# Jet Measurements with CMS

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# Why should we study jets in heavy ion collisions?

Jet Reconstruction: Enables study of jet quenching:

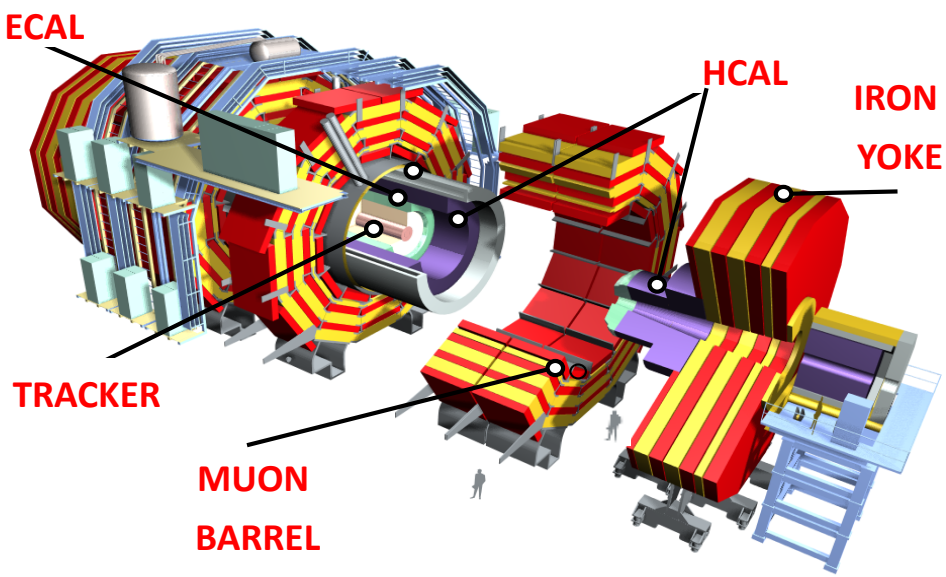
- At a uniquely large/wide kinematic reach
- With much reduced geometric biases in A+A
- Through multiple channels for consistency checks: Inclusive, di-jets, γ-jets, b-jets, Z-jets …
- Via qualitatively new observables: energy flow, jet substructure, fragmentation functions

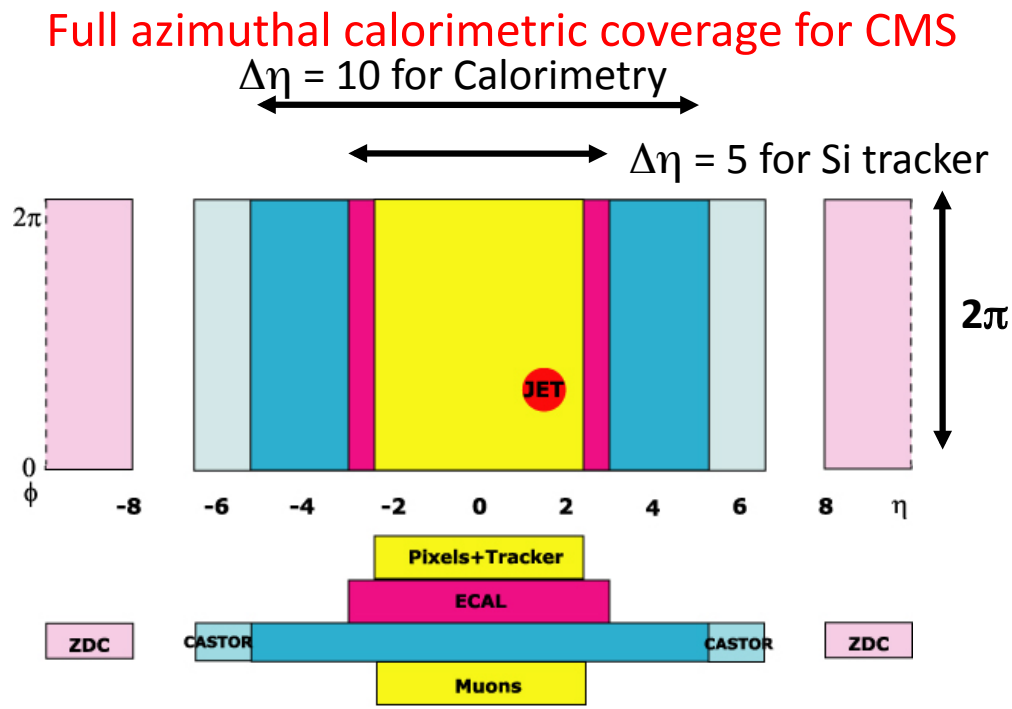
**Goal is Unbiased Jet Reconstruction:**

**Reconstructed jets should connect theory and experiment to study the properties of QGP quantatively.**

But are we succeeding?

# The CMS Detector: A Jet Detector




- Muon chambers outside 3.8 T magnet, interleaved with iron return yoke

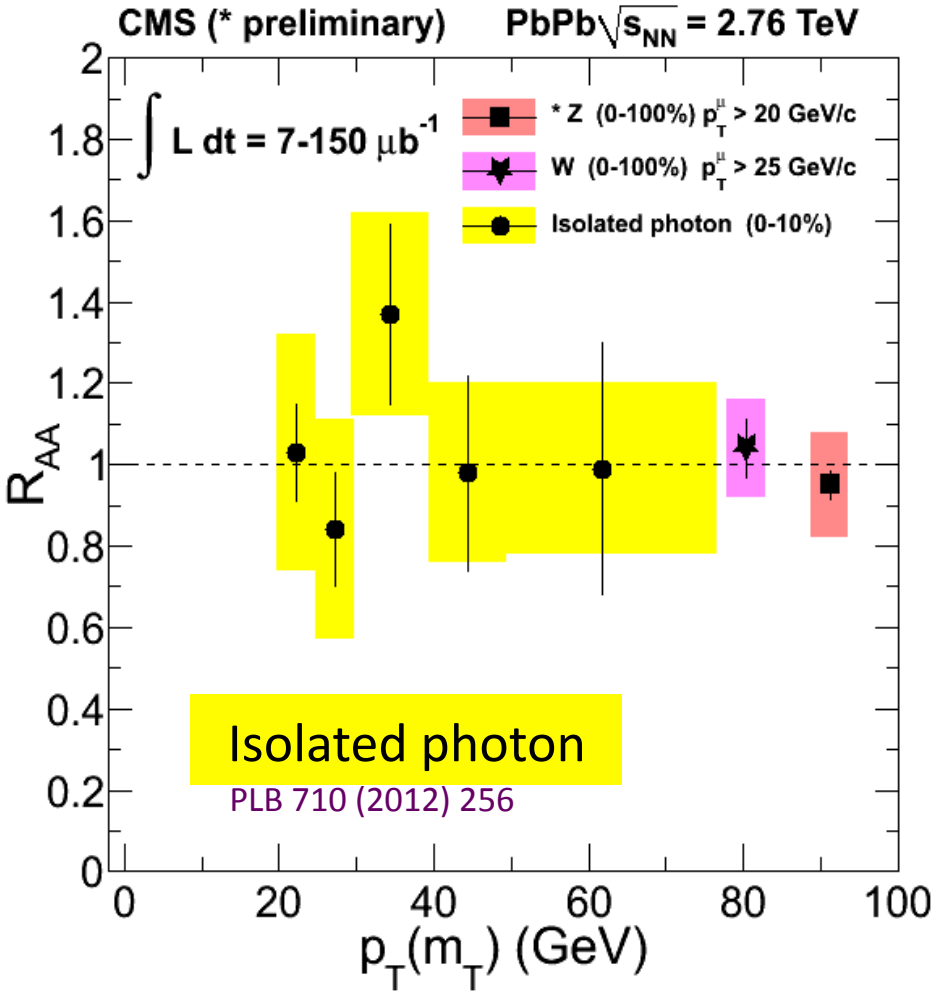
Tracking, ECAL and HCAL all embedded the solenoid magnet:

- Precise silicon pixel and silicon strip tracking system
- Fine-grained lead tungstate crystal ECAL
- Barrel+end cap HCAL, hadronic forward CAL

The CMS detector is well optimized for finding jets in heavy ion collisions

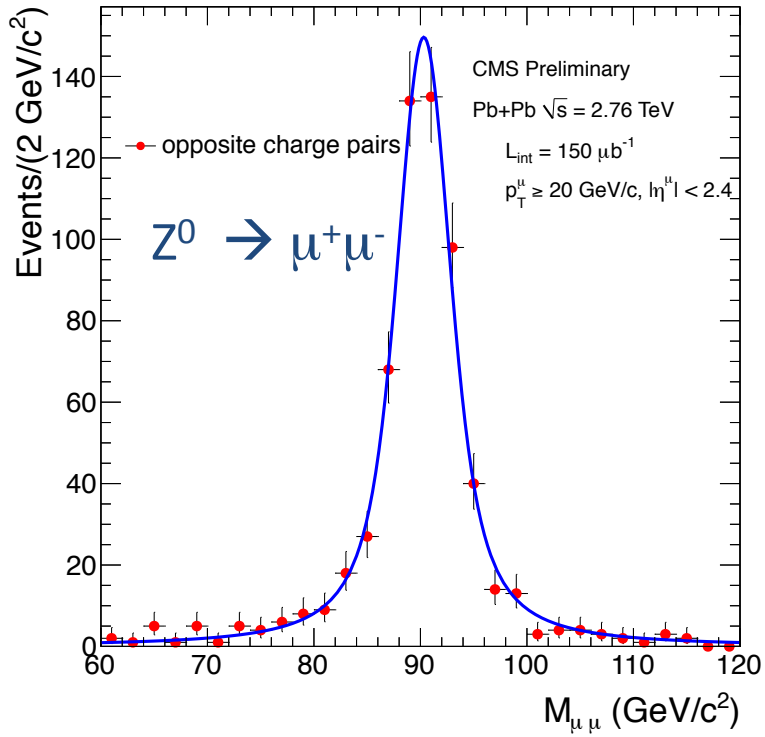
# Control Measurements: Vector Bosons

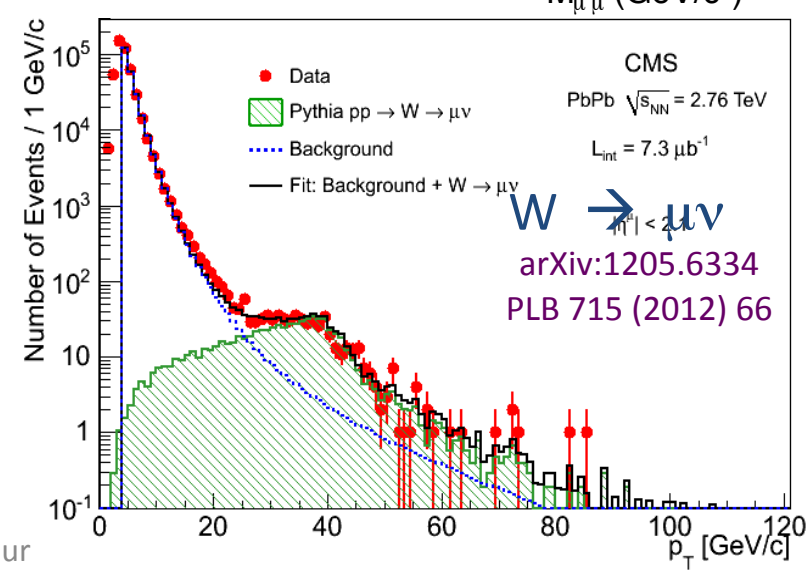
PRL 106 (2011) 212301
CMS-PAS HIN-12-008




