6th International Conference on New Frontiers in Physics (ICNFP)

Probing QCD with photons and jets with the ATLAS detector

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Outline

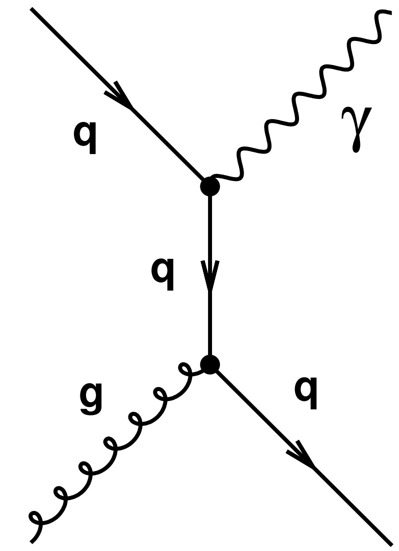
Physics with jets

- Inclusive jet at 8 TeV; (***arXiv:1706.03192***)
- Inclusive jets and di-jets at 13 TeV; (***ATLAS-CONF-2017-048***)
- Determination of α_s from Transverse Energy-Energy Correlation (TEEC) in multi-jet events; (***arXiv:1707.02562***)

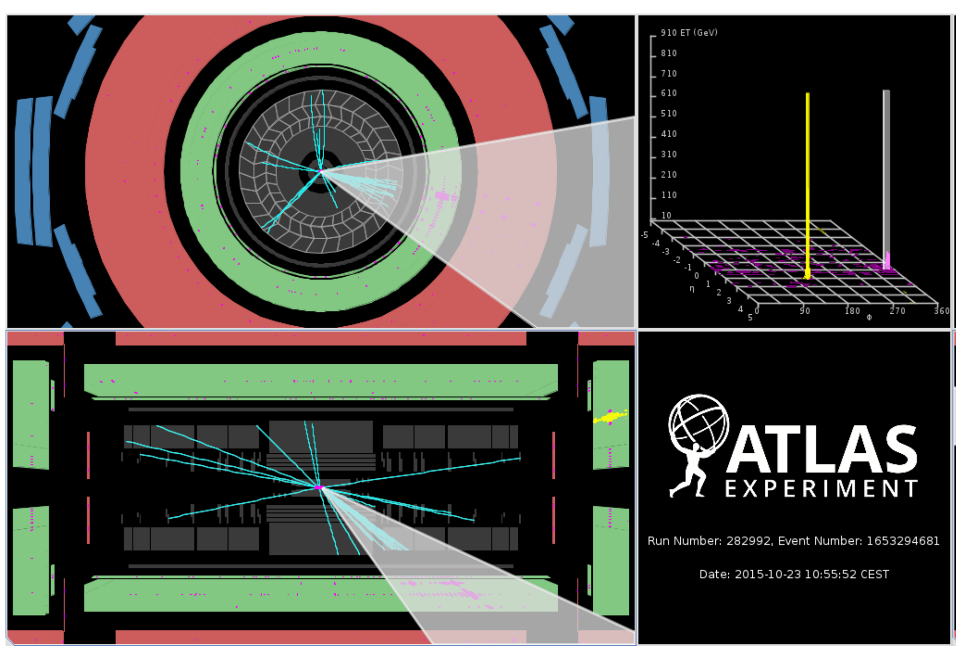
Physics with photon

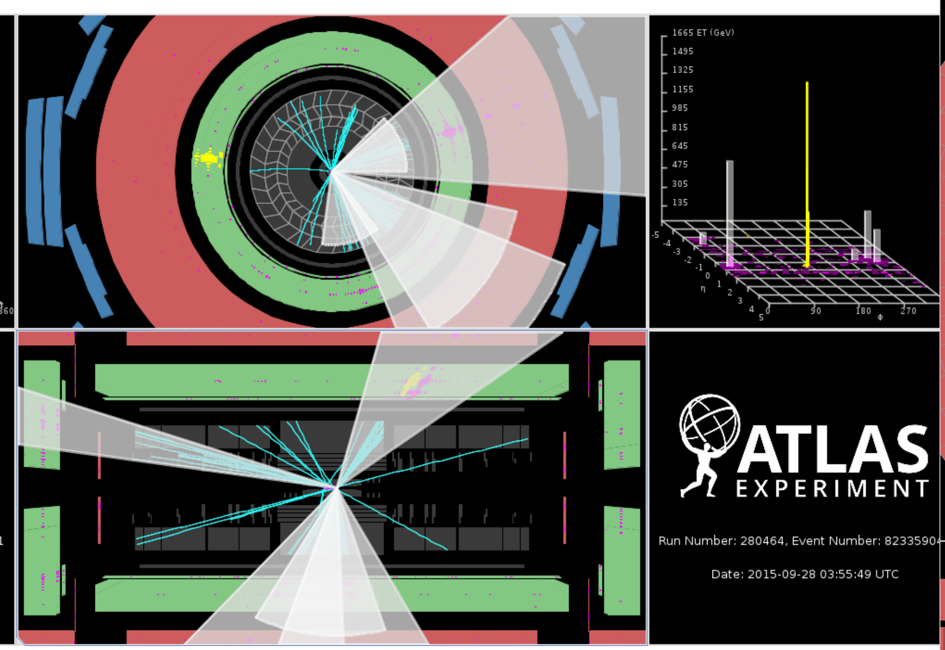
- Inclusive photon at 13 TeV; (***Phys. Lett. B 770 (2017) 473***)
- Photon + jet at 8 TeV; (***Nucl. Phys. B 918 (2017) 257***)
- Photon + jet at 13 TeV; (***ATLAS-CONF-2017-059***)
- Photon pair production at 8 TeV; (***Phys. Rev. D 95 (2017) 112005***)

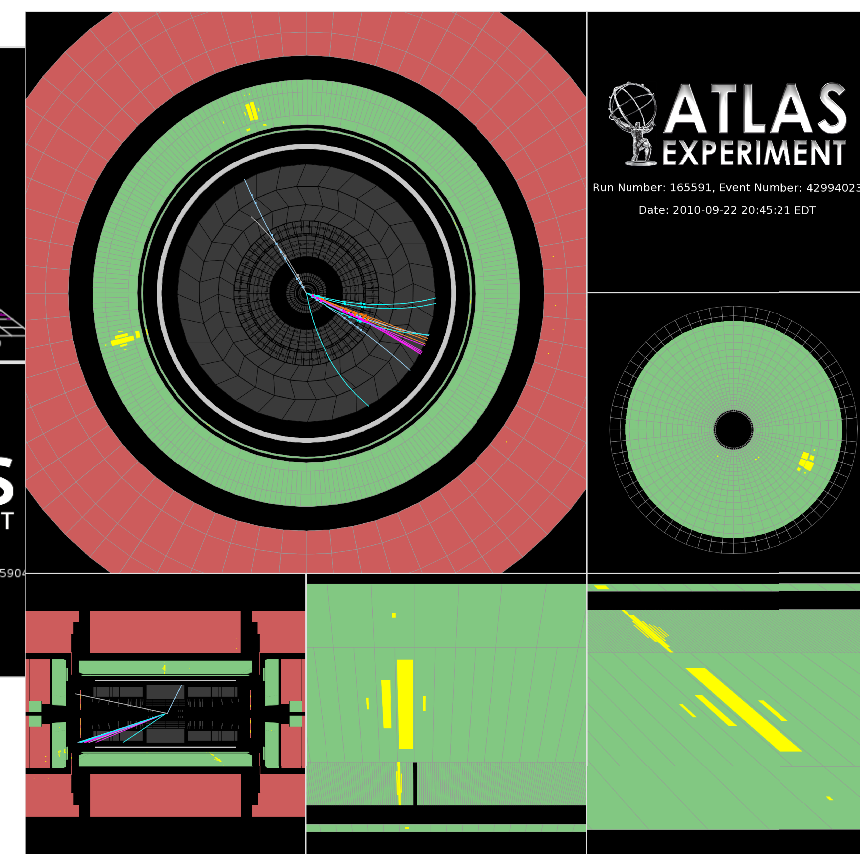
Motivation



- Test of perturbative QCD predictions;
- Constraint on proton PDFs;
- Determination of the strong coupling constant;
- Description of background event kinematic for different searches for new physics.







Jets

Inclusive Jet production

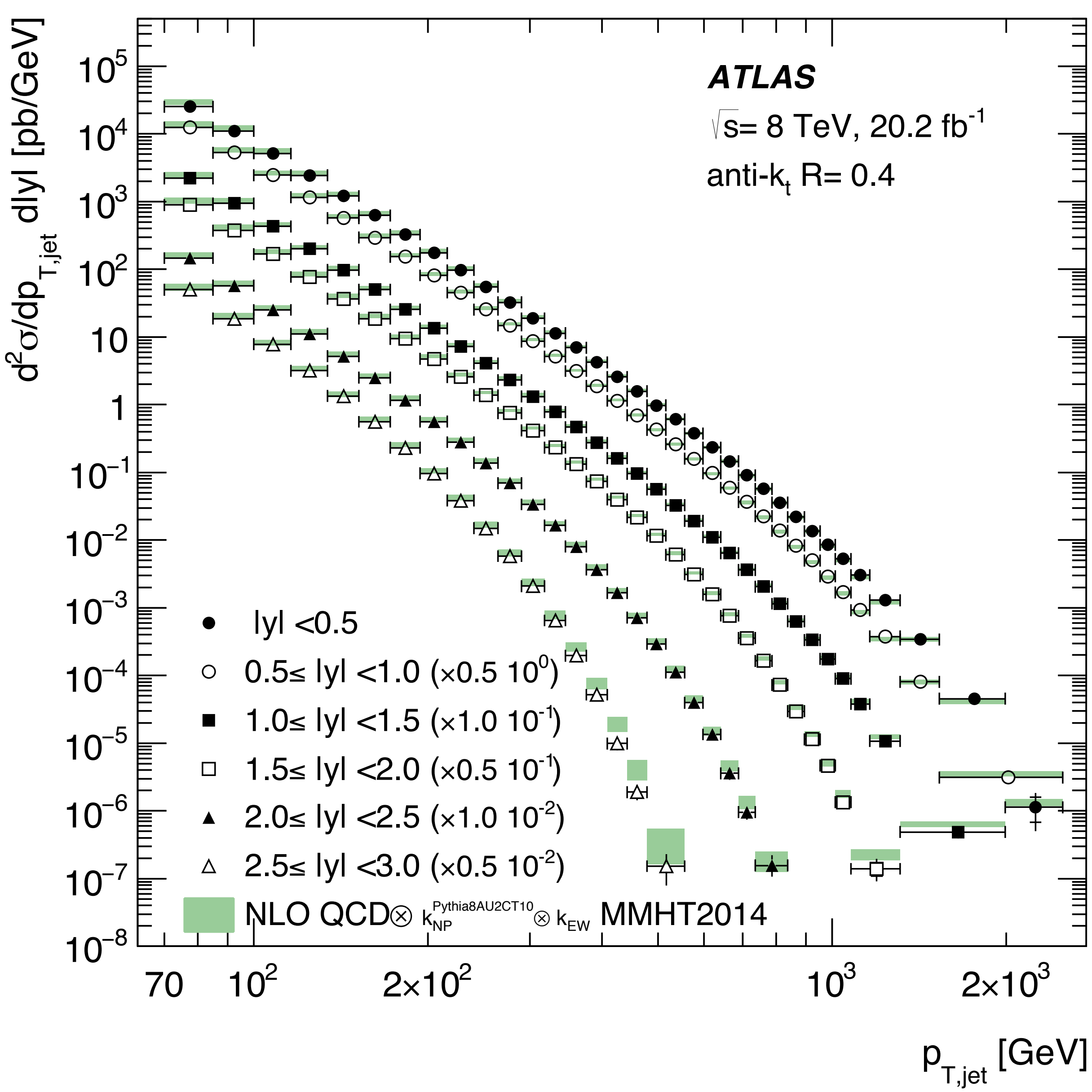
$\sqrt{s} = 8$ TeV $\quad$ $pp \to Jet + X$ $\quad$ $\sqrt{s} = 13$ TeV

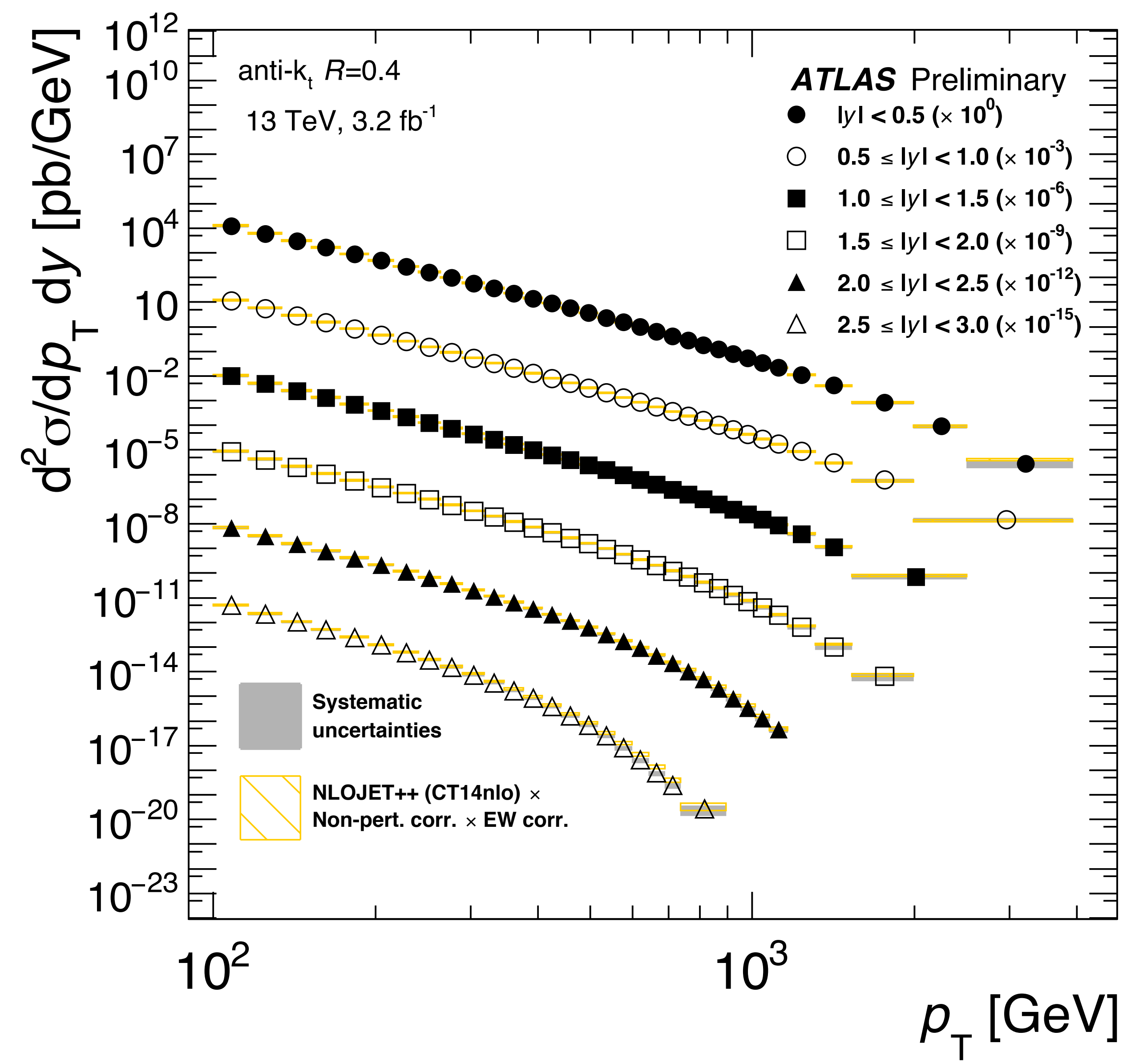
$\sqrt{s} = 8$ TeV:

- $P_T > 70$ GeV;
- $|y| < 3$;
- anti-k$_t$ jets with both R=0.4 and R=0.6;

$\sqrt{s} = 13$ TeV:

- $P_T > 100$ GeV;
- $|y| < 3$;
- Only R=0.4 anti-k$_t$ jets;

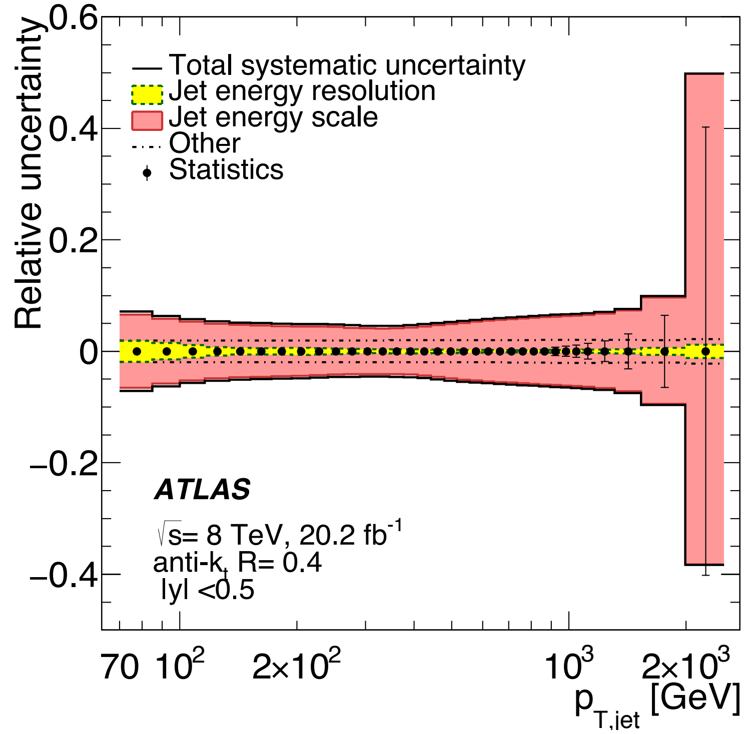


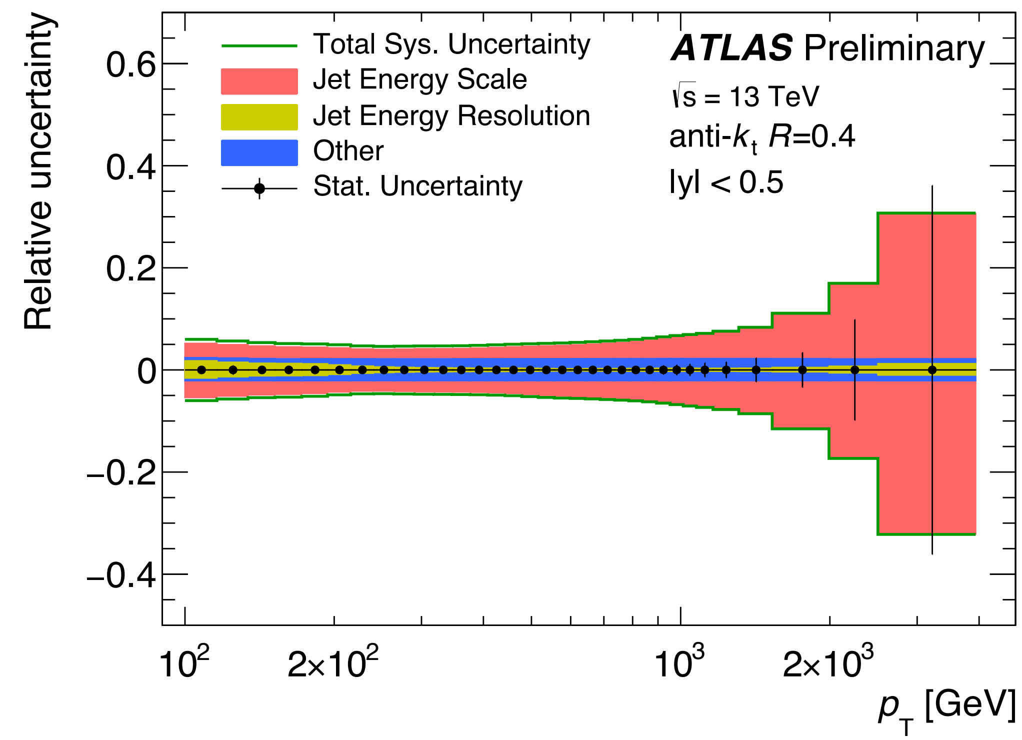


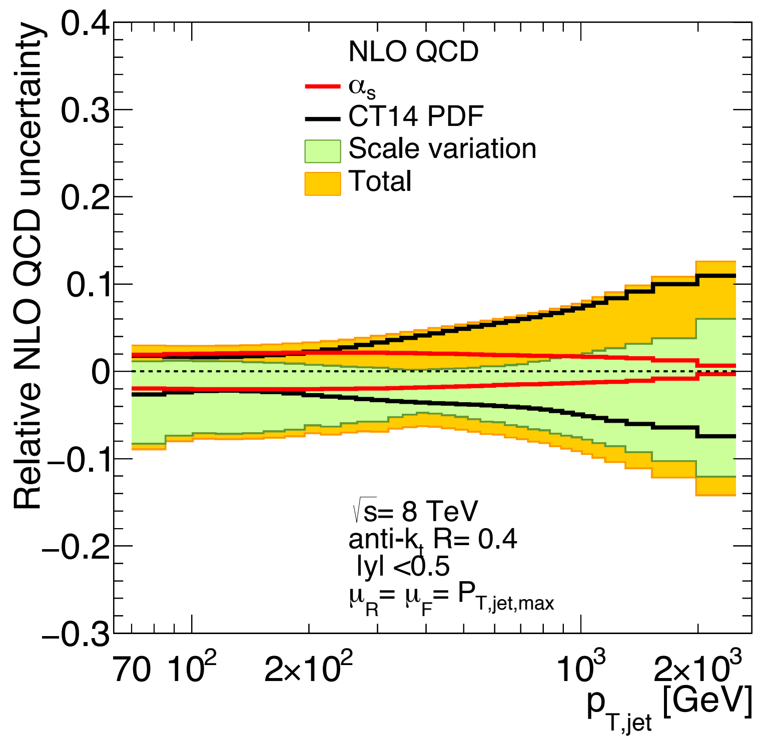
Inclusive Jet production

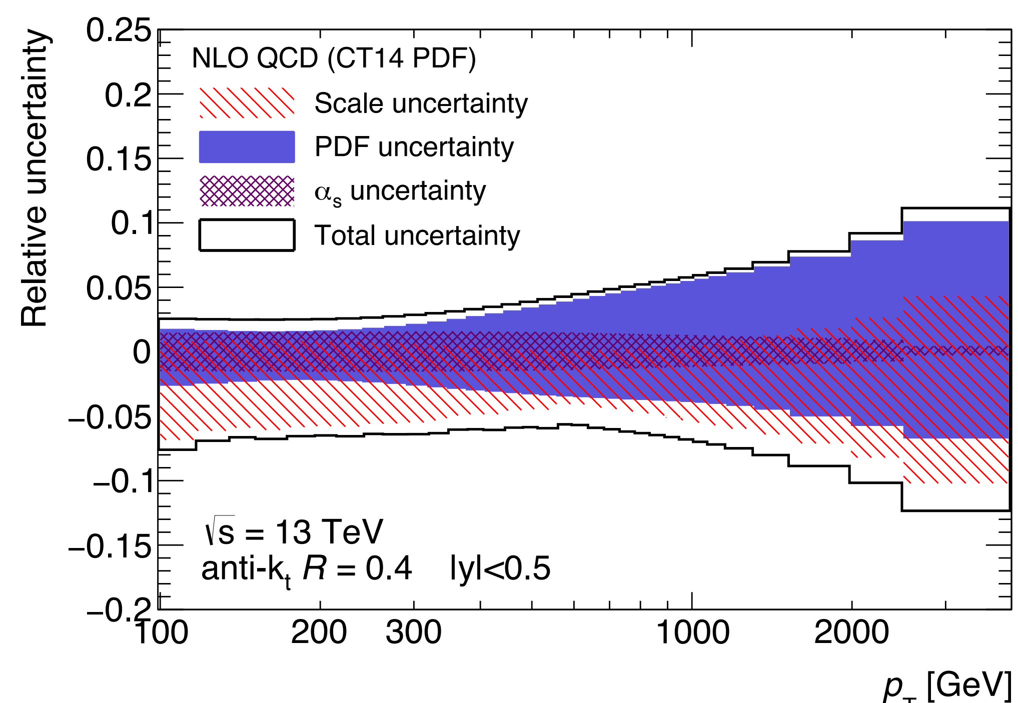
$\sqrt{s} = 8$ TeV $\sqrt{s} = 13$ TeV

- The dominant experimental uncertainties are the jet energy scale and jet energy resolution.
- Theory predictions corrected for non-perturbative and electroweak effects.



