Dark-sector physics at Belle II

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Deutsches Elektronen-Synchrotron (DESY)
Exploring Dark Sectors with Belle II

- Next generation B-Factory operating at SuperKEKB asymmetric $e^+e^-$ collider.
  - $\sqrt{s} = 10.58$ GeV corresponding to $\Upsilon(4S)$ resonance.
  - Targeting 50 ab$^{-1}$ dataset this decade.
- Exploring **Dark Sectors** at the luminosity frontier:

**Direct Production:**
\[ e^+e^- \rightarrow X_{\text{Dark}}X_{\text{SM}} \]

**Decays:**
\[ B/D/\tau \rightarrow X_{\text{Dark}}X_{\text{SM}} \]

**Precision Measurements and Rare Decays:**
\[ e^+e^- \rightarrow X_{\text{SM}} \]
\[ B/D/\tau \rightarrow X_{\text{SM}} \]
The Belle II Detector

Novel vertexing:
- 2 layer DEPFET pixel detector
- 4 layer double sided silicon strips

New Drift Chamber:
- Larger volume, smaller cells, new electronics

New charged particle identification detectors:
- Barrel: Time-of-Propagation
- Backward Endcap: Cherenkov-based

Upgraded CsI(Tl) Calorimeter:
- Improved timing
- Pulse shape discrimination

New $K_L^0/\mu$ detectors
- Inner Barrel/Endcaps: scintillating strips
- Outer Barrel: Resistive Plate Counters

Superconducting 1.5 T Magnet

~ 7 m

~ 7.5 m
Belle II Dataset and Dark Sector Triggers

- Since first collisions in 2018, total dataset integrated to-date of $180 \text{ fb}^{-1}$.
  - World record instantaneous luminosity achieved by SuperKEKB ($2.9 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$).
- New “Dark Sector” triggers make this dataset world-unique.

$e^+e^- \rightarrow X$ (in acceptance)

- ~1 MHz (Dominated by Bhabha and $2\gamma$)

**Level 1 Hardware Trigger**

- <30 kHz

**High Level Software Trigger**

- <10 kHz

✓ **Single photon trigger** operational for entire dataset.
  - Not present at Belle.
  - 53 fb$^{-1}$ recorded by BaBar with single photon trigger.
✓ **Single muon trigger** using KLM recently introduced.
✓ **3D track reconstruction at L1** using neural networks.
Invisibly Decaying Z’ Boson

• Z' boson - vector portal mediator between Dark Sector and Standard Model.
  ➡ Dark Matter, \((g - 2)\mu, b \rightarrow s\mu^+\mu^-\).

• Consider scenario:
  ➡ Z’ coupling only to 2nd and 3rd generation leptons (\(L_\mu - L_\tau\) model).
  ➡ Z’ decays primarily as \(Z' \rightarrow \chi\bar{\chi}\) (invisible)

• Hermetic Belle II detector and clean \(e^+e^-\) collisions allow precision determination of missing energy!

**Default channel:**

\[ e^+e^- \rightarrow \mu^±\mu^± + \text{Missing Energy} \]

**Lepton flavour violating channel:**

\[ e^+e^- \rightarrow \mu^±\bar{e}^± + \text{Missing Energy} \]

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Invisibly Decaying Z’ Boson Search

- Signal would produce narrow peak in distribution of recoil mass computed from $\mu^\pm \mu^\mp$ (LFV: $\mu^\pm e^\mp$).

- Dominant backgrounds:
  - $e^+ e^- \rightarrow \tau^+ \tau^-$: $\tau$’s decay single prong, missing energy from neutrinos.
  - $e^+ e^- \rightarrow \mu^+ \mu^-(\gamma)$, photon is undetected.

- No significant excess observed in either search.
Z’ Boson Limits and Exclusions

- 90% CL upper limits set on Z’-SM coupling (g’) excluding strengths from 1 down to $5 \times 10^{-2}$.
- LFV search sets first model independent limits on the $\epsilon \times \sigma[e^+e^- \rightarrow e^\pm\mu^\mp \text{invisible}]$ down to 10 fb.
- Results published: I. Adachi et al. (Belle II Collaboration) Phys. Rev. Lett. 124, 141801

![Graphs showing limits on Z’ boson mass and decay channel cross-sections]

**Default:** $\mu^\pm\mu^\mp$

**LFV:** $\mu^\pm e^\mp$

Belle II 2018

$\int Ldt = 276 \text{ pb}^{-1}$
Axion-Like Particles (ALP)

- GeV-scale ALPs ($a$) - pseudoscalar portal mediator between Dark Sector and Standard Model.
- If ALP-photon coupling ($g_{a\gamma\gamma}$) dominates, $B(a \rightarrow \gamma\gamma) \approx 100\%$.
- Search targets mass region where ALP decay is prompt and photons can be well resolved by Belle II.

