# Measurement of photon and photon+jet production cross sections at $\sqrt{s} = 7$ TeV and constraints to PDFs

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On behalf of the ATLAS collaboration


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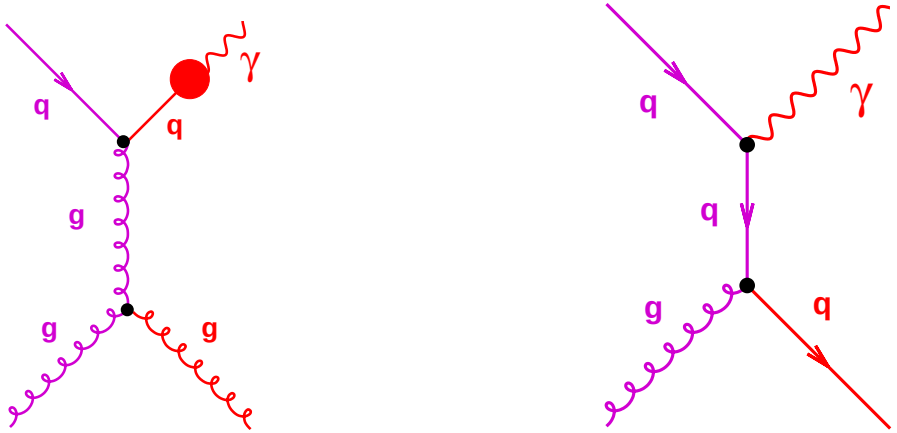
# Isolated prompt photon production

- In proton-proton collisions, high-$p_T$ prompt photons can be produced via two mechanisms:
  - $\rightarrow$ **fragmentation (F) process**
  - $\rightarrow$ **direct photon (DP) process**




$$\sigma^{pp\rightarrow\gamma+X} \sim \int_0^1 \int_0^1 dx_1 dx_2 f_{i/p}(x_1,\mu_F) f_{j/p}(x_2,\mu_F) \sigma^{ij\rightarrow\gamma(I)k} \{D_I(z,\mu_f)\}$$

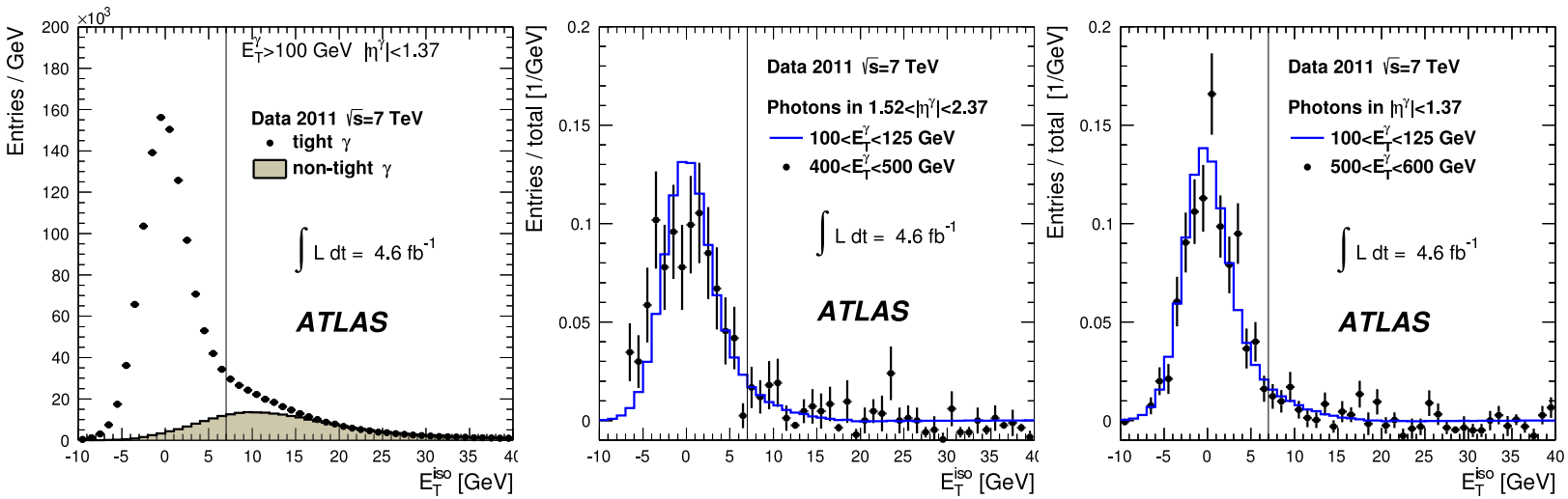
- $\rightarrow$ "sanity checks" of perturbative QCD (pQCD);
- $\rightarrow$ constraint on the gluon PDF in the proton;
- $\rightarrow$ constraint on the contribution of photon fragmentation processes;
- $\rightarrow$ background to Higgs studies and beyond standard model searches;

# Inclusive isolated prompt photon production at $\sqrt{s} = 7$ TeV with $\mathcal{L} = 4.7\ fb^{-1}$

Phys. Rev. D 89, 052004 (2014)