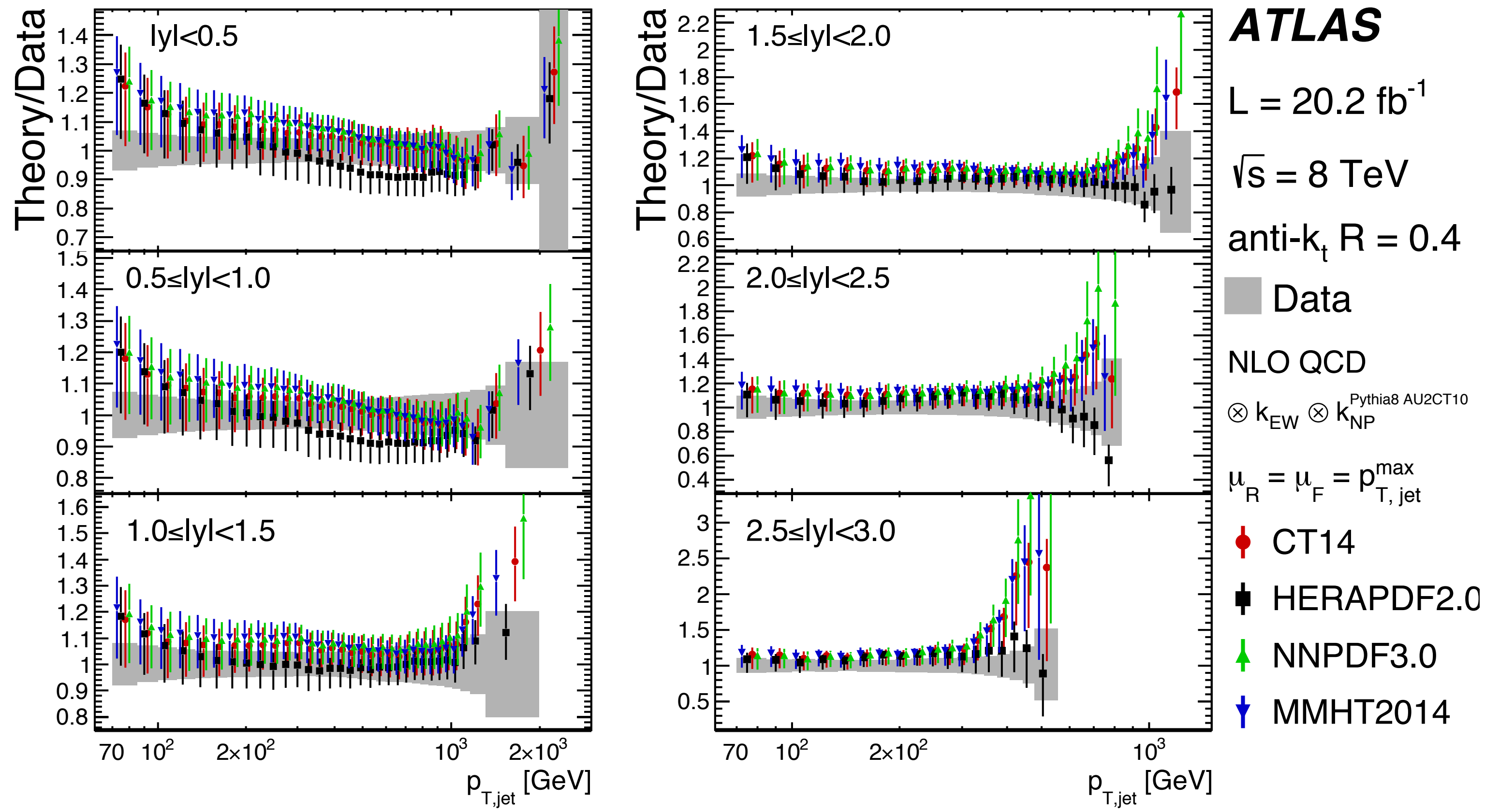






Inclusive Jet production

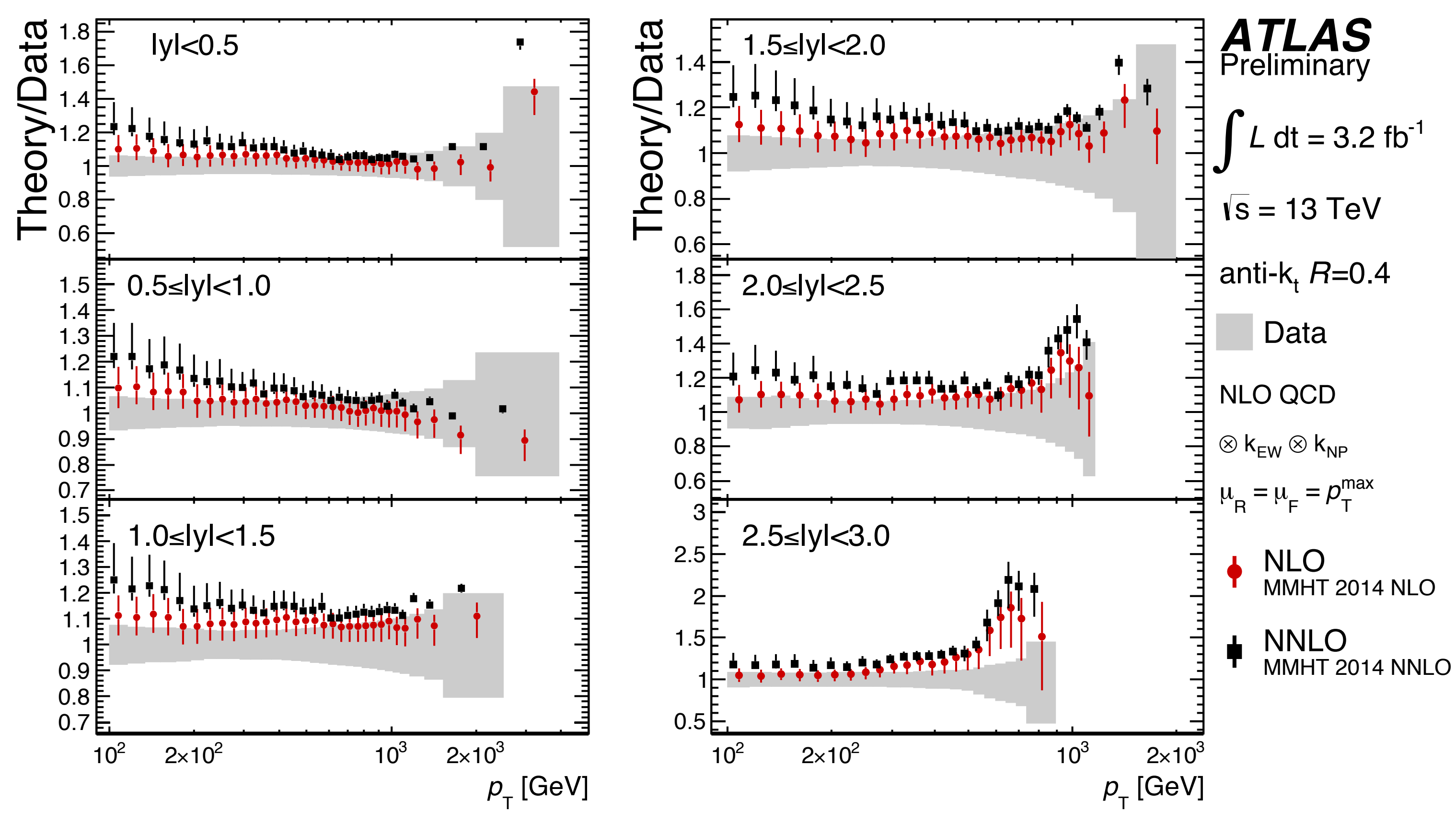
NLO QCD predictions are typically above the data for $P_T \leq 100$ GeV. Better agreement for higher P_T, except for $P_T > 1$ TeV where the NLO QCD predictions are higher (10-20%) than data.
Same behavior observed for different PDF sets.



NNLO pQCD prediction based on:

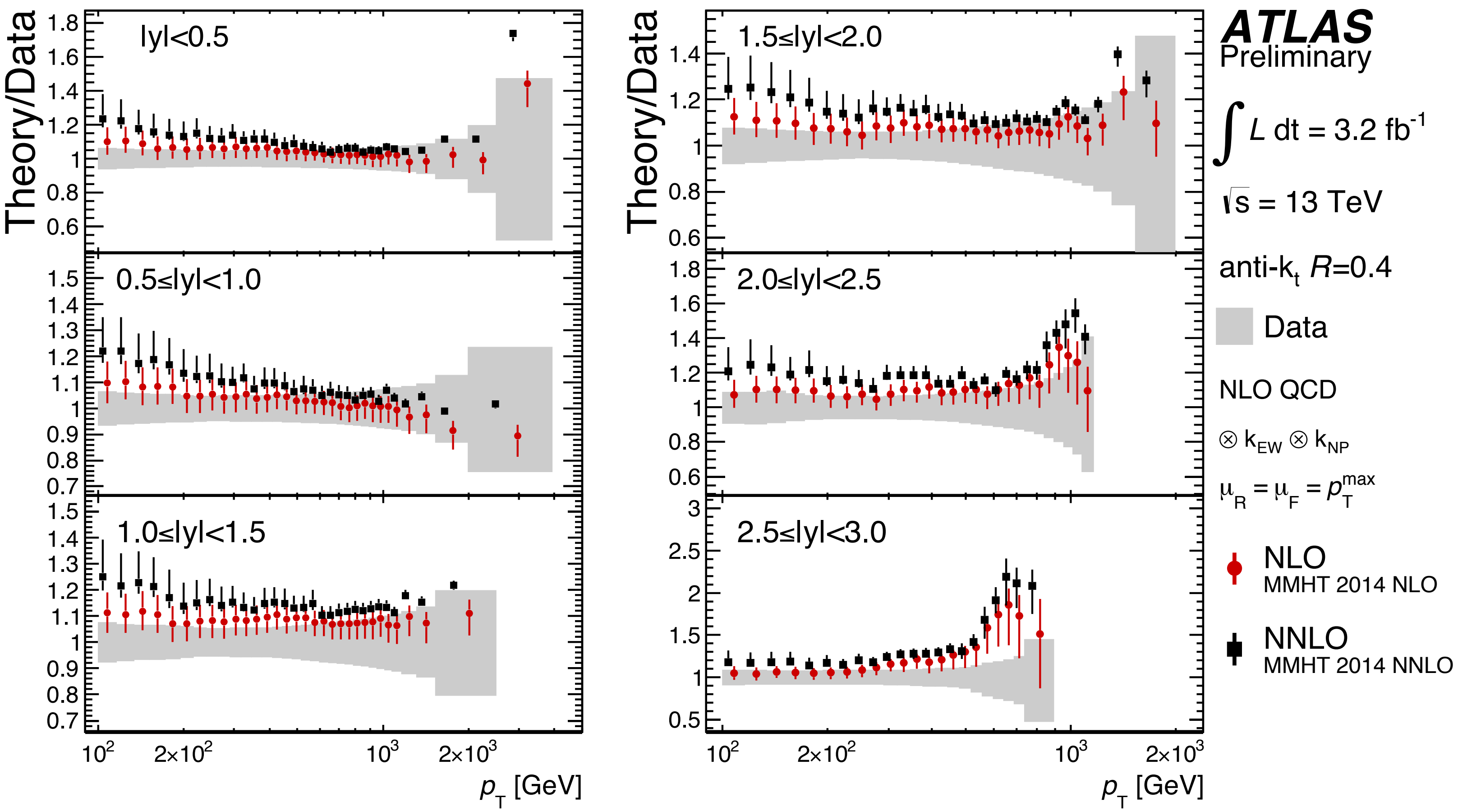
- ***arXiv: 1611.01460***;
- ***arXiv: 1704.00923***;

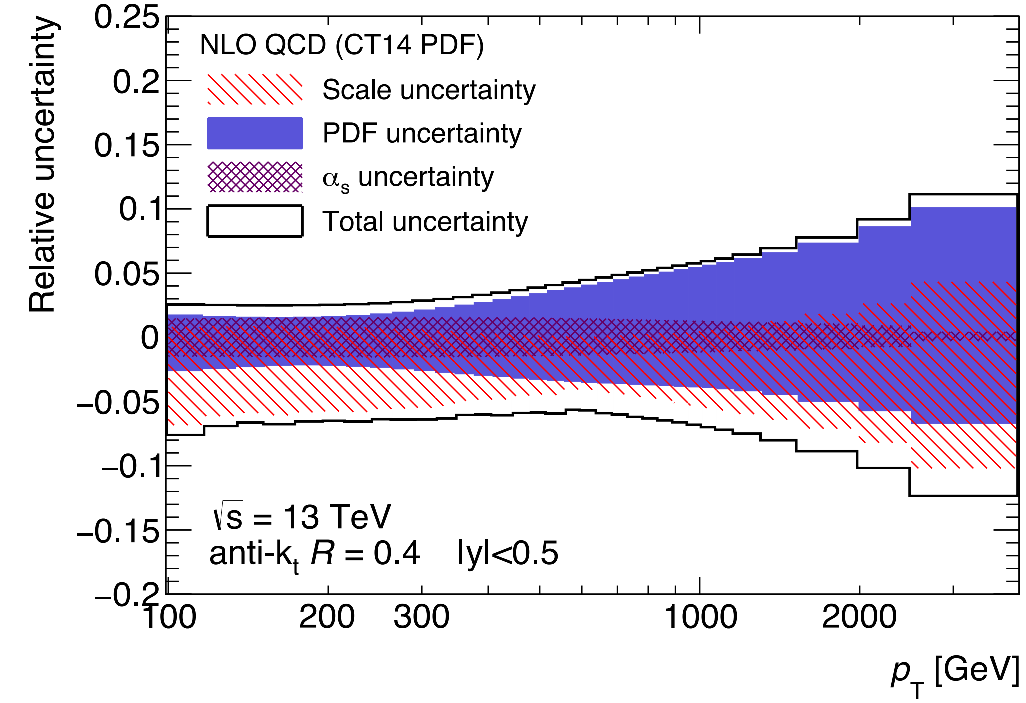
are available at 13 TeV.
No significant deviations from data are observed, except at $|y| > 2.5$.

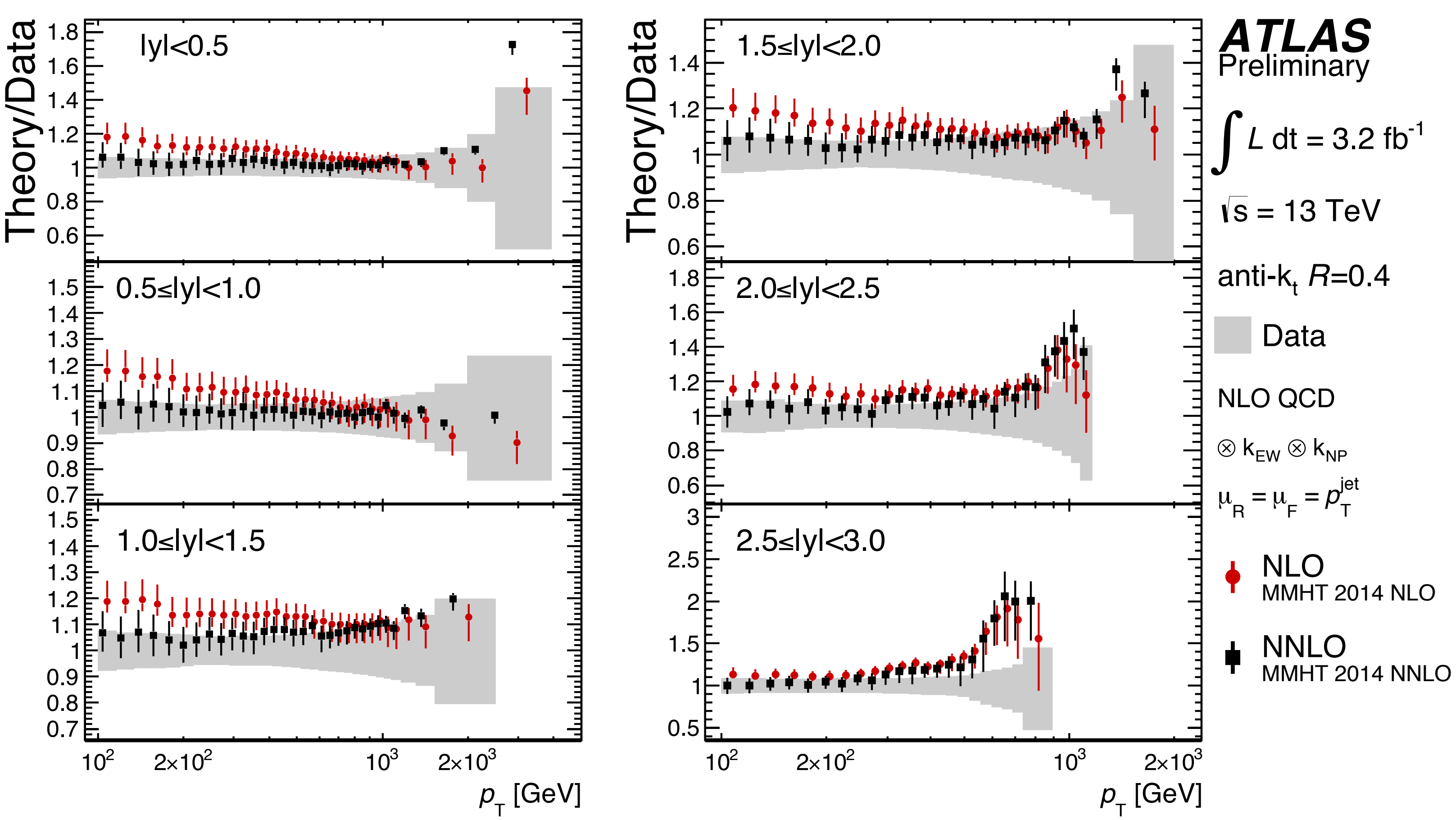


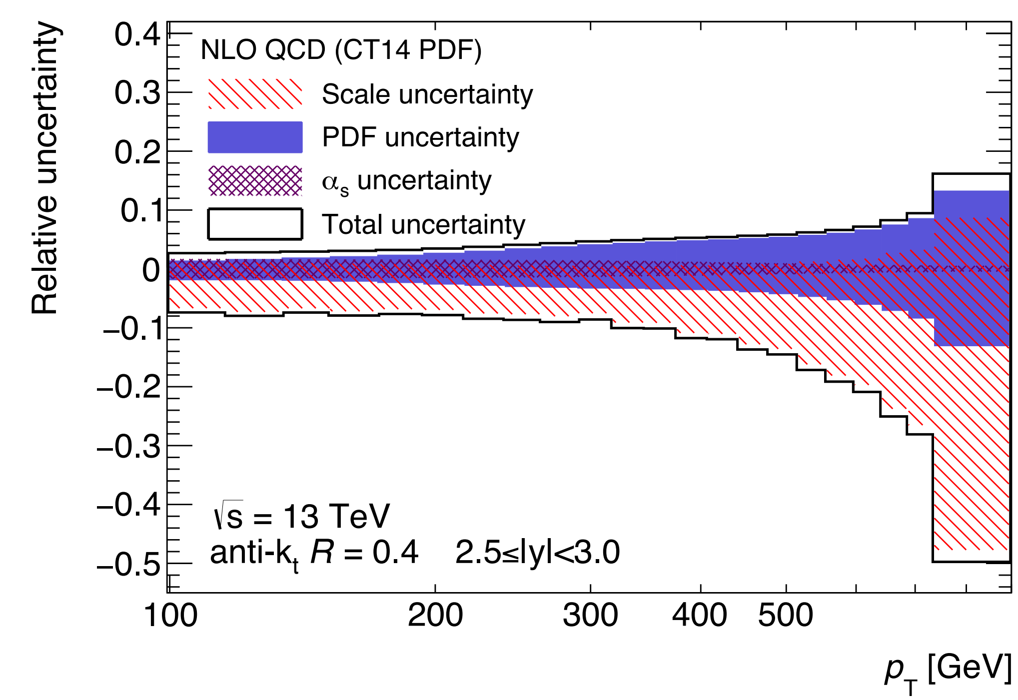
Inclusive Jet production

The differences between the two predictions are in agreement within the scale uncertainties.







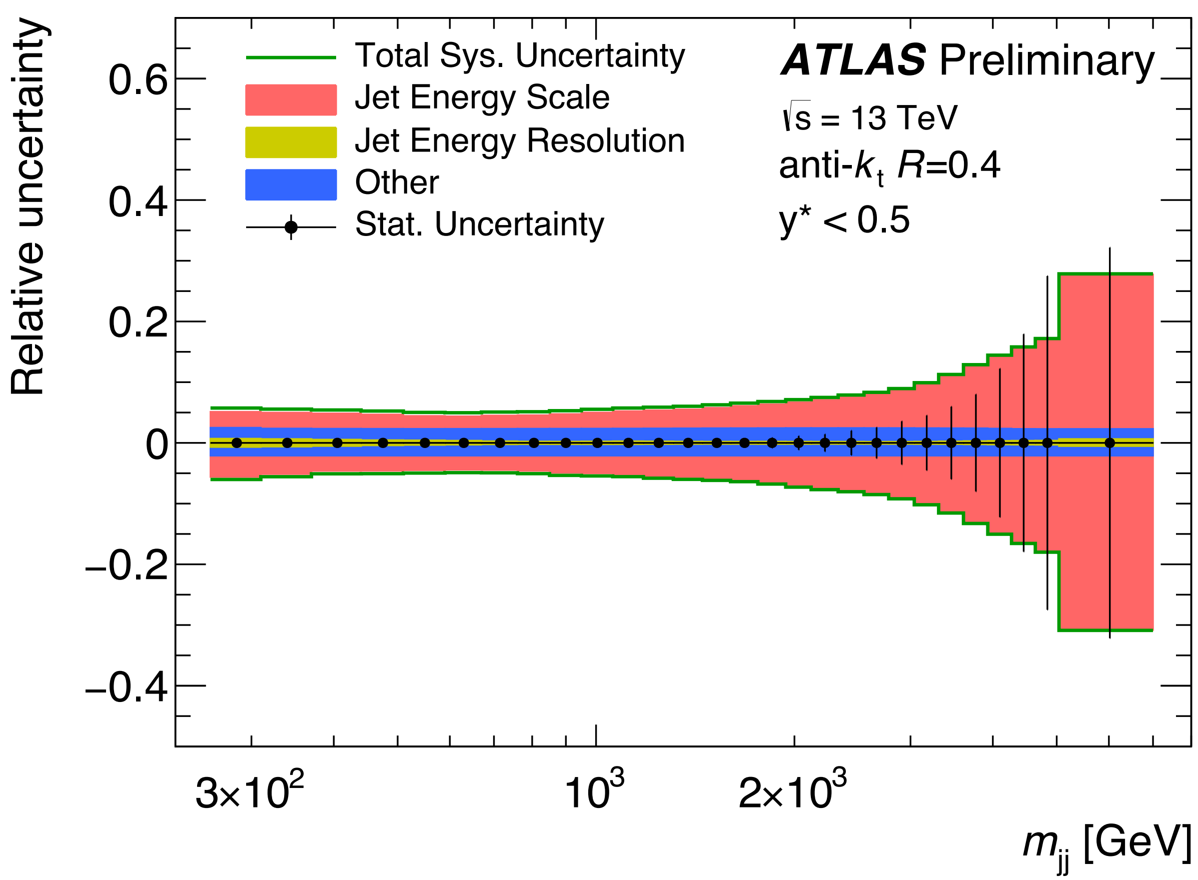


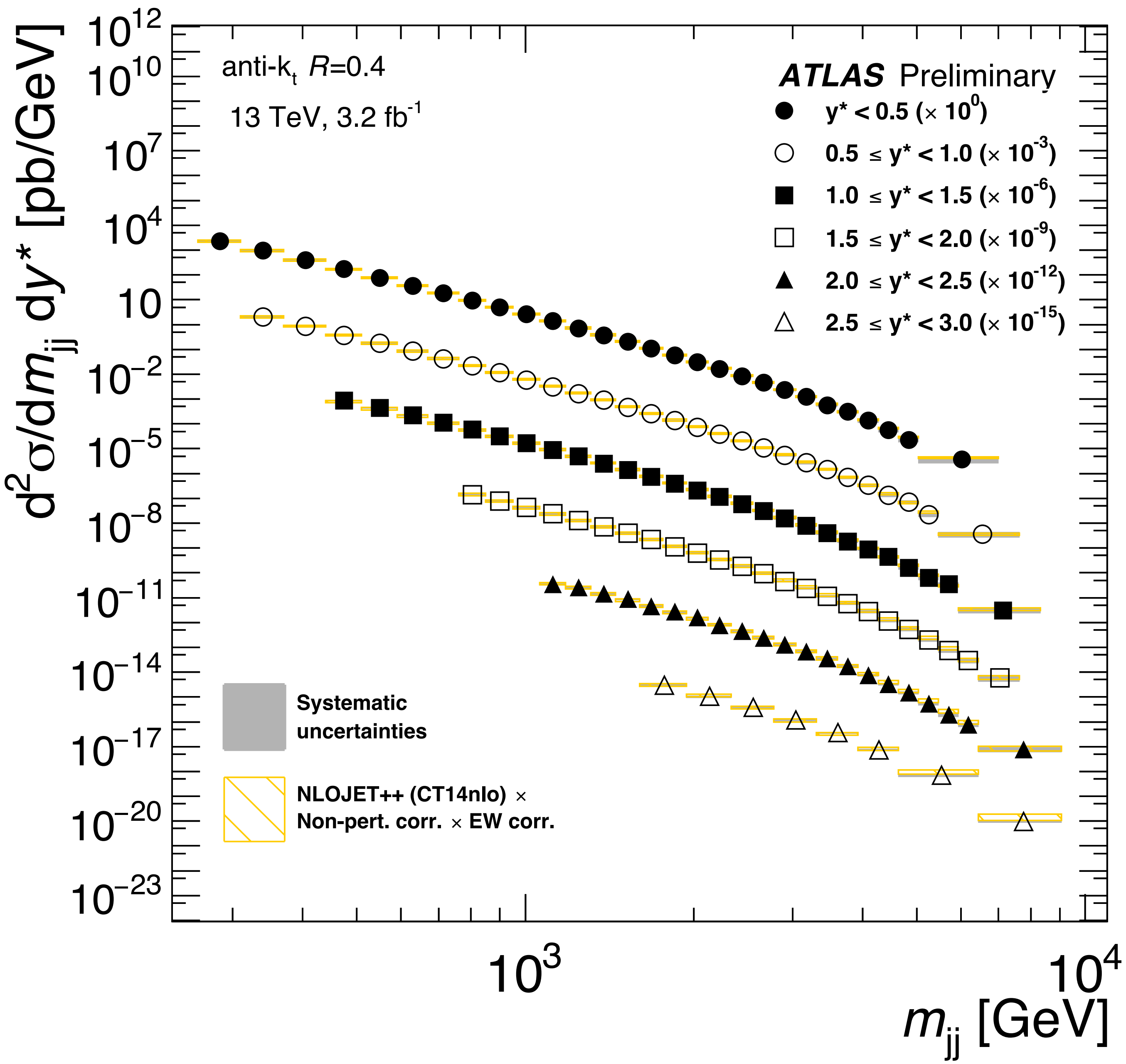
Di-Jet production at 13 TeV

- At least two jets with $P_T > 75$ GeV, within the interval $|y| < 3$;
- $H_{T,2} = P_{T1} + P_{T2}$ has to be higher than 200 GeV;

