Z and γ (+jet) measurements in lead-lead collisions with ATLAS

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for the ATLAS Collaboration

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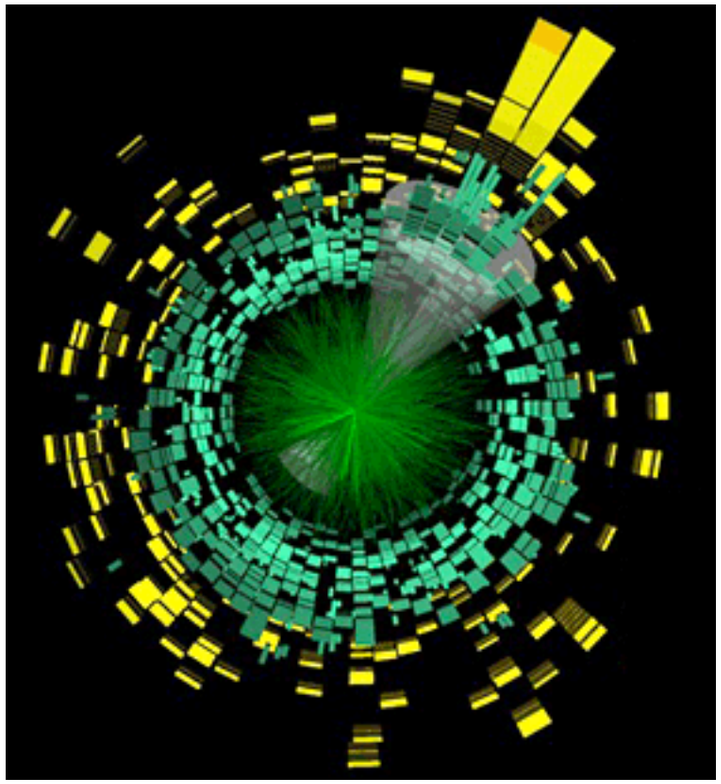
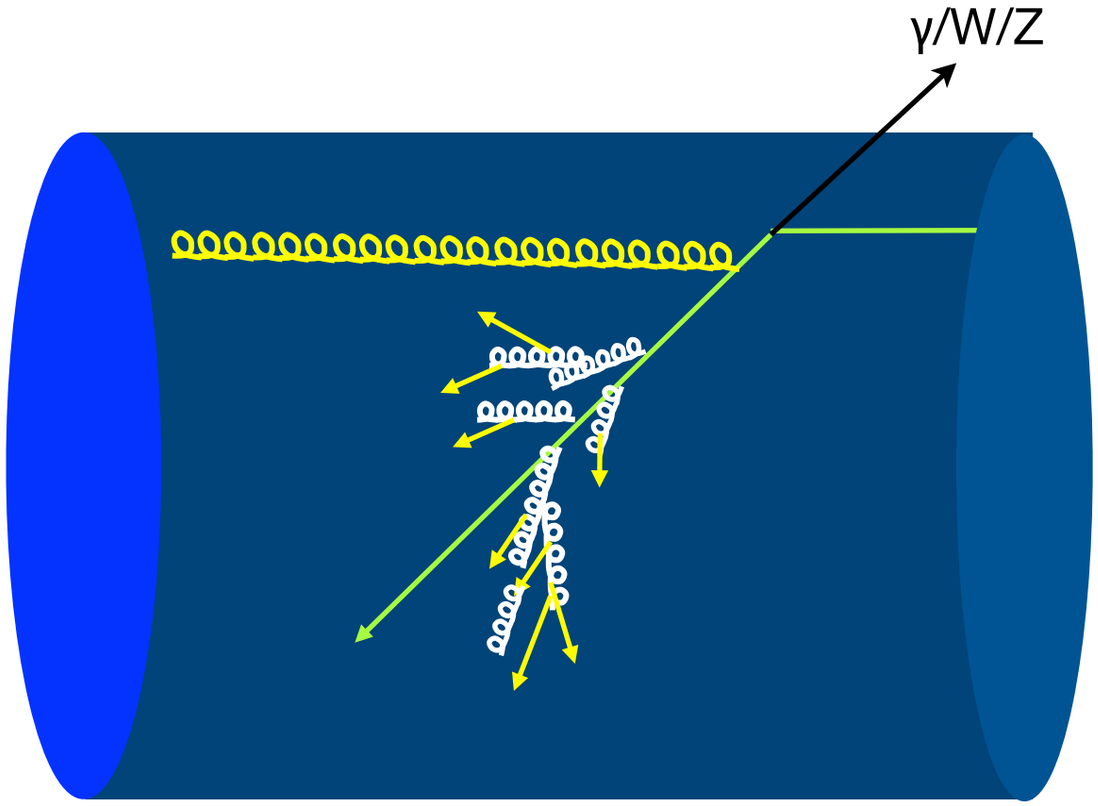
Quark Matter 2012, Washington, DC

Photon-jet and Z-jet production

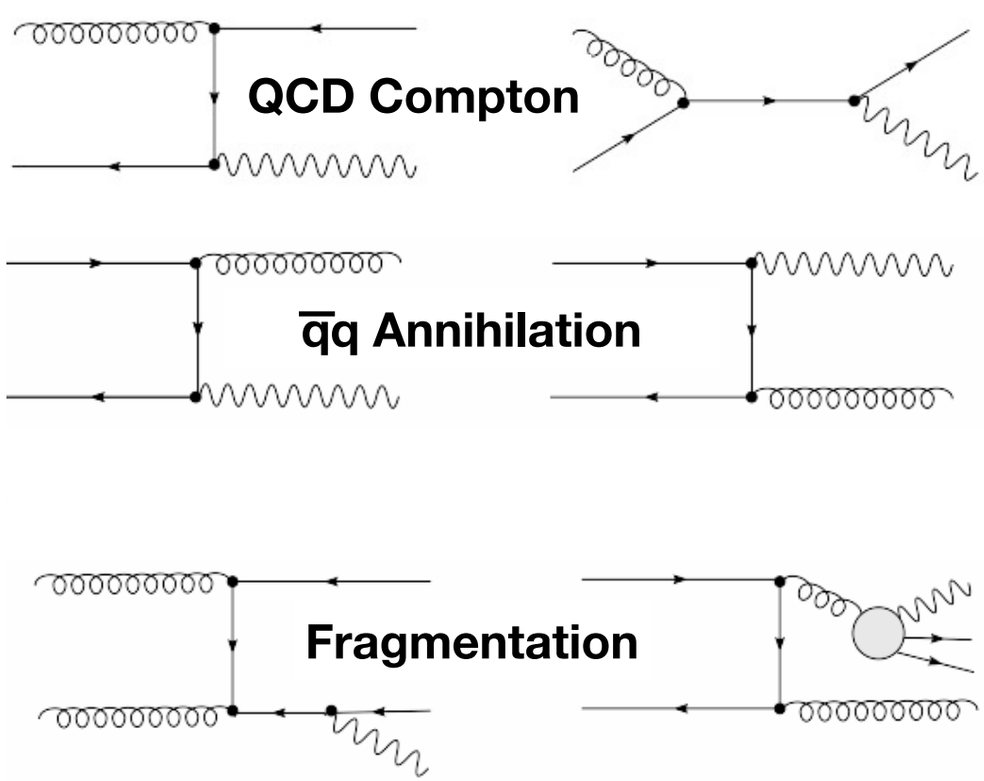


unlike for dijet events,
where both objects
are potentially modified
by the hot, dense medium...

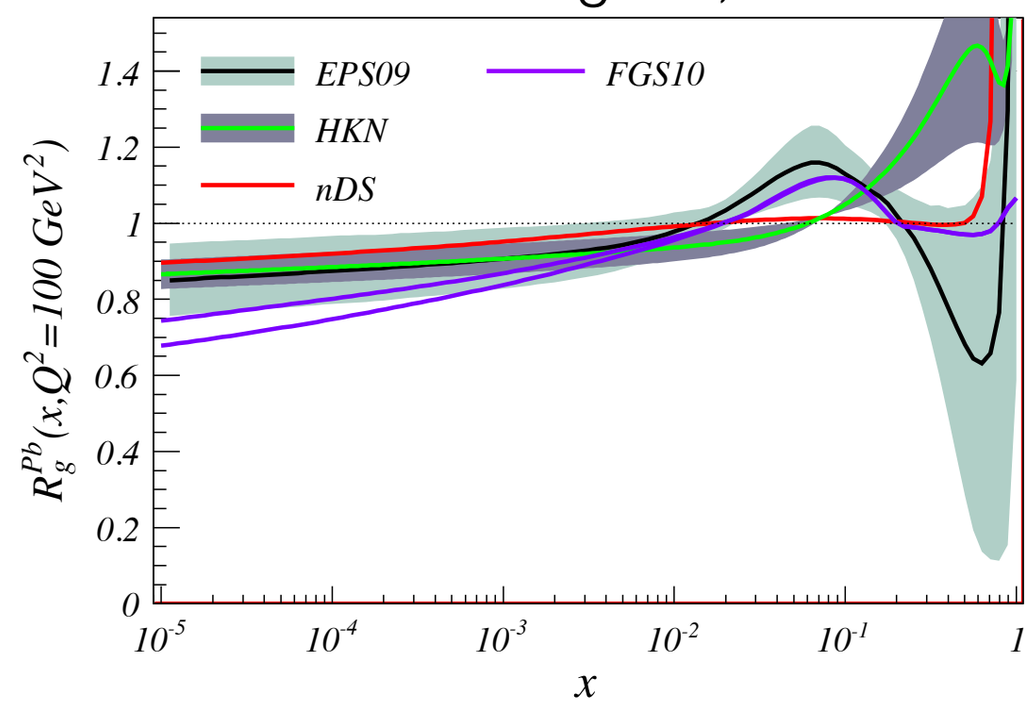


electroweak bosons are
unaffected by the medium,
allow us to calibrate scale of
hard process and directly
probe jet energy loss

Photons and Z's in nuclear collisions

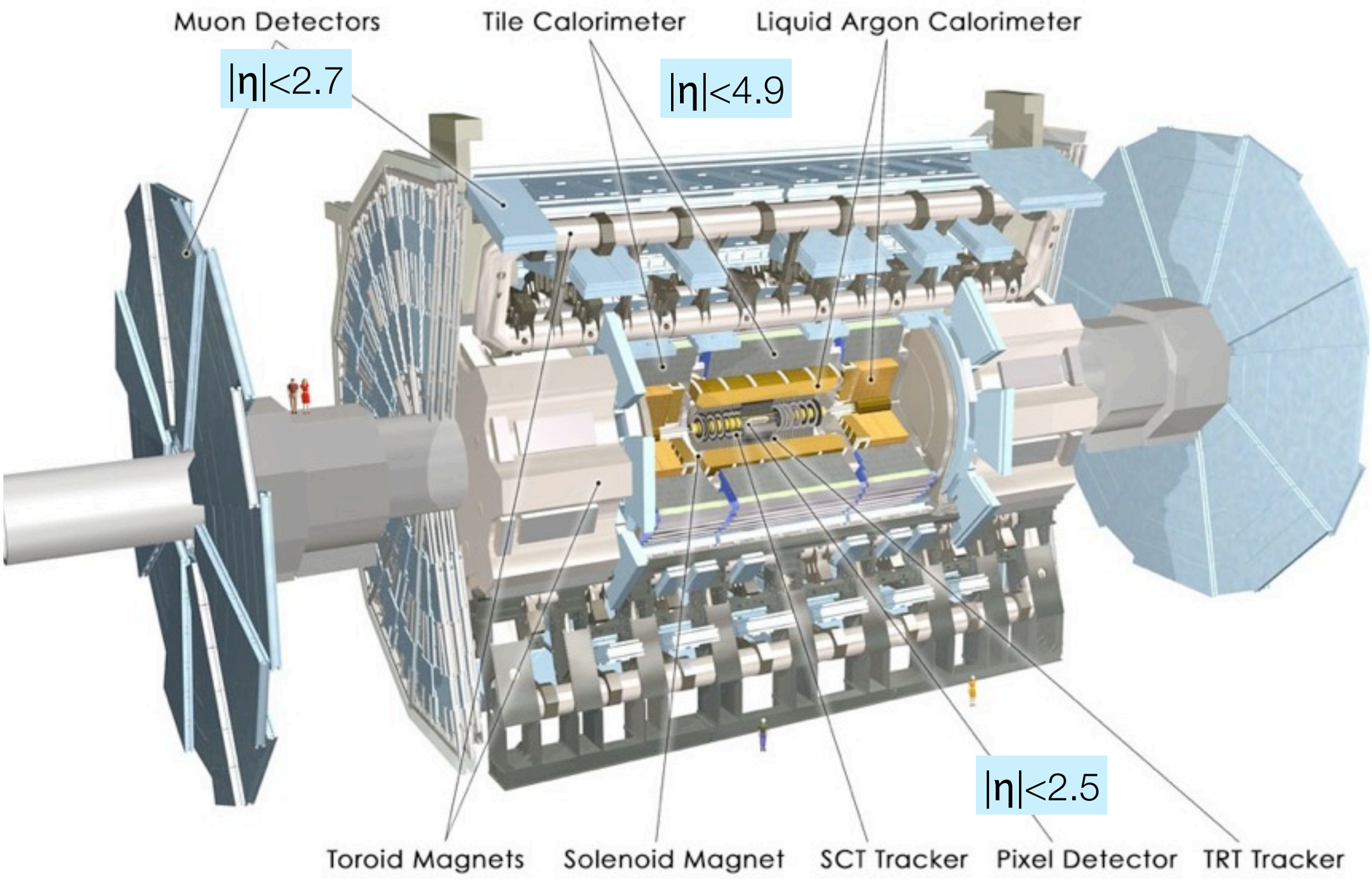


Salgado, et al 2011

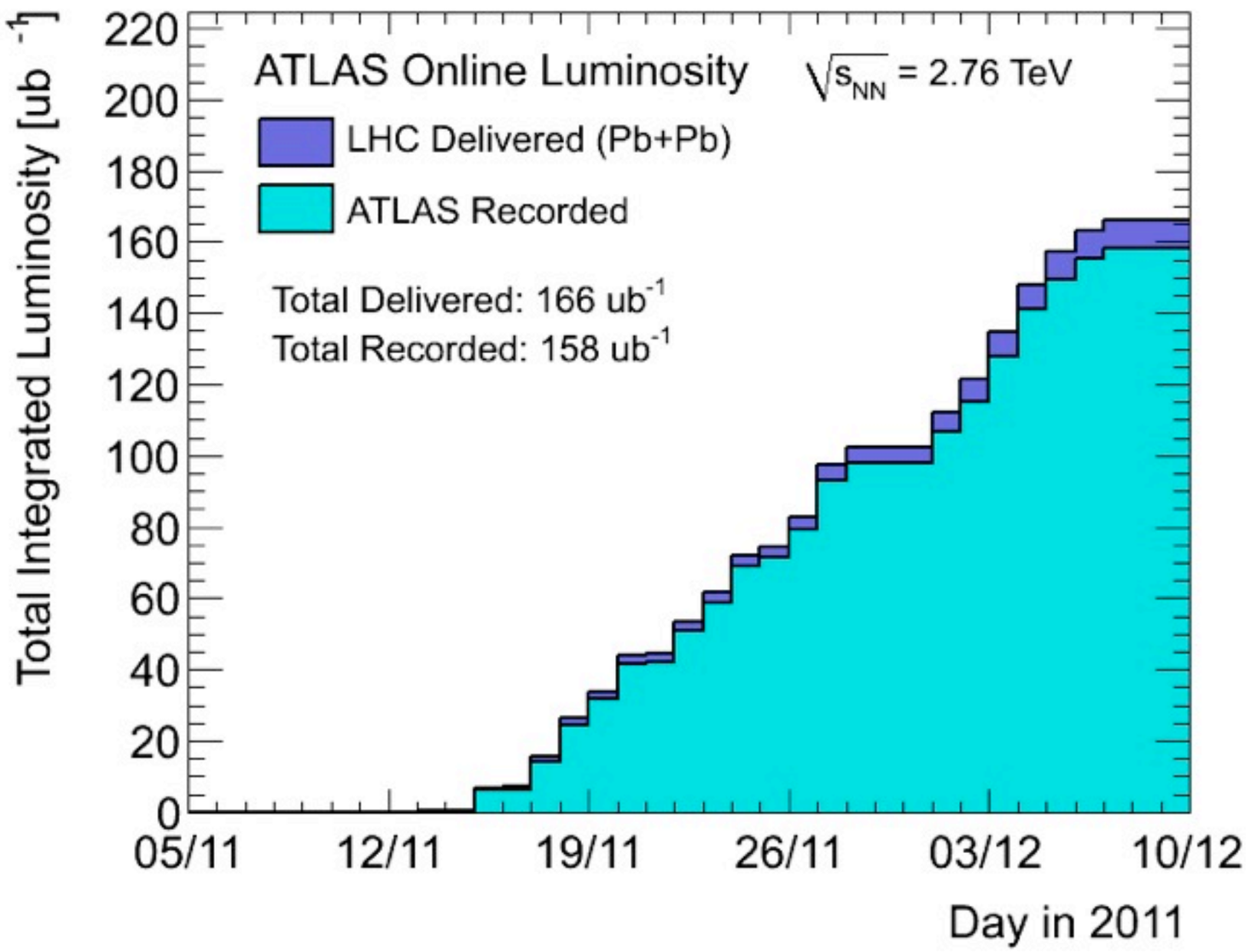


- **Photons & Z are penetrating probes of the hot, dense medium**
  - Boson-jet correlations will be an important contribution to understanding of jet quenching!
- **Important to check rates of production, calculable in pQCD @ NLO (γ) & NNLO (Z)**
  - e.g. photon diagrams include direct photons & photons from jet fragmentation
- **Fragmentation contributions for photons reduced using "isolation" condition**
  - Require a maximum energy in a cone **$R<R_{iso}$** around photon
- **Both probes are sensitive to nPDF effects (e.g. shadowing, antishadowing)**

