Measurements of prompt photon production with the ATLAS detector

Daniel Camarero, Universidad Autónoma de Madrid
on behalf of the ATLAS collaboration

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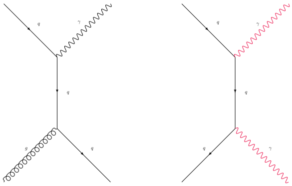
ATLAS EXPERIMENT

Outline

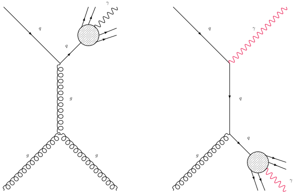
- Introduction
  - Prompt-photon production at the LHC
  - Reconstruction, identification and isolation of photons in ATLAS
  - Theoretical calculations
- Inclusive-photon at 13 TeV using $36\,\mathrm{fb}^{-1}$
- Photon plus two jets at 13 TeV
- Diphoton production at 13 TeV
- Summary and conclusions

Prompt-photon production at the LHC (I)

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



Direct processes



Fragmentation processes

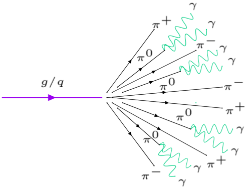
Measurements of prompt-photon production inclusively and in association with jets allow tests of pQCD and

- provide constraints on the proton PDF,
  - $\rightarrow$ sensitivity to gluon PDF already at LO via the $qg \rightarrow \gamma q$ process;
- allow a deeper understanding of the dynamics of direct and fragmentation underlying mechanisms;

In addition, measurements of diphoton production provide a better understanding of background processes for $H \rightarrow \gamma\gamma$ and BSM searches;

Prompt-photon production at the LHC (II)

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

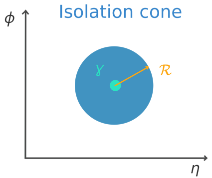


$\rightarrow$ Isolation mostly suppresses the contribution of photons inside jets and the fragmentation-photon processes.

- At experimental level, a *fixed-cone* isolation criterion is used, requiring the isolation transverse energy ($E_{\mathrm{T}}^{\mathrm{iso}}$) to fulfil

$$E_{\mathrm{T}}^{\mathrm{iso}} \equiv \sum_{\mathrm{i}} E_{\mathrm{T}}^{\mathrm{i}} < E_{\mathrm{T}}^{\mathrm{max}},$$

summing over the particles (except the photon) inside a cone of radius R centred on the photon in the $\eta - \phi$ plane.

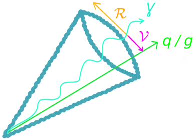


- Theoretical calculations can be considerably simplified if a *smooth-cone* (Frixione's) isolation criterion is applied:

$$E_{\mathrm{T}}^{\mathrm{max}}(\mathcal{V}) = \epsilon\, E_{\mathrm{T}}^{\gamma} \left(\frac{1 - \cos(\mathcal{V})}{1 - \cos(\mathcal{R})} \right)^{n}, \text{ for all } \mathcal{V} < \mathcal{R}.$$

However, its experimental application is not possible.

$\rightarrow$ The use of an **hybrid-cone isolation**, combining the smooth-cone and fixed-cone prescriptions is useful to reduce differences between experiment and theory.



Photon reconstruction in ATLAS

Photons are reconstructed from clusters of energy in the EM calorimeter (Lead-Liquid Argon, LAr). Three longitudinal layers:

- 1^{st} layer: high granularity in the η direction;
- 2^{nd} layer: collects most of the energy;
- 3^{rd} layer: used to correct for leakage.

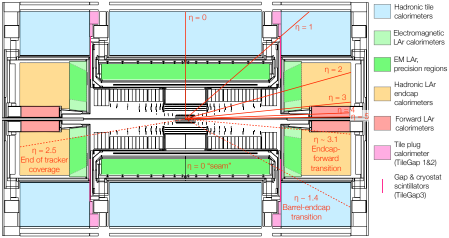
The **reconstruction of photons** is different for converted and unconverted categories:

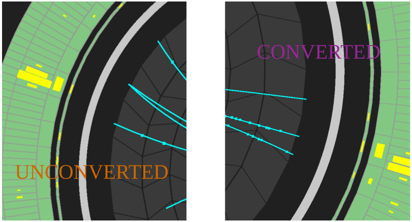
- **Unconverted photon candidate:** cluster of EM cells without a matching track or conversion vertex in the inner detector.
- **Converted photon candidate:** cluster of EM cells matched to a track (or pair of tracks) consistent with originating from a reconstructed photon conversion.

