Probing QCD with Photons and Jets produced in proton-proton collisions with the ATLAS Detector

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On behalf of the ATLAS collaboration

May 8, 2018

Pheno 2018

Outline

Physics with Jets

- Inclusive jet and dijet at 13 TeV ($p_{\mathrm{T}}^{\mathrm{jet}}$, m^{jj})

  Submitted to JHEP

- Jet soft drop mass at 13 TeV

  Submitted to PRL

Physics with Photons

- γ + jet at 13 TeV

  Phys. Lett. B 780 (2018) 578

- γ + HF jet at 8 TeV

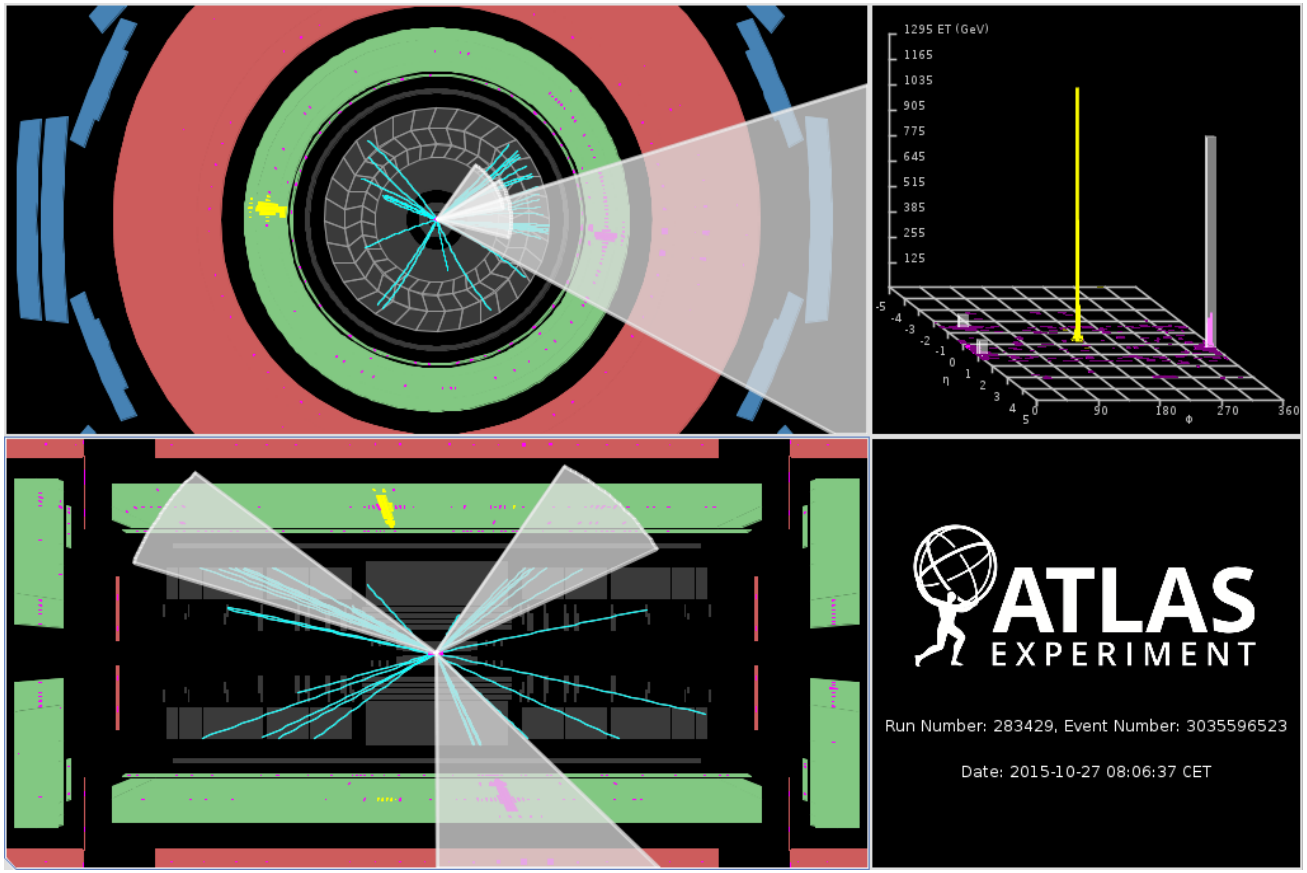
  Phys. Lett. B 776 (2018) 295

- $\gamma\gamma$ at 8 TeV

  Phys. Rev. D 95 (2017) 112005

- $\gamma\gamma\gamma$ at 8 TeV

  Phys. Lett. B 781 (2018) 55



→ γ + jet: E_{T}^{γ}, $p_{\mathrm{T}}^{\mathrm{jet}}$, $|\cos\theta^*|$, $m^{\gamma j}$ and $\Delta\phi^{\gamma j}$

→ γ + HF jet: E_{T}^{γ} for b and c-jets

→ $\gamma\gamma$: $m_{\gamma\gamma}$, $p_{\mathrm{T},\gamma\gamma}$, $\Delta\phi_{\eta}^{*}$, a_{T}, $|\cos\theta^*|$ and $\Delta\phi^{\gamma\gamma}$

→ $\gamma\gamma\gamma$: $m_{\gamma\gamma\gamma}$, $m_{\gamma\gamma}$, $\Delta\phi^{\gamma\gamma}$, $\Delta\eta^{\gamma\gamma}$ and E_{T}^{γ}

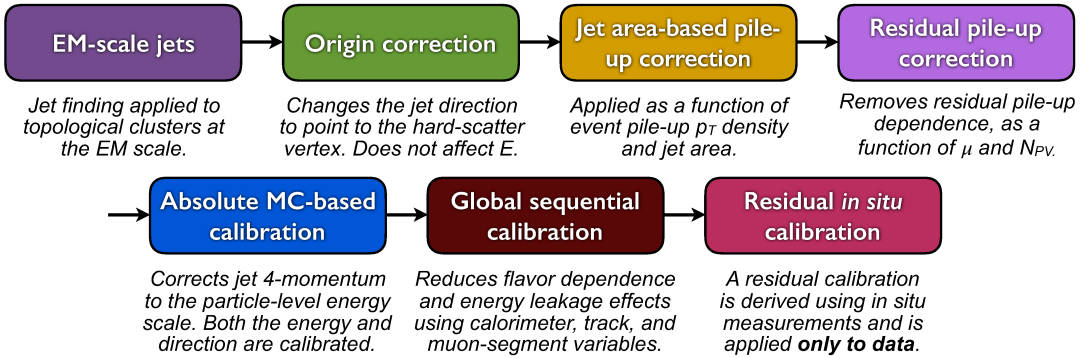
Jets

Physics with Jets

- Jet production is the dominant high-p_{T} process at the LHC
- Jet observables play an important role in the study of:
  - → The structure of the proton
  - → The color interaction and its coupling strength α_s
  - → Physics beyond the Standard Model.

$$\sigma_{pp\to\mathrm{jets}} = \sum_{i,j} \int dx_1 \; f_{i/1}(x_1, Q) \int dx_2 \; f_{j/2}(x_2, Q) \; \hat{\sigma}_{ij\to\mathrm{jets}}(x_1, x_2) \qquad (1)$$

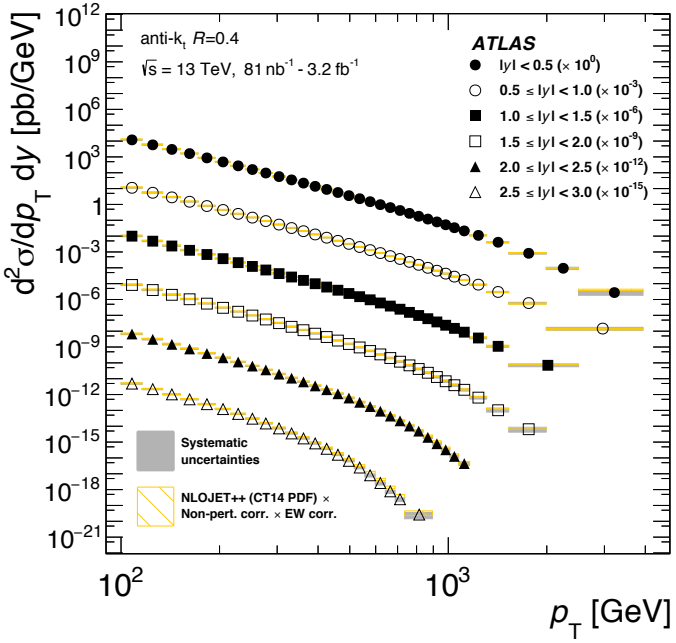
- Experimental reconstruction:
  - → 3D topological clusters of calorimeter cells as inputs of jet algorithms
  - → Anti-k$_T$ with R = 0.4, 0.6
  - → Multi-step process to calibrate the energy of the jet



Inclusive jet and dijet production at $\sqrt{s}$ = 13 TeV

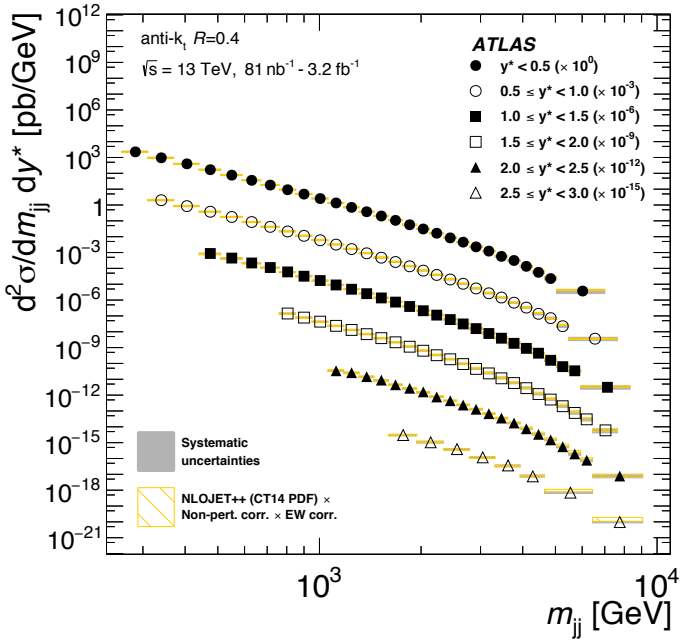
Inclusive jets

- L = 3.2 fb^{-1}
- 100 GeV $\leq p_{\mathrm{T}} \leq$ 4.0 TeV
- $|y| < 3$, in equal steps of 0.5



Dijet

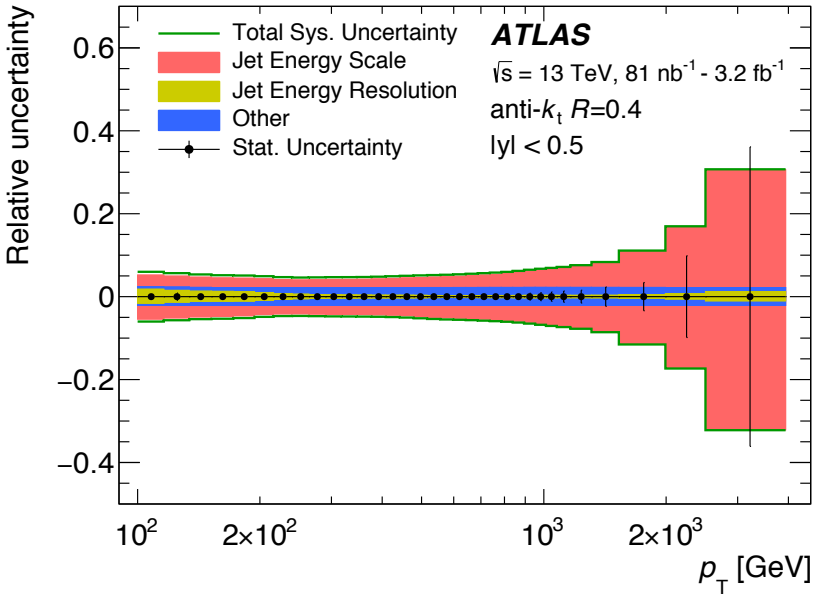
- L = 3.2 fb^{-1}
- 300 GeV $\leq m_{\mathrm{jj}} \leq$ 9 TeV
- $|y^*| = |\frac{y_{j_1} - y_{j_2}}{2}| < 3$, in equal steps of 0.5



