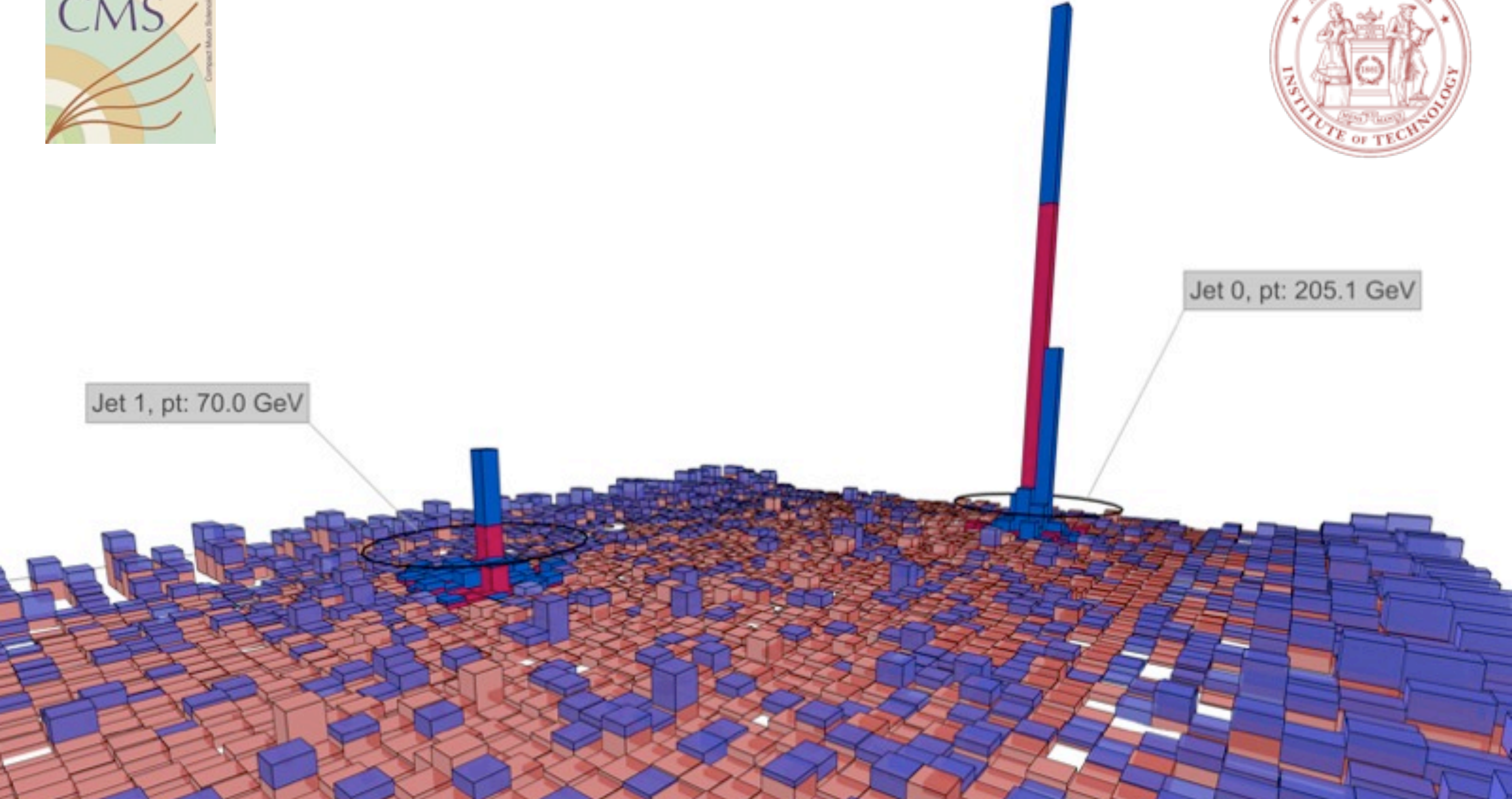


Observation and Studies of Jet Quenching in Pb+Pb collisions at 2.76 TeV

Edward Wenger for the CMS Collaboration

Fermilab W&C Seminar 28 Jan 2011

Overview

- Introduction to heavy-ion collisions and jet quenching
- Details of analysis techniques
- Dijet imbalance results from calorimeters
- Track-Jet correlations in search of missing energy

Motivation for Heavy Ions

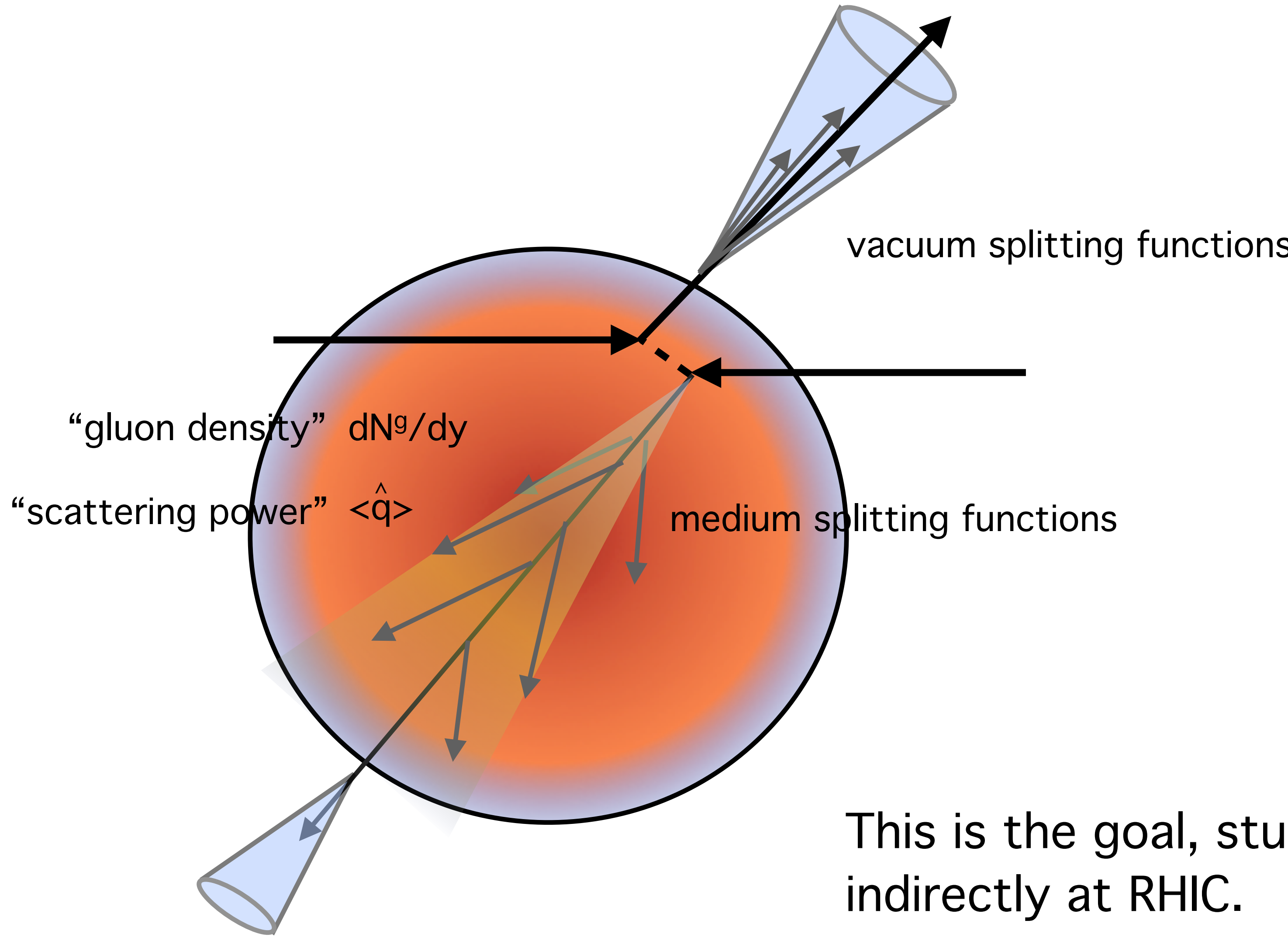
- Study QCD at extreme temperatures and densities (μs after Big Bang)
- Explore properties of new form of matter (QGP) proposed at high energy densities: above 1 GeV/fm^3
- Already at RHIC, conservative estimates of energy density in the early system are well above predicted crossover
- But our 'QGP' doesn't look like an ideal gas of deconfined quarks and gluons. So what are the properties of the strongly interacting matter produced at RHIC/LHC?

Summary of Results from RHIC

200 GeV Au+Au collisions (*BNL, 2000-present*)

Experimental Signature		**Property of sQGP**
• Early onset of collective behavior characterized by 'hydrodynamic' flowing medium	→	'Ideal fluid': vanishing shear viscosity and mean free path
• Dramatic modification of high-p_T particle production relative to p+p reference (jet quenching)	→	Partonic energy loss proportional to medium properties (e.g. gluon density, transport coefficient)

Jet Quenching = Tomographic QGP Probe

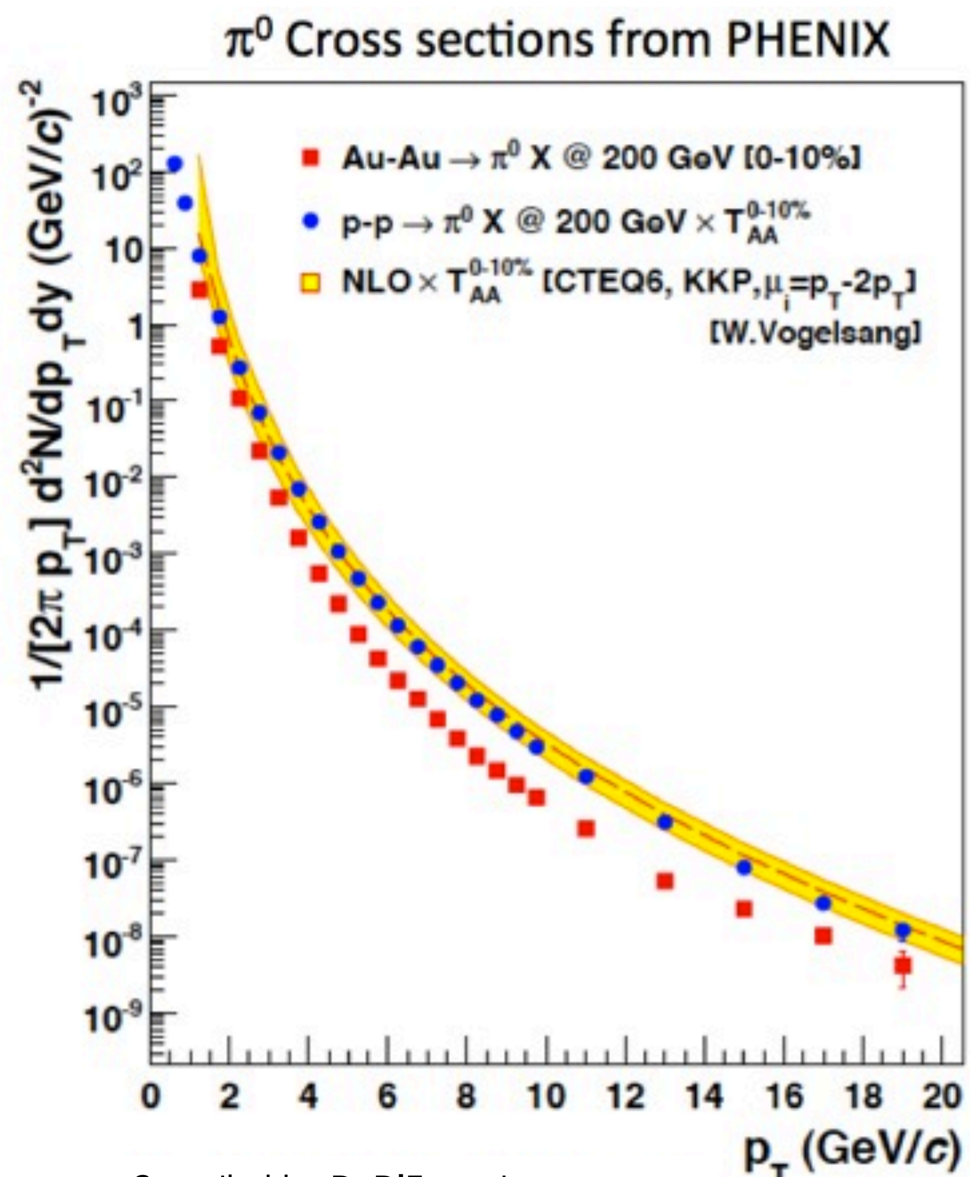


This is the goal, studied more indirectly at RHIC.

High-p_T Suppression at RHIC

- π^0 cross section measured in p+p and central (small impact parameter) Au+Au collisions @ 200 GeV
- Yields of high-p_T hadrons is suppressed by factor ~5 compared to p+p expectation*

* p+p data scaled by number of binary collisions N_{coll}



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

Dihadron correlations at RHIC

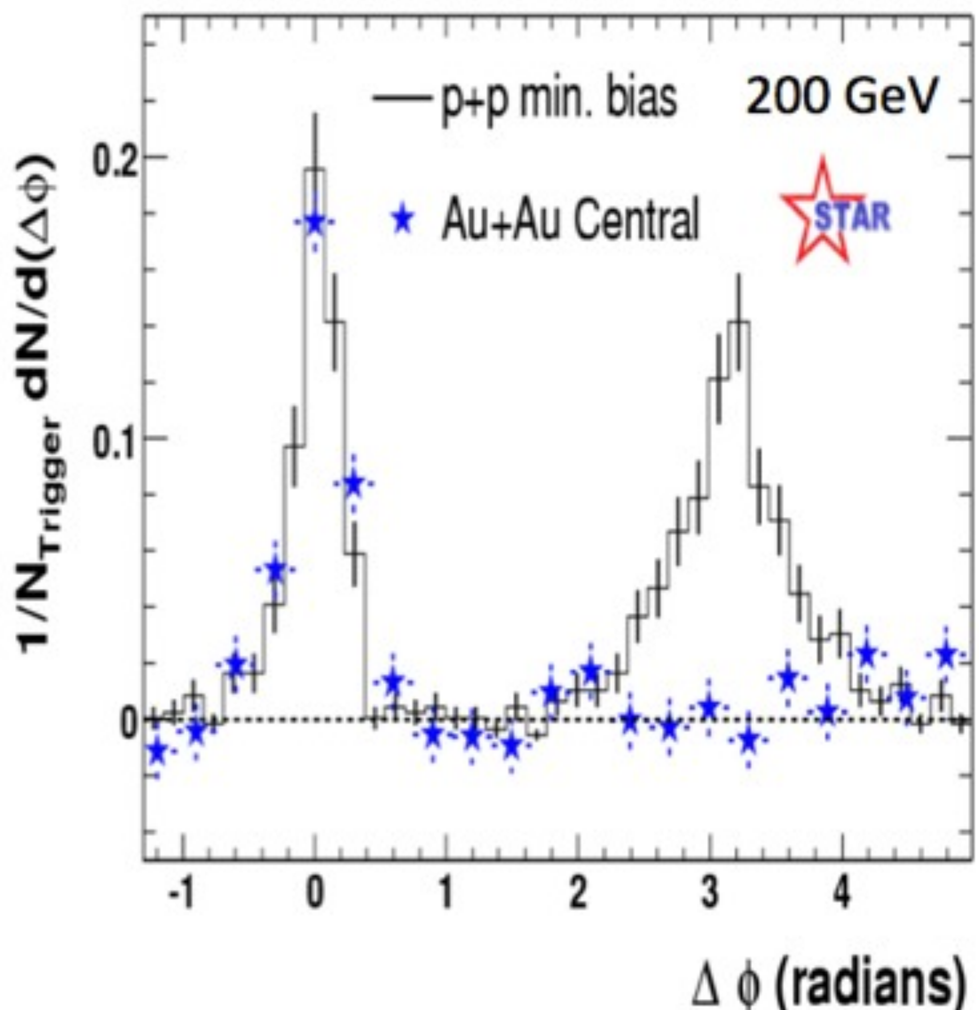
- Correlation of charged hadrons with:

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

- Near-side peak shows little modification

- Away-side jet correlation nearly extinguished in this p_T range

Dihadron Correlations (STAR)