Searching for Axion-Like Particles

- Select events that have three photons with invariant mass consistent with the collision $\sqrt{s}$.
- Search for narrow peak in $M^2_{\text{recoil}}$ or $M^2_{\gamma\gamma}$ (optimized for ALP resolution)

$Largest background from e^+e^- \rightarrow \gamma\gamma(\gamma)$

$M^2_{\gamma\gamma}$: $m_a < 6.85$ GeV

$M^2_{\gamma\gamma}$: $m_a \geq 6.85$ GeV

$$E^c.m._{\text{recoil}}\gamma = \frac{s - m_a^2}{2\sqrt{s}}$$
ALP Search Results

- Search spanned $0.2 < m_a < 9.7 \text{ GeV}/c^2$.
- No significant excess observed.
  - Largest local significance at $m_a = 0.477 \text{ GeV}/c^2$ corresponding to $2.8\sigma$. 
Exclusion on ALP-Photon Coupling

- Upper limit (95% CL) set on ALP-photon coupling reaching below $10^{-3}$.
  
  $\Rightarrow$ Limits exceed recast from $e^+e^- \rightarrow \gamma\gamma$ analysis by LEP-II.

- Results published: F. Abudinén et al. (Belle II Collaboration) Phys. Rev. Lett. 125, 161806 (2020)

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

- **Expanded Dark Sector** with two Dark Matter states:
  
  $\chi_1$ - Relic DM

  $\chi_2$ - Long-lived particle

  - Decays as $\chi_2 \rightarrow \chi_1 l^+ l^-, \ l^\pm = \text{SM fermion}$
  
  - Vector portal coupling to SM via Dark Photon, $A'$, mediator.

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Inelastic Dark Matter Search

- Background suppression using leptons from displaced $\chi_2$ decay vertex.
  - **Missing energy** in $\chi_2 \rightarrow \chi_1 l^+ l^-$ allows for suppression of $\gamma \rightarrow e^+ e^-$ and $K^0_S \rightarrow \pi^+ \pi^-$. 

- Search for peak in recoil mass of ISR photon.

- **Belle II Simulation**
  - $\log{\epsilon} = -2.8, m_{\chi_1} = 0.2 \text{ GeV}$
  - $\log{\epsilon} = -2.8, m_{\chi_1} = 0.5 \text{ GeV}$
  - $\log{\epsilon} = -3.6, m_{\chi_1} = 2.0 \text{ GeV}$
  - $\log{\epsilon} = -3.6, m_{\chi_1} = 3.2 \text{ GeV}$
  - $m_\chi = 2.5 \times m_{\chi_1}$

- **Entries**

- **Bhabha background excluded**
- **Signal Arb. Normalization**
- **3-body**
  - $\gamma \gamma(\gamma)$
- **2-body**
  - $\mu \mu$
  - $d \bar{d}$
  - $s \bar{s}$
  - $K^0_S \bar{K}^0_L$
  - $\tau^+ \tau^-$

**MC equivalent luminosity = 100 fb$^{-1}$**
Inelastic Dark Matter Prospects

• With current Belle II dataset expect to probe Dark Sector-Standard Model couplings down to $10^{-3} - 10^{-4}$.

• Search will also constrain extended iDM models featuring Dark Higgs Bosons.
Conclusions

• The Belle II experiment is exploring Dark Sectors at the luminosity frontier.

• New Dark Sector triggers enabled to target unique low-multiplicity final states.

• World-leading limits published on Z’ boson and ALP’s:

• New Inelastic Dark Matter analysis in progress, targeting expanded Dark Sectors with long-lived particles.
Thanks!
Extra Slides
$e^+e^- \rightarrow \tau^+\tau^- (\gamma)$ Suppression in Z’ Search

- Missing energy in signal arises from Z’ radiation off a final state muon.
- In background missing energy arises from both tracks due to neutrinos in tau decays.
- This difference allows the lepton kinematics to be used to suppress backgrounds from $e^+e^- \rightarrow \tau^+\tau^- (\gamma)$.
Future Reach of $Z'$ Searches

![Graph showing the future reach of $Z'$ searches. The graph plots $g'$ against $M_{Z'}$ in units of [GeV/c^2]. The $90\%$ CLs upper limit is shown for different luminosities and trigger conditions.](image)

- $\int L\, dt = 9\, fb^{-1}$
- $\int L\, dt = 50\, fb^{-1}$
- $\int L\, dt = 50\, fb^{-1}$ (more inclusive trigger)
- Belle II PRL124, 141801, $\int L\, dt = 0.276\, fb^{-1}$

(g - 2)$_\mu$ ± 2σ
FIG. 2. $M_{\gamma \gamma}^2$ and $M_{\text{recoil}}^2$ resolutions with uncertainty as a function of ALP mass $m_a$. The inset shows an enlargement of the low-mass region $m_a < 1 \text{ GeV}/c^2$. 
Projected Reach of Dark Photon Search

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

Expected sensitivity Belle II 20 fb\(^{-1}\) (simulation)

\( m_{A'} \) (GeV)

\( \epsilon \)

\( 10^{-4} \rightarrow 10^{-2} \)

E787, E949

(g-2)\(_e\) vs \( \alpha \)

(g-2)\(_\mu\) \( \pm 2\sigma \)

NA64

BaBar 2017

E. Kou et al. PTEP 2019 (2019) 123C01