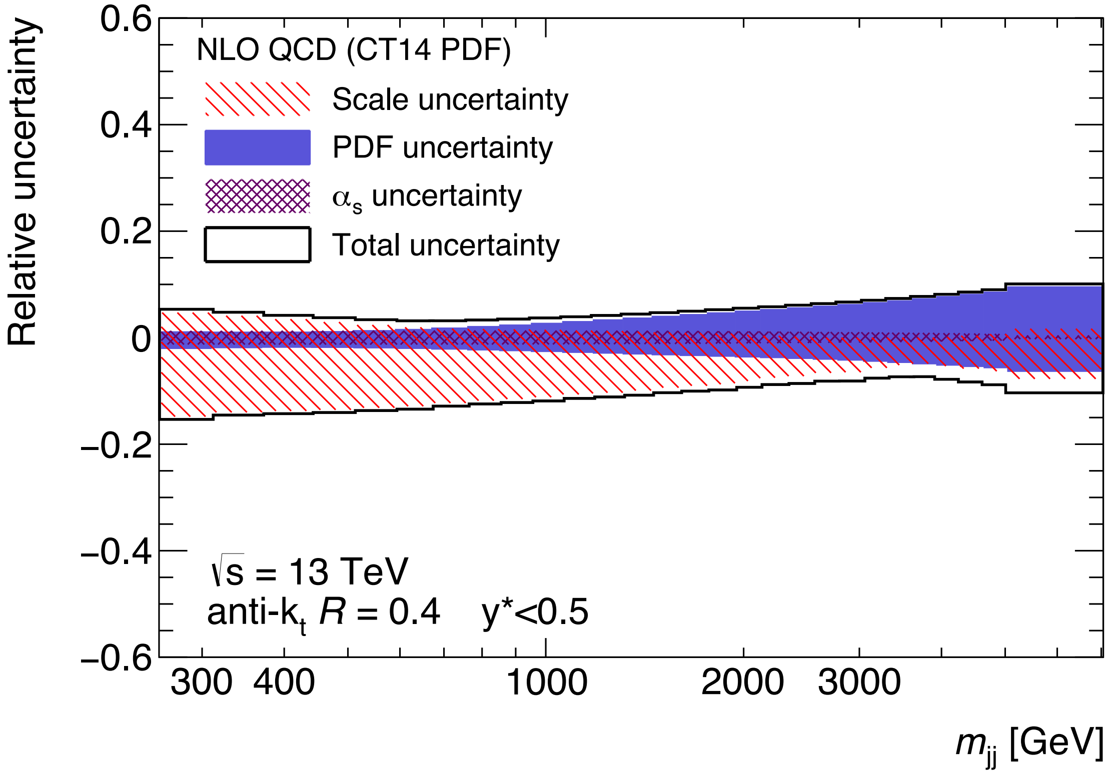
Double differential cross section is measured as a function of the invariant mass of the di-jet system, m_{jj}, in $y^* = |y_1 - y_2|/2$ bins.

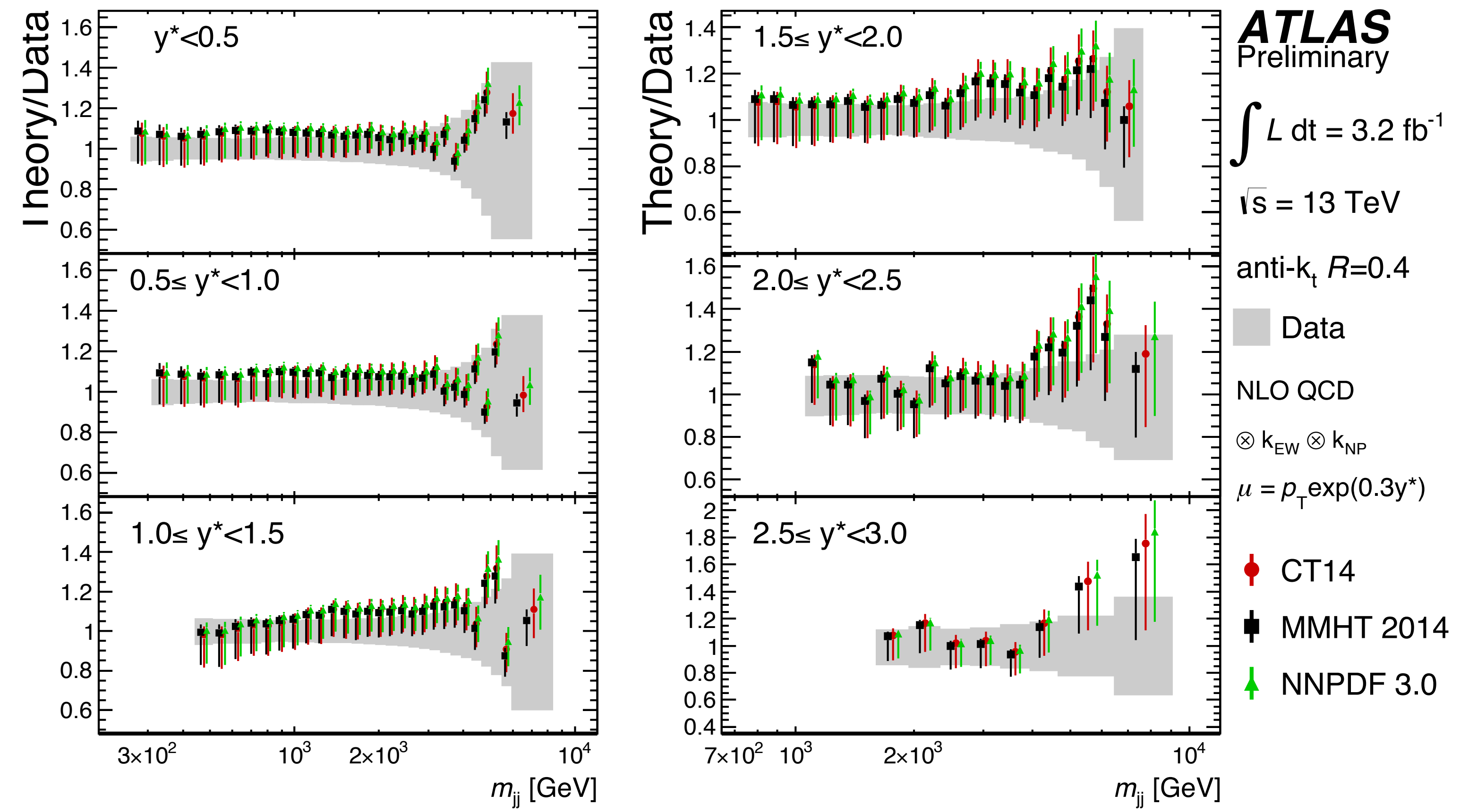
Experimental uncertainties around 5% until 1 TeV, then they rise to 30% at high m_{jj}.



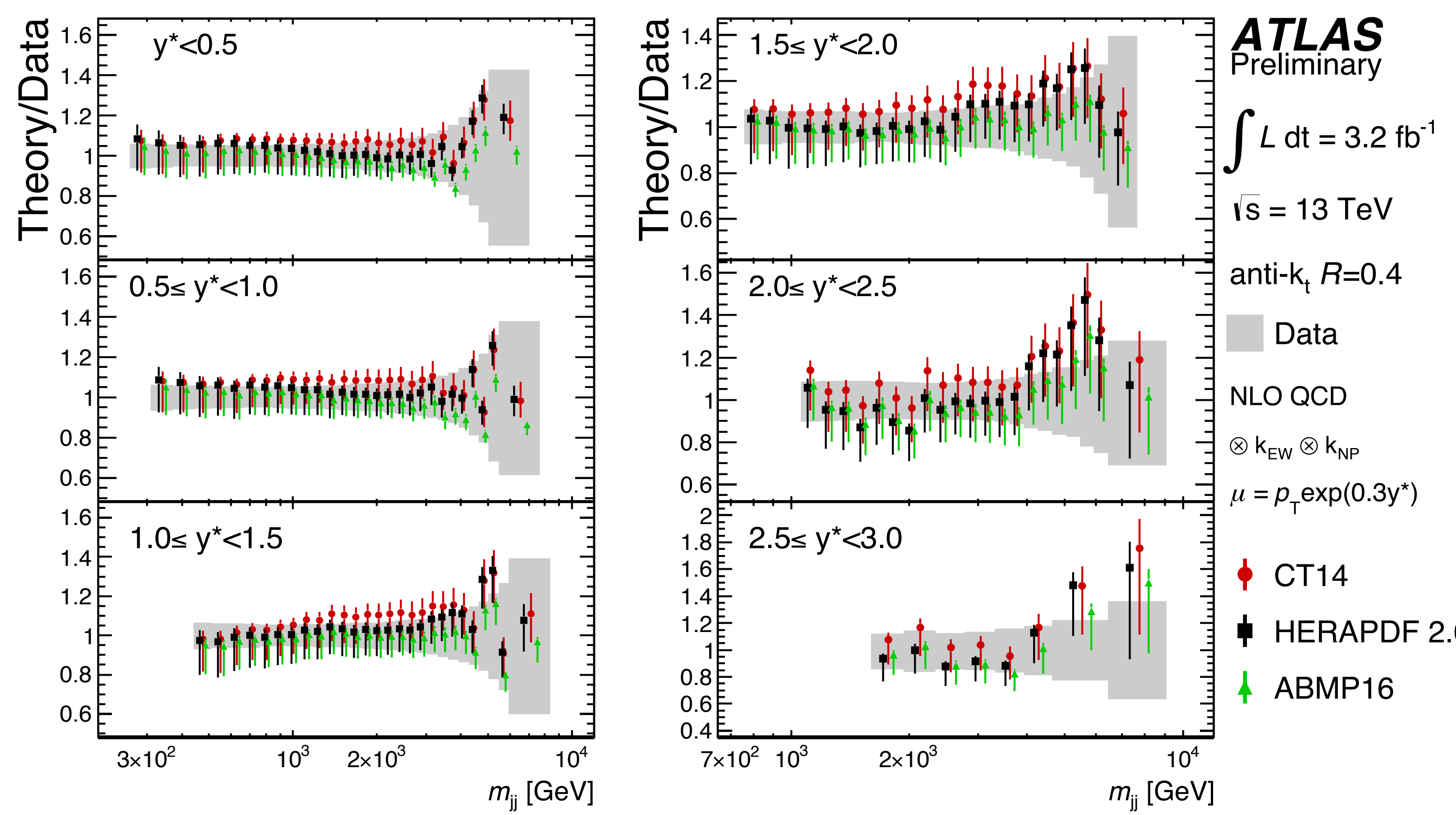


Di-Jet production at 13 TeV





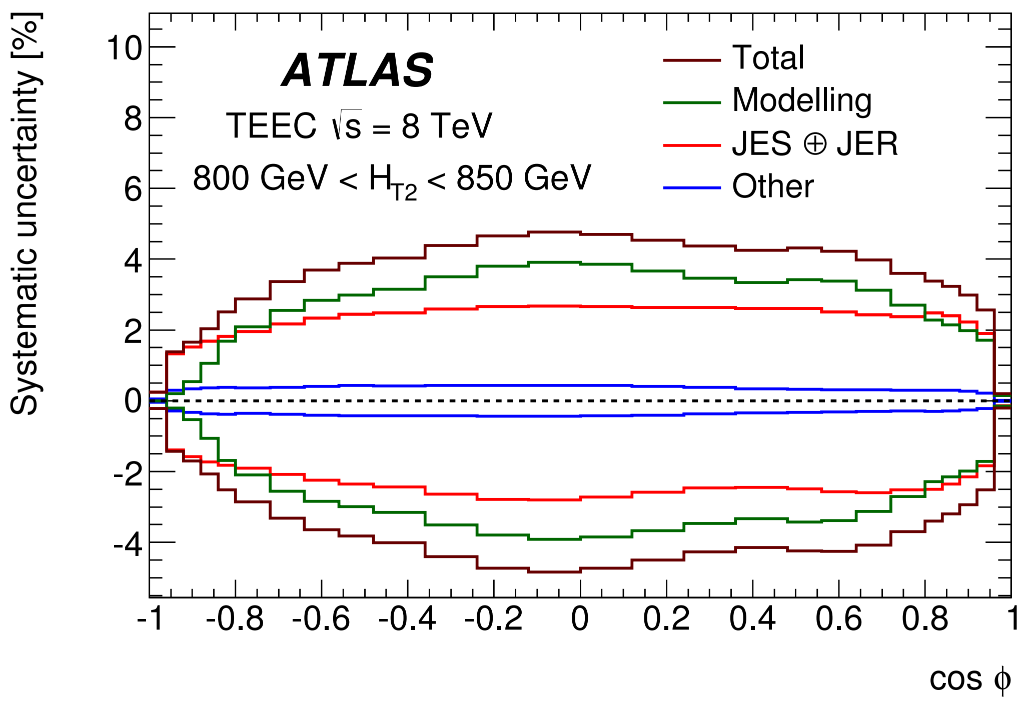
Fair agreement between data and NLO QCD predictions within the experimental uncertainties.



χ^2 tests made for each PDF set in individual m_{jj} and y^* bins and when fitting to all y^* regions (see backup). Good agreement between NLO QCD and data.

TEEC and ATEEC measurement

Transverse Energy-Energy Correlation defined as the energy-weighted angular distribution of hadron pairs. Event shape independent from the thrust axis and the sphericity tensor.

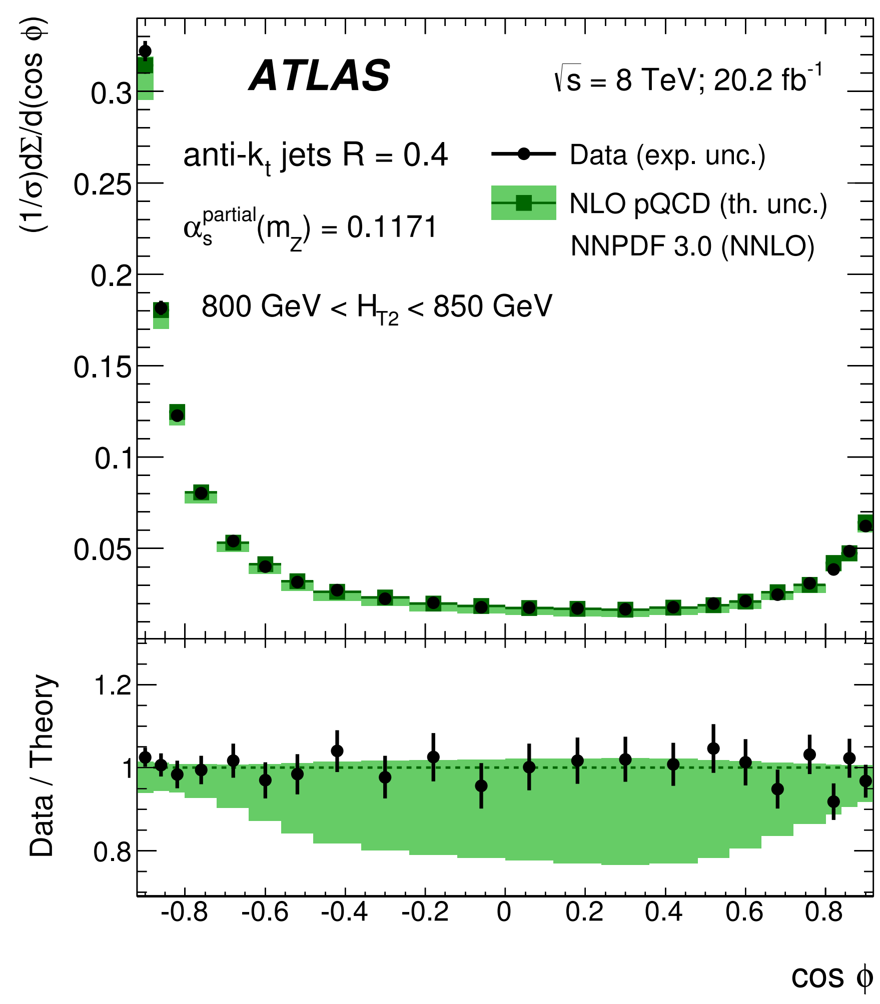


$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{T_i}\,dx_{T_j}\,d\cos\phi} x_{T_i} x_{T_j} dx_{T_i} dx_{T_j}$$

where $x_{T_i} = E_{T_i} / \sum_k E_{T_k}$

Its associated asymmetry ATEEC is defined as the difference between the forward and the backward part of the TEEC:

$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} \equiv \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$



Results obtained at 8 TeV:

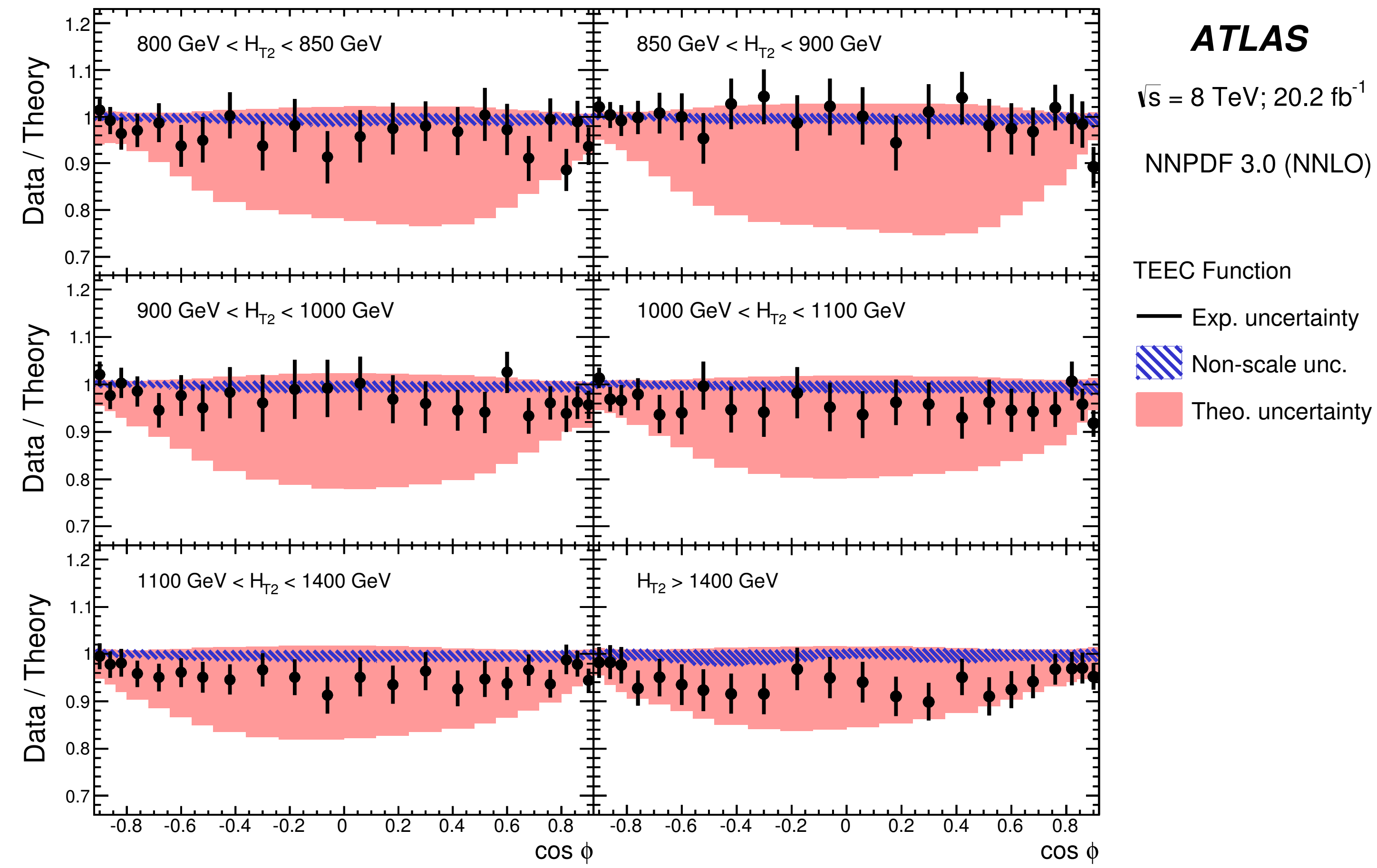
- Require two jets with $P_T > 100$ GeV with $|y| < 2.5$.
- Require $H_{T_2} = P_{T_1} + P_{T_2} > 800$ GeV;

Double differential distributions in H_{T_2} and $\cos\phi$.

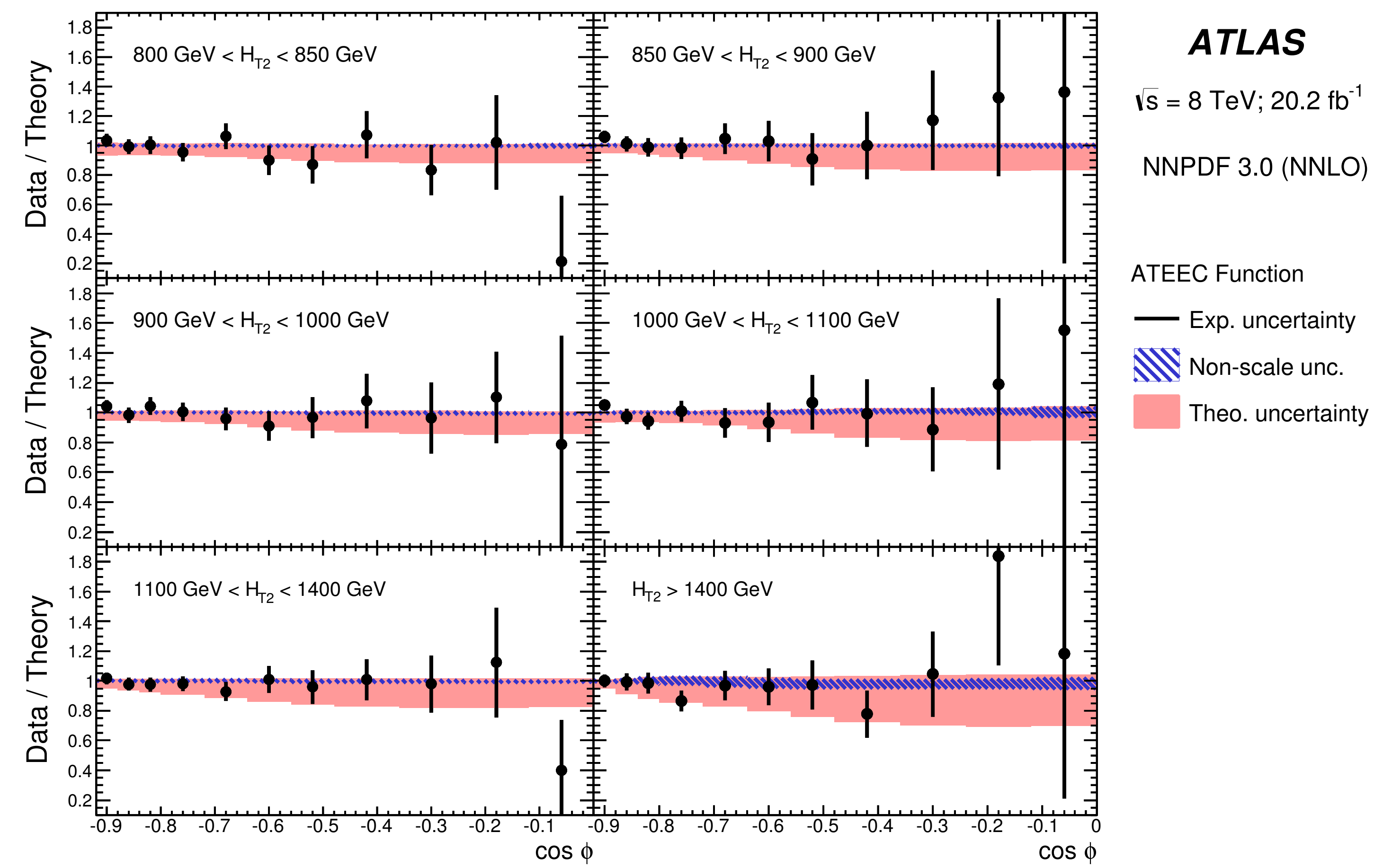
The distributions are unfolded at particle level and then compared to pQCD predictions of NLOJET++ corrected for non-perturbative effects.

