Jet quenching in PbPb collisions in CMS

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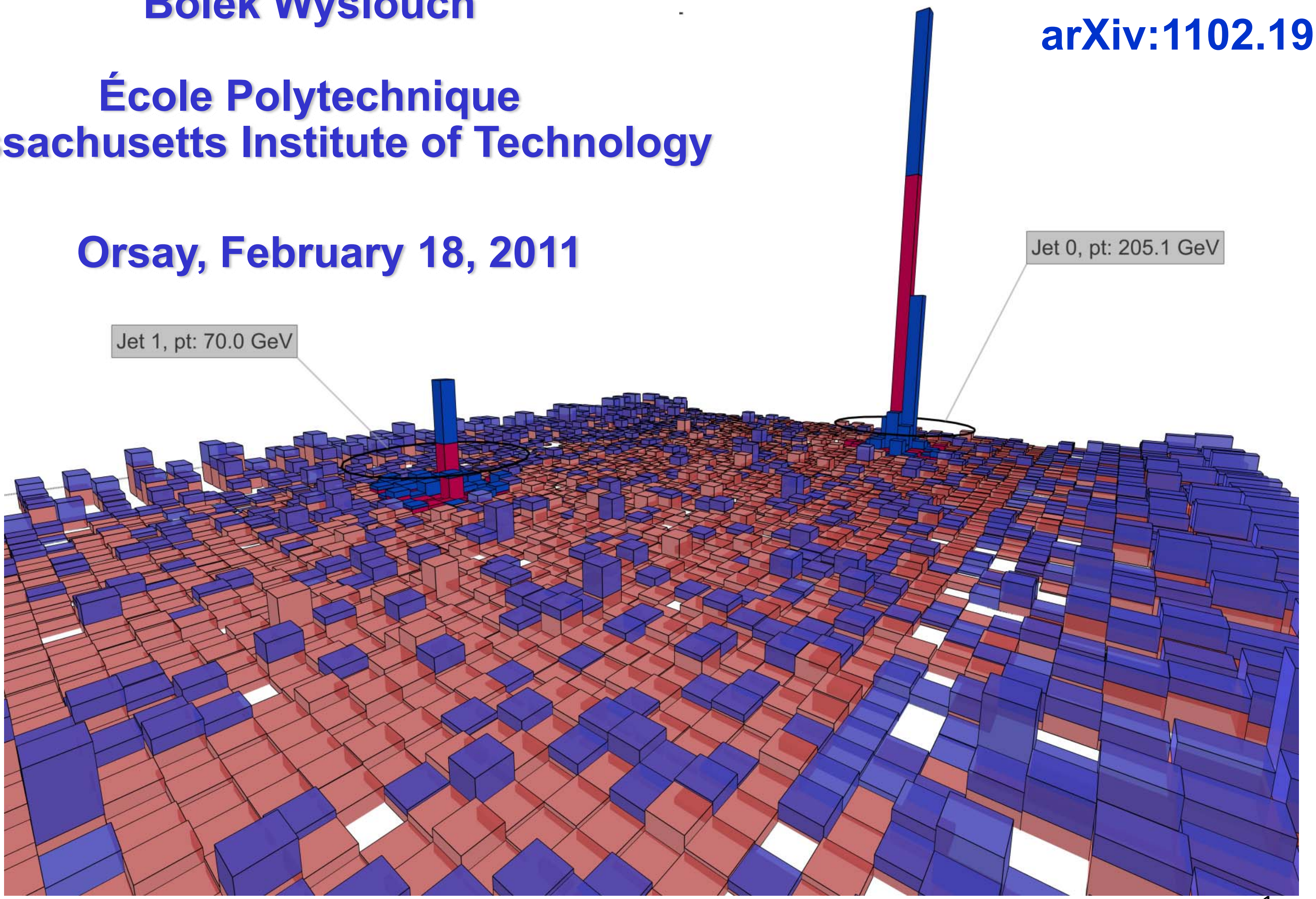


Heavy Ions at the LHC

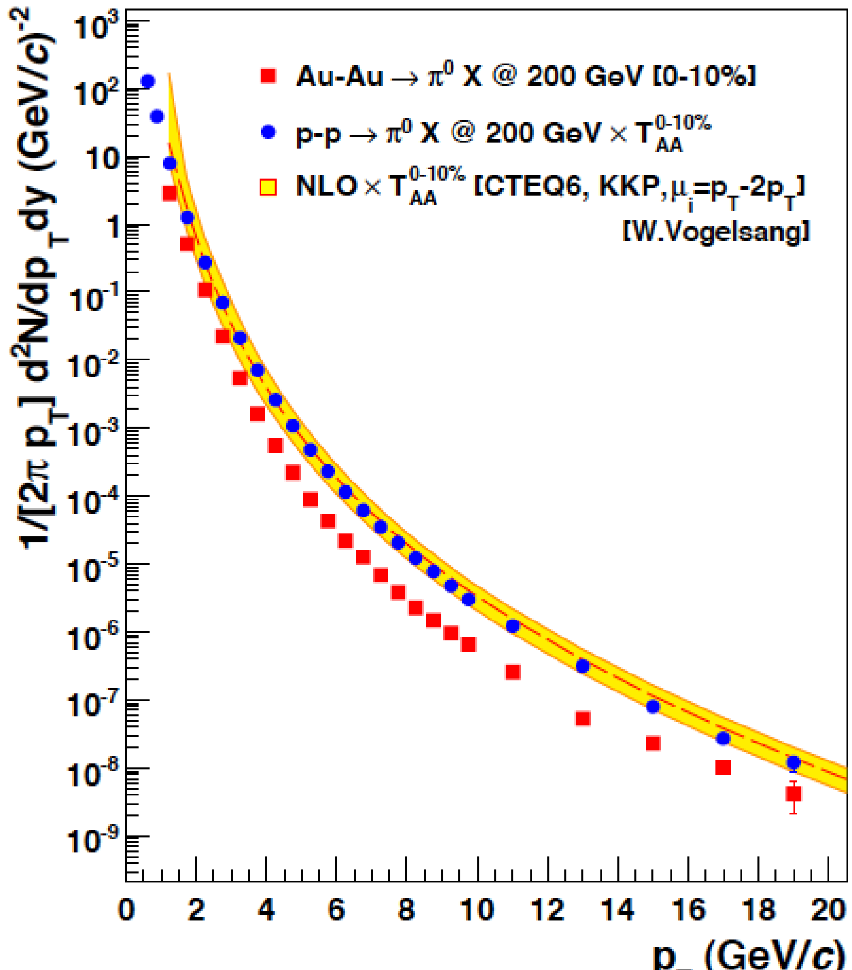
- Huge energy jump from RHIC: factor 14!
- Hottest nuclear matter ever created in the laboratory
- New probes or processes
- Excellent detectors
- Today from CMS:
  - Jets and the phenomenon of jet quenching

High p_T Suppression from RHIC

- **π^0 cross section measured in p+p and central (small impact parameter) Au+Au collisions @ 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 from RHIC

