Measurement of photon (also +jets) production cross sections, jets production cross sections and extraction of the strong coupling constant

ISMD2017

Tlaxcala City, Mexico

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on behalf of the ATLAS Collaboration

September 11, 2017

Outlook

- **Photon physics**
  - Inclusive γ at 13 TeV. (Phys. Lett. B770 (2017) 473-493)
  - Diphoton at 8 TeV. (Phys. Rev. D 95 (2017) 112005)
  - Inclusive γ + jet at 8 TeV. (Nucl.Phys. B918 (2017) 257-316)
  - Inclusive γ + jet at 13 TeV. (ATLAS-CONF-2017-059)

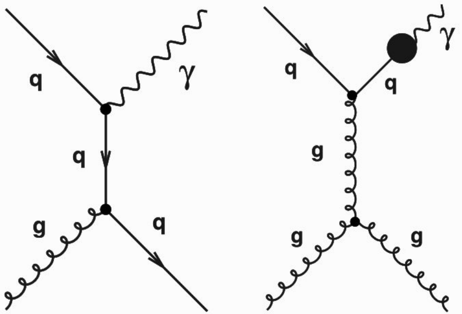
- **Jet physics**
  - Inclusive-jet cross-section at 8 TeV (20.2 fb^{-1}) (arXiv:1706.03192)
  - Inclusive-jet and dijet cross-sections at 13 TeV (3.2 fb^{-1}) (ATLAS-CONF-2017-048)
  - TEEC measurements and extraction of α_s (arXiv:1707.02562)

A complete list of ATLAS Standard Model results can be found here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Prompt photons in pp collisions

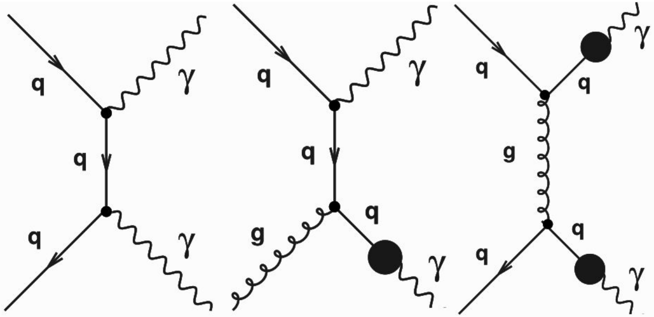
- Measurements of the production of high p_T prompt photons (in association with jets) and pairs of photons in hadron colliders provide
  - tests of pQCD predictions
  - constraints on the proton PDFs
  - input to understand QCD background to Higgs production and BSM searches

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



Prompt photon (plus jet) production

$$pp \longrightarrow \gamma(+\text{jet}) + \mathrm{X}$$



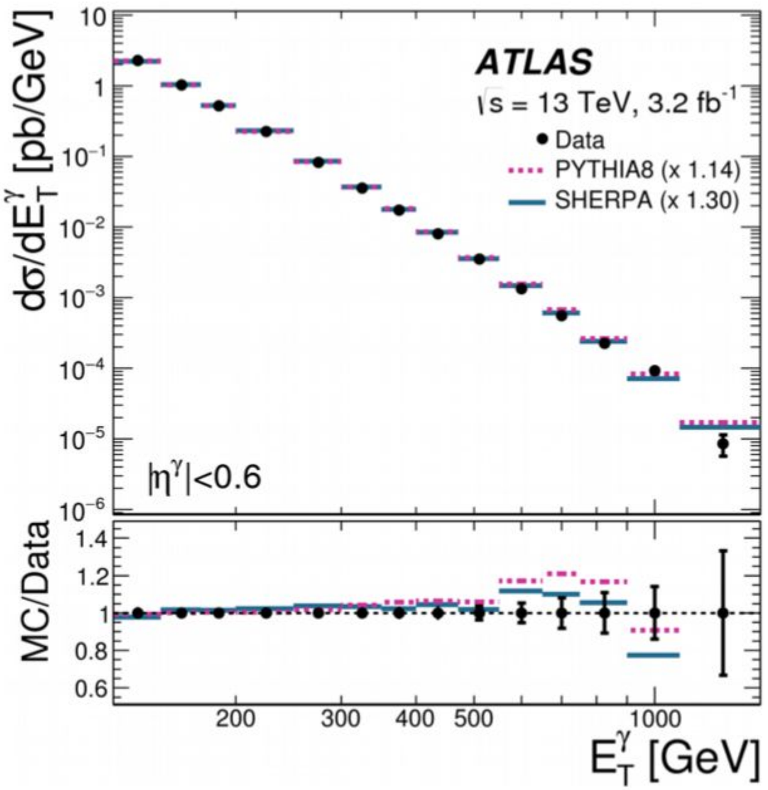
Diphoton production

$$pp \longrightarrow \gamma\gamma + \mathrm{X}$$

Inclusive isolated photons at 13 TeV

Phys. Lett. B 770 (2017) 473

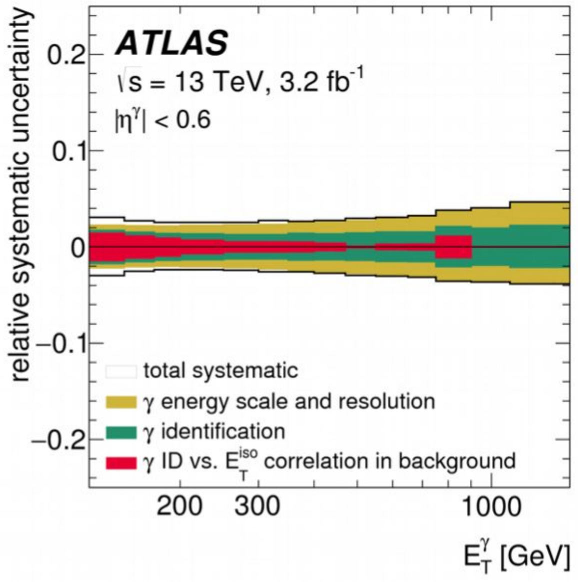
- Testing pQCD with a hard colourless probe
- Sensitive at LO to the gluon PDF
- Photon selection:
  - $E_T^\gamma > 125$ GeV and $|\eta^\gamma| < 2.37$, excluding the region $1.37 < |\eta^\gamma| < 1.56$
  - photon ID
  - photon isolation:
    E_T^{iso} (R = 0.4) < 4.8 GeV + $4.2 \cdot 10^{-3} \times E_T^\gamma$
- Background subtracted with data-driven technique

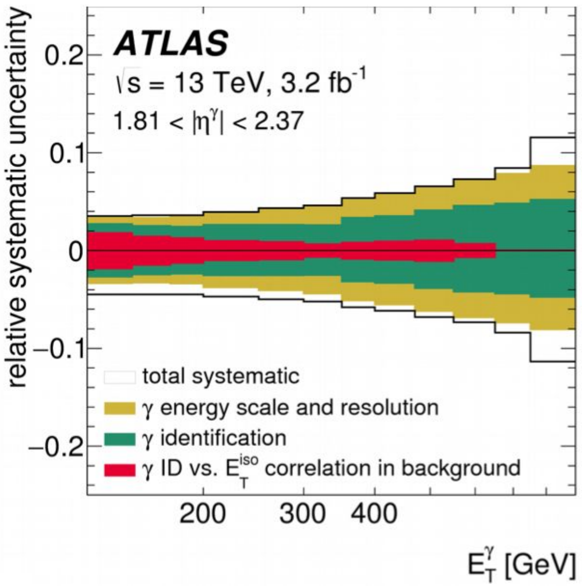


Inclusive isolated photons at 13 TeV

Phys. Lett. B 770 (2017) 473

- Photon energy scale is the dominant uncertainty at high E_T
- Background subtraction largest at low E_T
- Identification uncertainty ~5% at high E_T
- Uncertainties are larger in the forward regions

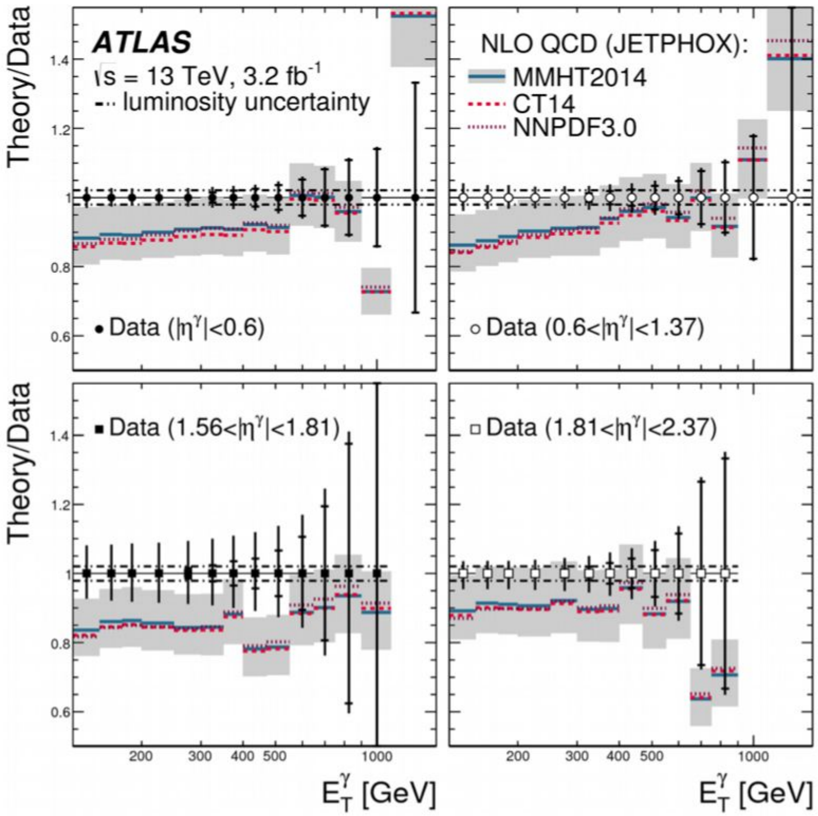




Inclusive isolated photons at 13 TeV

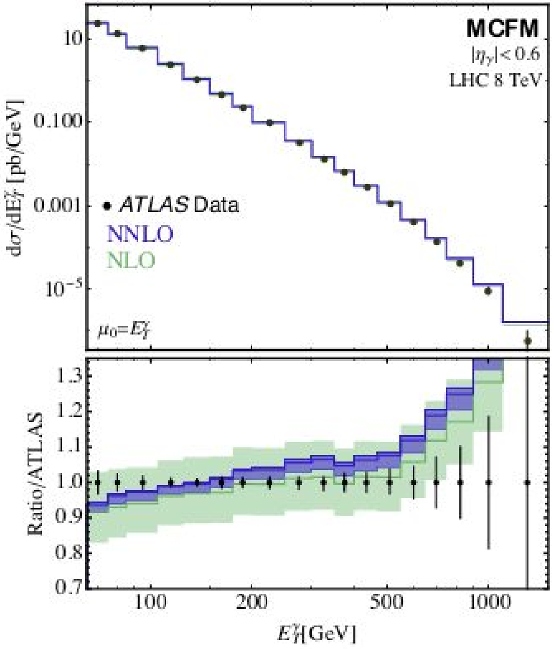
Phys. Lett. B 770 (2017) 473

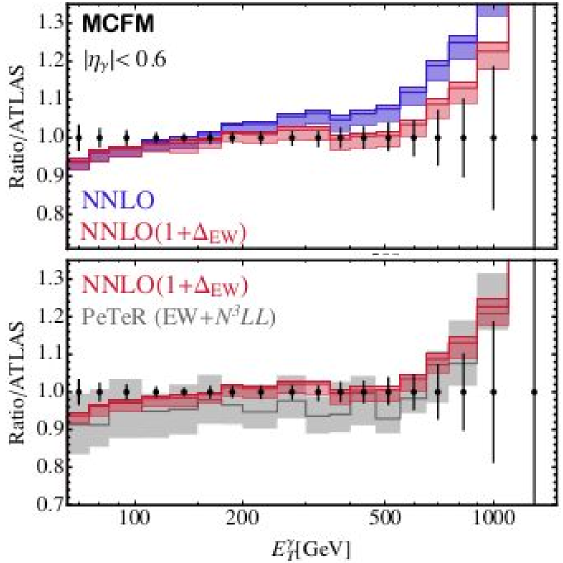
- NLO pQCD predictions (JetPhox)
  - underestimate the measurements
  - Theoretical uncertainties > experimental in most regions
  - Statistical uncertainty takes over beyond 1 TeV
  - Different PDFs show up to 15% difference
  - Demonstrates sensitivity to help constrain PDFs. Especially for large E_T
- Comparisons would benefit from reduced scale uncertainties



