Results with hard probes - CMS -

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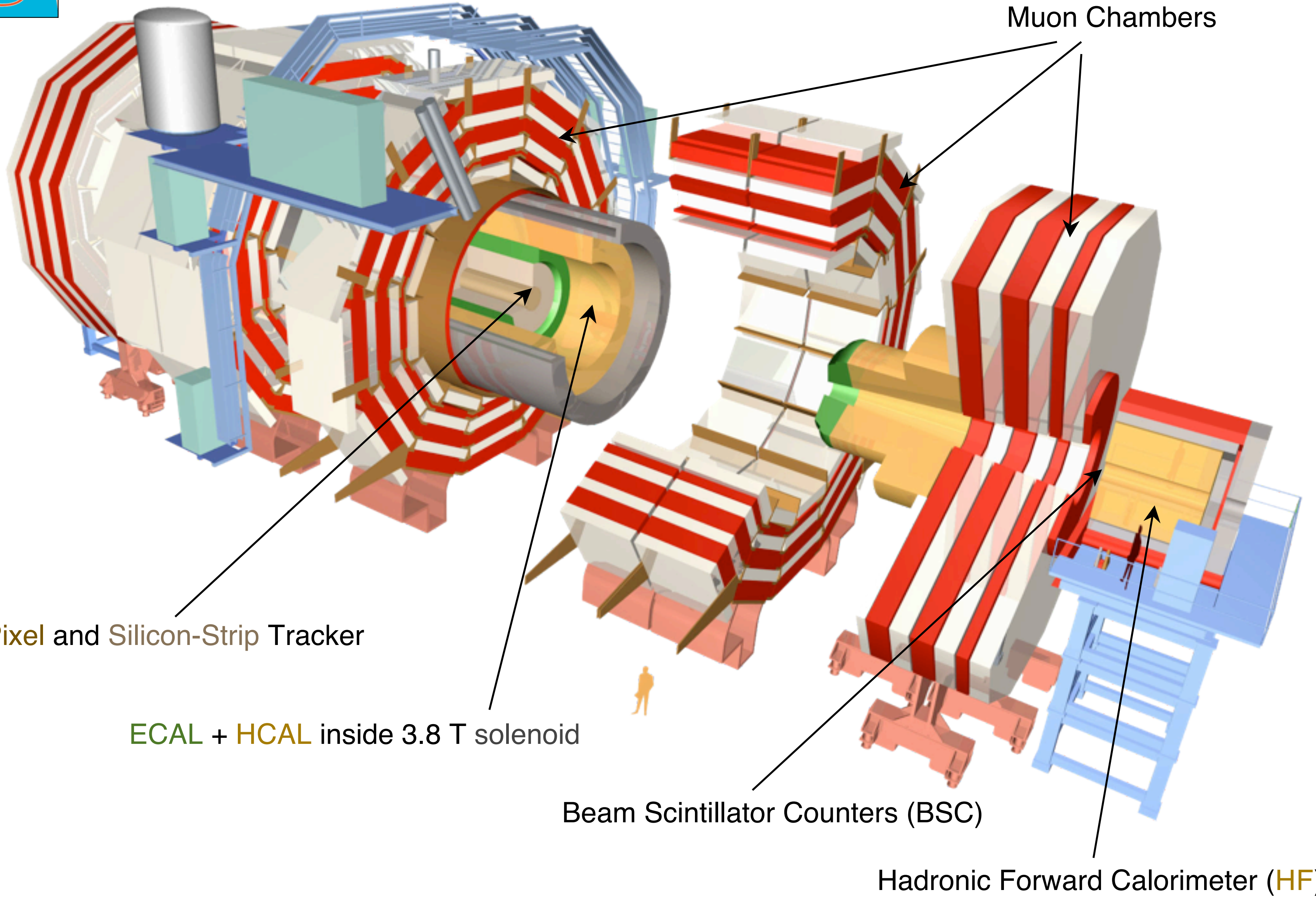
For the CMS Collaboration

LHC Physics Center at CERN

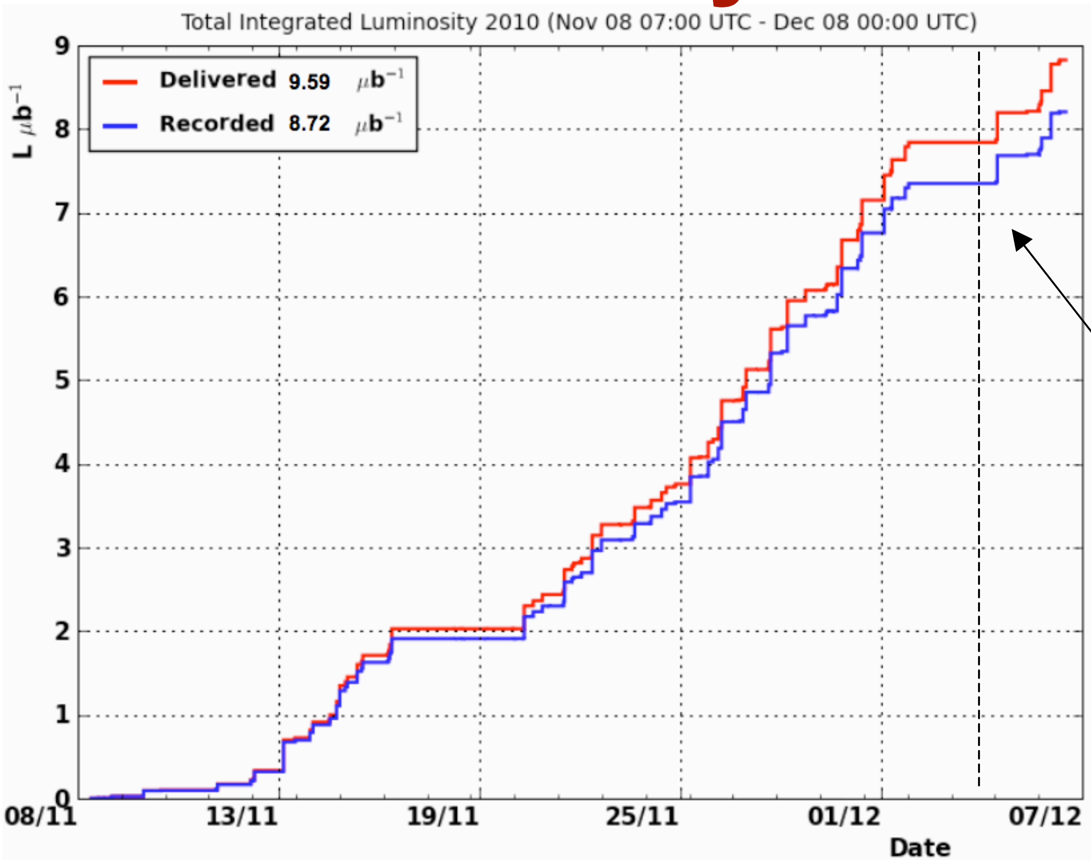
HI at the LHC: a first assessment

4th March, 2011

CMS Detector



LHC: 2010 Heavy Ion Run



Data taking without magnetic field

- 2010 has been a successful year at LHC
  - **After delivering over 40 pb^{-1} of p+p data, LHC delivered over 9 μb^{-1} of Pb+Pb**
    - **~7 μb^{-1} used in hard probes analysis**
    - **For rare processes, this is 'equivalent' to ~300 nb^{-1} of p+p**

Trigger Selection

DiMuon Trigger

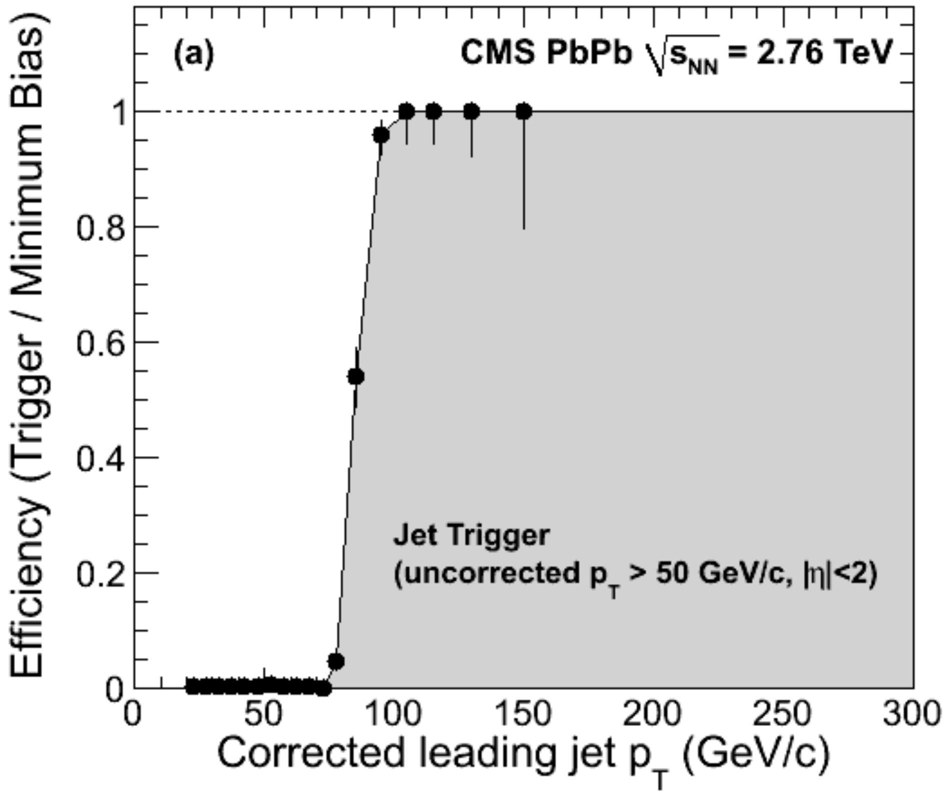
- Level-1: 2 hits in the Muon chambers
- HLT: 2 reconstructed tracks in the muon chambers with p_T > 3GeV/c
- ~94% efficient for Z->$\mu\mu$

Jet Trigger

- Level-1: Single Jet 30 GeV (uncorrected energy)
- HLT: Single Jet 50 GeV (bkgd subtracted uncorr. energy)
- Fully efficient for corrected energy above 100 GeV

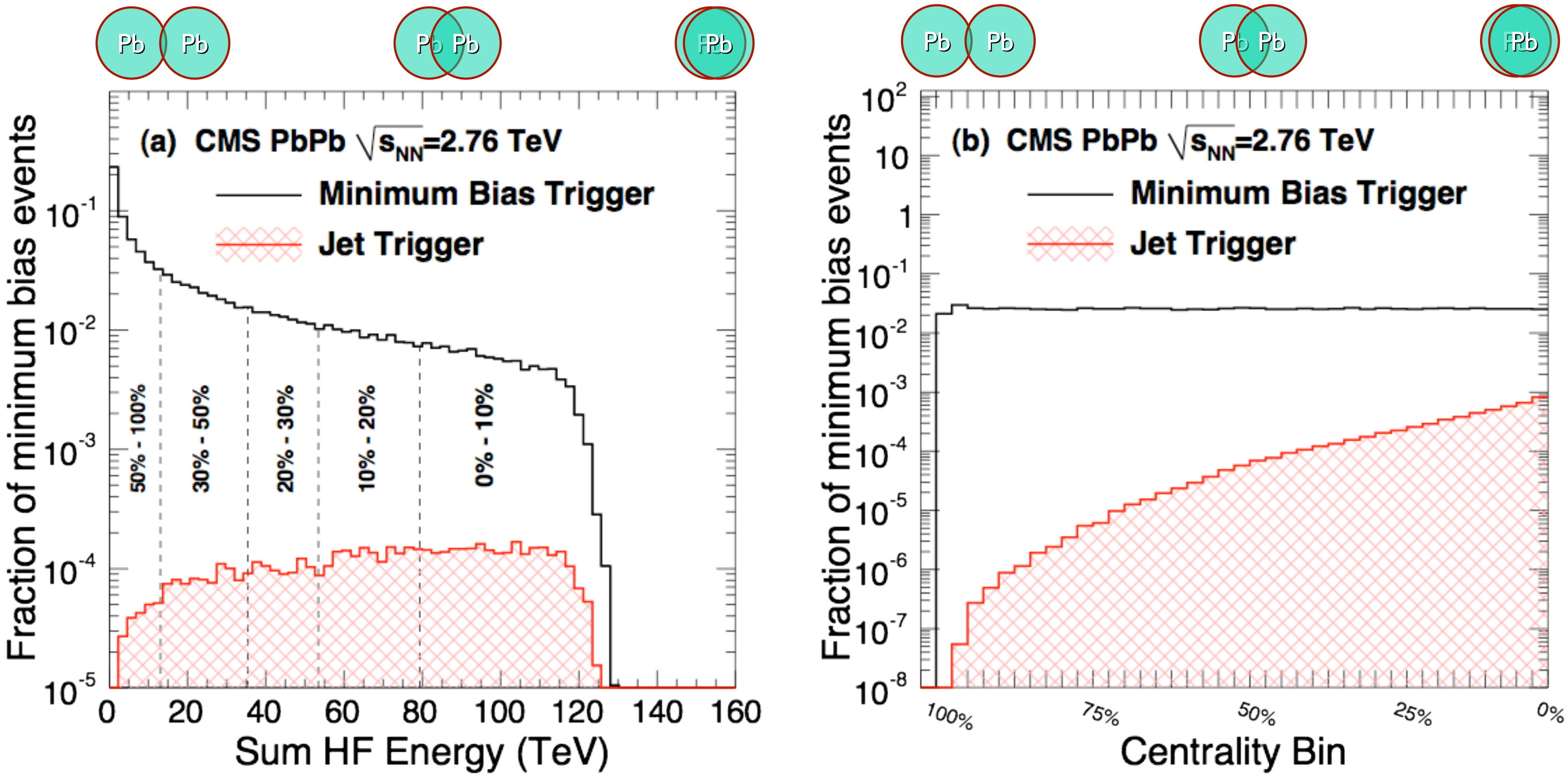
Minimum Bias Trigger

- HF or BSC firing in coincidence on both sides
- 97+/-3% efficient



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

Centrality Determination



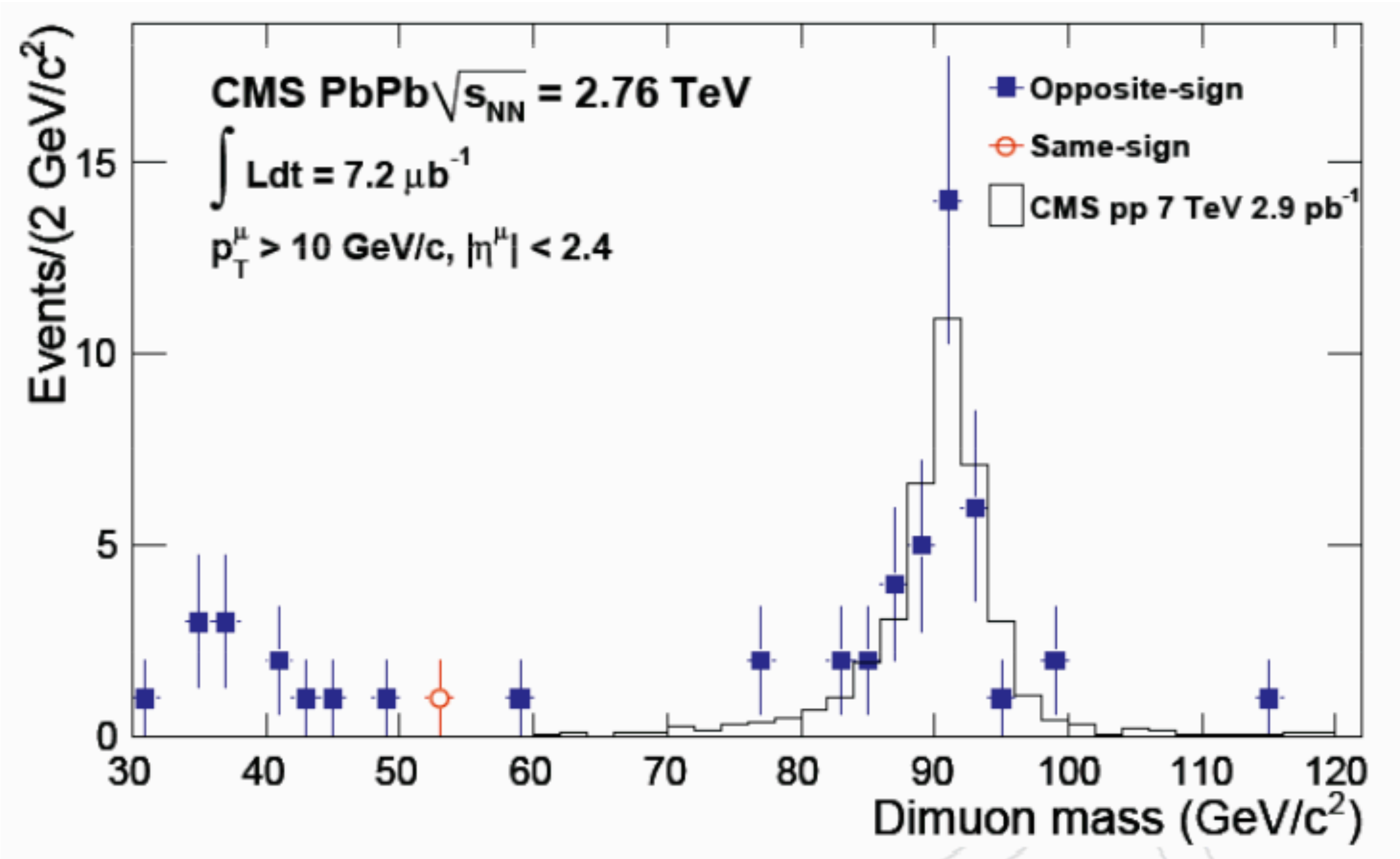
Events are classified according to the percentile of the Pb+Pb inelastic cross section based on total deposited HF energy

Probing the initial state

- The production rates for hard probes strongly depend in the initial state of the collision
  - **Choice of PDF**
  - **Nuclear shadowing**
  - **Saturation effects**
  - **Does collision scaling hold?**
- Start this program with a measurement of the Z^0 boson
  - **Clear experimental signature**
  - **Low Background**
  - **Does not interact with the medium**

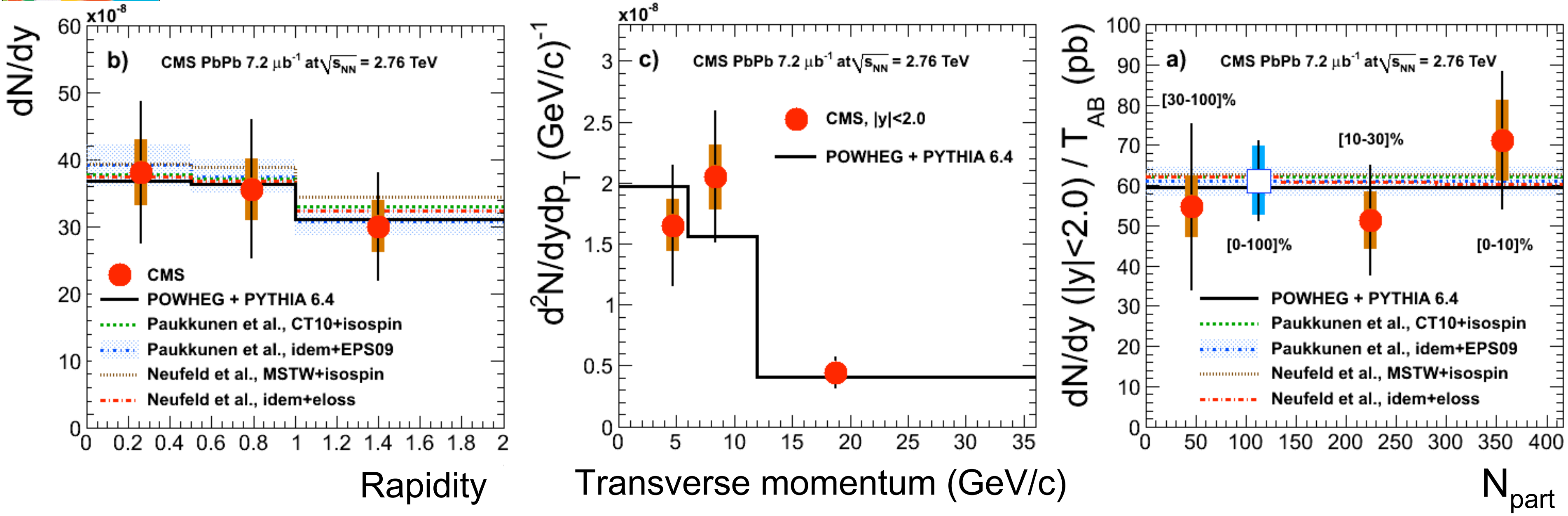
Submitted for publication: http://arxiv.org/abs/1102.5435

DiMuon Mass Spectrum



- 39 reconstructed Z^0's
  - **1 same-sign event in the Z^0 mass range [30,120] GeV/c^2**
- Dimuon Mass resolution comparable to p+p

Differential Z^0 distributions



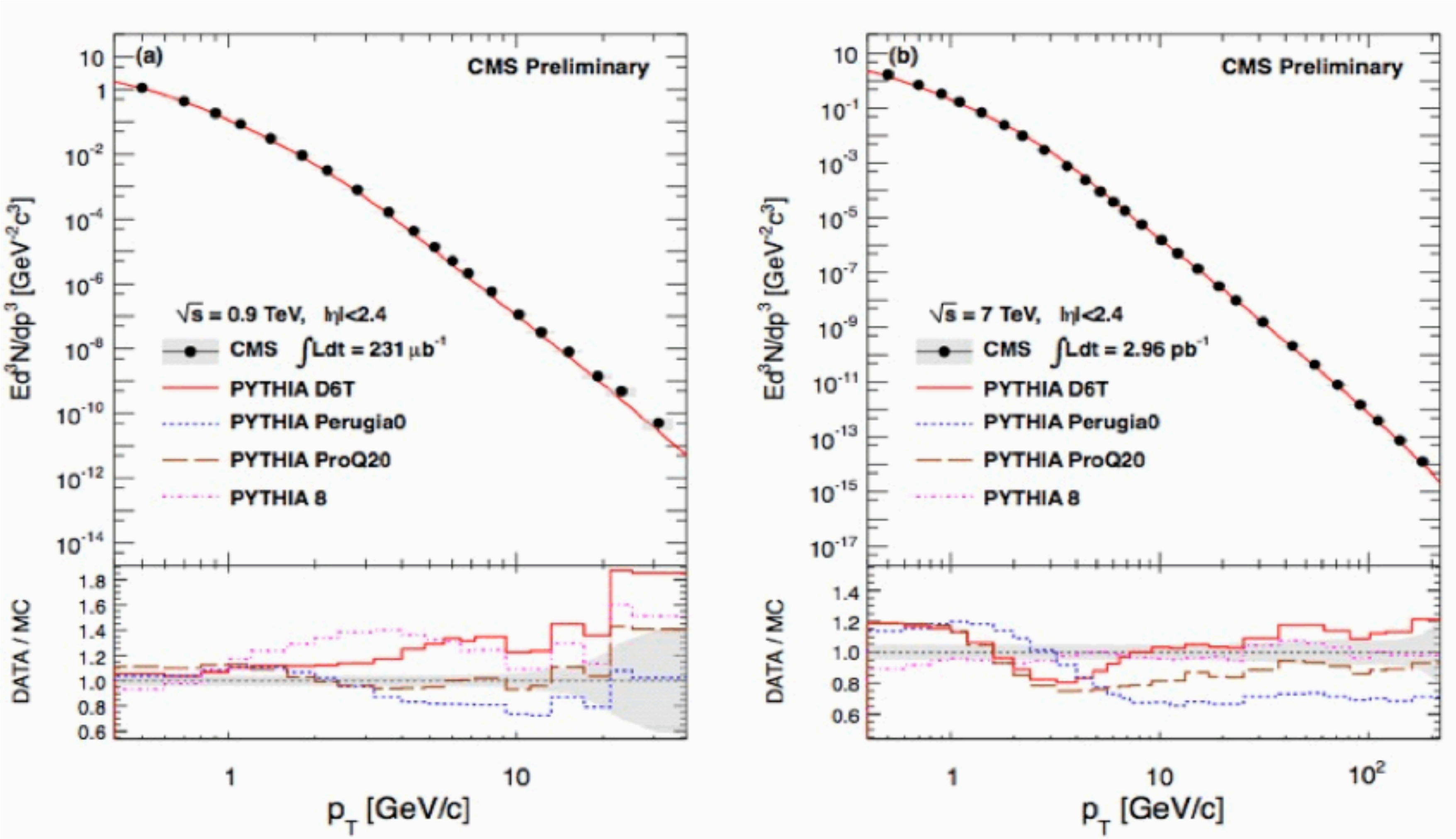
- Conclusion
  - **Kinematic distributions are consistent with pQCD calculations**
  - **Within uncertainties, no violation of binary-collision scaling is observed**

Probing the Medium

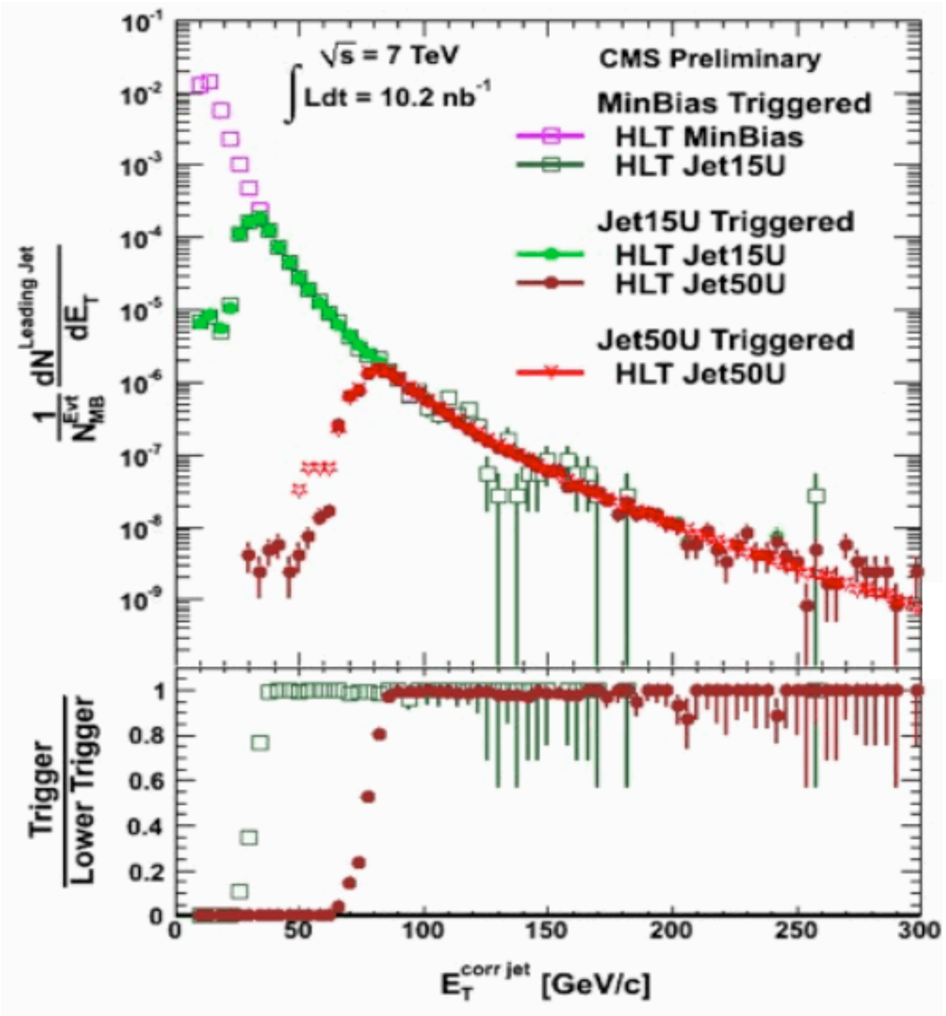
Menu du Jour:

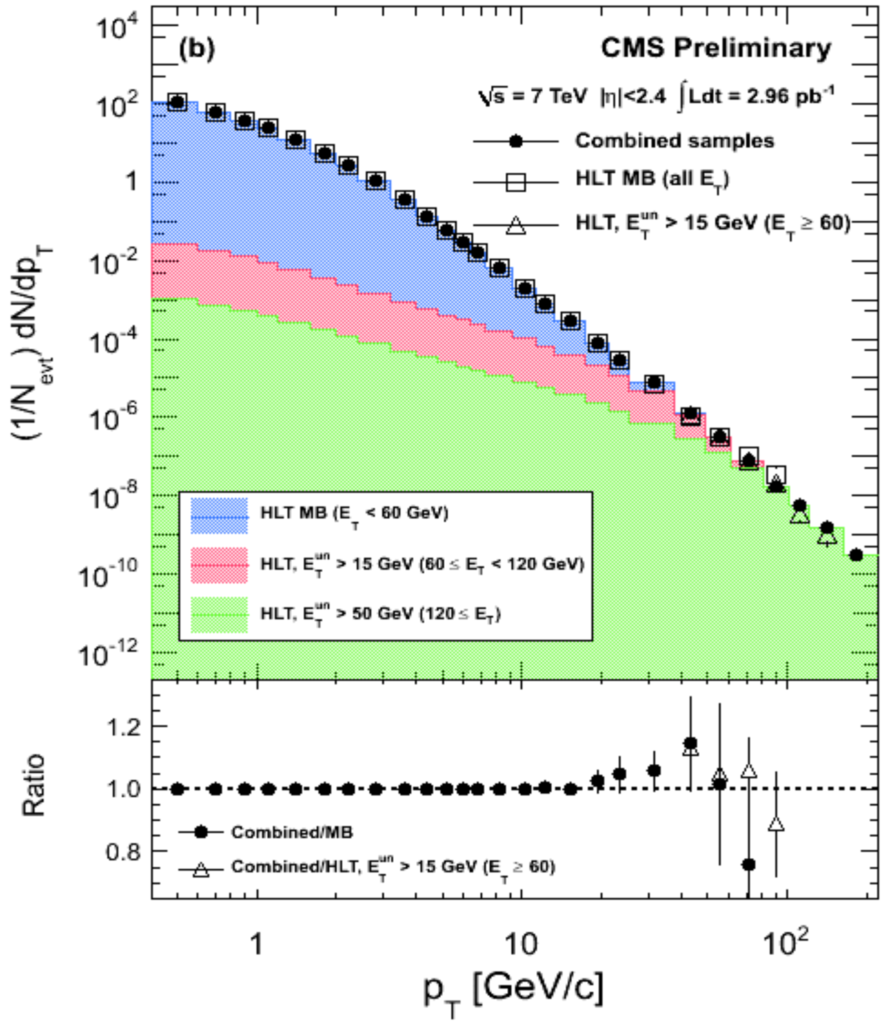
- Reference measurements from pp
  - **Charged hadron spectra as a reference for R_{AA}**
- Two particle correlations
  - **Ridge physics**
- Jet quenching
  - **Probe the medium with fully reconstructed dijets**

Charged particle spectra in pp at 900GeV and 7TeV



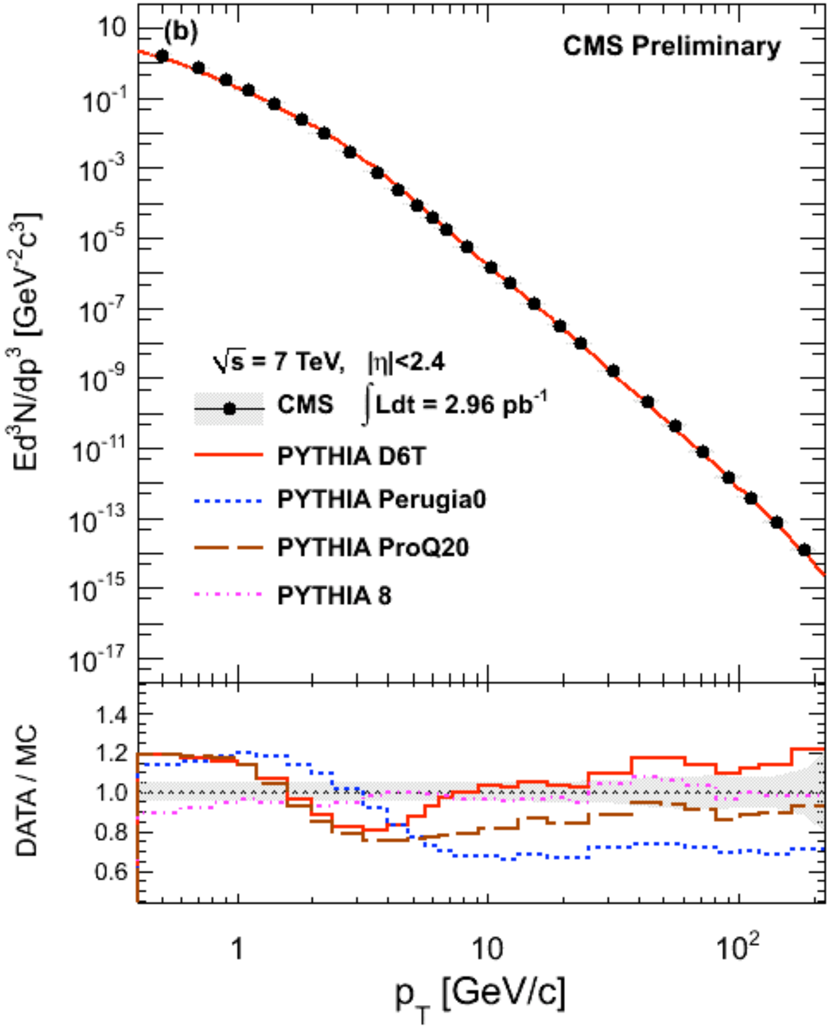
Charged particle spectra in pp

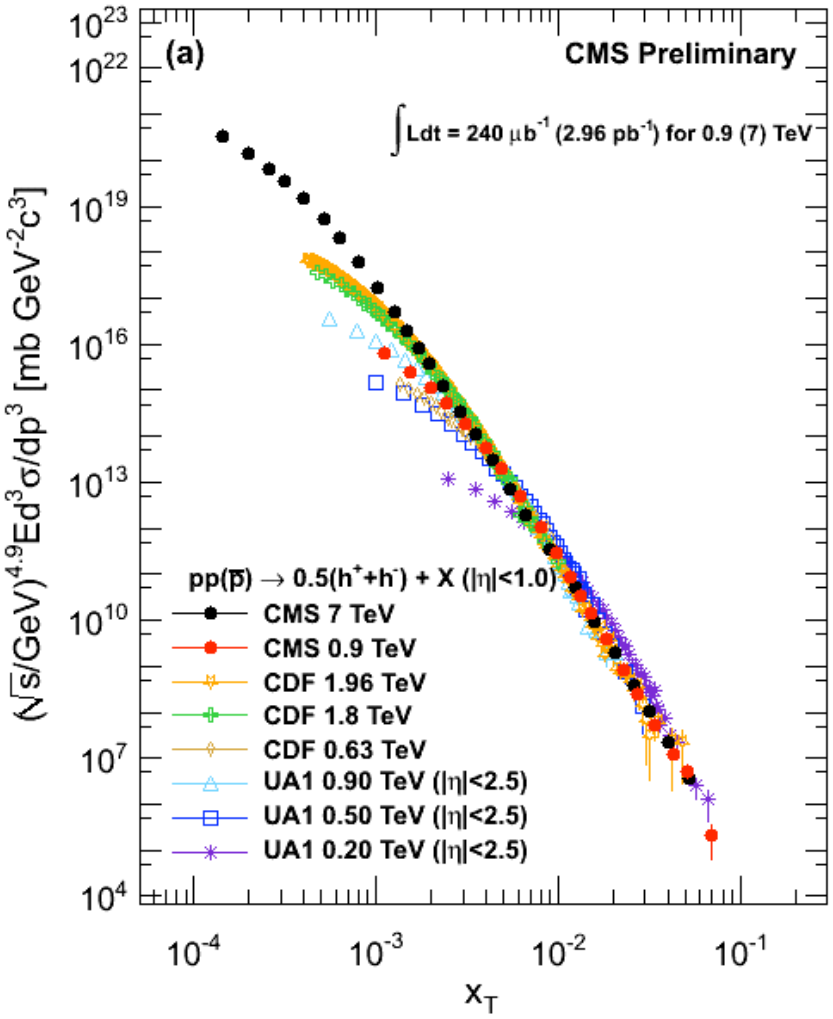




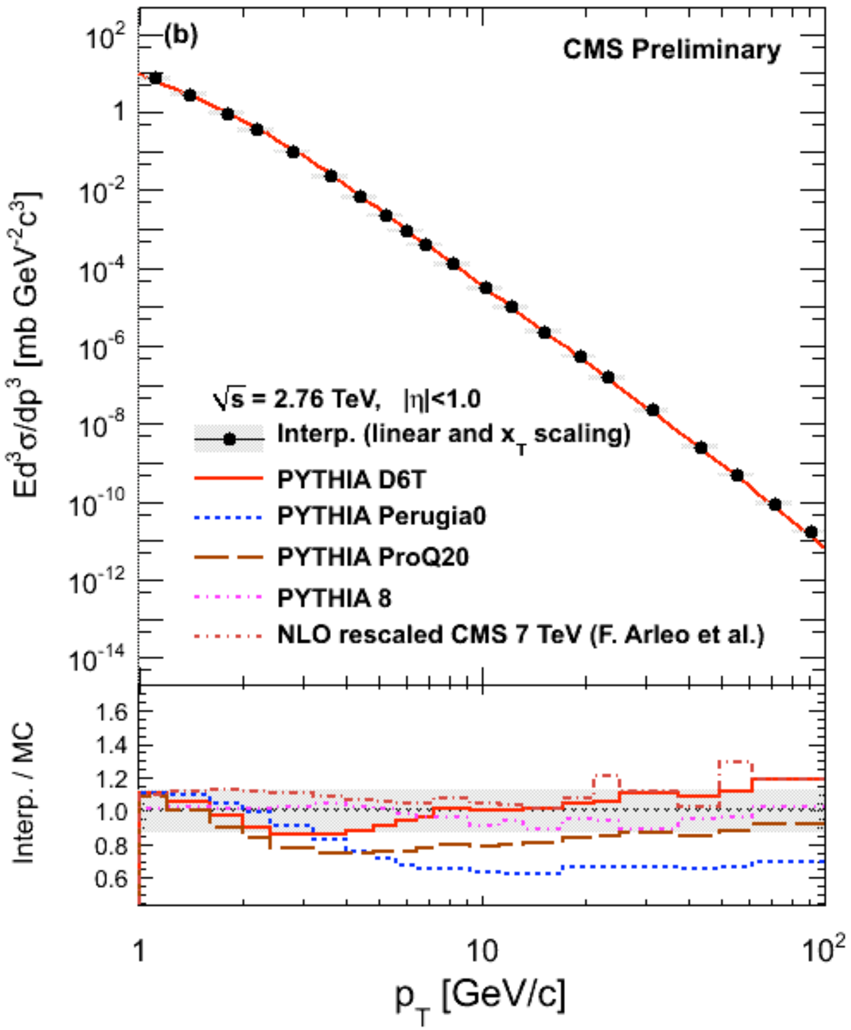
Jet triggered data sets are merged together to exploit the full recorded luminosity

Invariant Yield and x_T-Scaling





2.76 TeV pp Interpolation



Interpolation based on:

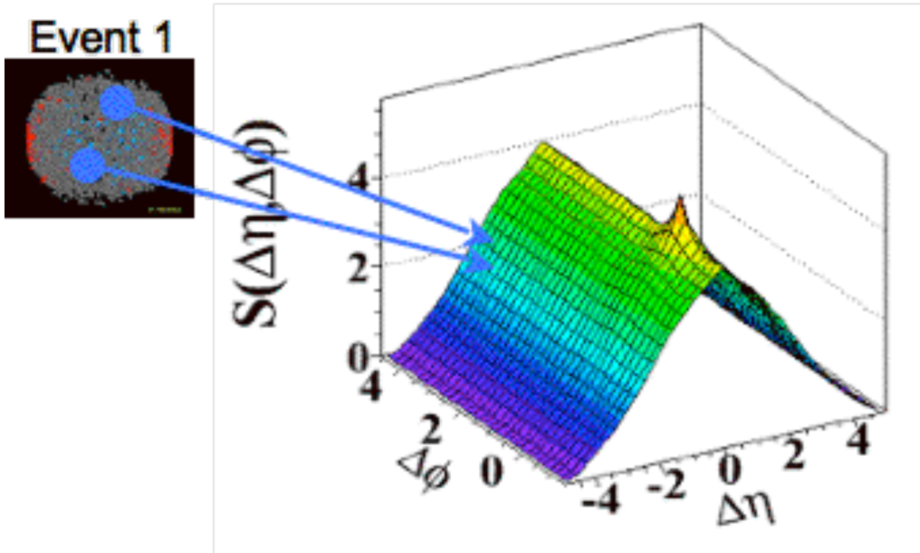
- p_T interpolation below 5 GeV/c
- linear combination of interpolation methods between 5-20 GeV/c
- x_T-scaling with NLO-based residual correction above 20 GeV/c

Total uncertainty:

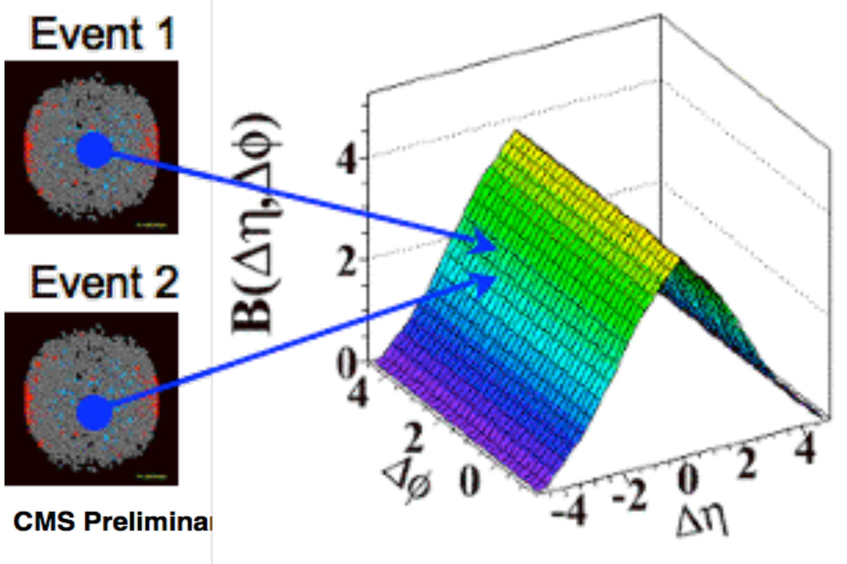
- 7% (interp.) + 11% (lumi) = 13%

Two-Particle Correlations

Pairs from the same event

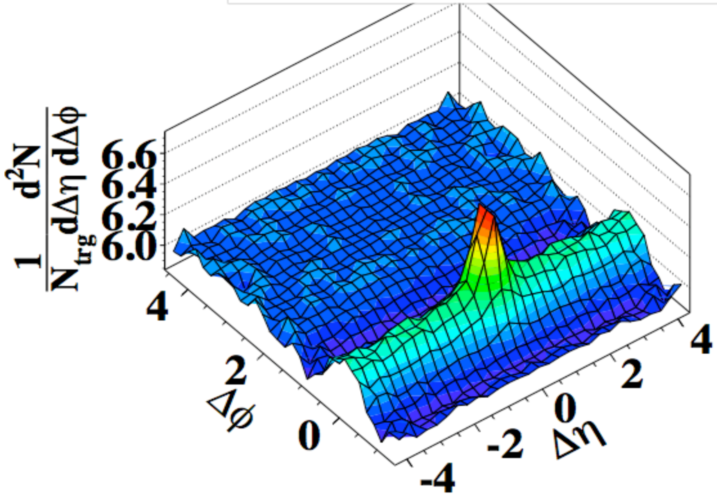


Pairs from mixed events



Associated yield per trigger:

$$\frac{1}{N_{trg}}\frac{d^2N}{d\Delta\eta d\Delta\phi} = B(0,0)\times\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

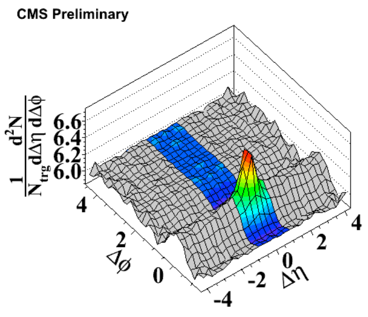


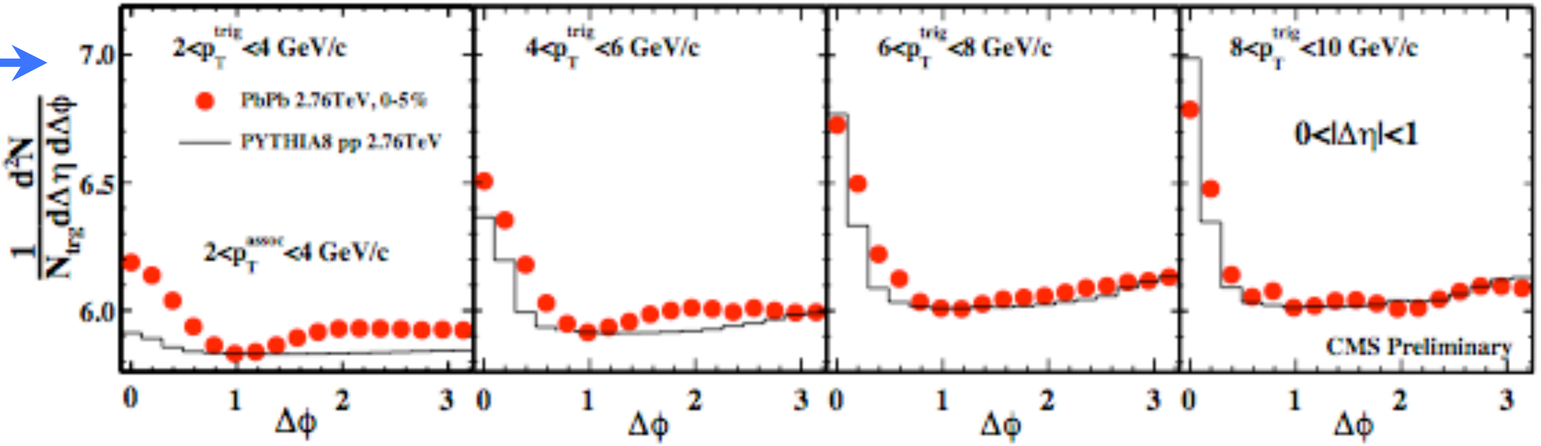
PbPb 2.76TeV, 0-5%

p_T^{trig} : 4 - 6 GeV/c, p_T^{assoc} : 2 - 4 GeV/c

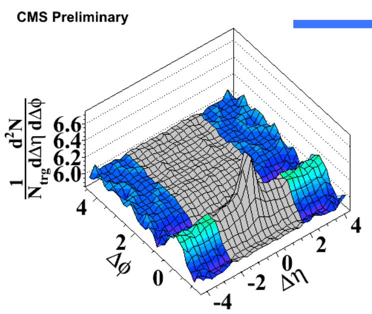
Two-Particle Correlations

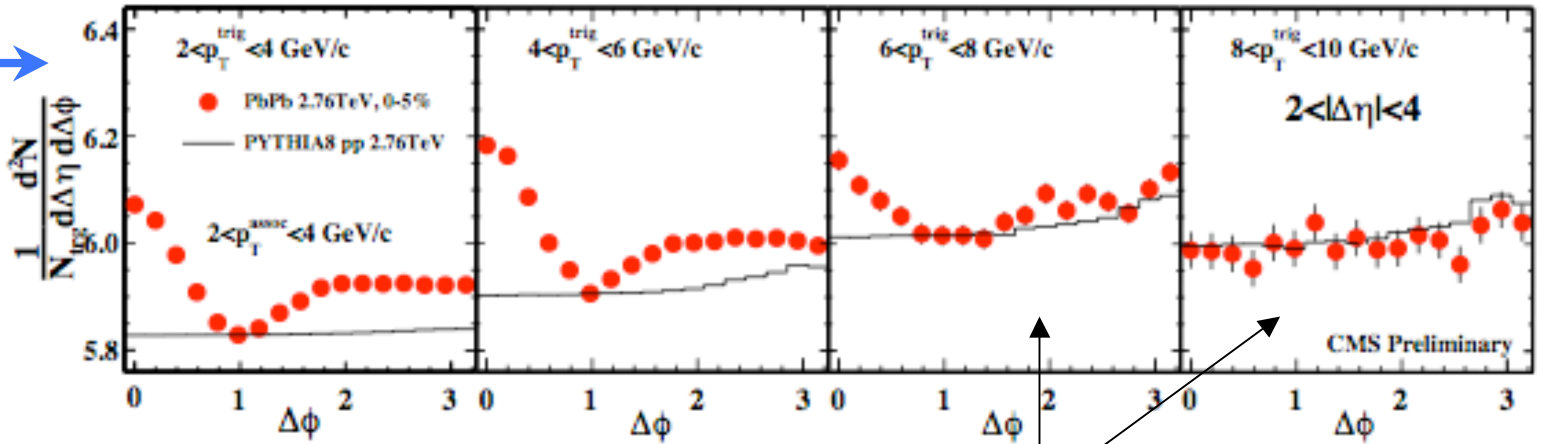
Short-range (0<|Δη|<1): **Jet + Ridge**





Long-range (2<|Δη|<4): **Ridge**



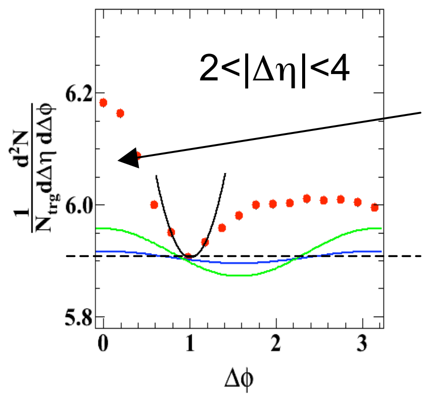


Ridge disappears at high p_T

Near-side Associated Yield

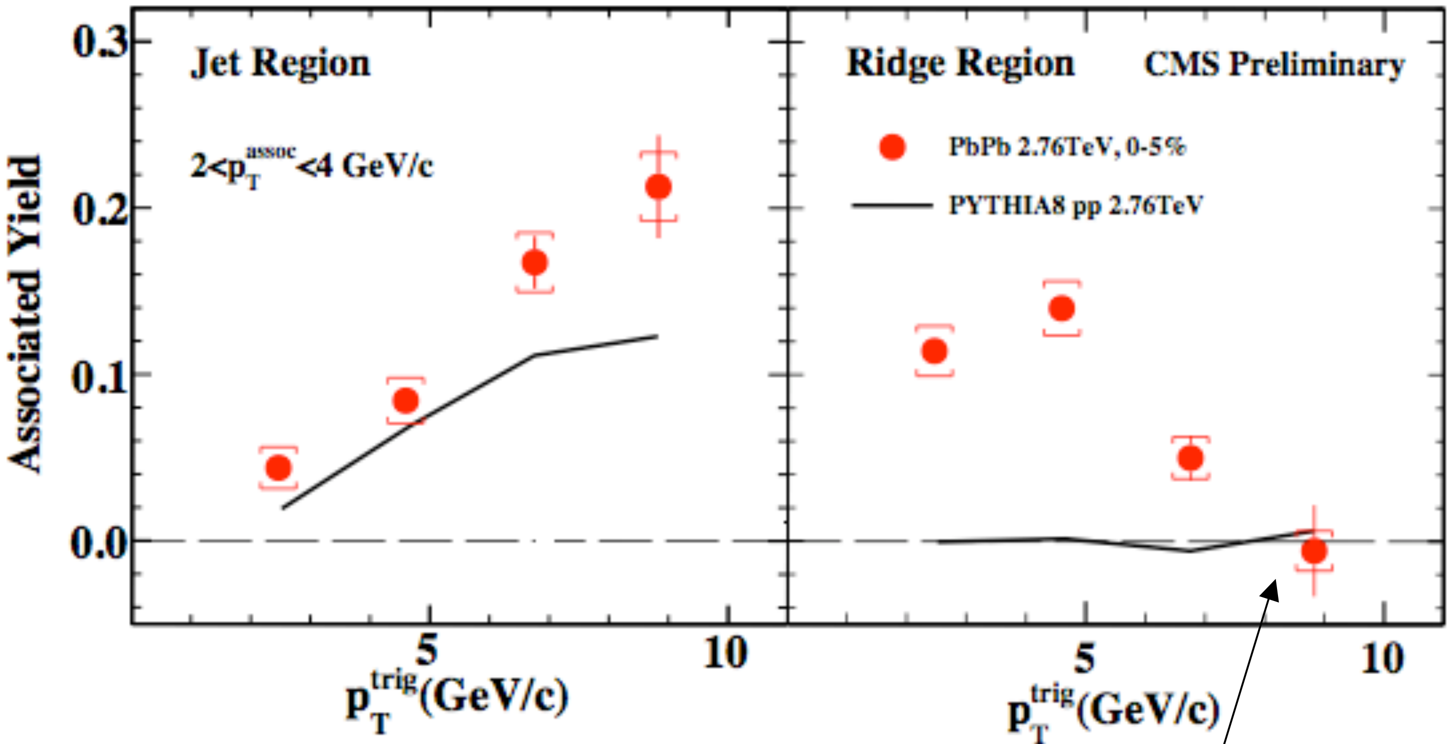
Near-side Associated Yield (Y) vs trigger p_T

Jet: Y(|Δη|<1)-Y(2<|Δη|<4)   Ridge: Y(2<|Δη|<4)



– v_2=3%
– v_2=5%

Elliptic flow not subtracted



Ridge disappears at high p_T

Ridge Fourier Decomposition

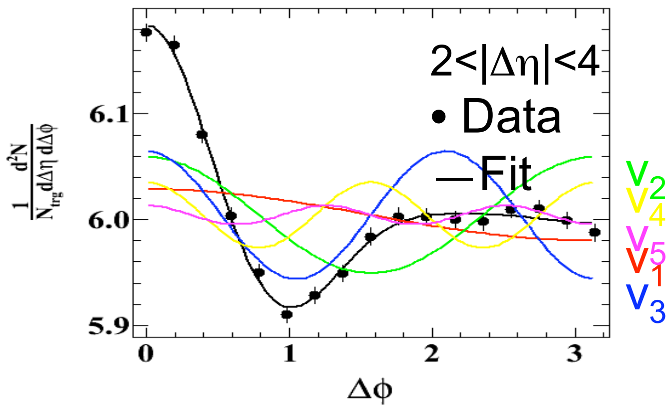
Describing the ridge using higher order Fourier terms (v_n)

