Measurement of the ratio of cross sections for inclusive isolated-photon production in pp collisions at $\sqrt{s} = 13$ and $8\,\mathrm{TeV}$

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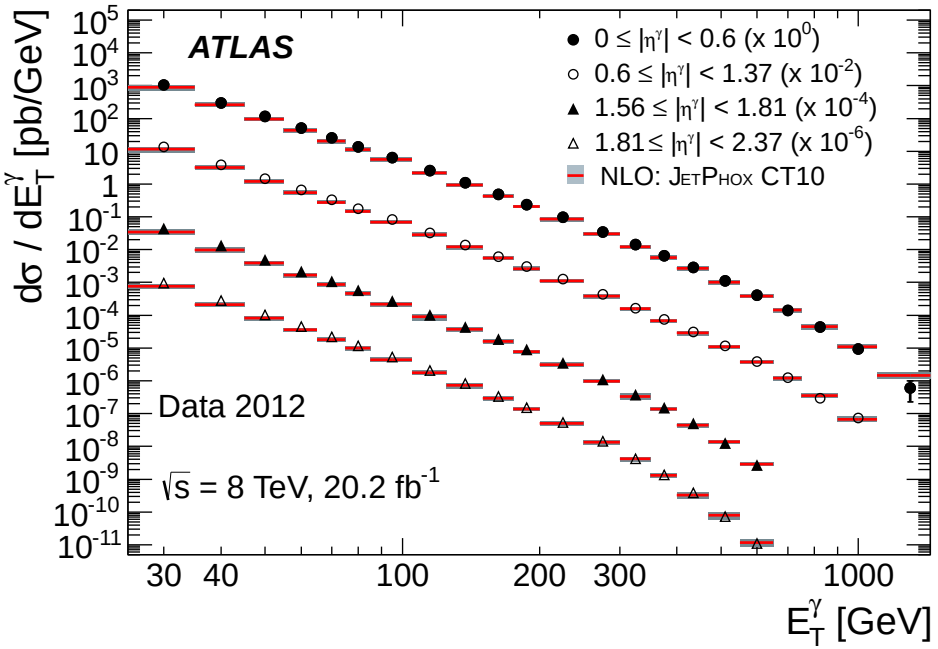
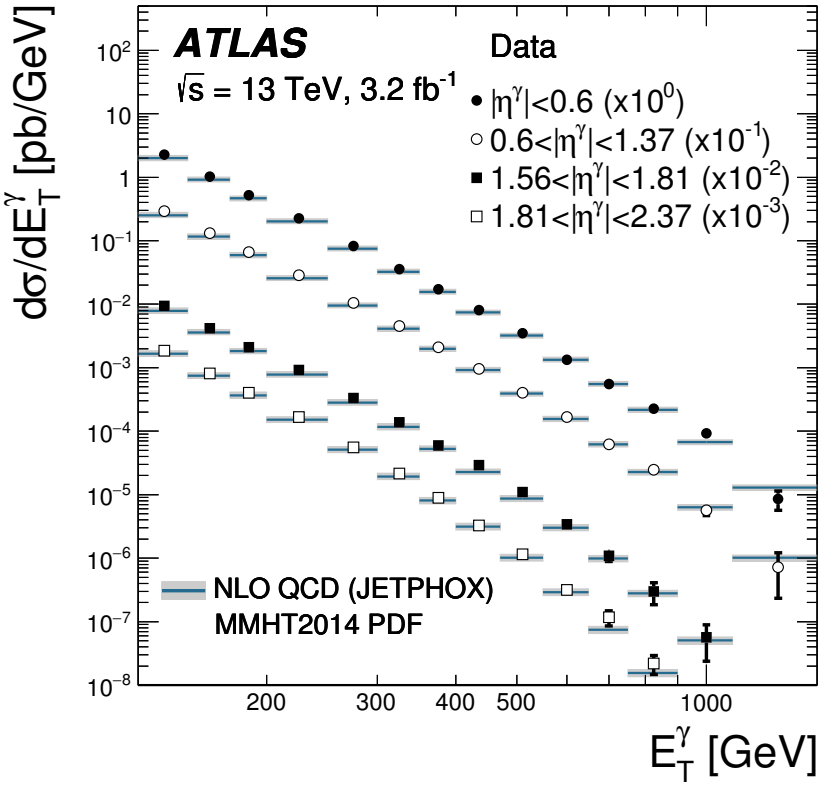
- Motivation
- Photons with the ATLAS detector
- Experimental uncertainties
- Fixed-order QCD predictions
- Results
- Summary and conclusions

Motivation (I)

The measurements of inclusive isolated-photon cross sections performed by ATLAS at 13 and 8 TeV were compared with the predictions of NLO pQCD;

$\rightarrow$ the theoretical uncertainties are dominant and larger than the experimental ones, **preventing more precise tests of the theory**.





