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Recent results on photon physics @ LHC

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ATLAS EXPERIMENT

CMS Compact Muon Solenoid

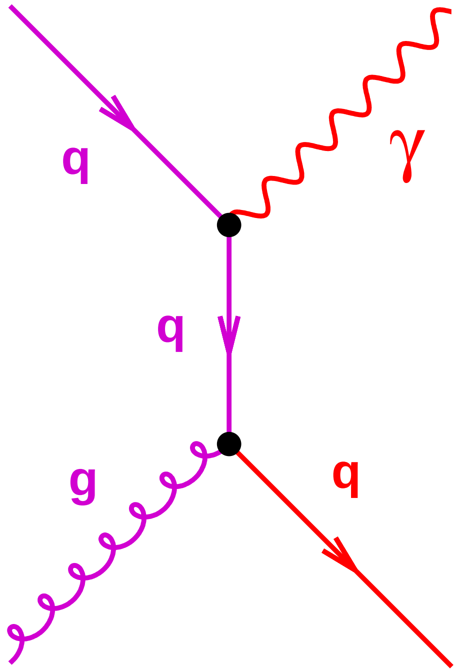
Physics with photons @ LHC

- **Measurements of the production of high p_T prompt photons (in association with jets) in hadron colliders provide**

  $\longrightarrow$ **tests of pQCD predictions**
  - ⋆ **the photon comes directly from the hard interaction (no hadronisation)**
    $\longrightarrow$ **cleaner reaction than jet production**
  - ⋆ **probe of the underlying production mechanism**

  $\longrightarrow$ **experimental information on the proton PDFs**
  - ⋆ **dominant production mechanism: $qg \rightarrow q\gamma$**
  - ⋆ **constraints on the proton PDFs, especially the gluon PDF at high x**

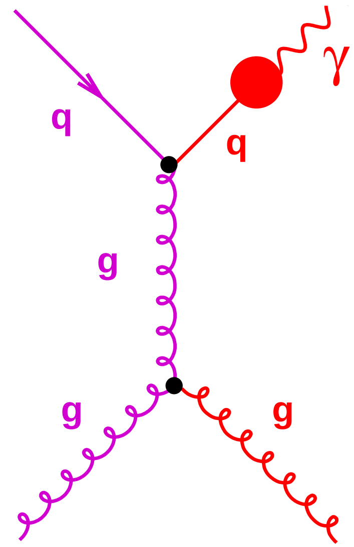
  $\longrightarrow$ **input to understand the background to Higgs production and BSM searches in photon decaying channels**
  - ⋆ **validation of Monte Carlo models**



direct photon (plus jet(s))

Physics with photons @ LHC

- Other sources of photons:
  - $\rightarrow$ hadron decays (eg, $\pi^0 \rightarrow \gamma\gamma$)
    - $\rightarrow$ photons are produced copiously inside jets
    - $\Rightarrow$ isolating photons largely removes this background
  - $\rightarrow$ photon bremsstrahlung off quarks $\longrightarrow$
    - $\Rightarrow$ fragmentation photon process: signal



fragmentation photon

- Thus, to study prompt photons in hadron colliders, it is essential to require the photon to be isolated

- This is achieved by requiring
  - ⋆ cone isolation: $E_T^{\rm iso}(R) \equiv \sum_i E_T^i < E_T^{\rm max}$, with the sum over the particles inside a cone of radius R centered on the photon in the $\eta - \phi$ plane
    - $\rightarrow$ used in experiment to suppress the contribution of photons inside jets
  - ⋆ Frixione isolation: $E_T^{\rm max}(\mathfrak{r}) = \epsilon E_T^{\gamma}((1-\cos\mathfrak{r})/(1-\cos\mathcal{R}))^{\rm n}$ for all $\mathfrak{r} < \mathcal{R}$, where $\mathcal{R}$ is the maximal cone size and ϵ is a constant
  - ⋆ hybrid (Frixione+cone) isolation
    - $\rightarrow$ Frixione or hybrid isolation can be used in theory to avoid divergencies in the matrix elements when the photon is collinear with a parton

Photons @ ATLAS and CMS

Photons @ ATLAS and CMS: photon isolation

- $E_T^{iso}(R)$ is computed by using all particles in a cone of $R = 0.2$, 0.3 or 0.4

- The underlying event and pileup contribute to E_T^{iso}
  $\rightarrow$ event-by-event correction can be computed using the jet-area method (M Cacciari et al, JHEP 0804 (2008) 005)

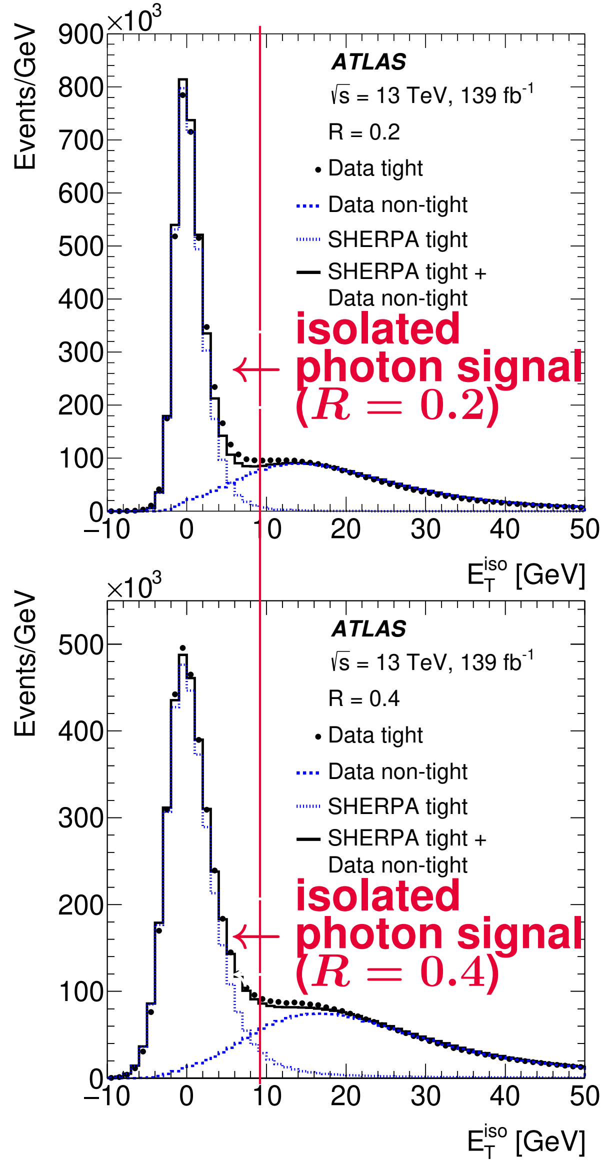
- Clear signal of photon production observed around $E_T^{iso}(R) \approx 0$

$\Rightarrow$ A photon candidate is considered isolated if

$$E_T^{iso}(R) < (E_T^{iso})^{cut}$$

with $(E_T^{iso})^{cut} = 4.2 \cdot 10^{-3} \cdot E_T^{\gamma} + 4.8$ GeV (ATLAS)
and $(E_T^{iso})^{cut} = 5$ GeV (CMS)

- Residual background removed using data-driven (ATLAS) and template-fit (CMS) methods



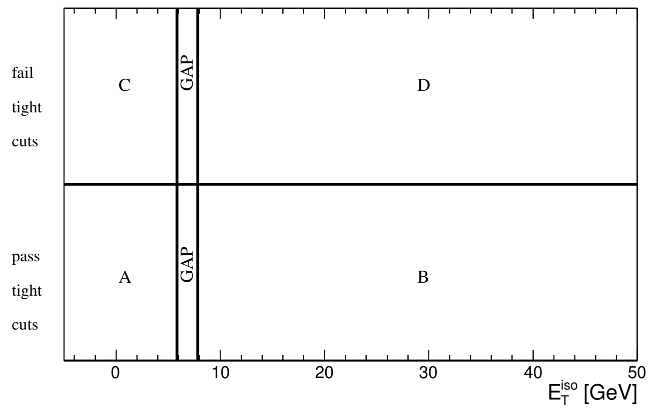
CMS Collab, JHEP 05 (2021) 285 & EPJC 79 (2019) 20 ATLAS Collab, JHEP 07 (2023) 086

Photons @ ATLAS: background subtraction

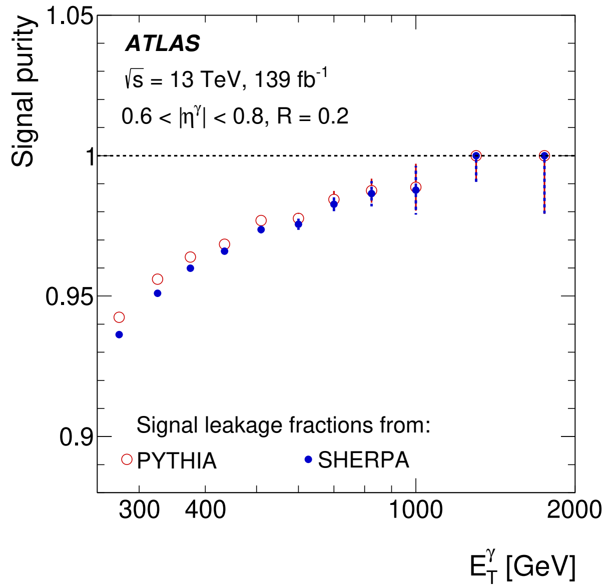
- The main source of background comes from jets misidentified as photons

- A data-driven method is used to avoid relying on detailed simulations of the background processes
  - → two-dimensional sideband method based on γID vs $E_{\mathrm{T}}^{\mathrm{iso}}$ plane and corrected for signal leakage
  - → γID and $E_{\mathrm{T}}^{\mathrm{iso}}$ are assumed to be uncorrelated for the background
  - → region A is the signal region and B, C, D are background control regions with suppressed signal contribution

  in each E_{T}^{γ} and η^{γ} bin measured



- The purity of the signal is estimated as $P = \frac{N_{\mathrm{A}}^{\mathrm{sig}}}{N_{\mathrm{A}}^{\mathrm{obs}}}$
  - → the measured signal purity is larger than 93% for $E_{\mathrm{T}}^{\gamma} > 250$ GeV



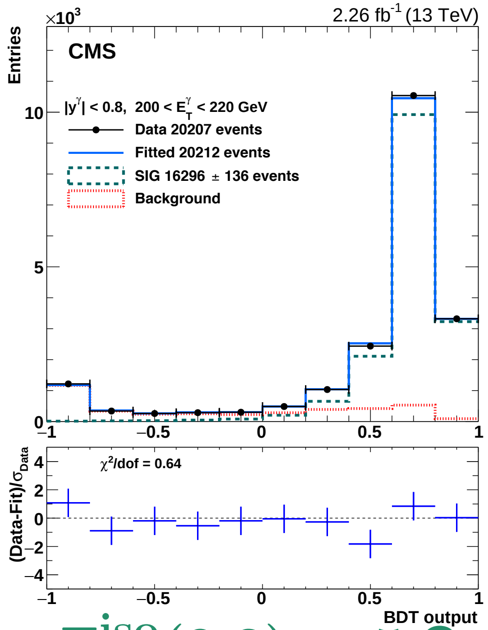
- In this analysis: $E_{\mathrm{T}}^{\mathrm{iso}}(R) < 4.2 \cdot 10^{-3} \cdot E_{\mathrm{T}}^{\gamma} + 4.8\ \mathrm{GeV}$

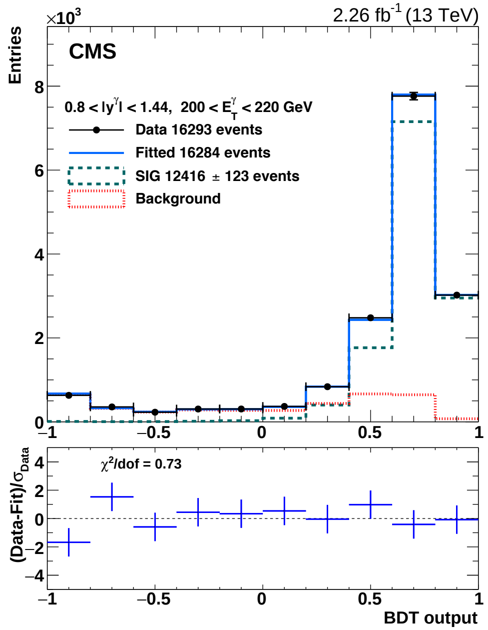
ATLAS Collab, JHEP 07 (2023) 086

Photons @ CMS: background subtraction

- The main source of background comes from jets misidentified as photons

- A template-fit method is used to estimate the photon yield in each p_T^γ and y^γ bin measured
  - $\rightarrow$ template composed of the sum of signal (from MC simulation) and background (from sideband region in data)
  - $\rightarrow$ number of isolated photons extracted from a binned maximum-likelihood fit to a BDT discriminant constructed from photon kinematics and shower shapes





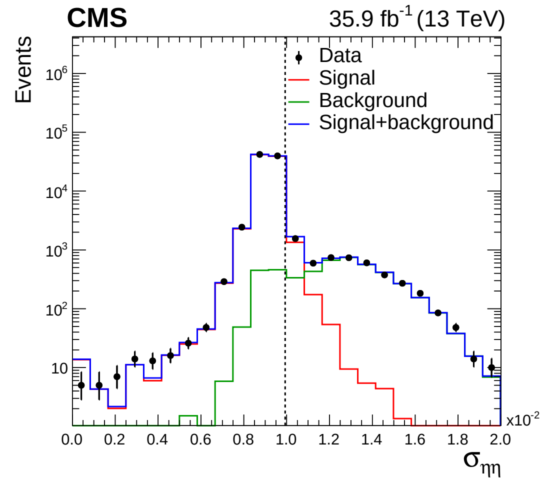
- In this analysis: $E_T^{iso}(0.3) < 5$ GeV