- **Correlation of hadrons of**

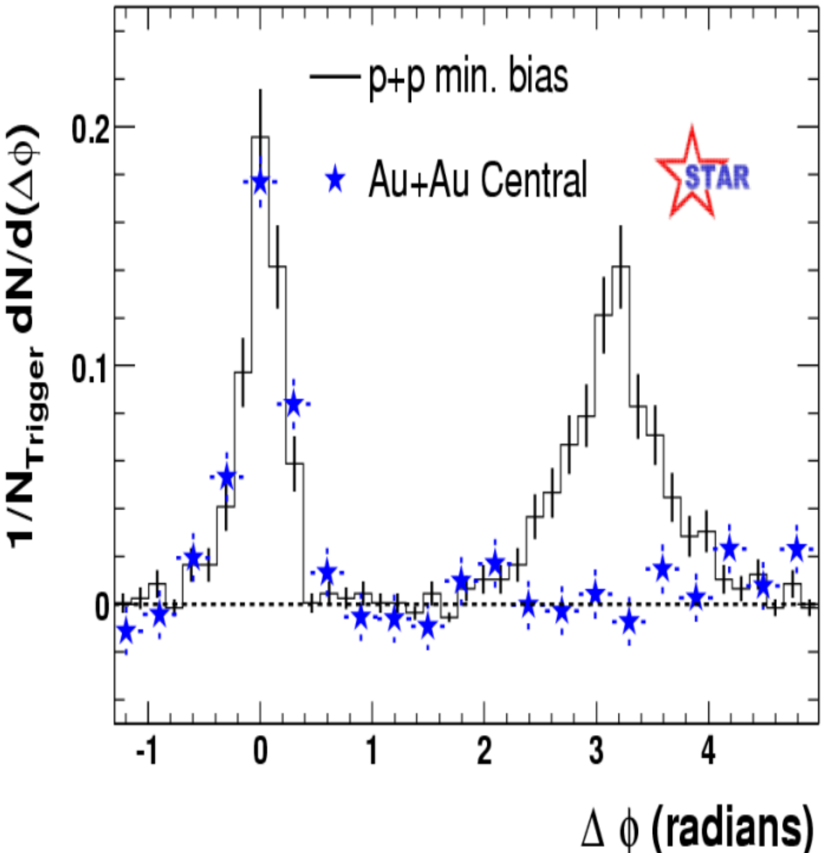
  4 GeV/c < $p_{T,\ trigger}$ < 6 GeV/c

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

- **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**

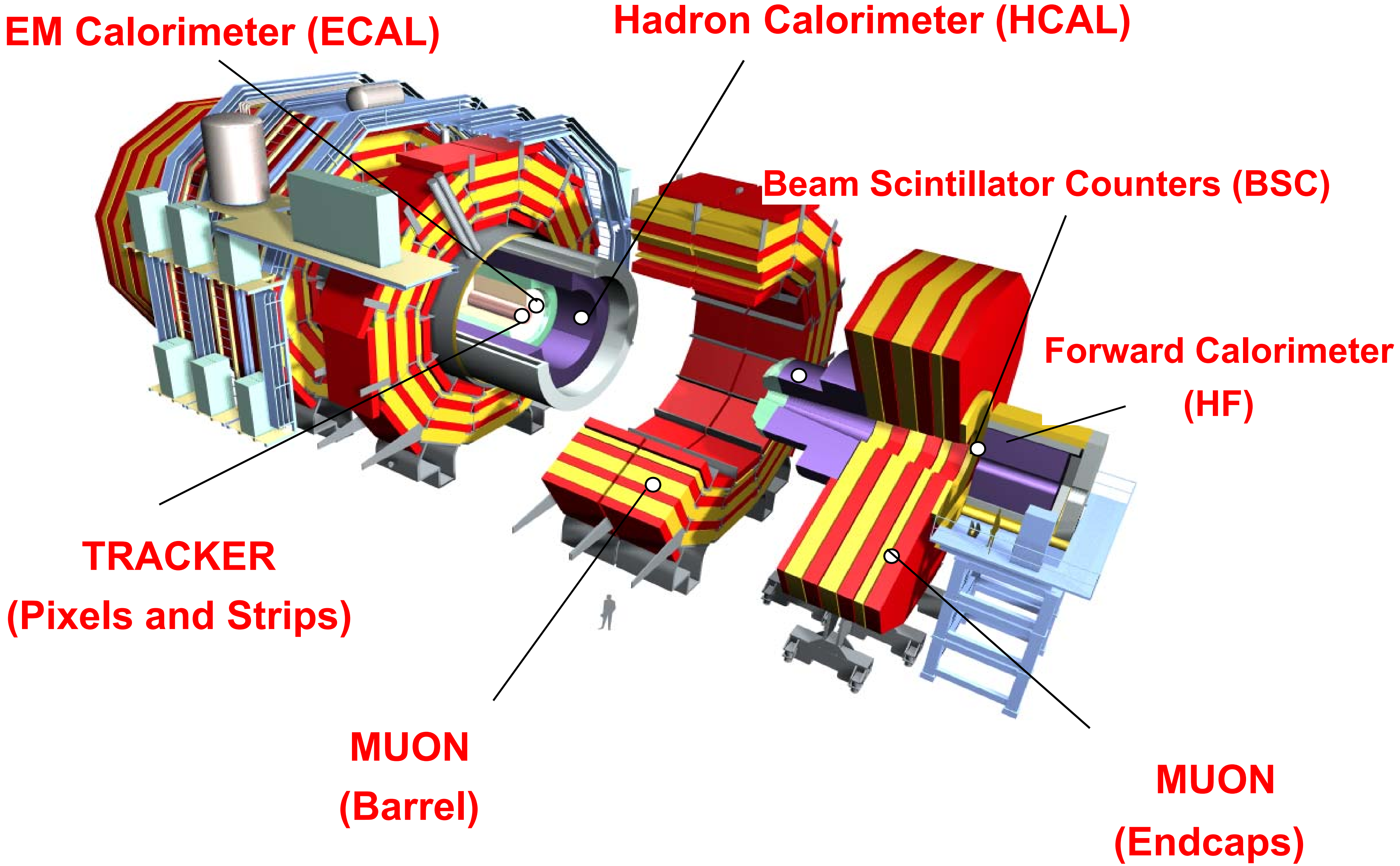
Dihadron Correlations from STAR

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

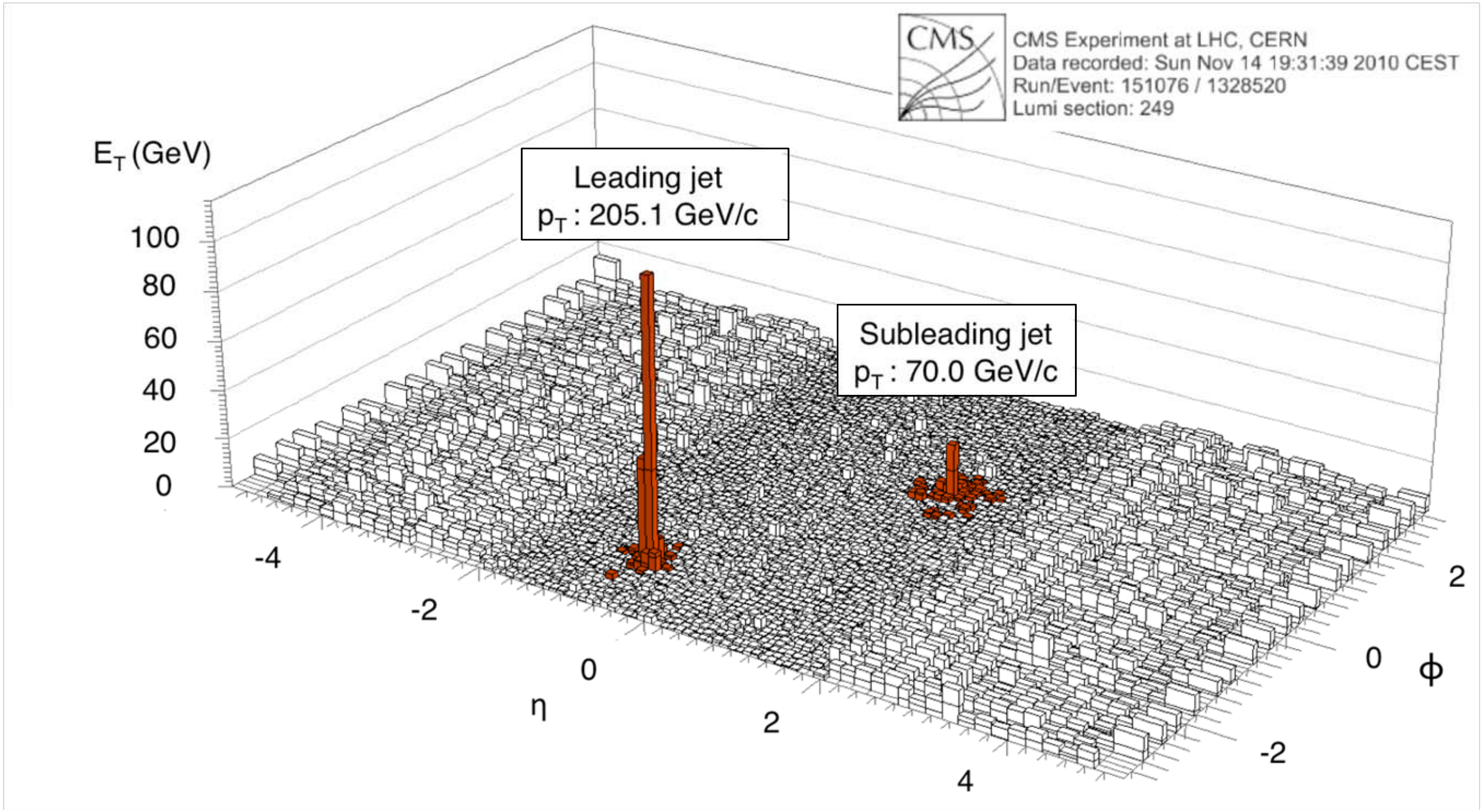


STAR collaboration,
Phys. Rev. Lett. 91 (2003) 072304

CMS detector at the LHC



A Dijet in Central PbPb

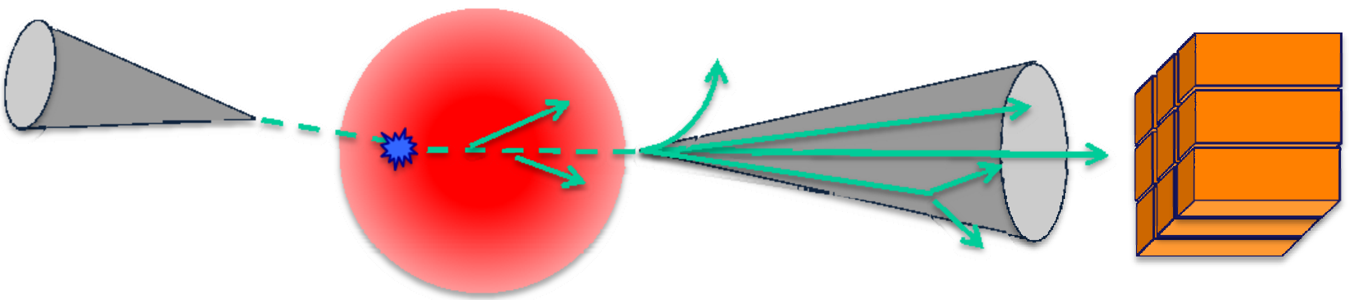


At LHC energies, jets with p_T of order 100 GeV/c cleanly separable from background fluctuations in central PbPb collisions

