Prompt photon measurements with the ATLAS detector

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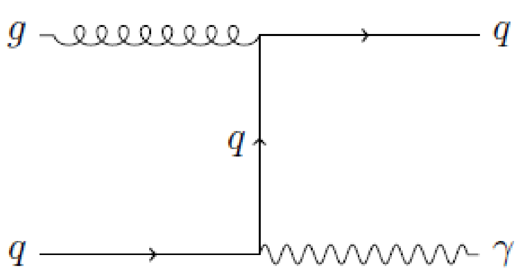
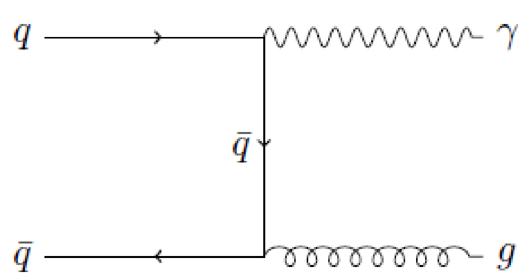
Photons at LHC

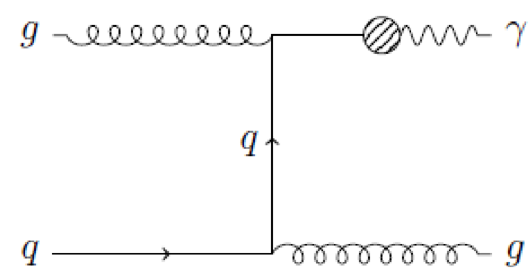
- Measurement of the single / double photon production cross sections (+ all the relevant distributions), photon+jet
  - test of QCD predictions.
  - Use direct photons as an input for PDFs: since the dominant process is qg scattering, direct photons can be used to probe the gluon content of the proton.
  - probe our capability to perform convincing measurements involving photons: main backgrounds for many ‘discovery’ channels like Higgs into 2 photons.



Compton Scattering

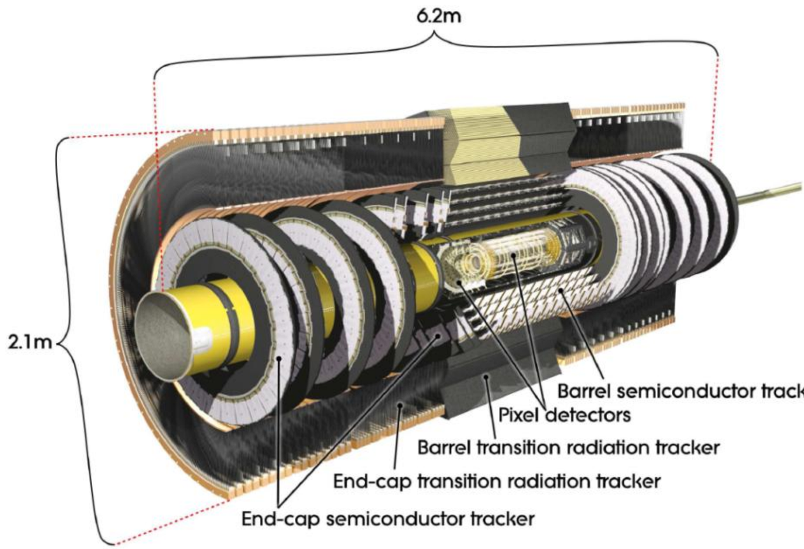


Annihilation



Fragmentation

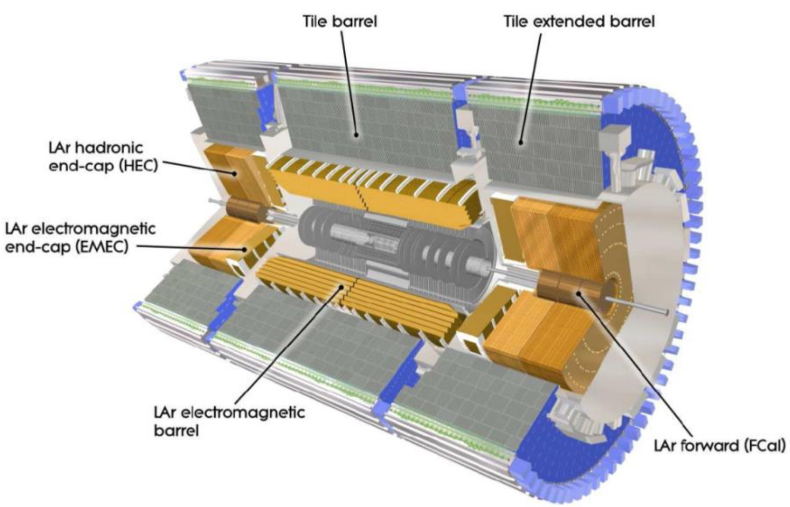
ATLAS : main subsystems



Inner Detector (ID) in 2 T solenoidal B-field

(b=barrel, e=endcap)

- ❑ Pixel: 3 layers(b)+2x3 disks(e) $\sigma_{r\varphi}\sim 10\mu m, \sigma_z \sim 115\mu m$
- ❑ SCT: 4 layers(b)+2x9 disks(e) $\sigma_{r\varphi}\sim 17\mu m, \sigma_z \sim 580\ \mu m$
- ❑ TRT: 73 layers (b) + 2 x 160 layers (e) $\sigma_{r\varphi}\sim 130\ \mu m$ (b)



Liquid Argon - Lead sampling calorimeter with an ‘accordion’ geometry :

❑ 3 longitudinal layers with cell of $\Delta\eta x \Delta\varphi$:

❑(0.003-0.006)x0.1 (1st layer)

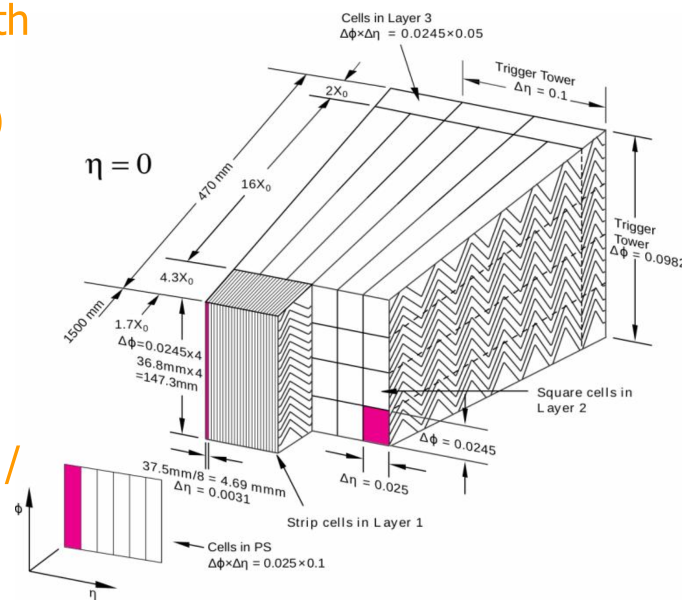
❑ 0.025x0.025 (2nd layer),

❑ 0.050x0.025 (3rd layer)

❑ Barrel-endcap crack (1.37-1.52)

❑ Presampler for $|\eta|<1.8$ $\Delta\eta x \Delta\varphi \sim 0.025x0.1$

❑ $\sigma(E)/E = (10\text{-}17\%)\ (\eta)\ / \sqrt{E\ (GeV)} \oplus (1.2\%\text{-}1.8\%)$



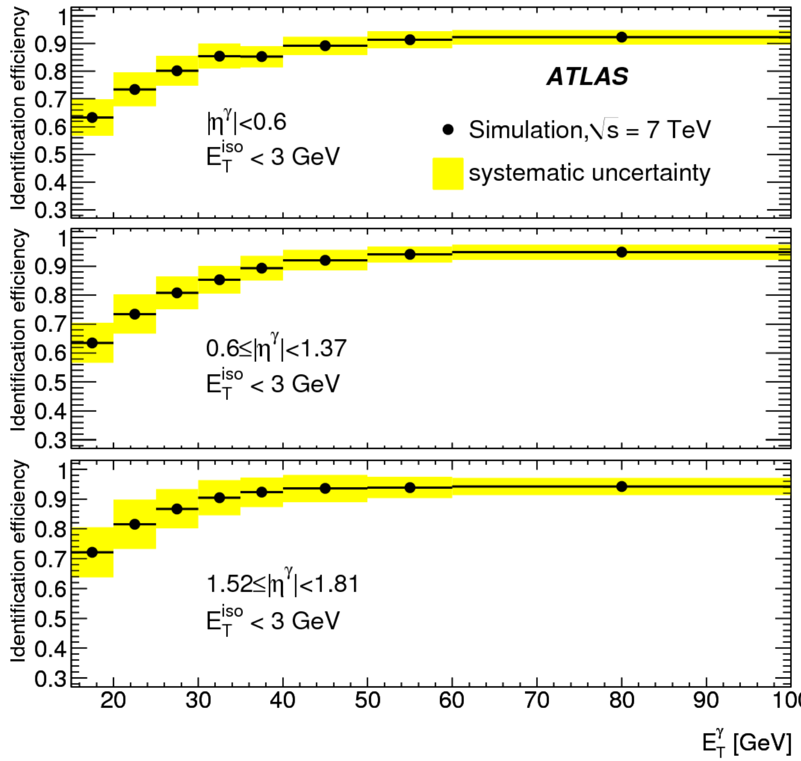
Photon reconstruction and identification

- Seeded by a cluster in EM calo with energy in 3x5 cells ($\Delta\eta \times \Delta\phi$) in 2nd layer > 2.5 GeV
  - No matched track : unconverted γ
  - Matched to track(s) from γ conversion in ID : converted γ. Single track conversions also

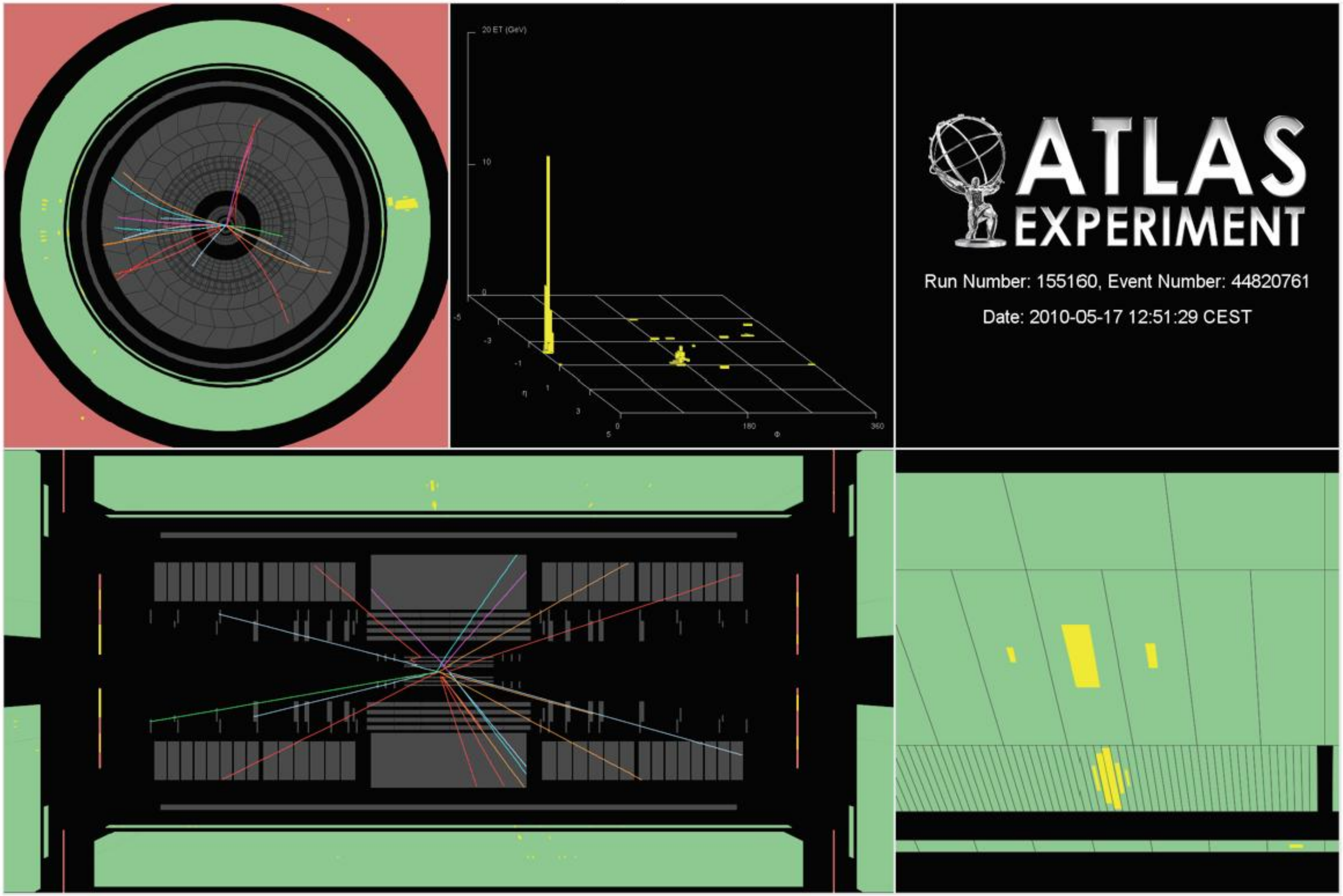
- Reconstruction efficiency ε_{reco} (from MC): ~80-85% in the barrel ($|\eta|<1.37$), ~70% in the endcap ($1.52<|\eta|<2.37$)
  - Inefficiency (malfunctioning connection links) recovered in 2011 winter shutdown

