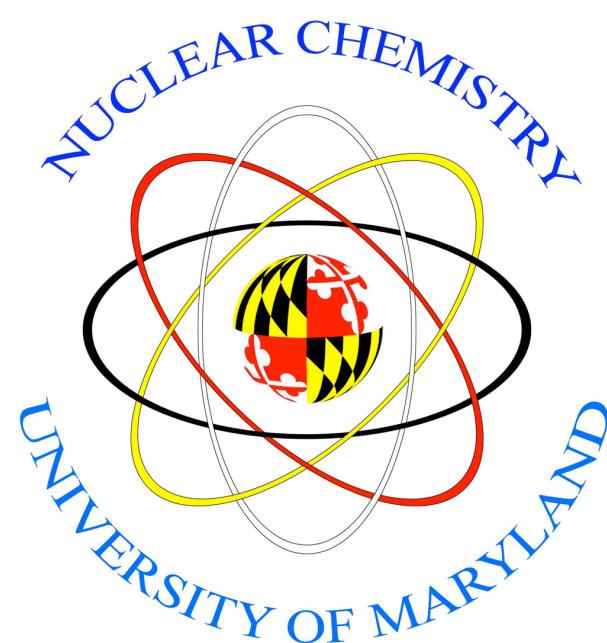
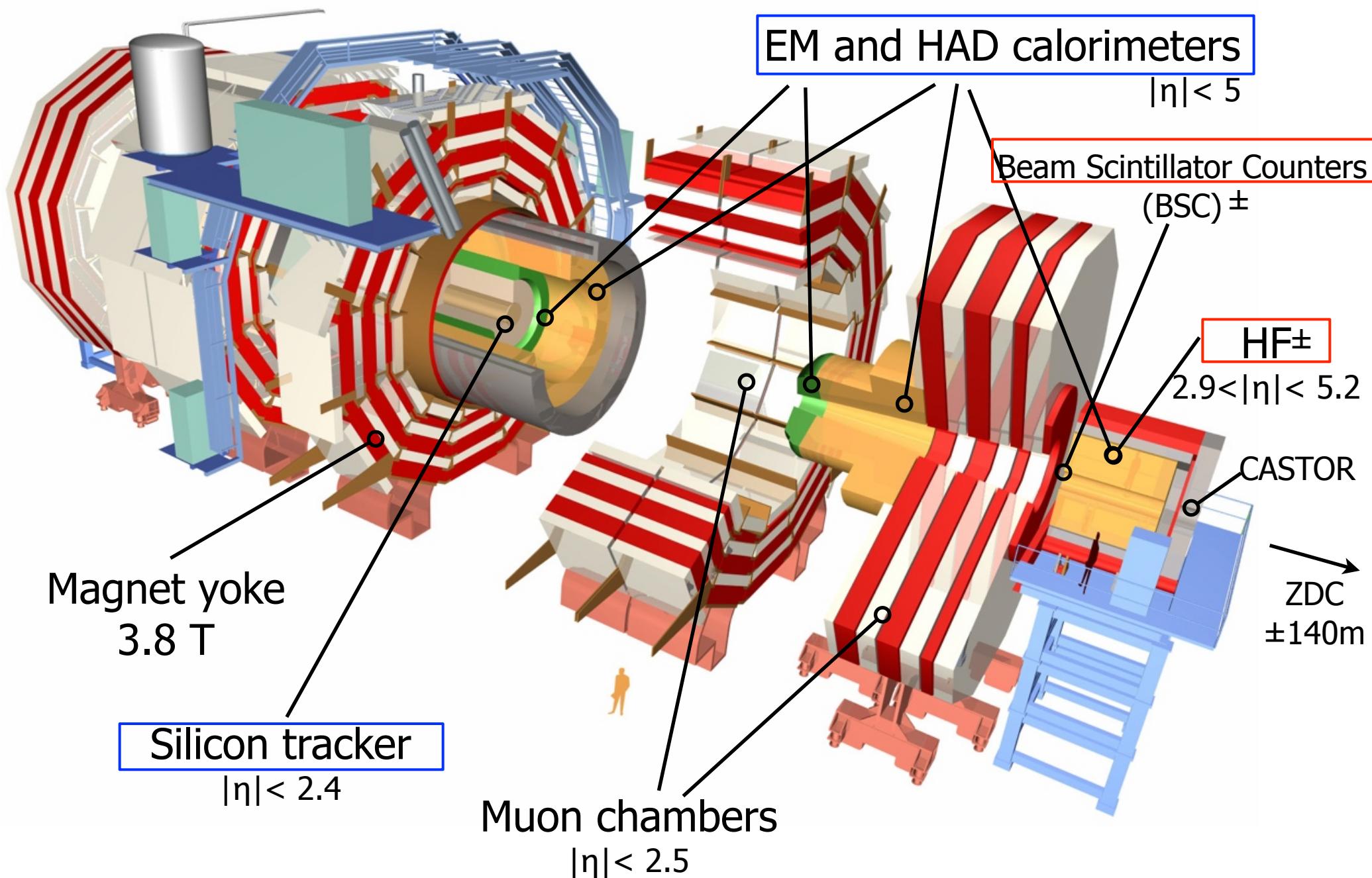


Study of Jet Quenching Using Dijets in PbPb Collisions with CMS

Marguerite Belt Tonjes
for the CMS Collaboration



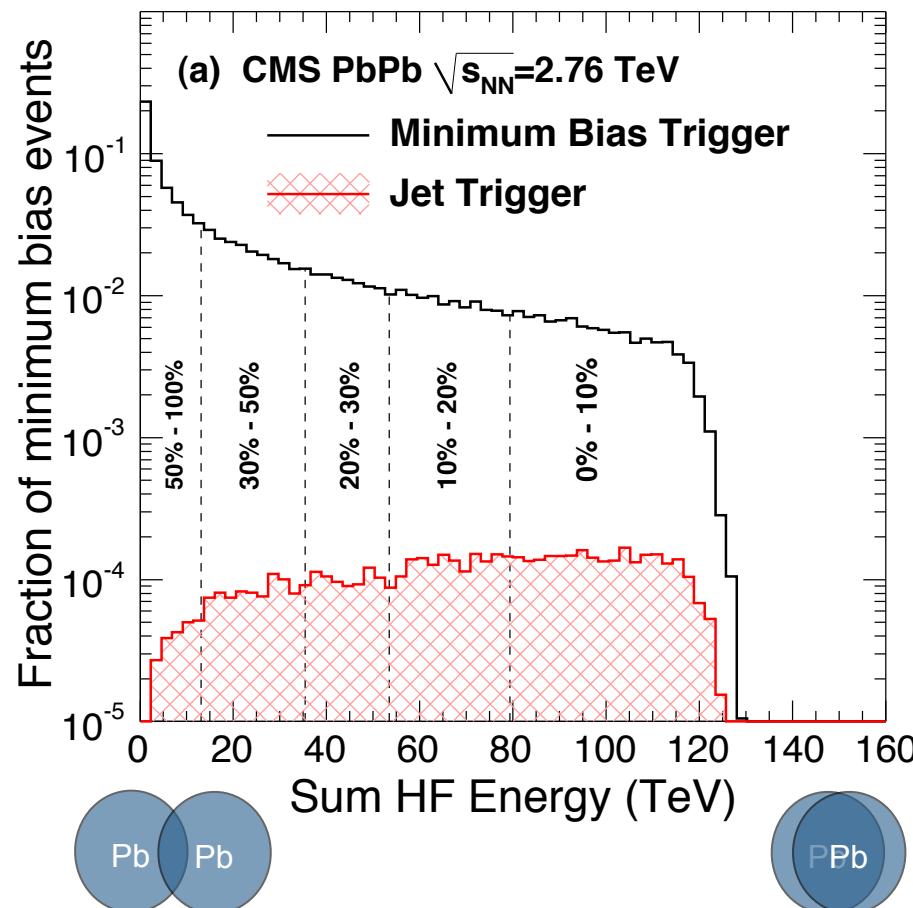
Compact Muon Solenoid (CMS)



Event Selection

CMS: arXiv:1102.1957

- November-December 2010
 - PbPb $\sqrt{s_{NN}} = 2.76$ TeV
- Jet Trigger
 - High level trigger: calorimeter jets found with same jet reconstruction algorithm used in this analysis
 - Trigger on single jets > 50 GeV/c (before energy correction)
 - Trigger: fully efficient for corrected jet $p_T > 100$ GeV/c
- Centrality: Determined by the total energy from both HF calorimeters
 - Centrality related to N_{part} with calculation based on Glauber model
- Simulations:
 - PYTHIA: QCD Dijets
 - PYTHIA+DATA: PYTHIA embedded in Minimum Bias PbPb data
 - PYTHIA+HYDJET: PYTHIA embedded in Minimum Bias HYDJET PbPb simulations



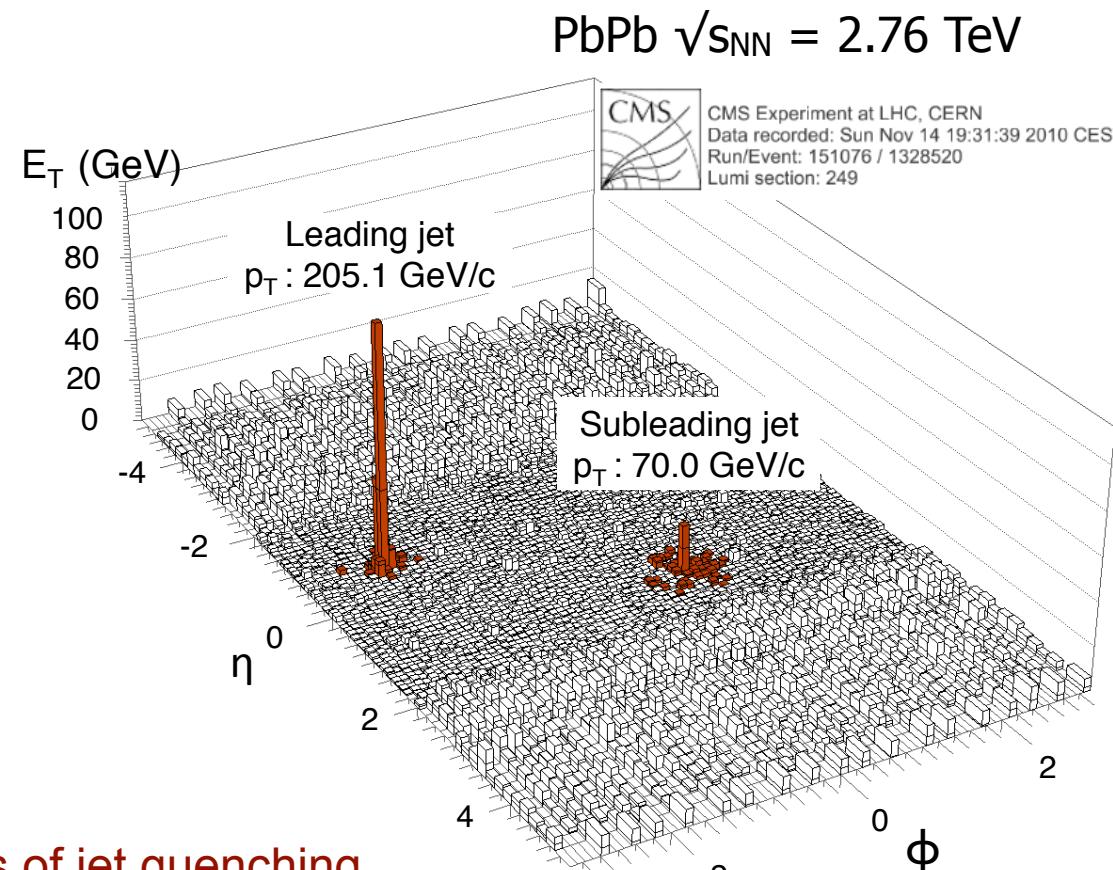
HYDJET: I. P. Lokhtin, Eur. Phys. J. C45 (2006) 211



Jet Selection

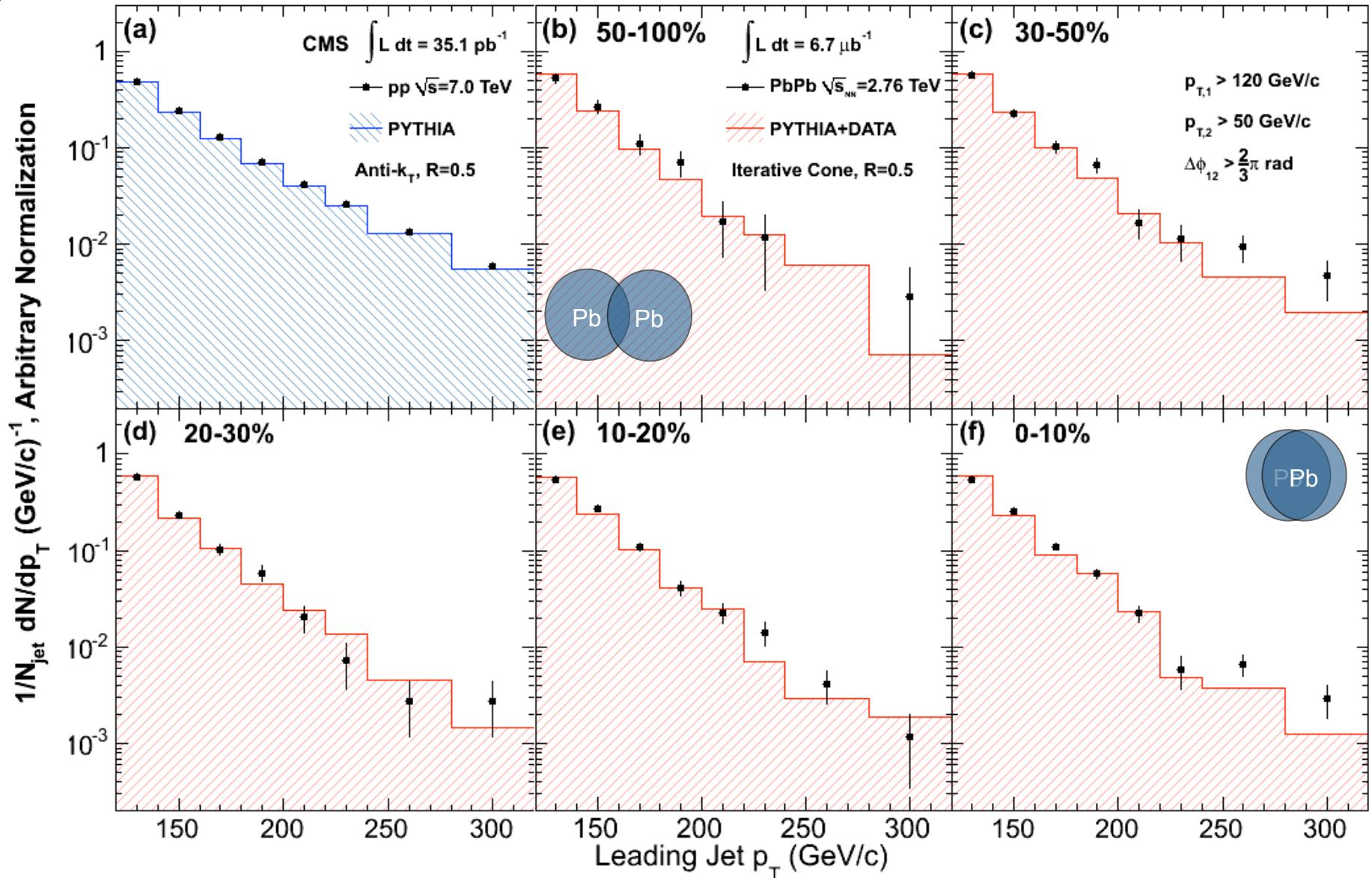
- Jets reconstructed with iterative cone $R=0.5$
- Heavy Ion background removed with iterative pileup subtraction
- Jets selected in $|\eta|<2$
 - Leading jet $p_{T,1}> 120 \text{ GeV}/c$
 - Subleading jet $p_{T,2} > 50 \text{ GeV}/c$
 - Corrections derived in pp applied to (ECAL+HCAL) jet energy

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



CMS collaboration: Observation and studies of jet quenching
in PbPb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$, arXiv:1102.1957
Submitted to Phys. Rev. C. 9 Feb 2011

Leading Jet p_T Distributions



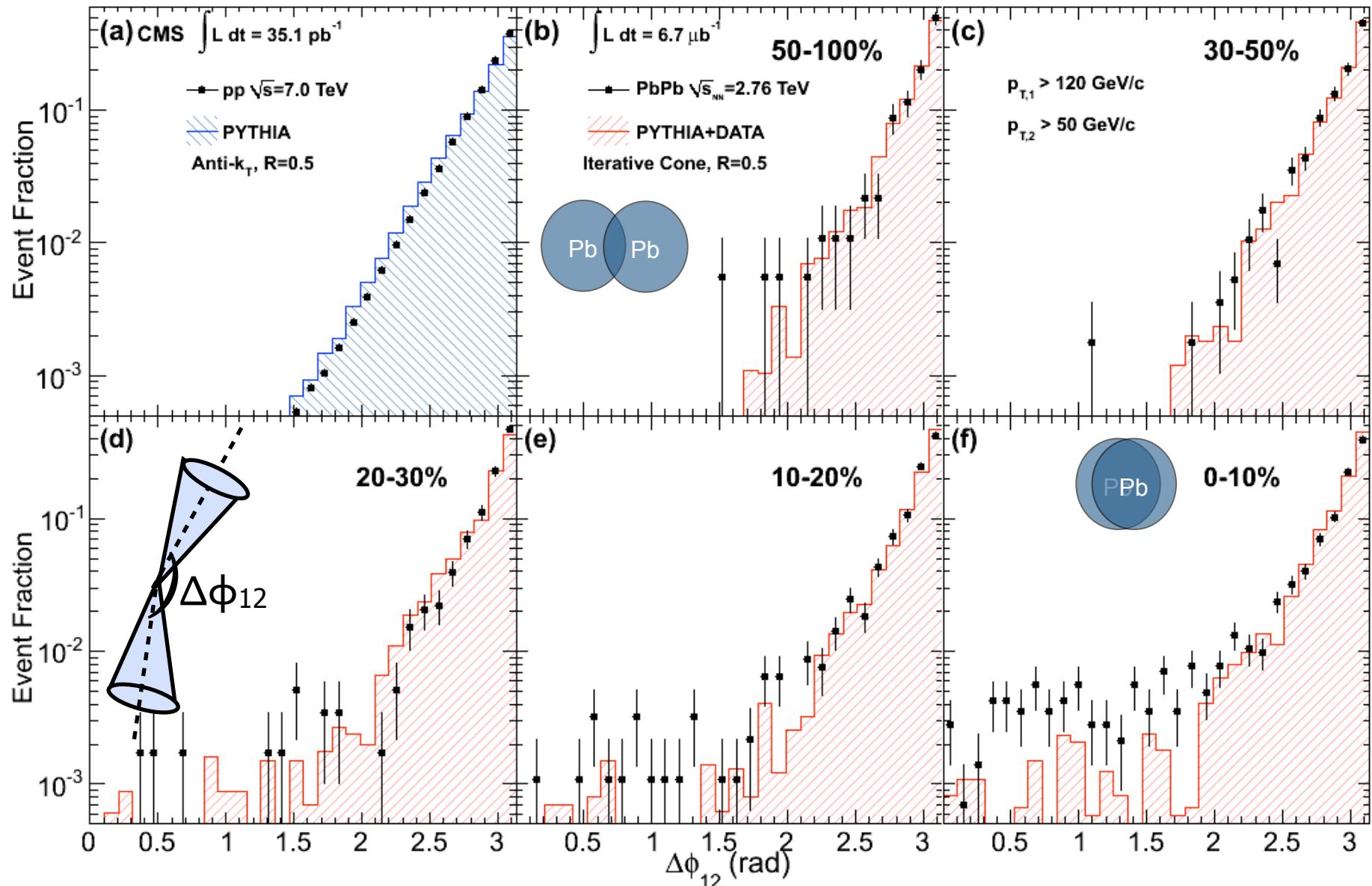
No strong modification to shape of leading jet spectrum

Note: spectra not unfolded

CMS: arXiv:1102.1957



Dijet Azimuthal Decorrelation



No strong angular deflection of reconstructed jets

CMS: arXiv:1102.1957



Marguerite Tonjes (UMD)

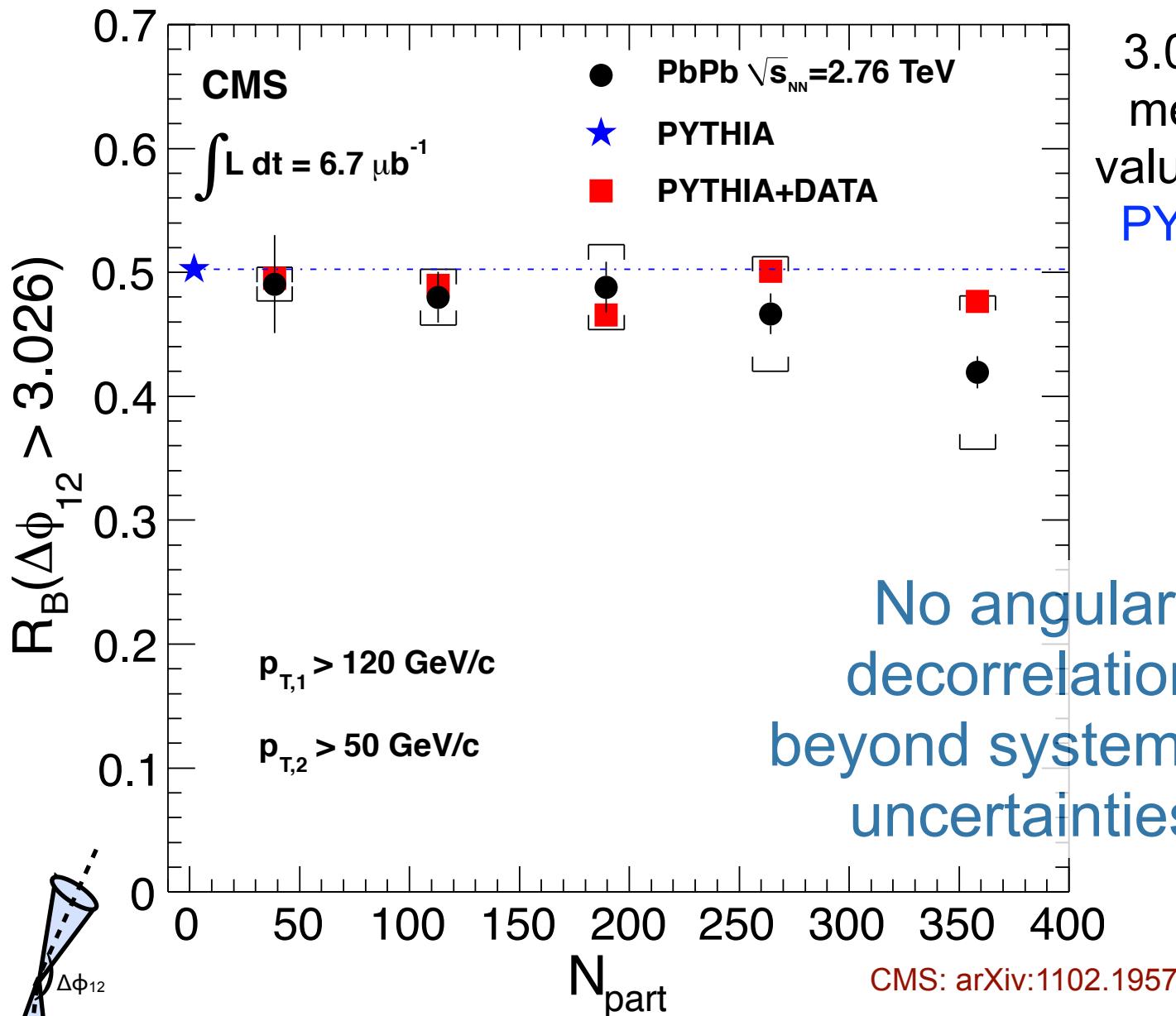
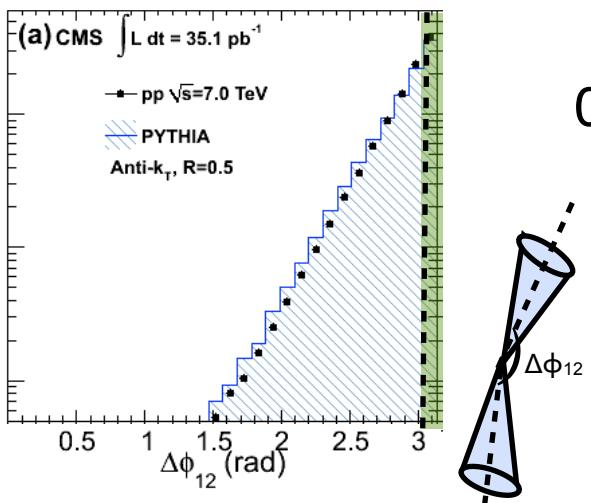
Quark Matter, Annecy, May 24 2011