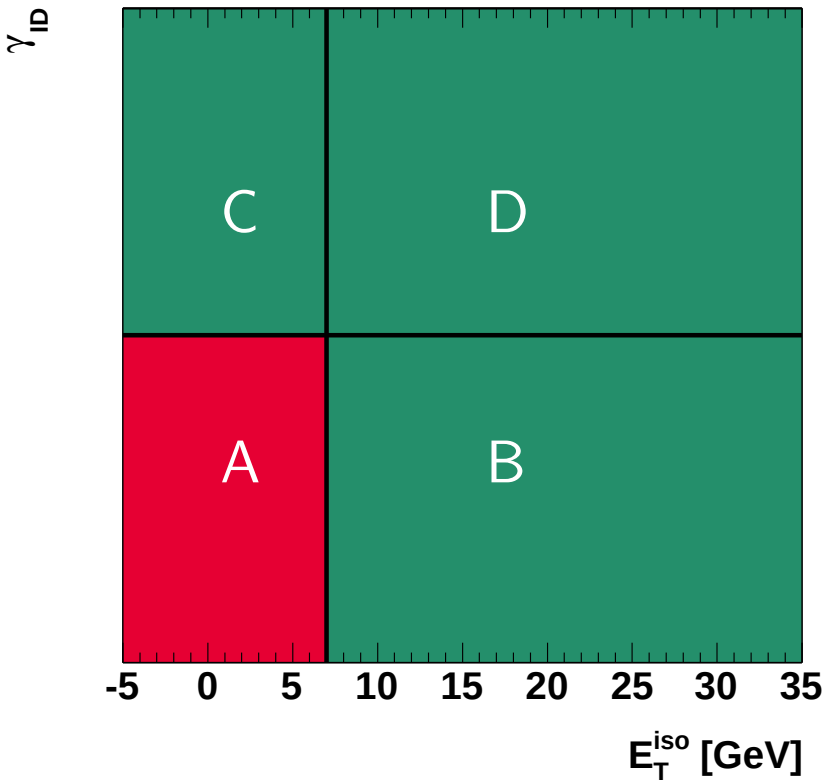
# Photon selection

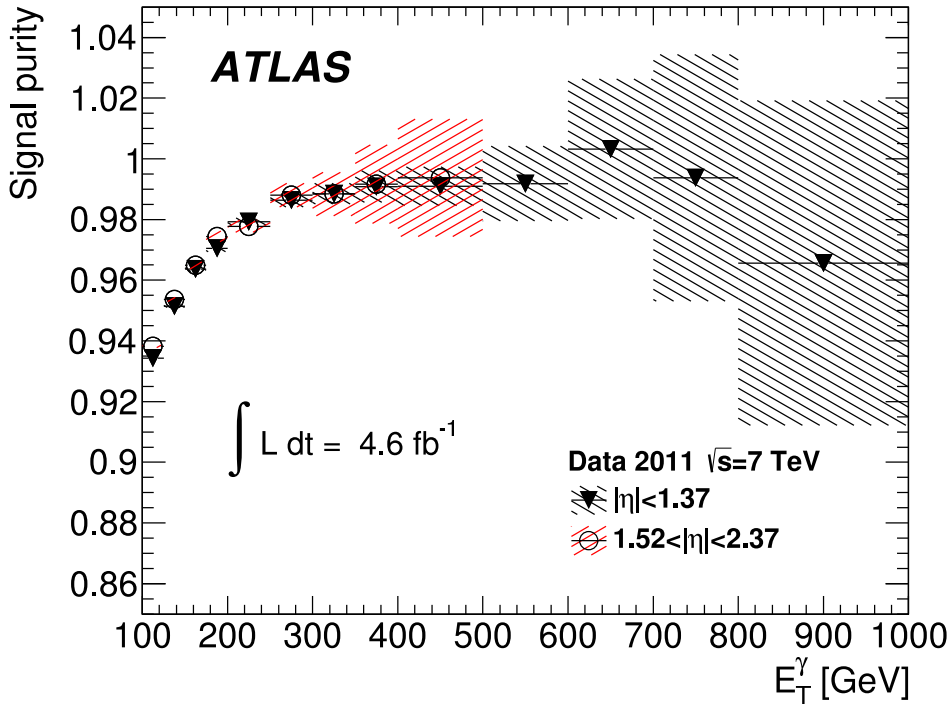
- Photon candidates required to have passed an 80 GeV trigger.
- $E_T^\gamma > 100$ GeV and $0.0 < |\eta^\gamma| < 2.37$ (excluding crack region $1.37 < |\eta^\gamma| < 1.52$)
- Tight ID criteria based on the electromagnetic shower profiles.
- Photon isolation selection $E_T^{\mathrm{iso}} < 7$ GeV
  - $\rightarrow$ computed using calorimeter cells in a cone of radius $\Delta R = 0.4$.
  - $\rightarrow$ the contribution from photon cells excluded in the calculations. ($\eta \times \phi = 5 \times 7$ second layer ECAL cells)
  - $\rightarrow$ small signal leakage from the photon shower outside the $5 \times 7$ region estimated from MC and subtracted.



# Background estimation

- The backgound ($\pi^0, \eta^0 \to \gamma\gamma$) is strongly reduced after ID and isolation cuts
- Residual background is estimated using the "two-dimensional side bands" data driven method.
  - $\to$ based on the definition of a "tight-isolated" signal region A and three background control regions B,C,D: "tight-nonisolated", "nontight-isolated", and "nontight-nonisolated".



# Systematic uncertainties

- The largest uncertainties are:
  - Uncertainty on the photon identification efficiency $\rightarrow \lesssim 2\%$
  - Uncertainty on the photon energy scale $\rightarrow \sim 2\%$ at low $E_T^\gamma$ and 6% at large $E_T^\gamma$
  - Uncertainty on the photon energy resolution $\rightarrow \sim 2\%$
  - Uncertainty on the model dependence $\rightarrow \sim 2\%$ at low $E_T^\gamma$ to 4% at $E_T^\gamma > 800$ GeV
  - Uncertainty on the background subtraction $\rightarrow$ varies between 2% and 3%
  - Uncertainty on the luminosity value $\rightarrow$ 1.8%. Fully correlated among all $E_T$ and $\eta$ bins

$\rightarrow$ Total systematic uncertainty is estimated by summing in quadrature all the contributions

$\rightarrow$ Final systematic uncertainty on the differential and total cross section in the $0.0 < |\eta^\gamma| < 1.37$ ($1.52 < |\eta^\gamma| < 2.37$) region is below 6% (7%)