Inclusive isolated photons at NNLO (8 TeV)

- New prediction for inclusive photon production at NNLO available! (ArXiv:1612.04333)
- QCD NNLO predictions have been compared to ATLAS inclusive photon measurements at 8 TeV





- Theoretical uncertainty reduced by a factor ~3 with respect to PeTeR
- Trend of the calculations to be above the data at high E_T

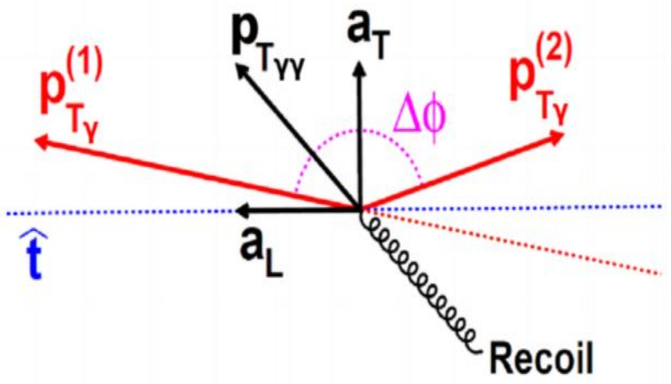
Diphoton at 8 TeV

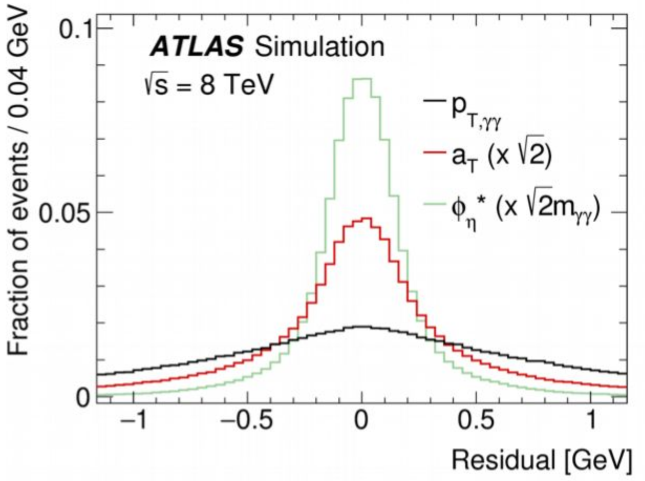
Phys. Rev. D 95 (2017) 112005

- Sensitive to α_s corrections
- Sensitive to QCD infrared emission
- Main background for $H \rightarrow \gamma\gamma$

Selection	Leading γ	Subleading γ
Min. transverse energy	$E^{\gamma}_{T,1} > 40$ GeV	$E^{\gamma}_{T,2} > 30$ GeV
Pseudorapidity	$\lvert\eta^{\gamma}\rvert < 1.37$ or $1.56 < \lvert\eta^{\gamma}\rvert < 2.37$	
Min. angular separation	$\Delta R_{\gamma\gamma} > 0.4$	
Max. transverse isolation energy	$E_T^{\text{iso,part}}(\Delta R = 0.4) < 11$ GeV	

- Variables sensitive to new physics: $m_{\gamma\gamma}$, $|\cos(\theta_\eta^*)|$
- Variables sensitive to higher order and QCD ISR: $p_{T,\gamma\gamma}$, $\Delta\phi_{\gamma\gamma}$
- New variables sensitive to QCD ISR emissions: a_T, ϕ_η^*
  - Nucl. Instrum. Meth. A 602 (2009) 432437
  - Eur. Phys. J. C 71 (2011) 1600



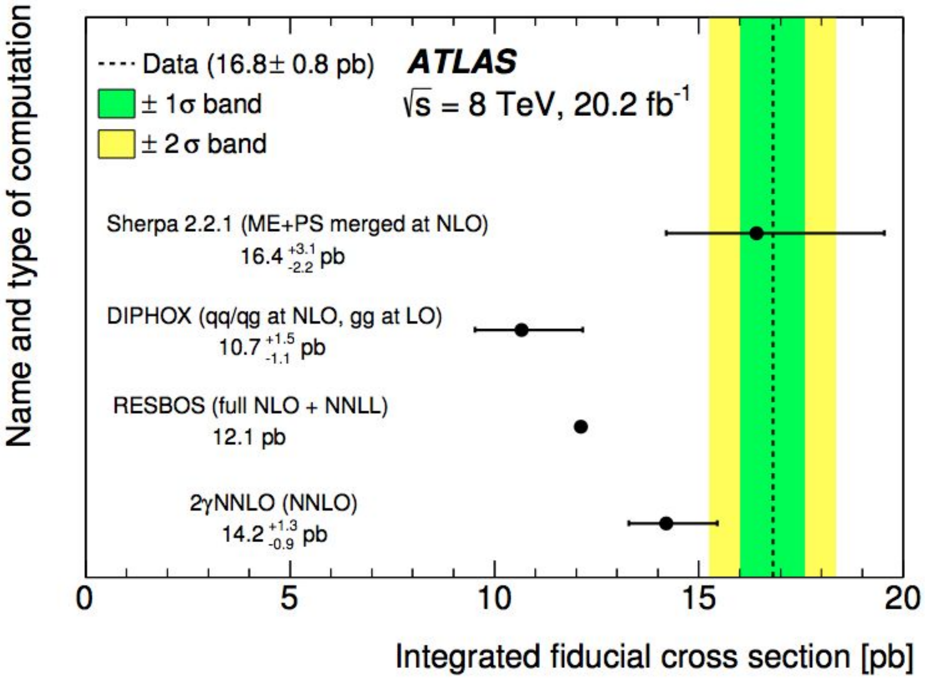


Diphoton at 8 TeV

Phys. Rev. D 95 (2017) 112005

- Main experimental systematic:
  - photon identification and isolation
  - less than factor 2 wrt 7 TeV

- Cross section from fixed order calculation lower than data
  - Improvement NLO→NNLO



$$\sigma^{\text{fid}} = 16.8 \pm 0.8\,\text{pb} = 16.8 \pm 0.1(\text{stat}) \pm 0.7(\text{exp}) \pm 0.3(\text{lumi})\,\text{pb}$$

Diphoton at 8 TeV

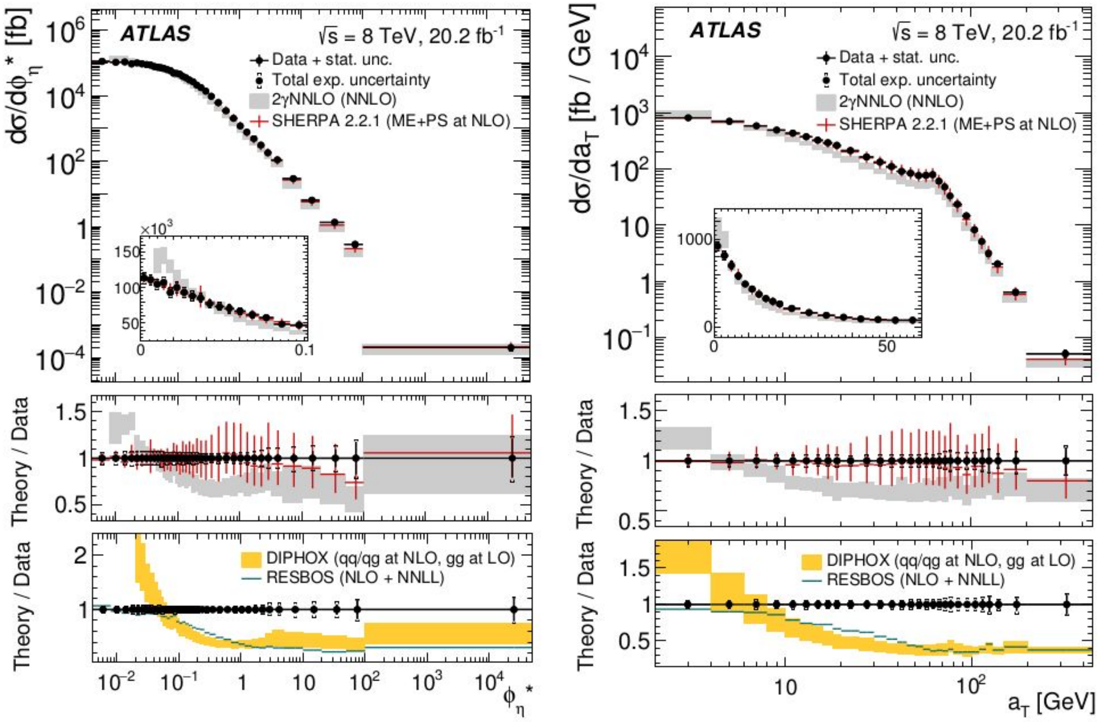
Phys. Rev. D 95 (2017) 112005

- Fixed-order calculations are not expected to give reliable predictions in regions sensitive to infrared emissions

- The effects of infrared emissions are well reproduced by the inclusion of soft-gluon resummation at NNLL

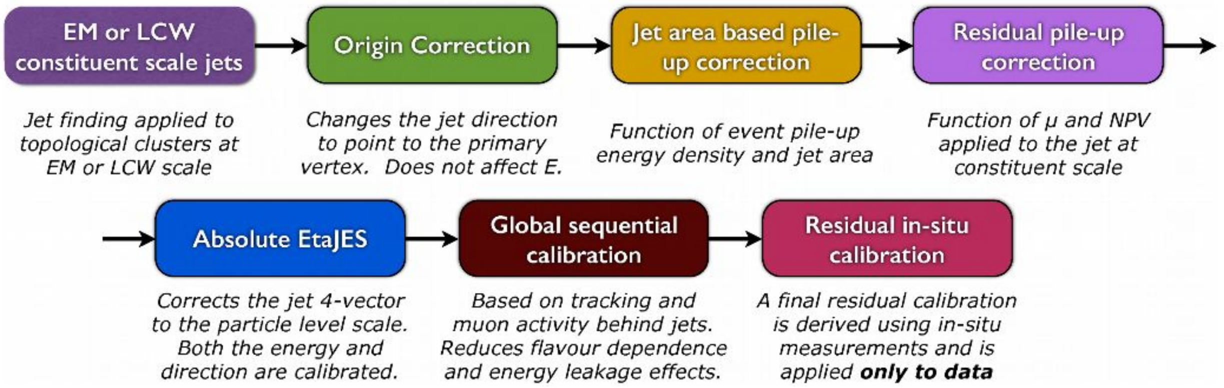
- Sherpa and RESBOS do a good job at low a_T or ϕ_η^*
  - PS and resummation