The ATLAS Detector



Integrated luminosity for 2011 Pb+Pb run

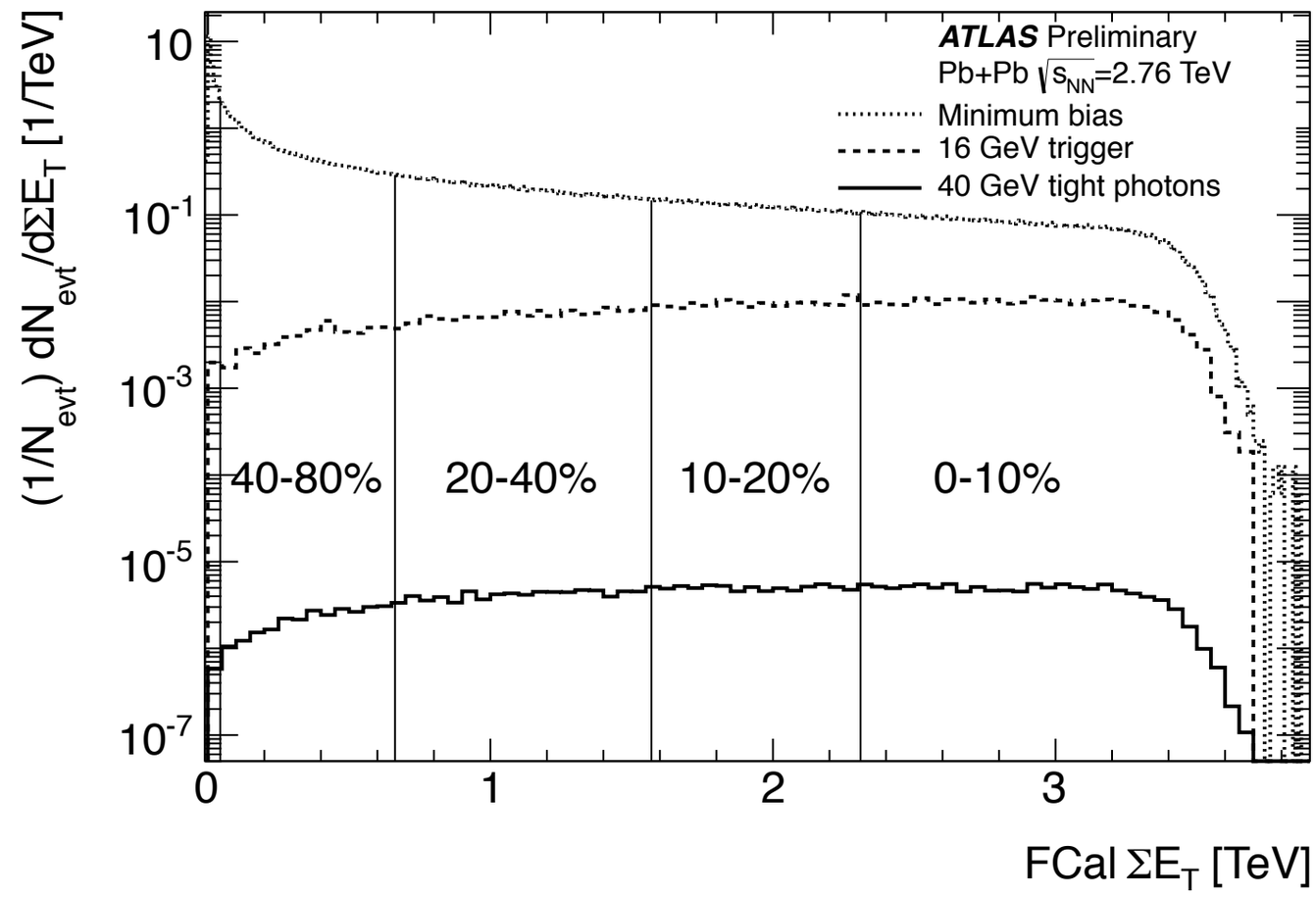


166 μb^{-1} delivered, 158 μb^{-1} recorded by ATLAS

Centrality selection

Centrality defined by ΣE_T in ATLAS forward calorimeter (FCal) $3.2<|\eta|<4.9$

FCal ΣE_T shape established to be identical to 2010 (after known 4.1% rescaling), where efficiency relative to total cross section known to be **98±2%**



Uncertainties on geometric parameters include cross section & Glauber uncertainties

Bin	ΣE_T range	$\langle N_{part} \rangle$	Error	$\langle N_{coll} \rangle$	Error	$\langle T_{AA} \rangle$	Error
0-10%	2.31-4 TeV	356	0.7%	1500	8%	23.4	3.0%
10-20%	1.57-2.31 TeV	261	1.4%	923	7%	15.1	3.1%
20-40%	0.66-1.57 TeV	158	2.5%	441	7%	6.88	5.2%
40-80%	0.044-0.66 TeV	46	6%	78	9%	1.22	9.4%

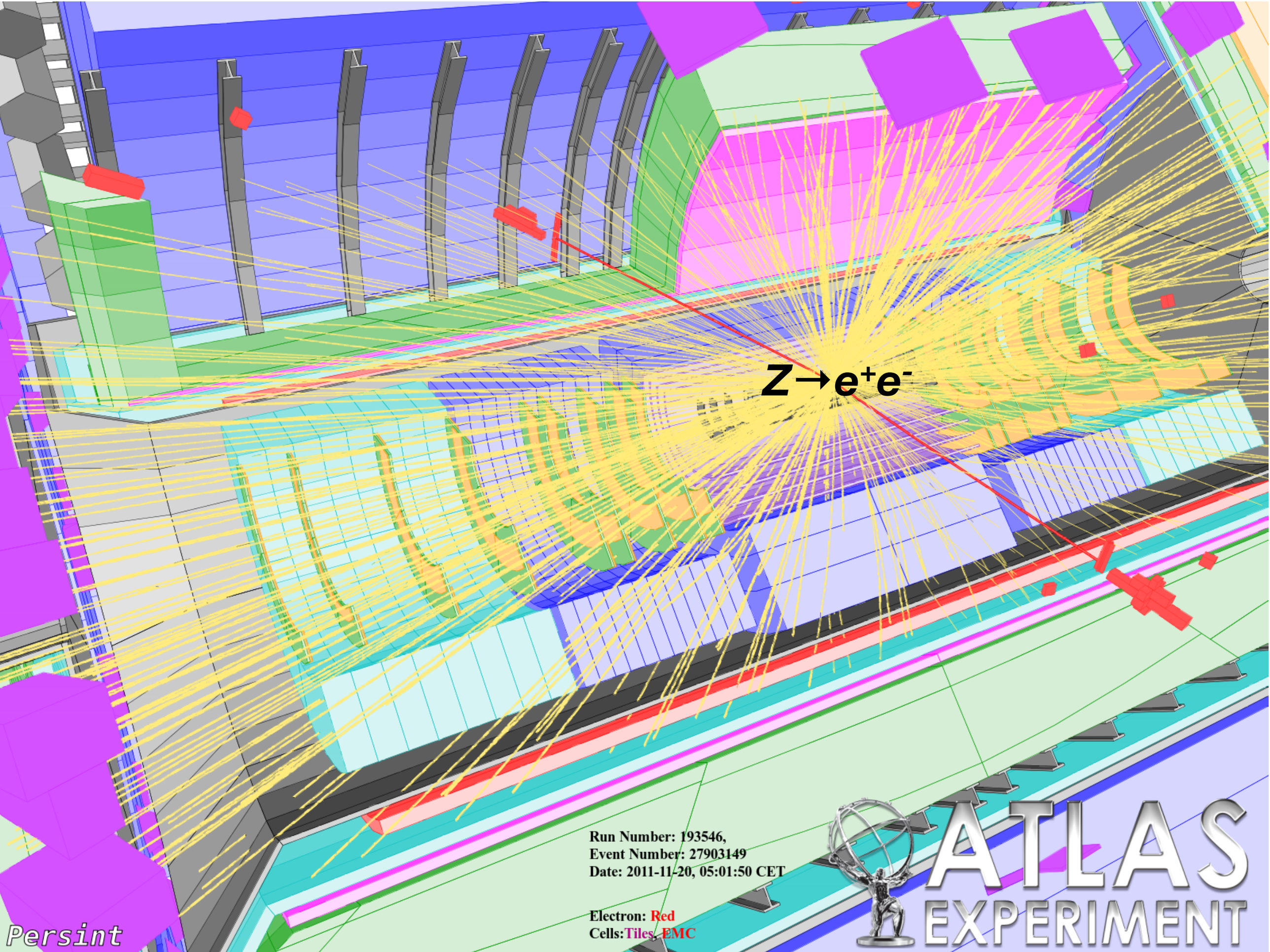
Data sample (photons)

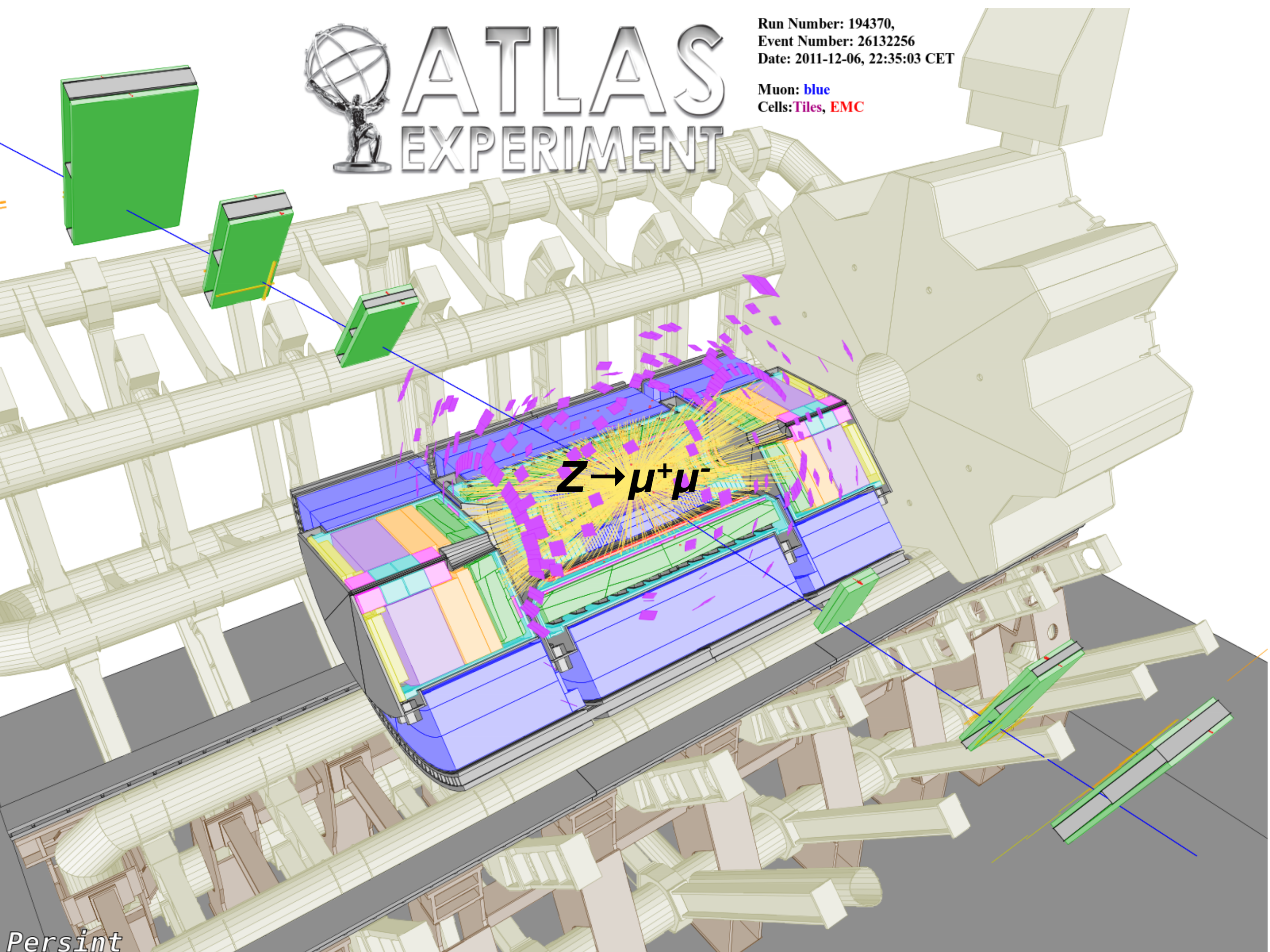
- **Using 0.13 nb^{-1} of 2011 lead-lead LHC run**
  - Detailed calibration of luminosity scale to accepted minimum bias events (in a special data stream) gives a total of 755M events with <1% precision for 0-80% centrality
- **Special selection of events triggered on 16 GeV EM cluster, with a photon or electron reconstructed offline with E_T>40 GeV**
  - From PYTHIA+HIJING simulations, 100% efficient for photon p_T>45 GeV
- **Underlying event (UE) is removed from every calorimeter cell**
  - Identical algorithm to that used for ATLAS jet analysis
  - Iterative elliptic-flow-sensitive subtraction performed in slices of $\Delta\eta$=0.1, after excluding regions around R=0.2 jets >25 GeV and R=0.4 track jets >10 GeV
- **Standard ATLAS photon & electron ("eGamma") reconstruction then applied to full set of UE-subtracted calorimeter cells**

Data sample (Z)

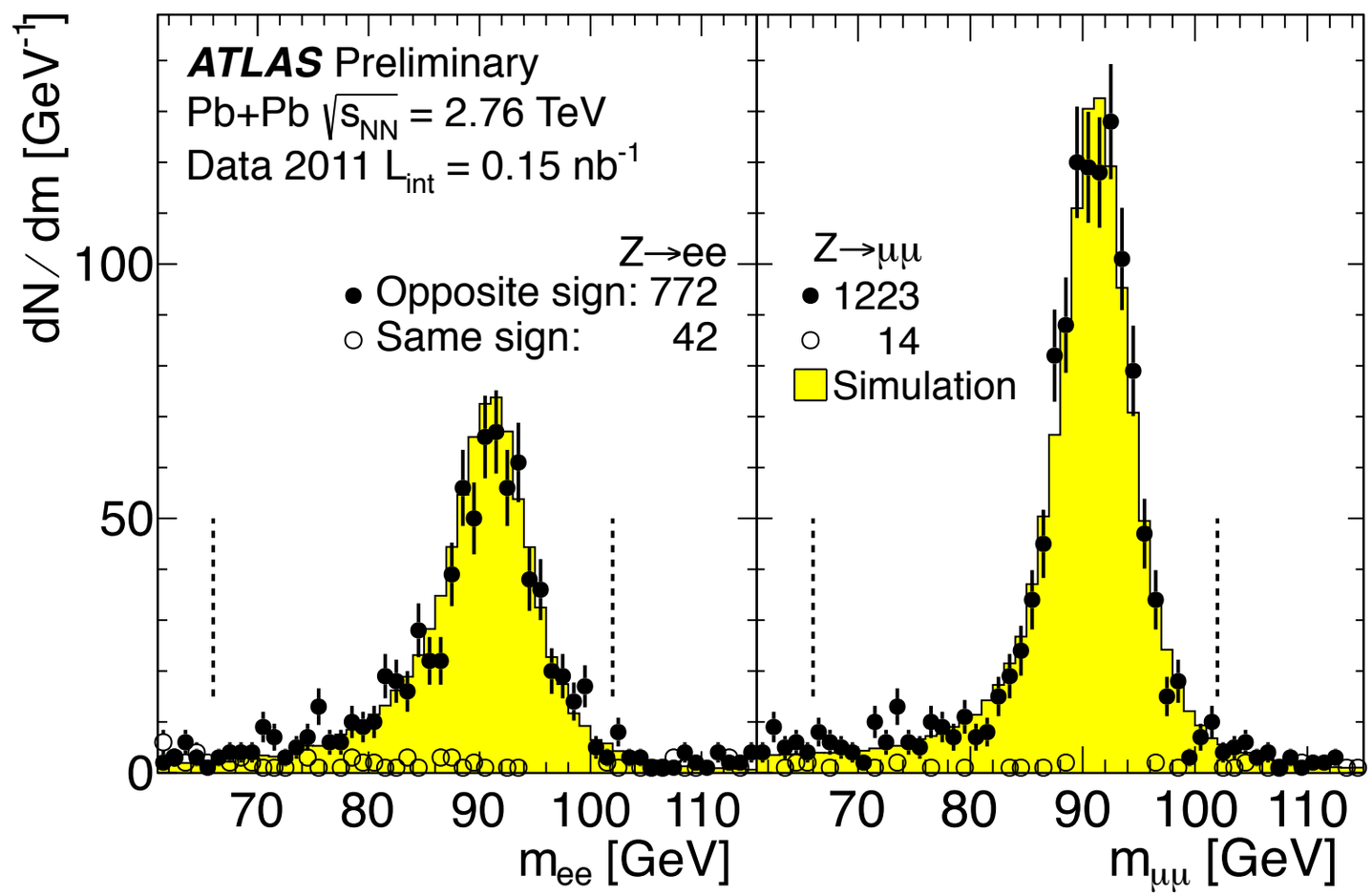
- **Z to electrons**
  - Triggered using similar EM trigger as for photons with 14 GeV threshold
  - No use of ATLAS high level trigger
  - Electron energy corrected for underlying event
- **Z to muons**
  - Full use of ATLAS trigger system
    - *4 GeV required at level 1*
    - *If accepted, track properties required using precision MDT and CSC information, as well as inner detector information*
    - *Also performed "full scan" reconstruction in the trigger system, for muons above 10 GeV, initiated with ZDC coincidence or a total ET > 10 GeV deposited in the ATLAS calorimeters*
- **Used full 2011 sample L_{int} = 0.15 nb^{-1}**
  - Sampled over 1 billion events

