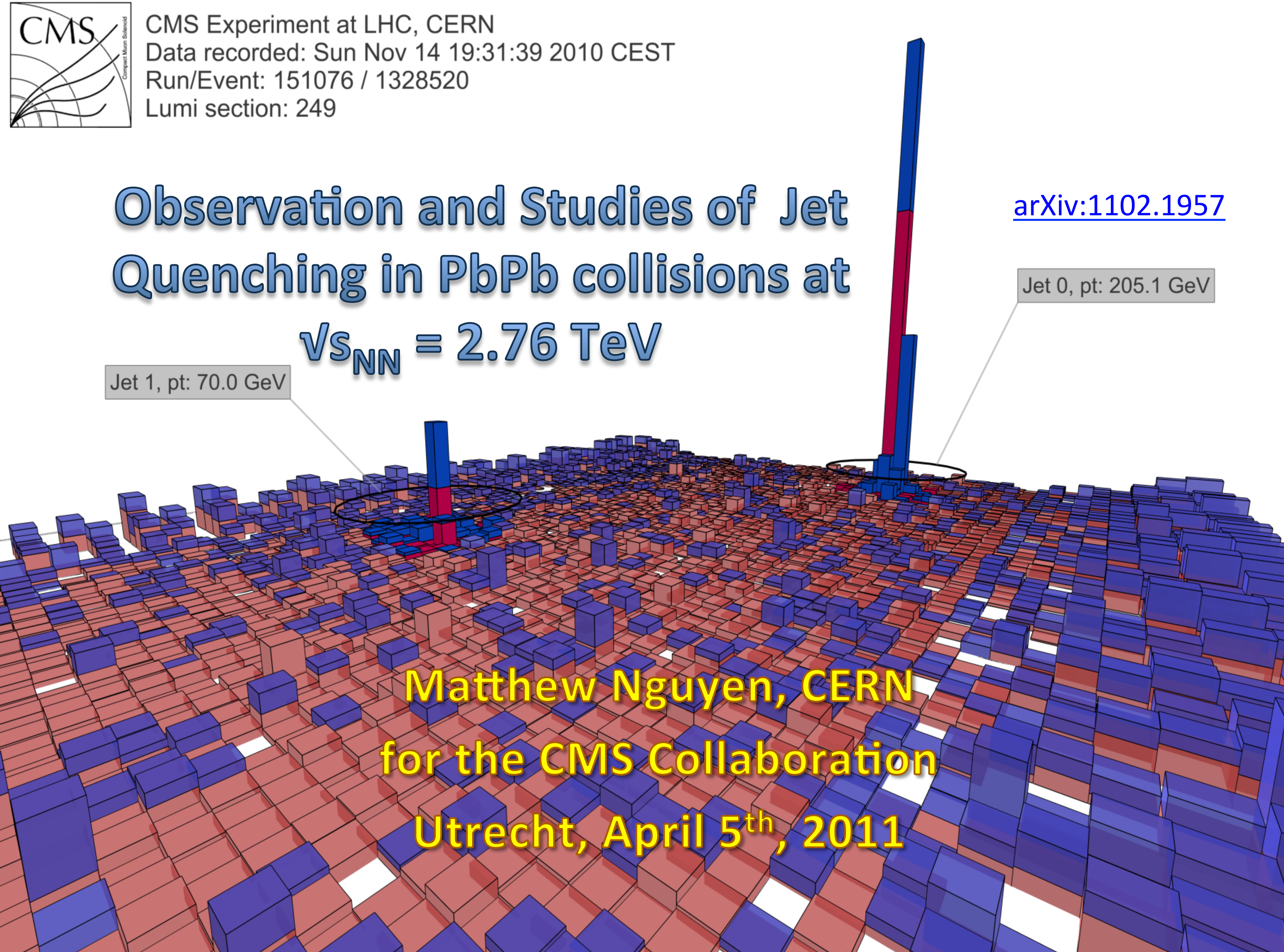
Observation and Studies of Jet Quenching in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

arXiv:1102.1957



Matthew Nguyen, CERN

for the CMS Collaboration

Utrecht, April 5th, 2011

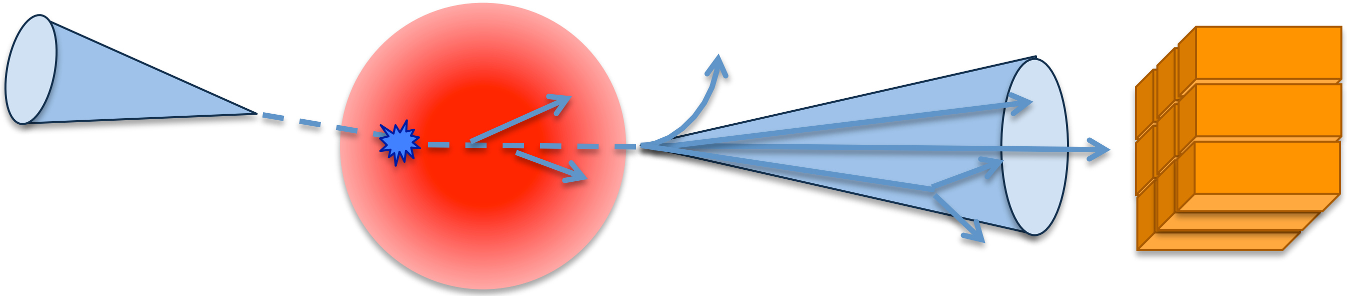
Overview

- Details of PbPb jet analysis in CMS
- Measurement of the dijet asymmetry with calorimeter jets
- Jet-track correlations to trace the fate of the energy lost by quenched jets

Jet Measurements in AA

Large background of soft particles, $dN_{ch}/d\eta \sim 1600$ for 0-5% PbPb @ 2.76 TeV

A schematic view of a jet measurement in heavy ions



Jets are reconstructed from energy reaching calorimeters

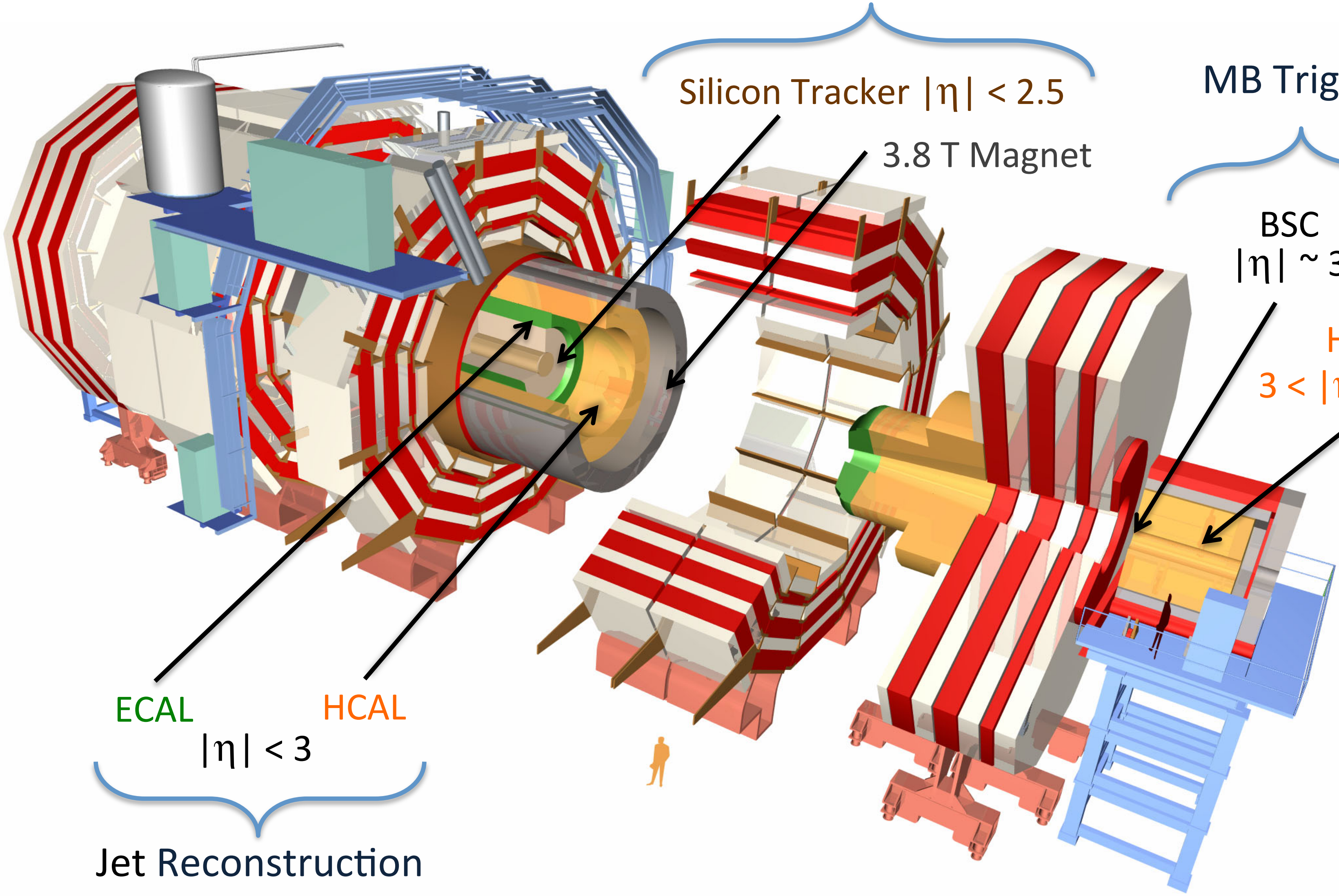
Partons lose energy as they traverse the dense medium

Some jet energy lost to
- Low p_T particles
- Large angle radiation
- Material interactions, decays, etc.

Modified jet fragmentation may result in:

- A different fraction of jet energy reaching the calorimeters
- A different response for non-linear calorimeters

Heavy Ions with CMS



Charged Particle Tracking

Silicon Tracker |η| < 2.5

3.8 T Magnet

MB Trigger

BSC
|η| ~ 3

HF
3 < |η| < 5

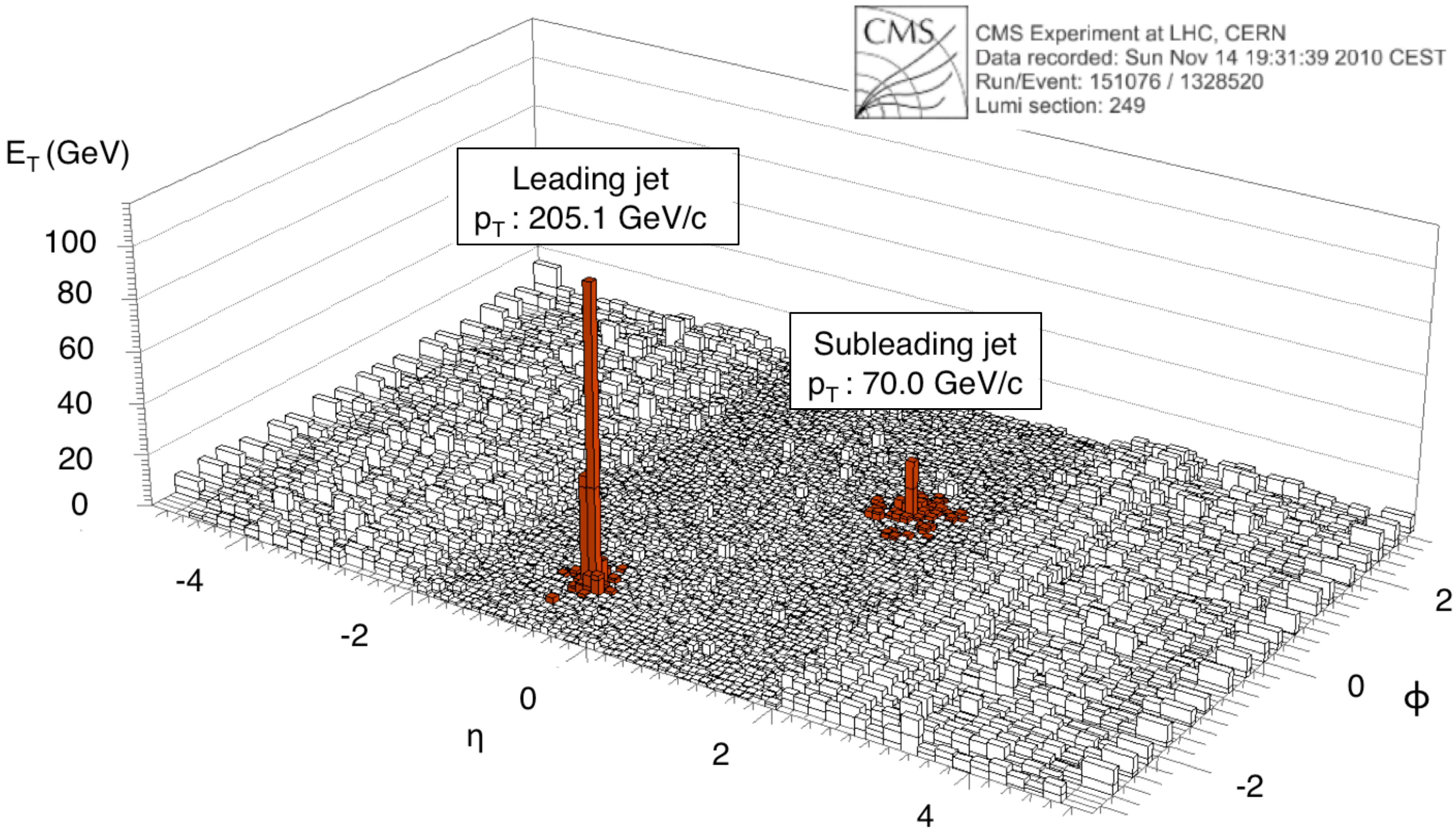
ECAL

HCAL

|η| < 3

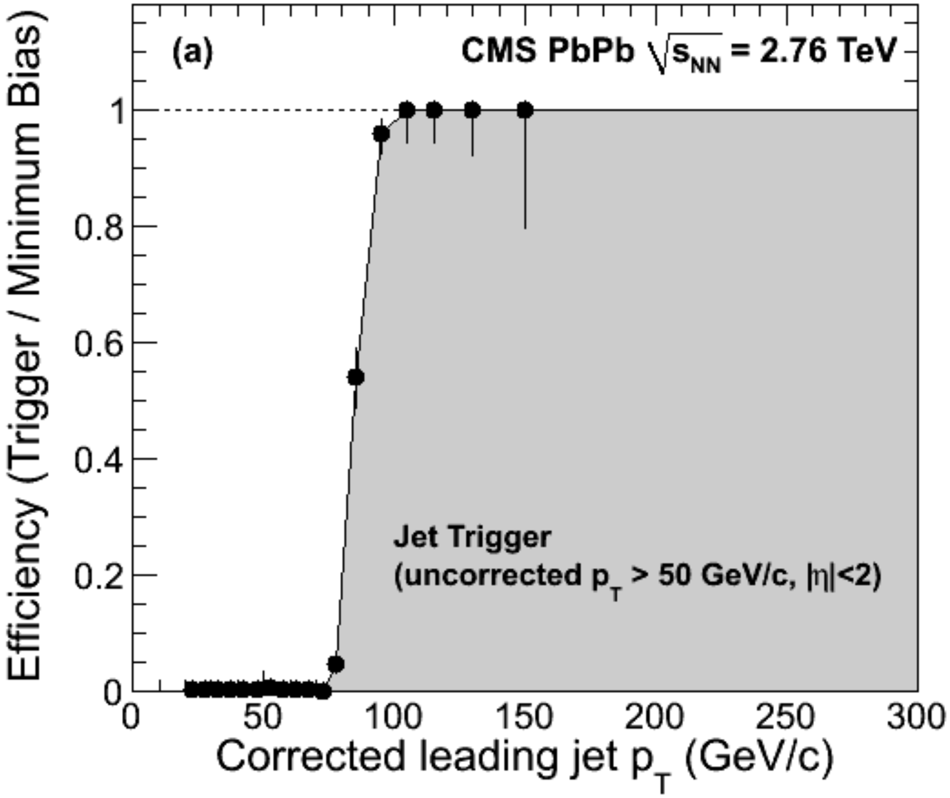
Jet Reconstruction

A Dijet in Central PbPb



At LHC energies, jets with p_T of order 100 GeV/c cleanly separable from background fluctuations in central PbPb collisions

Jet Trigger

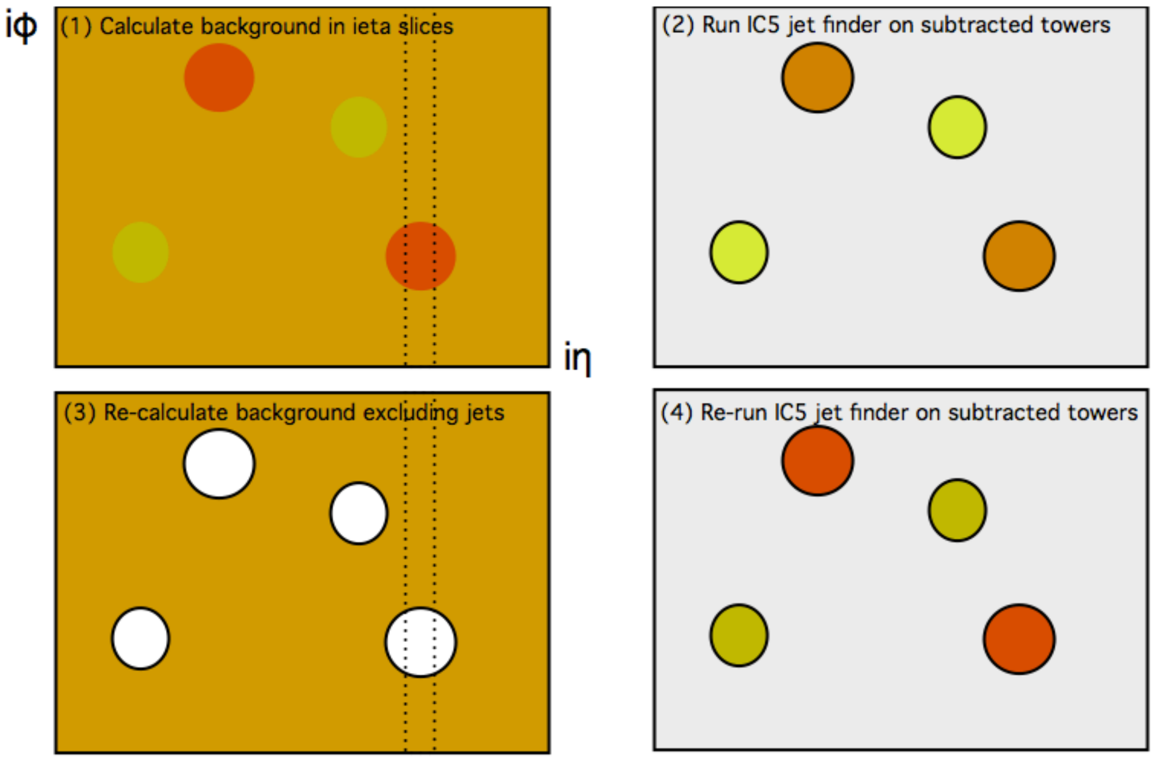


- Jet are triggered at HLT with a p_T = 50 GeV/c threshold (uncorrected, background subtracted)
- Fully efficient by corrected p_T of ~ 100 GeV/c

Background Subtraction Method

1. <E> and σ per tower calculated in strips of η
2. Iterative Cone (R=0.5) algorithm run on subtracted towers
3. Background energy recalculated excluding jets
4. Jet algorithm rerun on background subtracted towers, now excluding jets, to obtain final jets

Method: O. Kodolova et al., EPJC (2007) 117.