TEEC and ATEEC measurement

The theoretical uncertainty due to the choice of the scale, results to be the dominant one in this measurement (~20% in the central region of the TEEC distributions).

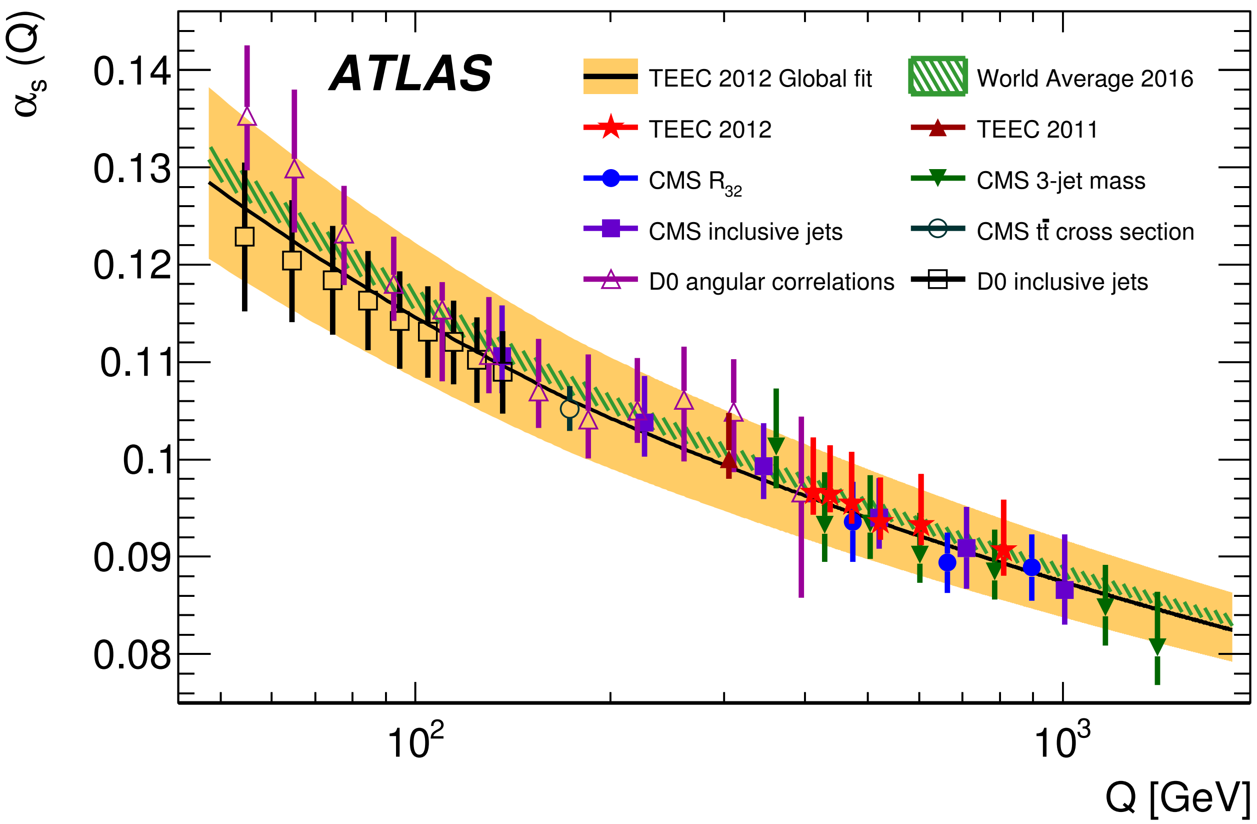


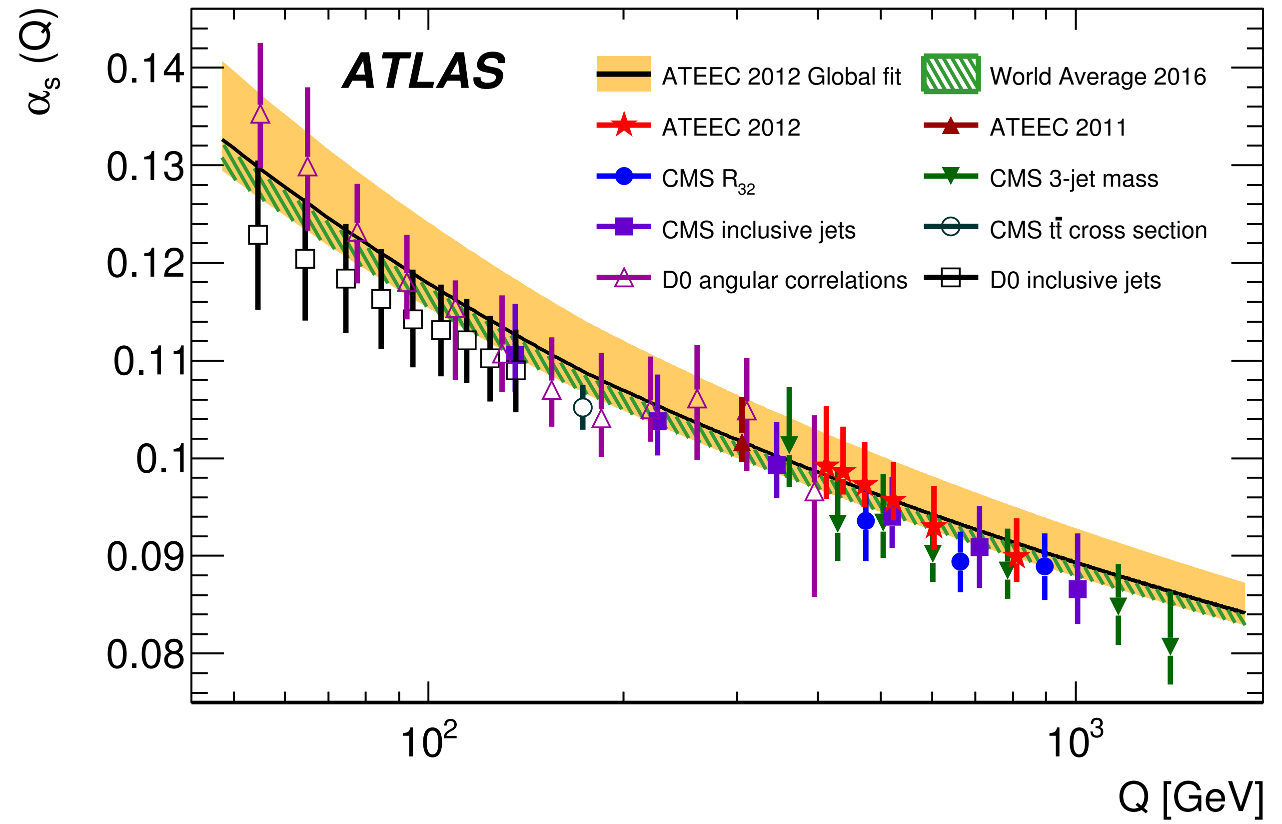
The theoretical predictions of NLOJET++ are in good agreement with the data within the theoretical uncertainties for both TEEC and ATEEC.



TEEC and ATEEC measurement

TEEC and ATEEC can be fitted by the NLOJET++ predictions varying α_s.
The fits to extract $\alpha_s(M_Z)$ are repeated for each bin of H_{T_2} separately.
Each value of $\alpha_s(M_Z)$ is then evolved to the Q scale using two loop RGE.





Global TEEC fit:

$$\alpha_s(M_Z) = 0.1162 \pm 0.0011\ (\text{exp.})\ {}^{+0.0076}_{-0.0061}\ (\text{scale})\ \pm 0.0018\ (\text{PDF})\ \pm 0.0003 (NP)$$

Global ATEEC fit:

$$\alpha_s(M_Z) = 0.1196 \pm 0.0013\ (\text{exp.})\ {}^{+0.0061}_{-0.0013}\ (\text{scale})\ \pm 0.0017\ (\text{PDF})\ \pm 0.0004 (NP)$$

Photons

Inclusive photon at 13 TeV

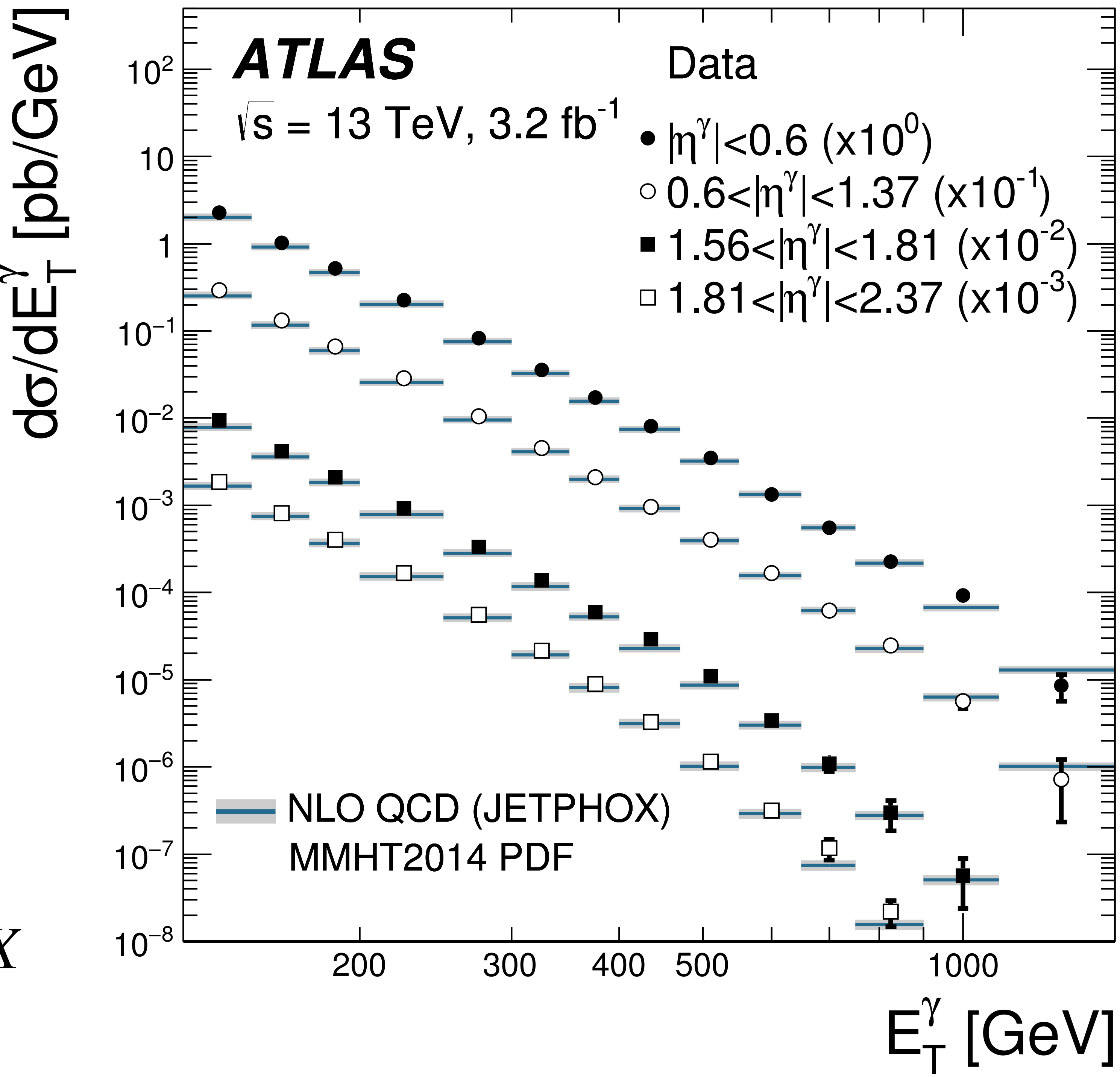
- Measurement of $d\sigma/dE_T^{\gamma}$ in four $|\eta^{\gamma}|$ bins for the range $125 < E_T^{\gamma} < 1500$ GeV.

- Photon identification and isolation cuts are applied:

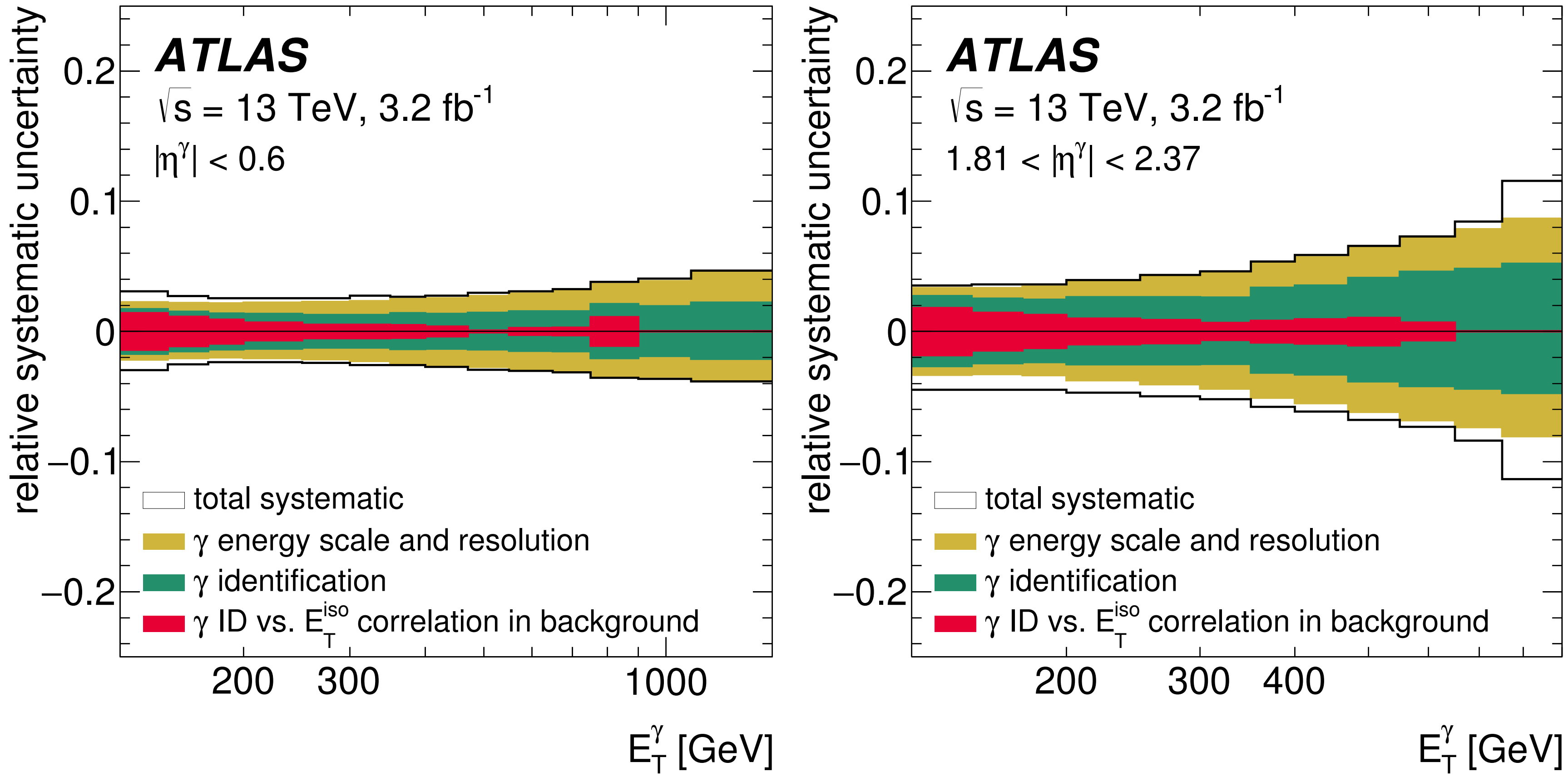
$$E_T^{iso} < 4.2 \cdot 10^{-3} \cdot E_T^{\gamma} + 4.8 \text{ GeV}$$

The background is then subtracted with a data-driven method.

The measured differential cross sections are compared with the NLO QCD predictions of *JETPHOX* using the MMHT2014 PDF set.



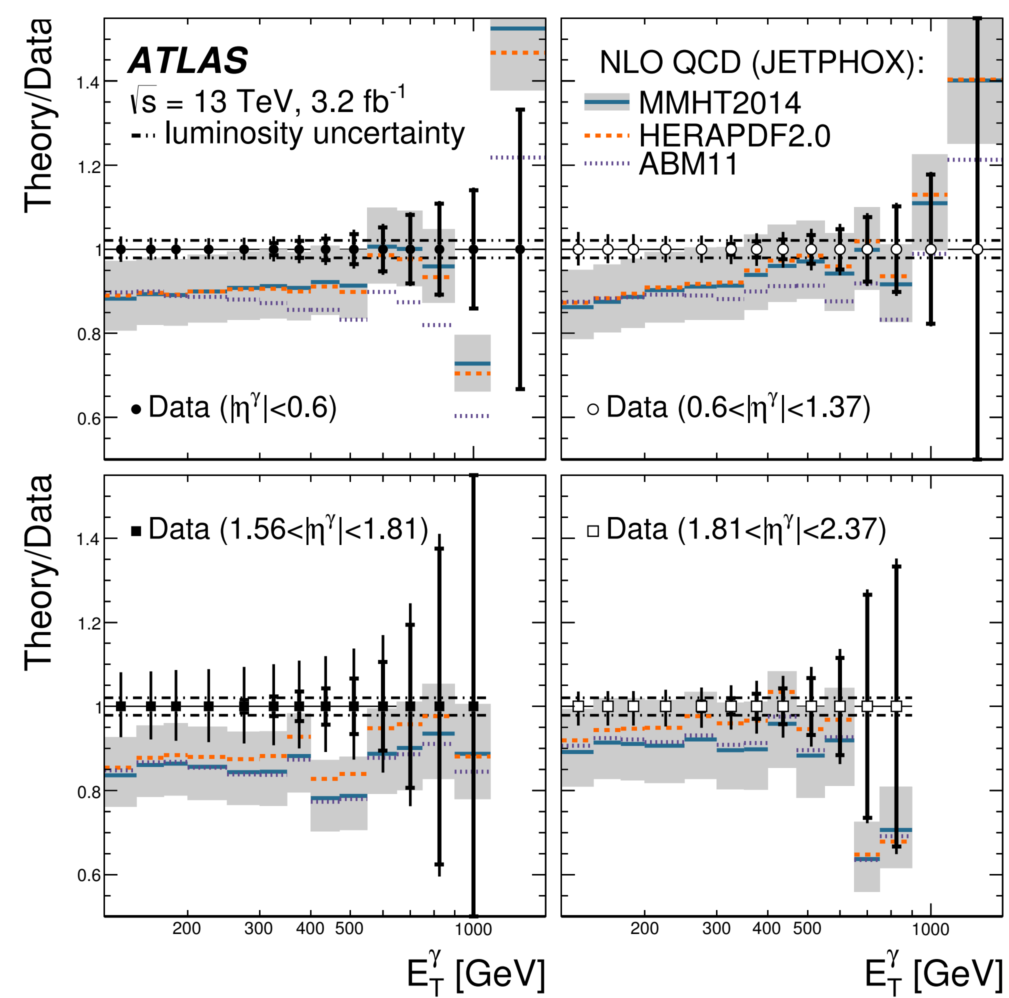
Inclusive photon at 13 TeV



The photon energy scale uncertainty dominates at high E_T^γ: 2-5% (7-18%) for $|\eta^\gamma| < 0.6$ $(1.81 < |\eta^\gamma| < 2.37)$.

The photon ID uncertainty gives a significant contribution at low E_T^γ.

- NLO QCD predictions underestimate the data: 10-15% (similar to the theoretical uncertainties);
- The theoretical uncertainties are larger than the experimental ones;
- For $E_T^\gamma \leq 600$ GeV the measurements are systematically limited;
- The NLO QCD predictions of *JETPHOX* give an adequate description of the data within the theoretical uncertainties.



Photon + Jet at 13 TeV

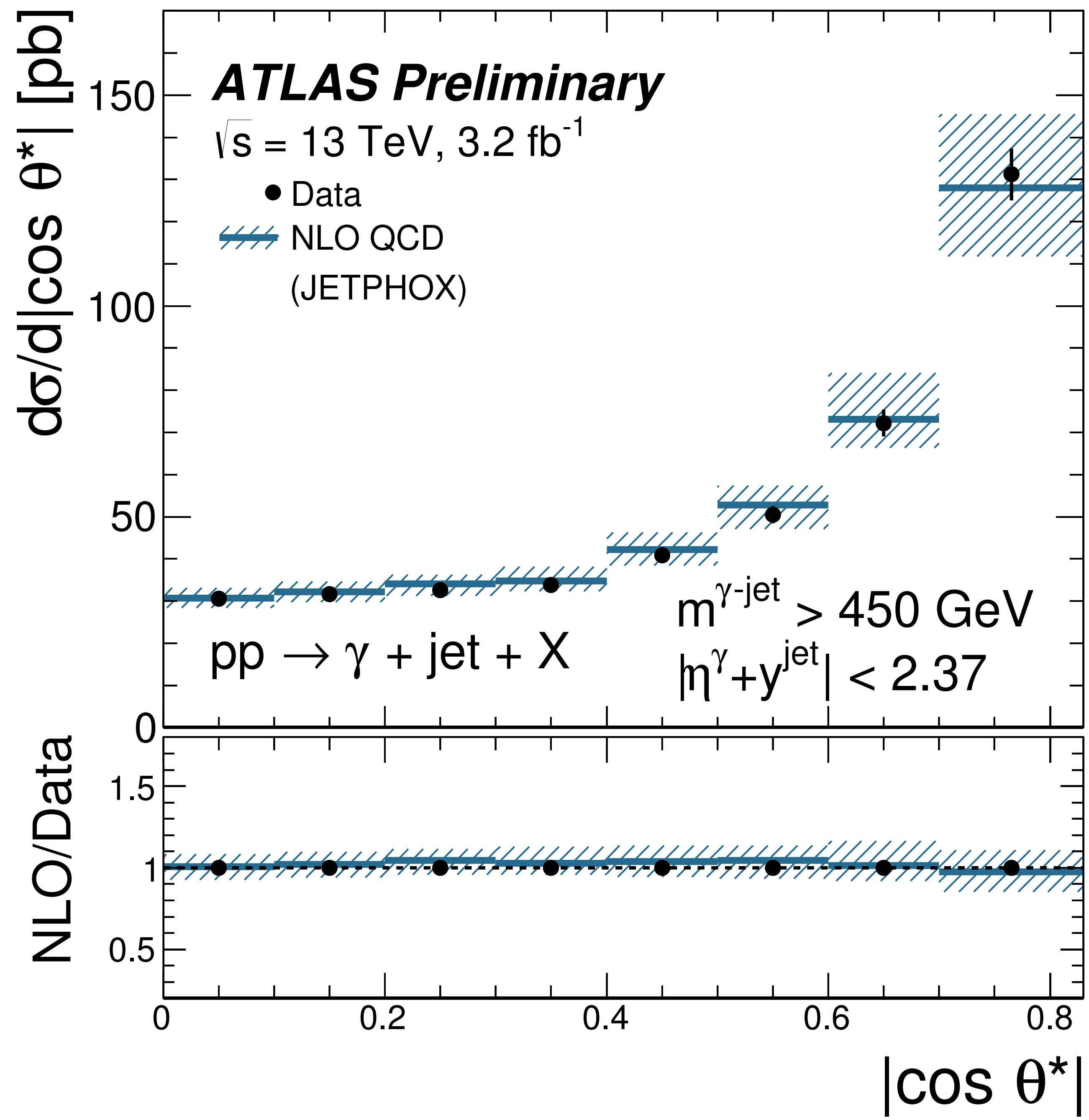
- Measurements of differential cross sections as a function of E_T^{γ}, P_T^{jet}, $\Delta\phi^{\gamma-jet}$, $m^{\gamma-jet}$ and $\cos\theta^*$ to study the γ + Jet dynamics.

$$\cos\theta^* = \tanh\ (\eta^{\gamma} - y^{jet})/2$$

where θ^* coincides with the scattering angle in the CM frame.

