Studies of Jet Quenching in PbPb Collisions at CMS

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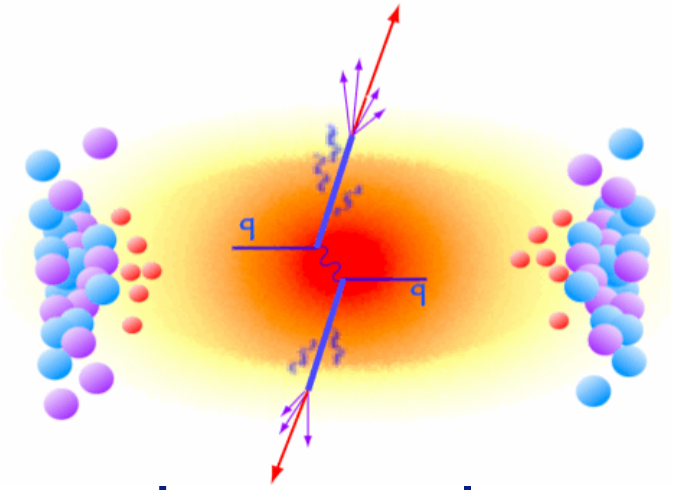
For the CMS Collaboration

Introduction

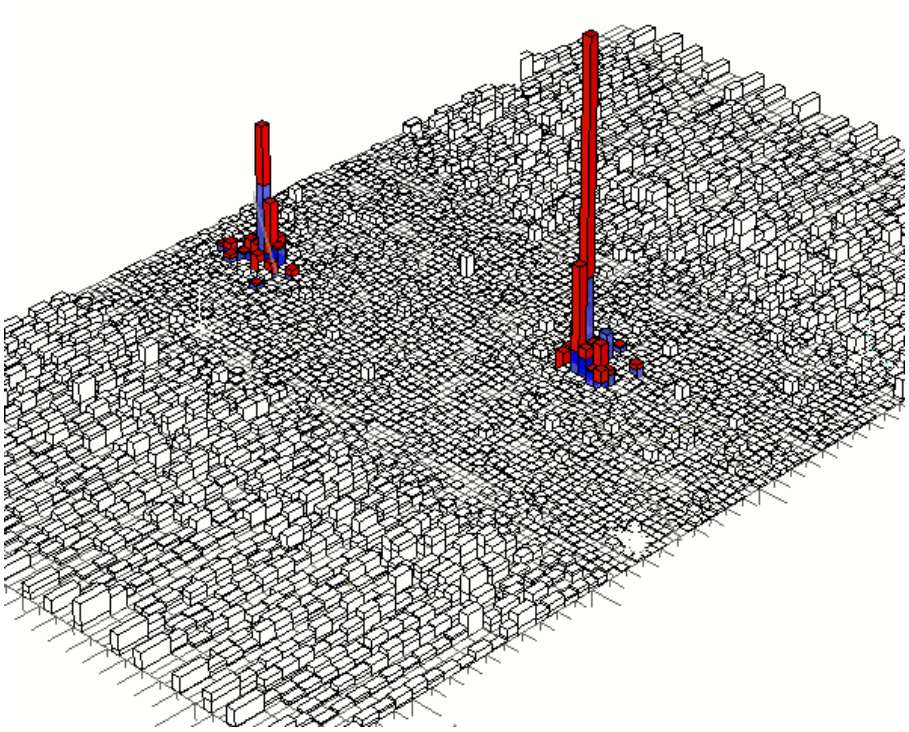
- The Goal
  - > Observing and characterizing the interaction of fast partons with the hot & dense matter created in heavy ion collisions



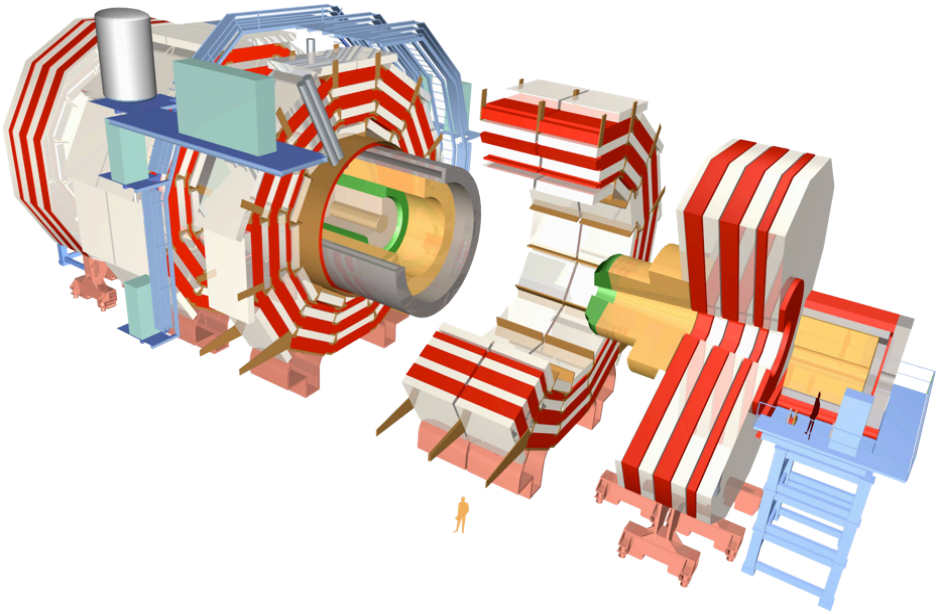
- The Tool: Dijets
  - > Fast partons from hard scattering are almost always accompanied by a second parton with close to the same transverse momentum and back-to-back in azimuthal angle

The LHC/CMS Advantage

- The rate of jets that stand out above the soft background is much higher at LHC energies



- The CMS detector is well optimized for finding jets in heavy ion collisions



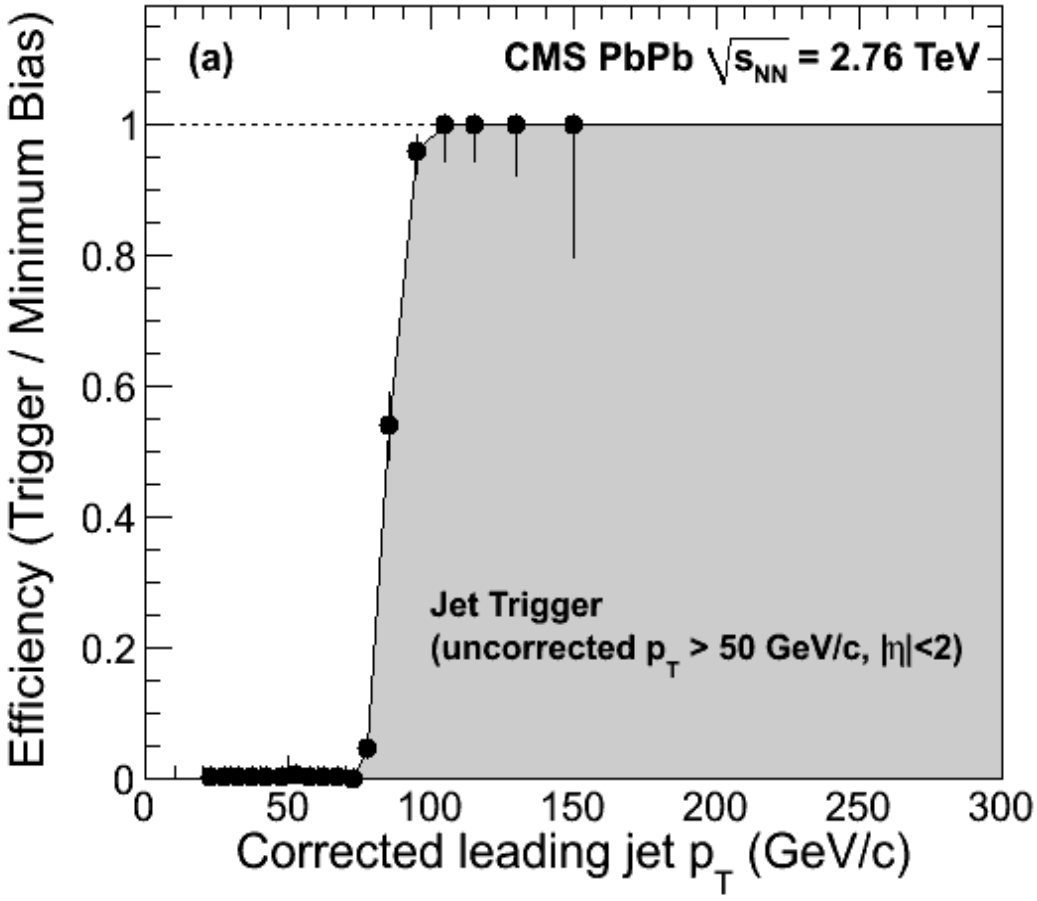
Another CMS Advantage: HLT Trigger

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

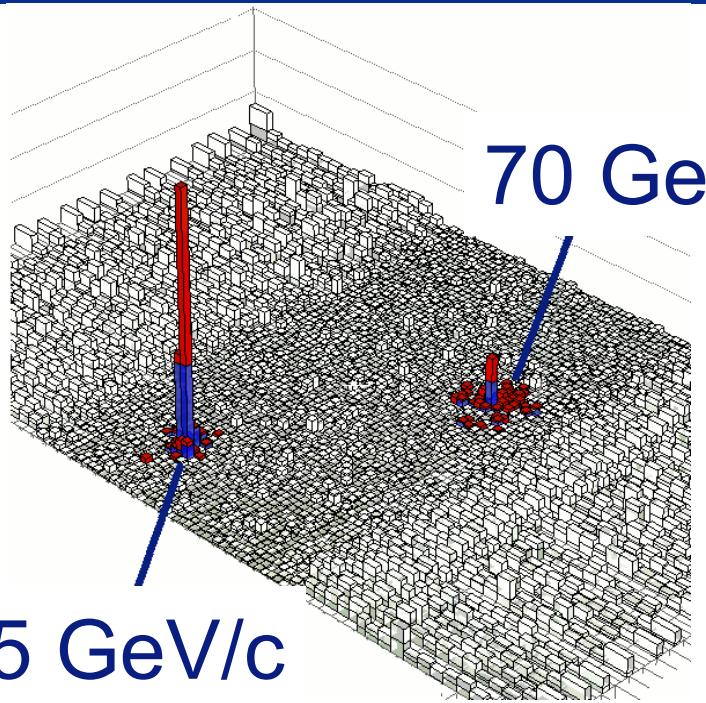


Collision Rate: 1-210 Hz, Jet50U Rate: < 1 Hz

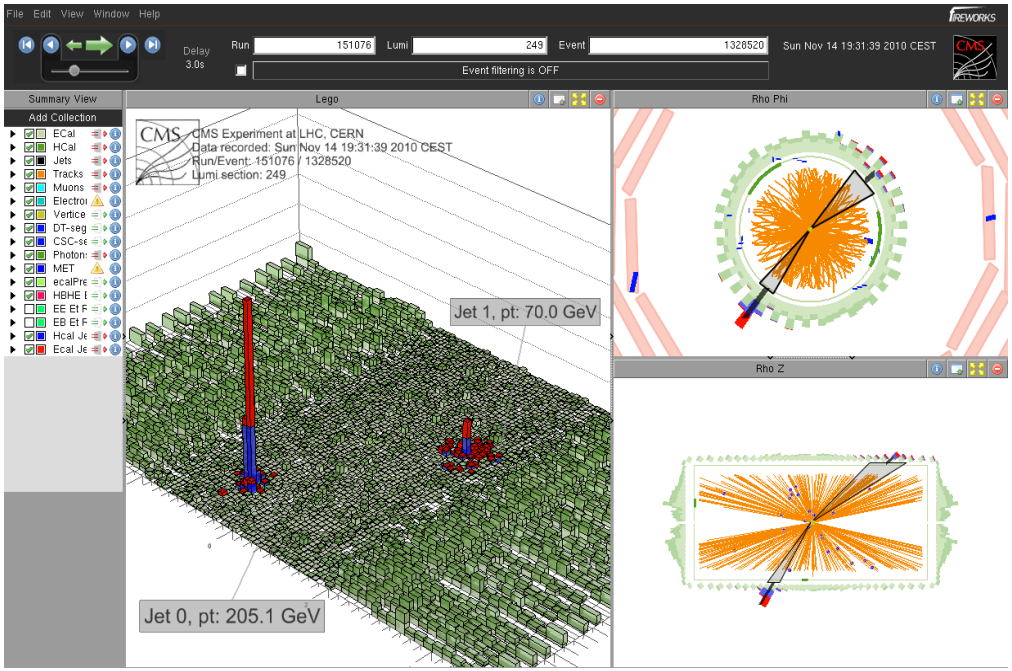
CMS-PAS-HIN-11-004 http://cdsweb.cern.ch/record/1354531?ln=en

Observation #1: Unbalanced Dijets

- In central PbPb collisions, many of the dijets are NOT balanced.