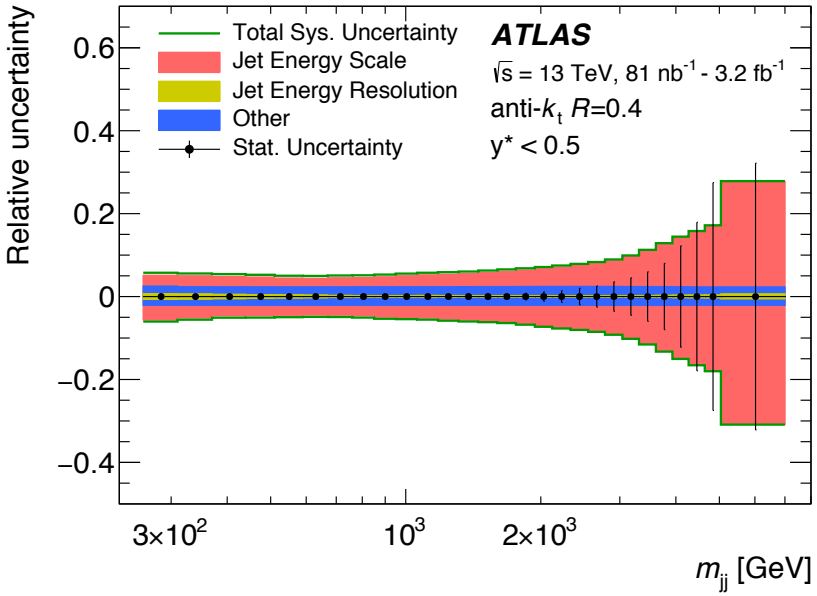
- 9 (8) orders of magnitude in central (most forward) rapidity region
- Adequate description (in log scale) of data by NLO QCD calculations

Inclusive jet and dijet production at $\sqrt{s}$ = 13 TeV

Inclusive jets

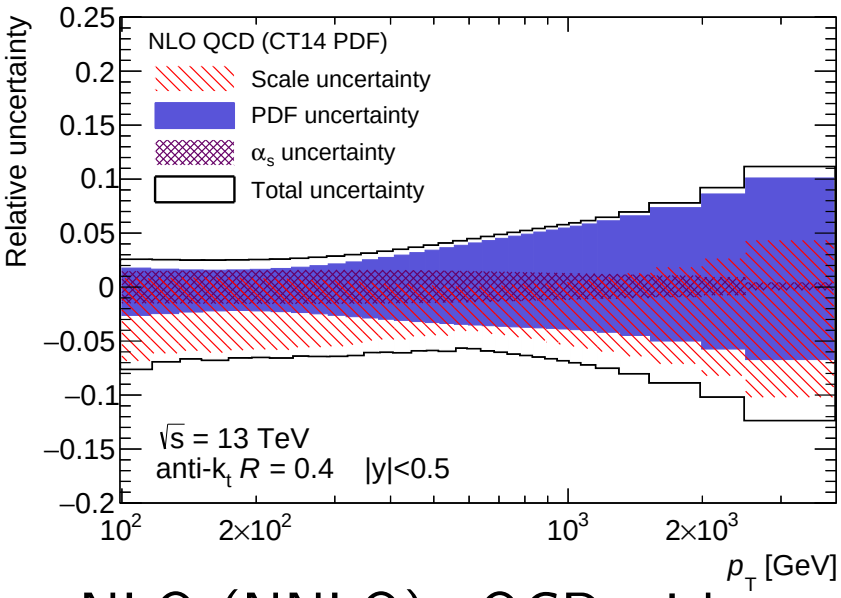


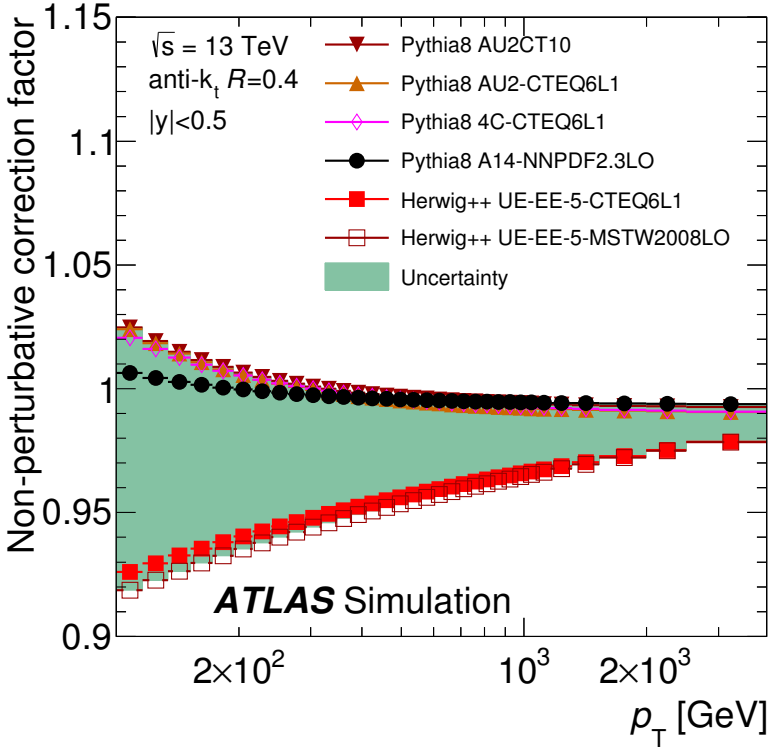
Dijet



- JES uncertainties ~ 5% for $p_{\mathrm{T}} < 1$ TeV (15-30% at $p_{\mathrm{T}} > 2$ TeV)
- Small effect due to JER uncertainty
- Single-hadron energy response main uncertainty at high-p_{T}

Inclusive jet and dijet production at $\sqrt{s}$ = 13 TeV



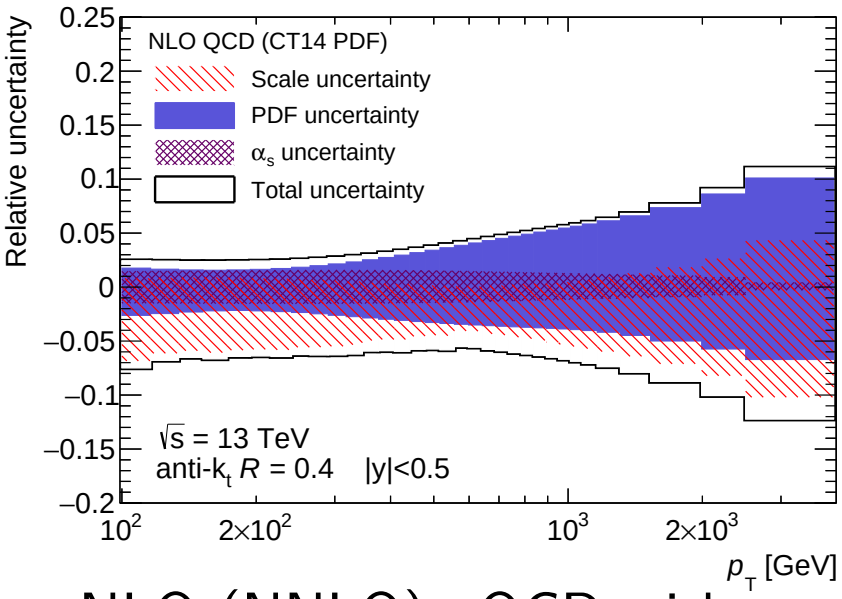


→ NLO (NNLO) pQCD with NLOJet++ (NNLOJet)

- $\mu_R = \mu_F = p_T^{\rm jet}$ ($p_T^{\rm jet,max}$)
- PDFs: CT14, MMHT2014, NNPDF3.0, HERAPDF2.0 and ABMP16
- PDFs, scale choice and α_s as theoretical uncertainties.

- $\sigma_{\rm theory} = \sigma_{NLO} \times k_{\rm NP} \times k_{\rm EW}$
- $k_{\rm NP} = \frac{\sigma({\rm hadrons})}{\sigma({\rm partons})}$
- $\Delta_{\rm NP}$ envelope of several LO MC predictions.
- $K_{\rm EW}$ electroweak correction factor

Inclusive jet and dijet production at $\sqrt{s}$ = 13 TeV



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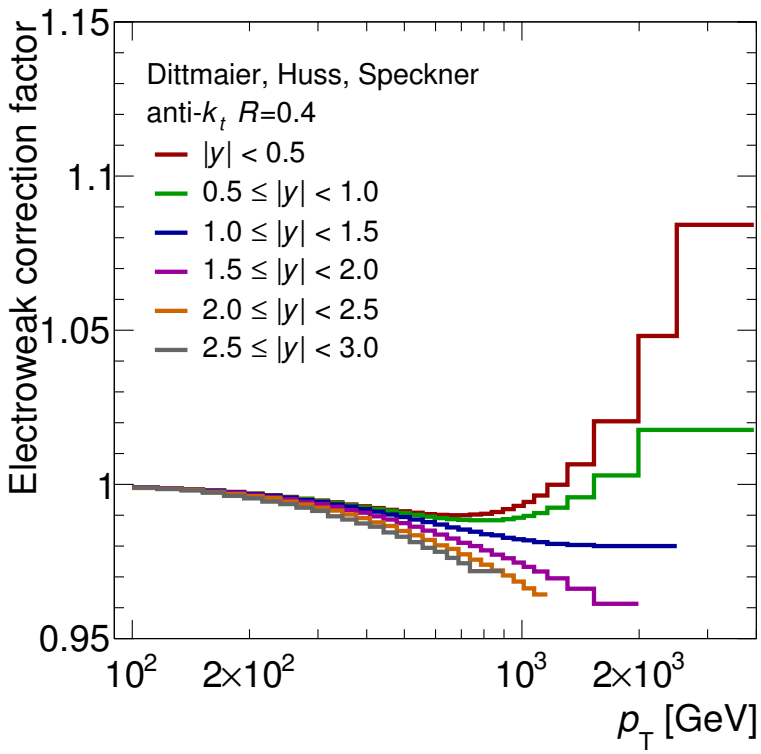

- $\sigma_{\text{theory}} = \sigma_{NLO} \times k_{\text{NP}} \times k_{\text{EW}}$
- $k_{\text{NP}} = \frac{\sigma(\text{hadrons})}{\sigma(\text{partons})}$
- K_{EW} electroweak correction factor:

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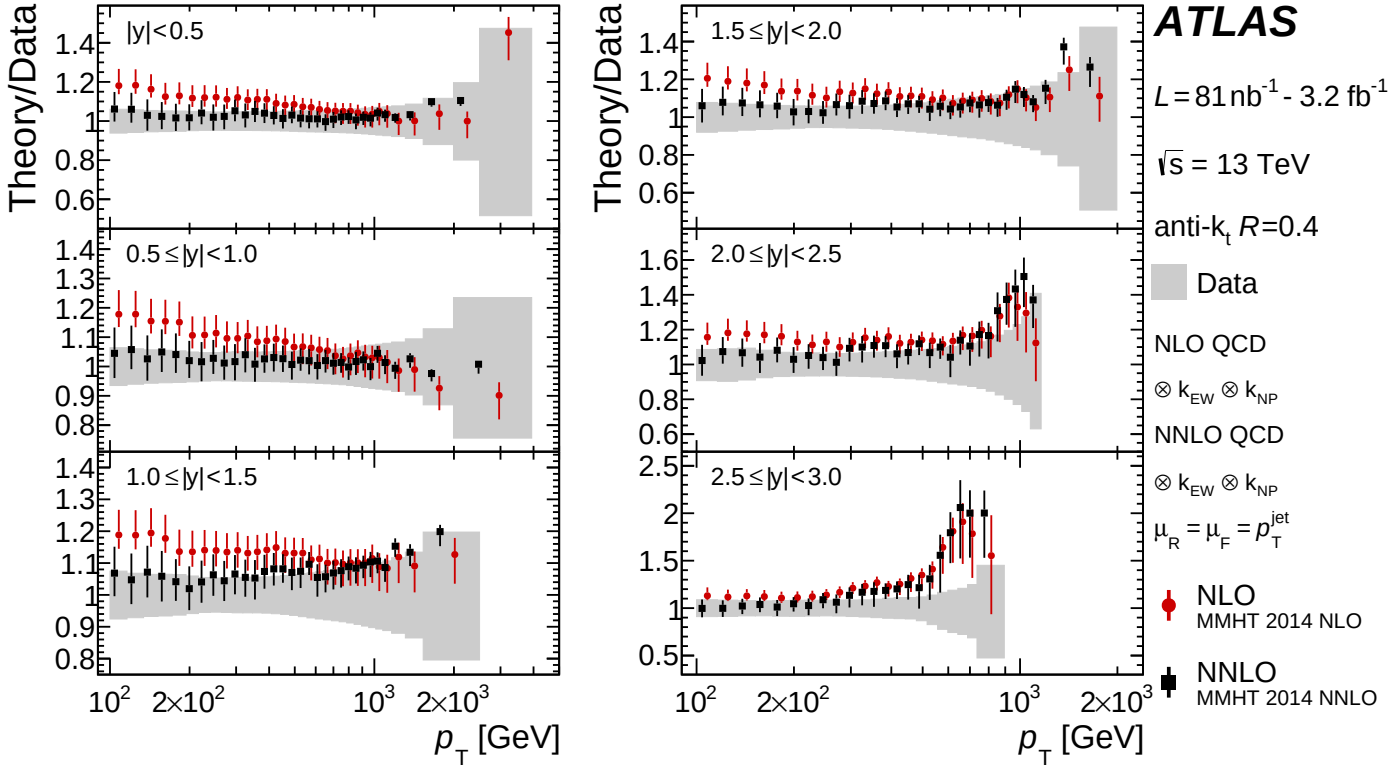
Inclusive jet and dijet production at $\sqrt{s}$ = 13 TeV

