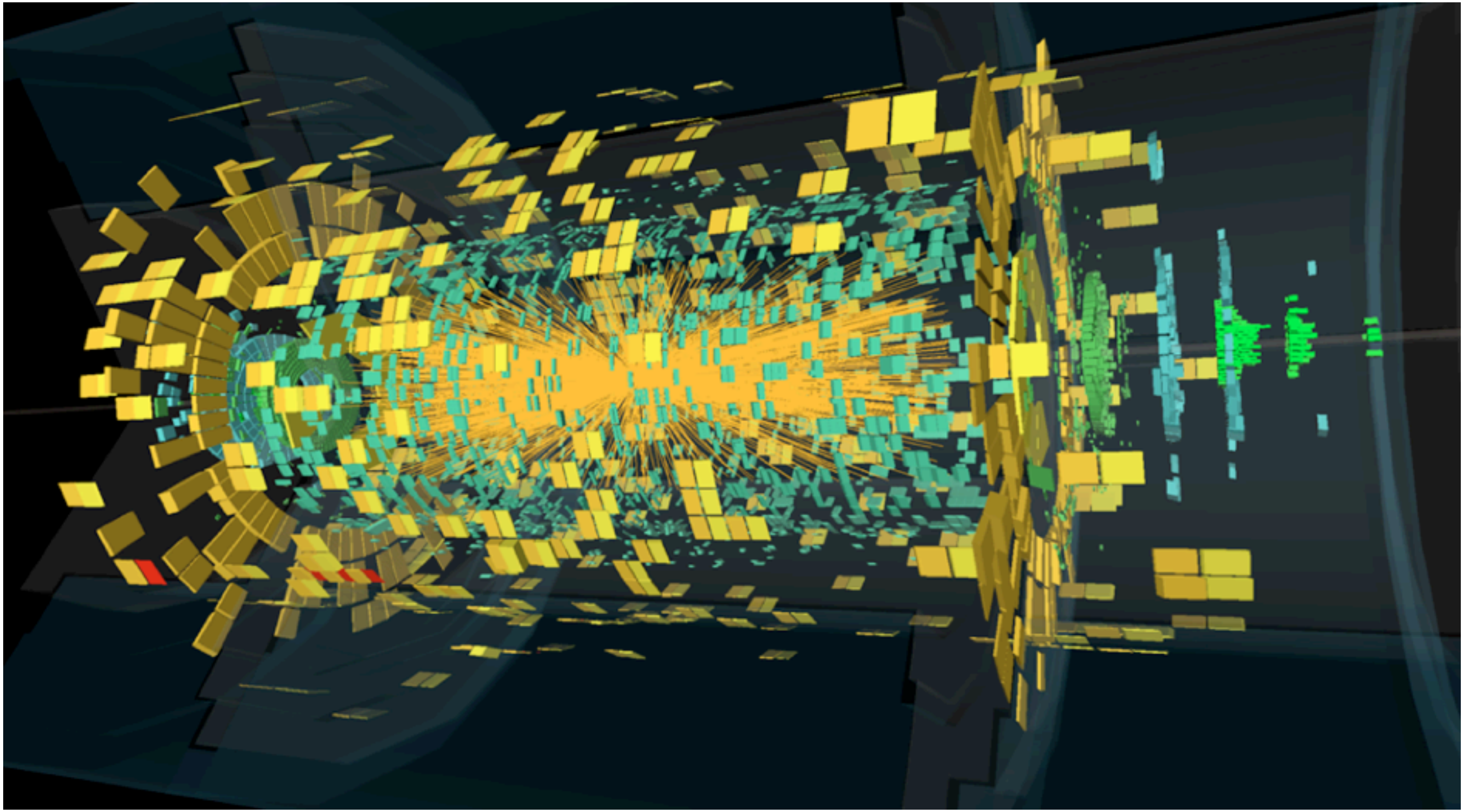

Overview of ATLAS Heavy Ions Results

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University of Sao Paulo
SILAFAE 2012

Outline

ATLAS detector

Pb+Pb data samples

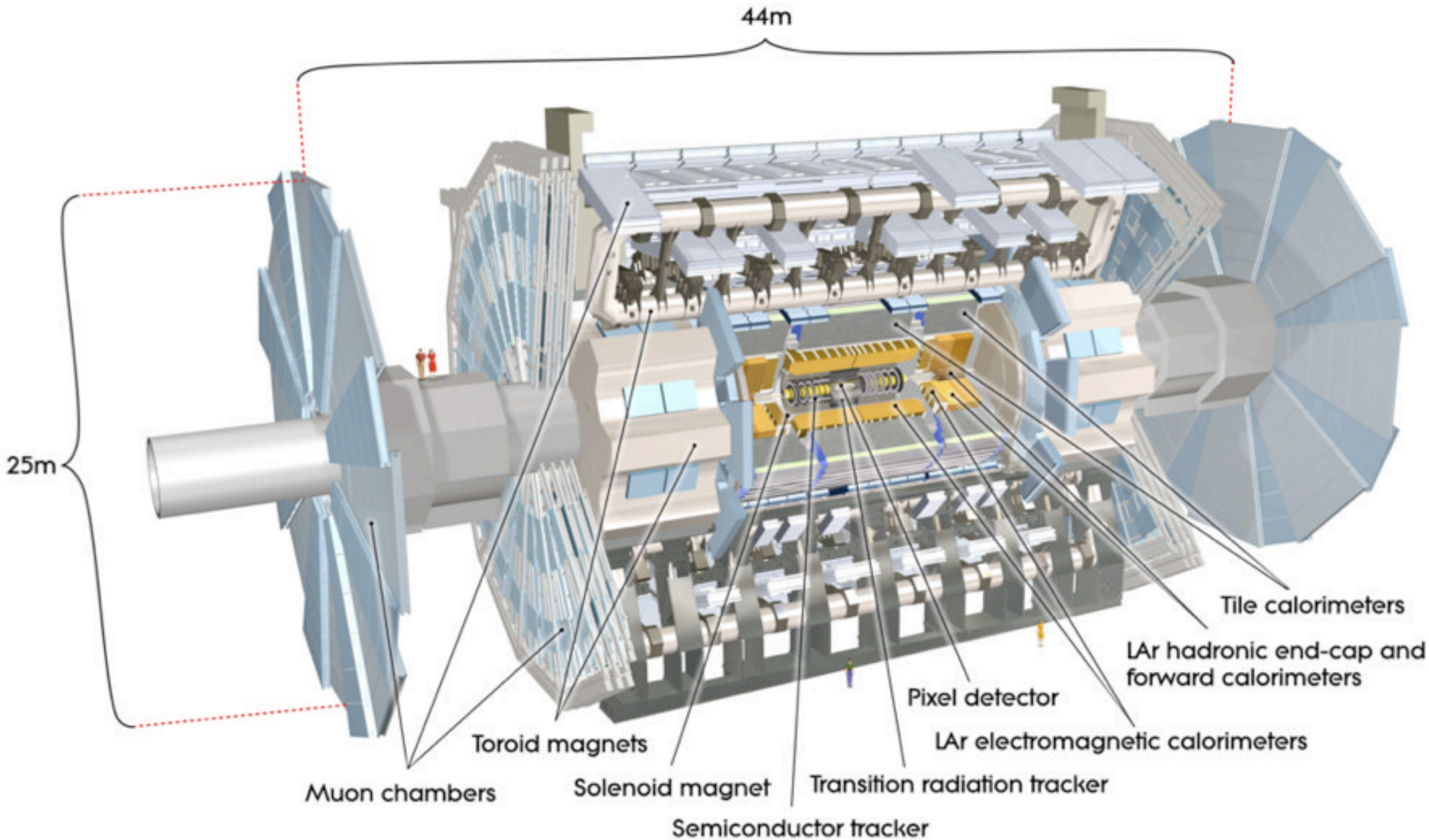
Jets
- Jet suppression
- Jet fragmentation

Photons and Z bosons

Photons,Z – jet correlations

Azimuthal anisotropy
- Event plane method
- Event by Event method
- Event plane correlations

ATLAS Detector



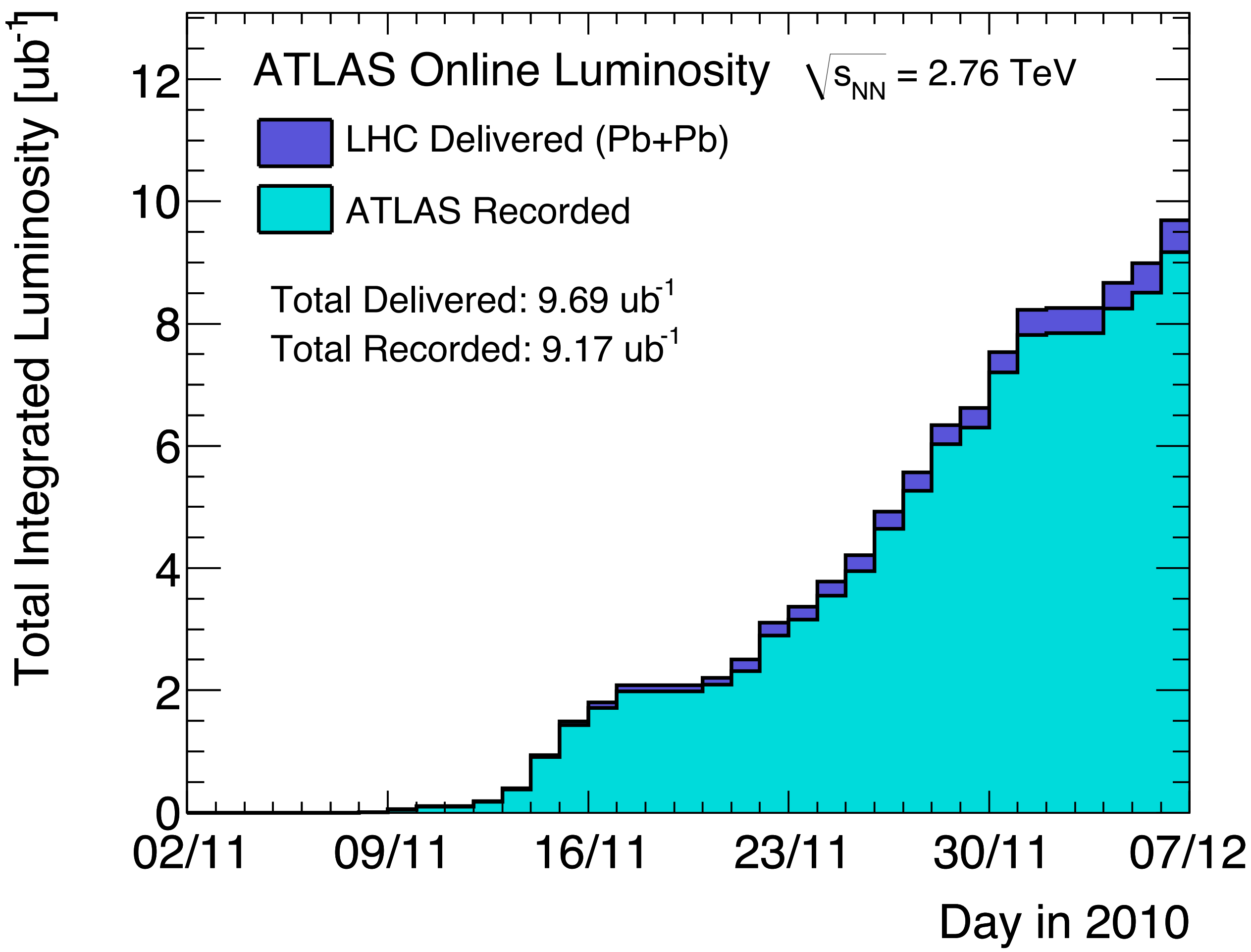
***Inner Detector* – Tracking |η|<2.5**

***Calorimetry* – |η|<4.9**

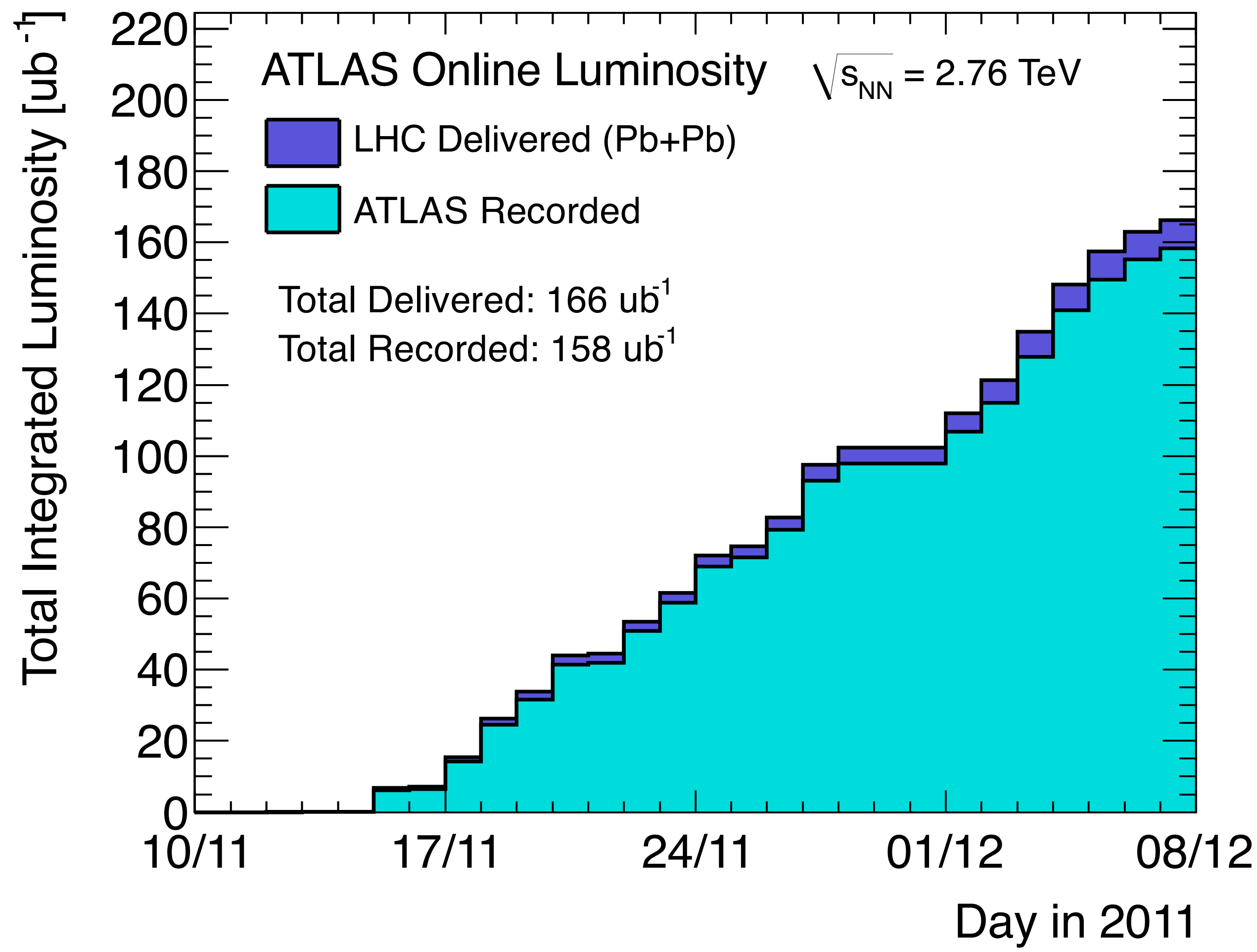
***Muon Spectrometer* - |η|<2.7**

Pb+Pb Data Samples

2010



2011

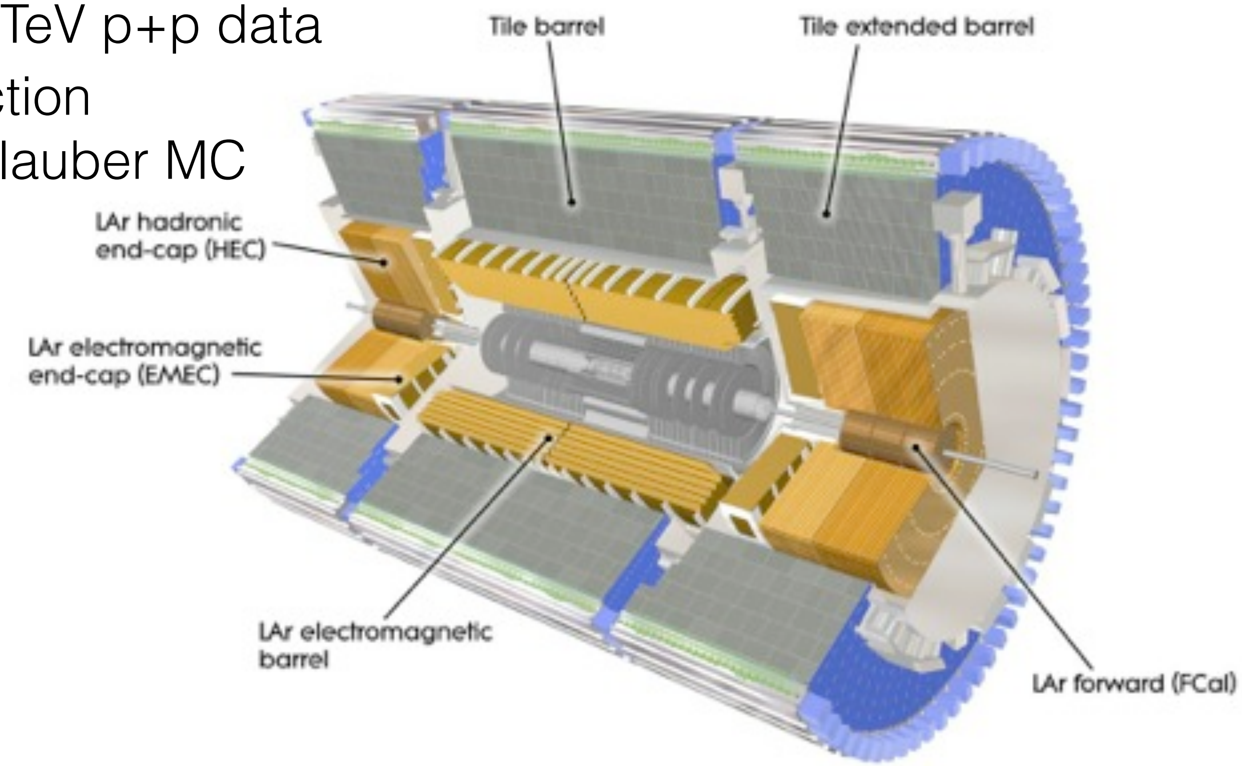


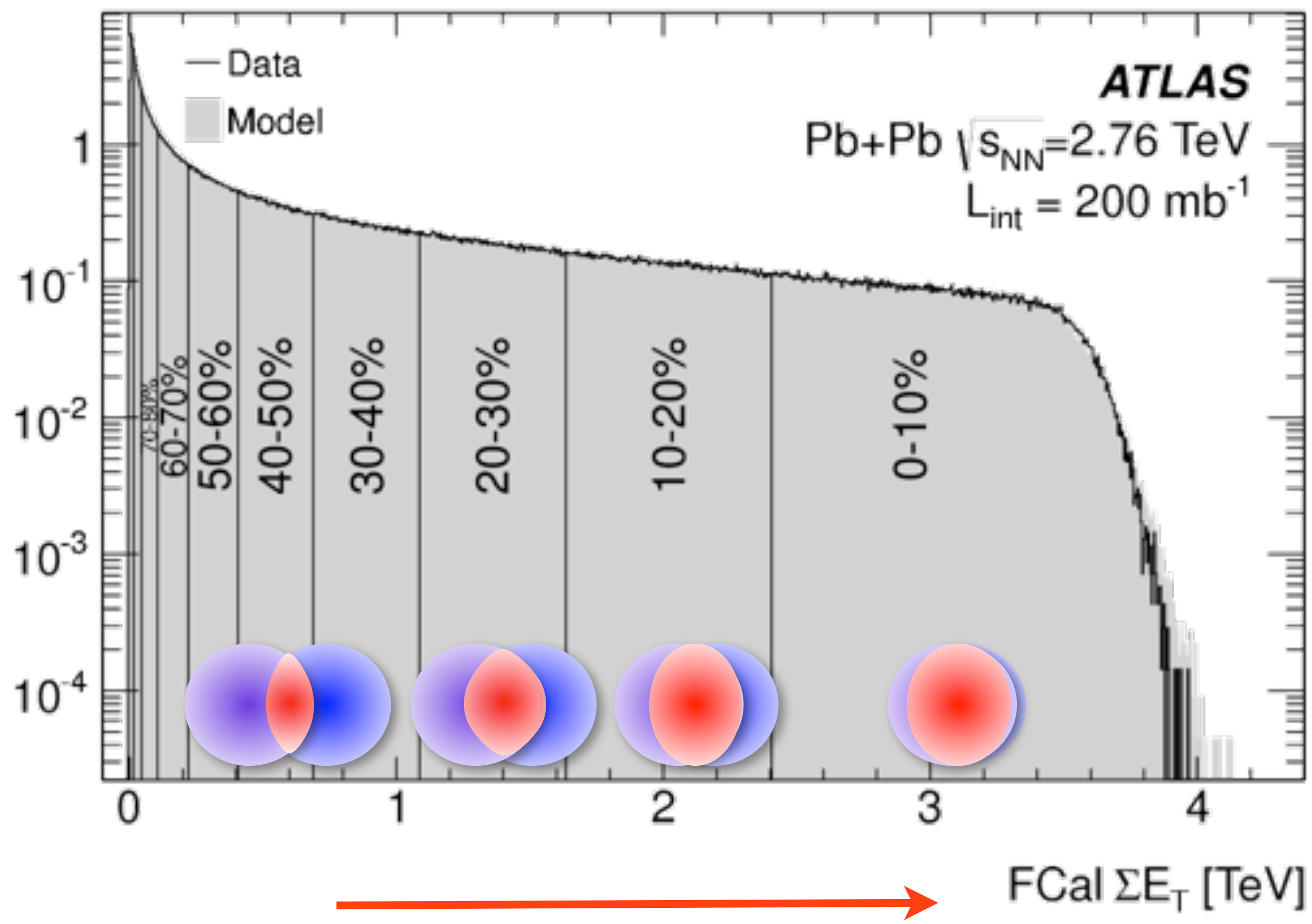
	2010	2011
L_{int}	8 μb^{-1}	0.15 nb^{-1}
Detector efficiency	> 97%	> 97%
Triggers	Minimum Bias (MB)	MB, e, μ, γ, jets, UPC
Events [X 10^6]	~ 50	~1000

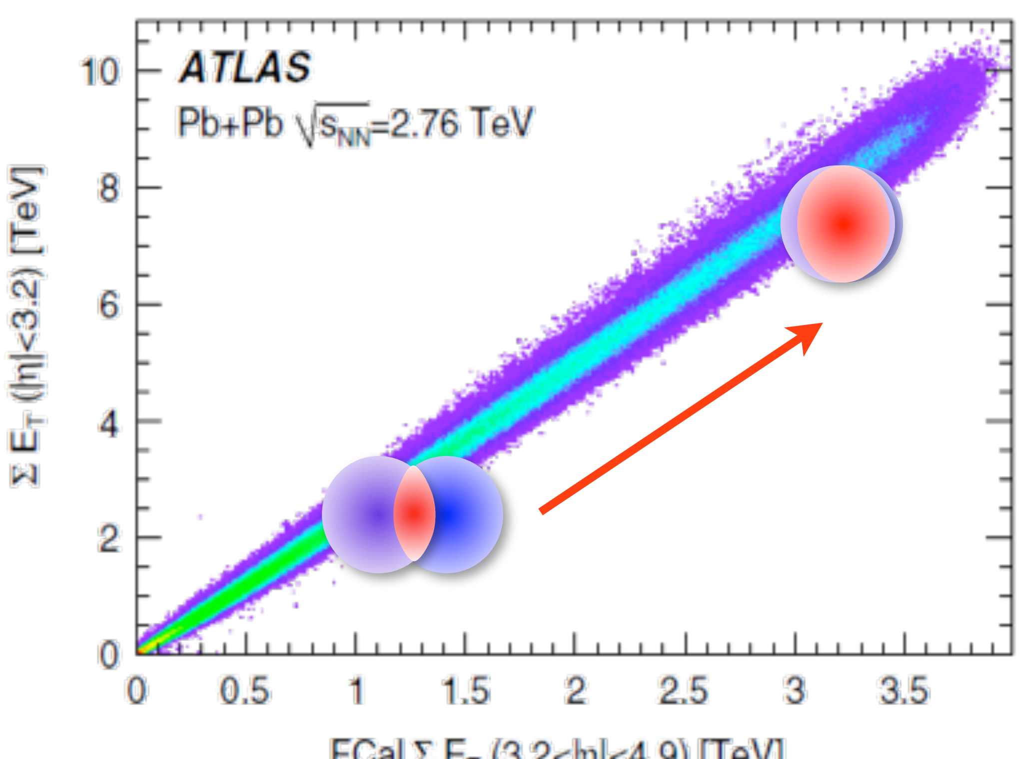
Pb+Pb Collision Centrality

Characterize centrality by percentiles of the total cross-section using forward calorimeter (FCal) ΣE_T ($3.2<|\eta|<4.9$)

Energy sum in FCal compared with Glauber MC ⊗ 2.76 TeV p+p data
Sampling fraction f = 98 ± 2% of total inelastic cross-section
Centrality parameters $\langle N_{part} \rangle$, $\langle N_{coll} \rangle$ calculated from Glauber MC (binning in the simulated FCal ΣE_T)



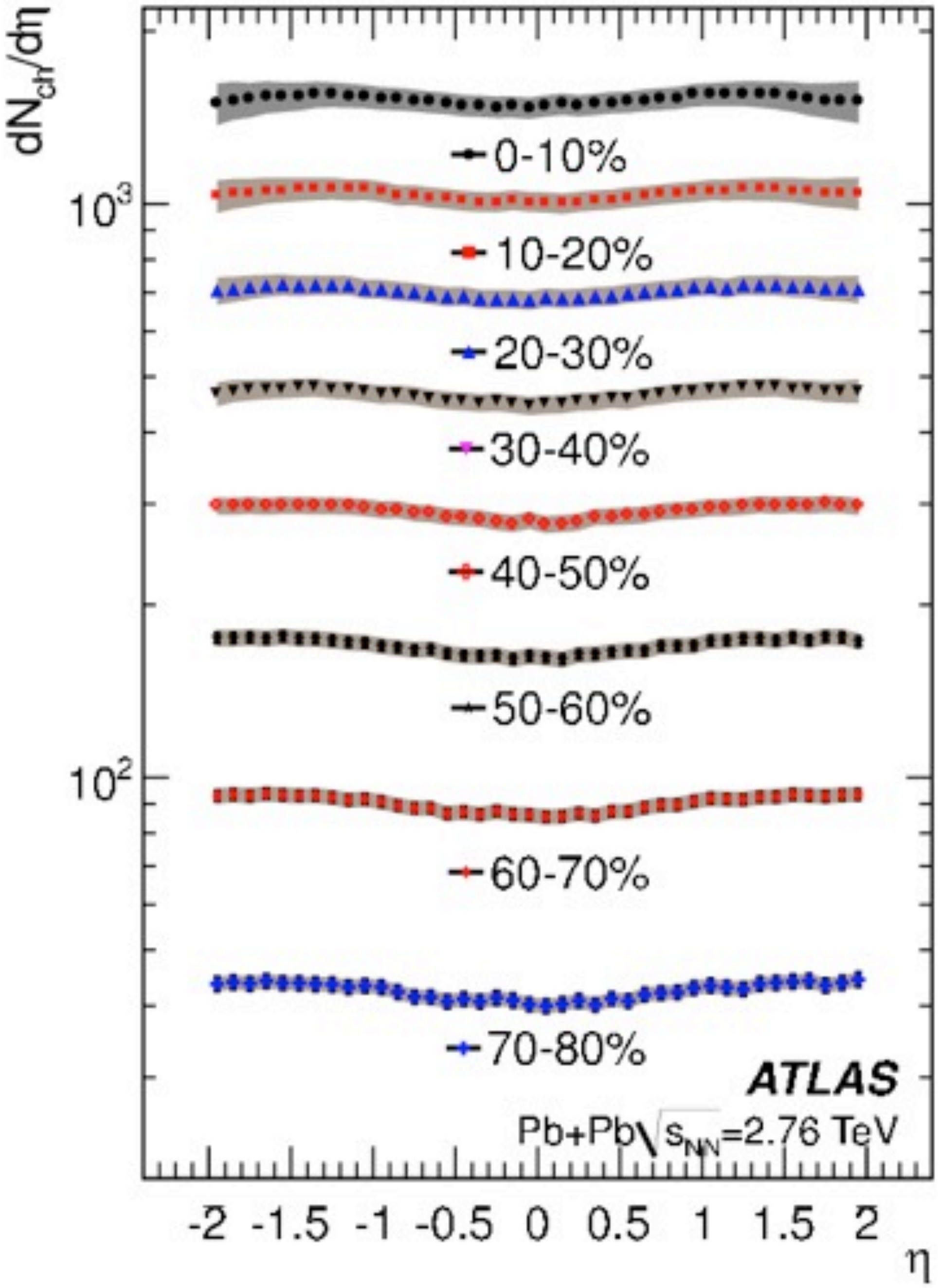


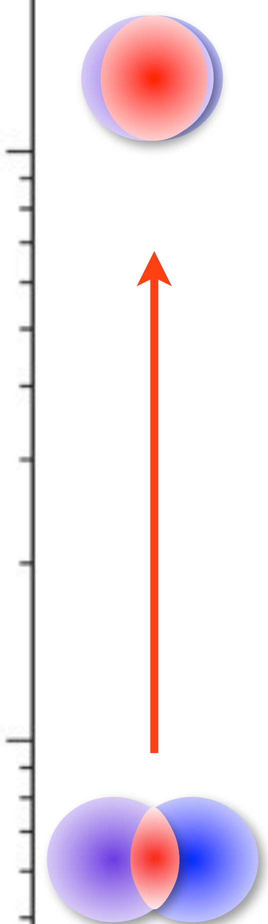


peripheral collisions → central collisions

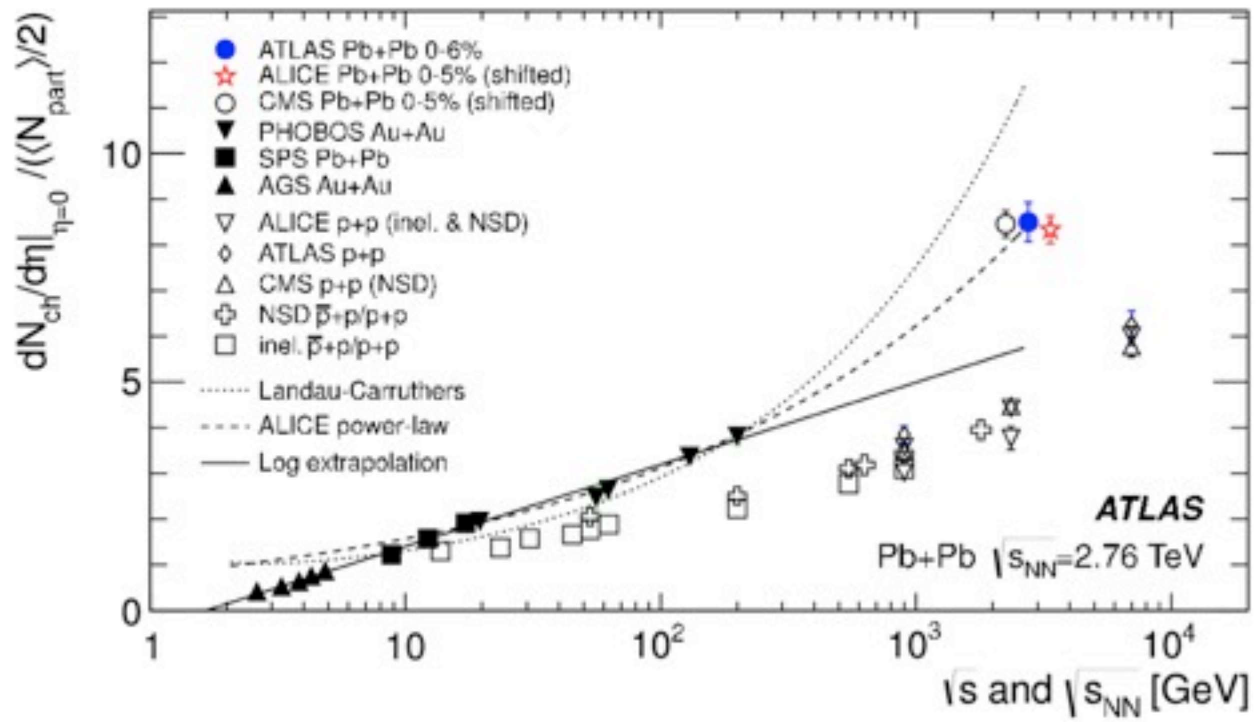
Multiplicity

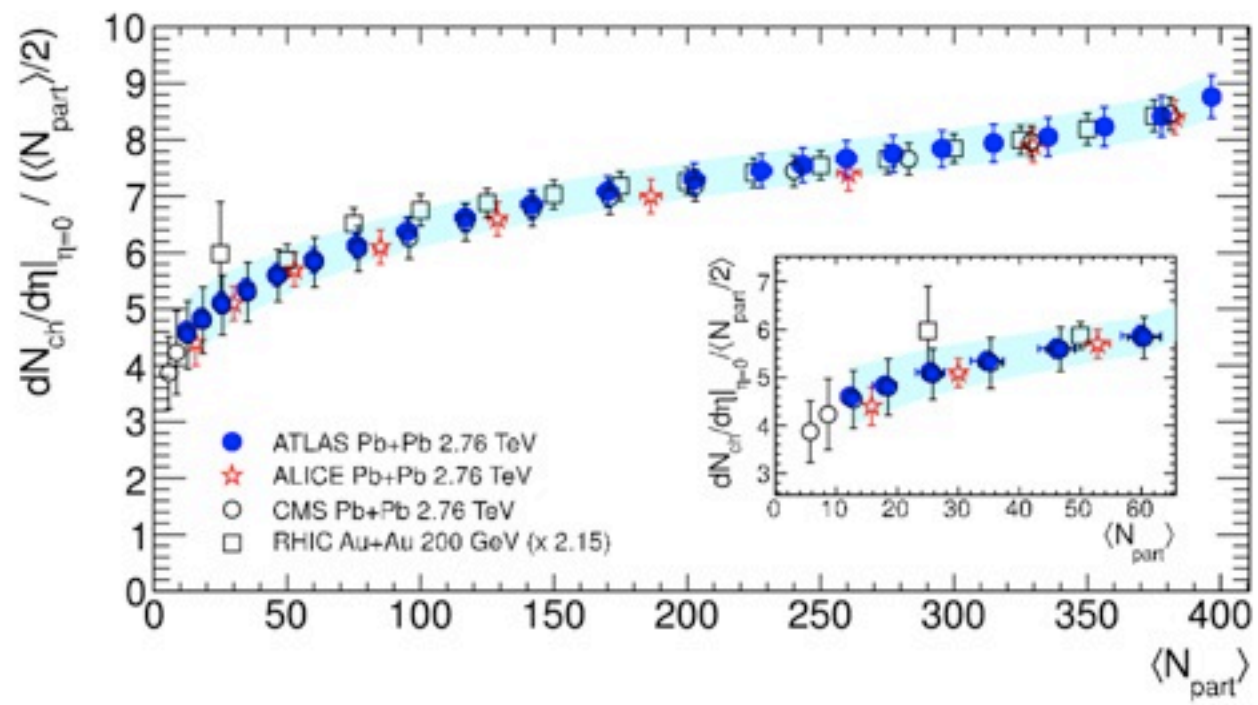
Phys.Lett. B710 (2012) 363-382





5% increase of yield from η~0 to η~1 in peripheral events (30-80% centrality class)