Z and photon yields


Z→e+e-
Run Number: 193546,
Event Number: 27903149
Date: 2011-11-20, 05:01:50 CET
Electron: Red
Cells:Tiles, EMC
ATLAS
EXPERIMENT
Persint


ATLAS
EXPERIMENT
Run Number: 194370,
Event Number: 26132256
Date: 2011-12-06, 22:35:03 CET
Muon: blue
Cells: Tiles, EMC
$Z \rightarrow \mu^+\mu^-$
Persint

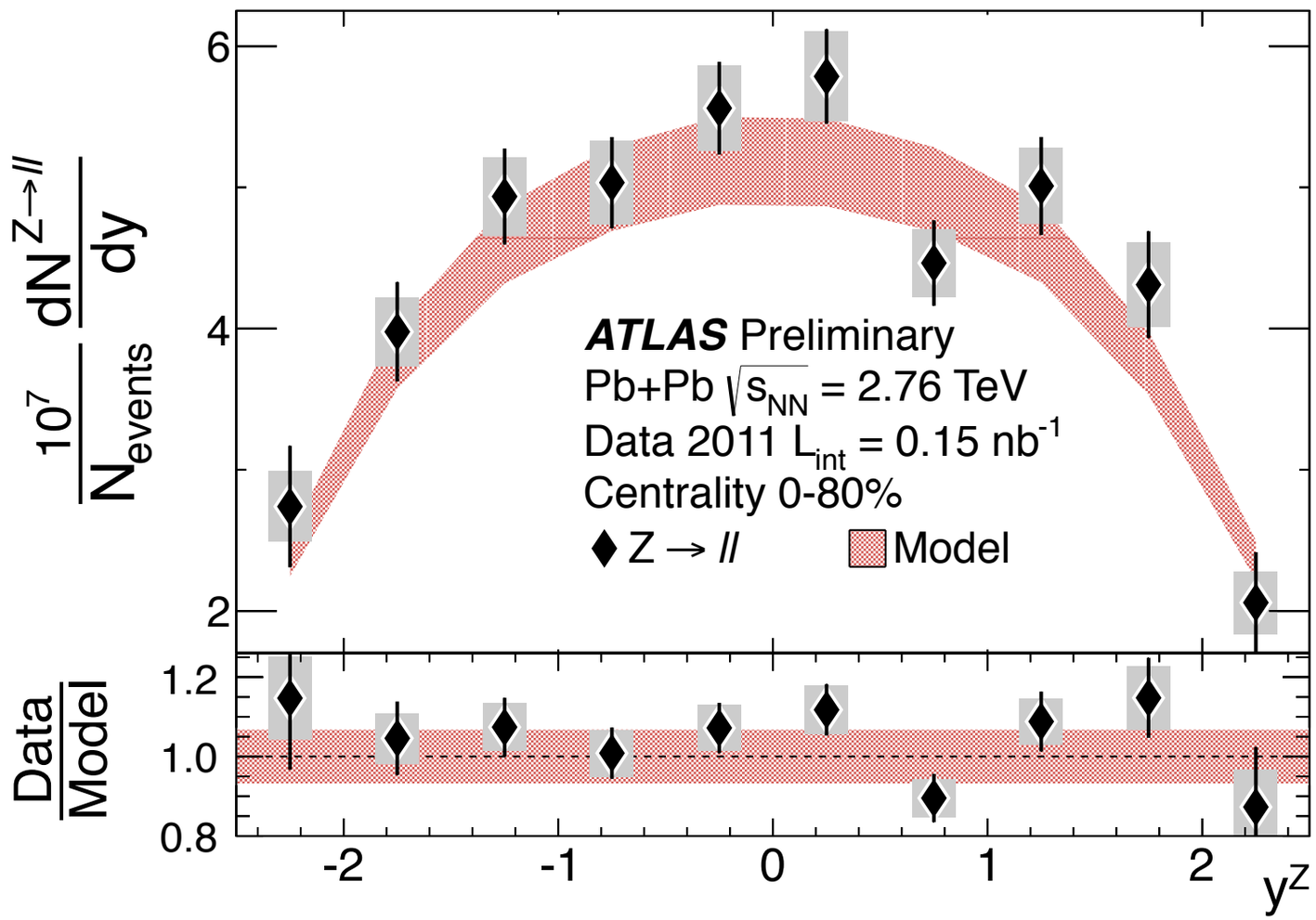
Z reconstruction in 2011 data



Electrons require match of track with EM cluster, along with shower shape cuts

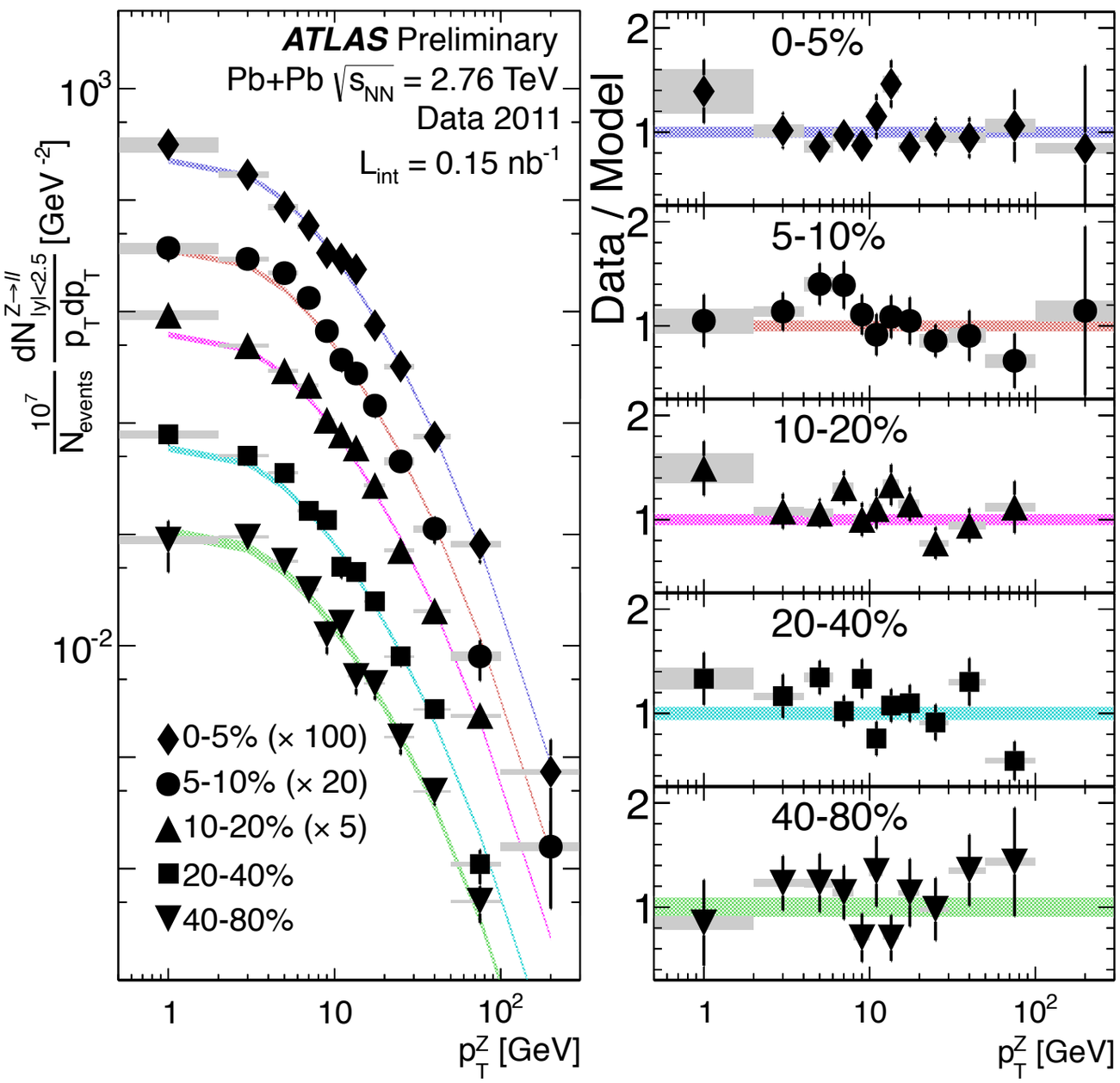
Muons reconstructed using combination of MS and/or ID: optimized for Z efficiency, high quality muons p_T>10 GeV lower quality p_T>20 GeV

Z rapidity distribution



Z yield shown for minimum bias events, normalized to the number of events and compared to the PYTHIA rapidity shape normalized to NNLO cross section x $\langle T_{AA} \rangle$

Z momentum distribution

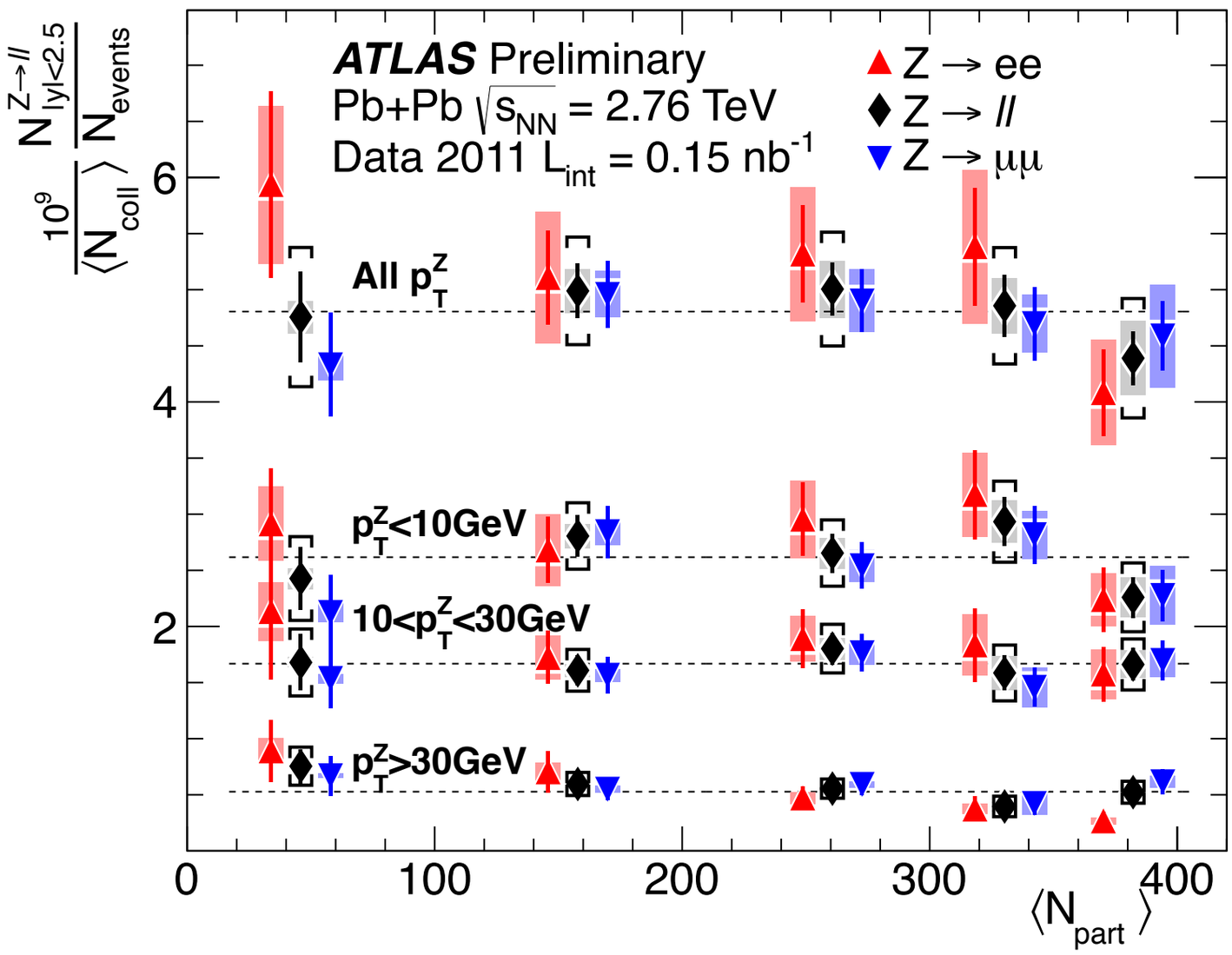


Transverse momentum distribution averaged over |y|<2.5

Spectral shape is centrality independent

Good agreement with PYTHIA shape, normalized to σ_{NNLO} & scaled by $\langle T_{AA} \rangle$

