25th International Workshop on
Deep Inelastic Scattering and
Related Topics (DIS2017)
April 3-7, 2017 (Birmingham, UK)

# Recent photon results from ATLAS

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**Outline:**

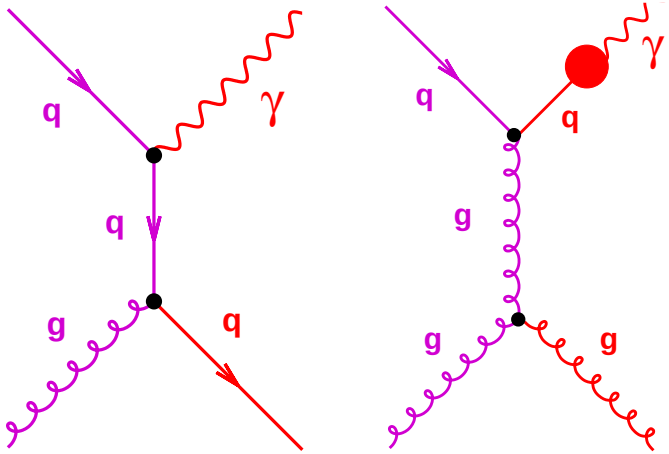
- Physics with photons
- Photons with the ATLAS detector
- Inclusive photon production
- Photon pair production
- Summary

# Prompt photons in $pp$ collisions at LHC

- **Measurements of the production of high $p_T$ prompt photons and pairs of photons in hadron colliders provide**

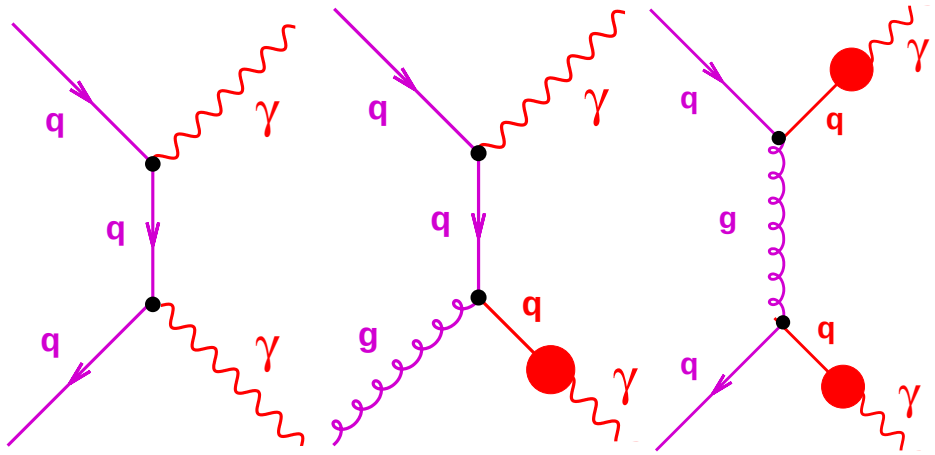
  $\rightarrow$ **tests of pQCD predictions in a cleaner reaction than jet production**
  $\rightarrow$ **constraints on the proton PDFs (especially gluon PDF: $qg \rightarrow q\gamma$ dominant)**
  $\rightarrow$ **input to understand QCD background to Higgs production and BSM searches (tuning of Monte Carlo models)**

- **Prompt photons in $pp$ collisions are produced via two mechanisms:**
  $\rightarrow$ **direct-photon (DP) and fragmentation (F) processes**




**Prompt photon production**

$pp \longrightarrow \gamma + X$



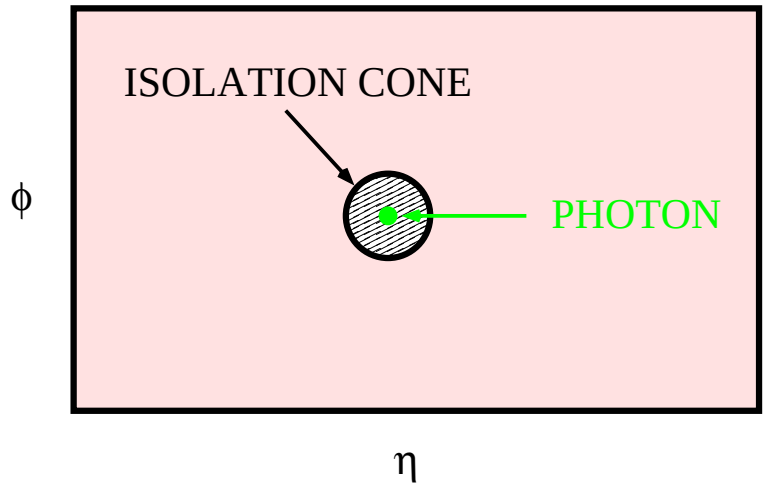

**Diphoton production**

$pp \longrightarrow \gamma\gamma + X$

# Prompt photons in $pp$ collisions: isolation

- In addition to prompt photons, photons are produced copiously inside jets (eg, $\pi^0$ decays)
  $\Rightarrow$ it is essential to require isolation to study prompt photons in hadron colliders

- This is achieved by requiring, eg
  $$E_{\mathrm{T}}^{\mathrm{iso}} \equiv \sum_i E_T^i < E_T^{\mathrm{max}}$$
  with the sum over the particles (except the photon) inside a cone of radius $R$ centered on the photon in the $\eta - \phi$ plane

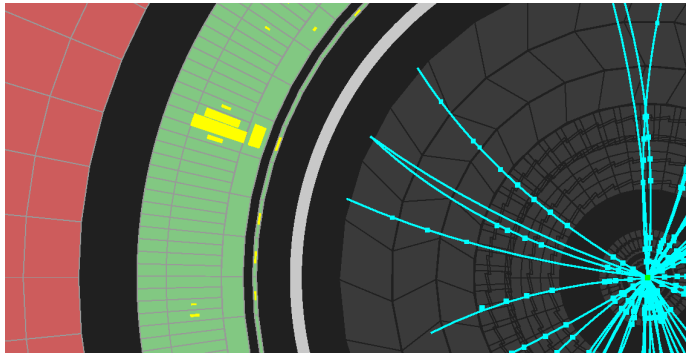



- The isolation requirement suppresses mostly the contribution of photons inside jets (from $\pi^0$'s and other neutral mesons decays) and the fragmentation contribution

# Photons with the ATLAS detector

# Photon reconstruction and identification in ATLAS LAr Calorimeter

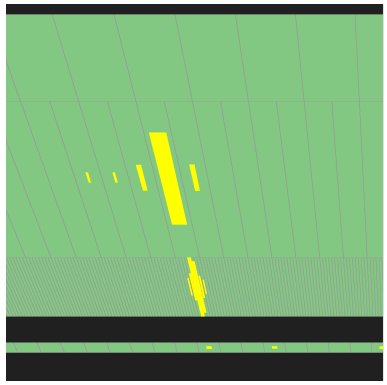
- **Reconstruction:**
  - **First layer: high granularity in $\eta$ direction**
  - **Second layer: collects most of the energy**
  - **Third layer: used to correct for leakage**

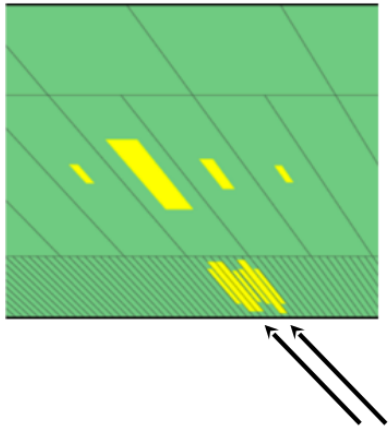


- **Cluster of EM cells without matching track: "unconverted" photon candidate**
- **Cluster of EM cells matched to a pair of tracks*: "converted" photon candidate**

(* or single track from conversion vertex)

- **Identification:**
  - **To discriminate signal vs background: shape variables from the lateral and longitudinal energy profiles of the shower in the calorimeters; "loose" (including leakage in hadronic calorimeter and width of shower) and "tight" (to discriminate single-photon showers from overlapping nearby showers) identification criteria are defined**





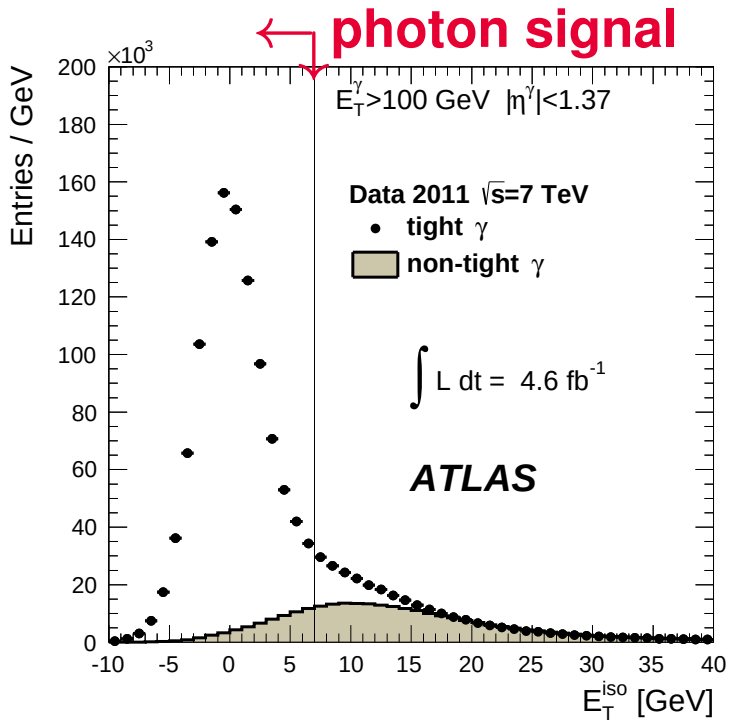
(ATLAS Collab, PRD 83 (2011) 052005)