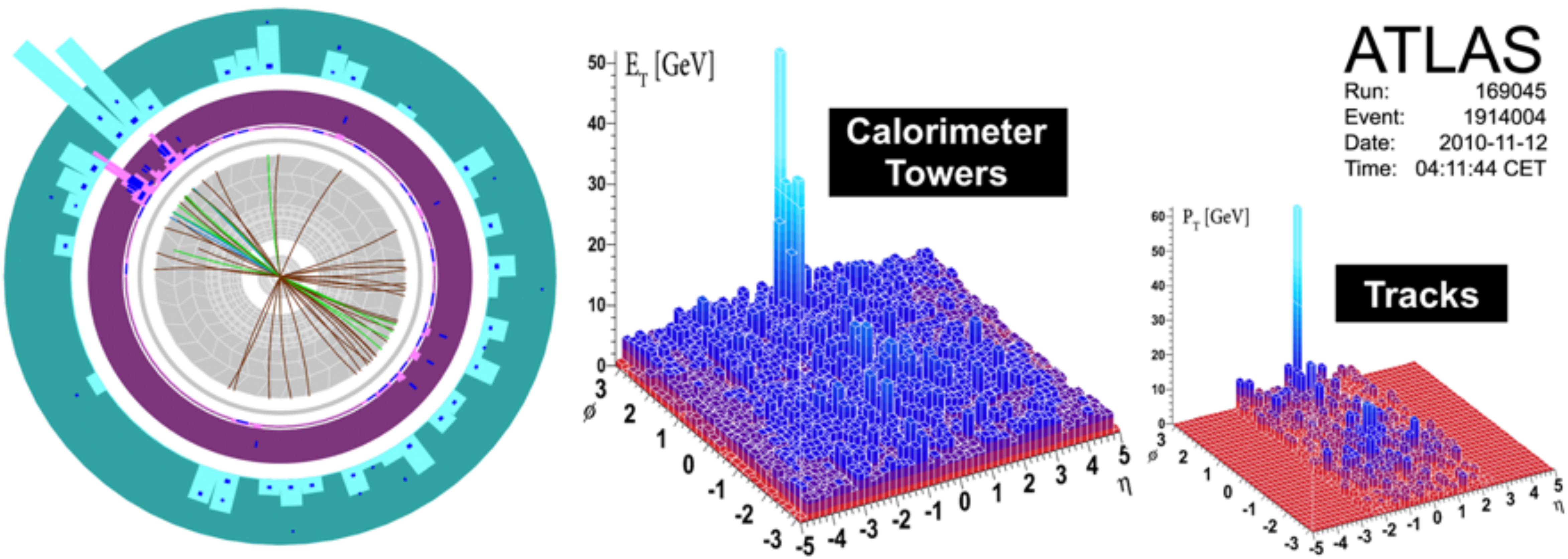




Up to 8,000 charged particles in ATLAS tracking @ $\sqrt{s_{NN}}$=2.76 TeV

Twice more particles per participant pair compared to p+p

Jets


E_T [GeV]
Calorimeter Towers
ATLAS
Run: 169045
Event: 1914004
Date: 2010-11-12
Time: 04:11:44 CET
P_T [GeV]
Tracks
η
ϕ

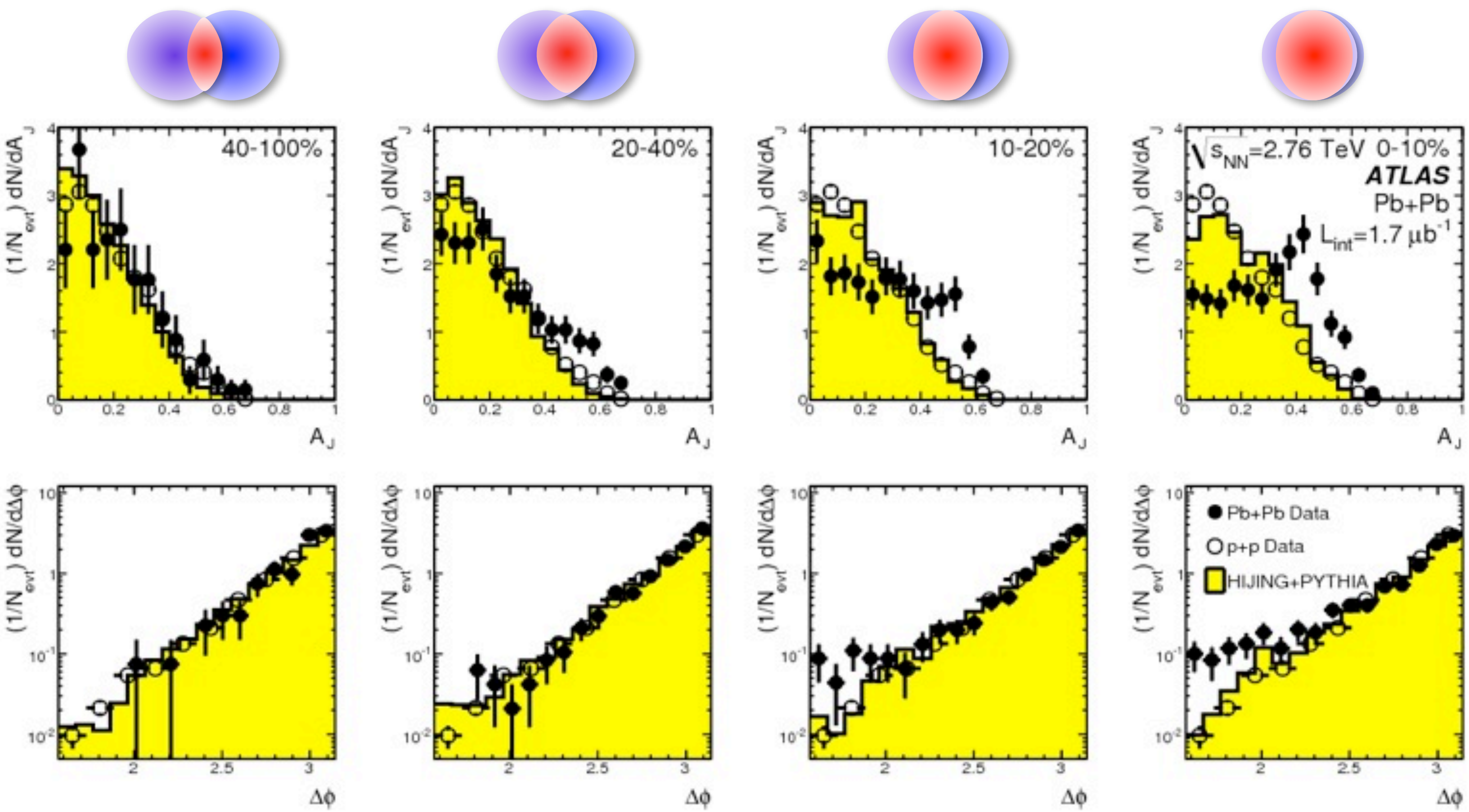
PRL 105, 252303 (2010) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

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

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta\phi > \frac{\pi}{2}$$

$$E_{T1} > 100 \quad \text{GeV}$$
$$E_{T2} > 25 \quad \text{GeV}$$

peripheral collisions → central collisions



Significant fraction of events with enhanced dijet asymmetry imbalance in E_T ...

...preserving the back-to-back angular correlation: dijet $|\Delta\phi|$ balance in E_T

Jet R_{CP}

Asymmetry alone cannot provide information about the details of parton energy loss

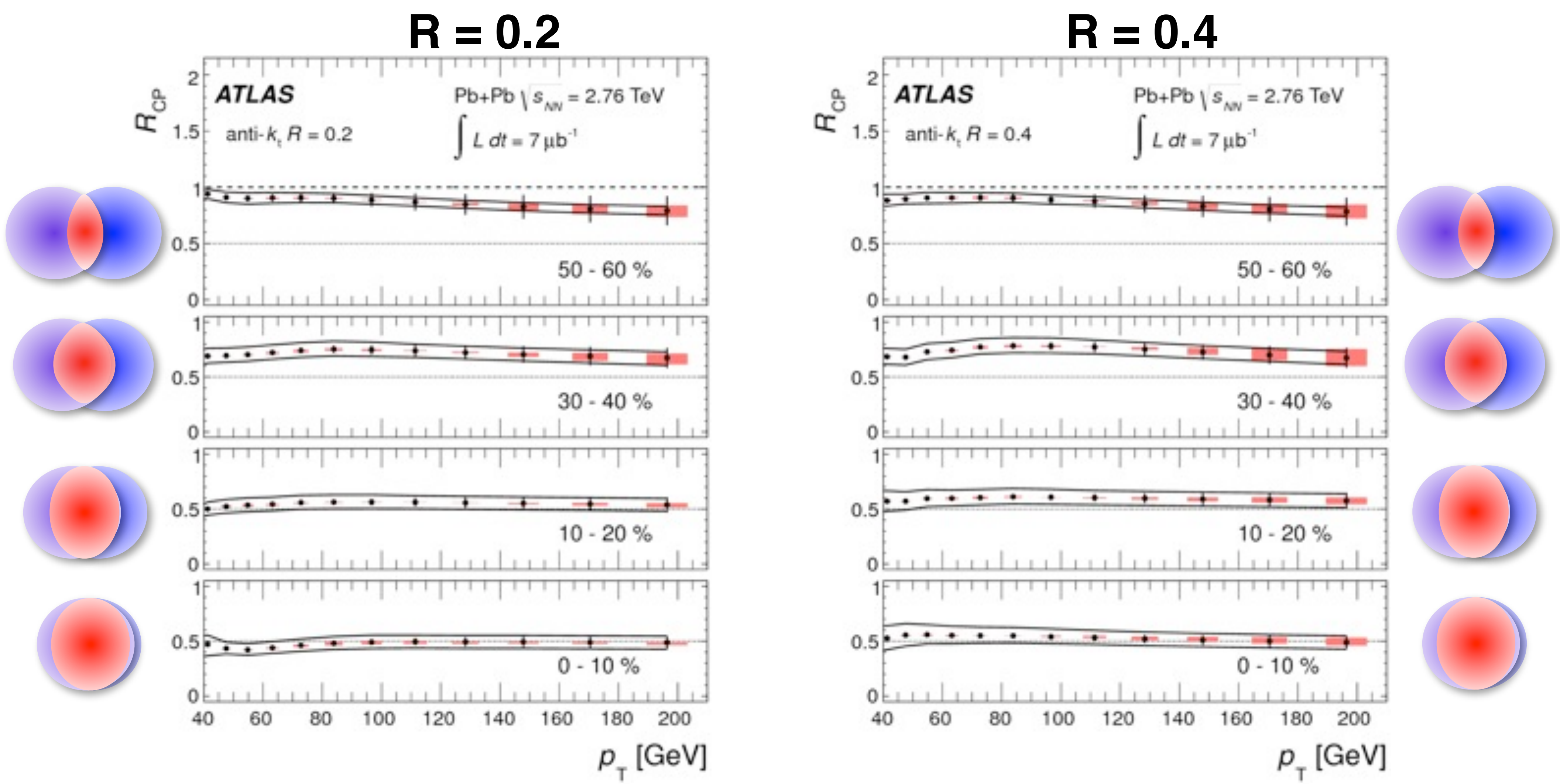
for radiative energy loss, jet energies can be reduced by greater “out of cone” radiation depending on the jet radii, according theoretical calculations (e.g., Y. He et al. *arXiv:1105.2566*).

Single inclusive jet spectra and central to peripheral ratio R_{CP}:

$$R_{CP} = \frac{\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN}{dp_T}\Big|_{cent}}{\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN}{dp_T}\Big|_{60-80}}$$

use anti-k_t algorithm with R=0.2, 0.3, 0.4 and 0.5;
result using SVD unfolding to remove detector effects;
~ 50 million events from 2010 PbPb data.

First LHC result on jet suppression (submitted to *PLB arXiv:1208.1967*)



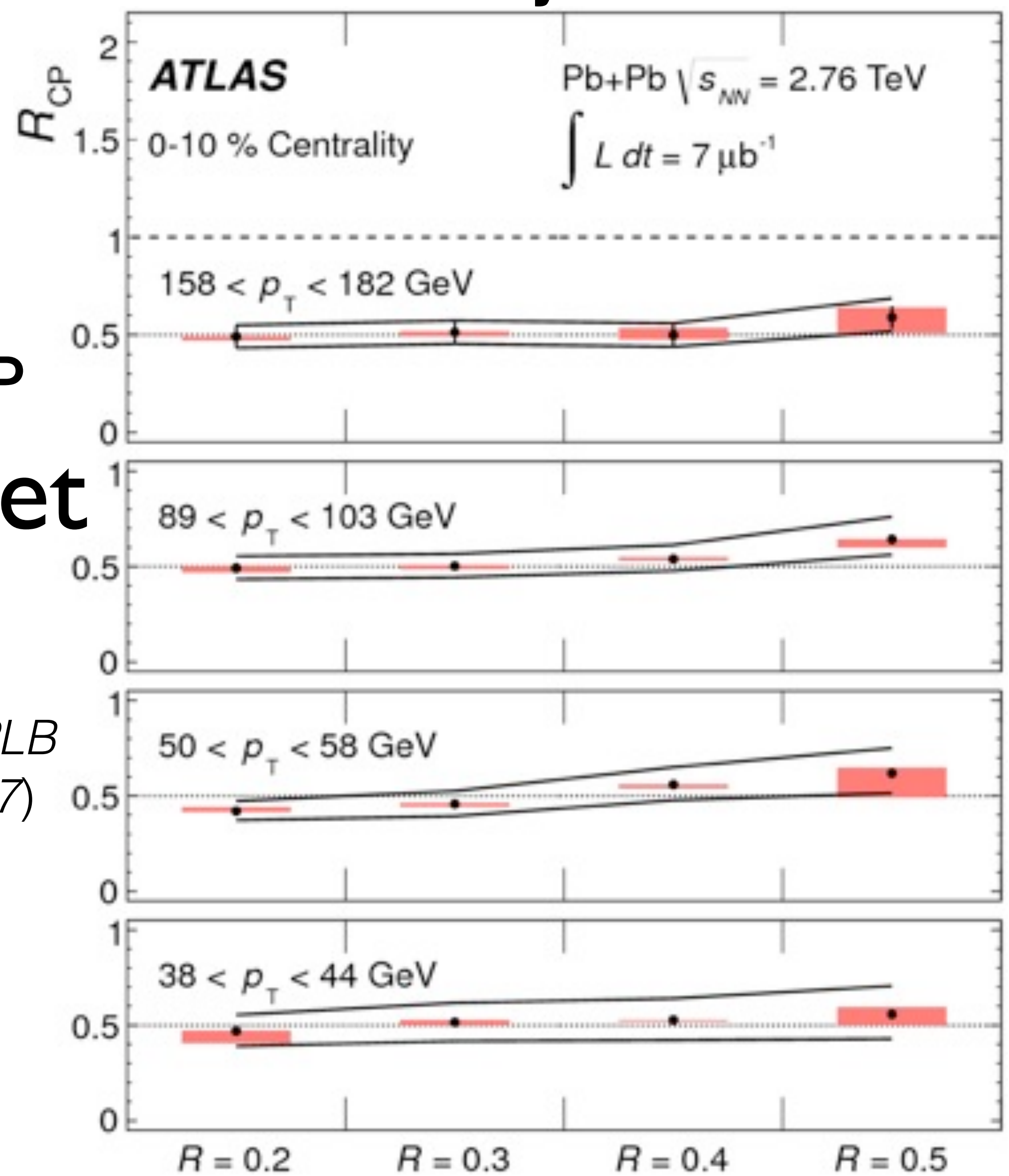
Suppression by a factor of 2 in central comparing to peripheral collisions.
R_{CP} for all centralities and for both radii show weak variation with pT.

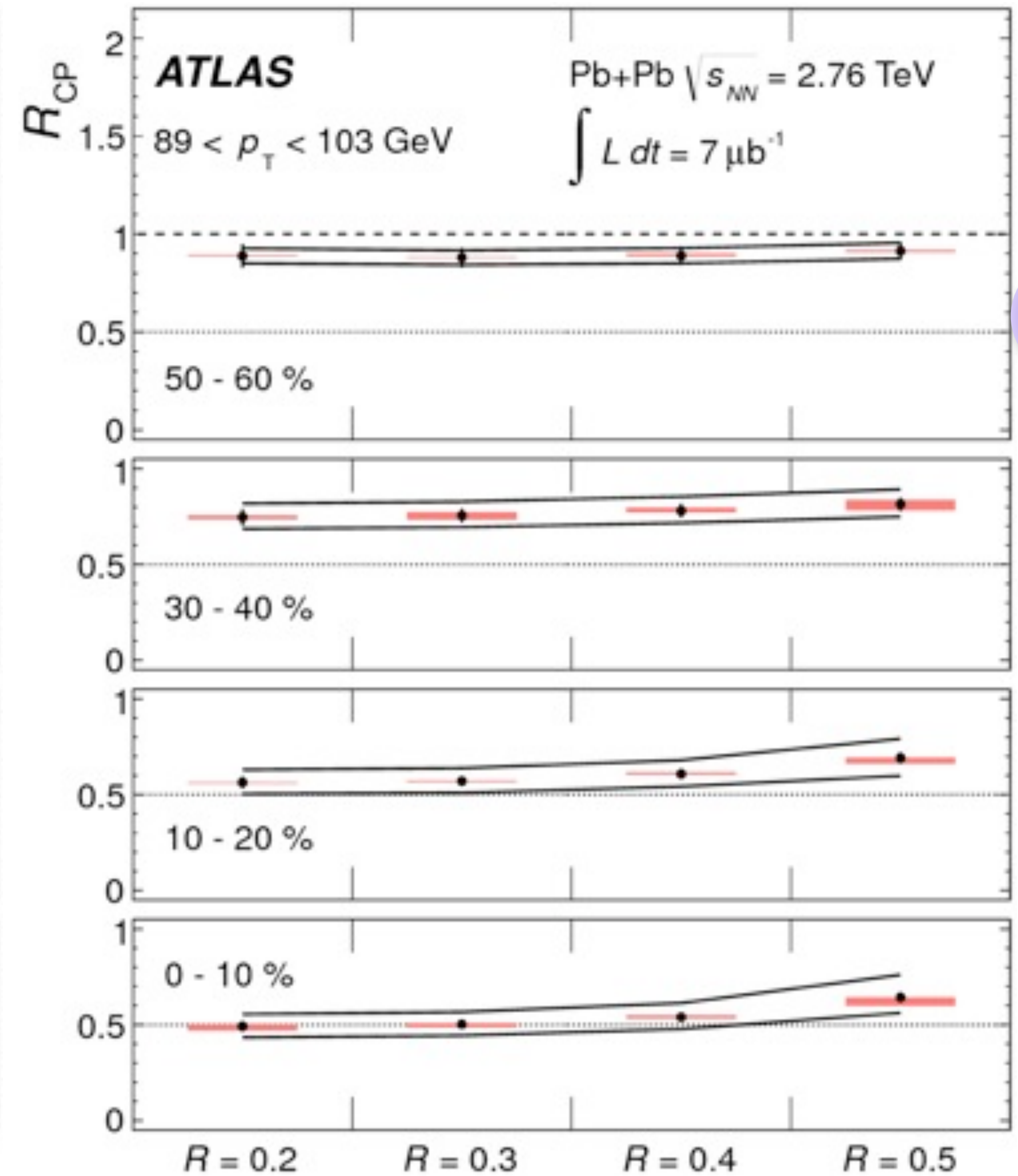
R_{CP} in 0-10% centrality bin

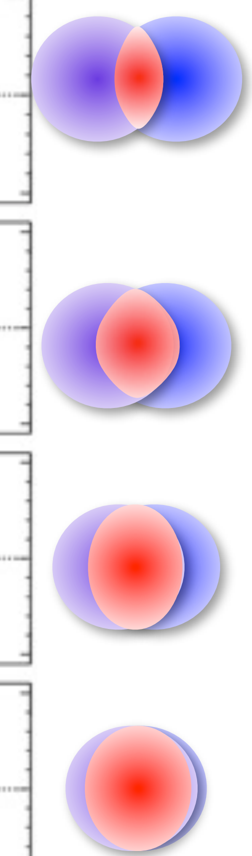
R_{CP} in 89< p_T < 103 GeV

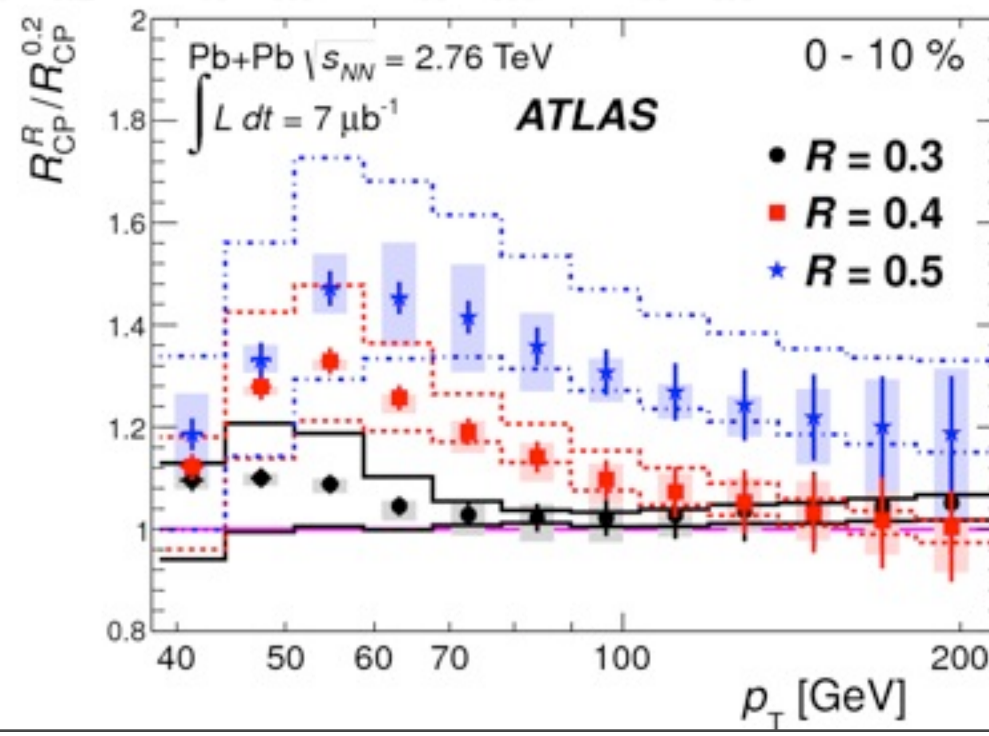
Jet R_{CP} versus jet size

(submitted to *PLB* *arXiv:1208.1967*)









Ratio of R_{CP} values between R=0.3, 0.4 and 0.5 jets and R=0.2 jets

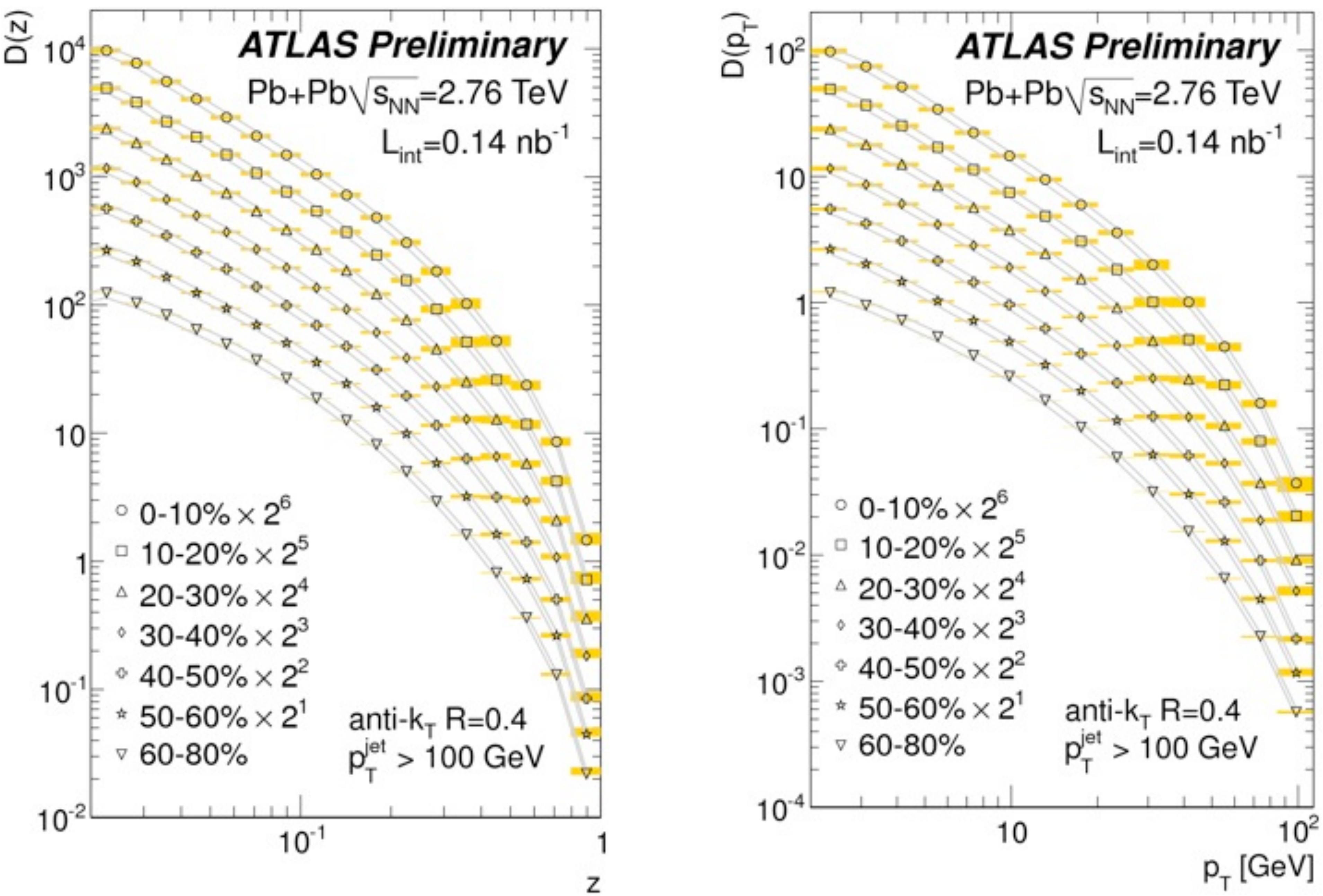
significant dependence of R_{CP} on jet radius!

Jet fragmentation

Asymmetry alone cannot provide information about the details of parton energy loss

A modification of jet internal structure was predicted by different theoretical models *N.Armesto et al., JHEP0802 (2008) 048.*

R = 0.4



ATLAS-CONF-2012-115

SVD unfolding was used to correct detector effects and to reduce the effect of statistical fluctuations:

D(z) unfolding accounts for track momentum and jet energy resolution;

D(pT) for track momentum resolution.

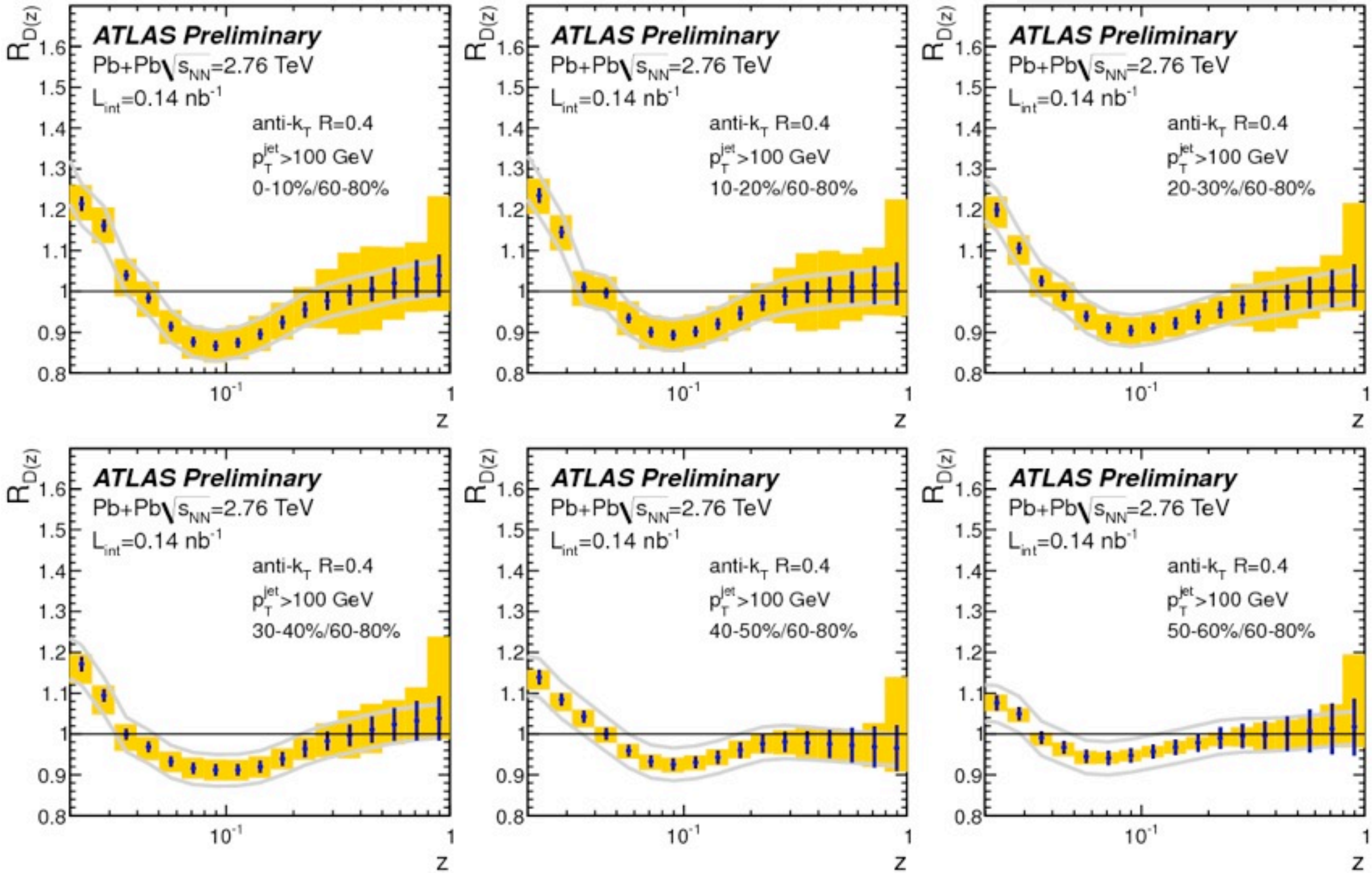
D(z) and D(pT) distributions have similar shape in all centrality bins.

