Parton Energy Loss and Jet Fragmentation in PbPb collisions

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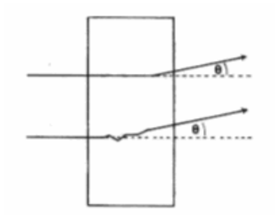
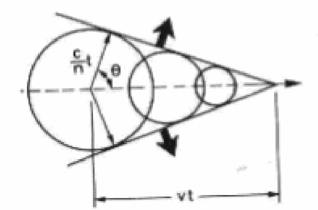
for the CMS Collaboration

Motivation

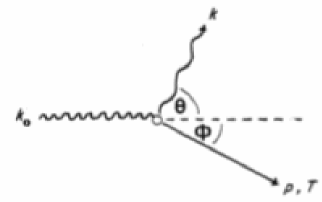
- Experimental handles on Energy Loss mechanisms



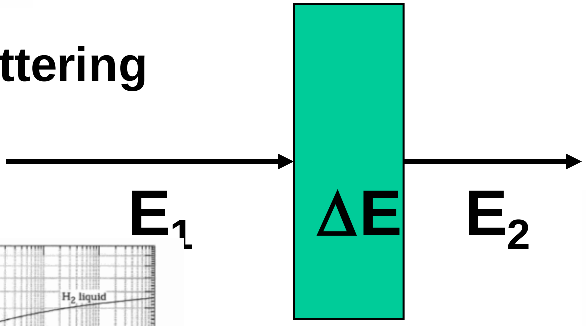
Multiple Scattering

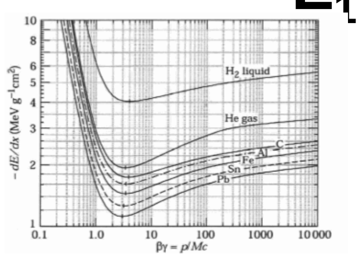


Cherenkov Radiation

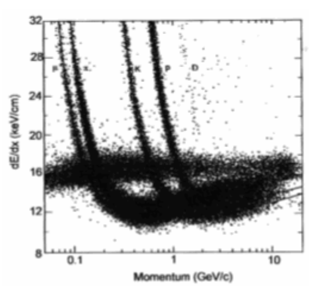


Compton Scattering





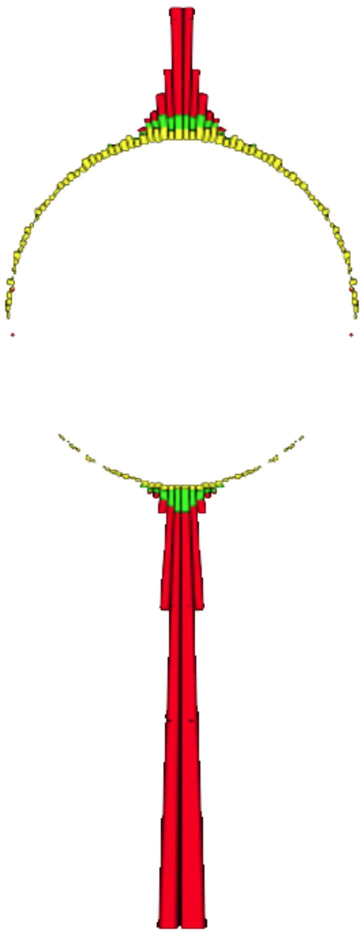
Bethe Bloch



Specific Ionization

- When studying the parton energy loss in a QGP we should look at all aspects of the energy loss mechanism

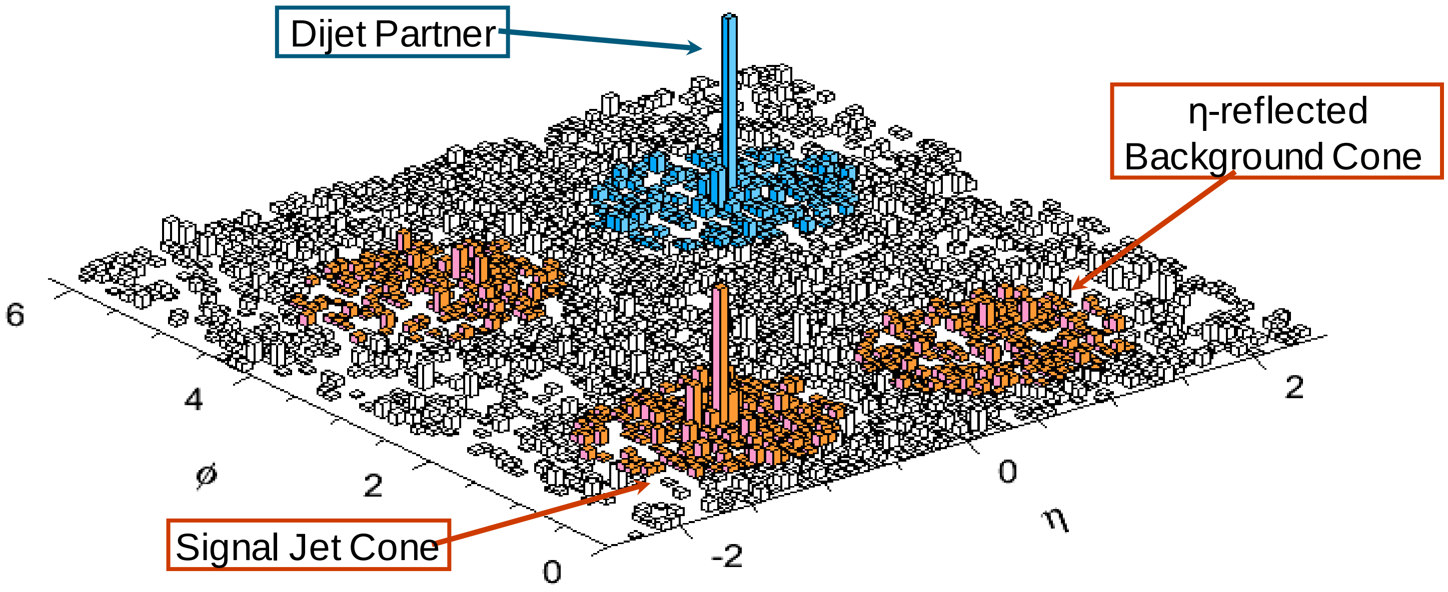
Jet Measurements in PbPb Collisions



- From Yetkin's presentation:
  - Angular correlation of dijets
    - Angular correlation of partons is not affected by the medium
    - Constrains the scattering mechanisms
  - Large dijet momentum imbalance observed
    - Direct observation of parton energy loss
    - Access to the ΔE of the energy loss mechanism
- More detailed studies:
  - Jet Track correlations
    - Do we find the "lost" energy in the vicinity of the jet?
    - Medium response to the jet
  - Missing p_T
    - Global p_T balance in the event can tell us where the energy lost by the parton manifests itself
  - Jet fragmentation functions
    - Is the jet itself modified due to the energy loss?

Track-Jet Correlations

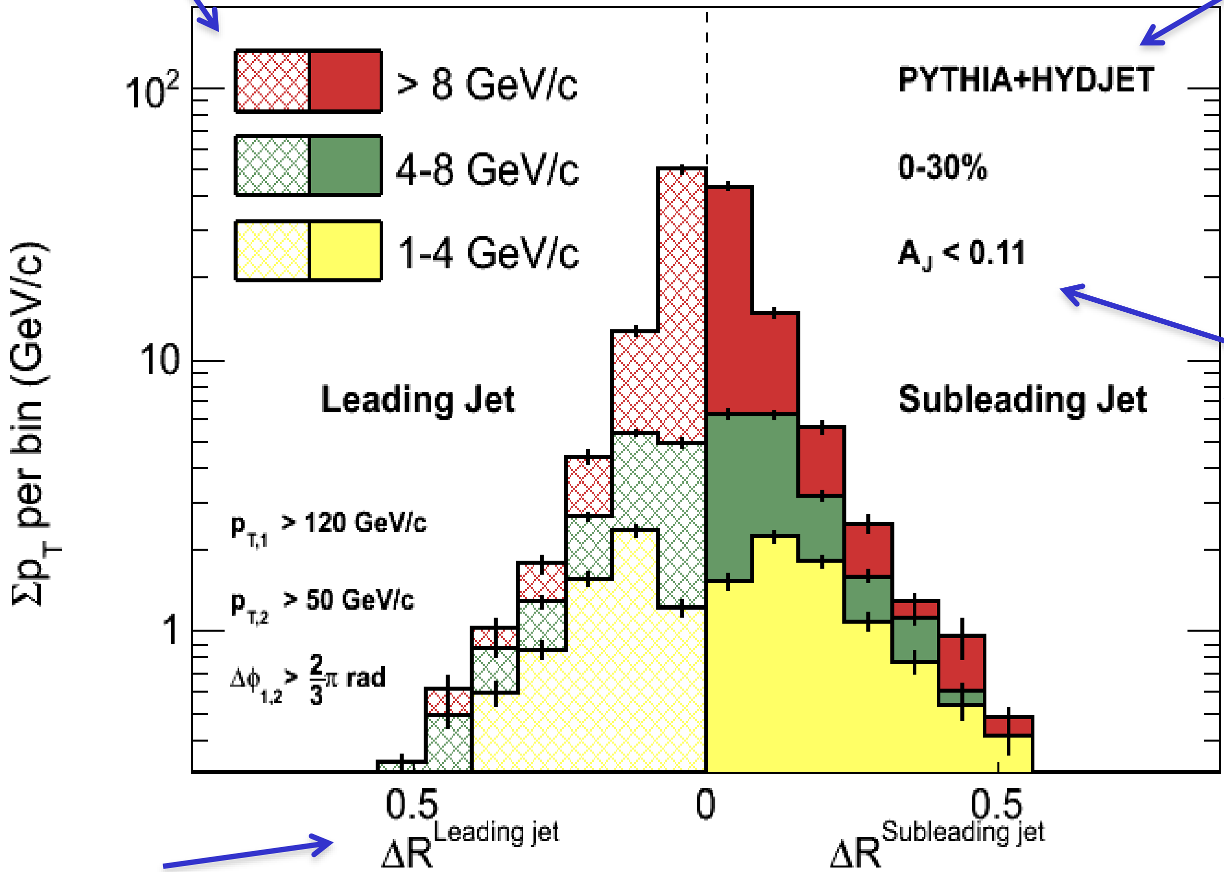
- Study charged particle distributions within jet cones
  - Use η reflected (η -> -η) reference cones for jet-by-jet subtraction of Pb+Pb underlying event
    - This avoids φ dependent variations due to elliptic flow
    - Exclude $|\eta_{Jet}| < 0.8$ and $|\eta_{Jet}| > 1.6$
  - Study associated track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



Track-Jet Correlations

Look at the sum p_T of charged tracks in 3 different p_T ranges

Baseline is PYTHIA+HYDJET where generator information is available for charged particles



Selected A_J range

Plot against ΔR from the jet axis for both the leading and subleading jet

Track-Jet Correlations

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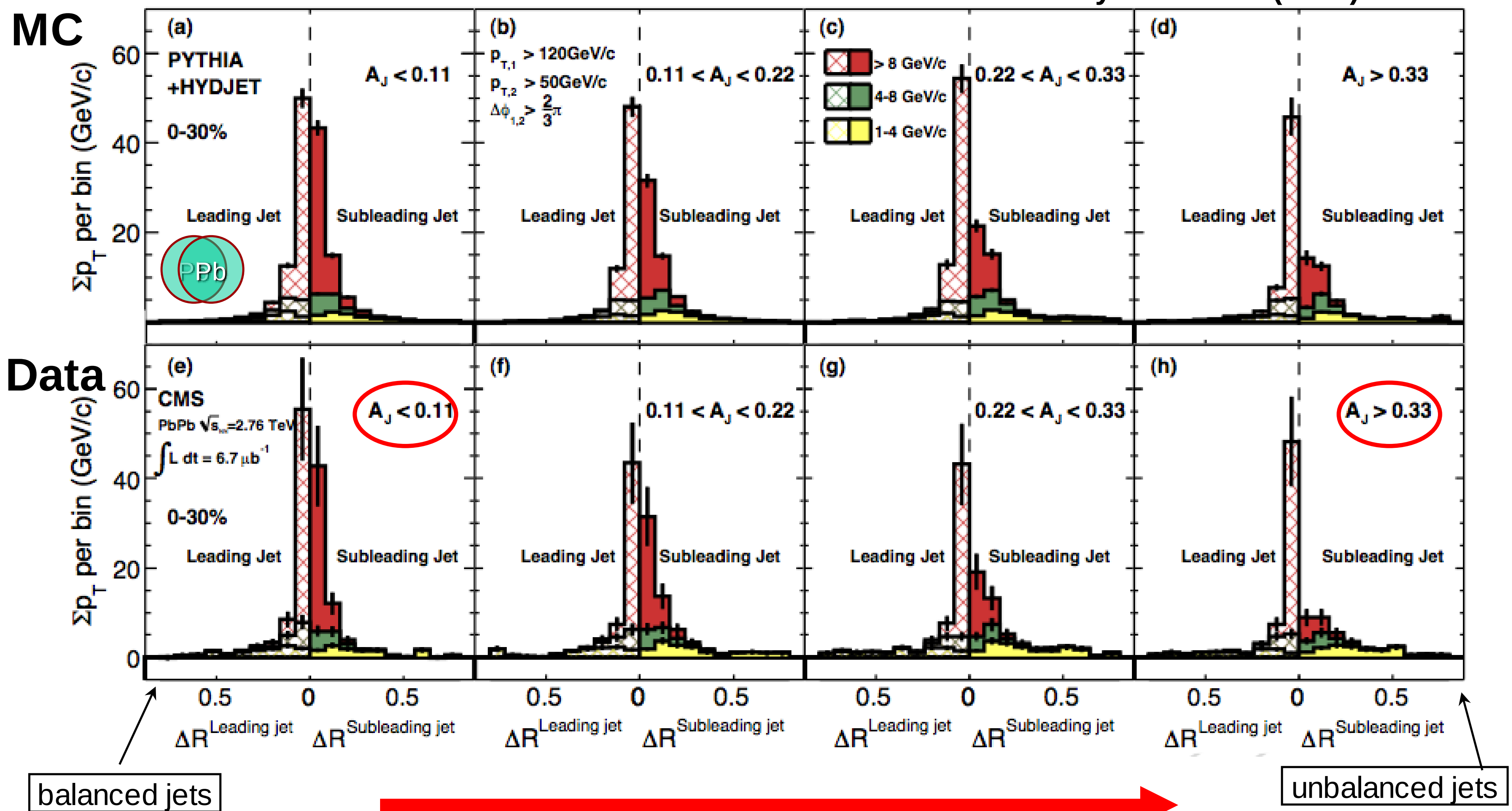

Increasing A_J

Track-Jet Correlations

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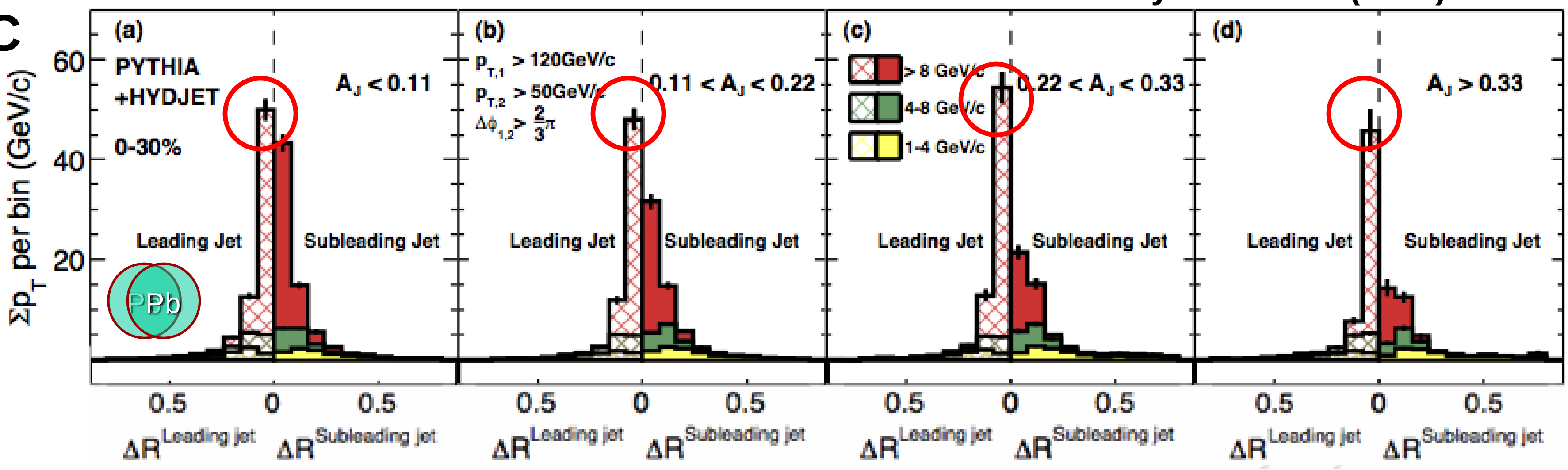
MC



- PYTHIA+HYDJET:
  - The leading jets show a fragmentation pattern of hard partons, i.e. large energy sum for high p_T particles

