Measurement of the inclusive photon and photon+jet production cross-sections at $\sqrt{s}$ = 7 TeV with the ATLAS detector

XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects @ Dallas, TX

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On behalf of the ATLAS collaboration

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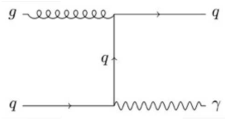
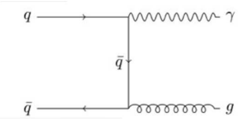
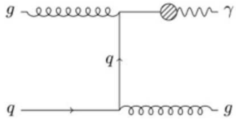
Isolated prompt photon production in ATLAS

- photons are produced from 3 different mechanisms in proton-proton collisions at the LHC:
  - From the hard parton scattering ⟶ **direct photons** $^{(*)}$
  - From parton fragmentation ⟶ **fragmentation photons** $^{(**)}$
  - From hadron and tau decays ⟶ **non prompt photons**







$(*)$ $(**)$

- Only **prompt photons (direct + fragmentation)** are measured in order to keep sensitivity to perturbative QCD

- **A maximum transverse energy deposit** around the candidates is required in order to reduce the non-prompt photon background and fragmentation

  ⟶ similar cut applied to theory
  ⟶ **measurement of isolated prompt photons**

Motivations

- **Test of perturbative QCD**

  $\longrightarrow$ Process very sensitive to higher order effects

  $\longrightarrow$ Full Next-to-Leading Order (NLO) calculation available: JETPHOX

- **Important for Higgs studies and many new physics searches**

  $\longrightarrow$ $H \rightarrow \gamma\gamma$, one of the most interesting Higgs decay channel at the LHC

  $\longrightarrow$ Composite Higgs, SUSY and extra-dimension searches look at final states with photons in ATLAS

- **Constraint on parton fragmentation**

  $\longrightarrow$ Poorly known theoretically: non-perturbative process

  $\longrightarrow$ Fragmentation functions fitted to data

- **Potential to constraint the gluon density function in the proton at high x**

  $\longrightarrow$ u-g main process for inclusive photon production

Measurement of the inclusive isolated prompt photon production at $\sqrt{s}$ = 7 TeV with $\mathcal{L}$ = 4.6 fb^{-1}

- $\gamma + X$ final states, **full 2011 dataset**
- Total fiducial cross section measurement:
  $\sigma(\gamma + X) = 236 \pm 2(stat)^{+13}_{-9}(syst) \pm 4(lumi)$ pb
- Differential cross section measurement for $E_{\mathrm{T}}^{\gamma} > 100$ GeV in $|\eta^{\gamma}| < 1.37$ (barrel) and $1.52 < |\eta^{\gamma}| < 2.37$ (end-caps)

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Event Selection

- **Online selection:** single photon trigger $E_T^\gamma > 80$ GeV
- **Offline selection:** good collision data, good photon candidate,
  $\rightarrow E_T^\gamma > 100$ GeV, $|\eta^\gamma| < 1.37$ OR $1.52 < |\eta^\gamma| < 2.37$
- **Huge background from boosted $\pi^0, \eta^0 \rightarrow \gamma\gamma$ decays**

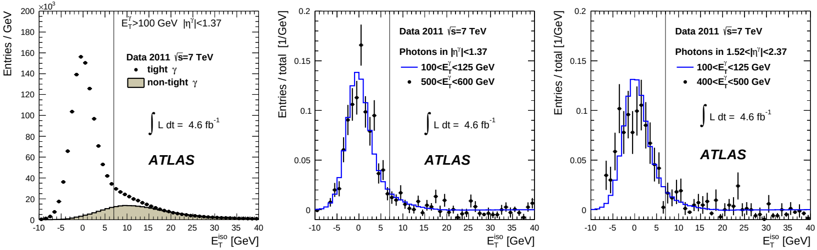
  $\rightarrow$ **Photon tight ID,** based on electromagnetic shower shape profiles

  $\rightarrow$ **Photon isolation energy $E_T^{iso} < 7$ GeV**

  Scalar sum of the calorimeter cell transverse energies within a cone of radius $\Delta R = 0.4$ around the photon candidate, corrected for photon contribution.

  Pile up and underlying event effects subtracted on an event by event basis.