CMS Collab, EPJC 79 (2019) 20

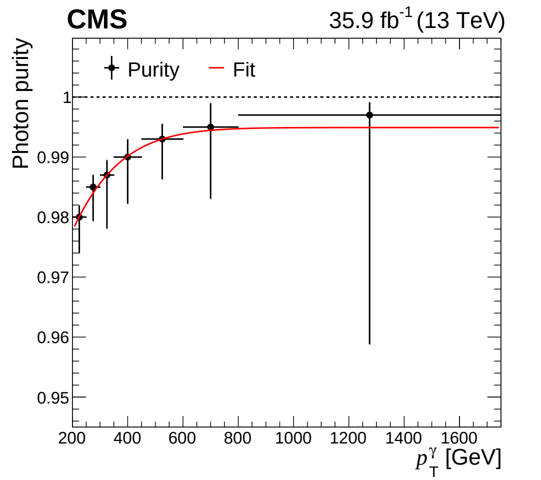
Photons @ CMS: background subtraction

- The main source of background comes from jets misidentified as photons

- A template-fit method is used to extract a value for the photon purity in each p_T^γ bin measured
  - → template composed of the sum of signal (from MC simulation) and background (from misidentified photons in data)
  - → number of isolated photons extracted from a binned maximum-likelihood fit to $\sigma_{\eta\eta}$ shower shape (length of shower along the η direction in ECAL)



- The purity of the signal is estimated as $P = \frac{N_{\rm data}^{\rm iso}}{N_{\rm data}^{\rm all\ sel}}$
  - → the purity as a function of p_T^γ is fitted with a functional form and used to extract the signal purity
  - → the measured signal purity is larger than 98% for $p_T^\gamma > 200$ GeV

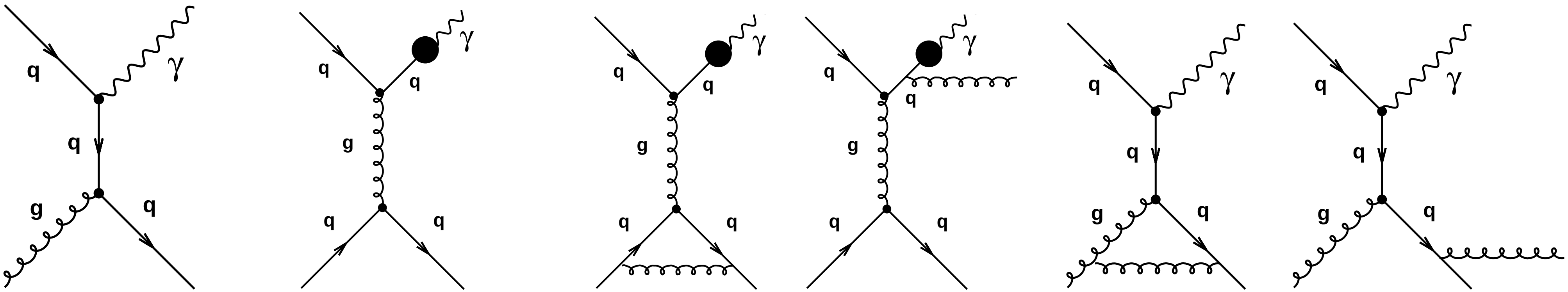


- In this analysis: $E_T^{\rm iso}(0.3) < 5$ GeV

CMS Collab, JHEP 05 (2021) 285

Photons @ QCD

Next-to-leading-order QCD calculations: JETPHOX

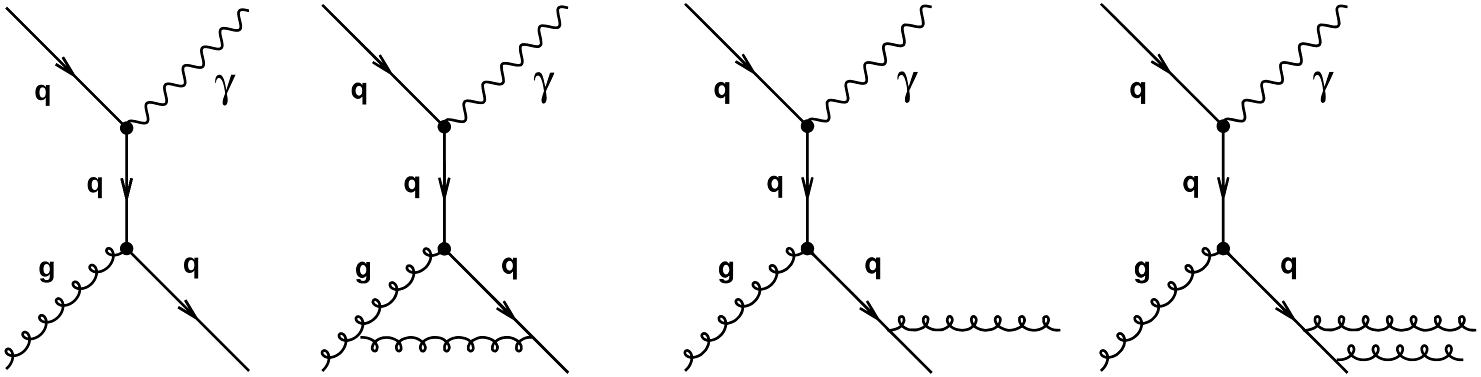


$$\sigma_{pp\to\gamma+X} = \sum_{i,j,a} \int_0^1 dx_1\, f_{i/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{j/p}(x_2,\mu_F^2)\ \hat{\sigma}_{ij\to\gamma a} +$$
$$\sum_{i,j,a,b} \int_{z_{\min}}^1 dz\, D_a^\gamma(z,\mu_f^2) \int_0^1 dx_1\, f_{i/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{j/p}(x_2,\mu_F^2)\ \hat{\sigma}_{ij\to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

- Full fixed-order NLO QCD calculations with direct and fragmentation processes
  $\to$ fragmentation contribution calculated as the convolution of jet cross section and fragmentation function
- Photon isolation requirement: cone isolation at parton level (as in experiment)
- Need corrections for hadronisation to compare with measurements

S Catani et al, JHEP 05 (2002) 028

Next-to-leading-order QCD calculations: SHERPA

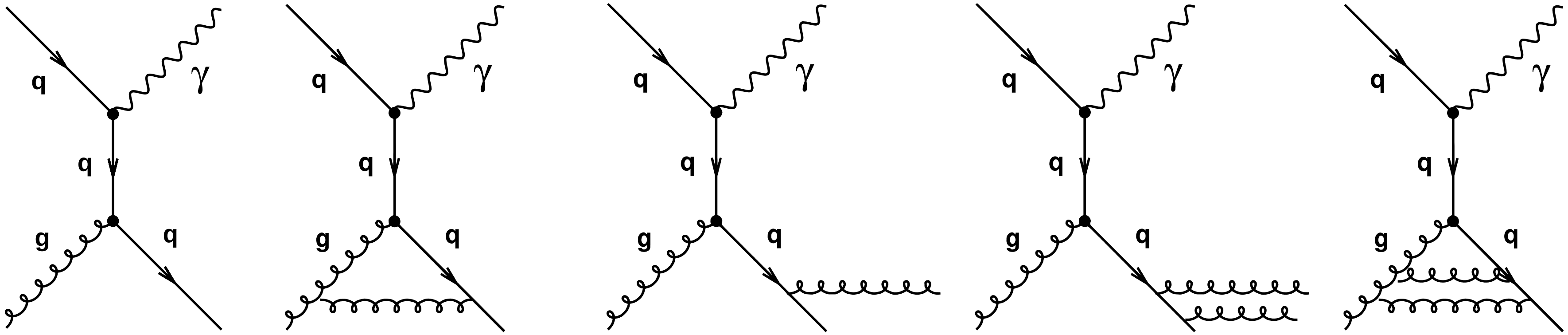


$$\sigma_{pp\to\gamma+\mathrm{X}} = \sum_{i,j,a} \int_0^1 dx_1\, f_{i/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{j/p}(x_2,\mu_F^2)\;\hat{\sigma}_{ij\to\gamma a}$$

- Full fixed-order NLO QCD calculations for $\gamma + 1,\ 2$ jets plus LO QCD calculations for $\gamma + 3,\ 4$ jets supplemented with parton shower and hadronisation
  $\rightarrow$ only direct and wide-angle fragmentation contributions
- Photon isolation requirement: hybrid isolation (Frixione isolation at parton level to remove divergencies in ME and cone isolation at hadron level)
- Predictions obtained at hadron level $\rightarrow$ direct comparison with measurements

T Gleisberg et al, JHEP 02 (2009) 007

Next-to-next-to-leading-order QCD calculations: NNLOJET (I)

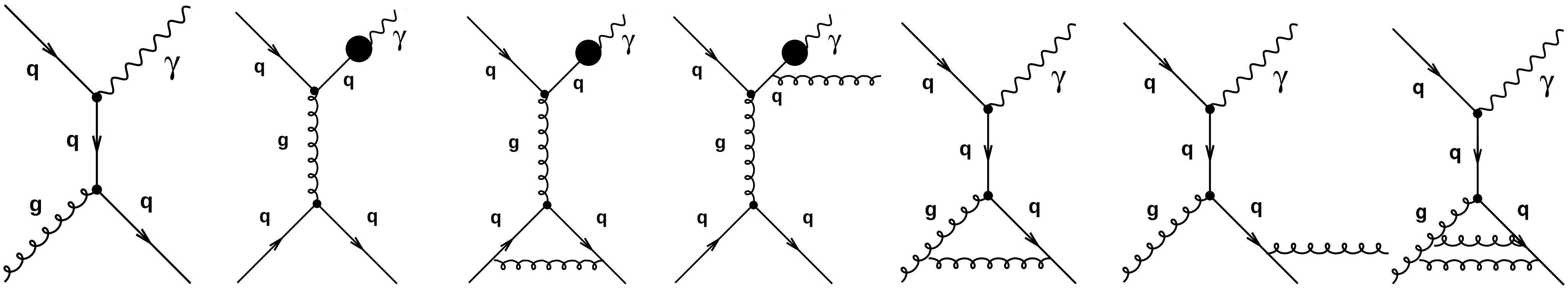


$$\sigma_{pp\to\gamma+X} = \sum_{i,j,a} \int_0^1 dx_1\, f_{i/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{j/p}(x_2,\mu_F^2)\ \hat{\sigma}_{ij\to\gamma a}$$

- Full fixed-order NNLO QCD calculations including two-loop corrections to γ+jet, virtual corrections to $\gamma + 2$ jets and tree-level $\gamma + 3$ jets
  $\to$ only direct contribution
- Photon isolation requirement: hybrid isolation at parton level (Frixione isolation to remove divergencies in ME and cone isolation to compare with measurements)
- Need corrections for hadronisation to compare with measurements

X Chen et al, JHEP 04 (2020) 166

Next-to-next-to-leading-order QCD calculations: NNLOJET (II)



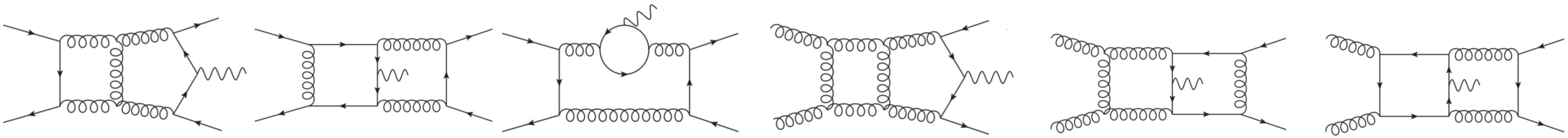
$$\sigma_{pp\to\gamma+X} = \sum_{i,j,a} \int_0^1 dx_1\, f_{i/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{j/p}(x_2,\mu_F^2)\ \hat{\sigma}_{ij\to\gamma a} +$$

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

- Full fixed-order NNLO QCD calculations with direct and fragmentation processes
  $\to$ fragmentation contribution calculated as the convolution of jet cross section and fragmentation function
- Photon isolation requirement: cone isolation at parton level (as in experiment)
- Need corrections for hadronisation to compare with measurements

T Gehrmann and R Schürmann, JHEP 04 (2022) 031 & X Chen et al, JHEP 08 (2022) 094

Next-to-next-to-leading-order QCD calculations: S Badger et al

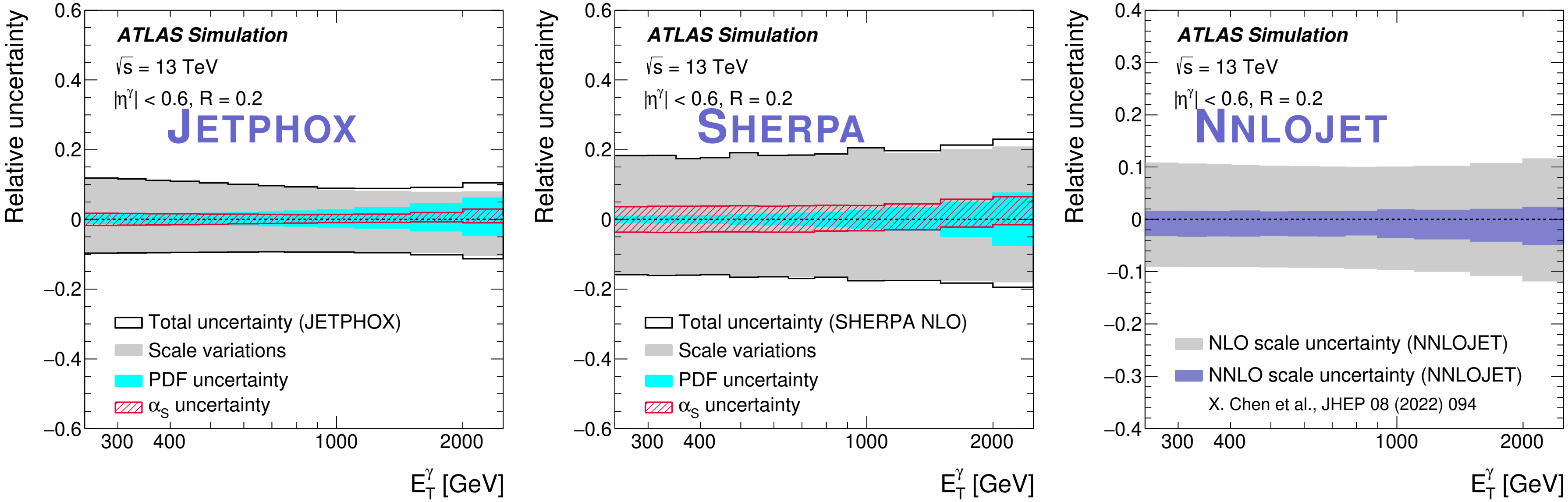


$$\sigma_{pp\to\gamma+\mathrm{X}} = \sum_{i,j,a} \int_0^1 dx_1\, f_{i/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{j/p}(x_2,\mu_F^2)\;\hat{\sigma}_{ij\to\gamma a}$$

