Measurements of Exclusive Dilepton Production at 7 and 8 TeV with the ATLAS Detector

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On behalf of the ATLAS Collaboration

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Introduction

- Initial state photons are emitted from high energy proton beams
  - pp collision can be considered as a $\gamma\gamma$ collision
  - protons deflected at small angles
  - better known initial conditions and simpler final states

- Exclusive production of a final state $X$ via the reaction $pp \rightarrow ppX$
  - Elastic: $pp \rightarrow pp(\gamma\gamma) \rightarrow pp\ell\ell$ where both protons remain intact
  - Single-dissociation: $pp \rightarrow pX'(\gamma\gamma) \rightarrow pX'\ell\ell$ where one proton dissociate
  - Double-dissociation: $pp \rightarrow X'X''(\gamma\gamma) \rightarrow X'X''\ell\ell$ where both protons dissociate

- Use **Equivalent Photon Approximation (EPA)** to calculate the $pp$ cross section
  - Significant corrections needed due to hadronic interactions between elastic scattered protons
Exclusive $\gamma\gamma$ production computed in QED with small uncertainty
- Possible to use $pp(\gamma\gamma) \rightarrow pp\mu^+\mu^-$ for luminosity measurement at the LHC

Exclusive $\ell^+\ell^-$
- Standard candle for photon physics
- Non-negligible background to Drell-Yan (DY) reactions

Exclusive $W^+W^-$
- Test of SM quartic gauge couplings of $W^+W^-\gamma\gamma$
- Probe anomalous quartic gauge couplings (aQGCs)

Exclusive Higgs
- Low systematics due to the clean production environment
- Potentially used for Higgs properties studies
Experimental signatures

- **Exclusive:** Large rapidity gaps between protons and $\ell^+\ell^-/W^+W^-$/Higgs
  - Clean signature with back-to-back leptons and no other activity in the central detectors
  - Absence of tracks in detector near those from $\ell^+\ell^-/W^+W^-$/Higgs
- **Inclusive:** Extra particles from additional parton emission, ISR, FSR, etc
  - Presence of tracks from same vertex in detector
- **Pileup:** additional interactions coming from a different proton-proton collision
- **Underlying event:** additional interactions from the same proton collision
Simulation

- **Exclusive $\ell^+\ell^-$**
  - Elastic - **Signal**: Herwig++ (EPA)
  - Single dissociation: LPAIR (Brase and Suri-Yennie structure function)
  - Double dissociation: Pythia8 (NNPDF2.3QED PDF)

- **Exclusive $W^+W^-$**
  - Elastic - **Signal**: Herwig++ generator
  - $\gamma\gamma \rightarrow W^+W^-$ with aQGC: FPMC
  - Exclusive Higgs
    - $pp \rightarrow pggp \rightarrow pHp$: FPMC
  - No available generator that supports exclusive $W^+W^-$ and Higgs when one or both of the initial protons dissociate
    - Necessary to estimate it using data-driven methods
Measurement of exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ production at 7 TeV
Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$: Event Selection

- **Physics Letters B 749 (2015)**
- **Data**: 4.6 fb$^{-1}$ at 7 TeV
- **Isolated** $e^+e^-$ or $\mu^+\mu^-$ candidates

- Exactly 2 tracks ($p_T > 400$ MeV) associated with the dilepton vertex
- Distance between dilepton vertex and closest vertex: $\Delta z_{\text{vtx}}^{\text{iso}} > 3\,\text{mm}$ to reject DY

<table>
<thead>
<tr>
<th>Variable</th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
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<tbody>
<tr>
<td>$p_T^\ell$</td>
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<td>$</td>
<td>\eta^\ell</td>
<td>$</td>
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<tr>
<td>$m_{\ell^+\ell^-}$</td>
<td>$&gt; 24$ GeV</td>
<td>$&gt; 20$ GeV</td>
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</table>