  $\rightarrow$ **after full selection, $\simeq 1 \times 10^6$ events in the barrel, half in the end-caps**



Residual background estimation

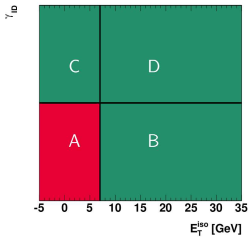
- After selection, **the residual background** from boosted $\pi^0, \eta^0 \rightarrow \gamma\gamma$ decays contaminates the signal region **(up to 6%)***

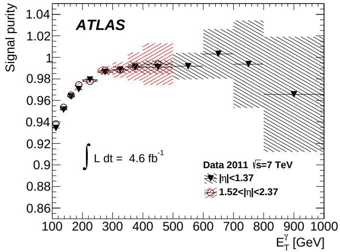
  *Some electrons misreconstructed as photons are also present (0.5% for $E_T^{\gamma} < 400$ GeV) and subtracted using a data-driven technique based on a Z mass peak study.

- In order to estimate it, **use of the 2D side band data-driven method**
- Another ID is used to define background control regions so that isolation and photon ID stay uncorrelated*

  *A systematic uncertainty is assigned to this assumption

- **Alternative background subtraction methods lead to differences from 2 to 3% on the cross-sections, taken as a systematic uncertainty**





Unfolding

- **The measured cross section is unfolded from detector effects using bin-by-bin corrections factors C_i:**

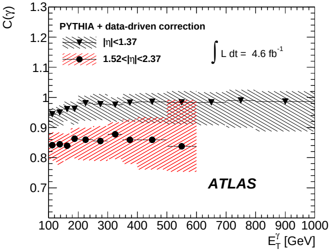
$$\left(\frac{d\sigma}{d\mathcal{O}}\right)_i = \frac{N^{obs.} - N^{bkg.}}{C_i^{MC}.\Delta\mathcal{O}.\mathcal{L}} \quad ; \quad C_i^{MC} = \frac{N^{MC}_{i,reconstructed}}{N^{MC}_{i,generated}}$$

- **C_i computed from the signal MC samples,**
  $\rightarrow$ take into account acceptance and smearing effects$^{(*)}$, identification efficiency$^{(*)}$, trigger efficiency$^{(**)}$

  $^{(*)}$ Correction factors for MC shower shapes are derived to match the ones observed in data

  $^{(**)}$ Very close to 100%. Estimated from data using photon triggers with lower thresholds.

- **Main systematic uncertainties from reconstruction (C_i):**



$\rightarrow$ **photon energy scale:** 2 to 6% from low to high E_T^γ

$\rightarrow$ **choice of the MC generator** for C_i computation: PYTHIA or HERWIG, 2 to 4% from low to high E_T^γ

$\rightarrow$ photon energy resolution: 2% along the E_T^γ spectrum

$\rightarrow$ photon ID efficiency: $< 2\%$ along the E_T^γ spectrum

above uncertainties are added in quadrature

+ 2011 data luminosity uncertainty, 1.8%

Theoretical predictions

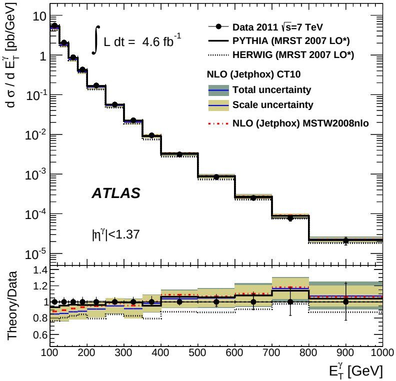
- **JETPHOX Monte Carlo program is used**
  - **Full NLO calculation $O(\alpha\alpha_s^2)$** for both direct and fragmentation components
  - **Fiducial selection:** $E_T^\gamma > 100$ GeV, $|\eta^\gamma| < 1.37$ OR $1.52 < |\eta^\gamma| < 2.37$
  - **Parton level isolation cut implemented$^{(*)}$,** $\Delta R = 0.4$, $E_T^{iso} < 7$ GeV