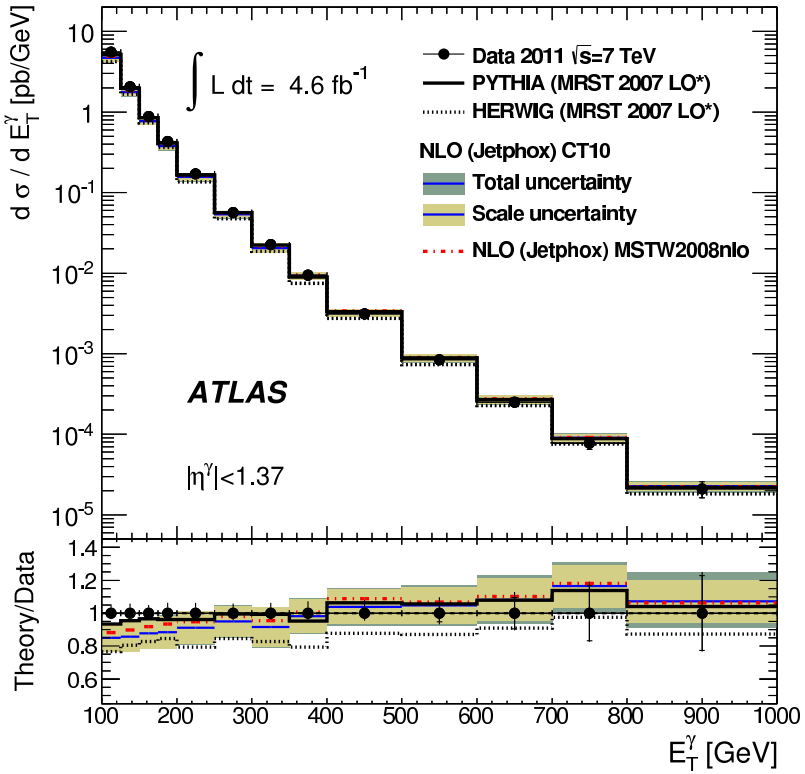
# Theoretical predictions

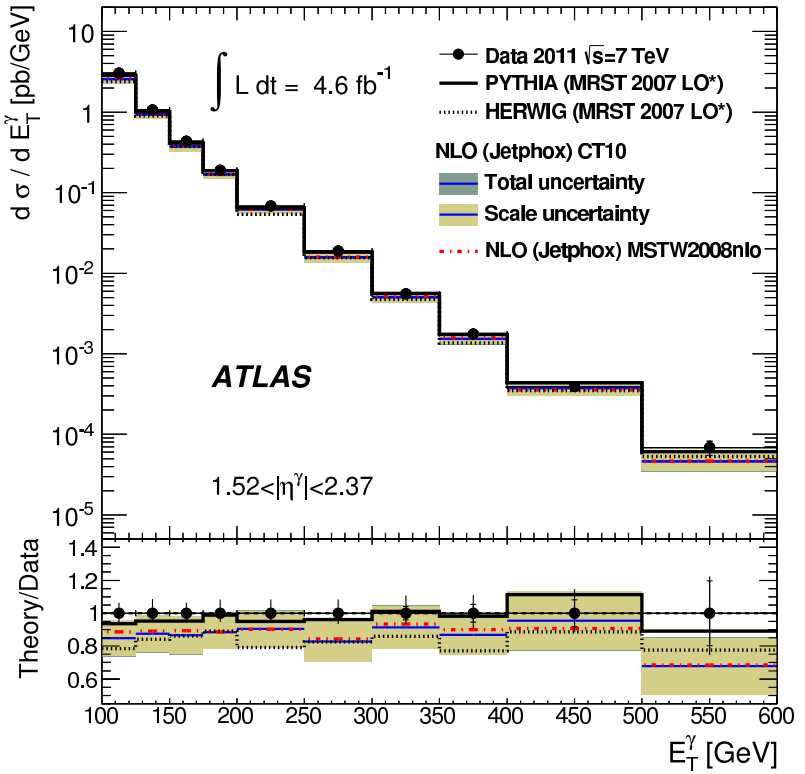
- The NLO QCD ($O(\alpha\alpha_s^2)$) calculations were computed using the program JETPHOX.
  - → parton-level isolation: total $E_T$ from partons inside a cone $\Delta R = 0.4$
  - → calculation uses BFG set II photon fragmentation function
  - → calculation done using CT10 and MSTW2008NLO proton PDFs
  - → $\mu_R = \mu_F = \mu_f = E_T^\gamma$
  - → hadronization + UE correction estimated using PYTHIA and HERWIG with different UE tunes → effect of $\pm$ 1%
- Theoretical uncertainties:
  - → scale uncertainty evaluated by varying the three scales $[\frac{E_T^\gamma}{2}, 2E_T^\gamma]$ → between 12% and 20%
  - → PDFs uncertainty evaluated by repeating the JETPHOX calculation for 52 eigenvector sets of the CT10 PDF → 5% at $E_T^\gamma = 100$ GeV and 15% at $E_T^\gamma \approx 900$ GeV
  - → uncertainty on the value of the $\alpha_s$ evaluated using different CT10 PDF sets with $\alpha_s$ value varied by $\pm 0.002$ around $\alpha_s = 0.118$ → 4.5% with small dependence on $E_T^\gamma$

# Results

→ Cross sections corrected for detector effects using the bin-by-bin method:

$$\left(\frac{d\sigma}{dA}\right)_i = \frac{N_i^{dat,bgs}}{C_i^{MC}\Delta A_i \mathcal{L}}, \text{ with } C_i^{MC} = \frac{N_{i,\mathrm{det}}^{MC}}{N_{i,\mathrm{truth}}^{MC}}$$



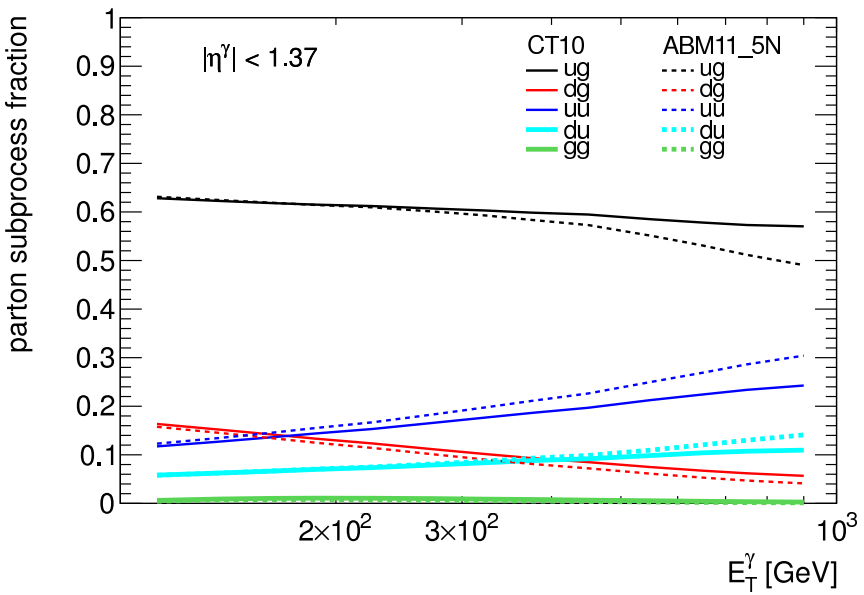

→ NLO lower than data for low $E_T^\gamma$ but in agreement within theoretical uncertainties

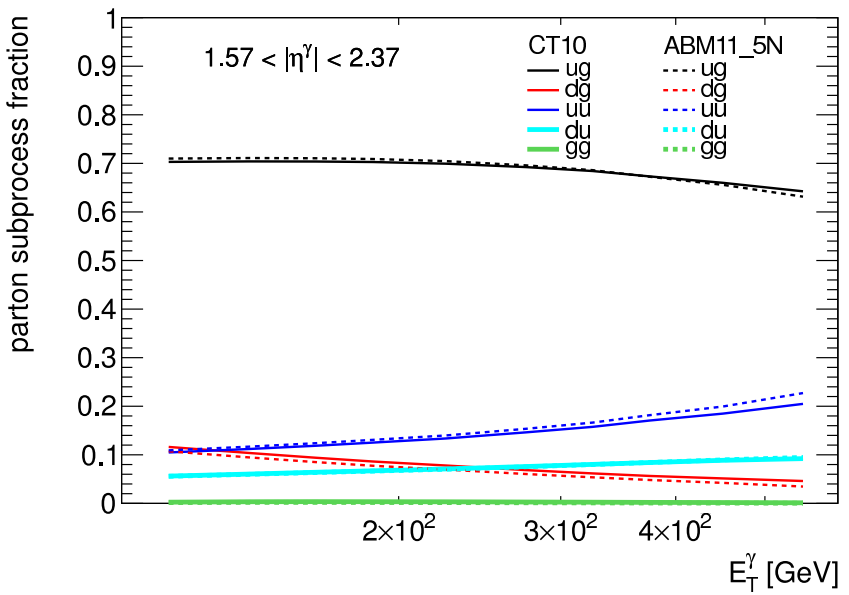
→ PYTHIA model describes fairly well the data.

