Search for Dark Particles at Belle (II)

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for the Belle/Belle II Collaborations

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Dark Sector connections
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Dark gauge bosons / Introduction

Dark gauge bosons, or dark photons, $A' = \gamma' = A = U$, have been searched since the late 80s and are postulated to have:

- Very small couplings to Standard Model particles
- Low mass: of order MeV to GeV

Recent interest in dark sector models (Unified DM) that:

- Explain observed anomalies
- Often introduce, in addition, a dark Higgs boson, $h'$, by a Higgs mechanism

Plot above shows astrophysical and cosmological constraints and experimental limits:
kinetic mixing ($\chi = \epsilon$) vs. $A'$ boson mass J. Jaeckel and A. Ringwald - arXiv:1002.0329v1

$\Rightarrow$ BaBar, Belle, and Belle II can cover region between a few MeV/$c^2$ and 10 GeV/$c^2$
KEKB and SuperKEKB

KEKB/SuperKEKB collider, located in Japan, Tsukuba, is the world's highest-luminosity electron-position collider

- 1999-2010: Belle collected $\mathcal{L}_{int} = 1050 \, fb^{-1}$ at $\Upsilon(1S, 2S, 3S, 4S, 5S)$ and continuum
- 2016-2026: Belle II (upgrade version of Belle) expects to collect $\mathcal{L}_{int} = 50 \, ab^{-1}$

Belle II $\mathcal{L}_{peak} = 8 \times 10^{35} \, cm^{-2} s^{-1}$
Belle and Belle II experiments

CP violation measurement in the B-meson system with Belle and BaBar, established the Kobayashi Maskawa mechanism as a valid description of CP violation in the Standard Model.

- Main motivations
  - Study of CP violation (i.e. matter-antimatter asymmetry)
  - Study of heavy flavor
  - Search for physics beyond the Standard Model

- Complementary to efforts at energy frontier

Belle II is an upgrade of Belle

Add PID in endcaps
Add $\mu$ ID in endcaps
Increase $K_S$ efficiency
Improve IP and secondary vertex resolution
Improve $\pi/K$ separation
Improve $\pi^0$ efficiency
Search for the dark photon and the dark Higgs boson

Presented today, new Belle limits (freshly accepted in PRL, arxiv:1502:00084). Production in the so-called Higgs-strahlung channels, $e^+e^- \rightarrow A'h'$, with $h' \rightarrow A'A'$.

- $A'$ and $h'$ assuming prompt decays
- $m_{h'} > 2m_{A'}$
- $0.1 < m_{A'} < 3.5 \text{ GeV}/c^2$ and $0.2 < m_{h'} < 10.5 \text{ GeV}/c^2$

$\alpha_D$: dark sector constant
$\varepsilon$: kinetic mixing

- 10 exclusive channels: $3(l^+l^-), 2(l^+l^-)(\pi^+\pi^-), 2(\pi^+\pi^-)(l^+l^-)$, and $3(\pi^+\pi^-)$, where $l^+l^-$ is an electron or muon pair
- 3 inclusive channels for $m_{A'} > 1.1 \text{ GeV}/c^2$: $2(l^+l^-)X$, where $X$ is a dark photon candidate detected via missing mass

If $\alpha_D = 1$, Higgs-strahlung channels most sensitive to $A'$
Event selection / Belle results

Reconstruction of exclusive(inclusive) lepton/hadron final states from $e^+e^- \rightarrow A'h' \rightarrow A'A'$

- 3(at least 2) lepton/hadron pairs of opposite charge
- Impact parameters and $\chi^2$ vertex fit cuts
- Require energy conservation
- Calculate invariant mass for each combination of leptons/hadrons consistent with three(two) distinct $A' \rightarrow l^+l^-$/hadrons
- Keep combinations with three masses “equal”
- Plots below show signal Monte Carlo simulation events surviving selection with $m_{h'} = 5$ GeV/$c^2$ and $m_{A'} = 2.19$ GeV/$c^2$