After reconstruction, a **calibration procedure** is applied to the photon candidates.

ATLAS coll., JINST **14** (2019) P12006

ATLAS coll., Eur. Phys. J. C **81** (2021) 689





Photon identification in ATLAS

To discriminate between signal and background photons, different cuts in shape variables from the lateral and longitudinal energy profiles of the shower in the calorimeters are studied.

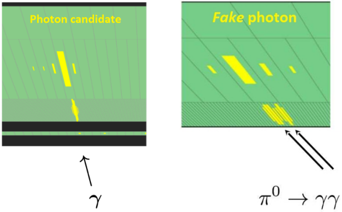
Loose and *Tight* identification criteria are used:

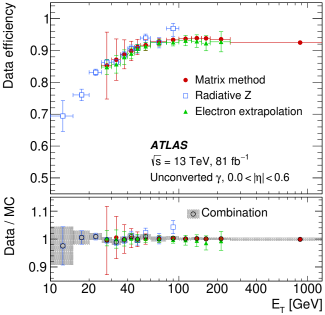
- **Loose identification criteria:**

Discrimination of γ from electrons and hadrons using the 2^{nd} and 3^{rd} layers of LAr and the 1^{st} layer of the hadronic calorimeter (HCAL).

- **Tight identification criteria:**

Discrimination of single-photon showers using the 1^{st} layer of the LAr from overlapping nearby showers, such as $\pi^0 \to \gamma\gamma$, in addition to tighter requirements on the shower shapes of the other layers.





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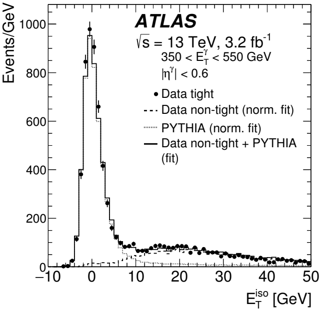
Photon isolation in ATLAS

The isolation transverse energy (E_T^{iso}) is computed at detector level using clusters of calorimeter cells (EMC and HCAL) in a cone of $R = 0.4$ or $R = 0.2$, excluding the area centred on the photon cluster.

Corrections applied:

– for the expected leakage of the photon energy into the isolation cone (few $\%$);

– for the underlying event and pile-up contributions to E_T^{iso} using the jet-area method.



ATLAS coll. Phys. Lett. B **780** (2018) 578

A photon candidate is considered isolated if the condition $E_T^{iso} < E_{T,cut}^{iso}$ is fulfilled.

Measurement	Detector level $E_{T,cut}^{iso}$ [GeV]	Particle level $E_{T,cut}^{iso}$ [GeV]
Inclusive γ ($R = 0.4$)	$4.2 \times 10^{-3} \times E_T^{\gamma} + 4.8$	
$\gamma + 2\,\mathrm{jet}$ ($R = 0.4$)	$4.2 \times 10^{-3} \times E_T^{\gamma} + 4.8$	$4.2 \times 10^{-3} \times E_T^{\gamma} + 10$
Diphoton ($R = 0.2$)	$0.05 \times E_T^{\gamma}$	$0.09 \times E_T^{\gamma}$

Residual background is still expected even after tight identification and isolation requirements.

Jet-area method (M. Cacciari et al., JHEP **04** (2010) 065)

Theoretical calculations

pQCD predictions used for the inclusive-photon and photon plus two jets analyses:

JETPHOX (fixed order):

– Full fixed-order NLO pQCD predictions for direct and fragmentation processes.
– Scales: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \mu_{\mathrm{f}} = E_{\mathrm{T}}^{\gamma}$ and $E_{\mathrm{T}}^{\gamma}/2$.
– Fragmentation functions: BFG set II.
– PDF: MMHT2014 NLO.
– Isolation: fixed cone at parton level.
– Non-perturbative corrections: consistent with unity within $\pm 1\%$ (no correction is applied).