Isolated photon

PLB 710 (2012) 256

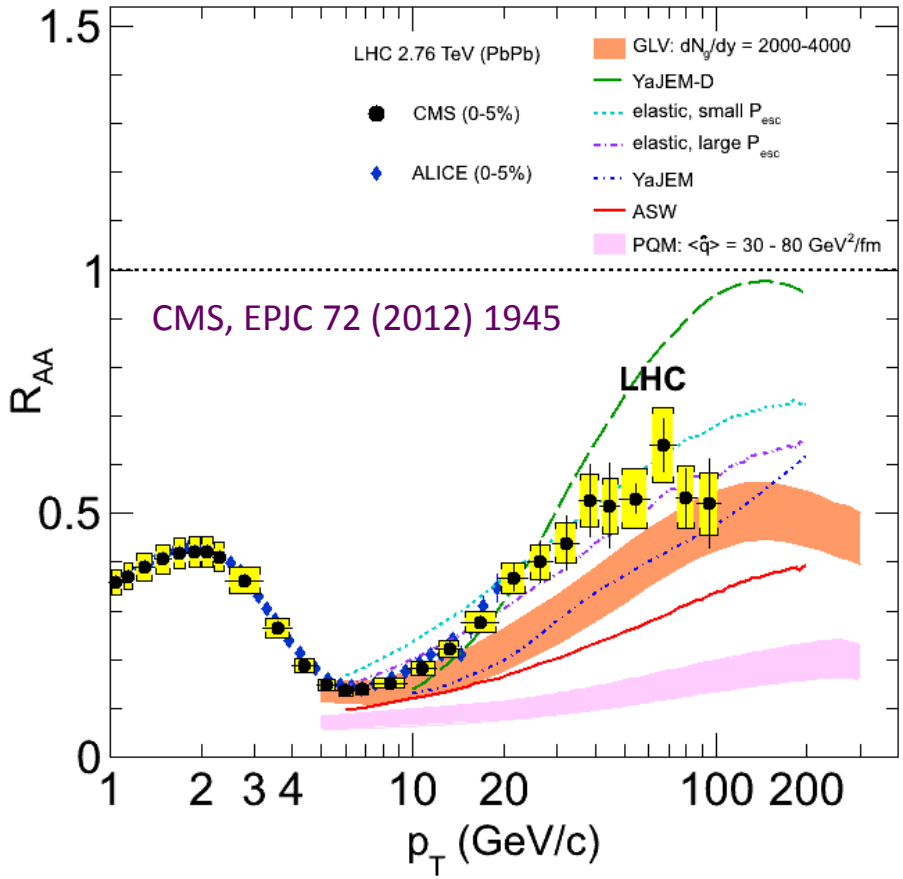



arXiv:1205.6334
PLB 715 (2012) 66

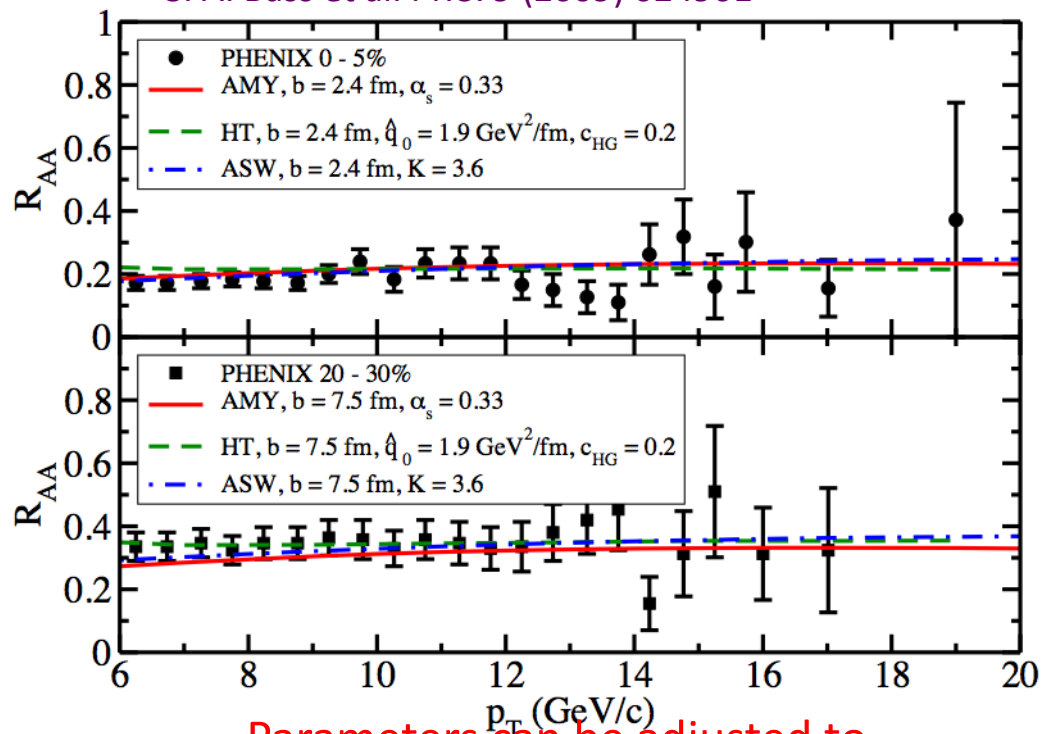
$N_{coll}$ scaling confirmed in PbPb collisions at 2.76 TeV

# Jet Quenching observed via jet fragments!




CMS, EPJC 72 (2012) 1945

S. A. Bass et al. PRC79 (2009) 024901

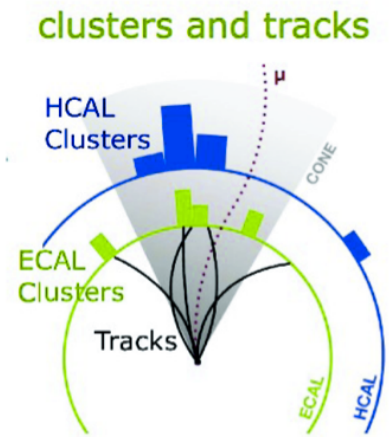


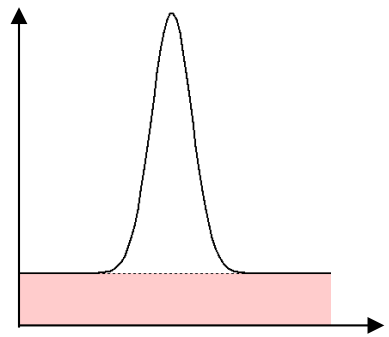

Parameters can be adjusted to describe data well: $\hat{q}$ varies between 4-18 GeV/c²

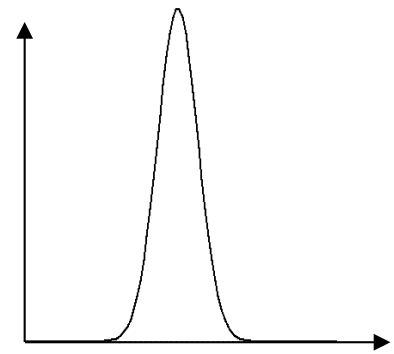
Strong discrimination power for parton radiative energy loss models but **limited discrimination in the derived medium properties.**

QGP properties to be derived next!

# CMS jet reconstruction and energy determination





Raw jet energy → Background subtraction → Jet energy correction

Particle Flow Jets (PFJ): Reconstructed particles utilizing all sub-detectors "a la Generator Level". Tracks with $p_T > 0.9$ (0.15) GeV/c are used in PbPb (pp & pPb)
**Anti-$K_T$ (R = 0.3)**

Iterative background subtraction in eta-rings
Other methods are investigated.

PYTHIA MC
Data driven residual correction from dijet and photon-jet

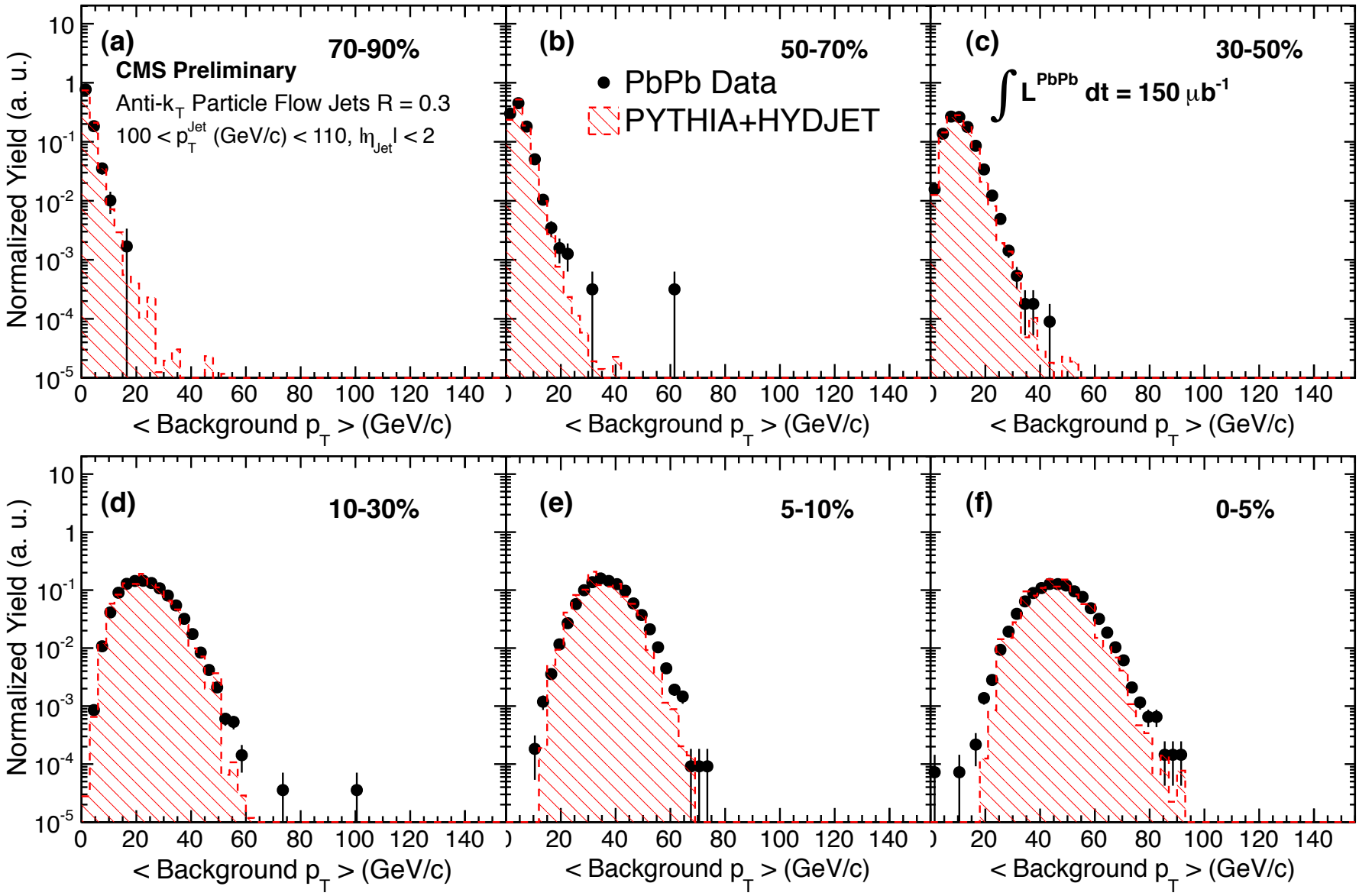
JINST 6 (2011) P11002

O. Kodolova, et al., Eur. Phys. J. C50 (2007) 117

M. Cacciari, G. P. Salam, and G. Soyez, JHEP 04 (2008) 063

CMS-PAS-HIN-11-004, J. Phys. G: Nucl. Part. Phys. 38 124151 (2011)