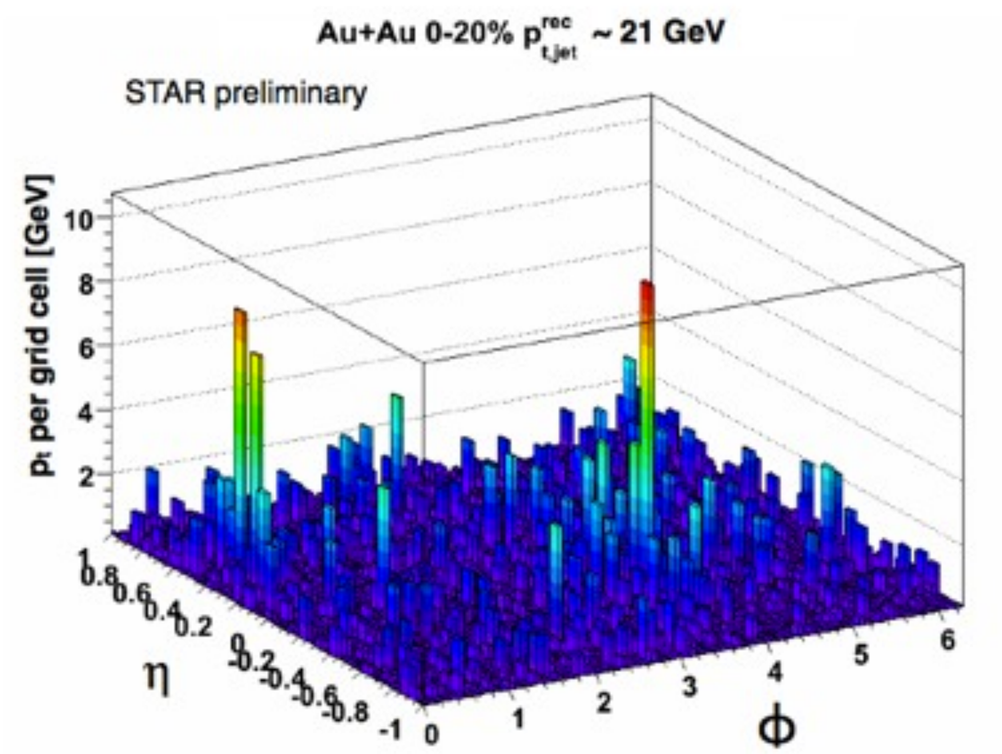


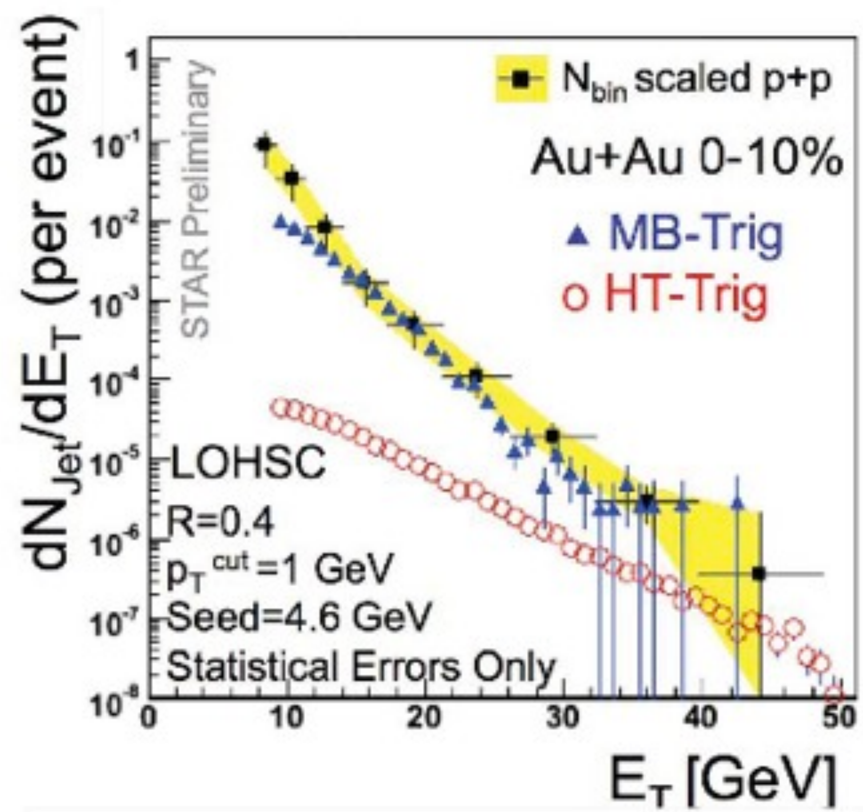
STAR Collaboration
Phys. Rev. Lett. 91 (2003) 072304

Jet Reconstruction at RHIC

STAR Collaboration, "First fragmentation function measurements from full jet reconstruction in heavy-ion collisions at $\sqrt{s_{NN}} = 200$ GeV by STAR", *Eur. Phys. J.* **C61** (2009) 629, arXiv:0809.1419. doi:10.1140/epjc/s10052-009-0904-7.

STAR Collaboration, "First Direct Measurement of Jets in $\sqrt{s_{NN}} = 200$ GeV Heavy Ion Collisions by STAR", *Eur. Phys. J.* **C61** (2009) 761, arXiv:0809.1609. doi:10.1140/epjc/s10052-009-0880-y.

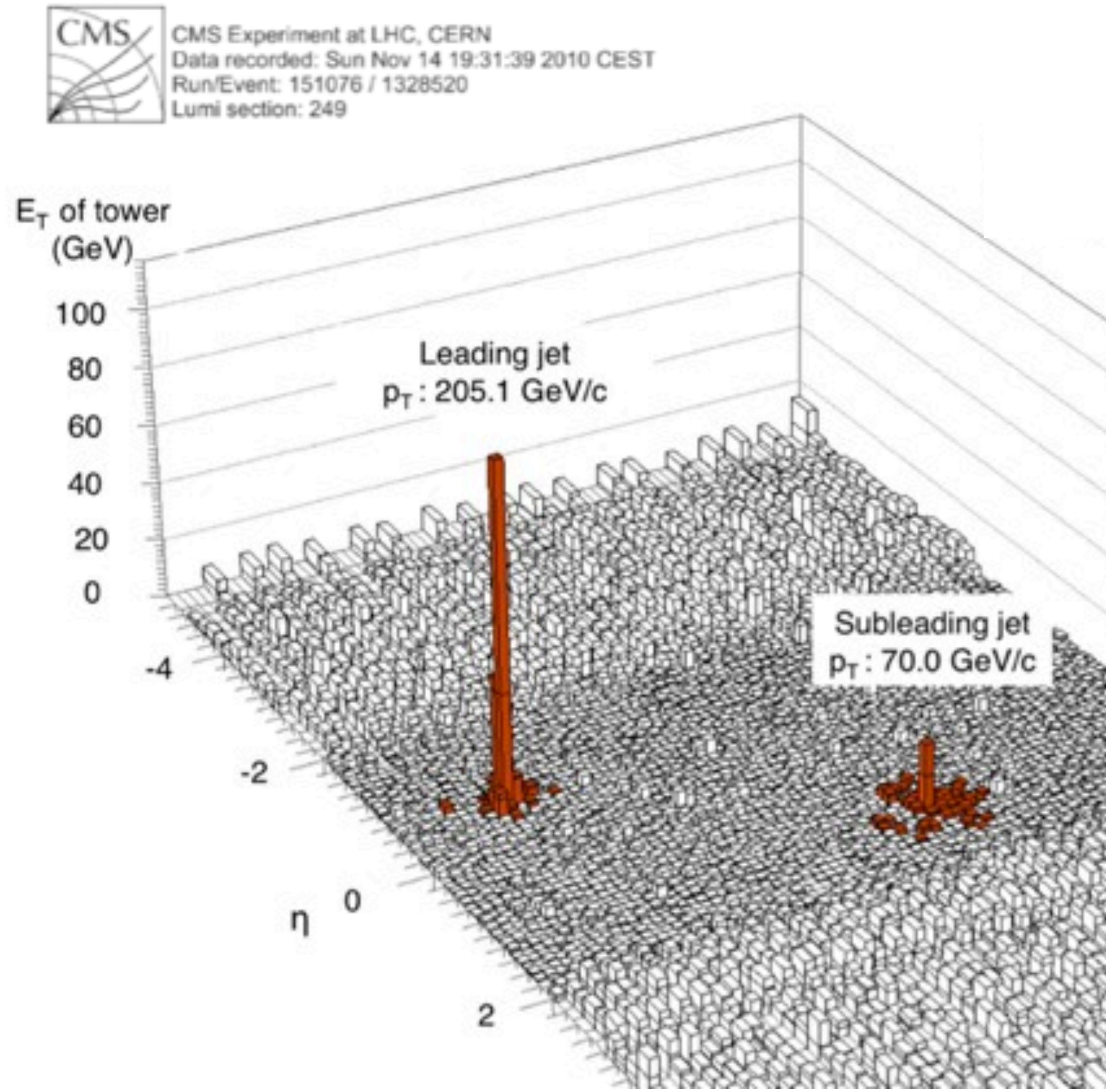




Strong jet quenching evident at RHIC, but direct jet reconstruction is challenging due to fluctuations in soft background

Jet Quenching at LHC

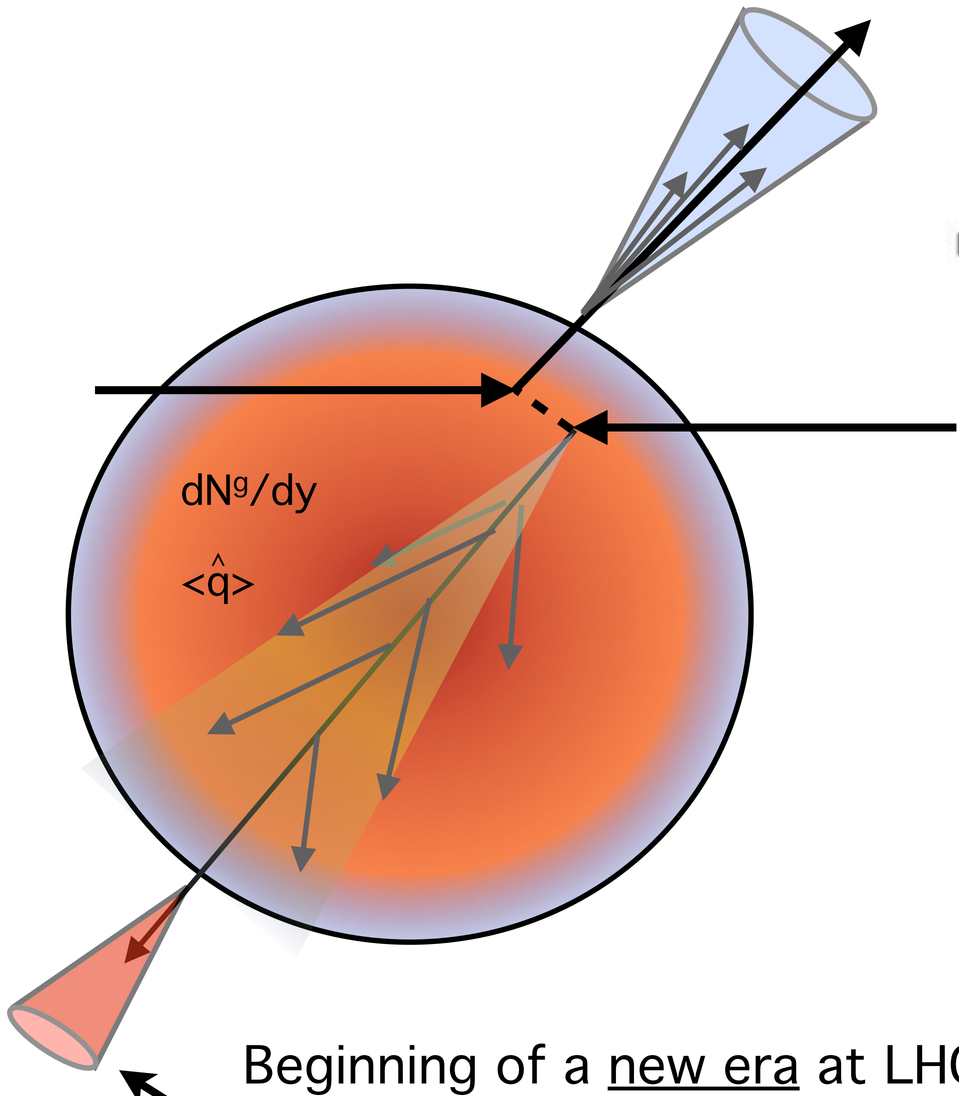
- At $\sqrt{s_{NN}}$ = 2.76 TeV, copious high-E_T jets (~100 GeV) give much larger separation between hard and soft scales
- Even looking at event displays in first days, significant imbalance was apparent in dijets

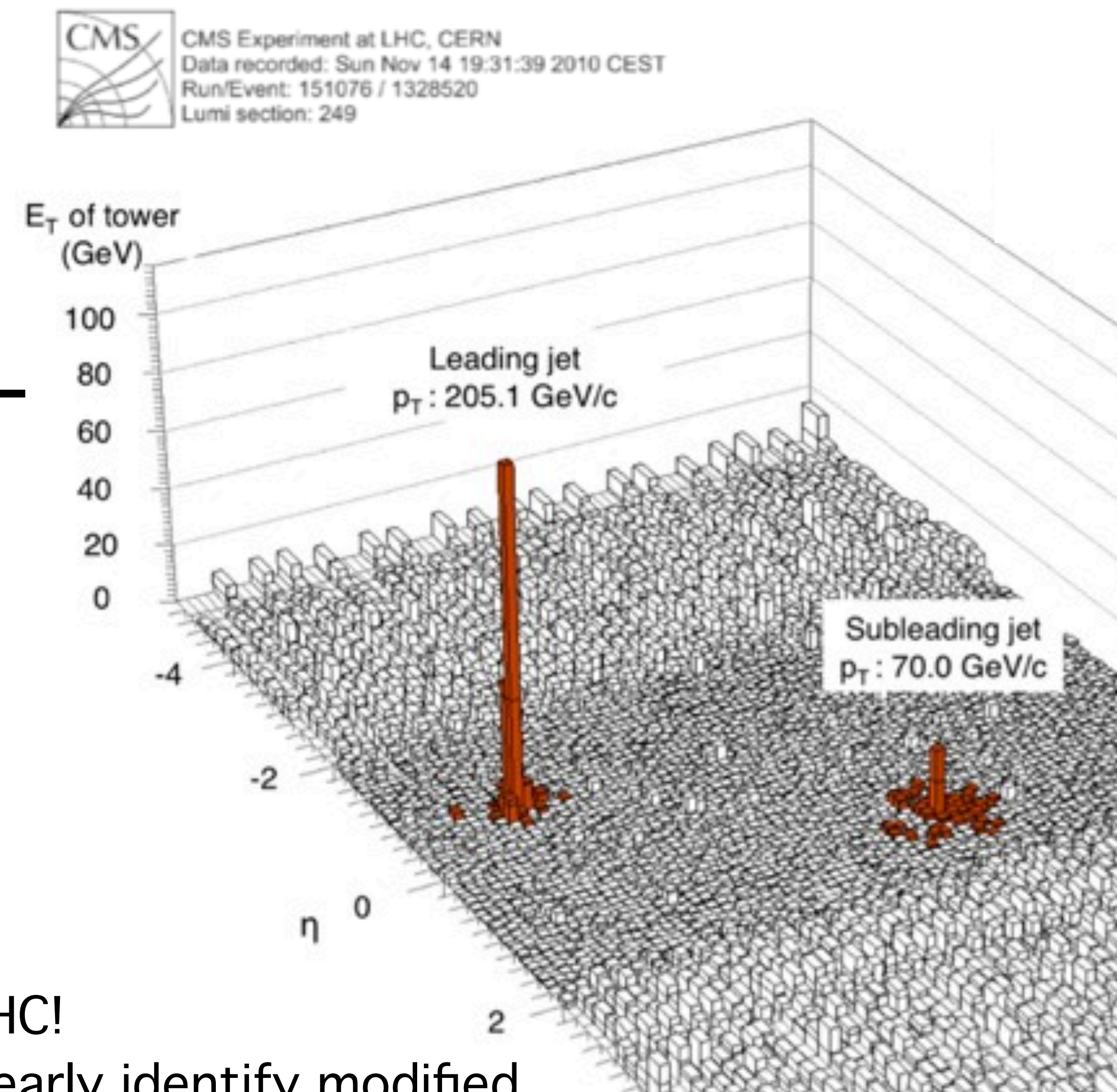


ATLAS Collaboration, "Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at sqrt(S_{NN})= 2.76 TeV with the ATLAS Detector at the LHC", *Phys. Rev. Lett.* **105** (2010) 252303, arXiv:1011.6182.

CERN Press Release (Nov 26, 2010): http://press.web.cern.ch/press/PressReleases/Releases2010/PR23.10E.html

