Measurement of photon production cross sections also in association with jets with the ATLAS detector

E.Tassi
On behalf of the ATLAS Collaboration

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OUTLINE

- inclusive photon production: $pp \longrightarrow \gamma + X$
- photon + jet production: $pp \longrightarrow \gamma + jet(s) + X$
- inclusive diphoton production: $pp \longrightarrow \gamma + \gamma + X$

Prompt photon production at LHC

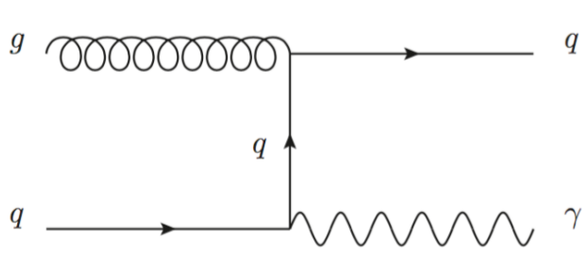
The production of prompt photons in pp collisions, pp $\longrightarrow \gamma$ + X, at the LHC:

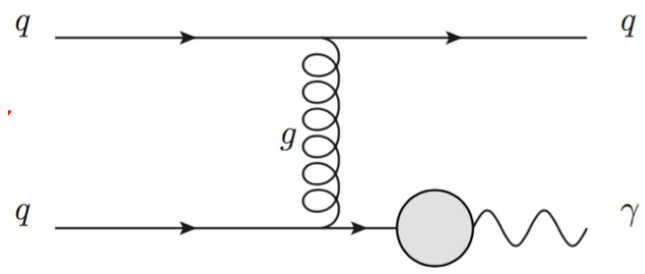
- provides a testing ground for pQCD with a hard colourless probe
- constrains the proton's gluon density

When studying the production of prompt photons in association with jets, pp $\longrightarrow \gamma$ + Jet(s)+ X, one can further study and test the dynamics of the hard scattering process

Prompt photons in pp collisions are produced via two mechanisms: direct-photon and fragmentation processes

direct-photon





fragmentation

$$d\sigma^{\gamma} = d\sigma^{(D)}(\mu^2, M^2, M_F^2) + \sum_{k=q,\bar{q},g} d\sigma_k^{(F)}(\mu^2, M^2, M_F^2) \otimes D_{\gamma/k}(M_F^2)$$

Inclusive prompt photon production

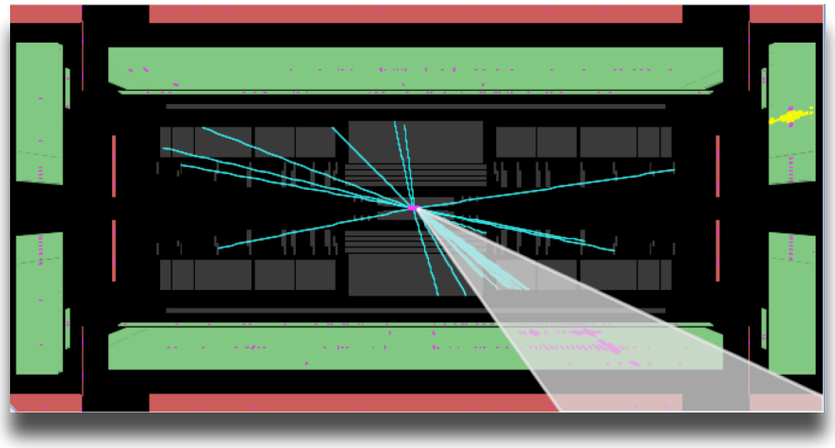
Phys. Lett. B 770 (2017) 473

Measured for the process, pp $\longrightarrow \gamma$ + X, the total fiducial cross section, σ_{meas}, and differential cross cross section $d\sigma/dE_{\text{T}}^{\gamma}$ in four η^{γ} regions

2015 data sample: 3.2 fb^{-1} at $\sqrt{s} = 13$ TeV

Photon selection:

- $125 < E_{\text{T}}^{\gamma} < 1500$ GeV
- $|\eta^{\gamma}| < 2.37$ (excluding $1.37 < |\eta^{\gamma}| < 1.56$)



Photon identification and isolation:

- $E_{\text{T}}^{\text{iso}}(\Delta R = 0.4) < 0.0042 \times E_{\text{T}}^{\gamma} + 4.8$ GeV

Remaining background (mostly jets misidentified as photons) subtracted with a data-driven method.

Measurements are compared to MC generators (PYTHIA8 and SHERPA) and to an NLO calculation (JETPHOX)

Inclusive prompt photon production

Comparison to PYTHIA and SHERPA MC generators

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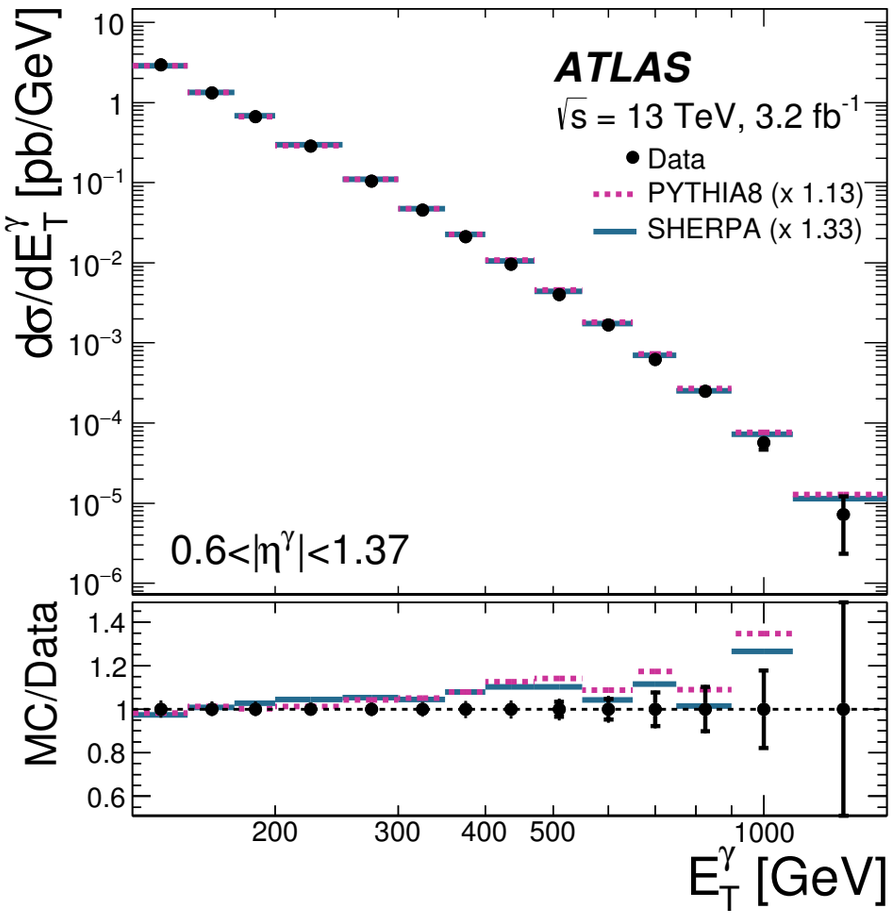
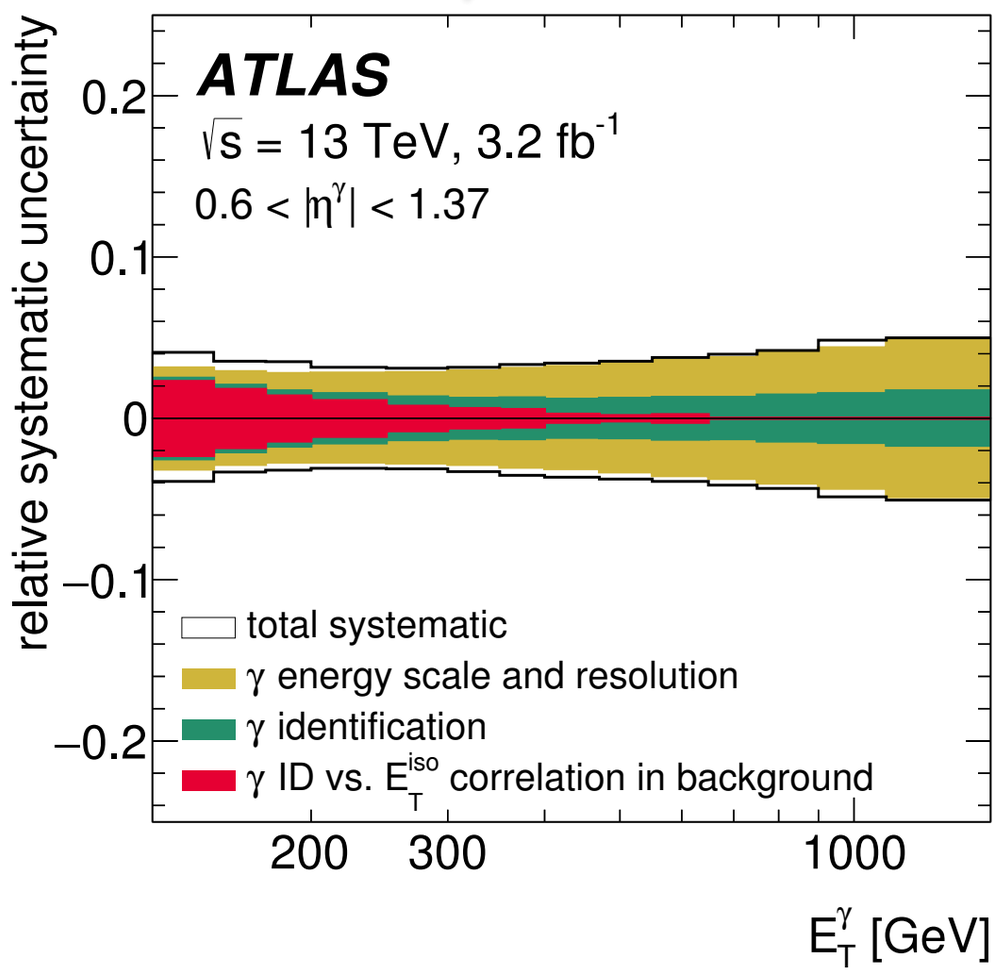
Main sources of the experimental uncertainty





- Good shape descriptions for E_{T}^{γ} < 500 GeV in the range $|\eta^{\gamma}|$ < 1.37 and for the whole E_{T}^{γ} range for 1.56 < $|\eta^{\gamma}|$ < 2.37
- Photon energy scale and resolution uncertainty dominates in the high-E_{T}^{γ} region
- For E_{T}^{γ} < 600 GeV the systematic uncertainty dominates

Inclusive prompt photon production

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Results

Total fiducial cross section:

$$\sigma_{\text{meas}} = 399 \pm 13(\text{exp.}) \pm 8(\text{lumi.}) \quad \text{pb}$$

Theory (NLO pQCD):

$$\sigma_{\text{NLO}} = 352^{+36}_{-29}(\text{scale}) \pm 3(\text{PDF}) \pm 6(\alpha_s) \pm 4(\text{NP}) \quad \text{pb}$$

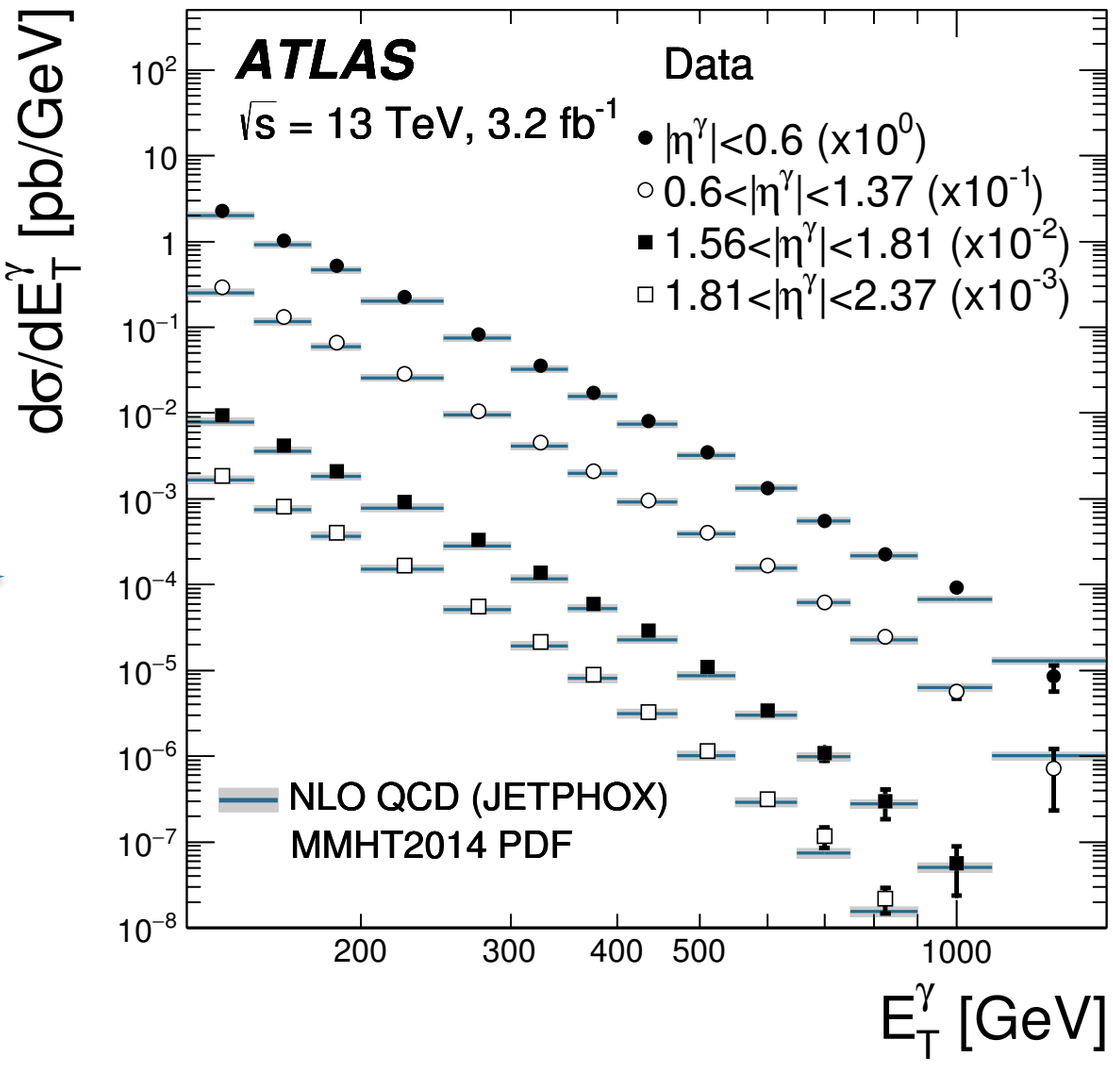
Differential cross sections decrease by approx. five order of magnitude in the measured range

NLO pQCD predictions have been obtained with the program JETPHOX

Default PDF set: MMHT2014
Fragmentation functions: BFG Set II

Theory prediction agrees with the measurement and is affected by large scale uncertainties