- **Efficiency: $97\ (85)\%$ for loose (tight) photons with $E_{\mathrm{T}}^{\gamma} > 20$ GeV**

$\pi^0 \to \gamma\gamma$

# Photon isolation and background subtraction in ATLAS

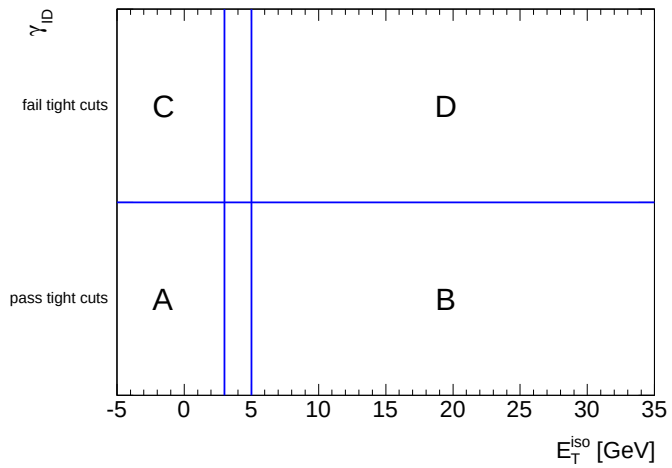
- $E_{\mathrm{T}}^{\mathrm{iso}}$ is computed using topological clusters (EM and HAD) in a cone of $R=0.4$, excluding the contribution from the photon
- The leakage of the photon energy is subtracted (few $\%$)
- The underlying event and pileup contribute to $E_{\mathrm{T}}^{\mathrm{iso}}$
  $\rightarrow$ event-by-event correction computed using the jet-area method
  (M Cacciari et al, JHEP 0804 (2008) 005)
- After these corrections, the $E_{\mathrm{T}}^{\mathrm{iso}}$ distribution is centered at zero
- A photon candidate is considered isolated if
  $$E_{\mathrm{T}}^{\mathrm{iso}} < (E_{\mathrm{T}}^{\mathrm{iso}})^{\mathrm{cut}}$$
- Clear signal of photon production observed
- However, even after tight identification and isolation requirements, residual background still expected



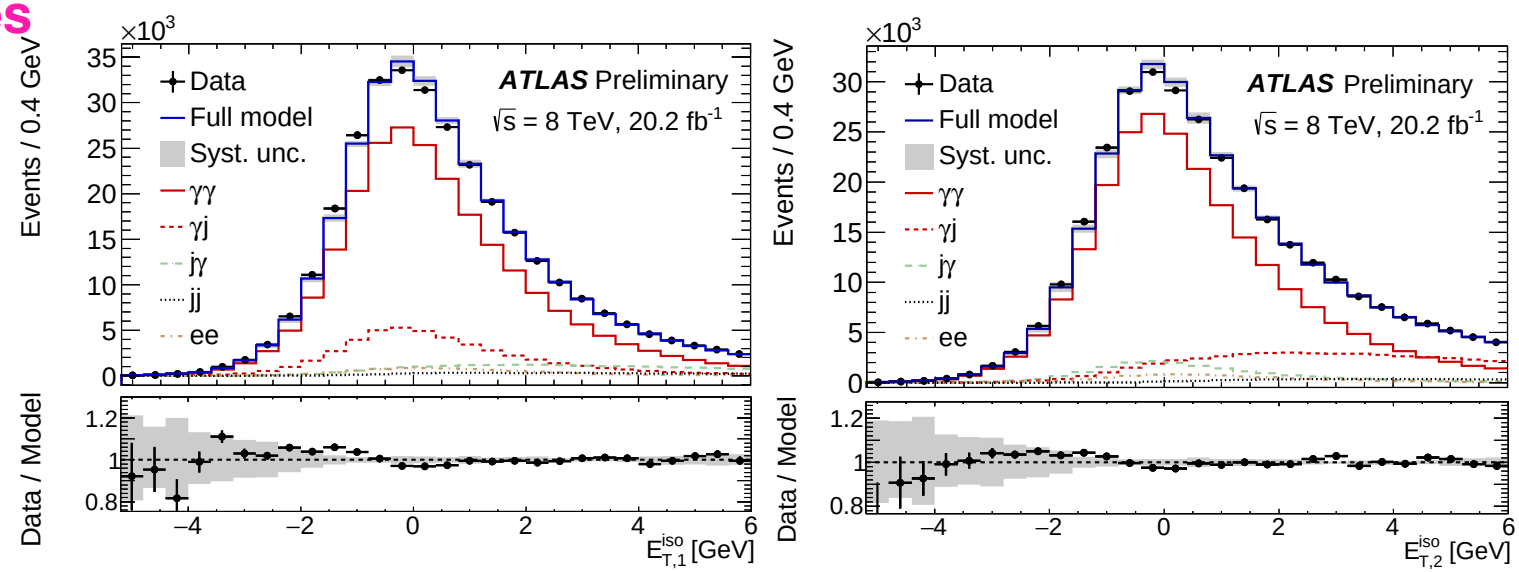

(ATLAS Collab, PRD 83 (2011) 052005)

# Photon isolation and background subtraction in ATLAS

- For inclusive photons, the main source of background is jets misidentified as photons
- A data-driven method used to avoid relying on detailed simulations of the background processes:
  $\rightarrow$ two-dimensional sideband method based on $\gamma_{ID}$ vs $E_{\mathrm{T}}^{\mathrm{iso}}$ plane and corrected for signal leakage




- For photon pairs, the main sources of background are $\gamma + \mathrm{jet}$, dijets and Drell-Yan processes
- A two-dimensional template fit was used to subtract the background, including the correlation in $E_{\mathrm{T}}^{\mathrm{iso}}$ of both photons

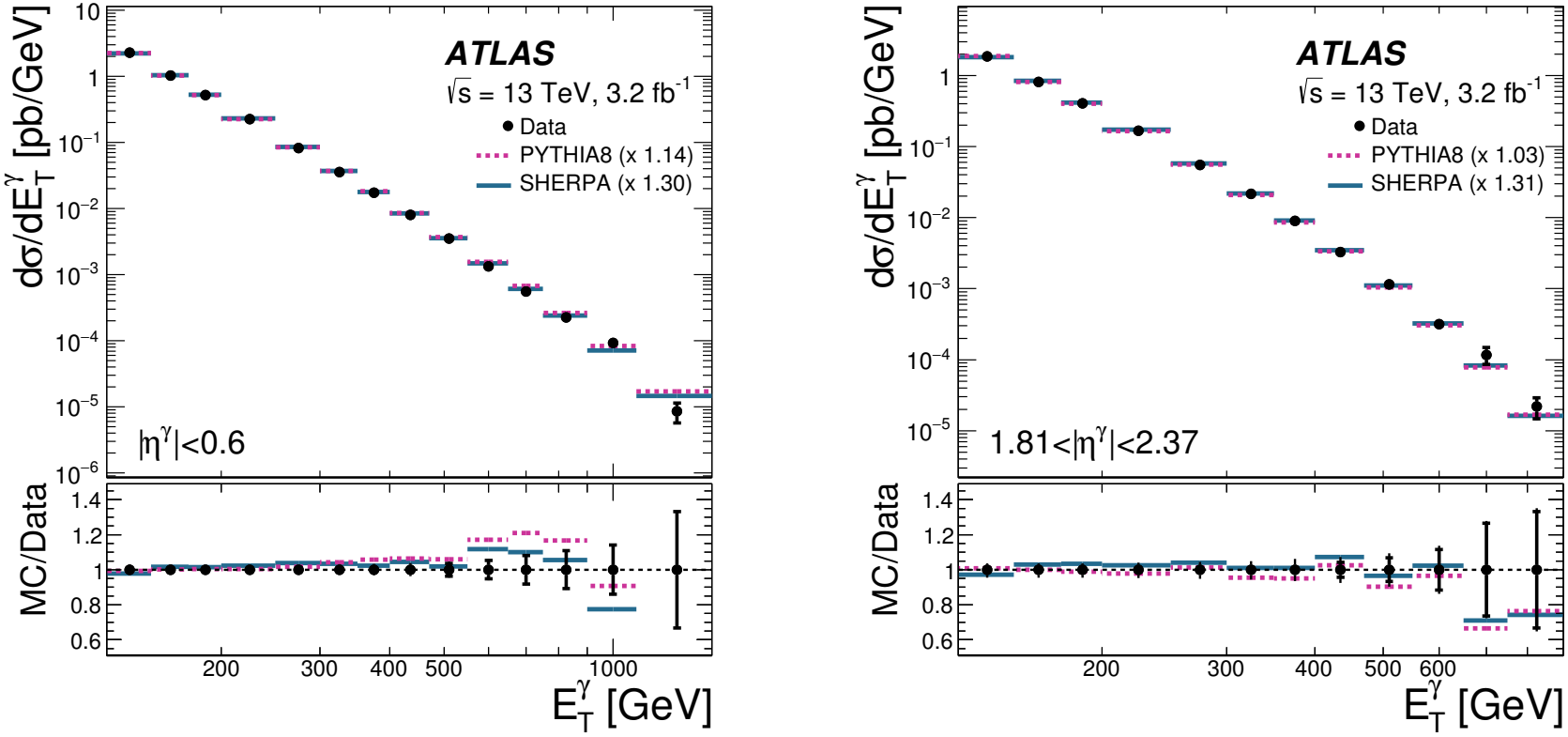



ATLAS Collab, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-15 (preliminary)