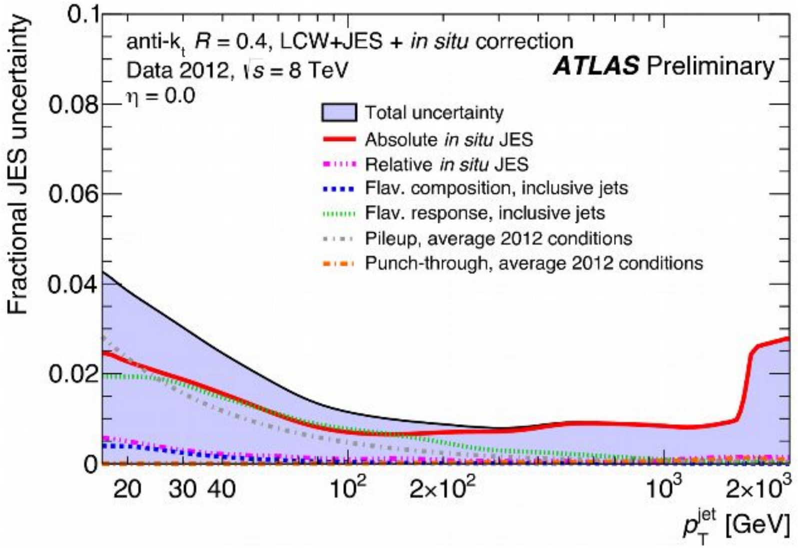
- DIPHOX and 2γNNLO do not



Jets in ATLAS

- Jet production is the dominant high-p_T process in 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
- Anti-k_T jets
- Built considering topological clusters of calorimeter cells
- Clusters corrected for pileup prior to jet building
- Multi-stage calibration scheme
- Larger energy scale uncertainty than photons





Photon + jets at 8 TeV

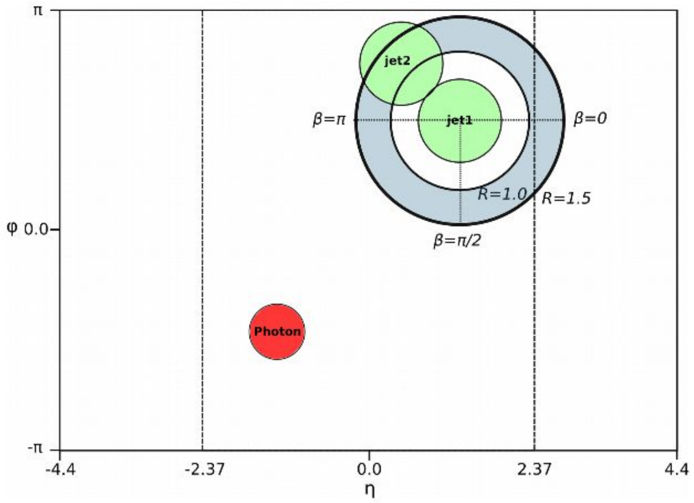
Nucl.Phys. B918 (2017) 257-316

- Constrain gluon PDF
- Tests kinematics of photon+multijet production
- Provides input for PDFs
- Testing ground for BSM physics

- Photon selection:
  - $E_T^\gamma > 130$ GeV and $|\eta^\gamma| < 2.37$, excluding the region $1.37 < |\eta^\gamma| < 1.56$
  - photon ID
  - photon isolation: E_T^{iso} (R = 0.4) < 4.8 GeV + $4.2 \cdot 10^{-3} \times E_T^\gamma$

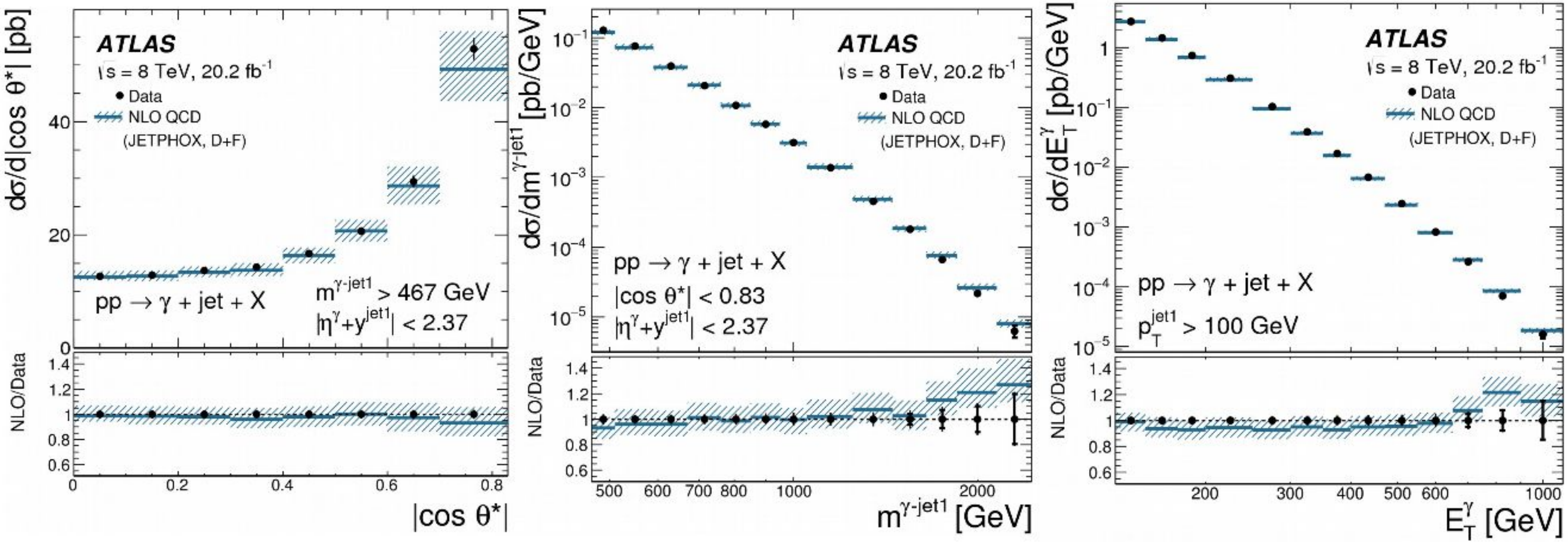
- Jet selection:
  - $P_T > 50$ GeV, $|y_j| < 4.4$

- 15 observables of the following types:
  - Kinematic: $E_{T,\gamma}$, $P_{T,jet}$
  - Dynamic: $m_{\gamma,jet}$, $\Delta\varphi_{\gamma,jet}$, $\Delta\varphi_{jet,jet}$
  - Virtual particle spin: $|\cos\theta^*|$
  - New: parton radiation around γ or jet1: β_γ, β_{jet1}



Photon + 1 jet at 8 TeV

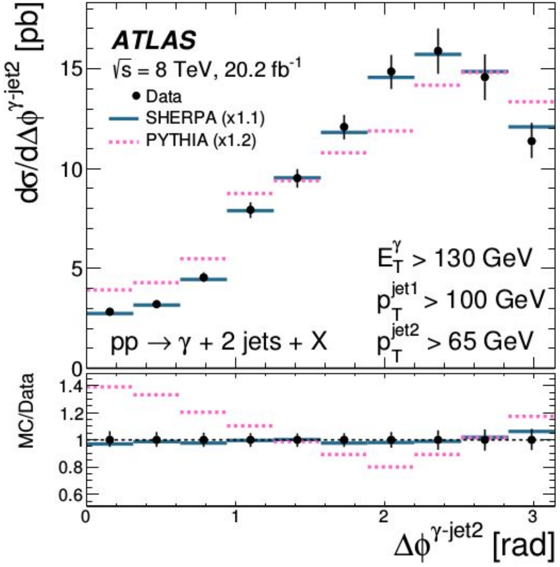
Nucl.Phys. B918 (2017) 257-316

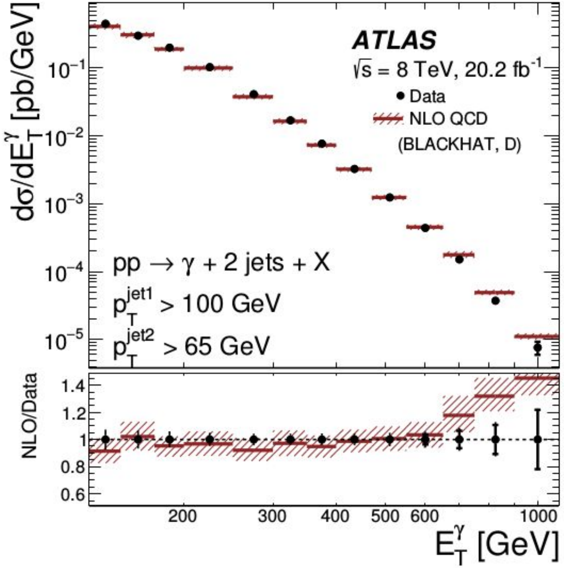


- NLO predictions with JetPhox + CT10 PDF
  - Give a good agreement in both normalization and shape

Photon + 2 jets at 8 TeV

Nucl.Phys. B918 (2017) 257-316



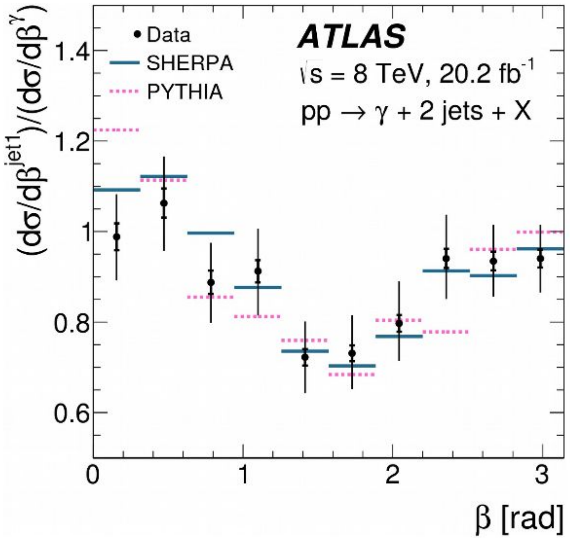


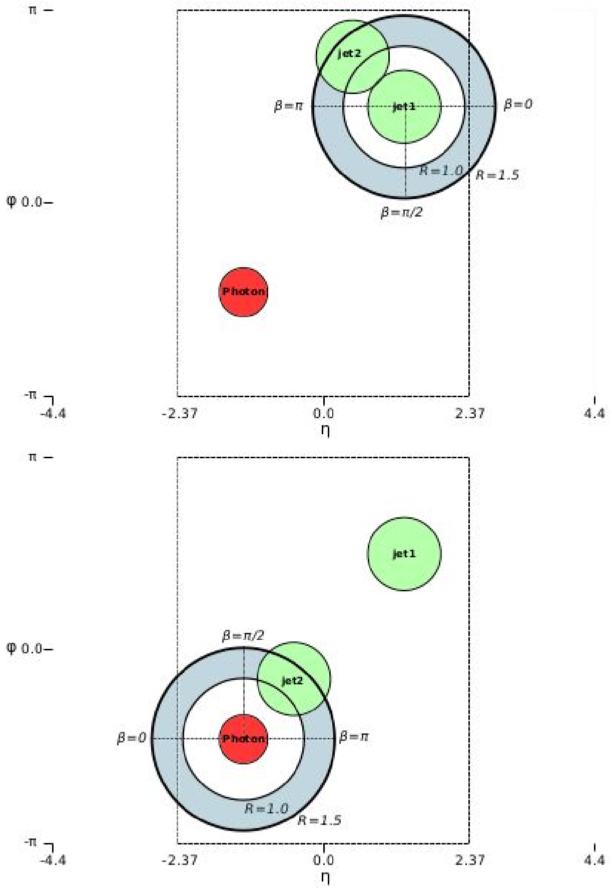
- SHERPA better than Pythia in multijet region
- Data are well described by BlackHat
  - Visible deviation for E_T > 750 GeV wrt NLO prediction

Photon + 2 jets at 8 TeV

Nucl.Phys. B918 (2017) 257-316

- First observation of different QCD radiation pattern around the photon and 1st jet