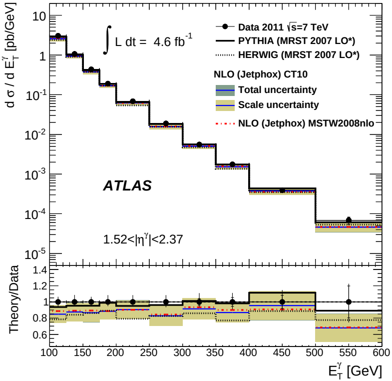
    $^{(*)}$ particle level correction factors derived from LO MC samples with Parton Shower (PYTHIA, HERWIG)
  - Fragmentation function: BFG set II, **PDF: CT10 and MSTW2008NLO**
  - Renormalization, factorization, fragmentation scales all set to E_T^γ
- **Theoretical uncertainties**
  - **3 scales varied** from $E_T^\gamma/2$ to $2\times E_T^\gamma$: **12 to 20% (largest)**
  - **PDF uncertainties** evaluated from CT10 eigenvectors: from **5 to 15%** from low to high E_T^γ
  - **α_s uncertainty:** varied $\pm 0.002 \rightarrow 4.5\%$ with small E_T^γ dependence
  - Added in quadrature

Inclusive photon at $\sqrt{s} = 7$ TeV: Final results

Total fiducial cross section: $\sigma(\gamma + X) = 236 \pm 2(stat)^{+13}_{-9}(syst) \pm 4(lumi)$ pb

JETPHOX predictions: $203(212) \pm 25(24)$ pb for CT10 (MSTW2008NLO) PDF sets



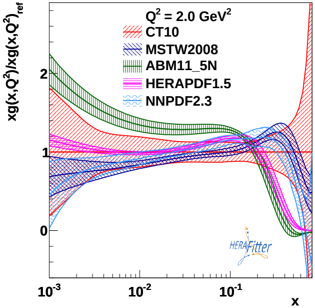


- **NLO (JETPHOX) in agreement with data,** even if lower at low E_T^γ
- Pythia description (LO) fairly good. HERWIG (LO) fails by 10-20%.
- **Theoretical uncertainties:** from 10 to 20%, dominated by the scale
- **Total experimental systematics:** $<6\%$ (7%) in barrel (end-caps)

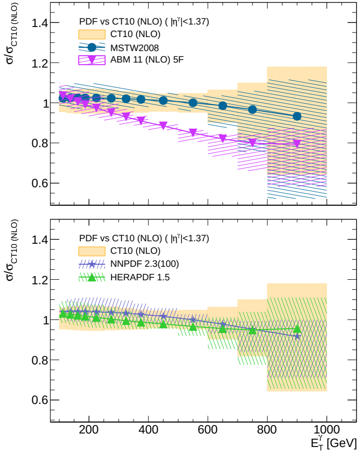
Sensitivity to the parton density distributions

ATL-PHYS-PUB-2013-018

- Inclusive photon production dominated by u-g process at the LHC
  $\longrightarrow$ **sensitivity to the gluon PDF**

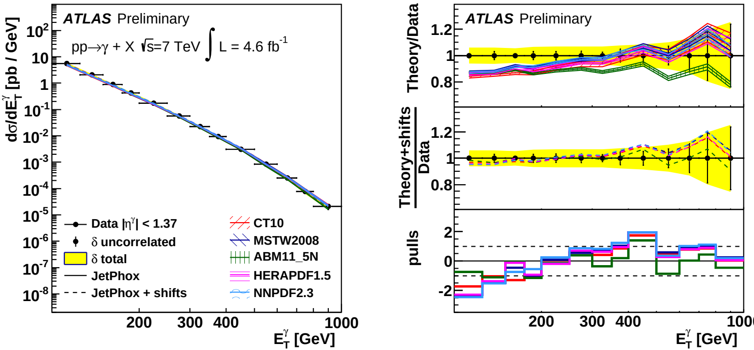


Tension between CT10 and ABM11_5N, HERAPDF1.5 at high x



- **(left)** gluon PDF ratio to CT10
  (right) inclusive cross section ratio to CT10 using different sets of PDFs
- **Good potential to constrain further the gluon PDF at high x**

Sensitivity to the parton density distributions



- **(left)** measurement vs JETPHOX predictions with various PDFs
- **(right)** ratio of the different predictions to measurement and pull distributions
- **The scale uncertainty from theory until mid-E_T^γ limits the final sensitivity to PDFs $\longrightarrow$ a NNLO calculation would be very profitable**
- No final statement can be made for now (fail at low E_T^γ?)

