Jet Measurements in PbPb Collisions with the CMS Detector

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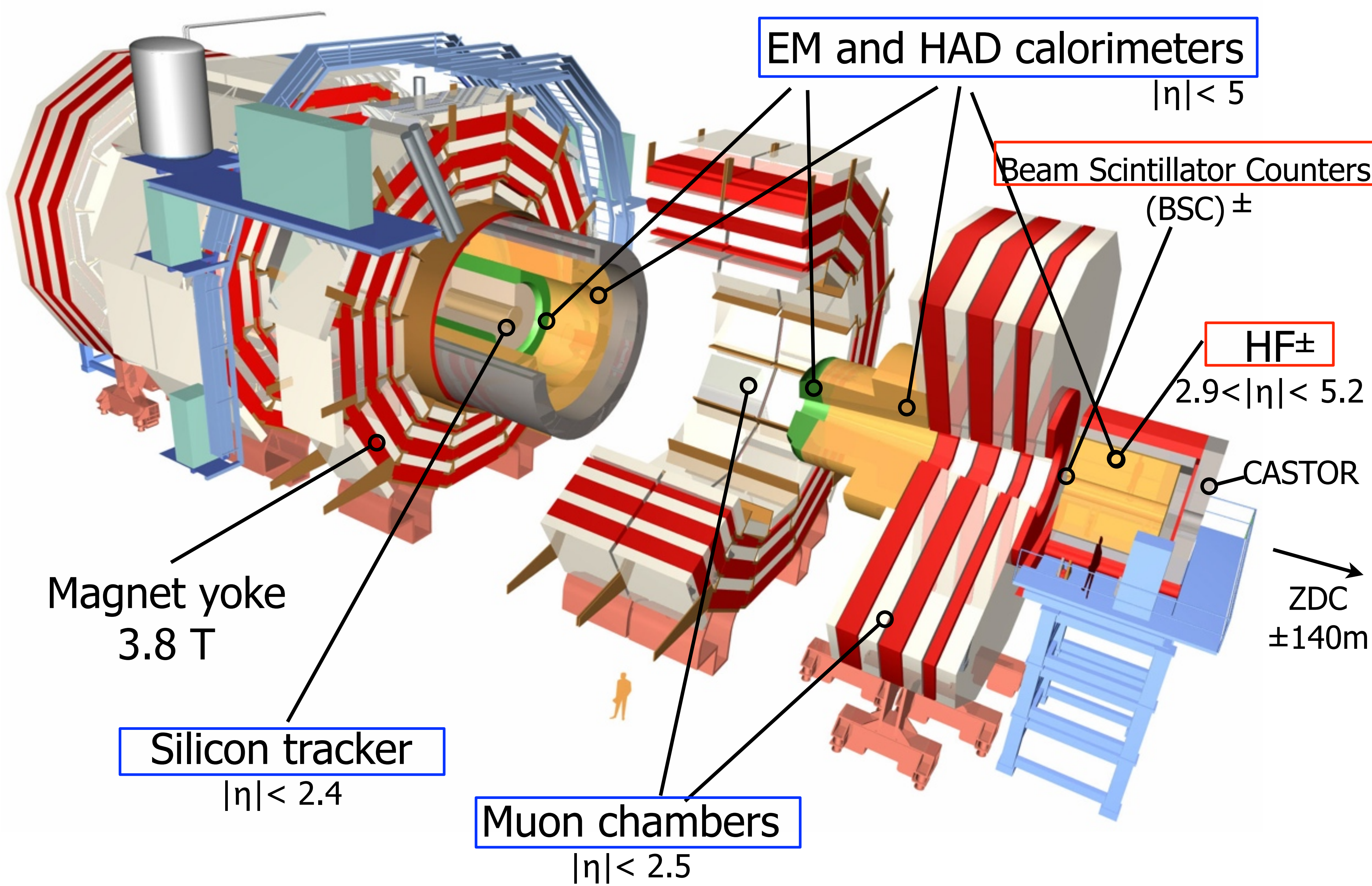
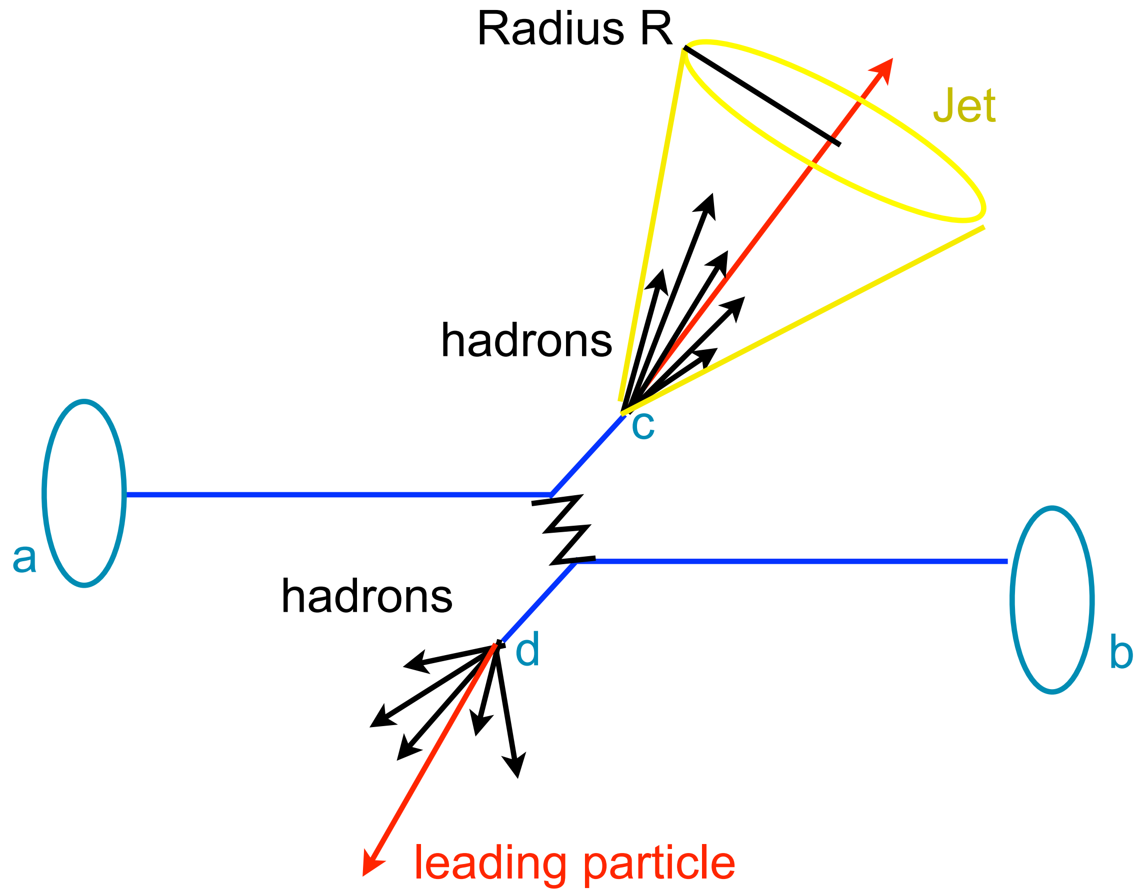
for the CMS Collaboration

Compact Muon Solenoid (CMS)



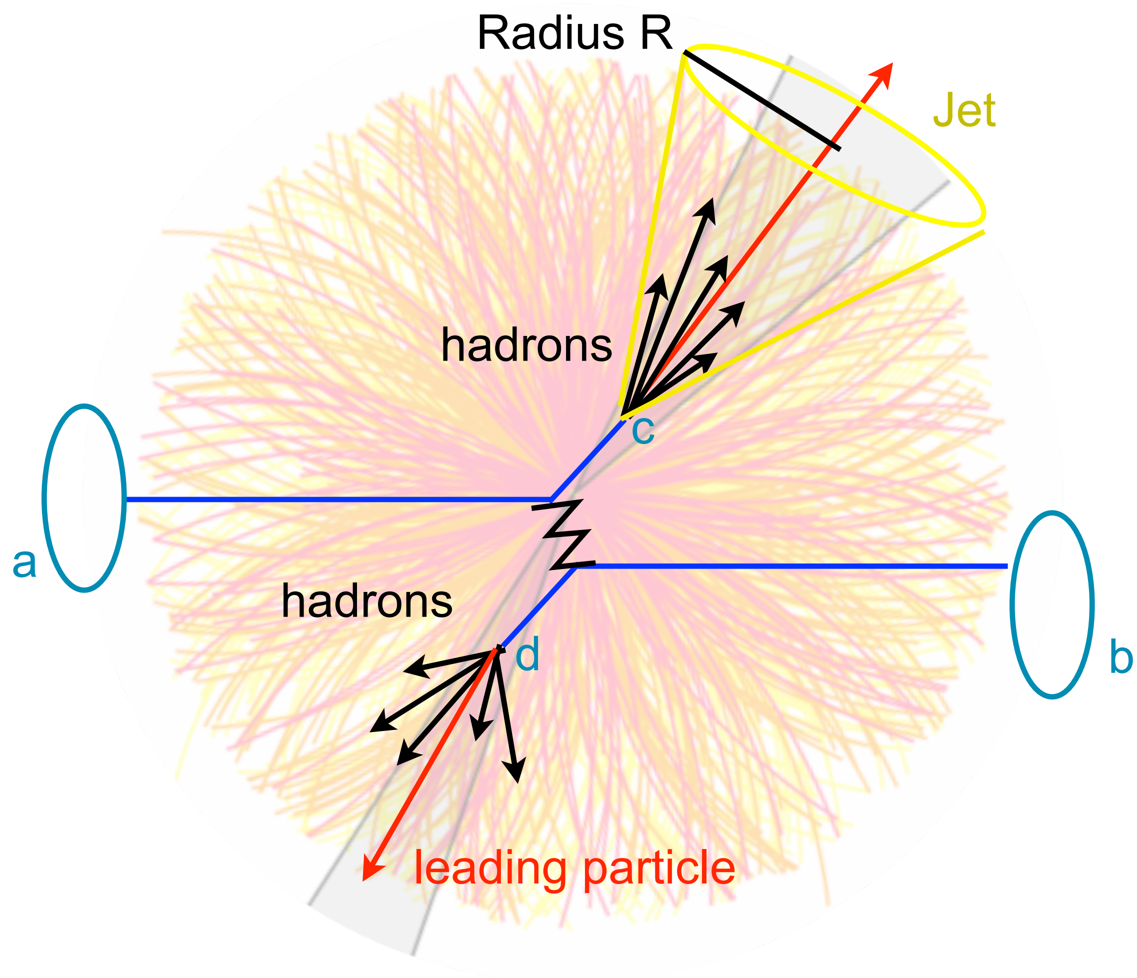
Jet Finding in Heavy Ion Events

- Jet: localized collection of hadrons that come from a fragmented parton



Jet Finding in Heavy Ion Events

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

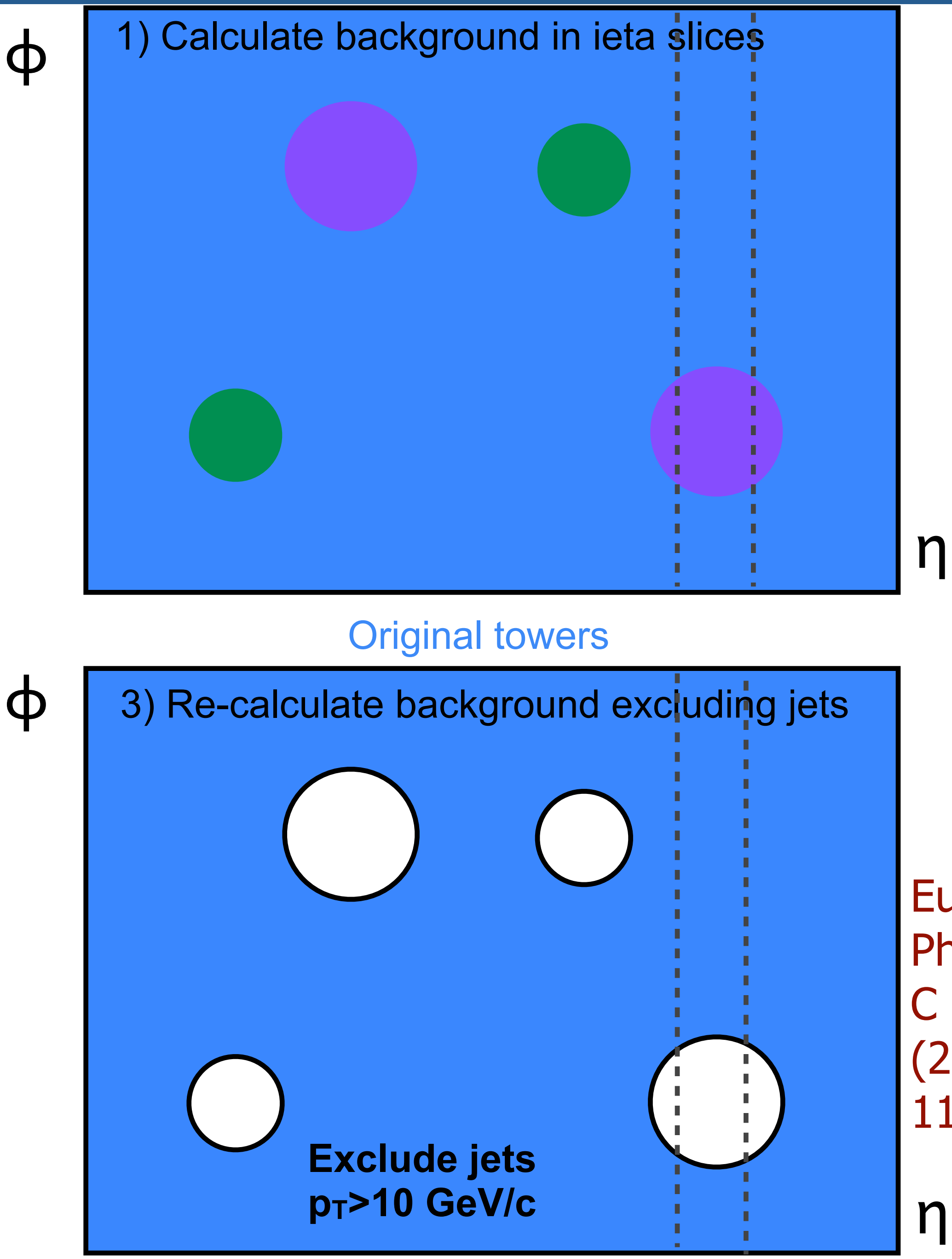


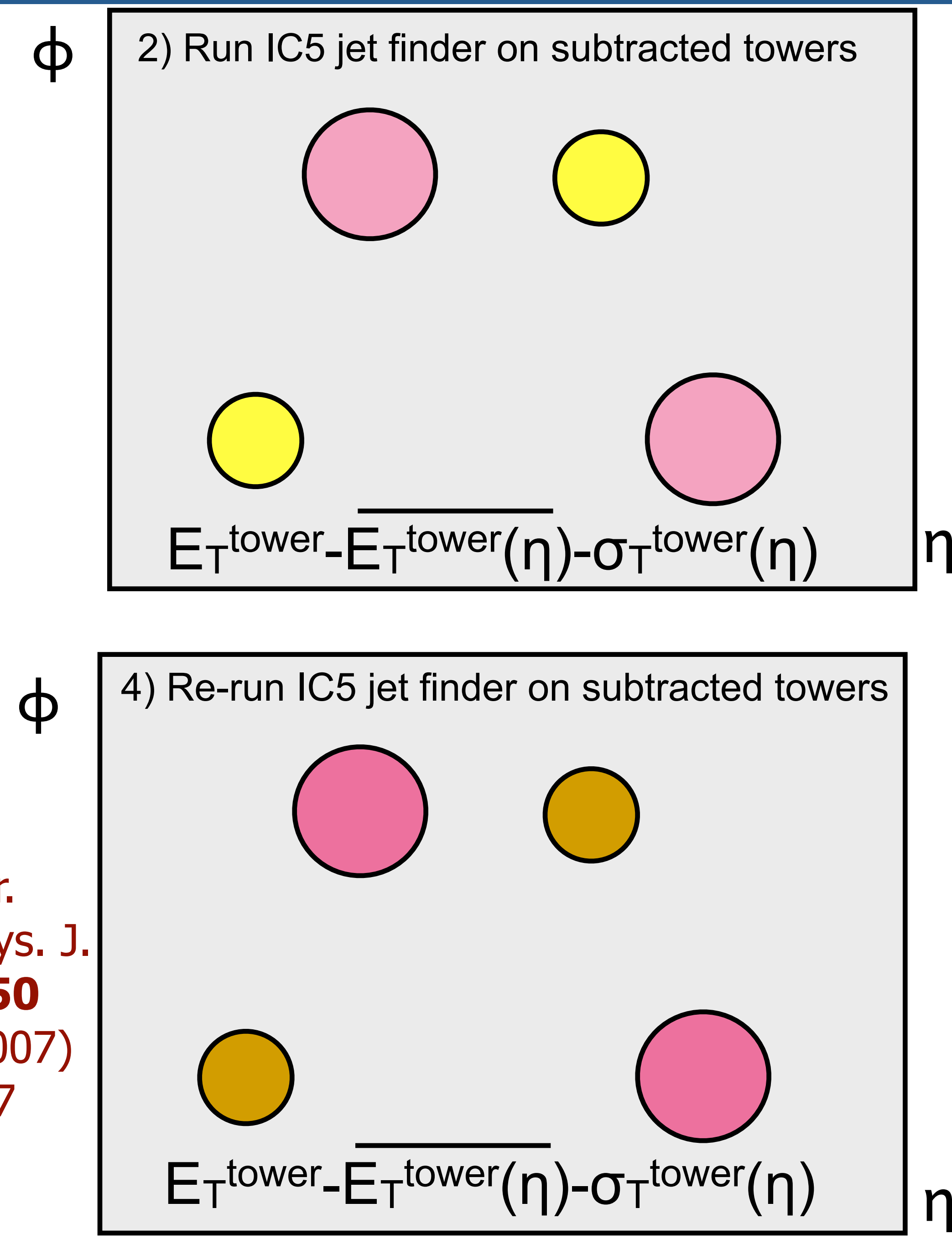
[*] O. Kodolova, et. al., Eur. Phys. J. **C50** (2007) 117

CMS Jet Finding

- CMS has non-linear calorimeter response in p_T and η, need jet energy corrections (which are well understood in pp)
  - iterative cone 0.5: use corrections derived in pp (and checked with pp data, including dijet asymmetry)
  - anti-k_T cone 0.3 with particle flow, heavy ion tracking: derive corrections using PYTHIA pp simulations ONLY
- Remove soft background (next slide)
- Particle Flow !=anisotropy, but is instead a method to utilize all subdetectors to the finest granularity: based on reconstructing all stable particles in the event to create higher level objects (jets)

Iterative Pileup Subtraction (Event by Event)





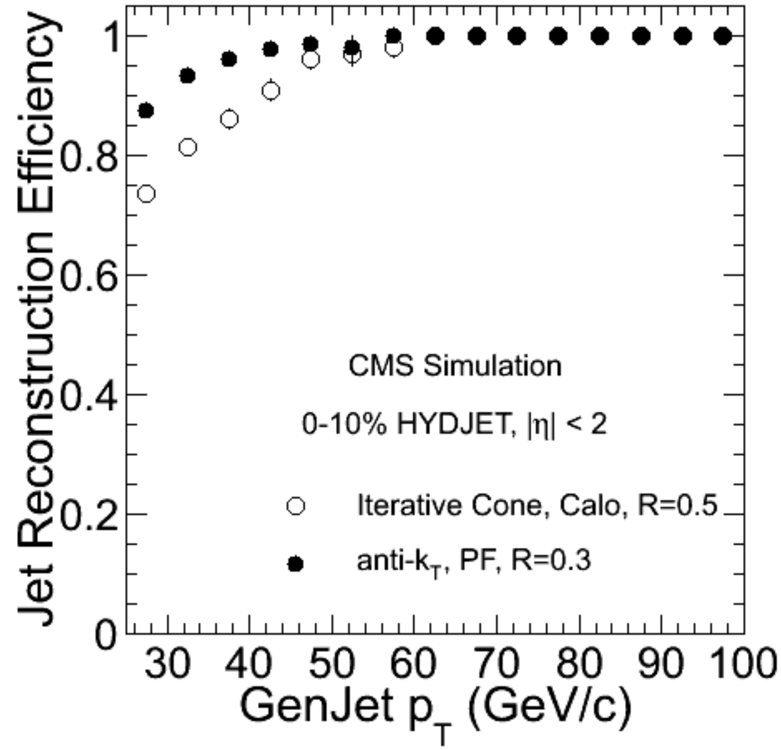
Eur. Phys. J. C **50** (2007) 117

Background Studies

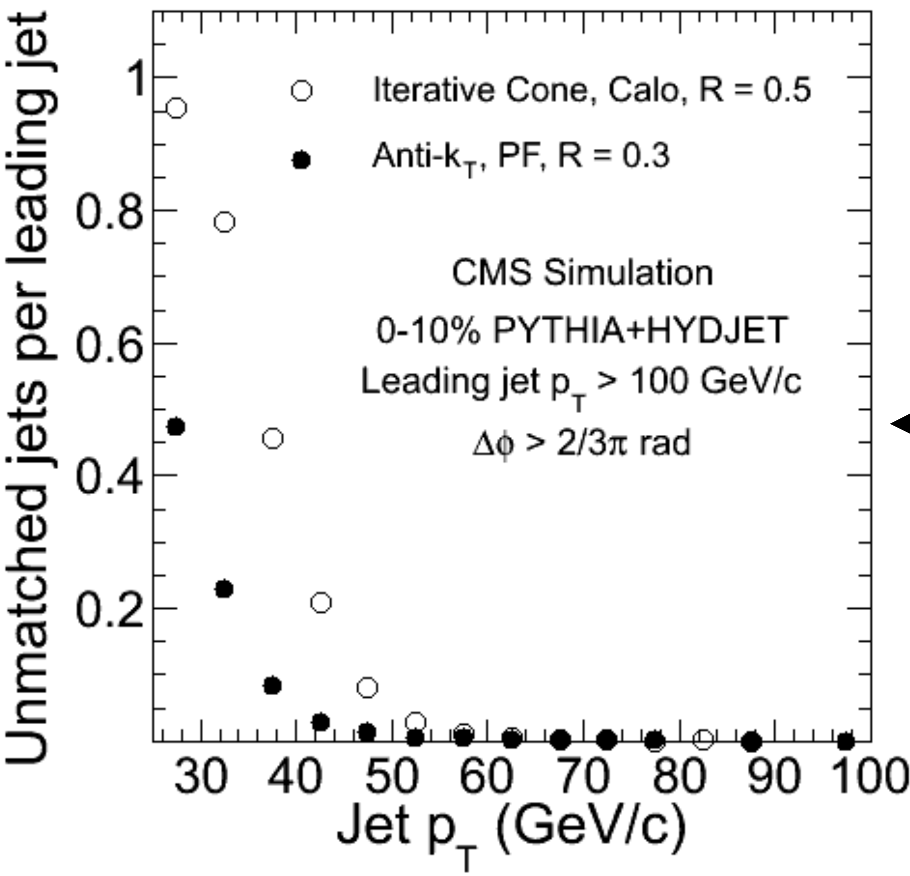
- Study PYTHIA embedded into MinBias PbPb data
- Study PYTHIA embedded in HYDJET
  - See same jet finding resolution for both
- Study background fluctuations with MC and data
  - Agree closely, differences included in systematic
- Extra background distributed from quenching added to systematic
- Background subtraction method used removes most low p_T content before it can contribute to jet
  - Soft fluctuations in background contribute little
  - High p_T fluctuations understood in jet resolution studies

Jet Efficiency and Dijet "Mismatch" Rate

Efficiency: fraction of reconstructed jets which match a generator jet in position



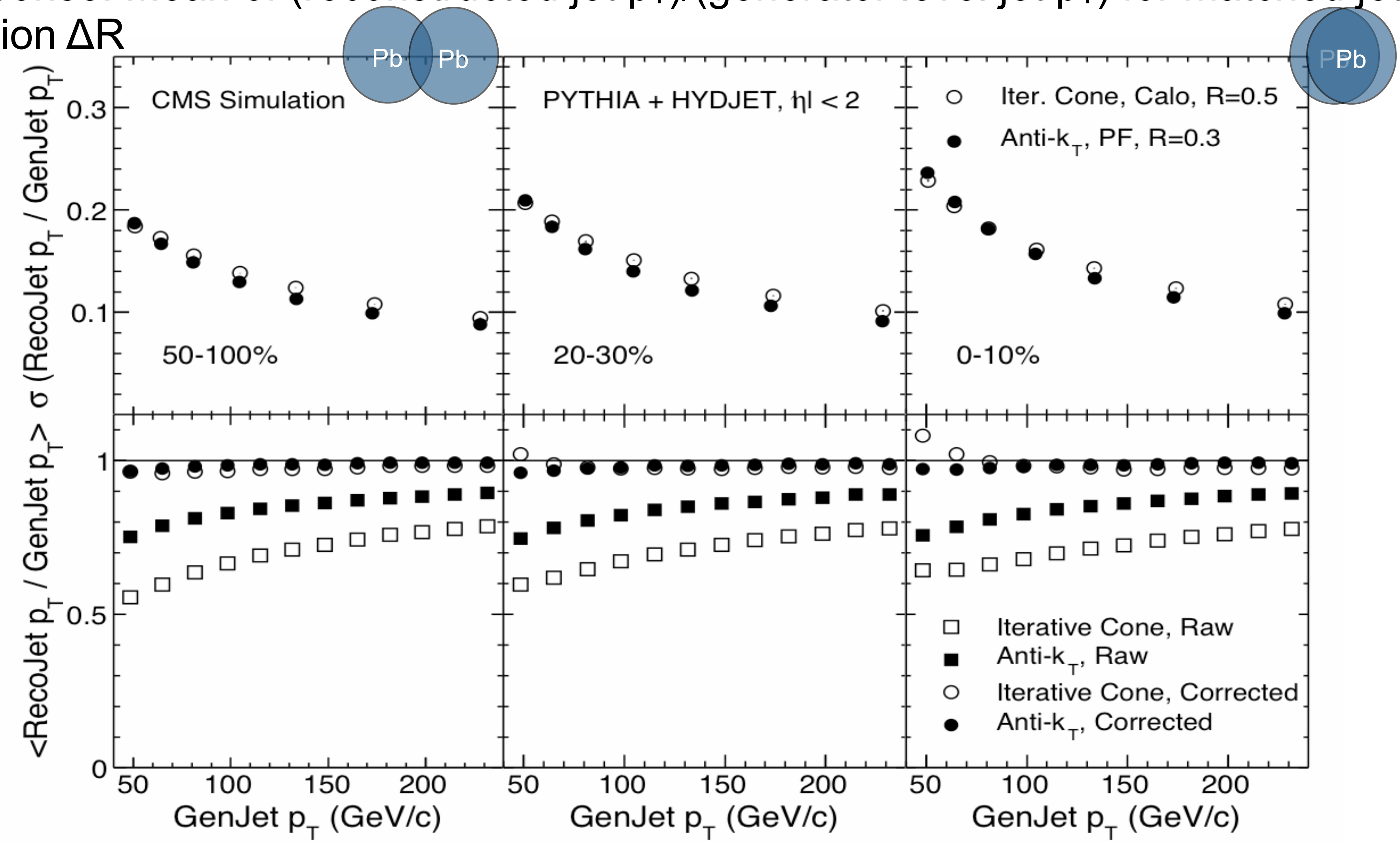
Smaller cone size less sensitive to background



- Require leading jet p_T > 100 GeV/c
- How often is an away-side jet not the true dijet partner?
- Count **all** away-jets per leading jet which do not match to PYTHIA jet

Inclusive Jet Performance in PbPb

Resolution: σ of (reconstructed jet p_T)/(generator level jet p_T) for matched jets in ΔR
Response: Mean of (reconstructed jet p_T)/(generator level jet p_T) for matched jets in position ΔR



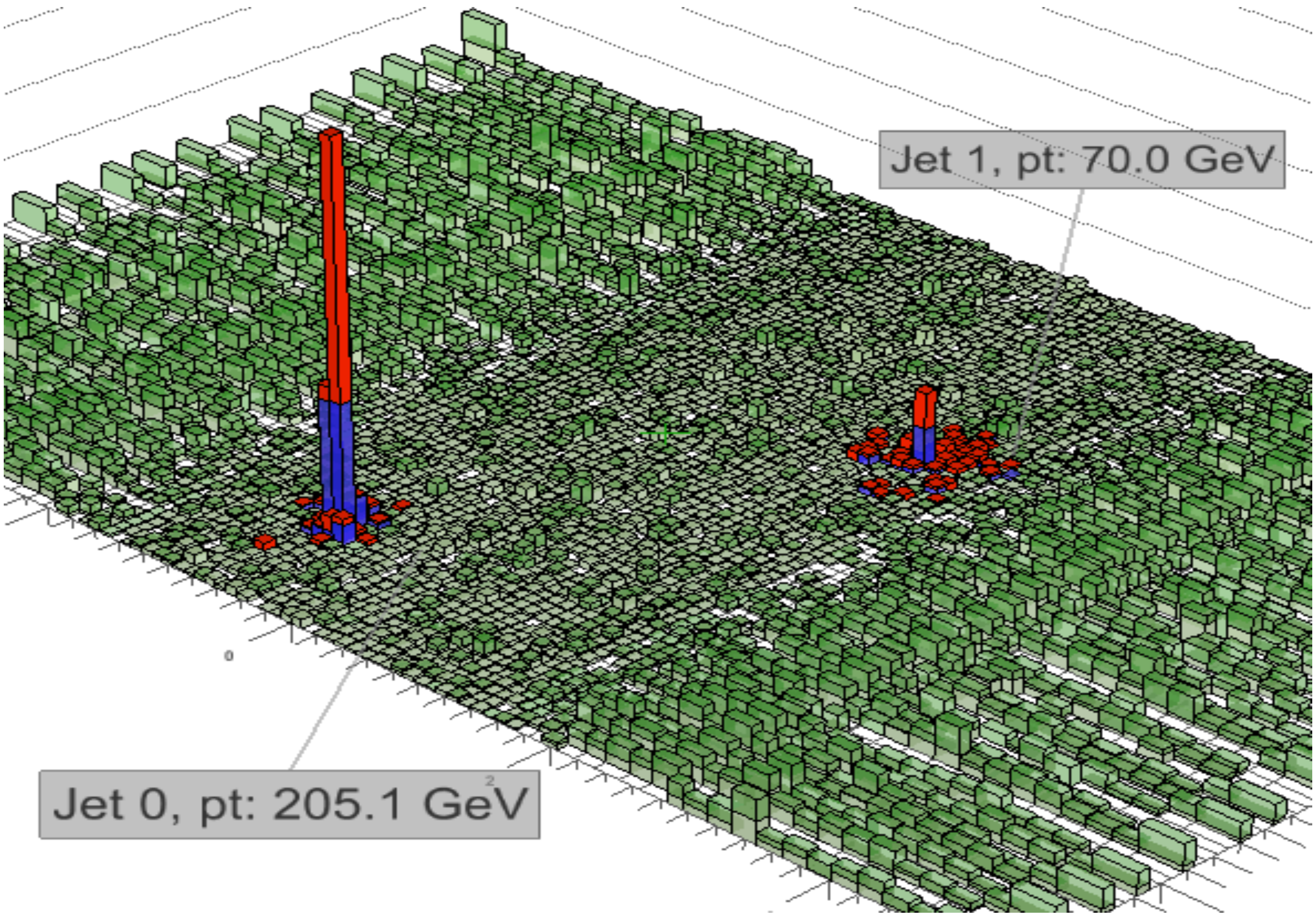
Particle flow improves response, especially at low p_T

Finding Dijets in PbPb Collisions

- Trigger on jet collisions (35U or 50U)
  - iterative cone 0.5 with iterative pileup subtraction in trigger
  - U means energy before p_T, η corrections applied
- Make sure they are minimum bias events
  - Also remove uncharacteristic detector signal events
- Select dijets with choices based on performance of jet finder in simulations, and trigger efficiency
  - anti-k_T particle flow, iterative pileup subtraction
    - leading p_T>100 GeV/c, subleading p_T>40 GeV/c
  - iterative cone 0.5 calorimeter jet, iterative pileup subtraction
    - leading p_T>120 GeV/c, subleading p_T>50 GeV/c
  - and $|\eta|<2$; $\Delta\phi_{1,2} > 2\pi/3$