- Full fixed-order NNLO QCD calculations including two-loop corrections to $\gamma+2$ jets, virtual corrections to $\gamma+3$ jets and tree-level $\gamma+4$ jets $\rightarrow$ only direct contribution
- Photon isolation requirement: Frixione isolation at parton level to remove divergencies in ME
- Need corrections for hadronisation to compare with measurements

S Badger et al, arXiv: 2304.06682

pQCD calculations: theoretical uncertainties



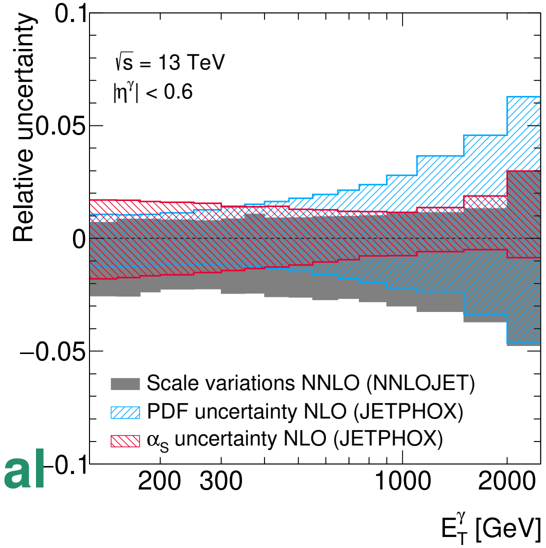
Inclusive photons: hadr cor $< 1\%$

	JETPHOX	SHERPA	NNLOJET
higher orders	$10 - 15\%$	$20 - 30\%$	$0.6 - 5\%$
PDFs	$1 - 6\%$	$1 - 9\%$	not provided
α_S	$< 3\%$	$6 - 12\%$	not provided

$\Rightarrow$ **reduction of a factor 2 to 20 in NNLO scale uncertainty wrt NLO (!) depending on region of phase space**

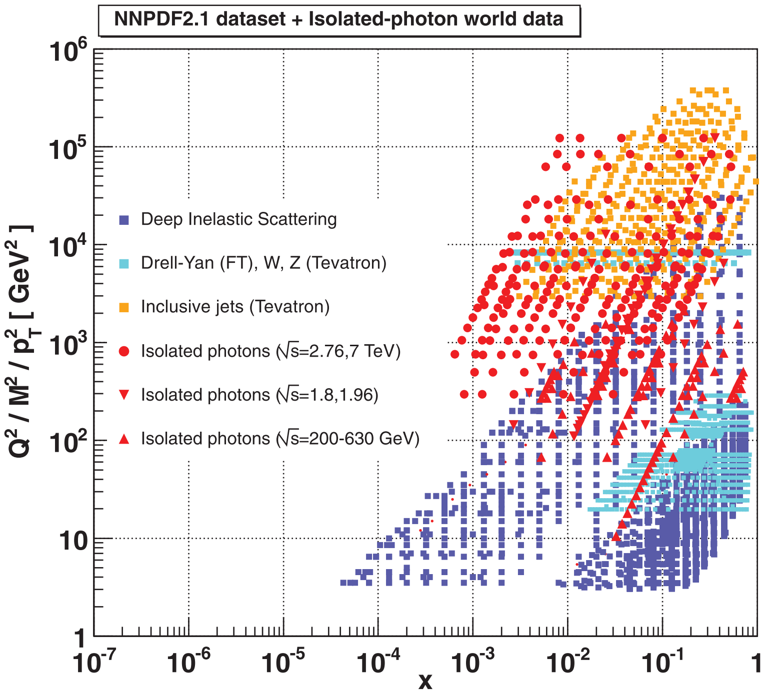
- **Comparison of NNLO scale uncertainty with PDF and α_S uncertainties (using JETPHOX)** →

  $\rightarrow$ **regions of phase space where the data have the potential to further constrain the PDFs clearly identified**

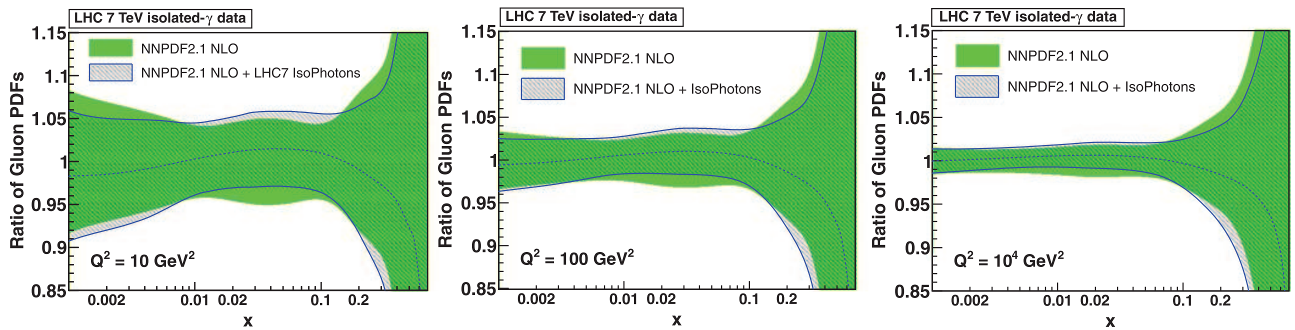


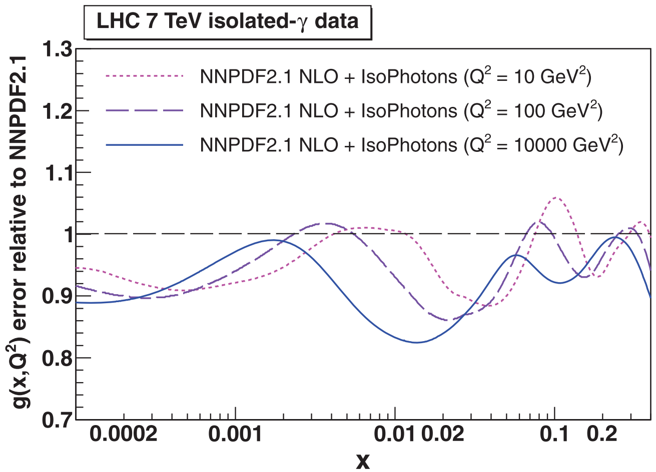
ATLAS Collab, JHEP 10 (2019) 203 & JHEP 07 (2023) 086

Impact of inclusive isolated photon measurements @ 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%**





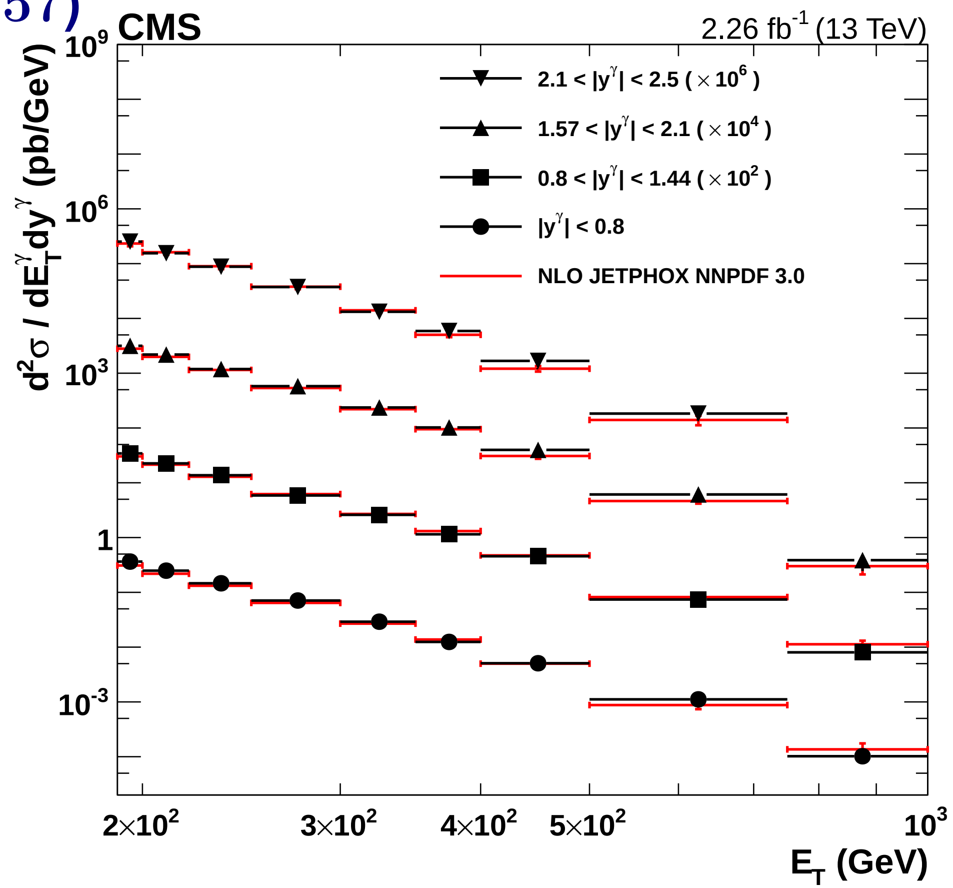
D d'Enterria and J Rojo, NPB 860 (2012) 311

Inclusive isolated-photon production

Inclusive isolated-photon production: testing pQCD

$pp \to \gamma + X$: inclusive isolated-photon cross sections $\mathcal{L} = 2.26$ fb^{-1}

- $E_T^\gamma > 190$ GeV, $E_T^{iso}(0.3) < 5$ GeV and $|y^\gamma| < 2.5$ (excluding $1.44 < |y^\gamma| < 1.57$)
- $d^2\sigma/dE_T^\gamma dy^\gamma$ decreases by four orders of magnitude in the measured range
- Values of E_T^γ up to 1 TeV are measured
- Shape of $d^2\sigma/dE_T^\gamma dy^\gamma$ similar for different y^γ regions



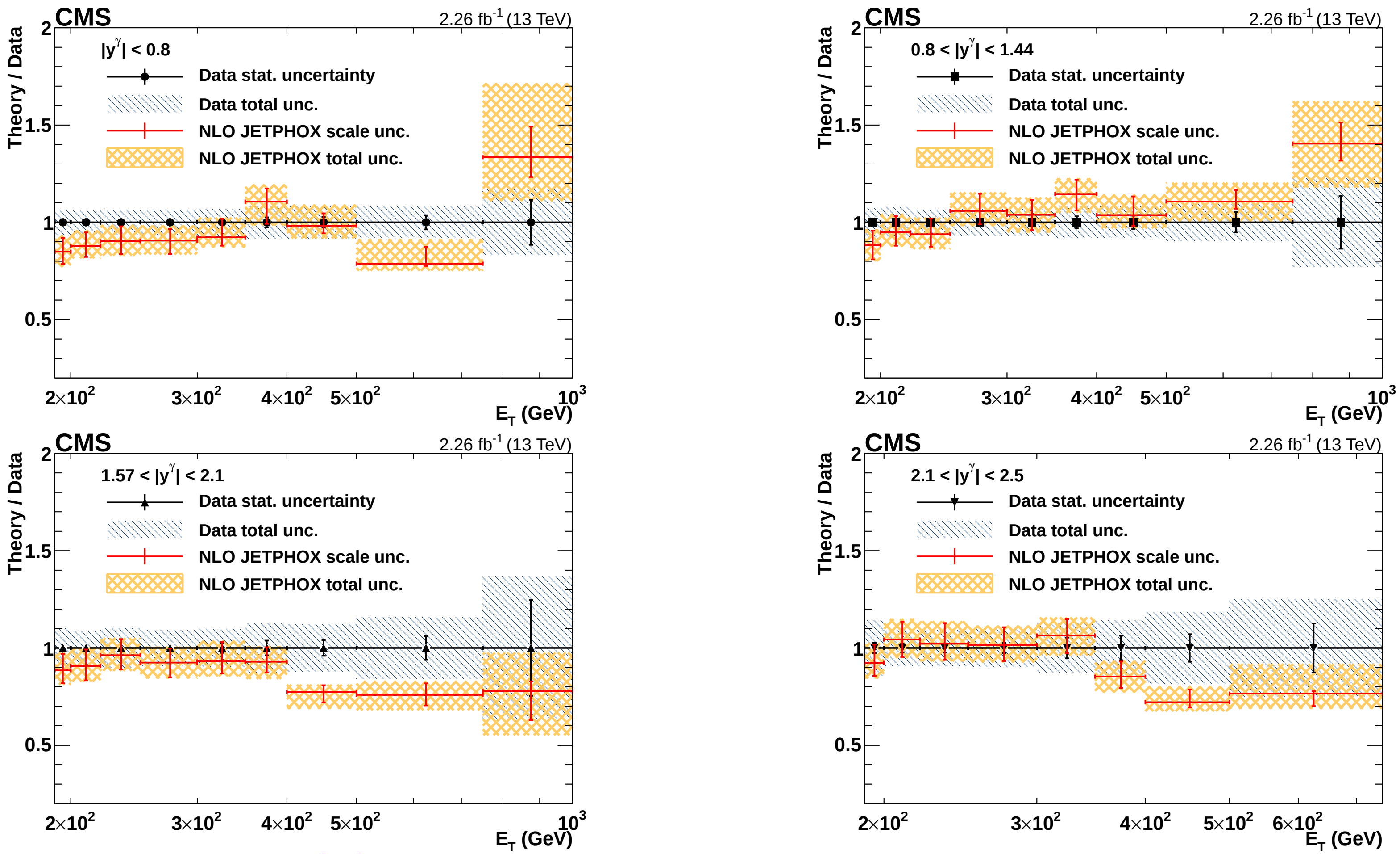
- Comparison with pQCD predictions:
  $\to$ NLO predictions from JETPHOX based on NNPDF3.0 NLO PDFs describe the data within the uncertainties