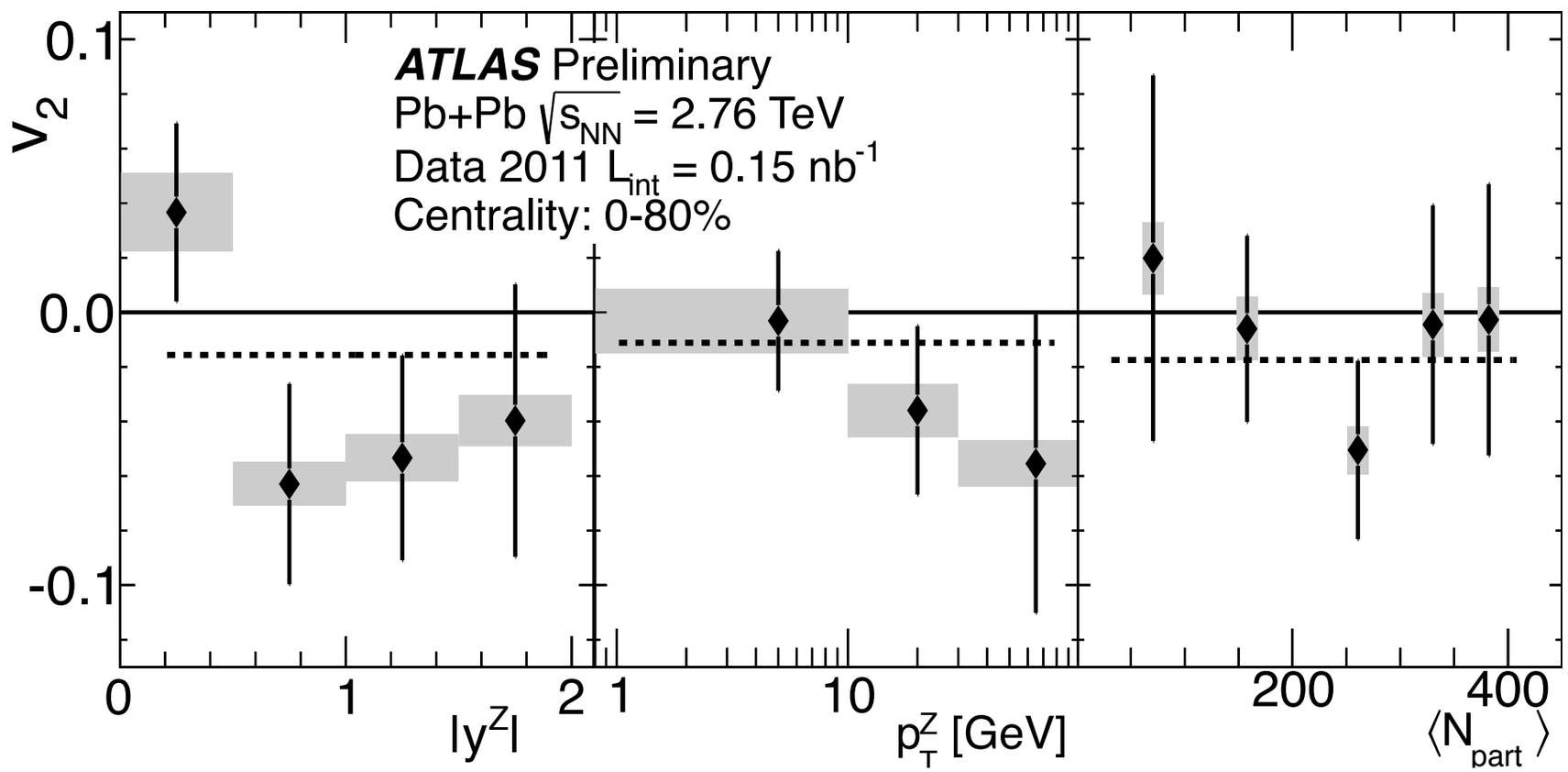
Scaling of Z with collision centrality



Integrated yields show a clear scaling with number of binary collisions

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

Elliptic flow (or lack thereof) of Z

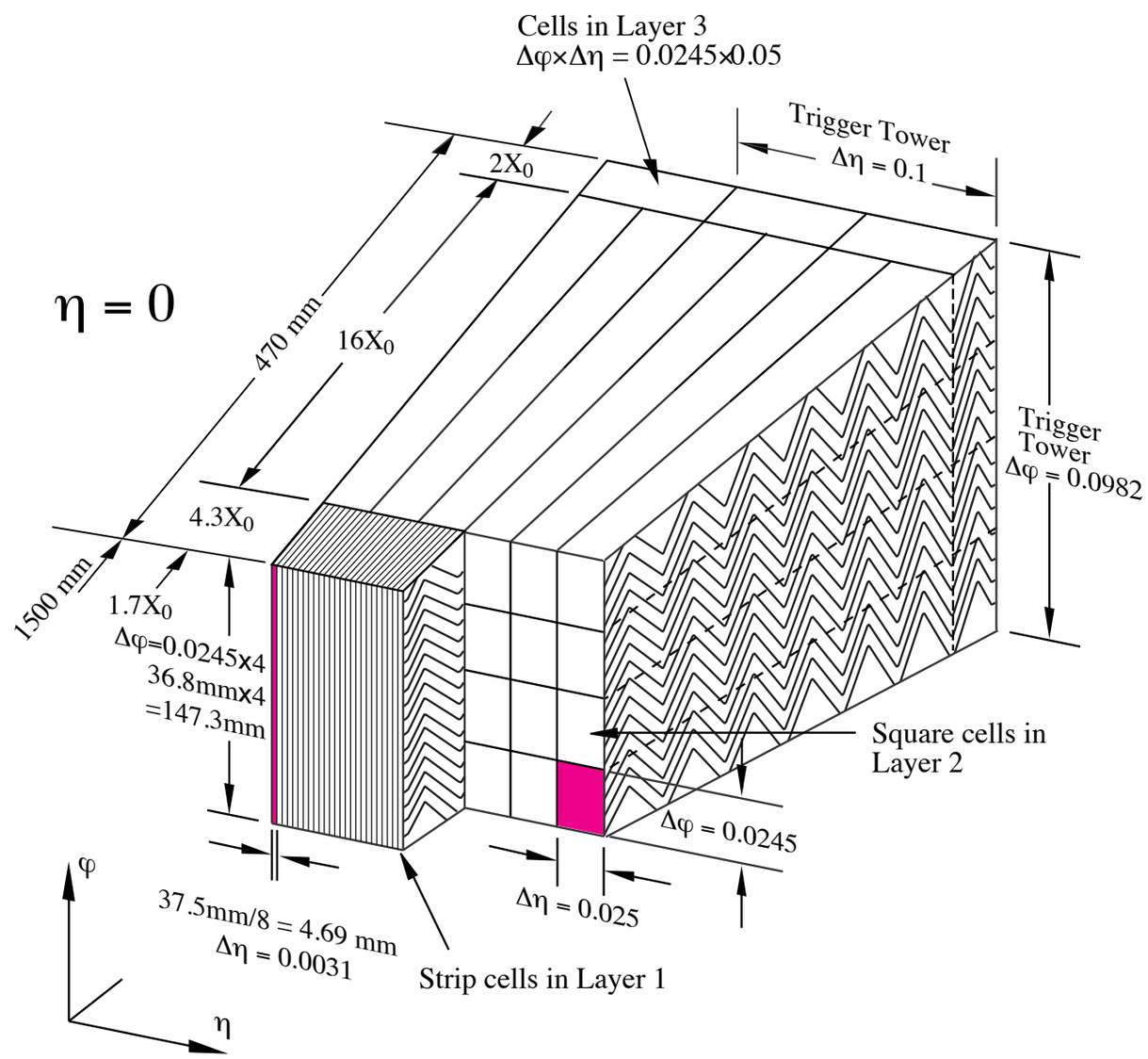


Z elliptic flow checked, to test influence of nuclear geometry (not expected).

Main uncertainty stems from influence of jet on reaction plane calculation, addressed by comparing random choice of EP side (+ or - η) with choice correlated with Z direction

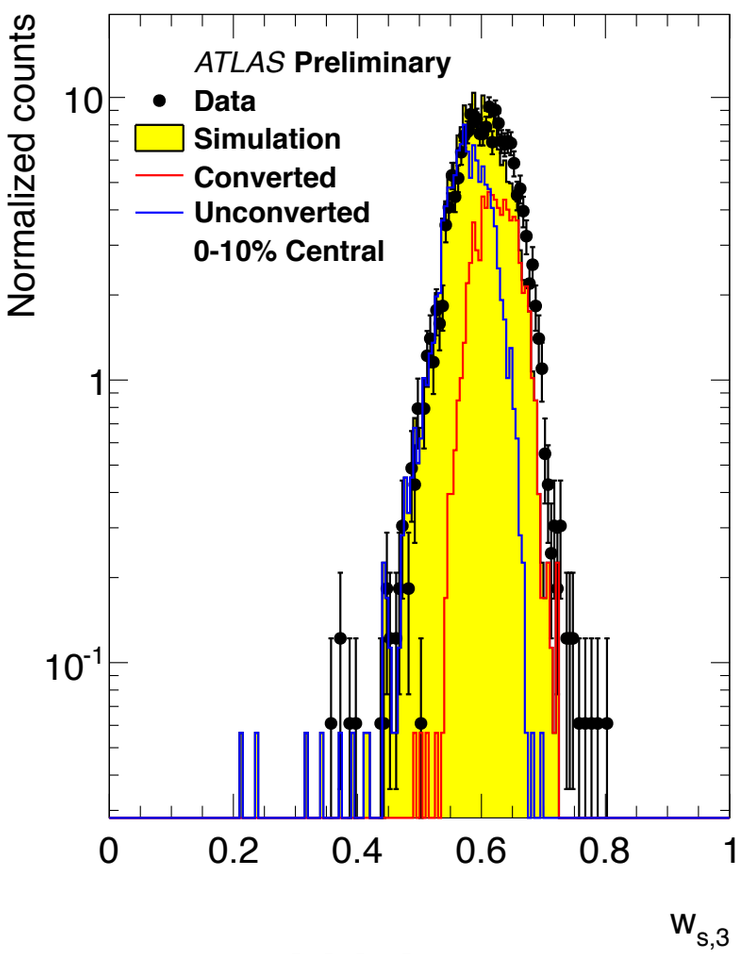
Photon reconstruction in the 2011 data

- **Photon reconstruction is seeded by calorimeter clusters of at least 2.5 GeV**
  - Sliding window algorithm applied in 2nd sampling layer, which gets >50% of photon energy.
- **No conversion recovery is applied: all photons treated as unconverted.**
  - High energy converted photons deposit most energy in only a slightly wider ϕ region than photons
- **Energy measurement is made using all three layers**
  - Area is 3x5 layer-2 cells (each cell is ΔηxΔϕ ~ 0.025 x 0.025)
  - Background subtraction gives corrections of O(1 GeV) even in central events

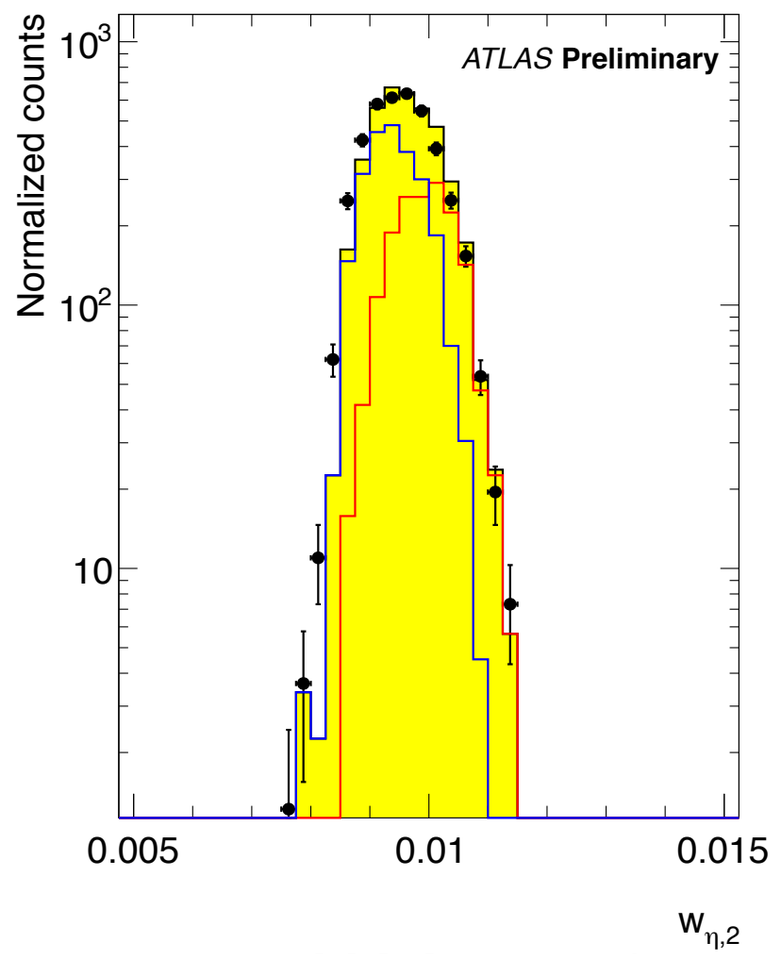


Photon performance: shower shapes

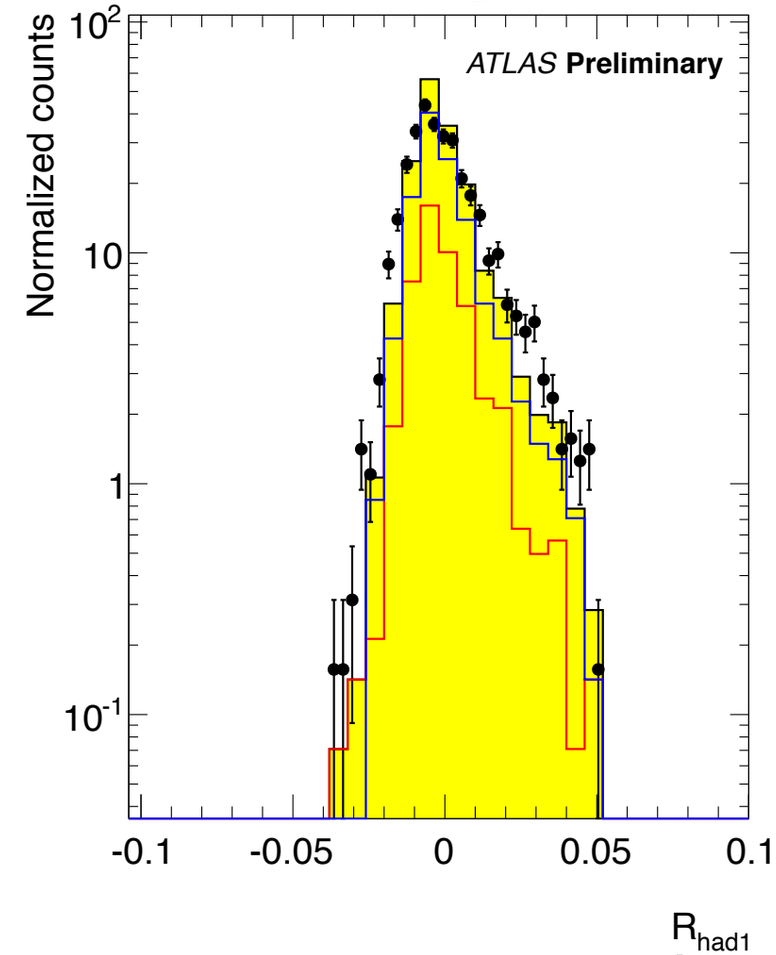
40 < p_T < 70 GeV tight photons



η width in layer 1 (strip units)



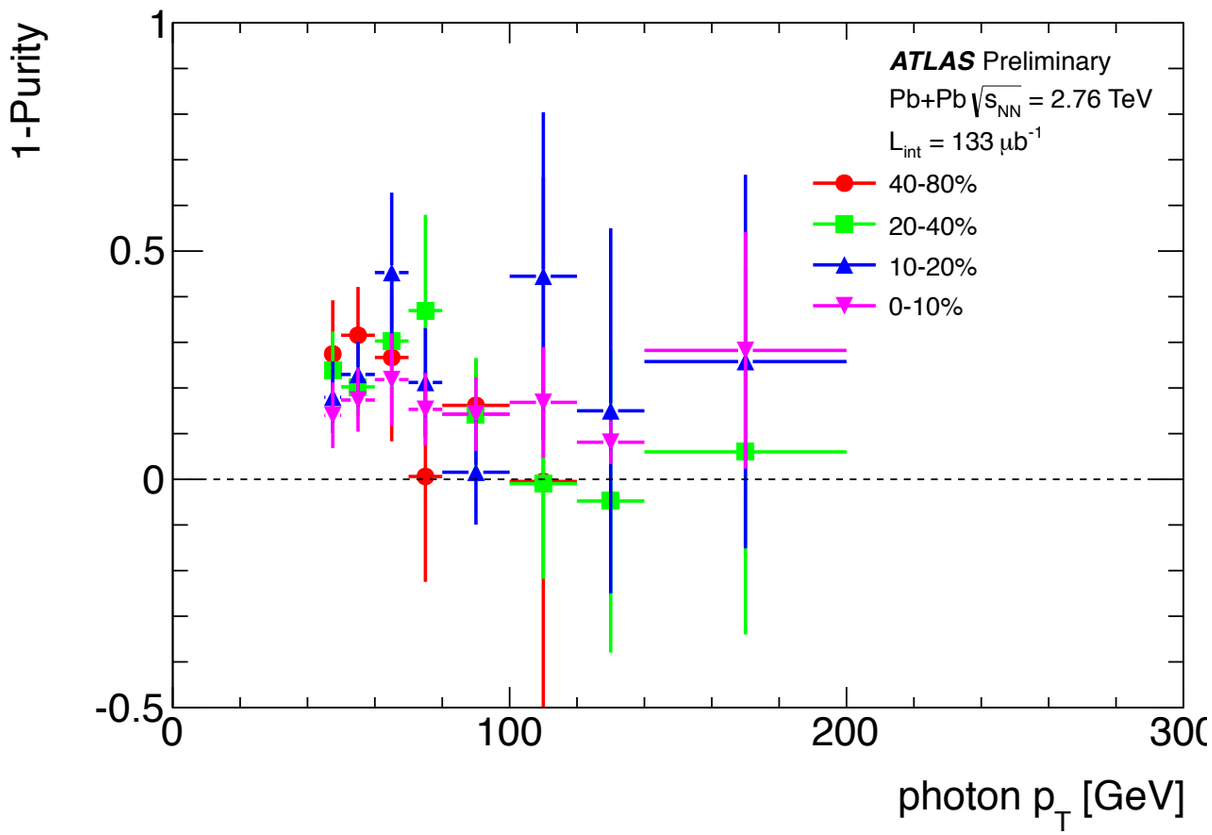
η width in layer 2 (η units)

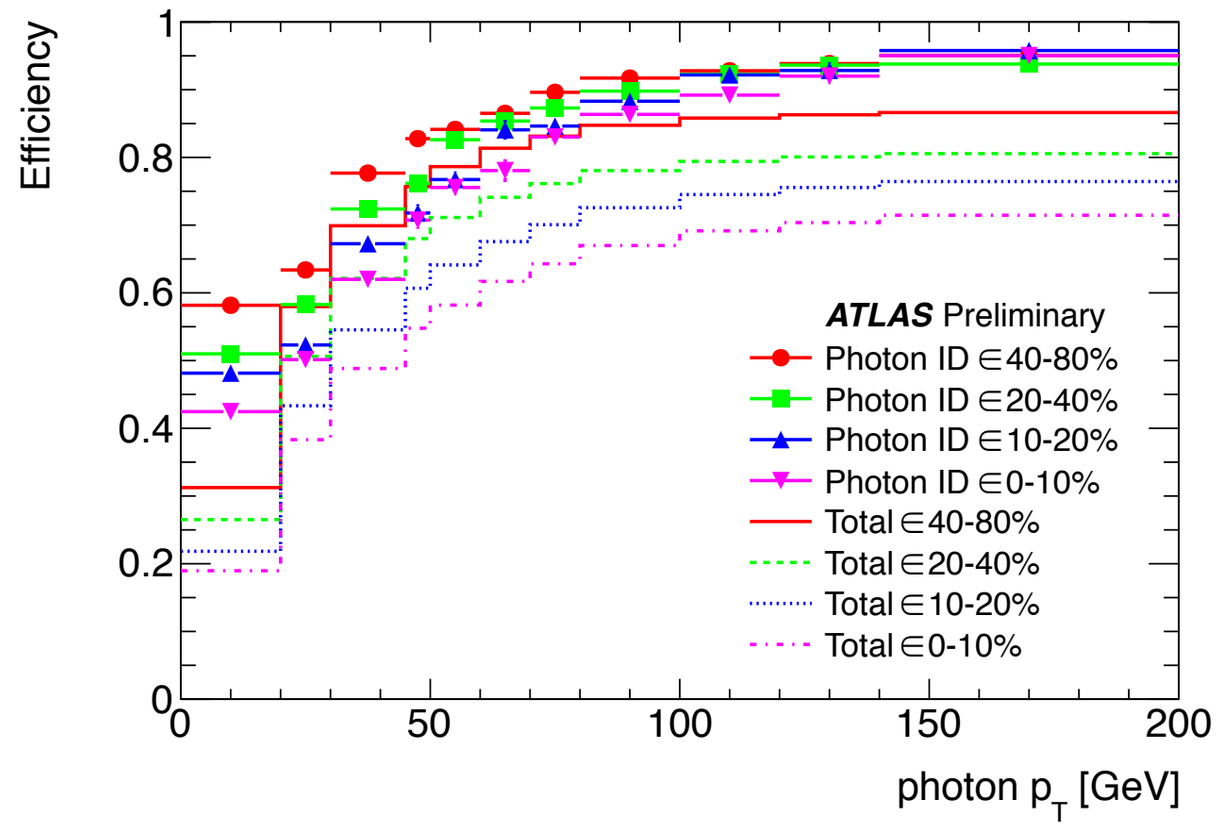


Hadronic energy/ cluster energy

Comparison of tight photons with fully simulated photon+jet events, **total MC (yellow)**, **unconverted (blue)**, and **converted (red)** photons. Small p_T and **η** dependent shifts (from pp) applied to MC.