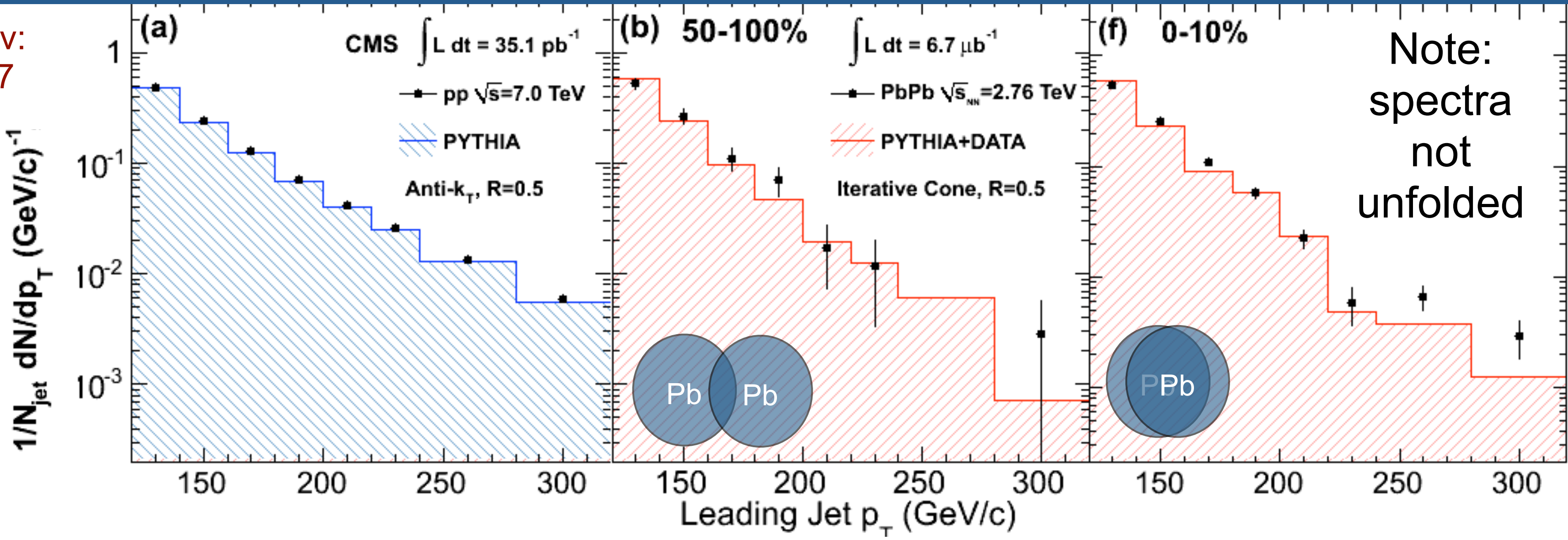
Finding Dijets in PbPb Collisions II

- Check some fraction by eye in event display

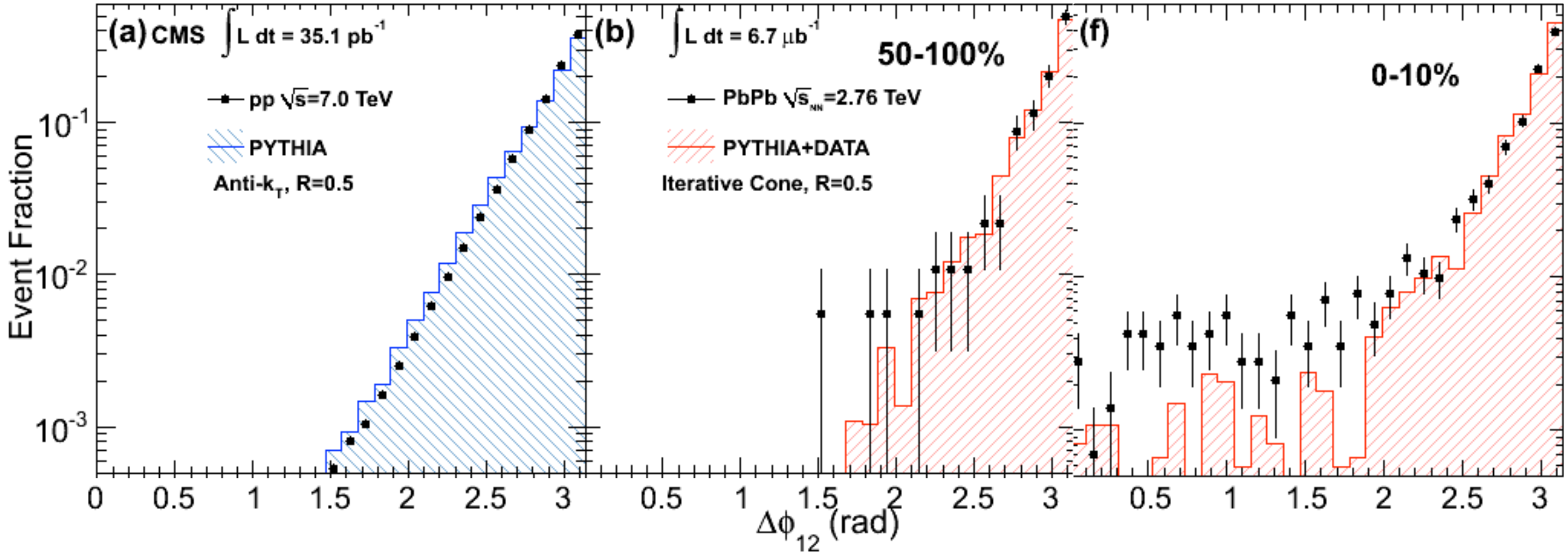


Checking for Modification by PbPb

CMS: arXiv: 1102.1957



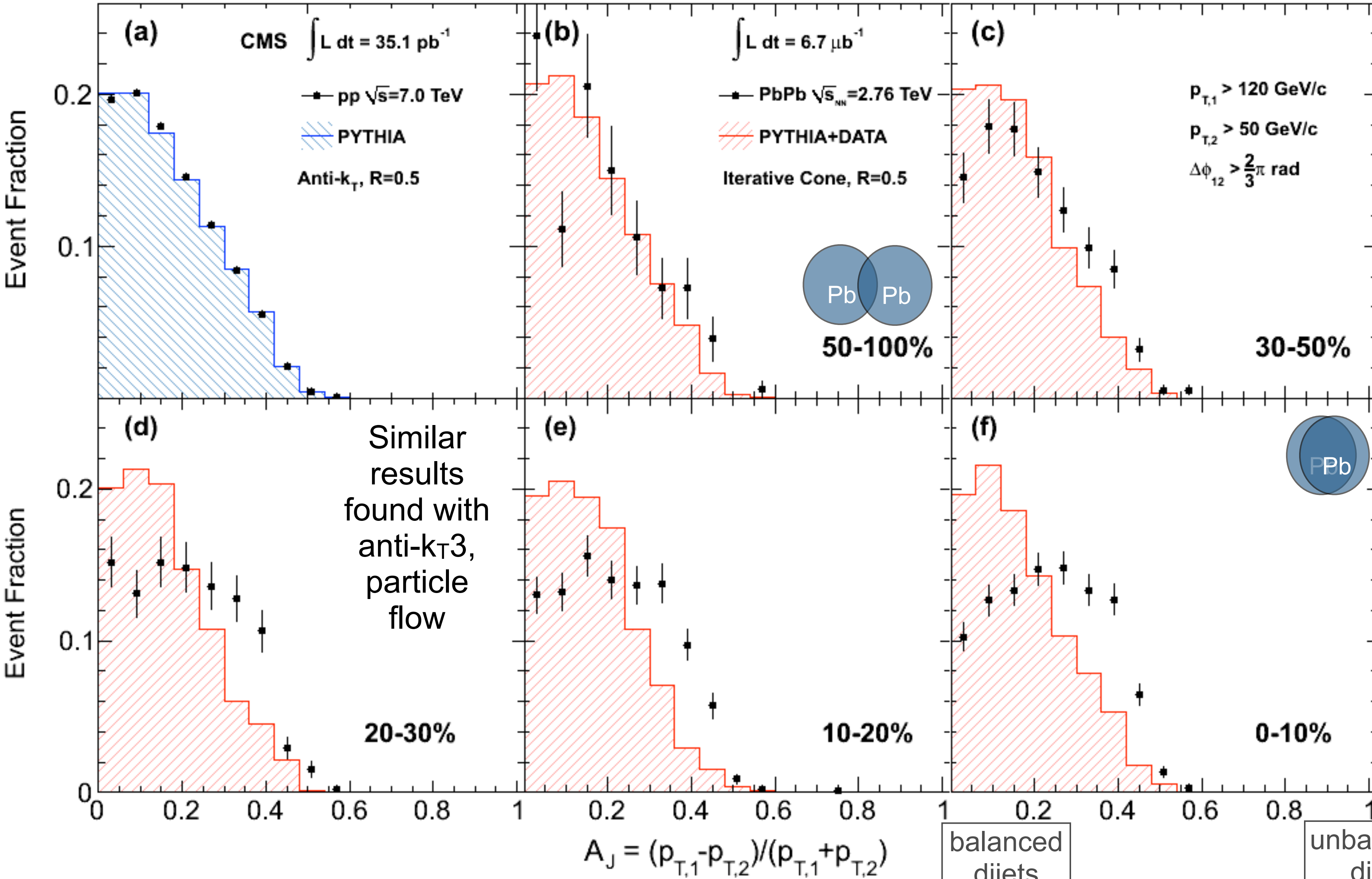
Note: spectra not unfolded



Similar results found with anti-k_T3, particle flow

The propagation of high p_T partons in a dense nuclear medium does not lead to a visible angular decorrelation

Dijet p_T Asymmetry



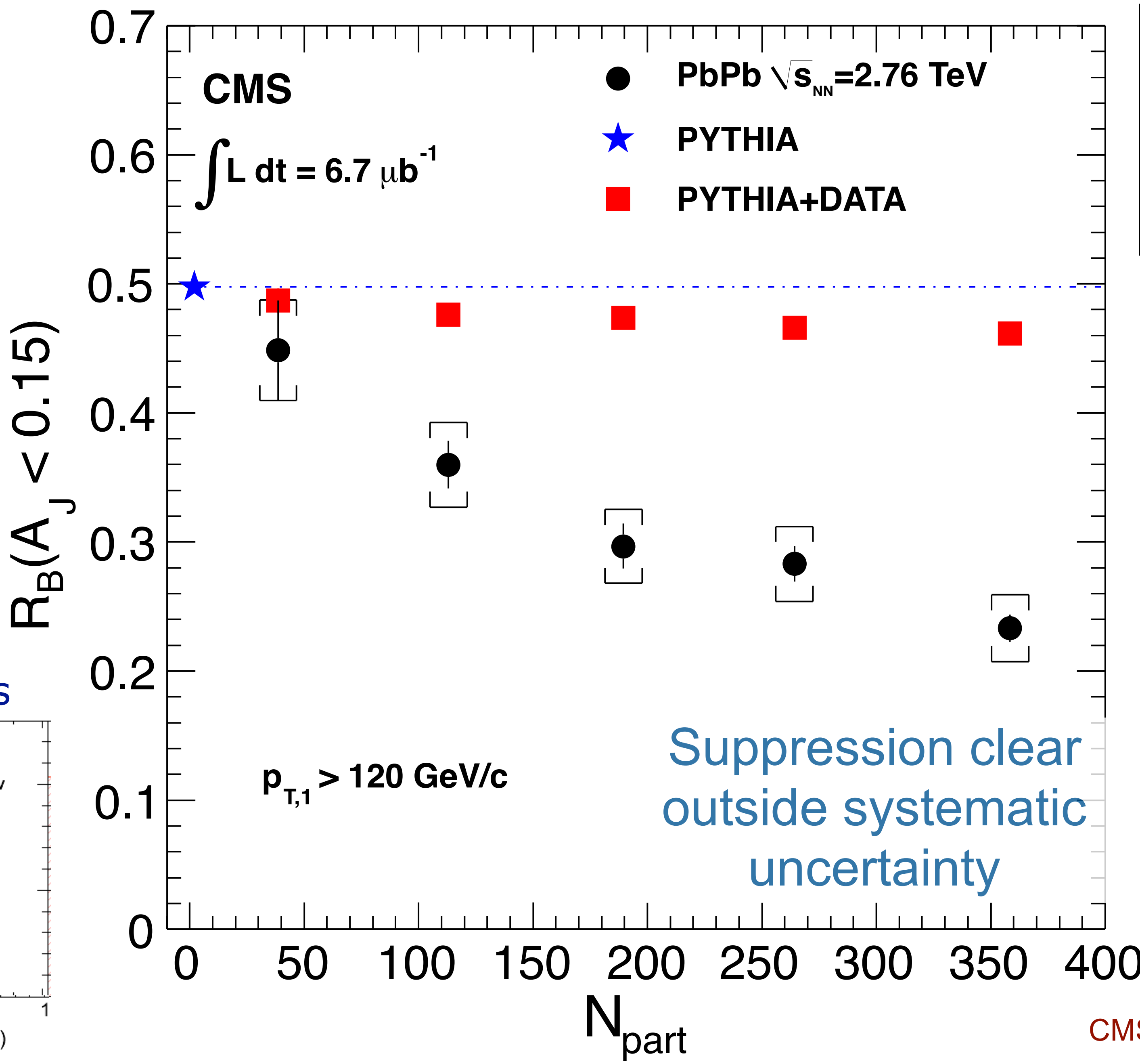
CMS: arXiv:1102.1957

balanced dijets

unbalanced dijets

Parton energy loss is observed as a pronounced energy imbalance in reconstructed dijets

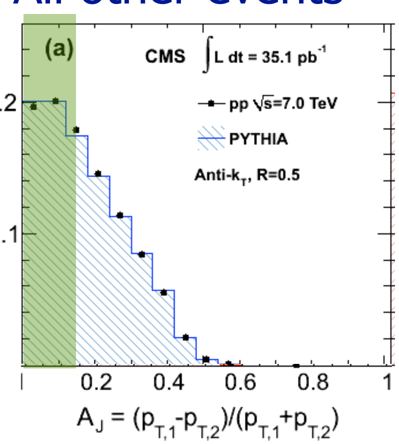
Dijet "Balanced" Fraction



$R_B(A_J)$ also includes apparent **'mono-jet'** events

0.15 is median A_J value from PYTHIA

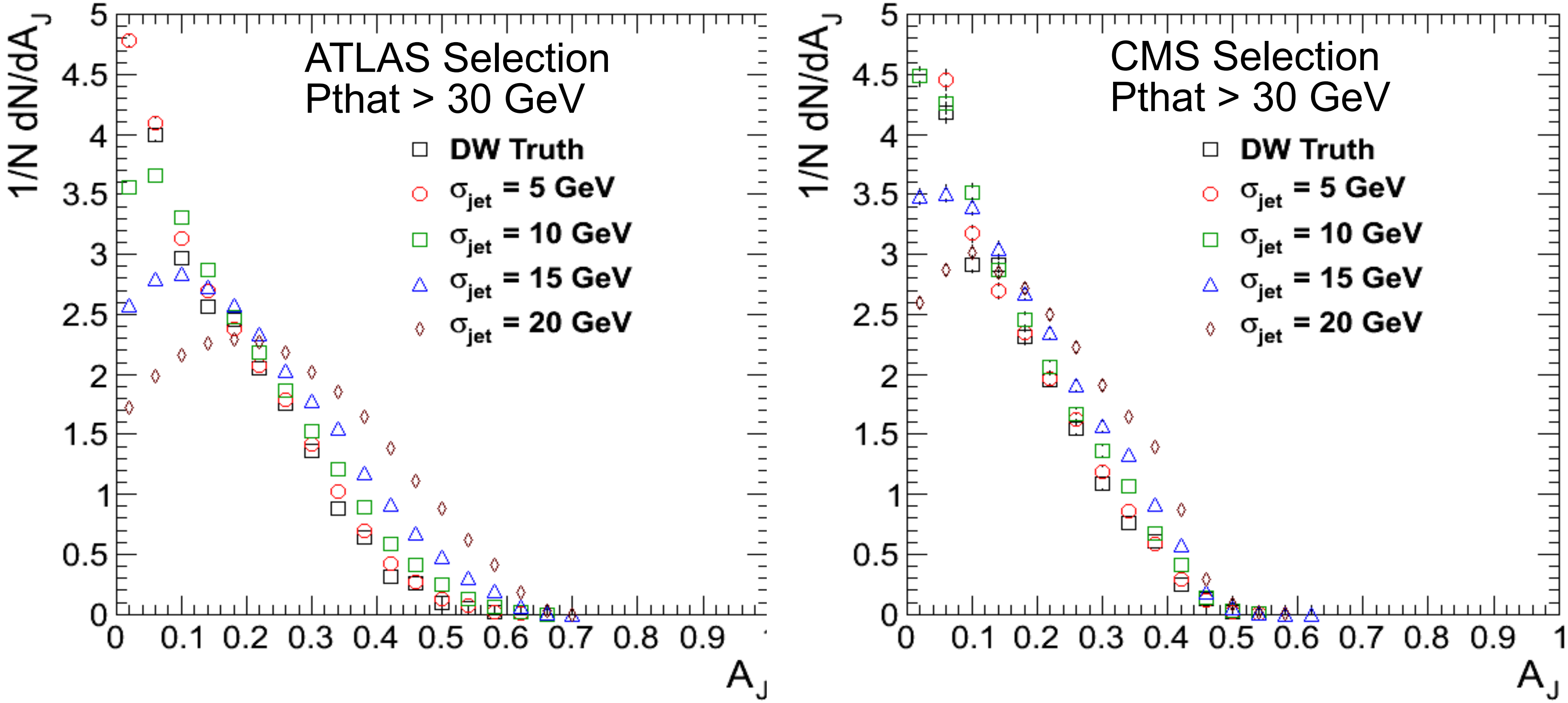
Balanced / All other events



CMS: arXiv:1102.1957

ATLAS vs CMS Dijet selection

Comparing the ATLAS and CMS dijet selection p_T hat > 30 GeV

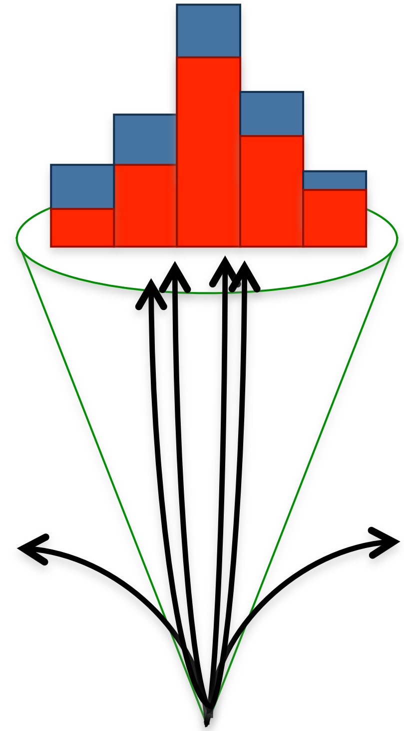


- With the higher jet thresholds used for the CMS paper we are less sensitive to background fluctuations
  - ATLAS 100/20, CMS: 120/50 for leading/sub-leading

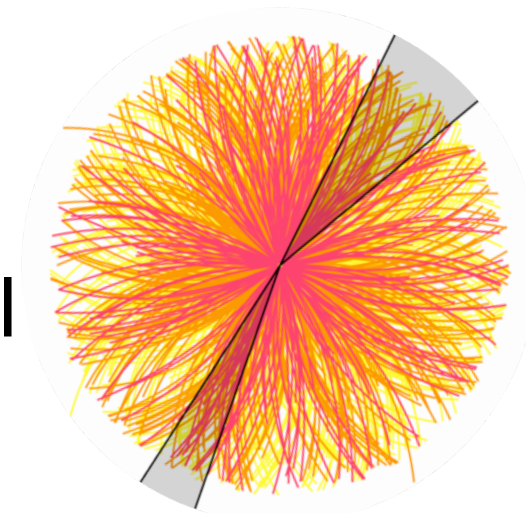
Slide added from backup per morning's discussion

Where Does the Missing Jet Energy Go?

- A large dijet energy imbalance is seen in the calorimeters



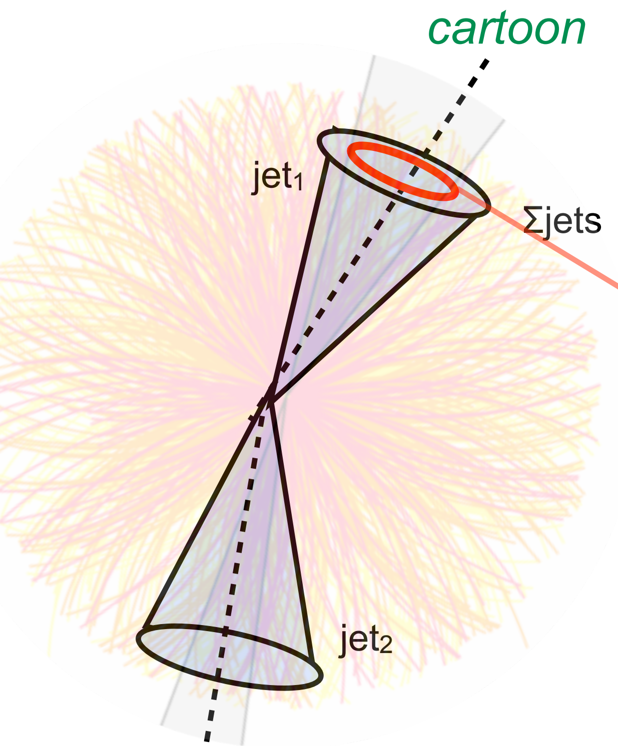
- By using the track information, we have an opportunity to do the *first in-depth studies* of where the energy goes
- Look at sum of tracks near jet cone



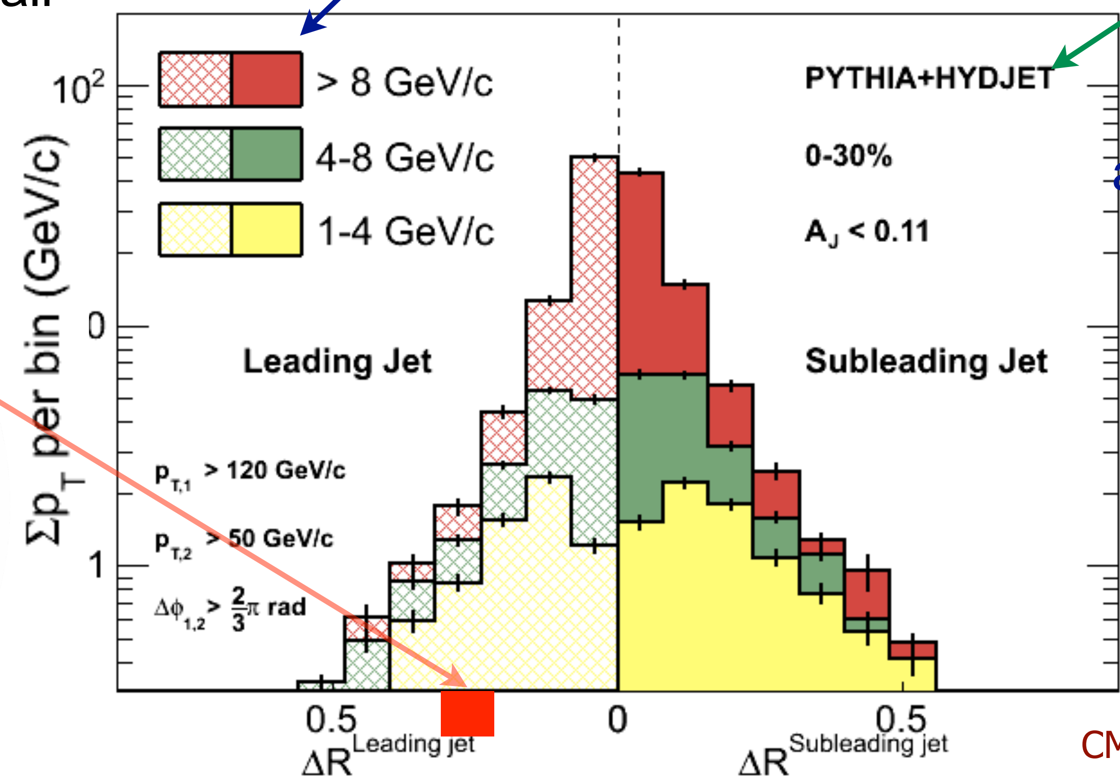
- Investigate missing momentum using all charged particle tracks

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



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



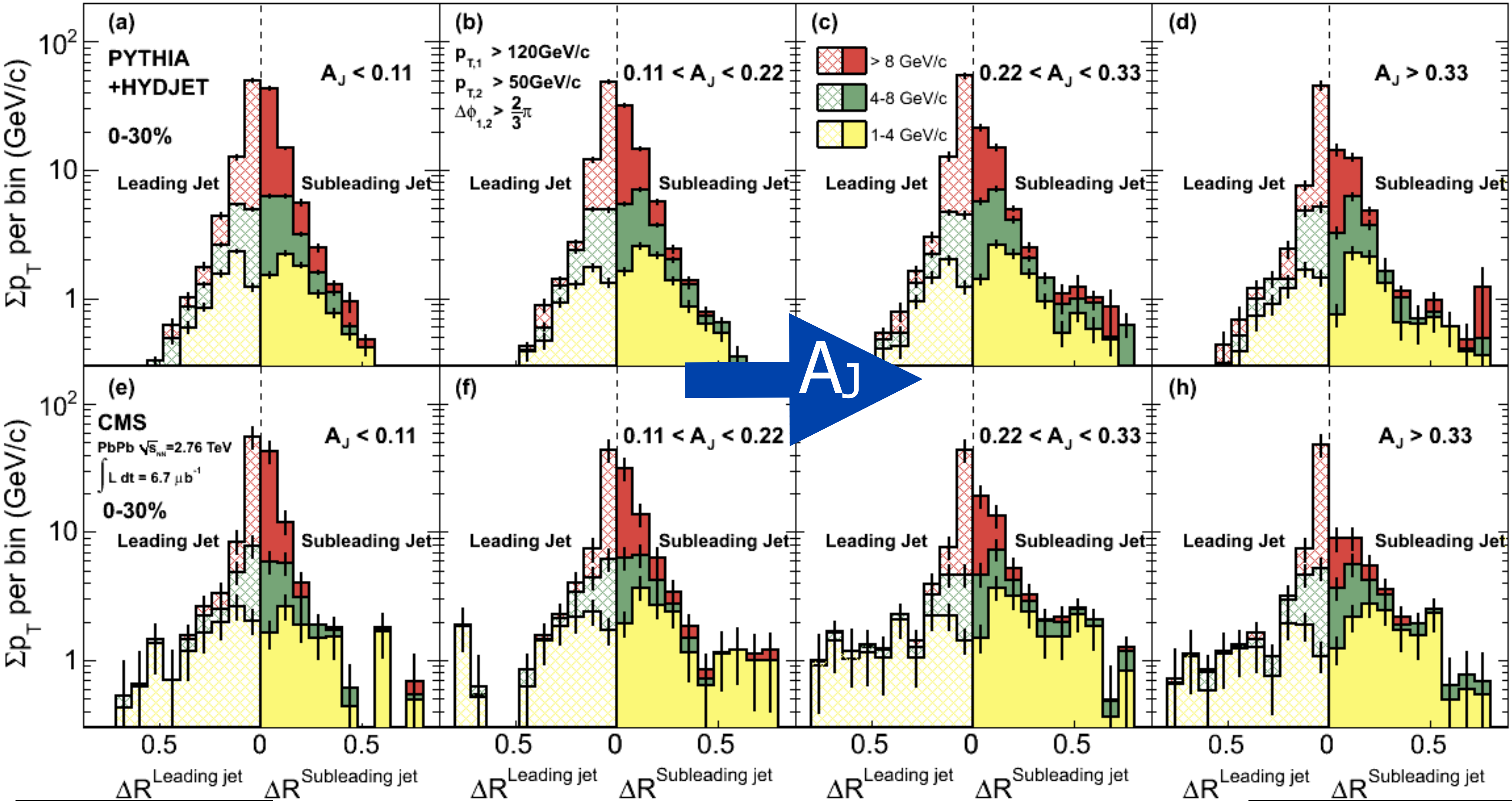
Baseline is PYTHIA +HYDJET where generator information is available for all charged particles

CMS: arXiv:1102.1957

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

Background (Underlying Event) is subtracted using a cone at same ϕ, but reflected in η (η → -η)

Asymmetry Dependence of Fragmentation



balanced jets

unbalanced jets

Note: sum of tracks

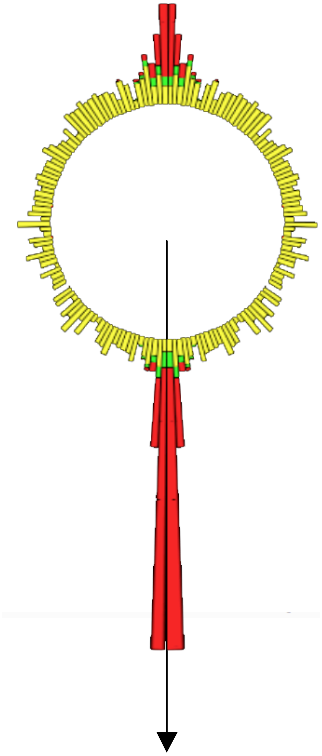
Enhancement of low p_T tracks at large cone, 0.8 not enough to balance momentum

CMS: arXiv: 1102.1957

Missing $p_T^{||}$

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

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



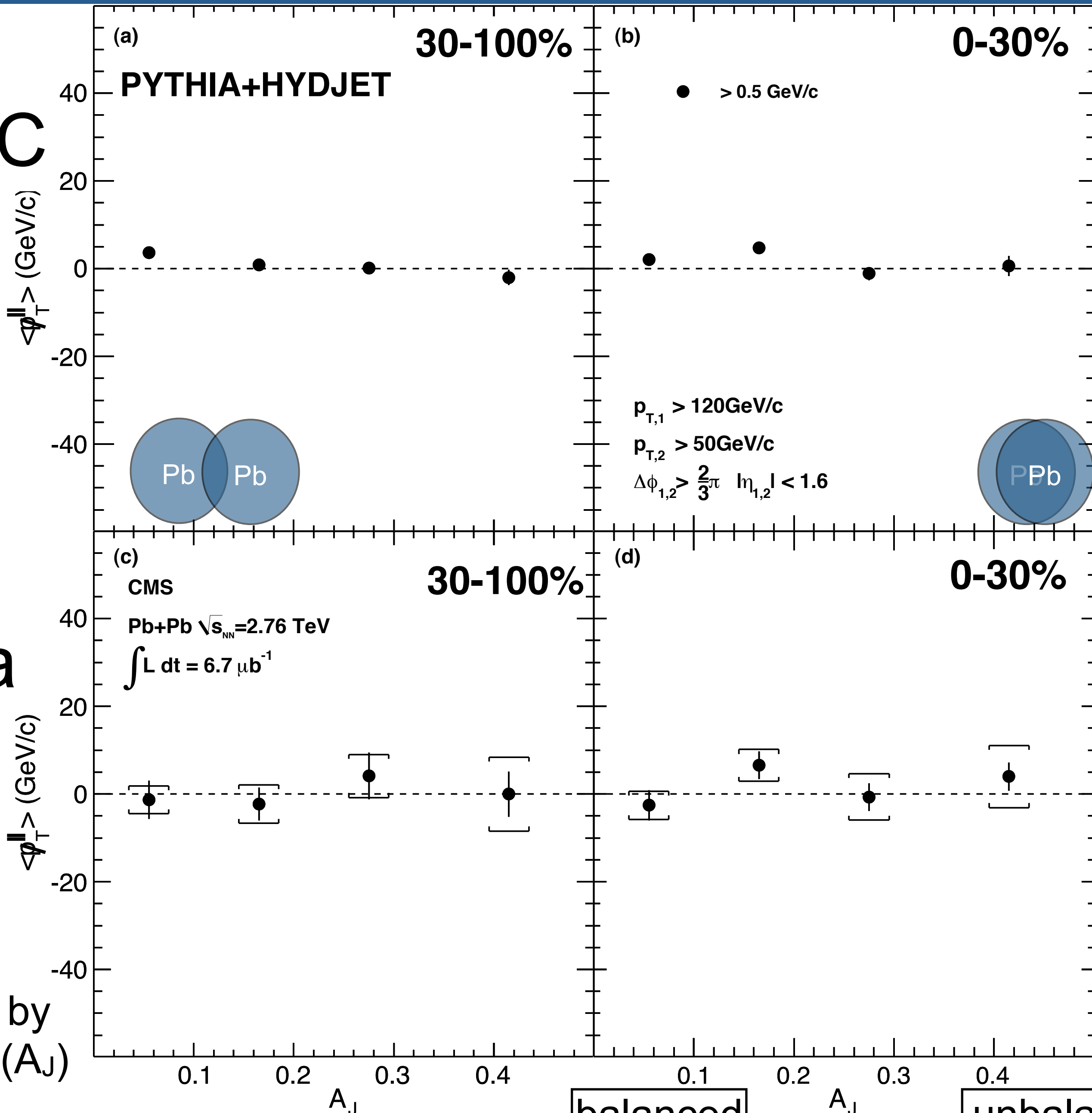
- Defined such that tracks on away side give a positive contribution
- Calculated for all tracks with p_T>0.5 GeV/c and $|\eta|$<2.4, various p_T ranges
- Averaged over events
- Allows us to see which p_T range carries the balance of the jet momentum
- Note this is a sum of differences, we are interested in the direction of excess (towards or away from leading jet)
  - Tracks could cancel out in some region
- No background subtraction needed

$<\not{p}_T^{||}>$ vs. A_J

All tracks in event used

MC

Data



- For **all** tracks of p_T> 0.5 GeV/c: momentum balance recovered

excess away from leading jet

excess towards leading jet

Only direction information is towards or away from leading jet

balanced dijets

unbalanced dijets

Classify events by dijet asymmetry (A_J)