Jet Measurements in AA

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

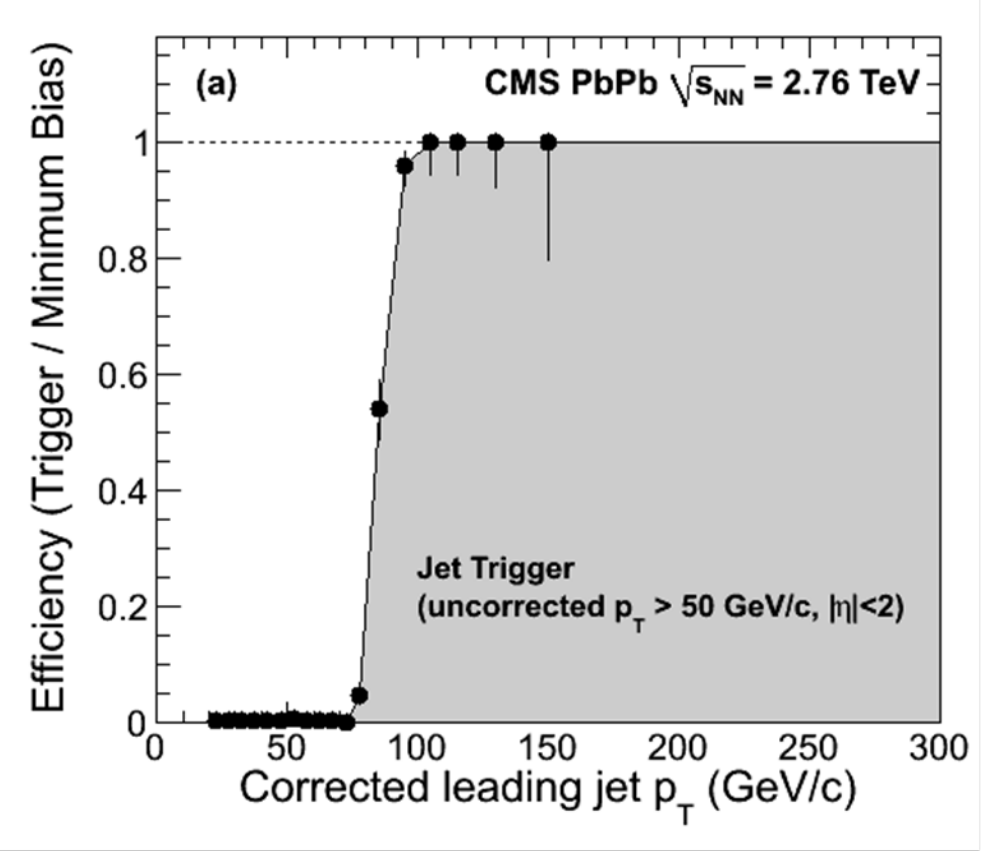
Some jet energy lost to
-Low p_T particles
-Large angle radiation
-Nuclear interactions, decays, etc.

Measurements of parton energy loss allow to

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

Triggers

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



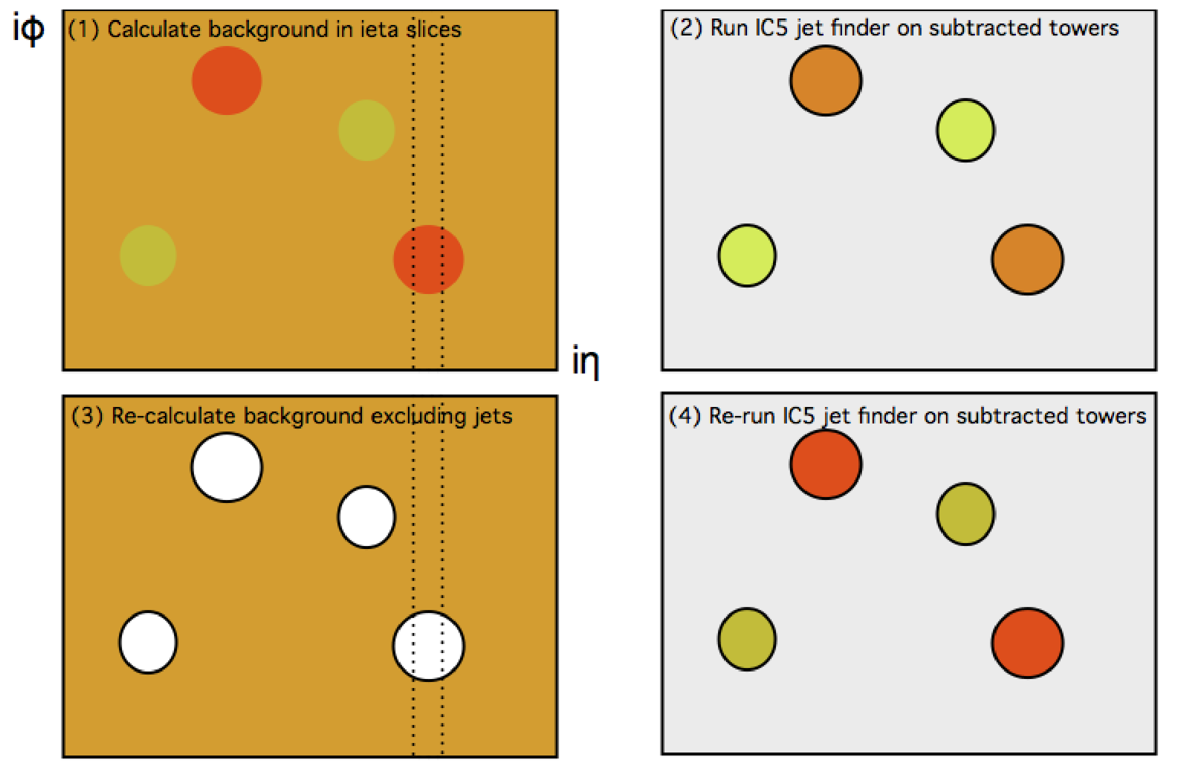
Reconstruction of Jets in HI collisions

- Jets are accompanied by the large “thermal background” or “underlying event” that depends on the overall event multiplicity
  - Use background subtraction procedures
- CMS uses several jet finding algorithms
  - Iterative Cone
  - Anti-k_T (M. Cacciari, G. P. Salam, G. Soyez, JHEP 0804:063,2008.)
- Jets are found using different sets of detectors
  - Calorimetric Jets: use ECAL and HCAL
  - Particle Flow Jets: use Tracker and Calorimeters
- Jet cone size can vary
  - We use R=0.5
- CMS HI “workhorse”
  - IC5 CaloJets with iterative background subtraction

  (O. Kodolova et al., EPJC (2007))

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**

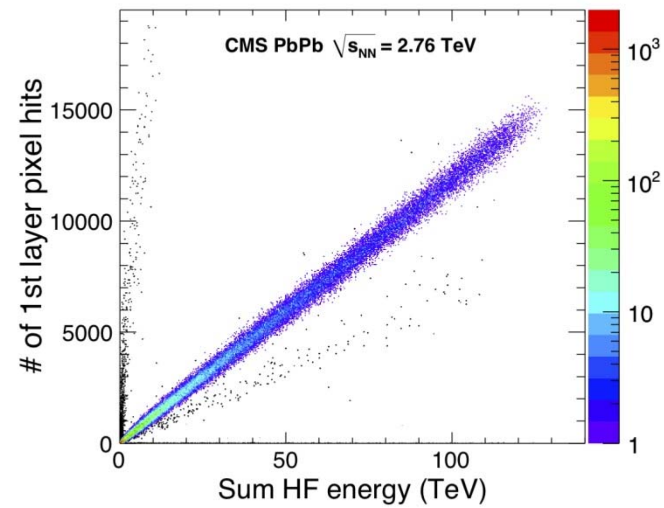


Method: O. Kodolova et al., EPJC (2007) 117.

