Measurement of photon production cross sections with the ATLAS detector

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on behalf of the ATLAS collaboration

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Introduction to photon measurements

- Photons are colourless probes, well suited to test QCD at hadron collisions
  - Clean signature
  - Test resummation, pQCD and EW corrections, gluon PDF, …
  - Fixed-order calculations available up to NNLO for $\gamma+X$ and $\gamma\gamma$
- Background to Higgs boson studies and searches for new phenomena
  - New resonances (scalar, graviton, $Z'$), SUSY, …
- Measurements of isolated $\gamma$ (13 TeV, 3.2 fb$^{-1}$), $\gamma\gamma$ and $\gamma\gamma\gamma$ (8 TeV, 20 fb$^{-1}$)

See also talk by Mark Stockton on $\gamma$+jets

Direct (reduced by isolation cuts)
Measurement strategy

- Main background from jets (with e.g. $\pi^0$) rejected by ID cuts and isolation
  - Finely segmented EM calorimeter ($|\eta| < 2.37$, excluding $1.37 < |\eta| < 1.56$)
  - Isolation corrected by photon, UE and pileup contributions
  - Data-driven background subtraction using ID and isolation (also $e \rightarrow \gamma$, usually small)
- Correction for detector effects, unfolding to particle-level (bin-by-bin)
  \[
  \frac{d\sigma}{dA}(i) = \frac{N^{\text{sig}}(i)C(i)}{\Delta A(i) \mathcal{L}}
  \]
- Systematic uncertainties dominant in most of the phase-space
- Efficiencies measured in data. e.g. photon ID
Inclusive isolated photons at 13 TeV

Candidate with $E_T = 1.3$ TeV

Run Number: 279284, Event Number: 768612867
Date: 2015-09-14 11:28:05 UTC
Inclusive isolated photons at 13 TeV

- 2015 dataset: 3.2 fb\(^{-1}\) at 13 TeV

- Selection (also at particle level):
  - \(E_T > 125\) GeV (trigger)
  - Isolation: \(E_T^{\text{iso}} < 4.8\) GeV + 4.2e-3 * \(E_T\)
  - Jet background subtracted with 2D sidebands methods (ID, iso)
  - Other sources (e.g. e \(\rightarrow\) \(\gamma\)) negligible

- Inclusive cross-section and d\(\sigma/dE_T\) in 4 \(\eta\) regions

- Syst uncertainties dominant for \(E_T < 600\) GeV
  - Energy scale and resolution: 2-5\%, larger for 1.56 < \(|\eta| < 1.81\)
  - Photon ID and background subtraction typically 1-2\%
Inclusive isolated photons at 13 TeV

- Comparison with NLO JETPHOX and MC generators (Pythia, Sherpa)
  \[ \sigma_{\text{meas}} = 399 \pm 13 \text{ (exp.)} \pm 8 \text{ (lumi.) pb.} \]
  \[ \sigma_{\text{NLO}} = 352^{+36}_{-29} \text{ (scale)} \pm 3 \text{ (PDF)} \pm 6 (\alpha_s) \pm 4 \text{ (non-perturb.) pb.} \]

- \( d\sigma/dE_T \) over 5 orders of magnitude

- Shape well described by MC, except for \( E_T > 500 \text{ GeV} \) in the regions \( |\eta| < 1.37 \)

- Adequate description by NLO calculation
  - Differences up to 10-15\%, covered by theoretical uncertainties (scale)
  - Calls for higher order calculation!
Inclusive isolated photons at 13 TeV

Comparison with NLO JETPHOX and MC generators (Pythia, Sherpa)

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[Graph showing the comparison between theory and data at different $|\eta|$ values and $E_T$ regions.]
Comparison with NNLO calculations of $pp \rightarrow \gamma + X$

- NNLO calculation: Campbell et al, *PRL* 118, 222001 (2017), 1802.03021
- Scale uncertainties halved
- Overall good agreement. Small discrepancies in the forward bin for 8 TeV, cancel out when taking the ratio to 13 TeV data

