Exclusive production in CMS

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on behalf of the CMS Collaboration
Outline

- CMS detector and capabilities for forward physics;
- Possibilities of meson photo-production in CMS;
- Probing central exclusive processes at high-energies;
  - Measurement of exclusive $\gamma\gamma \rightarrow e^+e^-, \mu^+\mu^-$ production;
- Measurement of exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ at large masses;
- Exclusive production of massive electroweak-boson pairs;
  - Search for exclusive $\gamma\gamma \rightarrow W^+W^-$ production;
  - Limits on anomalous quartic gauge couplings.
Large Hadron Collider

<table>
<thead>
<tr>
<th>Year</th>
<th>$E_{pp}$</th>
<th>$E_{PbPb}$</th>
<th>L (pb$^{-1}$)</th>
<th>L (μb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>7 TeV</td>
<td>2.76 TeV</td>
<td>44.22</td>
<td>7.00</td>
</tr>
<tr>
<td>2011</td>
<td>7 TeV</td>
<td>2.76 TeV</td>
<td>6.13</td>
<td>157.57</td>
</tr>
<tr>
<td>2012</td>
<td>8 TeV</td>
<td></td>
<td>23.30</td>
<td>-</td>
</tr>
<tr>
<td>2013</td>
<td>2.76 TeV</td>
<td>5.02 TeV</td>
<td>5.51</td>
<td>35.50</td>
</tr>
<tr>
<td>2015</td>
<td>13 TeV</td>
<td></td>
<td>L ~ 50.00</td>
<td>(expected)</td>
</tr>
</tbody>
</table>
The CMS experiment

- **Total weight**: 14k tonnes
- **Overall diameter**: 15.0 m
- **Overall length**: 28.7 m
- **Magnetic field**: 3.8 T

**Electromagnetic Calorimeter (ECAL)**
- EB (|\eta| < 1.48) + EE (1.48 < |\eta| < 3.00)

**Hadron Calorimeter (HCAL)**
- HB + HO: (|\eta| < 1.3)
- HE: 1.3 < |\eta| < 3.0

**Steel Return Yoke**
- 12,500 tonnes

**Superconducting Solenoid**
- Ni-Ti coil carrying 18,000 A

**Silicon Trackers**
- (|\eta| < 2.5)

**Muon Chambers**
- Preshower (1.65 < |\eta| < 2.6)

**Hadronic Forward (HF)**
- (2.9 < |\eta| < 5.2)

**CASTOR**: 5.3 < |\eta| < 6.6
- **ZDC**: |\eta| > 8.1
  - (not used in these analyses)
Outline

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  - Measurement of exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ at large masses;
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  - Search for exclusive $\gamma\gamma \rightarrow W^+W^-$ production;
  - Limits on anomalous quartic gauge couplings.
Exclusive processes at the LHC

- The exclusive production of light and heavy pairs is represented by:

\[ pp \rightarrow p^*(\gamma\gamma, \ell^+\ell^-, W^+W^-) + p^*(\gamma\gamma, \ell^+\ell^-, W^+W^-) \]

- Intact protons in the final states, however also accounting for proton dissociation \( p^* \);
- No other particles in the final states;
- \( \gamma\gamma \): tests for theoretical prediction for exclusive Higgs production and to measure gluon density at small-\( x \);
- \( \ell^+\ell^- \): comparison to precision QED predictions and to study of proton dissociation;
- \( W^+W^- \): study of exclusive processes at high mass and constraint of anomalous couplings.
Meson photo-production in CMS: $J/\psi \rightarrow \mu^+\mu^-$

- Simulation with exactly 2 opposite-sign muon tracks with no other tracks;
- Consider exclusivity cuts of $\Delta \phi(\mu\mu)/\pi > 0.9$ and $\Delta p_T(\mu\mu) < 1.5$ GeV.

