Photon-Photon Measurements in ATLAS

Chav Chhiv Chau
Carleton University

on behalf of the ATLAS Collaboration

Photon 2017
CERN, 22-26 May 2017
Introduction

- Two-photon measurements in ATLAS:
  - $pp \rightarrow pp\ell^+\ell^-$ at $\sqrt{s} = 7$ TeV, $4.6$ fb$^{-1}$(2011)
  - $pp \rightarrow ppW^+W^-$ at $\sqrt{s} = 8$ TeV, $20.2$ fb$^{-1}$(2012)
  - $Pb + Pb \rightarrow Pb + Pb + \mu^+\mu^-$ at $\sqrt{s} = 5.02$ TeV, $515$ $\mu$b$^{-1}$(2015)
  - $Pb + Pb \rightarrow Pb + Pb + \gamma\gamma$ at $\sqrt{s} = 5.02$ TeV, $480$ $\mu$b$^{-1}$(2015) ← S. Webb’s talk on Wednesday

- The two-photon measurements provide direct access to the elastic photon distributions in proton and nucleus
- The $pp \rightarrow ppW^+W^-$ production can probe physics beyond the electroweak scale and set limits on anomalous quartic gauge couplings ($WW\gamma\gamma$)
- The forward dimuon production in Pb+Pb collisions covers the high dimuon invariant mass, i.e. $m_{\mu\mu} > 10$ GeV
Photon-Photon Production

- Signal modelling is done using the Equivalent Photon Approximation (EPA)
- ATLAS proton–proton analyses considered the coherent (exclusive) and incoherent (dissociative) production

Elastic process is characterized by the production of back-to-back leptons, $p_{T}^{\ell\ell} \sim 0$, providing a way to separate the elastic from the dissociative production
- For lead–lead collisions, incoherent production was not considered
Exclusive Dilepton Production

- Measurement of exclusively produced electron and muon pairs
- $4.6 \text{ fb}^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV
- Exactly two good electrons/muons associated to the interaction vertex

\[ \gamma \gamma \rightarrow \ell^+ \ell^- \] Exclusive Event Selection

- **Triggering:**
  - A muon with \( p_T^{\mu} > 18 \) GeV or di-muon with \( p_T^{\mu} > 10 \) GeV for the muon channel
  - An electron with \( p_T^e > 20 \) GeV or di-electron with \( p_T^e > 12 \) GeV for the el channel

- **Selecting exclusive interactions:**
  1. Dilepton vertex have exactly two charged-particle tracks (\( p_{\text{track}}^{\gamma} > 0.4 \text{GeV} \))
  2. No additional tracks/vertices found within 3 mm (\( \Delta z_{\text{iso}}^{\gamma} > 3 \text{ mm} \)) of the vertex
\( \gamma \gamma \rightarrow \ell^+ \ell^- \) Selection of Elastic Interaction

- Veto the region \( 70 \text{ GeV} < m_{\ell^+ \ell^-} < 105 \text{ GeV} \) to reduce \( Z/\gamma^* \) background
- Select \( p_T^{\ell^+ \ell^-} < 1.5 \text{ GeV} \) to suppress the dissociative background
$\gamma\gamma \rightarrow \ell^+\ell^-$ Data-driven Correction Factors

- Fit acoplanarity distributions to determine the correction factor for the signal ($R^{\text{excl}}$) and single-dissociative ($R^{\text{s-diss}}$) background.
- Double-dissociative and Drell-Yan background are fixed to the MC predictions.

Acoplanarity $\equiv 1 - \frac{|\Delta\phi_{\ell^+\ell^-}|}{\pi}$, where $\Delta\phi_{\ell^+\ell^-}$ is the azimuthal opening angle between the leptons.

