Diphoton searches in ATLAS

Marco Delmastro
CNRS/IN2P3 LAPP
on behalf of the ATLAS Collaboration

Les Rencontres de Moriond EW 2016
Why diphoton searches?

- Clean signal over smooth and well known background (e.g. $H(125) \rightarrow \gamma\gamma$)
- Several extensions of the Standard Model predict high-mass states decaying to two photons
- Benchmark models...

Spin-0 analysis
e.g. extended Higgs sector

- 2HDM
  - 5 physical states $h^0, H^0, A^0, H^\pm$
  - Under certain conditions, scalar and/or pseudo-scalar states can have sizable branching ratio to diphoton

Spin-2 analysis
e.g. Randall-Sundrum graviton

- Model predicts tower of Kaluza-Klein graviton states with TeV mass scale
- Phenomenology
  - $m_{G^*} =$ mass of lightest KK excitation
  - $\kappa/M_{Pl} =$ dimensionless coupling to SM fields

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Diphoton searches in ATLAS
Recap of latest Run 1 results

Search for scalar diphoton resonances in the mass range 65-600 GeV with the ATLAS detector in pp collision data at $\sqrt{s} = 8$ TeV

Phys. Rev. Lett. 113, 171801

Search for high-mass diphoton resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

Overview of ATLAS 13 TeV analyses

- **Common pre-selections & photon identification**
  - $E_T^{γ1} > 40$ GeV, $E_T^{γ2} > 30$ GeV
  - Precision region of EM calorimeter: $|η| < 2.37$, 1.37-1.52 excluded
  - Tight photon identification based on shower moments in EM calorimeter
  - Photon isolation (calorimeter cone + track isolation)

- **Optimized for Higgs-like signal**
  - $E_T^{γ1} > 0.4 \, m_{γγ}$, $E_T^{γ2} > 0.3 \, m_{γγ}$
    - +20% significance for $m_X > 600$ GeV
    - Effectively deplete forward regions
  - **As model-independent as possible**
    - Limit on fiducial cross section
  - **Search range**
    - $m_X = [200 \text{ GeV} - 2 \text{ TeV}]$
    - $Γ_X/m_X = [0\% - 10\%]$

- **SPIN-0 ANALYSIS**

- **SPIN-2 ANALYSIS**

- **Loose selection**
  - $E_T^{γ1} > 55$ GeV, $E_T^{γ2} > 55$ GeV
    - Preserve acceptance at high mass
  - **Use RS graviton as (kinematic) benchmark**
  - **Search range**
    - $m_G = [500 \text{ GeV} - 3 \text{ TeV}]$
    - $κ/M_{Pl} = [0.01-0.3]$
    - $Γ_G/m_G ~ [0.01\% - 11\%]$
    - $Γ_G ~ 1.44 \left(\frac{κ}{M_{Pl}}\right)^2$
Photon energy calibration

- **MV regression to calibrate photon cluster energy, optimized on MC**
  - EMC longitudinal layers inter-calibration from from 2012 data + additional uncertainty
    - Mostly affecting constant term
  - Energy scale and resolution corrections validated with 13 TeV $Z\rightarrow ee$ events

- **At $E_T^{\gamma} > 100$-200 GeV, resolution dominated by constant term...**
  - $c = 0.6\% - 1.5\%$
  - \[
  \frac{\sigma E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c
  \]

- **Uncertainties**
  - Energy scale: $\pm(0.4\%-2\%)$
  - Energy resolution ($E_T^{\gamma}=300$ GeV): $\pm(80\%-100\%)$
Photon identification and isolation

- **Identification**
  - ✓ 85% \((E_T \sim 50 \text{GeV})\) - 95% \((E_T \sim 200 \text{GeV})\)
  - ✓ Uncertainty: full data/MC difference
    - ±1% - ±5% for \(E_T > 50 \text{GeV}\)
    - \(\eta\) dependent

- **Isolation**
  - ✓ Calorimeter \((\Delta R=0.4)\)
    - \(E_T^{\text{iso}} < 0.022 E_T^\gamma + 2.45 \text{ GeV}\)
  - ✓ Track \(p_T^{\text{iso}}\) \((\Delta R=0.2)\)
    - \(p_T^{\text{iso}} < 0.05 E_T^\gamma\)
  - ✓ Uncertainty: full data/MC difference
Sample composition

- Estimated for both selections using “2x2D-Sideband” and “Matrix Method”
  ✓ As in SM diphoton cross section measurements (e.g. New J. Phys. 15 (2013) 043007)

**SPIN-0 ANALYSIS**

\[ P_{\gamma\gamma} = 93 \pm 3 \% \]