Photon purity & efficiency





Purity determined from "double sideband" method:
fraction of di-jet background in photon sample: 20-30% in low p_T bins.

Efficiency controlled mainly by shower shape cuts & isolation selection:
reconstruction & ID quite efficient in central HI,
isolation leads to ~15-20% reduction

ATLAS photon yields for 45<p_T<200 GeV

For R=0.3, E_T<6 GeV

$$\frac{1}{N_{\mathrm{evt}}}\frac{dN_\gamma}{dp_{\mathrm{T}}}(p_{\mathrm{T}}, c) = \frac{N_A^{\mathrm{sig}}}{\epsilon_{\mathrm{tot}} \times N_{\mathrm{evt}} \times \Delta p_{\mathrm{T}}}$$

For each centrality and p_T bin, extracted signal counts scaled by

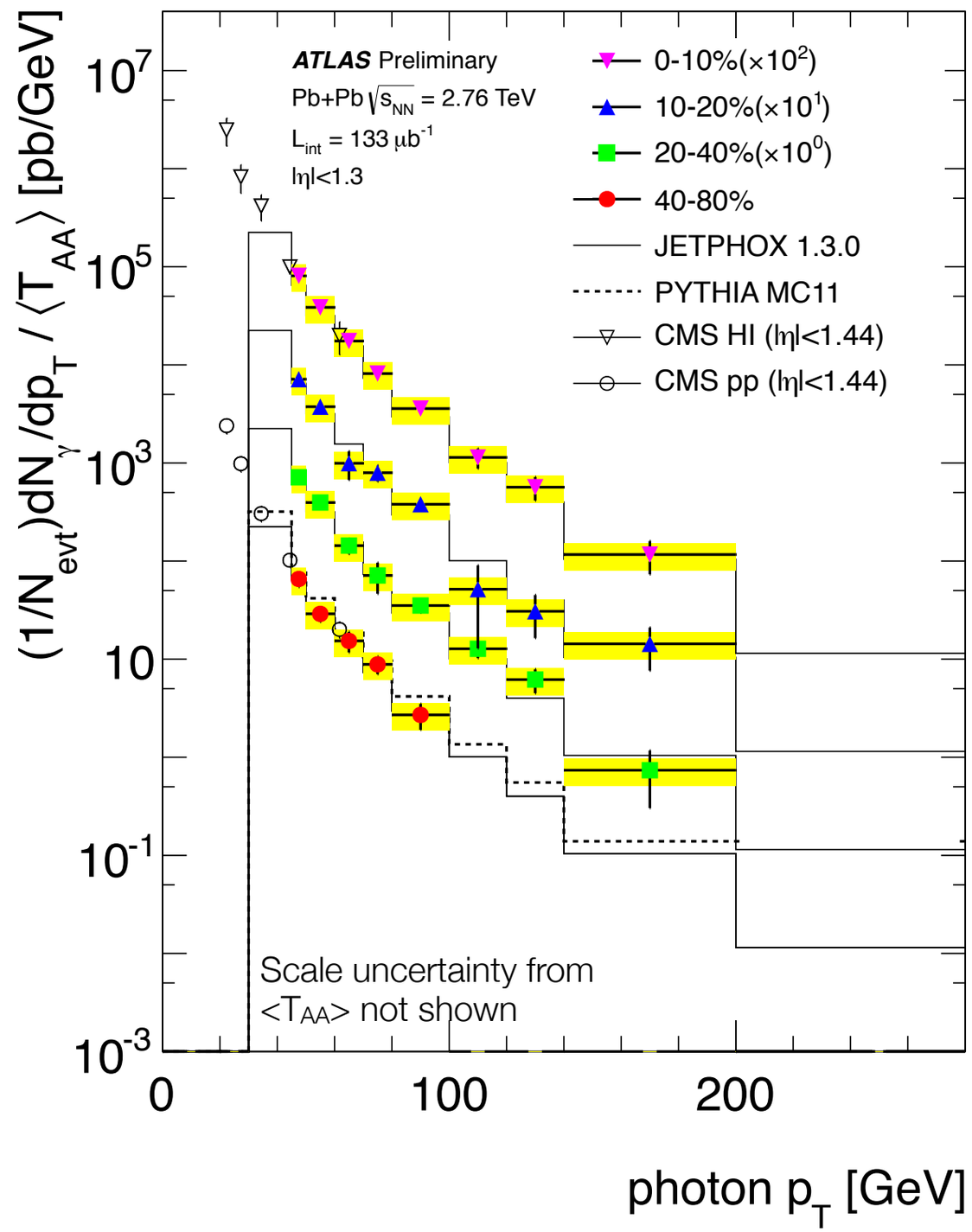
- total efficiency

- number of events

- width of p_T bin

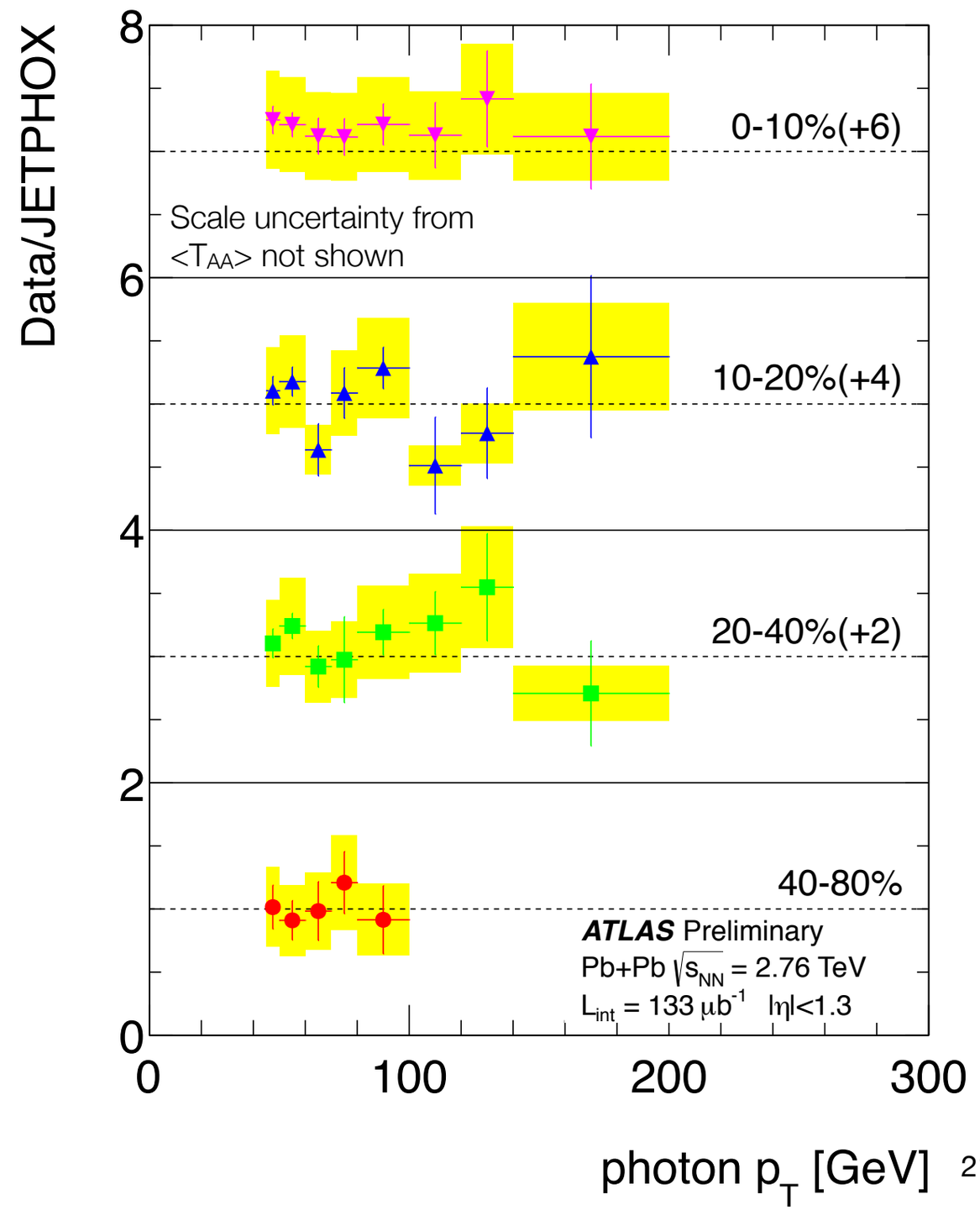
then scaled by <T_{AA}>

CMS *pp* & PbPb @ 2.76 TeV
JETPHOX 1.3 E_T(R=0.3)< 6 GeV
& PYTHIA MC11 tune
shown for comparisons



Ratios relative to JETPHOX

- **Comparisons of lead-lead data with *pp* cross sections from JETPHOX 1.3.0**
  - CTEQ 6.6 PDFs
  - BFG fragmentation functions
  - No isospin or nPDFs included
  - Scale uncertainties (factor of 2 coherent variation of $\mu_{I,F,R}$): ±13%
  - PDF uncertainties at 7 TeV: ±5%
- **Equivalent to R_{AA}, but with MC reference**
- **Within stated statistical and systematic uncertainties, good agreement of data and JETPHOX, for all centrality bins over wide range in p_T**



Z and photon correlations with jets

Probing jet energy loss with Z-jet and γ-jet

- **We test transverse momentum balance with "momentum fraction" (same notation as with first CMS results, arXiv:1205.0206)**

$$x_{JG} = p_{T\,J} / p_{T\,G}$$

$$x_{JZ} = p_{T\,J} / p_{T\,Z}$$

- **We test angular broadening of the correlation with Δϕ**

$$\Delta\phi_{JG} = |\phi_J - \phi_G|$$

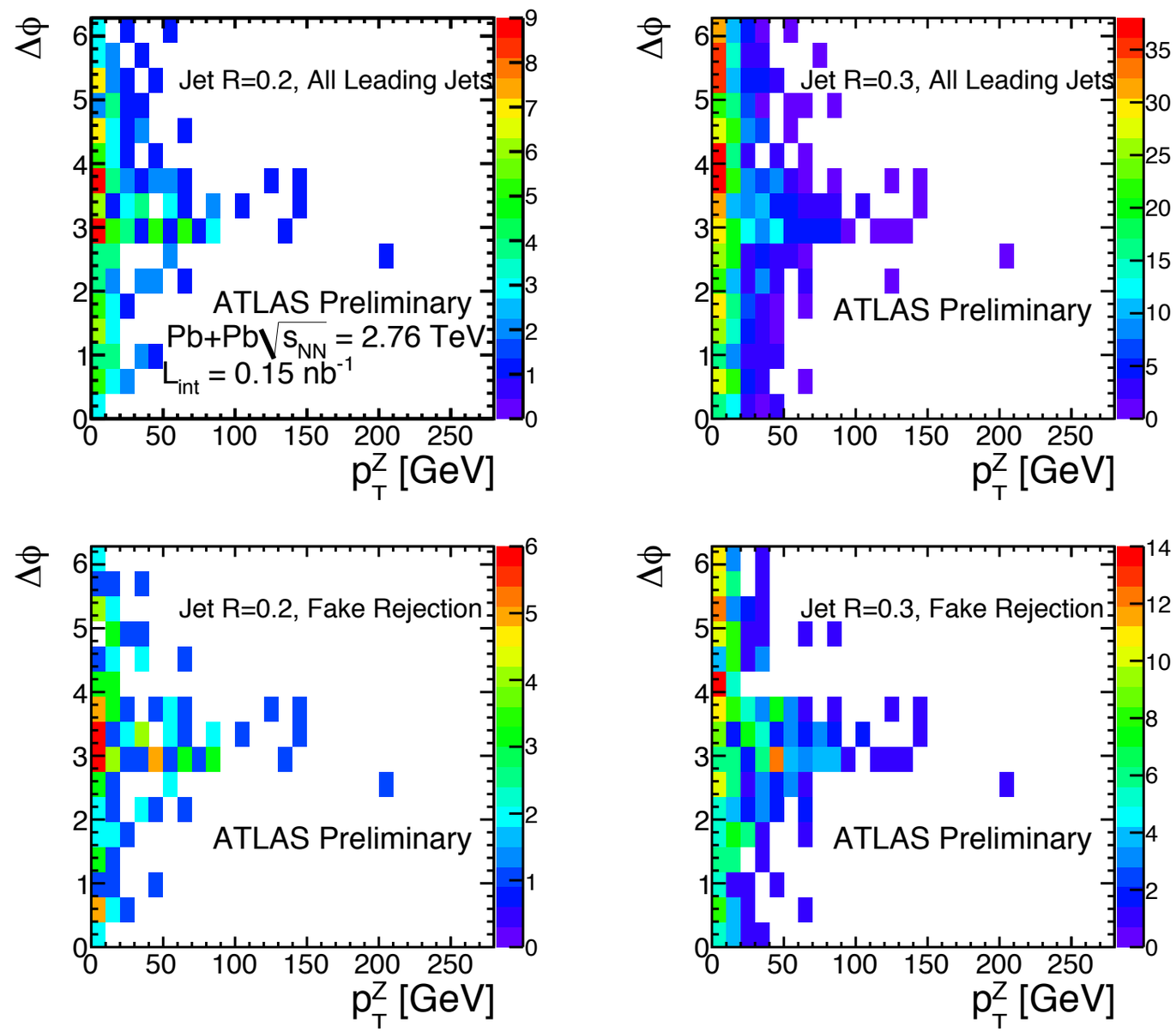
$$\Delta\phi_{JZ} = |\phi_J - \phi_Z|$$

Z-jet correlations

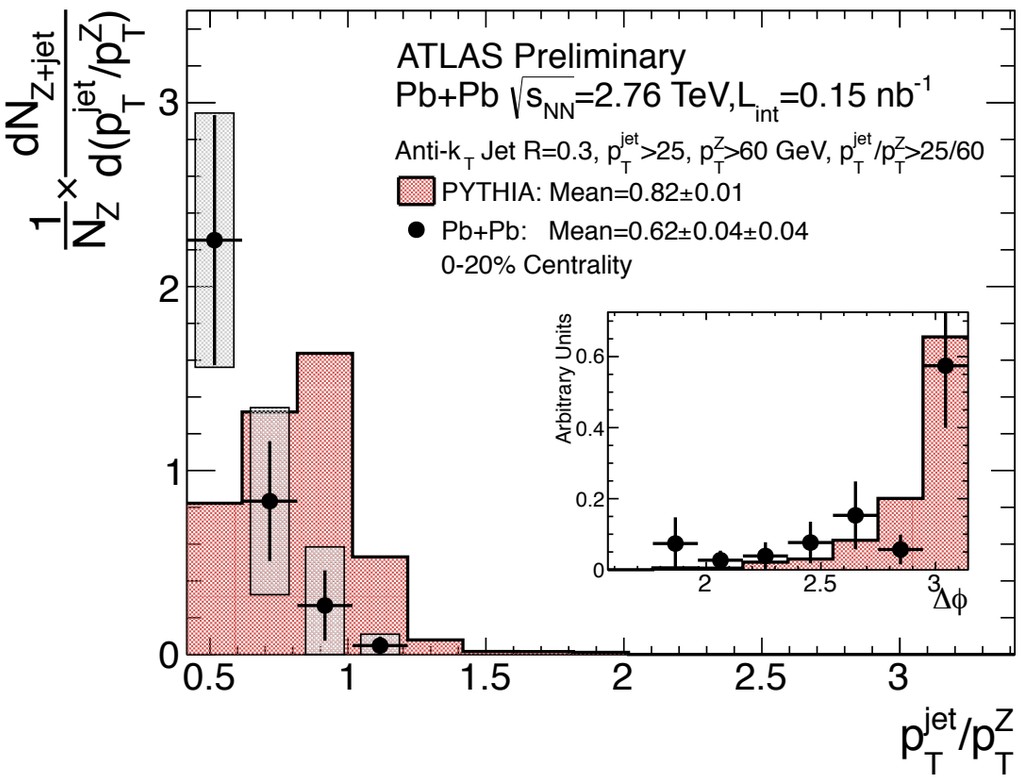
Jets reconstructed using standard iterative background subtraction