NNLOJET (fixed order):

– Fixed-order NNLO pQCD predictions for direct contributions.
– Scales: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = E_{\mathrm{T}}^{\gamma}$.
– PDF: NNPDF3.1 NNLO.
– Isolation: hybrid cone at parton level.
– Non-perturbative corrections: same estimation as for JETPHOX.

SHERPA NLO (multi-leg merged):

– Parton level calculations for $\gamma + 1, 2\ (3, 4)$ jets at NLO (LO) supplemented with PS.
– Only direct contributions (hybrid-cone isolation).
– Scales: dynamic scale setting (E_{T}^{γ}).
– PDF: NNPDF3.0 NNLO.
– Predictions at particle level.

Theoretical uncertainties:

– Scale variations (scales $\times 0.5$ or $\times 2$ varied singly or simultaneously).
– PDF and α_{S} (for NNLOJET, both uncertainties are included as estimated at NLO with JETPHOX).
– Non-perturbative corrections: $\pm 1\%$.

Inclusive-photon production at 13 TeV

Measurement of the differential cross section for inclusive isolated photon production in pp collisions at $\sqrt{s} = 13$ TeV using $36.1\,\text{fb}^{-1}$.

ATLAS coll., JHEP **10** (2019) 203

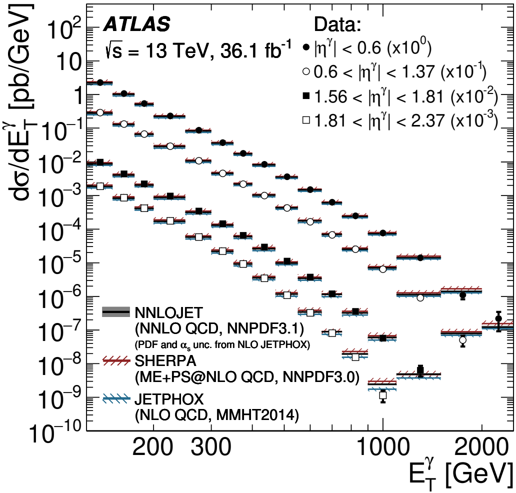
$\mathrm{d}\sigma/\mathrm{dE}_\mathrm{T}^\gamma$ measured as a function of E_T^γ in different regions of $|\eta^\gamma|$.

- Photons with $E_\mathrm{T}^\gamma > 125$ GeV and $|\eta^\gamma| < 2.37$ (excluding those in $1.37 < |\eta^\gamma| < 1.56$ region).

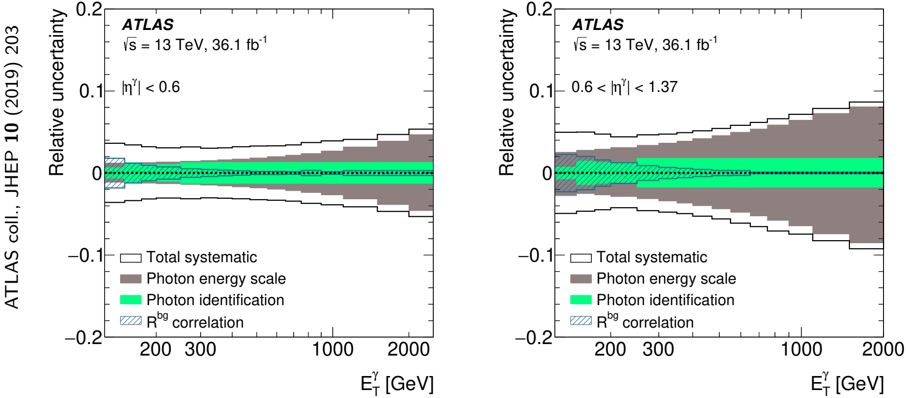
- The data was unfolded to the particle level with an isolation requirement:

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

- The E_T^γ reach has been extended to 2.5 TeV with respect to the previous measurement at 13 TeV thanks to the ten-fold increase in luminosity.