ATLAS-CONF-2012-115

D(z) centrality dependence

Ratios are needed to study centrality dependence

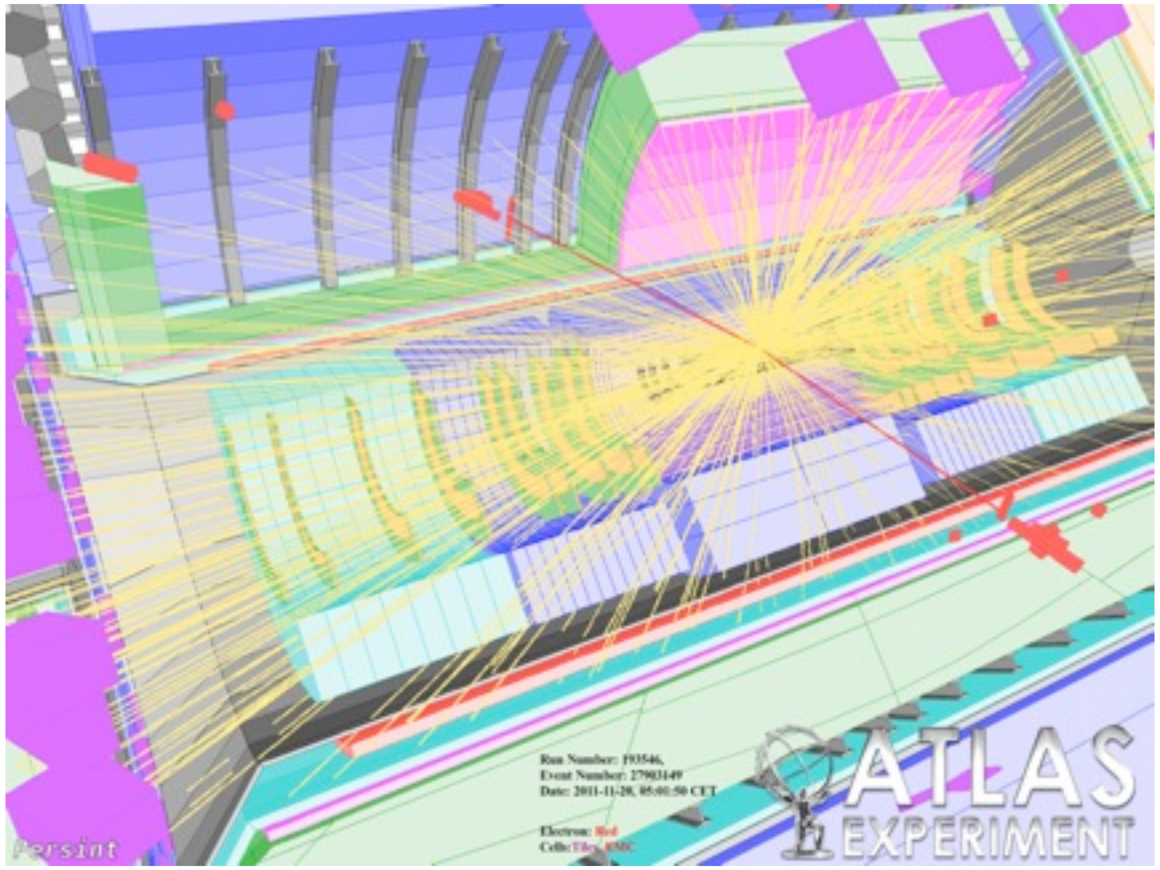
$$R_{D(z)} = \frac{D(z)|_{cent}}{D(z)|_{60-80\%}}$$



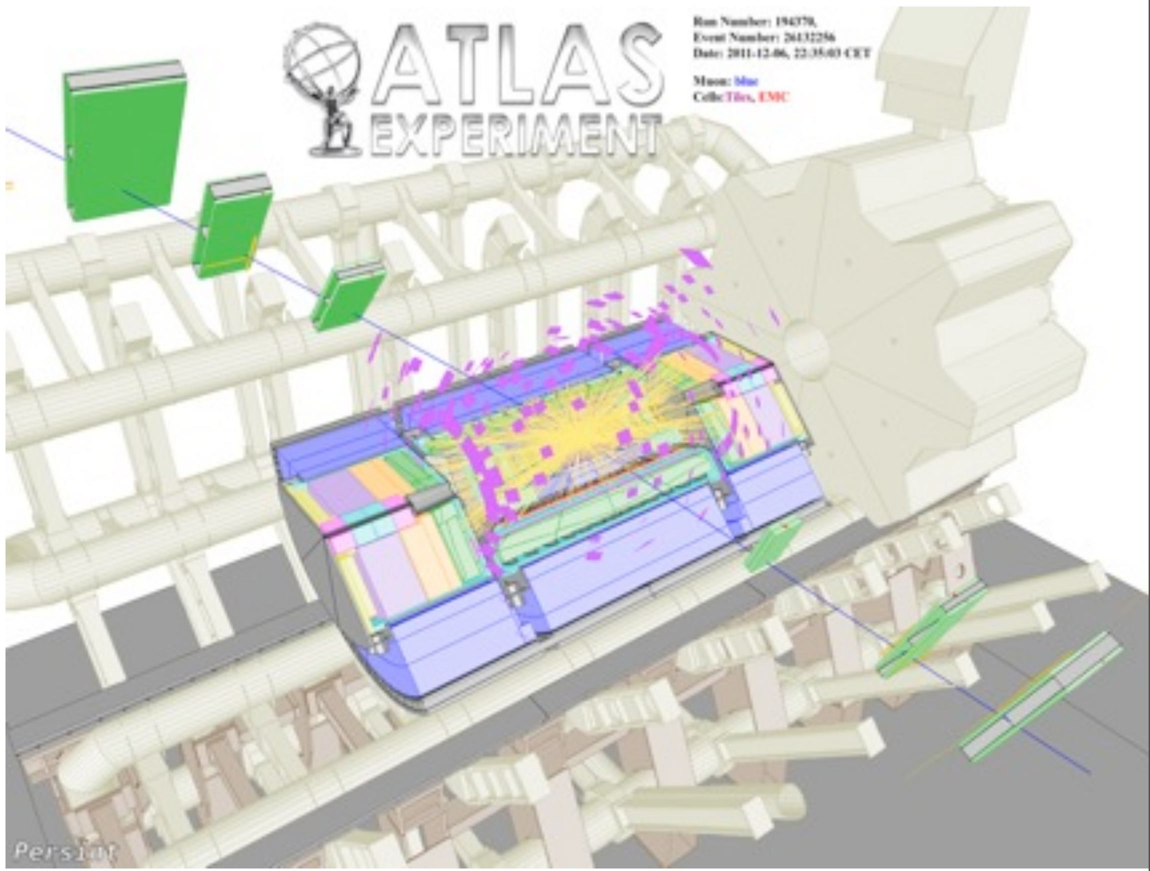
~15% suppression at intermediate z (~0.1) and 25% enhancement at very low z (~0.02)
no strong modification at large z in central collisions with respect to peripheral ones
similar results found for R=0.2 and 0.3 jets

Z bosons,

$Z \rightarrow e^+ e^-$



$Z \rightarrow \mu^+\mu^-$

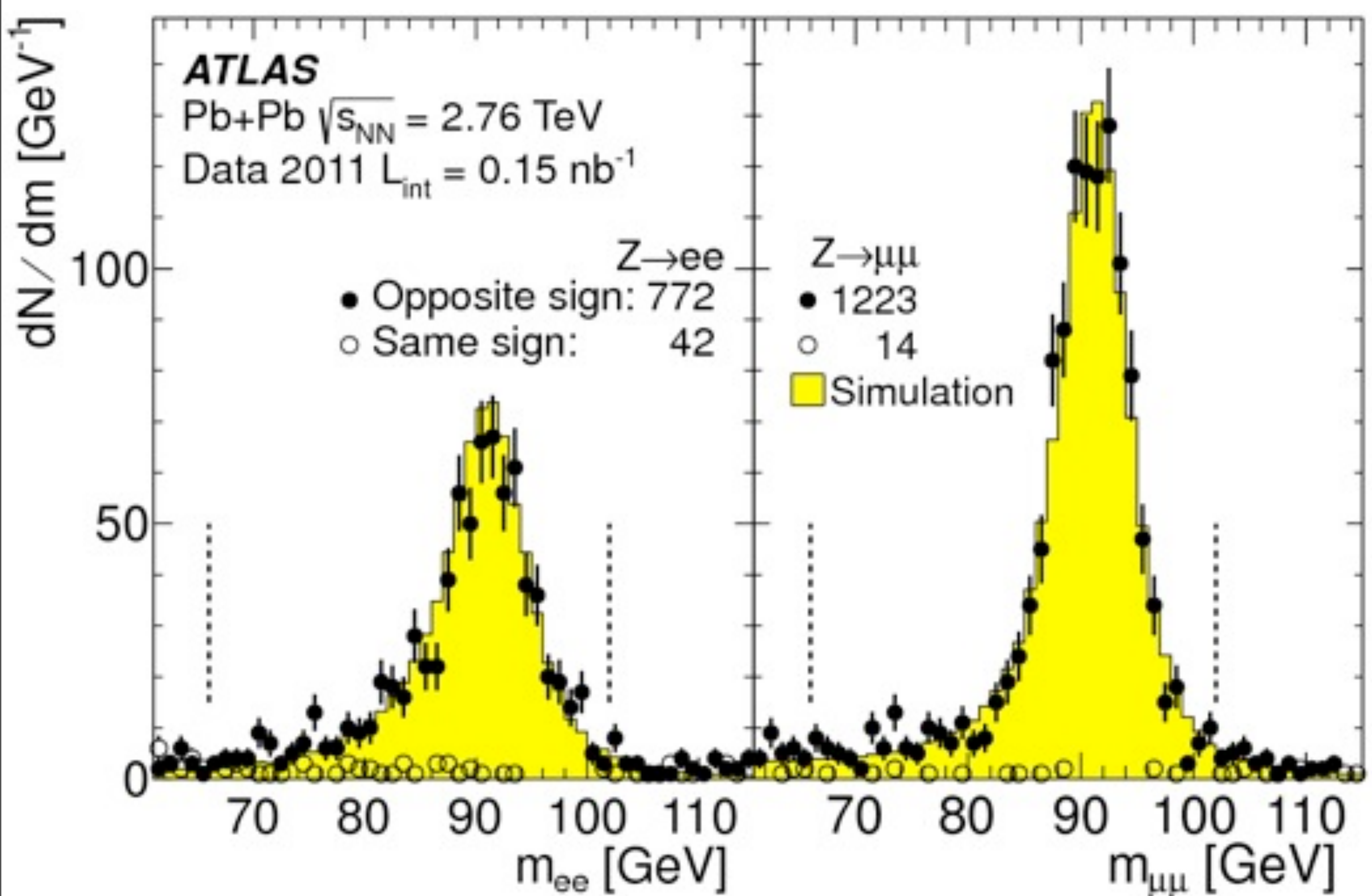


Photons
and
Z, photons - jet correlations

Z boson distributions

(submitted to *PRL, arXiv: 1210.6486*)

invariant mass

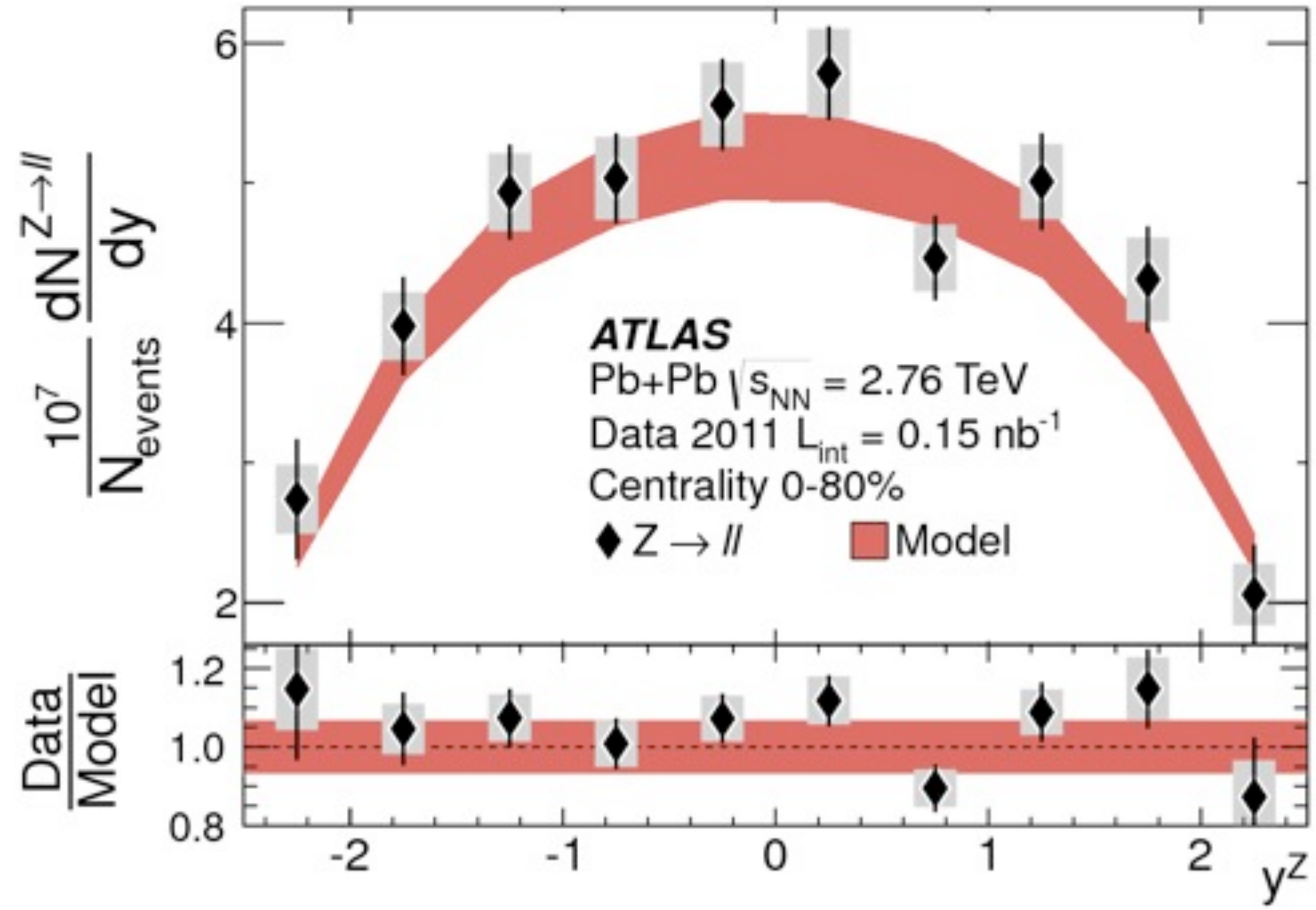


$Z \rightarrow e^+ e^-$
E_T >20 GeV, $|\eta|$<2.5
background ~5%

$Z \rightarrow \mu^+\mu^-$
p_T >10 GeV, $|\eta|$<2.5
background ~1%

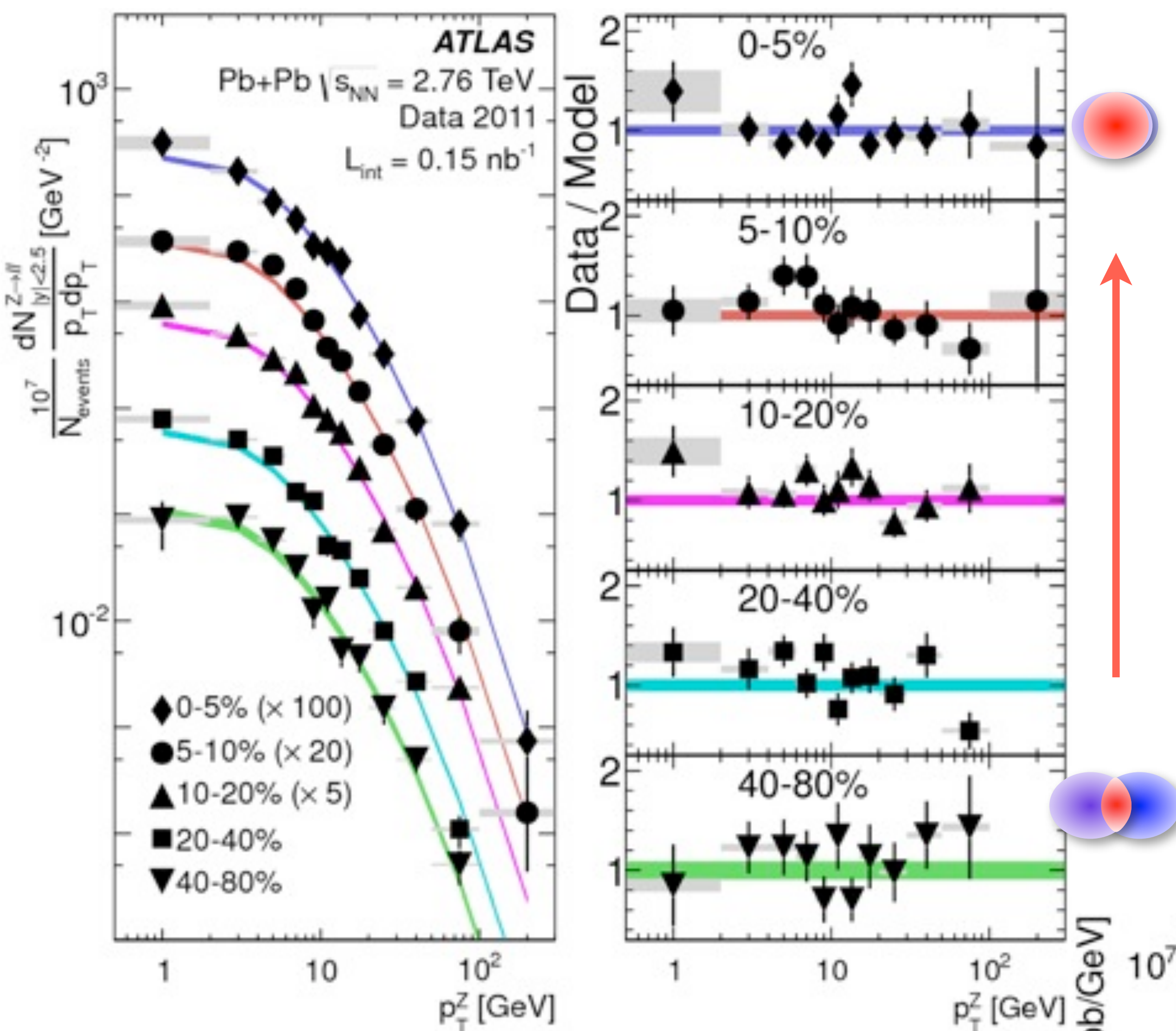
simulation weighted to match centrality distribution in data and normalized in the region of vertical dashed lines: $66 < m_{ll} < 102$ GeV

per event rapidity



consistent with PYTHIA simulations in p+p scaled to NNLO cross section ×<T_{AA}>

Z's



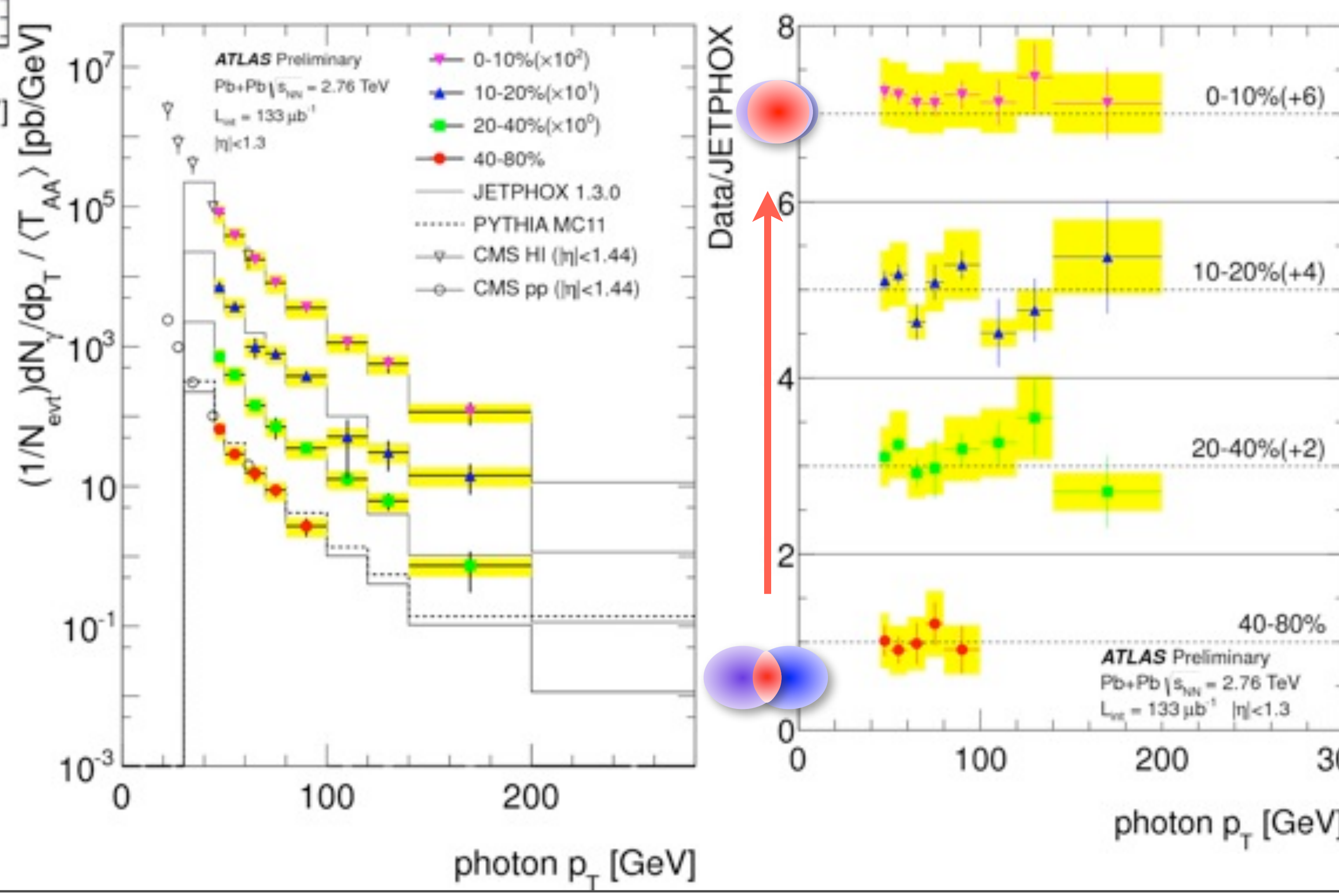
transverse momentum distribution averaged over |y|<2.5

spectral shape is centrality independent

consistent with PYTHIA simulations in p+p scaled to NNLO cross section × <T_{AA}>

(submitted to *PRL, arXiv: 1210.6486*)

Photons



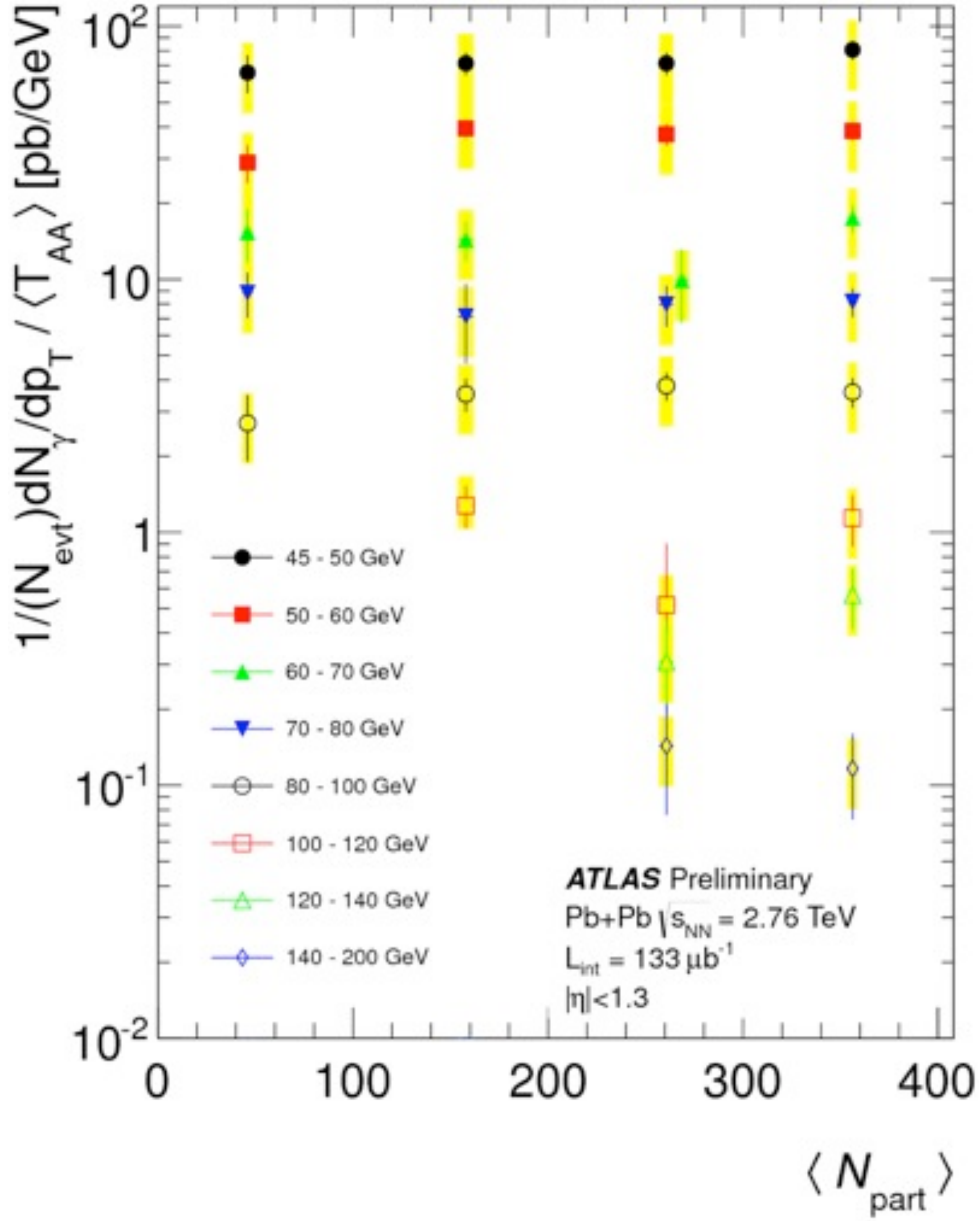
yields scaled by <T_{AA} > and compared to JETPHOX predictions

ratio: Data/JETPHOX ≈ 1

ATLAS-CONF-2012-051

Photon per-event yields

ATLAS-CONF-2012-051

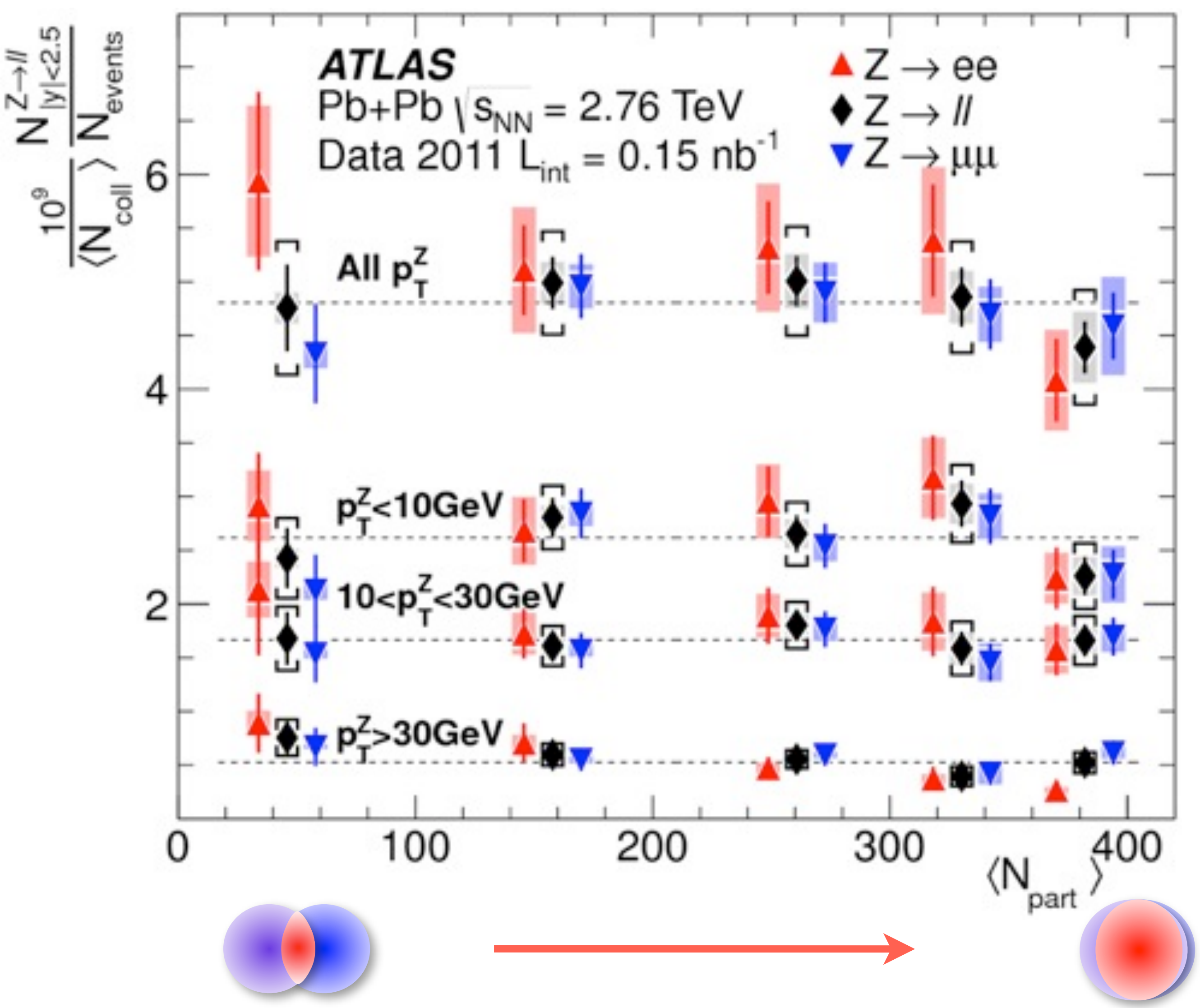


no centrality dependence in any of the measured p_T intervals

photon yields in HI collisions scale linearly with $\langle T_{AA}\rangle$ or equivalently with $\langle N_{coll}\rangle$

photon production rates are not affected by QGP

isolated direct photons seem to be a perfect probe to help in understanding of the jet quenching phenomenon



Z boson per-event yields

integrated yields show a clear scaling with number of binary collisions

same dependence observed for three momentum ranges (<10, 10-30, >30 GeV)

(submitted to *PRL*, *arXiv: 1210.6486*)