Dijet Back-to-Back Fraction

$R_B(\Delta\phi)$:
fraction of
dijets well
balanced in
azimuthal
angle

Back-to-Back
All other dijet pairs



No angular
decorrelation
beyond systematic
uncertainties

CMS: arXiv:1102.1957

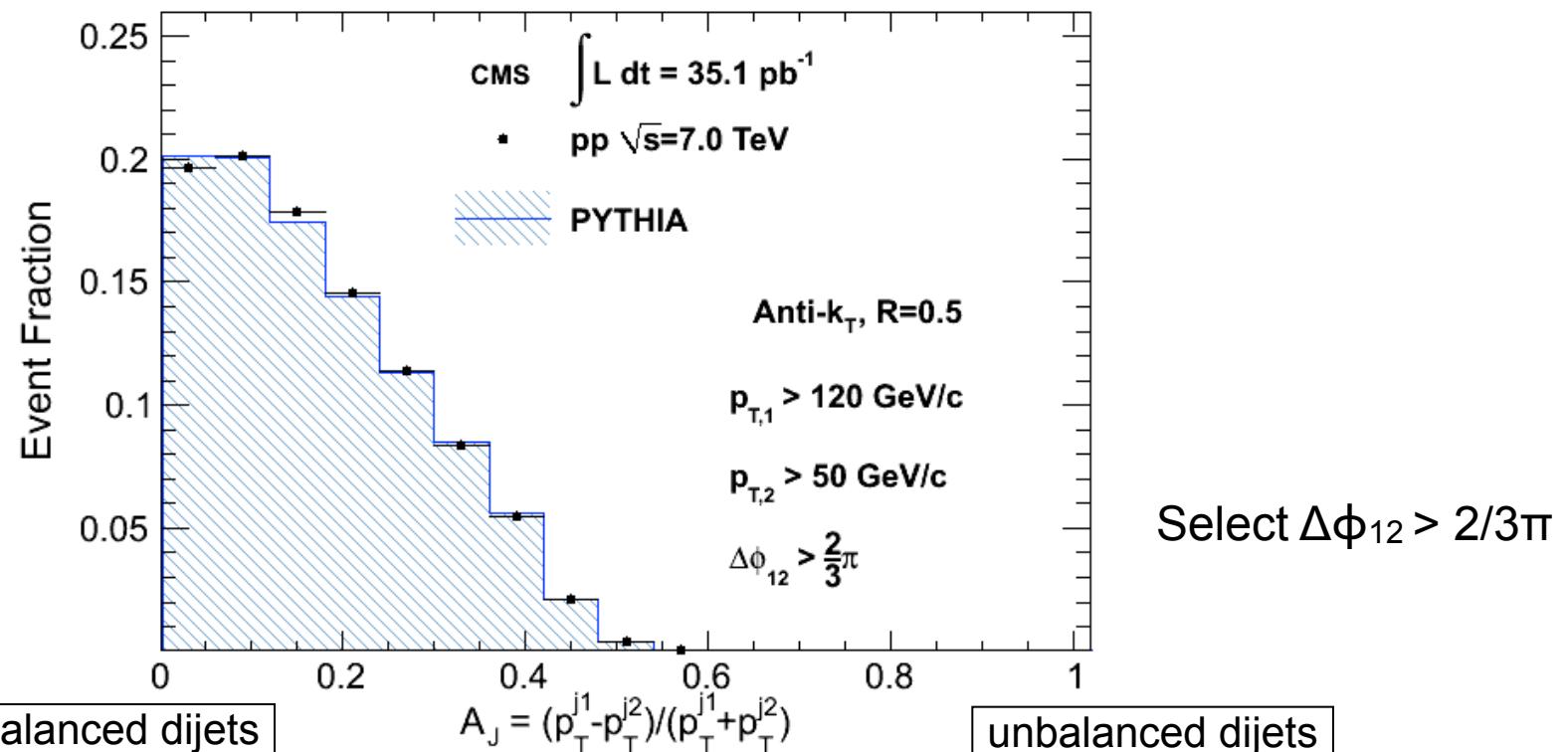
3.026 is
median
value from
PYTHIA

Dijet p_T Asymmetry

- Quantify dijet momentum 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

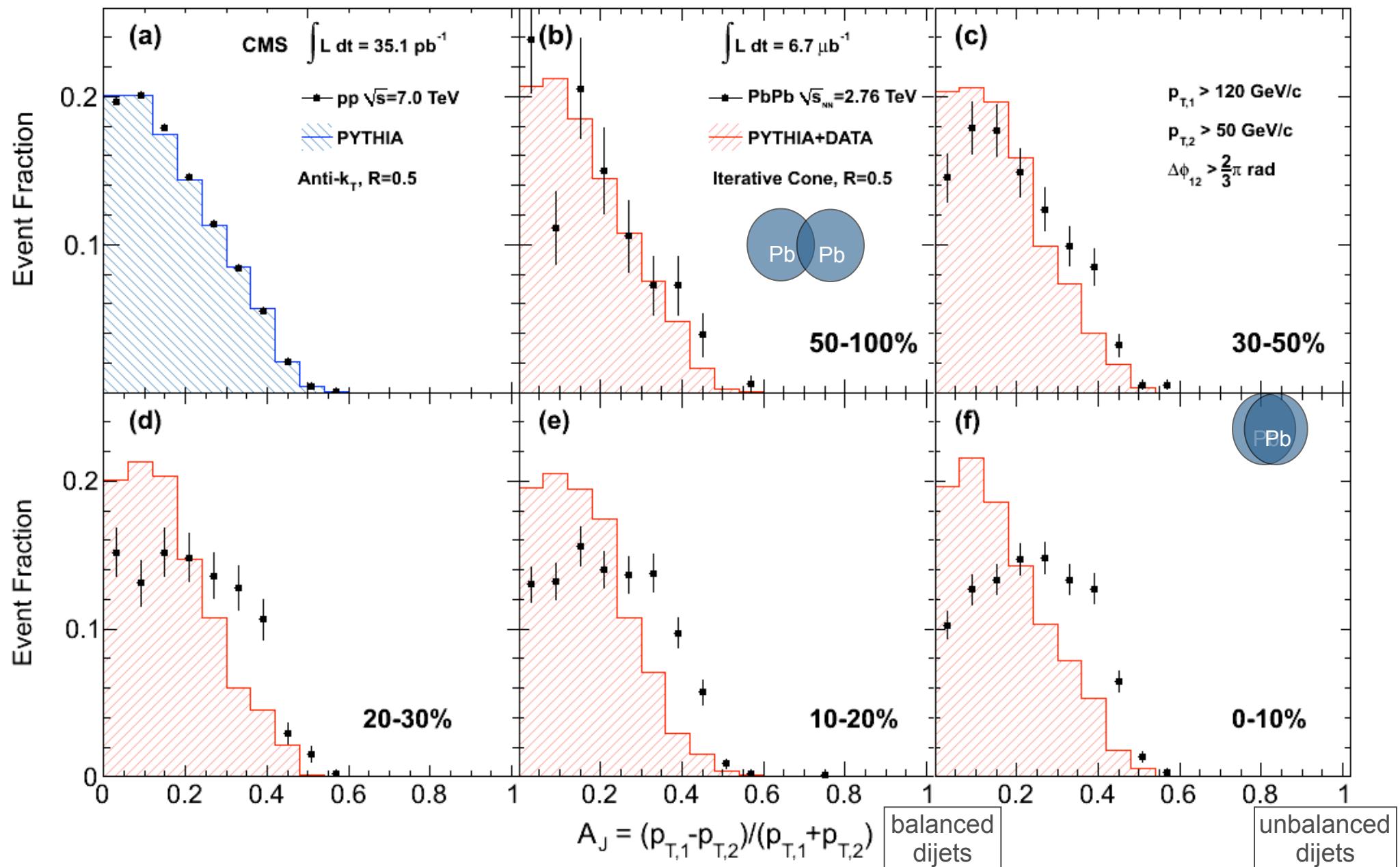


Jet p_T cuts place threshold on A_J ,

example: $p_{T,1} = 120 \text{ & } p_{T,2} > 50 \text{ GeV}/c \Rightarrow A_J < 0.41$



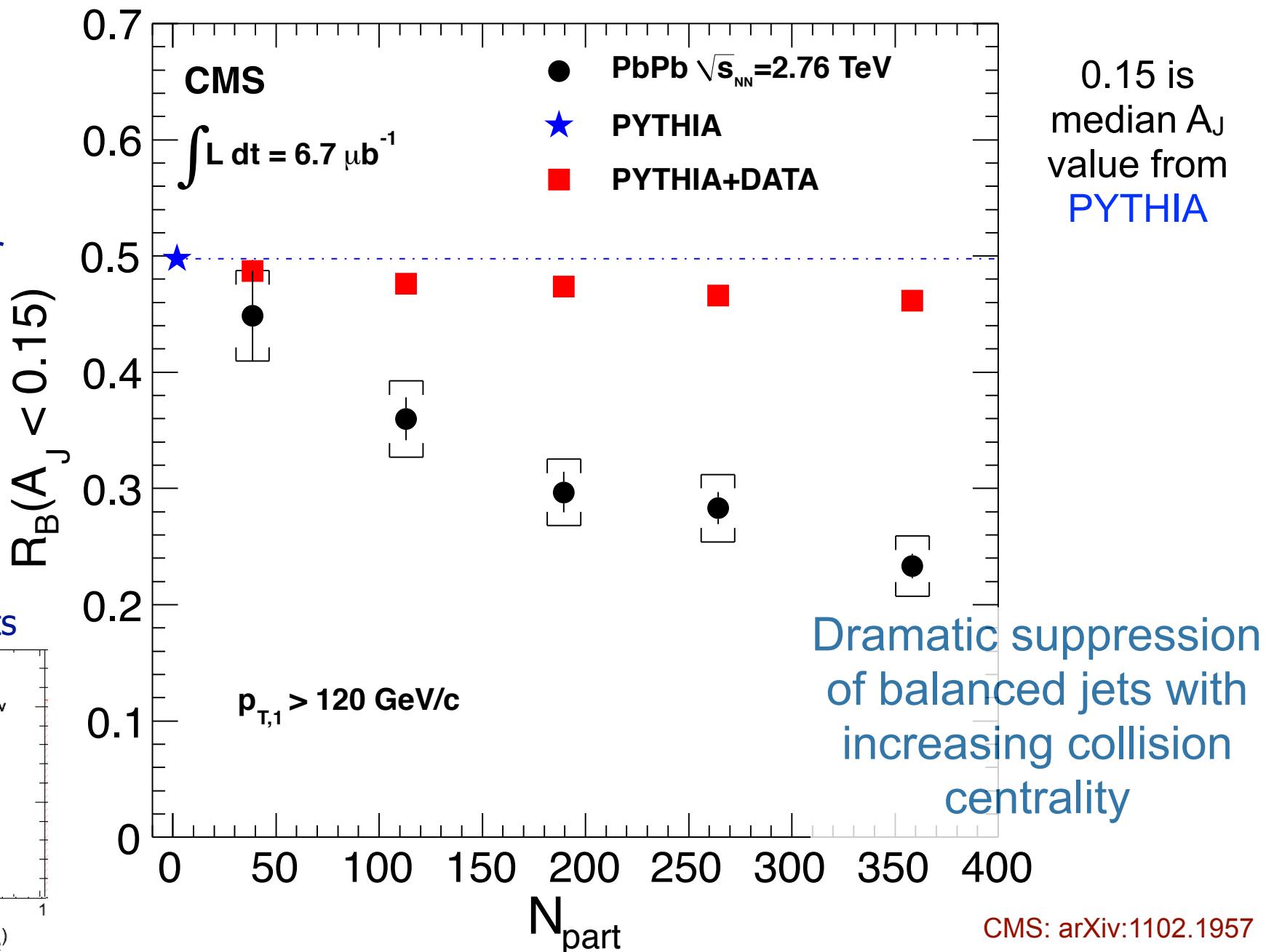
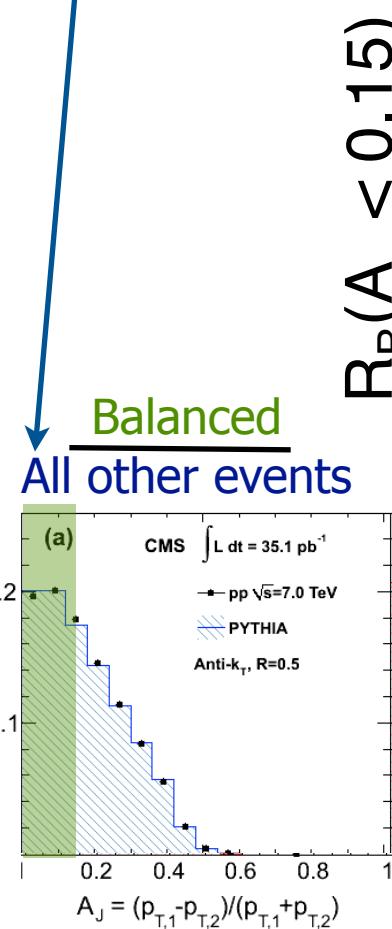
Dijet p_T Asymmetry



Striking enhancement of asymmetry in data with increased centrality

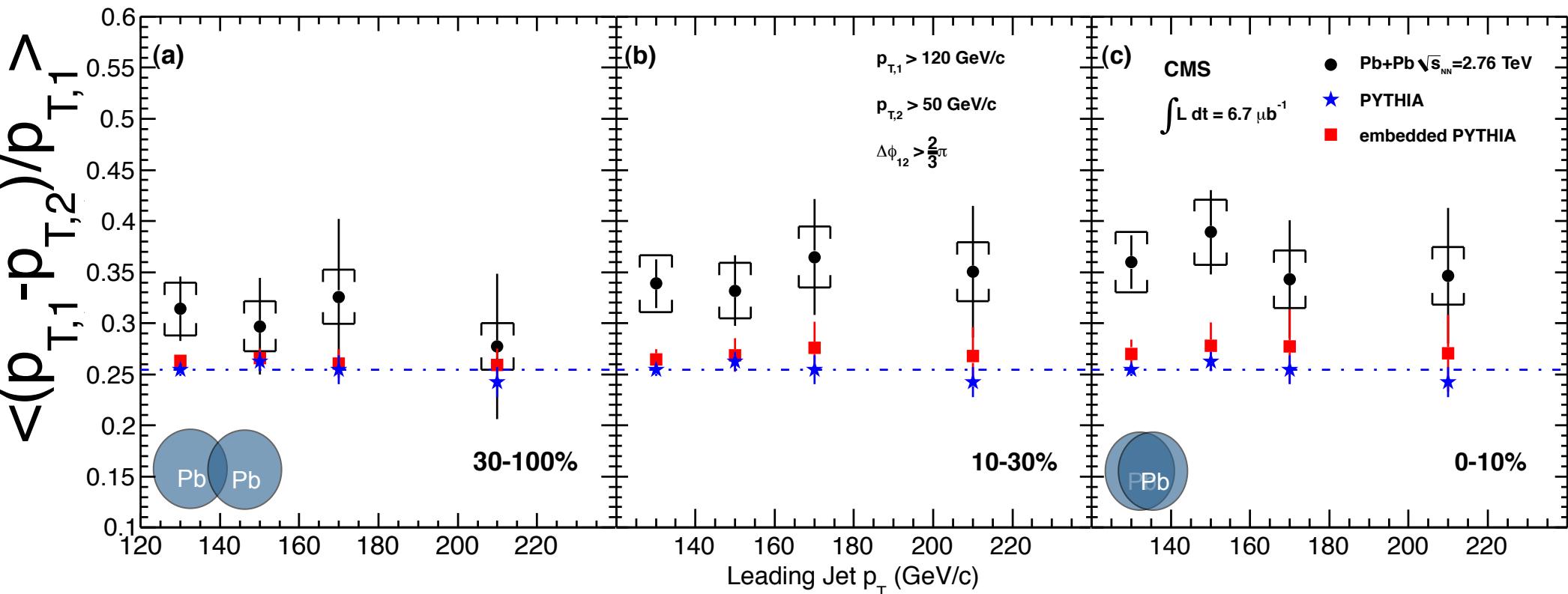
Fraction of Balanced Dijets

Apparent
'mono-jet'
events
included in
denominator



Leading Jet p_T dependence

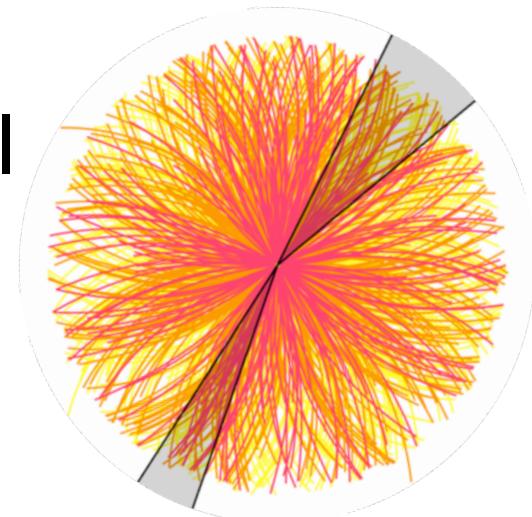
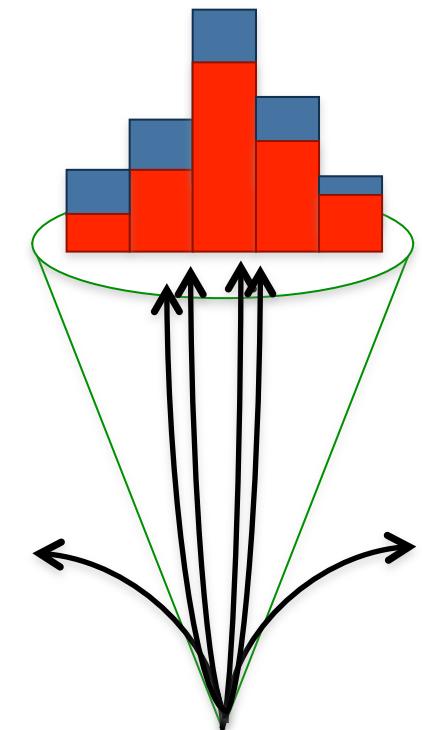
CMS: arXiv:1102.1957



Fractional imbalance varies little with leading jet p_T , even at highest leading jet p_T

Where Does the Missing Jet Energy Go?

- A large dijet energy imbalance is seen in the calorimeters
- By using the track information, we have an opportunity to do the *first in-depth studies* of where the energy goes
- Investigate missing momentum using all charged particle tracks



Missing p_T^{\parallel}

- Explore momentum balance to low p_T over all angles
- Projection of p_T onto leading jet axis:

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

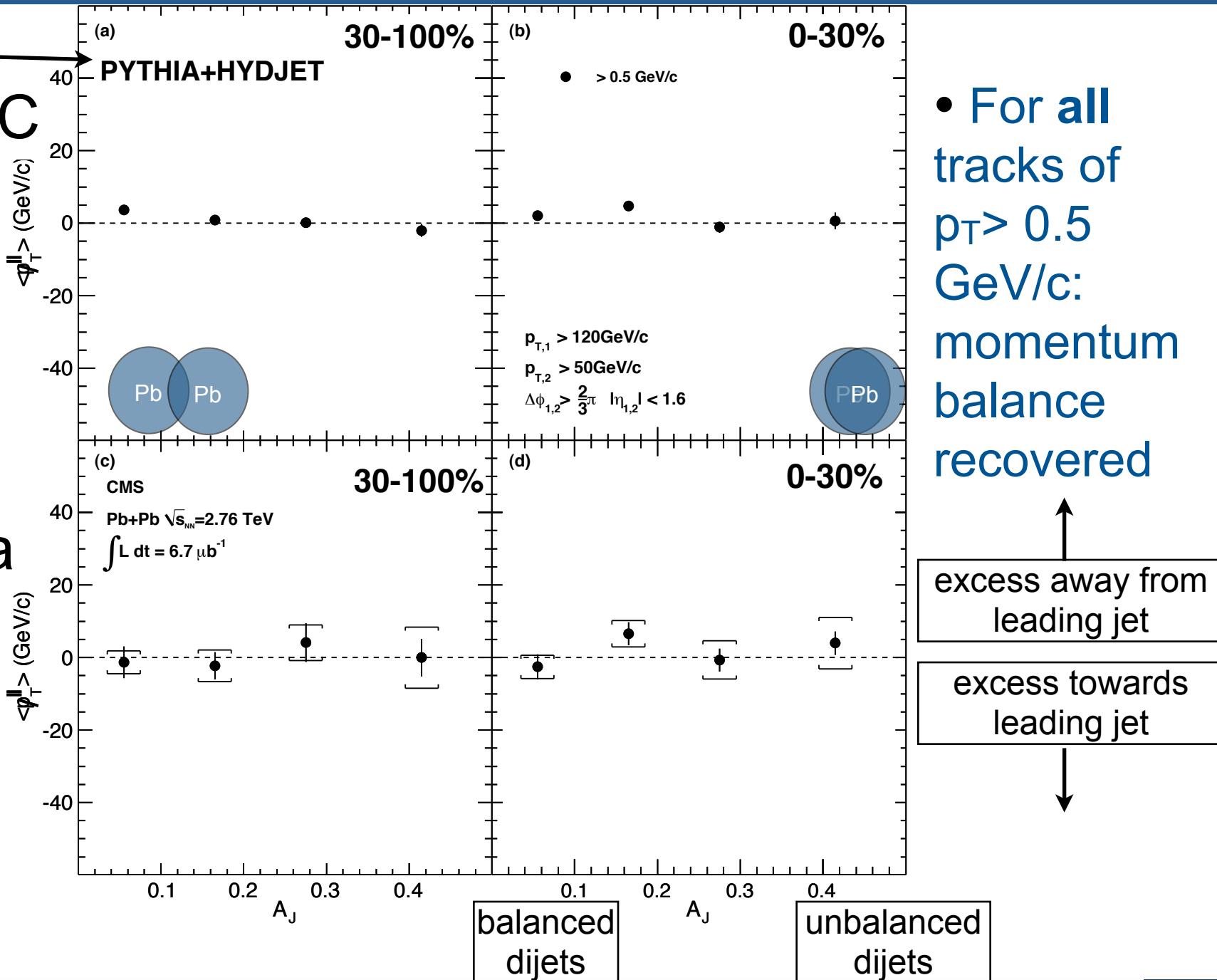
- Calculated for all tracks with $p_T > 0.5 \text{ GeV}/c$ and $|\eta| < 2.4$, and in various p_T ranges
- Averaged over events
- Allows us to see which p_T range carries the balance of the jet momentum
- Defined such that tracks on away side give a positive contribution
- No background subtraction needed



$\langle p_T \parallel \rangle$ vs. A_J

Baseline is
PYTHIA
+HYDJET MC
where
generator
information is
available for all
charged
particles

Data



CMS: arXiv:1102.1957



Marguerite Tonjes (UMD)

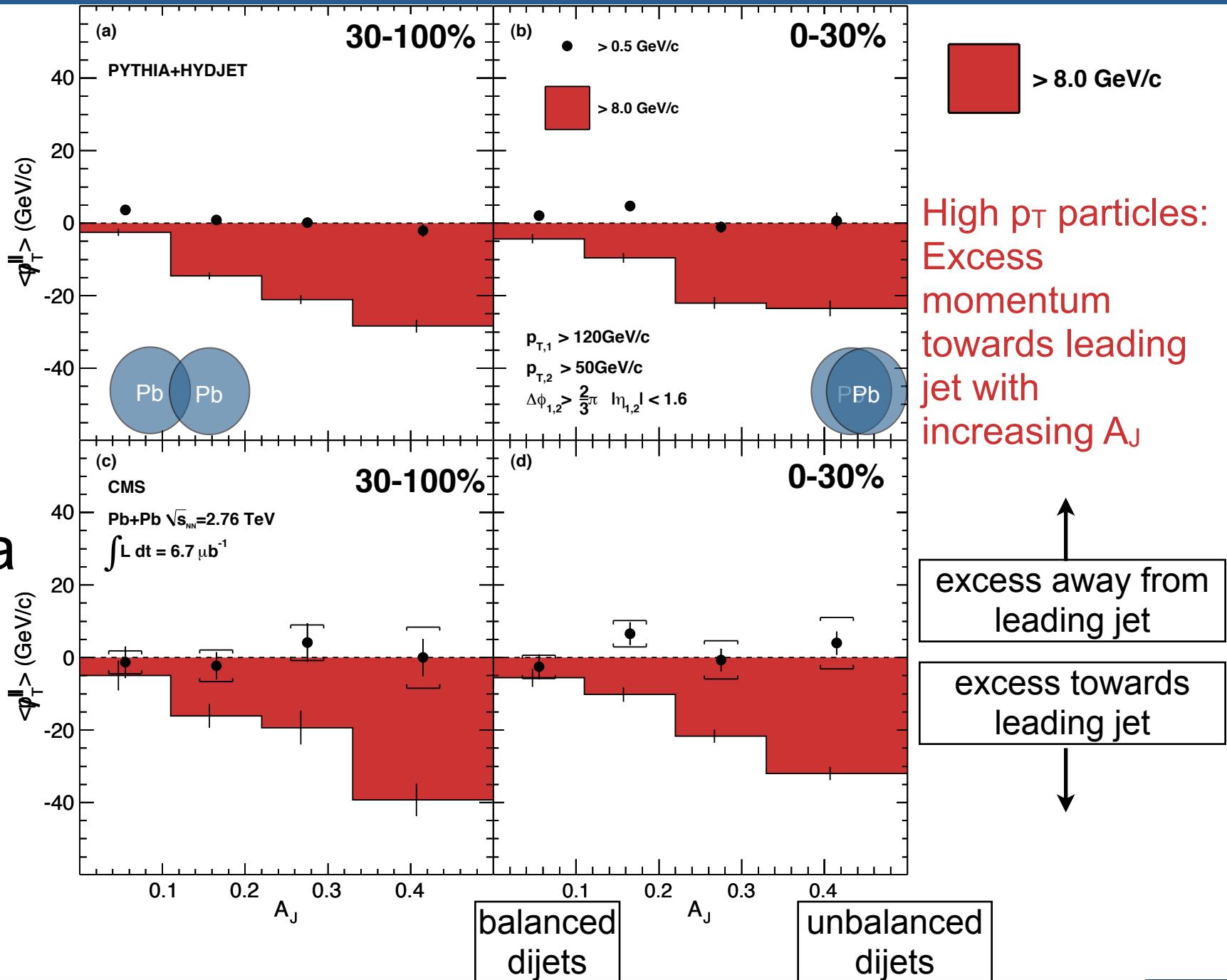
Quark Matter, Annecy, May 24 2011

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$\langle p_T \parallel \rangle$ vs. A_J

MC



CMS: arXiv:1102.1957



Marguerite Tonjes (UMD)