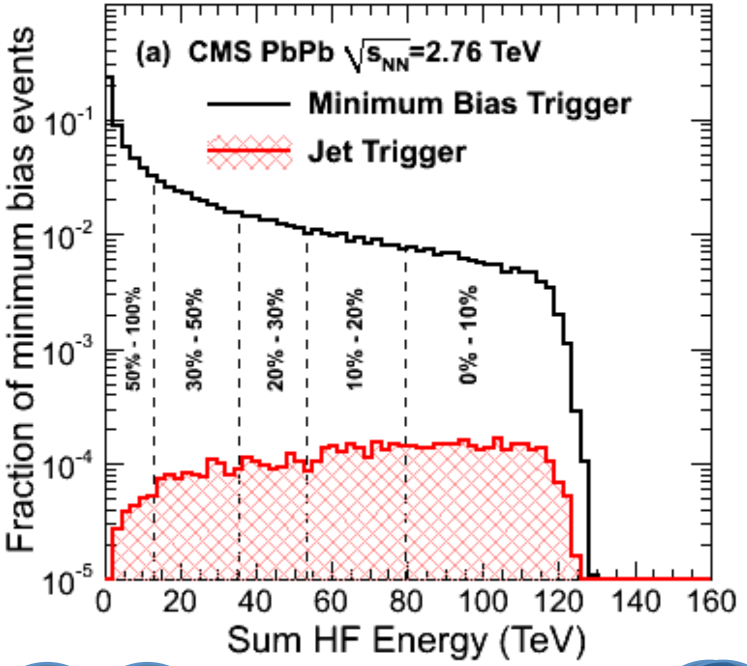


Note:

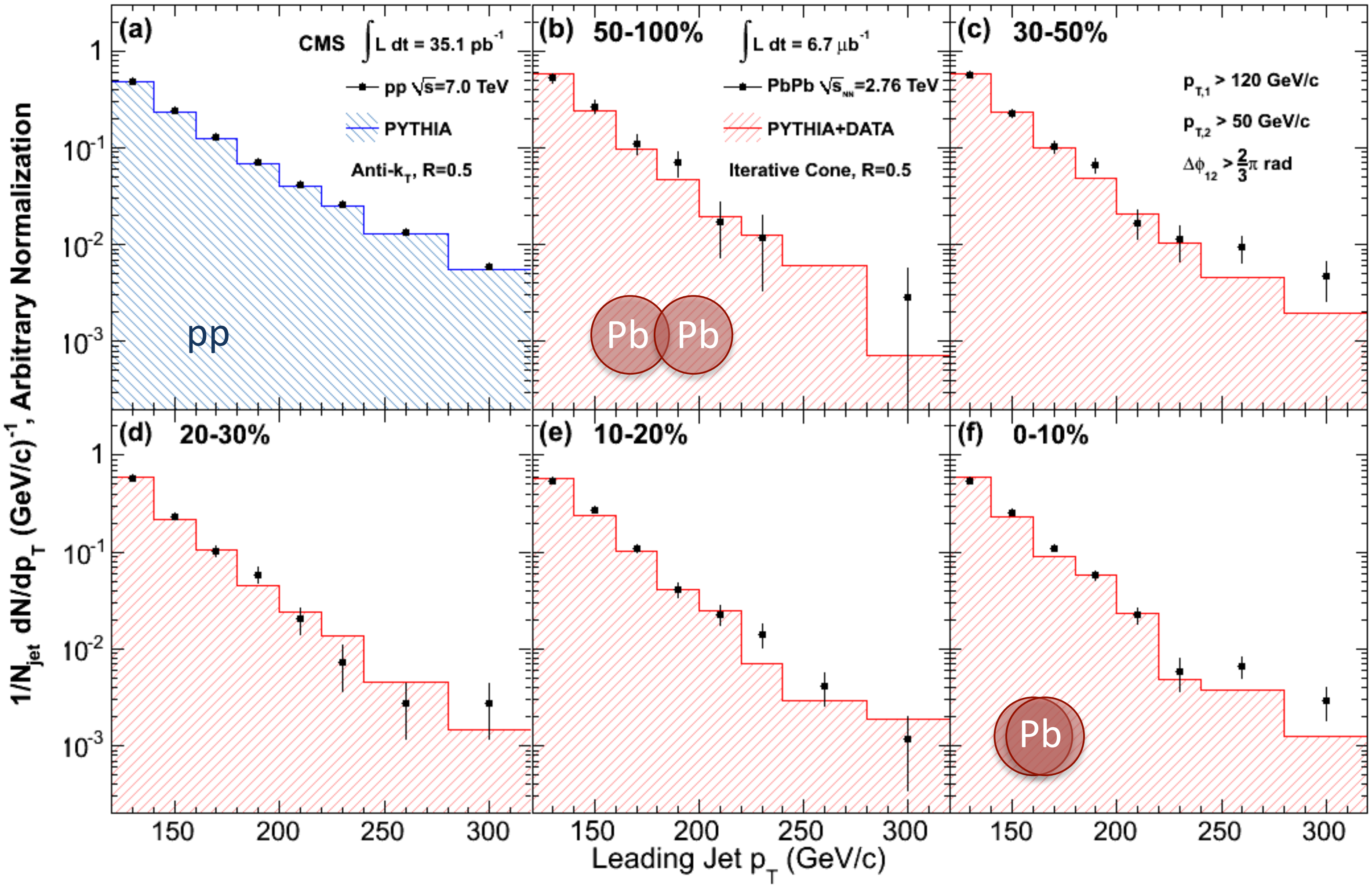
- Background energy = <E> + σ
- Towers with negative energy set to zero

Analysis Details

- Collision centrality determined from the energy in the forward calorimeters
- Dijet Selection
  - Leading jet: $p_{T,1} > 120$ GeV/c, $|\eta| < 2$
  - Subleading jet: $p_{T,2} > 50$ GeV/c, $|\eta| < 2$
  - Azimuthal Angle: $\Delta\varphi_{12} > 2/3\ \pi$ radians
- Monte Carlo
  - PYTHIA 6.423, tune D6T
  - Embedded in real data (PYTHIA+DATA) or simulated data (PYTHIA+HYDJET)

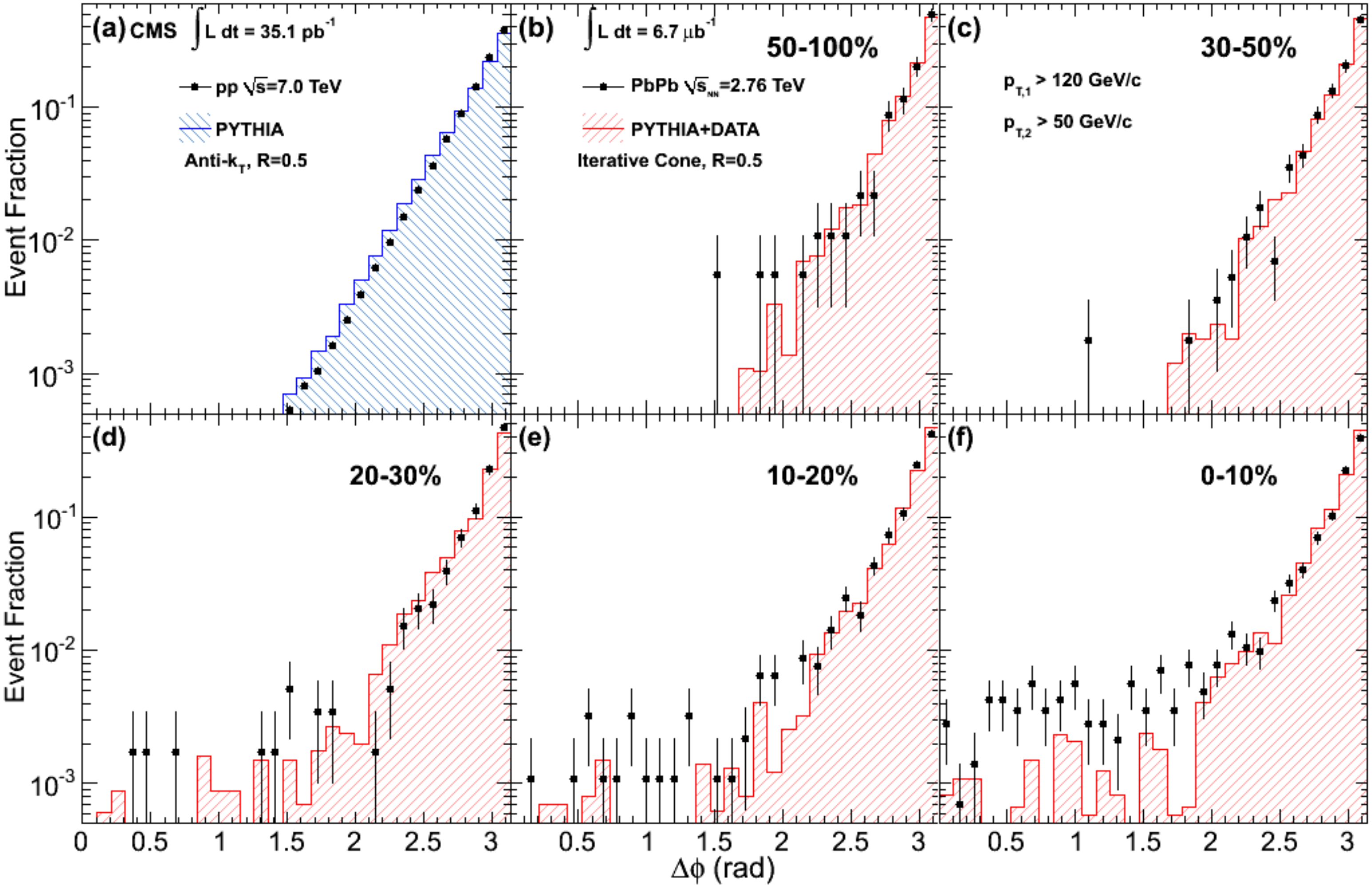


Leading Jet p_T Distributions



No strong modification to shape of leading jet spectrum

Dijet Azimuthal Correlations

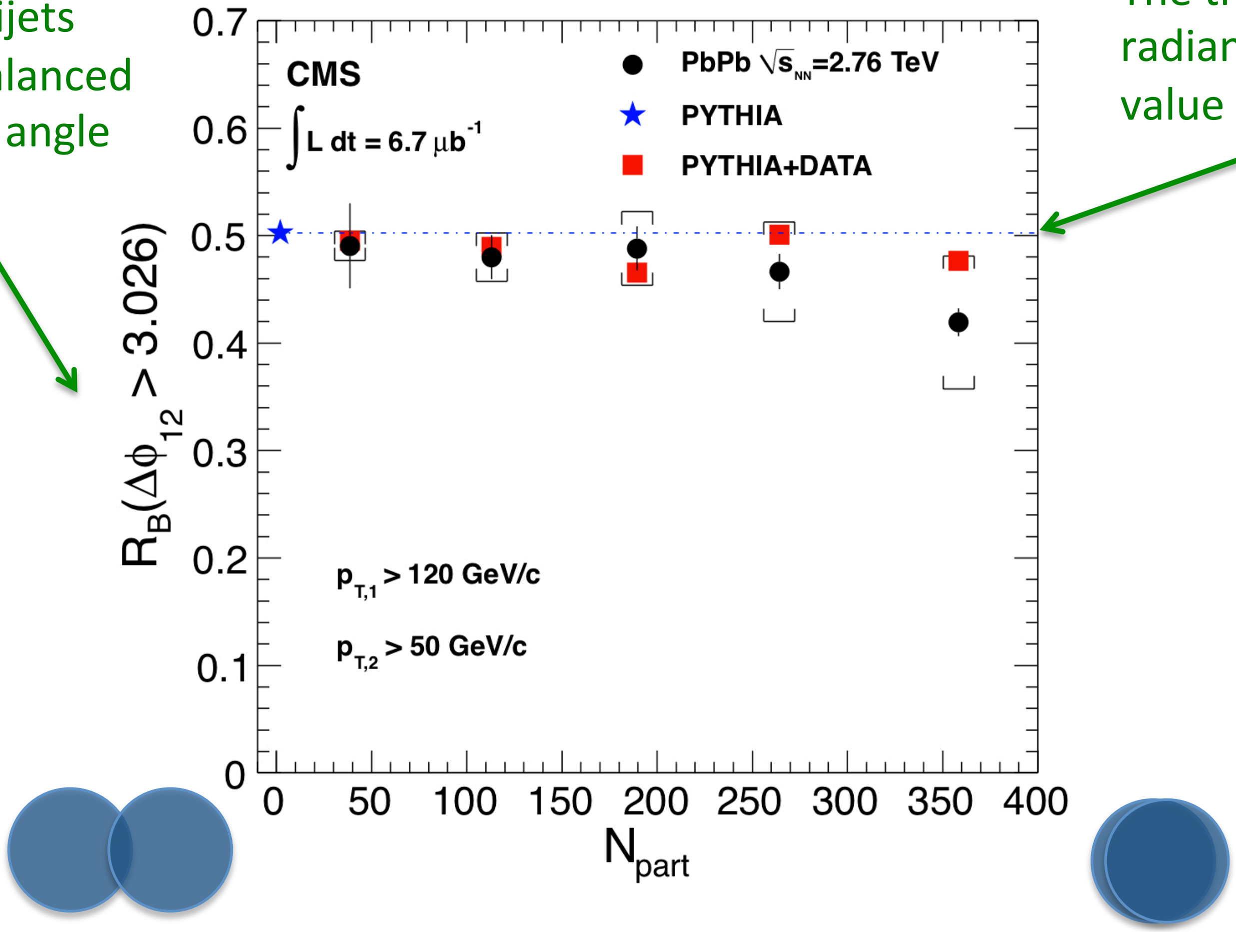


No strong angular deflection of reconstructed jets

Angular Decorrelation Quantified

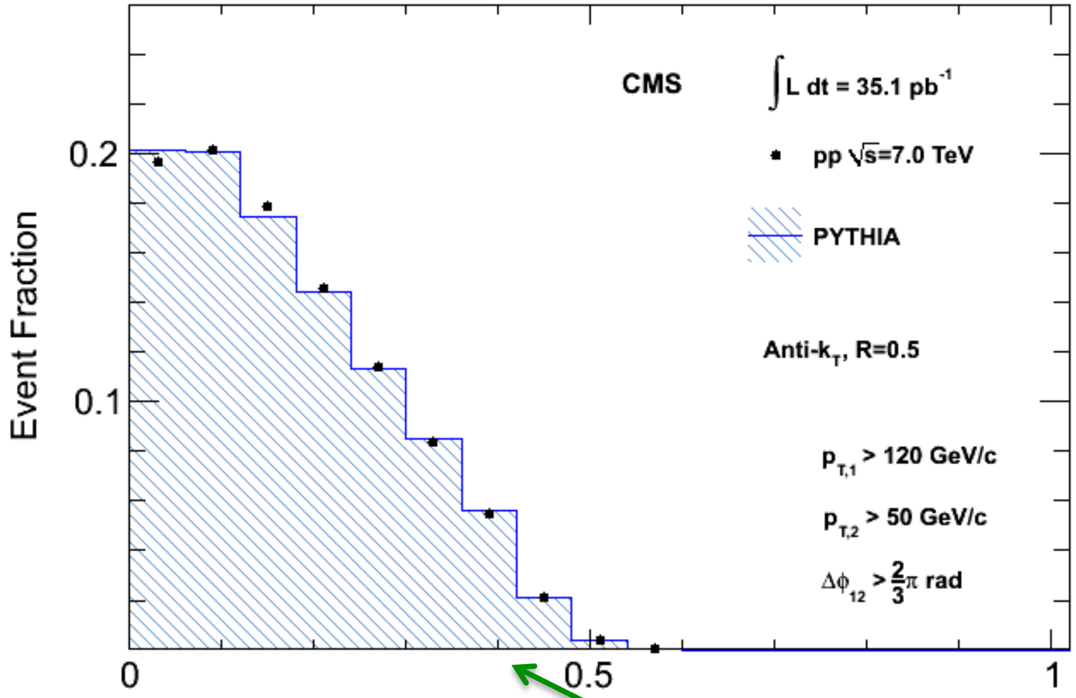
$R_B(\Delta\phi)$ is the fraction of dijets which are balanced in azimuthal angle