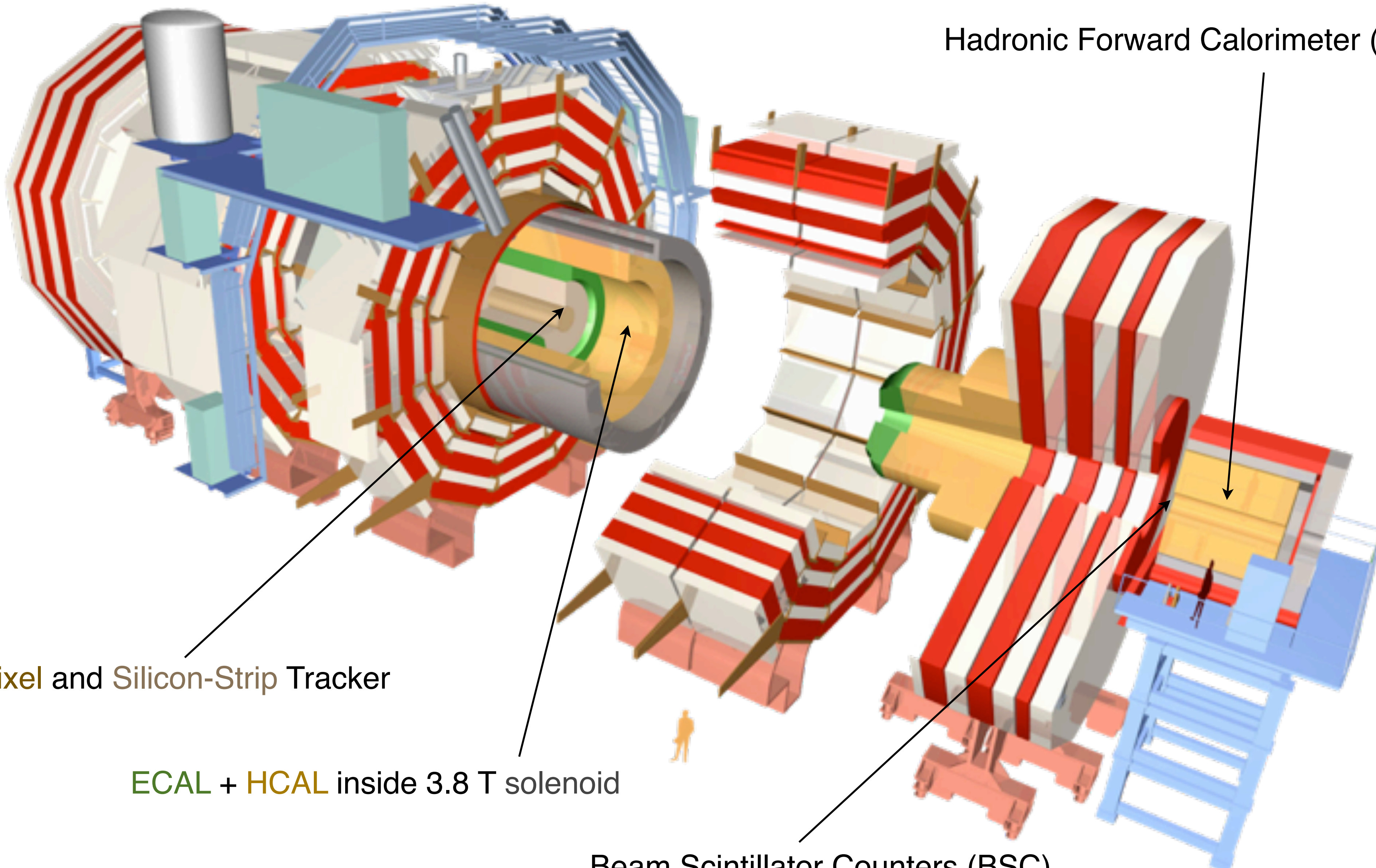
A New Era in Jet Quenching





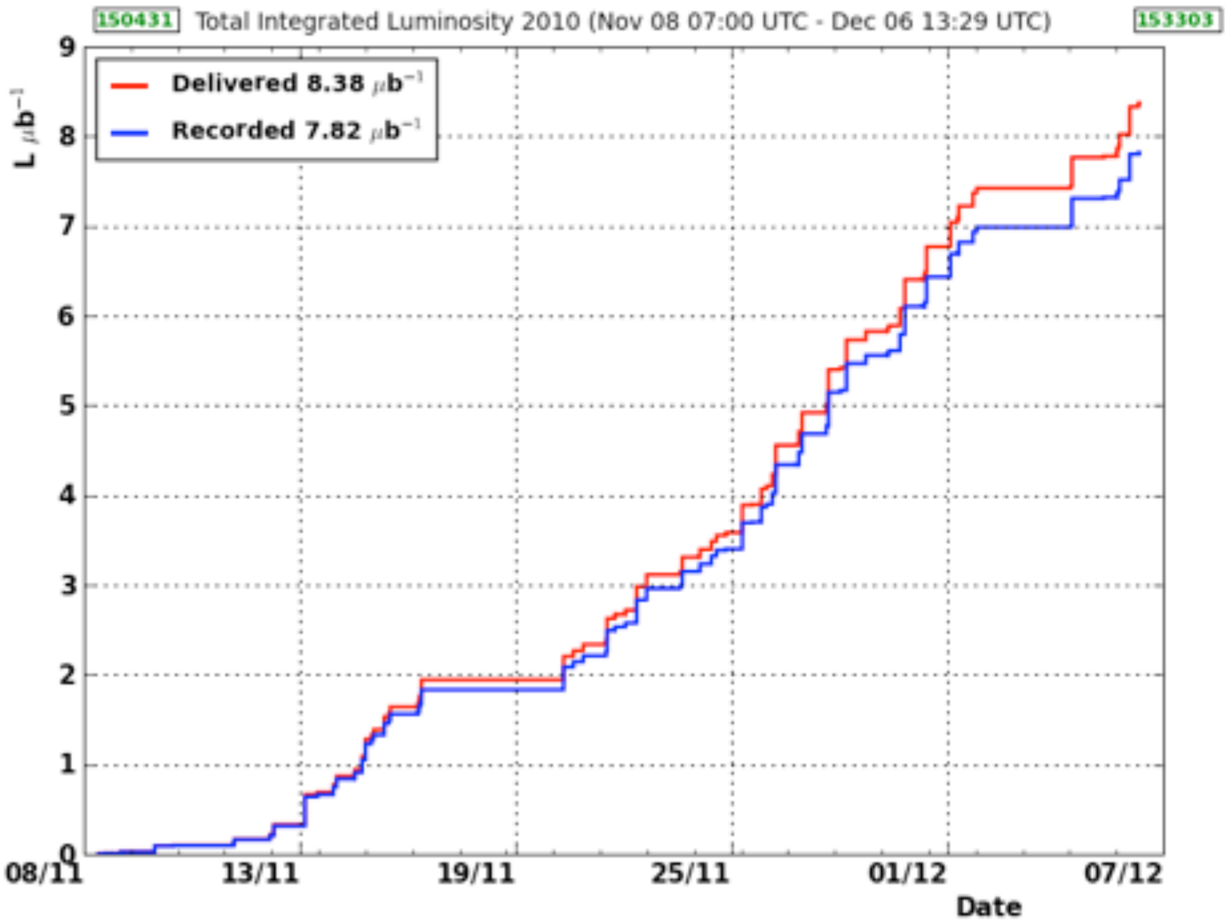
Beginning of a <u>new era</u> at LHC!
For the first time, we can clearly identify modified dijet partners.

CMS Detector



LHC: 2010 Heavy Ion Run

- 2010 has been a successful year at LHC
- After delivering over 40 pb^{-1} of p+p data, LHC delivered over 8 μb^{-1} of Pb+Pb
- For rare processes, this is 'equivalent' to ~300 nb^{-1} of p+p



6.7 μb^{-1} used in this dijet analysis

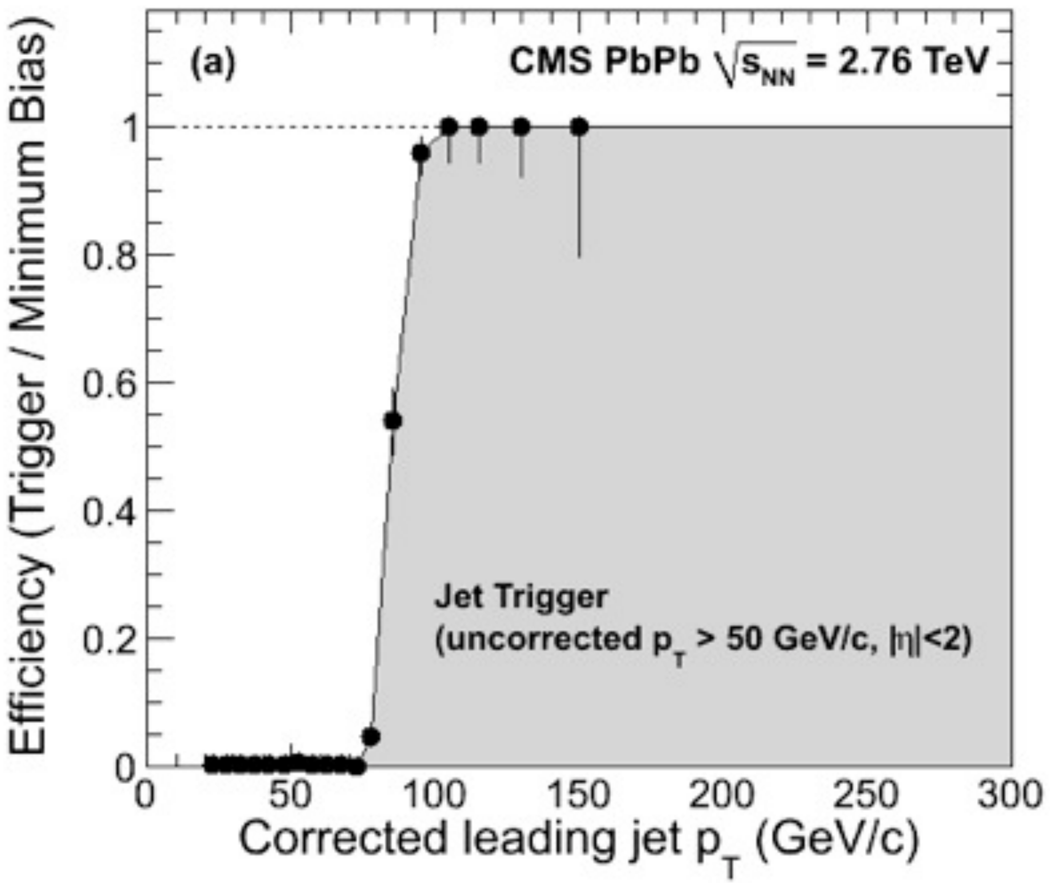
Trigger

Jet Trigger

- Level-1 Single Jet 30 GeV (uncorrected energy)
- HLT Single Jet 50 GeV (uncorrected energy)
- Fully efficient for corrected energy above 100 GeV

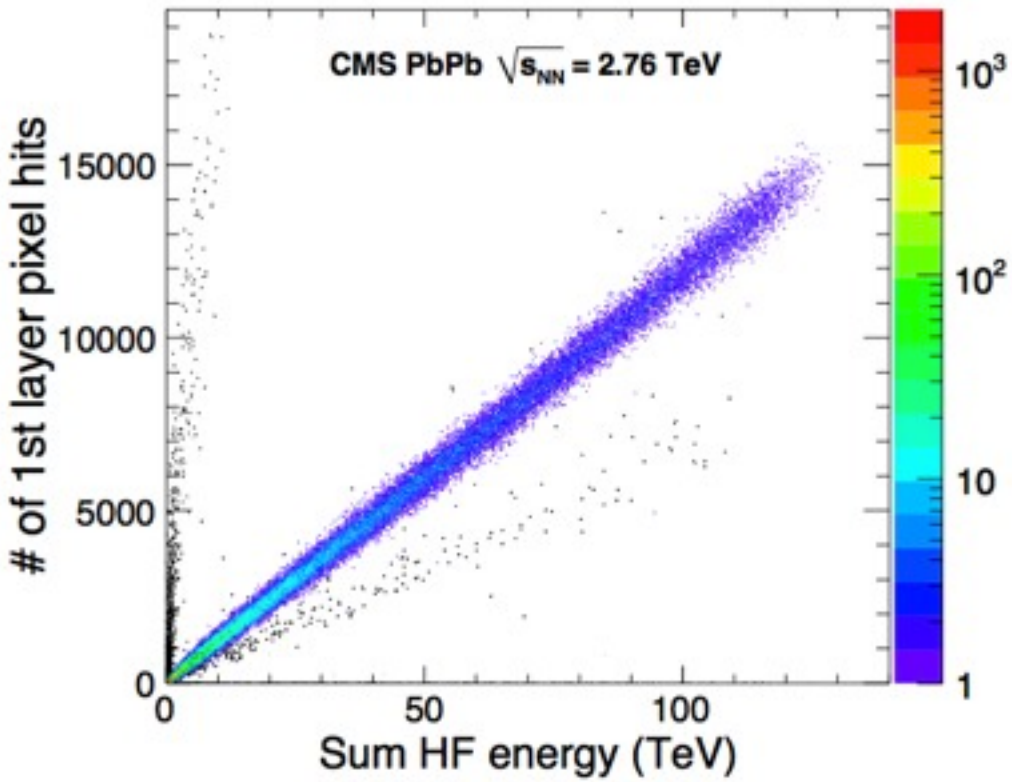
Minimum Bias Trigger

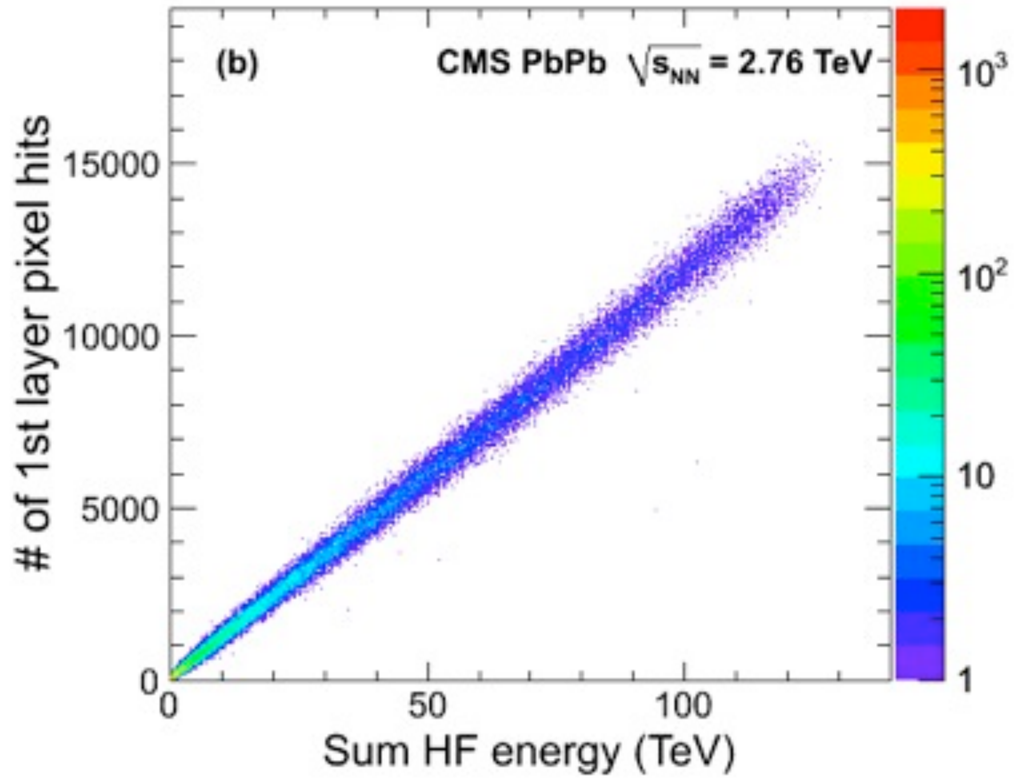
- HF or BSC firing in coincidence on both sides
- > 97% efficient



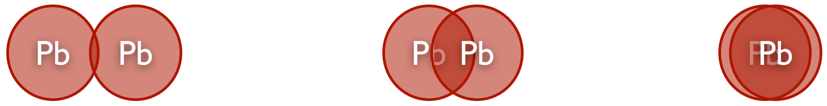
Collision Rate: 1-210 Hz, Jet50U Rate: < 1 Hz

Event Selection



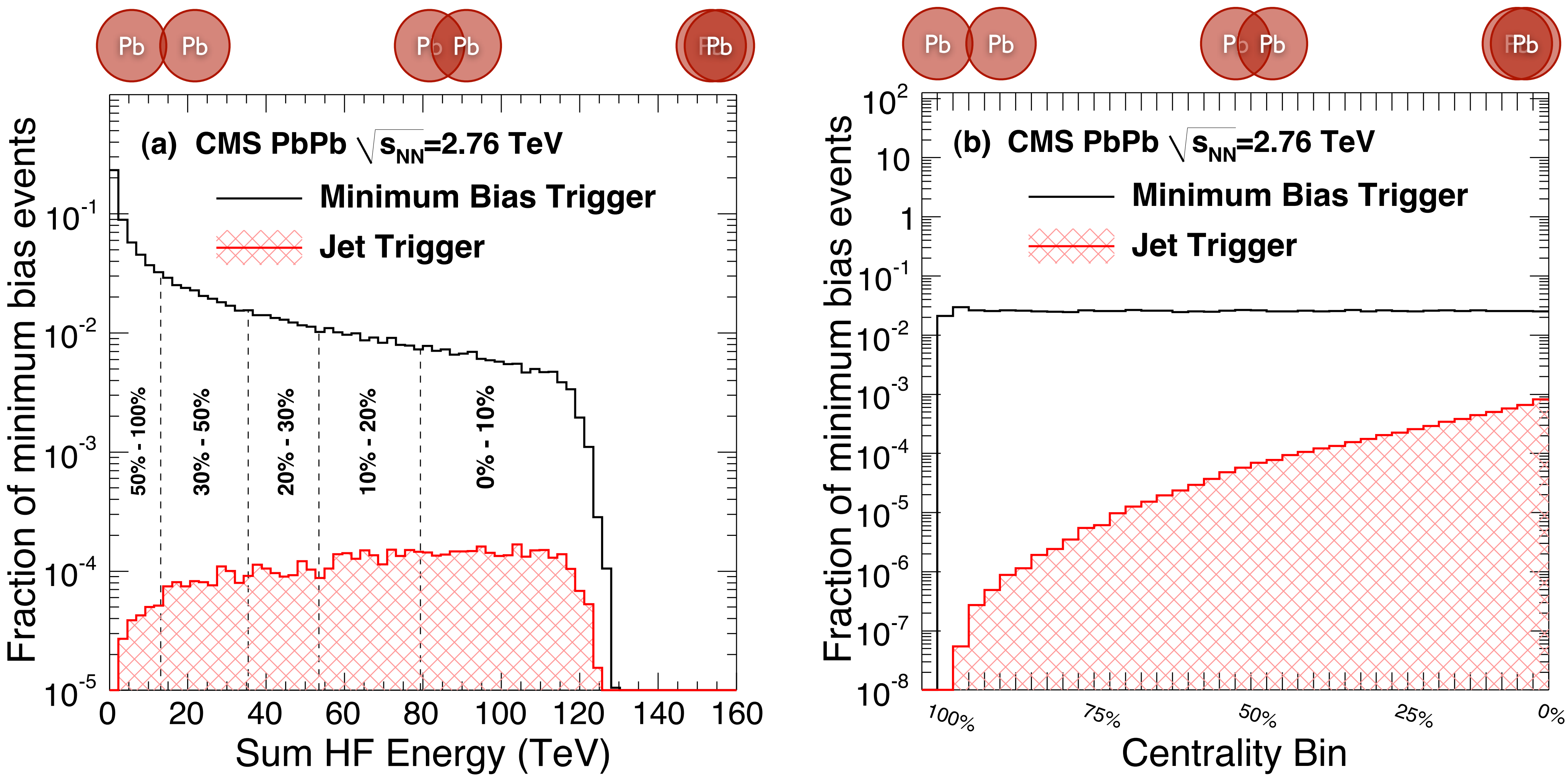


Jet triggered events ($p_T^{uncorr} > 50$ GeV/c)	149k
No beam halo, based on the BSC	148k
HF offline coincidence	111k
Reconstructed vertex	110k
Beam-gas removal	110k
ECAL cleaning	107k
HCAL cleaning	107k



