Prompt photon measurements with the ATLAS detector

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Photons at LHC

- Measurement of the single / double photon production cross sections (+ all the relevant distributions ), photon+jet
  - test of QCD predictions.
  - Use direct photons as an input for PDFs: since the dominant process is $qg$ scattering, direct photons can be used to probe the gluon content of the proton.
  - probe our capability to perform convincing measurements involving photons: main backgrounds for many ‘discovery’ channels like Higgs into 2 photons.

![Diagrams](image-url)

- Compton Scattering
- Annihilation
- Fragmentation
Main subsystems

Inner Detector (ID) in 2 T solenoidal B-field (b=barrel, e=endcap)
- Pixel: 3 layers(b)+2x3 disks(e) $\sigma_{r\phi} \sim 10\mu m, \sigma_z \sim 115\mu m$
- SCT: 4 layers(b)+2x9 disks(e) $\sigma_{r\phi} \sim 17\mu m, \sigma_z \sim 580\mu m$
- TRT: 73 layers (b) + 2 x 160 layers (e) $\sigma_{r\phi} \sim 130\mu m$ (b)

Liquid Argon - Lead sampling calorimeter with an ‘accordion’ geometry:
- 3 longitudinal layers with cell of $\Delta\eta \times \Delta\phi$:
  - (0.003-0.006)x0.1 (1st layer)
  - 0.025x0.025 (2nd layer),
  - 0.050x0.025 (3rd layer)
- Barrel-endcap crack (1.37-1.52)
- Presampler for $|\eta|<1.8$ $\Delta\eta \Delta\phi \sim 0.025 \times 0.1$
- $\sigma(E)/E = (10-17\%) (\eta) / \sqrt{E \text{ (GeV)}} \oplus (1.2\%-1.8\%)$
Photon reconstruction and identification

- Seeded by a cluster in EM calo with energy in 3x5 cells ($\Delta\eta \times \Delta\phi$) in 2nd layer $> 2.5$ GeV
  - No matched track: unconverted $\gamma$
  - Matched to track(s) from $\gamma$ conversion in ID: converted $\gamma$. Single track conversions also

- Reconstruction efficiency $\varepsilon_{\text{reco}}$ (from MC): $\sim$80-85% in the barrel ($|\eta|<1.37$), $\sim$70% in the endcap ($1.52<|\eta|<2.37$)
  - Inefficiency (malfunctioning connection links) recovered in 2011 winter shutdown

- Cuts on shower shape variables in the calorimeter:
  - Identification efficiencies from 60% (at 15 GeV) to $>90\%$ (for $E_T^{\gamma}> \sim 50$ GeV).
  - Uncertainty from 5% to 2%
  - Different cuts for converted and unconverted photons
  - Cuts on calo strips layer to reject $\pi^0$

- Trigger efficiency $\sim100\%$ (<1% uncertainty) measured in data (bootstrap, lower threshold triggers)
A nice photon candidate
A nice fake photon candidate
Photon isolation

Isolation is necessary to further reduce the jet background and (to some extent) of the fragmentation contribution: the definition of the isolation prescription is a tricky business

- **Calorimeter isolation**
  - Sum of energies in cells in cone $R<0.4$ in $\eta$-$\phi$ around the photon, removing the 5x7 cells core

- ** Corrections for residual leakage of photon energy outside the cluster into the isolation cone, using single photon MC samples**

- **Corrections for underlying event**
  - In 2010 data ($<\text{NPV} \sim 2$) average correction $\sim 540$ MeV + $\sim 170$ MeV (per vertex). MC: PYTHIA 440 MeV, HERWIG 550 MeV

- **Signal region**: Require ‘corrected’ isolation $< 3$ GeV

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DIS 2012 - Bonn
Signal extraction:

Data driven approach using a 2D-sidebands subtraction method: identification selection on one axis and calorimetric isolation on the other.

- Purity rapidly increases from 50% (15 GeV) to >95% above 100 GeV
- Systematic uncertainties from: 5 to 10%
- Results cross-checked with isolation template fit (signal template: electrons from W/Z in data; bkg template: photons failing the tight ID criteria). The results agree within 5%
Inclusive photon cross section

Two analysis with different integrated luminosity (very similar ingredients):

- 880 nb$^{-1}$ analysis (Phys. Rev. D 83, 052005 (2011)): from 15 GeV to 100 GeV, 3 eta bins [0.00, 0.60), [0.60, 1.37), [1.52, 1.81)
- 37 pb$^{-1}$ analysis (Phys. Lett B706, 150(2011), from 45 GeV to 400 GeV, 4 eta bins bins [0.00, 0.60), [0.60, 1.37), [1.52, 1.81), [1.81, 2.37). See also ATL-PHYS-PUB-2011-013

Measured cross section additional systematic uncertainties:
- Photon energy scale systematic uncertainty : 3% (leading to 10% on the cross section) in the 880 nb$^{-1}$ analysis and 1.5% (leading to 5% on the cross section)
- Bin to bin unfolding vs SVD or iterative (Bayesian) < 2% difference
- Luminosity uncertainty 11% down to 3.5%