Quark Matter, Annecy, May 24 2011

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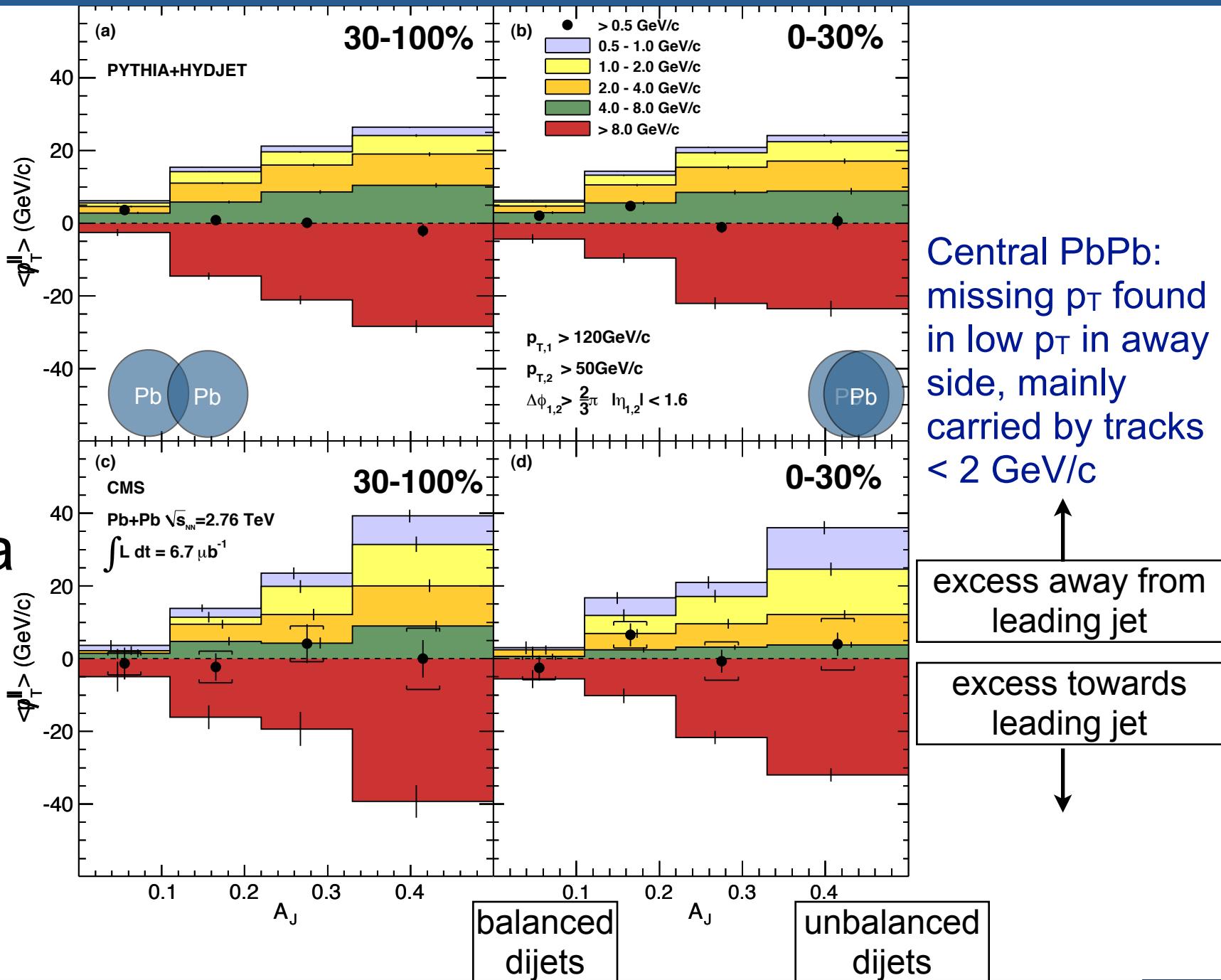


$\langle p_T \parallel \rangle$ vs. A_J

MC

MC: missing p_T
mostly carried
by tracks
 > 2 GeV/c

Data



CMS: arXiv:1102.1957



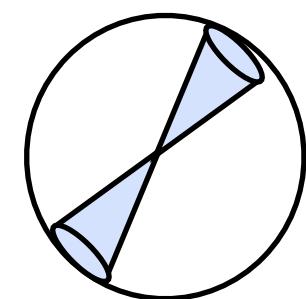
Marguerite Tonjes (UMD)

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Radial Dependence of $\langle \phi_T \parallel \rangle$

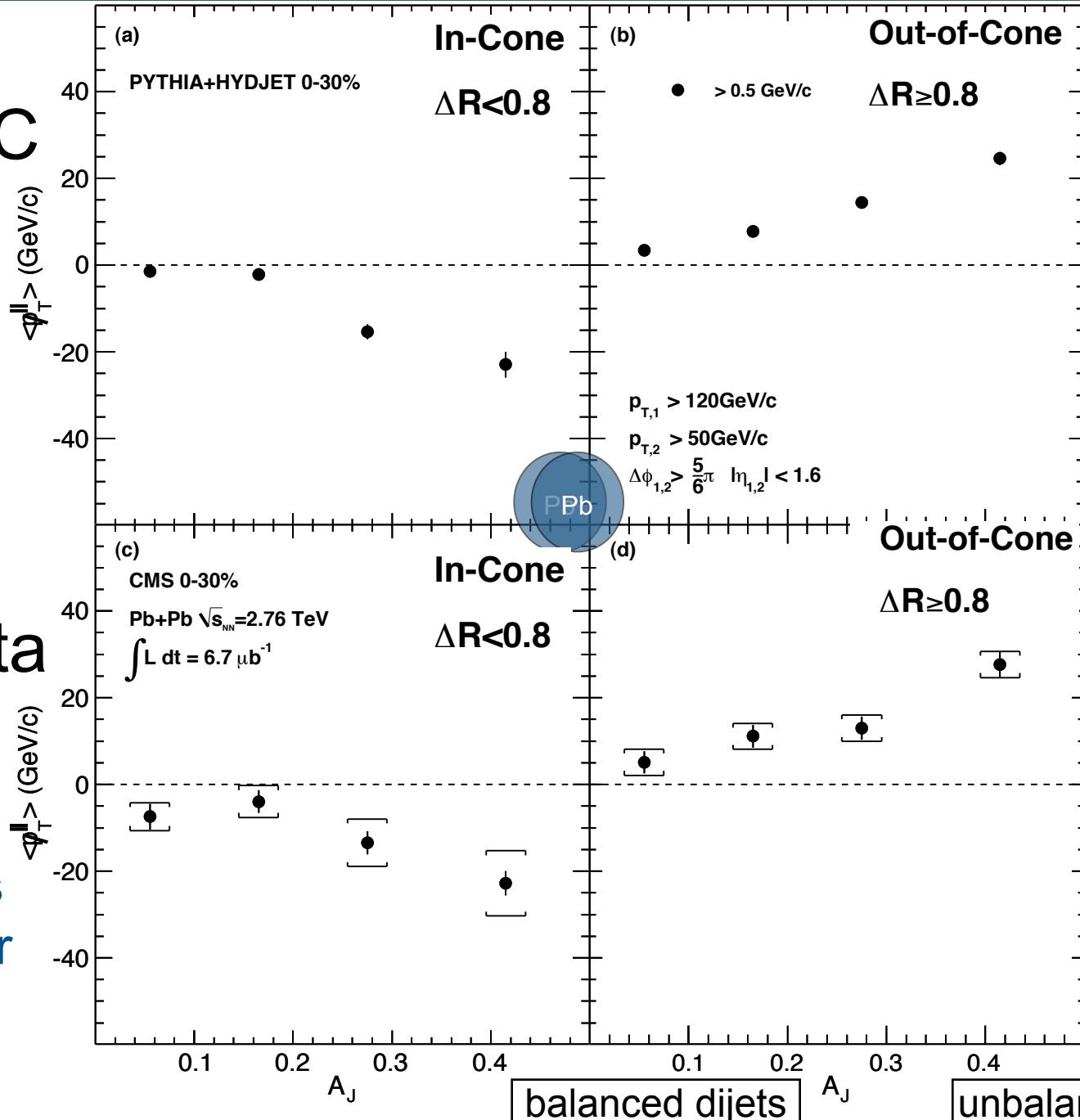


MC

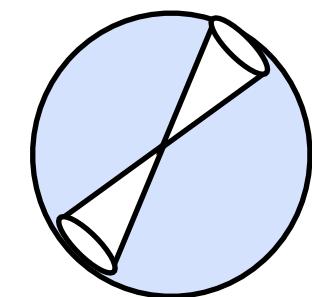
In-Cone
 $\Delta R < 0.8$

Data

In-cone
reproduces
Calorimeter
jet
asymmetry



Out-of-cone:
balance of
momentum
found



Out-of-Cone
 $\Delta R \geq 0.8$

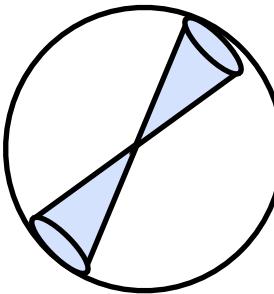
excess away from
leading jet

excess towards
leading jet

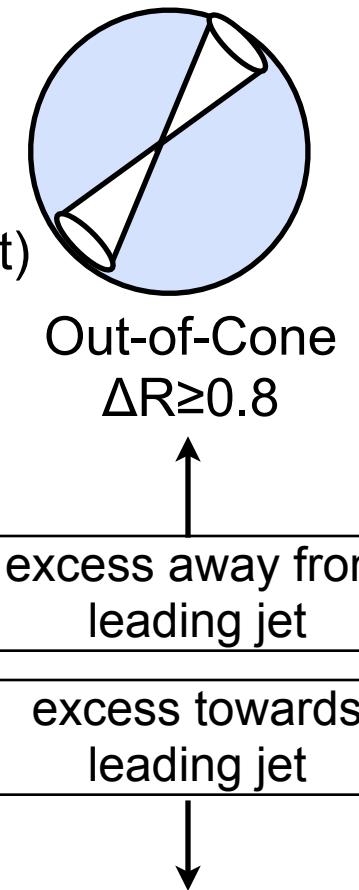
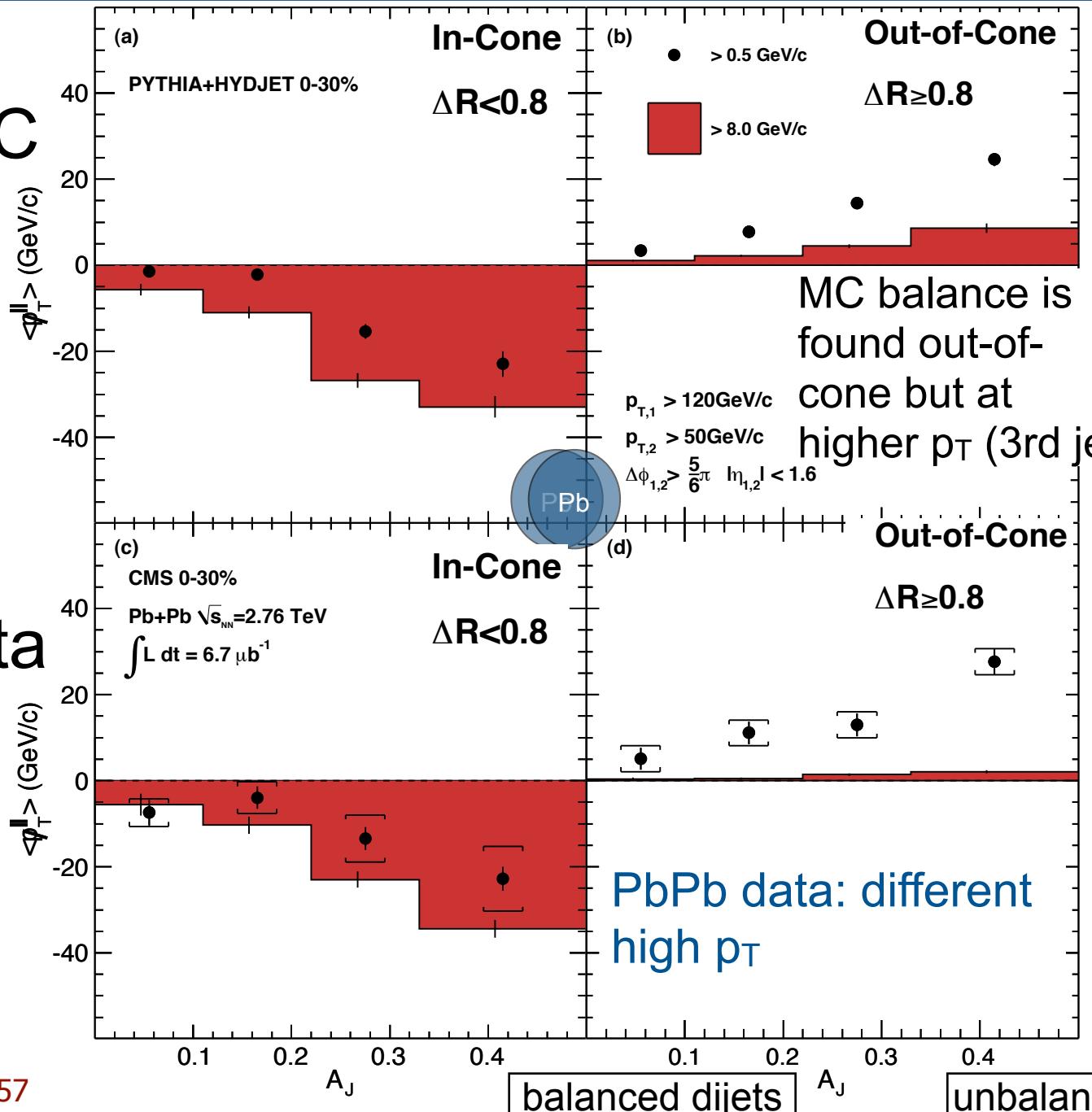


Radial Dependence of $\langle \vec{p}_T \parallel \rangle$

MC



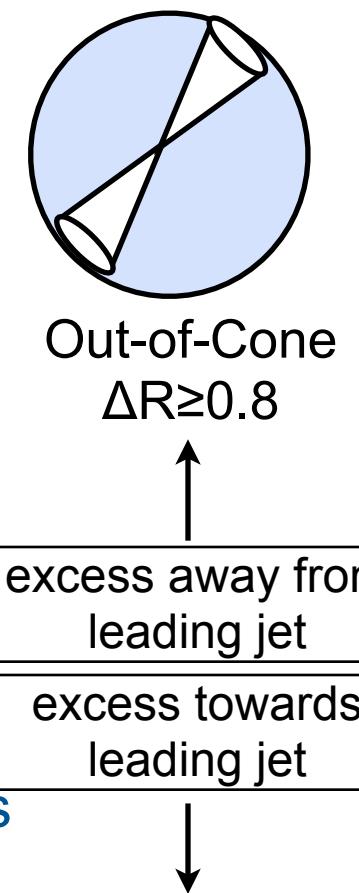
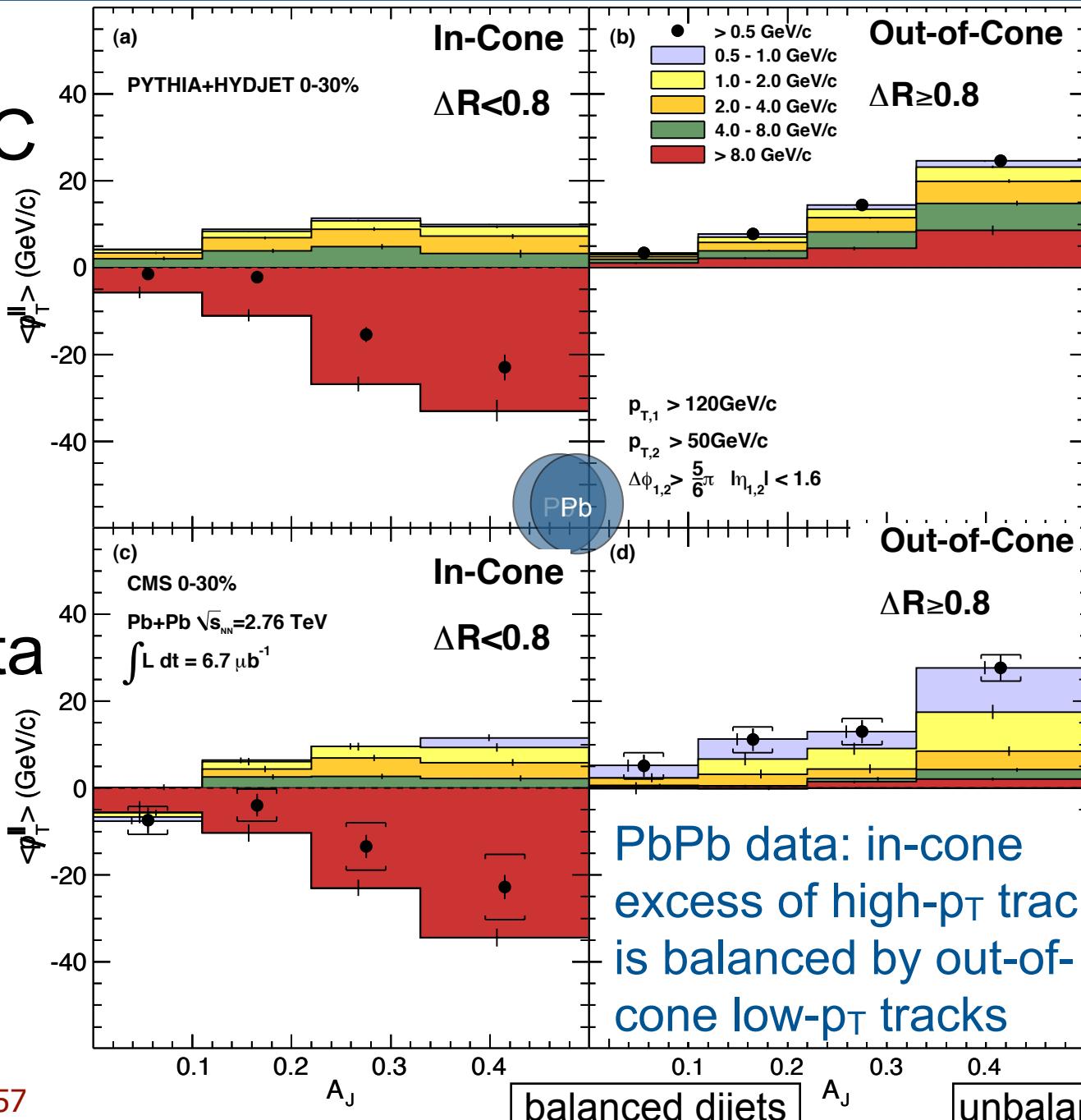
In-Cone
 $\Delta R < 0.8$



Radial Dependence of $\langle \phi_T \parallel \rangle$

MC

In-Cone
 $\Delta R < 0.8$



Summary

- Evidence for significant jet quenching in PbPb collisions has been observed
 - No large azimuthal decorrelation of jets
 - Large momentum imbalance with increasing centrality, extends to highest jet momenta measured (*above 200 GeV/c*)
 - Observed in calorimeter and charged particle tracks
 - Momentum transferred to low p_T particles ($p_T < 2 \text{ GeV}/c$)
 - A large fraction of the momentum is deposited outside the typical jet radius, away from the leading jet



More from CMS on Jets and High p_T Hadrons

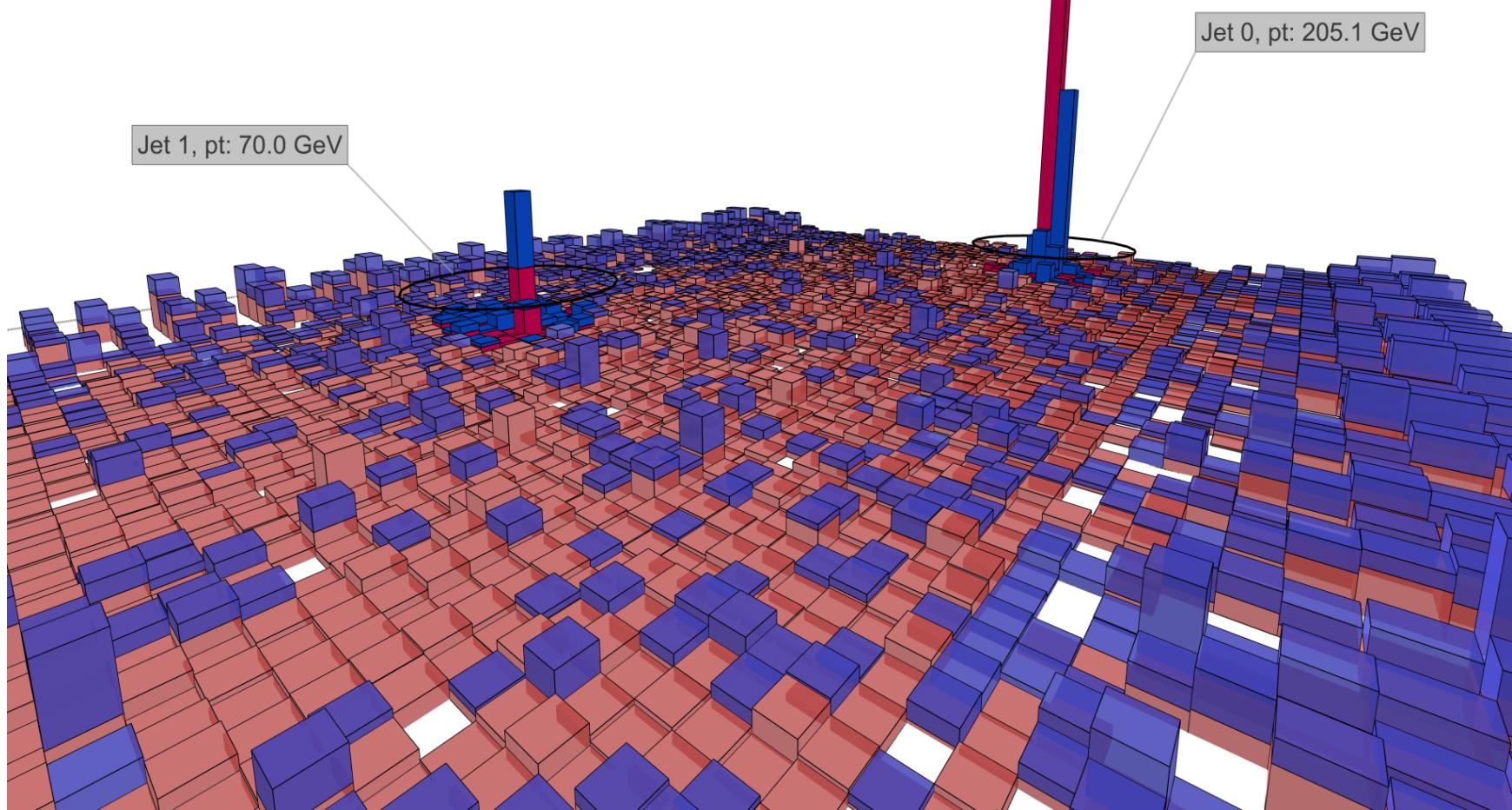
- *Yen-Jie Lee*, Wednesday 9:20am, plenary
 - Nuclear modification factors from the CMS experiment
- *Christof Roland*, Wednesday 11:35am, plenary
 - Jet measurements by the CMS experiment in pp and PbPb collisions,
- *Andre Yoon*, Thursday 4:20pm, parallel
 - Centrality and transverse momentum dependence of the nuclear modification of charged particle spectra in PbPb collisions at 2.76 TeV from CMS
- *Matthew Nguyen*, Friday 3:00pm, parallel
 - Jet Reconstruction with Particle Flow in Heavy-Ion Collisions with CMS
- *Yetkin Yilmaz*, Friday 5:30pm, parallel
 - Dijet Fragmentation Functions Measured in PbPb Collisions with CMS

Fin



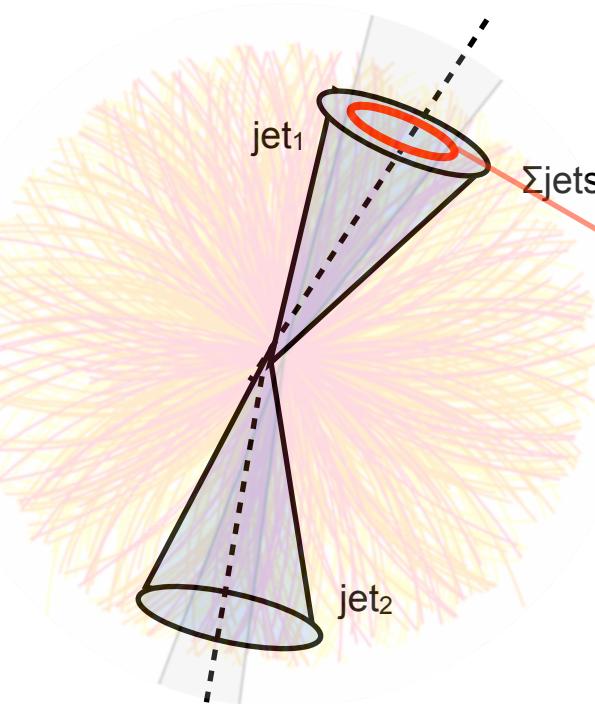
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249

PbPb $\sqrt{s_{NN}} = 2.76 \text{ TeV}$

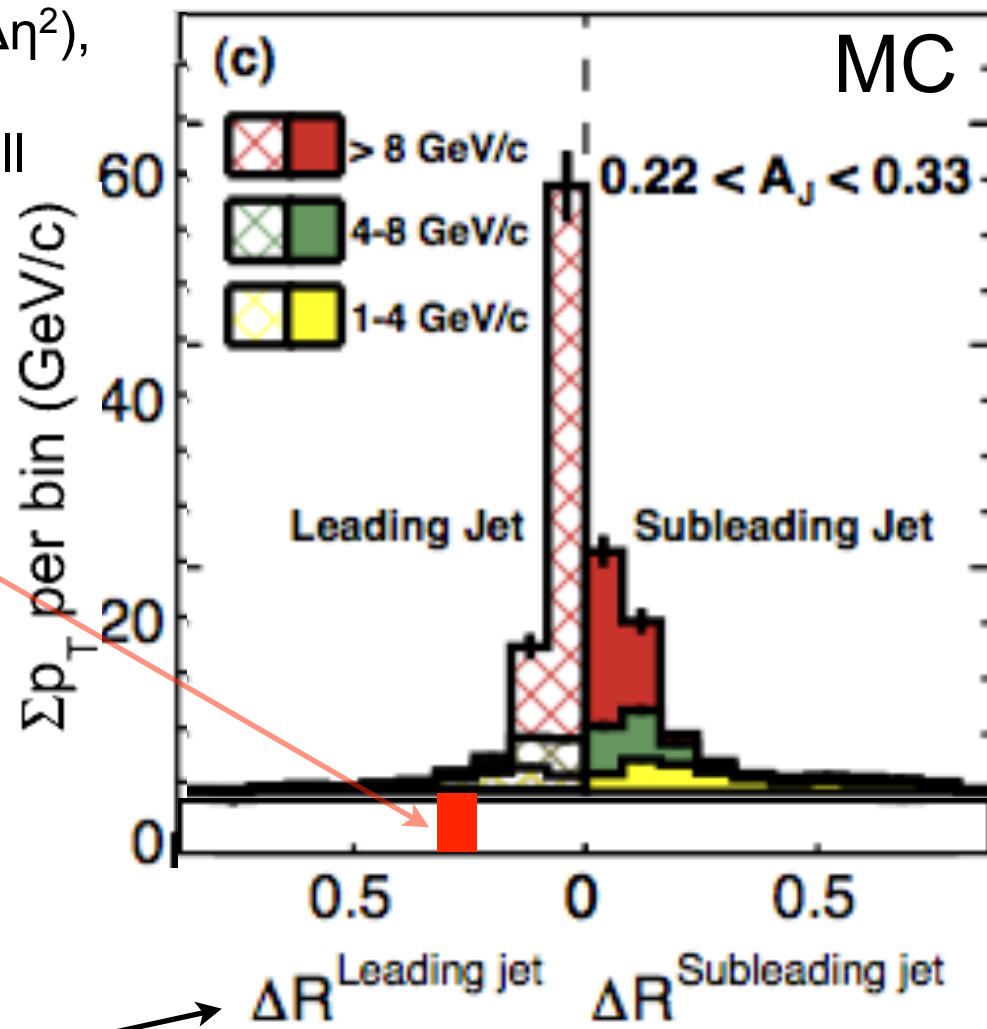


Jet-Track Correlations

p_T distribution of **tracks** found in a **ring** of $\Delta R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)}$, and width **0.08** around jet axes, then *summed* over all selected jets