**SPIN-2 ANALYSIS**

\[ P_{\gamma\gamma} = 94 \pm 3 \% \]
Signal modeling

**SPIN-0 ANALYSIS**

- **Heavy Higgs-like model**
  - Narrow-width ($\Gamma_X = 4$ MeV)
  - Large-width ($\Gamma_X \leq 10\% m_X$)
    - Powheg line-shape assuming SM couplings convoluted to detector response (ggF)
    - $m_X \pm 2\Gamma_X$
  - Double-Sided Crystal Ball

**SPIN-2 ANALYSIS**

- **RS-graviton-like model**
  - $k/M_{Pl} = 0.01$ ($\Gamma_G = 0.01\% m_G$) to measure and parameterize detector response (DSCB)

  - Analytical convolution of theoretical line-shape with detector response

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**ATLAS Simulation Preliminary**

$\sqrt{s} = 13$ TeV, $X \rightarrow \gamma \gamma$

$m_X = 600$ GeV

$\Gamma_X/m_X = 6\%$

**ATLAS Simulation Preliminary**

$\sqrt{s} = 13$ TeV, $G^* \rightarrow \gamma \gamma$

$m_{G^*} = 1000$ GeV

$k/M_{Pl} = 0.20$ ($\Gamma_{G^*}/m_{G^*} = 5.8\%$)
Background modeling

**SPIN-0 ANALYSIS**

- **Functional form ➔ sidebands**
  - Family of nested functions with increasing d.o.f.
    \[ f(k)(x; b, \{a_k\}) = N(1 - x^{1/3}) b x^{\sum_{j=0}^{k} a_j (\log x)^j} \]
    \[ x = \frac{m_{\gamma\gamma}}{\sqrt{s}} \]
  - Validated on MC+data template
  - All function parameters free

- **“Spurious signal” uncertainty**
  - S+B fits on MC+data template

- **F-test on binned data**
  - Validate need of additional d.o.f. (k=0 chosen)
    \[ F = \frac{\sum_{i}(y_i - f_1(x_i))^2 - \sum_{i}(y_i - f_2(x_i))^2}{\sum_{i}(y_i - f_2(x_i))^2} \]
    \[ \frac{p_2 - p_1}{n - p_2} \]

**SPIN-2 ANALYSIS**

- **MC+data template ➔ high mass**
  - Irreducible (\(\gamma\gamma\)) ➔ MC
    - DIPHOX NLO parton level
    - SHERPA \(\gamma\gamma\) including detector simulation, reweighted to DIPHOX \(m_{\gamma\gamma}\)
  - Reducible (\(\gamma j, j\gamma, jj\)) ➔ data
    - Inverting tight shower shape criteria
    - Varying loose criteria

- **Mixed according to data-driven purities**
Results

**SPIN-0 ANALYSIS**

*background-only fit*

![Graph](Image)

ATLAS Preliminary

- Data
- Background-only fit

Spin-0 Selection

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

Data - fitted background

2878 events ($m_{\gamma\gamma} > 200$ GeV)

---

**SPIN-2 ANALYSIS**

*background-only fit*

![Graph](Image)

ATLAS Preliminary

- Data
- Background-only fit

Spin-2 Selection

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

Data - fitted background

5066 events ($m_{\gamma\gamma} > 200$ GeV)

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Diphoton searches in ATLAS
Results

**SPIN-0 ANALYSIS**

ATLAS Preliminary \( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \) Spin-0 Selection

- Largest deviation from B-only hypothesis
  - \( m_X \sim 750 \text{ GeV}, \Gamma_X \sim 45 \text{ GeV} \) (6%)
  - Local \( Z = 3.9 \sigma \)
  - Global \( Z = 2.0 \sigma \)
    - \( m_X = [200 \text{ GeV} - 2 \text{ TeV}] \)
    - \( \Gamma_X/m_X = [1\% - 10\%] \)

**SPIN-2 ANALYSIS**

ATLAS Preliminary \( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \) Spin-2 Selection

- Largest deviation from B-only hypothesis
  - \( m_G \sim 750 \text{ GeV}, \kappa/M_{Pl} \sim 0.2 \) (\( \Gamma_G \sim 6\% m_G \))
  - Local \( Z = 3.6 \sigma \)
  - Global \( Z = 1.8 \sigma \)
    - \( m_X = [500 \text{ GeV} - 3.5 \text{ TeV}] \)
    - \( \kappa/M_{Pl} = [0.01 - 0.3] \)

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Diphoton searches in ATLAS
Properties of sideband and excess regions