ATLAS Coll., JHEP 06 (2016) 005

ATLAS Coll., Phys. Lett. B 770 (2017) 473

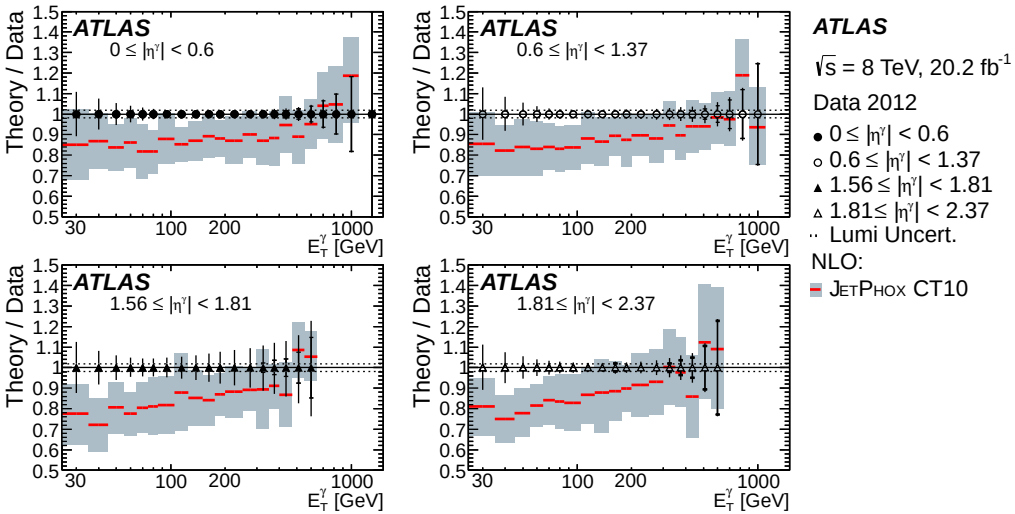
Motivation (II)

The measurement of the ratio of cross sections at different $\sqrt{s}$ allows:

$\rightarrow$ more stringent tests of the theory, since a significant reduction of the experimental and theoretical uncertainties is expected;

$\rightarrow$ tests of the evolution of the isolated photon production in pp collisions from $\sqrt{s} = 8$ to 13 TeV.

$\star$ Correlations in systematic and theoretical uncertainties are extremely important



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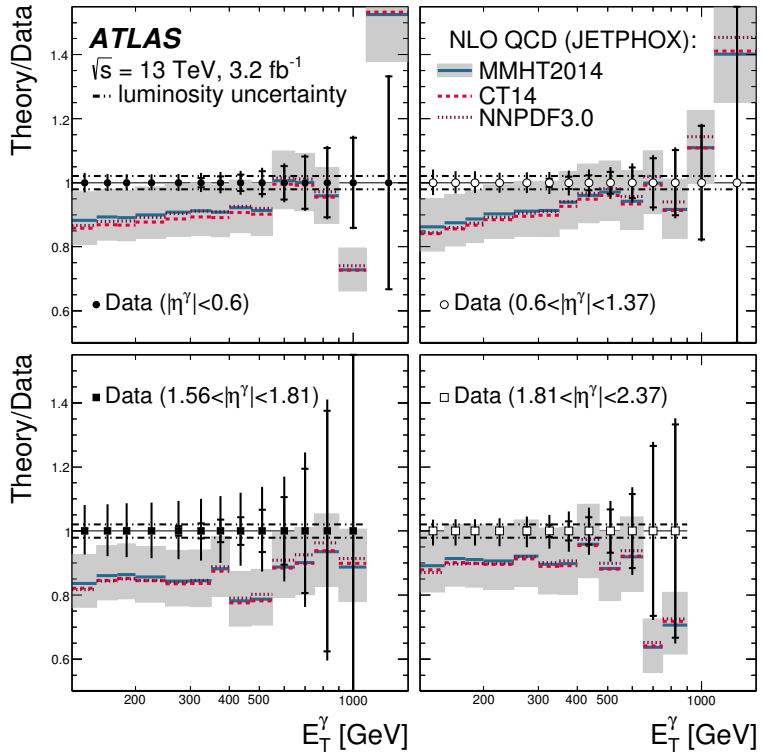

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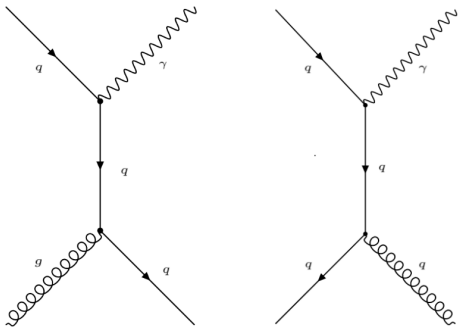
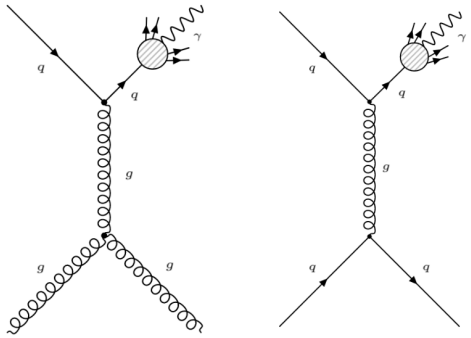
Photons with the ATLAS detector (I)

The production of high-p_{T} prompt-photons proceeds via two mechanisms:
(**prompt photon**: photon not coming from hadron decays)



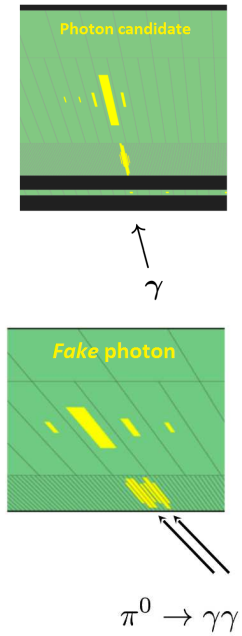
Direct



Fragmentation

Reconstruction: photons are reconstructed from clusters of energy in the EM calorimeter as unconverted or converted candidates.