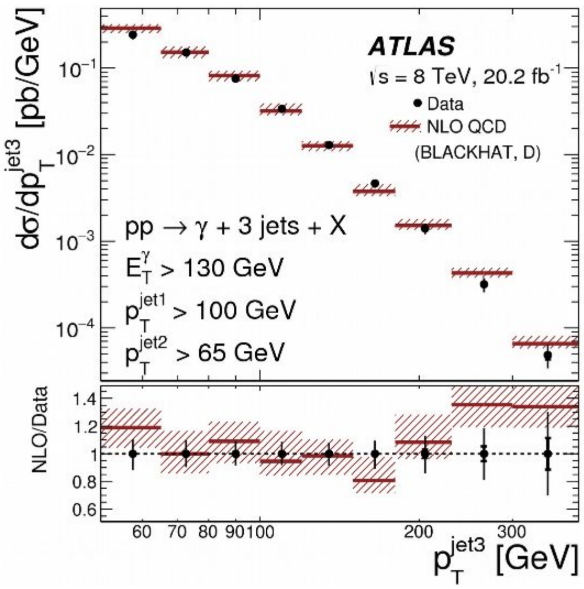


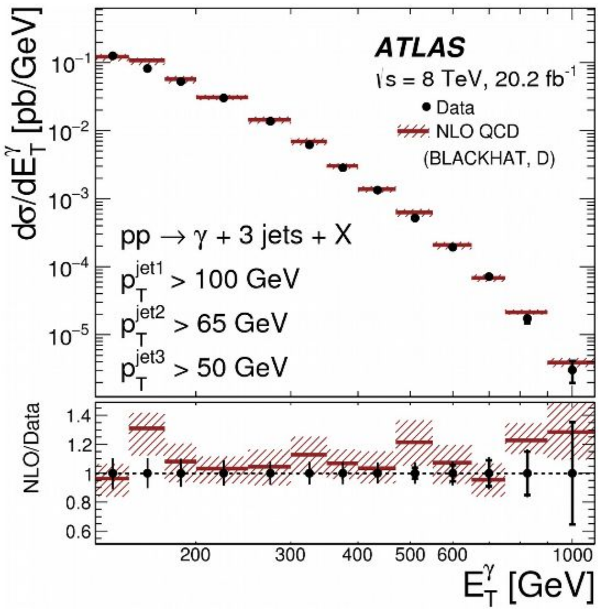
- Enhancements in the directions towards the beams
- Better agreement with SHERPA

Photon + 3 jets at 8 TeV

Nucl.Phys. B918 (2017) 257-316

- First measurement at ATLAS
- BlackHat calculation slightly overestimates the data

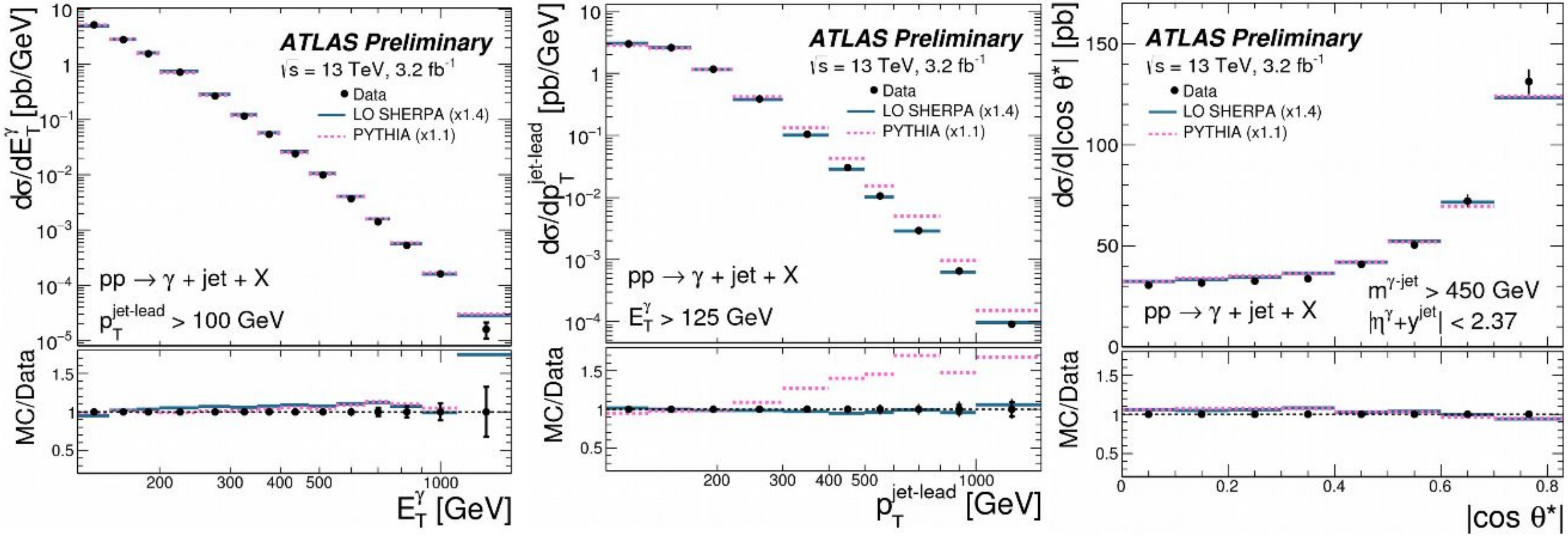




Photon + 1 jet at 13 TeV

ATLAS-CONF-2017-059

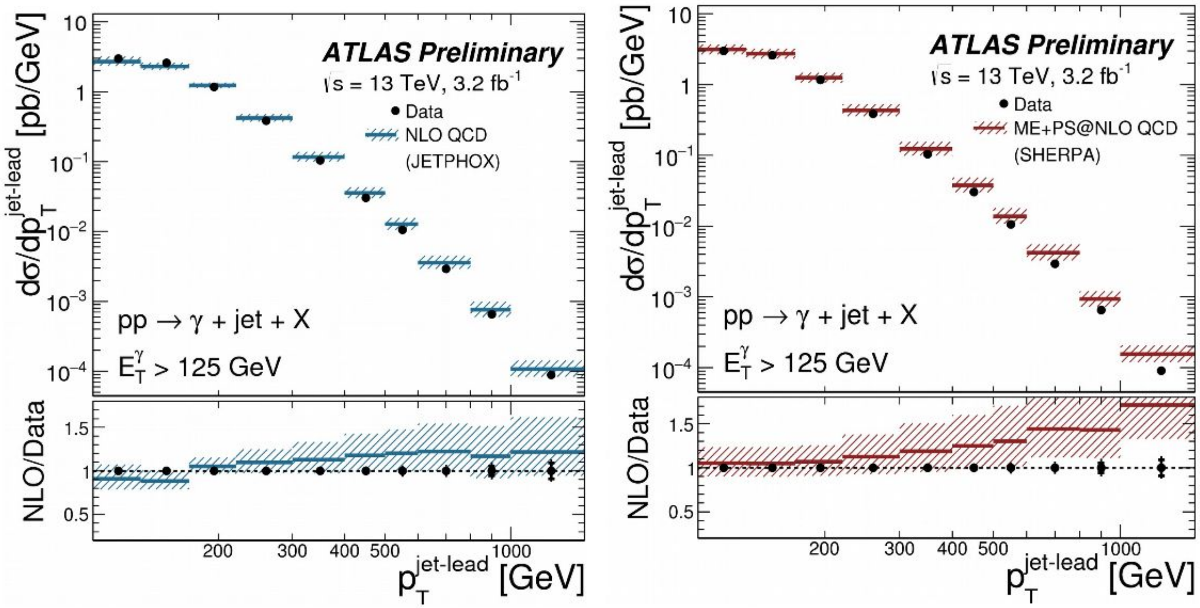
- Extended reach to E_T = 1.5 TeV
- Sherpa describes well the data
- Pythia overestimates jet P_T
  - large contribution from photon bremsstrahlung
- Both simulations describe angular distributions



Photon + 1 jet at 13 TeV

ATLAS-CONF-2017-059

- NLO predictions



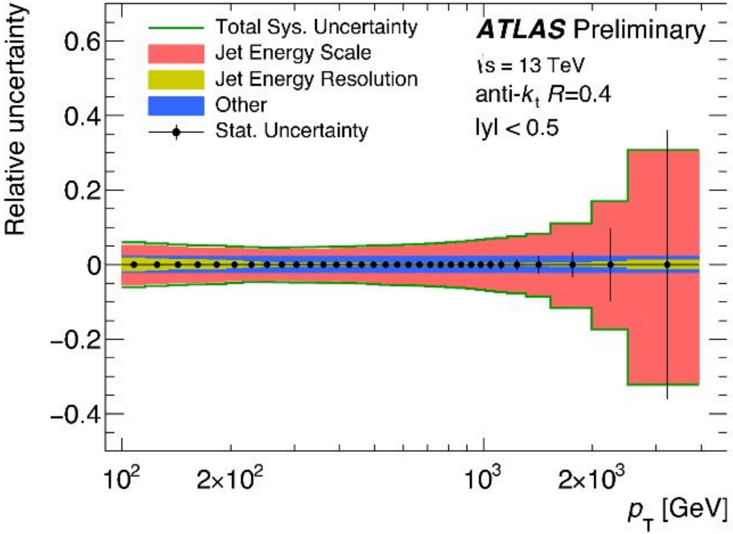
- JetPhox does the best job
- Sherpa (ME+PS@NLO QCD) fails to describe high jet P_T
- Theoretical uncertainties > experimental. Main contribution: terms beyond NLO

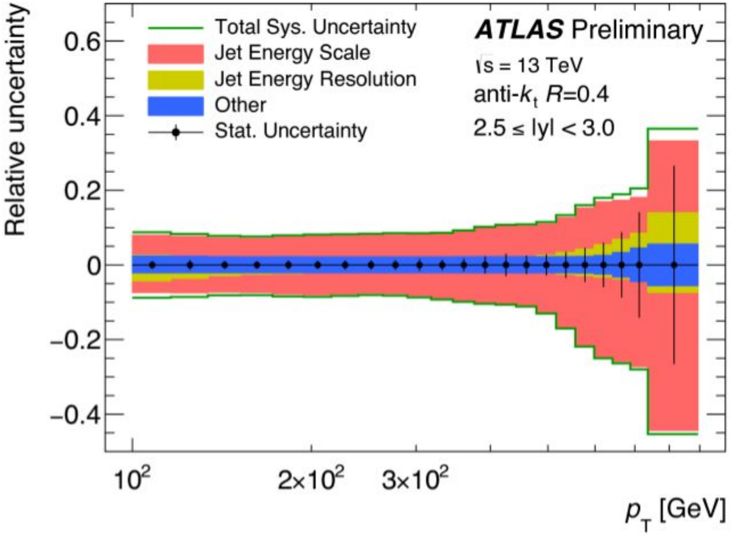
Inclusive jet production at 13 TeV

ATLAS-CONF-2017-048 (8 TeV measurement in arXiv:1706.03192)

- Measurement based on 3.2 fb^{-1} of data taken in 2015
  - R=0.4 anti-k_T jets
  - jet p_T > 100 GeV, jet rapidity |y| < 3

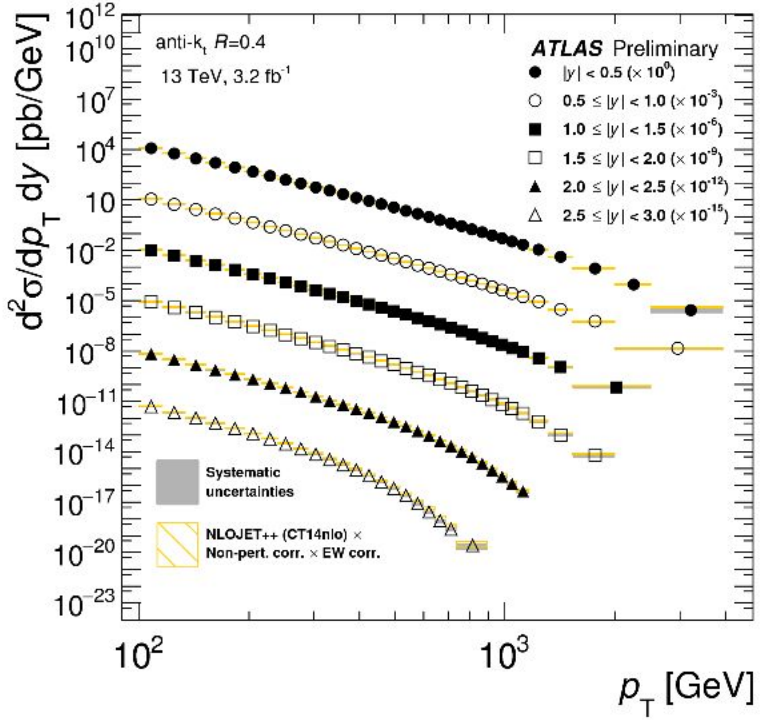
- Double differential measurement in jet p_T and y
  - jet energy scale and resolution uncertainties generally below 5% central, 10% forward





