Current measurements and future prospects for light-by-Light scattering and searches for Axion-like particles from ultra-peripheral PbPb collisions at CMS

Jeremi Niedziela (CERN)
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• the process could also proceed through new charged particles (**SUSY**) or new spin-even resonances (**axions, monopoles**).
**Introduction**

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- The process could also proceed through new charged particles (**SUSY**) or new spin-even resonances (**axions, monopoles**).
  - The only similar process experimentally confirmed: **Delbrück scattering** (γ deflection in the nucleus field),
  - The difficulty to observe this process comes from a **very low cross-section**: \( \sim \mathcal{O}(\alpha^4) \approx 10^{-9} \).
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  • the only similar process experimentally confirmed: **Delbrück scattering** (γ deflection in the nucleus field),
  • the difficulty to observe this process comes from a **very low cross-section**: $\sim \mathcal{O}(\alpha^4) \approx 10^{-9}$,

• several **experimental approaches** were proposed:
  ‣ **Compton** backscattered photons against laser photons,
  ‣ photon-photon collisions from **microwave waveguides, cavities of high-power lasers**,
  ‣ **photon colliders**: scattering laser-light off two e$^\pm$ beams,
  ‣ ultra-peripheral (electromagnetic) interactions of proton/lead beams at the LHC.
**Introduction**

Exclusive $\gamma \gamma \rightarrow \gamma \gamma$ is also sensitive to physics signals beyond the SM such as axions.

**Axions**
- Axions arise from Peccei-Quinn mechanism which promotes QCD mixing $\theta_{QCD}$ to a field,
- they solve in an elegant way the strong CP problem,
- they are a natural dark-matter candidates,
- characteristic two-photon vertex $\rightarrow$ light shining through the wall experiments,
- original axions (small masses, symmetry breaking scale $\approx$ EW scale) ruled out.

**Axion Like Particles (ALPs)**
- more general class of elementary pseudo-scalar particles, where mass-coupling relation is not fixed,
- axions or ALPs occur automatically in many extensions of SM.
**Light-by-Light in UPCs**

- Proposal: **use ultra peripheral heavy-ion collisions** (UPC of HI): $b > 2 \cdot R_{\text{Pb}}$,
- passing heavy ions generate **huge EM fields** ($10^{14} \text{T}$),
- **cross-section is amplified** by $Z^4$, for PbPb ($Z=82$) $\sigma_{\gamma\gamma \rightarrow \gamma\gamma}$ is $5 \cdot 10^7$ higher than for p-p or e$^+$e$^-$. 

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- **quasi-real photons** (coherence):
  $Q \sim \frac{1}{R} \approx 0.06 \text{ GeV (Pb)}, 0.28 \text{ GeV (p)},$
- **maximum $\gamma$ energies** at LHC
  $\omega_{\text{max}} \sim \frac{\gamma L}{R} \approx 80 \text{ GeV (Pb)}, 2.5 \text{ TeV (p)}.$
**Light-by-Light in UPCs**

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\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\end{figure}

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- **maximum $\gamma$ energies** at LHC $\omega_{max} \sim \gamma l/R \approx 80$ GeV (Pb), 2.5 TeV (p).

- generated with MadGraph v.5 MC generator;
- **$W^\pm$ contributions** only relevant for $m_{\gamma\gamma} > 2 \cdot m_W$, **hadronic loops** only for $m_{\gamma\gamma} \lesssim 2$ GeV,
- generated **cross-section**: $\sigma_{\gamma\gamma \rightarrow \gamma\gamma} = 1.85$ $\mu$b ($|\eta| < 5.0$, $m_{\gamma\gamma} > 2.5$ GeV).
**BACKGROUND PROCESSES**

**Exclusive QED $e^+e^-$**
- electrons may be misidentified as photons if they undergo hard bremsstrahlung and they are not reconstructed,
- generated with STARLIGHT,
- $\sigma_{\gamma\gamma\to ee} = 20.6$ mb (without $p_T$ and $\eta$ cuts),
- can be reduced with tight $\gamma$ identification cuts.