Differential cross sections



Inclusive prompt photon production

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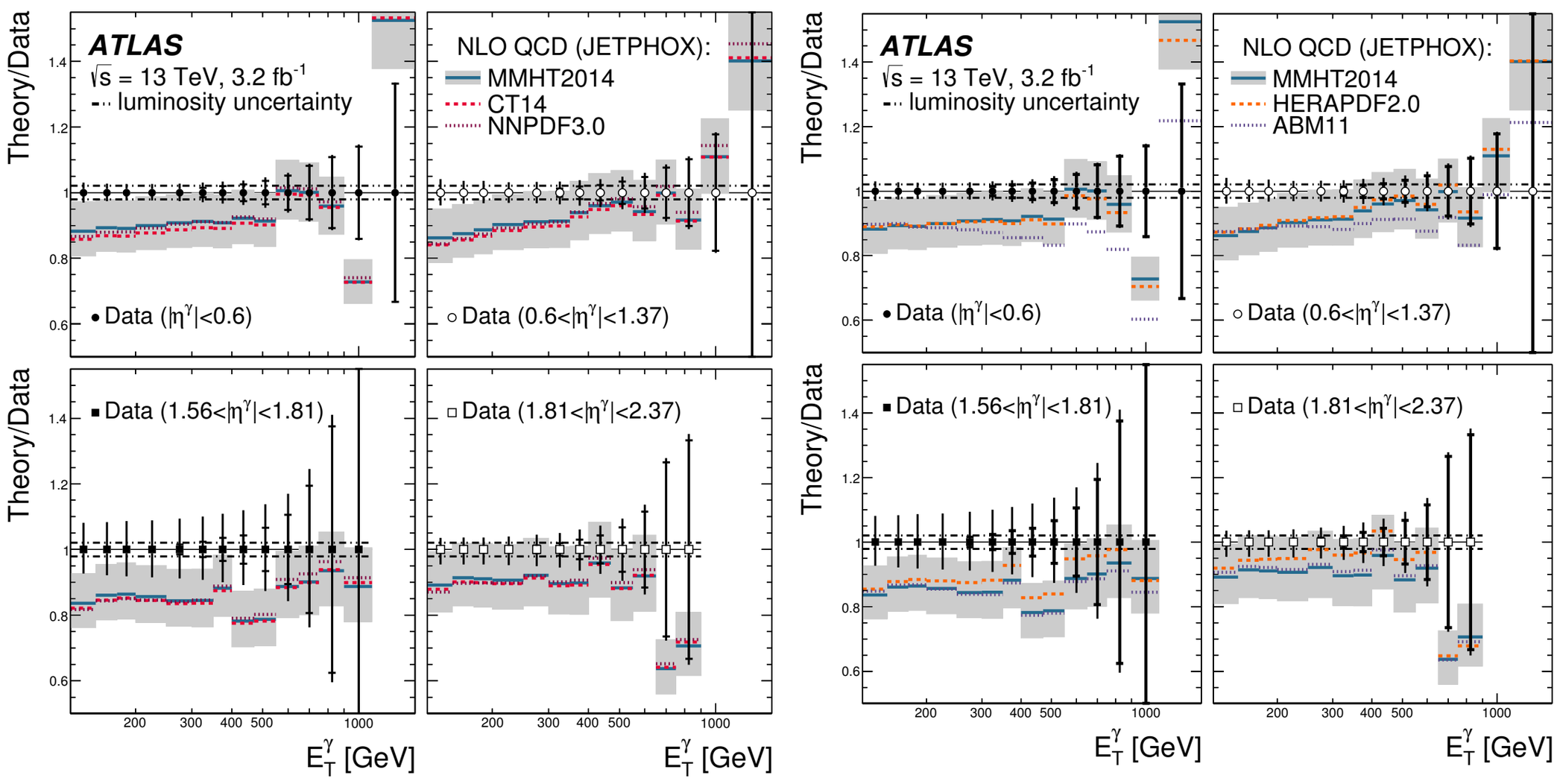
Theory-Data comparison and sensitivity to PDFs

Various PDF sets used: MMHT2014, CT14, NNPDF3.0, HERAPDF2.0 and ABM11



Differences are observed between data and predictions of up to 10-15%

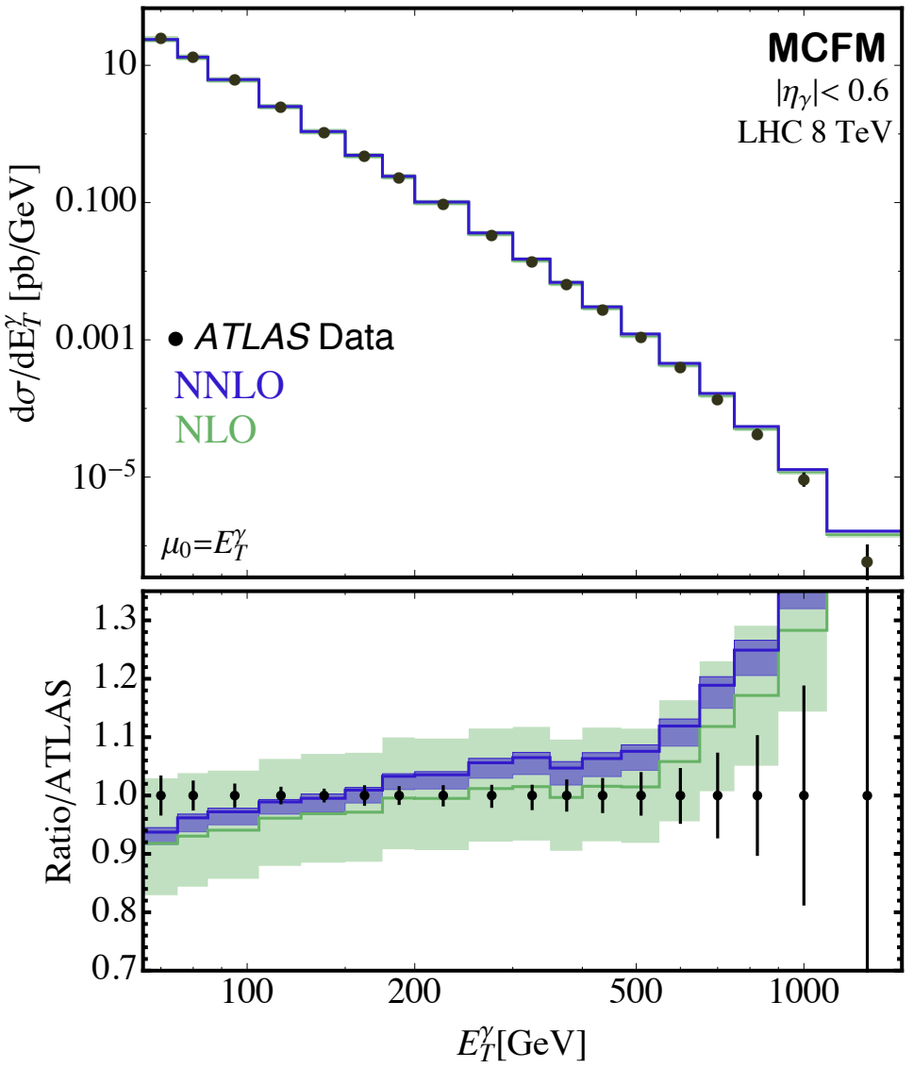
The large theoretical uncertainties (μ_R, μ_F scales) are typically larger than the experimental uncertainties

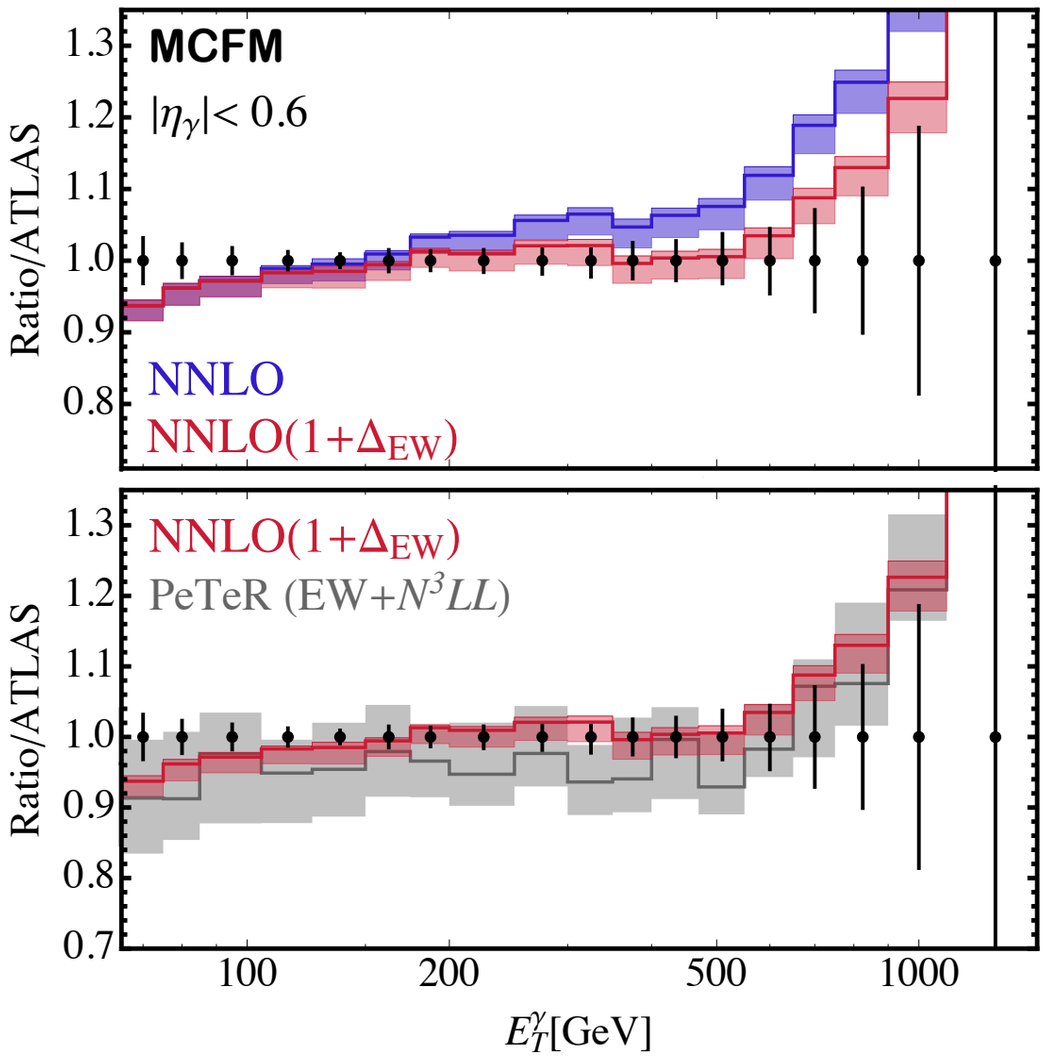
Overall fair agreement between data and theory

Inclusive prompt photon production: NNLO Calculations

NNLO pQCD calculations recently made available:

J.M Campbell, R. K. Ellis, C. Williams - Phys. Rev. Lett. 118, 222001 (2017)





- Theoretical uncertainties reduce by a factor of ~3
- EW contributions are important
- Progress that opens up the opportunity to perform precise tests of the SM at the LHC

Photon plus jet production @13 TeV

ATLAS-CONF-2017-059

Preliminary measurements of differential cross sections for the process pp $\longrightarrow \gamma$ + Jet+ X as a function of several variables:

$$E_{\mathrm{T}}^{\gamma},\ p_{\mathrm{T}}^{\mathrm{jet-lead}},\ \Delta\phi^{\gamma-\mathrm{jet}},\ m^{\gamma-\mathrm{jet}}\ \text{and}\ |\cos\theta^{*}|$$

2015 data sample: 3.2 fb^{-1} at $\sqrt{s} = 13\,\mathrm{TeV}$

Phase-space region:

- $E_{\mathrm{T}}^{\gamma} > 125\ \mathrm{GeV},\ |\eta^{\gamma}| < 2.37\ (\text{excluding}\ 1.37 < |\eta^{\gamma}| < 1.56)$
- $E_{\mathrm{T}}^{\mathrm{iso}} < 4.2 \cdot 10^{-3} \times E_{\mathrm{T}}^{\gamma} + 10\ \mathrm{GeV}$
- anti-kt algorithm with R=0.4
- $p_{\mathrm{T}}^{\mathrm{jet-lead}} > 100\ \mathrm{GeV},\ |y^{\mathrm{jet-lead}}| < 2.37$
- $\Delta R^{\gamma-jet} > 0.8$

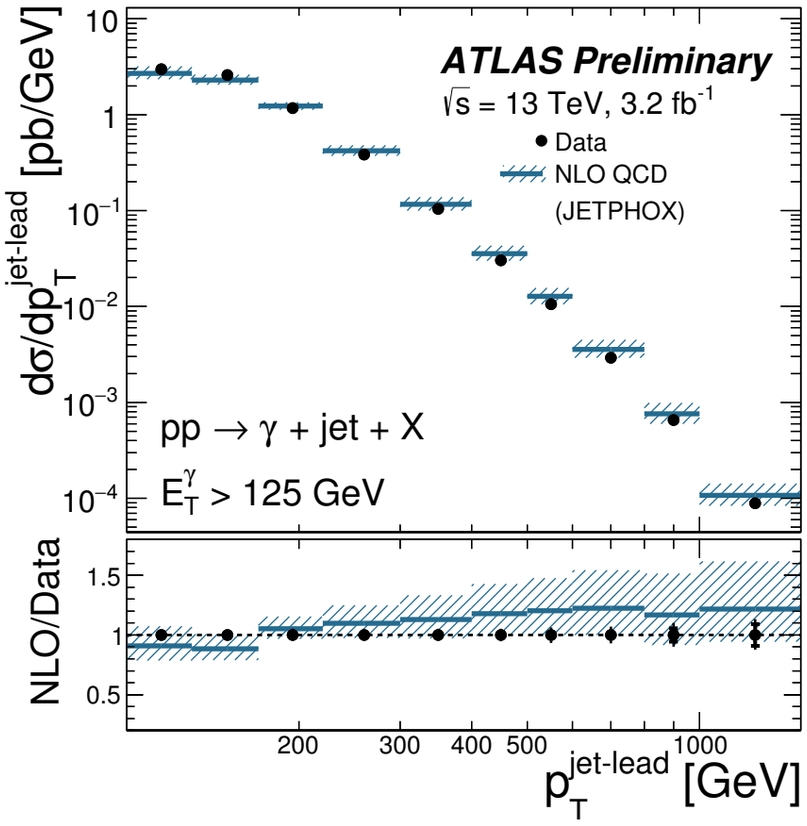
Additional cuts applied to $d\sigma/dm^{\gamma-\mathrm{jet}}$ and $d\sigma/d|\cos\theta^{*}|$ to perform measurements in an unbiased phase-space:

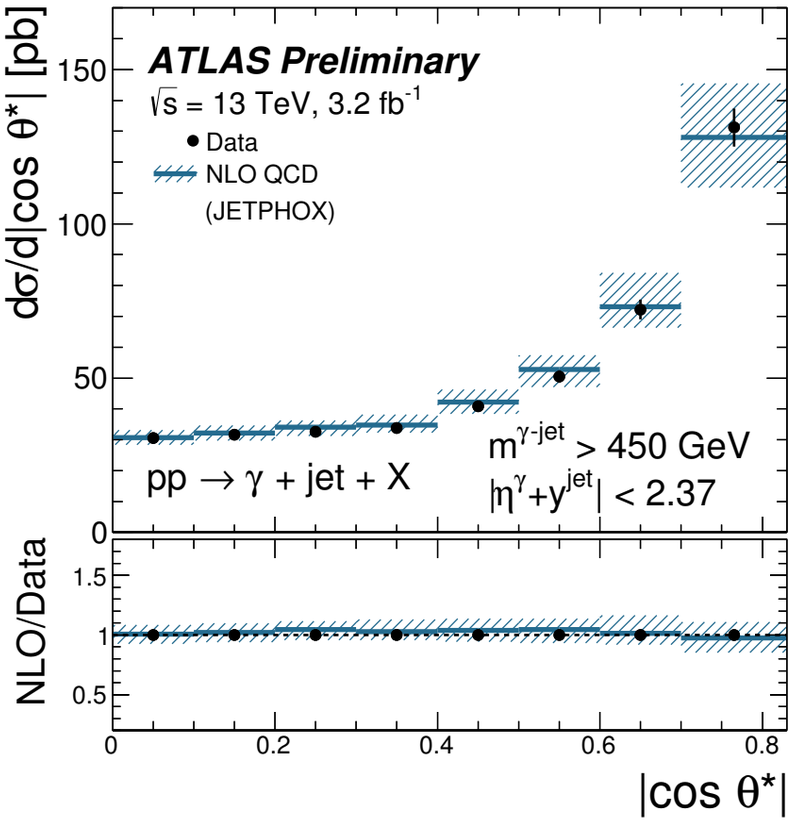
- $|\eta^{\gamma} + y^{\mathrm{jet}}| < 2.37$, $|\cos\theta^{*}| < 0.83$ and $m^{\gamma-\mathrm{jet}} > 450\ \mathrm{GeV}$