Inclusive jet production at 13 TeV

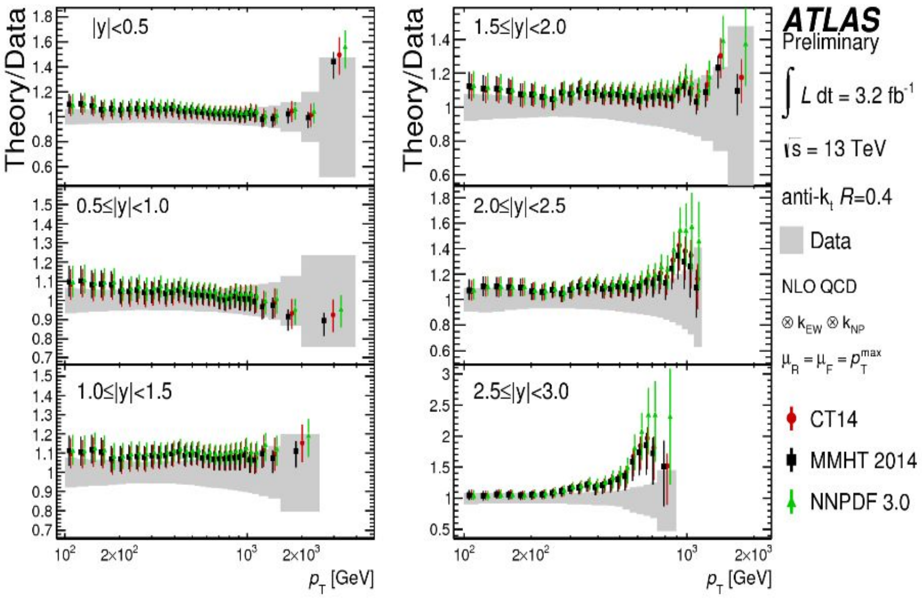
ATLAS-CONF-2017-048

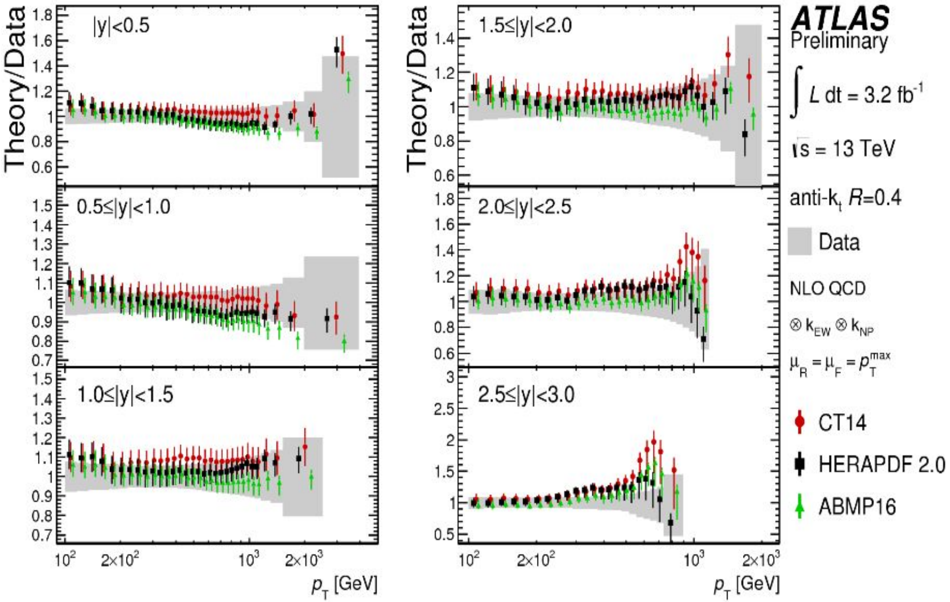


- Increased p_T reach wrt Run1 measurement (up to 3 TeV!)
- Good agreement with NLO predictions at log scale

Inclusive jet production at 13 TeV

ATLAS-CONF-2017-048



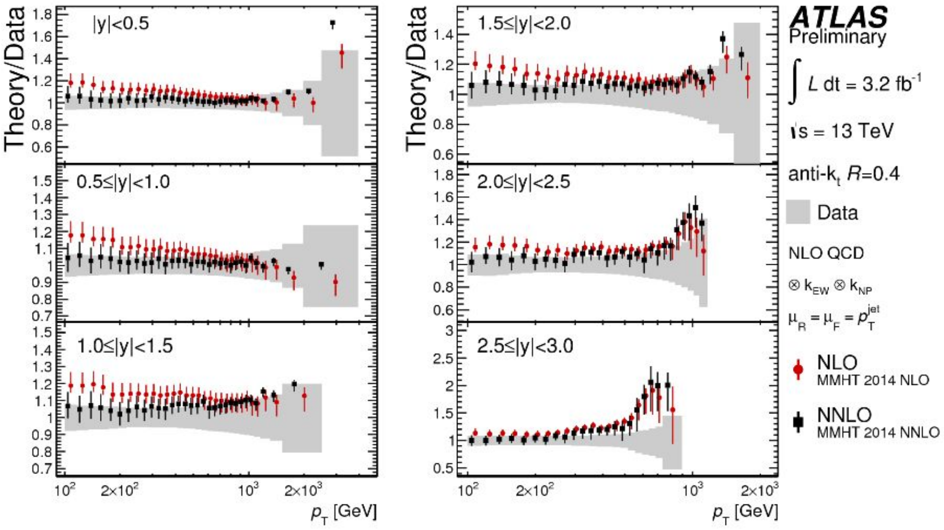


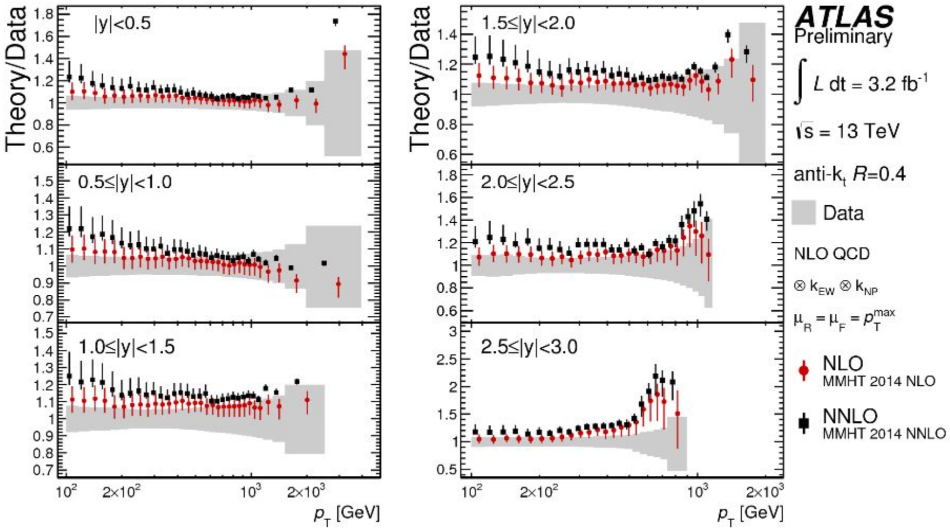
- Generally good agreement with NLO pQCD within uncertainties
- Shape consistent between various PDF sets
  - Exceptions are HERAPDF 2.0 and ABMP16 in the central region
- LO tends to overshoot data for |y| > 2.0 with CT14, MMHT 2014 & NNPDF 3.0

Inclusive jet production at 13 TeV

ATLAS-CONF-2017-048

- NNLO pQCD based on arXiv: 1611.01460v2, arXiv: 1704.00923
- Generated using the NNLOJET program & MMHT 2014 NNLO PDF
- Ratio of NLO and NNLO theory predictions to data





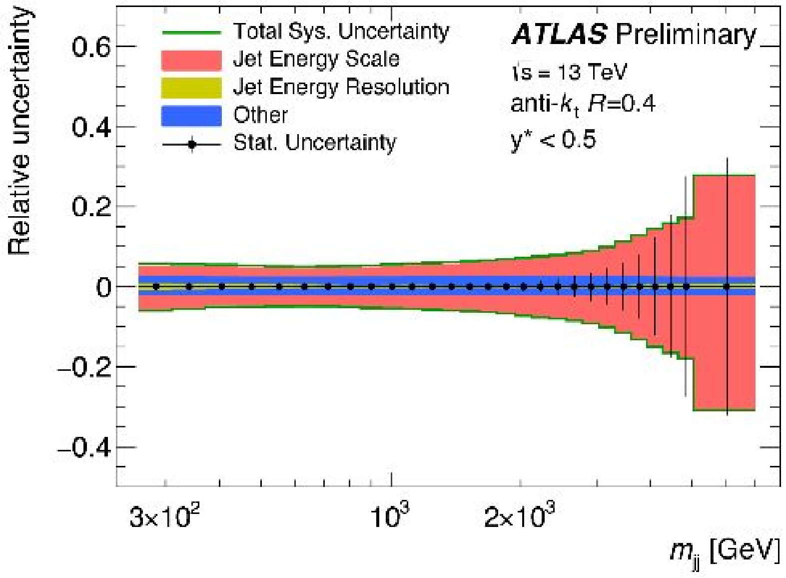
- p_T^{jet} better than p_T^{max} for the QCD scale

Dijet production at 13 TeV

ATLAS-CONF-2017-048

- Measurement based on 3.2 fb^{-1} of data taken in 2015
  - R=0.4 anti-k_T jets
  - jets with p_T > 75 GeV, jet rapidity |y| < 3
  - $H_{T2} = p_{T1} + p_{T2} > 200$ GeV
    - Reduces instabilities in the NLO cross-section calculation

- Double differential measurement in M_{jj} and $y^* = |y_1 - y_2| / 2$

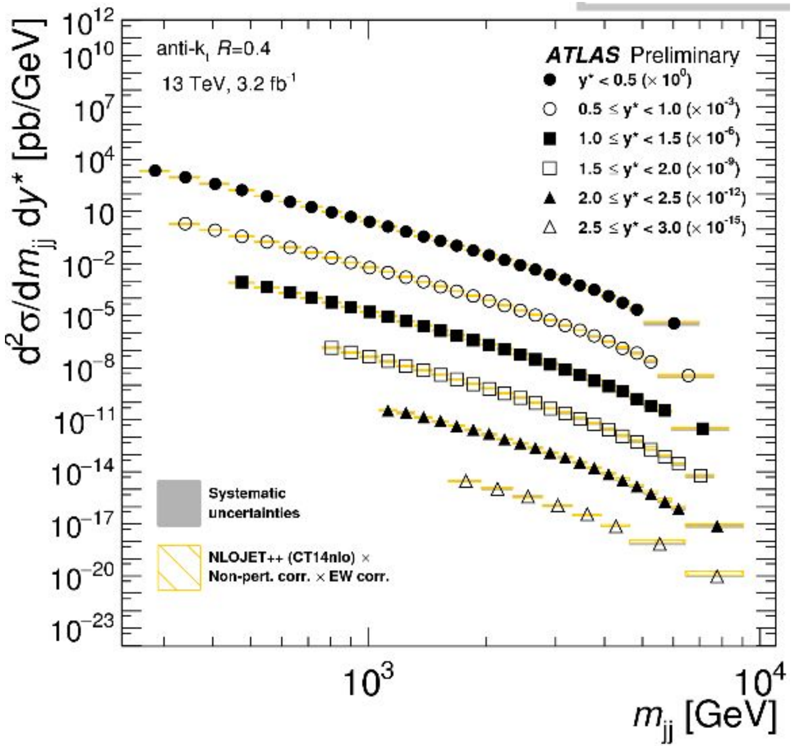


- Experimental systematic uncertainties near 5% for medium M_{jj}, rising to 30% at highest M_{jj}

