Inclusive photon, photon+jet(s) and diphoton production measurements from ATLAS and CMS

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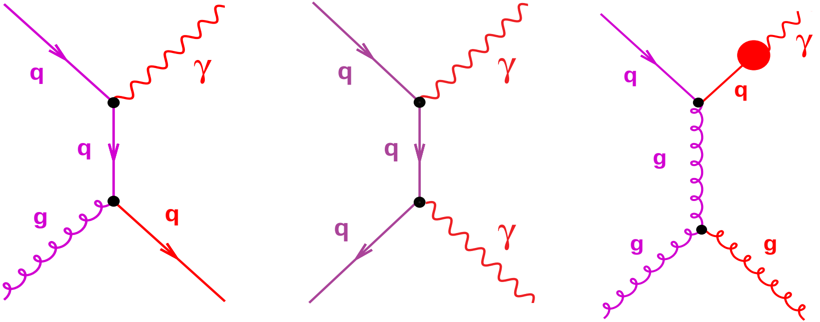
Outline:

★ **Introduction**
★ **Single-photon measurements @ $\sqrt{s} = 13$ TeV**
  ↪ **Inclusive photon and photon+jet (CMS)**
  ↪ **Inclusive photon, inclusive photon ratio and photon+ jet (ATLAS)**
★ **Multi-photon measurements @ $\sqrt{s} = 8$ TeV**
  ↪ **Diphoton (ATLAS)**
  ↪ **Triphoton (ATLAS)**
★ **Summary**

PROMPT PHOTONS: **Photons not coming from hadron decays**



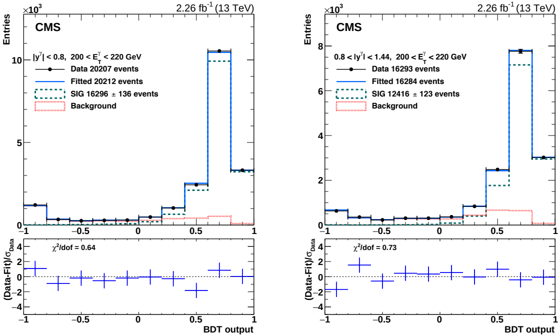
DIRECT **FRAGMENTATION**

- Test of pQCD with a hard colorless probe.
  - ↪ Sensitivity to gluon PDF at LO through Compton scattering.
- Background of BSM searches and SM measurements (H$\rightarrow \gamma\gamma$).
  - ↪ BSM: Monophoton/jet, extra dimensions, q*, exotic neutral particles, spin-2 gravitons, ...
- Possibilities of studies of inclusive production or in association with jets.
  - ↪ Study of the dynamics of the hard process.
  - ↪ Useful for improving MC modelling.

SINGLE-PHOTON MEASUREMENTS

Eur. Phys. J. C79 (2019) 20

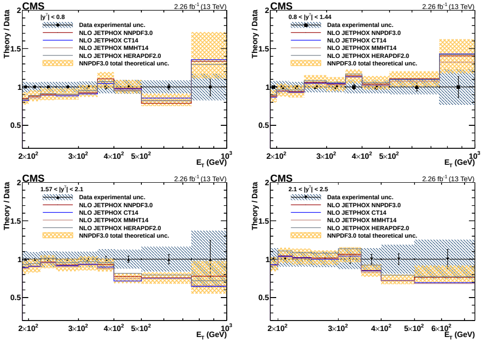
2015 data, $\mathcal{L} = 2.26$ fb^{-1}
$E_{\mathrm{T}}^{\gamma} > 190$ GeV, $|\eta^{\gamma}| < 2.5$
$\notin 1.44 < |\eta^{\gamma}| < 1.57$
$E_{\mathrm{T}}^{\mathrm{iso}} < 5$ GeV, $\Delta R^{\gamma-\mathrm{j}} > 0.4$
Anti-Kt4 jets, $p_{\mathrm{T}}^{\mathrm{jet}} > 30$ GeV, $|y^{\mathrm{jet}}| < 2.4$

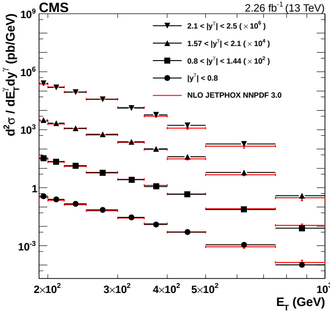


- Electron veto, requirements on H(HCAL)/E, photon and hadron isolation and shower shape variables
- Residual hadronic background removed with a BDT using photon kinematic variables, shower shape variables and ρ
- Photon yields from two-template LH fit using BDT distribution
  $\hookrightarrow$ In each bin of η^{γ} and E_{T}^{γ}
  $\hookrightarrow$ Signal from γ+jets MC (PYTHIA).
  Validated with $Z \to \mu\mu\gamma$ data and $Z \to ee$ with $e \to \gamma$ fakes.
- Background from sidebands in data (relaxed isolation)
- Total systematic uncertainty (w/o luminosity unc.) goes from 5.4 to 26.9% depending on the E_{T}^{γ} and η^{γ} regions. Lumi. unc. is 2.3%

Eur. Phys. J. C79 (2019) 20

- Inclusive isolated-photon results.
- Increase in cross-section by factor 3 to 5 wrt. previous 7 TeV CMS measurements.
- E_{T}^{γ} range extended up to 1 TeV.

