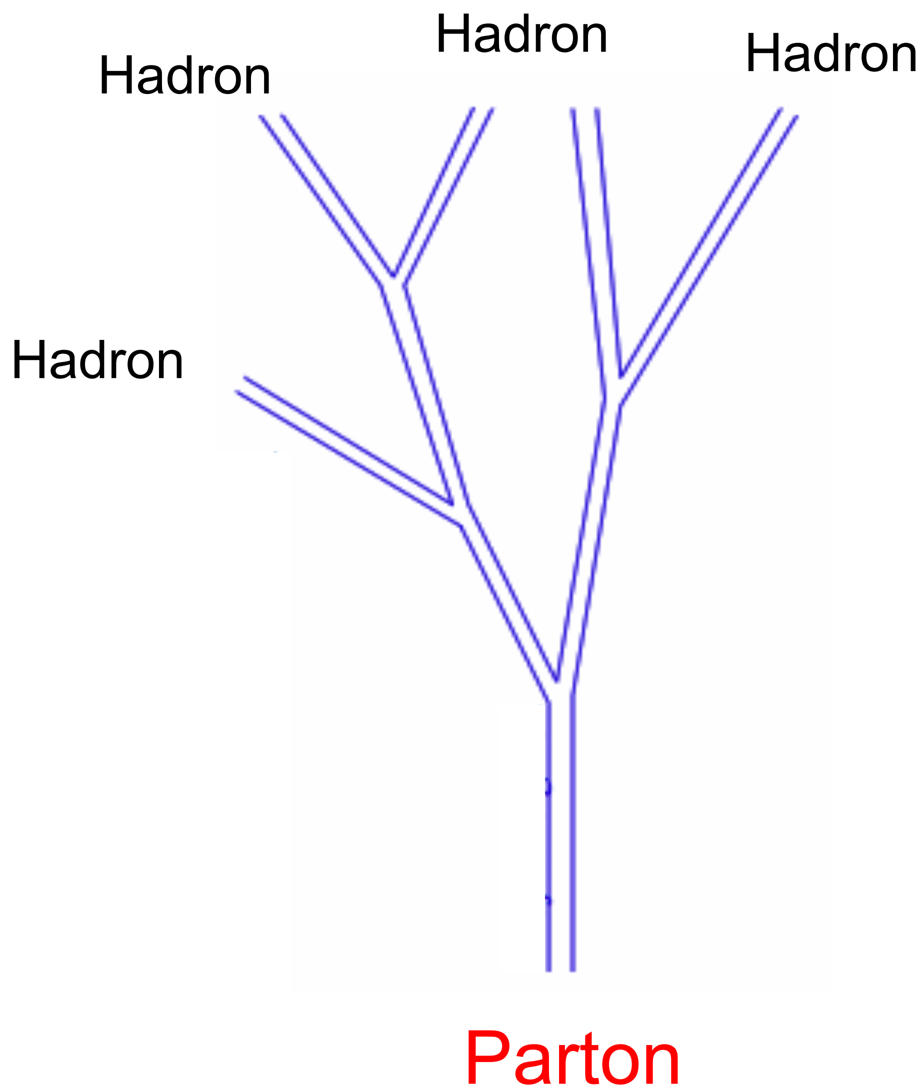


3rd Lesson:

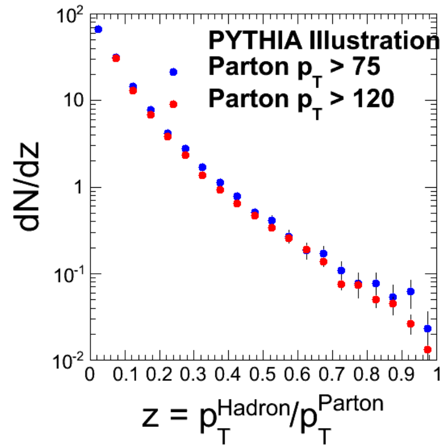
The momentum difference in the dijet is balanced by low p_T particles at large angles relative to the away side jet axis

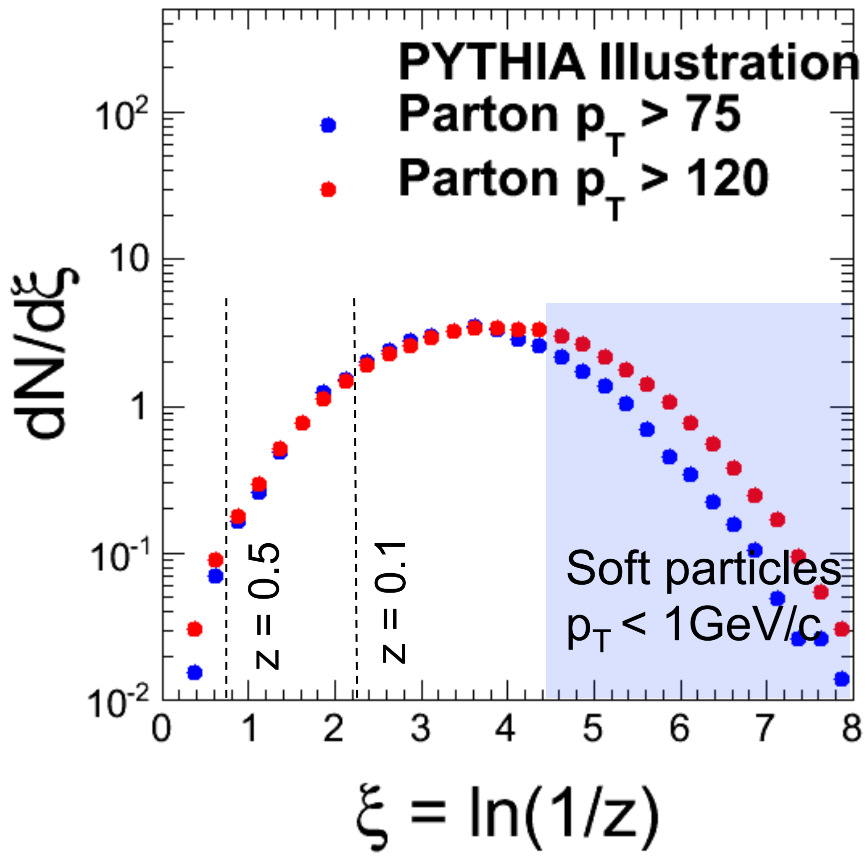
Jet Fragmentation

Partons fragment into hadrons



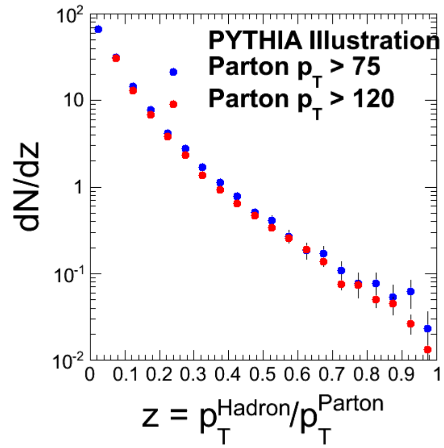
Jet Fragmentation Observable

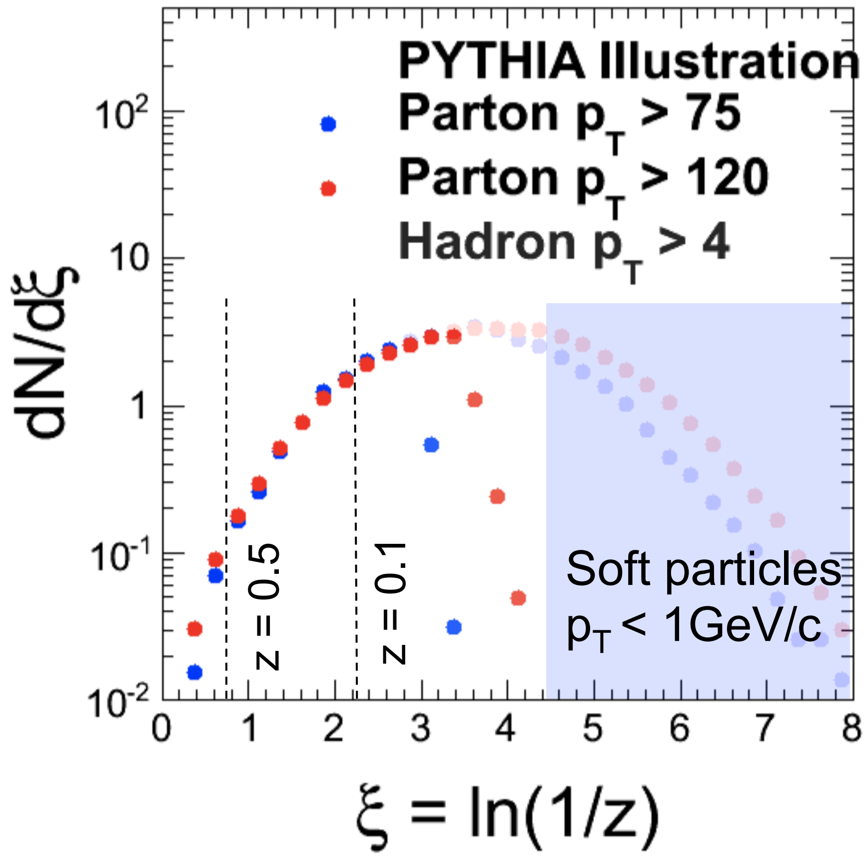


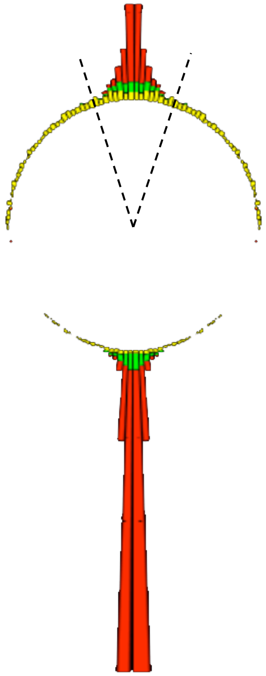


$z = p_T^{Hadron}/p_T^{Parton}$: fraction of jet energy a fragment hadron carries.

Jet Fragmentation Observable



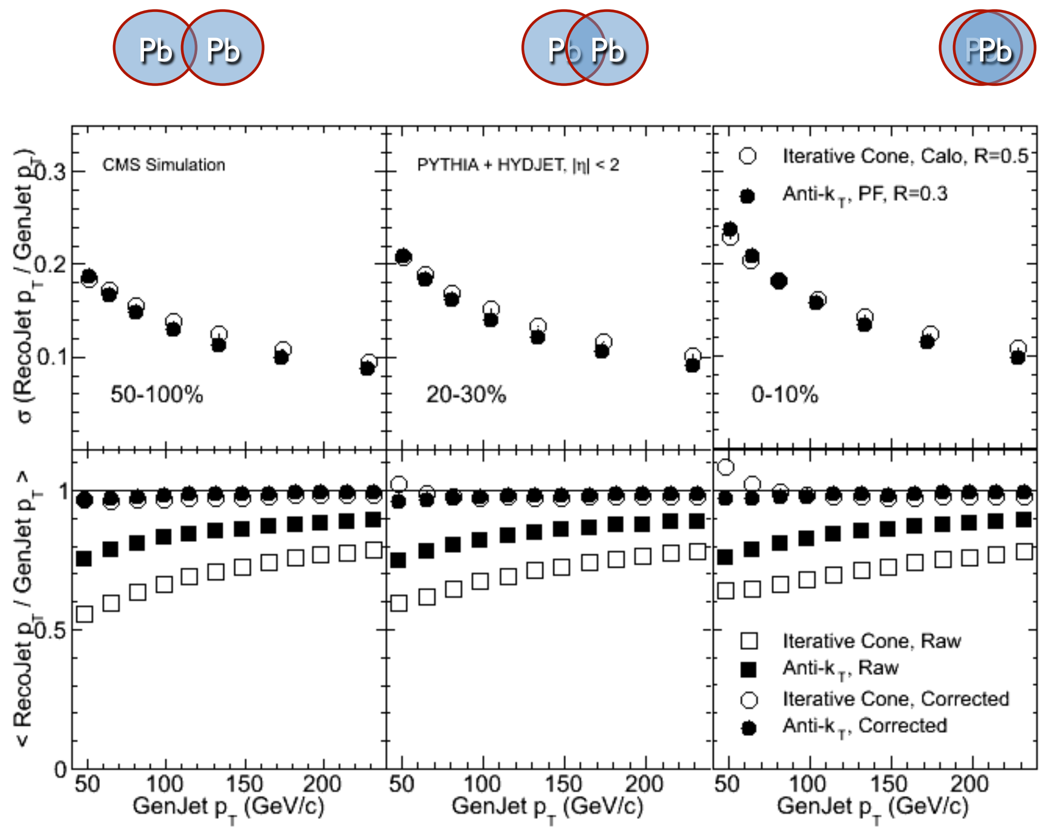




- Eliminate the underlying event contribution, $p_T > 4$ GeV/c
- Select particles in a ΔR=0.3 cone

Fragmentation Function in Data

- Particle Flow Jet Reconstruction
  - Anti k_T, R=0.3
  - Same background subtraction as calorimeter based jets
  - Fully efficient for p_T > 40GeV/c
  - Applied in pp and PbPb

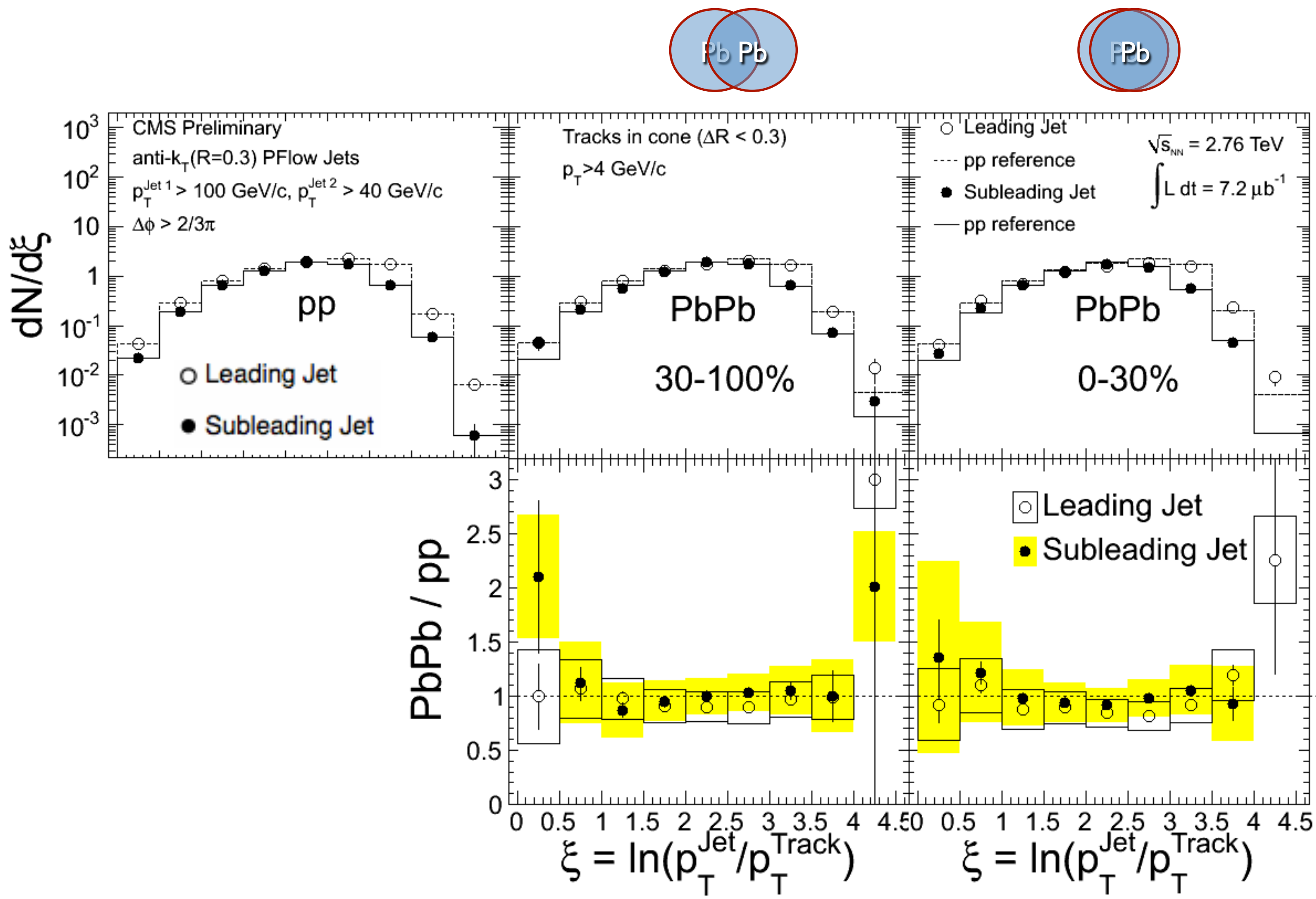


- Dijet selection
  - p_T^{Jet1} > 100 GeV/c
  - p_T^{Jet2} > 40 GeV/c
  - $\Delta\phi_{12} > 2\pi/3$