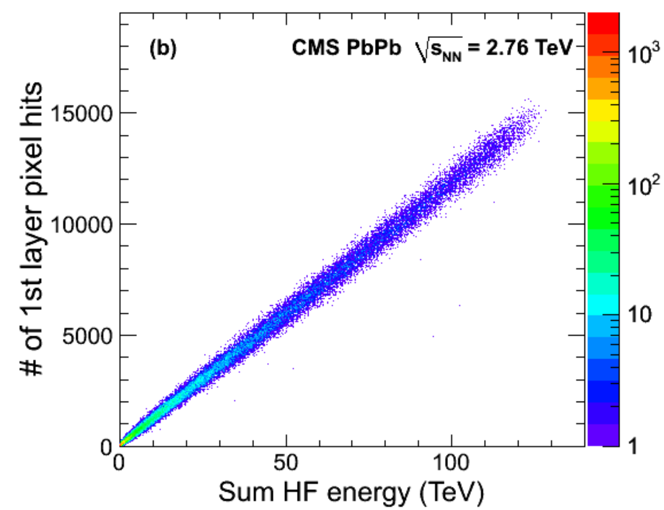
Analysis Details

- **Collision Selection**
  - **Reject Beam Halo (BSC)**
  - **HF Coincidence**
  - **Pixel cluster compatibility with vertex**
  - **ECAL/HCAL noise cleaning**
- **Dijet Selection**
  - **Leading jet: $p_{T,1} > 120$ GeV/c, $|\eta| < 2$**
  - **Subleading jet: $p_{T,2} > 50$ GeV/c, $|\eta| < 2$**
  - **Azimuthal Angle: $\Delta\phi_{12} > 2/3\ \pi$ 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**