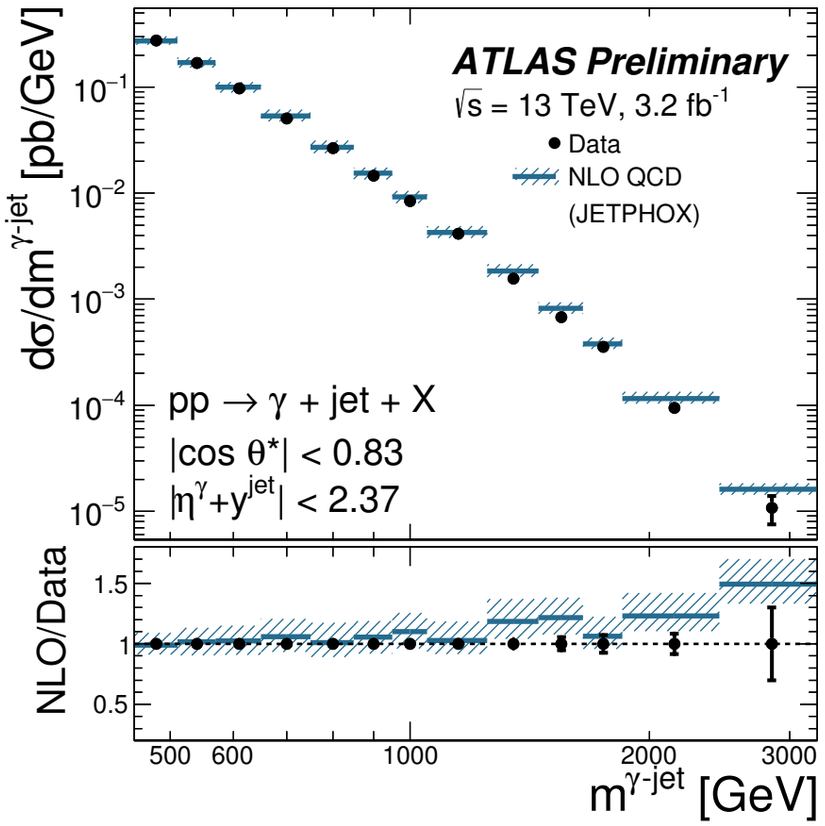
Measurements are compared to MC generators (PYTHIA8 and SHERPA) and NLO calculations (JETPHOX and SHERPA ME+PS NLO)

Photon plus jet production @13 TeV

ATLAS-CONF-2017-059







Good description by NLO pQCD (JETPHOX)

JETPHOX includes a full NLO pQCD calculation of both direct and fragmentation contribution. The parton level results are corrected for the small hadronization effects using PYTHIA.

Photon plus jet production @13 TeV

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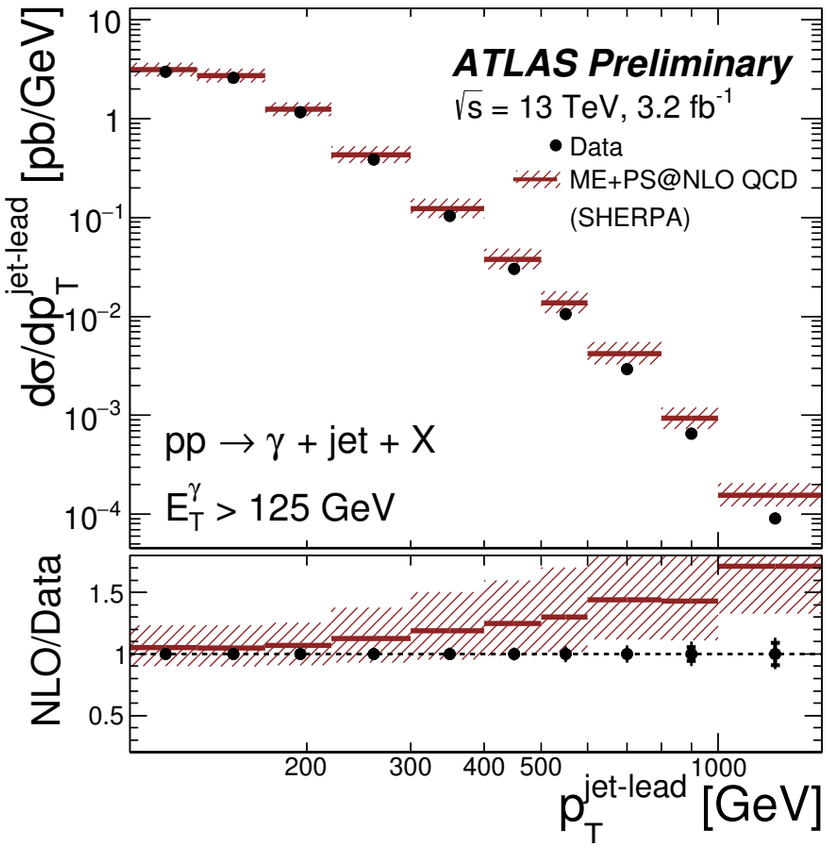
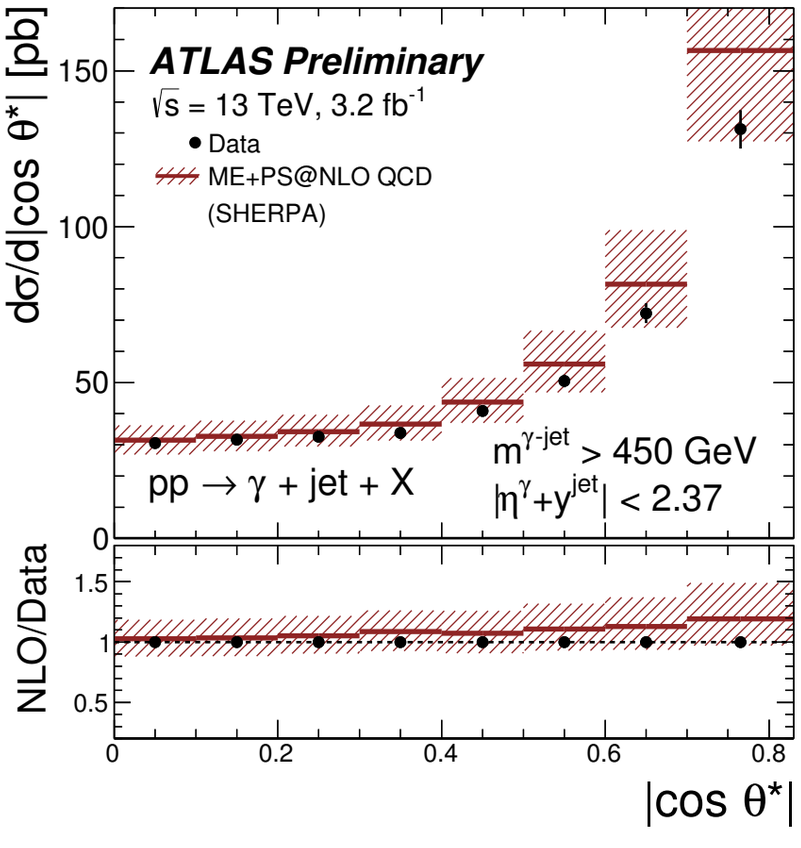
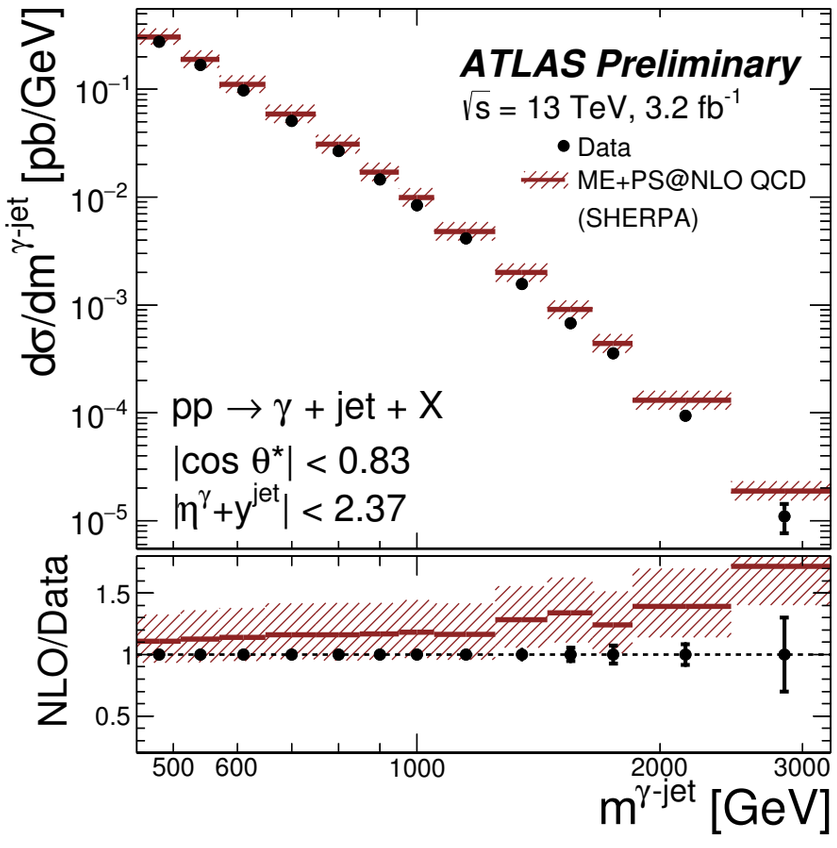






Good description by NLO pQCD (SHERPA ME+PS@NLO)

SHERPA combines parton-level calculations of γ +1,2 jets (at NLO) with γ +3,4 jets at (LO) supplemented with a parton shower and avoiding double-counting effects.

Photon plus njet (n=1,2,3) production @8 TeV

Nucl. Phys. B 918 (2017) 257

The larger data sample available at $\sqrt{s} = 8$ TeV (L= 20.2 fb^{-1}) has also allowed the study of (in addition to p+p $\longrightarrow \gamma$ + jet + X) the dynamics of the processes:

p+p $\longrightarrow \gamma$ +2 jets +X and p+p $\longrightarrow \gamma$ + 3 jets + X

Common selection:

At least one isolated photon, $E_{\mathrm{T}}^{\gamma} > 130\ \mathrm{GeV}$ and $|\eta^{\gamma}| < 2.37$

At least one jet (anti-kT, R=0.6): $P_{\mathrm{T}}^{\mathrm{jet}} > 50\ \mathrm{GeV},\ |y^{\mathrm{jet}}| < 4.4$

γ +2 jets selection:

$P_{\mathrm{T}}^{\mathrm{jet1}} > 100\ \mathrm{GeV},\ P_{\mathrm{T}}^{\mathrm{jet2}} > 65\ \mathrm{GeV}$

Measure: $d\sigma/dX$ with $X = E_{\mathrm{T}}^{\gamma},\ P_{\mathrm{T}}^{\mathrm{jet2}},\ \Delta\phi$ between objects (γ, jets)

γ +3 jets selection:

$P_{\mathrm{T}}^{\mathrm{jet1}} > 100\ \mathrm{GeV},\ P_{\mathrm{T}}^{\mathrm{jet2}} > 65\ \mathrm{GeV},\ P_{\mathrm{T}}^{\mathrm{jet3}} > 50\ \mathrm{GeV}$

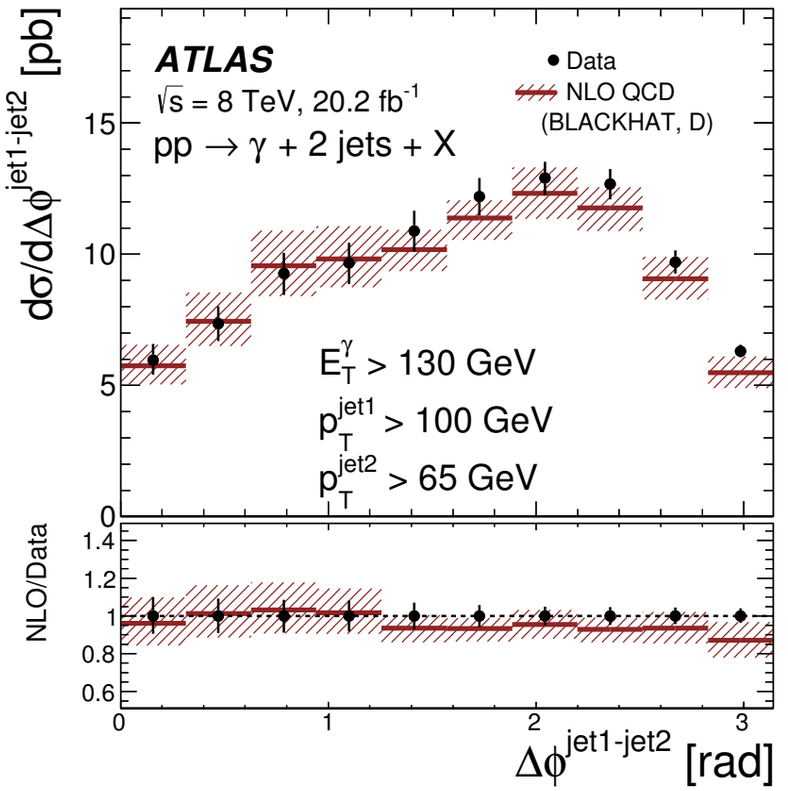
Measure: $d\sigma/dX$ with $X = E_{\mathrm{T}}^{\gamma},\ P_{\mathrm{T}}^{\mathrm{jet3}},\ \Delta\phi$ between objects (γ, jets)