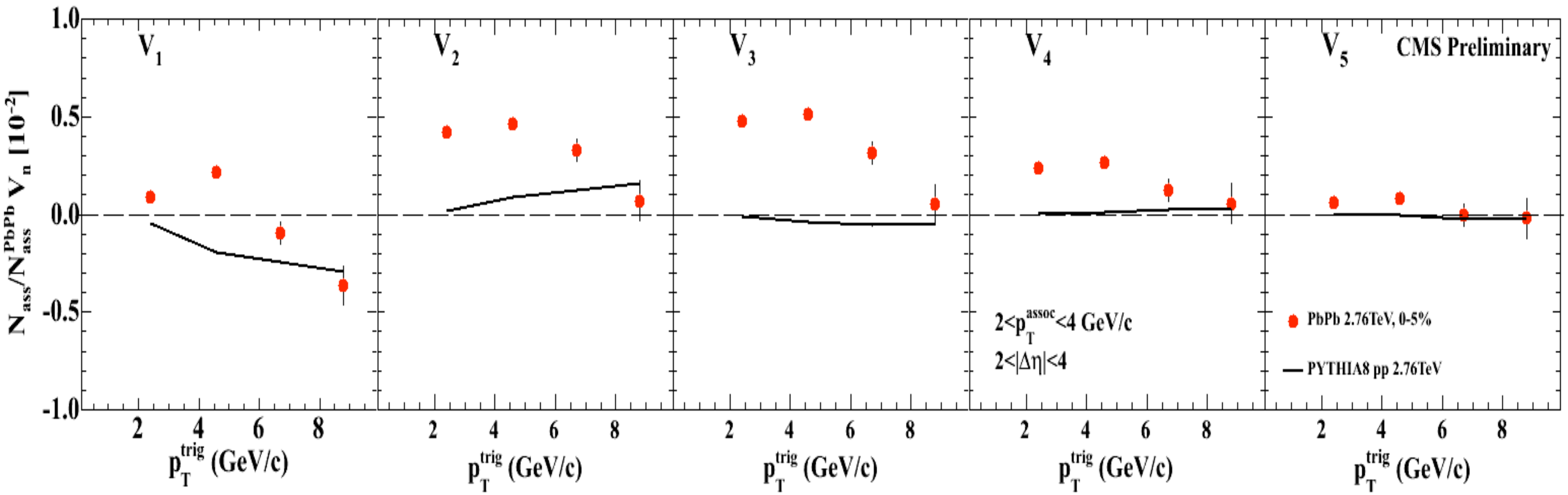
1D Δφ projected distribution fitted by Fourier series:

$$\frac{1}{N_{trig}}\frac{d^2N}{d\Delta\eta} = \frac{N_{assoc}}{2\pi}\left(1 + 2\sum_{n=1} V_n \cos(n\Delta\phi)\right)$$

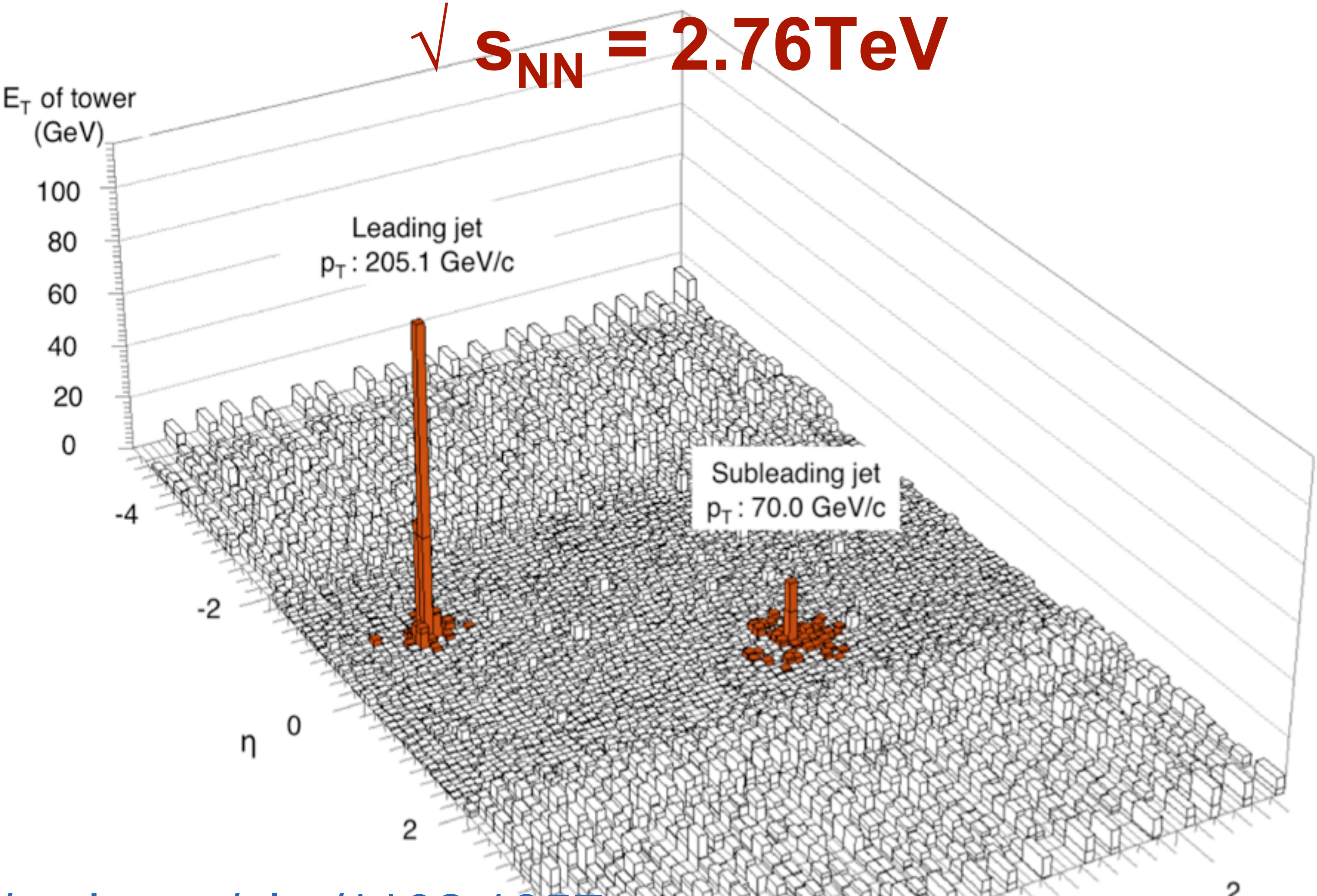
$V_n = v_n^{trig} v_n^{assoc}$ for pure hydro

Example fit with first 5 terms:



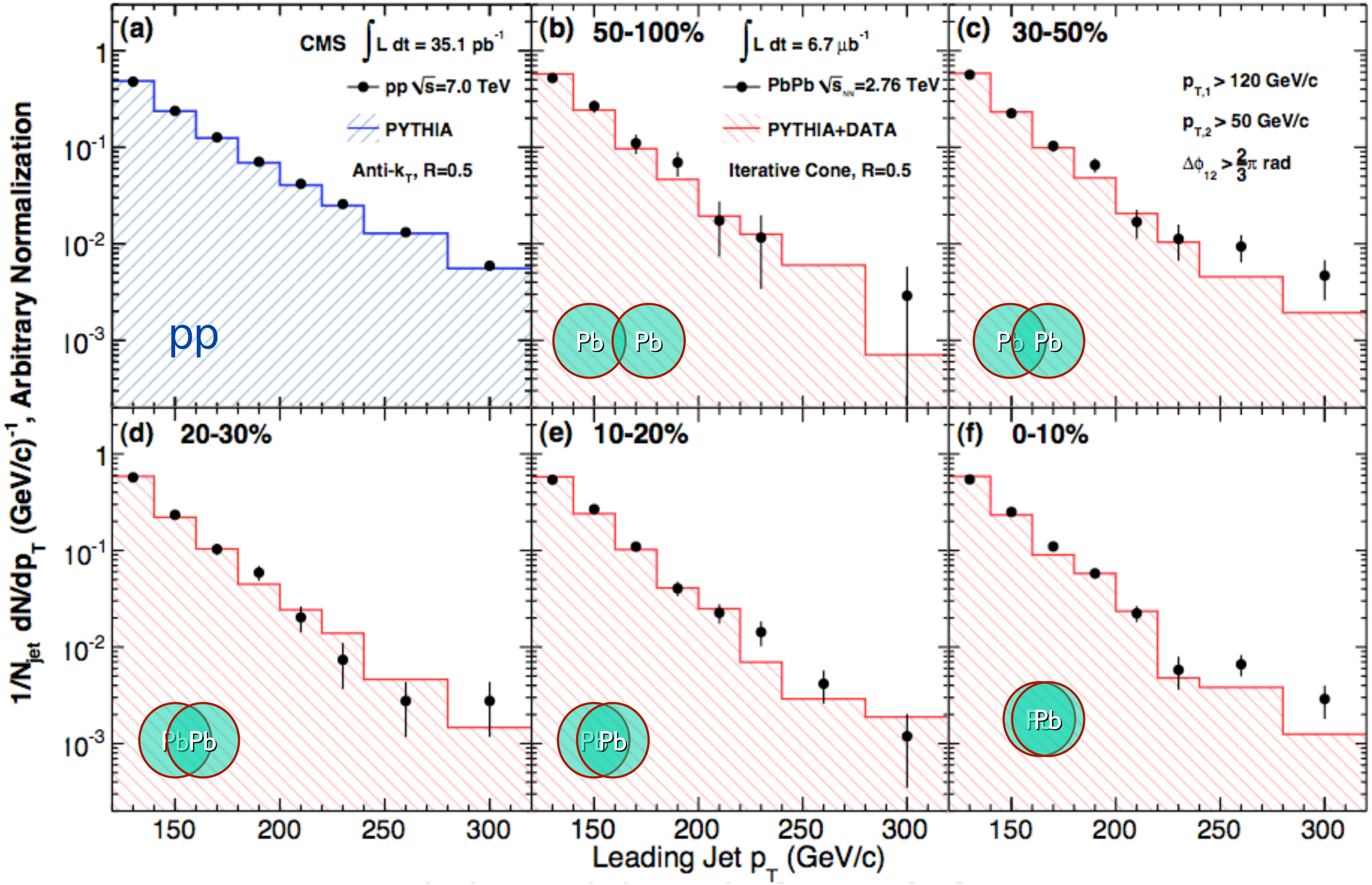


Observation and studies of jet quenching in PbPb collisions at $\sqrt{s_{NN}} = 2.76\text{TeV}$



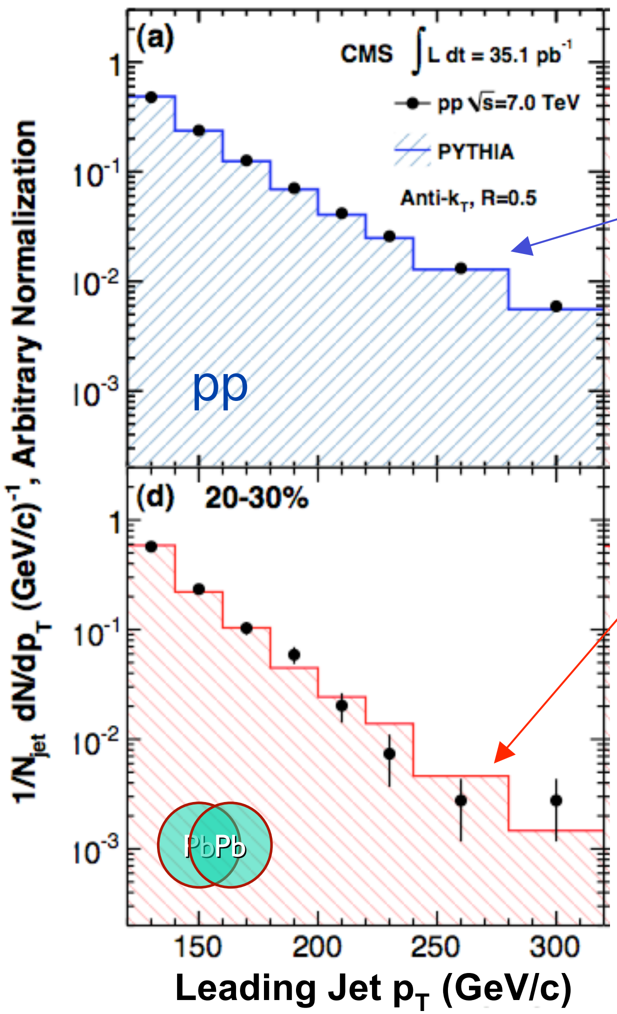
http://arxiv.org/abs/1102.1957

Leading Jet Spectra



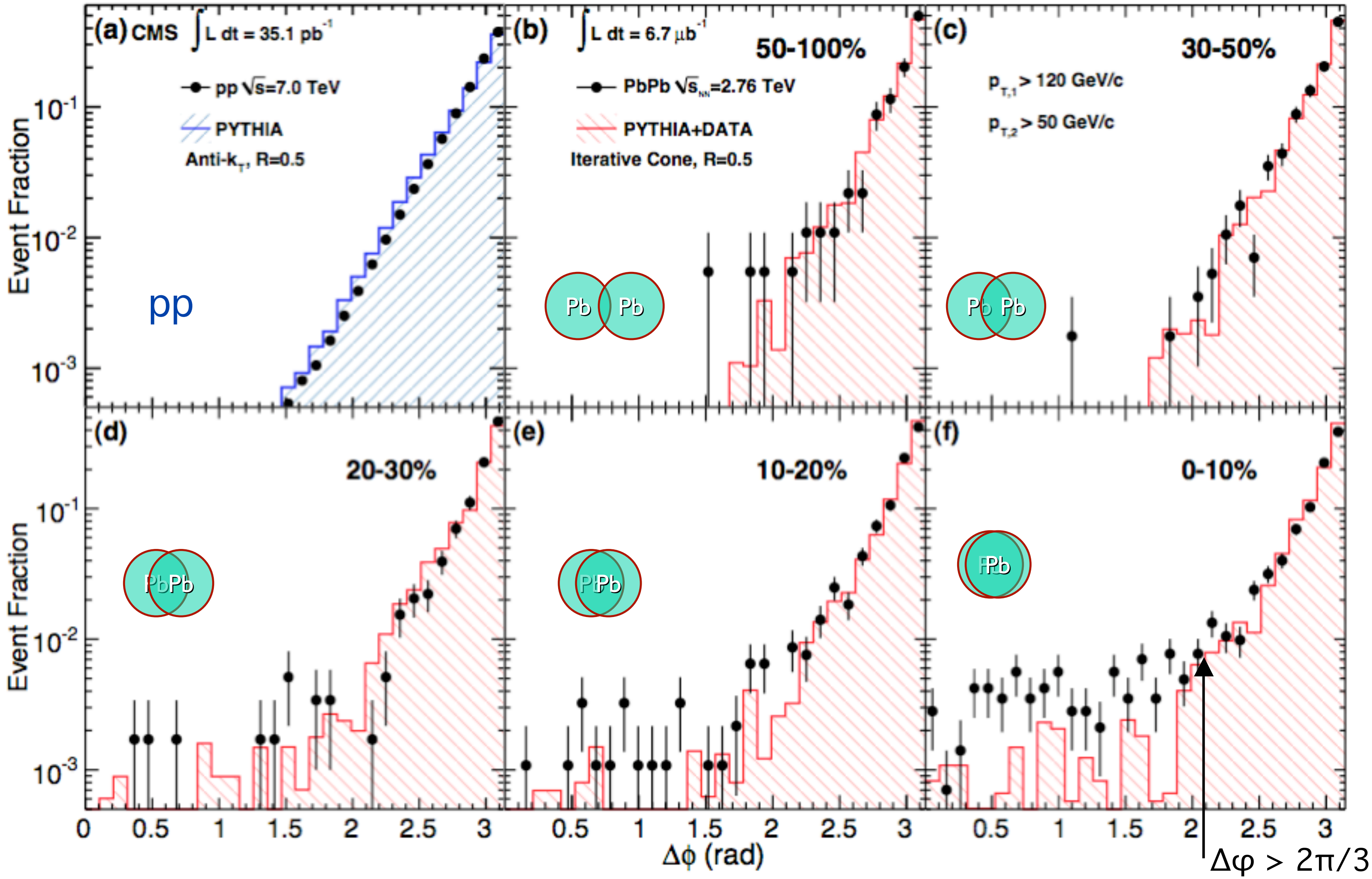
Shape of leading jet p_T spectrum not strongly modified compared to PYTHIA (spectra not corrected or deconvoluted)

Reference Distributions



- PYTHIA:
  - **D6T tune**
- PYTHIA + DATA:
  - **PYTHIA dijet events embedded into real data background**
  - **modified isospin ($^{208}_{82}Pb$)**

Dijet Azimuthal Decorrelation



Dijet Asymmetry Variable

Dijet selection:
- $|\eta_{jet}| < 2$
- Leading jet $p_T > 120$GeV/c
- Subleading jet $p_T > 50$GeV/c
- $\Delta\varphi_{1,2} > 2\pi/3$

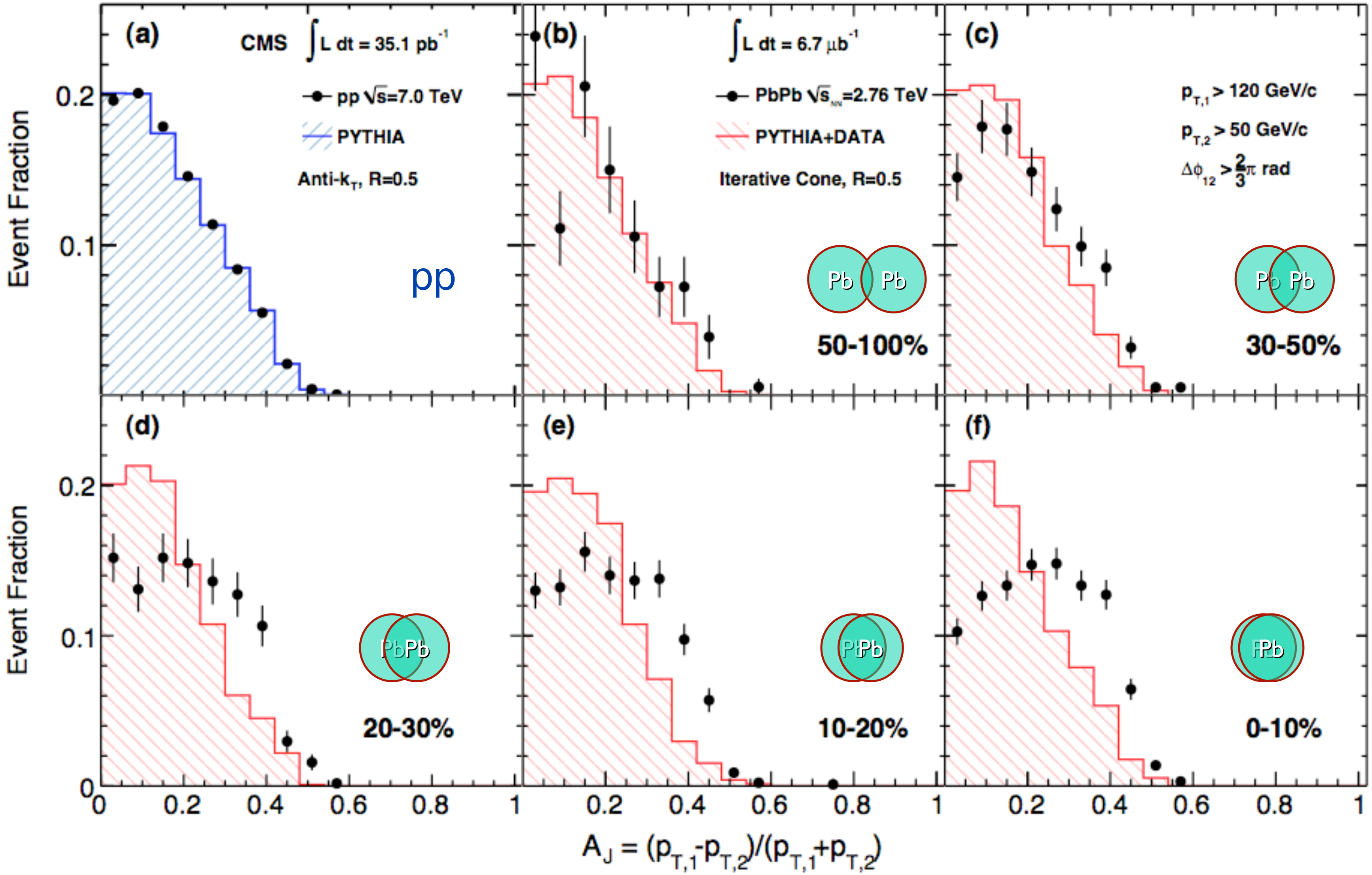
Quantify dijet energy imbalance by asymmetry ratio:

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

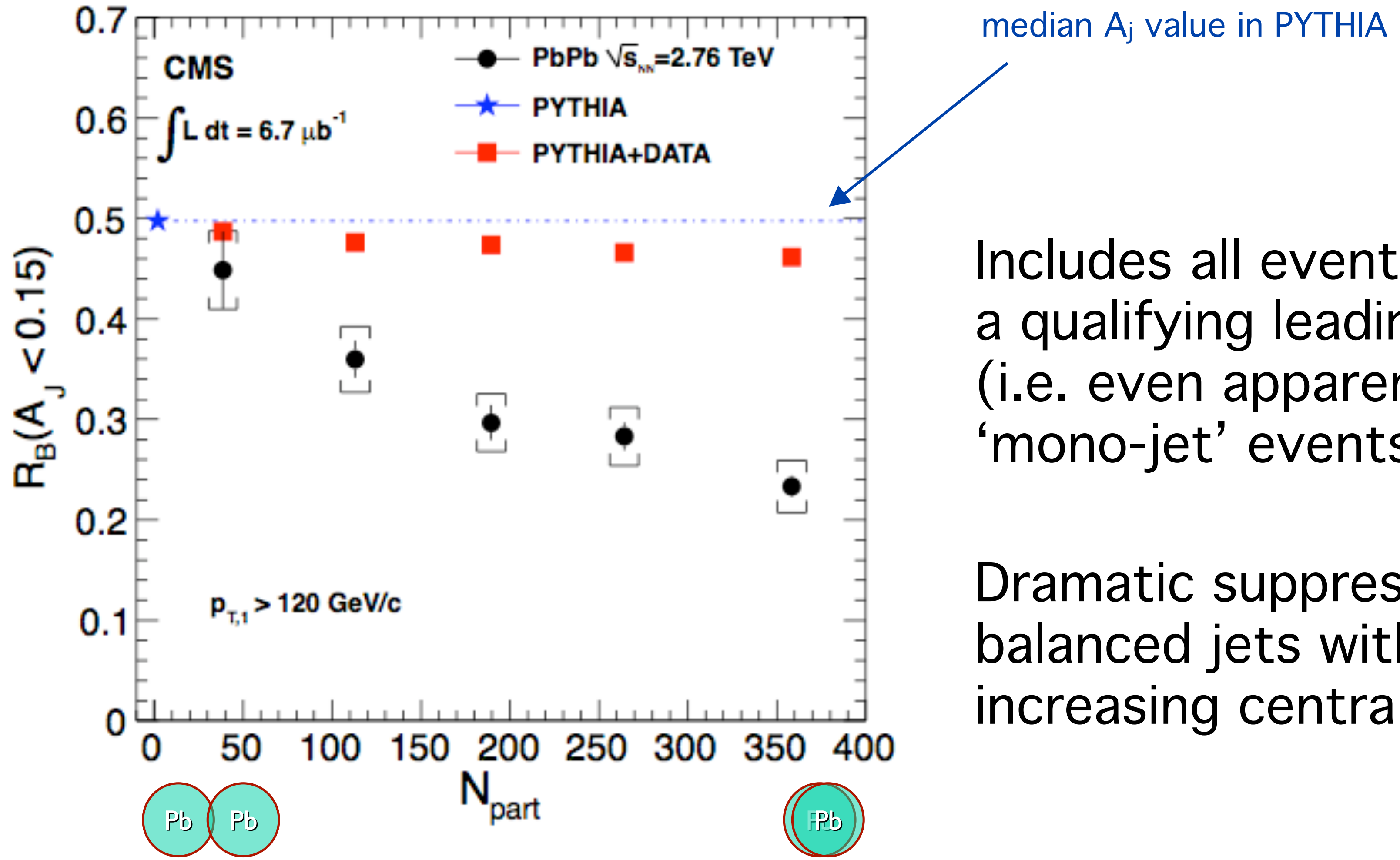
- Removes uncertainties in overall jet energy scale
- The lower limit on $p_{T,2}$ puts a p_T-dependent upper limit on A_j

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

Dijet Energy Imbalance



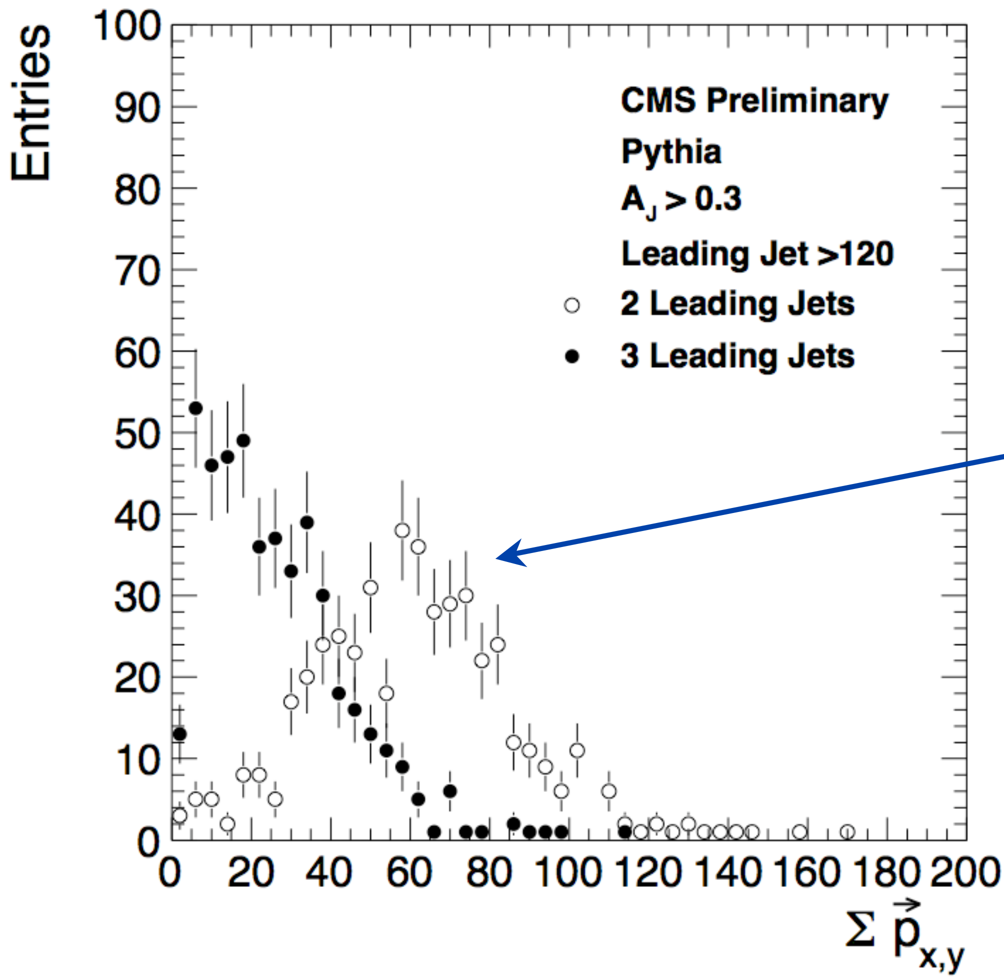
Dijet 'Balanced' Fraction

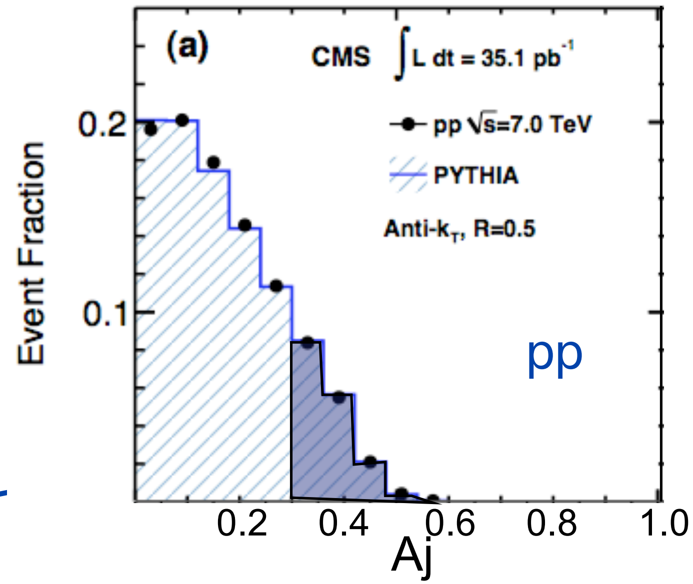


Includes all events with a qualifying leading jet (i.e. even apparent 'mono-jet' events)