**SPIN-0 ANALYSIS**

- $m_{\gamma\gamma} = [600-700]$ GeV
- $m_{\gamma\gamma} = [700-840]$ GeV
- $m_{\gamma\gamma} = [840-\infty]$ GeV

**SPIN-2 ANALYSIS**

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Diphoton searches in ATLAS
Properties of sideband and excess regions

**SPIN-0 ANALYSIS**

\( m_{\gamma\gamma} = [600-700] \text{ GeV} \)

**SPIN-2 ANALYSIS**

\( m_{\gamma\gamma} = [700-840] \text{ GeV} \)

\( m_{\gamma\gamma} = [840-\infty] \text{ GeV} \)
Diphoton searches in ATLAS

**Limit on fiducial cross-section**

**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, \ 3.2 \text{ fb}^{-1} \]

**Spin-0 selection**

**Observed \( CL_s \) limit**

**Expected \( CL_s \) limit**

- Expected \( \pm 1 \sigma \)
- Expected \( \pm 2 \sigma \)

- \( \Gamma_X/m_X = 1 \% \)
- \( \Gamma_X/m_X = 2 \% \)
- \( \Gamma_X/m_X = 6 \% \)
- \( \Gamma_X/m_X = 10 \% \)

**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, \ 3.2 \text{ fb}^{-1} \]

**Spin-0 Selection**

\[ E_T^{Y1} > 0.4 \ m_{YY}, E_T^{Y2} > 0.3 \ m_{YY} \]

\[ E_T^{iso} (\Delta R=0.4) < 0.05 \ E_T^{Y} + 6 \text{ GeV} \]

\[ m_X \pm 2 \Gamma_X \]
Limit on production cross section

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

Spin-2 Selection
\( G^* \rightarrow \gamma \gamma, \frac{k}{M_{Pl}} = 0.05 \)

\( \text{Observed } CL_s \text{ limit} \)
\( \text{Expected } CL_s \text{ limit} \)
\( \text{Expected } \pm \sigma \)
\( \text{Expected } \pm 2\sigma \)

95\% CL limits on \( \alpha \times \text{BR}(G^* \rightarrow \gamma \gamma) \) [fb]

\( m_{G^*} \) [GeV]

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
Spin-2 Selection
\( G^* \rightarrow \gamma \gamma, \frac{k}{M_{Pl}} = 0.10 \)

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
Spin-2 Selection
\( G^* \rightarrow \gamma \gamma, \frac{k}{M_{Pl}} = 0.20 \)

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
Spin-2 Selection
\( G^* \rightarrow \gamma \gamma, \frac{k}{M_{Pl}} = 0.30 \)
Compatibility with 8 TeV data

- 8 TeV data re-analyzed: latest Run 1 γ calibration + same Run 1 selections + 13 TeV analysis methods

**SPIN-0 ANALYSIS**

- Data
- Background-only fit

Spin-0 Selection
\( \sqrt{s} = 8 \text{ TeV, 20.3 fb}^{-1} \)

- 1.9 \( \sigma \) at \( m_X = 750 \text{ GeV} \), \( \Gamma_X/m_X = 6\% \)
- Compatibility with 13 TeV scalar
  - \( gg \) (scaling: 4.7) \( \rightarrow \) compatibility: 1.2 \( \sigma \)
  - \( qq \) (scaling: 2.7) \( \rightarrow \) compatibility: 2.1 \( \sigma \)

**SPIN-2 ANALYSIS**

- Data
- Background-only fit

Spin-2 Selection
\( \sqrt{s} = 8 \text{ TeV, 20.3 fb}^{-1} \)

- No significant excess
- Compatibility with 13 TeV graviton
  - \( gg \) \( \rightarrow \) compatibility: 2.7 \( \sigma \)
  - \( qq \) \( \rightarrow \) compatibility: 3.3 \( \sigma \)
Summary

• Search for new resonances decaying to diphotons performed with 3.2 fb⁻¹ 13 TeV data, with two analyses targeting “spin-0” and “spin-2” scenarios

• Most of the γγ spectrum consistent with B-only hypothesis

• Largest deviation from background-only hypothesis observed in broad region around 750 GeV, with global significance 2.0 (1.8) σ for the spin-0 (spin-2) analysis

• Numerous cross-checks of events with masses ~ 750 GeV performed

• 8 TeV data re-analyzed using latest Run1 calibration, compatibility with 13 TeV results assessed
  ✓ Scalar 1.2 σ (gg) – 2.1 σ (qq)
  ✓ Graviton 2.7 σ (gg) – 3.3 σ (qq)