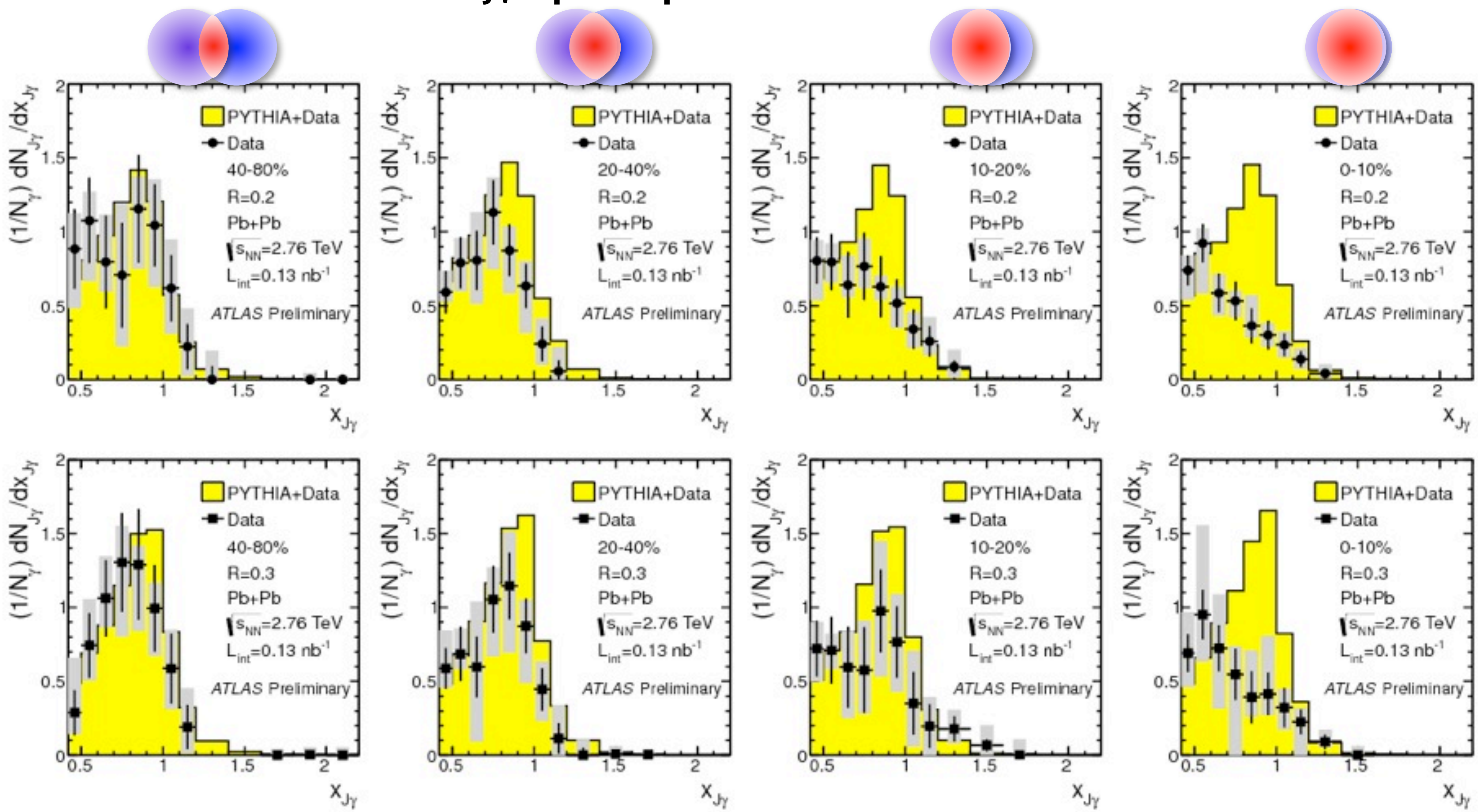
Photon- jet $x_{j\gamma}$ distributions

$E\gamma$ > 60 GeV: 60-90 GeV, $|\eta|<1.3$
Jet: anti-k_T, R=0.2, 0.3, p_T>25 GeV, $|\eta|<2.1$
γ-jet separation $\Delta\varphi > 7\pi/8$ (back-to-back)

$$x_{J\gamma}=p_T^{jet}/p_T^{\gamma}$$

R = 0.2

R = 0.3



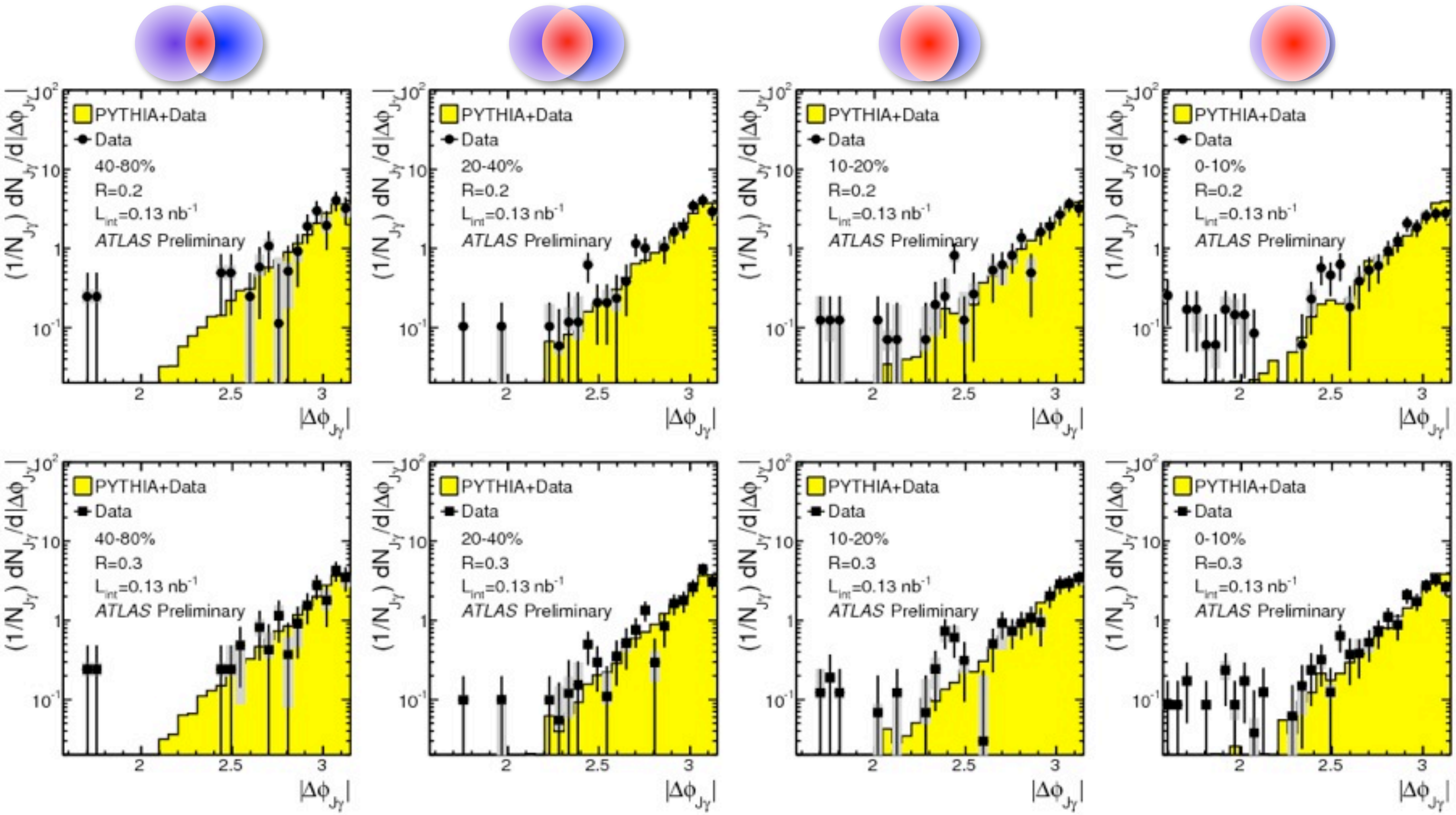
Shape and integral compatible with PYTHIA for peripheral collisions.
With increasing centrality shift towards smaller xJγ and reduction of the integral.

ATLAS-CONF-2012-121

Photon- jet ΔΦ distributions

R = 0.2

R = 0.3



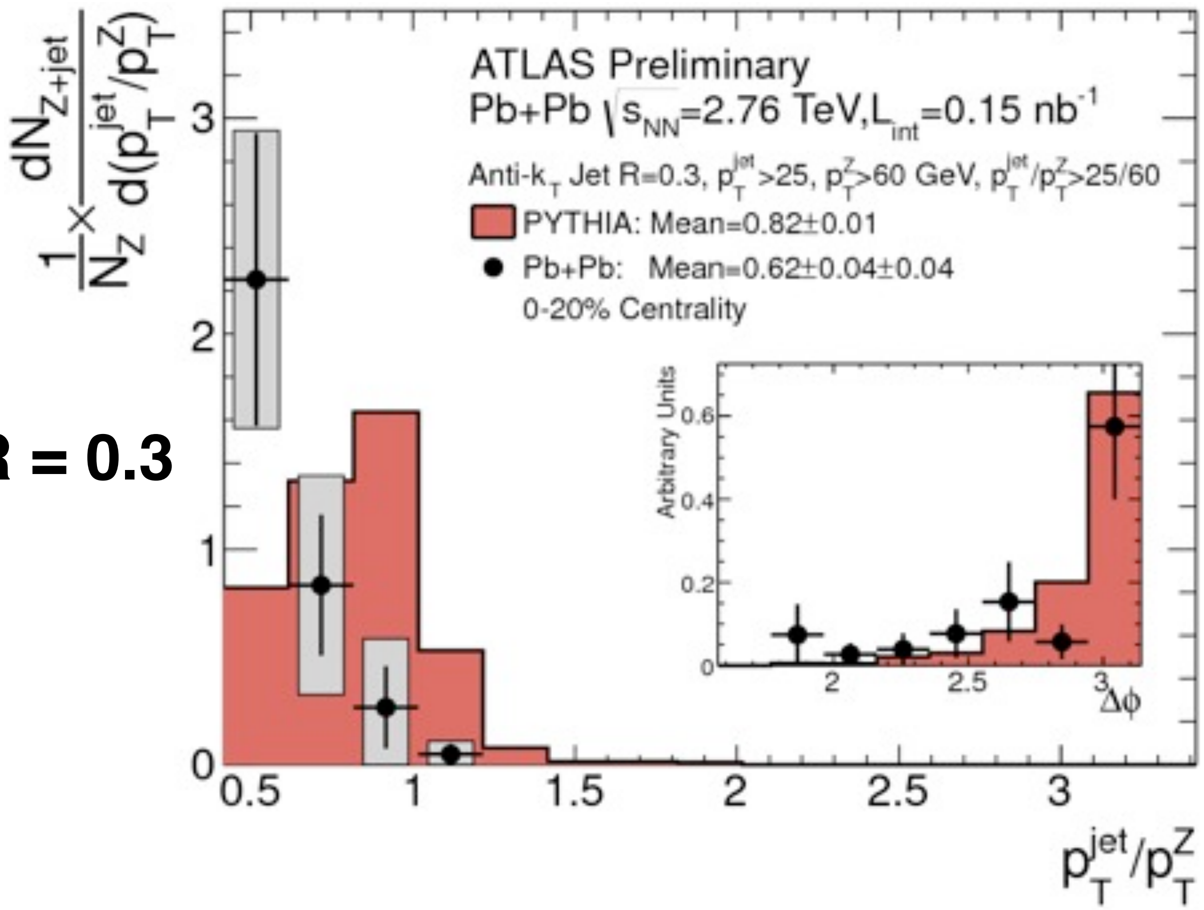
Δφ between photon and jet (normalized by integral).
Shapes are consistent between data and simulation in all centrality, jet cone size.

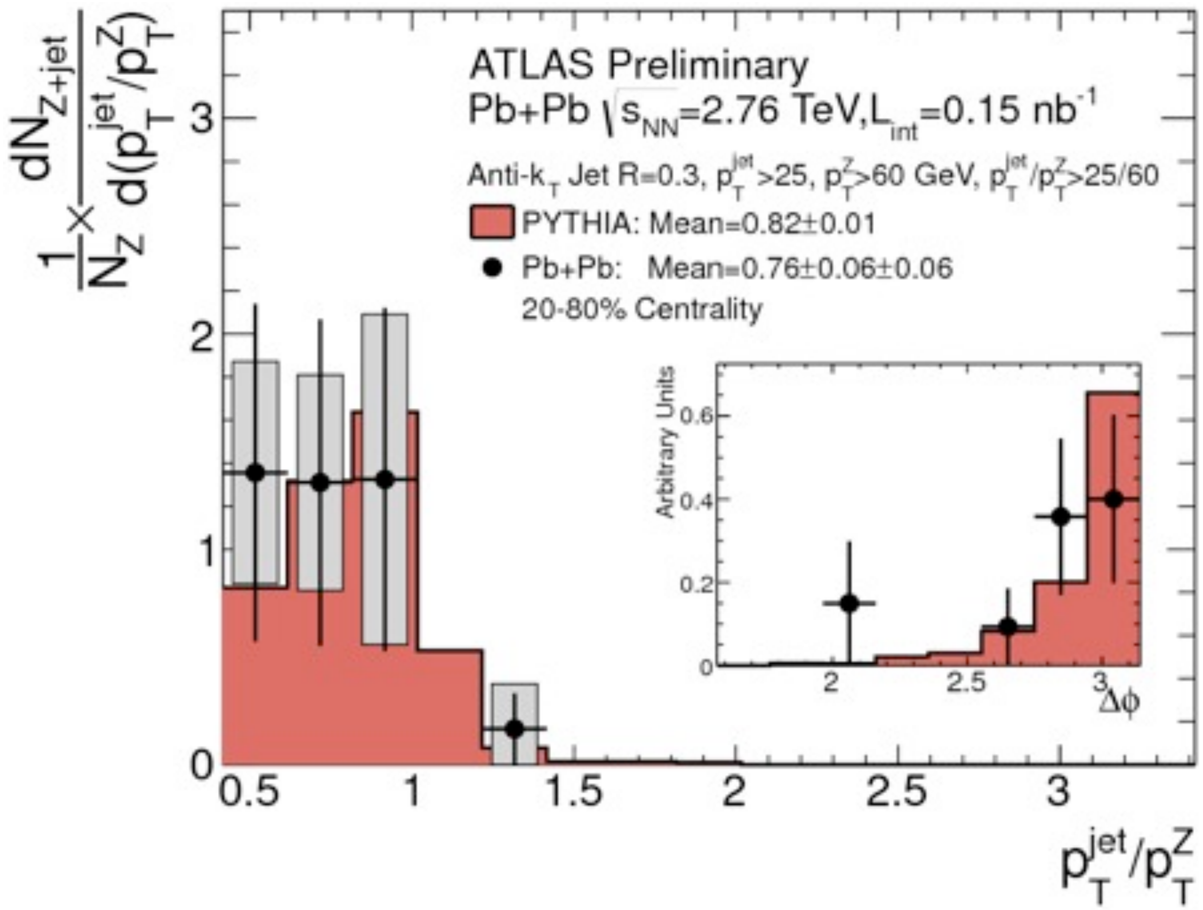
Z - jet correlations

0-20 % centrality

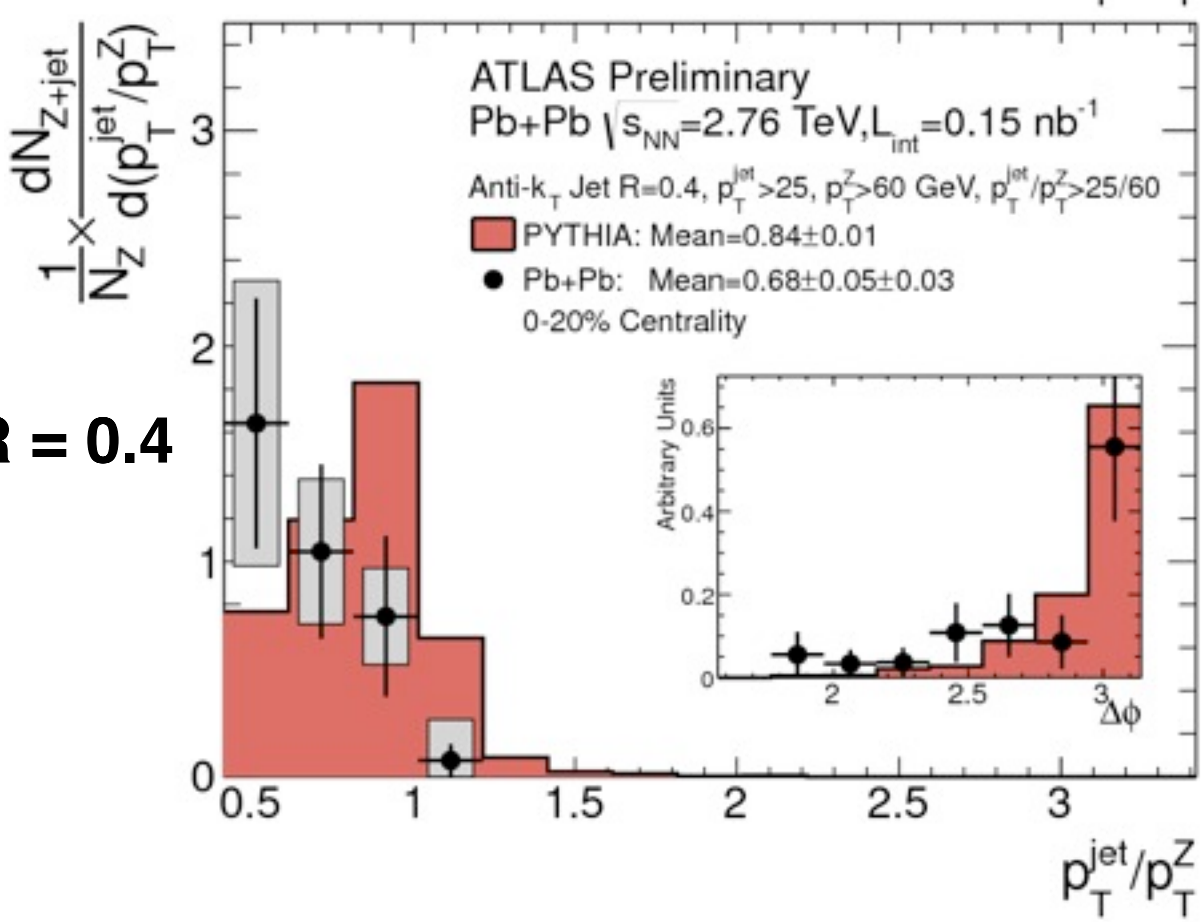
20-80 % centrality

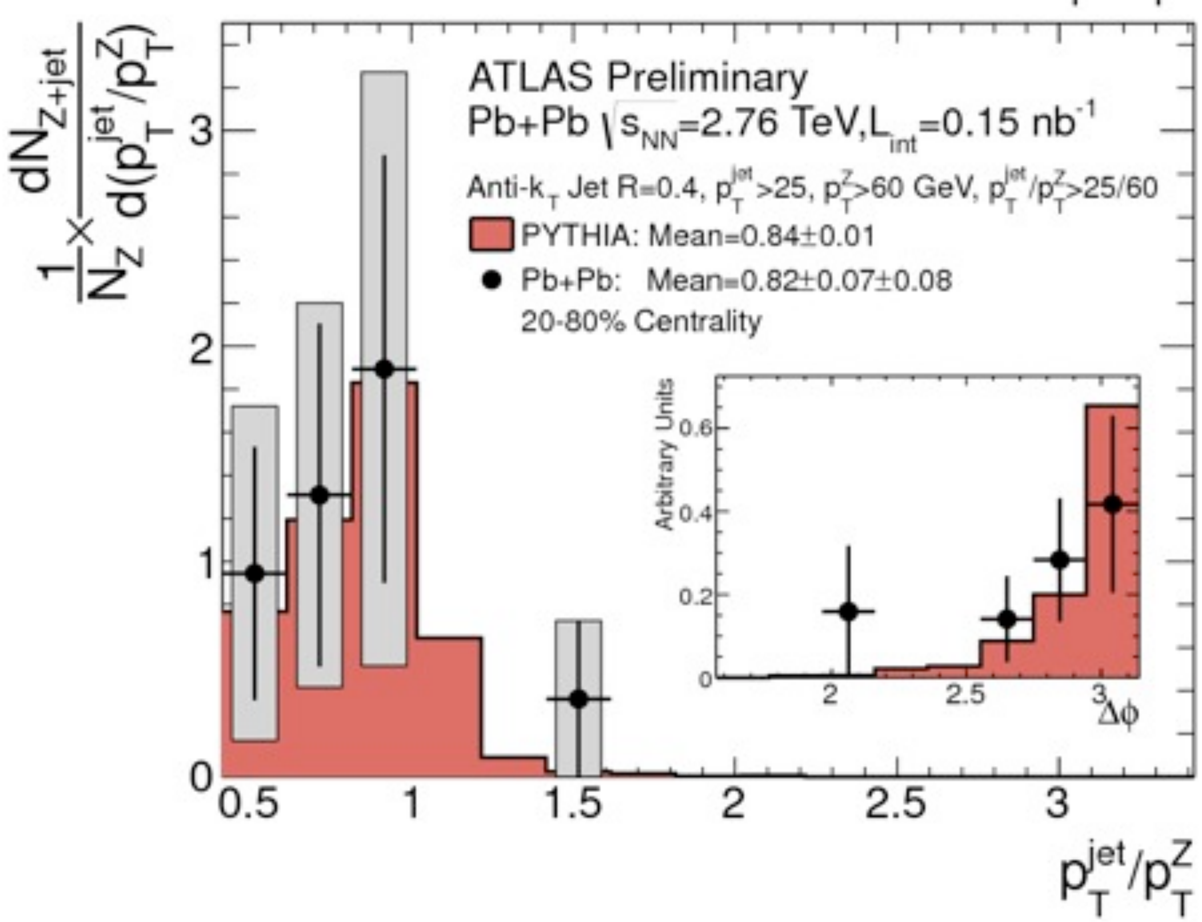
R = 0.3





R = 0.4





Centrality evolution I

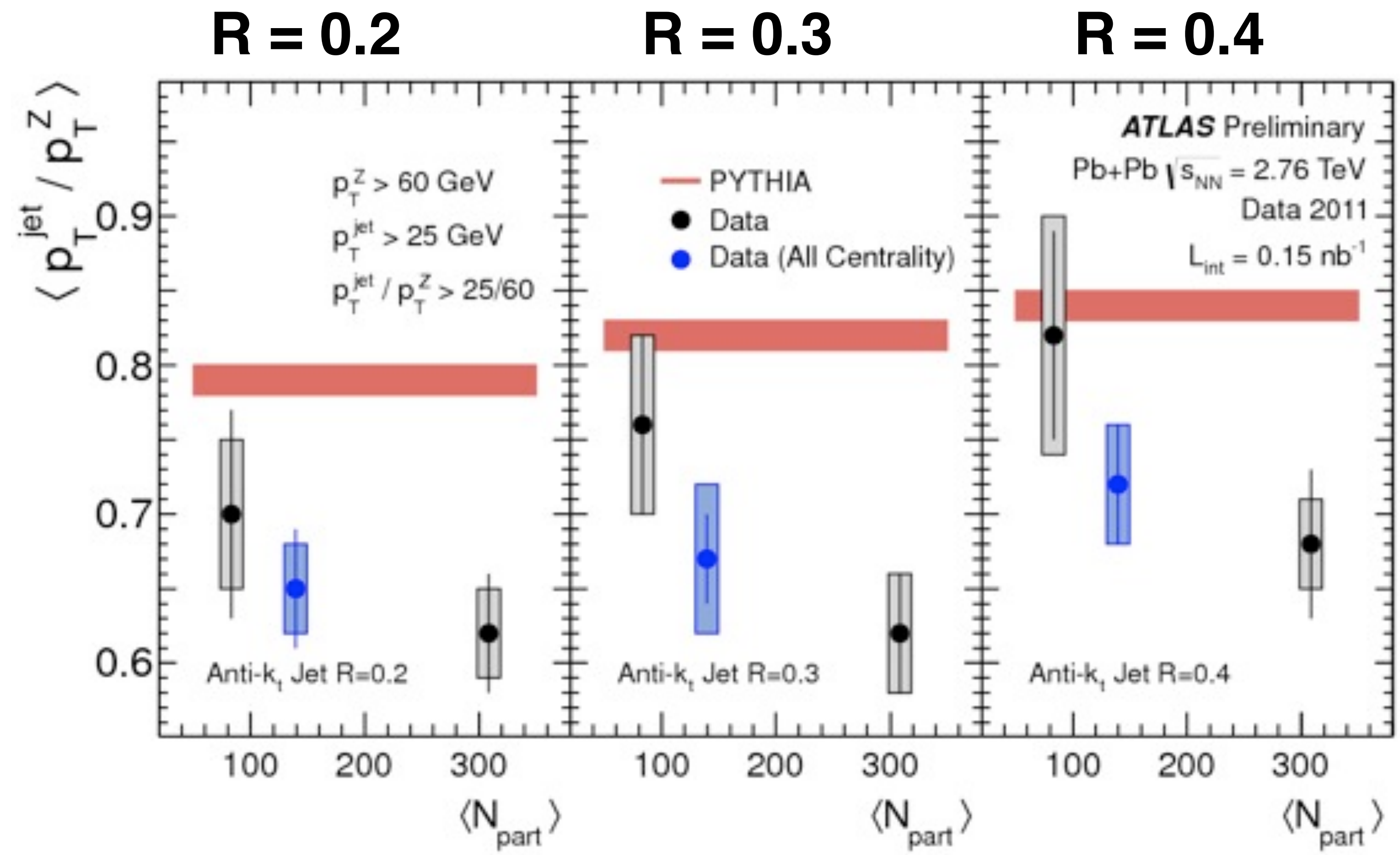
ATLAS-CONF-2012-119

Z's-jets

Extracted $\langle p_T^{jet}/p_T^Z \rangle$ relative to MC simulations with no energy loss (PYTHIA: Z+jet events).

Stronger suppression for more central collisions.

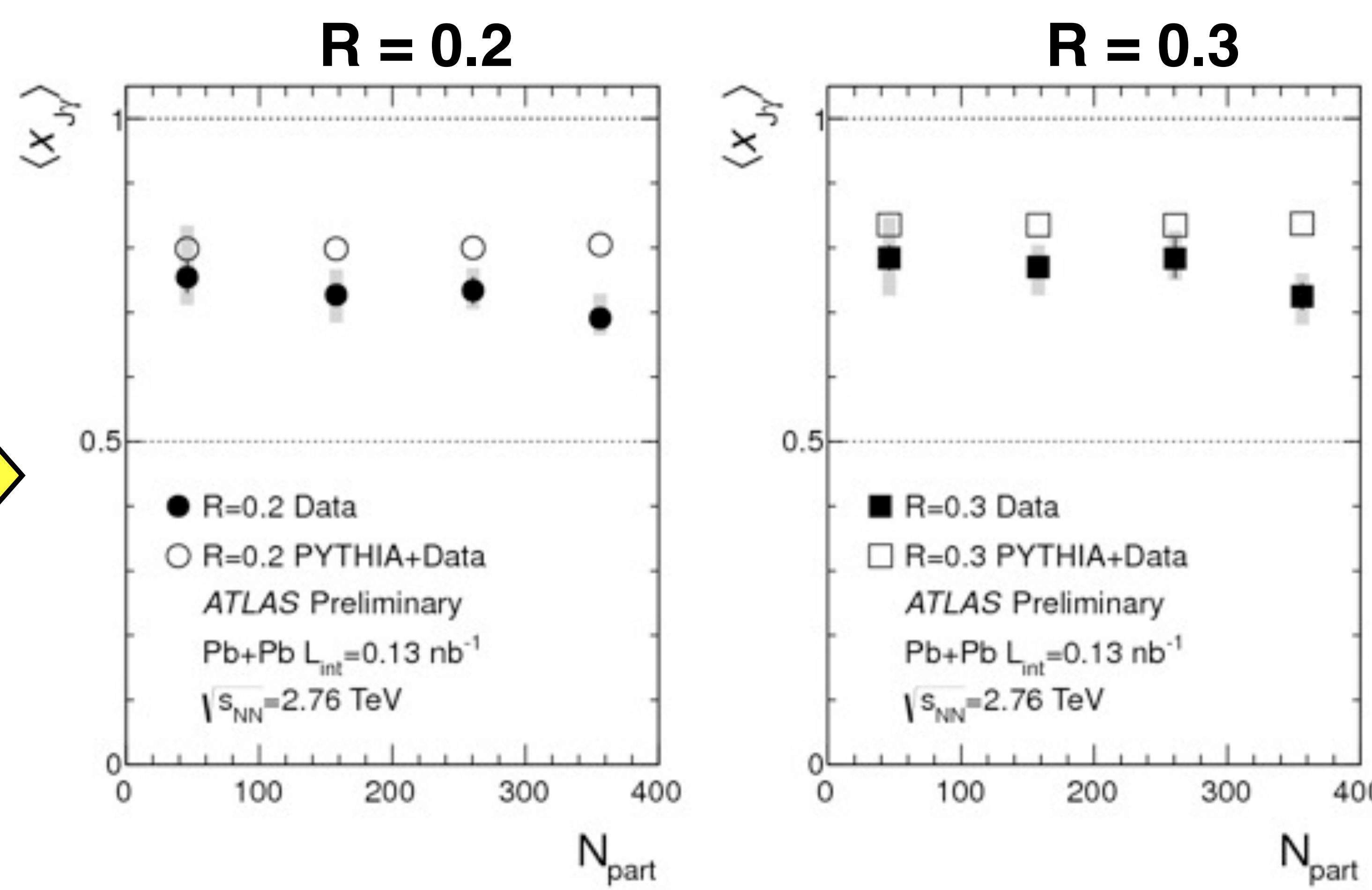
The blue points refer to 0-80% centrality, and therefore are not independent relative to the black points.



ATLAS-CONF-2012-121

Photons-jets

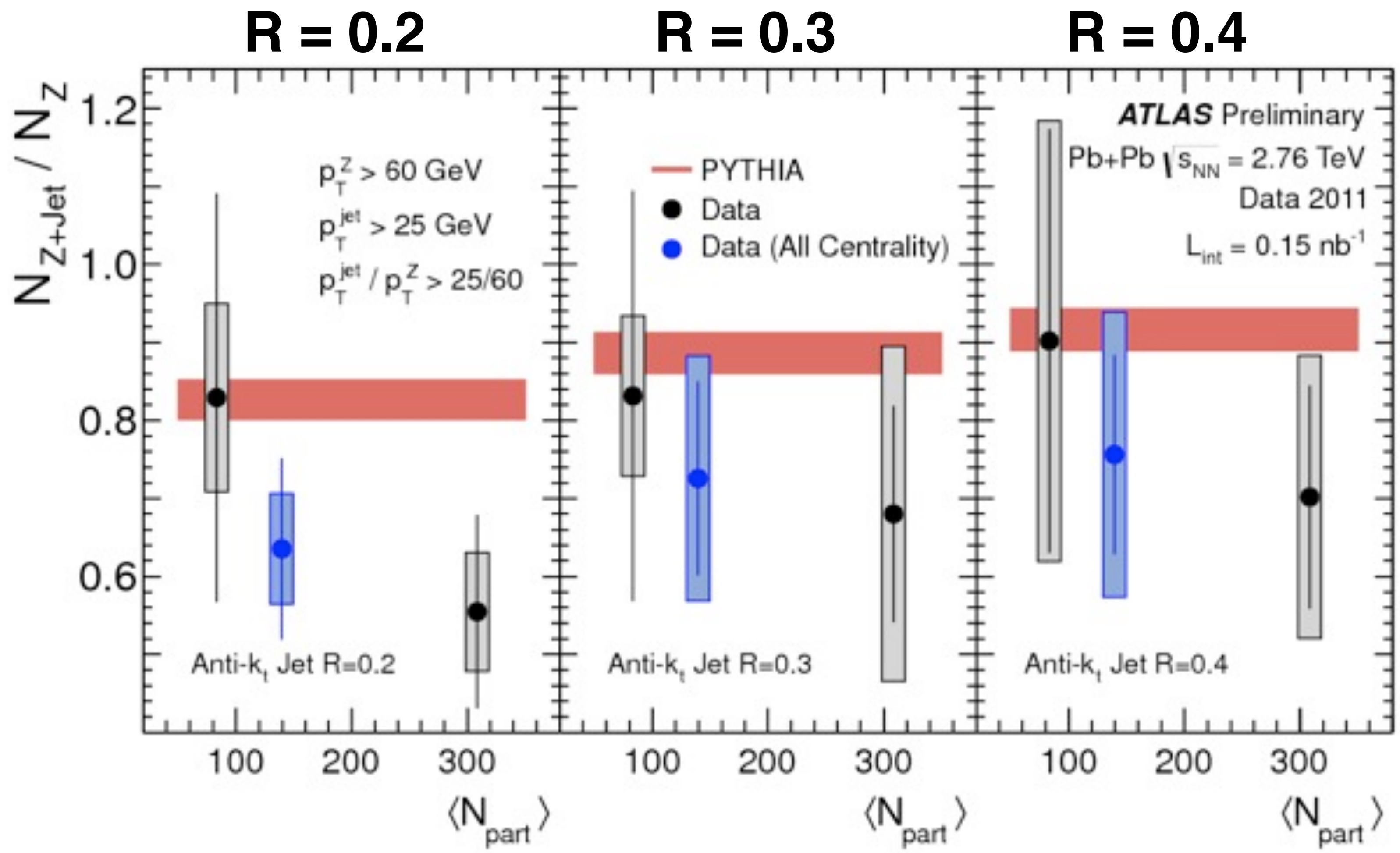
Downward shift of $\langle x_{j\gamma} \rangle$ (jets more quenched).