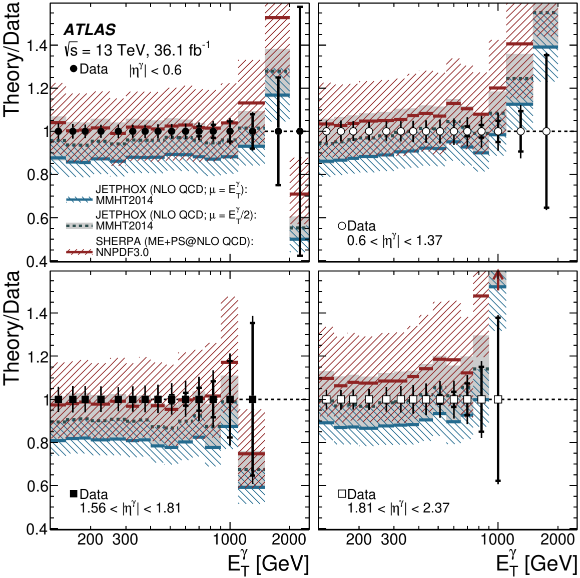
Inclusive-photon production at 13 TeV



- The uncertainty due to the photon energy scale dominates at high E_{T}^{γ}: $1\% - 8\%$, being larger in the region $1.56 < |\eta^{\gamma}| < 1.81$, where it is $4\% - 16\%$.
- The uncertainty due to the photon identification represents a significant contribution at low and medium E_{T}^{γ}: $1\% - 3\%$.

→ The range in which the measurement is limited by systematic uncertainties has been extended to $E_{\mathrm{T}}^{\gamma} \sim 1$ TeV for the region $|\eta^{\gamma}| < 1.37$ (it was ~ 600 GeV).

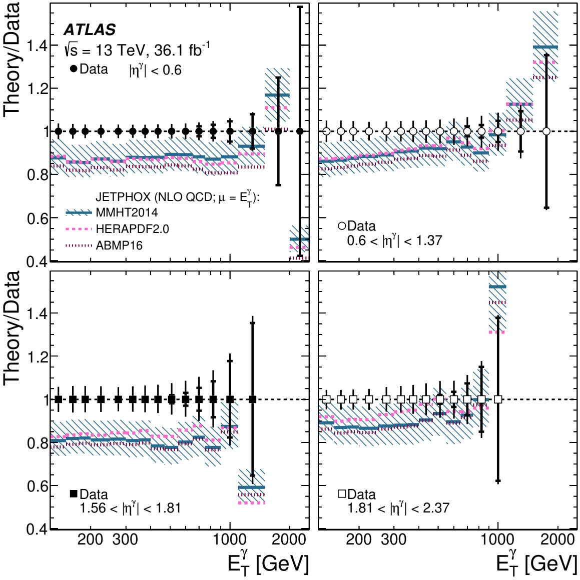
Inclusive-photon production at 13 TeV



- The theoretical predictions of JETPHOX and SHERPA NLO provide an adequate description of the data within the experimental and theoretical uncertainties.
- Comparison of data and theory limited by the theoretical uncertainties due to the terms beyond NLO.

ATLAS coll., JHEP **10** (2019) 203

Inclusive-photon production at 13 TeV



Sensitivity to the PDF:

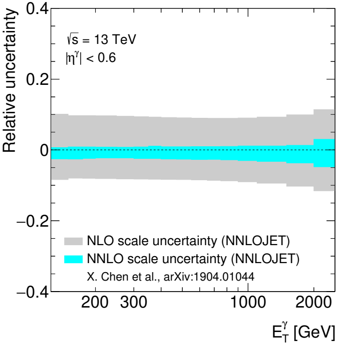
→ PDF: MMHT2014, HERAPDF2.0, and ABMP16

- Comparison with predictions based on different PDF parameterisations shows the sensitivity to the proton PDF.