- Phase-space region defined by: $E_T^{\gamma} > 125$ GeV, $|\eta^{\gamma}| < 2.37$ (excluding $1.37 < |\eta^{\gamma}| < 1.56$), $P_T^{jet} > 100$ GeV, $|y^{jet}| < 2.37$ and $\Delta R^{\gamma-jet} > 0.8$.

$$E_T^{iso} < 4.2 \cdot 10^{-3} \cdot E_T^{\gamma} + 10 \text{ GeV}$$

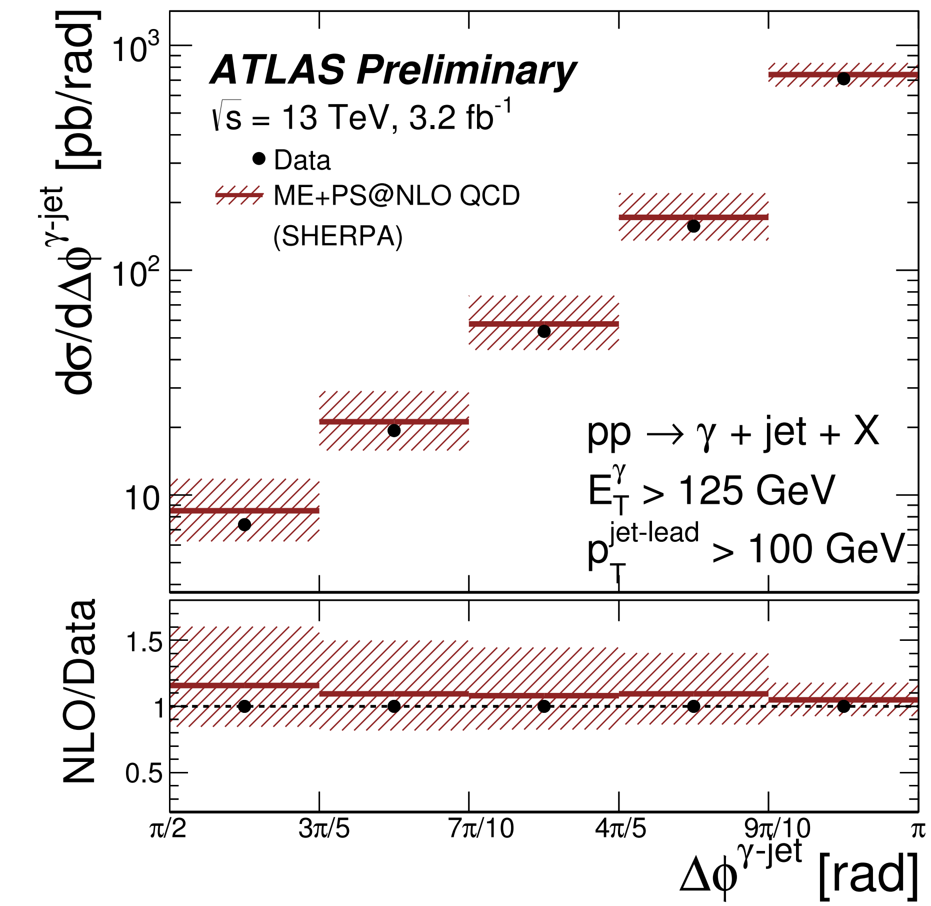


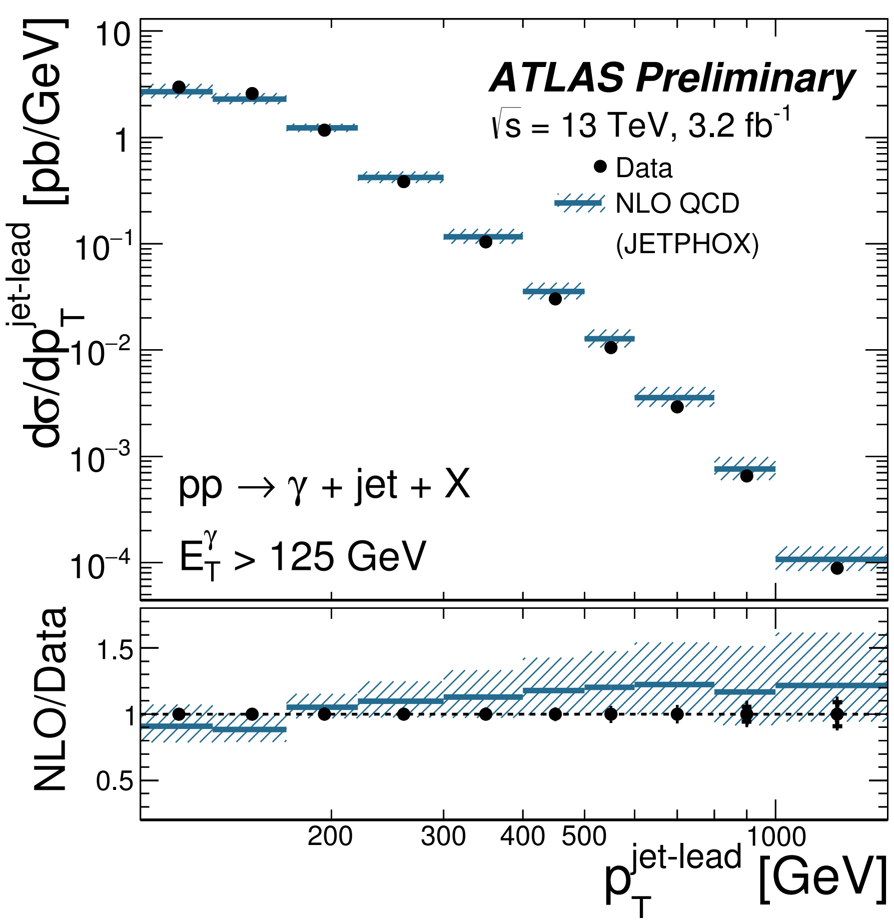
Additional cuts for $d\sigma/dm^{\gamma-jet}$ and $d\sigma/d|\cos\theta^*|$ to perform the measurement in an unbiased phase-space region :

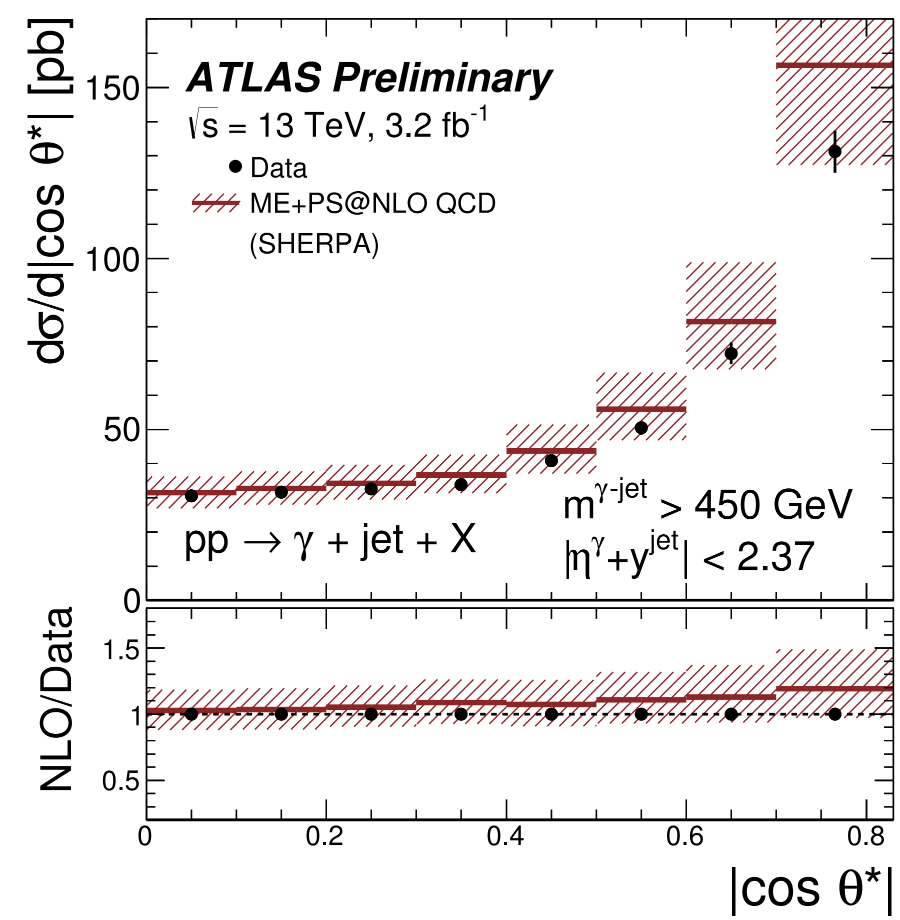
$$|\eta^{\gamma} + y^{jet}| < 2.37 \qquad |\cos\theta^*| < 0.83 \qquad m^{\gamma-jet} > 450 \text{ GeV}$$

Photon + Jet at 13 TeV

- Comparison with fixed-order NLO QCD predictions of *JETPHOX* and ME+PS@NLO SHERPA (NEW!);
- Values up to 1.5 TeV accessible for E_T^{γ} and P_T^{jet} ;
- $d\sigma / d|\cos\theta^*|$ increases as $|\cos\theta^*|$ increases in agreement with NLO expectations.
- The QCD predictions of JETPHOX and SHERPA give an adeguate description of the data within the theoretical uncertainties.

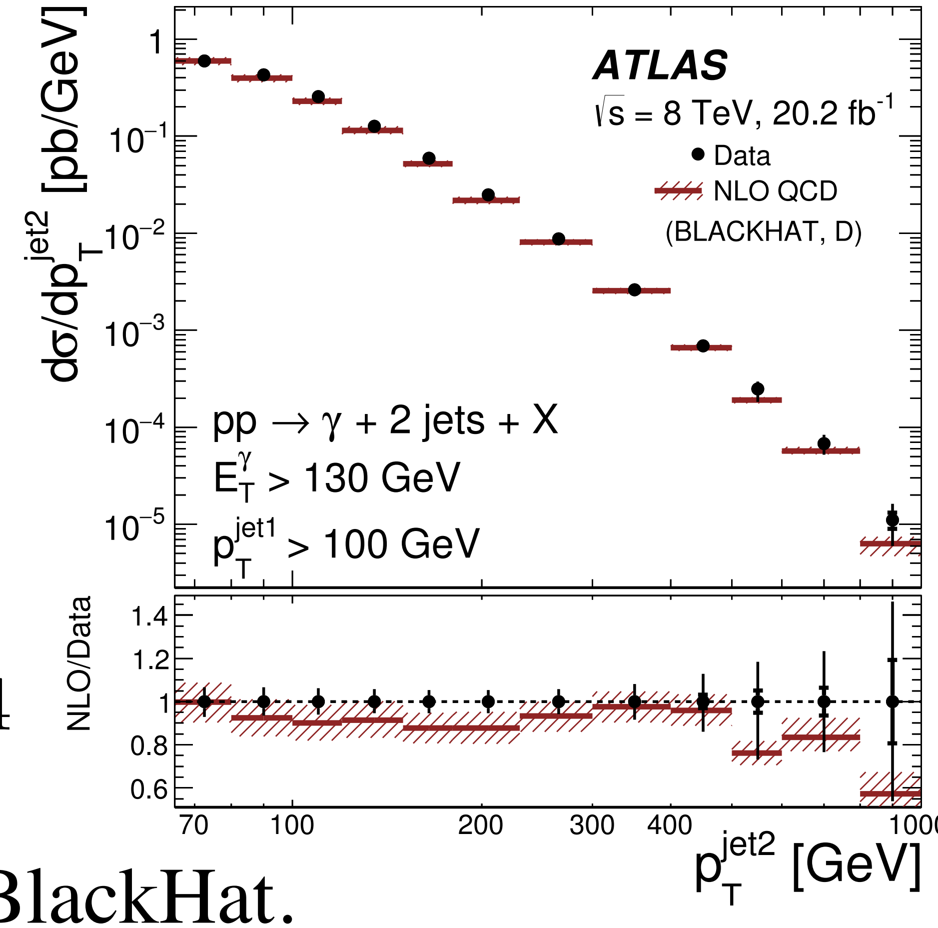






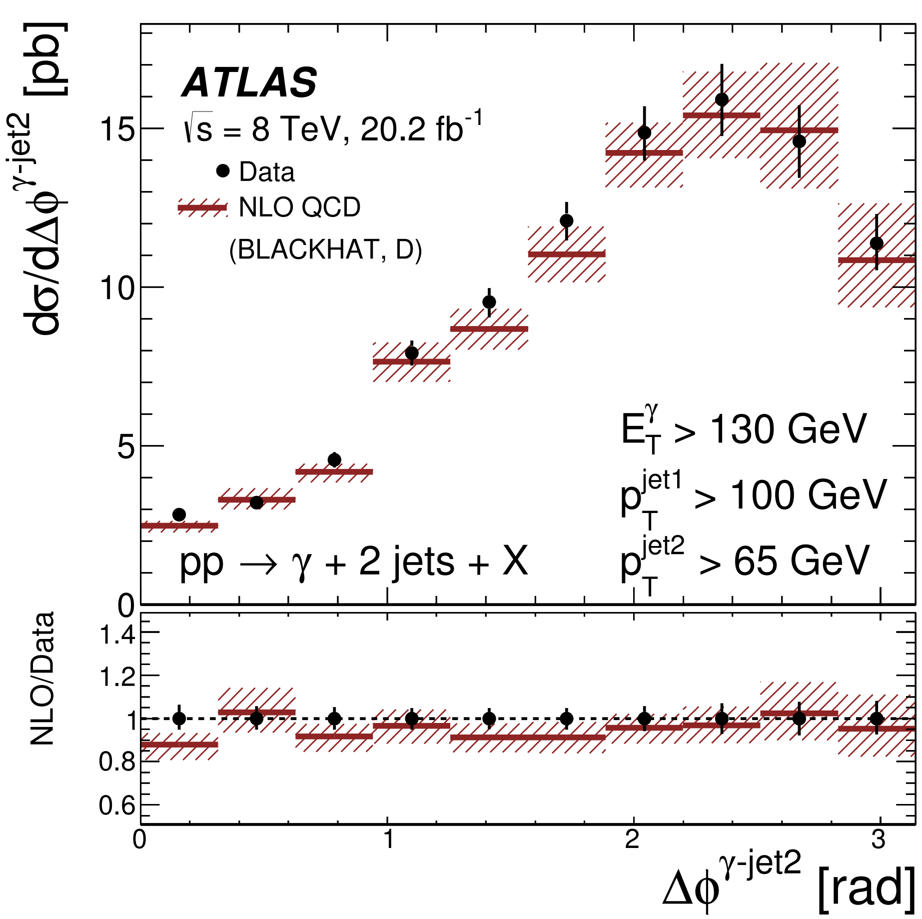
Photon + Jets at 8 TeV

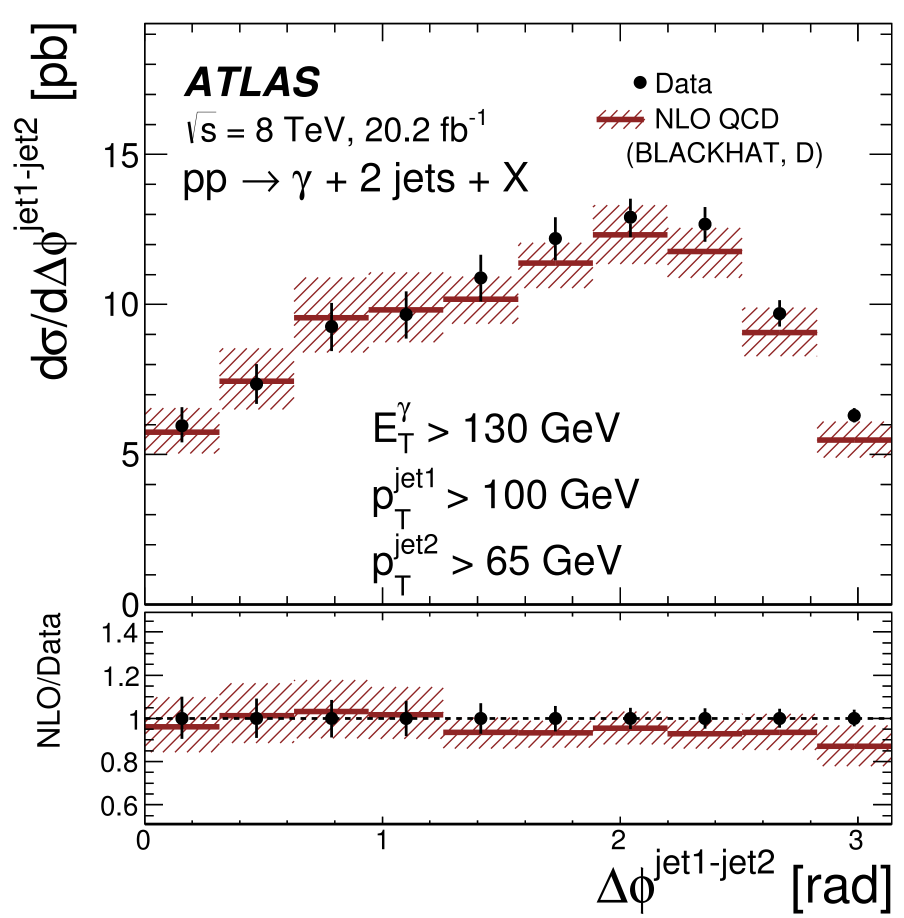
- γ + 1, 2, 3 dynamics has been studied at 8 TeV;
- Measurements of $d\sigma/dP_T^{jet1,2,3}$ and the angular correlations between the photon and the jets ($d\sigma/d\Delta\phi^{\gamma-jet2}$, $d\sigma/d\Delta\phi^{jet1-jet2}$);



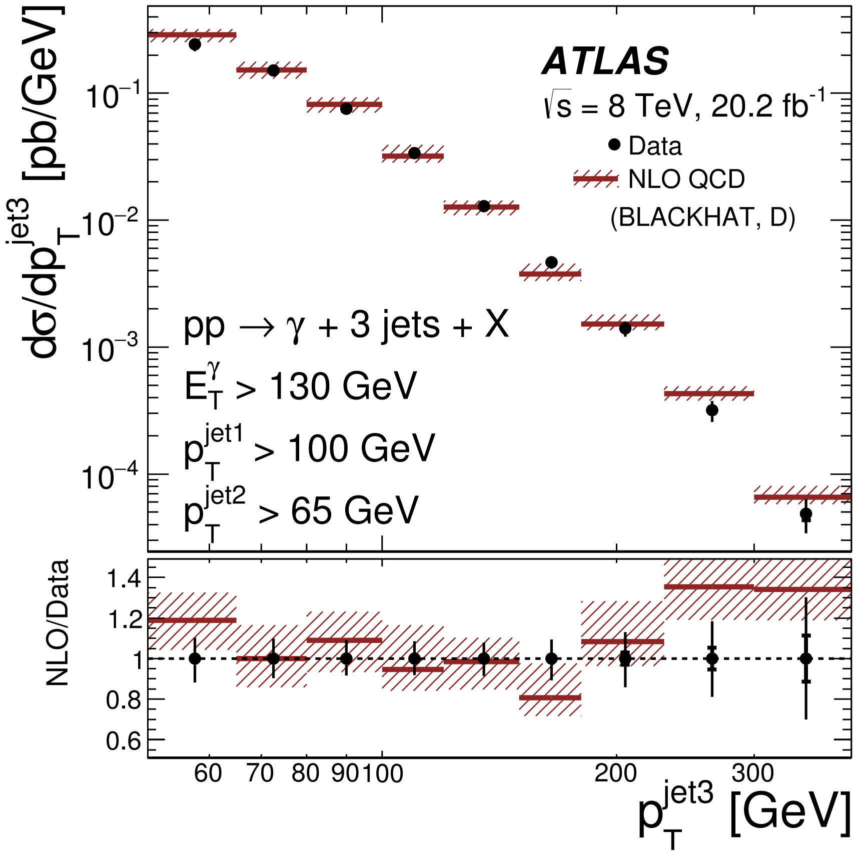
γ + 2 jets dynamics

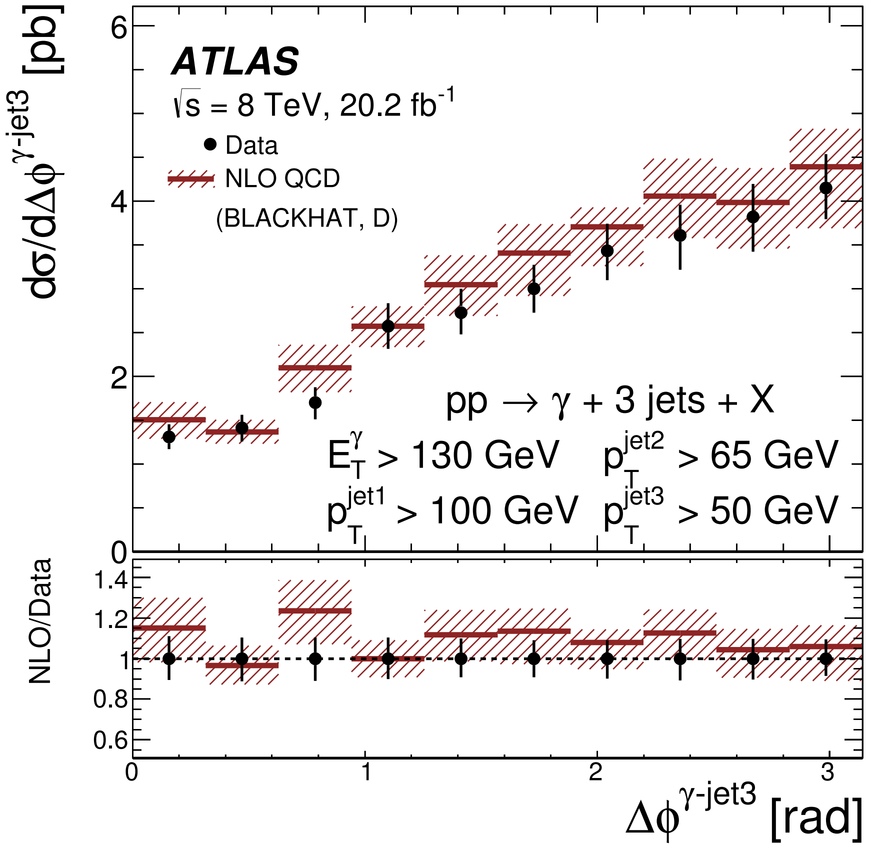
$E_T^\gamma > 130$ GeV , anti-k$_t$ jet (R=0.6) with $|y^{jet}| < 4.4$
$P_T^{jet1} > 100$ GeV and $P_T^{jet2} > 65$ GeV .
Good description of the NLO QCD predictions of BlackHat.