• More data needed to verify excess origin: looking forward to 2016 LHC run!
Additional information
Systematic uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty for spin-0 analysis</th>
<th>Uncertainty for spin-2 analysis</th>
<th>$p_0$ and limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background modelling (mass dependent)</td>
<td>spurious signal</td>
<td>± 7% to ± 35% on predicted shape</td>
<td>$p_0$ and limit</td>
</tr>
<tr>
<td></td>
<td>$2 \times 10^{-3}$ events for NWA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$20 \times 5 \times 10^{-3}$ events for $\Gamma / M = 7%$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal mass resolution (mass dependent)</td>
<td>$+5%$ to $-110%$</td>
<td>$-20%$ to $-40%$</td>
<td>$p_0$ and limit</td>
</tr>
<tr>
<td>Signal photon identification (mass dependent)</td>
<td>$\pm (3 - 2)%$</td>
<td></td>
<td>limit</td>
</tr>
<tr>
<td>Signal photon isolation (mass dependent)</td>
<td>$\pm (4 - 1)%$</td>
<td>$\pm (3 - 1)%$</td>
<td>limit</td>
</tr>
<tr>
<td>Signal production process dependence</td>
<td>$\pm 3%$ for NWA</td>
<td>$\pm 6%$ for larger decay width</td>
<td>limit</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>$\pm 0.6%$</td>
<td></td>
<td>limit</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\pm 5.0%$</td>
<td></td>
<td>limit</td>
</tr>
</tbody>
</table>
Background modeling

ATLAS Preliminary

- total sys
- reducible
- irreducible
- purity
- isolation

Relative uncertainty

$m_{\gamma\gamma}$ [GeV]
Acceptance

**SPIN-0 ANALYSIS**

- **Fiducial region**
  - $E_T^{\gamma 1} (\text{truth}) > 0.4 \ m_{\gamma\gamma}$, $E_T^{\gamma 2 (\text{truth})} > 0.3 \ m_{\gamma\gamma}$
  - $E_T^{\text{iso}} (\text{truth}) (R=0.4) < 0.05 \ E_T^{\gamma (\text{truth})} + 6 \ \text{GeV}$
  - $m_X \pm 2\Gamma_X$

- **ggF as baseline**
  - Difference to alternative production modes as systematics (ggF, VBF, WH, ZH, ttH)

- **As model-independent as possible**

- $C_X = 55\%-70\%$ for $m_X = 200\text{--}700 \ \text{GeV}$

**SPIN-2 ANALYSIS**

- **Total selection efficiency**
- **RS graviton as benchmark**

- $A_G \times C_G = 45\%-60\%$ for $m_G = 500\text{--}3000 \ \text{GeV}$

**Source of uncertainty**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Scalar</th>
<th>Common</th>
<th>Graviton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal photon identification (mass dependent)</td>
<td>±(3 - 2)%</td>
<td>±(3-1)%</td>
<td>±(3-1)%</td>
</tr>
<tr>
<td>Signal photon isolation (mass dependent)</td>
<td>±(4-1)%</td>
<td>±3% for NWA</td>
<td>N/A</td>
</tr>
<tr>
<td>Signal production process dependence</td>
<td>±3% for NWA</td>
<td>±6% for larger decay width</td>
<td>N/A</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>±0.6%</td>
<td>±5.0%</td>
<td>negligible</td>
</tr>
<tr>
<td>Luminosity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photon energy scale and resolution</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Compatibility between spin-0 and spin-2 analyses

- Events in spin-0 analysis are subset of events in spin-2 analysis for \( m_{\gamma\gamma} > 185 \) GeV, so two analyses are not independent

✓ Resampling techniques (bootstrap)
  - Union dataset is sliced into \( N \) blocks with 10 events in each block.
  - \( N \) blocks are randomly picked without considering possible duplication (i.e. the same block could be selected for more than one time).
  - Resampled dataset will then pass spin-0 and spin-2 selections, outcome spectra are fed into max LL S+B fit assuming same signal hypothesis
  - Procedure is repeated many times until decent statistics are accumulated for compatibility check

- Assuming spin-0 signal: 0.02 \( \sigma \)
- Assuming spin-2 signal: 0.9 \( \sigma \)
## 8 TeV analysis selections