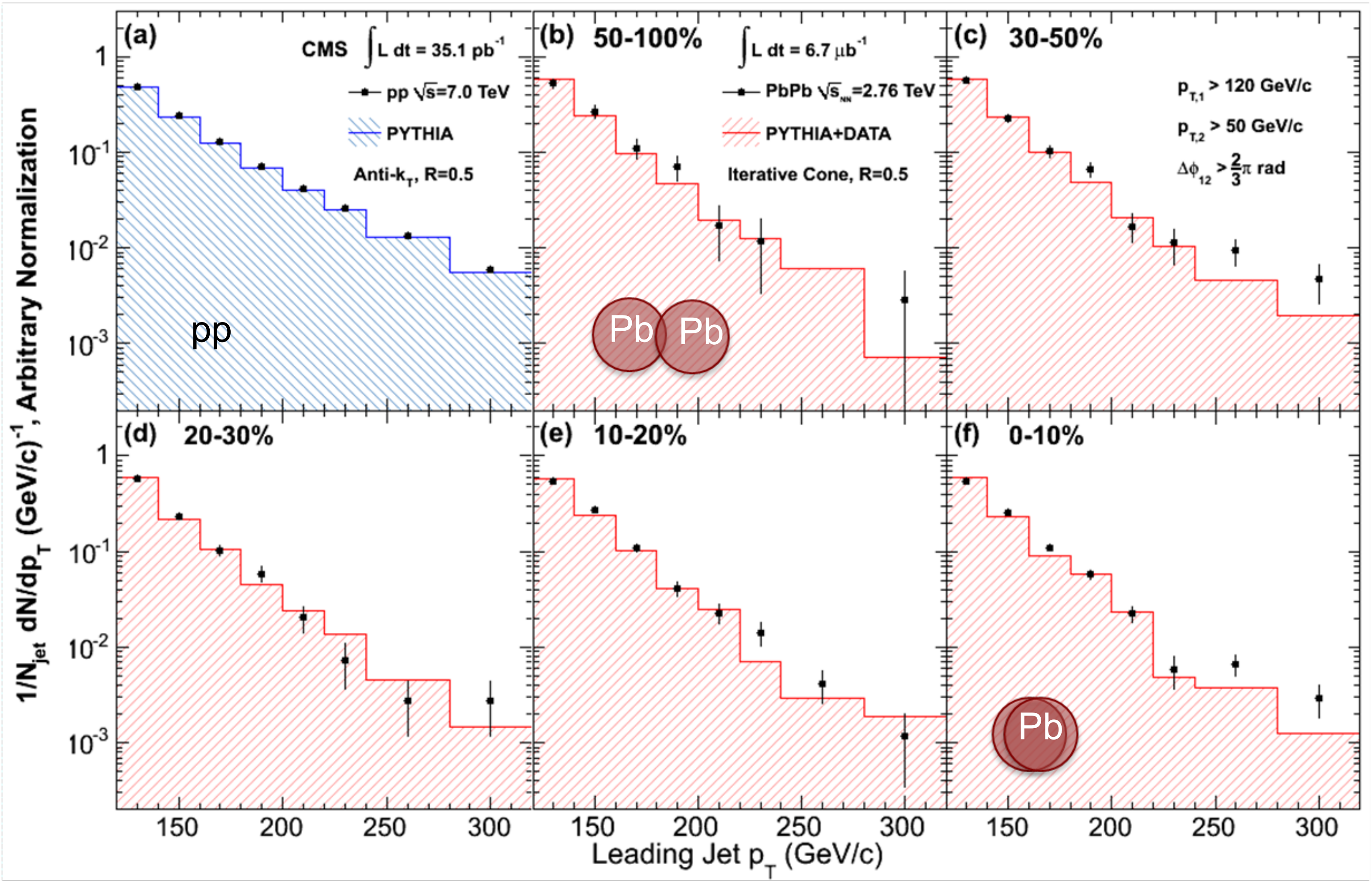
Before Collision Selection



After Collision Selection

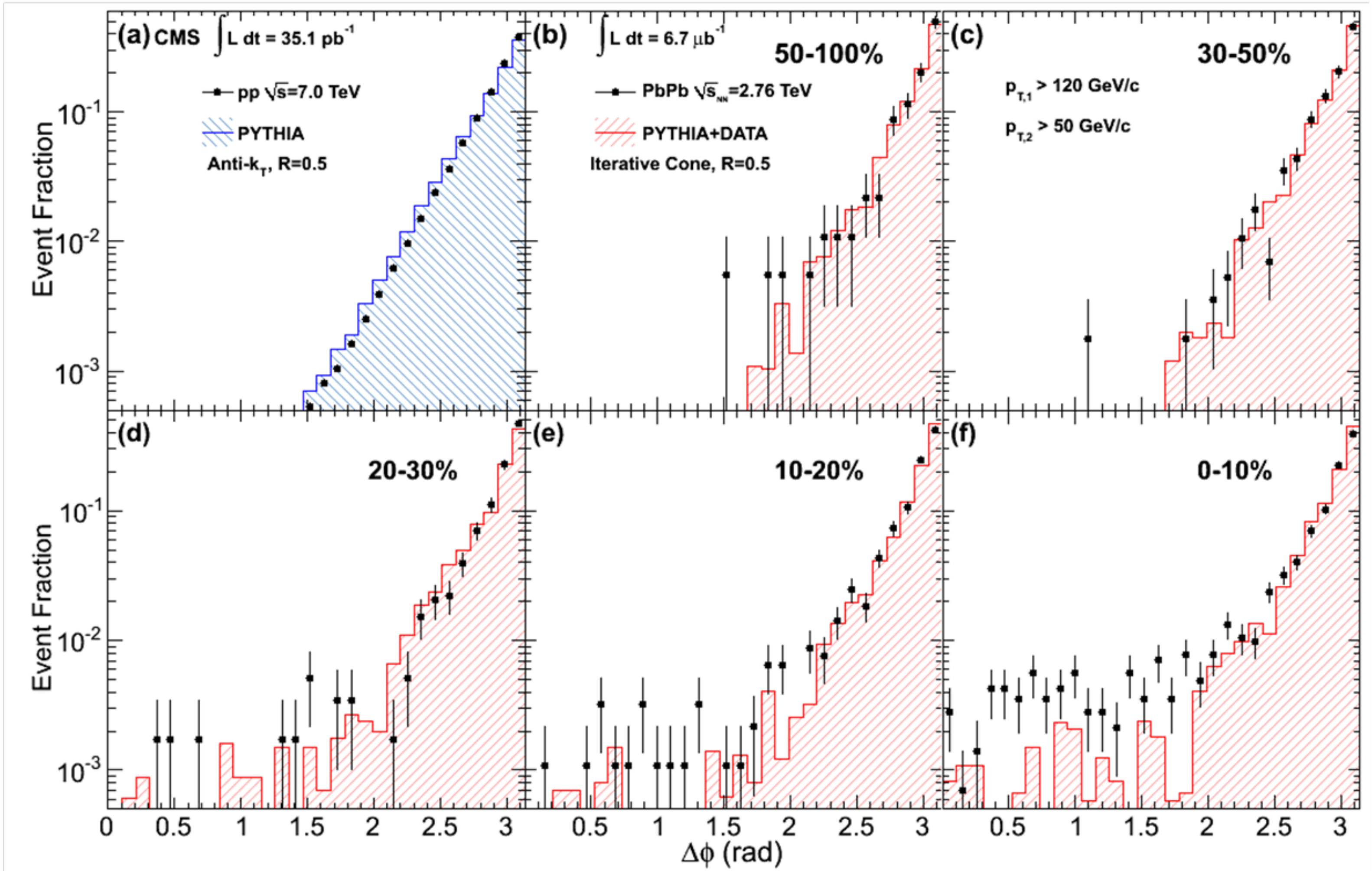


Leading Jet p_T Distributions



No strong modification to shape of leading jet spectrum

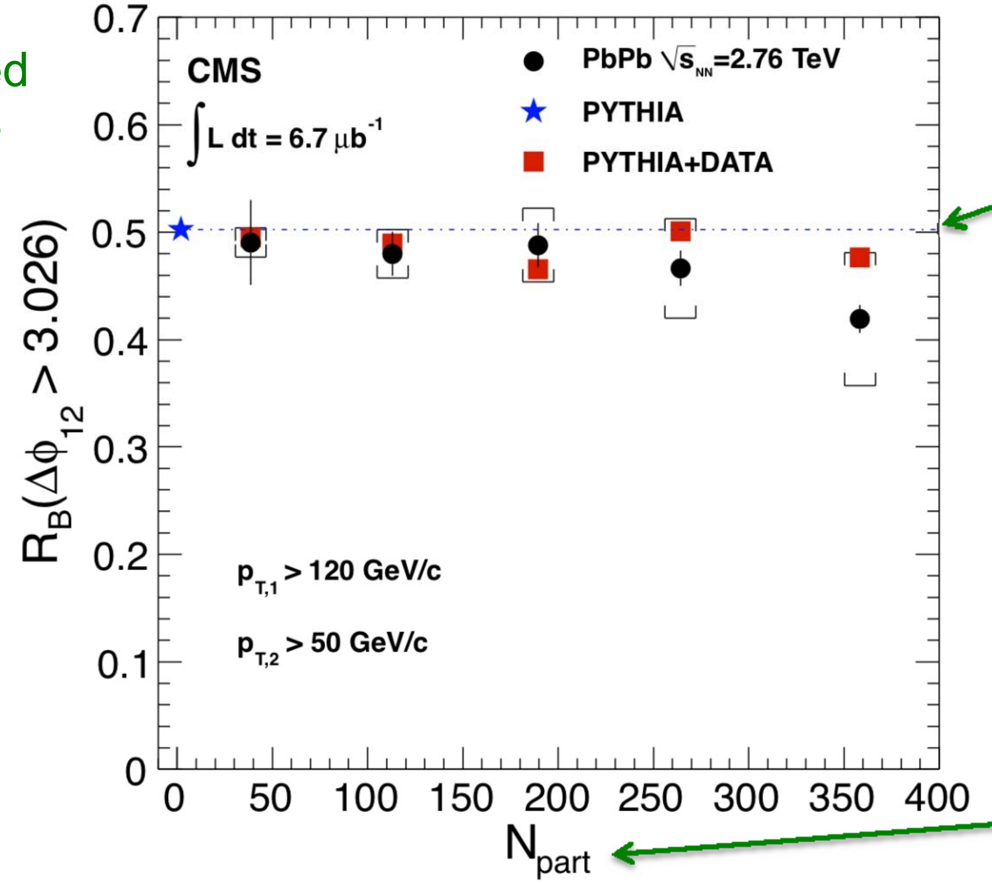
Dijet Azimuthal Correlations



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

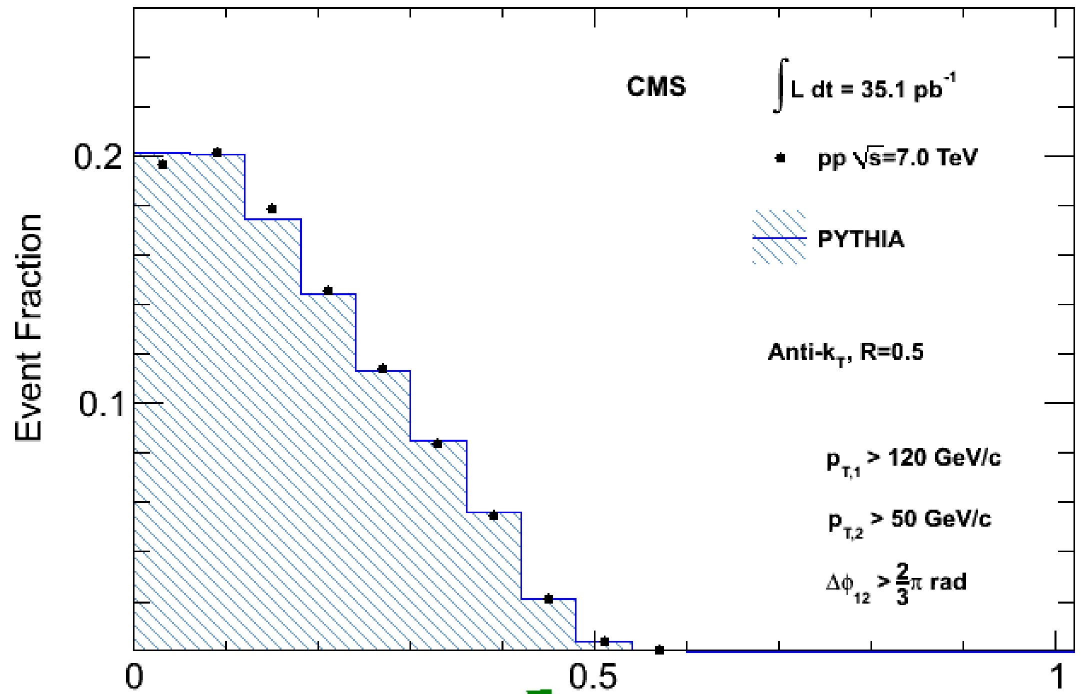


The threshold of 3.026 radians is the median value from PYTHIA

N_{part} is the number of participating nucleons

No angular decorrelation beyond systematic uncertainties

Dijet p_T Asymmetry

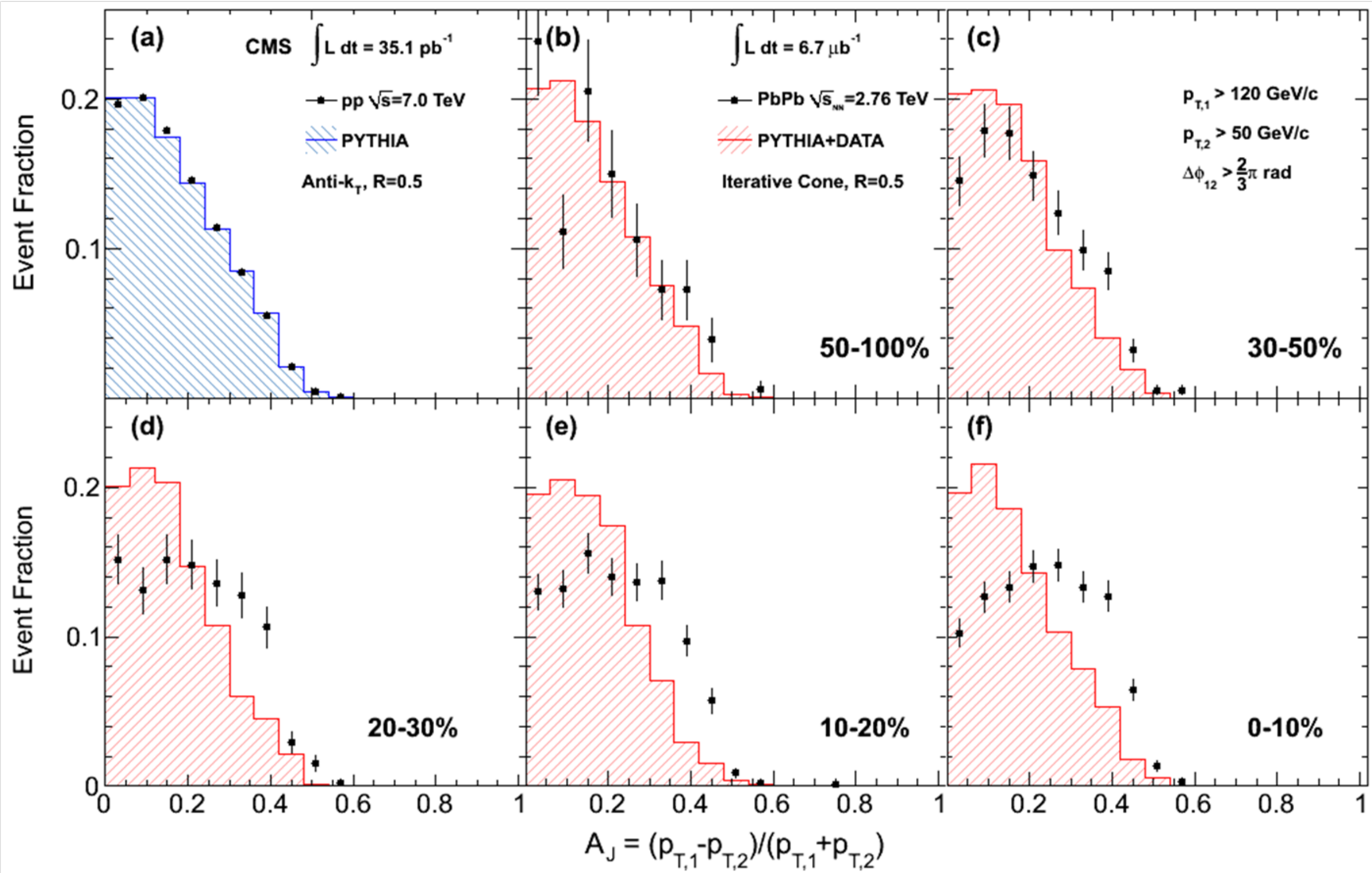


$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Dijet asymmetry quantified by A_J → insensitive to energy scale uncertainty