<table>
<thead>
<tr>
<th>$m = 3.05 \pm 0.03$ GeV</th>
<th>$\Delta \phi(\mu\mu)/\pi = 0.98$</th>
<th>$\Delta p_T(\mu\mu) = 0.05$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track: $p_T &gt; 0$ GeV</td>
<td>HCAL: $E &gt; 4$ GeV</td>
<td>ECAL: $E &gt; 2.5$ GeV</td>
</tr>
</tbody>
</table>
Meson photo-production in CMS: $\gamma \rightarrow \mu^+\mu^-$

- Studies in the **Upsilon mass** range with exactly 2 opposite-sign muon tracks with no other tracks in the event;
- Consider exclusivity cuts of $\Delta \phi(\mu\mu)/\pi > 0.9$ and $\Delta p_T(\mu\mu) < 1.5$ GeV.

<table>
<thead>
<tr>
<th>$m = 9.44 \pm 0.08$ GeV</th>
<th>$\Delta \phi(\mu\mu)/\pi = 0.99$</th>
<th>$\Delta p_T(\mu\mu) = 0.20$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track: $p_T &gt; 0$ GeV</td>
<td>HCAL: $E &gt; 4$ GeV</td>
<td>ECAL: $E &gt; 2.5$ GeV</td>
</tr>
</tbody>
</table>
Future prospects in $p$-Pb collisions

- Possibility of parallel data taking of CMS and TOTEM;
- Combination of CMS central detector and TOTEM roman pots.

- Photo-nuclear processes can be measured by the activity in the central detector and no activity in the forward calorimeter and ZDC;
- Pb beam intact after interaction with proton break-up.

From presentation by I. Katkov, PhotonLHC 2014
Future prospects in Pb-Pb collisions

- Possibility of measurements in CMS with forward calorimeter;
- Data can be obtained with single muon trigger and with the ZDC information.

From presentation by I. Katkov, PhotonLHC 2014
Outline

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  - Measurement of exclusive $\gamma\gamma \rightarrow e^+e^-$, $\mu^+\mu^-$ production;
  - Measurement of exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ at large masses;
- Exclusive production of massive electroweak-boson pairs;
  - Search for exclusive $\gamma\gamma \rightarrow W^+W^-$ production;
  - Limits on anomalous quartic gauge couplings.
Exclusive production of $e^+e^-$ pairs

- Selection requires vertex with two leptons tracks & nothing else;
  - $E_T(e) > 5.5$ GeV and $|\eta(e)| < 2.5$;
  - No additional tracks in the Tracker;
  - No additional towers above noise threshold in the calorimeters.

- MC predictions include elastic processes and contribution from proton dissociation:

- In the exclusive production of $e^+e^-$ pairs, it has been observed 17 (semi-)exclusive events in 36 pb$^{-1}$;

- Good agreement between LPAIR and the data.
Exclusive production of $\mu^+\mu^-$ pairs

- Selection requires vertex with two leptons tracks & nothing else:
  - Information from the Pixel and Silicon Tracker;
  - $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.1$;
  - $m(\mu^+\mu^-) > 11.5$ GeV to neglect $\Upsilon$ resonances;
  - Exclusivity cuts: $1 - |\Delta \phi/\pi| < 0.1$ and $|\Delta p_T| < 1.0$ GeV

- The contribution from proton dissociation is included:
Cross section for $\mu^+\mu^-$ pair production

- Measurement of exclusive $\mu^+\mu^-$ pairs results in $40 \text{ pb}^{-1}$:

$$\sigma(pp \rightarrow p\mu^+\mu^-p) = 3.38^{+0.58}_{-0.55} \text{ (stat.) } \pm 0.16 \text{ (syst.) } \pm 0.14 \text{ (lumi.) } \text{ pb}$$

- Good agreement between LPAIR and the data in the whole kinematic region.
Outline

- CMS detector and capabilities for forward physics;
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  - Measurement of exclusive $\gamma\gamma \rightarrow e^+e^-, \mu^+\mu^-$ production;
- Measurement of exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ at large masses;
- Exclusive production of massive electroweak-boson pairs;
  - Search for exclusive $\gamma\gamma \rightarrow W^+W^-$ production;
  - Limits on anomalous quartic gauge couplings.
Selection for $\mu^+\mu^-$ events at large mass

- Data collected in 2011 by the CMS detector at 7 TeV:
  - Events with opposite-sign muons corresponding to $5.24 \text{ fb}^{-1}$.