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



Separate into bins of dijet asymmetry

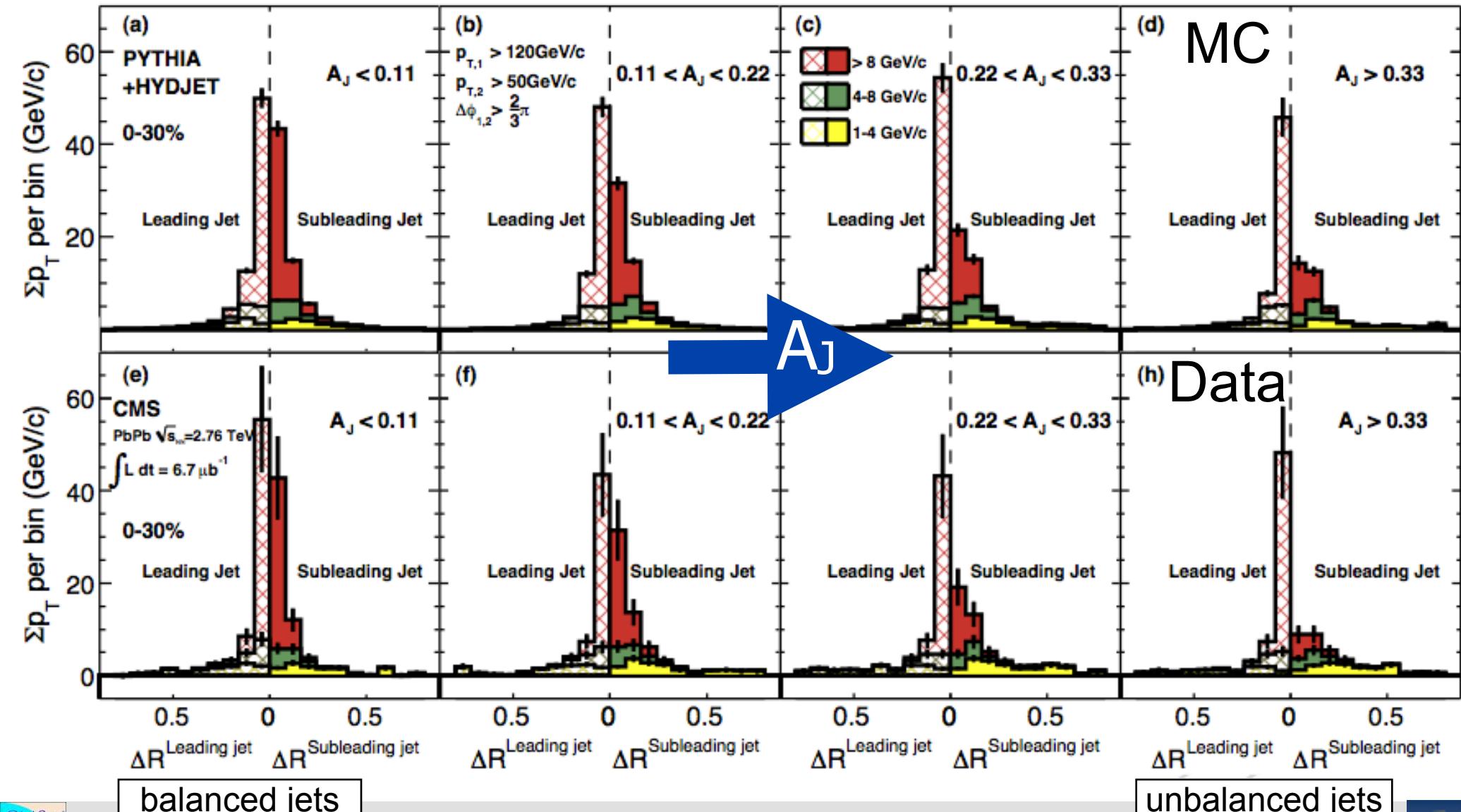


Look at the sum p_T of charged tracks in 3 different p_T ranges

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

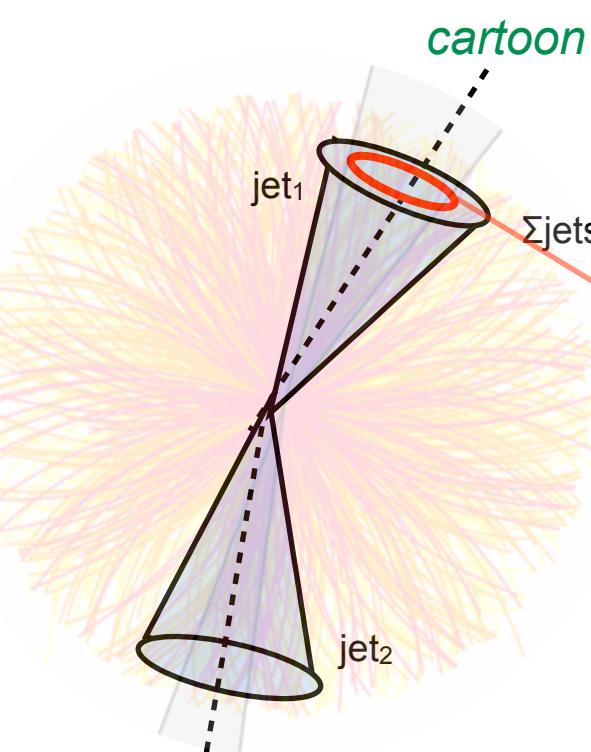
Asymmetry Dependence of Fragmentation

- Data & Monte Carlo, calorimeter asymmetry also evident in tracks
- Data: fraction of energy carried by low p_T tracks increases with asymmetry
- High A_J Data: enhancement of low p_T tracks at large angles is observed

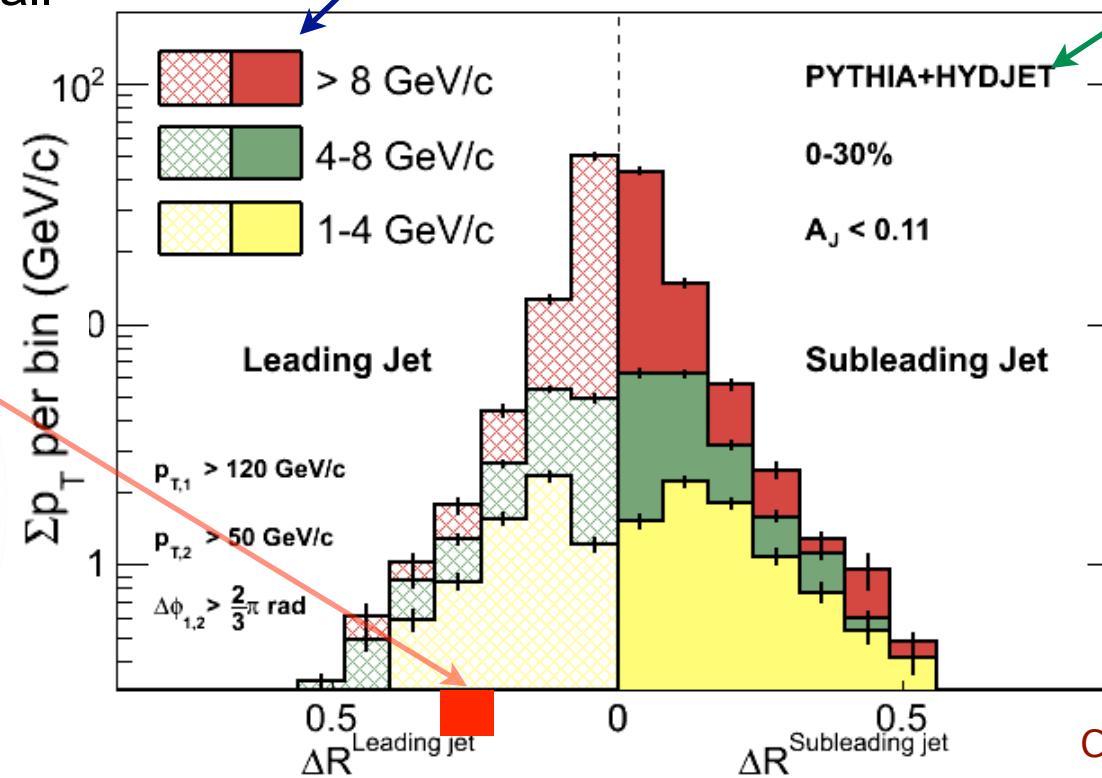


Jet-Track Correlations

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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 all charged particles

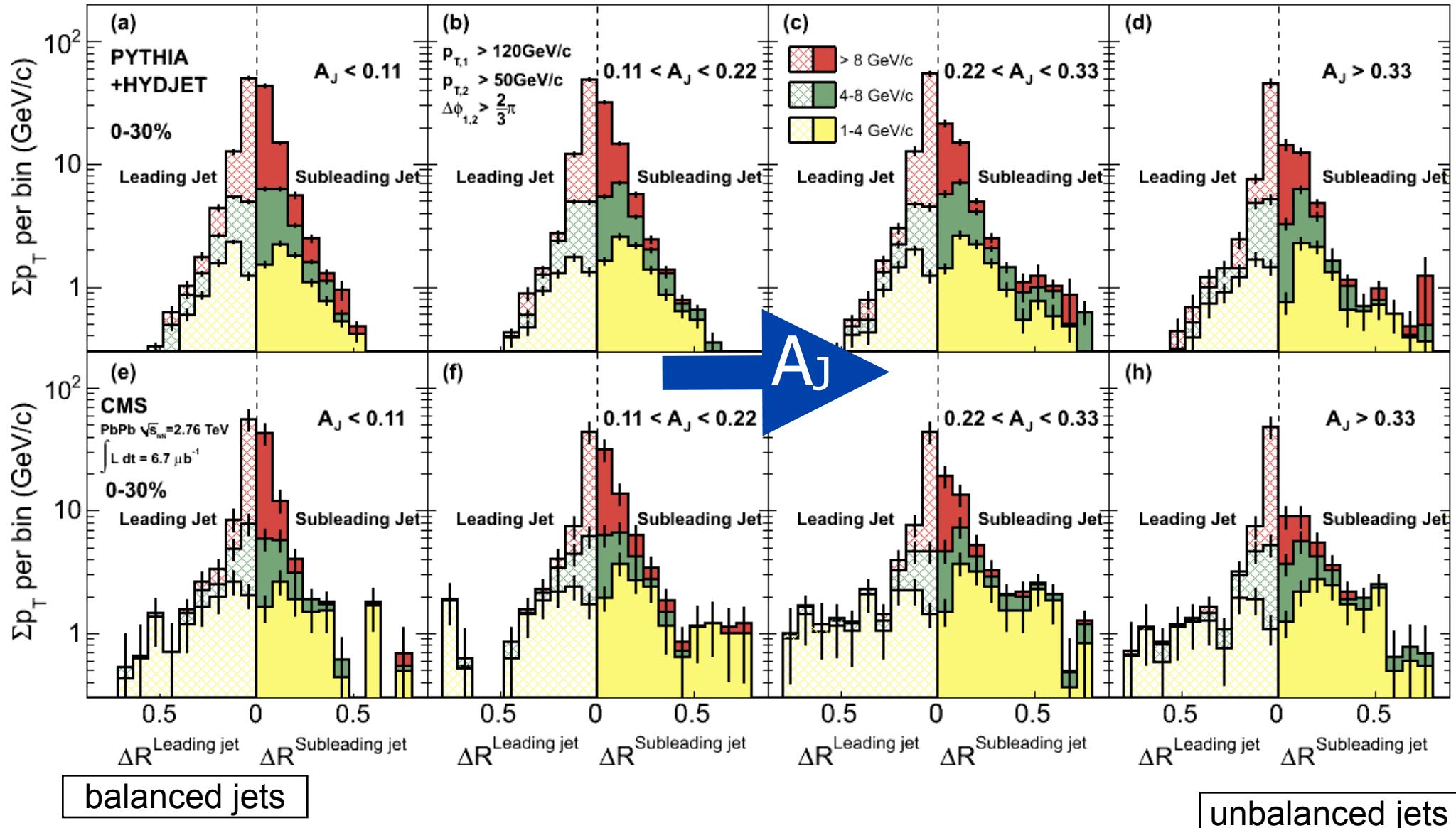
Plot against ΔR from the jet axis for both the leading and subleading jet

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Asymmetry Dependence of Fragmentation

- High A_J Data: Enhancement of low p_T tracks at large angles is observed



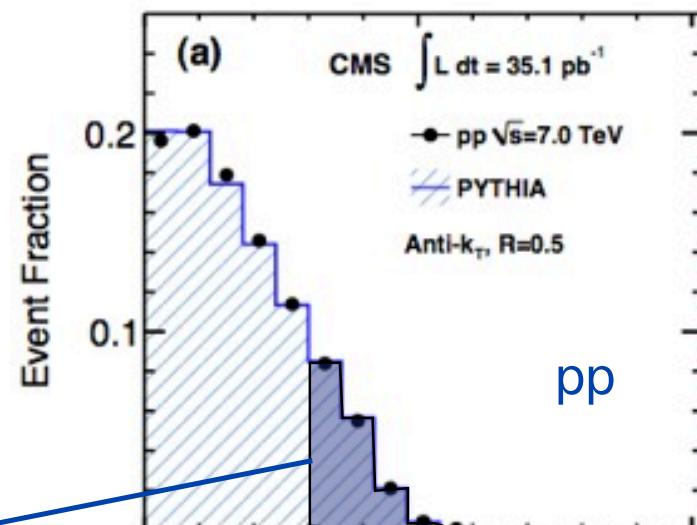
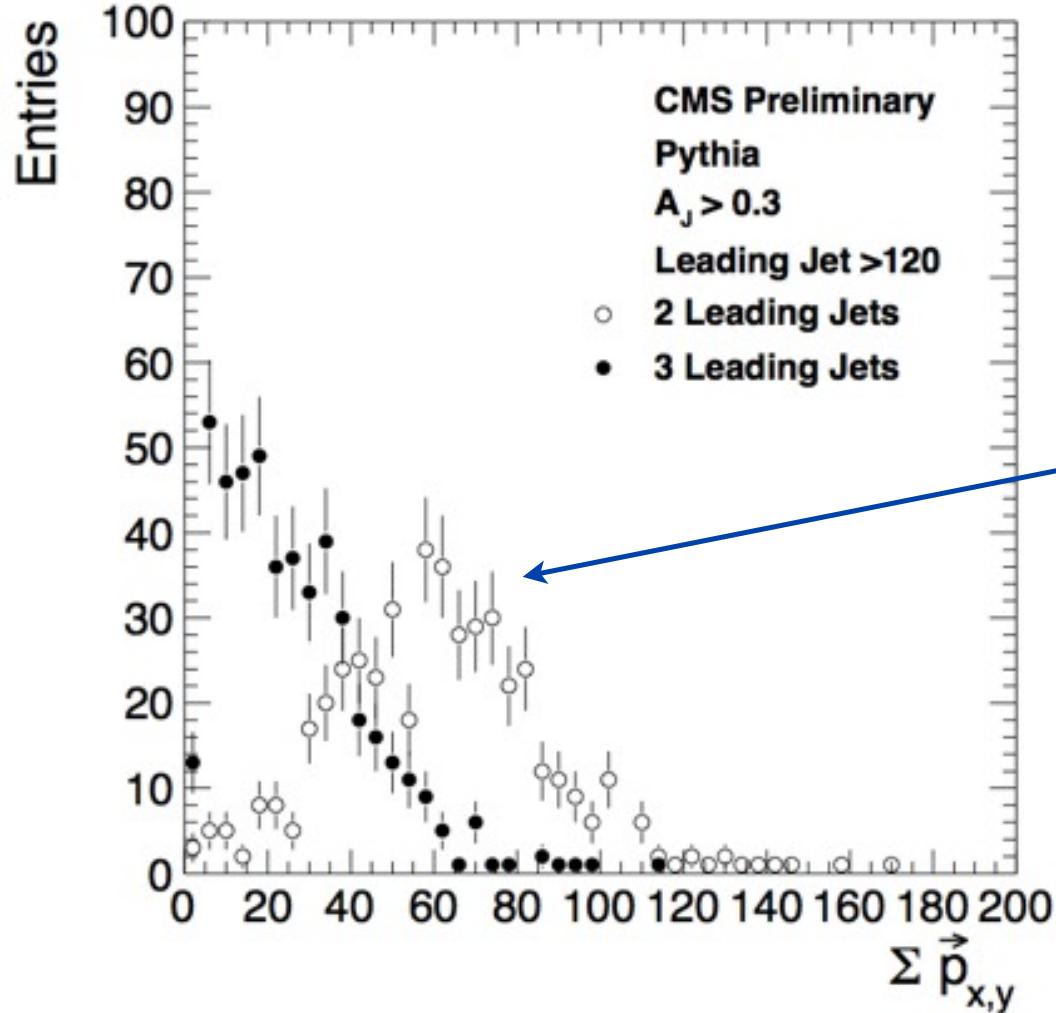
PYTHIA Momentum Balance

Intro to Heavy Ions

Analysis Methods

Calorimeter Jet Imbalance

Energy balance in charged tracks



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

Winter Workshop on Nuclear Dynamics, 2011



Edward Wenger - Slide 22



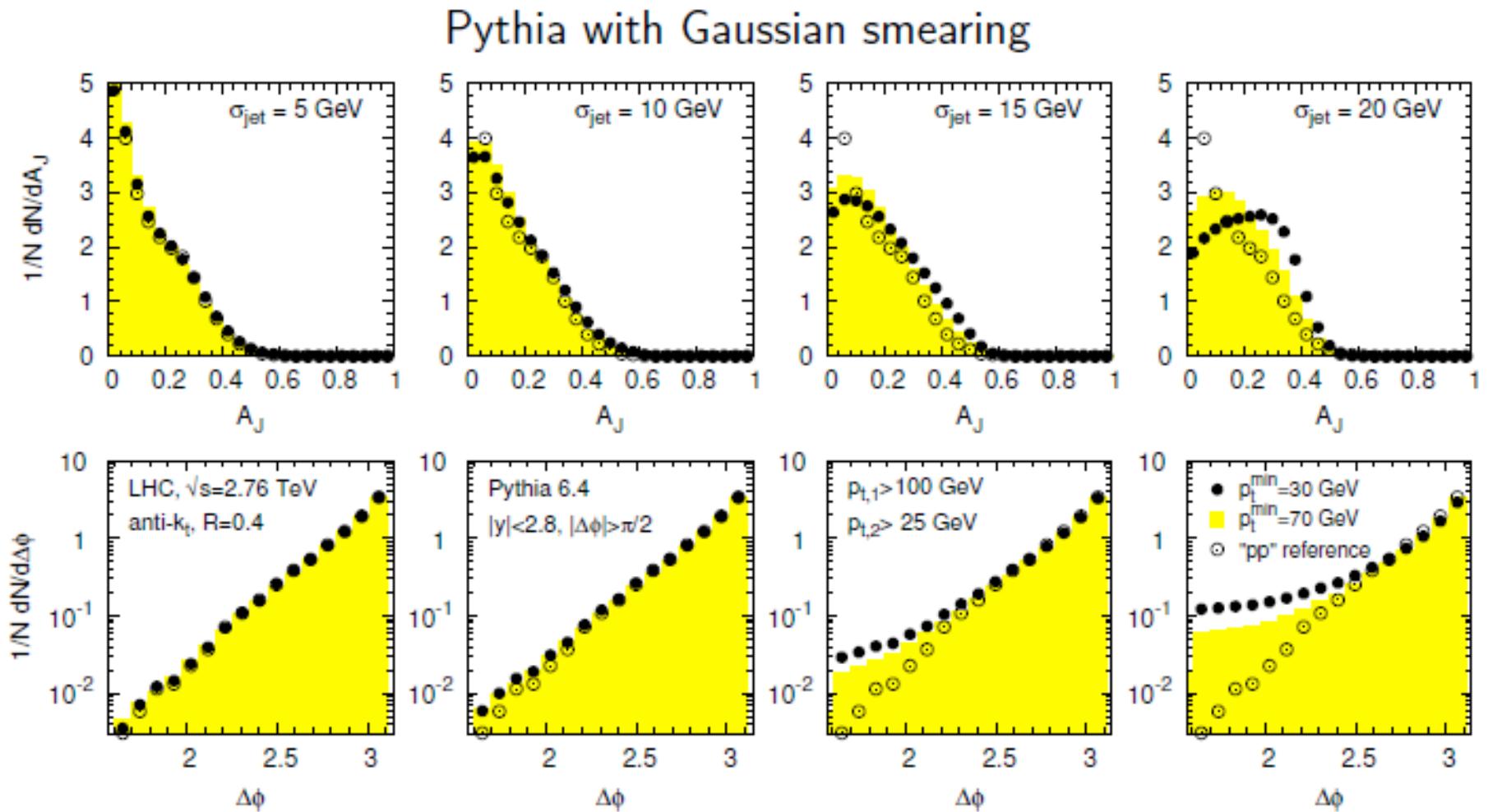
Marguerite Tonjes (UMD)

Quark Matter, Annecy, May 24 2011

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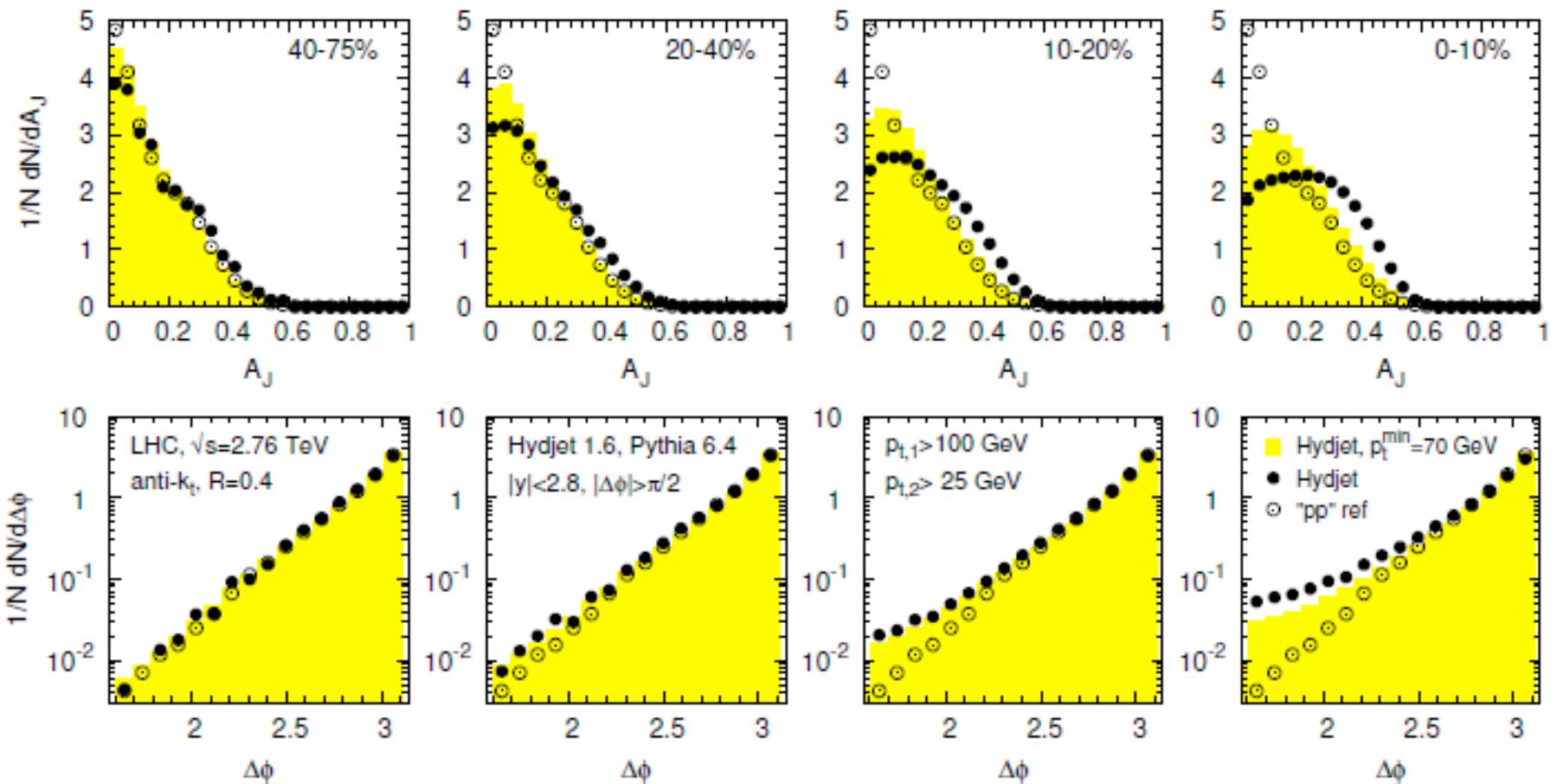
Different Gaussian smearing