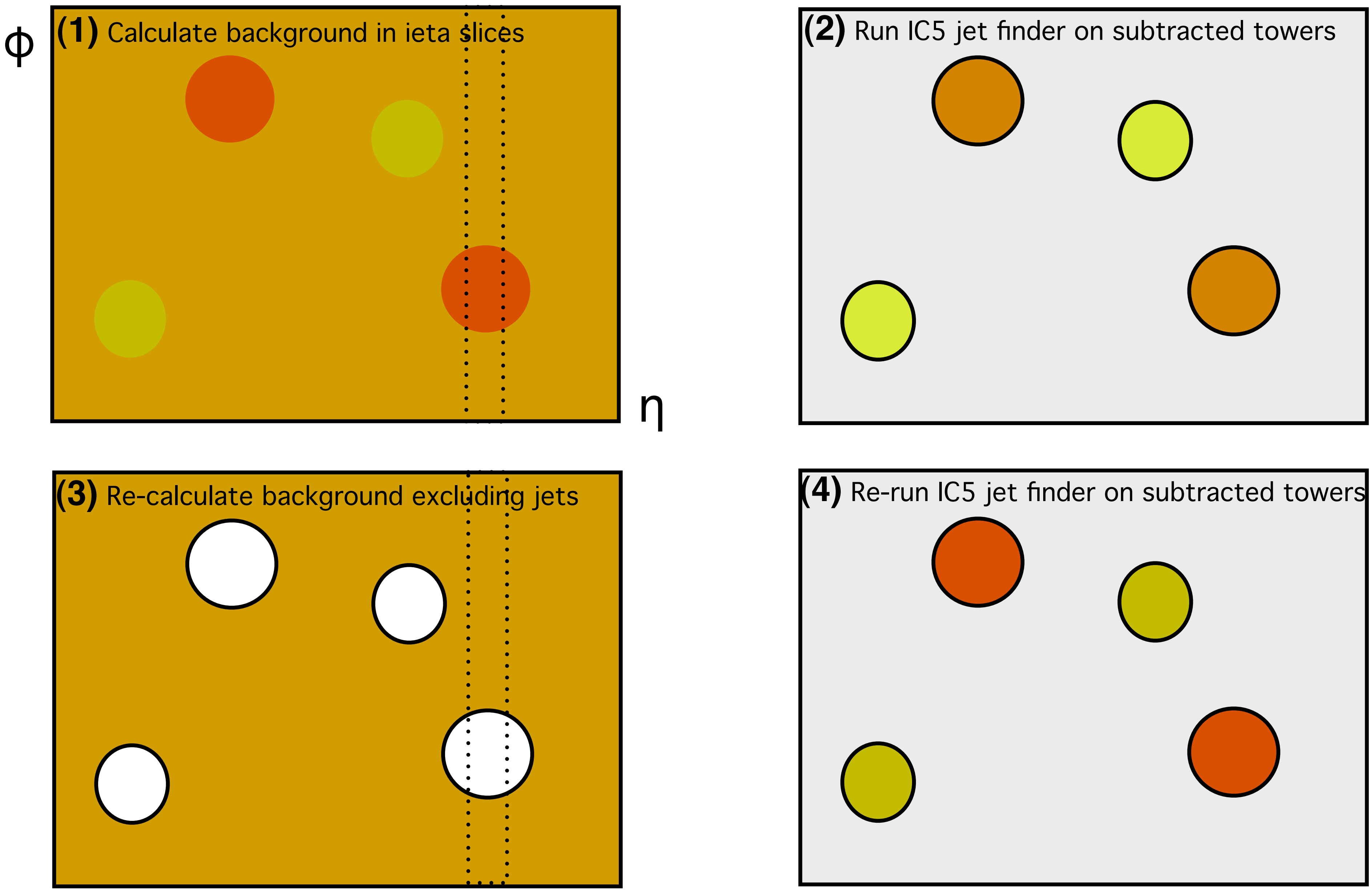
107k good jet-triggered collision events after all selections

Centrality Determination



Events are classified according to the percentile of the Pb+Pb inelastic cross section based on total deposited HF energy

Jet Algorithm

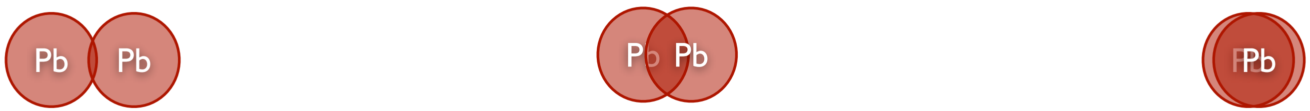


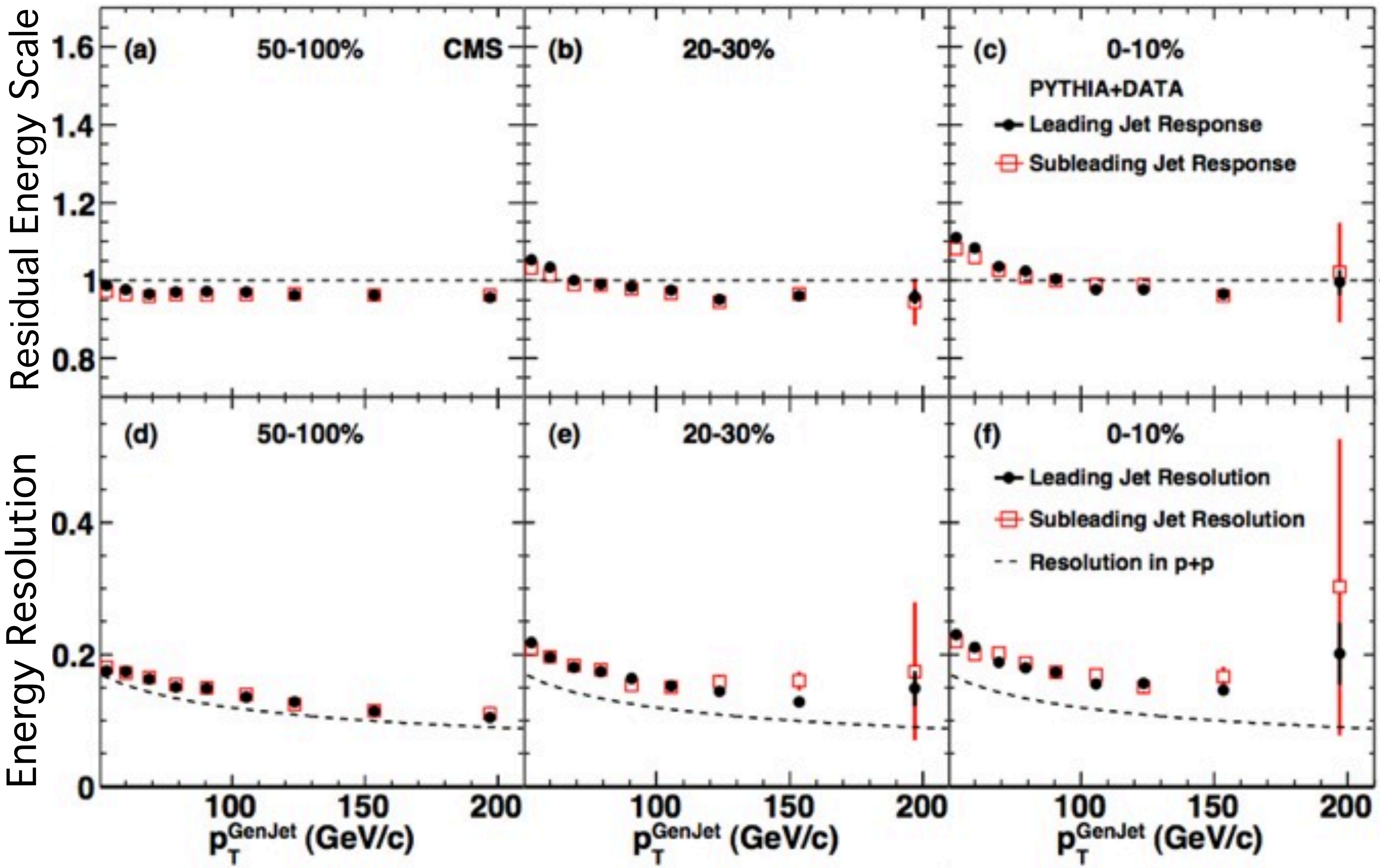
Simulated Data Samples

- PYTHIA: D6T tune, modified isospin (Pb^{208}_{82})
- PYTHIA + DATA: embedding PYTHIA dijet event into real data background
- PYTHIA + HYDJET*: embedding PYTHIA dijet event into simulated PbPb background

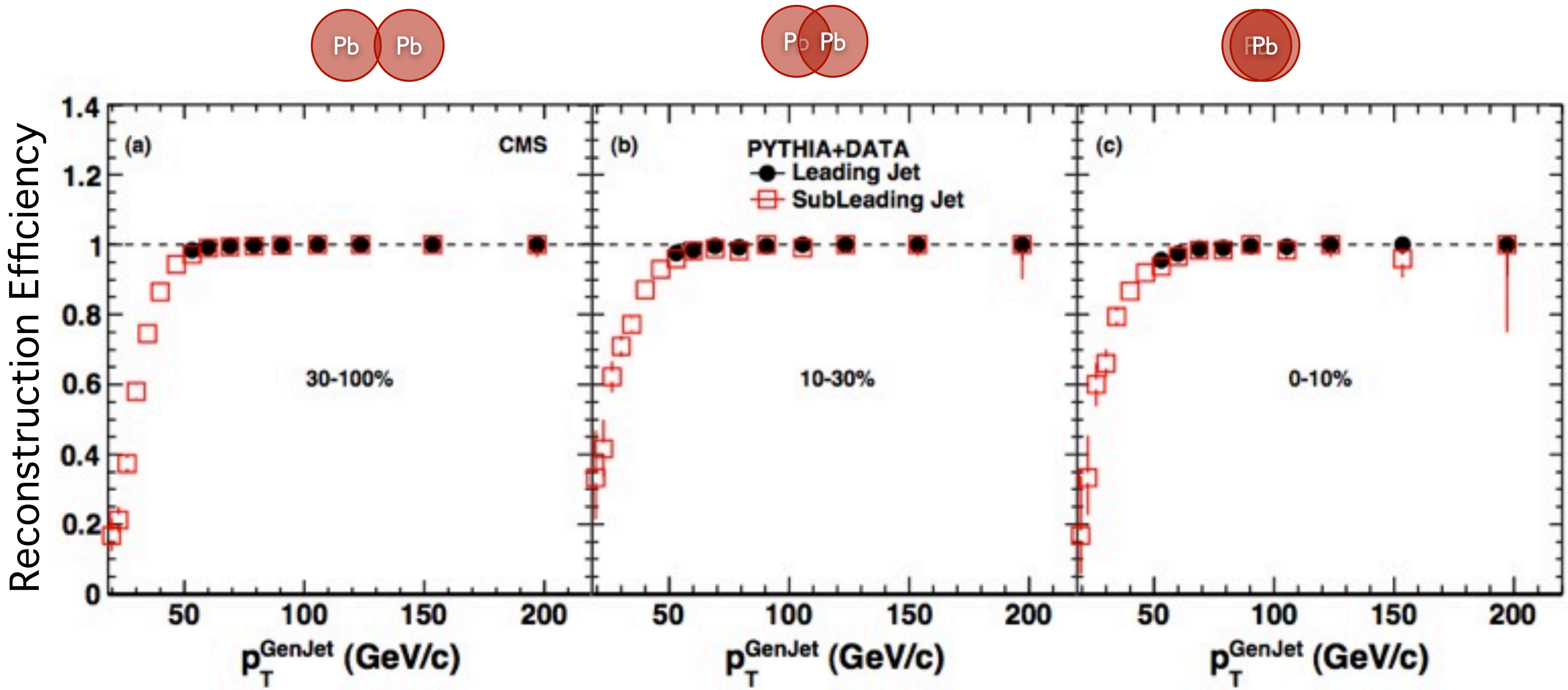
* HYDJET is a two-component heavy-ion generator: parameterized hydrodynamic soft-particle production + N_{hard} * PYTHIA ($\hat{p}_T$> 7 GeV/c)

Jet Energy Scale and Resolution





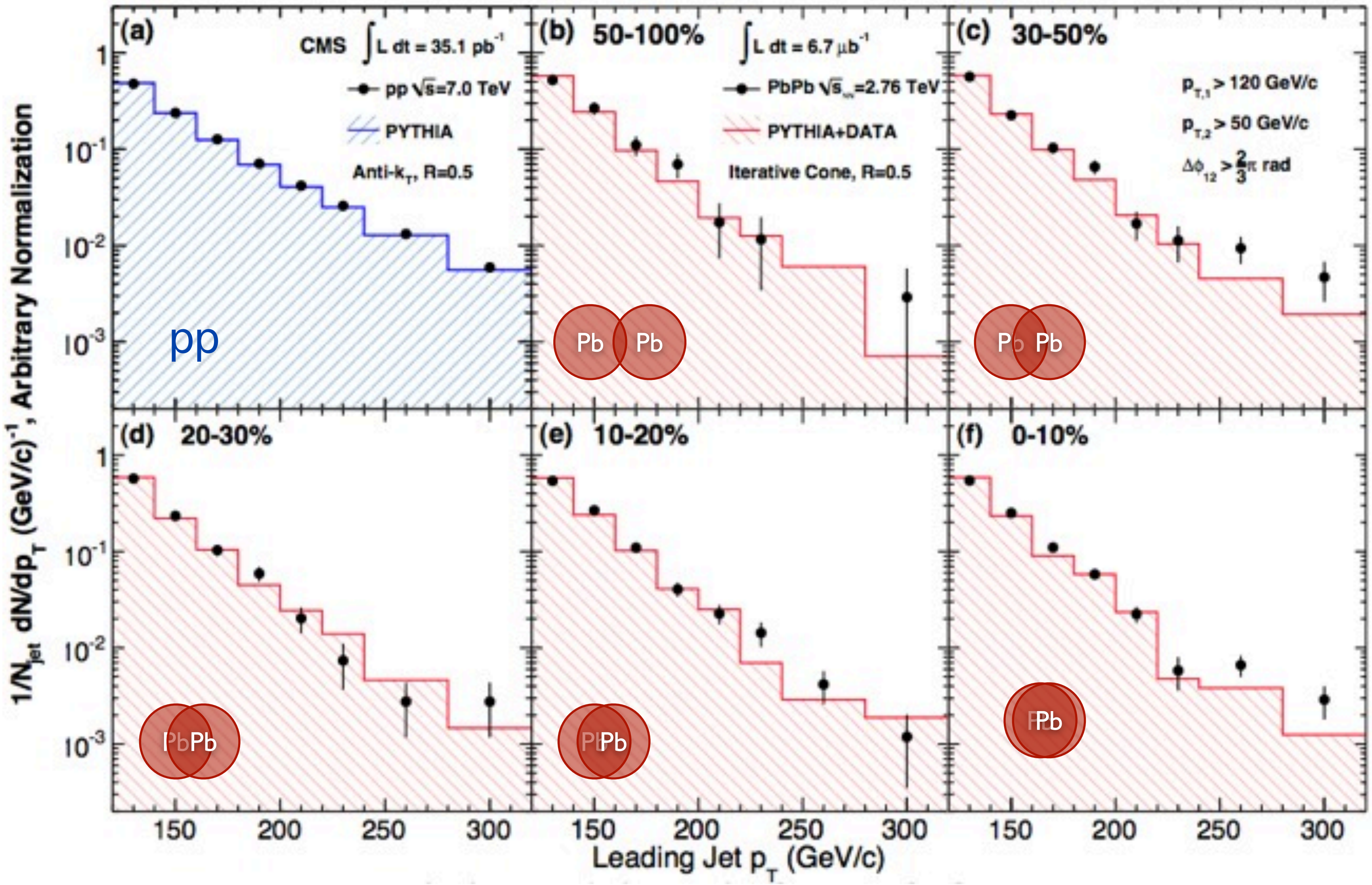
Jet-Finding Efficiency



Dijet Selections

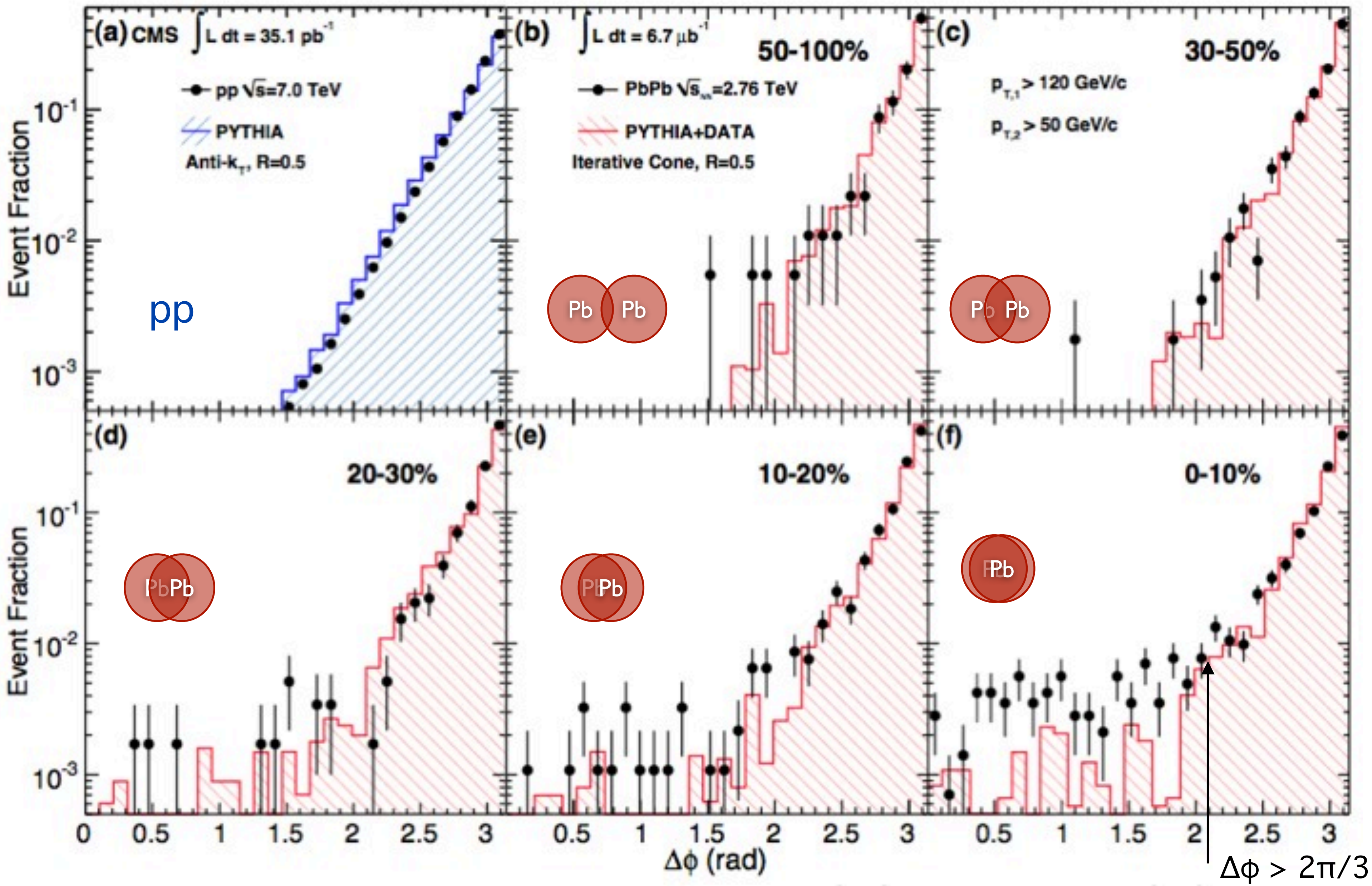
	# of Events
Leading jet $p_{T,1}$ > 120 GeV/c, $\lvert\eta_1\rvert < 2$	4216
Subleading jet $p_{T,2}$ > 50 GeV/c, $\lvert\eta_2\rvert < 2$	3684
Opening angle $\Delta\phi_{12} > 2\pi/3$	3514