→ HERWIG falls below the data by 10%-20%

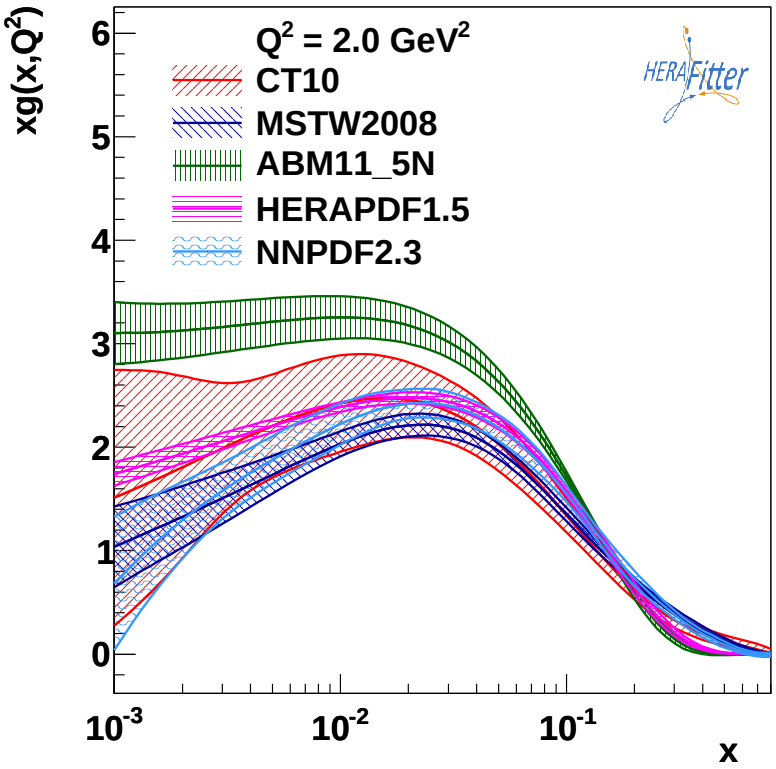
# Sensitivity to the proton parton distributions

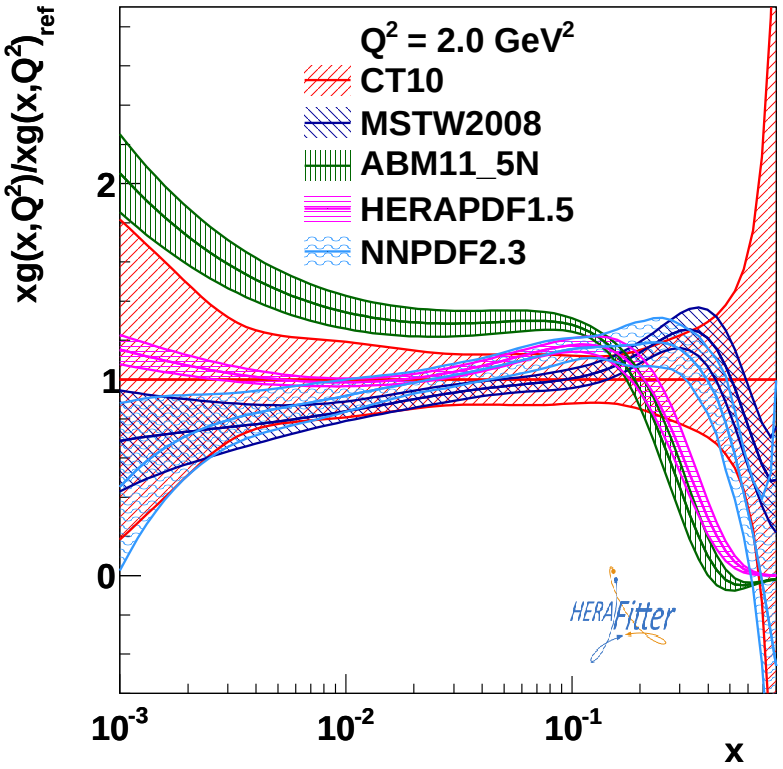
- Inclusive prompt photon production dominated by u-g process.
  - → larger charge of u-type quark and their prevalence in the proton.
  - → sensitive to the gluon pdf.



