Evidence for light-by-light scattering and Searches for axion-like particles in Ultraperipheral PbPb collisions at 5 TeV with CMS

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Light by light scattering and axion like particles

- Elastic light-by-light ($\gamma\gamma \rightarrow \gamma\gamma$) scattering, fundamental quantum-mechanical process

- Difficult to observe due to tiny cross-section: $\sim O(\alpha^4)$, Indirectly observed in Delbruck scattering & photon splitting Can be observed at the LHC using electromagnetic interaction from p, Pb beams

- In SM, the loop contains fermions and bosons but could also contain new charged particles (SUSY) or new spin-even resonances (axions, monopoles).

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

- Axions arise from Peccei-Quinn mechanism postulated to solve the strong CP problem, candidate of dark matter.

- Axion or axion-like particle occur in many extension of Standard Model.
Light by light in ultra-peripheral PbPb collisions

- Light-by-light scattering can be observed at the LHC using electromagnetic interaction from p, Pb beams.
- **Ultraperipheral collisions (UPCs)**: \( b_{\text{min}} > R_A + R_B \)
  Only electromagnetic interaction, no hadronic overlap.
- Accelerating hadrons radiate photons
  Coherent e.m. field of Z proton(s) =
  Weizsäcker-Wiliams equivalent photon spectrum.
- **Quasi-real photons**, \( Q \sim 1/R \sim 0.06 \text{ GeV (Pb)} \)
- Maximum photon energy: \( E_{\text{max}} \leq \gamma/R \approx 80 \text{ GeV (Pb)} \)
- **PbPb collisions favorable**, Photon flux \( \alpha Z^2 \),
  cross-section enhanced by \( Z^4 \) in AA
- Generated with MadGraph v.5 MC generator
- \( W^{\pm} \) contributions only relevant for \( m_{\gamma\gamma} > 2 \cdot m_W \),
  hadronic loops only for \( m_{\gamma\gamma} \leq 2 \text{ GeV} \).
The CMS detector

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm): ~16 m² ~66M channels
- Microstrips (80x180 μm): ~200 m² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niblum titanium coil carrying ~18,000 A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips: ~16 m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres: ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator: ~7,000 channels
Trigger
- 2 Electromagnetic shower with $E_T > 2$ GeV
- One of the Hadron Forward empty

Event selection
- Photons of interest: low $E_T$ (2-10 GeV)
  standard CMS high-$E_T$ e/$\gamma$ reco
  ($E_T > 10$ GeV) retuned for this analysis.
- 2 $\gamma$, $E_T > 2$ GeV, $|\eta| < 2.4$, $m(\gamma\gamma) > 5$ GeV
- Charged exclusivity:
  Reject events with any track
  with $p_T > 0.1$ GeV
- Neutral exclusivity:
  Reject events with any activity above noise threshold in the calorimeter
- Back-to-back 2 $\gamma$:
  $p_T(\gamma\gamma) < 1$ GeV, $A_\phi : (1-\Delta\phi/\pi) < 0.01$
Central exclusive production (CEP) + residual background

- Generated with SUPERCHIC (pp scaled by $A^2 R^4$, $S^2 = 100\%$).
- Larger theoretical uncertainty for CEP in PbPb collisions
- Normalized to data in control region $A_\phi > 0.02$

The background normalization factor:

$$f_{\text{norm}}^{\text{nonacoplanar}} = \frac{N_{\text{data}}(A_\phi > 0.02) - N_{\text{MC}}^{\text{LbL}}(A_\phi > 0.02) - N_{\text{MC}}^{\text{QED}}(A_\phi > 0.02)}{N_{\text{MC}}^{\text{CEP}}(A_\phi > 0.02)}$$

$$f_{\text{norm}}^{\text{nonacoplanar}} = 1.06 \pm 0.35 \text{ (stat)}.$$

- CEP + residual backgrounds in LbL signal region: $3.0 \pm 1.1 \text{ (stat)}$.

arXiv: 1810.04602
Background estimation

QED background: $\gamma\gamma \rightarrow e^+ e^-$

- Electrons mis-identified as $\gamma$, if track not reconstructed / undergo hard bremsstrahlung.
- Generated with STARLIGHT
- Analysis re-done with LbyL cuts, except requiring 2 opposite-sign electrons

QED background in LbL signal region: $1.0 \pm 0.3$ (stat).