- Muons are selected with the requirements:
  - $p_T(\mu) > 15 \text{ GeV}$ and $|\eta(\mu)| < 2.4$;
  - $m(\mu^+\mu^-) > 20 \text{ GeV}$ and $p_T(\mu^+\mu^-) > 30 \text{ GeV}$;

- An exclusivity selection is applied to each event:
  - $p_T(\mu)$ balance below 1 GeV;
  - Back-to-back leptons with $\Delta\phi(\mu\mu) > 0.9\pi$
  - **No extra tracks** in the vertex apart of the leptons.
Measurement of $\gamma\gamma \rightarrow \mu^+\mu^-$

- The study is performed in **two different kinematic regions** in order to discriminate the dominant contributions of elastic and inelastic interactions;

- The regions are defined as follows:

<table>
<thead>
<tr>
<th>Region</th>
<th>Elastic (quasi-exclusive)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1-</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$1-</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
</tbody>
</table>

**ELASTIC REGION**

- CMS, $\sqrt{s} = 7$ TeV, $L = 5.24$ fb$^{-1}$

**INELASTIC REGION**

- CMS, $\sqrt{s} = 7$ TeV, $L = 5.24$ fb$^{-1}$
Elastic region for $\gamma\gamma \rightarrow \mu^+\mu^-$

- The elastic region presents a good agreement with the MC predictions:

  - The contribution from both regions can be accounted in Data and MC:

<table>
<thead>
<tr>
<th>Region</th>
<th>Data</th>
<th>Simulation</th>
<th>Data/Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic</td>
<td>820</td>
<td>906 $\pm$ 9</td>
<td>0.91 $\pm$ 0.03</td>
</tr>
<tr>
<td>Dissociation</td>
<td>1312</td>
<td>1830 $\pm$ 17</td>
<td>0.72 $\pm$ 0.02</td>
</tr>
<tr>
<td>Total</td>
<td>2132</td>
<td>2736 $\pm$ 19</td>
<td>0.78 $\pm$ 0.02</td>
</tr>
</tbody>
</table>

- deficit observed in the data compared to LPAIR MC

- $1 - |\Delta\phi(\mu^+\mu^-)/\pi| < 0.1$
- $|\Delta p_T(\mu^+\mu^-)| < 1.0$
Proton dissociation in inelastic $\gamma\gamma \rightarrow \mu^+\mu^-$

- A deficit is observed in data which is not predicted by LPAIR – rescattering effects not included to the predictions;

- Proton dissociation in LPAIR is loosely constrained experimentally – a normalization factor is naturally employed for this component;

- We estimate a normalization factor for masses larger than the $W$-pair mass:

$$ F = \frac{N_{\mu\mu\text{ data}} - N_{DY}}{N_{elastic}} \bigg|_{m(\mu^+\mu^-)>160 \text{ GeV}} $$

$$ = 3.23 \pm 0.53. $$

- This factor is then used to re-scale the signal cross section in order to include the contribution from the proton dissociation.
Search for $\gamma \gamma \rightarrow W^+W^-$ production

- Data collected in 2011 by the CMS detector at 7 TeV:
  - Final state: $W^+W^- \rightarrow e^\pm \mu^\mp \nu\nu$ to suppress DY bkg;
  - Events with opposite-sign and flavor leptons: $5.05 \text{ fb}^{-1}$.

- Leptons are selected with the requirements:
  - $p_T(\ell) > 15 \text{ GeV}$ and $|\eta(\ell)| < 2.4$;
  - $m(\ell^+\ell^-) > 20 \text{ GeV}$ and $p_T(\ell^+\ell^-) > 30 \text{ GeV}$;

- Exclusivity selection:
  - $p_T(\ell)$ balance below 1 GeV;
  - Back-to-back leptons with $\Delta \varphi > 0.9\pi$
  - No extra tracks in the vertex apart of the leptons.

