Measurement of isolated prompt photon production in lead-lead collisions at $\sqrt{s_{NN}}$=2.76 TeV with ATLAS

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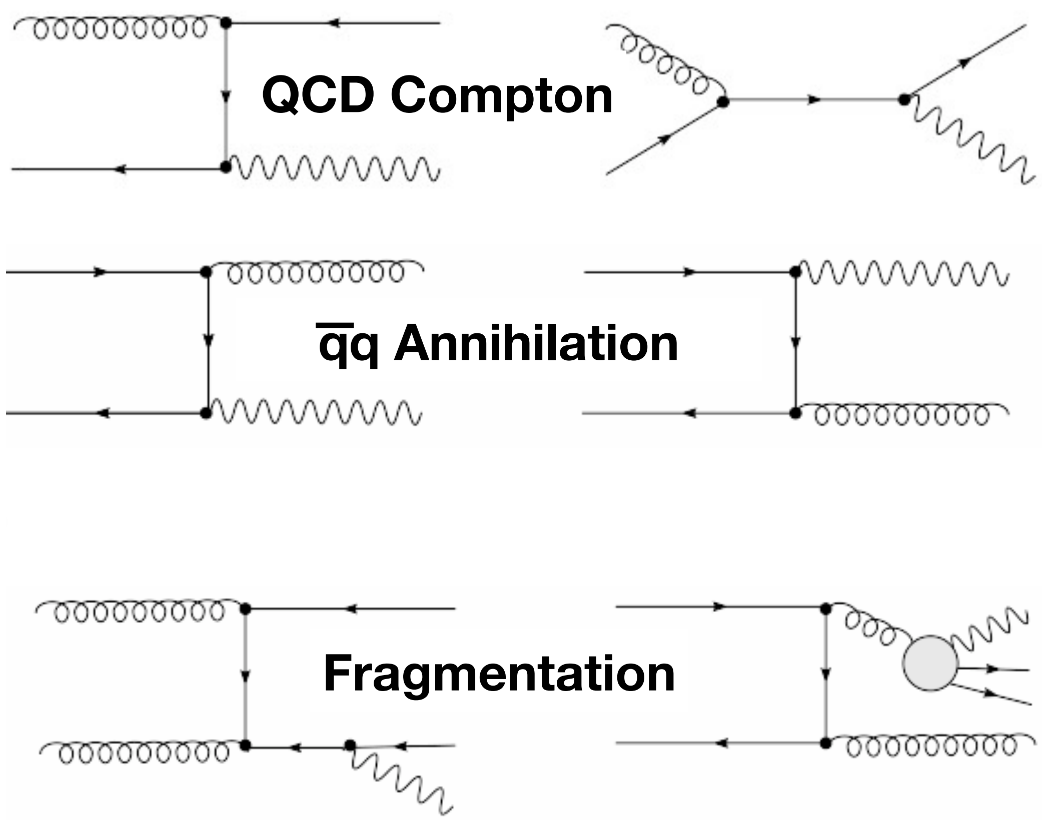
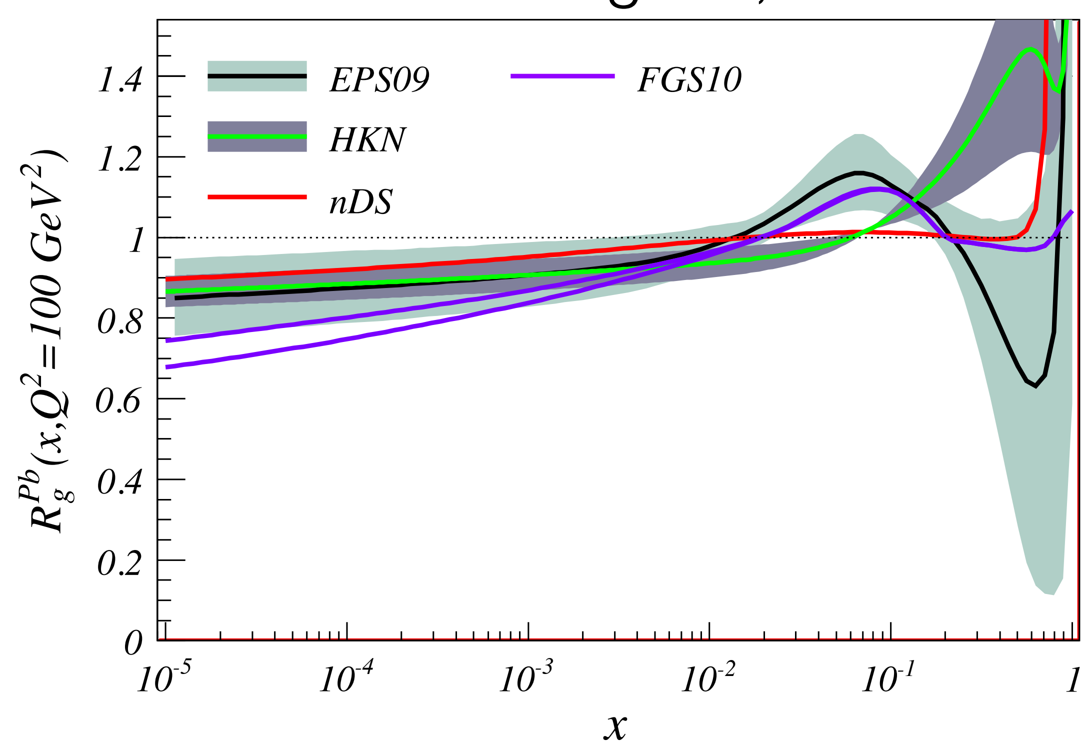
Prompt photons in nuclear collisions

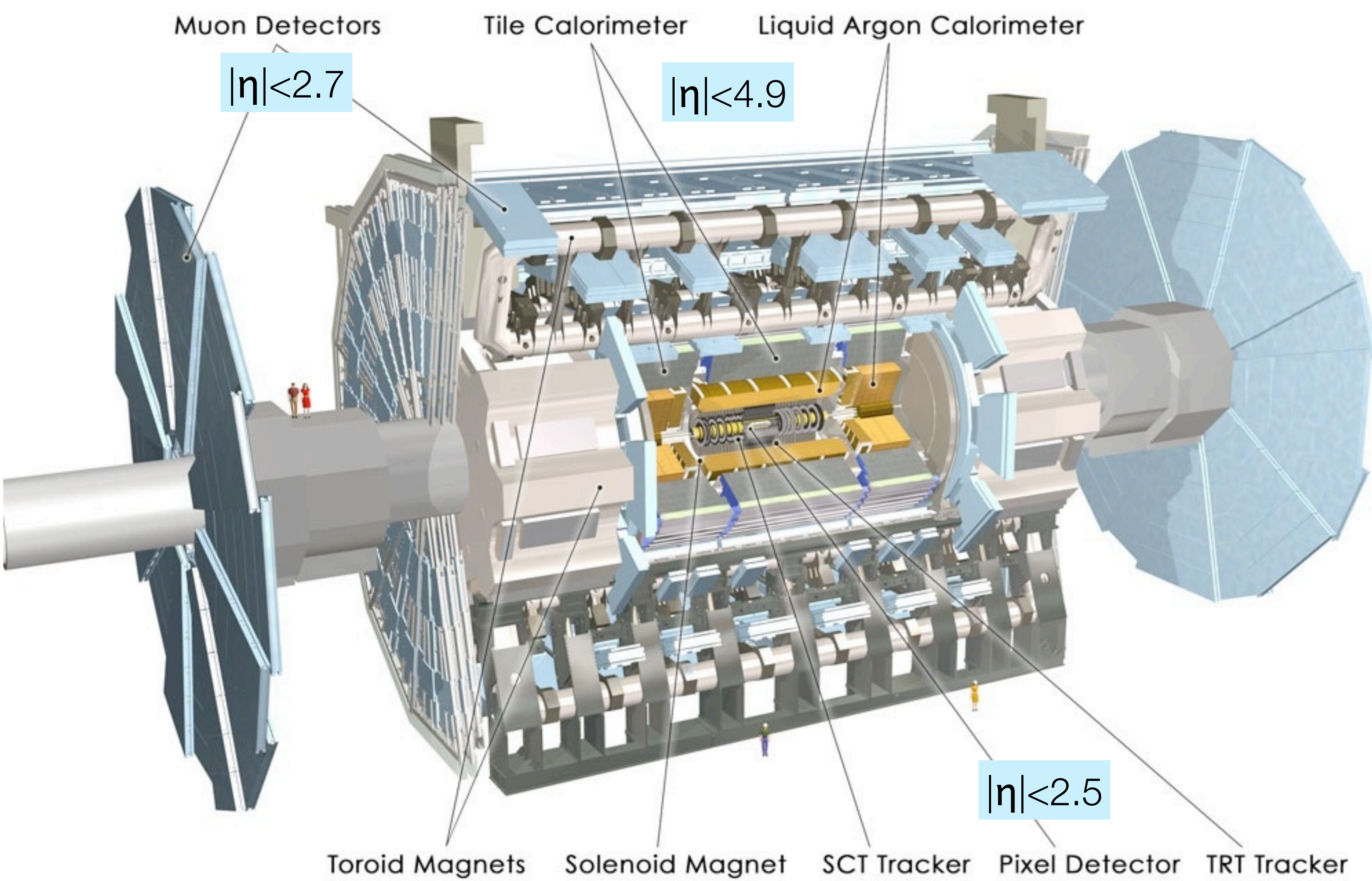


Salgado, et al 2011

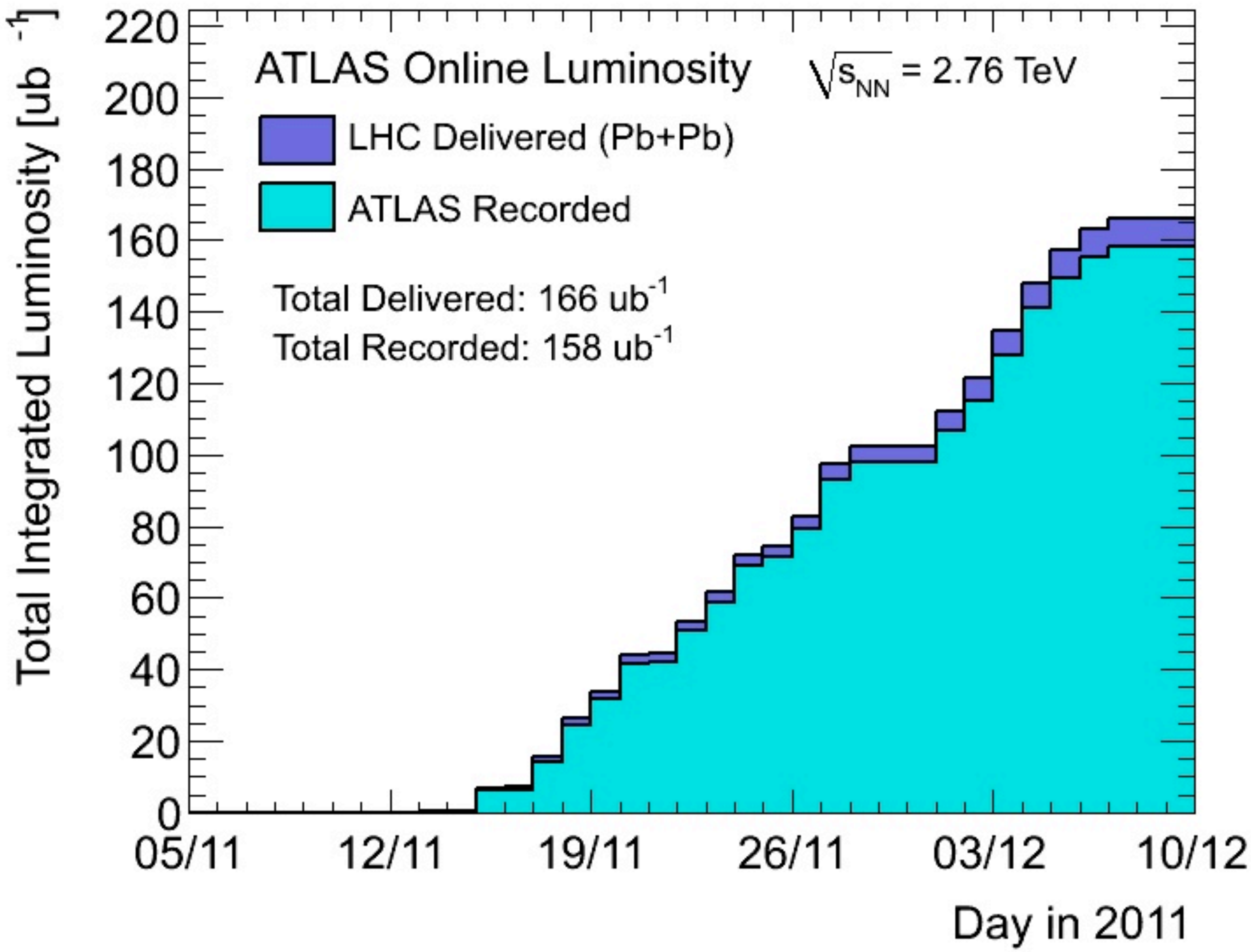


- **Photons are penetrating probes of the hot, dense medium**
  - Photon jet correlations will be an important contribution to understanding of jet quenching
- **Important to check rates of photon production, calculable in pQCD @ NLO**
  - Diagrams include direct photons & photons from jet fragmentation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