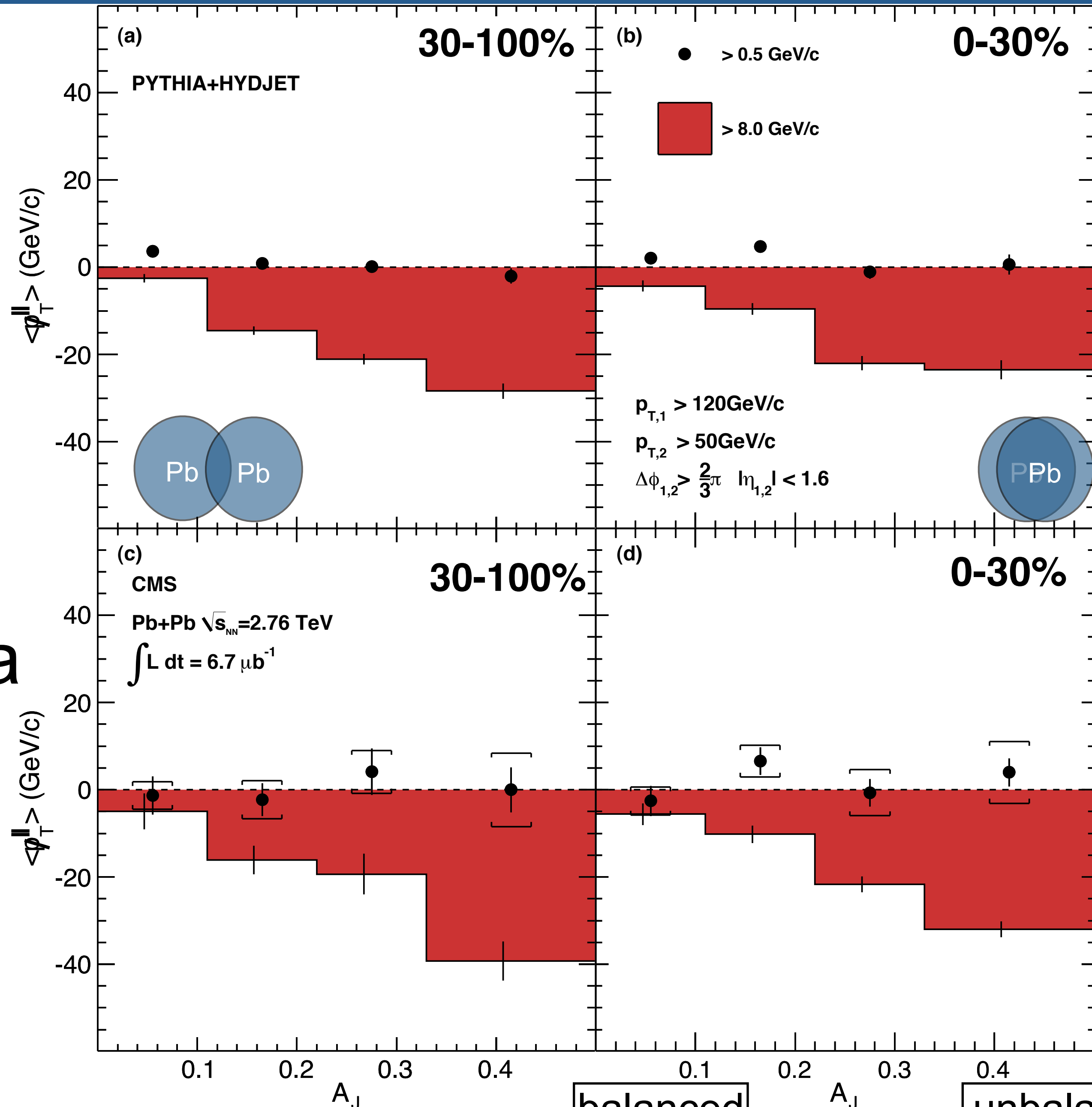
$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\text{T,track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$

$<\not{p}_T^{||}>$ vs. A_J

MC

There probably were some high pT particles in away side, just no Excess (sum of differences)

Data



> 8.0 GeV/c

High p_T particles: Excess momentum towards leading jet with increasing A_J

excess away from leading jet

excess towards leading jet

balanced dijets

unbalanced dijets

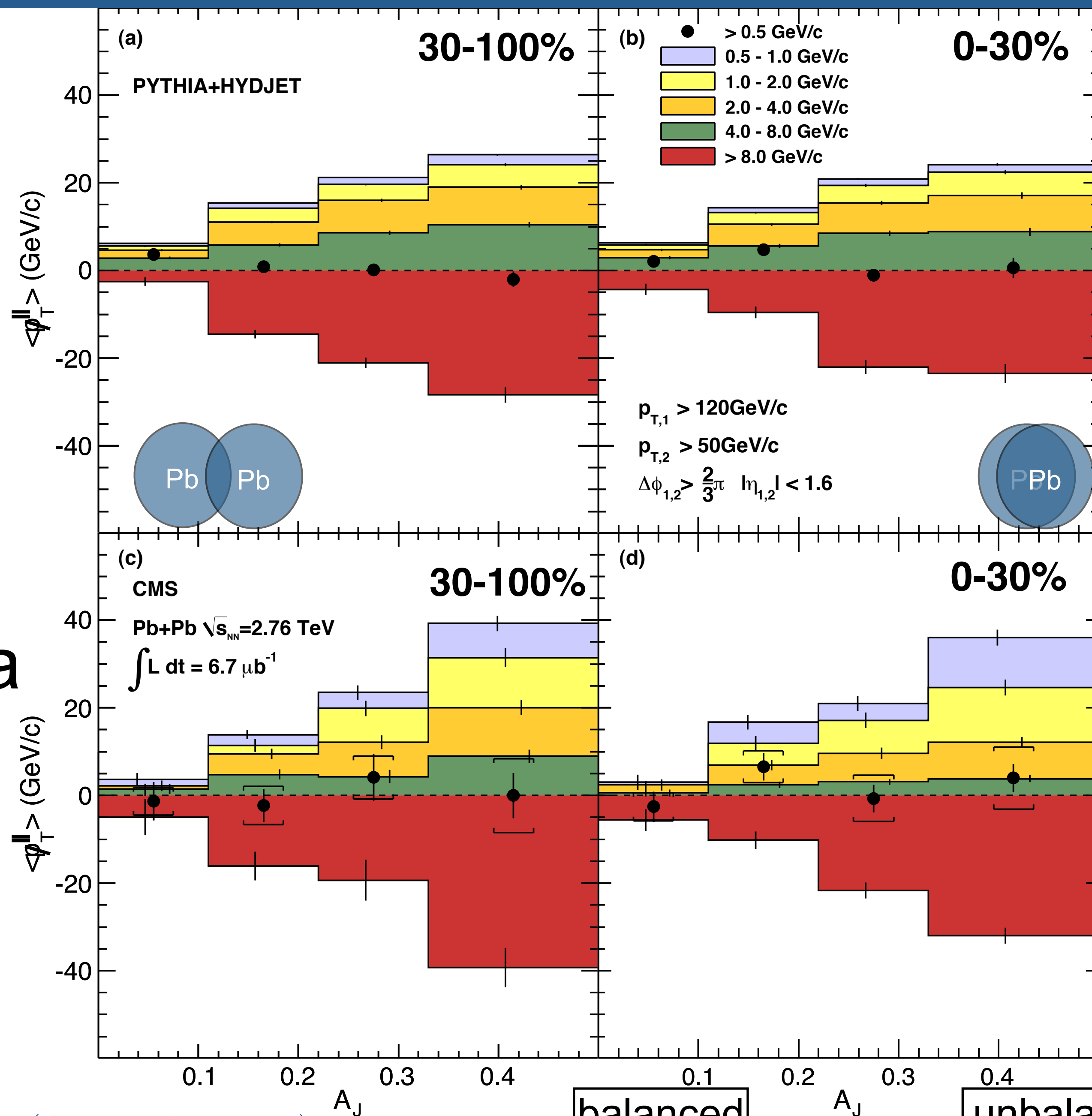
$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\mathrm{T,track}} \cos\left(\phi_{\mathrm{track}} - \phi_{\mathrm{leading\ jet}}\right)$$

$<\not{p}_T^{||}>$ vs. A_J

MC

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

Data



Central PbPb: missing p_T found in low p_T in away side, mainly carried by tracks < 2 GeV/c

excess away from leading jet

excess towards leading jet

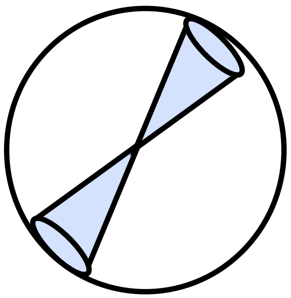
balanced dijets

unbalanced dijets

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

Radial Dependence of <$\not{p}_T^{||}$>

MC

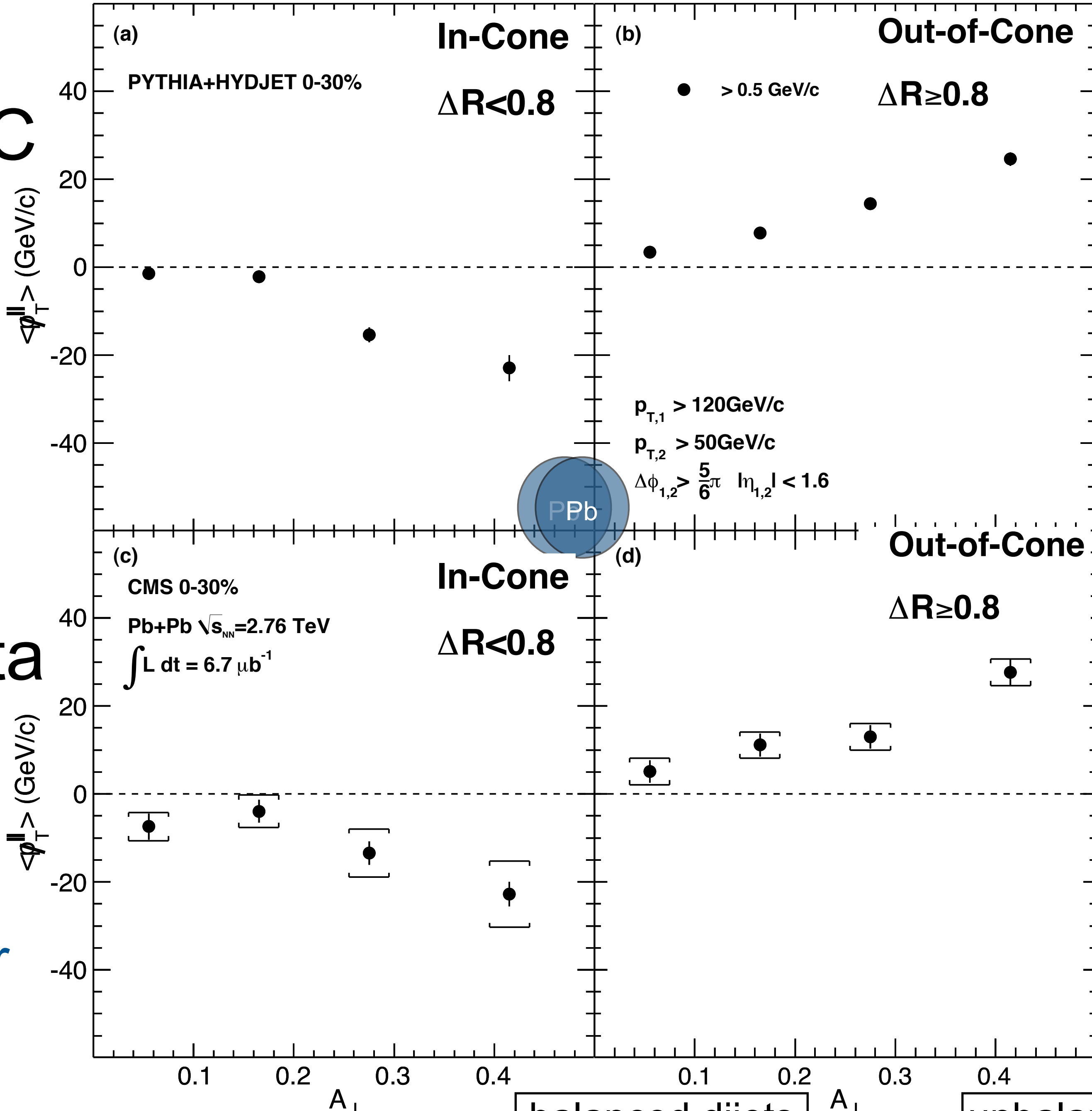


In-Cone

ΔR<0.8

Data

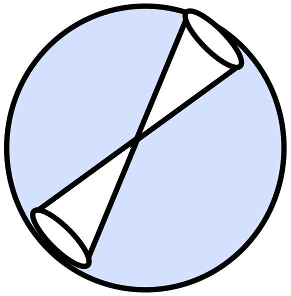
In-cone reproduces Calorimeter jet asymmetry



balanced dijets

unbalanced dijets

Out-of-cone: balance of momentum found



Out-of-Cone

ΔR≥0.8

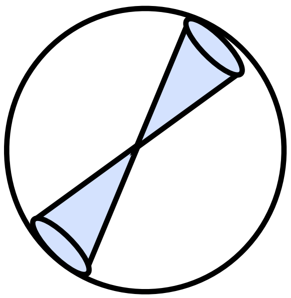
excess away from leading jet

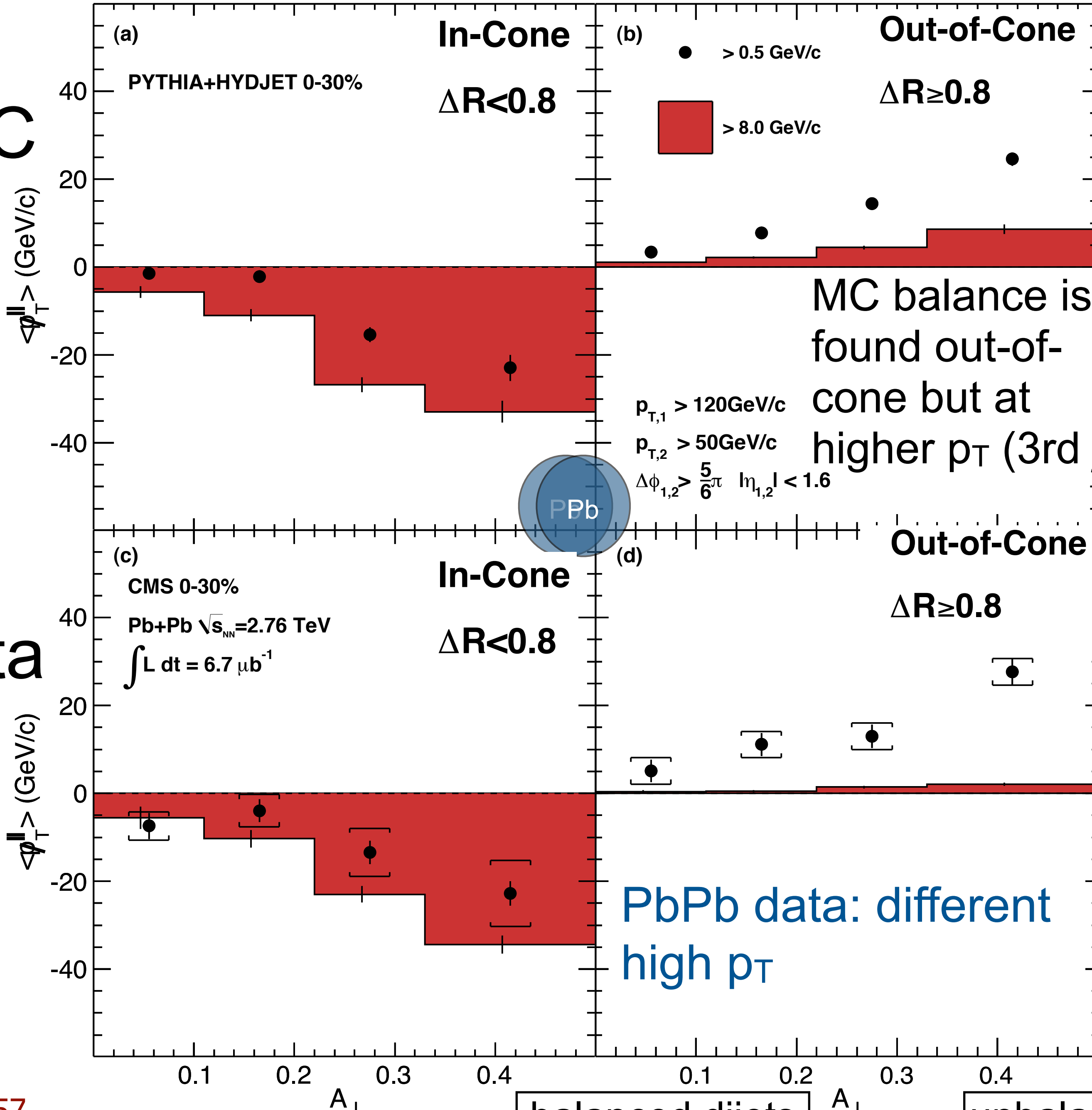
excess towards leading jet

Radial Dependence of <$\not{p}_T^{||}$>

MC

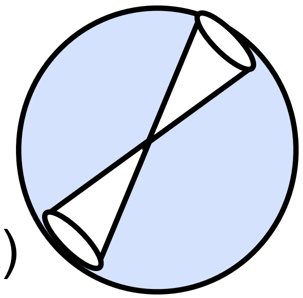
Data





MC balance is found out-of-cone but at higher p_T (3rd jet)

PbPb data: different high p_T



excess away from leading jet

excess towards leading jet

balanced dijets

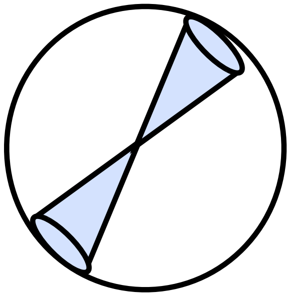
unbalanced dijets

CMS: arXiv:1102.1957

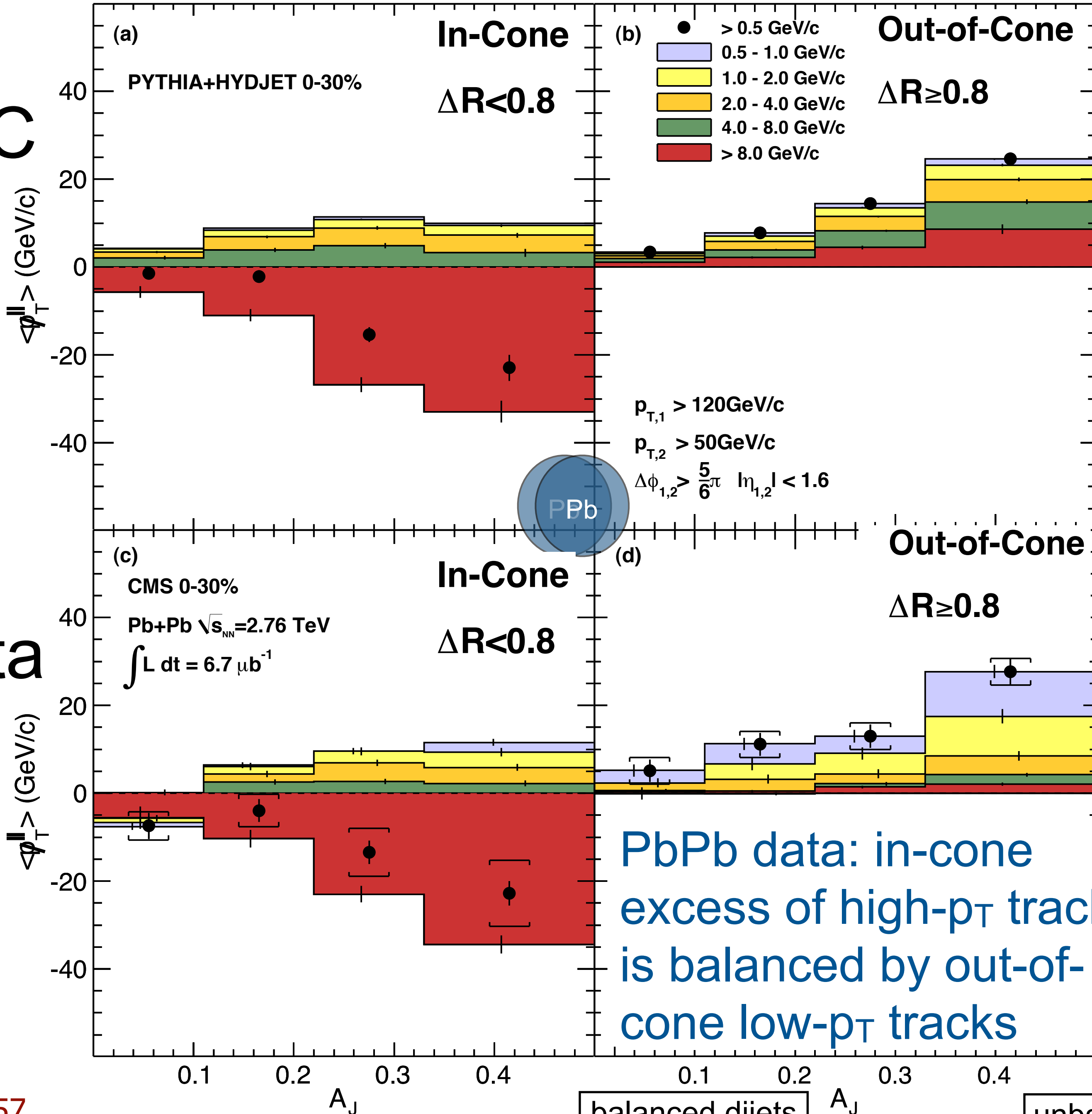
Radial Dependence of <$\not{p}_T^{||}$>

MC

Data



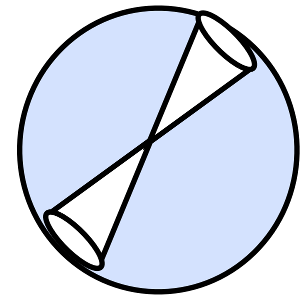
In-Cone
ΔR<0.8



balanced dijets

unbalanced dijets

PbPb data: in-cone excess of high-p_T tracks is balanced by out-of-cone low-p_T tracks



Out-of-Cone
ΔR≥0.8

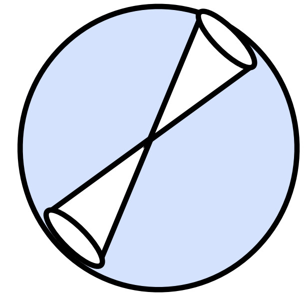
excess away from leading jet

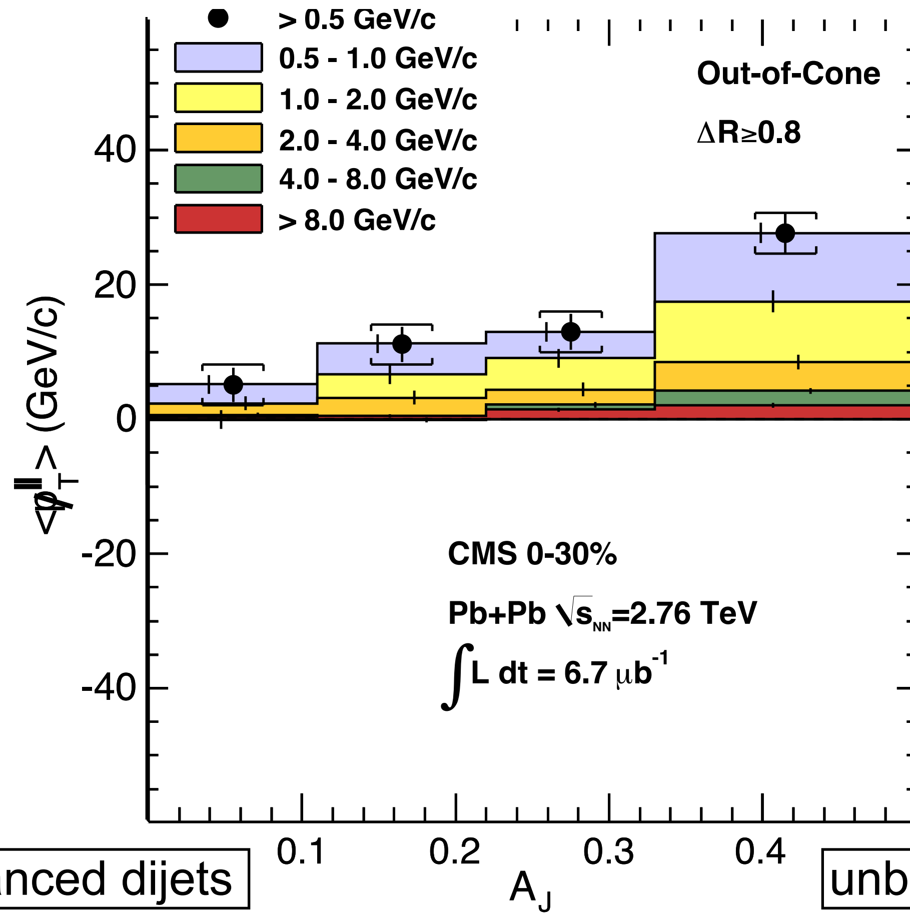
excess towards leading jet

CMS: arXiv:1102.1957

Learned from <$\not{p}_T^{||}$>

The momentum difference in the dijet is balanced by low p_T particles at large angles relative to the away side jet axis





excess away from leading jet

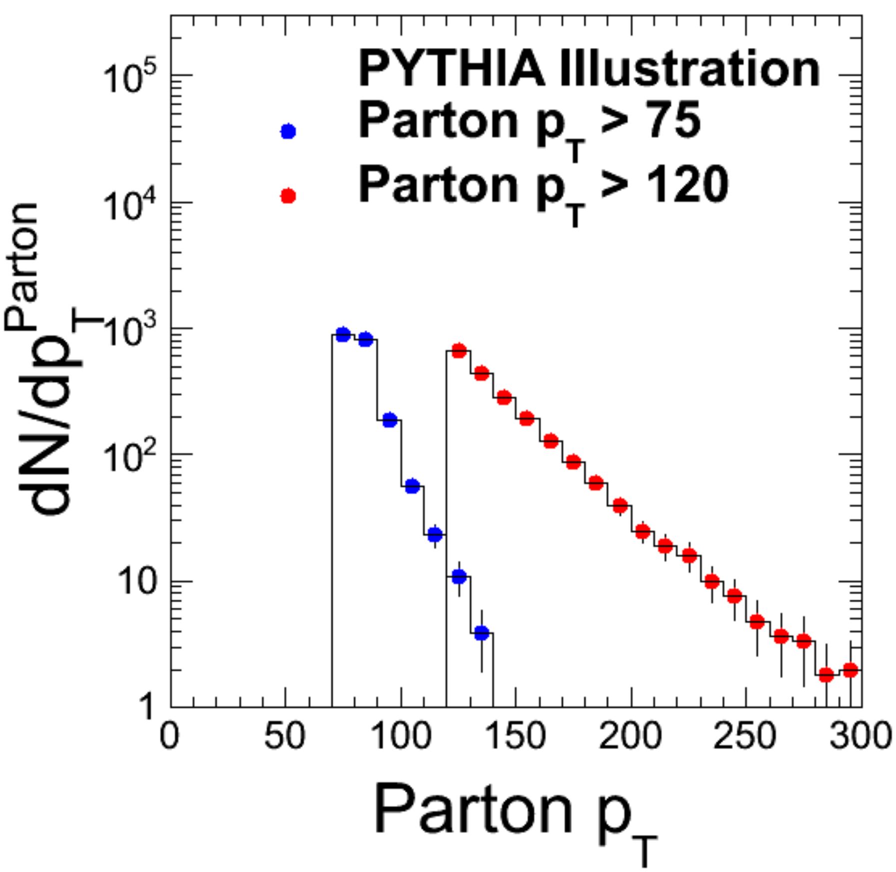
excess towards leading jet

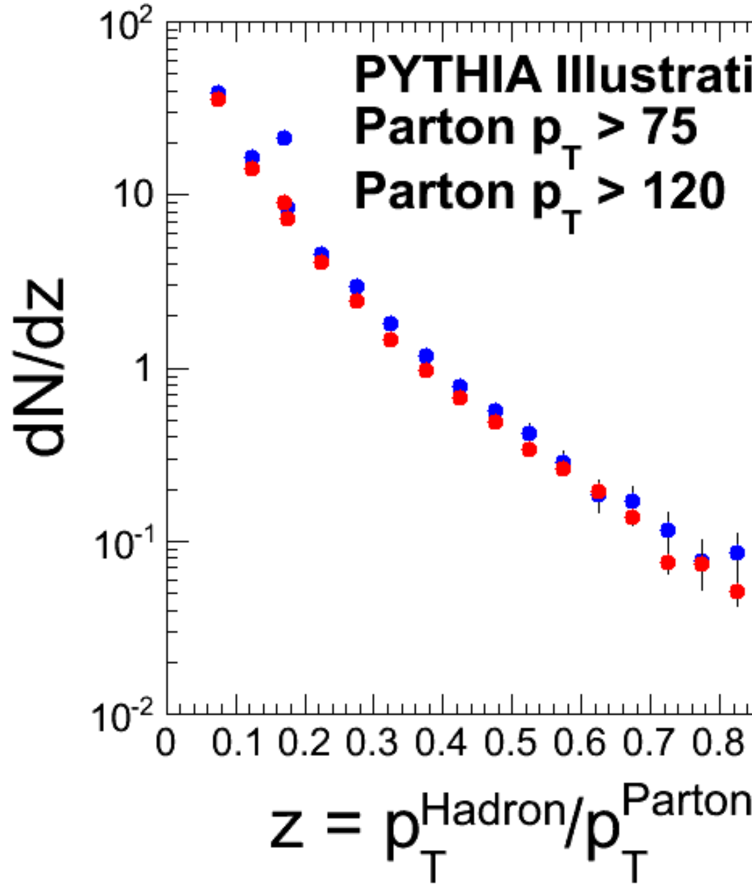
balanced dijets

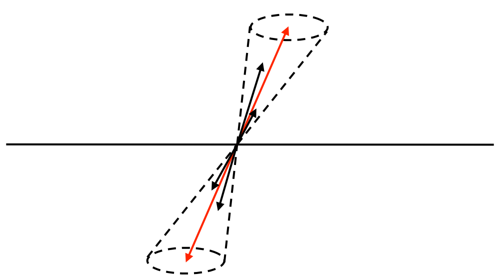
unbalanced dijets

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

Parton Fragmentation

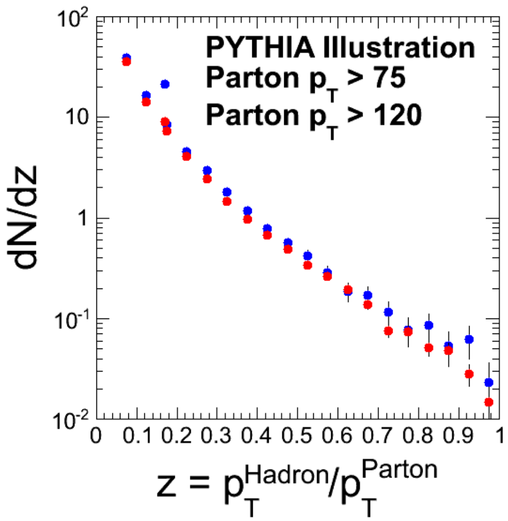




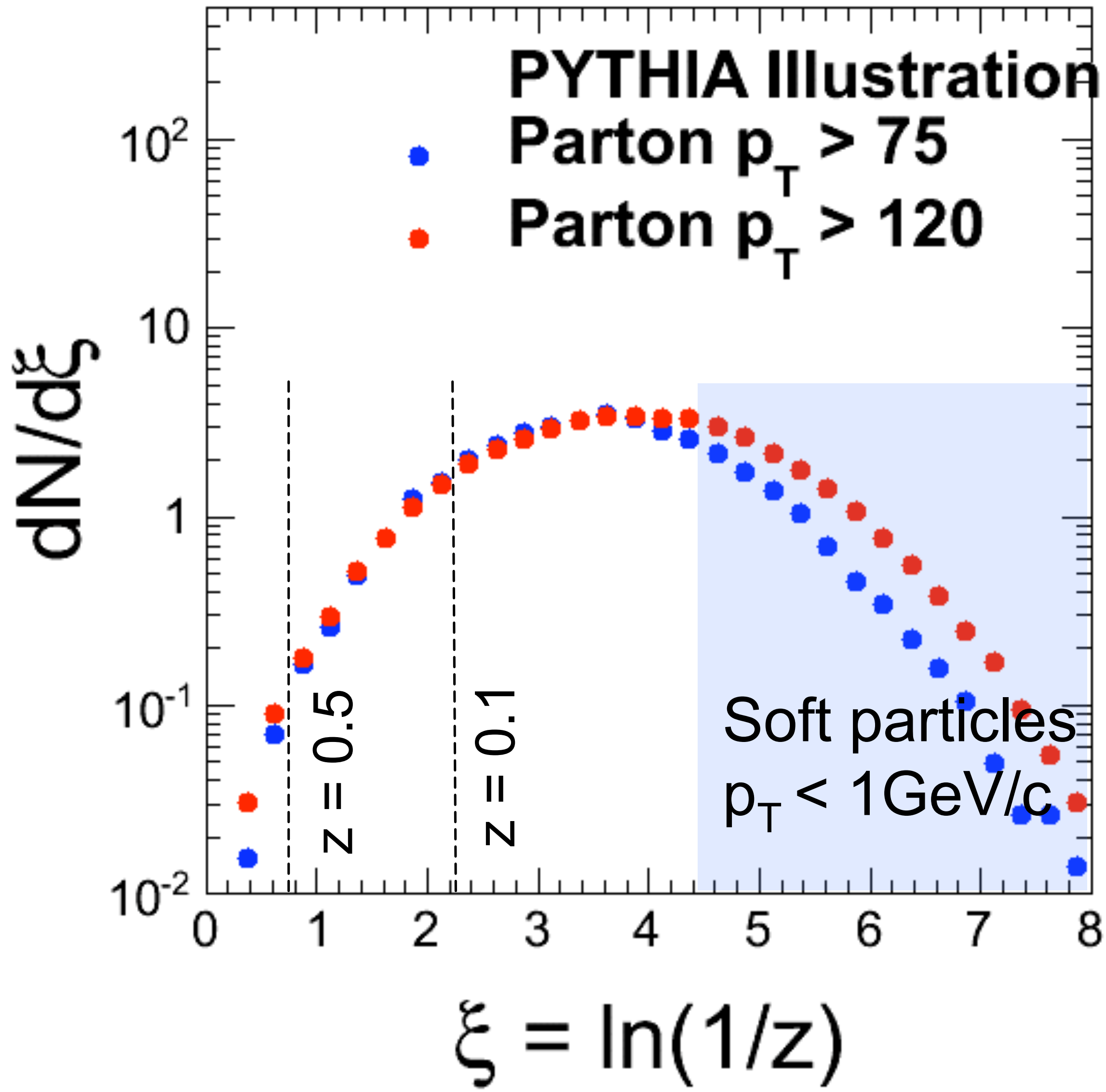


- Momentum Fraction z
  - characteristic of the parton showering process
  - $z=p_T^{hadron}/p_T^{parton}$