Centrality evolution II

ATLAS-CONF-2012-119

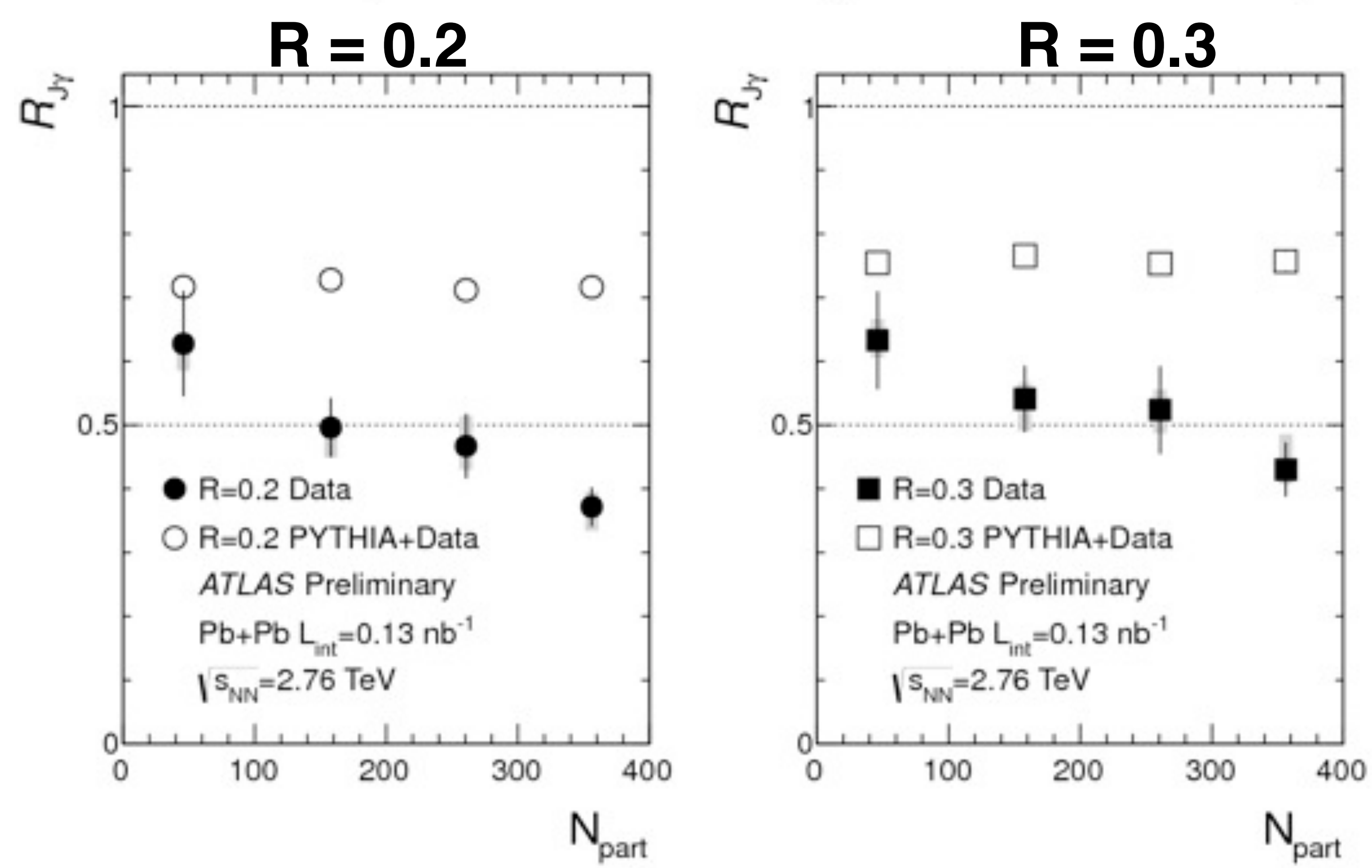
Z's-jets



The fraction of events with a Z boson ($p_T^Z > 60$ GeV) that also have a jet reconstructed ($p_T^{jet} > 25$ GeV, $p_T^{jet} / p_T^Z > 25/60$).

ATLAS-CONF-2012-121

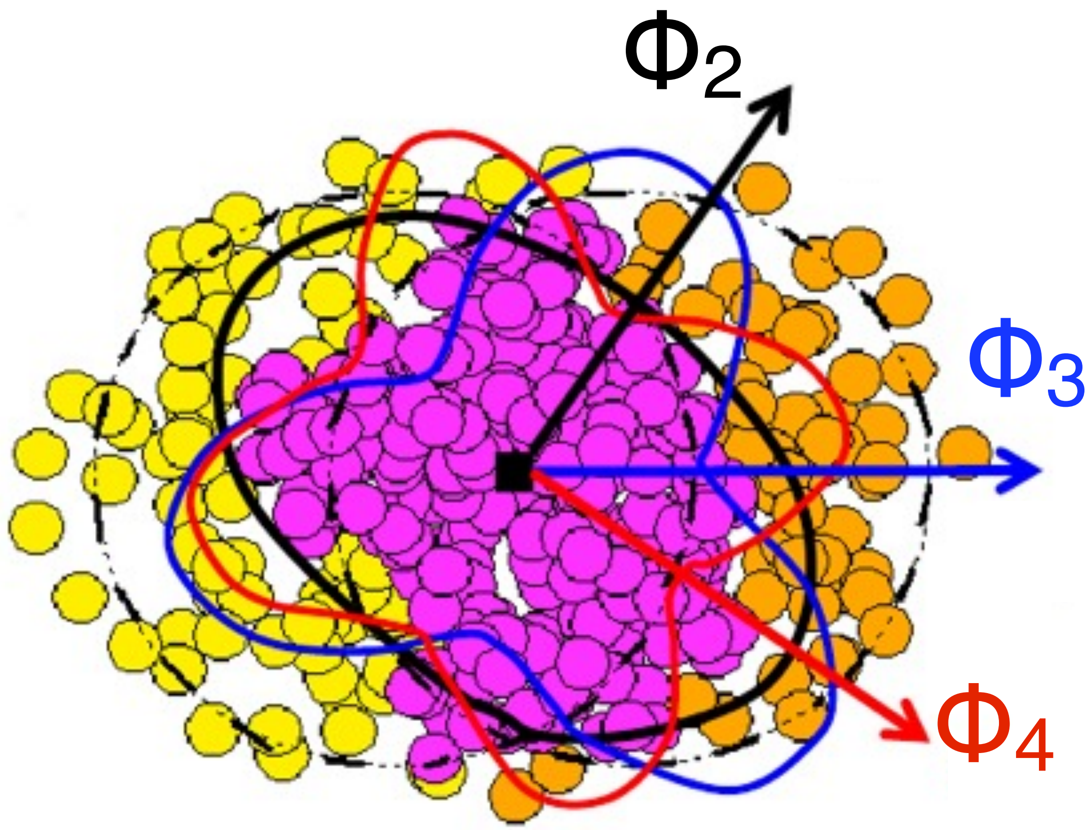
Photons-jets



Most peripheral events consistent with PYTHIA truth, and strong centrality dependence: nearly half of the photons in central events do not have a matching jet: downward shift of $R_{j\gamma}$.

Azimuthal anisotropy

Spatial deformations in the initial overlap region are transformed into the final state momentum anisotropy



studied via Fourier decomposition of the azimuthal angle distribution measured relative to the initial symmetry plane Φn
A.M. Poskanzer, S. A. Voloshin, Phys. Rev. C58, 1671 (1998) :

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T d\eta}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_T,\eta)cos[n(\phi - \Phi_n)]\right)$$

phase of v_n accumulated over many events;

this event-averaged v_n mostly reflects the hydrodynamic response of the created matter to the average collision geometry in the initial state.

$$v_n = \langle\cos[n(\phi - \Phi_n)]\rangle$$

Event plane is measured based on energy deposition in the first sampling layer of FCal
Fourier harmonics are reconstructed in inner detector from charged particle tracks:

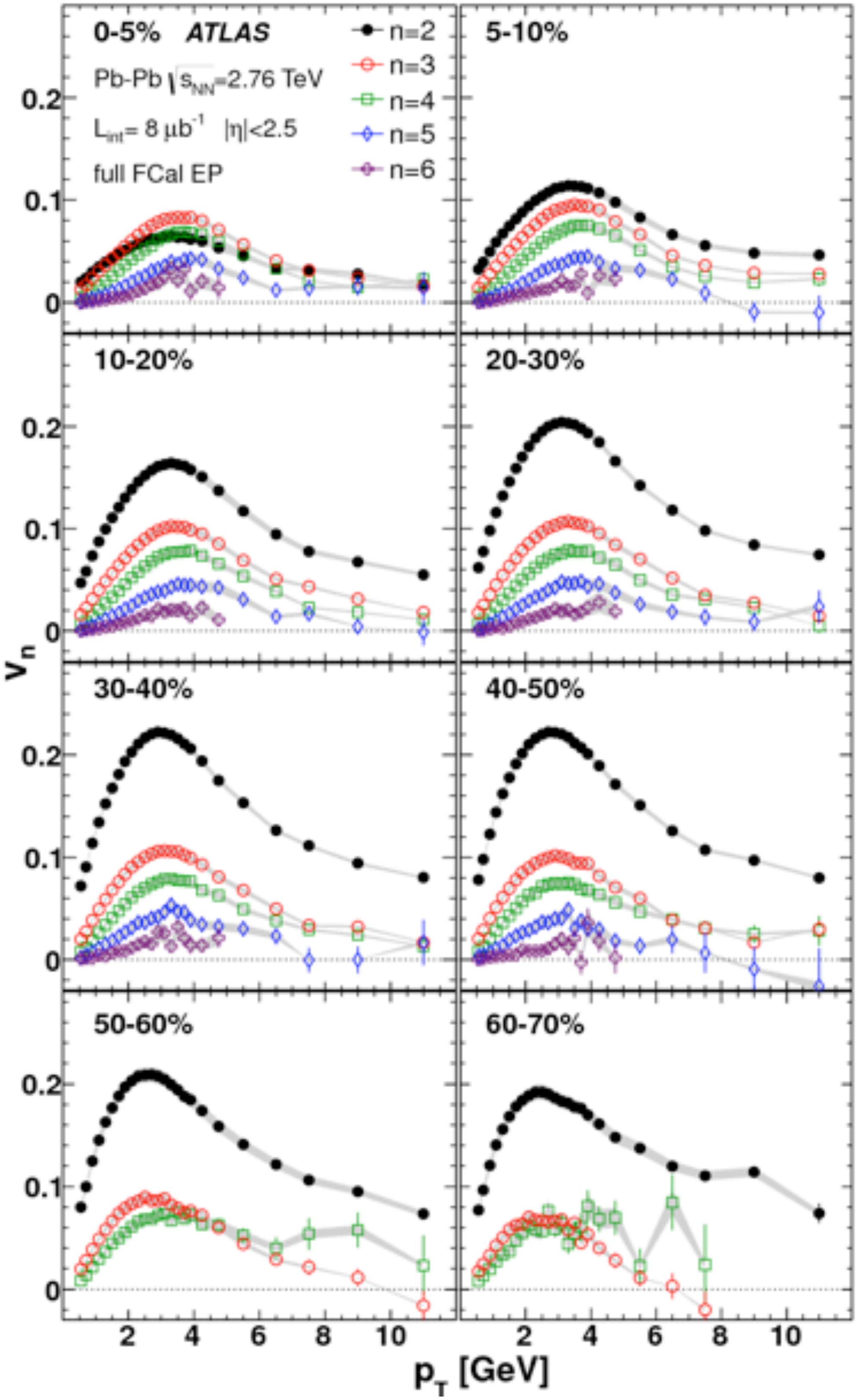
- p_T > 0.5 GeV
- η|<2.5
- Reaction plane (Ψ^{RP}) is approximated by event plane (Ψ_n^{EP}) measured in FCal:

$$\Psi_n^{EP} = \frac{1}{n}\tan^{-1}\frac{\sum_i E_{T,i}^{tower} w_i \sin(n\phi_i)}{\sum_i E_{T,i}^{tower} w_i \cos(n\phi_i)}$$

v2-v6 from the event plane method

PHYSICAL REVIEW C **86**, 014907 (2012)

Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions with the ATLAS detector

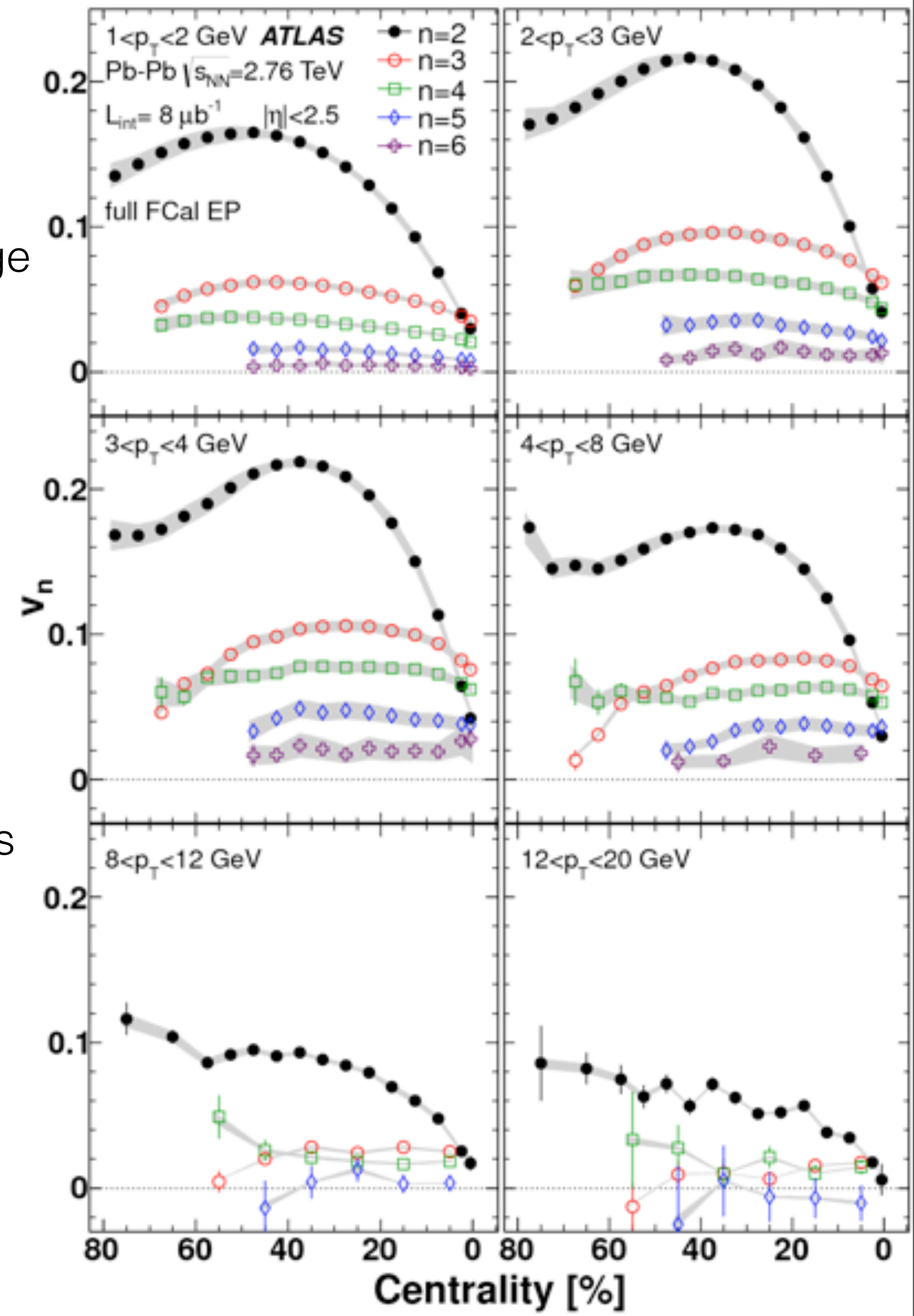


Significant $v_2 - v_6$ are measured in broad range of p_T, η and centrality.

p_T dependence for all measured amplitudes show similar trend.

Stronger centrality dependence of v_2 than higher order harmonics.

In most central collisions (0-5%): v_3, v_4 can be larger than v_2 .

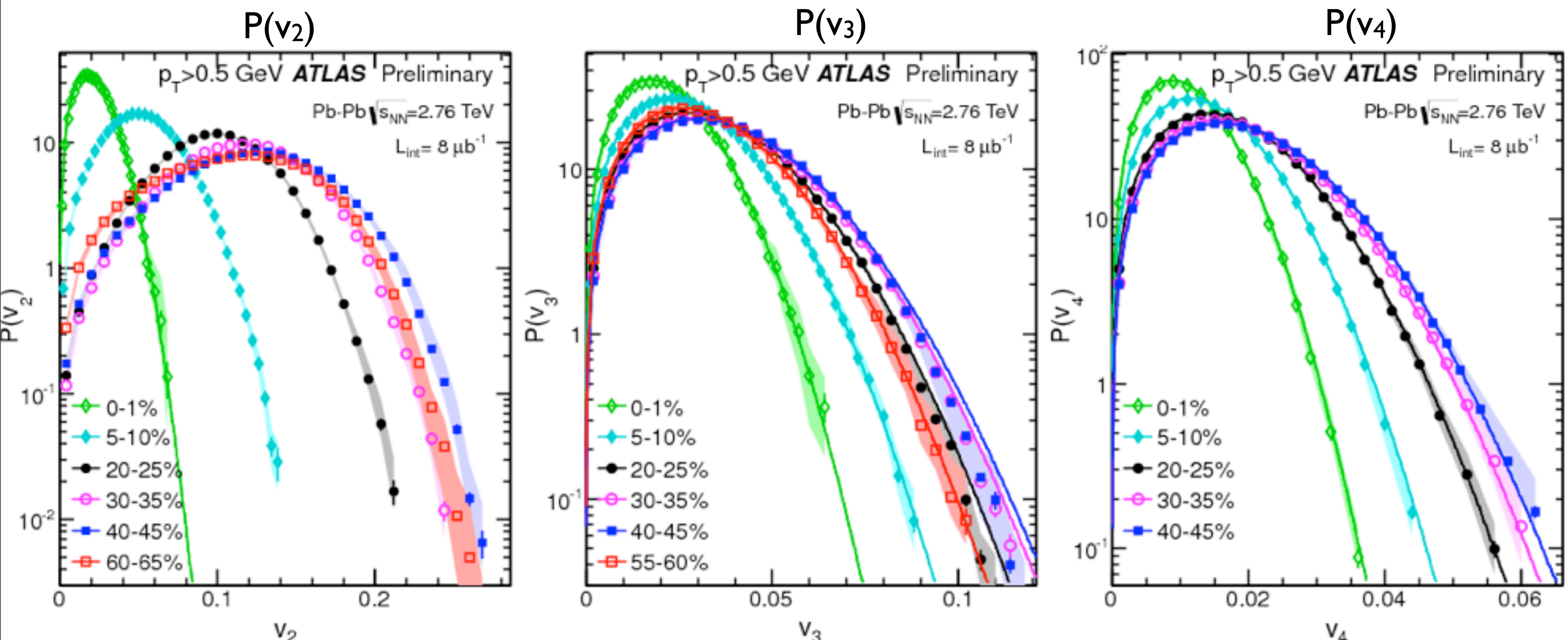


ATLAS-CONF-2012-114

Event-by-event flow harmonics

New technique – direct measure of flow harmonics fluctuations!

Event-by-event unfolded v_n distributions normalized to unit, for n=2 – 4



$$P(v_n) = \frac{v_n}{\sigma^2} e^{-\frac{v_n^2}{2\sigma^2}}, \sigma = \sqrt{\frac{2}{\pi}}\langle v_n \rangle$$

Quantities calculated directly from these distributions:

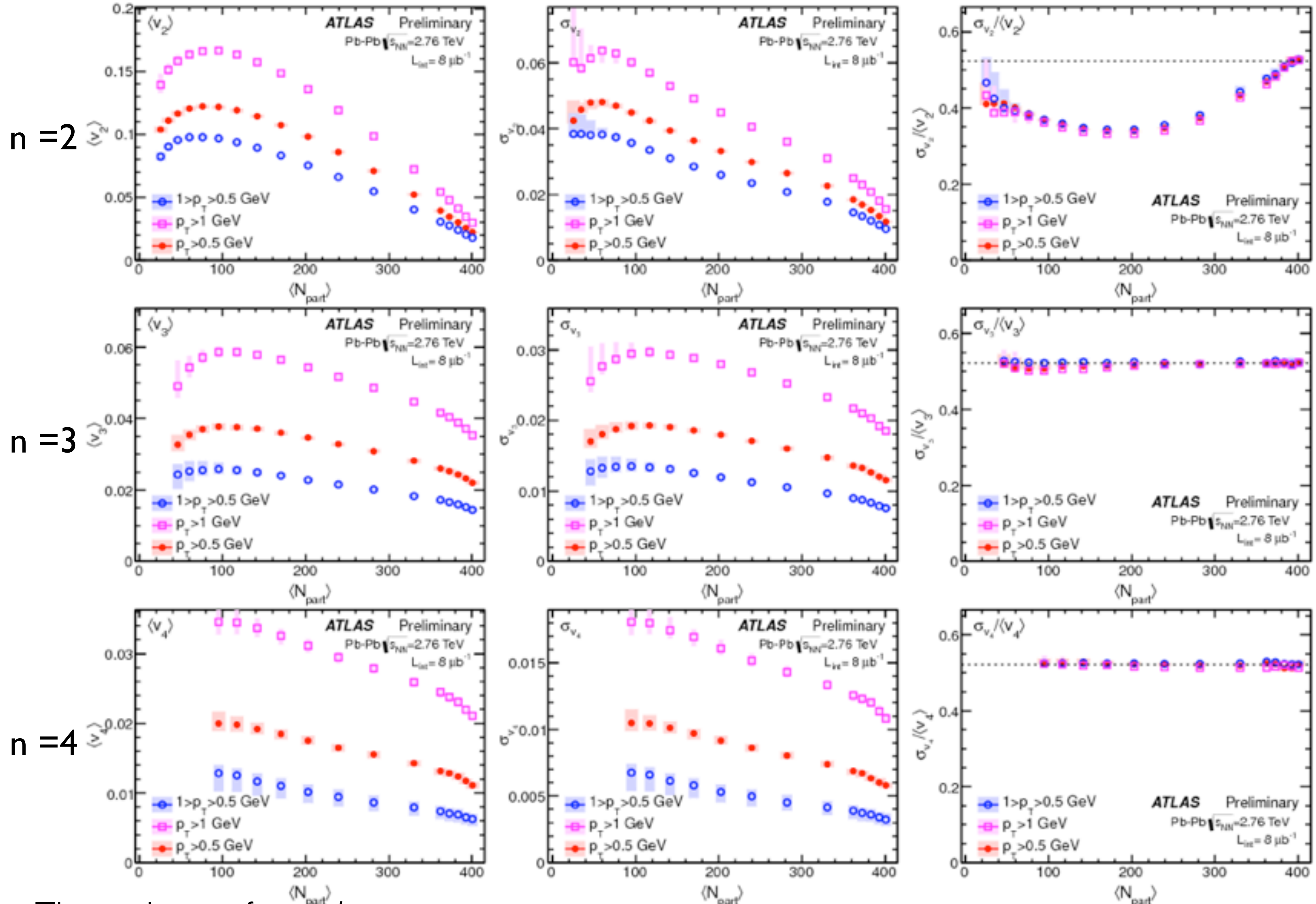
- mean $\langle v_n \rangle$,
- width σ_{vn} ,
- ratio $\sigma_{vn} / \langle v_n \rangle$

RMS value: $\sqrt{\langle v^2_n \rangle} \equiv \sqrt{(\langle v_n \rangle^2 + \sigma^2_{vn})}$

Lines represent radial projections of 2D Gaussians, rescaled to $<v_n>$

- for v_2 only in the 0-2% of most central collisions
- for v_3 and v4 over all centralities

ATLAS-CONF-2012-114 $\langle v_n \rangle$ σ_{vn} $\sigma_{vn} / \langle v_n \rangle$



$\sigma_{v2} / \langle v_2 \rangle$ shows significant centrality dependence

$\sigma_{v3} / \langle v_3 \rangle$,$\sigma_{v4} / \langle v_4 \rangle$ are consistent with Gaussian fluctuations

The values of $\sigma v_n / \langle v_n \rangle$:

found to be independent of p_T, suggesting that the hydrodynamic response to the eccentricity of the initial geometry has little p_T dependence,

found to reach a minimum of 0.34 for v2 around $\langle N_{part} \rangle$ ~ 200.

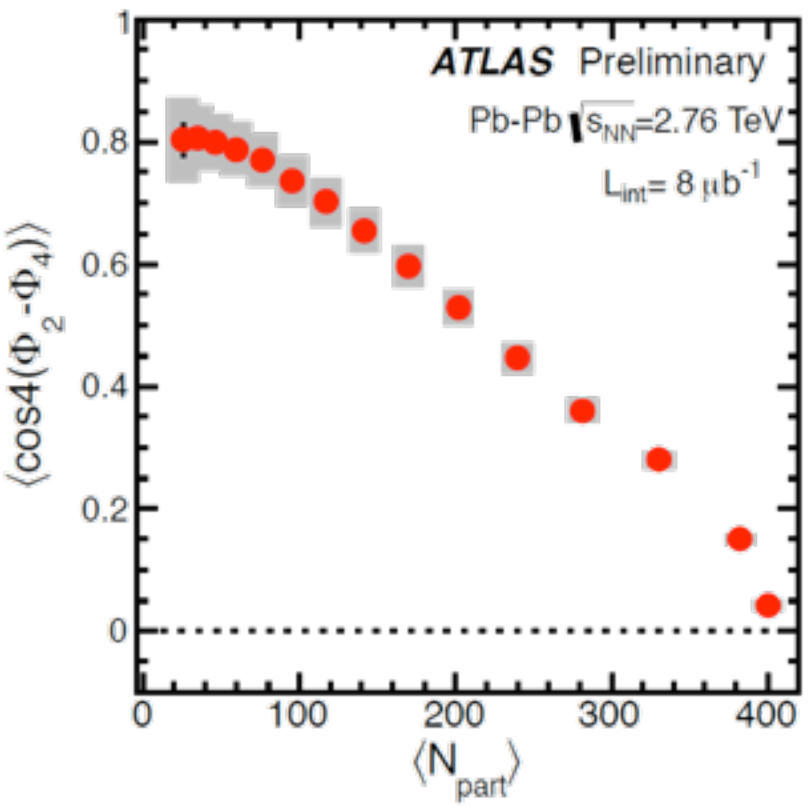
Event plane correlations

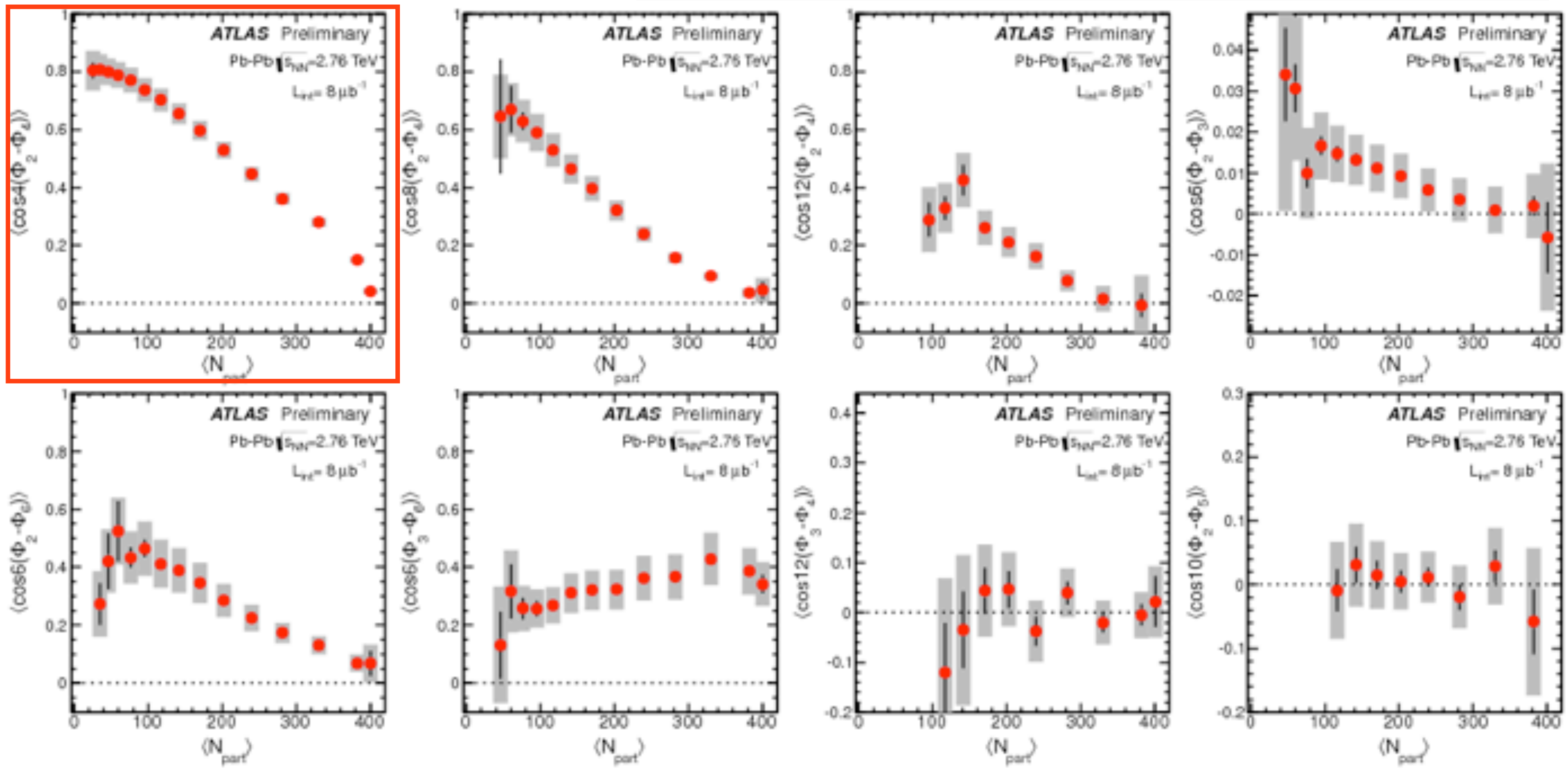
ATLAS-CONF-2012-049

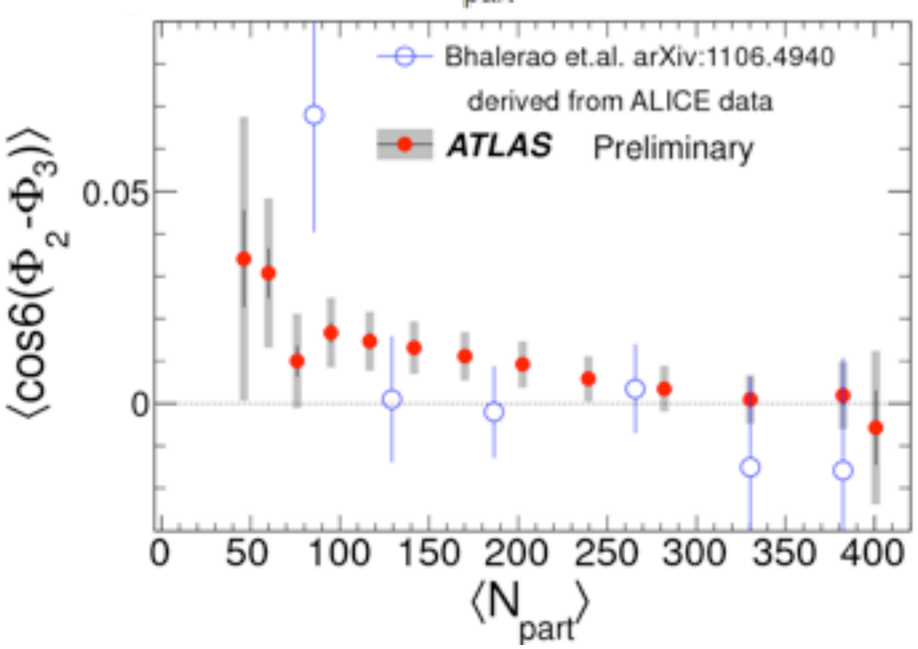
The resolution corrected correlations between EP of different orders: (Φn,Φm), (Φn,Φm,Φk)
Study non-linear response of the medium to initial fluctuations.

$$\frac{dN_{\text{events}}}{d(k(\Phi_n - \Phi_m))} \propto 1 + 2\sum_{j=1}^{\infty} V_{n,m}^{j} \cos jk(\Phi_n - \Phi_m),$$

$$V_{n,m}^{j} = < \cos jk(\Phi_n - \Phi_m) >$$







Model predicts even planes to be correlated.
Data shows strong correlation of Φ_2 and Φ_4, stronger than expected
Correlations between even and odd planes is not expected
Data shows significant correlations between Φ_2 and Φ_3

Summary

✴Jet yields suppressed by a factor of 2 in central collisions.