Track-Jet Correlations

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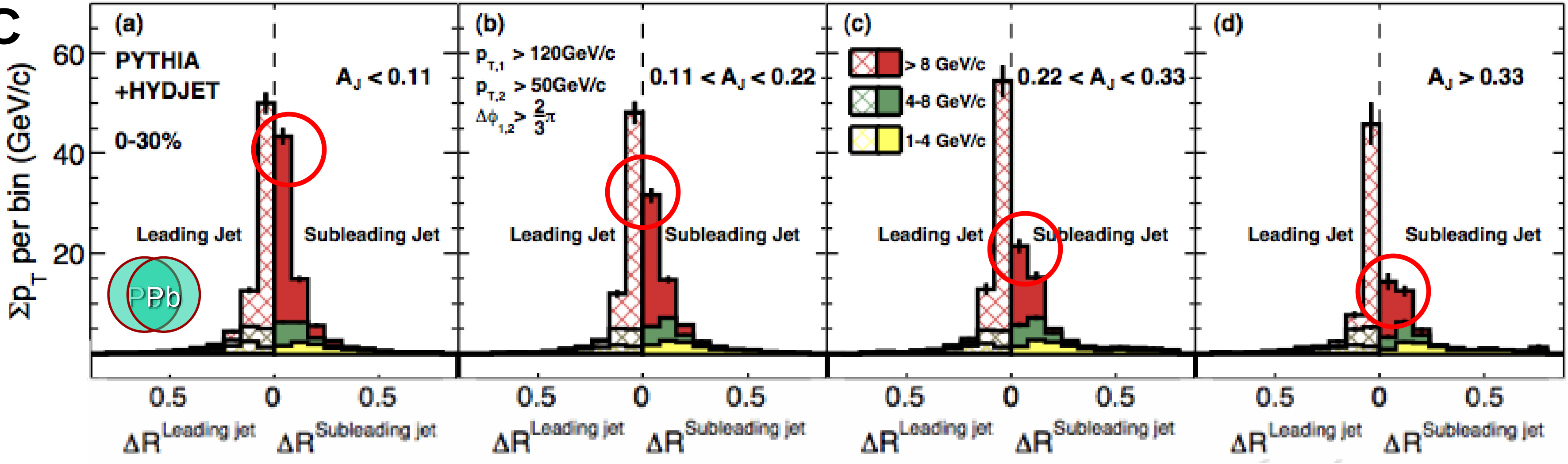
MC



- PYTHIA+HYDJET:
  - The associated subleading jets show a softer fragmentation pattern with increasing A_J
  - The asymmetry in the calorimeter jet energies is reflected in the fragmentation pattern into charged hadrons
  - The momentum balance in Pythia is carried by a third jet

Track-Jet Correlations

- Data:
  - The leading jets also show a fragmentation pattern of hard partons, even for A_J>0.33

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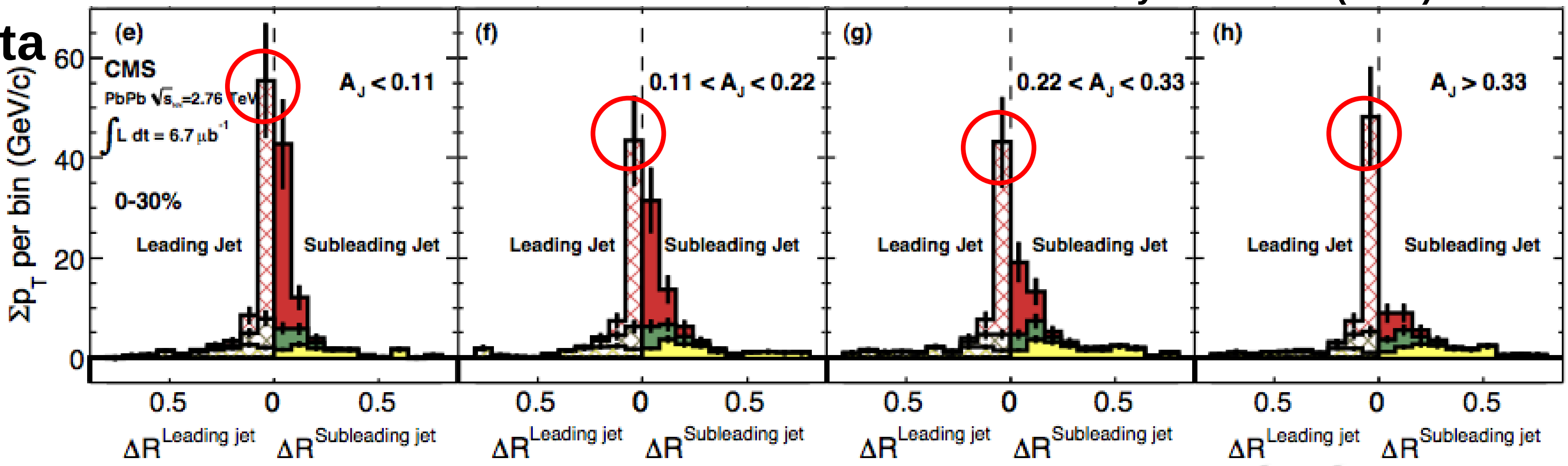
Data



Track-Jet Correlations

- Data:
  - The subleading jets also show softening of the fragmentation pattern with increasing A_J, i.e. lower jet energy

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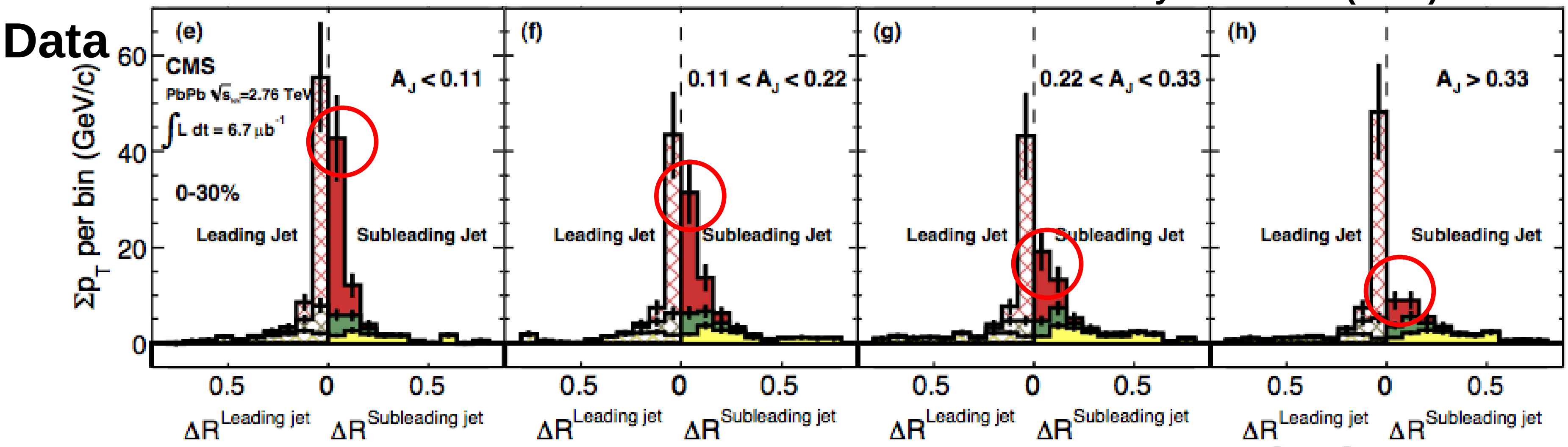

Track-Jet Correlations

- Data:
  - The observed calorimeter jet imbalance is reflected in the fragmentation pattern into charged particles
  - This supports the interpretation that we can infer a momentum imbalance in the fragmenting partons from the calorimeter jet imbalance

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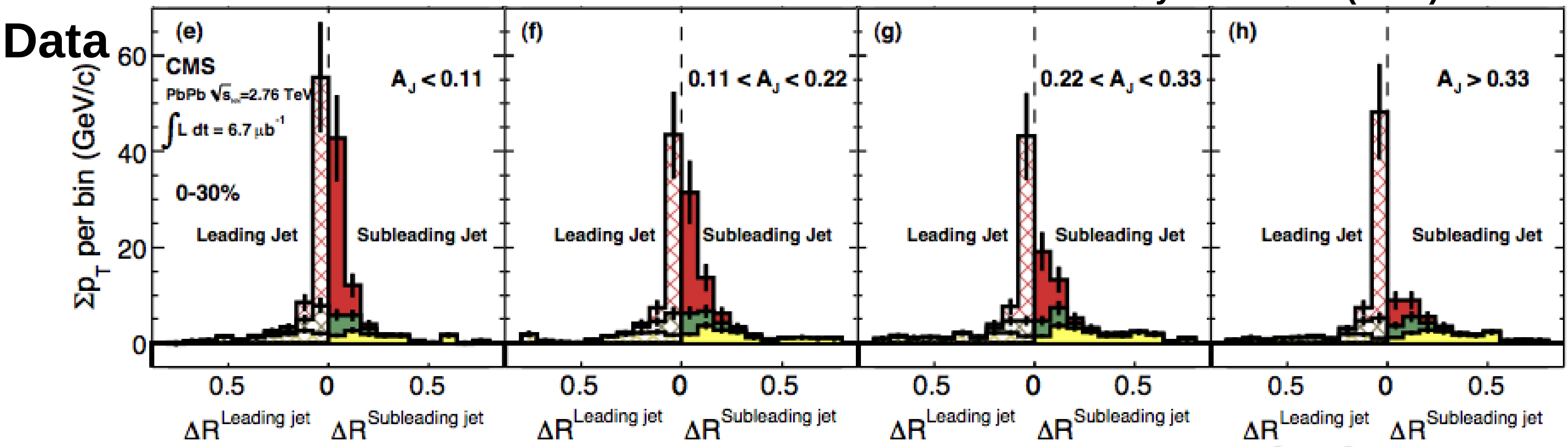

Track-Jet Correlations

- In dijet events with a large imbalance, A_J>0.33, we find significantly more energy in tracks below p_T of 4GeV/c at large ΔR
  - But, not nearly enough to restore the dijet balance
- No indication of cone like structures around the jet up to a cone size of 0.8

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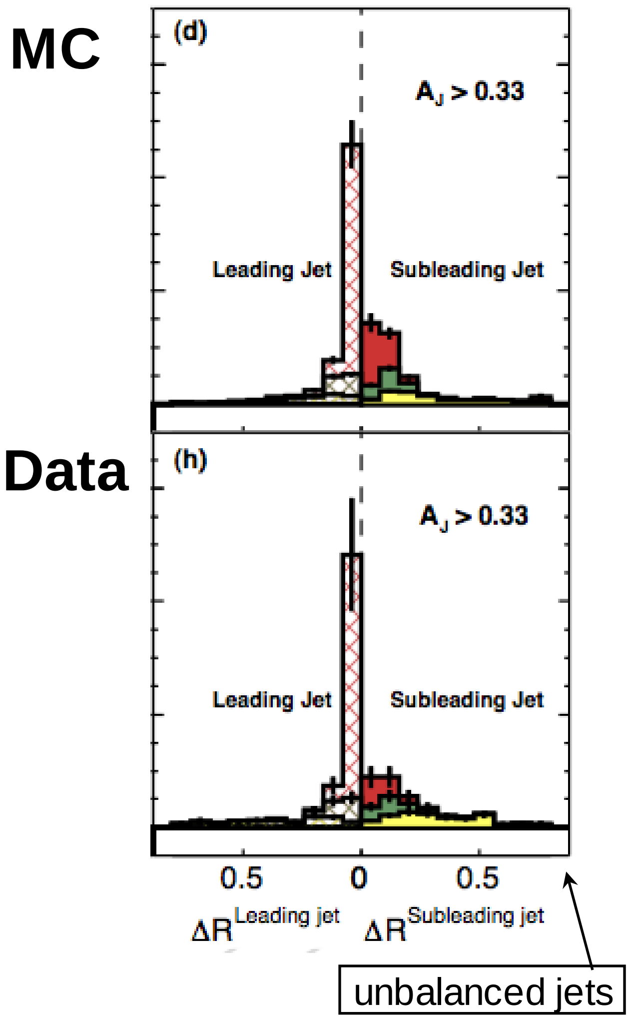


Missing-$p_T^{\parallel}$

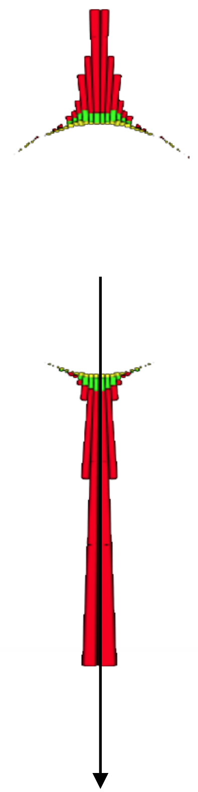
Missing $p_T^{\parallel}$:

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

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

$p_T > 0.5$ GeV/c and

$|\eta| < 2.4$



Leading jet defines direction

Missing-$p_T^{||}$

Missing $p_T^{||}$:

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

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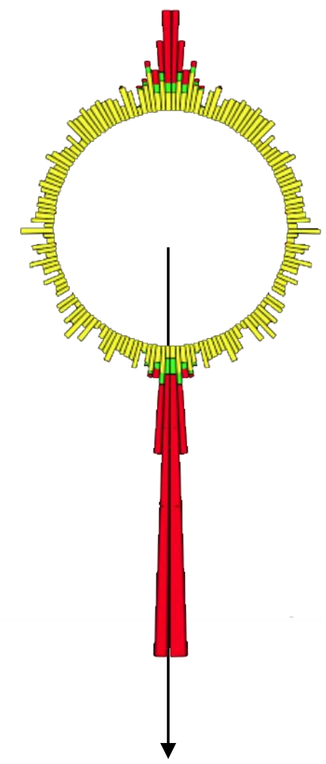


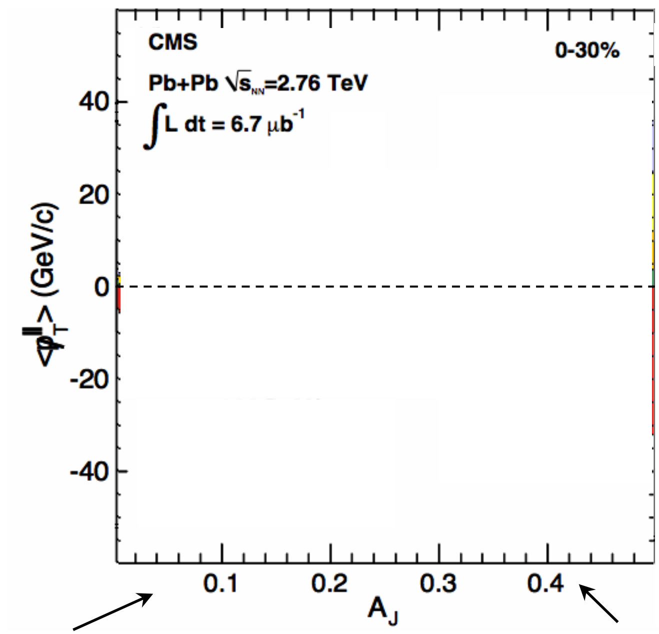
Sum all tracks in the event

Missing-$p_T^{||}$

Missing $p_T^{||}$:

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

0-30% Central PbPb

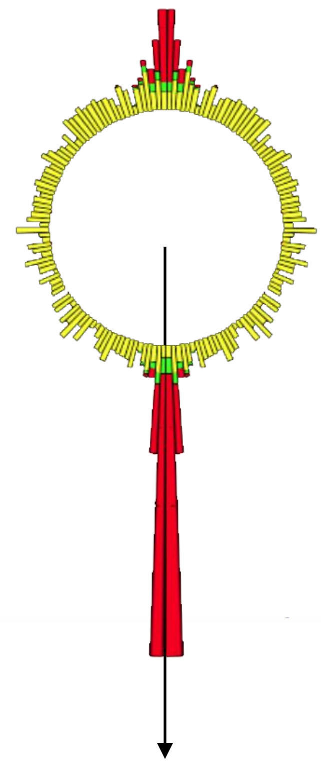


balanced jets

unbalanced jets

excess away from leading jet

excess towards leading jet



Missing-$p_T^{||}$

Missing $p_T^{||}$: □

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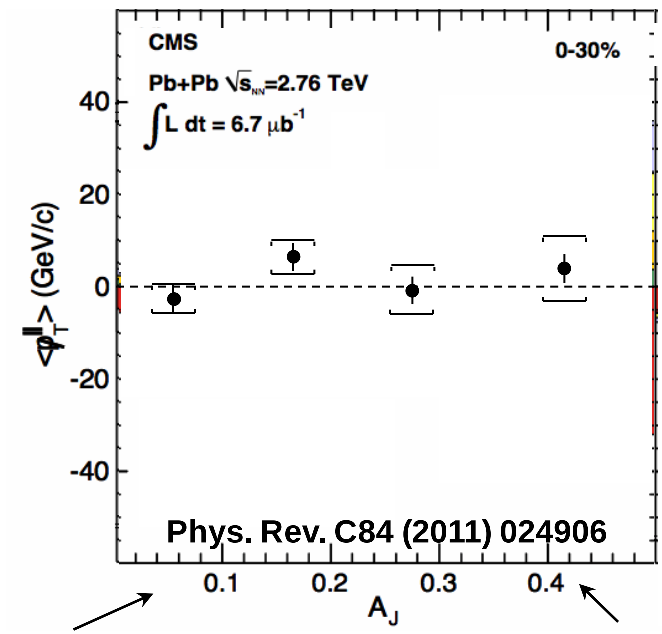
0-30% Central PbPb