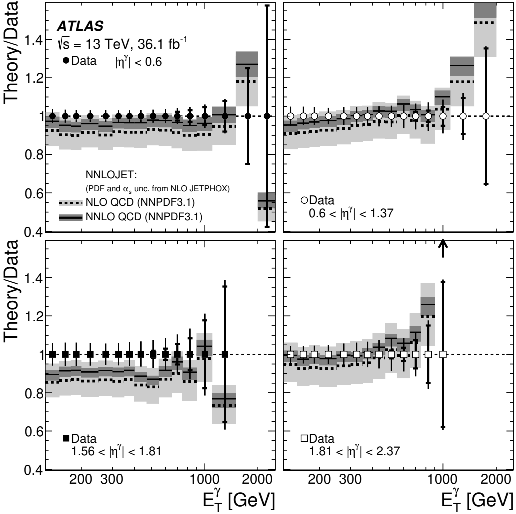
ATLAS coll., JHEP **10** (2019) 203

NNLO predictions improvements:

X. Chen et al., JHEP **04** (2020) 166



→ Uncertainties due to the scale variations reduced by more than a factor of 2 with respect to those of NLO calculations.



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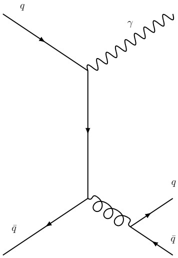
→ The NNLO pQCD calculation gives an excellent description of the data.

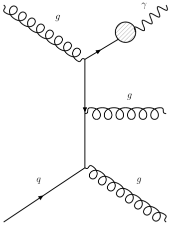
→ Stringent test of the theory for isolated photon production at $\mathcal{O}(\alpha_{\rm EM}\alpha_{\rm S}^3)$.

Photon plus two jets at 13 TeV

Measurement of the isolated-photon plus two-jet production in pp collisions at $\sqrt{s} = 13$ TeV using $36.1\,\mathrm{fb}^{-1}$.

- Study of the kinematics and dynamics of the $\gamma + 2$ jet system by measuring the cross section as a function of E_T^{γ}, p_T^{jet}, $|y^{\mathrm{jet}}|$, $\Delta\phi^{\gamma-\mathrm{jet}}$, $|\Delta y^{\gamma-\mathrm{jet}}|$, $m^{\mathrm{jet-jet}}$, $\Delta\phi^{\mathrm{jet-jet}}$, $|\Delta y^{\mathrm{jet-jet}}|$, and $m^{\gamma-\mathrm{jet-jet}}$.
- Enhanced sensitivity to the dynamics of direct and fragmentation underlying processes by studying two phase-space selections (in addition to the inclusive):
  - Direct enriched: $E_T^{\gamma} > p_T^{\mathrm{jet1}}$.
  - Fragmentation enriched: $p_T^{\mathrm{jet2}} > E_T^{\gamma}$.
- Phase space given by:
  - Tight-isolated photon with $E_T^{\gamma} > 150$ GeV and $|\eta^{\gamma}| < 2.37$ (excluding $1.37 < |\eta^{\gamma}| < 1.56$).
  - Jets with $p_T^{\mathrm{jet}} > 100$ GeV, $|y^{\mathrm{jet}}| < 2.5$, and $\Delta R^{\gamma-\mathrm{jet}} > 0.8$.

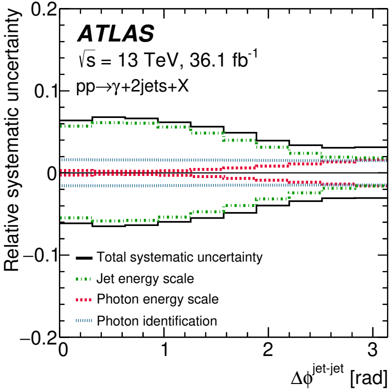


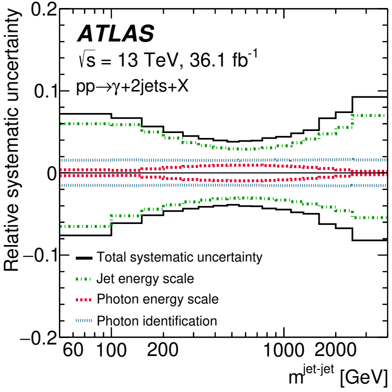


ATLAS coll., JHEP **03** (2020) 179

Photon plus two jets at 13 TeV

ATLAS coll., JHEP **03** (2020) 179





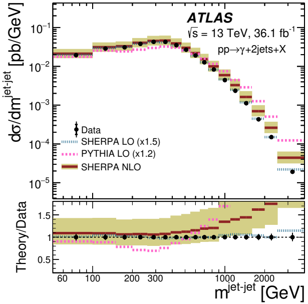
- The dominant systematic uncertainties are those due to the jet energy scale, photon energy scale and photon identification.
- In the inclusive phase space, the systematic uncertainty dominates the total experimental uncertainty except for $E_T^{\gamma} \gtrsim 1$ TeV, $p_T^{\text{jet}} \gtrsim 1.5$ TeV, and $m^{\text{jet-jet}} \gtrsim 4$ TeV.