- This effect is so common and dramatic, it was evident in the on-line event display



Jet Finding in Heavy Ion Events

- Compare jet results using multiple algorithms using calorimetry alone and calorimetry plus charged particle tracks
- Studies of event momentum distributions done with charged particle tracks alone
- Subtraction of the contribution from the underlying PbPb event is an important effect
- Calorimeter results are checked by embedding (at the detector level) dijets generated using PYTHIA into actual PbPb data events

Jet Reconstruction Details

Calorimeter based Jet Finder (IC5)

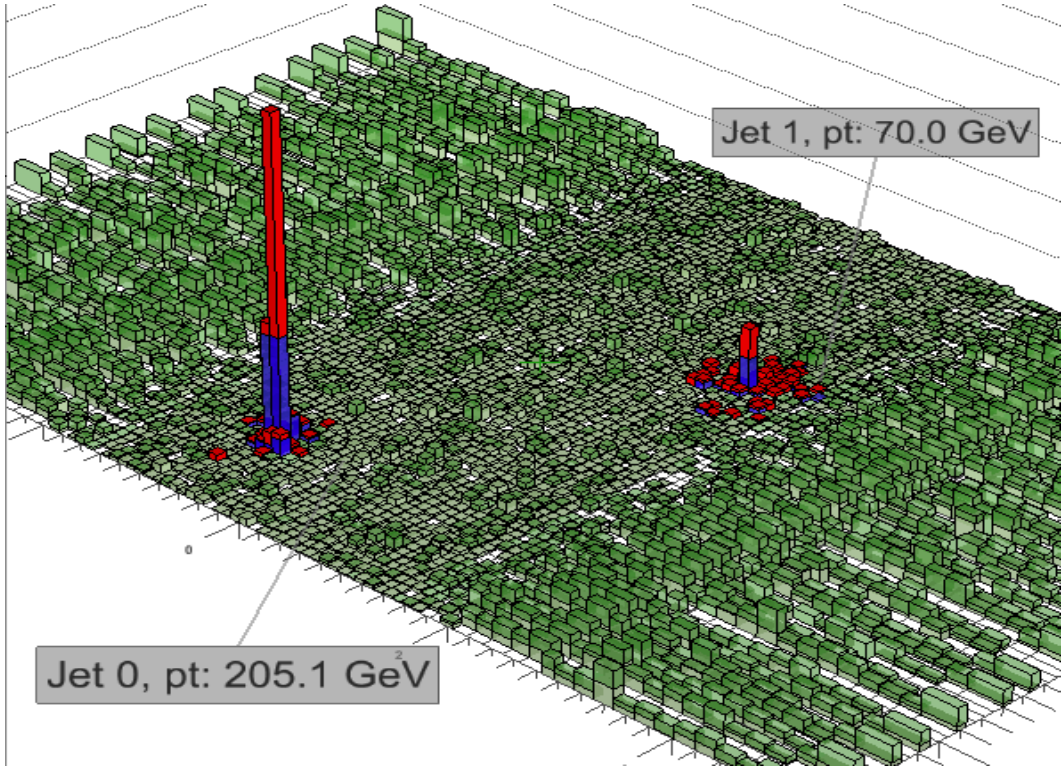
- Iterative Cone Algorithm
- R = 0.5
- arXiv:1102.1957 [nucl-ex]

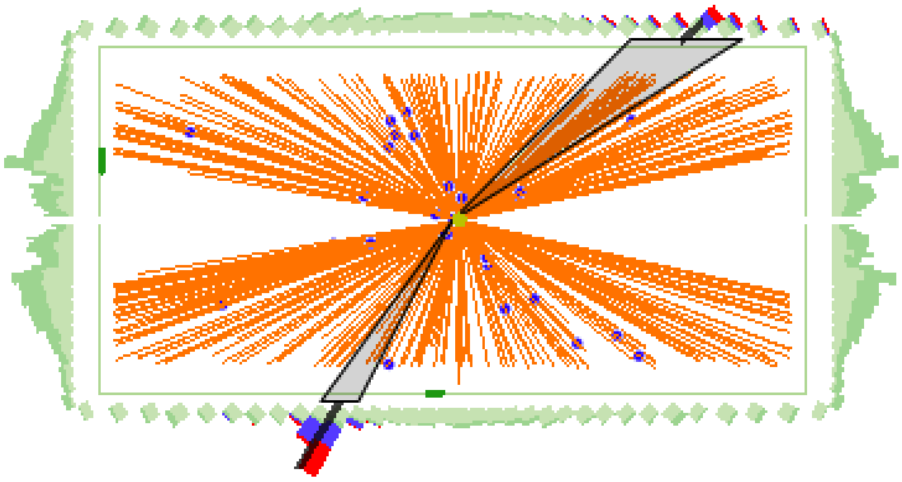
Particle Flow Jet Finder (PF)

- Anti-k_T Clustering Algorithm*
- R = 0.3

Underlying event subtraction

- Iterative PileUp subtraction**
  - Calculate average in rings of η
  - Subtract $\langle E_T \rangle + \sigma(E_T)$
  - Set negative cells to zero
  - Find jets, remove them, redo background, re-find jets, etc…
  - Extensively tested with jets in real data events, random cone, and other cross-checks





* M. Cacciari, G. P. Salam, and G. Soyez, JHEP 04 (2008) 063
** O. Kodolova, I. Vardanian, A. Nikitenko et al., Eur. Phys. J. C50 (2007)

Jet Reconstruction Efficiency

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Underlying event subtraction

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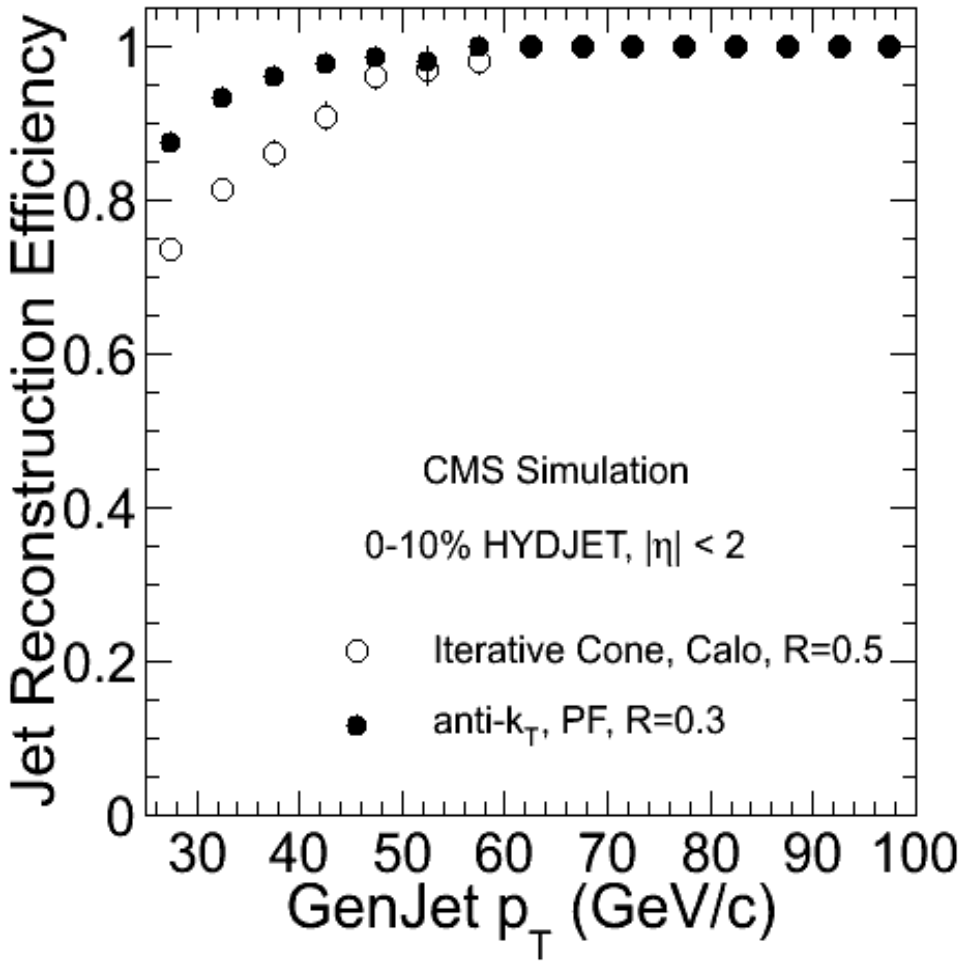

Jet Reconstruction fully efficient above:

- 50 GeV/c, Calorimeter Jets
- 40 GeV/c, Particle Flow Jets

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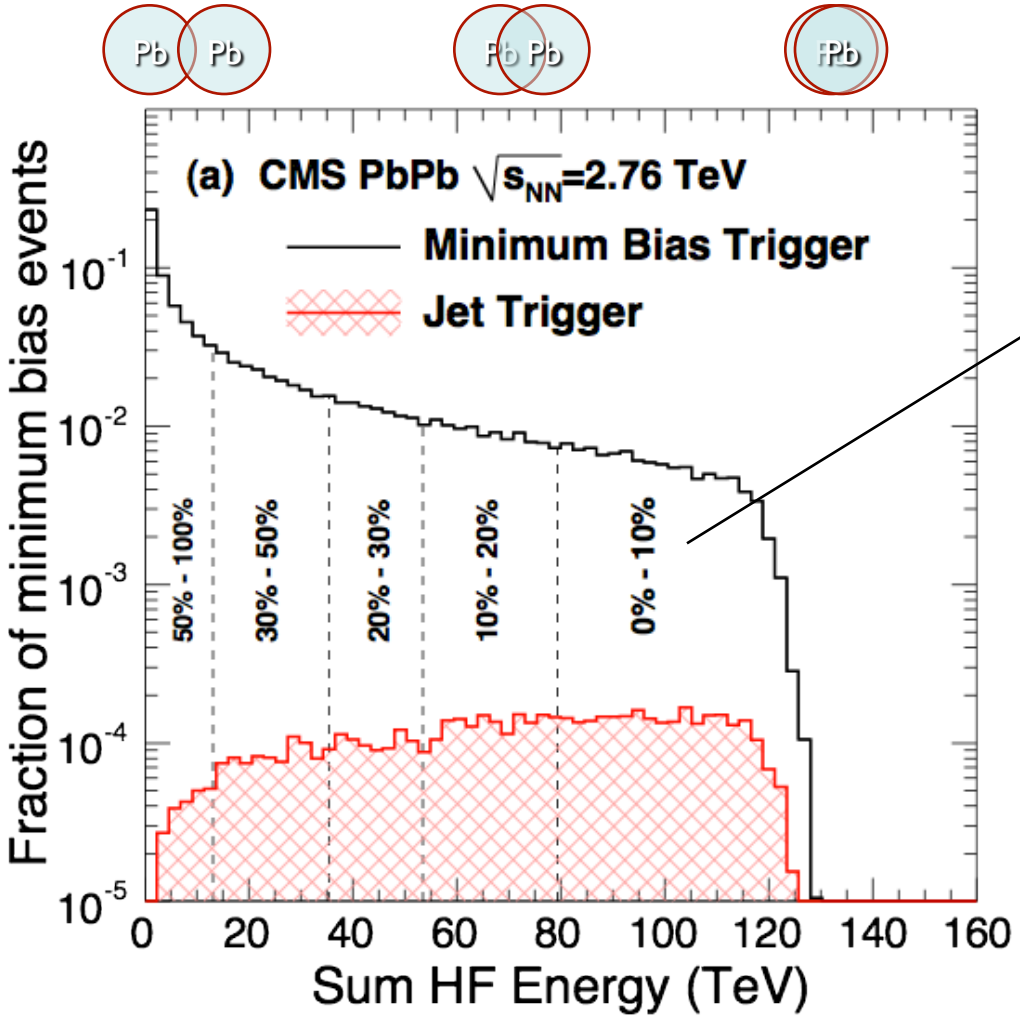
Heavy Ion Subtlety: Determining Centrality

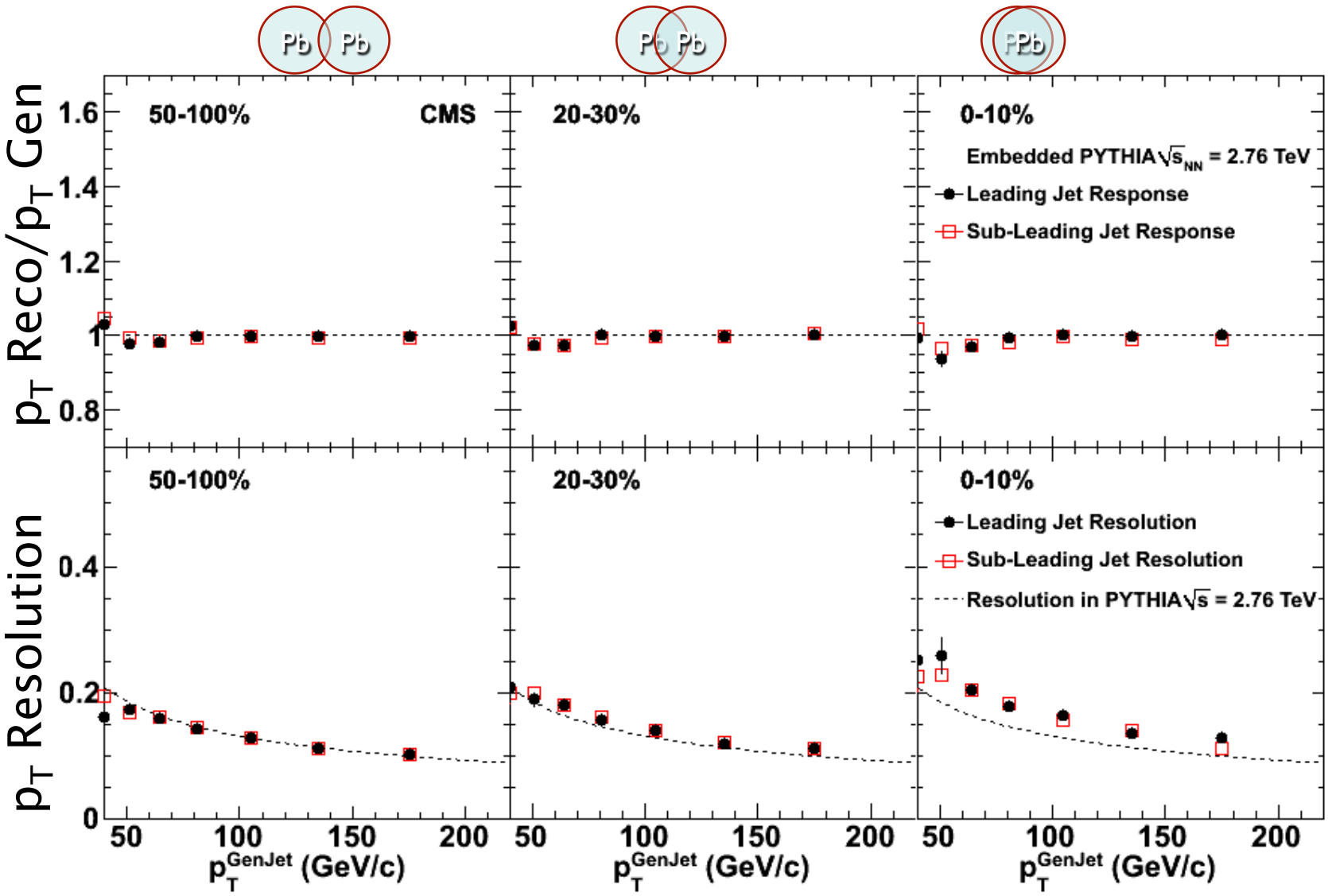


Centrality bins of equal PbPb inelastic cross section

Total HF (forward hadronic calorimeter) energy used to determine degree of PbPb overlap