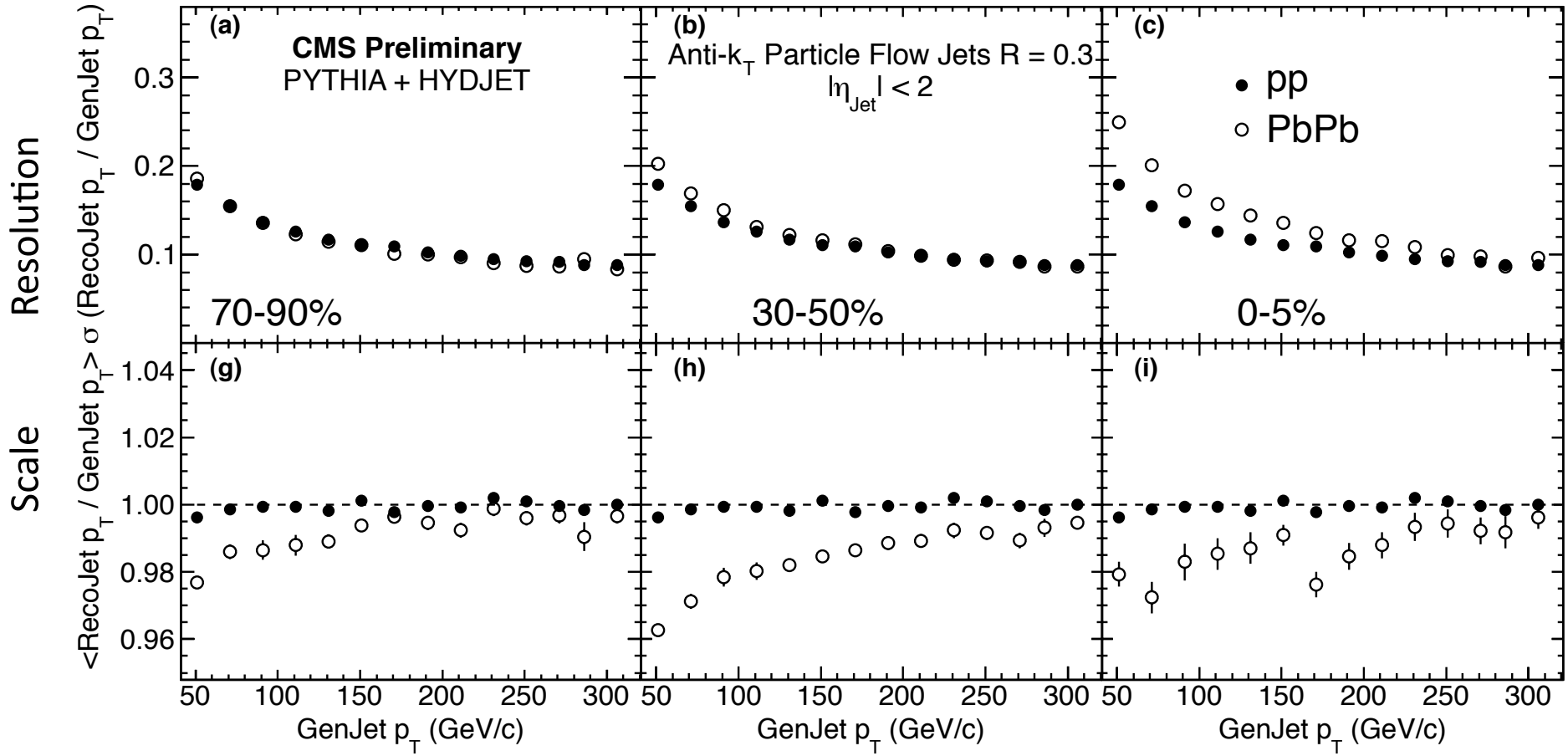
# Average PbPb Background:




HYDJET can describe the UE (as well as its fluctuation)

CMS: HIN-12-004-PAS

# Jet Performance

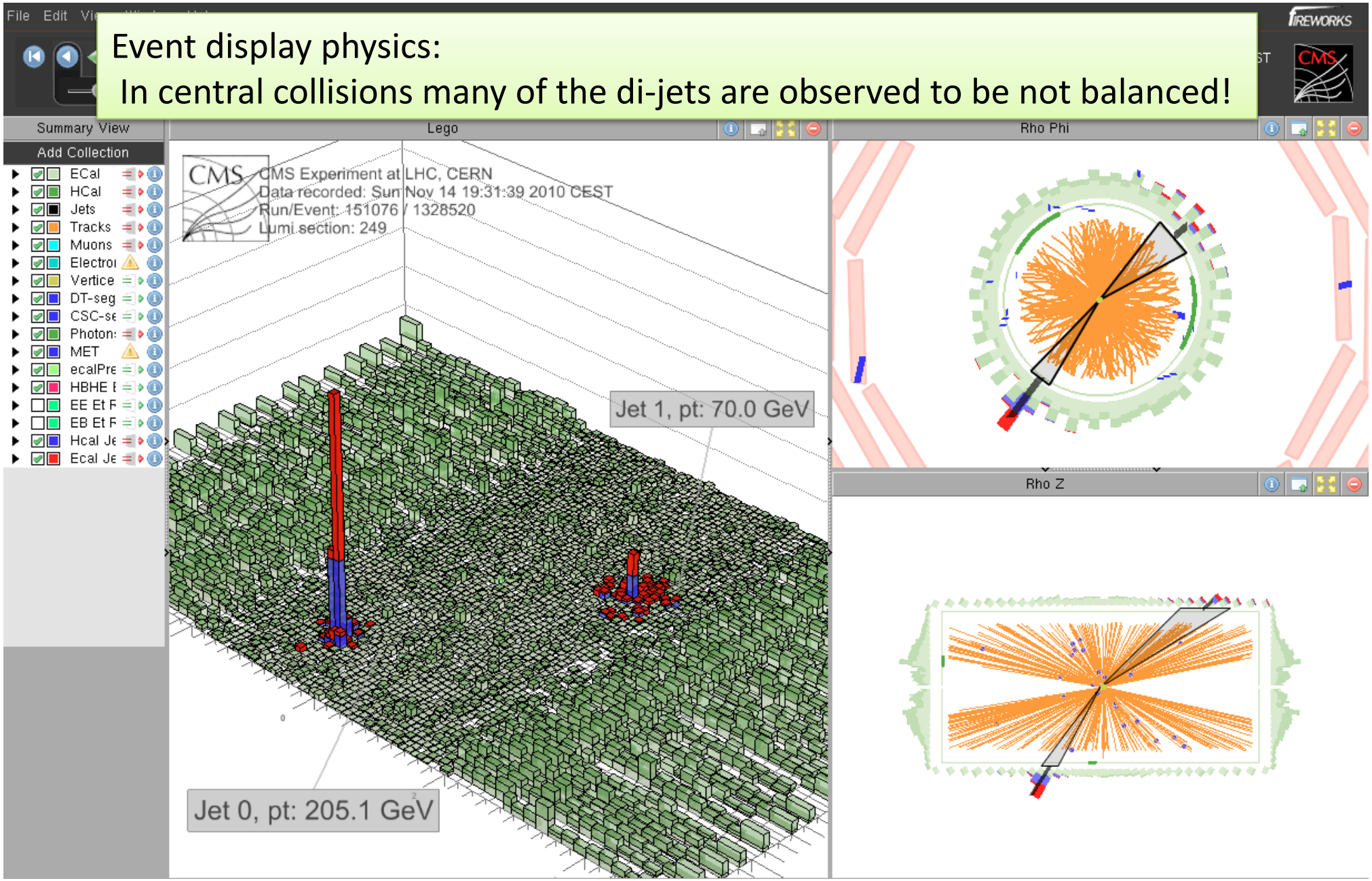



Comparison of generator jet to reconstructed jet.
Used for the unfolding!

CMS: HIN-12-004-PAS

# Jets: Lessons learned!

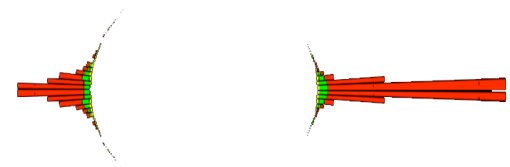
Event display physics:
In central collisions many of the di-jets are observed to be not balanced!



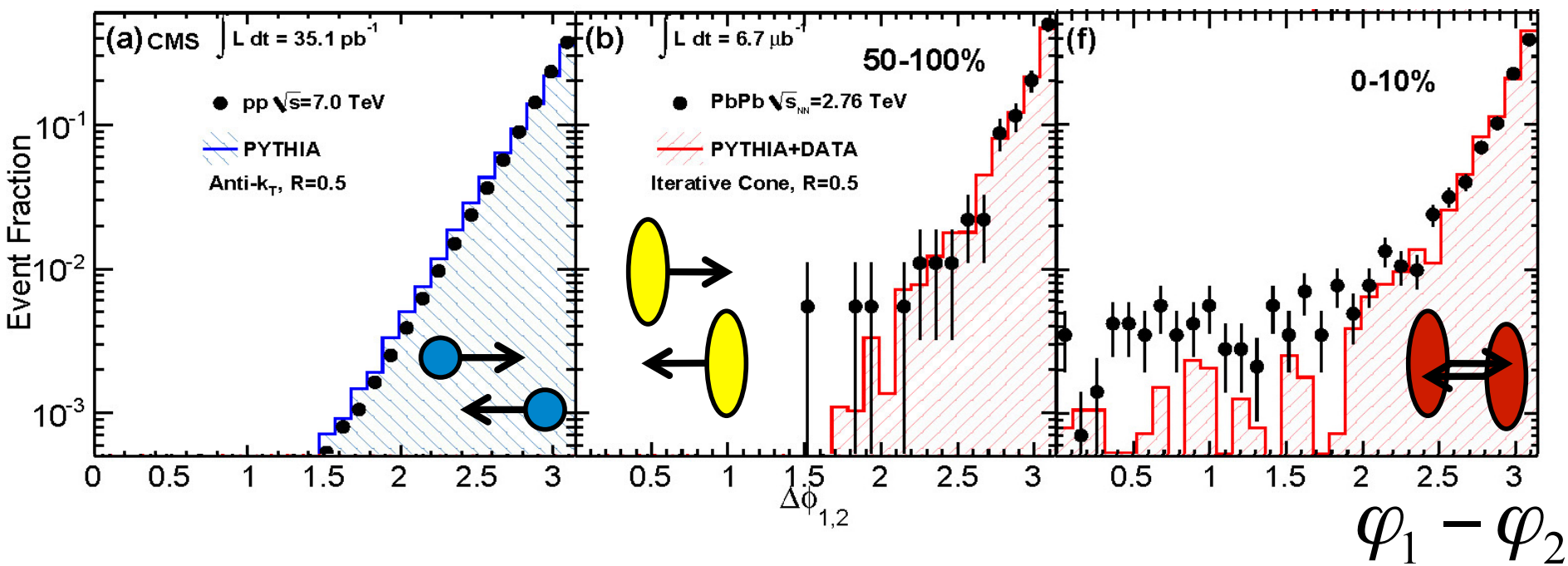
# Angular Correlations with jet-jet Measurements…

- The leading jet of $E_T^1 > 120$ GeV and the
- sub-leading jet $E_T^2 > 50$ GeV

stay essentially back-to back ($\Delta\phi = \pi$)