Photon plus two jets at 13 TeV

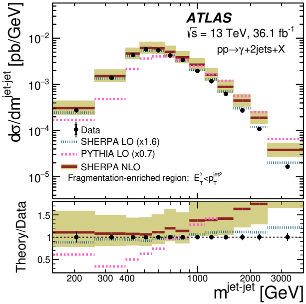
- Adequate description of the shape and normalisation of the data by SHERPA NLO within uncertainties except at high values of $|\Delta y^{\gamma-\mathrm{jet}}|$, $|\Delta y^{\mathrm{jet-jet}}|$, $m^{\mathrm{jet-jet}}$ and $m^{\gamma-\mathrm{jet-jet}}$.
- The predictions of the tree-level plus parton-shower MC models of PYTHIA and SHERPA LO are also compared with the data.

  $\rightarrow$ SHERPA LO provides a good description of the shape of the data except at high E_{T}^{γ}, $|\Delta y^{\mathrm{jet-jet}}|$ and $m^{\gamma-\mathrm{jet-jet}}$, while PYTHIA fails.

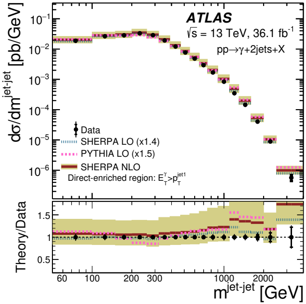
INCLUSIVE



FRAGMENTATION enriched



DIRECT enriched



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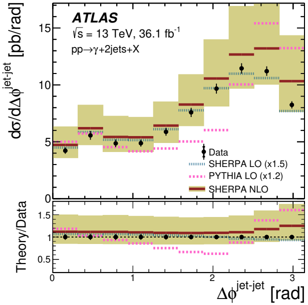
Photon plus two jets at 13 TeV

- The cross sections in the fragmentation- and direct-enriched phase space regions exhibit the expected features from the two underlying production mechanisms dominating in each sample.

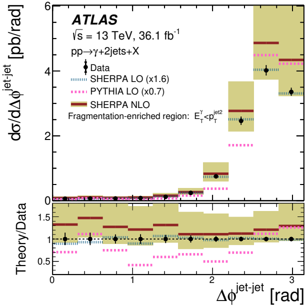
- Test of pQCD at energy scales as high as 2 TeV for the photon and jet p_{T}.

  $\rightarrow$ Theoretical uncertainties are much larger than the experimental ones, preventing a more precise test of the theory.

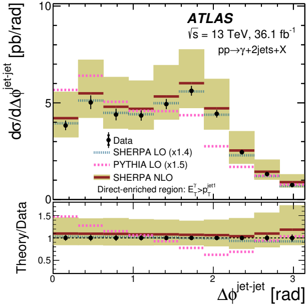
INCLUSIVE



FRAGMENTATION enriched



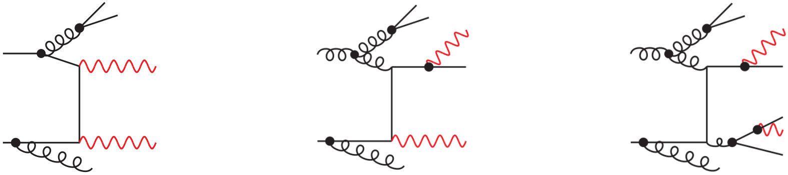
DIRECT enriched



ATLAS coll., JHEP **03** (2020) 179

Diphoton production at 13 TeV

Measurement of the production cross section of pairs of isolated photons in pp collisions at 13 TeV with the ATLAS detector using $139\,\mathrm{fb}^{-1}$.