CMS-PAS-HIN-11-004 http://cdsweb.cern.ch/record/1354531?ln=en

Jet p_T Resolution in PbPb Events



Fluctuations in the underlying PbPb event make only a small difference in the jet p_T resolution with respect to pp

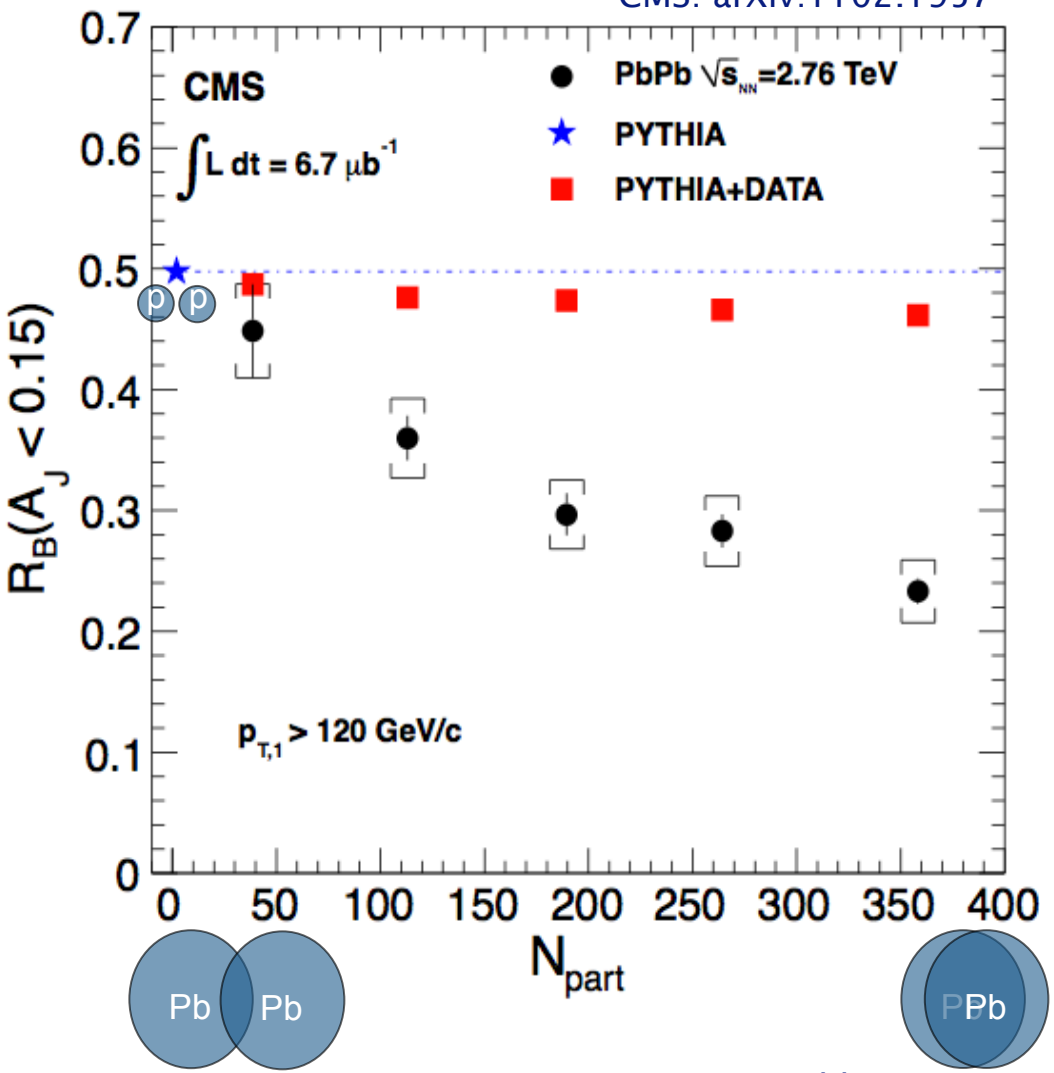
CMS-PAS-HIN-11-004 http://cdsweb.cern.ch/record/1354531?ln=en

Quantifying Dijet Imbalance

- Use asymmetry ratio: $A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$

- Look at fraction of PbPb events with a high p_T (>120 GeV/c) jet which are more unbalanced than the median event in pp

CMS: arXiv:1102.1957



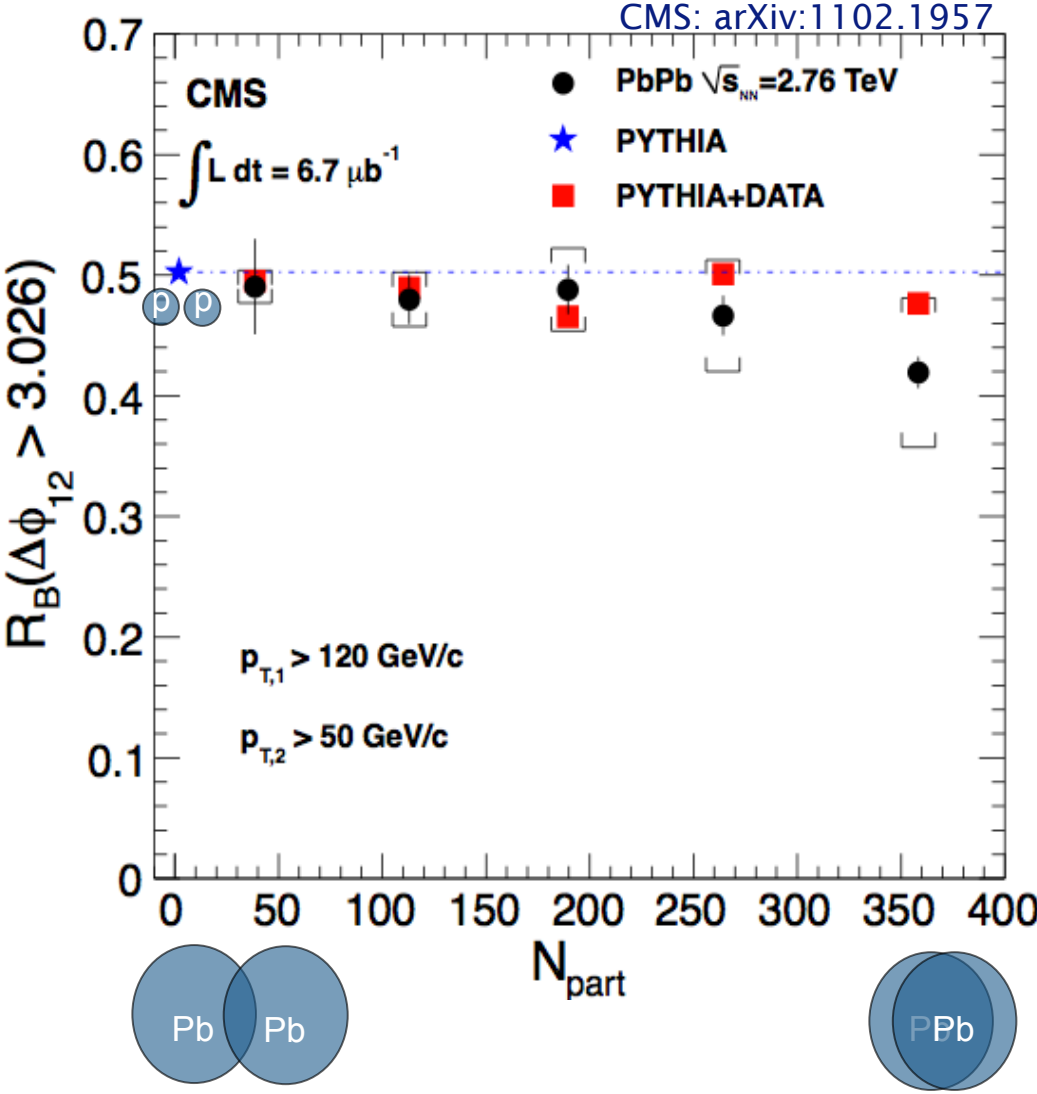
CMS: arXiv:1102.1957 Accepted by PRC

Observation#2: Azimuthal Alignment

- Look at fraction of PbPb events with a dijet which is farther from back-to-back than the median in pp

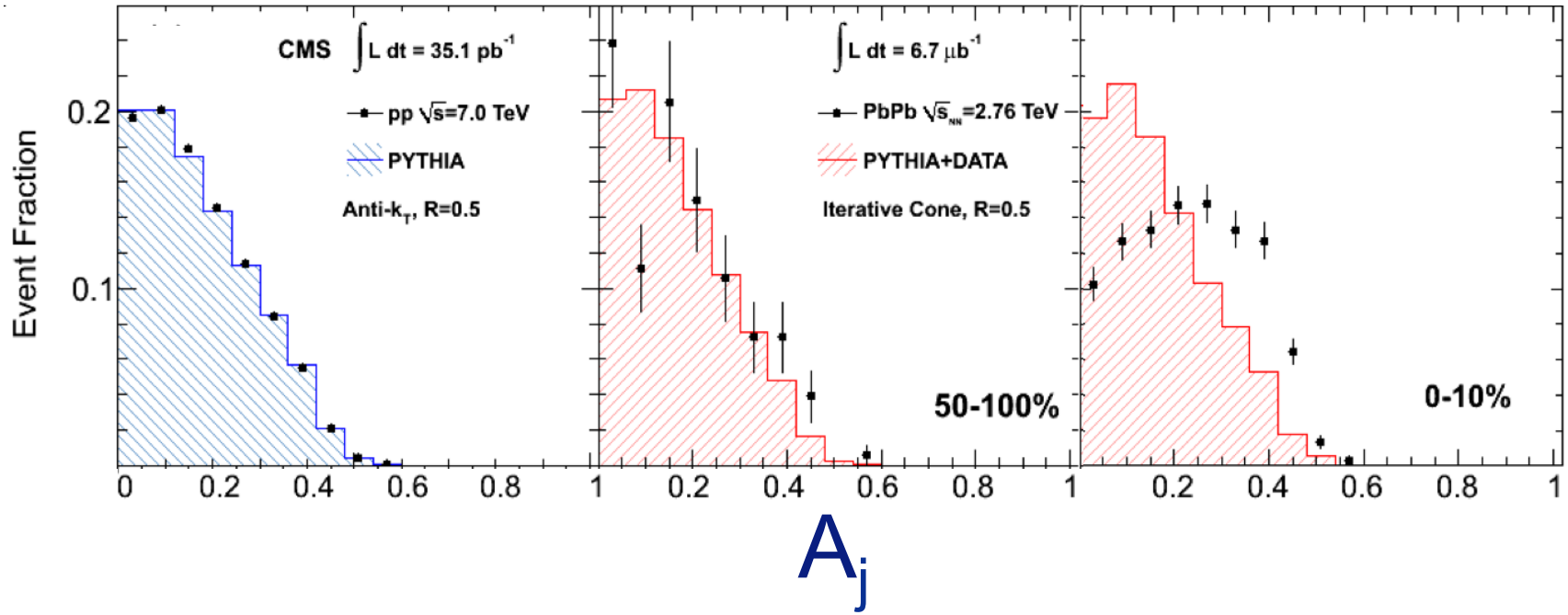
- Despite large imbalance in p_T between the two jets they are STILL back-to-back in azimuth