Theoretical predictions obtained with JETPHOX (NLO montecarlo which includes a consistent treatment of the fragmentation) using CTEQ6.6 (MSTW 2008/NNPDF2.0 3-5% difference).
- (parton) isolation in 0.4 cone set to 4 GeV
- Systematic uncertainties evaluated by varying PDF eigenvalues (4% to 2%), varying scales from $P_T^{\gamma}/2$ to $2*P_T^{\gamma}$ (20% to 8%), parton isolation cut varied from 2 to 6 GeV (2%)
Inclusive photon cross section

Results systematically limited across full $E_T$ range

- The two measurements are consistent in the overlapping $E_T$, $\eta$ bins
- Data/(NLO pQCD) comparison:
  - experimental uncertainty comparable to theoretical one
  - disagreement (ratio data/theory < 1) below 35 GeV for central photons, good agreement above
  - similar trend with other PDF sets (MSTW2008, NNPDF2.0)
Photon+jet cross section

Same ingredients for photons as for the inclusive analysis: based on 2010 data (37 pb⁻¹)

- The photon-jet correlations give additional information on fragmentation component:
  - Central photons ($|\eta^\gamma| < 1.37$) and 3 jet rapidity bins: $|y_j| < 1.2$ (central), $1.2 \leq |y_j| < 2.8$ (forward) and $2.8 \leq |y_j| < 4.4$ (very forward).
  - Same sign ($\eta^\gamma y_j \geq 0$) and opposite sign ($\eta^\gamma y_j < 0$) cross sections measured separately vs $E_T^\gamma$ (inspired by D0 - Phys.Lett.B666:435-445,2008).
  - Use anti-$K_T$ (R=0.4) jets with $P_T^{\gamma} > 20$ GeV.
  - Experimental systematic uncertainty 15%-8% in the central jet same-sign configuration, 40% to 22% in the very forward jet opposite-sign case.
Photon+jet cross section

- Theoretical predictions obtained with JETPHOX 1.3 using CTEQ10
  - isolation cut at 4 GeV in a R=0.4 cone
- Cross section corrected for non pert. effects:
  - \(~0.9\) at low \(E_T^\gamma\) rapidly reaching 1.
- Systematic uncertainties:
  - varying scales incoherently from \(E_T^\gamma/2\) to \(2E_T^\gamma\), 10% up to 40% (jet very forward)
  - varying PDF eigenvalues within 68% confidence level intervals (5% to 10% maximum)
  - parton isolation cut varied from 3 to 5 GeV (2% to 10% with a very forward jet)
  - uncertainty on non perturbative correction (3% up to 20%) using pythia/herwig and different pythia tunes.
- Also used MSTW2008 and NNPDF2.1 always within the total uncertainty
Photon+jet cross section

The main full event generators used in ATLAS has been stressed comparing the predictions in the different configurations against data:

- pure hard scattering photons (qg->qgamma + qqbar->ggamma) in PYTHIA 6
- hard scattering + brem photons (from quark radiation in QCD 2->2) in PYTHIA 6
- Sherpa

- Pure hard scattering sample is clearly missing the fragmentation component (central jet, opposite-side configuration)
- Good agreement with PYTHIA6 hard+brem photons and SHERPA
Photon+jet cross section

- The trend in the previous slide is even more visible when looking at the very forward jet, opposite side configuration where the fragmentation contribution is larger
  - pure hard scattering photons sample in PYTHIA 6 is unreliable
  - hard scattering + brems photons in PYTHIA 6 is not working properly in this ‘extreme’ configuration (although slightly better than in the previous case)
  - Sherpa is performing nicely over all configurations
Di-photon cross section: background subtraction methods

- 4x4 matrix: This is a technique used already by CDF and D0:
  - set a cut ($E_{T_{isol}} < 3$ GeV) and classify the events in 4 categories.
  - PP/PF/FP/FF: these numbers are connected to the true number of $\gamma\gamma$/\gamma-jet/jet-$\gamma$/jet-jet through an efficiency matrix $E$
  - the key point here is that these efficiencies are measured on data from the tight/non-tight isolation distributions

- Extend the 2D sidebands method to the case of 2 photon candidates
  - For events with the leading candidates in A region a second 2D matrix is used for the second candidate
  - After a bit of algebra

- 2D isolation template fits:
  - isolation templates for $\gamma\gamma$, $\gamma$-j and jet-jet events are built from data (using electrons and the non-tight control sample sample)
Extracting the signal yield

- Require two photons with $p_{T\gamma} > 16$ GeV within acceptance ($|\eta| < 2.37$, crack excluded), tight and isolated ($E_{T\text{iso}} < 3$ GeV)

- All three signal extraction flavours agree fairly well in extracting the signal yield with $\sim$ comparable systematic uncertainty ($\sim +/− 15\%$)

- Electron background subtracted using Zee MC + electron-$\gamma$ misidentification rate from data
Di-photon cross sections: data / theory comparison