The threshold of 3.026 radians is the median value from PYTHIA



No angular decorrelation beyond systematic uncertainties

Dijet p_T Asymmetry



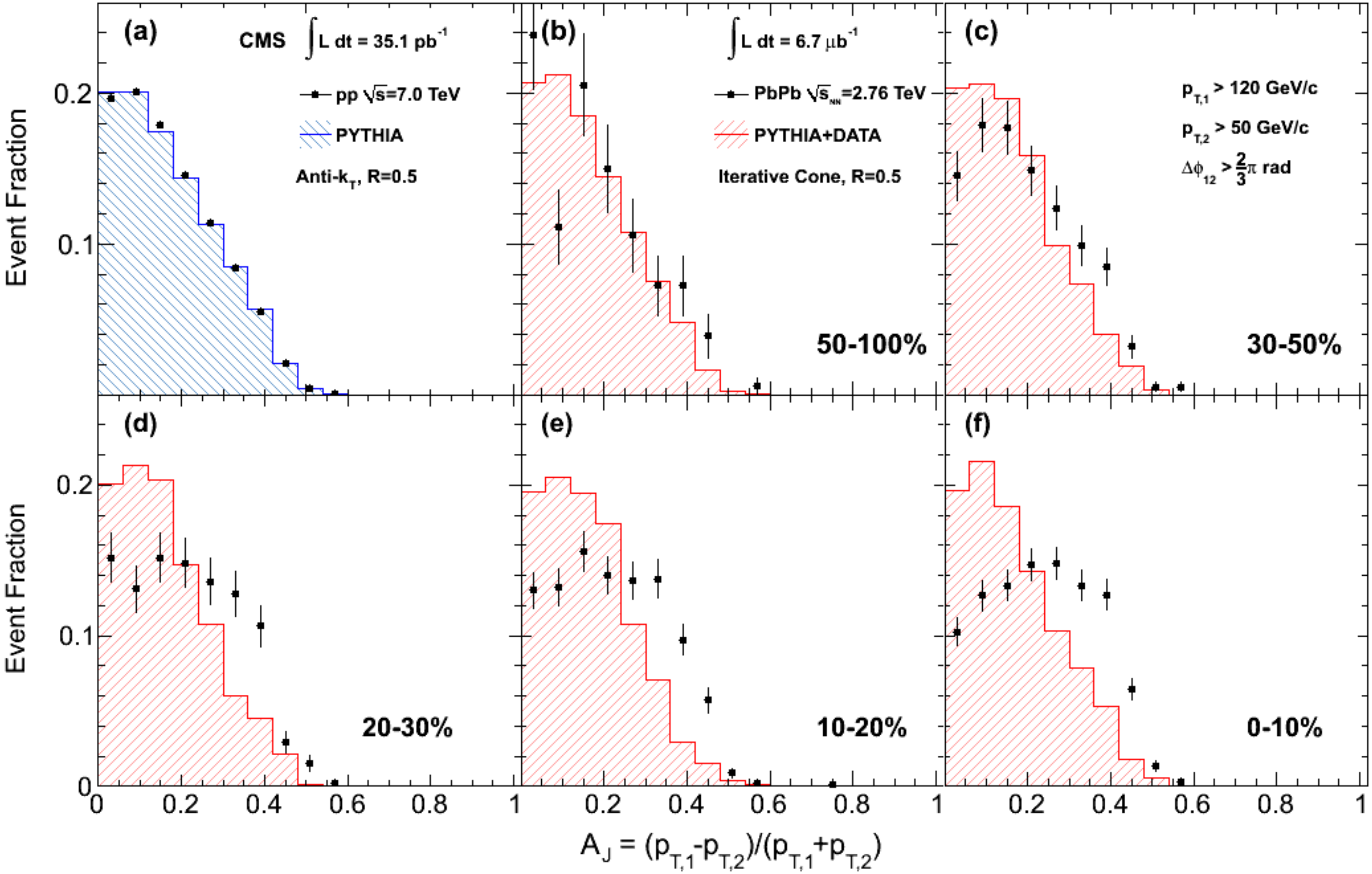
Imbalance

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

Dijet asymmetry quantified by A_J → insensitive to shift in energy scale

Jet p_T cuts place a threshold on A_J
e.g., $p_{T,1}$=120 & $p_{T,2}$=50 GeV/c → $A_J < 0.41$

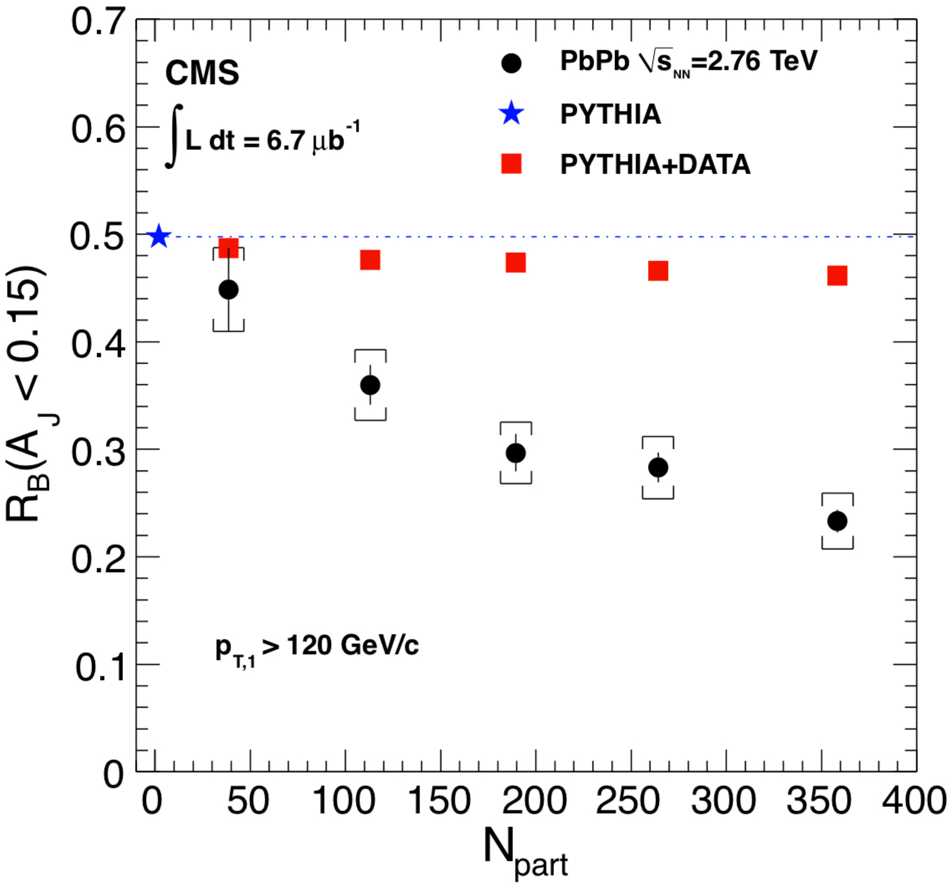
Dijet p_T Asymmetry



Striking enhancement of asymmetry with increasing centrality

Dijet Imbalance Quantified

$R_B(A_J)$ is the fraction of dijets balanced in p_T



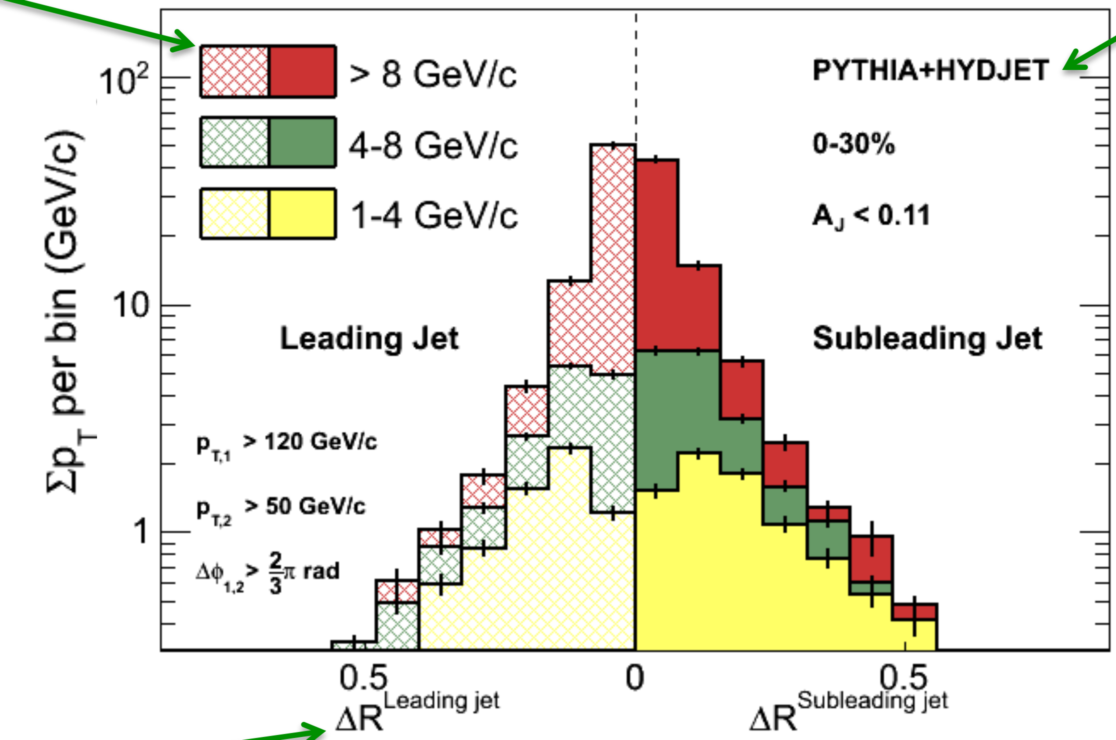
Smooth decrease in the fraction of balanced jets with increasing centrality

Jet-Track Correlations

Main idea: Use charged tracks to trace the fate of the energy lost by subleading jet

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



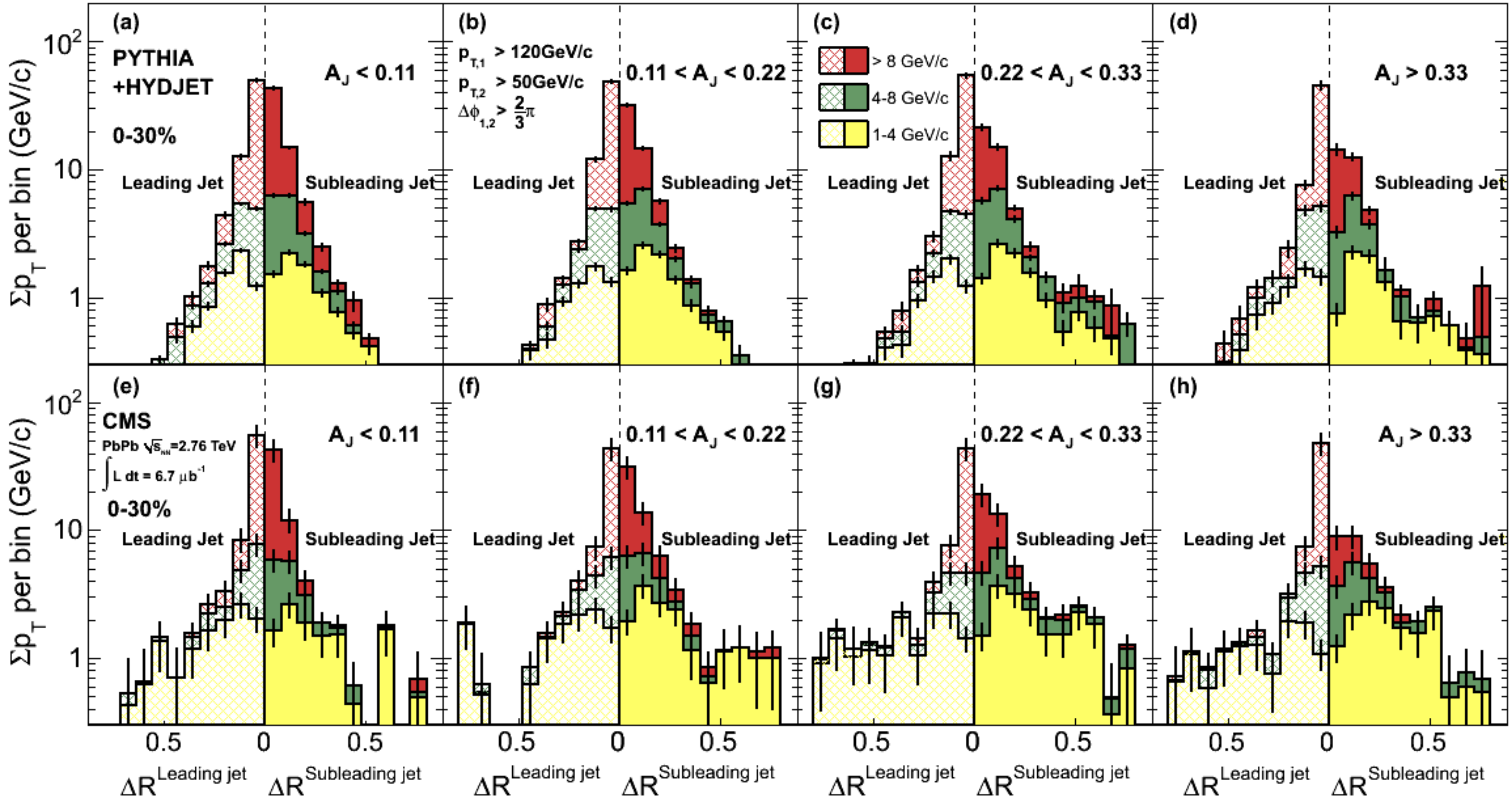
Plot against ΔR from the jet axis for both the leading and subleading jet

Background is subtracted using a cone at same ϕ, but reflected in η ($\eta \rightarrow -\eta$)

Asymmetry Dependence of Fragmentation

Imbalance

Dijet asymmetry reflected in high p_T charged tracks



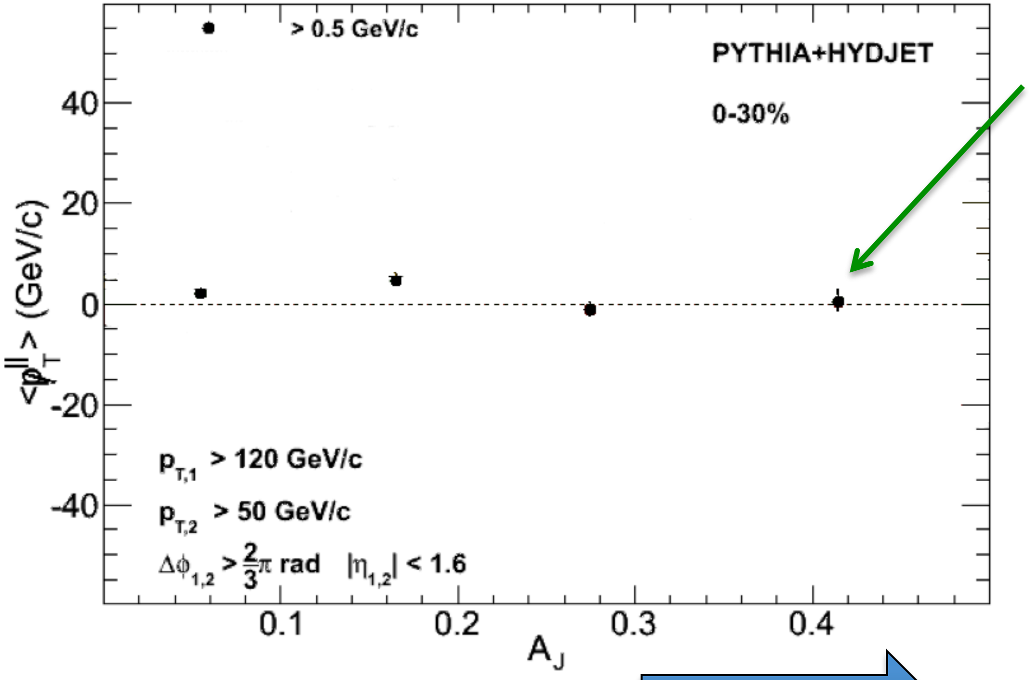
With increasing A_J, some enhancement of low p_T, large angle production appears

Missing p_T

Quantify overall p_T balance w.r.t. leading jet axis

$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\mathrm{T,track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$

Sum over all tracks of $p_T > 500$ MeV



Events balance even if two leading jets do not

Leading Jet

Imbalance

Missing p_T

Quantify overall p_T balance w.r.t. leading jet axis

$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\text{T,track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$

