Quasi-real photons from Pb ions @LHC

- Boosted nuclei are intense source of (quasi-real) photons
- Equivalent photon flux
  - $Q \sim 1/R \sim 0.06$ GeV
  - Lorentz factor $\gamma$ up to $\sim 2800$
  - $E_{\text{max}} \approx \gamma / R \sim 80$ GeV
  - Each flux scales with $Z^2$

- Various types of interactions possible:

  - Photon-pomeron (e.g. exclusive J/Psi)
  - Photo-nuclear (e.g. photoproduction of jets)
  - Photon-photon (e.g. LbyL scattering)

[Fermi, Nuovo Cim. 2 (1925) 143]
Motivation

- Light-by-light (\(\gamma \gamma \rightarrow \gamma \gamma\)) scattering
  - Tested indirectly in electron/muon g-2 measurements
  - Another example: Delbruck scattering and photon splitting processes

- At high energies, proposed as a clean channel to study:
  - Anomalous gauge couplings
  - Contributions from BSM particles

- Recent theoretical studies/predictions for Standard Model rates in Pb+Pb
  - [d'Enterria et al. PRL 111 (2013) 080405]
  - [Szczurek et al. PRC 93 (2016) 044907]
The ATLAS detector

Muon Detectors  Tile Calorimeter  Liquid Argon Calorimeter

Toroid Magnets  Solenoid Magnet  SCT Tracker  Pixel Detector  TRT Tracker

\( \eta = 0 \)

\( \theta = 90^\circ \)

\( \eta = 0.88 \)

\( \theta = 45^\circ \)

\( \eta = 2.44 \)

\( \theta = 10^\circ \rightarrow \eta = \infty \)

\( \theta = 0^\circ \rightarrow \eta = \infty \)

R

0 1 2 3 4 5 6 7 8 9 10

\( |\eta| \)

µ-chambers  Tracking  MBTS  FCAL  LUCID  TAS  ZDC/TAN

23 Aug 2018  M. Dyndal  LHC measurements of light-by-light scattering
γγ → μμ measurement

- Good cross-check for validity of calculations
  - Total uncertainty of the measurement: ~10%
  - Measurement in agreement with QED
  - Clear extension of ALICE measurement at lower mass


[ALICE Collaboration, EPJC 73 (2013) 2617]
Further cross-checks: $\gamma \gamma \rightarrow ee$

$\gamma \gamma \rightarrow ee$

**selection**

\[ \gamma \rightarrow e^{-}e^{+} \]

$\gamma \gamma \rightarrow e^{-}e^{+} \text{(hard-bremsst.)}$

**selection**

\[ \gamma \rightarrow e^{-}e^{+} \]

**Electrons / 0.5 GeV**

- Data, $480 \mu b^{-1}$
- $\gamma \gamma \rightarrow e^{-}e^{+}$ MC
- Pb+Pb $|s_{NN}|=5.02$ TeV
- $E_T^{e} > 2.5$ GeV, $|\eta| < 2.47$

**$E_T = E \sin(\theta)$**

**Events / 0.2 GeV**

- Data, $480 \mu b^{-1}$
- $\gamma \gamma \rightarrow e^{-}e^{+}$ MC
- Pb+Pb $|s_{NN}|=5.02$ TeV
- $E_T^{e} > 2.5$ GeV, $|\eta| < 2.47$

**$p_T^{e^{-}e^{+}}$ [GeV]**

- Data, $480 \mu b^{-1}$
- $\gamma \gamma \rightarrow e^{-}e^{+}$ MC
- Pb+Pb $|s_{NN}|=5.02$ TeV

**Events / 0.2 GeV**

- Data, $480 \mu b^{-1}$
- $\gamma \gamma \rightarrow e^{-}e^{+}$ MC
- Pb+Pb $|s_{NN}|=5.02$ TeV

$N_e=1$, $N_{\gamma}=1$

$E_T^{e} > 5$ GeV, $p_T^{e^{-}e^{+}} < 2$ GeV
Light-by-light scattering in Pb+Pb

- **Object selection**

- **Photons**
  - $E_T > 3$ GeV, $|\eta| < 2.37$
  - Standard photon identification scheme re-optimized based on several calorimeter shower-shape variables