CMS Collab, EPJC 79 (2019) 20

Inclusive isolated-photon production: testing pQCD

$pp \to \gamma + X$: inclusive isolated-photon cross sections

$\mathcal{L} = 2.26$ fb^{-1}



- Comparison with pQCD predictions:
  - $\to$ NLO predictions from JETPHOX based on NNPDF3.0 NLO PDFs describe the data within the uncertainties

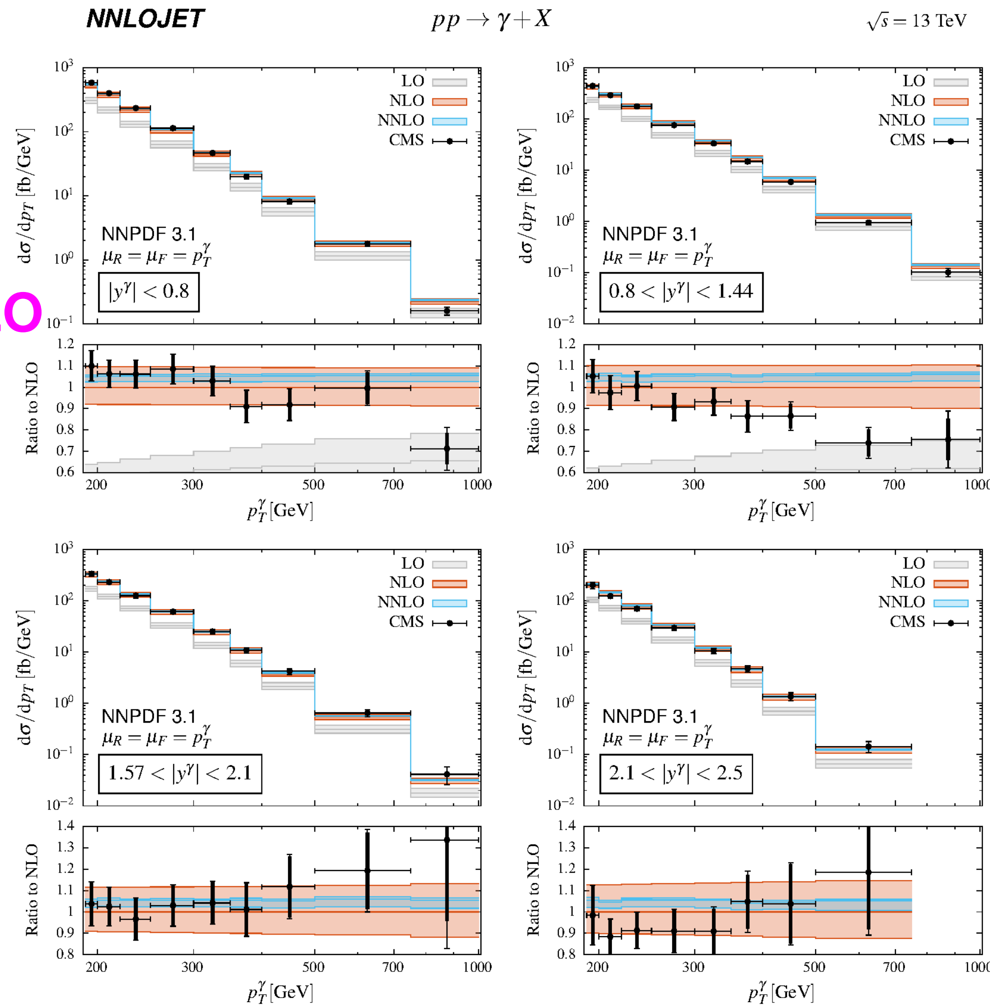
CMS Collab, EPJC 79 (2019) 20

Inclusive isolated-photon production: testing pQCD

$pp \to \gamma + X$: inclusive isolated-photon cross sections

$\mathcal{L} = 2.26$ fb^{-1}

- Comparison with NNLOJET predictions: (parton level, no hadr cor, no fragmentation, hybrid isolation)
  - $\to$ most data points agree with the NNLO prediction within the uncertainties
  - $\to$ discrepancies mainly observed at high p_T^γ
  - $\to$ the prediction for the slope of the p_T^γ cross section for $0.8 < |y^\gamma| < 1.44$ is harder than in the data
    - $\to$ might be attributed to the PDFs



CMS Collab, EPJC 79 (2019) 20
X Chen et al, JHEP 04 (2020) 166

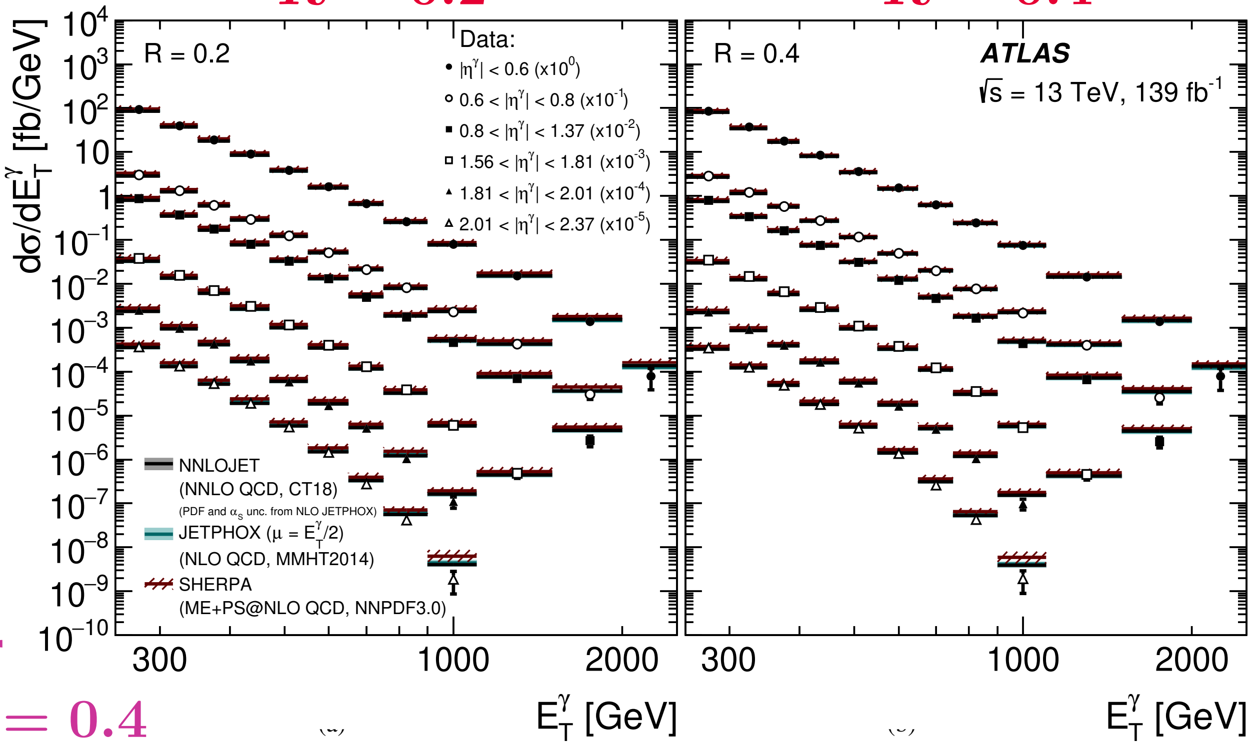
Inclusive isolated-photon production: testing pQCD

$pp \to \gamma + X$: inclusive isolated-photon cross sections

$\mathcal{L} = 139$ fb^{-1}

- $E_T^\gamma > 250$ GeV, $E_T^{\rm iso}(R) < 4.2 \cdot 10^{-3} \cdot E_T^\gamma + 4.8$ GeV and $|\eta^\gamma| < 2.37$ (excluding $1.37 < |\eta^\gamma| < 1.56$)
- $d\sigma/dE_T^\gamma$ decreases by six orders of magnitude in the measured range
- Values of E_T^γ up to 2.5 TeV are measured
- Shape of $d\sigma/dE_T^\gamma$ similar for different η^γ regions and radii
- Normalisation of $d\sigma/dE_T^\gamma$ for $R = 0.2$ is higher than for $R = 0.4$

$R = 0.2$ $R = 0.4$



- Comparison with pQCD predictions:
  $\to$ NLO and NNLO predictions generally describe the data within the uncertainties

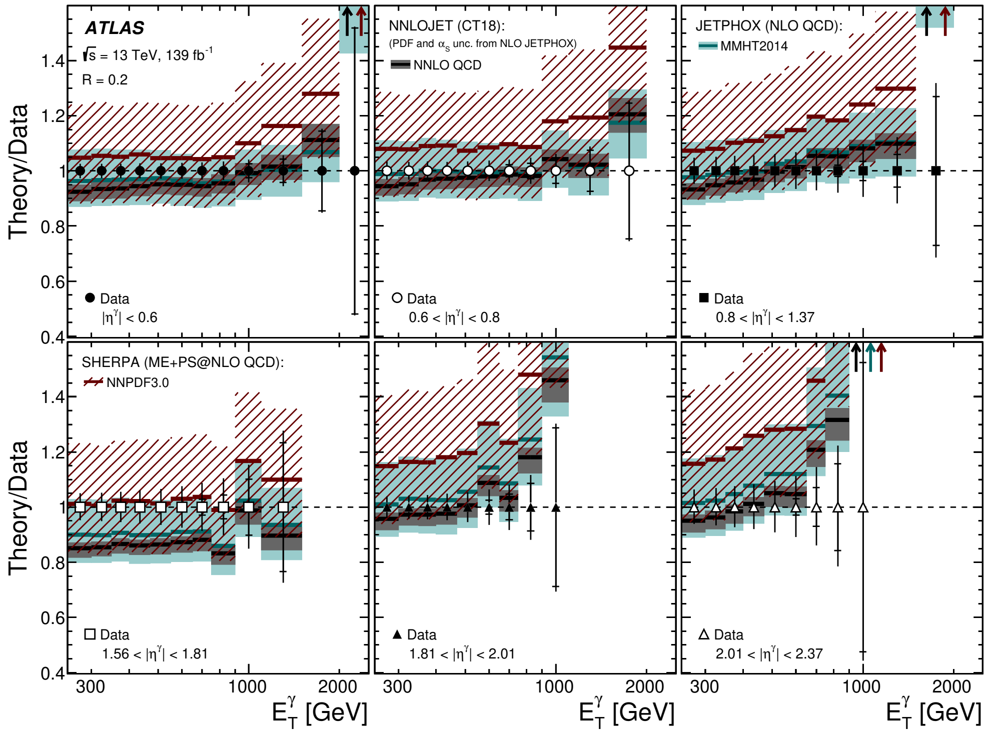
ATLAS Collab, JHEP 07 (2023) 086

Inclusive isolated-photon production: testing pQCD

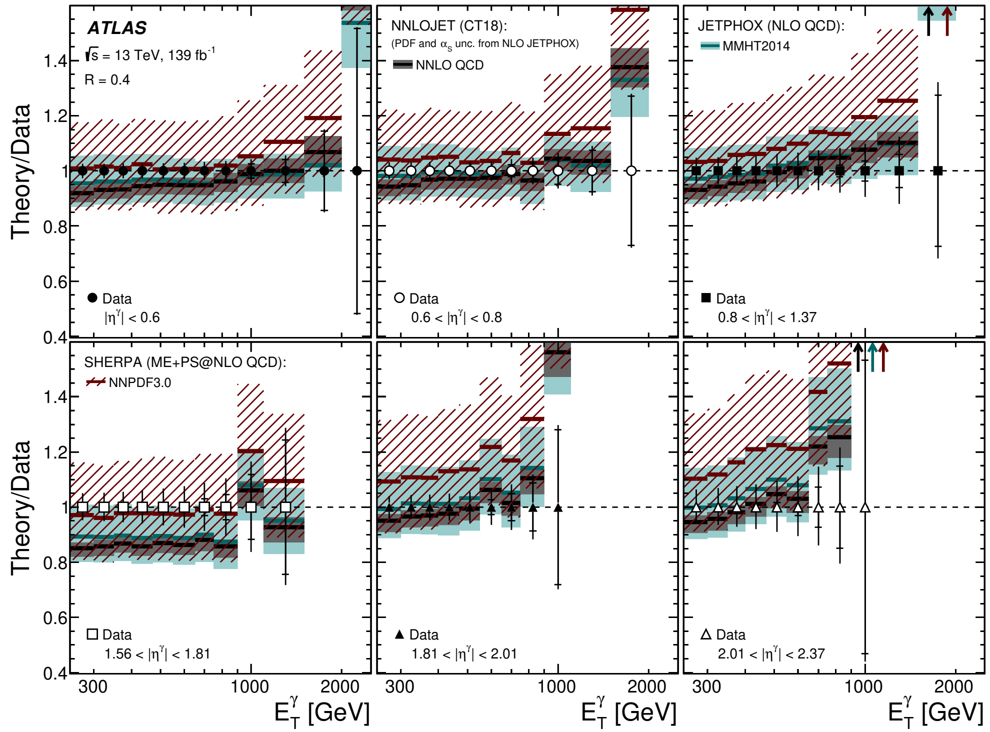
$pp \to \gamma + X$: inclusive isolated-photon cross sections