<table>
<thead>
<tr>
<th>Best-fit values</th>
<th>$R^{\text{excl}}$</th>
<th>$R^{\text{s-diss.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron channel</td>
<td>0.86 $\pm$ 0.07</td>
<td>0.76 $\pm$ 0.08</td>
</tr>
<tr>
<td>Muon channel</td>
<td>0.79 $\pm$ 0.04</td>
<td>0.76 $\pm$ 0.05</td>
</tr>
</tbody>
</table>
\( \gamma \gamma \rightarrow \ell^+ \ell^- \) Measured Cross-section

- Definition of the fiducial regions for which the cross-sections are measured:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Electron channel</th>
<th>Muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T^\ell )</td>
<td>( &gt; 12 \text{ GeV} )</td>
<td>( &gt; 10 \text{ GeV} )</td>
</tr>
<tr>
<td>(</td>
<td>\eta^\ell</td>
<td>)</td>
</tr>
<tr>
<td>( m_{\ell^+ \ell^-} )</td>
<td>( &gt; 24 \text{ GeV} )</td>
<td>( &gt; 20 \text{ GeV} )</td>
</tr>
</tbody>
</table>

- The fiducial cross-section is given by the following relation:

\[
\sigma_{\gamma \gamma \rightarrow \ell^+ \ell^-}^{\text{excl}} = R_{\gamma \gamma \rightarrow \ell^+ \ell^-}^{\text{excl}} \cdot \sigma_{\gamma \gamma \rightarrow \ell^+ \ell^-}^{\text{EPA}}
\]

- \( \sigma_{\gamma \gamma \rightarrow \ell^+ \ell^-}^{\text{EPA}} \) is the cross-section in the fiducial region calculated with \textsc{Herwig++} MC Generator

<table>
<thead>
<tr>
<th></th>
<th>Measured cross-section [pb]</th>
<th>Theoretical prediction with correction [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron channel</td>
<td>0.428 ± 0.035 (stat.) ± 0.018 (syst.)</td>
<td>0.398 ± 0.007 (theor.)</td>
</tr>
<tr>
<td>Muon channel</td>
<td>0.628 ± 0.032 (stat.) ± 0.021 (syst.)</td>
<td>0.638 ± 0.011 (theor.)</td>
</tr>
</tbody>
</table>

- Detail on the predictions can be found in Phys. Lett. B \textbf{741} (2015) 66
\[ \gamma\gamma \rightarrow \ell^+ \ell^- \] Comparison to Prediction

- Measured cross-sections are in agreement with the predicted values corrected for proton absorptive effects
- They are also consistent with the CMS measurement JHEP 1201 (2012) 052
Exclusive $\gamma\gamma \rightarrow W^+W^-$ production

- $\gamma\gamma \rightarrow W^+W^- \rightarrow e^\pm \mu^\mp$ process considered
- 20.2 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV

Exclusive $\gamma\gamma \rightarrow W^+W^-$ production

- Sensitive to the anomalous quartic gauge couplings (aQGCs)

- Consider both the elastic and dissociative (SD and DD) production as signal
- Estimate the SD&DD contribution from data using region $m_{\mu\mu} > 160$ GeV

\[ f_\gamma = \frac{\text{Elastic+SD+DD}}{\text{Elastic from MC}} = \frac{N_{\text{Observed}} - N_{\text{Background}}}{N_{\text{Elastic}}} \bigg|_{m_{\mu\mu}>160 \text{ GeV}} \]

- For the 1.0 mm exclusivity, data-driven scale factors is $f_\gamma = 3.30 \pm 0.23$
- Total expected signal $= f_\gamma \times \text{Elastic } \gamma\gamma \rightarrow W^+W^- \text{ (from Herwig++)}$
\( \gamma\gamma \rightarrow W^+W^- \) Exclusivity Selection

- Require any of the following triggers:
  - Single-muon \( (p_T^\mu > 24 \text{ GeV}) \) or single-electron \( (p_T^e > 24 \text{ GeV}) \)
    or electron-muon \( (p_T^e > 12 \text{ GeV} \text{ and } p_T^\mu > 8 \text{ GeV}) \)
- Select two good leptons with \( p_T^\ell > 20 \text{ GeV and } m_{\ell\ell} > 20 \text{ GeV} \)
- Reconstruct our own event vertex (not use primary vertex)
  - Distance between the two leptons be \( |z_{\ell 1}^0 - z_{\ell 2}^0| < 1 \text{ mm} \)