- Cuts on shower shape variables in the calorimeter:
  - Identification efficiencies from 60% (at 15 GeV) to >90% (for E_T^{γ}>~50 GeV).
  - Uncertainty from 5% to 2%
  - Different cuts for converted and unconverted photons
  - Cuts on calo strips layer to reject π^0

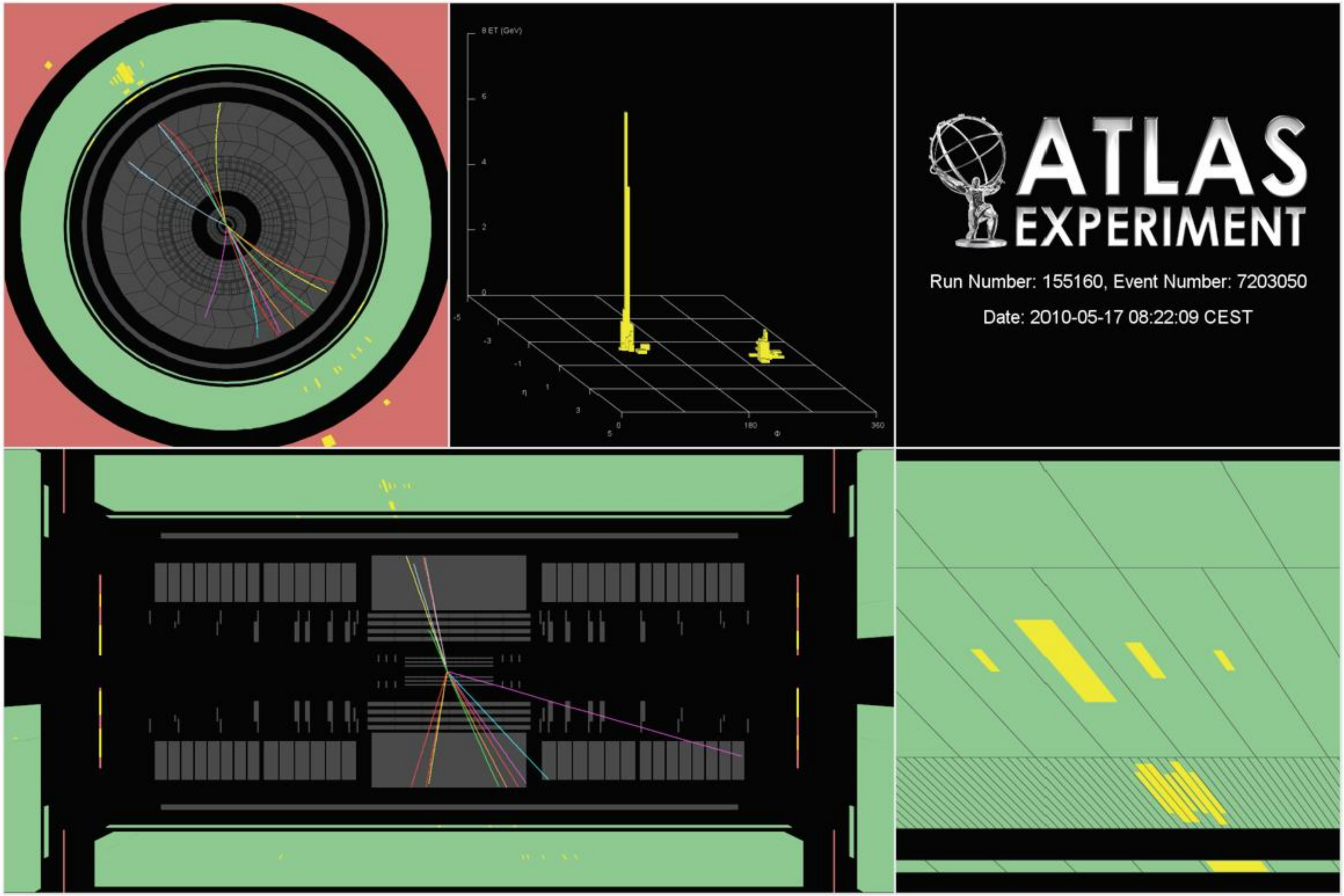
- Trigger efficiency ~100% (<1% uncertainty) measured in data (bootstrap, lower threshold triggers)



A nice photon candidate



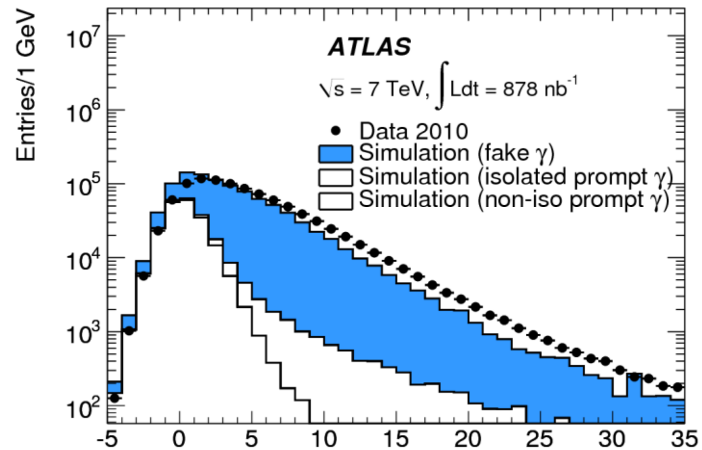
A nice fake photon candidate

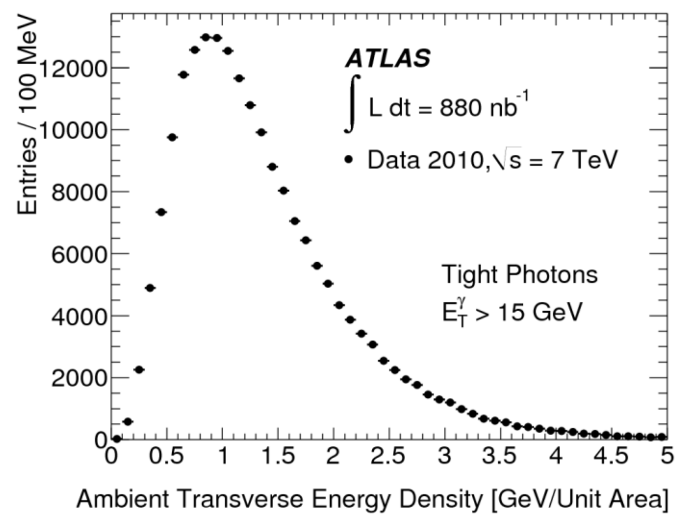


Photon isolation

Isolation is necessary to further reduce the jet background and (to some extent) of the fragmentation contribution: the definition of the isolation prescription is a tricky business

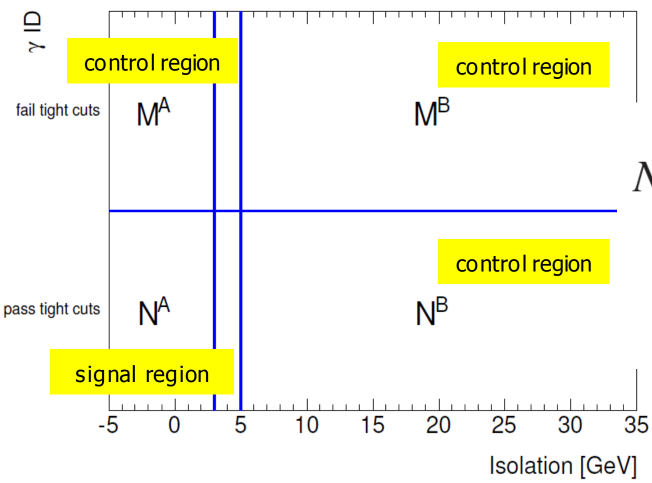
- Calorimeter isolation
  - Sum of energies in cells in cone R<0.4 in η-φ around the photon, removing the 5x7 cells core
- Corrections for residual leakage of photon energy outside the cluster into the isolation cone, using single photon MC samples
- Corrections for underlying event
  - Using ambient energy density estimated with low-p_T jets, (M. Cacciari, G. P. Salam, S. Sapeta, "On the characterisation of the underlying event", JHEP 04 (2010) 65)
  - In 2010 data (<NPV>~2) average correction ~540 MeV + ~170 MeV (per vertex). MC : PYTHIA 440 MeV, HERWIG 550 MeV
- Signal region : Require 'corrected' isolation < 3 GeV





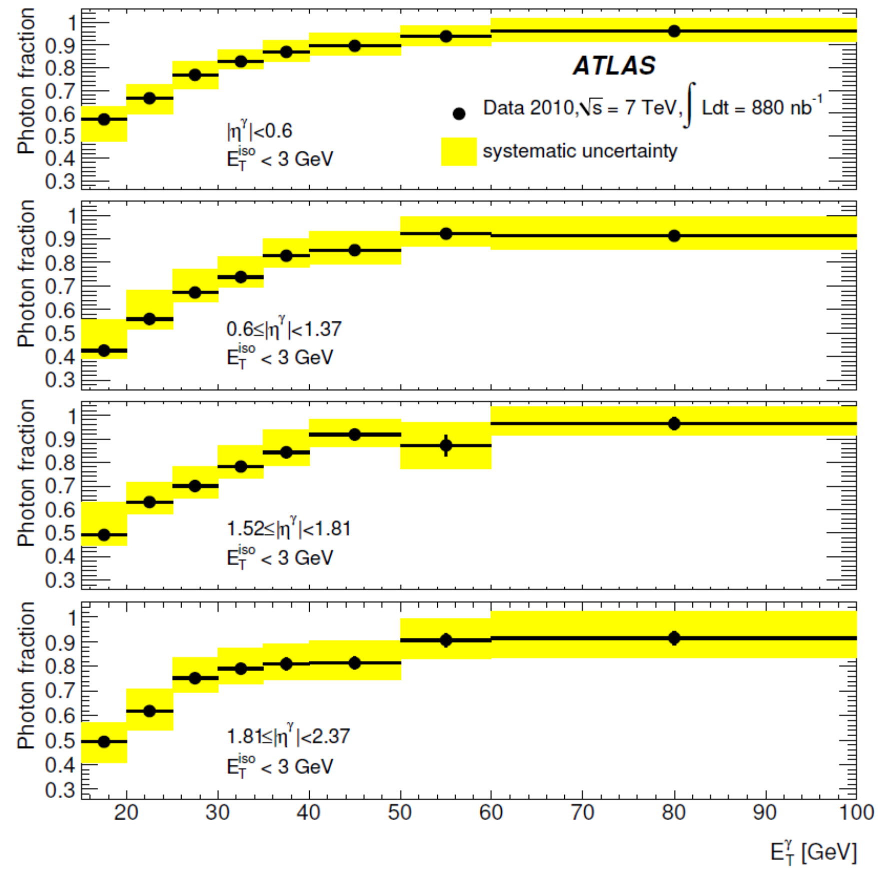
Signal extraction :

Data driven approach using a 2D-sidebands subtraction method: identification selection on one axis and calorimetric isolation on the other.