ξ=ln(1/z)

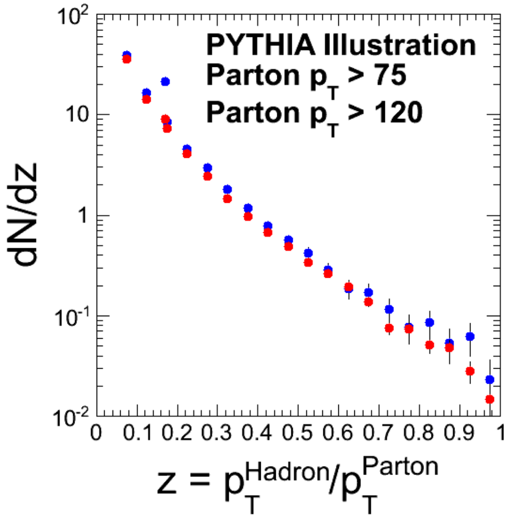


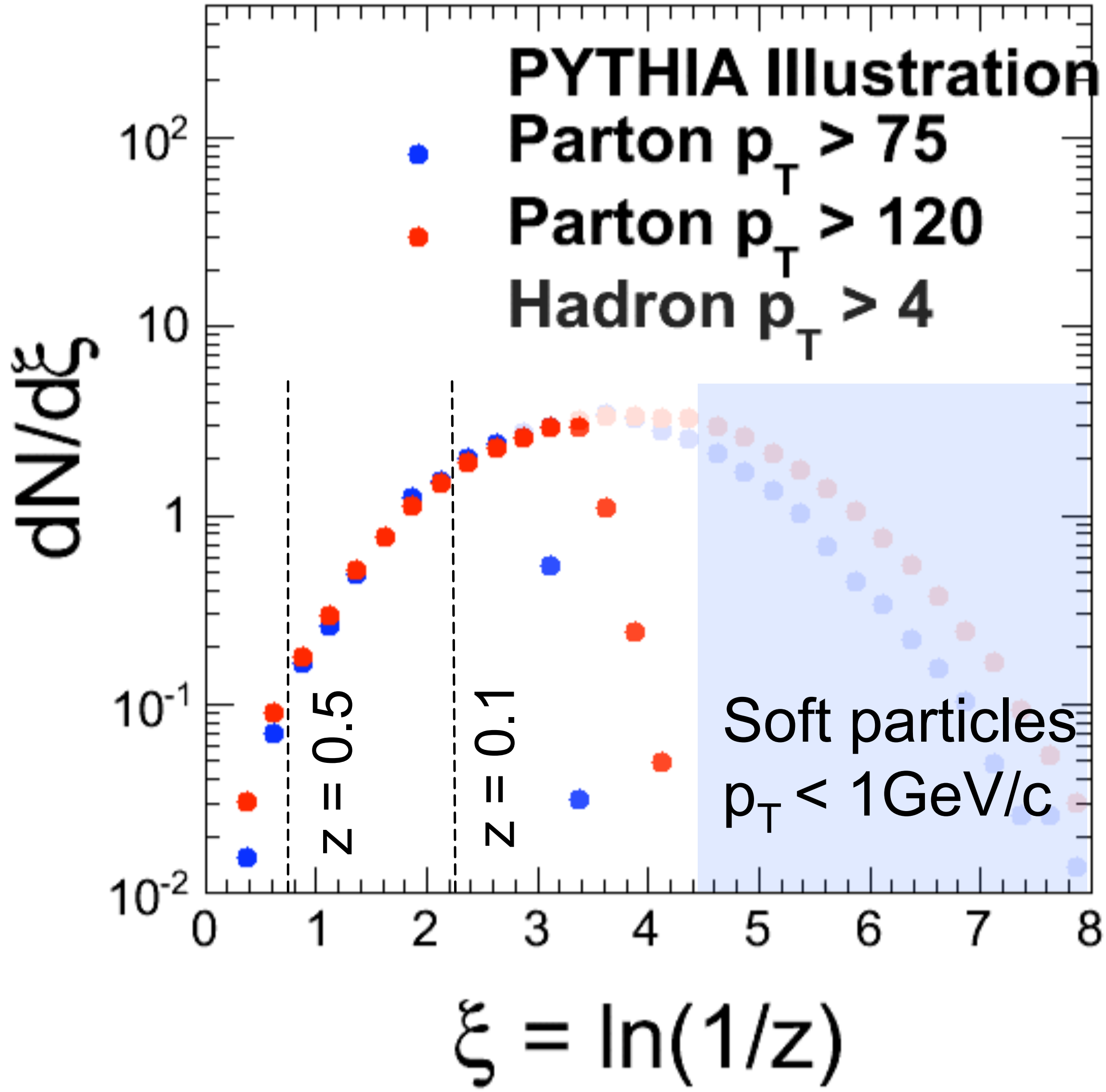
PYTHIA Illustration
Parton p_T > 75
Parton p_T > 120
dN/dz
$z = p_T^{Hadron}/p_T^{Parton}$



PYTHIA Illustration
Parton p_T > 75
Parton p_T > 120
dN/dξ
z = 0.5
z = 0.1
Soft particles
p_T < 1GeV/c
ξ = ln(1/z)

ξ=ln(1/z)



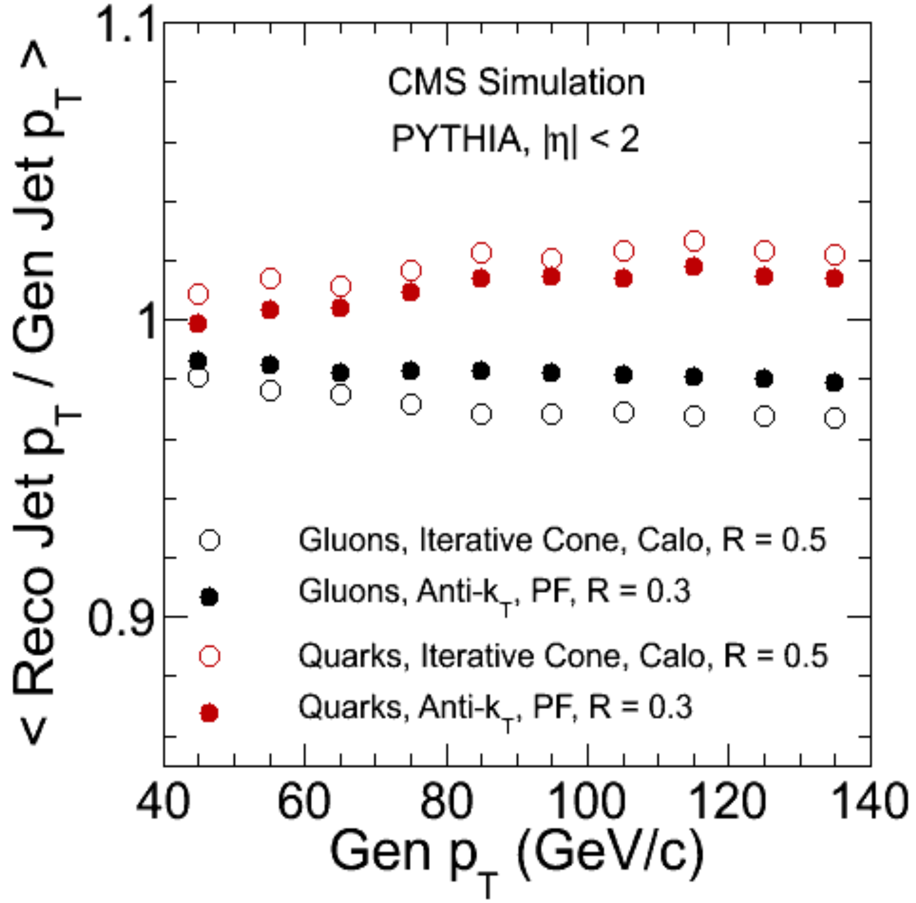


Select particles with p_T > 4GeV/c to eliminate the underlying event contribution

Particle Flow and Fragmentation

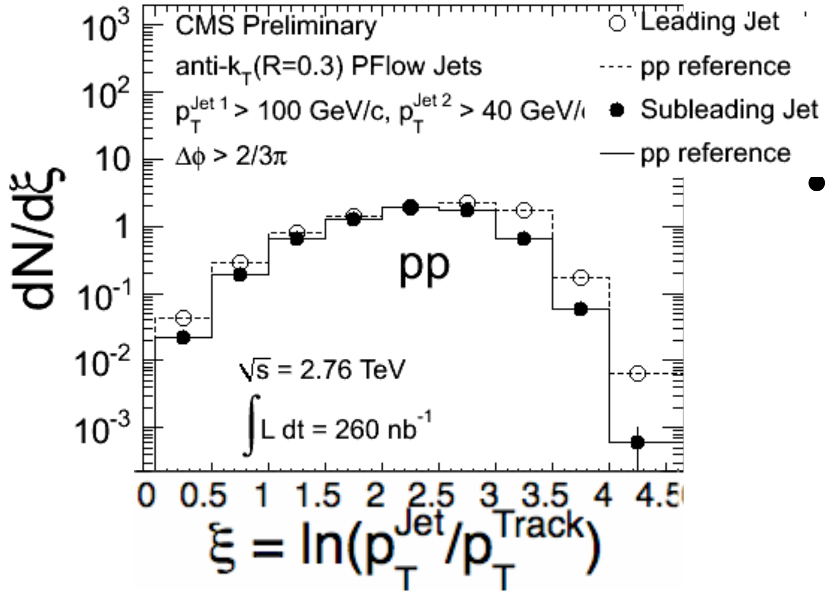
- Jet energy corrections are derived from inclusive jets in PYTHIA
- In real data response may differ due to:
  - Poor description of fragmentation
  - Different fraction of quark vs gluons
  - Possible jet quenching effects

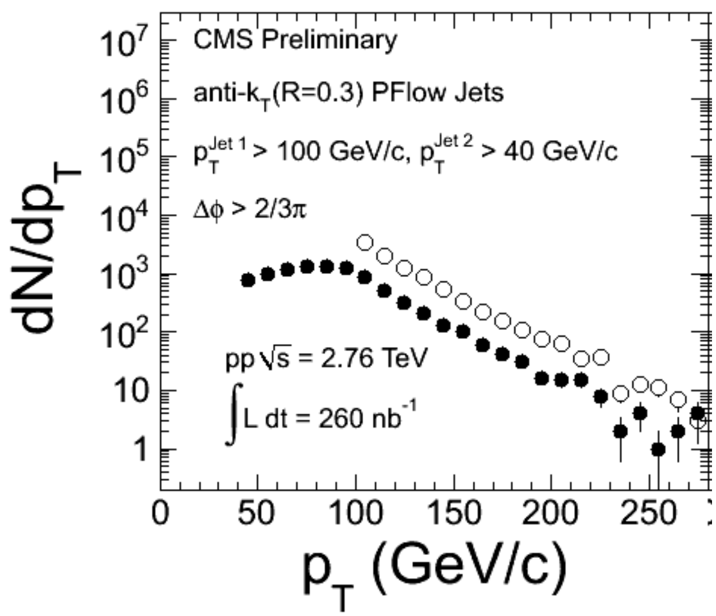
Corrected response to quark and gluon jets with heavy-ion Particle Flow configuration



Particle flow jets show reduced sensitivity to the fragmentation pattern

Fragmentation Functions in Data



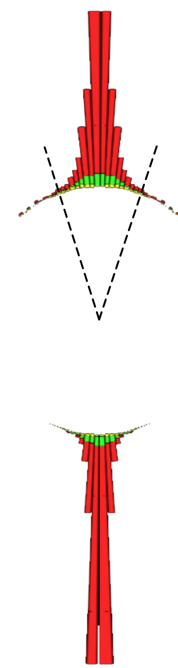


pp 2.76 TeV Data from 2011

- Particle Flow Jet Reconstruction
  - Anti k_T, R=0.3
  - Fully efficient for p_T > 40GeV/c
  - Good control of jet p_T scale
  - Applied in pp and PbPb

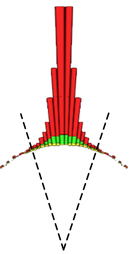
- Dijet selection
  - p_T^{Jet1}>100GeV/c
  - p_T^{Jet2}>40GeV/c
  - $\Delta\phi > 2\pi/3$

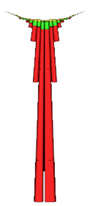
- Compare Leading and Subleading Jet

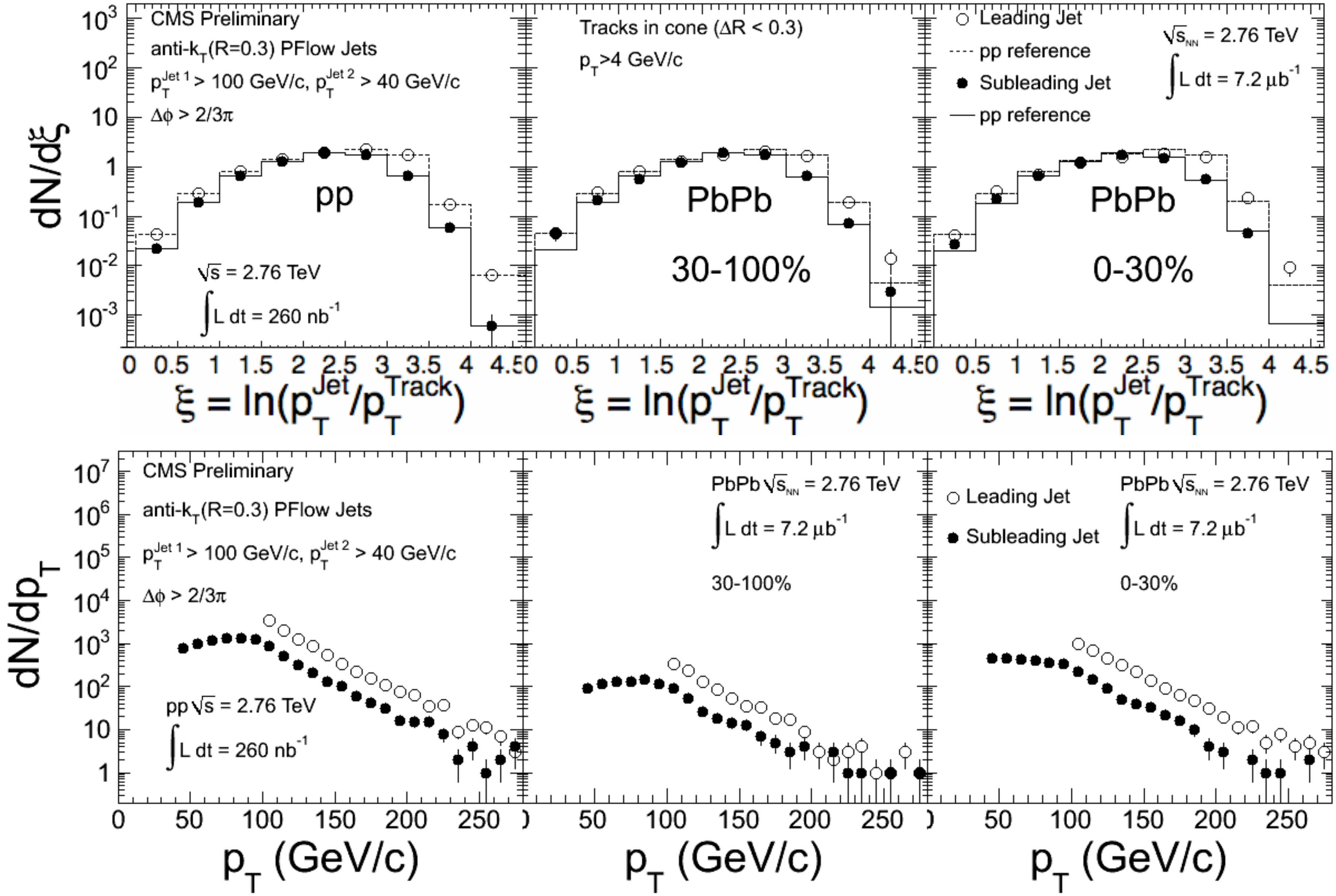


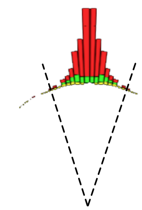
CMS-PAS-HIN-11-004

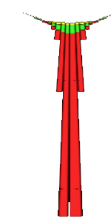
Fragmentation Functions, pp & PbPb









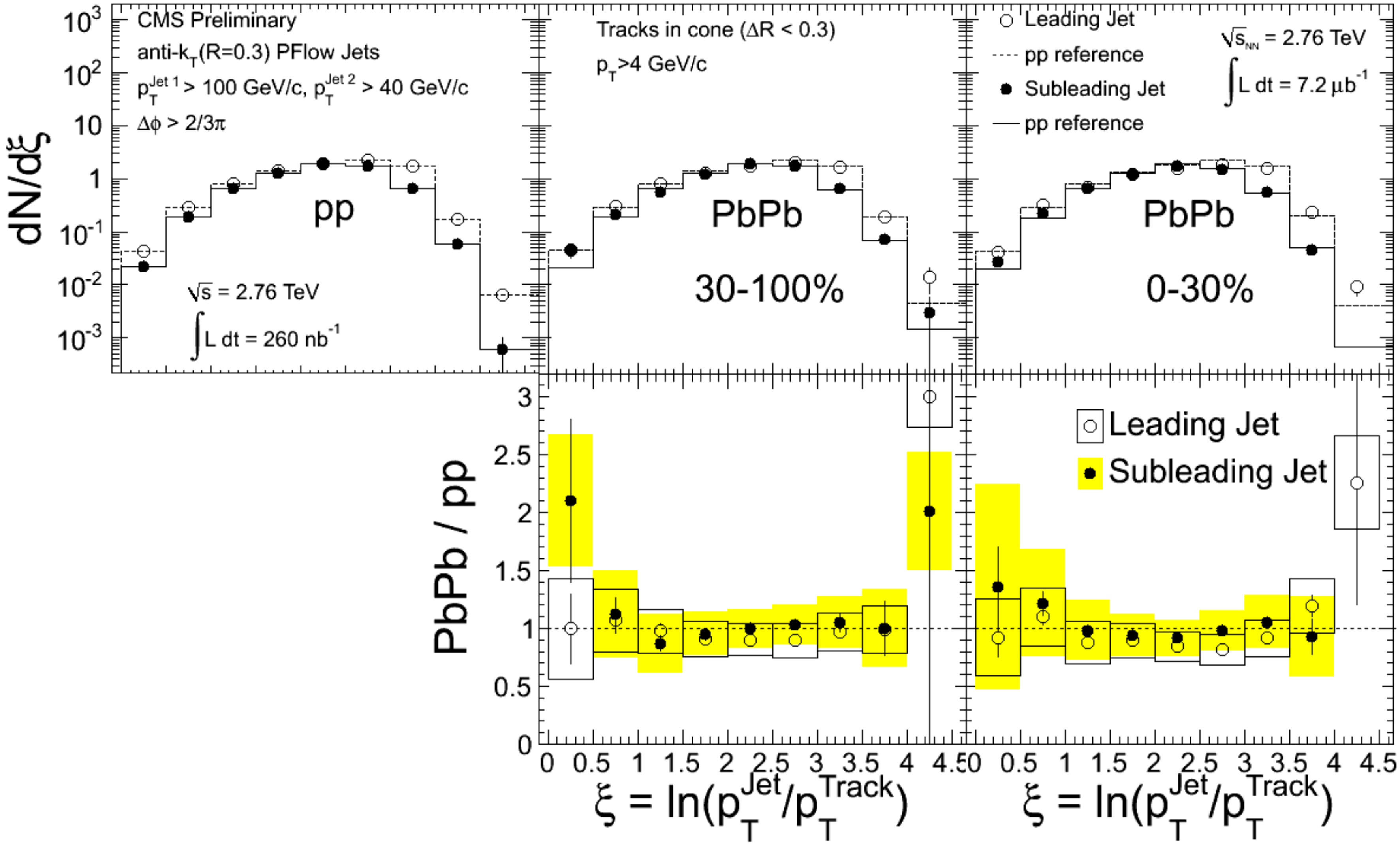


pp as reference for PbPb: Smear pp to PbPb jet p_T resolution

Reweight jet p_T spectrum to match PbPb

CMS-PAS-HIN-11-004

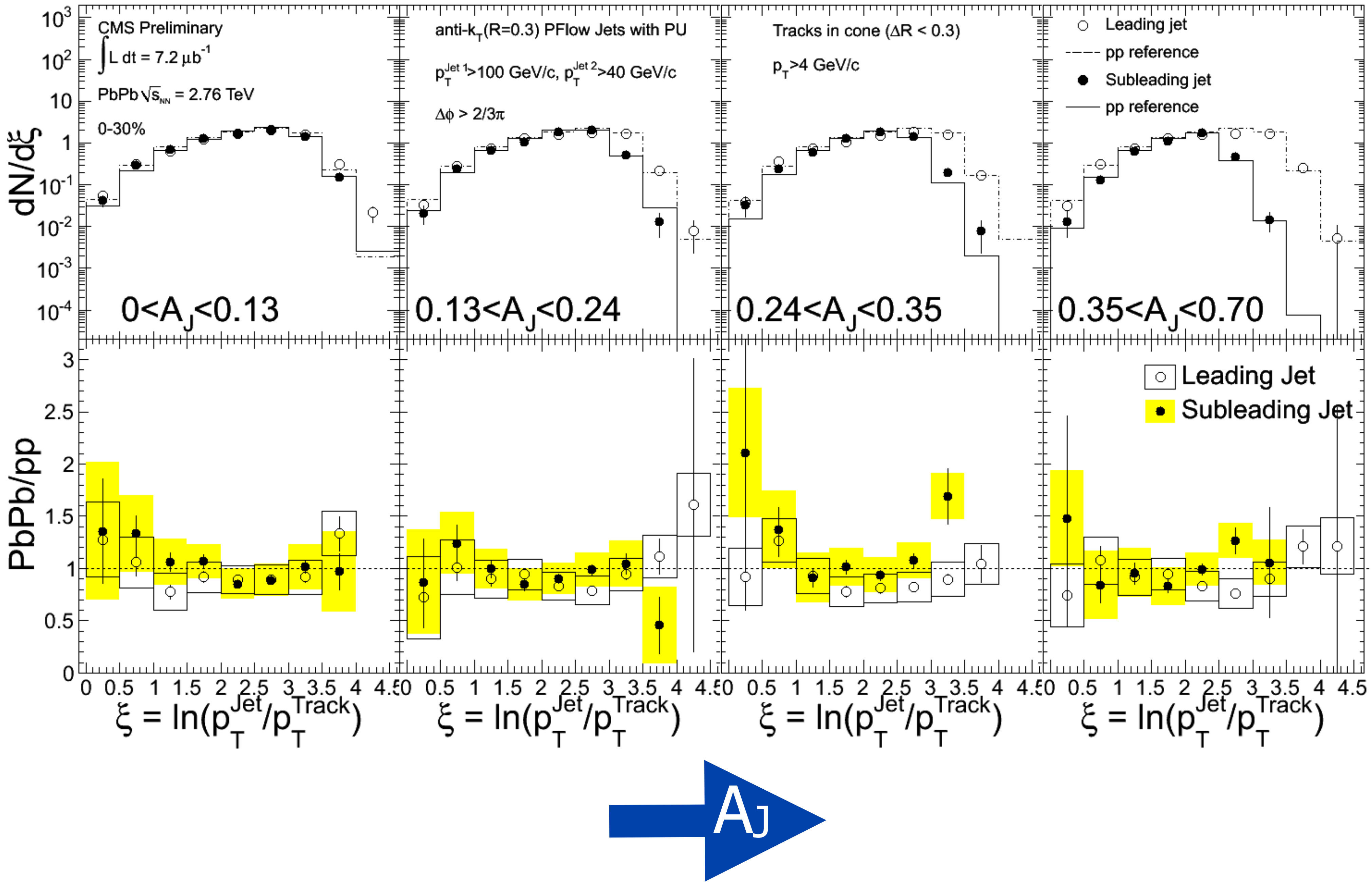
Fragmentation Functions, pp & PbPb



Reconstructed PbPb leading and subleading jets fragment like jets of corresponding energy from pp collisions

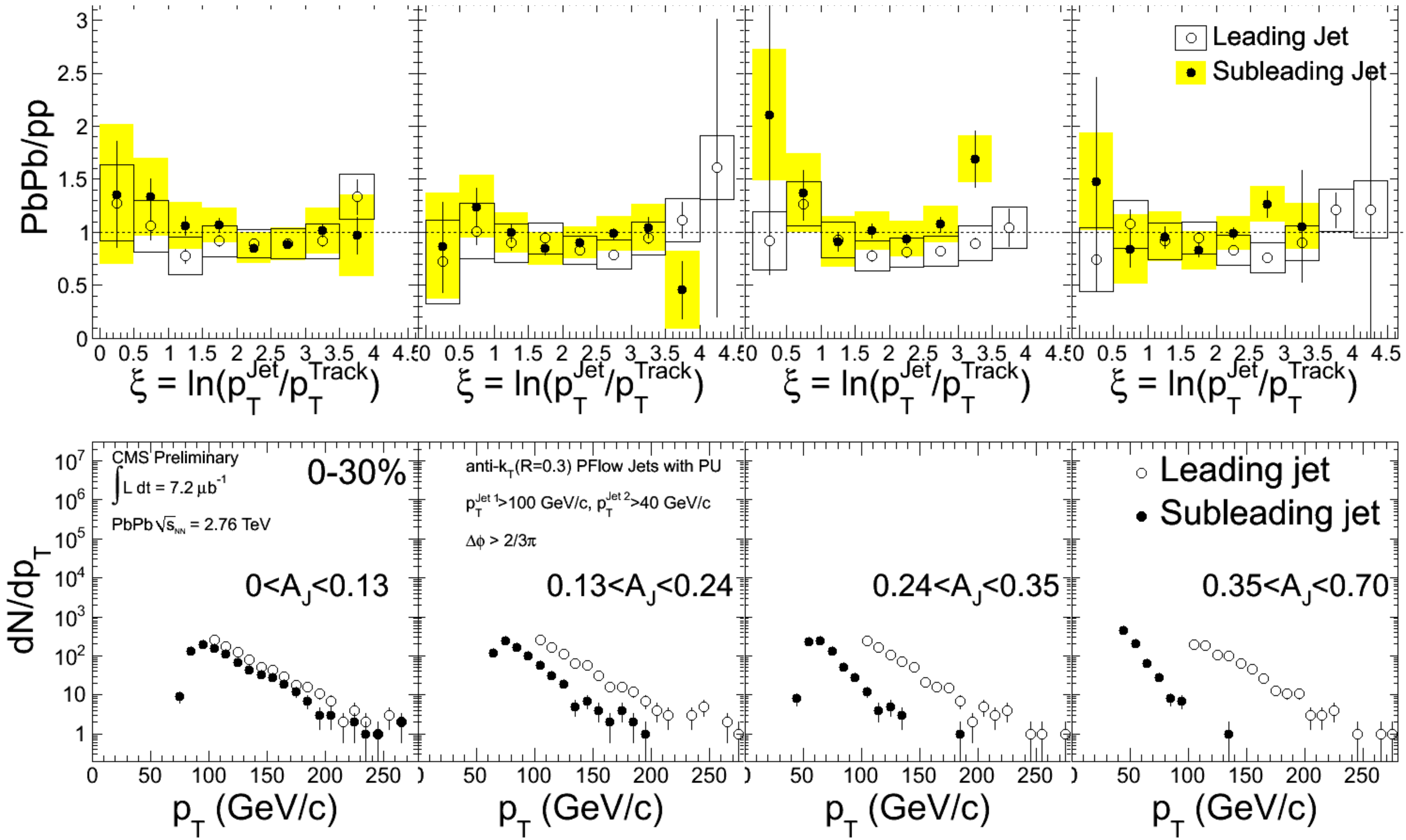
CMS-PAS-HIN-11-004

Select by Dijet Imbalance



CMS-PAS-HIN-11-004

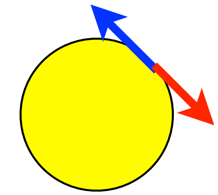
Note Different Jet p_T Distributions



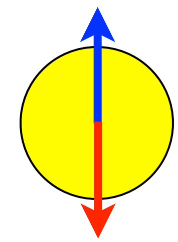
CMS-PAS-HIN-11-004

Dijet Possibilities

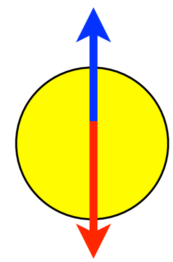
- Symmetric jets:



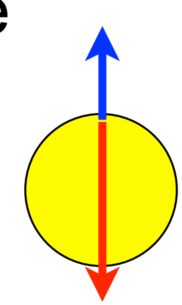
  – Neither jet interacted with medium: emitted at surface



  – Both jets quenched in medium ~ similar path length
  – Medium transparent to jets
    - Not the case, because we do observe quenching



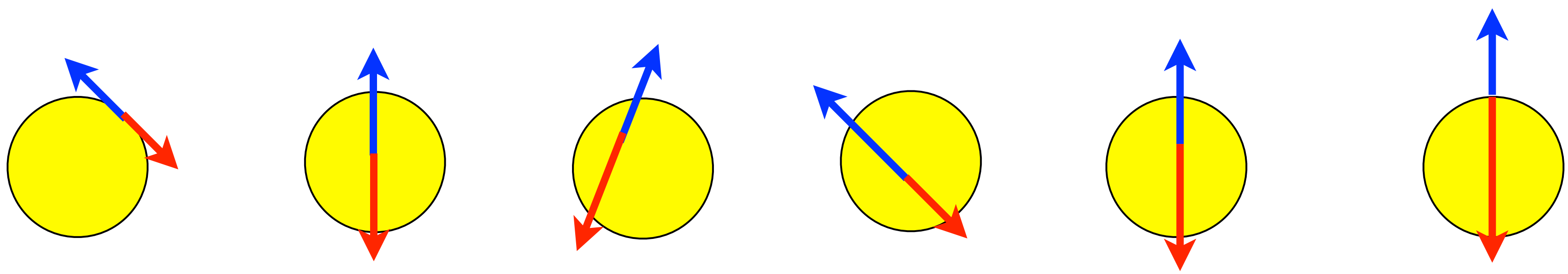
- Asymmetric jets:
  – Jets had different path lengths, but both interacted with medium
  – One jet on surface (no interaction), other went through the medium



  – Something not yet considered... ?