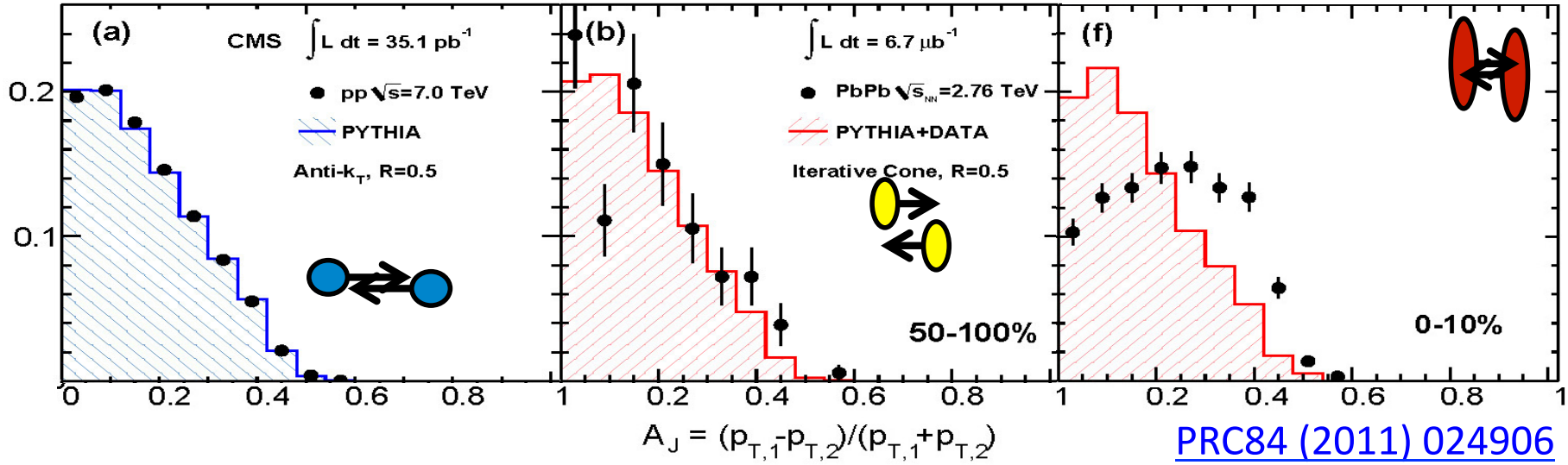


PRC84 (2011) 024906

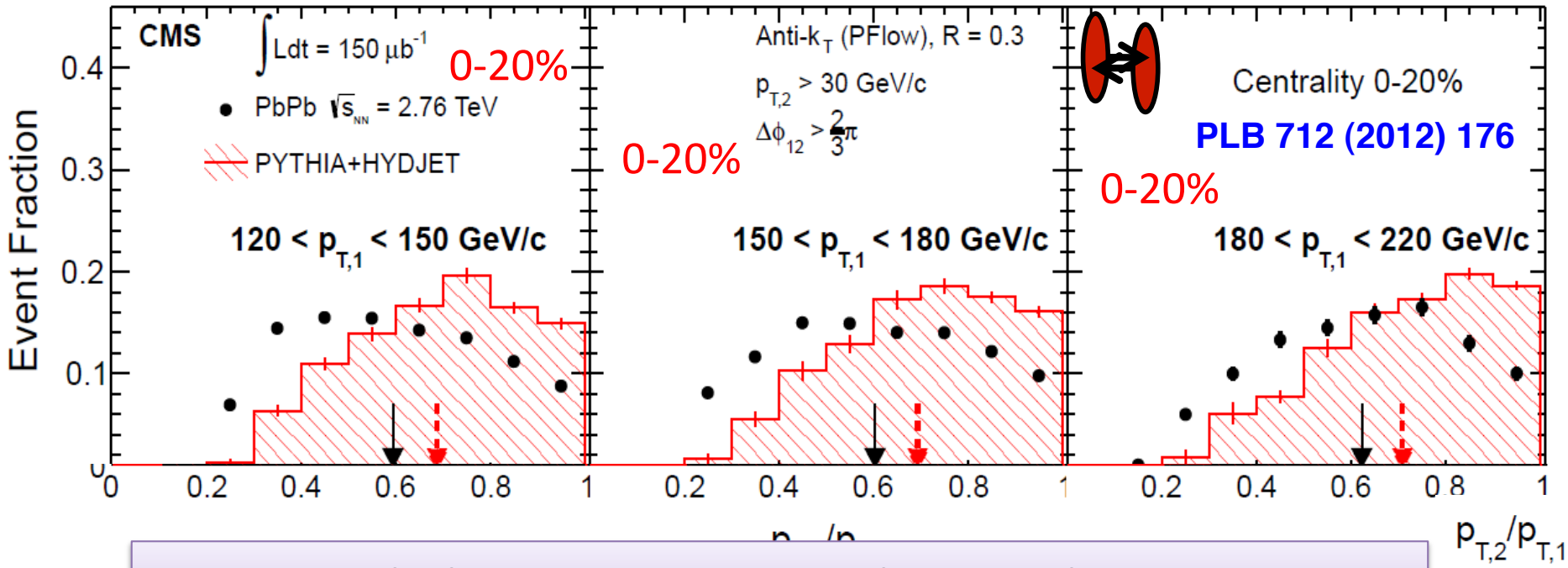



Angular correlations of jets is unmodified by the medium

# Quantifying Di-jet Measurements

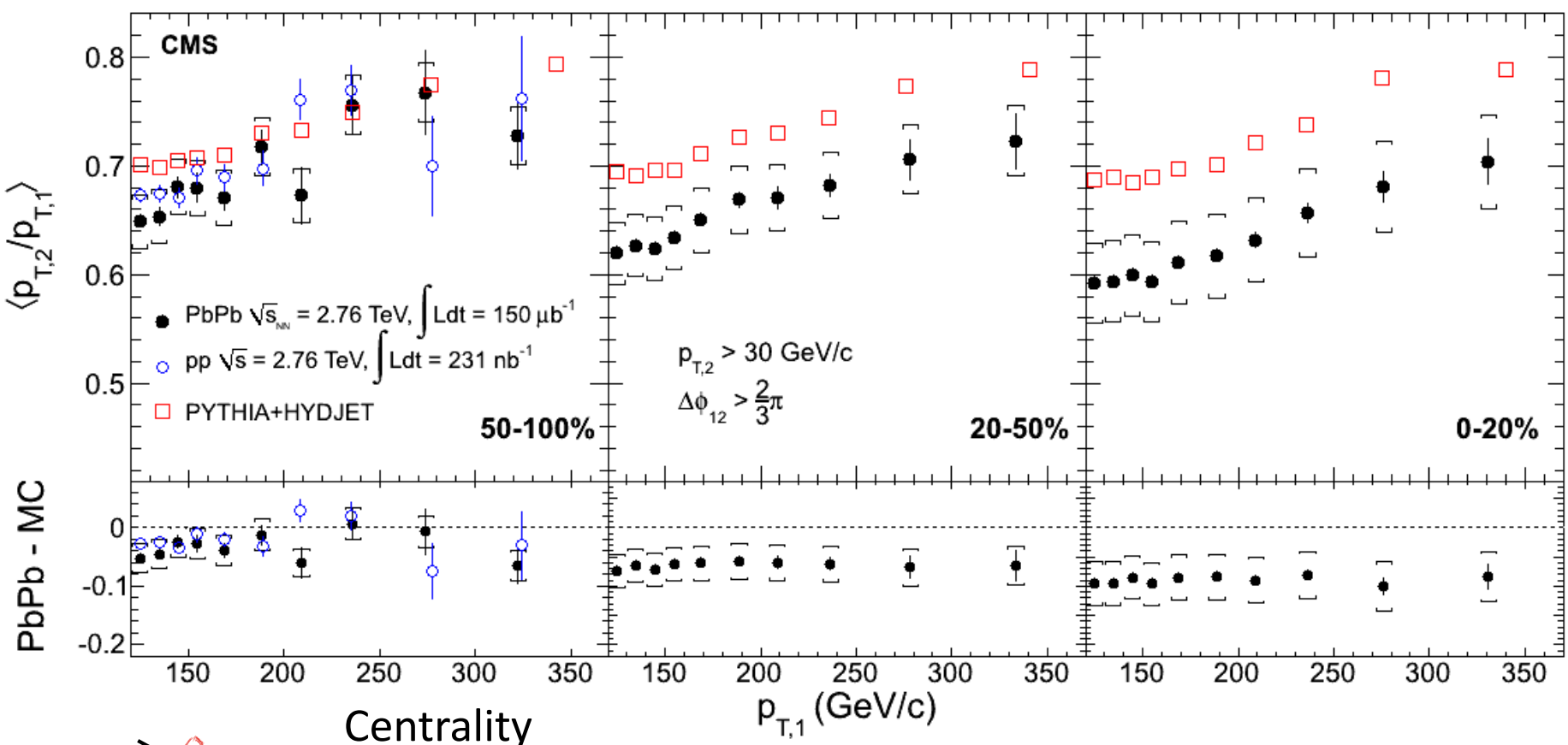



PRC84 (2011) 024906

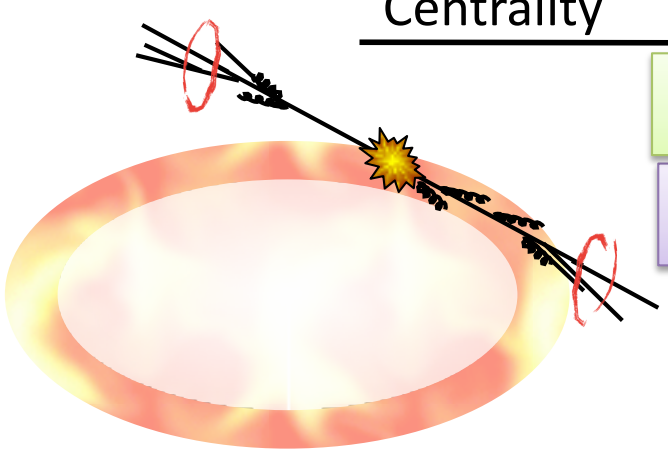



Energy imbalance increases with centrality!

# The $p_T$-dependence of jet quenching:




Centrality



No significant dependence on leading jet $p_T$

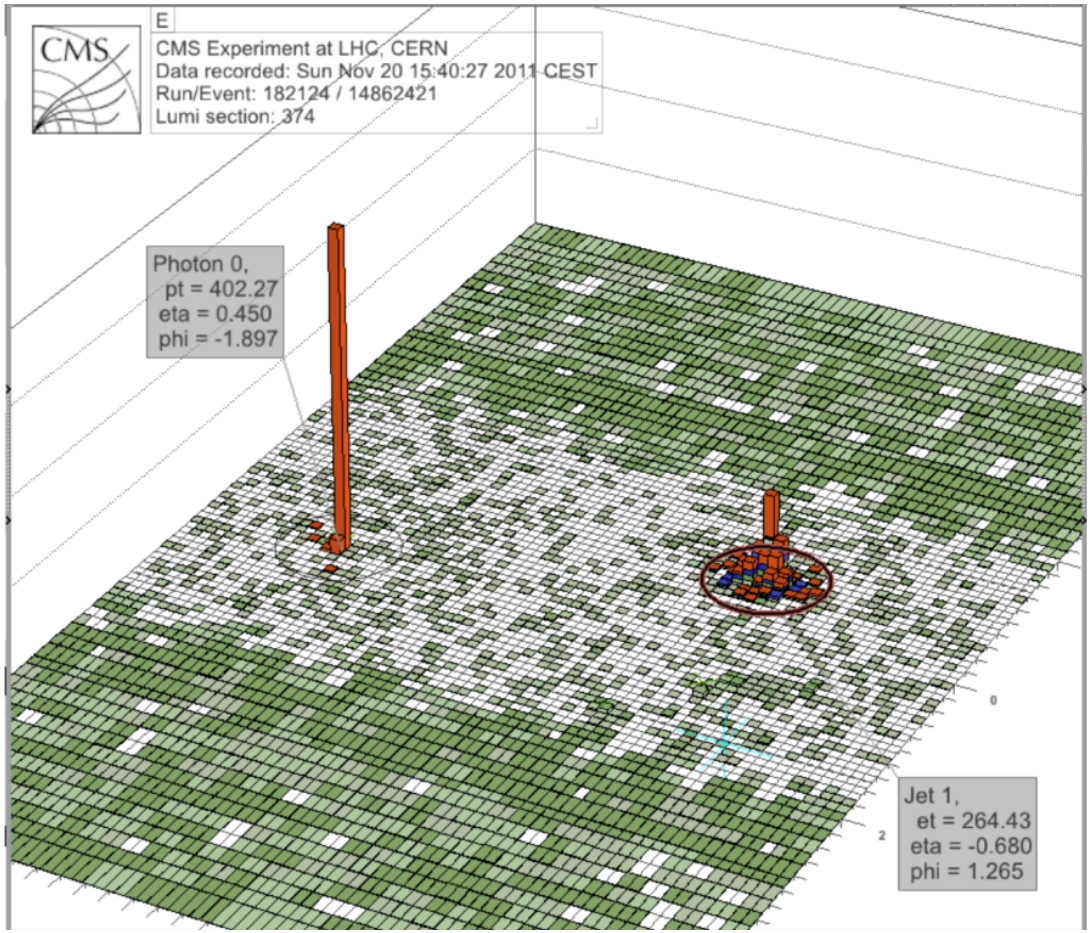
High $p_T$ jets are also quenched!

