Dark Sector Searches at Belle II

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Belle II and SuperKEKB
SuperKEKB

- super $B$-factory, located in Tsukuba, Japan
- asymmetric $e^+e^-$ collider ($e^-$ at 7 GeV, $e^+$ at 4 GeV, $\langle \beta y \rangle \approx 0.284$)
- commissioning run from Feb to Jul 2018
- regular operations started in Mar 2019
- operated around 10.58 GeV ($=m_{\Upsilon(4S)}$)
- design luminosity $6 \times 10^{35}$ cm$^2$ s$^{-1}$

→ 30 times higher luminosity

1.5x higher beam currents
20x smaller beam spot
Belle II

- 1102 members and 123 institutes
- 0.5 fb\(^{-1}\) collected during commissioning run in 2018
- 180 fb\(^{-1}\) collected up to now
- plan to collect 50 times more data than Belle
- rich physics program: \(B\) and \(D\) physics, quarkonium, \(\tau\), low mass dark sector, …
Belle II L1 Trigger

- Belle II trigger system consists of two levels
  - low level trigger implemented in hardware (L1)
  - software-based high level trigger (HLT)
- identify and select events over beam backgrounds (Touschek effect, beam-gas scattering)
- L1 trigger
  - maximum average trigger rate of 30kHz
  - 4 sub-detector triggers: CDC, ECL, TOP, KLM
  - trigger menu designed for different physics targets
- dedicated dark sector/low-multiplicity trigger lines
  - single photon trigger
  - single track trigger
  - 3D tracks are reconstructed with a neural network approach
  - combination of full/short/neuro tracks
  - ECL clusters with various energy levels and angular separation

![Graphs showing trigger efficiencies and distributions](image-url)
Dark Sector Searches

- probe light dark sectors with low-mass mediators $O(\text{GeV})$
- possible portals between SM and DM include
  - vector portal (dark photon $A'$, dark $Z'$)
  - pseudo-scalar portal (axion-like particle)
  - scalar portal
  - neutrino portal
- searches at Belle II profit from
  - hermetic detector
  - clean collision environment
  - excellent PID
  - dedicated low-multiplicity triggers (single photon/track trigger)
Search for an **Invisibly Decaying** \( Z' \) Boson at Belle II in \( e^+e^- \rightarrow \mu^+\mu^- (e^+\mu^+) \) Plus Missing Energy Final States

I. Adachi *et al.* (Belle II Collaboration)

**ABSTRACT**

Theories beyond the standard model (SM) suggest new particles that can be detected through specific processes. In the case of an invisible \( Z' \) boson, the process \( e^+e^- \rightarrow e^+\nu_e \gamma, e^-\bar{\nu}_e \gamma \) and \( e^+e^- \rightarrow \mu^+\mu^- \gamma, \mu^-\bar{\nu}_\mu \gamma \) can be used to set limits on the invisible \( Z' \) mass. Using data collected by the Belle II experiment, the first searches for the invisible \( Z' \) boson have been performed, resulting in upper limits on the cross section of the \( Z' \) boson, which is consistent with the SM prediction.

Search for **Axionlike Particles** Produced in \( e^+e^- \) Collisions at Belle II

F. Abudinén *et al.* (Belle II Collaboration)

**ABSTRACT**

We present a search for the direct production of a light pseudoscalar \( a \) decaying into two photons with the Belle II detector at the SuperKEKB collider. We search for the process \( e^+e^- \rightarrow \gamma a, a \rightarrow \gamma \gamma \) in the mass range \( 0.2 \text{ GeV} < m_a < 9.7 \text{ GeV} \) using data corresponding to an integrated luminosity of \( (445 \pm 3) pb^{-1} \). Light pseudoscalars interacting predominantly with standard model gauge bosons (so-called axionlike particles or ALPs) are frequently postulated in extensions of the standard model. We find no evidence for ALPs and set 95% confidence level upper limits on the coupling strength \( g_{a\gamma\gamma} \) of ALPs to photons at the level of \( 10^{-7} \text{ GeV}^{-1} \). The limits are the most restrictive to date for \( 0.2 < m_a < 1 \text{ GeV} \).