**Central Exclusive Production (CEP)**
- generated with SUPERCHIC 2.0,
- large theoretical uncertainty due to modeling of rapidity gap survival probability (normalized from data in control-region),
- $\sigma_{gg\to \gamma\gamma} = 15$ mb (without $p_T$ and $\eta$ cuts),
- larger $p_T$ exchange than LbL, photons less back-to-back. Suppressed by acoplanarity cuts.
• Photons from light-by-light scattering measurable in CMS over $|\eta|<2.4$, exclusivity condition over $|\eta|<5.2$,
• final state - just two tower in the ECAL, no activity in the tracker, hadron calorimeters, muon detectors.

**Electromagnetic Calorimeter**
- Barrel EB ($|\eta| < 1.479$)
- End-cap EE ($1.479 < |\eta| < 3.0$)
- $\approx 76,000$ scintillating PbWO$_4$ crystals

**Hadron Calorimeter**
- Barrel HB ($|\eta| < 1.3$)
- End-cap HE ($1.3 < |\eta| < 3.0$)
- Brass + Plastic scintillator
  $\approx 7000$ channels

**Hadron Forward Calorimeter**
- HF ($2.9 < |\eta| < 5.2$)
- Steel + Quartz fibers
  $\approx 2000$ channels
**Data Sample**

**Data sample**
- PbPb @ 5.02 TeV (2015),
- total integrated luminosity $L_{\text{int}} = 390 \, \mu\text{b}^{-1}$.

**Trigger**
- at least two photons/electrons in ECAL with $E_T > 2$ GeV each,
- at least one of the two Hadron Forward (HF) calos empty.

**Reconstruction**
- photons of interest in the low $E_T$ (2-10 GeV) region,
- standard CMS high-$E_T$ $e/\gamma$ reco ($E_T > 10$ GeV) retuned for this analysis,
- pre-selecting events with exactly two photons with $E_T > 2$ GeV,
- identification of photons:
  - removal of decay photons by shower shape: $\sigma_{\eta\eta} < 0.02$ (0.06) in barrel (endcap),
  - cleaning spikes (direct ionization of the photodiode) - four neighboring hits must contain significant fraction (>5%) of the highest energy hit.
**Data Selection**

**Neutral exclusivity cuts**
- reject events with towers above noise threshold in ECAL, HCAL or HF ($|\eta|<5.2$) far from photons candidates:
  - $|\Delta\eta|>0.15, |\Delta\phi|>0.7$ (0.4) in EB (EE),
  - any tower in hadron calorimeters (HB, HE or HF).

**Charged exclusivity cuts**
- reject events with any charged particle with $p_T > 0.1$ GeV.

**Acoplanarity**
- definition: $A_\Phi = 1-\Delta\Phi_{\gamma\gamma}/\pi$,
- signal has very low acoplanarity ($A_\Phi < 0.008$), CEP has flat $A_\Phi$ in range 0-0.2,
- cut applied: $A_\Phi < 0.01$.

**Other cuts**
- diphoton $p_{\gamma\gamma} < 1$ GeV to reduce all non-exclusive photon backgrounds.
BACKGROUND ANALYSIS

QED $e^+e^-$ background

- the same analysis repeated, now requiring exclusive $e^+e^-$ pair instead of $\gamma\gamma$,
- **kinematic distributions** reproduced well by the Starlight MC generator (except increasing acoplanarity tail from $\gamma\gamma \rightarrow e^+e^-(\gamma)$),
- **confirms quality** of:
  - electron/photon reconstruction,
  - event selection criteria,
  - MC predictions for PbPb UPCs,
- estimated $e^+e^-$ background after cuts: $1.0 \pm 0.3$ events.
CEP + other residual backgrounds

- normalized from acoplanarity measured in data for $A_\Phi > 0.02$, where LbL is negligible,
- acoplanarity cut ($A_\Phi < 0.01$) removes most of the CEP background,
- estimated CEP background after cuts: \(3.0 \pm 1.1\) events.
Kinematic Distributions

