Measurement of the cross section for inclusive isolated-photon production in pp collisions at $\sqrt{s} = 13$ TeV

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ATLAS EXPERIMENT

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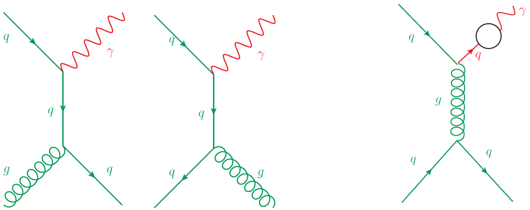
Outline:

- ★ **Introduction**
  - ⋆ **Prompt photon production at LHC**
  - ⋆ **Theoretical predictions**
- ★ **Photons in the ATLAS detector**
  - ⋆ **Photon reconstruction**
  - ⋆ **Photon identification**
  - ⋆ **Photon isolation**
  - ⋆ **Background subtraction**
- ★ **Results**
- ★ **Summary**

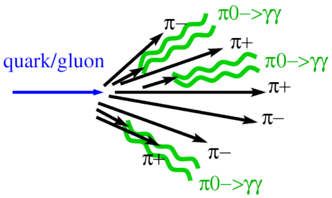
PROMPT PHOTONS

Photons not coming from hadron decays

DIRECT **FRAGMENTATION**



- Test of pQCD with a hard colorless probe
  - ↪ Aid to understand SM background to BSM processes
  - ↪ Useful for MC tuning
- Sensitivity to the gluon PDF already at LO ($gq \to \gamma q$)
  - ↪ Further constraints from measurements of the same process at different $\sqrt{s}$ with correlated uncertainties
- Recent usage of inclusive photon production data in ATLAS:
  - ↪ Investigation of novel approaches to the description of parton radiation arXiv:1606.02696
  - ↪ Importance of resummation of threshold logarithms in QCD and of electroweak corrections arXiv:1606.02313
  - ↪ First calculation of direct photon production at NNLO arXiv:1612.04333



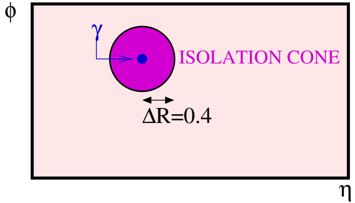
- Photons are copiously produced inside jets due to neutral meson decays
- In most configurations, these photons are **not isolated**

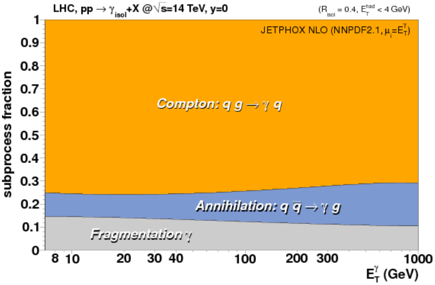
PHOTON ISOLATION

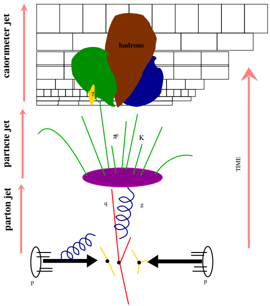
★ The isolation requirement suppresses the contribution of jets containing photons from: meson decays to pair of photons and fragmentation contribution

- In general, a fixed-cone isolation requirement is imposed

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







NLO QCD calculations (parton level)

PYTHIA

- 2→2 processes in matrix element (ME).
- QCD and QED radiation in parton shower

SHERPA

- up to 4 additional partons in ME
- QCD parton shower.