Three methods have been used to estimate the jet background due to photon-jet and jet-jet events:

1. Event weighting
2. Two-dimensional isolation fit
3. 2x2D sidebands method

Rather good agreement between data and theory in $m_{\gamma\gamma}$ (except for low $m_{\gamma\gamma}$) and $p_{T\gamma\gamma}$

05/07/2011  Physics with photons in ATLAS  17
Di-photon cross sections: data / theory comparison

- Some disagreement especially in the low $\Delta\phi$ region (which is also the low $m_{\gamma\gamma}$ region) and $\Delta\phi \sim \pi$

- Qualitatively compatible with the measurements from CMS and Tevatron

- Recent NNLO calculations fill the gap
Conclusion:

- First QCD photons measurements with the ATLAS detector: inclusive photon cross section and diphoton cross section with 2010 data already published. Photon+jet cross section with 2010 data is submitted to PRD.
  - The ATLAS detector has laid solid foundations for photon physics. Studies are ongoing to finalize 2011 data analyses to extend the kinematic reach.

- In general good agreement between measured cross sections and QCD predictions. Some discrepancies in the low $E_{T\gamma}$ in inclusive and photon+jet measurement.

- Main systematic uncertainties studied and understood. Improvements are expected with 2011 data:
  - Improved understanding of the detector geometry and performance, better understanding of the photon energy scale and resolutions, more data driven photon efficiency studies.

- Several exclusion limits on exotics channels involving photons already published. Excitement about the search for a SM Higgs boson decaying into 2 photons: 2012 data will tell us something more but ATLAS has proven to be able to perform serious photon physics.
The ATLAS detector
Di-photon cross section : background subtraction (event weighting method)

- This is a technique used already by CDF and D0:
  - define a cut on your photon candidates which characterize your signal: $E_T^{\text{isol}} < 3 \text{ GeV}$
  - classify the di-photon events candidates in 4 categories. PP/PF/FP/FF: these numbers are related connected the true number of $\gamma\gamma/\gamma\text{-jet/jet-}\gamma/\text{jet-jet}$ by an efficiency matrix

$$
\begin{pmatrix}
S_{PP} \\
S_{PF} \\
S_{FP} \\
S_{FF}
\end{pmatrix} = E
\begin{pmatrix}
W_{\gamma\gamma} \\
W_{\gamma j} \\
W_{j\gamma} \\
W_{jj}
\end{pmatrix}
$$

- $\varepsilon$ and $f$ are the probabilities for a true and fake photon respectively to pass the isolation cut. $\varepsilon$ is typically 80 to 95% while $f \sim$ from 20 to 40 %

- The key point here is that these efficiencies are measured on data from the tight/non-tight isolation distributions

- Actually the true efficiency matrix is a bit more complicated as there’s some correlation in the FF case.
Di-photon cross section: background subtraction (2D sidebands extension)

Extend the 2D sidebands method to the case of 2 photon candidates:
- Preselect events with 2 candidates passing a loose photon definition.
- As for the inclusive analysis the number of signal candidates in region A of the first matrix is

\[ N_{A}^{\text{sig}} = N_A - \left( (N_B - c_1 N_{A}^{\text{sig}}) \frac{N_C - c_2 N_{A}^{\text{sig}}}{N_D - c_1 c_2 N_{A}^{\text{sig}}} \right) R^{\text{bkg}} \]

- For events with the leading candidates in A region a second 2D matrix is used for the second candidate
- After a bit of algebra

\[ N_{\gamma\gamma}^{\text{TITI}} = \frac{\epsilon' \left( \alpha f' N_{A}^{\text{sig}} + (\alpha - 1) N_{A}^{\prime\text{sig}} \right)}{(\alpha - 1) \epsilon' + \alpha f'} \]

(\( \alpha \) has to be taken from MC while the other parameters from data)
Di-photon cross section: background subtraction (2D isolation template fit)

For all events with 2 photon candidates passing the tight isolation criteria
- isolation templates for $\gamma\gamma$, $\gamma$-j and jet-jet events are built from data (using electrons and the non-tight sample)
- the 2D distribution of the leading and subleading photon is built
- the sample decomposition comes from a maximum likelihood fit

$$N^{TT} F^{\text{obs}}(E_{T,1}^{\text{iso}}, E_{T,2}^{\text{iso}}) = N^{TT}_{\gamma\gamma} F_{\gamma_1}(E_{T,1}^{\text{iso}}) F_{\gamma_2}(E_{T,2}^{\text{iso}}) + N^{TT}_{\gamma j} F_{\gamma_1}(E_{T,1}^{\text{iso}}) F_{j_2}(E_{T,2}^{\text{iso}}) + N^{TT}_{j\gamma} F_{j_1}(E_{T,1}^{\text{iso}}) F_{\gamma_2}(E_{T,2}^{\text{iso}}) + N^{TT}_{jj} F_{j_1}(E_{T,1}^{\text{iso}}) F_{j_2}(E_{T,2}^{\text{iso}})$$

- due to correlations the jet-jet case can’t be factorized