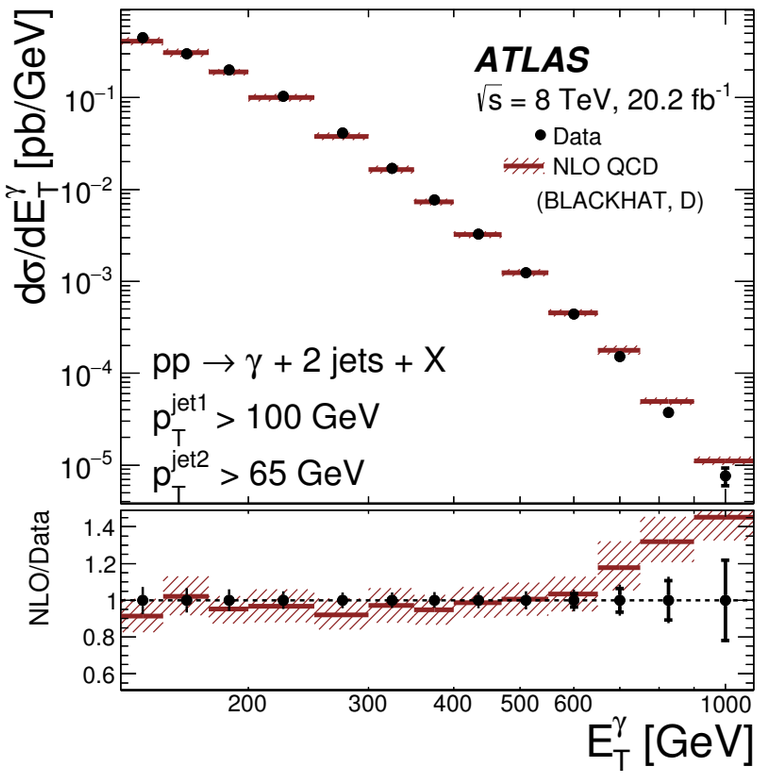
Photon plus 2 jet production @8 TeV

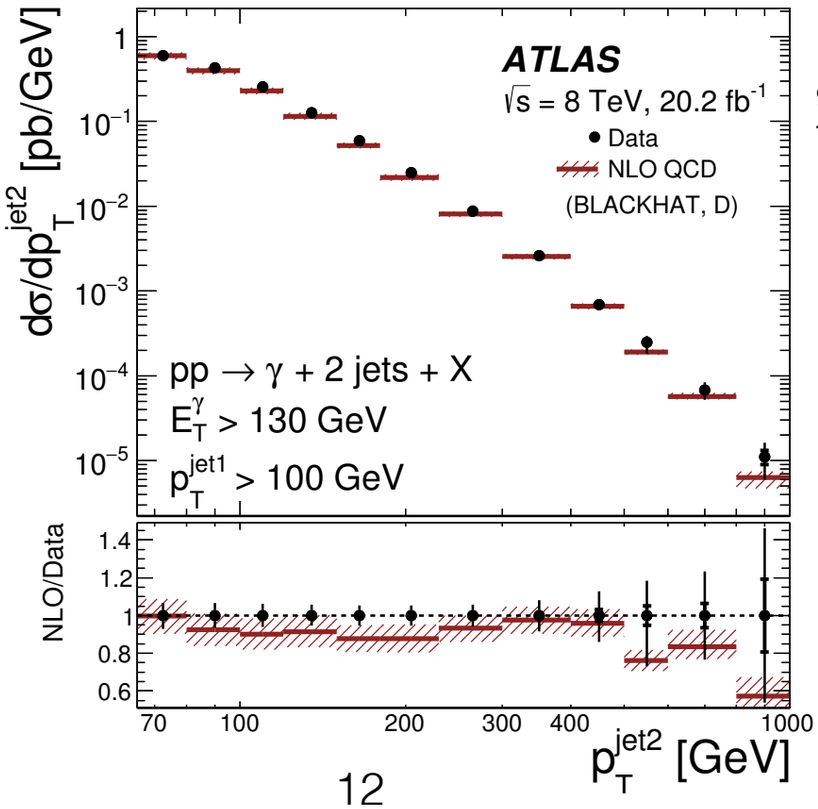
Nucl. Phys. B 918 (2017) 257

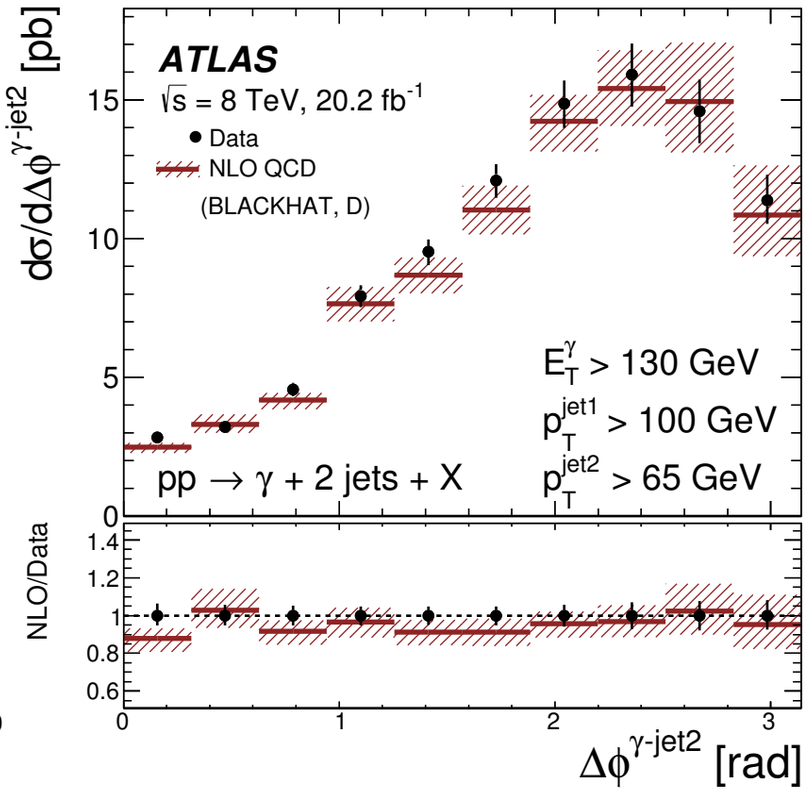
First ATLAS measurement of γ +2 jets dynamics

NLO pQCD predictions, obtained with BLACKHAT, describe well the measured cross sections (up to E_{T}^{γ} ~ 700 GeV)







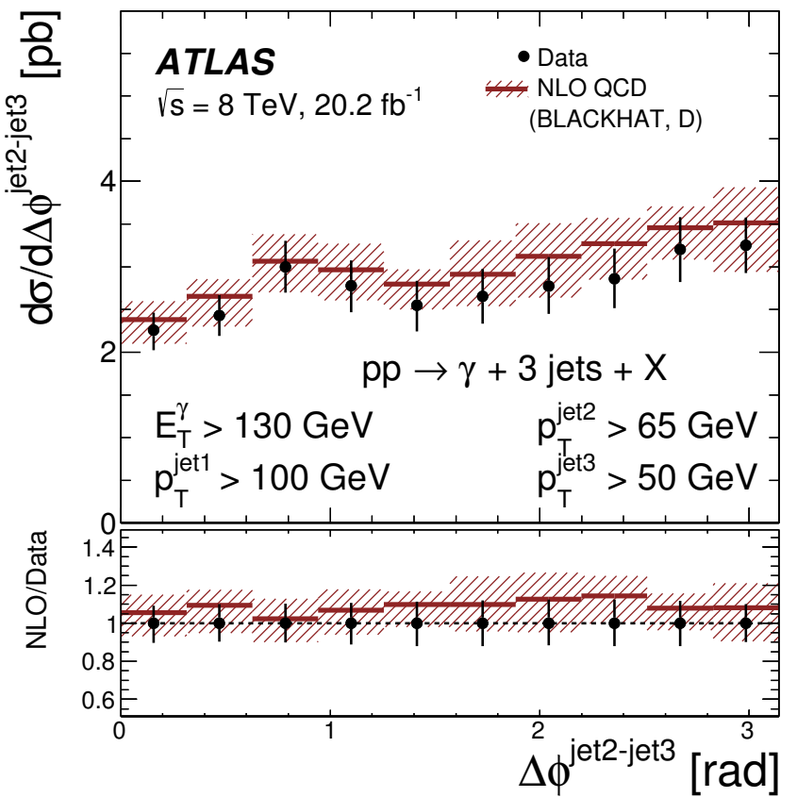


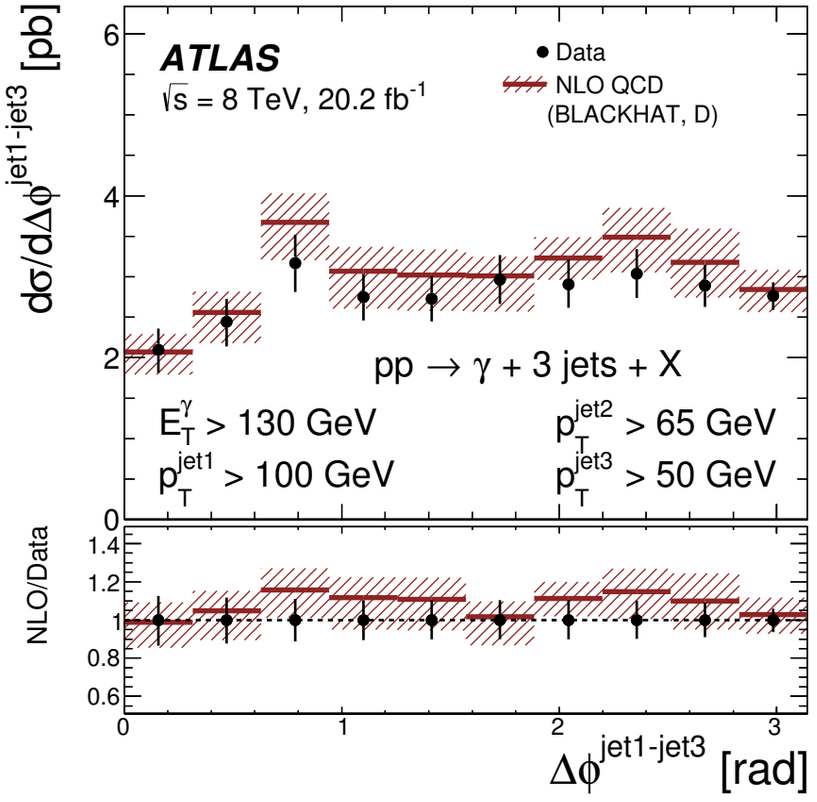
Photon plus 3 jet production @8 TeV

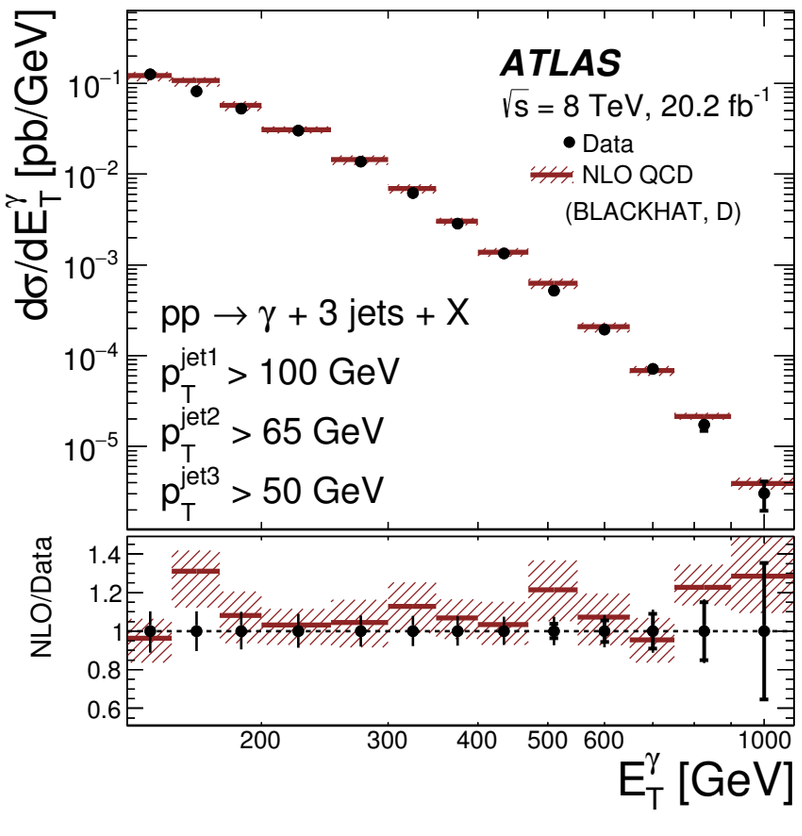
Nucl. Phys. B 918 (2017) 257

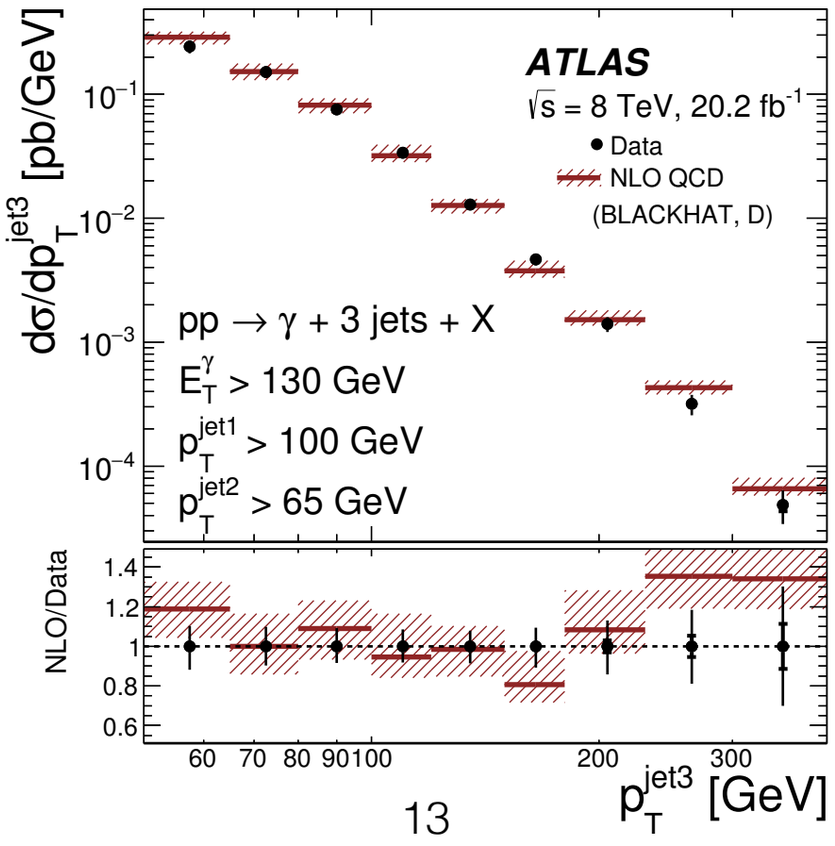
First ATLAS measurement of γ +3 jets dynamics

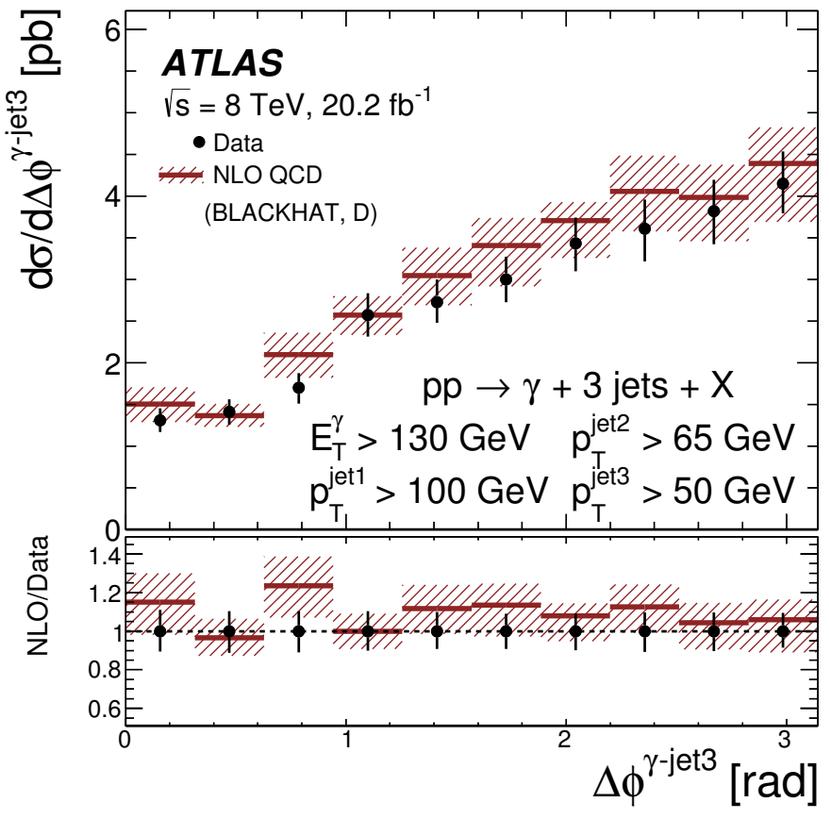
BLACKHAT predictions give a fair description of the measurements







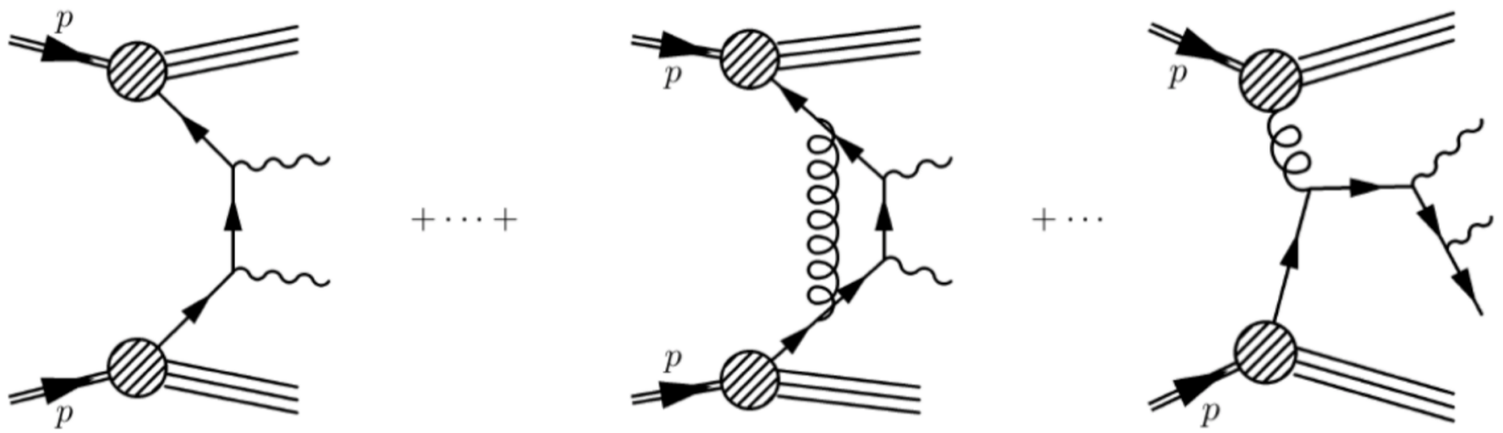




Inclusive Photon pair production @8 TeV

Phys. Rev. D 95 (2017) 112005

Although the process pp $\longrightarrow \gamma+\gamma+X$ at the LHC is best known as a Higgs discovery channel more than 99% of the photon-pairs in the finale state are produced by QCD interactions:



and so diphoton production offers an interesting testing ground of pQCD.