Dramatic suppression of balanced jets with increasing centrality

PYTHIA Momentum Balance

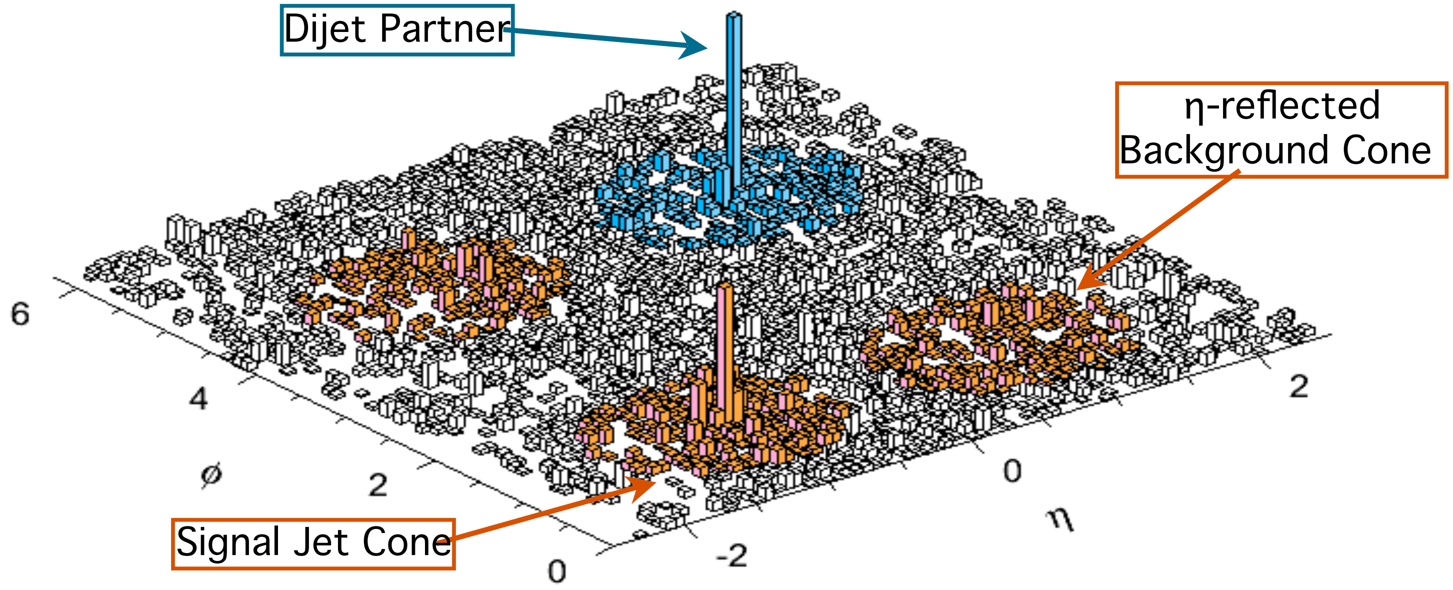




For unbalanced PYTHIA dijets ($A_j > 0.3$, 10% of the total), a 3rd jet provides most of momentum balance

Track-Jet Correlations

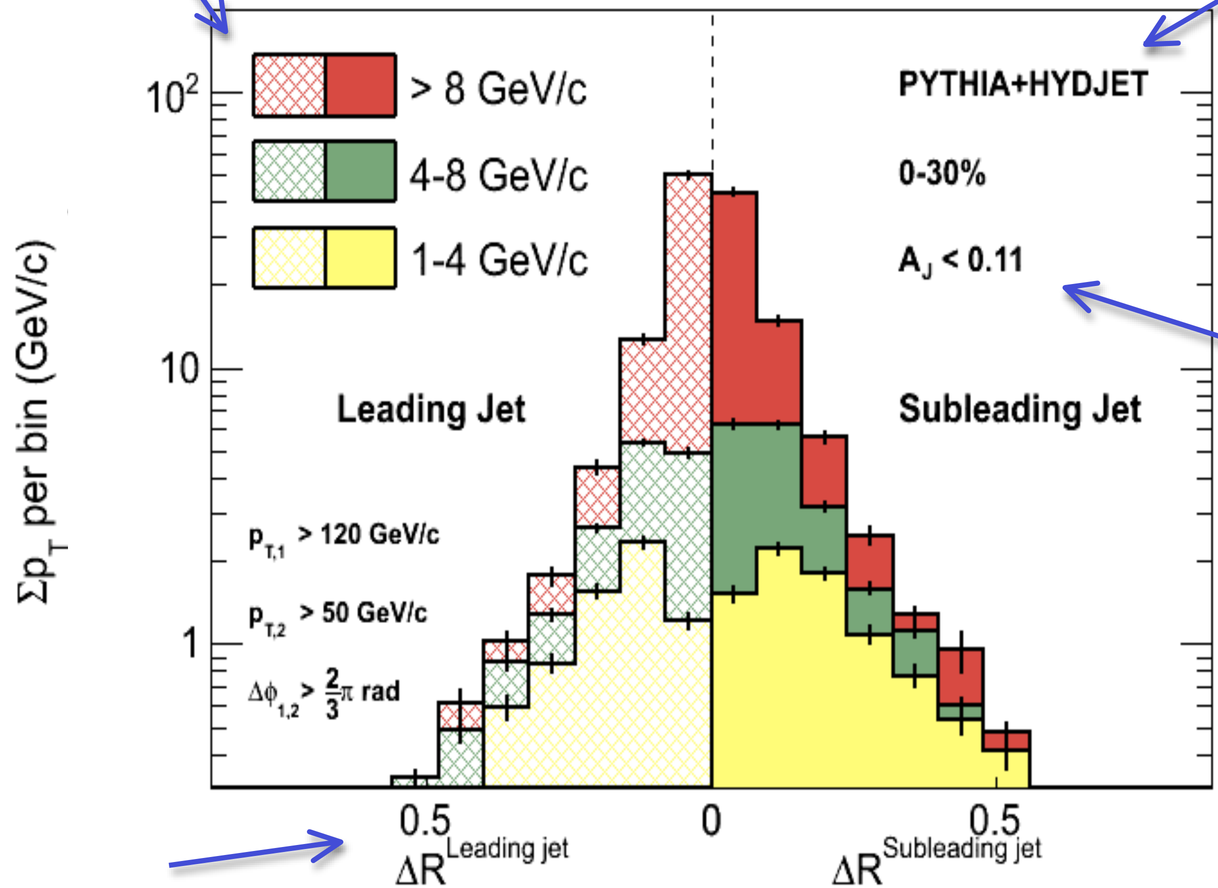
- Study charged particle distributions within jet cones
  - **Use η reflected (η -> -η) reference cones for jet-by-jet subtraction of Pb+Pb underlying event**
    - **This avoids φ dependent variations due to elliptic flow**
    - **Exclude $|\eta_{Jet}| < 0.8$ and $|\eta_{Jet}| > 1.6$**
  - **Study associated track distributions versus p_T and ΔR**
  - **Uncertainties in background subtraction limit this method to $p_T > 1$ GeV/c and ΔR < 0.8**



Track-Jet Correlations

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

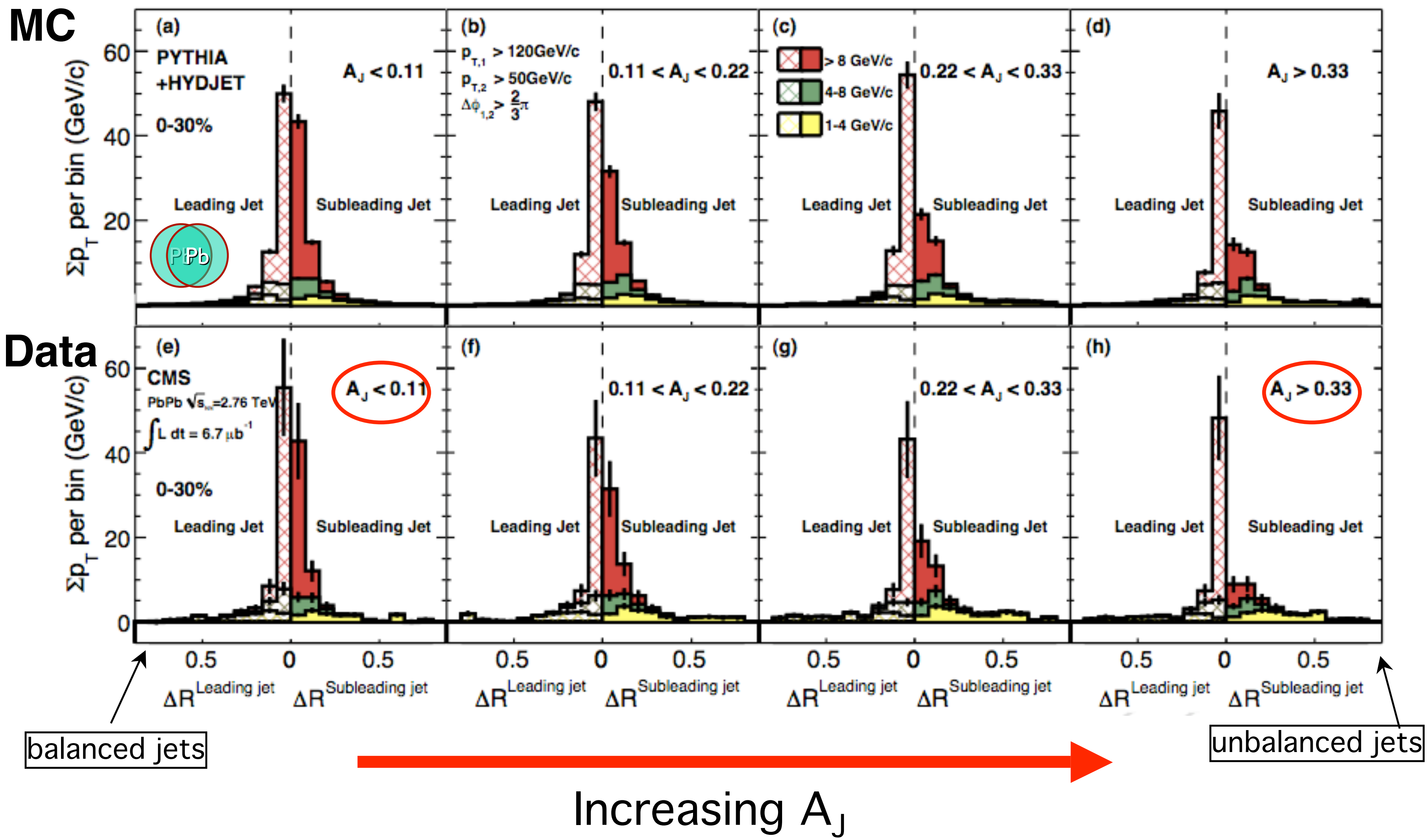
Baseline is PYTHIA+HYDJET where generator information is available for charged particles



Selected A_j range

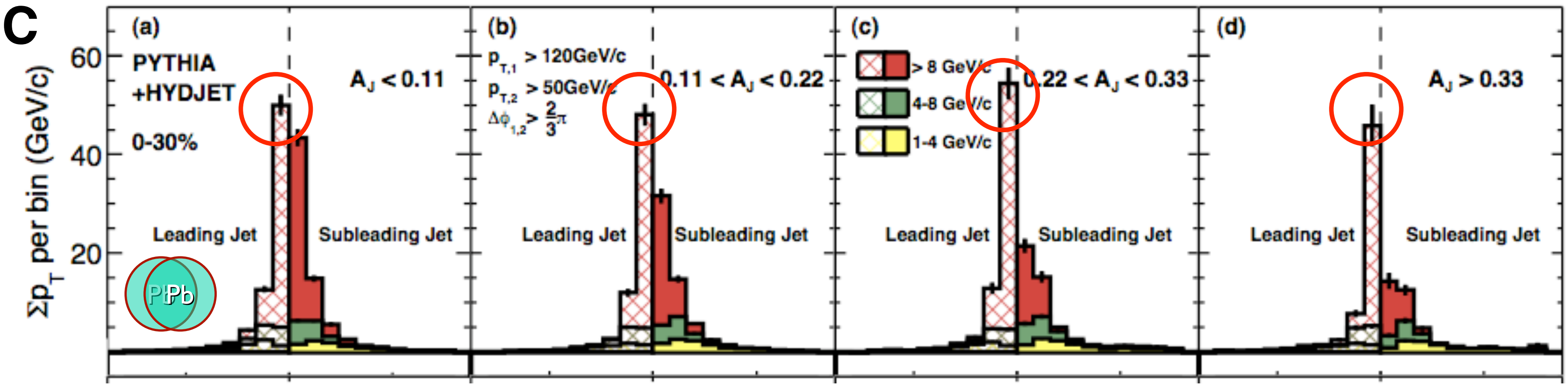
Plot against ΔR from the jet axis for both the leading and subleading jet

Track-Jet Correlations



Track-Jet Correlations

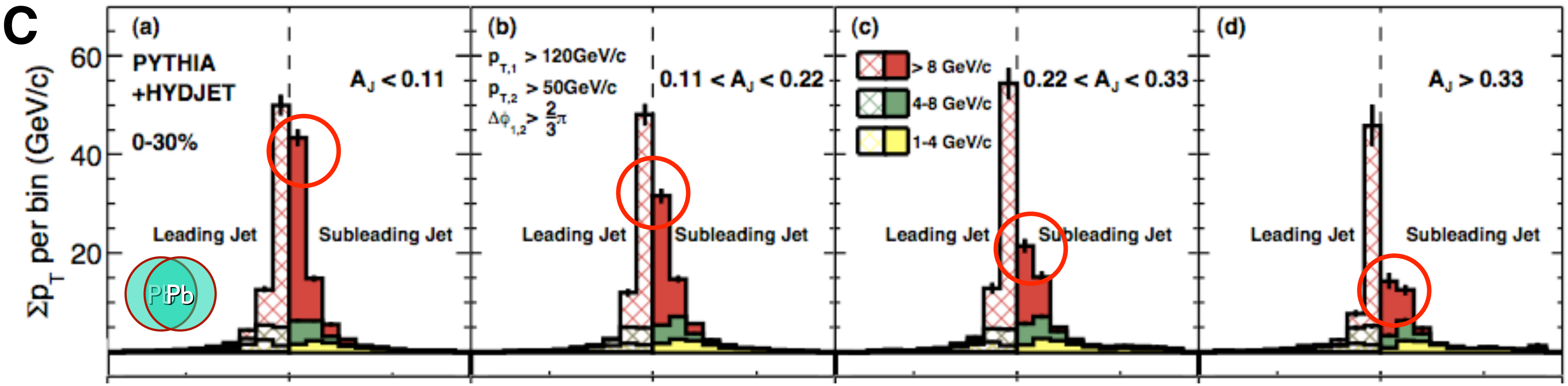
MC



- PYTHIA+HYDJET:
  - **The leading jets show a fragmentation pattern of hard partons, i.e. large energy sum for high p_T particles**

Track-Jet Correlations

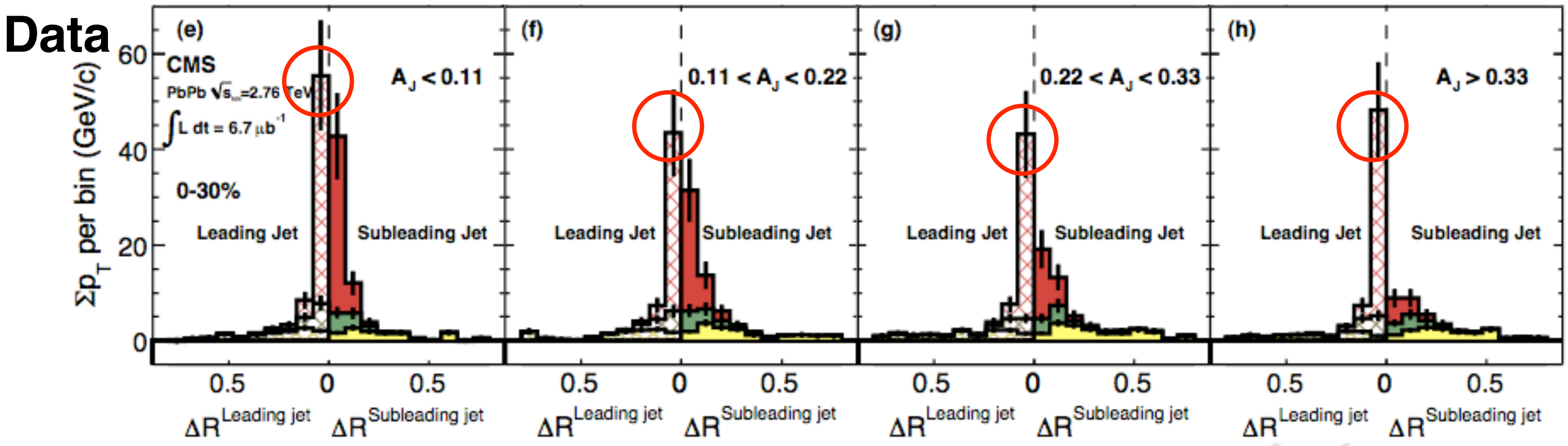
MC



- PYTHIA+HYDJET:
  - **The associated subleading jets show a softer fragmentation pattern with increasing A_j**
  - **The asymmetry in the calorimeter jet energies is reflected in the fragmentation pattern**
  - **The momentum balance in Pythia is carried by a third jet**

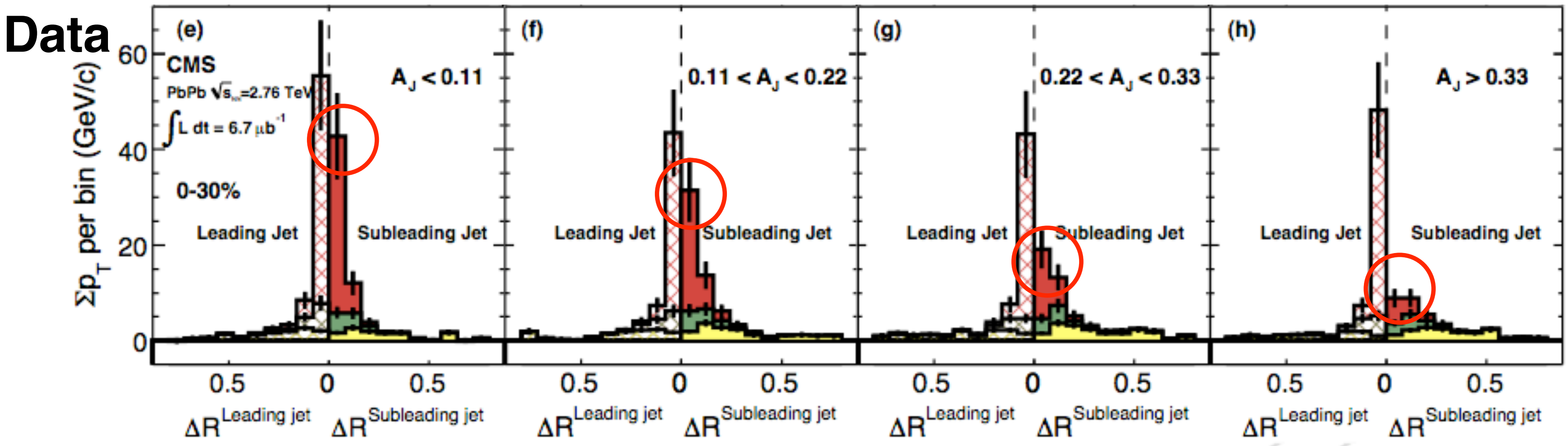
Track-Jet Correlations

- Data:
  - **The leading jets also show a fragmentation pattern of hard partons, even for $A_j>0.33$**



Track-Jet Correlations

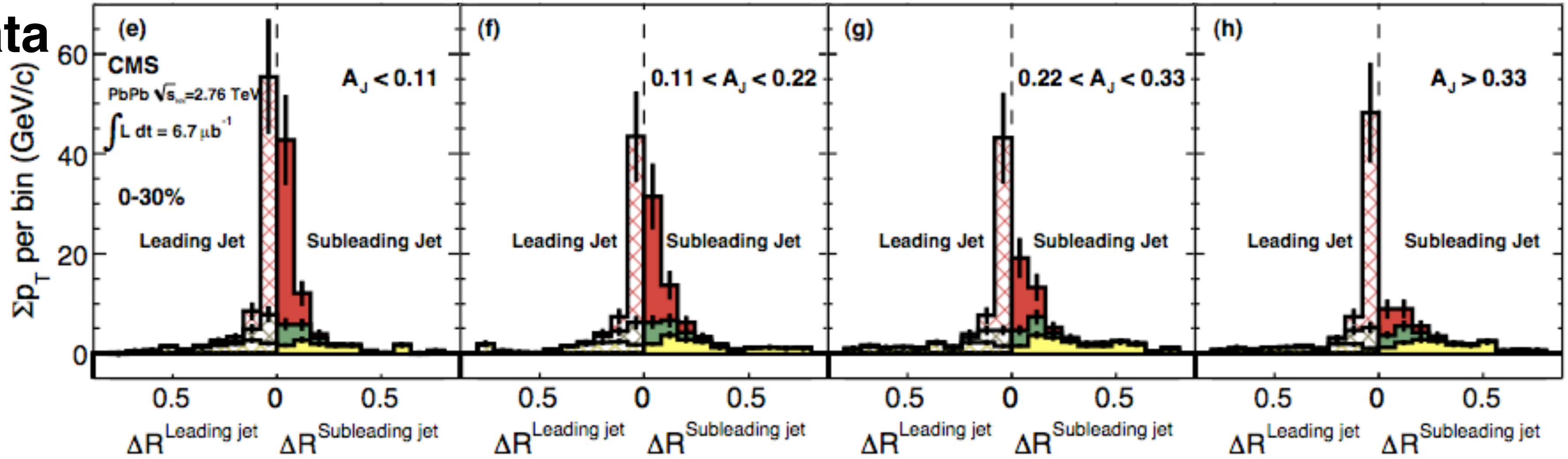
- Data:
  - **The subleading jets also show softening of the fragmentation pattern with increasing A_j, i.e. lower jet energy**



Track-Jet Correlations

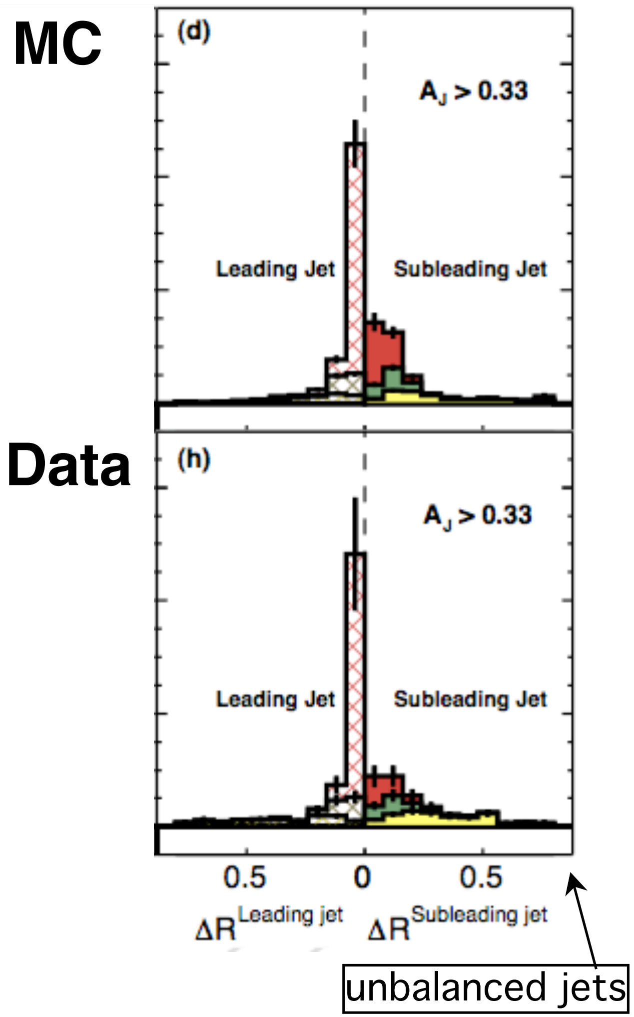
- Data:
  - **The observed calorimeter jet imbalance is reflected in the fragmentation pattern into charged particles**
  - **This supports the interpretation that we can infer a momentum imbalance in the fragmenting partons from the calorimeter jet imbalance**

Data



Track-Jet Correlations

- In dijet events with a large imbalance, A_j>0.33, we find significantly more energy in tracks below p_T of 4GeV/c at large ΔR
  - **But, not nearly enough to restore the dijet balance**



Missing p_T

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

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

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

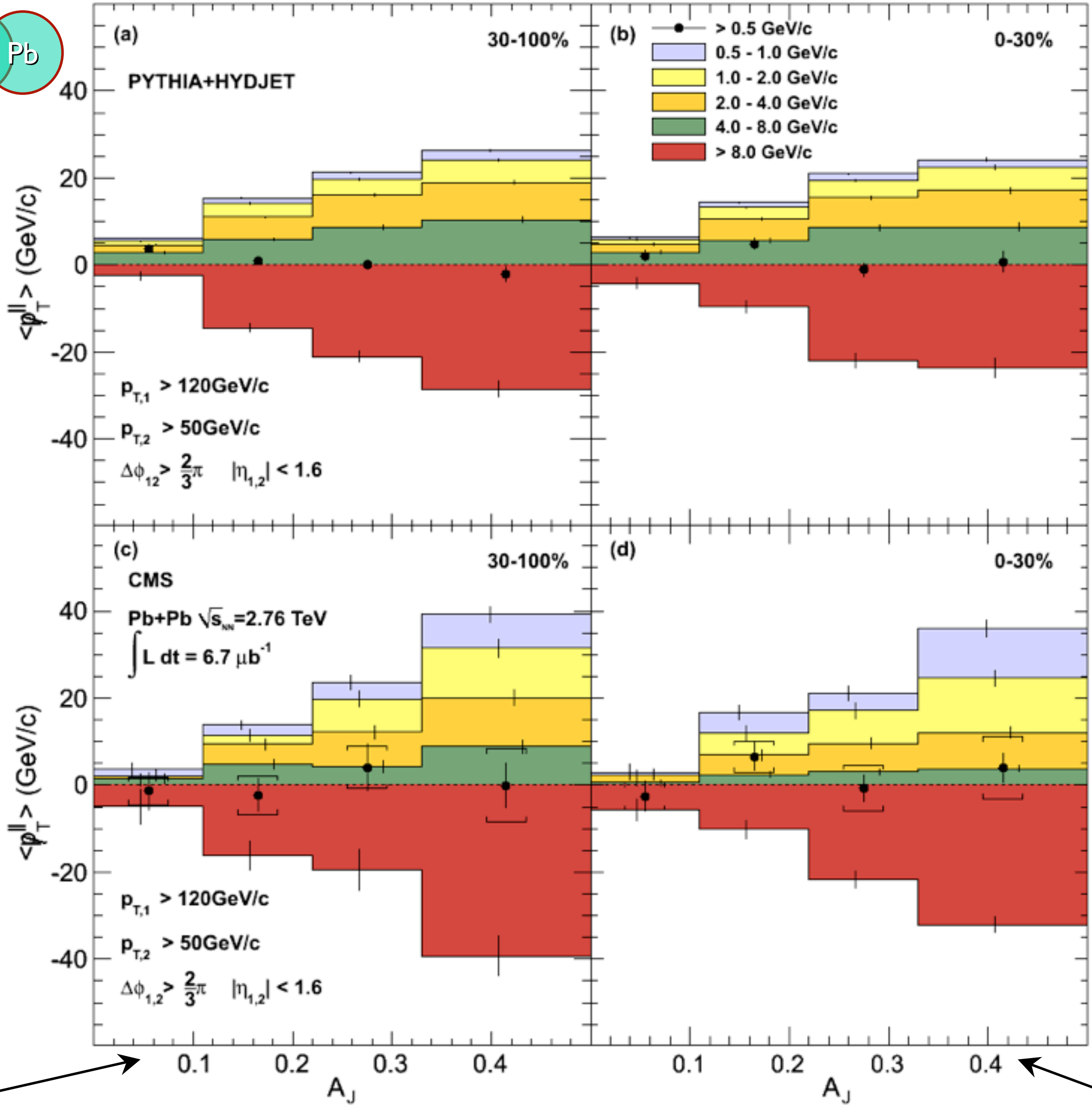
This allows us to see which p_T range carries the balance of the jet momentum.