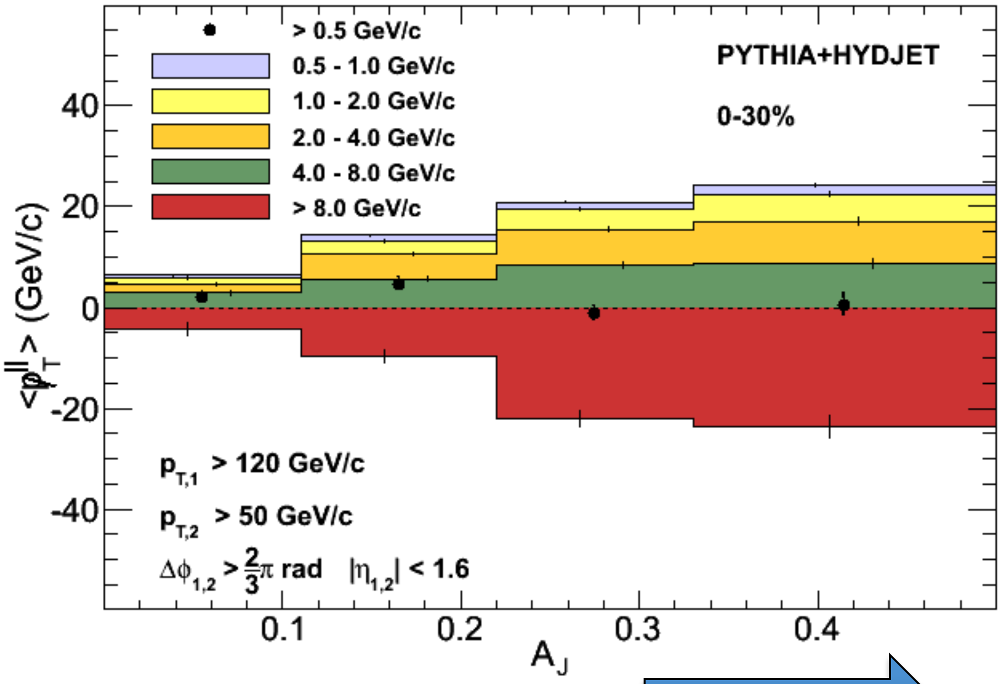
0.5 – 1

1 – 2

2 – 4

4 – 8

> 8 GeV



Leading Jet

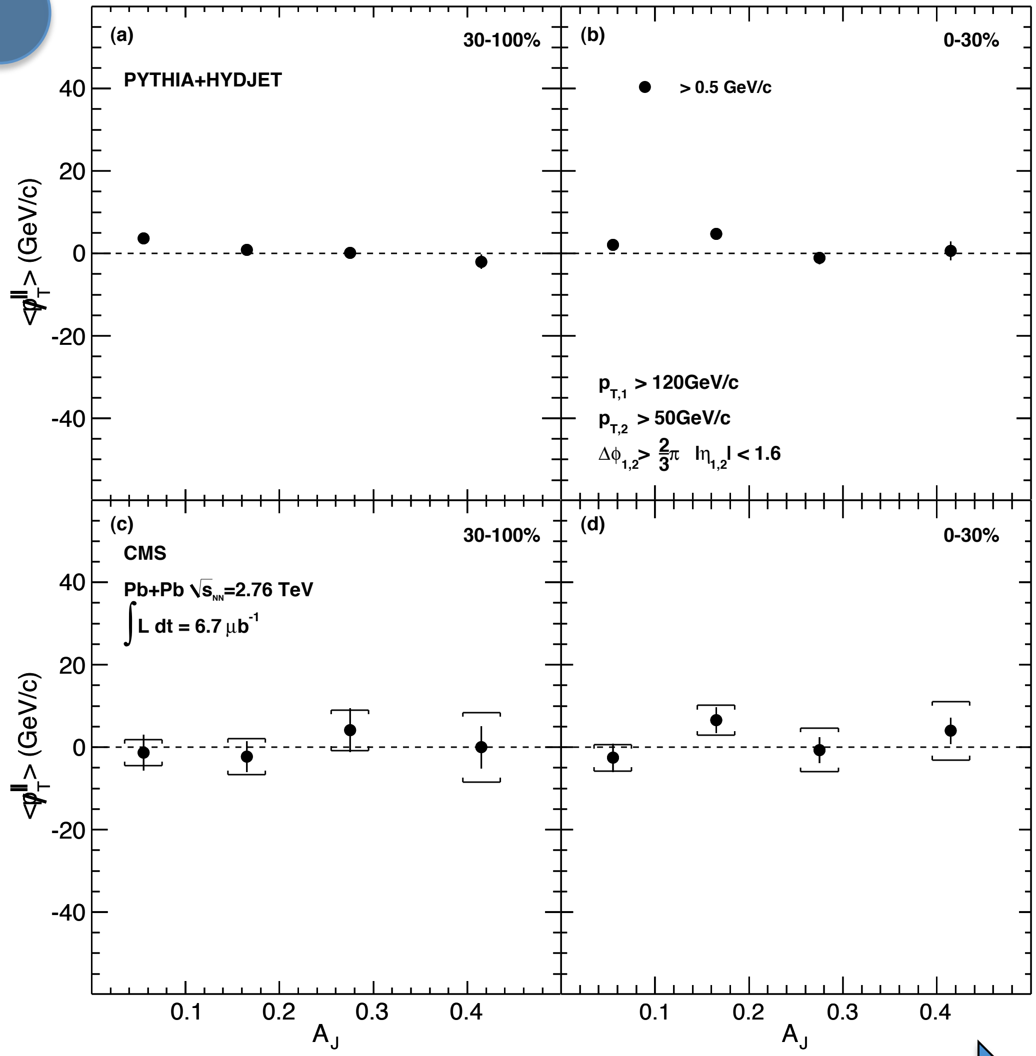
Imbalance

Find which ranges of p_T contribute to balance

Missing p_T: Data vs. MC

MC

DATA

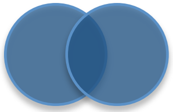


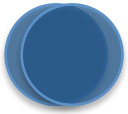
Leading Jet

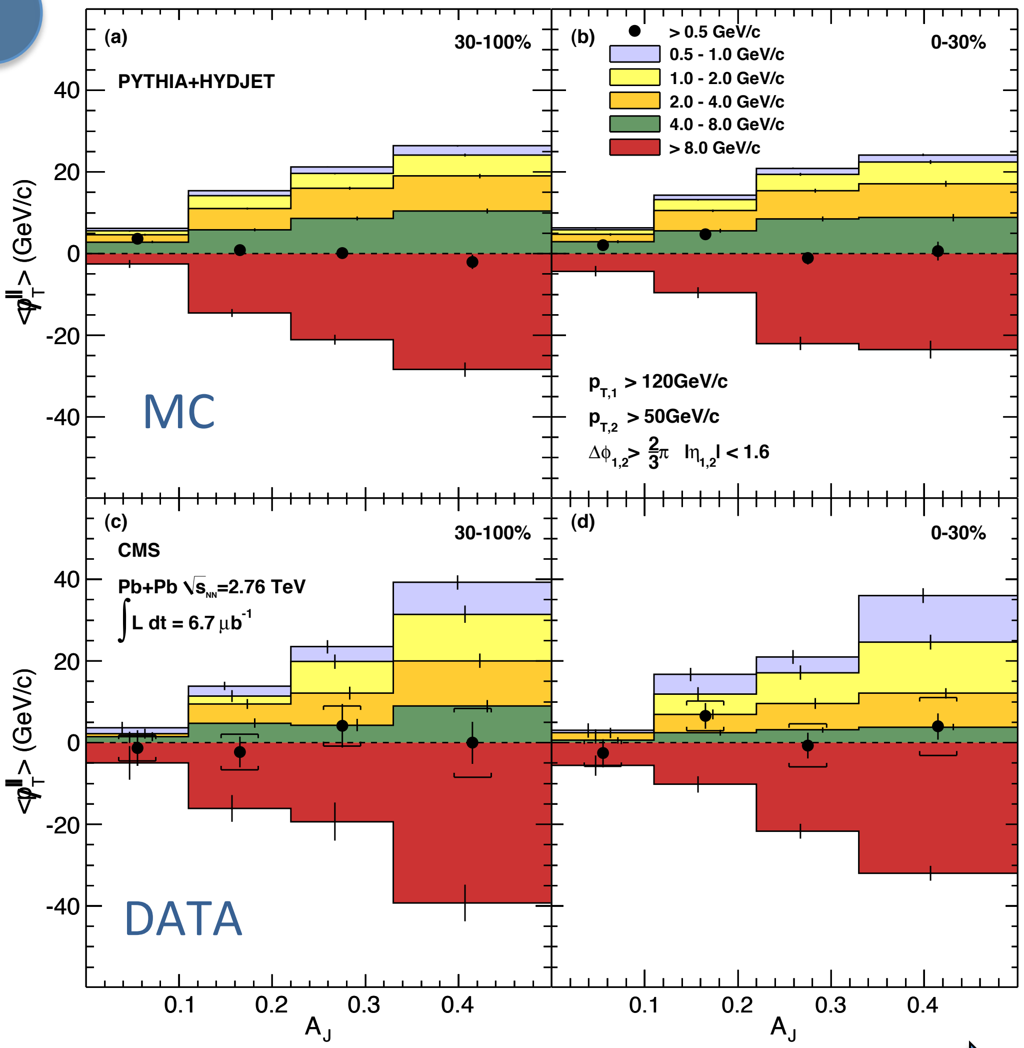
Imbalance

Despite large fraction of unbalanced jets, overall p_T balance above 500 MeV is not affected by quenching

Missing p_T: Data vs. MC







Leading Jet

Imbalance

0.5 – 1

1 – 2

2 – 4

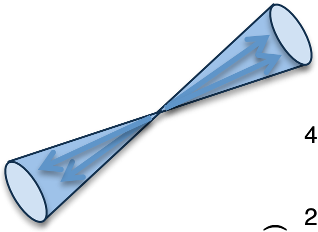
4 – 8

> 8 GeV

MC: Leading jet balanced by tracks of intermediate p_T (2-8 GeV/c)

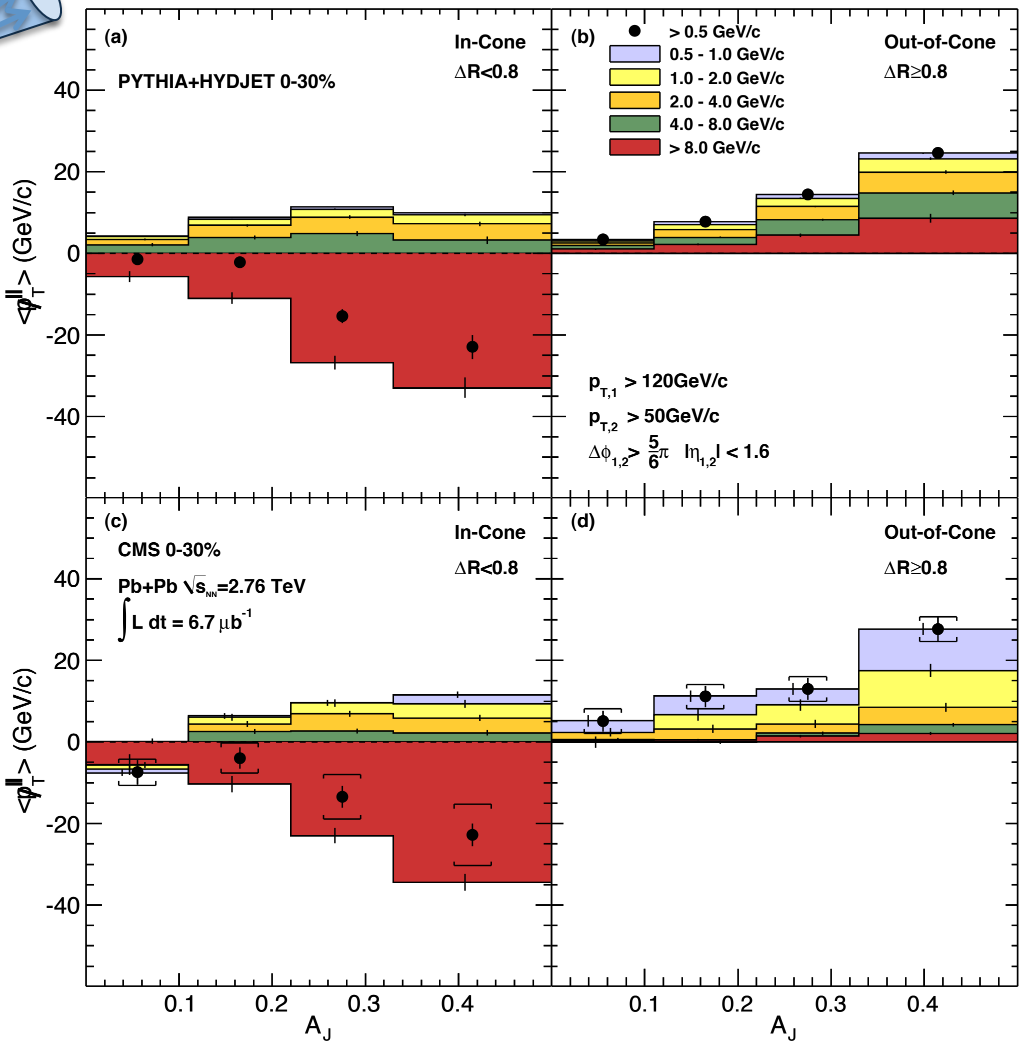
Data: Balance increasingly dominated by low p_T tracks, especially in central events

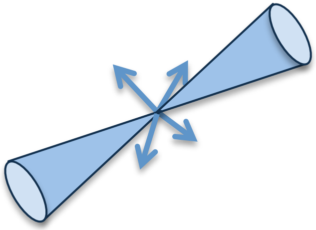
Missing p_T: In vs. Out-of-Cone



MC

DATA





MC: Large A_J events show balance carried by high p_T tracks at R > 0.8 → multi-jet events

Data:

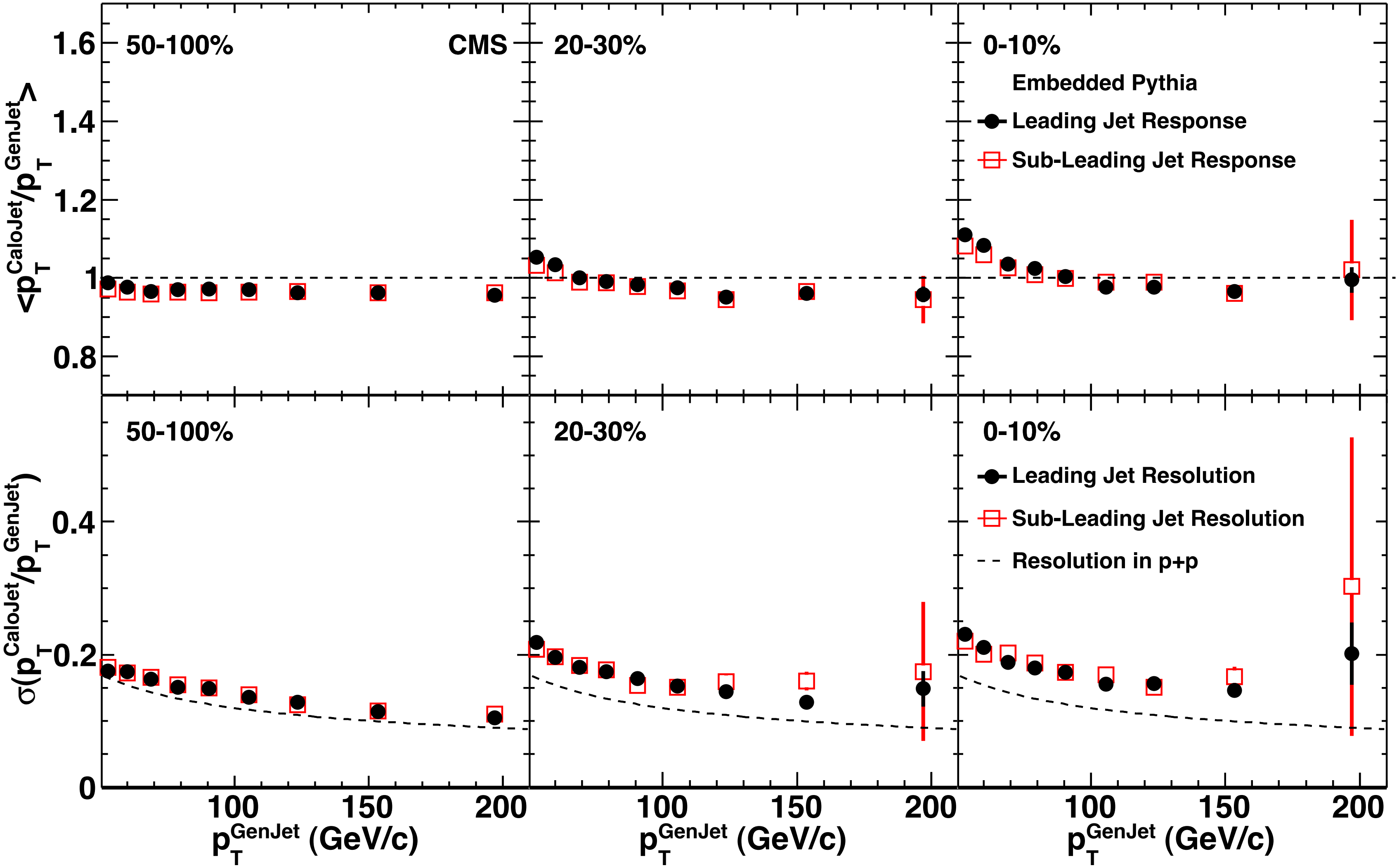
- In-cone balance not very different from MC
- Balance only recovered with low p_T tracks at large R

Conclusions

- Evidence for large jet quenching in PbPb collisions has been observed
  - No large azimuthal decorrelation
  - Large momentum imbalance with increased centrality
- Jet-track correlations demonstrate that
  - Energy is transferred to low p_T particles
  - This energy is deposited outside the typical jet radius
- Data places constraints on the nature of parton energy loss and should challenge conventional models