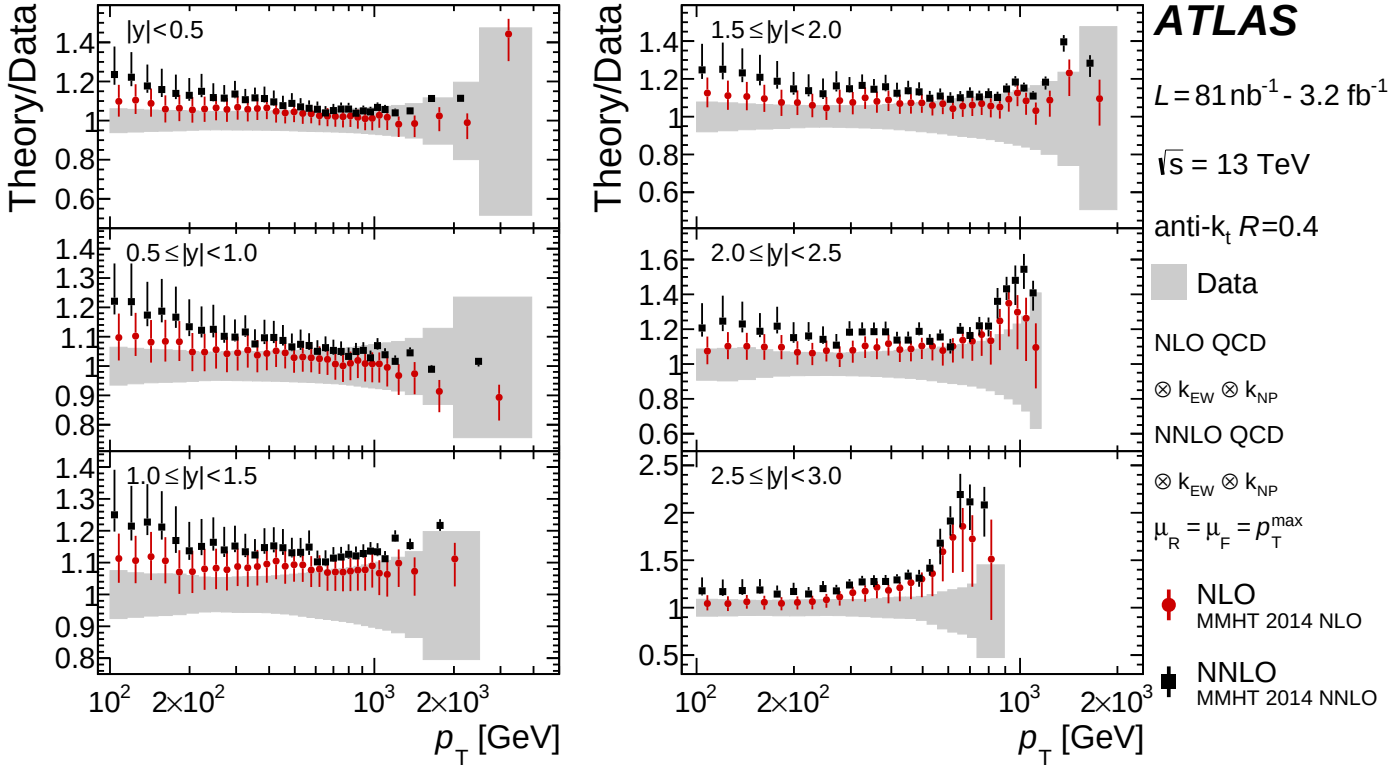
Inclusive jets ($\mu_R = \mu_F = p_{\mathrm{T}}^{\mathrm{jet}}$)



- NLO pQCD above the measurements for $p_{\mathrm{T}} \lesssim$ 200-500 GeV
- Toward higher p_{T} NLO pQCD closer to data
- $p_{\mathrm{T}} >$ 300 GeV and high y rise of NLO pQCD with respect to data (>20%)
- Similar behaviour for different PDF sets
- Good description by NNLO

Inclusive jet and dijet production at $\sqrt{s}$ = 13 TeV

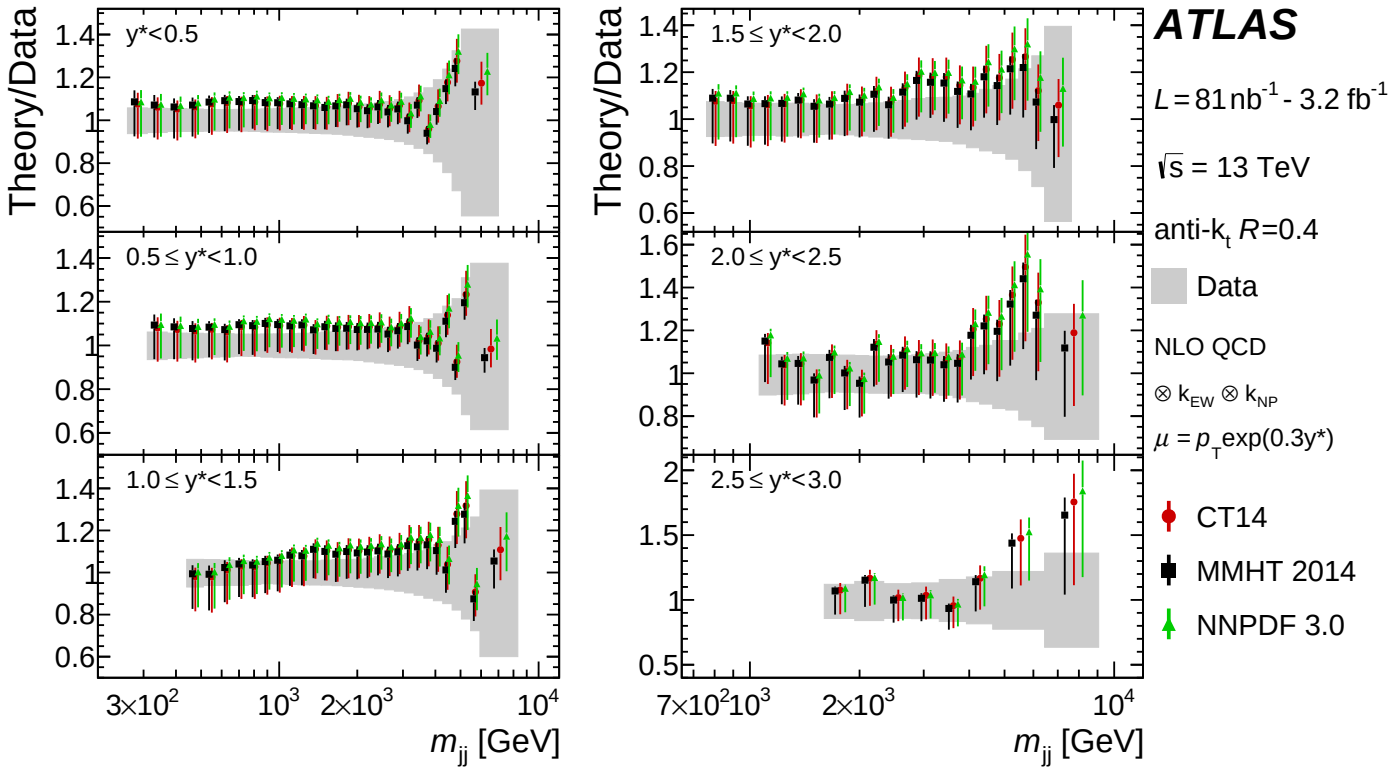
Inclusive jets ($\mu_R = \mu_F = p_{\mathrm{T}}^{\mathrm{jet,max}}$)



- NLO pQCD describes the measurements within uncertainties.
- Toward higher p_{T} NLO pQCD closer to data
- $p_{\mathrm{T}} > 300$ GeV and high y rise of NLO pQCD with respect to data (>20%)
- NNLO above measurements for $p_{\mathrm{T}} < 500$ GeV

Inclusive jet and dijet production at $\sqrt{s}$ = 13 TeV

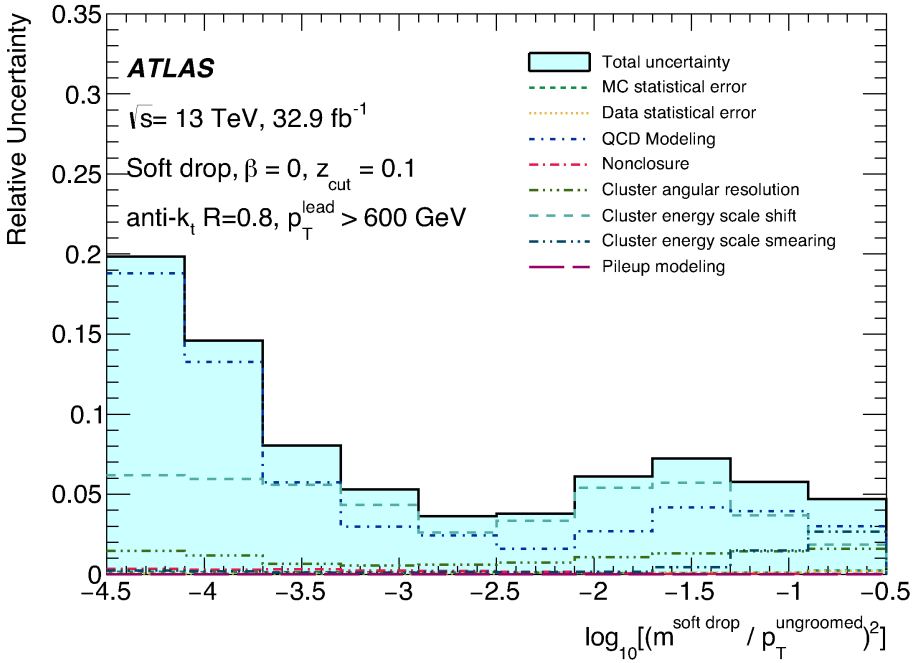
Dijet ($\mu_R = \mu_F = p_{\mathrm{T}} \cdot e^{0.3 \cdot y^*}$)

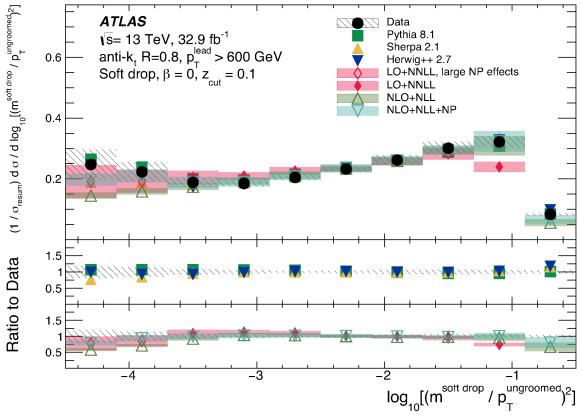


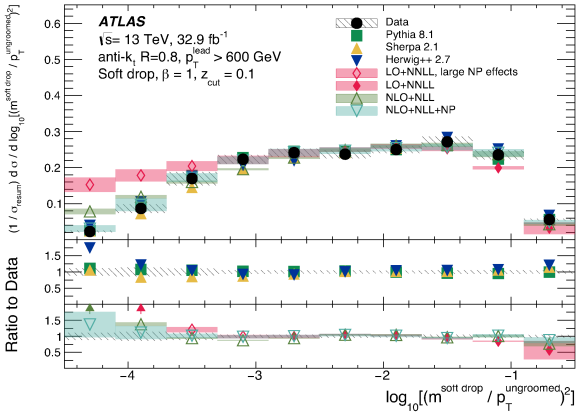
- Good description of data by NLO pQCD within the uncertainties.
- Similar shape predicted by the studied PDF sets.
- For $|y^*| > 2$, tendency for the NLO pQCD prediction to overestimate the measured cross-section in the high p_{T} range.