$\mathcal{L} = 139$ fb^{-1}

$R = 0.2$



$R = 0.4$



- **Comparison with pQCD predictions:**
  - $\to$ **NLO and NNLO predictions generally describe the data within the uncertainties**
  - $\to$ **NNLO prediction in $1.56 < |\eta^\gamma| < 1.81$ below the data**
  - $\to$ **Differences in slope between NNLO and data might be attributed to the PDFs**

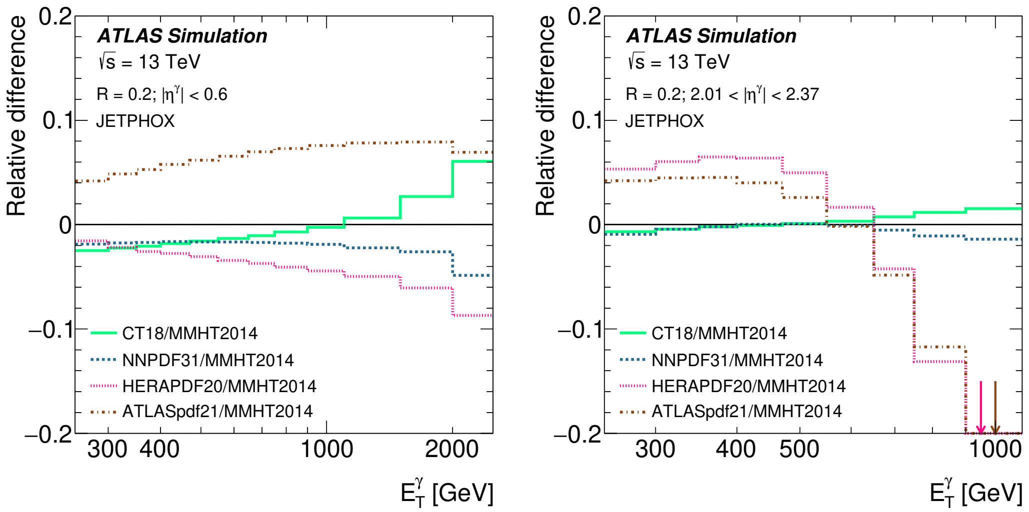
ATLAS Collab, JHEP 07 (2023) 086

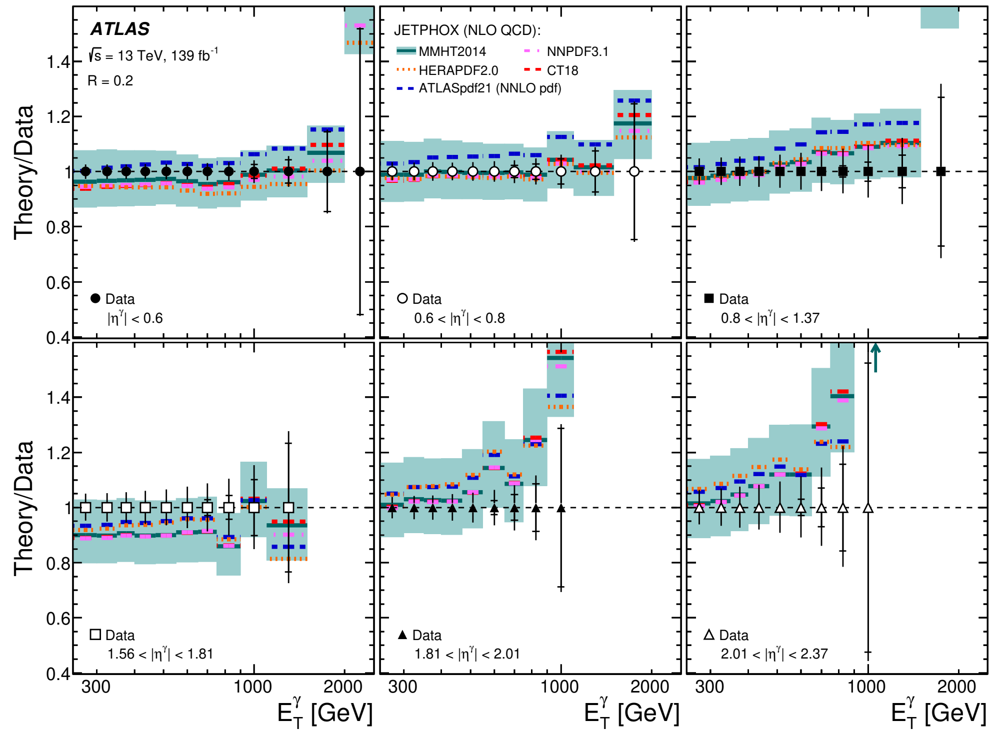
Inclusive isolated-photon production: sensitivity to PDFs

$pp \to \gamma + X$: inclusive isolated-photon cross sections

$\mathcal{L} = 139$ fb^{-1}

JETPHOX predictions based on different PDFs in two η^γ regions:





- Comparison of pQCD predictions based on different PDFs shows differences
  $\to$ The measurements have the potential to constrain further the PDFs

ATLAS Collab, JHEP 07 (2023) 086

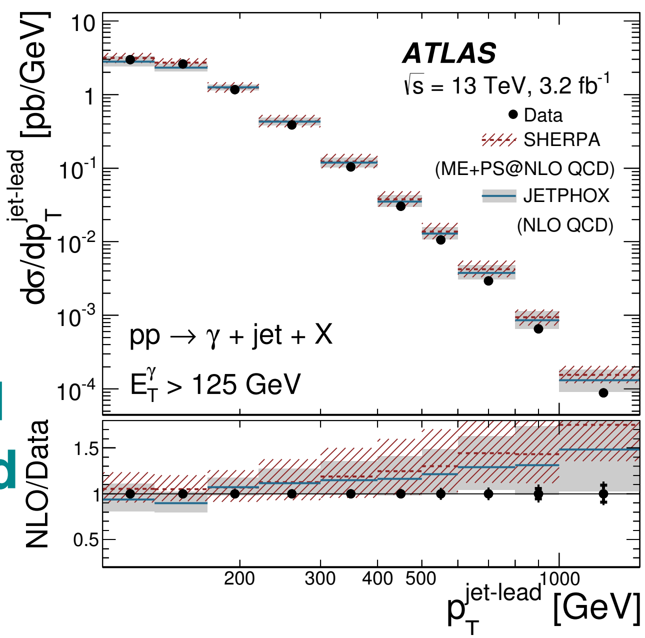
Photon plus jet production

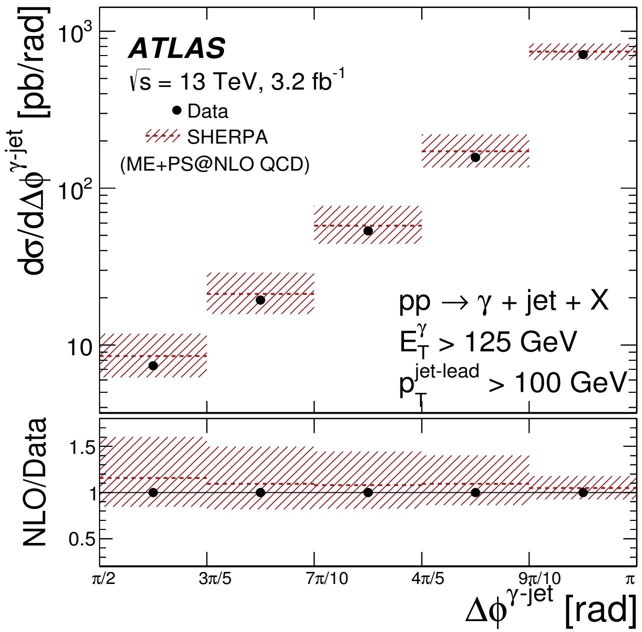
Photon plus jet production: testing colour dynamics

$pp \to \gamma + \text{jet} + X$: isolated-photon plus jet cross sections $\mathcal{L} = 3.2$ 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: $E_T^{\text{iso}}(0.4) < 4.2 \cdot 10^{-3} \cdot E_T^\gamma + 10$ GeV; $\Delta R^{\gamma-\text{jet}} > 0.8$
- Jet selection: anti-k_t algorithm with $R = 0.4$, leading jet with $p_T^{\text{jet}} > 100$ GeV and $|y^{\text{jet}}| < 2.37$

- $d\sigma / dp_T^{\text{jet-lead}}$ decreases by more than four orders in the measured range
  $\to$ values of up to 1.5 TeV are measured
- $d\sigma / d\Delta\phi^{\gamma-\text{jet}}$ is restricted to $\Delta\phi^{\gamma-\text{jet}} > \pi/2$ to avoid the phase-space region dominated by photon production in association with a multi-jet system





- Comparison to NLO predictions of JETPHOX (+ hadr cor) and SHERPA:
  $\to$ good description of data within experimental and theoretical uncertainties

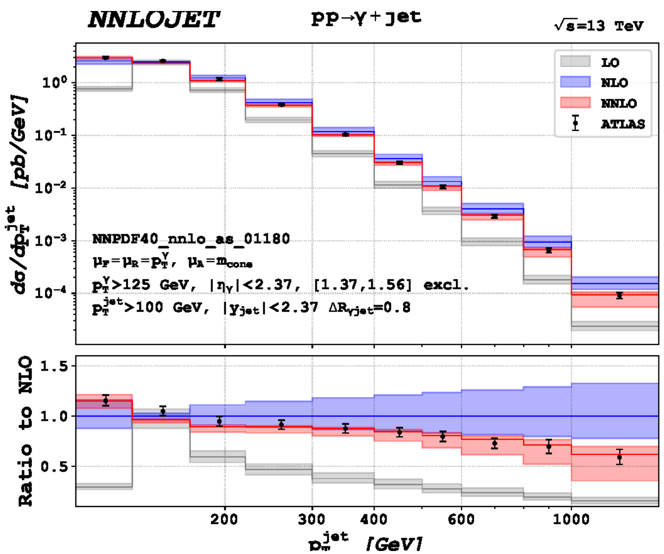
ATLAS Collab, PLB 780 (2018) 578

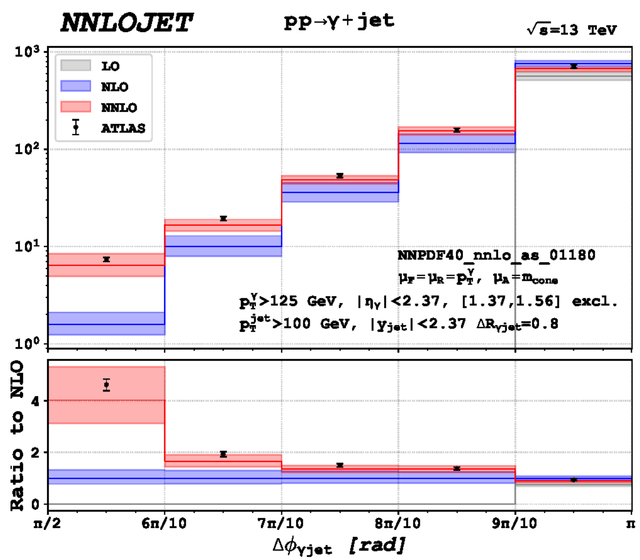
Photon plus jet production: testing pQCD

$pp \to \gamma + \text{jet} + X$: isolated-photon plus jet cross sections $\mathcal{L} = 3.2$ 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: $E_T^{\text{iso}}(0.4) < 4.2 \cdot 10^{-3} \cdot E_T^\gamma + 10$ GeV; $\Delta R^{\gamma-\text{jet}} > 0.8$
- Jet selection: anti-k_t algorithm with $R = 0.4$, leading jet with $p_T^{\text{jet}} > 100$ GeV and $|y^{\text{jet}}| < 2.37$

- Comparison with NNLOJET predictions:
  (parton level, no hadr cor, with fragmentation, cone isolation)
  $\to$ excellent description of data with reduced scale uncertainty





- For $100 < p_T^{\text{jet}} < 125$ GeV and $\pi/2 < \Delta\phi^{\gamma-\text{jet}} < 6\pi/10$, the calculation is effectively only of NLO-type and uncertainty is large
- The region $p_T^{\text{jet}} > 500$ GeV is dominated by events with two hard recoiling jets and a relatively soft photon $\to$ these configurations are also effectively at NLO accuracy resulting in increasing scale uncertainties

