Photon Measurements in the CMS Experiment at the LHC

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1. Prompt Photon Physics

- Production Mechanisms
  - Direct photons
    - Quark-gluon annihilation
    - Quark-anti-quark Compton scattering
  - Fragmentation photons

- Physics Motivation
  - Tests for perturbative QCD calculations
    - Verification of theoretical cross section and parton distribution functions (PDFs)
  - Searches for low mass Higgs boson
    - \( H \rightarrow \gamma \gamma \) decay channel
  - Presence in the final state of new physics signatures
    - Randall-Sundrum (RS) model
    - Supersymmetry (SUSY)
    - Large Extra Dimensions
2. Experimental Setup

- **Large Hadron Collider (LHC)**
  - 7 TeV p-p collider (14 TeV design)
    - 4T magnet (8T design)
    - Circumference of 27 km
    - 1232 dipoles (NbTi) for steering
    - 392 quadrupoles for focusing
  - Luminosity of **3.5x10^{33} cm^{-2}s^{-1} (2011)**
    - Design: 10^{34} cm^{-2}s^{-1}
  - Acceleration process
    - Linac2, produces 50 MeV protons
    - PSB increases energy to 1.4 GeV
    - PS increases energy to 24 GeV
    - SPS increases energy up to 450 GeV
  - Luminosity calculation
    \[ \mathcal{L} = \frac{N_b^2 \cdot n_b \cdot f}{A_{eff}} \quad A_{eff} = \frac{4\pi \cdot \epsilon_n \cdot \beta^*}{\gamma_r \cdot F} \]
    - Integrated Luminosity (L)
      \[ L = \int \mathcal{L} dt \]
2. Experimental Setup

- Compact Muon Solenoid (CMS)
2. Experimental Setup

- CMS Geometry (η-Φ space)

Barrel |η| < 1.444

Endcap |η| > 1.566

Barrel & Endcap:
- E & H: 72 Φ x 56 η
- (|η| < 3.0)

Forward:
- H only: 18 Φ x 4 η
- (3.0 < |η| < 5.0)
2. Experimental Setup

- CMS Electromagnetic Calorimeter (ECAL)
  - Measures e/γ energy using 76,832 lead tungstate (PbWO₄) crystals
  - Energy of photons from the energy deposit of groups of crystals (superclusters)

Lead tungstate crystals:
- Density 8.3 g/cm³
- Molière radius 2.2 cm
- Radiation length 0.89 cm
- Crystal size: 2.2x2.2 cm x 25.8 X₀

ECAL coverage extends to |η|<2.5
2. Experimental Setup

- **Level-1 Trigger (L1)**
  - 40 MHz frequency collision rate needs to be reduced (~25 ns bunch crossings), not all of the 0.25 MB events can be stored
  - L1 trigger electronics select 50-100 kHz of interesting events
  - Triggers
    - Electron/photon
      - 12 or 15 GeV
      - ~100% efficient
    - Jets
    - Missing $E_T$
    - Muon
2. Experimental Setup

- High Level Trigger (HLT)
  - Software trigger
    - Multi-processor farm
    - Reduces Level-1 rate from 100kHz to 300 Hz
    - Processes events every 40 ms (compared to L1 in 3.2 µs)
  - Photon HLT
    - Start from L1 electron/photon seed \((E_T = 12 \text{ or } 15 \text{ GeV})\)
    - Energy deposits (superclusters) in the ECAL
      - \(H/E < 0.05\)
    - Track reconstruction
    - Match ECAL and track information
    - Required 20, 30, 50, 75, 90, 125, 135 or 400 GeV photon (2011)
      - Additional selection applied as the luminosity increased
      - 2011 HLT photon paths are highly prescaled
      - Photon isolation cuts applied at the HLT level (more on this later)
3. Photon Measurements in the CMS

- **Photon Reconstruction**
  - Reconstructed from superclusters of the ECAL
    - In the ECAL barrel region ($|\eta| < 1.4442$), 35 crystals wide in $\phi$ and 5 crystals in $\eta$
    - In the ECAL endcap region ($1.566 < |\eta| < 2.5$), arrays of 5x5 crystals
  - Similar with electron reconstruction
  - Hybrid (in Barrel) and Multi5x5 (in Endcap) clustering algorithms are used
  - Energy is corrected for better resolution (the material losses in front of the tracker)
3. Photon Measurements in the CMS

- **Photon Identification**
  - Jet background ($\pi^0, \eta \rightarrow \gamma\gamma$) needs to be suppressed by limiting the energy of other particles surrounding photon in different sub-systems.
  - Different isolation variables are used, \( H/E, \text{ECAL Iso}, \text{HCAL Iso}, \text{TRACK Iso} \)