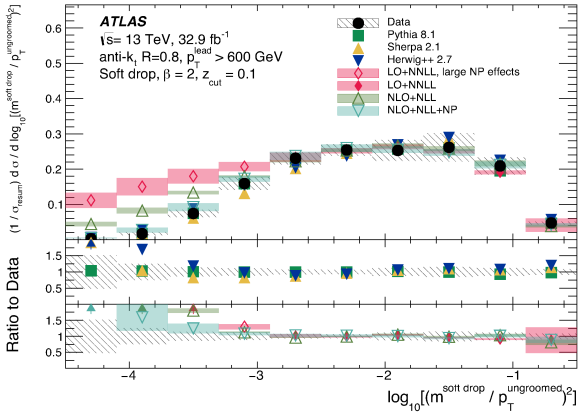
Soft-drop jet mass at $\sqrt{s} = 13$ TeV

- Normalized differentical cross section as a function of $\log_{10}(\rho^2)$ ($\rho = m^{\text{soft drop}}/p_{\text{T}}$);
- Soft drop condition: $\min \frac{(p_{\text{T}}^{\text{j1}}, p_{\text{T}}^{\text{j2}})}{(p_T^{\text{j1}} + p_T^{\text{j2}})} > z_{\text{cut}}(\frac{\Delta R_{12}}{R})^{\beta}$; $z_{\text{cut}} = 0.1$ and $\beta = 0, 1, 2$
- $\Delta_{\text{sys}} \sim$ 5-20% (5%) for $\log_{10}(\rho^2) <$ (>) -3.5









→ More dependence on soft radiation at higher β.

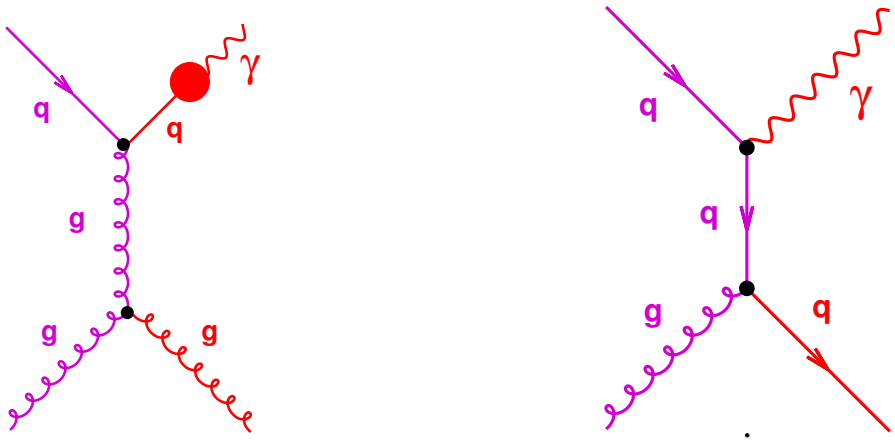
→ Resummation region -3.7 < $\log_{10}(\rho^2)$ < -1.7.

Photons

Physics with Photons

- Photon production allows to test pQCD and PDFs information.
- Prompt photons represent a cleaner probe of a hard interaction than jet production.
- Inclusive photons can be produced by two main mechanism:
  - → Direct-photon: γ produced in the hard interaction
  - → Fragmentation: γ coming from the fragmentation of a high-p_{T} parton

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

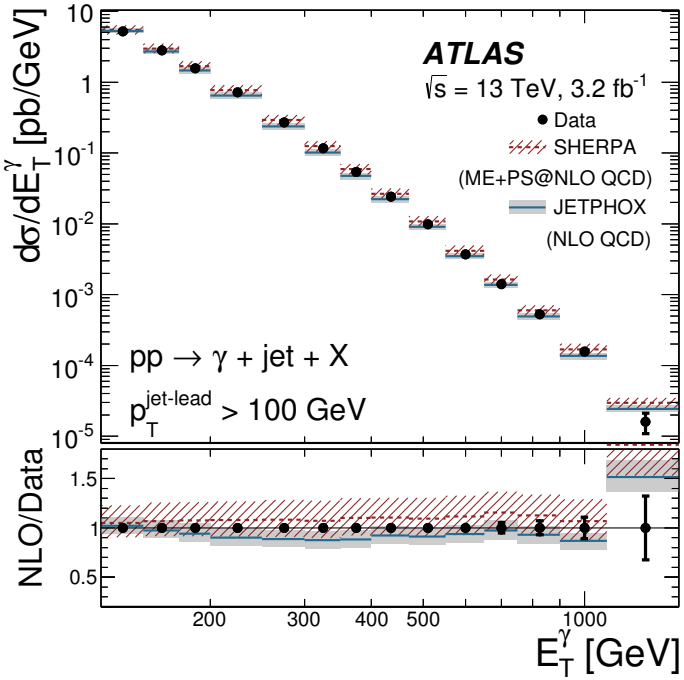


- Essential to require the photon to be isolated; $E_{\mathrm{T}}^{\mathrm{iso}} < E_{\mathrm{T}}^{\mathrm{max}}$ in a cone of radius R=0.4 (suppress $\pi^0(\eta^0...) \to \gamma\gamma$ and fragmentation contribution)

γ + jets production

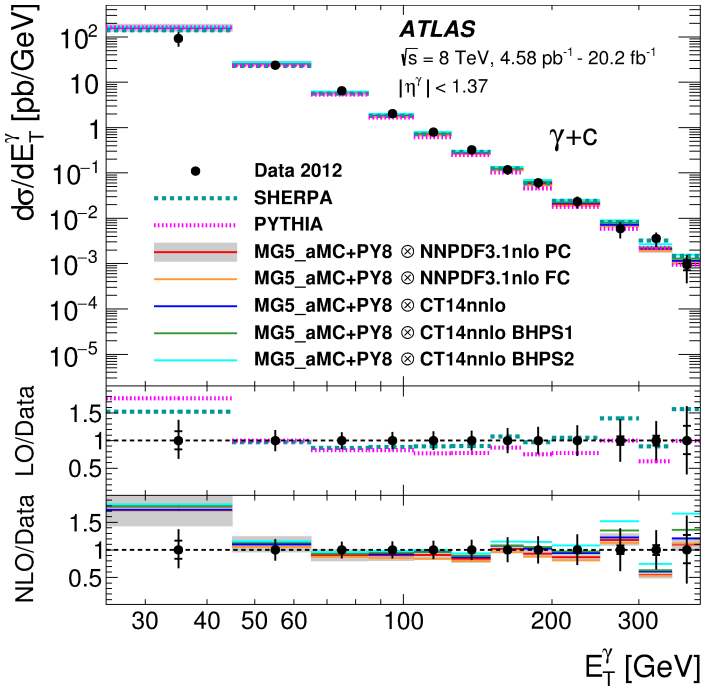
γ + jet, $\sqrt{s}$ = 13 TeV

- $E_{\mathrm{T}}^{\gamma} \geq 125$ GeV, $p_{\mathrm{T}}^{\mathrm{jet}} > 100$ GeV
- $E_{\mathrm{T}}^{\mathrm{iso}} < 4.2 \cdot 10^{-3} \cdot E_{\mathrm{T}}^{\gamma} + 10$ GeV



γ + HF jet, $\sqrt{s}$ = 8 TeV

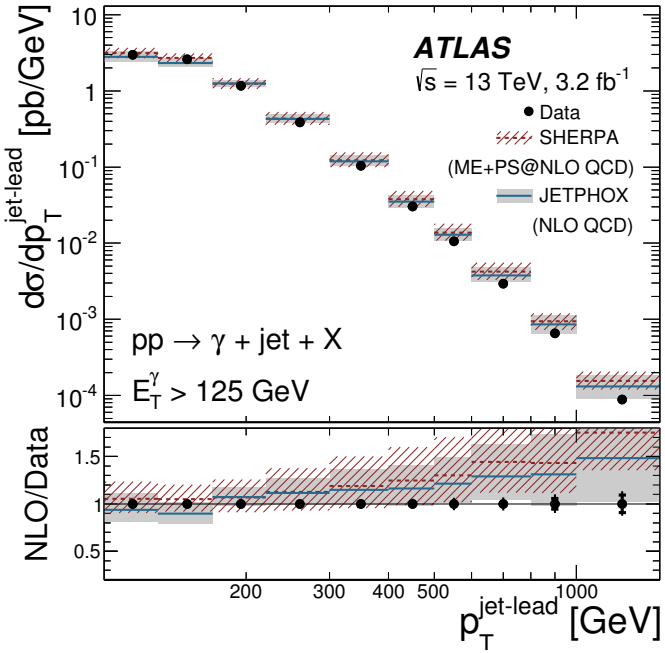
- $E_{\mathrm{T}}^{\gamma} \geq 25$ GeV, $p_{\mathrm{T}}^{\mathrm{jet}} > 20$ GeV
- $E_{\mathrm{T}}^{\mathrm{iso}} < 4.2 \cdot 10^{-3} \cdot E_{\mathrm{T}}^{\gamma} + 4.8$ GeV



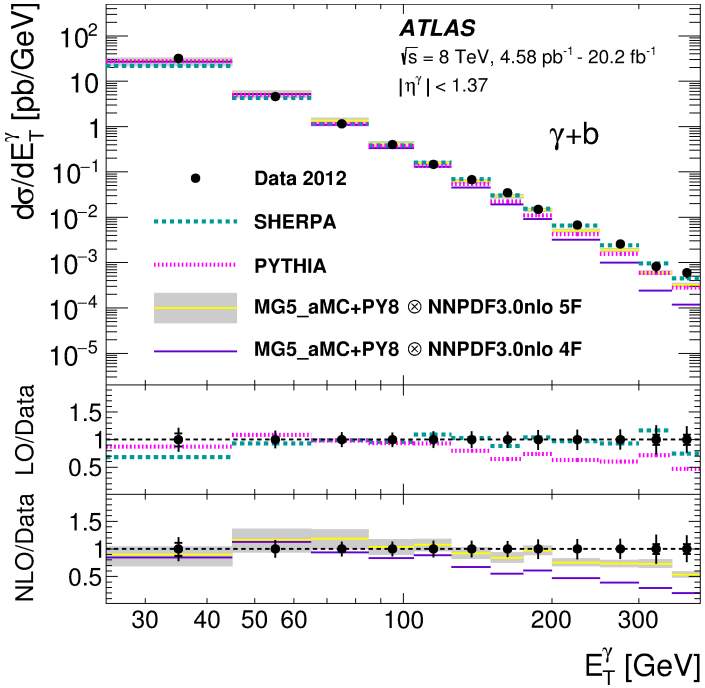
- γ + jet: $\Delta_{\mathrm{sys}} \sim 5\%$ (10% at $p_T^{\mathrm{jet}} \sim 1.5$ TeV)
- γ + HF jet: $\Delta_{\mathrm{sys}} \sim 15\%$ → main contribution due to jet flavour determination (stat. dominated in the E_T^{γ} tails 13-37%.).
- Good description within the uncertainties.

γ + jets production

γ + jet, $\sqrt{s}$ = 13 TeV



γ + HF jet, $\sqrt{s}$ = 8 TeV

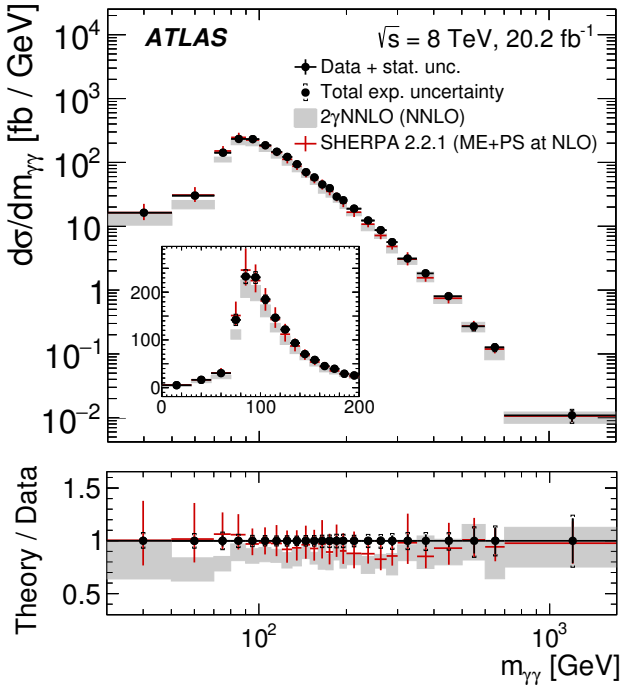


- γ + jet: JETPHOX (NLO) and SHERPA (NLO @0j and @1j) used for QCD calculations. ($\Delta_{\rm th}$ ~ 10%-30%, dominated by $\mu_{\rm R}$ and $\mu_{\rm F}$ choice.)
  - → Tend to be above the measurements at high $p_T^{\rm jet}$
- γ + HF jet: MG5_AMC@NLO (NLO) with several PDF sets → different IC content/model and 5F/4F flavor-schemes comparison.
  - → 4F worse description at high E_T^γ (large $\log(m_{\rm b}/E_{\rm T}^\gamma)$ terms).

