Searching for Axion-like particles with heavy-ions

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PhysRevLett.118.171801
New Physics @LHC

- Must leave no stone unturned!
- There may be many surprises!
  - 750 GeV (false alarm)

- Can we be missing cousins of 750 GeV?
- Yes:
  - What is resonance is lighter?
  - Axion-like particle $\sim aF\tilde{F}$
Axion-like Particle

- Only couple to EM

\[ \mathcal{L}_a = \frac{1}{2} (\partial a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{a}{4\Lambda} F \tilde{F} \]

- Decay rate

\[ \Gamma_{a \rightarrow \gamma\gamma} = \frac{1}{64\pi} \frac{m_a^3}{\Lambda^2} \]

- Heavy ALPs mainly constrained by colliders

- UV completion straightforward (750 GeV literature)

J. Jaeckel et al. 1509.00476
Heavy-ion as a $\gamma$ source

- **Old idea** A. Balantekin et.al. 1985, M. Greiner et.al. 1993...
- **Enhanced production at** Heavy-ion collisions (~GeV)
- **QED is strongly coupled!**
- $Z^4 \sim 50 \times 10^6$ enhancement

**Can observe LBL scattering**

D. d’Enterria et.al. 1305.7142

![Diagram of Pb collisions](image)

**ATLAS 1702.01625***
Ultra-Peripheral Collisions

- Grazing collision, ion does NOT breakup
- ALPs are created in the strong EM field of the ions (photons almost on-shell)
- Luminosity $\sim$ classical formula (lead flashlight)
- Coherence requires photon wavelength $\gtrsim$ Pb radius / boost
- $2E_\gamma < 170$ GeV $\left(\frac{7 \text{ fm}}{R}\right) \left(\frac{\sqrt{s_{NN}}}{5.5 \text{ TeV}}\right)$
Photon Luminosity

- Photon-photon luminosity:
  \[ \mathcal{L}_{\gamma\gamma} = \frac{1}{\hat{s}} \int \, d\vec{b}_{1,2} \, dE_{1,2} \, N_1 \, N_2 \]
  \[ \times \, \delta(\hat{s} - 4E_1 E_2) \, P \]
- \( N_{1,2} = \) flux from Pb
- \( P = \) probability that no breakup occurs
- \( N_{1,2} \sim \) charge form factor
- Low energy \( \sim \frac{2\alpha Z^2}{\pi} \log \frac{E_{\max}}{E_\gamma} \)
- \( P \sim \theta(b_2 - 2R) \)
- Requires nuclear physics to get all factors correct
<table>
<thead>
<tr>
<th></th>
<th>p-p Collisions</th>
<th>Pb-Pb Collisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>~ 1000 fb⁻¹</td>
<td>~ 10⁻⁶ fb⁻¹ (1 nb⁻¹)</td>
</tr>
<tr>
<td>(Z^4) Enhancement</td>
<td>None</td>
<td>~ 5 \times 10⁷</td>
</tr>
<tr>
<td>Max (\gamma) Energy</td>
<td>~ 1 TeV (elastic)</td>
<td>~ 170 GeV</td>
</tr>
<tr>
<td>Background</td>
<td>Large pile-up background</td>
<td>Clean exclusive events</td>
</tr>
<tr>
<td>Regions of sensitivity</td>
<td>(m_a \sim 100) GeV</td>
<td>(m_a \sim 10) GeV</td>
</tr>
</tbody>
</table>
**Signal**
- Intact Pb-Pb ions, no tracks, very little calorimeter activity
- Veto on tracks
- Two ~GeV back to back photons (cut on $\Delta \phi_{\gamma\gamma}$)
- Intact ions may be tagged
- Prominent mass peak!

**Background**
- LBL scattering
  - Irreducible
  - Has been measured! Can be calculated reliably
- Electrons fakes/brem and CEP (photons from QCD)
  - Photons not back to back
- All background smoothly falling in $m_{\gamma\gamma}$!
Search Strategy

Signal Selection

- Veto tracks with \( p_T > 1 \text{ GeV}, |\eta| < 2.5 \)
- Two photons \( p_T > 2 \text{ GeV}, |\eta| < 2.5 \)
- \( |\Delta \phi_{\gamma\gamma} - \pi| < 0.04 \)
- Efficiency \( \sim 70\% \) low mass to \( \sim 90\% \) at high mass
- Signal MC implemented in Starlight
  (w/ help from S. Klein)
- Background:
  - Analytic approx. for \( \gamma\gamma \)-lumi
  - ME done analytically / Madgaph5

Integrated lumi \( \sim 1 \text{ nb} \) eventually
Results

- Collider searches dominated by associated production
  - $p + p \rightarrow \gamma^* \rightarrow a + \gamma$
  - LEP/CMS/ATLAS comparable
- Photon fusion sub-dominant
- 8 TeV re-cast (13 TeV high lumi results will be stronger)
Results

- Introduces $aZ\gamma$ coupling
  - $p + p \rightarrow \gamma/Z^* \rightarrow a + \gamma/Z$
  - On-shell $Z \rightarrow a + \gamma$
- Heavy-ion limits comparable to 8 TeV results
- High-Luminosity LHC will likely yield stronger limits
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ \int L dt = 480 \mu \text{b}^{-1} \]

Current best limit on ALPs with EM coupling!
Future Directions?

**New decay channel?**
- $b\bar{b}/\tau\tau$ decay for light scalar mixing with higgs?
- Invisible decay? Can we measure the outgoing beam?
- Exotic decay into hidden sector? e.g. long-lived particles?

**New production?**
- New kinds of coherent enhancement (baryon number)?
- Lighter ALPs? (pair production and off-shell rates are too small)
- Changes in inclusive elastic cross-sections?
Backup Slides
$p_T$ distribution

- $p_T \sim$ virtuality of the photon
- Correction beyond equivalent photon approximation

- ALPs: $p_T \sim 1/R \sim 60$ MeV
- CEP: $p_T \sim \Lambda \sim$ GeV
  - p-p collisions shown
  - Pb-Pb requires convolution with breakup factor
Form Factors Effects

M. Klusek-Gawenda et.al.
1601.07001