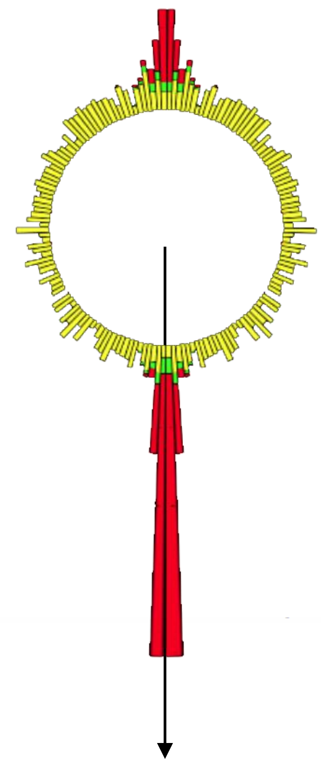


balanced jets

unbalanced jets

excess away from leading jet

excess towards leading jet



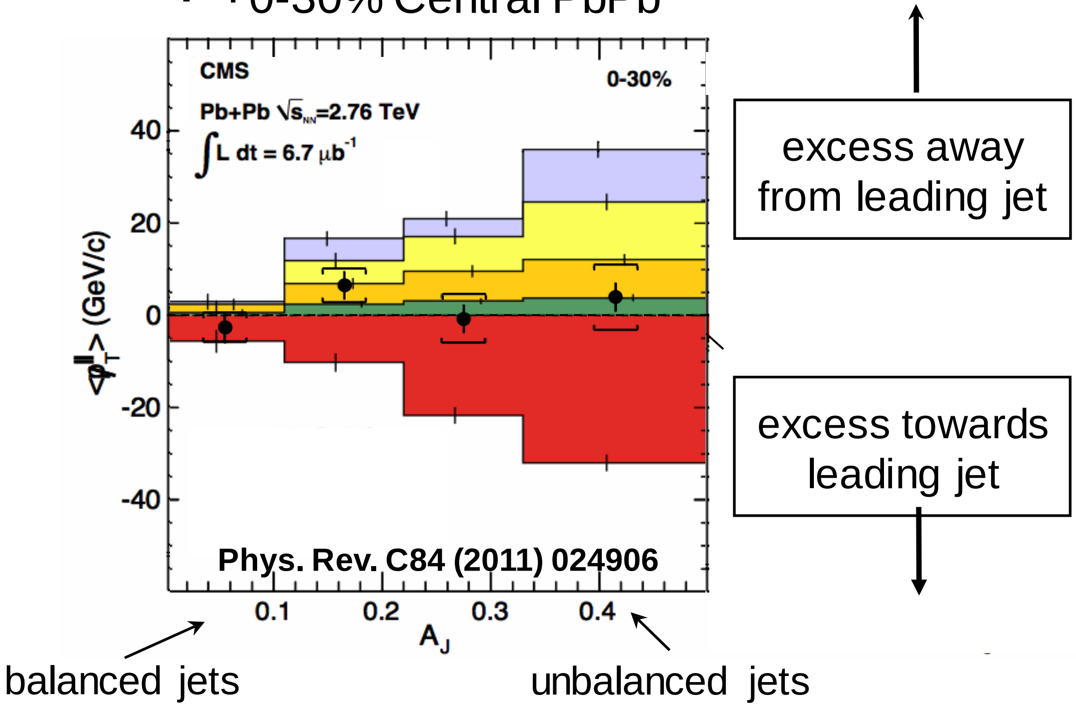
Integrating over the whole event final state the momentum balance is restored

Missing-$p_T^{||}$

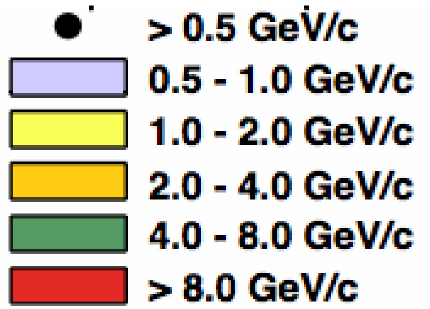
Missing $p_T^{||}$: □

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

0-30% Central PbPb

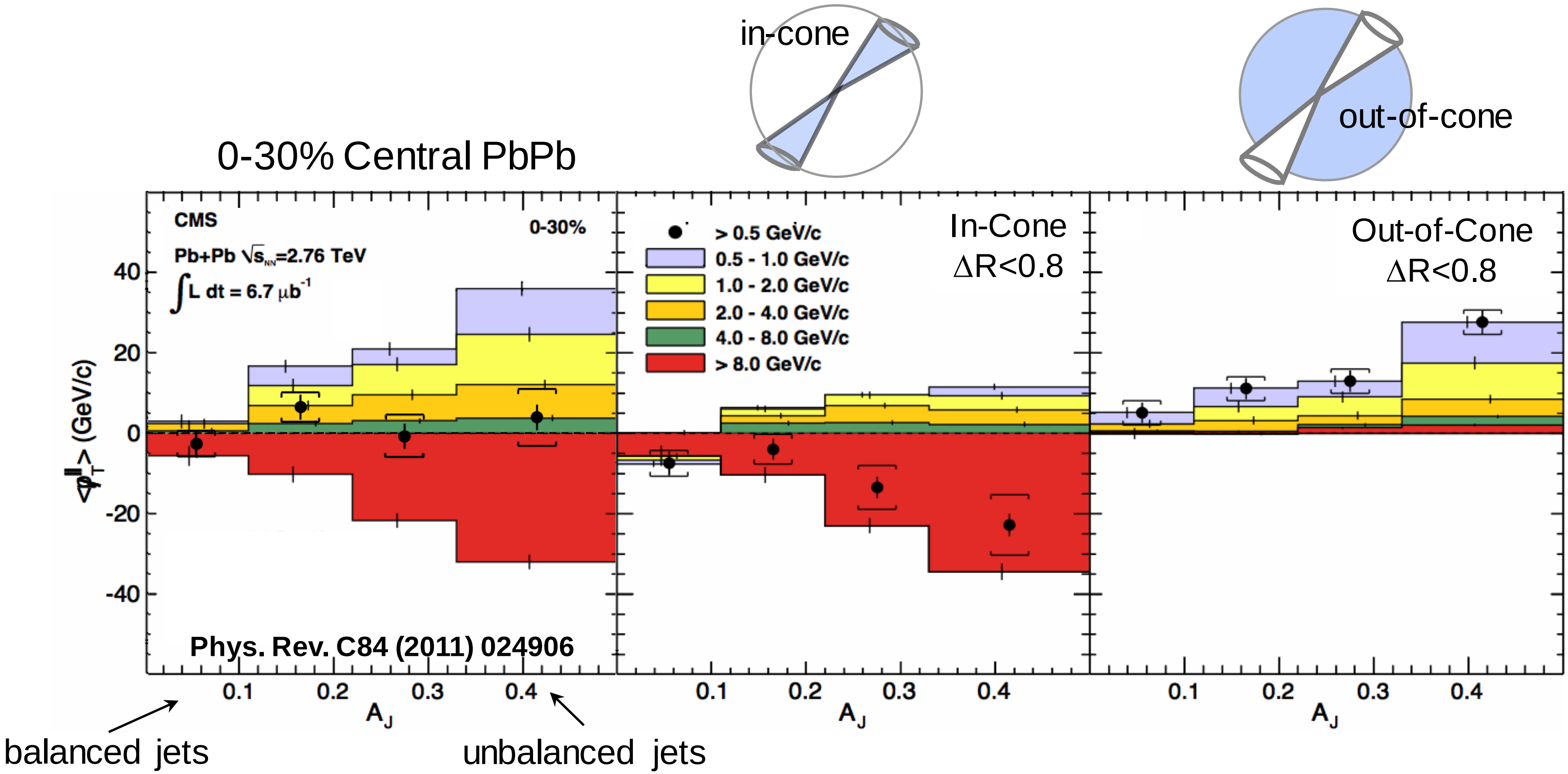


Calculate missing p_T in ranges of track p_T:



The momentum difference in the dijet is balanced by low p_T particles

Missing-$p_T^{||}$


in-cone
out-of-cone
0-30% Central PbPb
CMS
0-30%
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV
$\int L\,dt = 6.7\ \mu b^{-1}$
> 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
In-Cone
ΔR<0.8
Out-of-Cone
ΔR<0.8
$\langle p_T^{||} \rangle$ (GeV/c)
40
20
0
-20
-40
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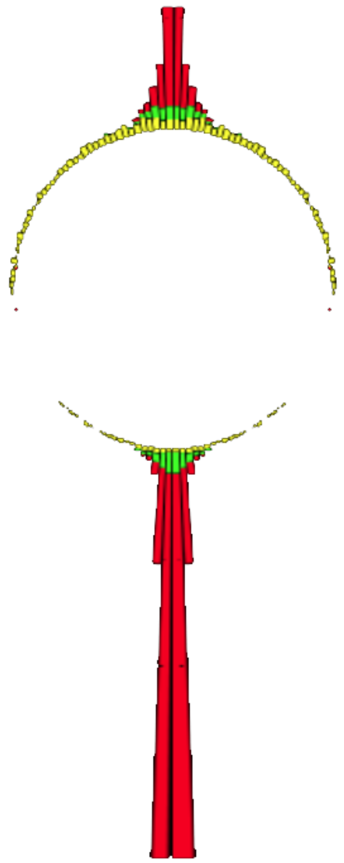
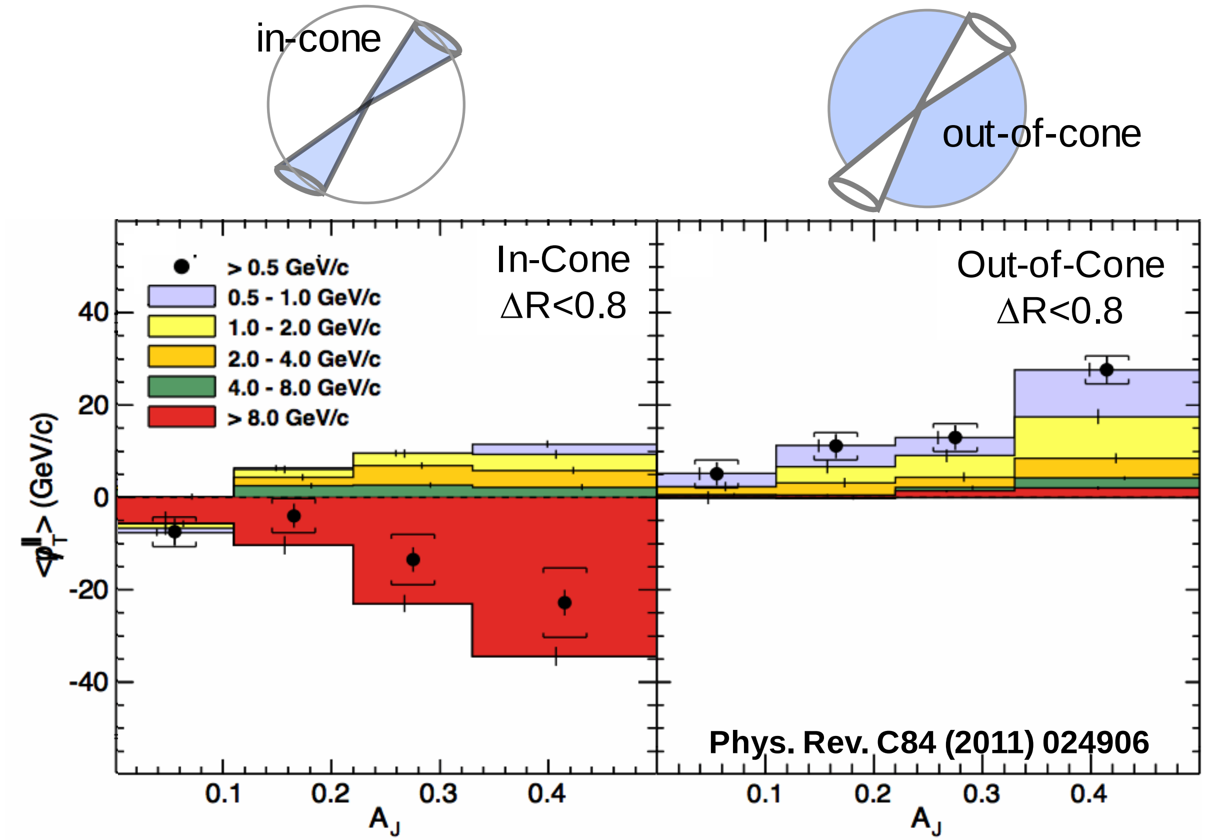
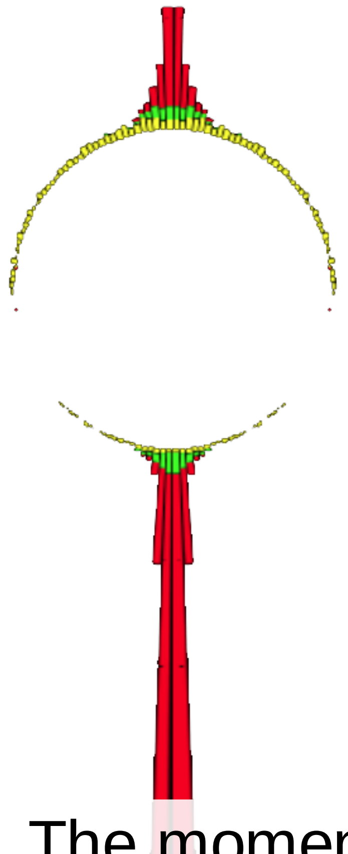
0.1
0.2
0.3
0.4
A_J
balanced jets
unbalanced jets

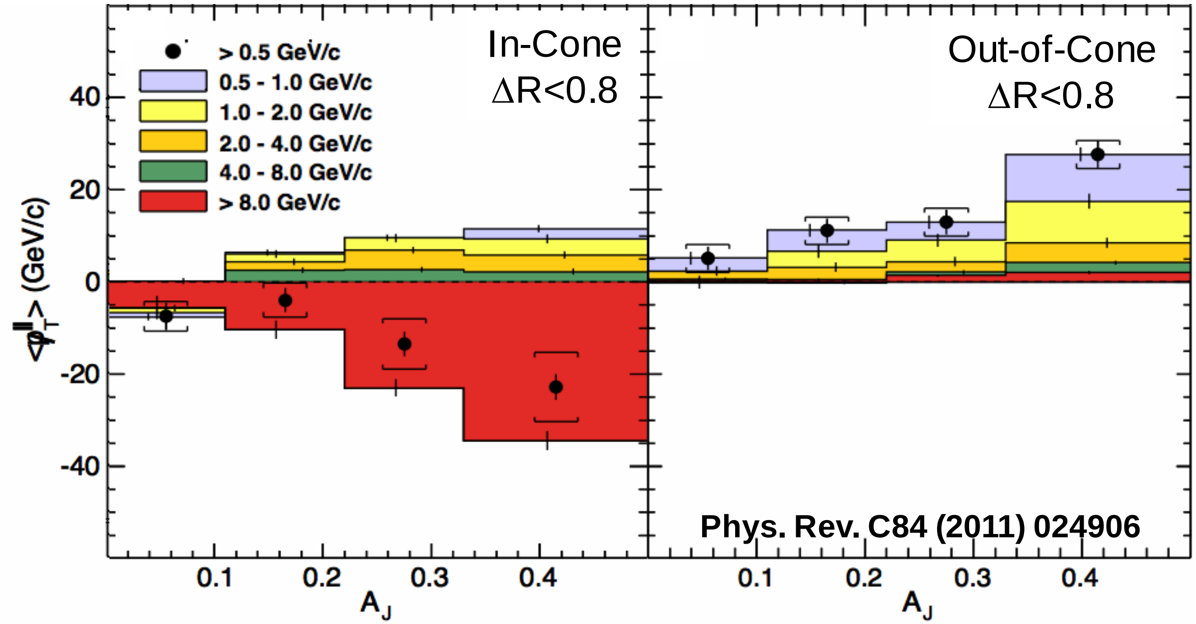
Missing-$p_T^{||}$




in-cone
out-of-cone
In-Cone
ΔR<0.8
Out-of-Cone
ΔR<0.8
> 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
<$p_T^{||}$> (GeV/c)
40
20
0
-20
-40
0.1
0.2
0.3
0.4
A_J
Phys. Rev. C84 (2011) 024906