Dijet production at 13 TeV

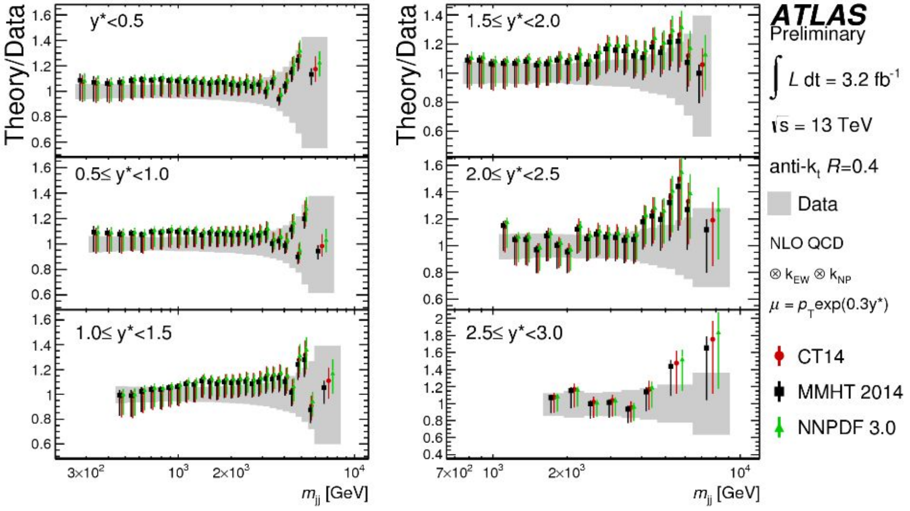
ATLAS-CONF-2017-048

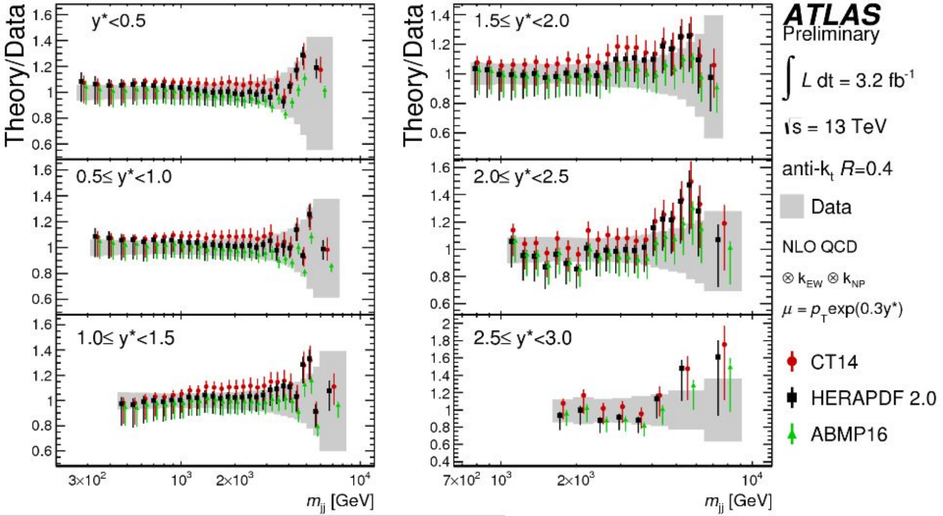
- First measurement of dijet cross-section at 13 TeV



Dijet production at 13 TeV

ATLAS-CONF-2017-048





- Good agreement between NLO pQCD and data within uncertainties
- Detailed χ^2 tests made for each PDF set
    - fair agreement in individual M_{jj} and y* bins
    - fair agreement as well when fitting to all y* regions

TEEC in multi-jet events at 8 TeV

arXiv:1707.02562

- Transverse energy-energy correlation (TEEC):

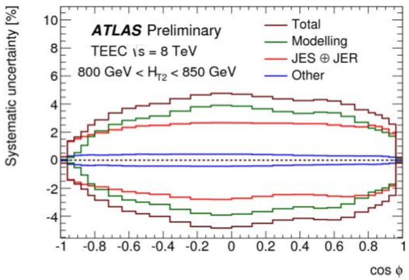
$$\frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d(\cos\phi)} x_{Ti}x_{Tj}dx_{Ti}dx_{Tj}$$

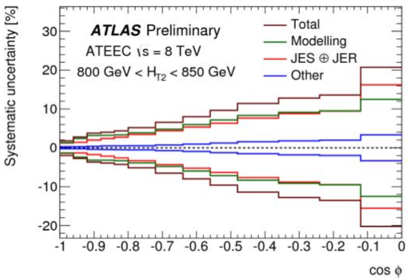
where $x_{Ti} = E_{Ti}/E_T$ and $E_T = \sum_i E_{Ti}$

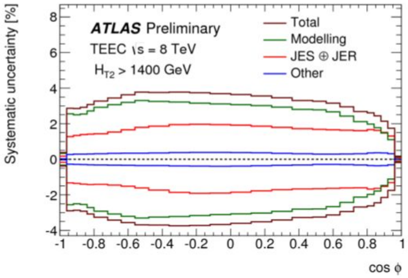
- Event shape used in e^+e^-, adapted to pp
- Essentially an energy-weighted ratio of three-jet to two-jet cross-sections
- Exhibits quadratic dependence on α_s
- Measures angular distributions of jet pairs weighted by

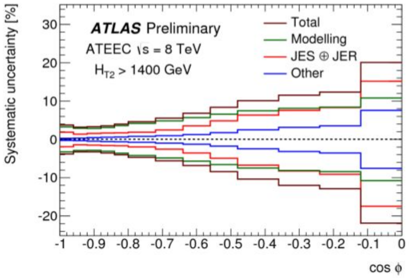
$$w_{ij} = x_{Ti}x_{Tj} = \frac{E_{Ti}E_{Tj}}{(\sum_k E_{Tk})^2}$$

- Analysis strategy:
  - at least 2 jets with $p_T > 100$ GeV, $|y^{jet}| < 2.5$
  - $p_{T1} + p_{T2} > 800$ GeV
  - Total uncertainty is about 5%







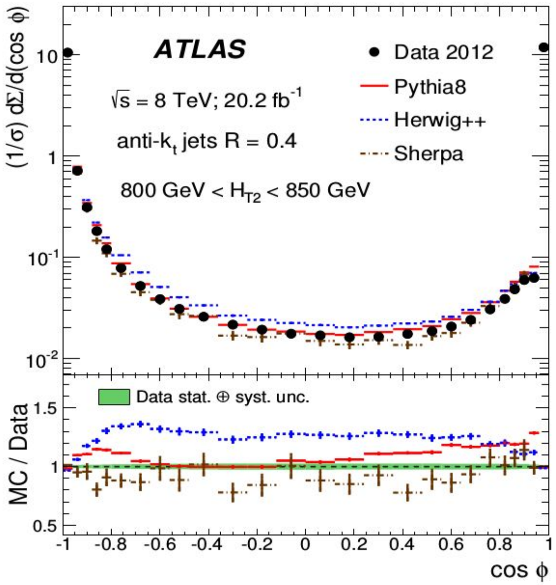


TEEC in multi-jet events at 8 TeV

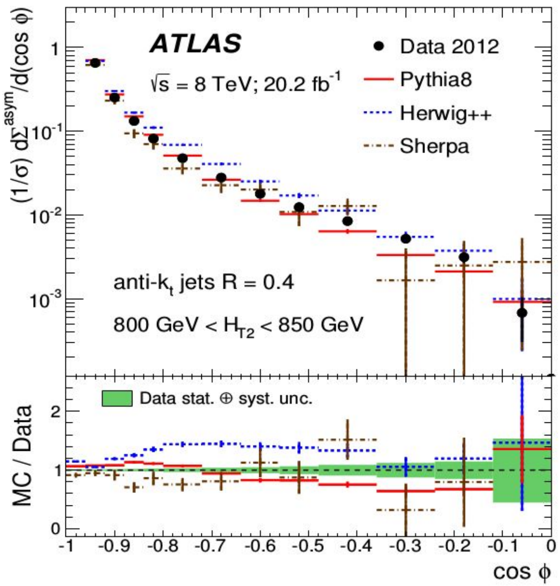
arXiv:1707.02562

- Resulting detector-level distributions are normalized to the total number of events
- Data distributions are unfolded back to the particle level
    - Iterative Bayesian method. Pythia used to build transfer matrix
- Compared with Pythia8, Sherpa, and Herwig++

TEEC



ATEEC

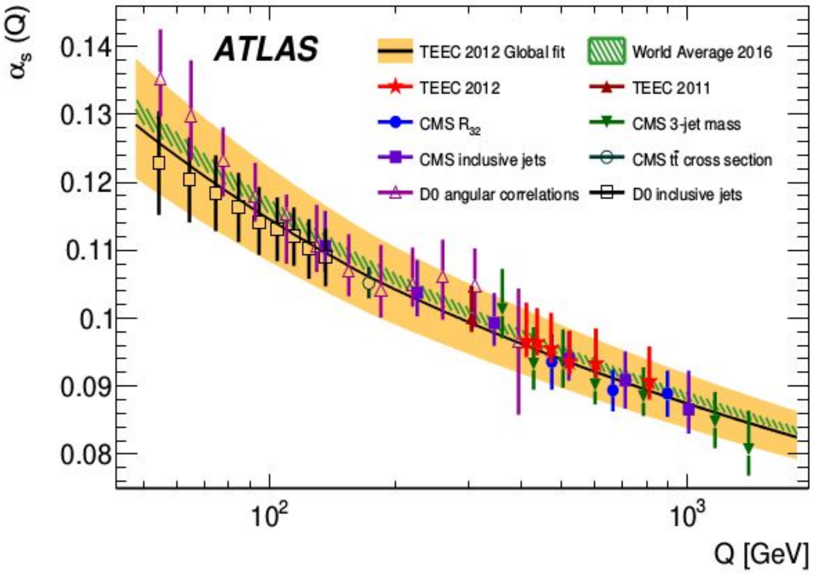


TEEC in multi-jet events at 8 TeV: $\alpha_s(m_Z)$ measurement

arXiv:1707.02562

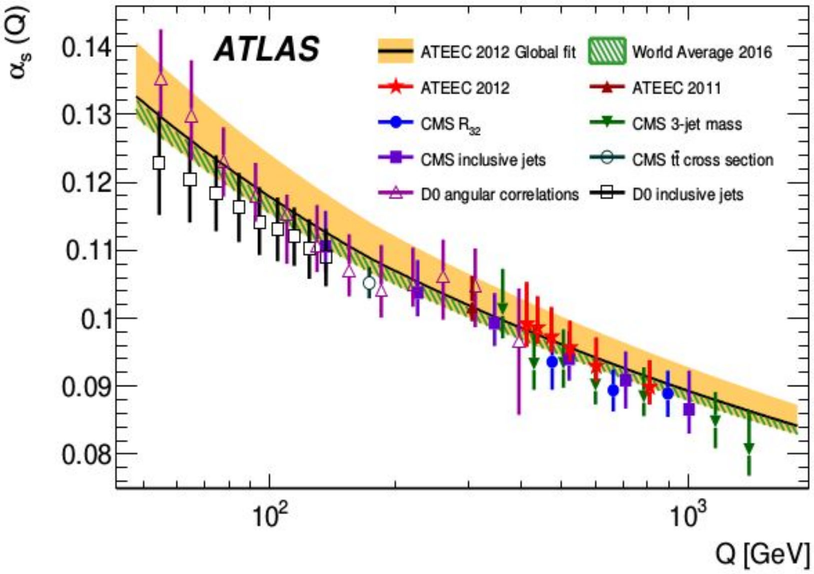
- $\alpha_s(m_Z)$ extraction from χ^2 fit of TEEC and ATEEC NLO predictions to data varying the value of α_s in NLOJet++

TEEC



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

ATEEC



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

- Excellent compatibility between World Average and ATLAS jet-based measurements
- Very good experimental precision. Uncertainty dominated by the unc. in theory predictions