Cacciari, Salam, Soyez: arXiv: 1101.2878

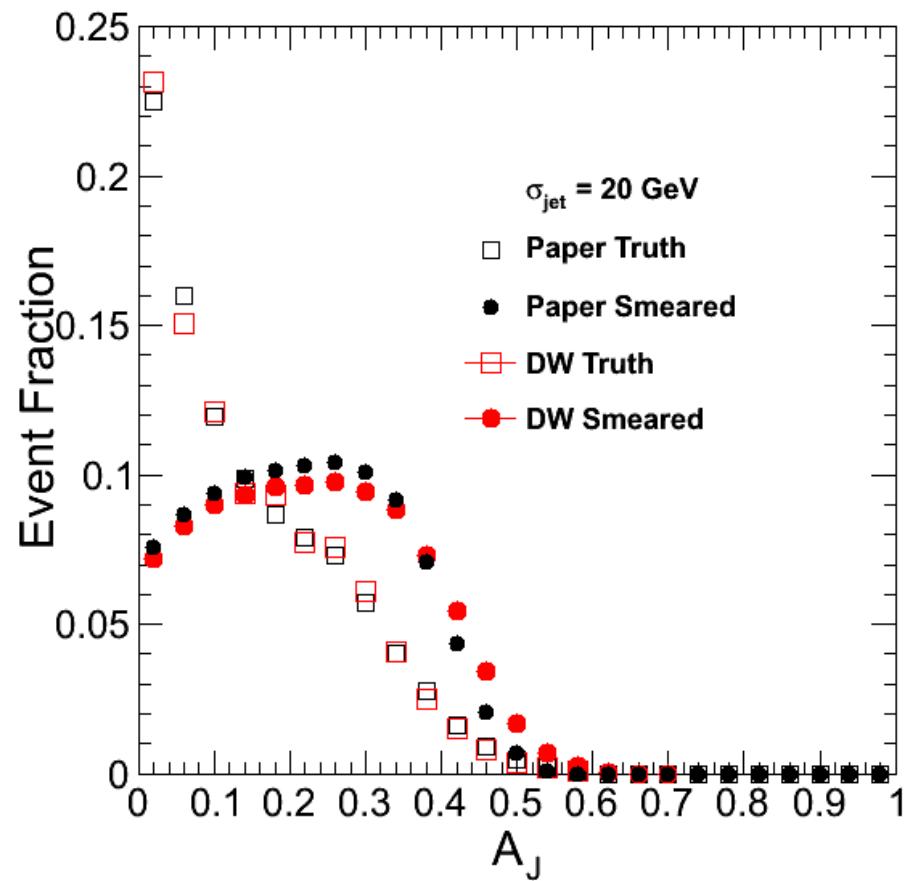
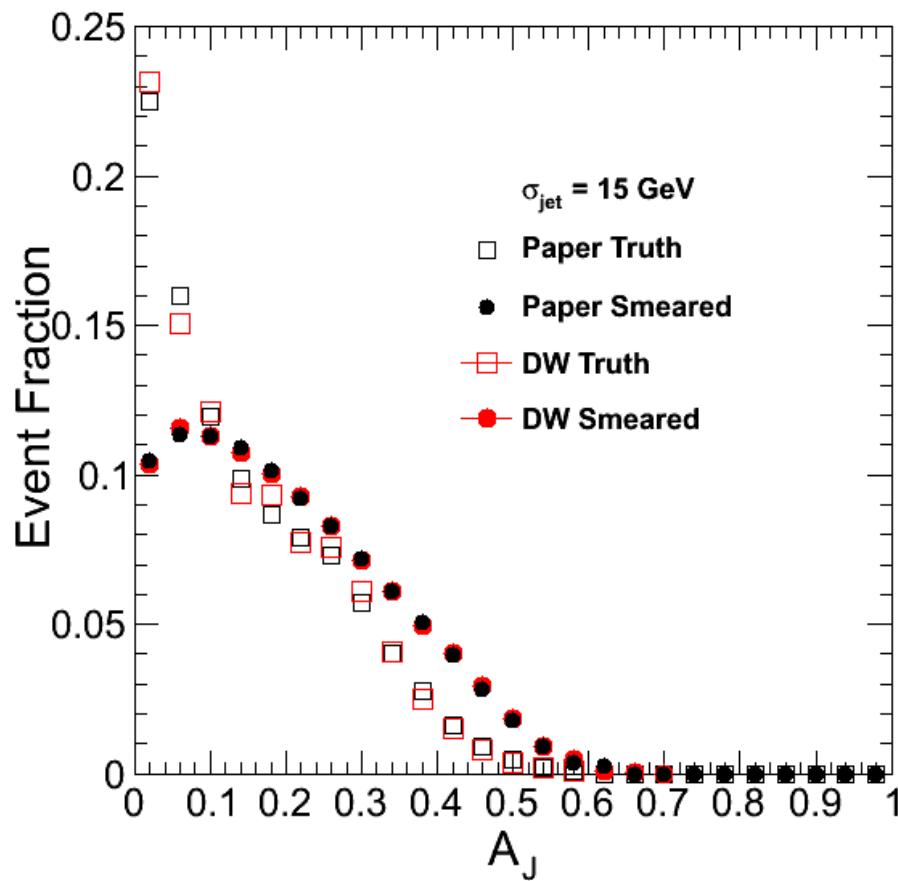
PYTHIA+HYDJET

Pythia embedded in HYDJET



Cacciari, Salam, Soyez: arXiv: 1101.2878

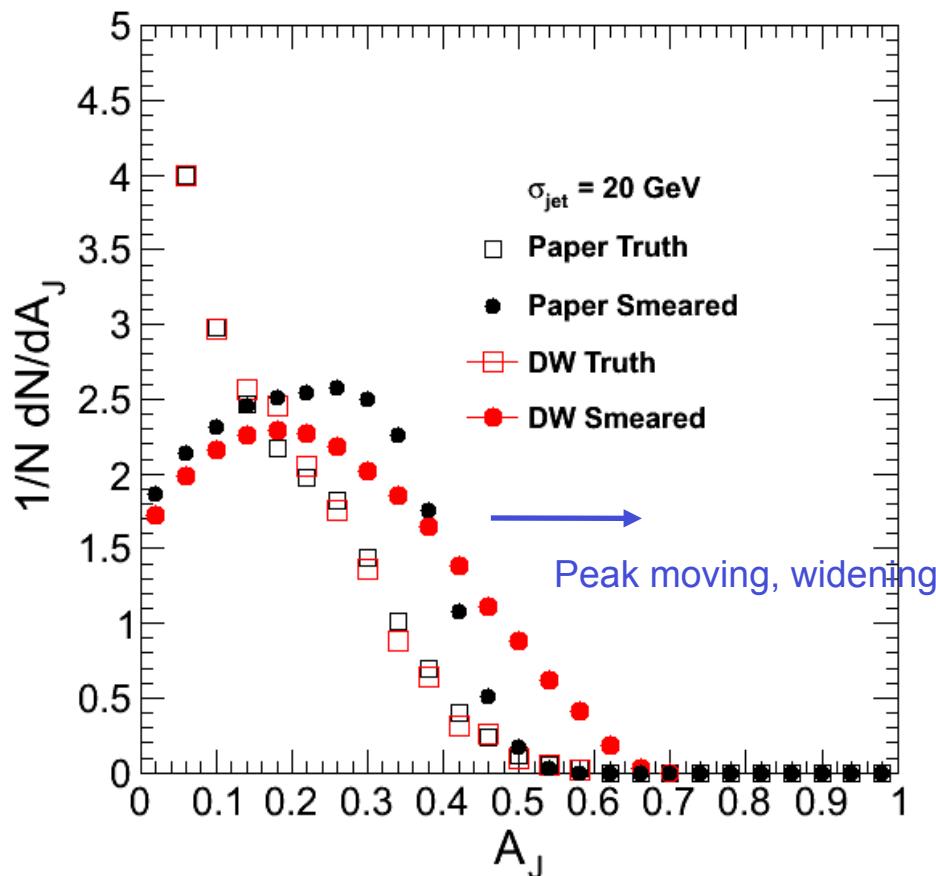
PYTHIA + Fluctuations



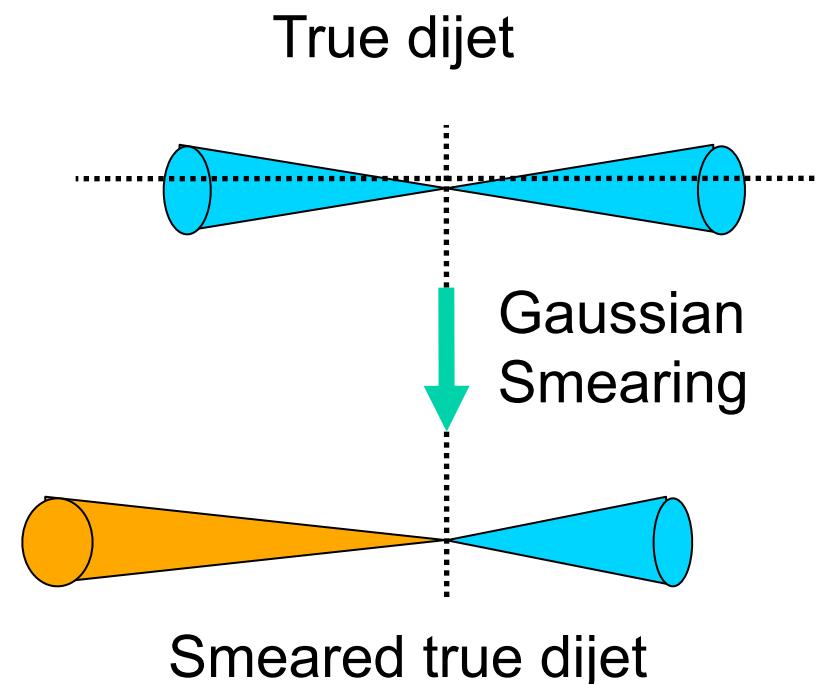
- Apply ATLAS's selection on the smeared jets:
 - $p_{T1} > 100 \text{ GeV}$, $p_{T2} > 25 \text{ GeV}$, $d\phi > \pi/2$
 - GenJet $p_T > 0 \text{ GeV}$
- Applying a gaussian smearing to PYTHIA we can reproduce the results of the Salam paper.



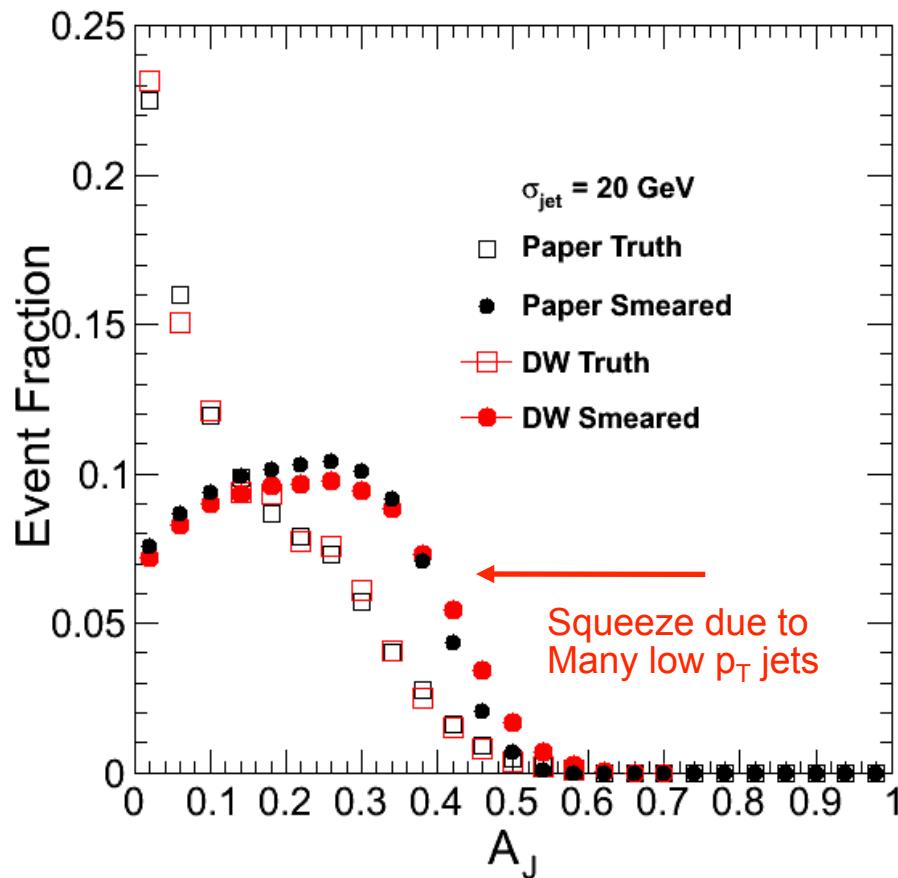
Ingredients



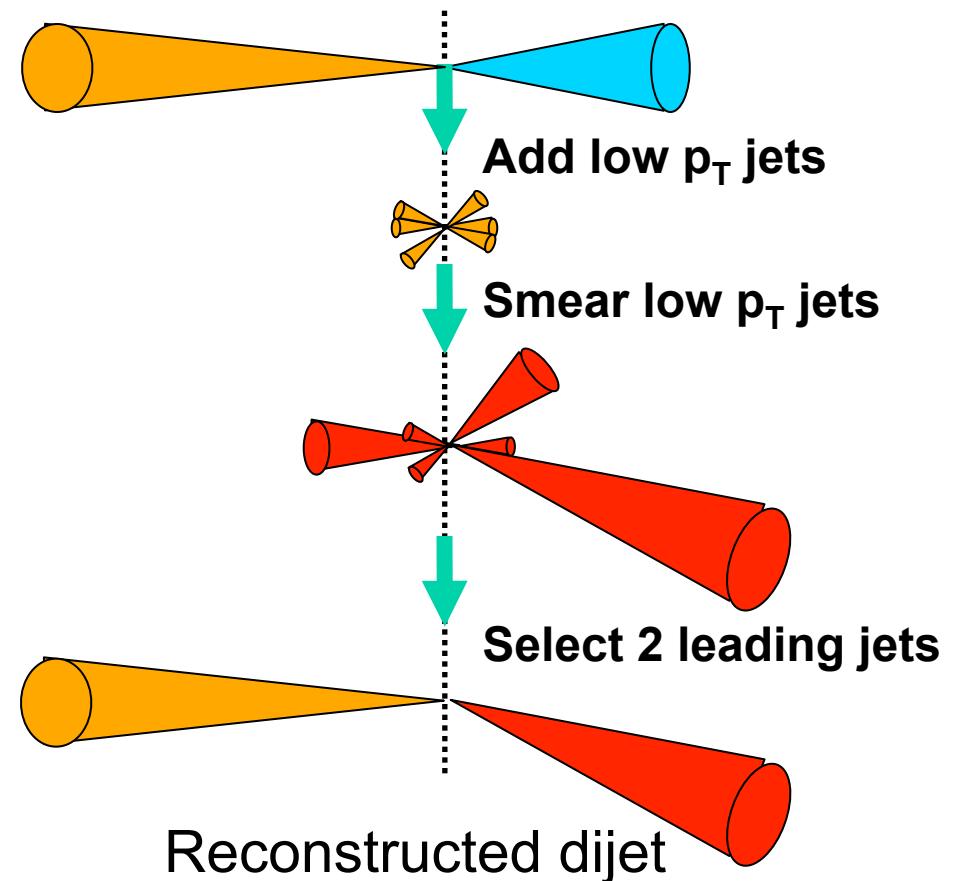
- Gaussian smearing of the leading jet makes the A_J distribution wider
 - Select only Jets above $p_T = 3 \text{ GeV}$



Ingredients II

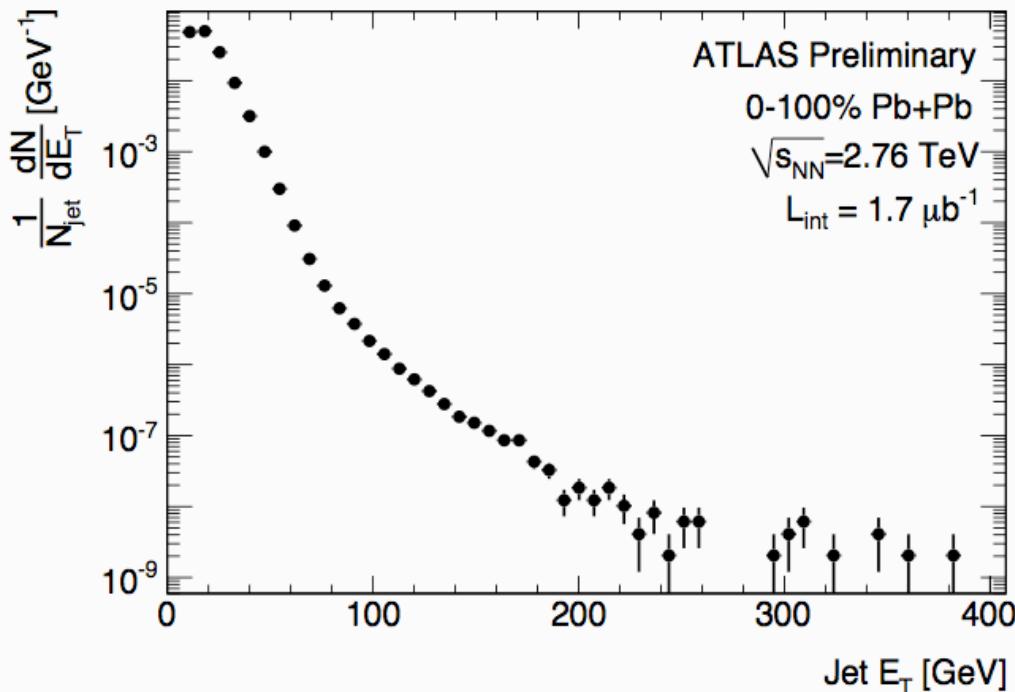
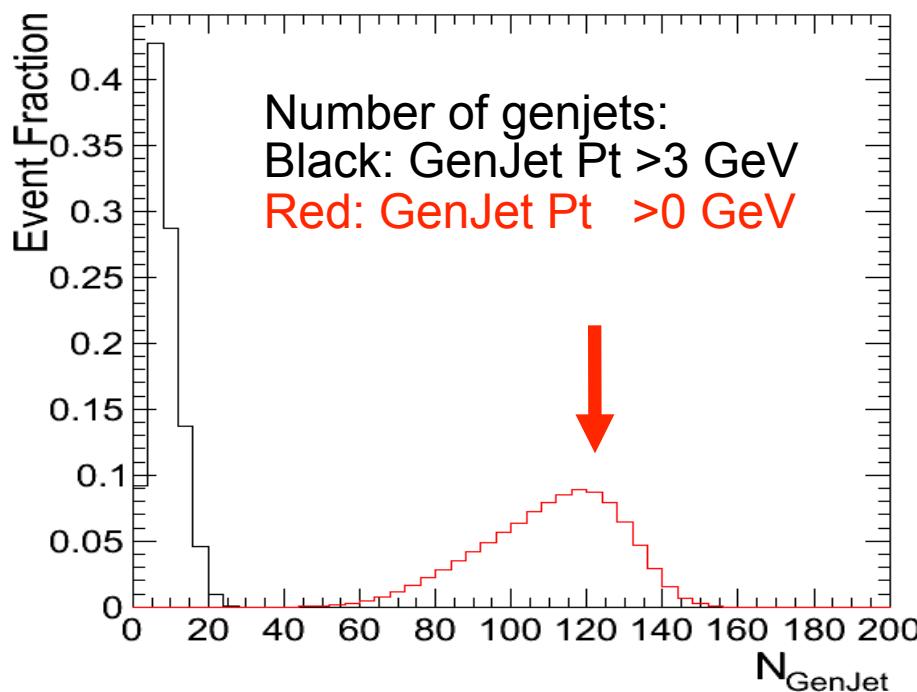


Smeared true dijet



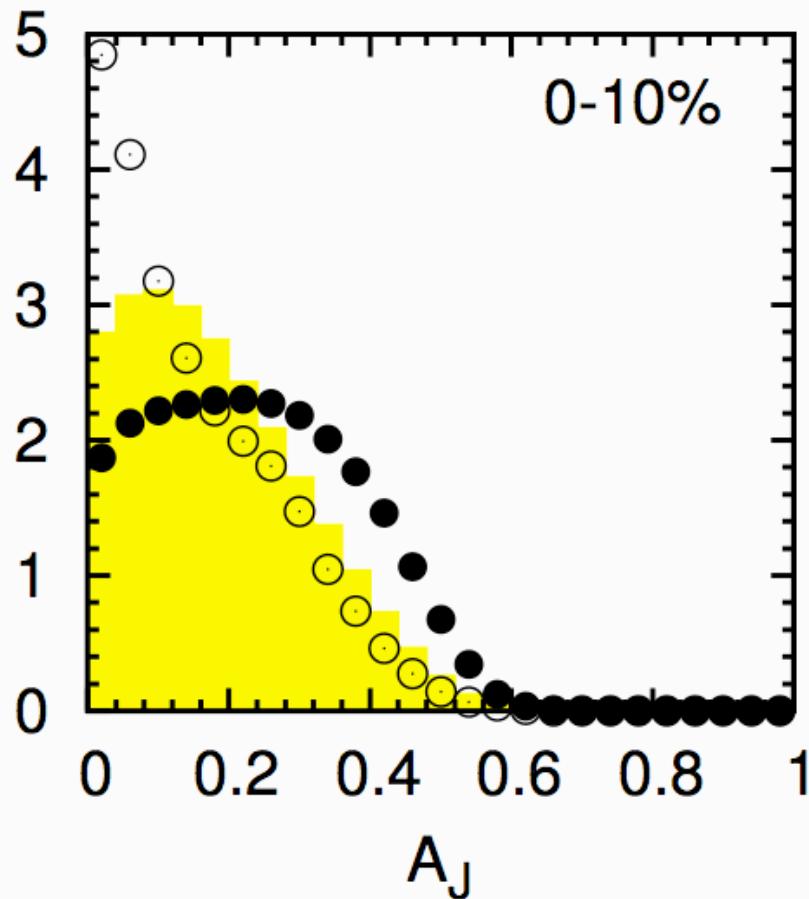
- Adding many low p_T jets, smeared to higher p_T than the true away side jet, compresses the A_J distribution
 - Tested by adding the 0-3GeV jets in the analysis

Ingredients III

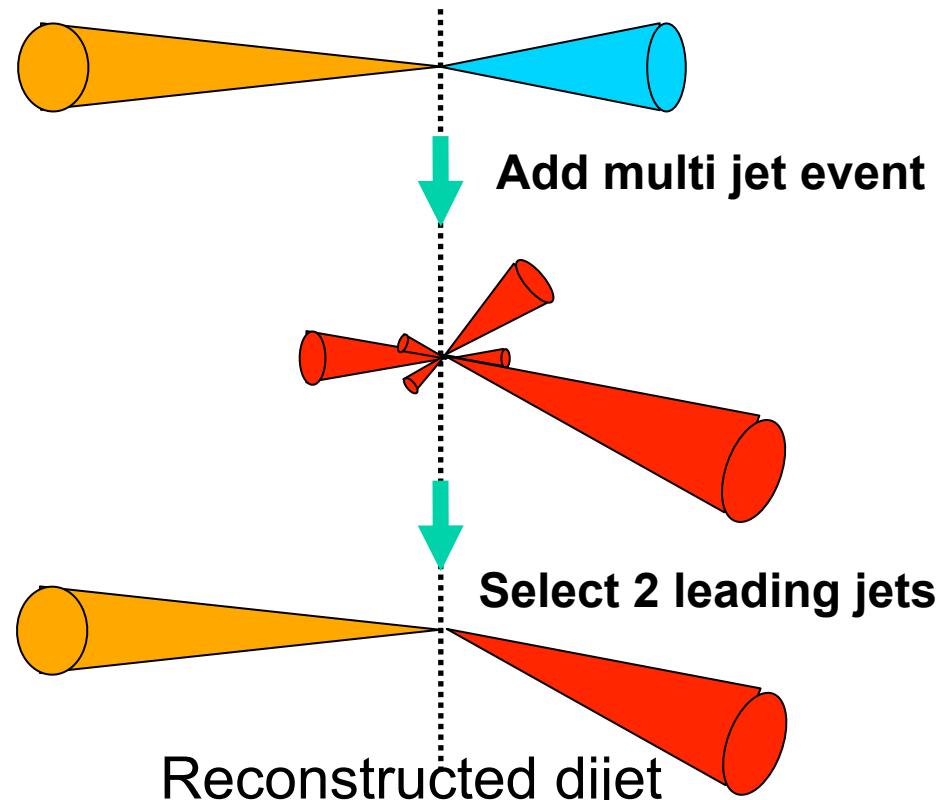


- Balanced dijets + fluctuations can fake a wide A_J distribution
 - Needs a very large number (~ 100) of low p_T jets per event
 - Remember: $dN/d\eta^{\text{ch}} \sim 6$ in $|\eta| < 5 \rightarrow \sim 60$ charged particles/event
 - And a very large σ (20 GeV) for the smearing
 - based on a Gaussian fit to the low p_T part of the ATLAS min bias jet spectrum
 - ATLAS reports $\sigma \sim 8 \text{ GeV}$ for their background fluctuations