# Sensitivity to the proton parton distributions

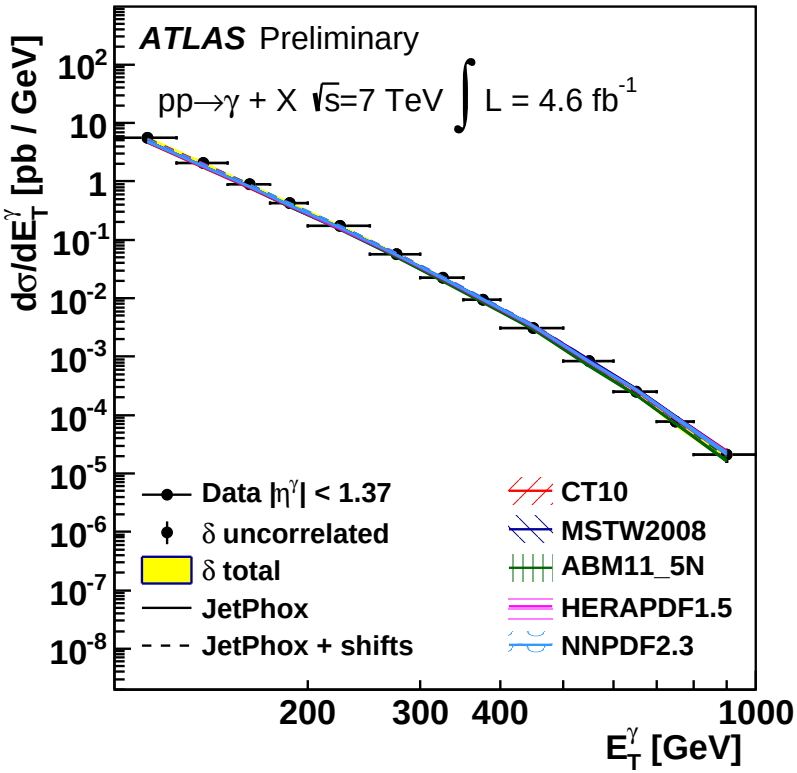


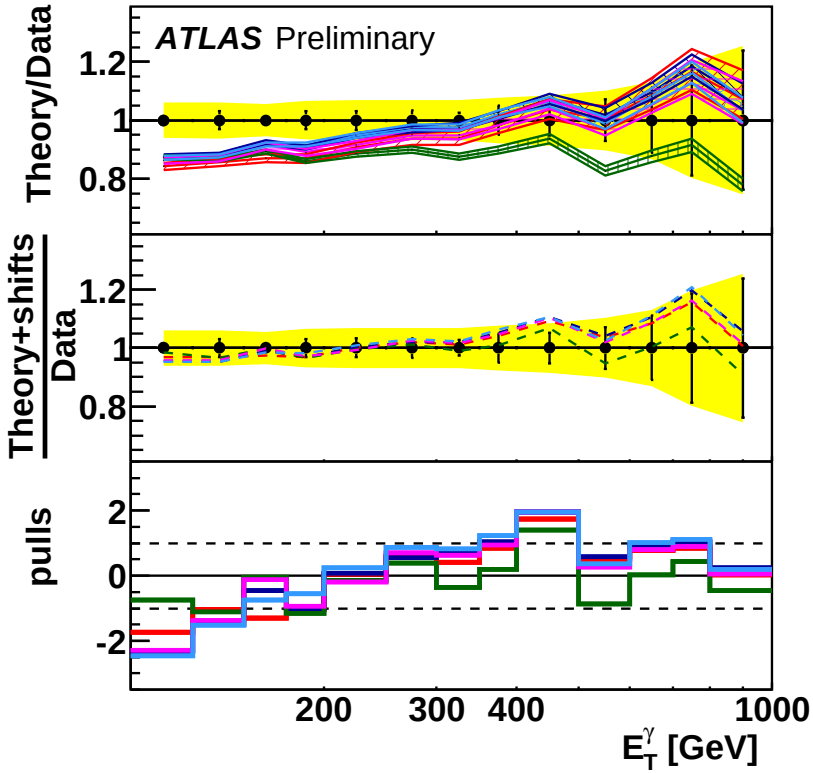




- ABM11_5N PDF has a softer gluon distribution at high-x
  - → contribution from processes with gluons in the initial state is smaller at high $E_T^\gamma$ than that obtained using CT10.

# Sensitivity to the proton parton distributions

- Comparison between JETPHOX prediction with different PDF sets and data.



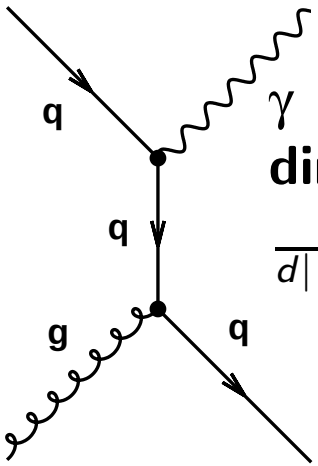

- Tension between data and the predictions of the current PDF sets
- At intermediate $E_T^\gamma$ where data are most precise $\rightarrow$ scale uncertainty is dominant
  - $\rightarrow$ NNLO calculations (currently unavailable) may be necessary to fully exploit the measurement.

# Dynamics of isolated-photon and jet production at $\sqrt{s} = 7$ TeV with $\mathcal{L} = 37\ pb^{-1}$

Nucl. Phys, B 875 (2013) 483-535

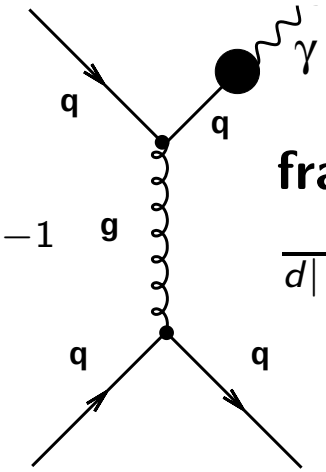
# Dynamics of isolated-photon and jet production: measurements

- The kinematics and dynamics of isolated photon plus jet production was studied by measuring the following cross sections:
  - photon and jet properties: $d\sigma/dE_T^{\gamma}$, $d\sigma/dP_T^{\mathrm{jet}}$, $d\sigma/d|y^{\mathrm{jet}}|$
  - photon plus jet properties: $d\sigma/d\Delta\phi^{\gamma\mathrm{j}}$, $d\sigma/dM^{\gamma\mathrm{j}}$, $d\sigma/d|\cos\ \theta^{\gamma\mathrm{j}}|$
- Cuts $|\eta^{\gamma} + y^{\mathrm{jet}}| < 2.37$, $|\cos\ \theta^{\gamma\mathrm{j}}| < 0.83$ and $M^{\gamma\mathrm{j}} > 161$ GeV were applied for unbiased measurements of $d\sigma/dM^{\gamma\mathrm{j}}$ and $d\sigma/d|\cos\ \theta^{\gamma\mathrm{j}}|$
  $\rightarrow$ angular distribution $d\sigma/d|\cos\ \theta^{\gamma\mathrm{j}}|$ sensitive to the spin of the exchange (virtual) particle: quark (1/2) vs gluon(1).




**direct-photon process**

$$\frac{d\sigma}{d|\cos\ \theta^{\gamma\mathrm{j}}|} \sim (1 - |\cos\ \theta^{\gamma\mathrm{j}}|)^{-1}$$




**fragmentation process**

$$\frac{d\sigma}{d|\cos\ \theta^{\gamma\mathrm{j}}|} \sim (1 - |\cos\ \theta^{\gamma\mathrm{j}}|)^{-2}$$

# Photon/jet selection and background subtraction

- Photon:

→ Photon candidates required to have passed an 40 GeV trigger.

→ $E_T^\gamma > 45$ GeV and $0.0 < |\eta^\gamma| < 2.37$ (excluding crack region $1.37 < |\eta^\gamma| < 1.52$)

→ Tight ID criteria based on the electromagnetic shower profiles.

→ Photon isolation selection $E_T^{\mathrm{iso}}(\mathrm{reco}) < 3$ GeV

- Jet:

→ jets reconstructed with Anti-kt algorithm with R = 0.6

→ $p_T^{\mathrm{jet}} > 40$ GeV and $0.0 < |y^{\mathrm{jet}}| < 2.37$

→ $\Delta R^{\gamma-\mathrm{jet}} > 1.0$

→ Background subtracted using 2D side-band method ($\sim 10\%$)

# Systematic uncertainties

- Main sources of systematic uncertainty (uncertainty quoted for $|cos\theta^{\gamma-jet}|$ cross section):
  - → jet energy scale:$\approx$ 5.0%
  - → jet energy resolution:$\approx$ 1.0%
  - → photon energy scale:$\approx$ 1.0%
  - → photon energy resolution:$\approx$ 0.2%
  - → background subtraction:$\approx$ 3.6%
  - → detector material uncertainty:$\approx$ 5.0%
  - → jet efficiency uncertainty:$\approx$ 2.0%
  - → fudge factor uncertainty:$\approx$ 2.0%
  - → model dependence (HERWIG vs PYTHIA):$\approx$ 1.0%
  - → Brem/Hard admixture dependence:$\approx$ 2.0%
  - → luminosity uncertainty (37.1$\pm$ 1.3 $pb^{-1}$): 3.4%