Fragmentation Function Lesson

- The hard part of the fragmentation function gives the same results for leading, subleading, symmetric, and balanced jets
- Any issues with surface bias or path length are not important for this measurement: the result is the same



Fragmentation pattern independent of energy lost in medium
Consistent with partons fragmenting in vacuum

Summary

- Angular correlation of partons not affected by the medium
  - Favors multiple soft interactions with medium
- Large dijet momentum imbalance observed
  - Direct observation of parton energy loss

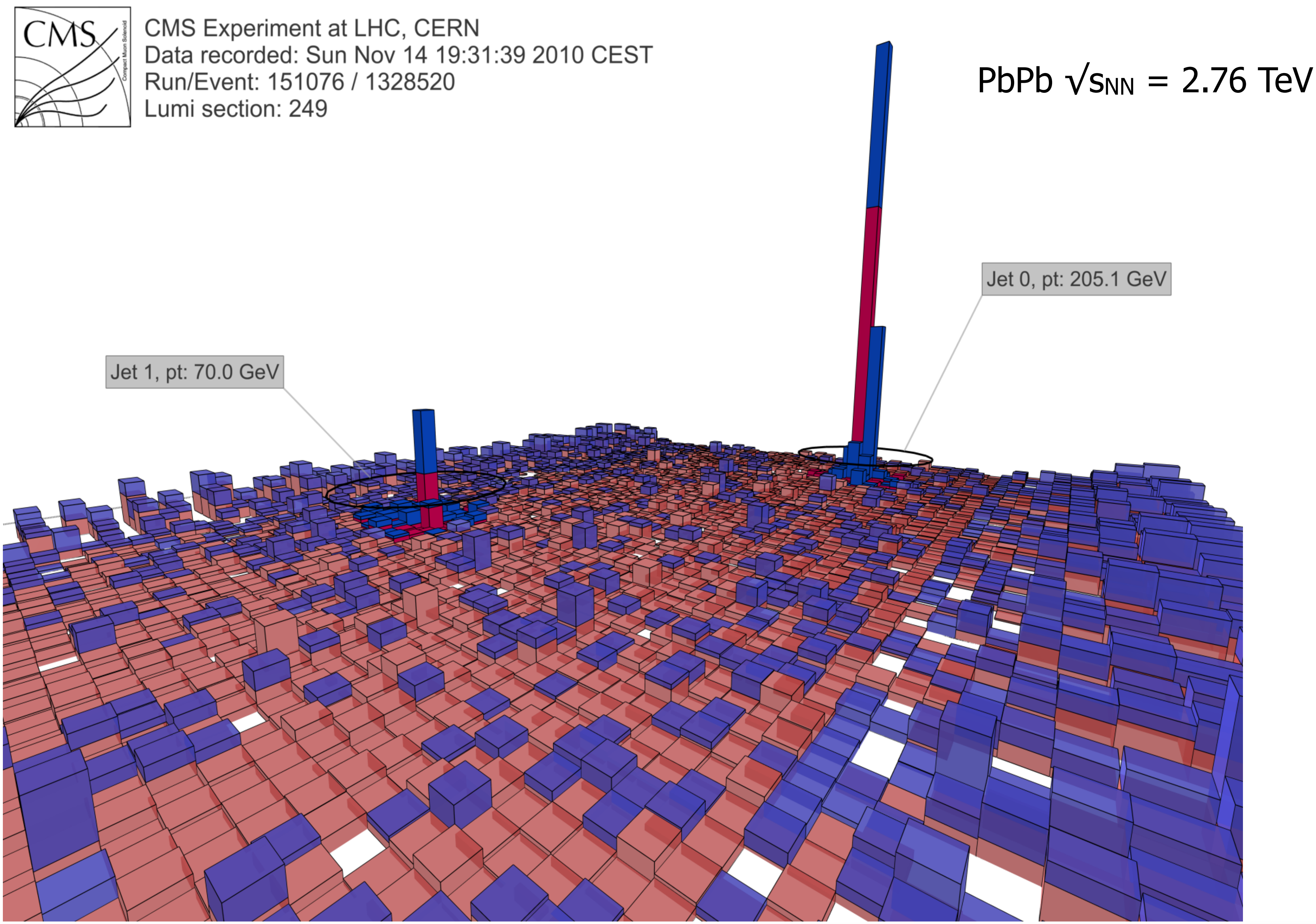
- Momentum difference in the dijet balanced by low p_T particles at large angles relative to the away side jet

- Measurement of jet fragmentation functions in PbPb
  - Jets in pp and in PbPb show a similar pattern
    - High p_T fragmentation pattern is independent of the energy lost in the medium
  - Consistent with partons fragmenting in vacuum

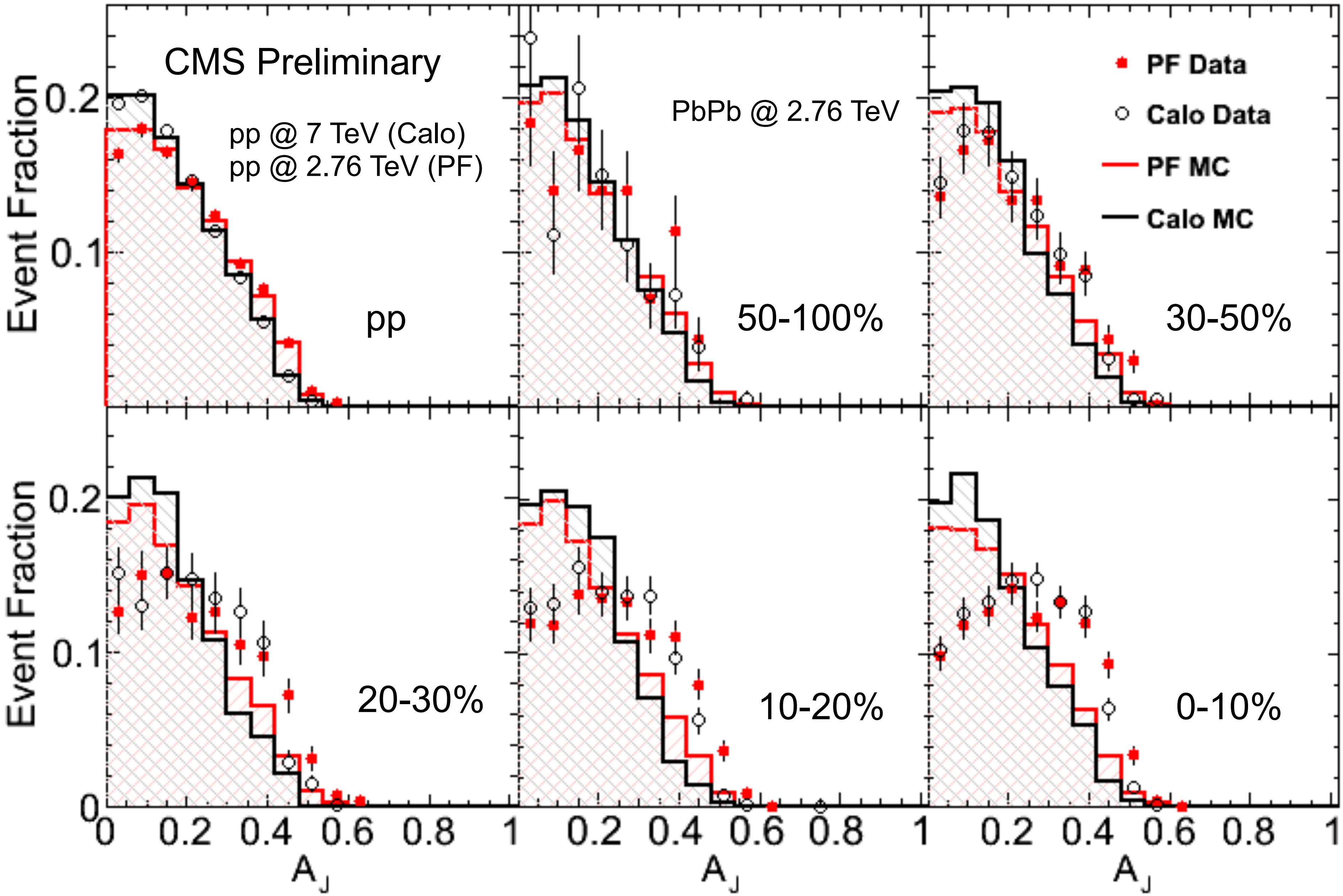
Stop to Reflect

Musée D'Orsay 2008, photo by M. Tonjes

Fin

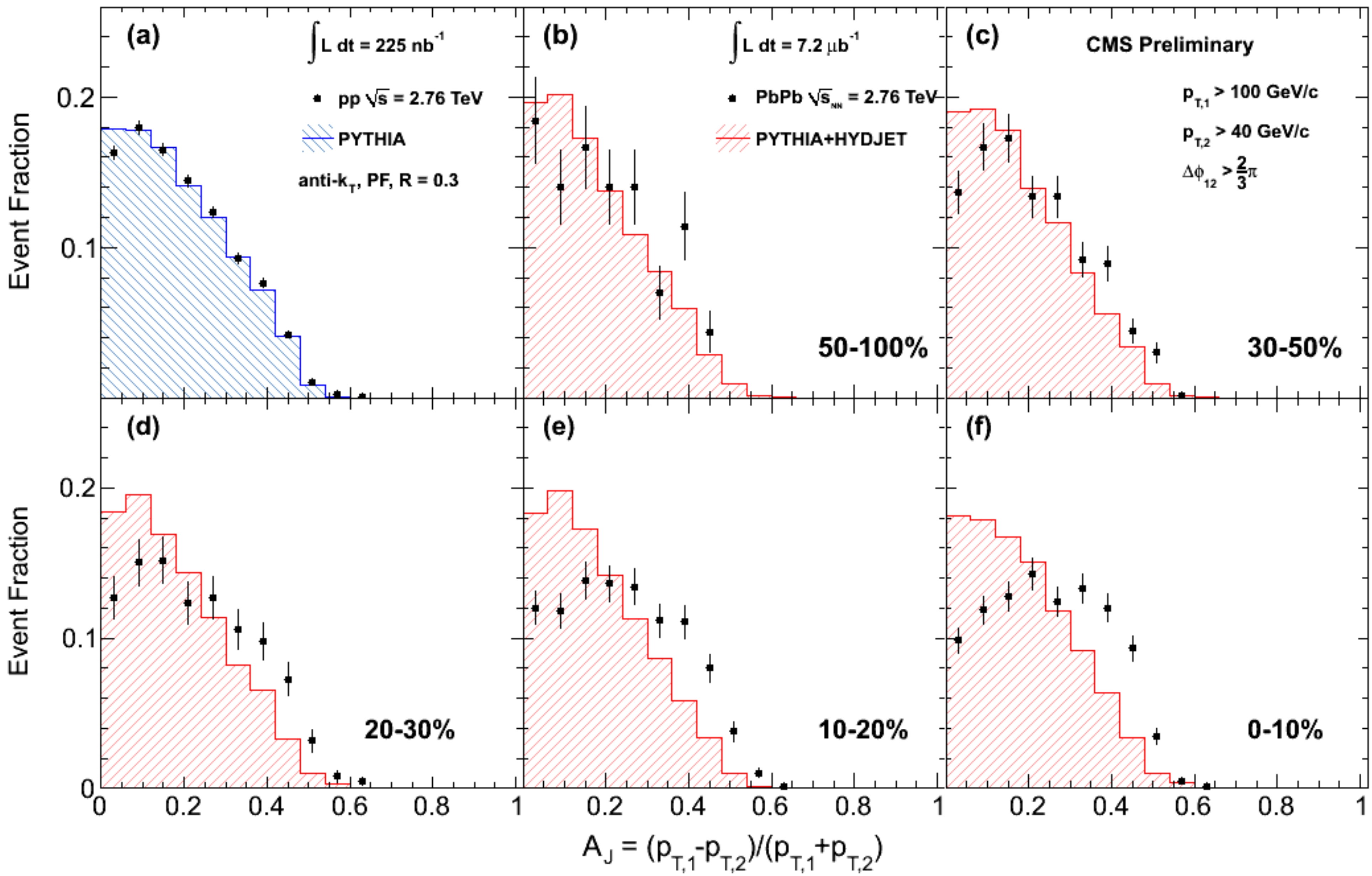

CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
PbPb √sNN = 2.76 TeV
Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV

Calorimeter Imbalance Comparison



Results are in good agreement with previous Calorimeter jet measurement

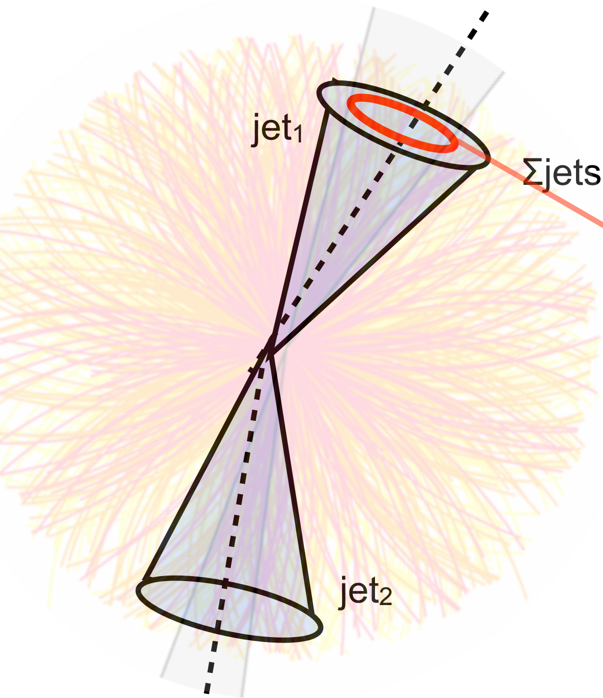
Dijet Imbalance ak3

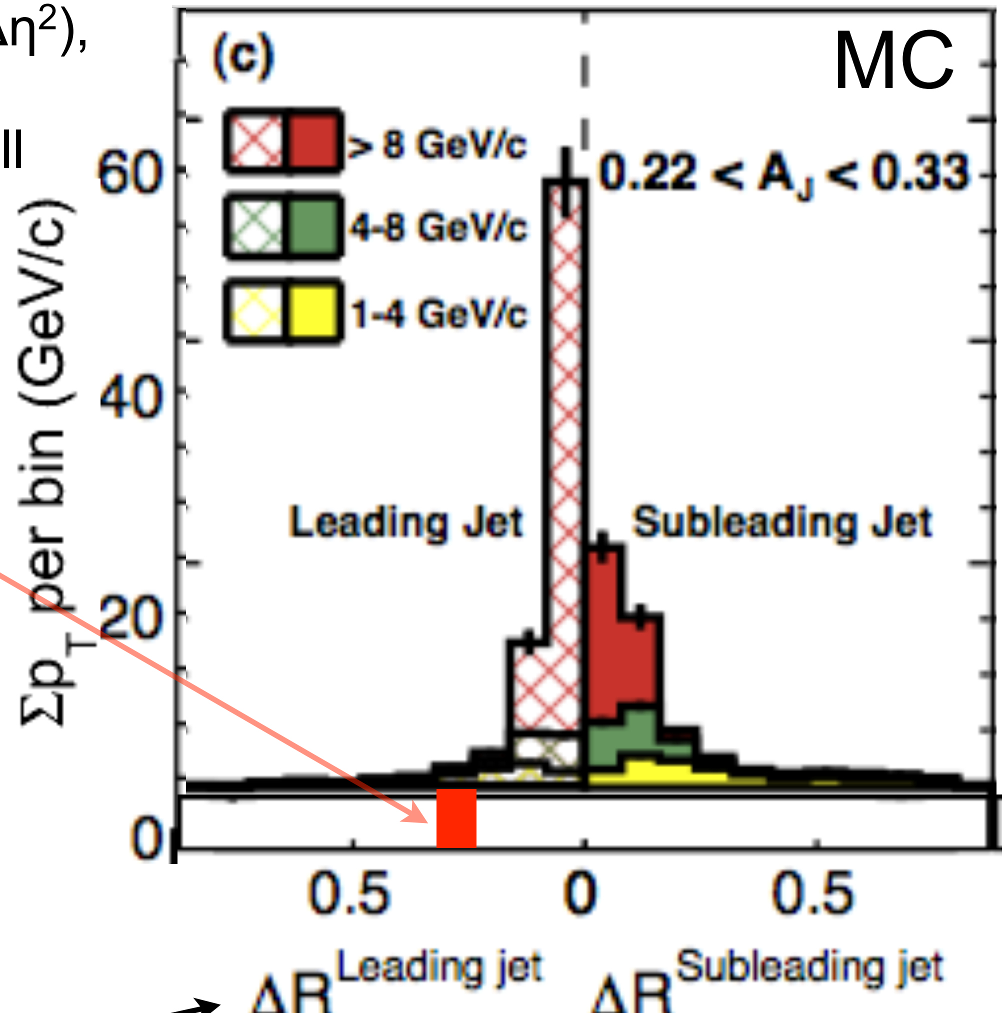


Excess of unbalanced jets persists with PF, R=0.3 dijet selection

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





Separate into bins of dijet asymmetry

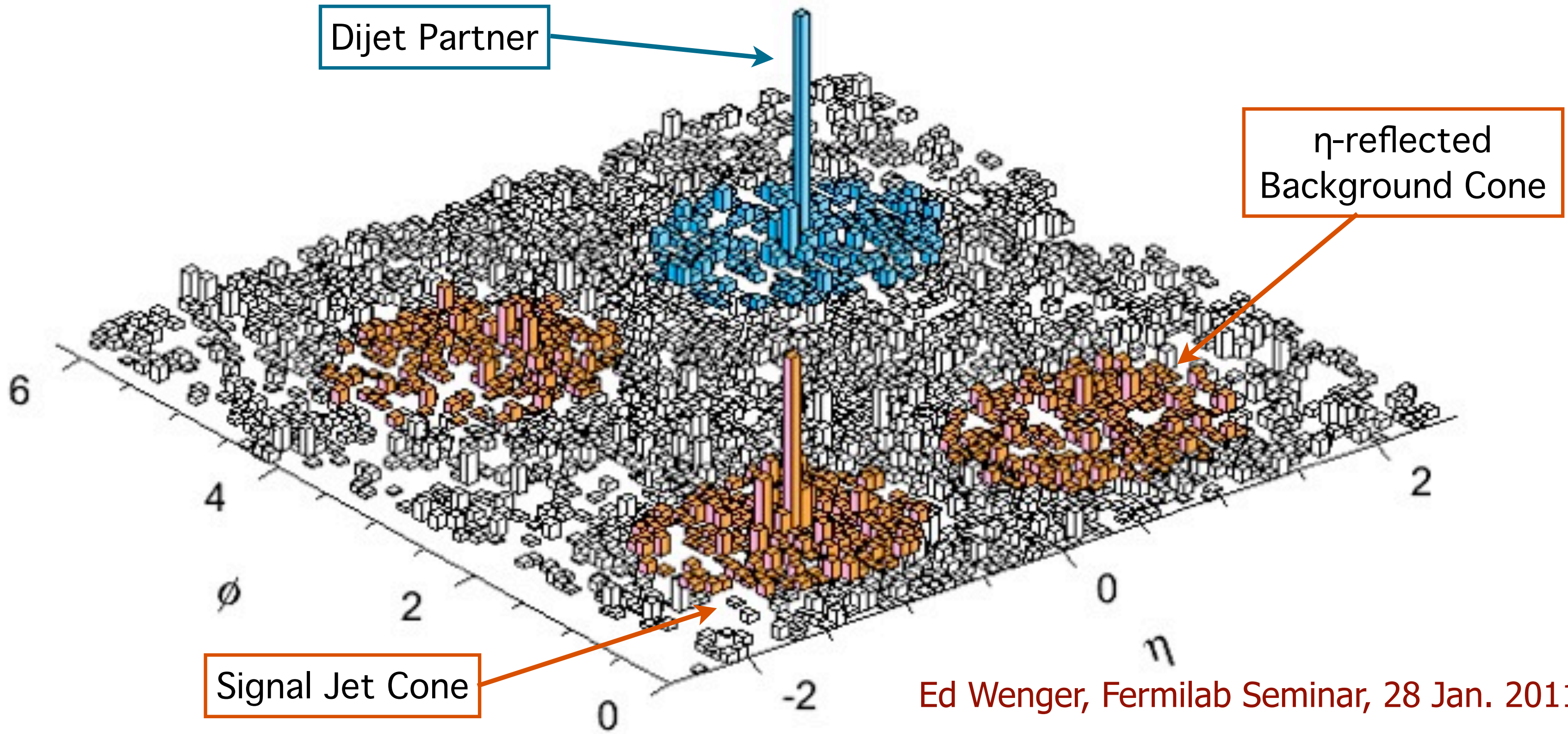
Look at the sum p_T of charged tracks in 3 different p_T ranges

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

Background (Underlying Event) is subtracted using a cone at same ϕ, but reflected in η (η → -η)

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

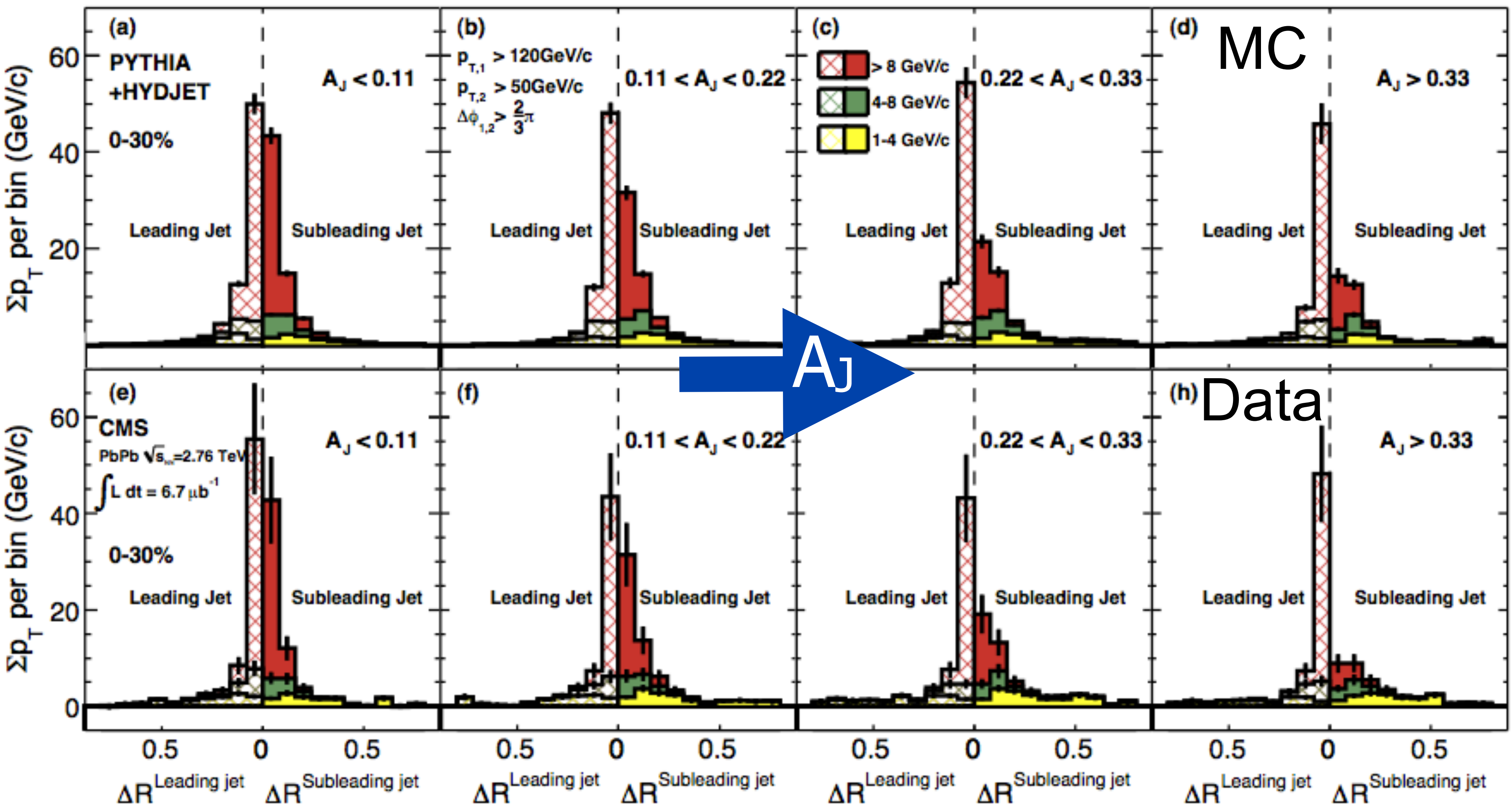


Ed Wenger, Fermilab Seminar, 28 Jan. 2011

Asymmetry Dependence of Fragmentation

Linear scale

Similar results found with anti-kt3, particle flow



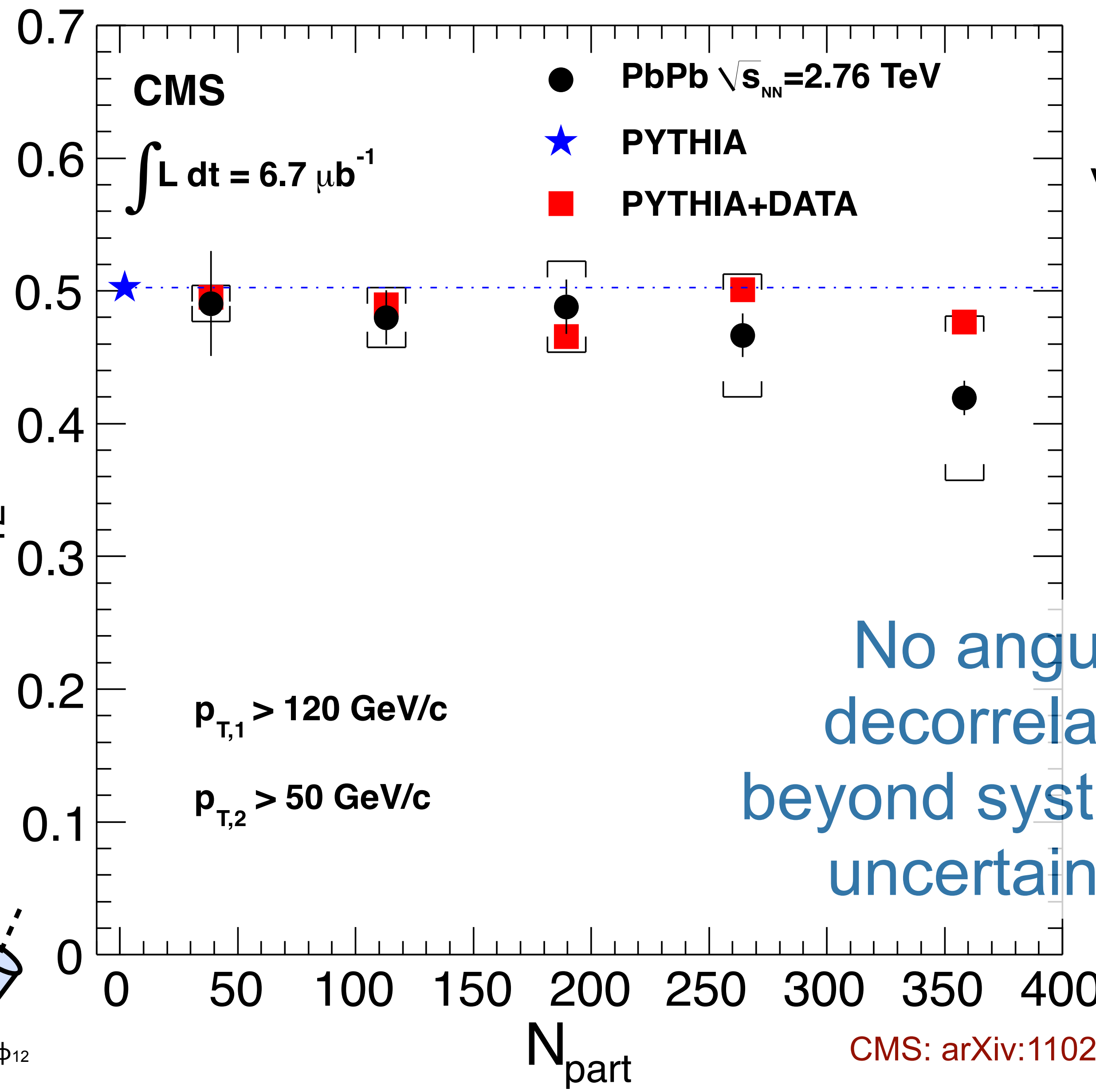
balanced jets

unbalanced jets

CMS: arXiv:1102.1957

Dijet Back-to-Back Fraction

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

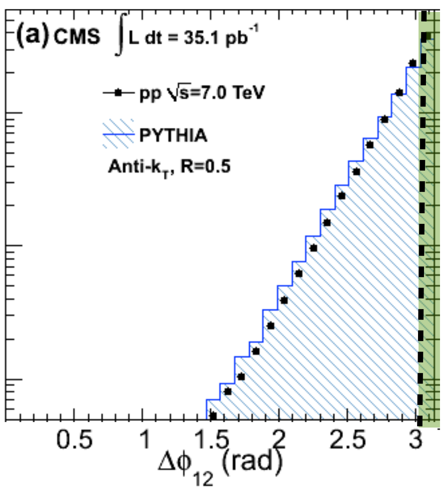


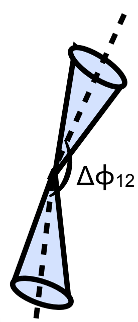
3.026 is median value from PYTHIA

No angular decorrelation beyond systematic uncertainties

CMS: arXiv:1102.1957

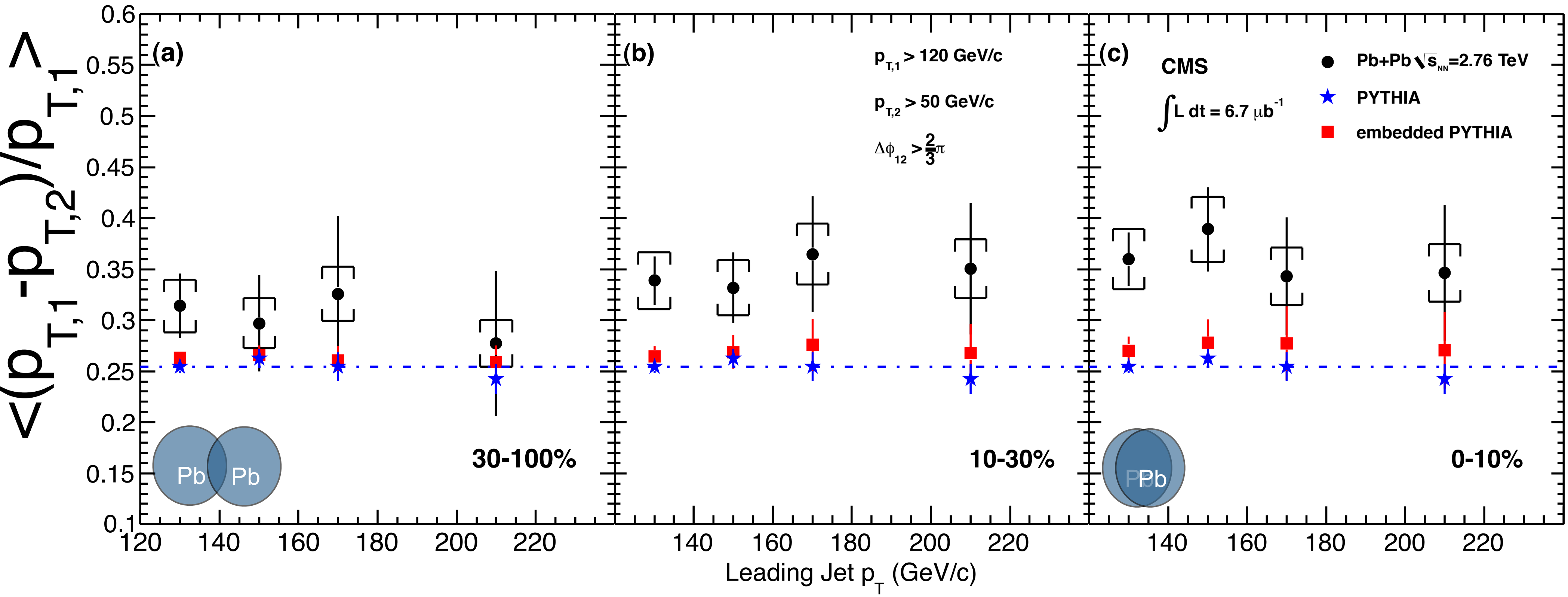
Back-to-Back / All other dijet pairs





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

Iterative Pileup Subtraction Algorithm

1. Make a tower of ECAL + HCAL energy
2. Find average tower $E_T(\eta)$ and $\sigma_T(\eta)$ at each η ring in each event
   - Recalculate tower energy by subtracting mean energy and dispersion, dropping negative towers
3. Find jets with iterative cone algorithm and corrected tower energy (E_T> 10 GeV pedestal cut)
4. Using original tower energy, calculate E_T and σ_T for those towers outside of the jets
   - Correct tower energy again, dropping negative towers
5. Find jets with iterative cone algorithm with current background subtracted energies

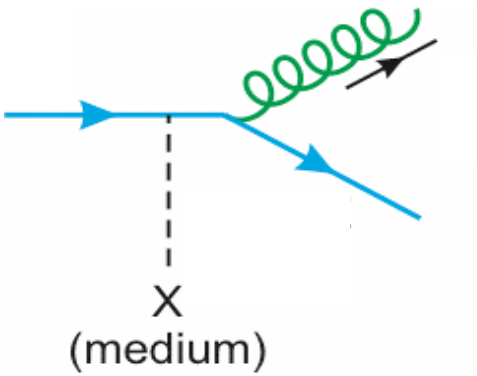
Parton Energy Loss

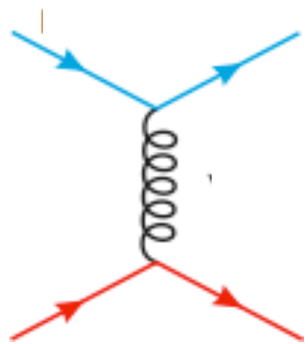
- Key ingredients of parton energy loss calculations:

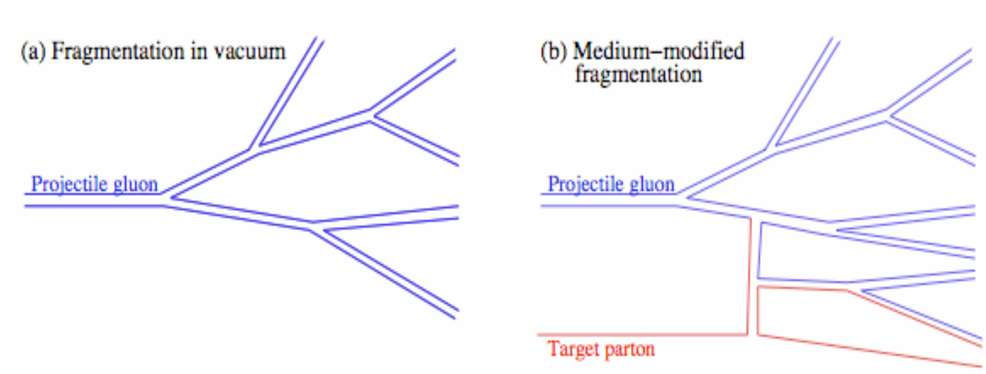
Parton propagation in the nuclear medium

Radiative- Collisional-energy loss

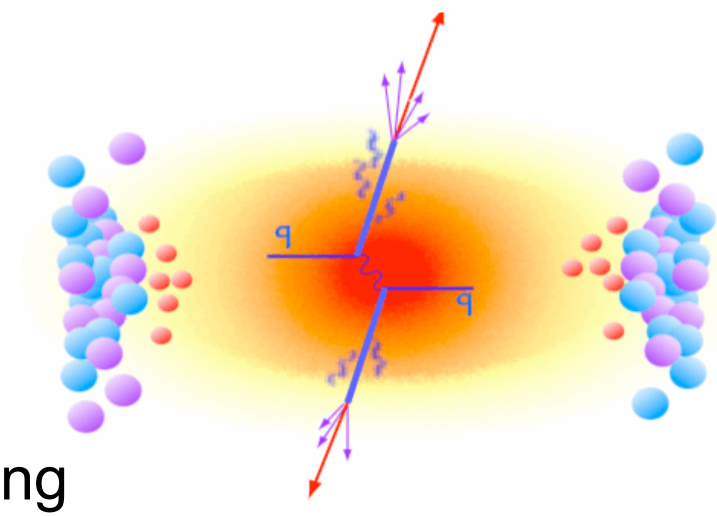
Parton Showering (Fragmentation)







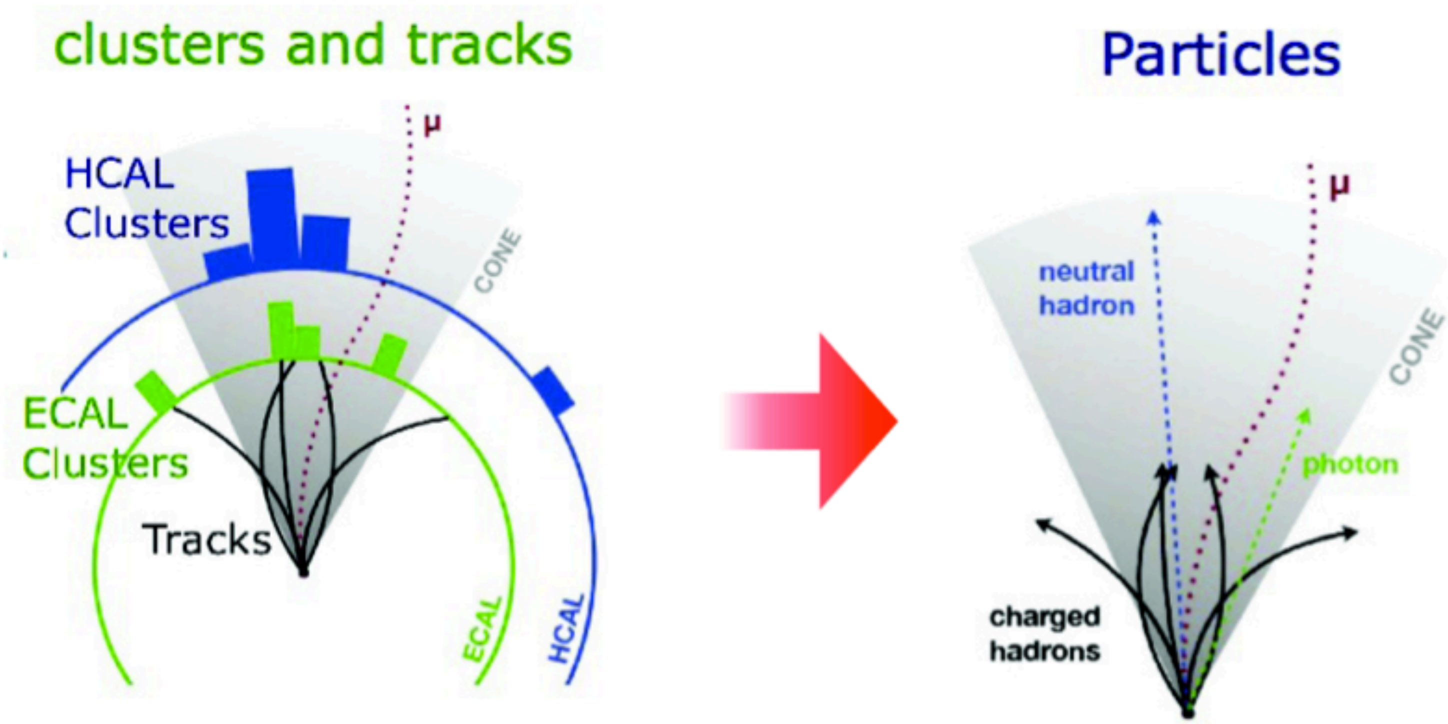
- Components sensitive to
  - medium properties
  - where and when the process happens
- Reconstructed dijets
  - full final state of hard scatterings
  - study the individual components contributing to the parton energy loss



What is Particle Flow?