- **Shower shape variable:**

  \[
  \sigma_{\eta\eta}^2 = \frac{\sum_i^{5\times5} w_i(\eta_i - \bar{\eta}_{5\times5})^2}{\sum_i^{5\times5} w_i}, \quad w_i = \max(0, 4.7 + \ln \frac{E_i}{E_{5\times5}})
  \]

- **Pixel seed match veto:** ensures that background from electrons no longer contaminate signal photon spectra

Mapping of the hollow cones comes from MC theory level studies

Transverse shape of the supercluster in \( \eta \) direction
3. Photon Measurements in the CMS

- **Signal Extraction Templates**
  - Photon ID selection might not make sure fully that neutral hadrons do not fake prompt photon signal, so templates are developed.
  - Two complementary templates are used
- **Shower Shape template**
  - Use $\sigma_{\text{in} \eta}$ and apply calorimetric isolation to fit by the extended maximum likelihood method to extract photon signal
- **Isolation template**
  - Use **Sum Iso** and apply shower shape variable cut to fit by the ARGUS function and Lifetime function with Gaussian distribution to have signal photon yield

$$\mathcal{L} = -\ln L = -(N_S + N_B) + \sum_{i=1}^{n} N_i \ln(N_S S_i + N_B B_i)$$

$$S(x) = \frac{1}{p_0} \times e^{\left(p_2^2/2p_0^2\right)-\left((x-p_1)/p_0\right)} \times \left[1 - \text{Freq}\left(p_2/p_0 - (x - p_1)/p_2\right)\right]$$

$$B(x) = \left[1 - e^{p_3(x-p_4)}\right] \times \left[1 - p_5(x - p_4)\right]^{p_6}$$

**Minimization of maximum likelihood function**

**Lifetime fnc. for signal and ARGUS fnc. for background**
3. Photon Measurements in the CMS

- **Signal Extraction Templates**
  - Shower Shape template selections

<table>
<thead>
<tr>
<th>Variable</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>pixel seed</td>
<td>require none</td>
</tr>
<tr>
<td>Tracker Isolation</td>
<td>$&lt; 2.0 + 0.002 \cdot E_T^\gamma$ GeV</td>
</tr>
<tr>
<td>ECAL Isolation</td>
<td>$&lt; 4.2 + 0.012 \cdot E_T^\gamma$ GeV</td>
</tr>
<tr>
<td>HCAL Isolation</td>
<td>$&lt; 2.2 + 0.005 \cdot E_T^\gamma$ GeV</td>
</tr>
<tr>
<td>H/E</td>
<td>$&lt; 0.05$</td>
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**Photon ID signal selection for SS**

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</tr>
<tr>
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</tr>
<tr>
<td>H/E</td>
<td>$&lt; 2.2 + 0.005 \cdot E_T^\gamma$ GeV</td>
</tr>
<tr>
<td></td>
<td>$&lt; 0.05$</td>
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</tbody>
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**Photon ID side-band selection for SS**

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<th>Selection</th>
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<tbody>
<tr>
<td>pixel seed</td>
<td>require none</td>
</tr>
<tr>
<td>$\sigma_{\eta\eta}$ (Barrel)</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>$\sigma_{\eta\eta}$ (Endcap)</td>
<td>$&lt; 0.028$</td>
</tr>
<tr>
<td>H/E</td>
<td>$&lt; 0.05$</td>
</tr>
</tbody>
</table>

**Photon ID signal selection for Iso**

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<tr>
<td>pixel seed</td>
<td>require none</td>
</tr>
<tr>
<td>$\sigma_{\eta\eta}$ (Barrel)</td>
<td>$&gt; 0.011$</td>
</tr>
<tr>
<td>$\sigma_{\eta\eta}$ (Endcap)</td>
<td>$&gt; 0.035$</td>
</tr>
<tr>
<td>H/E</td>
<td>$&lt; 0.05$</td>
</tr>
</tbody>
</table>

**Photon ID side-band selection for Iso**

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<td>Tracker Isolation</td>
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</tr>
<tr>
<td>ECAL Isolation</td>
<td>$&lt; 4.2 + 0.012 \cdot E_T^\gamma$ GeV</td>
</tr>
<tr>
<td>HCAL Isolation</td>
<td>$&lt; 2.2 + 0.005 \cdot E_T^\gamma$ GeV</td>
</tr>
<tr>
<td>H/E</td>
<td>$&lt; 0.05$</td>
</tr>
</tbody>
</table>

