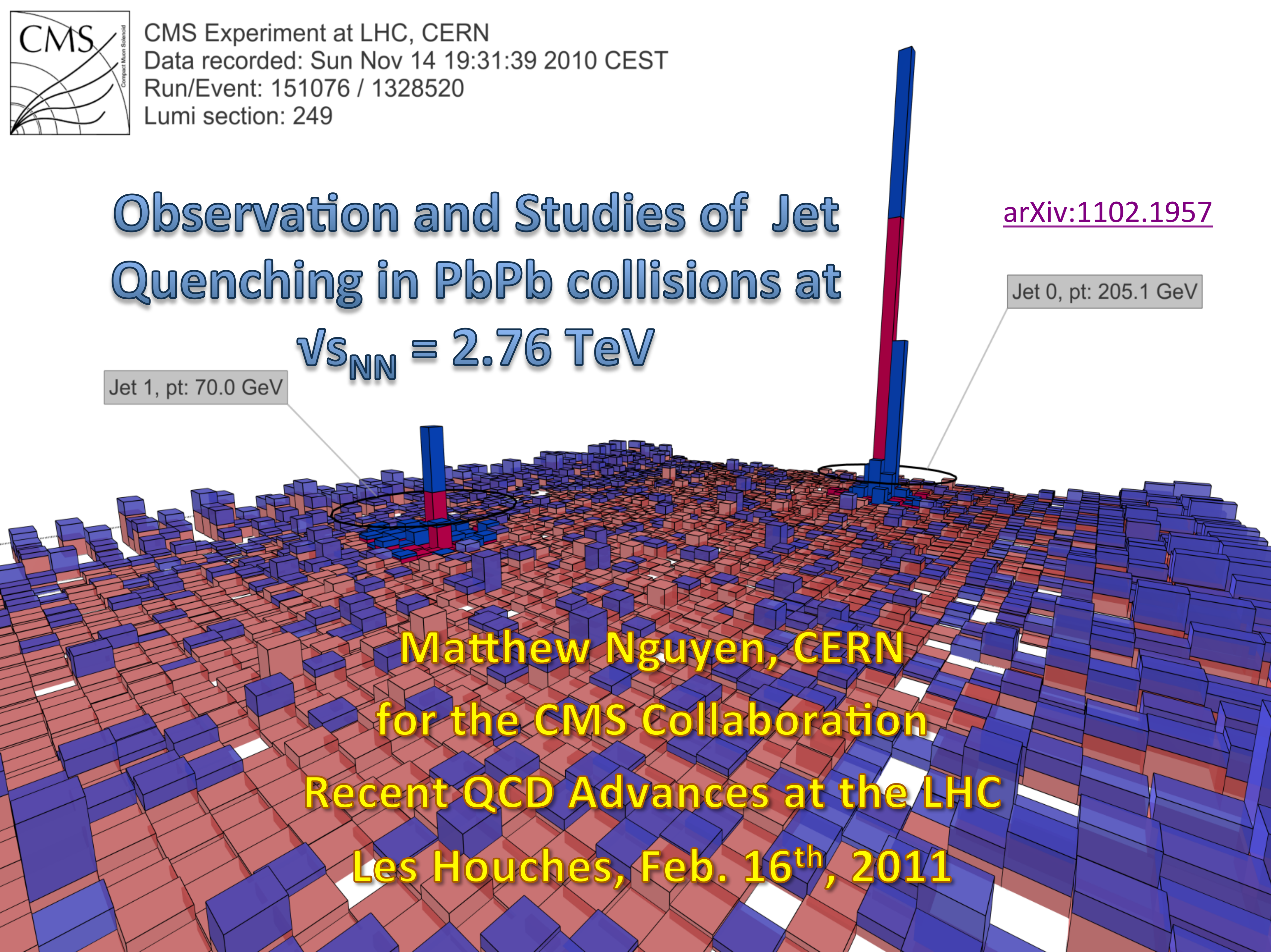


Observation and Studies of Jet Quenching in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

arXiv:1102.1957

Matthew Nguyen, CERN
for the CMS Collaboration

Recent QCD Advances at the LHC

Les Houches, Feb. 16th, 2011

Overview

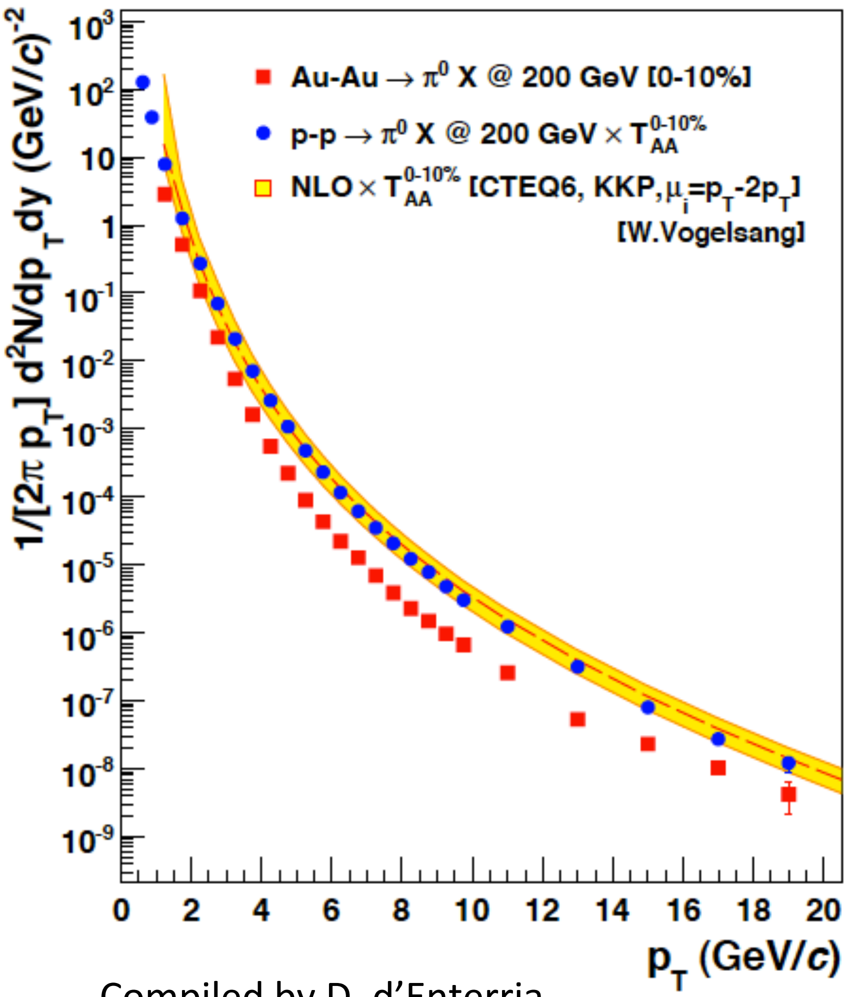
- A brief introduction to jet quenching in heavy-ion collisions
- Details of PbPb jet analysis in CMS
- Measurement of the dijet asymmetry with calorimeter jets
- Jet-track correlations to trace the fate of the missing energy of quenched jets

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

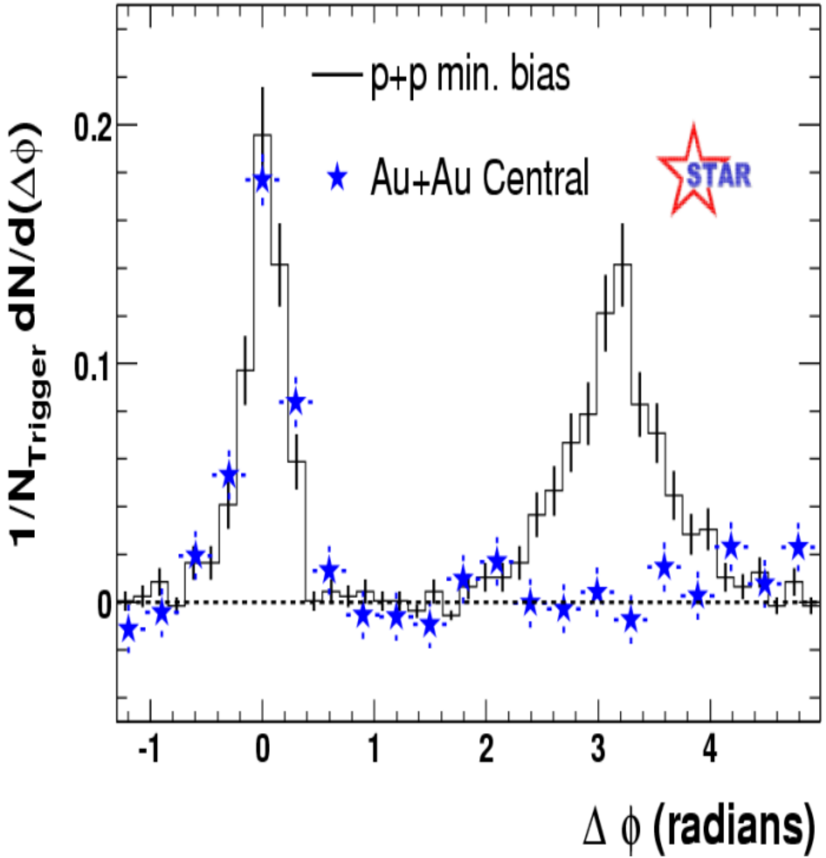
- Correlation of hadrons of

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

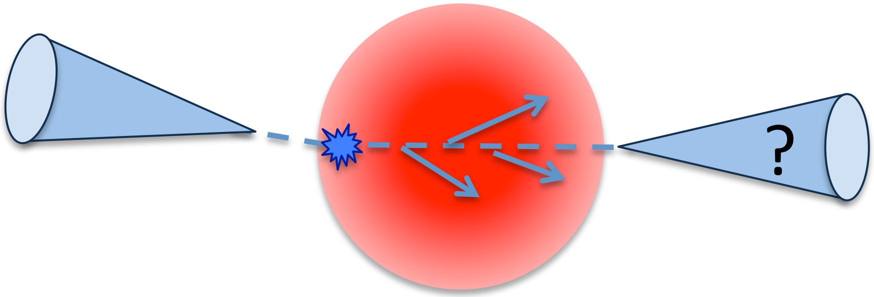
- Near-side peak shows similar jet correlation in p+p and Au+Au
- Away-side jet correlation nearly extinguished in this p_T range
- Supports a geometrical picture of energy loss

Dihadron Correlations from STAR

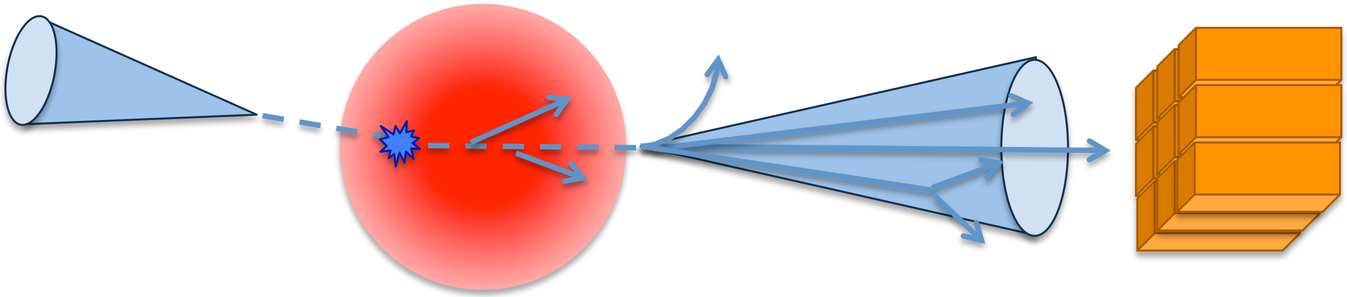
$\sqrt{s_{NN}} = 200$ GeV



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



Jet Measurements in A+A



Large background of soft particles, $dN_{charged}/d\eta \sim 1600$ for 5% most central events