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

Missing-p_T Results

MC

Data



excess away from leading jet

excess towards leading jet

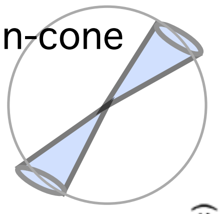
High-p_T (> 8 GeV) excess towards leading jet balanced by tracks below 8 GeV

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

balanced jets

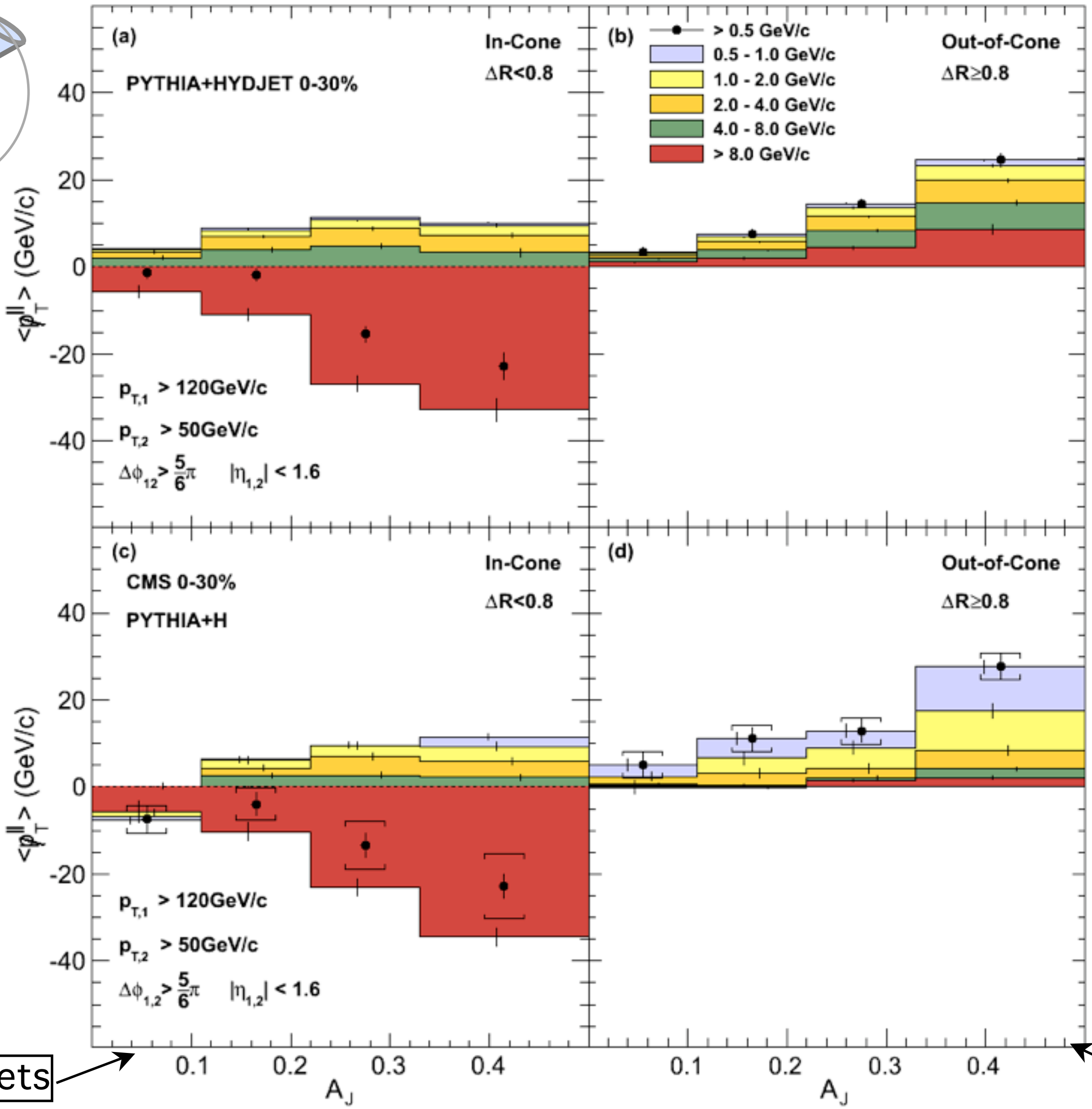
unbalanced jets

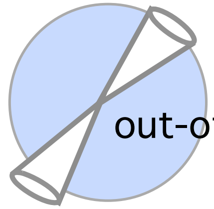
Radial Dependence of MPT



MC

Data





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

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

balanced jets

unbalanced jets

Jet Quenching Summary

- We observe a large dijet momentum imbalance, increasing with centrality.
  - **Imbalance extends to highest jet energies measured ($p_{T,1}$ > 200 GeV/c)**
  - **Imbalance in calorimeter measurement reflected also in the fragmentation pattern of the jets into high p_T charged hadrons**

- The momentum balance is recovered by including tracks at low-p_T and at large angles from the jet
  - **In data (but not PYTHIA) a large fraction of the balance is carried by tracks with p_T < 2.0 GeV/c and ΔR > 0.8**

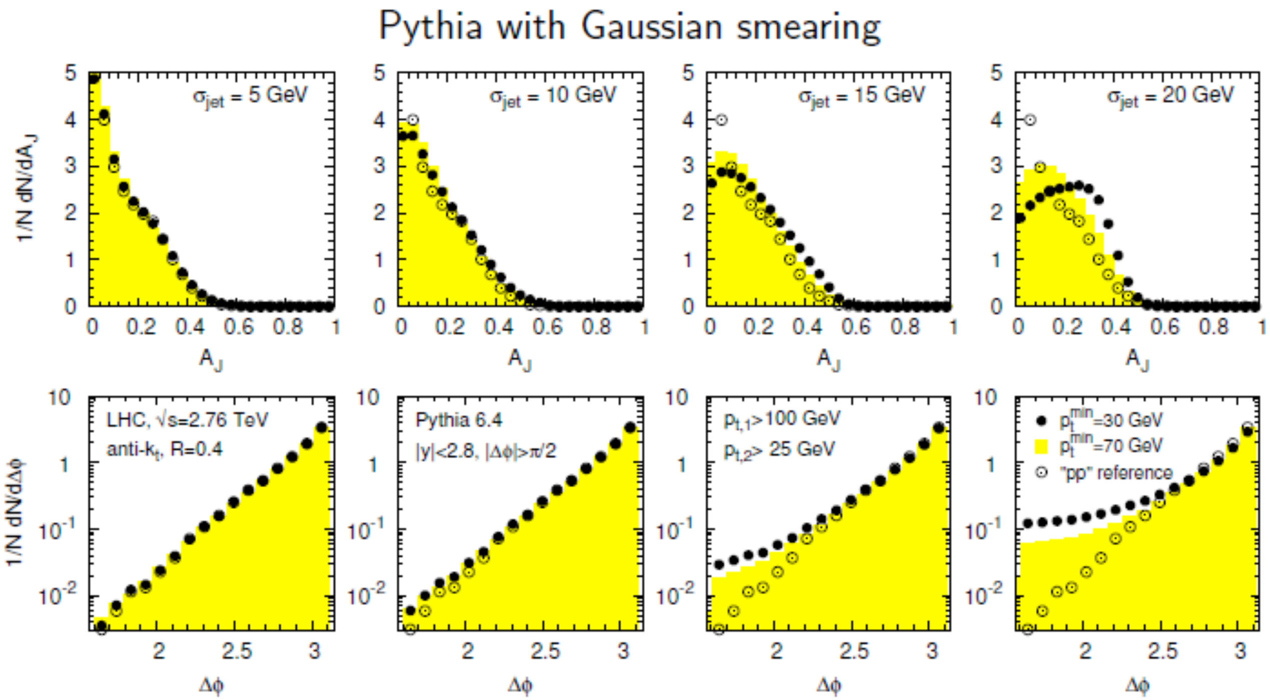
Conclusions

- LHC energies bring new era to jet quenching studies:
  - **unambiguous identification of both partners in copious, asymmetric dijets.**
- This is just the beginning! Future studies:
  - **detailed fragmentation functions**
  - **differential studies of jet quenching e.g. via**
    - **Z^0/gamma-jet correlations,**
    - **multi-jet events**
    - **heavy flavor tagged jets**
- We look forward to detailed theory comparison to our data!

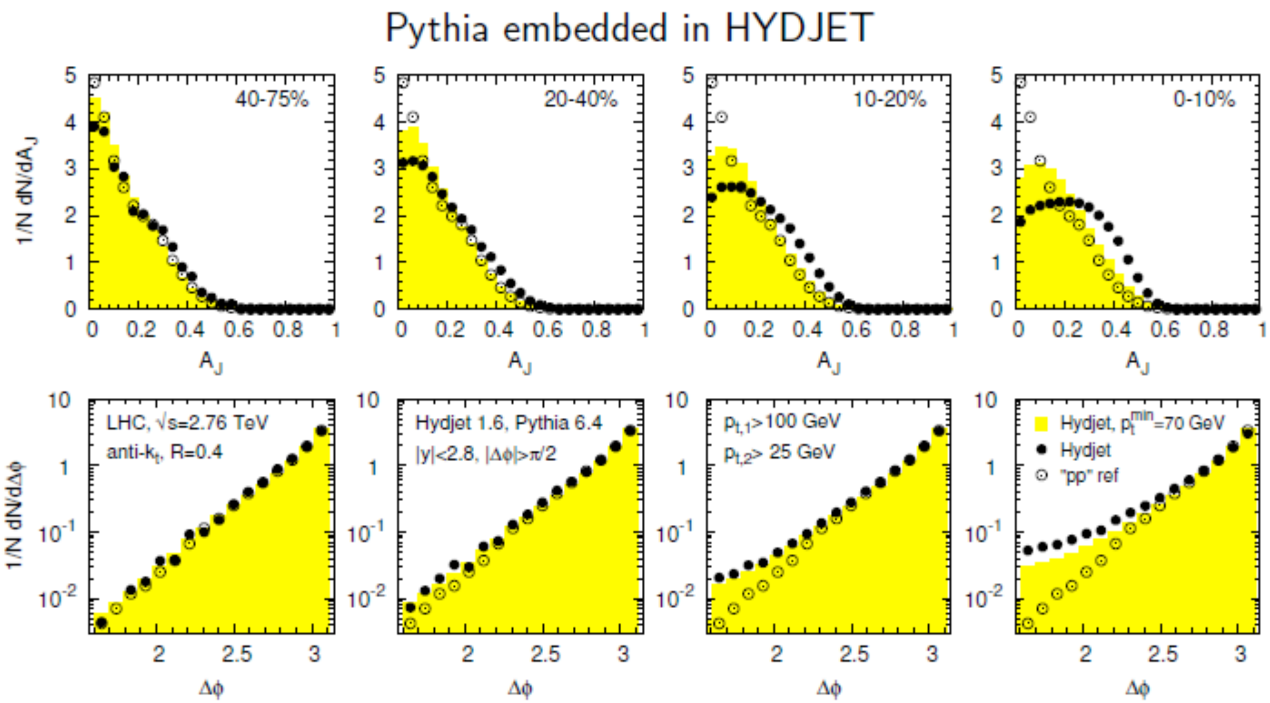
Backup Slides

A_j broadening due to Fluctuations

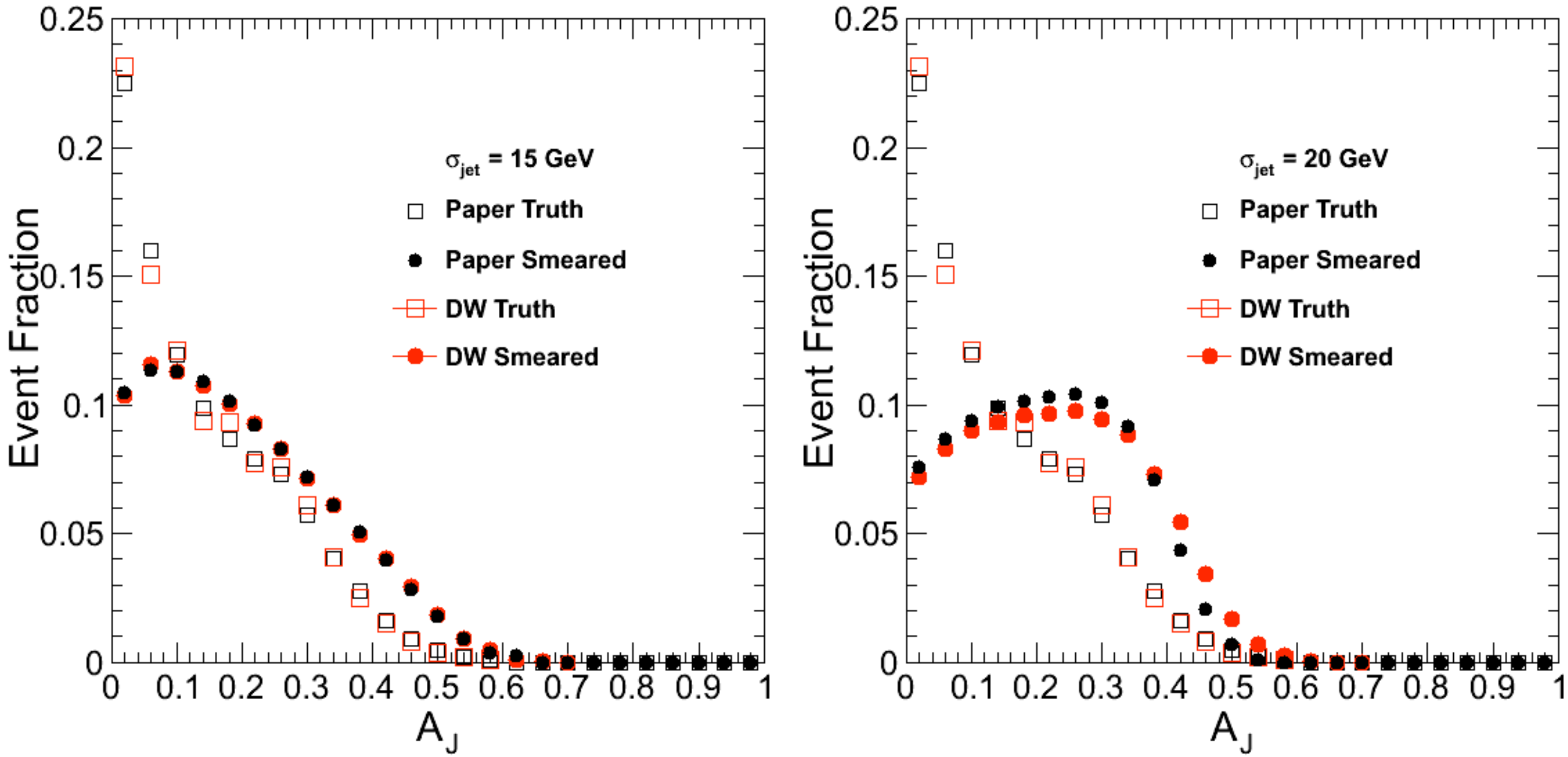
Different Gaussian smearing



PYTHIA+HYDJET

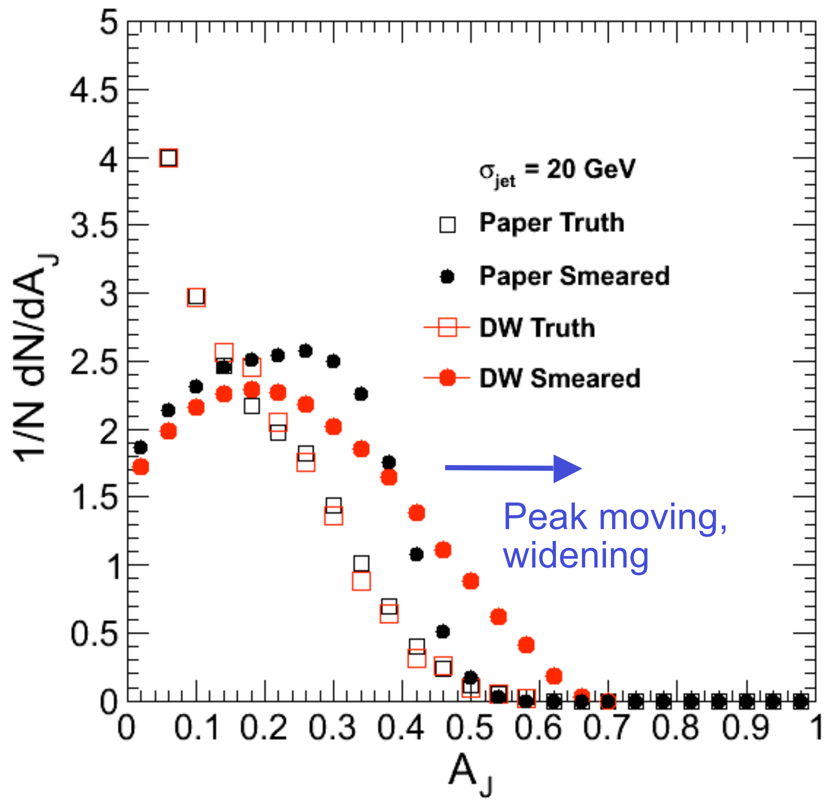


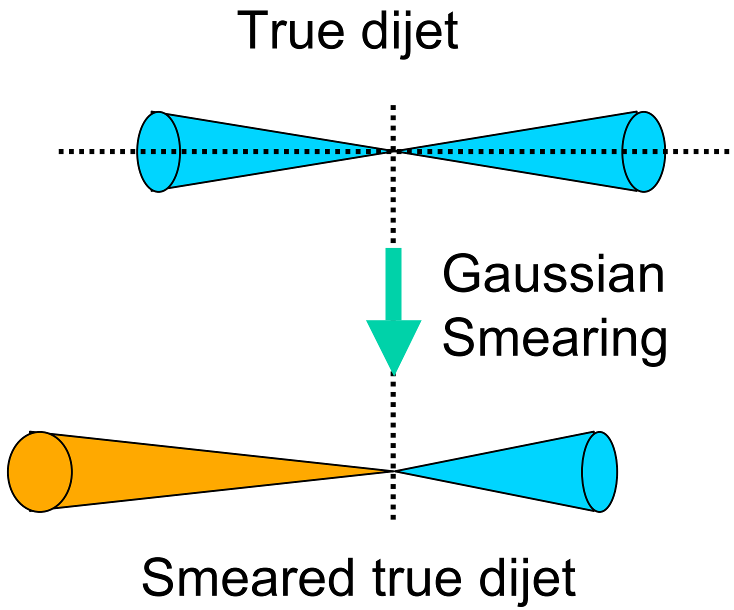
PYTHIA + Fluctuations



- 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.

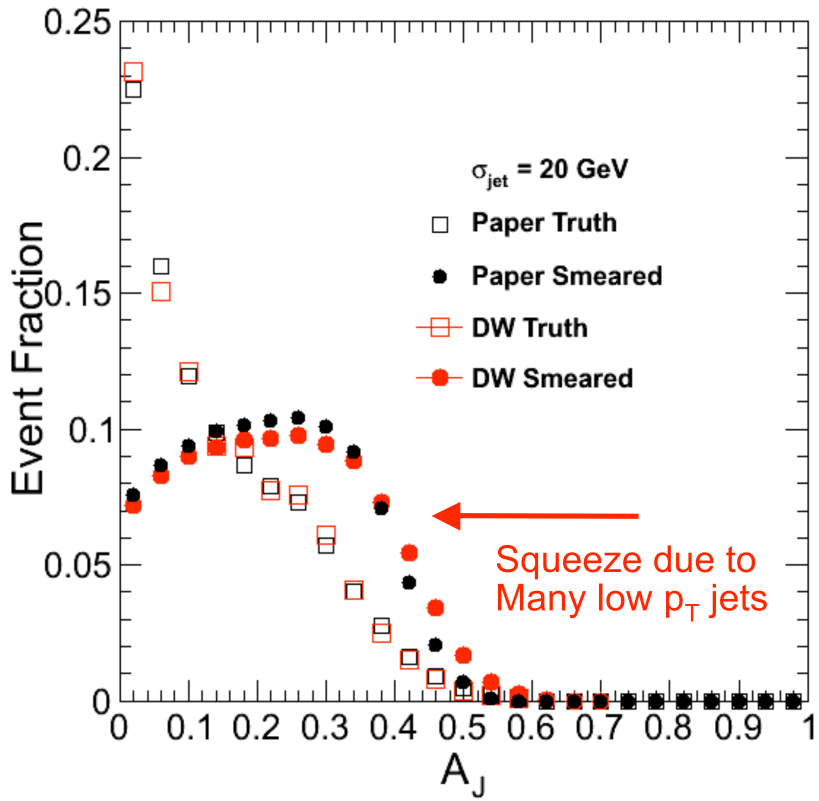
Ingredients

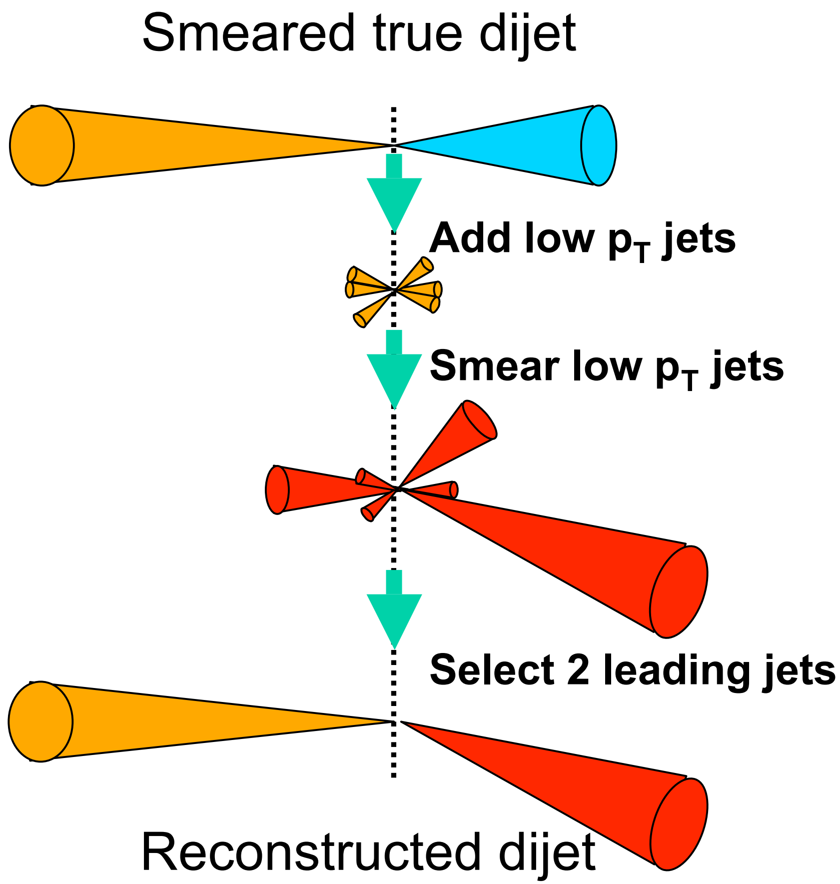




- **Gaussian smearing of the leading jet makes the Aj distribution wider**
  - **Select only Jets above p_T = 3GeV**

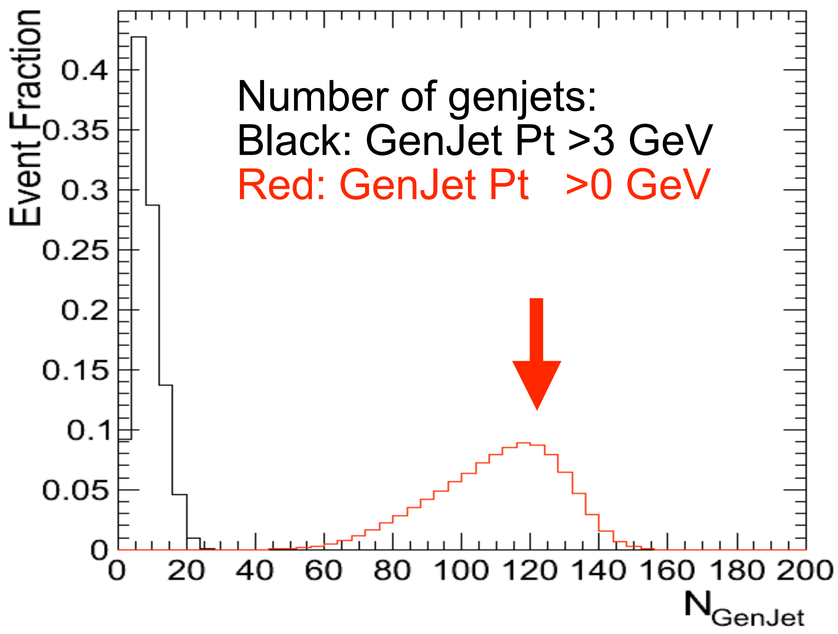
Ingredients II

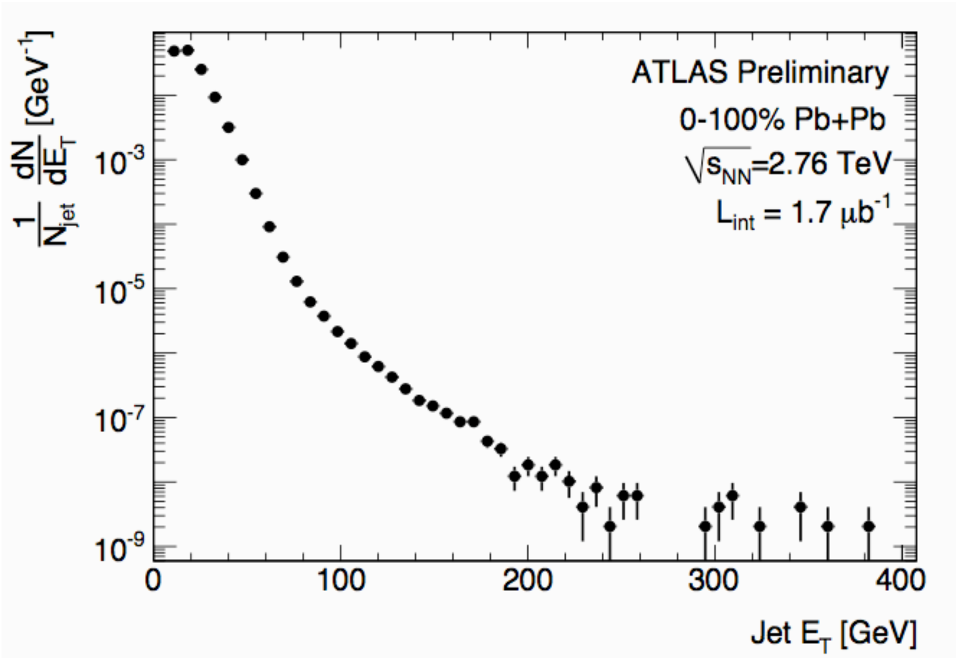




- **Adding many low p_T jets, smeared to higher p_T than the true away side jet, compresses the Aj distribution**
  - **Tested by adding the 0-3GeV jets in the analysis**