- **Isolation template selections**

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30.12.2011
3. Photon Measurements in the CMS

- Signal Extraction Templates
  - Examples to the isolation templates

![Graphs showing photon measurements in the CMS](image-url)
3. Photon Measurements in the CMS

• Previous Cross Section Measurements
  • Elements of isolated single photon cross section measurements in the CMS.

\[
\frac{d^2 \sigma^\gamma_{\text{isolated}}}{dE_T^\gamma d\eta^\gamma} = \frac{1}{\Delta E_T^\gamma \cdot \Delta \eta^\gamma} \frac{N^\gamma_{\text{signal}} \cdot U}{L \cdot \epsilon}
\]

- Photon ET size
- Unfolding
- Photon ET size
- Int. luminosity
- Photon yields
- Efficiency

• The earliest measurements of prompt photon production were carried out at the ISR (Intersecting Storage Rings) hadron collider at CERN
• Later studies (ZEUS HERA, PHENIX RHIC, TEVATRON FERMILAB, LHC results) established prompt photons as a useful probe of hadron interactions

3. Photon Measurements in the CMS

• Previous Cross Section Measurements (the most recent studies)
4. Photon Efficiency Measurements

• Introduction

• Goal is to measure photon trigger, reconstruction, and identification efficiencies from collision data and Monte Carlo simulation samples for the inclusive photon and photon+jet cross section measurements

\[ \epsilon = \epsilon_{\text{trigger}} \times \epsilon_{\text{RECO}} \times \epsilon_{\text{ID}}. \]

• \( \epsilon_{\text{trigger}} \) is the probability for a reconstructed signal photon to be selected by the trigger system

• \( \epsilon_{\text{RECO}} \) represents the probability for a signal photon produced inside the detector geometrical acceptance to be reconstructed by the clustering algorithms

• \( \epsilon_{\text{ID}} \) is the probability for a reconstructed signal photon to pass the photon identification criteria

• We used 2011 data (2.2 fb\(^{-1}\) integrated luminosity) recorded by the CMS detector at a center-of-mass energy of 7 TeV to measure efficiencies.
4. Photon Efficiency Measurements

- **Trigger Efficiency**
  - Measure single photon HLT efficiencies from 2011 collision data

### Structure of single photon HLT paths

<table>
<thead>
<tr>
<th>HLT trigger path</th>
<th>Run range</th>
<th>Eff. (pb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_Photon50_CaloIdVL_Isol</td>
<td>161217-163261</td>
<td>40.95</td>
</tr>
<tr>
<td>HLT_Photon75_CaloIdVL</td>
<td>160431-163869</td>
<td>216.06</td>
</tr>
<tr>
<td>HLT_Photon75_CaloIdVL_Isol</td>
<td>160431-165633</td>
<td>355.5</td>
</tr>
<tr>
<td>HLT_Photon90_CaloIdVL_Isol</td>
<td>165088-167913</td>
<td>934.0</td>
</tr>
<tr>
<td>HLT_Photon125</td>
<td>165088-166967</td>
<td>665.70</td>
</tr>
<tr>
<td>HLT_Photon135</td>
<td>167039-173198</td>
<td>1053.98</td>
</tr>
</tbody>
</table>

- **WPs**
  - Very Loose 'VL':
    - $\text{IsoECAL} < 0.0+0.012\times p_T$ GeV
    - $\text{IsoECAL} < 4.0+0.005\times p_T$ GeV
    - H/E < 0.15
    - $\sigma_{\text{trig}} < 0.024$
    - $\sigma_{\text{trig}} < 0.040$
  - Loose 'L':
    - $\text{IsoECAL} < 5.5+0.012\times p_T$ GeV
    - $\text{IsoECAL} < 3.5+0.005\times p_T$ GeV
    - $\text{IsoTRACK} < 4.0+0.002\times p_T$ GeV
    - H/E < 0.15
    - $\sigma_{\text{trig}} < 0.014$
    - $\sigma_{\text{trig}} < 0.035$
  - Tight 'T':
    - $\text{IsoECAL} < 5.0+0.012\times p_T$ GeV
    - $\text{IsoECAL} < 3.0+0.005\times p_T$ GeV
    - $\text{IsoTRACK} < 3.5+0.002\times p_T$ GeV
    - H/E < 0.10
    - $\sigma_{\text{trig}} < 0.011$
    - $\sigma_{\text{trig}} < 0.031$
  - VeryTight 'VT':
    - NA
    - H/E < 0.05
    - $\sigma_{\text{trig}} < 0.011$
    - $\sigma_{\text{trig}} < 0.031$