Leading Jet Spectra

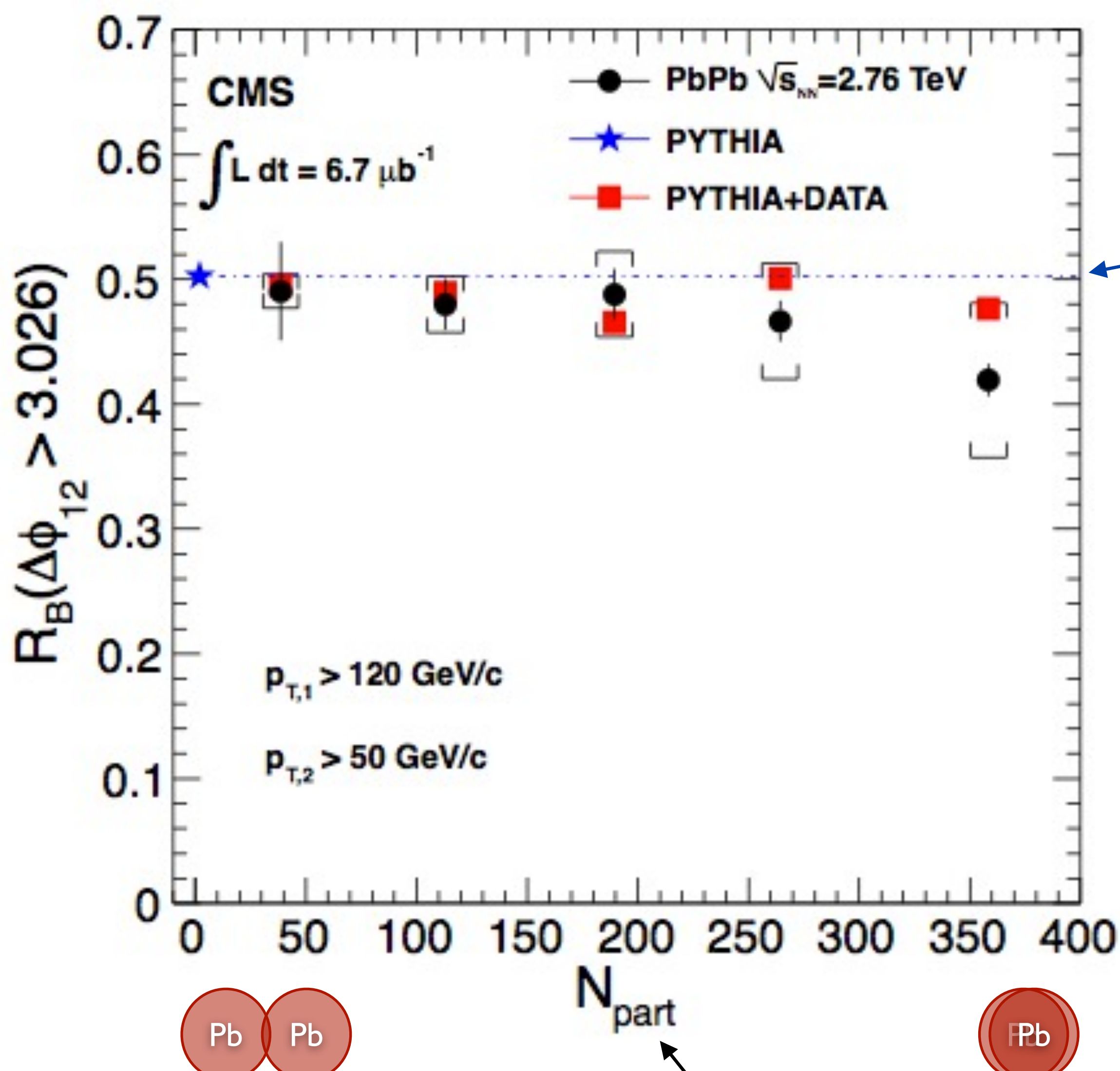


Shape of leading jet p_T spectrum not strongly modified compared to PYTHIA

Dijet Azimuthal Decorrelation



Dijet ‘Back-to-Back’ Fraction



median $\Delta\phi$ value in PYTHIA (dominated by 3-jet events)

Number of nucleons participating in collisions (1+1 ➔ 208+208)

Slightly fewer back-to-back jets in data than ‘unquenched’ jets embedded into HI background

Dijet Asymmetry Variable

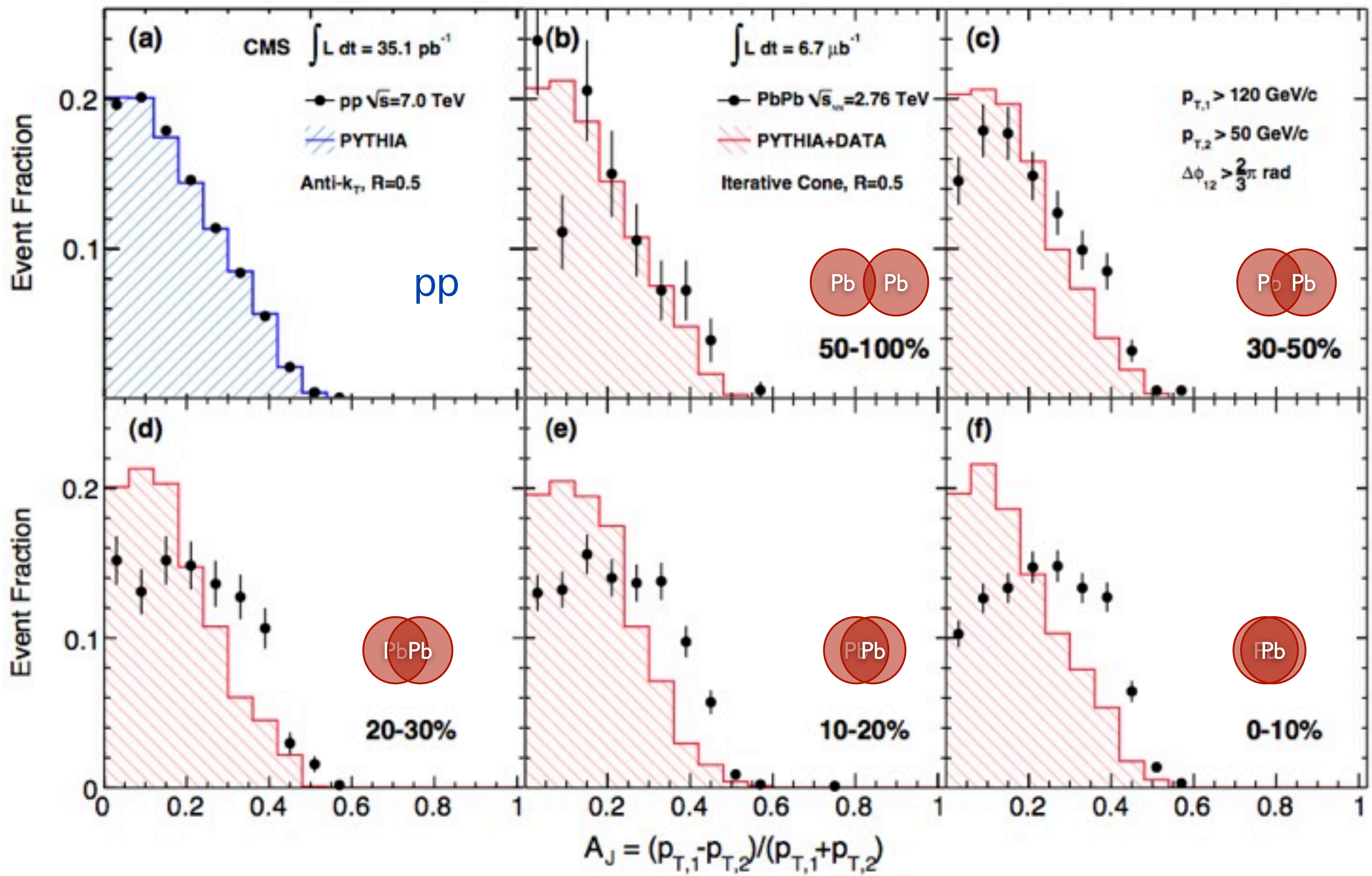
Quantify dijet energy imbalance by asymmetry ratio:

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

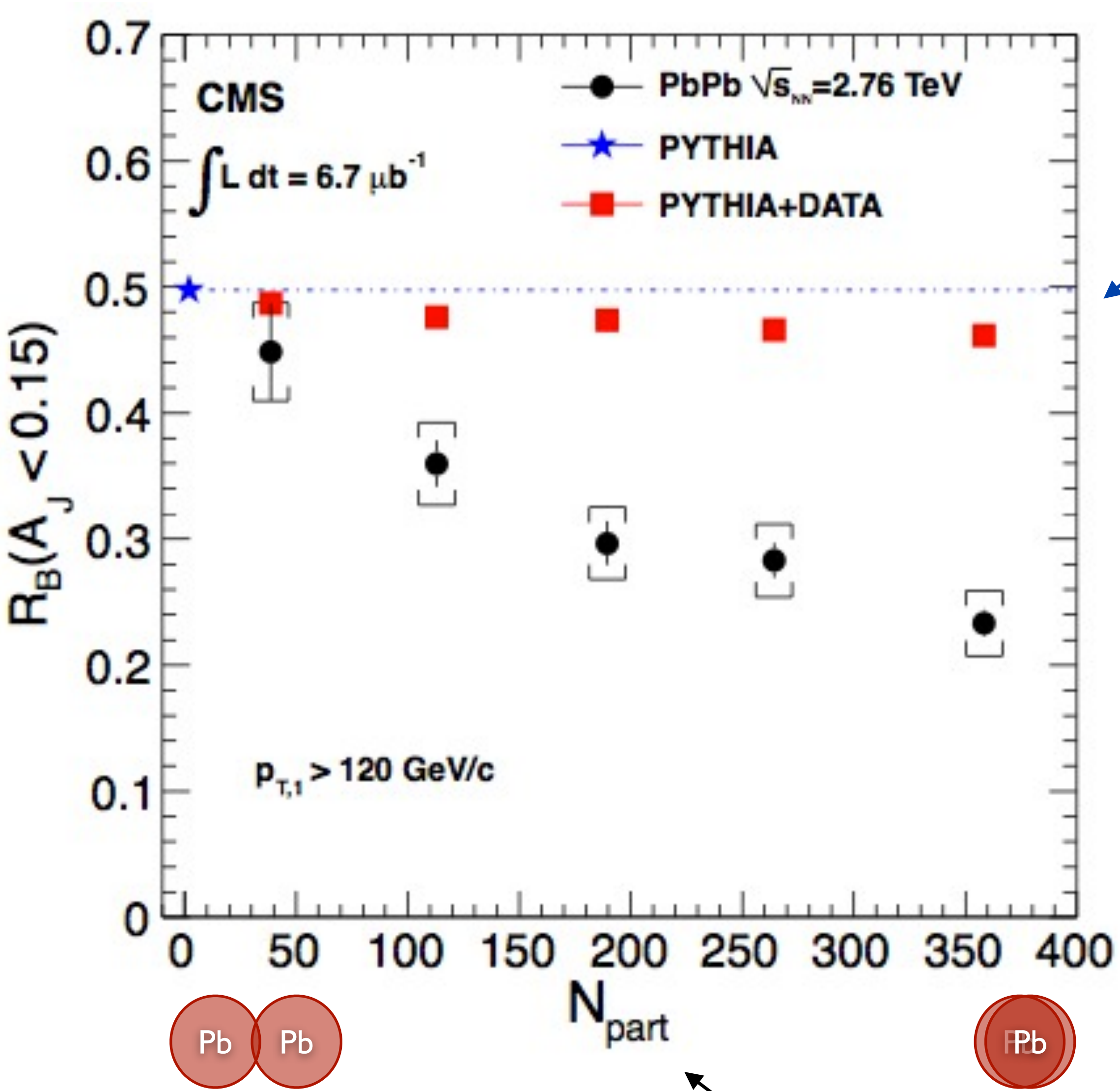
- Removes uncertainties in overall jet energy scale
- Limit on $p_{T,2}$ puts a p_T-dependent upper limit on A_j

e.g. (120-50) / (120+50) = 0.41

Dijet Energy Imbalance



Dijet 'Balanced' Fraction



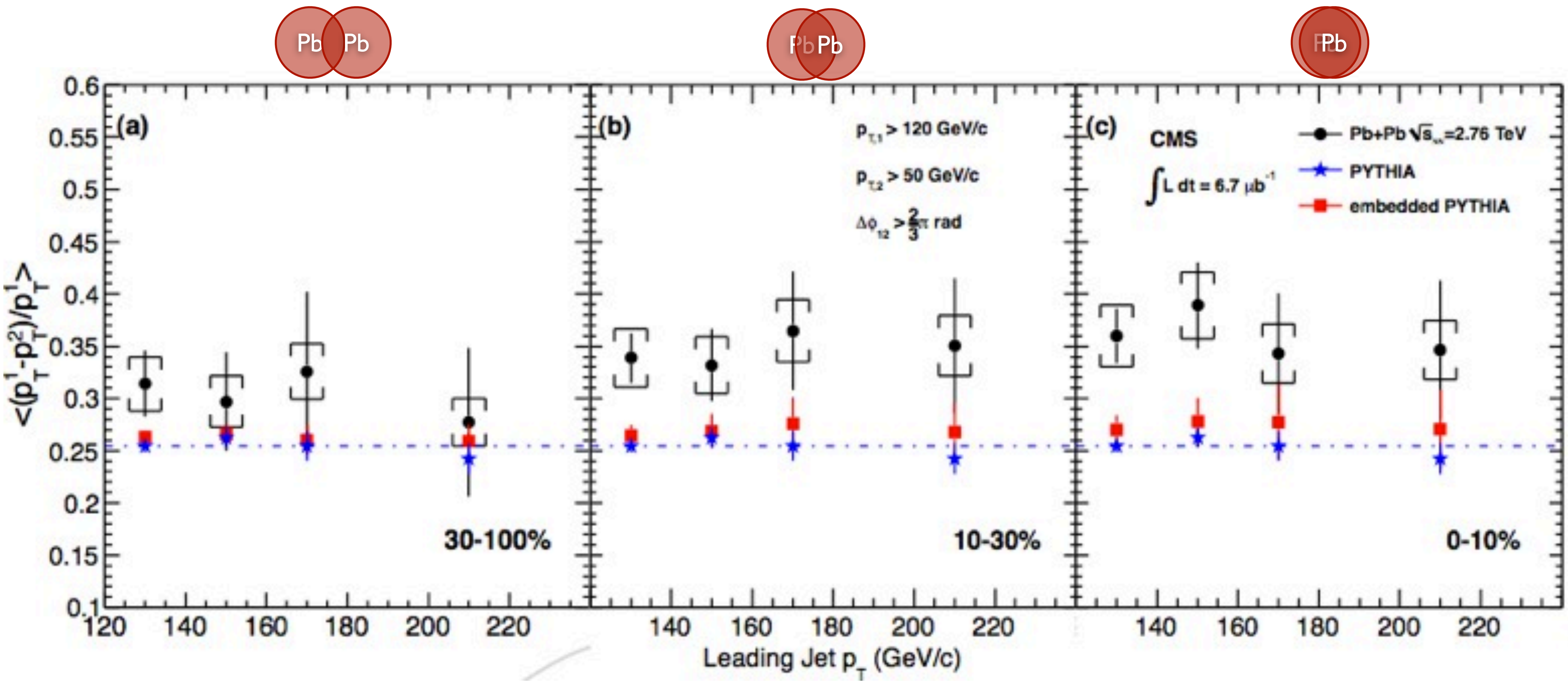
median A_j value in PYTHIA
(dominated by 3-jet events)