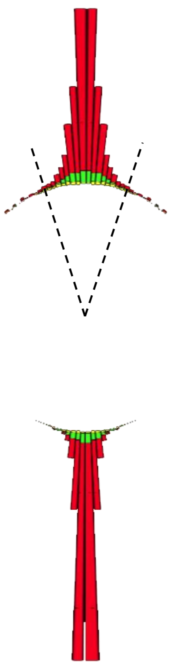
Missing-$p_T^{||}$

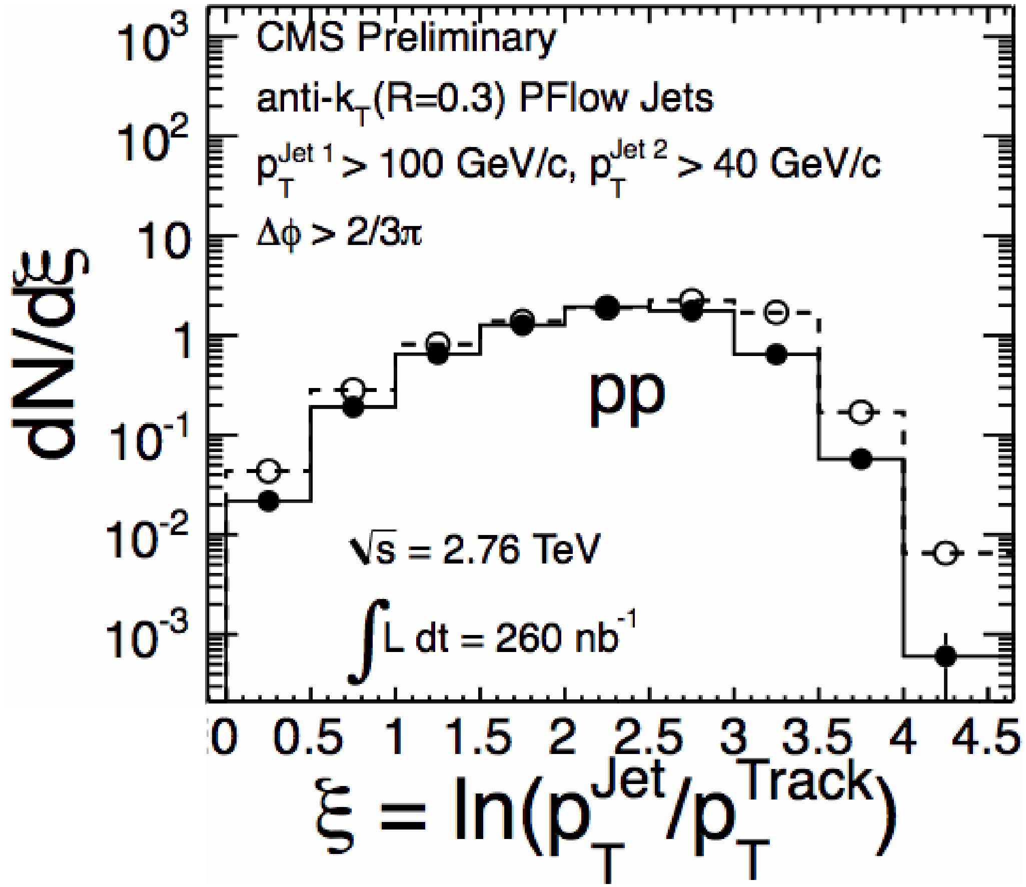




The momentum difference in the dijet is balanced by low p_T particles at large angles relative to the away side jet axis

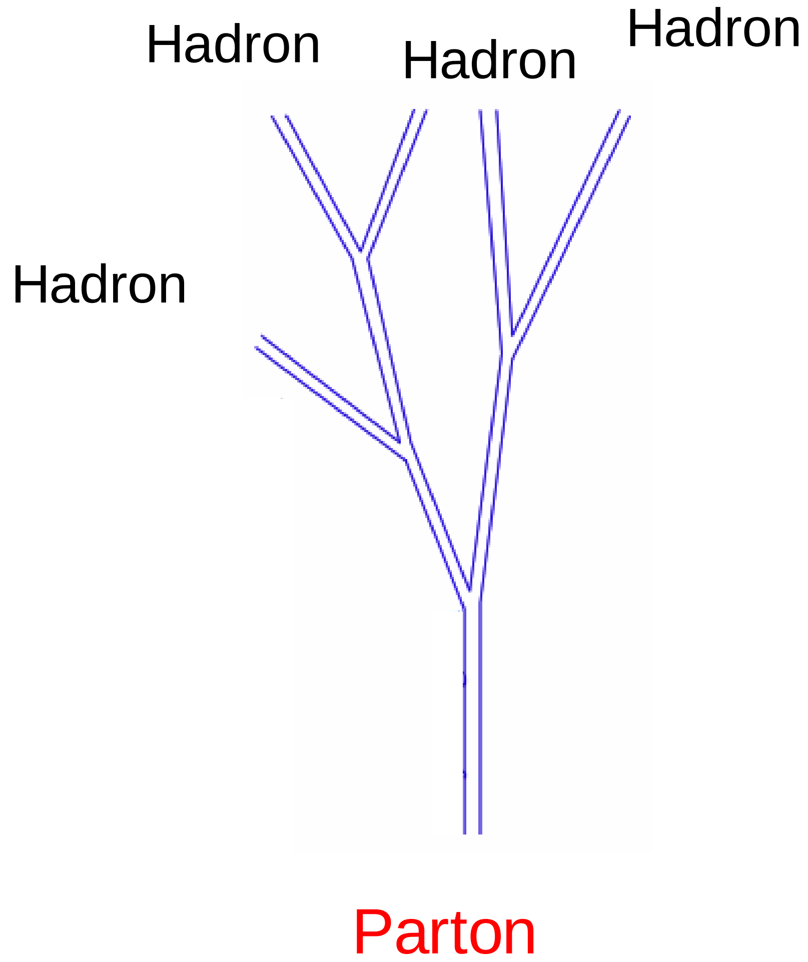
Fragmentation Functions



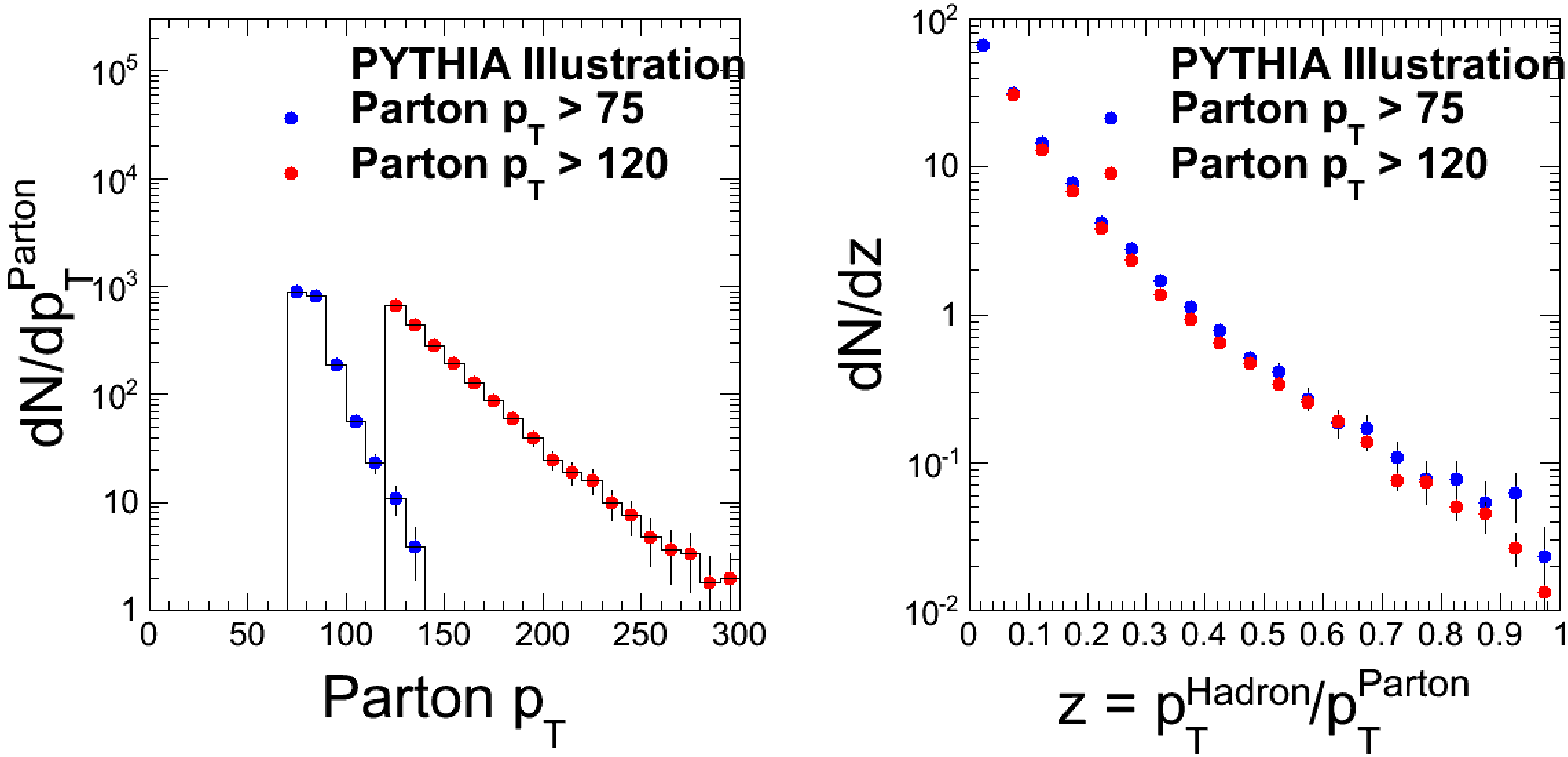


Parton Fragmentation

Partons fragment to Hadrons

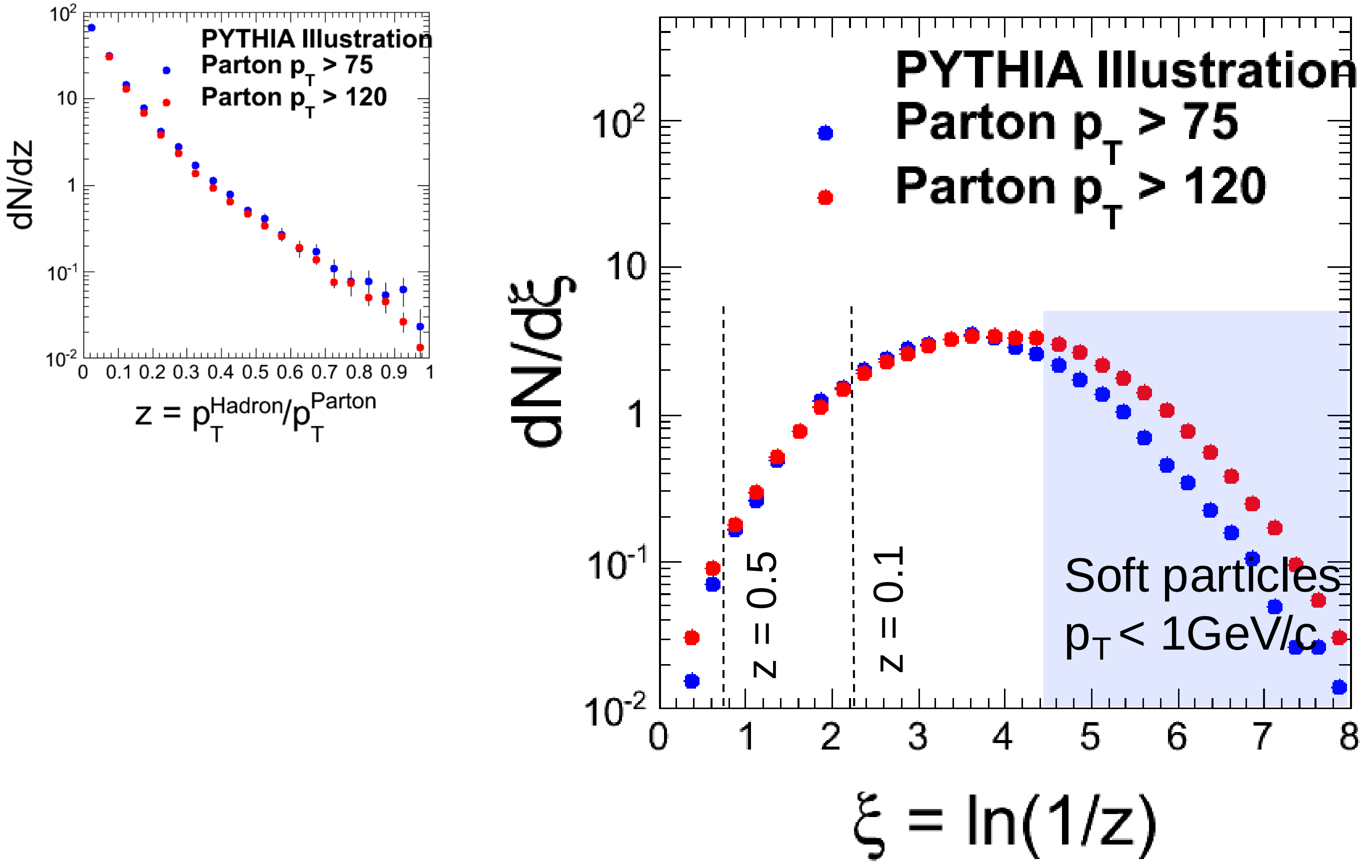


Parton Fragmentation

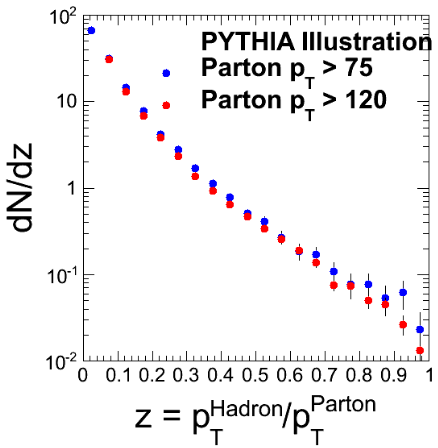


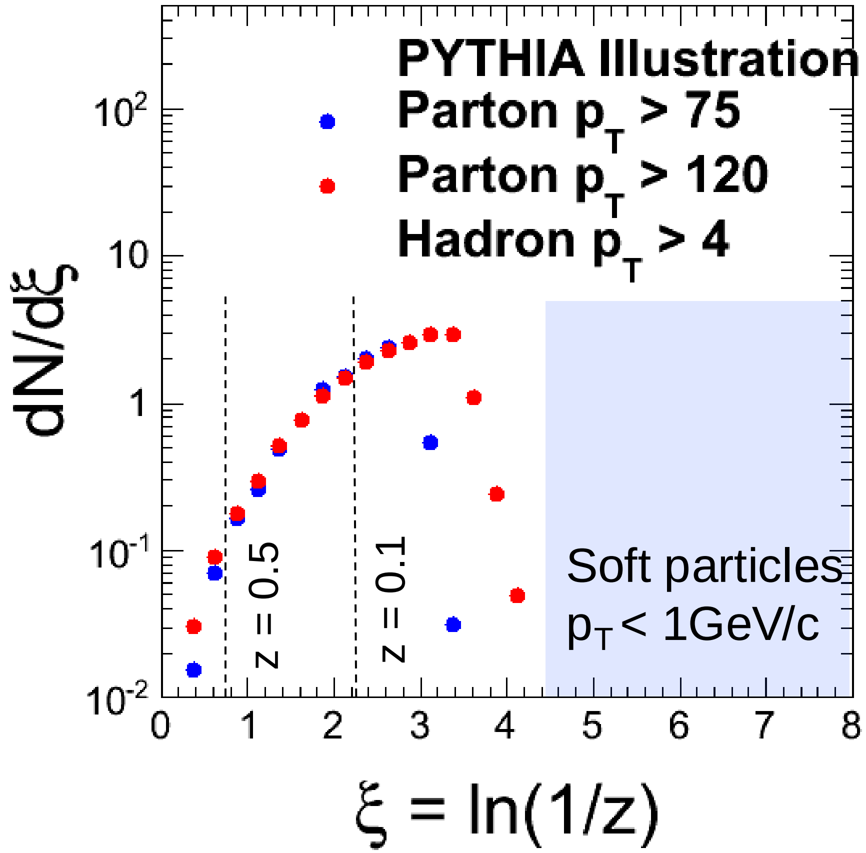
- Momentum Fraction z
  - characteristic of the parton showering process
  - $z = p_T^{hadron}/p_T^{parton}$

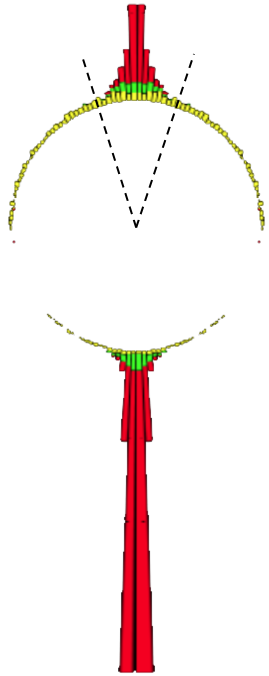
$\xi = \ln(1/z)$ Representation



ξ=ln(1/z) Representation

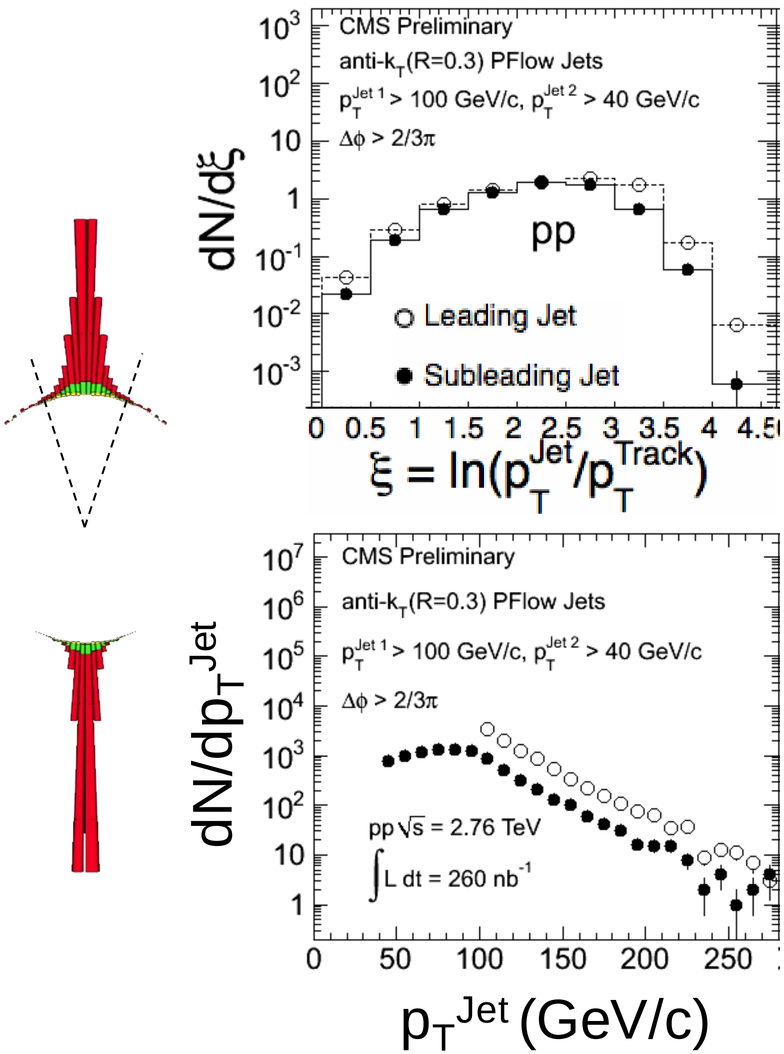






- Eliminate the underlying event contribution, p_T > 4GeV/c
- Select particles in a ΔR=0.3 cone