Lepton vertex = \( \frac{z_{\ell 1}^0 + z_{\ell 2}^0}{2} \)

- Compute distance between track \( z_0 \) and the lepton vertex
  - Consider all tracks with \( p_T > 0.4 \text{ GeV} \)
  - Skip all tracks matched to selected leptons
  - Matched if \( \Delta R(\text{track}, \ell) < 0.01 \text{ and } |z_{\ell}^0 - z_{\text{track}}^0| < 1 \text{ mm} \)
- Require zero extra track in a \( \Delta z_0^{\text{iso}} = 1.0 \text{ mm} \) window around the lepton vertex
\[ \gamma \gamma \rightarrow W^+ W^- \] Sanity Checks Using Exclusive Di-muon

**Correction factor for elastic \( \gamma \gamma \rightarrow \mu \mu \):**
- Select \( p_T^{\mu} > 20 \) GeV, \( m_{\mu \mu} > 45 \) GeV and \( |m_{\mu \mu} - m_Z| > 15 \) GeV
- Best-fitted value for the ratio data/prediction:
  \[
  f_{EL} = 0.76 \pm 0.04(\text{stat.}) \pm 0.10(\text{sys.})
  \]

**Pileup modelling:**
- Distribution of the exclusive events (including SD and DD) are flat
- Drell-Yan peaks at zero, since it is likely to have more than two tracks
\( \gamma \gamma \rightarrow W^+W^- \) Control Regions

- Same selection criteria as the exclusive \( WW \) region, except the exclusivity selection requires 1 to 4 extra tracks within \( \Delta z_{0}^{\text{iso}} = 1 \text{ mm} \)
  - \( p_T^{\mu} < 30 \text{ GeV} \): Drell-Yan \( \tau\tau \) control region
  - \( p_T^{\mu} > 30 \text{ GeV} \): inclusive \( WW \) control region
\( \gamma \gamma \rightarrow W^+ W^- \) Event Selection

| Preselection \( p_T^{e\mu} > 30 \text{ GeV} \) | Signal \( 22.6 \pm 1.9 \) 99424 97877 | Data \( 11443 \) 21.4 1385 85029 | Total Bkg \( 17.6 \pm 1.5 \) 63329 63023 | Incl \( WW \) \( 8072 \) 4.30 896.3 54051 | Excl. \( \tau \tau \) \( 6.6 \pm 2.5 \) 1.4 \( 0.3 \pm 0.2 \) – – | non-\( WW \) \( 23 \) 8.3 \( 1.4 \pm 0.3 \) \( 0.3 \pm 0.2 \) | Other Bkg \( 0.98 \) MC/Data 1.00 |
| Exclusivity selection \( p_T^{e\mu} > 120 \text{ GeV} \) | Incl WW \( 9.3 \pm 1.2 \) 23 8.3 \( 1.4 \pm 0.3 \) \( 0.3 \pm 0.2 \) | Excl. \( \tau \tau \) \( 6.6 \pm 2.5 \) 1.4 \( 0.3 \pm 0.2 \) – – | non-\( WW \) \( 23 \) 8.3 \( 1.4 \pm 0.3 \) \( 0.3 \pm 0.2 \) | Other Bkg \( 0.77 \) |

- Preselection: exactly two \( e^\pm \mu^\mp \) with \( p_T^{\ell_1} > 25 \text{ GeV} \) and \( p_T^{\ell_2} > 20 \text{ GeV} \), \( m_{e\mu} > 20 \text{ GeV} \)
- Observed significance over the background-only hypothesis is \( 3\sigma \), constituting evidence of \( \gamma \gamma \rightarrow W^+ W^- \) production

**Notes:**

- **ATLAS** for the signal region:
  - \( E_{\text{T}} = 8 \text{ TeV}, 20.2 \text{ fb}^{-1} \)
  - **Data 2012**
  - **Incl WW**
  - **Excl. WW**
  - **Excl. \( \tau \tau \)**
  - **Other VV**
  - **sys. \& stat.**