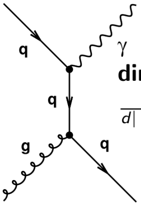
Dynamics of isolated-photon + jet production at $\sqrt{s}$ = 7 TeV with $\mathcal{L}$ = 37 pb^{-1}

- γ + jet + X final states, **full 2010 dataset**
- Differential cross section measurement for E_T^{γ}, p_T^{jet}, $|y^{jet}|$, $\Delta\phi^{\gamma jet}$, $m^{\gamma jet}$, $\cos\theta^{\gamma jet}$.
- Additional motivations:
  - Angular correlation measurement (MC tuning)
  - Check of one of the main $H \to \gamma\gamma$ reducible background

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

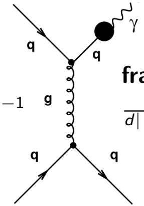
Event Selection and cos $\theta^{\gamma j}$ observable

- **Online selection:** single photon trigger $E_{\mathrm{T}}^{\gamma} > 40$ GeV
- **Photon selection:** similar to $\gamma + X$ measurement but $E_{\mathrm{T}}^{\gamma} > 45$ GeV, **isolation requirement:** $E_{\mathrm{T}}^{\mathrm{iso}} < 3$ GeV, $\Delta R = 0.4$.
- **Jet selection:** at least 1 reconstructed with anti-k_{T} algorithm of R = 0.6, $p_{\mathrm{T}}^{jet} > 40$ GeV, $|y^{jet}| < 2.37$, $\Delta R^{\gamma j} > 1$, quality requirements.
- **$\theta^{\gamma j}$ corresponds to the scattering angle in the center-of-mass frame.** $|cos\theta^{\gamma j}| = |tanh(\Delta y/2)|$ is sensitive to the spin of the exchanged particle
  $\rightarrow$ *interesting to differentiate direct/fragmentation photons.*
- Additional cuts for $m_{\gamma j}$ and $|cos\theta^{\gamma j}|$ measurements: $|\eta^{\gamma} + y_{\mathrm{jet}}| < 2.37$, $|cos\theta^{\gamma j}| < 0.83$ and $m_{\gamma j} > 161$ GeV to get a uniform coverage.



direct-photon process

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



fragmentation process

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

Residual background subtraction, unfolding and related systematic uncertainties

- **Around 124,000 selected events after selection**
- **Main residual background from jets faking photons,** $\simeq$ 10% of events. **systematic uncert.** $\simeq$ **2%** $^{(*)}$

  $^{(*)}$ Similar to inclusive photon measurement, 2D sideband data-driven method used.

  → *the direct/fragmentation photon ratio of LO MC samples (PYTHIA, HERWIG) is fitted for each observable in order to improve the data/MC agreement for unfolding.*

- **Bin by bin correction factors used for unfolding** $^{(*)}$.
  Integrated efficiency $\simeq$ 68%.
  Main uncertainties in the case of $|cos\ \theta^{\gamma j}|$, added in quadrature:

  $^{(*)}$ Similar to inclusive photon measurement

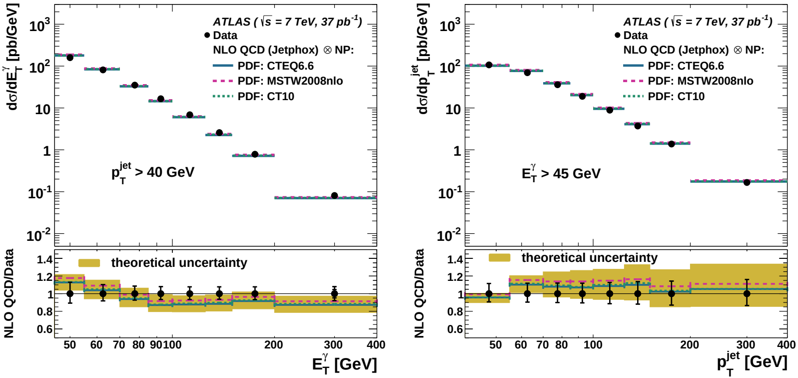
  - **Jet energy scale** ($\simeq$ 5%)
  - **Detector material uncertainty** ($\simeq$ 5%)
  - Photon isolation ($\simeq$ 4%)
  - Photon identification (2%), photon energy scale (1%)