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

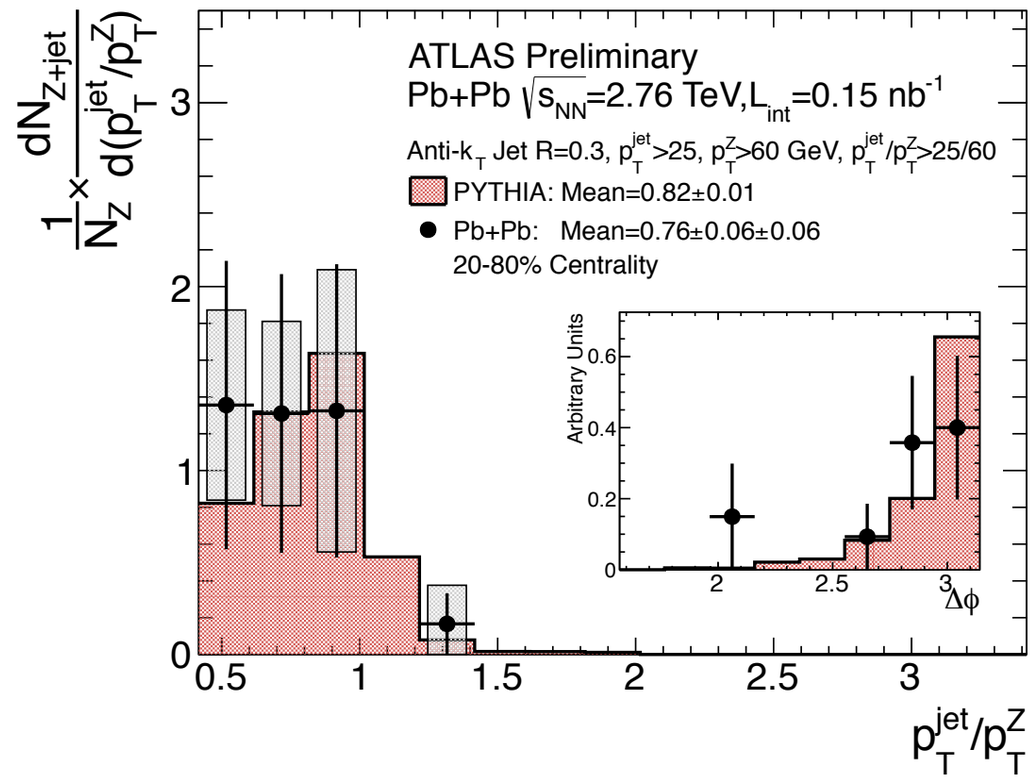
Fake rejection (based on track jet or EM cluster within jet), removes uncorrelated jets (esp. in R=0.3)



Z jet correlations



0-20% central

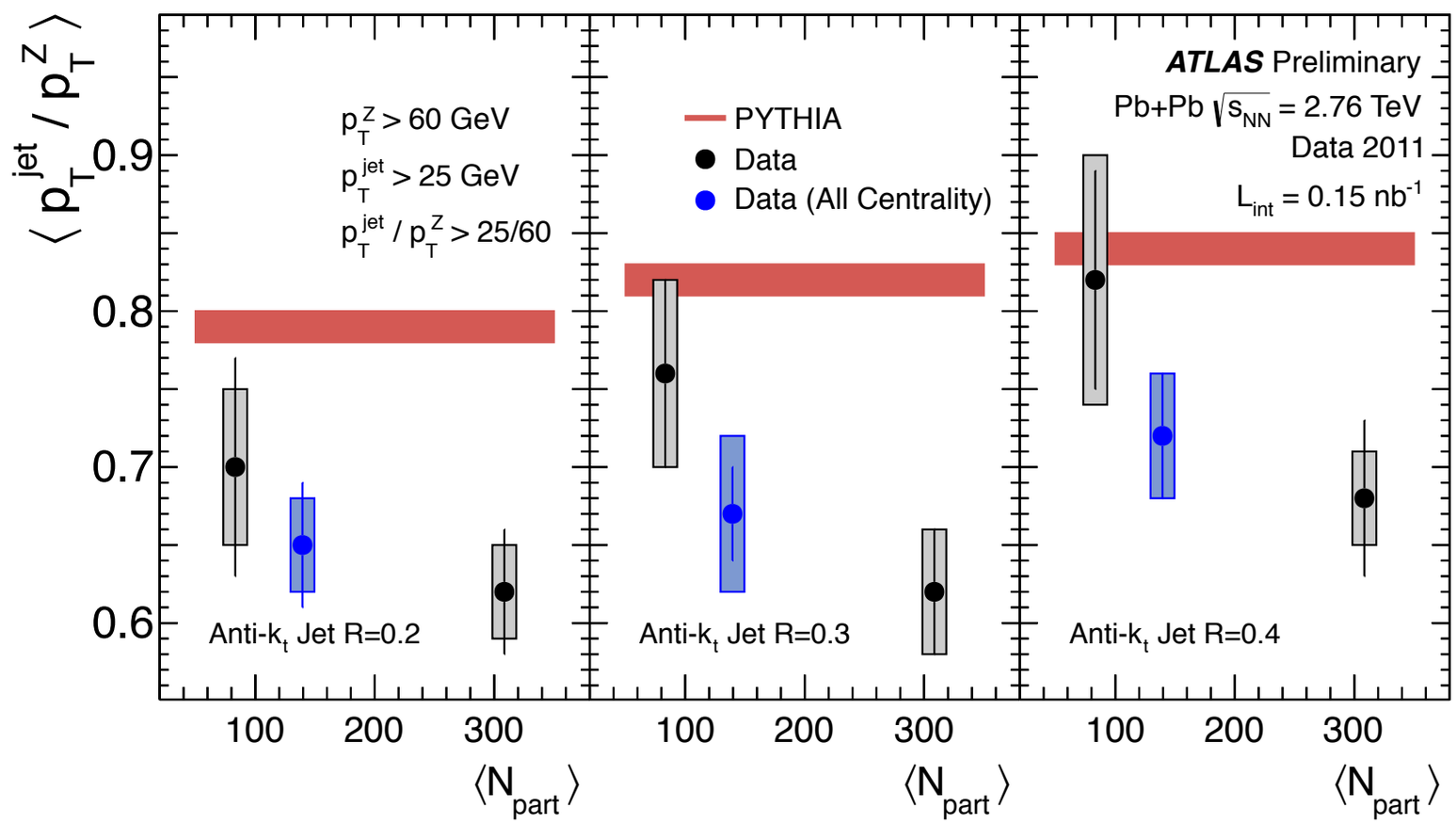


20-80% central

Bin-by-bin unfolding in p_T performed to correct for finite jet resolution

Clear modification of x_{JZ} distribution seen even in minimum-bias selected events (over half being in 0-10%)

Shift of transverse momentum ratios

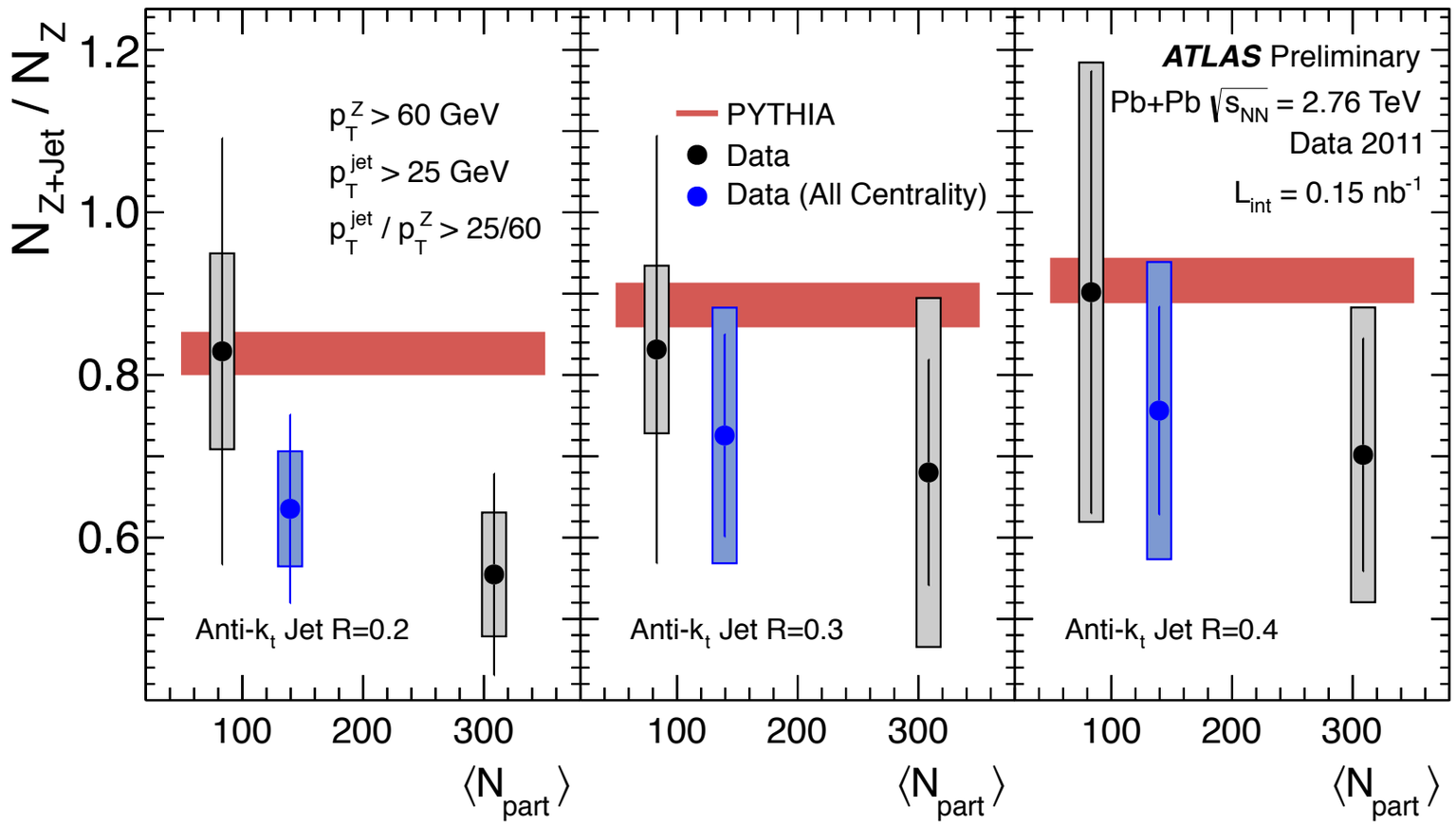


Centrality dependence: 0-20% vs. 20-80%

Peripheral bins consistent with PYTHIA predictions.

0-20% events show a clear downward shift of energy fraction

Reduction of Z+jet fraction



Centrality dependence: 0-20% vs. 20-80%

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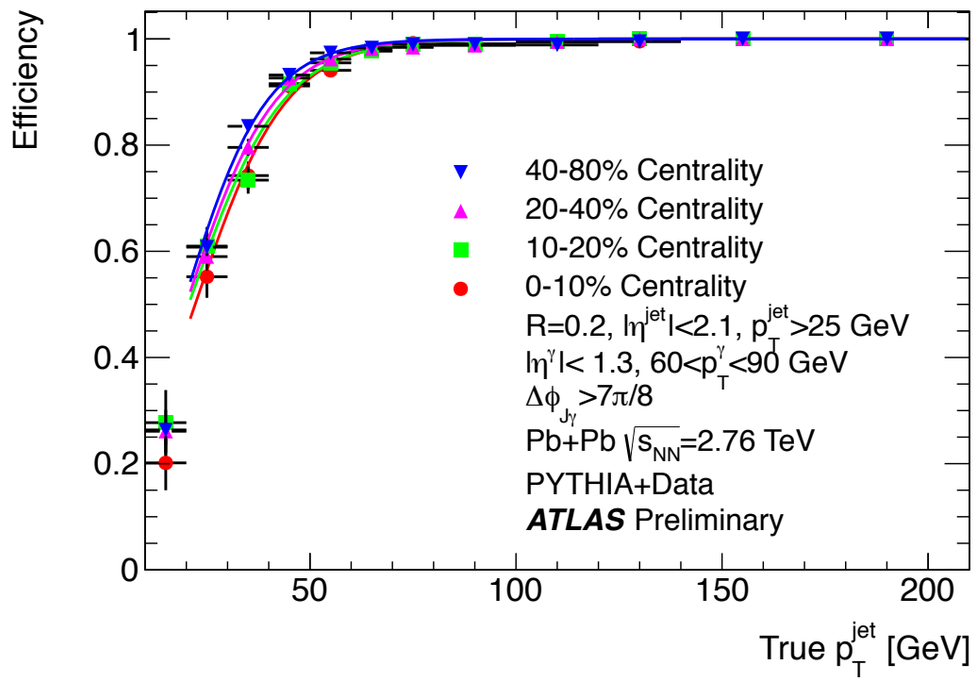
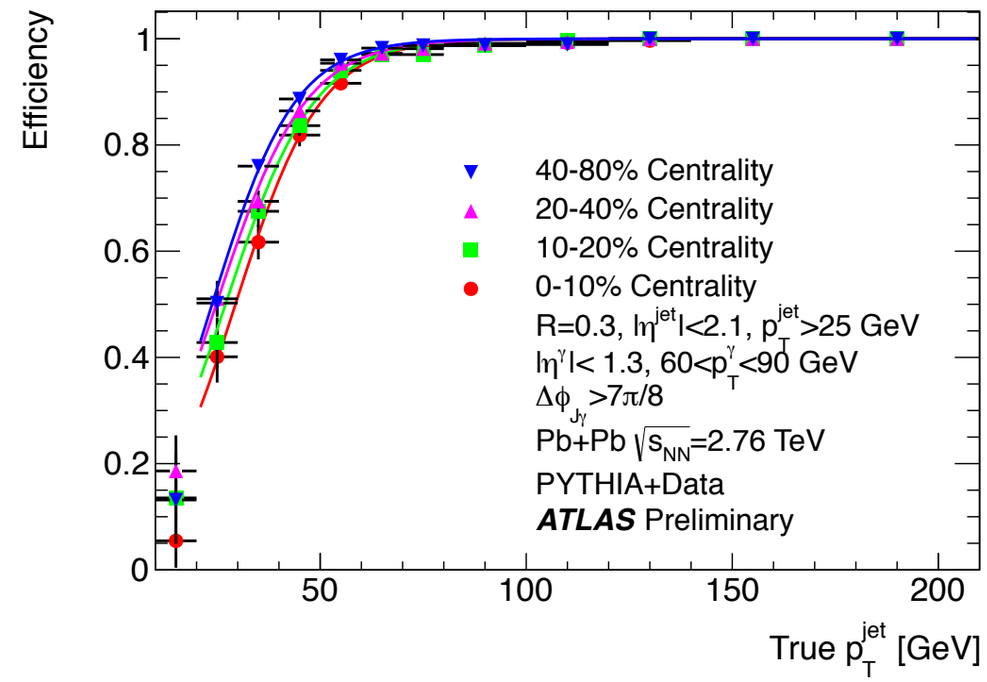
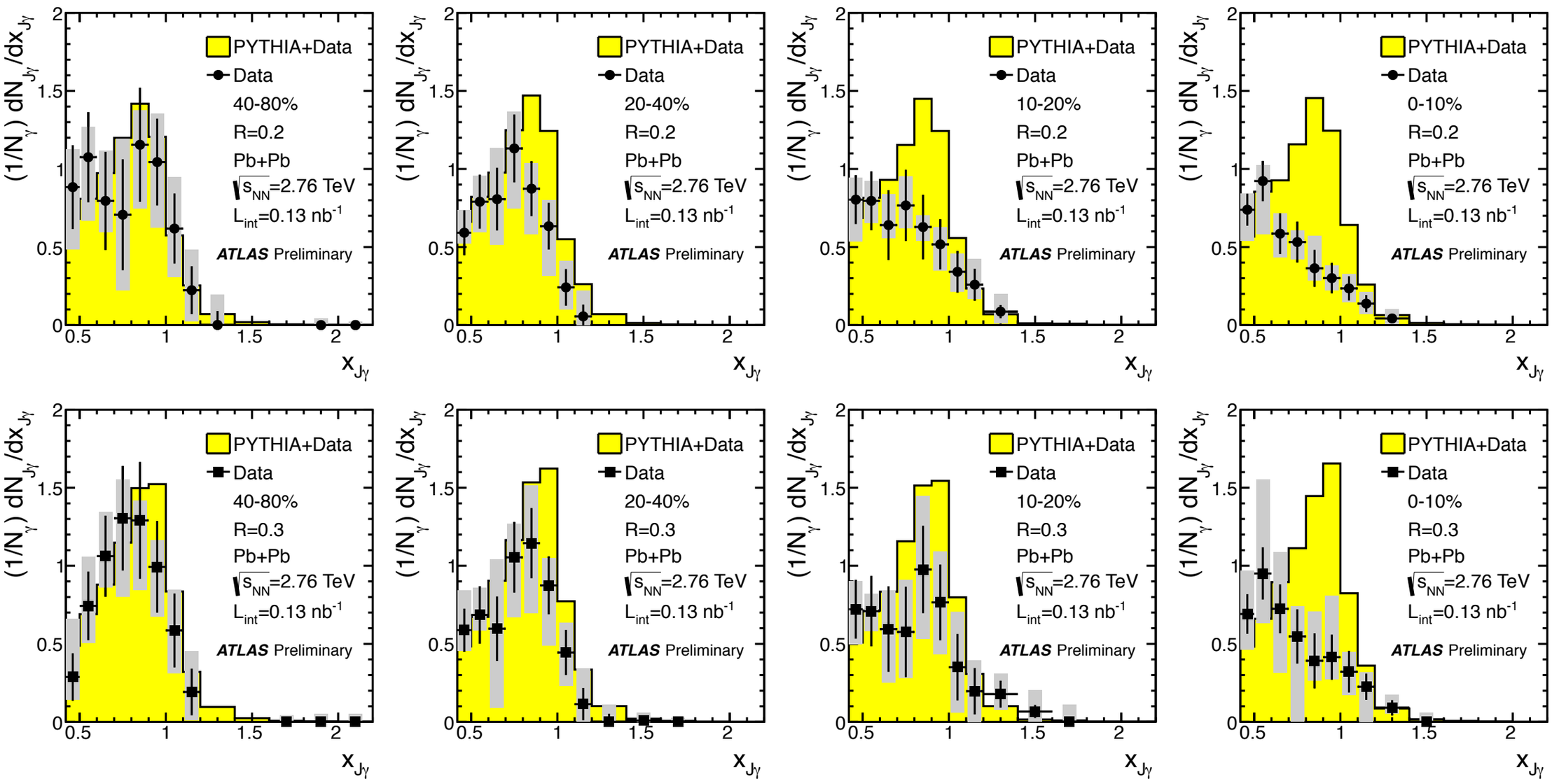
γ-jet correlations