# Inclusive photon production

# Inclusive isolated photons @ 13 TeV ($\mathcal{L} = 3.2$ fb$^{-1}$)

- **Photon selection:** $E_T^\gamma > 125$ **GeV and** $|\eta^\gamma| < 2.37$**, excluding the region** $1.37 < |\eta^\gamma| < 1.56$
- **Photon isolation:** $E_T^{iso} < 0.0042 \times E_T^\gamma + 4.8$ **GeV; signal purity:** $> 90\%$ **for** $E_T^\gamma > 125$ **GeV**

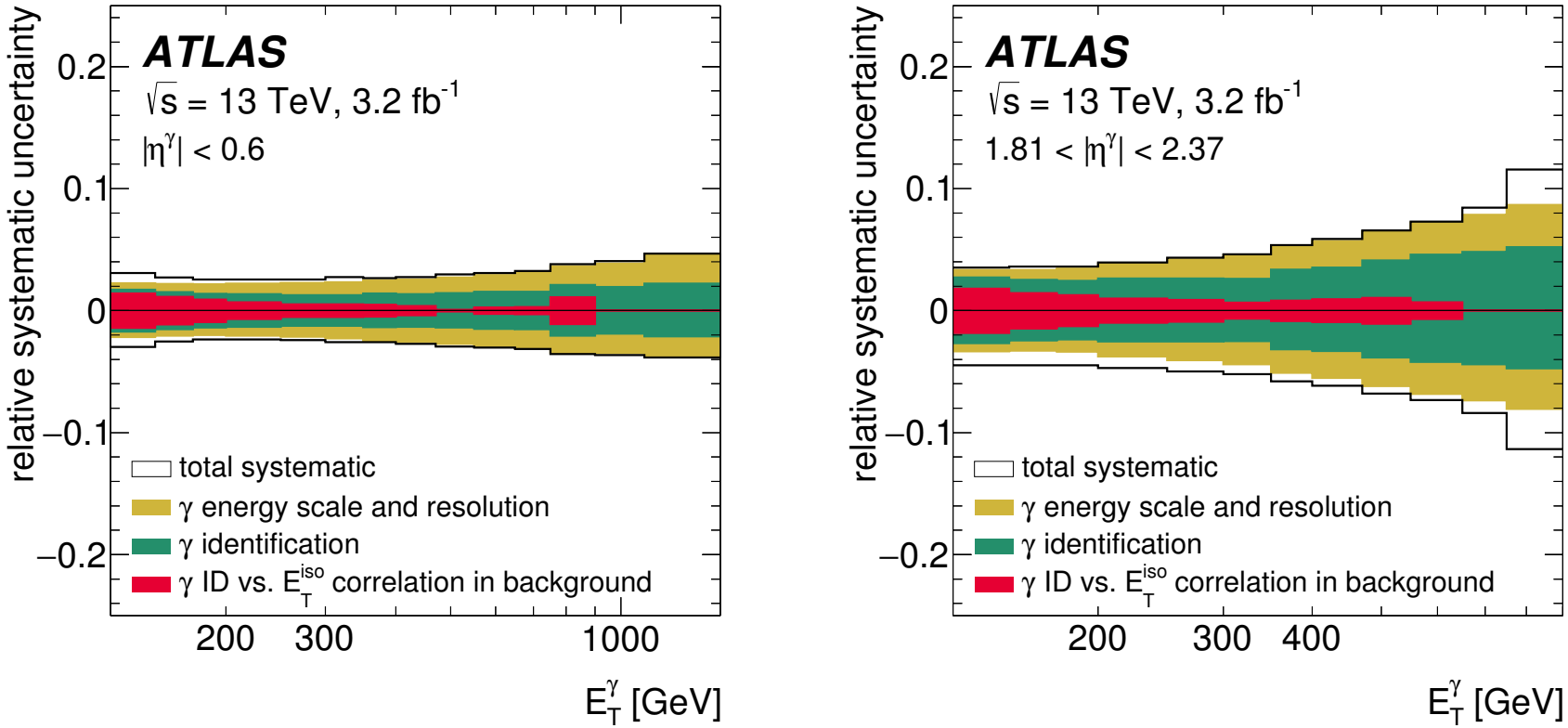



- **Comparison to tree-level MC predictions:**
  - $\rightarrow$ **PYTHIA:** $2 \rightarrow 2$ **in ME, with QCD and QED radiation in parton shower**
  - $\rightarrow$ **SHERPA: up to four additional partons in ME, with QCD parton shower**
  - $\Rightarrow$ **Good description of data by PYTHIA and SHERPA for** $E_T^\gamma \lesssim 500$ **GeV**

ATLAS Collab, arXiv:1701.06882

# Inclusive isolated photons @ 13 TeV ($\mathcal{L} = 3.2$ fb$^{-1}$)

- **Major sources of experimental uncertainty:**



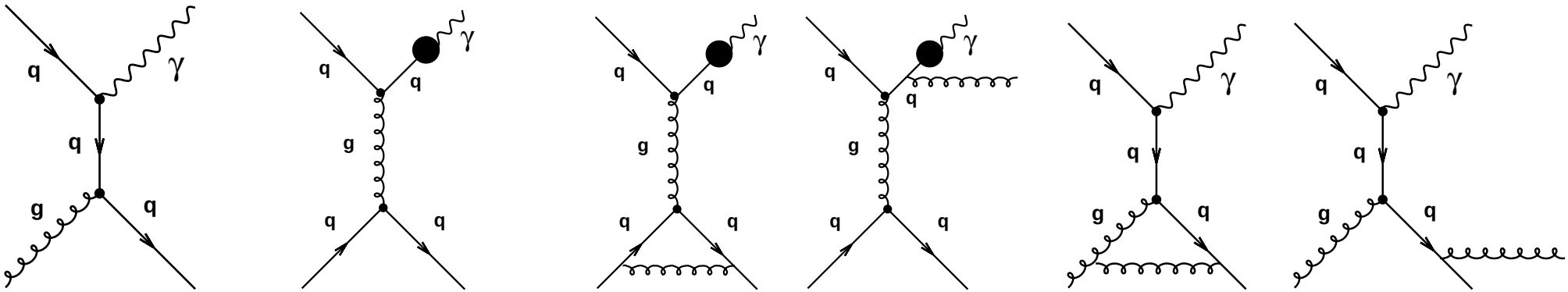

→ **total uncertainty: $< 5\%$ for $|\eta^\gamma| < 1.37$;**
**for $1.56 < |\eta^\gamma| < 1.81$ ($1.81 < |\eta^\gamma| < 2.37$), from $8\ (4)\%$ at $E_T^\gamma = 125$ GeV to $19\ (11)\%$ at $E_T^\gamma = 1.5$ TeV**

→ **for $E_T^\gamma \lesssim 600$ GeV, systematic uncertainty dominates**

→ **for higher $E_T^\gamma$ values, statistical uncertainty limits precision**

ATLAS Collab, arXiv:1701.06882

# NLO QCD calculations for inclusive photon production




$$\sigma_{pp\to\gamma+X} = \sum_{i,j,a} \int_0^1 dx_1\, f_{i/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{j/p}(x_2,\mu_F^2)\ \hat{\sigma}_{ij\to\gamma a} +$$

$$\sum_{i,j,a,b} \int_{z_{\min}}^1 dz\, D_a^\gamma(z,\mu_f^2) \int_0^1 dx_1\, f_{i/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{j/p}(x_2,\mu_F^2)\ \hat{\sigma}_{ij\to ab}$$

