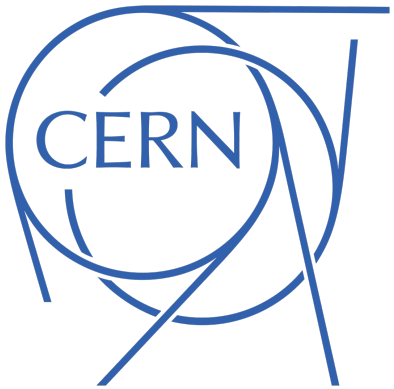
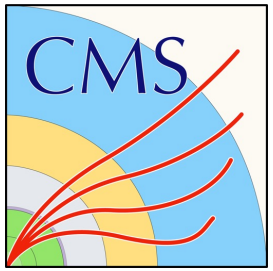
Precision meaurements of photon production at the LHC

Francesco Giuli (on behalf of the ATLAS and CMS collaborations)





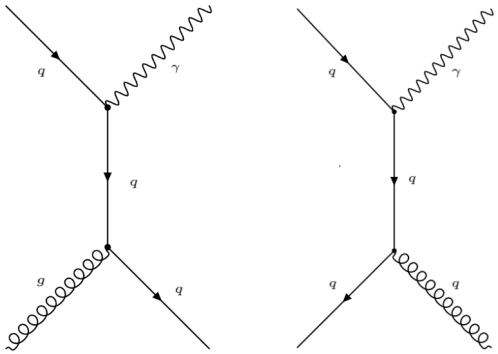
QCD@LHC2022
Orsay, France
30/11/2022

Precision QCD at the LHC

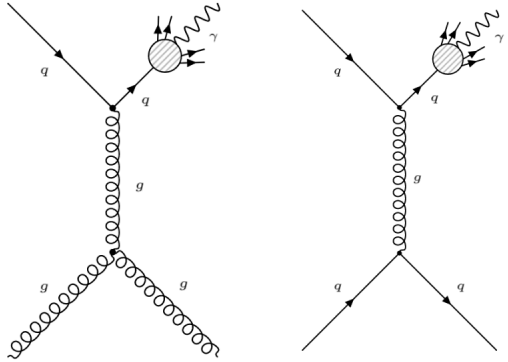
- LHC dataset enables precise tests of QCD
  - Tests of perturbative QCD predictions, especially at high scales
  - Extracting the strong coupling constant and its running
  - Studying the parton showers and hadronization mechanisms
- Huge dataset and precise object reconstruction enable increased precision and more granular measurements
- Focusing on 3 measurements today:
  - Inclusive-photon production and its dependence on photon isolation at $\sqrt{s}$ = 13 TeV using 139 fb^{-1} of ATLAS data - ATLAS-CONF-2022-065
  - Measurements of triple-differential cross sections for inclusive isolated-photon+jet events in pp collisions at $\sqrt{s}$ = 13 TeV - 1807.00782
  - Measurement of the production cross section of pairs of isolated photons in pp collisions at 13 TeV with the ATLAS detector - 2107.09330

Inclusive photon production

- The production of high-p_T prompt photons (not coming from hadron decays) proceeds via 2 mechanisms:



Direct processes

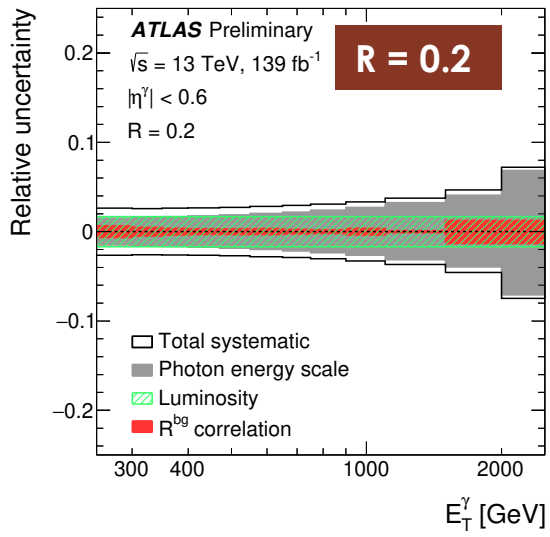


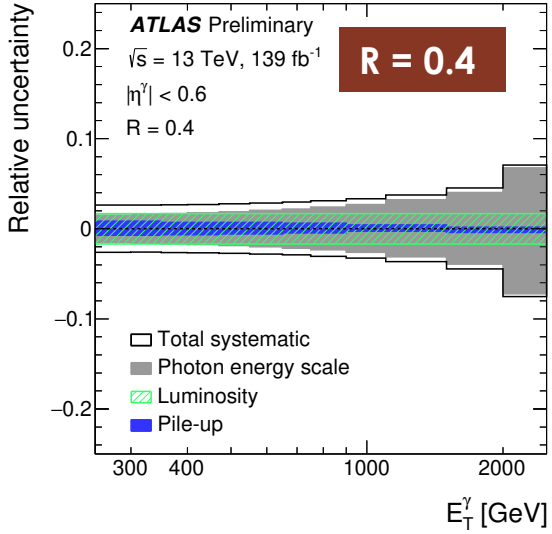
Fragmentation processes

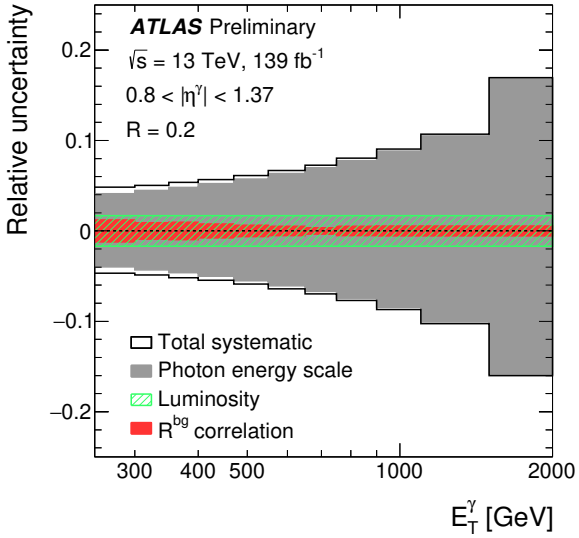
- Measurements of inclusive isolated-photon cross sections
  - Provide a testing ground for pQCD with a hard colourless probe
  - Are sensitive to the gluon PDF (via $qg \rightarrow q\gamma$) → input for global QCD fits

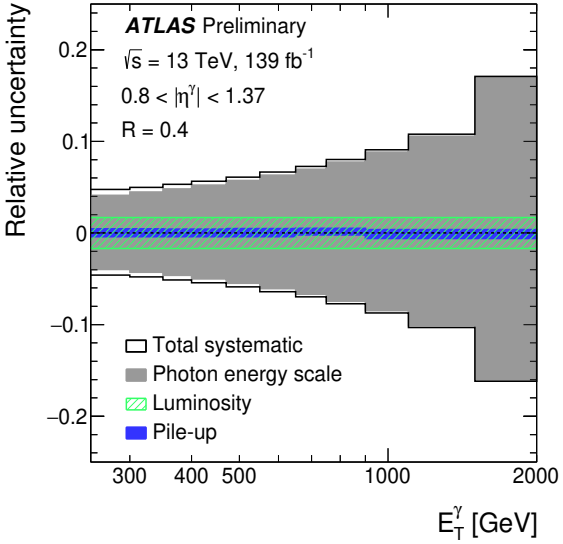
- Previous studies performed using 36 fb^{-1} from 2015+2016 data taking
  - Including the full Run-2 data provides higher E_T^γ values with smaller statistical uncertainties
  - The new measurements benefit from reduced systematics thanks to the work of the ATLAS Combined Performance groups

Inclusive photon production









- Total systematic uncertainty and dominant contributions
- Dominant sources:
  - Photon energy scale
  - Luminosity measurement
  - R^{bg} correlation (Pile up) for R = 0.2 (R = 0.4)
- Photon ID efficiency uncertainty significantly reduced wrt the previous analysis (1-3% → ~0.6%)

Inclusive photon production

JETPHOX (fixed order)

- **Full fixed-order NLO pQCD calculations for direct and fragmentation processes**
- **Scales:** $\mu_R = \mu_F = \mu_f = E_T^\gamma/2\,(E_T^\gamma)$
- **Fragmentation functions:** BFG II
- **PDFs:** MMHT2014, CT18, NNPDF3.1, and HERAPDF2.0 at NLO; ATLASpdf21 at NNLO
- **Isolation:** fixed cone at parton level
- **Non-perturbative corrections:** estimated using PYTHIA samples. Consistent with unity within $\pm 1\,\%$ (no correction applied)

SHERPA NLO (multi-leg merged)

- **Parton-level calculations for $\gamma + 1{,}2\,(3{,}4)$ jets at NLO (LO) supplemented with PS**
- Only direct contribution (Frixione's isolation at ME level)
- **Scales:** dynamic scale setting (E_T^γ)
- **PDFs:** NNPDF3.0 NNLO
- **Fragmentation into hadrons and UE simulated as for SHERPA LO**
- **Isolation:** fixed cone at particle level

NNLOJET (fixed order)