A schematic view of a jet measurement in heavy ions

Jets are reconstructed from energy reaching calorimeters

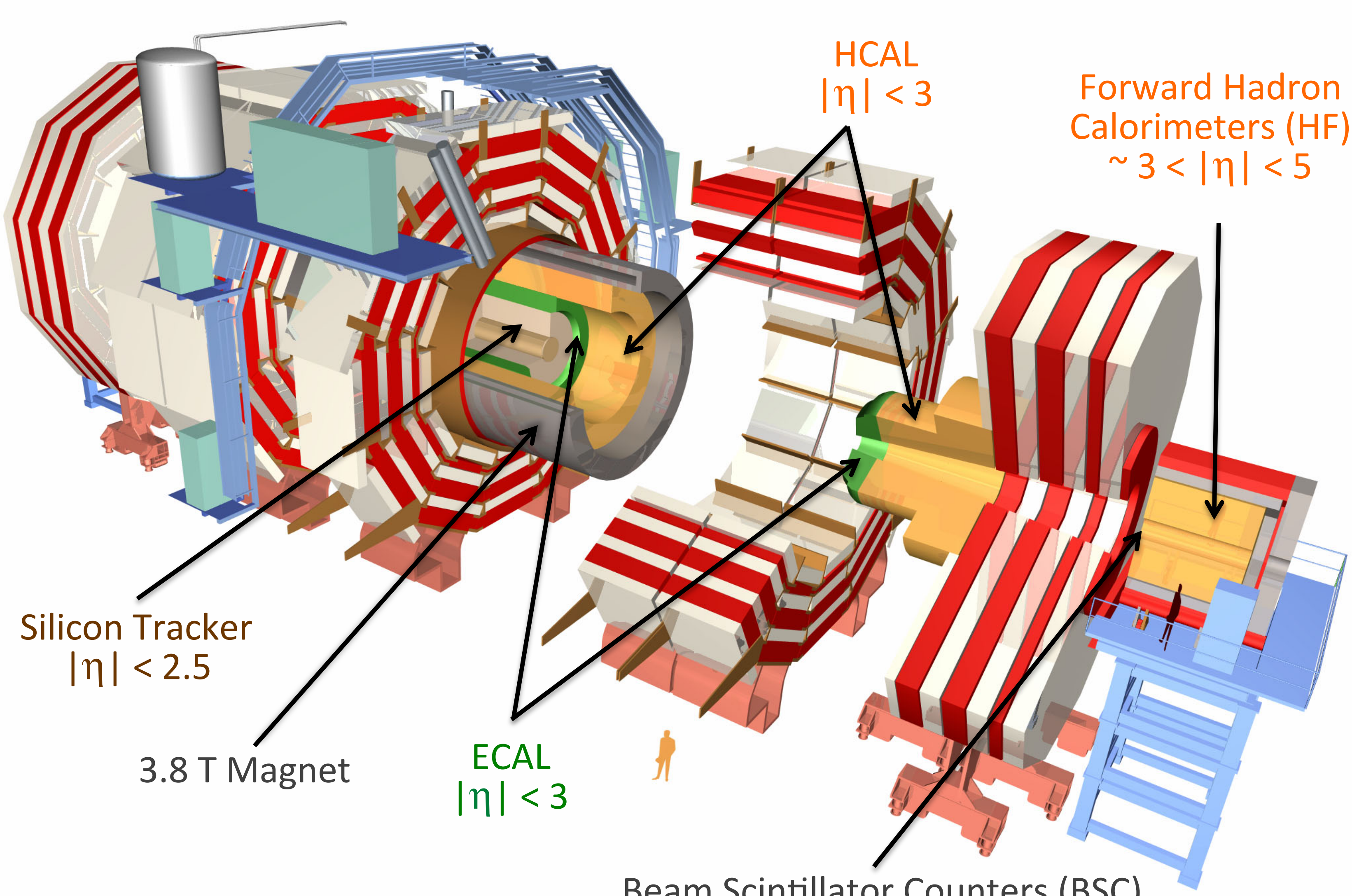
Partons lose energy as they traverse the dense medium

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

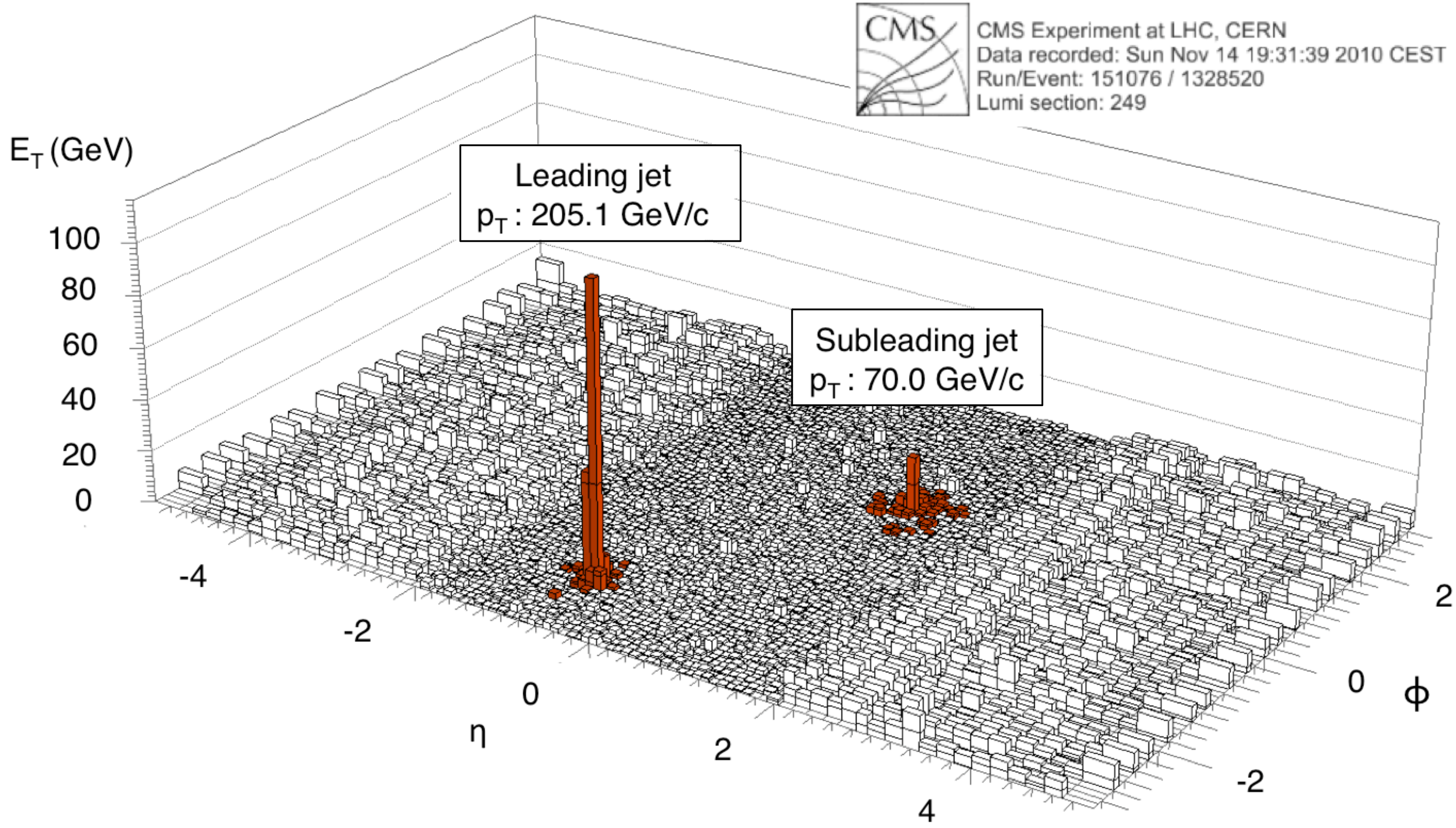
Measurements of jet modification allow to

- Determine the nature of QCD radiation at finite T/ρ
- Determine the transport properties of the QGP

The CMS Detector



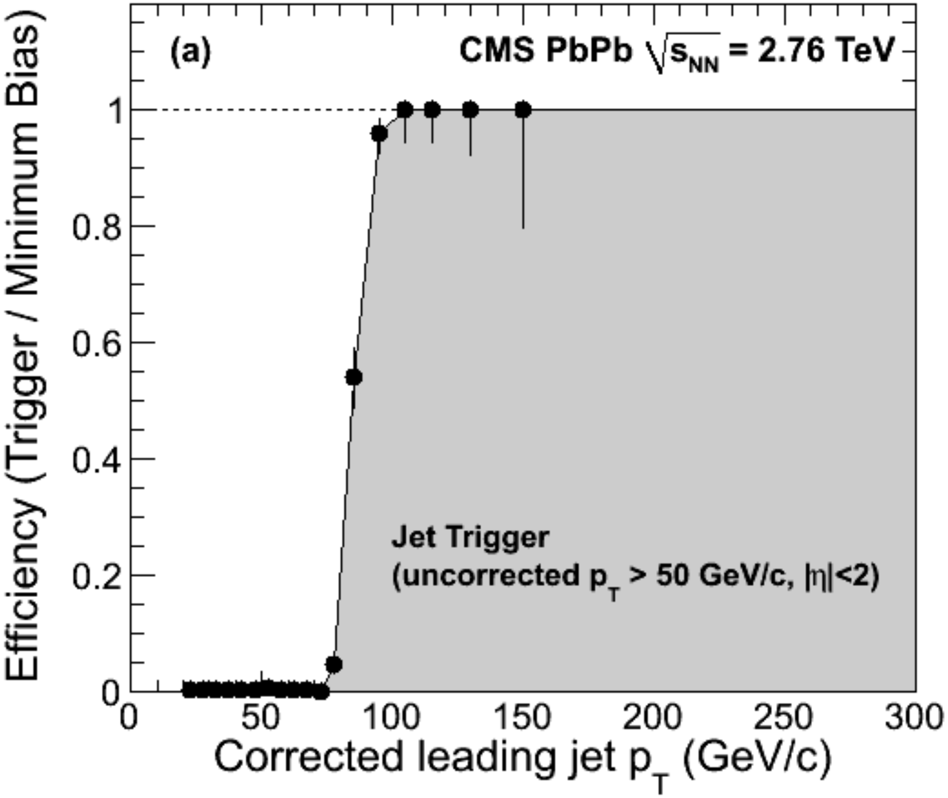
A Dijet in Central PbPb



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

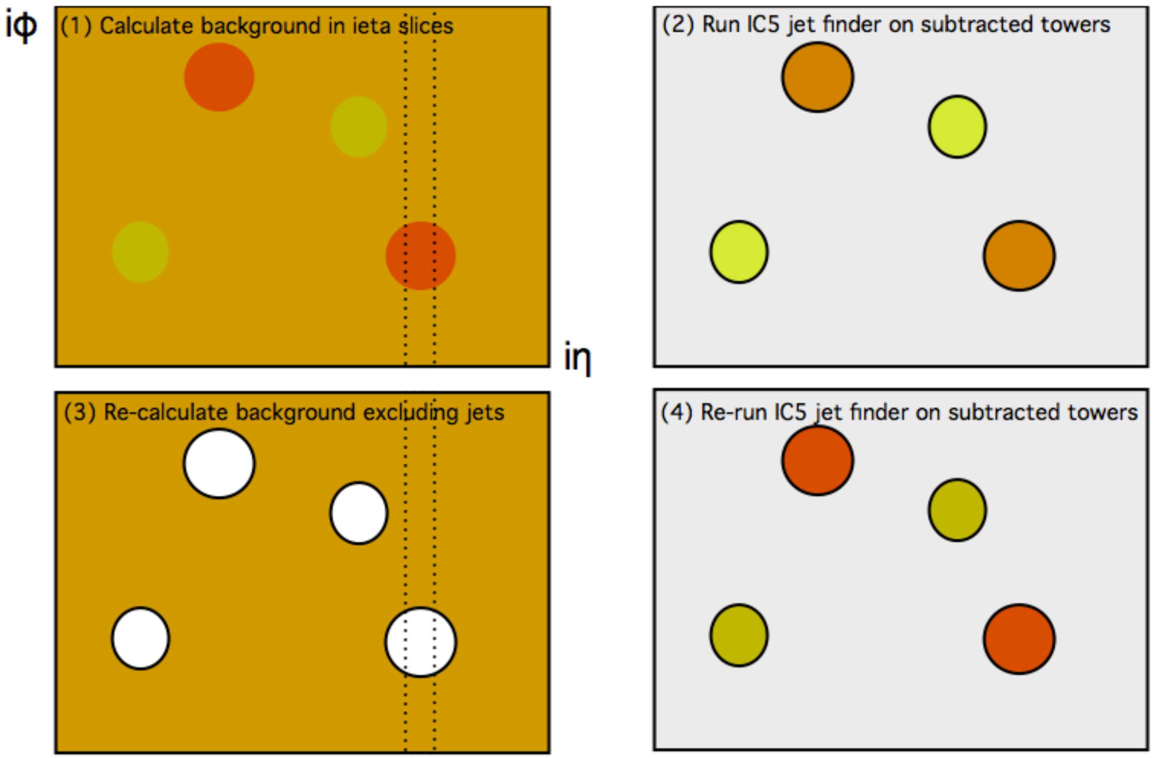
Triggers

- Minimum bias collisions are triggered by a coincidence on either side of the HF or BSC
- Jet are triggered at HLT with a p_T = 50 GeV/c threshold (uncorrected, background subtracted)
- The jet trigger is fully efficient around corrected p_T of 100 GeV/c