$\gamma\gamma$ and $\gamma\gamma\gamma$ production

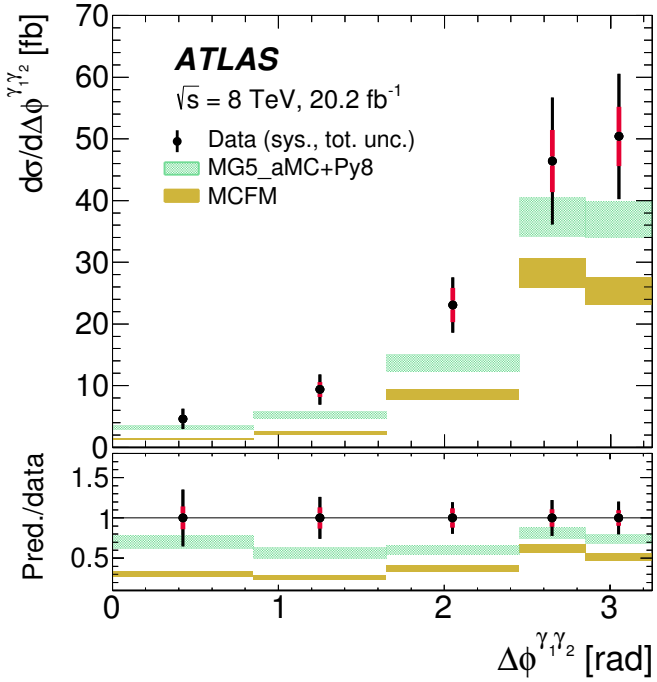
$\gamma\gamma$ + X, $\sqrt{s}$ = 8 TeV

- $E_T^{\gamma} \geq 40$ GeV and 30 GeV
- $E_T^{iso} < 11$ GeV, $\Delta R^{\gamma\gamma} > 0.4$



$\gamma\gamma\gamma$ + X, $\sqrt{s}$ = 8 TeV

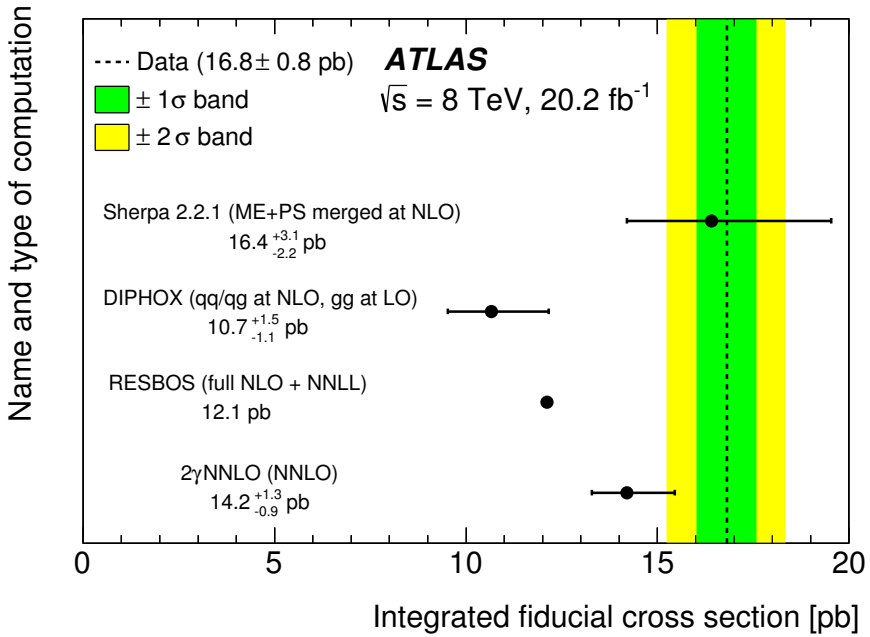
- $E_T^{\gamma} \geq 27$ GeV, 22 GeV and 15 GeV
- $E_T^{iso} < 10$ GeV, $\Delta R^{\gamma\gamma} > 0.45$



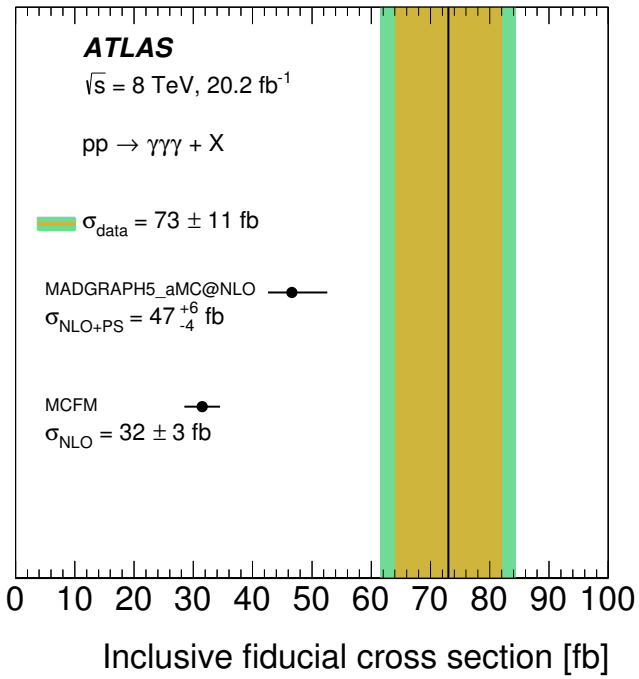
- $\gamma\gamma$: $\Delta_{sys} \sim 4.5\%$ ($P_{\gamma\gamma} \approx 74\%$) → γ-ID data-MC differences (2.5%) and γ-iso modelling (2.0%).
- $\gamma\gamma\gamma$: $\Delta_{sys} \sim 13\%$ ($P_{\gamma\gamma\gamma} \approx 55\%$) → dominated by uncertainties on $\gamma\gamma\gamma$ yield estimation.

$\gamma\gamma$ and $\gamma\gamma\gamma$ production

$\gamma\gamma$ + **X,** $\sqrt{s}$ **= 8 TeV**



$\gamma\gamma\gamma$ + **X,** $\sqrt{s}$ **= 8 TeV**



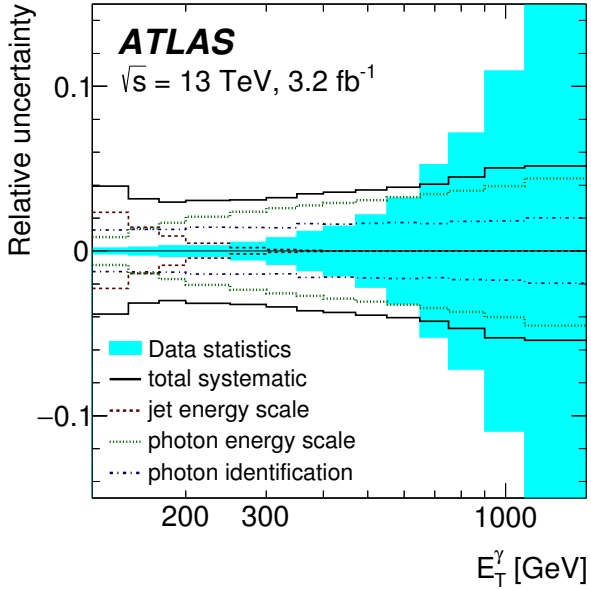
- $\gamma\gamma$: NLO (DIPHOX and RESBOS), 2γ-NNLO and SHERPA (NLO @0j and @1j).
  - → NLO underestimate the measurements by 40-50%.
  - → Adequate description by beyond NLO calculations.
- $\gamma\gamma\gamma$: NLO MCFM and NLO+PS (MG5_AMC@NLO).
  - NLO underestimate the measurements by 36-55%.
  - Beyond NLO calculations not available.

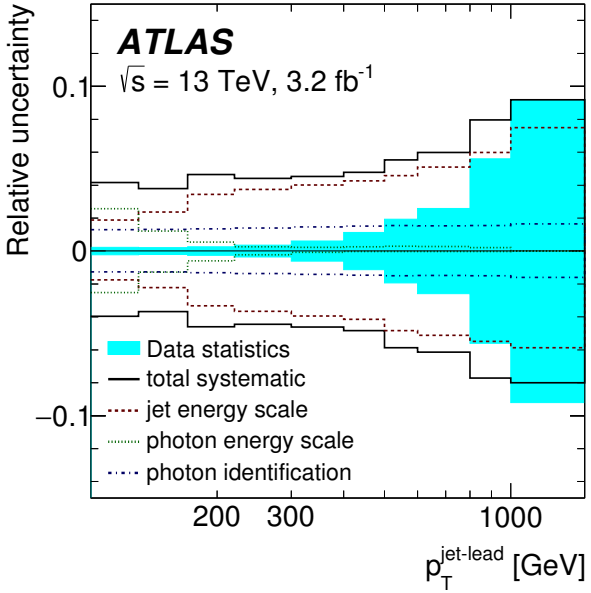
Conclusions

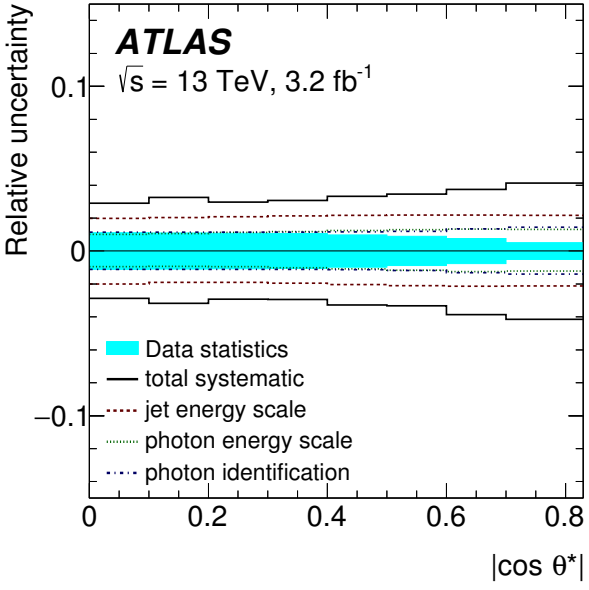
- Measurements with jets or photons produced in the final state in pp collisions at $\sqrt{s}$ = 8 and 13 TeV have been presented.
- NLO QCD calculations overestimate jet measurements at low p_T ($\mu_F = \mu_R = p_T^{\mathrm{jet}}$):
  - → good description by NNLO calculations
  - → Using $\mu_F = \mu_R = p_T^{\mathrm{jet,max}}$ data/NNLO agreement gets worse.
- Adequate description by NLO within uncertainties of $d\sigma/\mathrm{d}m_{\mathrm{jj}}$ and jet soft-drop mass.
- Adequate description by the NLO of $d\sigma/dE_T^{\gamma}$ for γ + jet and γ + HF jet processes.
  - → NLO tends to overestimate the measurements at high p_T^{jet}.
- NLO predictions underestimate $\sigma_{\gamma\gamma}$ and $\sigma_{\gamma\gamma\gamma}$:
  - → Addition of PS effects improve the description of $\Delta\phi^{\gamma\gamma}$ in $\gamma\gamma\gamma$ production.
  - → Beyond NLO calculations improve the description of $\sigma_{\gamma\gamma}$.