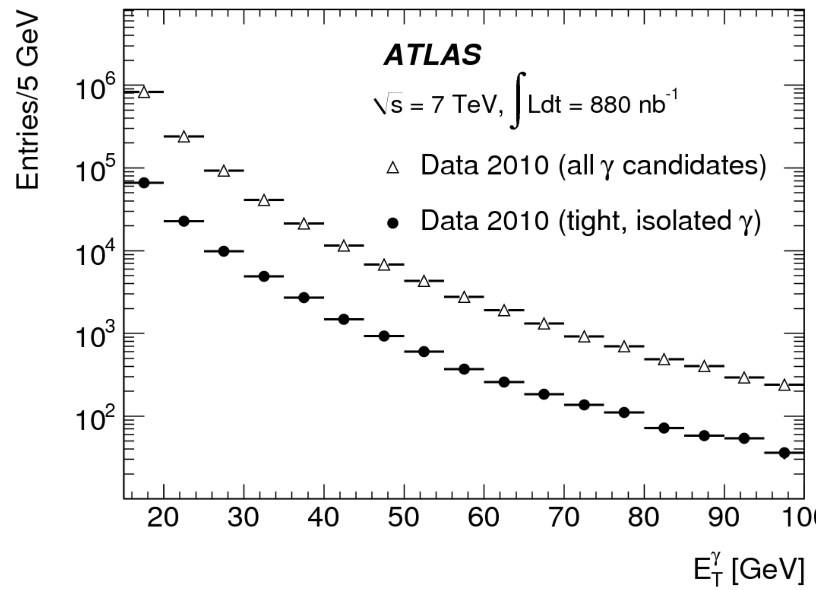
$$N^A_{\rm sig} = N^A - N^B \frac{M^A}{M^B}$$

$$P = 1 - \frac{N^B}{N^A} \frac{M^A}{M^B}$$



- Purity rapidly increases from 50% (15 GeV) to >95% above 100 GeV
- Systematic uncertainties from: 5 to 10%
- Results cross-checked with isolation template fit (signal template: electrons from W/Z in data; bkg template: photons failing the tight ID criteria). The results agree within 5%

Inclusive photon cross section



Two analysis with different integrated luminosity (very similar ingredients) :

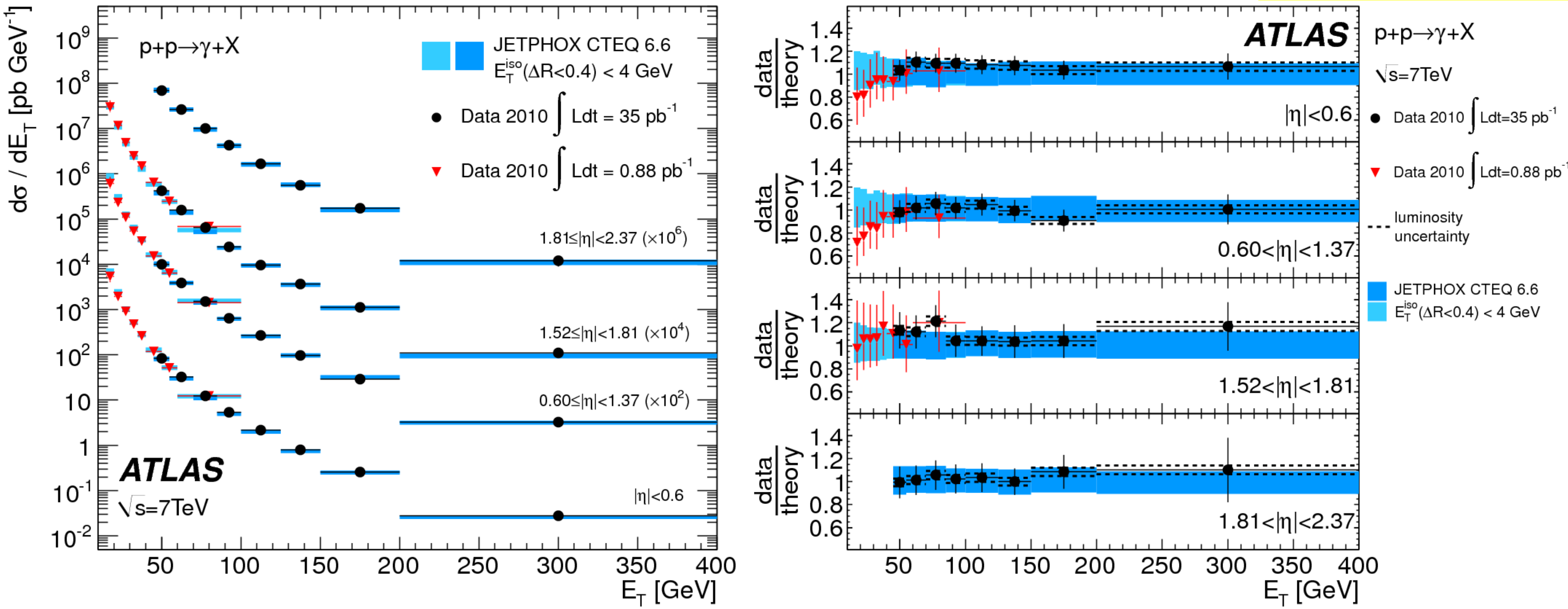
- 880 nb^{-1} analysis (Phys. Rev. D 83, 052005 (2011): from 15 GeV to 100 GeV, 3 eta bins [0.00, 0.60), [0.60, 1.37), [1.52,1.81)
- 37 pb^{-1} analysis (Phys. Lett B706, 150(2011), from 45 GeV to 400 GeV, 4 eta bins bins [0.00, 0.60), [0.60, 1.37), [1.52,1.81), [1.81,2.37). See also ATL-PHYS-PUB-2011-013

- Measured cross section additional systematic uncertanties:
  - Photon energy scale systematic uncertainty : 3% (leading to 10% on the cross section) in the 880 nb^{-1} analysis and 1.5% (leading to 5% on the cross section)
  - Bin to bin unfolding vs SVD or iterative (Bayesian) < 2% difference
  - Luminosity uncertainty 11% down to 3.5%

- Theoretical predictions obtained with JETPHOX (NLO montecarlo which includes a consistent treatment of the fragmentation) using CTEQ6.6 (MSTW 2008/NNPDF2.0 3-5% difference).
  - (parton) isolation in 0.4 cone set to 4 GeV
  - Systematic uncertainties evaluated by varying PDF eigenvalues (4% to 2%), varying scales from $P_T^{\gamma}/2$ to $2*P_T^{\gamma}$ (20% to 8%), parton isolation cut varied from 2 to 6 GeV (2%)

Phys.Rev.D 83,052005(2011)
Phys.Lett.B706 150(2011)
ATL-PHYS-PUB-2011-013

Inclusive photon cross section



Results systematically limited across full E_T^{γ} range

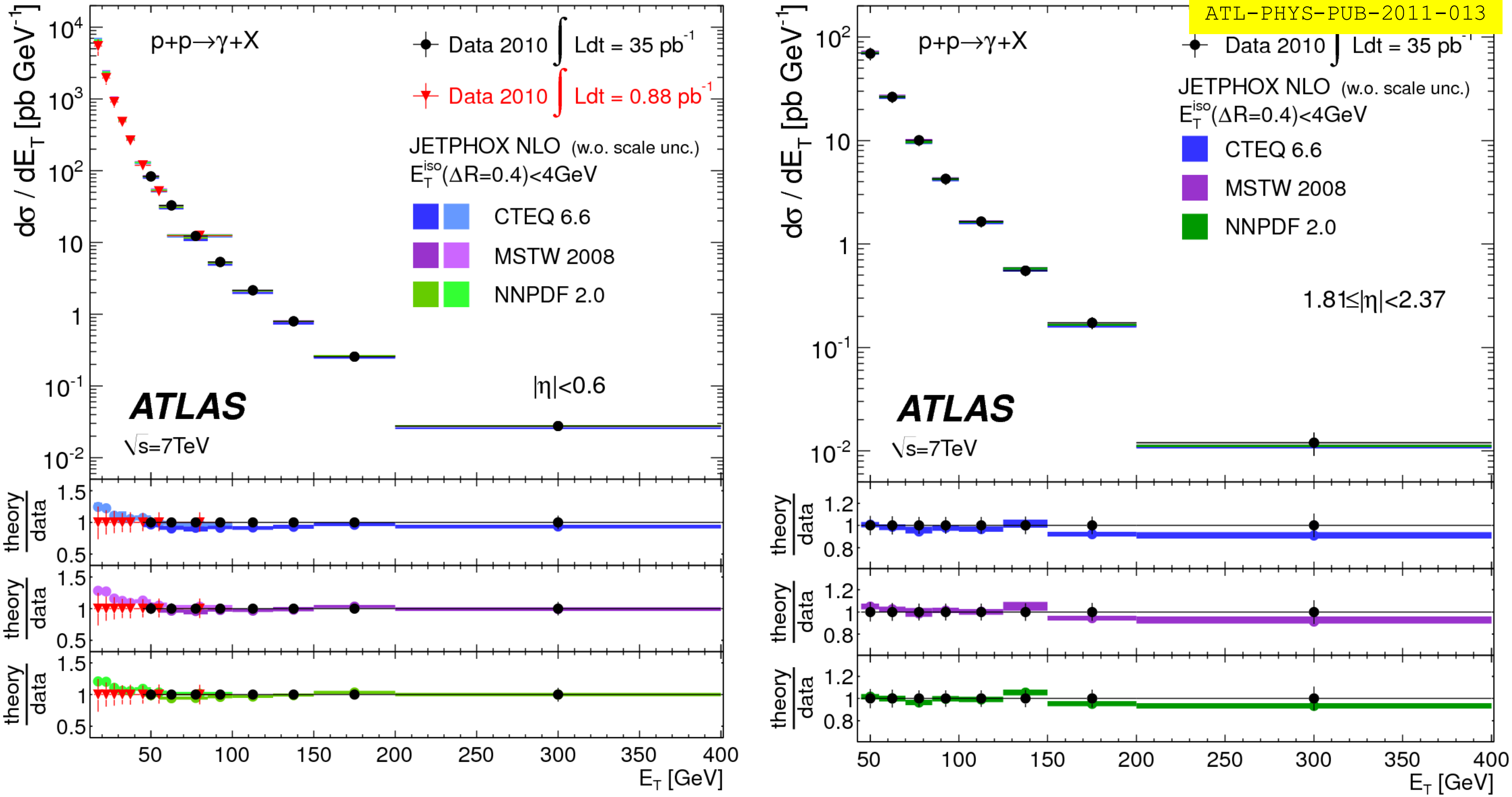
- ❑ The two measurements are consistent in the overlapping ET, η bins
- ❑ Data/(NLO pQCD) comparison:
  - ❑ experimental uncertainty comparable to theoretical one
  - ❑ disagreement (ratio data/theory<1) below 35 GeV for central photons, good agreement above
  - ❑ similar trend with other PDF sets (MSTW2008, NNPDF2.0)

Inclusive photon cross section

Phys.Rev.D 83,052005(2011)

Phys.Lett.B706 150(2011)