Potential to include measurements in PDF fits
Photon pair production at 8 TeV

- Integrated cross-section and differential as a function of 6 variables:
  \[ m_{\gamma\gamma}, \ p_{T,\gamma\gamma}, \ \Delta\phi_{\gamma\gamma}, \ |\cos\theta^*_\eta|, \ a_T, \ \phi^*_\eta \]

- Larger dataset (20 fb\(^{-1}\)), reduced uncertainties and new variables w.r.t. to previous result at 7 TeV (better sensitivity to soft-gluon emission)

- \( E_T > 40 \text{ GeV}, 30 \text{ GeV}; \Delta R > 0.4; E_{T,\text{part,iso}} < 11 \text{ GeV} \)

- Jet and electron backgrounds from template fit to calo isolation
Photon pair production at 8 TeV

- Syst. uncertainties dominated by photon ID (2.5%), isolation modelling (2%) and efficiency (1.5%), background control region def. (+1.5%-1.7%)

$$\sigma_{\text{fid.}}^{\text{tot}} = 16.8 \pm 0.1 \text{ (stat)} \pm 0.7 \text{ (syst)} \pm 0.3 \text{ (lumi)} \text{ pb}$$

- Compared to calculations up to NNLO or NLO + PS / gluon-resummation:
Photon pair production at 8 TeV

- Uncertainties typically < 5% per bin, up to 25% in few bins with low stats
- Sherpa 2.2.1 with ME+PS at NLO describes the data well
- Impact of IR emissions ($a_T$ and $\phi^*$) well reproduced by gluon resummation

![Graphs showing data and theoretical predictions for photon pair production at 8 TeV]
Production of three photons at 8 TeV

- Integrated cross-section and differential as a function of $E_{T1,2,3}$, $\Delta \Phi_{\gamma\gamma}$ and $\Delta \eta_{\gamma\gamma}$, $m_{\gamma\gamma}$ and $m_{3\gamma}$

- $E_T > 27, 25, 15$ GeV; $m_{3\gamma} > 50$ GeV; $\Delta R > 0.45$; $E_{Tiso,part} > 10$ GeV

- Jet background subtracted by 2D sideband method (ID and iso); $e \rightarrow \gamma$ from MC, checked with data around $m_Z$
Production of three photons at 8 TeV

- Stat uncertainty: ~9%. Syst: ~13%
  - ID eff. (7.9%)
  - Correlation between ID and iso (7.7%)
  - Iso modelling (5.8%)
- Compared to NLO (MCFM with BFG II frag.) and NLO+PS (MG5_aMC@NLO+Pythia)
  - Scale uncertainty: 10-12%
  - Underestimate the data by ~ factor 2
- Would benefit from NNLO
Production of three photons at 8 TeV

- Differential cross-section as a function of $E_{T1,2,3}$, $\Delta\phi_{\gamma\gamma}$ and $\Delta\eta_{\gamma\gamma}$, $m_{\gamma\gamma}$ and $m_{3\gamma}$
  - Stat 20-50% in some bins. Dominates for $E_{T1,2} > 50$ GeV or $E_{T3} > 30$ GeV
  - Syst: 15-10%

- Significant discrepancies between data and theory at low $E_T$ and low inv. masses. Adequate description of $\Delta\eta_{\gamma\gamma}$, less so of $\Delta\phi_{\gamma\gamma}$
Summary

- Measurements of cross-sections of $pp \rightarrow$ up to 3 photons
  - Reach ~1 TeV in $E_T$ and $m_{\gamma\gamma}$
  - Differential measurements of several variables
  - Precision of few % in many cases, similar or better than theory errors
- Comparisons with calculations up to NNLO or NLO+PS
  - Some discrepancies but overall agreement with data ok (less so for $3\gamma$)
- Looking forward to improved calculations and updated measurements
Backup slides
Photon pair production at 8 TeV

Measurement of photon production cross sections with the ATLAS detector

Bruno Lenzi (CERN)
Three photon production at 8 TeV

\[ \frac{d\sigma}{dE_T} \text{ [fb/GeV]} \]

**ATLAS**

$\sqrt{s} = 8 \text{ TeV}, 20.2 \text{ fb}^{-1}$

- Data (sys., tot. unc.)
- MG5\_aMC+Py8
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