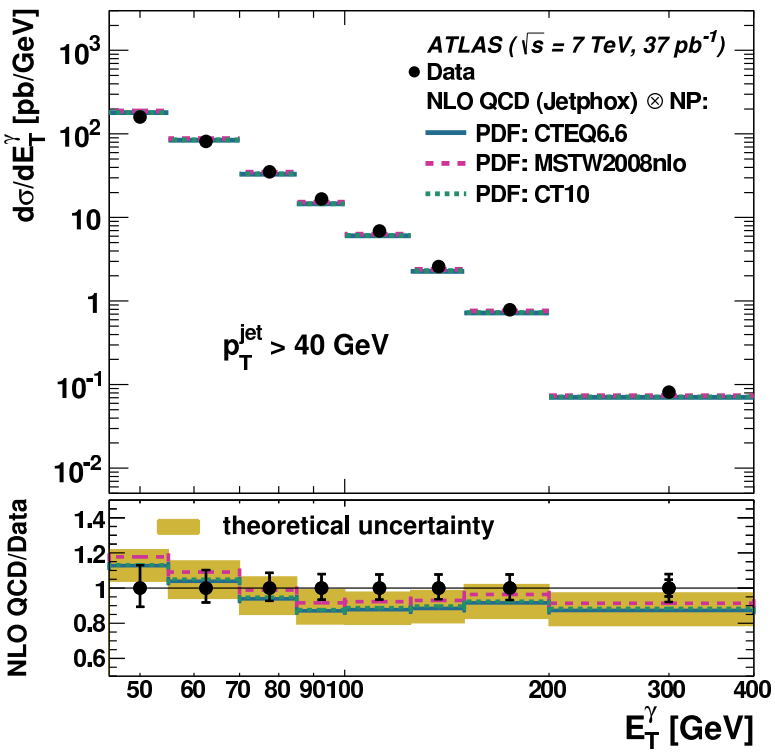
→ Total systematic uncertainty is estimated by summing in quadrature all the contributions

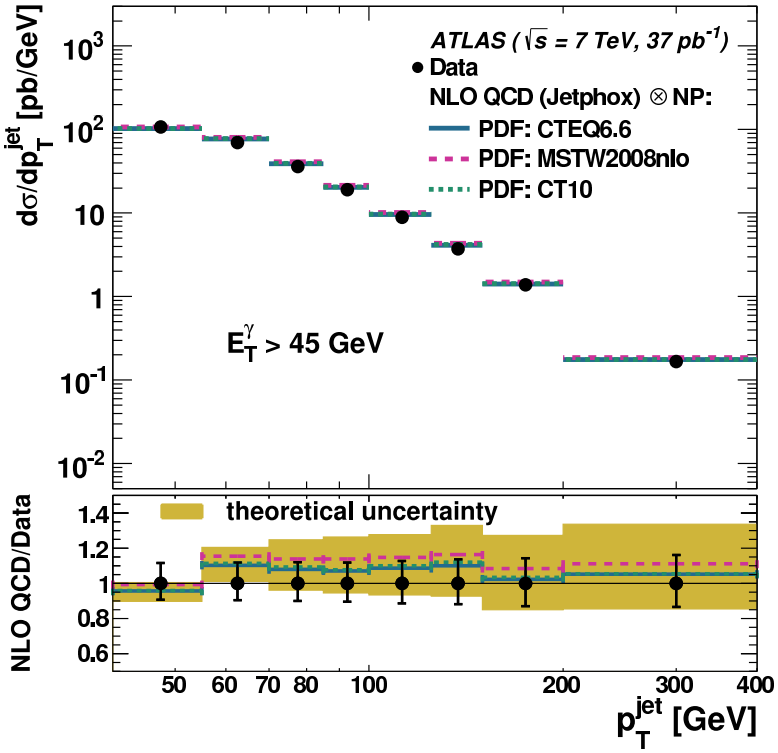
→ Final systematic uncertainty on the differential cross sections varies between 8% and 15% depending on the phase space region of the measurements.

# Dynamics of isolated-photon and jet production

→ "sanity checks" of perturbative QCD (pQCD)

→ theoretical calculation estimated with JETPHOX (corrected by the effect of hadronization and UE)

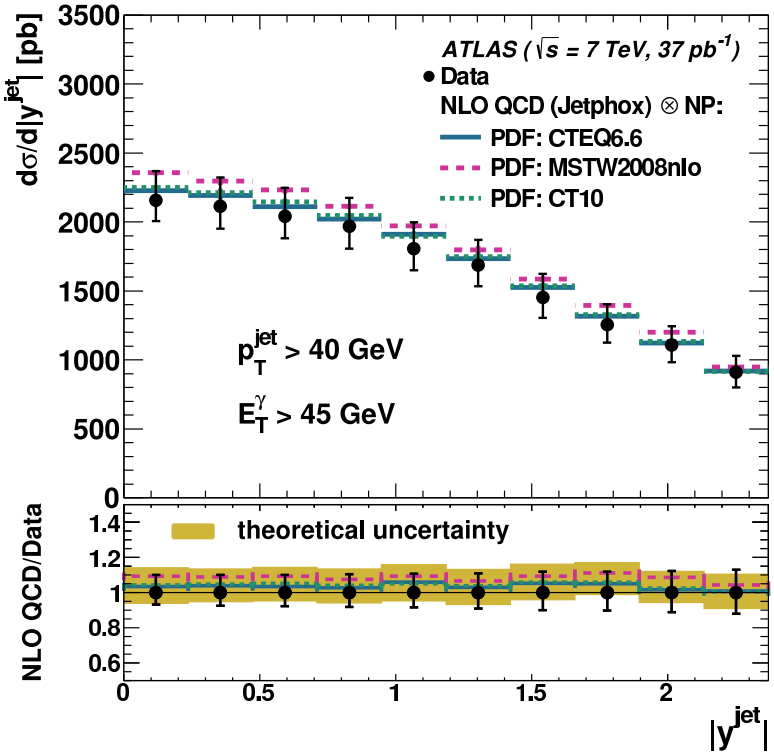


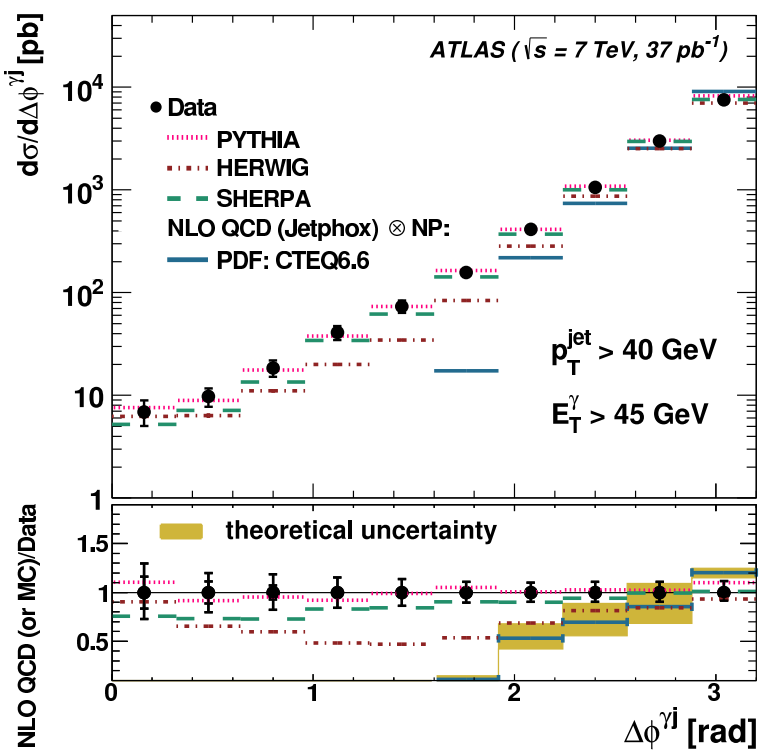




→ Good description of data by NLO pQCD for $d\sigma/dE_T^{\gamma}$, $d\sigma/dP_T^{\mathrm{jet}}$