ATLAS Collab, PLB 780 (2018) 578 X Chen et al, JHEP 08 (2022) 094

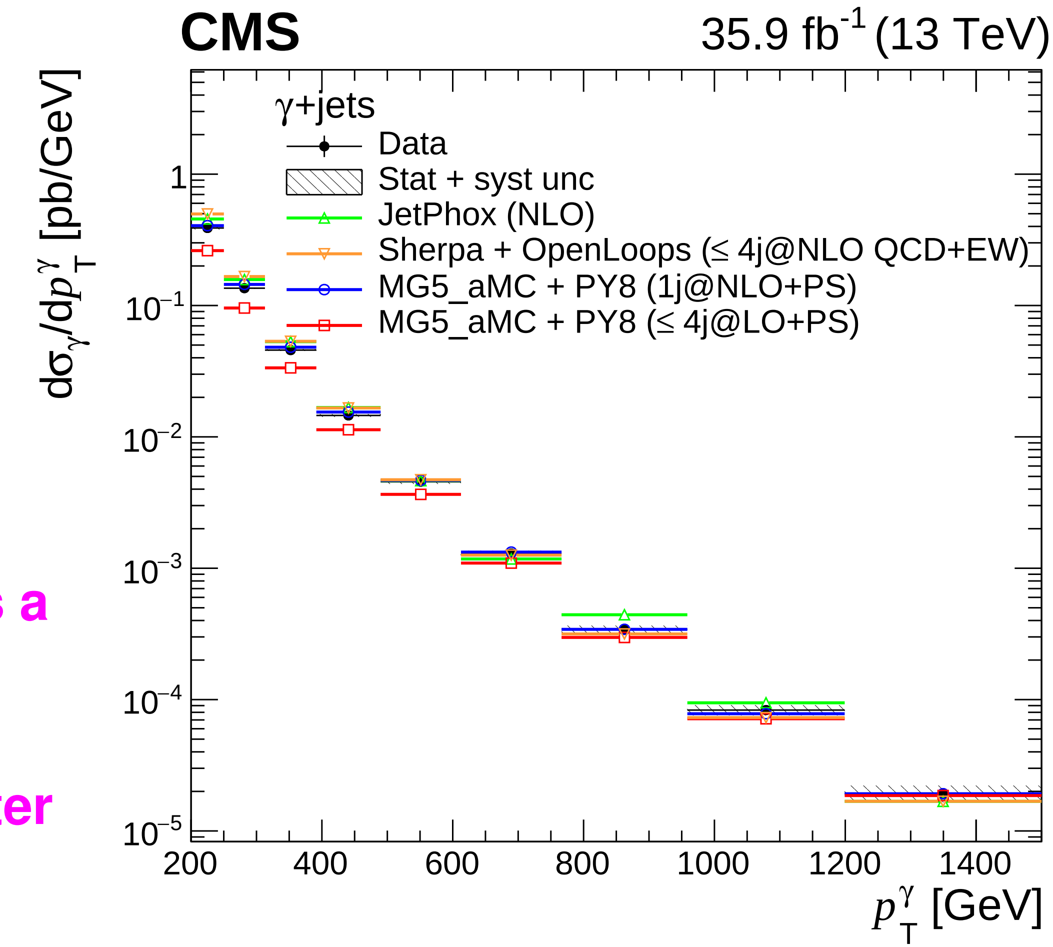
Photon plus jet production: testing pQCD

$pp \to \gamma + \text{jet} + X$: isolated-photon plus jet cross sections $\mathcal{L} = 35.9\ \text{fb}^{-1}$

- Photon selection: $p_T^\gamma > 200$ GeV and $|y^\gamma| < 1.4$
- Photon isolation: $E_T^{\rm iso}(0.3) < 5$ GeV; $\Delta R^{\gamma-\rm jet} > 0.5$
- Jet selection: anti-k_t algorithm with $R = 0.4$, leading jet with $p_T^{\rm jet} > 100$ GeV and $|y^{\rm jet}| < 2.4$

- $d\sigma/dp_T^\gamma$ decreases by five orders of magnitude in the measured range
- Values of p_T^γ up to 1.5 TeV are measured

- Comparison with pQCD predictions:
  - → LO prediction from aMC@NLO has a different shape than the data
  - → NLO predictions from aMC@NLO, JETPHOX and SHERPA show a better agreement with the data



CMS Collab, JHEP 05 (2021) 285

Photon plus jet production: testing pQCD

$pp \to \gamma + \text{jet} + X$: isolated-photon plus jet cross sections

$\mathcal{L} = 35.9$ fb^{-1}

- Photon selection: $p_T^\gamma > 200$ GeV and $|y^\gamma| < 1.4$
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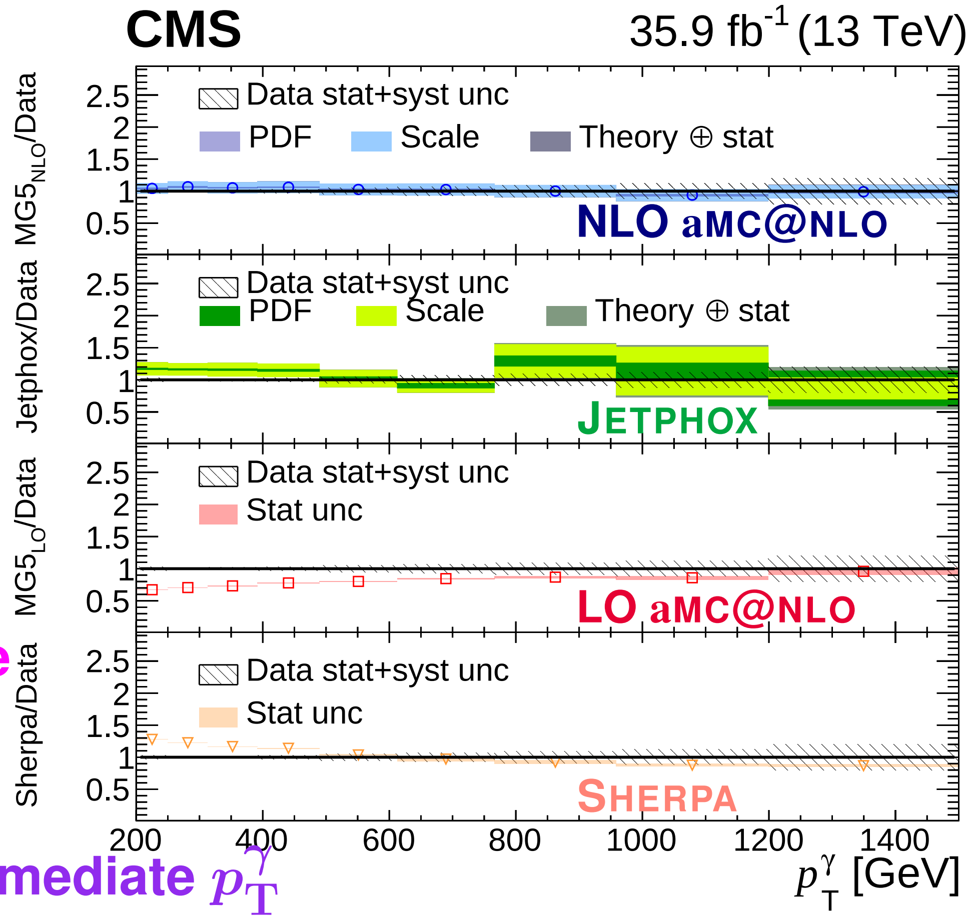
- Jet selection: anti-k_t algorithm with $R = 0.4$, leading jet with $p_T^{\rm jet} > 100$ GeV and $|y^{\rm jet}| < 2.4$

- Comparison with pQCD predictions:
  - → LO aMC@NLO has $(10-30)\%$ disagreement in shape with the data for $p_T^\gamma \lesssim 600$ GeV
  - → NLO aMC@NLO is in agreement with the data within uncertainties
  - → SHERPA is above (consistent with) the data for $p_T^\gamma < (>) 500$ GeV
  - → JETPHOX is above (consistent with) the data for $p_T^\gamma < (>) 500$ GeV



- Experimental uncertainties smaller than theoretical uncertainties for low and intermediate p_T^γ
  - → The measurements have the potential to constrain further the PDFs

CMS Collab, JHEP 05 (2021) 285

Ratios of cross sections

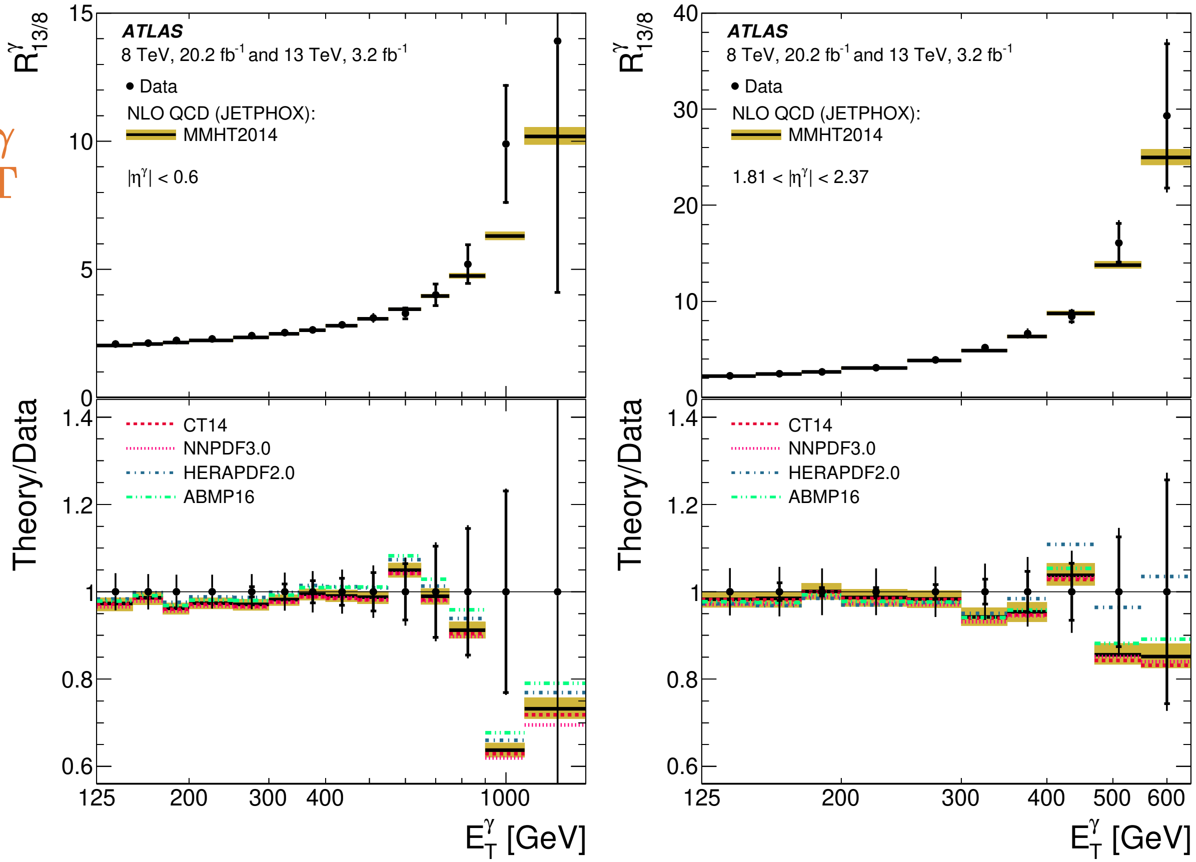
Ratio of inclusive-photon cross sections: tests of pQCD

$pp \to \gamma + X$: inclusive isolated-photon cross sections

- $R^{\gamma}_{13/8} = [d\sigma/dE^{\gamma}_{T}(\sqrt{s} = 13\ \text{TeV})]/[d\sigma/dE^{\gamma}_{T}(\sqrt{s} = 8\ \text{TeV})]$

$\mathcal{L} = 20.2$ fb^{-1} (8 TeV) and 3.2 fb^{-1} (13 TeV)

- The measured ratio
  - → increases as E^{γ}_{T} increases from ≈ 2 at $E^{\gamma}_{T} = 125$ GeV to $\approx$ an order of magnitude at the end of the spectrum
  - → increases as $|\eta^{\gamma}|$ at fixed E^{γ}_{T}



- The NLO QCD predictions reproduce the measured $R^{\gamma}_{13/8}$
  - → in particular, the increase with E^{γ}_{T} or $|\eta^{\gamma}|$ at fixed E^{γ}_{T} for all PDF sets considered within much reduced uncertainties

⇒ Very stringent test of pQCD and of its scale evolution

ATLAS Collab, JHEP 04 (2019) 093

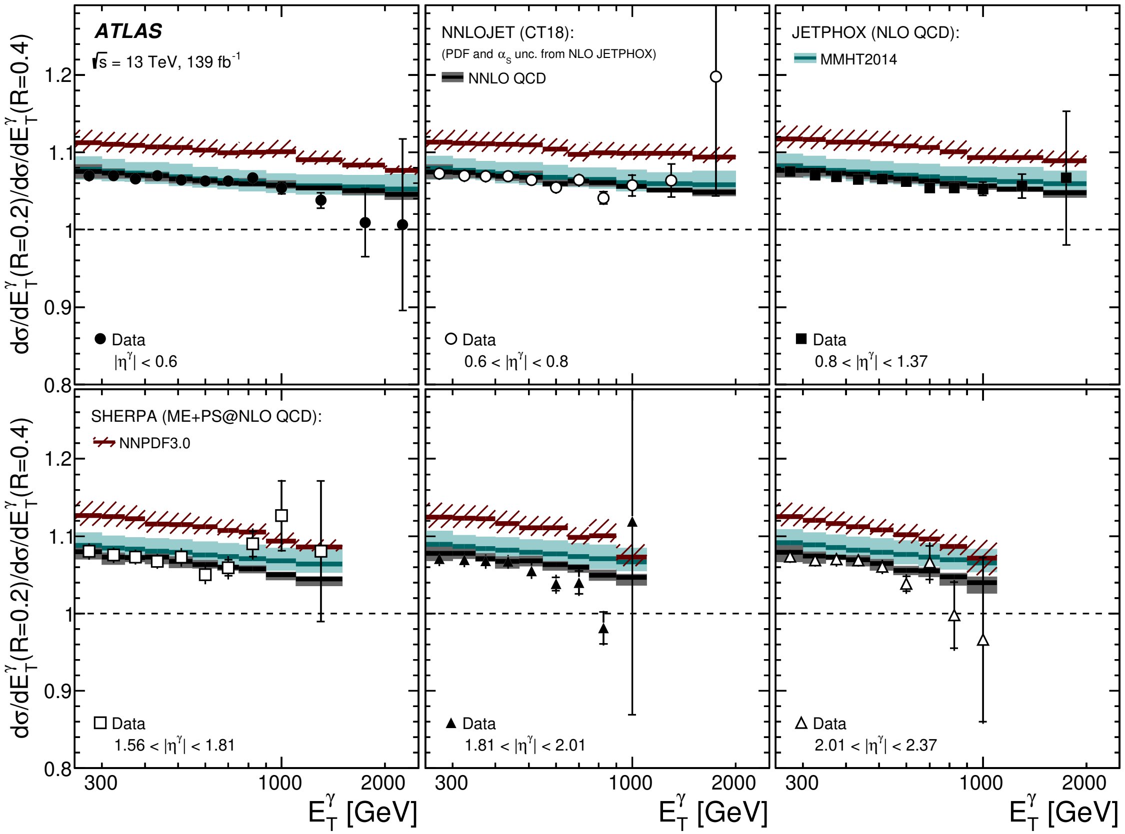
Ratio of inclusive-photon cross sections: tests of pQCD

$pp \rightarrow \gamma + \mathrm{X}$: inclusive isolated-photon cross sections

$\mathcal{L} = 139$ fb^{-1}

- Dependence on R studied by measuring the ratios of the differential cross sections for $R = 0.2$ and $R = 0.4$ as functions of E_{T}^{γ} in different regions of η^{γ}

- These measurements provide a very stringent test of pQCD with reduced experimental and theoretical uncertainties (both $\approx 1\%$!)