Loss of information about the initial properties & surface bias.

See also Yetkin's talk

PLB 712 (2012) 176

# What about Z/Photon+Jet?

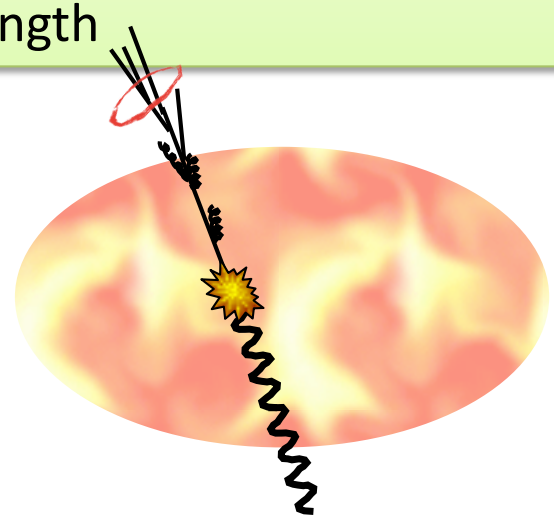



P. Stankus, Ann. Rev. Nucl. Part. Sci. 55, 517 (2005)

X. Wang, Z. Huang, Phys.Rev.C55:3047-3061 (1997)

Isolated photons are unmodified!

- Access to the initial parton energy via isolated photon
- Access to the final parton energy via jet reconstruction
- Better handle on the path length

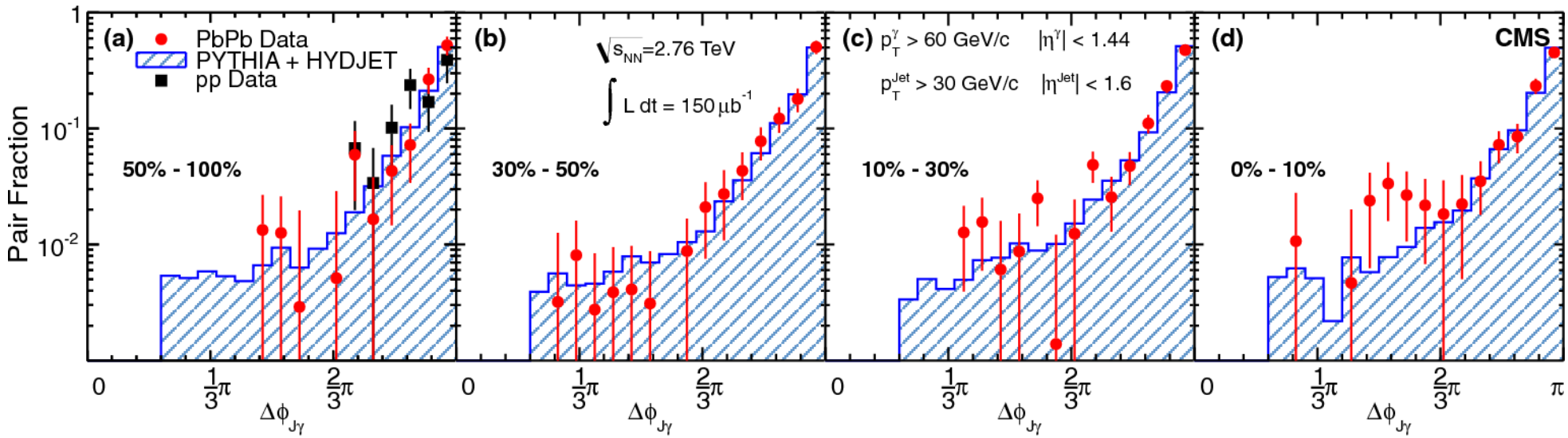


Limited Statistics: 10 Z+jet,O(100) γ+jet O($10^5$) jet+jet
More statistics after the long shutdown!

# Isolated Photon+Jet

## 1) Azimuthal decorrelation:


- $p_T^{\gamma}$ > 60 GeV/c (to have sufficient phase space)
- $p_T^{Jet}$ > 30 GeV/c (constrained by efficiency)




Distribution is consistent with pp & PYTHIA+Hydjet

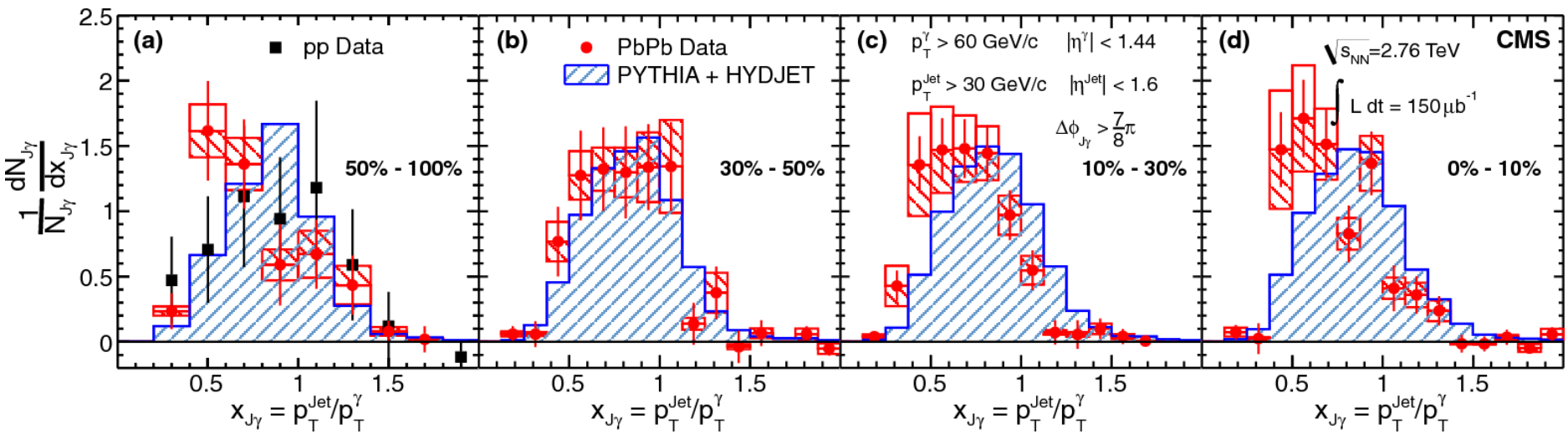
CERN-PH-EP-2012-089.
CMS PLB 718 (2013) 773

Quenched jet is still back-to-back to γ:
Jet energy not lost in single hard gluon-radiation.

# Isolated Photon+Jet

## 2) Momentum Imbalance:

- $p_T^{\gamma}$ > 60 GeV/c (to have sufficient phase space)
- $p_T^{Jet}$ > 30 GeV/c (constrained by efficiency)


CERN-PH-EP-2012-089.
CMS PLB 718 (2013) 773

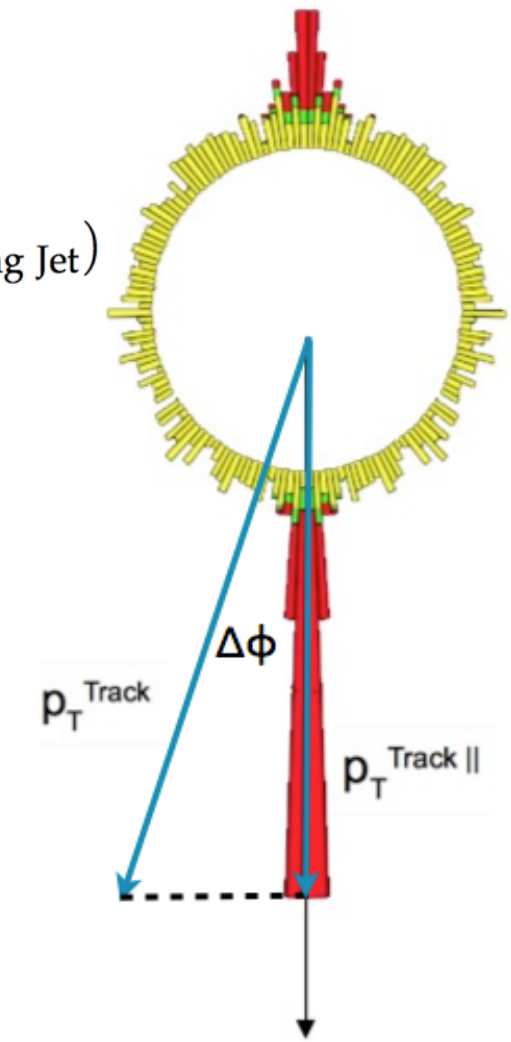
Energy lost (momentum ratio shifts) depends on centrality.

# Can we find the missing $p_T$?

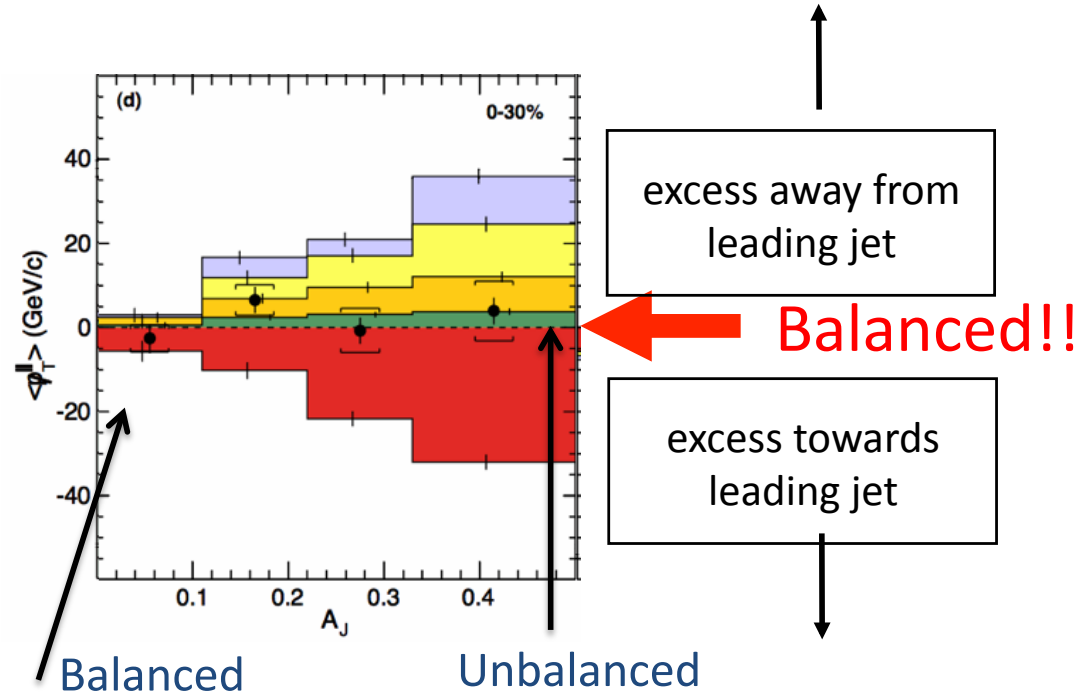
With respect to leading jet axis:

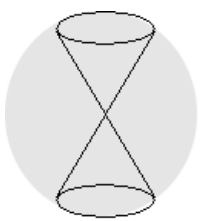
Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