- **Full fixed-order NNLO pQCD calculations for direct and fragmentation processes**
- **Scales:** $\mu_R = \mu_F = E_T^\gamma$

$$\mu_f = \sqrt{E_T^\gamma \cdot E_T^{\max}} \cdot R$$

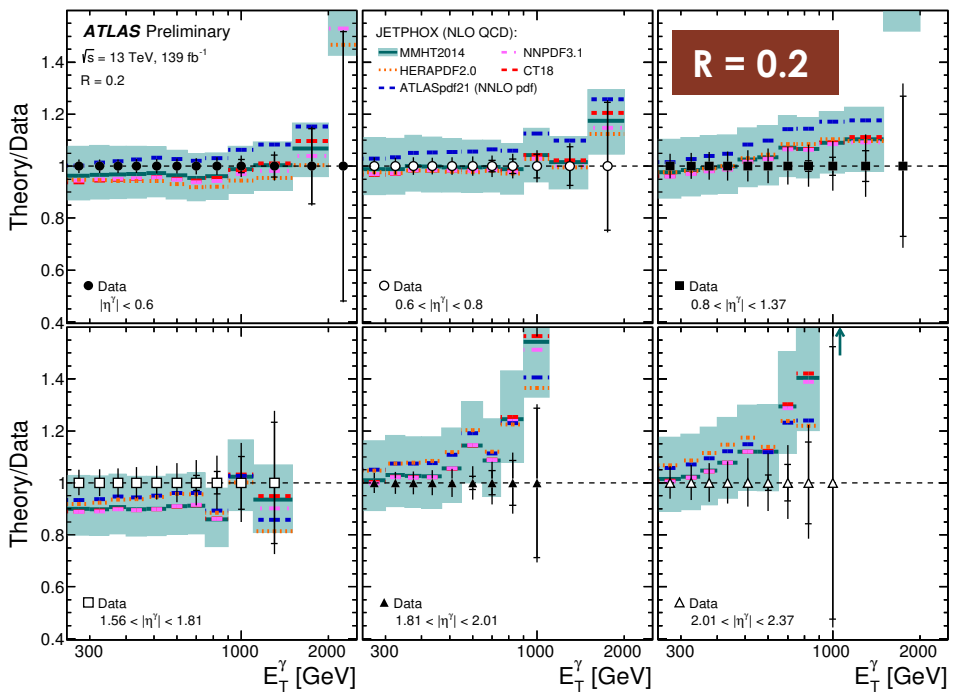
- **Fragmentation functions:** BFG II
- **PDFs:** CT18 NNLO
- **Isolation:** fixed cone at parton level
- **Non-perturbative corrections:** same estimation as for JETPHOX

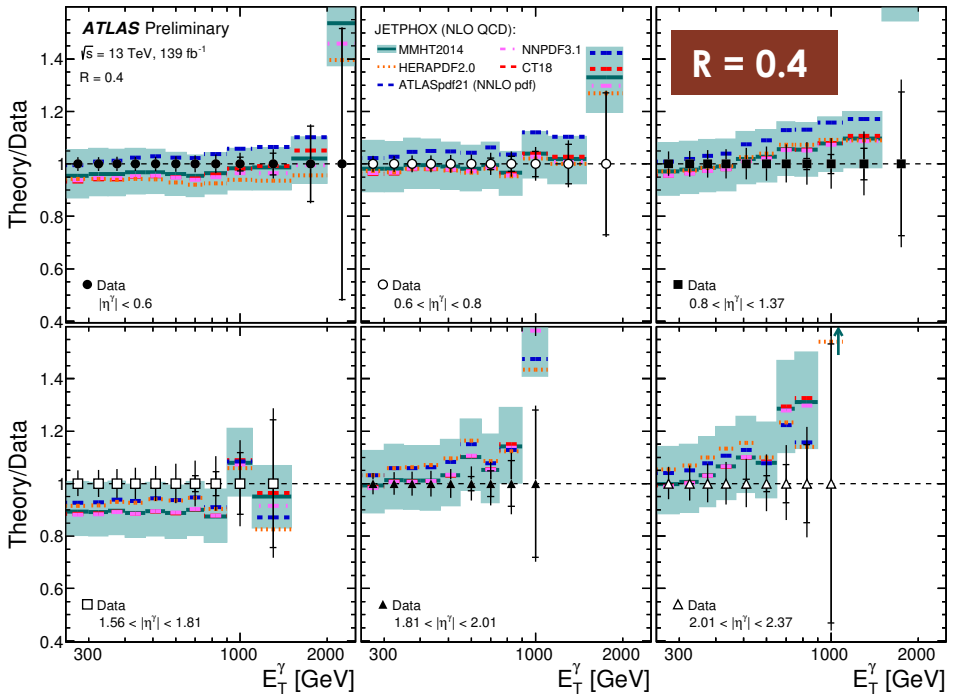
- Theoretical uncertainties: scale variations ($\mu_R, \mu_F \cdot 0.5$, 2 varied singly or simultaneously), μ_f (fragmentation scale) PDFs, α_S, non-perturbative corrections (only JETPHOX and NNLOJET)

- NNLOJET scale uncertainties reduced by more than a factor of 2 wrt NLO calculations of JETPHOX and SHERPA

Inclusive photon production

- The NLO pQCD predictions of JETPHOX compared to the measured differential cross sections as functions of E_T^γ in different $|y^\gamma|$ regions
  - Several PDFs: MMHT14, CT18, NNPDF3.1, HERAPDF2.0 and ATLASpdf21



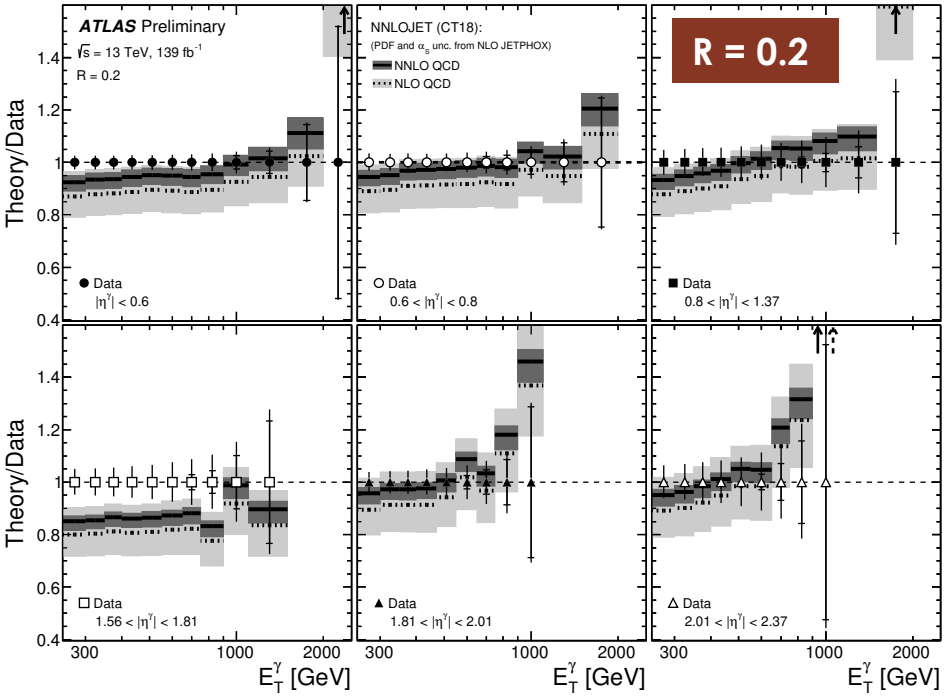


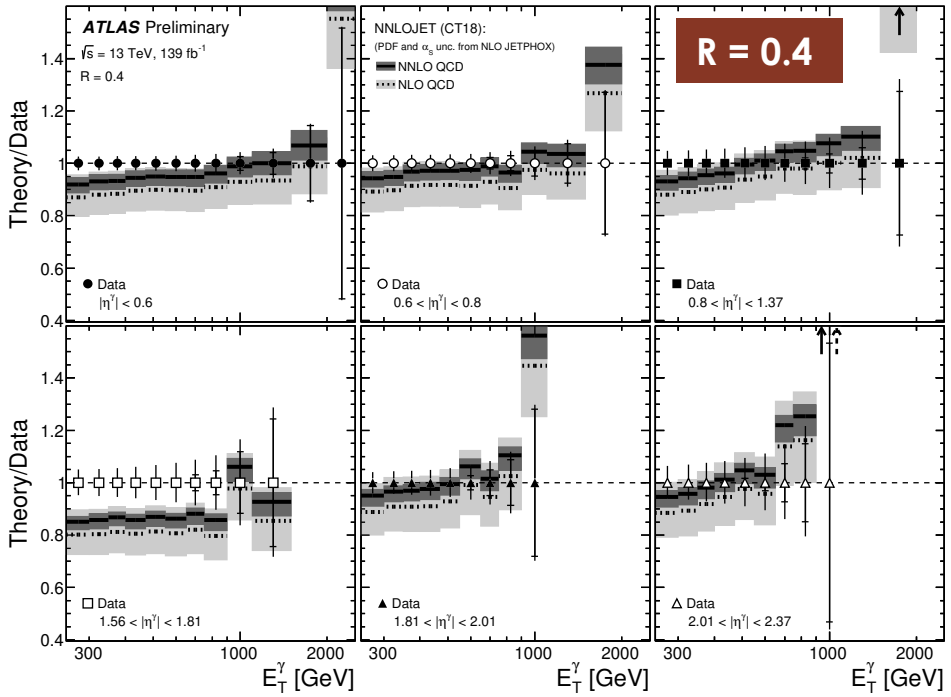
- Adequate description of the data within experimental and theoretical uncertainties