✴Jet suppression depends on the jet size in central collisions.

✴Jet fragmentation function shows no modification at high z, but significant suppression with centrality at $z \approx 0.1$ and enhancement at very low z is observed.

✴Jet quenching also studied with Z,γ - jet correlations.

✴Z and γ production consistent with Ncoll scaling.

✴ATLAS measured significant flow harmonics of charged particles in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV.

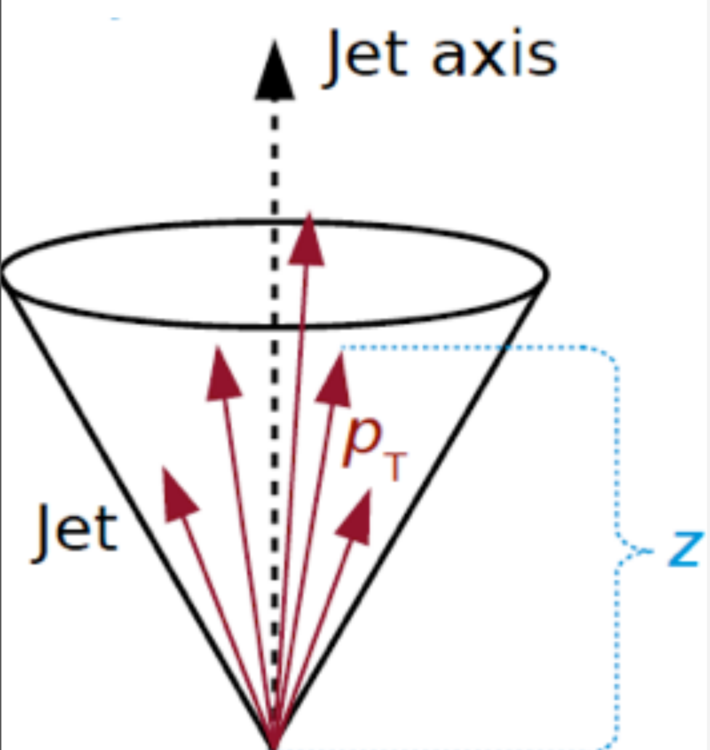
✴New results on flow harmonics fluctuations.

✴Mixed reaction plane correlations were obtained.

Thank you!

Additional Slides

Jet fragmentation



Spectra of charged particles in jets

$$D(p_T)(p_T^{\text{jet}}) = \frac{1}{N_{\text{jet}}}\frac{1}{\epsilon}\frac{dN}{dp_T}(p_T^{\text{jet}}) =$$

$$\frac{1}{N_{\text{jet}}(p_T^{\text{jet}})}\frac{1}{\epsilon(p_T,\eta)}\left(\frac{\Delta N_{ch}(p_T,p_T^{\text{jet}})}{\Delta p_T} - \frac{\Delta N_{ch}^{UE}(p_T,p_T^{\text{jet}})}{\Delta p_T}\right)$$

Tracking efficiency corrected

Underlying event subtracted

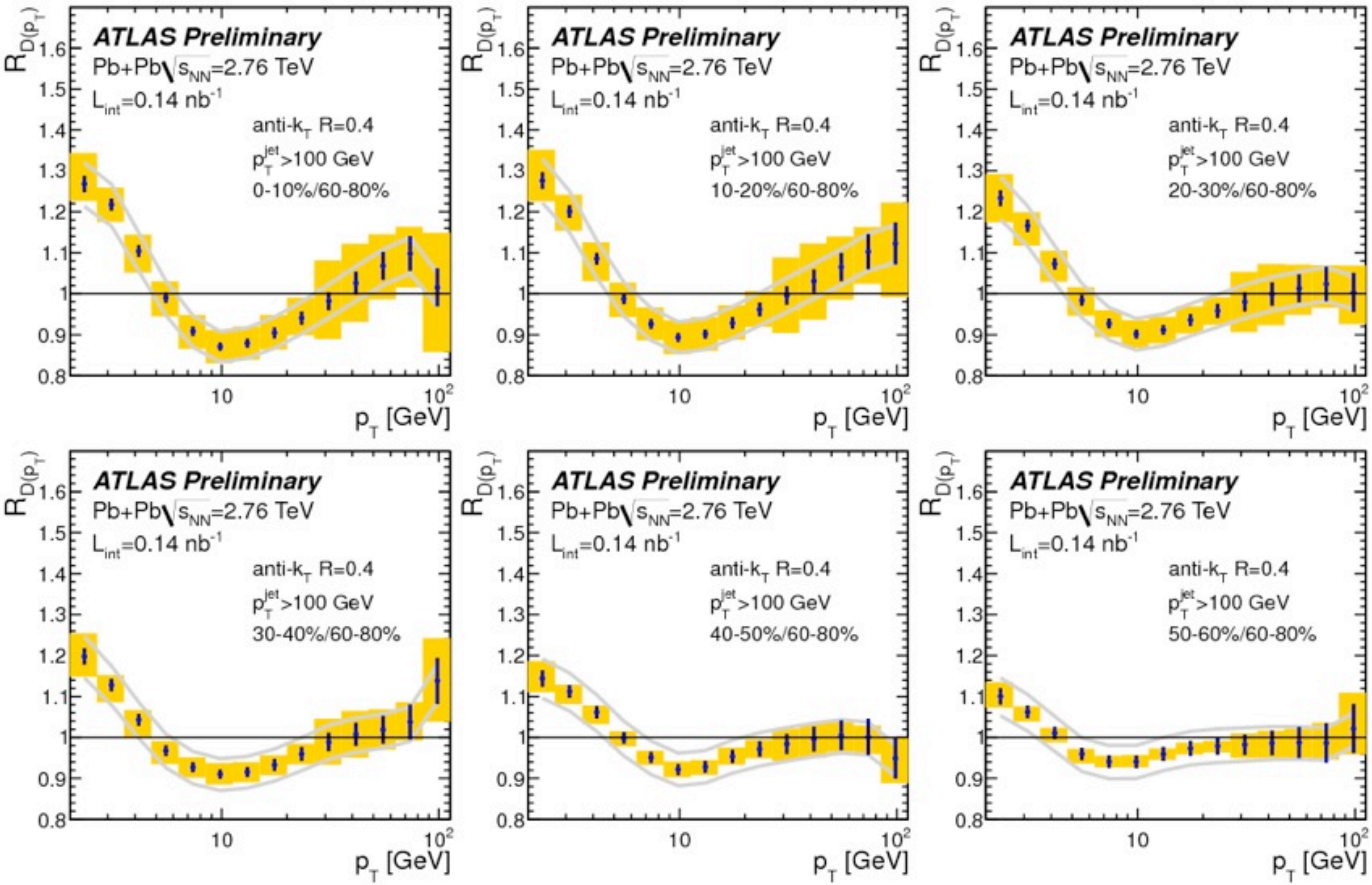
$$D(z)(p_T^{\text{jet}}) = \frac{1}{N_{\text{jet}}}\frac{1}{\epsilon}\frac{dN}{dz}(p_T^{\text{jet}}) =$$

$$\frac{1}{N_{\text{jet}}(p_T^{\text{jet}})}\frac{1}{\epsilon(p_T,\eta)}\left(\frac{\Delta N_{ch}(z,p_T^{\text{jet}})}{\Delta z} - \frac{\Delta N_{ch}^{UE}(z,p_T^{\text{jet}})}{\Delta z}\right)$$

$$z = p_T/p_T^{\text{jet}}\cos\Delta R$$

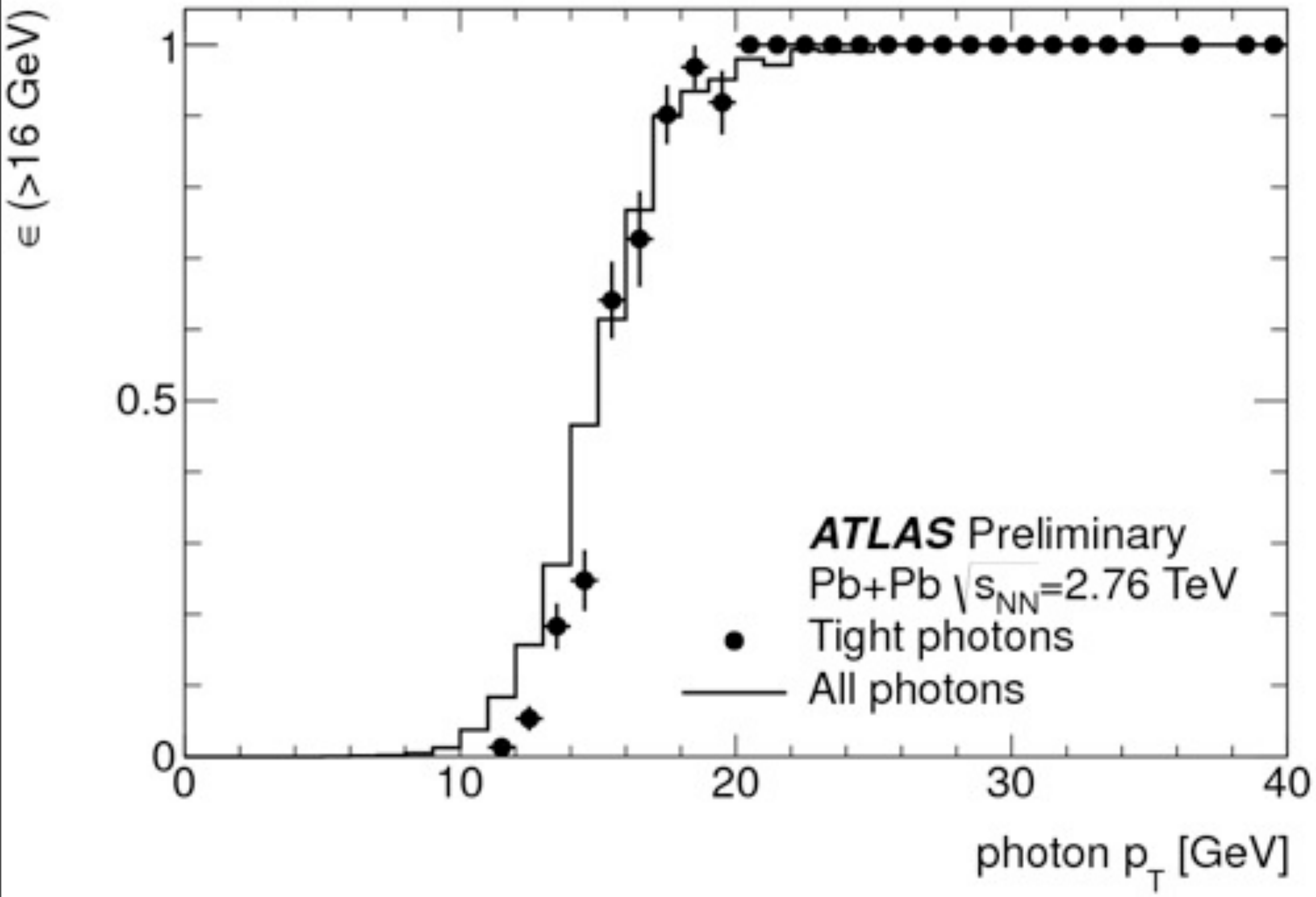
D(p_T) centrality dependence

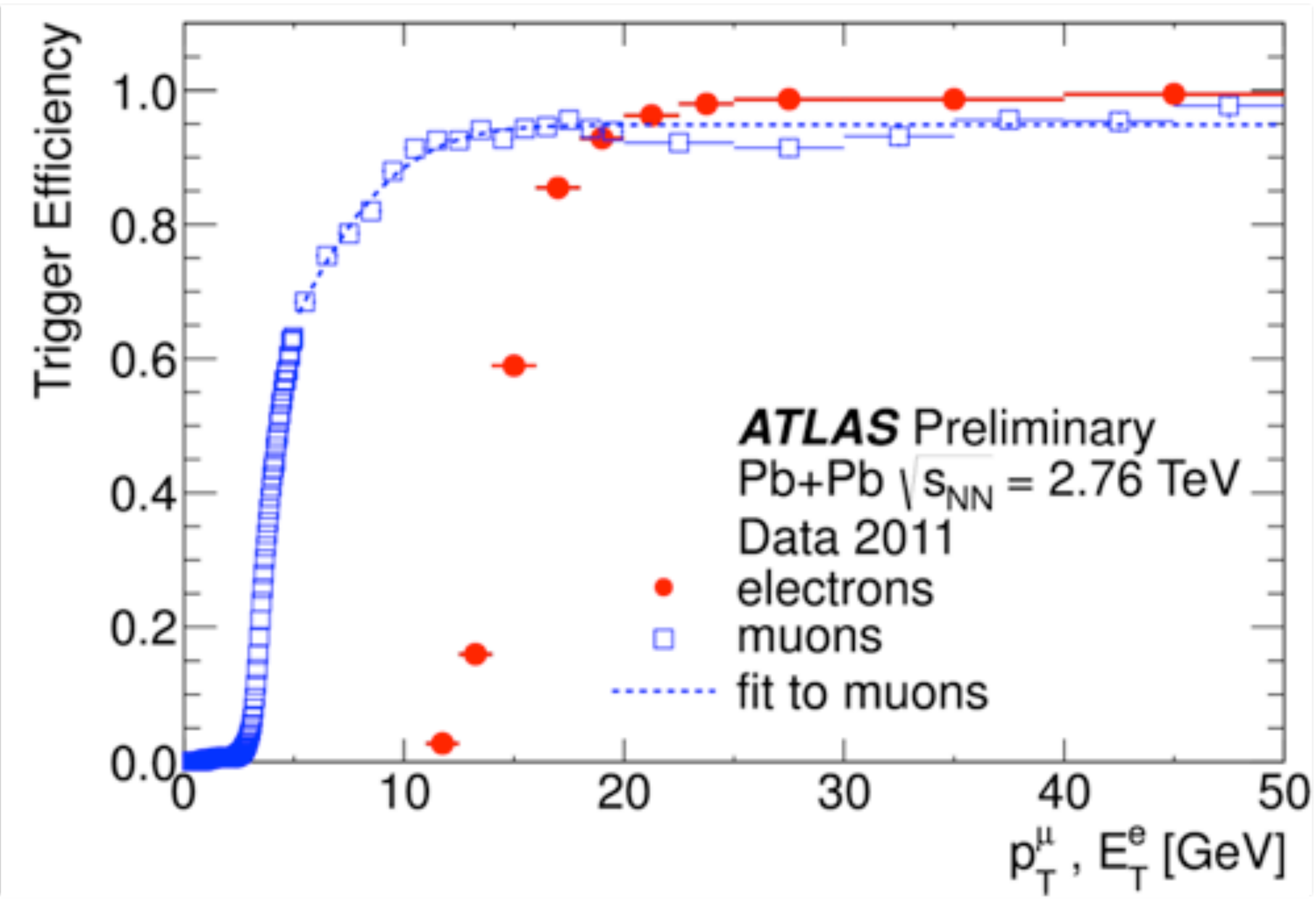
Ratios are needed to study centrality dependence



Similar behaviour as for D(z) distribution.

Event selection and triggers





Photons and electrons

based on EM calorimeter

efficiency > 98% for E_T > 20 GeV

Muons

L1 μ trigger with p_T > 4 GeV, HLT (MS OR MS + ID), additional p_T > 10 GeV μ scan

efficiency > 90% above 10 GeV

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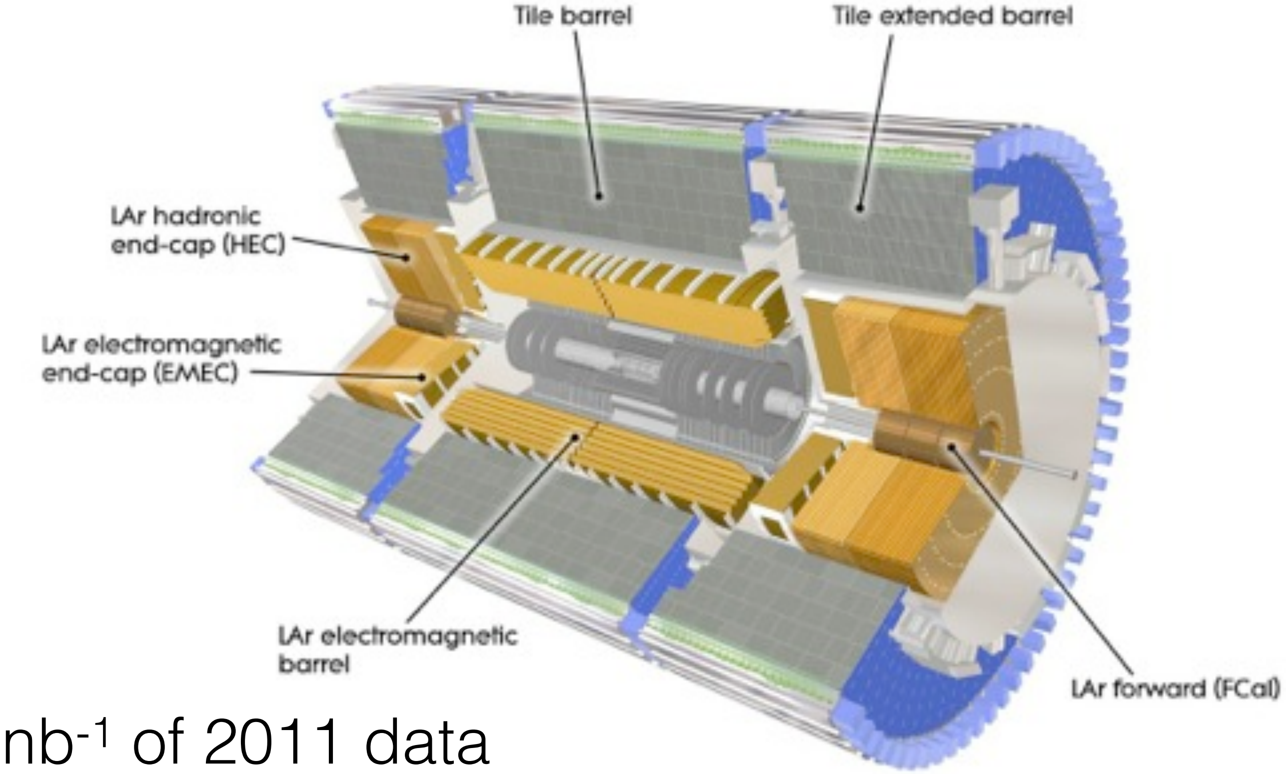
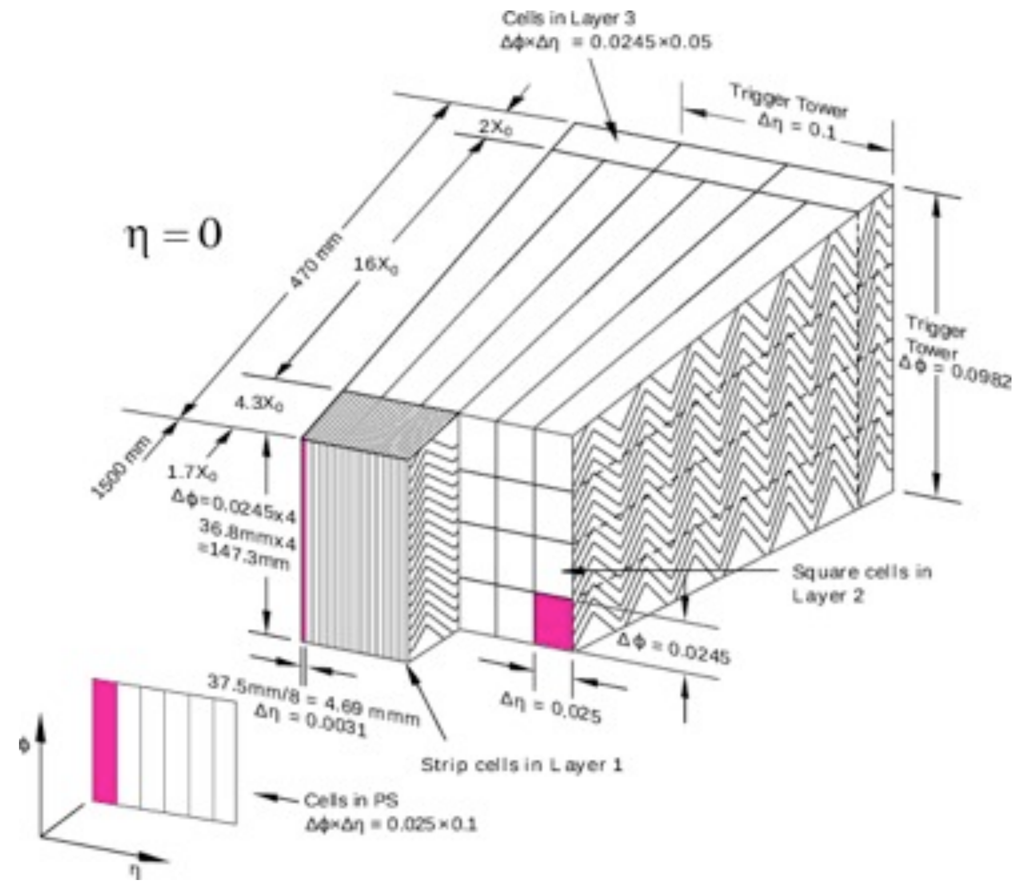
Direct Photon Reconstruction



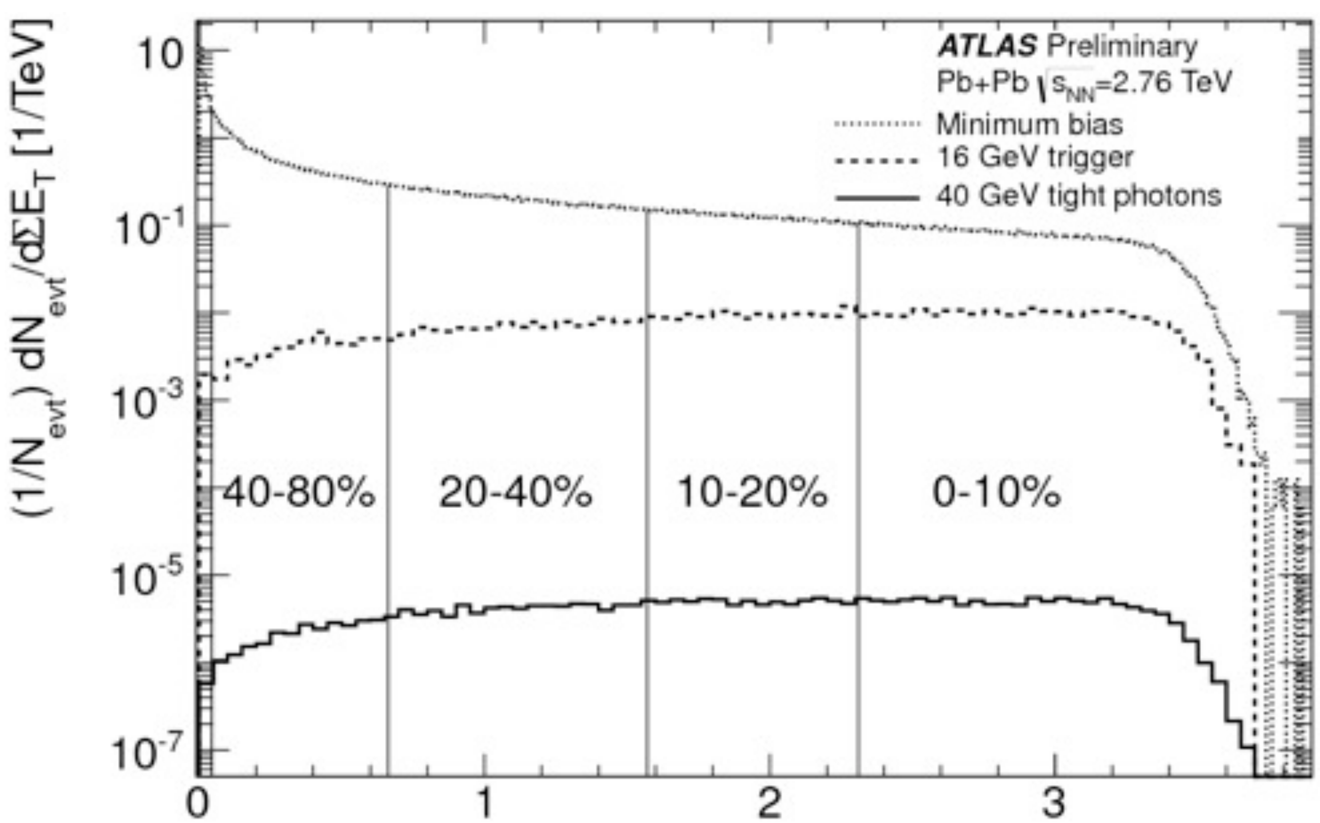


0.13 nb^{-1} of 2011 data

Trigger: EM cluster with E_T >16 GeV at L1

100% efficient for photons with E_T > 20 GeV

Underlying-event background (UE) is subtracted event-by-event



Photon reconstruction with a sliding window algorithm seeded by clusters of at least 2.5 GeV in the second sampling layer.

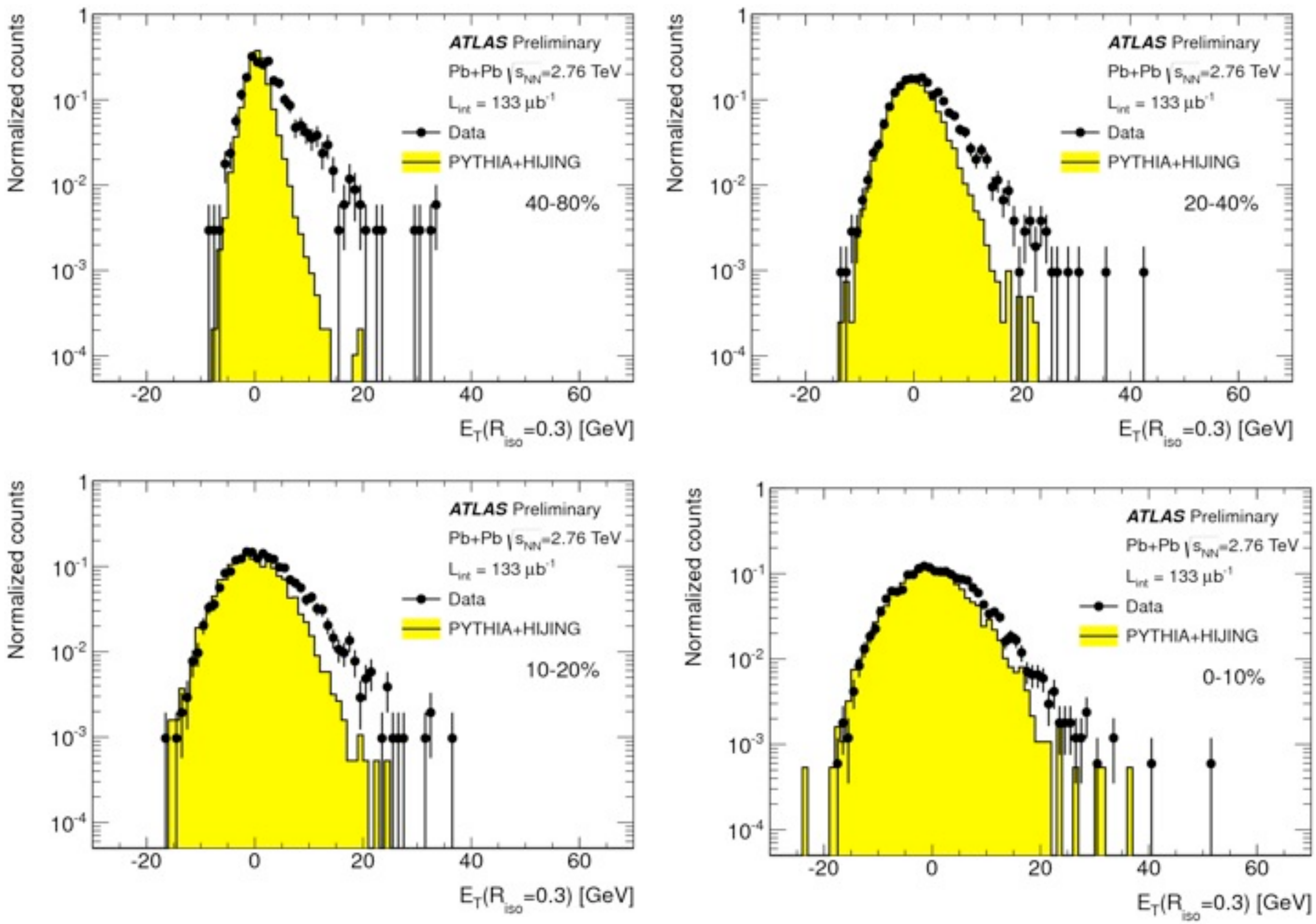
Photon energy using all three layers and the presampler.

Photon conversions are not reconstructed in the HI environment.

Nine shower-shape variables used to choose high-quality photons (tight photons).