Background Subtraction Method

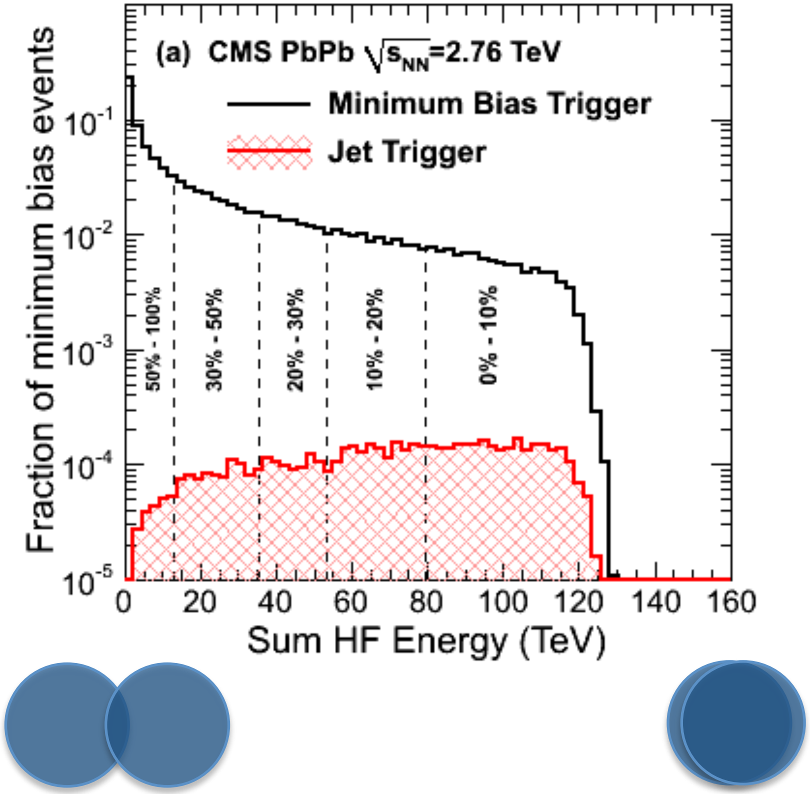
1. Background energy per tower calculated in strips of η.
2. Iterative Cone (R=0.5) algorithm run on subtracted towers
3. Background energy recalculated excluding jets
4. Jet algorithm rerun on background subtracted towers, now excluding jets, to obtain final jets



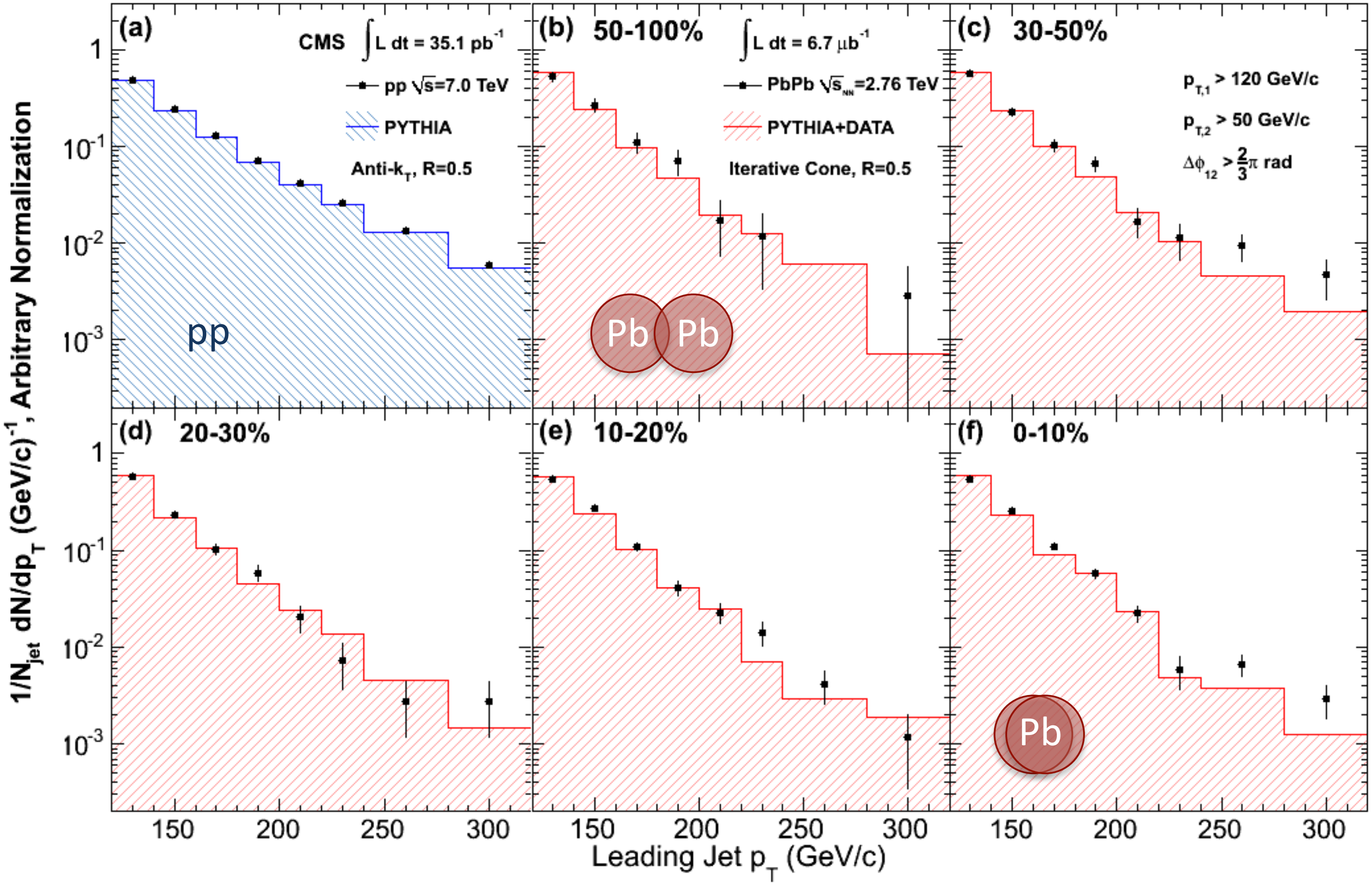
Method: O. Kodolova et al., EPJC (2007) 117.

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
    - Adjusted for isospin ratio of Pb(208)
    - Embedded in real data or simulated data using the HYDJET generator

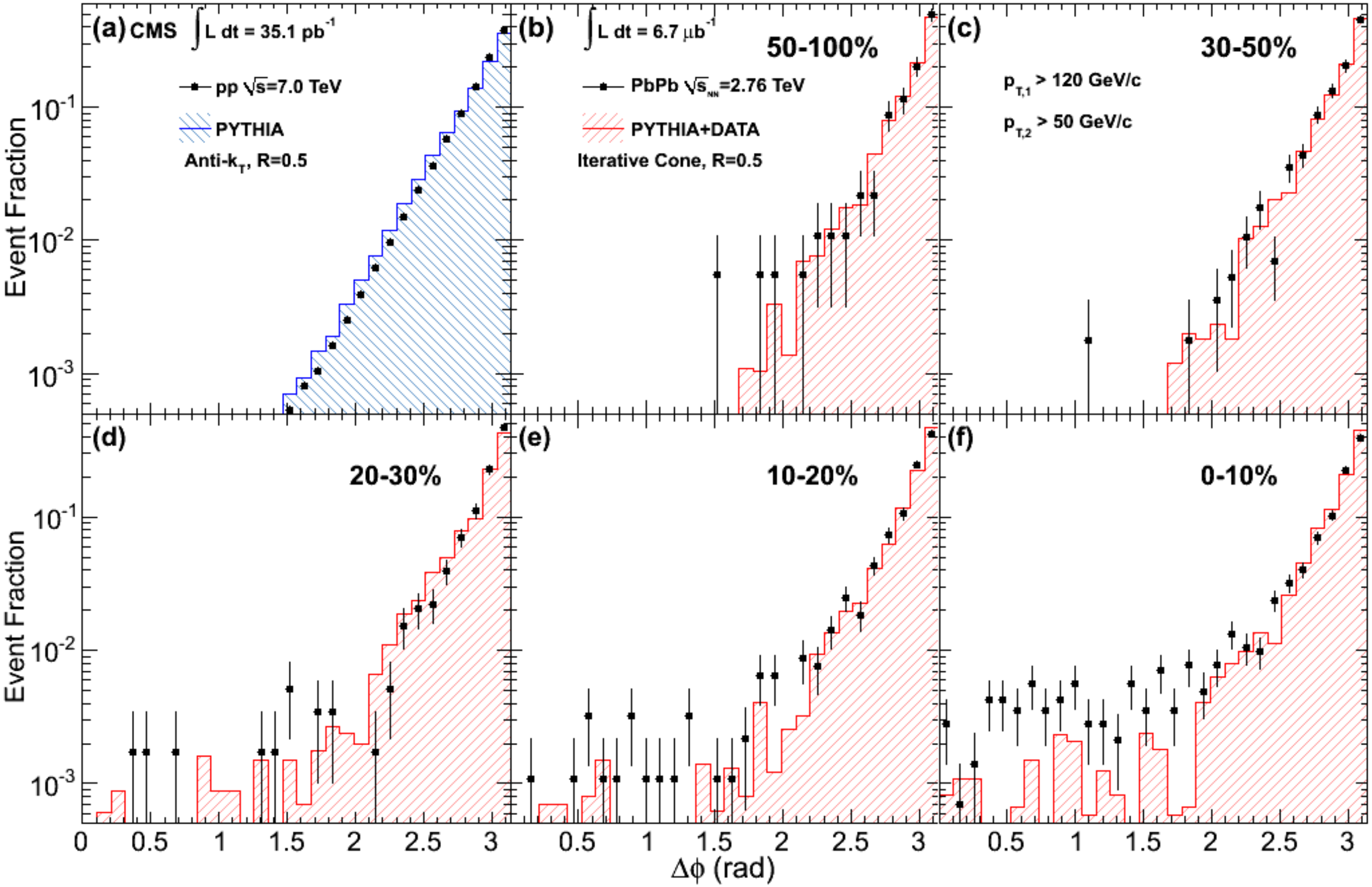


Leading Jet p_T Distributions



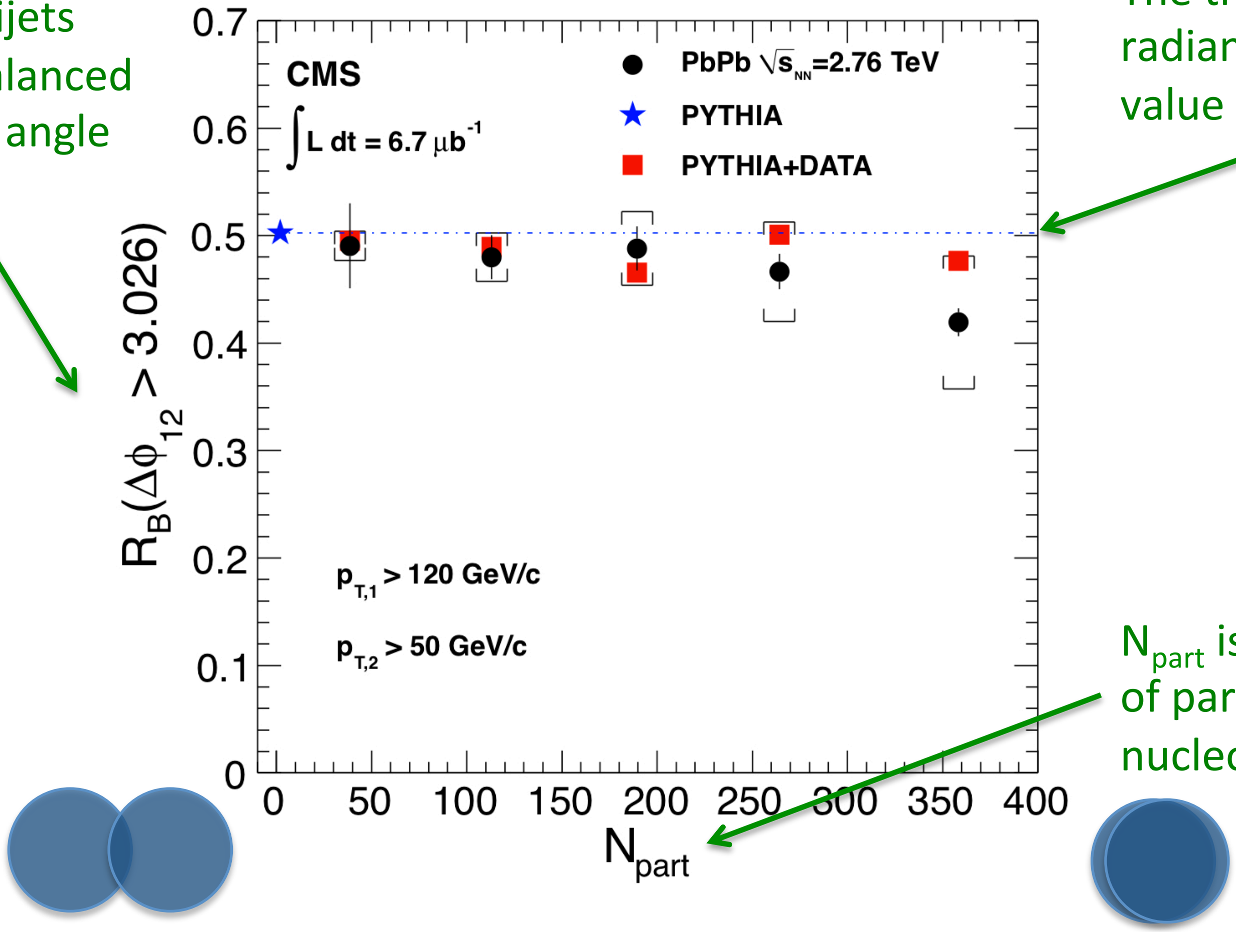
No strong modification to shape of leading jet spectrum