- **Different isolation radii for the first time** as requested by theorists - 1904.01044

Inclusive photon production

- The NNLO pQCD predictions of NNLOJET compared to the measured differential cross sections as functions of E_T^γ in different $|y^\gamma|$ regions

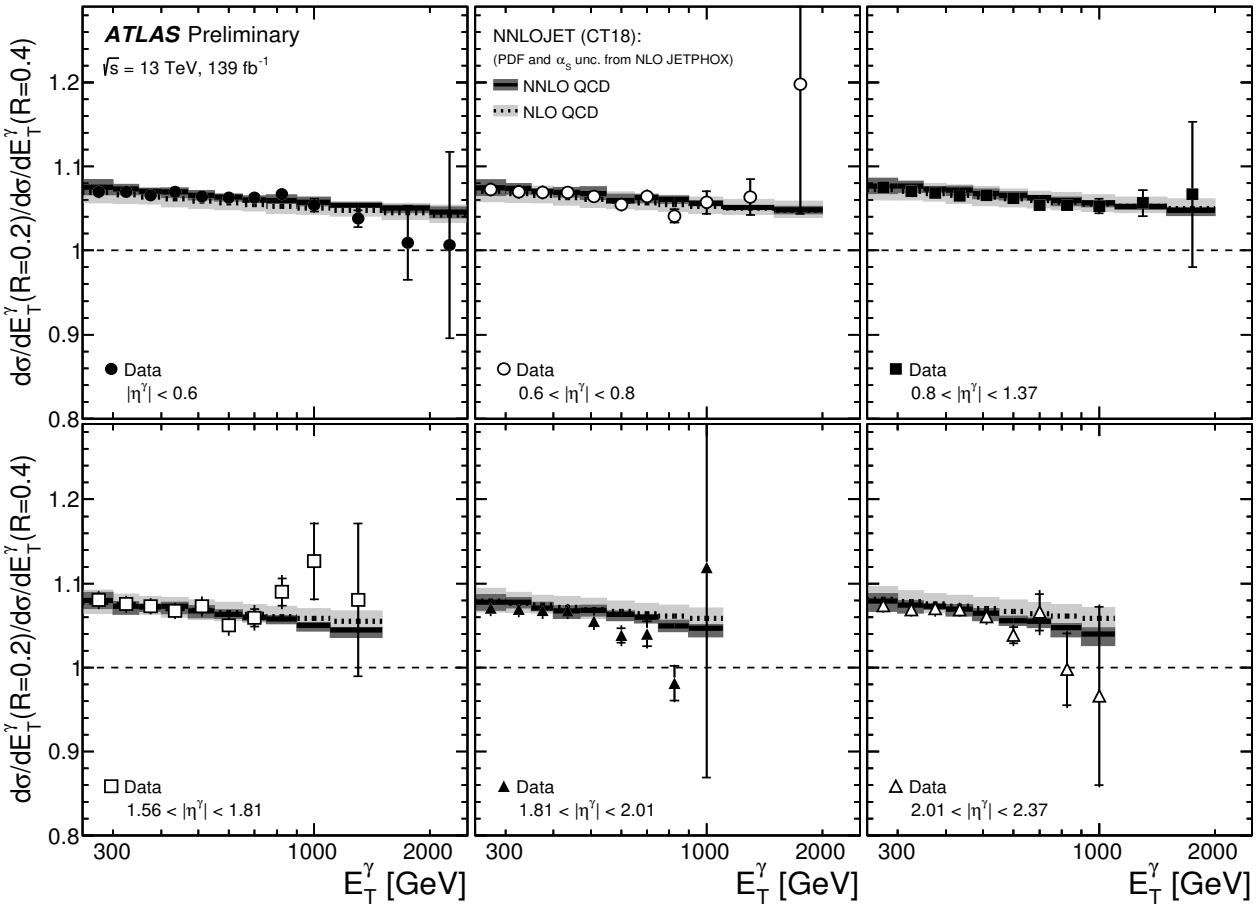




- Predictions are consistent with the measurements within uncertainties, except in the region $1.56 < |y^\gamma| < 1.81$, where the NNLO predictions underestimate the data

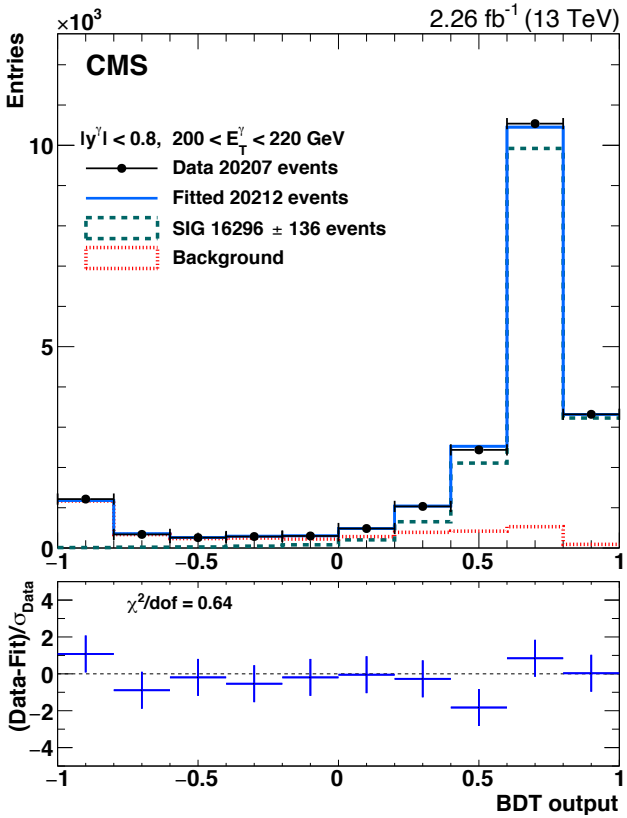
Inclusive photon production

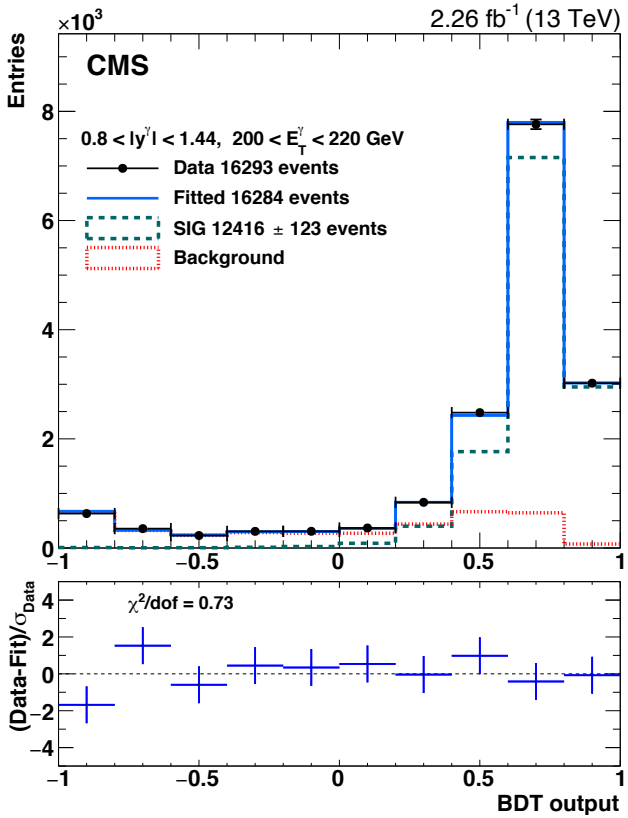
- Ratios of differential cross sections for R = 0.2, 0.4 as functions of E_T^γ in the different $|\eta_\gamma|$ regions
- These measurements provide a stringent test of pQCD (systematics at ~1%-level)
- Nice overall data/MC agreement