Measured distributions reproduced well by the sum of LbL signal and QED + CEP backgrounds:
**RESULTS**

**Number of events**

- signal region: $|\eta| < 2.4$, $E_T > 2$ GeV, $m_{\gamma\gamma} > 5$ GeV,
- observed: **14 light-by-light events**,  
- expected: **11.1 ± 1.1** (th) signal and **4.0 ± 1.2** (stat) background events,
- significance (from acoplanarity distribution) → observed: **4.1\sigma** (expected: 4.4\sigma)
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**Lbl to QED cross-sections ratio**
- $\sigma_{\gamma\gamma\rightarrow\gamma\gamma}/\sigma_{\gamma\gamma\rightarrow e^+e^-}$ extracted, taking into account:
  - efficiency of the trigger,
  - $\gamma$/electron reconstruction and identification efficiency,
  - stat. uncertainty on MC background estimation,
- exclusivity (neutral and charged) uncertainties cancel out,
- measured:
  $$\frac{\sigma_{\gamma\gamma\rightarrow\gamma\gamma}}{\sigma_{\gamma\gamma\rightarrow e^+e^-}} = [25.0 \pm 9.6 \text{ (stat)} \pm 5.8 \text{ (syst)}] \times 10^{-6}$$

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**Summary of Efficiencies**

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon reconstruction and identification</td>
<td>(2 $\times$ 9)%</td>
</tr>
<tr>
<td>Electron reconstruction and identification</td>
<td>(2 $\times$ 2.5)%</td>
</tr>
<tr>
<td>Trigger</td>
<td>12%</td>
</tr>
<tr>
<td>MC backgrounds (stat.)</td>
<td>8%</td>
</tr>
<tr>
<td>Total</td>
<td>24%</td>
</tr>
</tbody>
</table>
RESULTS

Number of events

• signal region: \(|\eta| < 2.4, E_T > 2 \text{ GeV}, m_{\gamma\gamma} > 5 \text{ GeV},

• observed: \textbf{14 light-by-light events},

• expected: \textbf{11.1 ± 1.1 (th) signal and 4.0 ± 1.2 (stat) background} events,

• significance (from acoplanarity distribution) → observed: \textbf{4.1 \sigma} (expected: 4.4 \sigma)

Fiducial LbL cross section

• from STARLIGHT, \(\sigma_{\gamma\gamma\rightarrow e^+e^-} = 4.82 \pm 0.15 \text{ (th) mb},

• expected: \textbf{138 ± 14 nb},

• measured: \textbf{120 ± 46 (stat) ± 28 (syst) ± 4 (th) nb}.

LbL to QED cross-sections ratio

• \(\sigma_{\gamma\gamma\rightarrow\gamma\gamma}/\sigma_{\gamma\gamma\rightarrow e^+e^-}\) extracted, taking into account:
  ‣ efficiency of the trigger,
  ‣ \(\gamma/\text{electron reconstruction and identification efficiency},
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• exclusivity (neutral and charged) uncertainties cancel out,

• measured:

\[\sigma_{\gamma\gamma\rightarrow\gamma\gamma}/\sigma_{\gamma\gamma\rightarrow e^+e^-} = [25.0 \pm 9.6 \text{ (stat) ± 5.8 (syst)}] \times 10^{-6}\]


color box: Photon reconstruction and identification: (2 \times 9)\% \nElectron reconstruction and identification: (2 \times 2.5)\% \nTrigger: 12\% \nMC backgrounds (stat.): 8\% \nTotal: 24\%

Legend:

Data
LbL \(\gamma\gamma \rightarrow \gamma\gamma\) (MC)
CEP (gg \(\rightarrow \gamma\gamma\)) + other bkg
QED \(\gamma\gamma \rightarrow e^+e^-\) (MC)
Axion-like particle searches

- Exclusive diphoton final-state from resonant CP-odd axion-like particles (ALPs) production and decay,
- LbL, QED and CEP considered as background in this analysis,

- ALP samples
  - generated with STARLIGHT \((m_a = 5-90 \text{ GeV})\),
  - injected signals at various \(m_a\) analyzed after full detector simulation,
  - the same reconstruction procedure as in LbL analysis.
Axion-like particle searches

- no significant ALP excess observed in data above LbL+ backgrounds continuum,
- limits in $\sigma_{\gamma\gamma \rightarrow a \rightarrow \gamma\gamma}$ at 95% confidence, 100% $\gamma\gamma$ branching ratio
  (CLs criterion with a profile likelihood as a test statistic).

