Axion results from the LHC, including future prospects

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Introduction to Axion Like Particles (ALPs)

- Axions have been postulated in 1977 to solve the strong CP problem
- Very light (pseudo)scalars particles
  - If no dependence between mass and coupling → ALPs!
- ALPs are pseudo Nambu-Goldstone bosons associated to Spontaneous Symmetry Breaking

- Several motivations to search for ALPs:
  - Could be valid DM candidate, or DM mediator
  - Could explain g-2 discrepancies

- ALPs can couple to different sectors of the SM
  - Different kind of searches at colliders!
Overview of LHC results

- $pp \rightarrow pp\gamma\gamma$
- $pp \rightarrow a \rightarrow \gamma\gamma$
- $PbPb \rightarrow a \rightarrow \gamma\gamma$
- $H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$
- $pp \rightarrow pp\gamma\gamma$
- $pp \rightarrow a \rightarrow \gamma\gamma$
Goal: search for forward proton scattering with light-by-light scattering

Dataset: 2017 data, with $\mathcal{L} = 14.6$ fb$^{-1}$ and $\sqrt{s} = 13$ TeV

Tag forward protons (with AFP) while detecting pair of photons in the central detector

Target mass range: $150 < m_a < 1600$ GeV

Three possible interactions: exclusive, single (SD) and double dissociative (DD)

Diphoton trigger: two EM clusters with $E_T > 25.35$ GeV

Tight selection requirements:

- $E_T > 22$ GeV, $|\eta| < 2.37$
- $p_T > 40$ GeV
- $|\Delta \xi| = |\xi_{\text{AFP}} - \xi_{\gamma\gamma}| < 0.004 + 0.1 \xi_{\gamma\gamma}$, where $\xi = 1 - E_{\text{scattered}}/E_{\text{beam}}$

Signal modeling with DSCB fitting MADGRAPH simulations

Main background: pair of photons (or misidentified jet) in the same bunch crossing
$pp \rightarrow pp\gamma\gamma$

- Unbinned maximum-likelihood fit it to $m_{\gamma\gamma}$
- Fit procedure dominated by statistical uncertainty
- Systematic uncertainties are included as nuisance parameters
- 441 events are found in the [150,1600] GeV range
- Local $p$-value evaluation shows an excess at $m_{\gamma\gamma} = 454$ GeV

- Upper limits computed at 95% CL assuming a 100% BR to photons
- No signal is observed and data are compatible with SM
\[ pp \rightarrow a \rightarrow \gamma\gamma \]

- Goal: search for boosted diphoton resonances, with \( 10 < m_{\gamma\gamma} < 70 \text{ GeV} \)
- Dataset: Run 2 data, with \( \mathcal{L} = 138 \text{ fb}^{-1} \) and \( \sqrt{s} = 13 \text{ TeV} \)
- Boosted topology \( \rightarrow \) allows for search to lower masses

- Tight selection requirements for photons:
  - \( E_T > 22 \text{ GeV}, |\eta| < 2.37 \)
  - Shape of EM showers and leakage in HCAL
  - Photons are isolated
  - \( p_T^{\gamma\gamma} > 50 \text{ GeV} \)

- Signal modeling with DSCB fitting MADGRAPH simulations
- Background components: \( \gamma\gamma, \gamma + j \) and \( jj \)
- Data-driven technique to model backgrounds with analytic functions
  - Main uncertainty: limited size of simulated samples
pp → a → γγ

- Evaluation of $\sigma \cdot \mathcal{B}(a \rightarrow \gamma\gamma)$ in fiducial region
  $\rightarrow \sigma_{\text{fid}} \cdot \mathcal{B}(a \rightarrow \gamma\gamma) = \frac{N}{C \cdot \mathcal{L}}$
- $N$ extracted with a binned maximum-likelihood fit to $m_{\gamma\gamma}$
- Systematic uncertainties are included as nuisance parameters
  - Highest uncertainty comes from background modelling
  - No significant deviations from SM predictions are found

- Limits on $\sigma_{\text{fid}} \cdot \mathcal{B}(a \rightarrow \gamma\gamma)$ are recast in the parameter space of ALP
- Upper limit on $\sigma_{\text{fid}} \cdot \mathcal{B}(a \rightarrow \gamma\gamma)$ results in a lower limit on $f_a$
- Large portion of ALP parameter space is covered
**PbPb $\rightarrow a \rightarrow \gamma\gamma$**

- Equivalent photon flux scales with $Z^4$
  - Pb beams optimal source of high energy photons
- Goal: measure light-by-light scattering based on PbPb collisions
- Dataset: Run 2 data, with $\mathcal{L} = 2.2$ nb$^{-1}$ and $\sqrt{s_{\text{NN}}} = 5.02$ TeV
- Target mass range: $6 < m_a < 100$ GeV

- Requiring exactly two photons with:
  - $E_T > 2$ GeV, $|\eta| < 2.37$
  - $m_{\gamma\gamma} > 5$ GeV, $p_T^{\gamma\gamma} < 1$ GeV
- Veto on charged-particle tracks

- Main backgrounds: $\gamma\gamma \rightarrow ee$ and CEP $\gamma\gamma$
  - Data-driven estimation with control regions
**PbPb → a → γγ**

- Differential cross section as a function of $m_{γγ}$, $|y_{γγ}|$, $(p_T^{γ1} + p_T^{γ2})/2$ and $|\cos(θ^*)|$
- Cross-section extracted as $σ_{fid} = (N_{data} - N_{bckg})/(C \cdot ℳ)$