- aQGC: search is performed in the kinematical region with $p_T(\mu e) > 100 \text{ GeV}$.
Signal from $W^+W^- \rightarrow \mu^\pm e^\mp \nu\bar{\nu}$

- Events passing all the requirements:
  - Signal: $2.2 \pm 0.4$evt
  - Bkg: $0.84 \pm 0.15$evt

<table>
<thead>
<tr>
<th>Selection step</th>
<th>Signal $e \times A$</th>
<th>Events in data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger and preselection</td>
<td>28.5%</td>
<td>9086</td>
</tr>
<tr>
<td>$m(\mu^\pm e'^\mp) &gt; 20$ GeV</td>
<td>28.0%</td>
<td>8200</td>
</tr>
<tr>
<td>Muon ID and Electron ID</td>
<td>22.6%</td>
<td>1222</td>
</tr>
<tr>
<td>$\mu^\pm e'^\mp$ vertex with 0 extra tracks</td>
<td>13.7%</td>
<td>6</td>
</tr>
<tr>
<td>$p_T(\mu^\pm e'^\mp) &gt; 30$ GeV</td>
<td>10.6%</td>
<td>2</td>
</tr>
</tbody>
</table>

$\sigma \cdot \text{BR with } 95\% \text{ CL:}$

$$\sigma(p p \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)} \mu^\pm e'^\mp p^{(*)}) = 2.1^{+3.1}_{-1.9} \text{ fb}$$

2.2 evt expected
2 observed
Search for aQGC

- The upper limit on the cross section times Branching fraction is found as

$$\sigma(pp \rightarrow p^(*) W^+ W^- p^(*) \rightarrow p^(*) \mu^\pm e^\mp p^(*)) < 10.6 \text{ fb}$$

**CMS, \sqrt{s} = 7 \text{ TeV}, L = 5.05 \text{ fb}^{-1}**

- Data
- Drell-Yan $\tau^+ \tau^-$
- Inclusive $W^* W$
- Diffractive $W^* W$
- $t\bar{t}$
- $W+$jets
- Elastic $\gamma\gamma \rightarrow \tau^+ \tau^-$
- Inelastic $\gamma\gamma \rightarrow \tau^+ \tau^-$

$$\gamma\gamma \rightarrow W^* W \quad (\text{SM})$$

$$\gamma\gamma \rightarrow W^* W \left( \frac{a_0^w}{\Lambda^2} = 2 \times 10^{-4}, \frac{a_0^w}{\Lambda^2} = 0, \Lambda_{\text{cut off}} = 500 \text{ GeV} \right)$$

$$\gamma\gamma \rightarrow W^* W \left( \frac{a_0^w}{\Lambda^2} = -2 \times 10^{-4}, \frac{a_0^w}{\Lambda^2} = -8 \times 10^{-4}, \Lambda_{\text{cut off}} = 500 \text{ GeV} \right)$$

No extra event found

- $p_T(\mu e) > 100 \text{ GeV}$
The upper limit on the cross section times Branching fraction is found as

\[-0.00015 < a_C^W / \Lambda^2 < 0.00015 \text{ GeV}^{-2} \ (a_C^W / \Lambda^2 = 0, \ \Lambda_{\text{cutoff}} = 500 \text{ GeV}),\]

\[-0.0005 < a_C^W / \Lambda^2 < 0.0005 \text{ GeV}^{-2} \ (a_C^W / \Lambda^2 = 0, \ \Lambda_{\text{cutoff}} = 500 \text{ GeV}).\]

\[-4.0 \times 10^{-6} < a_0^W / \Lambda^2 < 4.0 \times 10^{-6} \text{ GeV}^{-2} \ (a_C^W / \Lambda^2 = 0, \ \text{no form factor}),\]

\[-1.5 \times 10^{-5} < a_C^W / \Lambda^2 < 1.5 \times 10^{-5} \text{ GeV}^{-2} \ (a_0^W / \Lambda^2 = 0, \ \text{no form factor}).\]
Summary

- Encouraging results showing **excellent** forward capabilities of the CMS detector;
- Studies show the possibility to measure exclusive **meson photo-production** in CMS;
  - Photo-production of $J/\psi$ and $\Upsilon$ to be explored in $p$-$p$, $p$-$Pb$ and Pb-Pb collisions.
- CMS has successfully measured exclusive processes at **low** and **high** masses;
  - The observed cross sections are in agreement with the QED predictions:

  $17$ (semi-)exclusive events in exclusive production of $e^+e^-$ pairs
  \[
  \sigma(pp \rightarrow p\mu^+\mu^-p) = 3.38^{+0.58}_{-0.55} \text{ (stat.)} \pm 0.16 \text{ (syst.)} \pm 0.14 \text{ (lumi.) pb}
  \]