The ATLAS Detector



Integrated luminosity for 2011 Pb+Pb run



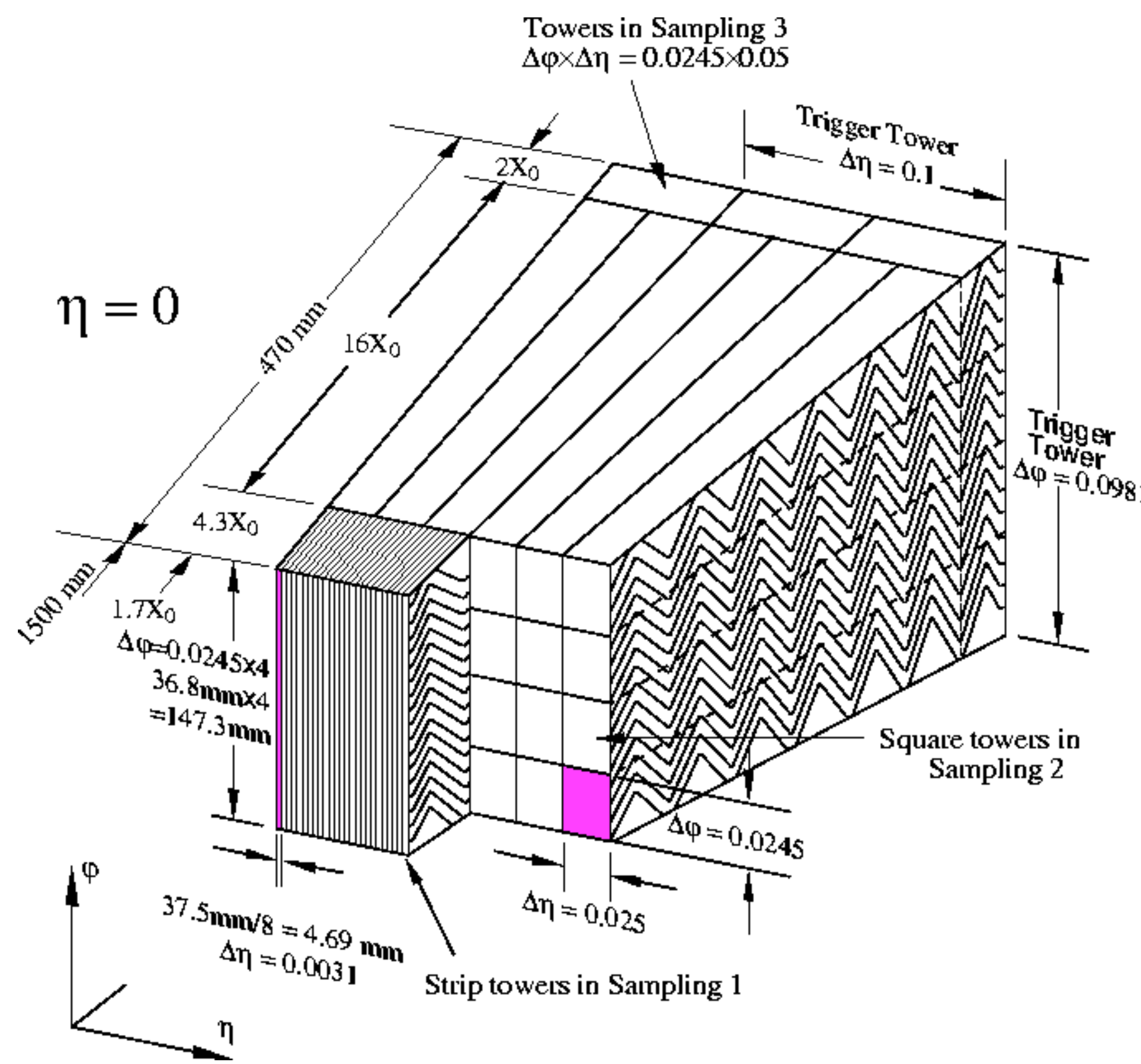
166 μb^{-1} delivered, 158 μb^{-1} recorded by ATLAS

Data sample

- **Using 133 μb^{-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 trigged on 16 GeV EM cluster, with a photon or electron reconstructed offline with E_T>40 GeV**
  - From PYTHIA+HIJING simulations, 98% 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**

Photon reconstruction

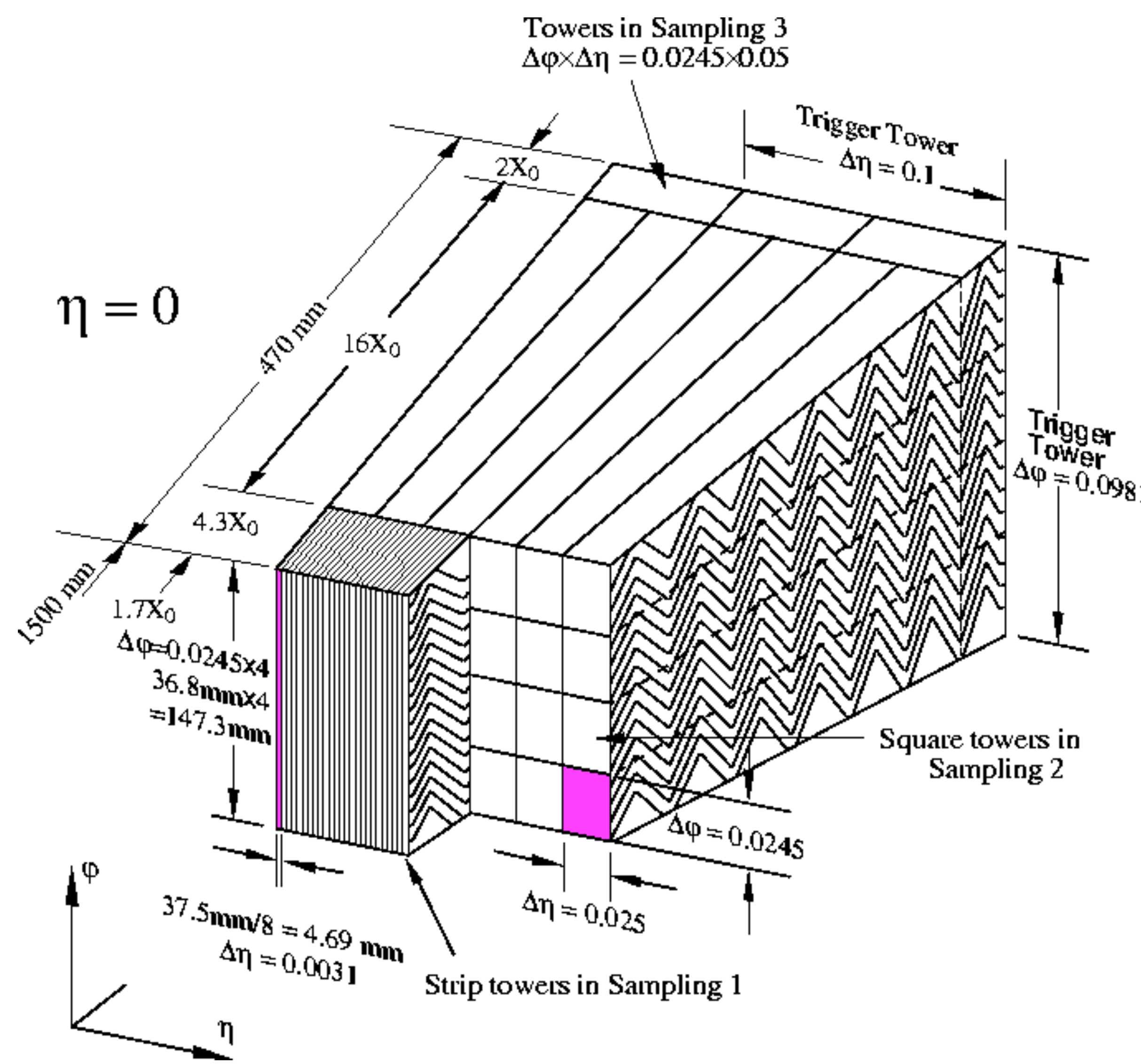
- **Photon reconstruction is seeded by calorimeter clusters of at least 2.5 GeV**
  - Sliding window algorithm applied in 2nd sampling layer, which gets >50% of photon energy.
- **No conversion recovery is applied: all photons treated as unconverted.**
  - High energy converted photons deposit most energy 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