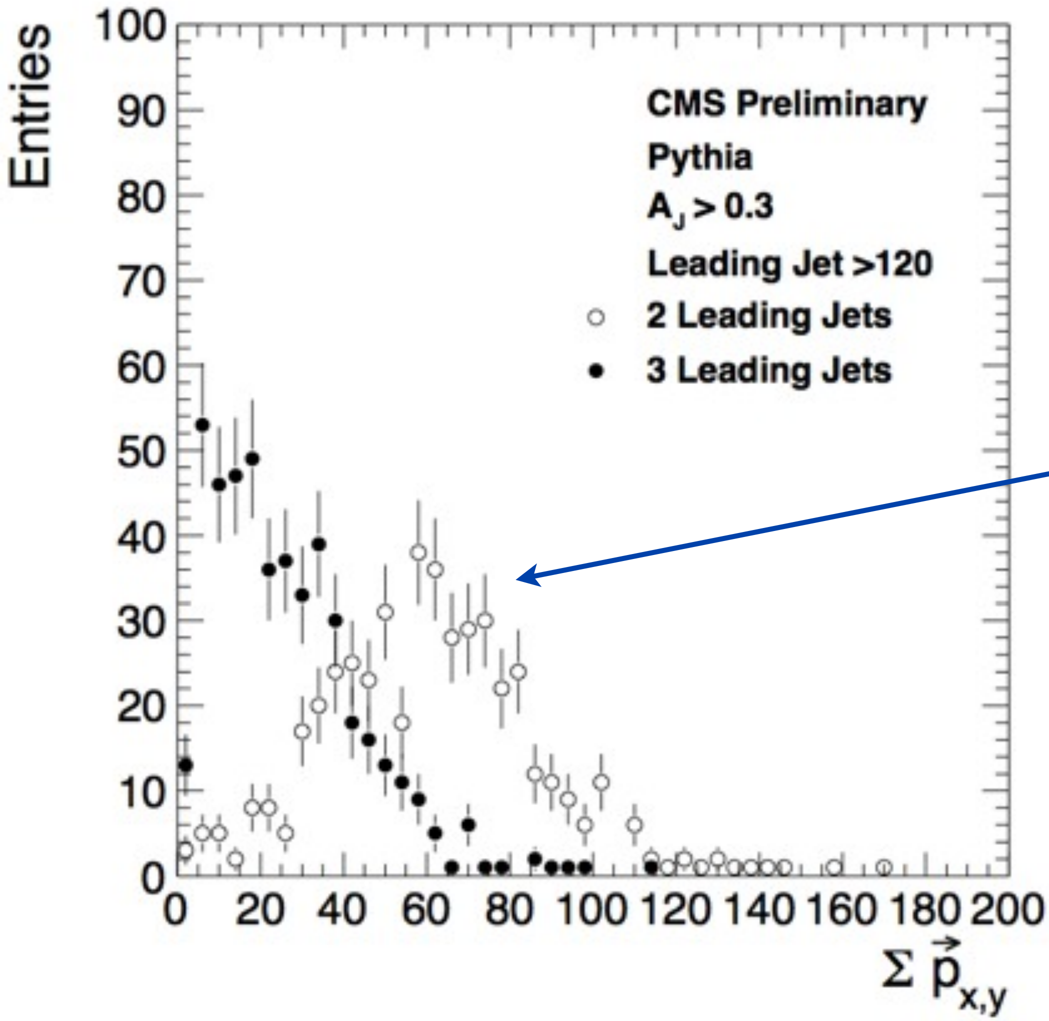
Hint: It's got nothing to do with hydrodynamics

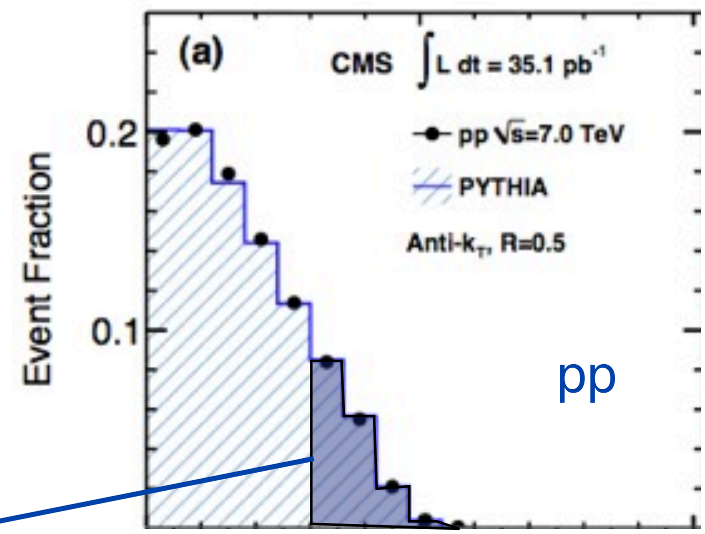
Particle flow reconstructs all stable particle in the event: $h^{+/-}$, γ, h^0, e, μ



- On average jets are:
  ~ 65% charged hadrons, ~ 25% photons, ~ 10 % neutral hadrons
- Using the silicon tracker (vs. HCAL) to measure charged hadrons
  - Improves resolution, avoids non-linearity
  - Decreases sensitivity to the fragmentation pattern of jets
- Used extensively in ALEPH, CMS and proposed for the ILC

PYTHIA Momentum Balance

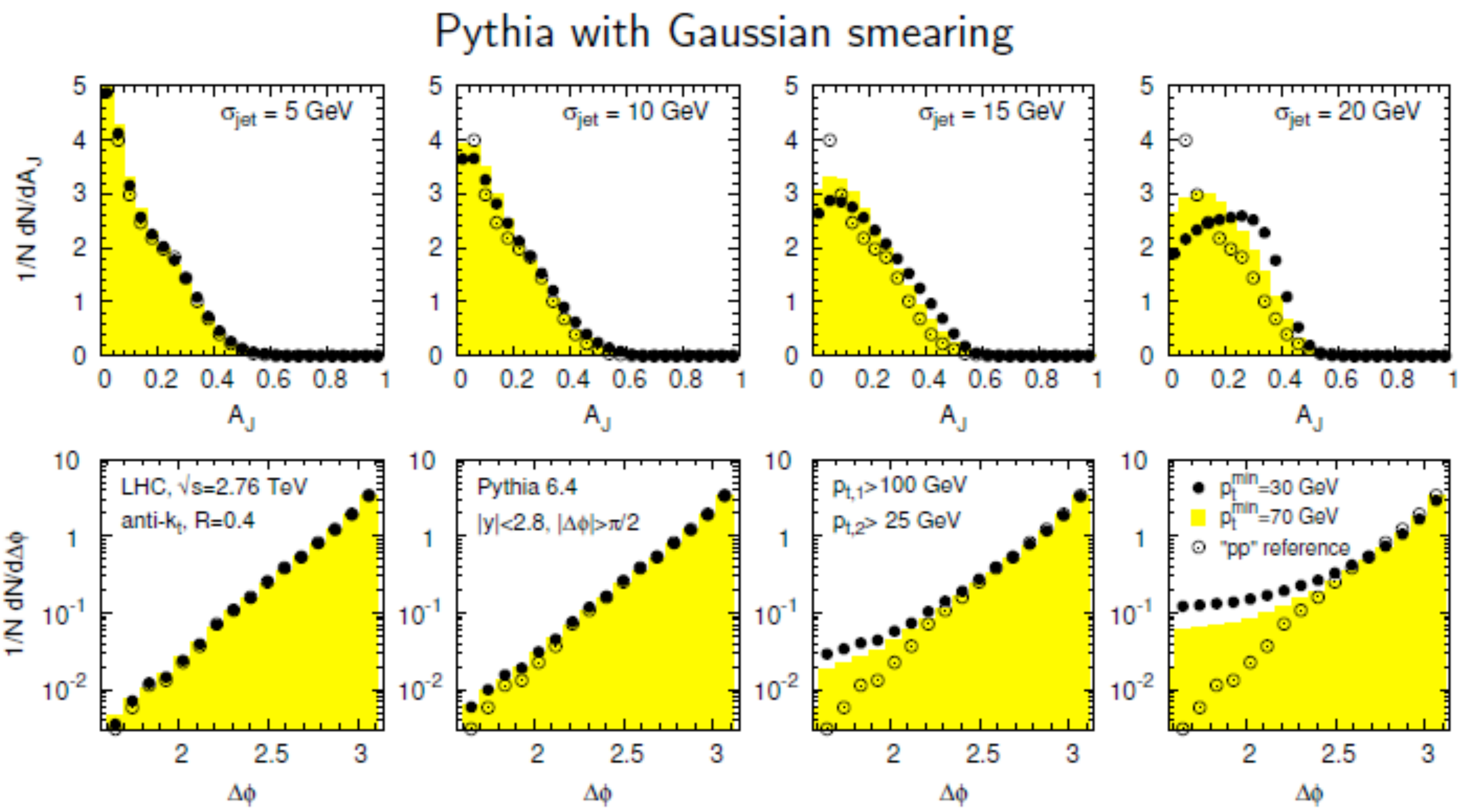




For the ~10% of unbalanced PYTHIA dijets ($A_j > 0.3$), a 3rd jet provides most of momentum balance

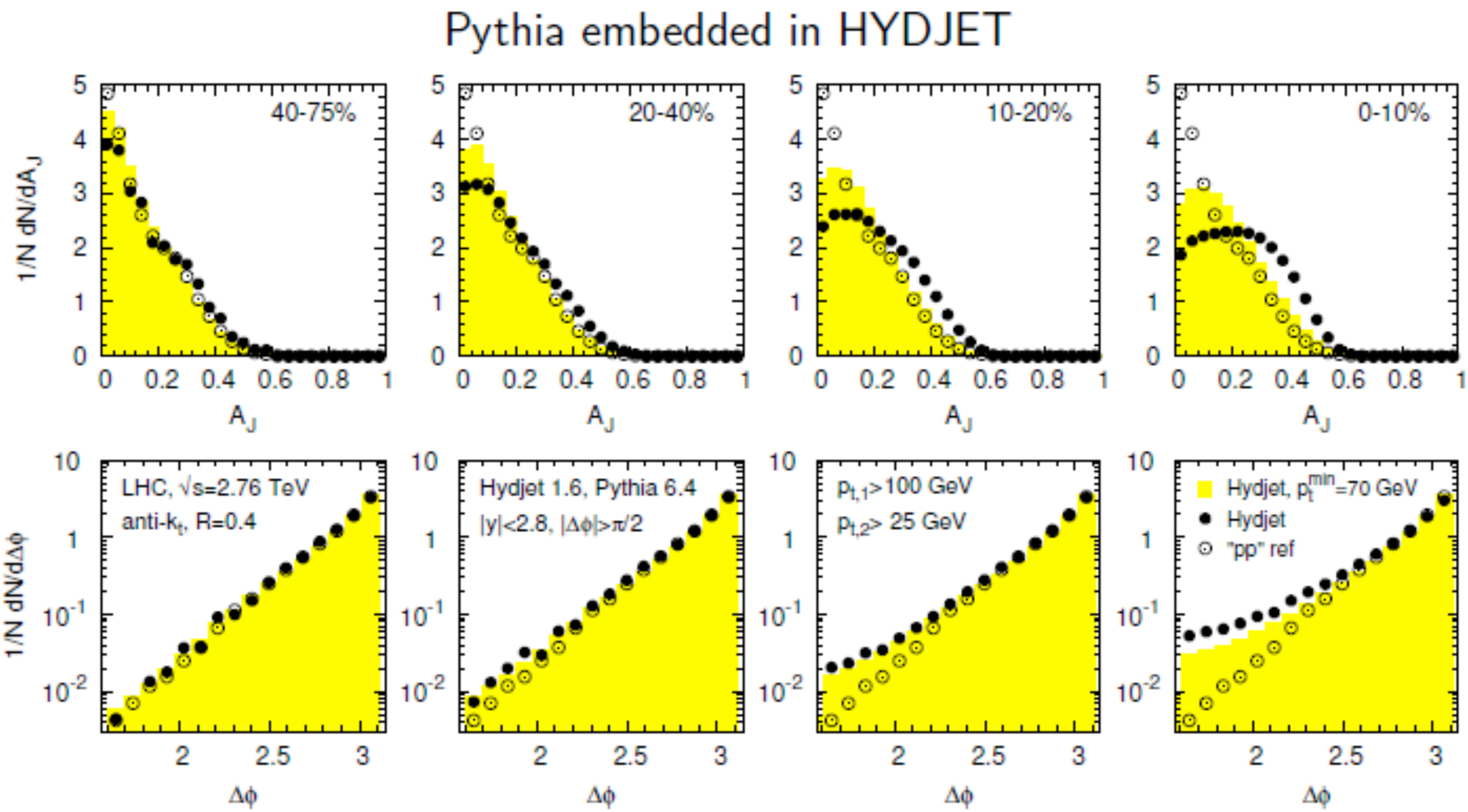
Winter Workshop on Nuclear Dynamics, 2011

Different Gaussian smearing



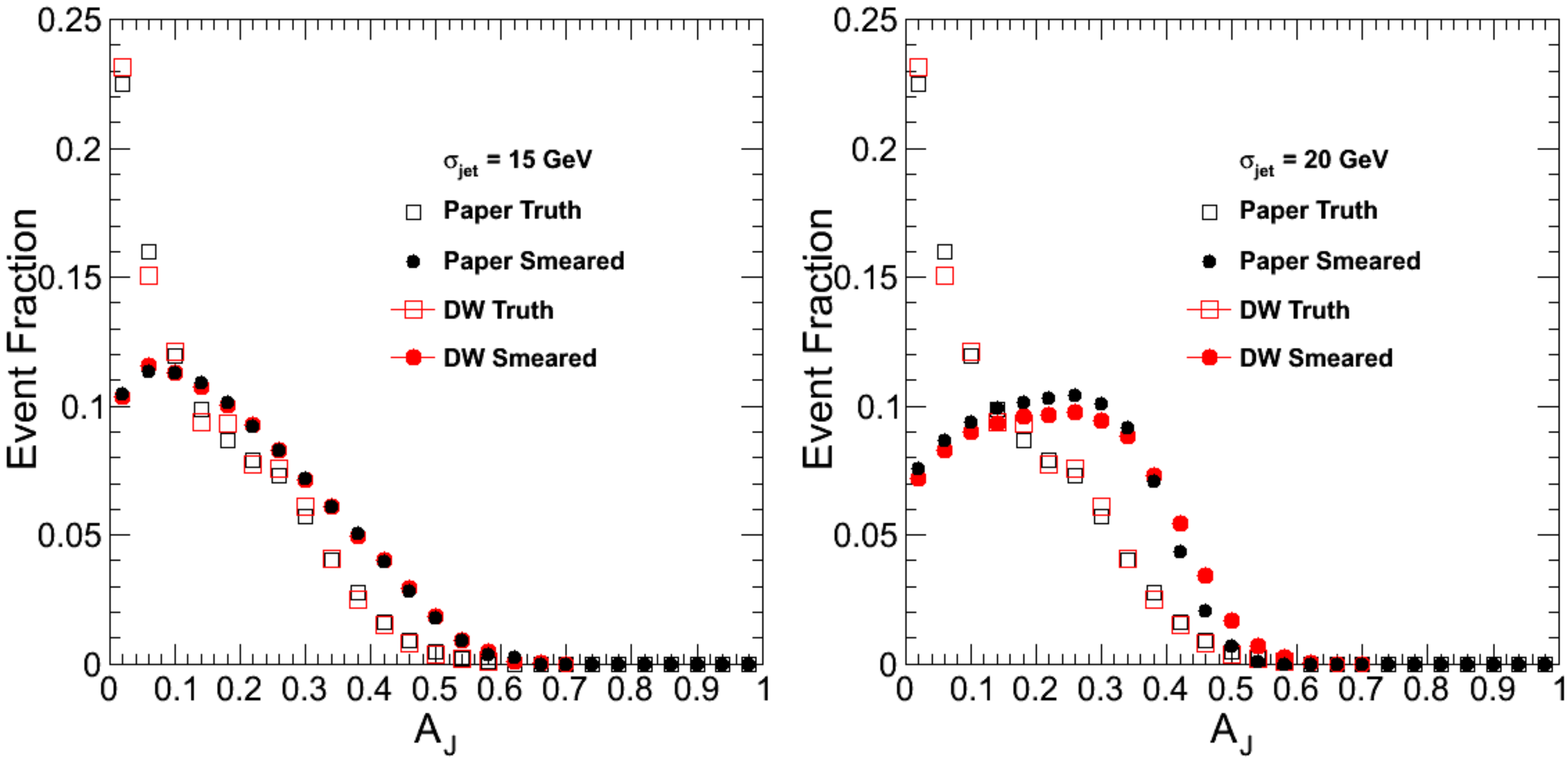
Cacciari, Salam, Soyez: arXiv: 1101.2878

PYTHIA+HYDJET



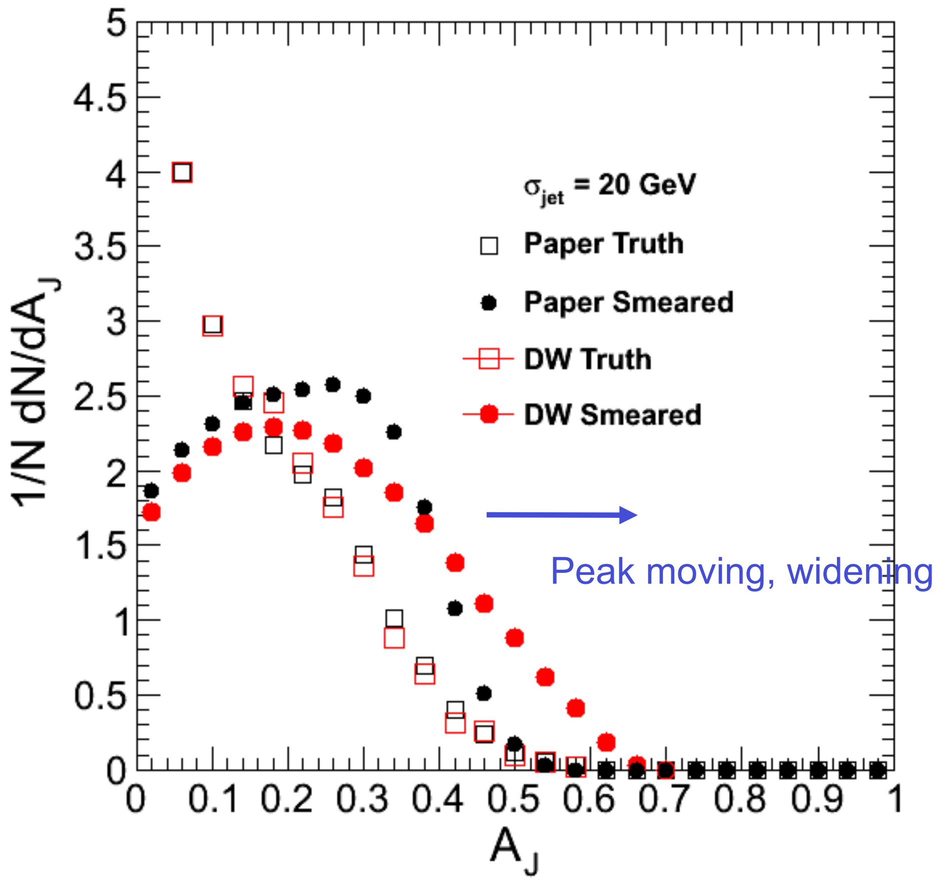
Cacciari, Salam, Soyez: arXiv: 1101.2878

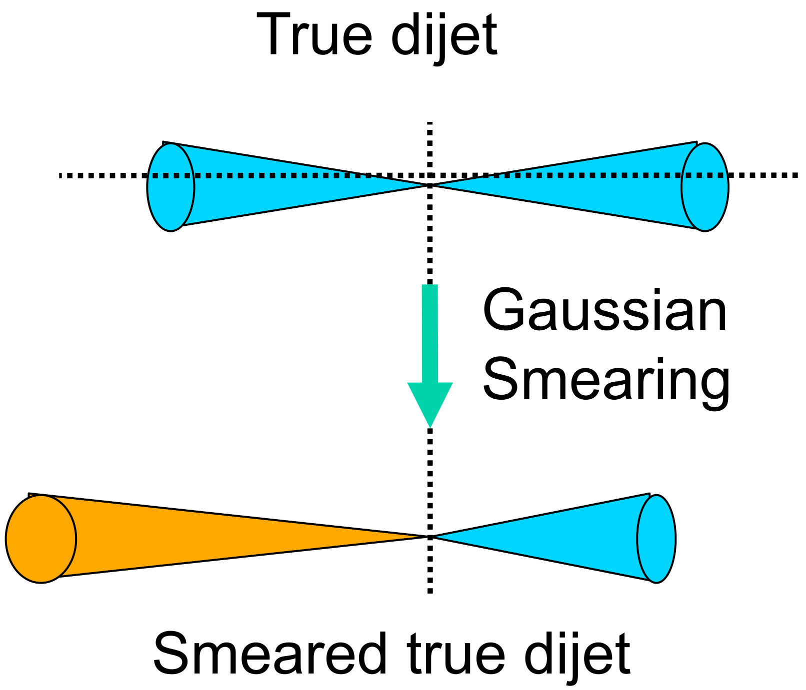
PYTHIA + Fluctuations



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

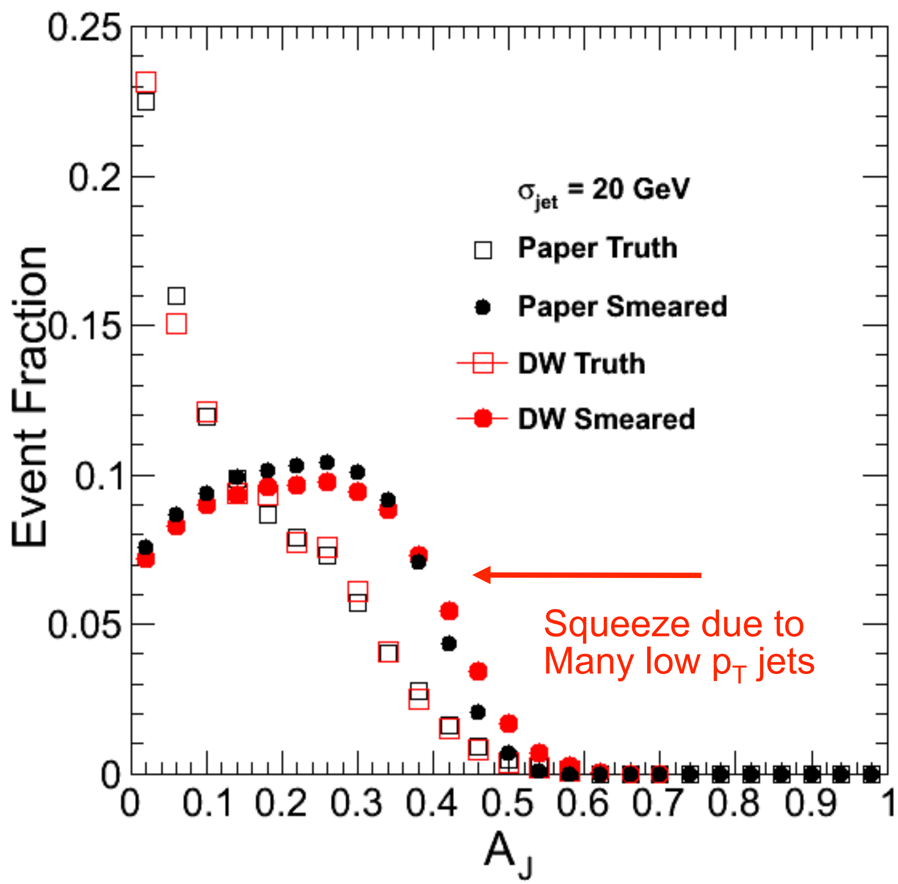
Ingredients

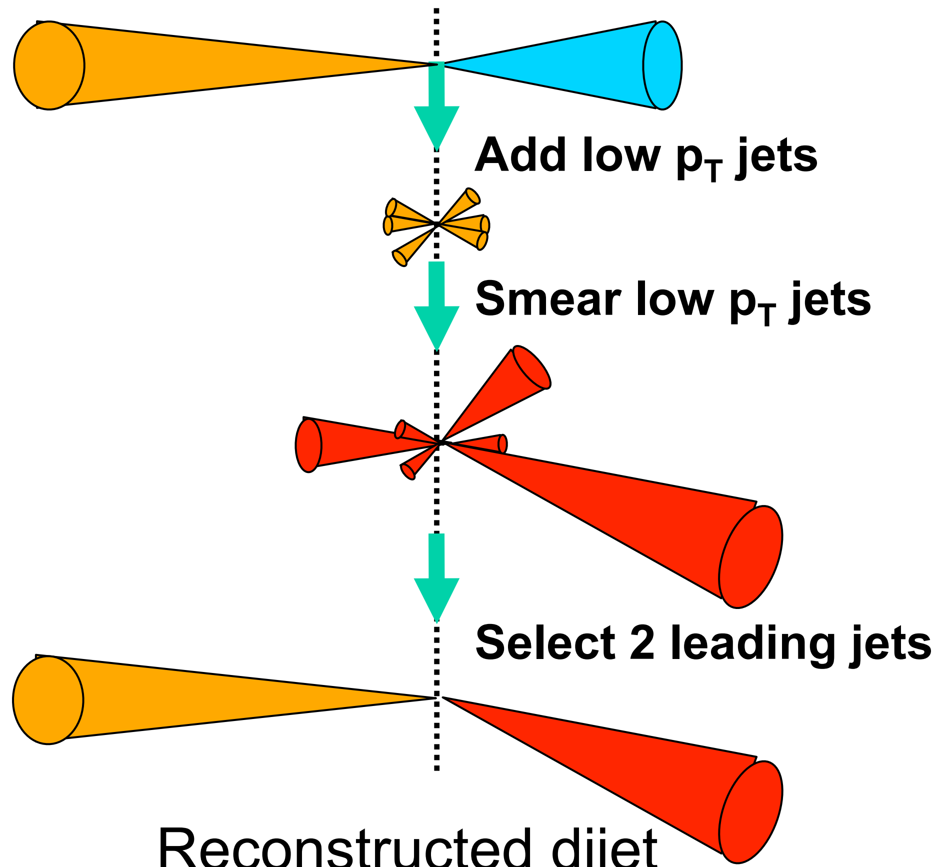




– Gaussian smearing of the leading jet makes the A_J distribution wider
  - Select only Jets above p_T = 3GeV

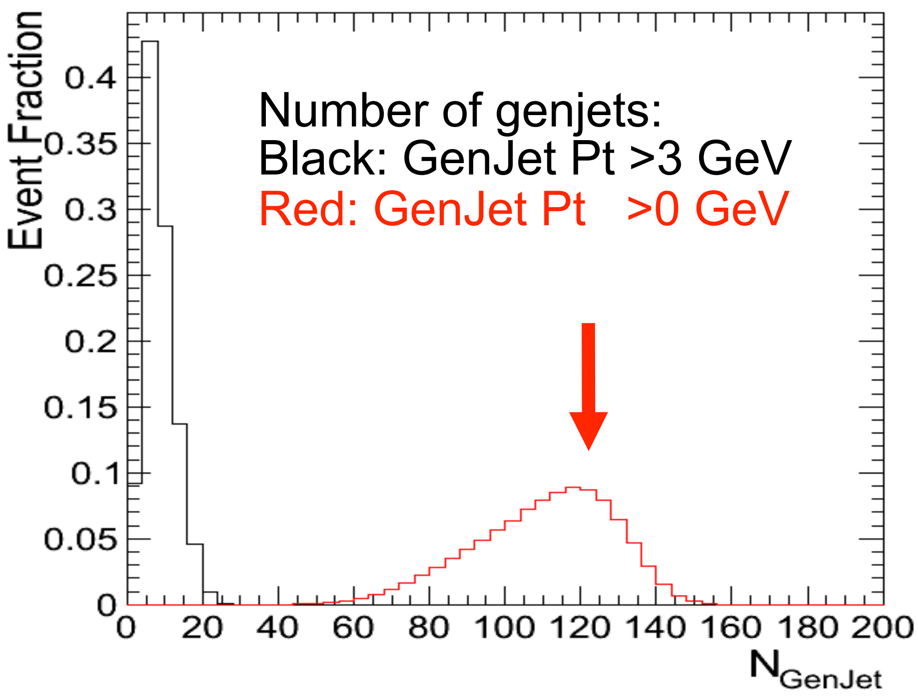
Ingredients II

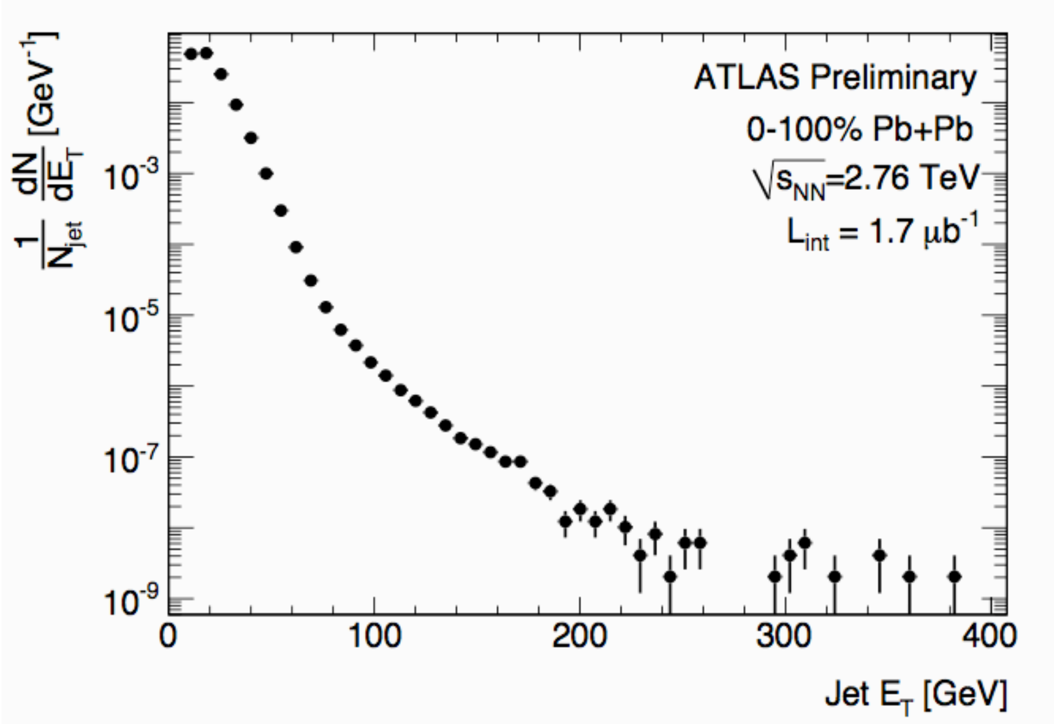




– Adding many low p_T jets, smeared to higher p_T than the true away side jet, compresses the A_J distribution
  - Tested by adding the 0-3GeV jets in the analysis