Triple differential cross sections

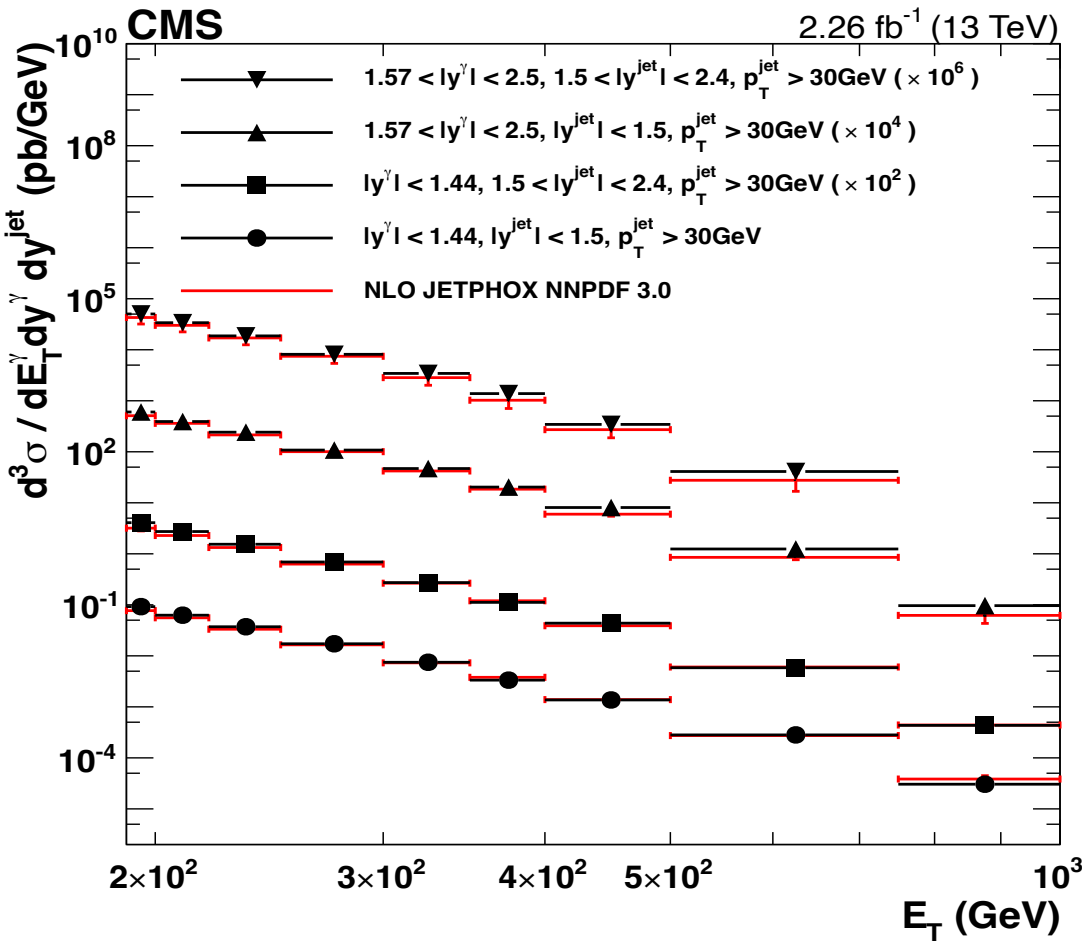
- γ + jets measurement directly probes QCD and is sensitive to the gluon PDF over a wide range of Bjorken x and Q^2
- Using 2.26 fb^{-1} of data at 13 TeV
- Dominant background from QCD multijet
- Use BDT to identify prompt photons – photon yield extracted from BDT shape





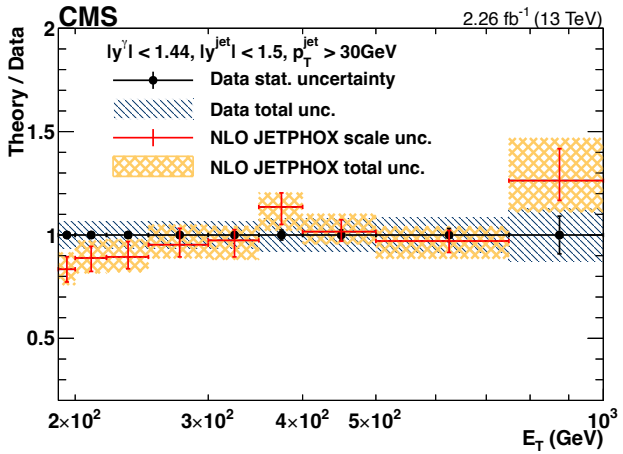
Triple differential cross sections

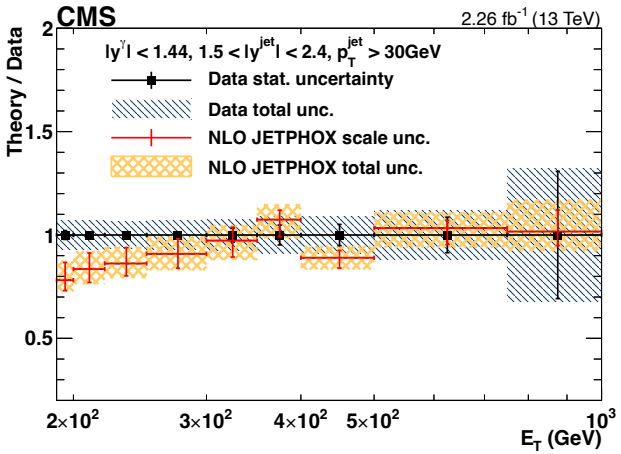
- γ + jets cross section measured as a function of:
  - E_T^{γ} for $E_T^{\gamma} > 190$ GeV
  - $|y^{\gamma}|$ for $|y^{\gamma}| < 2.5$
  - Rapidity of the leading jet for $|y^{jet}| < 2.5$
- Measured cross section compared with NLO calculation from JETPHOX

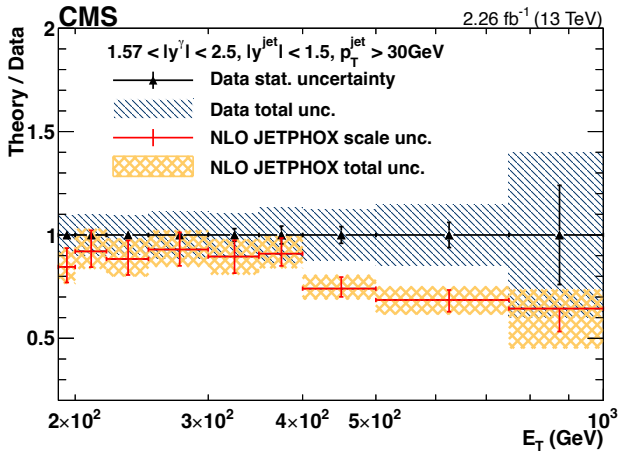


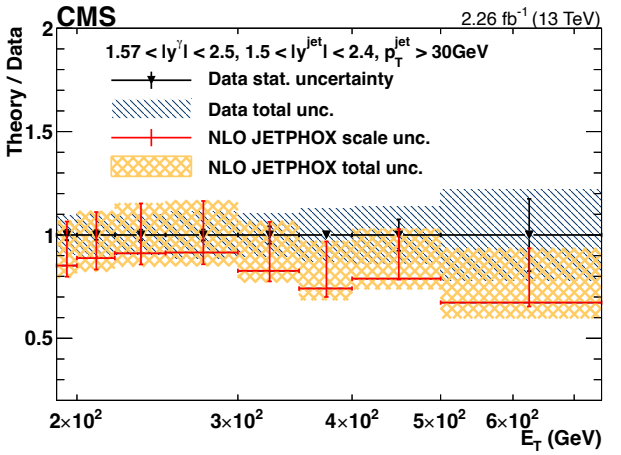
Triple differential cross sections

- Ratio of theoretical predictions to data for 2 bins of $|y^{\gamma}|$ and $|y^{jet}|$
- Measurement extends the E_T^{γ} range from 300 GeV in the 7 TeV analysis to 1 TeV
- For low to moderate E_T^{γ} range, experimental uncertainties smaller or comparable to theoretical ones
- Potential to constrain PDFs



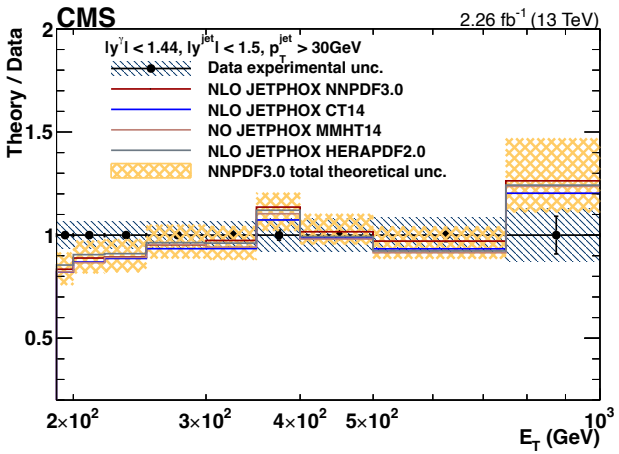


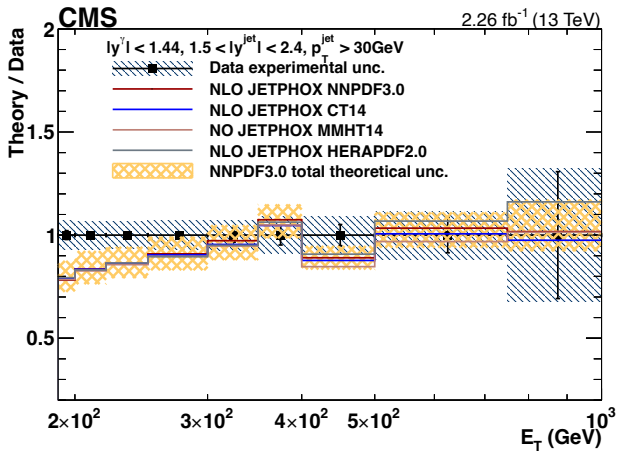


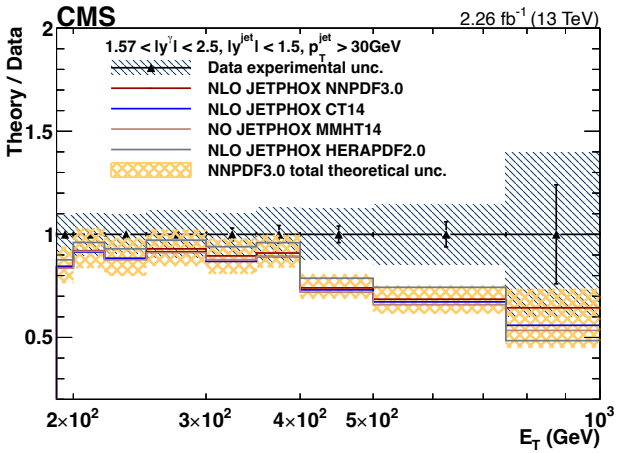


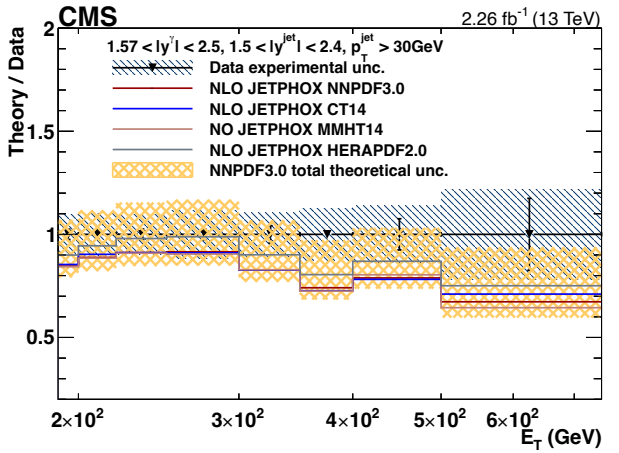
Triple differential cross sections

- Comparison with different PDF sets: NNPDF3.0, CT14, MMHT14, HERAPDF2.0
- Differences between different PDF sets are small, within the uncertainties computed using NNPDF3.0
- At low $|y^{\gamma}|$, better data/theory agreement at high E_T^{γ}
- At high $|y^{\gamma}|$, better data/theory agreement at low E_T^{γ}