ATL-PHYS-PUB-2011-013



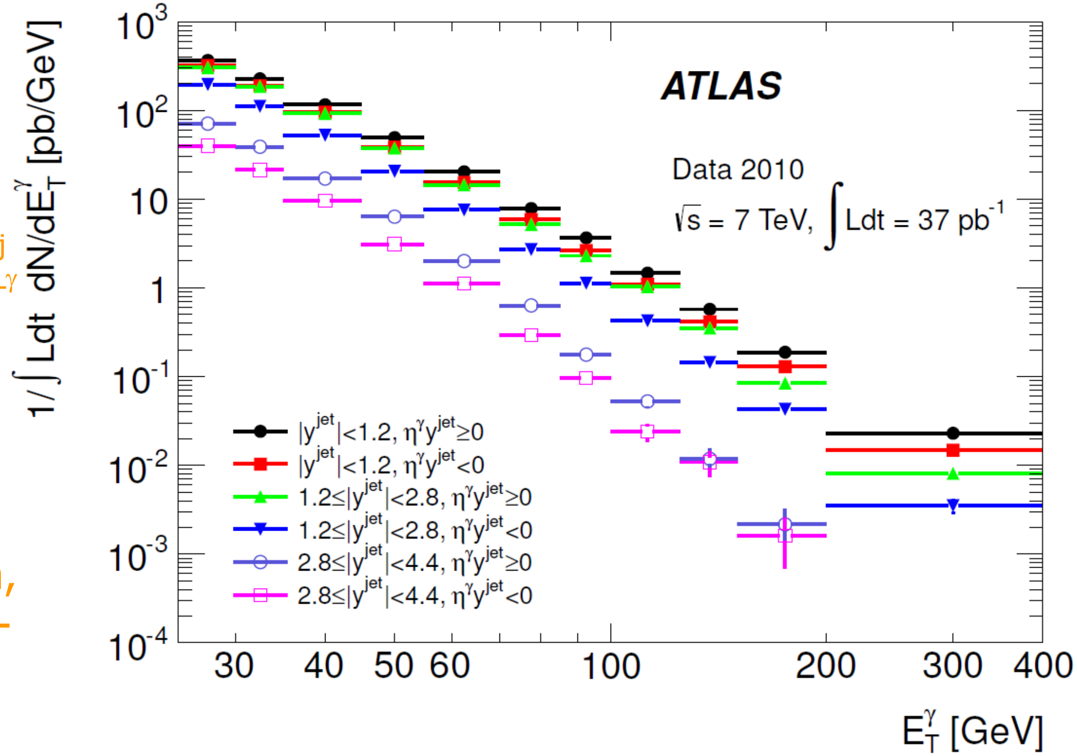
Photon+jet cross section

Phys.Rev.D 85,092014(2012)

Same ingredients for photons as for the inclusive analysis : based on 2010 data (37 pb^{-1})

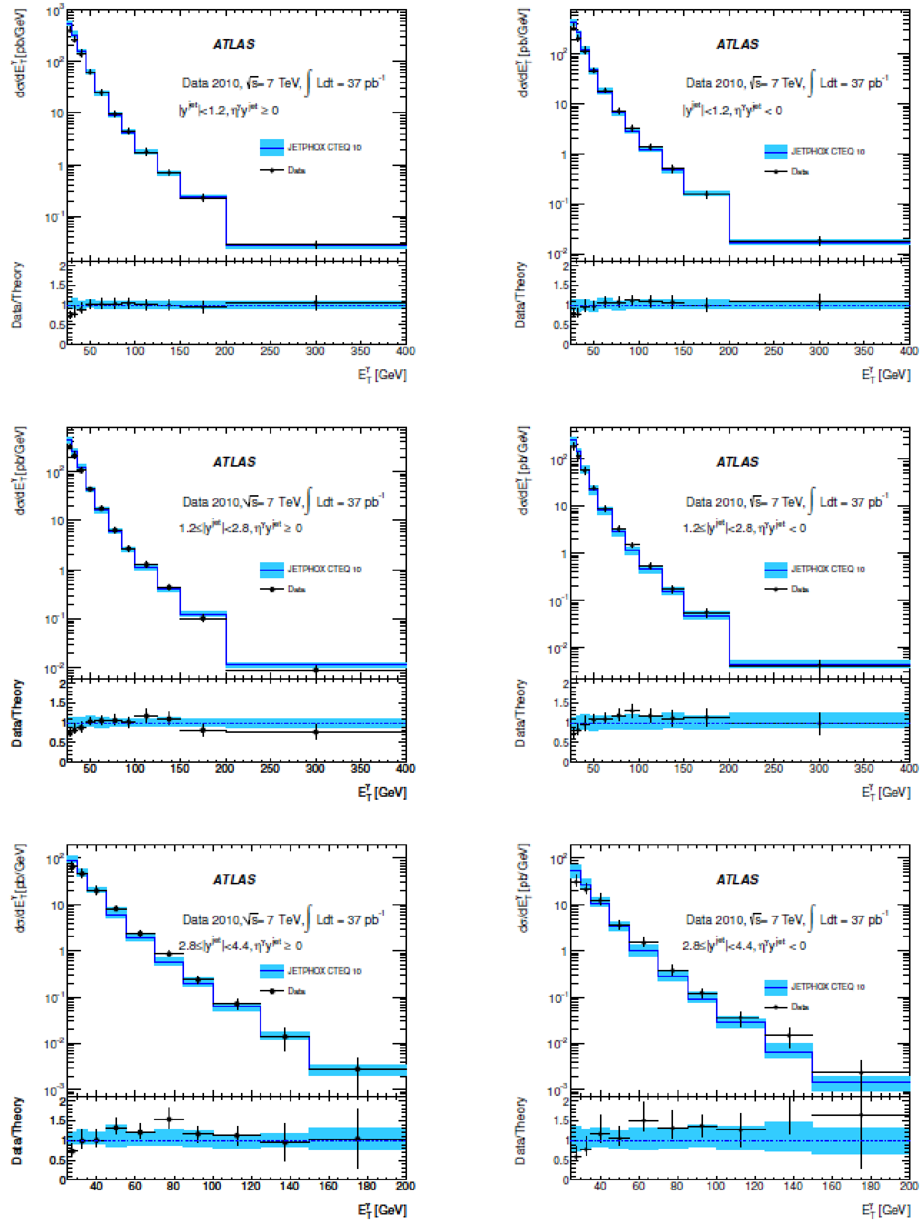
❑ The photon-jet correlations give additional information on fragmentation component :

- ❑ central photons ($|\eta_\gamma|< 1.37$) and 3 jet rapidity bins : $|y_j|<1.2$ (central) , $1.2\leq|y_j|<2.8$ (forward) and $2.8 \leq |y_j|<4.4$ (very forward).
- ❑ Same sign ($\eta_\gamma y_j \geq 0$) and opposite sign ($\eta_\gamma y_j <0$) cross sections measured separately vs E_T^γ (inspired by D0 - Phys.Lett.B666:435-445,2008)
- ❑ use anti-K_T (R=0.4) jets with P_T^j>20 GeV
- ❑ Experimental systematic uncertainty 15%-8% in the central jet same-sign configuration, 40% to 22% in the very forward jet opposite-sign case



Photon+jet cross section

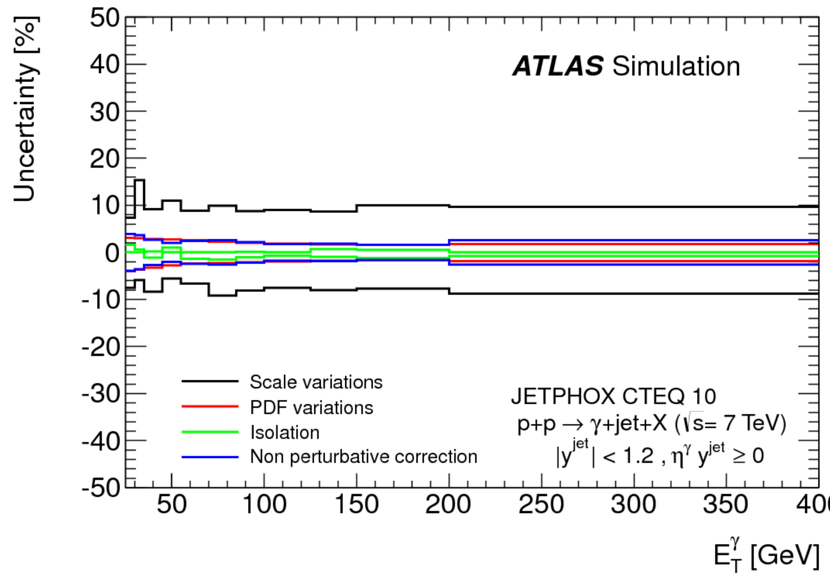
- ❑ Theoretical predictions obtained with JETPHOX 1.3 using CTEQ10
  - ❑ isolation cut at 4 GeV in a R=0.4 cone
- ❑ Cross section corrected for non pert. effects :
  - ❑ ~0.9 at low E_T^{γ} rapidly reaching 1.
- ❑ Systematic uncertainties :
  - ❑ varying scales incoherently from $E_T^{\gamma}/2$ to $2E_T^{\gamma}$, 10% up to 40% (jet very forward)
  - ❑ varying PDF eigenvalues within 68% confidence level intervals (5% to 10% maximum)
  - ❑ parton isolation cut varied from 3 to 5 GeV (2% to 10% with a very forward jet)
  - ❑ uncertainty on non perturbative correction (3% up to 20%) using pythia/herwig and different pythia tunes.
- ❑ Also used MSTW2008 and NNPDF2.1 always within the total uncertainty

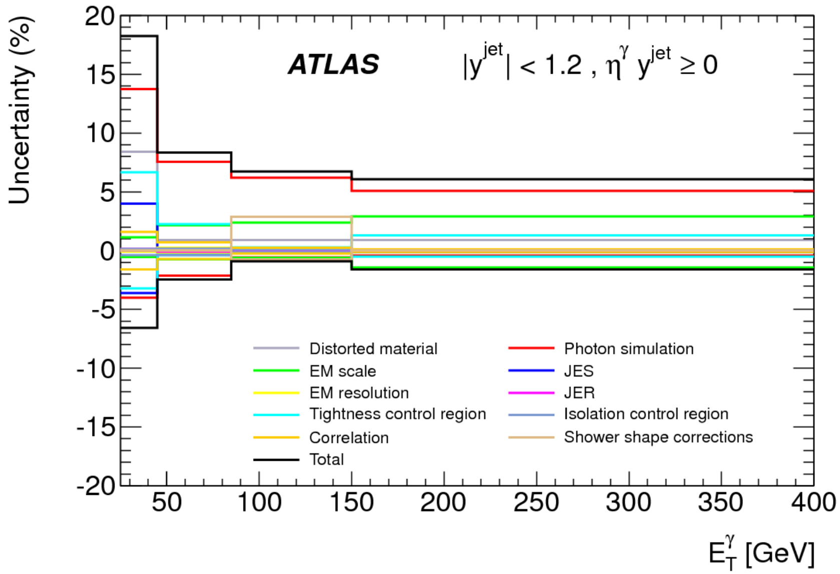


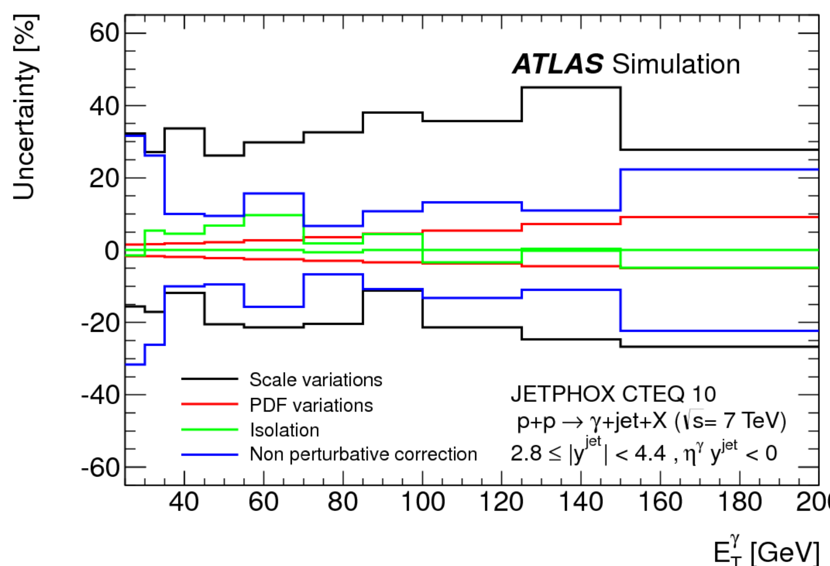
Photon+jet cross section : a closer look at systematic uncertainties