CMS: arXiv:1102.1957

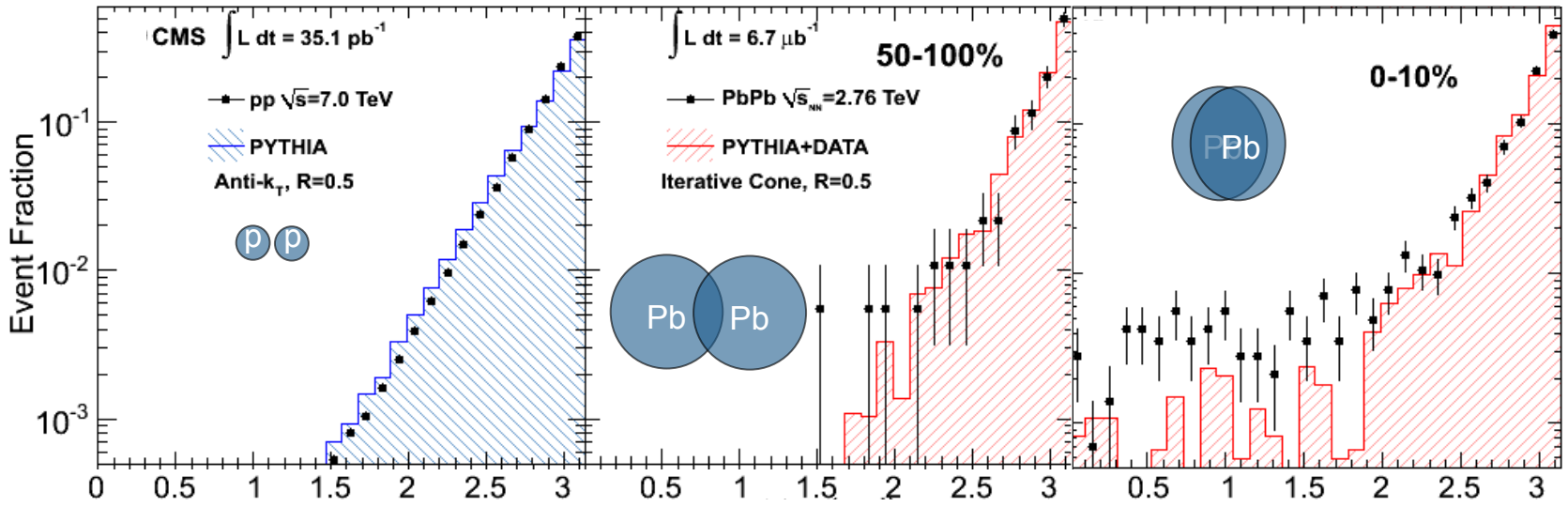


CMS: arXiv:1102.1957 Accepted by PRC

PbPb Compared to PYTHIA+Data



A_j



$\Delta\phi$

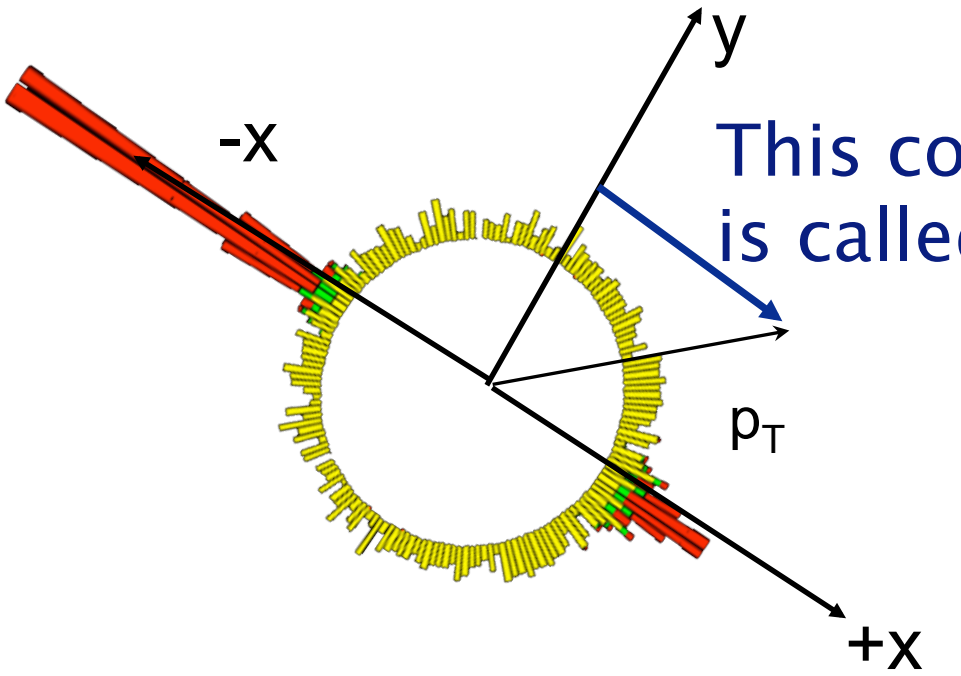
CMS: arXiv:1102.1957 Accepted by PRC

Further Analysis: Finding "Missing" p_T

Add up the total component of transverse momentum along an axis parallel to the leading (highest p_T) jet (x-axis shown below)

Chose direction opposite to leading jet to be positive

Use charged particle tracks for best p_T resolution

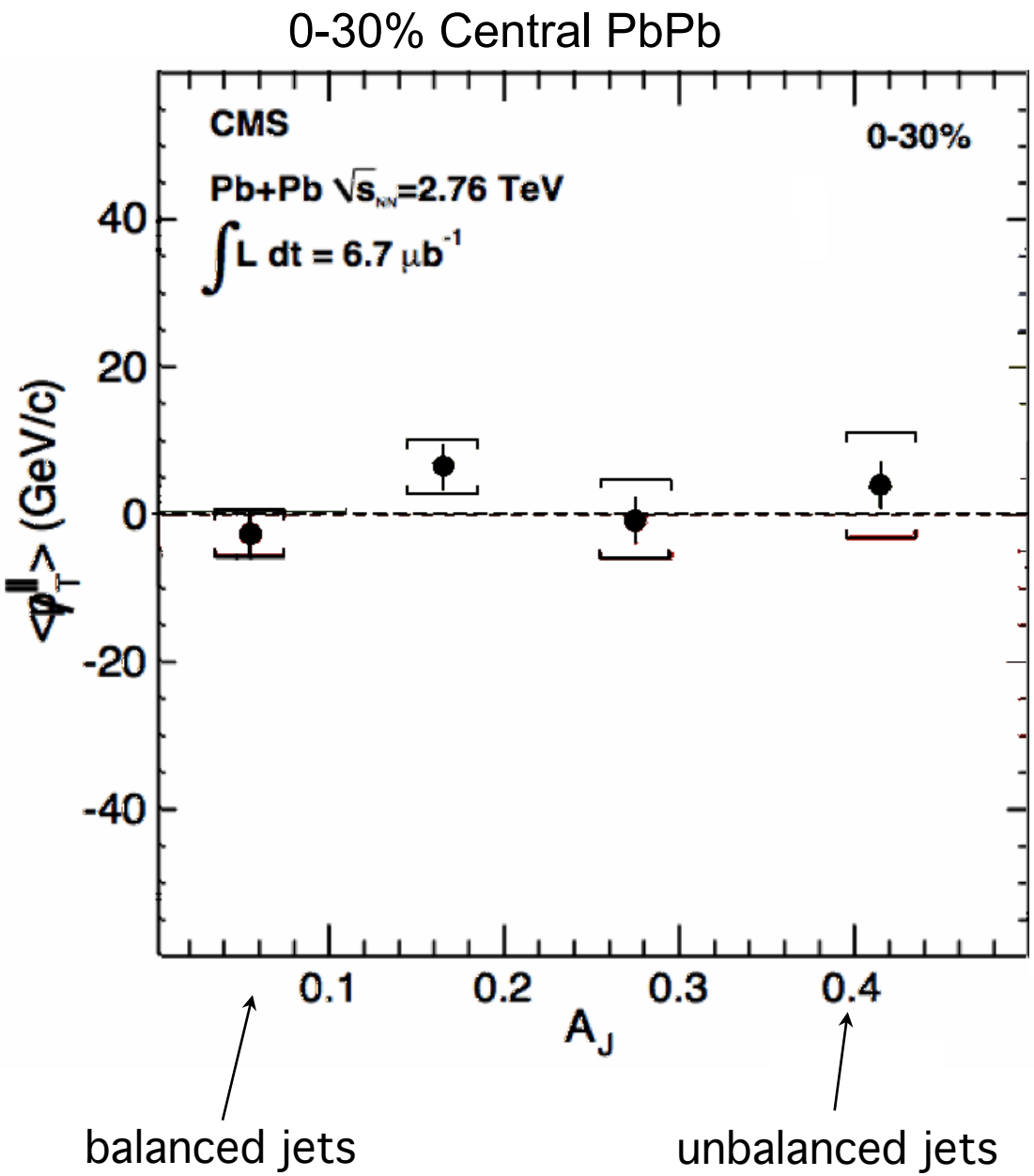


This component is called $p_T^{||}$

"Missing" $p_T^{||}$:

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

Sanity Check: Total Event p_T

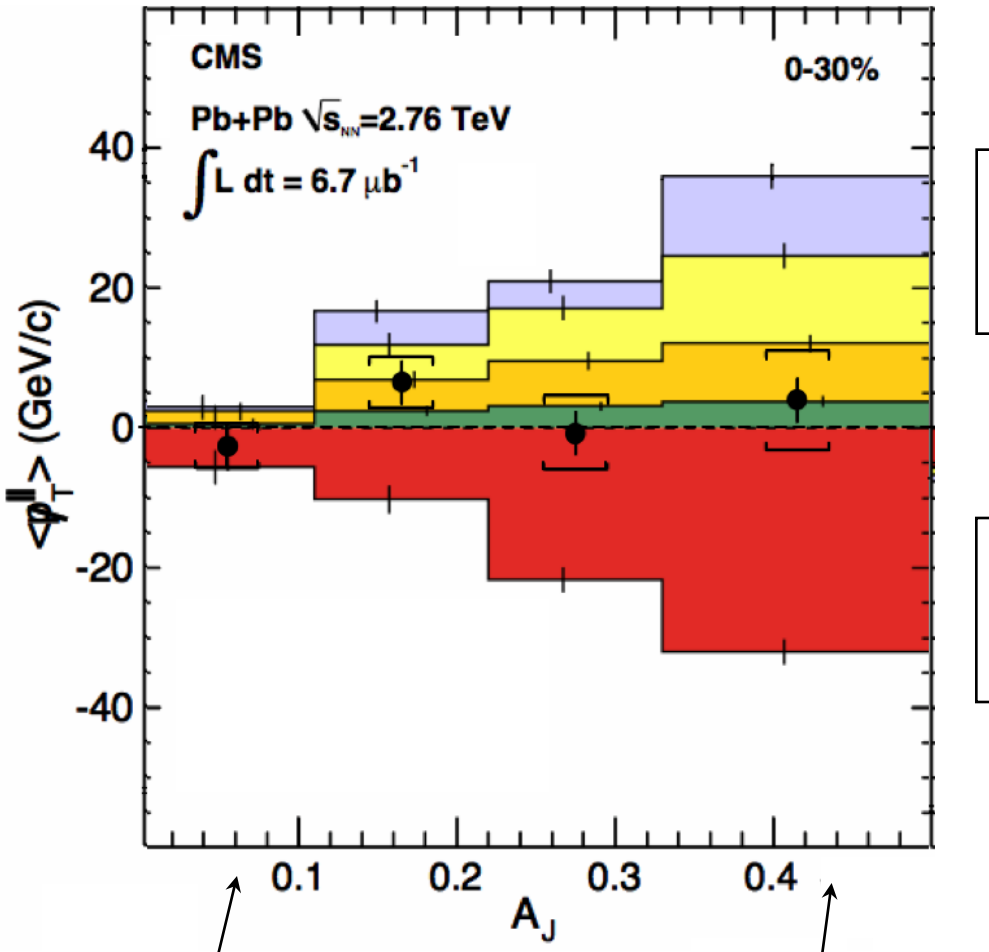


excess away from leading jet

excess towards leading jet

Observation #3: "Missing" p_T is in low p_T tracks

0-30% Central PbPb



excess away from leading jet

excess towards leading jet

balanced jets

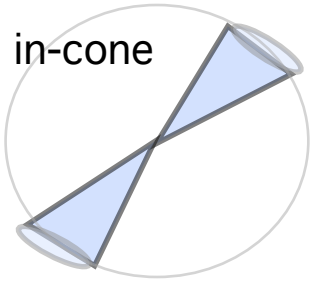
unbalanced jets

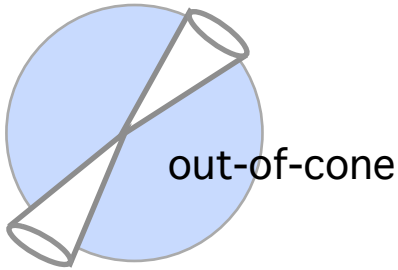
Calculate missing p_T in ranges of track p_T:

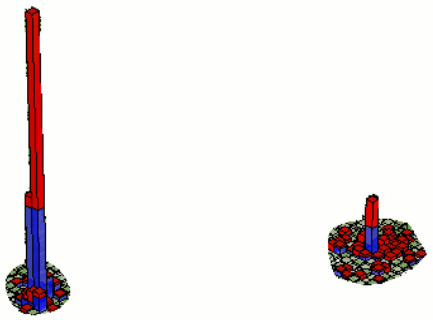
- > 0.5 GeV/c
- 0.5 - 1.0 GeV/c
- 1.0 - 2.0 GeV/c
- 2.0 - 4.0 GeV/c
- 4.0 - 8.0 GeV/c
- > 8.0 GeV/c

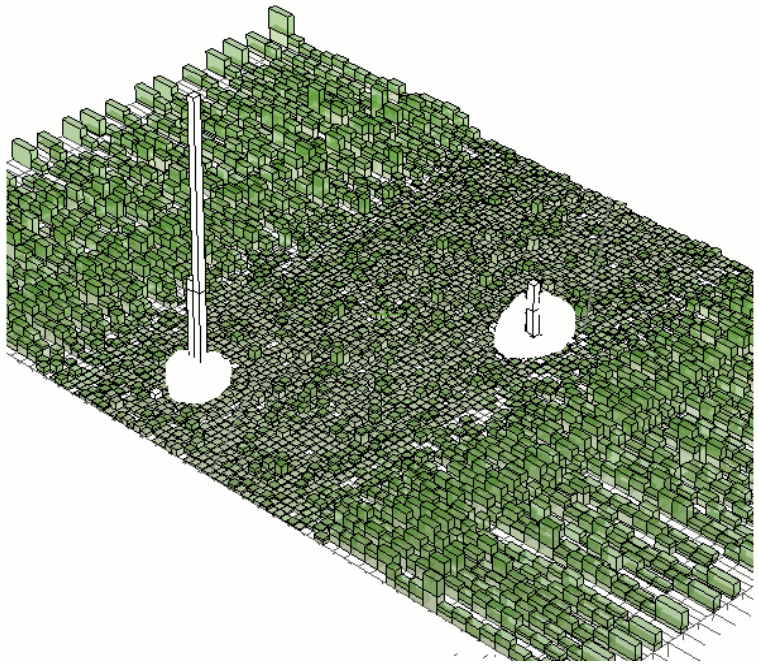
Δϕ Dependence of "Missing" p_T

- Look separately at "missing" $p_T^{||}$ in the cones around the jet and away from those cones