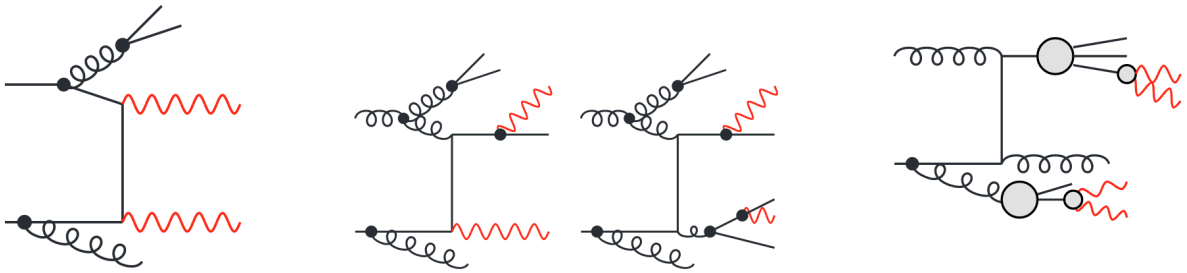




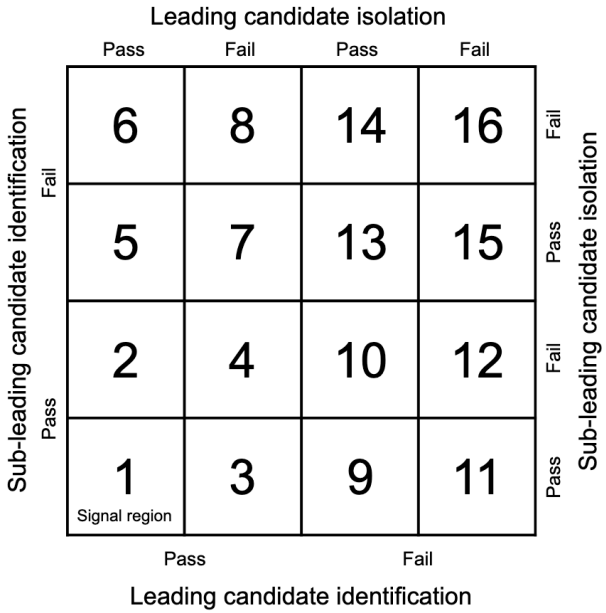




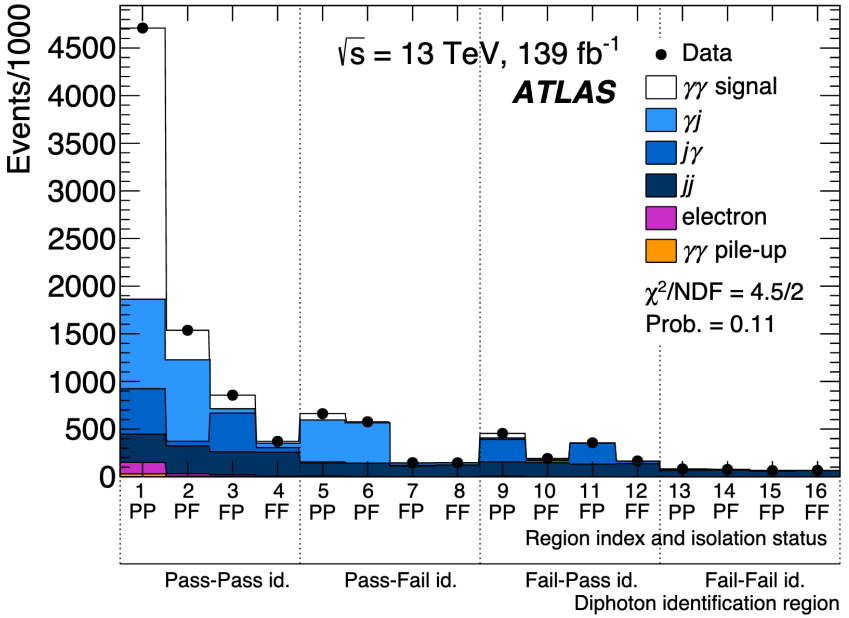
Measurement of diphoton production



(a) Direct photons (b) Single- and double-fragmentation photons (c) Non-prompt photons

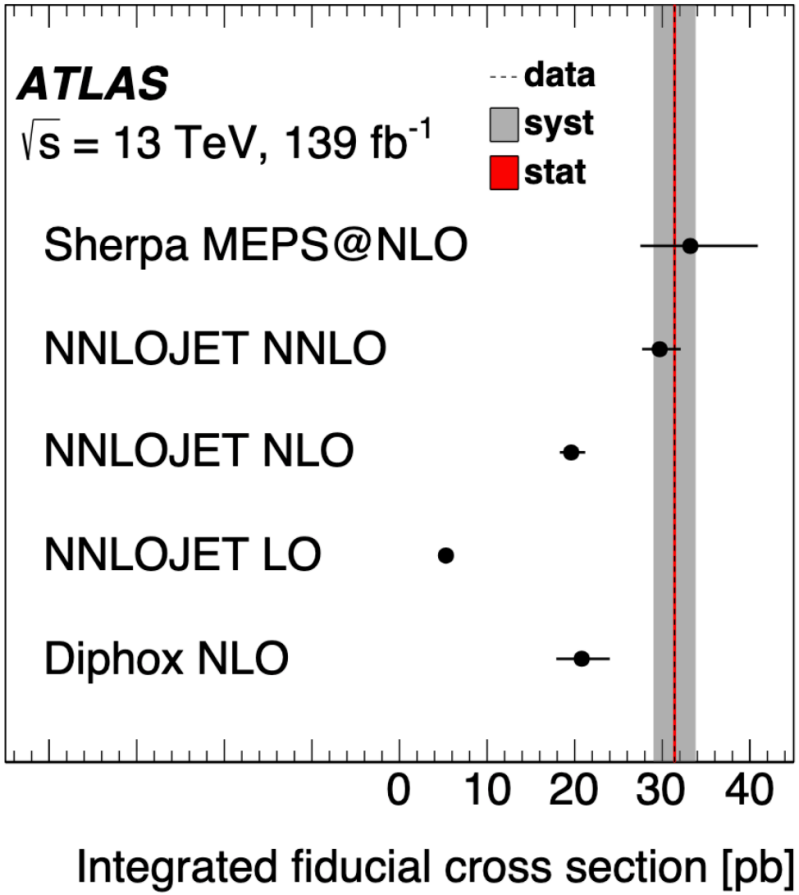


- Diphoton final state very sensitive to QCD
- Direct and fragmentation photon processes are sensitive to different effects
- Important background for Higgs production
- Measuring the inclusive and differential diphoton cross-section
- Using isolation and photon ID to estimate the background contributions
  - Most background is from jets misidentified as photons