“Tight” photons

Photons are selected using 9 shower shape variables in |η|<1.3

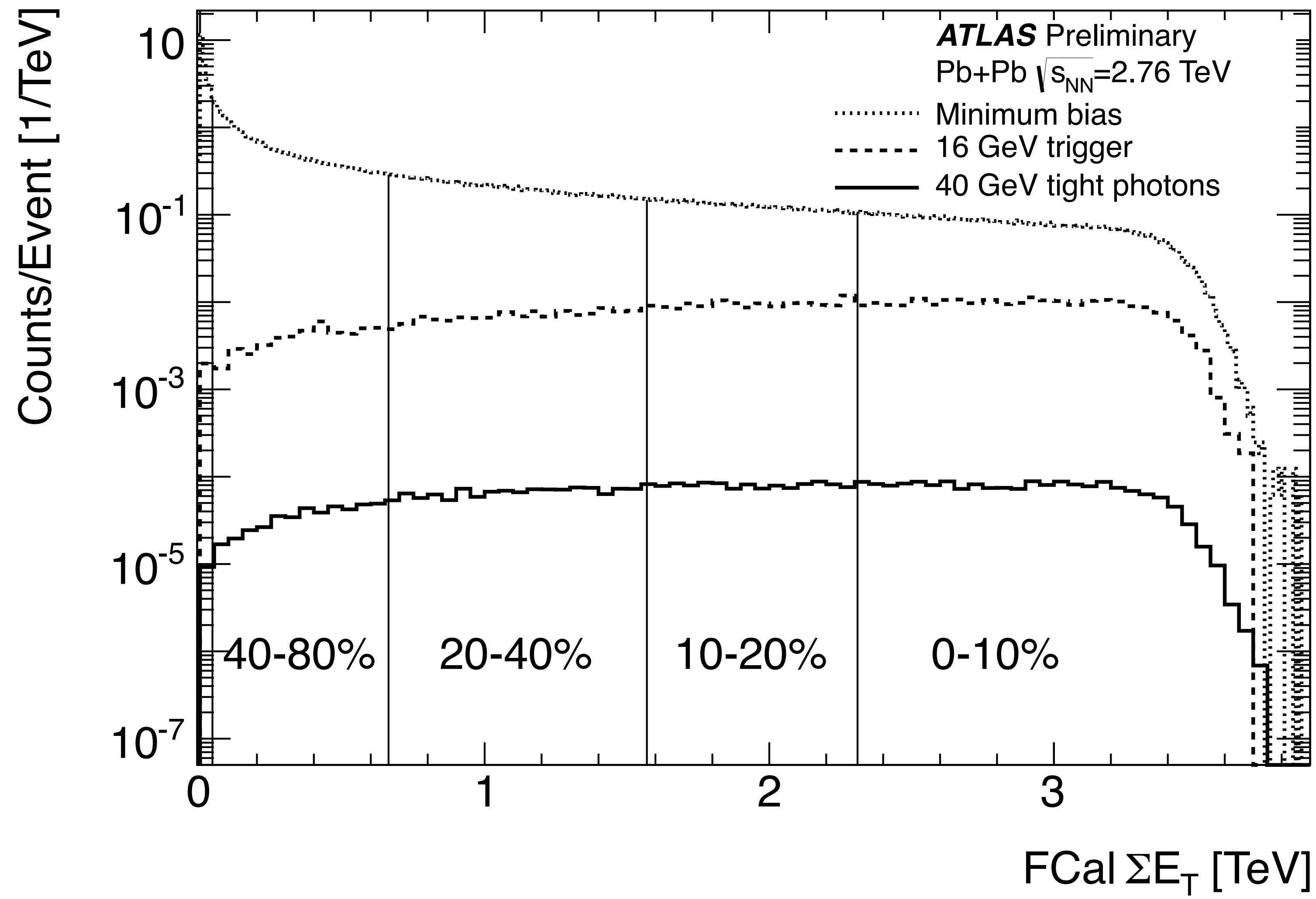
- **Second layer**
  - Containment in η and ϕ, using uniform segmentation
- **First layer**
  - Detailed shower shape in η direction, allowing selection of very narrow clusters & rejection of neutral hadron decays from jets
- **Hadronic section**
  - Measurement of hadronic energy associated with the cluster to reject jets



Details of full set of variables in extra slides

Centrality selection

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

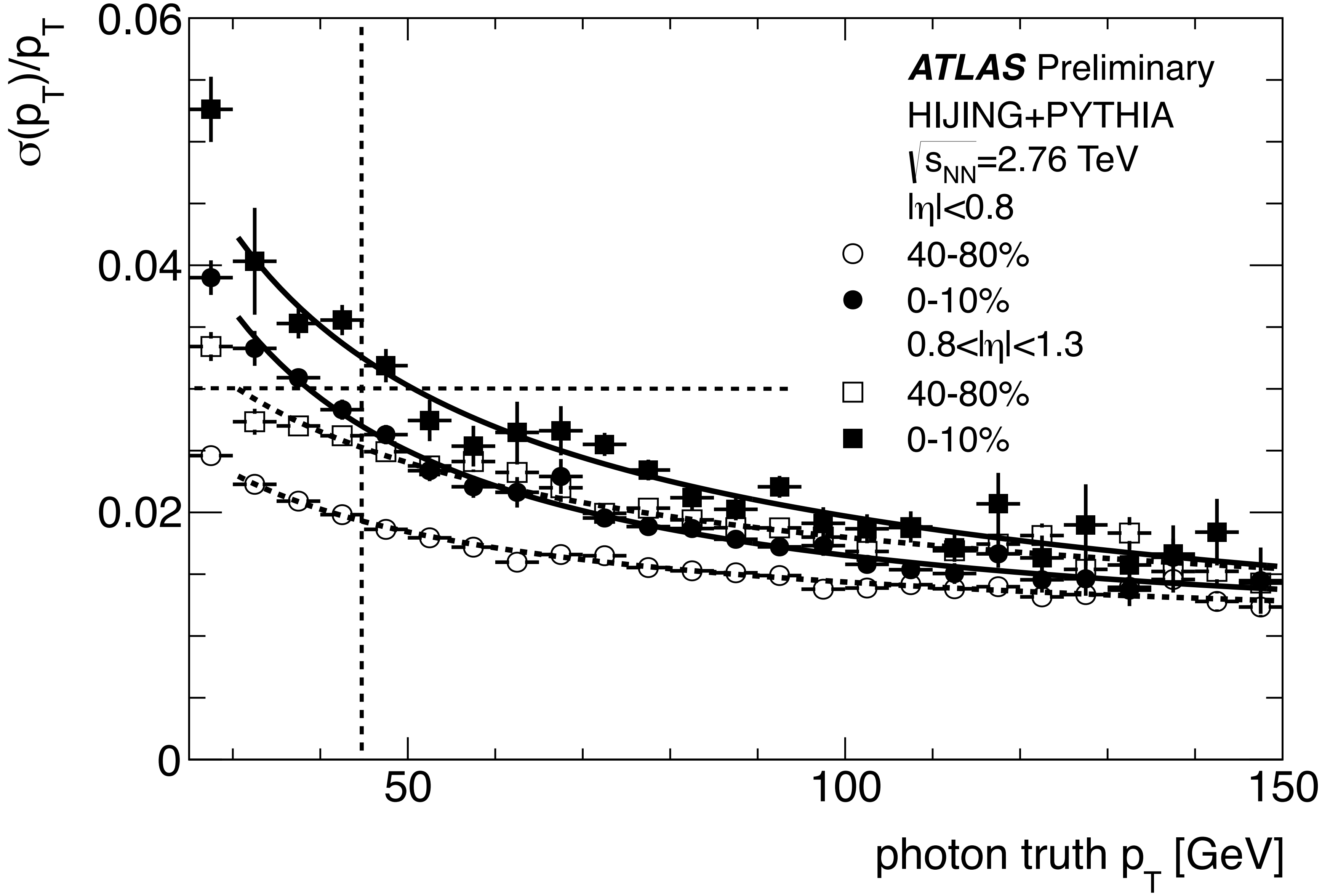


FCal ΣE_T shape established to be identical to 2010 (after known 4.1% rescaling), where efficiency relative to total cross section known to be **98±2%**

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	45.9	6%	77.8	9%	1.22	9.4%

Photon performance: resolution



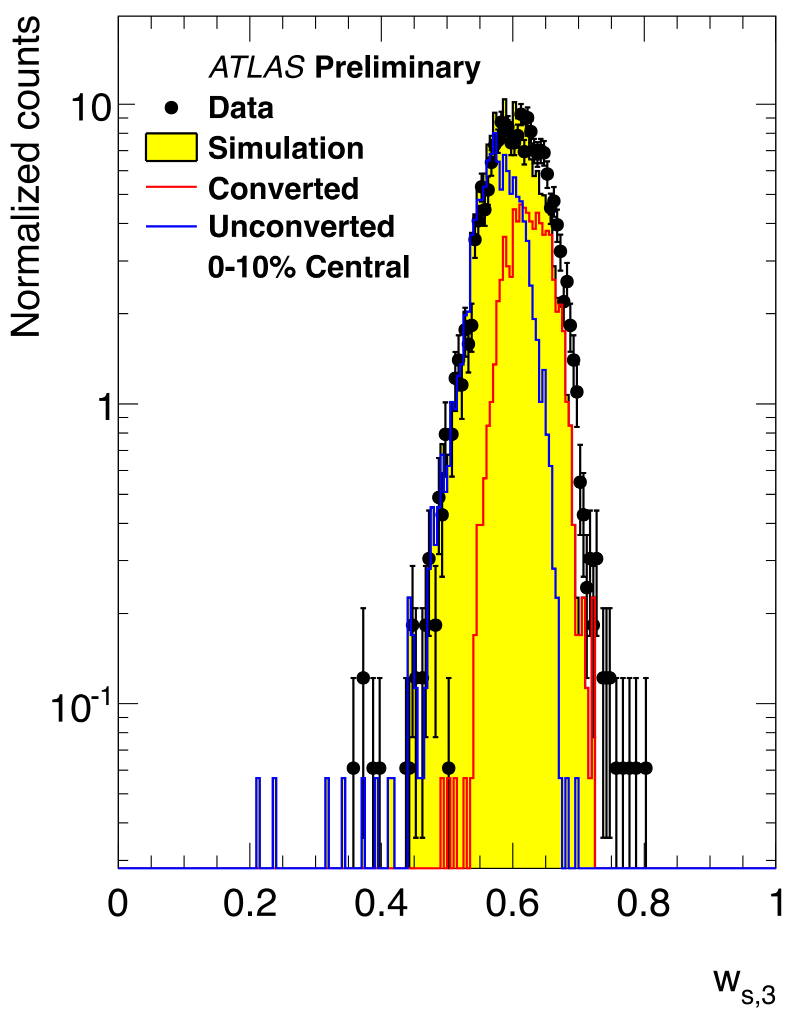
Energy resolution for photons in PYTHIA+HIJING samples.

Fits to $\boldsymbol{\sigma(E_T)/E_T = a \oplus b/\sqrt{E_T} \oplus c/E_T}$

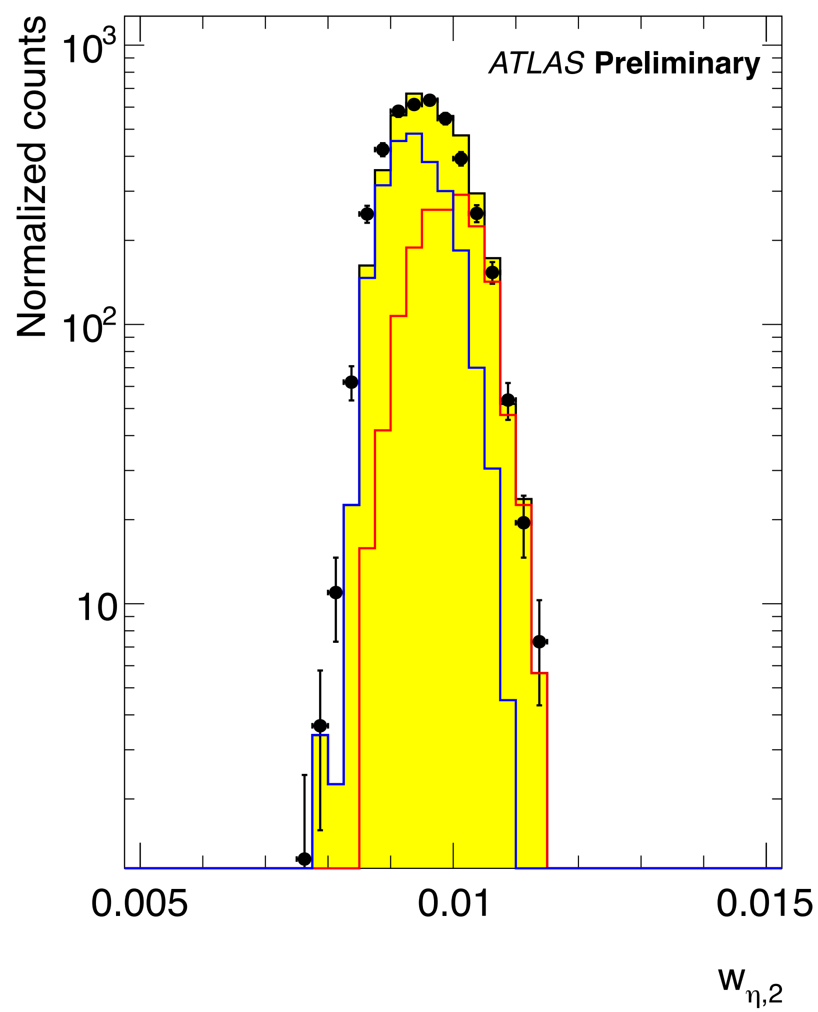
For photon energy range considered, $p_T > 45$ GeV, photon energy resolution ~3% or less