$\Rightarrow$ 20 % detection efficiency on average for all channels
Background estimation method / Belle results

- Estimate background using "same sign" events $e^+e^- \rightarrow (l^+l^+)(l^+l^-)(l^-l^-)$
- Order masses of lepton(hadron) pairs $m_1^{ll} > m_2^{ll} > m_3^{ll}$ and plot $m_1^{ll} - m_3^{ll}$ vs. $m_1^{ll}$
- Select region in $m_1^{ll}$ and predict background there using same sign
- Sideband used to normalize same sign to opposite sign
- Background estimated from the number of counts in the signal regions of the same sign distributions

$m_1^{\pi\pi} - m_3^{\pi\pi}$ vs. $m_1^{\pi\pi}$ for $6\pi$

Projection on $m_1^{\pi\pi} - m_3^{\pi\pi}$ for $m_1^{\pi} = 2$ GeV/$c^2$

Expected background estimated by a data driven method
Number of events observed / Belle results

- 18.5% of events due to $3(\pi^+\pi^-)$
- 73.5% of events due to $2(l^+l^-)X$, where $X$ is a dark photon candidate detected via missing mass

Left: 10 exclusive channels: $3(l^+l^-)$, $2(l^+l^-)(\pi^+\pi^-)$, $2(\pi^+\pi^-)(l^+l^-)$, and $3(\pi^+\pi^-)$, where $l^+l^-$ is an electron or muon pair. Right: 3 inclusive channels for $m_{A'} > 1.1$ GeV/$c^2$: $2(l^+l^-)X$
Number of events observed / Belle results

Comparison between predicted background and number of events observed

- Number of events observed after all selection criteria are applied

- Background: Standard Model $2\gamma$ processes with $\rho$'s or $\omega$'s in the final state
- Discontinuity at 1.1 GeV/$c^2$ due to $2(l^+l^-)X$

Events measured consistent with background estimation
Belle limits / new results

- Belle limits for $\mathcal{L} = 977 \text{ fb}^{-1}$ on $\mathcal{B} \times \sigma_{\text{Born}}$ and $\sigma_{\text{Born}}$
  
  90% CL upper limit for each of the 13 final states
  
  90% CL upper limit on the combined Born cross section

Belle limits for $A'$ use of Markov Chain Monte Carlo

90% Credibility Level (CL) upper limit determined by Bayesian inference method with the use of Markov Chain Monte Carlo $A'$. Caldwell et al., CPC 180 (2009) 2197-2209

Limits from $3(\pi^+\pi^-)$ and $2(e^+e^-)X$ are the first placed by any experiment

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Limits on the product of $\alpha_D \varepsilon^2$ / new results

Belle combined limits compared to BaBar combined limits

- Belle limits for $\mathcal{L} = 977$ fb$^{-1}$ based on the Born cross section, ISR effect non negligible
- BaBar limits for $\mathcal{L} = 520$ fb$^{-1}$ based on the visible cross section PRL 108 211801 (2012)

<table>
<thead>
<tr>
<th>$m_A^2$ [GeV$/h'm^2$]</th>
<th>$m_{h'}^2$ [GeV$/h'm^2$]</th>
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<tbody>
<tr>
<td>$m_A^2 = 0.3$ GeV$/h'm^2$</td>
<td>$m_{h'}^2 = 1$ GeV$/h'm^2$</td>
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<tr>
<td>$m_A^2 = 0.5$ GeV$/h'm^2$</td>
<td>$m_{h'}^2 = 3$ GeV$/h'm^2$</td>
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<td>$m_A^2 = 1.0$ GeV$/h'm^2$</td>
<td>$m_{h'}^2 = 5$ GeV$/h'm^2$</td>
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<td>$m_A^2 = 1.5$ GeV$/h'm^2$</td>
<td>$m_{h'}^2 = 7$ GeV$/h'm^2$</td>
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<tr>
<td>$m_A^2 = 3.0$ GeV$/h'm^2$</td>
<td>$m_{h'}^2 = 9$ GeV$/h'm^2$</td>
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</table>