This analysis significantly improved the 7 TeV analysis(*):

- reduced systematics by almost a factor two (despite larger pileup)
- new additional variables to test specific QCD effects and comparison to different theoretical models

(*) JHEP 01 (2013) 086

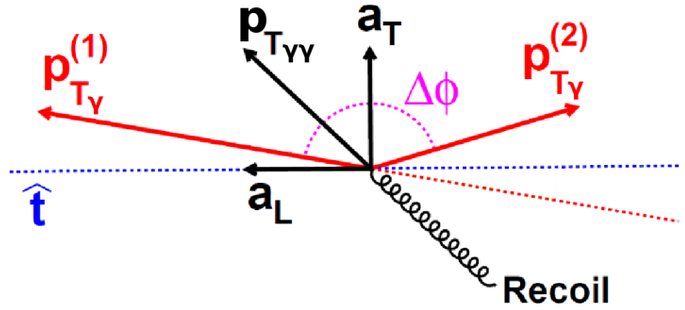
Inclusive Photon pair production @8 TeV

Phys. Rev. D 95 (2017) 112005

Measured total fiducial cross section and differential cross cross sections as a function of the following variables: $m_{\gamma\gamma},\ p_{\mathrm{T},\gamma\gamma},\ \Delta\phi_{\gamma\gamma},\ |\cos\theta^*_\eta|,\ a_{\mathrm{T}}, \phi^*_\eta$

Where:

- a_T=transverse component of $p_{T,\gamma\gamma}$ wrt the thrust axis
- $|\cos\theta^*_\eta| = \tanh(|\Delta\eta_{\gamma\gamma}|/2)$
- $\phi^*_\eta = \tan((\pi - \Delta\phi_{\gamma\gamma})/2)\sin\theta^*_\eta$



Phase-space region:

- $E^{\gamma}_{\mathrm{T},1} > 40\ \mathrm{GeV},\ E^{\gamma}_{\mathrm{T},2} > 30\ \mathrm{GeV}$ with $\Delta R_{\gamma\gamma} > 0.4$
- $|\eta^{\gamma}| < 2.37$ (excluding $1.37 < |\eta^{\gamma}| < 1.56$)
- $E^{\mathrm{iso}}_{\mathrm{T}} < 11\ \mathrm{GeV}$

Cross sections compared to different QCD predictions

Inclusive Photon pair production @8 TeV

Phys. Rev. D 95 (2017) 112005

Result: Integrated fiducial cross section

$$\sigma_{\text{tot}}^{\text{fid.}} = 16.8 \pm 0.1(\text{stat}) \pm 0.7(\text{syst}) \pm 0.3(\text{lumi}) \text{ pb} = 16.8 \pm 0.8 \text{ pb}$$

Compared to different theoretical predictions:

SHERPA 2.2.1:

- ME+PS merged at NLO

DIPHOX:

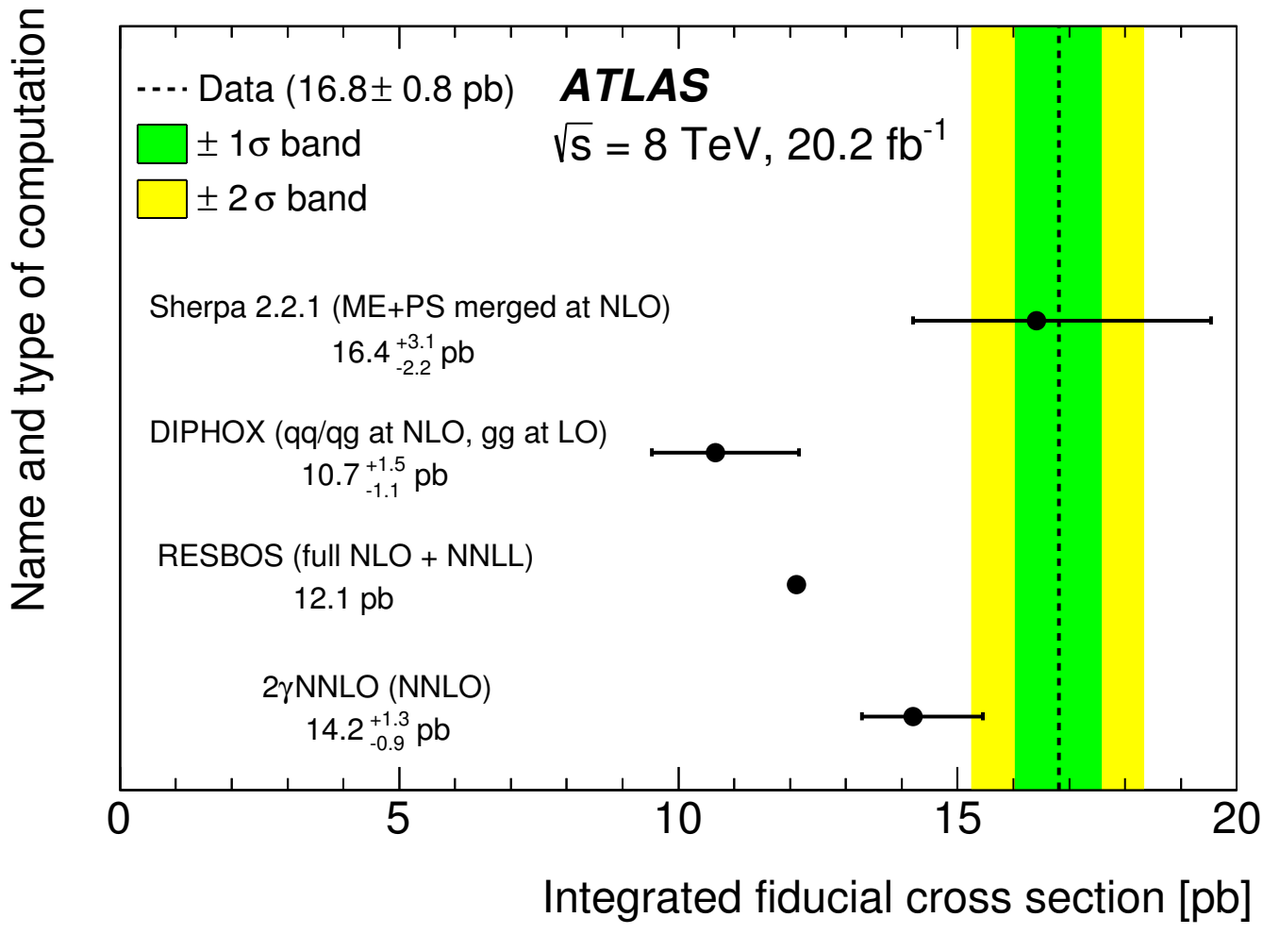
- Direct γ + fragmentation at NLO
- g+g → γ+γ at LO

RESBOS:

- NLO+NNLL
  (only central value provided)

2γNNLO:

- Direct γ at NNLO



Best agreement obtained for the SHERPA 2.2.1 prediction

Inclusive Photon pair production @8 TeV

Result: Differential cross sections

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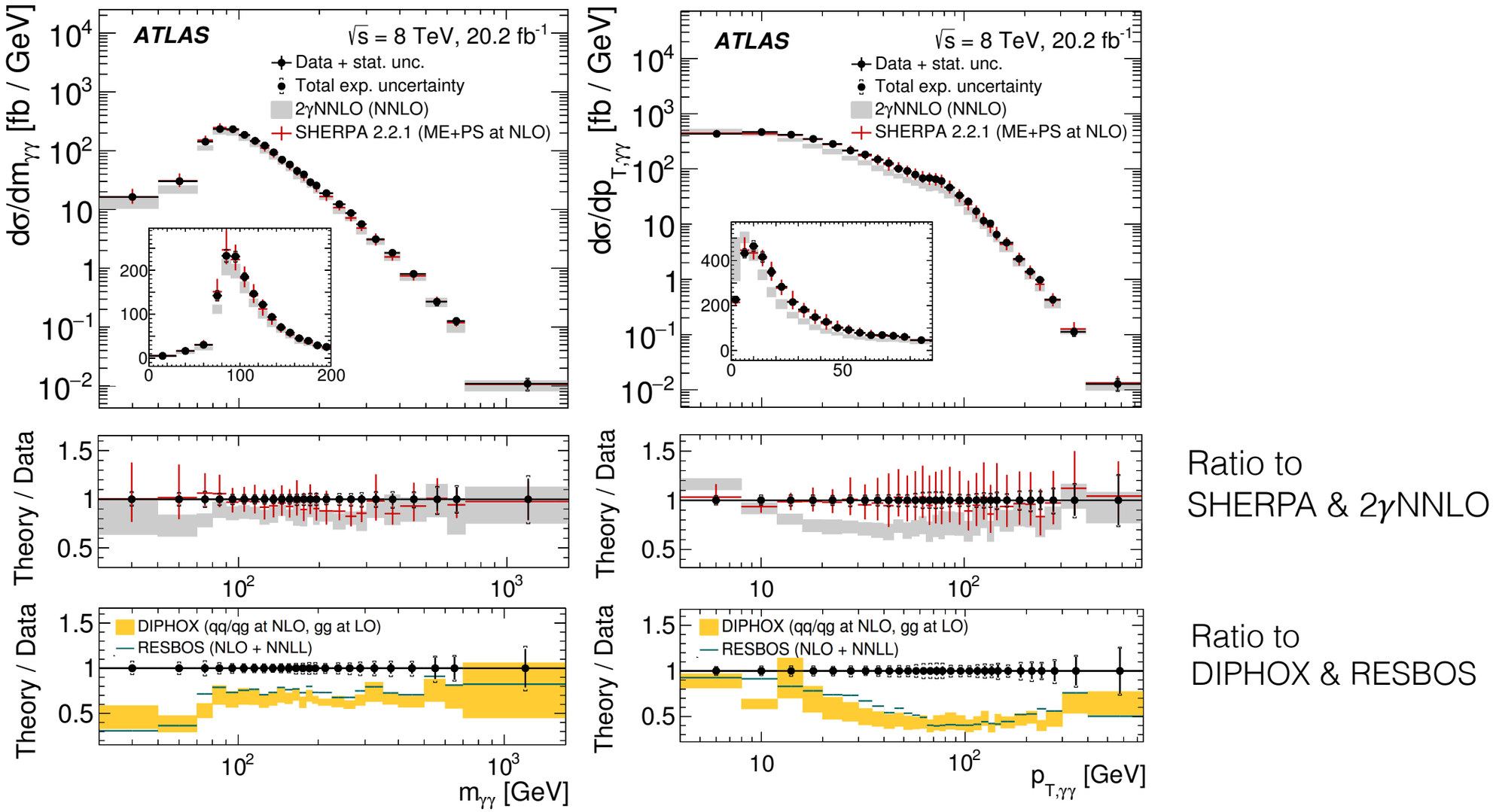


Ratio to
SHERPA & 2γNNLO

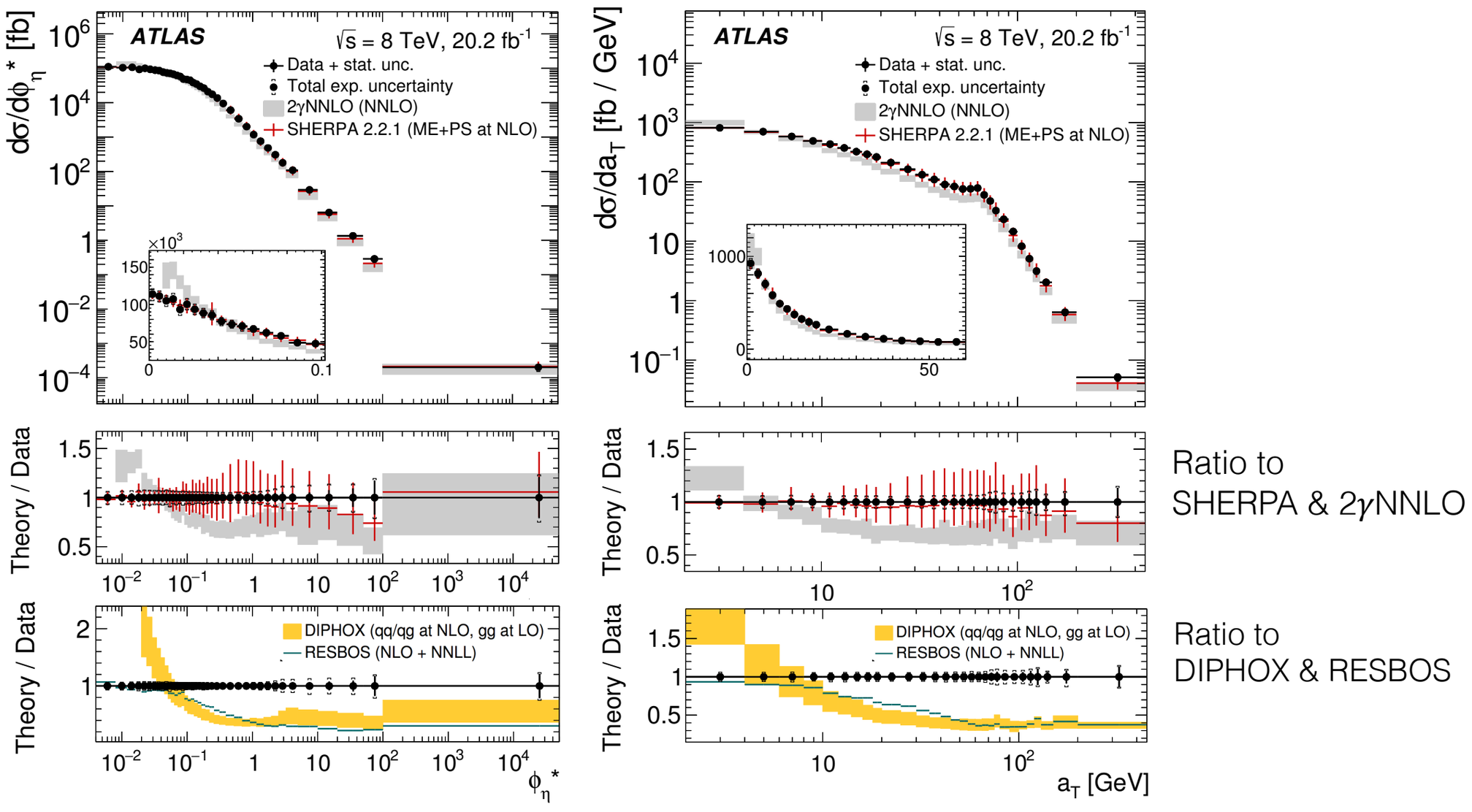
Ratio to
DIPHOX & RESBOS

- DIPHOX (NLO): mostly fails to describe the data
- RESBOS (NLO+NNLL): soft gluon resummation improve description in IR sensitive regions (low $p_{T,\gamma\gamma}$ region)
- 2γNNLO(NNLO): higher order improves the description
- SHERPA (ME+PS NLO): gives best description of the data