- Theoretical systematic uncertainties dominated by scale variations in all configurations

- The photon simulation (mainly isolation) is playing a sizeable role in assessing the experimental systematic uncertainties



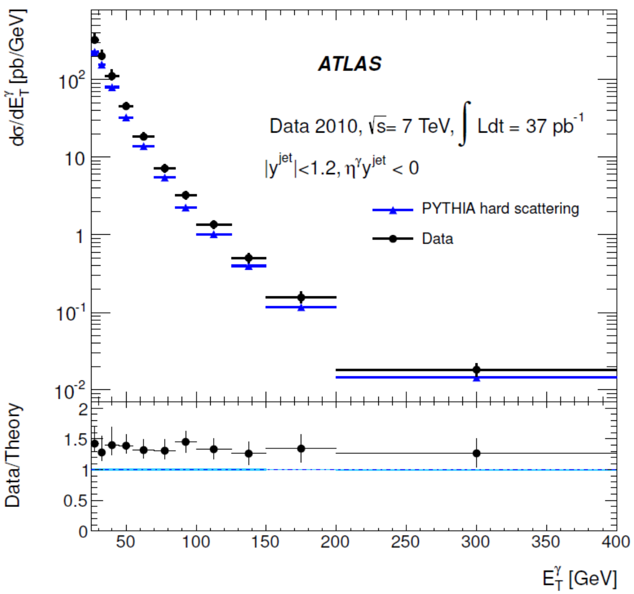


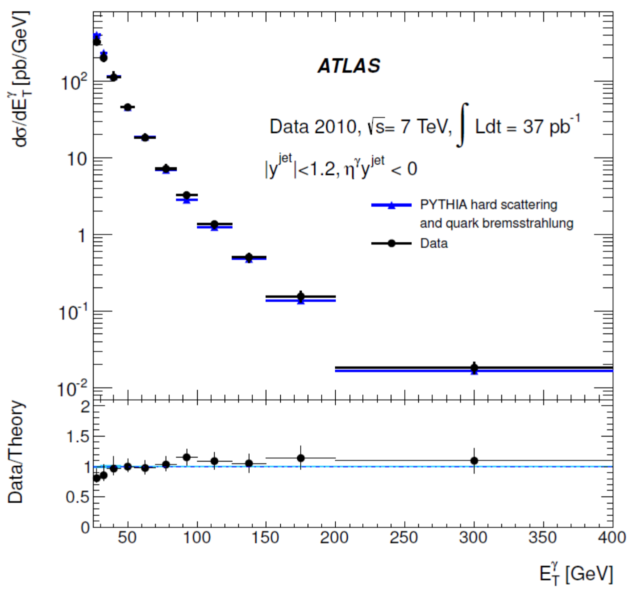


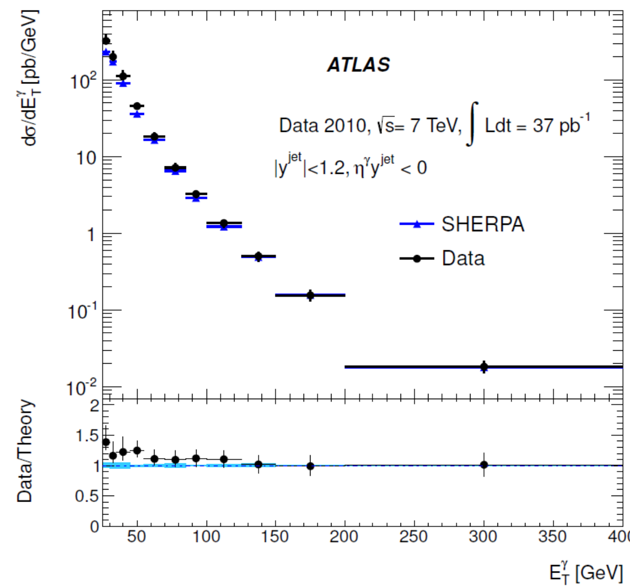
Photon+jet cross section

The main full event generators used in ATLAS has been stressed comparing the predictions in the different configurations against data (errors are statistical only) :

- ❑ pure hard scattering photons (qg->qgamma + qqbar->ggamma) in PYTHIA 6
- ❑ hard scattering + brem photons (from quark radiation in QCD 2->2) in PYTHIA 6
- ❑ Sherpa





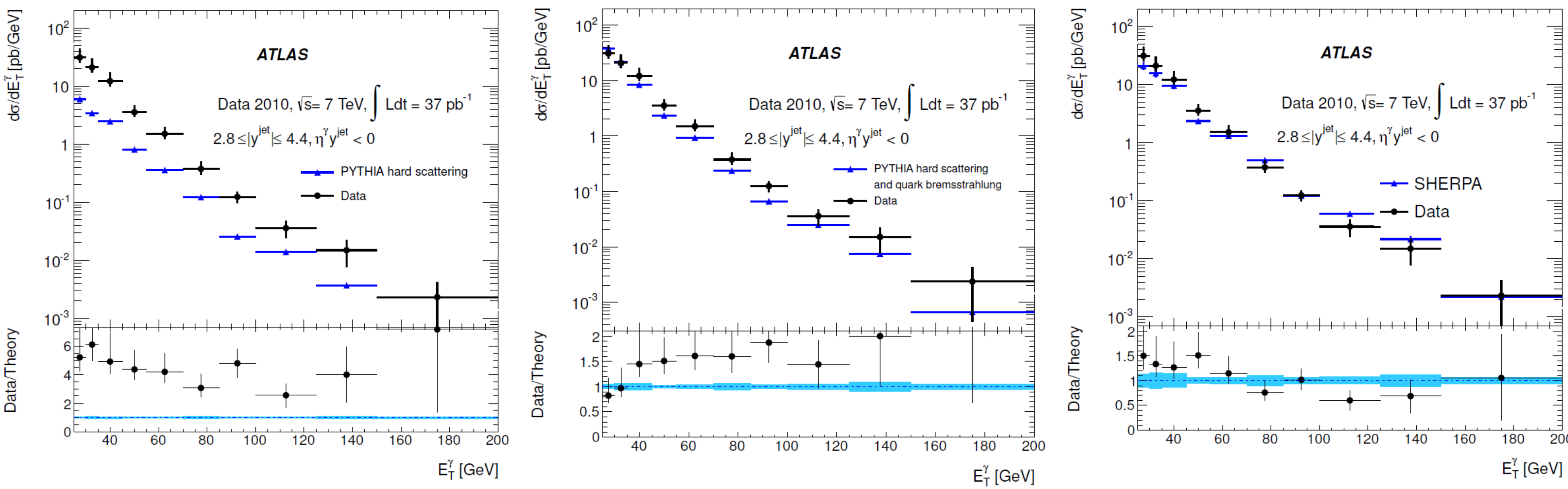


- ❑ Pure hard scattering sample is clearly missing the fragmentation component (central jet, opposite-side configuration)
- ❑ Good agreement with PYTHIA6 hard+brem photons and SHERPA

Photon+jet cross section

❑ The trend in the previous slide is even more visible when looking at the very forward jet, opposite side configuration where the fragmentation contribution is larger

- ❑ pure hard scattering photons sample in PYTHIA 6 is unreliable
- ❑ hard scattering + brem photons in PYTHIA 6 is not working properly in this ‘extreme’ configuration (although better than in the previous case)
- ❑ Sherpa is performing rather nicely over all configurations



Di-photon cross section : background subtraction methods

Phys. Rev. D 85, 012003(2012)

❑ 4x4 matrix : This is a technique used already by CDF and D0 :

❑ set a cut (E^T_{isol} < 3 GeV) and classify the events in 4 categories. PP/PF/FP/FF : these numbers are connected to the true number of γγ/γ-jet/jet-γ/jet-jet through an efficiency matrix E

❑ the key point here is that these efficiencies are measured on data from the tight/non-tight isolation distributions

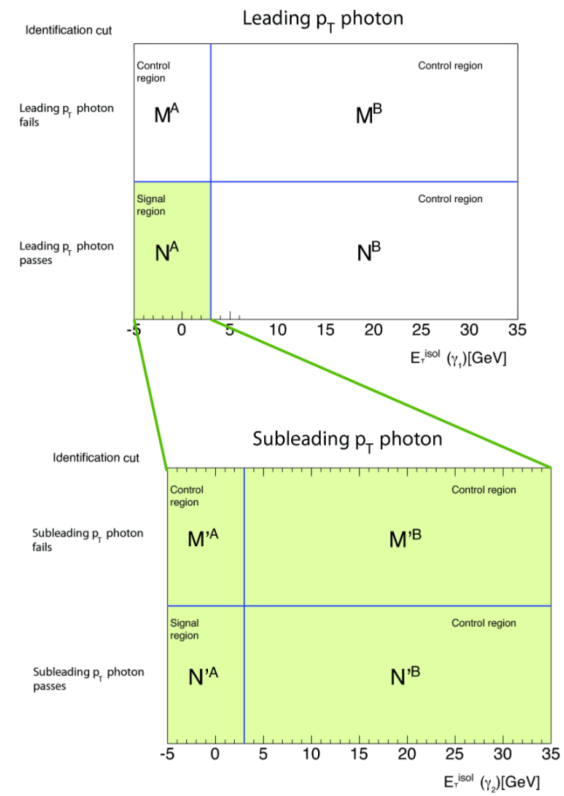
$$\begin{pmatrix} S_{\mathrm{PP}} \\ S_{\mathrm{PF}} \\ S_{\mathrm{FP}} \\ S_{\mathrm{FF}} \end{pmatrix} = \mathbf{E} \begin{pmatrix} W_{\gamma\gamma} \\ W_{\gamma\mathrm{j}} \\ W_{\mathrm{j}\gamma} \\ W_{\mathrm{jj}} \end{pmatrix}$$

❑ Extend the 2D sidebands method to the case of 2 photon candidates

❑ For events with the leading candidates in A region a second 2D matrix is used for the second candidate

❑ After a bit of algebra

$$N^{\mathbf{TITI}}_{\gamma\gamma} = \frac{\epsilon'\left(\alpha f' N^{\mathrm{sig}}_{A} + (\alpha-1)N'^{\,\mathrm{sig}}_{A}\right)}{(\alpha-1)\epsilon' + \alpha f'}$$



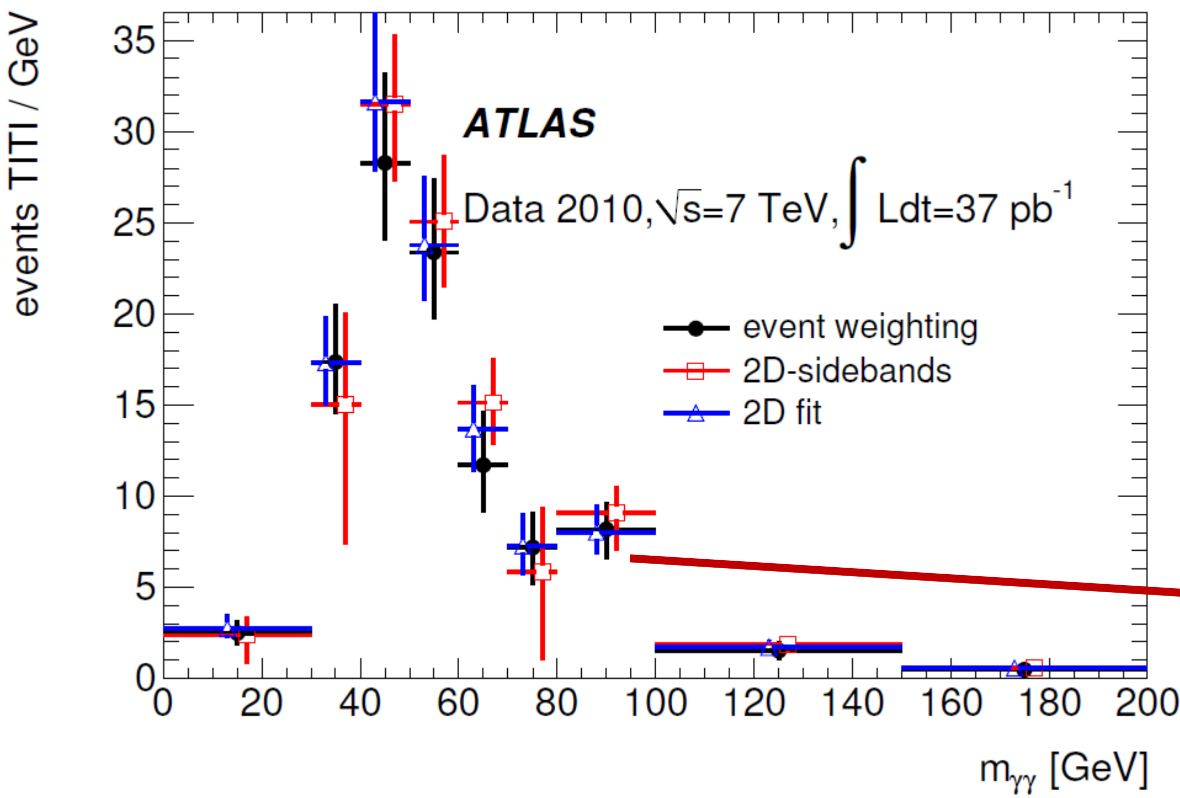
❑ 2D isolation template fits :