- **Excl.WW signal region**
  - \( \Delta \phi_{e\mu} \text{ [rad]} \):
    - 10
    - 9
    - 8
    - 7
    - 6
    - 5
    - 4
    - 3
    - 2
    - 1
    - 0
    - 0.5
    - 1
    - 1.5
    - 2
    - 2.5
    - 3

![Events / 10 GeV](chart1)

![Events / 0.2 rad](chart2)
$\gamma\gamma \rightarrow W^+W^-$ Measurement

- The measured cross-section times branching ratio:

$$\sigma(\gamma\gamma \rightarrow W^+W^- \rightarrow e^+\mu^-) = 6.9 \pm 2.7 \text{ fb}$$

- Predicted cross-section times branching ratio: 4.4 fb

- 95% C.L. limits set on anomalous quartic gauge couplings
Dimuons in Lead-Lead Collisions

- Process considered: $\text{Pb} + \text{Pb} \rightarrow \mu^+ + \mu^- + \text{Pb}^\ast + \text{Pb}^\ast$
- Data sample: $515 \, \mu b^{-1}$ of Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV
- Measurement reported in: ATLAS-CONF-2016-025
Dimuons in Lead-Lead Collisions

- Triggering on events with a muon and little additional activity in the detector
- Selecting vertices with exactly two good opposite-charged muons
- Signal modelled by STARLIGHT, predicting coverage of $m_{\mu\mu}$ up to 100 GeV
PbPb → \( \mu^+ \mu^- \) PbPb Acoplanarity Distribution

- Fit acoplanarity in three rapidity bins for 10 GeV < \( m_{\mu\mu} \) < 100 GeV
  - |\( Y_{\mu\mu} \)| < 0.8, 0.8 < |\( Y_{\mu\mu} \)| < 1.6, 1.6 < |\( Y_{\mu\mu} \)| < 2.4
- Consider two cases for acoplanarity tail, since its origin hasn’t been clarified
  - All activity in the tails is due to signal
  - All activity in the tails is due to background
**PbPb → μ⁺μ⁻PbPb Cross-Section**

- Measured the cross-section in the fiducial region: $p_T^μ > 4$ GeV, $|\eta^μ| < 2.4$ and $m_{μμ} > 10$ GeV
  - $σ = 32.2 ± 0.3$(stat.)$^{+4.0}_{-3.4}$(syst.) $μb$
  - consistent with the STARLIGHT prediction of $31.64 ± 0.04$(stat.) $μb$
2017 Data Taking Started

- ATLAS recently started taking data again
- Expected at least another $45 \text{ fb}^{-1}$ of $pp$ collisions for the 2017 operation
- The new ATLAS Forward Proton detector opens up many possibilities
  - M. Trzebinski’s talk
- A lot of exciting results in the coming months
Summary

- Two-photon production of lepton pairs and $W$-boson pairs have been measured with the ATLAS Detector
  - $\gamma\gamma \rightarrow \ell^+\ell^-$ production using $4.6 \text{ fb}^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B 749 (2015) 242-261 (arXiv:1506.07098)
  - $\gamma\gamma \rightarrow W^+W^- \rightarrow e^\pm\mu^\mp$ production using $20.2 \text{ fb}^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV, Phys. Rev. D 94 (2016) 032011 (arXiv:1607.03745)
  - $\gamma\gamma \rightarrow \mu^+\mu^-$ production using $515 \mu\text{b}^{-1}$ of Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV, ATLAS-CONF-2016-025

- Observed suppression in $\gamma\gamma \rightarrow \ell^+\ell^-$ production in $pp$ collisions with respect to calculations based on EPA

- Set 95% C. L. limits on the anomalous quartic gauge couplings $WW\gamma\gamma$

- Photon-photon measurements provide direct access to the elastic photon distributions in proton/nucleus

Thank You!
Additional materials
ATLAS Detector

- Inner Detector ($|\eta| < 2.5$)
- Calorimeters ($|\eta| < 4.9$)
- Muon spectrometer ($|\eta| < 2.7$)
- Minimum Bias Trigger Scintillator ($2.1 < |\eta| < 3.9$)
\[ \gamma \gamma \rightarrow \ell^+ \ell^- \]