Backup Slides

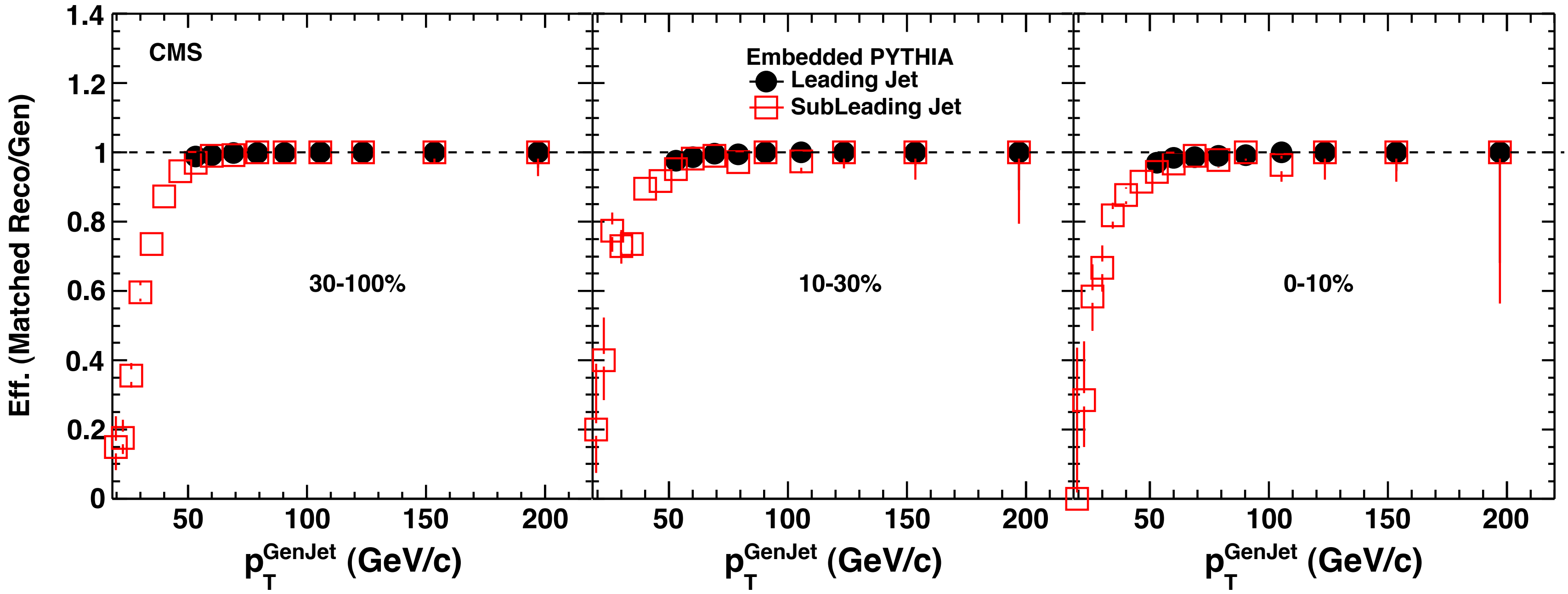
Jet Response and Resolution



Resolution determined from pythia embedded in data

Resolution degraded by ~ 30% by heavy-ion background in most central events

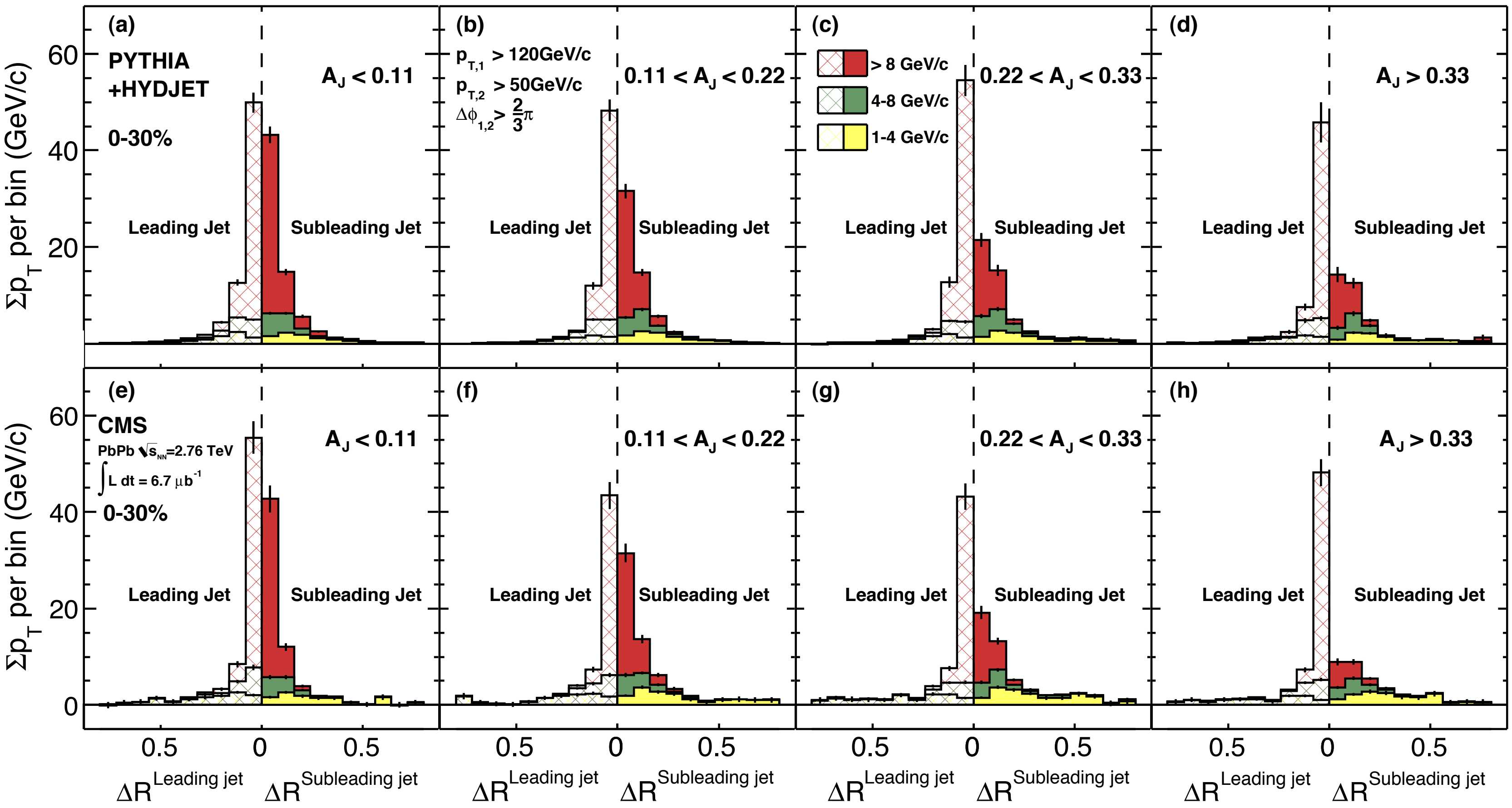
Jet Reconstruction Efficiency



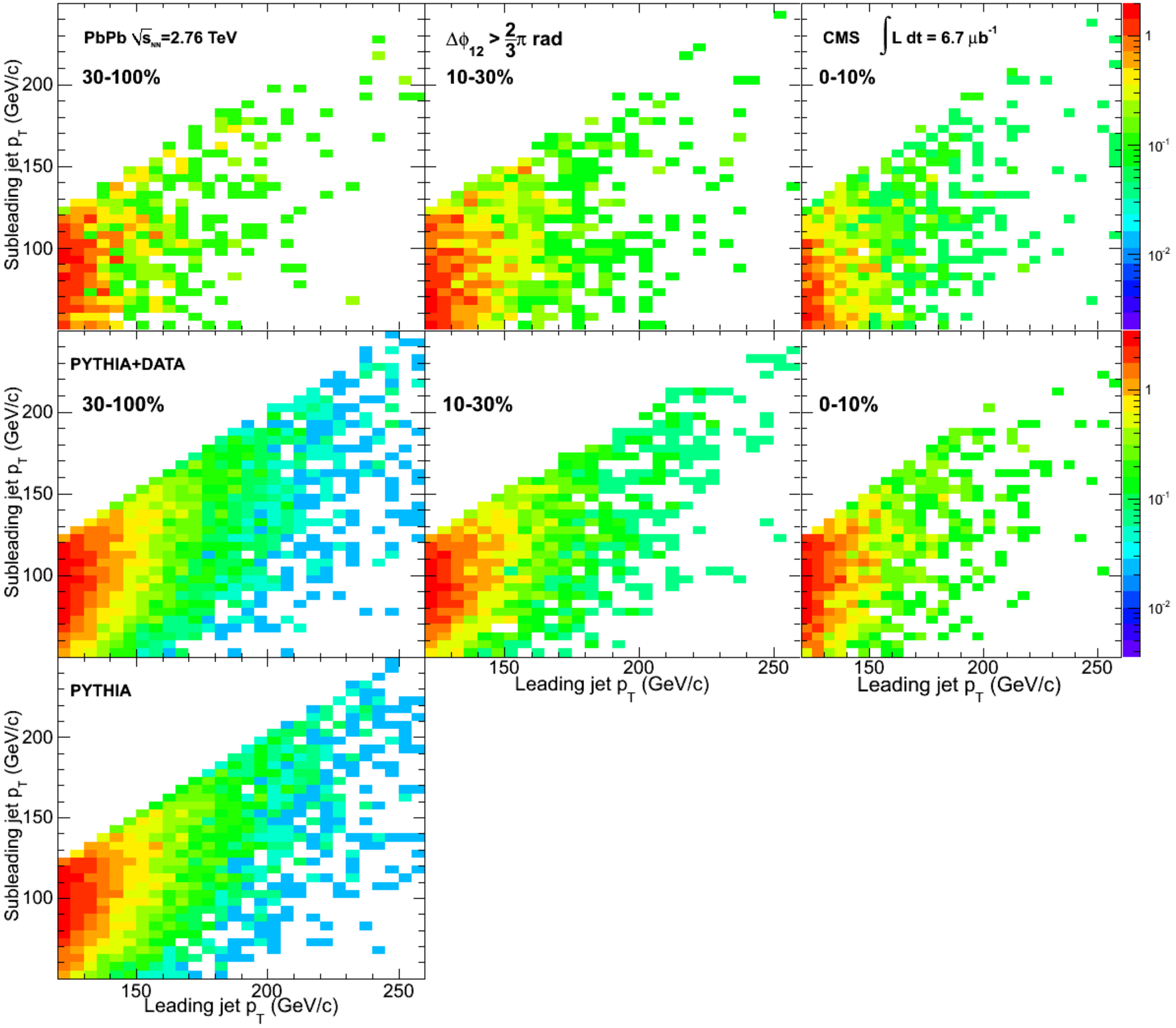
Fully efficient for leading jet selection (> 120 GeV/c)

High efficiency (~ 90%) for subleading jet sections (> 50 GeV/c)

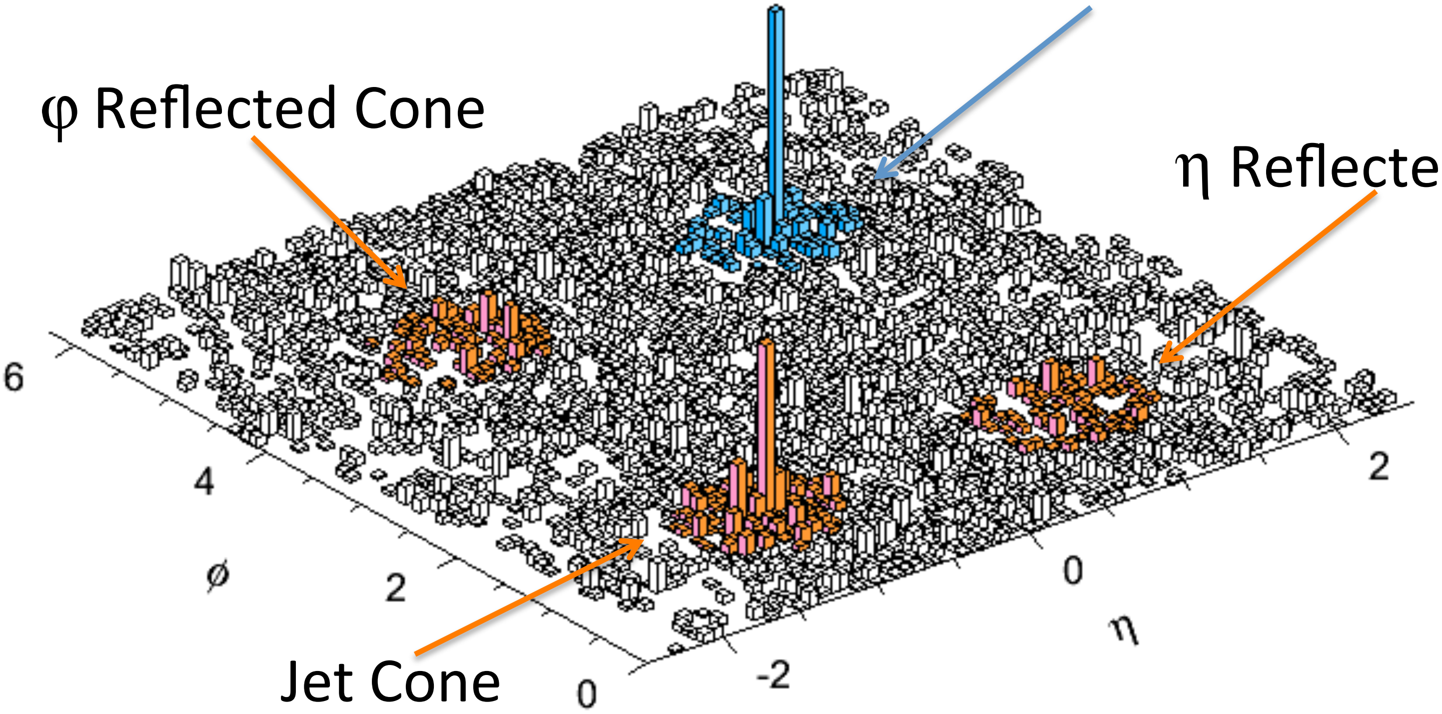
Jet-Track on Linear Scale



Leading vs. Subleading Jet p_T



η Reflection Method



Partner Jet Cone

φ Reflected Cone

η Reflected Cone

Jet Cone

The background is evaluated within the cone symmetric about η
This avoids φ dependent variations due detector efficiency or hydrodynamic flow
The regions around mid-rapidity, |η| < 0.8, and |η| > 1.6 are excluded

ATLAS Results

arXiv:1011.6182

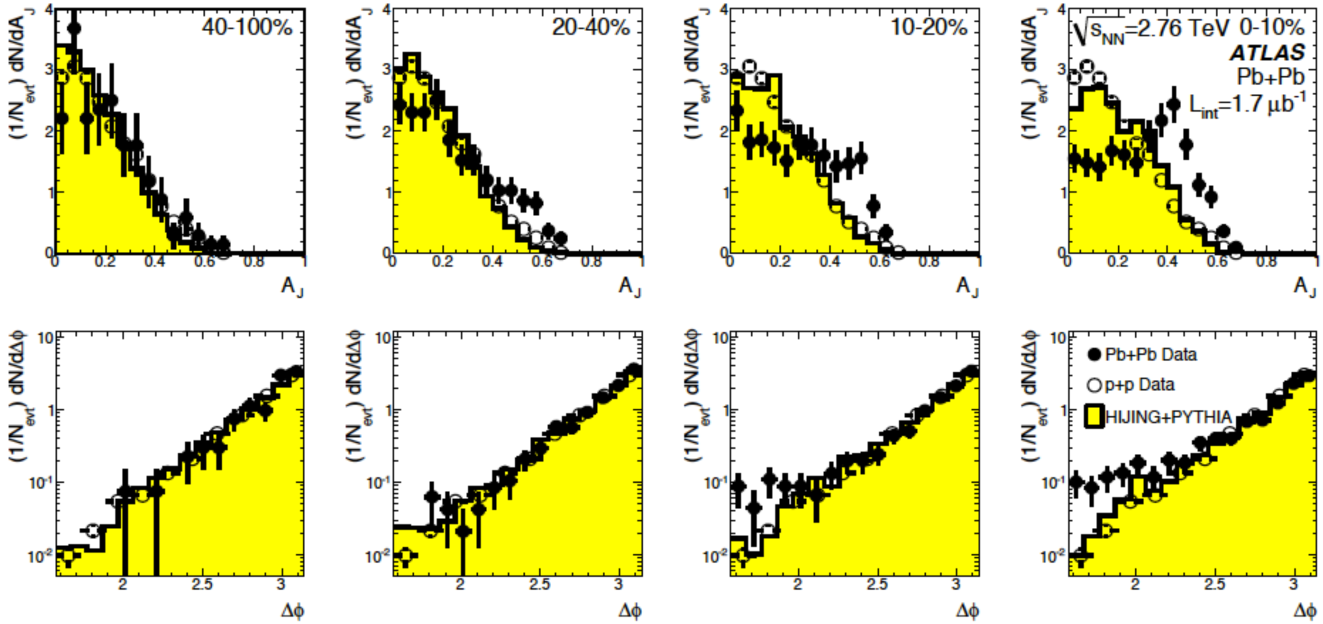
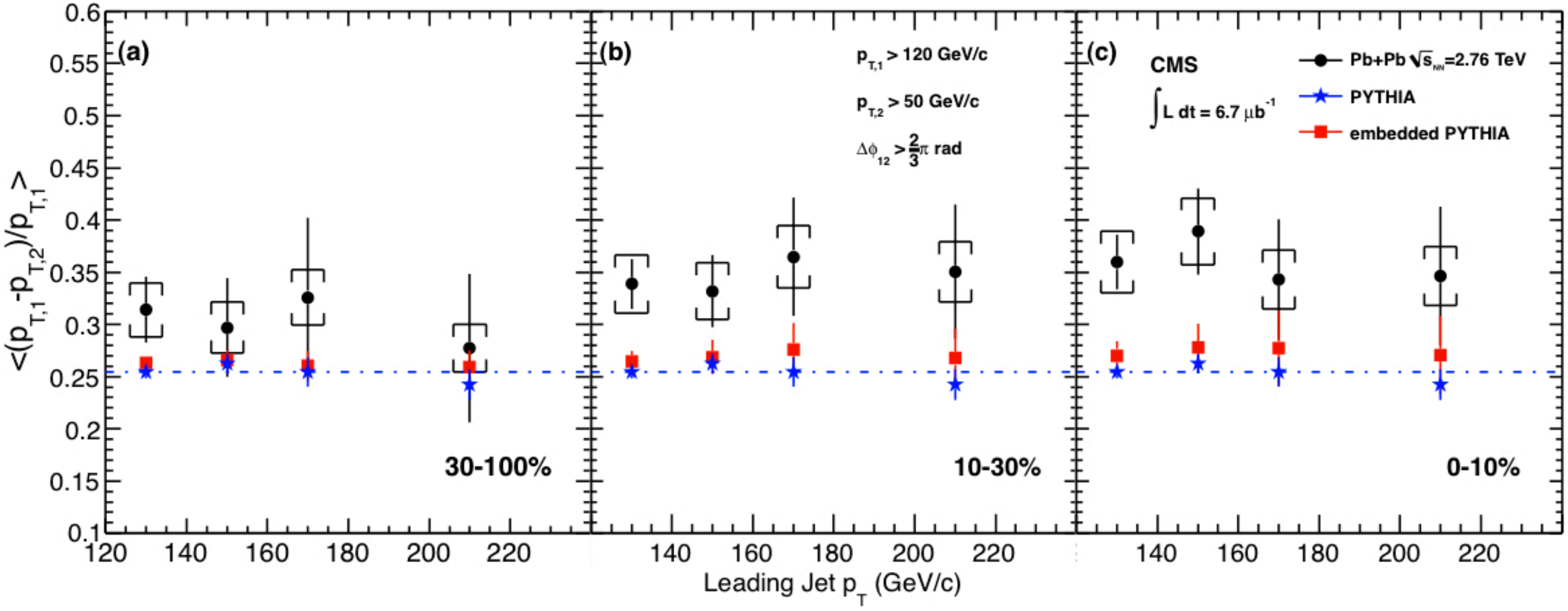
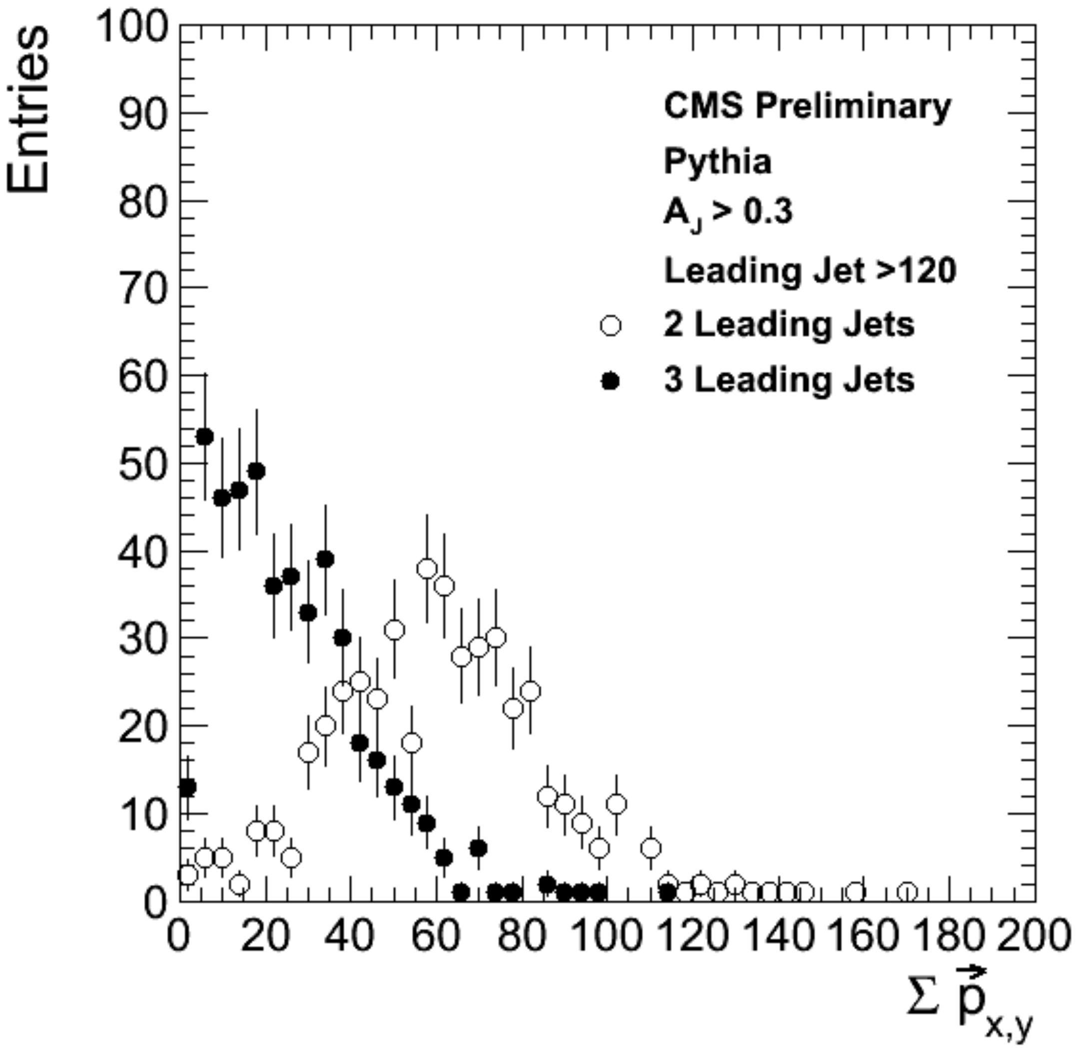