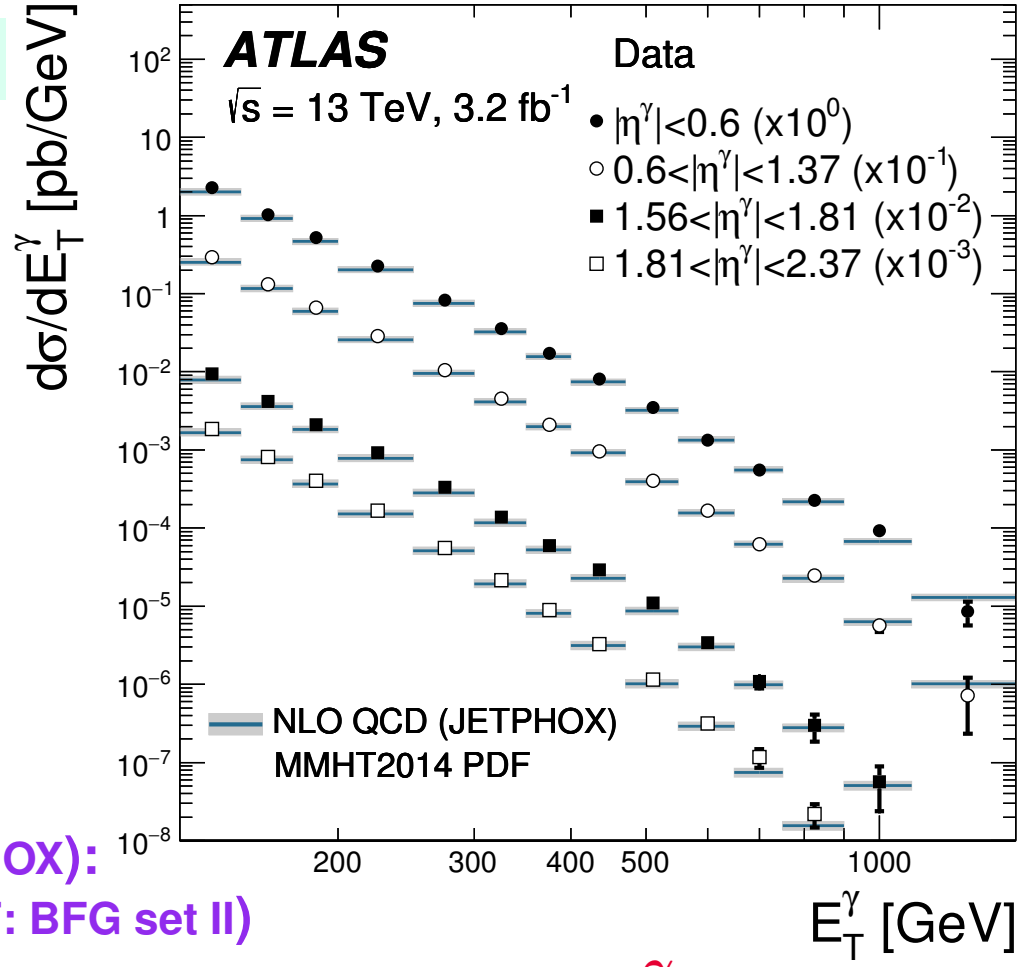
- The calculations include NLO corrections for direct-photon and fragmentation and implement the photon isolation requirement at parton level
- Corrections for hadronisation and underlying event (affecting $E_T^{iso}$, $< 1\%$)
- Theoretical uncertainties: higher orders, PDF-induced uncertainty, uncertainty on $\alpha_s$ and on non-perturbative corrections

JETPHOX (S. Catani et al, JHEP 0205 (2002) 028)

# Inclusive isolated photons: testing pQCD

$\sigma_{\rm meas} = 399 \pm 13\ ({\rm exp}) \pm 8\ ({\rm lumi})$ **pb**

$\sigma_{\rm NLO} = 352^{+36}_{-29}\ ({\rm scale})$
$\pm 3\ ({\rm PDF}) \pm 6\ (\alpha_s) \pm 4\ ({\rm NP})$ **pb**



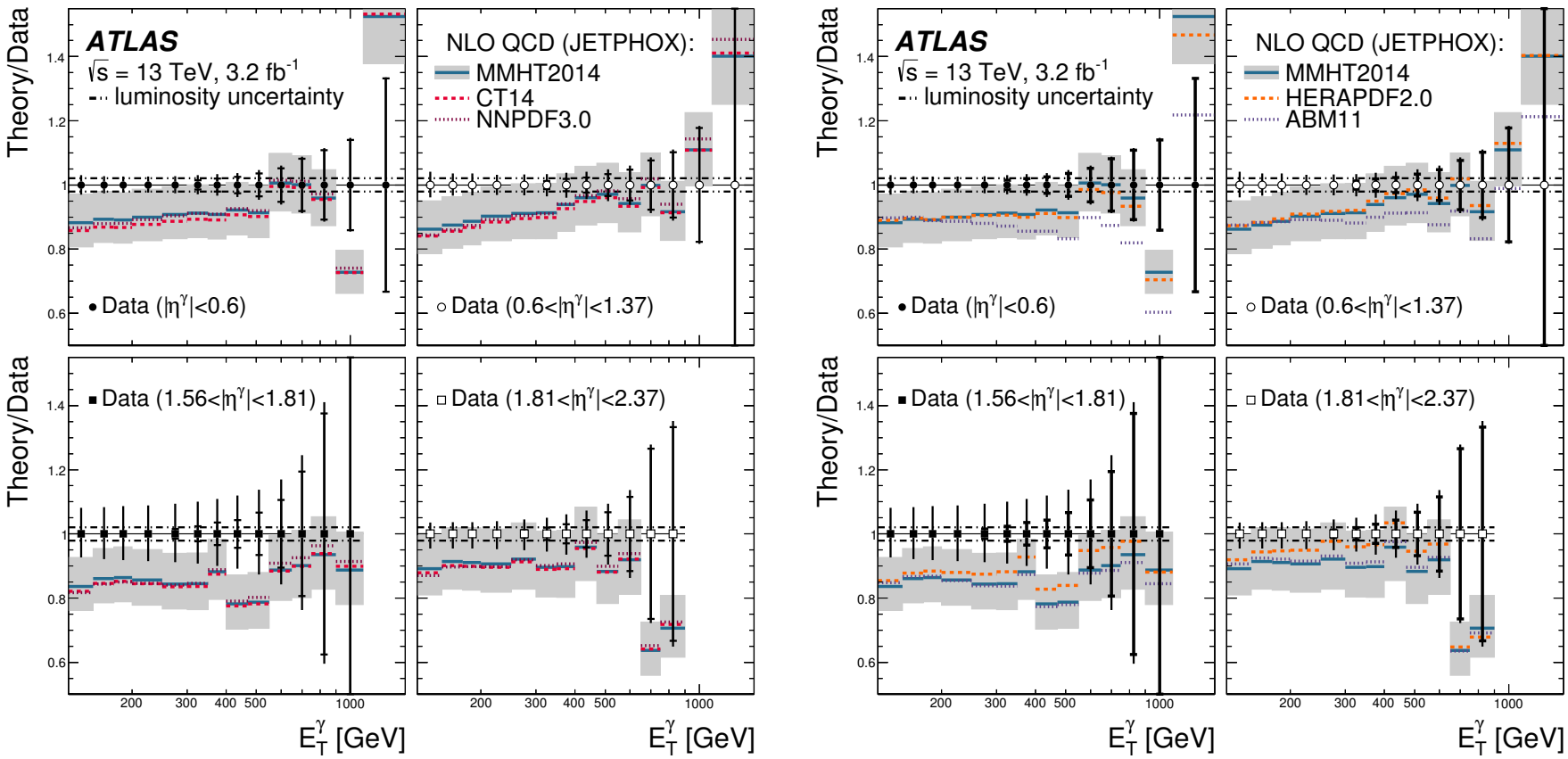

- **Theoretical uncertainties:**
  - → **terms beyond NLO:** $10 - 15\%$
  - → **PDFs:** $1\%$ **at** $E_{\rm T}^{\gamma} = 125$ **GeV and** $(3-4)\%$ **at high** $E_{\rm T}^{\gamma}$
  - → **value of** $\alpha_s$**:** $< 2\%$
  - → **NP corrections:** $1\%$

- **Comparison to NLO predictions (JETPHOX):**
  ($\mu_R = \mu_F = \mu_f = E_{\rm T}^{\gamma}$; **PDFs: MMHT2014; FF: BFG set II**)
  ⇒ **The NLO calculations agree with the data up to the highest** $E_{\rm T}^{\gamma}$ **(1.5 TeV)**

- **First NNLO calculations for prompt photons are now available!**
  **(Campbell, Ellis & Williams, arXiv:1612:04333)**

ATLAS Collab, arXiv:1701.06882

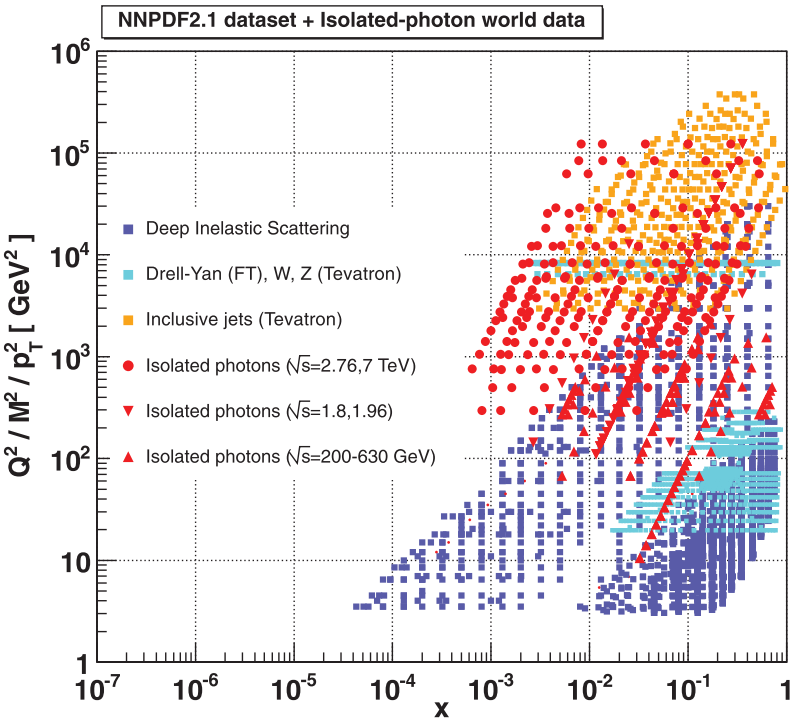
# Inclusive isolated photons: sensitivity to proton PDFs



