DARK SECTOR PHYSICS WITH BELLE II
BELLE II AT SUPERKEKB: INTENSITY FRONTIER AT 10.58 GEV

**Belle II**
700+ physicists.
100+ institutes.
23 countries.
"Phase 2" goal:
Peak luminosity as at the end of Belle:
\(1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)

SuperKEKB and Timeline

\begin{itemize}
  \item New high-current photo-cathode RF gun developments
  \item New positron capture section
  \item Damping ring construction
  \item Optimized beam optics and correction
  \item Precise beam orbit control with long-baseline alignment
  \item Simultaneous top-up injection to DR/HER/LER/PF/PFAR
\end{itemize}

Balanced injection for the both photon science and elementary particle physics experiments

Mission of Electron/positron Injector in SuperKEKB

Linac Mission in FY2016-FY2017

The single injector would behave as multiple injectors to multiple storage rings by the concept of virtual accelerator

SuperKEKB luminosity projection

Goal of Belle II @ SuperKEKB

<table>
<thead>
<tr>
<th>Calendar Year</th>
<th>Peak Luminosity ((10^{33} \text{ cm}^{-2}\text{s}^{-1}))</th>
<th>Integrated Luminosity ((\text{ab}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cosmic run without VXD</td>
<td>Full detector</td>
</tr>
<tr>
<td>2017</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>2018</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>2019</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>2020</td>
<td>10</td>
<td>2</td>
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<tr>
<td>2021</td>
<td>10</td>
<td>2</td>
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<tr>
<td>2022</td>
<td>10</td>
<td>2</td>
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<tr>
<td>2023</td>
<td>10</td>
<td>2</td>
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<tr>
<td>2024</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>2025</td>
<td>10</td>
<td>2</td>
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Belle → Belle II: x40 luminosity

Peak Luminosity

<table>
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<th>Calendar Year</th>
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Belle → Belle II:

x40 luminosity

"Phase 2" goal: Peak luminosity as at the end of Belle: 
\(1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
Possibly upgrade

Electromagnetic Calorimeter (ECL):
- CsI(Tl), waveform sampling (barrel)
- Pure CsI + waveform sampling (endcaps)

K_{L} and muon detector (KLM):
- Resistive Plate Counter (barrel)
- Scintillator + WLSF + MPPC (endcaps)

Particle Identification (PID):
- Time-of-Propagation counter (barrel)
- Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
- 2cm diameter

Vertex Detector:
- 2 layers DEPFET
- 4 layers DSSD

Central Drift Chamber (CDC):
- He(50%):C_{2}H_{6}(50%), Small cells, long lever arm, fast electronics

Need to cope with much higher luminosity and beam backgrounds.
BELLE II DETECTOR: ELECTROMAGNETIC CALORIMETER (ECL)

Effects of beam background:
> Degrades energy resolution.
> Radiation damage.
> Pile-up and increased event size.
> Physics background.

→ Upgrades of hardware (detector) and software (reconstruction) are crucial.
**WHY BELLE II FOR DARK SECTOR SEARCHES?**

**Belle II 2018 ("Phase 2"):**
Low initial luminosity (like Belle), but trigger and computing can already handle $20 \times$Belle rate:
$\rightarrow$ Unique chance to use novel triggers for small datasets.

**Belle II 2025:**
Huge dataset of 50 ab$^{-1}$.
(x50 Belle, x100 BaBar)

**Belle II vs Belle:**
New low multiplicity triggers.
Larger drift chamber.

**Belle II vs BaBar:**
Non-projective calorimeter (much more hermetic).
Better muon detector.
SEARCHING FOR DARK MATTER: VECTOR PORTAL

- In the so-called Vector Portal, a (massive) Dark Photon $A'$ can mix with the SM photon with strength $\varepsilon$.

\[
\begin{align*}
\text{Standard Model} & : \quad \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_{Y} \\
\text{Dark Sector} & : \quad \text{U}(1)_{D} \text{ (massive)}
\end{align*}
\]