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

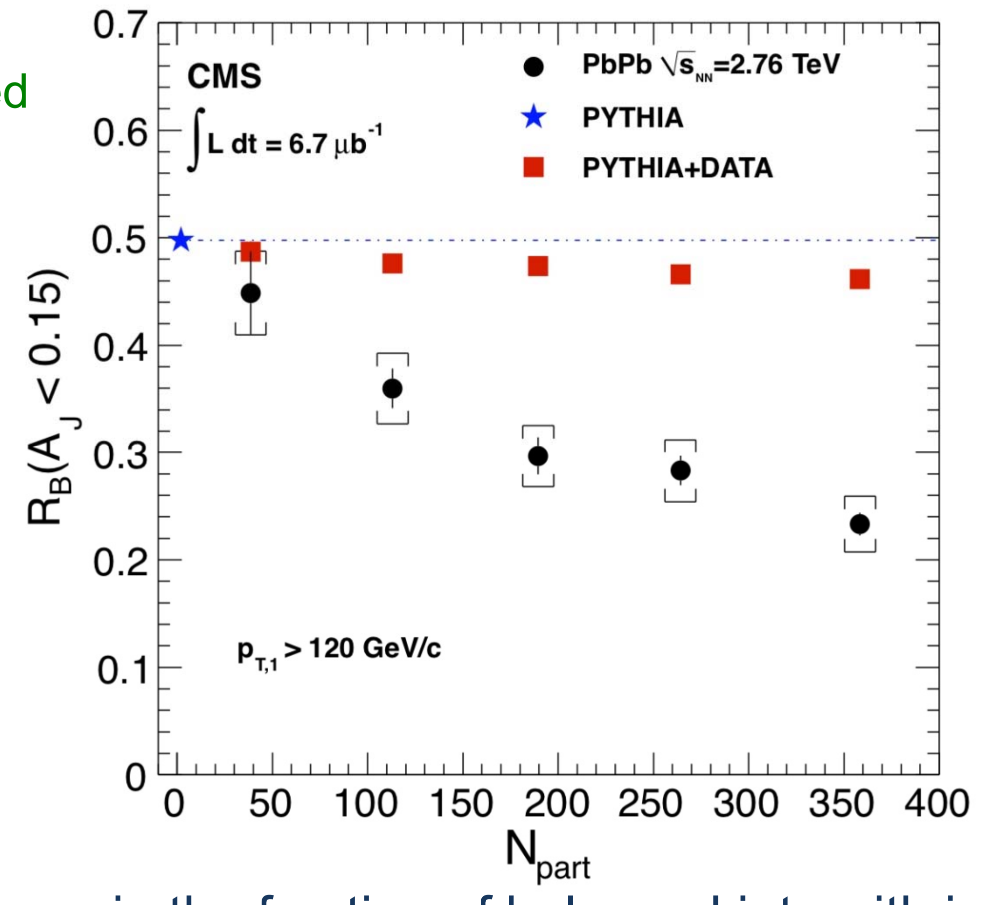
Dijet p_T Asymmetry



Striking enhancement of asymmetry with increasing centrality

Dijet Imbalance Quantified

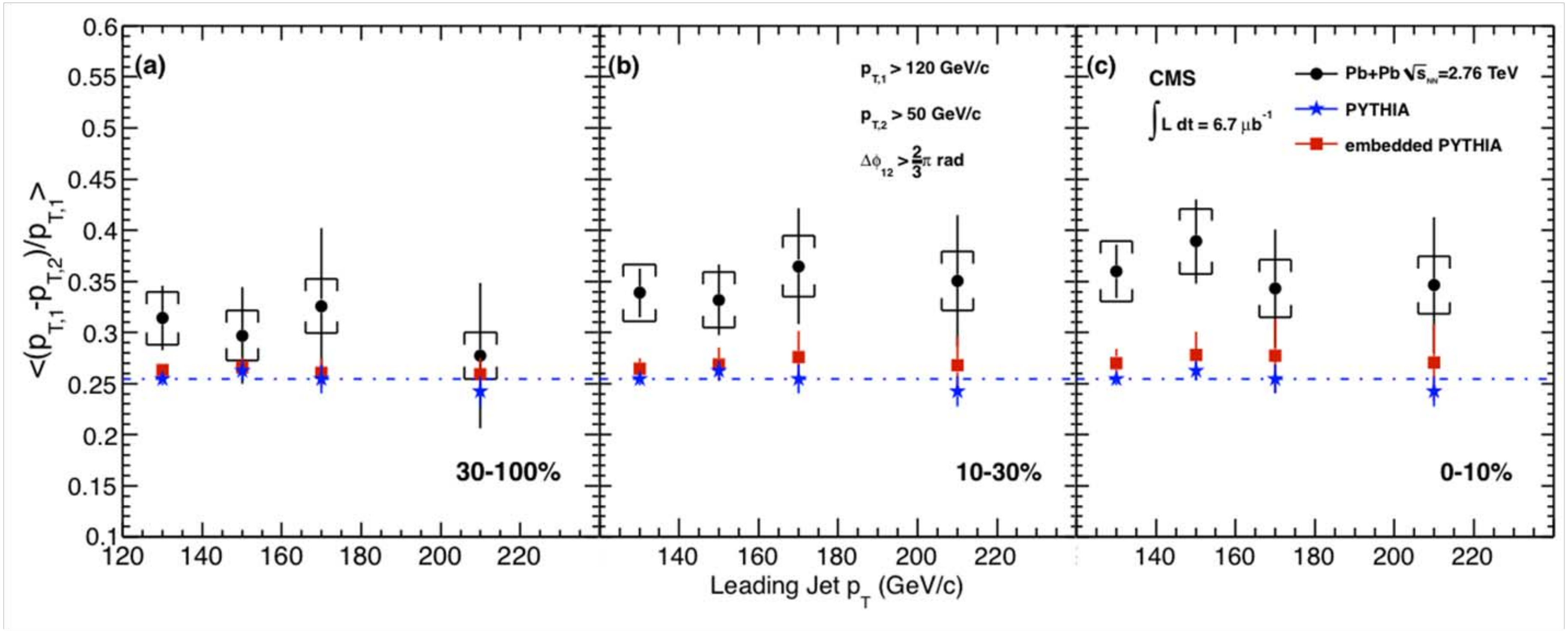
Here $R_B(A_J)$ is the fraction of dijets which are balanced in momentum