- Very good data-MC agreement over $m_{ee} \sim 5-90$ GeV.
- Confirms quality of e/$\gamma$ reco. validity of exclusive event selection criteria, as well as of MC predictions for PbPb UPCs.
γγ differential distributions (after all cuts)

Data: 14 evts, \(N_{\text{sig}} = 11.1 \pm 1.1, \ N_{\text{bkg}} = 4.0 \pm 1.2\) expected.
The measured yields and kinematic distributions are in good agreement with the MC expectations (LbyL + QED + CEP + other)
LbyL cross-section & signal significance

- Measured the ratio of LbyL to QED e+e- cross section
- Reduces uncertainties related to luminosity
- The main sources of uncertainties: trigger, single $\gamma/e^\pm$ efficiencies

<table>
<thead>
<tr>
<th>Component</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon reconstruction and identification ($SF_{\gamma,\text{reco+ID}}$)</td>
<td>(2x9)%</td>
</tr>
<tr>
<td>Electron reconstruction and identification ($SF_{ee,\text{reco+ID}}$)</td>
<td>(2x2.5)%</td>
</tr>
<tr>
<td>Trigger</td>
<td>12%</td>
</tr>
<tr>
<td>Size of simulated background samples</td>
<td>6%</td>
</tr>
<tr>
<td>Total</td>
<td>23%</td>
</tr>
</tbody>
</table>

$$R = \frac{\sigma_{\text{fid}} (\gamma\gamma \rightarrow \gamma\gamma)}{\sigma_{\text{fid}} (\gamma\gamma \rightarrow e^+e^-)} = [25.0 \pm 9.6 \text{ (stat.)} \pm 5.8 \text{ (syst)}] \times 10^{-6}$$

- Fiducial LbyL cross section derived from R and QED e$^+e^-$ X-section from STARLIGHT = 4.82 ± 0.15 (th) mb
  $$\sigma_{\text{fid}} (\gamma\gamma \rightarrow \gamma\gamma) = 120 \pm 46 \text{ (stat)} \pm 28 \text{ (syst)} \pm 4 \text{ (th)} \text{ nb},$$
  consistent with SM prediction: $\sigma(\text{fid}) = 138 \pm 14 \text{ nb}$.

- Compatibility of the data with background-only hypothesis, via profile-likelihood ratio of acoplanarity distribution:
  LbyL significance: 4.1σ observed (4.4σ expected).

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arXiv: 1810.04602
The measured diphoton invariant mass distribution used to search for pseudoscalar axion-like particles $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$

- ALP samples for masses: 5-90 GeV, generated from STARLIGHT
- No significant ALP excess observed in data above LbL+ backgrounds
- 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 statistics).
Search for axion-like particles

- Limits in cross-section $\rightarrow$ limits in $g_{a\gamma}$ vs. $m_a$ plane
- ALPS coupling only to photons (left plot)
  - Best exclusion limits so far over the $m_a = 5$–$50$ GeV
- ALPS coupling to photons or hypercharge (right plot)
  - New constraints in the $m_a = 5$–$10$ GeV.

ArXiv: 1810.04602
Summary

- Evidence for light by light scattering, 4.1 (4.4)σ observed (expected)
- 14 light-by-light events observed - consistent with the SM predictions,
- No significant excess observed
- Competitive exclusion limits on axion-like particles

Analysis ongoing with four times more luminosity with 2018 PbPb data.
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Stay tuned!