- Compare Leading and Subleading Jet
  - Select Tracks in ΔR=0.3 cone
  - p_T > 4 GeV/c

CMS PAS HIN-11-004

Jet Fragmentations: pp vs PbPb

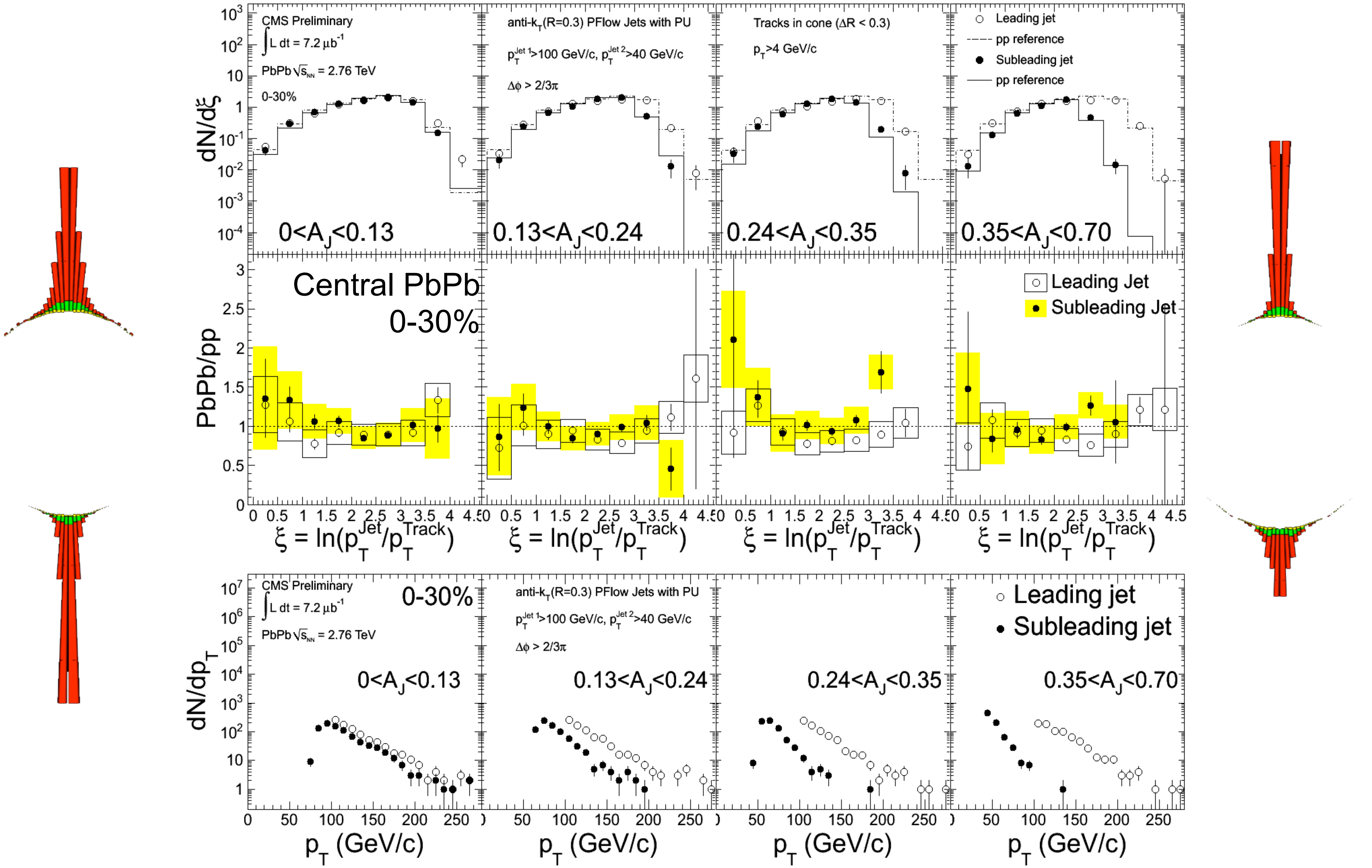


Leading and subleading jet in PbPb fragment like jets of corresponding energy in pp collisions

CMS PAS HIN-11-004

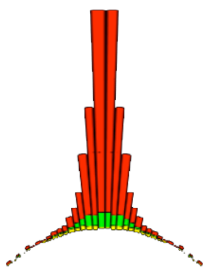
(reference ξ: Smear pp to PbPb jet p_T resolution, reweight jet p_T spectrum to match PbPb)

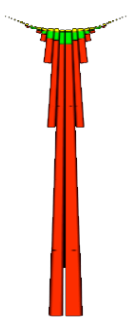
PbPb/pp vs Dijet imbalance

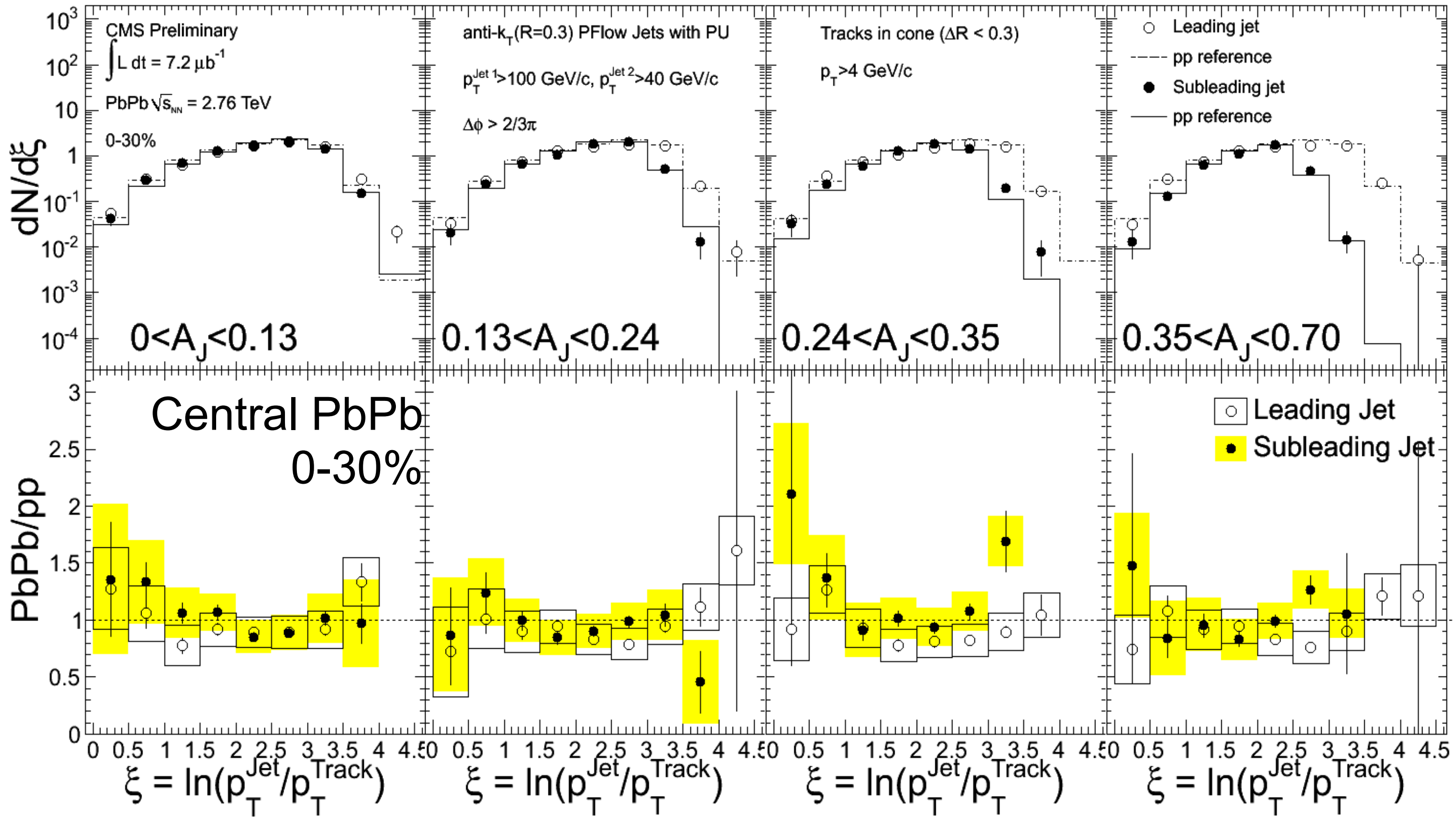


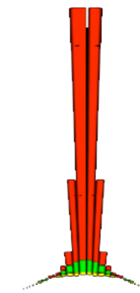
CMS PAS HIN-11-004

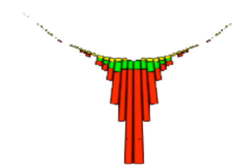
PbPb/pp vs Dijet imbalance











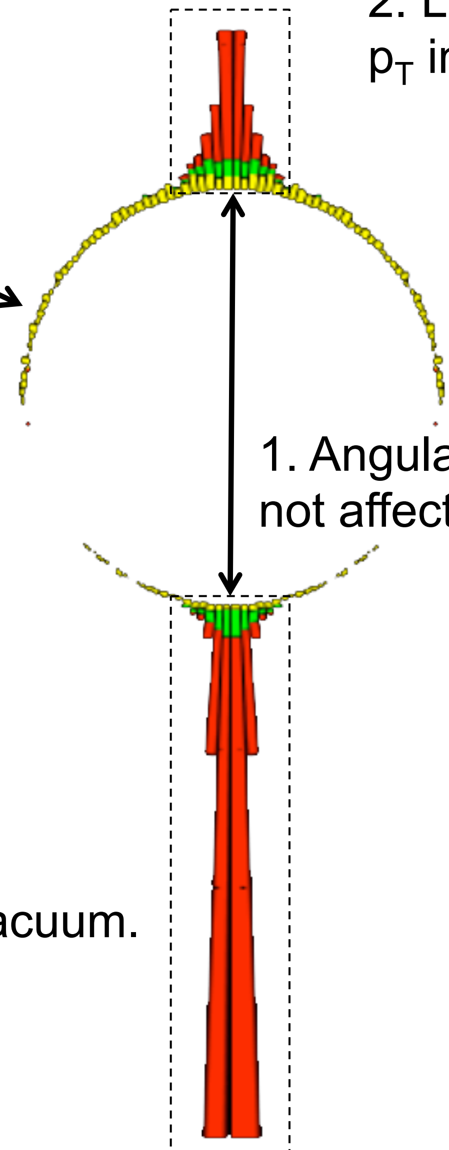
4th Lesson:

Fragmentation pattern independent of energy lost in medium
Consistent with partons fragmenting in vacuum