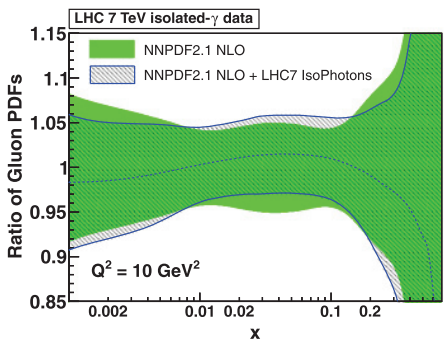

- **Sensitivity to proton PDFs:** comparison of measurements and NLO calculations based on MMHT2014, CT14, NNPDF3.0, HERAPDF2.0 and ABM11 shows potential to constrain further the PDFs, especially at **high** $E_{\mathrm{T}}^{\gamma}$
- **Ready to test NNLO predictions!**
  $\rightarrow$ reduction of scale uncertainty $\rightarrow$ increase of sensitivity to PDFs

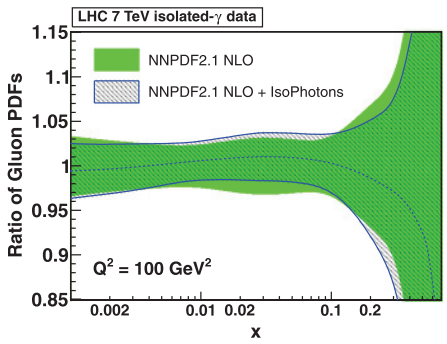
ATLAS Collab, arXiv:1701.06882

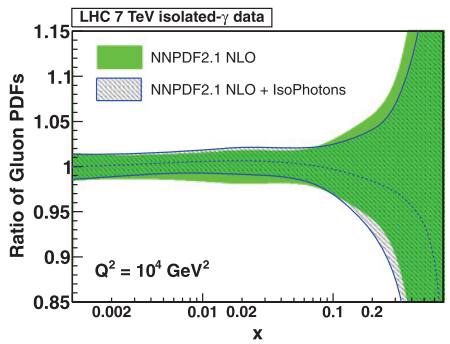
# Impact of inclusive isolated photon measurements at LHC on PDFs

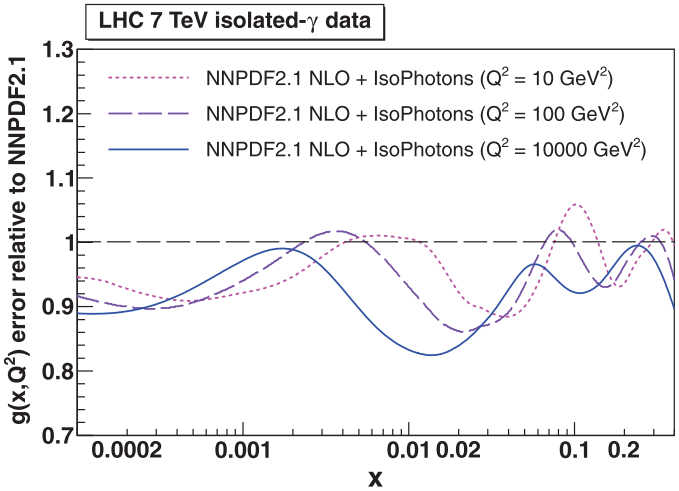



- **Study of the impact on the gluon density of existing isolated-photon measurements from a variety of experiments, from $\sqrt{s} = 200$ GeV up to 7 TeV**
  - $\rightarrow$ **those at LHC are the most constraining datasets**
  - $\rightarrow$ **reduction of gluon uncertainty up to $20\%$ localised in the range $x \approx 0.002$ to $0.05$**
    - $\Rightarrow$ **improved predictions for low mass Higgs production in gluon fusion: PDF-induced uncertainty decreased by $20\%$**




D d'Enterria and J Rojo (NPB 860 (2012) 311)

# Photon pair production

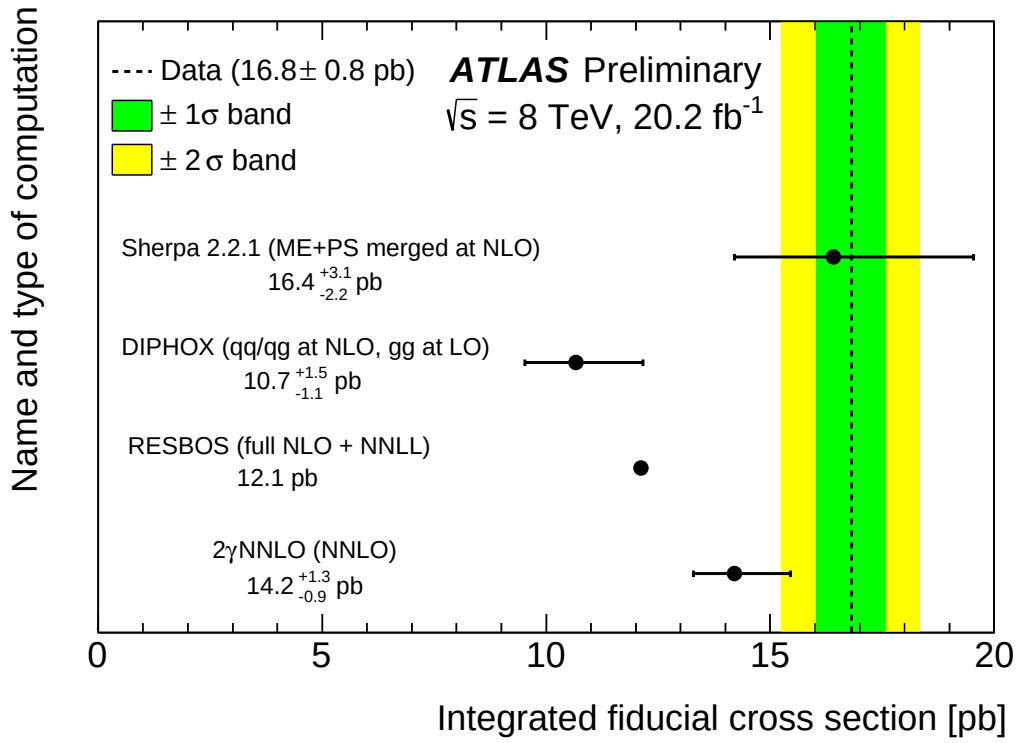
# Inclusive isolated photon pairs @ 8 TeV ($\mathcal{L} = 20.2$ fb$^{-1}$)

- **Photon selection:** $E_T^\gamma > 40, 30$ **GeV and** $|\eta^\gamma| < 2.37$**, excluding the region** $1.37 < |\eta^\gamma| < 1.56$
- **Photon isolation:** $E_T^{iso} < 11$ **GeV; signal purity:** $\approx 75\%$ **(**$60 - 98\%$ **depending on observable)**

- **Main irreducible background to** $H \to \gamma\gamma$

$\sigma_{meas} = 16.8 \pm 0.8$ **pb**

- **Theoretical predictions (uncertainty):**
  ($\mu_R = \mu_F (= \mu_f) = m_{\gamma\gamma}$; **PDFs: CT10)**
  - $\to$ **SHERPA 2.2.1: ME+PS merged at NLO** ($10 - 40\%$)
  - $\to$ **DIPHOX: DP+F at NLO,** $gg \to \gamma\gamma$ **at LO** ($30\%$)
  - $\to$ **RESBOS*: NLO + NNLL**
    (* **uncertainties not given)**
  - $\to$ **2**$\gamma$**NNLO: DP at NNLO** ($20\%$)
    **(Frixione isolation!)**
  - $\to$ **PDF uncertainty:** $2\%$
  - $\to$ **NP uncertainty:** $< 5\%$




$\Rightarrow$ **The prediction from SHERPA 2.2.1 is in best agreement with the data**

$\to$ **experimental uncertainty:** $4.7\%$
- $\to$ **major sources:** $\gamma$**ID** ($2.5\%$)
  **modelling of** $E_T^{iso}$ ($2\%$)
  **luminosity** ($1.9\%$)

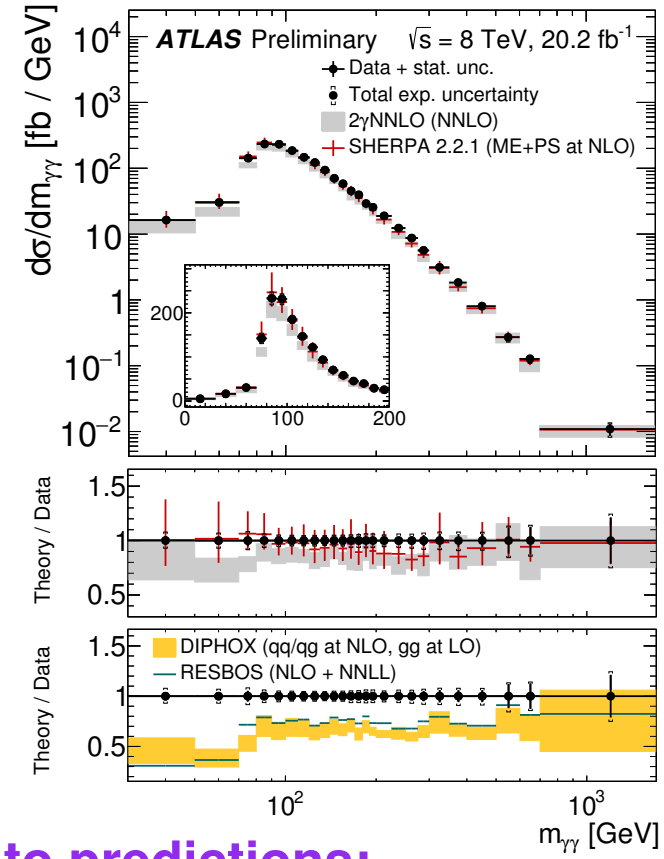
ATLAS Collab, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-15 (preliminary)