- $\mu_R = \mu_F = \mu_f = E_T^\gamma$
- Five massless quark flavours
- $\alpha_s(m_Z)$ as in the nominal PDF

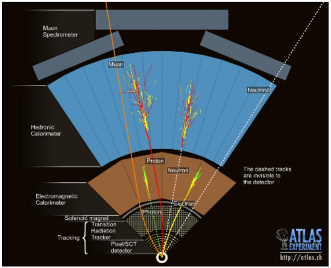
JETPHOX ($pp \to \gamma + X$)

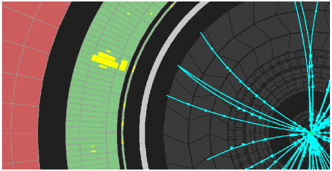
- NLO corrections to direct and fragmentation contributions (**undistinguishable beyond LO**). Different PDFs investigated, BFGII fragmentation function
- Fixed-cone isolation computed with the (few) partons at parton level
- Corrections for hadronisation and underlying event needed: estimated using the MC generators, the multiplicative correction is 1 within 1%

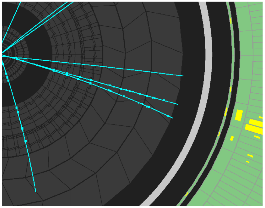
- Theoretical uncertainties on the choice of the scales ($\times 1/2$ or $\times 2$ variations singly or simultaneously), $\alpha_s(m_Z)$, PDFs and non-perturbative corrections

Photon reconstruction in ATLAS

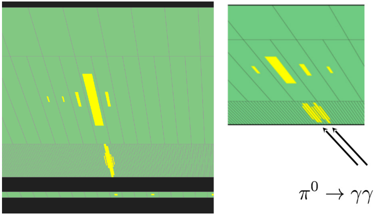
- Photon candidates are reconstructed from clusters of energy in the EM calorimeter (Lead-liquid Argon). Three longitudinal layers:
  - First layer: High granularity in η which allows signal photons identification
  - Second layer: Collects most of the deposited energy
  - Third layer: Used to correct for leakage
- The presampler helps to correct for energy lost upstream of the calorimeter
- Tracking information ($|\eta| < 2.5$) is also used to recover photons decaying into e^+e^- pairs
- Candidates without a matching track or reconstructed conversion vertex in the inner detector are classified as **unconverted photons**
- Candidates with a matching reconstructed conversion vertex or a matching track consistent with originating from a photon conversion are classified as **converted photons**







ATLAS, ATL-PHYS-PUB-2016-014



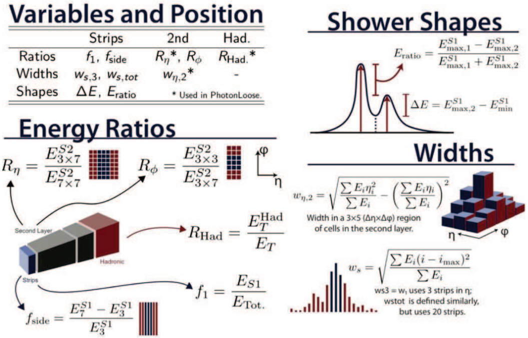
- The characteristics of the energy deposits in the EM calorimeter is used to discriminate signal photons from photons coming from π^0 decays

"Loose" identification criteria

- Ratios: R_{had} (hadronic) and R_η (2^{nd} layer)
- RMS width in the 2^{nd} layer $\omega_{\eta,2}$

"Tight" identification criteria

- Tighten loose criteria
- Ratios R_ϕ (2^{nd} layer), f_{side} (1^{st} layer)
- Shower shapes variables in the 1^{st} layer: E_{ratio} and ΔE
- Widths (1^{st} layer): ω_{s3} and ω_{stot}

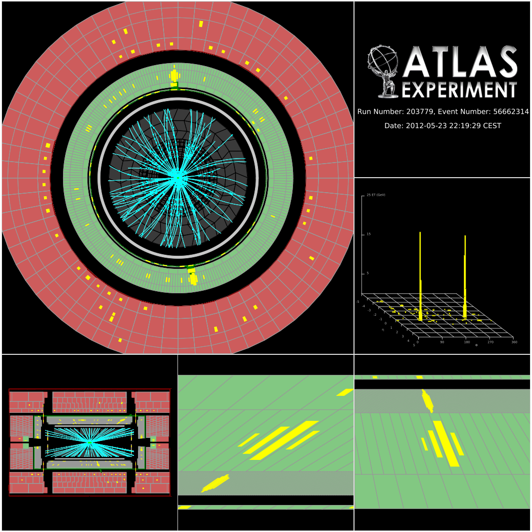


↪ Signal photons considered in this analysis are required to pass the tight id. criteria