- The search for the exclusive production of $W$ pairs results in **two potential candidates** with observed cross section in agreement with the SM expectation:

  $\sigma(pp \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)}\mu^\pm e^\mp p^{(*)}) = 2.2^{+3.3}_{-2.0} \text{ fb}$,

- AQGC limits: **two orders of magnitude** more stringent than the limits of LEP & Tevatron;
Backup slides
The CMS experiment

CASTOR: $5.3 < |\eta| < 6.6$
ZDC: $|\eta| > 8.1$

(not used in these analyses)

SILICON TRACKER
$(|\eta| < 2.5)$

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
EB $(|\eta| < 1.48)$ + EE $(1.48 < |\eta| < 3.00)$

PRESHOWER
$(1.65 < |\eta| < 2.6)$

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A

HADRON CALORIMETER (HCAL)
HB + HO: $(|\eta| < 1.3)$
HE: $1.3 < |\eta| < 3.0$
HF: $3.0 < |\eta| < 5.2$

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

Total weight: 14000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T
### Dielectron Analysis

<table>
<thead>
<tr>
<th>Selection criterion</th>
<th>Events remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>3,023,496</td>
</tr>
<tr>
<td>Electron reconstruction</td>
<td>132,271</td>
</tr>
<tr>
<td>Electron identification</td>
<td>1,668</td>
</tr>
<tr>
<td>Cosmic-ray rejection</td>
<td>1,321</td>
</tr>
<tr>
<td>Exclusivity requirement</td>
<td>17</td>
</tr>
</tbody>
</table>

### Cutflow & Efficiency

<table>
<thead>
<tr>
<th>Category</th>
<th>Data</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>el-el</td>
<td>0.371 ± 0.037</td>
<td></td>
</tr>
<tr>
<td>inel-el</td>
<td>0.438 ± 0.035</td>
<td></td>
</tr>
<tr>
<td>inel-inel</td>
<td>0.430 ± 0.030</td>
<td></td>
</tr>
<tr>
<td>el-el</td>
<td>0.979 ± 0.009</td>
<td></td>
</tr>
<tr>
<td>inel-el</td>
<td>0.822 ± 0.008</td>
<td></td>
</tr>
<tr>
<td>inel-inel</td>
<td>0.639 ± 0.006</td>
<td></td>
</tr>
<tr>
<td>el-el</td>
<td>0.927 ± 0.005</td>
<td></td>
</tr>
<tr>
<td>inel-el</td>
<td>0.666 ± 0.049</td>
<td></td>
</tr>
<tr>
<td>inel-inel</td>
<td>0.299 ± 0.041</td>
<td></td>
</tr>
<tr>
<td>el-el</td>
<td>0.143 ± 0.008</td>
<td></td>
</tr>
<tr>
<td>inel-el</td>
<td>0.143 ± 0.008</td>
<td></td>
</tr>
<tr>
<td>inel-inel</td>
<td>0.143 ± 0.008</td>
<td></td>
</tr>
<tr>
<td>el-el</td>
<td>0.0481 ± 0.0055</td>
<td></td>
</tr>
<tr>
<td>inel-el</td>
<td>0.0343 ± 0.0042</td>
<td></td>
</tr>
<tr>
<td>inel-inel</td>
<td>0.0117 ± 0.0019</td>
<td></td>
</tr>
</tbody>
</table>
$\gamma\gamma \rightarrow e^+e^-$: background expectation

<table>
<thead>
<tr>
<th>Dielectron analysis</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Background</strong></td>
<td>Events</td>
</tr>
<tr>
<td><strong>Non-exclusive</strong></td>
<td>$0.80 \pm 0.28$</td>
</tr>
<tr>
<td><strong>Exclusive $\Upsilon(1S,2S,3S) \rightarrow e^+e^-$</strong></td>
<td>Negligible</td>
</tr>
<tr>
<td><strong>Cosmic ray</strong></td>
<td>$0.05 \pm 0.01$</td>
</tr>
<tr>
<td><strong>Exclusive $\pi^+\pi^-$</strong></td>
<td>Negligible</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$0.85 \pm 0.28$</td>
</tr>
</tbody>
</table>
### Low mass $\gamma\gamma\rightarrow\mu^+\mu^-$: cutflow