❑ isolation templates for γγ, γ-j and jet-jet events are built from data (using electrons and the non-tight control sample sample)

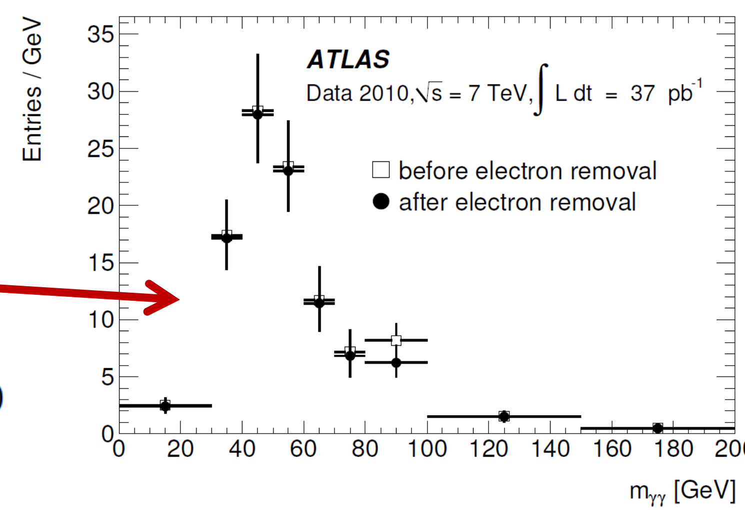
$$\begin{aligned} N^{\mathrm{TT}} F^{\mathrm{obs}}(E^{\mathrm{iso}}_{\mathrm{T},1}, E^{\mathrm{iso}}_{\mathrm{T},2}) = {} & N^{\mathrm{TT}}_{\gamma\gamma} F_{\gamma_1}(E^{\mathrm{iso}}_{\mathrm{T},1}) F_{\gamma_2}(E^{\mathrm{iso}}_{\mathrm{T},2}) \\ & + N^{\mathrm{TT}}_{\gamma\mathrm{j}} F_{\gamma_1}(E^{\mathrm{iso}}_{\mathrm{T},1}) F_{\mathrm{j}_2}(E^{\mathrm{iso}}_{\mathrm{T},2}) \\ & + N^{\mathrm{TT}}_{\mathrm{j}\gamma} F_{\mathrm{j}_1}(E^{\mathrm{iso}}_{\mathrm{T},1}) F_{\gamma_2}(E^{\mathrm{iso}}_{\mathrm{T},2}) \\ & + N^{\mathrm{TT}}_{\mathrm{jj}} F_{\mathrm{jj}}(E^{\mathrm{iso}}_{\mathrm{T},1}, E^{\mathrm{iso}}_{\mathrm{T},2}) \end{aligned}$$

Extracting the signal yield

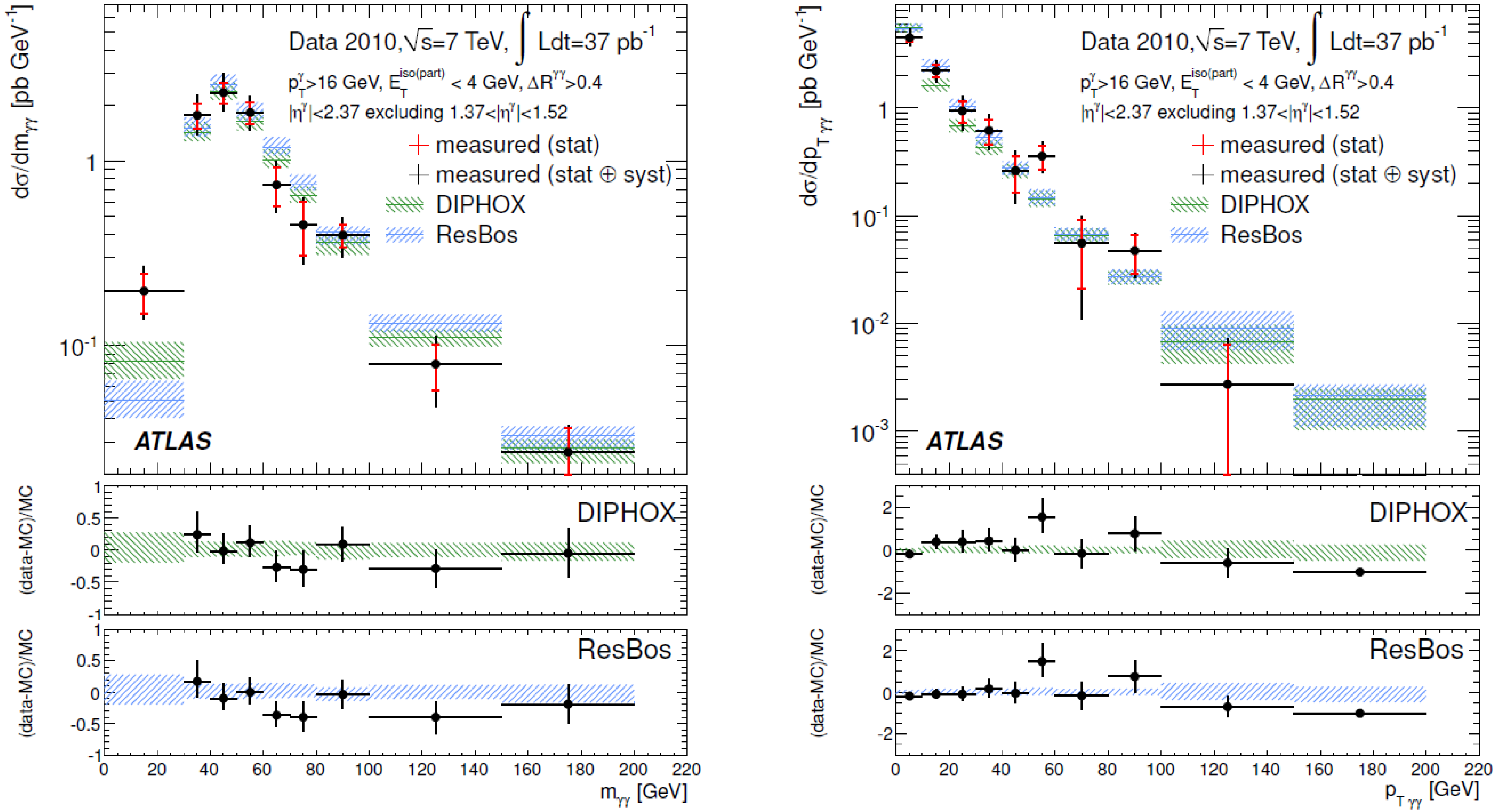
- Require two photons with $p_T^{\gamma} > 16$ GeV within acceptance ($|\eta| < 2.37$, crack excluded), tight and isolated ($E^T_{iso} < 3$ GeV)
- All three signal extraction flavours agree fairly well in extracting the signal yield with ~ comparable systematic uncertainty (~ +/- 15%)



- electron background subtracted using Zee MC + electron->gamma misidentification rate from data

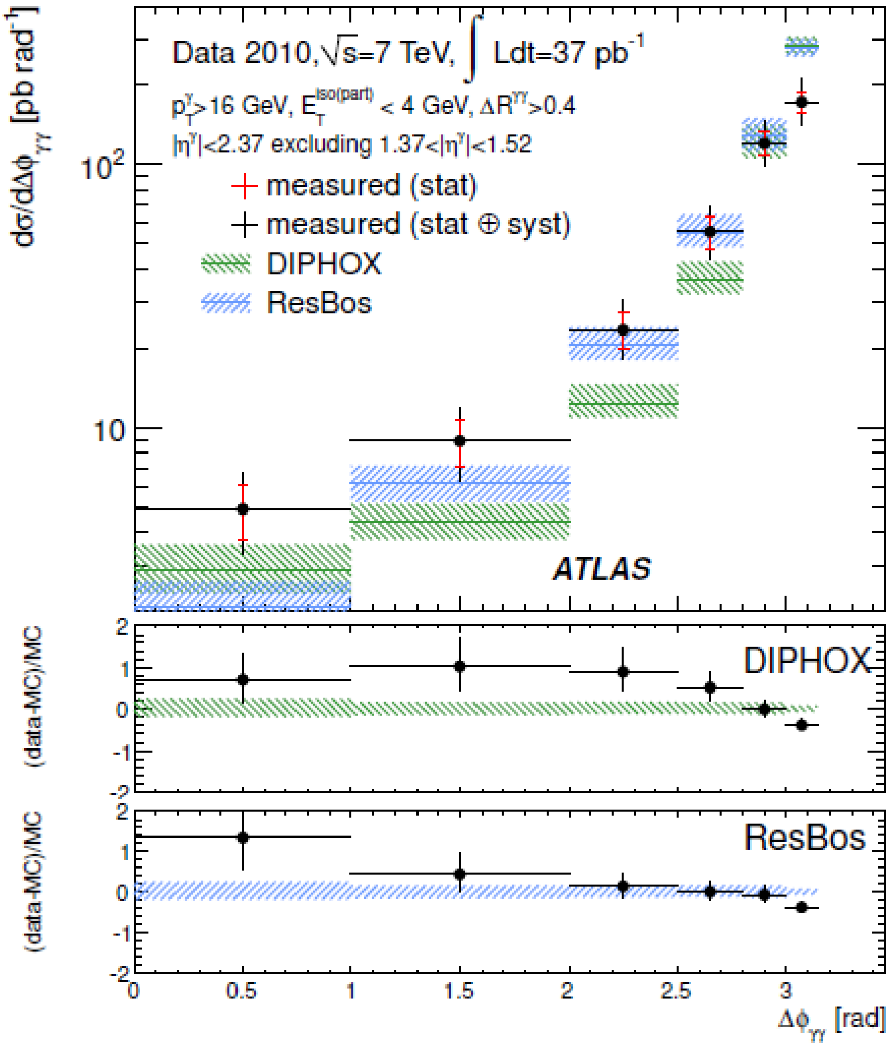


Di-photon cross sections : data / theory comparison



Rather good agreement between data and theory in $m_{\gamma\gamma}$ (except for low $m_{\gamma\gamma}$) and $p_{T\gamma\gamma}$