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

<table>
<thead>
<tr>
<th>Tracks associated with di-muon vertex</th>
<th>Events</th>
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<tr>
<td>2</td>
<td>Data / MC</td>
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<td>7</td>
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<tr>
<td>8</td>
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<tr>
<td>9</td>
<td>1.4</td>
</tr>
<tr>
<td>10</td>
<td>1.5</td>
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</tbody>
</table>

**Data** / **MC**
Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$: Event Selection

- Remove Z-region dominated by DY
- $p_T$ of the dilepton system $p_T^{\ell\ell} < 1.5$ GeV: low virtuality of incoming photons

![Graph showing event selection criteria](image-url)
Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ : Yields

- Observed 869/2124 while expected 1030/2630 in $e^+e^-/\mu^+\mu^-$ channels
- Number of selected events in data 20% lower than expectation
- due to proton absorptive corrections not included in MC
- Proton has a finite size, the impact parameter dependence is non-negligible [arXiv:1410.2983]

<table>
<thead>
<tr>
<th>Selection</th>
<th>Signal $\gamma\gamma \rightarrow \ell^+\ell^-$</th>
<th>S-diss. $Z/\gamma \rightarrow \ell^+\ell^-$</th>
<th>D-diss. $Z/\gamma \rightarrow \ell^+\ell^-$</th>
<th>Multi-jet $Z/\gamma \rightarrow \ell^+\ell^-$</th>
<th>Di-boson $Z/\gamma \rightarrow \ell^+\ell^-$</th>
<th>Total predicted</th>
<th>Data</th>
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<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
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<td>0</td>
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<td>0</td>
<td>3</td>
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</table>
Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$: Signal extraction

- Binned maximum-likelihood fit of signal (exclusive) and background (single dissociation) to the measured dilepton acoplanarity distribution.
- DY and double dissociation fixed.
- Both exclusive and single dissociation requires scaling down:
  - $R_{\gamma\gamma \rightarrow e^+e^-}^{\text{excl.}} = 0.863 \pm 0.070$, $R_{\gamma\gamma \rightarrow e^+e^-}^{s-diss} = 0.759 \pm 0.080$
  - $R_{\gamma\gamma \rightarrow \mu^+\mu^-}^{\text{excl.}} = 0.791 \pm 0.041$, $R_{\gamma\gamma \rightarrow \mu^+\mu^-}^{s-diss} = 0.762 \pm 0.049$
Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$: Results

- Cross section extracted by measuring suppression factor $R^{\text{excl.}}_{\gamma\gamma \rightarrow \ell^+\ell^-}$ applied to prediction:

$$\sigma^{\text{excl.}}_{\gamma\gamma \rightarrow \ell^+\ell^-} = R^{\text{excl.}}_{\gamma\gamma \rightarrow \ell^+\ell^-} \times \sigma^{\text{pred.}}_{\gamma\gamma \rightarrow \ell^+\ell^-}$$

- The fiducial cross sections:
  - $\sigma^{\text{excl.}}_{\gamma\gamma \rightarrow e^+e^-} = 0.428 \pm 0.035 \text{ (stat.)} \pm 0.018 \text{ (syst.) pb}$
  - $\sigma^{\text{excl.}}_{\gamma\gamma \rightarrow \mu^+\mu^-} = 0.628 \pm 0.032 \text{ (stat.)} \pm 0.021 \text{ (syst.) pb}$

- The measurement is statistically limited:
  - Statistical = 8.2% for $e^+e^-$ and 5.1% for $\mu^+\mu^-$
  - Systematic = 4.3% for $e^+e^-$ and 3.3% for $\mu^+\mu^-$