Inclusive Photon pair production @8 TeV

Result: Differential cross sections

Phys. Rev. D 95 (2017) 112005



- DIPHOX (NLO): mostly fails to describe the data
- RESBOS (NLO+NNLL): soft gluon resummation improve description in IR sensitive regions (low a_T and ϕ_η^*)
- 2γNNLO(NNLO): higher order improves the description
- SHERPA (ME+PS NLO): gives best description of the data

Summary

Measurements of inclusive γ production in pp collisions:

- precise measurement at 13 TeV
- looking forward to comparison with NNLO predictions and studies of the proton's gluon density

Measurements of γ+ nJet production in pp collisions:

- first measurement of γ+ Jet production at 13 TeV
- rich dynamics studied in γ+ nJet (n=1,2,3) final states at 8 TeV

Precision measurements of $\gamma\gamma$ final states in pp collisions:

- reduced systematic uncertainties
- interesting tests of various QCD effects
- control background to H $\rightarrow\gamma\gamma$

Backup

Inclusive prompt photon production

Comparison to PYTHIA and SHERPA MC generators

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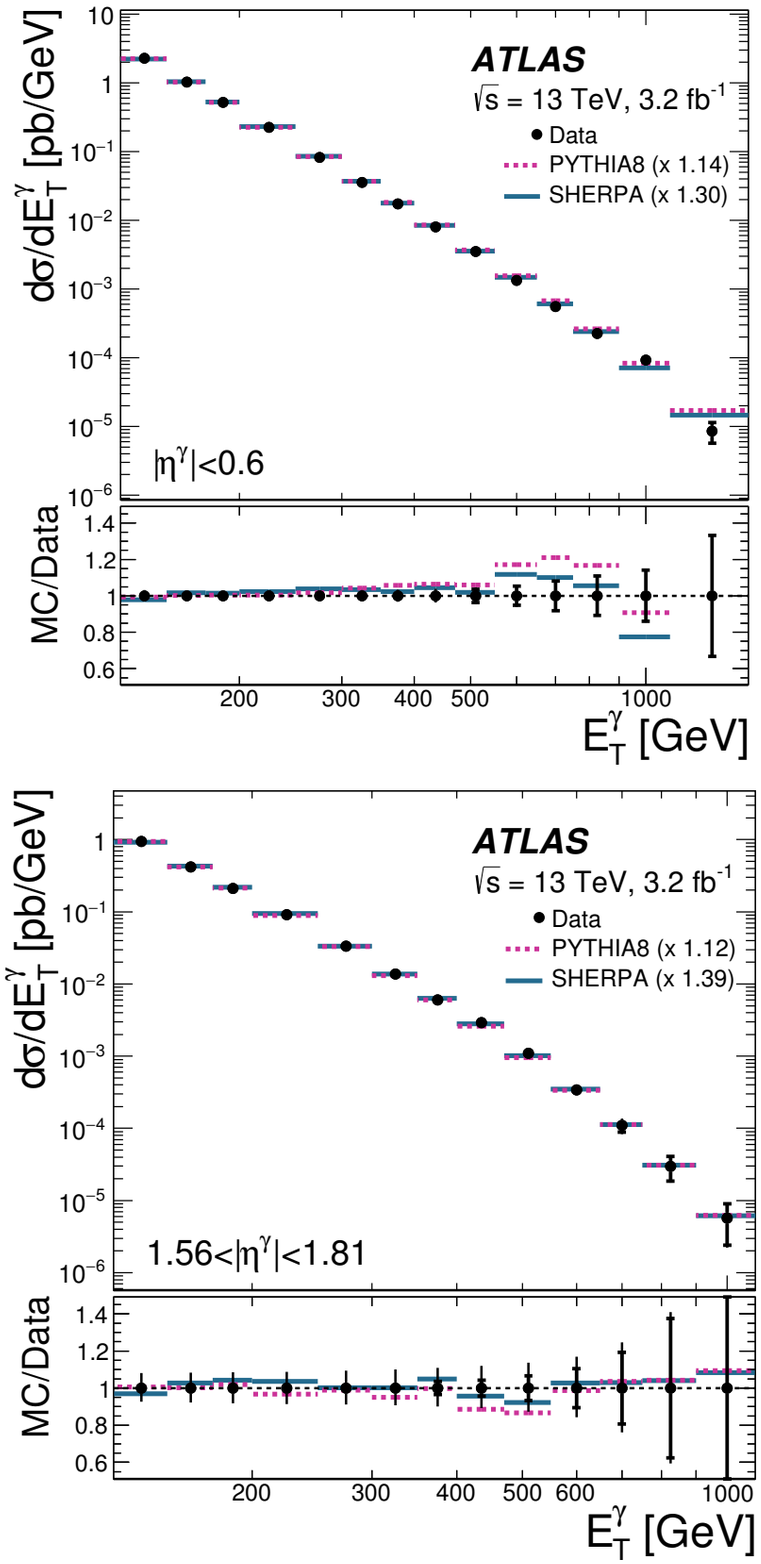
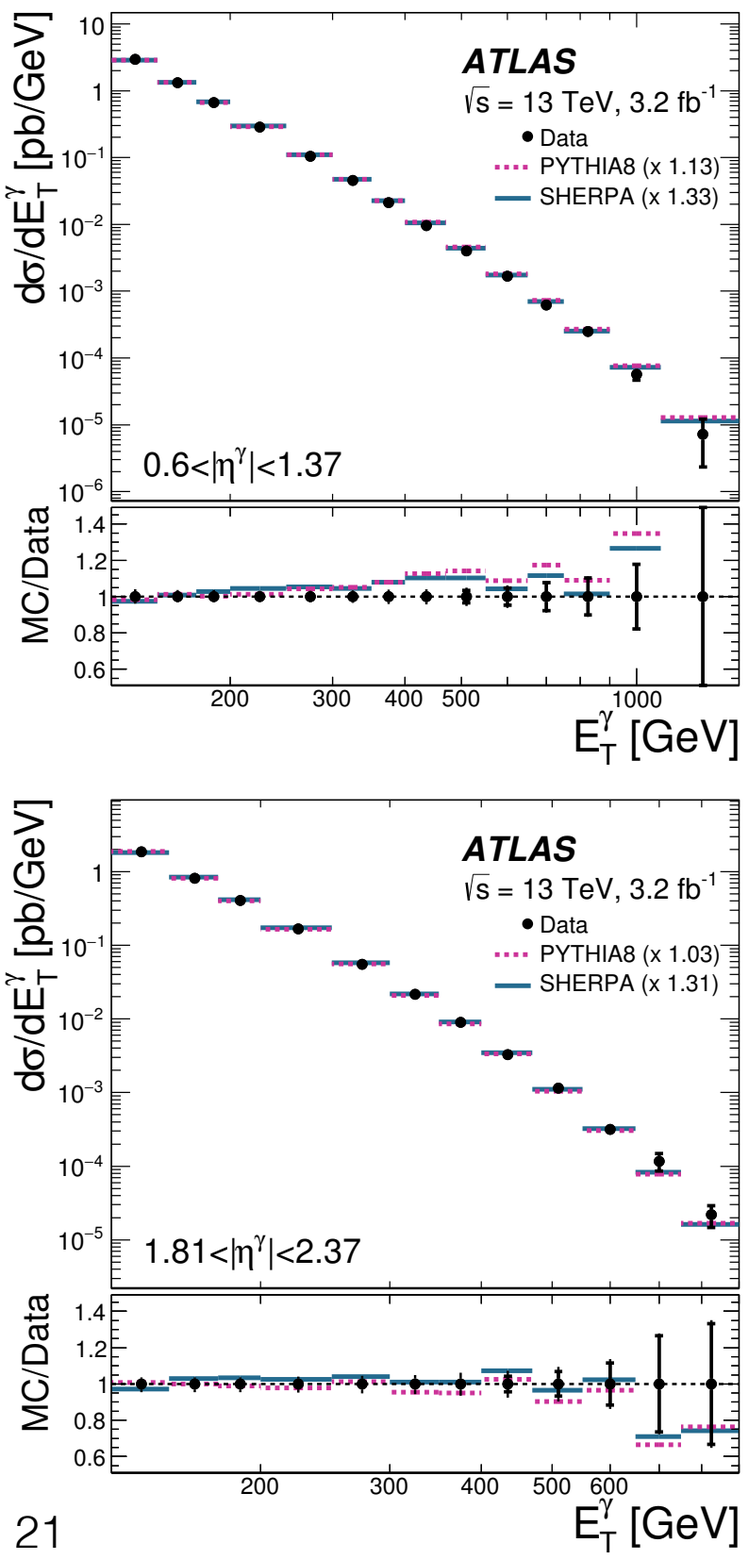
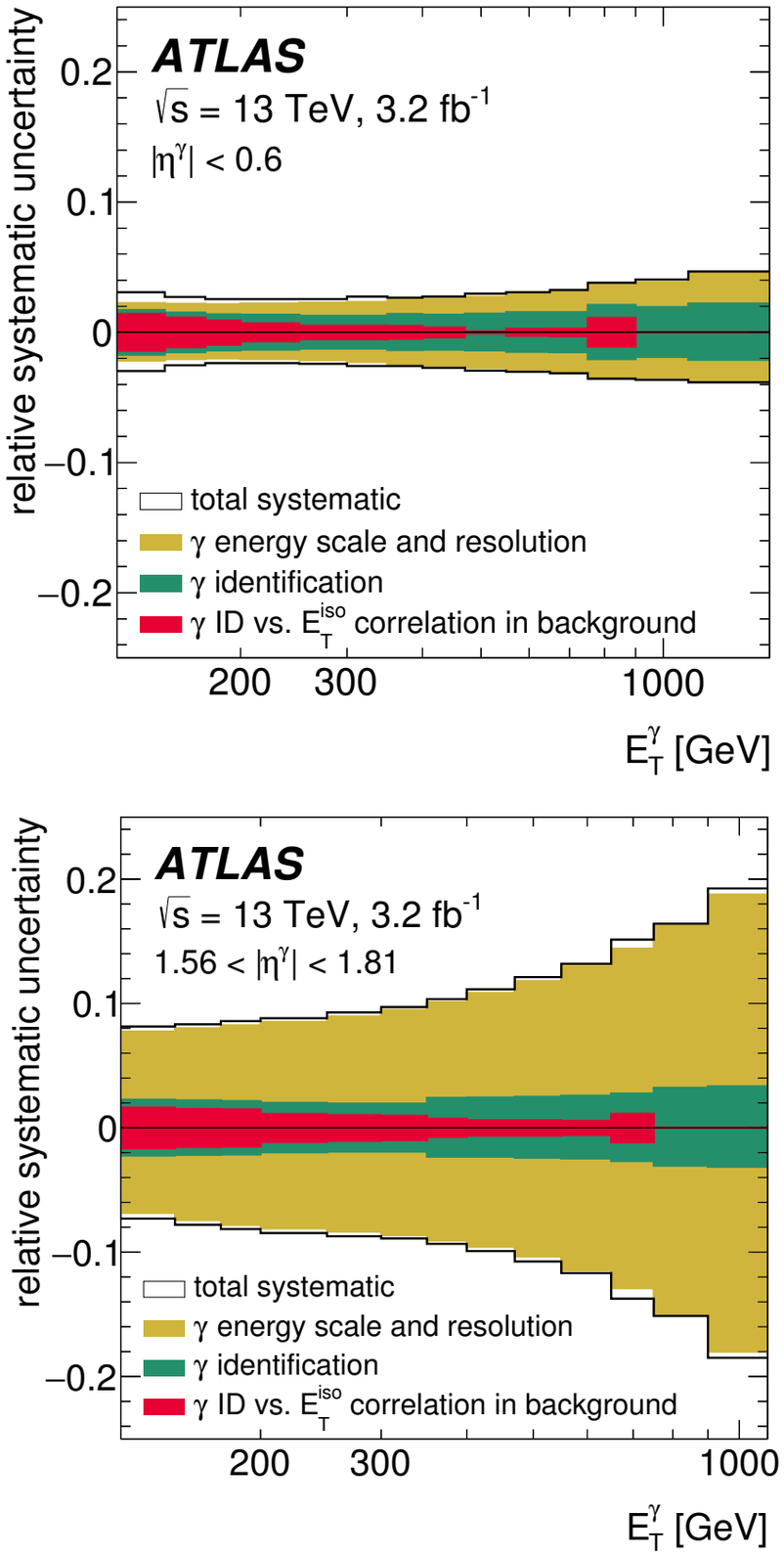