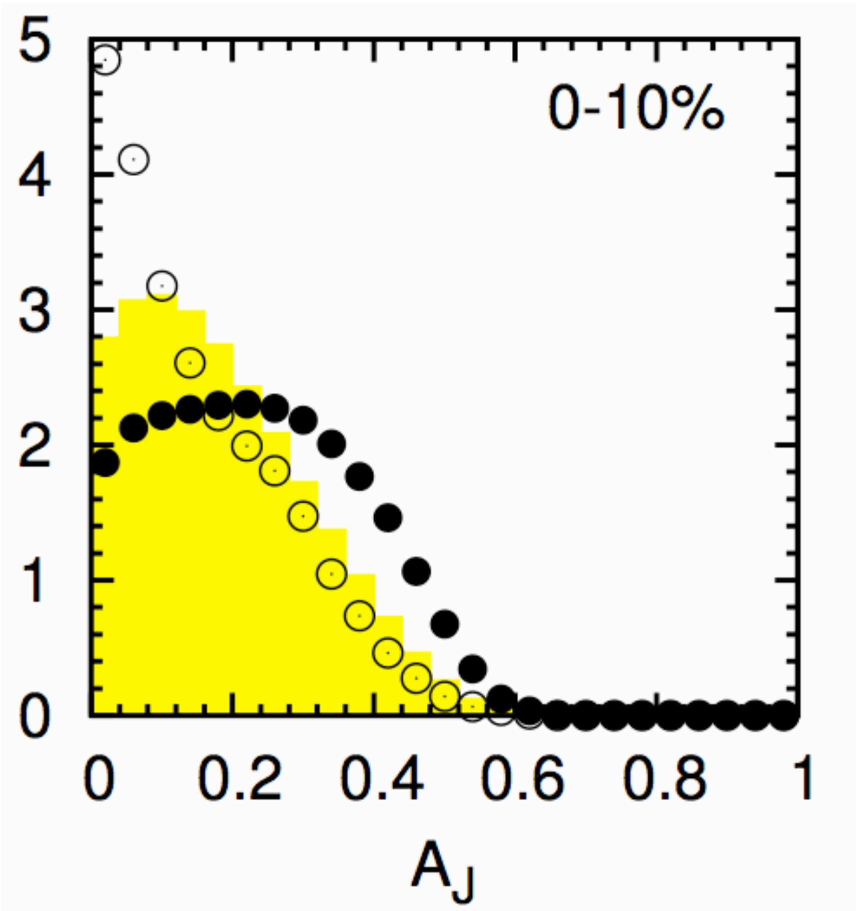
Ingredients III

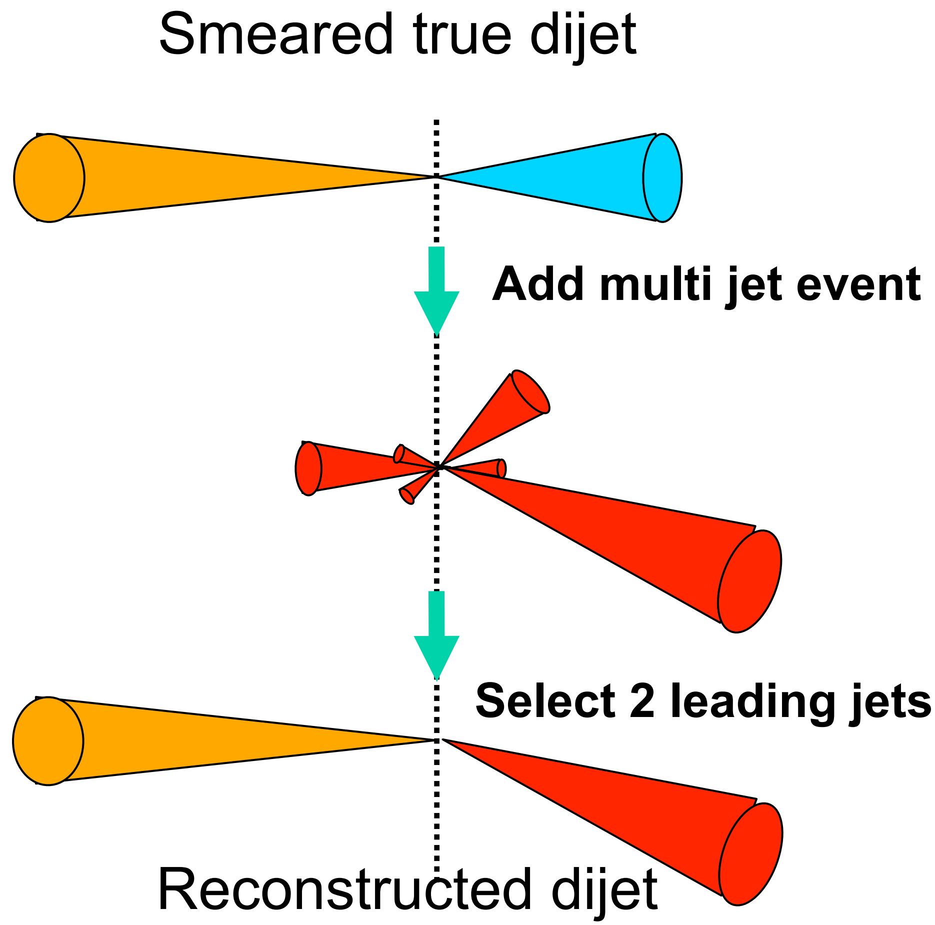




- Balanced dijets + fluctuations can fake a wide A_J distribution
  - Needs a very large number (~100) of low p_T jets per event
    - Remember: dn/dη^{ch} ~6 in |eta| < 5 -> ~60 charged particles/event
  - And a very large σ (20GeV) for the smearing
    - based on a Gaussian fit to the low p_T part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

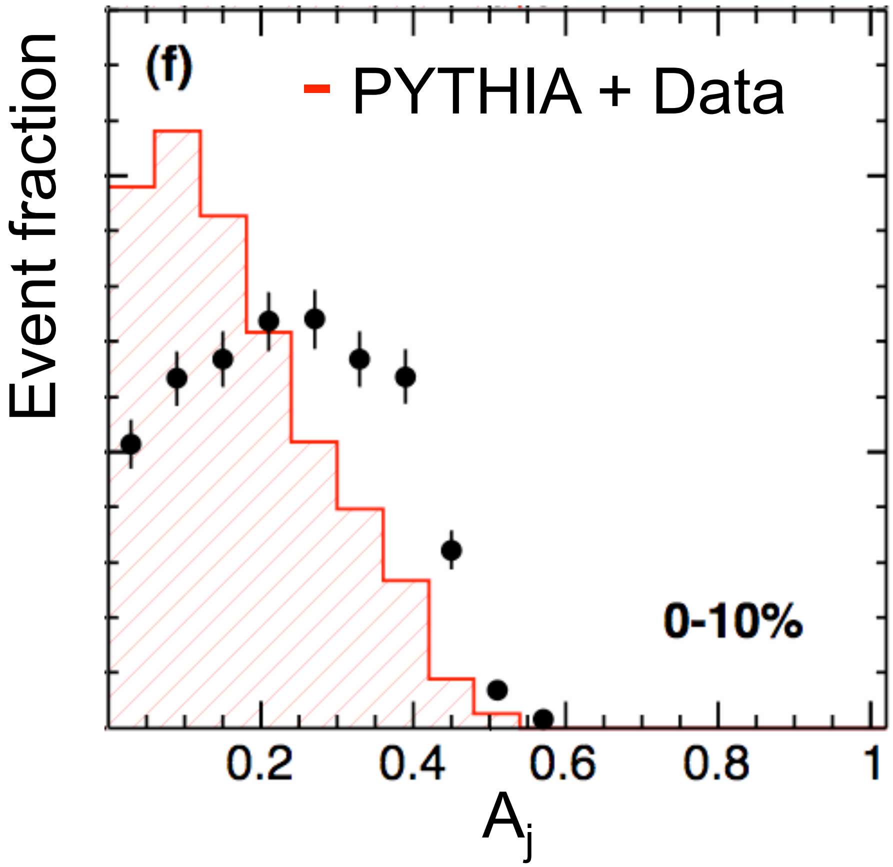
Hydjet

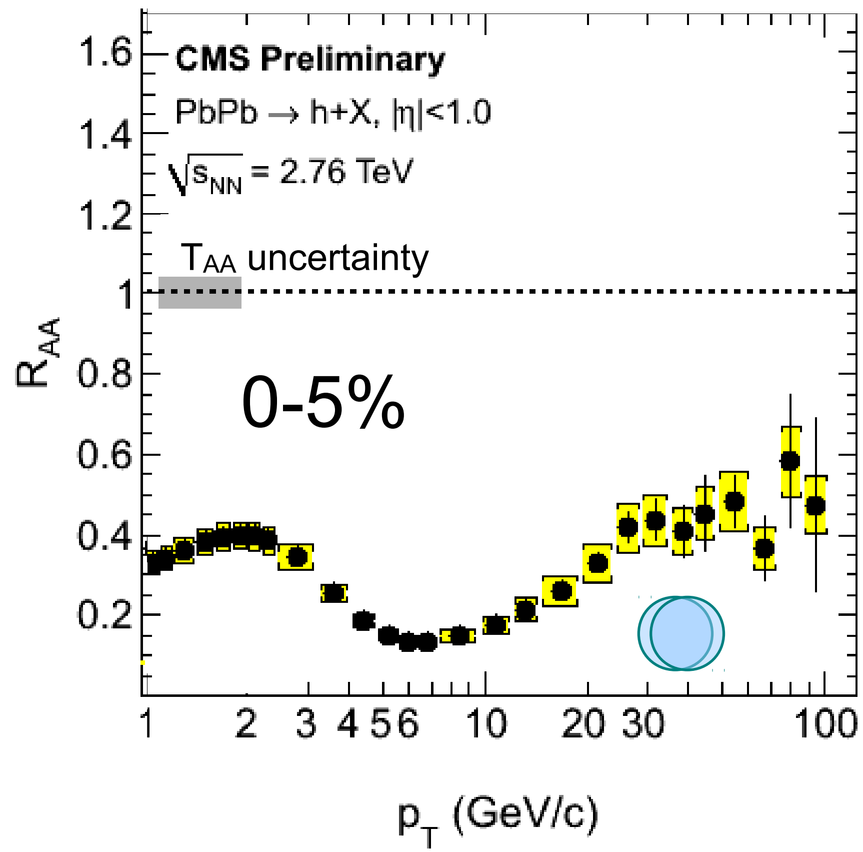




- The HYDJET A_J distribution is created by the same mechanism
  - The hard part of a central HYDJET event consists of ~300 unquenched PYTHIA events with $p_T$hat of ~7GeV
  - Low p_T jets smear the leading jets by superposition and cause a combinatorial problem

Is unquenched Hydjet a good background reference?

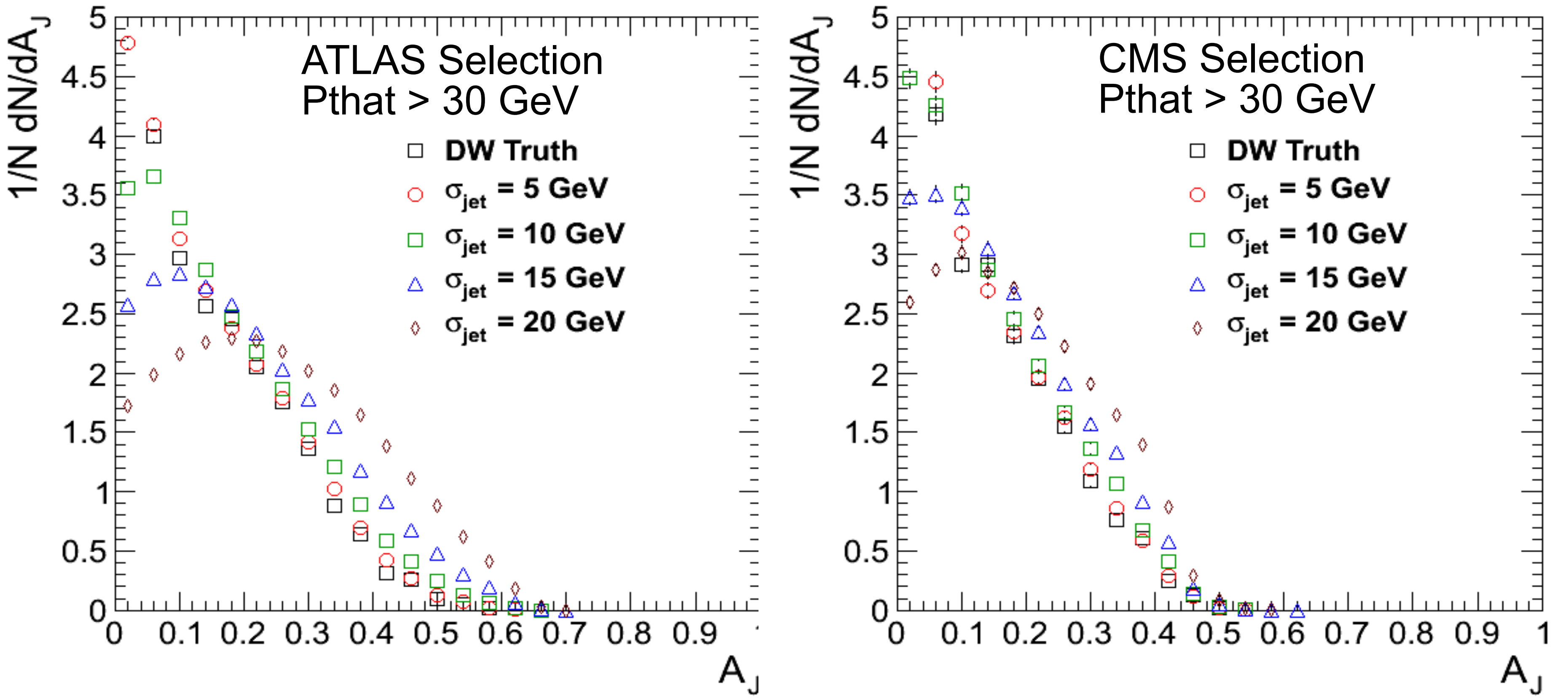




- PYTHIA embedded in real data, including all background fluctuations and resolution effects does not show a widened A_J distribution
  - A cross check with $p_T$hat = 30GeV embedded in a large min bias data sample gave an identical reference distributions
  - R_{AA} shows a strong hadron suppression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

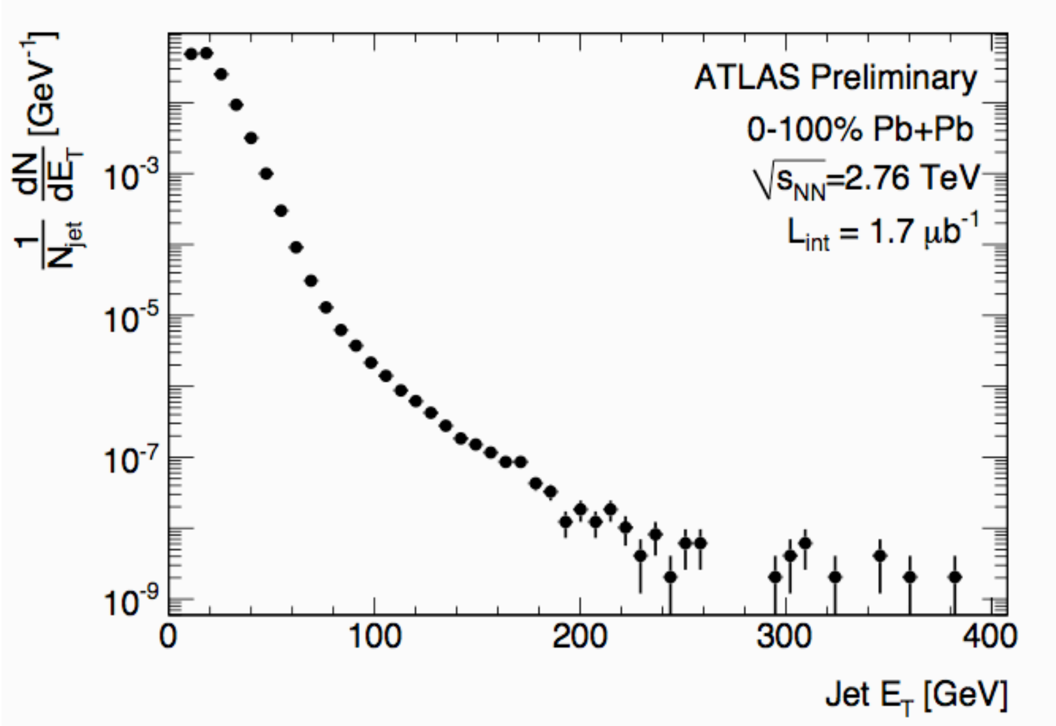
ATLAS vs CMS Dijet selection

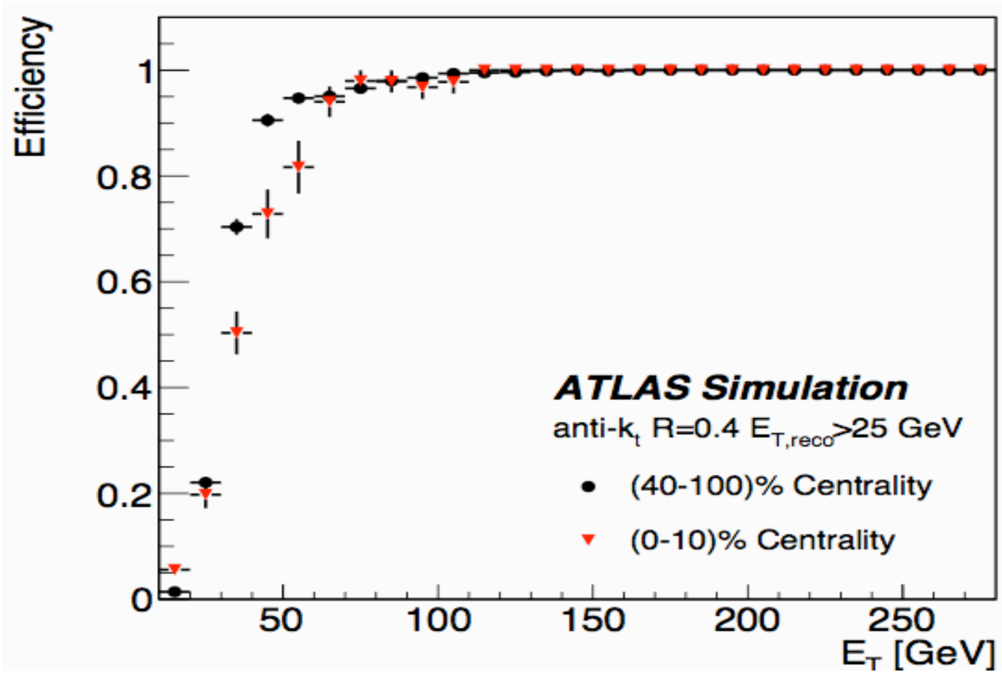
Comparing the ATLAS and CMS dijet selection p_T hat > 30 GeV



- 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

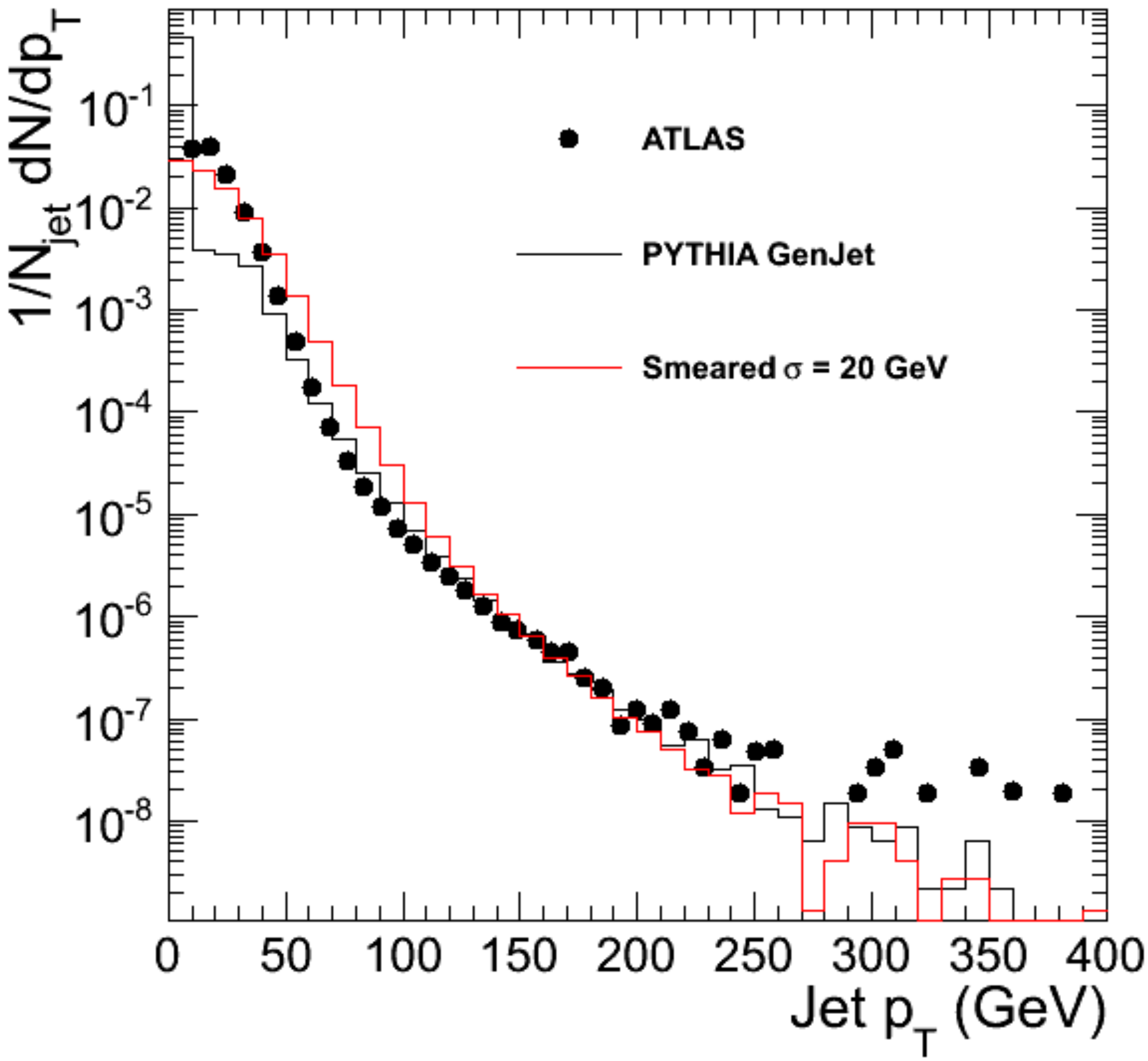
ATLAS input





- 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 σ ~8 GeV for their background fluctuations

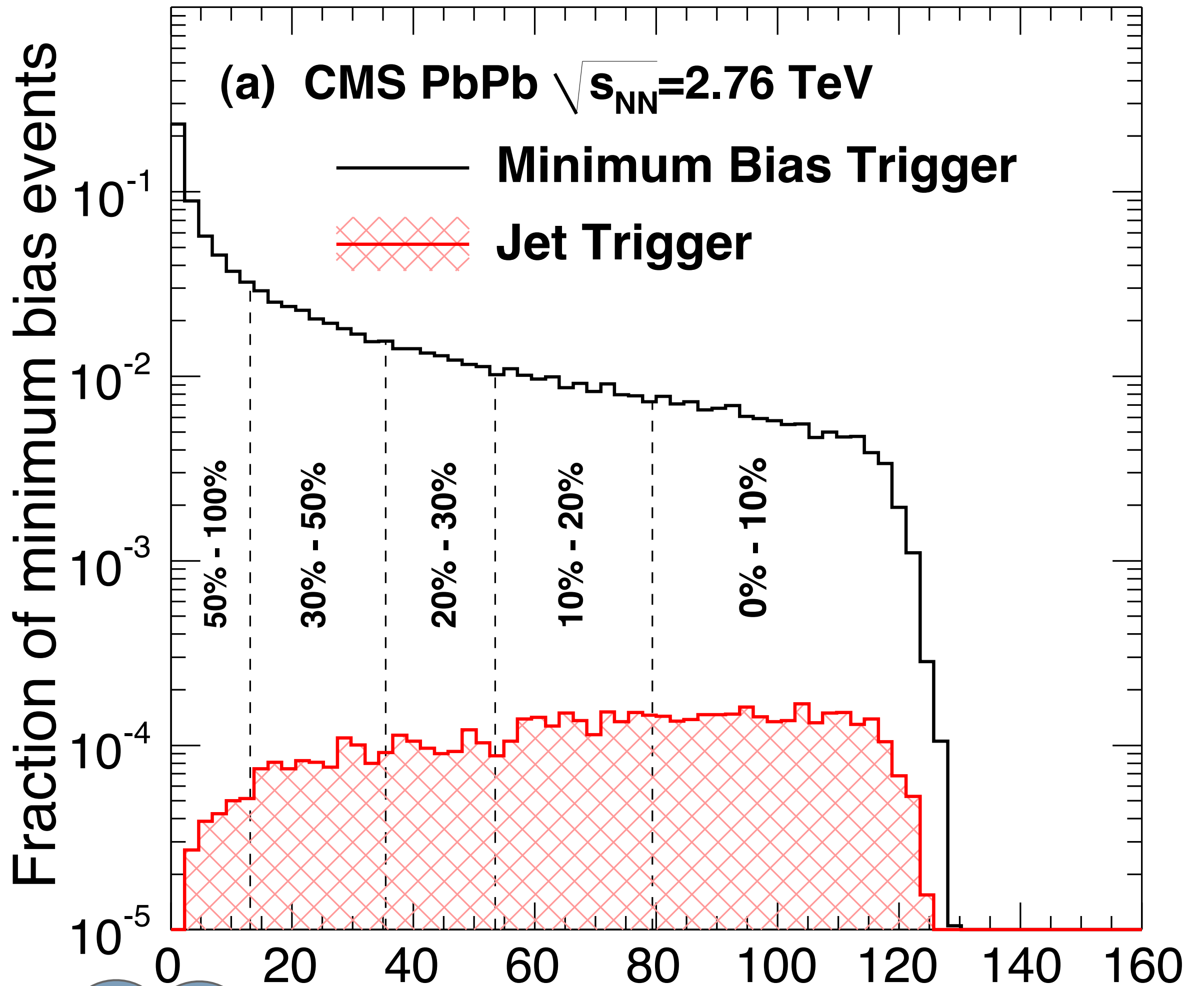
20GeV smearing closure test

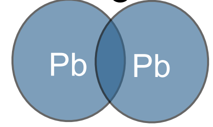


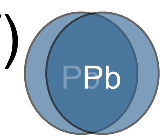
Centrality definition

- Determined by the total energy from both HF calorimeters
- Split minimum bias events into centrality bins
- Relate to <N_{part}> 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







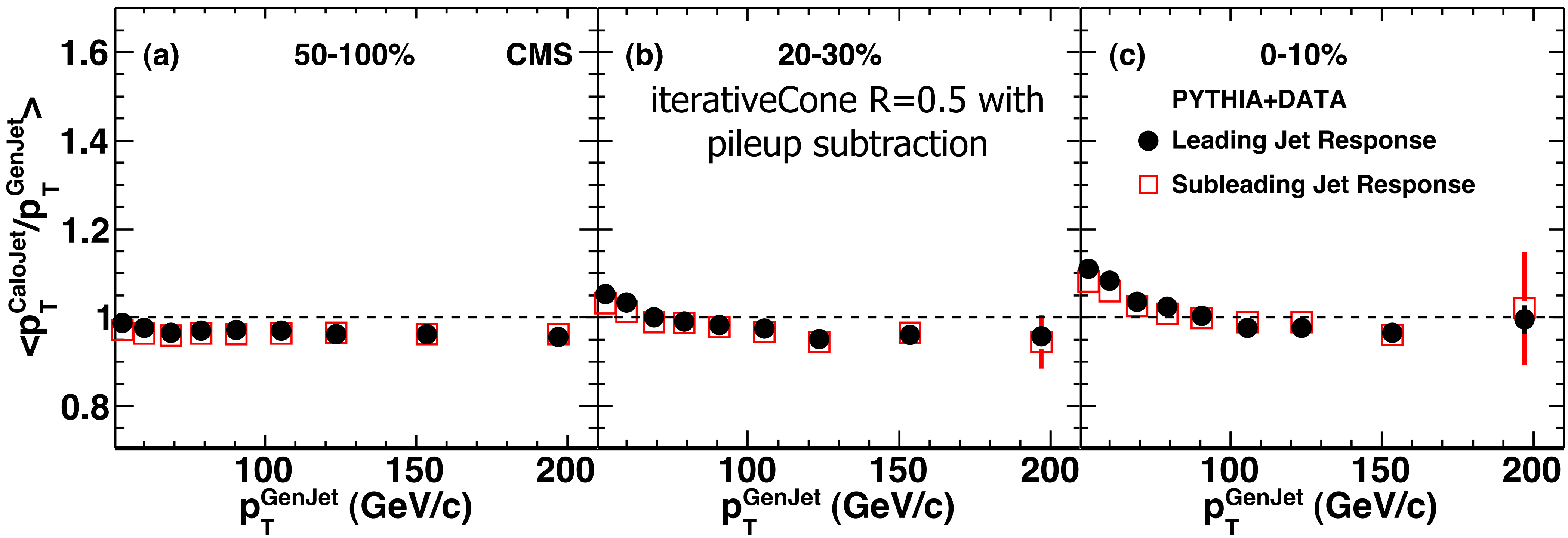
CMS: arXiv:1102.1957

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

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)

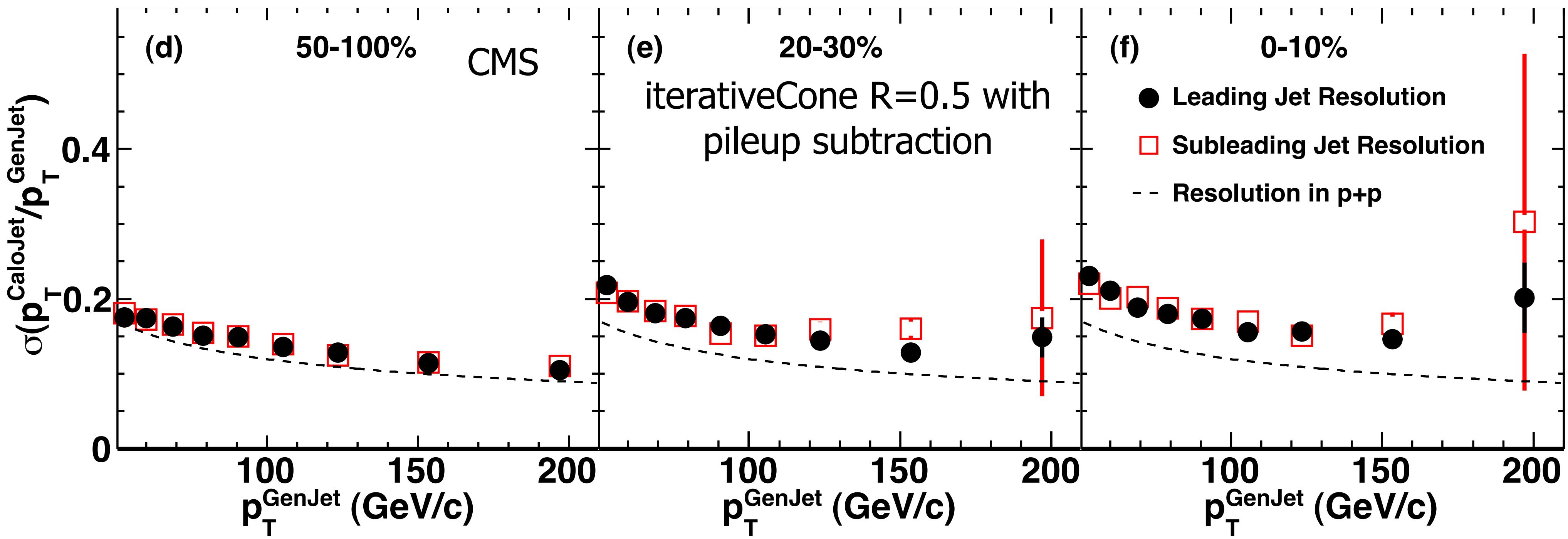
CMS: arXiv:1102.1957



Jet Resolution

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

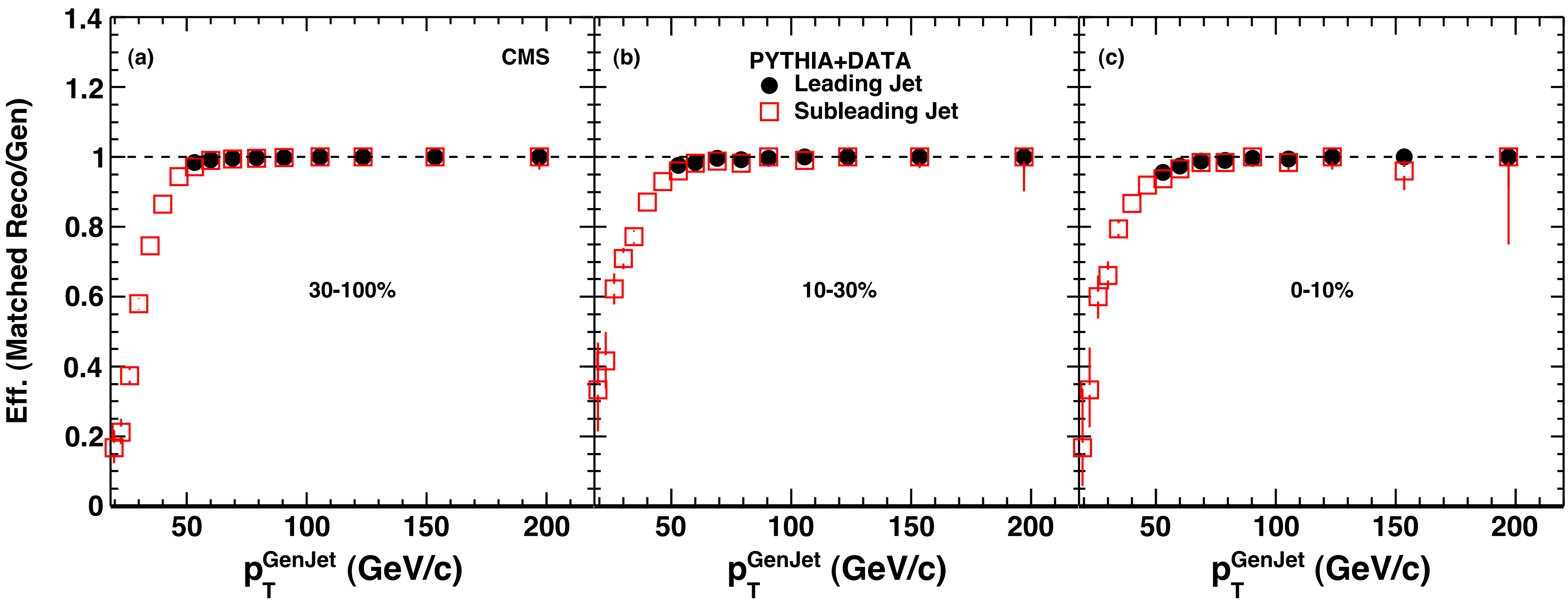
CMS: arXiv:1102.1957



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 GeV/c)
- High efficiency for subleading jet selection ($p_{T,2}$> 50 GeV/c)
- PYTHIA (QCD dijet) + DATA (PbPb Minimum Bias)