Photon performance: shower shapes

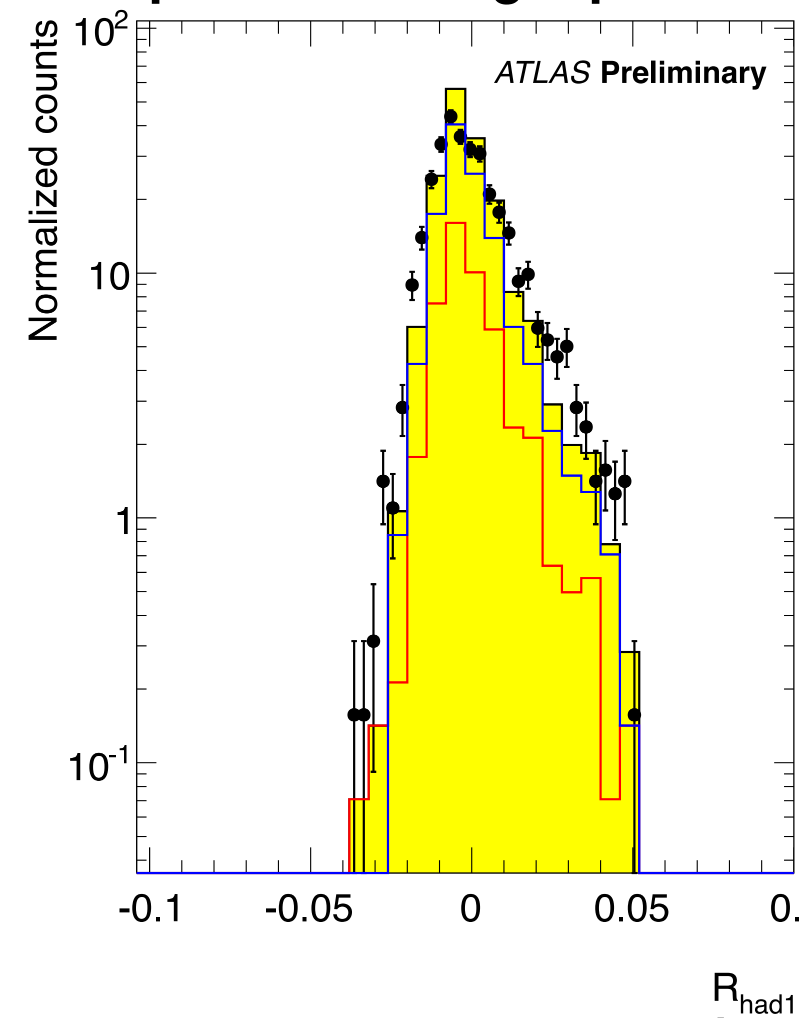
$40 < p_T < 70$ GeV tight photons



η width in layer 1 (strip units)



η width in layer 2 (η units)

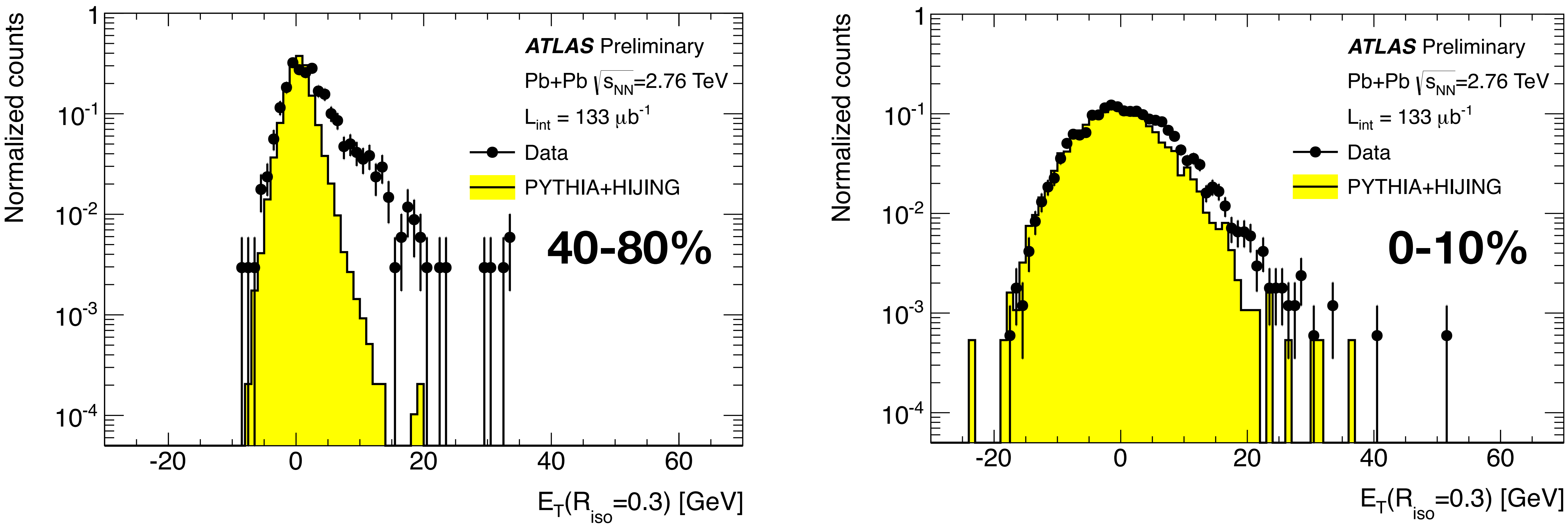


Hadronic energy/ cluster energy

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.

Isolation distributions $E_T(R_{iso}=0.3)$

40 < p_T < 70 GeV tight photons



Sum of transverse energy within R=0.3 cone

EM energy in 5x7 cells removed to remove photon

Normalized here for $E_T(R=0.3)$ < 0 GeV - good data & MC agreement

In MC, width of distribution in 0-10% photon+jet events is ~6 GeV

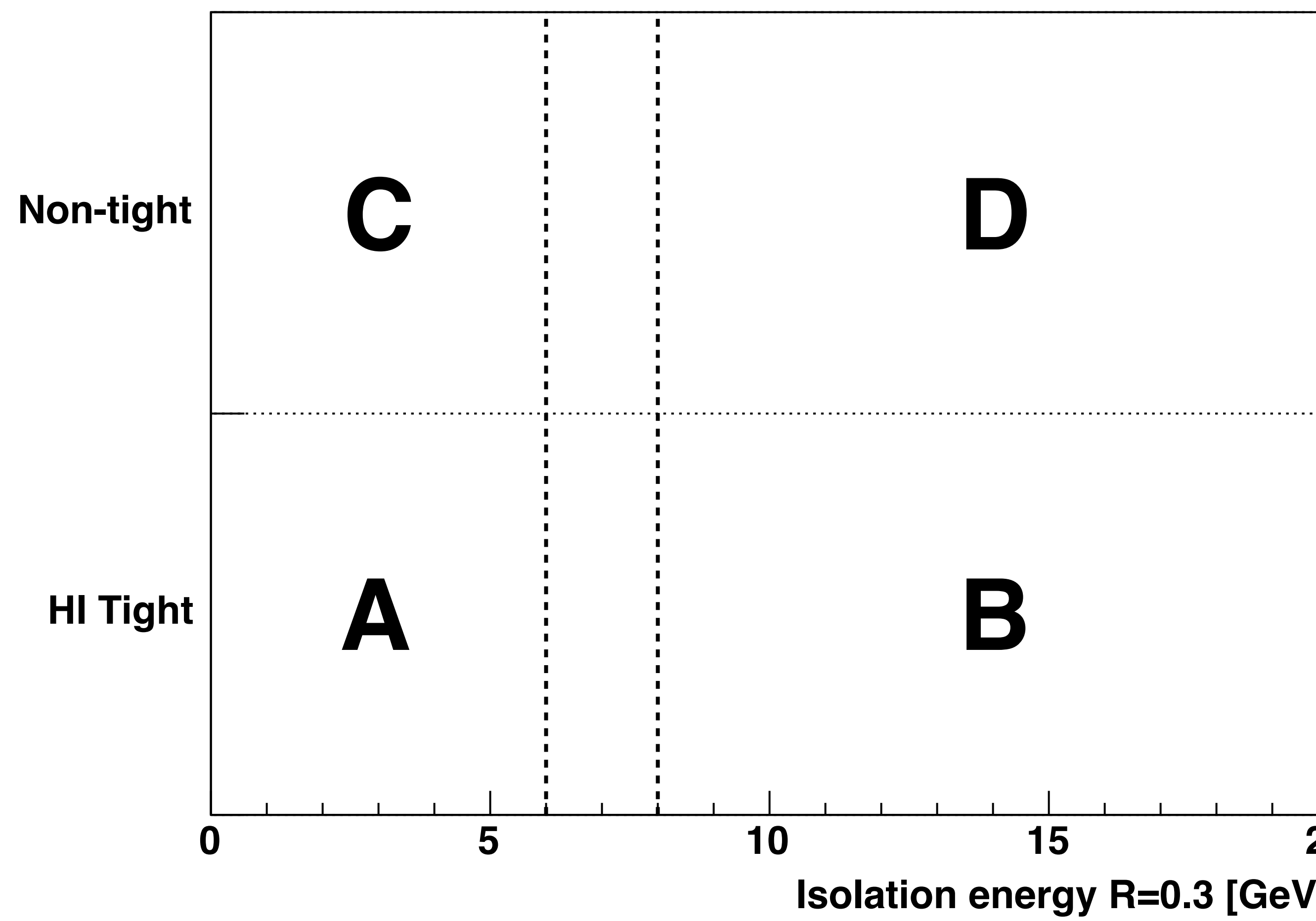
Double sideband technique: ideal

"ABCD" method previously used for prompt photon measurements in ATLAS (& SUSY, etc.)

Two-dimensional distribution: **Isolation** vs.**purity**

"Non-tight" photon candidates fail subset of cuts: enhance jets

The ratio N_C/N_D provides information on background A, given the number of counts in B



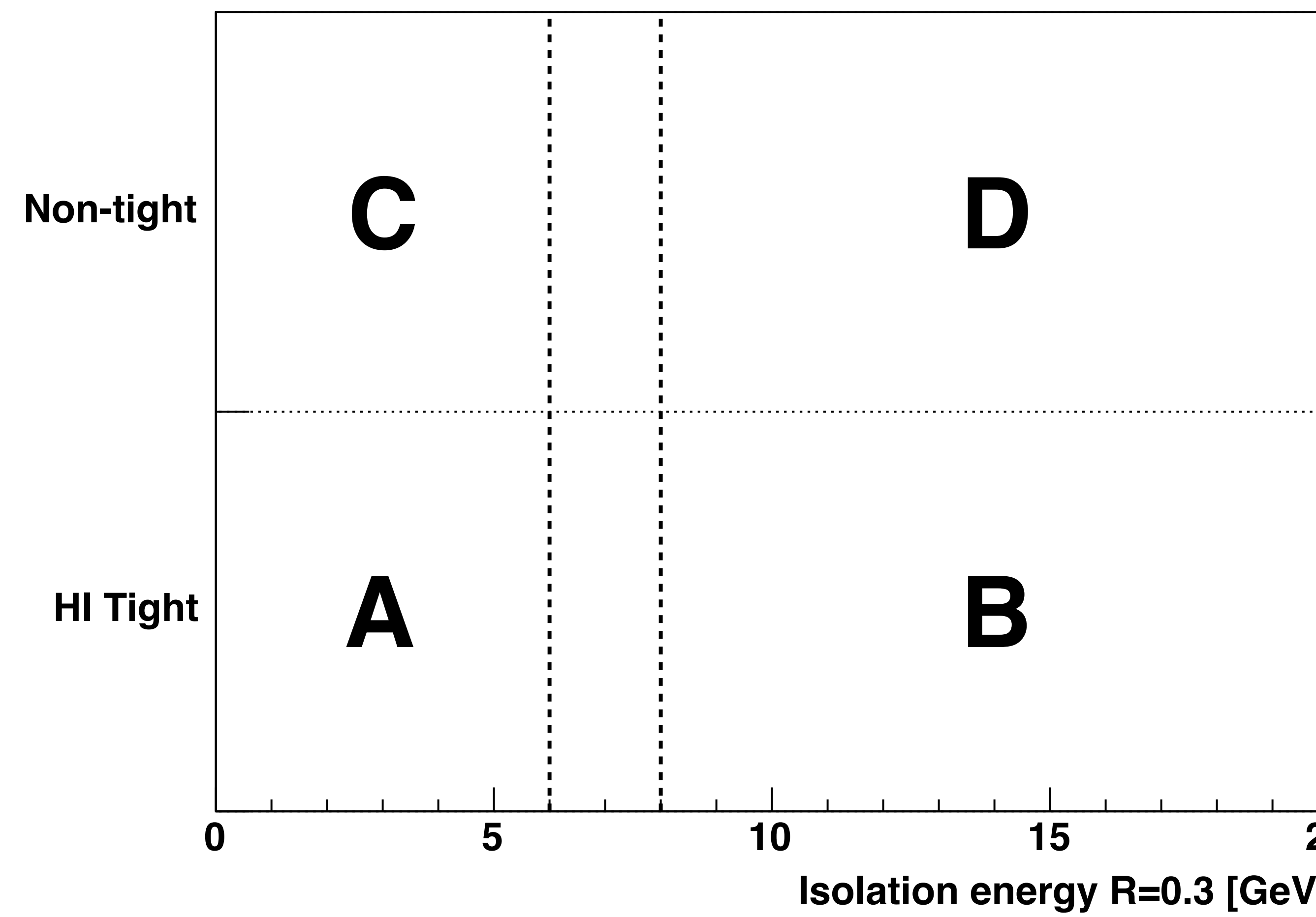
$$N^{\rm sig} = N_A^{\rm obs} - N_B^{\rm obs} \frac{N_C^{\rm obs}}{N_D^{\rm obs}}$$