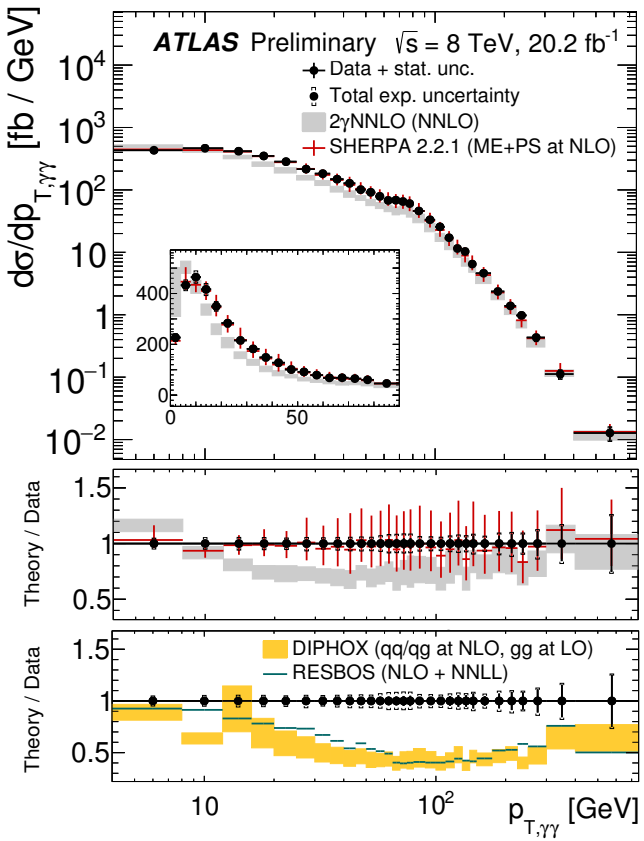
# Isolated photon pairs: understanding the QCD background

**invariant mass**

**SHERPA/data**

**DIPHOX/data**




**and transverse momentum of photon-pair system**

**2γNNLO/data**

**RESBOS/data**

- **Comparison to predictions:**
  - → **DIPHOX (NLO): fails to describe the data**
  - → **RESBOS (NLO+NNLL): inclusion of soft-gluon resummation improves description in regions sensitive to infrared emission (low $p_{T,\gamma\gamma}$)**
  - → **2γNNLO (NNLO): the additional order improves the description**
  - → **SHERPA (ME+PS NLO): gives a good description of the data**

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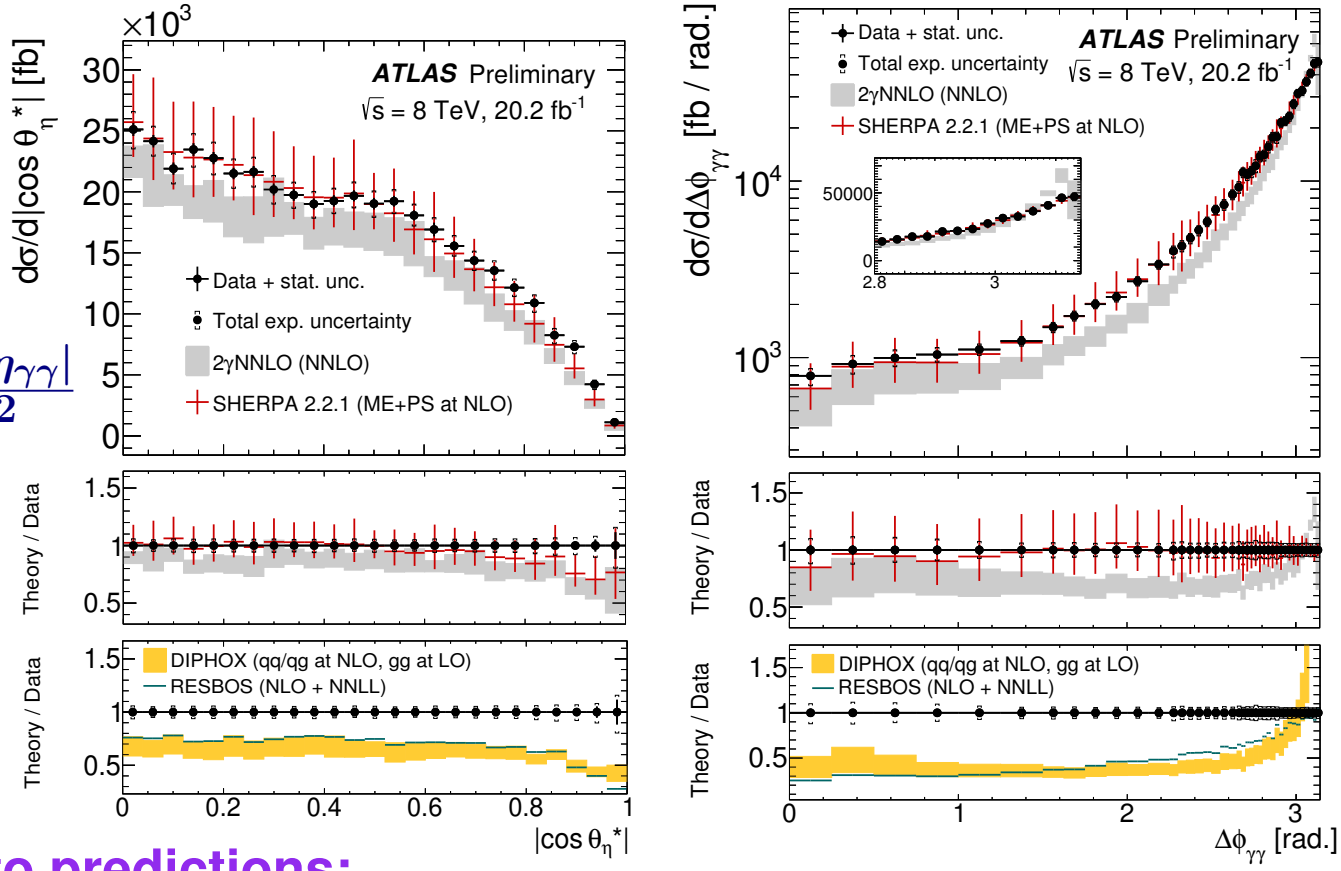
# Isolated photon pairs: understanding the QCD background