Direct Photon Reconstruction

- 6435 tight photon candidates with p_T>45 GeV and $|\eta|$<1.3 before applying the isolation requirement
- Isolation criterion optimized for HI photons: $E_T(R_{iso}=0.3)$ – transverse energy in a cone of R_{iso} around the photon axis
  - Enhancement of data for $E_T(R_{iso}=0.3)>0$ due to two components: UE energy fluctuations and di-jet background
  - Width of $E_T(R_{iso}=0.3)$ in 0-10% photon+jet events is 6 GeV
    - Isolation requirement: $E_T(R_{iso}=0.3)$ < 6 GeV



Double side banded method

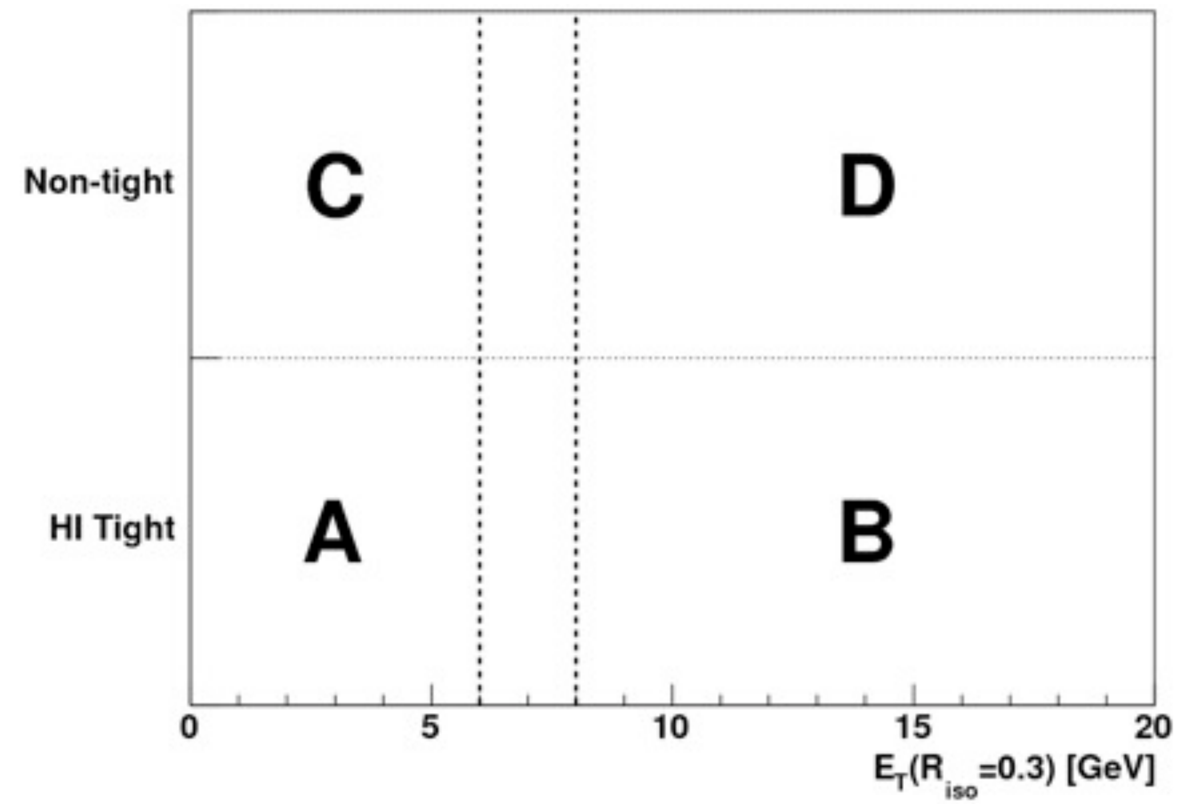
used for background subtraction. All photon candidates classified to one of four regions:

A: Primary signal region

B: Photons which happen to be in the vicinity of a jet or an UE fluctuation

C:Isolated jet fragments or photons which have shower shape fluctuations which fail the cuts

D:Primary background region



Leak of the signal to other regions is evaluated using MC

Leakage factors $c_i = N^{sig}_i / N^{sig}_A$

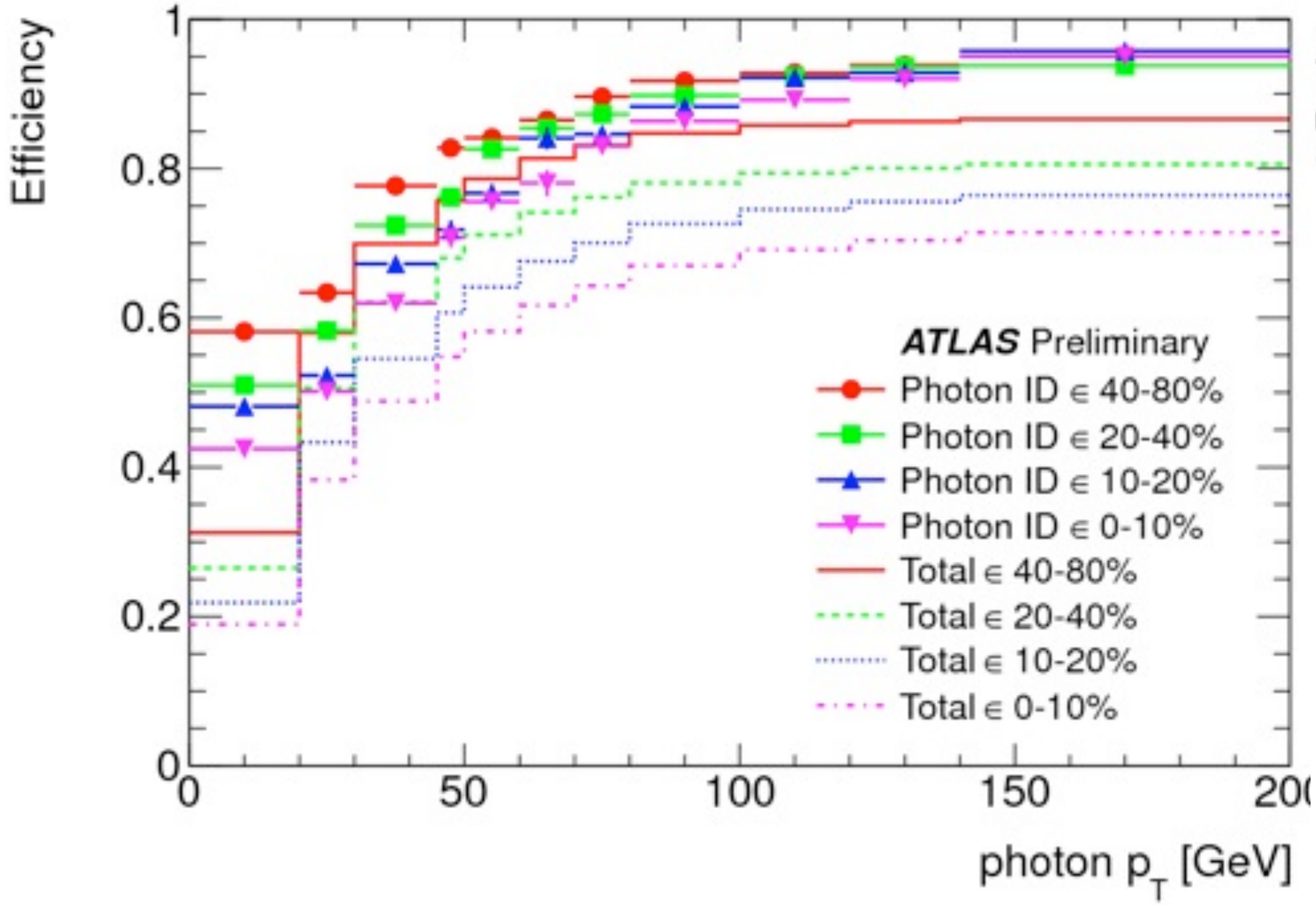
c_i range from 0.005-0.06, no dependence on centrality

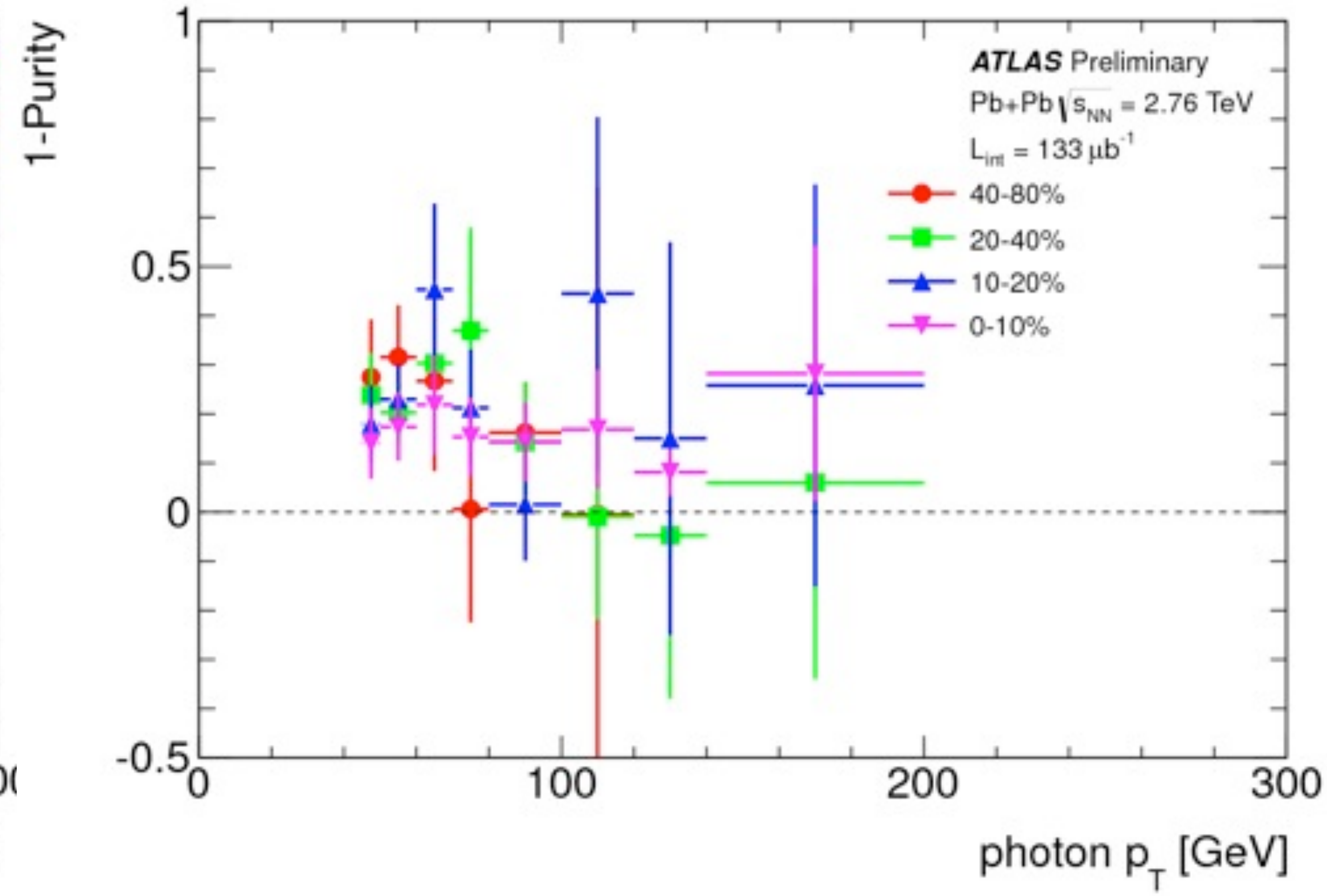
$$N_A^{sig} = N_A^{obs} - (N_B^{obs} - c_B N_A^{sig}) \frac{(N_C^{obs} - c_C N_A^{sig})}{(N_D^{obs} - c_D N_A^{sig})}$$

Photon purity and efficiency

Efficiencies extracted from MC and normalized to all PYTHIA isolated photons with $E_T(R_{iso}=0.3)<6GeV$ (the isolation removes 1.5% photons)

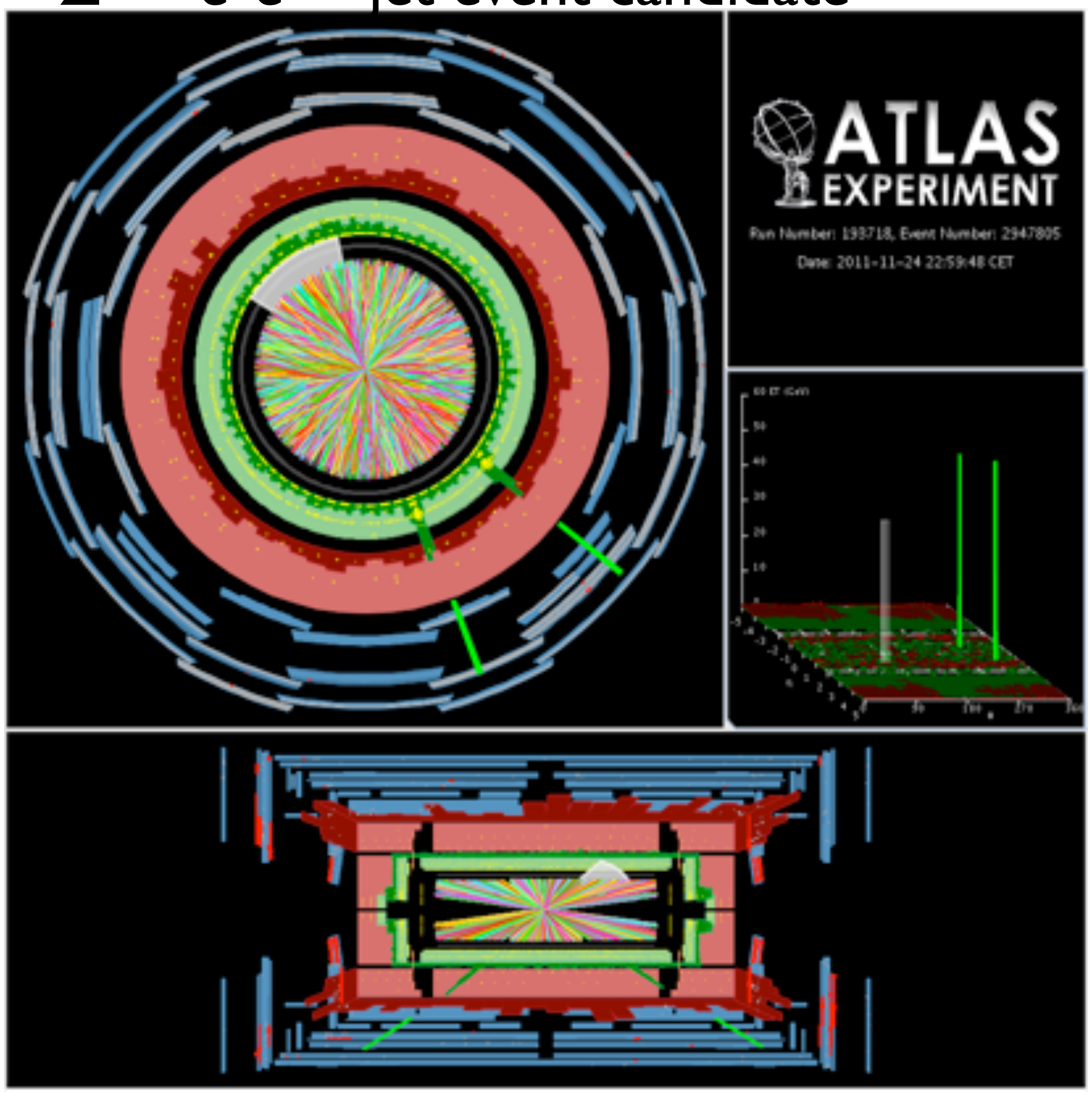
Purity is determined by double side band method: fraction of di-jet background in photon sample: 20-30% in low p_T bins



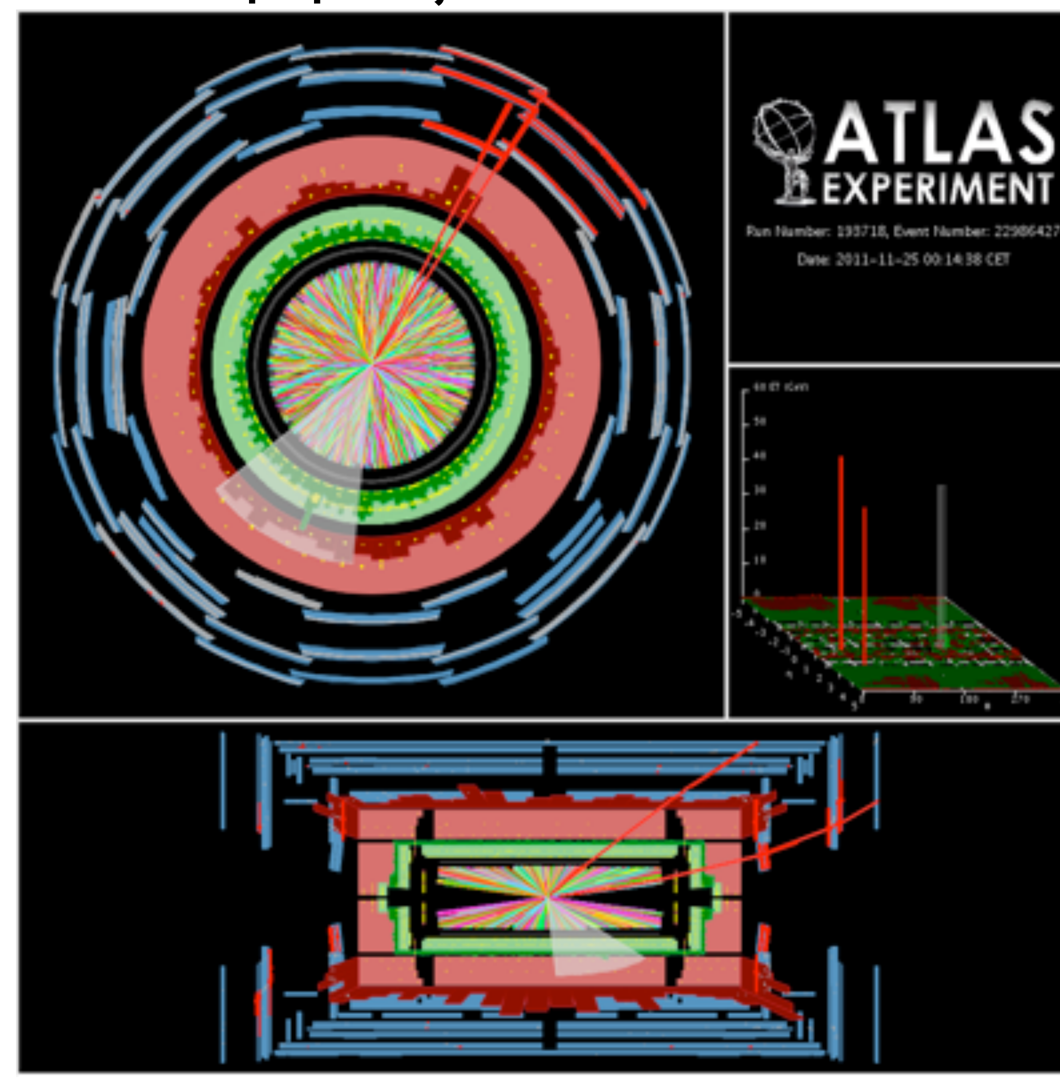


Z - jet correlations

$Z \rightarrow e^+e^-$ + jet event candidate

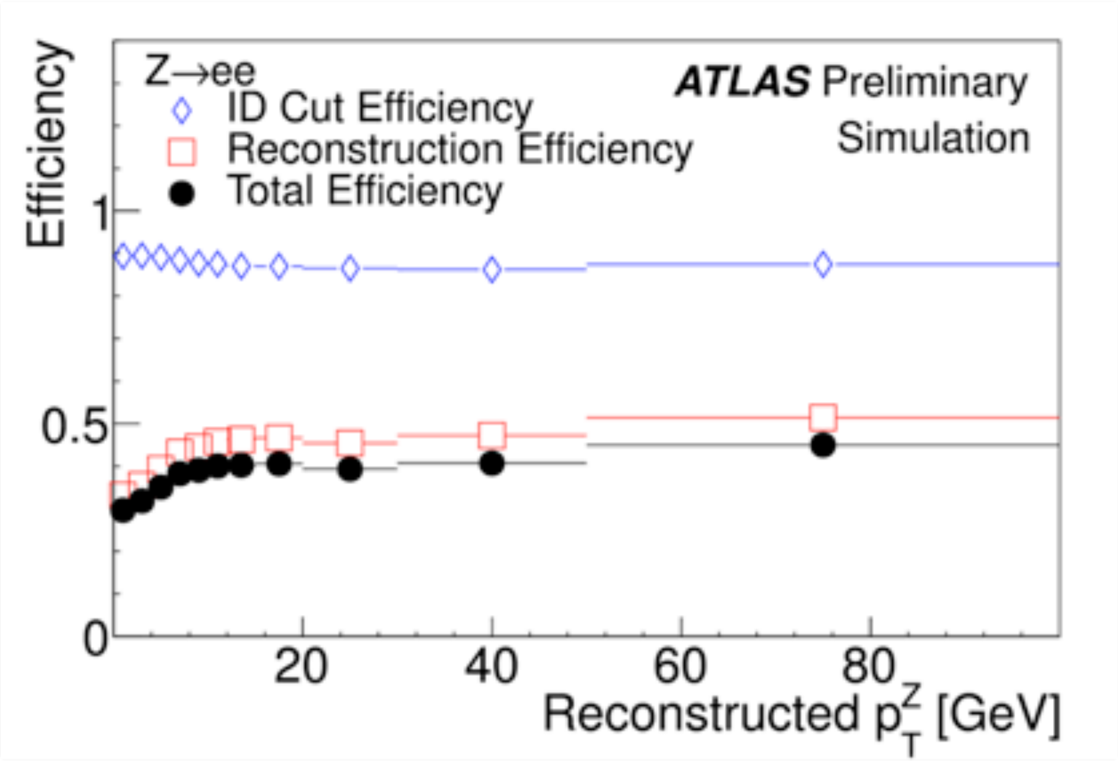


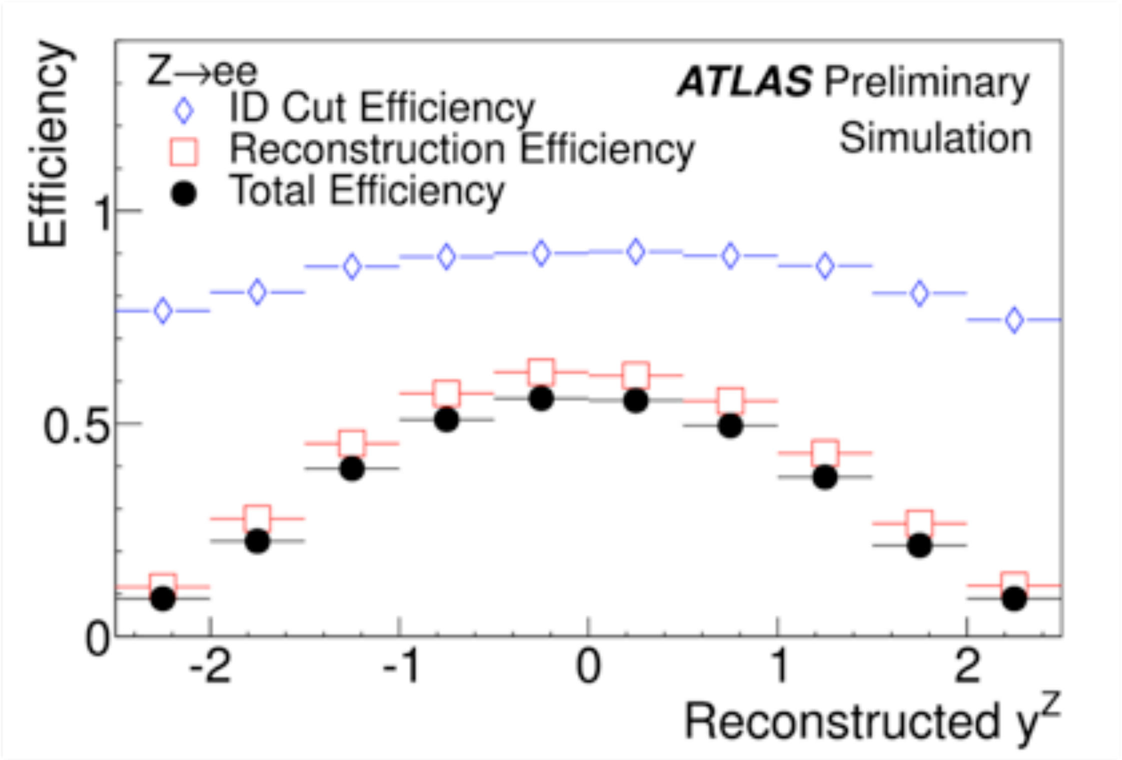
$Z \rightarrow \mu^+\mu^-$ + jet event candidate



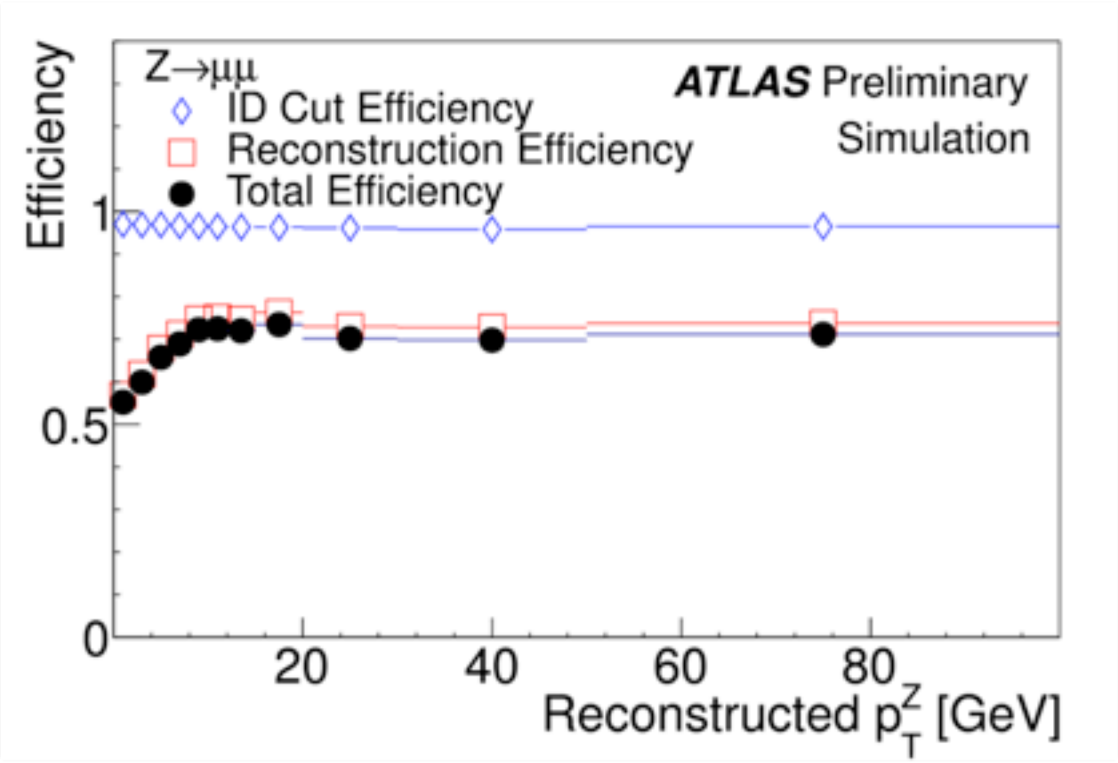
Z boson efficiencies

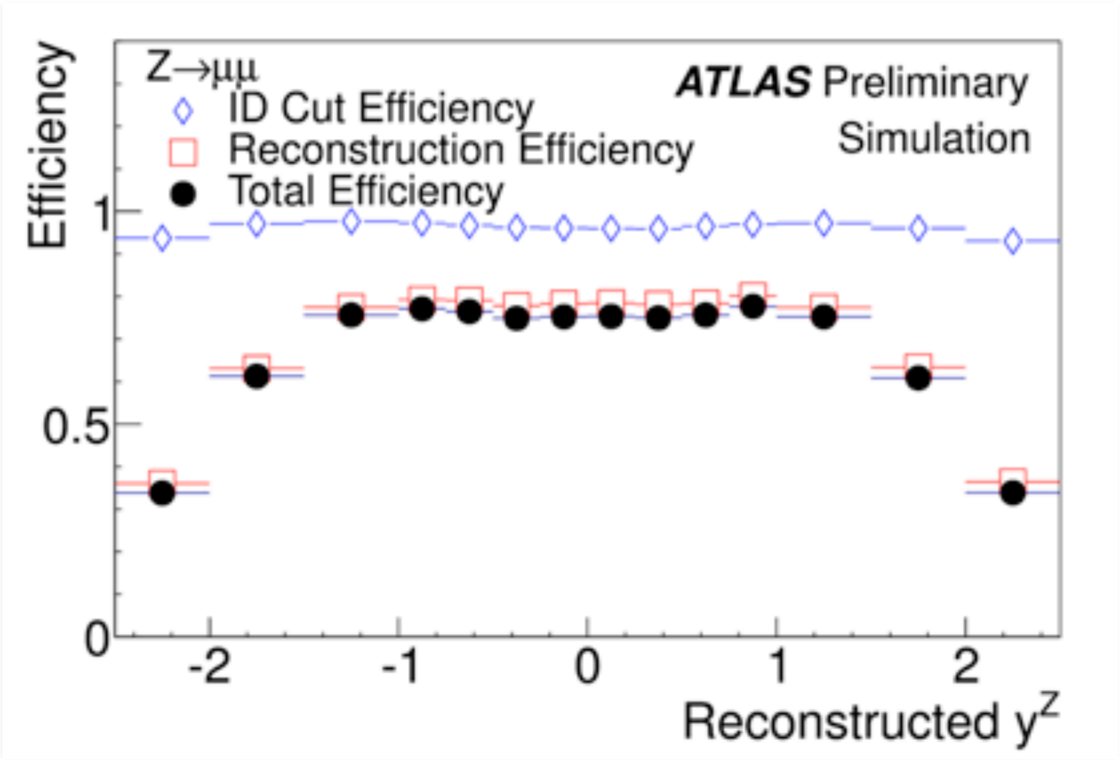
electrons





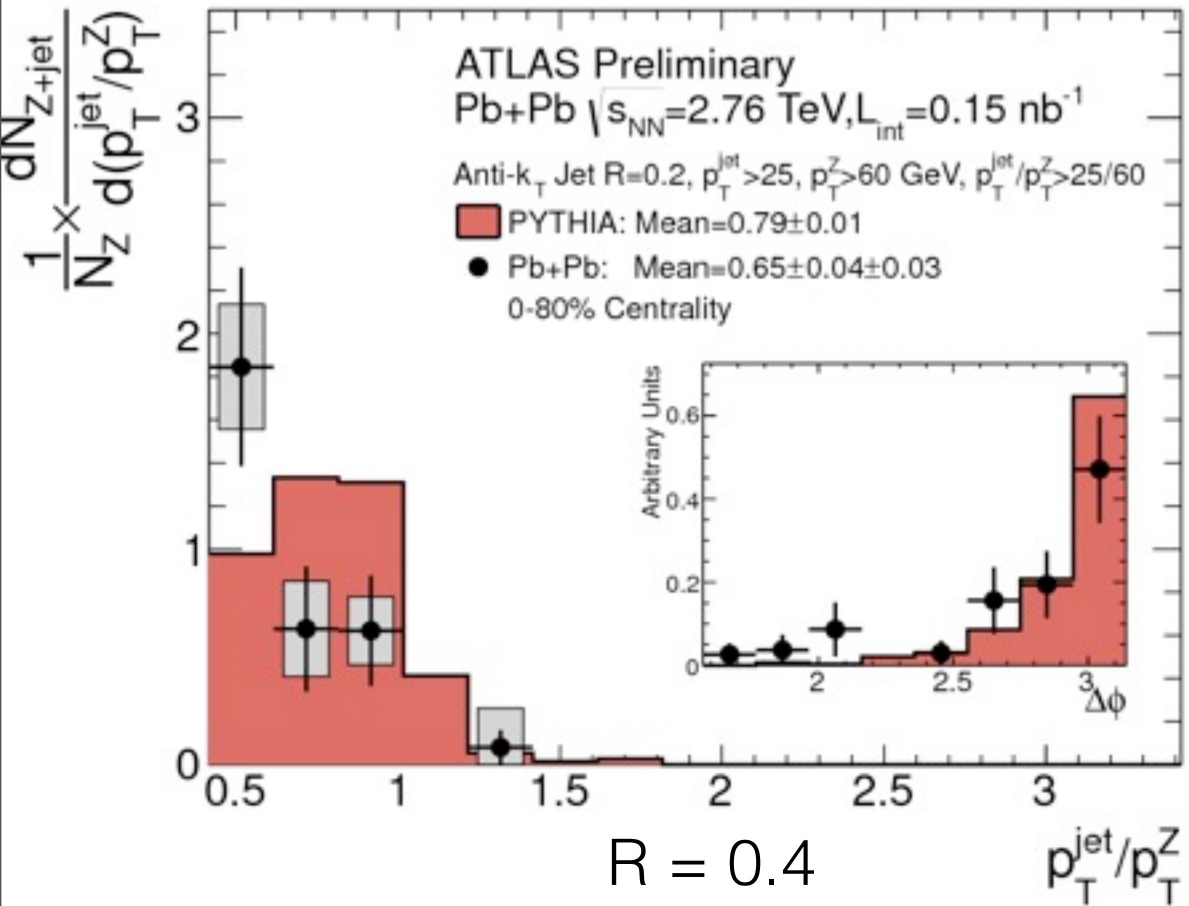
muons



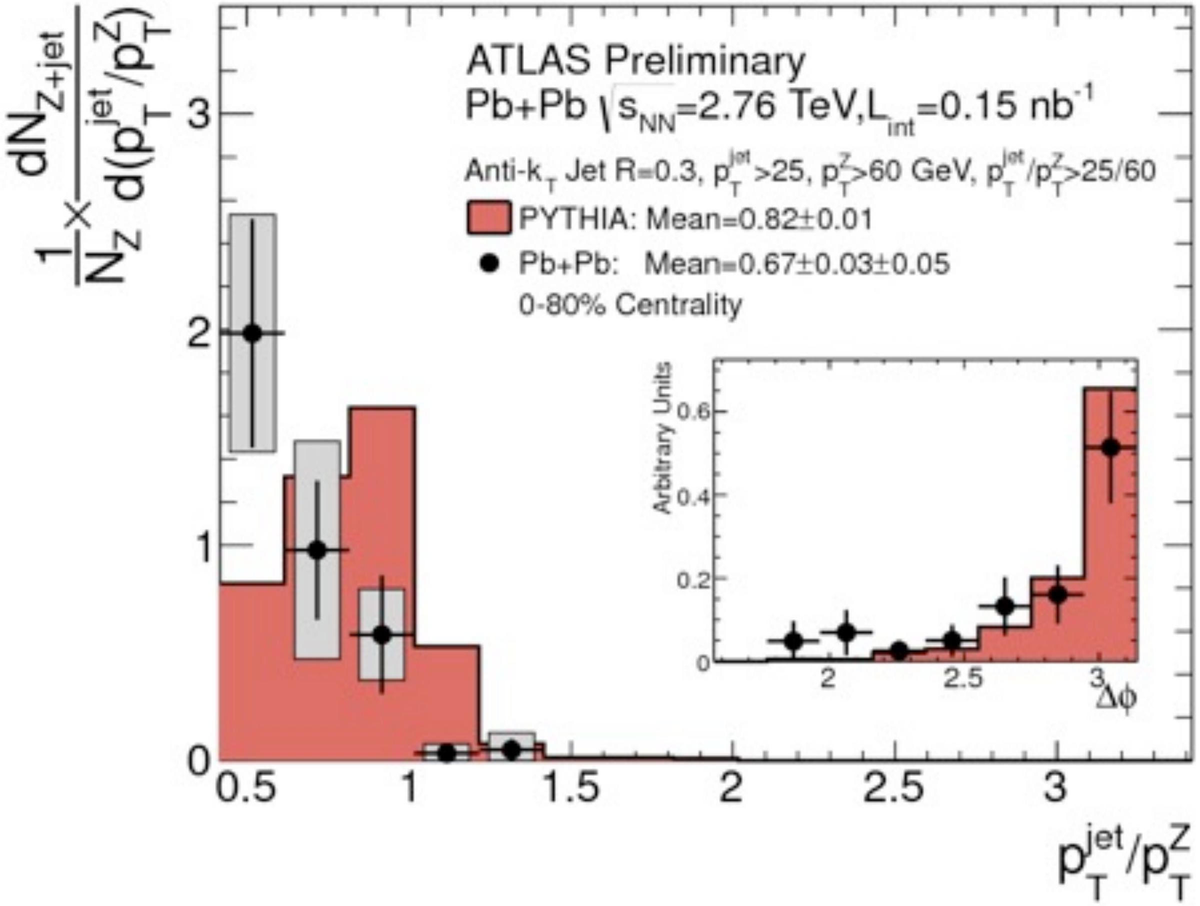


Z - jet correlations 0-80% centrality

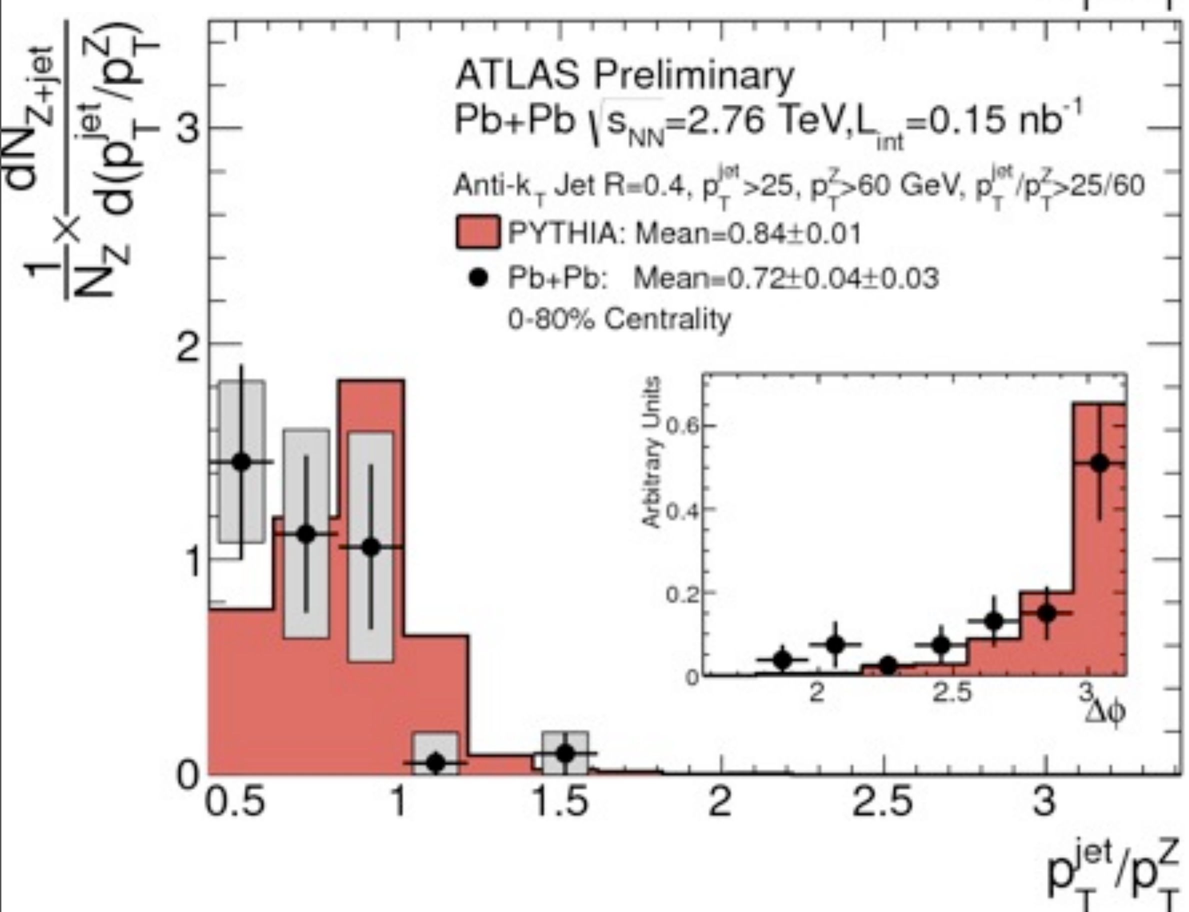
R = 0.2



R = 0.3



R = 0.4



Ratio of jet and Z boson transverse momenta.
Normalized per Z boson.
Inset $\Delta\phi$ distribution, normalized to unity
Low statistics but data distributions in the momentum ratio are
different from PYTHIA null hypothesis