- **2010 dataset luminosity uncertainty: 3.4%**

Theoretical predictions and related systematic uncertainties

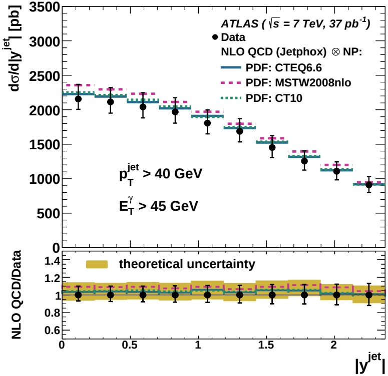
- **JETPHOX Monte Carlo program is used**
  - Number of flavours set to 5.
  - **Full NLO calculation $O(\alpha\alpha_s^2)$** for both direct and fragmentation components
  - **Parton level isolation cut implemented,** $\Delta R = 0.4$, $E_T^{iso} < 4$ GeV. Corrected for non perturbative effects to match the cut applied on data
  - Fragmentation function: BFG set II, **PDF: CTEQ6.6, CT10 and MSTW2008NLO**
  - Renormalization, factorization, fragmentation scales all set to E_T^γ
- **Theoretical uncertainties (for $|cos\ \theta^{\gamma j}|$)**
  - **3 scales varied** from $E_T^\gamma/2$ to $2\times E_T^\gamma$: $\simeq$14%
  - **PDF uncertainties** evaluated from CTEQ6.6: $\simeq$ 3.5%
  - **α_s uncertainty:** varied $\pm 0.002 \rightarrow$ 2.5%
  - **Non-perturbative corrections of partonic isolation** (0.5%) $^{(*)}$
    $^{(*)}$ similar but neglected in the case of the inclusive photon cross section measurement
  - Added in quadrature

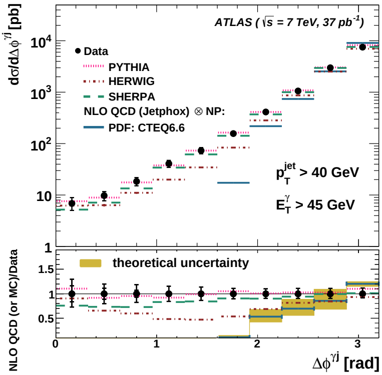
Final results: E_{T}^{γ}, p_{T}^{jet}



- Check of perturbative QCD before looking at angular correlations
- **Good description of data by JETPHOX NLO calculation**
- MSTW2008nlo rises the predictions by 5% with respect to CTEQ6.6, CT10
- Using LO calculation, one can show that **fragmentation effects decrease as a function of E_{T}^{γ} and p_{T}^{jet}**

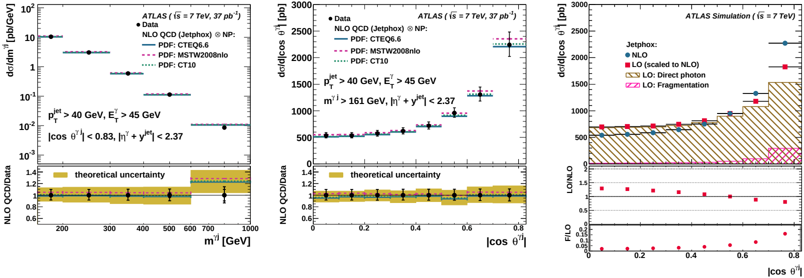
Final results: $|y^{jet}|$, $\Delta\phi^{\gamma jet}$





- Good description of $|y^{jet}|$ by JETPHOX NLO calculation
- Fragmentation stable as a function of $|y^{jet}|$
- **Expected failure of NLO calculation for $\Delta\phi^{\gamma j}$ due to two/three-body final state and momentum conservation: $\Delta\phi^{\gamma j} > \pi/2$** (no parton shower)
- **$\Delta\phi^{\gamma j}$: Good description by Pythia, HERWIG fails**

Final results: $m^{\gamma jet}$, $\cos\theta^{\gamma jet}$



- **Main angular correlation results: $m^{\gamma jet}$, $|\cos\theta^{\gamma jet}|$**
- Good description of $m^{\gamma jet}$ but large error bars
- Good description of $|\cos\theta^{\gamma jet}|$, variable very sensitive to the fragmentation component at high values
- **$|\cos\theta^{\gamma jet}|$ shape consistent with a predominance of spin 1/2 exchange**