- The theory predictions with absorptive corrections (20% effect):
  - $\sigma^{\text{EPA,corr.}}_{\gamma\gamma \rightarrow e^+e^-} = 0.398 \pm 0.007 \text{ pb}$
  - $\sigma^{\text{EPA,corr.}}_{\gamma\gamma \rightarrow \mu^+\mu^-} = 0.638 \pm 0.011 \text{ pb}$
Exclusive $\gamma\gamma \rightarrow W^+ W^-$ and Higgs production at 8 TeV
Exclusive $\gamma\gamma \to W^+W^-$ and Higgs: Event Selection

- Define dilepton vertex $z_0^{av}$ as $e^\pm\mu^\mp$ average $z_0$ position
- Exclusivity selection: No additional tracks in $\Delta z_0^{iso} = |z_0^{track} - z_0^{av}| = \pm 1$ mm
- Optimal $\Delta z_0^{iso} = 1$ mm, $\epsilon = 58 \pm 6\%$
- Rest of the selection:

<table>
<thead>
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<th>Variable</th>
<th>7 TeV</th>
<th>8 TeV</th>
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<td>Vertex $\Delta z_0$</td>
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<td>z_0^{track} - z_0^{PV}</td>
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<td>$p_T^{lep}$ $m_{e\mu}$</td>
<td>&gt; 25, 20 GeV</td>
<td>&gt; 25, 15 GeV</td>
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<tr>
<td>$p_T^{he}$ $m_{e\mu}$</td>
<td>&gt; 20 GeV</td>
<td>&gt; 10 GeV</td>
</tr>
<tr>
<td>$\Delta z_0^{iso}$</td>
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<td>&gt; 30 GeV</td>
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<tr>
<td>$p_T^{e\mu}$ (aQGC)</td>
<td>1mm 1mm</td>
<td>1mm 1mm</td>
</tr>
</tbody>
</table>

- Higgs selection has a lower $p_T$ and mass because one $W$ is offshell
- Additional selection in Higgs meant to reduce $W^+W^-$
**Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: Exclusivity validation**

- Validated in a $\gamma\gamma \rightarrow \mu^+\mu^-$ selection
  - $f_{EL} = \text{ratio of observed elastic } \gamma\gamma \rightarrow \mu^+\mu^- \text{ to prediction}$
  - Extracted from template fits in acoplanarity $(1 - |\Delta\phi_{\mu\mu}|/\pi)$
  - Vary $p_T^{\mu\mu}$ and $\Delta z_{iso}^0$ to evaluate systematic uncert. (total 14%)
  - Systematic error due to pileup at the 10% level

$$f_{EL} = 0.76 \pm 0.04(\text{stat.}) \pm 0.10(\text{sys.})$$

**Exclusive $\mu^+\mu^-$ at 8 TeV**

**Exclusive $\mu^+\mu^-$ at 7 TeV**

pileup: extra track flat for exclusive

compatible with $R_{\gamma\gamma \rightarrow \mu^+\mu^-}^{\text{excl.}} = 0.791 \pm 0.041$  

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Exclusive Dilepton Production

June, 09 2016

14 / 20
Exclusive production of $W^+W^-$ and $\ell^+\ell^-$ are similar.

Since there is no simulation for SD and DD $\gamma\gamma \to W^+W^-$, a correction factor $f_\gamma$ is extracted from data.

Same $\gamma\gamma \to \mu^+\mu^-$ selection is applied except for $m_{\mu\mu} > 160$ GeV and no $p_T^{\mu\mu}$ cut.

$$f_\gamma = \frac{N_{Data} - N_{POWHEG}^{Background}}{N_{HERWIG++}^{ELASTIC}} = 3.30 \pm 0.22{\text{(stat.)}} \pm 0.06{\text{(syst.)}}$$

Exclusive $\gamma\gamma \to W^+W^-$ estimate is scaled by $f_\gamma$.

The systematic uncertainty is obtained by varying DY contribution by 20%.