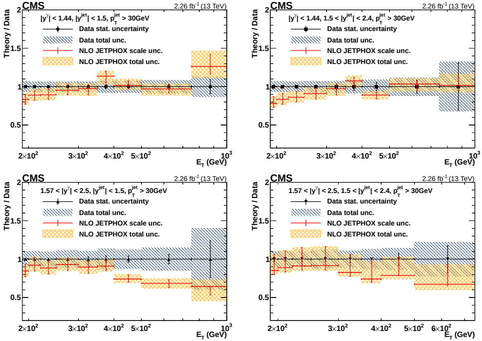


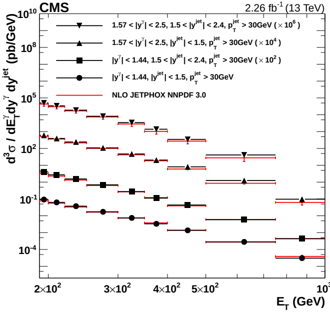


- Good description by NLO pQCD predictions from JETPHOX
  - $\mu_R = \mu_F = \mu_f = E_{\mathrm{T}}^{\gamma}$, NNPDF3.0 PDF and BFG set II.
  - Uncertainties as a quadratic sum of scale variation, PDF- and α_S-induced uncertainties and non-perturbative corrections (from PYTHIA).

Eur. Phys. J. C79 (2019) 20

- Isolated-photon plus jet results. Shown in two $|\eta^{\gamma}|$ and two $|y^{\mathrm{jet}}|$ bins.
- Increase in cross-section by factor 3 to 5 wrt. previous 7 TeV CMS measurements.
- E_{T}^{γ} range extended up to 1 TeV.





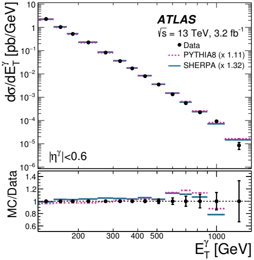
- Adequate description by NLO pQCD predictions from JETPHOX
  - $\mu_R = \mu_F = \mu_f = E_{\mathrm{T}}^{\gamma}$, NNPDF3.0 PDF and BFG set II.
  - Uncertainties as a quadratic sum of scale variation, PDF- and α_S-induced uncertainties and non-perturbative corrections (from PYTHIA).

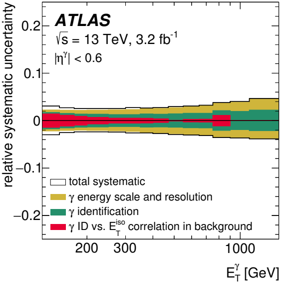
Inclusive isolated-photon at $\sqrt{13}$ TeV. ATLAS

Phys. Lett. B770 (2017) 473

2015 data, $\mathcal{L} = 3.2$ fb^{-1}
$E_T^\gamma >125$ GeV, $|\eta^\gamma| < 2.37$
$\notin 1.37 < |\eta^\gamma| < 1.56$
$E_T^{\rm iso} < 0.0042 E_T^\gamma + 4.8$ GeV

- Photon identification (based on requirements on shower shape variables) and calorimetric isolation applied
- Residual hadronic background removed using 2D-sideband method in the photon identification vs. photon isolation plane
- Negligible electron background estimated from MC samples.
- MC samples used for unfolding and estimation of signal leakage in background control regions.
  ↪ Pythia: 2→ 2 QCD processes + QCD and QED parton shower
  ↪ Sherpa: multi-leg, up to 4 additional partons + QCD parton shower. Frixione's isolation at ME level

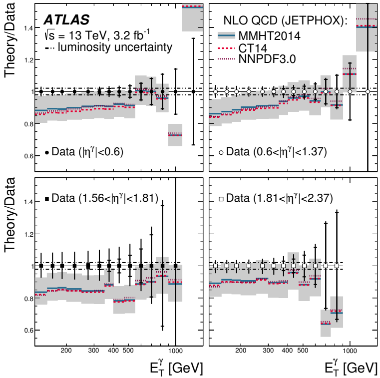


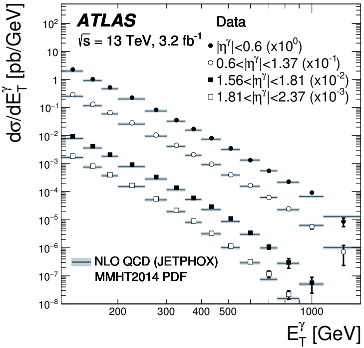


- Systematic uncertainties dominated by γES-RES. Larger in forward regions.

Phys. Lett. B770 (2017) 473

- Cross-section falls by more than 5 orders of magnitude.
- Similar or higher reach in E_{T}^{γ} than 8 TeV ATLAS analysis thanks to the increase of $d\sigma/dE_{\mathrm{T}}^{\gamma}$ with $\sqrt{s}$ (factor 2 (10) at E_{T}^{γ} >125 (1000) GeV).

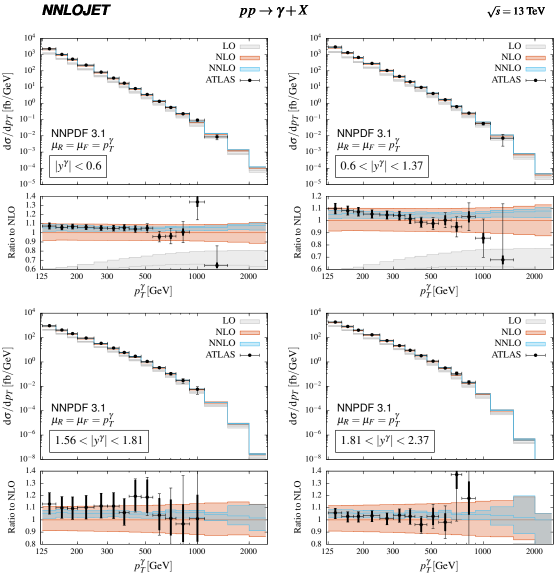




- Adequate description by NLO pQCD predictions from JETPHOX within uncertainties (theory unc. larger than experimental unc. in most of the phase-space)
  - $\mu_R = \mu_F = \mu_f = E_{\mathrm{T}}^{\gamma}$, MMHT2014 PDF and BFG set II.
  - Uncertainties as a quadratic sum of scale variation, PDF- and α_S-induced uncertainties and NP corrections.