Photon isolation in ATLAS

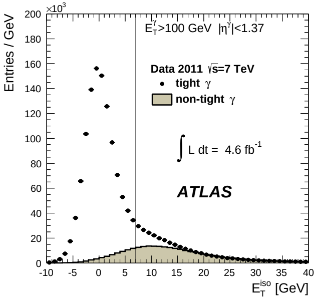
- The isolation transverse energy, $E_T^{\rm iso}$, is computed from topological clusters (EM and HAD) in a cone of $R = 0.4$ excluding the area centered $(\Delta\eta \times \Delta\phi = 0.125 \times 0.175)$ on the photon cluster
- $E_T^{\rm iso}$ is corrected for the photon leakage into the cone
- An additional event-by-event correction helps to suppress the contribution from the pile-up and underlying event to $E_T^{\rm iso}$. The jet-area method is used
- Isolation condition in this analysis:

$$E_T^{\rm iso} < 0.0042 \times E_T^{\gamma} + 4.8 \text{ GeV}$$



→ Residual background contribution even after the application of the isolation and tigh-ID requirements

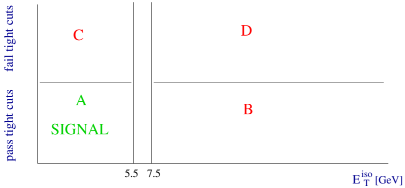
ATLAS, Phys.Rev. D83 (2011) 052005



ATLAS, Phys. Rev. D 89, 052004 (2014)

→ Clear signal observed after applying tight and isolation requirements
→ But residual background contamination remains in the signal region

- Data-driven background subtraction:
  → 2D-sideband method used in the γ_{ID} vs. $E_T^{\rm iso}$ plane
  → The leading loose' photon is classified into one of the four regions in the plane



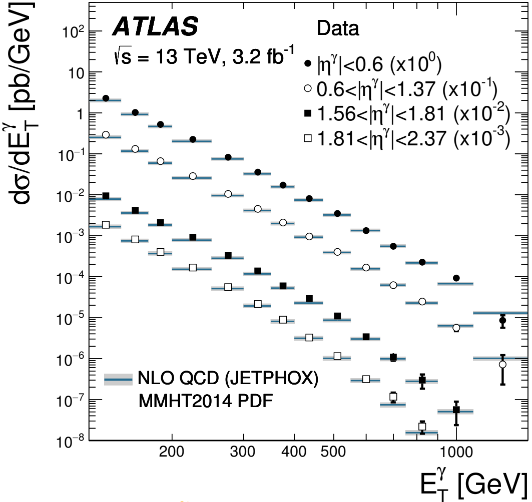
- Loose' definition: Tight cuts on $R_{\rm had}$, R_η, R_ϕ, $\omega_{\eta,2}$, $\omega_{\rm tot,s}$

Assuming no correlation between $E_T^{\rm iso}$ and $\gamma_{\rm ID}$ for the background. And accounting for the signal leakage fractions, ϵ_i (from MC).The final signal yield is extracted using:

$$N_A^{\rm sig} = N_A - (N_C - \epsilon_C N_A^{\rm sig}) \frac{(N_B - \epsilon_B N_A^{\rm sig})}{(N_D - \epsilon_D N_A^{\rm sig})}$$