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>Signal</th>
<th>Single-pdiss.</th>
<th>Double-pdiss.</th>
<th>DY</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex and track-exclusivity</td>
<td>921</td>
<td>247</td>
<td>437</td>
<td>197</td>
<td>56</td>
<td>937</td>
</tr>
<tr>
<td>Muon ID</td>
<td>724</td>
<td>193</td>
<td>336</td>
<td>160</td>
<td>53</td>
<td>741</td>
</tr>
<tr>
<td>$p_T &gt; 4\text{ GeV},</td>
<td>\eta</td>
<td>&lt; 2.1</td>
<td>438</td>
<td>132</td>
<td>241</td>
<td>106</td>
</tr>
<tr>
<td>$m(\mu^+\mu^-) &gt; 11.5\text{ GeV}$</td>
<td>270</td>
<td>95</td>
<td>187</td>
<td>86</td>
<td>13</td>
<td>380</td>
</tr>
<tr>
<td>3D angle $&lt; 0.95\pi$</td>
<td>257</td>
<td>87</td>
<td>178</td>
<td>83</td>
<td>12</td>
<td>361</td>
</tr>
<tr>
<td>$1 -</td>
<td>\Delta\phi/\pi</td>
<td>&lt; 0.1$</td>
<td>203</td>
<td>87</td>
<td>126</td>
<td>41</td>
</tr>
<tr>
<td>$</td>
<td>\Delta p_T</td>
<td>&lt; 1.0\text{ GeV}$</td>
<td>148</td>
<td>86</td>
<td>79</td>
<td>16</td>
</tr>
</tbody>
</table>

#### CMS, $\sqrt{s} = 7\text{ TeV}, L = 40\text{ pb}^{-1}$

- **Data**
- **Signal** $\gamma\gamma\rightarrow\mu^+\mu^-$
- **Single dissociative** $\gamma\gamma\rightarrow\mu^+\mu^-$
- **Double dissociative** $\gamma\gamma\rightarrow\mu^+\mu^-$
- **DY $Z\gamma\rightarrow\mu^+\mu^-$**

**Events/1.5 GeV**

![Graph of CMS data](image)

**Events/0.005**

![Graph of CMS data](image)

76 GeV
Low mass $\gamma\gamma \to \mu^+\mu^-$: distributions
High mass $\gamma\gamma \rightarrow \mu^+\mu^-$: invariant mass

![Graph showing high mass $\gamma\gamma$ events](image)
High mass $\gamma\gamma \rightarrow \mu^+\mu^-$: acoplanarity

CMS, $\sqrt{s} = 7$ TeV, $L = 5.24$ fb$^{-1}$

Z region ($70 < m(\mu\mu) < 106$ GeV)

- Data
- LPAIR $\gamma\gamma \rightarrow \mu^+\mu^-$ (double-dissociation)
- LPAIR $\gamma\gamma \rightarrow \mu^+\mu^-$ (single-dissociation)
- LPAIR $\gamma\gamma \rightarrow \mu^+\mu^-$ (elastic)
- Drell-Yan $\mu^+\mu^-$

CMS, $\sqrt{s} = 7$ TeV, $L = 5.24$ fb$^{-1}$

$m(\mu\mu) > 20$ GeV with Z region removed

- Data
- LPAIR $\gamma\gamma \rightarrow \mu^+\mu^-$ (double-dissociation)
- LPAIR $\gamma\gamma \rightarrow \mu^+\mu^-$ (single-dissociation)
- LPAIR $\gamma\gamma \rightarrow \mu^+\mu^-$ (elastic)
- Drell-Yan $\tau^+\tau^-$
- Drell-Yan $\mu^+\mu^-$
High mass $\gamma\gamma \rightarrow \mu^+\mu^-$: transv. momentum

CMS, $\sqrt{s} = 7$ TeV, $L = 5.24$ fb$^{-1}$

Z region ($70 < m(\mu\mu) < 106$ GeV)

