Electromagnetic processes in ultra peripheral lead-lead collisions with ATLAS

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The LHC and the ATLAS detector
The ATLAS detector components

2015 Pb+Pb data

\[ L \approx 0.5 \text{ nb}^{-1} \]

\[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \]
Electromagnetic interactions in Pb+Pb collisions

\[ 2R_{\text{Pb}} < b \]

\[ v \approx c \]

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\[ \text{em–fields} \]

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\[ \text{Equivalent Photon Approximation (EPA)} \]

\[ \sigma_{\text{EPA}}^{A_1A_2(\gamma\gamma)\rightarrow A_1A_2X} = \int \int d\omega_1 d\omega_2 n_1(\omega_1) n_2(\omega_2) \sigma_{\gamma\gamma\rightarrow X}(W_{\gamma\gamma}) \]

\[ \text{with} \quad n(b, \omega) = \frac{Z^2 \alpha_{\text{em}}}{\pi \omega} \left| \int dq_{\perp} q_{\perp}^2 \frac{F(Q^2)}{Q^2} J_1(bq_{\perp}) \right|^2 \]

\[ Q^2 < \frac{1}{R^2} \quad \text{and} \quad \omega_{\text{max}} \approx \frac{\gamma}{R} \]
LHC as a photon-photon collider

pp collisions

Pros

- harder EPA $\gamma$ spectrum ($\omega_{\text{max}} \sim \text{TeV}$)
- more data available ($\sim 35 \text{ fb}^{-1}$)

Cons

- large pile-up (multiple interactions per bunch crossing)
- problems with triggering on low $p_T$ objects

Pb+Pb collisions

Pros

- AA ($\gamma\gamma$) x-sec $\propto Z^4$
- gluonic x-sec $\propto A^2$ $\Rightarrow$ lower QCD bkg.
- low pile-up ($< 1\%$)

Cons

- softer EPA $\gamma$ spectrum ($\omega_{\text{max}} \sim 0.1\text{TeV}$)
- relatively small data sample

[PR D94 (2016) 3, 032011]

[ALICE Collaboration, EPJC 73 (2013) 2617]
Measurement of high-mass di-muon pairs

**Motivation**

Extension of ALICE’s di-lepton mass measurement (m_{ll} up to 10 GeV)

**Event selection**

- 2 opposite-sign and good-quality muons with p_T > 4 GeV, |\eta| < 2.4, m_{\mu\mu} > 10 GeV
- reconstructed vertex with no additional tracks
Run: 287038
Event: 71765109
2015-11-30 23:20:10 CEST

Dimuons UPC Pb+Pb 5.02 TeV
Measurement of high-mass di-muon pairs

[ATLAS-CONF-2016-025]

Signal modelling

Starlight 1.1 (EPA + LO QED)

Total of 12069 di-muon pairs were selected in data

Corrections

- Trigger efficiency (data-driven) $\sim 80\%$
- Muon reco & identification efficiency (MC+scale factors) $\sim 90\%$
- Vertex efficiency (MC-driven) $\sim 95\%$

\[ \frac{1}{N} \frac{dN_\mu}{d\eta} \]

\[ \frac{1}{N} \frac{dN_\mu}{dp_T} \]

\[ \begin{align*}
\text{ATLAS Preliminary} \\
Pb+Pb \rightarrow Pb^{0}+Pb^{0}+\mu^{+}+\mu^{-} \\
\sqrt{s_{NN}}=5.02 \text{ TeV} \quad L_{int} = 515 \mu b^{-1} \\
\end{align*} \]
Measurement of high-mass di-muon pairs

[ATLAS-CONF-2016-025]

**Acoplanarity distributions**

- di-muon pairs expected to be produced back-to-back
- presence of small tail in acoplanarity
- two assumptions tested:
  - a) tail due to background
  - b) tail due to higher order QED effects
    (not included in Starlight)
- average of a) and b) taken as a central value and a difference as a systematic uncertainty

\[
A_{\text{co}} = 1 - |\Delta \phi / \pi|
\]
Results:

- main contribution to systematics from the luminosity uncertainty; total \( \sim 10\% \)
- total x-sec: \( \sigma = 32.2 \pm 0.3 \) (stat.) ± 4.0 (syst.) \( \mu b \)
- good agreement with Starlight in differential (with respect to \( m_{\mu\mu}, y_{\mu\mu} \)) and total x-sec’s (\( \sigma_{\text{Starlight}} = 31.6 \mu b \))
Motivation

- first direct observation of $\gamma\gamma \rightarrow \gamma\gamma$ scattering
- previous indirect measurements used:
  a) multi-photon Breit-Wheeler reaction
     \[ (\omega + n\omega_0 \rightarrow e^+e^-) \text{ [PRL 79 (1997) 1626]} \]
  b) photon splitting
  c) Delbrück scattering

Recent SM Predictions for ATLAS

[A. Szczurek et al. PRC 93 (2016) 4, 044907], [D. d’Enterria et al. PRL 111 (2013) 080405]
Search for light-by-light scattering

[arXiv:1702.01625]

**Trigger**
- total $E_T$ in calorimeter between 5 and 200 GeV
- no more than one hit in inner MBTS
- less than 10 hits in the pixel detector

**Event Selection**
- two photons with $E_T > 3$ GeV, $|\eta| < 2.37$
- no tracks from IP
- $m_{\gamma\gamma} > 6$ GeV, $p_{T\gamma\gamma} < 2$ GeV
- $Aco = \left(1 - \frac{\Delta\phi}{\pi}\right) < 0.01$