Conclusion

- The standard model predictions of the inclusive photon and photon + jet production processes in *pp* collisions at $\sqrt{s} = 7$ TeV have been checked successfully

- **The inclusive photon measurement have the potential to constrain the gluon density of the proton at Run 2**

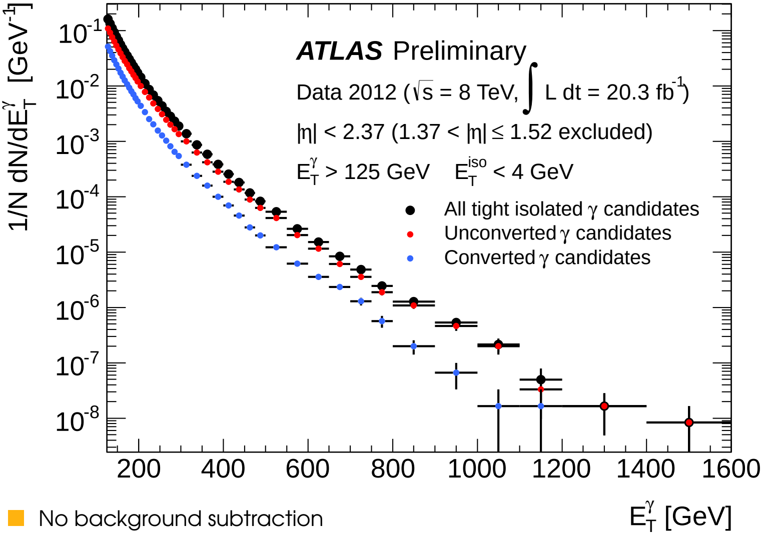
  $\rightarrow$ a NNLO calculation to decrease the scale uncertainty of the predictions would be very profitable

- The measurement of several observables sensitive to fragmentation has been done, ex: $|cos\ \theta^{\gamma jet}|$.

  $\rightarrow$ In general, a good agreement is observed.

- **Very useful to tune MC generators and understand better the main reducible background for H$\rightarrow \gamma\gamma$**

Inclusive photon at $\sqrt{s} = 8$ TeV, $\mathcal{L} = 20.3$ fb^{-1}



- No background subtraction
- No unfolding
- Measurement of inclusive photon, photon + jet at 8 TeV in progress!

Measurement of the inclusive photon and photon+jet production cross-sections at $\sqrt{s}$ = 7 TeV with the ATLAS detector

Backup slides

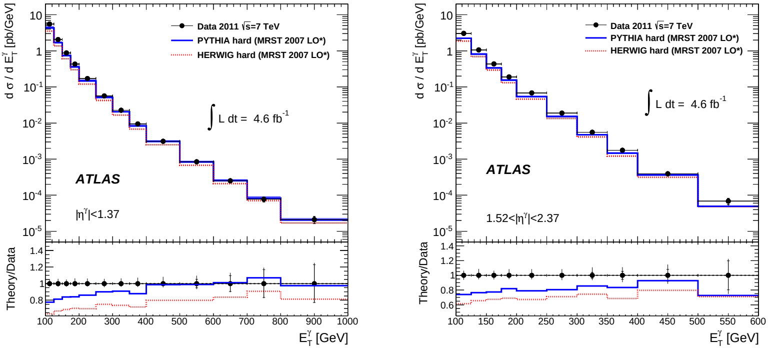
Matthias Saimpert[1]

On behalf of the ATLAS collaboration

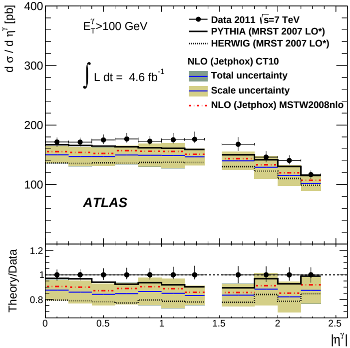
[1]CEA Saclay, Irfu/SPP - France

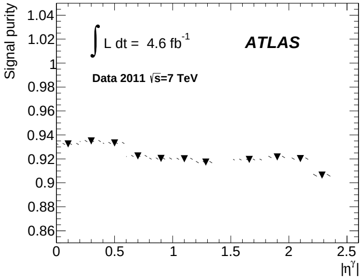
April 29th 2015

Inclusive photon measurement: comparison with LO generators (direct component only)