$\Rightarrow$ Validation of the underlying pQCD theoretical description up to $\mathcal{O}(\alpha_{\mathrm{s}}^2)$

ATLAS Collab, JHEP 07 (2023) 086

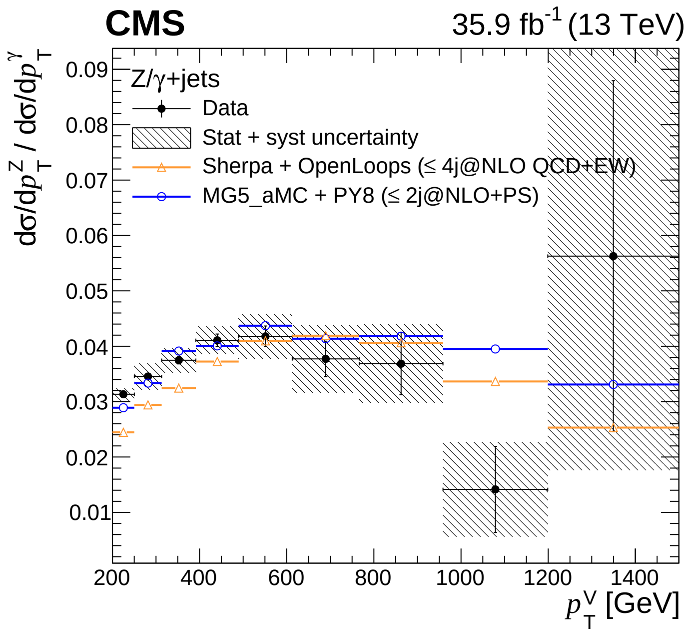
Ratio of Z and photon cross sections: tests of pQCD

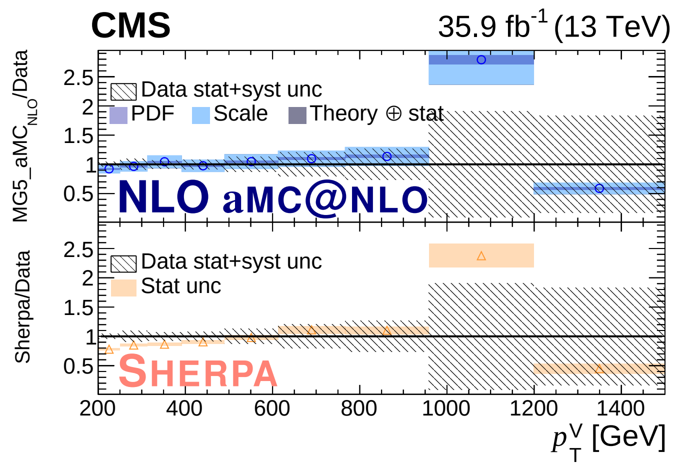
$pp \to Z + \text{jets}$ and $\gamma + \text{jets}$

$\mathcal{L} = 35.9$ fb^{-1}

- Measurement of $[d\sigma/dp_T^Z]/[d\sigma/dp_T^\gamma]$ as a function of p_T
- The ratio
  - $\to$ increases as p_T increases from ≈ 0.03 at $p_T = 200$ GeV to ≈ 0.05 at $p_T = 1.4$ TeV
- Comparison with NLO QCD predictions:
  - $\to$ aMC@NLO is in agreement with the data within uncertainties
  - $\to$ SHERPA is below (consistent with) the data for $p_T < (>) 300$ GeV

$\Rightarrow$ Very stringent test of pQCD





CMS Collab, JHEP 05 (2021) 285

Photon plus two-jets production

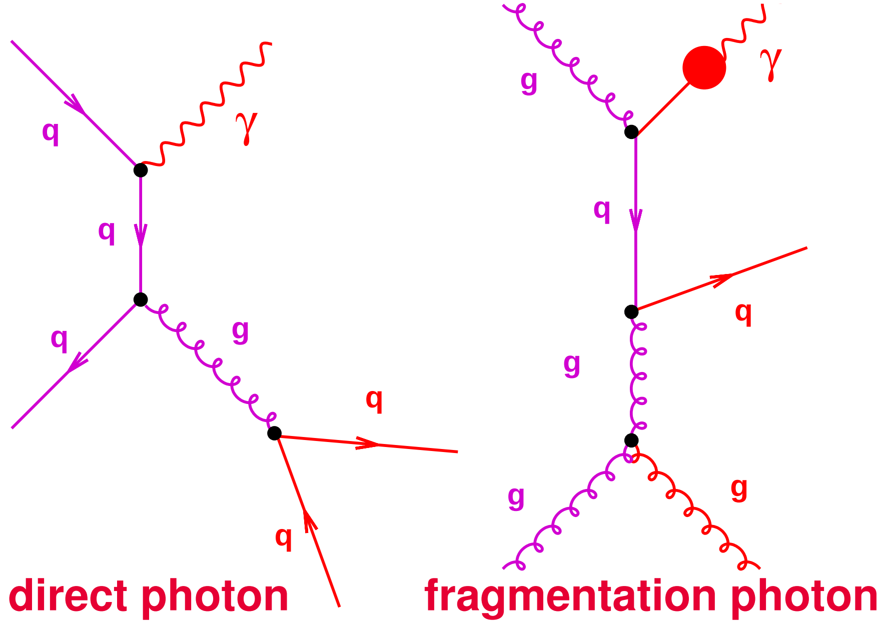
Photon+2 jets: probing the production mechanisms

$pp \to \gamma + 2$ jets: isolated-photon plus two-jets cross sections $\mathcal{L} = 36.1$ fb^{-1}

- Photon selection: $E_T^\gamma > 150$ GeV and $|\eta^\gamma| < 2.37$, excluding the region $1.37 < |\eta^\gamma| < 1.56$
- Photon isolation: $E_T^{iso}(0.4) < 4.2 \cdot 10^{-3} \cdot E_T^\gamma + 10$ GeV; $\Delta R^{\gamma-\text{jet}} > 0.8$
- Jet selection: anti-k_t algorithm with $R = 0.4$, leading jet with $p_T^{\text{jet}} > 100$ GeV and $|y^{\text{jet}}| < 2.5$

- The photon and the leading and subleading jets are considered to study the dynamics of prompt-photon production when accompanied by jets
  $\to$ the photon + 2 jets final state provides a deeper understanding of the fragmentation component which remains after the isolation requirement

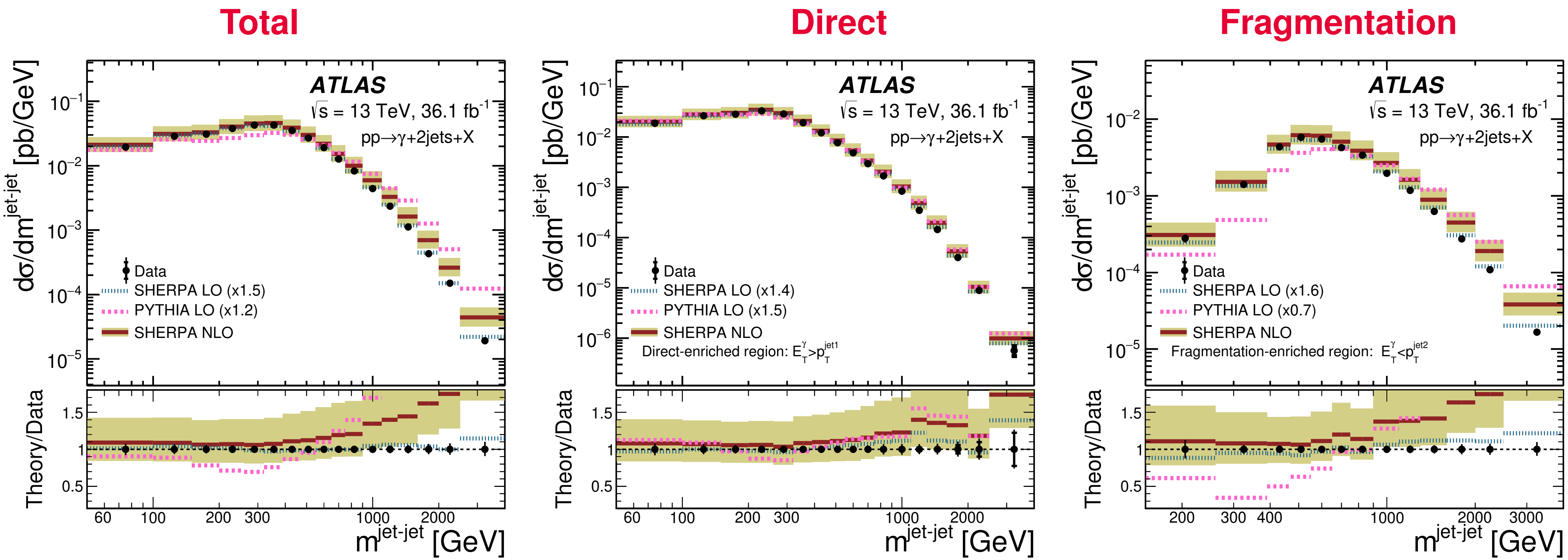
- Three phase-space selections:
  $\to$ total: all photon + 2 jets events
  $\to$ direct-entiched: $E_T^\gamma > p_T^{\text{jet1}}$
  $\to$ fragmentation-enriched: $p_T^{\text{jet2}} > E_T^\gamma$



ATLAS Collab, JHEP 03 (2020) 179

Photon+2 jets: probing the production mechanisms

- Differential cross sections as functions of $m^{\rm jet-jet}$ in different regions:



- The characteristics observed in the measured cross sections in the fragmentation and direct regions are in agreement with the expectations based on the two underlying mechanisms which dominate each sample

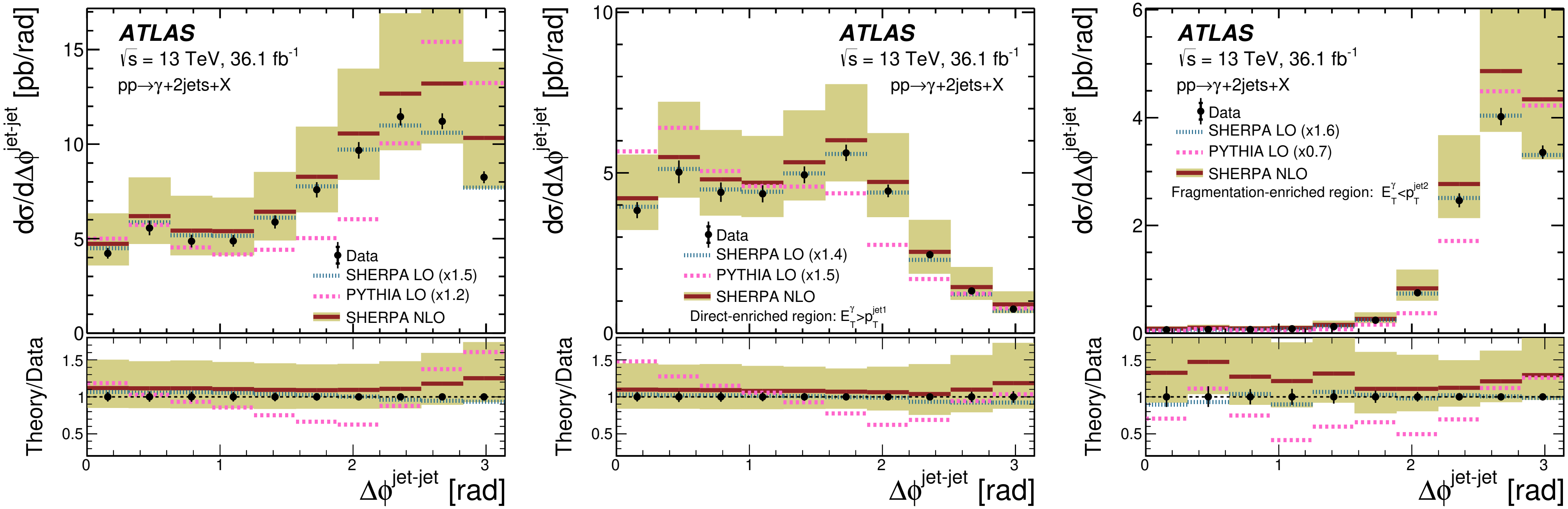
- Comparison with NLO QCD calculations:
  → Adequate description of the shape and normalisation of the data by SHERPA NLO within uncertainties, except at high $m^{\rm jet-jet}$ values

ATLAS Collab, JHEP 03 (2020) 179

Photon+2 jets: probing the production mechanisms

- Differential cross sections as functions of $\Delta\phi^{\mathrm{jet-jet}}$ in different regions:

Total **Direct** **Fragmentation**



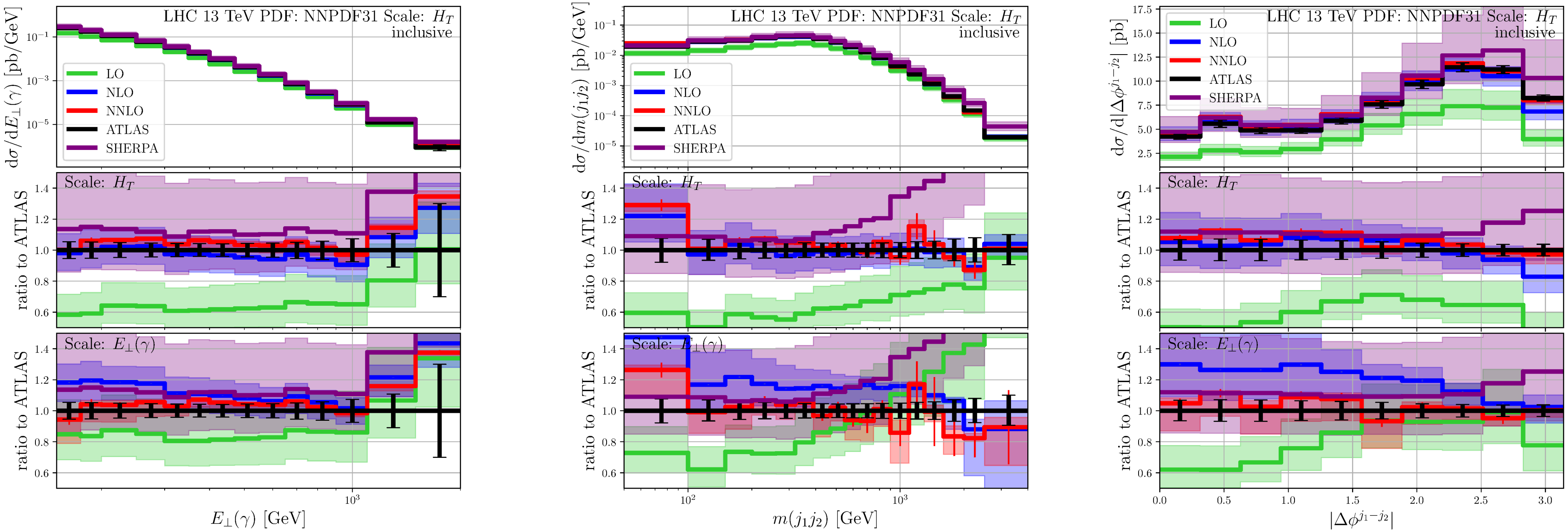
- The characteristics observed in the measured cross sections in the fragmentation and direct regions are in agreement with the expectations based on the two underlying mechanisms which dominate each sample
- Comparison with NLO QCD calculations:
  - → Adequate description of the shape and normalisation of the data by SHERPA NLO within uncertainties

ATLAS Collab, JHEP 03 (2020) 179

Photon+2 jets: testing pQCD

- Differential cross sections for photon+2jets as functions of

E_T^{γ} $m^{\rm jet-jet}$ $\Delta\phi^{\rm jet-jet}$



- Comparison with NNLO QCD calculations:

(parton level, no hadr cor, no fragmentation, Frixione isolation)

→ improved description of the data with smaller uncertainties than NLO

→ differences for $E_T^{\gamma} > 1$ TeV → attributed to electroweak effects (not included)

→ differences for $m^{\rm jet-jet} < 100$ GeV → attributed to different isolation (resummation effects should play no role in this region)

→ for $\Delta\phi^{\rm jet-jet}$, NNLO corrections essential to describe shape of distribution

ATLAS Collab, JHEP 03 (2020) 179 S Badger et al, arXiv: 2304.06682

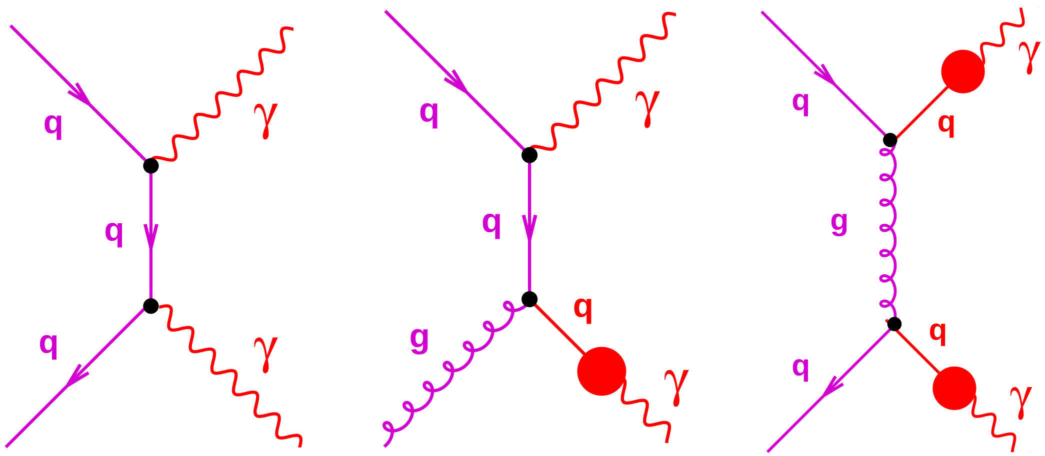
Diphoton production

Diphoton production @ LHC

$pp \to \gamma\gamma + \mathrm{X}$: isolated-diphoton cross sections $\mathcal{L} = 139$ fb^{-1}

- Photon selection: $p_{\mathrm{T},\gamma_1(2)} > 40\ (30)$ GeV and $|\eta^\gamma| < 2.37$, excluding the region $1.37 < |\eta^\gamma| < 1.52$
- Photon isolation: $E_{\mathrm{T}}^{\mathrm{iso}}(0.2) < 0.09 \cdot p_{\mathrm{T}}^{\gamma}$ GeV; $\Delta R^{\gamma\gamma} > 0.4$

- Measurements of diphoton production in pp collisions provide
  - $\to$ tests of pQCD predictions
  - $\to$ input to understand the background to Higgs production and BSM searches in diphoton decaying channels $\to$ validation of Monte Carlo models
- Diphotons are produced via two mechanisms: direct and fragmentation processes



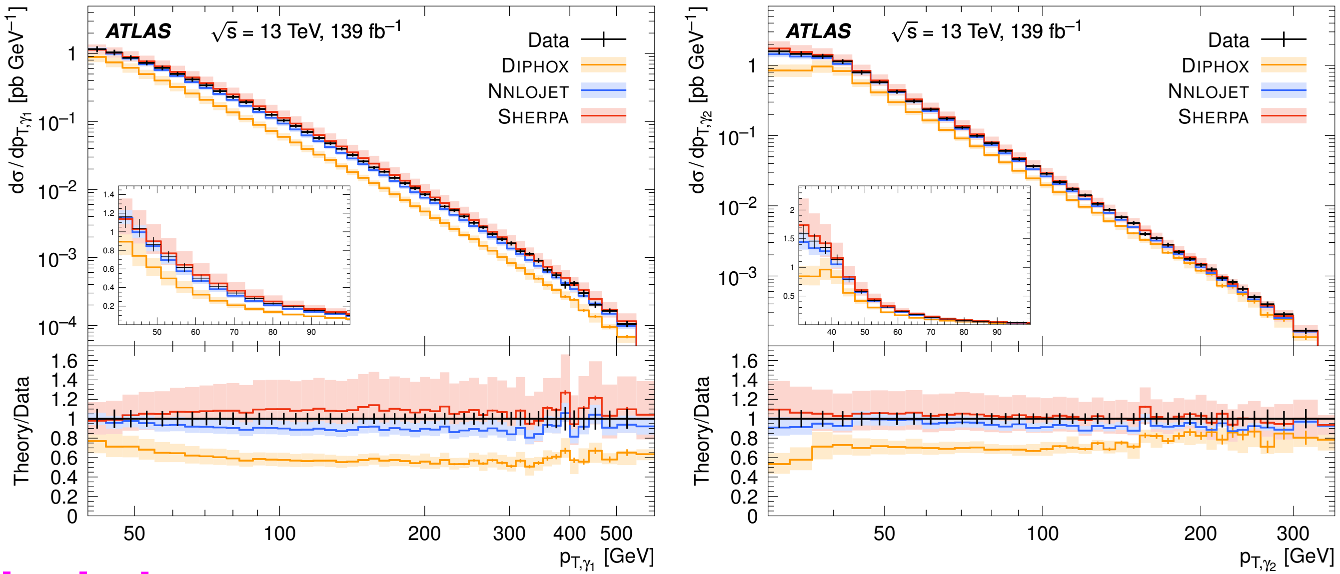
- Main challenge and source of uncertainty
  - $\to$ estimation of the background from non-prompt photons in jet events
  - $\to$ data-driven technique is used to estimate this background

ATLAS Collab, JHEP 11 (2021) 169

Diphoton production: testing pQCD

- **Differential cross sections as functions of p_{T,γ_1} and p_{T,γ_2}:**

- **The measured $d\sigma/dp_{\mathrm{T},\gamma_1}(p_{\mathrm{T},\gamma_2})$ decreases by four (three) orders of magnitude in the measured range**



- **Comparison with pQCD calculations:**

	Fixed-order accuracy						Fragmentation		QCD	NP
	$\gamma\gamma$	$+1j$	$+2j$	$+3j$	$+\geq 4j$	$gg\to\gamma\gamma$	single	double	res.	effects
DIPHOX	NLO	LO	-	-	-	LO	NLO		–	–
NNLOJET	NNLO	NLO	LO	-	-	LO	–	–	–	–
SHERPA	NLO		LO		PS	LO	ME+PS		PS	✓

→ fixed-order DIPHOX and NNLOJET predictions not expected to be valid in regions where effects of multiple collinear or soft QCD emissions are relevant

→ ME+PS@NLO SHERPA provides remarkably good agreement with data in these regions

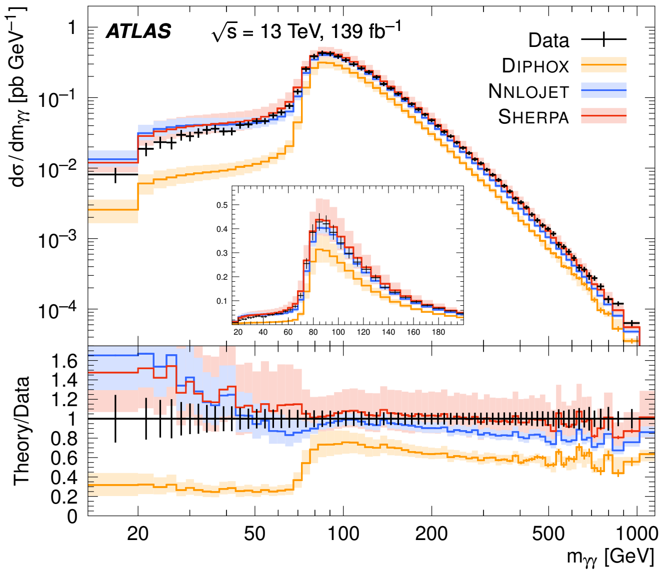
→ DIPHOX describes the shape but not the normalisation of the data, except for $p_{\mathrm{T},\gamma_2} < 40$ GeV

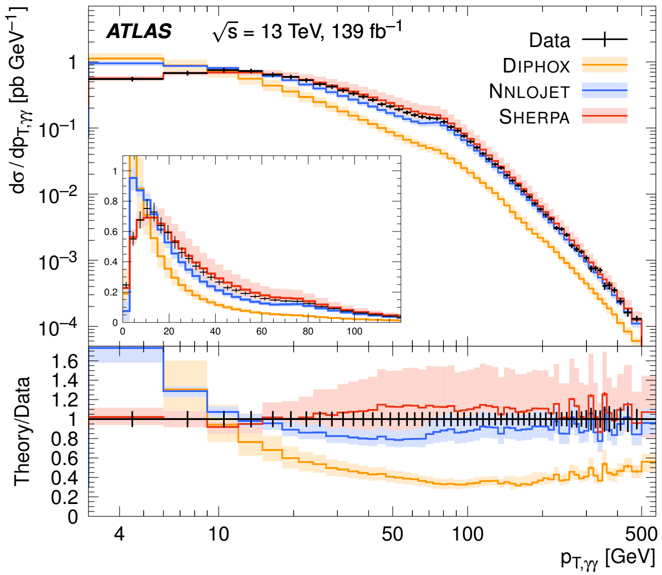
→ NNLOJET and SHERPA are compatible with the data over the full measured range

ATLAS Collab, JHEP 11 (2021) 169

Diphoton production: testing pQCD

- Differential cross sections as functions of $m_{\gamma\gamma}$ and $p_{\mathrm{T},\gamma\gamma}$:





- The shape of the $m_{\gamma\gamma}$ distribution is governed by the p_{T}^{γ} requirements $\rightarrow$ the region $m_{\gamma\gamma} < p_{\mathrm{T},\gamma_1} + p_{\mathrm{T},\gamma_2}$ is suppressed and only populated by $\gamma\gamma$+multi-jet configurations, which are not modelled well by NLO DIPHOX and benefit significantly from higher-order contributions included in NNLOJET and SHERPA

- DIPHOX fails to describe the data
- NNLOJET gives an improved description of the data, but there are regions in which an even higher-order calculation is needed to describe the data
- SHERPA agrees with the data within the (large) uncertainties

ATLAS Collab, JHEP 11 (2021) 169

Summary: shedding light on QCD @ LHC...

- Measurements of inclusive-photon, photon+jet, photon+2jets and diphoton production and ratios of cross sections from ATLAS and CMS @ $\sqrt{s} = 13$ TeV have been presented

  $\rightarrow$ very precise measurements with smaller uncertainties than in theory
  $\rightarrow$ very stringent tests of pQCD up to NNLO
  $\rightarrow$ sensitivity to PDFs $\rightarrow$ potential to constrain further the PDFs
  $\rightarrow$ tests of colour dynamics
  $\rightarrow$ tests of underlying production mechanisms

- The most recent results indicate that there are regions of phase space in which even higher-order calculations together with improved PDFs might be needed to improve the description of the precision measurements