Search for Axion-Like Particles produced in $e^+e^-$ collisions at the Belle II experiment.

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SuperKEKB and Belle II.
SuperKEKB

- **Asymmetric e^+e^- collider**
  @ Υ(4S) energy = 10.58 GeV
- **Second-generation B factory**
  (optimized to produce a lot of B mesons)
- **50 times** increase in luminosity
  with respect to predecessor KEKB: ~50 ab^{-1}
  - Up to now: ~90 fb^{-1} = ~0.09 ab^{-1}
  - For this analysis: 445 pb^{-1} = 0.000445 ab^{-1}
    (early 2018 data only)
• **Hermetic detector** (90% of solid angle)
• **Dedicated triggers for low multiplicity**
• **Clean environment** (e⁺e⁻ collider)
Axion-Like Particles.
Physical process

- Axions: proposal to solve strong CP problem
- Axion-like particles (\(a\), ALPs): \(~\)axions, but no mass-coupling constraint
  Massive, neutral, pseudoscalar
- Possible portals to Dark Sector

\(e^+\) \(\rightarrow\) \(e^-\) \(\gamma\) \(\rightarrow\) \(a\) \(\gamma\) \(\gamma^*\) \(\rightarrow\) \(\gamma\) \(\gamma\)

\textit{Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, JHEP 1712 (2017) 094}

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Physical process

**Signal**: $e^+e^- \rightarrow \gamma a, a \rightarrow \gamma \gamma$
- 3-\gamma final state
- No tracks
- No missing energy

**Main backgrounds**:
- $e^+e^- \rightarrow \gamma \gamma (\gamma)$
- $e^+e^- \rightarrow e^+e^- (\gamma)$
  (if we don’t reconstruct the tracks)
- $e^+e^- \rightarrow \pi^0/\eta/\eta'$\gamma
  negligible peaking backgrounds

- **Peak hunt** throughout the kinematically-allowed mass spectrum
- Scan mass range $m_a \in [0.2, 9.7]$ GeV/c$^2$
- **1D fit** of signal peak over smooth background
Previous status of searches

[Graph showing the search for Axion-Like Particles produced in $e^+e^-$ collisions at the Belle II experiment.]

$g_{a\gamma\gamma}$ $[\text{GeV}^{-1}]$

$g_{a\gamma Z} = 0$

$m_a \ [\text{GeV}/c^2]$

Previous status of searches
Selection performances

- Background rate
- Signal efficiency

**Belle II simulation**

\[ \int L \, dt = 497 \, \text{pb}^{-1} \]

- Diphon signal \( \varepsilon \)
- Recoil signal \( \varepsilon \)
- Diphon bkg events
- Recoil bkg events
Signal & background modeling

- **Signal:**
  - **Peaking** component: modeled with a **Crystal Ball** (CB):
    fit each MC sample
    interpolate parameters **fixed** for the final fit
  - **Combinatorial** component:
    modeled with a **Kernel Density Estimator** (KDE)
    fixed for the final fit

- **Background:**
  - Modeled with a **polynomial**
  - Choice of **polynomial order** and **fit range**:
    reduced $\chi^2$ and smoothness criteria
  - Polynomial parameters are **floating** for the final fit
Data/MC comparison

Great agreement already in 2018 (data taking for calibration & tuning purposes)

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10.1103/PhysRevLett.125.161806
Upper Limit (UL) extraction

- Binned NLL approach, CLs method
- Allow only positive signal yields, i.e. cross section $\sigma_{a\gamma\gamma} \geq 0$
- ALP mass scan in steps of 0.5 $\sigma_{CB}$ to search for signal peaks
- If no global significance $> 3$ is found (with systematics): we set limits
  - No local significance $> 3$ has been found
Systematic uncertainties

**Systematic** uncertainties are **small wrt statistical** uncertainties.

Systematics are from:

- **Choice of background polynomial order & fit range** (least irrelevant):
  - Modify order and range and re-perform UL extraction, take the weakest limit (highest UL $\iff$ lowest significance)

- **Signal efficiency**
- **Signal resolution**
  from photon resolution studies

10.1103/PhysRevLett.125.161806
Results

Max local significance:

$2.8 \sigma @ m_a = 0.477 \text{ GeV/c}^2$

10.1103/PhysRevLett.125.161806
Results

![Graph showing 95% CL upper limit on $\sigma(e^+ e^- \rightarrow y\alpha)$](image)