Inclusive photon production at $\sqrt{s} = 13$ TeV

- Measurement of $d\sigma/dE_T^\gamma$ in four regions of η^γ for $|\eta^\gamma| < 2.37$
- Using $\mathcal{L} = 3.2$ fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV
- $125 < E_T^\gamma < 1500$ GeV
- Unfolded to particle level to the same fiducial volume
- The cross section falls by more than five orders of magnitude
- $d\sigma/dE_T^\gamma$ increases by a factor 2 (10) at 125 (1000) GeV wrt. $\sqrt{s} = 8$ TeV



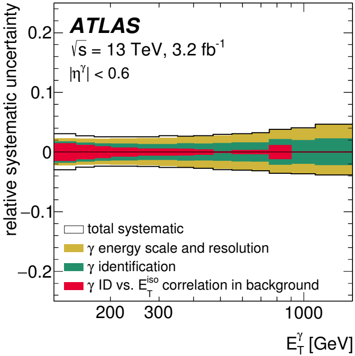
ATLAS, arXiv:1701.06882

- Reach higher in E_T^γ than at 8 TeV (highest E_T^γ: 1.5 (1.6) TeV at 8 (13) TeV)
- Measurements compared with the NLO QCD predictions computed with JetPhox using the MMHT2014 PDF parametrisation
- Good agreement between predictions and the measured cross sections in logarithmic scale

- Primary sources of systematic uncertainties

Stacked histograms

ATLAS, arXiv:1701.06882

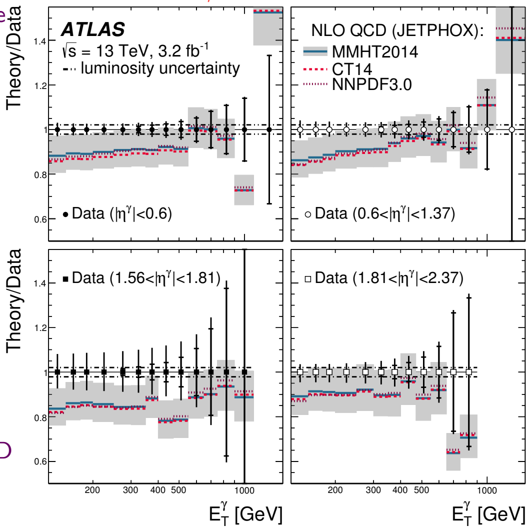


- ▶ The uncertainty in the photon energy scale dominates at high E_T^γ: 2–5% except for $1.56 < |\eta^\gamma| < 1.81$, where it is 7–18%
- ▶ The uncertainty in the photon identification represents also a significant contribution at low E_T^γ: it increases from 1–2% at 125 GeV to 2–6% at ~ 1 TeV
- ▶ The uncertainty in the correlation between the photon identification variables and the isolation is a significant contribution at low E_T^γ: typically smaller than 2%

- Ratio of NLO predictions computed with JETPHOX to data

ATLAS, arXiv:1701.06882

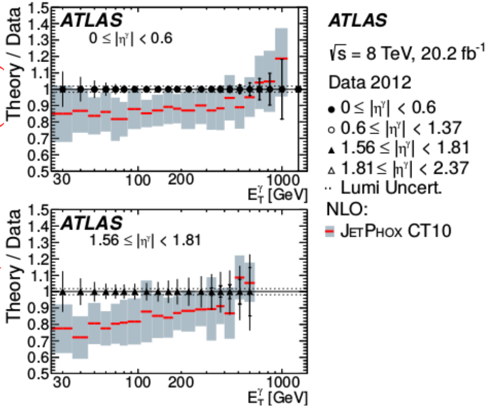
- NLO QCD predictions underestimate the data by up to ≈10–15% depending on E_T^γ and $|\eta^\gamma|$.
- Theoretical uncertainty (10–15%) much larger than experimental uncertainties preventing a more precise test of the SM
- For $E_T^\gamma \gtrsim 600$ GeV the statistical uncertainties limit the measurement
- Results obtained with different PDF parametrizations. No significant differences between them
- NLO QCD provides an adequate description of the data within uncertainties
- Ready for comparison to NNLO QCD calculations!