- Differential cross sections as a function of several diphoton observables: p_{T,γ_1}, p_{T,γ_2}, $m_{\gamma\gamma}$, $|\cos\theta^*|^{(\mathrm{CS})}$, ϕ^*_η, $\pi - \Delta\phi_{\gamma\gamma}$, $p_{\mathrm{T},\gamma\gamma}$ and $a_{\mathrm{T},\gamma\gamma}$.

  $\rightarrow$ $\phi^*_\eta = \tan((\pi - \Delta\phi_{\gamma\gamma})/2)\,\sin\theta^*_\eta$, and $a_{\mathrm{T},\gamma\gamma}$ is the transverse component of $p_{\mathrm{T},\gamma\gamma}$ with respect to the thrust axis.

- Variables $m_{\gamma\gamma}$ and $p_{\mathrm{T},\gamma\gamma}$ are sensitive to higher-order corrections, and $\pi - \Delta\phi_{\gamma\gamma}$, $a_{\mathrm{T},\gamma\gamma}$ and ϕ^*_η are specially sensitive to infrared emissions.

- Phase space selection:
  - Tight-isolated photons with $p_{\mathrm{T},\gamma_{1(2)}} > 40\,(30)$ GeV, $|\eta^\gamma| < 2.37$ (excluding $1.37 < |\eta^\gamma| < 1.52$), and $\Delta R_{\gamma\gamma} > 0.4$.

ATLAS coll., arXiv:2107.09330 (Submitted to JHEP)

Diphoton production at 13 TeV

- **Backgrounds that affect this measurement:**
  (a) Dominant background from jets faking photons: estimated using a data-driven method.
  (b) Few percent from the e^+e^- background.
  (c) Sub-percent contribution of pile-up background.
  $\rightarrow$ **Purities above 50%** in all observables except in the low $m_{\gamma\gamma}$ region.

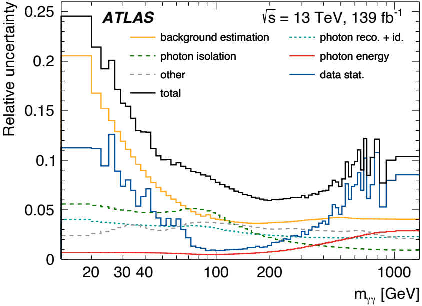
- **Sources of systematic uncertainties:**

– **Background estimation:** dominated by the component from the multi-jet background. Typically $< 5\%$.

– **Photon selection:** dominated by the photon isolation ($\sim 1\% - 6\%$), reconstruction and identification (typically $< 3\%$).

– **Other components:** dominated by the data period stability and luminosity uncertainties. Uncertainty in the range $2\% - 7\%$.

– **Data statistics:** dominant at high p_{T} & $m_{\gamma\gamma}$.



ATLAS coll., arXiv:2107.09330

Diphoton production at 13 TeV

pQCD predictions used for the diphoton measurement:

DIPHOX (fixed order):

- Fixed-order NLO pQCD predictions for direct, single- and double-fragmentation processes.
- Scales: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \mu_{\mathrm{f}} = m_{\gamma\gamma}$.
- PDF: CT10 NLO.
- Isolation: fixed cone at parton level.
- Non-perturbative corrections: negligible except in soft or collinear regions of phase space. Not applied.

NNLOJET (fixed order):

- Fixed-order NNLO pQCD predictions for direct contributions.
- Scales: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = m_{\gamma\gamma}$.
- PDF: NNPDF3.0 NNLO.
- Isolation: hybrid cone at parton level.
- Non-perturbative corrections: same strategy as for DIPHOX.

SHERPA NLO (multi-leg merged):

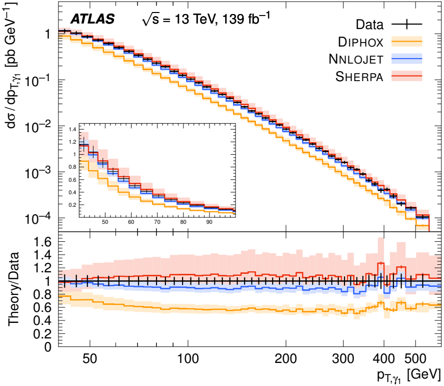
- Parton level calculations for $\gamma\gamma + 0, 1$ $(2, 3)$ jets at NLO (LO) supplemented with PS.
- Only direct contributions (hybrid-cone isolation).
- Scales: dynamic scale setting.
- PDF: NNPDF3.0 NNLO.
- Predictions at particle level.