Dijet Azimuthal Correlations



No strong angular deflection of reconstructed jets

Angular Decorrelation Quantified



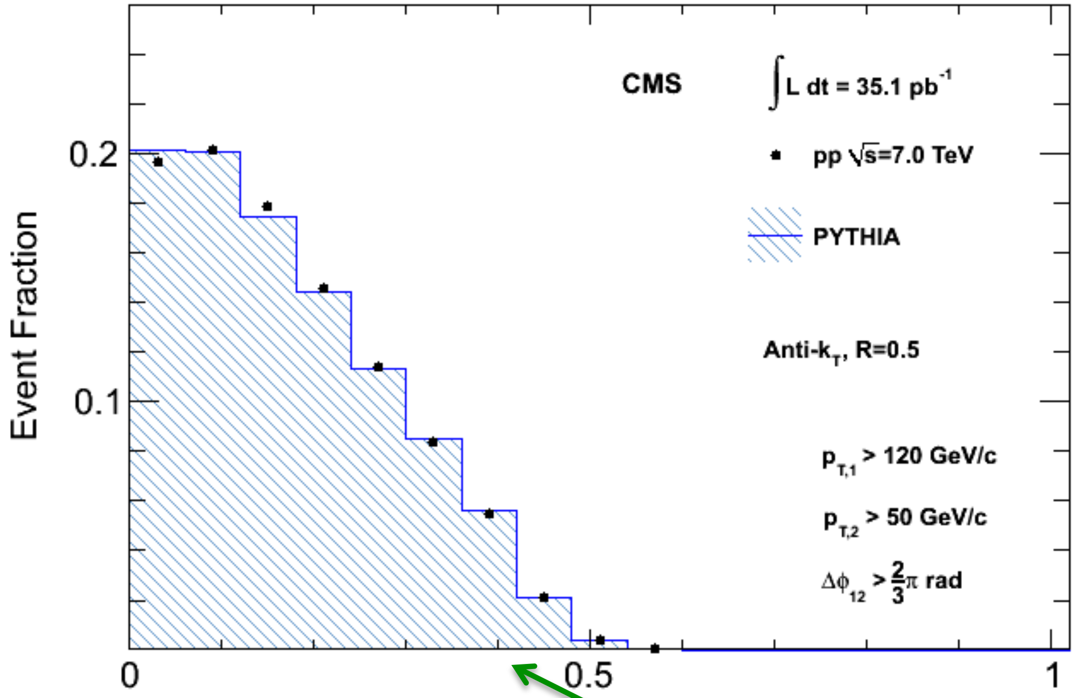
$R_B(\Delta\phi)$ is the fraction of dijets which are balanced in azimuthal angle

The threshold of 3.026 radians is the median value from PYTHIA

N_{part} is the number of participating nucleons

No angular decorrelation beyond systematic uncertainties

Dijet p_T Asymmetry



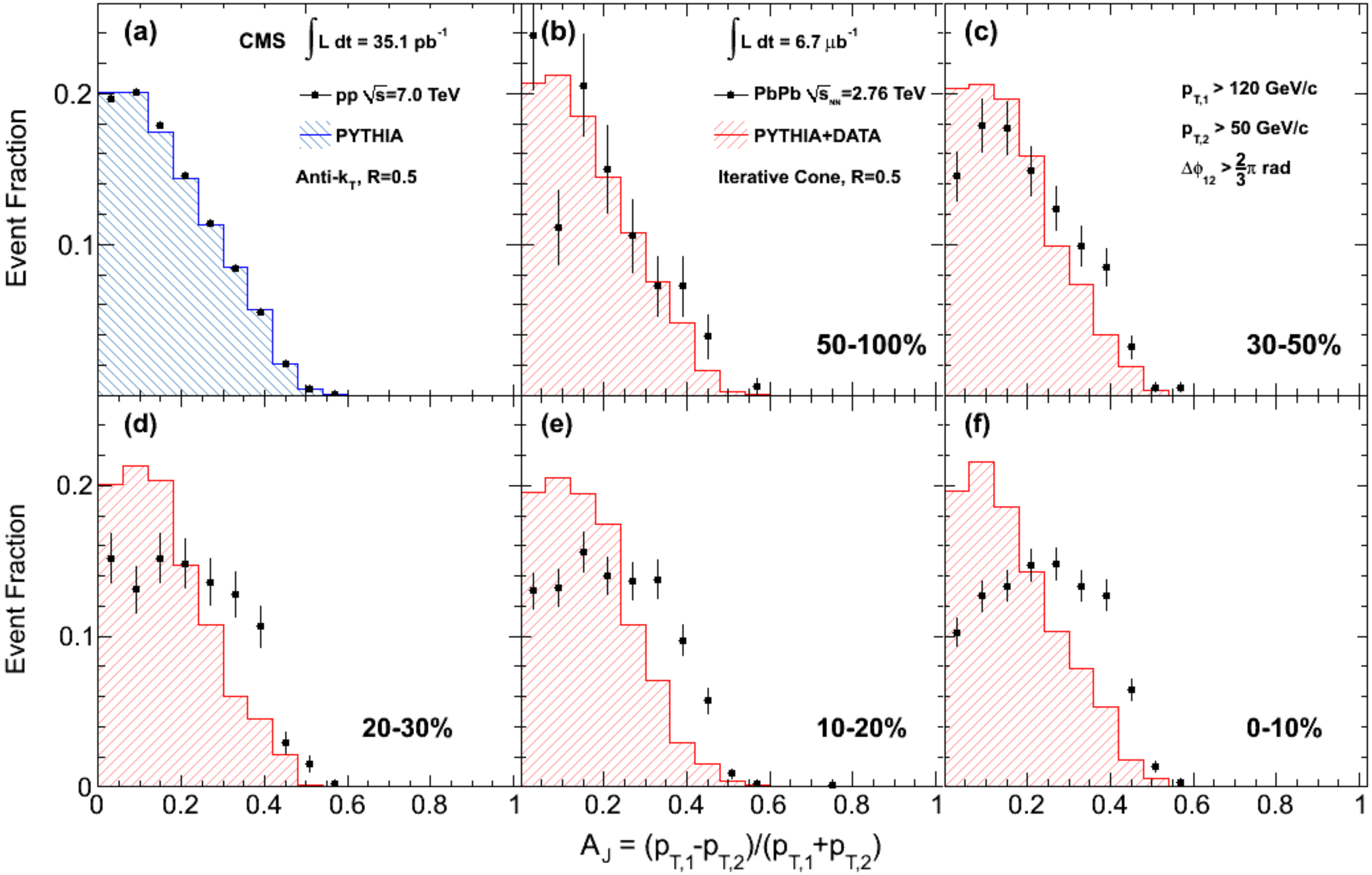
$$A_J = \frac{p_{\mathrm{T},1} - p_{\mathrm{T},2}}{p_{\mathrm{T},1} + p_{\mathrm{T},2}}$$

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 → $A_J < 0.41$

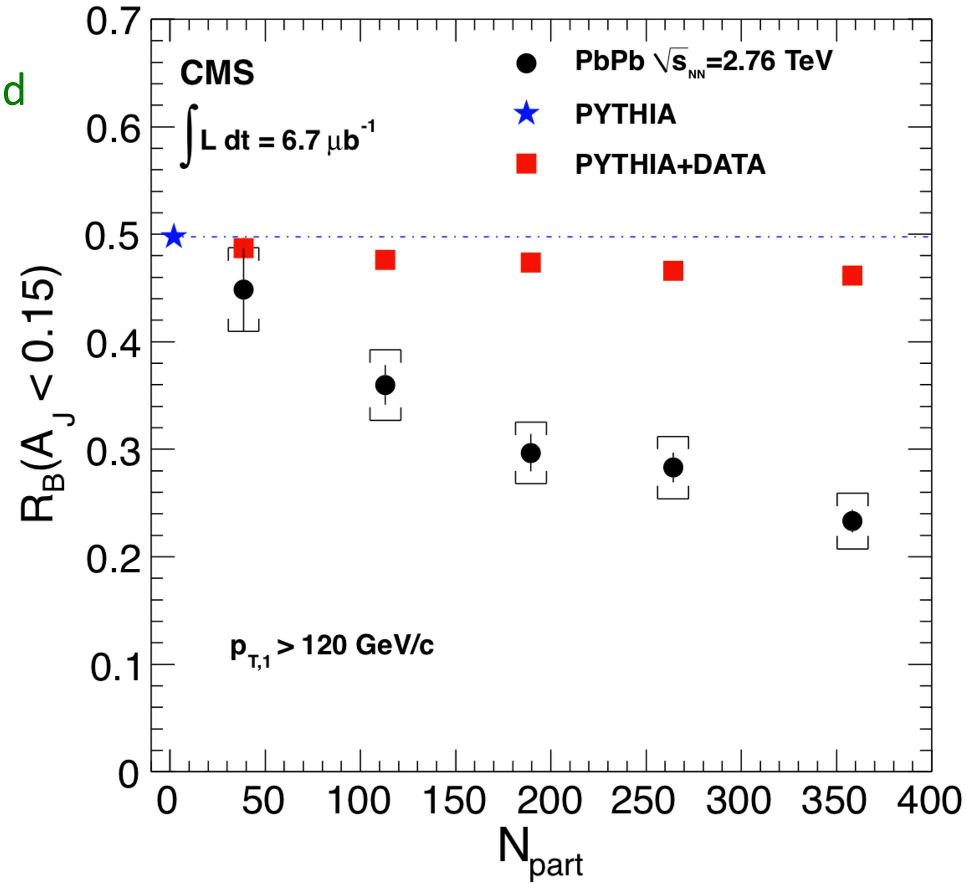
Dijet p_T Asymmetry



Striking enhancement of asymmetry with increasing centrality

Dijet Imbalance Quantified

Here $R_B(A_J)$ is the fraction of dijets which are balanced in momentum



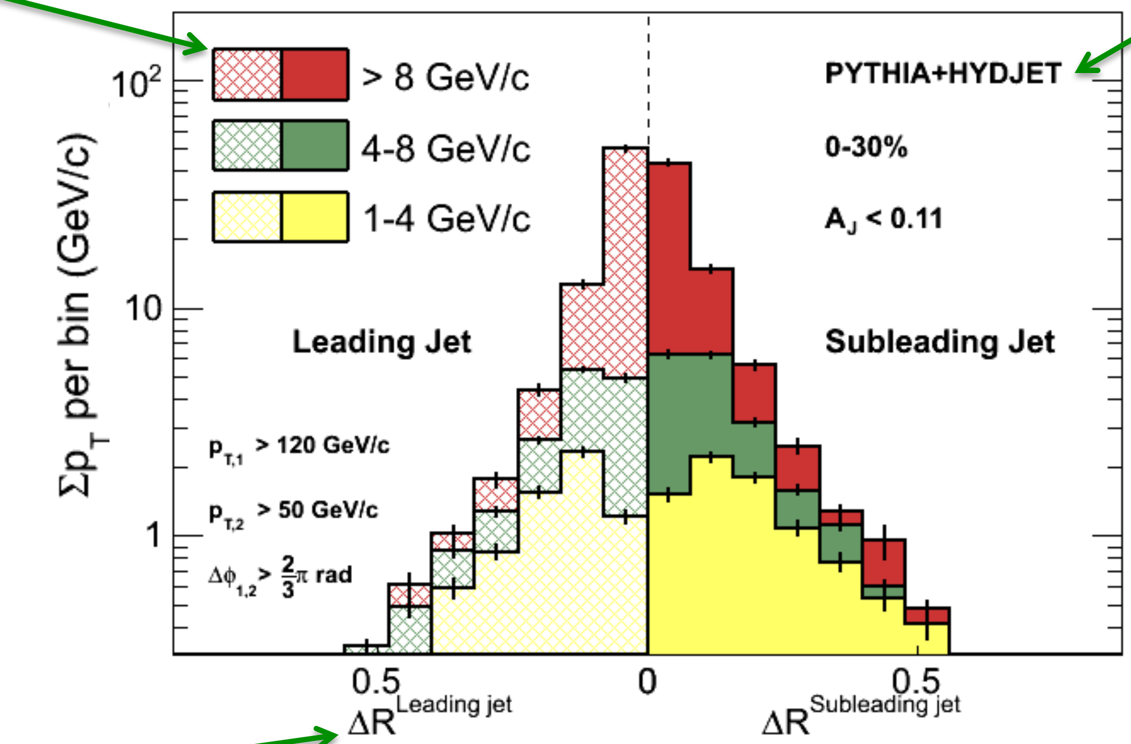
Smooth decrease in the fraction of balanced jets with increasing centrality
Note: Dijets in which no subleading jet found above threshold are included