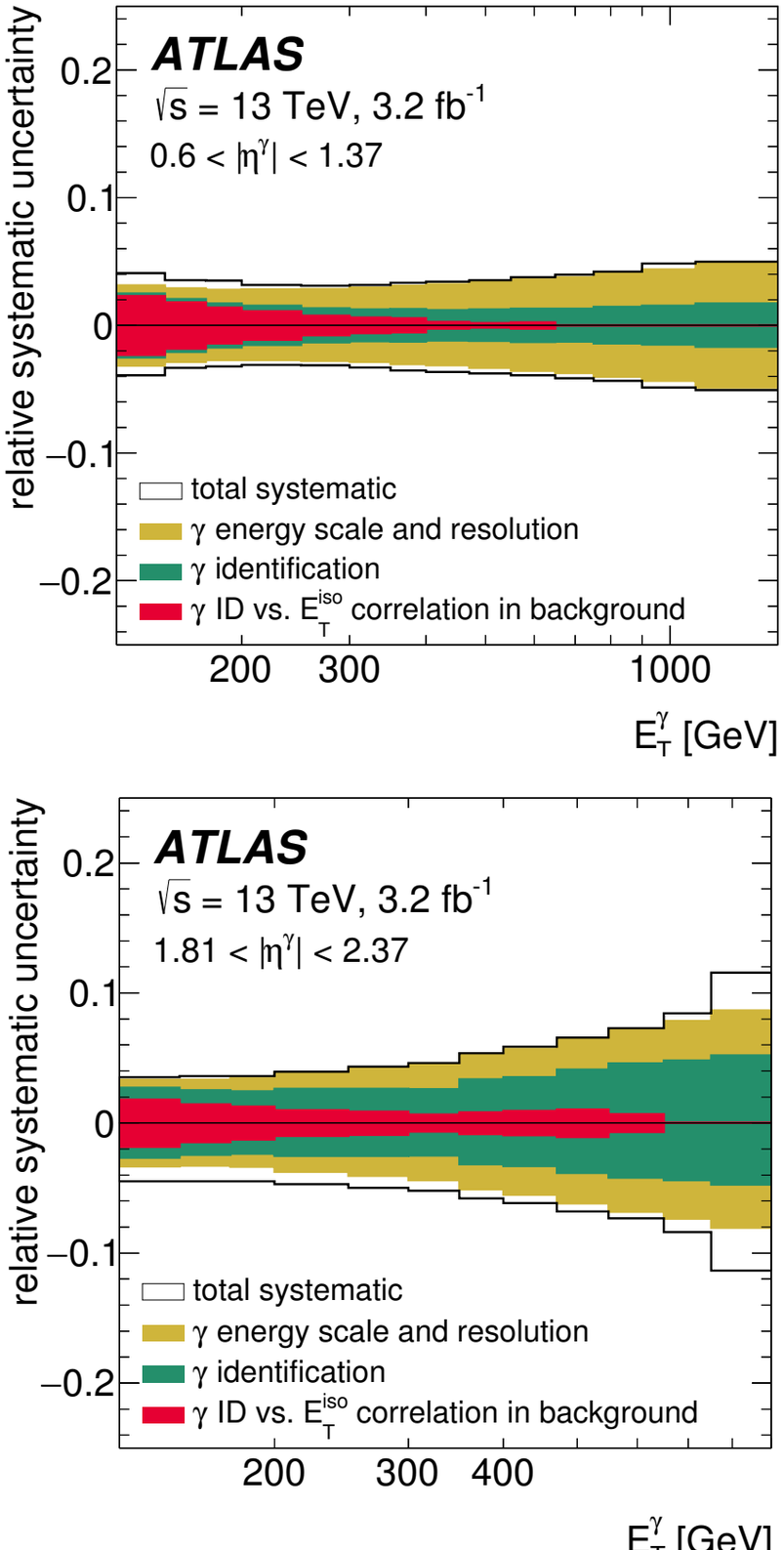


Inclusive prompt photon production

Main sources of svstematic uncertaintv

Phys. Lett. B 770 (2017) 473

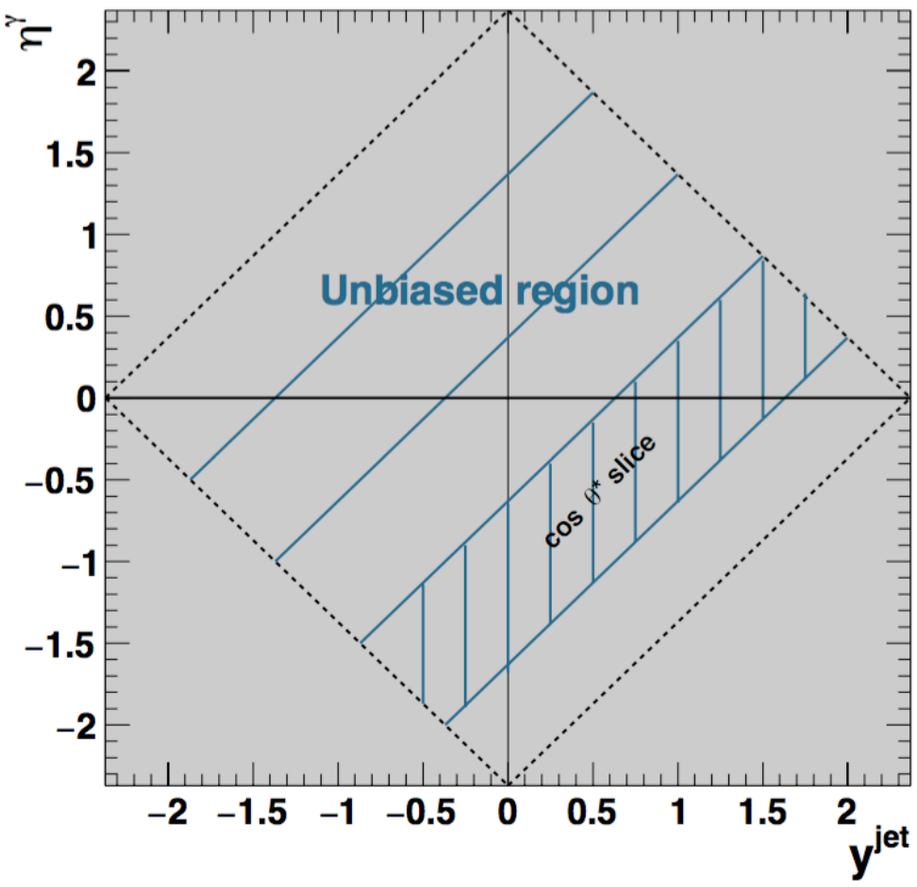


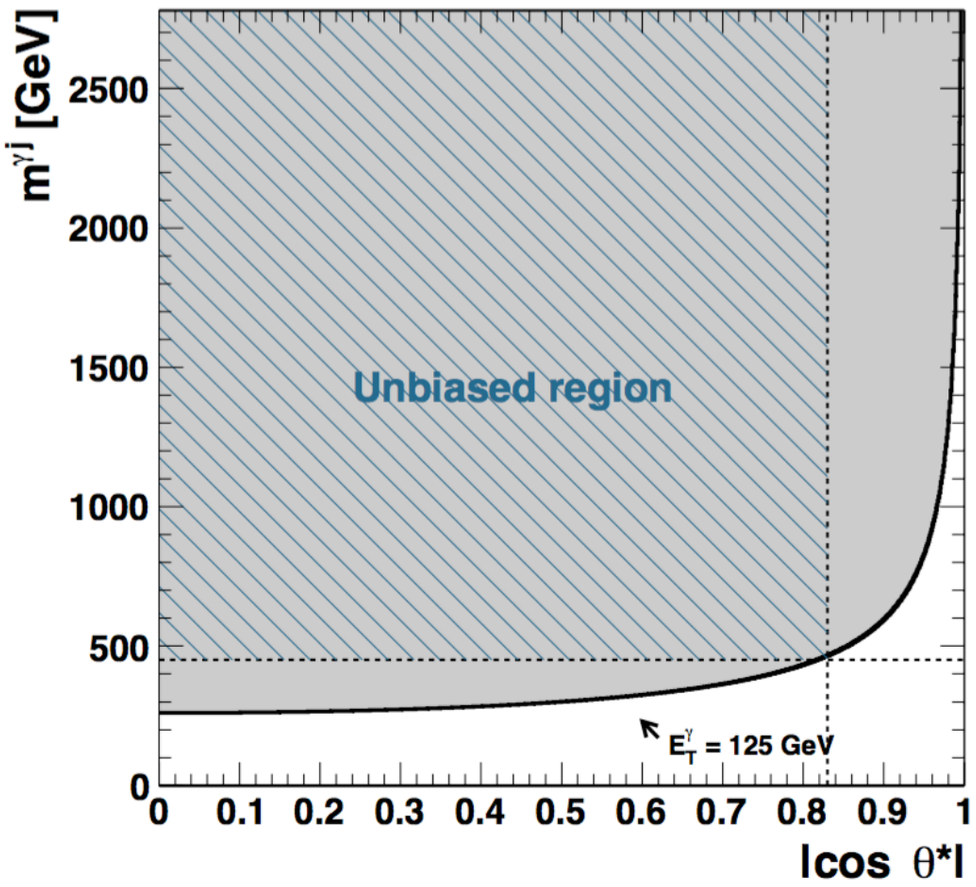


Unbiased region to measure dσ/dm$^{\gamma\text{-jet}}$ and dσ/d|cosϑ|*

Additional cuts are imposed:

$$|\eta^{\gamma} + y^{\mathrm{jet}}| < 2.37\ ,\ |\cos\theta^{*}| < 0.83 \quad \text{and} \quad m^{\gamma-\mathrm{jet}} > 450\ \mathrm{GeV}$$



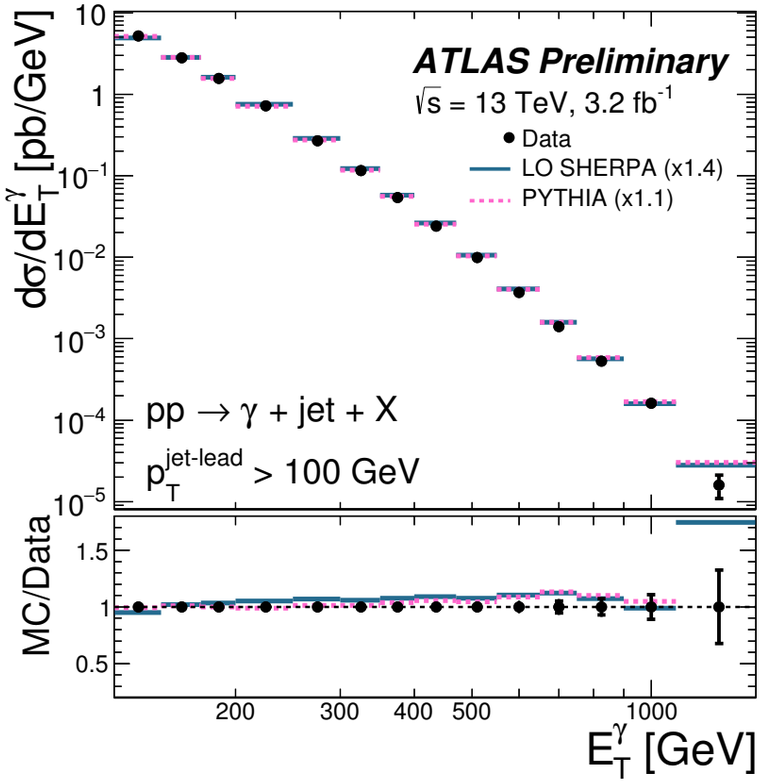


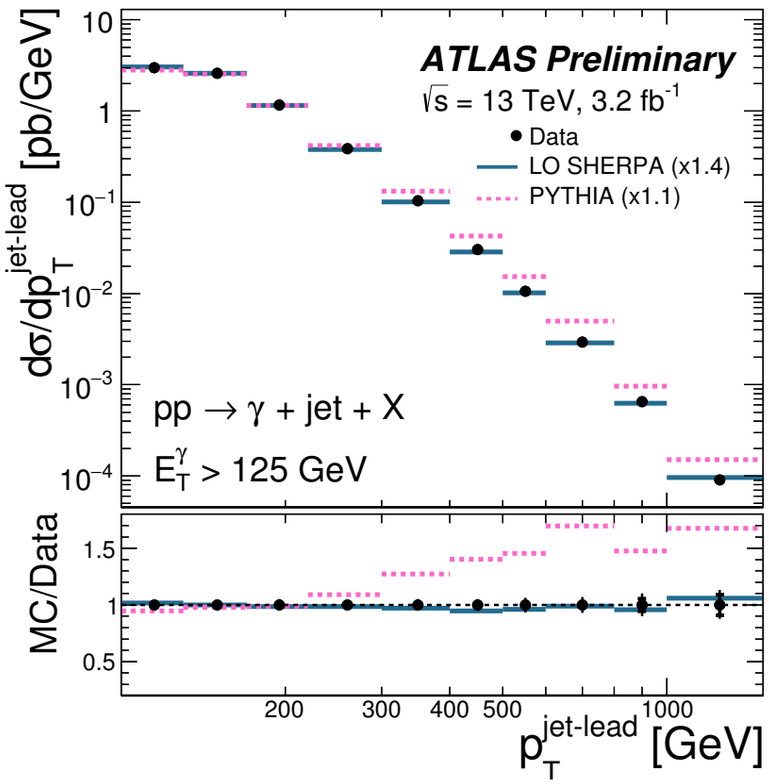
- First two requirements avoid bias induced by cuts in η^{γ} and y^{jet}
- Third requirement avoids bias due to $E_{\mathrm{T}}^{\gamma} > 125\ \mathrm{GeV}$

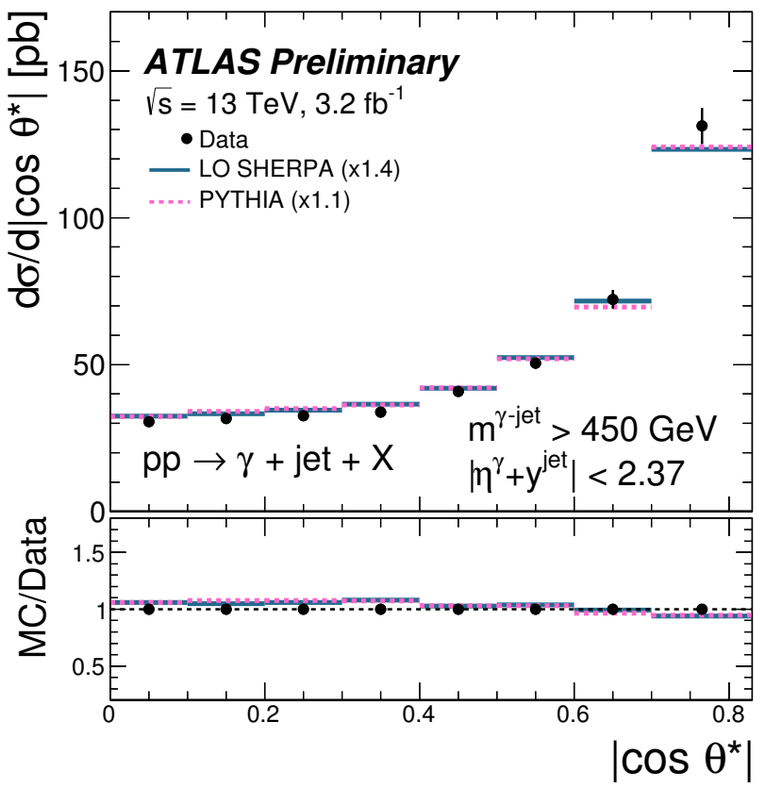
Photon plus jet production @13 TeV

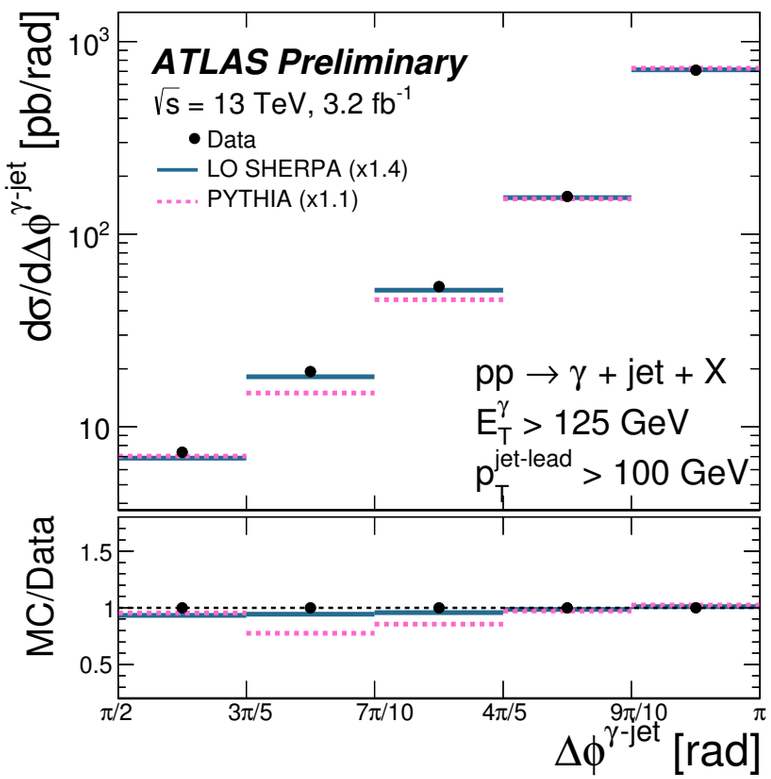
Comparison to PYTHIA and SHERPA MC generators