- **Photon ID selection for CaloIdVL_Isol**
  - H/E < 0.05
  - Shower shape ($\sigma_{\text{trig}}$) < 0.010 for ECAL Barrel ($|\eta| < 1.4442$)
  - Shower shape ($\sigma_{\text{trig}}$) < 0.028 for ECAL Endcap (1.566 < |$\eta$| < 2.5)

- **Photon ID selection for CaloIdVL**
  - H/E < 0.05
  - Shower shape ($\sigma_{\text{trig}}$) < 0.020 for ECAL Barrel ($|\eta| < 1.4442$)
  - Shower shape ($\sigma_{\text{trig}}$) < 0.039 for ECAL Endcap (1.566 < |$\eta$| < 2.5)
4. Photon Efficiency Measurements

- Trigger Efficiency
  - Number of passing and failing probe photons after HLTs

<table>
<thead>
<tr>
<th>HLT path</th>
<th>$E_T$ (GeV)</th>
<th>Passing</th>
<th>Failing</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_Photon50_CaloIdVL_IsoL</td>
<td>&gt; 50</td>
<td>1686</td>
<td>417</td>
<td>2103</td>
</tr>
<tr>
<td>HLT_Photon75_CaloIdVL</td>
<td>&gt; 75</td>
<td>889</td>
<td>154</td>
<td>1043</td>
</tr>
<tr>
<td>HLT_Photon75_CaloIdVL_IsoL</td>
<td>&gt; 75</td>
<td>1209</td>
<td>218</td>
<td>1427</td>
</tr>
<tr>
<td>HLT_Photon90_CaloIdVL_IsoL</td>
<td>&gt; 90</td>
<td>1728</td>
<td>237</td>
<td>1965</td>
</tr>
<tr>
<td>HLT_Photon125</td>
<td>&gt; 125</td>
<td>351</td>
<td>36</td>
<td>387</td>
</tr>
<tr>
<td>HLT_Photon135</td>
<td>&gt; 135</td>
<td>624</td>
<td>80</td>
<td>704</td>
</tr>
</tbody>
</table>

- Trigger turn-on curves to exploit maximally efficient region on photon $p_T$
4. Photon Efficiency Measurements

- Trigger Efficiency (results)
- Counting method

<table>
<thead>
<tr>
<th>HLT path</th>
<th>Probe $E_T$ (GeV)</th>
<th>$-\eta$ Endcap</th>
<th>Barrel</th>
<th>$+\eta$ Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HLT_{\text{Photon50}}<em>{\text{CaloIdVL}</em>\text{Isol}}$</td>
<td>60 - Inf.</td>
<td>93.5 ± 3.5</td>
<td>97.8 ± 0.8</td>
<td>96.4 ± 3.4</td>
</tr>
<tr>
<td>$HLT_{\text{Photon75}}_{\text{CaloIdVL}}$</td>
<td>85 - Inf.</td>
<td>100 ± 1.4</td>
<td>99.8 ± 0.3</td>
<td>100 ± 1.6</td>
</tr>
<tr>
<td>$HLT_{\text{Photon75}}<em>{\text{CaloIdVL}</em>\text{Isol}}$</td>
<td>85 - Inf.</td>
<td>97.7 ± 2.2</td>
<td>97.3 ± 0.7</td>
<td>95.6 ± 2.7</td>
</tr>
<tr>
<td>$HLT_{\text{Photon90}}<em>{\text{CaloIdVL}</em>\text{Isol}}$</td>
<td>100 - Inf.</td>
<td>95.6 ± 2.1</td>
<td>97.3 ± 0.5</td>
<td>95.1 ± 2.6</td>
</tr>
<tr>
<td>$HLT_{\text{Photon125}}$</td>
<td>135 - Inf.</td>
<td>100 ± 3.7</td>
<td>100 ± 0.4</td>
<td>100 ± 4.4</td>
</tr>
<tr>
<td>$HLT_{\text{Photon135}}$</td>
<td>145 - Inf.</td>
<td>92.6 ± 5.4</td>
<td>99.8 ± 0.3</td>
<td>94.8 ± 4.1</td>
</tr>
</tbody>
</table>

- Fitting method (fitted to electron-photon inv. mass using the convolution of a Bereit Wigner and a Crystal-Ball function,}
4. Photon Efficiency Measurements

- Photon Reconstruction Efficiency (geometrical acceptance eff.)
- Measure it from photon+jets MC samples

\[
\epsilon_{RECO} = \frac{G_R(p_T, \eta) G(p_T, \eta)}{G(p_T, \eta) G_R(p_T, \eta)}
\]