Sum over all selected tracks with $p_T > 0.5$ GeV/c and $|\eta| < 2.4$



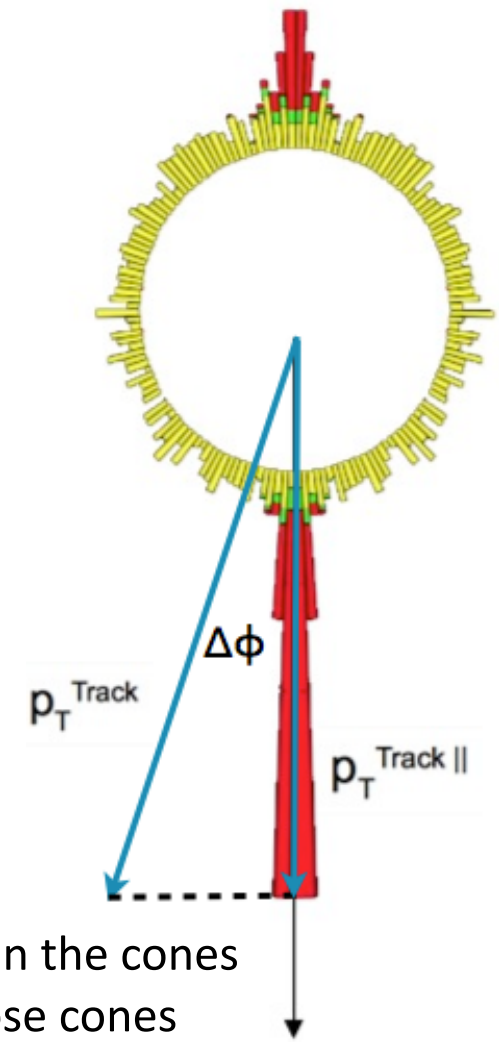
# Can we find the missing $p_T$?



All tracks

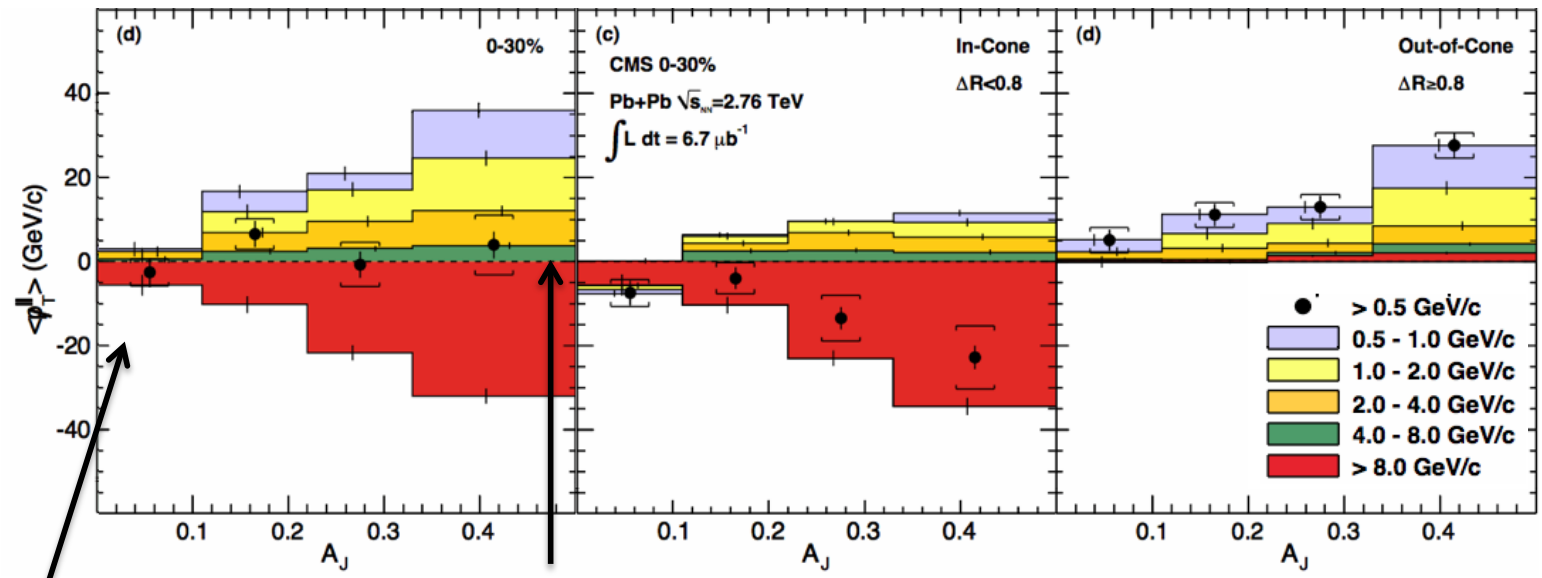
- > 0.5 GeV/c
- 0.5 - 1.0 GeV/c
- 1.0 - 2.0 GeV/c
- 2.0 - 4.0 GeV/c
- 4.0 - 8.0 GeV/c
- > 8.0 GeV/c

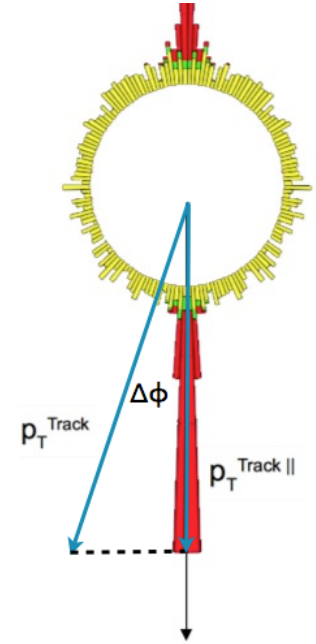



Look separately at "missing" $p_T^{||}$ in the cones around the jet and away from those cones

# Finding the missing $p_T$

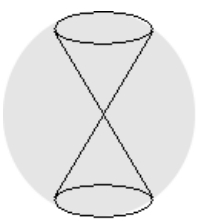
Missing $p_T^{\parallel}$: $\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$



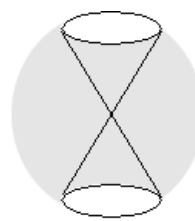

Balanced

Unbalanced



All tracks

Tracks in the jet cone ΔR<0.8

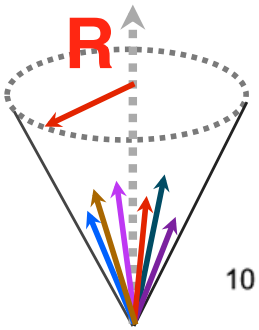


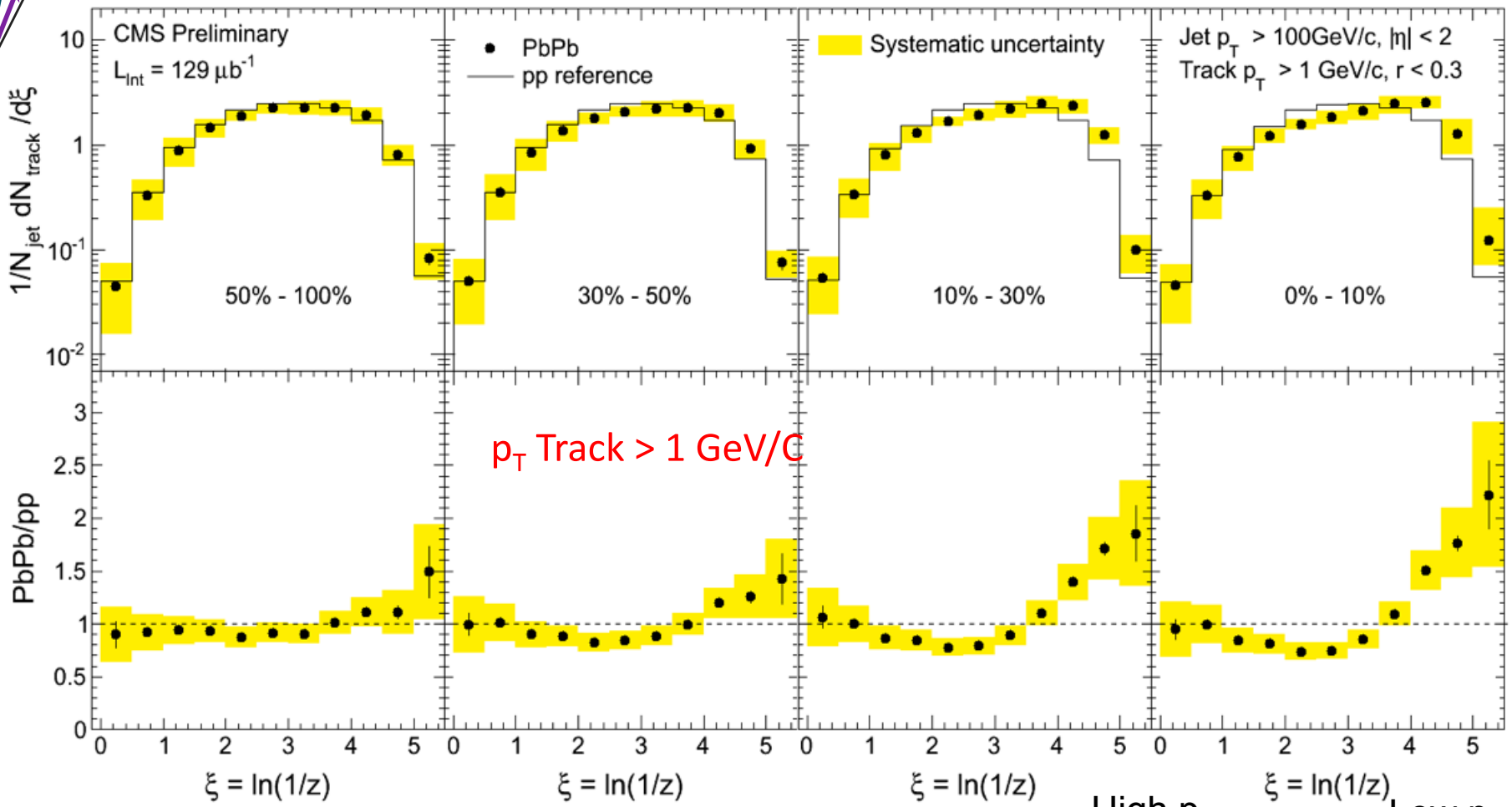
Tracks out of the jet cone ΔR>0.8

PRC84 (2011) 024906

7) Energy lost from the jet is transferred to many low $p_T$ particles at large angles to the jet direction.

# Jet Structures: Fragmentation Functions



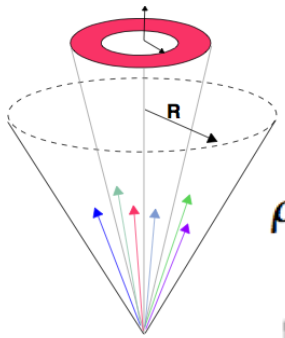

High $p_T$ particles

Low $p_T$ particles

Structure of reconstructed jets is modified towards an excess of particles at low pT!