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Scalar analysis</th>
<th>Graviton analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td><strong>EF_g35_loose_g25_loose</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>v61-pro14-02_DQDefects-00-01-00_PHYS_StandardGRL_All_Good</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>LArError, TileError, event corruption</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>At least one PV with 3 associated tracks or more</td>
<td></td>
</tr>
<tr>
<td></td>
<td>At least two photons passing loose ID, OQ, photon cleaning</td>
<td></td>
</tr>
<tr>
<td></td>
<td>with $</td>
<td>\eta_{S2}</td>
</tr>
<tr>
<td>Presel.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_T$ cuts</td>
<td>$E_{T,1} &gt; 0.4 \times m_{\gamma\gamma}$ and $E_{T,2} &gt; 0.3 \times m_{\gamma\gamma}$</td>
<td>$E_{T,1} &gt; 50 \text{ GeV}$ and $E_{T,2} &gt; 50 \text{ GeV}$</td>
</tr>
<tr>
<td>Photon ID</td>
<td>Require both candidates to pass tight photon ID</td>
<td></td>
</tr>
<tr>
<td>Isolation</td>
<td>$\left{ \begin{array}{ll} E_{T,\text{iso,calo}} \leq 6 \text{ GeV} &amp; \text{if } E_T \leq 80 \text{ GeV} \ E_{T,\text{iso,calo}} \leq 6 \text{ GeV} + 0.7% (E_T - 80 \text{ GeV}) &amp; \text{if } E_T &gt; 80 \text{ GeV} \end{array} \right.$ and $E_{T,\text{iso,track}} \leq 2.6 \text{ GeV}$</td>
<td>$E_{T,\text{iso,calo}} &lt; 8 \text{ GeV}$ and $E_T &lt; 80 \text{ GeV}$</td>
</tr>
<tr>
<td>$m_{\gamma\gamma}$</td>
<td>$m_{\gamma\gamma} &gt; 150 \text{ GeV}$</td>
<td></td>
</tr>
</tbody>
</table>
Properties of sideband and excess regions

**SPIN-0 ANALYSIS**

$m_{\gamma\gamma} = [600-700] \text{ GeV}$

**SPIN-2 ANALYSIS**

$m_{\gamma\gamma} = [700-840] \text{ GeV}$

$m_{\gamma\gamma} = [840-\infty] \text{ GeV}$
Properties of sideband and excess regions

**SPIN-0 ANALYSIS**

$m_{\gamma\gamma} = [600-700]$ GeV

- Data
- MC $\gamma\gamma$

**SPIN-2 ANALYSIS**

$m_{\gamma\gamma} = [700-840]$ GeV

- Data
- MC $\gamma\gamma$

$m_{\gamma\gamma} = [840-\infty]$ GeV

- Data
- MC $\gamma\gamma$
EOYE NW results

- Largest deviation from B-only hypothesis
  - $m_X \sim 750$ GeV
  - Local $Z = 3.6 \sigma$
  - Global $Z = 2.0 \sigma$
    - $m_X = [200 \text{ GeV} - 2 \text{ TeV}]$
Recap of latest Run 1 results

Search for scalar diphoton resonances in the mass range 65-600 GeV with the ATLAS detector in pp collision data at $\sqrt{s} = 8$ TeV

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Search for high-mass diphoton resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

Recap of latest Run 1 results

Search for Extra Dimensions in diphoton events using proton-proton collisions recorded at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC

Data sample & Selections

• **Luminosity & Trigger**
  
  ✓ Trigger: $E_T^{\gamma_1} > 35$ GeV, $E_T^{\gamma_2} > 25$ GeV + loose EM shower identification
  
  • ~99% efficient w.r.t. final selections
  
  ✓ 3.2 fb$^{-1} \pm 5$

SCALAR

• $E_T^{\gamma_1} > 0.4 \ m_{\gamma\gamma}, \ E_T^{\gamma_2} > 0.3 \ m_{\gamma\gamma}$

• 7391 events ($m_{\gamma\gamma} > 150$ GeV)

• 2878 events ($m_{\gamma\gamma} > 200$ GeV)

GRAVITON

• $E_T^{\gamma_1} > 55$ GeV, $E_T^{\gamma_2} > 55$ GeV

• 5066 events ($m_{\gamma\gamma} > 200$ GeV)
Background modeling

**IRREducible**

*born*  
\[ q \rightarrow \bar{q} \rightarrow \gamma \]
\[ \bar{q} \rightarrow \gamma \]

*box*  
\[ g \rightarrow g \rightarrow \gamma \]
\[ g \rightarrow \gamma \]

*parton fragmentation*  
\[ g \rightarrow q \rightarrow \gamma \]
\[ g \rightarrow q \rightarrow \gamma \]

**REducible**

jets in $\gamma j$ and $jj$ events with a neutral meson decaying in collimated photon pairs

\[ q \rightarrow \gamma \]
\[ g \rightarrow q \rightarrow \gamma \]
\[ q \rightarrow \gamma \]
\[ g \rightarrow \gamma \]

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Diphoton searches in ATLAS
A photon showers in the EMC. Most of its energy is lost in Pb