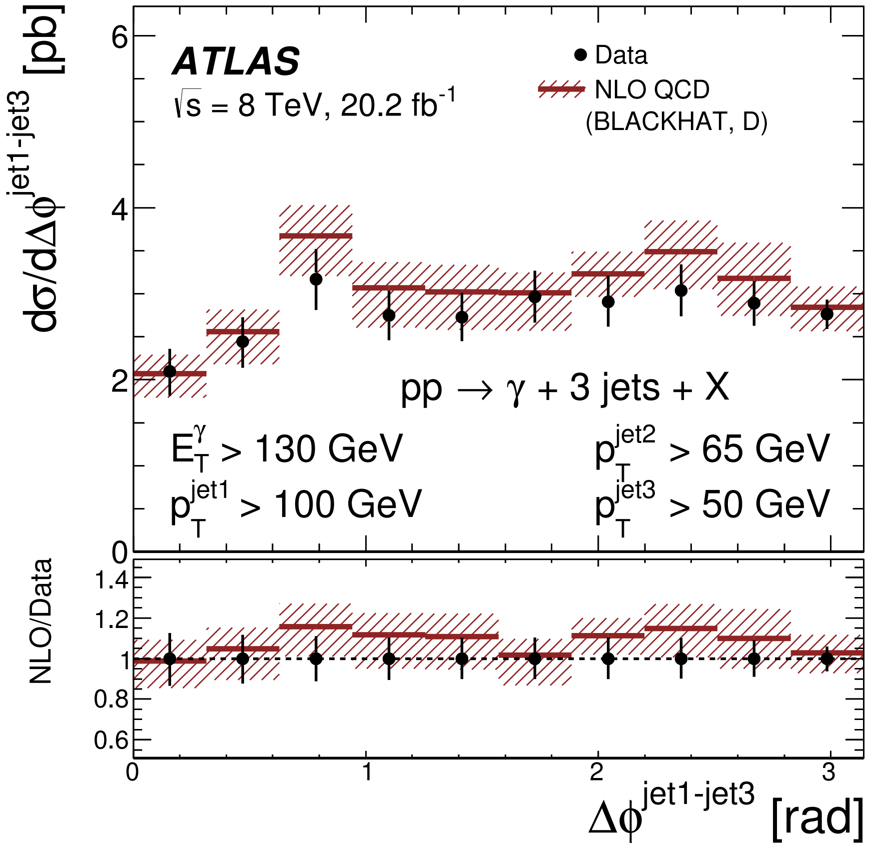


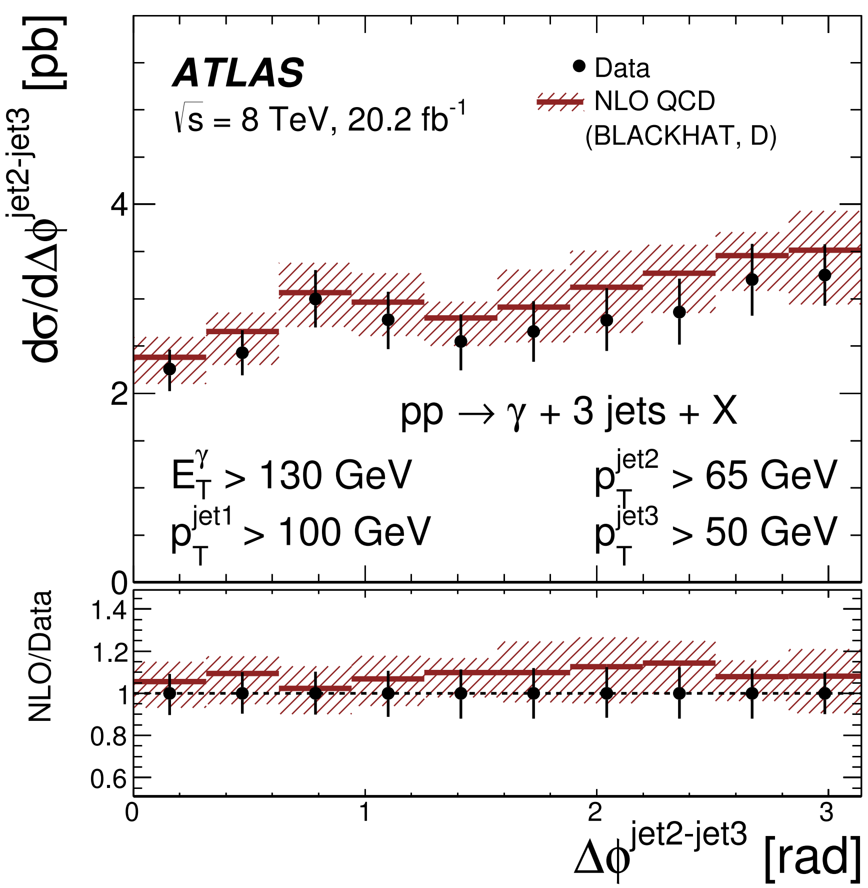


Photon + Jet at 8 TeV









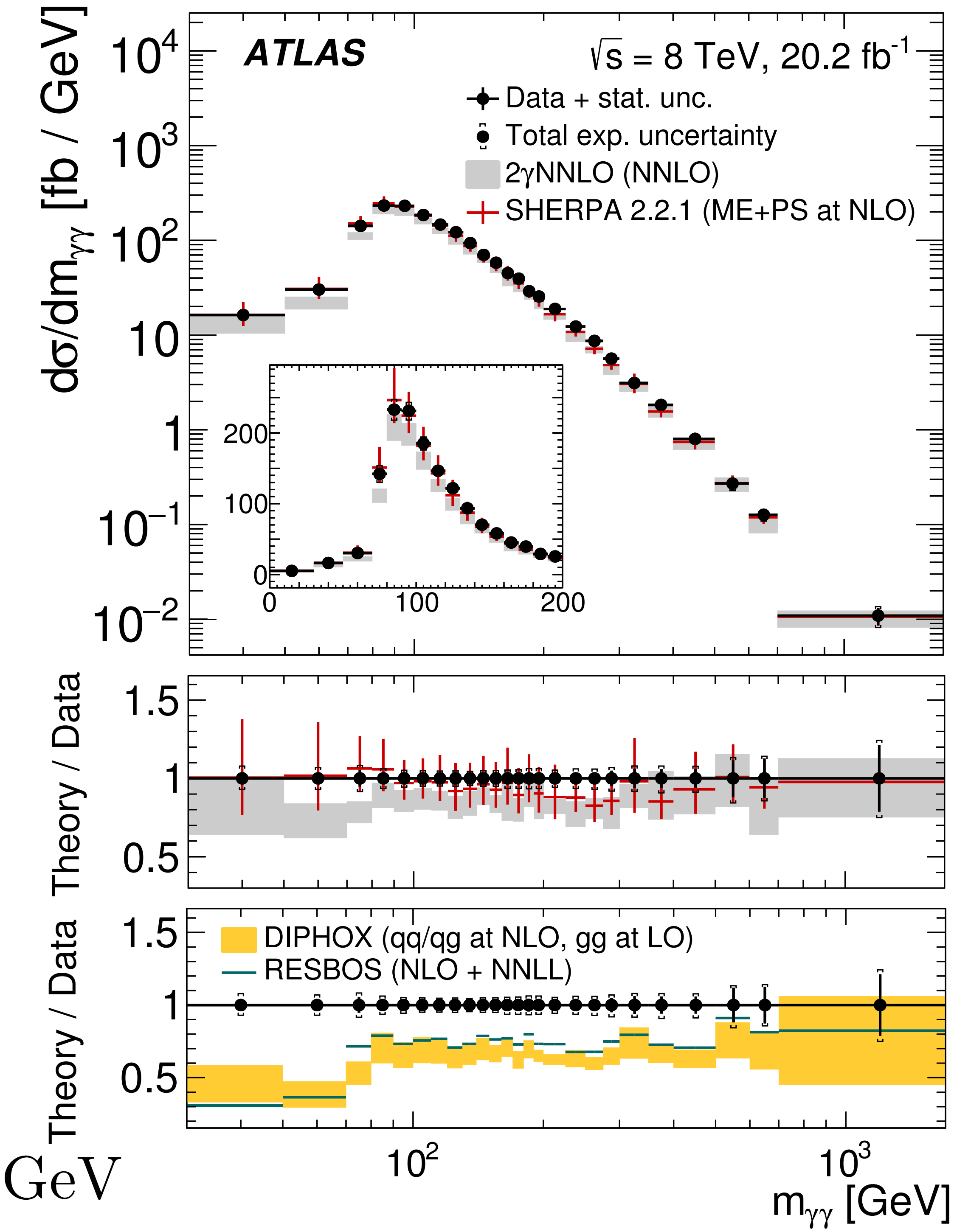
γ + 3 jets dynamics

$E_T^{\gamma} > 130$ GeV, anti-k$_t$ jet (R=0.6) with $|y^{jet}| < 4.4$
$P_T^{jet1} > 100$ GeV, $P_T^{jet2} > 65$ GeV and $P_T^{jet3} > 50$ GeV
Good description of the NLO QCD predictions of BlackHat.

Photon pair production

Study of the process $pp \to \gamma\gamma + X$ by measuring differential cross sections as functions of:

- diphoton invariant mass $m_{\gamma\gamma}$;
- diphoton transverse momentum $P_{T,\gamma\gamma}$;
- azimuthal separation between the photons $\Delta\phi_{\gamma\gamma}$;
- $\cos\theta^*_\eta$ • $\phi^*_\eta \equiv \tan(\frac{\pi - \Delta\phi_{\gamma\gamma}}{2}) \sin\theta^*_\eta$;
- transverse component of $\vec{P}_{T,\gamma\gamma}$ respect to the thrust axis a_T.

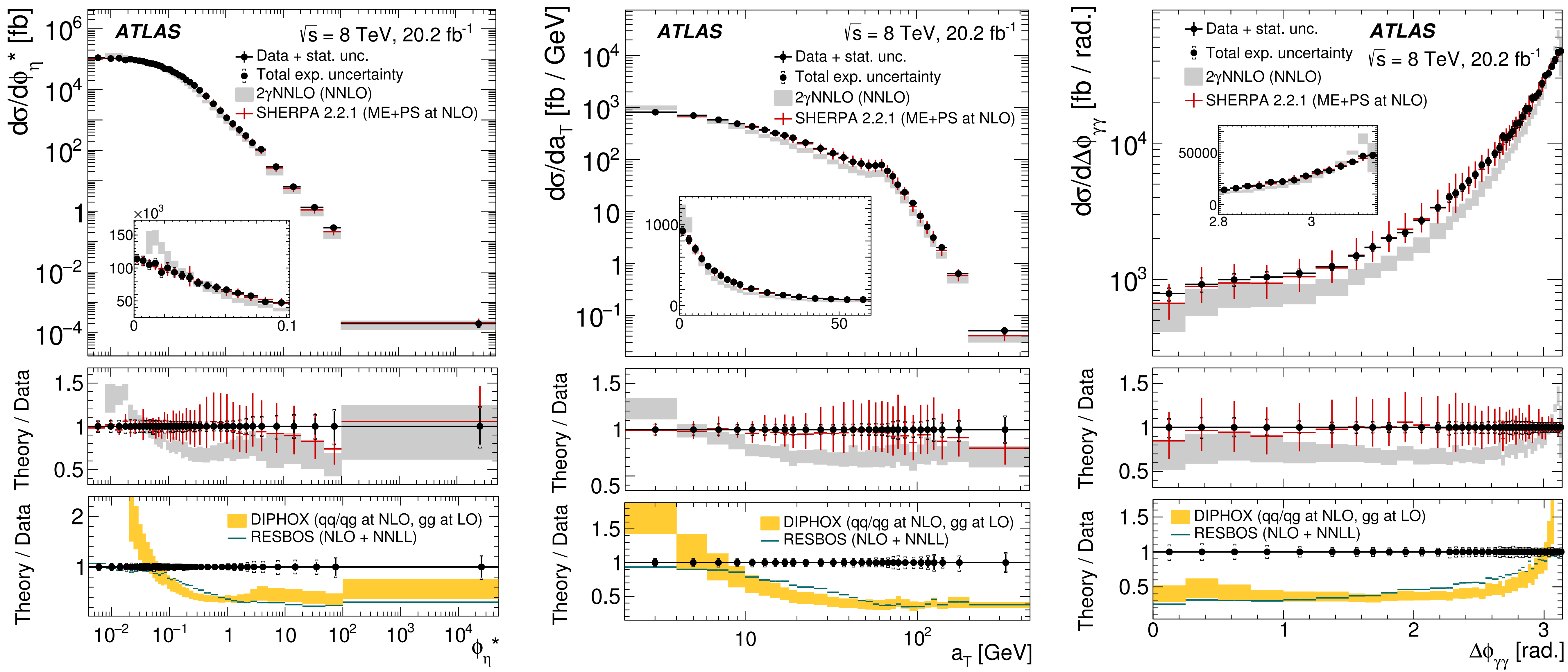


Phase-space region selected: $E_T^{\gamma(1)} > 40$ GeV, $E_T^{\gamma(2)} > 30$ GeV, $|\eta^\gamma| < 2.37$ (excluding $1.37 < |\eta^\gamma| < 1.56$), $\Delta R_{\gamma\gamma} > 0.4$ and $E_T^{iso} < 11$ GeV

Comparison with:

- Fixed-Order QCD calculations of: 2gNNLO, DIPHOX and RESBOS;
- SHERPA (v2.2.1), combining $\gamma\gamma$ and $\gamma\gamma + 1$ p at NLO, $\gamma\gamma + 2$ p and $\gamma\gamma + 3$ p at LO and parton shower.

Photon pair production



- NLO QCD calculations (DIPHOX and RESBOS) are not sufficient;
- NNLO corrections (2gNNLO) improve the description of the data, but it is still insufficient.
- Effects of the infrared emission ($\Delta\phi_{\gamma\gamma} \sim \pi$ and low values of ϕ_η^* and a_T) are well reproduced by (RESBOS and SHERPA).
- Very good agreement between data and SHERPA.

Summary and Conclusions

In all the presented results the pQCD predictions describe the data within the theoretical uncertainties.

Jets

→ The inclusive jet analysis can be used to constraint the PDFs;
→ First comparison of the measured cross sections with NNLO at 13 TeV;
→ First measurement of di-jet cross sections at 13 TeV;
→ The α_s values from the TEEC and ATEEC measurements in agreement with the world average value (PDG);

Photons

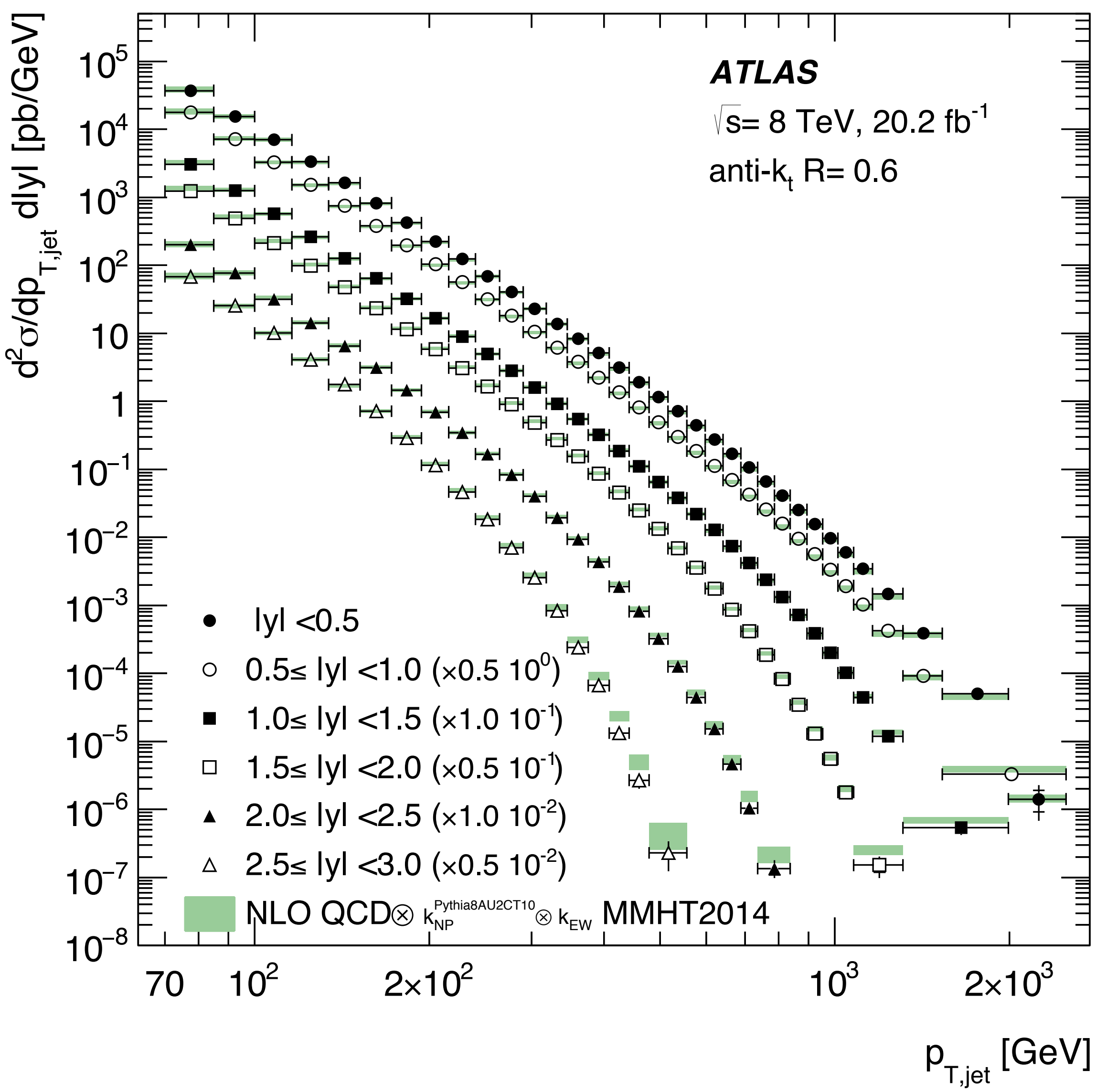
→ Theoretical uncertainties larger than the experimental ones (looking forward to compare with NNLO predictions) in the incl. photon analysis;
→ First measurement of the photon + jet production at 13 TeV;
→ γ +2 and 3 jet dynamics exploited at 8 TeV;
→ Measurements of diphoton production → study the background of $H \to \gamma\gamma$ (in pQCD);

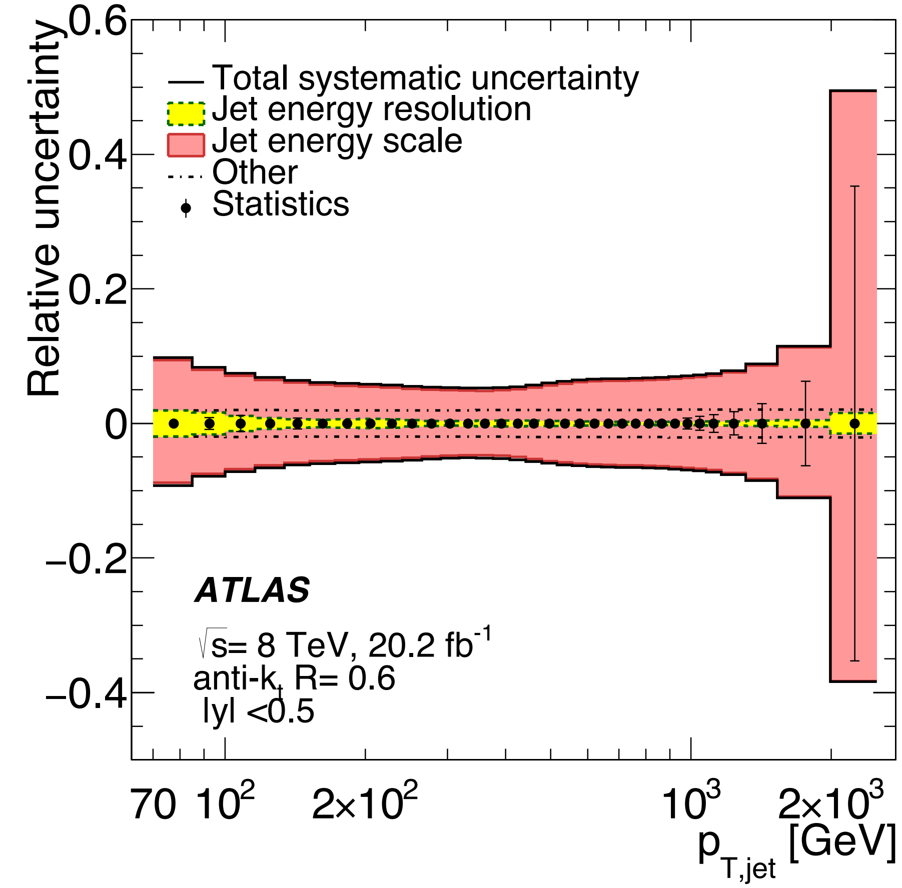
Thank you for your attention!