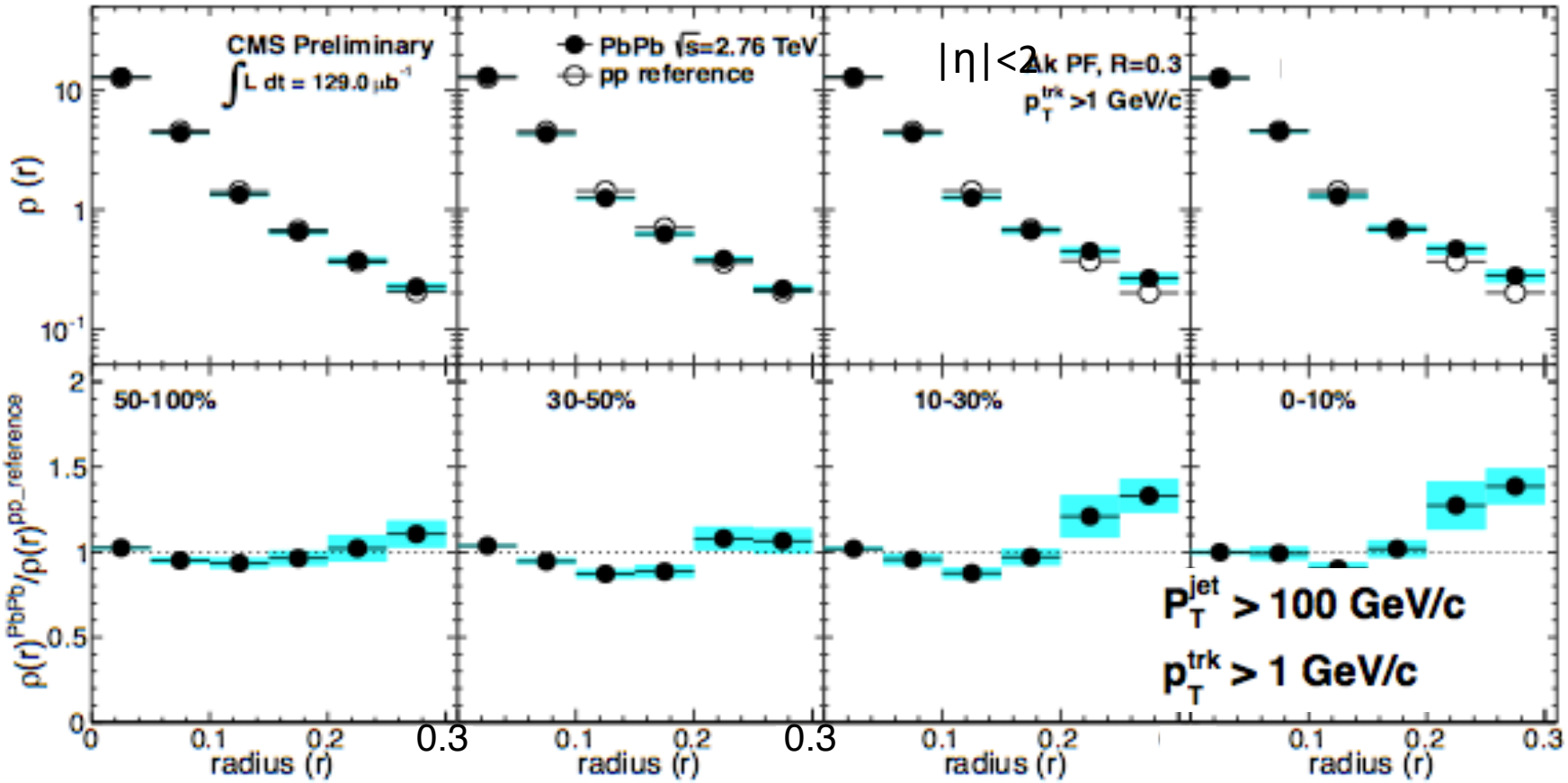
**CMS PAS HIN-12-013**

# More on jet structures: Jet Shapes




$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\rm jet}}\sum_{\rm jets}\frac{p_{\rm T}(r-\delta r/2, r+\delta r/2)}{p_{\rm T}^{\rm jet}}$$

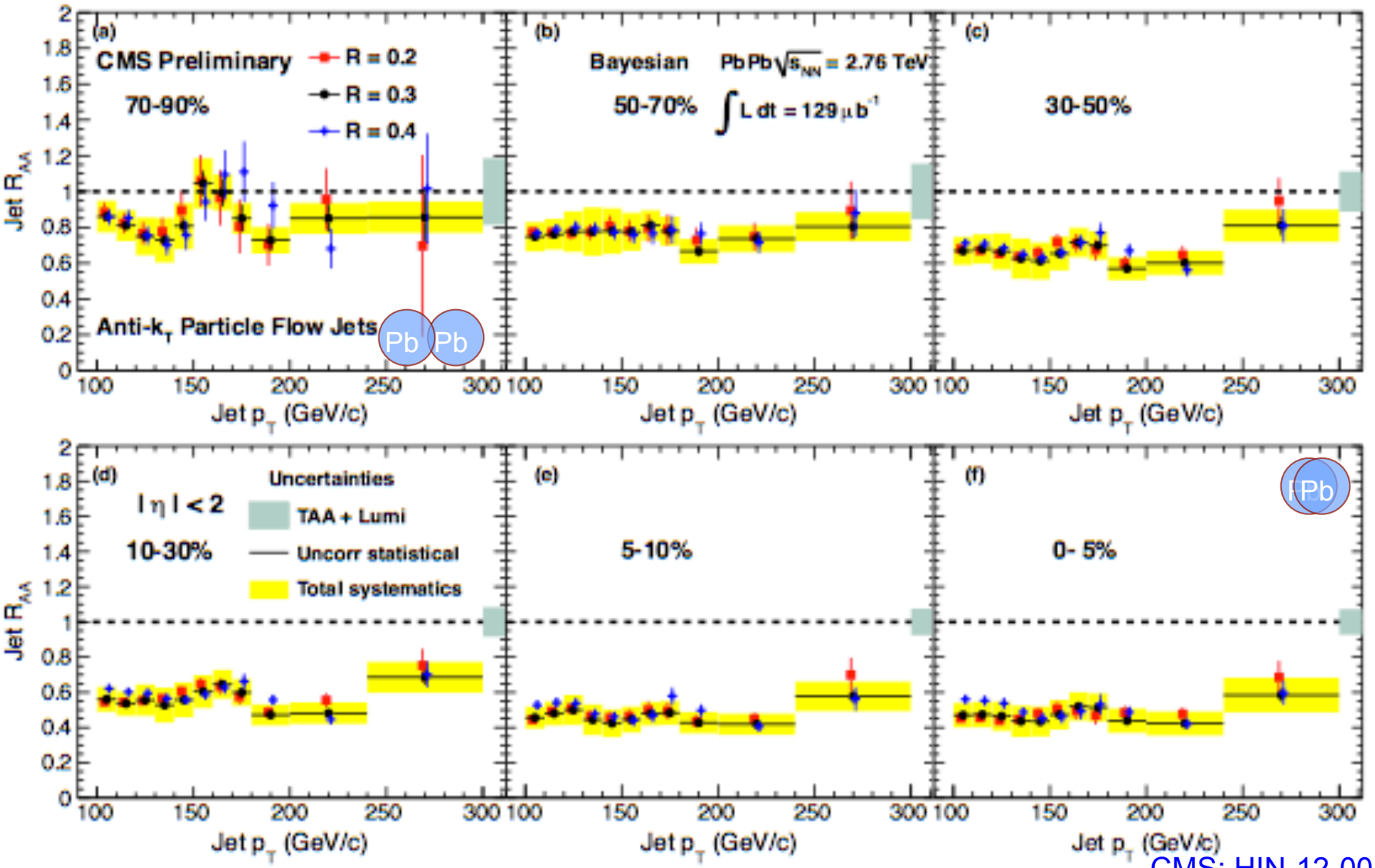
The transverse momentum fraction inside a given radial annulus in η-ϕ space




Structure of reconstructed jets is slightly modified towards an excess of particles far from the jet axis!

**CMS PAS HIN-12-013**

# Inclusive Jet $R_{AA}$: Resolution parameter dependence

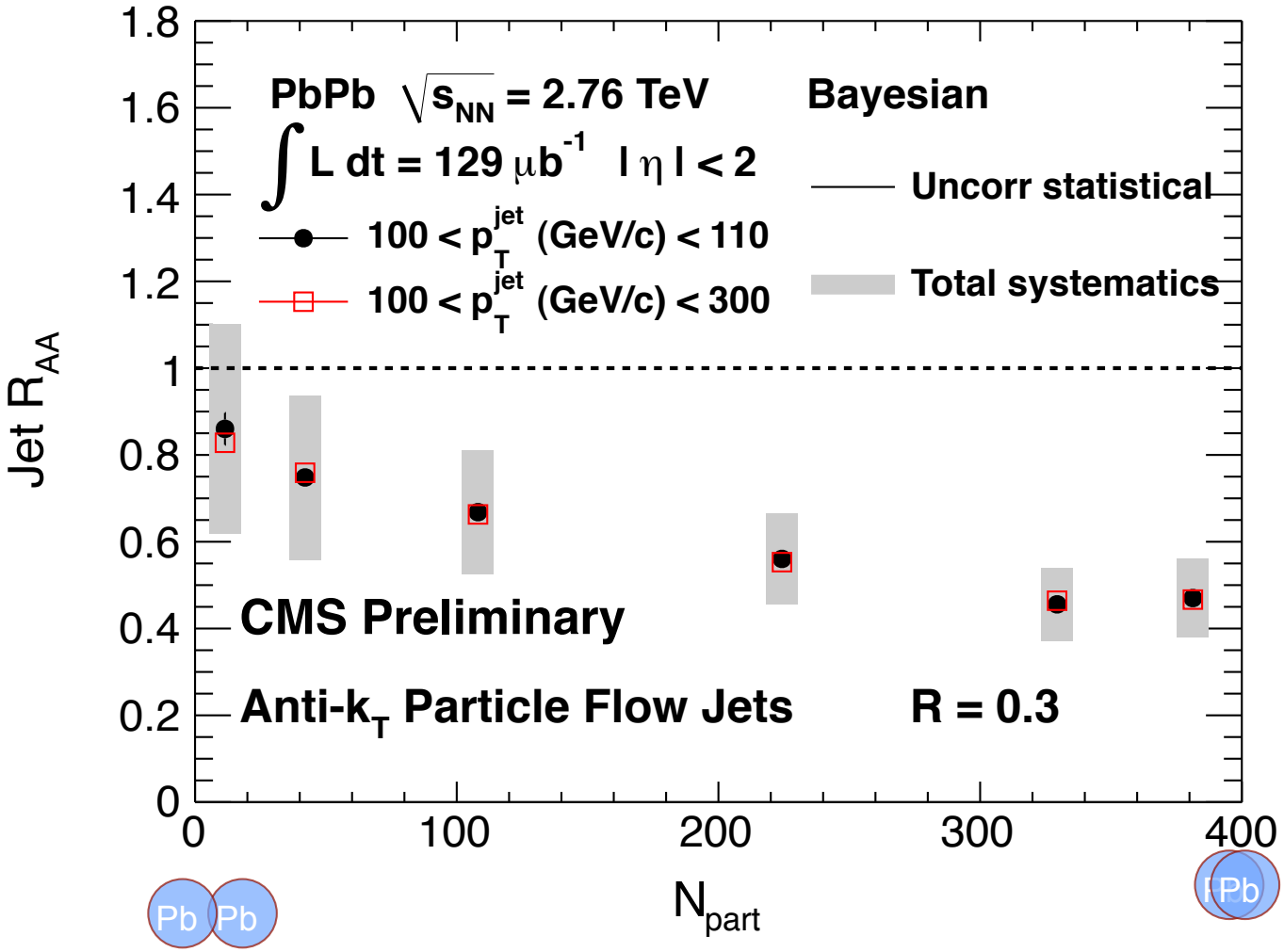



total systematic R=0.3

CMS: HIN-12-004-PAS

No strong dependence on jet radius!