- Data
- LPAIR $\gamma\gamma \rightarrow \mu^+\mu^-$ (double-dissociation)
- LPAIR $\gamma\gamma \rightarrow \mu^+\mu^-$ (single-dissociation)
- LPAIR $\gamma\gamma \rightarrow \mu^+\mu^-$ (elastic)
- Inclusive WW
- Drell-Yan $\mu^+\mu^-$

Events / 2.5 GeV

$p_T(\mu\mu)$ [GeV]
\[ \gamma \gamma \rightarrow W^+W^- : \text{efficiencies} \]

<table>
<thead>
<tr>
<th>Selection step</th>
<th>Signal ( \epsilon \times A )</th>
<th>Visible cross section (fb)</th>
<th>Events in data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger and preselection</td>
<td>28.5%</td>
<td>1.1</td>
<td>9086</td>
</tr>
<tr>
<td>( m(\mu^\pm e^\mp) &gt; 20 \text{ GeV} )</td>
<td>28.0%</td>
<td>1.1</td>
<td>8200</td>
</tr>
<tr>
<td>Muon ID and Electron ID</td>
<td>22.6%</td>
<td>0.9</td>
<td>1222</td>
</tr>
<tr>
<td>( \mu^\pm e^\mp ) vertex with zero extra tracks</td>
<td>13.7%</td>
<td>0.6</td>
<td>6</td>
</tr>
<tr>
<td>( p_T(\mu^\pm e^\mp) &gt; 30 \text{ GeV} )</td>
<td>10.6%</td>
<td>0.4</td>
<td>2</td>
</tr>
</tbody>
</table>
$\gamma\gamma \rightarrow W^+W^-$: background expectation

<table>
<thead>
<tr>
<th>Region</th>
<th>Background process</th>
<th>Data</th>
<th>Sum of backgrounds</th>
<th>$\gamma\gamma \rightarrow W^+W^-$ signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inclusive $W^+W^-$</td>
<td>43</td>
<td>46.2 ± 1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>Inclusive Drell-Yan $\tau^+\tau^-$</td>
<td>182</td>
<td>256.7 ± 10.1</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>$\gamma\gamma \rightarrow \tau^+\tau^-$</td>
<td>4</td>
<td>2.6 ± 0.8</td>
<td>0.7</td>
</tr>
</tbody>
</table>
**\( \gamma \gamma \rightarrow W^+ W^- \): systematic uncertainties**

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Signal Uncertainty</th>
<th>Background Uncertainty (events)</th>
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</thead>
<tbody>
<tr>
<td>Trigger and lepton identification</td>
<td>4.2%</td>
<td>0.02</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.2%</td>
<td>0.005</td>
</tr>
<tr>
<td>Vertexing efficiency</td>
<td>1.0%</td>
<td>0.005</td>
</tr>
<tr>
<td>Exclusivity and pileup dependence</td>
<td>10.0%</td>
<td>0.05</td>
</tr>
<tr>
<td>Proton dissociation factor</td>
<td>16.3%</td>
<td>0.02</td>
</tr>
</tbody>
</table>
$\gamma\gamma \rightarrow W^+W^- : \text{ missing } E_T$
Efficiencies in aQGC

<table>
<thead>
<tr>
<th></th>
<th>( a_0^W / \Lambda^2 ) [GeV(^{-2})]</th>
<th>( 2 \times 10^{-4} )</th>
<th>(-2 \times 10^{-4} )</th>
<th>( 7.5 \times 10^{-6} )</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( a_C^W / \Lambda^2 ) [GeV(^{-2})]</td>
<td>0</td>
<td>0</td>
<td>(-8 \times 10^{-4} )</td>
<td>0</td>
</tr>
<tr>
<td>( \Lambda ) [GeV]</td>
<td>—</td>
<td>500</td>
<td>500</td>
<td>No form factor</td>
<td>No form factor</td>
</tr>
<tr>
<td>Efficiency</td>
<td>( 30.5 \pm 5.0% )</td>
<td>( 29.8 \pm 2.1% )</td>
<td>( 31.3 \pm 1.8% )</td>
<td>( 36.0 \pm 1.7% )</td>
<td>( 36.3 \pm 1.8% )</td>
</tr>
</tbody>
</table>