Summary

- **Photon physics**
  - Direct photons at 13 TeV
    - NLO predictions provide an adequate description.
    - Theoretical uncertainties > experimental: NNLO pQCD corrections are needed
  - Diphoton at 8 TeV:
    - Systematic uncertainty decreased by a factor 2 wrt 7 TeV on the cross section
    - Precise probe of QCD infrared emissions (a_T, ϕ_η^*) complementary to Drell-Yan
    - Improvement with NNLO but still more than 2σ away
    - Soft gluon resummation at NNLL (RESBOS) provides a good description of infrared emissions
    - SHERPA 2.2.1 (ME+PS at NLO) provides good predictions at particle level
  - Photon+jet(s) at 8 TeV
    - Very detailed analysis: 6 regions, 35 cross sections
    - First observation of different QCD radiation pattern around the photon and 1st jet
    - Stringent tests of pQCD up to $O(\alpha_{EM}\ \alpha_s^4)$
  - Photon+jet at 13 TeV
    - Comparison with SHERPA ME+PS@NLO

Summary

- **Jet pythics**
  - Inclusive jet cross section at 7, 8 and 13 TeV
    - Good agreement of pQCD at NLO
    - NNLO comparisons
    - Test of PDFs particularly in the forward rapidities
  - First measurement of dijet cross-sections at 13 TeV
  - Transverse energy-energy correlations in dijet events
    - Used to extract the strong coupling constant
    - TEEC/ATEEC:

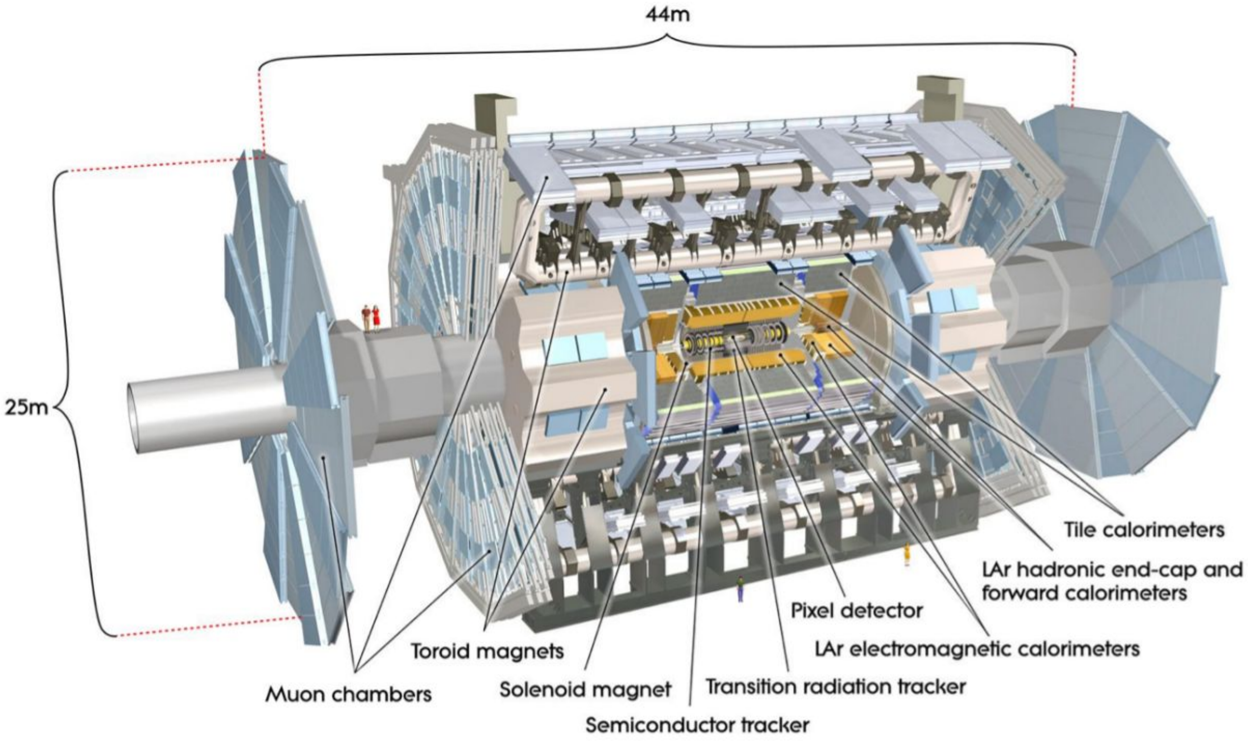
$$\alpha_s(m_Z) = 0.1162 \pm 0.0011\,(\text{exp.})\,^{+0.0076}_{-0.0061}\,(\text{scale}) \pm 0.0018\,(\text{PDF}) \pm 0.0003\,(\text{NP}),$$
$$\alpha_s(m_Z) = 0.1196 \pm 0.0013\,(\text{exp.})\,^{+0.0061}_{-0.0013}\,(\text{scale}) \pm 0.0017\,(\text{PDF}) \pm 0.0004\,(\text{NP}).$$

    - Comparable to 7 TeV result:

$$\alpha_s(m_Z) = 0.1173 \pm 0.0010\,(\text{exp.})\,^{+0.0065}_{-0.0026}\,(\text{theo.})$$

Thanks

The ATLAS detector

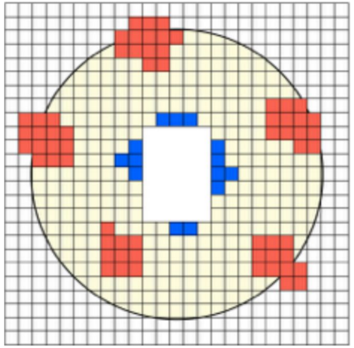


Prompt photon in pp collisions

- In addition to prompt photons, photons are produced copiously inside jets (eg, π^0 decays)
  - it is essential to require isolation to study prompt photons in hadron colliders

- The isolation requirement is based on the energy deposited inside a circle of radius R centered on the photon in the η–ϕ plane (not counting energy depositions coming from the photon itself)

$$E_{\mathrm{T}}^{\mathrm{iso}} \equiv \sum_i E_T^i < E_T^{\mathrm{max}}$$

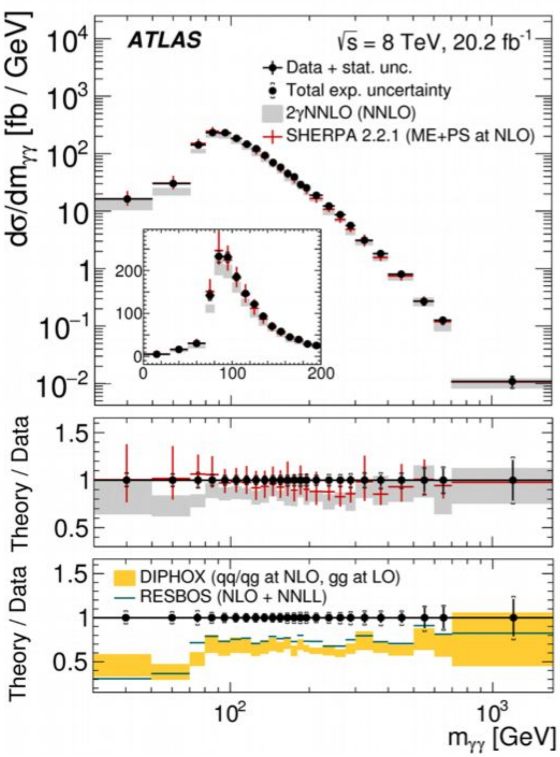


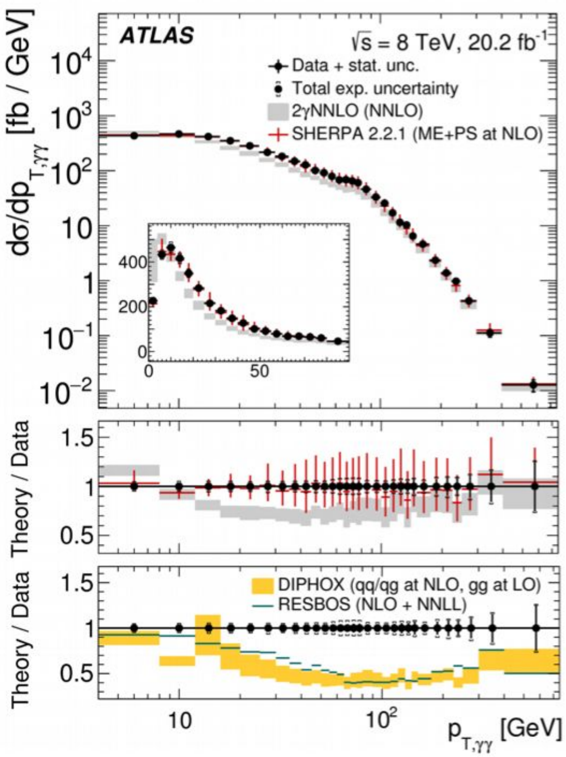
- It is able to suppress most of the contribution of photons inside jets (from π^0's and other neutral mesons decays) and the fragmentation contribution

Diphoton at 8 TeV

Phys. Rev. D 95 (2017) 112005

- In most parts of the phase space, the fixed order predictions are unable to reproduce the data
- Improvement NLO -> NNLO
- SHERPA provides the best description
- 2γNNLO performs well at high mass and P_T

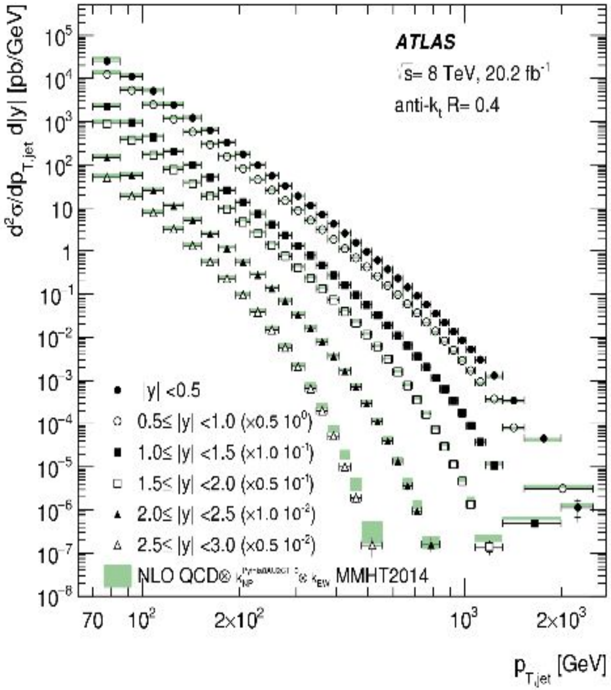


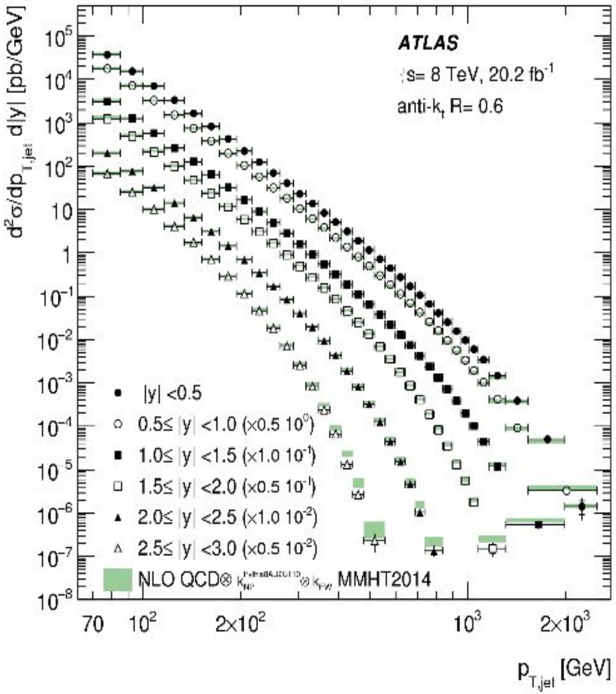


Inclusive jet production at 8 TeV

arXiv:1706.03192

- Selection
  - jet p_T > 70 GeV
  - jet rapidity |y| < 3
- Measurement made with both R=0.4 and 0.6 jets
- Double differential measurement in jet p_T and y