FIG. 3: (top) Dijet asymmetry distributions for data (points) and unquenched HIJING with superimposed PYTHIA dijets (solid yellow histograms), as a function of collision centrality (left to right from peripheral to central events). Proton-proton data from $\sqrt{s} = 7$ TeV, analyzed with the same jet selection, is shown as open circles. (bottom) Distribution of $\Delta\phi$, the azimuthal angle between the two jets, for data and HIJING+PYTHIA, also as a function of centrality.

p_T Dependence of Quenching



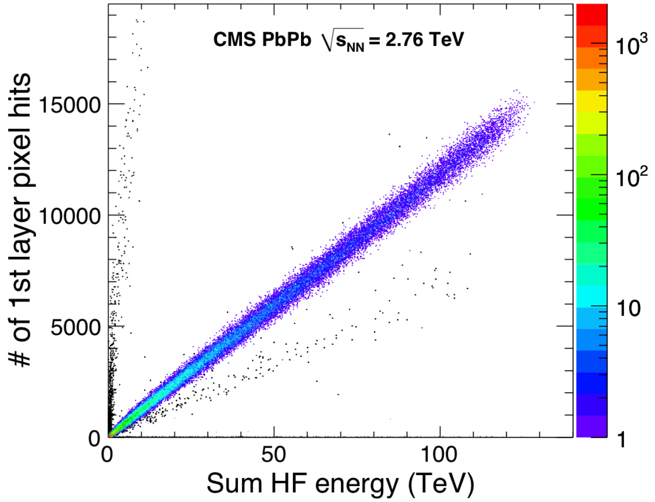
Including the 3rd jet in PYTHIA



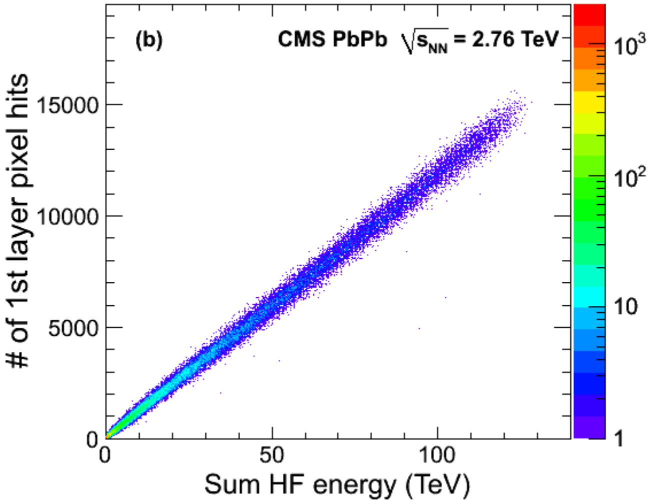
Collision Selection

- Reject Beam Halo (BSC)
- HF Coincidence
- Pixel cluster compatibility with vertex
- ECAL/HCAL Noise cleaning

Before Collision Selection



After Collision Selection



Systematic Uncertainties on R_B

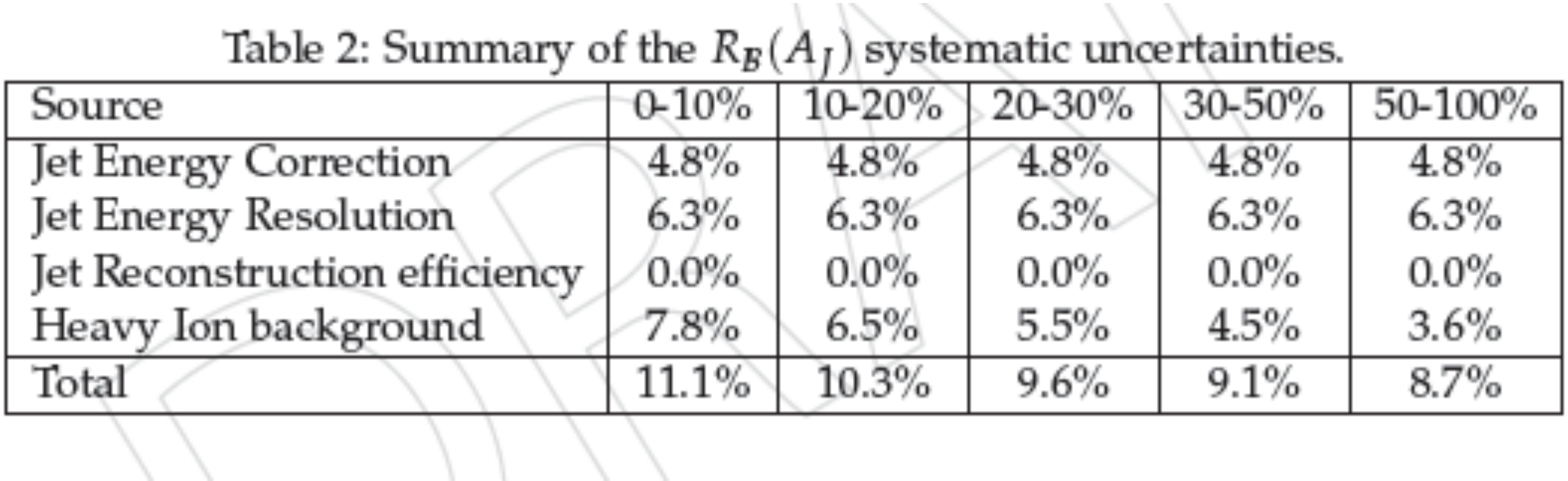


Table 2: Summary of the $R_B(A_J)$ systematic uncertainties.

Source	0-10%	10-20%	20-30%	30-50%	50-100%
Jet Energy Correction	4.8%	4.8%	4.8%	4.8%	4.8%
Jet Energy Resolution	6.3%	6.3%	6.3%	6.3%	6.3%
Jet Reconstruction efficiency	0.0%	0.0%	0.0%	0.0%	0.0%
Heavy Ion background	7.8%	6.5%	5.5%	4.5%	3.6%
Total	11.1%	10.3%	9.6%	9.1%	8.7%

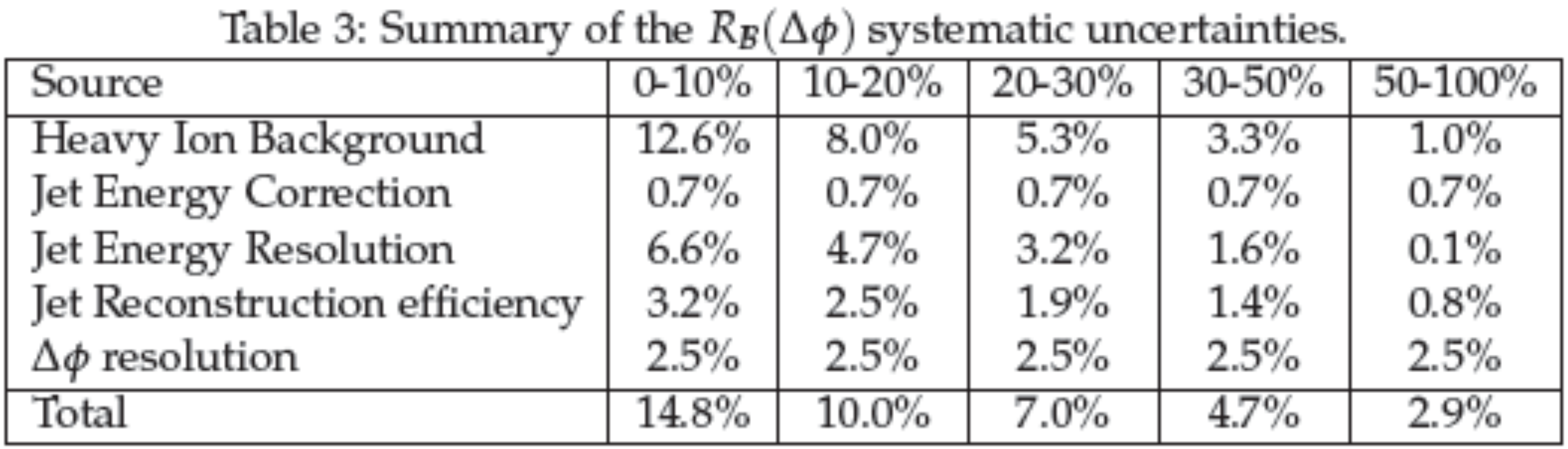


Table 3: Summary of the $R_B(\Delta\phi)$ systematic uncertainties.

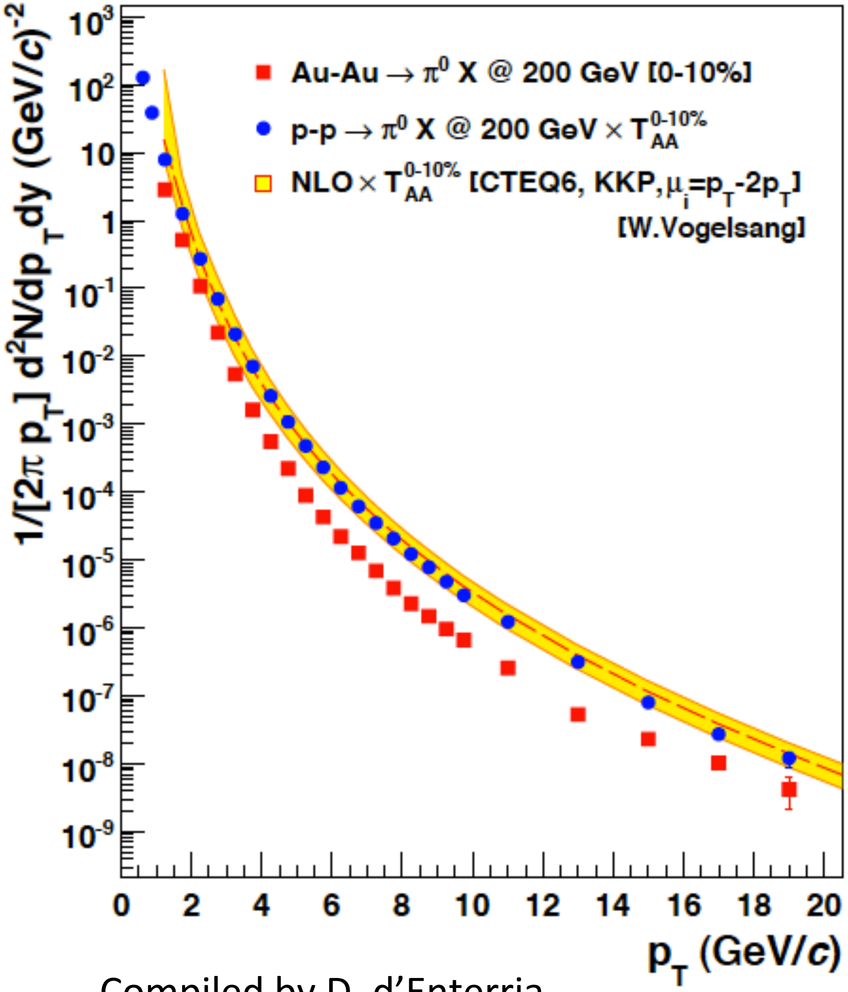
Source	0-10%	10-20%	20-30%	30-50%	50-100%
Heavy Ion Background	12.6%	8.0%	5.3%	3.3%	1.0%
Jet Energy Correction	0.7%	0.7%	0.7%	0.7%	0.7%
Jet Energy Resolution	6.6%	4.7%	3.2%	1.6%	0.1%
Jet Reconstruction efficiency	3.2%	2.5%	1.9%	1.4%	0.8%
$\Delta\phi$ resolution	2.5%	2.5%	2.5%	2.5%	2.5%
Total	14.8%	10.0%	7.0%	4.7%	2.9%

High p_T Suppression at RHIC

- π^0 yields measured in p+p and central Au+Au @ 200 GeV
- The yield of high p_T hadrons is suppressed by a ~ 5 x compared to p+p expectation*

* p+p data scaled by the number of binary collisions

π^0 Yields from PHENIX



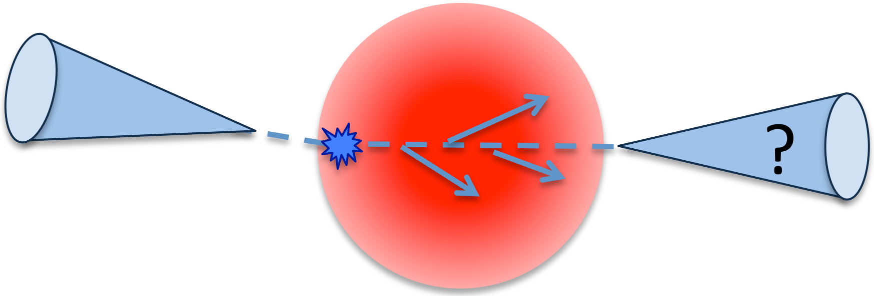
Compiled by D. d'Enterria
Springer Verlag. Landolt-Boernstein Vol. 1-23A.

Dihadron Correlations at RHIC

- Correlation of hadrons of

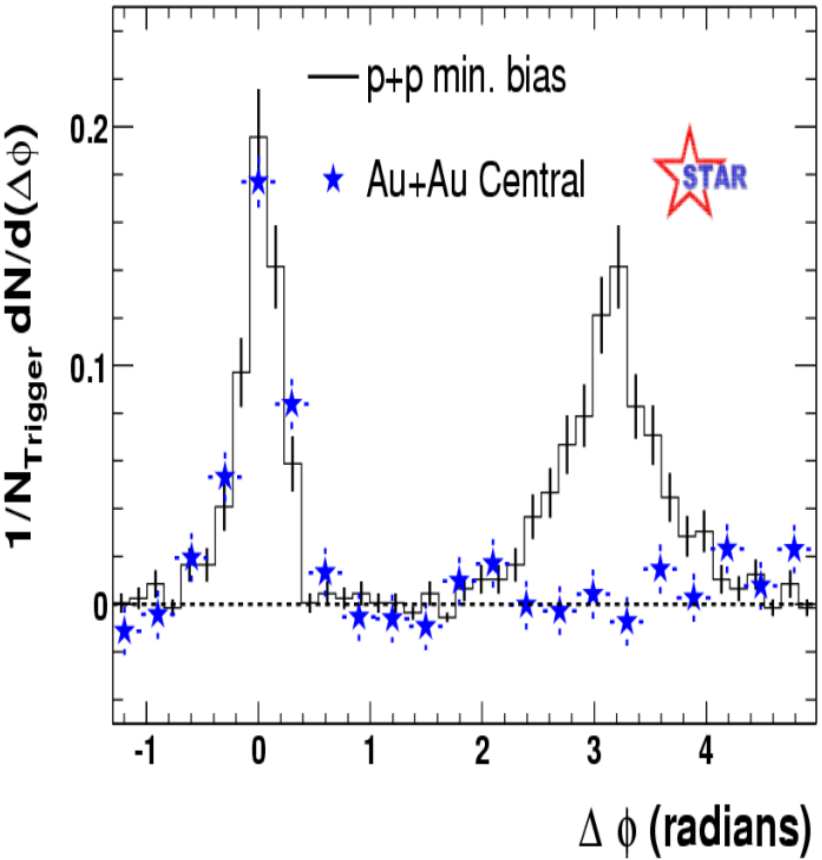
  $4\ \text{GeV}/c < p_{T,\ \text{trigger}} < 6\ \text{GeV}/c$
  $2\ \text{GeV}/c < p_{T,\ \text{partner}} < p_{T,\ \text{trigger}}$

- Near-side peak shows similar jet correlation in p+p and Au+Au
- Away-side jet correlation nearly extinguished in this p_T range
- Supports a geometrical picture of energy loss