Includes all events with a qualifying leading jet (i.e. even apparent 'mono-jet' events)

Dramatic suppression of balanced jets with increasing centrality

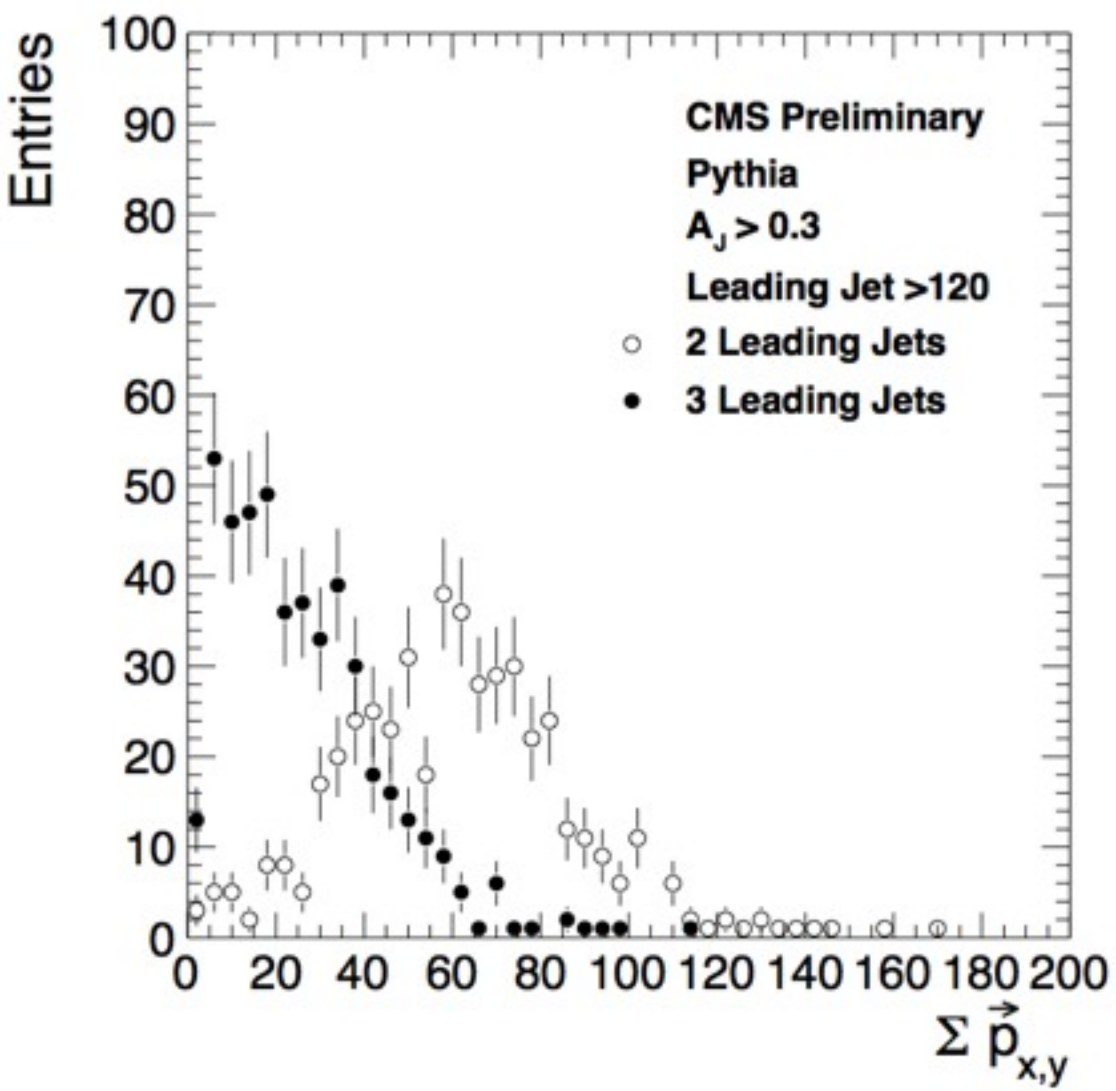
Number of nucleons participating in collisions (1+1 ➔ 208+208)

Leading Jet p_T Dependence



Fractional imbalance varies little with leading jet p_T, though the present errors do not rule out a constant Δp_T

PYTHIA Momentum Balance



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

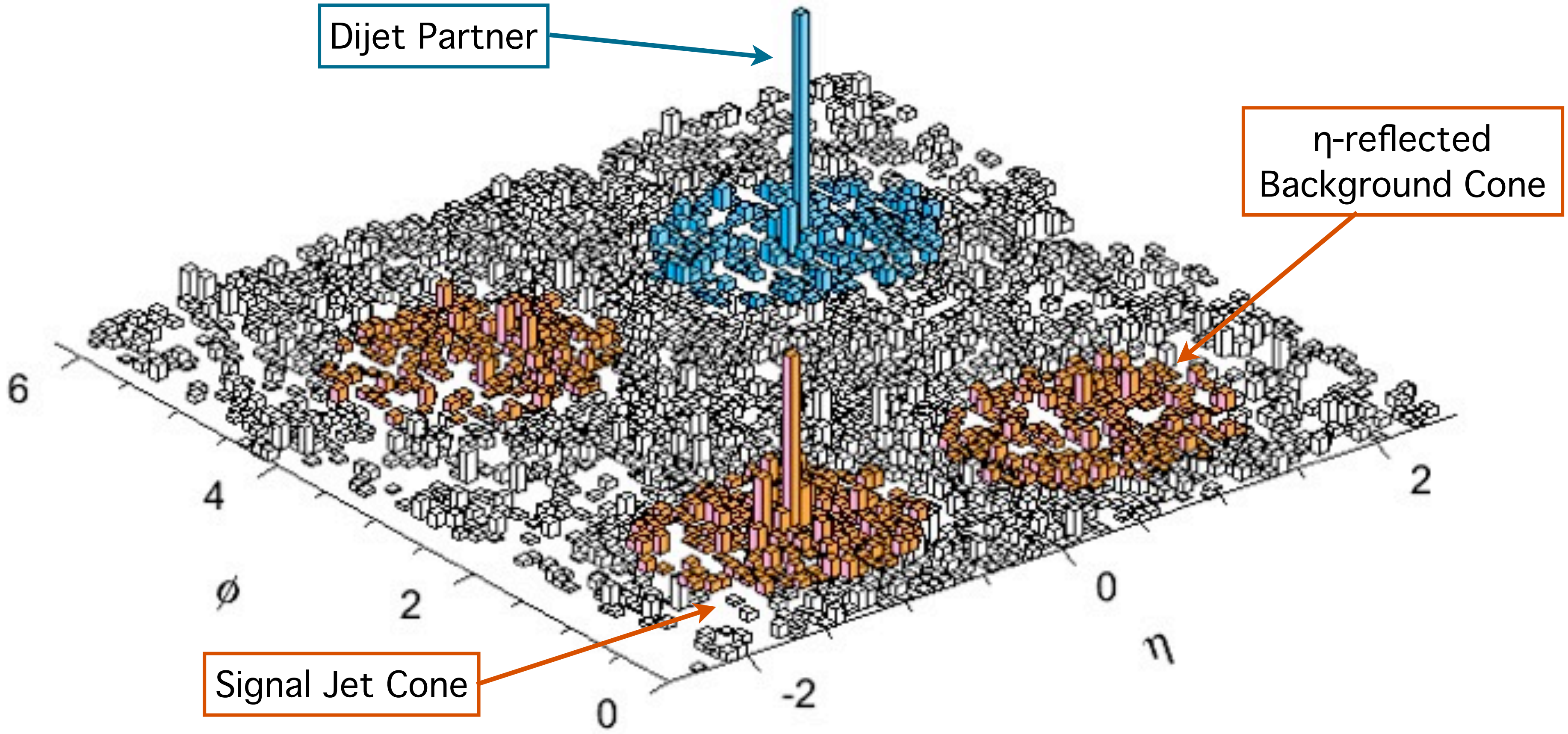
Where does energy go?

- Large dijet energy imbalance seen in calorimeters.
- By using track information, we have an opportunity to do the first in-depth studies of where the energy goes (low-p_T, large angle)
  - Explore fragmentation properties with angular correlations of tracks to jet axes after subtracting combinatorial background
  - Explore global momentum balance of tracks -- missing p_T projected along dijet axis -- in various p_T ranges

Track-Jet Correlations

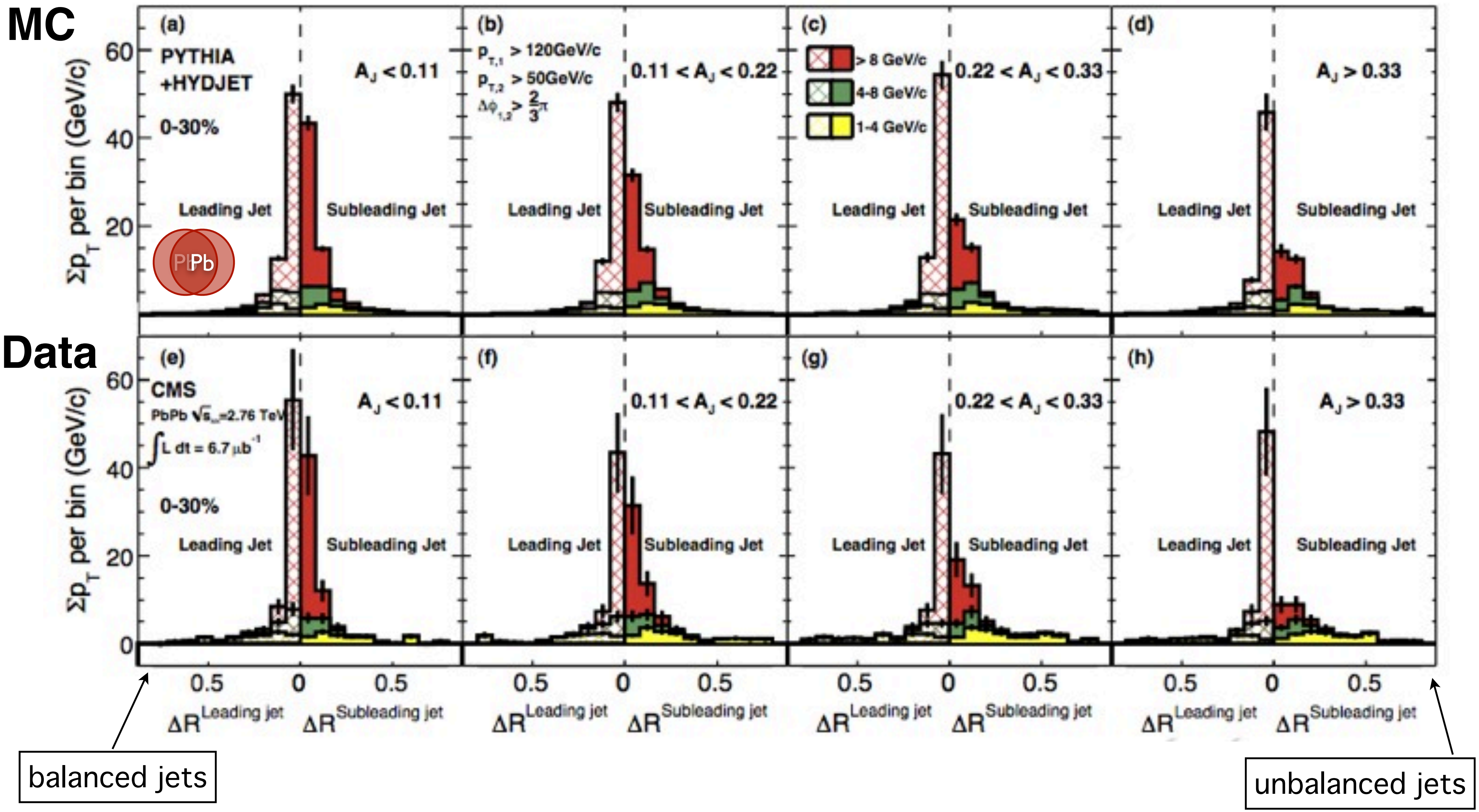
- Find tracks “associated” with the jets using jet-by-jet subtraction of Pb+Pb underlying event
- Study associated track distributions versus p_T and ΔR
- Uncertainties in background subtraction limit this method to $p_T > 1$ GeV/c and $\Delta R < 0.8$

η-Reflection Method



- Background evaluated within R=0.8 cone symmetric about η
- Avoids ϕ-dependent variations due to detector effects and hydrodynamic flow
- Single jets required to be in $0.8 < |\eta| < 1.6$

Track-Jet Correlation Result

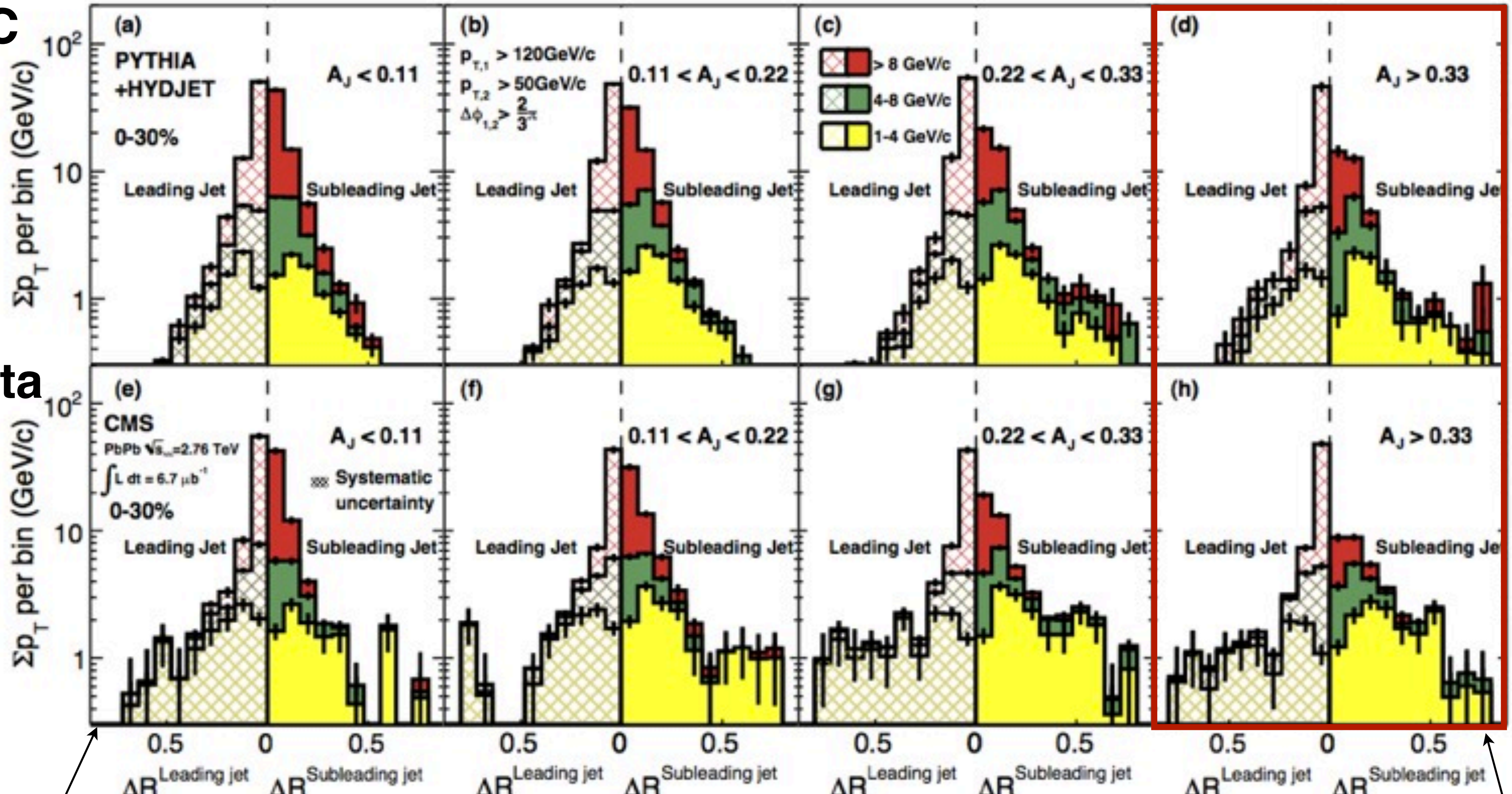


Jet asymmetry in calorimeters is mirrored in tracks

Track-Jet Correlation Result

MC

Data



balanced jets

unbalanced jets

Significantly more energy in large-ΔR tracks below 4 GeV/c

Missing p_T

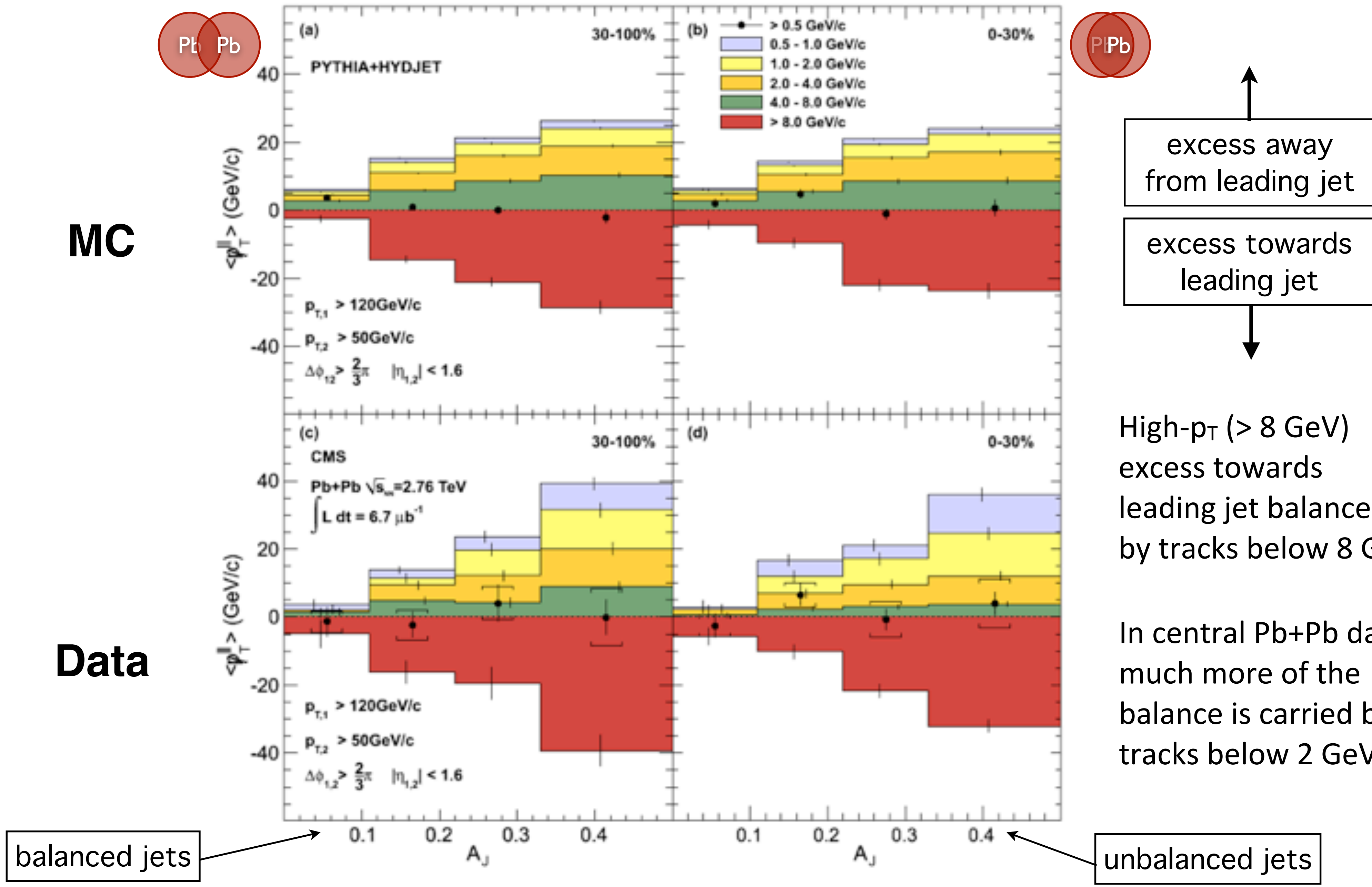
Calculate projection of p_T on leading jet axis and average over selected tracks:

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{Tracks}} -p_{\mathrm{T}}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

This was calculated for all tracks with $p_T > 0.5$ GeV/c and $|\eta| < 2.4$ and also for tracks in various p_T ranges.

This allows us to see which p_T range carries the balance of the jet momentum.

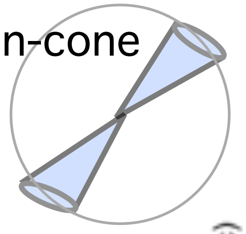
Missing-p_T Results

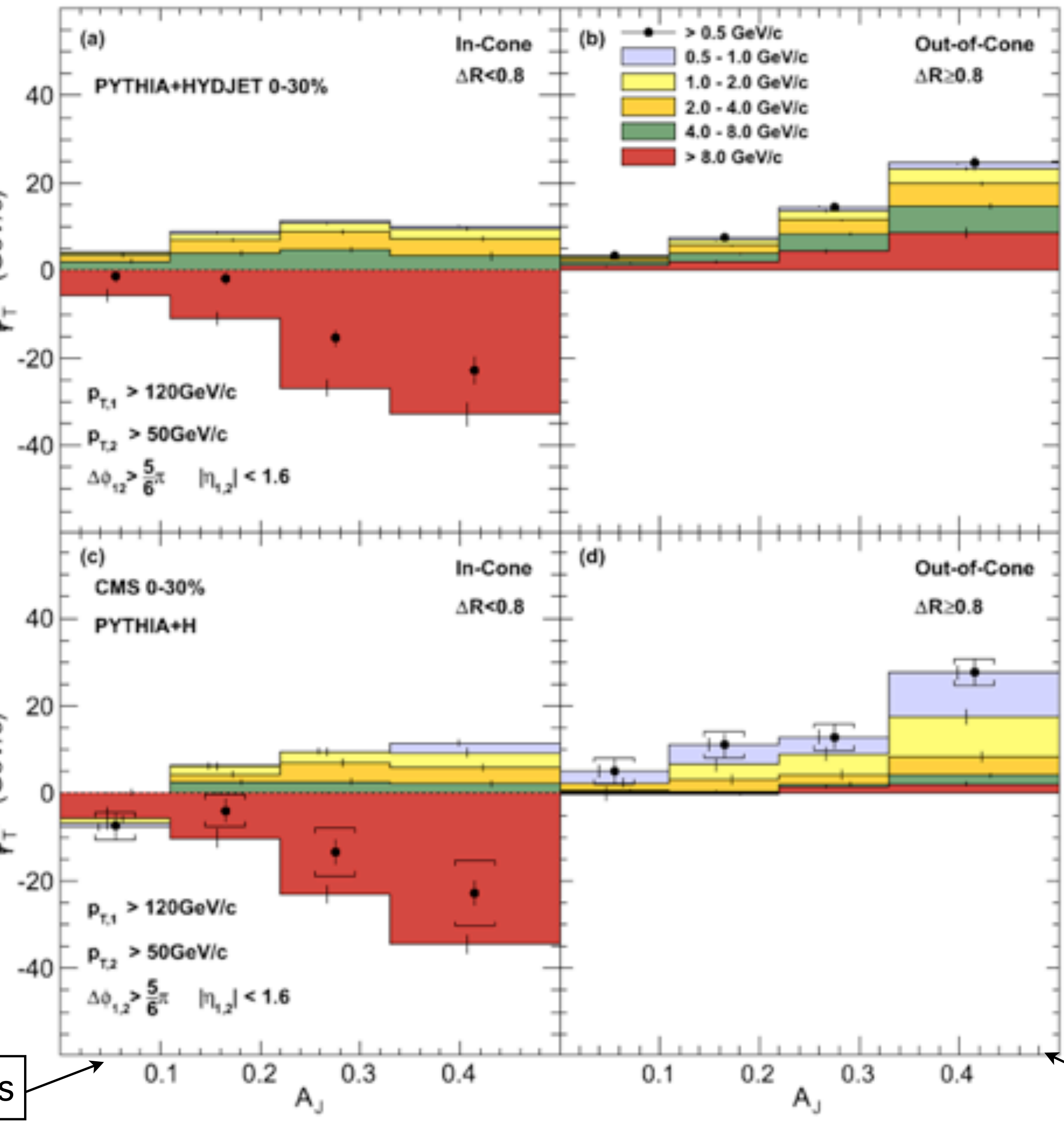


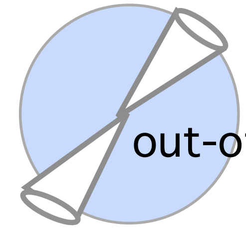
High-p_T (> 8 GeV) excess towards leading jet balanced by tracks below 8 GeV

In central Pb+Pb data, much more of the balance is carried by tracks below 2 GeV

Radial Dependence of MPT







In PYTHIA, balance is found out-of-cone as well, but at higher p_T (third jets!)

For data, in-cone excess of high-p_T tracks is balanced by out-of-cone low-p_T tracks

Summary

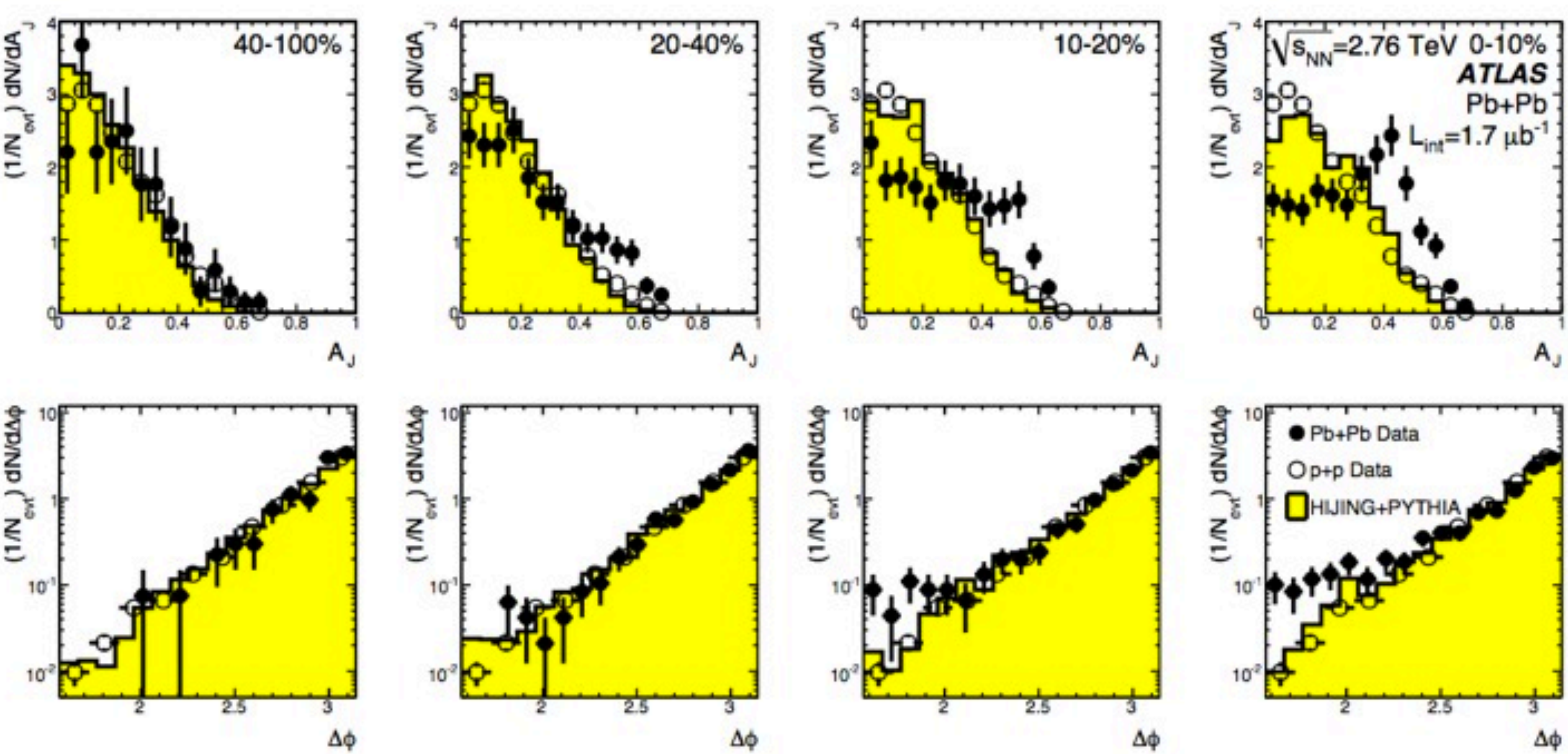
- Large dijet momentum imbalance, increasing with centrality.
- Imbalance extends to highest jet energies measured ($p_{T,1} > 200$ GeV/c)
- Imbalance in calorimeter measurement reflected also in charged tracks
- Momentum balance recovered by including tracks at low-p_T and at large angle
- In data (but not PYTHIA) a large fraction of the balance is carried by tracks with $p_T < 2.0$ GeV/c and $\Delta R > 0.8$

Conclusions

- LHC energies bring new era to jet quenching studies: unambiguous identification of both partners in copious, asymmetric dijets.
- This is just the beginning! Future studies: medium-modified fragmentation functions, flavor-dependence of jet quenching (e.g. via gamma-jet correlations, multi-jet events, heavy flavor tagged jets)
- More powerful, quantitative constraints on transport properties of QCD matter will be possible via data-model comparisons

BACKUP SLIDES

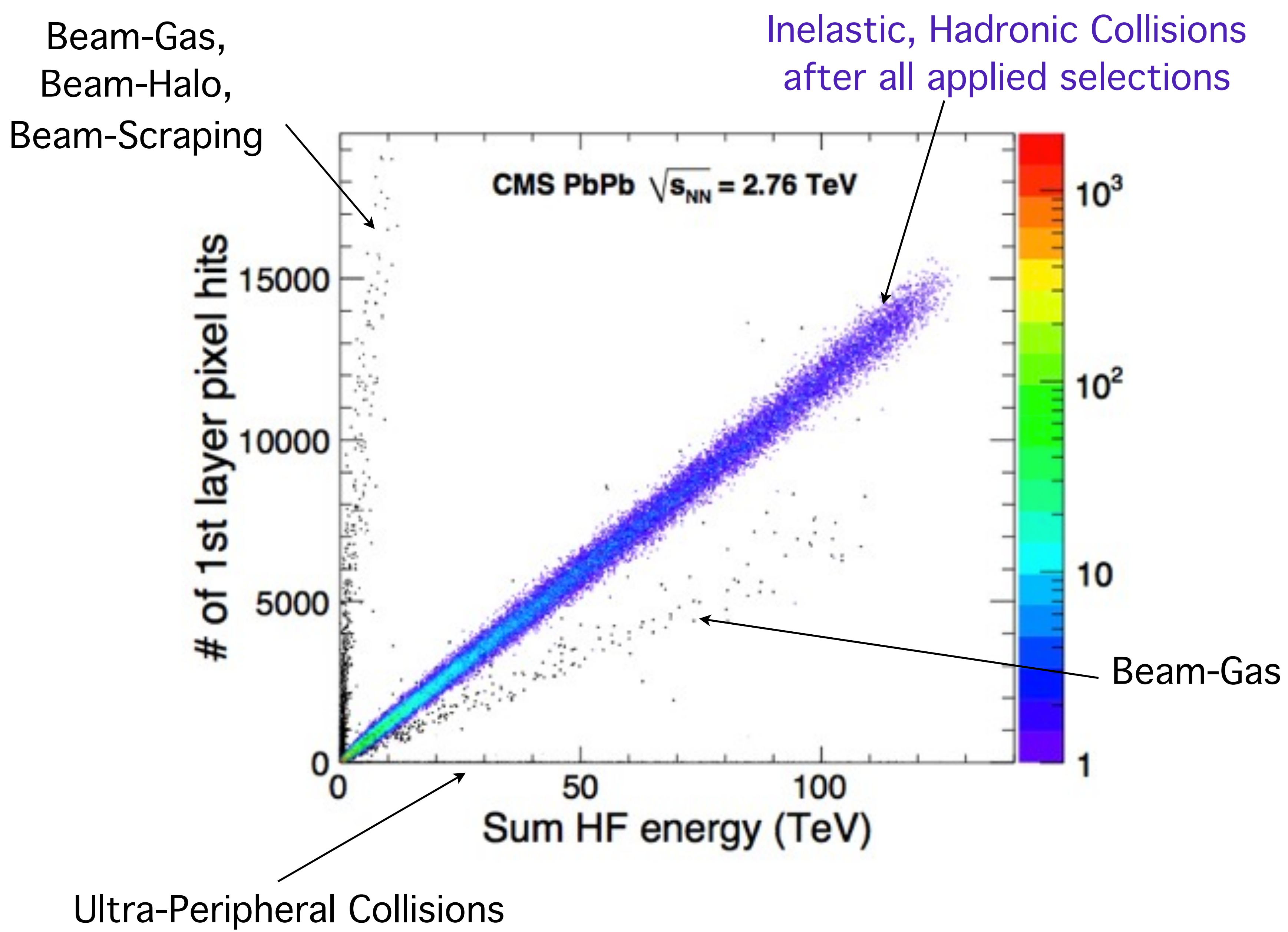
ATLAS Dijet Asymmetry



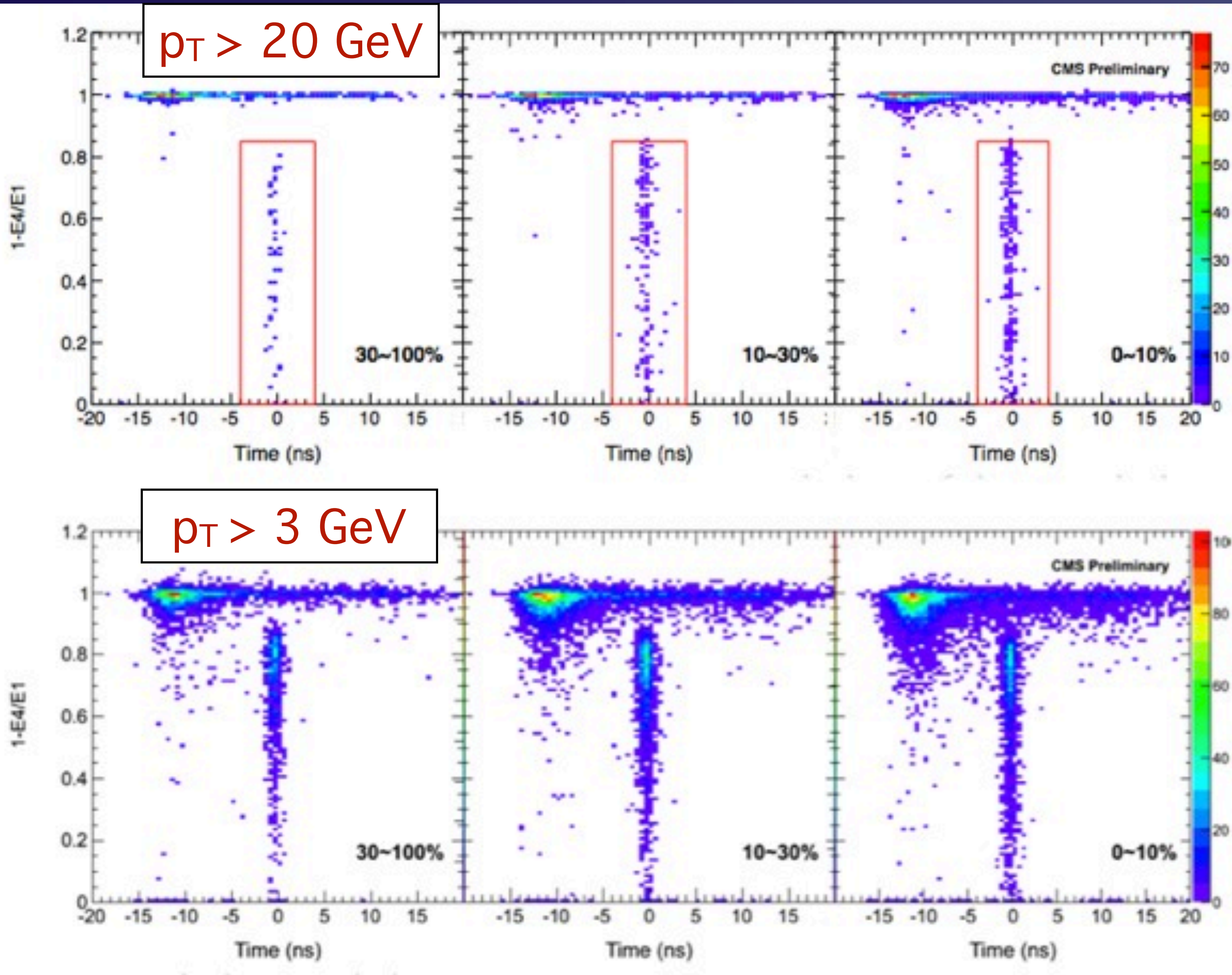
$p_{T,1} > 100$ GeV
$p_{T,2} > 25$ GeV
$\Delta\phi_{1,2} > \pi/2$
$|\eta_{jet}| < 2.8$

ATLAS Collaboration, "Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at sqrt(S_{NN})= 2.76 TeV with the ATLAS Detector at the LHC", *Phys. Rev. Lett.* **105** (2010) 252303, `arXiv:1011.6182`.