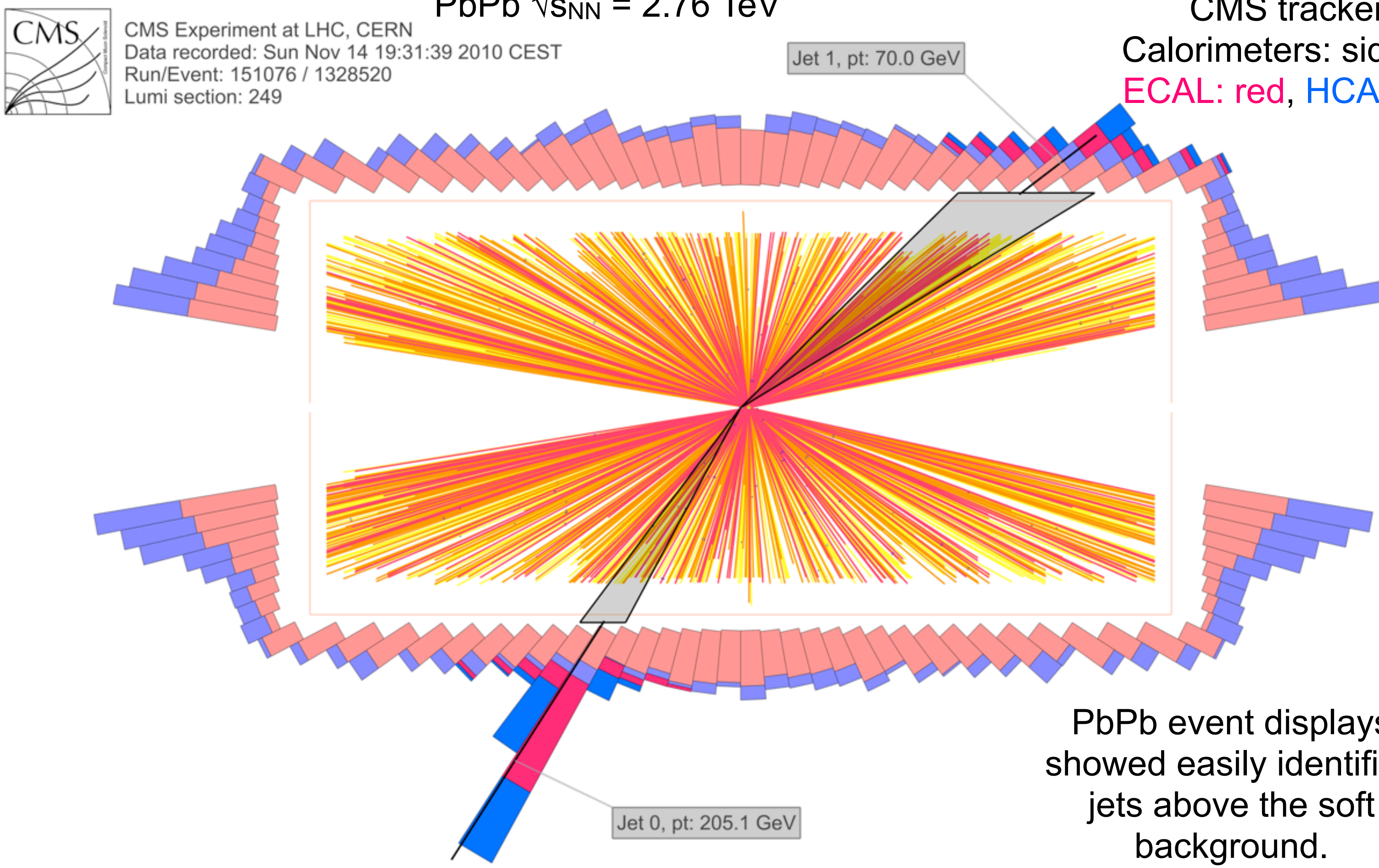
CMS: arXiv:1102.1957



PbPb Collision with CMS

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

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

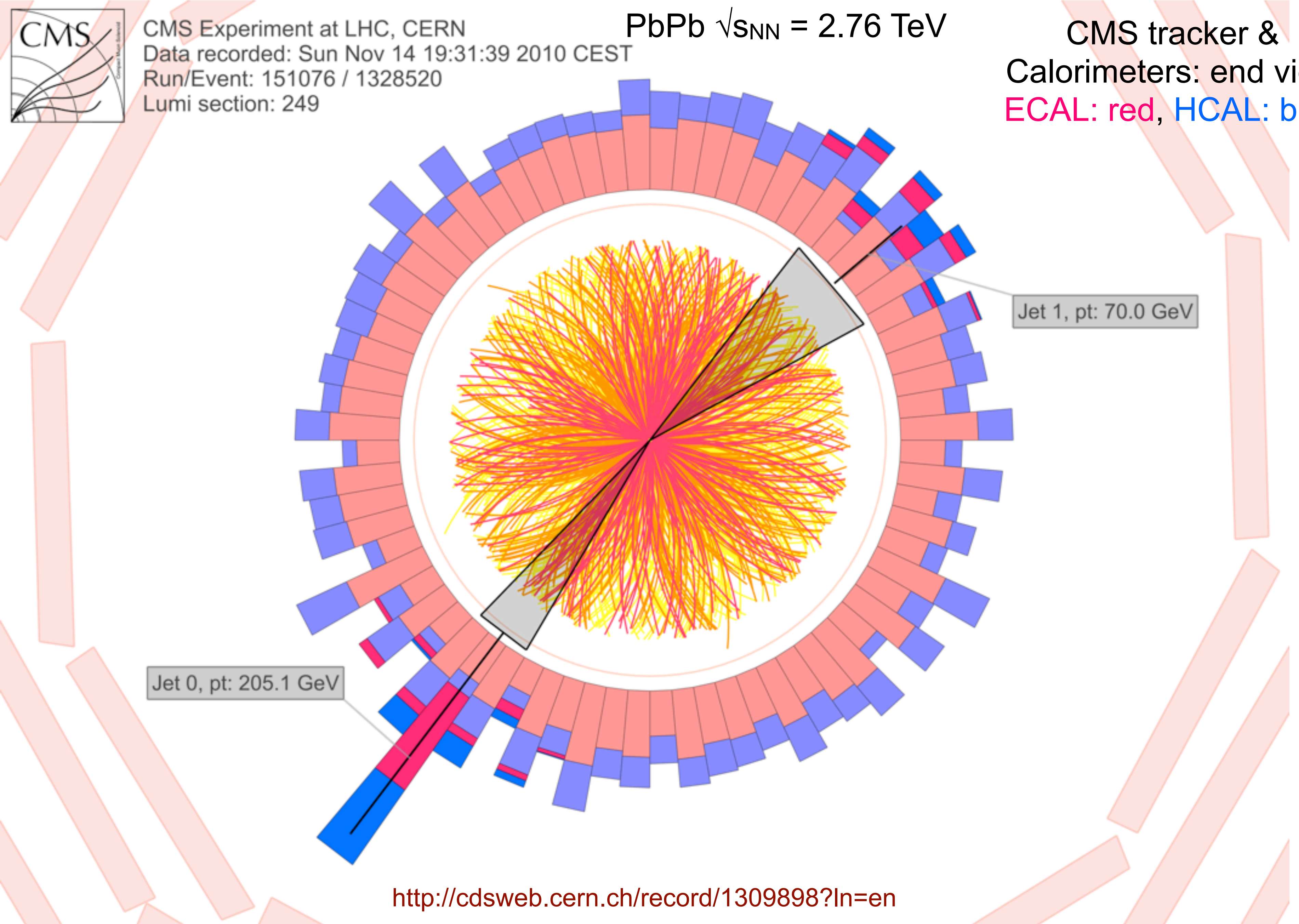


PbPb event displays showed easily identified jets above the soft background.

Calorimeter towers = ECAL+HCAL
$\Delta\eta \times \Delta\phi = 0.087 \times 0.087$

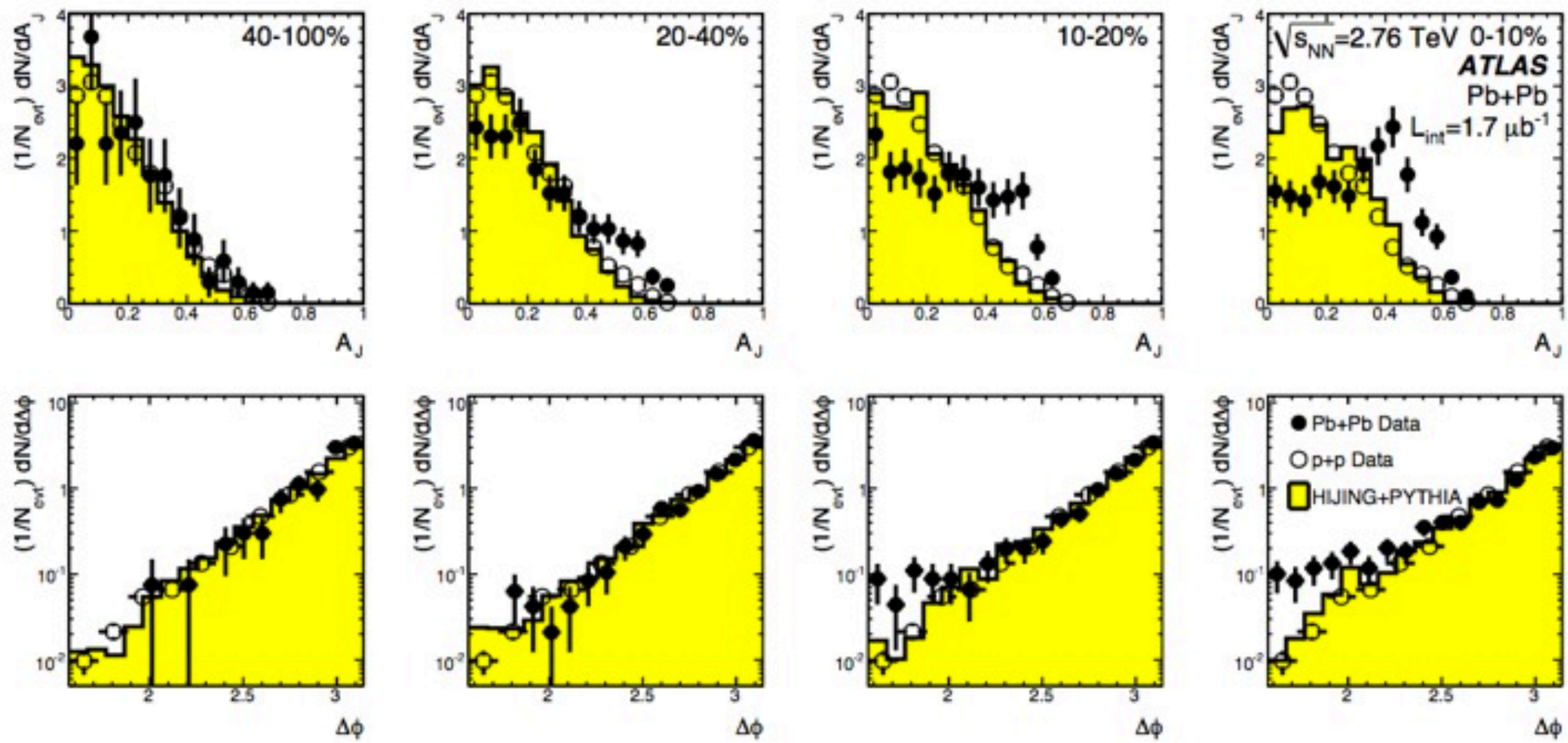
http://cdsweb.cern.ch/record/1309898?ln=en

PbPb Collision with CMS



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

ATLAS Dijet Asymmetry

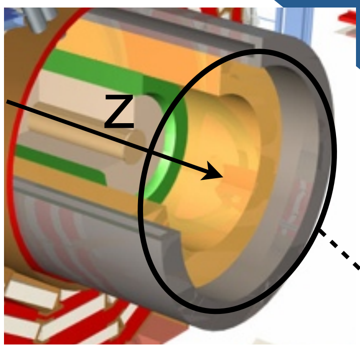


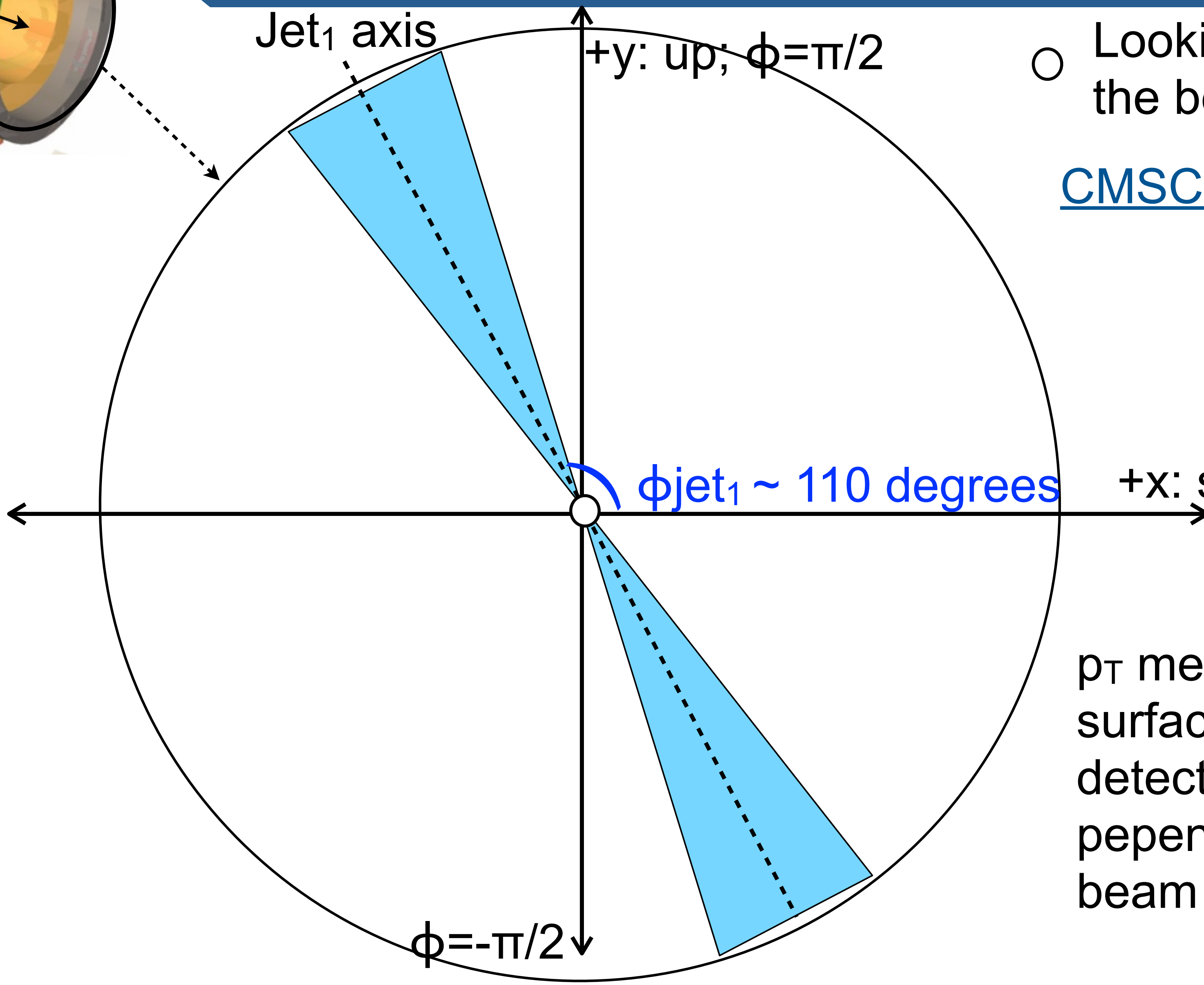
$p_{T,1} > 100$ GeV
$p_{T,2} > 25$ GeV
$\Delta\phi_{1,2} > \pi/2$
$|\eta_{jet}| < 2.8$

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`.

Winter Workshop on Nuclear Dynamics, 2011

ϕ definition (for $\langle \not{p}_T^{||} \rangle$)





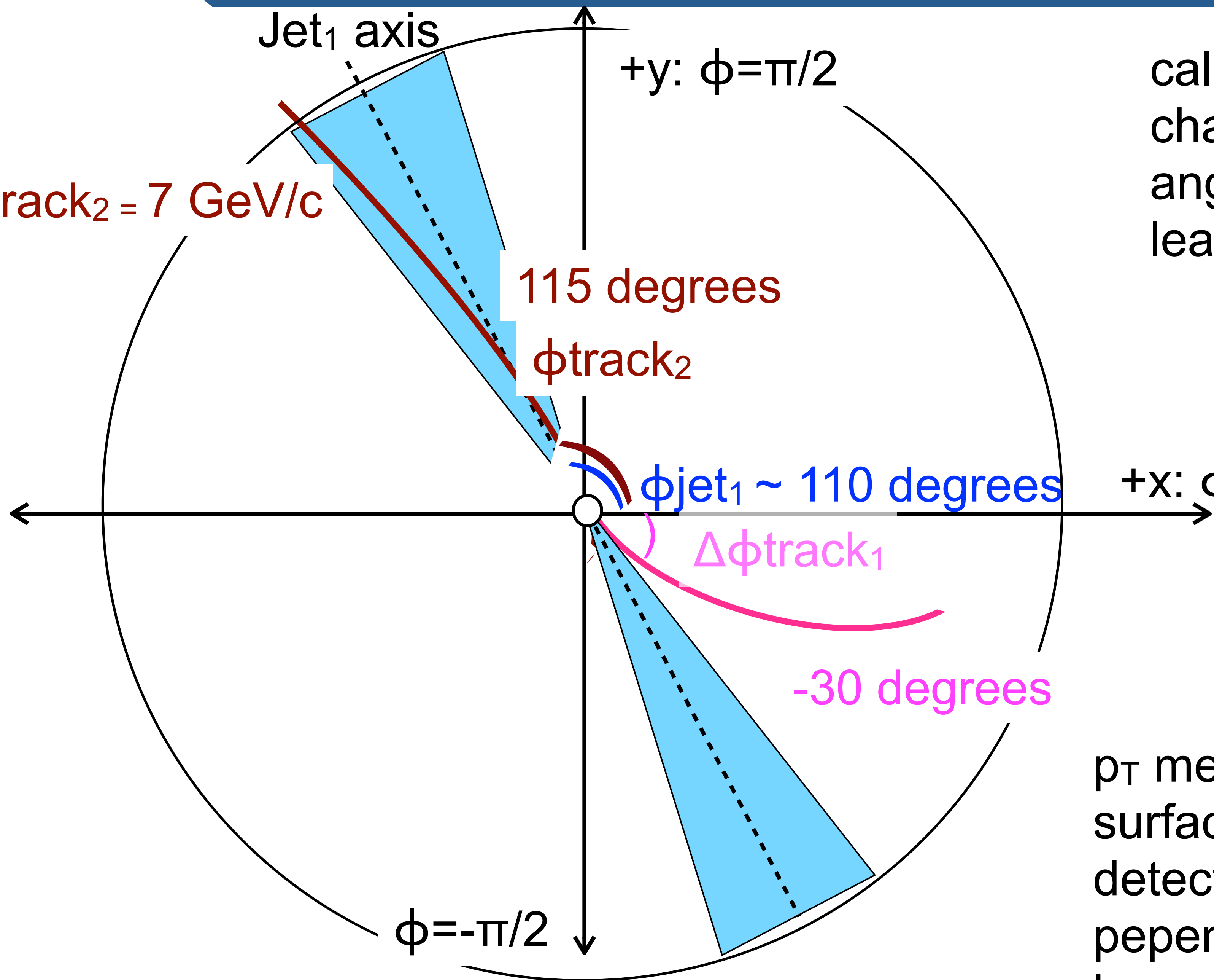
- Looking down the beam axis

CMSConventions

p_T measured at surface of detector pependicular to beam axis

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

Pictoral <$\not p_T^{||}$> Example

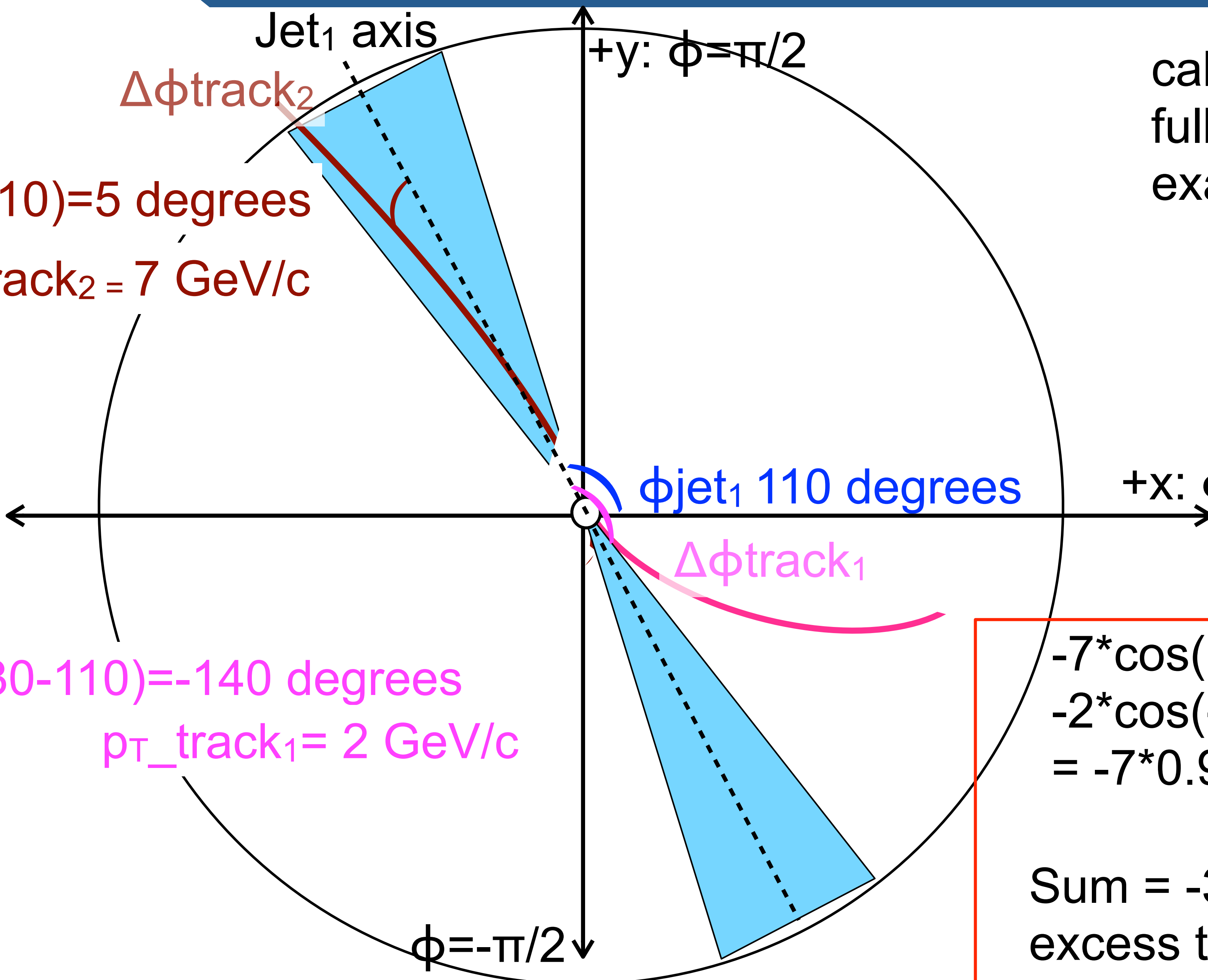


calculate change in angle from leading jet

p_T measured at surface of detector pependicular to beam axis

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

Pictoral $\langle \not{p}_T^{||} \rangle$ Example



calculate full $\langle p_T^{||} \rangle$ example

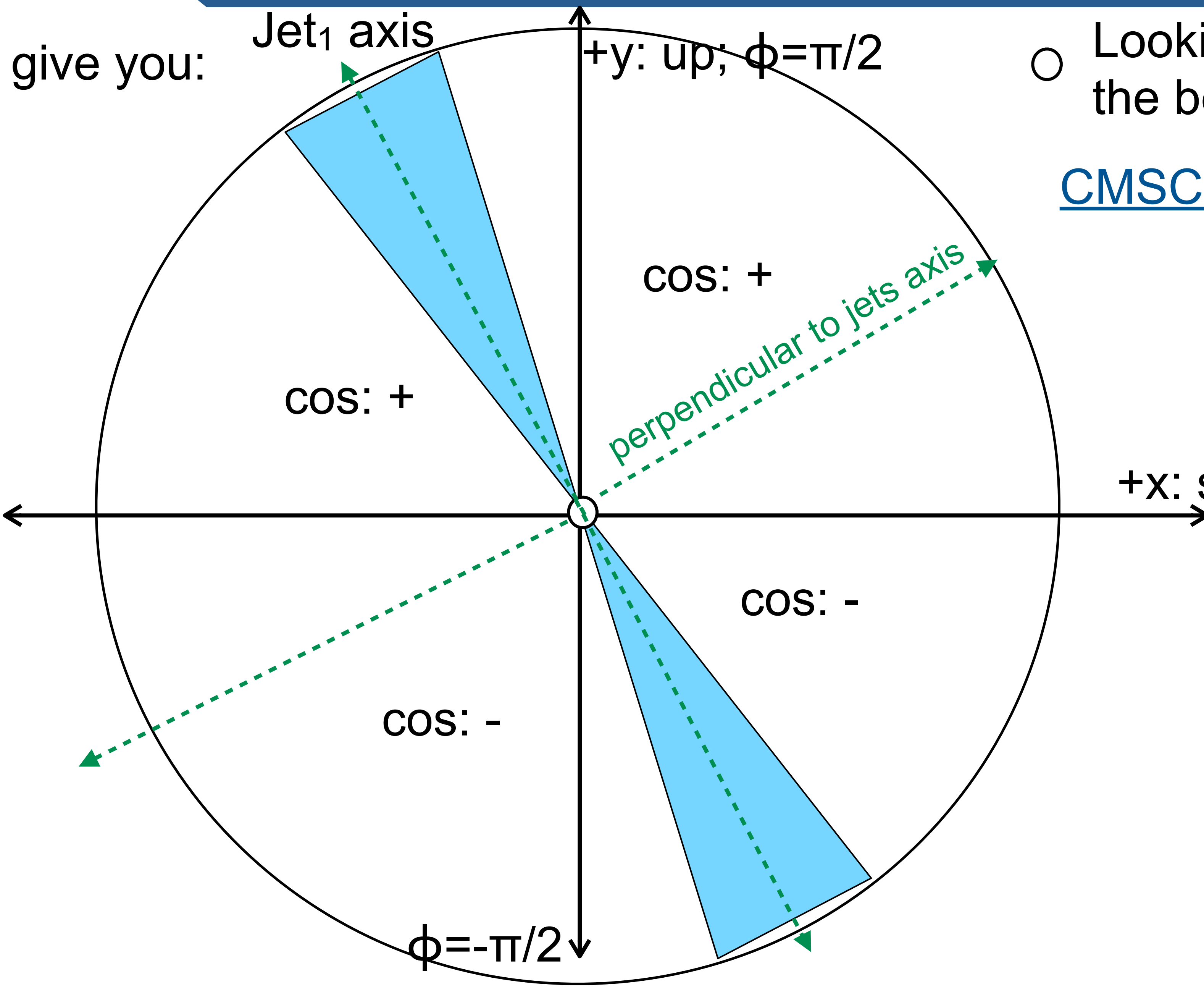
-7*cos(5°)
-2*cos(-140°)
= -7*0.99+2*0.77

Sum = -3.8
excess towards leading jet

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

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

cos will give you:
+ or -



○ Looking down the beam axis

CMSConventions

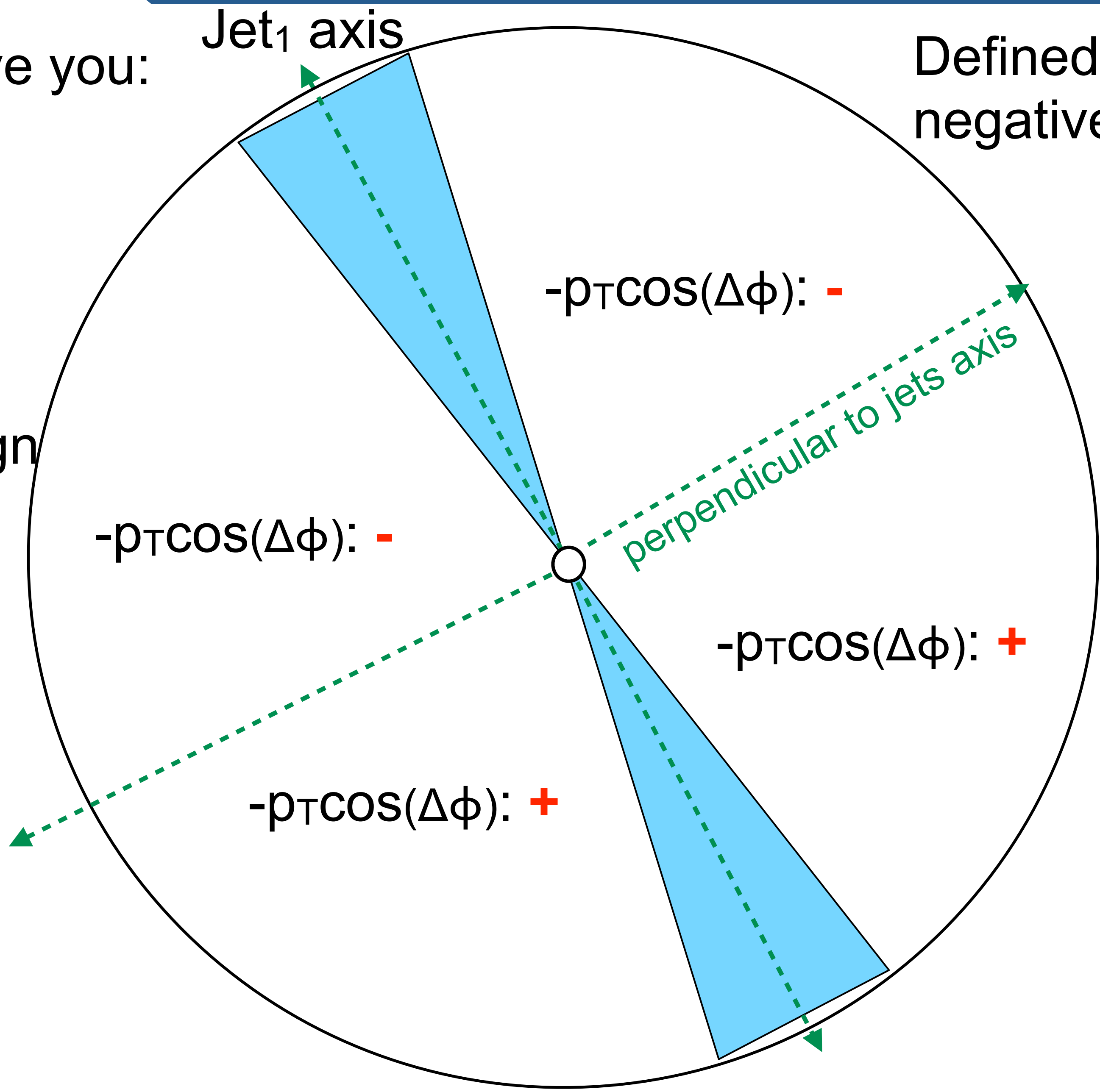
$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\text{T,track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$

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

cos will give you:
+ or -

multiply by
$-p_T$,
quadrants
reverse sign

Defined as
negative towards leading



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