Electrons in EM shower ionize LAr

Ionization electrons produce current

Current is collected, amplified, shaped, sampled and digitized for each EMC cell

Photon energy scale is adjusted to EM scale from $Z \rightarrow ee$ events

Cluster energy is corrected for loss to get photon energy

Cluster energies are corrected for detectors effects

Cells are grouped in clusters

Energy in a cell is reconstructed from signal samples

“in-situ” intercalibration

MVA calibration

cluster corrections

clustering

electronic calibration
ATLAS liquid argon electromagnetic calorimeters

\[ \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \]

- S0 (Presampler)
- S1 (Strips)
- S2 (Middle)
- S3 (Back)

Energy loss correction
- Energy loss correction
- $\gamma/\pi^0$ separation $4.3 X_0$
- Main energy deposit $16 X_0$
- High energy showers $2 X_0$

- $\Delta \phi = 0.0245 \times 0.05$
- $\Delta \eta = 0.1$
- $\Delta \phi = 0.0245$
- $\Delta \eta = 0.0031$
- $\Delta \eta \times \Delta \phi = 0.025 \times 0.1$

Cells in Layer 3
- Sampling calorimeter Pb-LAr
- Trigger Tower
- Cells in Layer 1
- Strip cells in Layer 1
- Square cells in Layer 2
- Cells in PS
- $\Delta \eta \times \Delta \phi = 0.025 \times 0.1$
ATLAS Inner Detector

- + IBL!
- Properties of track from charged particles
  - momentum
  - charge
- Transition Radiation
  - $e/\pi$ discrimination
- $e/\gamma$ discrimination
- $\gamma$ conversion reconstruction
Electrons and photons in ATLAS

Electron and photon candidates in ATLAS are built from EM “sliding window” fixed-size rectangular clusters, that can be associated to tracks

- $\Delta \eta \times \Delta \phi = 0.075 \times 0.175$ (Barrel), $0.125 \times 0.125$ (Endcap)
- Unified between electrons and photons in 2015
- Size is trade-off between energy leakage and noise pickup

- Cells in EM clusters are calibrated to “EM scale”
  - Including expected average sampling fraction, from simulated electron at 100 GeV

- Several corrections needed for $e$ and $\gamma$, mostly based on simulation
  - e.g. energy losses outside cluster, losses in upstream material, variable sampling fraction…
Photon conversion reconstruction

- **Candidate photon conversion vertices reconstructed from tracks pre-selected as loosely matching EMC clusters**
  - 1 or 2 tracks
  - 1-track conversions from tracks that missing the hit in innermost ID layer
- **Photon reconstruction expected efficiency**
  - ~ 98% for photons $E_T > 25$ GeV
  - > 99% for unconverted photons
  - ~ 95% for converted (R < 80 cm)
- **Expected fraction of converted photons**
  - ~ 20% at $|\eta| \sim 0$ - ~ 45% $|\eta| \sim 1.6$
- **Relative fraction of reconstructed photon conversion depends on:**
  - Material upstream EMC
  - In MC, on conversion model…
Photon conversion reconstruction

**ATLAS** Preliminary

\( \sqrt{s} = 13 \text{ TeV}, \int L \, dt = 19 \text{ pb}^{-1} \)

**Unconverted**  
**Converted**  
**Single track conversion**  
**Double track conversion**

\[ |\eta^\gamma| < 2.37 \text{ (1.37 < |\eta^\gamma| ≤ 1.52 excluded), } E_T^\gamma > 125 \text{ GeV} \]
Photon pointing

- z position of diphoton primary vertex obtained by combining average beam-spot position with photon pointing, enhanced by using tracks from photon conversions with conversion radii in Si volume
  - Resolution ~15 mm in z direction
- NN discriminant with $\sum p_T, \sum p_T^2$, diphoton balancing with vertex tracks, trajectory from calorimeter segmentation (z pointing) to choose best vertex candidate
  - After this procedure contribution of the opening angle resolution to the mass resolution is negligible.
  - Efficiency to reconstruct the correct primary vertex within ±0.3 mm is about 88%.
Photon identification

S3 ("Back")

S3 ("Middle")

S1 ("Strips")

Presampler

\( \gamma \) candidate

\( \pi^0 \) candidate

\( \eta \)
Photon identification

Variables and Position

<table>
<thead>
<tr>
<th>Strips</th>
<th>2nd</th>
<th>Had.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratios</td>
<td>$f_1, f_{\text{side}}$</td>
<td>$R_\eta^*, R_\phi$</td>
</tr>
<tr>
<td>Widths</td>
<td>$w_{s,3}, w_{s,\text{tot}}$</td>
<td>$w_{\eta,2}^*$</td>
</tr>
<tr>
<td>Shapes</td>
<td>$\Delta E, E_{\text{ratio}}$</td>
<td>-</td>
</tr>
</tbody>
</table>