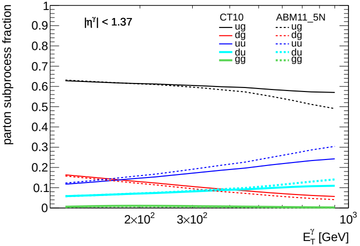


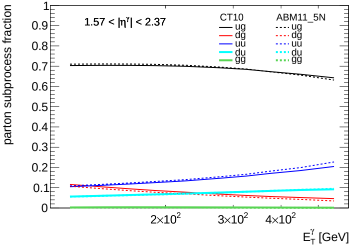
Inclusive photon measurement: cross section vs $|\eta^\gamma|$ and signal purity



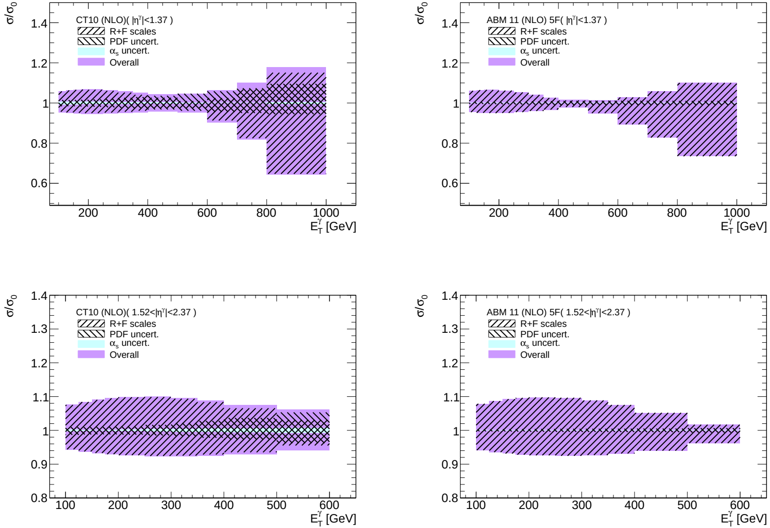


combined LO and NLO contributions to the inclusive photon cross section

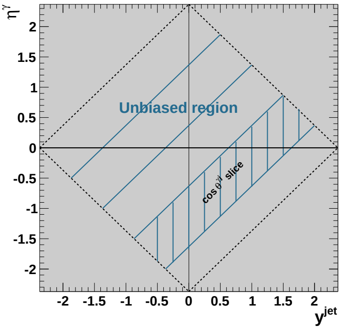


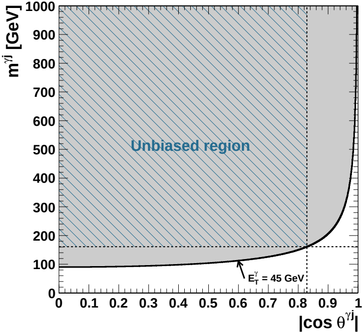


Analysis of inclusive photon cross section uncertainties using CT10 or ABM 11 PDF