**Belle II** (2018)

$\int L dt = 445 \text{ pb}^{-1}$

10.1103/PhysRevLett.125.161806
Results

$g_{a\gamma} [\text{GeV}^{-1}]$

$g_{a\gamma} = 0$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-5}$

$m_a [\text{GeV}/c^2]$

10^{-3} 10^{-2} 10^{-1} 10^0 10^1

NA64

proton beam dumps

ee$\rightarrow$γ + inv.

electron beam dumps

Belle II

10.1103/PhysRevLett.125.161806
Summary
Summary

• **Search** for the direct production of a light pseudoscalar **ALP** $a$ decaying into two photons
  
  • $e^+e^- \rightarrow \gamma a, a \rightarrow \gamma\gamma$
  
  • $m_a \in [0.2, 9.7]$ GeV/c$^2$

• **No evidence for ALPs**

• Set 95% CL UL on $g_{a\gamma\gamma}$
  
  • These are the strongest limits to date for $m_a \in [0.2, 1]$ GeV/c$^2$
  
  • Prospects: ~20 stronger limits with full Belle II data set

• Results published in **PRL**: 10.1103/PhysRevLett.125.161806
Backup.
Selection variables

Cuts are listed in the order they are applied

- $E_\gamma \geq 650 \text{ MeV}$ if $m_a \geq 4.0 \text{ GeV/c}^2$
- $E_\gamma \geq 1000 \text{ MeV}$ if $m_a < 4.0 \text{ GeV/c}^2$
- $37.3^\circ \leq \theta_\gamma \leq 123.7^\circ$ (barrel acceptance)
- $\text{clusterNHits} > 1.5$
- 3 most energetic $\gamma$
- $0.88 \sqrt{s} \leq m_{\gamma\gamma\gamma} \leq 1.03 \sqrt{s}$
  $(9.31\text{ GeV/c}^2 \leq m_{\gamma\gamma\gamma} \leq 10.90\text{ GeV/c}^2)$
- $\text{TimeVar}^* < 10$
- 0 good tracks
- $\Delta \theta \geq 0.014 \text{ rad OR } \Delta \phi \geq 0.4 \text{ rad}$
- $\text{clusterZernikeMVA}$ of most isolated photon $> 0.6$

*) $\text{TimeVar} = \left| \left( t - \sum \left( \frac{t}{\Delta t^2} \right) / \left( \sum \left( \frac{1}{\Delta t^2} \right) \right) \right) / \Delta t \right|$
ALPs - theory

\[ s^{1/2} = 10.58 \text{ GeV}, \ g_{\gamma\gamma} = 10^{-4} \text{ GeV}^{-1} \]

Photon-fusion

\[ e^+ \quad e^- \quad \gamma \quad e^+ \quad e^- \quad \gamma \]

ALP-strahlung

\[ e^+ \quad \gamma^* \quad a \quad \gamma \quad \gamma \]


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ALPs - analysis

Two of the photons overlap or **merge**

ALP decays outside of the detector or decays into **invisible** particles: single photon final state

**Current focus**

Three **resolved**, high energetic photons


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Selection variables

Selection optimization via maximization of Punzi Figure of Merit (PFM)

- PFM as function of 1 variable
  - Other variables fixed
- Vary cut on that variable
- For multiple ALP masses
- Repeat for all variables

\[ PFM = \frac{\epsilon s}{\frac{a}{2} + \sqrt{B}} \]

Signal efficiency

\# bkg candidates passing the cuts

Number of sigmas corresponding to one-sided Gaussian tests at a given significance (a=5)
Signal peaking

- $m_a = 0.5 \text{ GeV/c}^2$
- $m_a = 3.0 \text{ GeV/c}^2$
- $m_a = 5.0 \text{ GeV/c}^2$
- $m_a = 9.2 \text{ GeV/c}^2$

Squared diphoton mass
Squared recoil mass
Background modeling

Choice of polynomial order & fit range with reduced $\chi^2$ and smoothness criteria

- $m_a \in [0.2, 0.5] \text{ GeV}/c^2 \implies$ 2nd order, fit range $[m_a^2 - 20 \cdot \sigma_{CB}, m_a^2 + 30 \cdot \sigma_{CB}]$
- $m_a \in [0.5, 6.85^*] \text{ GeV}/c^2 \implies$ 4th order, fit range $[m_a^2 - 20 \cdot \sigma_{CB}, m_a^2 + 30 \cdot \sigma_{CB}]$
- $m_a \in [6.85^*, 9.7] \text{ GeV}/c^2 \implies$ 5th order, fit range $[m_a^2 - 25 \cdot \sigma_{CB}, m_a^2 + 25 \cdot \sigma_{CB}]$