Hydjet

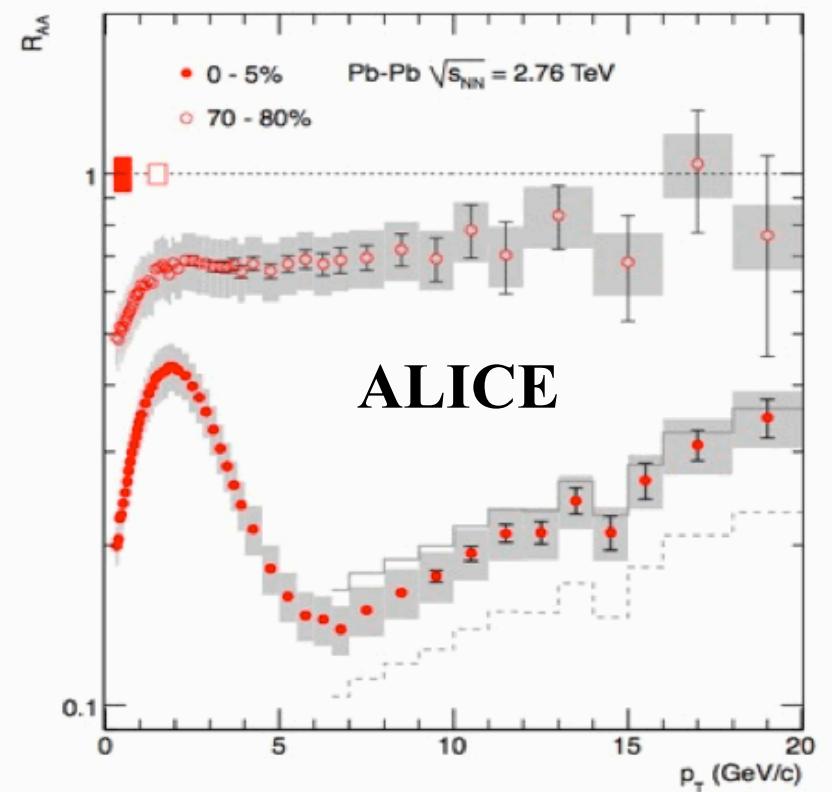
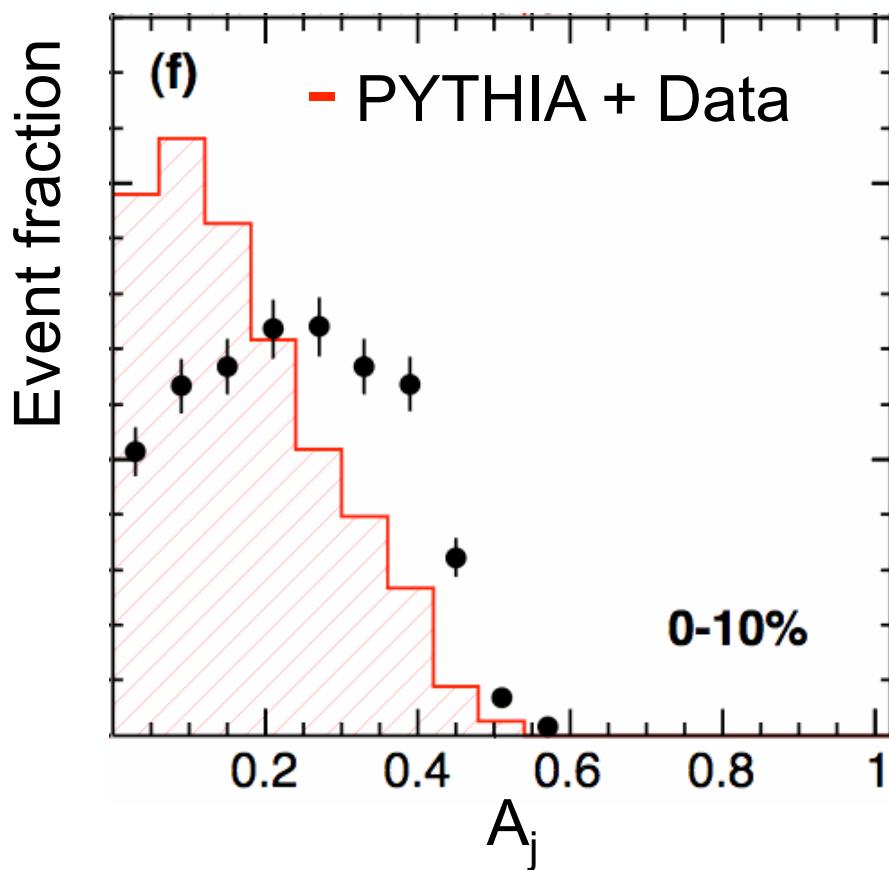


Smeared true dijet



- 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

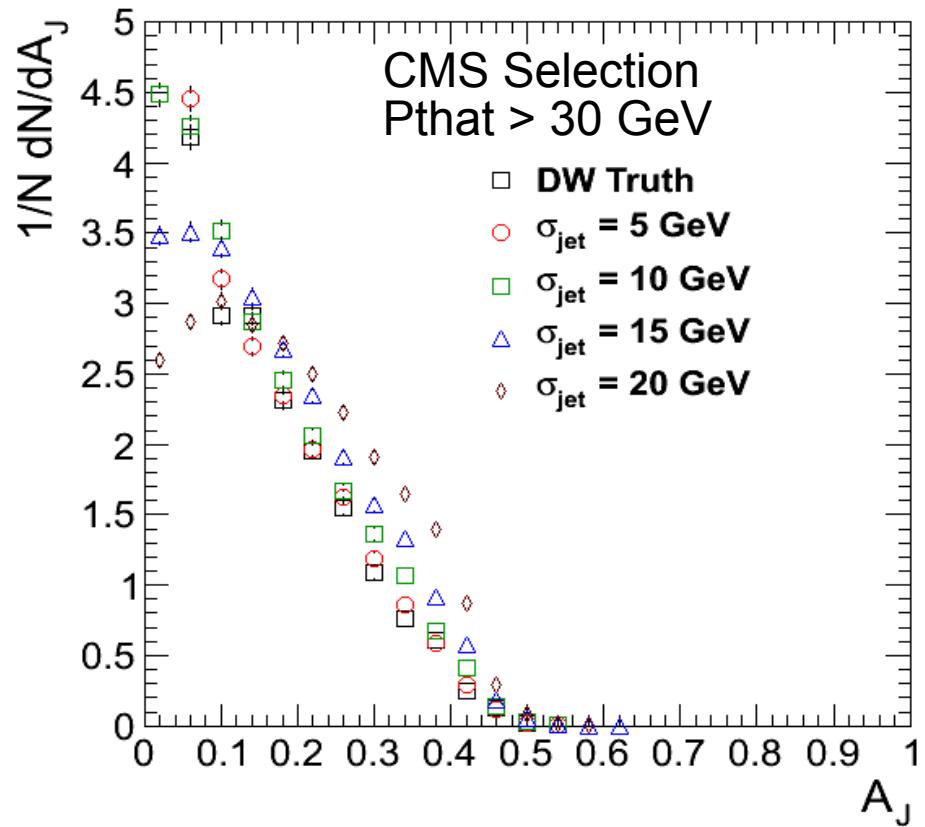
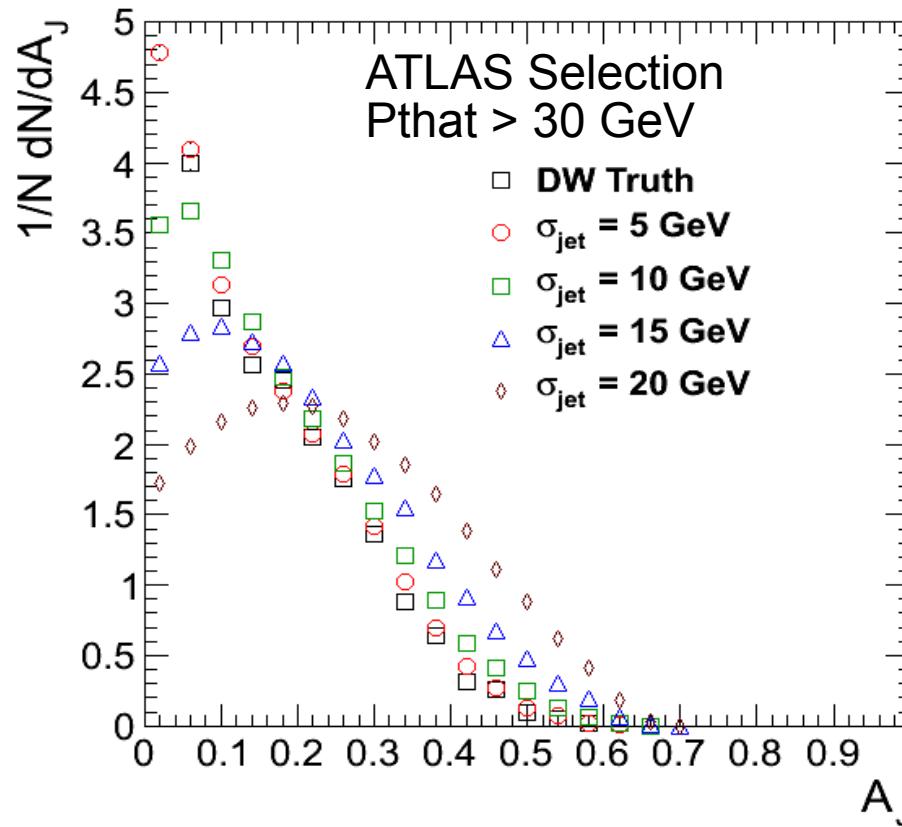
Is unquenched Hydjet a good background reference?



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

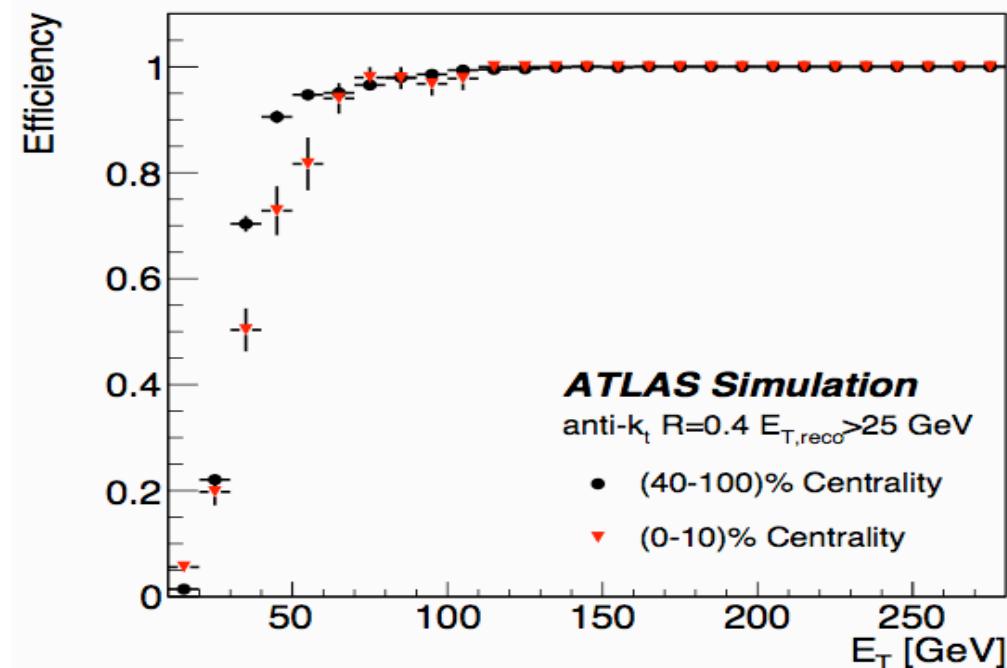
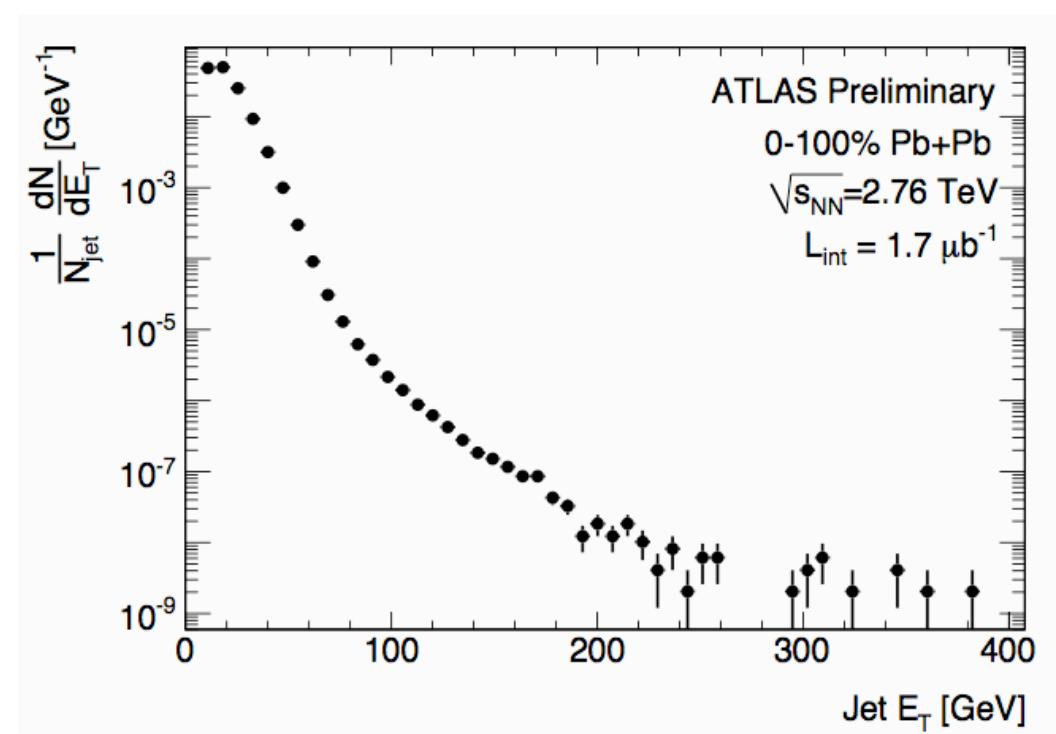
ATLAS vs CMS Dijet selection

Comparing the ATLAS and CMS dijet selection $p_T \hat{}$ > 30 GeV



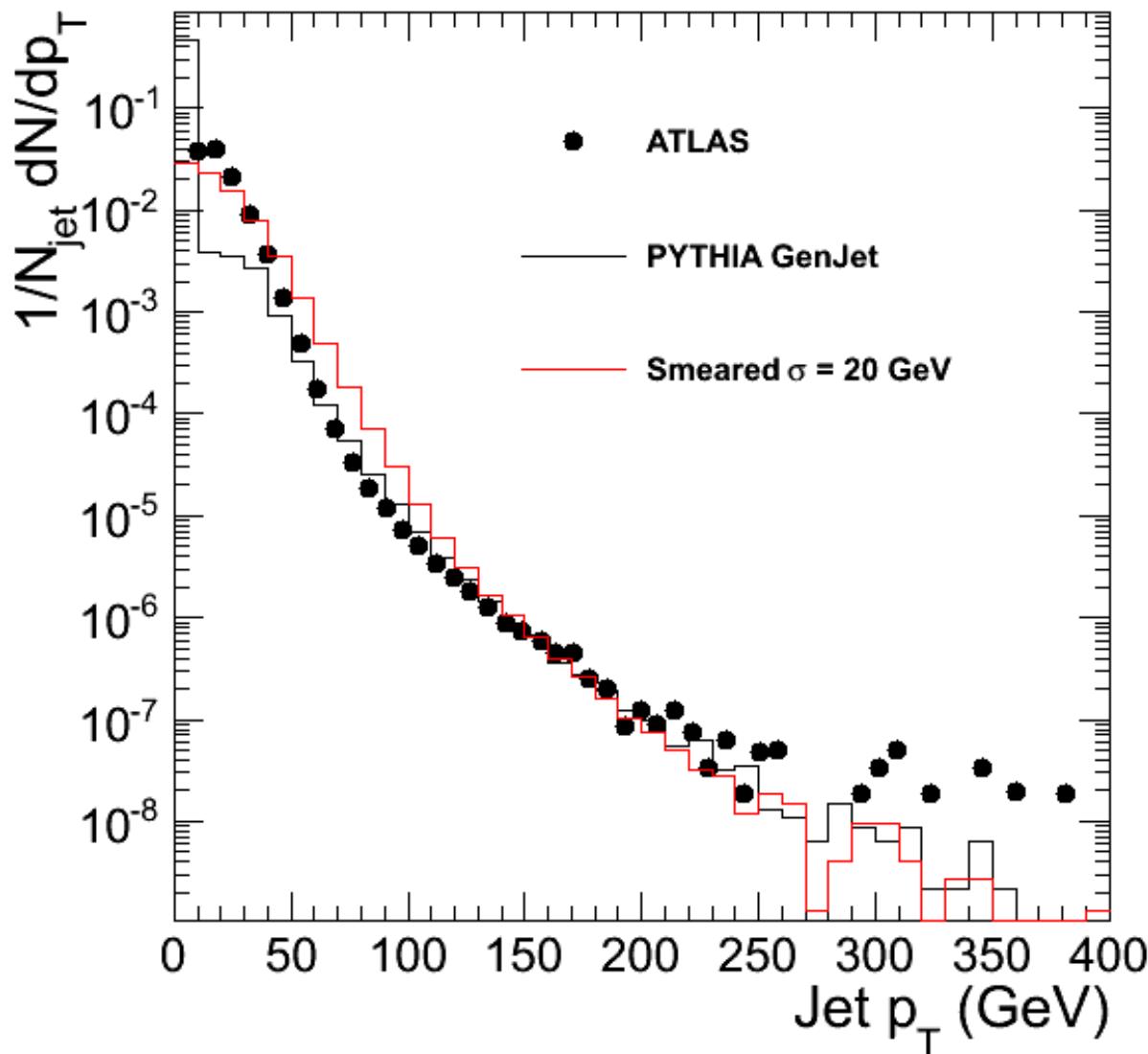
- With the higher jet thresholds used for the CMS paper we are less sensitive to background fluctuations
 - ATLAS 100/20, CMS: 120/50 for leading/sub-leading

ATLAS input



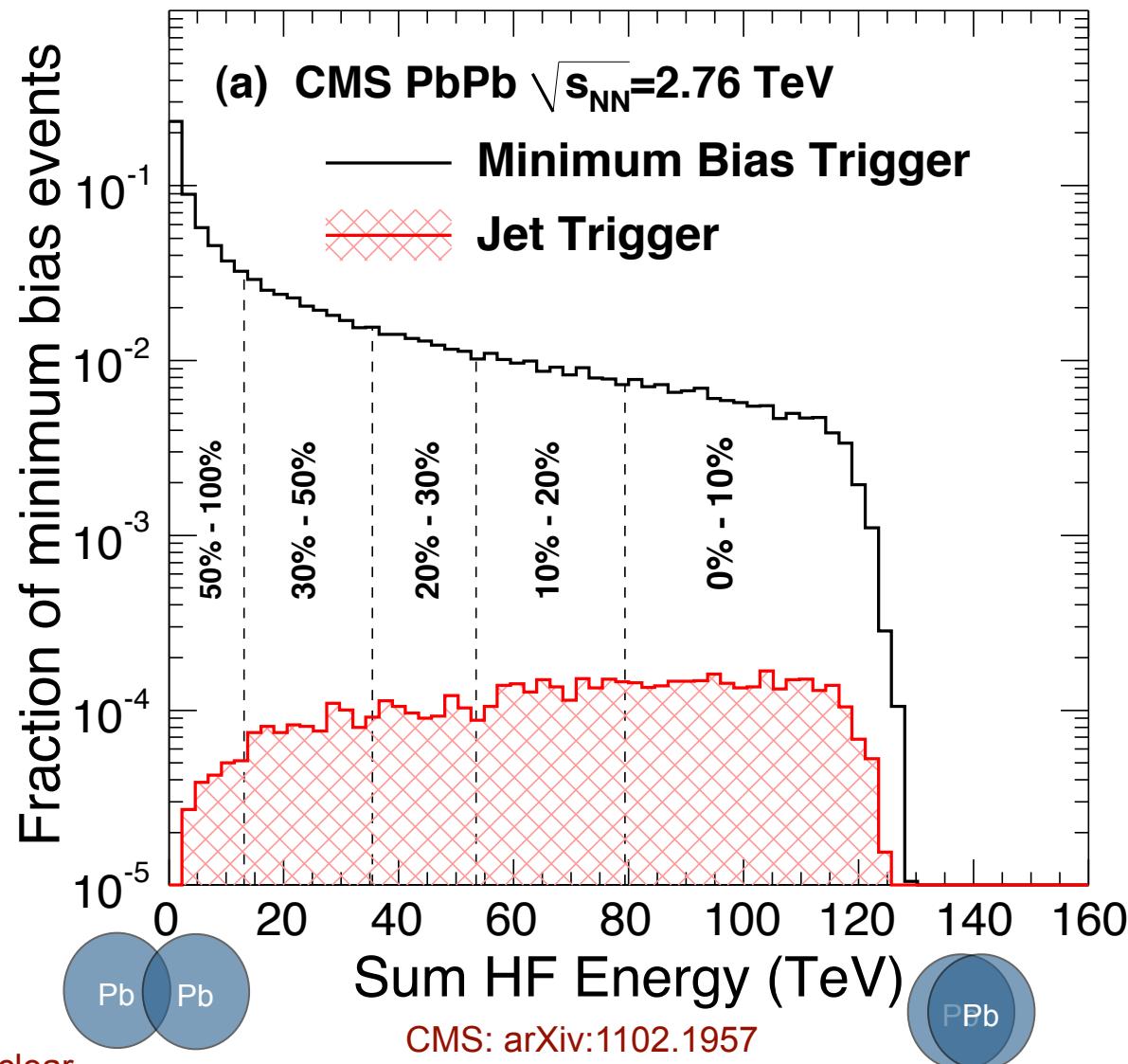
- The large σ (20GeV) smearing is based on a Gaussian fit to the low p_T part of the ATLAS min bias jet spectrum
 - ATLAS reports $\sigma \sim 8$ GeV for their background fluctuations

20GeV smearing closure test



Centrality definition

- Determined by the total energy from both HF calorimeters
- Split minimum bias events into centrality bins
- Relate to $\langle N_{\text{part}} \rangle$ with calculation based on a Glauber model (nucleon-nucleon scattering)
 - Finite detector resolution effects from fully simulated Monte Carlo AMPT events



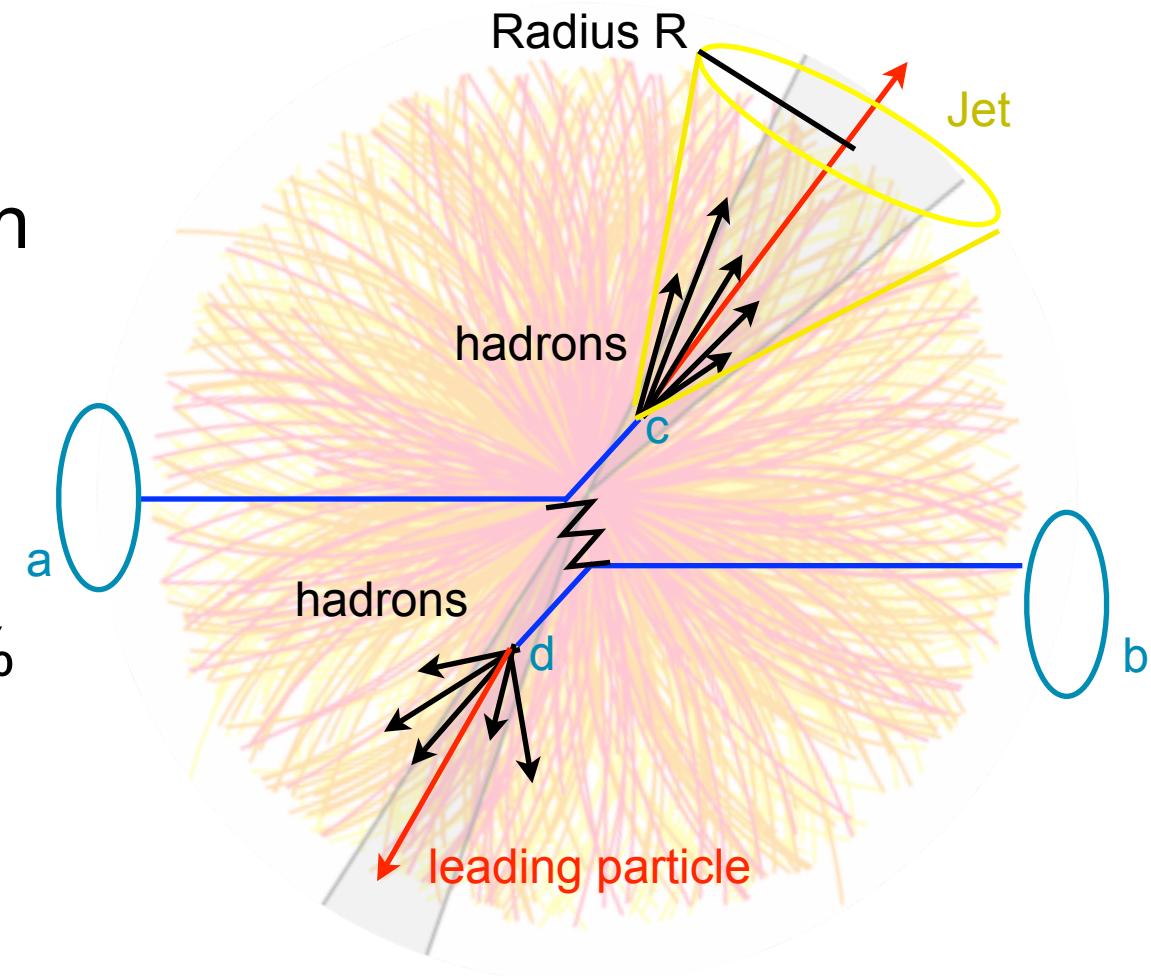
M.L. Miller et al., Glauber modeling in high energy nuclear collisions, Ann. Rev. Nucl. Part. Sci **57** (2007) 205

- Selecting rare processes (high p_T jets): bias towards central collisions



Jet Finding in Heavy Ion Events

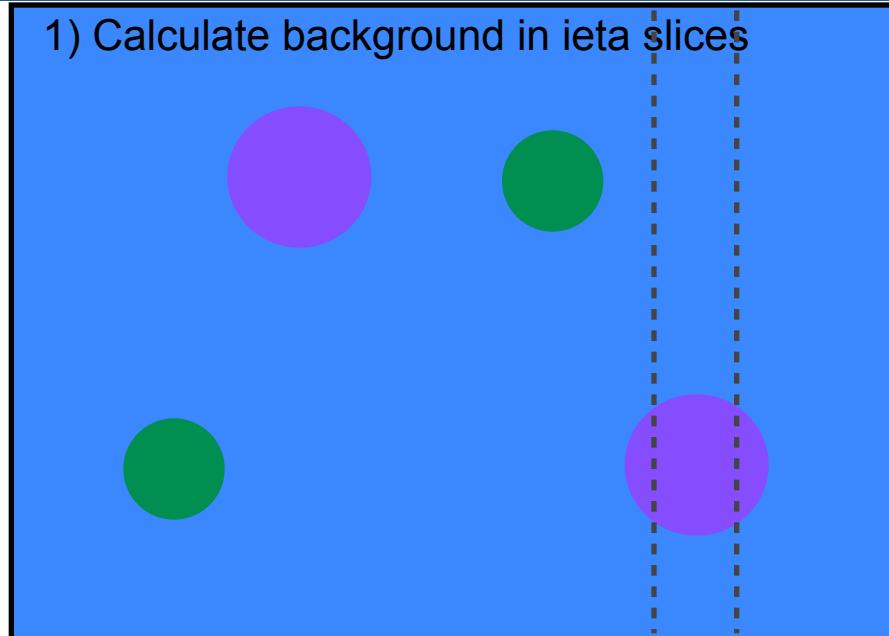
- Jet: localized collection of hadrons that come from a fragmented parton
- Problem: finding jet above significant soft background
 - $dN_{\text{charged}}/d\eta \sim 1600$ for 5% most central events
- Approach: use pileup subtraction technique to remove background underlying event
 - Check with Monte Carlo