Measurement of diphoton production

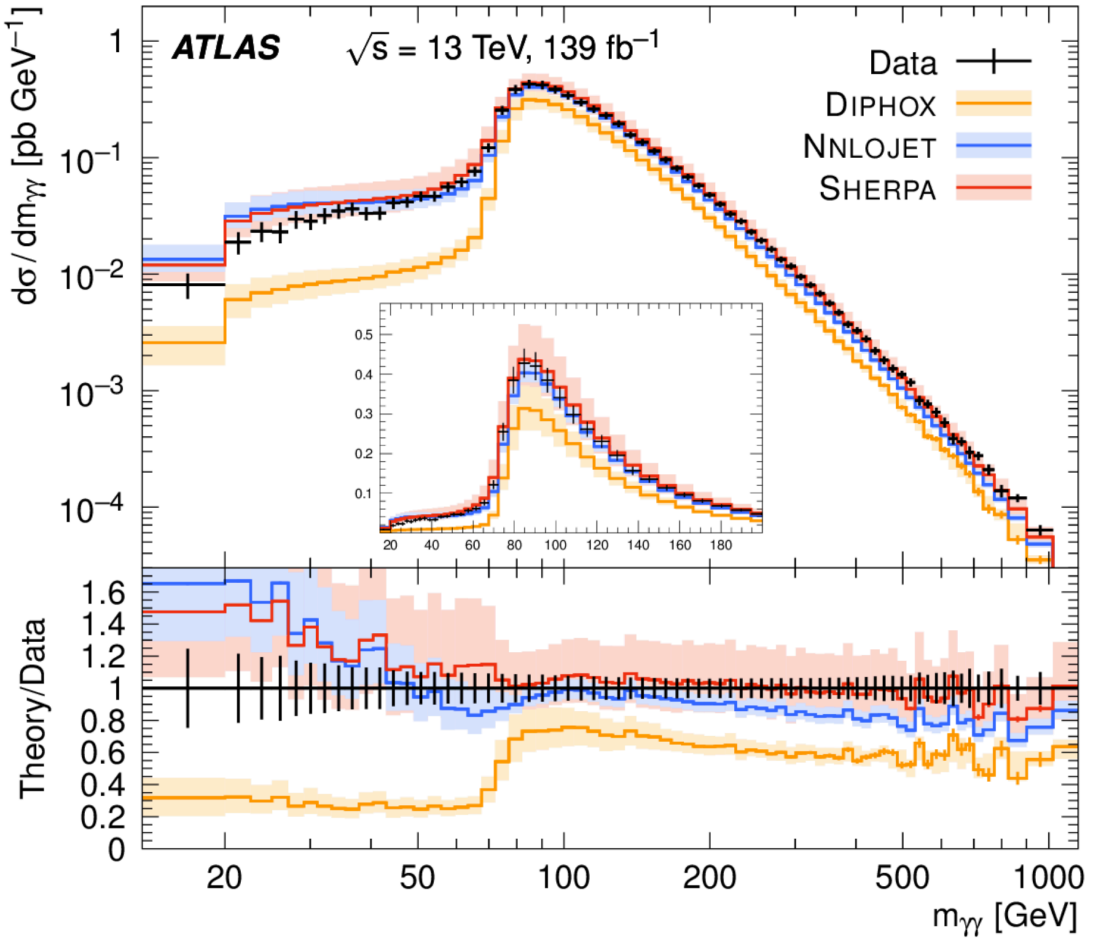
- Comparing inclusive cross-section measurements to several theoretical predictions
- Important to include higher jet multiplicity contributions i.e. from $\gamma\gamma + (2j, 3j)$
- Best agreement with either higher order computations or NLO predictions matched to PS
- Summary of the theoretical predictions below:



	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	✓

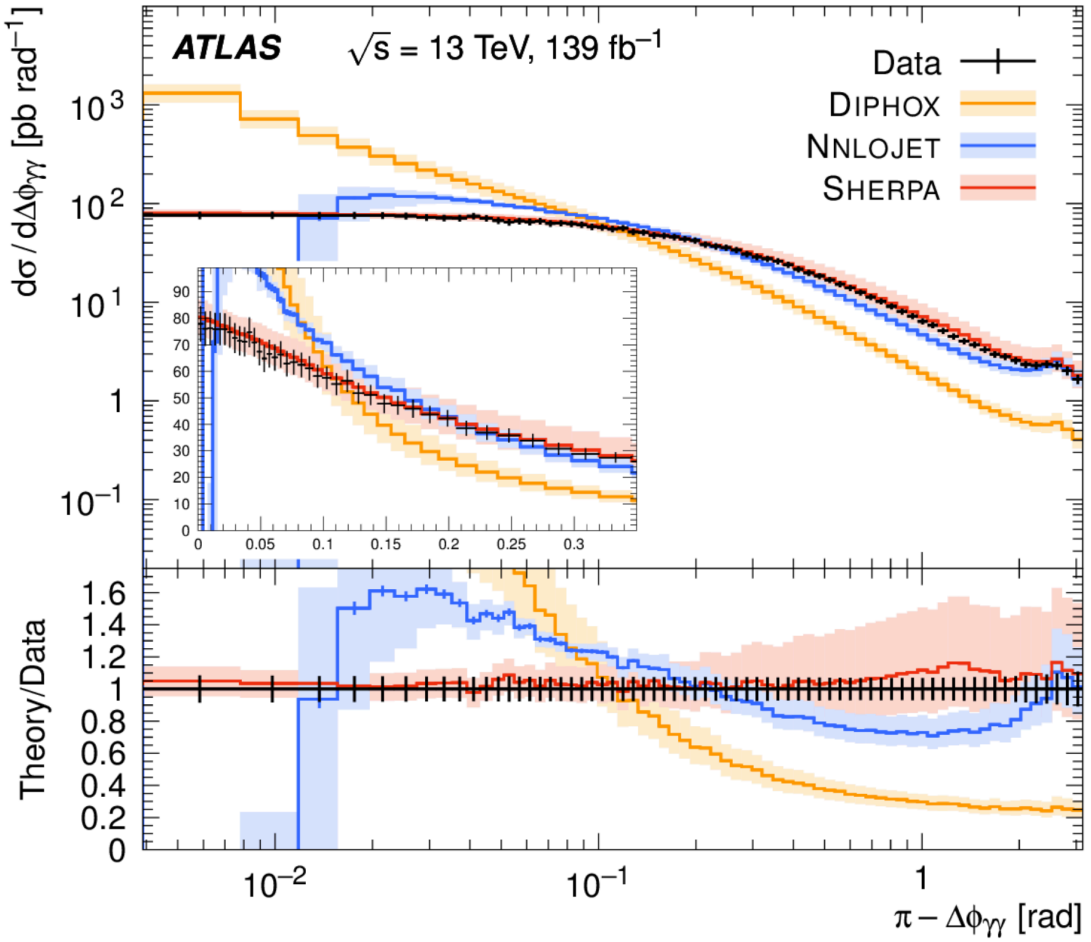
Measurement of diphoton production

- $m_{\gamma\gamma} < p_T^1 + p_T^2$ is suppressed
  - Only populated because of $\gamma\gamma$ + multijet
- Low-mass distribution is dependent on photon kinematic
- DIPHOX does not model data well
- NNLOJET and Sherpa do (they include higher order contributions)
- Slight underestimation from NNLOJET at high $m_{\gamma\gamma}$



Measurement of diphoton production

- Very small azimuthal decorrelation means very collinear → large impact from soft emissions
  - Difficult to model well, large disagreements with fixed-order predictions
- Sherpa includes resummation of these effects, and is able to model this fairly well
- Some underestimation from NNLOJET on the intermediate region
- DIPHOX does not model this well anywhere