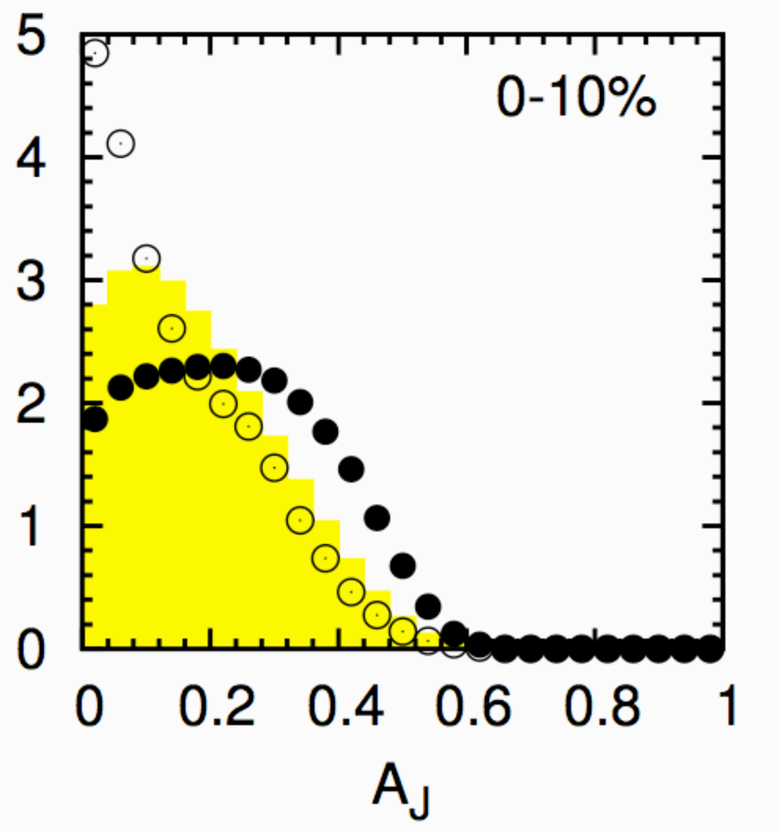
Ingredients III

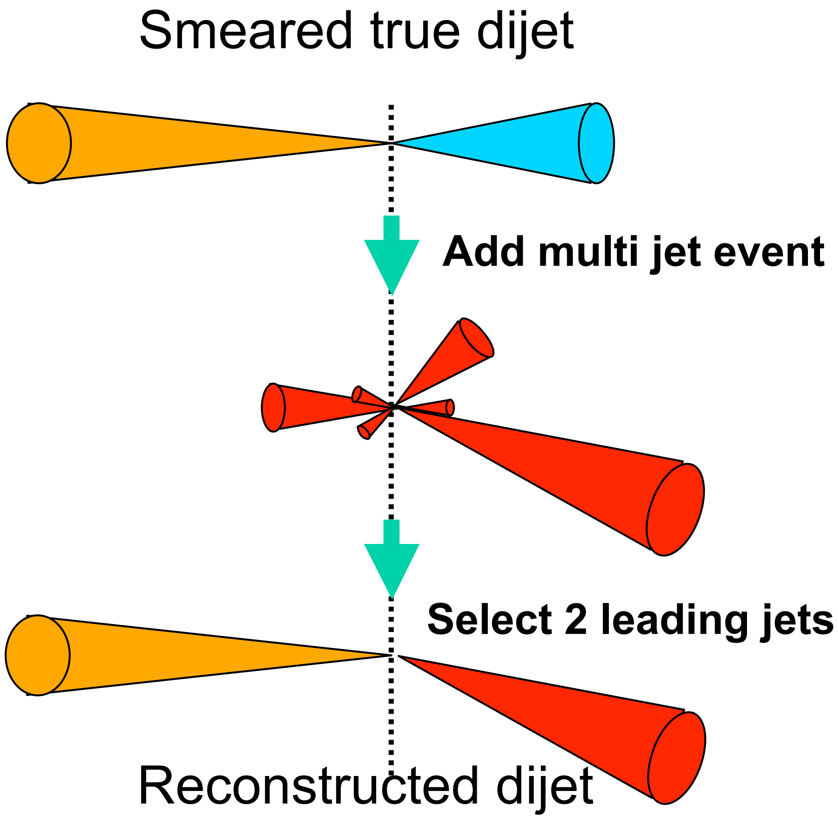




- Balanced dijets + fluctuations can fake a wide Aj distribution
  - **Needs a very large number (~100) of low p_T jets per event**
    - **Remember: $dn/d\eta^{ch}$ ~6 in |eta| < 5 -> ~60 charged particles/event**
  - **And a very large σ (20GeV) for the smearing**
    - **based on a Gaussian fit to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

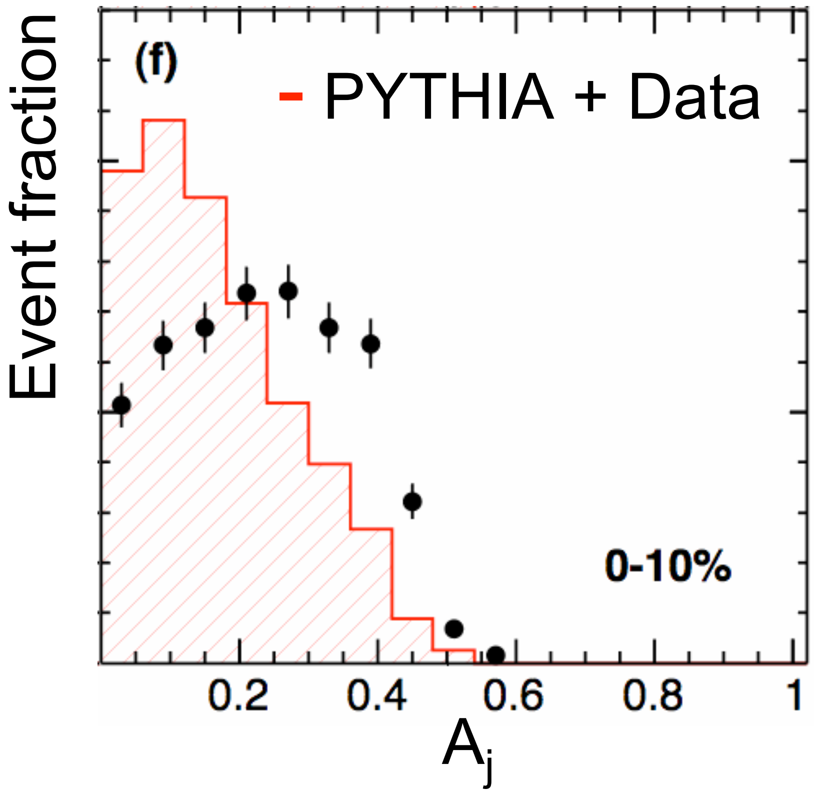
Hydjet

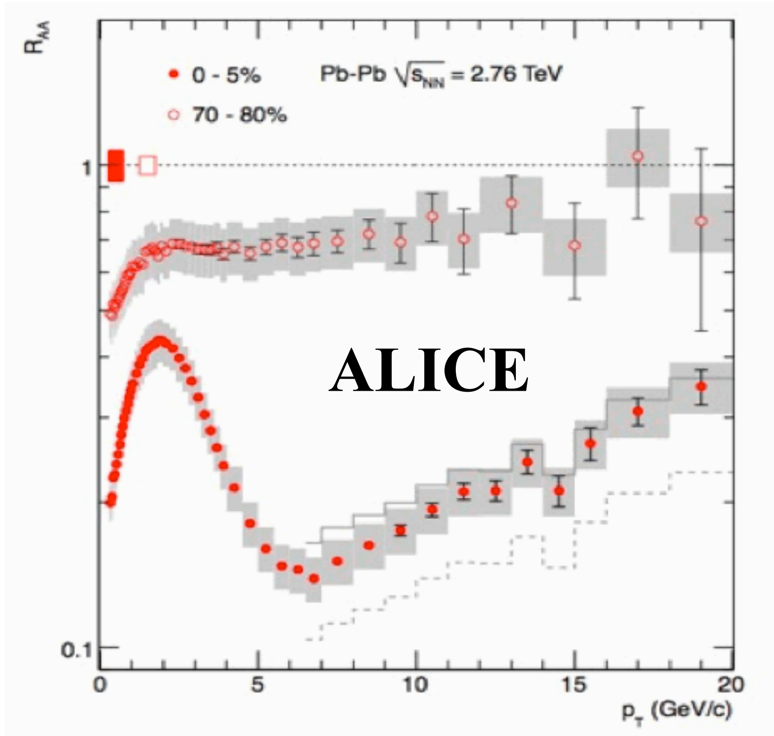




- The HYDJET A_j distribution is created by the same mechanism
  - The hard part of a central HYDJET event consists of ~300 unquenched PYTHIA events with $p_T$hat of ~7GeV
  - Low p_T jets smear the leading jets by superposition and cause a combinatorial problem

Is unquenched Hydjet a good background reference?

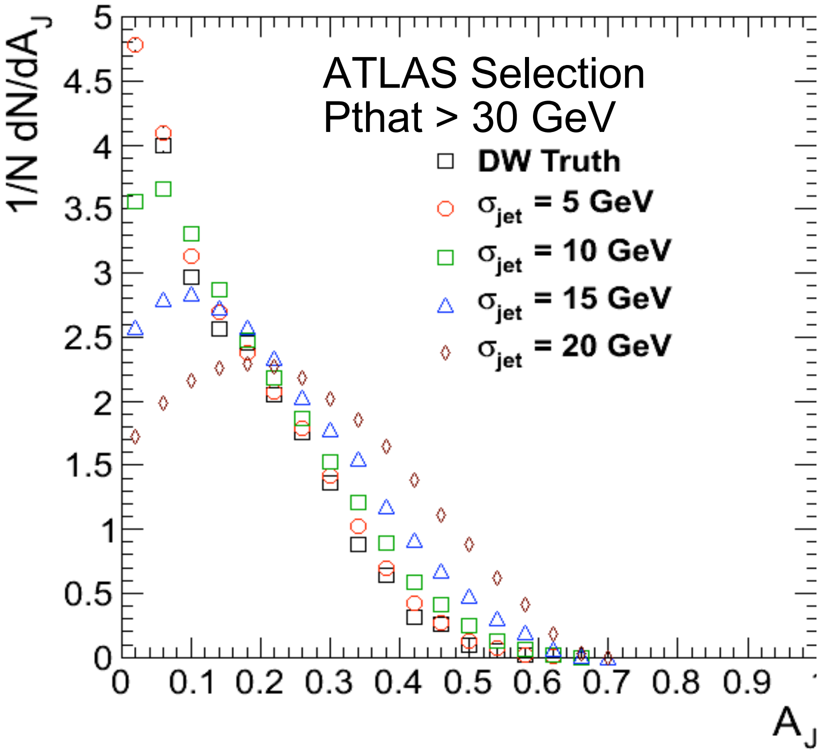


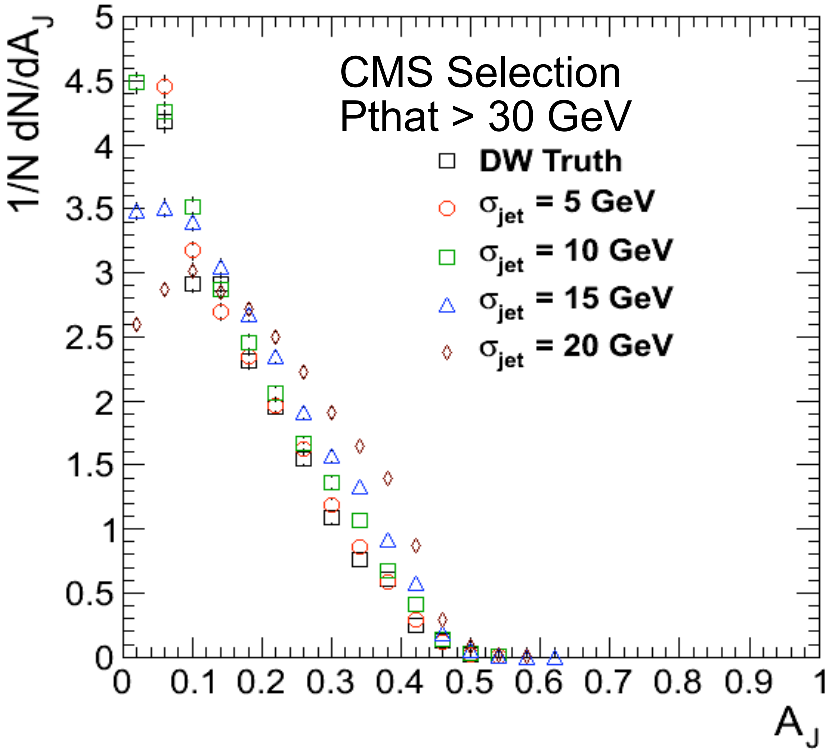


- PYTHIA embedded in real data, including all background fluctuations and resolution effects does not show a widened A_j distribution
  - **A cross check with $p_T$hat = 30GeV embedded in a large min bias data sample gave an identical reference distributions**
  - **ALICE R_{AA} shows a strong hardon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

ATLAS vs CMS Dijet selection

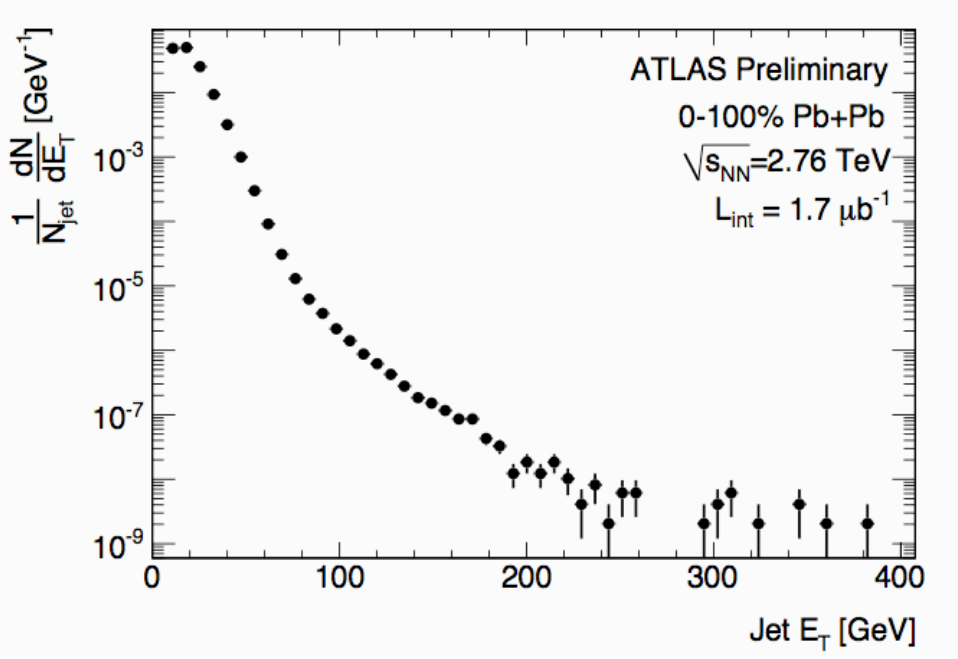
Comparing the ATLAS and CMS dijet selection pT hat > 30 GeV

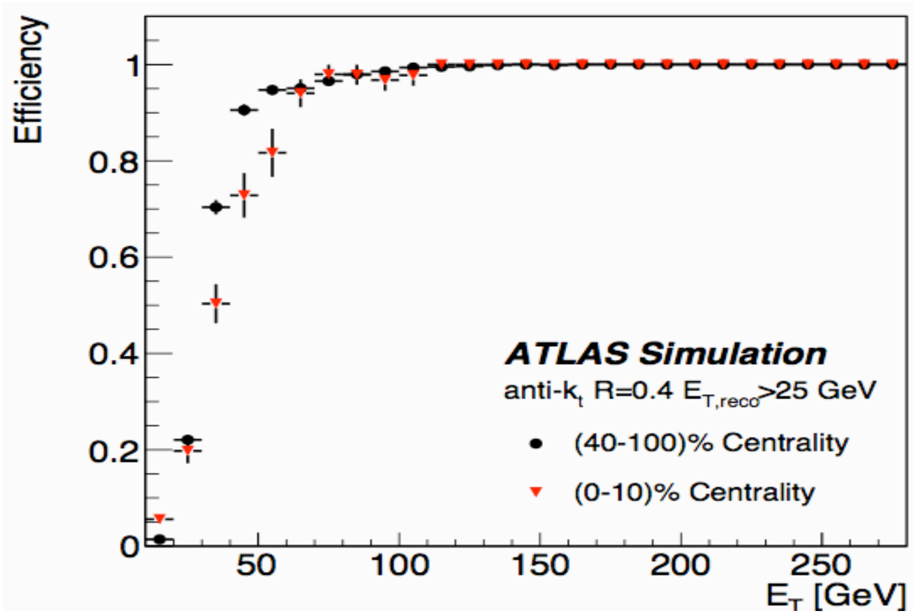




- With the higher jet thresholds used for the CMS paper we are less sensitive to background fluctuations
  - **ATLAS 100/20, CMS: 120/50 for leading/sub-leading**

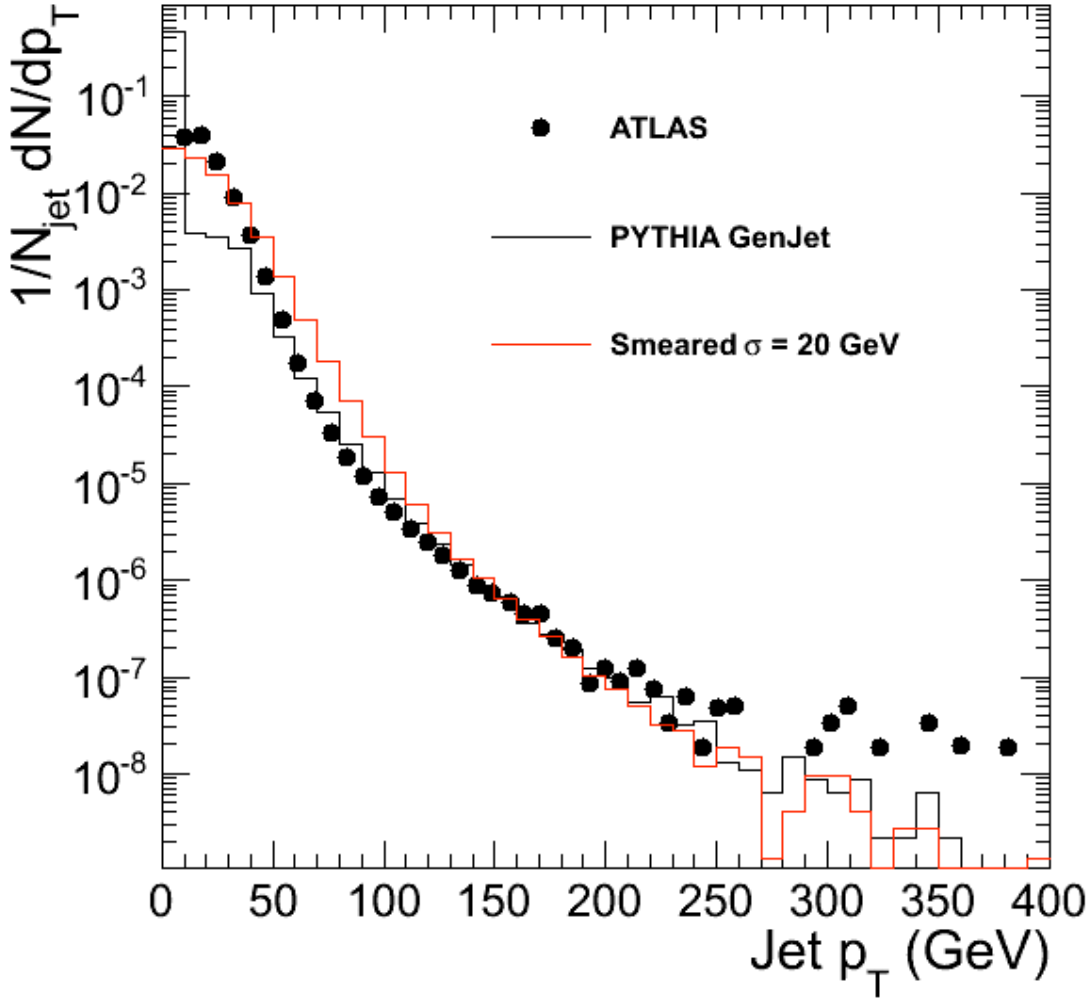
ATLAS input



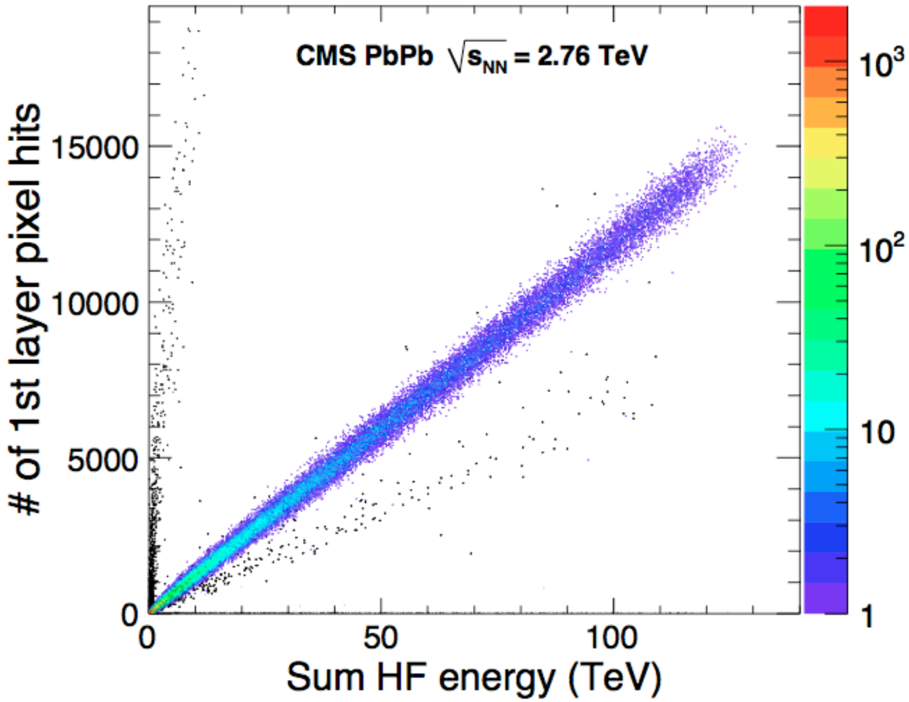


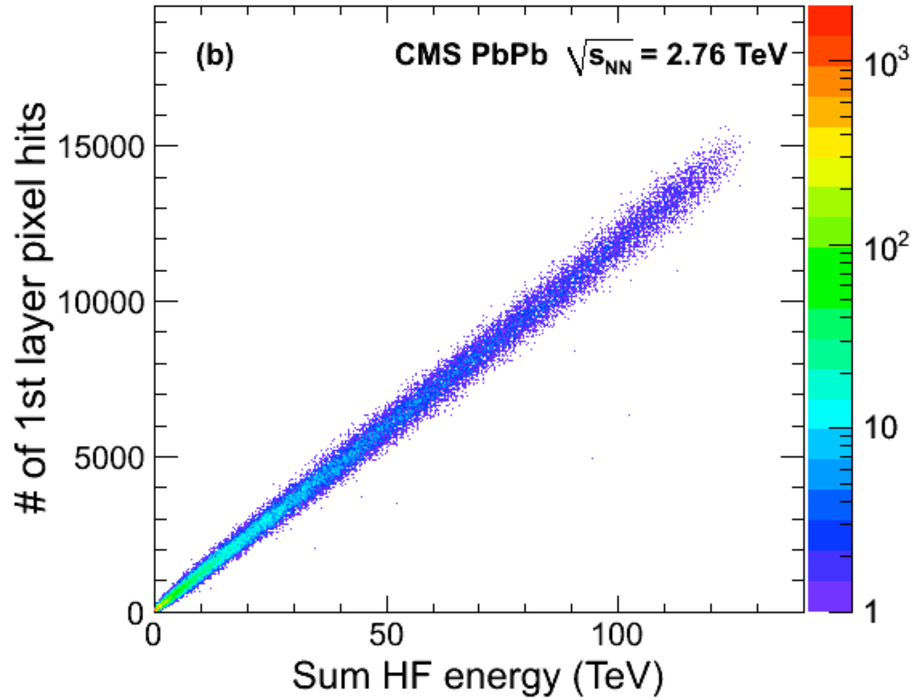
- The large σ (20GeV) smearing is based on a Gaussian fit to the low p_T part of the ATLAS min bias jet spectrum
  - **ATLAS reports σ ~8 GeV for their background fluctuations**

20GeV smearing closure test

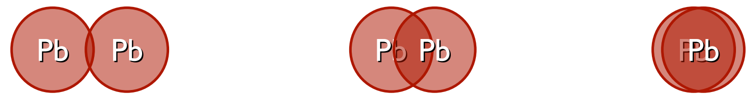


Event Selection



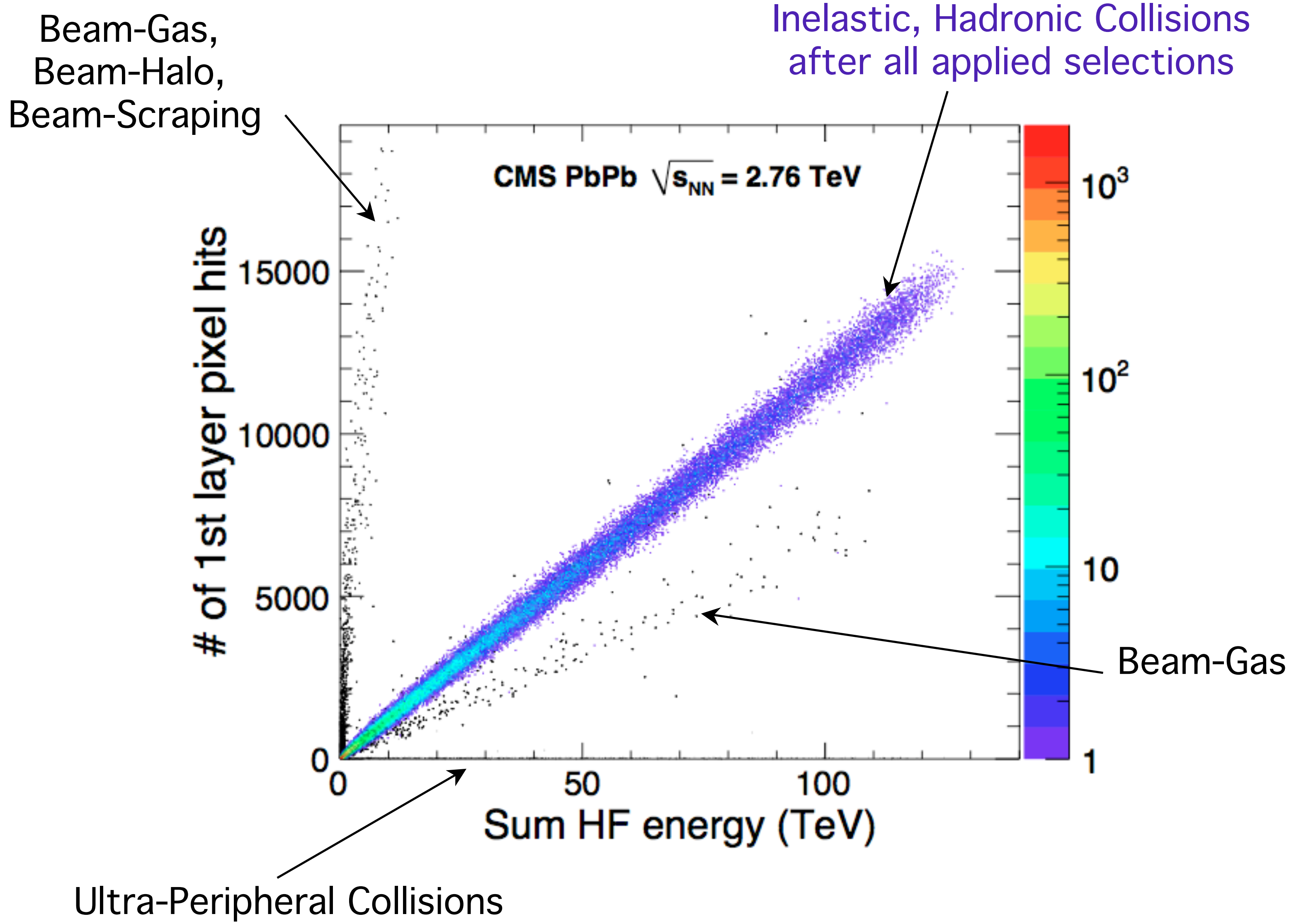


Jet triggered events ($p_T^{uncorr} > 50$ GeV/c)	149k
No beam halo, based on the BSC	148k
HF offline coincidence	111k
Reconstructed vertex	110k
Beam-gas removal	110k
ECAL cleaning	107k
HCAL cleaning	107k