Energy Ratios

$$R_\eta = \frac{E_{S_2}^{S_2}}{E_{7\times 7}^{S_2}}$$

$$R_\phi = \frac{E_{S_2}^{S_2}}{E_{3\times 3}^{S_2}}$$

$$R_{\text{Had.}} = \frac{E_{\text{Had.}}}{E_T}$$

Shower Shapes

$$E_{\text{ratio}} = \frac{E_{S_1}^{S_1,1} - E_{S_1}^{S_1,2}}{E_{S_1}^{S_1,1} + E_{S_1}^{S_1,2}}$$

$$\Delta E = E_{S_1}^{S_1,2} - E_{S_1}^{S_1,\text{min}}$$

Widths

$$w_{\eta,2} = \sqrt{\sum E_i E_i \eta_i^2 - \left( \sum E_i \eta_i \right)^2}$$

Width in a $3\times 5$ ($\Delta\eta \times \Delta\phi$) region of cells in the second layer.

$$w_s = \sqrt{\sum E_i (i - i_{\text{max}})^2 \sum E_i}$$

$w_{s,3} = w_1$ uses ±1 strips (three total); $w_{s,tot}$ is defined similarly, but uses 20×2 strips.
Photon identification 2015

![Graphs showing photon identification efficiency as a function of $E_T$ for different kinematic regions.](image)
Photon isolation

- Calorimetric isolation energy corrected event-by-event
  - Leakage of photon cluster
  - Underlying event and pileup contributions
    - Average correction for 1 PV ~540MeV

Marco Delmastro

Diphoton searches in ATLAS

Simulation Preliminary

Cacciari, Salam and Soyez, JHEP 04, 005 (2008)
Cacciari, Salam and Sapeta, JHEP 04, 065 (2010)
Photon isolation 2015

**ATLAS** Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
125 < \( p_T \) < 145 [GeV]
0.00 < |\( \eta \)| < 0.60

- **Data**
- **Bkg template**
- **Sherpa**
- **Pythia**

Events

**ATLAS** Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
125 < \( p_T \) < 145 [GeV]
0.60 < |\( \eta \)| < 1.37

- **Data**
- **Bkg template**
- **Sherpa**
- **Pythia**

Events

**ATLAS** Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
125 < \( p_T \) < 145 [GeV]
1.52 < |\( \eta \)| < 1.81

- **Data**
- **Bkg template**
- **Sherpa**
- **Pythia**

Events

**ATLAS** Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
125 < \( p_T \) < 145 [GeV]
1.81 < |\( \eta \)| < 2.37

- **Data**
- **Bkg template**
- **Sherpa**
- **Pythia**

Events
Background estimates

2x2D-sidebands

L’L’ sample, leading candidate

C
D

non-TIGHT

TIGHT

Identification cut

Control region

Signal region

A
B

ATLAS Data 2010, \( \sqrt{s} = 7 \text{ TeV} \), \( \int L dt = 37 \text{ pb}^{-1} \)

\( E_T^{\text{iso}} > 16 \text{ GeV} \)

\( \gamma\gamma \)
\( \gamma j \)
\( j\gamma + jj \)
\( \gamma\gamma + \gamma j + j\gamma + jj \)

ATLAS

(leading photon)

Control region

A' sample, sub-leading candidate

C'
D'

non-TIGHT

TIGHT

Identification cut

Control region

Signal region

A'
B'

ATLAS

(sub-lead photon)

Control region

Non-TIGHT

TIGHT

Identification cut

Control region

Signal region

A' sample, sub-leading candidate

C'
D'

non-TIGHT

TIGHT

Identification cut

Control region

Signal region

A'
B'

ATLAS

(sub-lead photon)

Control region

Non-TIGHT

TIGHT

Identification cut

Control region

Signal region

Marco Delmastro

photon and diphoton production at ATLAS

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Background estimates

$$
\begin{pmatrix}
PP \\
PF \\
FP \\
FF
\end{pmatrix} =
\begin{pmatrix}
\epsilon_1 \epsilon_2 & \epsilon_1 f_2 & f_1 \epsilon_2 & f_1 f_2 \\
\epsilon_1 (1 - \epsilon_2) & \epsilon_1 (1 - f_2) & f_1 (1 - \epsilon_2) & f_1 (1 - f_2) \\
(1 - \epsilon_1) \epsilon_2 & (1 - \epsilon_1) f_2 & (1 - f_1) \epsilon_2 & (1 - f_1) f_2 \\
(1 - \epsilon_1)(1 - \epsilon_2) & (1 - \epsilon_1)(1 - f_2) & (1 - f_1)(1 - \epsilon_2) & (1 - f_1)(1 - f_2)
\end{pmatrix}
\begin{pmatrix}
W_{\gamma\gamma} \\
W_{\gamma j} \\
W_{j \gamma} \\
W_{jj}
\end{pmatrix}
$$