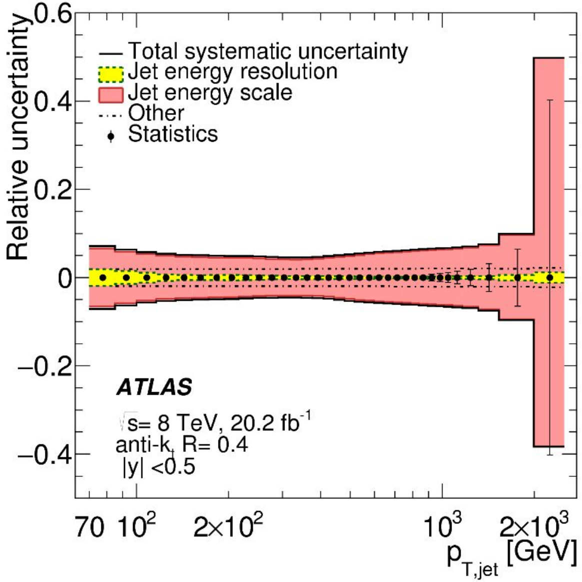


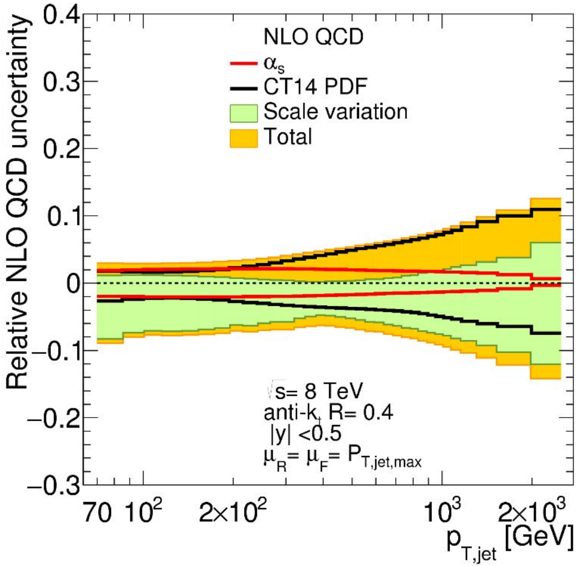
- 11 orders of magnitude for central rapidity!
- Good agreement with NLO theory on log scale

Inclusive jet production at 8 TeV

arXiv:1706.03192

- Dominant experimental uncertainties are jet energy scale and resolution
  - both well below 10% except at highest jet p_T



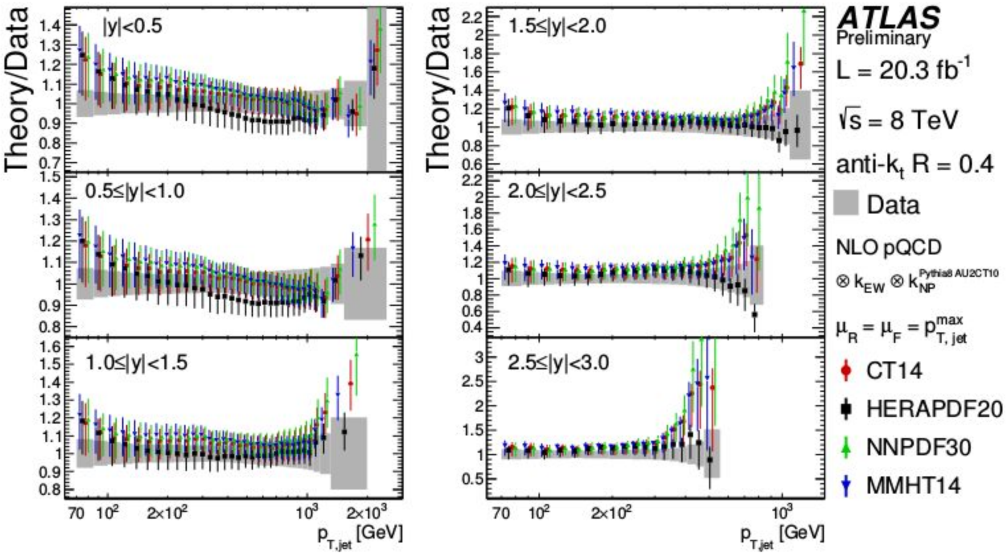


- PDFs, renormalization and factorization scales, α_S variations in theory systematic uncertainty

Inclusive jet production at 8 TeV

arXiv:1706.03192

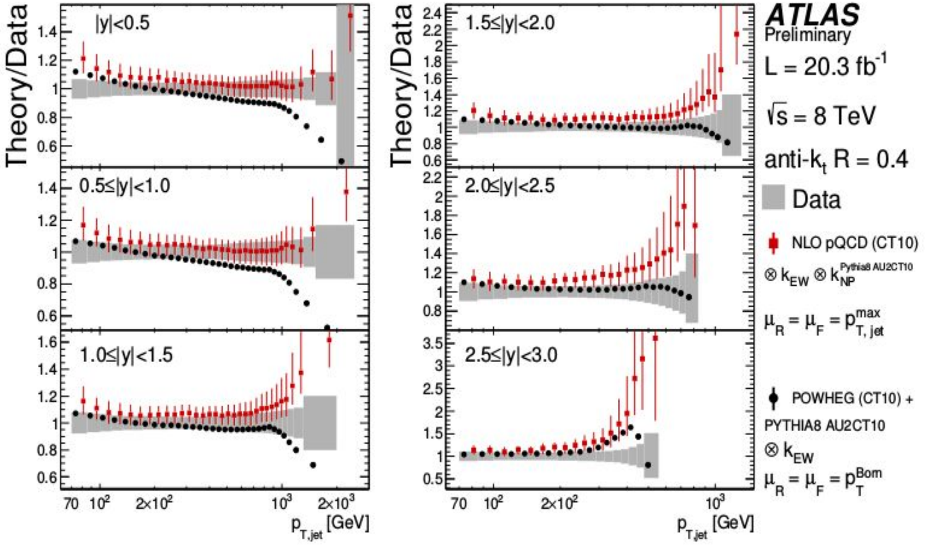
- Theory predictions corrected for non-perturbative and electroweak effects
- Use a variety of PDFs

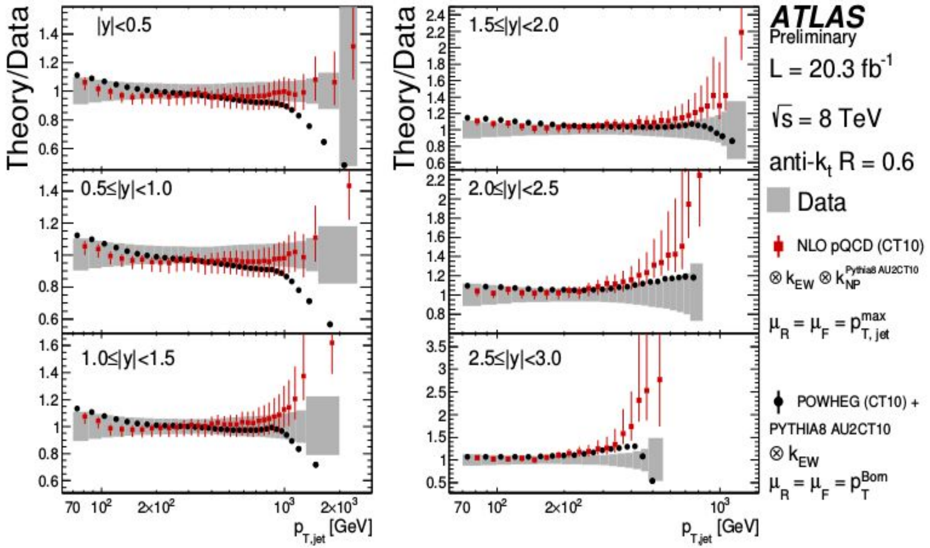


- Good agreement with NLO pQCD prediction (NLOJet++) at higher jet p_T
- NLO overestimates data for jet p_T below 100 GeV and above 1 TeV
- HERAPDF2.0 is significantly lower than data in $300 < p_T < 1000$ GeV

Inclusive jet production at 8 TeV

arXiv:1706.03192



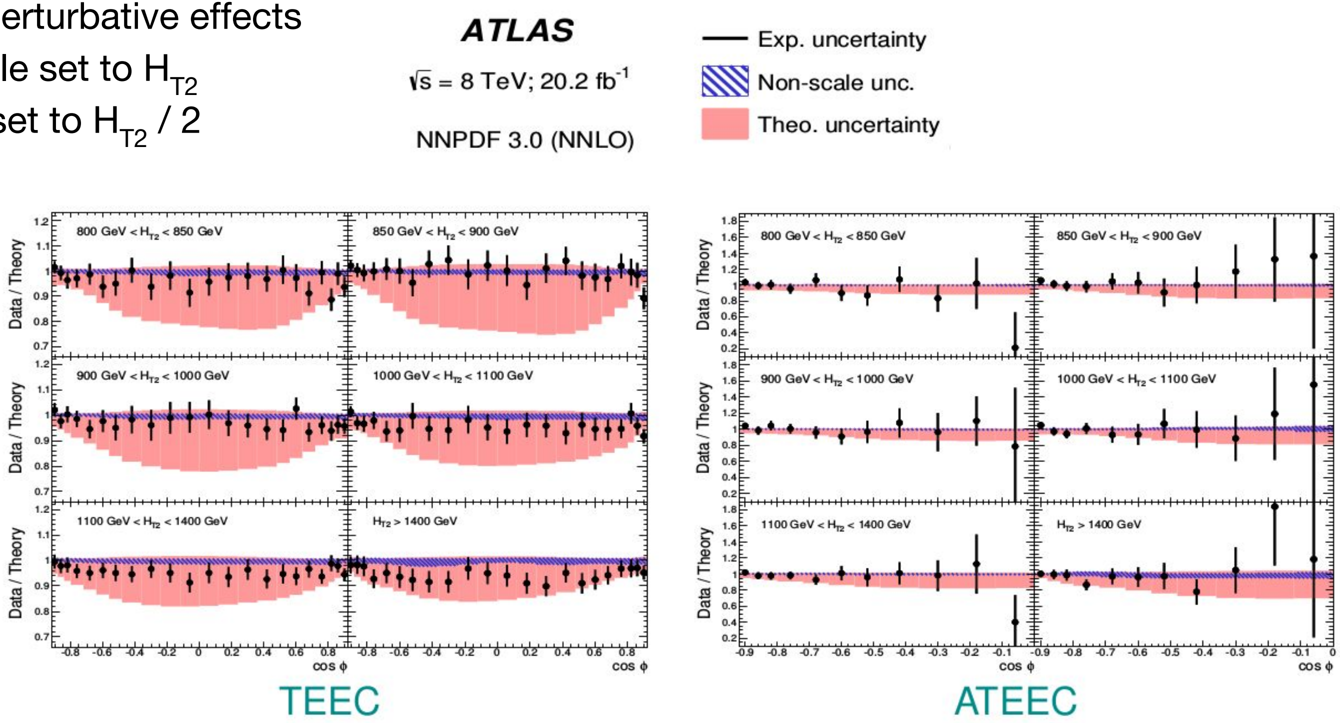


- Powheg (NLO+PS) below NLOJet++ at low p_T
  - tendency to be below the data toward higher p_T
  - for p_T > 1 TeV different behaviour than NLO QCD
- Powheg prediction less dependent on the jet radius

TEEC in multi-jet events at 8 TeV

arXiv:1707.02562

- Compared to NLO pQCD predictions using NLOJET++
  - corrected for non-perturbative effects
  - renormalization scale set to H_{T2}
  - factorization scale set to H_{T2} / 2



- pQCD correctly describes the data within uncertainties