The total uncertainty is 7% dominated by the statistical uncertainty.
Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: Track multiplicity

- Underlying event emits additional tracks from the lepton vertex
- Necessary to validate modeling of underlying event in simulation
- Extract scale factors $\frac{\epsilon_{\text{Data}}}{\epsilon_{\text{MC}}}$ from Z peak data region since it is DY dominated with no exclusive dileptons
- Same $\gamma\gamma \rightarrow \mu^+\mu^-$ selection with $80 \text{ GeV} < m_{\mu\mu} < 100 \text{ GeV}$ and no $p_T^{\mu\mu}$ cut

- Data/MC scale factors are stable within $\pm 20\%$ over a wide $m_{\mu\mu}$ range
- Scale factors are validated in a $Z \rightarrow \tau\tau$ control region with $N_{\text{trk}} = 1 - 4$ and an $e\mu$ selection
Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: Inclusive $W^+W^- +$ Other

- Powheg+Pythia8 known to underestimate $W^+W^-$ yields
  - Extract a scale factor from data
  - Use the Higgs selection (slide13) with $55 \text{ GeV} < m_{\ell\ell} < 100 \text{ GeV}$, $\Delta\phi_{\ell\ell} < 2.6$ and 0 jets
  - Uncertainties dominated by statistics (5%)

- Estimate inclusive $W^+W^- + (\text{DY, } W+\text{jets, } \text{Top})$ from data
- Used as a constraint in excl. Higgs and aQGC
- Use the excl. $W^+W^-$ selection (slide13) with 1 to 4 extra tracks
- Estimate bracketed by
  - Upper bound: Data prediction - (Excl. + other VV)
  - Lower bound: Predicted $W^+W^-$ from Powheg+Pythia8
- Extrapolate to the 0 track bin by: $N_{0}^{\text{Est.}} = N_{1-4}^{\text{Est.}} \times \frac{N_{\text{WW}}^{\text{Pred.}, 0}}{N_{\text{WW}}^{\text{Pred.}, 1-4}}$
Exclusive $\gamma\gamma \rightarrow W^+W^-$: Results

- Exclusive $W^+W^-$ event yields: Data=23, Background = 8.3 ± 2.6, Signal = 9.3 ± 1.2
- Observed signal exceeds predicted signal by 50% leading to a measurement significance of 3σ
- aQGC event yields ($p_T^{e\mu} > 120$ GeV): Data=1, Background = 0.37 ± 0.13, SM Signal = 0.37 ± 0.04

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Exclusive Dilepton Production
June, 09 2016 18 / 20
Exclusive and inclusive $W^+W^-$ are the dominant background

Use the result from exclusive $W^+W^-$ to predict its contribution

Exclusive Higgs event yields: Data=6, Background = $3.0 \pm 0.8$, Signal = $0.023 \pm 0.003$

Observed and expected limits are in agreement

Upper limit $400 \times \sigma_{H}^{predicted}$ (which predicts just the elastic process)
Studies of exclusive dilepton production processes have been conducted by ATLAS.

Cross section of the exclusive $\gamma\gamma \to \ell^+\ell^-$ production has been measured.

Observation is consistent with the suppression (20%) expected due to proton absorption contributions.

No simulation available for SD and DD exclusive $W^+W^-$ production requiring data driven estimates.

Track-based technique for selecting exclusive processes was developed and validated.

Evidence of SM exclusive $W^+W^-$ production was found to be at the level of $3\sigma$.

No evidence for an excess in the kinematic region targeting aQGC.

Limits on exclusive Higgs total production cross section set to $400 \times \sigma_H^{predicted}$

$\sigma_H^{predicted}$ for elastic process only.
Backup
Equivalent Photon Approximation (EPA)

- Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$
  \[
  \sigma_{pp(\gamma\gamma)\rightarrow \ell^+\ell^-}^{EPA} = \int \int P(x_1) P(x_2) \sigma_{\gamma\gamma \rightarrow \ell^+\ell^-} \left( m_{\ell^+\ell^-}^2 \right) \, dx_1 dx_2
  \]