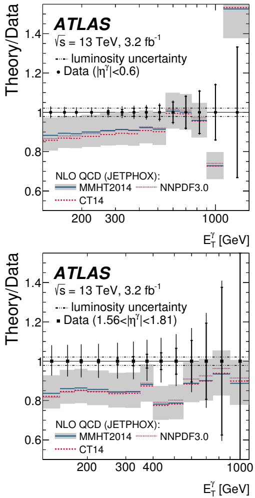


- First measurements of inclusive photon production in the new kinematic regime opened by the $\sqrt{s} = 13$ TeV collisions

Comparison to inclusive photon measurement at $\sqrt{s} = 8$ TeV

ATLAS, JHEP 1608 (2016) 005





ATLAS, arXiv:1701.06882

- Similar comparison to NLO QCD in the region $E_T^\gamma > 125$ GeV
- Similar sizes of theoretical and experimental uncertainties
  ↪ Correlations are under control and, thus, the combination of these two measurements can provide further constraints to the gluon PDF
- Higher reach in E_T^γ, especially in the forward regions where the increase of the differential cross section is of order 10 at high E_T^γ

- **Measurements of $d\sigma/dE_T^\gamma$ in different regions of $|\eta^\gamma|$ at $\sqrt{s} = 13$ TeV**

◇ **First measurement in the new kinematic regime provided by the LHC running at 13 TeV**

◇ **The range $125 < E_T^\gamma < 1500$ GeV is covered**

◇ **Experimental uncertainties smaller than the theoretical uncertainties; room for improvement in the theoretical predictions (NNLO just became available)**

◇ **Experimental input to constrain further the proton PDFs**

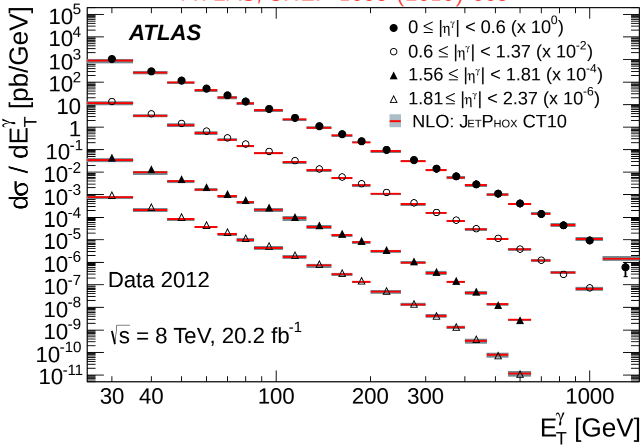
Thank you!

BACKUP

Inclusive photon production at $\sqrt{s} = 8$ TeV

- Measurement of $d\sigma/dE_T^\gamma$ in four regions of η^γ for $|\eta^\gamma| < 2.37$
- Using $\mathcal{L} = 20.2$ fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV
- $25 < E_T^\gamma < 1500$ GeV
- Unfolded to particle level with: $E_T^{\text{iso}} < 0.0042 \times E_T^\gamma + 4.8$ GeV
- The cross section falls by ten orders of magnitude

ATLAS, JHEP 1608 (2016) 005

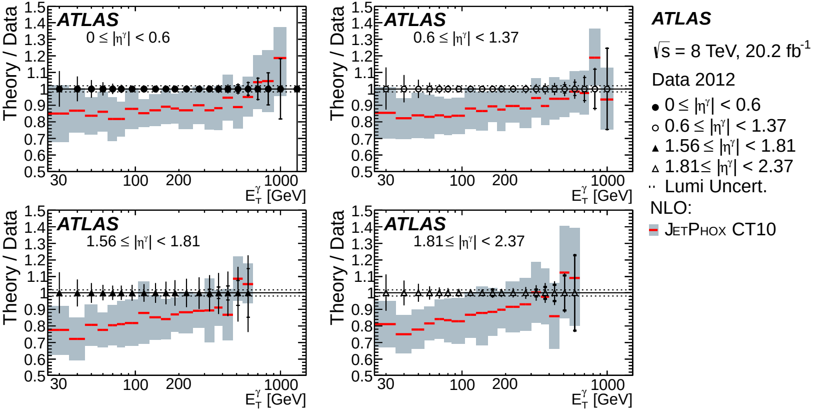


- Significant improvement of the systematic uncertainties
- Measurements compared to the NLO QCD predictions computed with JetPhox using the CT10 PDF parametrisation
- Good agreement between predictions and the measured cross sections in logarithmic scale