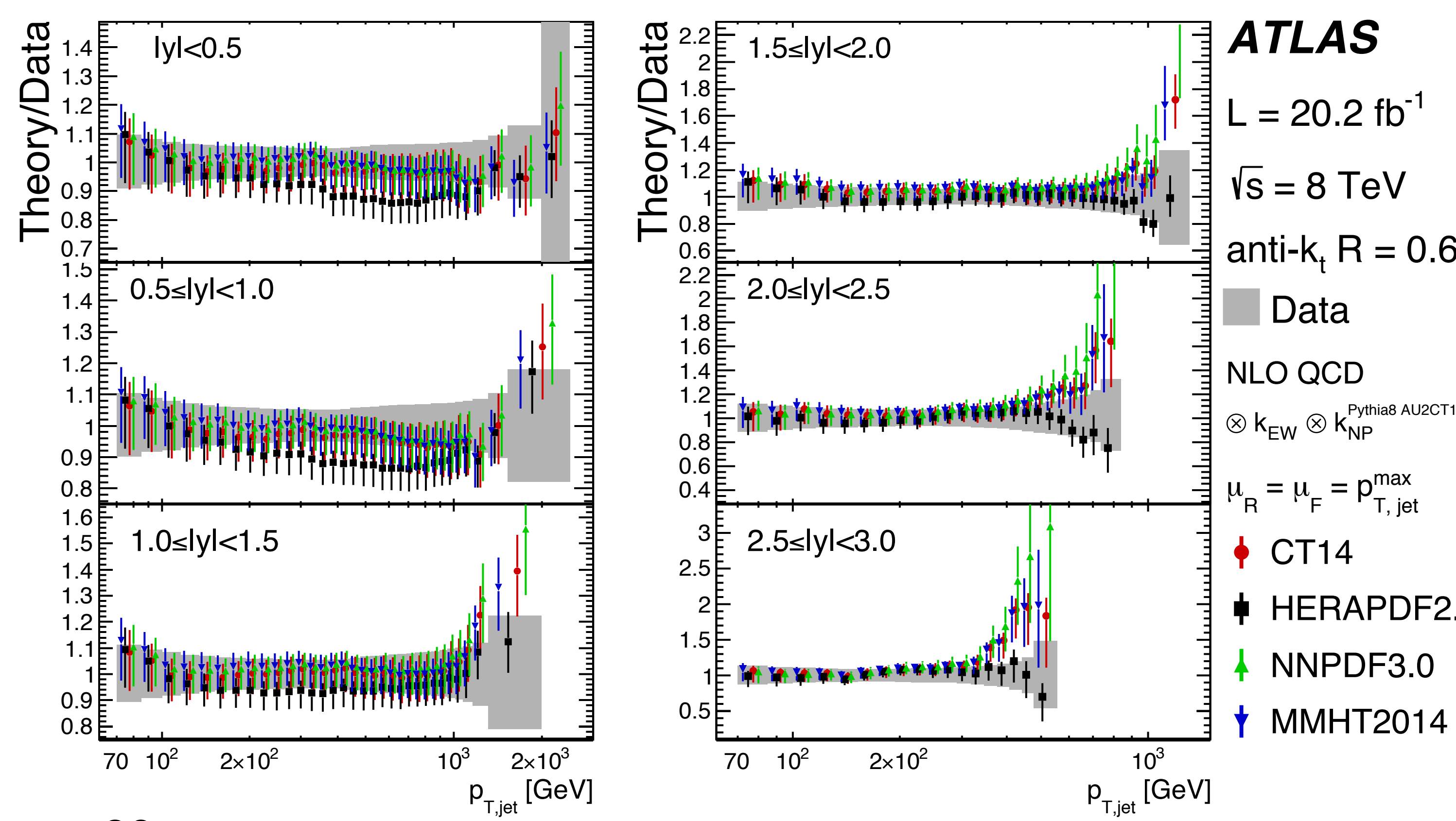
Backup

Inclusive Jet production

$$\sqrt{s} = 8 \text{ TeV}$$





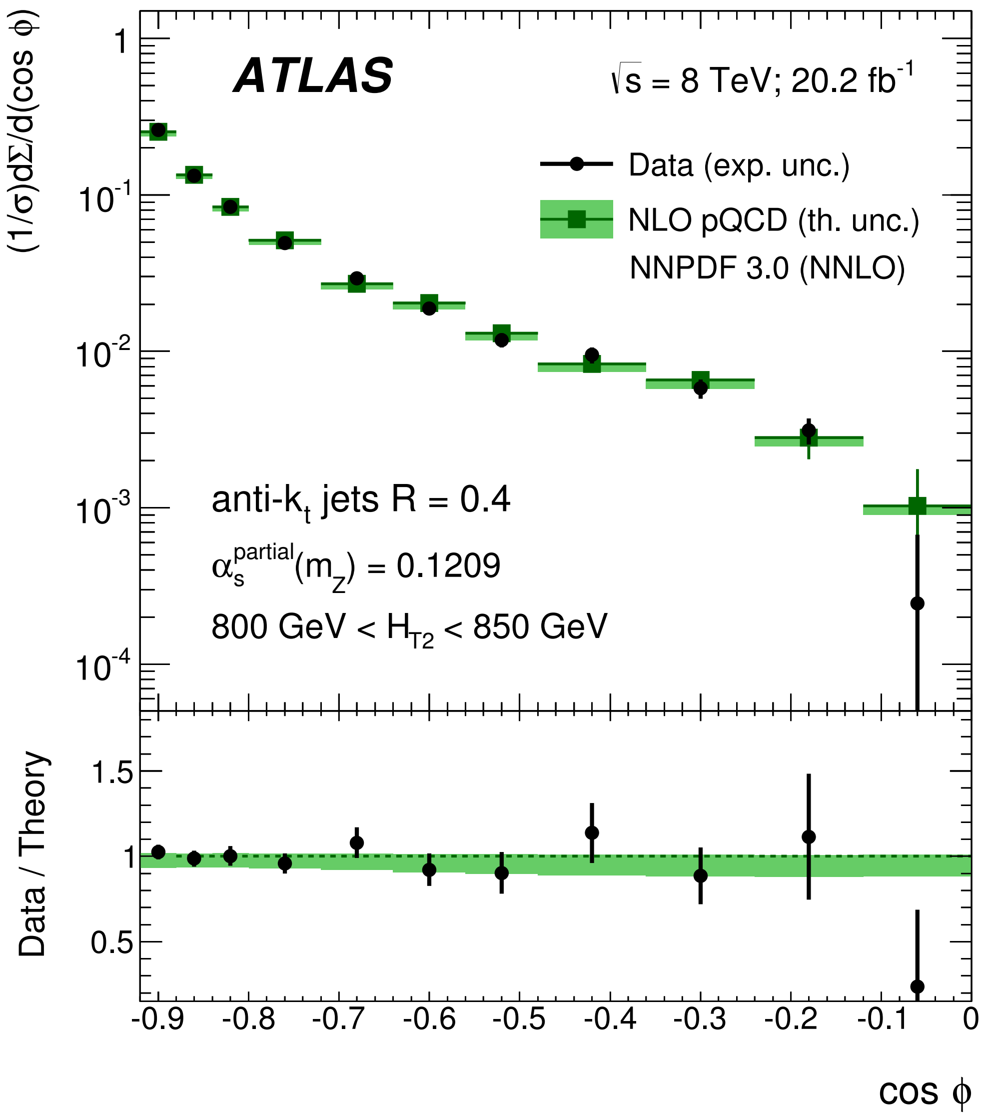


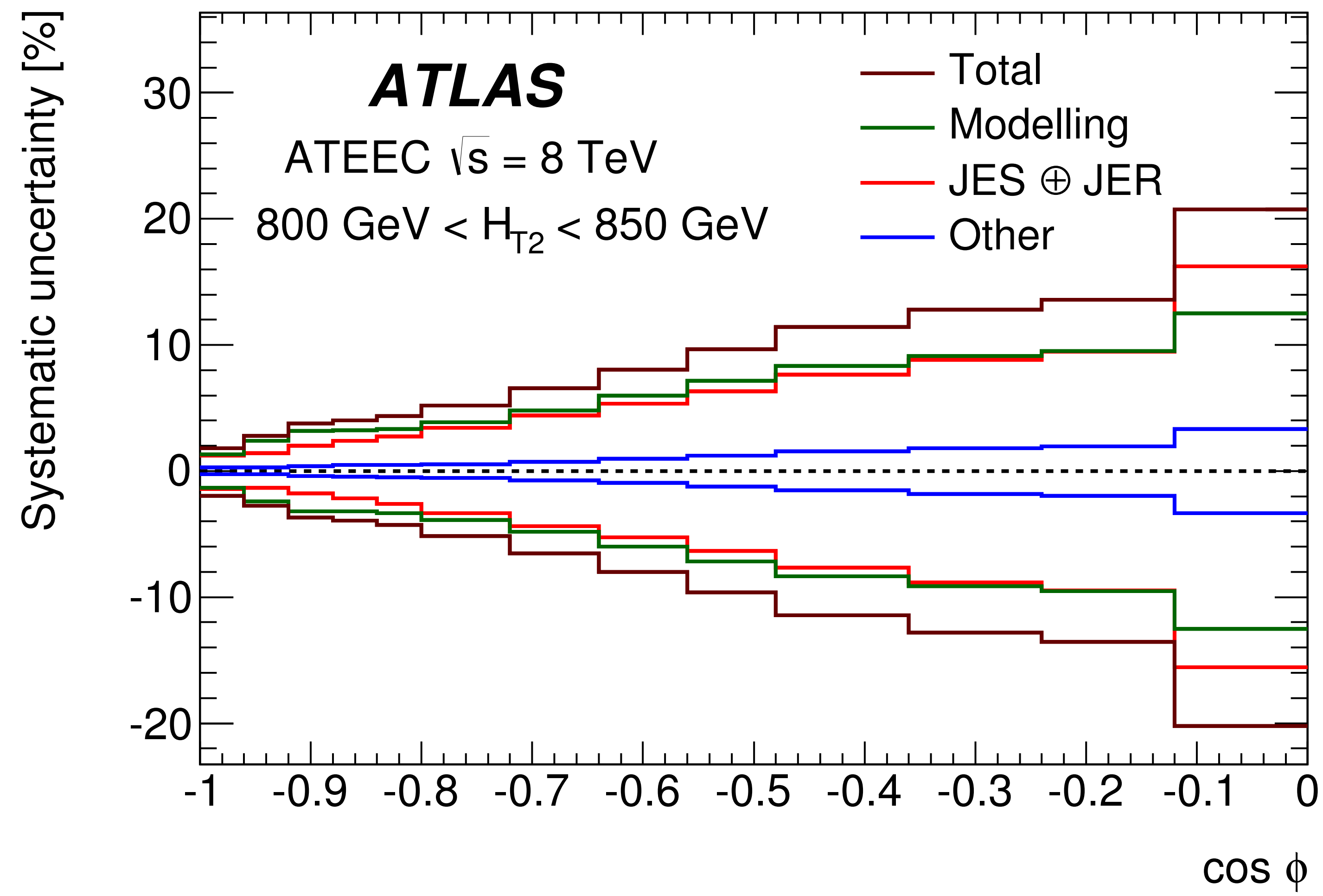
Di-Jet production at 13 TeV

Summary of the p-values obtained from the comparison of the di-jet cross section and the NLO pQCD predictions for various PDFs and for each y^* bin.

	P_{obs}				
y^* ranges	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%

TEEC and ATEEC measurement





TEEC

$\langle Q \rangle$ (GeV)	$\alpha_s(m_Z)$ value (NNPDF 3.0)	$\chi^2/N_{\rm dof}$
412	0.1171 ± 0.0021 (exp.) $^{+0.0081}_{-0.0022}$ (scale) $\pm$ 0.0013 (PDF) $\pm$ 0.0001 (NP)	24.3 / 21
437	0.1178 ± 0.0017 (exp.) $^{+0.0073}_{-0.0017}$ (scale) $\pm$ 0.0014 (PDF) $\pm$ 0.0002 (NP)	28.3 / 21
472	0.1177 ± 0.0017 (exp.) $^{+0.0079}_{-0.0023}$ (scale) $\pm$ 0.0015 (PDF) $\pm$ 0.0001 (NP)	27.7 / 21
522	0.1163 ± 0.0017 (exp.) $^{+0.0067}_{-0.0016}$ (scale) $\pm$ 0.0016 (PDF) $\pm$ 0.0001 (NP)	22.8 / 21
604	0.1181 ± 0.0017 (exp.) $^{+0.0082}_{-0.0022}$ (scale) $\pm$ 0.0017 (PDF) $\pm$ 0.0005 (NP)	24.3 / 21
810	0.1186 ± 0.0023 (exp.) $^{+0.0085}_{-0.0035}$ (scale) $\pm$ 0.0020 (PDF) $\pm$ 0.0004 (NP)	23.7 / 21

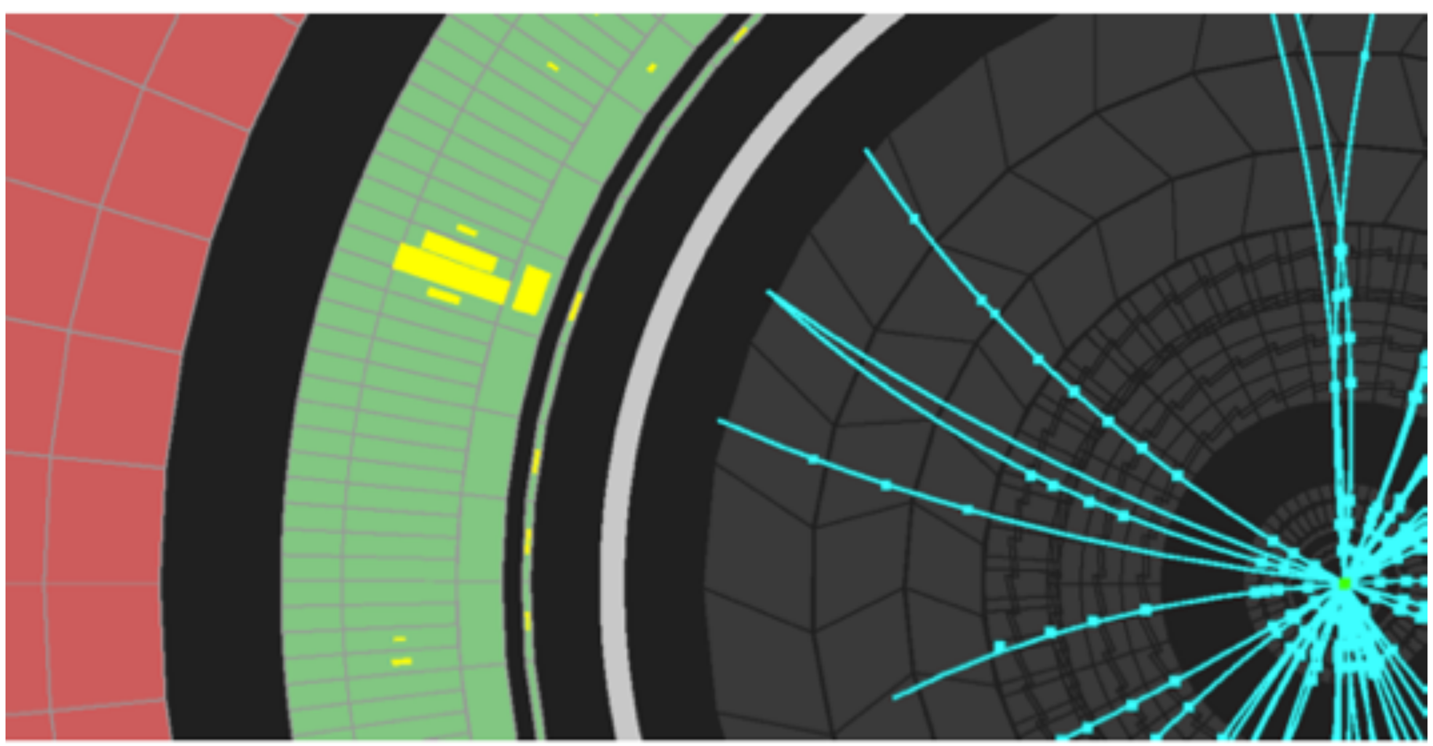
ATEEC

$\langle Q \rangle$ (GeV)	$\alpha_s(m_Z)$ value (NNPDF 3.0)	$\chi^2/N_{\rm dof}$
412	0.1209 ± 0.0036 (exp.) $^{+0.0085}_{-0.0031}$ (scale) $\pm$ 0.0013 (PDF) $\pm$ 0.0004 (NP)	10.6 / 10
437	0.1211 ± 0.0026 (exp.) $^{+0.0064}_{-0.0014}$ (scale) $\pm$ 0.0015 (PDF) $\pm$ 0.0010 (NP)	6.8 / 10
472	0.1203 ± 0.0028 (exp.) $^{+0.0060}_{-0.0013}$ (scale) $\pm$ 0.0016 (PDF) $\pm$ 0.0002 (NP)	8.8 / 10
522	0.1196 ± 0.0025 (exp.) $^{+0.0054}_{-0.0010}$ (scale) $\pm$ 0.0017 (PDF) $\pm$ 0.0004 (NP)	10.9 / 10
604	0.1176 ± 0.0031 (exp.) $^{+0.0058}_{-0.0008}$ (scale) $\pm$ 0.0020 (PDF) $\pm$ 0.0005 (NP)	6.4 / 10
810	0.1172 ± 0.0037 (exp.) $^{+0.0053}_{-0.0009}$ (scale) $\pm$ 0.0022 (PDF) $\pm$ 0.0001 (NP)	9.8 / 10

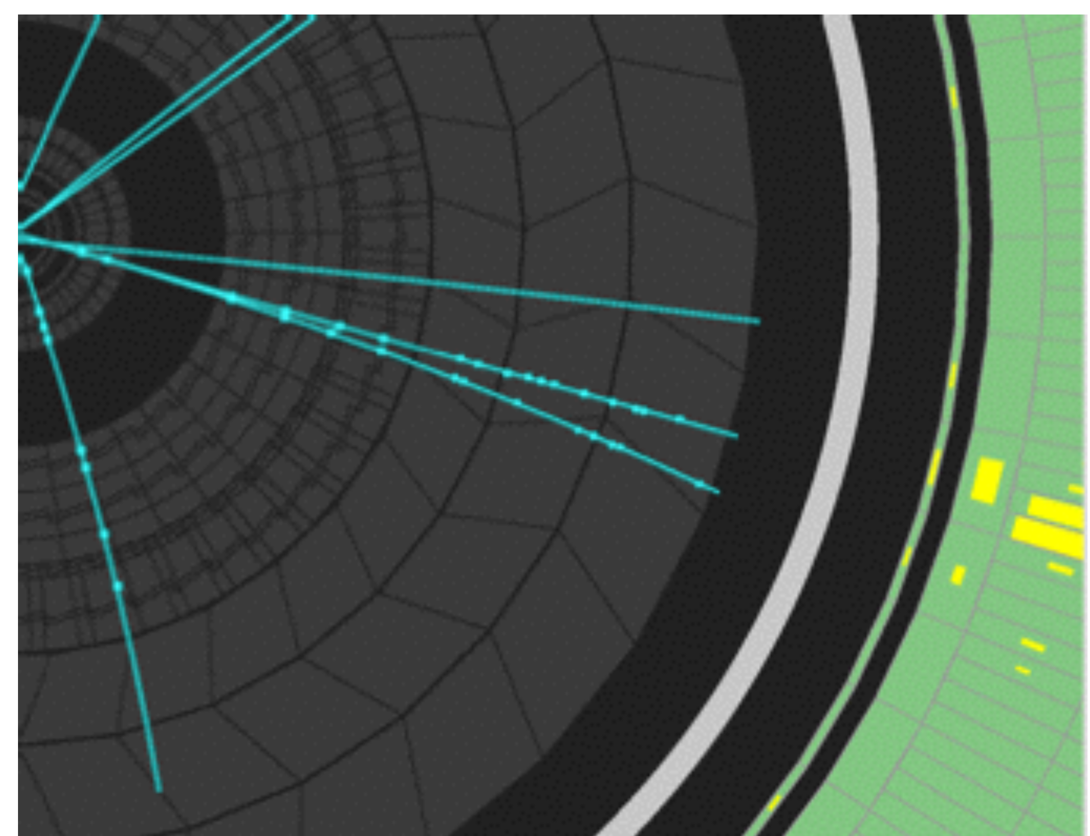
Photon reconstruction and identification

- unconverted photon candidates → no match with any track
- converted photon candidate → match with a converted vertex

- Unconverted γ



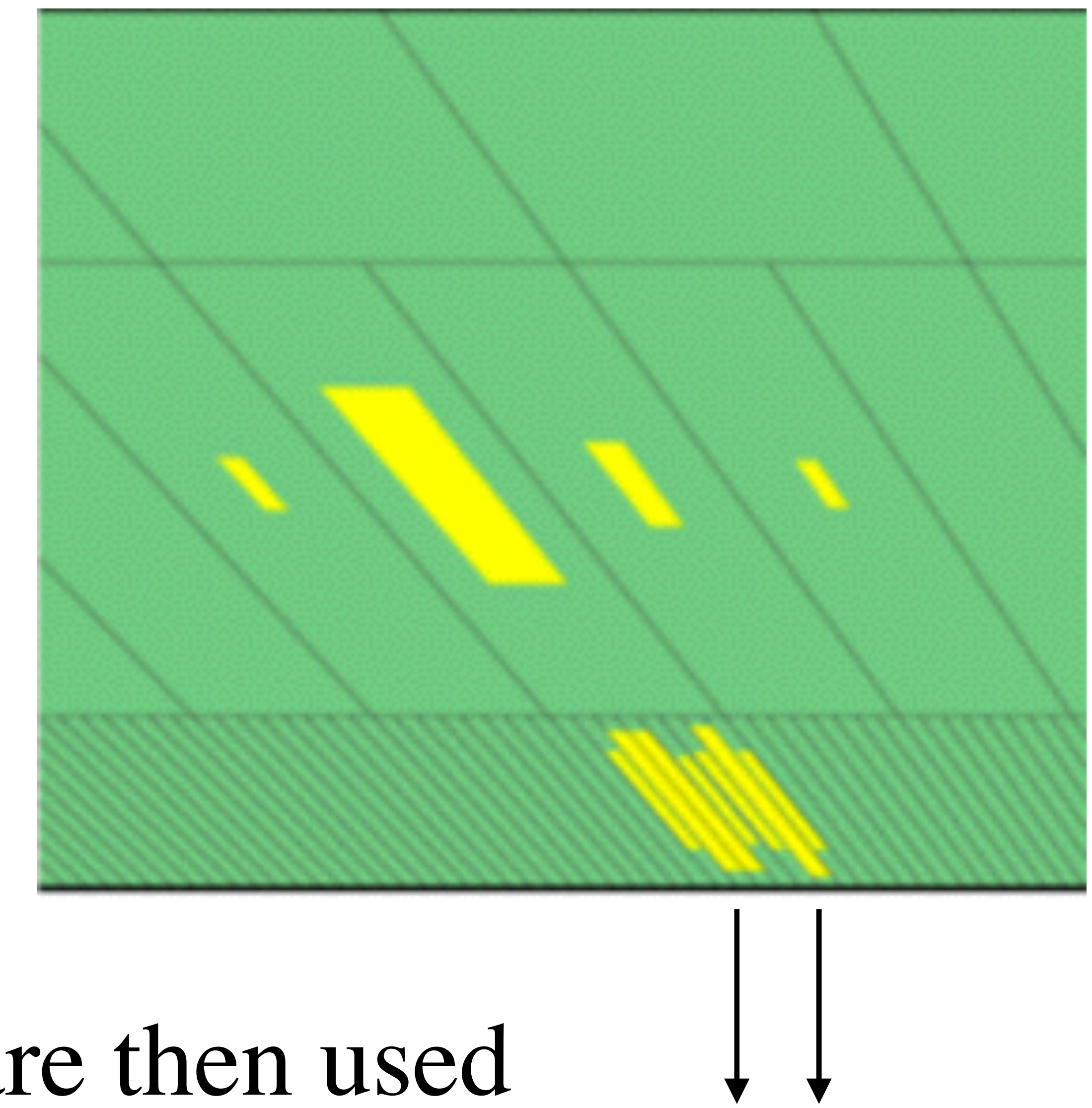
- Converted γ



Background sources

The main background sources are π^0 and η two photon decay

Two photon identification criteria ("Loose" and "Tight") are introduced according to the shower shapes in the ATLAS calorimeter system.

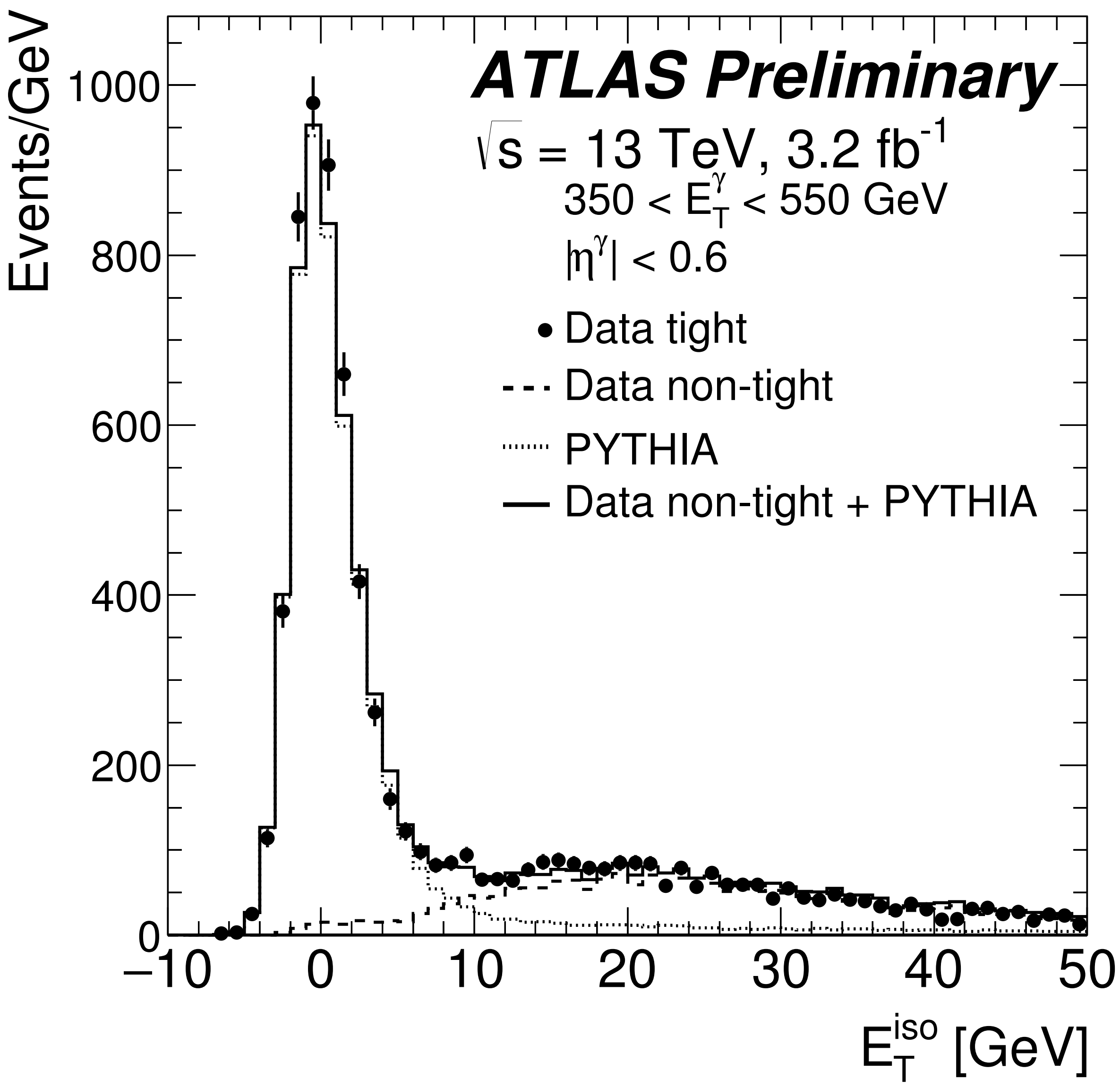


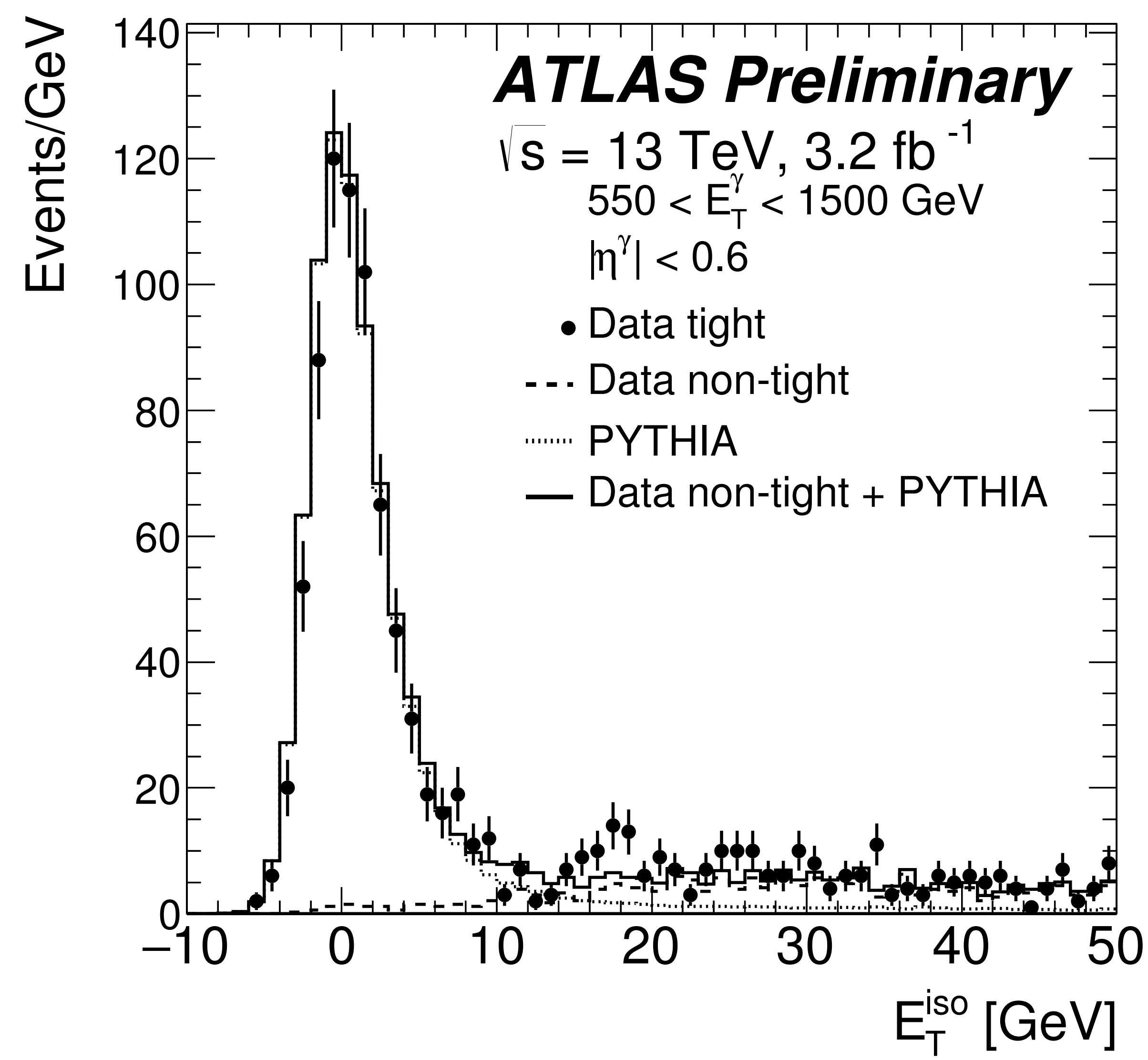
$$\pi^0 \to \gamma\gamma$$

Loose and Tight photon candidates are then used in a data-driven method for the background estimation.

Photon isolation

E_T^{iso} is computed summing the transverse energy of clusters of calorimeter cells in a cone of radius 0.4, excluding the contribution from the photon.