Summary of Jet Quenching at LHC

2. Large average dijet p_T imbalance

3. p_T difference found at low p_T far away from jet

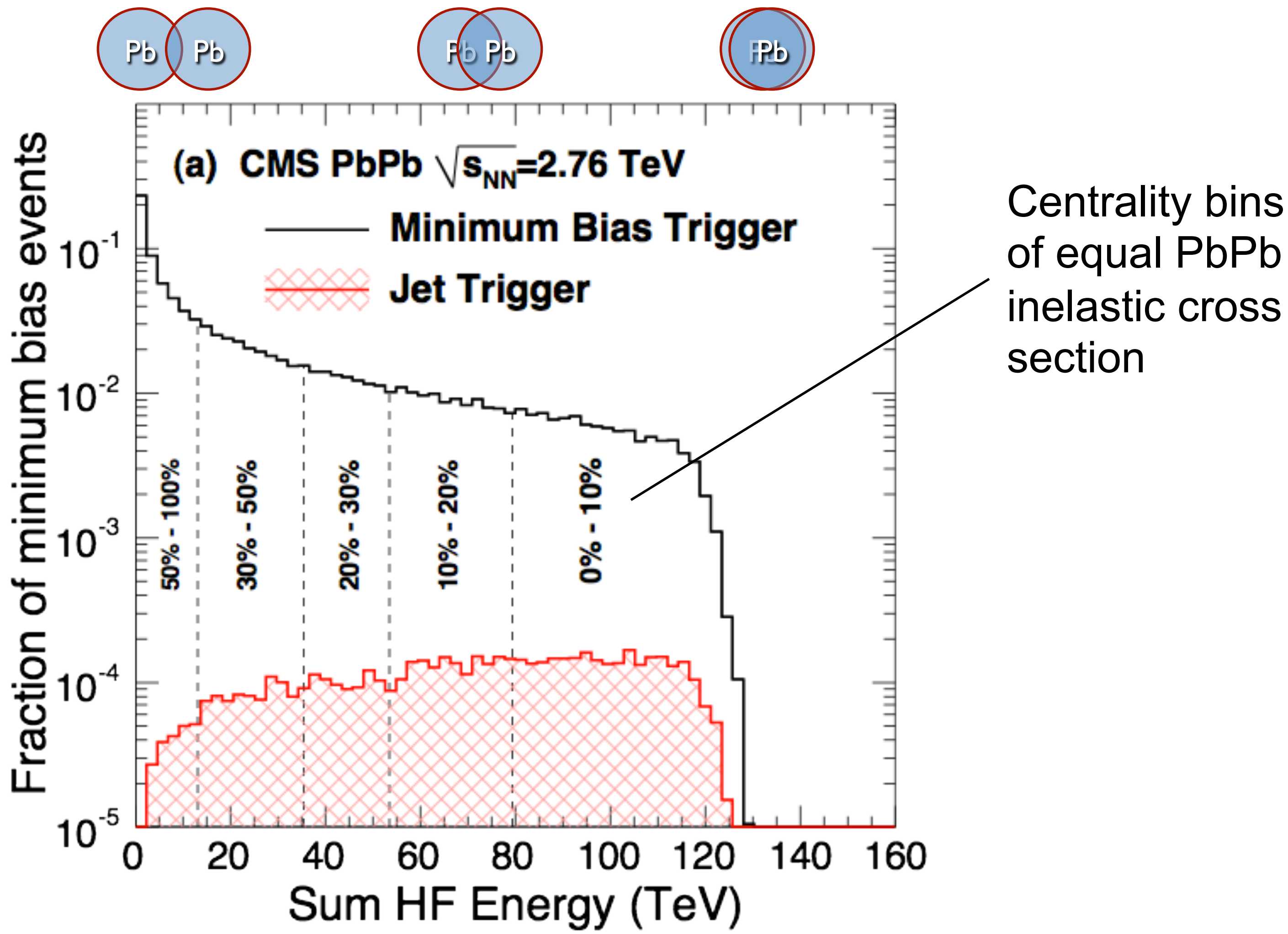


1. Angular correlation of partons not affected by the medium

4. Partons fragment as in vacuum.

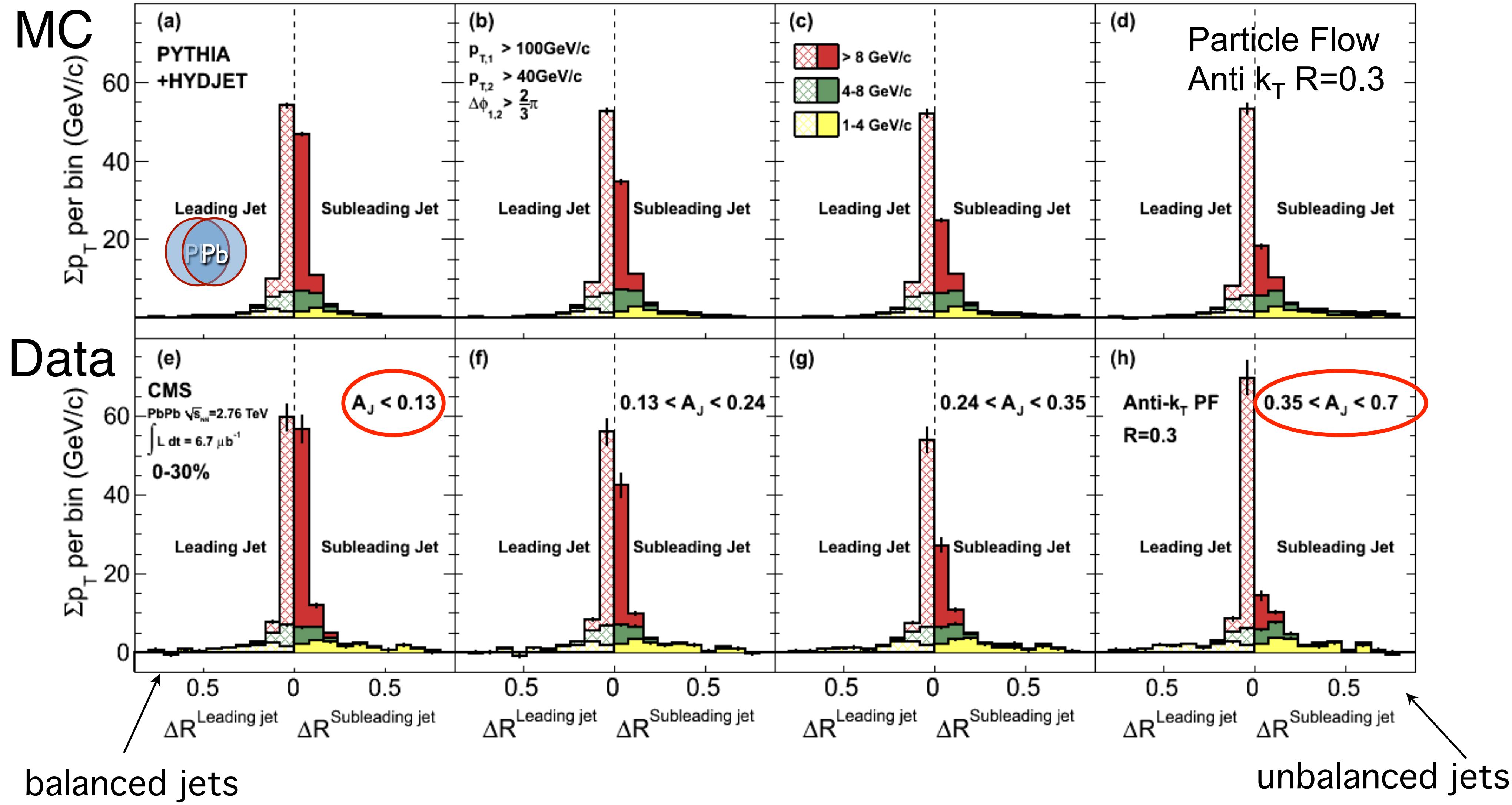
Backups

Heavy ion Trivia: Centrality



Total HF energy used to determine PbPb impact parameter.

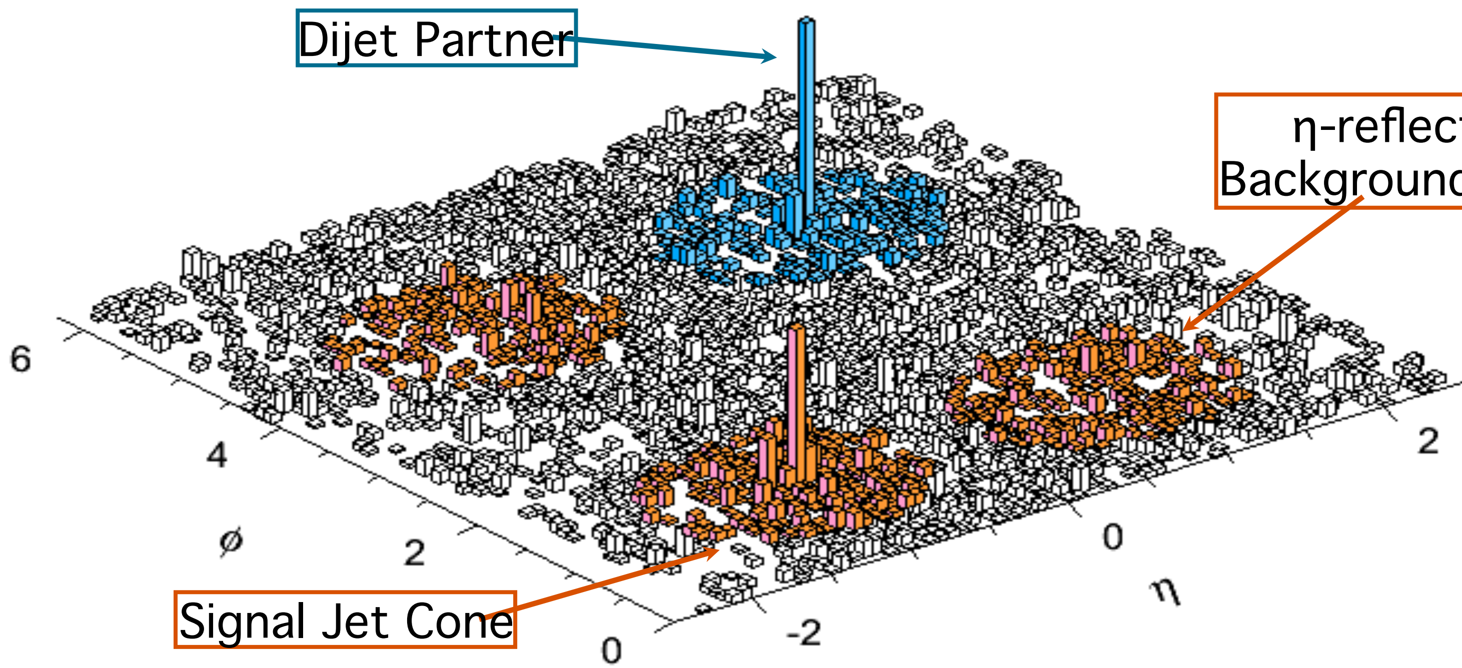
Track-Jet Correlations



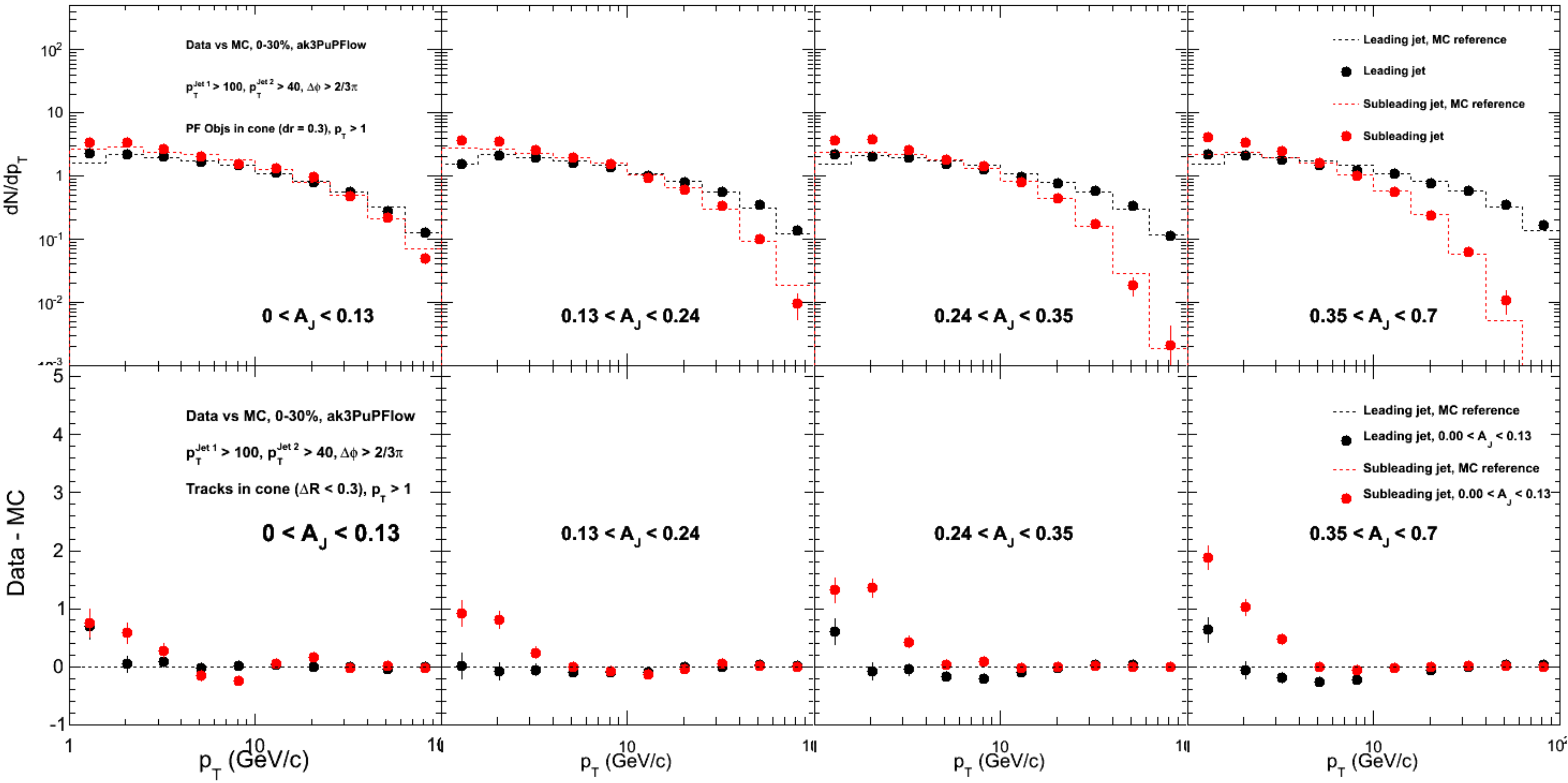
Underlying event contribution subtracted

Track-Jet Correlations

- Study charged particle distributions within jet cones
  - Use η reflected (η -> -η) reference cones for jet-by-jet subtraction of Pb+Pb underlying event
    - This avoids ϕ dependent variations due to elliptic flow
    - Exclude $|\eta_{Jet}| < 0.8$ and $|\eta_{Jet}| > 1.6$
  - Study associated track distributions versus p_T and ΔR
  - Uncertainties in background subtraction limit this method to $p_T > 1$ GeV/c and $\Delta R < 0.8$