- **Uses photon performance from PYTHIA+Data simulations**
  - Efficiencies, purities consistent with PYTHIA+HIJING
- **Jet performance determined from photon-jet "overlay"**
  - Fluctuations of data built-in by construction
  - Efficiencies determined for lower jet p_T cut of 25 GeV
- **Jet response unfolded for jet energy resolution from PYTHIA+Data**
  - Uses SVD method to unfold inclusive jet distributions
  - Unfolding matrix then applied to single jet p_T and mapped into $x_{J\gamma}$

Centrality & radius dependence



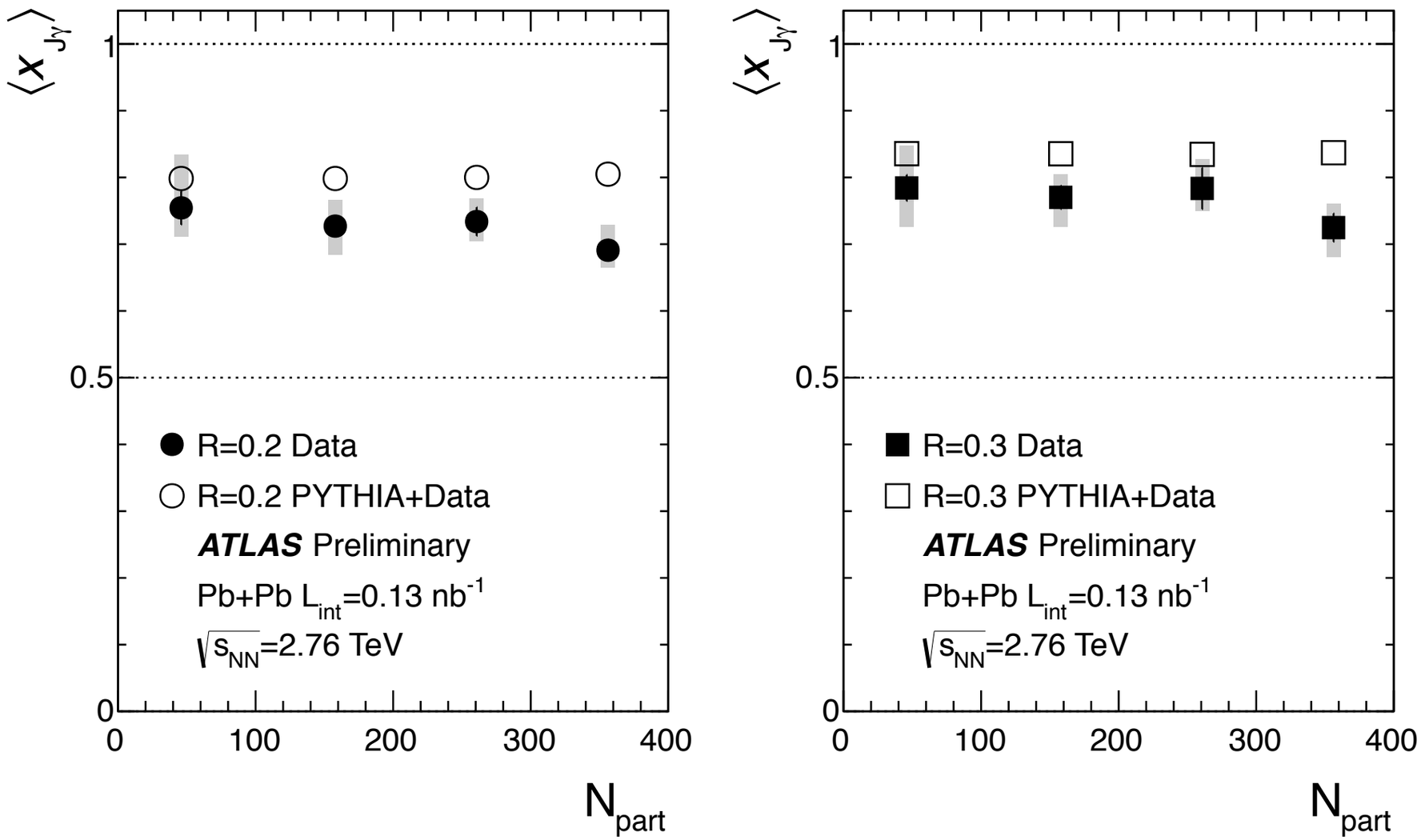
R=0.2

R=0.3

$$60 < p_T^{\gamma} < 90\ \text{GeV},\ |\eta_\gamma| < 1.3,\ \ p_T^{\text{jet}} > 25\ \text{GeV},\ |\eta^{\text{jet}}| < 2.1\ \text{and}\ |\Delta\phi_{J\gamma}| > 7\pi/8.$$

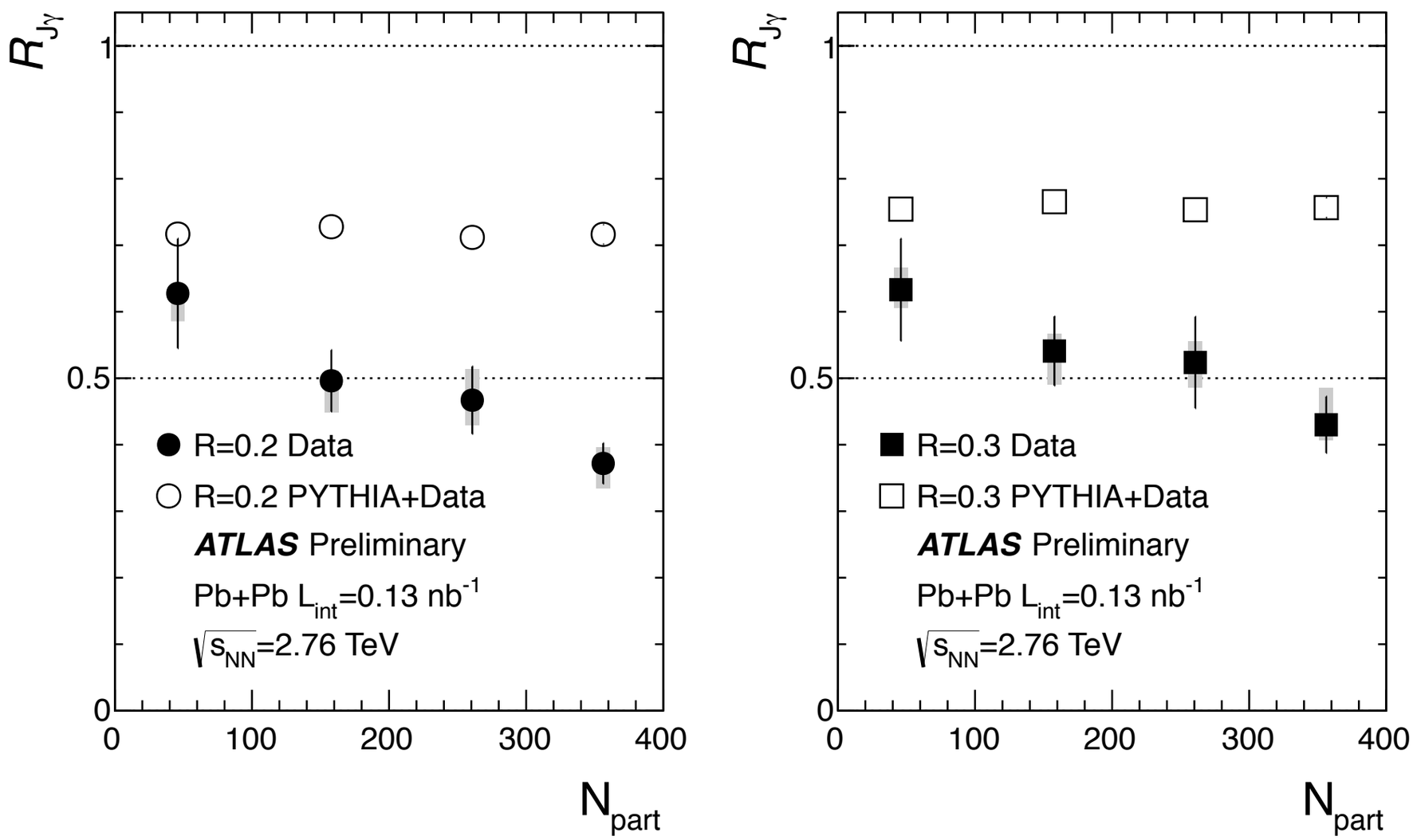
Fully unfolded result, normalized *per photon*. Uncertainties include both jet & photon. Compared to PYTHIA true photon/truth jet quantities in events selected with same isolation and selection criteria as reconstructed events

Centrality evolution of $\langle x_{J\gamma} \rangle$



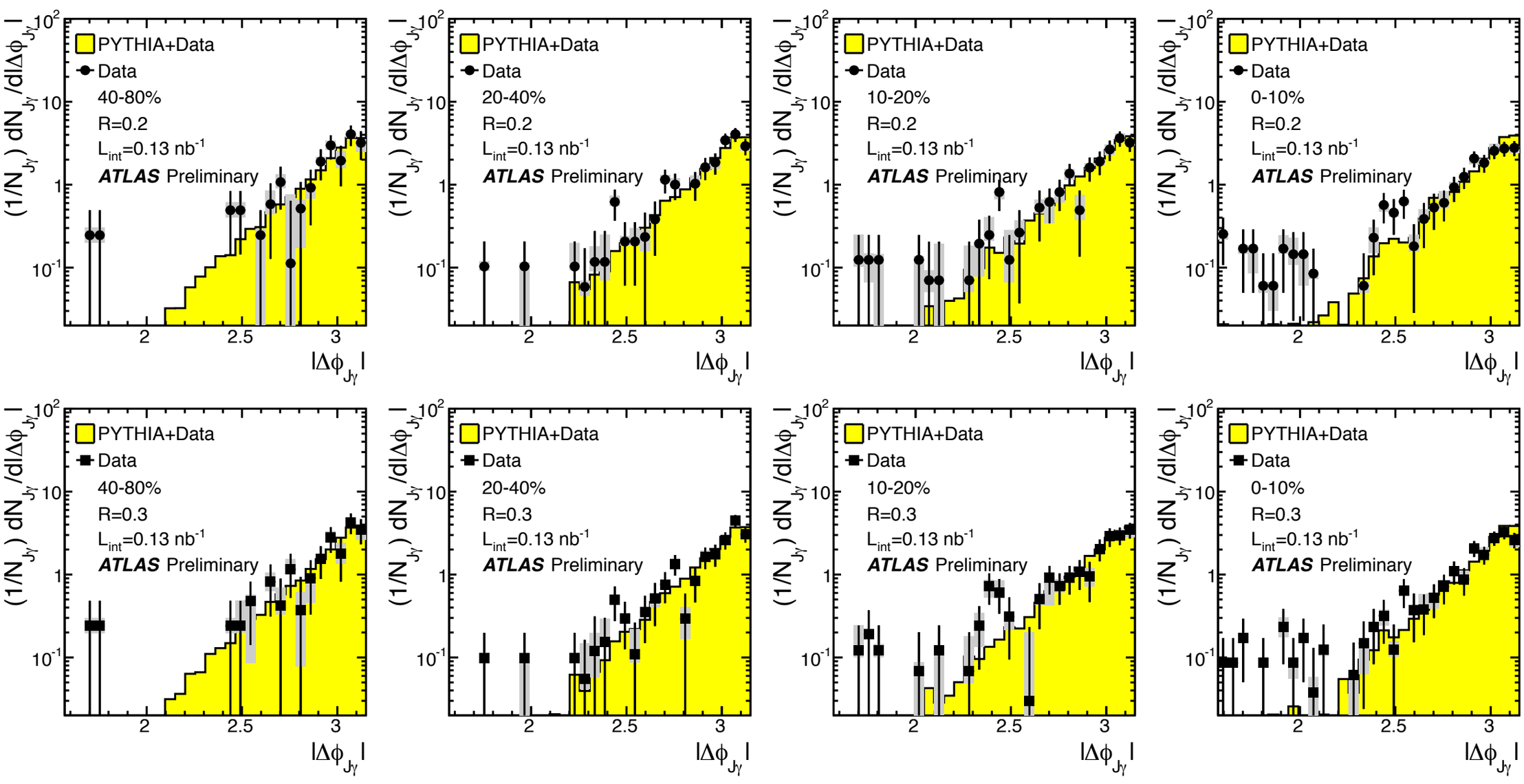
In narrow photon p_T bin (60-90 GeV),
systematic but slow evolution of mean of x_{Jg}:
clear degradation of average energy fraction of jet vs. photon

Suppression of overall photon-jet yield



Most peripheral events consistent with PYTHIA truth, and strong centrality dependence: nearly <u>half</u> of the photons in central events do not have a matching jet

Δϕ distributions



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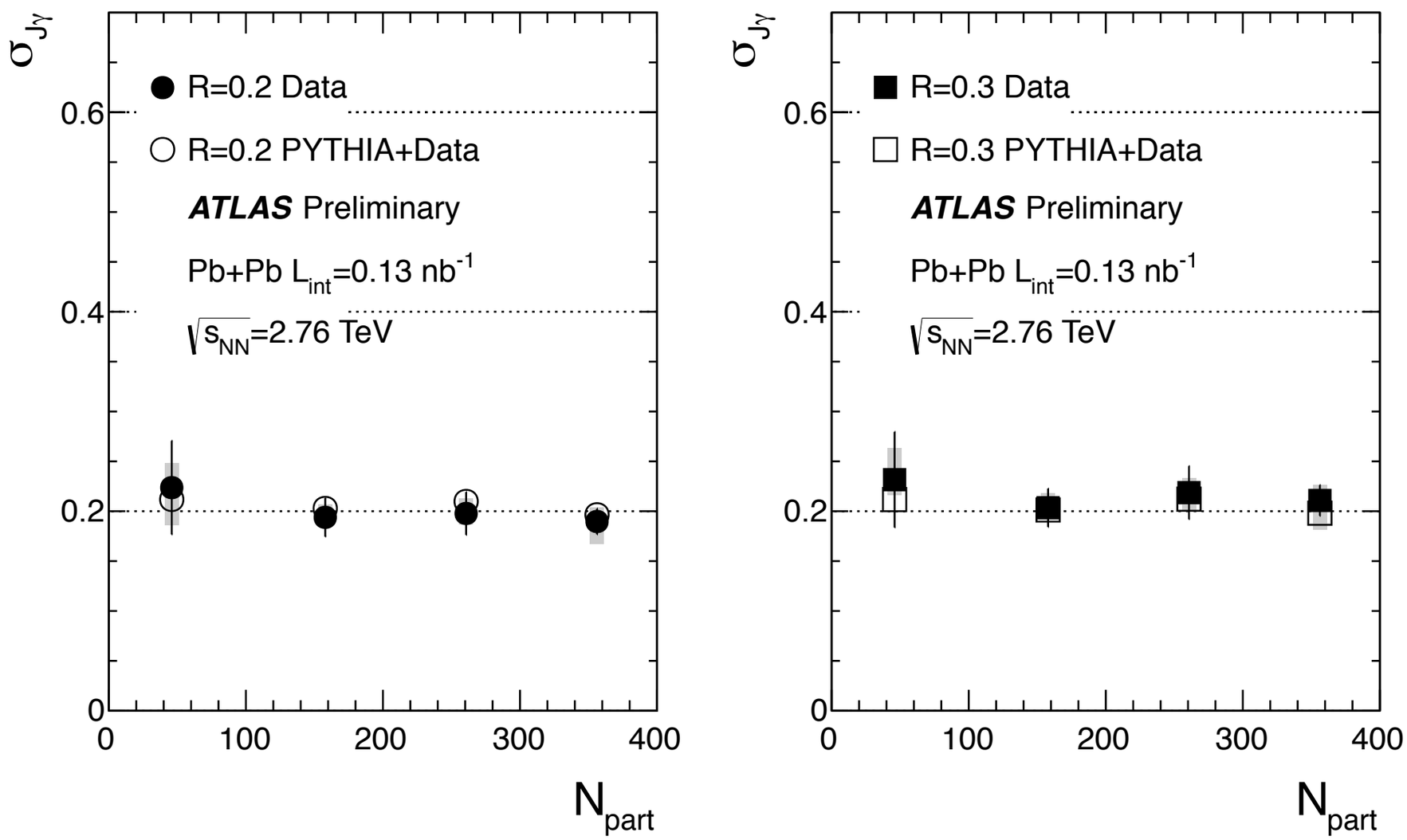
No unfolding performed: comparing background-subtracted data with fully-reconstructed simulated events