Inclusive photon production at $\sqrt{s} = 8$ TeV

- Ratio of NLO predictions computed with JetPhox to data

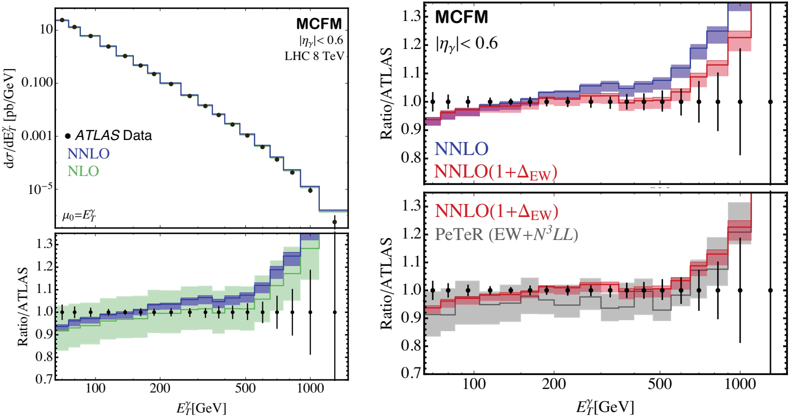
ATLAS, JHEP 1608 (2016) 005



- The NLO QCD predictions underestimate the data by a ≈15–20% in the low E_T^γ range in all regions of $|\eta^\gamma|$.
- Theoretical uncertainty is much larger than experimental uncertainties preventing a more precise test of the SM
- Looking forward to NNLO predictions with reduced theoretical uncertainties (currently dominated by the choice of scales)

- First calculation of direct photon production at NNLO accuracy in QCD
- Infrared singularities regulated using a N-jettiness slicing procedure
- Results were compared to ATLAS 8 TeV data:

J. M. Campbell, R. K. Ellis, C. Williams; arXiv: 1612.04333

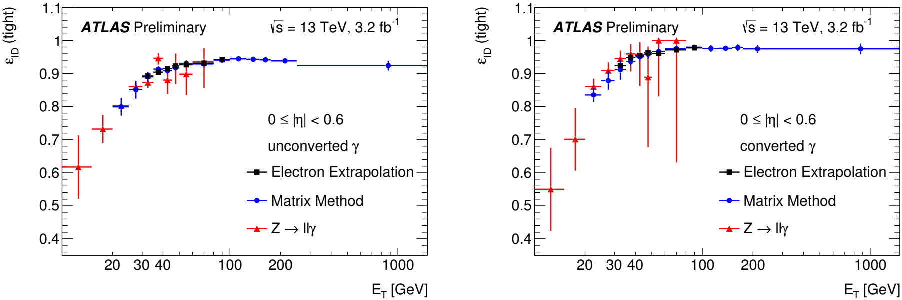


↪ NNLO + EW corrections provide a good description of the data with reduced theoretical uncertainties

ATL-PHYS-PUB-2016-014

UNCONVERTED

CONVERTED



- Data-driven measurements of photon identification efficiency for converted and unconverted photons (extrapolation from $e^{\pm}$, matrix method and radiative Z decays).