Smooth decrease in the fraction of balanced jets with increasing centrality

Note: Dijets in which no subleading jet found above threshold are included

p_T Dependence of Quenching

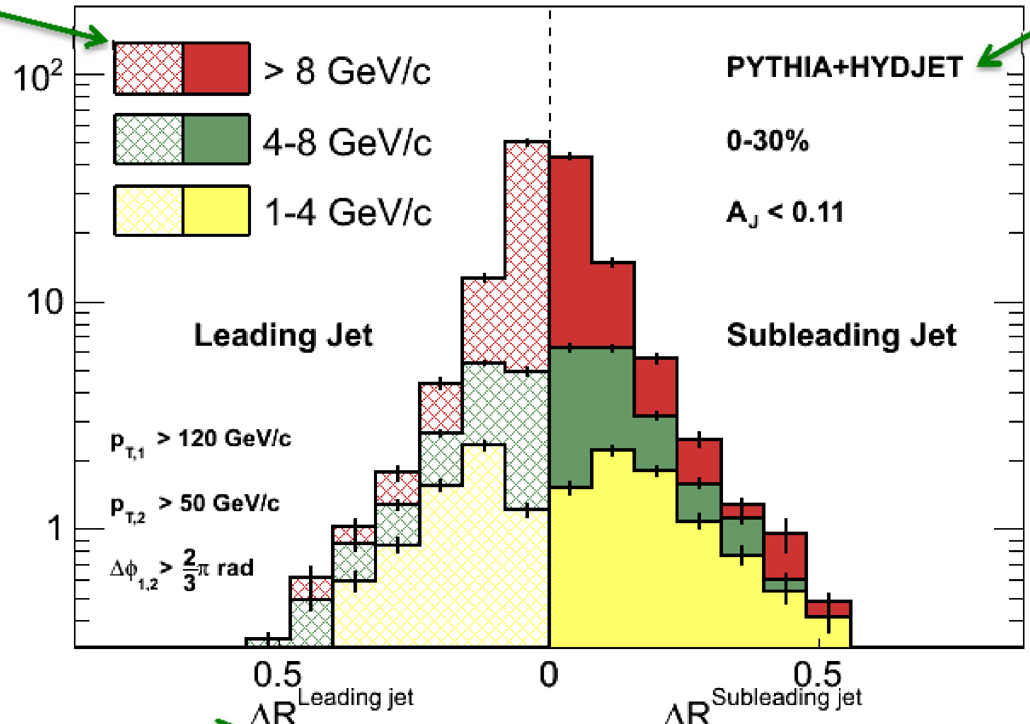


Jet-Track Correlations

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

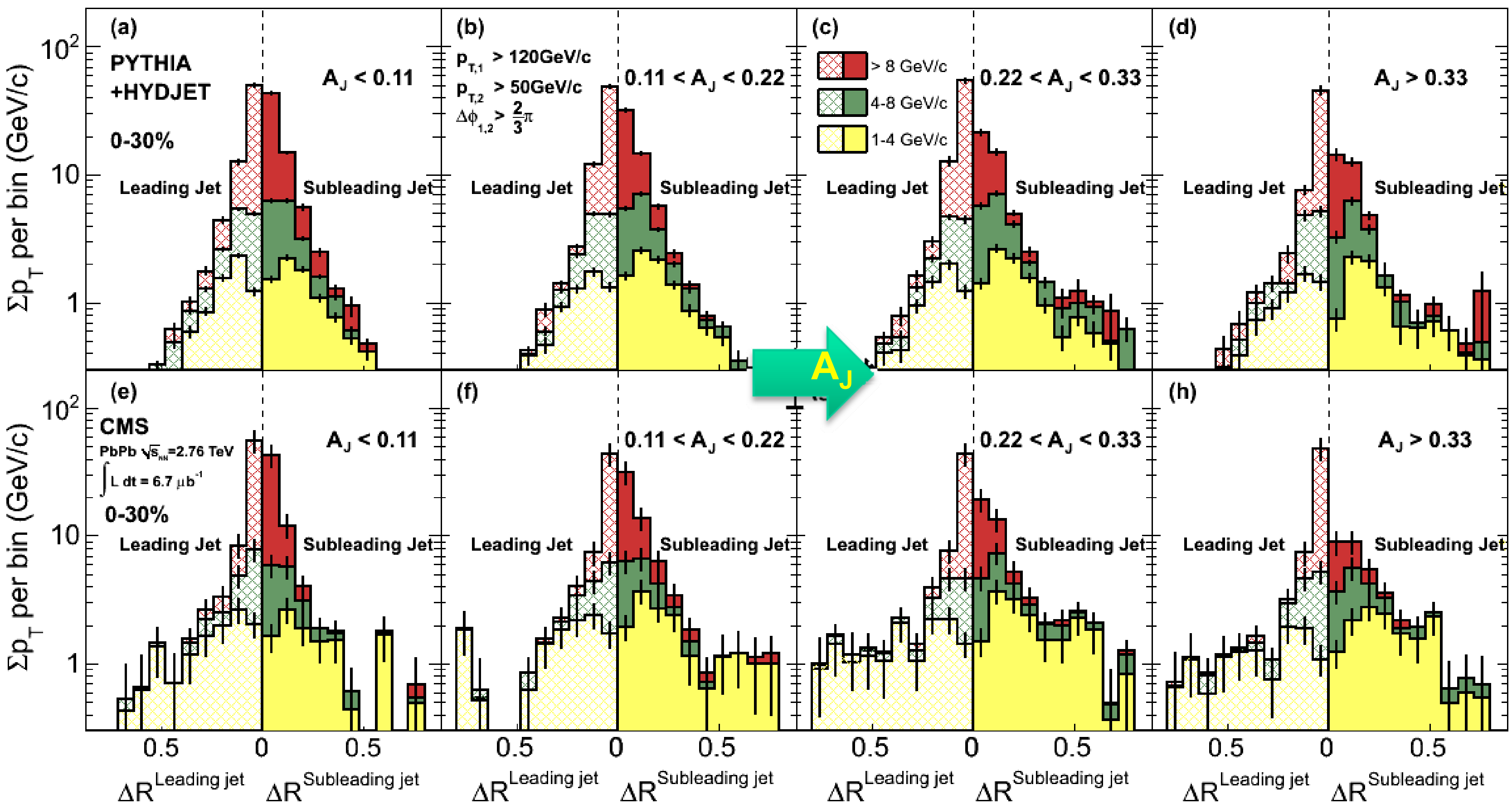
Background is subtracted using a cone at same ϕ, but reflected in η ($\eta \rightarrow -\eta$)

Asymmetry Dependence of Fragmentation

- 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

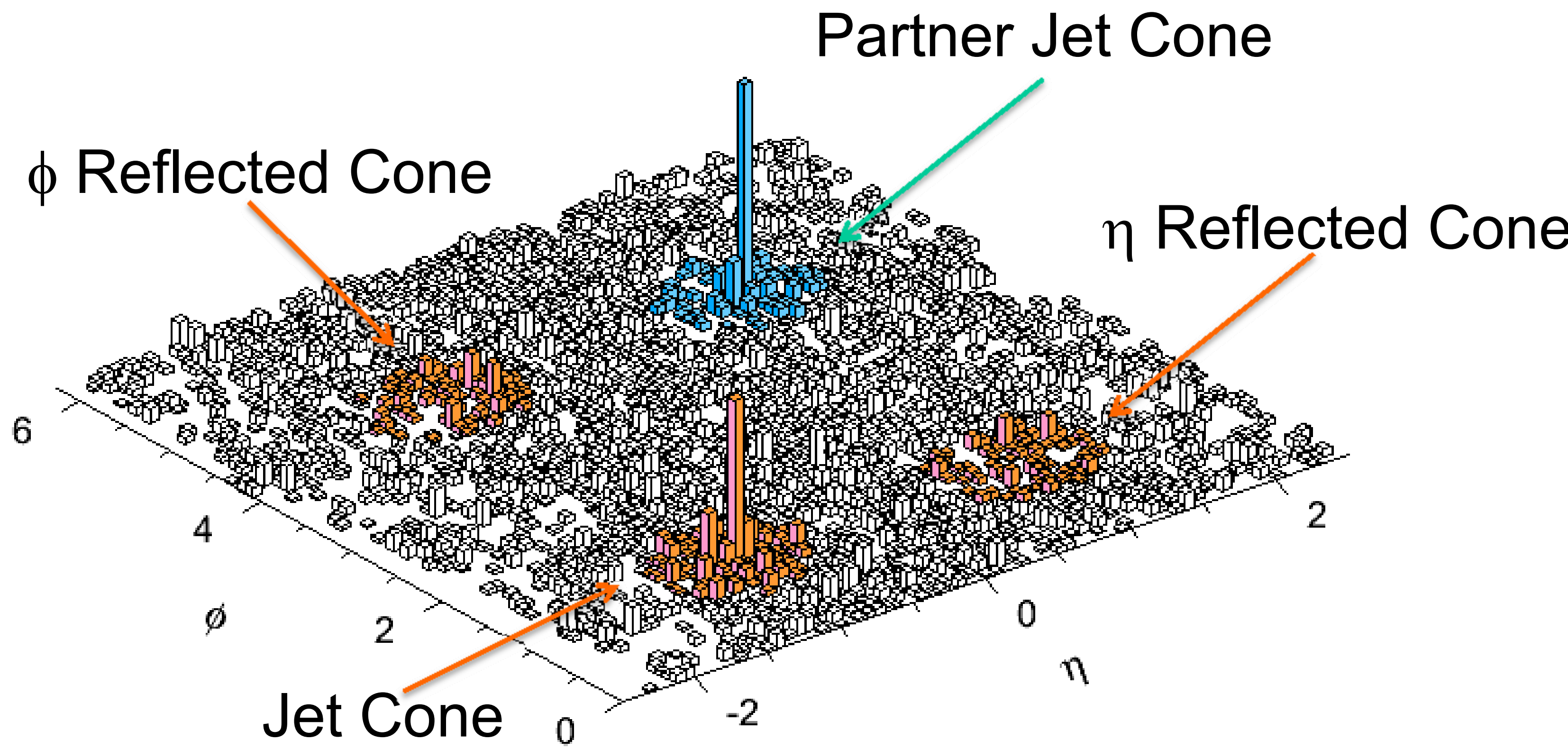
MC

DATA



- Both data and MC show that dijet asymmetry is also apparent in charged tracks
- 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

η, ϕ Reflection Method



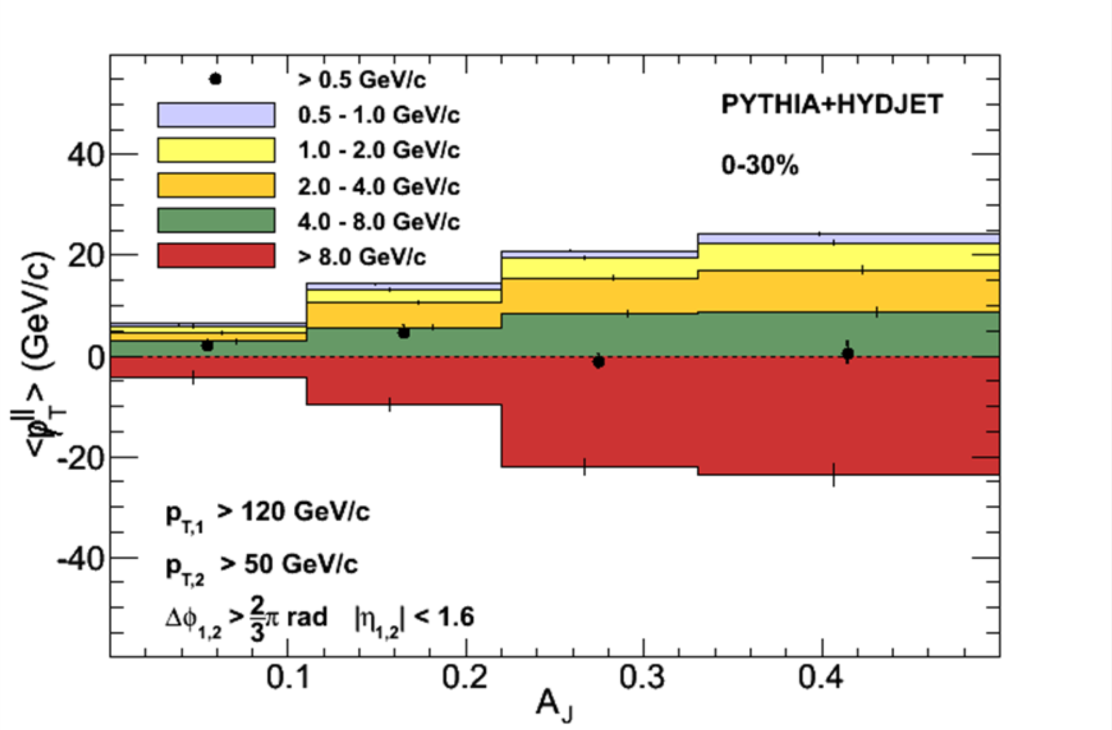
The background is evaluated within the cone symmetric about η