Main Backgrounds and Pileup

- Main background are single-dissociative, double-dissociative and \( Z/\gamma^* \) production

- Single-dissociative events, \( pp(\gamma\gamma) \rightarrow p\ell\ell X' \), are generated using \textsc{Lpair} 4.0 with the Brasse and Suri-Yennie structure function for proton dissociation

- Double-dissociative reactions are simulated using \textsc{Pythia} 8.175 with NNPDF2.3QED which uses LO QED and NNLO QCD to construct the photon parton distribution function

- \( Z/\gamma^* \) processes are generated using \textsc{Powheg} 1.0 interfaced with \textsc{Pythia} 6.425 (CTEQ6L1) to simulate the parton shower and underlying event

- Pileup affects the efficiency of selecting exclusive events
  - Average pileup during the 2011 run is between 6.3 and 11.6
**Event Selection**

Events must satisfy the following pre-selection criteria:

<table>
<thead>
<tr>
<th>Electron channel</th>
<th>Muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least one vertex that has at least two charged-particle tracks with $p_T &gt; 0.4$ GeV</td>
<td></td>
</tr>
<tr>
<td>Single-electron ($p_T &gt; 20$ GeV) trigger or di-electron ($p_T &gt; 12$ GeV) trigger</td>
<td>Single-muon ($p_T &gt; 18$ GeV) trigger or di-muon ($p_T &gt; 10$ GeV) trigger</td>
</tr>
<tr>
<td>$p^e_T &gt; 12$ GeV</td>
<td>$p^\mu_T &gt; 10$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta^e</td>
</tr>
<tr>
<td>Standard &quot;medium&quot; ATLAS identification criteria</td>
<td>Isolated muons ($\Sigma p_T$ of tracks $p_T &gt; 1$ GeV in a $\Delta R &gt; 0.2$ cone less than $0.1 p^\mu_T$)</td>
</tr>
<tr>
<td>Two oppositely charged same-flavour leptons</td>
<td></td>
</tr>
<tr>
<td>$m_{e^+e^-} &gt; 24$ GeV</td>
<td>$m_{\mu^+\mu^-} &gt; 20$ GeV</td>
</tr>
</tbody>
</table>
$\gamma\gamma \rightarrow l^+l^-$ Exclusive Event Selection in Electron Channel

Same criteria for selecting exclusive di-electron events as for di-muon events

**Data 2011**

- $\sqrt{s} = 7$ TeV, 4.6 fb$^{-1}$

Baseline selection

- Double-diss. $\gamma\gamma \rightarrow e^+e^-$
- Single-diss. $\gamma\gamma \rightarrow e^+e^-$
- Exclusive $\gamma\gamma \rightarrow e^+e^-$

**Tracks associated with di-electron vertex**

- 1
- 10
- 20
- 30
- 40
- 50

**Events / 5 GeV**

<table>
<thead>
<tr>
<th>$p_T^{e^+}$ [GeV]</th>
<th>Data / MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>60</td>
<td>1.5</td>
</tr>
<tr>
<td>80</td>
<td>2</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>120</td>
<td>10</td>
</tr>
<tr>
<td>140</td>
<td>50</td>
</tr>
<tr>
<td>160</td>
<td>100</td>
</tr>
<tr>
<td>180</td>
<td>150</td>
</tr>
<tr>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>

**Di-electron vertex isolation distance [mm]**

<table>
<thead>
<tr>
<th>$\Delta z_{iso}^{vtx}$ [mm]</th>
<th>Events / mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
</tr>
</tbody>
</table>

**Baseline selection**

- + exclusivity veto
- + Z region removed

**Data / MC**

- 0.5
- 1
- 1.5

**Z region**

- $\sqrt{s} = 7$ TeV, 4.6 fb$^{-1}$

Baseline selection

- Double-diss. $\gamma\gamma \rightarrow e^+e^-$
- Single-diss. $\gamma\gamma \rightarrow e^+e^-$
- Exclusive $\gamma\gamma \rightarrow e^+e^-$