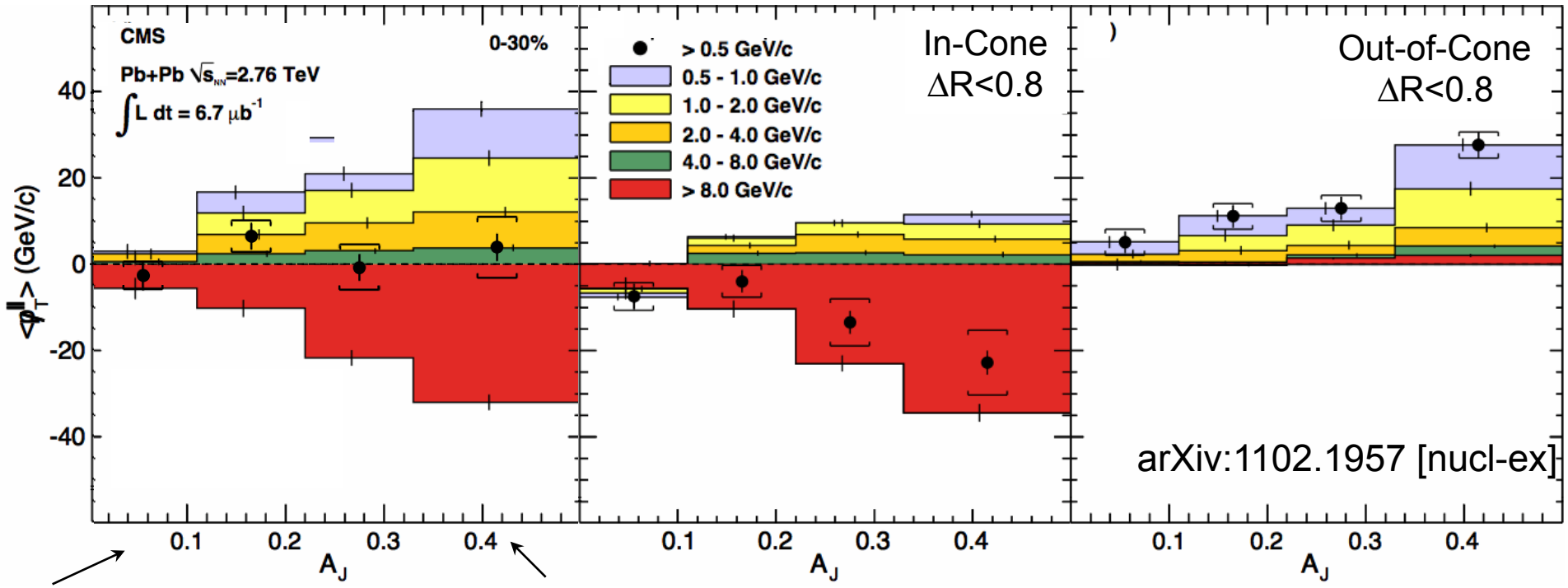




Observation #4:Low p_T tracks are out-of-cone

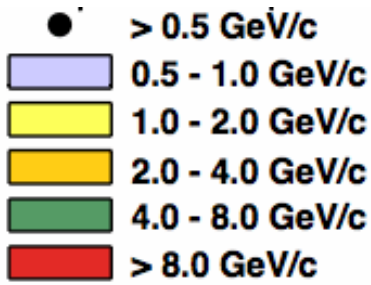
0-30% Central PbPb

CMS: arXiv:1102.1957



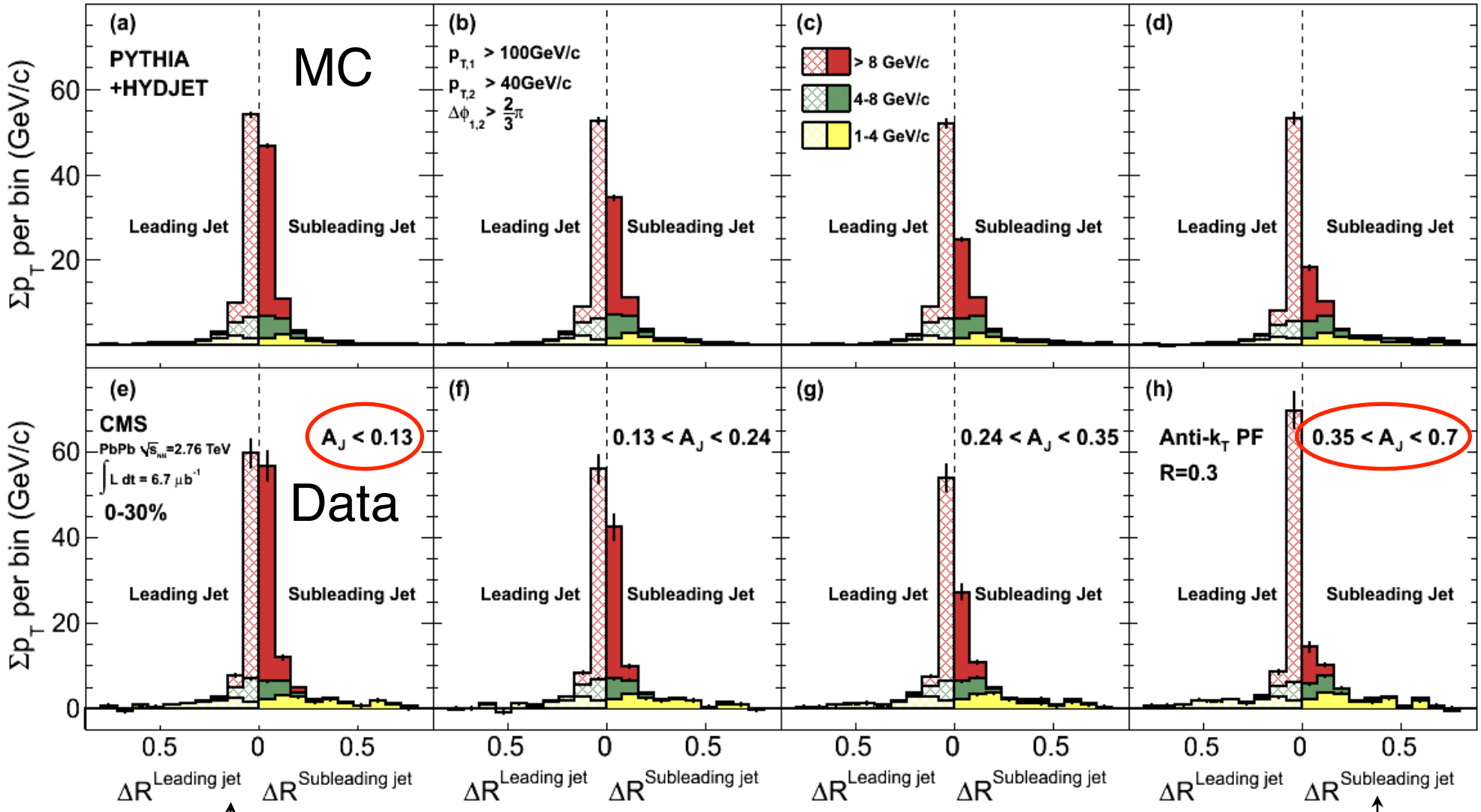
balanced jets

unbalanced jets



CMS: arXiv:1102.1957 Accepted by PRC

More Differential Track-Jet Correlations



balanced jets

unbalanced jets

Underlying event contribution subtracted

CMS: arXiv:1102.1957 Accepted by PRC

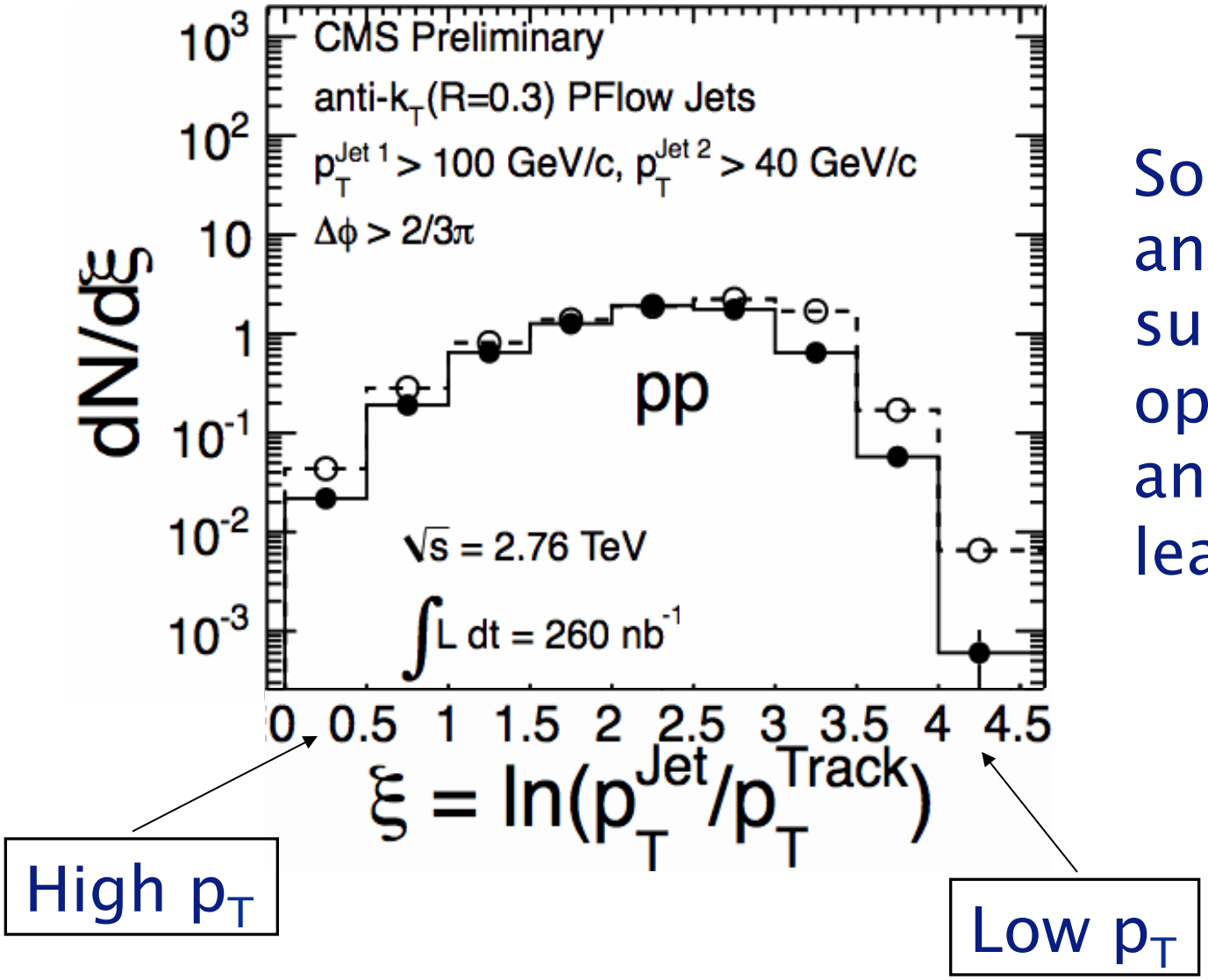
More Jet Properties: Fragmentation Function

- The fragmentation of fast partons into a jet of hadrons will distribute the momentum to the individual hadrons in a characteristic pattern
- Does this pattern change for the partons that have experienced the dramatic effects of the medium in PbPb collisions?
- One variable commonly used in such studies is

$$\xi = \ln\left(p_T^{Jet} / p_T^{Track}\right)$$

- Note that complications of subtracting the contribution due to the PbPb background restrict this study for now to p_T>4 GeV/c

Jet Fragmentation Function Example: pp



Solid symbols and lines are subleading jet, open symbols and dashes are leading jet