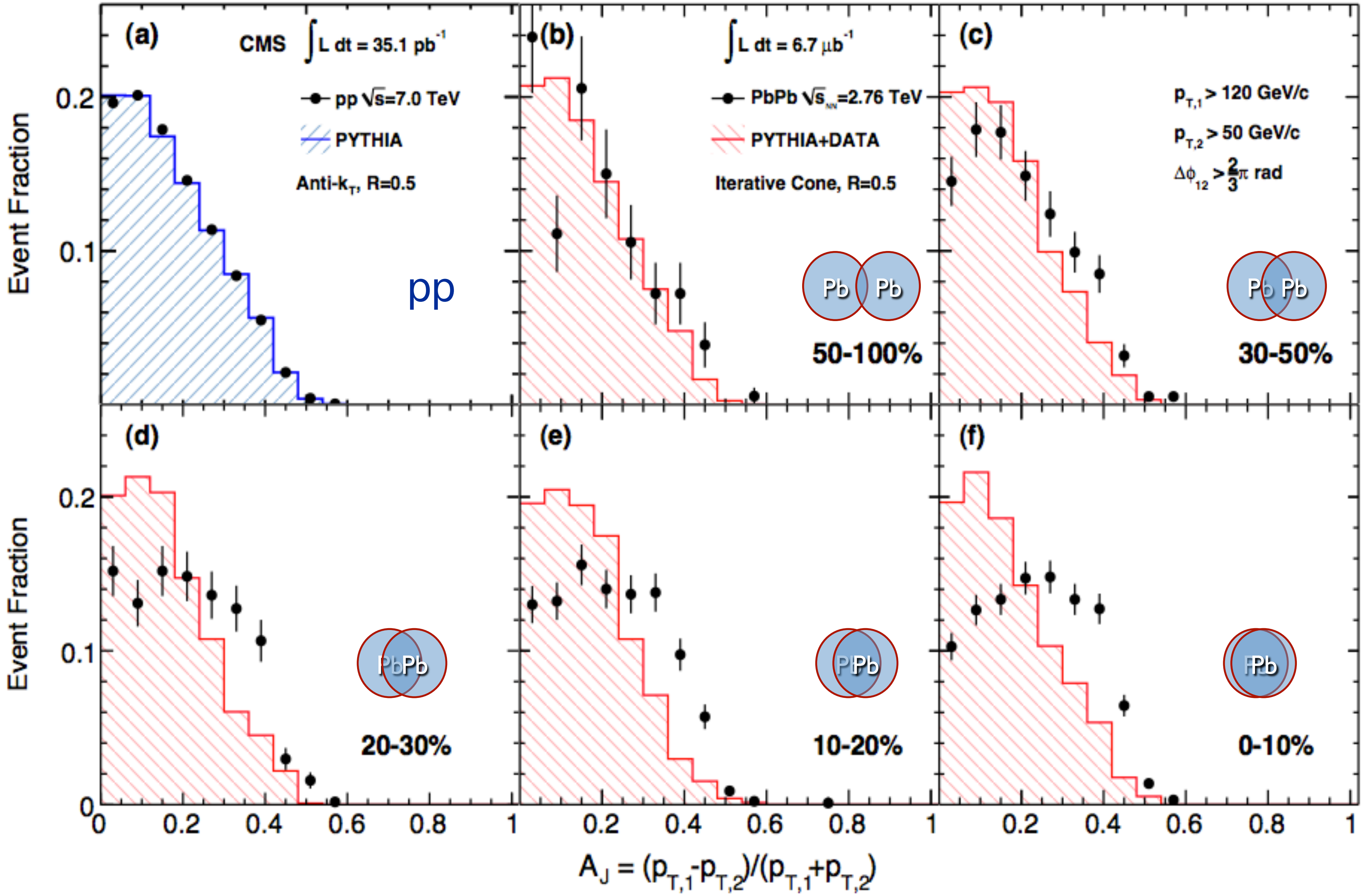


Residual quenched energy in jets

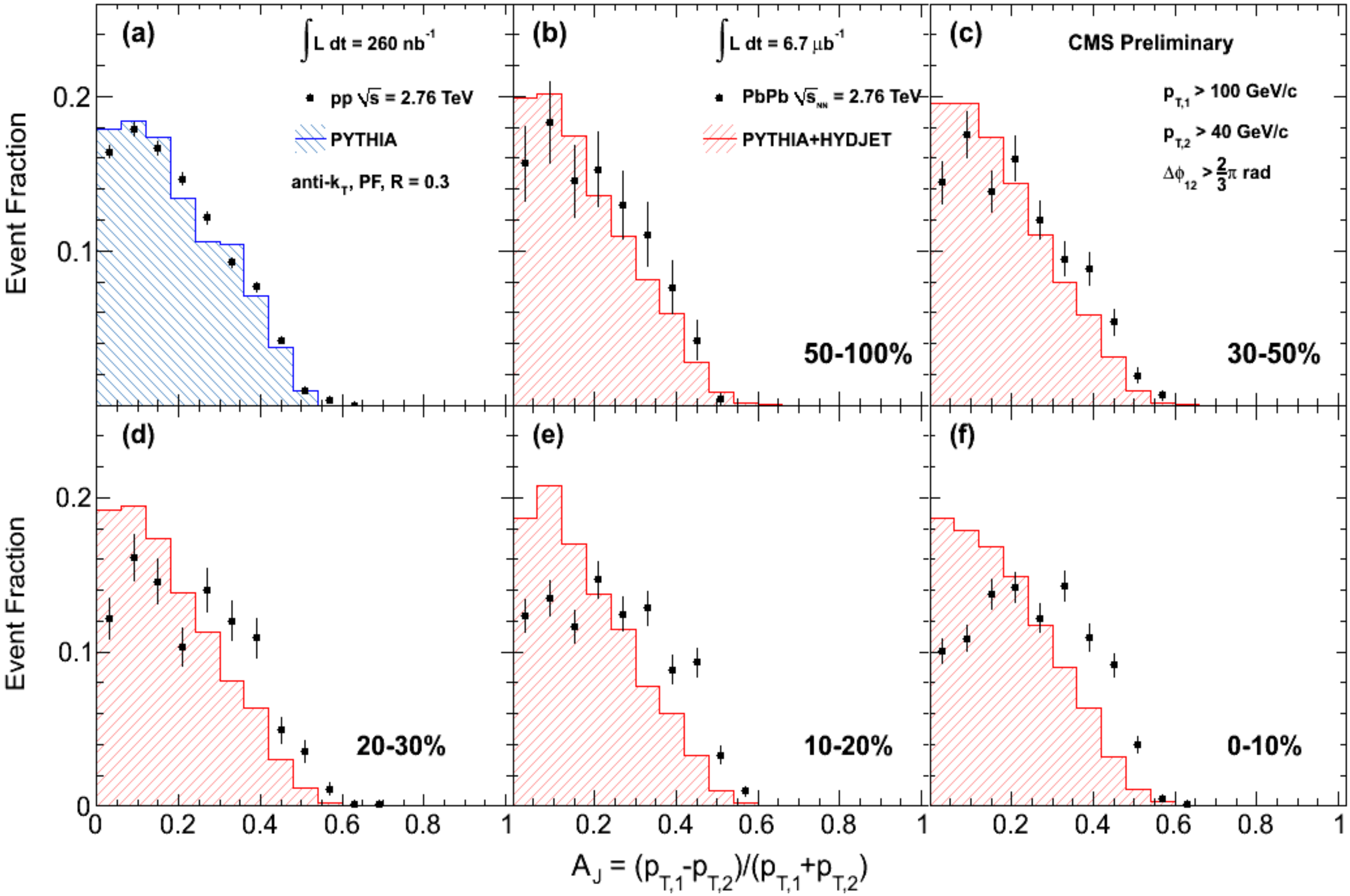


Residual quenched energy in a R = 0.3 cone

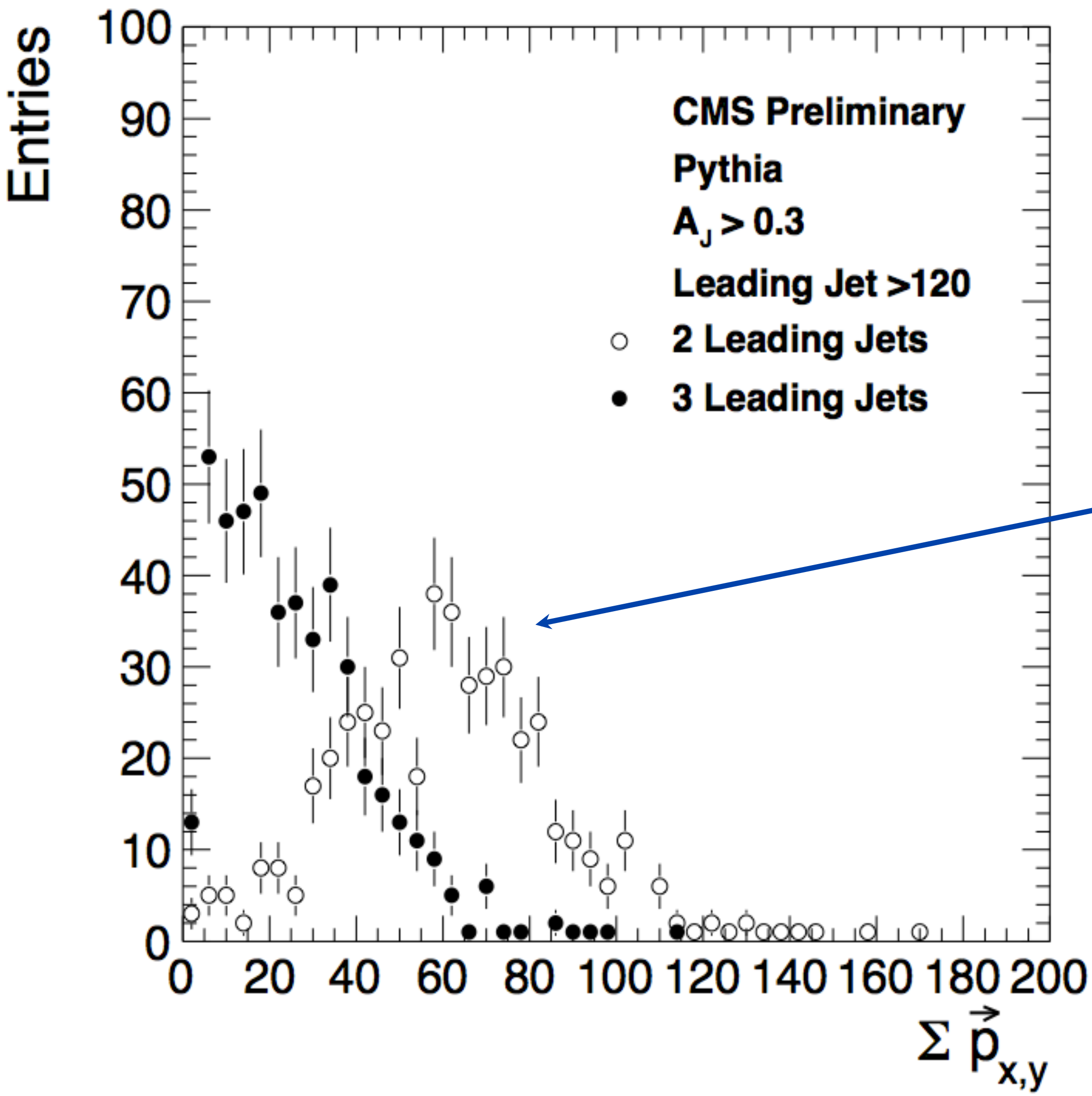
Dijet Energy Imbalance R=0.5

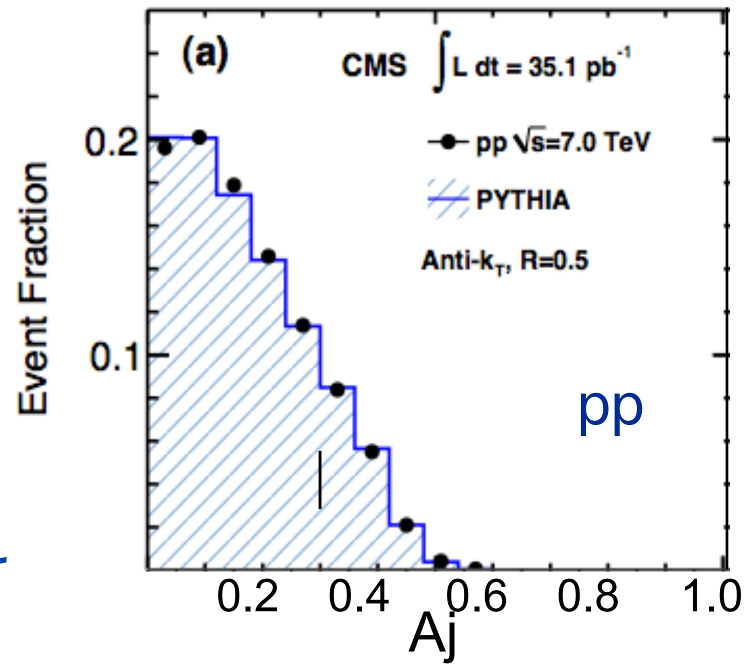


Dijet Imbalance A_J R=0.3



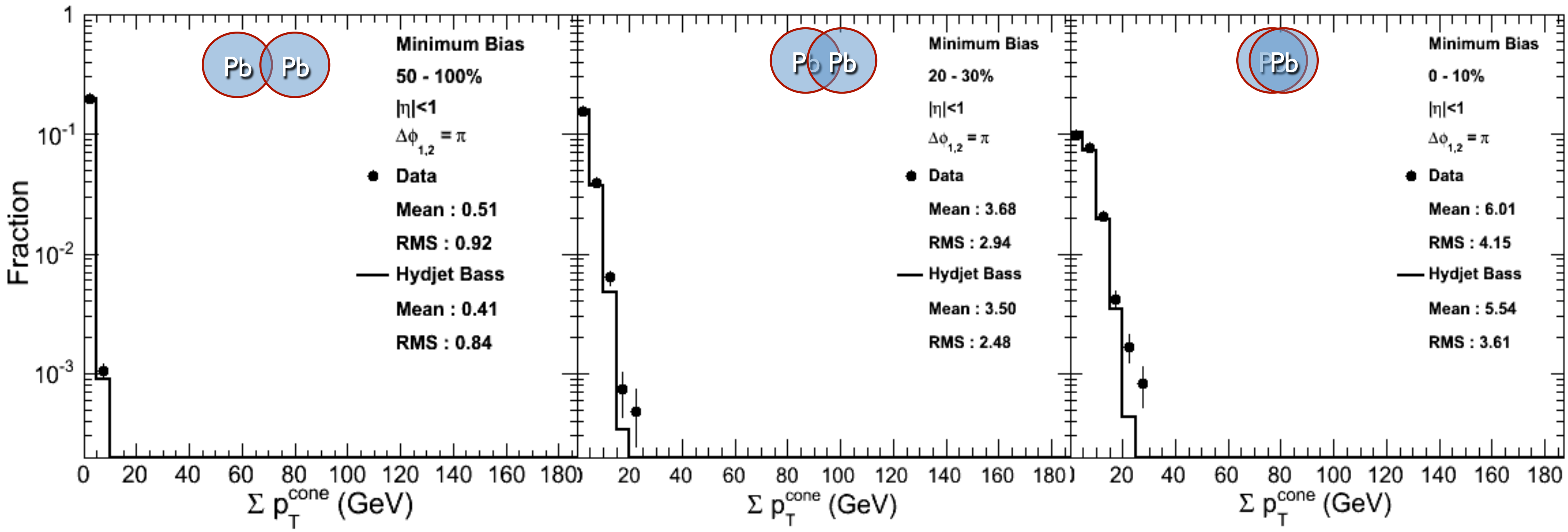
PYTHIA Momentum Balance



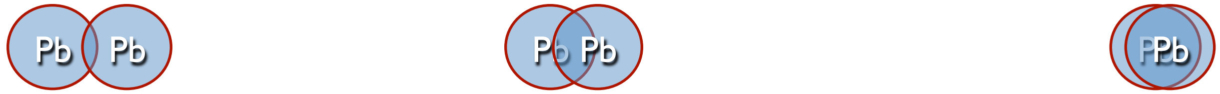


For unbalanced PYTHIA dijets (A_j > 0.3, 10% of the total), a 3rd jet provides most of momentum balance

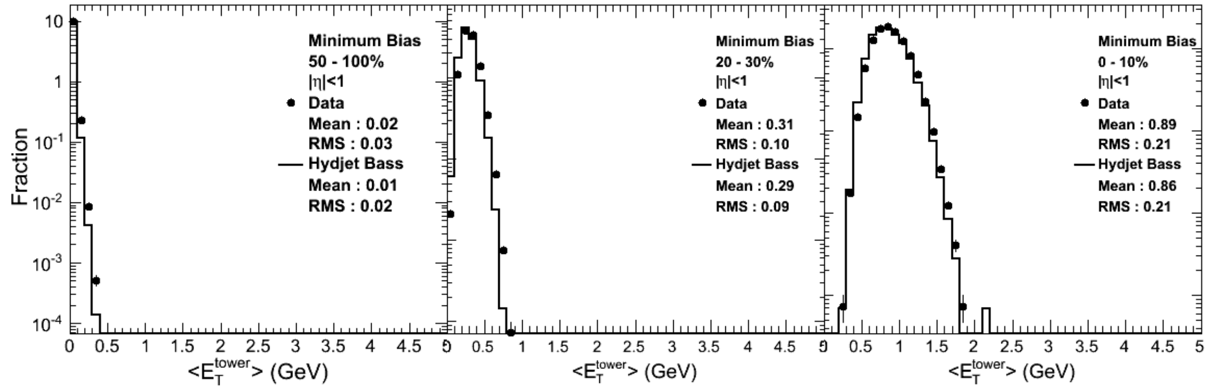
Random Cone Background



Pileup subtraction per tower

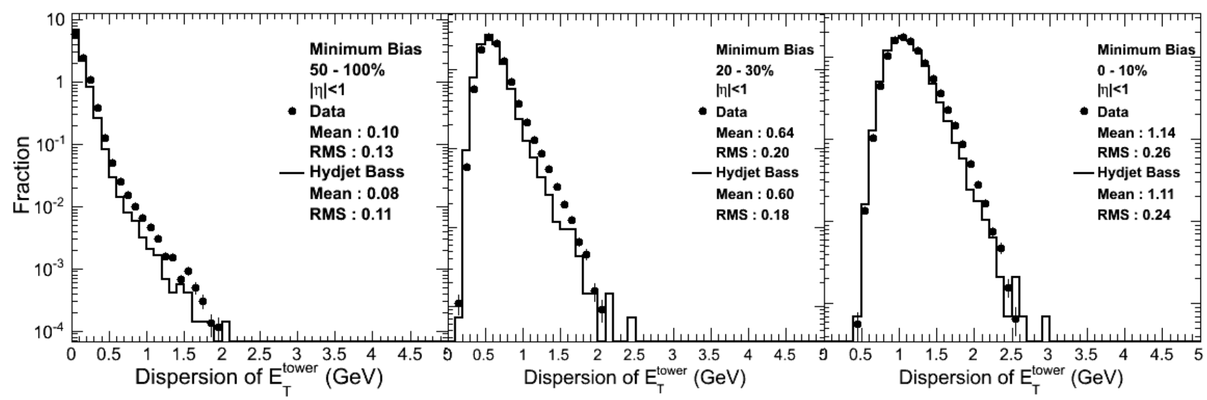


Mean:



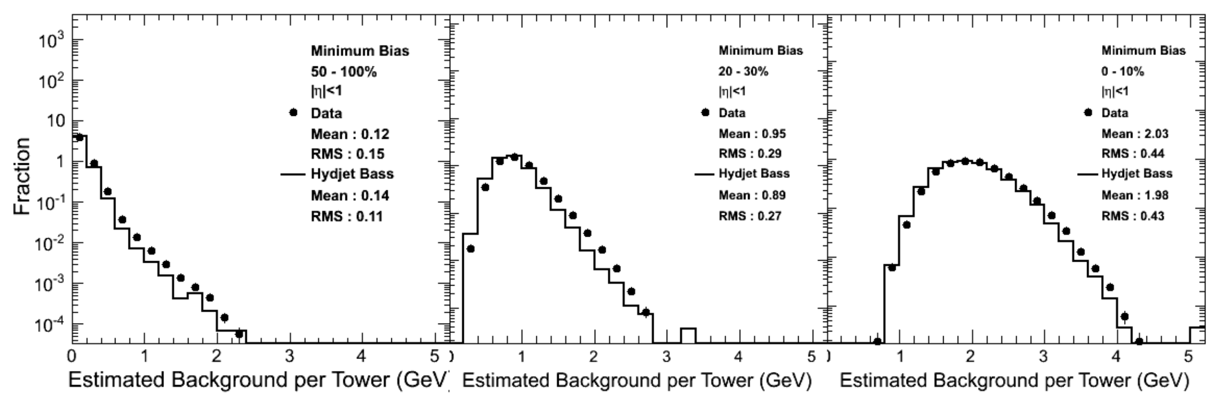
PAS

Dispersion:



PAS

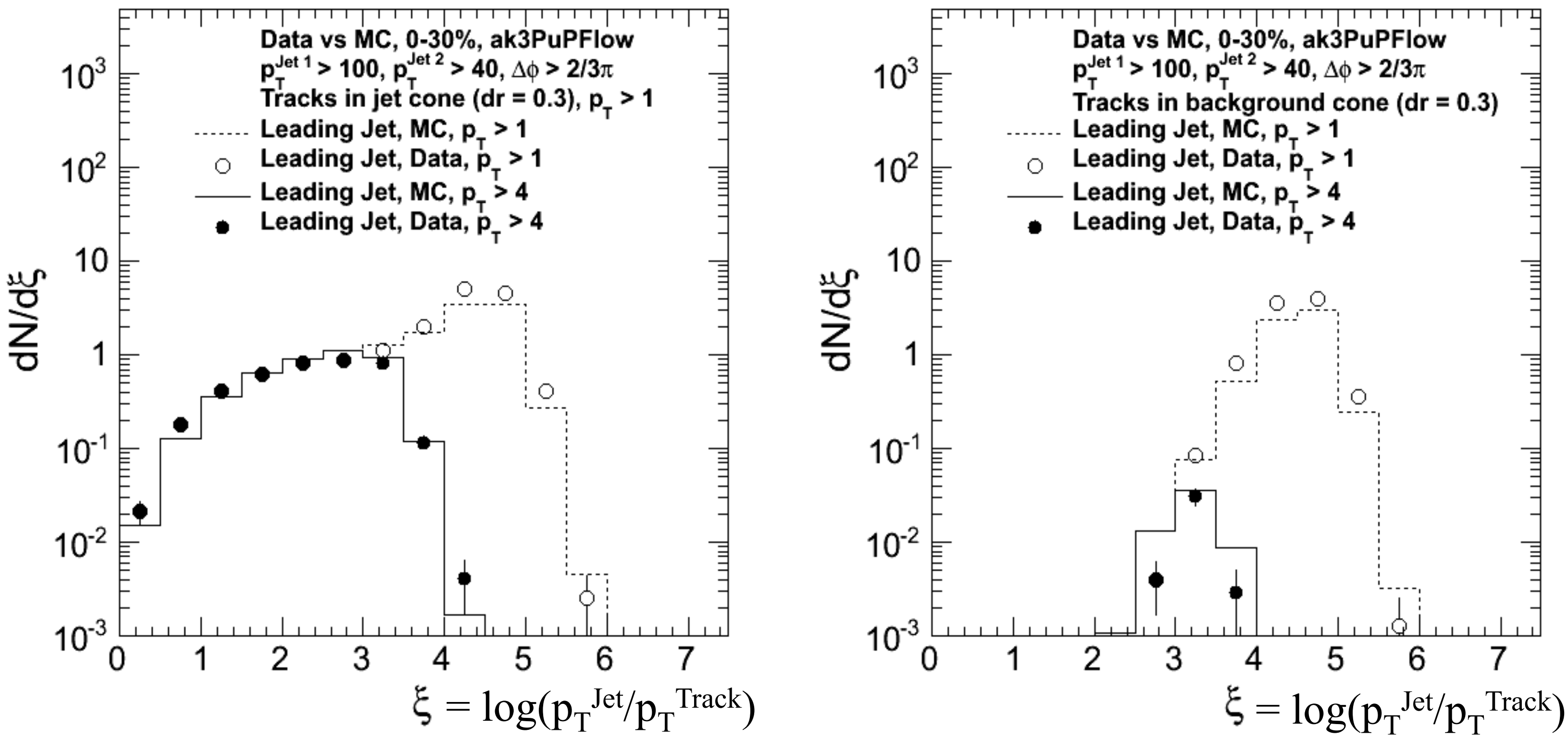
Subtracted Energy:



PAS

Fragmentation Functions

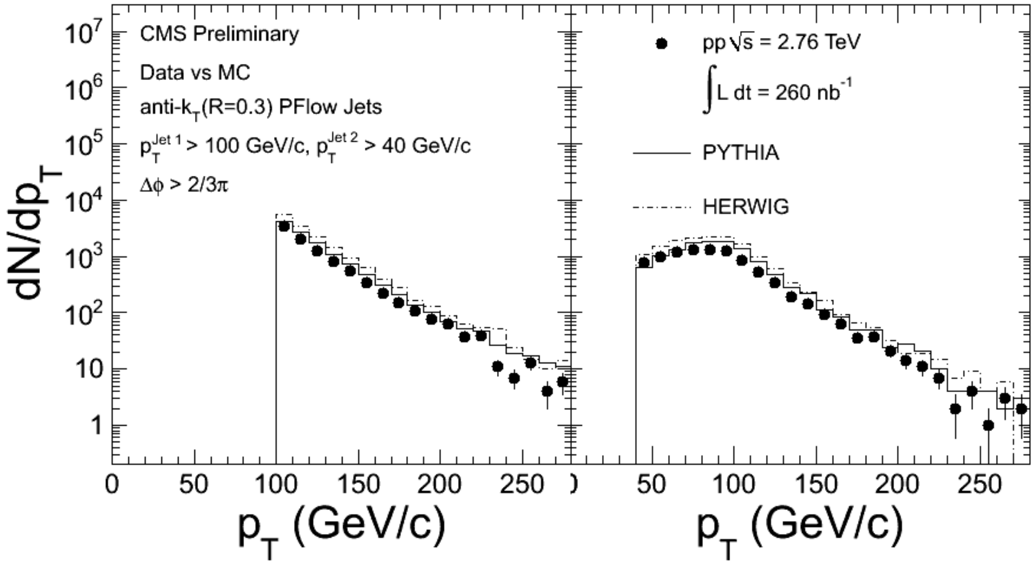
Central Events



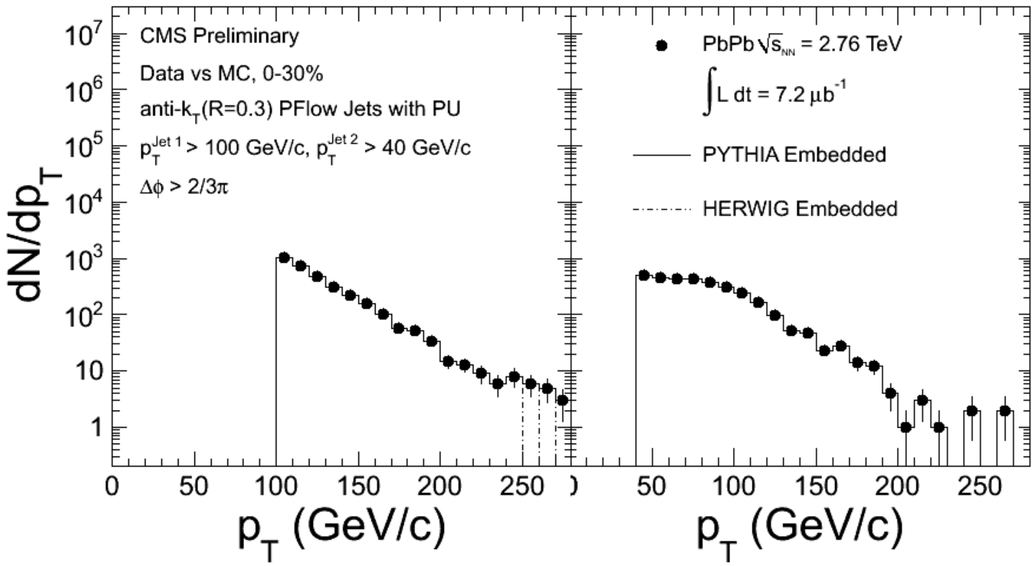
- Fragmentation Functions are reconstructed by correlating the tracks in a R=0.3 cone around the jet axis with the corresponding jets
  - p_T>4GeV cut applied to the tracks to eliminate the underlying event contribution

Jet p_T reweighting

pp, MC:

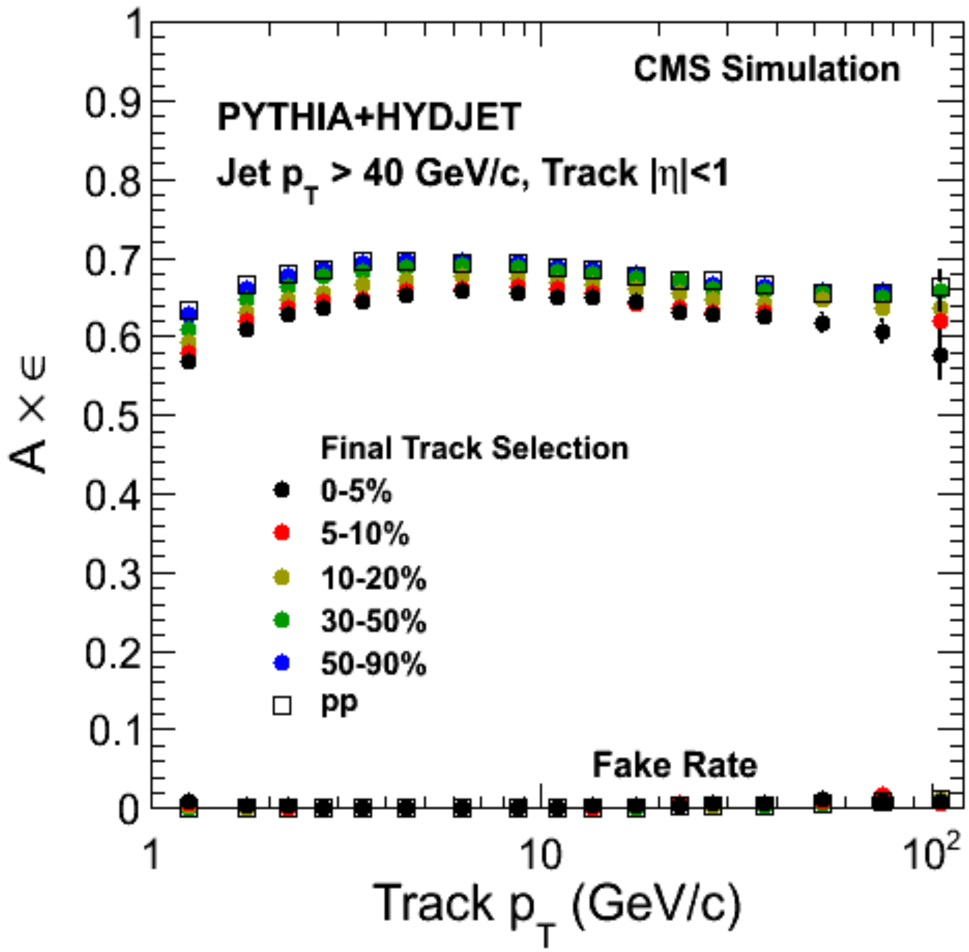


PbPb, embedded MC:

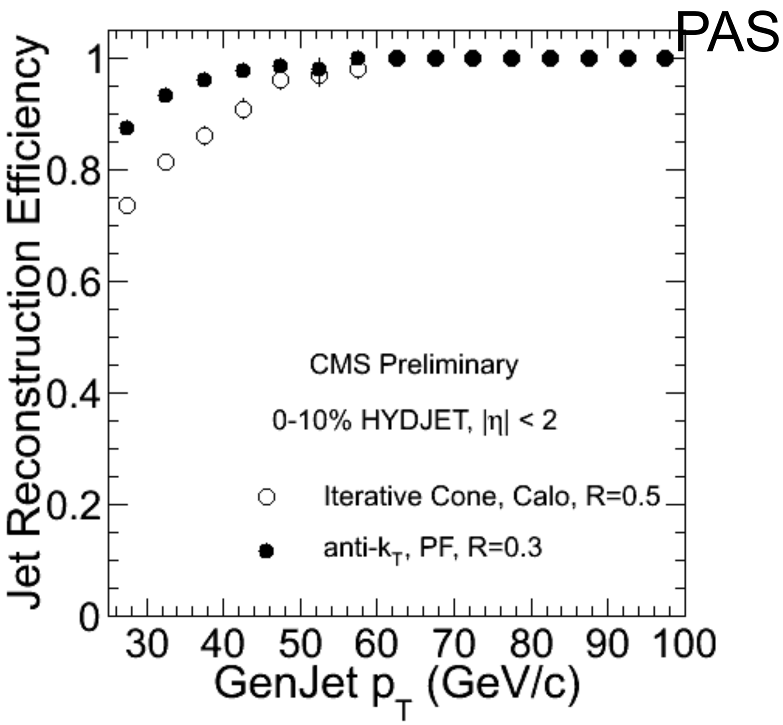


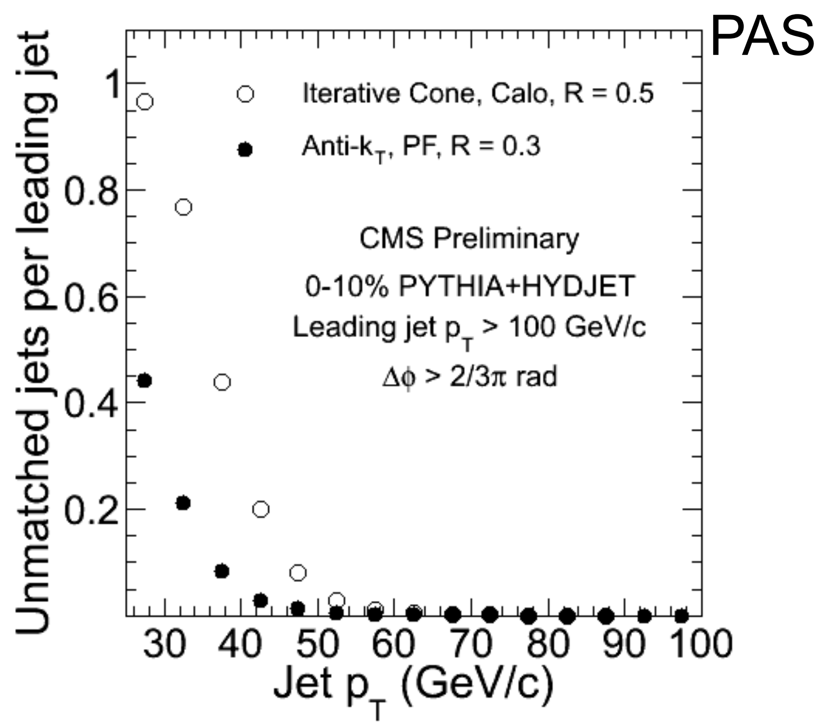
- PbPb data show different jet p_T spectra compared to MC
- To compare the fragmentation functions the jet p_T distributions in embedded MC are reweighted to match the PbPb reconstructed spectrum

Heavy Ion Track Reconstruction



Jet Reco. Performance

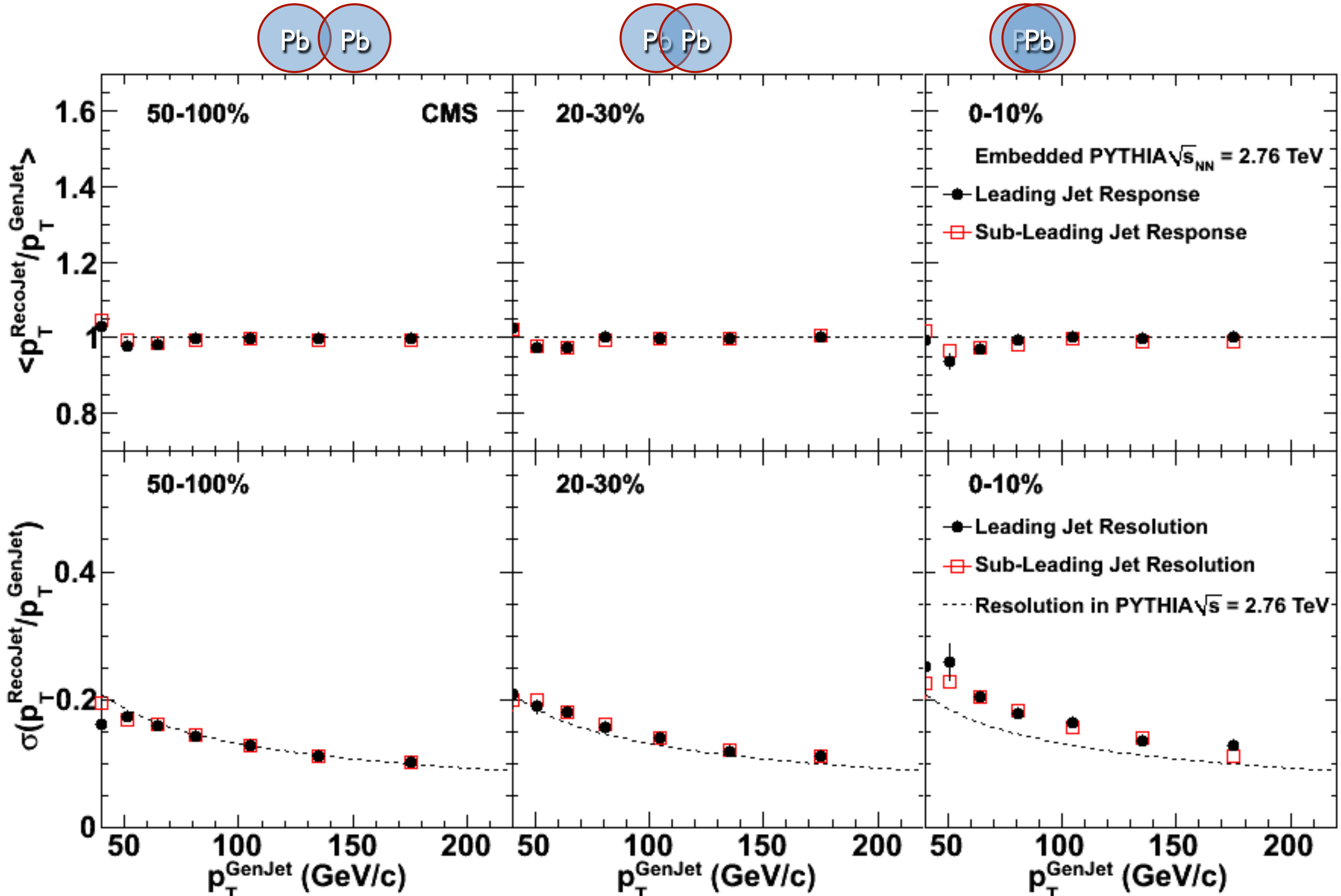




- Comparing Anti-k_T Particle Flow and Calorimeter based Iterative Cone type jet finder
  - Anti-k_T PF gives significantly higher efficiency for low jet p_T
    - Particle Flow Objects have a lower effective seed threshold
  - Small cone size is less prone to background fluctuations and shows lower fake jet rate at low p_T

Jet p_T resolution compared to pp

PAS



- Fluctuations in the underlying PbPb event deteriorate the jet p_T resolution with respect to pp

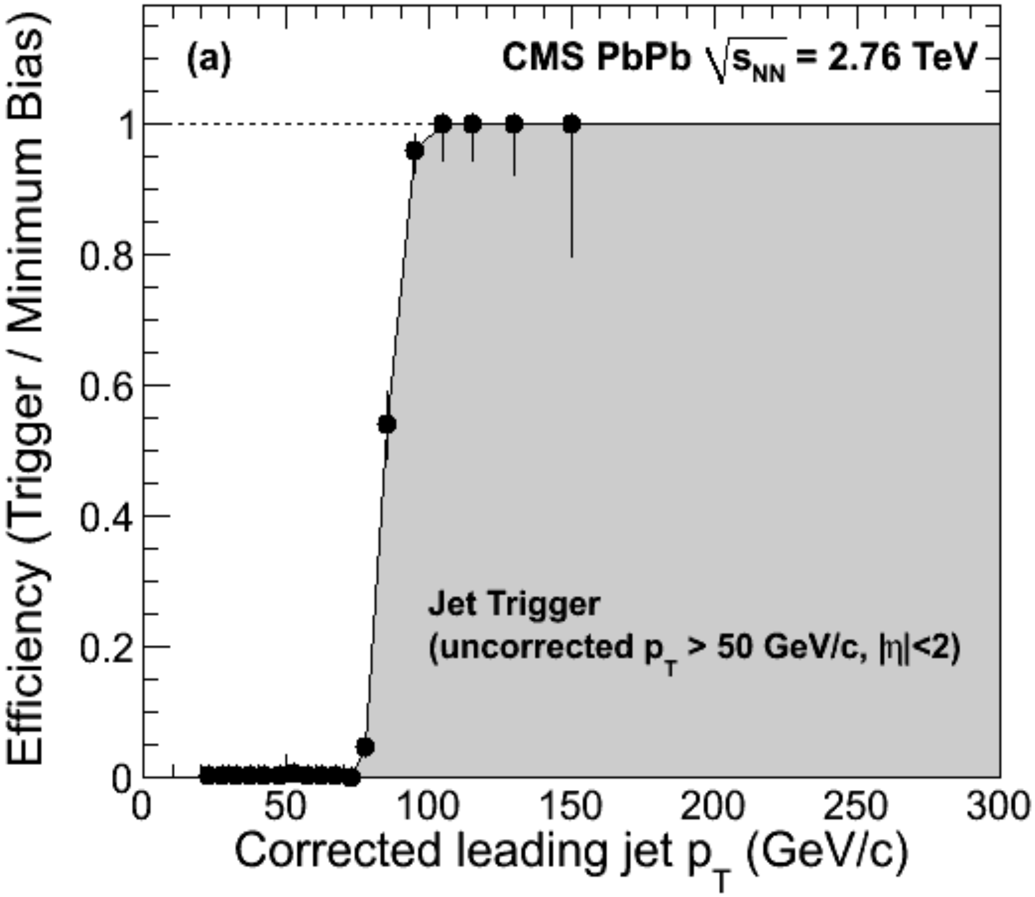
Trigger Selection

Minimum Bias Trigger

- HF or BSC firing in coincidence on both sides
- 97+/-3% efficient

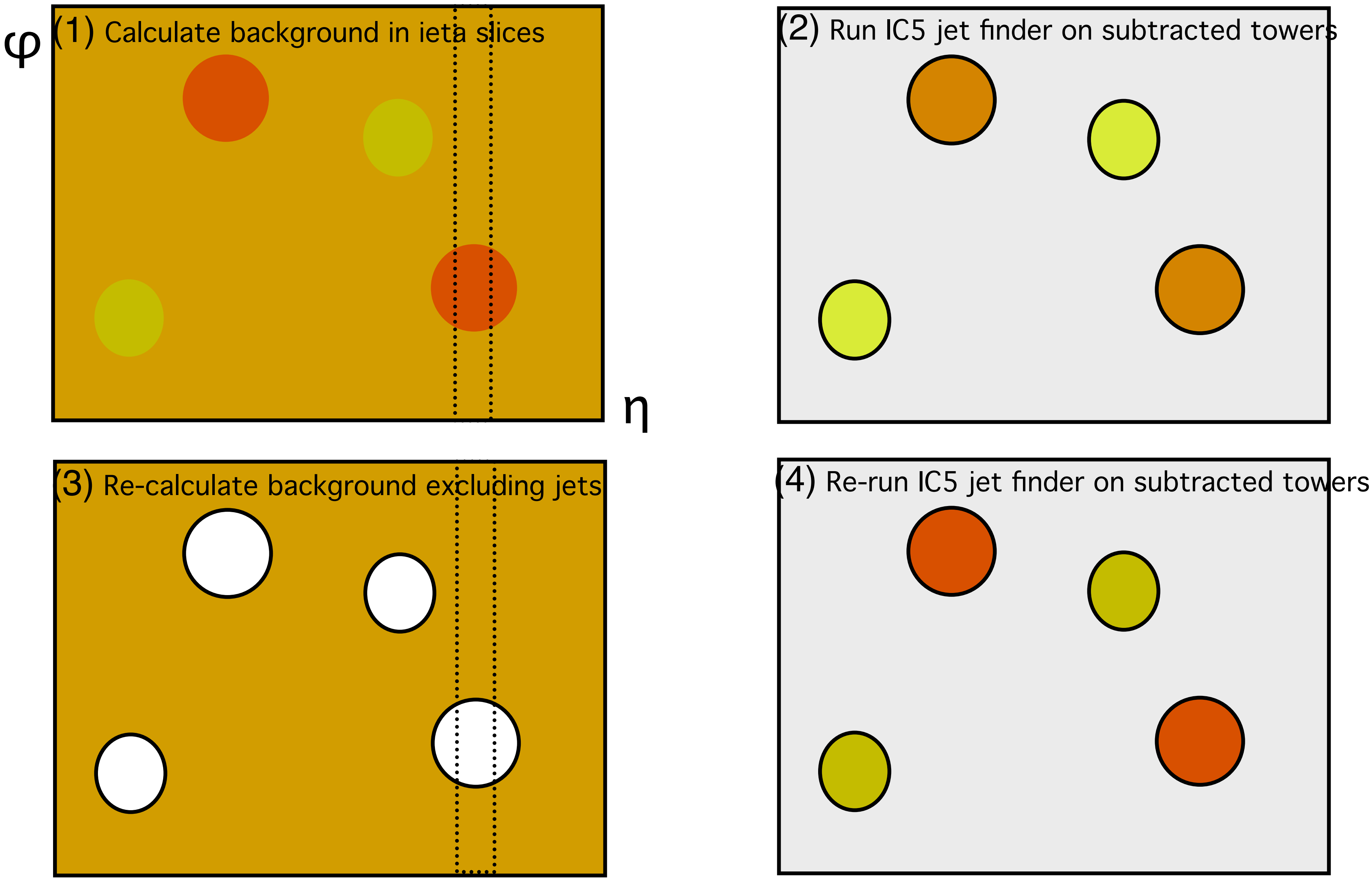
Jet Trigger

- Level-1: Single Jet 30 GeV (uncorrected energy)
- HLT: Single Jet 50 GeV (bkgd subtracted uncorr. energy)
- Fully efficient for corrected energy above 100 GeV