Iterative Pileup Subtraction

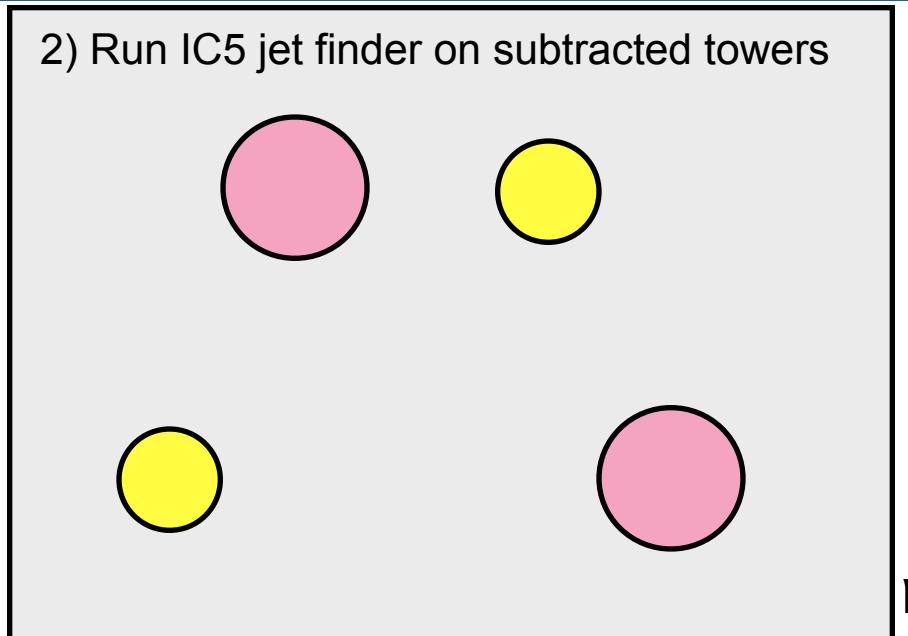
ϕ

1) Calculate background in ieta slices



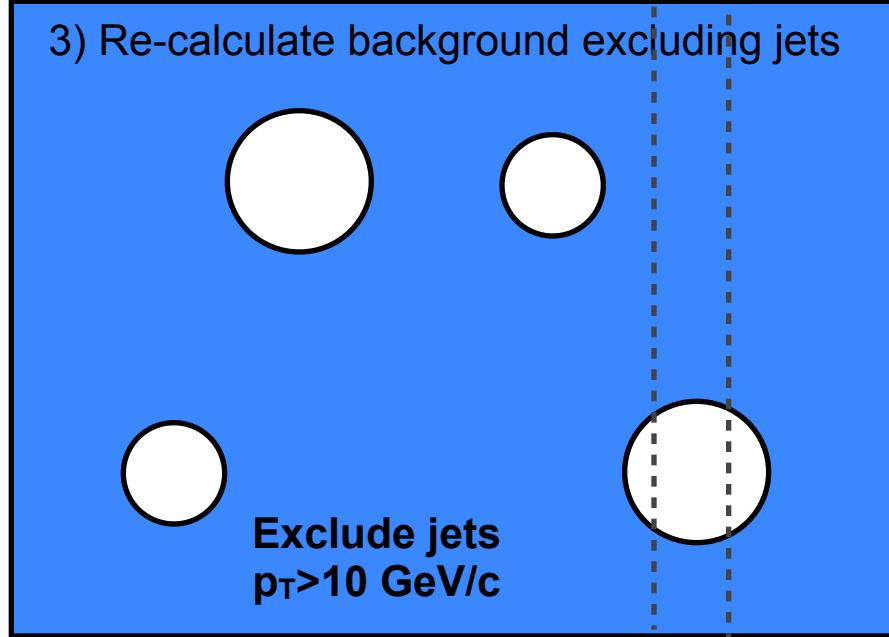
ϕ

2) Run IC5 jet finder on subtracted towers



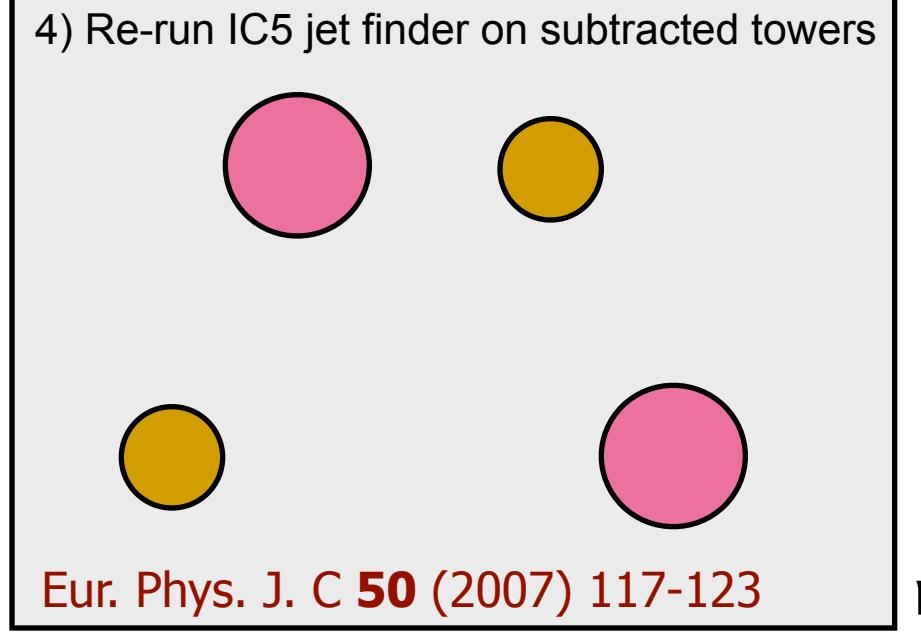
ϕ

3) Re-calculate background excluding jets



ϕ

4) Re-run IC5 jet finder on subtracted towers



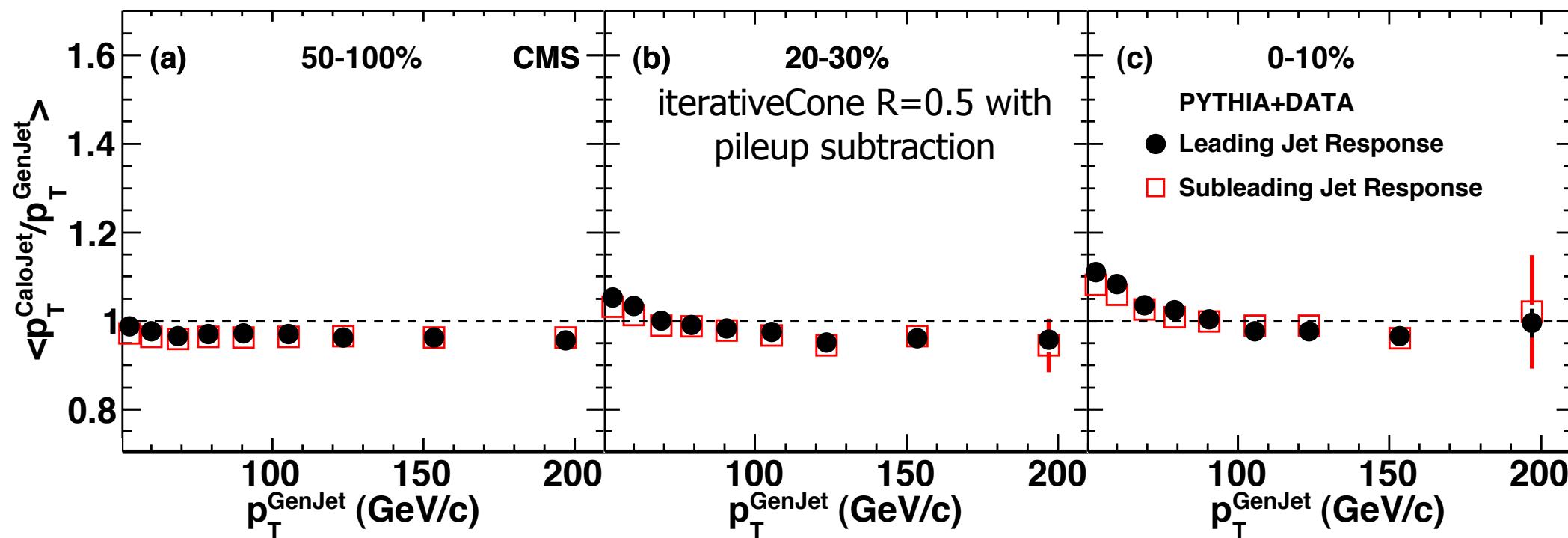
Eur. Phys. J. C **50** (2007) 117-123



Jet Energy Scale

- Match reconstructed CaloJet to GenJet within a cone $\Delta R = 0.3$ ($\Delta R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)}$)
 - CaloJet: jet reconstructed from calorimeter towers after detector simulation
 - GenJet: jet reconstructed from PYTHIA Generator particles
- Leading Jet $p_{T,1} > 120$ GeV/c, $|\eta| < 2$ → for this analysis
- Subleading Jet (in same event) $p_{T,2} > 50$ GeV/c, $|\eta| < 2$ → for this analysis
- Residual *not* used to correct energy, but is included in systematic uncertainty
- PYTHIA (QCD dijet) + DATA (PbPb Minimum Bias)

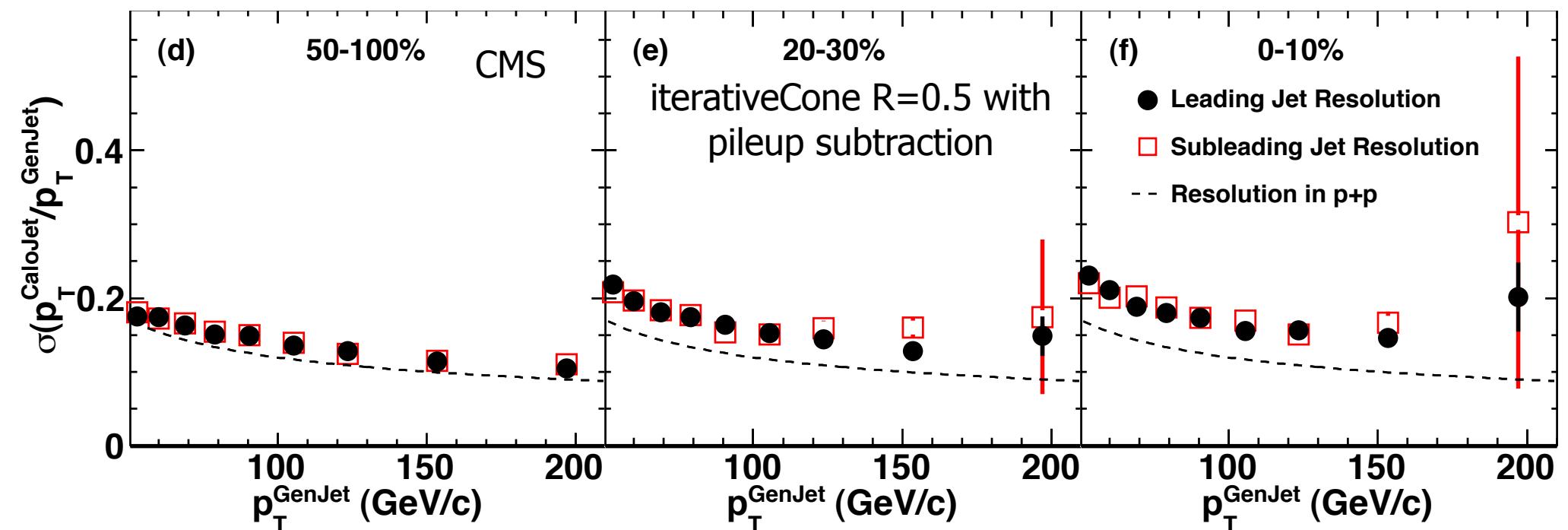
CMS: arXiv:1102.1957



Jet Resolution

- Match reconstructed CaloJet to GenJet within a cone $\Delta R = 0.3$
- Resolution is standard deviation of Gaussian CaloJet/GenJet response
- Resolution degraded by $\sim 30\%$ due to heavy-ion background in most central events
- PYTHIA (QCD dijet) + DATA (PbPb Minimum Bias)

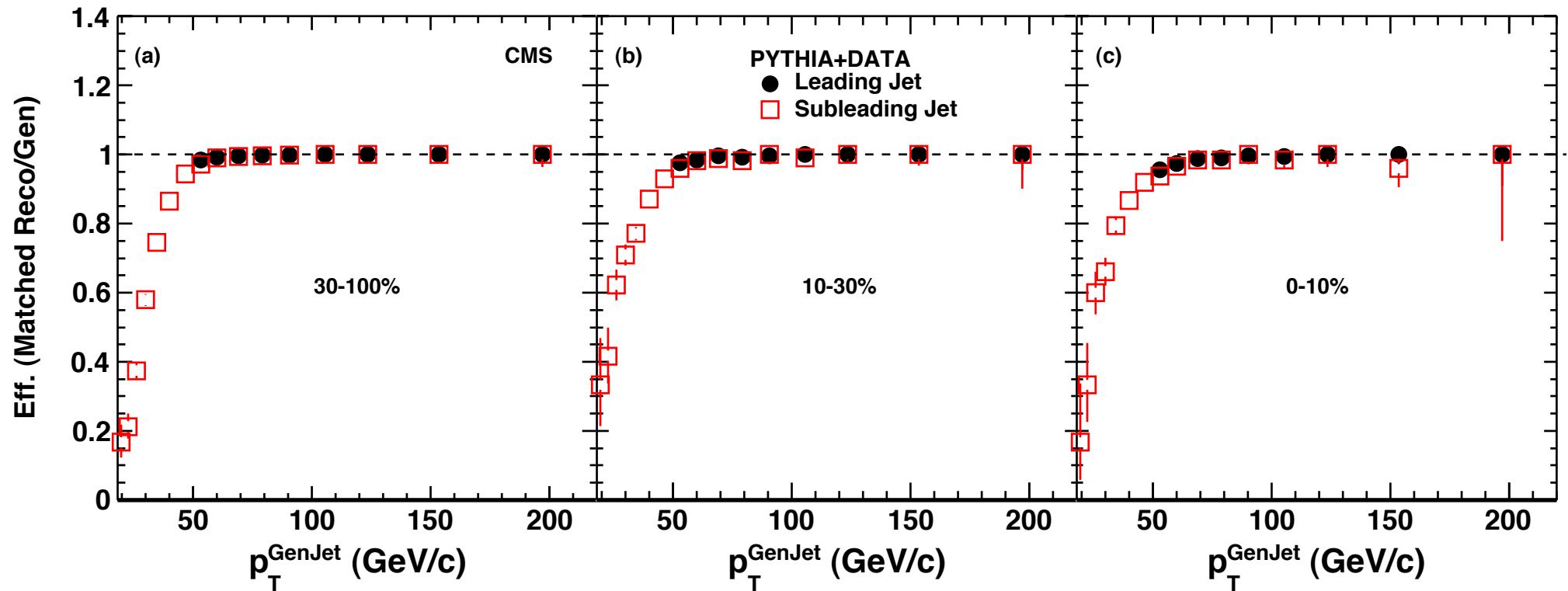
CMS: arXiv:1102.1957



Jet Finding Efficiency

- Match reconstructed CaloJet to GenJet within a cone $\Delta R = 0.3$
- Fully efficient for leading jet selection ($p_{T,1} > 120 \text{ GeV}/c$)
- High efficiency for subleading jet selection ($p_{T,2} > 50 \text{ GeV}/c$)
- PYTHIA (QCD dijet) + DATA (PbPb Minimum Bias)

CMS: arXiv:1102.1957



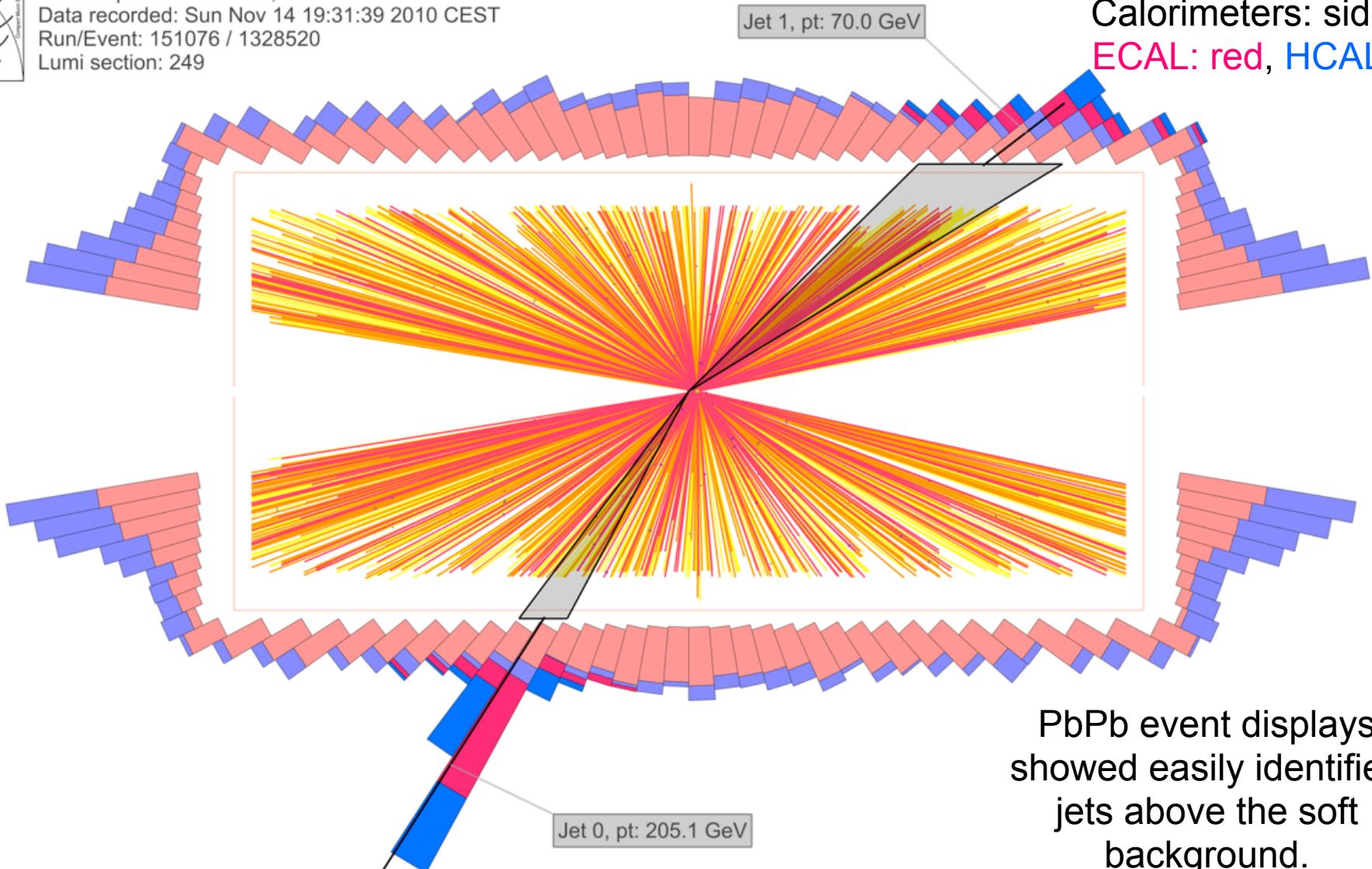
PbPb Collision with CMS



CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249

PbPb $\sqrt{s_{NN}} = 2.76$ TeV

CMS tracker &
Calorimeters: side view
ECAL: red, HCAL: blue



PbPb event displays
showed easily identified
jets above the soft
background.