90% CL upper limit on the product $\alpha_D \times \varepsilon^2$ versus dark photon mass (top row) and dark Higgs boson mass (bottom row)

- Assuming branching fractions and couplings versus cross section from B. Batell et al. PRD 79 (2009) 115008

Results scale nearly linearly with integrated luminosity. This bodes well for future searches with Belle II.
Belle II prospects for the Higgs-strahlung channels

Predicted Belle II upper limits $U_{\alpha_D \epsilon^2}$ in the $\alpha_D \epsilon^2$ vs $m_{A'}$ vs $m_{h'}$ plane by scaling the Belle limits linearly with the integrated luminosity:

$$\frac{U_{\alpha_D \epsilon^2}}{U^0_{\alpha_D \epsilon^2}} = \frac{\mathcal{L}^0}{\mathcal{L}},$$

where the superscript 0 corresponds to Belle values. $\mathcal{L}$ is integrated luminosity. The scaling uses both statistical and systematic uncertainties.

![Graphs showing Belle II upper limits for different mass values.](image-url)
Belle (II) prospect for the radiative decays

Predicted Belle II upper limits extrapolated from BaBar [PRL 113, 201801 (2014)] (C. Hearty, B2TIP2014)

1. $e^+e^- \to \gamma A', A' \to l^+l^-$, with $l = e$ or $\mu$
2. Require an improved low multiplicity trigger in Belle II

Left: Belle II prediction. Right: preliminary Belle and Belle II preliminary detection efficiency for $A' \to \mu^+\mu^-$

Belle preliminary detector efficiency for $A' \to \mu^+\mu^-$ competitive compared to BaBar
Belle (II) prospect for the radiative decays

Predicted Belle II upper limits extrapolated from BaBar [PRL 113, 201801 (2014)] (C. Hearty, B2TIP2014)

- $e^+e^- \rightarrow \gamma A', A' \rightarrow l^+l^-$, with $l = e$ or $\mu$
- Eg Belle II dimuon invariant mass resolution improved by $\sim 35\%$ compared to Belle

\[ m_{A'} (\text{GeV}) = \begin{cases} 4.9, & \text{count [a.u.]} \\ 4.95, & 1 \\ 5, & 0.5 \\ 5.05, & 0 \\ \end{cases} \]

Belle II prediction. Right: simulation for $m_{A'} = 5.015 \text{ GeV}/c^2$

Complementary to fixed target experiments

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Belle (II) prospect for the radiative decays

Predicted Belle II upper limits extrapolated from BaBar arxiv:0808.0017 (C. Hearty, B2TIP2014)

- $e^+e^- \rightarrow \gamma A', A' \rightarrow \chi\chi$, $\chi$ light dark matter R. Essig et al. arXiv:1309.5084
- Require implementation of a single photon trigger in Belle II

Left: Belle II prediction. Right: Simulated mono-energetic photon signature for $m_{A'} = 6 \text{ GeV}/c^2$

Belle II could search for light dark matter
Conclusion

- New Belle limits for prompt decays of the dark photon and the dark Higgs boson:
  - $0.1 < m_{A'} < 3.5 \text{ GeV}/c^2$
  - $0.2 < m_{h'} < 10.5 \text{ GeV}/c^2$
  - We found that:
    - No significant excess over the background estimation
    - Belle limit improvement scales nearly linearly with integrated luminosity

- Belle II will search for dark photon, dark Higgs boson, and dark light matter
- With 50 $ab^{-1}$, Belle II might potentially also cross-check any signals discovered by fixed target experiments

![Efficiency map for $A' \rightarrow \mu^+\mu^-$](image)

Preliminary Belle detection efficiency vs. vertex position and dark photon mass of $e^+e^- \rightarrow \gamma A', A' \rightarrow \mu^+\mu^-$ (I. Gianluca)

Belle (II) can contribute to the dark sector searches for the prompt decay and displaced vertex
Thanks for your attention

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