- **Charged-particle tracks**
  - $p_T > 100$ MeV, $|\eta| < 2.5$
  - Requiring no tracks in LbyL analysis
Light-by-light scattering in Pb+Pb

- Photon performance validation

- $\gamma\gamma \rightarrow ee$ events are used for:
  - Trigger efficiency studies
  - Photon reconstruction/identification efficiencies
  - Photon energy scale/resolution (EM di-cluster properties from $\gamma\gamma \rightarrow ee$)

- Systematic uncertainties
  - Dominated by photon reco/PID efficiency uncertainty

<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>
</tbody>
</table>
Light-by-light scattering in Pb+Pb

- **Main background**
  - Central Exclusive Production $gg \rightarrow \gamma\gamma$
  - Misidentified electrons from $\gamma\gamma \rightarrow ee$
  - Dedicated control regions are used

- **Other background processes** (found to be small or negligible)
  - Fake photons induced by cosmic-ray muons
  - Fake photons from hadrons (e.g. $\gamma\gamma \rightarrow qq$)
  - Exclusive $\pi^0\pi^0$ production
  - Double-bremsstrahlung from the ions
  - Bottomonia ($\gamma\gamma \rightarrow \eta_b \rightarrow \gamma\gamma$ or $\gamma\text{Pb} \rightarrow \gamma \rightarrow \gamma\eta_b \rightarrow 3\gamma$)
Light-by-light scattering in Pb+Pb

- Results

- 13 events observed in data
- 7.3 signal events and 2.6 background events expected

<table>
<thead>
<tr>
<th>Selection</th>
<th>$\gamma\gamma \rightarrow e^+e^-$</th>
<th>CEP $gg \rightarrow \gamma\gamma$ 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>
</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>
</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>
</tr>
<tr>
<td>Aco $&lt; 0.01$</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>
</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>
</tr>
</tbody>
</table>
Light-by-light scattering in Pb+Pb

- **Results**

- **Observed significance:** 
  \[ 4.4\sigma \text{ (3.8}\sigma \text{ expected)} \]

- **Fiducial cross section estimated for:**
  - \( p_T^\gamma > 3\, \text{GeV}, \left| \eta^\gamma \right| < 2.4 \)
  - \( m_{\gamma\gamma} > 6\, \text{GeV} \)

- \( \sigma_{\text{fid}} = 70 \pm 20 \) (stat.) \( \pm 17 \) (syst.) nb

- **SM predictions:**
  - 45 \( \pm 9 \) nb 
    [PRL 111 (2013) 080405]
  - 49 \( \pm 10 \) nb 
    [PRC 93 (2016) 044907]
Summary & outlook

- Using LHC as a photon-photon collider works extremely well

- Evidence for LbyL scattering by ATLAS
  - 4.4σ significance (3.8σ expected)
- Recent CMS collaboration (prelim.) measurement
  - Similar analysis strategy -> 4.1σ (4.4σ) evidence

- New Pb+Pb LHC runs this November
  - 1-5x more statistics expected
References


- ATLAS Collaboration (preliminary), *Measurement of high-mass dimuon pairs in ultra-peripheral lead-lead collisions at √sNN = 5.02 TeV with the ATLAS detector at the LHC*, ATLAS-CONF-2016-025

PbPb ($\gamma\gamma$) $\rightarrow$ PbPb X process calculations

Strong fields, up to $10^{25}$ Vm$^{-1}$ at the LHC

Impact parameter $> 2R$

The cross section for AA ($\gamma\gamma$) $\rightarrow$ AA X process can be calculated using:

(1) Number of equivalent photons (EPA) by integration of relevant EM form factors:

$$n(b, \omega) = \frac{Z^2 \alpha_{em}}{\pi^2 \omega} \left| \int dq_\perp q^2 \frac{F(Q^2)}{Q^2} J_1(bq_\perp) \right|^2$$

$$Q^2 < \frac{1}{R^2}, \quad \omega_{\text{max}} \approx \frac{\gamma}{R}$$

(2) EW $\gamma\gamma \rightarrow X$ (elementary) cross section

$$\sigma_{A_1A_2(\gamma\gamma)\rightarrow A_1A_2X} = \int \int d\omega_1 \, d\omega_2 \, n_1(\omega_1) \, n_2(\omega_2) \, \sigma_{\gamma\gamma\rightarrow X}(W_{\gamma\gamma})$$