Dihadron Correlations from STAR

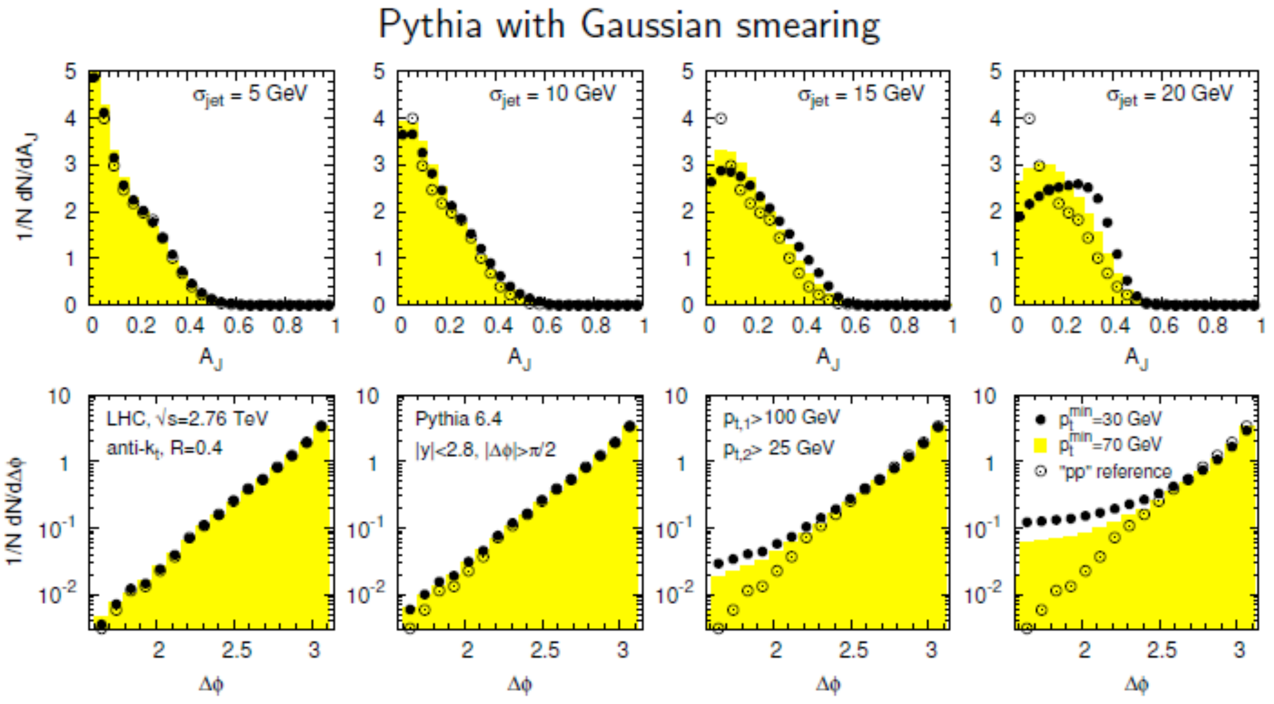
$\sqrt{s_{NN}} = 200$ GeV



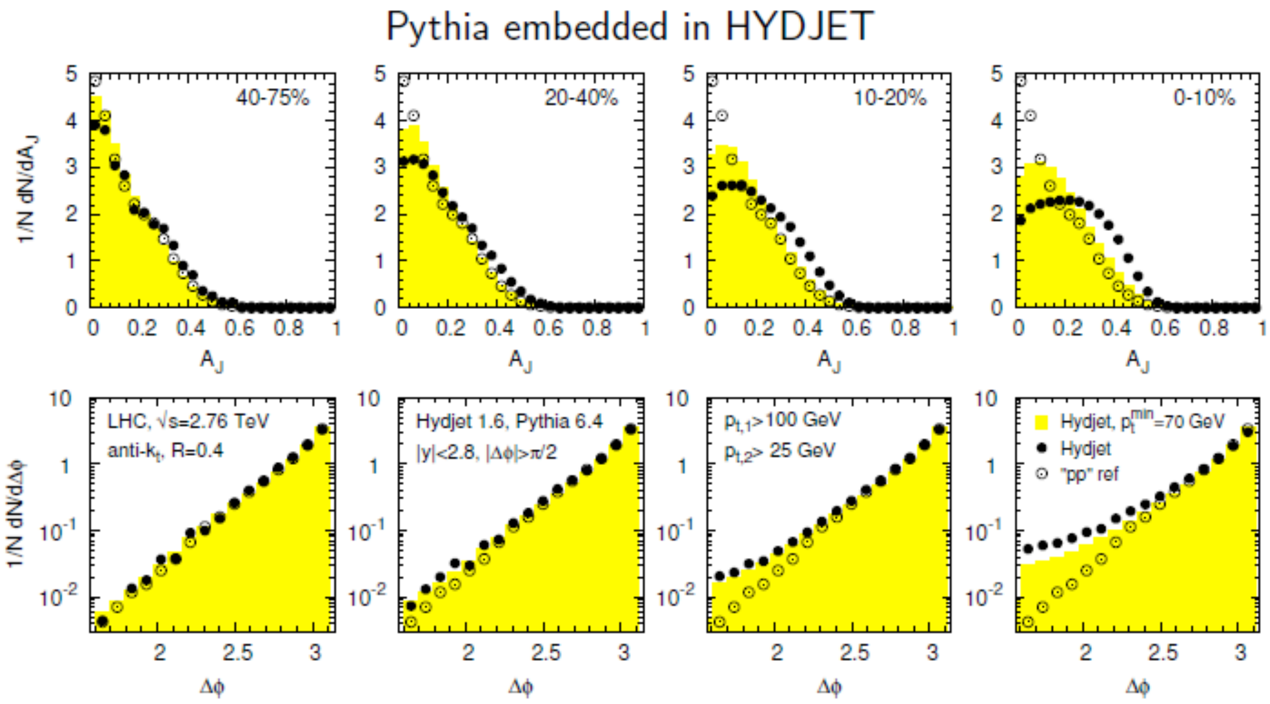
STAR collaboration,
Phys. Rev. Lett. 91 (2003) 072304

A_j broadening due to Fluctuations

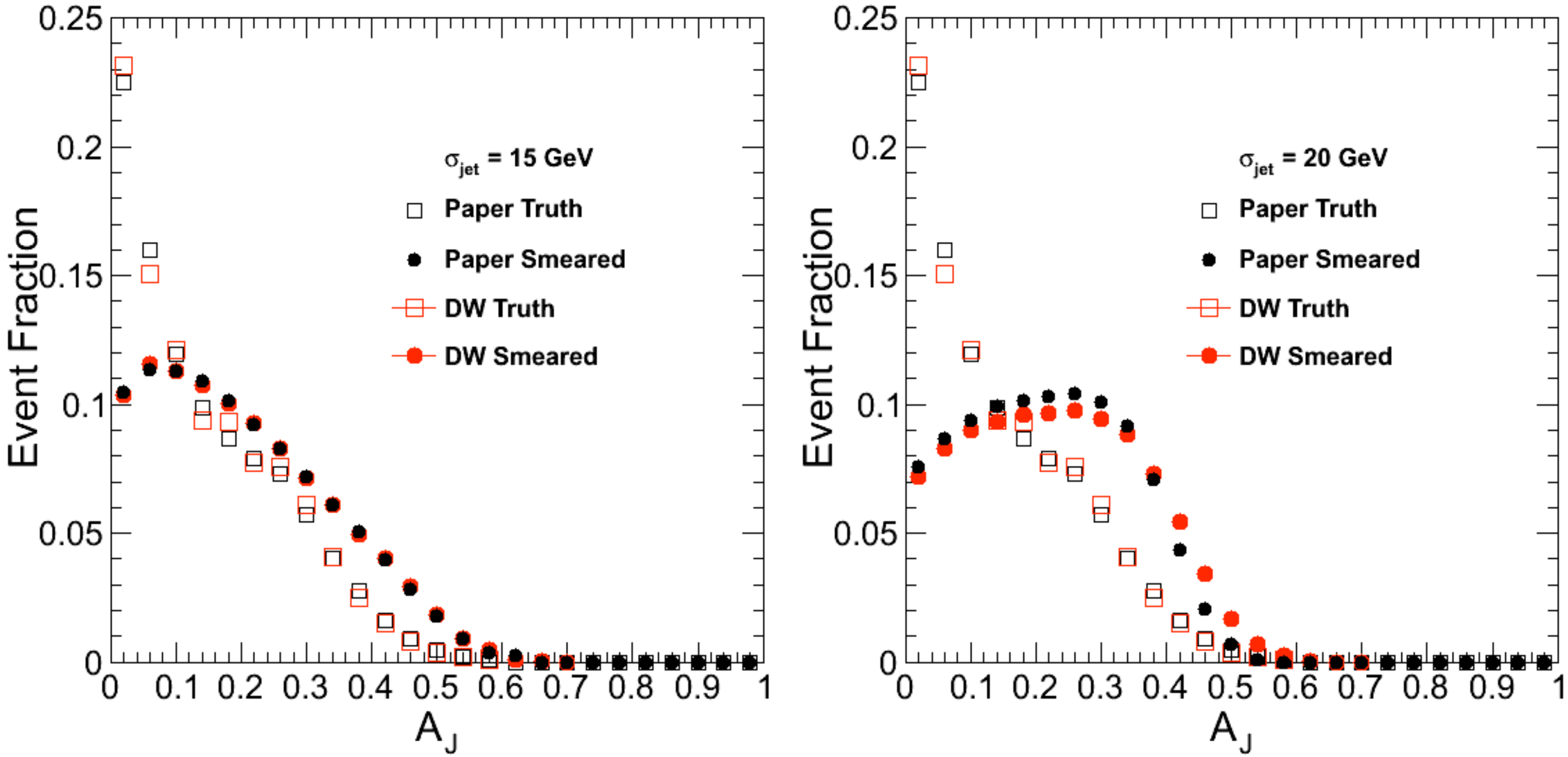
Different Gaussian smearing



PYTHIA+HYDJET

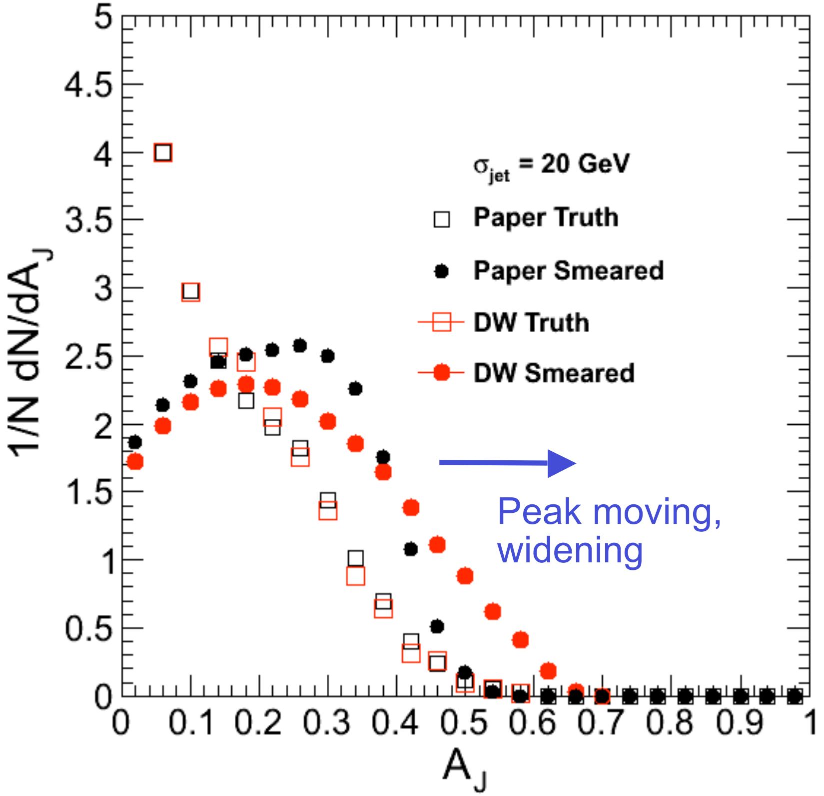


PYTHIA + Fluctuations

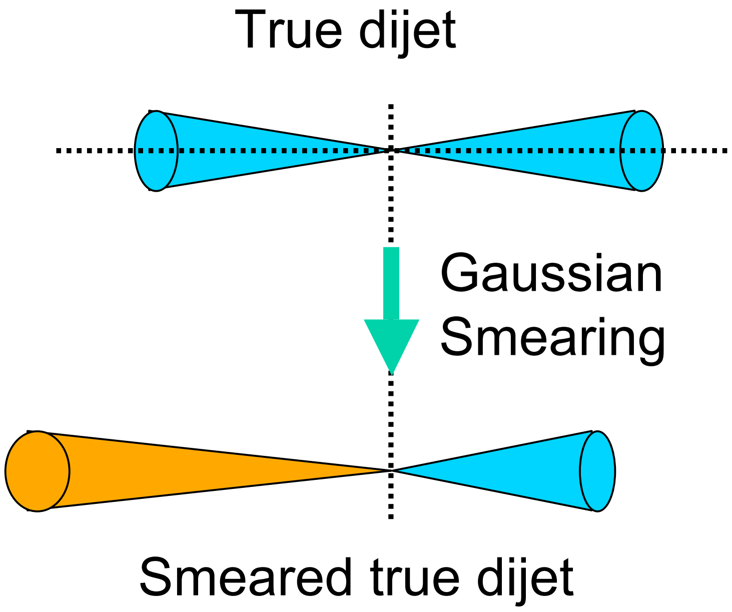


- Apply ATLAS's selection on the smeared jets:
  - **p_{T1} > 100 GeV, p_{T2} > 25 GeV, dphi > pi/2**
  - **GenJet p_T > 0 GeV**
- Applying a gaussian smearing to PYTHIA we can reproduce the results of the Salam paper.

Ingredients

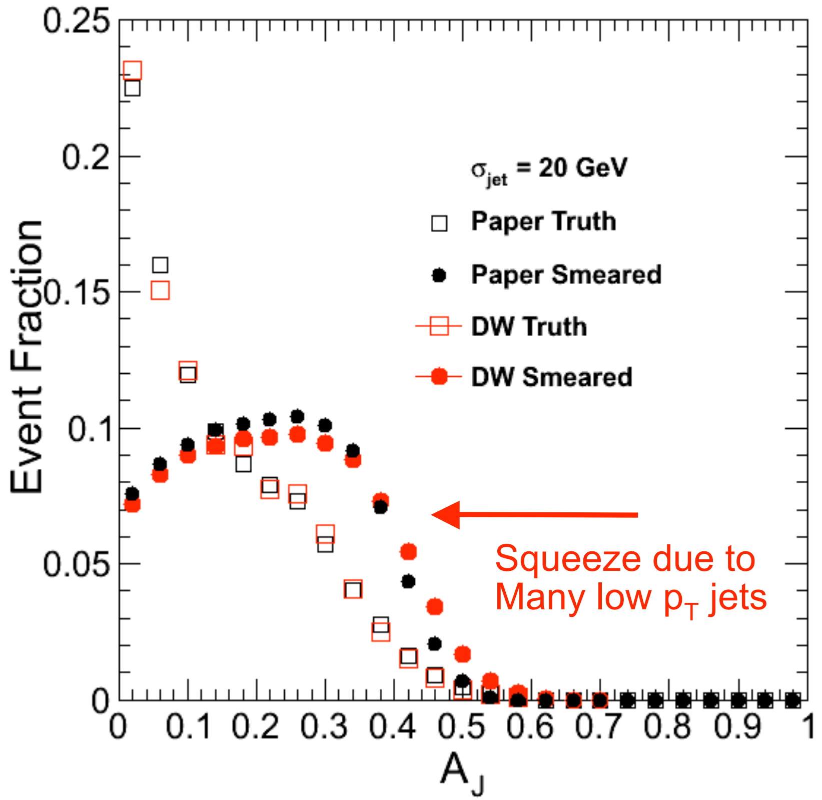


Peak moving, widening

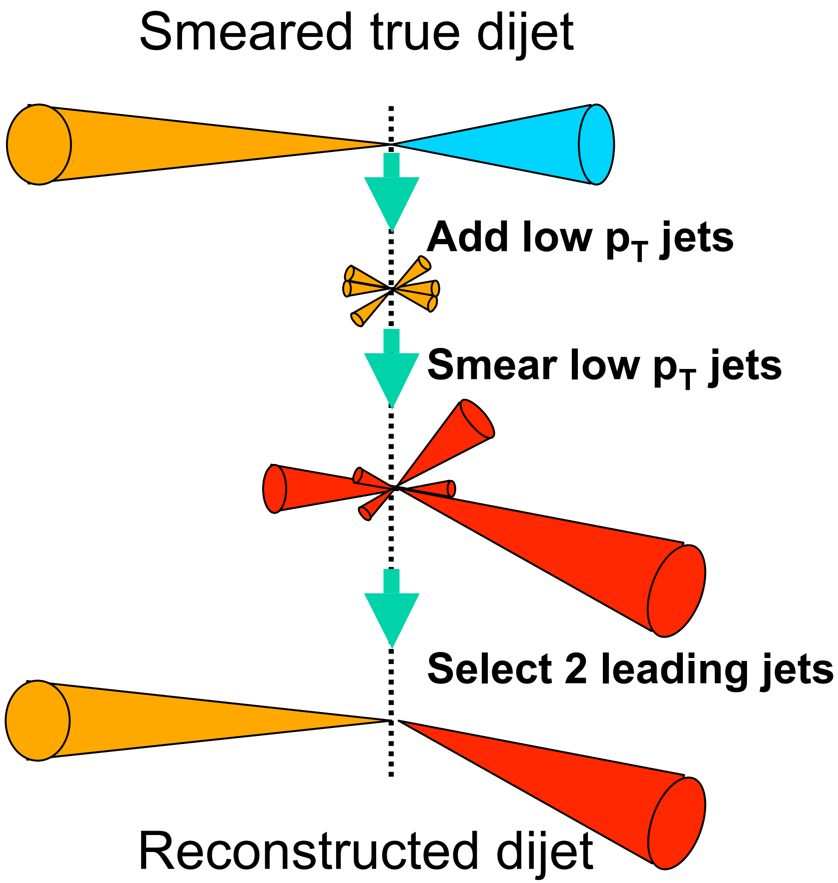


- **Gaussian smearing of the leading jet makes the Aj distribution wider**
  - **Select only Jets above p_T = 3GeV**