Double sideband technique: in practice

Fluctuations in photon response lead to signal contamination into regions BCD

Use MC to extract "leakage factors" ($c_X = N^{sig}_X / N^{sig}_A$)

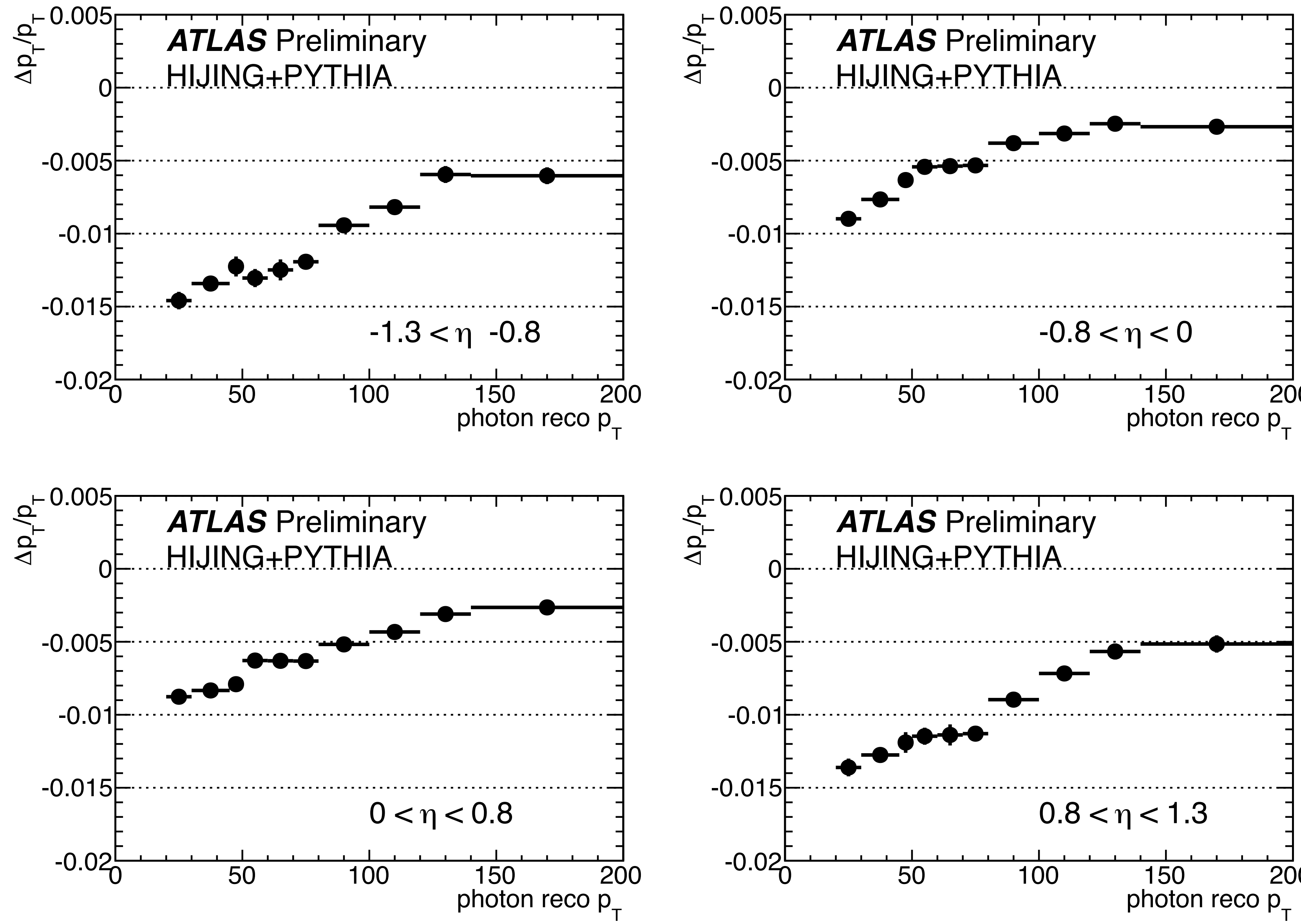
Quadratic equation for N^{sig}_A, solved numerically and statistical uncertainties of data and MC counts fully propagated



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

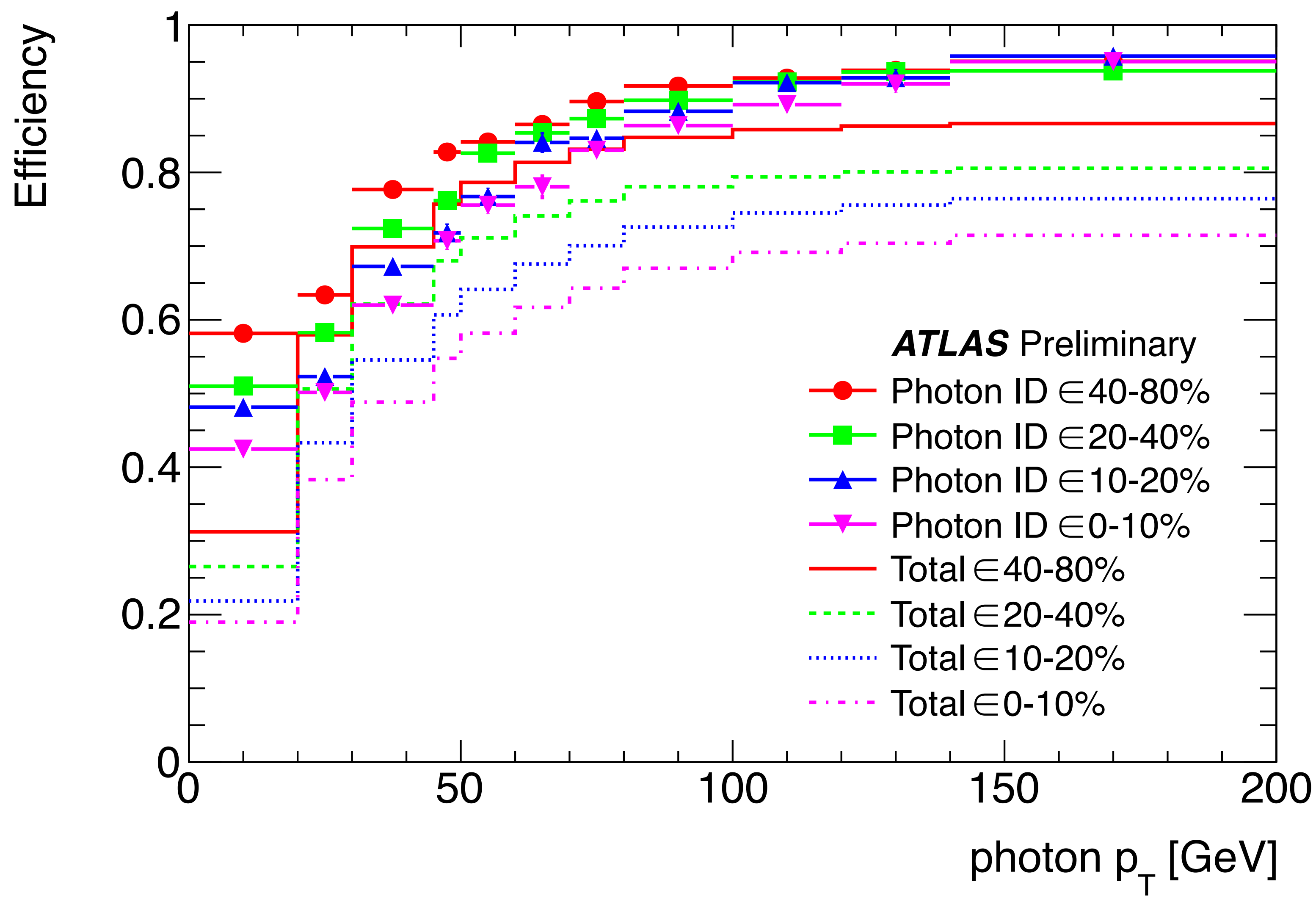
Photon performance: energy scale

Photon energy scale correction ($\Delta p_T/p_T$) for tight & isolated from PYTHIA+HIJING as function of reconstructed photon energy



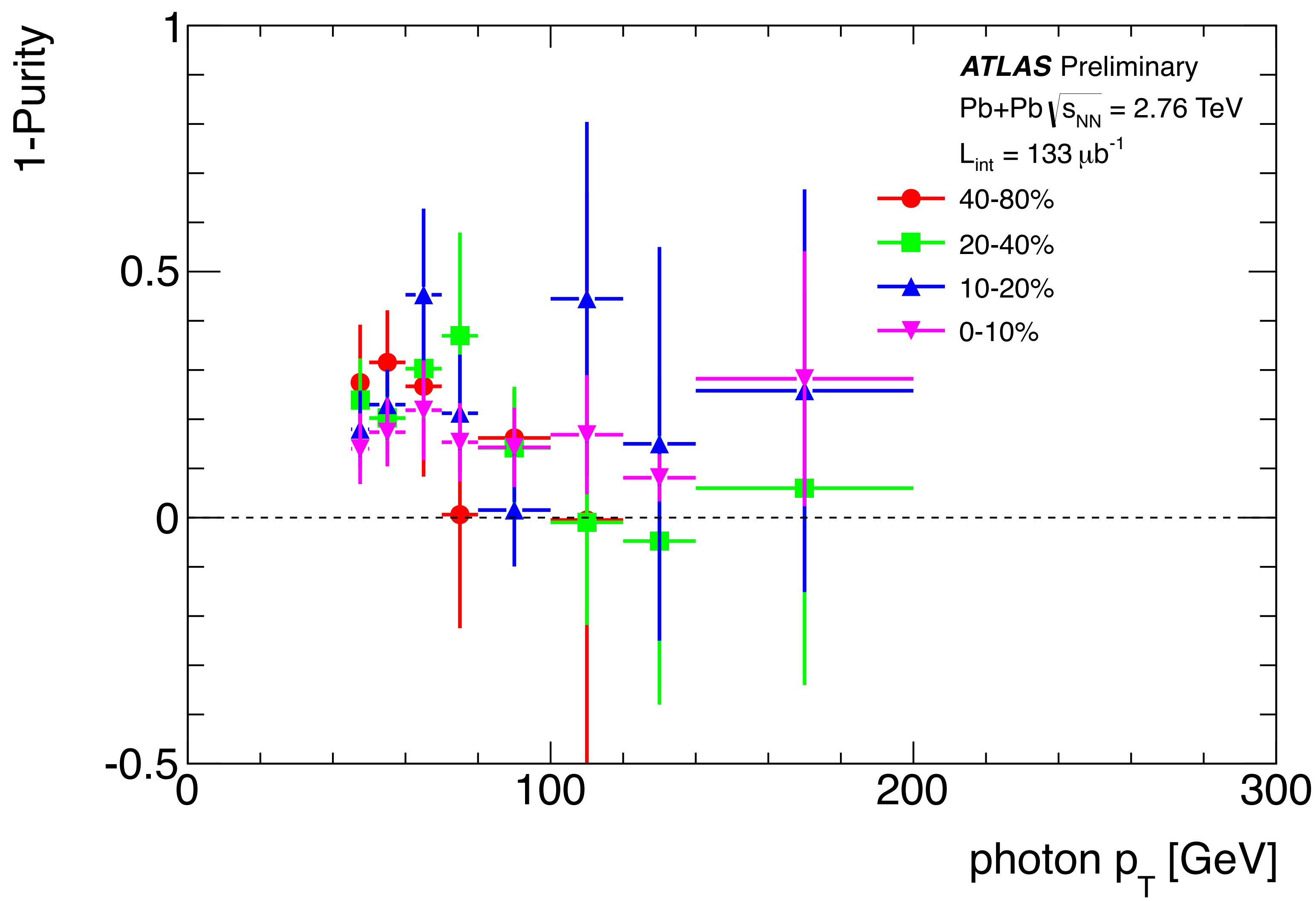
In PYTHIA+HIJING scale good to 1.5% or better (typically O(.5%)): Include 3% systematic uncertainty from testbeam studies