Inclusive isolated-photon production at $\sqrt{13}$ TeV. ATLAS

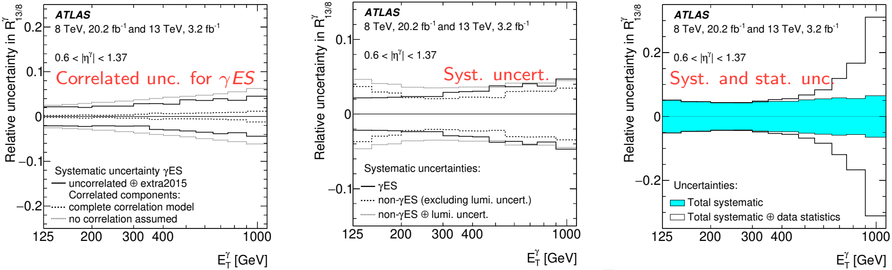
Better description of the measurements by the NNLO predictions
↪ arXiv:1904.01044 (X. Chen, T. Gehrmann, N. Glover, M. Hoefer, A. Huss)



$E_{\mathrm{T}}^{\gamma} > 125$ GeV, $|\eta^{\gamma}| < 2.37 \notin 1.37 < |\eta^{\gamma}| < 1.56$
$E_{\mathrm{T}}^{\mathrm{iso}} < 4.2 \cdot 10^{-3} E_{\mathrm{T}}^{\gamma} + 4.8$ GeV in $\Delta R = 0.4$

- Based on: JHEP 06 (2016) 005 and Phys. Lett. B 770 (2017) 473
- Theory-to-data comparison limited by size of theory unc. (reduced in ratio)
- Stringent test of NLO pQCD + test of the evolution between $\sqrt{s}$
- Full correlation of uncertaintes is only used when justified.
  ↪ Mainly in the estimation of the photon energy scale (extra uncertaintes at 13 TeV for changes in configuration of the ATLAS detector)
  ↪ Other uncertainties taken conservatively as uncorrelated: changes in running conditions, optimization of the photon identification or differences in the estimation of the systematic uncertainties.

JHEP 04 (2019) 093



- Luminosity uncertainty (2.8%, uncorrelated between $\sqrt{s}$) plays a role.

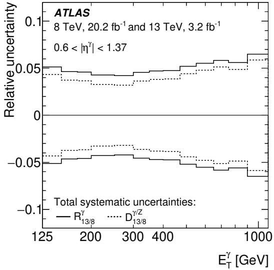
Inclusive cross-section ratios between $\sqrt{s} = 13$ and 8 TeV

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

- Double ratio free of luminosity uncertainty.
- $\sigma^{\text{fid}}_{Z}(13\,TeV)/\sigma^{\text{fid}}_{Z}(8\,TeV)$ measured by ATLAS in JHEP 02 (2017) 117

$$1.537 \pm 0.001 \quad (\text{stat}) \pm 0.010 \quad (\text{syst}) \pm 0.044 \quad (\text{lumi})$$

- Systematic uncertainty of 0.7% dominated by lepton efficiency; three times smaller than systematic uncertainties in $R^{\gamma}_{13/8}$. Small correlations between e and γ energy scale are safely neglected.



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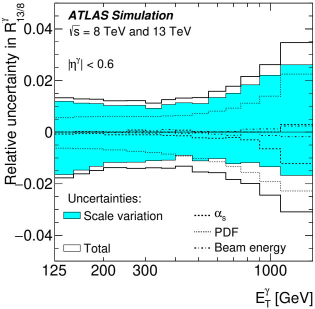
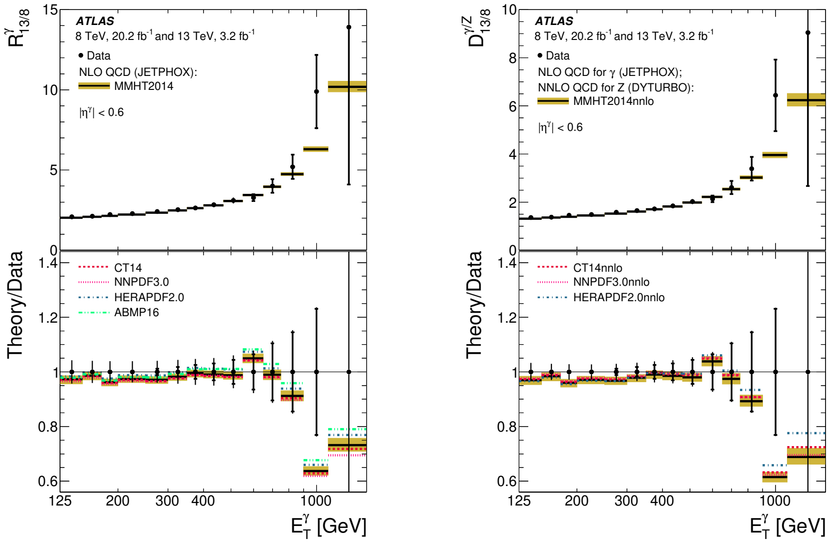


- Theoretical predictions for $R^{\gamma}_{13/8}$ at NLO QCD obtained using JETPHOX.
- $\sigma^{\text{fid}}_{Z}(13\,TeV)/\sigma^{\text{fid}}_{Z}(8\,TeV)$ predictions computed with DYTURBO at NNLO QCD.

↪ Uncertainties due to scale variations, PDF, α_s, beam energy and non-perturbative corrections correlated between both $\sqrt{s}$ in $R^{\gamma}_{13/8}$. Scale variations uncorrelated in $D^{\gamma/Z}_{13/8}$.

→ Large reduction of the theoretical uncertainties compared to those of the individual inclusive photon predictions.

▶ Measured $R^{\gamma}_{13/8}$ and $D^{\gamma/Z}_{13/8}$ compared to pQCD predictions



↪ Predictions agree with the measured $R^{\gamma}_{13/8}$ and $D^{\gamma/Z}_{13/8}$ within the reduced experimental and theoretical uncertainties (2-4%).