Identification: to separate between signal and background photons, different cuts in shape variables from the lateral and longitudinal energy profiles of the shower in the calorimeters are applied.



Photons with the ATLAS detector (II)

In addition to prompt-photons, photons are copiously produced inside jets due to neutral meson decays;

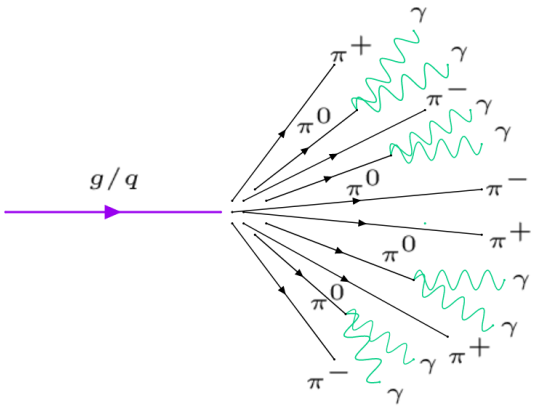
→ it is essential to require isolation to study prompt-photons in hadron colliders.

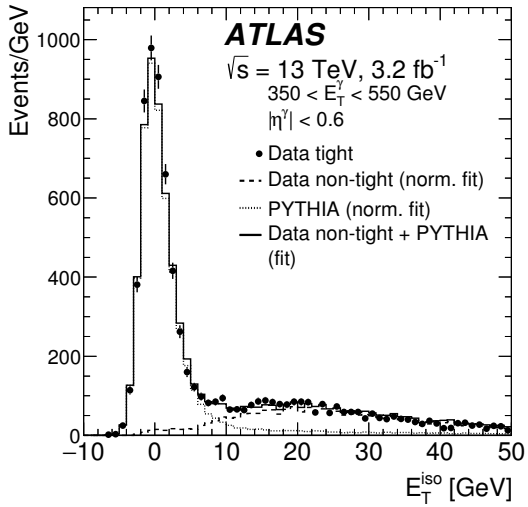
The isolation requirement mostly suppresses the contribution of photons inside jets and the fragmentation-photon processes.

The isolation transverse energy ($E_{\mathrm{T}}^{\mathrm{iso}}$) is computed at detector level using clusters of calorimeter cells (EMC and HCAL) in a cone of R = 0.4, excluding the area ($\Delta\eta \times \Delta\phi = 0.125 \times 0.175$) centred on the photon cluster;

→ A photon is considered isolated if the condition $E_{\mathrm{T}}^{\mathrm{iso}} < (E_{\mathrm{T}}^{\mathrm{iso}})^{\mathrm{cut}}$ is fulfilled, with isolation cut:

$$(E_{\mathrm{T}}^{\mathrm{iso}})^{\mathrm{cut}} = 4.2 \times 10^{-3} E_{\mathrm{T}}^{\gamma} + 4.8 \text{ GeV}\,.$$





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Experimental uncertainties in $R^{\gamma}_{13/8}$: photon energy scale

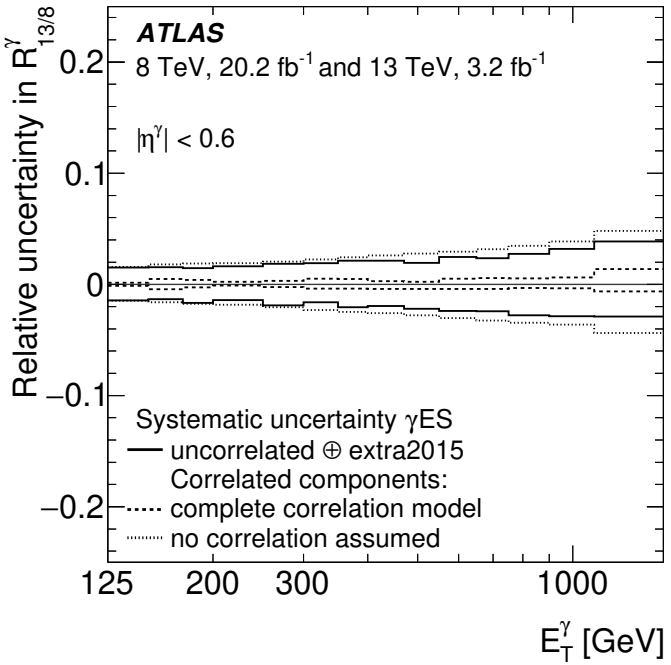
- The systematic uncertainty associated with the **photon energy scale** (γES) represents the **dominant experimental uncertainty** in the measurements of the cross sections for inclusive isolated-photon production at both $\sqrt{s}$.