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

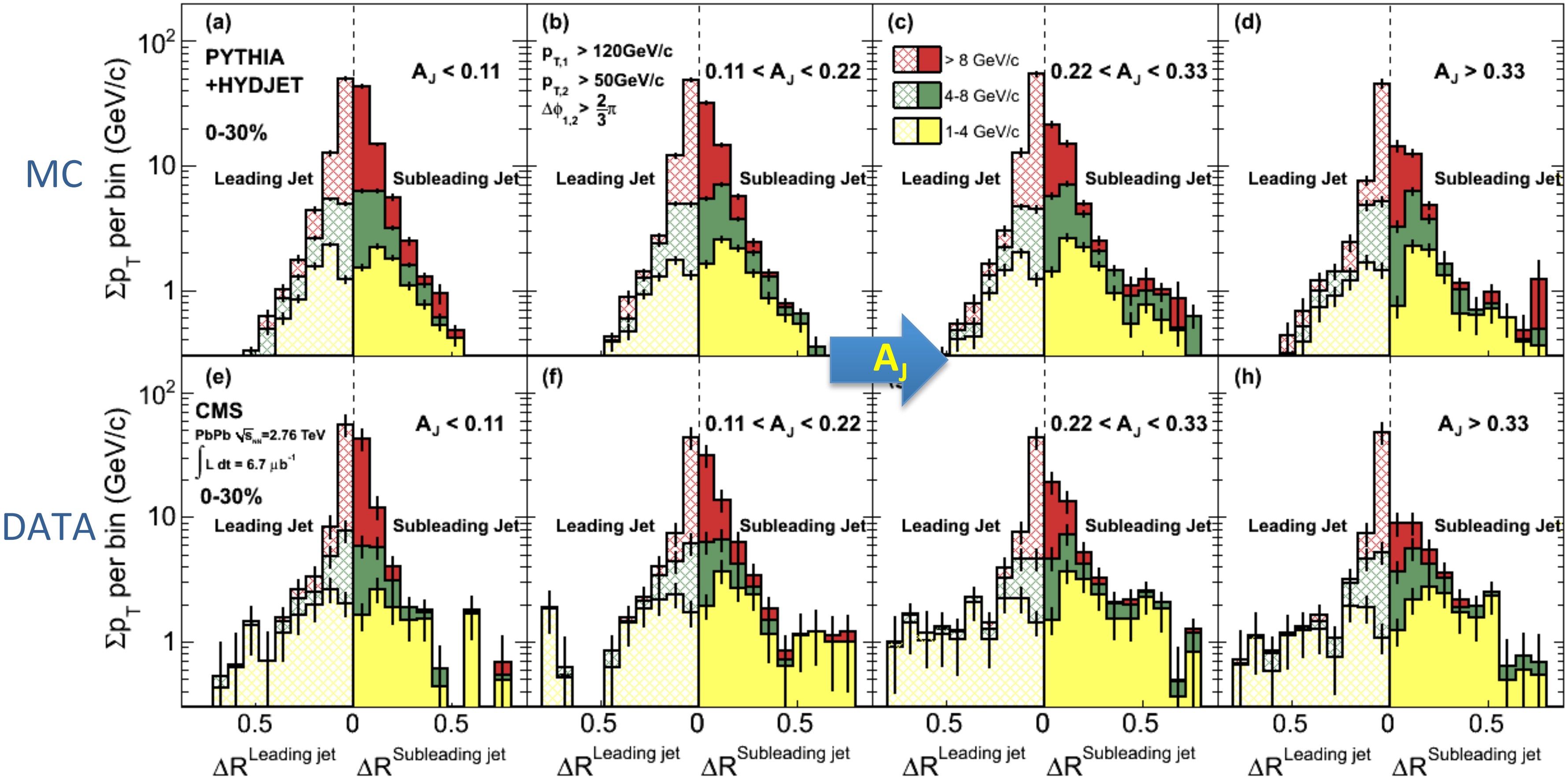


Plot against ΔR from the jet axis for both the leading and subleading jet

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

Asymmetry Dependence of Fragmentation

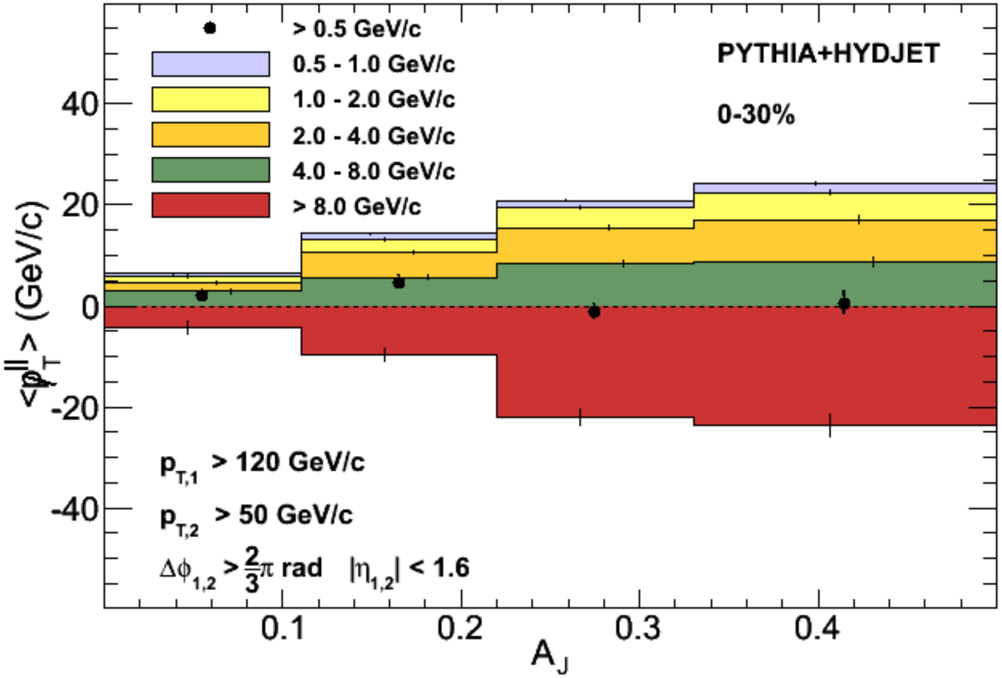
- Both data and MC show that dijet asymmetry is also apparent in charged tracks
- In MC, rare asymmetric dijets are due to the presence of a third jet
- Relative abundance of tracks in the 3 ranges is largely unchanged with asymmetry



- In data the fraction of energy carried by low p_T tracks increases with asymmetry
- An enhancement of low p_T tracks at large angles is observed in asymmetric dijets

Missing p_T

To explore momentum balance to low p_T over all angles, calculate the “missing p_T”

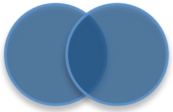


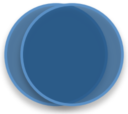
Sum the track transverse momenta projected onto the leading jet axis:

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

Defined such that tracks on the away side give a positive contribution

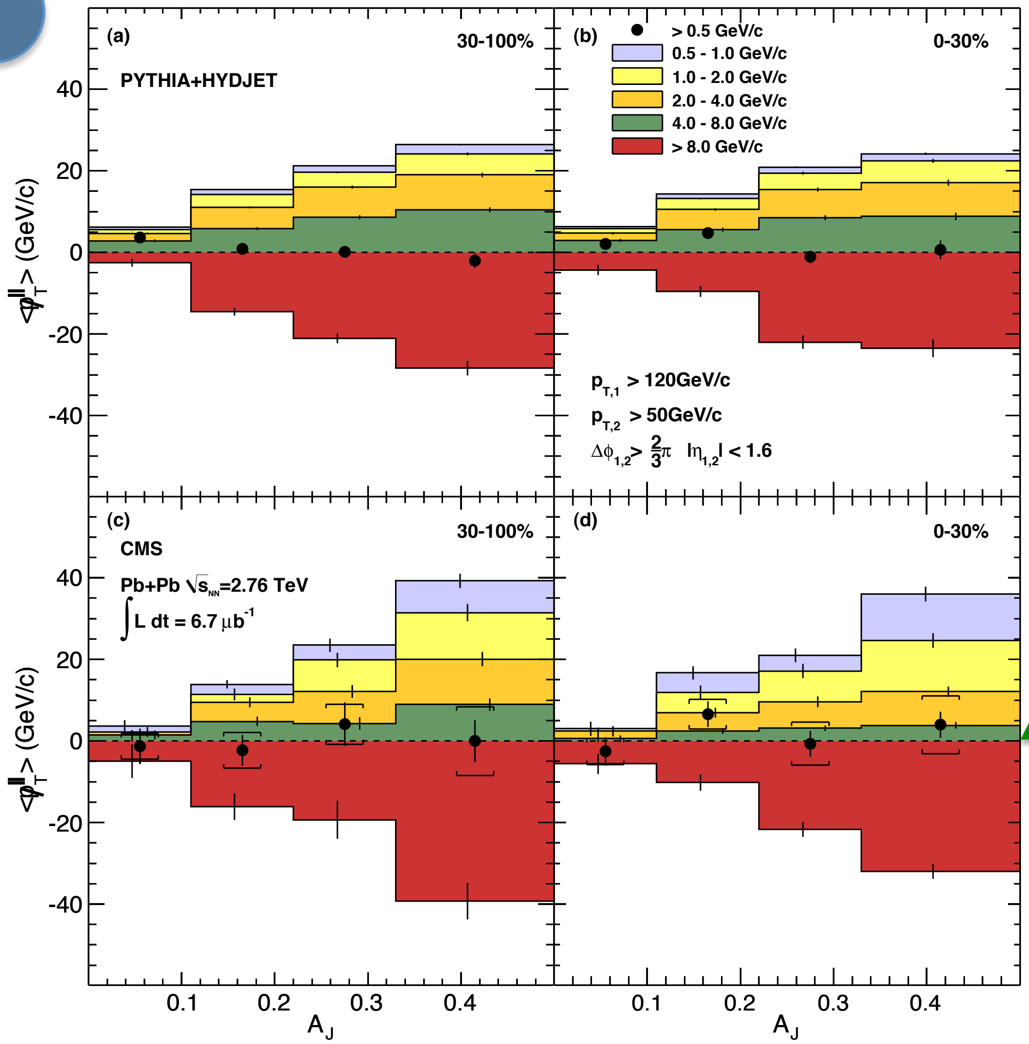
Missing p_T: Data vs. MC





MC

DATA

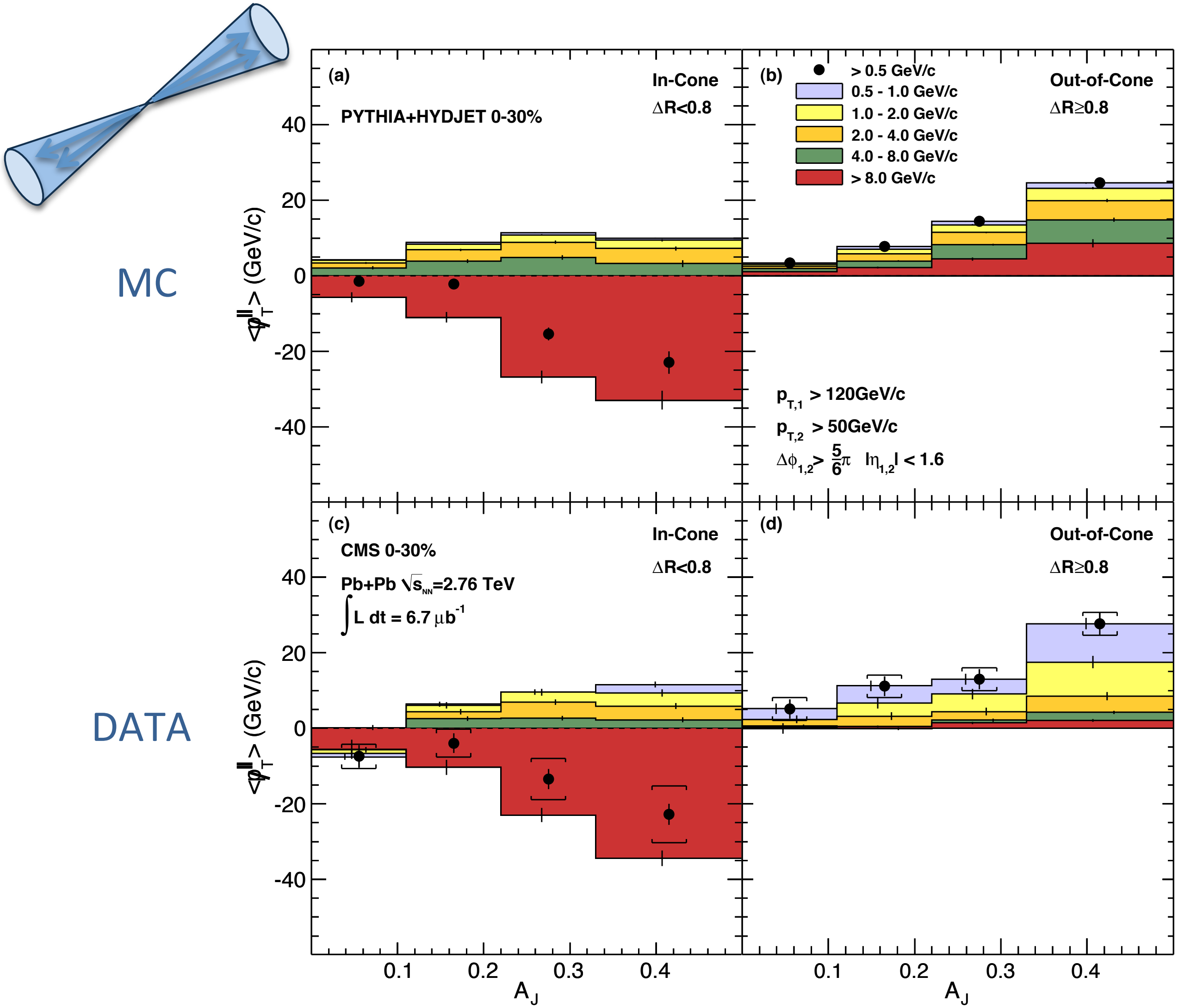


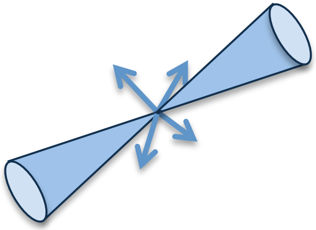
In MC, events are balanced, p_T composition is independent of centrality

For p_T > 500 MeV, p_T balance recovered!