Calorimeter towers = ECAL+HCAL

$$\Delta\eta \times \Delta\phi = 0.087 \times 0.087$$

<http://cdsweb.cern.ch/record/1309898?ln=en>



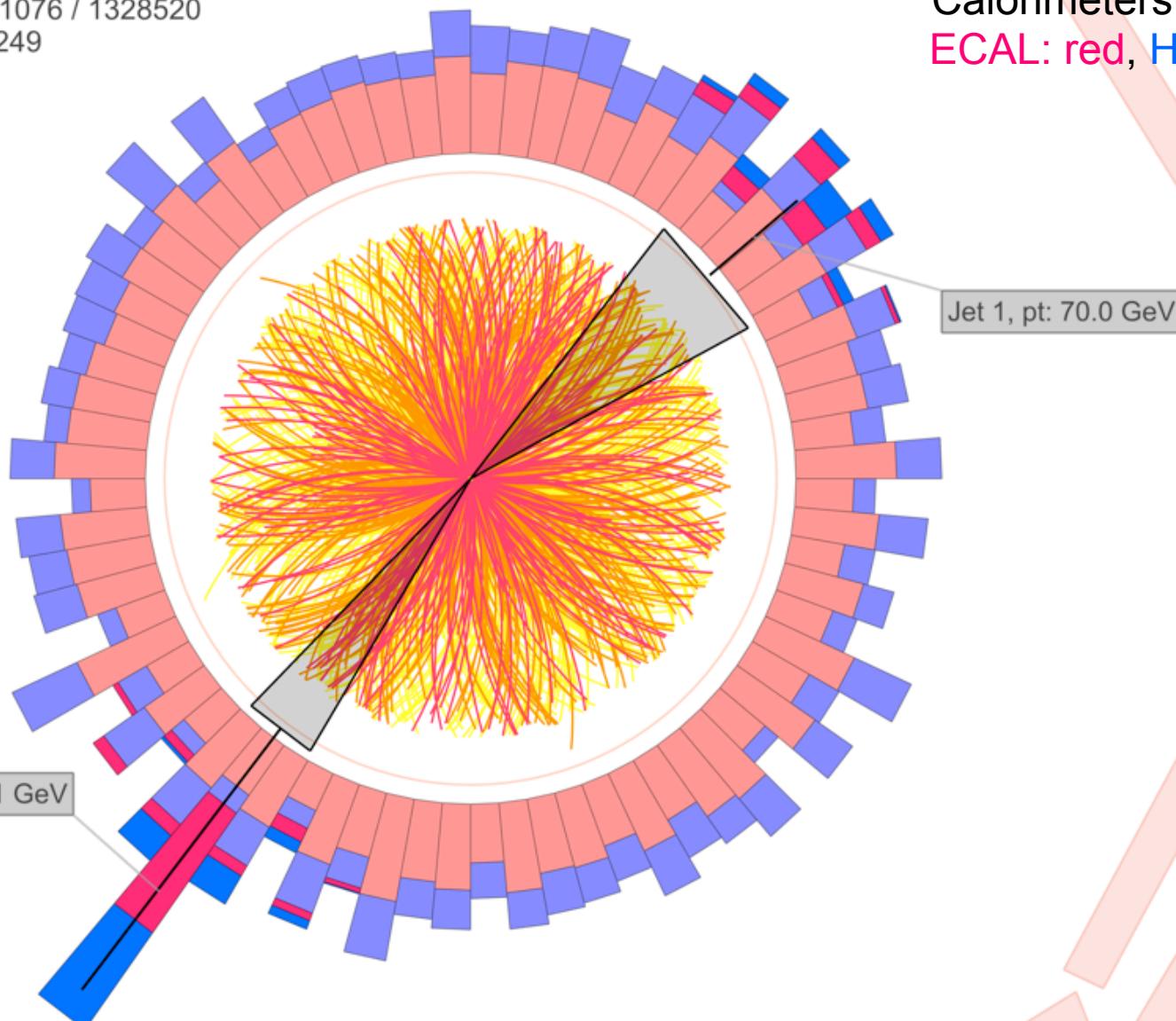
PbPb Collision with CMS



CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249

PbPb $\sqrt{s_{NN}} = 2.76 \text{ TeV}$

CMS tracker &
Calorimeters: end view
ECAL: red, HCAL: blue

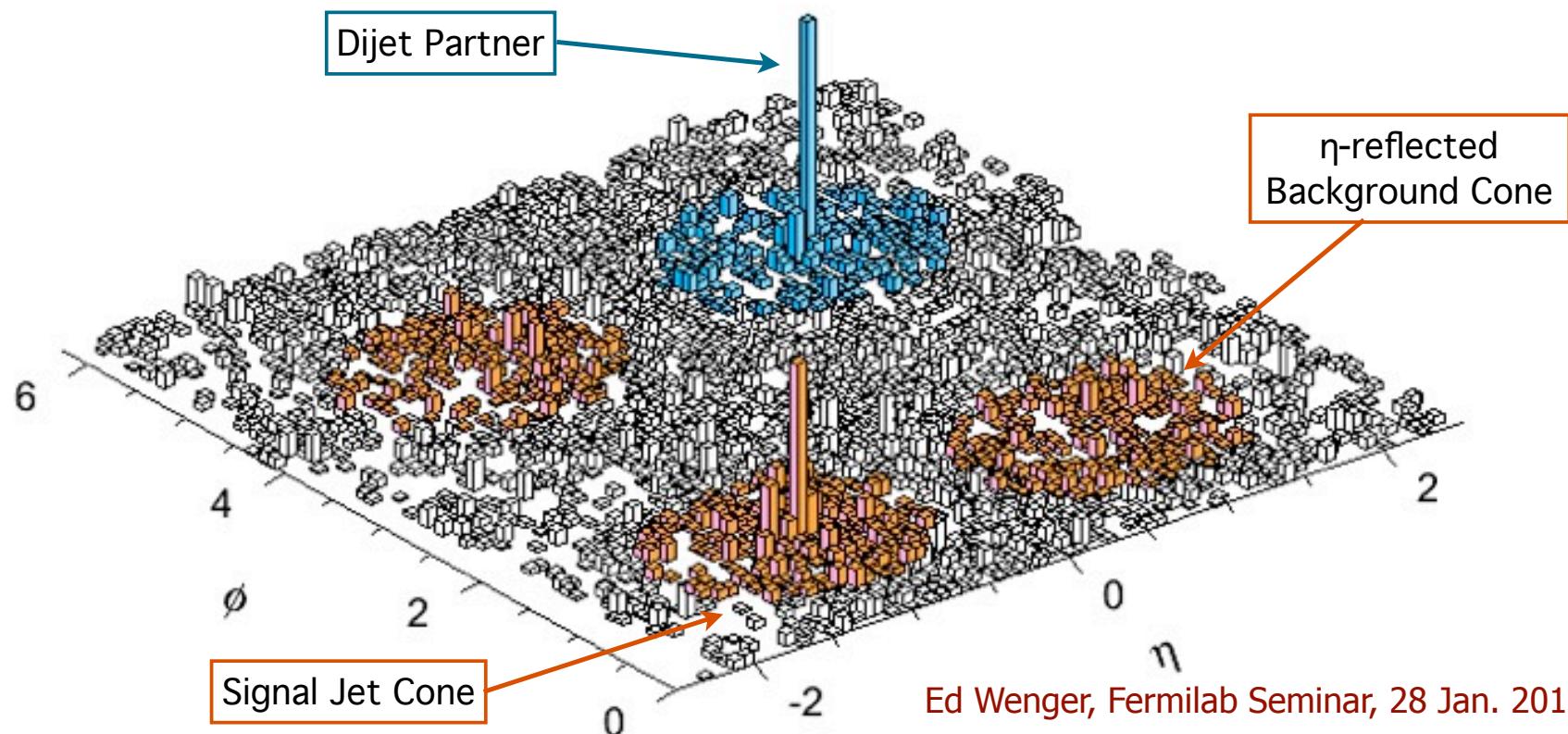


<http://cdsweb.cern.ch/record/1309898?ln=en>



Jet-Track Background

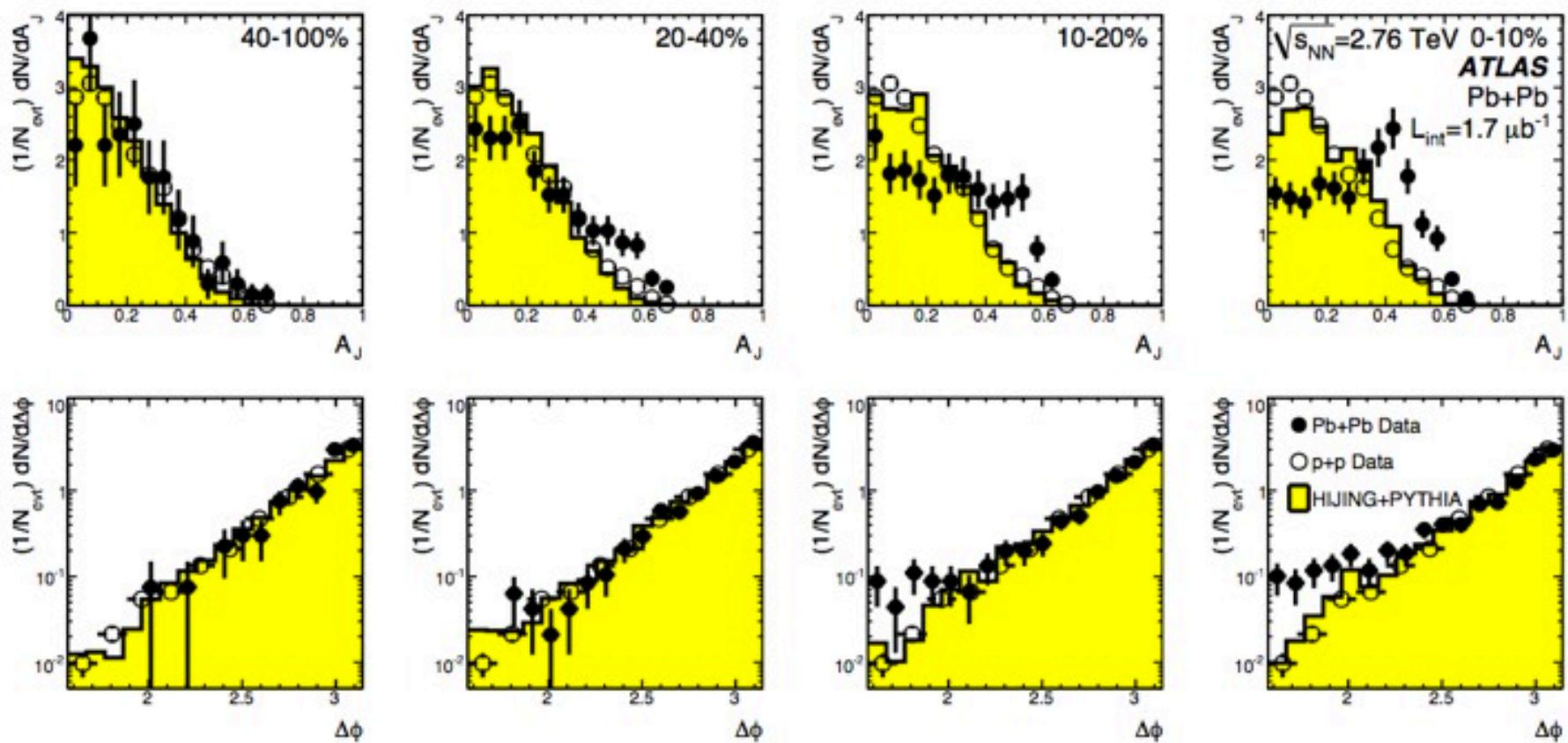
- Background evaluated within $R=0.8$ cone symmetric about η
- Avoids ϕ dependent variations due to detector effects and event anisotropy
- Single jets required to be within $0.8 < |\eta| < 1.6$
 - To contain 0.8 radius of tracks around jet axis



Ed Wenger, Fermilab Seminar, 28 Jan. 2011



ATLAS Dijet Asymmetry



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

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

Winter Workshop on Nuclear Dynamics, 2011



Edward Wenger - Slide 37



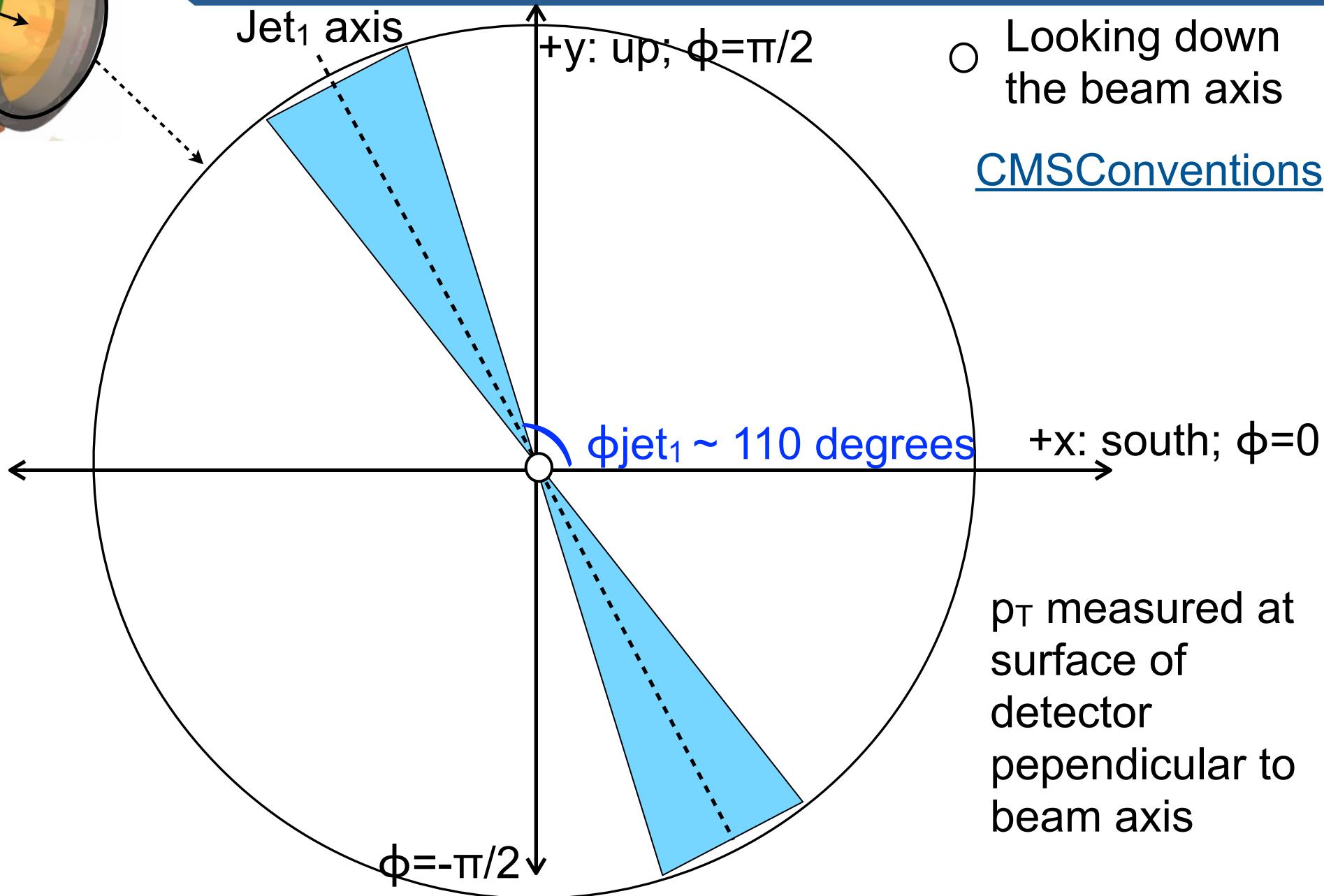
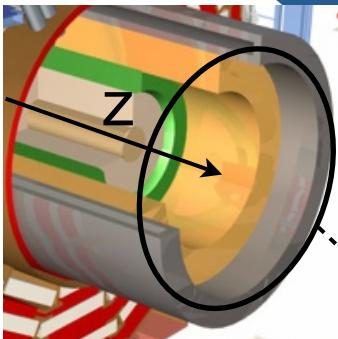
Marguerite Tonjes (UMD)

Quark Matter, Annecy, May 24 2011

48



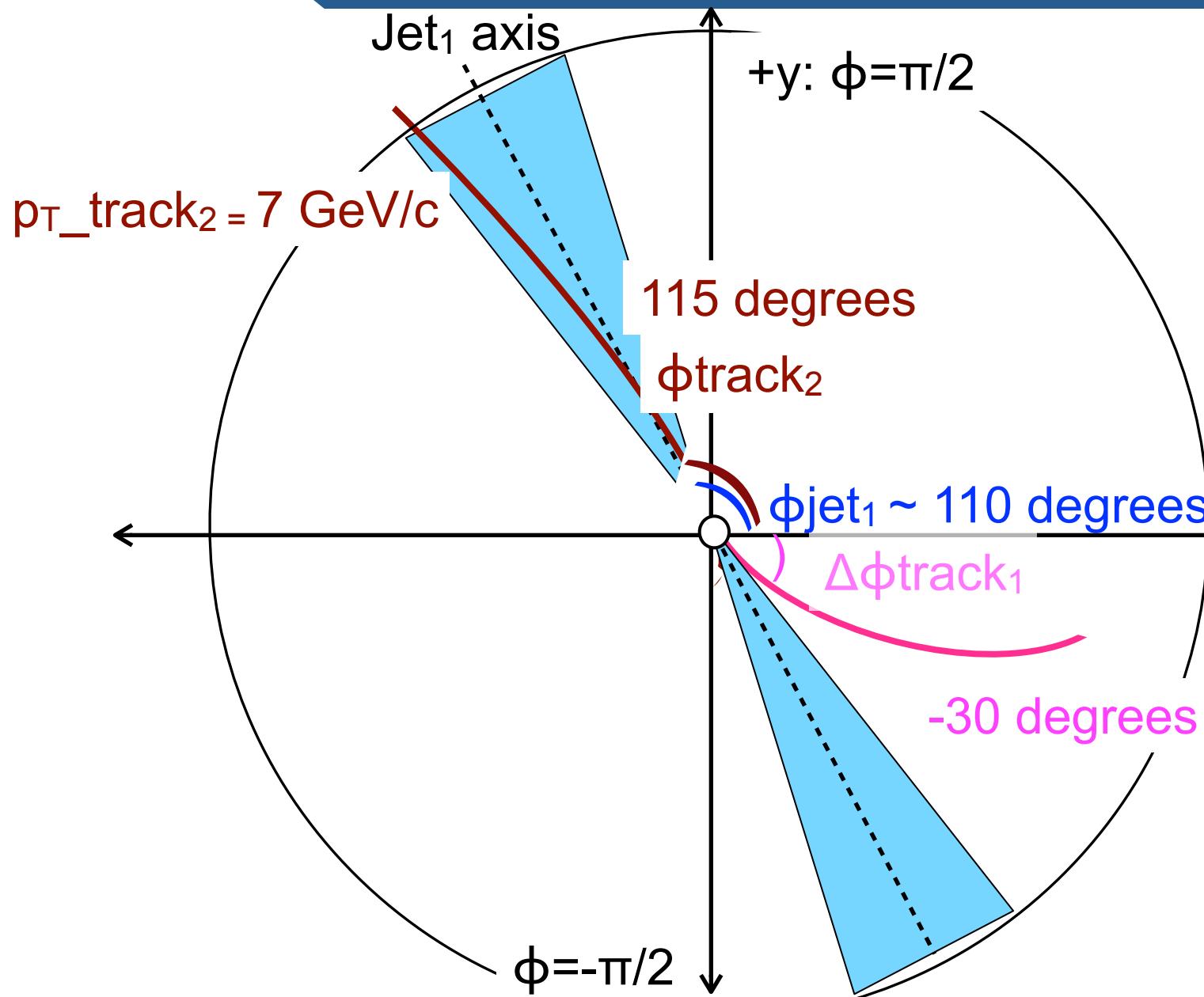
ϕ definition (for $\langle p_T \parallel \rangle$)



$$\langle p_T^{\parallel} \rangle \equiv \sum_{\text{tracks}} -p_{T,\text{track}} \cos(\phi_{\text{track}} - \phi_{\text{leading jet}})$$



Pictoral $\langle p_T^{\parallel} \rangle$ Example



calculate
change in
angle from
leading jet

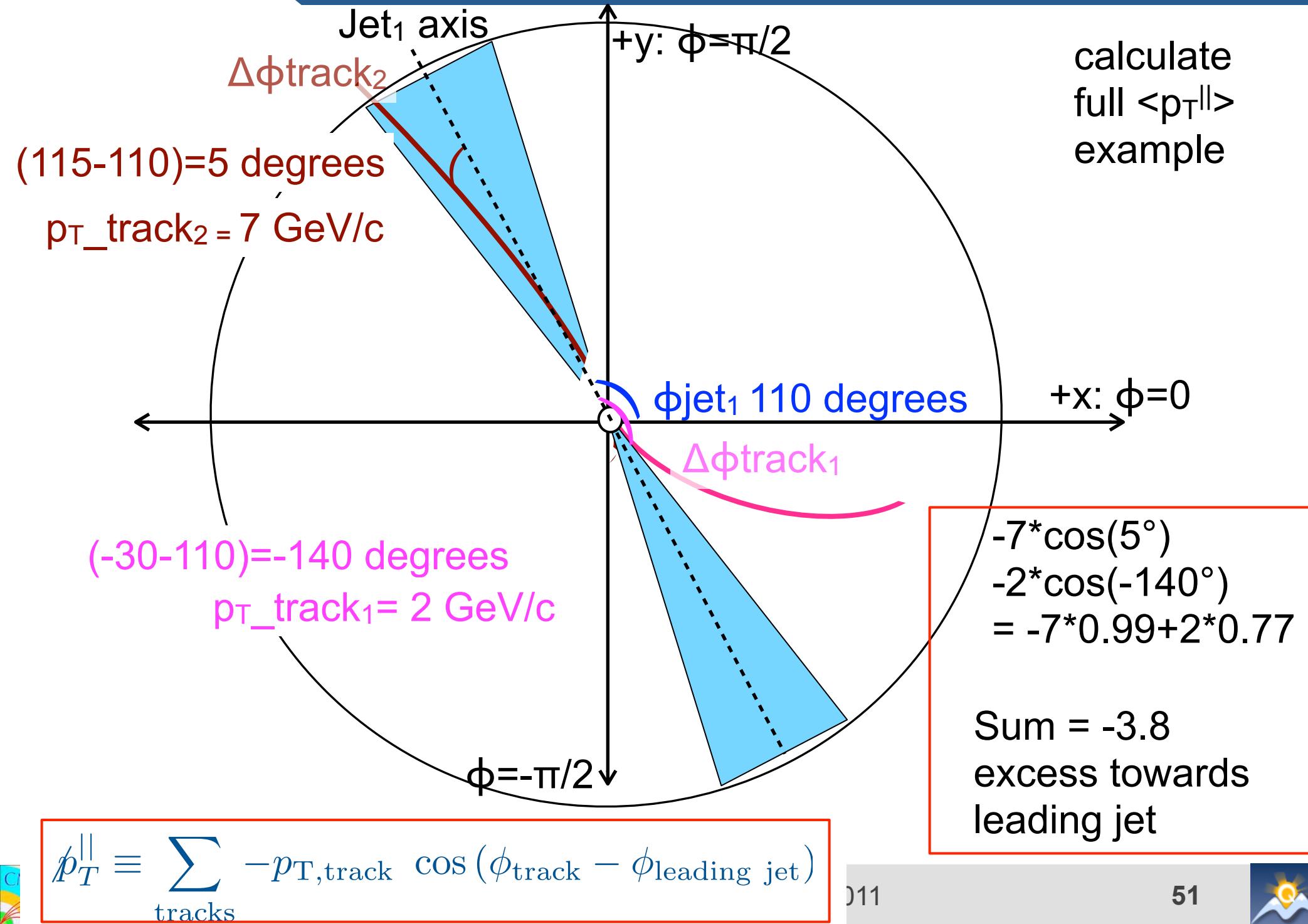
$+x: \phi=0$

p_T measured at
surface of
detector
perpendicular to
beam axis

$$\langle p_T^{\parallel} \rangle \equiv \sum_{\text{tracks}} -p_{T,\text{track}} \cos (\phi_{\text{track}} - \phi_{\text{leading jet}})$$

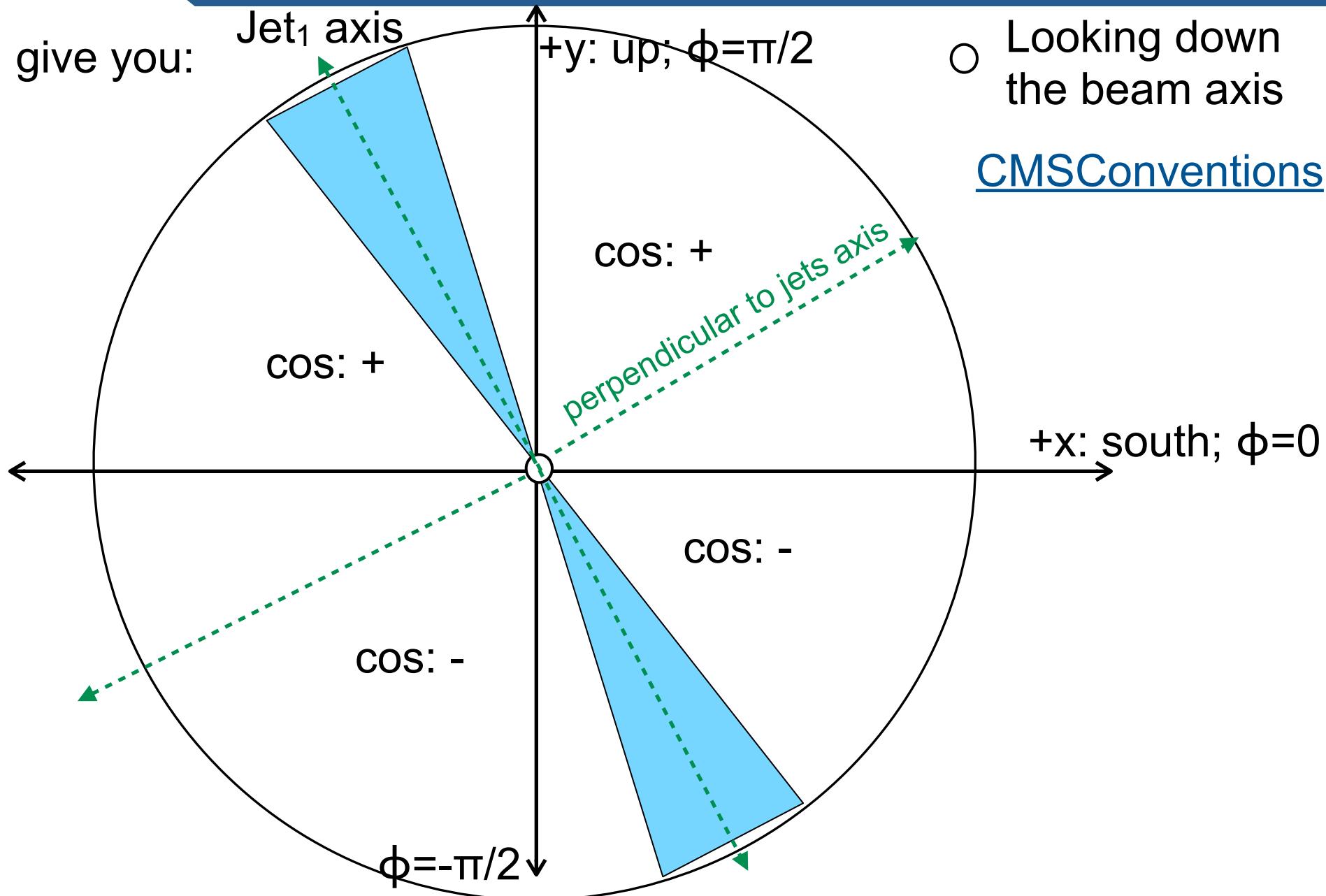


Pictoral $\langle p_T^{\parallel} \rangle$ Example



Result of the $\cos(\phi_{\text{track}} - \phi_{\text{jet1}})$

\cos will give you:
+ or -



$$\not{p}_T^{\parallel} \equiv \sum_{\text{tracks}} -p_{T,\text{track}} \quad \boxed{\cos(\phi_{\text{track}} - \phi_{\text{leading jet}})}$$



$$-p_{T,\text{track}} \cos(\phi_{\text{track}} - \phi_{\text{jet1}})$$

\cos will give you:

+ or -

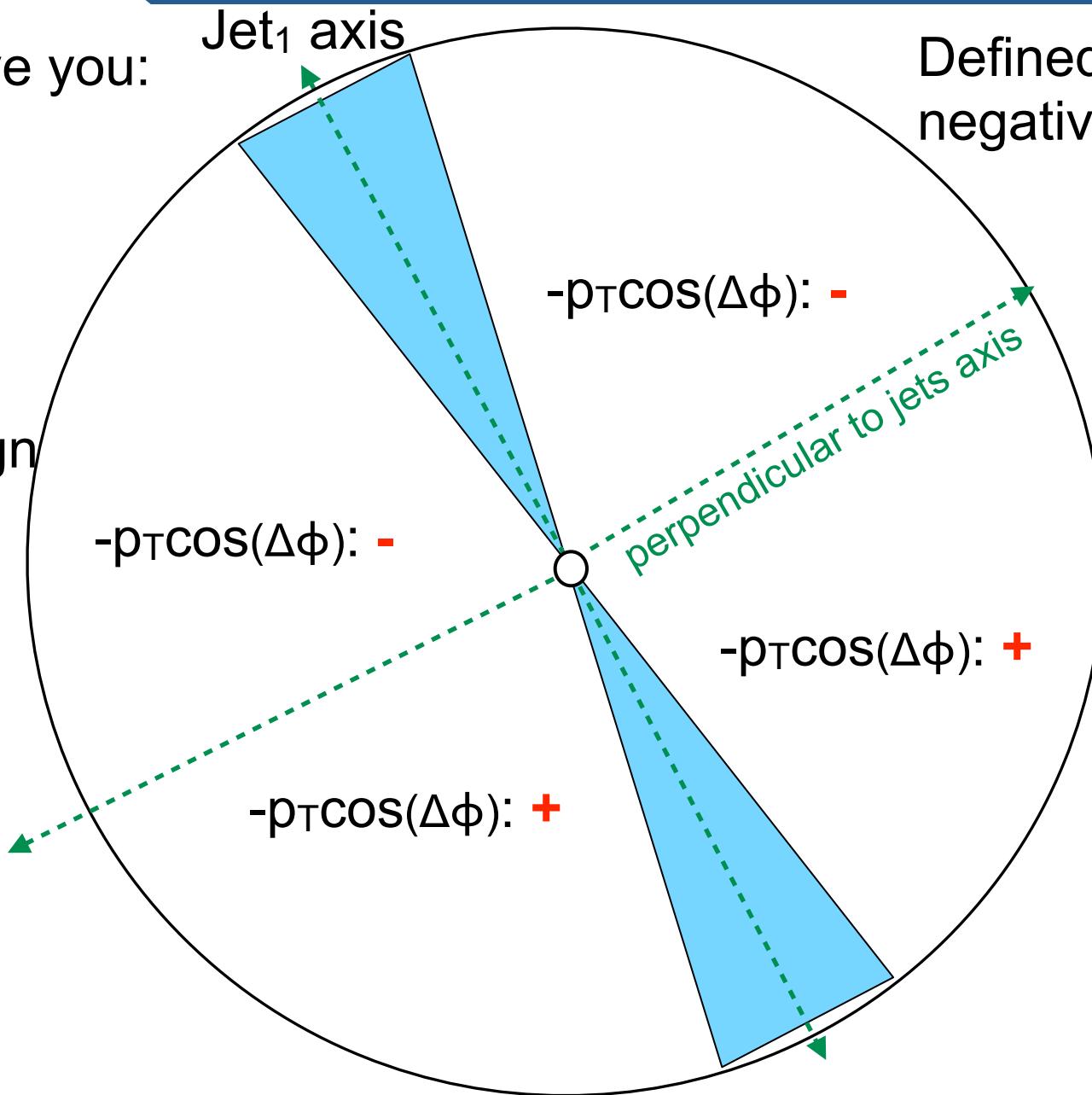
multiply by

$-p_T$,

quadrants

reverse sign

Defined as
negative towards leading



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