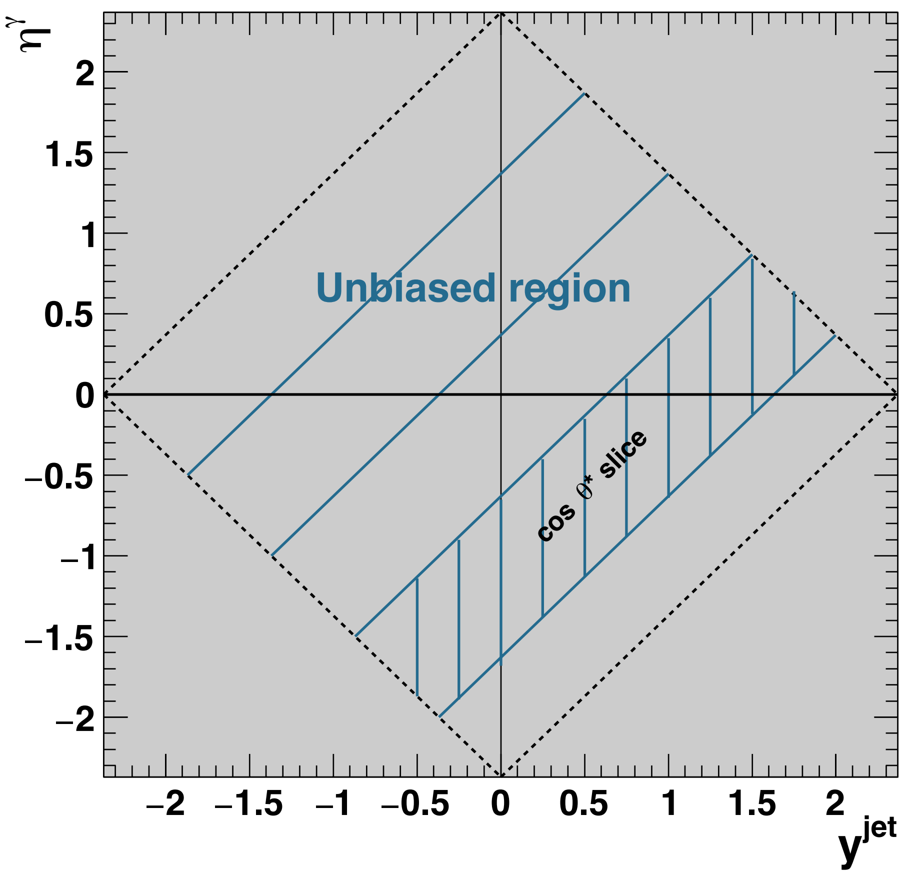


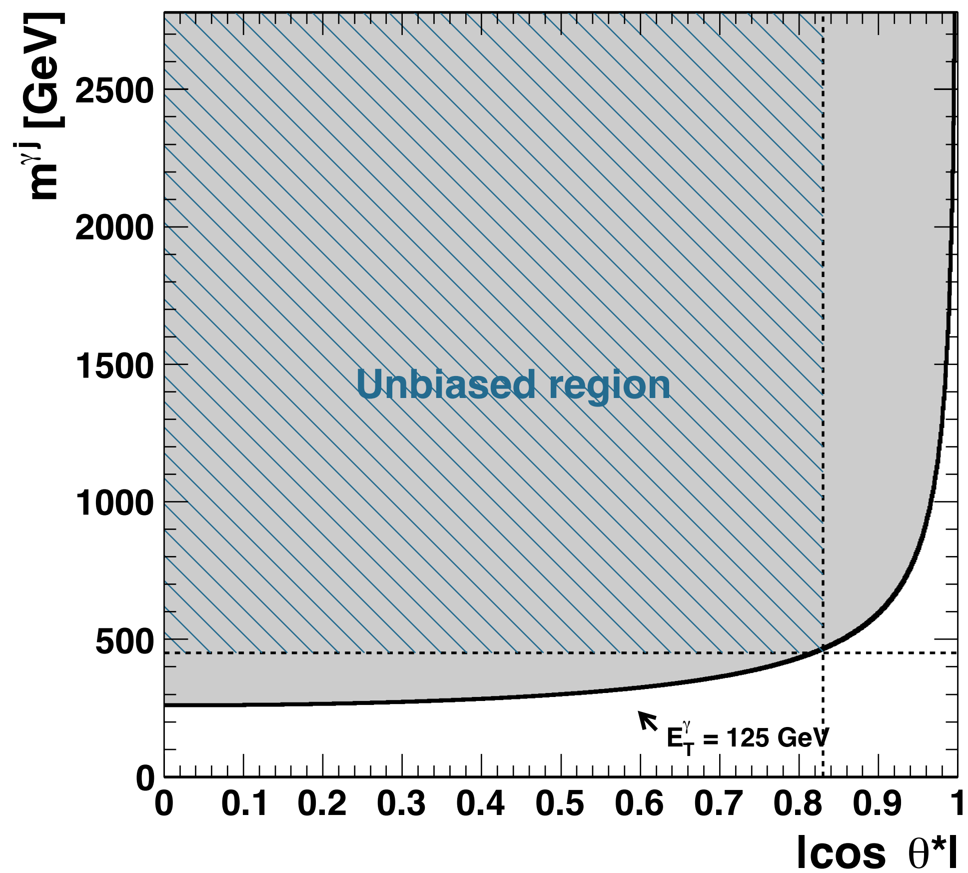


Additional cuts

Selection of unbiased region to measure $|\cos\theta^*|$ and $m^{\gamma-jet}$ cross sections:

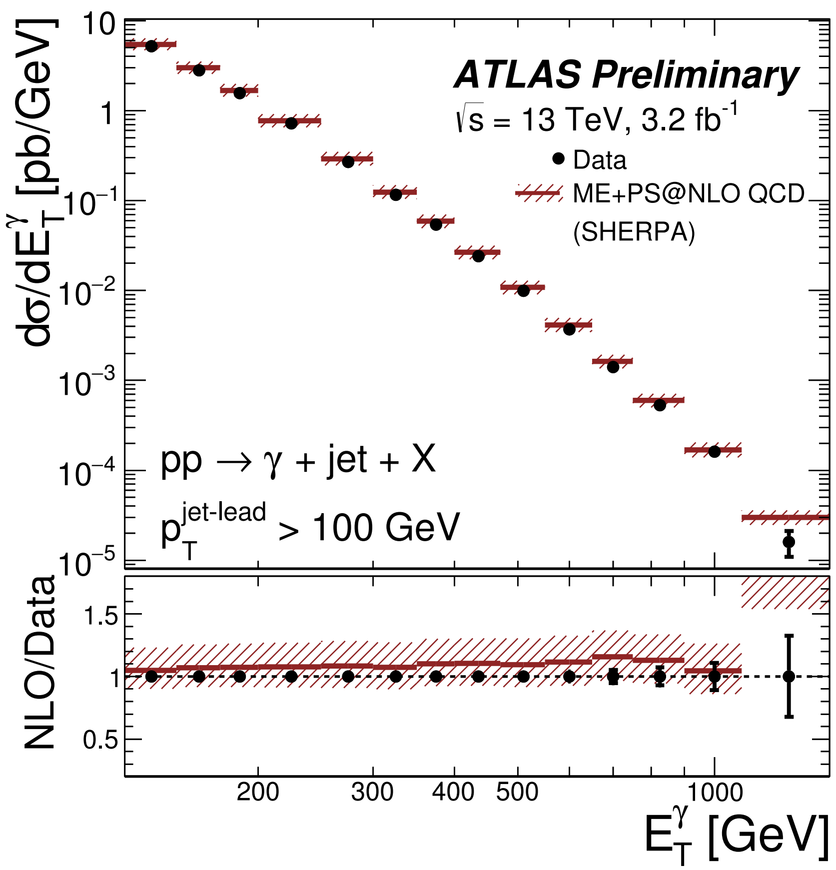
$$|\eta^\gamma + y^{jet}| < 2.37 \qquad |\cos\theta^*| < 0.83 \qquad m^{\gamma-jet} > 450 \text{ GeV}$$

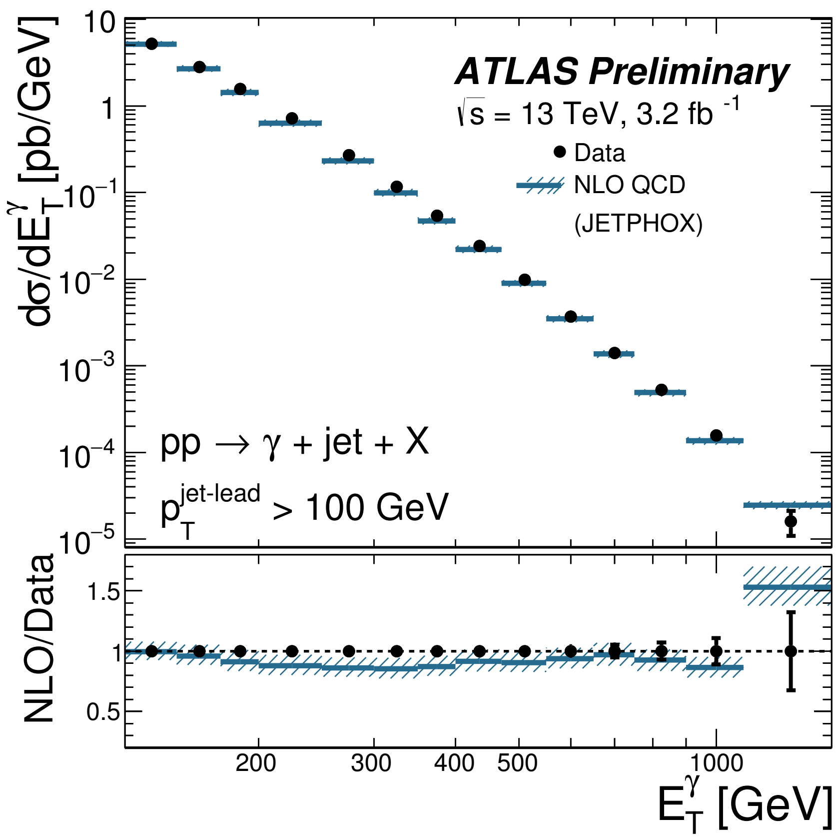


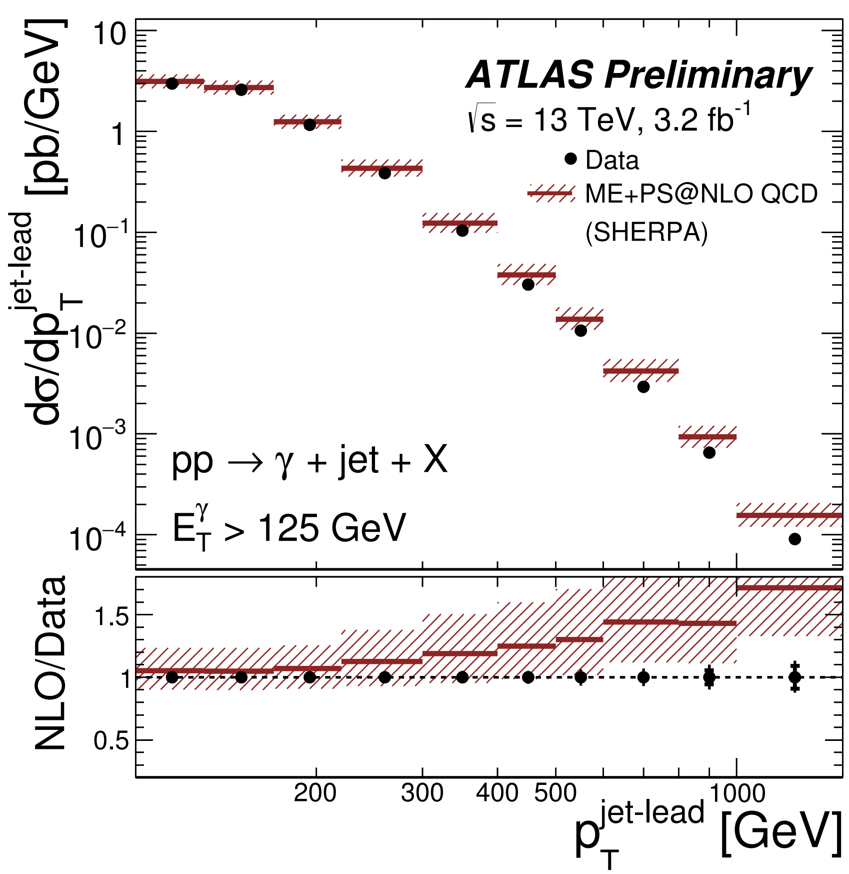


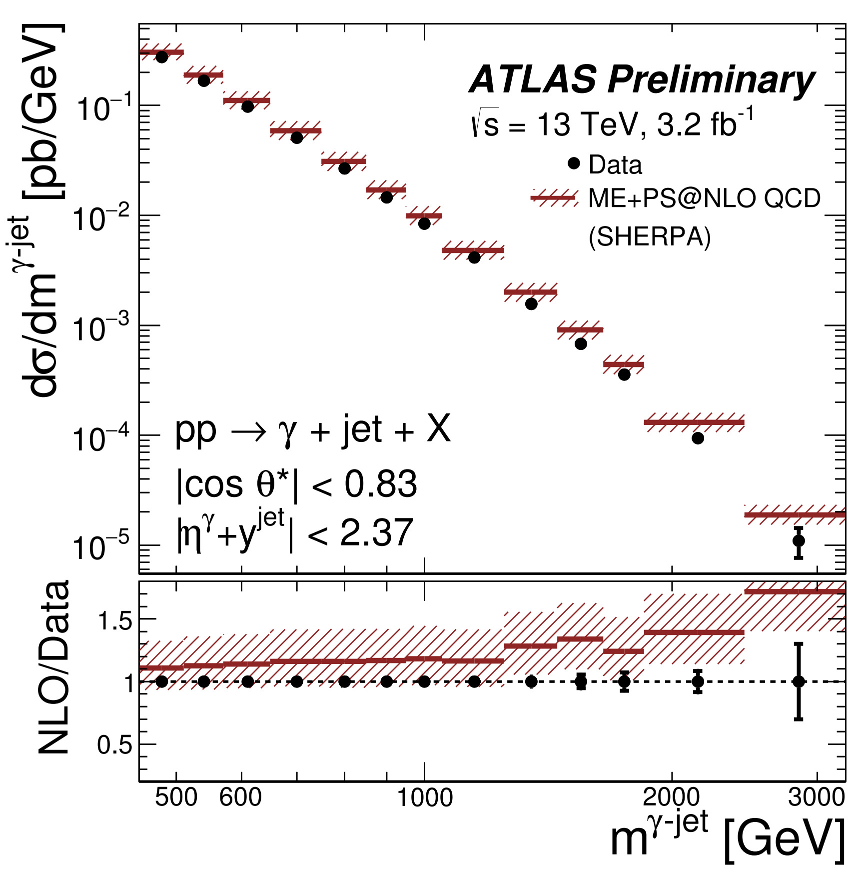
The first two requirements avoid the bias induced by the cut on $|\eta^\gamma|$ and y^{jet}. The third requirement avoids the bias due to the E_T^γ cut in the ($|\cos\theta^*| - m^{\gamma-jet}$) plane.

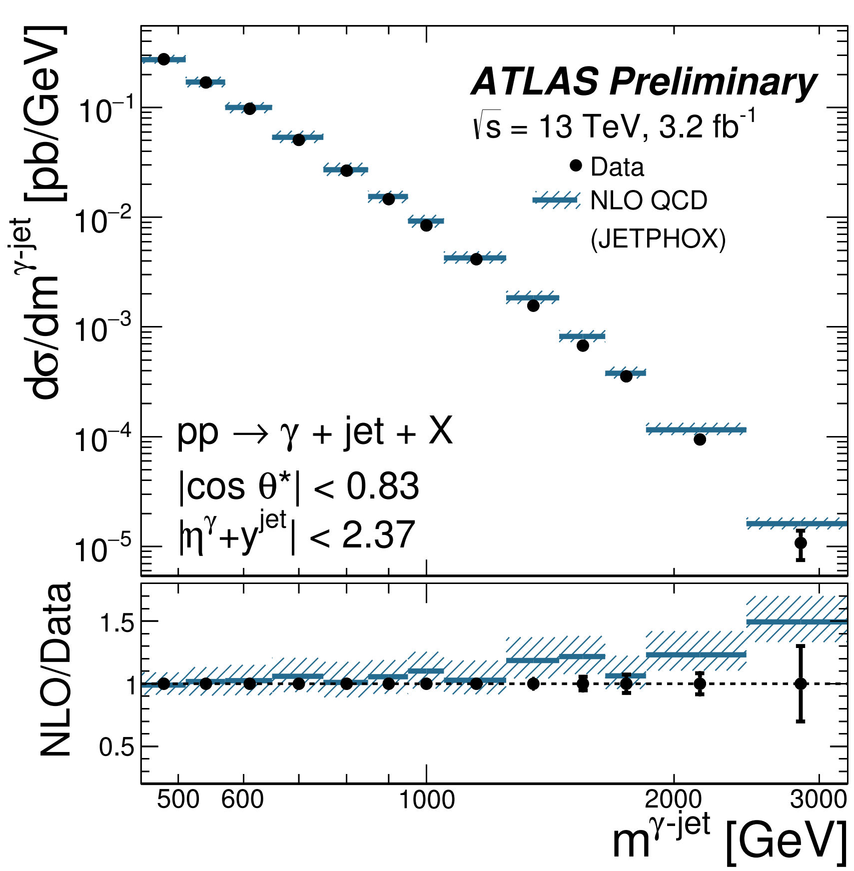
Photon + Jet at 13 TeV



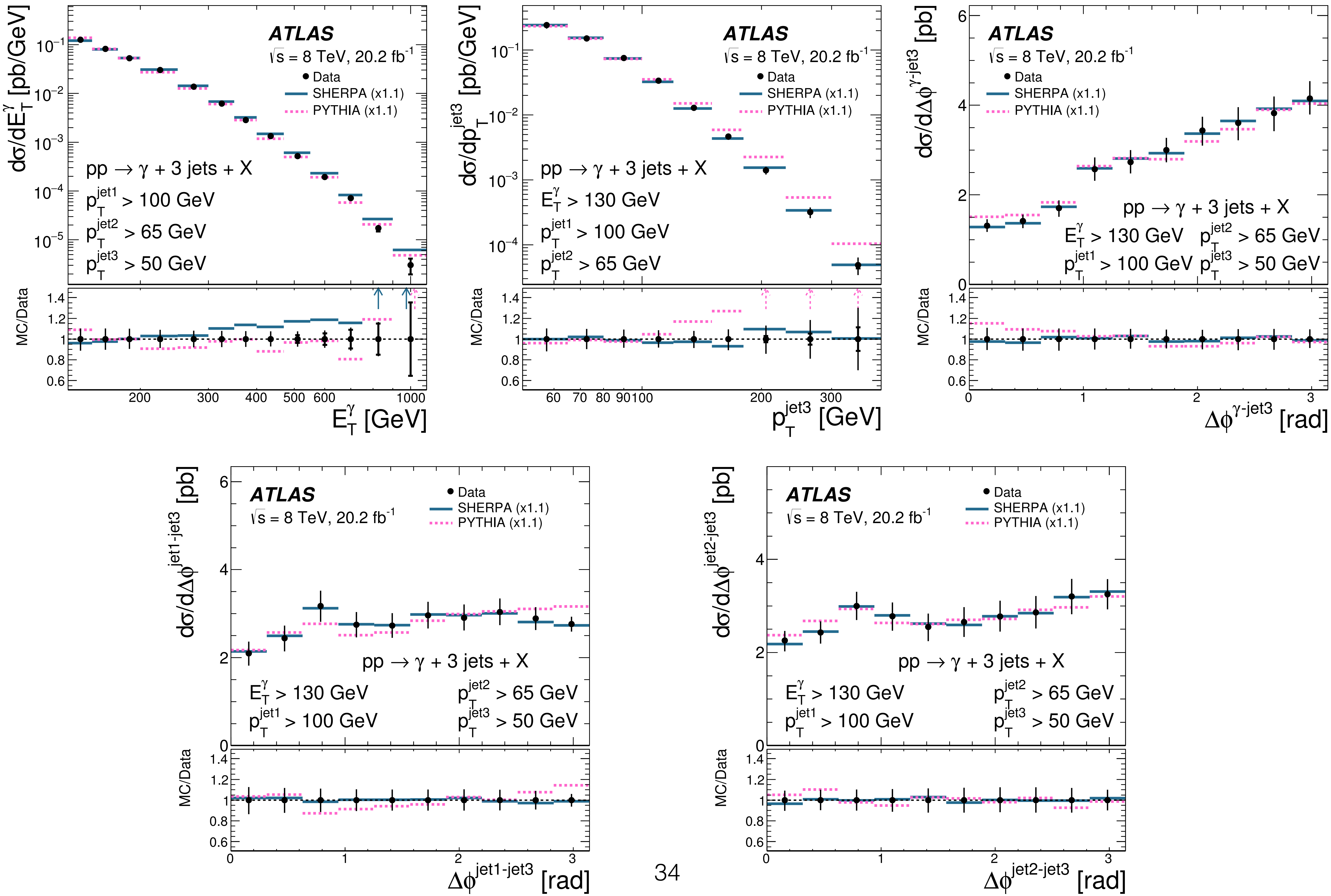




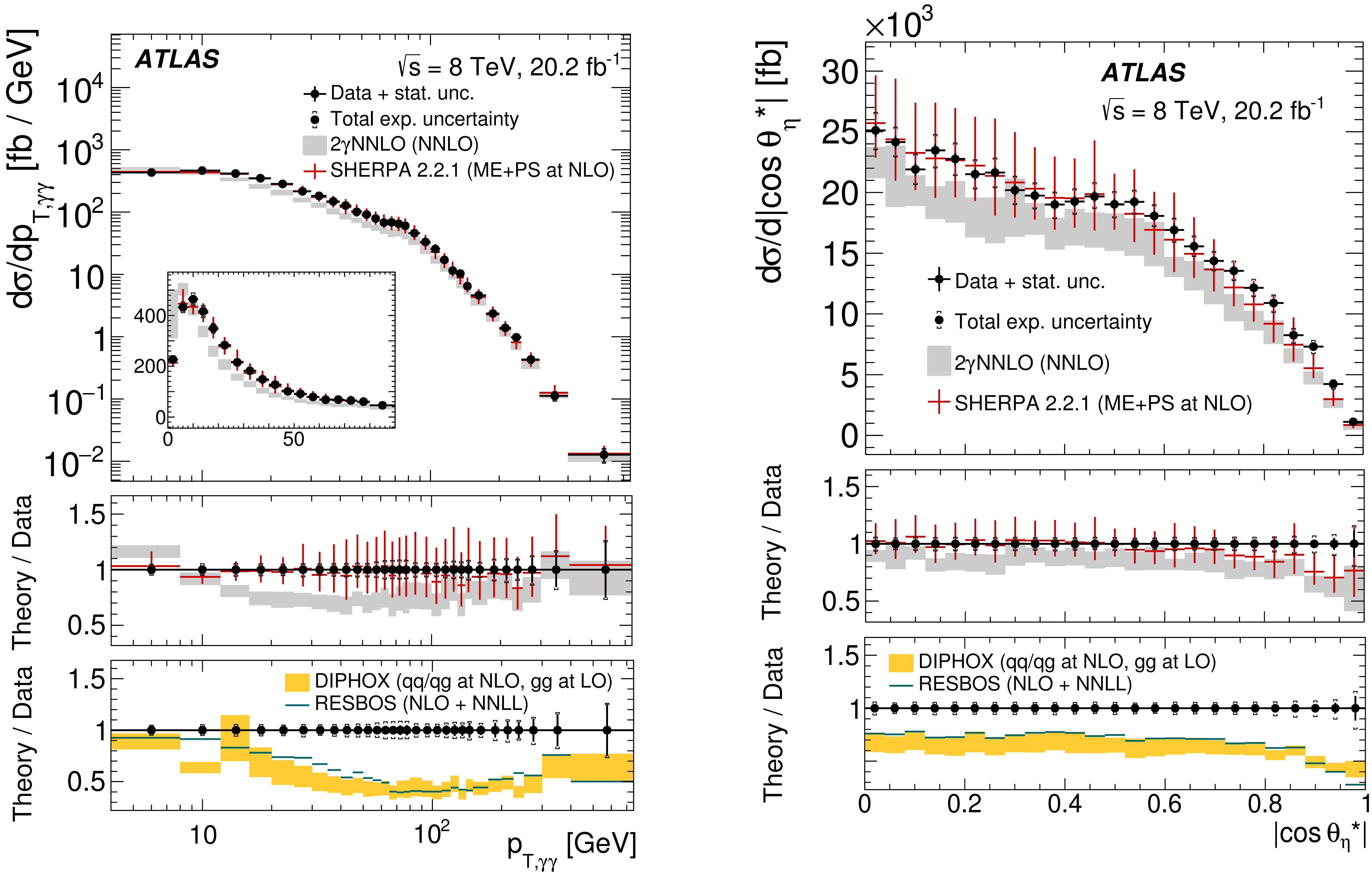




Photon + Jet at 8 TeV



Photon pair production



Photon pair production