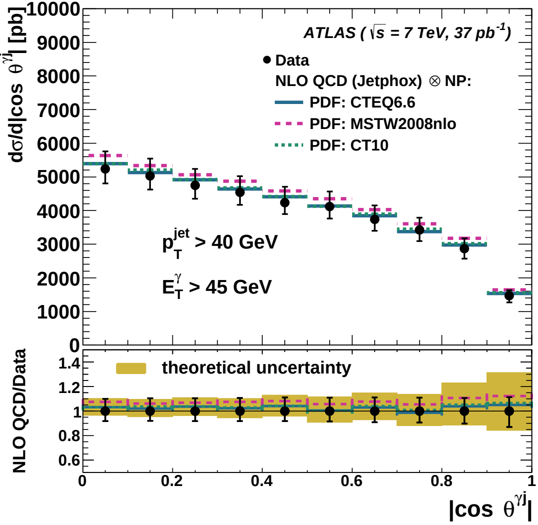


Photon + jet measurement: bias regions



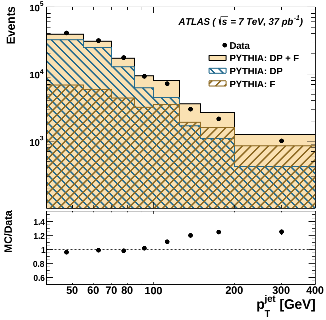


Photon + jet measurement: no extra cut

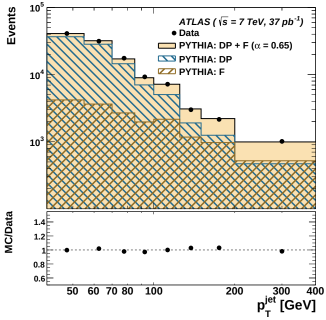


Photon + jet measurement: Fit of the direct/fragmentation component

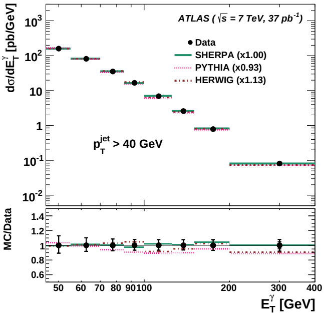
nominal ratio

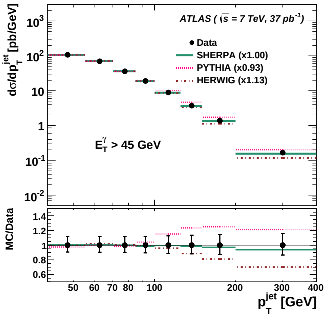


fitted ratio



Photon + jet measurement: comparison with LO generators





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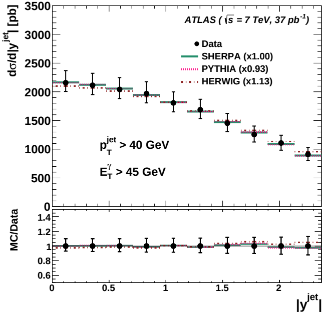
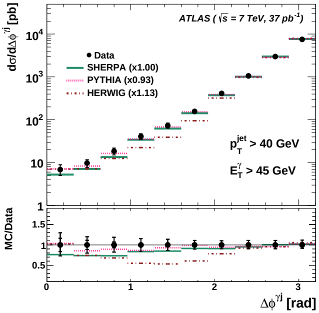
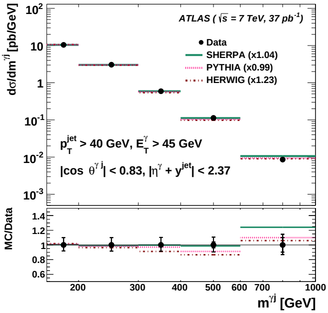
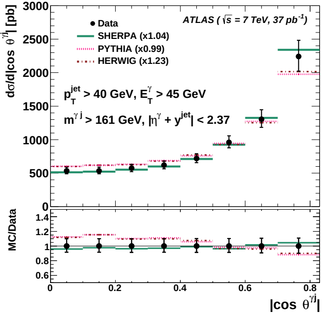


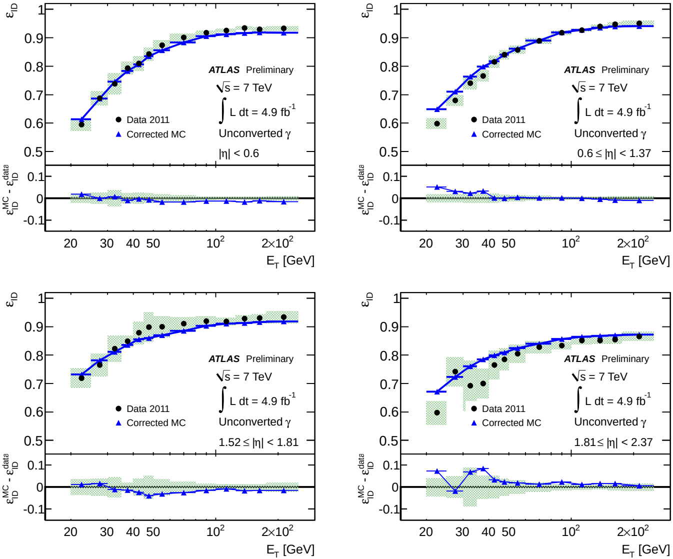


Photon + jet measurement: comparison with LO generators





Photon identification performance: 2011 vs 2012



Photon identification performance: 2011 vs 2012