This avoids ϕ dependent variations due detector efficiency or hydrodynamic flow

The regions around mid-rapidity, $|\eta| < 0.8$, and $|\eta| > 1.6$ are excluded

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:

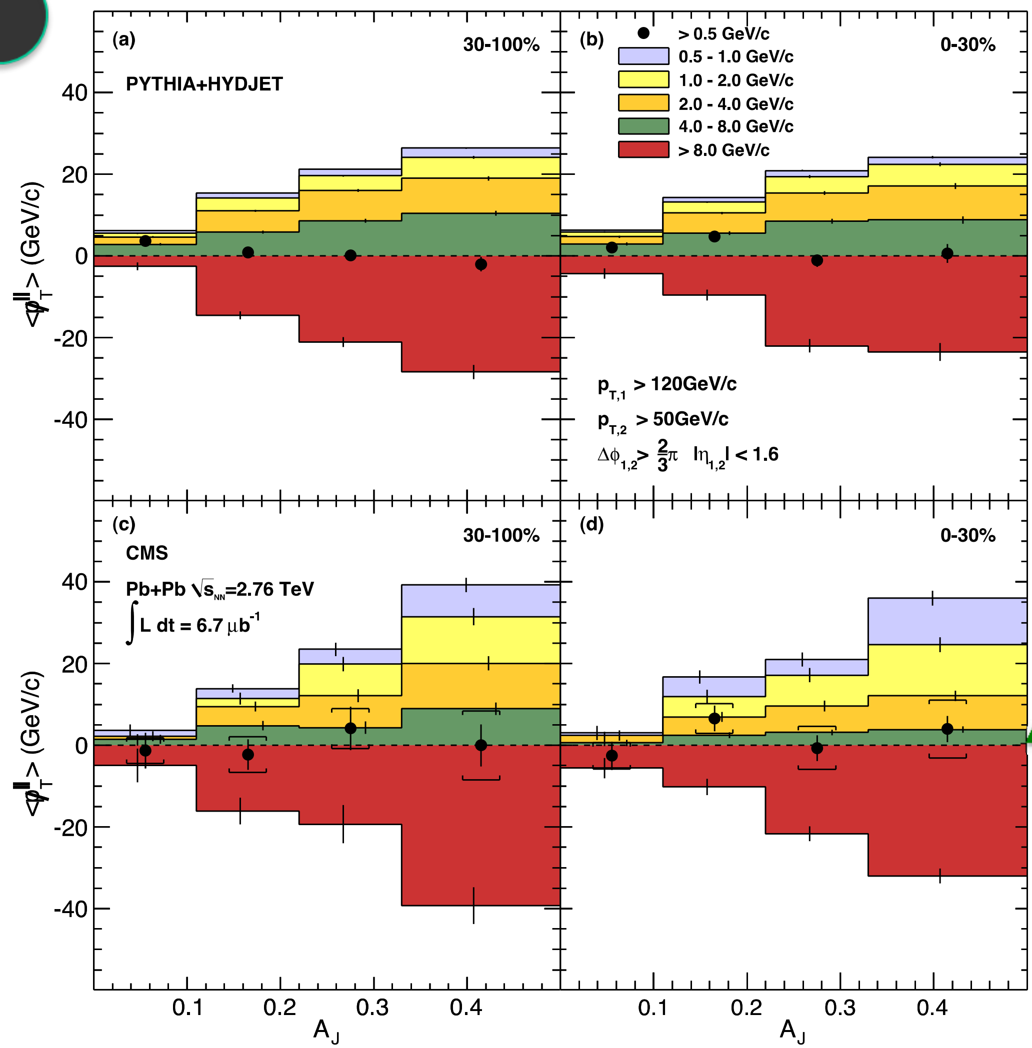
$$\not{p}_T^{||} \equiv \sum_{\mathrm{tracks}} -p_{\mathrm{T,track}} \cos\left(\phi_{\mathrm{track}} - \phi_{\mathrm{leading\ jet}}\right)$$

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

Missing p_T: Data vs. MC

MC

DATA

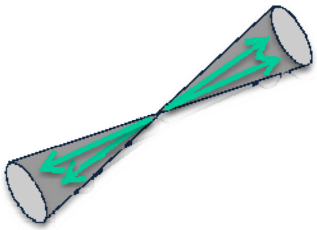


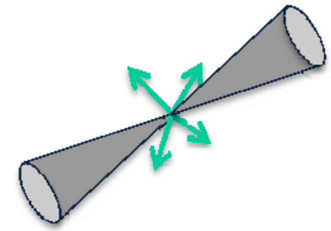
In MC, events are balanced,
p_T composition is independent of centrality

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

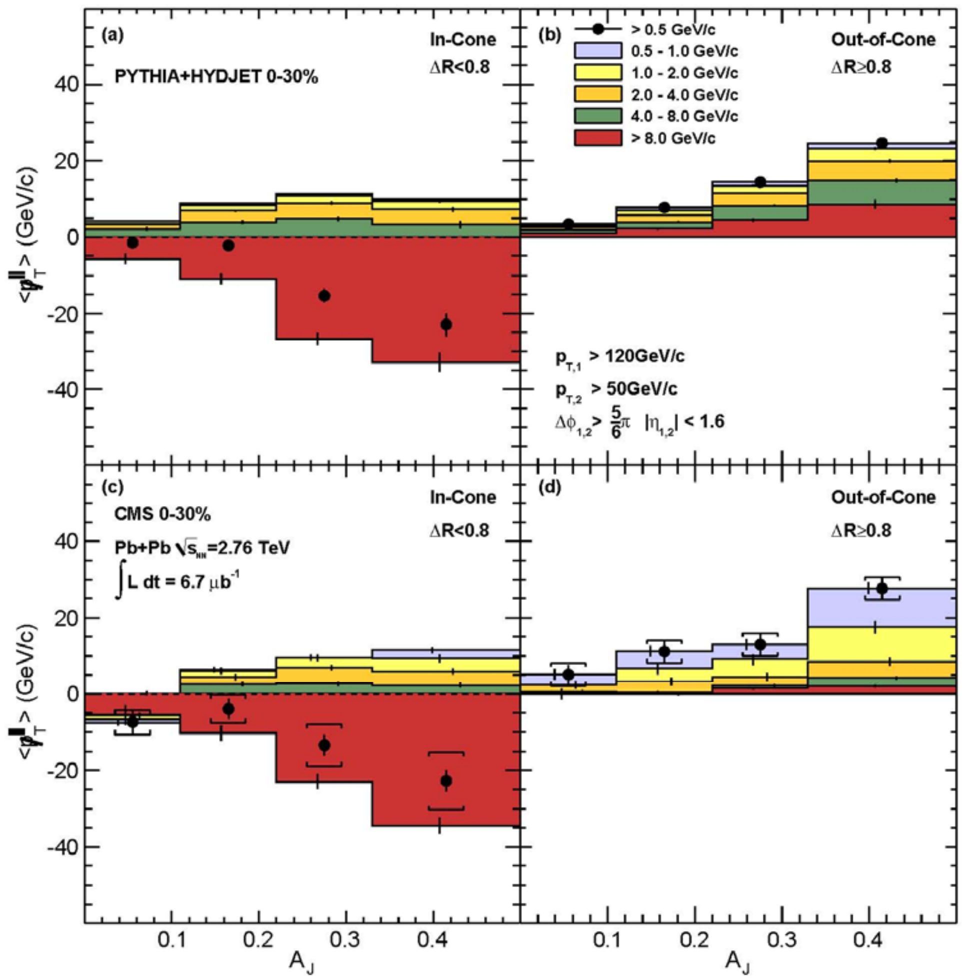
Missing p_T: In vs. Out-of-Cone





MC

DATA



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

In-cone, p_T balance in data fairly similar to MC

Out-of-cone, p_T balance in data dominated by low p_T tracks

Summary

- During the first LHC Heavy Ion run CMS collected ~8.7 μb-1 with heavy ion collisions at B=3.8T and B=0 corresponding to >60M Min Bias events
- The analysis of data continues, our first paper summarizes detailed studies of jets with large apparent calorimetric energy imbalance
- The large acceptance of the CMS tracker allowed us to demonstrate large shift of energy to low p_T particles and demonstrate that most of these particles are outside of the jet cone