- A total of **22 individual components** influencing the energy scale and resolution of the photon are considered:

  – 20 common to 13 and 8 TeV;

  – 2 specific for 13 TeV;

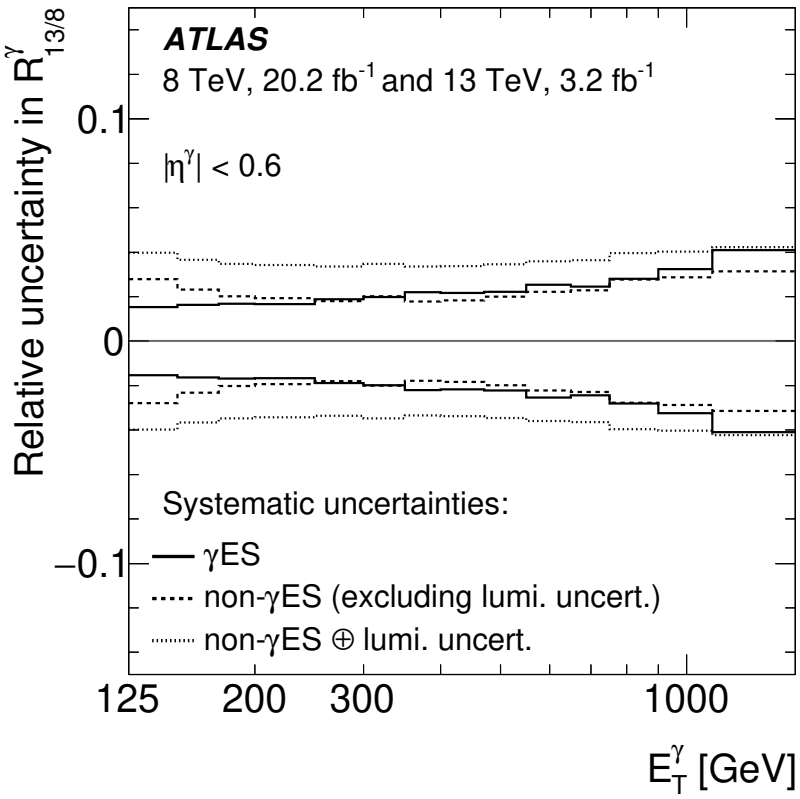
  + Calibration differences due to the change of optimal filtering coefficients and LAr timing samples considered as another source of uncertainty.

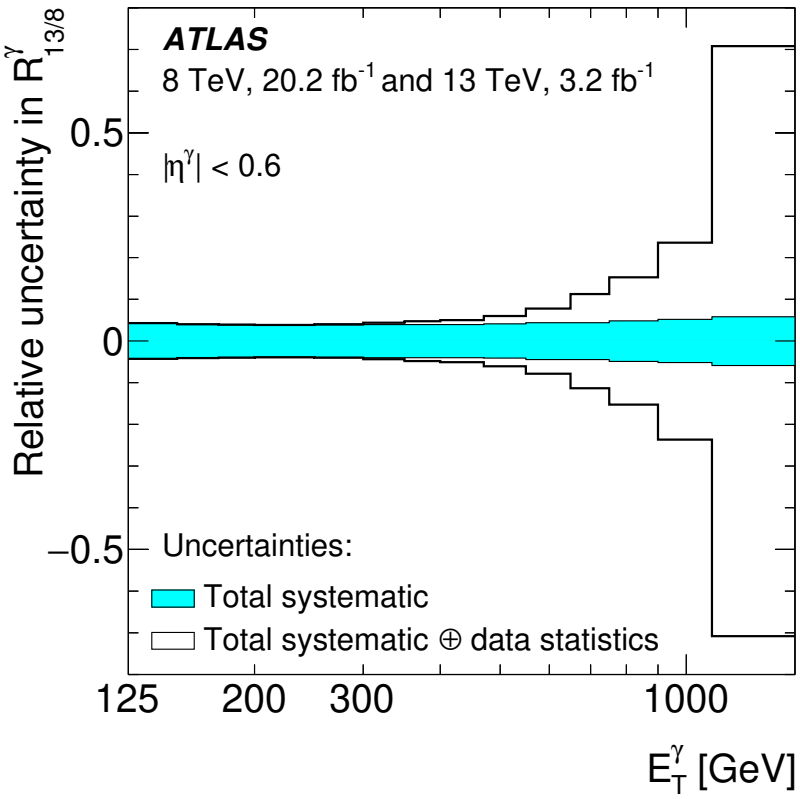


⋆ All the uncertainties are taken as fully correlated except for that on the overall energy scale adjustment using $Z \to e^+e^-$ events and the uncertainties specific to the 13 TeV measurement.