**scattering angle wrt proton beam direction**

$$|\cos\theta^*_\eta| = \tanh\frac{|\Delta\eta_{\gamma\gamma}|}{2}$$

**SHERPA/data**

**DIPHOX/data**




**and opening angle of photons in azimuthal plane**

**2γNNLO/data**

**RESBOS/data**

- **Comparison to predictions:**
  - → **DIPHOX (NLO): fails to describe the data**
  - → **RESBOS (NLO+NNLL): inclusion of soft-gluon resummation improves description in regions sensitive to infrared emission ($\Delta\phi_{\gamma\gamma} \sim \pi$)**
  - → **2γNNLO (NNLO): the additional order improves the description**
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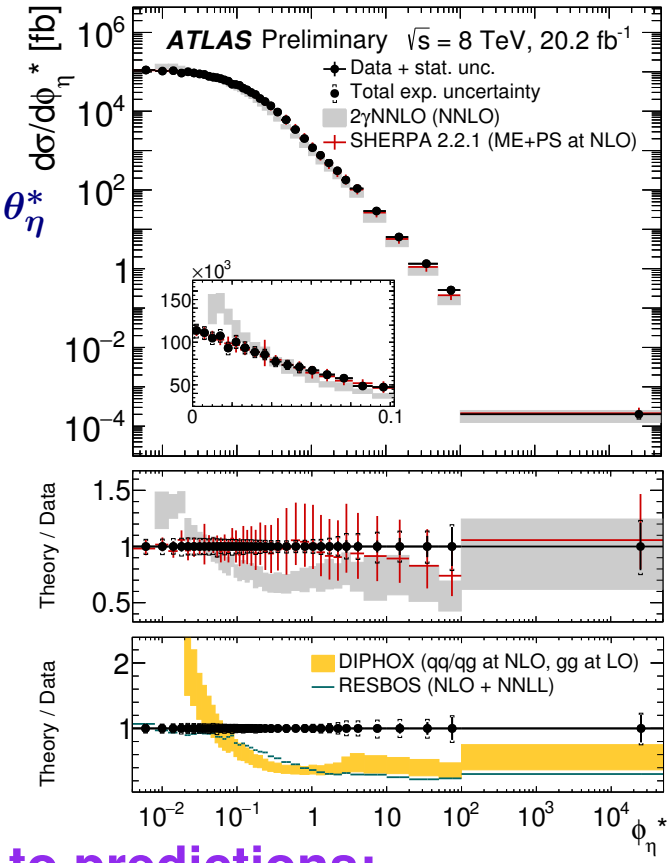
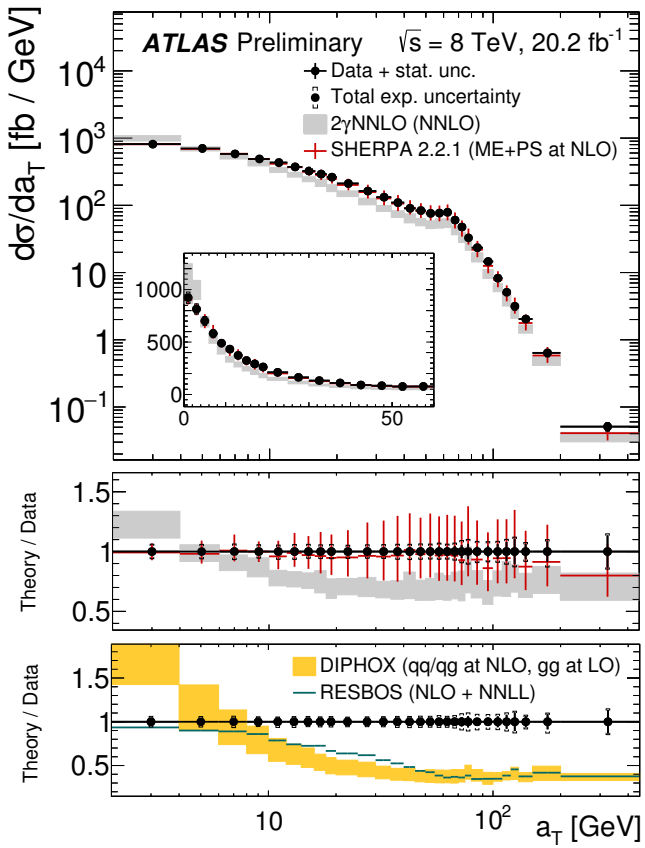
ATLAS Collab, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-15 (preliminary)

# Isolated photon pairs: understanding the QCD background

$\phi^*_\eta = \tan(\frac{\pi - \Delta\phi_{\gamma\gamma}}{2}) \sin\theta^*_\eta$




**SHERPA/data**

**DIPHOX/data**

**and transverse component of $p_{T,\gamma\gamma}$ wrt thrust axis**

**2$\gamma$NNLO/data**

**RESBOS/data**

- **Comparison to predictions:**
  - → **DIPHOX (NLO): fails to describe the data**
  - → **RESBOS (NLO+NNLL): inclusion of soft-gluon resummation improves description in regions sensitive to infrared emission (low $a_T$ and $\phi^*_\eta$)**
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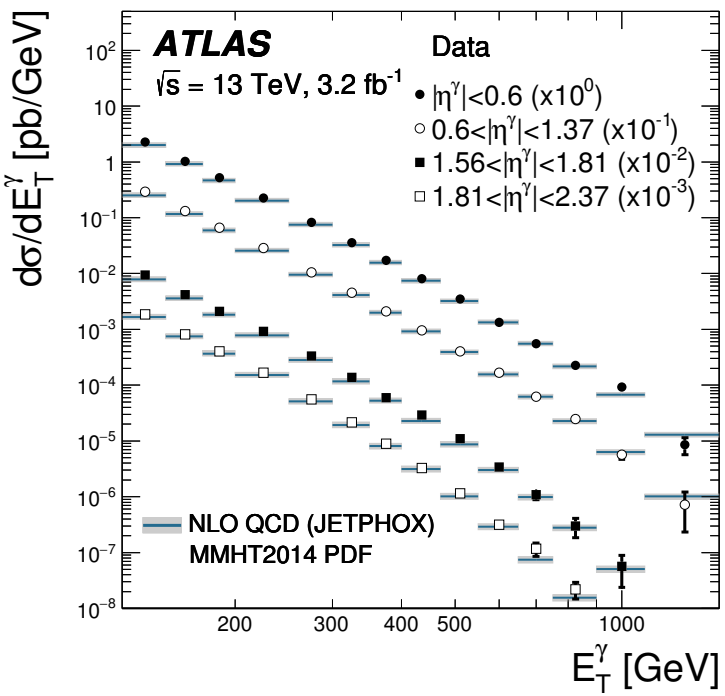
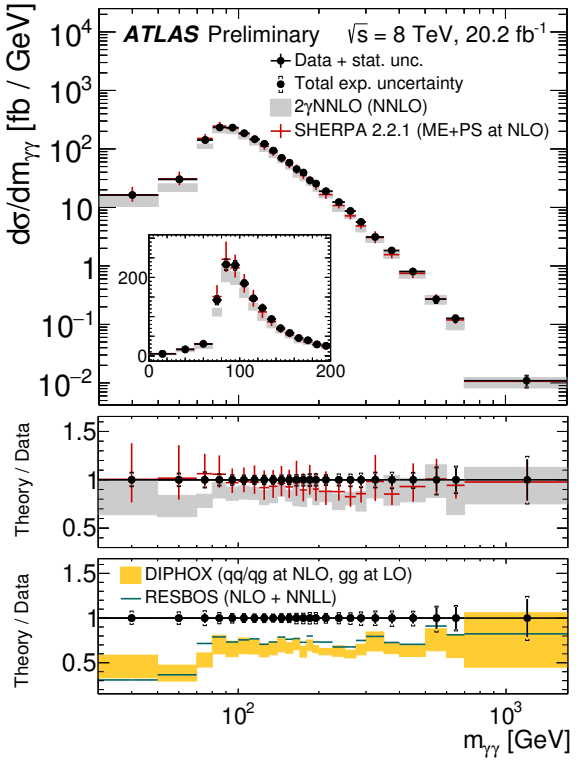
# Summary



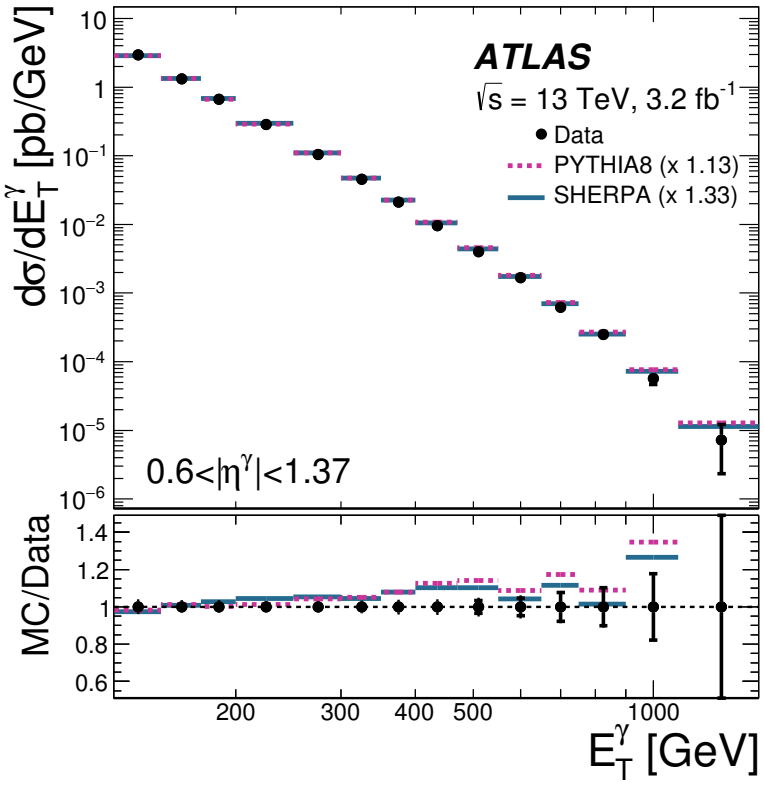



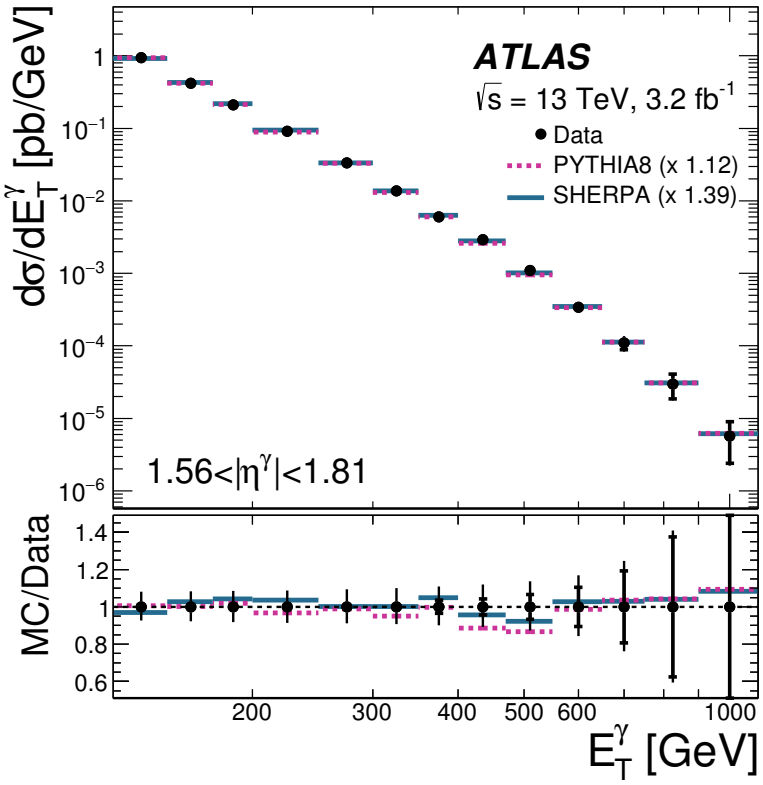

- **Exploration of isolated photon production in $pp$ collisions up to $E_{\mathrm{T}}^{\gamma} \sim 1.5$ TeV**
  **$\Rightarrow$ additional experimental information on the gluon density in the proton**
- **Measurements of diphoton production**
  **$\Rightarrow$ understanding of background to $H \to \gamma\gamma$ in terms of pQCD**
- **Overall, perturbative QCD succeeds in describing the data!**

