Dark sector searches at Belle II

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The SuperKEKB $e^+e^-$ collider

- SuperKEKB is an asymmetric $e^+e^-$ - collider located in Tsukuba, Japan
- CM energy: 10.58 GeV ($\Upsilon$(4S) resonance)
  Tuneable between $\Upsilon$(2S) and $\Upsilon$(6S) resonance as well

**Target peak luminosity :** $6 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$

**Achieved (May 2021) :** $2.8 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$
B-factories at the intensity frontier

- Pilot run in 2018: 500 pb$^{-1}$ recorded
- Integrated luminosity (May 2021): $>150$ fb$^{-1}$

Objective: 50 ab$^{-1}$ by 2030

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Phenomenology 2021
The Belle II detector

**Electromagnetic calorimeter (ECL)**
- CsI(Tl) crystals

**Vertex Detectors (VXD)**
- 1 layer DEPFET pixel detectors (PXD)
- 4 layer double-sided silicon strip detectors (SVD)

**Central Drift Chamber (CDC)**
- He (50%):C$_2$H$_6$ (50%), small cells, fast electronics

**Particle Identification (PID)**
- Time-of-Propagation counter (TOP) (barrel)
- Aerogel Ring-Imaging Cerenkov Counter (ARICH)

**K$_L$ and muon detector (KLM)**
- Resistive Plate Counter (RPC) (barrel)
- Scintillator + WLSF + MPPS (end-caps)
Dark matter (DM) searches

Models for low-mass (sub-)GeV DM with light dark mediator between Standard Model (SM) and DM

Possible portals between DM and SM

- Vector portal (dark photon $A'$, dark $Z'$)
- Pseudo-scalar portal (axion-like particle)
- Scalar portal (dark scalars)
- Neutrino portal (sterile neutrino)
Search for Dark Matter

Dark matter searches at Belle II profit from:

- Well-defined initial conditions
- Hermetic detector
- Clean collision environment
- Excellent PID
- Dedicated low-multiplicity triggers

QCD axions
ultralight dark matter
hidden sector dark matter
muon g-2
Higgs
black holes

Off-shell
Invisible
Visible
Long-lived

Mediator mass
DM mass

arXiv:1707.04591
In invisibly decaying $Z'$ boson

- $L_\mu - L_\tau$ model: new light gauge boson $Z'$ arises that only couples to 2nd and 3rd lepton family

- Model might explain:
  - Dark matter puzzle
  - $(g - 2)_\mu$ anomaly
  - $B \to K^{(*)}\mu\mu$, $R_{K^{(*)}}$ anomalies

- Experimental search for $Z'$ decaying invisibly
  - Searching for peak in the recoil system against $\mu\mu$

Shuve et al. (2014) Phys. Rev. D 89, 113004
Altmannshofer et al. (2016) JHEP 1612 106
Invisibly decaying $Z'$ boson

- Search performed with only 276 pb$^{-1}$ that was taken during the 2018 pilot run of Belle II
- Improvements:
  - New triggers
  - PID system
  - Analysis techniques based on machine learning

90% CL upper limits

First Belle II physics paper:
PRL 124, 141801 (2020)
In invisibly decaying $Z'$ boson

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- Short term projections with several improvements:
  - Much higher integrated luminosity (already on tape).
  - Analysis improvements.
  - KLM $\mu$ID
  - MVA selection
  - New triggers.

- Starting to probe the $(g - 2)_{\mu}$ band with $50 \text{ fb}^{-1}$

**Preliminary (conservative) systematics estimate**
Axion Like Particles (ALPs)

- Axion Like Particles (ALPs) are pseudo-scalars coupling to bosons which appear in several BSM models.
- Analysis performed with $445 \text{ pb}^{-1}$ recorded during 2018 pilot run.
- Search for peak in:
  - Diphoton invariant mass (low $m_a$)
  - Recoil invariant mass (high ALP mass $m_a$)

Belle II focusing on ALPs coupling to photons

**ALP-Strahlung**

\[ e^- \rightarrow a \rightarrow \gamma + \gamma \]

\[ e^+ \rightarrow \gamma + \gamma \]

\[ M_Y^2 \text{[GeV}^2/c^4] \]

\[ M_{recoil}^2 \text{[GeV}^2/c^4] \]
Axion Like Particles (ALPs)

- Mass range between 0.2 to 9.7 GeV/c² studied
- No excess was found
- Upper limits on cross section translated to coupling constant

90% CL upper limits on the cross section

\[ \sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\text{QED}}}{24} \left( 1 - \frac{m_a^2}{s} \right)^3 \]

Belle II physics paper:
PRL 125, 161806 (2020)
Dark Photon to Invisible

- **Dark photon A’**: new massive gauge boson coupling to SM photon by kinetic mixing with mixing strength $\varepsilon$

- **Invisible decay**: $e^+e^- \rightarrow \gamma_{ISR} A' \rightarrow \gamma_{ISR} \chi \bar{\chi}$

- **Search for single photon in the detector**

- **Requires single photon trigger and precise knowledge of detector acceptance to reject background**

- **Background sources:**
  - $e^+e^- \rightarrow e^+e^- \gamma(\gamma)$
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$
  - Cosmics
Summary and Outlook

• Belle II has an extensive program of dark sector searches

• First results published:
  • Z’ to invisible \( \text{PRL 124, 141801 (2020)} \)
  • Search for ALPs \( \text{PRL 125, 161806 (2020)} \)

• Many more results expected in the near future

• More details:
  • The Belle II Physics Book, December 2019, arXiv:1808.10567

Other ongoing studies:

• Dark Higgs-Strahlung
• Dark Scalar
• Other Z’ decays
• Inelastic dark matter
• And many more
BACK-UP
Unsupervised anomaly detection

Search for rare events (anomalies) in background

• Classifier is trained on background only (either simulated or data) and later presented to a dataset that potentially contains signal.

Example: Simulation of magnetic monopoles (MM)

• Classifier tags anomalous data (high classifier loss) that is worth undergoing a detailed study.

• Model independent search
  ➔ No models for background and new physics scenario.

Beam background
MM: m = 1 GeV
MM: m = 4 GeV

Classifier loss [a.u.]