Exponential slope



Exponential fit performed over range $\Delta\phi > 2\pi/3$ (floating normalization)
Slope parameter shows **no dependence** over full centrality range: back-to-back emission persists

Conclusions

- **New results on Z and photon production, both yields and in correlation with jets**
- **Z**
  - Rapidity and momentum distribution agree well PYTHIA scaled by NNLO cross section
  - Scaling with binary collisions observed
  - No elliptic flow of Z observed
  - Correlation with jet shows clear attenuation of jet energy
- **Photons**
  - Yields measured out to 200 GeV, after background subtraction for dijets
  - Good agreement with JETPHOX 1.3.0, binary scaling observed
  - Correlation with jets shows clear back-to-back correlation but strong centrality-dependent attenuation of jet energy & reduction of fraction of photons with associated jet

Thanks to ATLAS Collaboration

Z. Citron, 1B, **Study of correlations between neutral bosons and jets in lead-lead collisions at 2.76 TeV with the ATLAS detector**

I. Grabowska-Bold, 4C, **Measurement of isolated direct photons in lead-lead collisions at 2.76 TeV with the ATLAS detector**

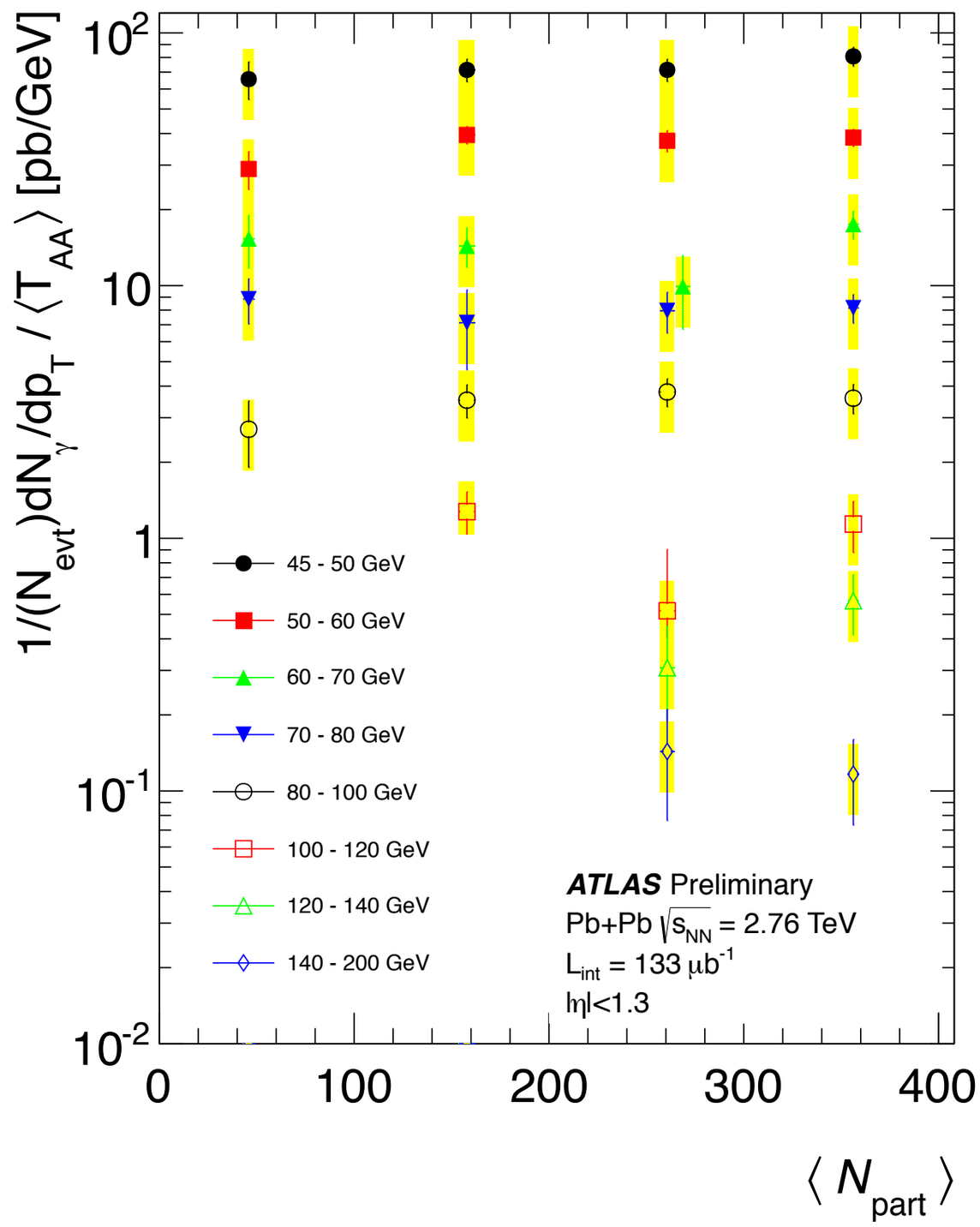
J. Dolejsi, 4C, **Measurements of W and Z boson production in Pb+Pb collisions at 2.76 TeV with the ATLAS detector.**

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Extra slides

Centrality dependence of yields

- **Even without a reference distribution, can look at centrality dependence in bins of photon p_T**
- **Centrality represented here as mean number of participants in each bin**
- **No dependence on N_{part} within statistical (error bars) and systematic uncertainties**

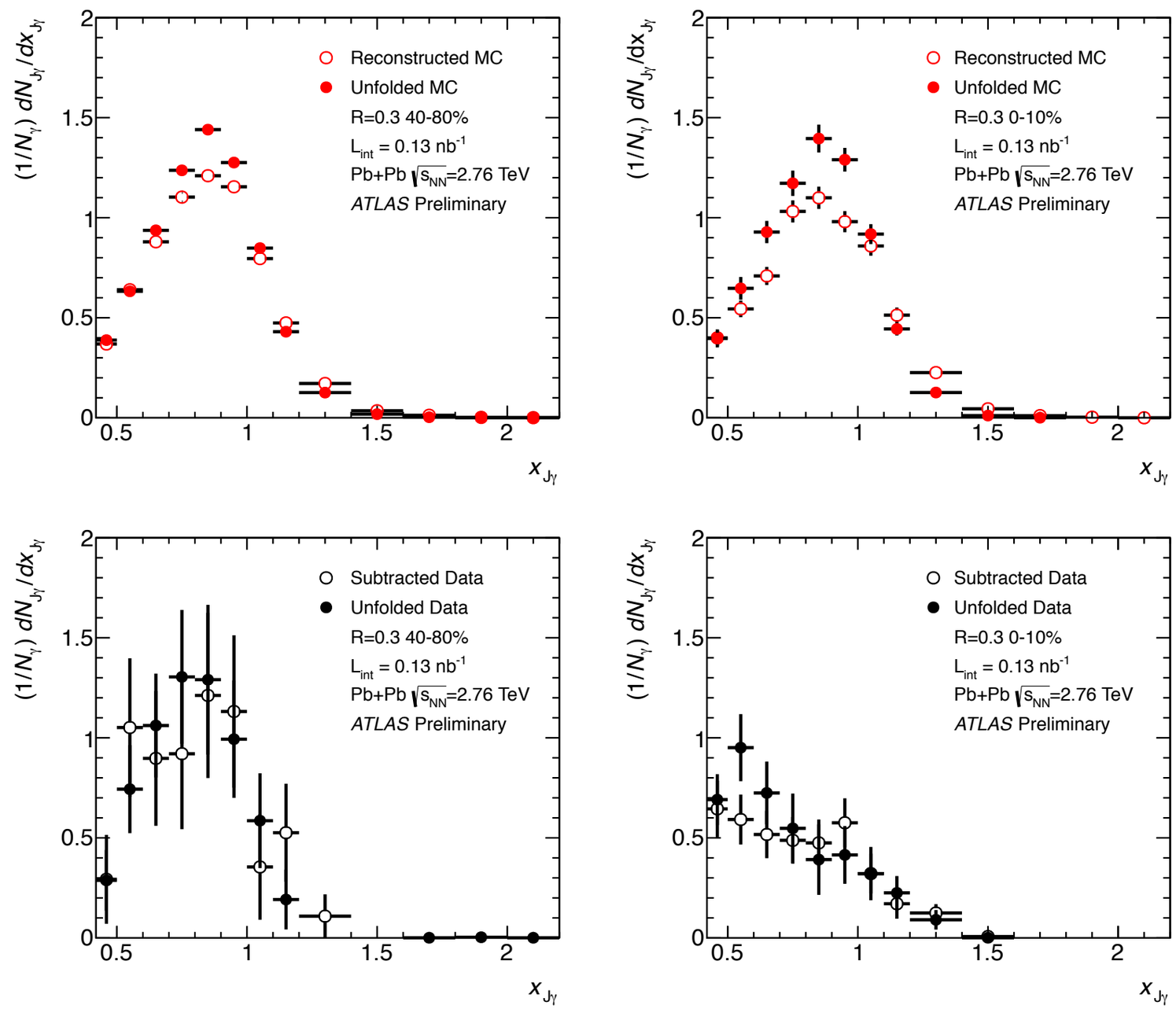


Unfolding photon-jet correlations

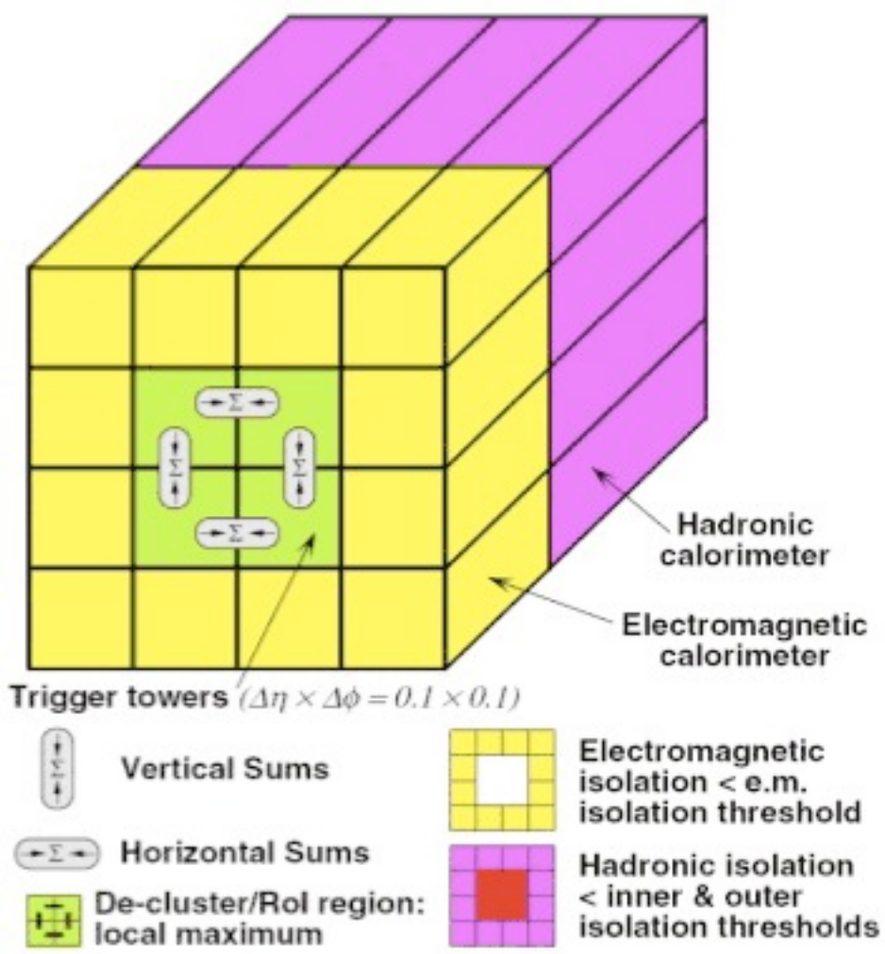
Unfolding performed on inclusive jet sample using SVD method, with response matrices determined from simulated gamma-jet events.

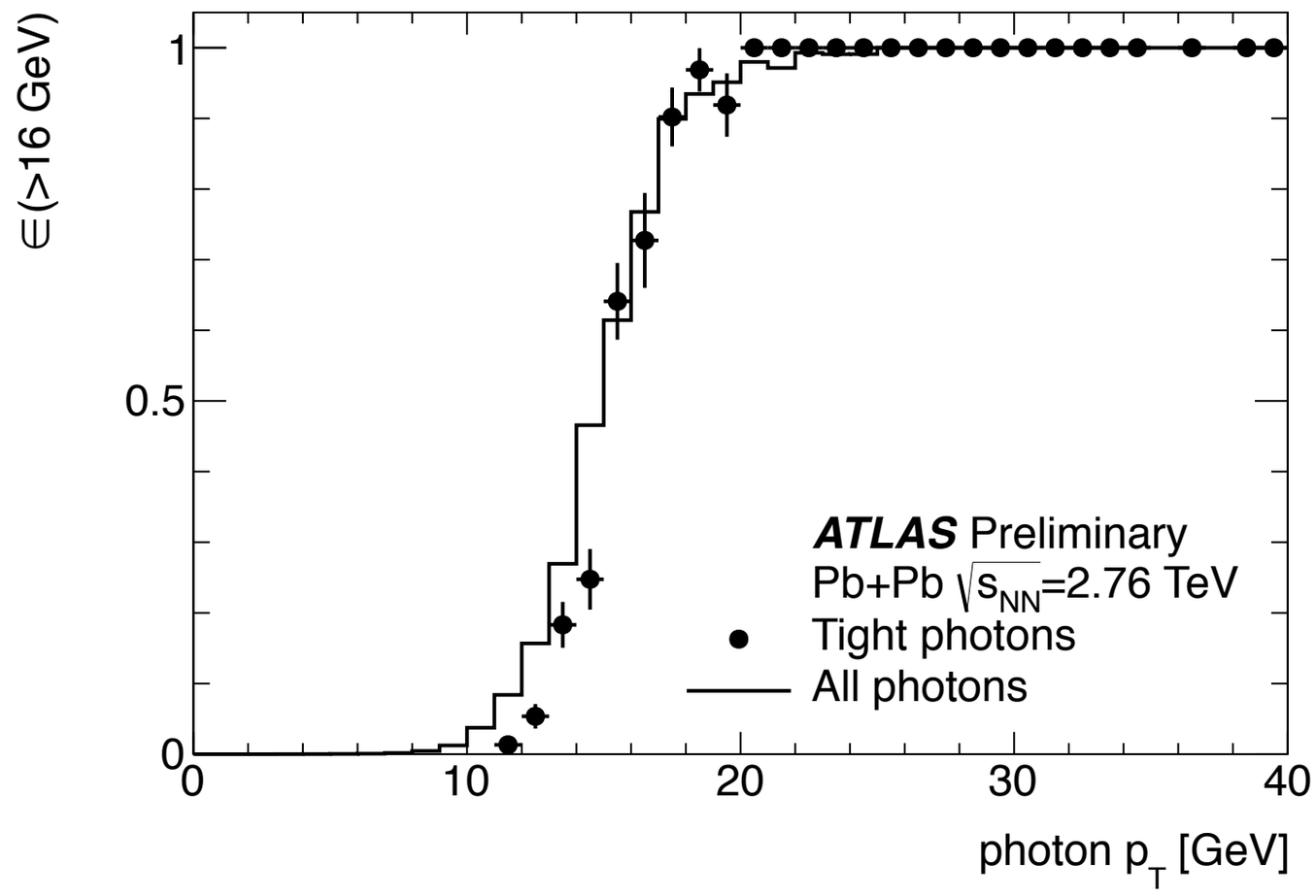
Unfolding matrix then applied to individual jets, and unfolded event filled into $x_{J\gamma}$ distribution

Clear narrowing of unfolded MC, mild effect on data



Trigger efficiency





Use ATLAS electromagnetic object trigger, based on combinations of 0.1x0.1 “towers” and threshold of 16 GeV: 0.2x0.2 sliding window but trigger is only on 0.2x0.1 regions