# Back-up slides

# Inclusive isolated photons @ 13 TeV ($\mathcal{L} = 3.2$ fb$^{-1}$)

- **Photon selection:** $E_T^\gamma > 125$ **GeV and** $|\eta^\gamma| < 2.37$**, excluding the region** $1.37 < |\eta^\gamma| < 1.56$
- **Photon isolation:** $E_T^{iso} < 0.0042 \times E_T^\gamma + 4.8$ **GeV; signal purity:** $> 90\%$ **for** $E_T^\gamma > 125$ **GeV**

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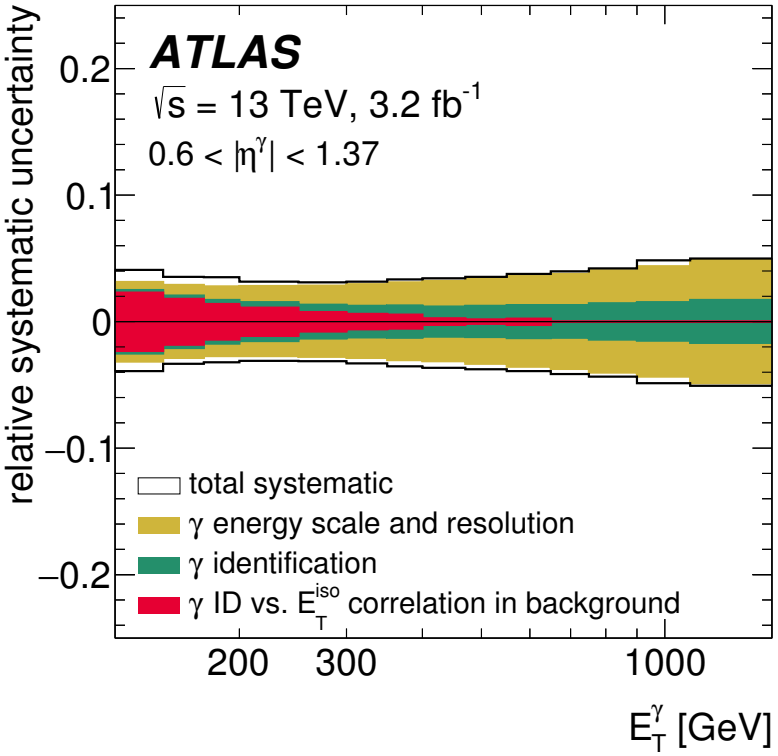
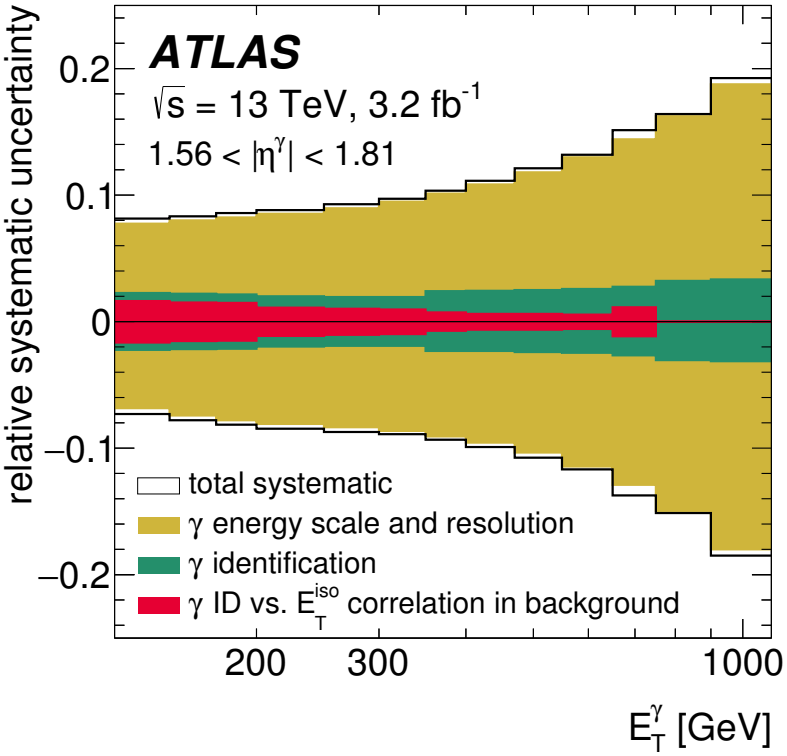
ATLAS Collab, arXiv:1701.06882

# Inclusive isolated photons @ 13 TeV ($\mathcal{L} = 3.2$ fb$^{-1}$)

- **Major sources of experimental uncertainty:**



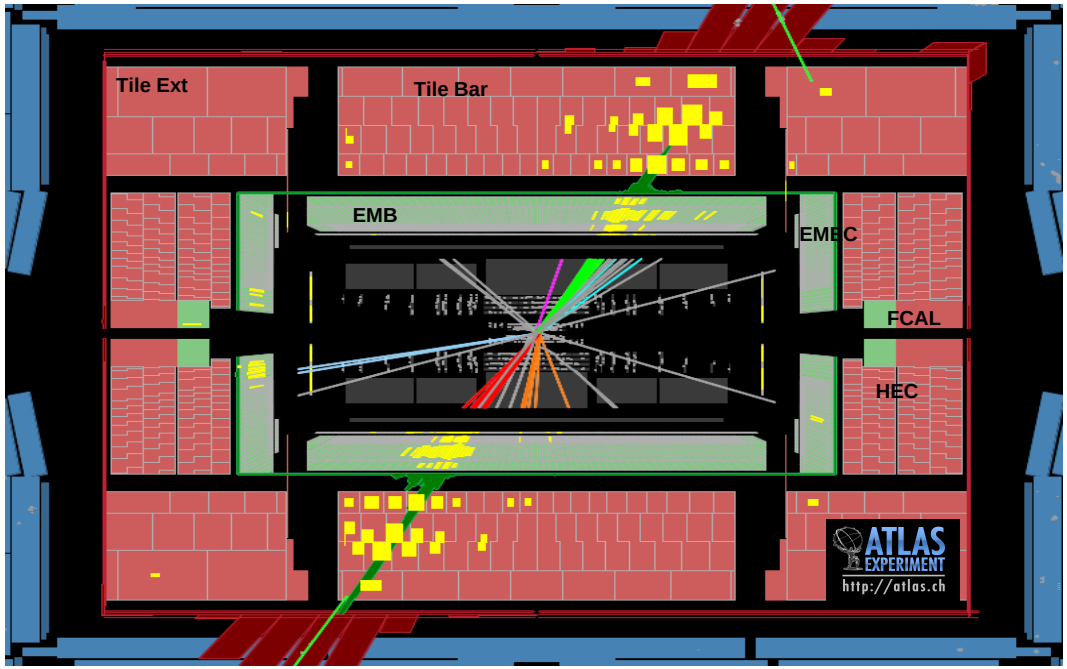

→ **total uncertainty: $< 5\%$ for $|\eta^\gamma| < 1.37$;**
**for $1.56 < |\eta^\gamma| < 1.81$ ($1.81 < |\eta^\gamma| < 2.37$), from $8\ (4)\%$ at $E_T^\gamma = 125$ GeV to $19\ (11)\%$ at $E_T^\gamma = 1.5$ TeV**

→ **for $E_T^\gamma \lesssim 600$ GeV, systematic uncertainty dominates**

→ **for higher $E_T^\gamma$ values, statistical uncertainty limits precision**

ATLAS Collab, arXiv:1701.06882

# The ATLAS detector




- **Inner detector (ID): tracking and PI in $|\eta| < 2.5$ (silicon pixels and strips, TRT)**
- **Calorimeters:**
  **electromagnetic (LAr) $\rightarrow$ barrel: $|\eta| < 1.475$, endcap: $1.375 < |\eta| < 3.2$ (and forward: $3.1 < |\eta| < 4.9$); three longitudinal layers**
  **hadronic (scintillator/steel, LAr/Cu, LAr/W) $\rightarrow$ barrel: $|\eta| < 0.7$, extended barrel: $0.8 < |\eta| < 1.7$, endcap: $1.5 < |\eta| < 3.2$ and forward: $3.1 < |\eta| < 4.9$**

**are the main components for photon reconstruction and identification in ATLAS**