- Exclusive $\gamma\gamma \rightarrow W^+W^-$
  \[
  \sigma_{pp(\gamma\gamma)\rightarrow W^+W^-}^{EPA} = \int \int P(x_1) P(x_2) \sigma_{\gamma\gamma \rightarrow W^+W^-} \left( m_{\gamma\gamma}^2 \right) \, dx_1 dx_2
  \]

- $P(x_1), P(x_2)$ are the equivalent photon spectra for the protons
- $x_1$ and $x_2$ are the fractions of the proton energy carried away by the emitted photons
- $m_{\ell^+\ell^-}$ is the invariant mass of the two leptons
- $m_{\gamma\gamma}$ is the two photons center-of-mass energy
Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$: Control distributions

- Apply scaling factors to MC, use acoplanarity < 0.008 instead of $p_T^{\ell\ell} < 1.5$ GeV
- Good modeling of data seen in both channels
### Exclusive $\gamma\gamma \to \ell^+\ell^-$: Breakdown of systematic uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty [%] $\gamma\gamma \to e^+e^-$</th>
<th>Uncertainty [%] $\gamma\gamma \to \mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron reconstruction and identification efficiency</td>
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<td>-</td>
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<tr>
<td>Electron energy scale and resolution</td>
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<td>Electron trigger efficiency</td>
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<td>Muon reconstruction efficiency</td>
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<td>Muon momentum scale and resolution</td>
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<td>Luminosity</td>
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<td>Total systematic uncertainty</td>
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<td>Data statistical uncertainty</td>
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Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$: Fit results

**ATLAS**

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

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

- 68% C.L.
- 95% C.L.
- Theory

$\gamma\gamma \rightarrow \mu^+\mu^-$
acoplanarity fit

- 68% C.L.
- 95% C.L.
- Theory
Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: $\gamma\gamma \rightarrow \mu^+\mu^-$ selection

- 2 $\mu$ with $p_T^{\mu} > 20$ GeV
- 45 GeV < $m_{\mu\mu}$ < 75 GeV or $m_{\mu\mu}$ > 105 GeV
- $p_T^{\mu\mu} < 3$ GeV and $\Delta z_0^{iso} = 1.0$ mm
Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: pileup

- Effect of pileup on exclusivity selection must be quantified
- Evaluate a factor: $f = \frac{Data}{Elastic+SD+DD}$ in nominal exclusivity vs. pileup-prone exclusivity regions
- Nominal exclusivity:
  - Require acoplanarity $< 0.0015$ and $p_{\mu\mu}^T < 3$ GeV to enhance elastic events with $\Delta z_0^{iso} = 1$mm
  - $f = 0.73 \pm 0.03$ (stat.) $\pm 0.01$ (syst.)
- Pileup-prone exclusivity:
  - Similar but ask for exactly one track in $\Delta z_0^{iso} = 3$mm expected to be from pileup
  - Extra track distribution in $\Delta z_0^{iso}$ is flat for exclusive events
  - $f = 0.70 \pm 0.06$ (stat.) $\pm 0.03$ (syst.)
- 2 scale factors compatible at 10%: assign a systematic error of 10%
## Exclusive $\gamma\gamma \rightarrow W^+ W^-$ and Higgs: Selection

<table>
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<tr>
<th>Variable</th>
<th>Excl $W^+ W^-$</th>
<th>Excl Higgs</th>
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<td>$p_T^{lep}$</td>
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<td>$&gt; 25, 15 \text{ GeV}$</td>
</tr>
<tr>
<td>$m_{e\mu}$</td>
<td>$&gt; 20 \text{ GeV}$</td>
<td>$&gt; 10 \text{ GeV}$</td>
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<td>$p_T^{e\mu}$</td>
<td>$&gt; 30 \text{ GeV}$</td>
<td>$&gt; 30 \text{ GeV}$</td>
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<tr>
<td>$\Delta z_0^{iso}$</td>
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<td>1mm</td>
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