Event Selection

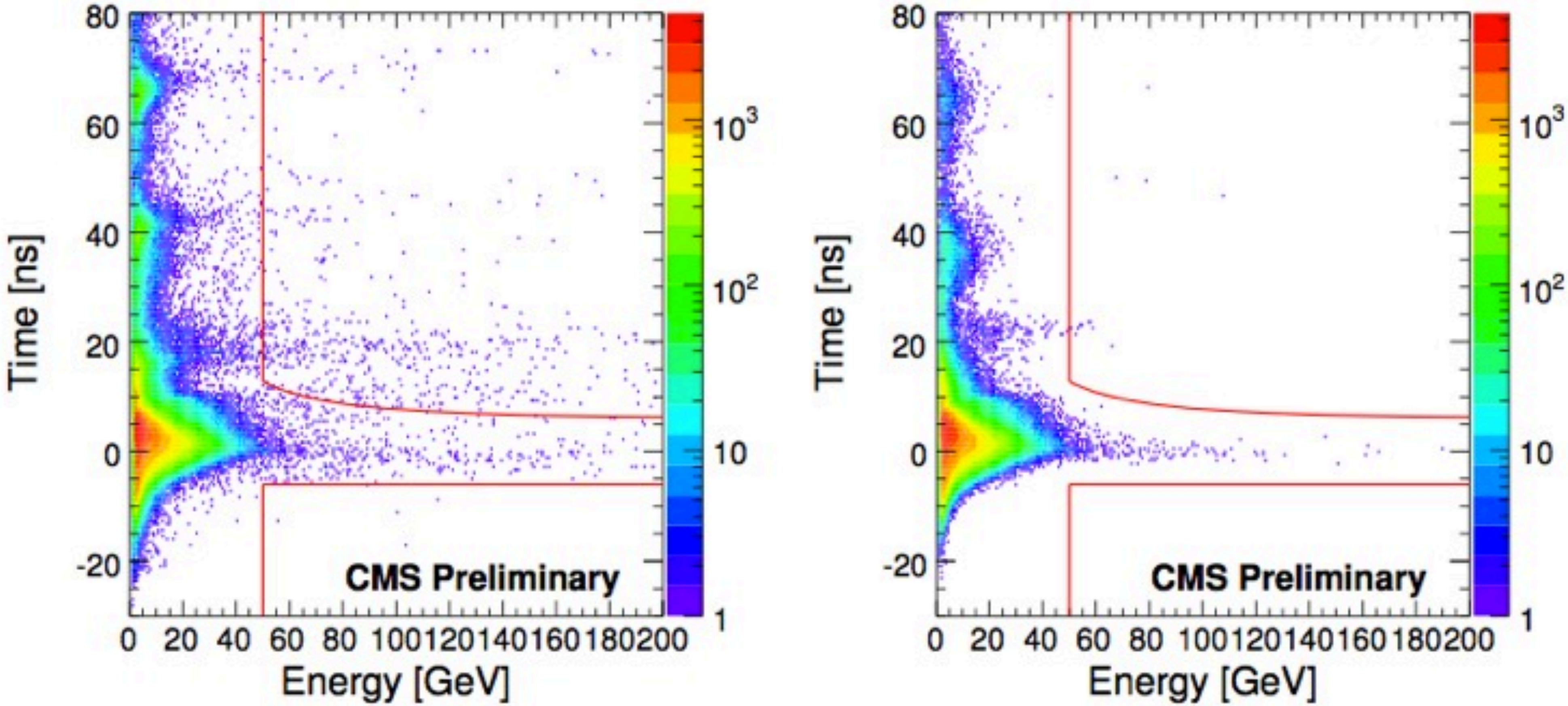


ECAL APD hit cleaning



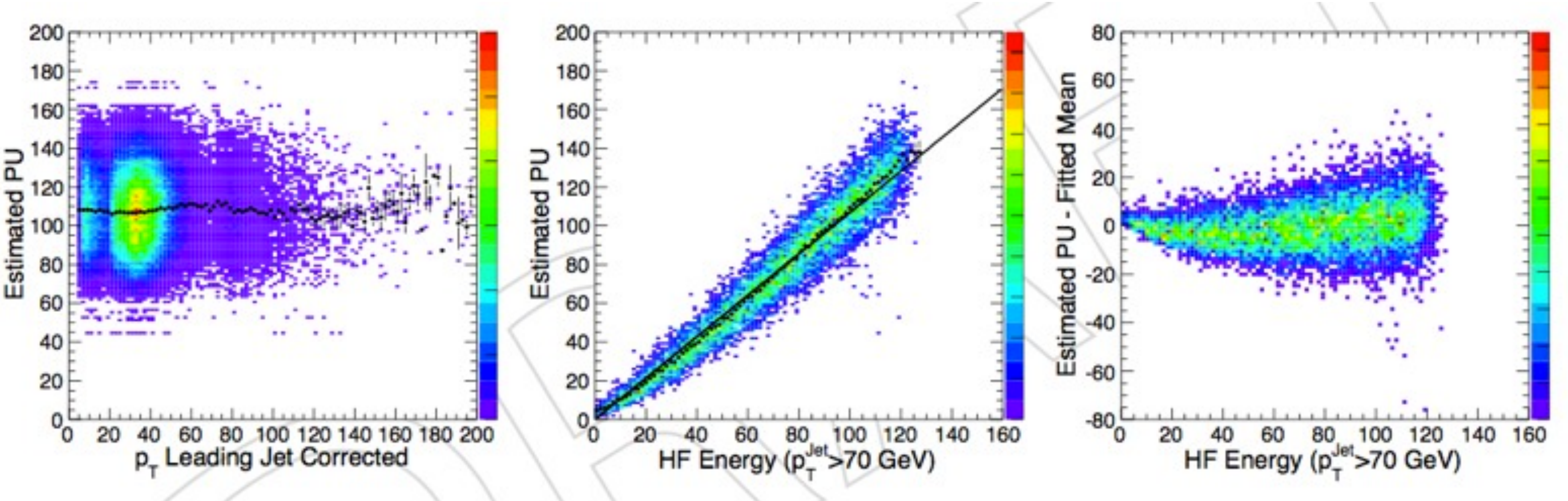
CMS Collaboration, "Electromagnetic calorimeter commissioning and performance with 7 TeV data", *CMS Note* **EGM-10-002** (2010).

HCAL noise cleaning

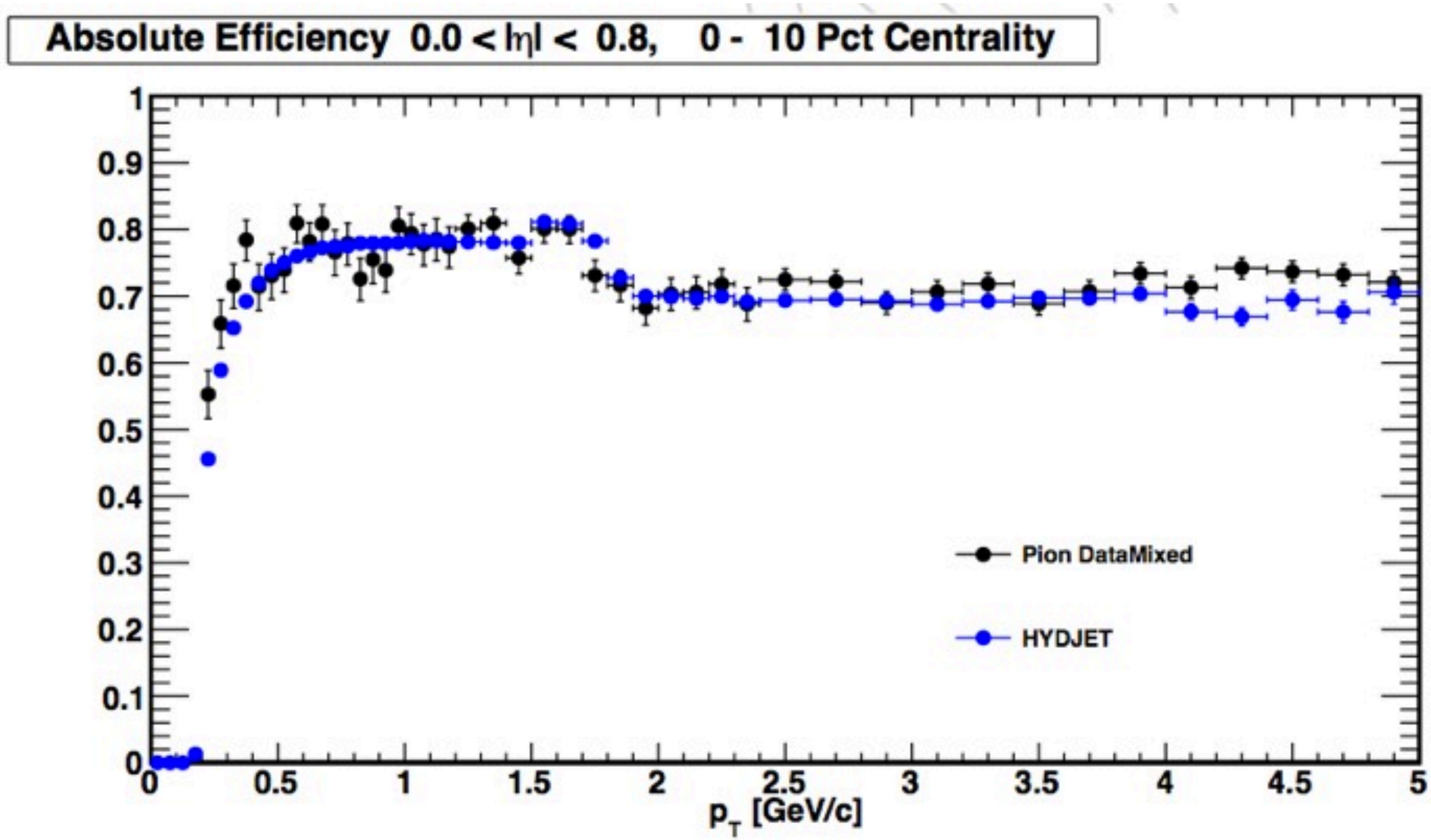


CMS Collaboration, "Identification and Filtering of Uncharacteristic Noise in the CMS Hadron Calorimeter", *JINST* **5** (2010) T03014, arXiv:0911.4881. doi:10.1088/1748-0221/5/03/T03014.

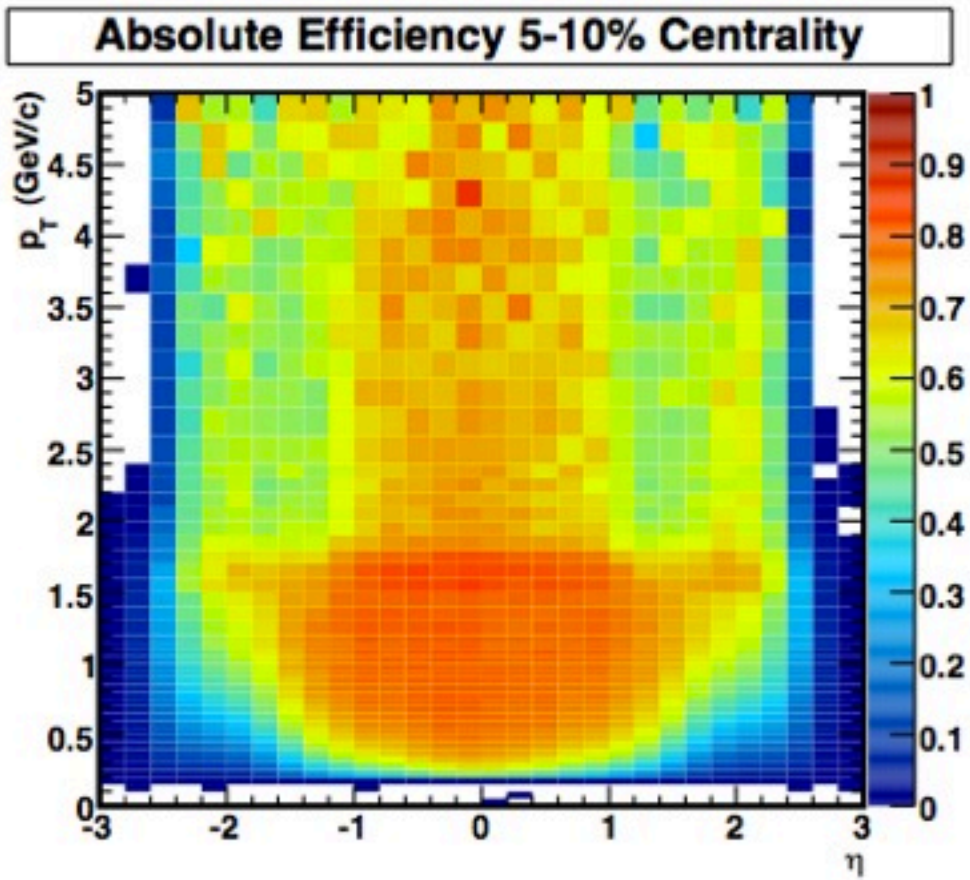
Underlying Event in Jet Cone

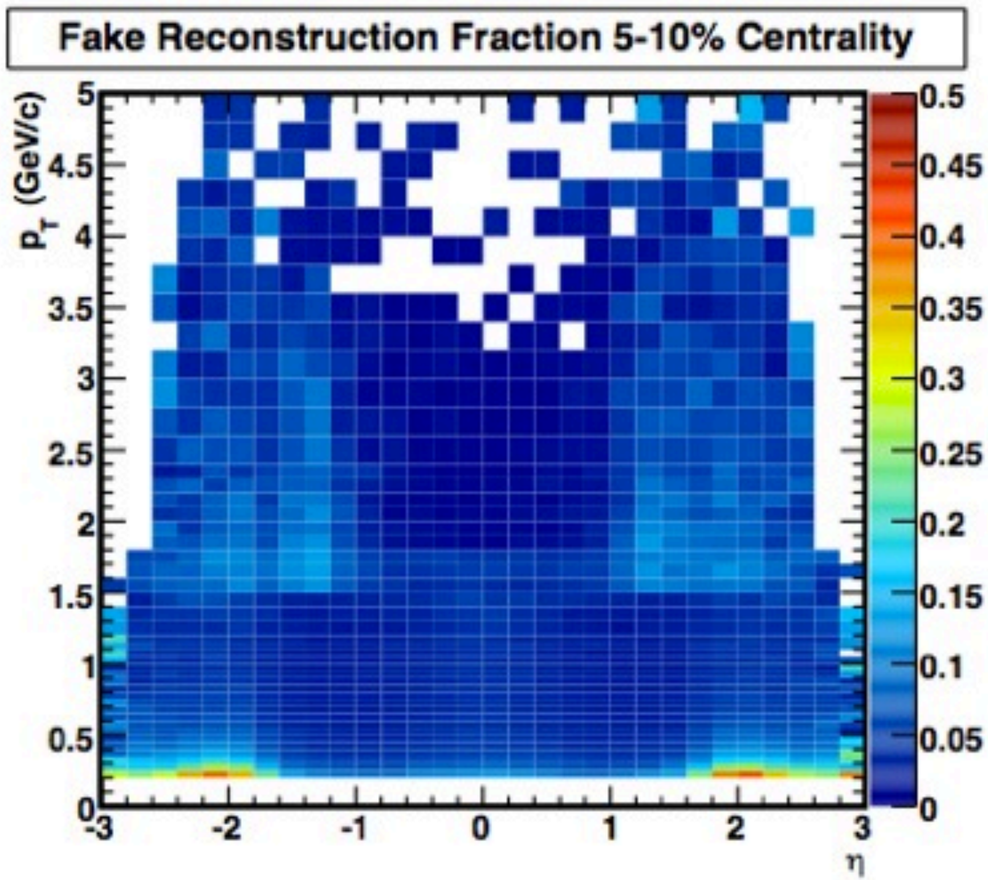


Data-Driven Efficiency



Tracking Performance





In-Cone MPT vs. J-T Corr