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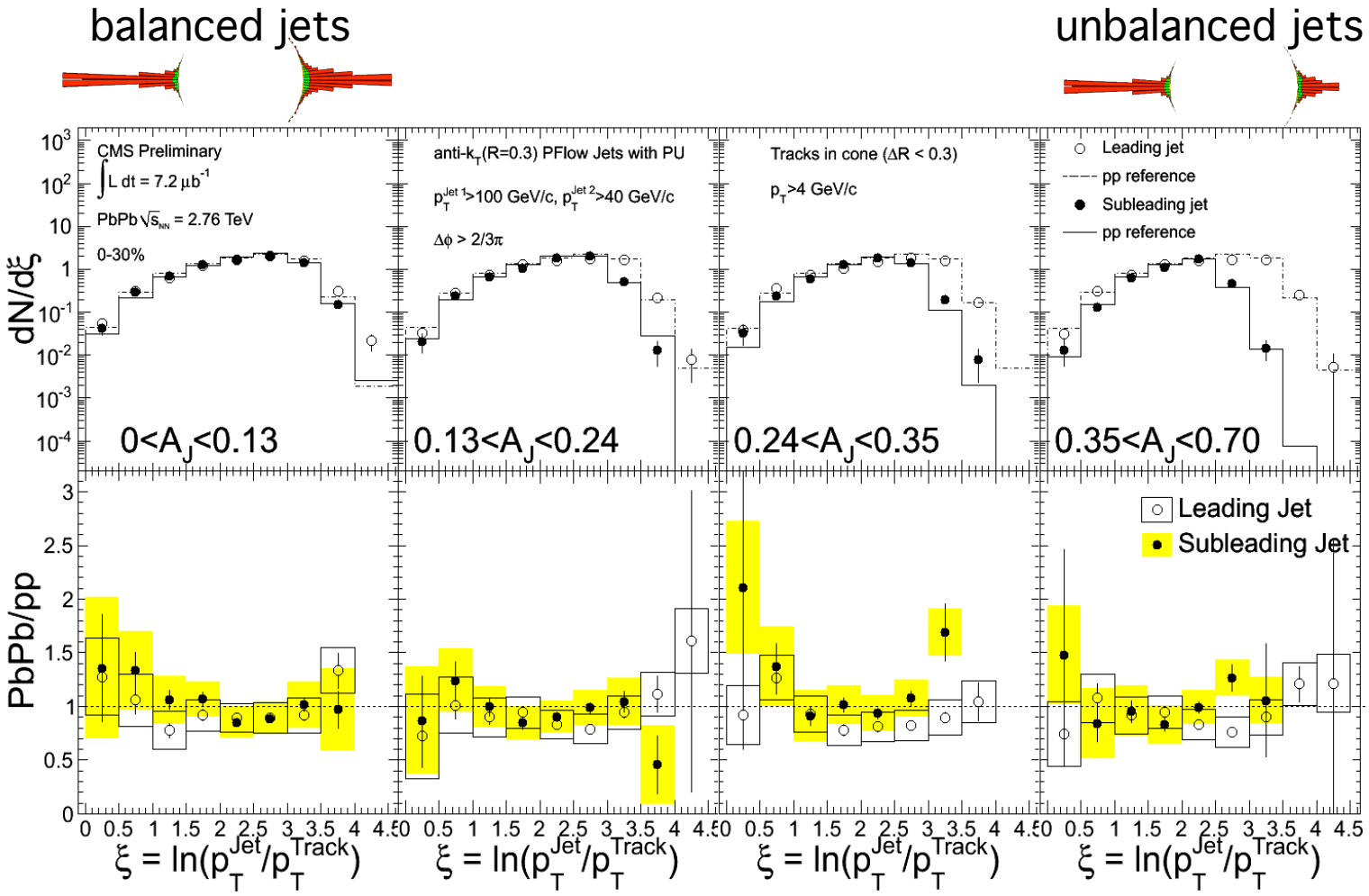
Observations #5: PbPb & pp Fragment Similarly



Solid symbols and lines are subleading jet, open symbols and dashes are leading jet

Given the distribution of tracks with p_T>4GeV/c in a jet of a certain transverse momentum, it's impossible to distinguish PbPb from pp, even in the case of very unbalanced jet pairs

CMS-PAS-HIN-11-004 http://cdsweb.cern.ch/record/1354531?ln=en

Summary

- Dijet imbalance provides unambiguous evidence of energy loss of fast partons in heavy ion collisions
- Even when losing a lot of energy, jets are undeflected
- Energy lost from the jet is transferred to many low p_T particles at large angles to the jet direction
- The fragmentation of the jet momentum into hadrons is indistinguishable between PbPb and pp, at least for the higher p_T (>4 GeV/c) particles, even for jets that lose a large fraction of their energy

Backup

Jet Reconstruction

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- R = 0.5
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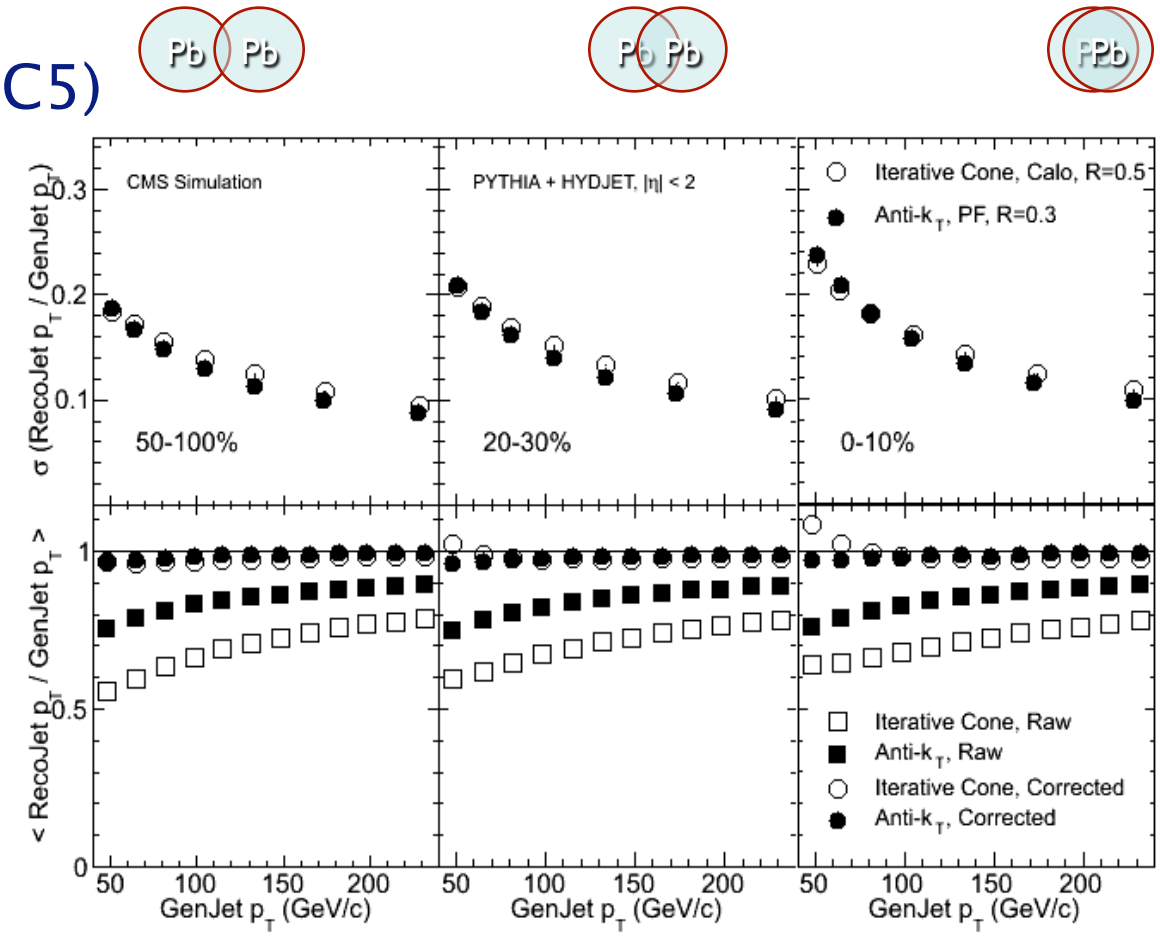
Particle Flow Jet Finder (PF)

- Anti-k_T Clustering Algorithm
- R = 0.3
- See Presentation by M. Nguyen Parallel Session, Friday

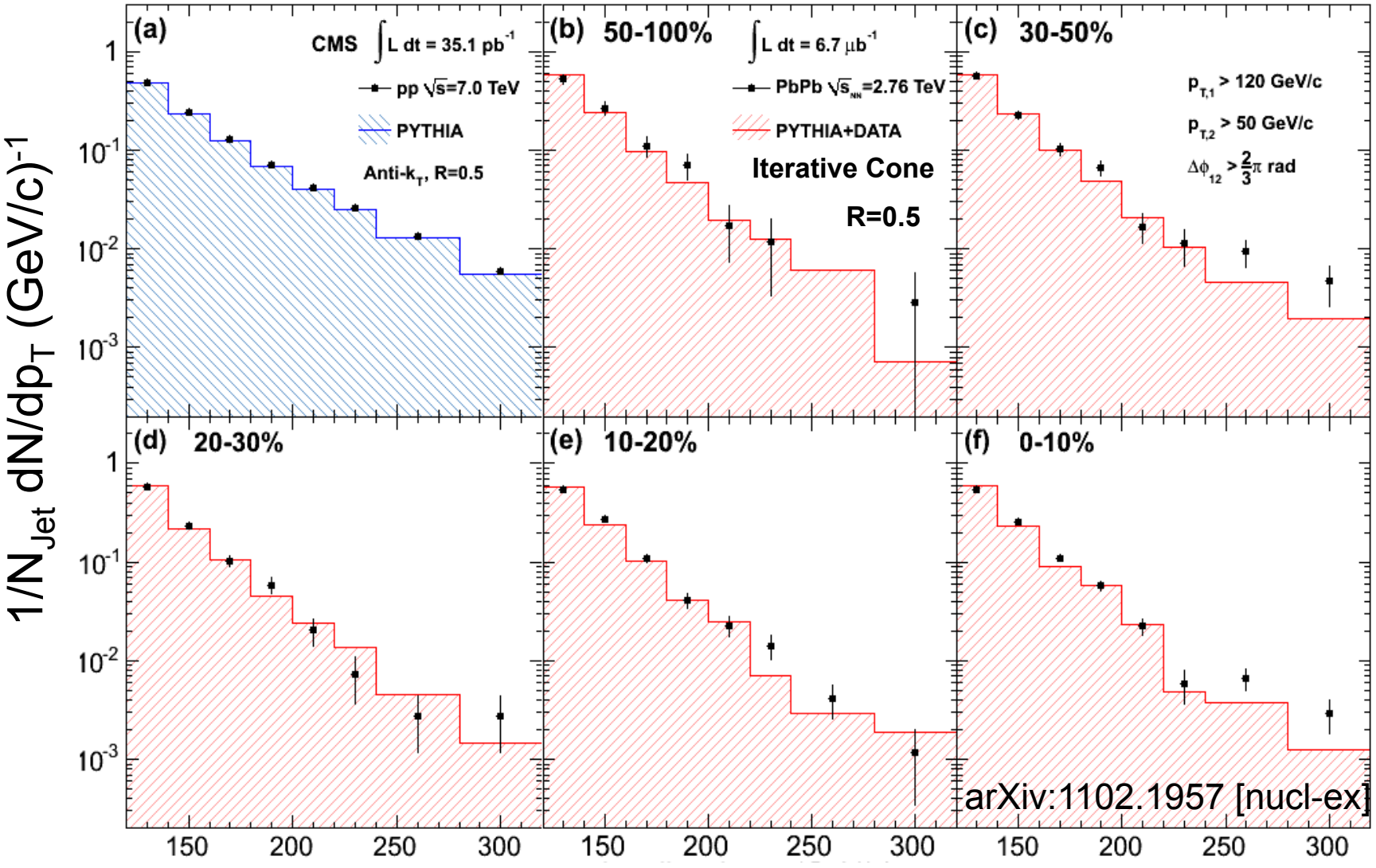
Underlying event subtraction

- Iterative PileUp subtraction



- Good Jet p_T resolution
- Jet p_T corrected to **generator final state particle level**
  - Correction derived from PYTHIA