ATLAS Coll. JHEP 04 (2019) 093

Experimental uncertainties in $R^{\gamma}_{13/8}$: other sources





⋆ The γES is no longer the dominant uncertainty, except for $E^{\gamma}_{\mathrm{T}} > 300$ GeV in the regions $0.6 < |\eta^{\gamma}| < 1.37$ and $1.56 < |\eta^{\gamma}| < 1.81$;

- **Region $|\eta^{\gamma}| < 0.6$**: the total systematic uncertainty is $\sim 4\%$ from $E^{\gamma}_{\mathrm{T}} = 125$ GeV up to 750 GeV; it rises to $\sim 6\%$ at the end of the spectrum.

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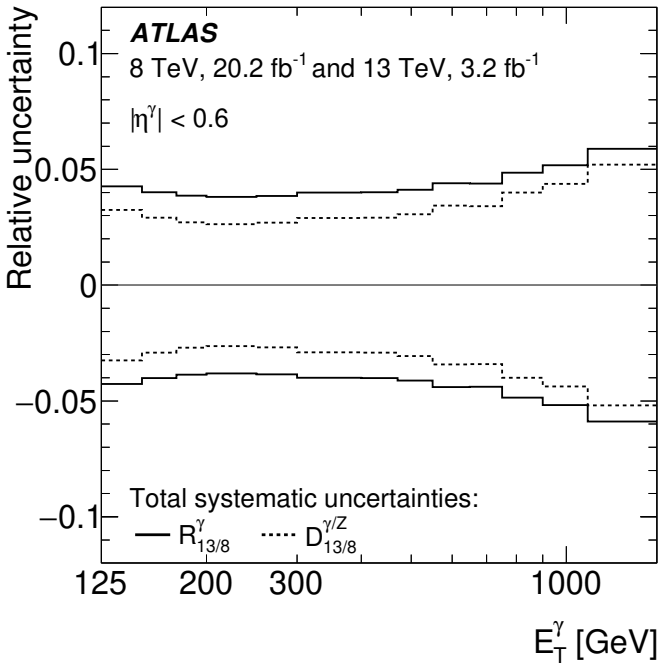
Measurements of $D^{\gamma/Z}_{13/8}$ and experimental uncertainties

The **double ratio** $D^{\gamma/Z}_{13/8}$ is defined as:

$$D^{\gamma/Z}_{13/8} = \frac{R^{\gamma}_{13/8}(E^{\gamma}_{\mathrm{T}})}{\sigma^{\mathrm{fid}}_{Z}(13\mathrm{TeV})/\sigma^{\mathrm{fid}}_{Z}(8\mathrm{TeV})} .$$

⋆ Results and predictions at NNLO pQCD for $\sigma^{\mathrm{fid}}_{Z}(13\mathrm{TeV})/\sigma^{\mathrm{fid}}_{Z}(8\mathrm{TeV})$ ($R^{Z}_{13/8}$) from the ATLAS paper: JHEP 1702 (2017) 117

→ The measured double ratio $D^{\gamma/Z}_{13/8}$ benefits from the **cancellation of the uncertainty in the luminosity**, which has a significant impact in $R^{\gamma}_{13/8}$.



⋆ The ATLAS measurement of $R^{Z}_{13/8}$: $1.537 \pm 0.001\,(\mathrm{stat}) \pm 0.010\,(\mathrm{syst}) \pm 0.044\,(\mathrm{lumi})$

- **Statistical uncertainty of** 0.1%, **uncorrelated** with that of $R^{\gamma}_{13/8}$.
- **Luminosity uncertainty of** 2.8%, **cancels** in the double ratio $D^{\gamma/Z}_{13/8}$.
- **Systematic uncertainty of** 0.7%, **uncorrelated** with that of $R^{\gamma}_{13/8}$.
  → **The effect of adding in quadrature this systematic uncertainty has a small impact.**

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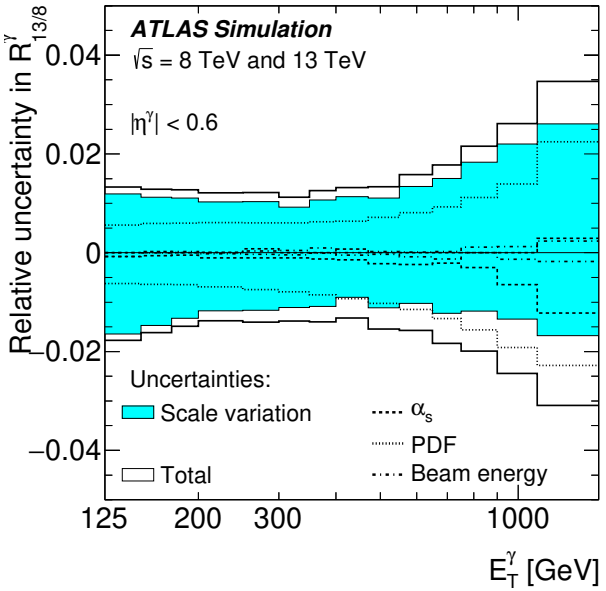
Predictions and uncertainties in the ratio $R^{\gamma}_{13/8}$

- Theoretical predictions for the inclusive isolated-photon cross sections have been obtained using JETPHOX for 8 and 13 TeV :
  - **Full fixed-order NLO pQCD** predictions for **direct** and **fragmentation** contributions.
  - **Scales**: $\mu_R = \mu_F = \mu_f = E^{\gamma}_{\mathrm{T}}$.
  - **PDFs**: **MMHT2014 (baseline)**, CT14, NNPDF3.0, HERAPDF2.0 and ABMP16.
  - **BFG set II of fragmentation functions**.
  - **Fixed-cone isolation at parton level**.
- Uncertainties in the theoretical predictions: terms beyond NLO, α_S, PDFs, beam energy and non-perturbative effects.