→ first physics papers!
Invisible Z’
**Invisible Z’**

- extend SM by adding a $U(1)’$ group
- new massive gauge boson $Z’$ couples only to leptons of 2$^{nd}$ and 3$^{rd}$ generation
- $Z’$ coupled to $L_{\mu}-L_{\tau}$ via $g’$
- focus on invisible $Z’$ decay produced with a pair of muons
- invisible decay channel explored for the first time

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\[ M_{Z’} < 2M_\mu \implies BF[Z' \to \text{invisible}] = 1, \]
\[ 2M_\mu < M_{Z’} < 2M_\tau \implies BF[Z' \to \text{invisible}] \simeq 1/2, \]
\[ M_{Z’} > 2M_\tau \implies BF[Z' \to \text{invisible}] \simeq 1/3. \]

if $M_{Z’} > 2M_\chi$

\[ BF(Z’ \to \chi\bar{\chi}) = 1 \]

\[ \mathcal{L} = \sum_\ell \theta g’ \bar{\ell} \gamma^\mu Z’_\mu \ell \]

★ may serve as mediator between SM and DS  
★ may explain $(g-2)_\mu$  
★ may address anomalies in $b \to s\mu^+\mu^-$
Invisible $Z'$

- reconstruct recoiling mass against $\mu\mu$-pair, require nothing else to be in rest of event
- look for a peak in recoil mass distribution
- main bkgds arise from QED processes:
  - $\mu^+\mu^-(\gamma)$
  - $\tau^+\tau^-(\gamma)$, $\tau\rightarrow\mu\nu\bar{\nu}$
  - $\mu^+\mu^-e^+e^-$

\[ \int Ldt = 276 \text{ pb}^{-1} \]

\[ M_{Z'} \text{ [GeV/c}^2\text{]} \]

\[ (g-2) > 6 \text{ [GeV/c}^2\text{]} \]

\[ \sigma^\text{inv} = 1 \text{ expected UL} \]

\[ \text{Data} \]

\[ \text{Belle II} 2018 \]

\[ \text{PRL 124, 141801 (2020)} \]
Invisible $Z'$

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- main bkgs arise from QED processes:
  $\mu^+\mu^-(\gamma)$
  $\tau^+\tau^-(\gamma)$
  $\tau \rightarrow \mu \nu \nu$
  $\mu^+\mu^-e^+e^-$

\[
\begin{align*}
\sigma_{\mu}^2 \pm \mu (g-2) & = 90\% \text{ CL UL} \\
\sigma_{\mu} & = 1 \text{ (obs.)} \quad \text{expected UL}
\end{align*}
\]
Invisible Z' - LFV

- look for LFV Z' that couples to $e\mu$
- model-independent search with same selection criteria
- included in same publication

\[
\begin{align*}
\text{Belle II} & \quad 2018 \\
\int Ldt & = 276 \text{ pb}^{-1}
\end{align*}
\]

\[
\begin{align*}
\epsilon \sigma (\text{obs.}) & \quad 90\% \text{ CL UL} \\
\epsilon \sigma (\text{expected UL}) &
\end{align*}
\]
ALPs
ALPs

- axion-like particles are pseudoscalar particles that couple to bosons and appear in different extensions to the SM
- coupling and mass of ALPs are taken to be independent
- simplest approach at Belle II is via two photon coupling
  - photon-fusion, high QED background
  - ALP-strahlung, most promising channel

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

\[ \sigma \ [\text{pb}] \]

\[ m_a \ [\text{GeV}] \]

**JHEP 1712 (2017) 094**
• different topologies according to ALP mass and coupling
• search for 3 photons with energies summing up to beam energy and no tracks in event
• look for peak in di-photon and recoil mass
• bkgs:
  ○ $\gamma\gamma$ (dark green region labelled SN 1987a)
  ○ $e^+e^-$ (light green region labelled SN 1987a in Fig. 1).
  ○ $P\gamma$, $P=\pi^0/\eta/\eta'$, $P\rightarrow\gamma\gamma$. 