Electron and photon calibration in ATLAS

- After electron and photon reconstruction, three main steps are followed:

  - Uniformity corrections are applied to data to equalise the detector response
  - A multivariate regression algorithm calibrates the energy of electromagnetic particles correcting for the energy deposited in front of the calorimeter and outside the cluster
  - The energy scale of electrons is extracted using $Z \to ee$ events through an in-situ procedure

Energy mis-calibration: $E_i^{\text{data}} = E_i^{\text{MC}}(1 + \alpha_i)$

Energy resolution: $\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + \frac{b}{E} + c$

$a \equiv$ sampling term (shower fluctuations)

$b \equiv$ electronic noise term

$c \equiv$ constant term

Energy resolution difference:

$$\left(\frac{\sigma(E)}{E}\right)_i^{\text{data}} = \left(\frac{\sigma(E)}{E}\right)_i^{\text{MC}} + c_i'$$

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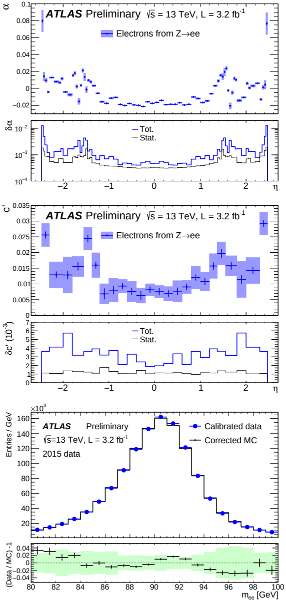
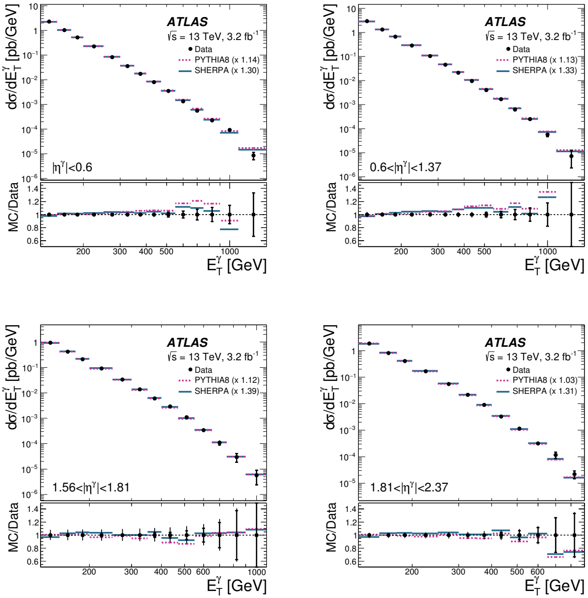


- Comparison to LO +LL parton shower MC generators

ATLAS, arXiv:1701.06882

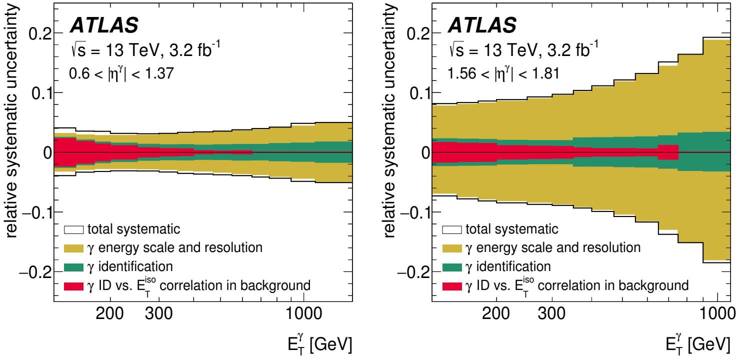


- Predictions of MC generators normalized to data
- Difference in normalization between data and PYTHIA (SHERPA) is 10% (30%)
- Good description of the shape of the distribution by PYTHIA and SHERPA for $E_T^\gamma < 500$ GeV for $|\eta^\gamma| < 1.37$ and in the whole range on E_T^γ for $|\eta^\gamma| > 1.56$
- Leading systematic uncertainty is the one in the photon energy scale