Z production – e, μ selection and efficiencies

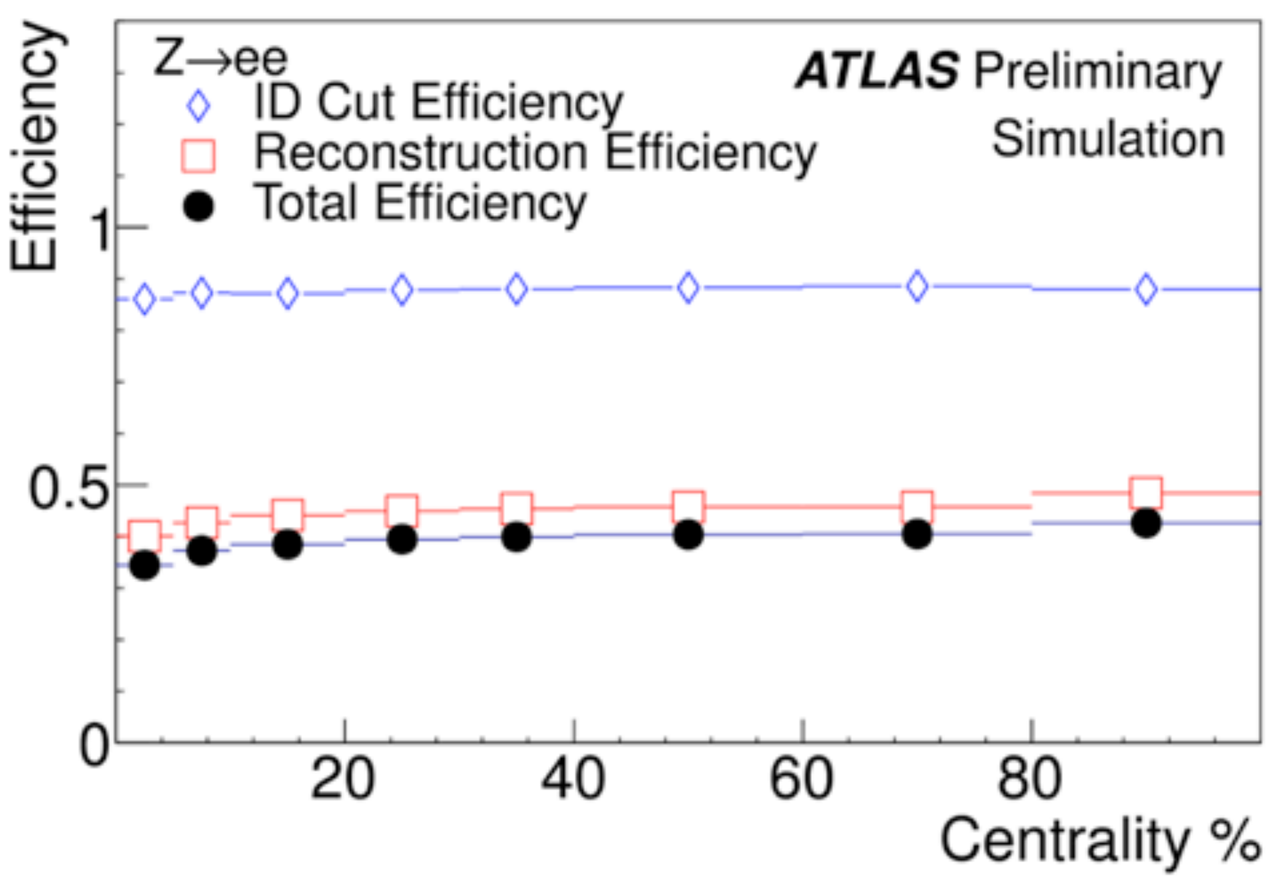
electrons:

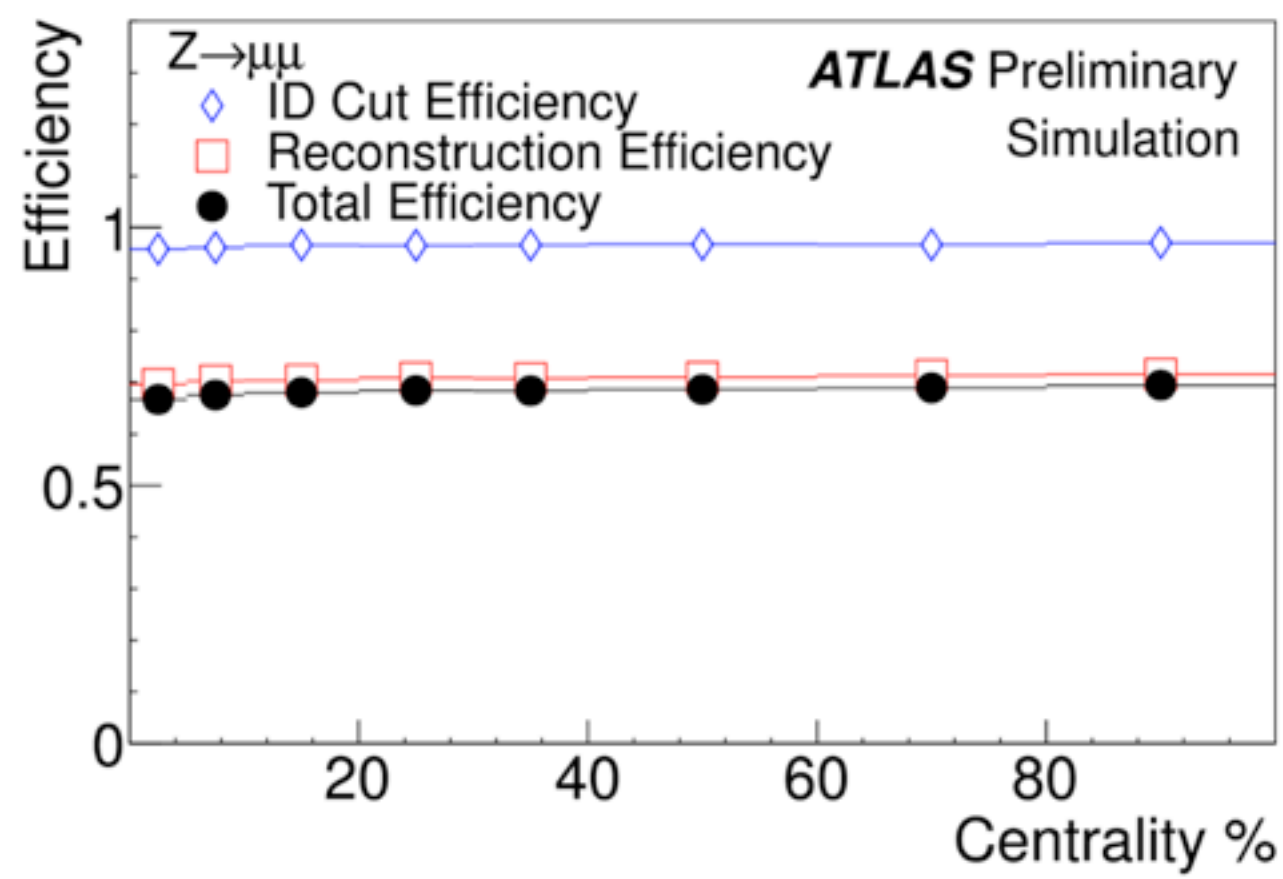
identified at L1 as a cluster of cells in the electromagnetic calorimeter, formed into $(\Delta\phi\times\Delta\eta) = 0.1 \times 0.1$ trigger towers;
$|\eta| < 2.5$, excluding the transition region between calorimeter sections ($1.37 < |\eta| < 1.52$)
$E_T > 14$ GeV.

muons:

selected using all three trigger levels;
combination of MS and/or ID:
" high quality" MS & ID, combined: pT > 10 GeV required for both,
"low quality", pT > 20 GeV required for both

weak centrality dependence:





Photon- jet correlations

Jet quenching physics:

- opening angle between leading jet and photon, $\Delta\varphi$;
- transverse momentum ratio, $x_{j\gamma}=p_T^{jet}/p_T^{\gamma}$;
- $R_{j\gamma} = (1/N_\gamma)dN_{j\gamma}/dx_{j\gamma}$, fraction of photon events that have a jet.

Correlation between the photon and the leading jet with:

- $p_T^{jet} > 25$ GeV, $|\eta^{jet}|<2.1$;
- $60 < p_T^{\gamma} < 90$ GeV, $|\eta^{\gamma}|<1.3$;
- (For $x_{j\gamma}$ and $R_{j\gamma}$) $\Delta\varphi>7/8\pi$, and $x_{j\gamma}>25/60$.

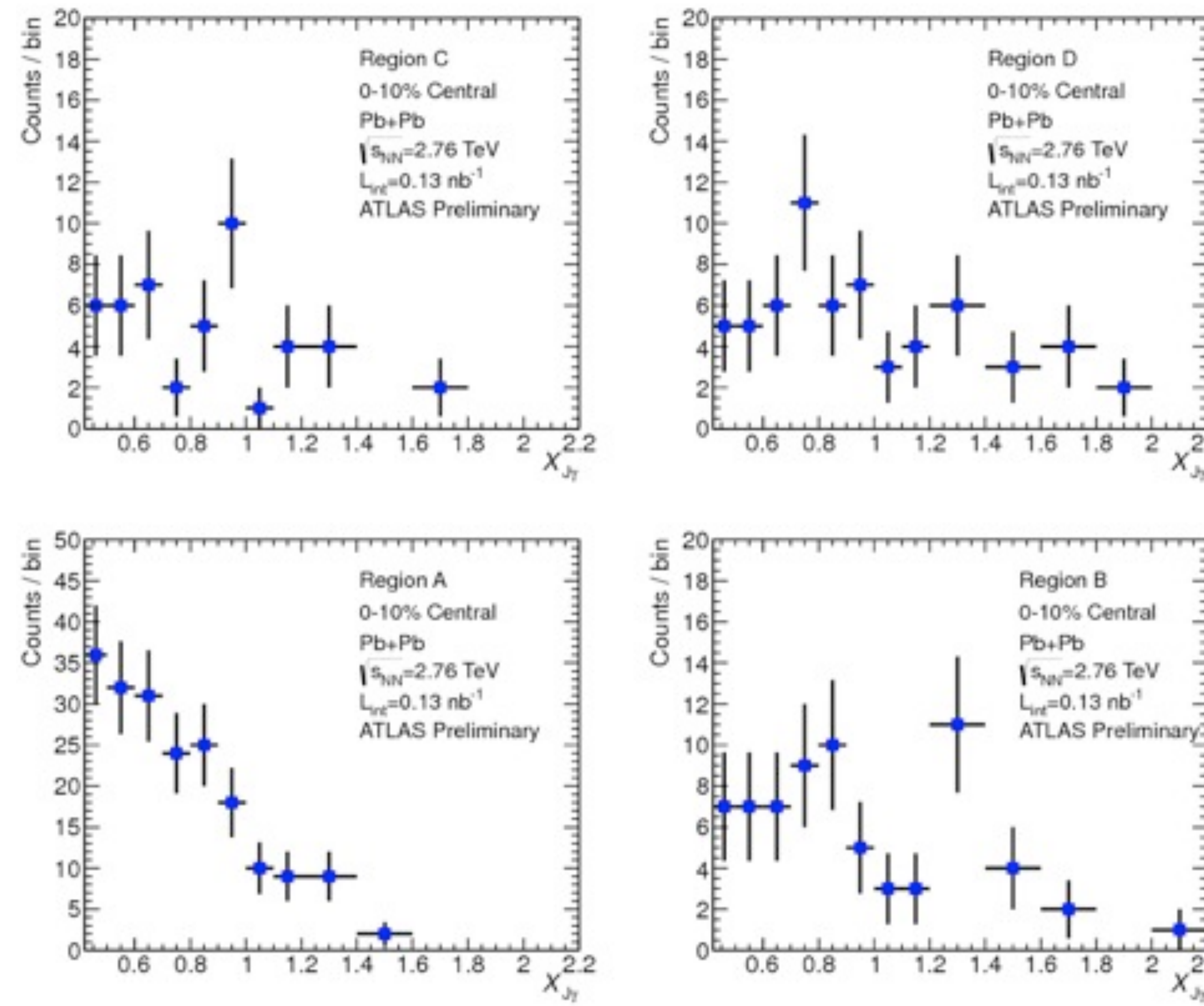
Background subtraction

“double sideband” method to find the background.

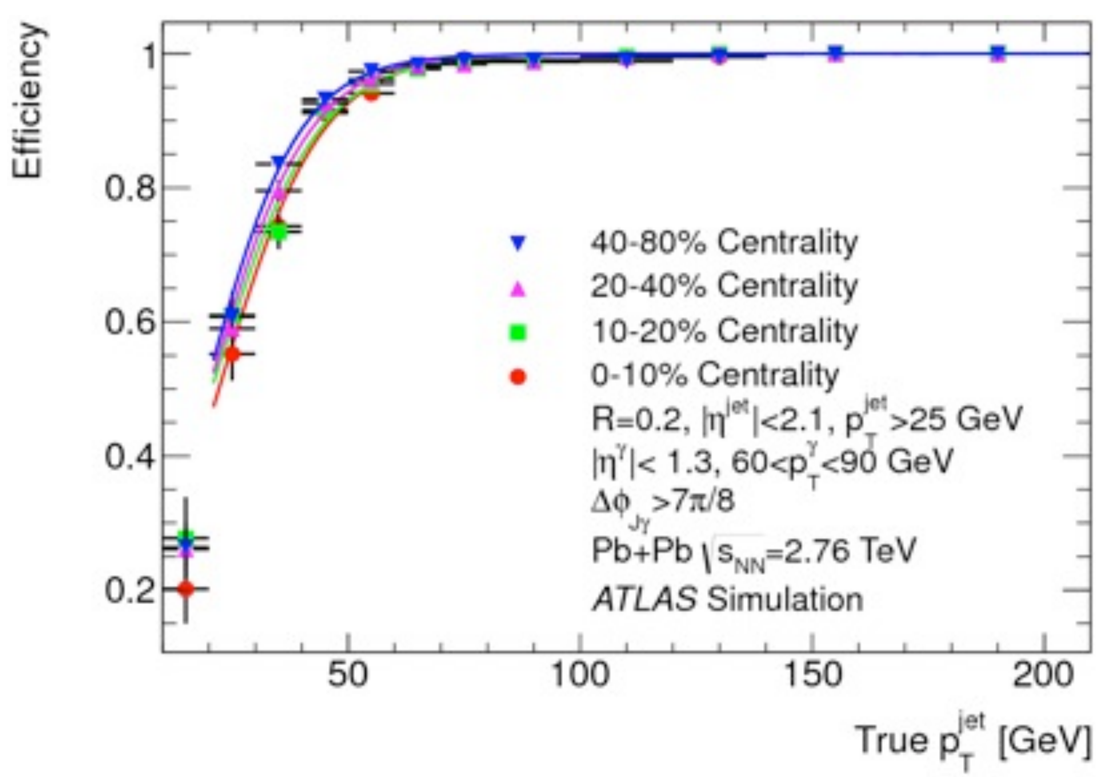
Unfold jet spectrum

- unfolding matrix for inclusive jets (SVD) from PYTHIA embedded into data;
- apply to single events;
- p_T^{jet} mapped to different values with different weights;
- fill $x_{j\gamma}$ distribution.

Raw $x_{j\gamma}$ distributions

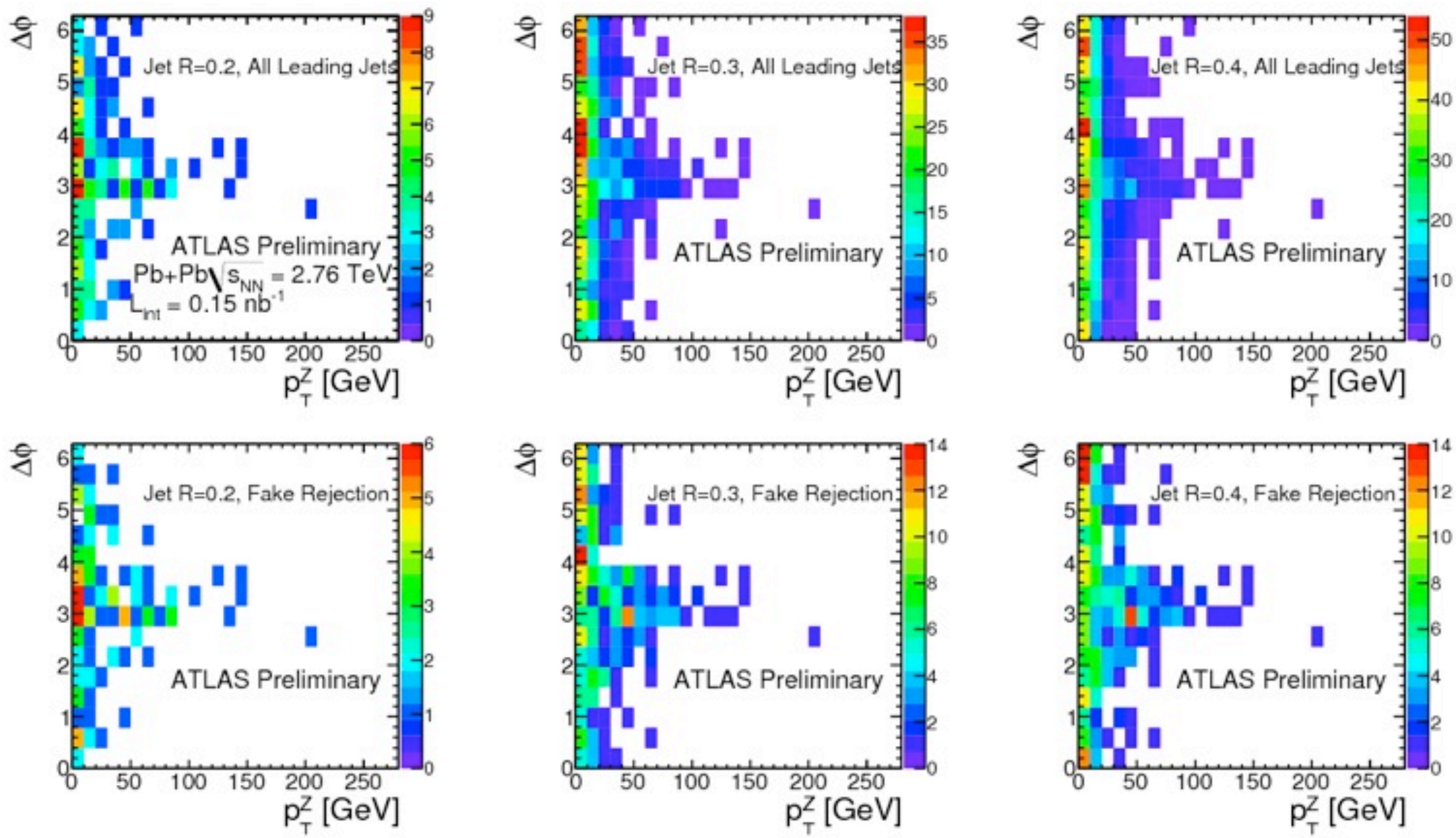


Photon efficiency



Jet reconstruction efficiency in photon-jet events.

Z - jet correlations



Jets reconstructed using standard iterative background subtraction.

Above 50-60 GeV jet and Z are emitted back to back.

Fake rejection (based on track jet or EM cluster within jet), removes uncorrelated jets (esp. in R=0.3).

Similar to photon – jet analysis

- Lower statistics
- Higher purity

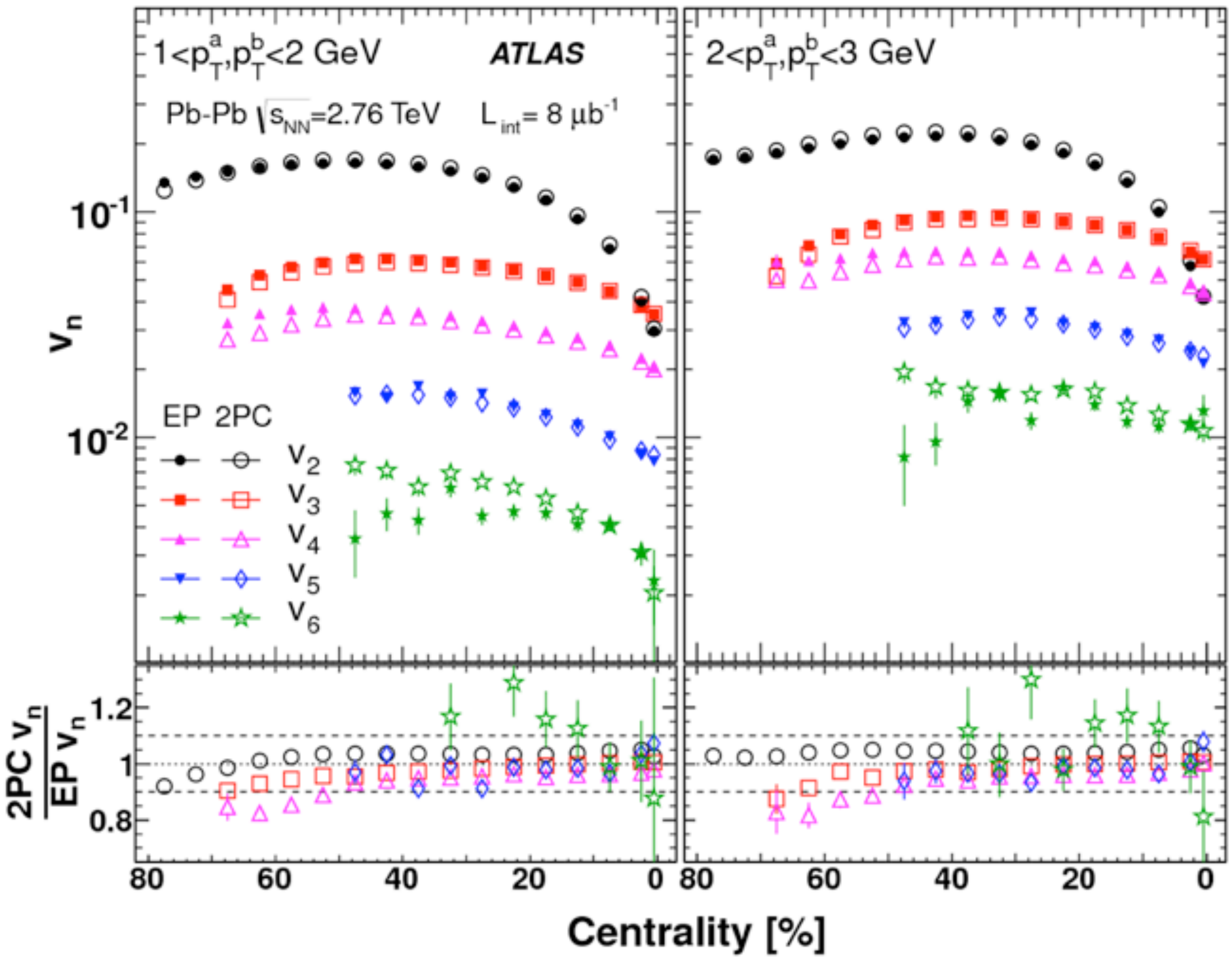
Correlation between Z boson and leading jet with:

- $p_T^{jet} > 25$ GeV, $|\eta^{jet}|<2.1$
- $p_T^Z > 60$ GeV
- $\boldsymbol{\Delta\varphi}>1/2\pi$, and $x_{jZ}>25/60$

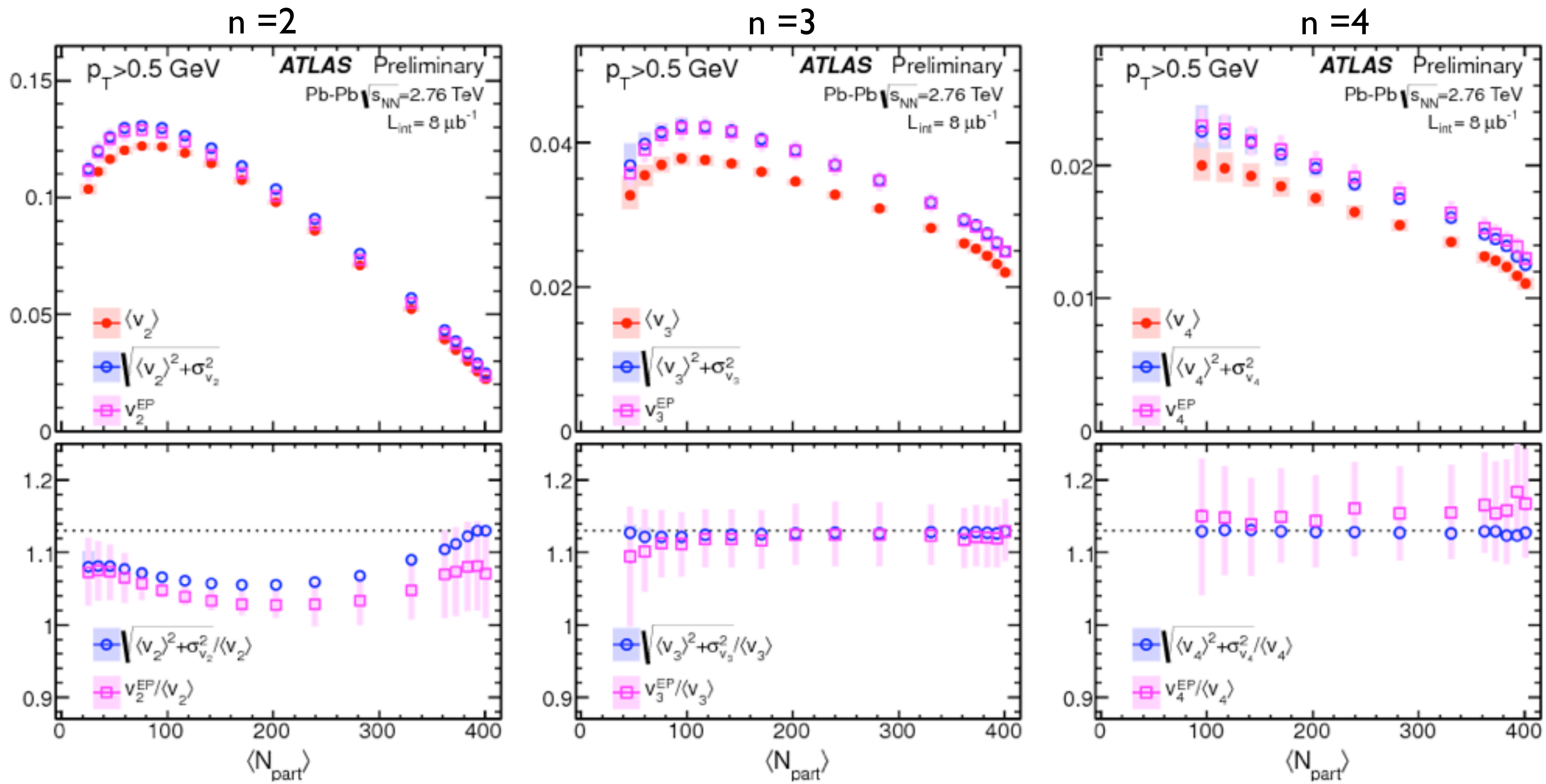
The result: 2PC compared to EP

PHYSICAL REVIEW C **86**, 014907 (2012)

Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions with the ATLAS detector



EP method in general is known to measure a v_n value between the simple average and the RMS of the true v_n: $\langle v_n \rangle \leq v_n^{EP} \leq \sqrt{\langle v^2_n \rangle}$ *Phys.Rev.C77,014906(2008).*



for v3 e v4 the values of v_n^{EP} are almost identical to RMS $\sqrt{\langle v^2_n \rangle}$;

for v2 the values of v_n^{EP} are in between $\langle v_n \rangle$ and $\sqrt{\langle v^2_n \rangle}$: they are closer to $\langle v_n \rangle$ in mid-central collisions where the EP resolution factor is close to one, and approach $\sqrt{\langle v^2_n \rangle}$ in peripheral collisions where the resolution factor is small.