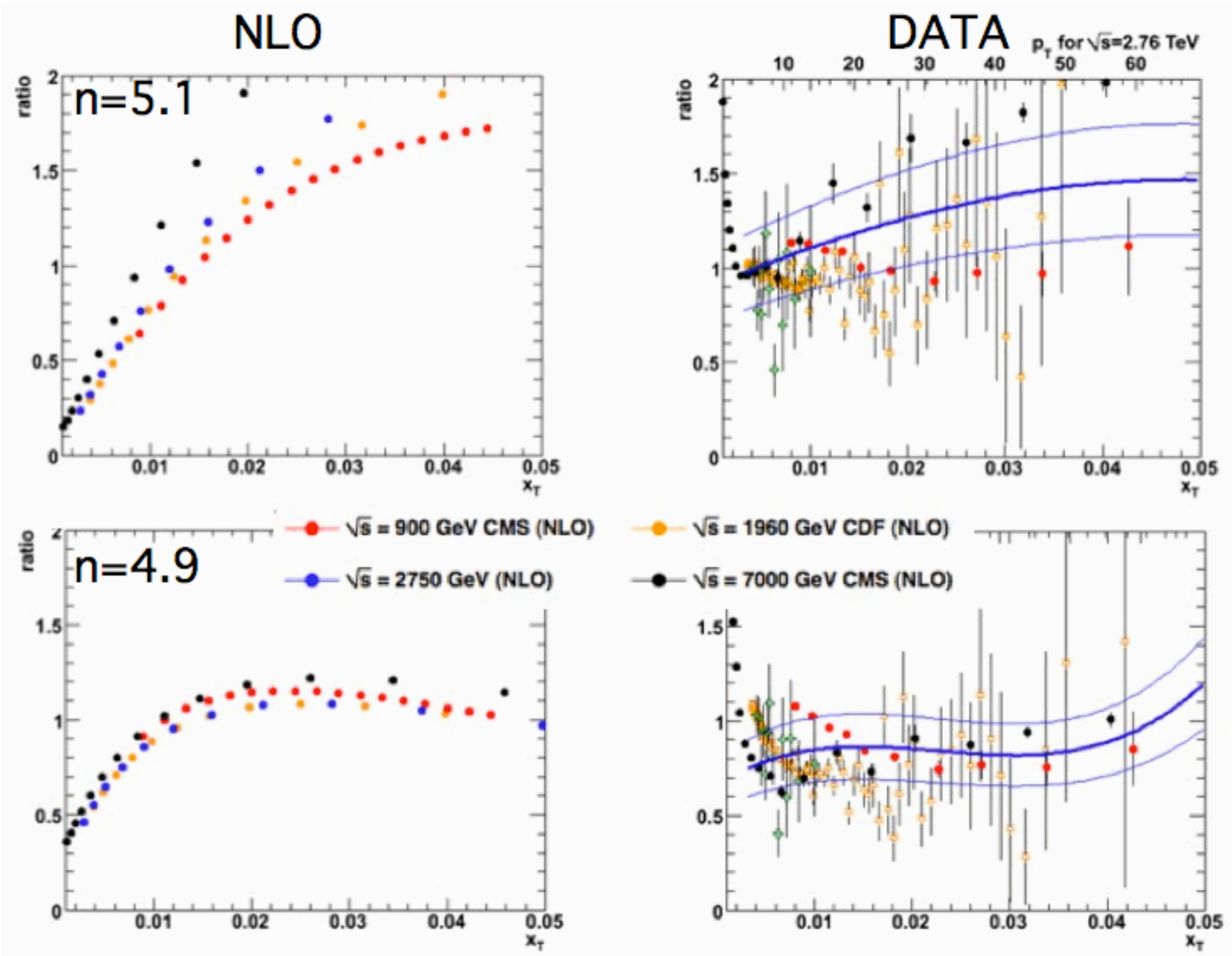
107k good jet-triggered collision events after all selections

Event Selection

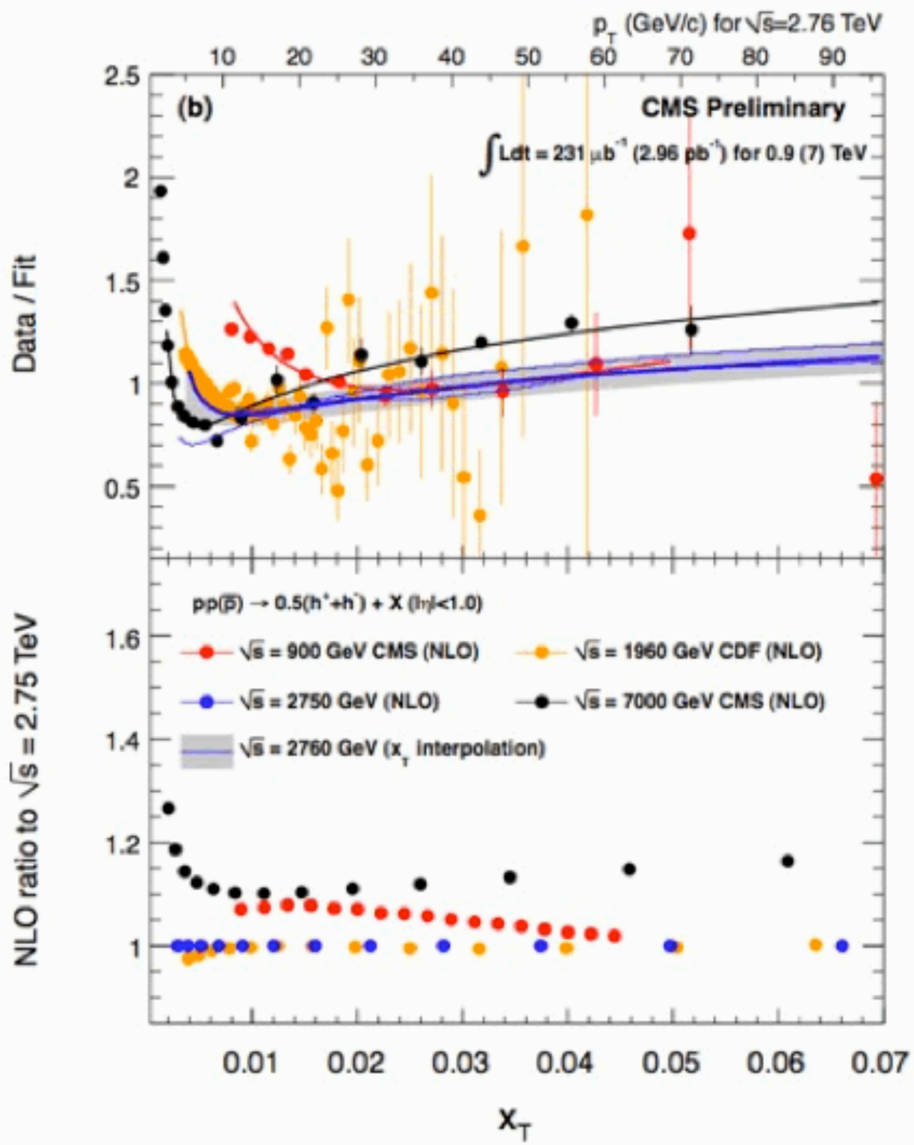


pp Spectra Backup

xT scaling exponent



Scaling violation Correction

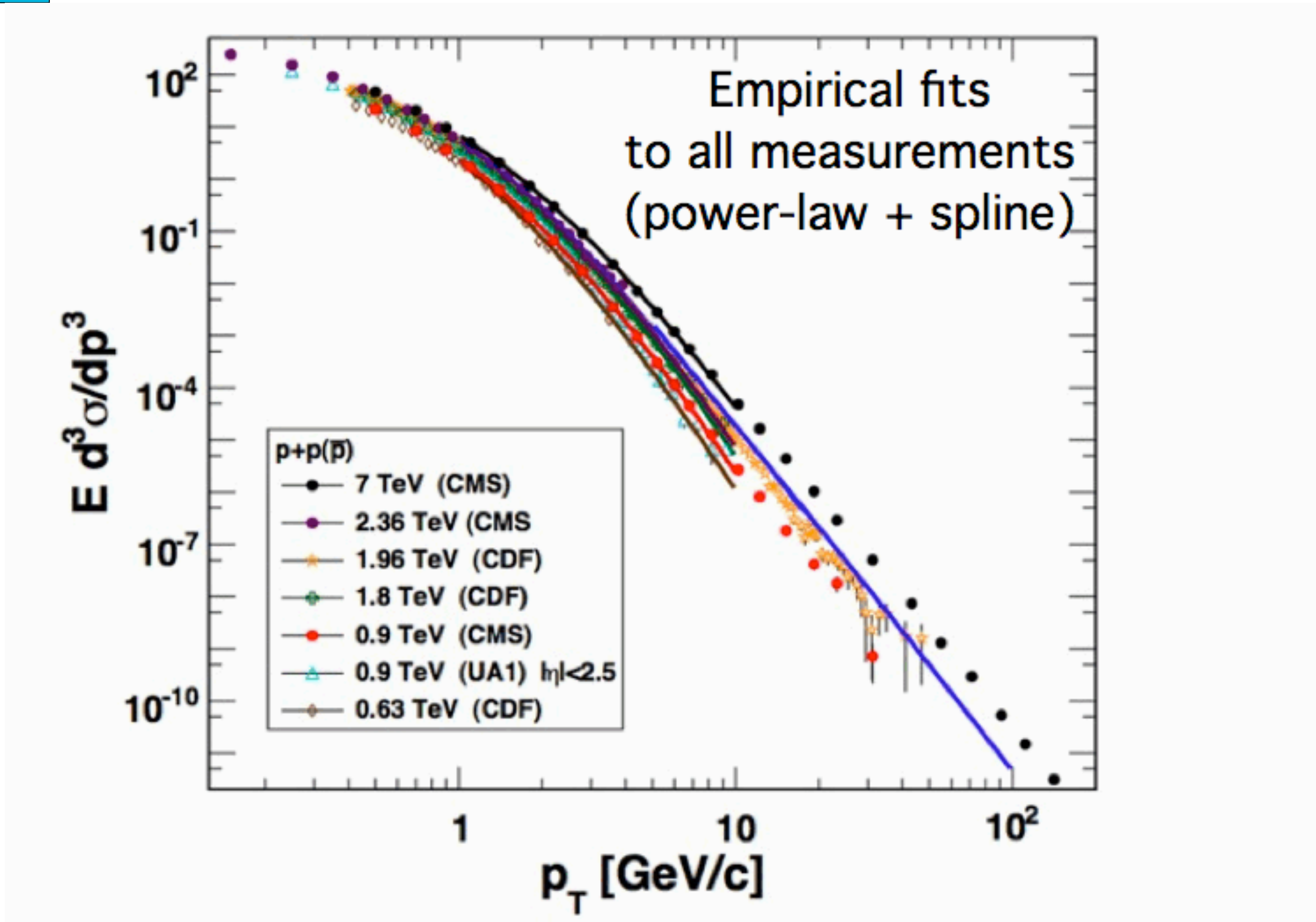


$\sqrt{s}$ and p_T dependence of x_T-scaling violation similar to NLO (for particles with $p_T > 8$ GeV/c)

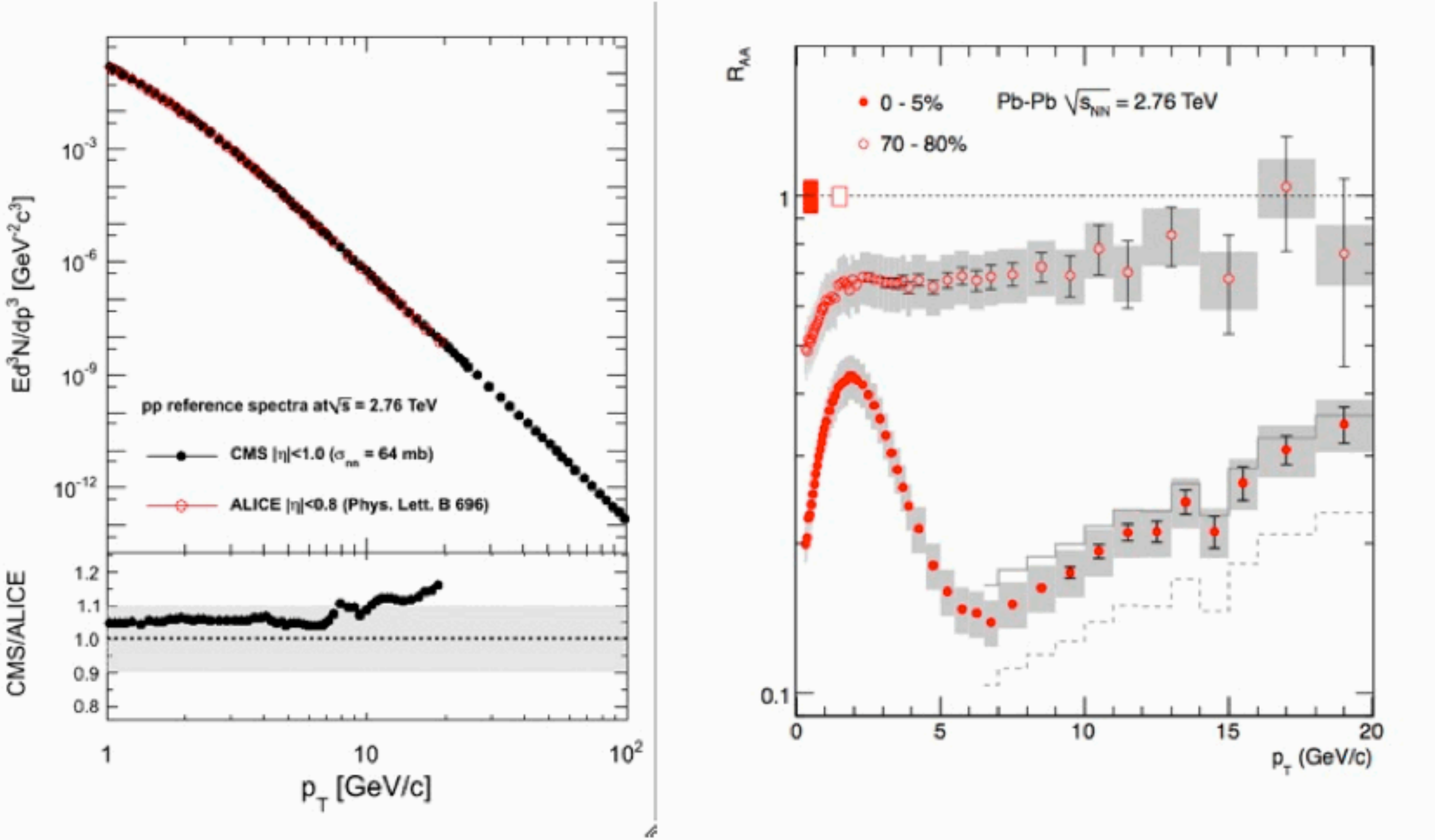
Using scaling violation from NLO, each measurement can be corrected to 2.76 TeV

Variation of ~7% between 3 independent estimates

Direct pT interpolation

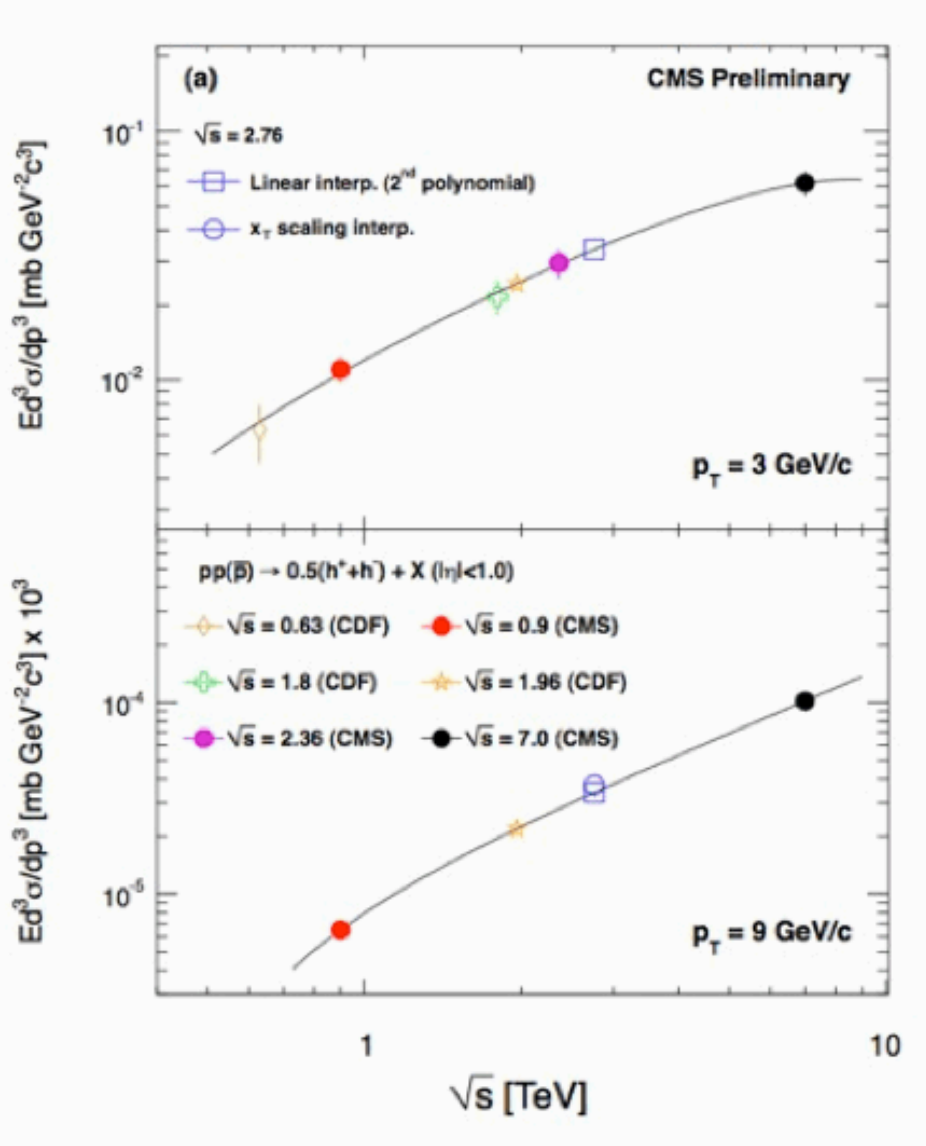


Comparison to ALICE ref.



arXiv:1012.1004

Direct pT interpolation



Evaluate empirical fits at fixed values of p_T

Fit 2nd-order polynomial to √s evolution (errors are statistical + systematic including lumi uncertainty)

Fit errors typically 5-10% until 15 GeV/c, where 0.9 TeV statistics is limiting

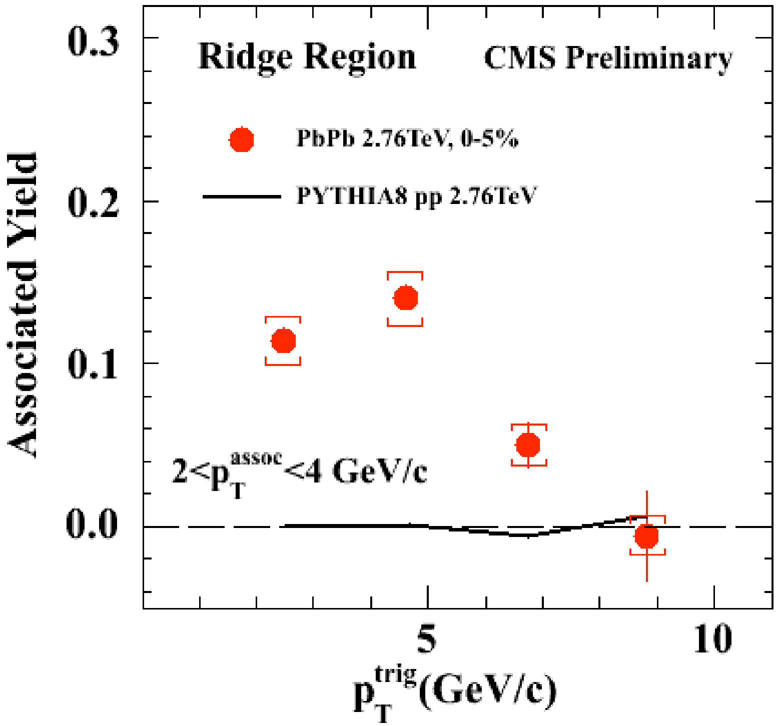
Agrees at 10% level with x_T-scaling technique in overlap region

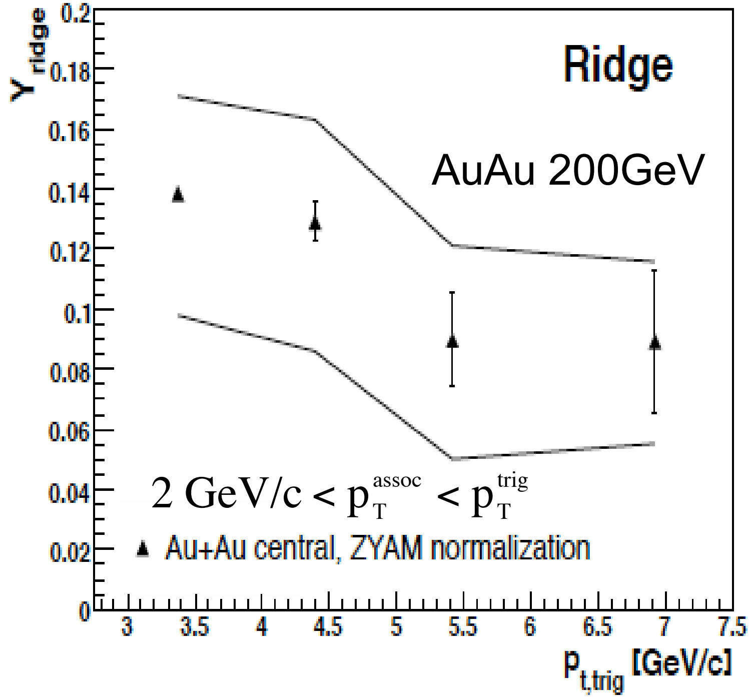
Two Particle Backup

Compare to RHIC results

Direct comparison to RHIC results

STAR at RHIC



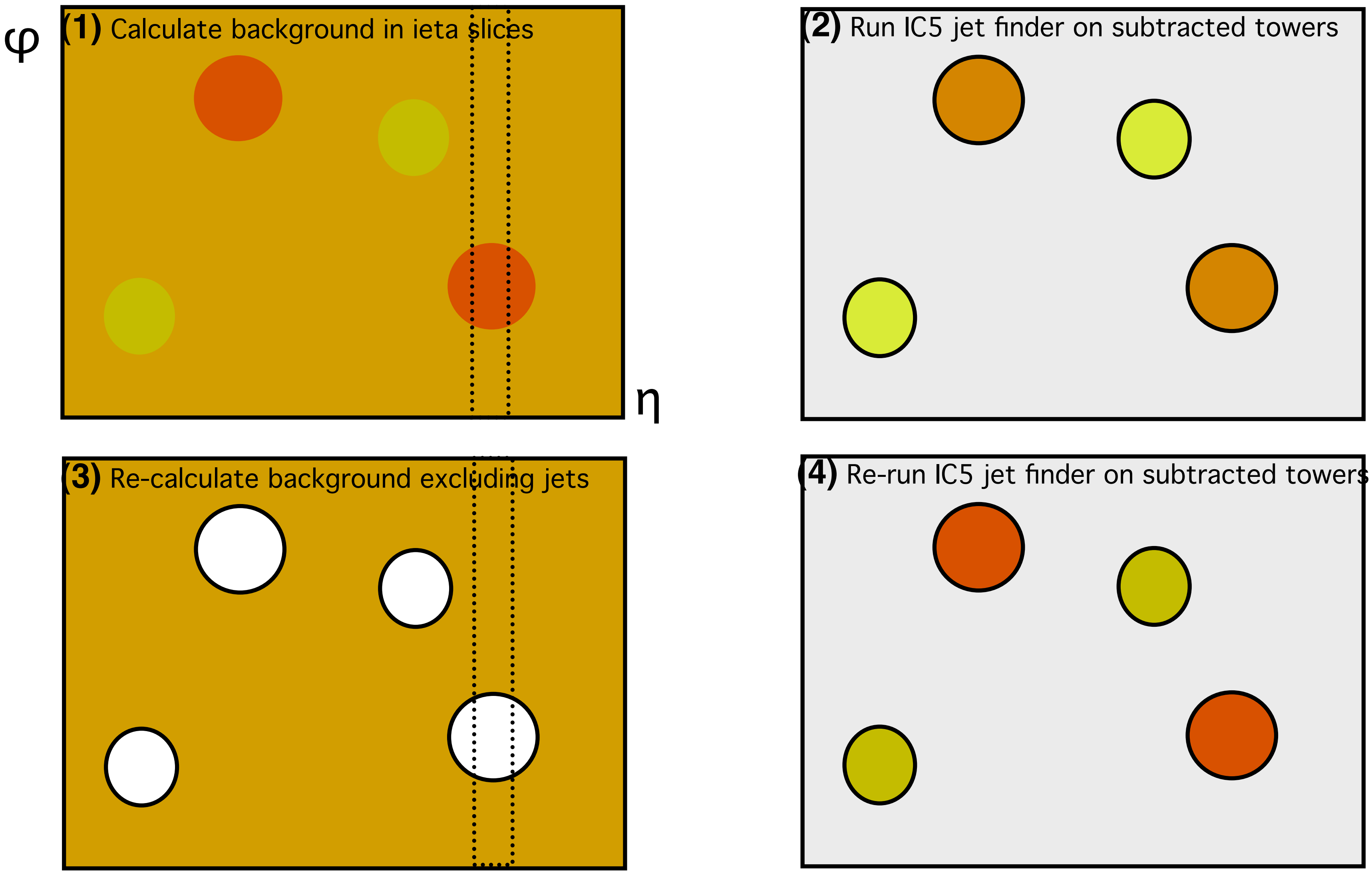


Caveat:

- |Δη| range: 2<|Δη|<4 for CMS and 0.7<|Δη|<1.7 for STAR
- Elliptic flow subtracted in STAR, whereas "upper limit" in CMS