Passes or Fails isolation cut

$\epsilon_i = \text{probability for a } \gamma \text{ to pass isolation cut (data-driven)}$

$f_i = \text{probability for a jet to pass isolation cut (data-driven)}$

Event weights

accounting for the correlation of the isolation energy of the 2 $\gamma$ candidates
Do we need an additional free parameter?

- One might be tempted to use a more complex function to fit the data
  - If a “more complex” function $f_b(x; \{p_b\})$ embeds the simpler one $f_a(x; \{p_a\})$ (e.g. there exist a choice of $\{p_b\}$ such that $f_b(x; \{p_b\}) = \text{one } f_a(x; \{p_a\})$, then the function with more degrees of freedom will have a smaller $\chi^2$
- The problem is to decide whether $f_b$ is more motivated than $f_a$
  - Eyes are not good judges…
  - **F-test** $\rightarrow$ the function $F$ has Fisher distribution $f(F; p_1, p_2)$ if the added parameter is not improving the model

\[
F = \frac{\sum_i (y_i - f_1(x_i))^2 - \sum_i (y_i - f_2(x_i))^2}{\sum_i (y_i - f_2(x_i))^2} \cdot \frac{p_2 - p_1}{n - p_2}
\]

One rejects the hypothesis that the additional parameter if useless if $P < 0.05$, where $P$ is the probability of observing a $F$ value at least as extreme as the one in data, if drawn from a Fisher distribution with the same degrees of freedom.
Statistical procedure

\[ N_S f_S(m_{\gamma\gamma}) + N_B f_B(m_{\gamma\gamma}) \]

\[ q_0(m_X, \alpha) = -2 \log \frac{L(0, m_X, \alpha, \hat{\nu})}{L(\hat{\sigma}, m_X, \alpha, \hat{\nu})} \]

\[ p_{\text{global}} \approx E[\phi(A_u)] = p_0 + e^{-u/2}(N_1 + \sqrt{u}N_2) \]
Double-Sided Crystal Ball function

\[
N \cdot \begin{cases} 
 e^{-t^2/2} & \text{if } -\alpha_{\text{low}} \geq t \geq \alpha_{\text{high}} \\
 e^{-0.5\alpha_{\text{low}}^2} \left[ \frac{n_{\text{low}}}{n_{\text{low}}} \left( \frac{n_{\text{low}}}{\alpha_{\text{low}}} + t - \alpha_{\text{low}} \right) \right]^{n_{\text{low}}} & \text{if } t < -\alpha_{\text{low}} \\
 e^{-0.5\alpha_{\text{high}}^2} \left[ \frac{n_{\text{high}}}{n_{\text{high}}} \left( \frac{n_{\text{high}}}{\alpha_{\text{high}}} + t - \alpha_{\text{high}} \right) \right]^{n_{\text{high}}} & \text{if } t > \alpha_{\text{high}},
\end{cases}
\]

\[
t = \Delta m_X / \sigma_{CB}, \quad \Delta m_X = m_X - \mu_{CB}
\]
Signal modeling

**ATLAS Simulation Internal**
\( \sqrt{s} = 13 \text{ TeV}, X \rightarrow \gamma \gamma \)
- \( m_X = 600 \text{ GeV} \)
- \( \Gamma_X = 4 \text{ MeV} \)

**ATLAS simulation internal**
- \( m_G = 1000 \text{ GeV} \)
- \( k/M_{Pl} = 0.01 \)

**ATLAS Simulation Internal**
- \( \sqrt{s} = 13 \text{ TeV}, X \rightarrow \gamma \gamma \)
- \( m_X = 600 \text{ GeV} \)
- \( \Gamma_X/m_X = 6\% \)

**ATLAS simulation internal**
- \( m_G = 1000 \text{ GeV} \)
- \( k/M_{Pl} = 0.20 \)
Jet Vertex Fraction

\[
JVF(jet, \text{vtx}_j) = \frac{\sum_k p_T(trk^j_{\text{jet}}, \text{vtx}_j)}{\sum_n \sum_l p_T(trk^j_{\text{jet}}, \text{vtx}_n)}
\]