- Primary sources of systematic uncertainties

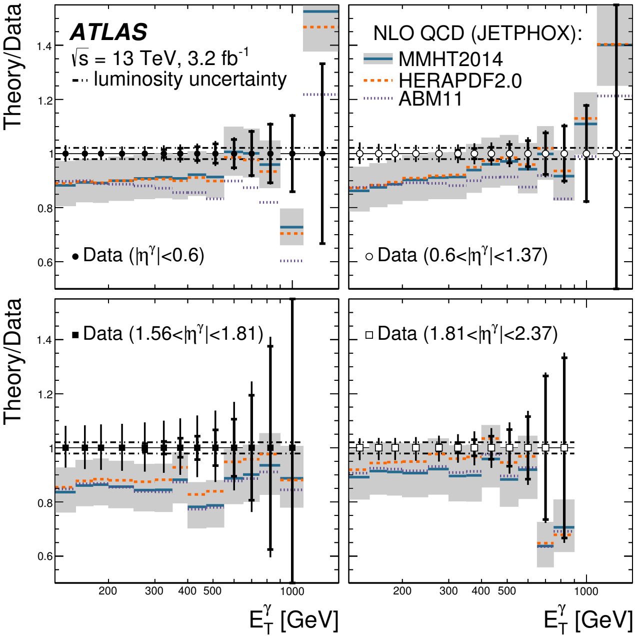
Stacked histograms

ATLAS, arXiv:1701.06882



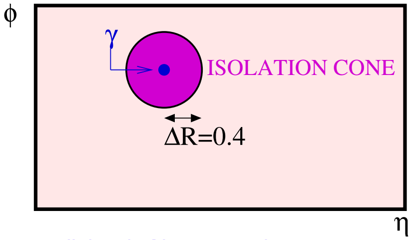
- The uncertainty in the photon energy scale dominates at high E_T^γ: 2–5% except for $1.56 < |\eta^\gamma| < 1.81$, where it is 7–18%
- The uncertainty in the photon identification represents also a significant contribution at low E_T^γ: it increases from 1–2% at 125 GeV to 2–6% at ~ 1 TeV
- The uncertainty in the correlation between the photon identification variables and the isolation is a significant contribution at low E_T^γ: typically smaller than 2%

NLO QCD with other PDFs



ATLAS, arXiv:1701.06882

- The measurements are corrected for detector effects to "particle" level
- The isolation at particle level is computed from all final-state particles (except muons and neutrinos) and corrected using the jet-area method for underlying event effects



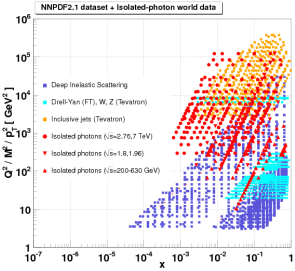
- NLO QCD calculations are performed at "parton" level. Non-perturbative effects (hadronisation and underlying event) are not accounted for
- In order to compare measurements at particle level with NLO QCD predictions correction factors are applied to the latter

$$C_{NP} = \frac{\sigma_{\gamma+X}(MC, \mathrm{particle\quad level, UE})}{\sigma_{\gamma+X}(\mathrm{MC, parton\quad level, noUE})}$$

- Less dependence on the modelling of the final state by having subtracted the "extra" transverse energy contribution to E_T^{iso} with the jet-area method

→ The resulting corrections are found to be consistent with 1 for the inclusive measurements presented here

Impact of inclusive isolated photon measurements on PDFs



- Analysis by D. d'Enterria and J.Rojo (Nucl. Phys. B860 (2012) 311)
- Study of the impact on the gluon density of existing isolated-photon measurements from a variety of experiments, from $\sqrt{s} = 200$ GeV up to 7 TeV

→ Those at LHC are the more constraining datasets

→ reduction of gluon uncertainty up to 20%

→ localised in the range $x \approx 0.002$ to 0.05

- Improved predictions for low mass Higgs production in gluon fusion, PDF-induced uncertainty decreased by 20%