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⋆ The estimation of the uncertainty due to terms beyond NLO is quite different whether **full** or null **correlation** is assumed. **The coherent approach leads to large cancellations** in the uncertainties of the predictions for $R^{\gamma}_{13/8}$ (from $\mathcal{O}(10\%)$ for the individual predictions to be below $\mathcal{O}(2\%)$ for $R^{\gamma}_{13/8}$ across most of the range in E^{γ}_{T});

→ supported by an alternative approach **considering the difference between the LO and NLO predictions** for $R^{\gamma}_{13/8}$ (differences up to 3.5%).

⋆ All the sources of uncertainty are considered as **fully correlated** between the two $\sqrt{s}$.

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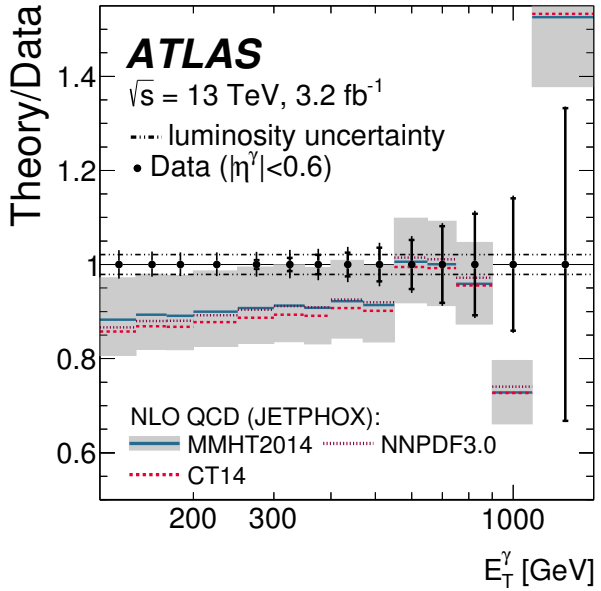

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Predictions and uncertainties in the double ratio $D^{\gamma/Z}_{13/8}$

- The theoretical predictions for $D^{\gamma/Z}_{13/8}$ have been obtained from:
  - ⋆ For $R^{Z}_{13/8}$: NNLO pQCD calculations using DYTURBO;
    - → Predictions **available** for MMHT2014nnlo, NNPDF3.0nnlo, HERAPDF2.0nnlo and CT14nnlo.
  - ⋆ For $R^{\gamma}_{13/8}$: NLO pQCD calculations using JETPHOX;
    - → Predictions **produced** using MMHT2014nnlo, NNPDF3.0nnlo, HERAPDF2.0nnlo and CT14nnlo **for consistency and to account for correlations**.
- Uncertainties in the theoretical predictions for $D^{\gamma/Z}_{13/8}$:
  - **Scale variations**: considered as uncorrelated between Z boson and isolated γ production; $^{+0.02}_{-0.3}\%$ uncertainty in $R^{Z}_{13/8}$.
  - **PDFs uncertainties**: treated as fully correlated between Z boson and isolated γ production; $^{+0.9}_{-0.8}\%$ uncertainty in $R^{Z}_{13/8}$.
  - α_S **uncertainties**: treated as fully correlated between Z boson and isolated γ production; -0.03% ($\alpha_S(M_Z)$ up) and -0.3% ($\alpha_S(M_Z)$ down) uncertainty in $R^{Z}_{13/8}$.

Results on the ratio $R^{\gamma}_{13/8}$

- $R^{\gamma}_{13/8}$ increases with E^{γ}_{T}, from ~ 2 at $E^{\gamma}_{\mathrm{T}} = 125$ GeV to $\sim 8-29$ at the end of the spectrum;
- $R^{\gamma}_{13/8}$ increases as $|\eta^{\gamma}|$ increases for a fixed E^{γ}_{T} value;
- The NLO pQCD predictions reproduce the measured $R^{\gamma}_{13/8}$ for all the PDF sets considered within much reduced uncertainties.