Collision Rate: 1-210 Hz, Jet50U Rate: < 1 Hz

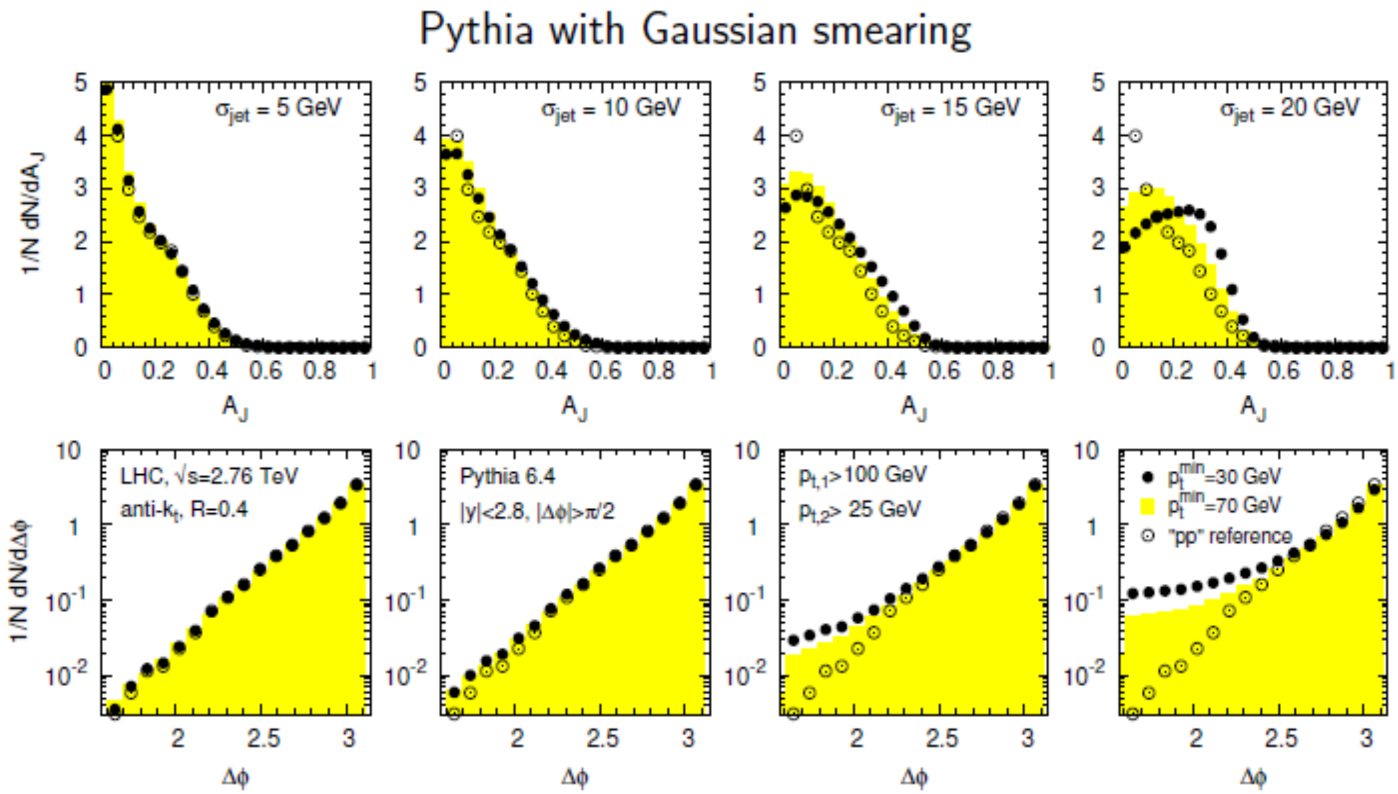
Jet Algorithm



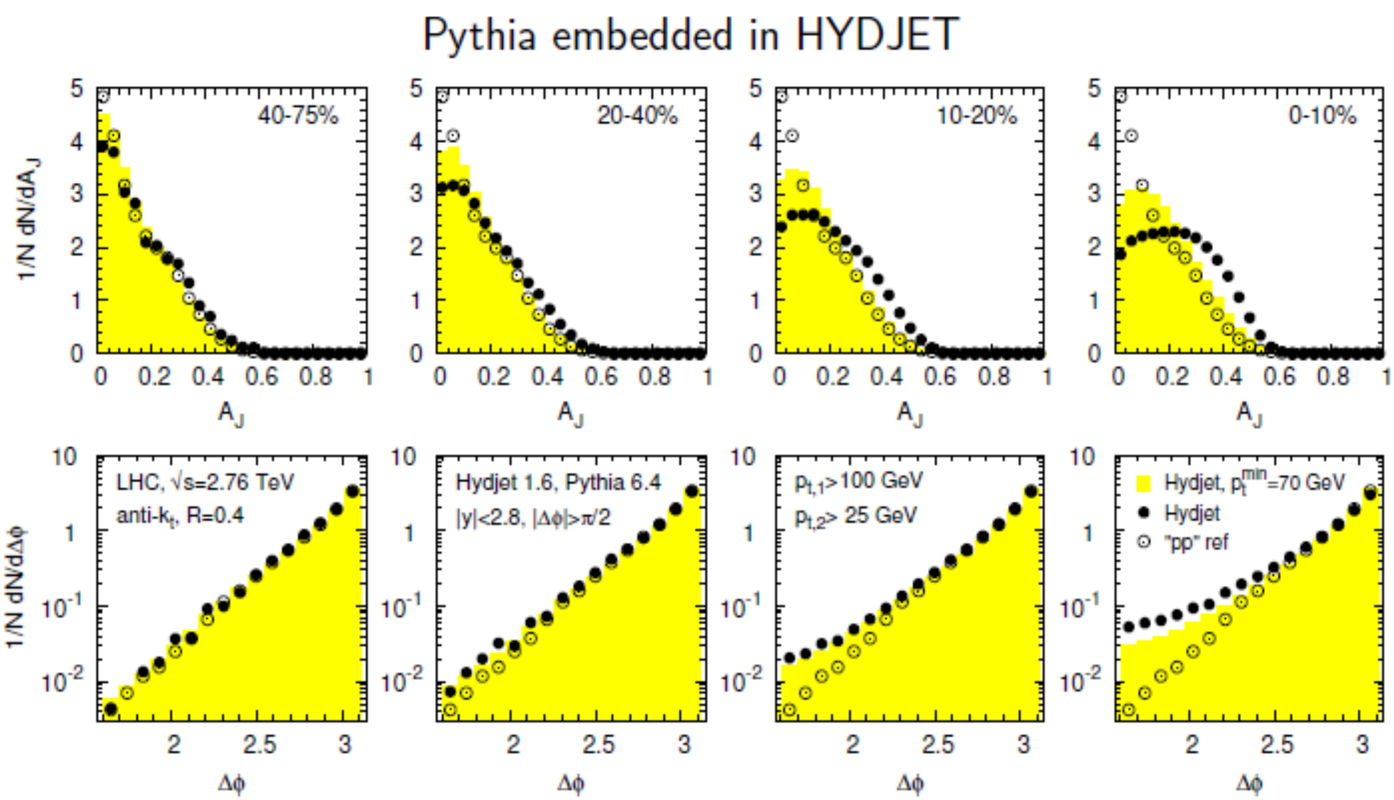
O. Kodolova, I. Vardanian, A. Nikitenko et al., Eur. Phys. J. C50 (2007)

A_j broadening due to Fluctuations

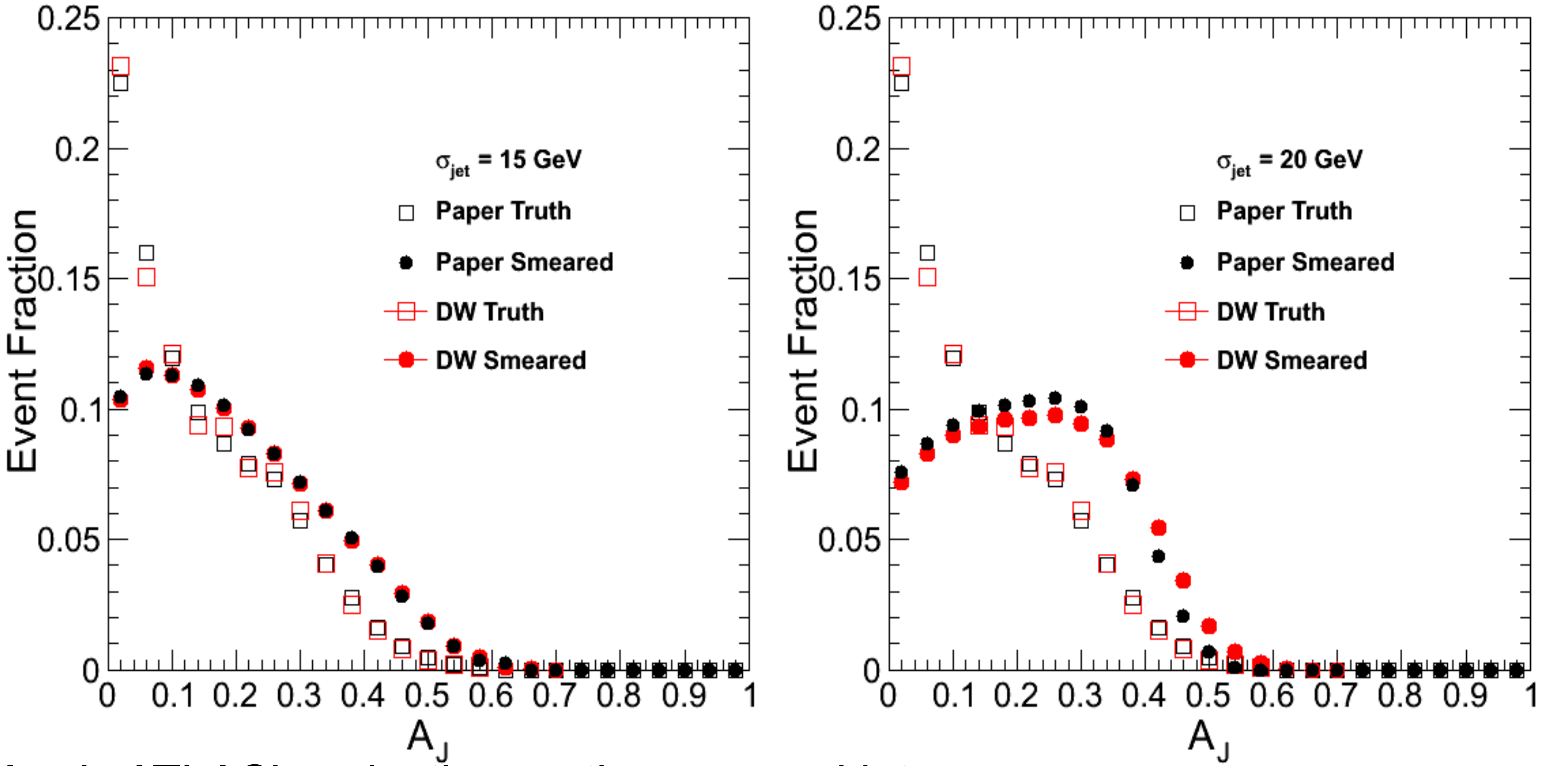
Different Gaussian smearing



PYTHIA+HYDJET

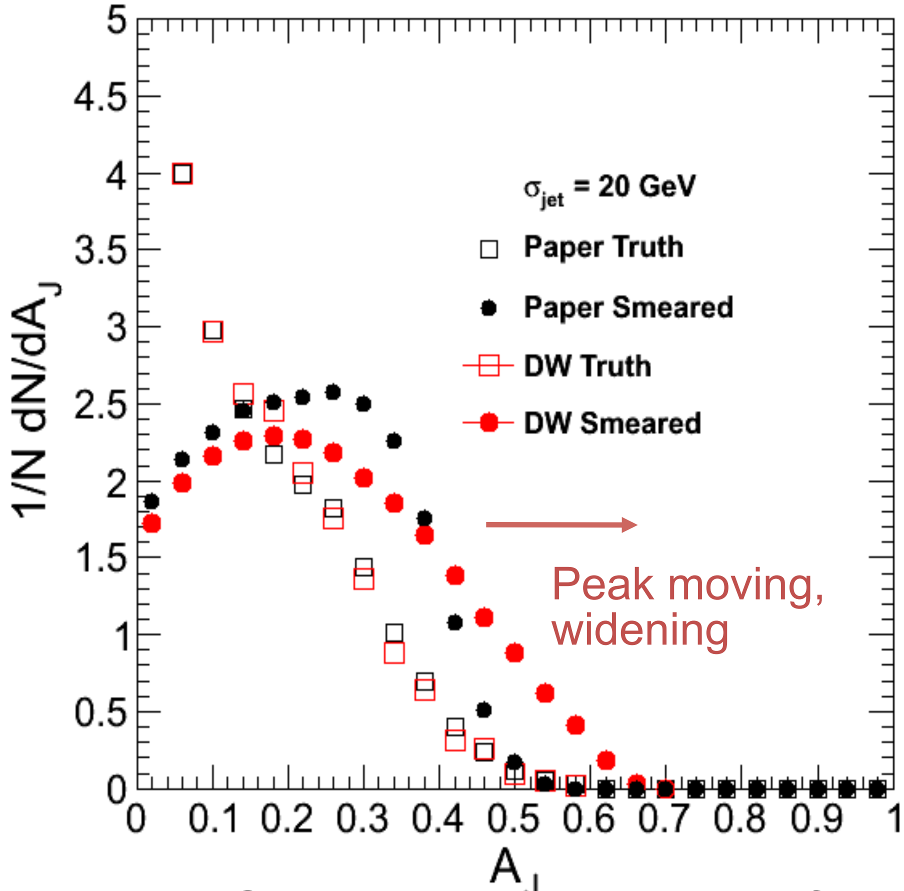


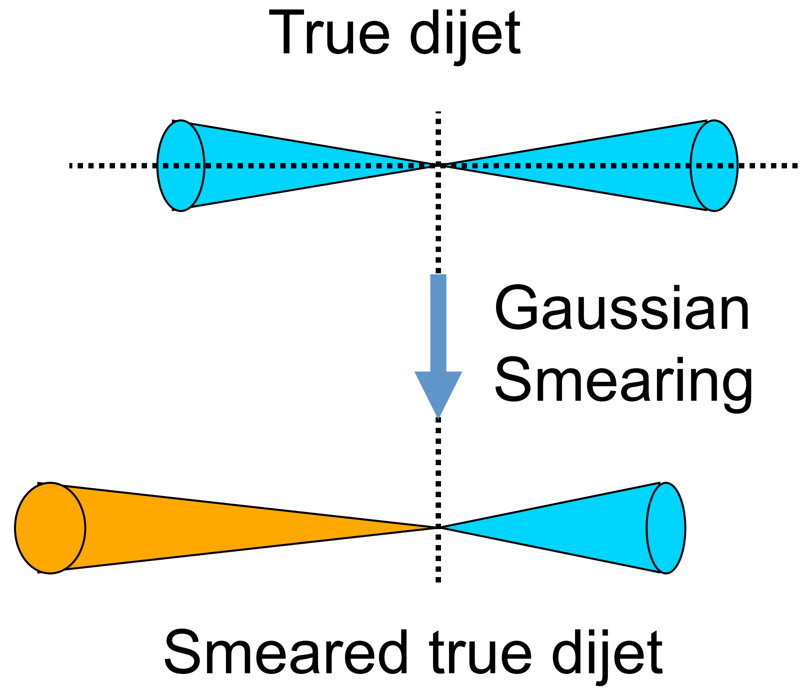
PYTHIA + Fluctuations



- Apply ATLAS's selection on the smeared jets:
  - p_{T1} > 100 GeV, p_{T2} > 25 GeV, dphi > pi/2
  - GenJet p_T > 0 GeV
- Applying a gaussian smearing to PYTHIA we can reproduce the results of the Salam paper.