**Events**

- $\gamma\gamma \rightarrow e^+e^-$
- $\gamma\gamma \rightarrow e^+e^-$
- $\gamma\gamma \rightarrow e^+e^-$
- $\gamma\gamma \rightarrow e^+e^-$

**Di-electron vertex isolation distance [mm]**

<table>
<thead>
<tr>
<th>$\Delta z_{iso}^{vtx}$ [mm]</th>
<th>Events / mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
</tr>
</tbody>
</table>

**Data / MC**

- 0.5
- 1
- 1.5

**Events / 1.5 GeV**

<table>
<thead>
<tr>
<th>$m_{e^+e^-}$ [GeV]</th>
<th>Data / MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
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<tr>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>140</td>
<td>200</td>
</tr>
<tr>
<td>160</td>
<td>250</td>
</tr>
<tr>
<td>180</td>
<td>300</td>
</tr>
<tr>
<td>200</td>
<td>350</td>
</tr>
<tr>
<td>220</td>
<td>400</td>
</tr>
<tr>
<td>240</td>
<td>450</td>
</tr>
<tr>
<td>260</td>
<td>500</td>
</tr>
</tbody>
</table>

**Photon-Photon Measurements in ATLAS**

Chav Chhiv Chau (Carleton)  
Photon-Photon Measurements in ATLAS  
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\( \gamma\gamma \rightarrow \ell^+\ell^- \) Event Yields

<table>
<thead>
<tr>
<th>Selection</th>
<th>( \gamma\gamma \rightarrow \ell^+\ell^- )</th>
<th>( Z/\gamma^* \rightarrow \ell^+\ell^- )</th>
<th>Multi- ( Z/\gamma^* \rightarrow \tau^+\tau^- )</th>
<th>( t\bar{t} ) boson</th>
<th>Total</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>898</td>
<td>1,460,000</td>
<td>83,000</td>
<td>3,760</td>
<td>4610</td>
<td>1,950</td>
</tr>
<tr>
<td>Exclusivity veto</td>
<td>661</td>
<td>3,140</td>
<td>0</td>
<td>9</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Z region removed</td>
<td>569</td>
<td>380</td>
<td>600</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>( p_T^\ell^+\ell^- &lt; 1.5 \text{ GeV} )</td>
<td>438</td>
<td>100</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Muon channel (( \ell = \mu ))</th>
<th>( \gamma\gamma \rightarrow \ell^+\ell^- )</th>
<th>( Z/\gamma^* \rightarrow \ell^+\ell^- )</th>
<th>Multi- ( Z/\gamma^* \rightarrow \tau^+\tau^- )</th>
<th>( t\bar{t} ) boson</th>
<th>Total</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>1,774</td>
<td>2,300,000</td>
<td>98,000</td>
<td>7,610</td>
<td>6,710</td>
<td>2,870</td>
</tr>
<tr>
<td>Exclusivity veto</td>
<td>1,313</td>
<td>3,960</td>
<td>3</td>
<td>8</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Z region removed</td>
<td>1,215</td>
<td>760</td>
<td>3</td>
<td>8</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>( p_T^\ell^+\ell^- &lt; 1.5 \text{ GeV} )</td>
<td>1,174</td>
<td>210</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Background estimated**
  - from simulation: double-dissociative, \( Z/\gamma^* \), diboson and top-quark pair production
  - from data: multi-jet production
- **Exclusivity requirement suppresses most of inclusive production** (multijet, \( t\bar{t} \), diboson, etc.)
- **Simulated events have 20% higher acceptance than data**
\[ \gamma \gamma \rightarrow \ell^+ \ell^- \text{ Acoplanarity Contour Plots} \]

- Confidence level contour plots for the exclusive versus the single-dissociative \[ \gamma \gamma \rightarrow \ell^+ \ell^- \] fraction for the electron (left) and muon (right) channel
  - Points indicate the best-fit values
  - Dashed (68% C.L.) and dotted (95% C.L.) contours represent the statistical uncertainties of the measurement
  - Red solid line indicates the prediction with proton absorptive corrections
Predictions are in good agreement with the data