Ingredients II



Squeeze due to Many low p_T jets



Smeared true dijet

Add low p_T jets

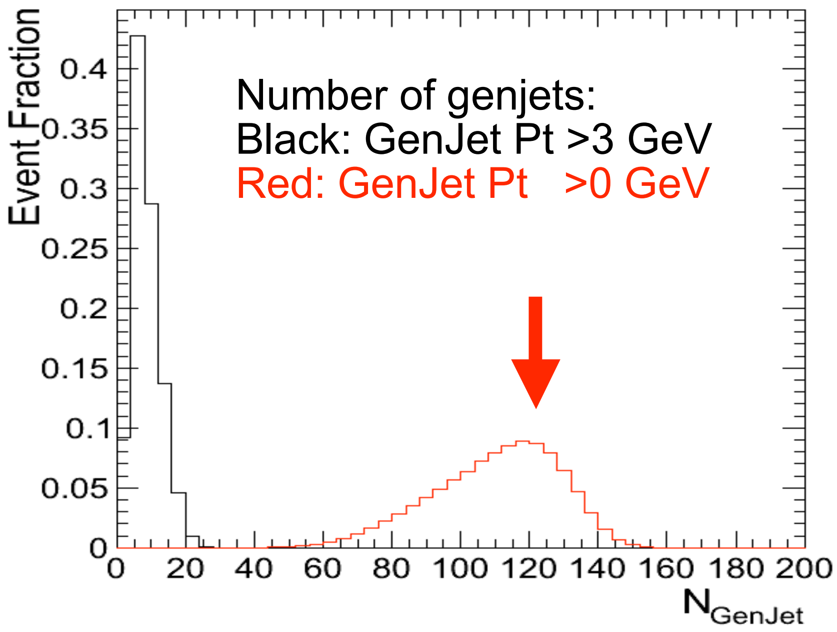
Smear low p_T jets

Select 2 leading jets

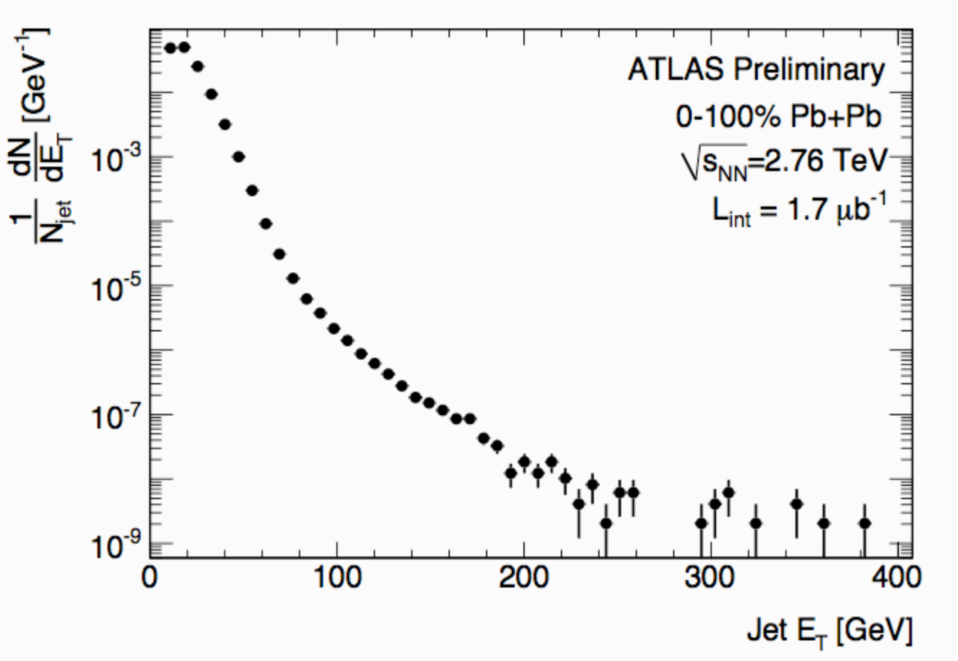
Reconstructed dijet

- **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

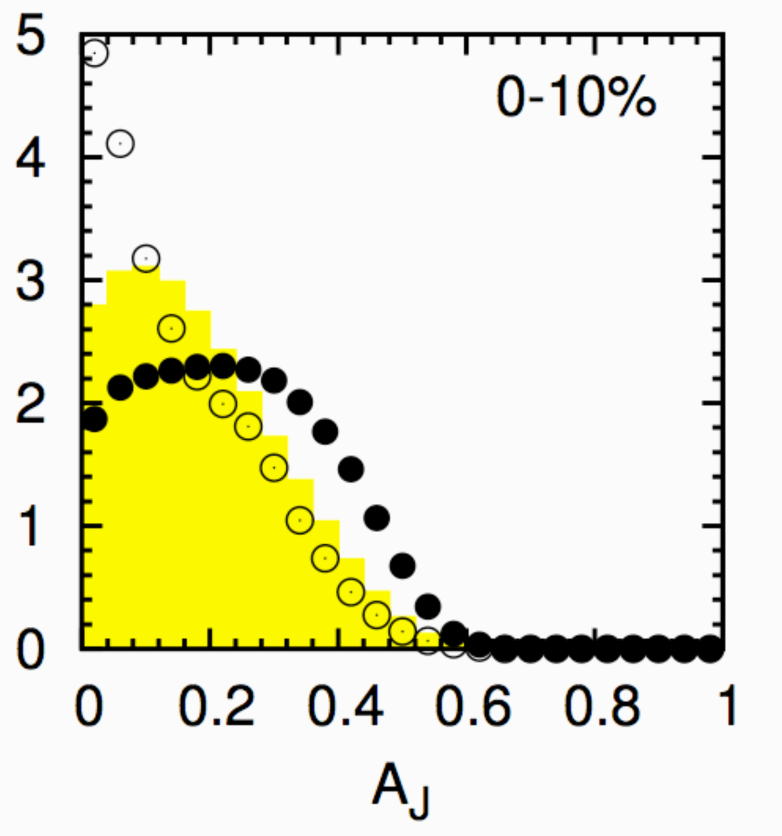


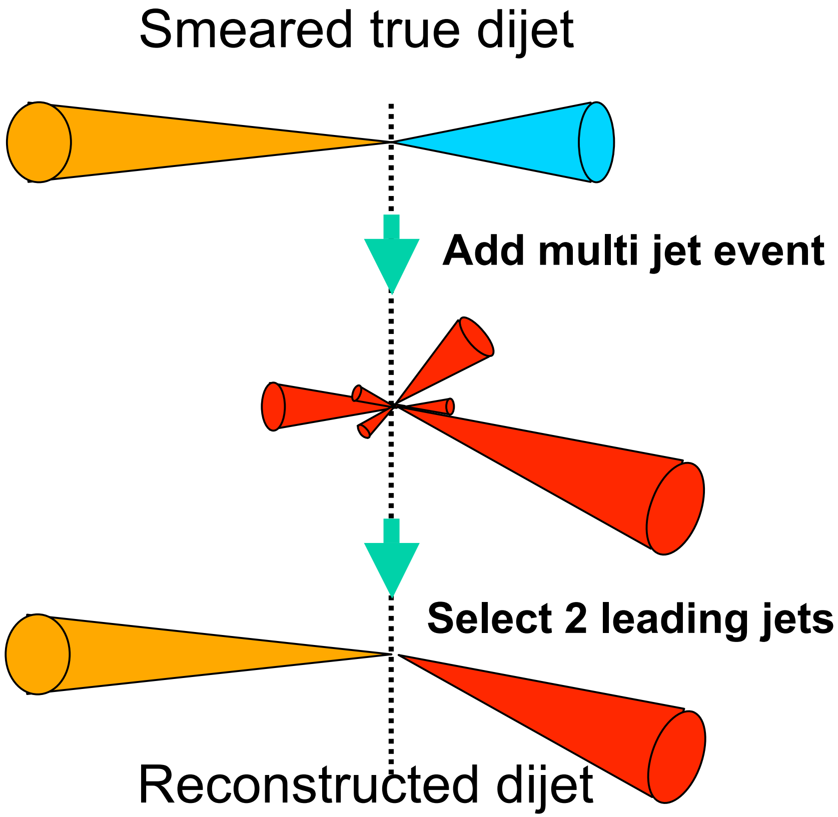
Number of genjets:
Black: GenJet Pt >3 GeV
Red: GenJet Pt >0 GeV



- 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**

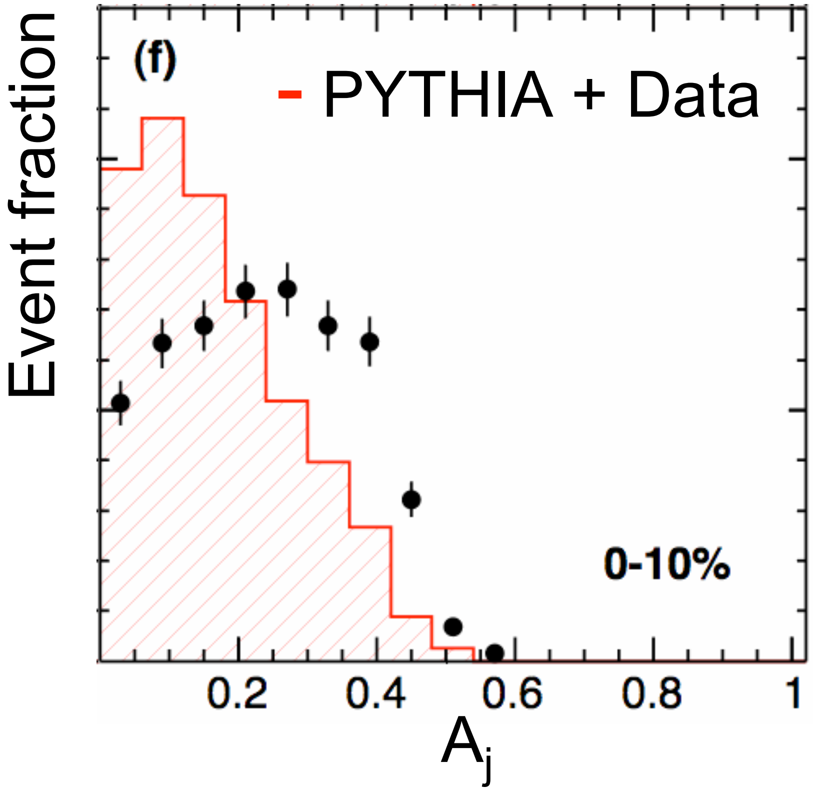
Hydjet

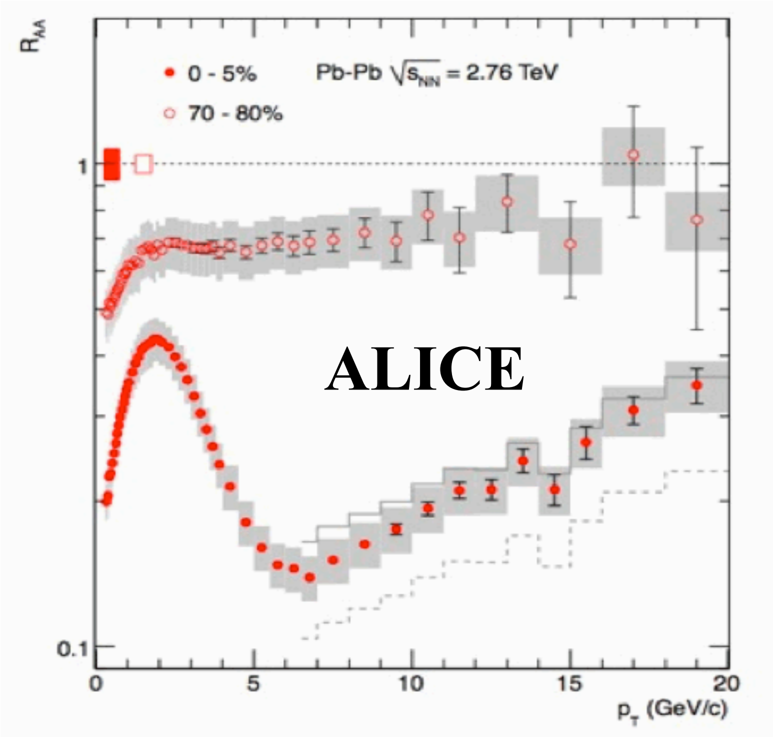




- The HYDJET A_j distribution is created by the same mechanism
  - The hard part of a central HYDJET event consists of ~300 unquenched PYTHIA events with $p_T$hat of ~7GeV
  - Low p_T jets smear the leading jets by superposition and cause a combinatorial problem

Is unquenched Hydjet a good background reference?

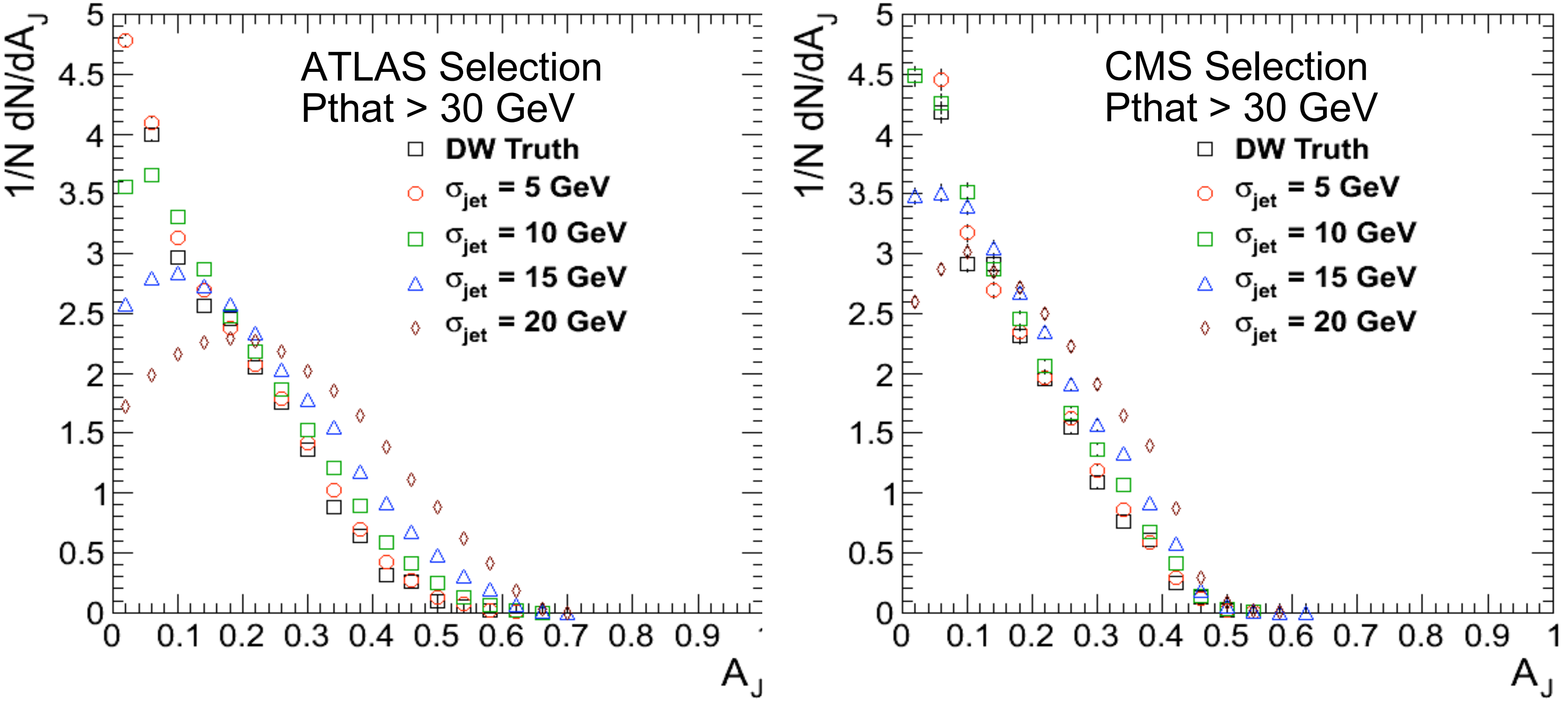




- PYTHIA embedded in real data, including all background fluctuations and resolution effects does not show a widened A_j distribution
  - **A cross check with $p_T$hat = 30GeV embedded in a large min bias data sample gave an identical reference distributions**
  - **ALICE R_{AA} shows a strong hardon suppression at 5-10GeV**
  - **Low p_T jets seem to be strongly suppressed**

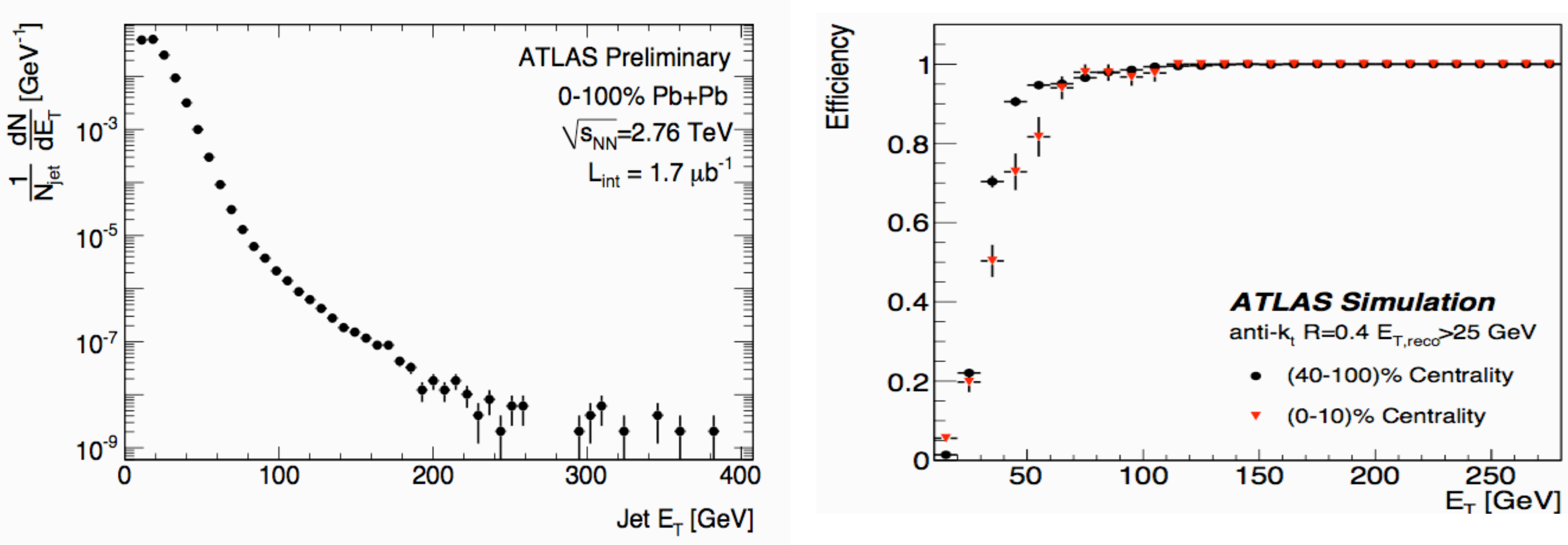
ATLAS vs CMS Dijet selection

Comparing the ATLAS and CMS dijet selection pT hat > 30 GeV



- With the higher jet thresholds used for the CMS paper we are less sensitive to background fluctuations
  - **ATLAS 100/20, CMS: 120/50 for leading/sub-leading**

ATLAS input



- The large σ (20GeV) smearing is 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**

20GeV smearing closure test