→ Similar prediction for CTEQ6.6 and CT10 proton PDFs; MSTW2008nlo 5% higher

# Dynamics of isolated-photon and jet production



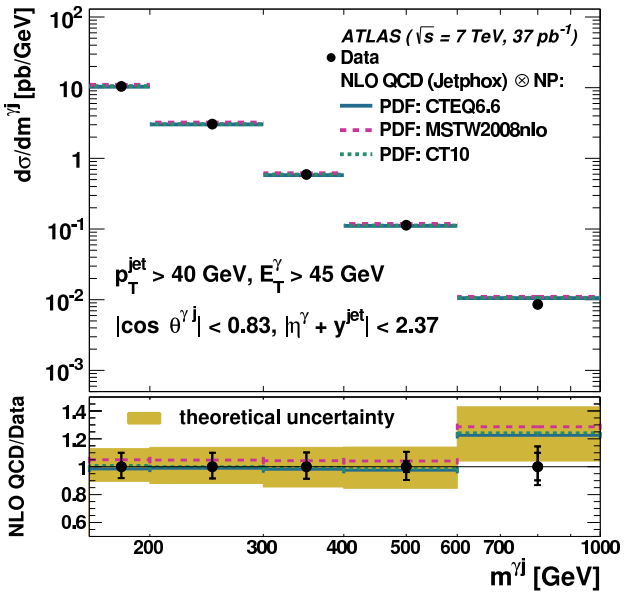



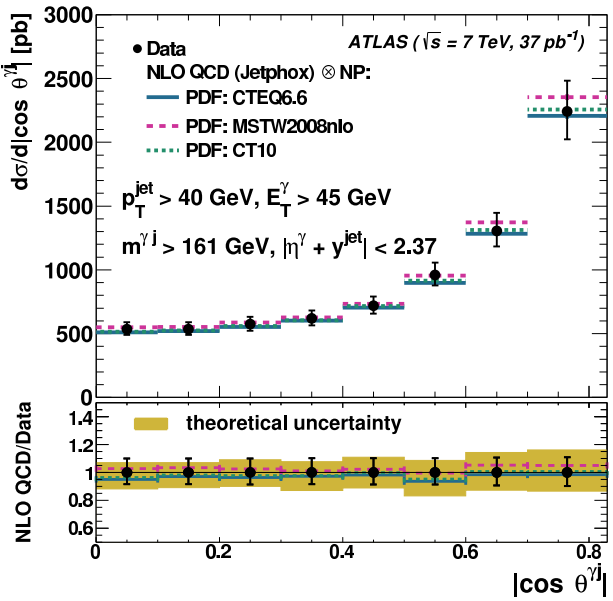

→ Good description of data by NLO pQCD for $d\sigma/d|y^{\mathrm{jet}}|$

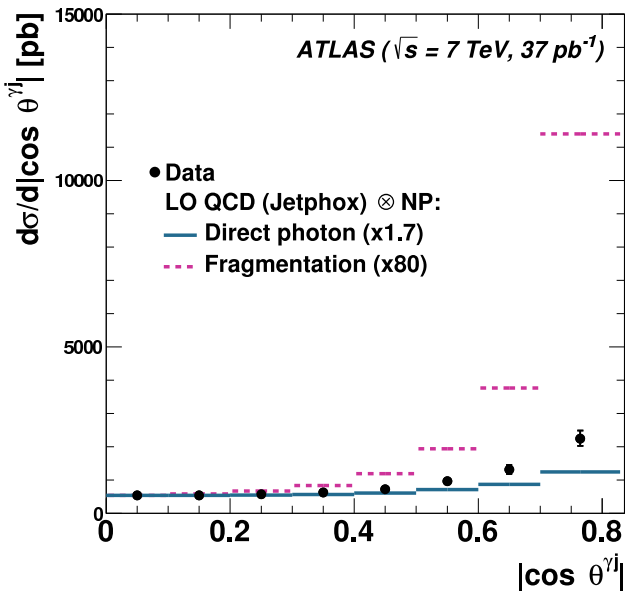
→ Bad description for $d\sigma/d\Delta\phi^{\gamma-\mathrm{jet}}$(expected, in NLO pQCD calculation $\Delta\phi^{\gamma-\mathrm{jet}} > \pi/2$ due to transverse momentum conservation).

→ Good description of $d\sigma/d\Delta\phi^{\gamma-\mathrm{jet}}$ by PYTHIA.

# Dynamics of isolated-photon and jet production




- Good description of data by NLO pQCD for $d\sigma/dM^{\gamma \mathrm{j}}$, $d\sigma/d|\cos\ \theta^{\gamma \mathrm{j}}|$
- The shape of the measured $d\sigma/d|\cos\ \theta^{\gamma-\mathrm{jet}}|$ is much closer to that of DP than that of F processes which is consistent with dominance of processes in which the exchanged particle is a quark.
- Useful for tuning the relative contributions of the DP and F components.

# Conclusions

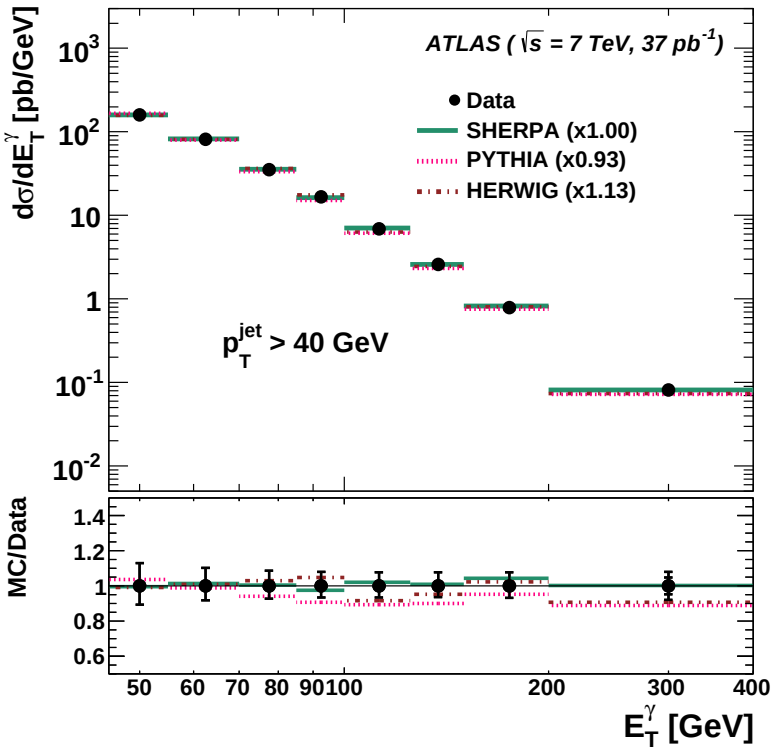
- Measurements of inclusive isolated prompt-photon production have the potencial to constrain the gluon density in the proton.
  - $\rightarrow$ NNLO calculations may be necessary to fully exploit the measurements.