Events satisfying all selection criteria, except $p_T^{\ell^+\ell^-}$ cut is replaced

- Using the cut acoplanarity < 0.008 instead of $p_T^{\ell^+\ell^-}$ < 1.5 GeV

- Exclusive and single-dissociative yields normalized according to the fit results

- Predictions are in good agreement with the data
\( \gamma \gamma \rightarrow \ell^+ \ell^- \) Systematic Uncertainties

- Main sources of systematic uncertainty are from background modelling (\( \sim 2\% \))
  - Normalization of Drell-Yan
  - Photon PDF used in estimation of double-dissociative background
- At most 1.2\% MC-Data deviation in efficiency for different isolation window
- Choice of acoplanarity shapes affects the signal yields up to 1\%

- Data statistical uncertainty is shown for comparison, it is larger than the total systematic uncertainty
\[ \gamma\gamma \rightarrow W^+W^- \] Parametrization of aQGCs

- We could extend the Standard Model to dimension-6: \[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_6^0 + \mathcal{L}_6^C \]

\[ \mathcal{L}_6^0 = \frac{e^2}{8} \frac{a^W_0}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_{-\alpha} \]

\[ \mathcal{L}_6^C = \frac{-e^2}{16} \frac{a^W_C}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W_{-\beta} + W^{-\alpha} W^{+\beta}) \]

- These two D-6 operators conserve U(1), SU(2)$_C$, charge conjugation, parity
- Also consider dimension-8 operators with coefficients $f_{M,1,2,3,4}$
\[ \gamma\gamma \to W^+W^- \] Normalization of dimuons

- The description of the data is reasonable for dimuon mass \( m_{\mu\mu} > 120 \text{ GeV} \)
- The \( f_\gamma \) factor doesn’t depend on the dimuon mass
\( \gamma \gamma \rightarrow W^+W^- \) Calibration Using Drell-Yan \( \mu\mu \) Events

- Selection criteria:
  - \( p_T\ell > 20 \) GeV
  - \( m_{\ell\ell} > 45 \) GeV

- Pre-exclusivity (small marker) distributions are normalized to the data at the \( Z \) peak

- No additional normalization after requiring exclusivity (large marker) of 1.0mm

- Data-driven scale factors extracted:

<table>
<thead>
<tr>
<th></th>
<th>Powheg+Pythia8</th>
<th>Alpgen+Herwig</th>
<th>Alpgen+Pythia6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale Factors</td>
<td>0.58</td>
<td>0.21</td>
<td>0.69</td>
</tr>
</tbody>
</table>

- These scale factors are to be applied to simulated events after exclusivity
Some kinematics distributions before requiring the exclusivity selection.
\( \gamma \gamma \rightarrow W^+ W^- \) Cross-Section

- The measured cross-section is determined to be:

\[
(\sigma \cdot BR)_{\gamma \gamma \rightarrow W^+ W^-}^{\text{Measured}} = \frac{N_{\text{data}} - N_{\text{background}}}{(\mathcal{L} \epsilon A)} = 6.9 \pm 2.7 \text{ fb}
\]

- \( \epsilon A = (10.5 \pm 1.2)\% \)

- Predicted cross-section times branching ratio is

\[
(\sigma \cdot BR)_{\gamma \gamma \rightarrow W^+ W^-}^{\text{Predicted}} = 4.4 \text{ fb}
\]

- Sources of uncertainty on the measured exclusive \( WW \) cross-section

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>33%</td>
</tr>
<tr>
<td>Background normalization</td>
<td>18%</td>
</tr>
<tr>
<td>Exclusivity signal efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>All other</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>Total</td>
<td>39%</td>
</tr>
</tbody>
</table>
\( \gamma \gamma \rightarrow W^+ W^- \) Limits on anomalous quartic couplings

- Allowed intervals for the aQGCs \( a_{0,C}/\Lambda^2 \)
- Regions outside the intervals are excluded at 95% confidence level