**Main sources of bkg.**
- Central Exclusive Production (CEP) $gg \rightarrow \gamma\gamma$
- misidentification of electrons from $\gamma\gamma \rightarrow ee$

![Graph showing acoplanarity cut]
Search for light-by-light scattering
[arXiv:1702.01625]

Run: 287924
Event: 106830493
2015-12-12 19:41:56 CEST
Search for light-by-light scattering
[arXiv:1702.01625]

Photon Performance Studies
(done with $\gamma\gamma \rightarrow l^+l^-$ events)

- trigger efficiency studies
- $\gamma$ reconstruction with hard bremsstrahlung
- $\gamma$ PID with FSR radiation
- $\gamma$ energy scale and resolution

Systematic Uncertainty

dominated by:

- $\gamma$ reco
- $\gamma$ PID

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>5%</td>
</tr>
<tr>
<td>Photon reco efficiency</td>
<td>12%</td>
</tr>
<tr>
<td>Photon PID efficiency</td>
<td>16%</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>7%</td>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>11%</td>
</tr>
<tr>
<td>Total</td>
<td>24%</td>
</tr>
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</table>
Results: data - 13 event, expected - 7.3 signal and 2.6 bkg. events

<table>
<thead>
<tr>
<th>Selection</th>
<th>$\gamma\gamma \rightarrow e^+e^-$</th>
<th>CEP $gg \rightarrow \gamma\gamma$</th>
<th>Hadronic fakes</th>
<th>Other fakes</th>
<th>Total background</th>
<th>Signal</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>74</td>
<td>4.7</td>
<td>6</td>
<td>19</td>
<td>104</td>
<td>9.1</td>
<td>105</td>
</tr>
<tr>
<td>$N_{trk} = 0$</td>
<td>4.0</td>
<td>4.5</td>
<td>6</td>
<td>19</td>
<td>33</td>
<td>8.7</td>
<td>39</td>
</tr>
<tr>
<td>$p_T^{\gamma\gamma} &lt; 2$ GeV</td>
<td>3.5</td>
<td>4.4</td>
<td>3</td>
<td>1.3</td>
<td>12.2</td>
<td>8.5</td>
<td>21</td>
</tr>
<tr>
<td>$Aco &lt; 0.1$</td>
<td>1.3</td>
<td>0.9</td>
<td>0.3</td>
<td>0.1</td>
<td>2.6</td>
<td>7.3</td>
<td>13</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>0.3</td>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
<td>0.7</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>
Results:

- significance of $4.4\sigma$ estimated using profile likelihood method (expected significance of $3.8\sigma$)
- x-sec measured in fiducial region of $p_T^{\gamma} > 3$ GeV, $|\eta^{\gamma}| < 2.4$, $m_{\gamma\gamma} > 6$ GeV, $p_T^{\gamma\gamma} < 2$ GeV, $A_{\text{co}} < 0.01$
  $\sigma = 70 \pm 20$ (stat.) $\pm 17$ (syst.) nb

SM predictions: $45 \pm 9$ nb ([PRL 111 (2013) 080405]), $49 \pm 10$ nb ([PRC 93 (2016) no.4, 044907])
Cross-section for the exclusive production $\gamma\gamma \rightarrow \mu^+\mu^-$ was measured with ATLAS Pb+Pb data at $\sqrt{s_{NN}} = 5.02$ TeV. Good agreement with LO QED predictions of Starlight.

The first direct evidence for $\gamma\gamma \rightarrow \gamma\gamma$ scattering with significance of 4.4$\sigma$ has been reported. Improvements in the precision expected with more Pb+Pb data to be collected in 2018.
Thank You for Your Attention!
Backup
\[ L_a = \frac{1}{2} (\partial a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} \frac{a}{\Lambda} F \tilde{F} \]

expected axion searches sensitivity

![Expected Axion Searches Sensitivity](image-url)
$$L_{\text{QED}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \rightarrow L_{\text{BI}} = \beta^2 \left( 1 - \sqrt{1 + \frac{1}{2\beta^2} F_{\mu\nu} F^{\mu\nu} - \frac{1}{6\beta^4} (F_{\mu\nu} \tilde{F}^{\mu\nu})^2} \right)$$

\begin{itemize}
  \item $m_{\gamma\gamma} > 6$ GeV
  \item Pb+Pb \( (\gamma\gamma) \rightarrow \text{Pb}(\ast) + \text{Pb}(\ast) \gamma\gamma$
\end{itemize}

95% CL exclusion by ATLAS

\begin{axis}[ymin=1e-2, ymax=1e5, xtick={50,100,150,200,250,300,350}, xticklabels={50,100,150,200,250,300,350}, xlabel=$\sqrt{\beta}$ [GeV], ylabel=$\sigma_{\text{fid.}}$ [nb]]
\end{axis}
LbyL - Photon Identification

γ cuts: $E_T > 3 \text{ GeV}, |\eta| < 2.37$

Shower shape variables used to γ PID

- $E_{\text{ratio}} \equiv$ ratio of the energy difference associated with the largest and second largest energy deposits to the sum of these deposits in the first layer of EM calo
- $f_1 \equiv$ fraction of energy reconstructed in the first layer with respect to the total energy of the cluster
- $W_{\text{eta}2} \equiv$ lateral width of the shower in the middle layer