- Measurement limited by statistical uncertainty in all kinematic regions
- No signal events are observed
- Cross-section limits are interpreted as limits on the ALP couplings, assuming a 100% BR decay into photons
PbPb $\rightarrow a \rightarrow \gamma\gamma$

- Similar study similar to the one performed by ATLAS
- Goal: measure light-by-light scattering based on PbPb collisions
- Dataset: Run 2 data, with $\mathcal{L} = 2.2$ fb$^{-1}$ and $\sqrt{s_{NN}} =$ 5.02 TeV
- Same selection requirements and analysis procedure as ATLAS

- Cross-section limits interpreted as limits on ALPs couplings:
  - ALPs coupling only to photons
  - ALPs coupling also to $Z$

**$H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$**

- **Goal:** search for exotic Higgs decay to a pair of light pseudoscalars
- **Dataset:** Run 2 data, with $\mathcal{L} = 132$ fb$^{-1}$ and $\sqrt{s} = 13$ TeV
- **Identify 4 high-energetic and well-isolated photons**

- Quite standard selections for at least 4 photons:
  - $|\eta| < 2.37$ for all photons
  - $p_T > 30$ GeV ($p_T > 18$ GeV) for (sub)leading photon, $p_T > 15$ GeV for remaining photons
  - Electron veto
  - $110 < m_{\gamma\gamma\gamma\gamma} < 180$ GeV
  - 4-photon classifier (BDT) to distinguish signal versus background

- Background estimation using data-driven method through “event mixing”
$H \rightarrow aa \rightarrow \gamma\gamma\gamma$

- Simultaneous unbinned maximum-likelihood fit of $m_{\gamma\gamma}$ in all analysis categories
- No deviation from SM expectation is found

- Upper limits at 95% CL
- Pseudoscalar bosons ranging in mass in [15, 62] GeV range
**Goal:** search for forward proton scattering with light-by-light scattering

**Dataset:** 2016 data, with $\mathcal{L} = 9.4$ fb$^{-1}$ and $\sqrt{s} = 13$ TeV, CMS+TOTEM

**Target mass range:** $m_{\gamma\gamma} > 350$ GeV

**Selection requirements:**
- $p_T^\gamma > 75$ GeV, $|\eta^\gamma| < 2.5$
- Cut on cluster shape to ensure isolation ($R_\gamma$ variable)
- Cuts on $\bar{\xi}_{\gamma\gamma}$, $\xi_{\gamma\gamma}$

**Background contributions:**
- Inclusive $\gamma\gamma$
- $\gamma$+jet, $\gamma + Z, \gamma + W$
- Tighter requirements keep only inclusive $\gamma\gamma$
$pp \rightarrow pp\gamma\gamma$

- Limits on cross-section are used to probe 4-photon anomalous quartic gauge couplings

$$L^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\mu\rho} F^{\nu\sigma} F_{\rho\sigma}$$

- This analysis provided the first limit for the SM for light-by-light production cross-section at high energies
**pp → a → γγ**

- Currently, light ALPs are not reachable by ATLAS and CMS → LHCb can go to lower masses!
- Dedicated trigger lines (B_s → γγ) to select low-energy photons
- Limits extraction using 80 pb⁻¹ of LHCb public data

<table>
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<tr>
<th>Variable</th>
<th>0CV</th>
<th>1CV LL</th>
<th>1CV DD</th>
<th>2CV</th>
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</thead>
<tbody>
<tr>
<td>Calo γ CL</td>
<td>&gt; 0.3</td>
<td>&gt; 0.3</td>
<td>&gt; 0.3</td>
<td>–</td>
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<tr>
<td>Calo γ p [GeV/c]</td>
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<td>&gt; 6</td>
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<tr>
<td>Calo γ E_T [GeV]</td>
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<td>&gt; 3</td>
<td>&gt; 3</td>
<td>–</td>
</tr>
<tr>
<td>Converted γ p_T [GeV/c]</td>
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<tr>
<td>Converted γ M [MeV/c²]</td>
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<tr>
<td>Converted γ χ²_T</td>
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<td>&gt; 0</td>
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<tr>
<td>∑ p_T,γ [GeV]</td>
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<td>&gt; 5.5</td>
<td>&gt; 5.5</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>B_p p_T [GeV/c]</td>
<td>&gt; 3.0</td>
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<td>B_p χ²旭</td>
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<tr>
<td>M_p [GeV/c²]</td>
<td>[4.3,6.3]</td>
<td>[4.3,6.3]</td>
<td>[4.3,6.3]</td>
<td>[4.5,6.1]</td>
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<td>Fraction of signal</td>
<td>83.4%</td>
<td>4.3%</td>
<td>11.7%</td>
<td>0.6%</td>
</tr>
</tbody>
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- Experimental analysis currently ongoing
  - Analysing data from 2018, using ∆L = 2.07 fb⁻¹
  - Currently relying only on unconverted photons
Future prospects

- ALPs searches are generally limited by statistics
- Therefore, simply acquiring more data will help
- Also, different channels where different experiments can pose more stringent limits
- Last but not least, improving performance of analysis using advanced Machine Learning algorithms
Conclusions

• In recent years, ALPs have been studied quite precisely and extensively
  • Different mass scales
  • Different signatures probing different couplings to SM (gluons, Higgs, photons,...)
• Results so far do not show signatures of ALPs

• In the next years, we definitely expect more and more interesting results to come
Thank you for your attention