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**Graphical Representation:**

- Observed
- Expected
  - 68% expected
  - 95% expected

**Legend:**

- CMS
- PbPb 390 $\mu$b$^{-1}$ (5.02 TeV)

**Axes:**
- $m_a$ (GeV)
- 95% CL upp. lim. on $\sigma(\gamma\gamma \rightarrow a \rightarrow \gamma\gamma)$ (nb)

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**Diagram:**

- Diagram illustrating the process with fermions propagating to photons.
**AXION-LIKE PARTICLE SEARCHES**

- Limits in cross-section → **limits in** $g_{a\gamma}$ vs. $m_a$ plane ($g_{a\gamma} = 1/\Lambda$)
- left plot: coupling only to photons (with operator $\frac{1}{4\Lambda} aF\tilde{F}$),
- right plot: coupling to hypercharge (with operator $\frac{1}{4\Lambda \cos^2 \theta_W} aB\tilde{B}$),
- new limits on axion-like particles over $m_a = 5$-50 GeV.

\[ \frac{1}{\Lambda} (\text{GeV}^{-1}) \equiv g_{a\gamma, aF\tilde{F}} \]

- Beam dumps
- $e^+e^- \rightarrow 2\gamma$ (OPAL)
- $pp \rightarrow 2\gamma$ (CMS)
- $pp \rightarrow 3\gamma$ (ATLAS)
- $pp \rightarrow 8\gamma$ (ATLAS)

**Coupling to photons only**

- PbPb (5.02 TeV) → $\gamma\gamma$, observed
- PbPb (5.02 TeV) → $\gamma\gamma$, expected

**Coupling to hypercharge**

- PbPb (5.02 TeV) → $\gamma\gamma$, observed
- PbPb (5.02 TeV) → $\gamma\gamma$, expected
PROSPECTS FOR HL-LHC

With the HL-LHC data:

• significantly higher number of events,
• extended reach in coupling-mass plane
  (4 times smaller couplings, masses up to 140 GeV).

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s_{NN}}$</td>
<td>5.02 TeV</td>
<td>5.02 TeV</td>
</tr>
<tr>
<td>$L_{\text{int}}$</td>
<td>0.4 nb$^{-1}$</td>
<td>10 nb$^{-1}$</td>
</tr>
<tr>
<td>Tracker acceptance</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$N_{\gamma\gamma\rightarrow\gamma\gamma}$ events</td>
<td>14</td>
<td>640</td>
</tr>
</tbody>
</table>

![Graph showing the coupling-mass plane comparison between LHC and HL-LHC](image-url)
CONCLUSION

1. **Ultra-peripheral PbPb collisions** at LHC used to study **Light-by-Light** scattering,

2. QED and CEP identified as the main backgrounds,

3. Measurement of two-photon events with no other significant activity performed on 390 \( \mu b^{-1} \) PbPb @ 5.02 TeV,

4. **Evidence of LbL scattering**: 4.1 (4.4) sigma significance observed (expected)

5. **14 Light-by-Light events observed** - consistent with the SM predictions,

6. **Measured fiducial cross section**

\[ \sigma_{\gamma\gamma \rightarrow \gamma\gamma} = 120 \pm 46 \text{ (stat)} \pm 4 \text{ (th)} \text{ nb} \]
- consistent with the SM predictions,

7. No significant excess in \( m_{\gamma\gamma} \) distribution
    \( \rightarrow \) competitive **limits on axion-like particles.**

8. **HL-LHC** will extend capabilities to study LbL and searches for ALPs