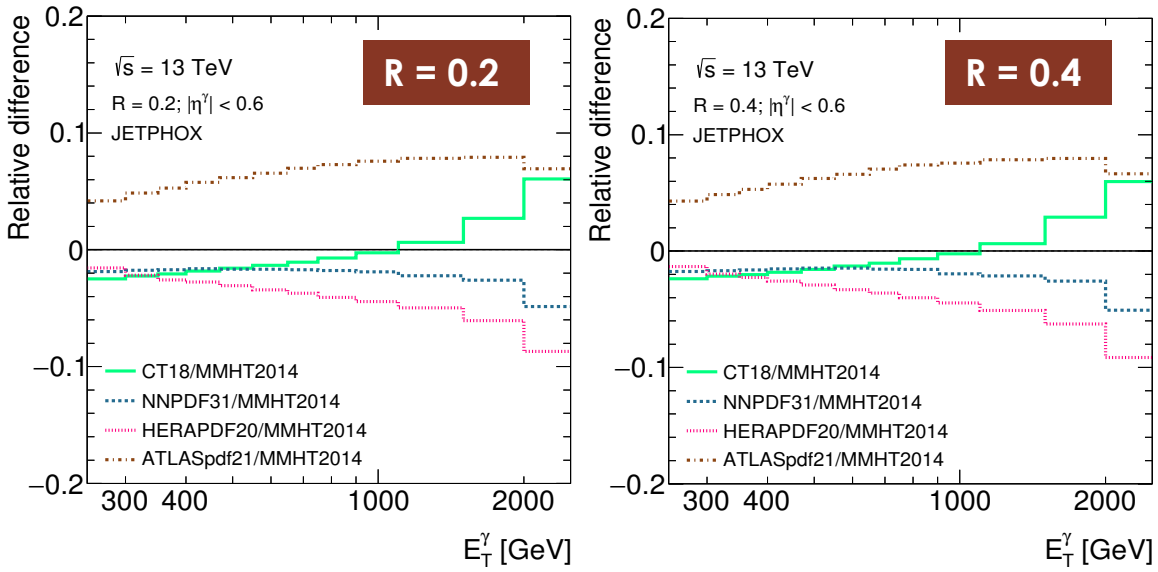


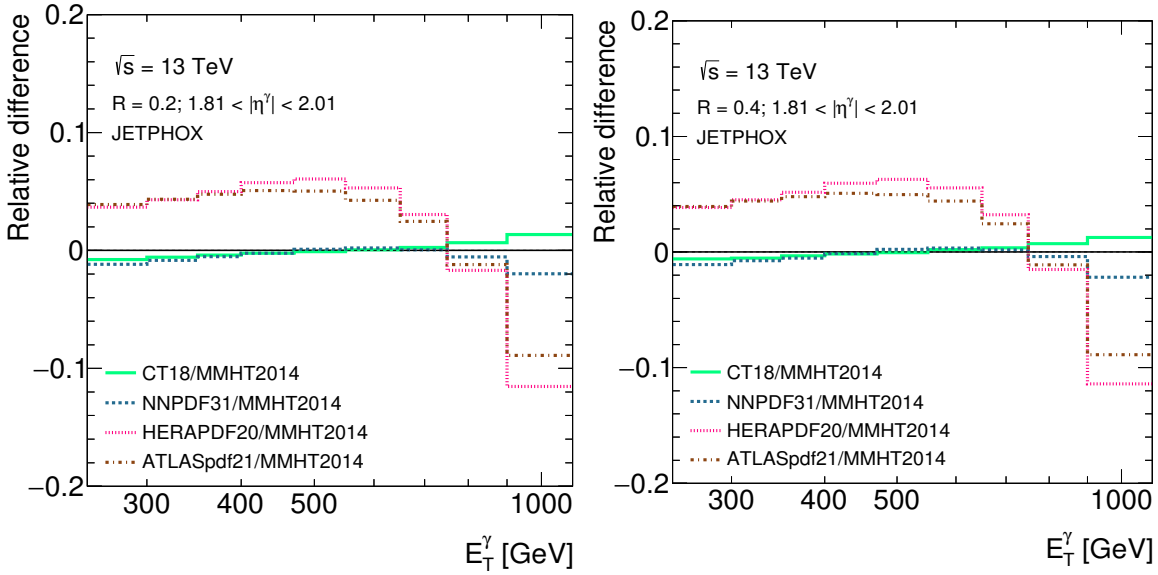
Conclusion & outlook

- LHC provides a rich playground for studying QCD
  - Able to study to high scales not tested by other experiments
  - Large dataset enables very precise measurements
- Advances in theoretical predictions enable studying a wide range of effects
- Inclusive isolated-photon production provides a stringent test of the SM predictions in a wide range of E_T^γ, as well as more detailed information for future PDF fits
- γ + jets measurement directly probes QCD and is sensitive to the gluon PDF over a wide range of Bjorken x and Q^2
- Measurement of diphotons provides strong tests of higher order QCD effects
- With the on going Run 3 data taking, very interesting times ahead
- More measurements and data coming soon so… **STAY TUNED!**

Backup Slides

Inclusive photon production

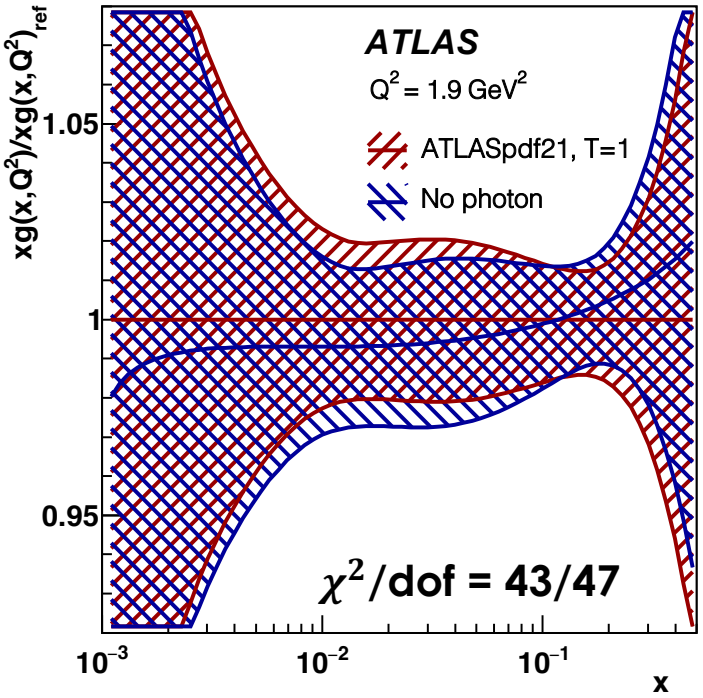


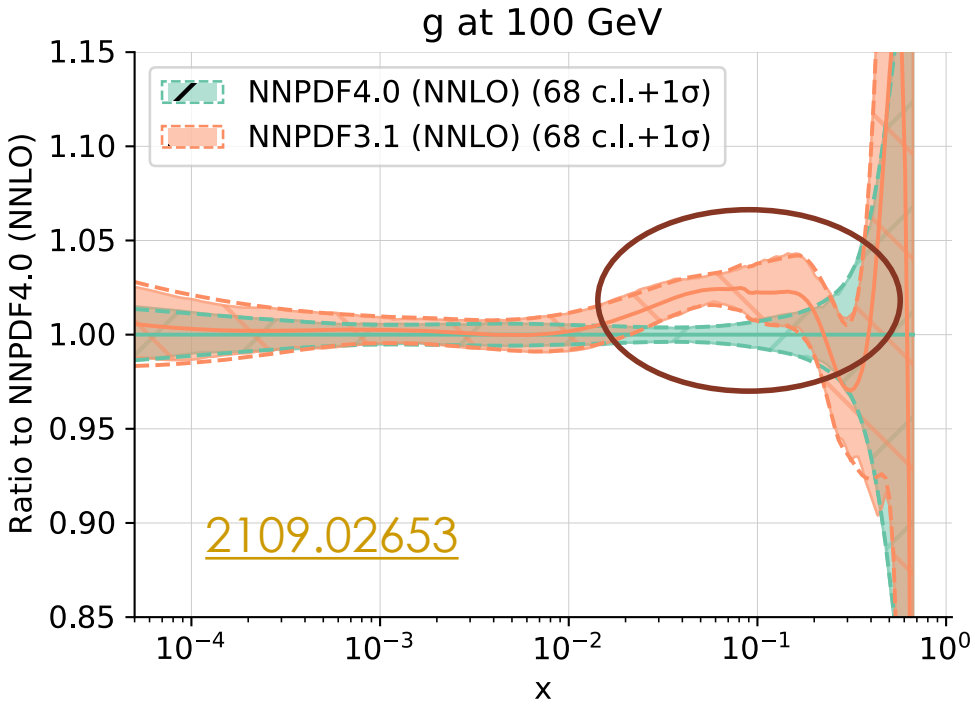


- The sensitivity to the PDFs investigated by comparing based on different PDFs
- MMHT14 as baseline
- Predictions based on the CT18/NNPDF3.1 are within 2%
- Predictions based on the HERAPDF2.0/ATLASpdf21 show differences of ~10%

Impact of the photon data sets on PDFs

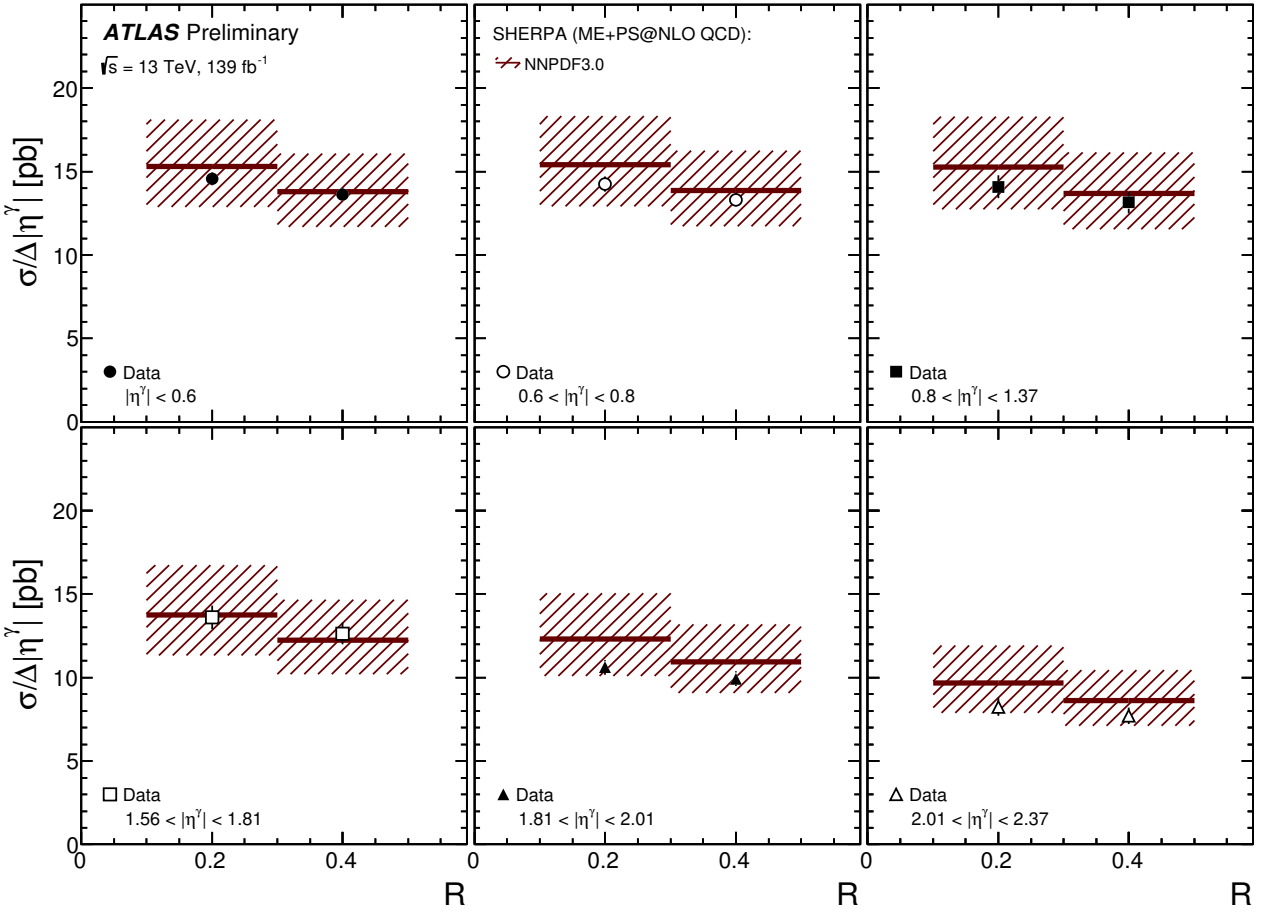
- **ATLASpdf21** is a PDF fit to **multiple ATLAS data sets** - EPJC 82 (2022) 5, 438
- We removed all the **13/8 TeV isolated photon ratio data** - 1901.10075
- This results in a marginal softening of the high-x gluon (blue to red), no decreased uncertainty – confirmed in NNPDF4.0 studies (much more data in!)
- These data do not have a large impact on PDFs… but very good to know that NNLO predictions describe these data nicely!