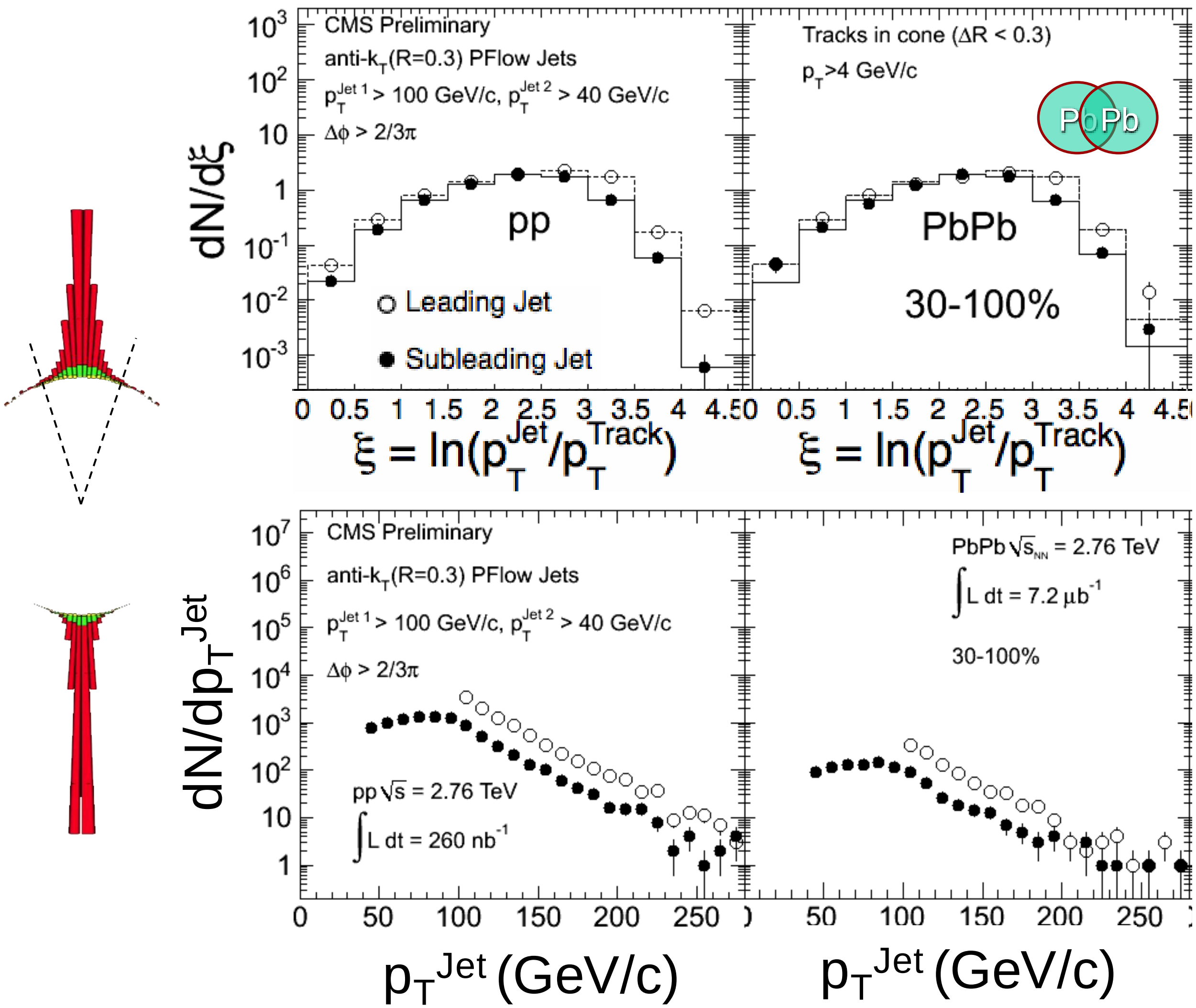
Fragmentation Functions in Data



- Particle Flow Jet Reconstruction
  - Anti k_T, R=0.3
  - Fully efficient for p_T > 40GeV/c
  - Good control of jet p_T scale
  - Applied in pp and PbPb
- Dijet selection
  - p_T^{Jet1}>100GeV/c
  - p_T^{Jet2}>40GeV/c
  - $\Delta\phi_{12}$>2π/3
- Compare Leading and Subleading Jet
  - Select Tracks in ΔR=0.3 cone
  - p_T> 4 GeV/c

CMS-PAS-HIN-11-004
http://cdsweb.cern.ch/record/1354531

Fragmentation Functions, pp and PbPb



CMS-PAS-HIN-11-004
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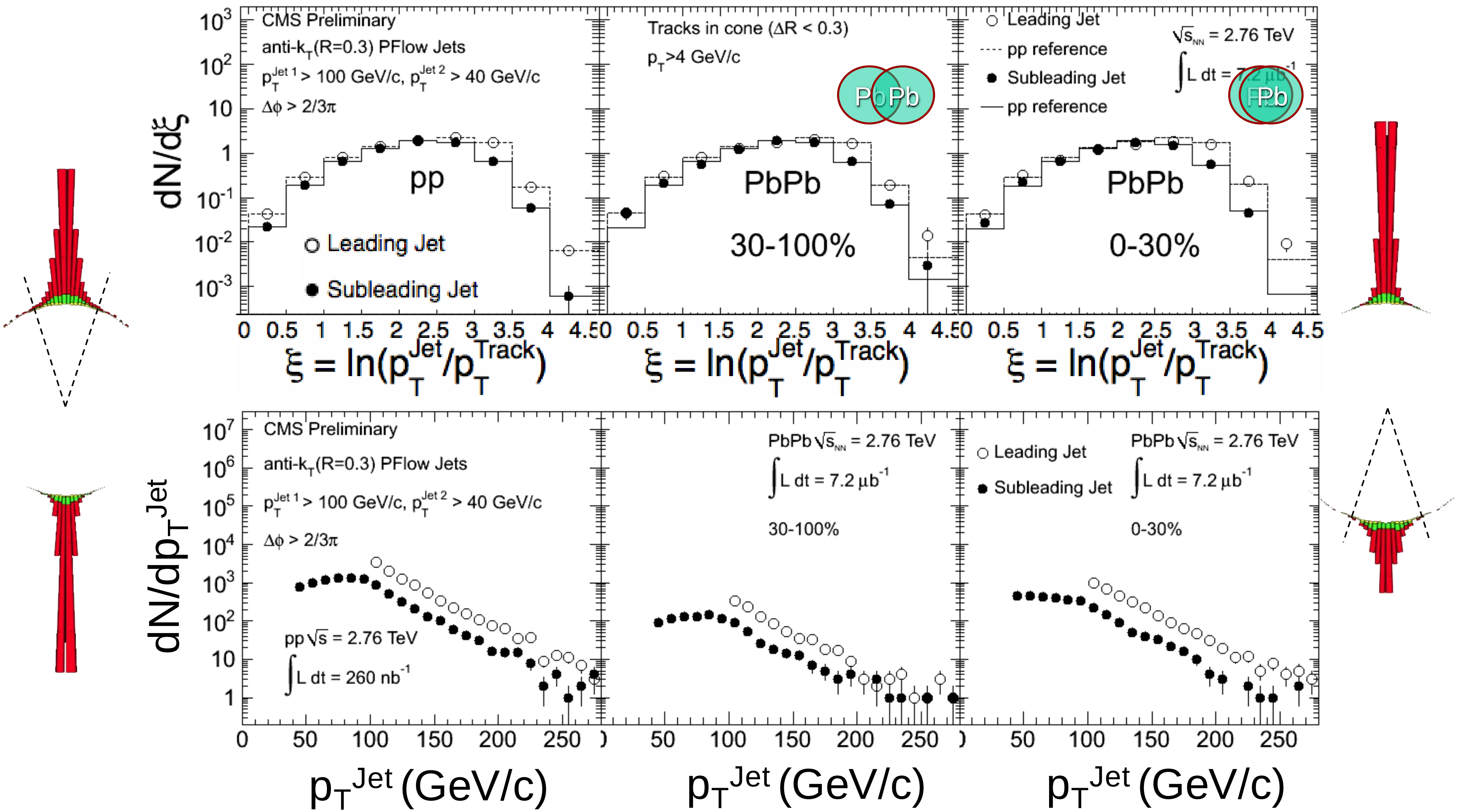
Fragmentation Functions, pp and PbPb



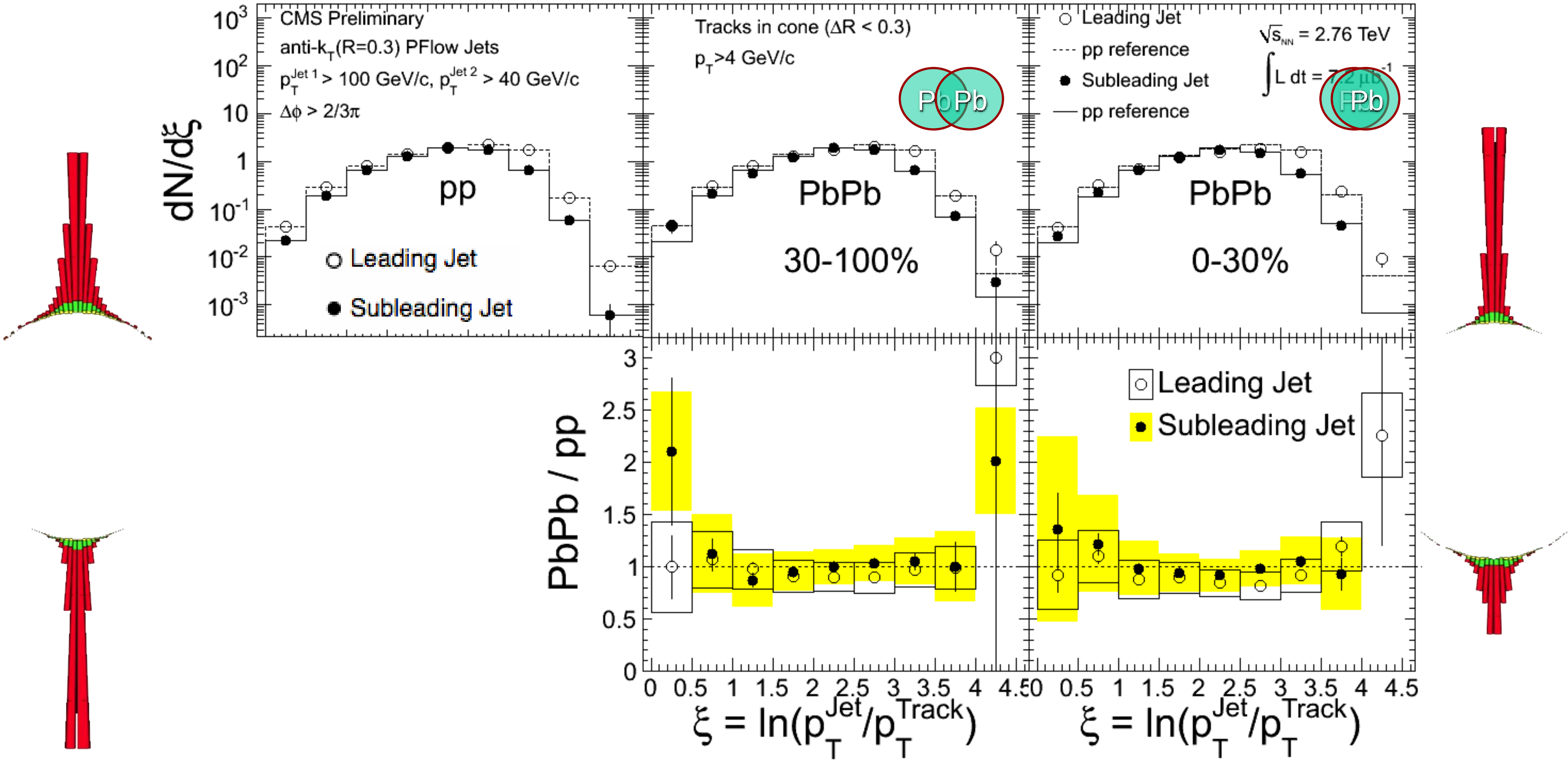
pp as reference for PbPb: Smear pp to PbPb jet p_T resolution

Reweight jet p_T spectrum to match PbPb

CMS-PAS-HIN-11-004

http://cdsweb.cern.ch/record/1354531

Fragmentation Functions, pp and PbPb



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

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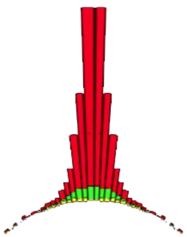
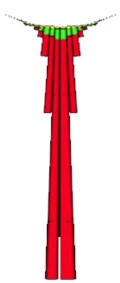
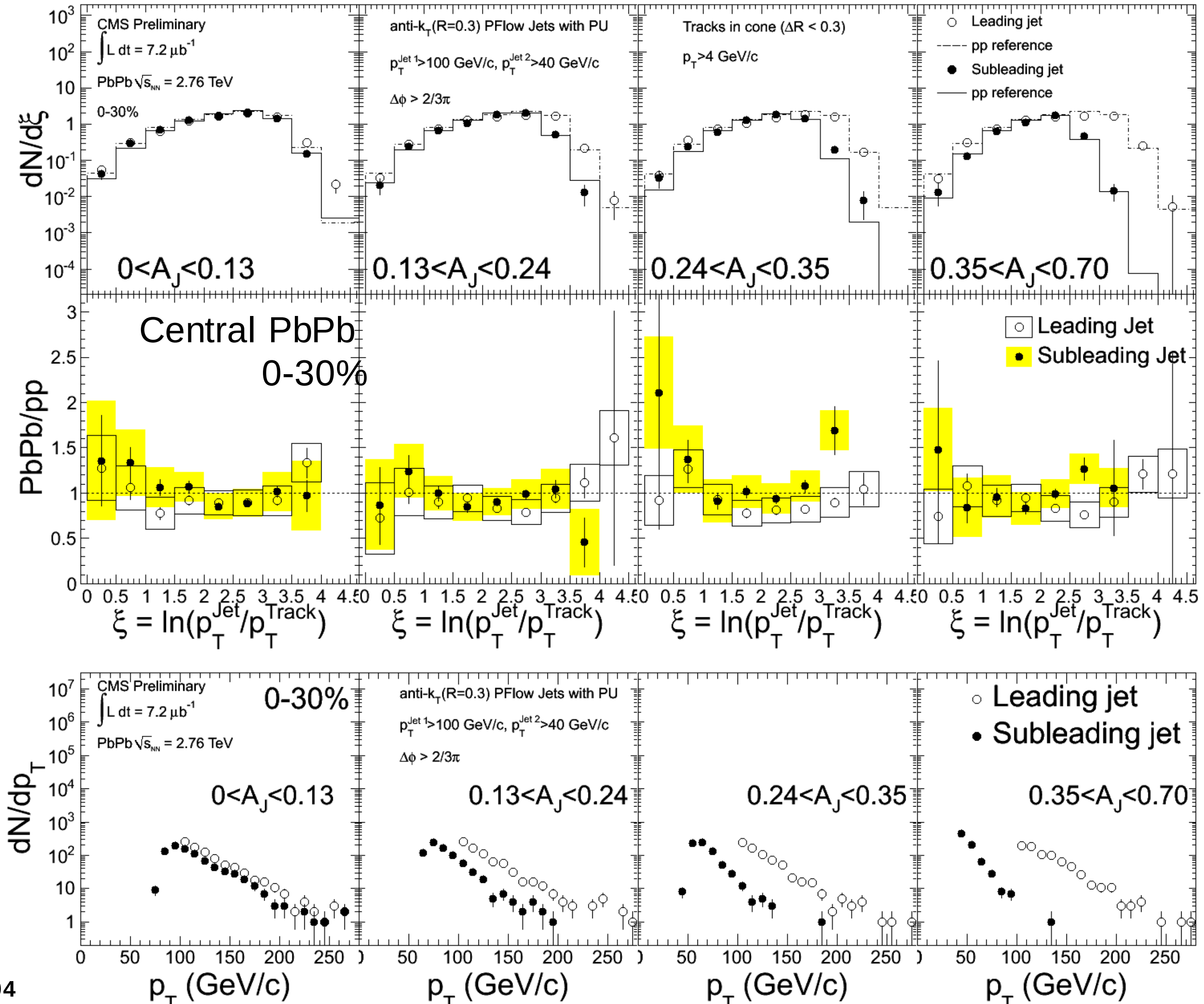
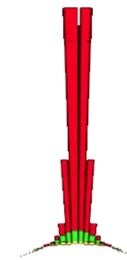
http://cdsweb.cern.ch/record/1354531