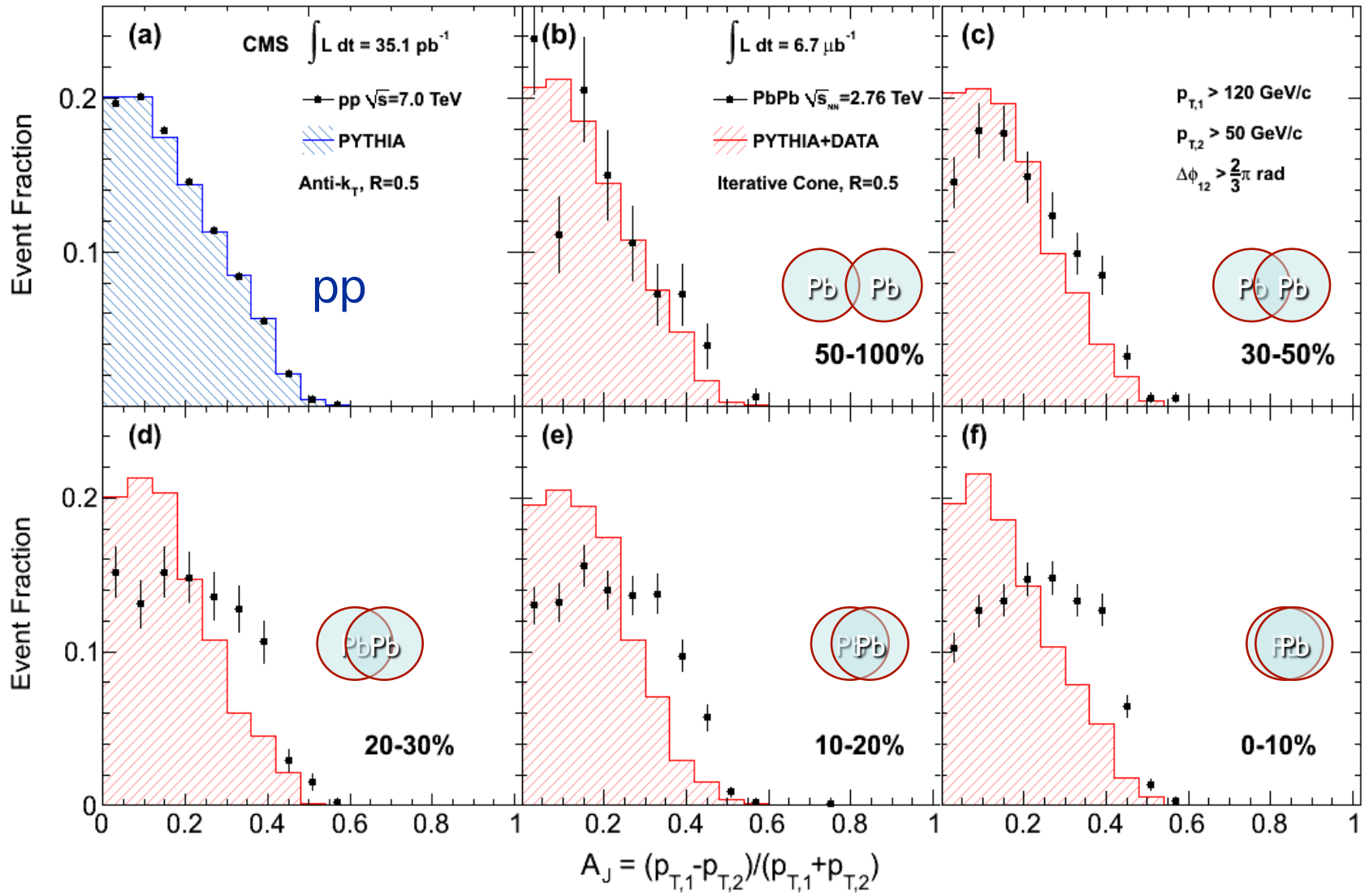
Jet Spectra and Reference



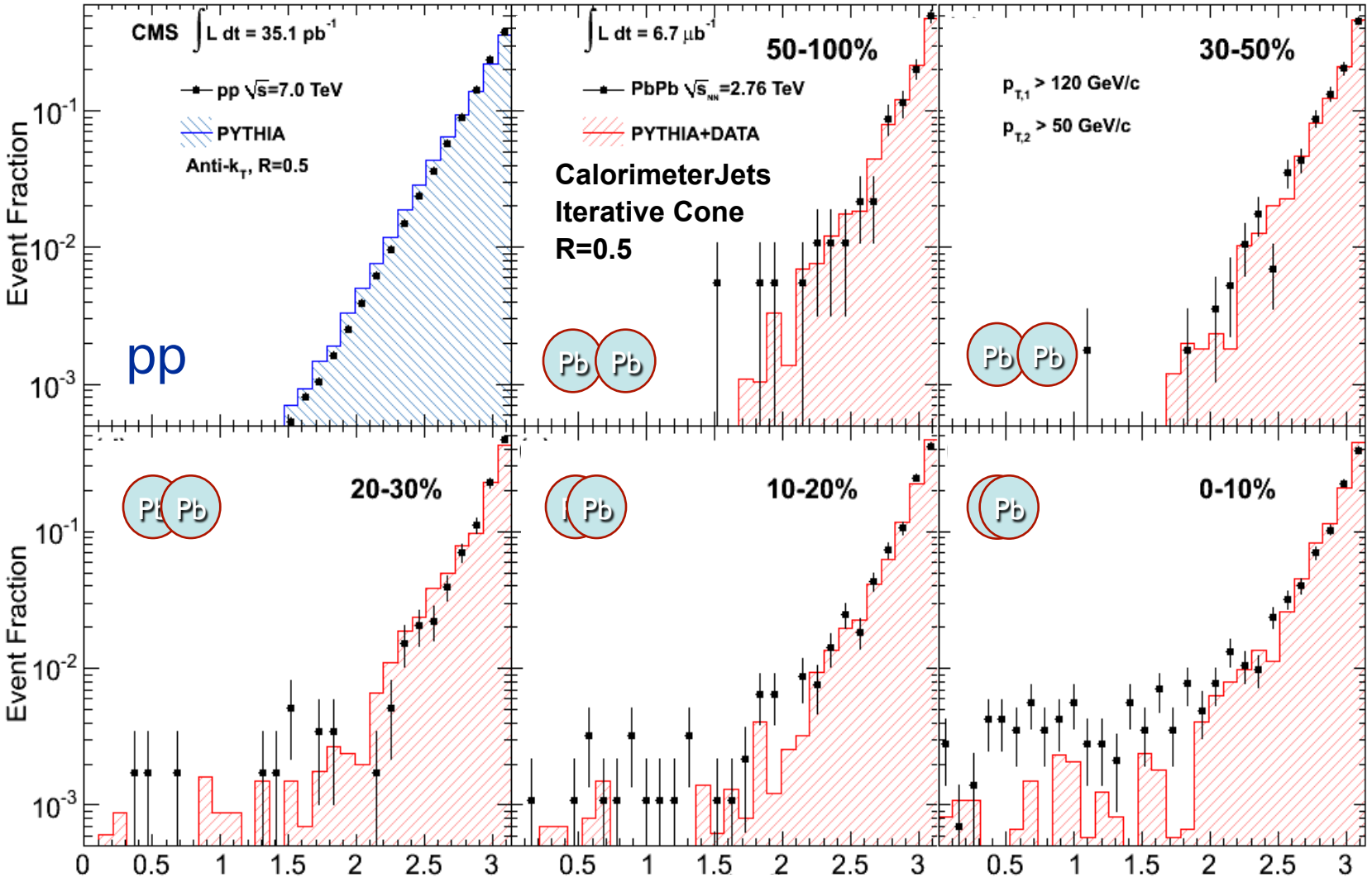
Large data sample, reach to very high jet p_T

*Uncorrected for p_T resolution

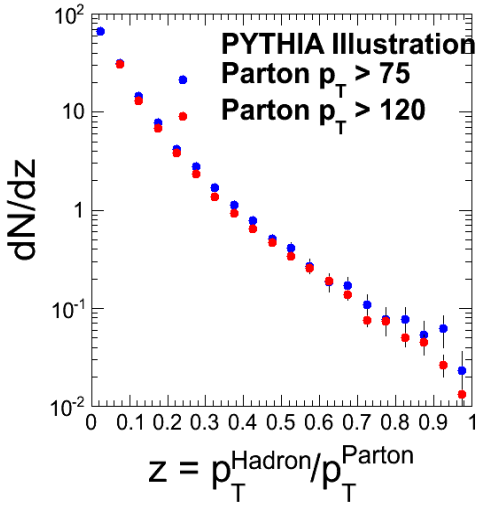
Dijet Energy Imbalance

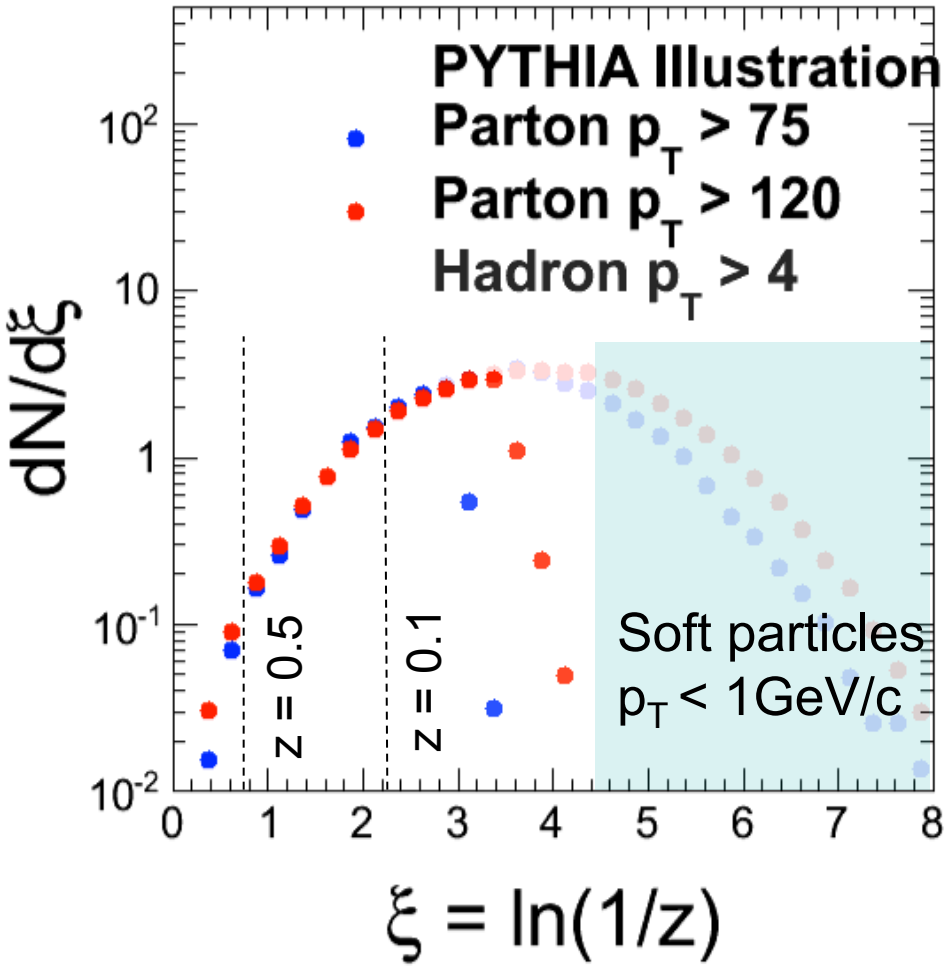


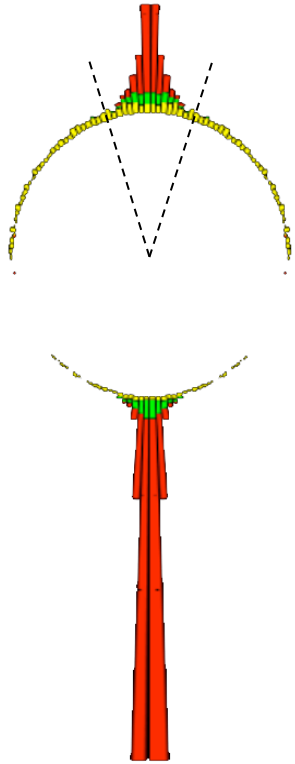
Jet Angular Correlation



ξ=ln(1/z) Representation

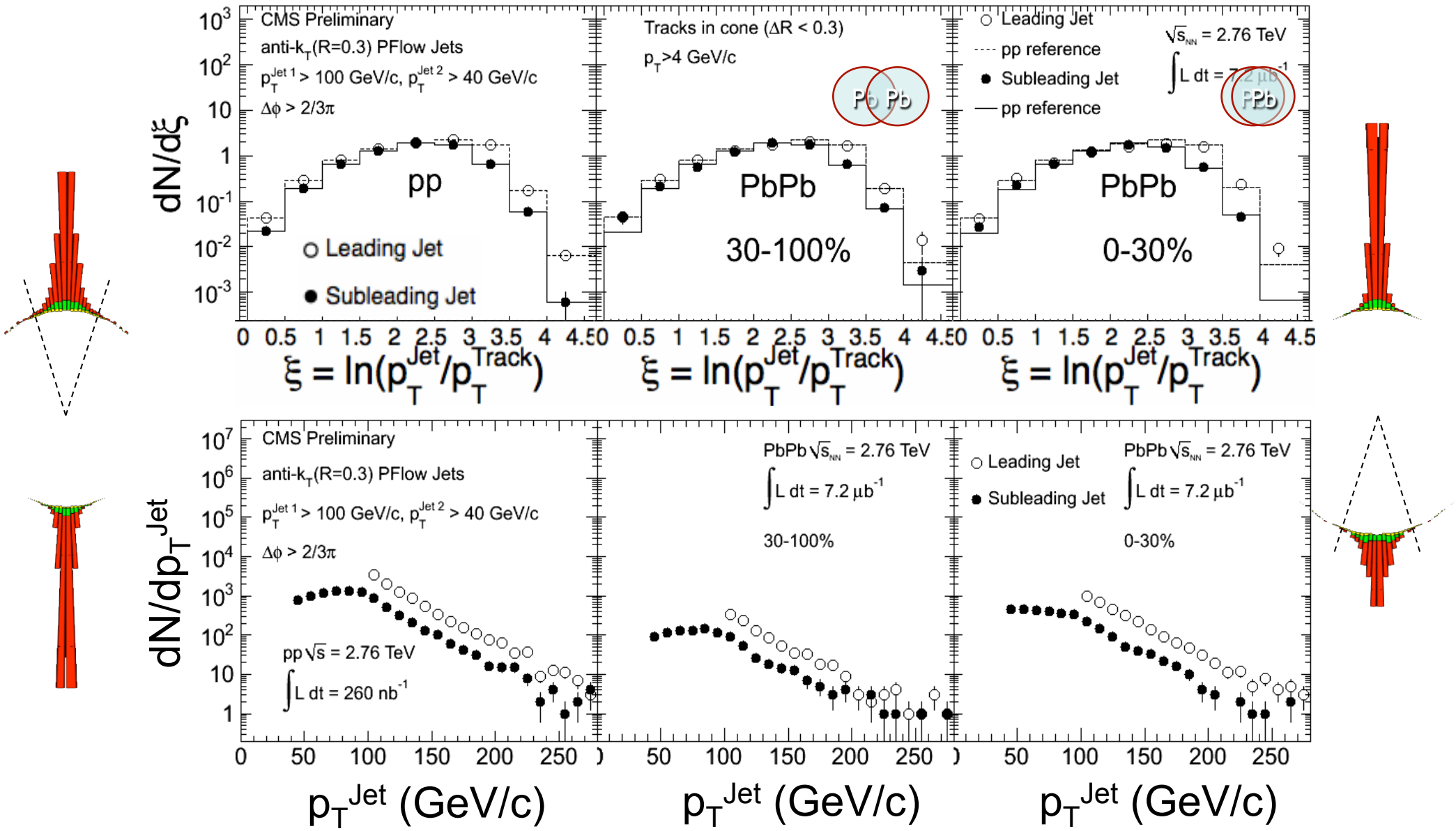






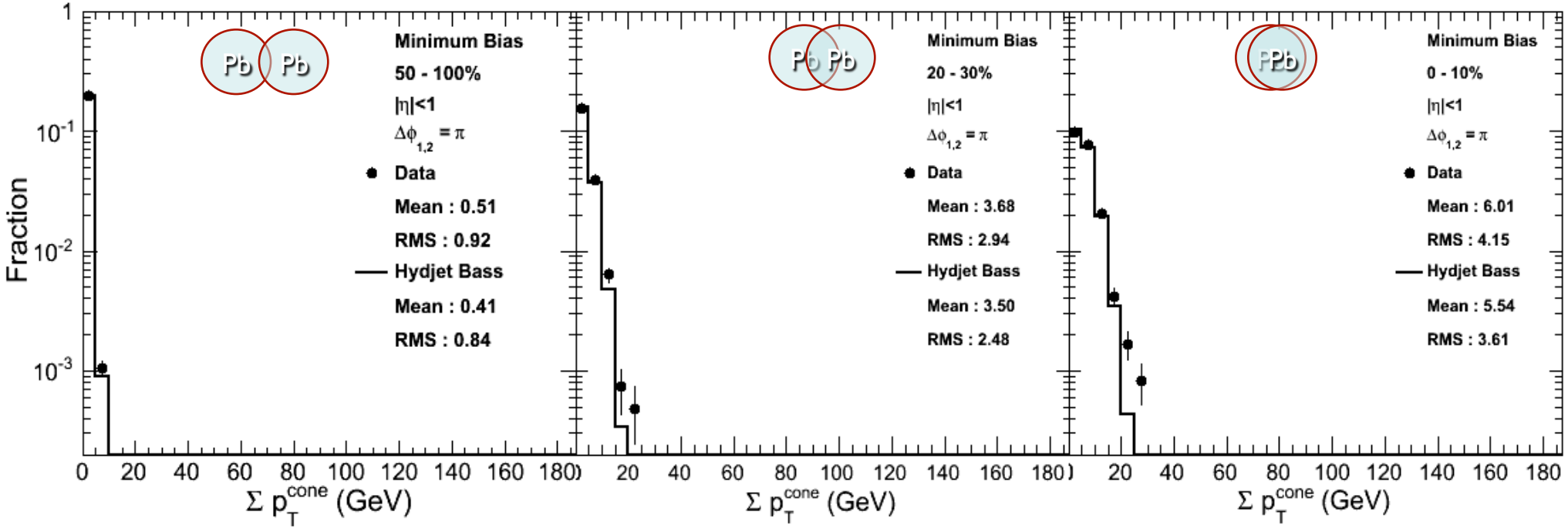
- Eliminate the underlying event contribution, p_T > 4GeV/c
- Select particles in a ΔR=0.3 cone