In data, for asymmetric events, leading jet is balanced by low p_T tracks, particularly in central events

Missing p_T: In vs. Out-of-Cone





Asymmetric events in MC show significant energy beyond R=0.8, carried by high p_T tracks → 3 jet events

Little modification of jet fragmentation in-cone

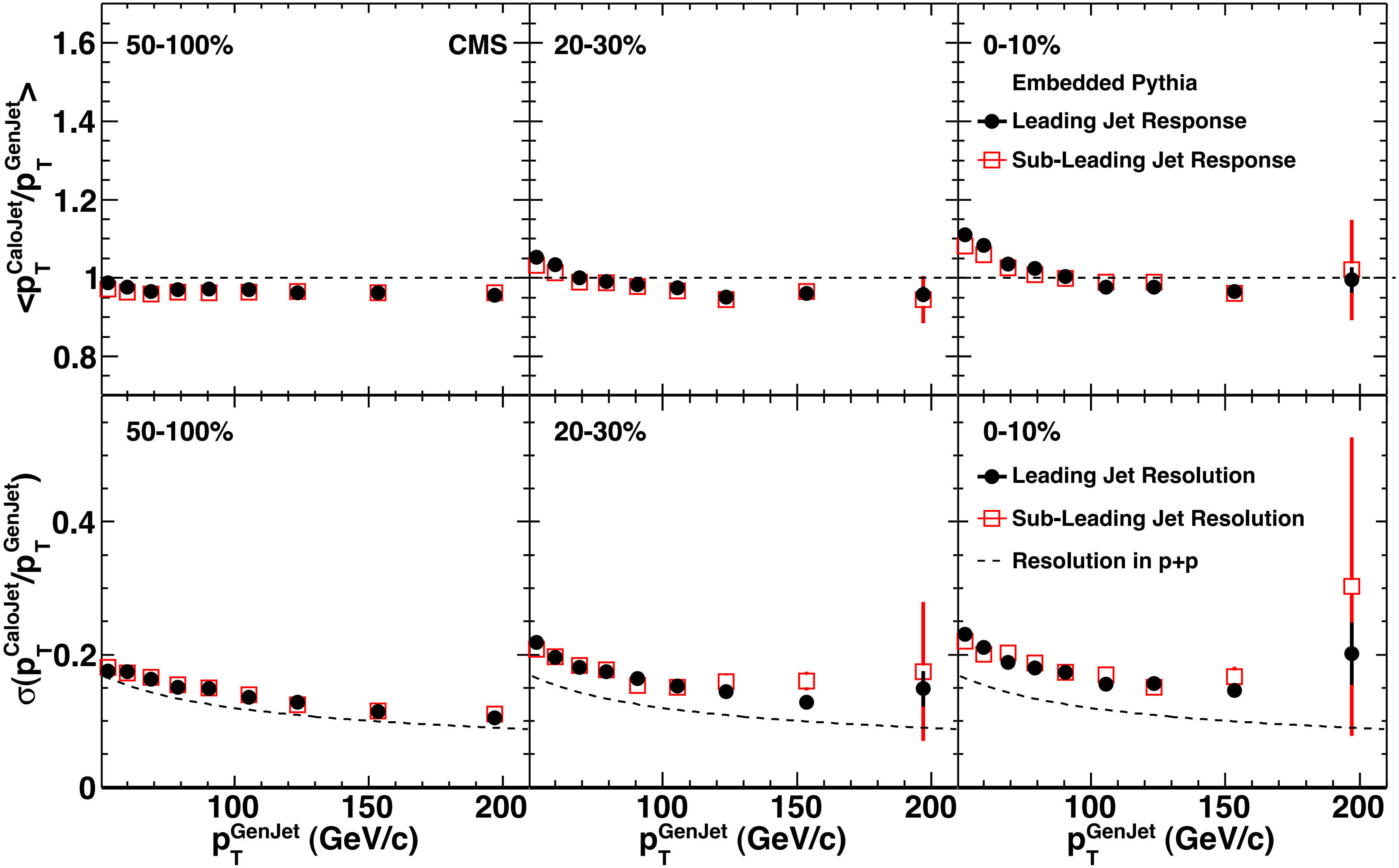
Majority of p_T balance recovered by low p_T tracks outside of R=0.8 cone

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
- Future studies will further constrain energy loss via, e.g.,
  - More differential studies of jet fragmentation, energy redistribution, reaction plane dependence
  - Flavor dependence with γ+jets and heavy-flavor tagged jets