JHEP 04 (2019) 093

Photon plus jet at $\sqrt{s} = 13$ TeV. ATLAS

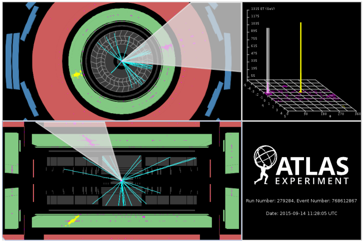
- Measurement of the differential cross sections as functions of E_T^γ, $p_T^{\rm jet}$, $\Delta\phi^{\gamma-{\rm jet\ lead}}$, $m^{\gamma-{\rm jet}}$ and $|\cos\theta^\star|$ with $\mathcal{L} = 3.2$ fb^{-1}.

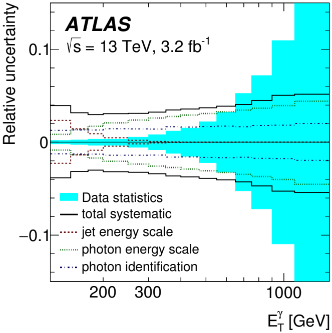
$E_T^\gamma > 125$ GeV, $|\eta^\gamma| < 2.37 \notin 1.37 < |\eta^\gamma| < 1.56$

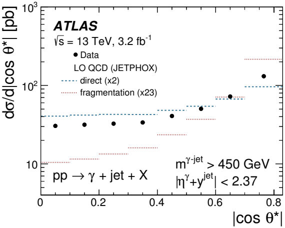
$E_T^{\rm iso} < 4.2\cdot10^{-3} E_T^\gamma + 10$ GeV, $\Delta R^{\gamma-{\rm j}} > 0.8$

$p_T^{\rm jet} > 100$ GeV, $|y^{\rm jet}| < 2.37$

Unbiased selection for $\cos\theta^\star$ and $m^{\gamma-{\rm jet}}$:
$|\eta^\gamma| + |y^{\rm jet}| < 2.37$, $m^{\gamma-{\rm jet}} > 450$ GeV



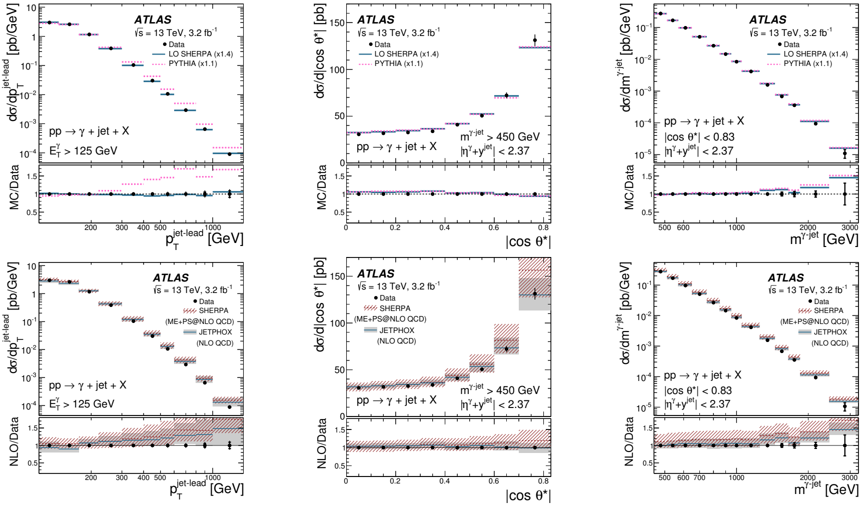




- Total systematic uncertainty (4–5%) dominated by jet energy scale, photon energy scale and photon identification.
- Dominance of the t-channel quark exchange (direct contribution)

Phys. Lett. B 780 (2018) 578

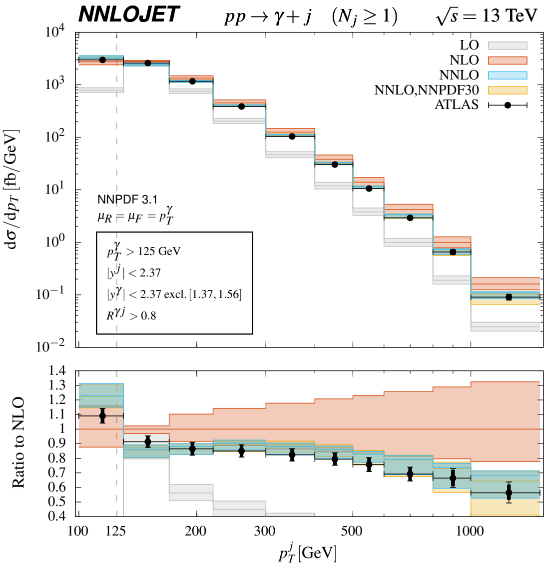
- Comparison of the measured cross sections to the normalized LO SHERPA (multileg) and PYTHIA predictions, and NLO predictions from SHERPA (+ PS) and JETPHOX (corrected for non-perturbative effects) Phys. Lett. B 780 (2018) 578



▶ First measurement of photon + jet production in pp collisions at $\sqrt{s} = 13$ TeV.

Photon plus jet at $\sqrt{s} = 13$ TeV. ATLAS

Impressive improvement on the p_T^{jet} description by higher-order predictions
$\hookrightarrow$ arXiv:1904.01044 (X. Chen, T. Gehrmann, N. Glover, M. Hoefer, A. Huss)



MULTI-PHOTON MEASUREMENTS

$pp \to \gamma + \gamma + X$ at $\sqrt{s} = 8$ TeV

- Differential cross section as a functions of variables sensitive to new physics ($m_{\gamma,\gamma}$, $\cos\theta^\star_\eta$), higher order corrections ($\Delta\phi_{\gamma\gamma}$, $p_{T,\gamma\gamma}$) and to soft gluon emissions (a_T, $\phi^\star_\eta$)- not present at LO.

  $\phi^\star_\eta = \tan\left(\frac{\pi - \Delta\phi_{\gamma\gamma}}{2}\right)\sin\theta^\star_\eta$; a_T = transverse component of $p_{T,\gamma\gamma}$ wrt. the $\vec{t} = \vec{p_{T,\gamma1}} - \vec{p_{T,\gamma2}}$.