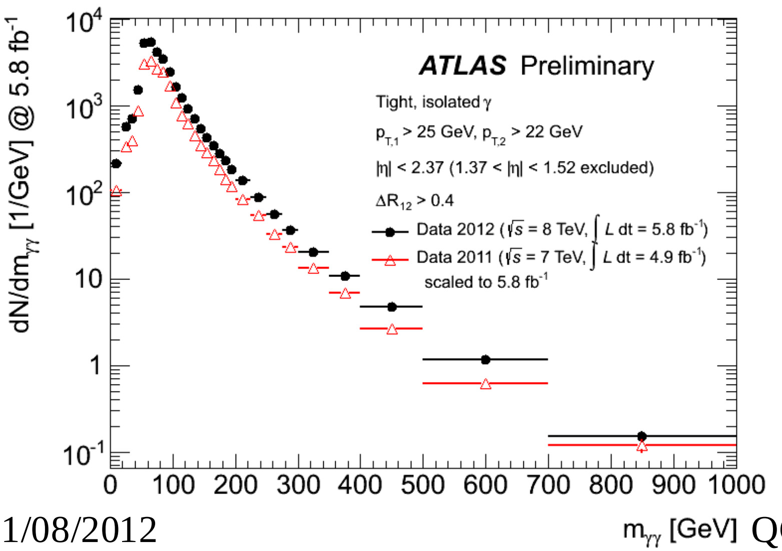
Di-photon cross sections : data / theory comparison

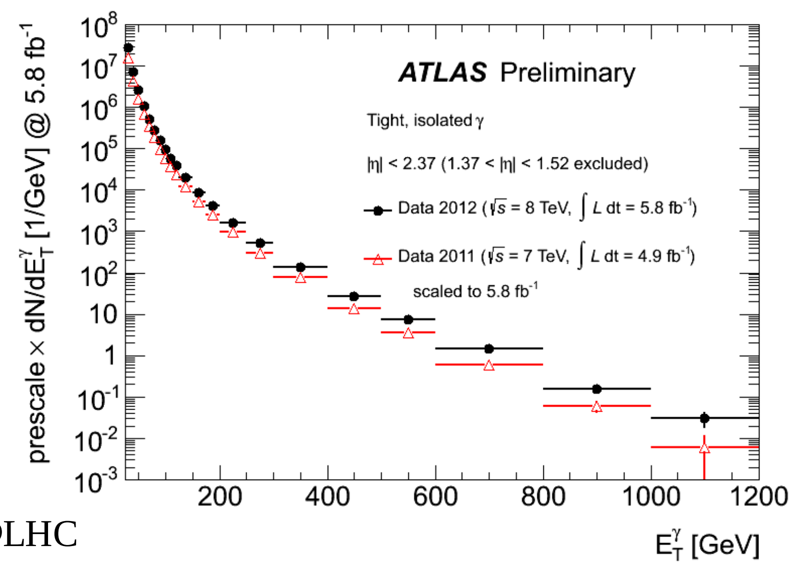


- ❑ Some disagreement especially in the low $\Delta\phi$ region (which is also the low $m_{\gamma\gamma}$ region) and $\Delta\phi \sim \pi$
- ❑ Qualitatively compatible with the measurements from CMS and Tevatron
- ❑ recent NNLO calculations fill the gap

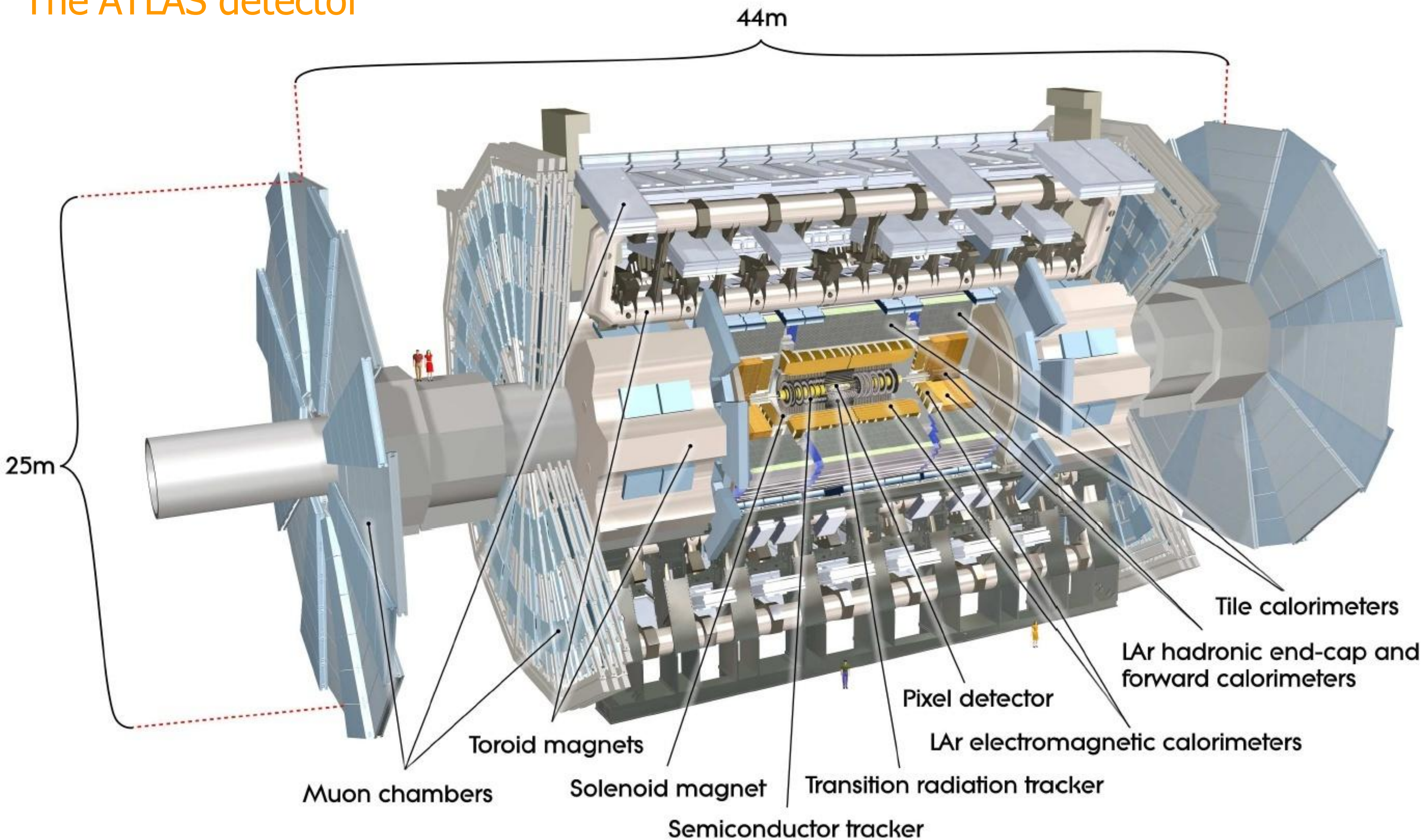
Conclusion :

- ATLAS has published a complete set of QCD photons measurements:
  - The ATLAS detector has laid solid foundations for photon physics.
- In general good agreement between measured cross sections and predictions
  - Some tensions in the low E_T^γ in inclusive and photon+jet measurement.
  - Comparisons of diphoton cross section with NNLO calculation ongoing
  - Sherpa is at the moment the best full event generator to describe photon physics
- Studies are ongoing to finalize 2011 data analyses to extend the kinematic reach and improved understanding of systematic uncertainties :
  - new diphoton and inclusive photon cross section measurements with full 2011 statistic are in the pipeline.





The ATLAS detector



Di-photon cross section : background subtraction (event weighting method)

- This is a technique used already by CDF and D0 :
  - define a cut on your photon candidates which characterize your signal : $E^T_{isol} < 3$ GeV
  - classify the di-photon events candidates in 4 categories. PP/PF/FP/FF : these numbers are related connected the true number of γγ/γ-jet/jet-γ/jet-jet by an efficiency matrix

$$\begin{pmatrix} S_{\rm PP} \\ S_{\rm PF} \\ S_{\rm FP} \\ S_{\rm FF} \end{pmatrix} = \mathbf{E} \begin{pmatrix} W_{\gamma\gamma} \\ W_{\gamma \rm j} \\ W_{\rm j\gamma} \\ W_{\rm jj} \end{pmatrix}$$

- ε and f are the probabilities for a true and fake photon respectively to pass the isolation cut. ε is typically 80 to 95% while f ~ from 20 to 40 %
- the key point here is that these efficiencies are measured on data from the tight/non-tight isolation distributions
- Actually the true efficiency matrix is a bit more complicated as there's some correlation in the FF case

$$\begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1(1-\epsilon_2) & \epsilon_1(1-f_2) & f_1(1-\epsilon_2) & f_1(1-f_2) \\ (1-\epsilon_1)\epsilon_2 & (1-\epsilon_1)f_2 & (1-f_1)\epsilon_2 & (1-f_1)f_2 \\ (1-\epsilon_1)(1-\epsilon_2) & (1-\epsilon_1)(1-f_2) & (1-f_1)(1-\epsilon_2) & (1-f_1)(1-f_2) \end{pmatrix}$$

Di-photon cross section : background subtraction (2D sidebands extension)

Extend the 2D sidebands method to the case of 2 photon candidates :

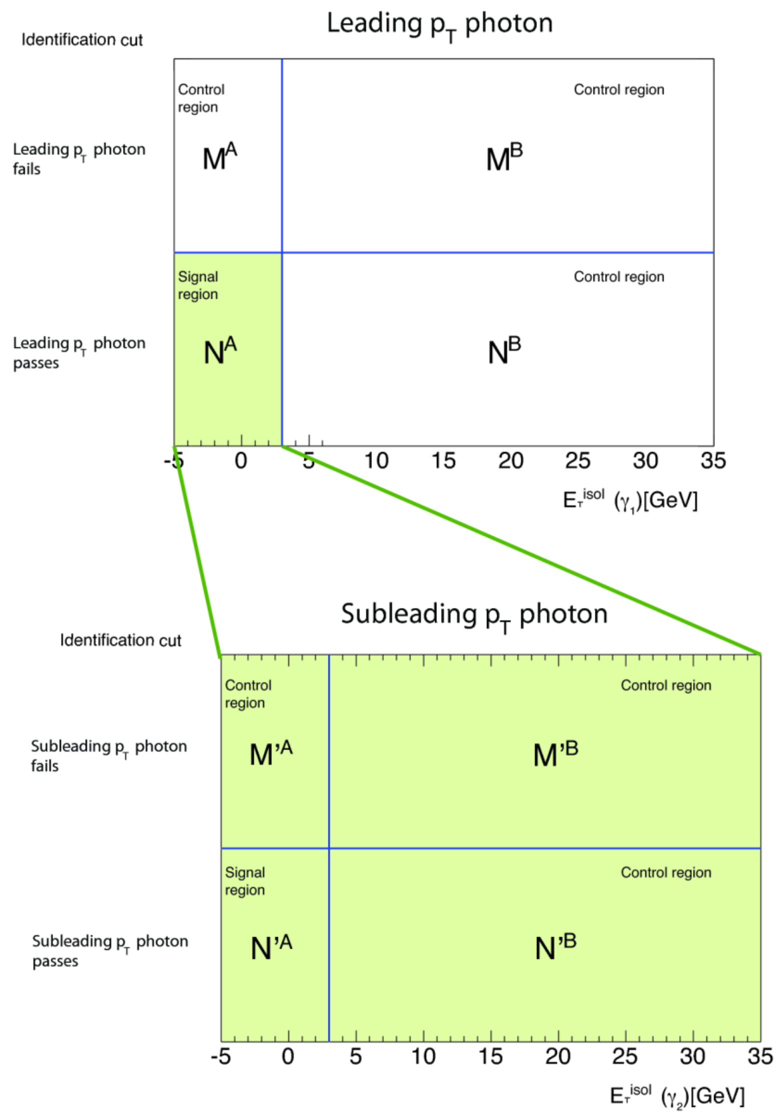
- preselect events with 2 candidates passing a loose photon definition.
- As for the inclusive analysis the number of signal candidates in region A of the first matrix is

$$N_A^{\mathrm{sig}} = N_A - \left[(N_B - c_1 N_A^{\mathrm{sig}}) \frac{N_C - c_2 N_A^{\mathrm{sig}}}{N_D - c_1 c_2 N_A^{\mathrm{sig}}} \right] R^{\mathrm{bkg}}$$

- For events with the leading candidates in A region a second 2D matrix is used for the second candidate
- After a bit of algebra

$$N_{\gamma\gamma}^{\mathbf{TITI}} = \frac{\epsilon' \left(\alpha f' N_A^{\mathrm{sig}} + (\alpha - 1) {N'}_A^{\mathrm{sig}} \right)}{(\alpha - 1)\epsilon' + \alpha f'}$$