PbPb/pp vs Dijet Imbalance









CMS-PAS-HIN-11-004

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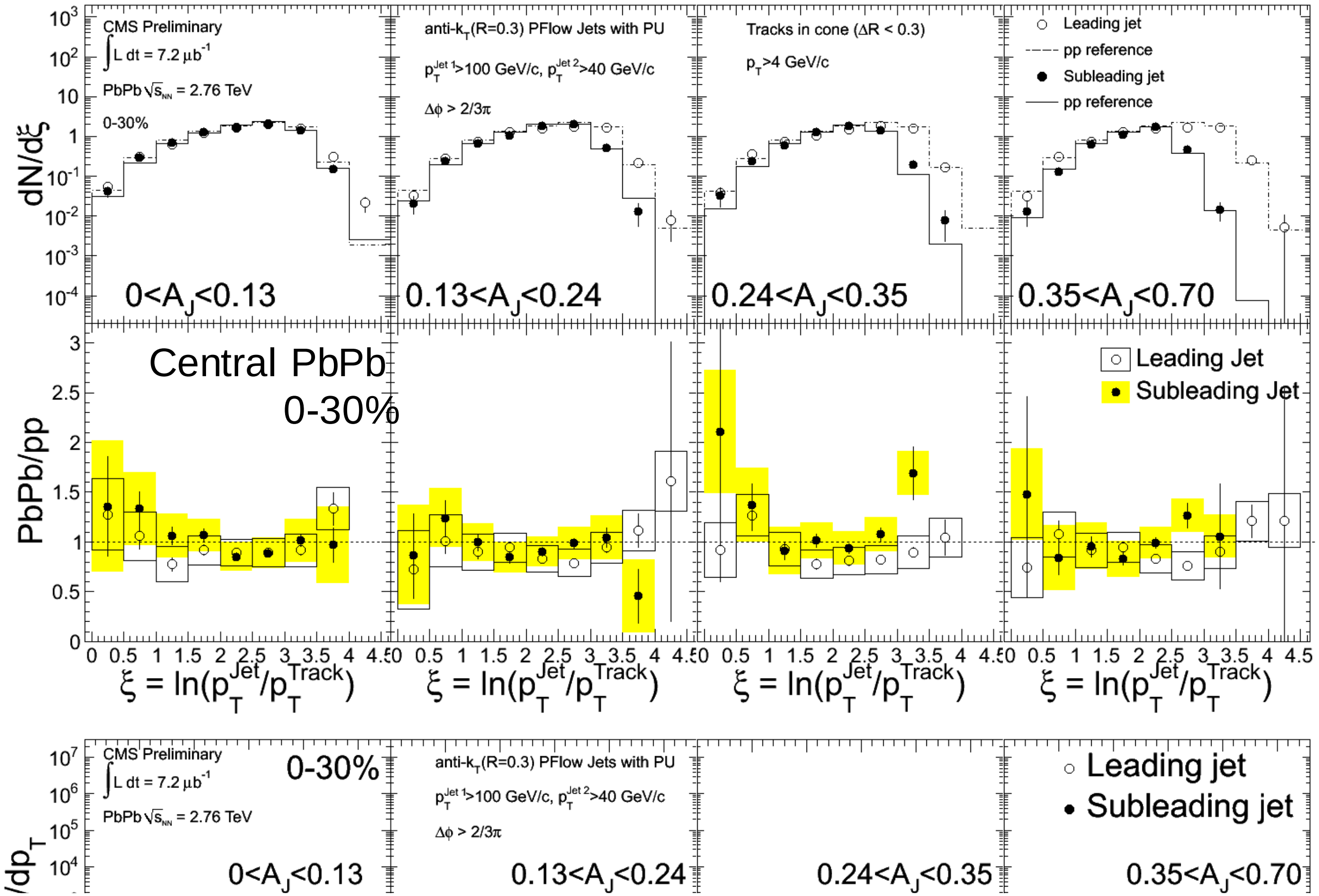
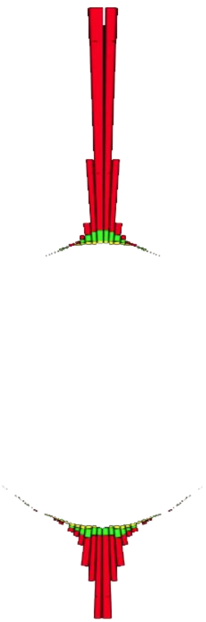
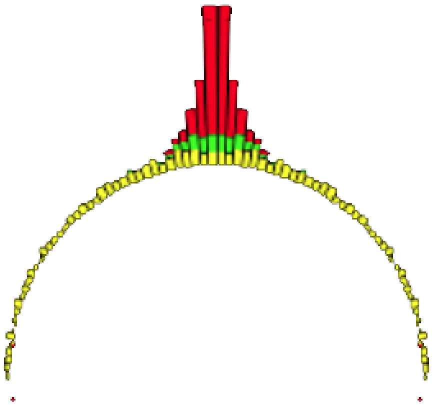
PbPb/pp vs Dijet Imbalance



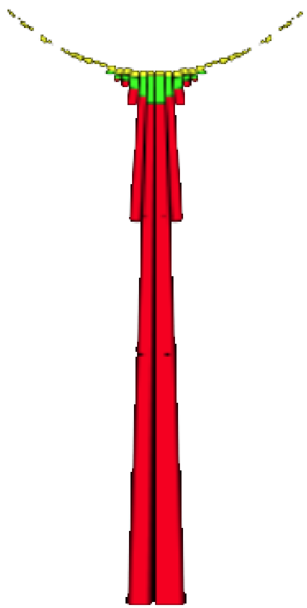


The jet fragmentation pattern is independent of energy lost in medium. Consistent with partons fragmenting in vacuum

Summary



- Jet Track correlations
  - Energy excess in the vicinity of the jet does not account for the energy lost by the parton in the medium
  - No indication of cone like structures around the jet up to a cone size of 0.8



- Momentum difference in the dijet is balanced by low p_T particles at large angles relative to the away side jet
- Jet fragmentation functions in PbPb
  - Jets in pp and in PbPb show a similar pattern
    - Independent of the energy lost in the medium
  - Consistent with partons fragmenting in vacuum

Backup Slides

Jet Reconstruction

Calorimeter based Jet Finder (IC5)

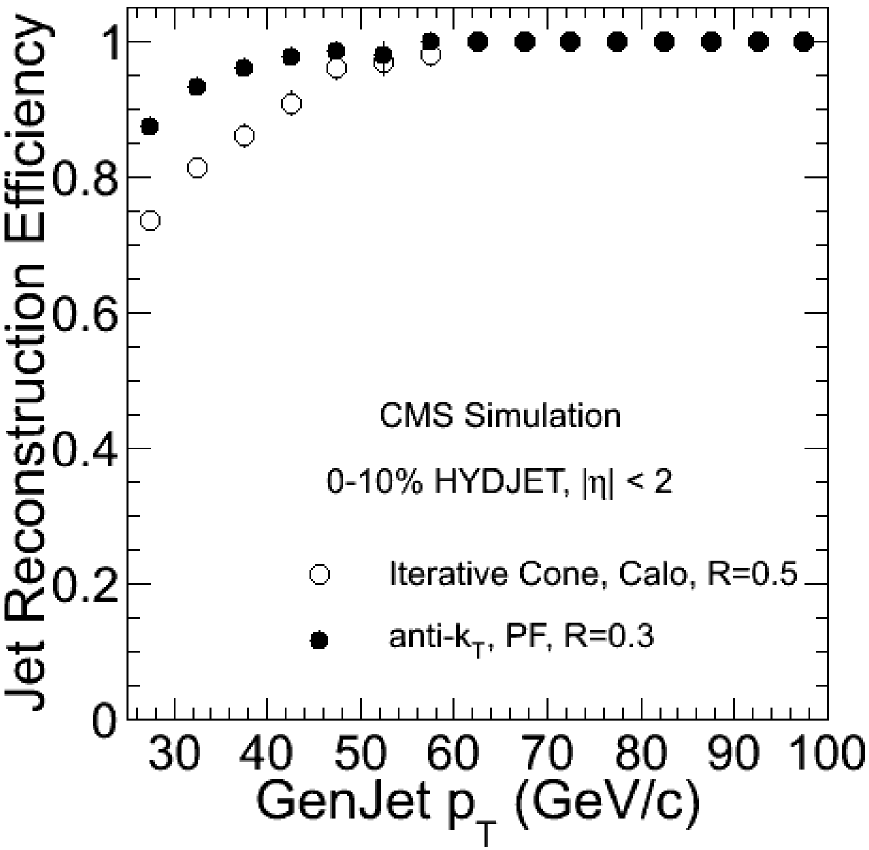
- Iterative Cone Algorithm
- R = 0.5
- arXiv:1102.1957 [nucl-ex]

Particle Flow Jet Finder (PF)

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

Underlying event subtraction

- Iterative PileUp subtraction



Jet Reconstruction fully efficient above:

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

Jet Reconstruction

Calorimeter based Jet Finder (IC5)
- Iterative Cone Algorithm
- R = 0.5
- arXiv:1102.1957 [nucl-ex]

Particle Flow Jet Finder (PF)
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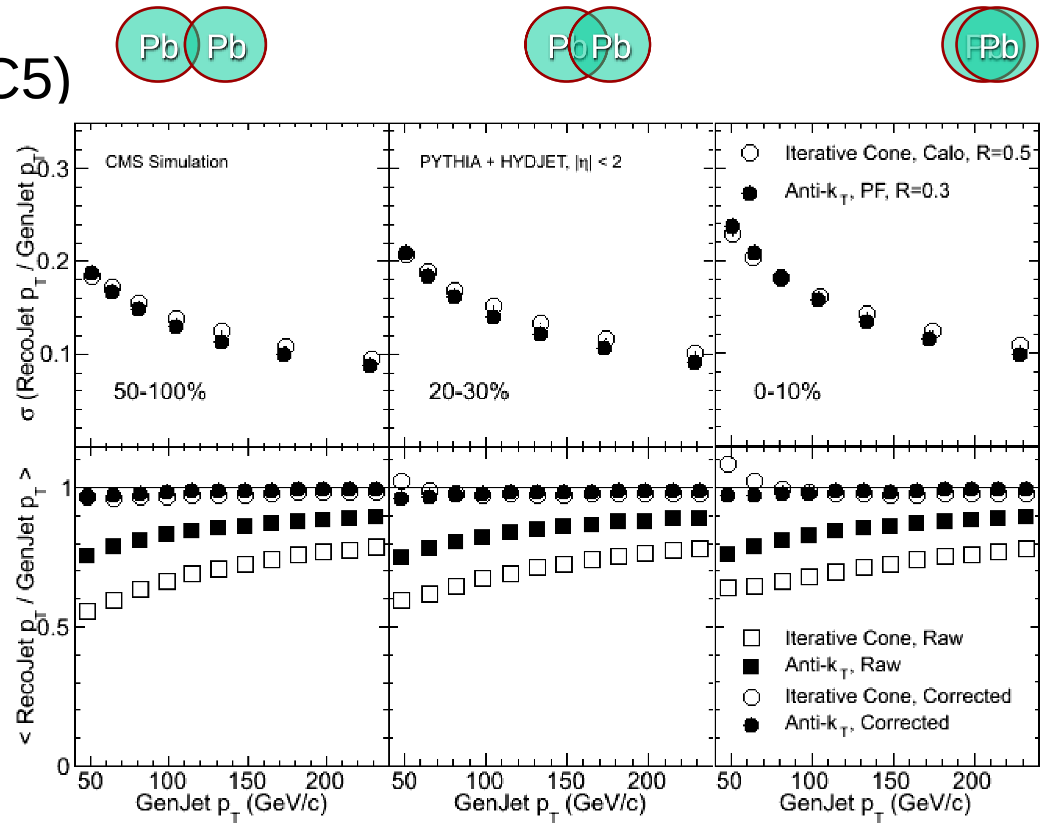
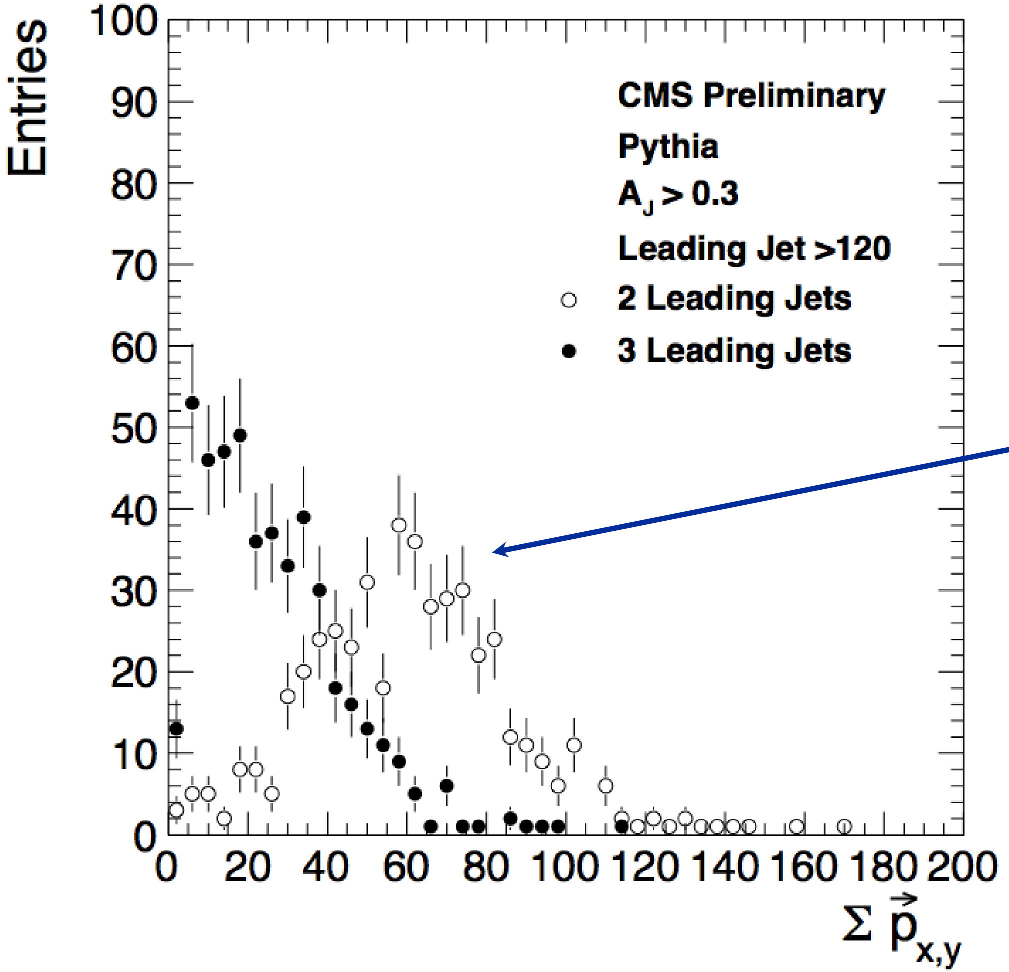
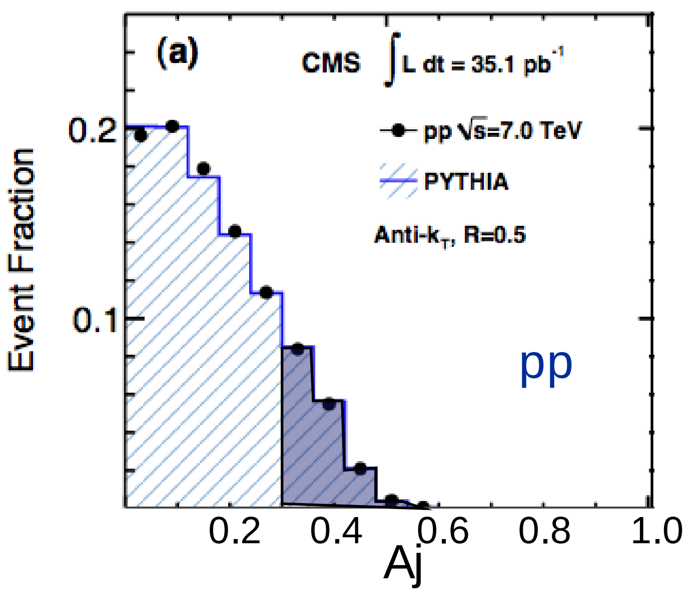
Underlying event subtraction
- Iterative PileUp subtraction



