Dark sector searches at Belle II.

Sascha Dreyer on behalf of the Belle II collaboration

32\textsuperscript{nd} Rencontres de Blois — Beyond the Standard Model & Dark Matter parallel session
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sascha.dreyer@desy.de
Light dark sector coupled to Standard Model

Possible portal interactions:
- Vector → Dark Photons $A'$, $Z'$
- Pseudo-scalar → ALPs
- Scalar → Dark Higgs
- Neutrino → Sterile Neutrinos
SuperKEKB collider & Belle II experiment.

- Accelerator: SuperKEKB
- Running at the $\Upsilon(4S)$ resonance
- Target 50 ab$^{-1}$ ($50 \times$ Belle)
  - Higher beam currents
  - Smaller beam spot
- Collected 213 fb$^{-1}$ up to now
- Updated detector: Belle II
Dark Sectors with Belle II.

- Design focus as $B$ & $\tau$ factory
- And: Light dark sectors
- Well known initial conditions and less/no pile-up
- Special low multiplicity triggers
  - Single photon trigger (not available at Belle)
  - Single muon trigger
  - 3D track reconstruction at L1 using NN
  - Single track trigger using NN

\[ e^+e^- \rightarrow X \rightarrow \chi\chi \text{ or SM} \]
\[ e^+e^- \rightarrow \Upsilon(4S) \rightarrow B[\bar{B} \rightarrow KX] \]
Published searches
Search for an invisibly decaying Z’ boson.

- Additional massive gauge boson $Z'$
  - $(g - 2)_\mu$
  - $b \to s\mu\mu$
- Study mass recoiling against $\mu\mu$ system
- Backgrounds:
  - $e^+e^- \to \tau^+\tau^-$
  - $e^+e^- \to \mu^+\mu^-(\gamma)$
  - $e^+e^- \to e^+e^-\mu^+\mu^-$

Search for an invisibly decaying Z’ boson.

- Two tracks in barrel calorimeter
  - Azim. opening angle > 90 deg
- Particle identification via $E$ and $E/p$
- Recoil momentum isolated & within barrel
- $\tau$ pair background suppression
  - Z’ is radiated from one muon leg
  - Neutrinos in $\tau$ decay from both legs
- LFV mode studied as well

Published! Phys. Rev. Lett. 124, 141801
Search for an invisibly decaying Z’ boson.

Phys. Rev. Lett. 124, 141801
Search for Axion Like Particles (ALP).

- Pseudoscalar ALP $a$
- Events with three $\gamma$ consistent with $\sqrt{s}$
- Search for a peak in reconstructed ALP mass distribution
- Using two different ways to reconstruct ALP mass

Published!
Phys. Rev. Lett. 125, 161806
Search for Axion Like Particles (ALP).

- Backgrounds mainly $e^+e^- \rightarrow \gamma\gamma(\gamma)$
- Determine background normalisation directly in data by fitting mass sidebands
Search for Axion Like Particles (ALP).

Phys. Rev. Lett. 125, 161806
Ongoing searches
Search for a Dark Higgs

- Dark photon $A'$ with a Dark Higgs $h'$
- $h'$ Invisible (very long-lived, $m_{h'} < m_A$)
- Dark photon decay into $\mu\mu$
- Search for a 2D peak in $M_{\mu\mu}$ vs. $M_{\text{recoil}}$
  - Scan using elliptical, tilted windows of varying size
- Main backgrounds:
  - $e^+e^- \rightarrow \mu^+\mu^- (\gamma)$
  - $e^+e^- \rightarrow \tau^+\tau^- (\gamma)$
- Submitting soon!
Search for a Dark Photon.

- Dark photon $A'$ with kinematic mixing parameter $\epsilon$
- Vanilla benchmark-model
- Invisible decay to Dark Matter $\chi$ (or very long-lived)
- Search for a bump in ISR $\gamma$ energy

![Graph showing L1 trigger efficiency vs. $E^*$ [GeV]]

**Belle II** 2019
\[ \int L dt = 4.6 \text{ fb}^{-1} \]
1 GeV cluster trigger

**Graph showing $\varepsilon$ vs. $m_{A'}$ (GeV/c²)**

- Belle II simulation 20 fb$^{-1}$
- NA62 4.12x10$^{14}$ e²
- Majorana relic target
- Solar relic target
- Pseudo-Dirac fermion relic target
- $\alpha_S = 0.5$, $m_\chi = m_{A'}/3$
Search for $B \rightarrow K h'$.

- Long-lived Dark Higgs $h'$ in $b \rightarrow s$ transitions
- Form signal $B$ meson candidate

Adapted from T. Ferber

$B$ meson decay

Ongoing!

A. Filimonova, R. Schäfer, S. Westhoff

$\pi \pi + KK$
$B$abar $\mu \mu$
$\pi \pi$
$\mu \mu$
$\tau \tau$

Dark sector searches at Belle II
Search for B→Kh′.

- Search for bump in reconstructed $h′$ (LLP) mass
- Mostly backgrounds at low displacements

**Belle II Simulation**

- Background 200 fb$^{-1}$, LLP→$μ^+ μ^-$
- $m=0.80 \text{ GeV}/c^2$, $ct=50.0 \text{ cm}$

**Preliminary selection**

- $e^+ e^- \rightarrow u\bar{u}$
- $e^+ e^- \rightarrow c\bar{c}$
- $e^+ e^- \rightarrow s\bar{s}$
- $e^+ e^- \rightarrow d\bar{d}$
- $e^+ e^- \rightarrow b\bar{b}$
- $e^+ e^- \rightarrow B^+ B^-$
- $e^+ e^- \rightarrow B^0 \bar{B}^0$

**Ongoing!**

- $e, μ, π, K$

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Sascha Dreyer

Dark sector searches at Belle II
Summary.

- Results published with early datasets:
  - Invisible $Z'$ Phys. Rev. Lett. 124, 141801
  - ALPs search Phys. Rev. Lett. 125, 161806
- Ongoing searches:
  - Dark Photon, Dark Higgs
  - Inelastic Dark Matter, Long-lived Dark Higgs
  - … many more!
- Belle II will be leading the field of light dark matter in the coming years
Backup.
Search for Inelastic Dark Matter.

- Dark photon $A'$ and two Dark Matter states $\chi_1, \chi_2$
- Long-lived $\chi_2$, relic candidate $\chi_1$ with $m_{\chi_2} > m_{\chi_1}$
- Initial state radiation $\gamma$ for triggering

$e^+ e^- \rightarrow A' \gamma \chi_1 \chi_2$


Search for Inelastic Dark Matter.

- Reconstruct displaced $\chi_2$ vertex
- Search in recoil mass of the ISR $\gamma$
- Background suppression:
  - Non-pointing vertex
  - Missing energy: $K_S^0$ and $\gamma$ conversion

**Belle II Simulation**

- $\log \mu = -2.8$, $m_{\chi_2} = 0.2$ GeV
- $\log \mu = -2.8$, $m_{\chi_1} = 0.5$ GeV
- $\log \mu = -3.6$, $m_{\chi_1} = 2.0$ GeV
- $\log \mu = -3.6$, $m_{\chi_1} = 3.2$ GeV

Initial state radiation photon