Fragmentation Functions, pp and PbPb



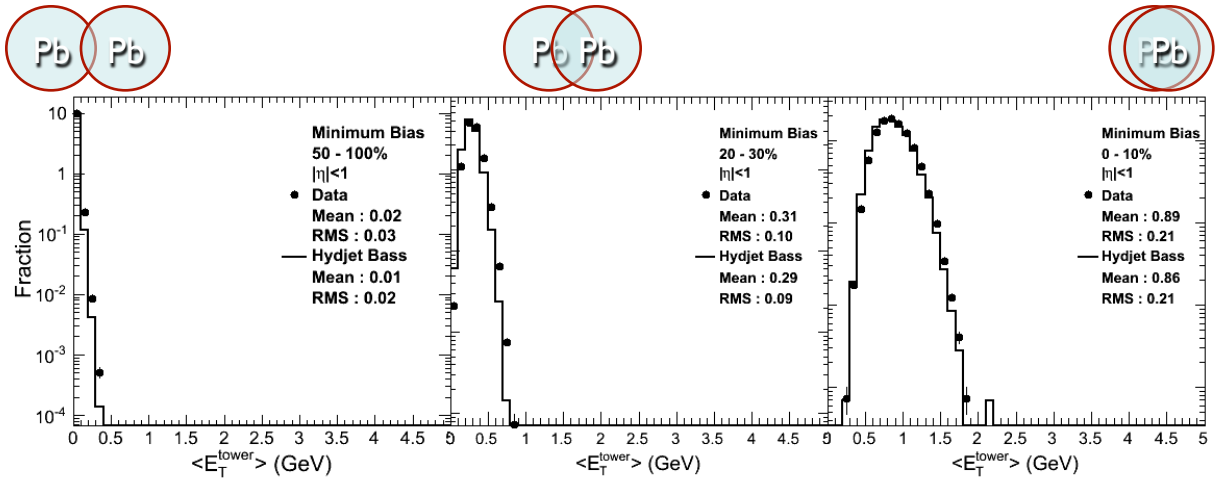
pp as reference for PbPb: Smear pp to PbPb jet p_T resolution
Reweight jet p_T spectrum to match PbPb

Random Cone Background



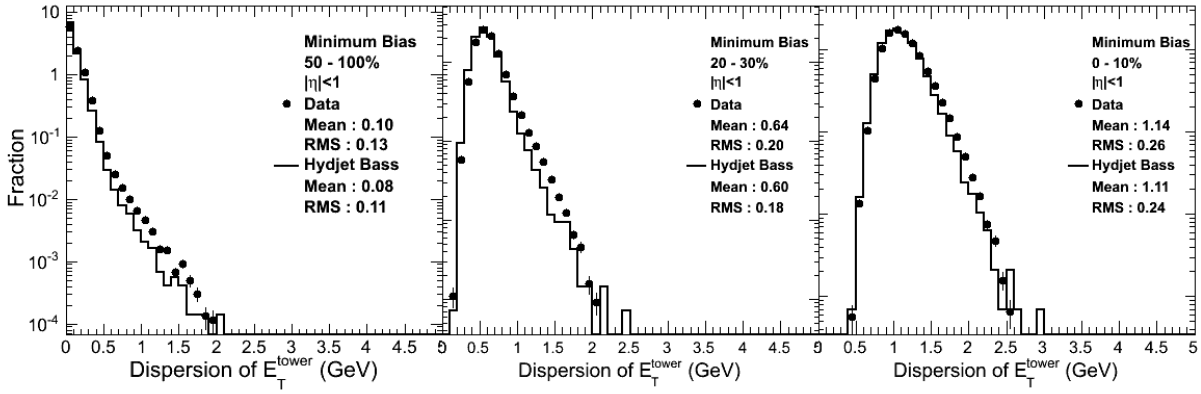
Pileup subtraction per tower

Mean:



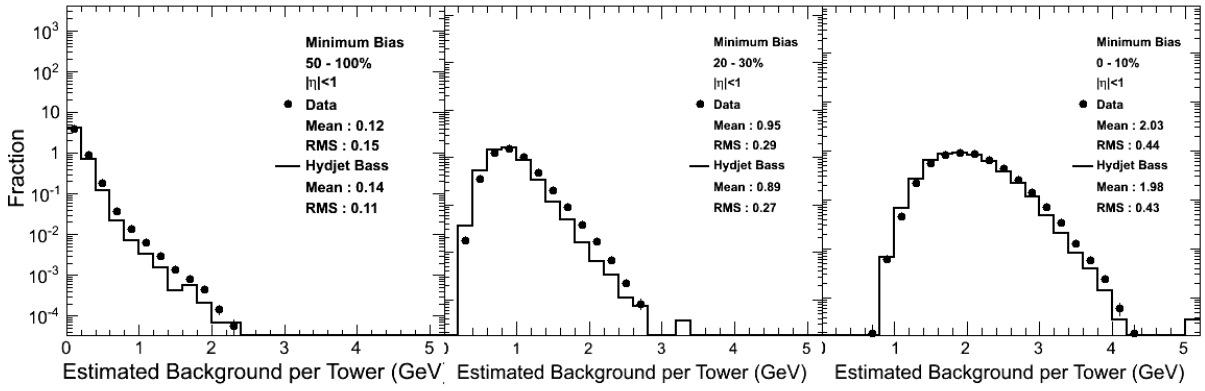
PAS

Dispersion:



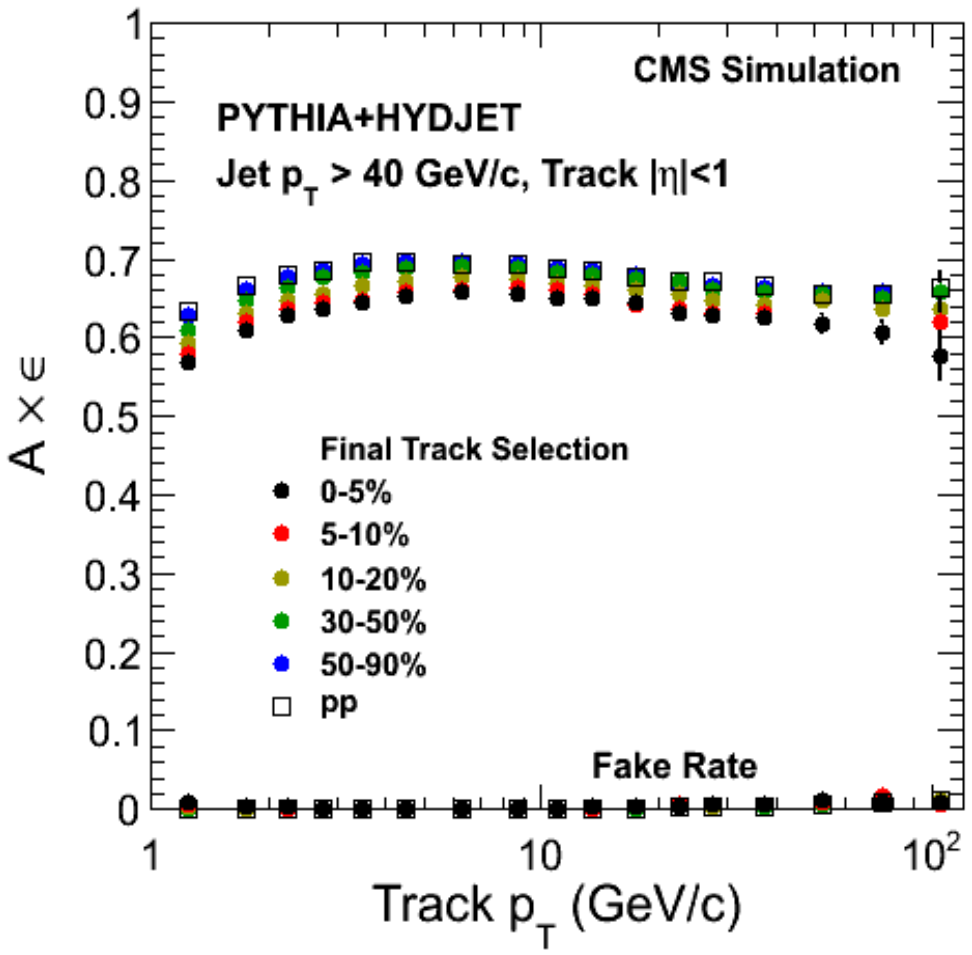
PAS

Subtracted Energy:

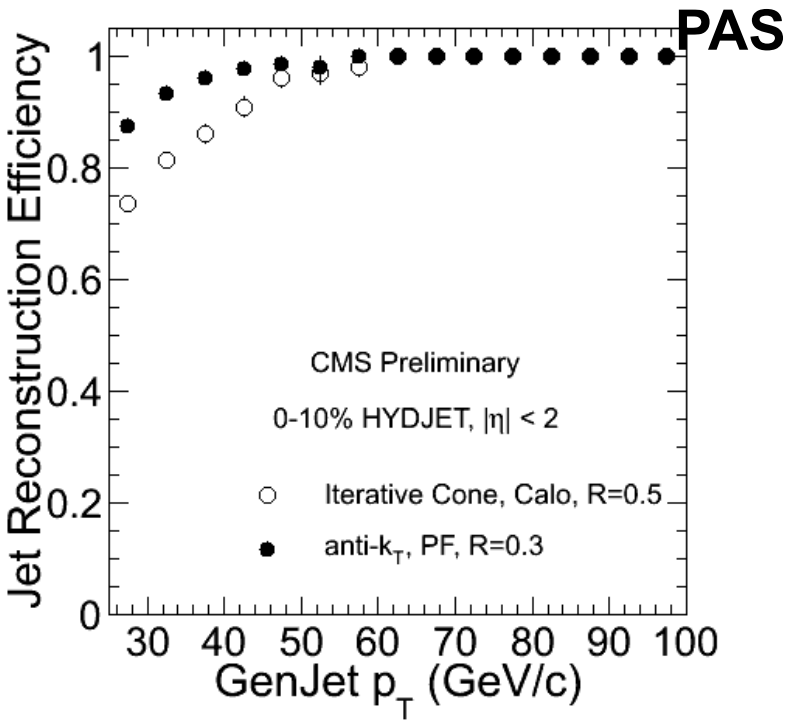


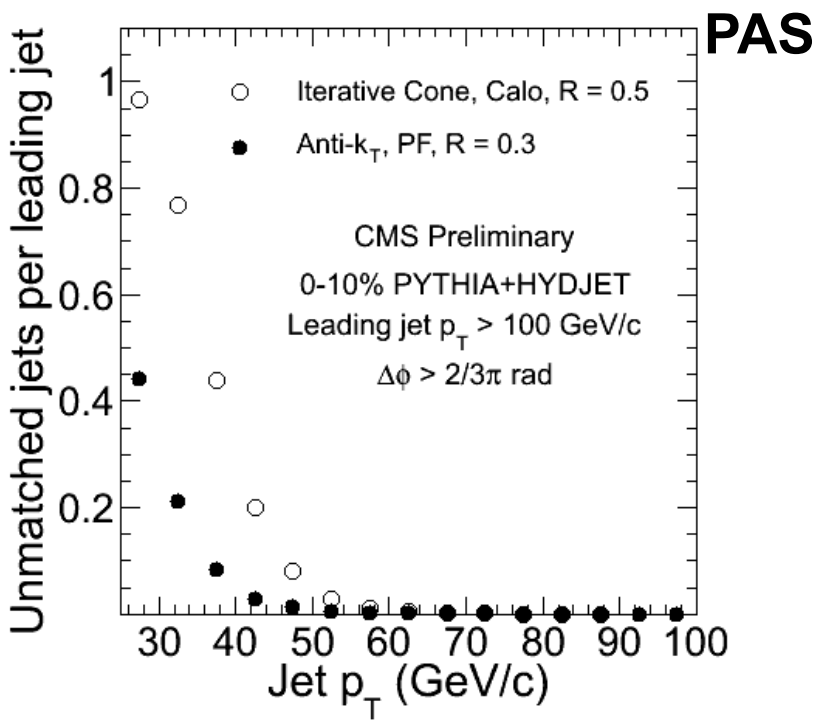
PAS

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