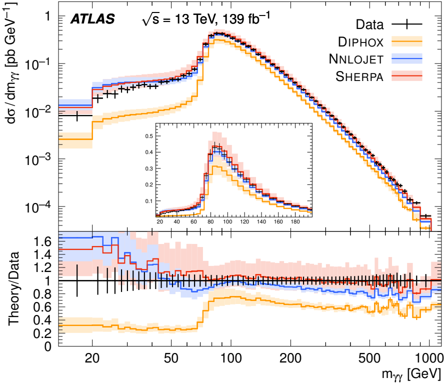
Theoretical uncertainties:

- Scale variations (scales $\times 0.5$ or $\times 2$ varied singly or simultaneously).
- PDF and α_{S} (only included for SHERPA).

Diphoton production at 13 TeV

- Good agreement generally found with predictions of SHERPA and NNLOJET:
  - The multi-leg merged prediction of SHERPA yields larger uncertainties but gives the best description of the data.
  - Satisfactory description of the data by NNLOJET except in the intermediate and low regions of $p_{\mathrm{T},\gamma\gamma}$, $\pi - \Delta\phi_{\gamma\gamma}$, $a_{\mathrm{T},\gamma\gamma}$ and ϕ^*_η, which are sensitive to collinear and low-energy emissions.





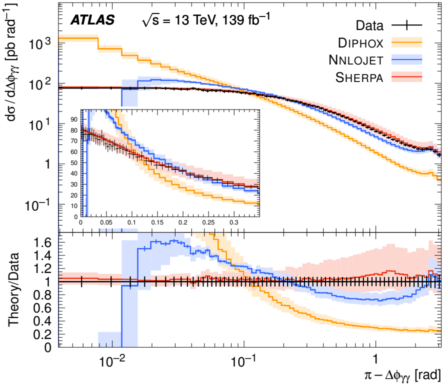
ATLAS coll., arXiv:2107.09330

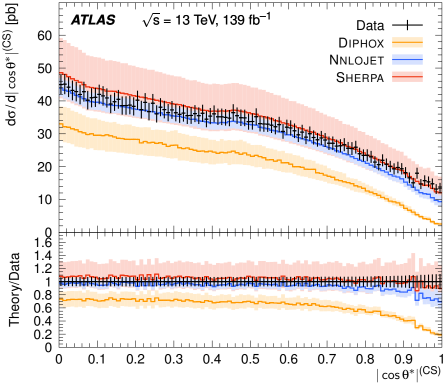
Diphoton production at 13 TeV

– The fixed-order prediction from DIPHOX fails describing the normalisation and shape of the different observables and the associated uncertainties are severely underestimated.

- An impressive improvement is observed from the higher-order terms in pQCD included for SHERPA and NNLOJET predictions.

→ The inclusion of QCD resummation through parton shower in SHERPA improves the prediction in regions sensitive to infrared parton emissions.





ATLAS coll., arXiv:2107.09330

Summary and conclusions

Inclusive-photon measurement at 13 TeV using $36\,\mathrm{fb}^{-1}$:

- The NNLO pQCD prediction gives an excellent description of the data, with significantly reduced theoretical uncertainties.
- The measurement has the potential to constrain the PDF within a global NNLO QCD fit.

Photon plus two jets at 13 TeV using $36\,\mathrm{fb}^{-1}$:

- The measurements in the fragmentation- and direct-photon enriched phase space regions exhibit the features expected from the two underlying mechanisms.
- Test of pQCD at energy scales as high as 2 TeV for the photon and jet p_{T} and scrutiny of the NLO QCD description of the dynamics of $\gamma + 2\,\mathrm{jet}$ production.

Diphoton production at 13 TeV using $139\,\mathrm{fb}^{-1}$:

- Diphoton variables sensitive to different aspects of higher-order corrections in pQCD are studied and compared with state-of-the-art theory calculations.
- Only a merged approach with multi-leg matrix elements at NLO (SHERPA) and a fixed-order NNLO calculation (NNLOJET) give a satisfactory description of the data.