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

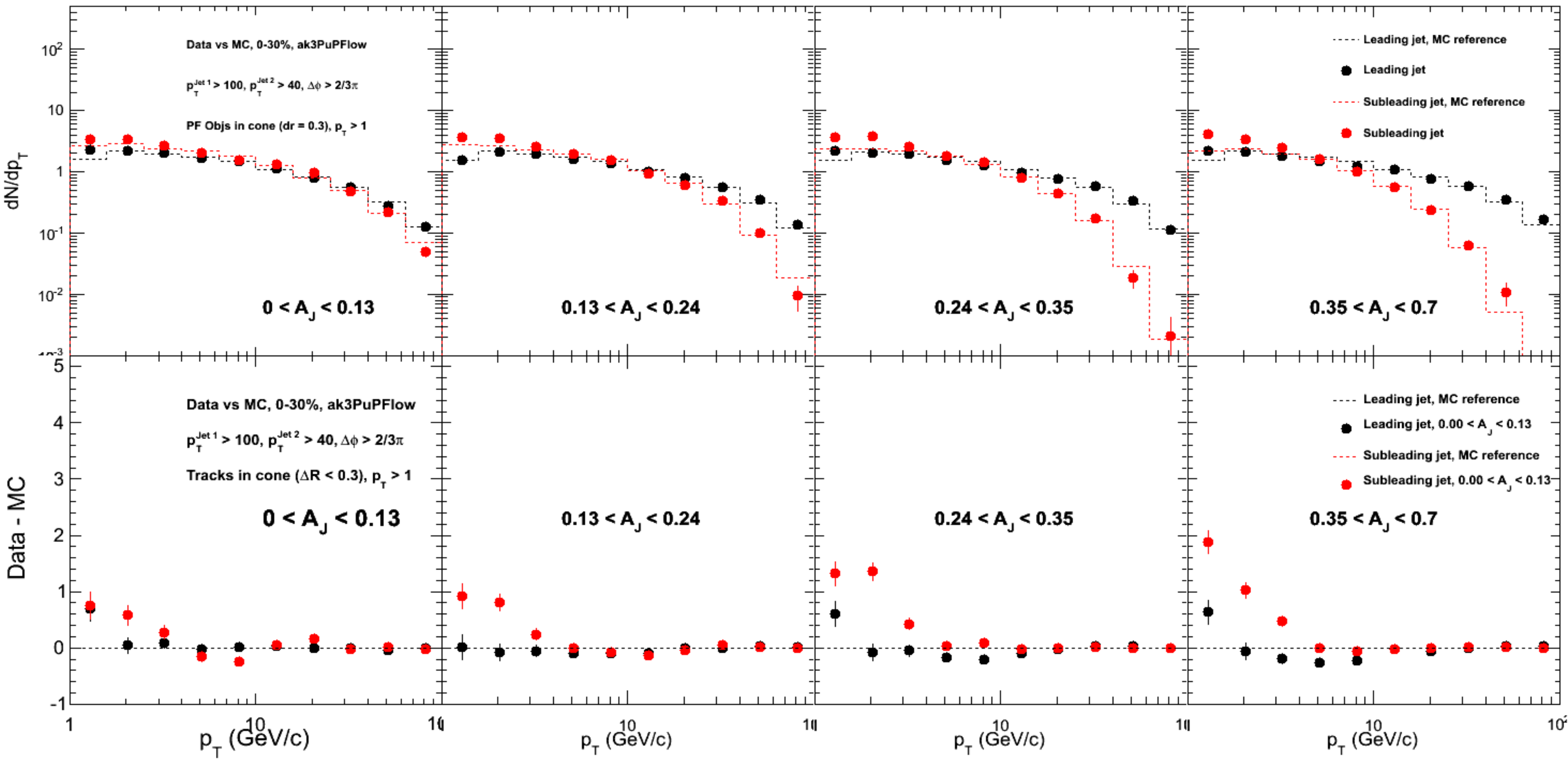
PYTHIA Momentum Balance





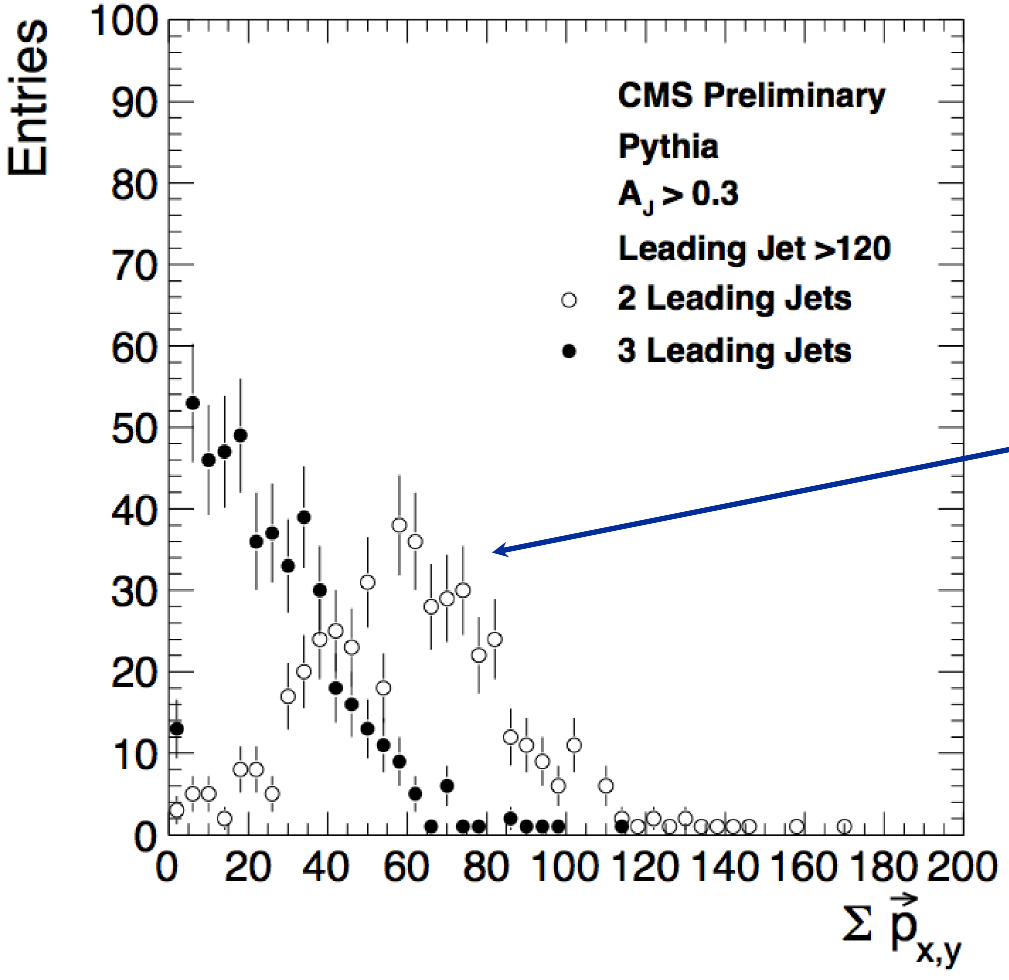
For unbalanced PYTHIA dijets ($A_j > 0.3$, 10% of the total), a 3rd jet provides most of momentum balance

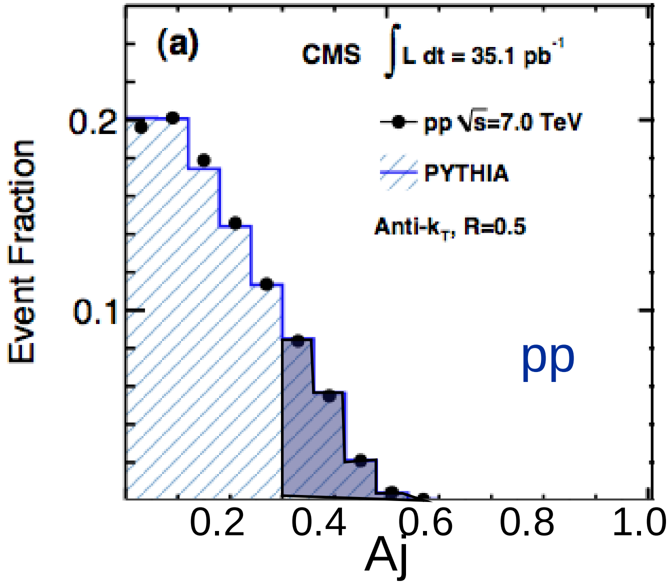
Residual quenched energy in jets



Residual quenched energy in a R = 0.3 cone

PYTHIA Momentum Balance

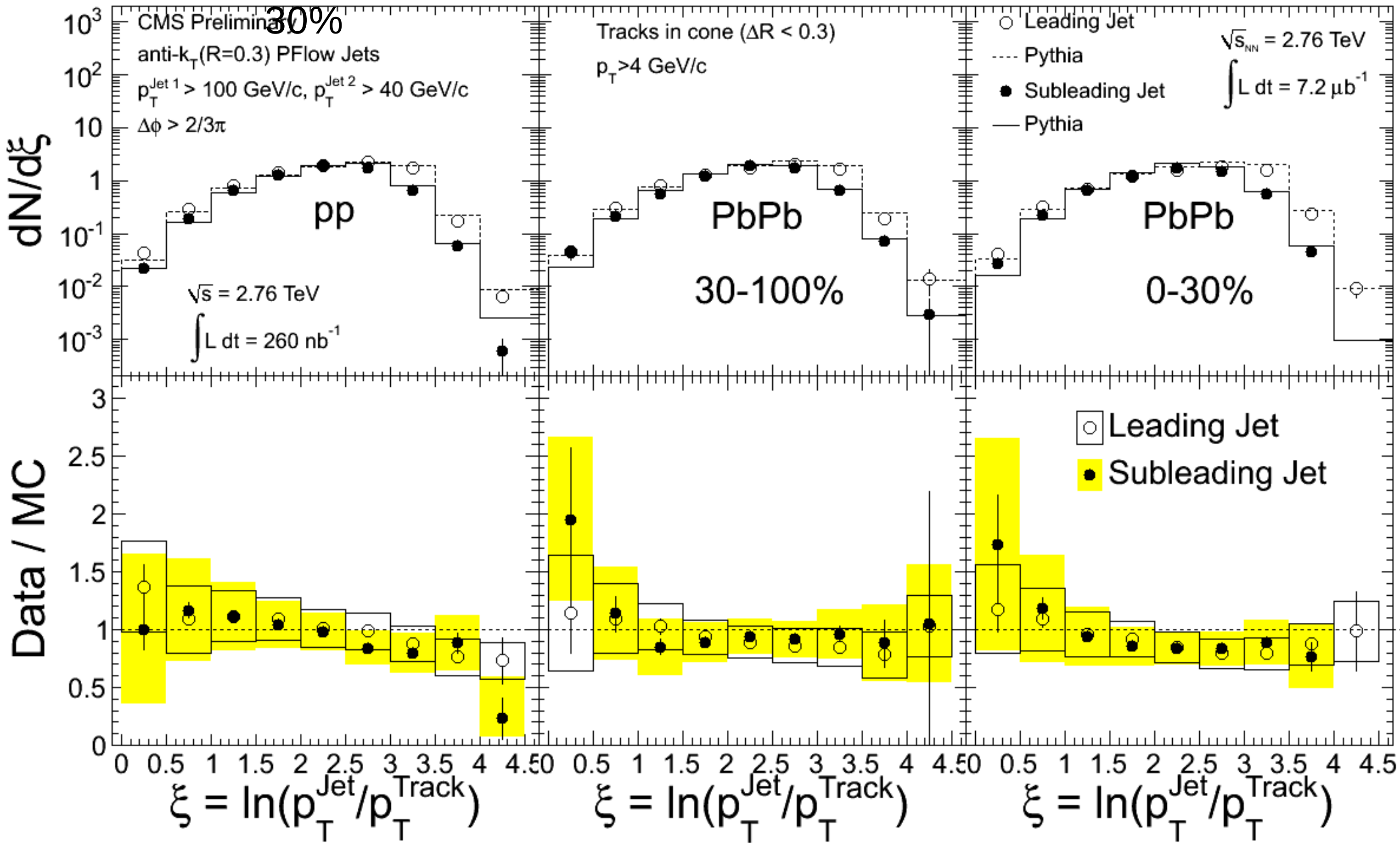




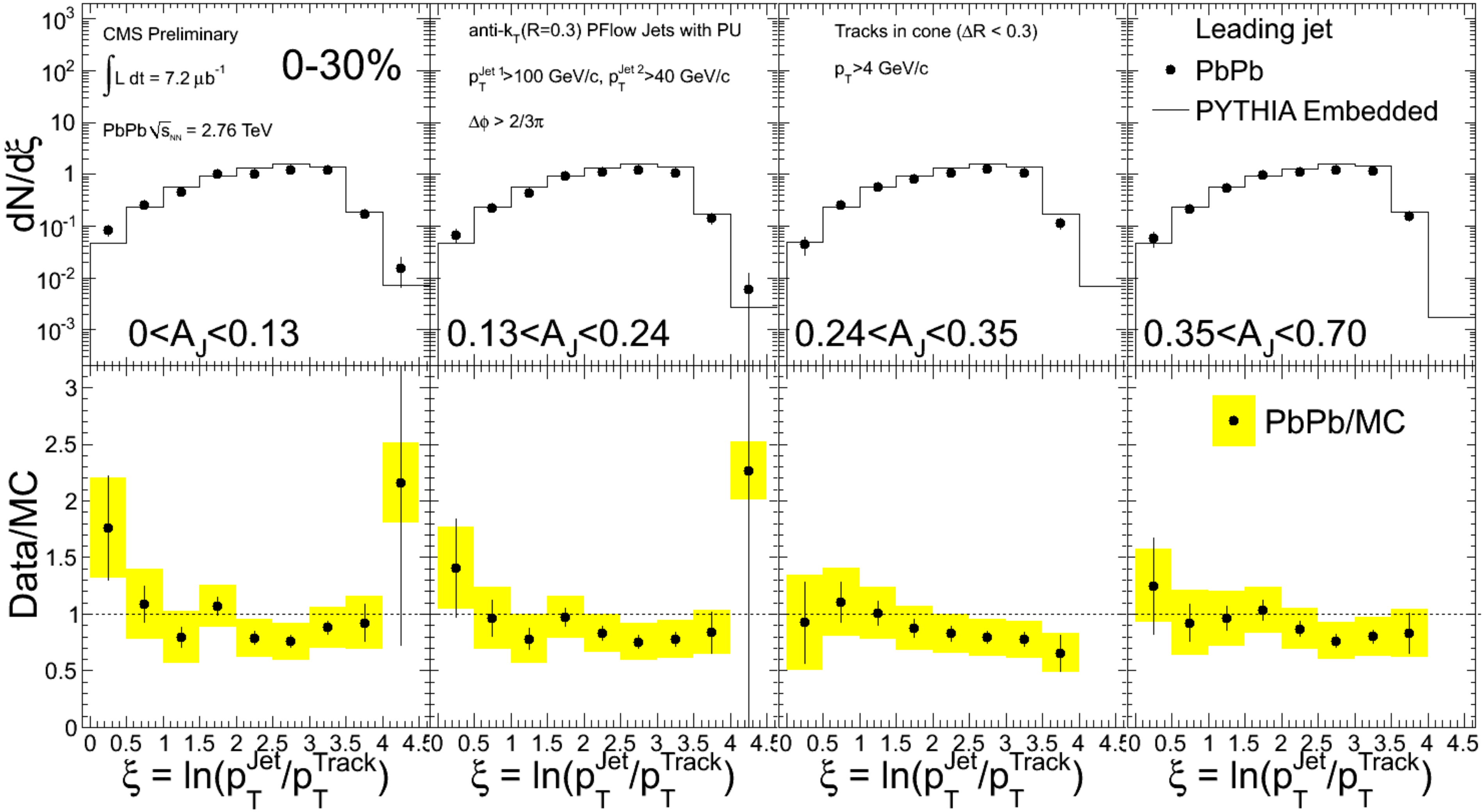
For unbalanced PYTHIA dijets ($A_j > 0.3$, 10% of the total), a 3rd jet provides most of momentum balance