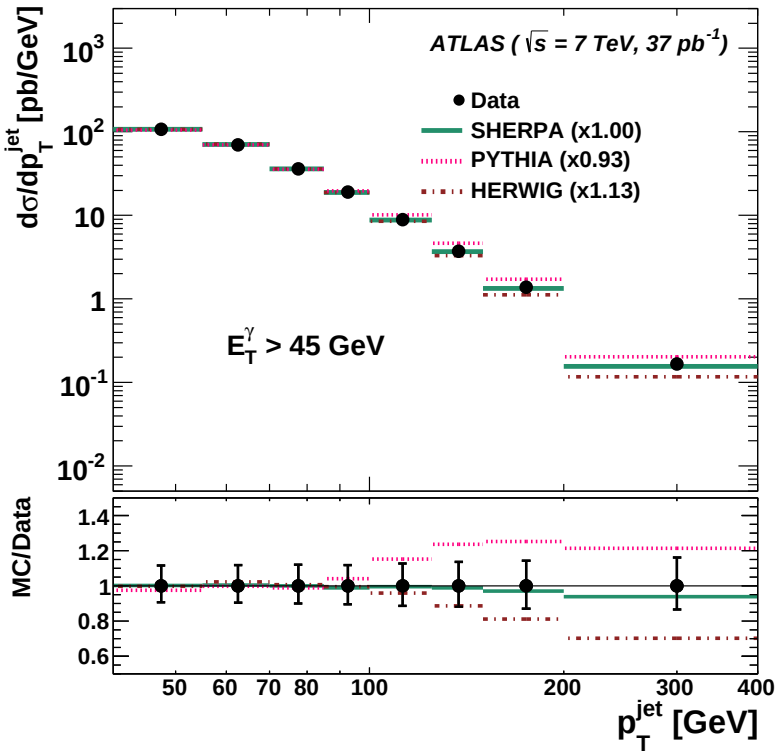
- NLO pQCD calculations give an adequate description of data in a wide range of the phase-space.
  - $\rightarrow$ regions of the phase space have been identified which are particularly sensitive to the contributions from fragmentation
  - $\rightarrow$ the measured dependence with $|\cos\theta^{\gamma-\mathrm{jet}}|$ is consistent with the dominance of processes in which a quark is being exchanged.

- An understanding of isolated photon production at LHC in terms of the SM has been achieved
  - $\rightarrow$ Useful for Higgs studies ($H \rightarrow \gamma\gamma$) and BSM searches.

# BACKUP

# Dynamics of isolated-photon and jet production



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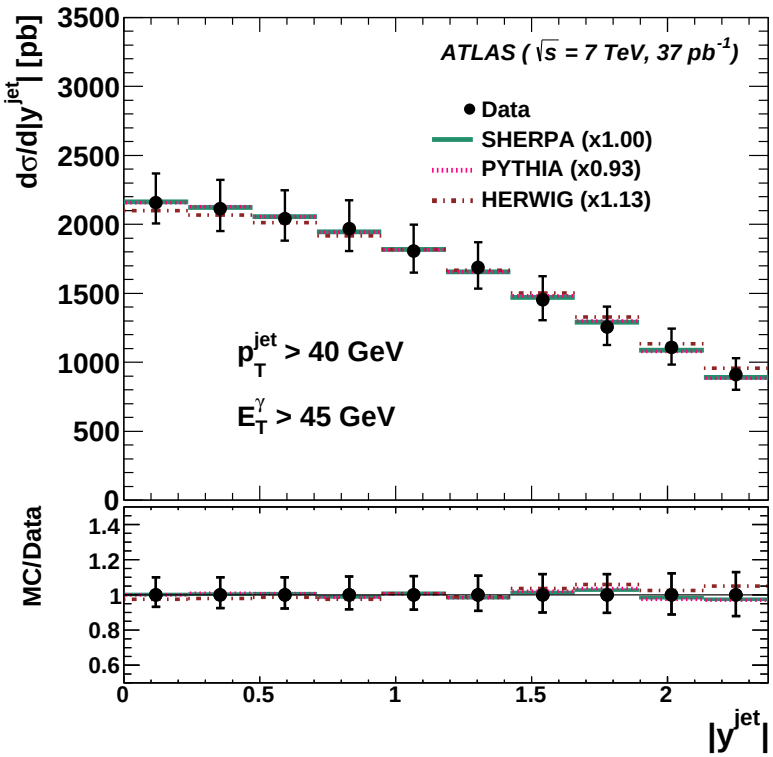


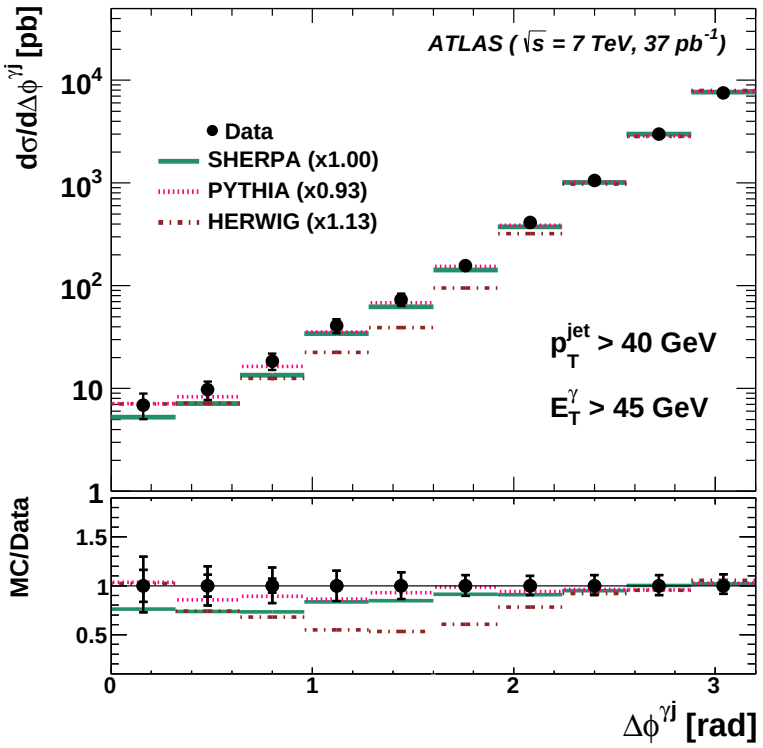

# Dynamics of isolated-photon and jet production