Prospects for long-lived particle searches at Belle II.

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**Super B-factory accelerator: SuperKEKB**

- Asymmetric beam energies: e.g. 7.0 GeV (e⁻) / 4.0 GeV (e⁺)
- Large crossing angle of 83 mrad
- Major upgrade to the accelerator with 30× the KEKB design luminosity (6×10^{35} cm⁻²s⁻¹, 50 ab⁻¹ (50× Belle))
  - 1.5× higher beam currents, 20× smaller beam spot (σ_y=50 nm)
- Record: 3.12×10^{34} cm⁻²s⁻¹ (June 22 2021)
- Total dataset up to now: 213 fb⁻¹
Super B-factory detector: Belle II

Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

Central drift chamber (CDC):
He(50%):C2H6 (50%), small cells,
fast electronics

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter
Long-lived particle (LLP) signatures

• LLPs from $B$ meson decays:
  • Mediator mass limited by meson mass ($\sim 5$ GeV)
  • Couplings to top quarks or $W$ bosons (dark Higgs, ALPs)

• LLPs in $e^+e^-$ collisions:
  • Mediator mass limited to collision energy ($\sim 10$ GeV)
  • Coupling to photons or leptons (dark photons, ALPs)
Long-lived particle performance

- **Tracking:**
  - Vertex efficiency >30% out to ~60 cm
  - Vertex resolution <100μm

- **Calorimeter (ECL):**
  - Timing resolution ~2ns @ 2GeV
  - No longitudinal segmentation, coarse lateral segmentation → no pointing resolution

- **Trigger**
  - No dedicated displaced vertex track trigger, but can exploit the other B for searches in B decays (at Belle II, B’s come from \( \Upsilon(4S) \rightarrow B\bar{B} \))
  - Calorimeter triggers are efficient if there are electrons or photons in the final state
Prospects for long-lived particle searches at Belle II (Torben Ferber)

**B → Kh’**

- h' is long-lived
- $m_{xx}$ peak hunt on small smooth background ($x = (e), \mu, \pi, K$)
- LHCb and Belle II complementary due to very different B momenta, BaBar search is inclusive and recast is not competitive
- Reach towards even smaller mixing angle $\theta$ by searching for $B \rightarrow K \rightarrow \gamma h'$
- Recasting existing $B \rightarrow K \nu \nu$ SM limits untrivial (3-body vs 2-body final state)

Belle II collaboration, "Search for $B^+ \rightarrow K^+ \nu \nu$ decays using an inclusive tagging method at Belle II" (arXiv:2104.1262)
\[ \text{B} \rightarrow \text{Kh}' \]

- Event selection is very clean, but not quite at zero background

- Mild lifetime dependence on mass resolution and mass asymmetries
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$B \rightarrow Ka$

- Search for ALPs that predominantly couple to electroweak gauge bosons
  - Dominant decay for $m_a \ll m_W$ into photons:
    \[
    \Gamma(a \rightarrow \gamma\gamma) = \frac{g_{aW}^2 \sin^4 \theta_W M_a^3}{64\pi}
    \]
  - Light ALPs naturally long-lived, but decay in general model-dependent

\[\begin{array}{c}
\text{Figure 66: Limit on } B^+ \rightarrow K^+ a, a^+ \text{ branching fraction as a function of ALP mass and lifetime from Run 3 data.}
\end{array}\]
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**B → Ka at BaBar**

![Graph showing the 90% CL limit on the branching fraction for B → K^± a) x BF(a → γγ) vs. m_a (GeV).]

![Diagram illustrating the beam dump and BABAR 90% CL limit.]

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**References:**

2. "Improve limit on g_{aW}."
Inelastic Dark Matter

five free parameters:
- dark photon mass \( m_{A'} \) (fixed relative to \( m_{\chi_1} \))
- \( \chi_1 \) mass (stable dark matter candidate) (scan)
- mass difference \( \Delta = m_{\chi_2} - m_{\chi_1} \) (categorical)
- dark coupling \( \alpha_D \) (fixed to benchmarks)
- kinetic mixing parameter \( \epsilon \) (limit)
Clusters trigger, and the displaced vertex trigger separately for an integrated luminosity of 20 fb$^{-1}$.

Sensitivity of Belle II to the parameter space of inelastic DM for an integrated luminosity of 20 fb$^{-1}$.

Figure 6: Sensitivity of Belle II to the parameter space of inelastic DM for an integrated luminosity of 20 fb$^{-1}$.

$\alpha_D = 0.1, m_\nu = 2.5 m_{\chi_1}, \Delta = 0.05 m_{\chi_1}$

$\alpha_D = 0.1, m_\nu = 2.5 m_{\chi_1}, \Delta = 0.1 m_{\chi_1}$

$\alpha_D = 0.1, m_\nu = 2.5 m_{\chi_1}, \Delta = 1.3 m_{\chi_1}$

$\alpha_D = 0.1, m_\nu = 2.5 m_{\chi_1}, \Delta = 0.4 m_{\chi_1}$

Inelastic Dark Matter

displaced search
invisible search
increased mass splitting
GAZELLE

• Study “realistic” dedicated LLP detector near Belle II: GAZELLE*

  *GAZELLE is the Approximately Zero-background Experiment for Long-Lived Exotics

• Three benchmarks studied (HNL, iDM, ALPs)

• No significant gain compared to Belle II due to moderate boost, and excellent solid angle coverage and low backgrounds for missing energy searches at Belle II

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**Clean $\tau$ production**

$\Rightarrow$ HNLs: $N$

**Displaced vertices**

$\Rightarrow$ iDM: $h'$

**Rare $B$ decays**

$\Rightarrow$ ALPs: $a$
Summary

• Existing LLP triggers at Belle II rely on calorimeter information, dedicated LLP track trigger development has started

• Study of a possible dedicated LLP detector GAZELLE revealed excellent LLP sensitivity for Belle II itself

• Multiple searches with LLPs in the final state started using the existing 200 fb\(^{-1}\) Belle II dataset: \(B\rightarrow Kh'\), \(B\rightarrow Ka\), inelastic DM, dark Higgs, ...
Backup
Inelastic Dark Matter and Dark Higgs

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$m_{\chi_1}(\text{GeV})$

10^{-1}  10^{0}  10^{1}

$m_A = 4m_{\chi_1}$
$m_H = 1\text{GeV}$
$\theta = 10^{-5}$, $\Delta = m_{\chi_1}$
$\alpha_D = 0.1$

10^{-5}  10^{-4}  10^{-3}  10^{-2}  10^{-1}  10^{0}  10^{1}$

$\epsilon$

$100 \text{ fb}^{-1}$  $50 \text{ ab}^{-1}$

HERA

LHeC

BaBar mono $\gamma$

$\text{EWPT}$

Thermal relic

$\text{mono-} \gamma$

displaced $\gamma$

displaced

$\text{BaBar mono-} \gamma$