$\mathcal{L} = 20.2\ \text{fb}^{-1}$; $E_T^{\gamma1,2} > 40(30)$ GeV
$E_{\mathrm{T}}^{\mathrm{iso}} <$11 GeV in $\Delta R = 0.4$, $\Delta R_{\gamma\gamma} > 0.4$

▶ Dominant systematic uncertainty is the γID

Theoretical tools:

→ **Sherpa 2.2.1**: ME+PS merged at NLO. Combines:

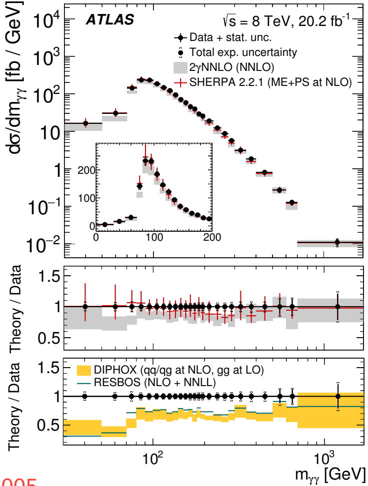
↪ $\gamma\gamma + 0, 1j$ at NLO, $\gamma\gamma + 2, 3j$ at LO

Fixed-order QCD calculations (NP corrected):

→ 2γ**NNLO**: NNLO calculation of direct photon (no fragmentation).

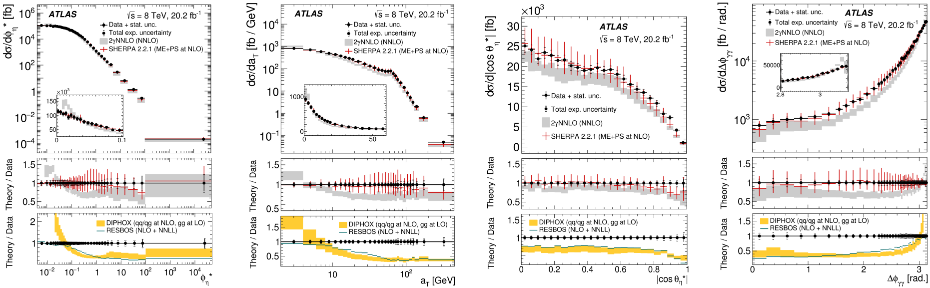
→ **DIPHOX**: Full fixed NLO calculation for direct and fragmentation contribution. Box gluon diagram included (at LO).

→ **RESBOS**: NLO + NNLL.



ATLAS, Phys. Rev. D 95 (2017) 112005

$pp \to \gamma + \gamma + X$ at $\sqrt{s} = 8$ TeV

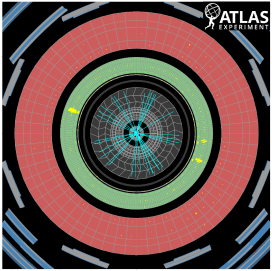


- Theoretical uncertainties dominated by missing higher orders ($\sim 5 - 20\%$). PDF uncertainties around 2%
- Parton-level computations corrected for non-perturbative effects, tipically $< 5\%$.
- At $\Delta\phi_{\gamma\gamma} \sim \pi$ or at low values of $p_{T,\gamma\gamma}$, a_T and $\phi^\star_\eta$, where soft gluon resummation becomes important, RESBOS and SHERPA do well.
- NLO QCD calculations without higher order terms (DIPHOX, RESBOS) are not sufficient and underestimate the data.
- NNLO corrections of 2γNNLO improve the description (although still lies under the data).
- SHERPA predictions provide an improved description of the data for all observables considered.

ATLAS, Phys. Rev. D 95 (2017) 112005

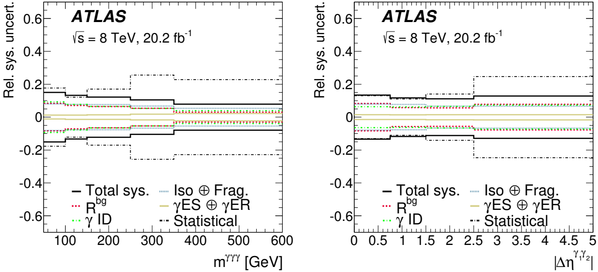
Phys. Lett. B 776 (2018) 295

- First measurement of the differential cross sections (SM rare process) as functions of $E_T^{\gamma1,2,3}$, $\Delta\phi^{\gamma1,1,2-\gamma2,3,3}$, $|\Delta\eta^{\gamma1,1,2-\gamma2,3,3}|$, $m_{\gamma1,1,2-\gamma2,3,3}$ and $m_{\gamma1\gamma2\gamma3}$ with $\mathcal{L} = 20.2\ \text{fb}^{-1}$

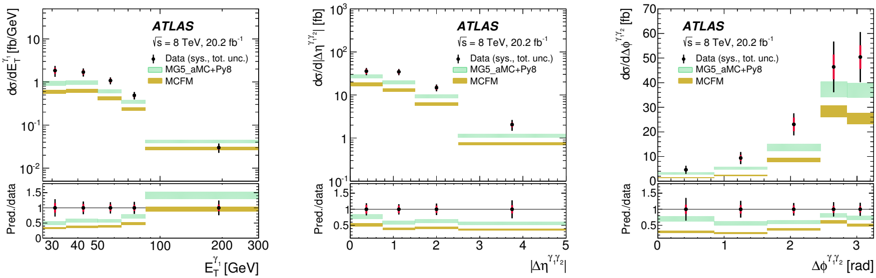


$E_T^{\gamma1(2,3)} > 27(22,15)$ GeV, $|\eta^\gamma| < 2.37 \notin 1.37 < |\eta^\gamma| < 1.56$; $m^{\gamma\gamma\gamma} > 50$ GeV
$E_{\mathrm{T}}^{\mathrm{iso}} < 10$ GeV, $\Delta R^{\gamma,\gamma} > 0.45$

- Dominant systematic uncertainties are related with the background subtraction method and photon identification. Statistically limited.