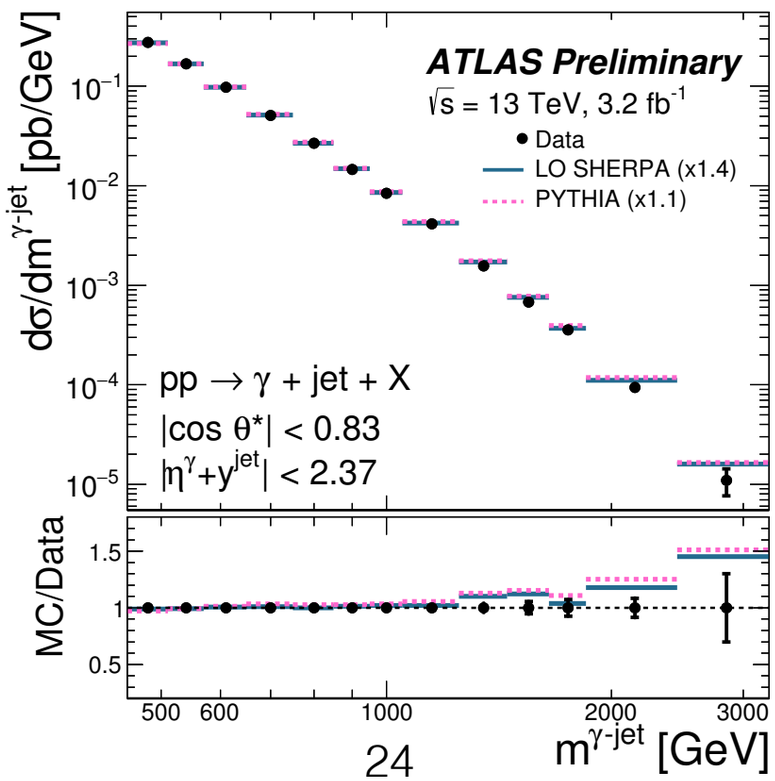
ATLAS-CONF-2017-059











Photon plus njet (n=1,2,3) production @8 TeV

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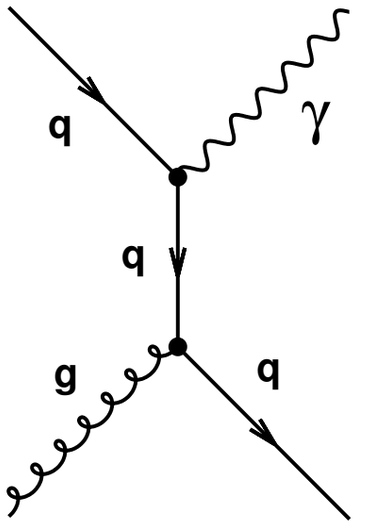
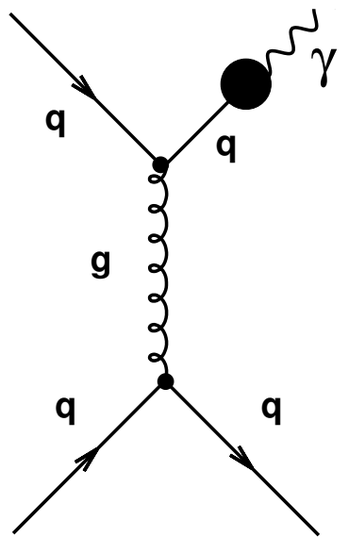
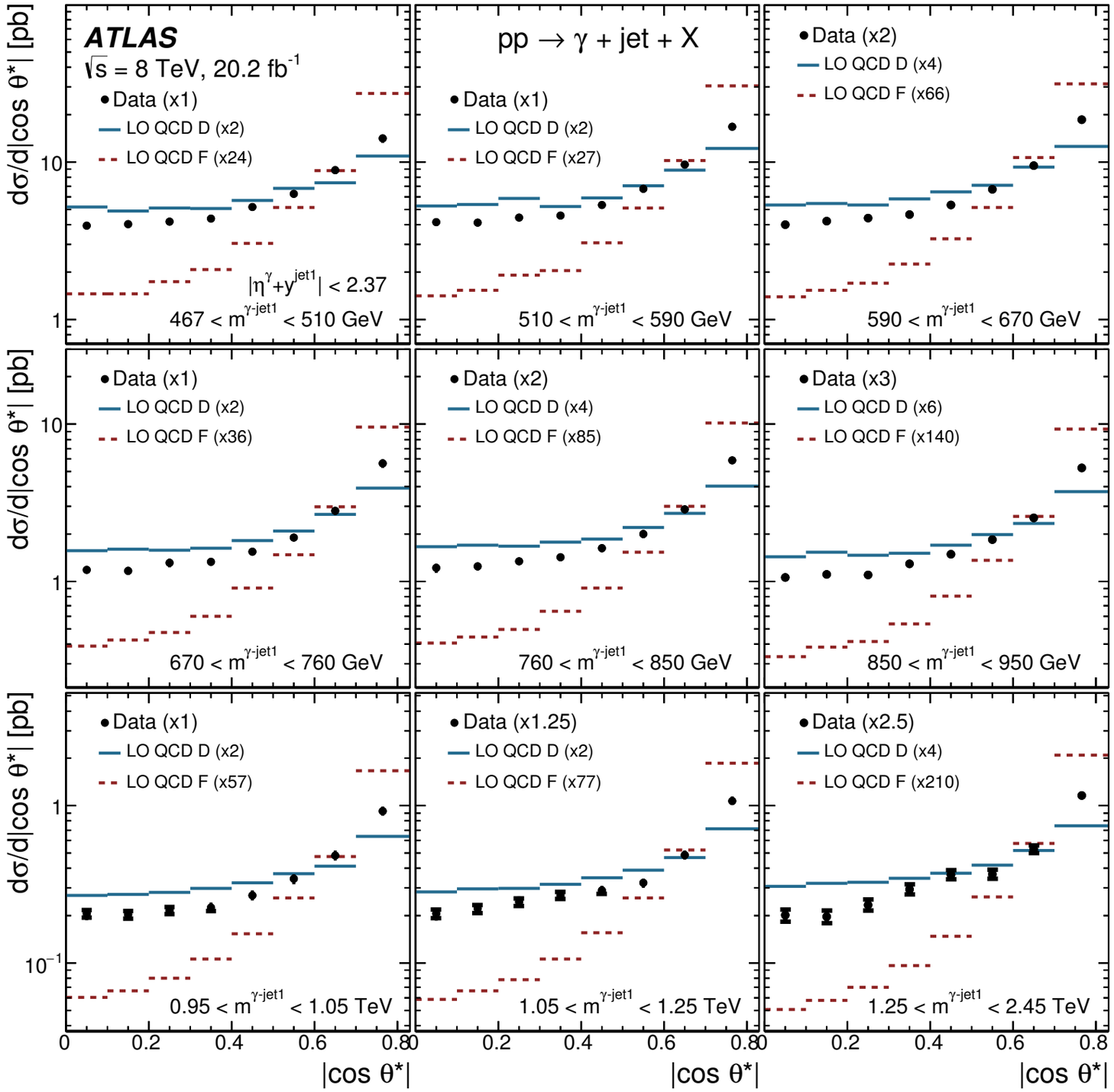
Differential cross sections as a function of cosϑ^*



$(1-|\cos\theta^*|)^{-1}$



$(1-|\cos\theta^*|)^{-2}$



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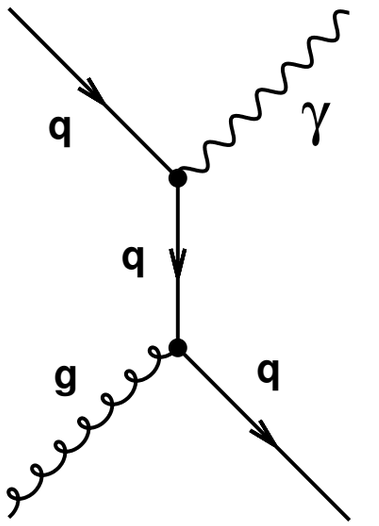

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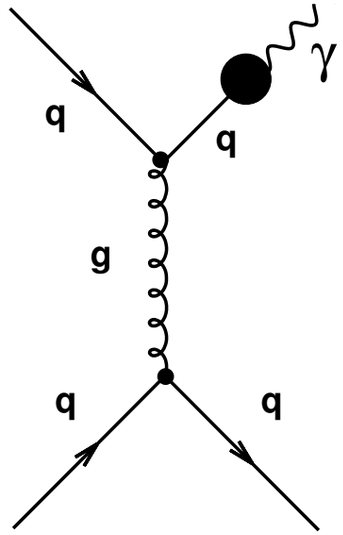
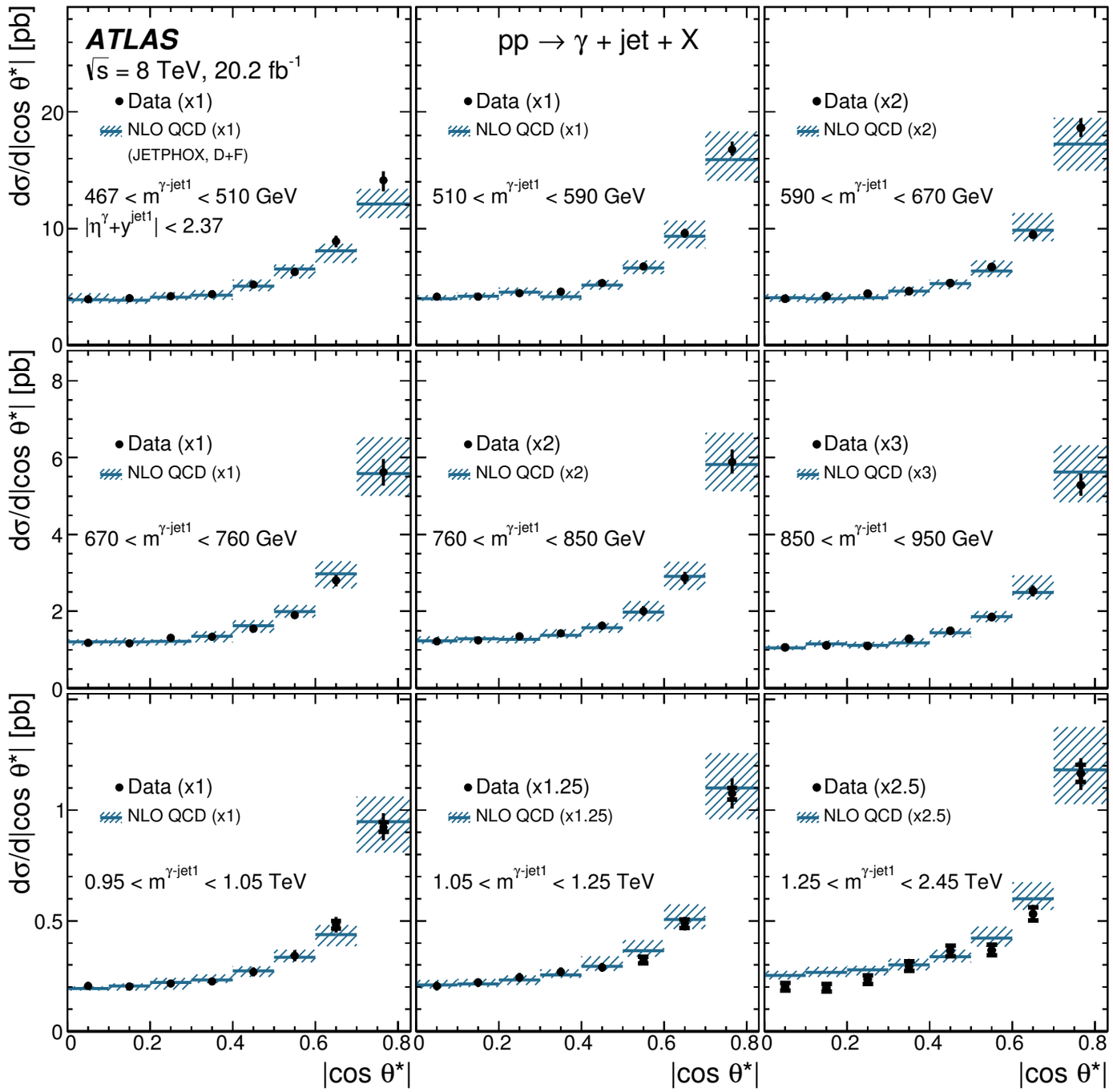


$(1 - |\cos\theta^*|)^{-2}$



Inclusive Photon pair production @8 TeV

Result: Differential cross sections

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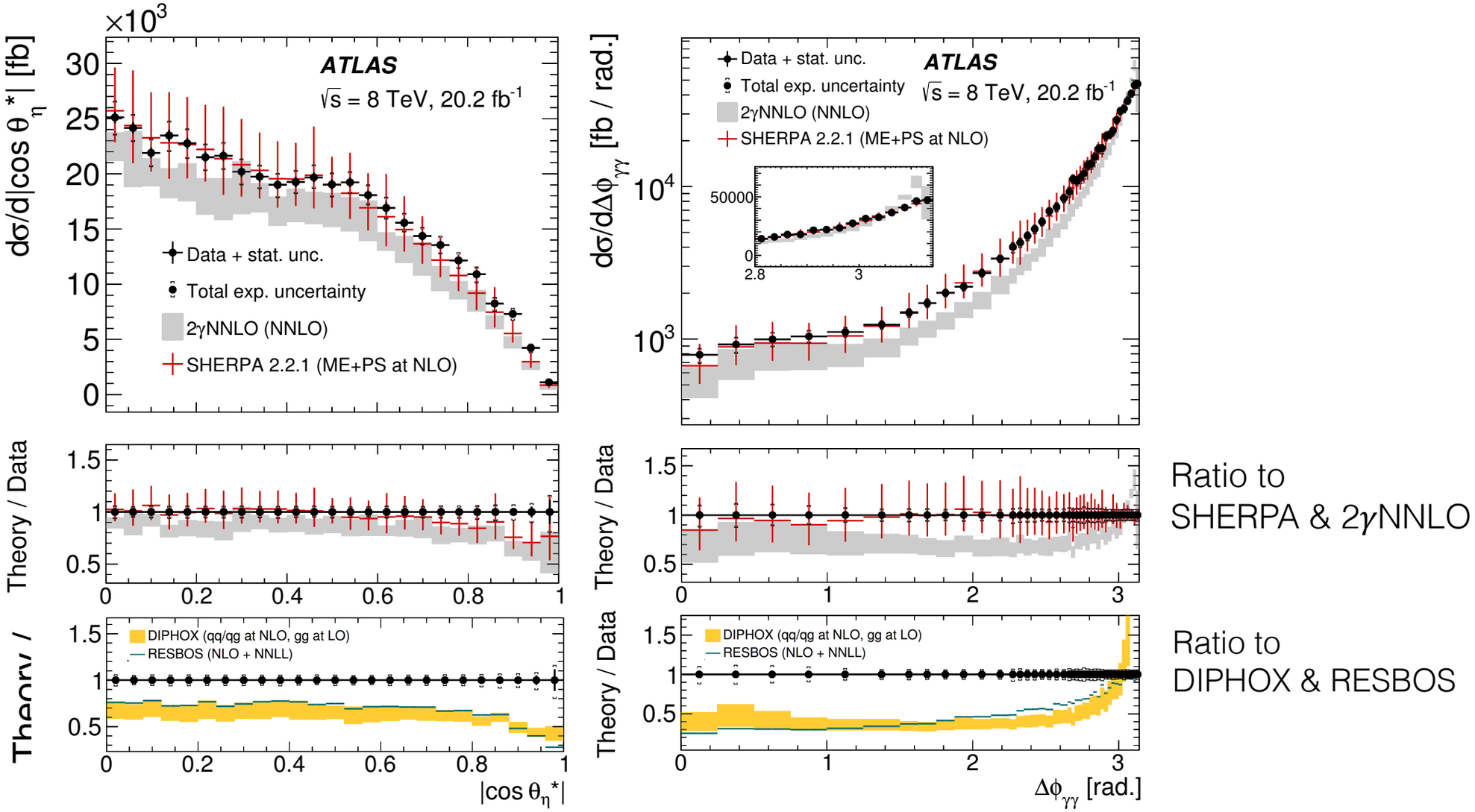

- DIPHOX (NLO): mostly fails to describe the data
- RESBOS (NLO+NNLL): soft gluon resummation improves description in IR sensitive regions ($\Delta\phi_{\gamma\gamma} \sim \pi$)
- 2γNNLO(NNLO): higher order improves the description
- SHERPA (ME+PS NLO): gives best description of the data