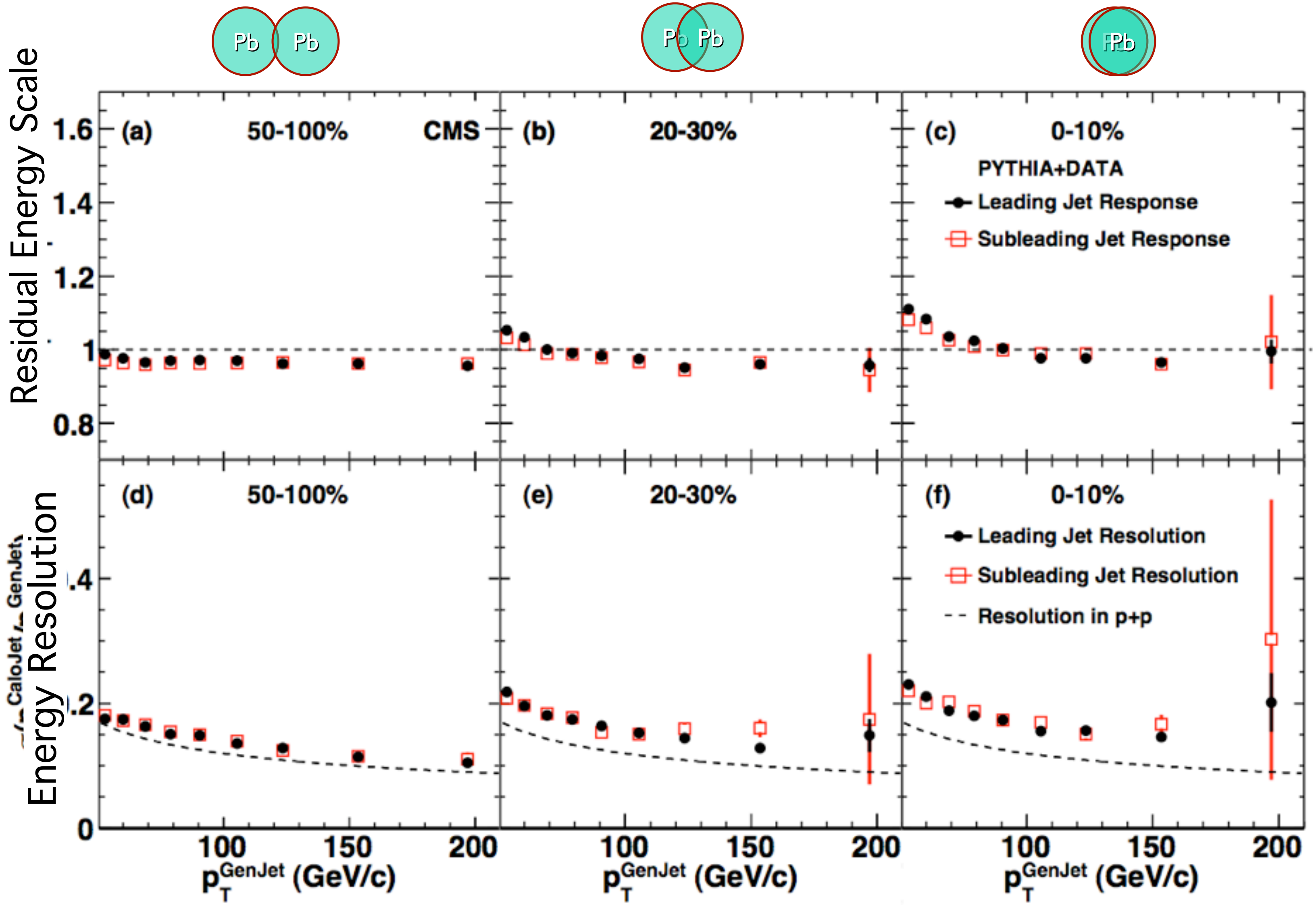
Jet Backup

Jet Algorithm

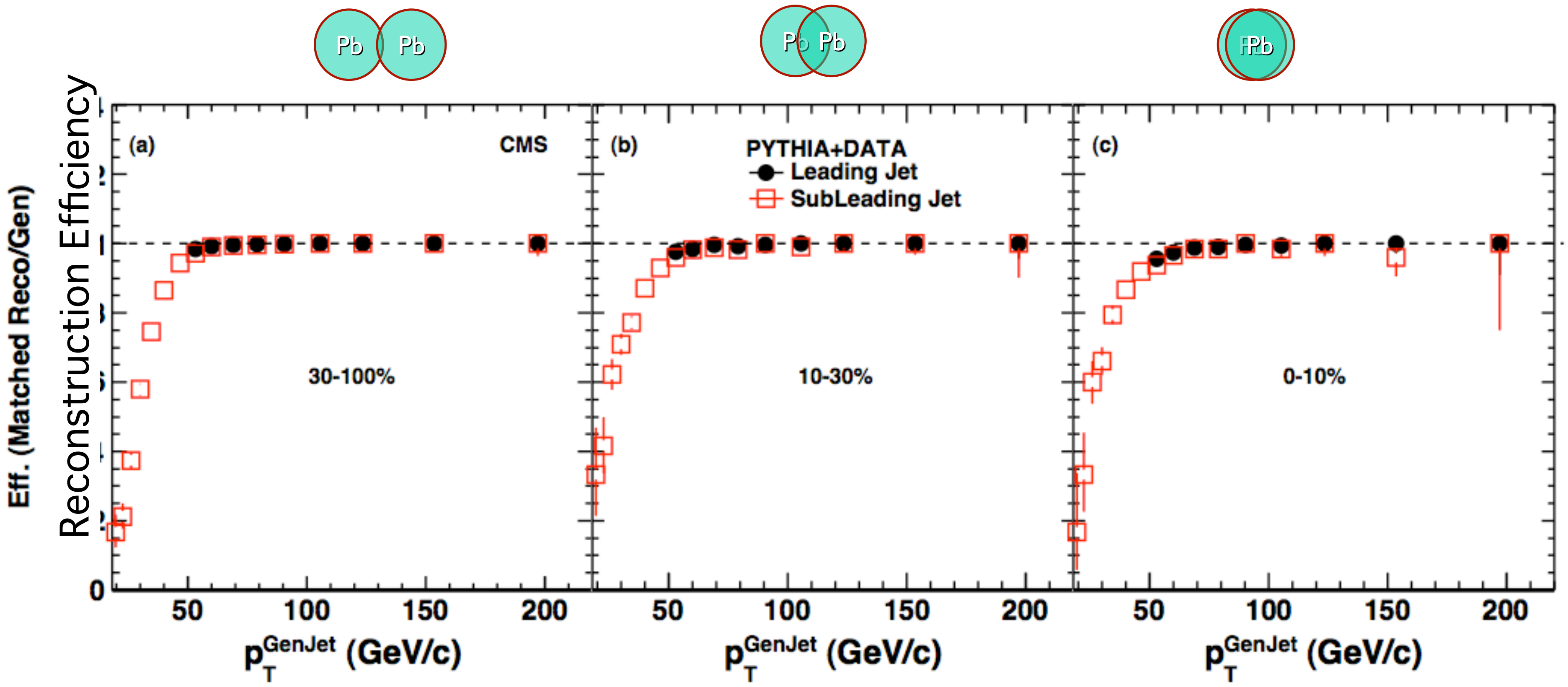


O. Kodolova, I. Vardanian, A. Nikitenko et al., Eur. Phys. J. C50 (2007)

Jet Energy Scale and Resolution



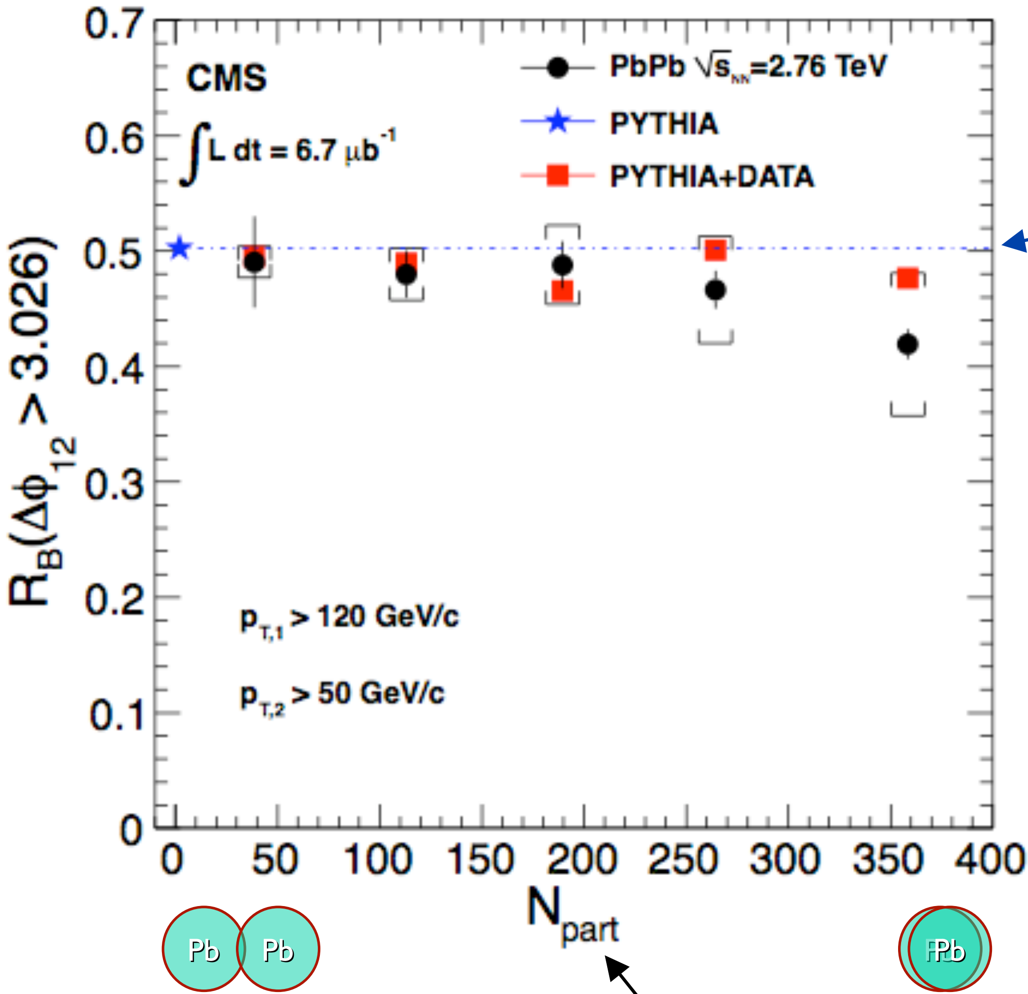
Jet-Finding Efficiency



Dijet Selections

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

Dijet 'Back-to-Back' Fraction

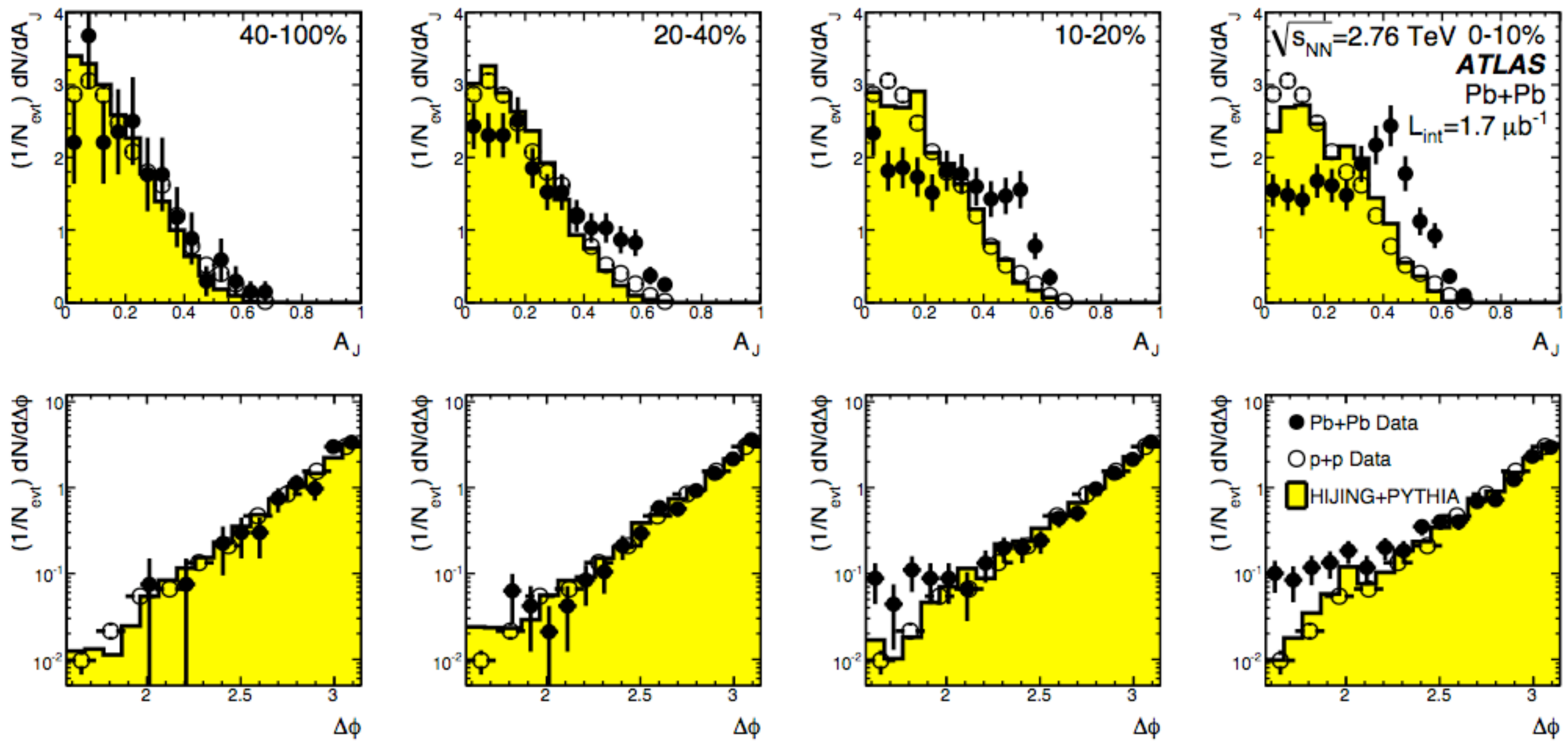


median Δφ value in PYTHIA (dominated by 3-jet events)

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

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

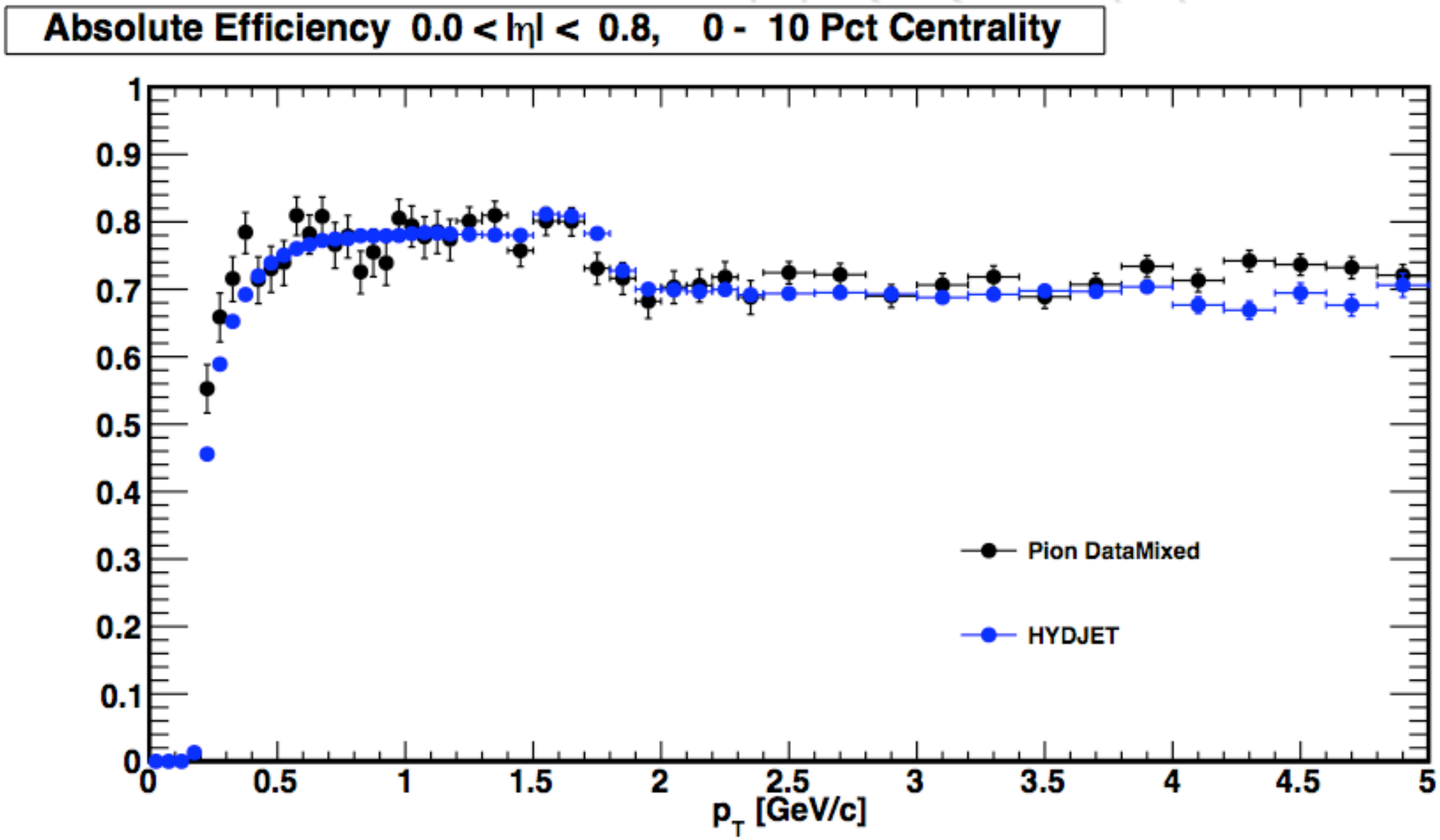
ATLAS Dijet Asymmetry



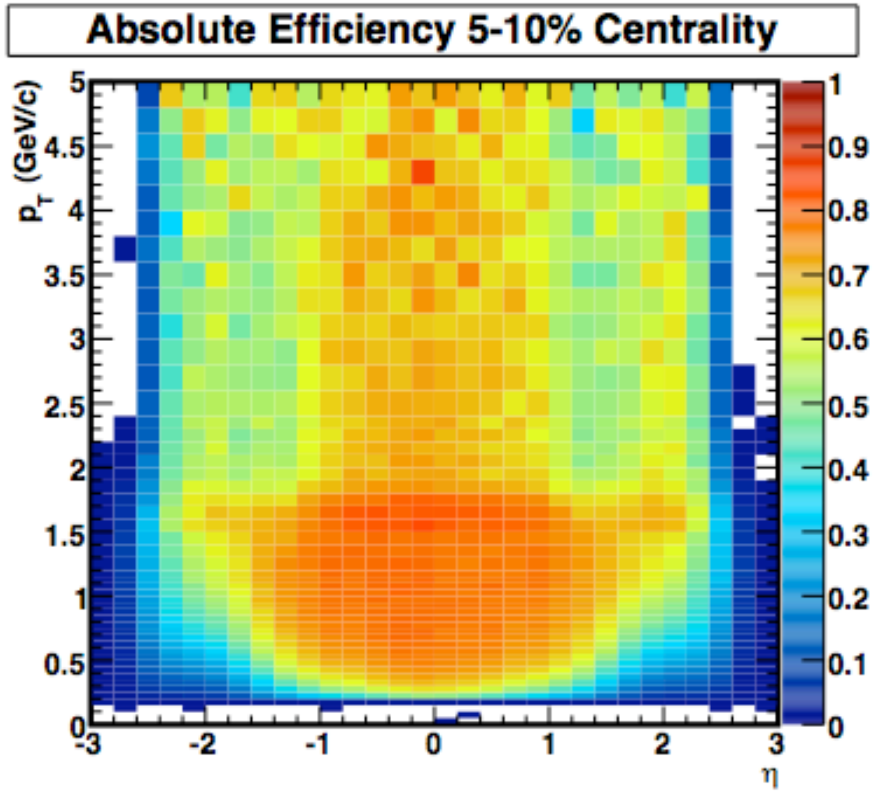
$p_{T,1}$ > 100 GeV
$p_{T,2}$ > 25 GeV
$\Delta\varphi_{1,2} > \pi/2$
$|\eta_{jet}| < 2.8$

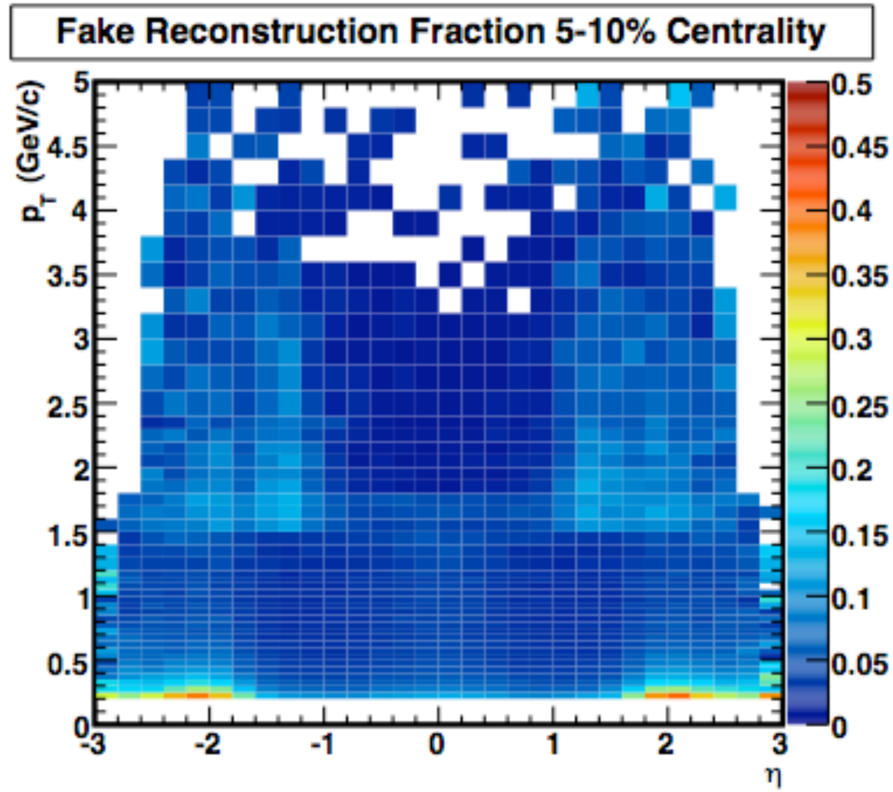
ATLAS Collaboration, "Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at sqrt(S_{NN})= 2.76 TeV with the ATLAS Detector at the LHC", *Phys. Rev. Lett.* **105** (2010) 252303, `arXiv:1011.6182`.

Data-Driven Efficiency

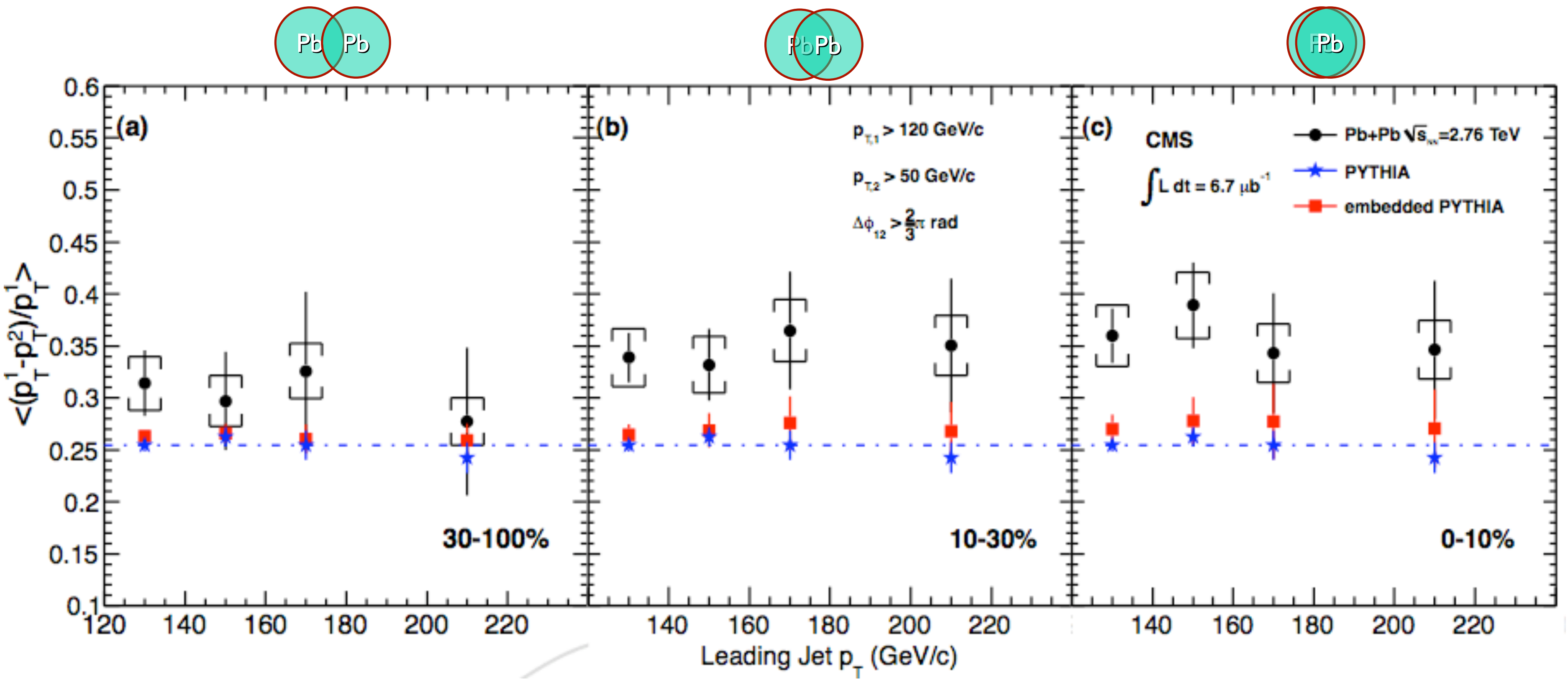


Tracking Performance



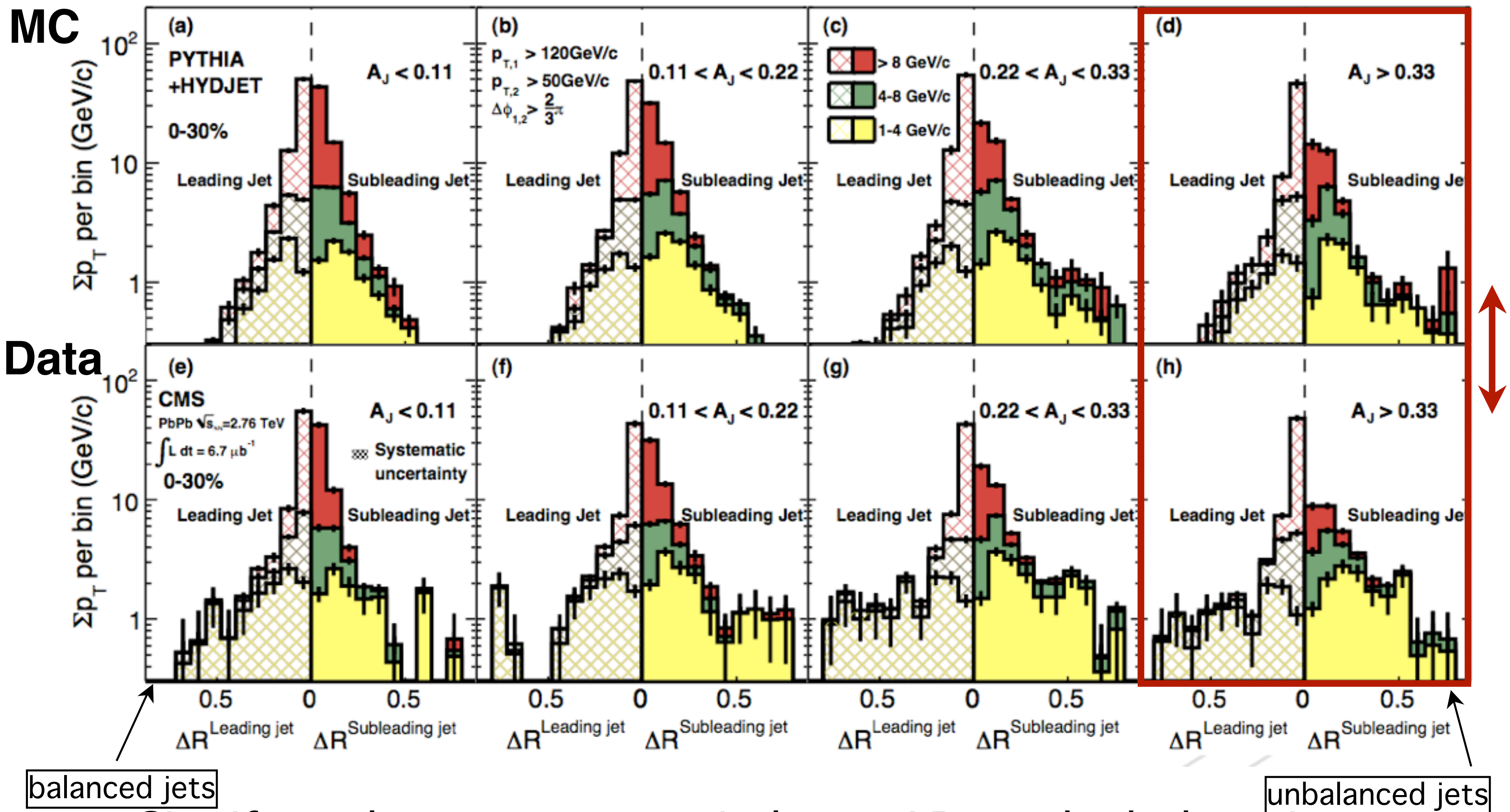


Leading Jet p_T Dependence



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

Track-Jet Correlation Result



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