[Fermi, Nuovo Cim. 2 (1925) 143]

[Weizsacker, Z. Phys. 88 (1934) 612]

[Williams, Phys. Rev. 45 (10 1934) 729]
Role of QCD meson exchanges

- Large effect at $m < 4$ GeV

Light-by-light scattering in Pb+Pb

- LbyL measurement: impact on specific BSM models

Knapen et al.
PRL 118 (2017) 171801
arXiv:1709.07110

Ellis et al.
PRL 118 (2017) no.26, 261802

\[ \mathcal{L}_{\text{QED}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \rightarrow \]

\[ \mathcal{L}_{\text{BI}} = \beta^2 \left( 1 - \sqrt{1 + \frac{1}{2\beta^2} F_{\mu\nu} F^{\mu\nu}} - \frac{1}{16\beta^4} (F_{\mu\nu} F^{\mu\nu})^2 \right) \]

\begin{align*}
\text{OPAL, } a_{F \tilde{F}} \\
\text{CMS, } a_{F \tilde{F}} \\
\text{ATLAS, } 2\gamma \\
\text{ATLAS, } 3\gamma
\end{align*}

\[ \sigma_{\text{fid}} \text{ [nb]} \]

\[ 95\% \text{ CL exclusion by ATLAS} \]
Positioned at ±365 cm from the ATLAS IP (perpendicular to the beam direction)
- Consist of 12 scintillator paddles per side (2 cm thick) organized into two disks
- Each disk is divided into an inner (8 pads) and outer (4 pads) rings
- Cover $2.1 < |\eta| < 2.8$ and $2.8 < |\eta| < 3.9$
- Typically used during low pile-up pp runs and during heavy-ion collisions (to select minimum bias events)
- Can be used to veto charged-particle activity in fwd direction, e.g. in photon-induced processes (cf. LHCb Herschel / ALICE AD counters)
Zero Degree Calorimeters

- Installed at ±140 m from the ATLAS IP (where the beam pipe splits)
- Detect very forward (8.3 < |η| < +∞) neutral particles (incl. neutrons)
- Usually used in HI collisions to provide a measurement of the centrality (correlated to the number of forward neutrons)
- Very useful to tag the ultra-peripheral events (e.g. 0nXn or XnXn topologies)

![Diagram of photon production and dissociation](image_url)
Light-by-light scattering in Pb+Pb

- CEP $gg \rightarrow \gamma\gamma$ background
  - MC simulation (with data-driven normalization) is cross-checked in the analysis of ZDC activity
    - Aco > 0.01 used as a control region
    - Energy deposits corresponding to at least 1 forward neutron emission

- Expectations:
  - Pb+Pb CEP occurs at relatively small impact parameters ($b \sim 2R$)
    - large probability for nuclear break-up
  - Moreover: the probability for extra Coulomb break-up is \( \sim 80\% \) for $b=2R$ (from STARlight)

- Conclusions:
  - What we see in the detector (Aco > 0.01) is likely the semi-exclusive CEP background
    (signal region: 11/13 events have no ZDC activity)
LHC as a photon-photon collider

- Many interesting measurements can be done with pp/Pb+Pb beams of quasi-real photons at the LHC

- pp collisions
  + harder EPA spectrum ($\omega_{\text{max}} \sim \text{TeV}$)
  - large pile-up (multiple interactions per bunch crossing)
  + large datasets available, O(10 fb$^{-1}$)
  - hard to trigger on low-\(p_T\) objects

- Pb+Pb collisions
  - softer EPA spectrum ($\omega_{\text{max}} \sim 100 \text{ GeV}$)
  + AA ($\gamma\gamma$) cross-sections scale as $Z^4$
  + gluonic cross-sections scale as $\sim A^2$ (lower QCD bkg expected wrt pp)
  + low pile-up (<1%)*
  - Short LHC Pb+Pb campaigns (cf. pp)
Cross-sections at $\sqrt{s} = 13$ TeV

- $O(\text{pb})$ for $W_{\gamma\gamma} > 10$ GeV ($\gamma\gamma \rightarrow l^+l^-$)
- $O(\text{fb})$ for $W_{\gamma\gamma} > 200$ GeV ($\gamma\gamma \rightarrow W^+W^-$)

$pp (\gamma\gamma) \rightarrow pp X$ at the LHC: example cross-sections