Efficiency



- **Measured relative to isolated photons in PYTHIA (6 GeV @ hadron level)**
- **Efficiency is product of reconstruction efficiency, identification efficiency & isolation efficiency**
  - Isolation efficiency is probability of truth photon passing isolation cut

Purity extracted from double-sidebands



1-Purity = $1-N^{sig}_A/N^{obs}_A$ is the % correction applied to the number of measured counts to remove di-jet background: 20-30% in low p_T bins.

Limited data and MC statistics induce fluctuations. in higher-p_T bins. Negative (1-P) results from limited statistics.

Systematic uncertainties

Source	Effect on yield
Tight cut definition	20%
Non-tight definition	3%
Isolation criterion	20%
Energy scale	12%
Unfolding	3%
Event counting	1%
Total	**31%**

Total uncertainty on photon yield estimated at 31%, assigned independent of p_T and centrality

ATLAS photon yields for 45<pT<200 GeV

For R=0.3, ET<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 pT bin, extracted signal counts scaled by

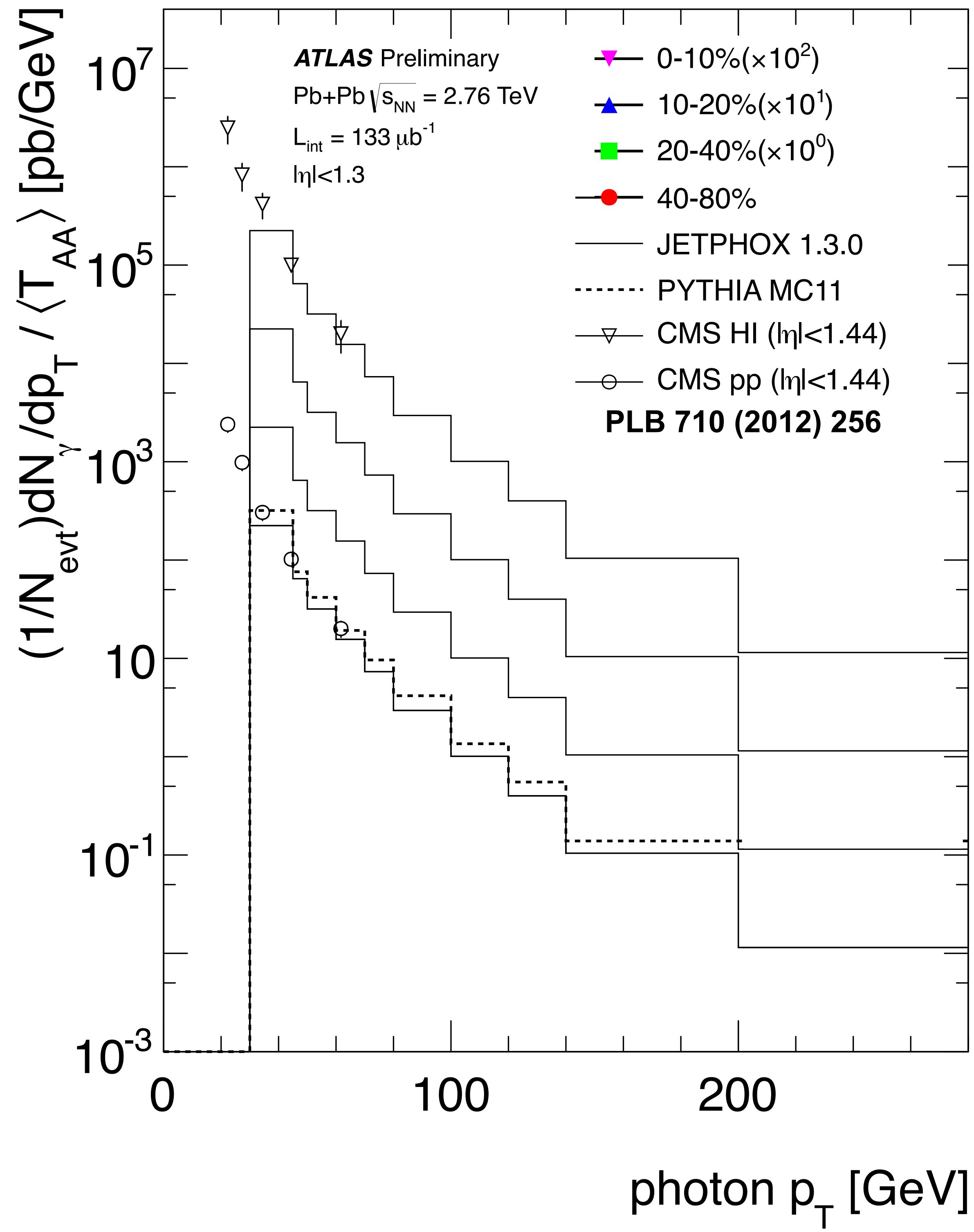
- total efficiency

- number of events

- width of pT bin

then scaled by <TAA>

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



ATLAS photon yields for $45<p_T<200$ GeV

For $R=0.3$, $E_T<6$ GeV

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

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 $<T_{AA}>$

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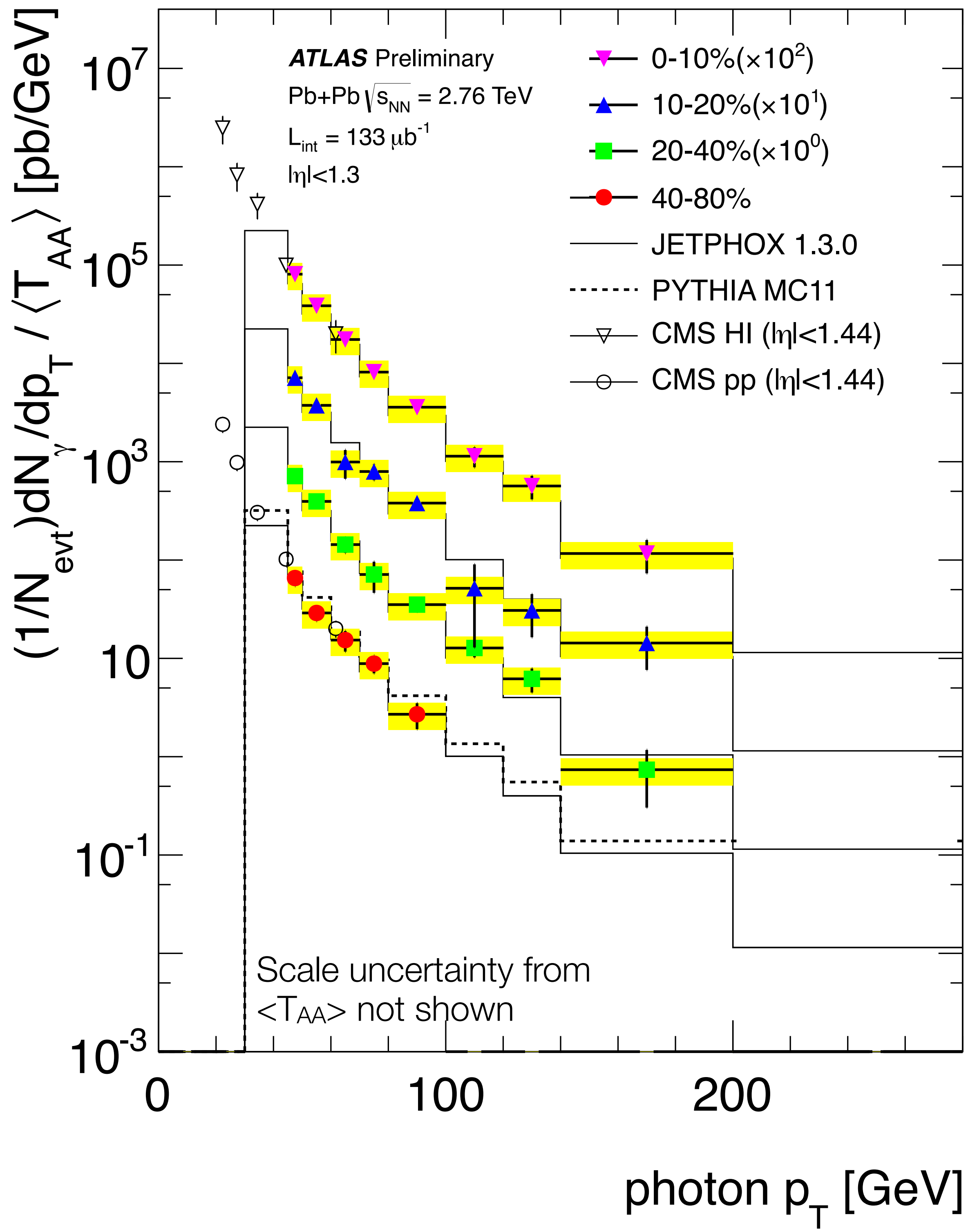
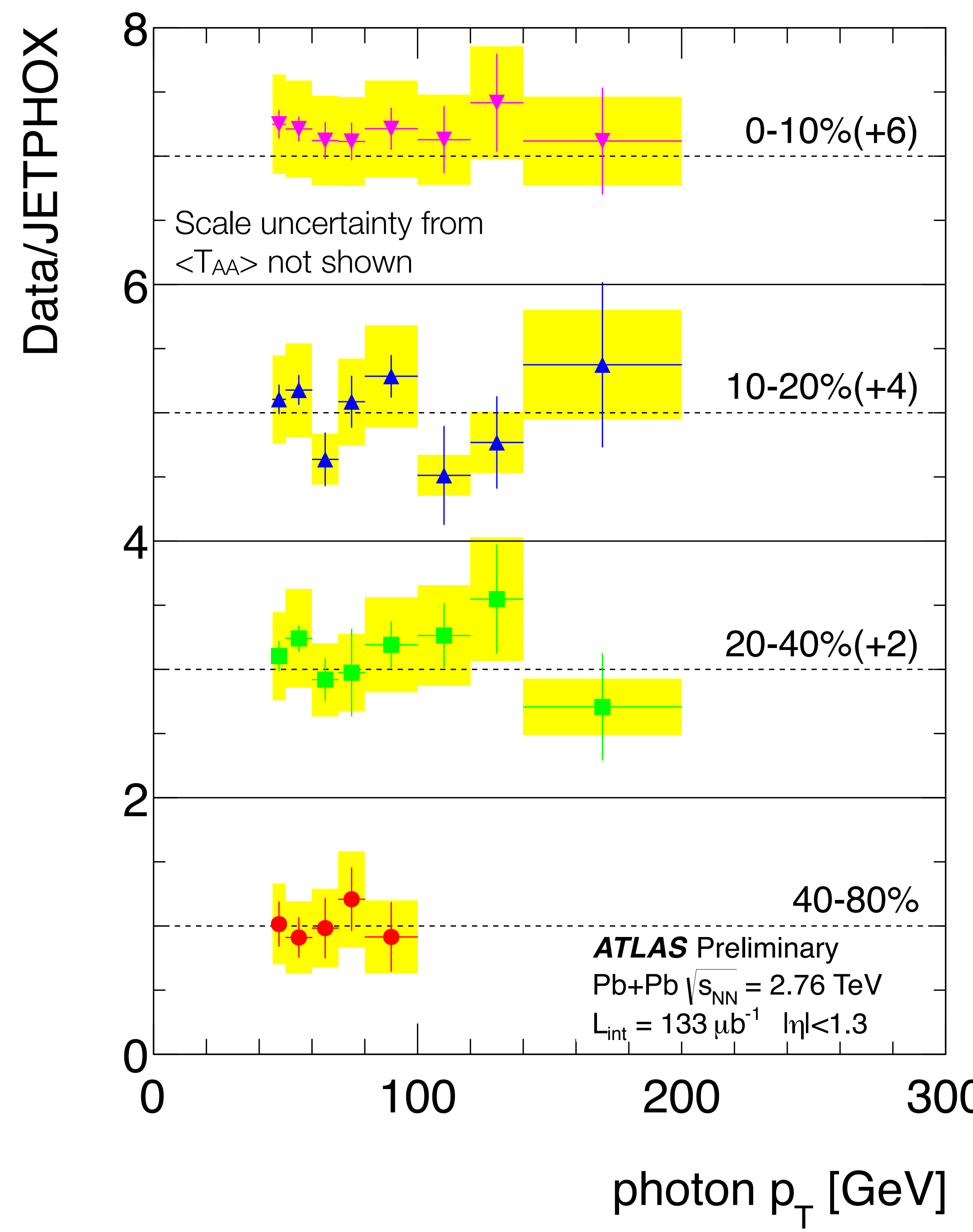