ALPs

ALPs with masses below neutrino detectors (light green region labelled SN 1987a in Fig. 1). For very light emission, which would reduce the measured neutrino burst below the...
performed search in mass range from 0.2 to 9.7 GeV/c²
- no excess was found
- upper limits on cross section translated to coupling constant
- to be repeated with more data
Dark Photon
Dark Photon

- explore invisible decay first, $A' \rightarrow \chi_1 \chi_2$
- require one ISR photon and nothing else in the event
- needs a single photon trigger (not available in Belle, 10% of data in BaBar)
- bkgs include $\gamma\gamma$ (γ), e+e-γ (γ) and cosmics
- advantages over BaBar
  - no projective cracks in ECL
  - more hermetic calorimeter
  - KLM veto
introduce in analogy to SM a spontaneous symmetry breaking mechanism of $U(1)$ with new particle, dark Higgs $h'$

$e^+e^- \rightarrow A'h'$ (Higgsstrahlung)
- focus on $m_{h'} < m_{A'}$
- $h'$ has large lifetime to escape detection, $A'$ decays into SM particles
- 2 charged particle final state plus missing energy
- find a peak in two dimensional distribution of recoiling mass vs dimuon mass
- previously only investigated by KLOE

$\sigma \propto e^2 \times \alpha_D$
What about a Dark Higgs?

- main SM background contributions arise from
  - $\mu^+\mu^-(\gamma)$
  - $\tau^+\tau^-(\gamma)$
  - $e^+e^-\mu^+\mu^-$
- background suppression based on kinematic features
- improvements w.r.t KLOE result
  - probing unconstrained regions in 2D mass plane
  - probing non trivial regions of $\varepsilon^2\alpha_D$
- ongoing analysis, recently started unblinding
- expect results soon

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Conclusion

• broad and active program of DS physics at Belle II
• available phase-space is probed with many different models
• further analysis include Inelastic Dark Matter, Z’ to visible, DM searches in B decays…
• first results published
• much more to come
Backup
**Additional searches**

- Search for inelastic Dark Matter
  - long-lived particle detector signature and unconstrained parameter space
  - displaced pair of electrons, muons or hadrons
- Search for long-lived scalar in rare $B$ meson decays
  - $B \rightarrow K S, S \rightarrow \mu \mu, \pi \pi, K K$
  - generic scalar that mixes with the Higgs sector
  - small mixing leads to large lifetime and small production cross section

**Figure 2**: The Feynman diagram depicting the photon and displaced fermion signature in the context of the inelastic DM scenario. The decay vertex can be reconstructed, one obtains a displaced signature. In this section we will first review the relevant aspects of the Belle II experiment, present our implementation of the inelastic DM model and then discuss the sensitivity of Belle II for both of these signatures.

**3.1 The Belle II experiment**

The Belle II experiment at the SuperKEKB accelerator is a second generation $B$-factory and successor of the Belle and BaBar experiments [19]. Construction was completed in early 2019. SuperKEKB is a circular asymmetric $e^+e^-$ collider with a nominal collision energy of $p_s = 10.58$ GeV. The design instantaneous luminosity is $8 \times 10^{35} \text{cm}^2\text{s}^{-1}$, which is about 40 times higher than at the predecessor collider KEKB.

The Belle II detector is a large-solid-angle magnetic spectrometer. The following sub-detectors are particularly relevant for the searches described in this paper: a tracking system that consists of six layers of vertex detectors (VXD), including two inner layers of silicon pixel detectors (PXD) and four outer layers of silicon vertex detectors (SVD), and a 56-layer central drift chamber (CDC) which covers a polar angle region of $(17^\circ, 150^\circ)$. The electromagnetic calorimeter (ECL) comprising CsI(Tl) crystals with an upgraded waveform sampling readout for beam background suppression covers a polar angle region of $(12^\circ, 155^\circ)$ and is located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. The ECL has inefficient gaps between the endcaps and the barrel for polar angles between $(31.3^\circ, 32.2^\circ)$ and $(128.7^\circ, 130.7^\circ)$. An iron flux-return is located outside of the magnet coil and is instrumented with resistive plate chambers and plastic scintillators to mainly detect $K_0^L$ mesons, neutrons, and muons (KLM) that covers a polar angle region of $(25^\circ, 145^\circ)$.

We study the Belle II sensitivity for a dataset corresponding to an integrated luminosity of $20 \text{fb}^{-1}$ for consistency with [20]. This dataset is expected to be recorded by Belle II in early 2020. To show the potential reach of Belle II we also estimate the sensitivities for both $10^9$ and $10^{10}$.