Triphoton at $\sqrt{s} = 8$ TeV



- Comparisons to MG5_aMC@NLO+PYTHIA parton shower predictions (Frixione's isolation) and fixed-order calculations with MCFM (NLO direct and LO fragmentation).
- Differences up to 60% between measurement and predictions. Normalisation of MG5_aMC@NLO closer to data.
- Adequate description of the shape of angular variables.
- Need for improved modelling of this process:
  - Significant improvement by the NNLO for $\gamma\gamma$ (not available for $\gamma\gamma\gamma$)

Phys. Lett. B 776 (2018) 295

- **Overview of the latest results published by ATLAS and CMS in prompt-photon, photon + jet, diphoton and triphoton production and inclusive photon cross-sections ratios.**

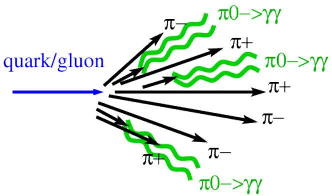
- **Single-photon measurements:**
  → Test of pQCD.
  → Test of the QCD evolution with $\sqrt{s}$ in inclusive-photon production.
  → Experimental input for constraining the gluon PDF together with NNLO calculations.
  → Validity of the description of the dynamics of isolated photon plus jet production up to $\mathcal{O}(\alpha_{\rm EM}\alpha_{\rm s}^3)$.

- **Multi-photon measurements:**
  → Main background for $H \to \gamma\gamma$ and many BSM searches
  → Test of pQCD. Probe of QCD infrared emissions
  → Improvement of the calculations needed for triphoton analysis
  → No measurement results at 13 TeV.

- **New results to come with $\sqrt{s} = 13$ TeV.**

Thank you!

BACK UP



- Photons are copiously produced inside jets due to neutral meson decays.
- In most configurations, these photons are **not isolated**.

PHOTON ISOLATION

★ The isolation requirement suppresses the contribution of photons inside jets: meson decays to pair of photons and fragmentation contribution.

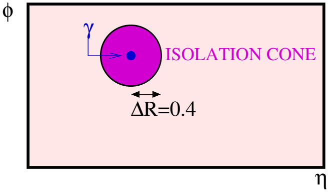
- In general, a fixed-cone isolation requirement is imposed.

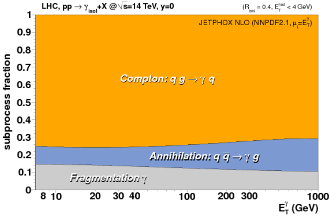
$$E_T^{\rm iso} \equiv \sum_i E_T^i < E_T^{\rm max}$$

- Theoretical predictions are greatly simplified if a smooth-cone isolation (Frixione's) criteria is applied.

$$\chi(R) = \epsilon_s \left(\frac{1-\cos R}{1-\cos R_0}\right)^n ; \quad E_T^{\rm iso}(R) \le E_T^{\gamma}\chi(R)$$

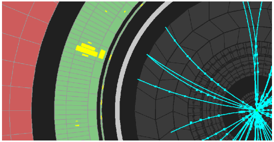
→ Avoid any fragmentation contribution.
→ Impossible experimental implementation.



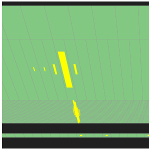


Nucl.Phys. B860(2012) 311-338

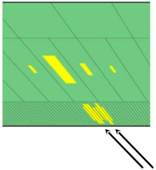
- Photon candidates are reconstructed from clusters of energy in the EM calorimeter (Lead-liquid Argon).
  - ↪ Presampler: To correct for losses upstream of the calorimeter.
  - ↪ First layer: High granularity in η which allows signal photons identification.
  - ↪ Second layer: Collects most of the deposited energy.
  - ↪ Third layer: Used to correct for leakage.



- **"Unconverted"** (cluster of EM cells without matching track) and **"converted"** (clusters of cells with matching track(s) consistent with conversion vertex) photon candidates considered.
- Photon identification from shape variables of the lateral and longitudinal energy profiles of the showers in the calorimeters.
  - ↪ **"loose"**: leakage in the hadronic calorimeter, energy ratios and shower width in the 2^{nd} layer.
  - ↪ **"tight"**: using also information from the first layer.



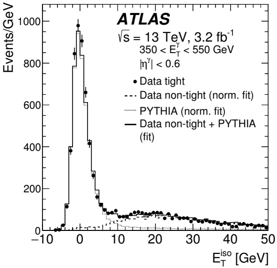
signal photon



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

- The isolation transverse energy, E_T^{iso}, is computed from topological clusters (EM and HAD) in a cone of $R = 0.4$ excluding the area centered on the photon cluster ($\Delta\eta \times \Delta\phi = 0.125 \times 0.175$).
- E_T^{iso} is corrected for the photon leakage out of the photon cluster cells and for pile-up and underlying event effects (jet-area method)

→ The isolation requirement is optimized for each analysis.



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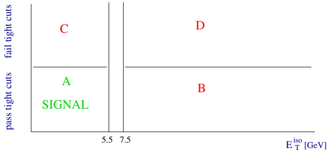
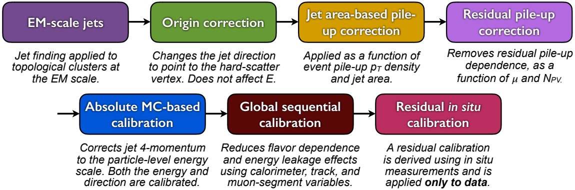
→ Residual background contribution even after the application of the isolation and tight-ID requirements coming from jets misidentified as photons or Drell-Yan processes.

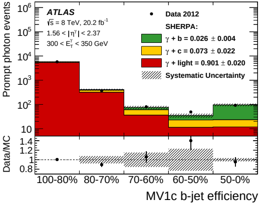


- Data-driven 2D-sideband method:
  $$N_A^{\text{sig}} = N_A - R_{\text{bg}} \frac{(N_B - \epsilon_B N_A^{\text{sig}})(N_C - \epsilon_C N_A^{\text{sig}})}{(N_D - \epsilon_D N_A^{\text{sig}})}$$
- Signal leakage fractions (ϵ_K) and correlations for the background between regions (R_{bg}) taken into account.