Ratios relative to JETPHOX

- **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**



Conclusions

- **Measurement of isolated prompt photons in 2.76 TeV lead-lead collisions by ATLAS over a broad kinematic range**
  - p_T = 45-200 GeV, $|\eta|<1.3$
- **Photons reconstructed in longitudinally-segmented ATLAS calorimeter**
  - Tight shower shape cuts used to reject contributions from jets
- **Jets subtracted using double sideband technique**
  - Purity measured to be 70-80% at low p_T, increasing with increasing p_T
- **Good agreement with JETPHOX *pp* cross sections**
  - No significant dependence on transverse momentum or centrality
- **Photons will be useful for studying recoil jet in more detail**
  - Stay tuned for wider rapidity range and correlations with jets

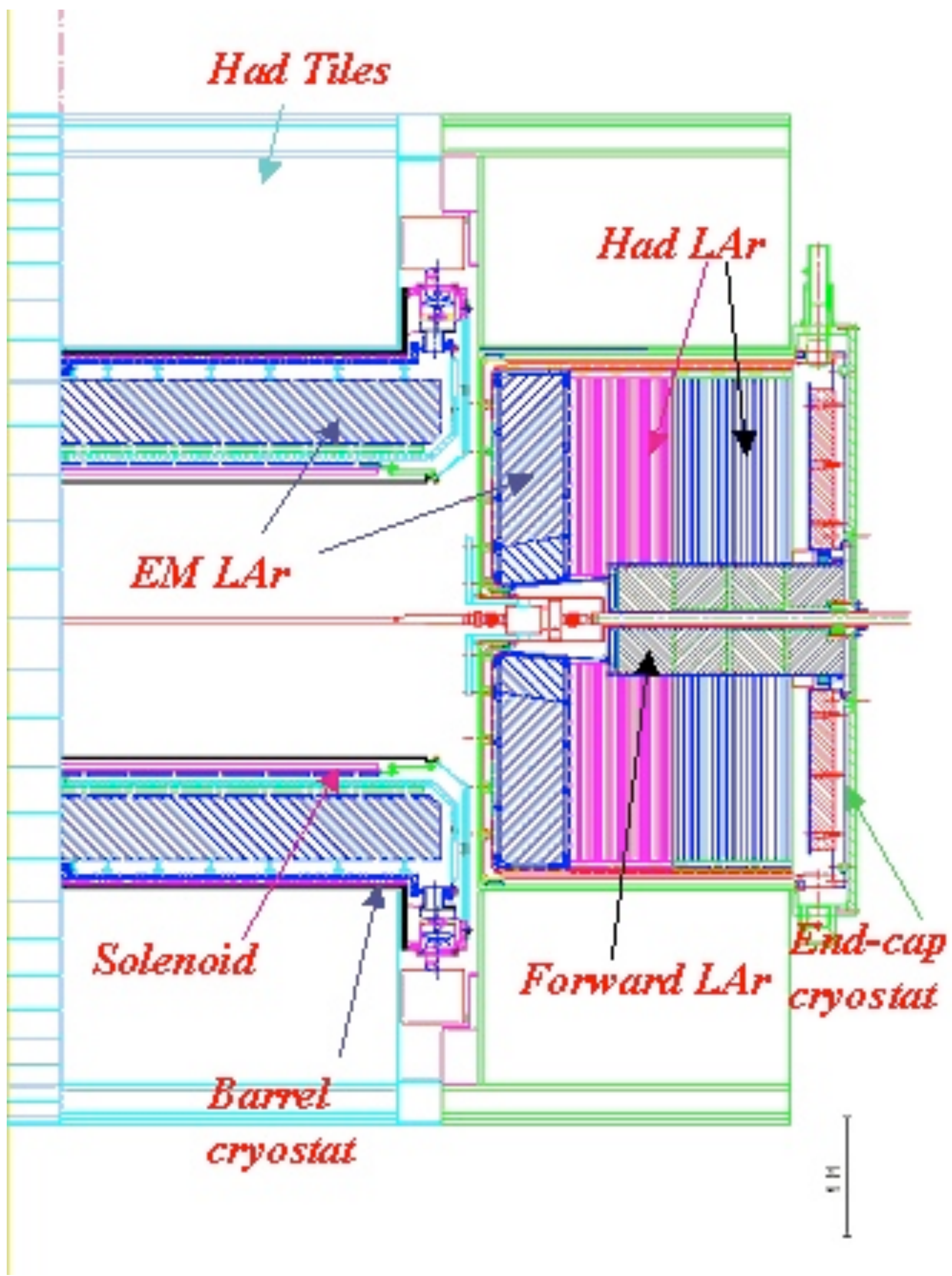
Extra slides

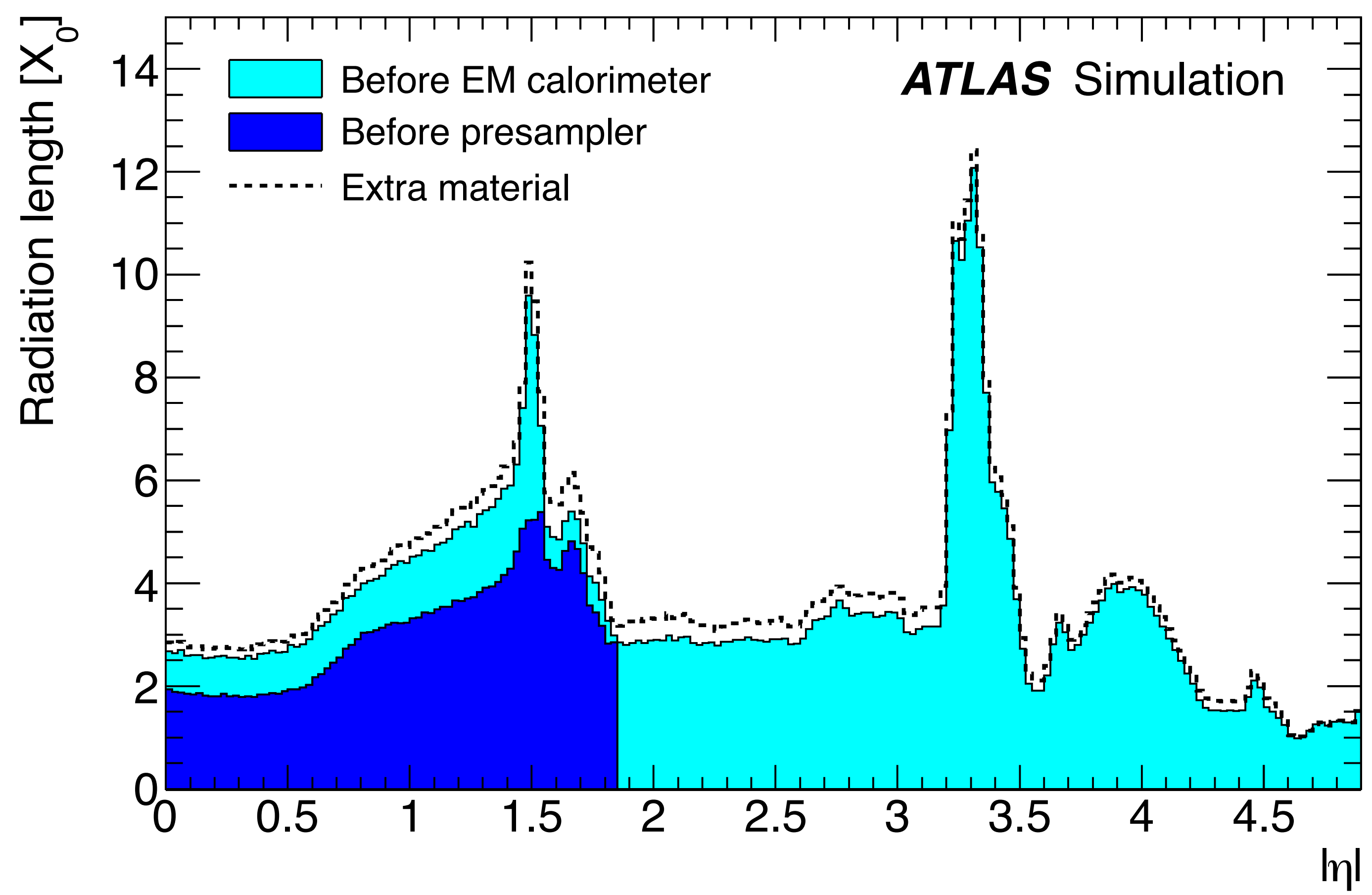
Systematic uncertainties

- **Tight photon definition**
  - The tight cuts were varied to account for varying levels of optimization and adjustment to MC. Variations of the result were within ±20%
- **Non tight cuts**
  - The definition of non-tight cuts was varied and results were consistent within 3%
- **Isolation criteria**
  - The isolation criteria were varied both in cone size, energy, and possible misestimates of shower leakage. Variations were within ±20%
- **Energy scale**
  - Very conservative estimate on energy scale uncertainty based on 3% seen in testbeam, 12% variations in yield
- **Event counting**
  - Proportionality between measured luminosity and number of events checked throughout 2011 run, and stable within <1%
- **Unfolding corrections**
  - Not applied in this analysis, estimated to be 3% in lowest p_T bin, applied to all bins

Total uncertainty on photon yield estimated at 31%, independent of p_T and centrality

Material description in front of calorimeter





“Tight” photons

Using granular calorimeter cells, define 9 “shower shape” variables (all used in pp) with