Backup Slides

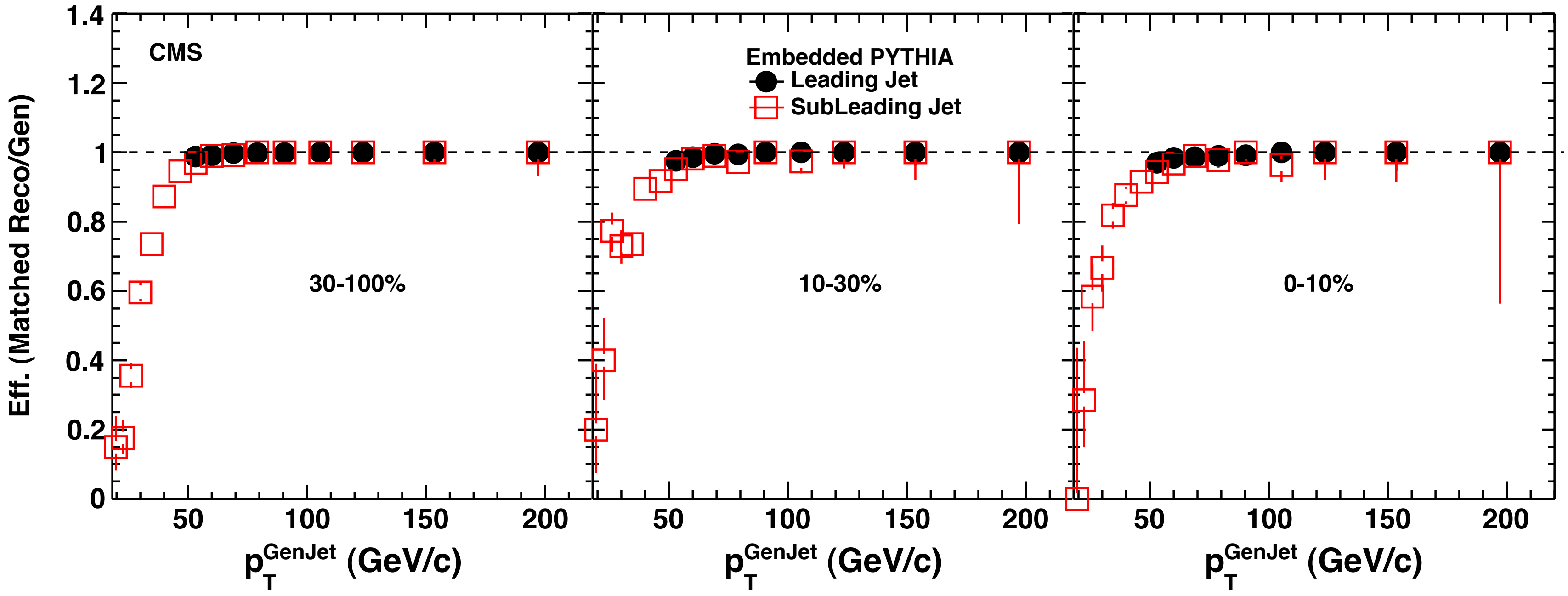
Jet Response and Resolution



Resolution determined from pythia embedded in data

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

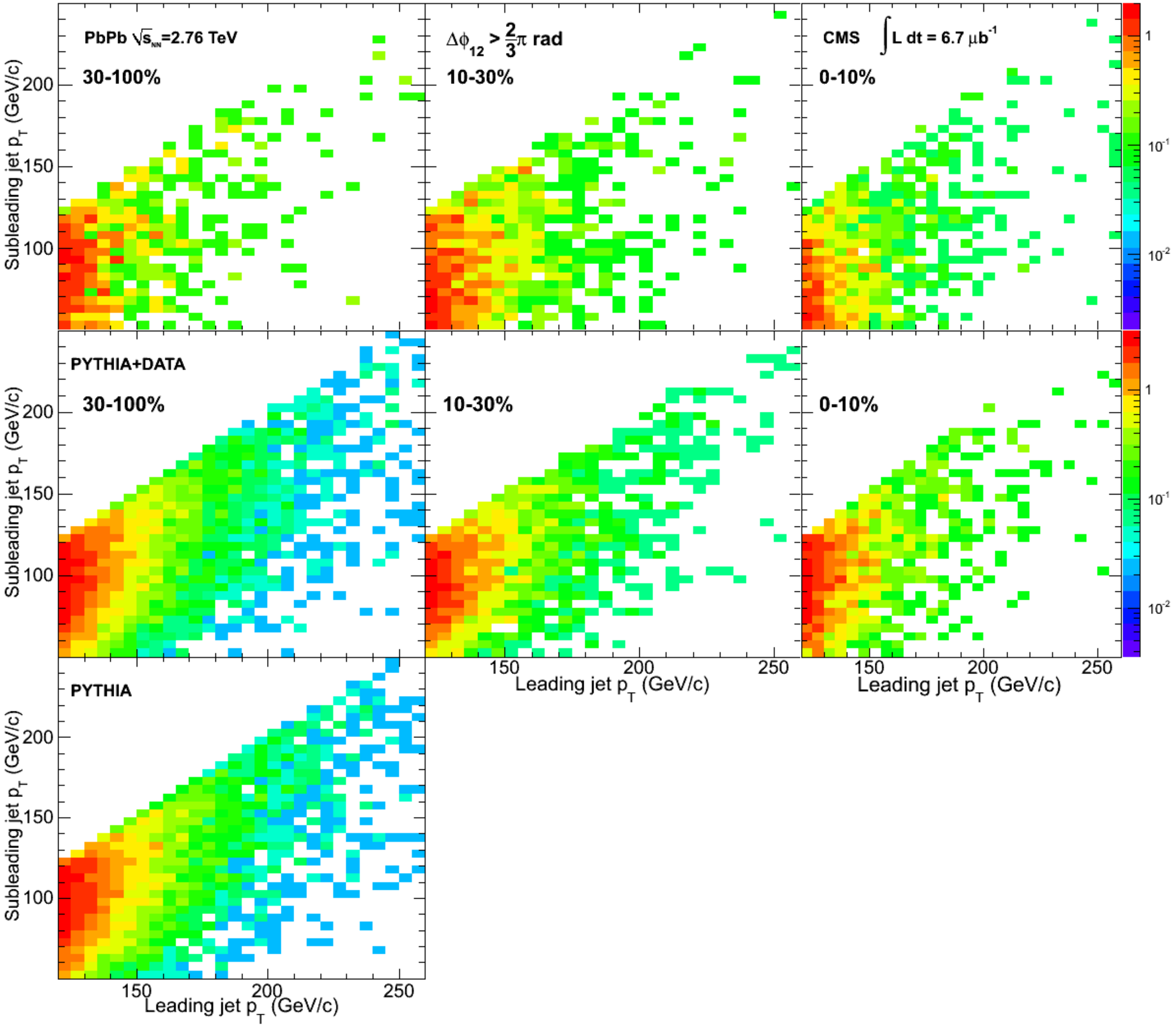
Jet Reconstruction Efficiency



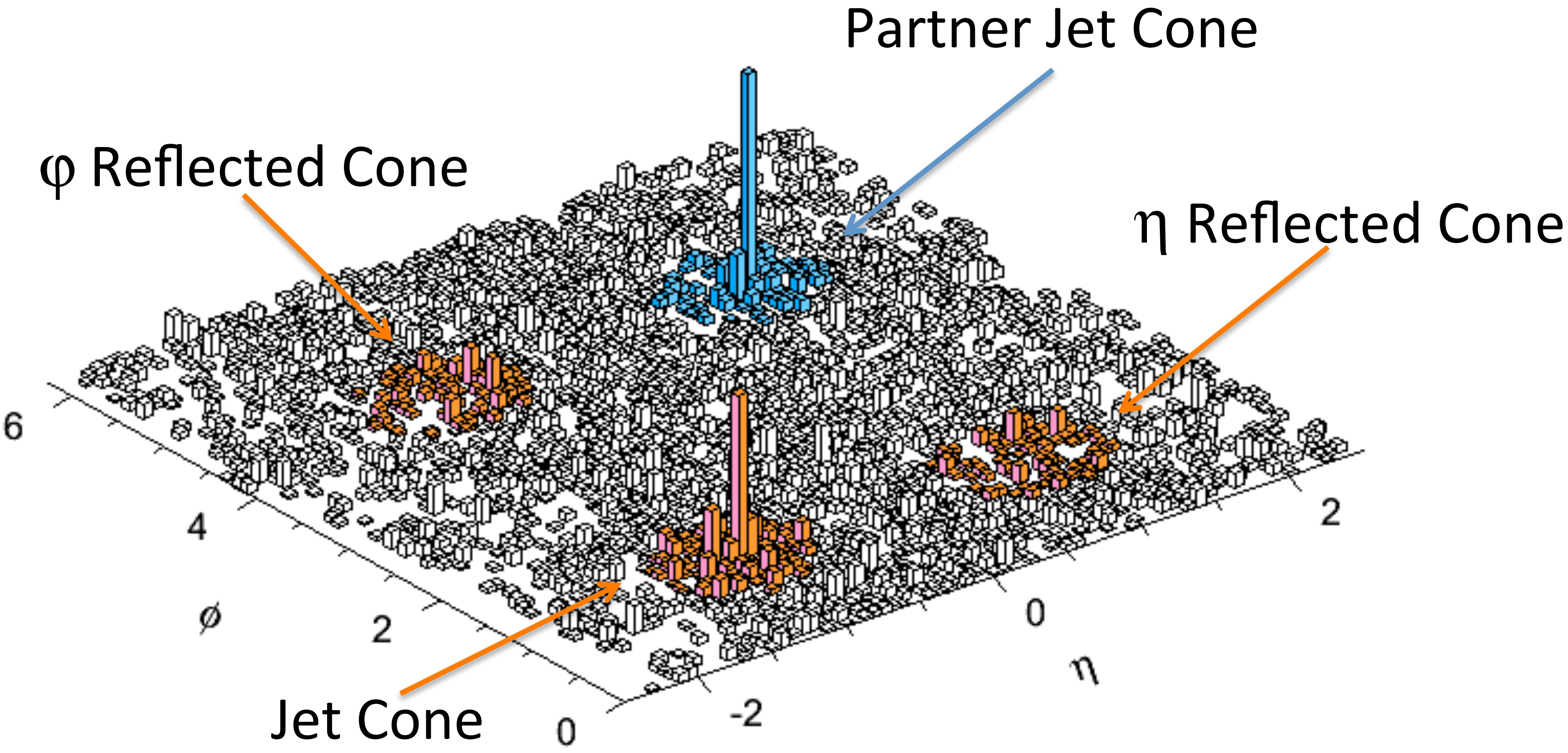
Fully efficient for leading jet selection (> 120 GeV/c)

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

Leading vs. Subleading Jet p_T



η Reflection Method



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

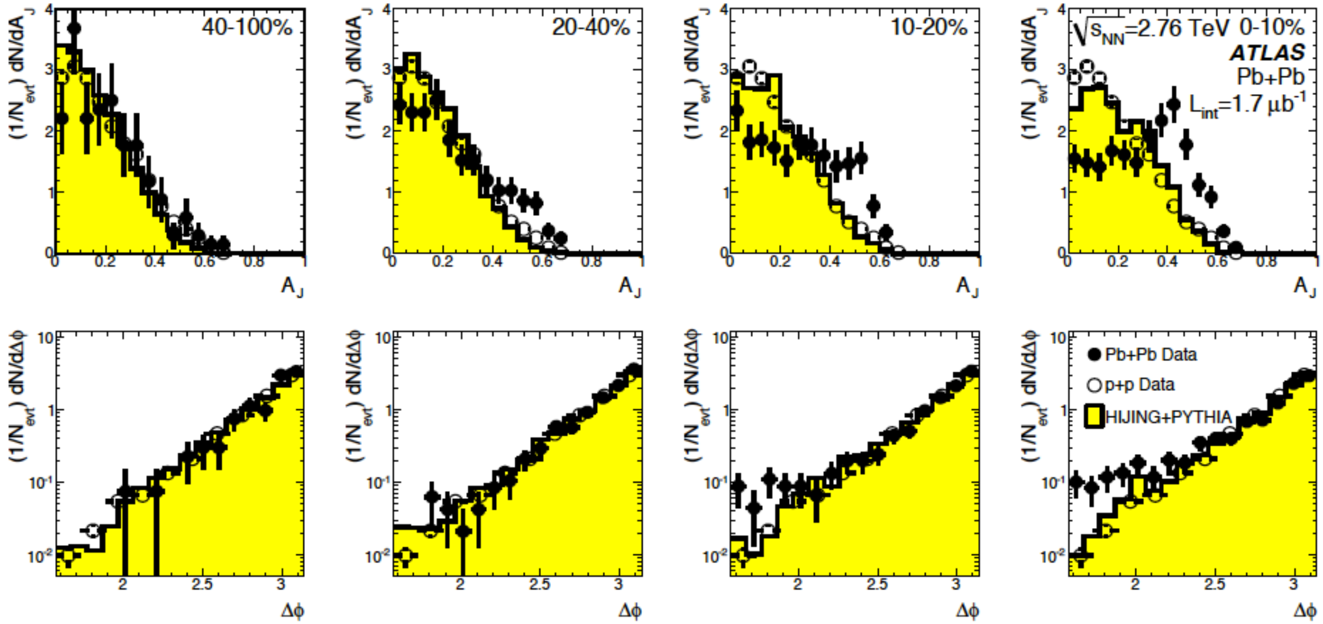
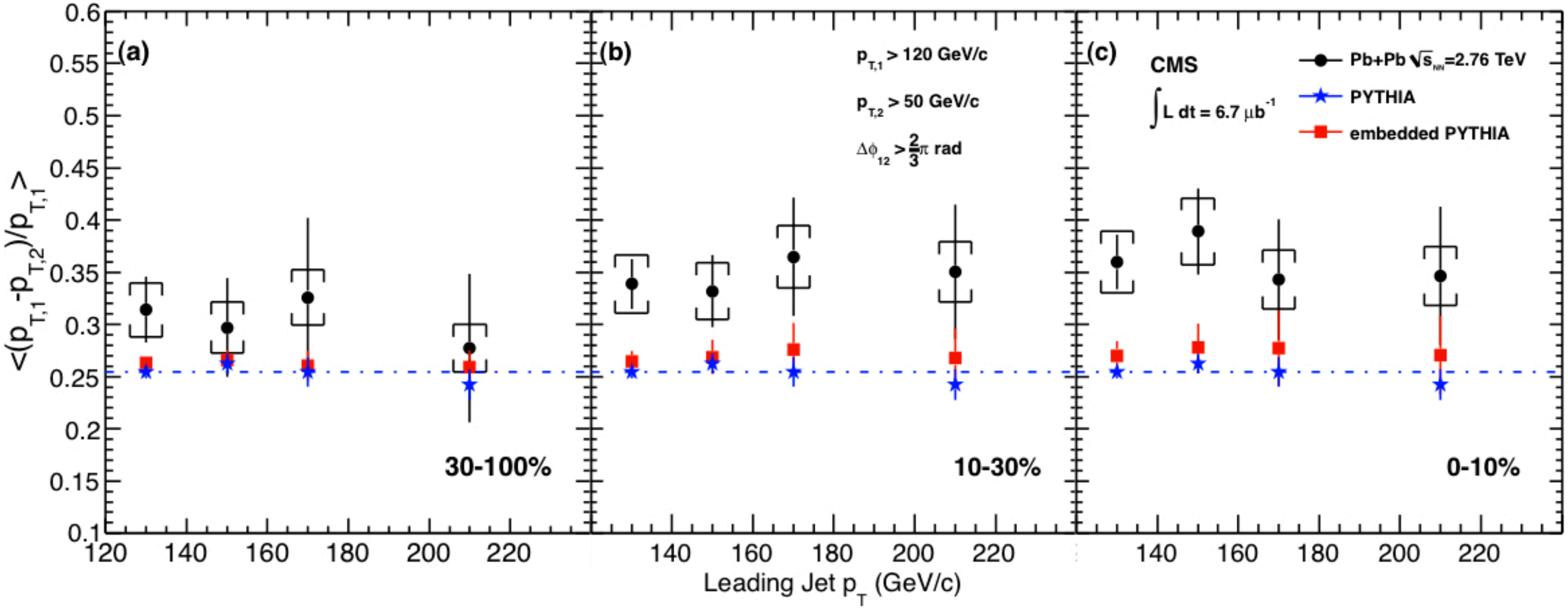
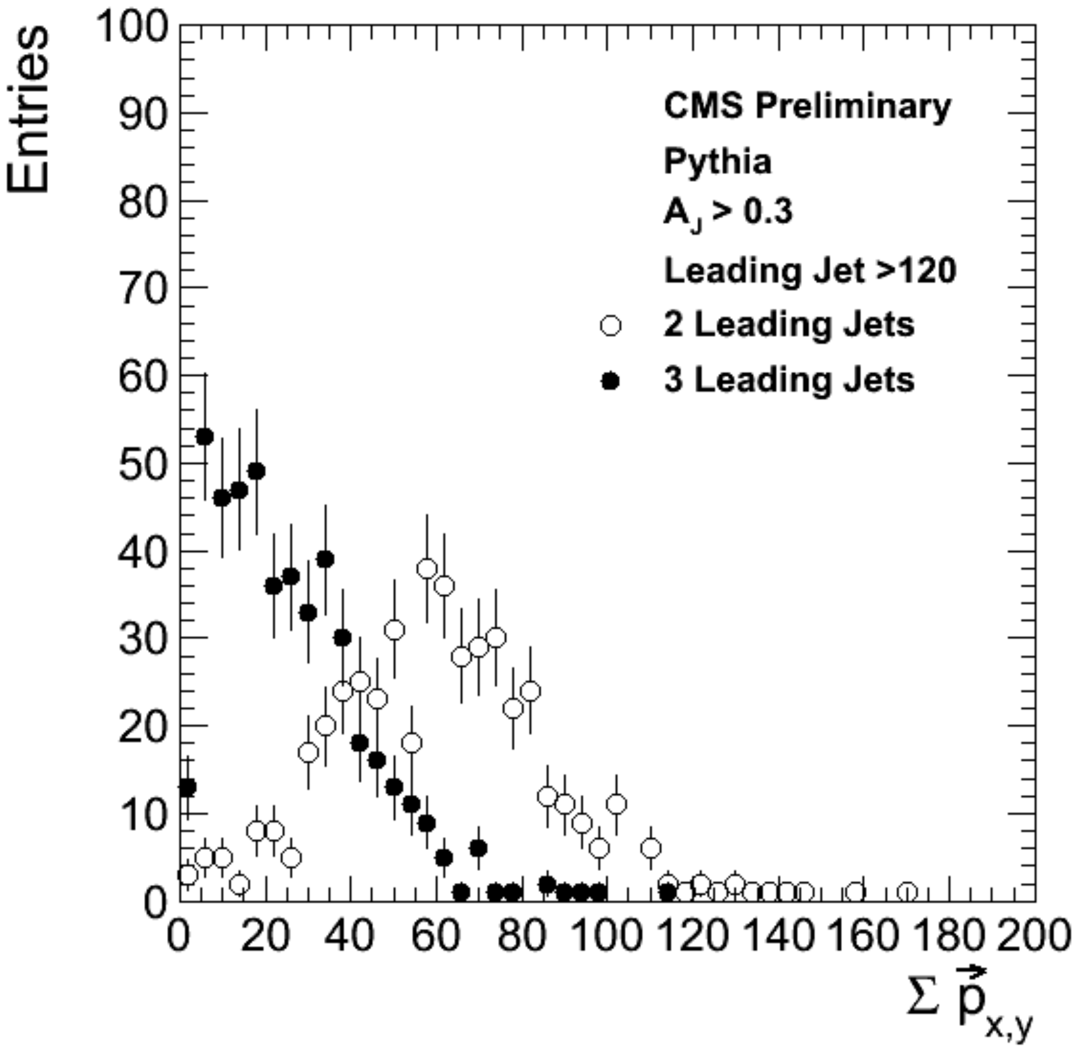


FIG. 3: (top) Dijet asymmetry distributions for data (points) and unquenched HIJING with superimposed PYTHIA dijets (solid yellow histograms), as a function of collision centrality (left to right from peripheral to central events). Proton-proton data from $\sqrt{s} = 7$ TeV, analyzed with the same jet 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.