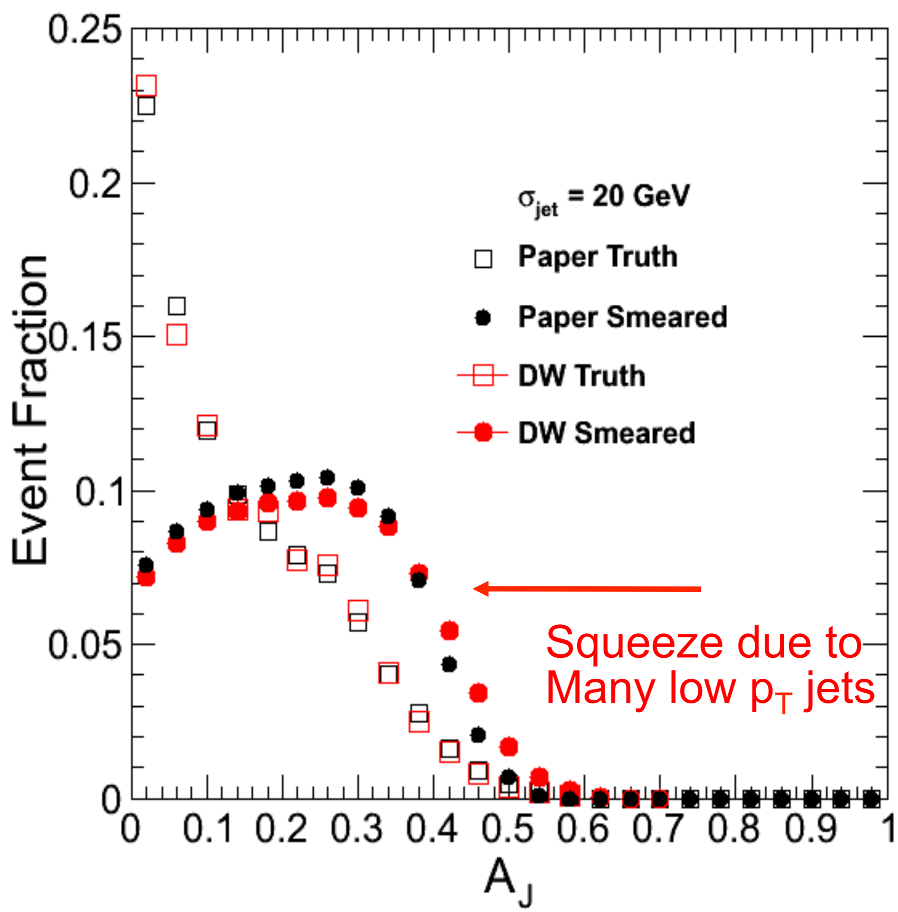
Ingredients

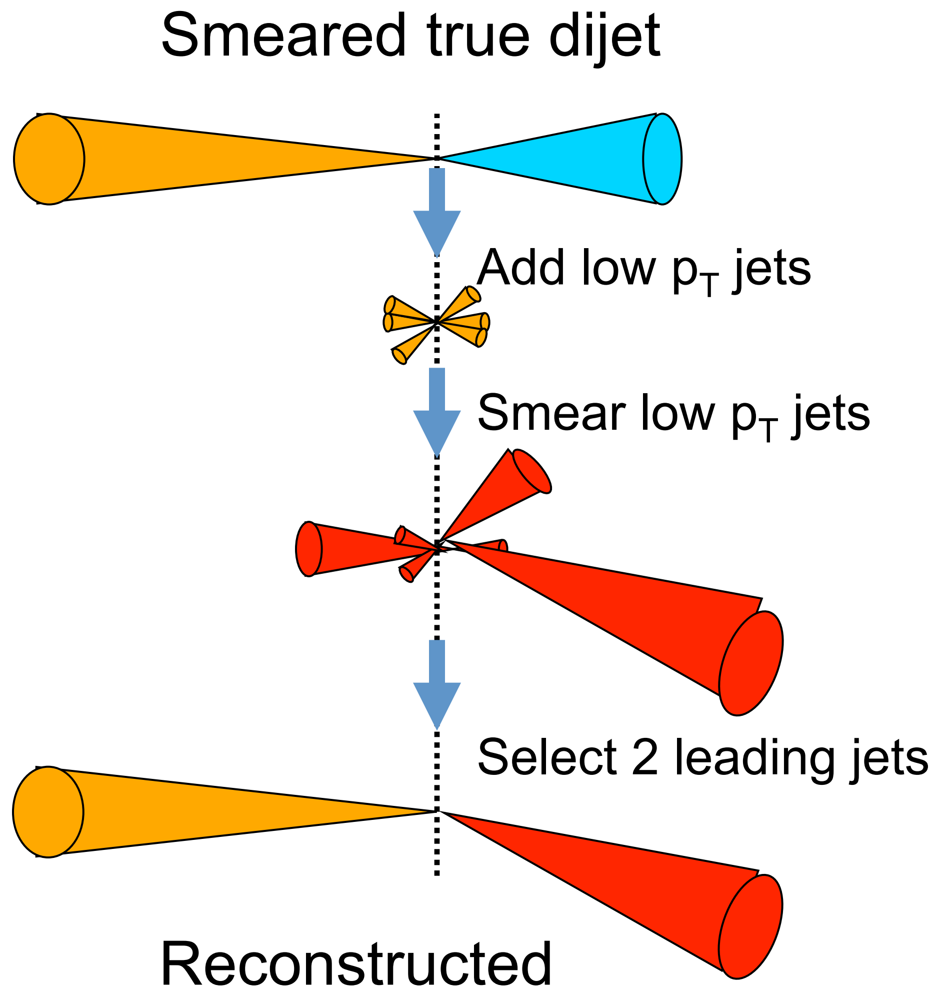




- Gaussian smearing of the leading jet makes the Aj distribution wider
  - Select only Jets above p_T = 3GeV

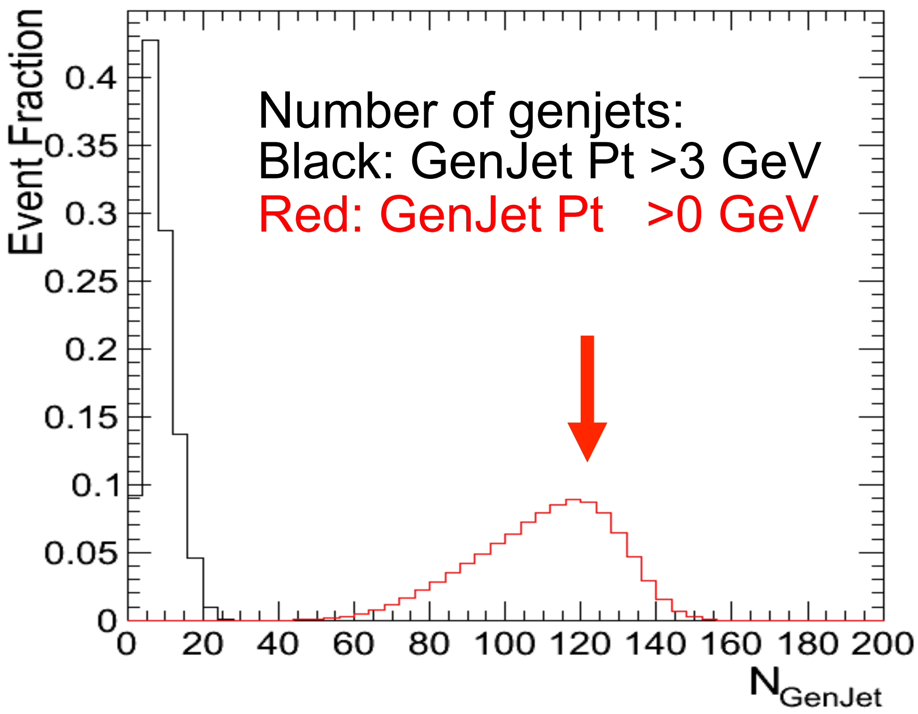
Ingredients II

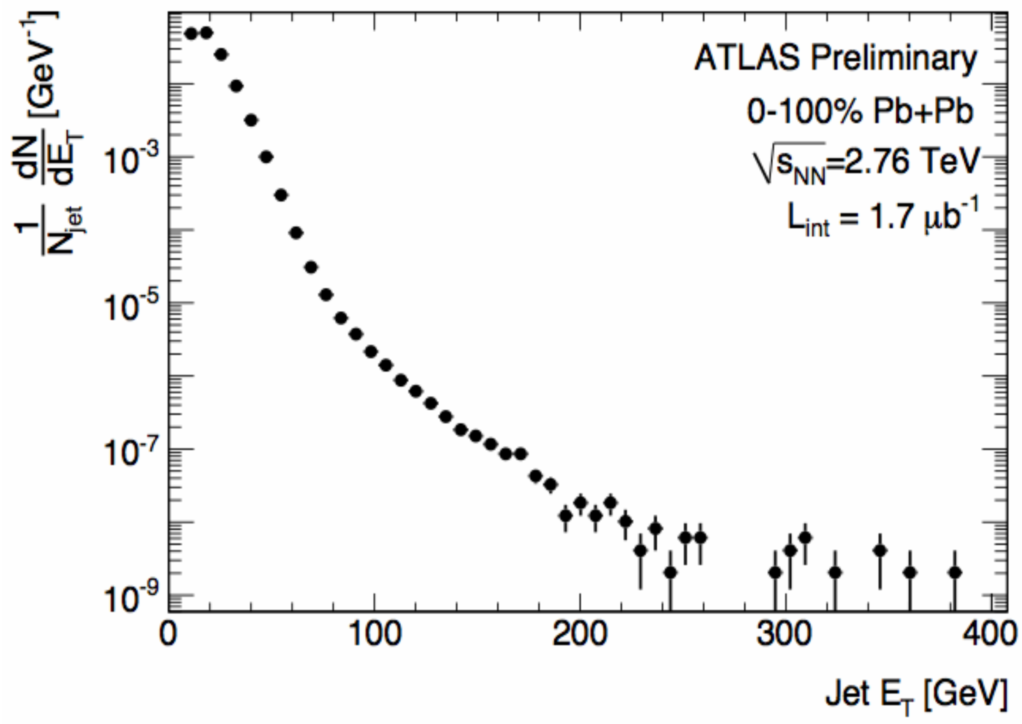




– Adding many low p_T jets, smeared to higher p_T than the true away side jet, compresses the Aj distribution
  - Tested by adding the 0-3GeV jets in the analysis

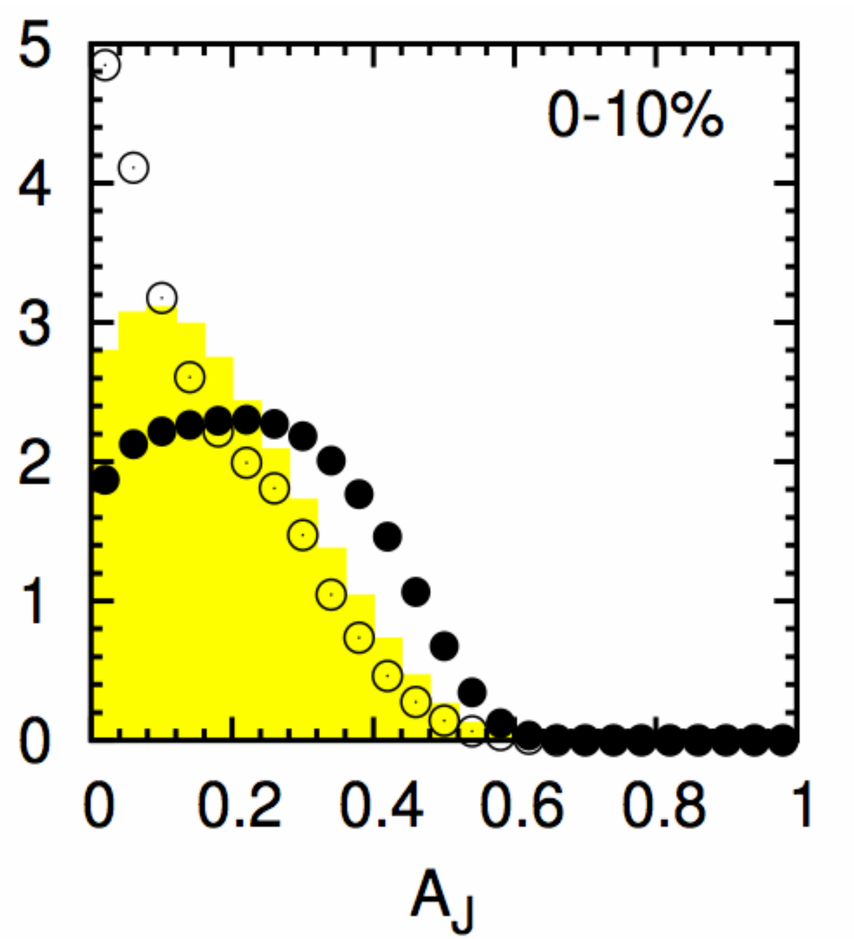
Ingredients III

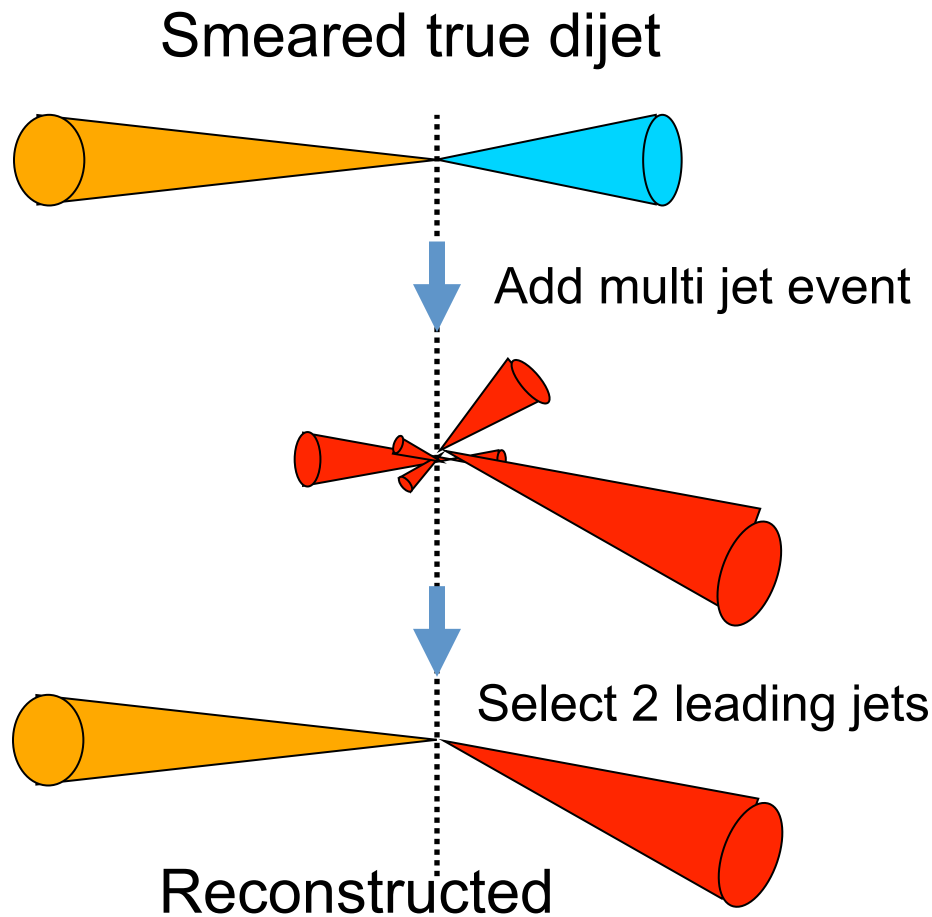




- Balanced dijets + fluctuations can fake a wide Aj distribution
  - Needs a very large number (~100) of low p_T jets per event
    - Remember: dn/dη^{ch} ~6 in |eta| < 5 -> ~60 charged particles/event
  - And a very large σ (20GeV) for the smearing
    - based on a Gaussian fit to the low p_T part of the ATLAS min bias jet spectrum
    - ATLAS reports σ ~8 GeV for their background fluctuations

Hydjet





- The HYDJET A_j distribution is created by the same mechanism
  - The hard part of a central HYDJET event consists of ~300 unquenched PYTHIA events with $p_T$hat of ~7GeV
  - Low p_T jets smear the leading jets by superposition and cause a combinatorial problem