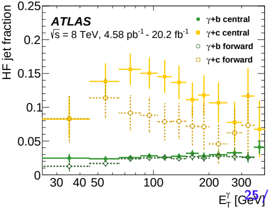
- Built using the anti-k_t algorithm with radius R=0.4 using topoclusters as input.



↪ Backgrounds from beam-halo or beam-gas events, cosmic-ray muons or calorimeter noise removed.



- Flavour-tagging algorithms based on the presence of a secondary vertex or tracks with large impact parameters combined with neural networks to build a discriminant.
- Separate calibration for b-, c- and light jets using $t\bar{t}$, $D^{*\pm}$ or inverting the tagging criteria, respectively.
- Background subtraction in each bin of the measurement and each bin of the discriminant variable.
- Template fits to the discriminant variable to extract the fractions of γ+c and γ+b.



$pp \to \gamma +$ HF at $\sqrt{s} = 8$ TeV

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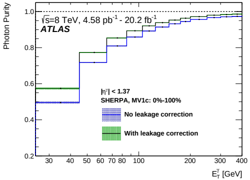
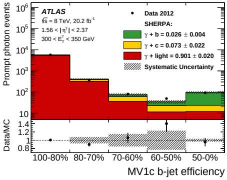
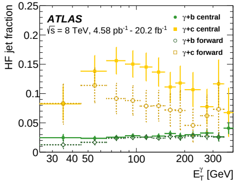
- First measurement of differential cross section as a function of E_T^{γ} in $|\eta^{\gamma}| < 1.37$ and $1.56 < |\eta^{\gamma}| < 2.37$ with $\mathcal{L} = 4.6$ pb^{-1} up to 20.2 fb^{-1}.

$E_T^{\gamma} > 25$ GeV, $|\eta^{\gamma}| < 2.37 \notin 1.37 < |\eta^{\gamma}| < 1.56$
$E_T^{iso} < 4.2 \cdot 10^{-3} E_T^{\gamma} + 4.8$ GeV, $\Delta R^{\gamma - j} > 1.0$
c-/b-tagged jets with $p_T^{jet} > 20$ GeV, $|y^{jet}| < 2.5$

- Signal photon purity larger than 60%. Increase with E_T^{γ}.
- Background subtraction in each bin of the measurement and each bin of the MV1c discriminant efficiency bin. c and b fractions obtained from template fits to the MV1c tagger distribution.







- Dominant systematic uncertainty: flavour tagging efficiency (larger in $\gamma + c$).

Total uncertainty (%)			
$\gamma + b$		$\gamma + c$	
central	forward	central	forward
13–27	14–54	15–62	26–66

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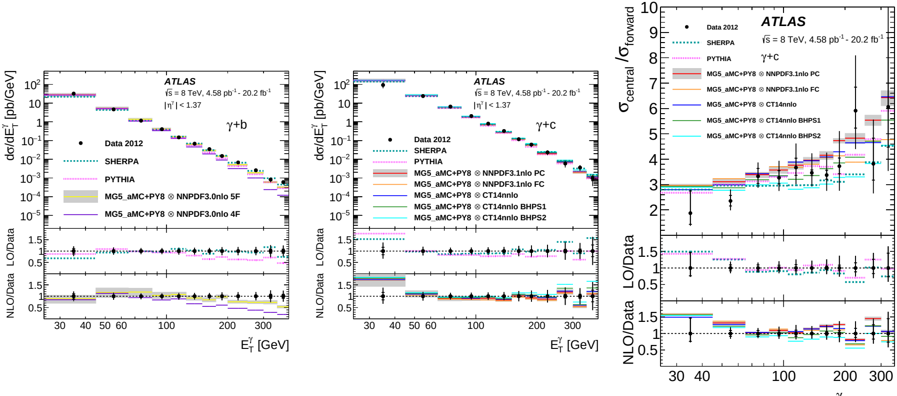

- $\gamma + b$: Madgraph5_aMC@NLO+Pythia8 in 4FS underestimates the data above 125 GeV $\to$ better suited for energies close to the b-quark mass.
- Both FS underestimate the data for $E_T^\gamma > 200$ GeV. $\to$ Significant gluon-splitting contribution; only at LO in the 5F scheme.
- Higher-order calculations needed to improve the description of the data.
- $\gamma + c$: Comparisons to PDF sets with different intrinsic charm contribution
- Precision of the measurement comparable to the size of the deviations observed between diffe rent predictions. $\to$ Better precision in the data is needed to discriminate between models.

Fiducial cross section

- Predictions of MCFM
  $\hookrightarrow$ NLO pQCD predictions for the direct contribution. Fragmentation contribution at LO.
  $\hookrightarrow$ $\mu_{\rm R} = \mu_{\rm F} = \mu_{\rm f} = m^{\gamma\gamma\gamma}$; CT10 PDF; BFGII FF; $\alpha_s(m_Z) = 0.118$; $\alpha_{\rm EM} = 1/137$
  $\hookrightarrow$ Corrected for hadronisation and UE effects.

- Predictions of MadGraph5_aMC@NLO
  $\hookrightarrow$ NLO pQCD contributions for direct process (Frixione's isolation).
  $\hookrightarrow$ Interfaced with PYTHIA8 PS to include ISR and FSR.
  $\hookrightarrow$ $\mu_{\rm R} = \mu_{\rm F} =$ transverse mass of final-state photons and jets; CT10 PDF; $\alpha_s(m_Z) = 0.118$; $\alpha_{\rm EM} = 1/137$.

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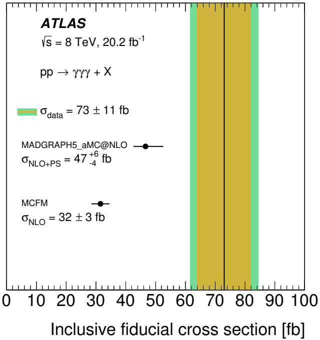

Golden band: systematic uncert.
Green band: syst. + stat. uncert.