→ **Successful stringent test of the Standard Model predictions.**

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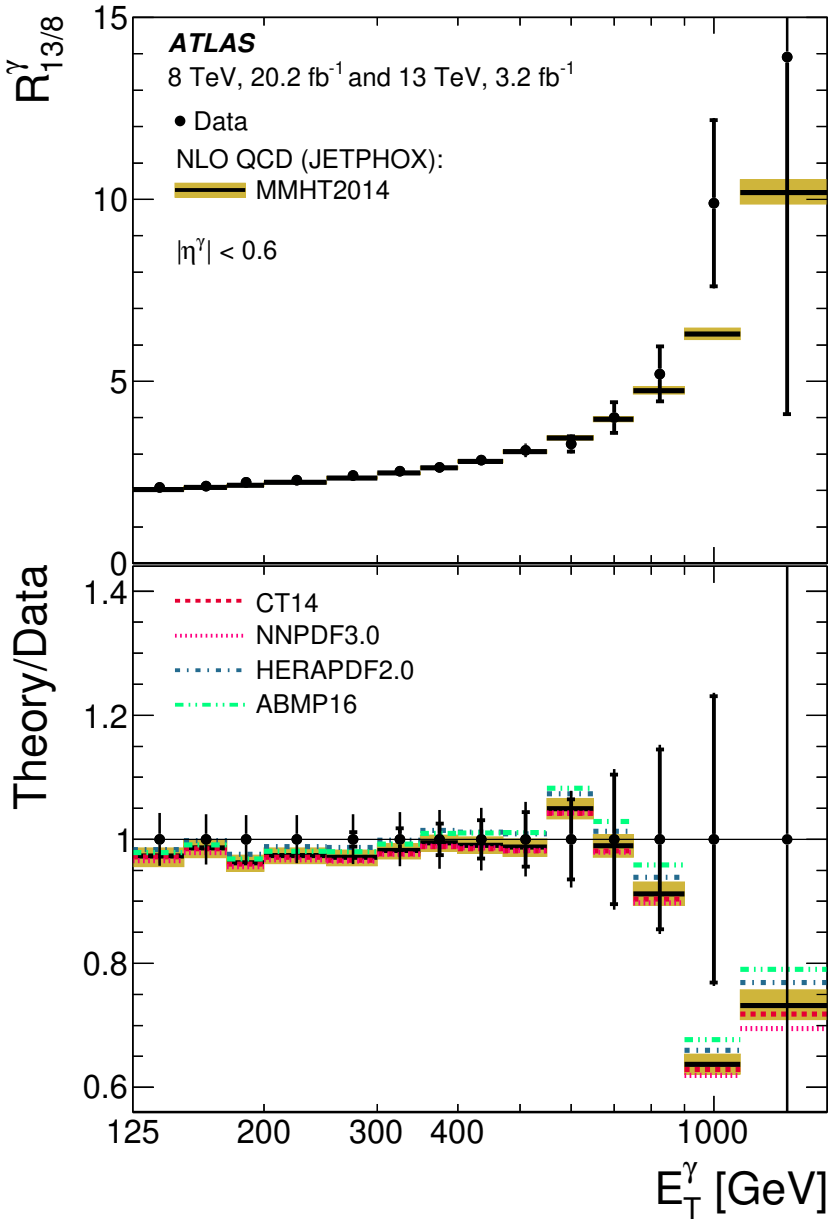

Results on the double ratio $D^{\gamma/Z}_{13/8}$

- $D^{\gamma/Z}_{13/8}$ increases with E^{γ}_{T}, from ~ 1.4 at $E^{\gamma}_{\mathrm{T}} = 125$ GeV to $\sim 5 - 19$ at the end of the spectrum;
- $D^{\gamma/Z}_{13/8}$ increases as $|\eta^{\gamma}|$ increases for a fixed E^{γ}_{T} value;
- The pQCD predictions reproduce the measured $D^{\gamma/Z}_{13/8}$ for all the PDF sets considered within much reduced uncertainties.

⋆ **Even smaller experimental uncertainties in $D^{\gamma/Z}_{13/8}$ than in $R^{\gamma}_{13/8}$.**