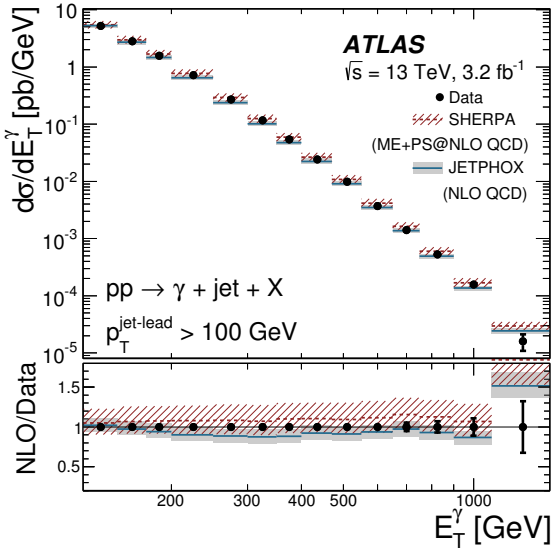
Backup

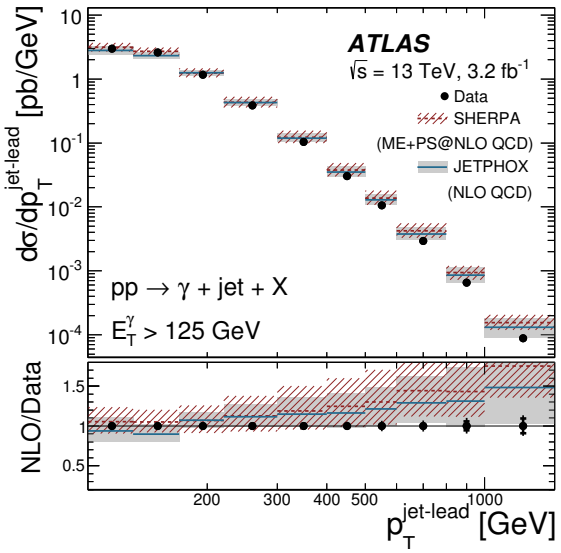
Photon + jets production

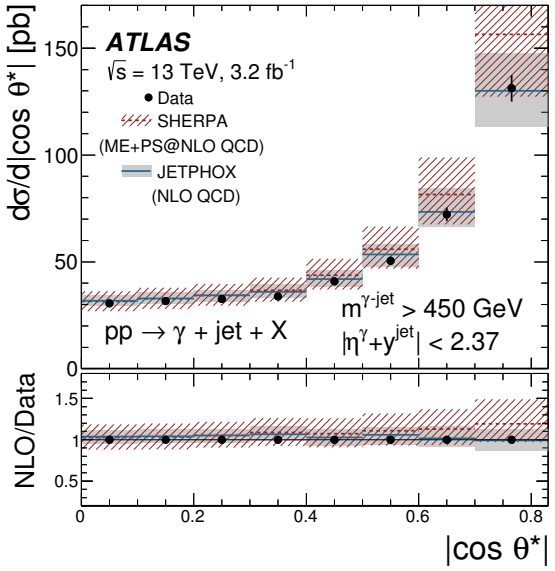




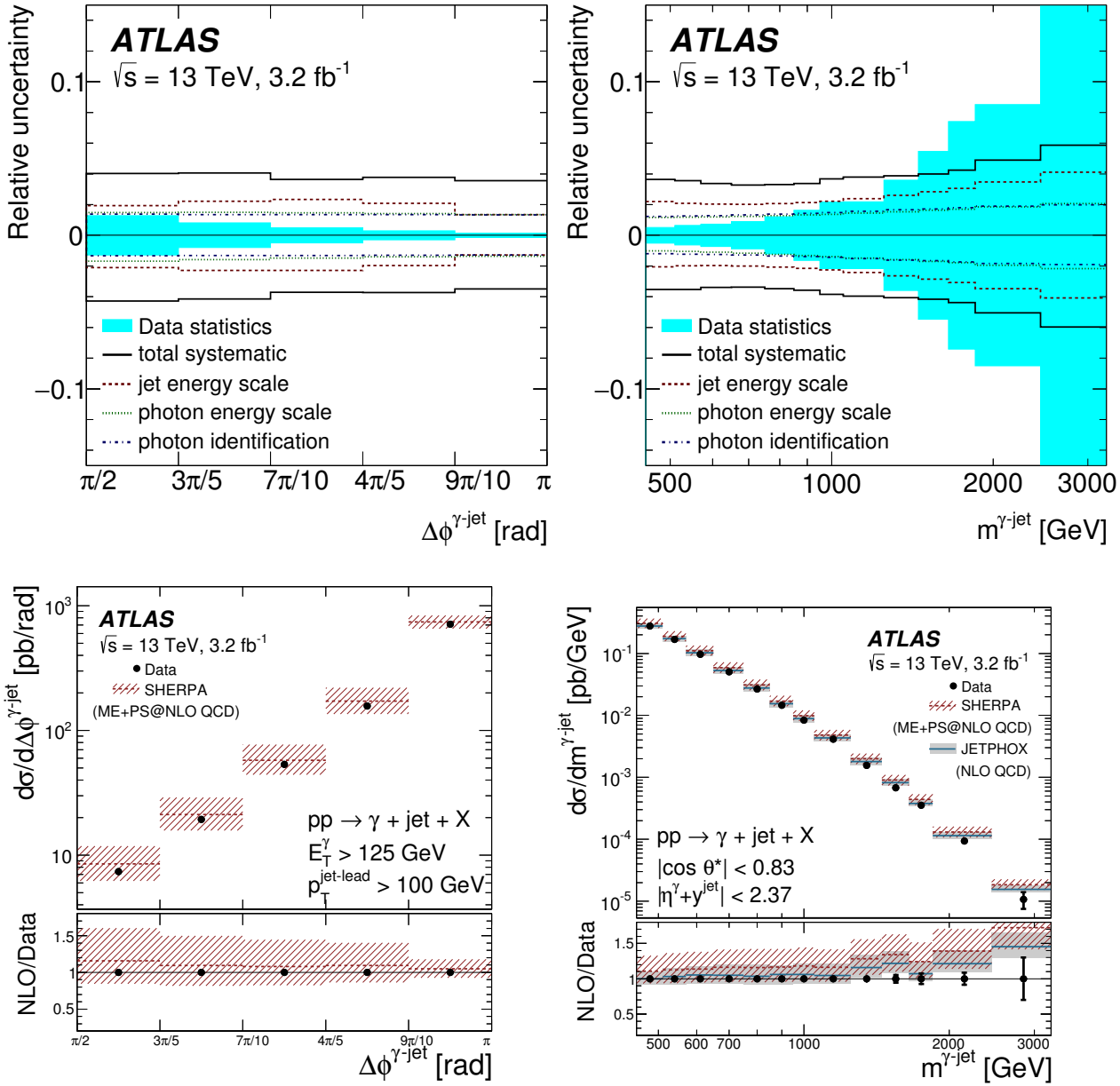




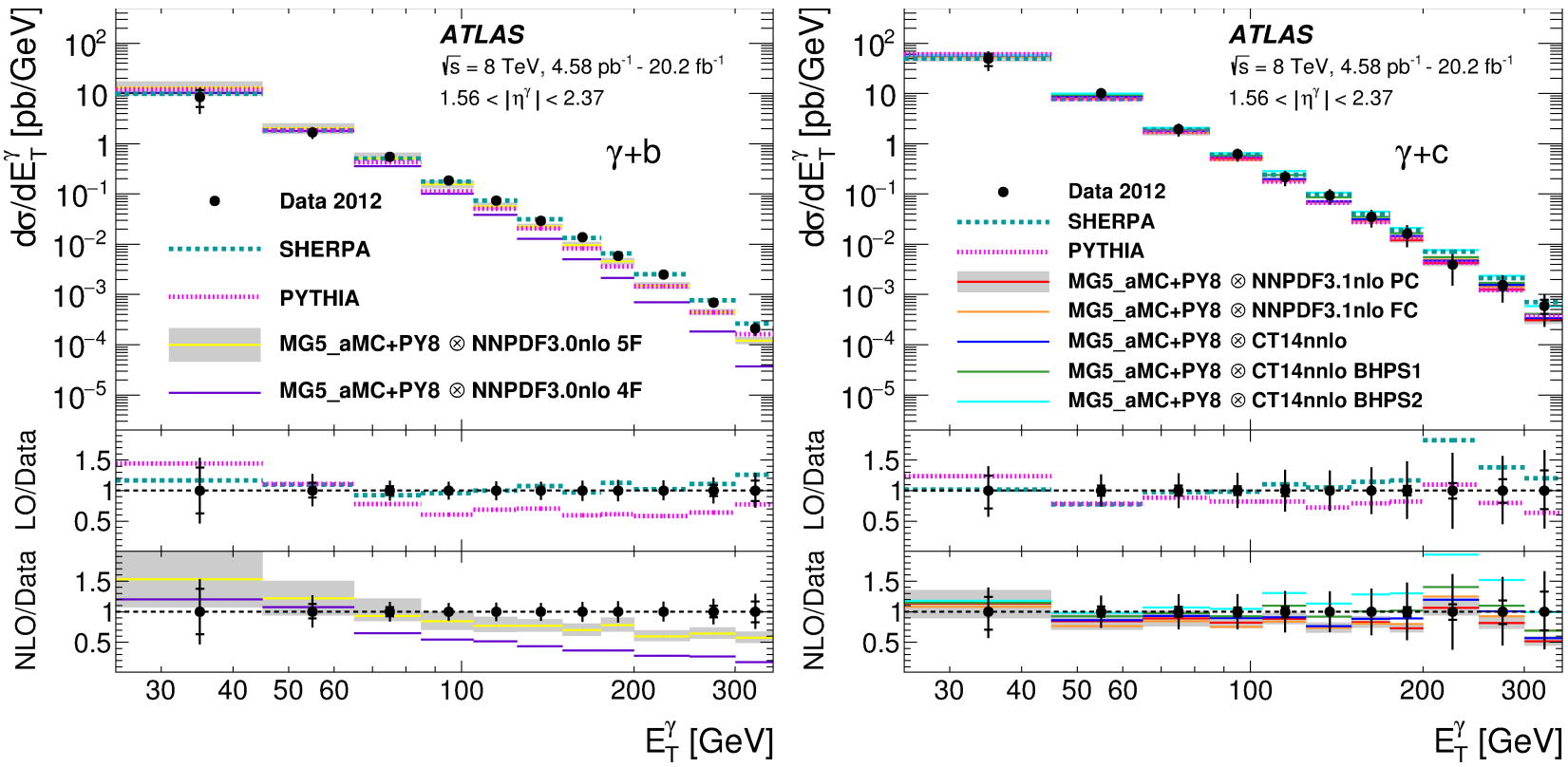




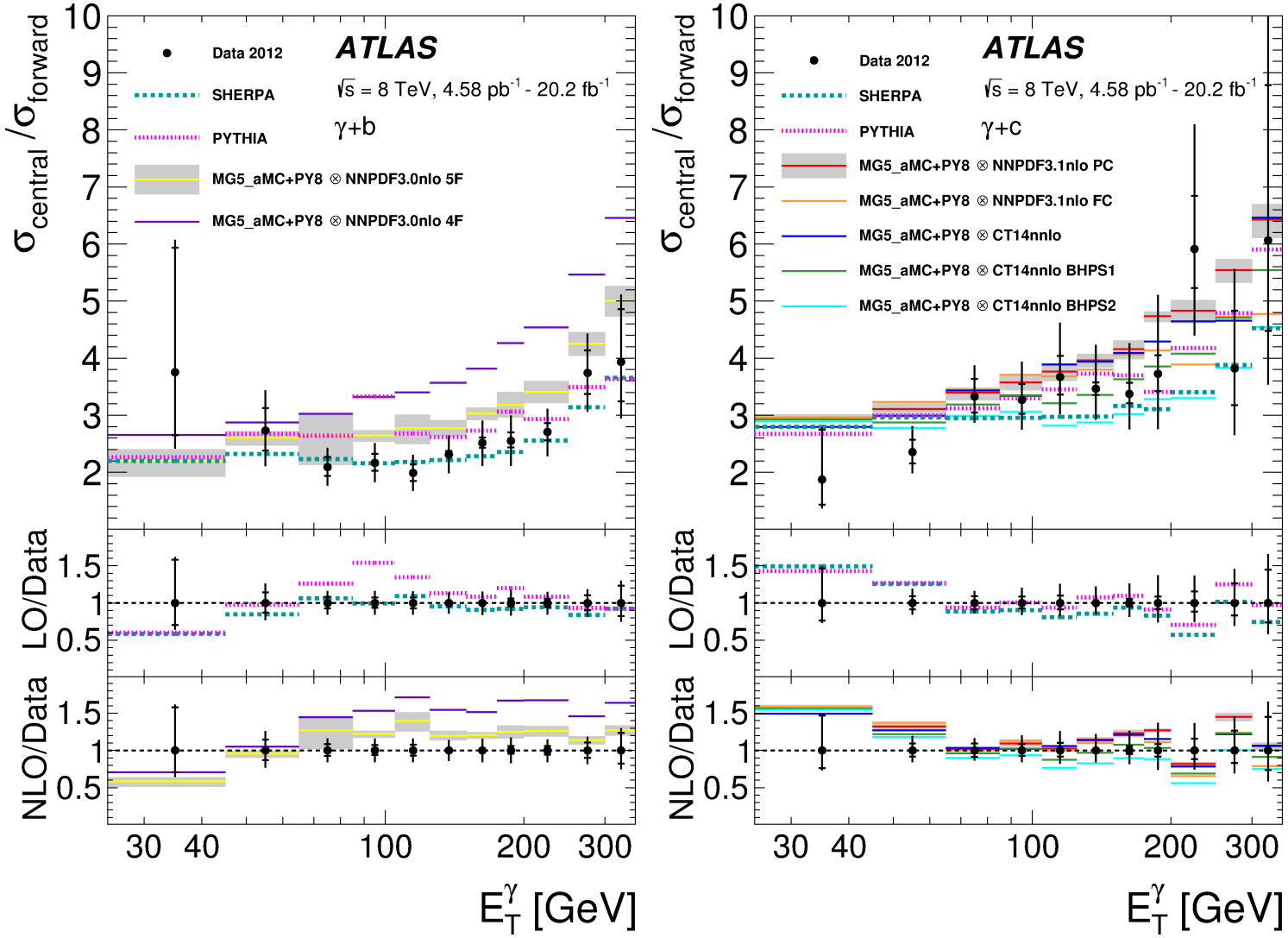
Photon + jets production



Photon + HF jet production

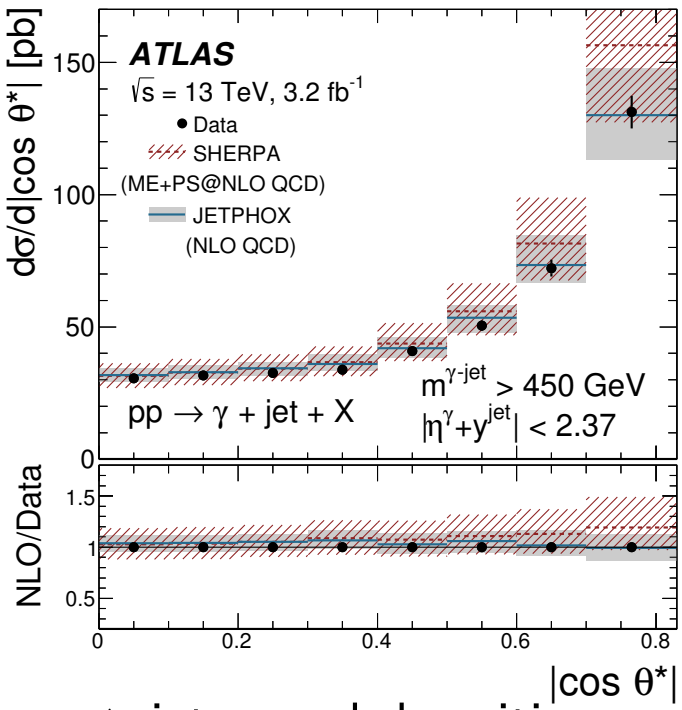


Photon + HF jet production