- second layer gives rough measurement of shower width

- hadronic calorimeter used for tag obvious jets

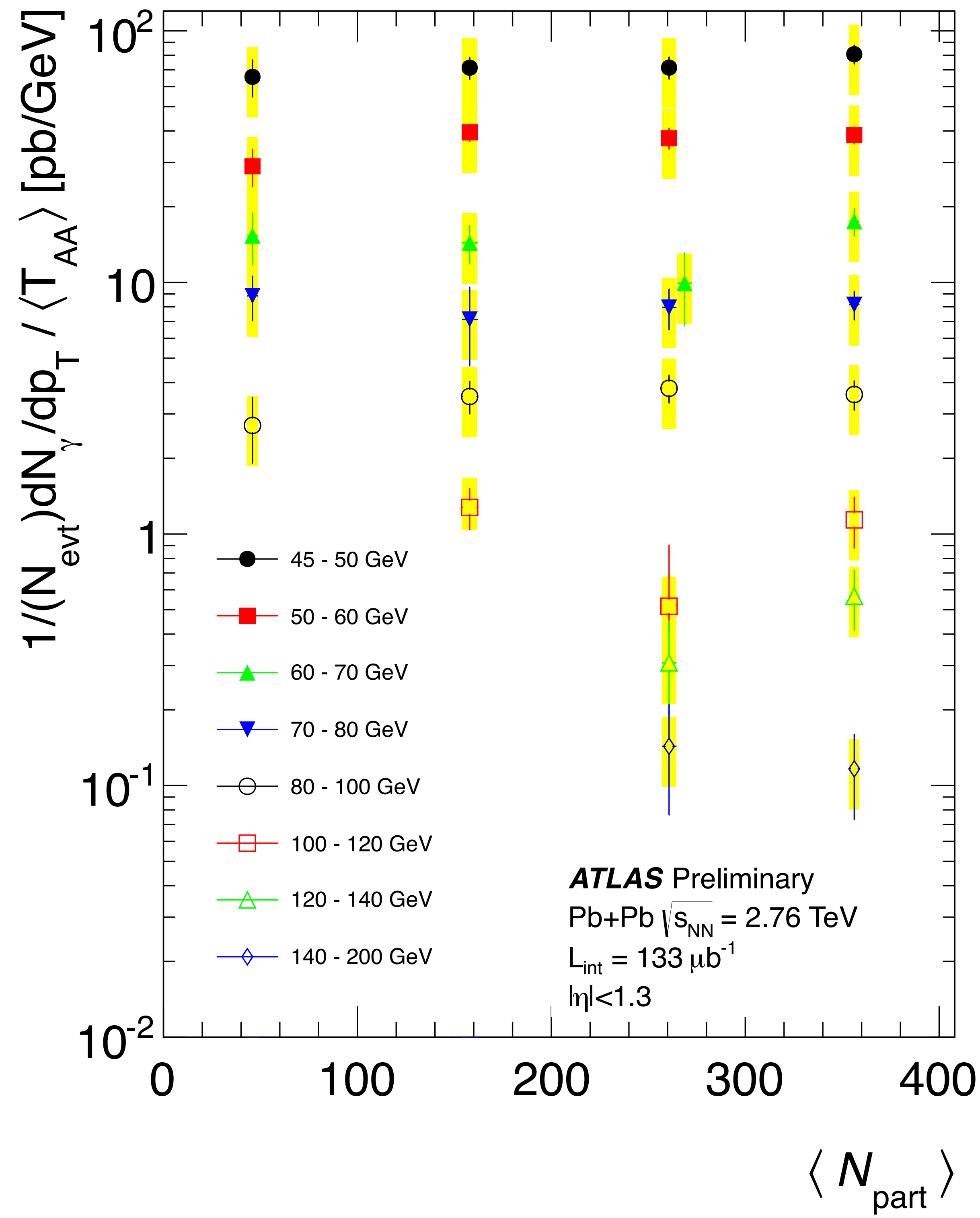
- first layer used to reject π^0 and **η**

- R_η, the ratio of energies deposited in a 3×7 $(\eta \times \phi)$ window to that deposited in a 7×7 window, in units of the second layer cell size.
- $w_{\eta,2}$, the root-mean-square width of the energy distribution of the cluster in the second layer in the η direction
- R_{had}, the ratio of leakage into the hadronic calorimeter to the energy of the photon cluster.
- R_ϕ, the ratio of energies deposited in a 3×3 $(\eta \times \phi)$ window in the second layer to that deposited in a 3×7 window, in units of the second layer cell size.
- $w_{\mathrm{s,tot}}$, the total RMS of the energy distribution in the η direction in the first sampling “strip” layer
- ● $w_{\mathrm{s,3}}$, the RMS width of the three “core” strips including and surrounding the cluster maximum in the strip layer
- ● F_{side}, the fraction of energy in seven first-layer strips surrounding the cluster maximum, not contained in the three core strips (i.e. $(E(\pm 3) - E(\pm 1))/E(\pm 1)$)
- ● E_{ratio}, the asymmetry between the energies in the first and second maxima in the strip layer
- ● ΔE, the energy difference between the first maximum and first minimum between the first and second maxima

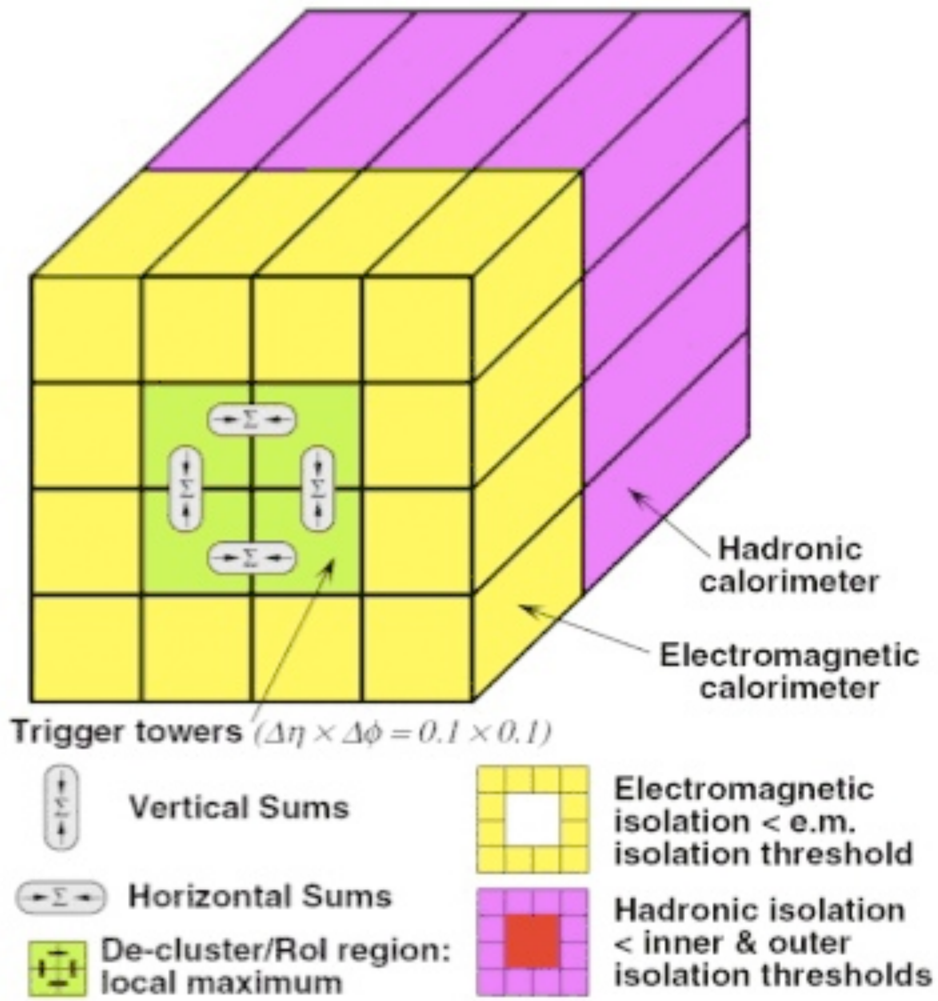
Satisfying all 9 cuts: “tight”
Failing any of 4 first layer cuts (●): “non tight”

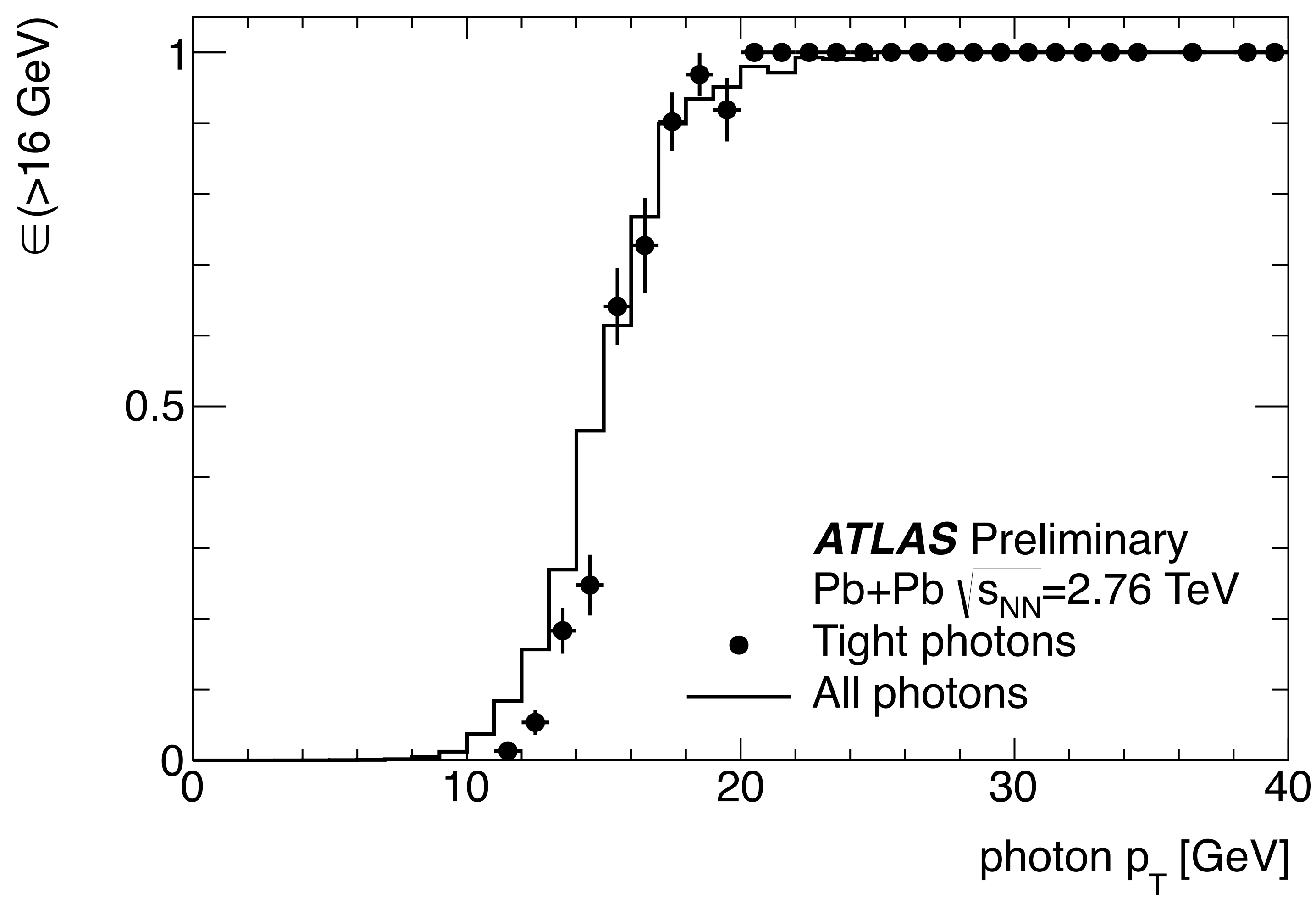
Centrality dependence of yields

- **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 (grey bands, will be yellow)**



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