→ **Successful stringent test of the Standard Model predictions.**

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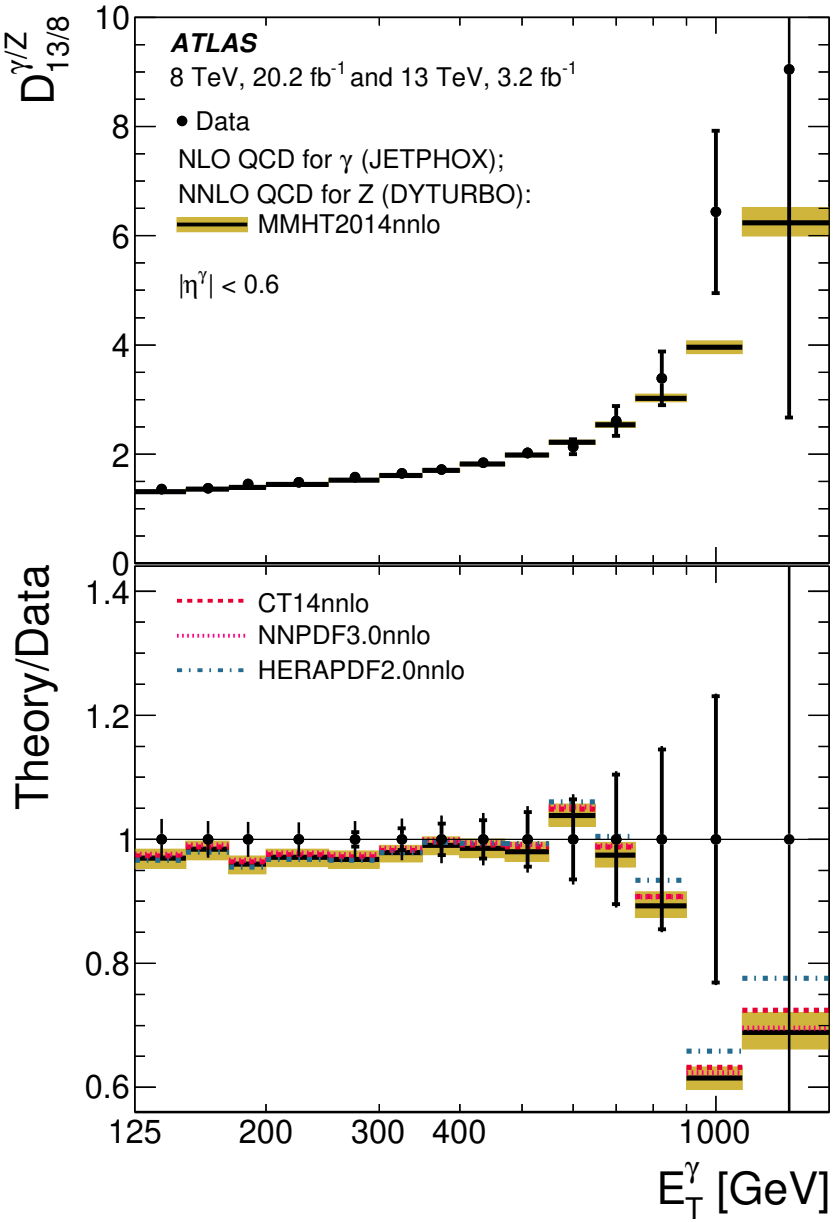
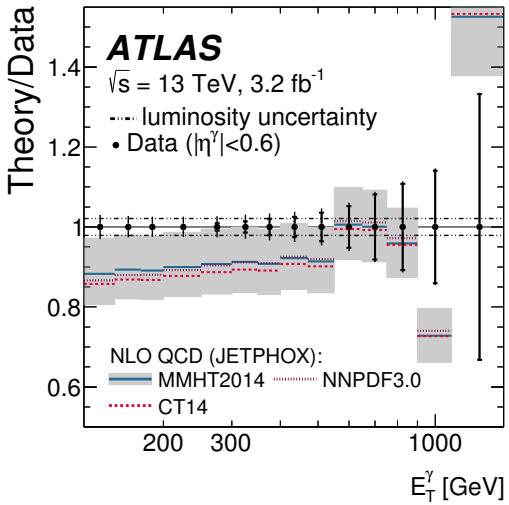
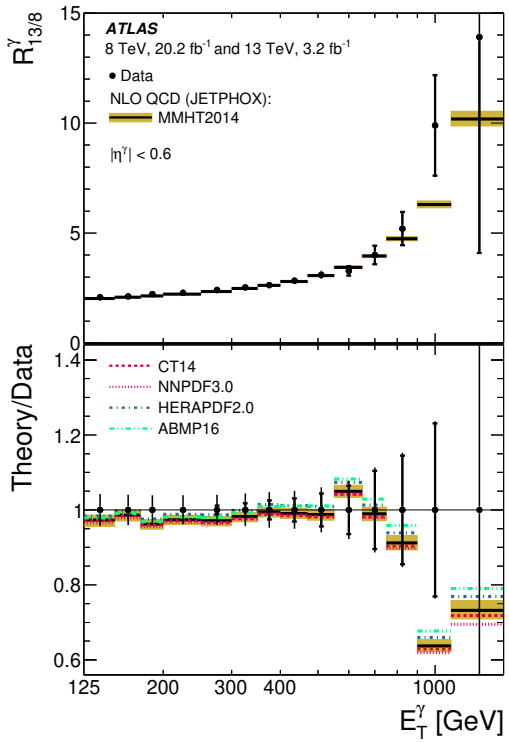


Summary and conclusions

- Measurement of the ratio $R^{\gamma}_{13/8}$ of cross sections for inclusive isolated-γ production in pp collisions at $\sqrt{s} = 13$ and 8 TeV.
- The **systematic uncertainties in the ratio $R^{\gamma}_{13/8}$ account for the** correlations between the measurements at the two $\sqrt{s}$:
  $\rightarrow$ The γ**ES uncertainty is reduced significantly** in the ratio.
  $\rightarrow$ The **total systematic uncertainty is below 5%** for most of the phase space.
- The measured $R^{\gamma}_{13/8}$ is compared to the predictions from NLO pQCD. **The theoretical uncertainties are evaluated taking into account the correlations** between the two $\sqrt{s}$, resulting in a **significant reduction**.
- The NLO pQCD predictions based on different PDFs agree with the data, being consistent within the uncertainties. The level of agreement achieved **validates the description of the evolution of isolated-photon production** in pp collisions from $\sqrt{s} = 8$ to 13 TeV.
- Measurements of the double ratio of $D^{\gamma/Z}_{13/8}$ lead to **a more precise measurement of the evolution** of the inclusive-photon cross section with the $\sqrt{s}$, normalised to that of Z boson production.





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