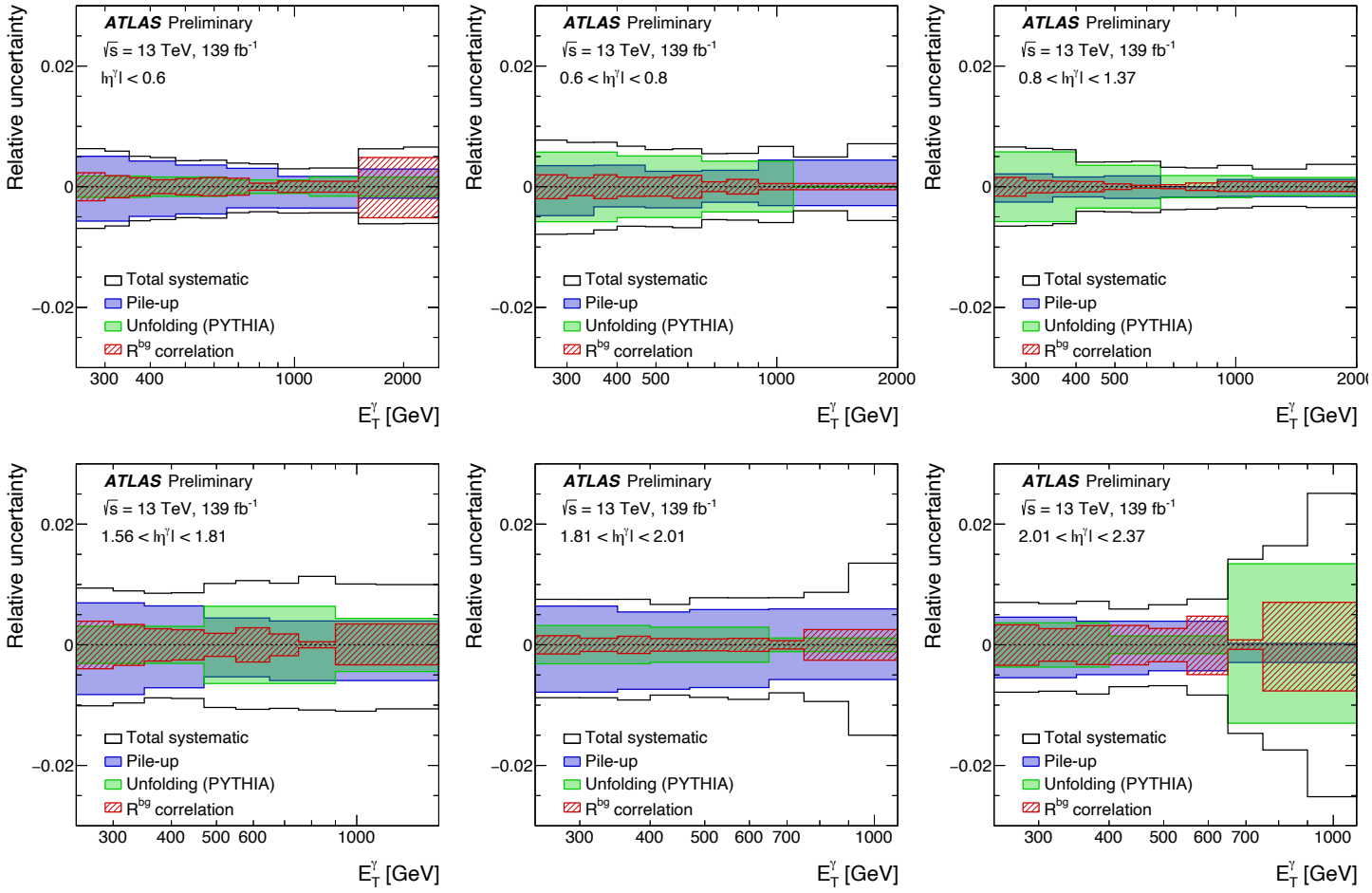
Inclusive photon production

- Fiducial cross section in each $|\eta^{\gamma}|$ region, dived by the width of each $|\eta^{\gamma}|$ region
- To test R-dependence of the inclusive photon cross section
- NLO predictions from Sherpa describe this dependence within the uncertainties



Inclusive photon production

- Total and dominant systematic uncertainties on the differential cross sections ratios

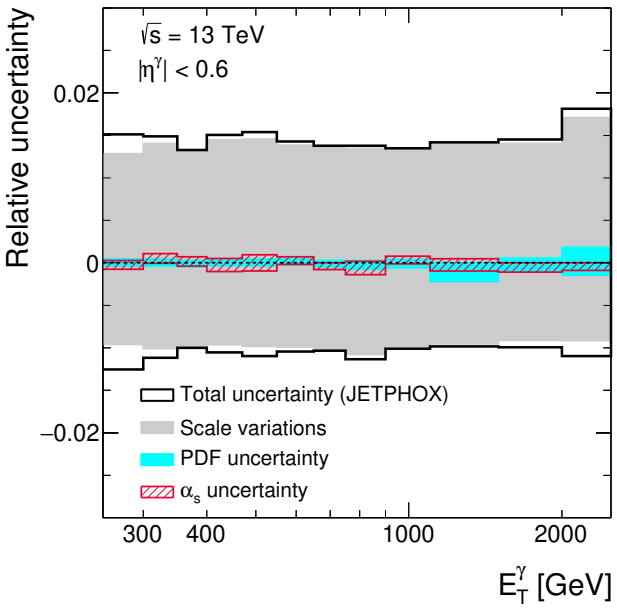


- From a 3-20% total uncertainty to a tipically < 1% uncertainty for the ratios

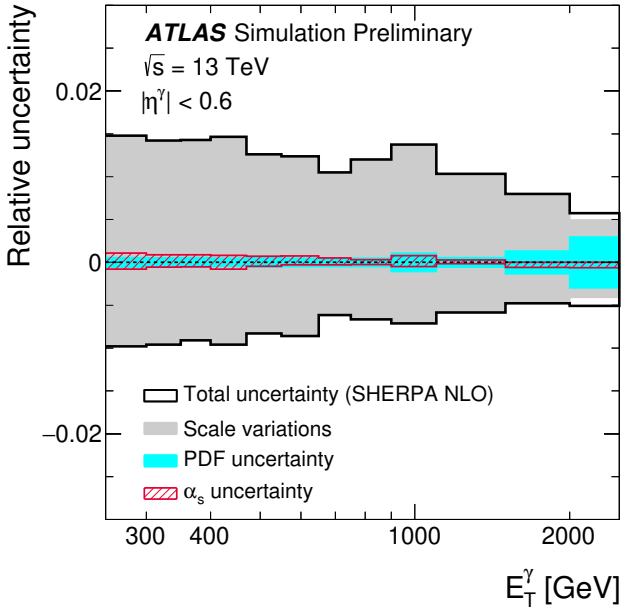
Inclusive photon production

- The theoretical uncertainties for these calculations are computed as fully correlated
- Scale variations, PDFs, α_S and non-perturbative corrections (only for JETPHOX and NNLOJET)

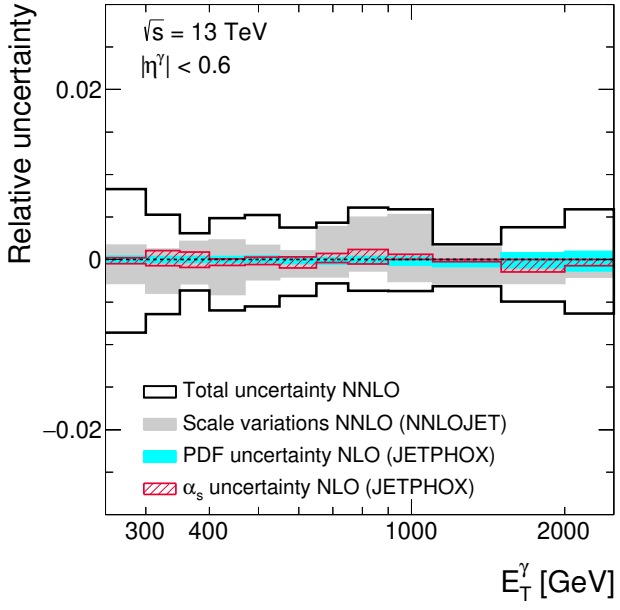
JETPHOX



SHERPA



NNLOJET



- Significant reduction obtained for the uncertainty on the ratios: from 10-20% (2-7.5%) total uncertainty to a ~1.5% (1%) uncertainty for the NLO (NNLO) predictions