<table>
<thead>
<tr>
<th>Coupling</th>
<th>( \Lambda_{\text{cutoff}} )</th>
<th>Observed allowed range [GeV(^{-2})]</th>
<th>Expected allowed range [GeV(^{-2})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0^W/\Lambda^2 )</td>
<td>500 GeV</td>
<td>([-0.96 \times 10^{-4}, 0.93 \times 10^{-4}])</td>
<td>([-0.90 \times 10^{-4}, 0.87 \times 10^{-4}])</td>
</tr>
<tr>
<td>( a_C^W/\Lambda^2 )</td>
<td>500 GeV</td>
<td>([-3.5 \times 10^{-4}, 3.3 \times 10^{-4}])</td>
<td>([-3.3 \times 10^{-4}, 3.1 \times 10^{-4}])</td>
</tr>
<tr>
<td>( a_0^W/\Lambda^2 )</td>
<td>(\infty)</td>
<td>([-1.7 \times 10^{-6}, 1.7 \times 10^{-6}])</td>
<td>([-1.5 \times 10^{-6}, 1.6 \times 10^{-6}])</td>
</tr>
<tr>
<td>( a_C^W/\Lambda^2 )</td>
<td>(\infty)</td>
<td>([-6.4 \times 10^{-6}, 6.3 \times 10^{-6}])</td>
<td>([-5.9 \times 10^{-6}, 5.8 \times 10^{-6}])</td>
</tr>
</tbody>
</table>

- 95% C.L. limits on dimension-8 couplings

<table>
<thead>
<tr>
<th>Coupling</th>
<th>( \Lambda_{\text{cutoff}} )</th>
<th>Observed allowed range [GeV(^{-4})]</th>
<th>Expected allowed range [GeV(^{-4})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{M,0}/\Lambda^4 )</td>
<td>500 GeV</td>
<td>([-3.7 \times 10^{-9}, 3.6 \times 10^{-9}])</td>
<td>([-3.5 \times 10^{-9}, 3.4 \times 10^{-9}])</td>
</tr>
<tr>
<td>( f_{M,1}/\Lambda^4 )</td>
<td>500 GeV</td>
<td>([-13 \times 10^{-9}, 14 \times 10^{-9}])</td>
<td>([-12 \times 10^{-9}, 13 \times 10^{-9}])</td>
</tr>
<tr>
<td>( f_{M,0}/\Lambda^4 )</td>
<td>(\infty)</td>
<td>([-6.6 \times 10^{-11}, 6.6 \times 10^{-11}])</td>
<td>([-5.8 \times 10^{-11}, 6.2 \times 10^{-11}])</td>
</tr>
<tr>
<td>( f_{M,1}/\Lambda^4 )</td>
<td>(\infty)</td>
<td>([-24 \times 10^{-11}, 25 \times 10^{-11}])</td>
<td>([-23 \times 10^{-11}, 23 \times 10^{-11}])</td>
</tr>
</tbody>
</table>
PbPb $\rightarrow \mu^+\mu^-\text{PbPb}$ Event Triggering

- Require a Level-1 region of interest associated with a track in the MS
- Reject event if the calorimeter system contained $E_T > 50$ GeV
- Reject event if Minimum Bias Trigger Scintillator registers more than one hit
- Select event having at least one track reconstructed in the high level trigger system with $p_T > 400$ MeV
PbPb $\rightarrow \mu^+\mu^-\text{PbPb}$ Kinematics Distributions

- Normalized $p_T$ and $\eta$ distributions of muon in data compared to simulation
- Good data-to-simulation agreement is observed
PbPb → $\mu^+\mu^-\text{PbPb}$ Systematics Uncertainties

- Muon trigger efficiency: 2% or less
- Muon reconstruction efficiency: 2–5%
- Background estimation: 6% for $|Y_{\mu\mu}| < 1.6$, up to 10% for $m_{\mu\mu} > 15$ GeV in the $1.6 < |Y_{\mu\mu}| < 1.6$
- Monte Carlo self-consistency: 2%
- Luminosity: 7%
- Pileup: 0.5%
Two-photon Production in $pp$ Collisions