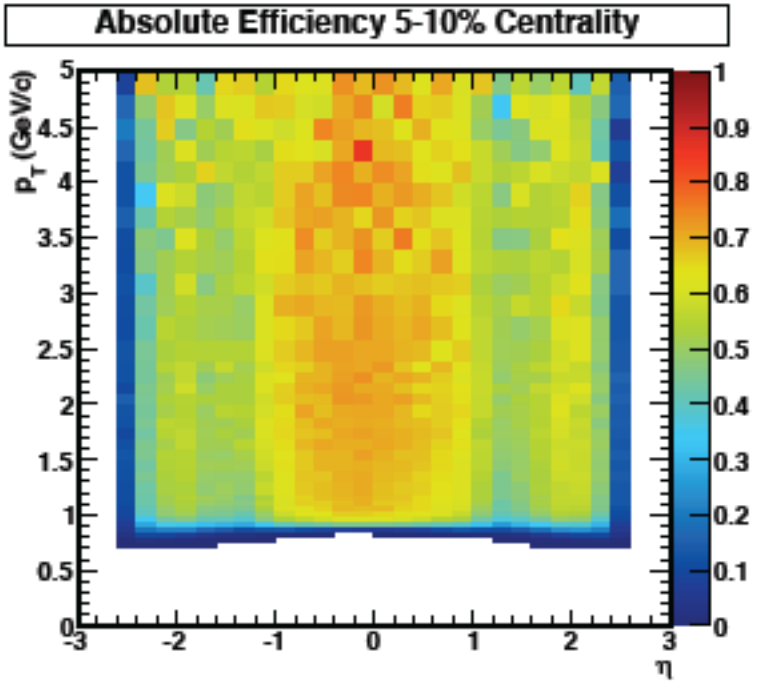
p_T Dependence of Quenching

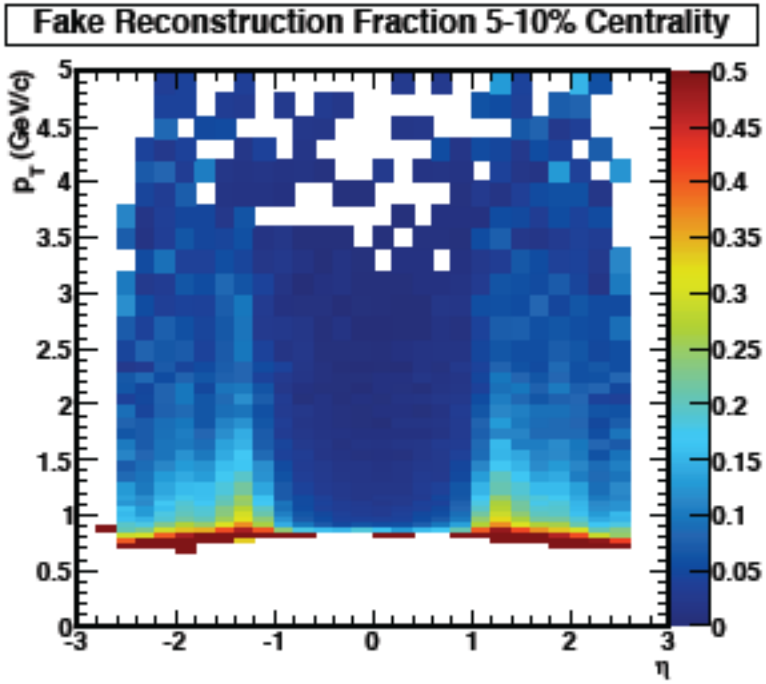


Including the 3rd jet in PYTHIA

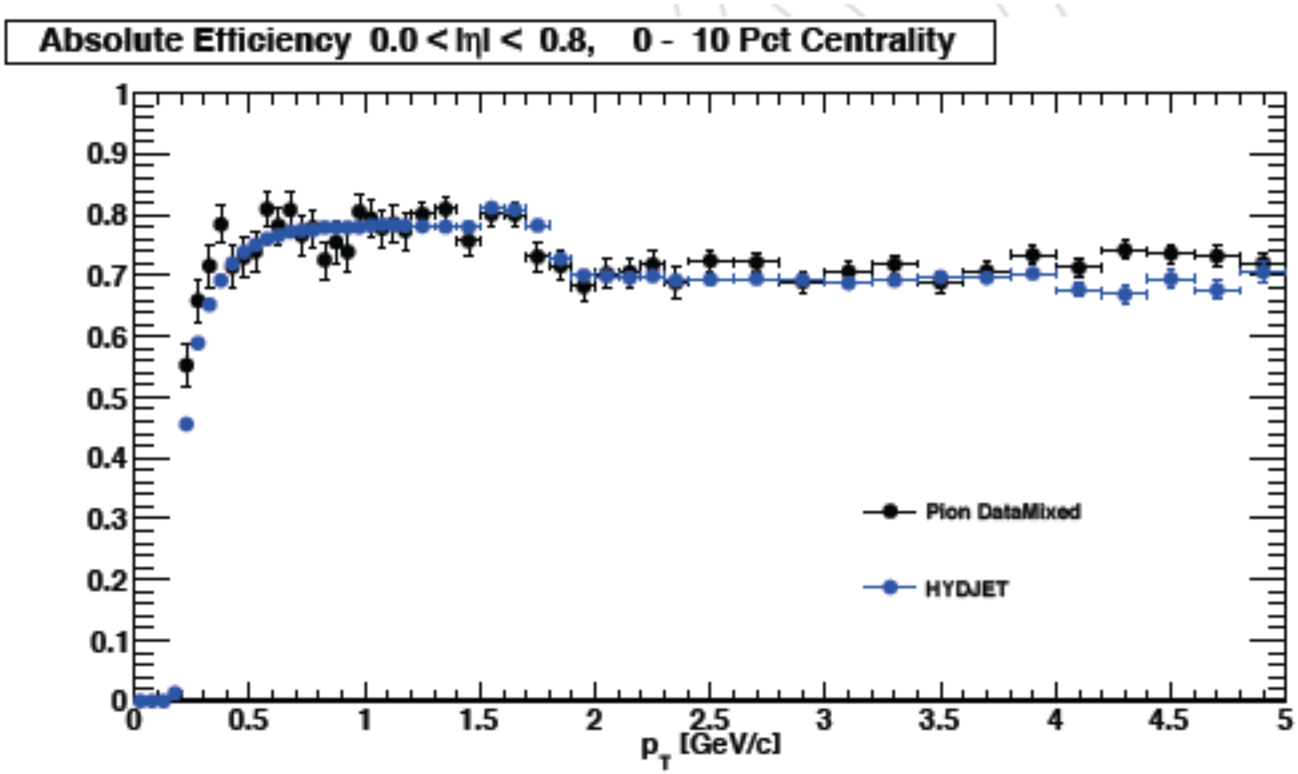


Tracking Efficiency / Fake Rate in HI





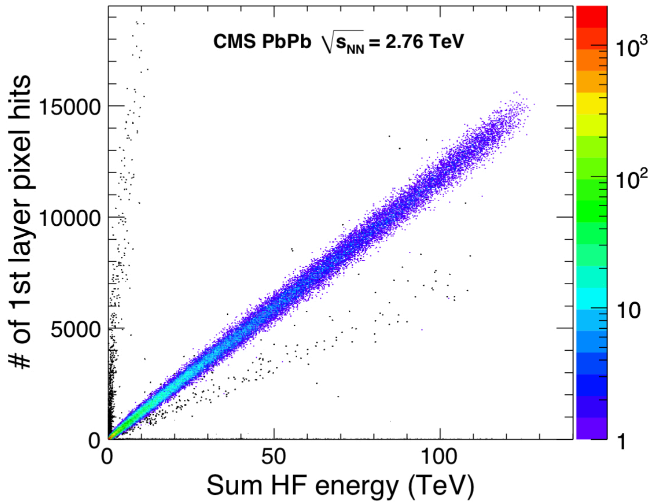
Tracking Efficiency



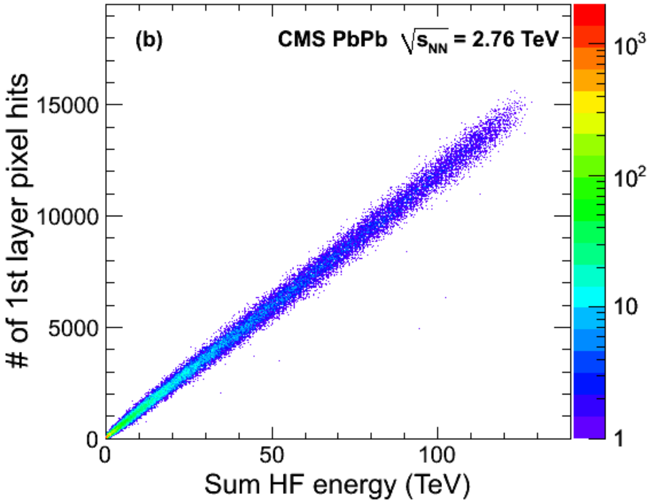
Collision Selection

- 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

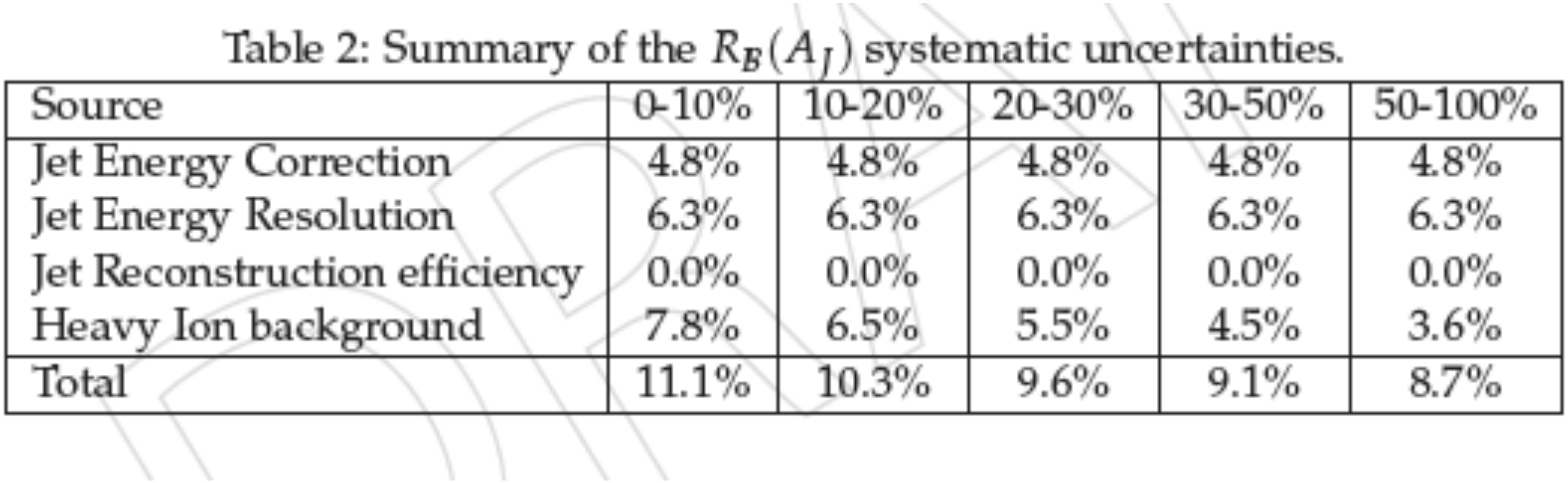


Table 2: Summary of the $R_B(A_J)$ systematic uncertainties.

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%

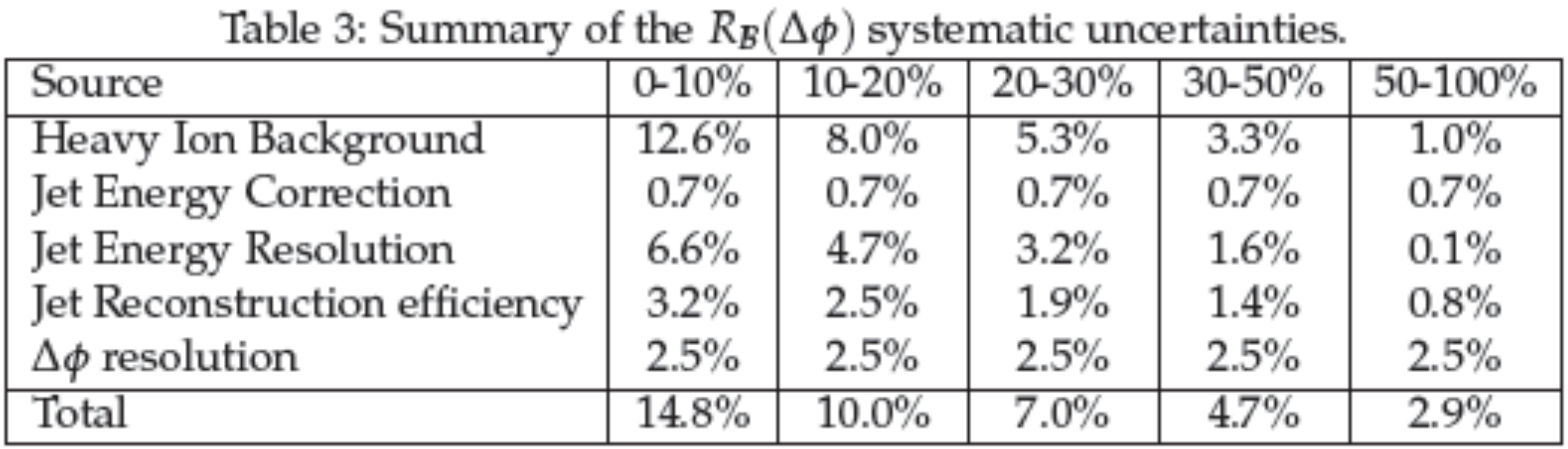


Table 3: Summary of the $R_B(\Delta\phi)$ systematic uncertainties.

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%