(α has to be taken from MC while the other parameters from data)



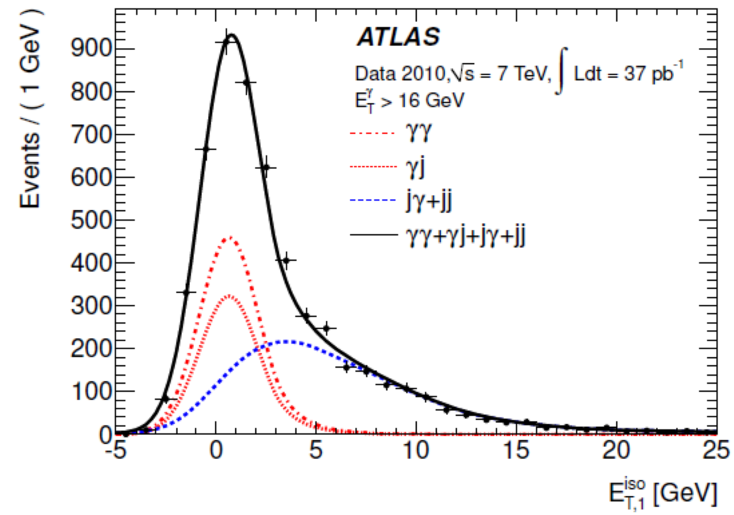
Di-photon cross section : background subtraction (2D isolation template fit)

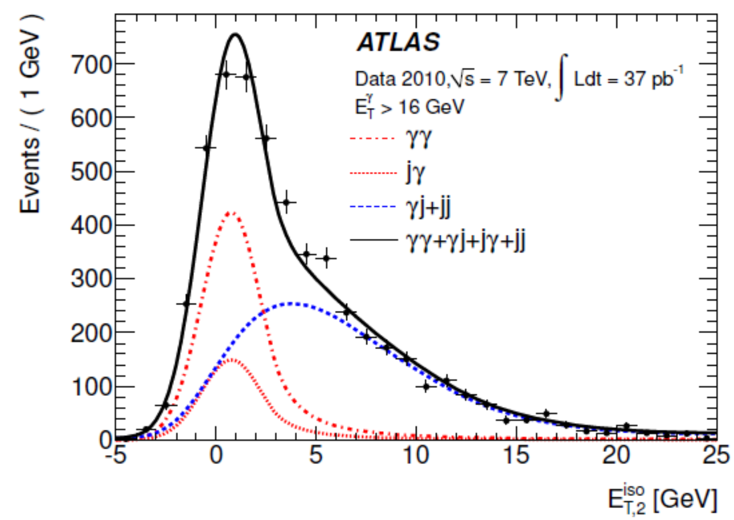
For all events with 2 photon candidates passing the tight isolation criteria

- ❑ isolation templates for γγ, γ-j and jet-jet events are built from data (using electrons and the non-tight sample)
- ❑ the 2D distribution of the leading and subleading photon is built
- ❑ the sample decomposition comes from a maximum likelihood fit

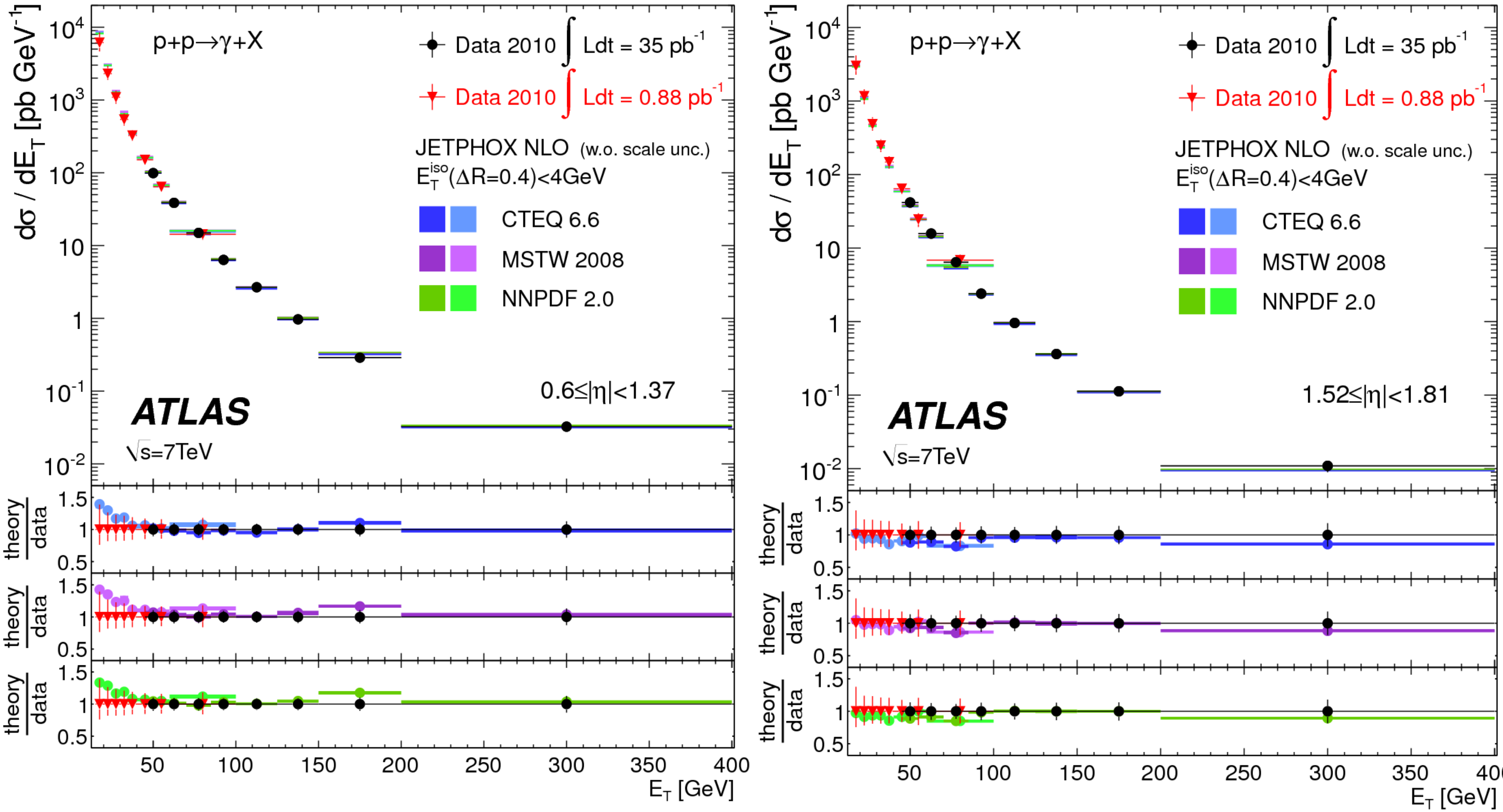
$$
\begin{aligned}
N^{\mathbf{TT}} F^{\mathrm{obs}}(E_{\mathrm{T},1}^{\mathrm{iso}}, E_{\mathrm{T},2}^{\mathrm{iso}}) = & \; N_{\gamma\gamma}^{\mathbf{TT}} F_{\gamma_1}(E_{\mathrm{T},1}^{\mathrm{iso}}) F_{\gamma_2}(E_{\mathrm{T},2}^{\mathrm{iso}}) \\
& + N_{\gamma \mathrm{j}}^{\mathbf{TT}} F_{\gamma_1}(E_{\mathrm{T},1}^{\mathrm{iso}}) F_{\mathrm{j}_2}(E_{\mathrm{T},2}^{\mathrm{iso}}) \\
& + N_{\mathrm{j}\gamma}^{\mathbf{TT}} F_{\mathrm{j}_1}(E_{\mathrm{T},1}^{\mathrm{iso}}) F_{\gamma_2}(E_{\mathrm{T},2}^{\mathrm{iso}}) \\
& + N_{\mathrm{jj}}^{\mathbf{TT}} F_{\mathrm{jj}}(E_{\mathrm{T},1}^{\mathrm{iso}}, E_{\mathrm{T},2}^{\mathrm{iso}})
\end{aligned}
$$

- ❑ due to correlations the jet-jet case can't be factorized

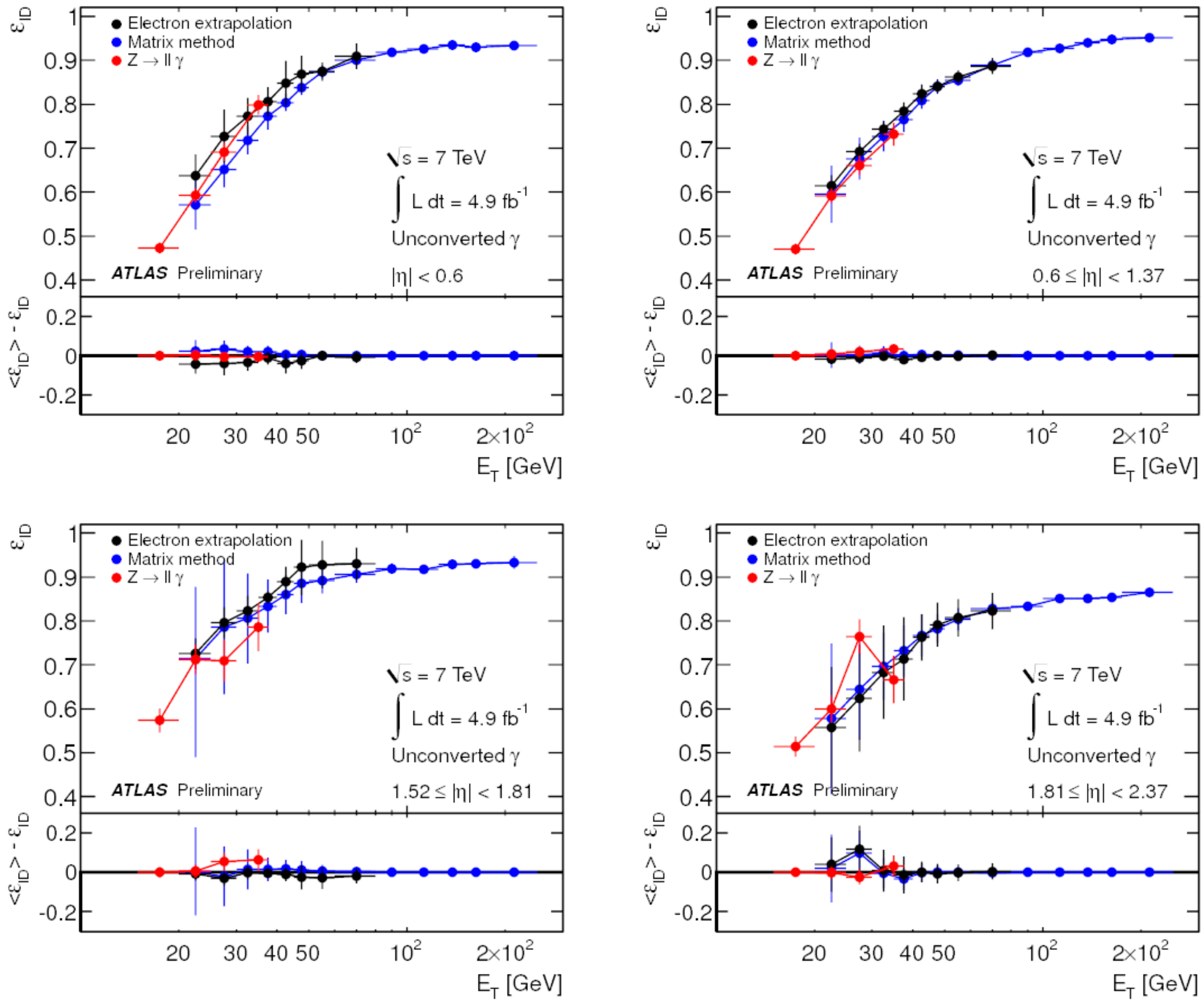




Inclusive photon cross section (backup)



Data driven photon efficiency measurements



Data driven photon efficiency measurements