- ◇ Theoretical uncertainties include: missing higher orders (dominant), $\alpha_{\rm s}$ and PDF induced uncertainties and the uncertainty on the non-perturbative corrections for MCFM.
- ◇ Similar discrepancies found for $\gamma\gamma$, $W\gamma\gamma$ and $Z\gamma\gamma$ at NLO
  $\hookrightarrow$ Significant improvement by the NNLO for $\gamma\gamma$ (not available for $\gamma\gamma\gamma$).

$pp \to \gamma + Njet + X$ with $N = 1, 2, 3$ at $\sqrt{s} = 8$ TeV

- Measurement of the differential cross sections as functions of: E_T^γ, $p_T^{j1,j2,j3}$, $m_{\gamma,j1}$, $|\cos\theta^\star|$, $\Delta\phi_{\gamma-j1,j2,j3}$, $\Delta\phi_{j1,j1,j2-j2,j3,j3}$
- $E_T^\gamma > 130$ GeV
- Jets (anti-kt, R=0.6) with $p_T^{\text{j1,j2,j3}}$ >100 GeV, 65 GeV and 50 GeV, $|y^{\text{ jet}}| < 4.4$ and $\Delta R^{\gamma-jet} > 1.0$
- Unfolded to particle level with $E_T^{\text{iso}} < 10$ GeV
- The main systematic uncertainty is the one coming from the JES.

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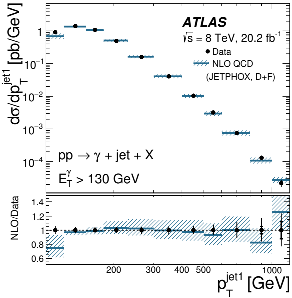
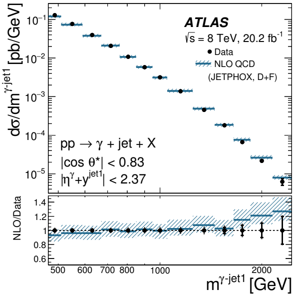
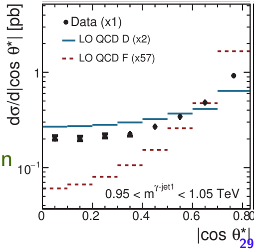
Photon + 1 jet results:

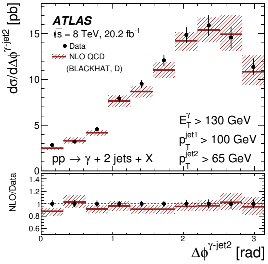


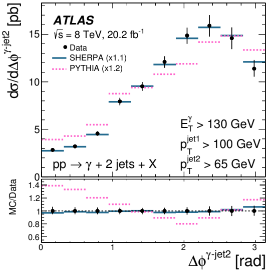


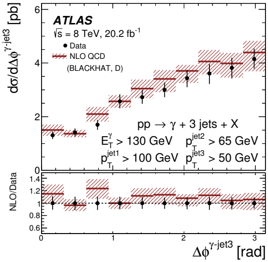
- Increased range with respect to previous measurements.
- Good description of the measured cross sections by the NLO QCD predictions comp uted with JETPHOX.
- $|\cos\theta^*| = |\tanh(\Delta y^{\gamma-\text{jet}}/2)|$ sensitive to the spin of the exchanged particle. Shape closer to the direct contribution (quark exchange in the t-channel).



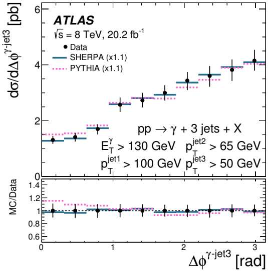
Photon + 2 and 3 jet results (first measurements of these final states at LHC):



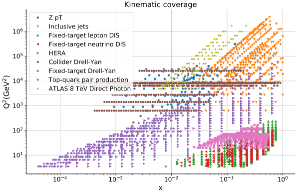


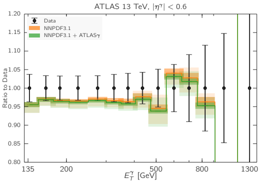


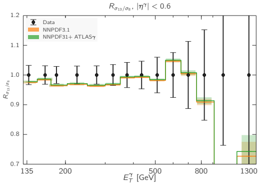
- Comparisons to: Sherpa (higher-order tree-level ME), Pythia (only $2 \to 2$ ME) and BlackHat (NLO direct photon computation corrected for non-perturbative effects and Frixione's isolation cut)
- Sherpa is, in general, superior than Pythia in describing the angular corre lations.
- Good (adequate) description of the shape and the normalisation of the data by the NLO QCD prediction obtained with BlackHat for the γ+2 jet ($\gamma + 3$ jet) sample. Tendency to overestimate the data in the $\gamma + 3$ jet sample.

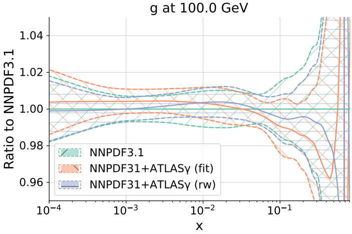


- Direct photon production at NNLO QCD +LL EW; NNPDF3.1NNLO PDF; Frixione's isolation parameters: $\epsilon = 0.1$, $n = 2$, $R_0 = 0.4$; $\mu_R = \mu_F = E_{\mathrm{T}}^{\gamma}$; $\alpha_{\mathrm{EM}}(m_Z) = 1/127.9$.









"LHC direct photon production data leads to both a moderate reduction of the gluon uncertainties at medium–x and a preference for a somewhat softer central value at large–x. These effects are more marked when the direct photon data is added on top of fits based on reduced datasets, in particular the NNPDF3.1 no-LHC fit. [...] collider direct photon production should be rightfully restored to its well-deserved position as a full member of the global PDF analysis toolbox."

J. M. Campbell, J. Rojo, E. Slade, C. Williams; arXiv: 1802.03021