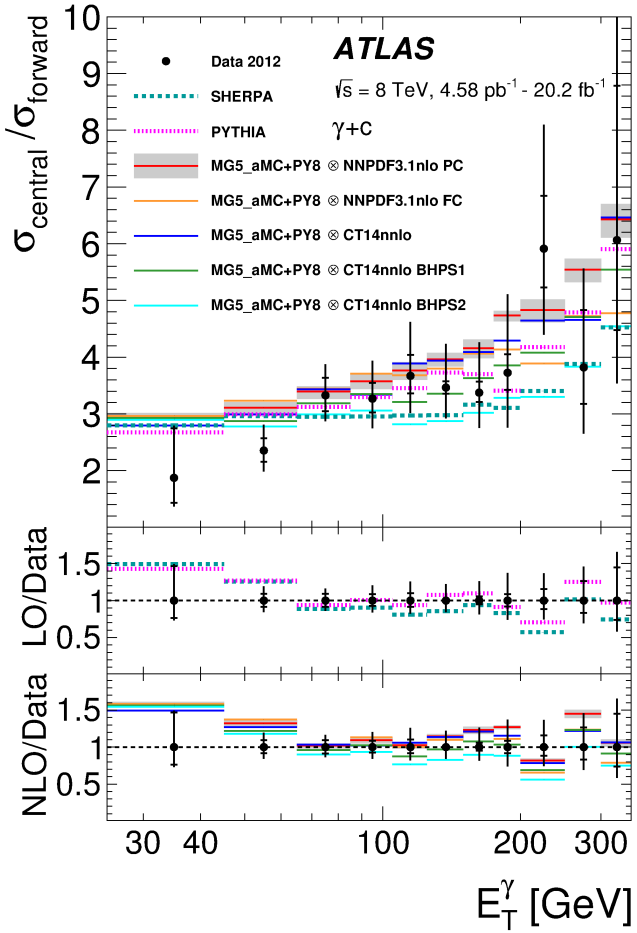


γ + jets production

γ + jet, $\sqrt{s}$ = 13 TeV

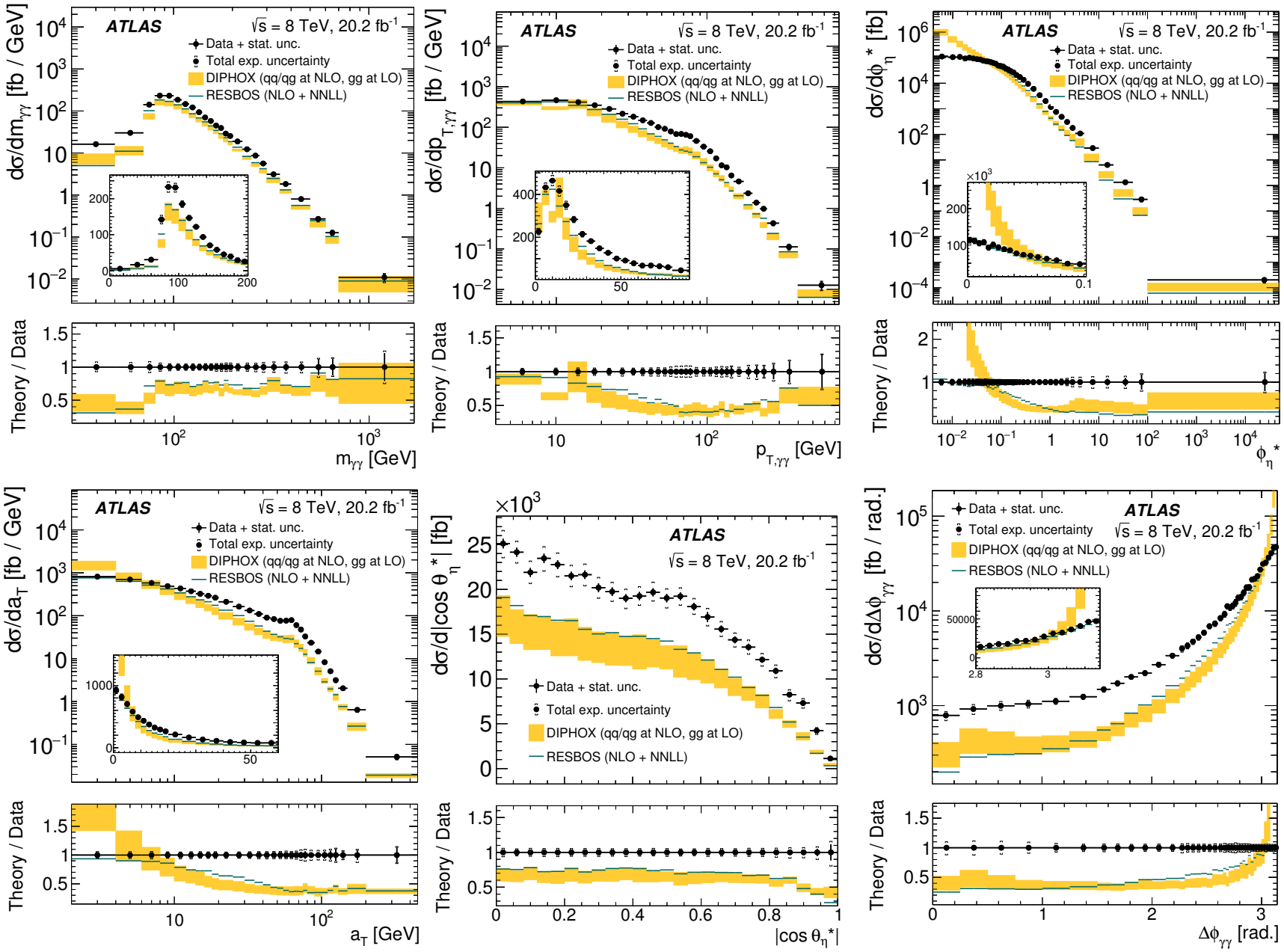


γ + HF jet, $\sqrt{s}$ = 8 TeV

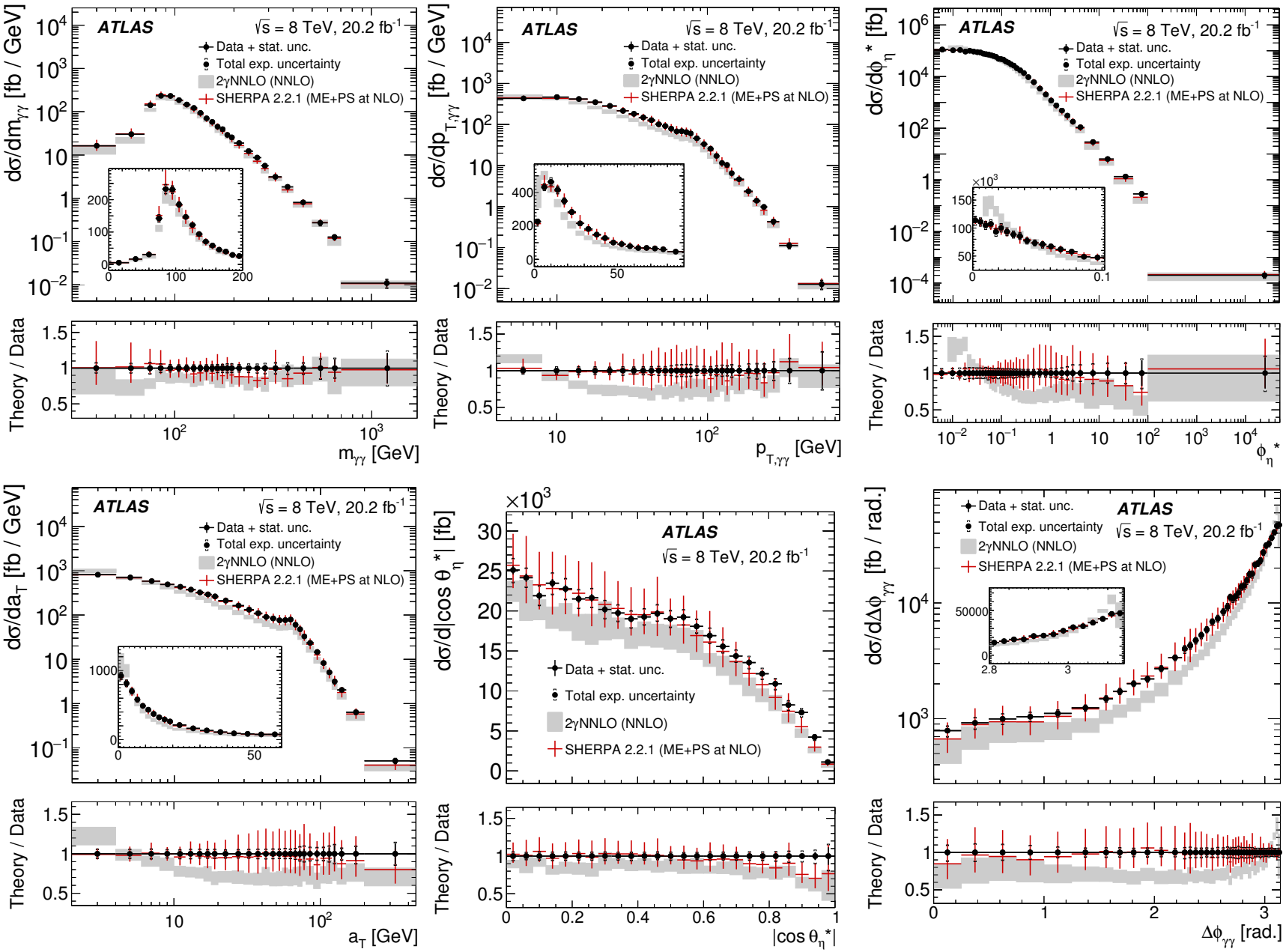


- γ + jet: good descrition → spin of exchanged particle compatible with fermions.
- γ + HF jet: cancellation of syst. uncert. on the ratio (higher stat. uncertainty)
  - → Sensitive to IC content of the proton (higher contribution at high η^{γ})