- Generated photon spectrum
- Generated photon spectrum with a reco match

---

**PYTHIA6 RECO EFFICIENCY**

**MADGRAPH RECO EFFICIENCY**

**Simulation results**

CMS Preliminary 2011
\(\sqrt{s} = 7\) TeV

- 50, 100, 150, 200, 250, 300, 350, 400, 450, 500 GeV/c
4. Photon Efficiency Measurements

- Photon Reconstruction Efficiency (geometrical acceptance eff.)

| Photon $p_T$ | $|\eta| < 0.9$ | $0.9 < |\eta| < 1.4442$ | $1.566 < |\eta| < 2.1$ | $2.1 < |\eta| < 2.5$ |
|-------------|--------------|-----------------|-----------------|-----------------|
| 40-60       | 93.00 ± 0.06 | 91.72 ± 0.08    | 90.10 ± 0.09    | 90.40 ± 0.10    |
| 60-85       | 98.26 ± 0.03 | 97.67 ± 0.04    | 98.24 ± 0.03    | 97.84 ± 0.06    |
| 85-100      | 98.76 ± 0.02 | 98.13 ± 0.04    | 98.50 ± 0.03    | 98.00 ± 0.05    |
| 100-145     | 98.94 ± 0.02 | 98.41 ± 0.03    | 98.76 ± 0.03    | 98.37 ± 0.04    |
| 145-300     | 99.12 ± 0.01 | 98.61 ± 0.02    | 98.60 ± 0.02    | 98.24 ± 0.03    |
| 300-500     | 99.40 ± 0.01 | 98.67 ± 0.01    | 98.32 ± 0.02    | 98.20 ± 0.07    |

- Photon Identification Efficiency

\[
\epsilon_{ID} = \frac{R_{ID}(p_T, \eta)}{R(p_T, \eta)}
\]

**Photon ID selection for SS template**
- $H/E < 0.05$
- Tracker Isolation $< 2.0 + 0.002 \times p_T$ GeV
- ECAL Isolation $< 4.2 + 0.012 \times p_T$ GeV
- HCAL Isolation $< 2.2 + 0.005 \times p_T$ GeV
- Shower shape ($\sigma_{\eta\eta}$) $< 0.020$ for ECAL Barrel ($|\eta| < 1.4442$)
- Shower shape ($\sigma_{\eta\eta}$) $< 0.039$ for ECAL Endcap ($1.566 < |\eta| < 2.5$)

**Photon ID selection for Iso template**
- $H/E < 0.05$
- Shower shape ($\sigma_{\eta\eta}$) $< 0.010$ for ECAL Barrel ($|\eta| < 1.4442$)
- Shower shape ($\sigma_{\eta\eta}$) $< 0.028$ for ECAL Endcap ($1.566 < |\eta| < 2.5$)
4. Photon Efficiency Measurements

- Photon Identification (ID) Efficiency

**Simulation results**

**Shower shape template**

| Photon p_T | $|\eta| < 0.9$ | $0.9 < |\eta| < 1.4442$ | $1.566 < |\eta| < 2.1$ | $2.1 < |\eta| < 2.5$ |
|------------|---------------|-----------------|-----------------|-----------------|
| 40-60      | 81.44 ± 0.08  | 85.77 ± 0.09    | 81.40 ± 0.10    | 78.84 ± 0.13    |
| 60-85      | 83.32 ± 0.07  | 86.75 ± 0.08    | 83.75 ± 0.09    | 80.70 ± 0.12    |
| 85-100     | 83.74 ± 0.07  | 86.77 ± 0.08    | 84.08 ± 0.09    | 81.20 ± 0.12    |
| 100-145    | 85.32 ± 0.06  | 88.11 ± 0.07    | 85.75 ± 0.08    | 83.35 ± 0.11    |
| 145-300    | 86.55 ± 0.04  | 89.06 ± 0.05    | 87.15 ± 0.06    | 85.38 ± 0.10    |
| 300-500    | 88.12 ± 0.03  | 90.47 ± 0.04    | 88.57 ± 0.07    | 88.18 ± 0.18    |
5. Outlook

- Prompt photon cross section measurements at hadron colliders are driven by several motivations.
- Photon efficiencies (in parallel to other ingredients) must be measured from data and simulation samples to correct final cross section spectra.
- We measure differential gamma+jet cross section with 2011 collision data that will be published in *JHEP* for the CMS collaboration: (CMS Internal) K. Ocalan et al., Measurement of the triple differential $\gamma$+jet cross section using 2011 data, CMS Analysis Note CMS-AN-11-31, (2011).

Many thanks to the colleagues in the CMS QCD Photons physics group for their collaboration.
6. References