Fragmentation Functions compared to MC

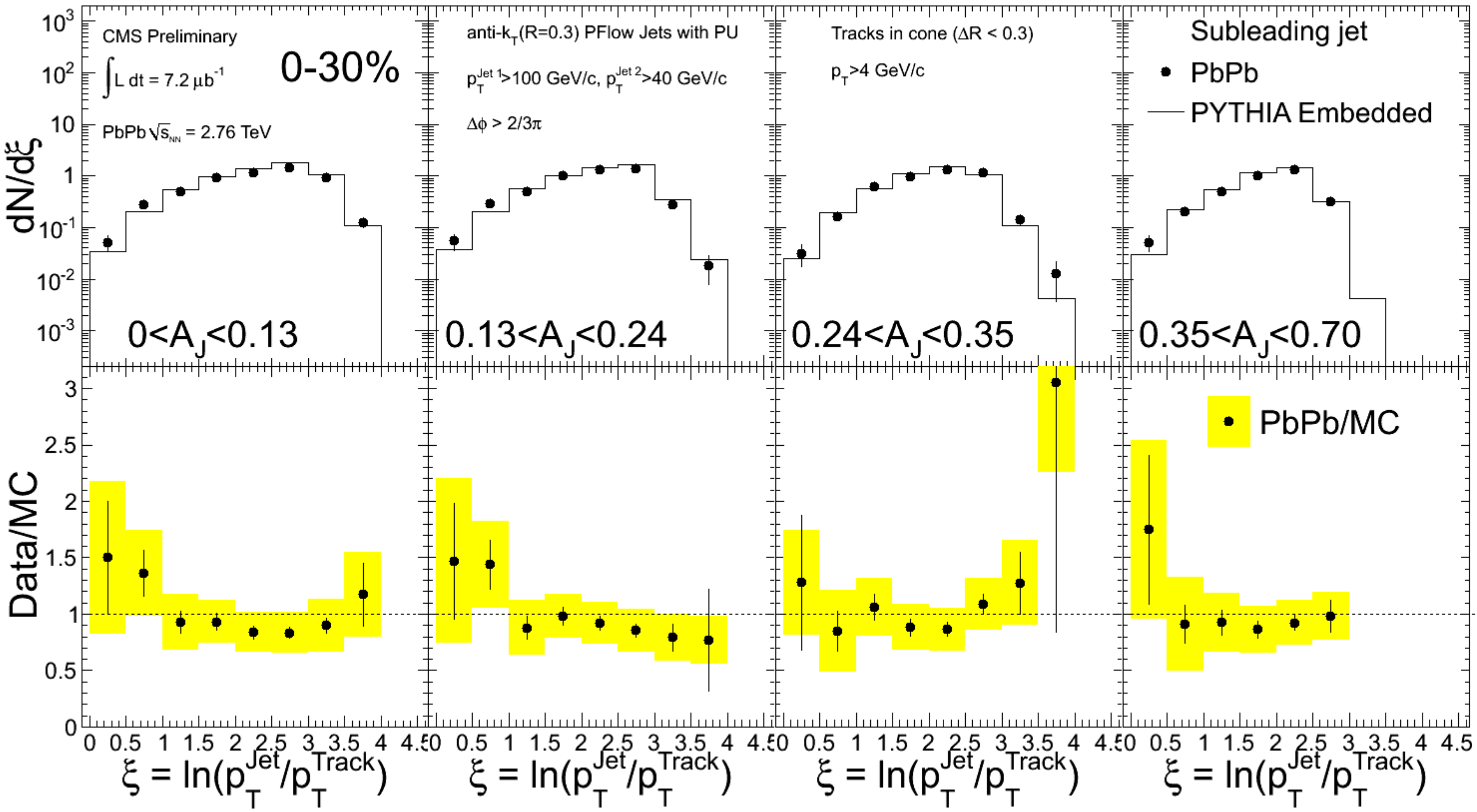
pp PbPb, Peripheral 30 - 100% Central 0 - 30%



Uncorrected Leading

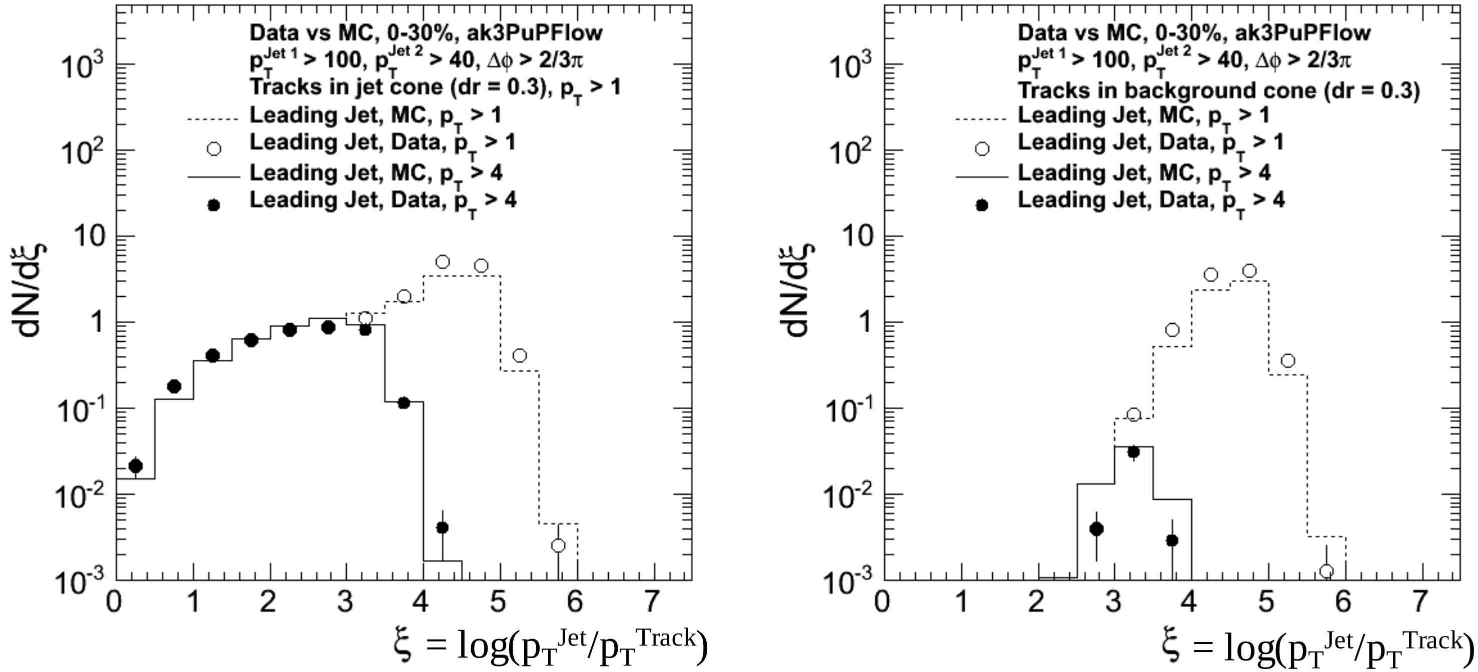


Uncorrected Subeading



Fragmentation Functions

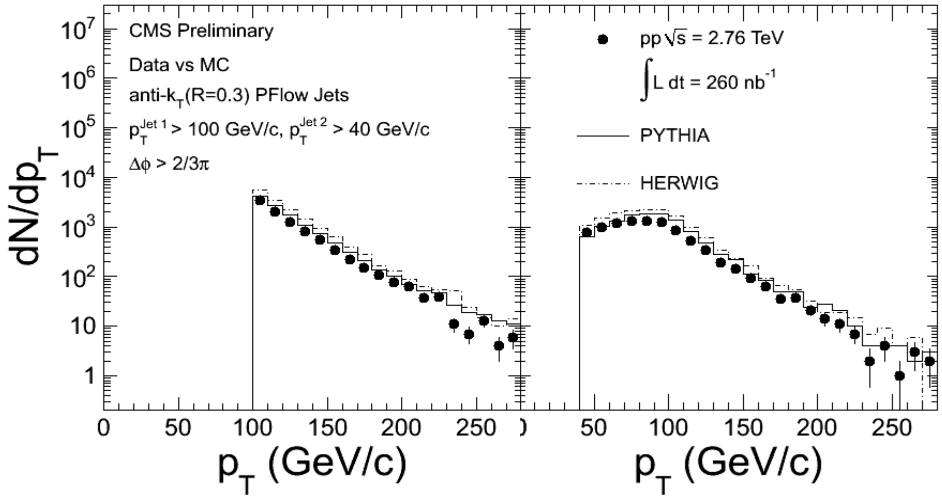
Central Events PbPb



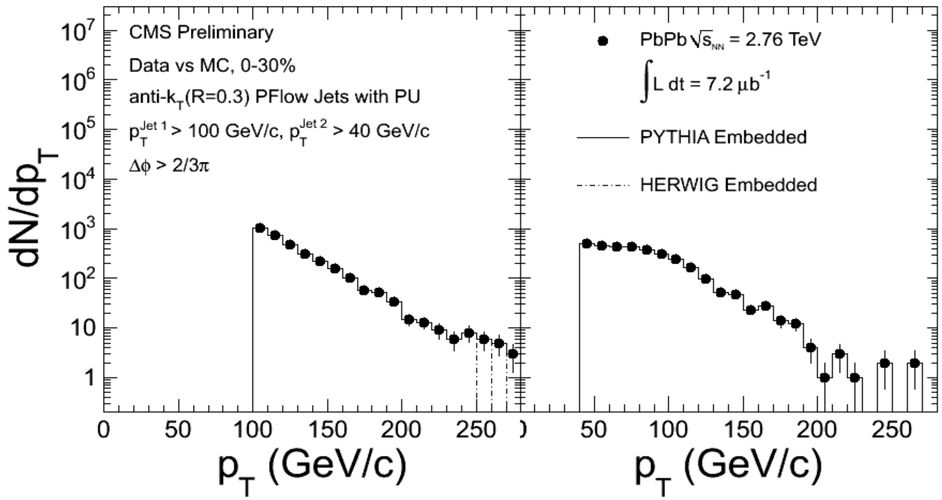
- Fragmentation Functions are reconstructed by correlating the tracks in a R=0.3 cone around the jet axis with the corresponding jets
  - p_T>4GeV cut applied to the tracks to eliminate the underlying event contribution

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

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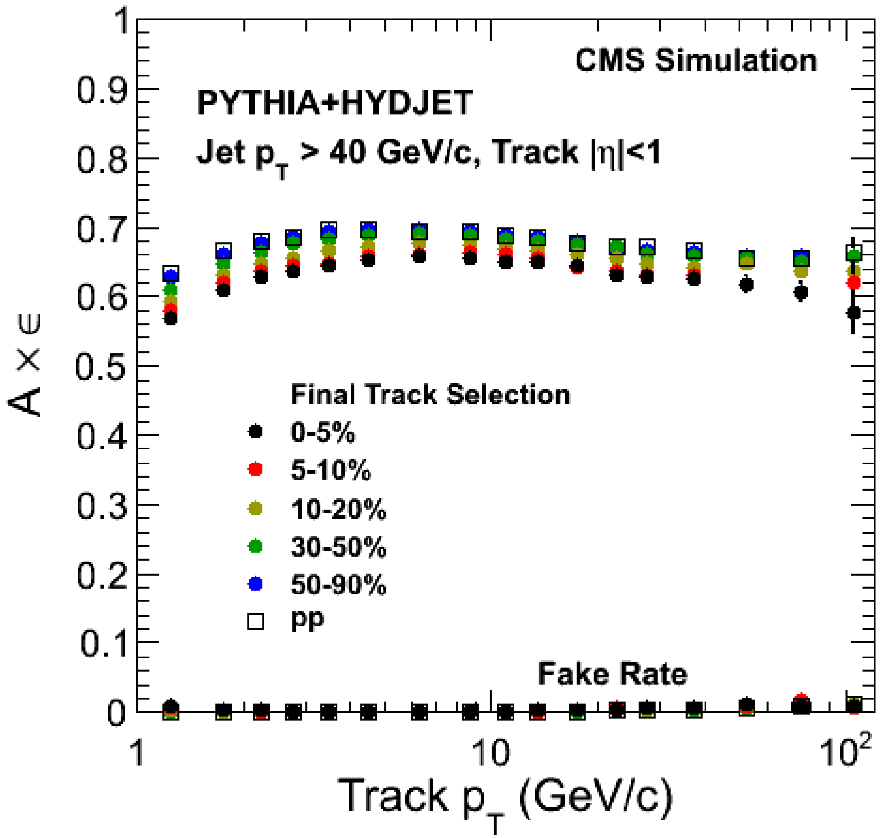
Heavy Ion Track Reconstruction



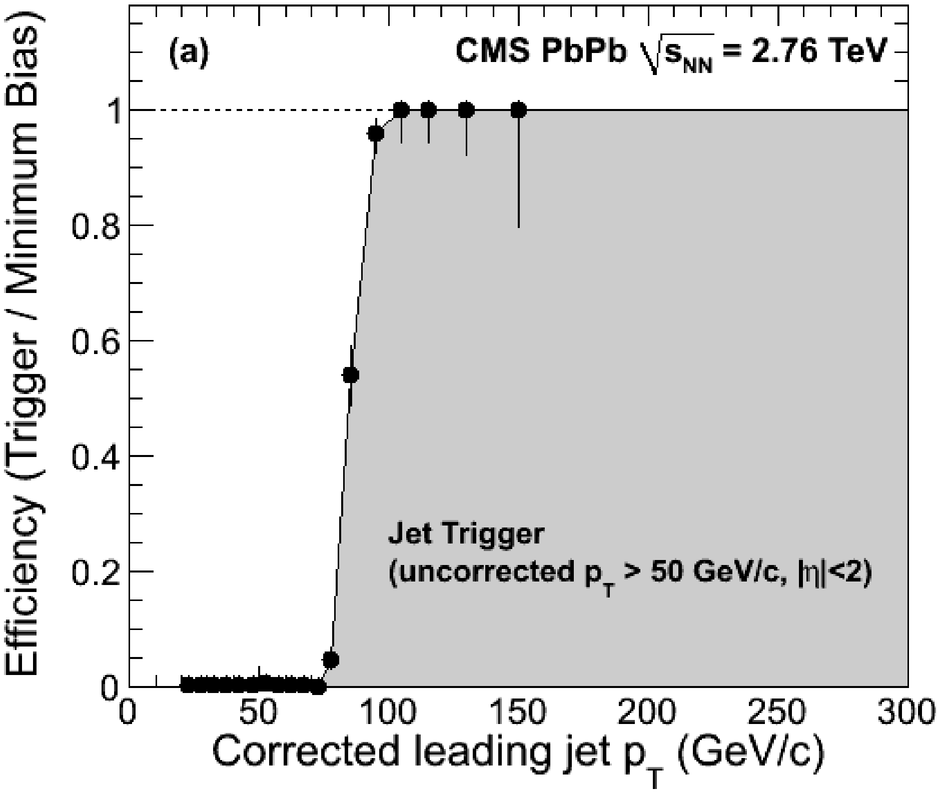
Trigger Selection

Minimum Bias Trigger

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

Jet Trigger

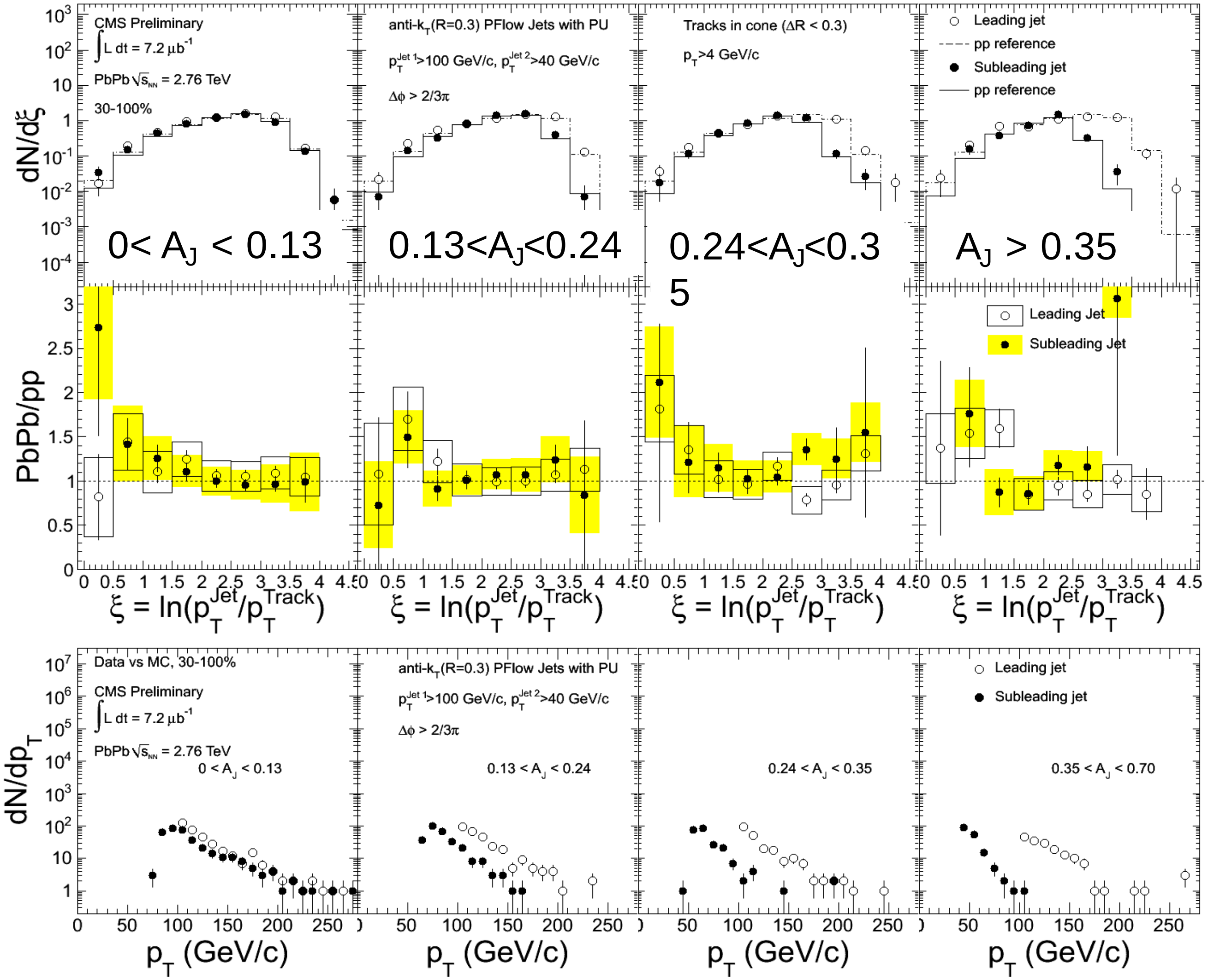
- Level-1: Single Jet 30 GeV (uncorrected energy)
- HLT: Single Jet 50 GeV (bkgd subtracted uncorr. energy)
- Fully efficient for corrected energy above 100 GeV



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

PbPb/pp Peripheral Events

Overlay of leading and subleading jet



PAS

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