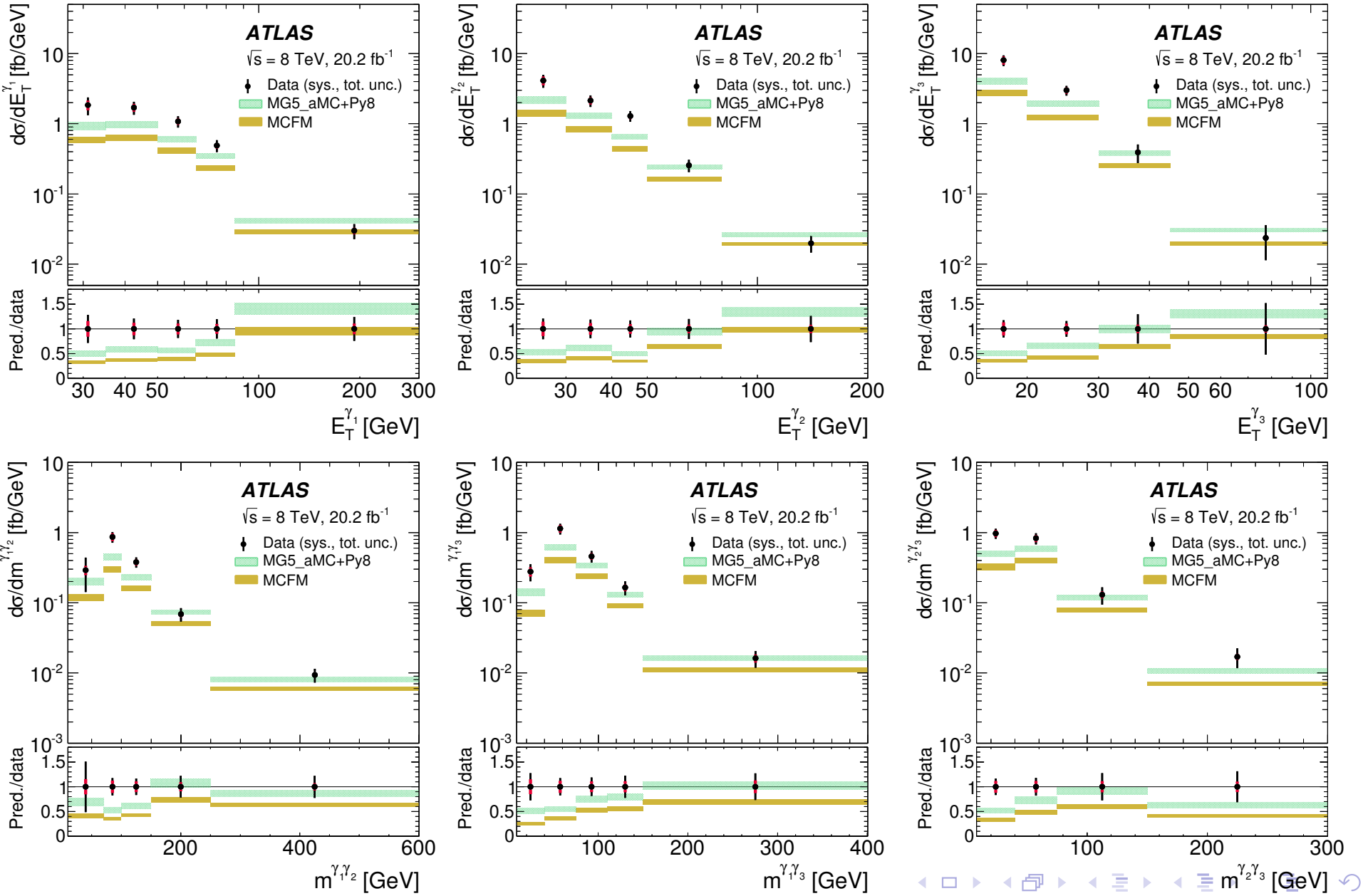
$\gamma\gamma$ production



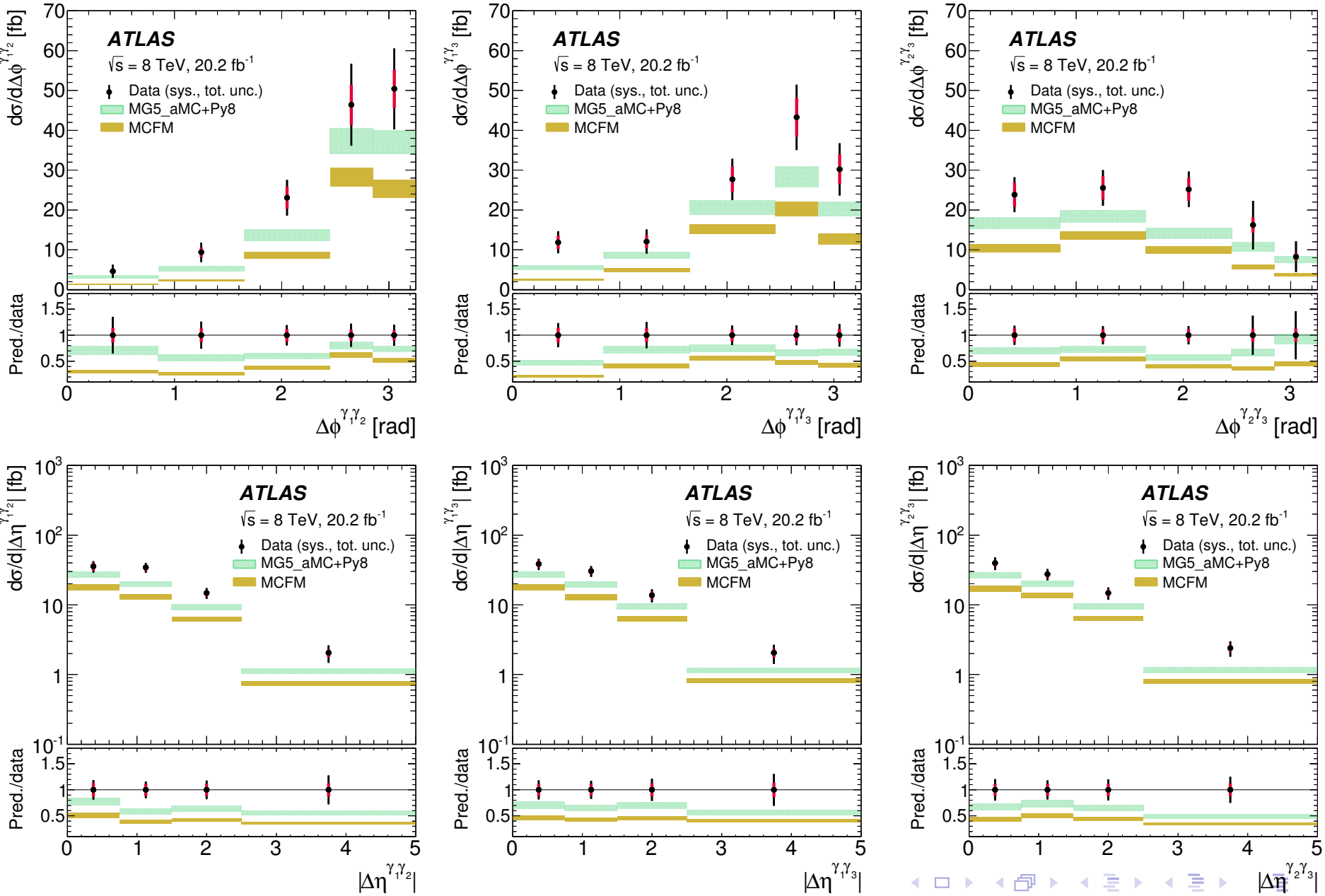
$\gamma\gamma$ production



$\gamma\gamma\gamma$ production

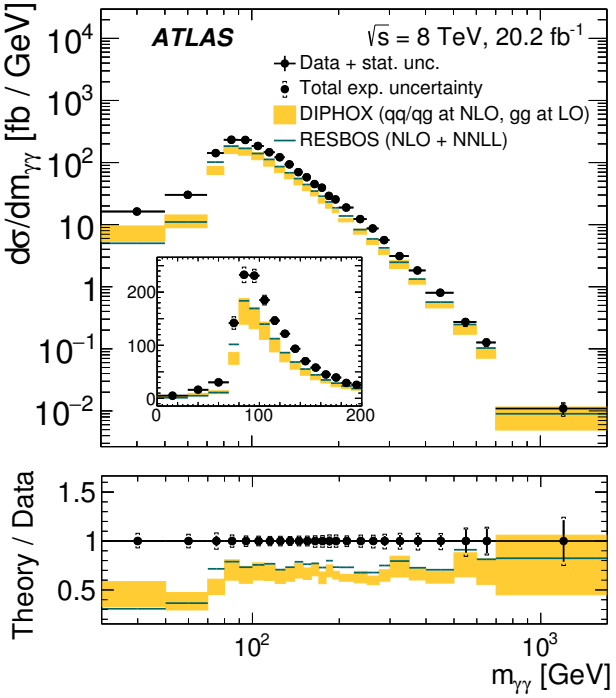


$\gamma\gamma\gamma$ production

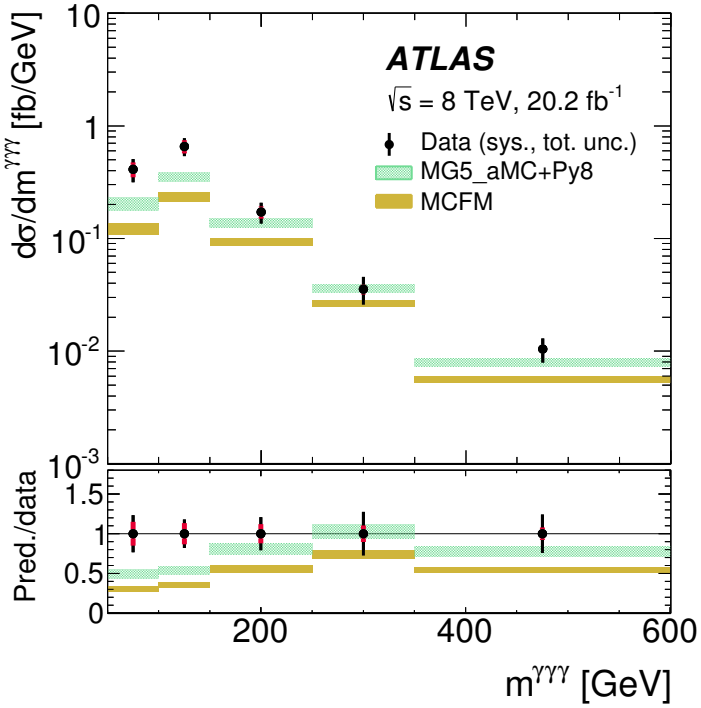


$\gamma\gamma$ and $\gamma\gamma\gamma$ production

$\gamma\gamma$ + X, $\sqrt{s}$ = 8 TeV



$\gamma\gamma\gamma$ + X, $\sqrt{s}$ = 8 TeV



- $\gamma\gamma$: NLO (DIPHOX and RESBOS), 2γ-NNLO and SHERPA (NLO @0j and @1j).
  - → Description highly improved by including beyond NLO terms.
- $\gamma\gamma\gamma$: NLO MCFM and NLO+PS (MG5_AMC@NLO).
  - PS allows to improve the description as function of $\Delta\phi_{\gamma_1\gamma_2}$, $\Delta\phi_{\gamma_1\gamma_3}$ and $\Delta\phi_{\gamma_2\gamma_3}$.

Inclusive jet and dijet production at $\sqrt{s}$ = 13 TeV

Rapidity ranges	$P_{\rm obs}$ CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
$p_{\rm T}^{\rm max}$					
$\lvert y\rvert < 0.5$	67%	65%	62%	31%	50%
$0.5 \leq \lvert y\rvert < 1.0$	5.8%	6.3%	6.0%	3.0%	2.0%
$1.0 \leq \lvert y\rvert < 1.5$	65%	61%	67%	50%	55%
$1.5 \leq \lvert y\rvert < 2.0$	0.7%	0.8%	0.8%	0.1%	0.4%
$2.0 \leq \lvert y\rvert < 2.5$	2.3%	2.3%	2.8%	0.7%	1.5%
$2.5 \leq \lvert y\rvert < 3.0$	62%	71%	69%	25%	55%
$p_{\rm T}^{\rm jet}$					
$\lvert y\rvert < 0.5$	69%	67%	66%	30%	46%
$0.5 \leq \lvert y\rvert < 1.0$	7.4%	8.9%	8.6%	3.4%	2.0%
$1.0 \leq \lvert y\rvert < 1.5$	69%	62%	68%	45%	54%
$1.5 \leq \lvert y\rvert < 2.0$	1.3%	1.6%	1.4%	0.1%	0.5%
$2.0 \leq \lvert y\rvert < 2.5$	8.7%	6.6%	7.4%	1.0%	3.6%
$2.5 \leq \lvert y\rvert < 3.0$	65%	72%	72%	28%	59%

χ^2/dof all $\lvert y\rvert$ bins	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
$p_{\rm T}^{\rm max}$	419/177	431/177	404/177	432/177	475/177
$p_{\rm T}^{\rm jet}$	399/177	405/177	384/177	428/177	455/177

y^* ranges	$P_{\rm obs}$ CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
$y^* < 0.5$	79%	59%	50%	71%	71%
$0.5 \leq y^* < 1.0$	27%	23%	19%	32%	31%
$1.0 \leq y^* < 1.5$	66%	55%	48%	66%	69%
$1.5 \leq y^* < 2.0$	26%	26%	28%	9.9%	25%
$2.0 \leq y^* < 2.5$	43%	35%	31%	4.2%	21%
$2.5 \leq y^* < 3.0$	45%	46%	40%	25%	38%
all y^* bins	8.1%	5.5%	9.8%	0.1%	4.4%

- Quantitative comparison between the measurements and the NLO pQCD for different PDF sets.
- Syst. and theor. uncertainties incluced in the χ^2. Asymm. and correlations also considered.
- Each syst. and theor. uncert. uncorr. among each other and fully correlated across $p_{\rm T}$, $\lvert y\rvert$.
- Correlations of stat. uncer. considered using covariance matrices.