# Inclusive Jet Measurements

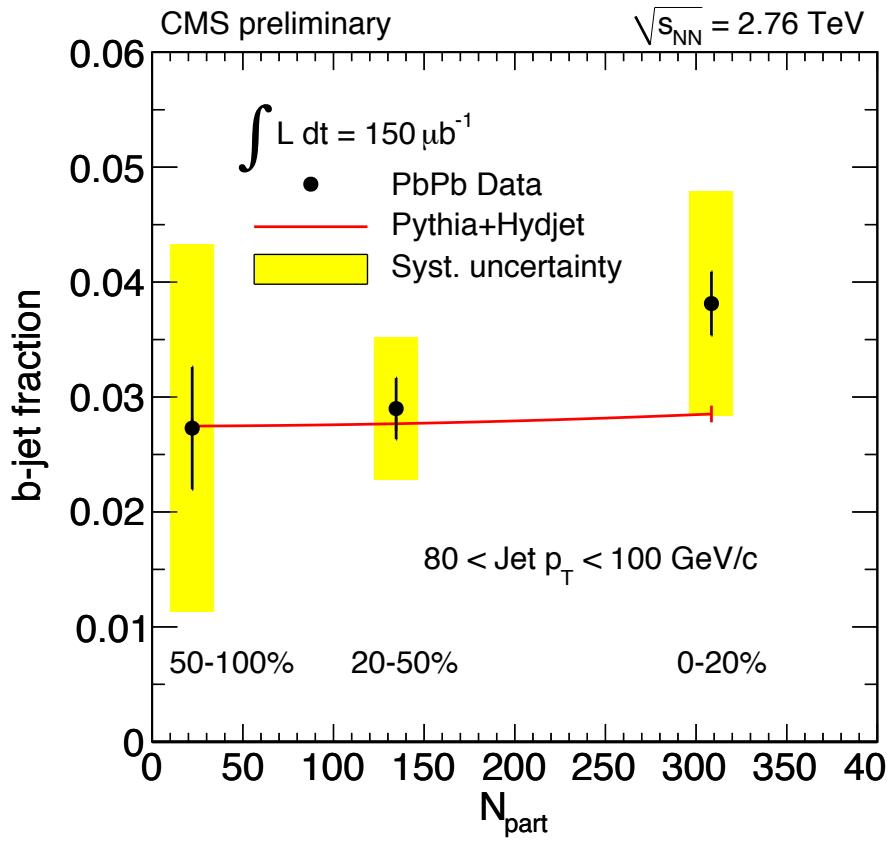


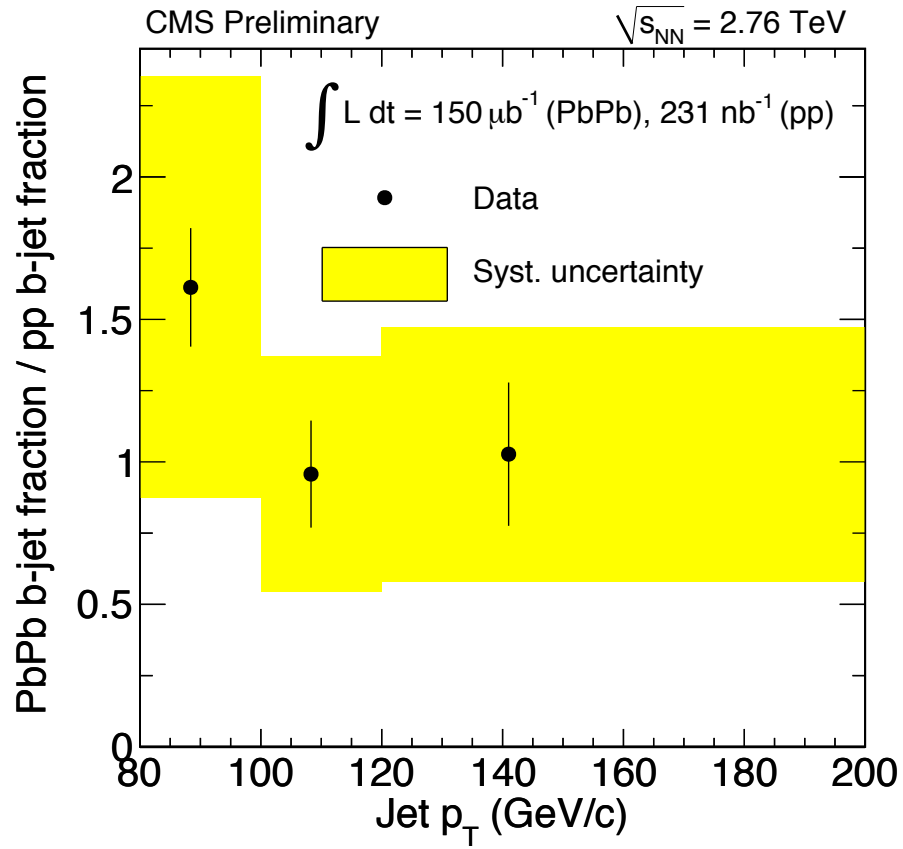

Strong suppression of inclusive high $p_T$ jets!
→Jet Energy not recovered within the jet cone.

CMS: HIN-12-004-PAS

# Flavor dependence?:

Exploit the lifetime of b quarks by looking for displaced (secondary) vertices.




- Within errors, the suppression of b quarks and light quarks are the same
- Result is independent of centrality and jet $p_T$

More detailed conclusions require analysis of larger 2013 pp dataset and future (2015 and beyond) high luminosity PbPb running.

See also Matt's talk

**CMS PAS HIN-12-003**

# Conclusions:

In central PbPb collisions at LHC, jet modifications are seen via measurements of:

$A_j$: di-jet and γ-jet $p_T$ imbalance while angular correlations are conserved.

Missing $p_T$: Energy is carried away by low $p_T$ particles far away from the jet axis.

Fragmentation Functions: Structure of reconstructed jets is modified towards an excess of particles at low $p_T$.

Jet Shapes: Structure of reconstructed jets modified towards an excess of particles far from the jet axis.

Inclusive Jets: Jet energy is not removed independent of R.

Flavored Jets: B-quarks are suppressed as much as u/d-quarks

# Are we there yet?

- In the works: The 2013 pp data

  Improvements in the background estimation

  Reaction plane dependence

- Open questions investigated: Impact of vacuum fragmentation on medium jet energy corrections

  High $p_T$ track selection on jet structures

  Jet selection bias; quark vs gluon jets

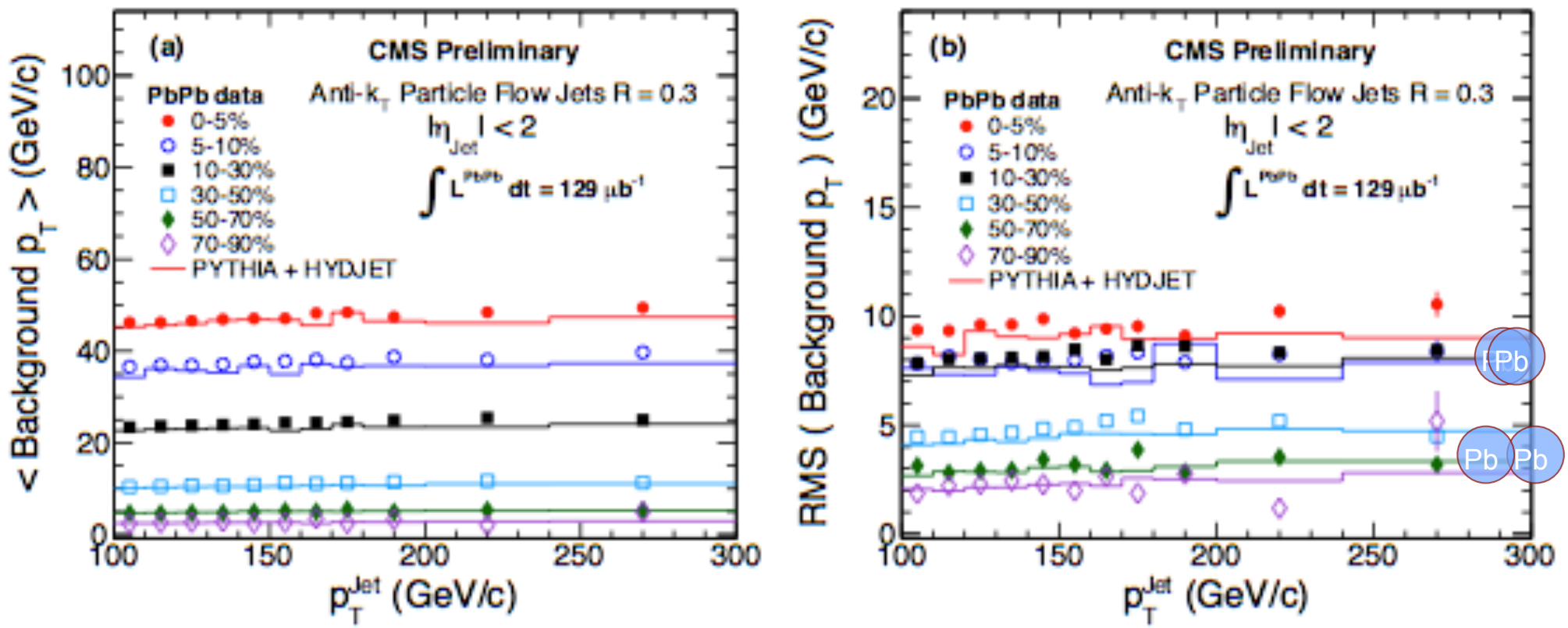
  Resolution parameter of jets and quenching

  and many more…

**The Age of Quantitative Jet Tomography has begun,**

**but we have yet to characterize medium parton interactions in detail.**

extras

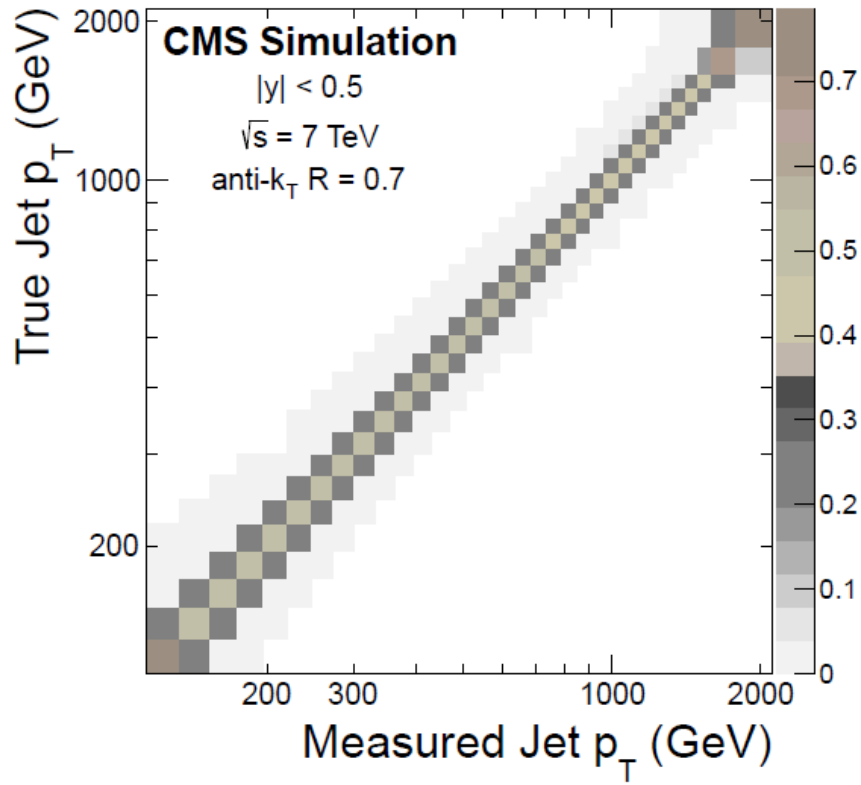



- Mean and width for background $p_T$ subtracted from jets
- Not detector η & $p_T$ energy corrected (factor ~10-25%)
  - ➡Be careful when comparing directly to jet $p_T$

# Final jet energy determination via unfolding:

- Measured jet spectra are corrected for jet energy resolution and energy scale using "unfolding techniques"
- Methods considered:
  - Bayesian unfolding as main results
  - Cross-check with bin-by-bin and SVD unfolding
  - Cross-check with "folding" (smear the pp reference)

pp collisions at 7 TeV




PRD 87 (2013) 112002