*Holdom, Phys. Lett B166, 1986

![Graph](image-url)
SEARCHING FOR DARK MATTER: VECTOR PORTAL

- Search for a bump in the photon recoil mass spectrum.
- Main backgrounds: $ee\rightarrow ee\gamma$ and $ee\rightarrow \gamma\gamma(\gamma)$ with all but one $\gamma$ undetected.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>YY</th>
<th>Bhabha</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 GeV*</td>
<td>0.2 nb</td>
<td>0.4 nb</td>
<td>1.6 nb</td>
</tr>
<tr>
<td></td>
<td>E*$&gt;1$ GeV and second cluster E*$&lt;0.2$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 GeV*</td>
<td>0.5 nb</td>
<td>2.9 nb</td>
<td>0.1 nb</td>
</tr>
<tr>
<td></td>
<td>E*$&gt;2$ GeV and eclbhabhaveto and bhabhveto</td>
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$m_A = 7$ GeV
SEARCHING FOR DARK PHOTONS AT BELLE II

\[ y = \varepsilon^2 \alpha_D \left( \frac{m}{m_{A'}} \right)^4 \]

\[ 10^{-7} \quad 10^{-5} \quad 10^{-3} \quad 10^{-1} \quad 1 \]

\[ m_\chi \ [\text{GeV/c}^2] \]

LEP

NA64

E137

LSND

Scalar Relic Target

Pseudo-Dirac Fermion Relic Target

Belle II (Phase 2)

Belle II (Phase 3)

LDMX1@4GeV

LDMX2@8GeV

\[ \alpha_D = 0.5 \]

\[ 3m_\chi = m_{A'} \]

B2TIP, to be submitted to PTEP (2017).
SEARCHING FOR AXION LIKE PARTICLES

- Axion-like particles (ALPs) are pseudo-scalars and couple to bosons. Unlike Axions, ALPs have no relation between mass and coupling.

- They can be Dark Matter candidates, Dark Sector mediators, and they appear in many BSM scenarios.

- Focus on coupling to photons for Belle II.

![Feynman diagram of (a) Dark Photon and (b) ALP production and decay into photons.](image)
**SEARCH FOR AXION LIKE PARTICLES AT BELLE II**

ALP decays outside of the detector: Single photon final state.

Two of the photons overlap or merge.

Three resolved, high energetic photons (focus in this talk).

FIG. 1. Excluded regions in ALP parameter space (figure adapted from [6, 10–12] with added limits from [13–19]). Our bound is shown in dark blue (“SN decay”).

For sufficiently heavy ALPs with masses in the 10 keV - 100 MeV region however, an-
SEARCH FOR AXION LIKE PARTICLES

- Focus on the resolved $3\gamma$ final state with $m_A \geq 0.2$ GeV.
- Search for a bump in the two photon invariant mass spectrum.
- Main backgrounds:
  - $ee \rightarrow \gamma \gamma \gamma$
  - $ee \rightarrow \gamma \gamma$ + beam induced background photon
  - $ee \rightarrow \gamma \gamma$ ($\gamma \rightarrow ee$) pair conversion outside tracking detectors.

<table>
<thead>
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<th>Total ($\gamma \gamma$)</th>
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<tbody>
<tr>
<td><em><em>2 GeV</em> Barrel</em>*</td>
<td>1.7 nb</td>
</tr>
<tr>
<td>$E^* &gt; 2$ GeV and polar angle in ECL barrel</td>
<td>rate@1/40 lumi: 0.03 kHz</td>
</tr>
<tr>
<td></td>
<td>rate@final lumi.: 1.36 kHz</td>
</tr>
<tr>
<td><em><em>2 GeV</em> ECL</em>*</td>
<td>2.8 nb</td>
</tr>
<tr>
<td>$E^* &gt; 2$ GeV and polar angle in ECL trigger acceptance excluding extreme endcaps</td>
<td>rate@1/40 lumi: 0.06 kHz</td>
</tr>
<tr>
<td></td>
<td>rate@final lumi.: 2.24 kHz</td>
</tr>
</tbody>
</table>
SEARCH FOR AXION LIKE PARTICLES

ALP coupling to two photons only.

DARK SECTOR PHYSICS WITH BELLE II

work in progress: M. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg

Update soon:
- Belle II merged photons and ee→ee+ALP.
- Belle II single photon search.

data from:
- Jaeckel, Spannowski, Phys. Let. B. 753 (2016)
- Doebrich et al., JHEP 1602 (2016)
The early running of Belle II offers possibilities for unique physics analyses in the dark sector (including visible and displaced topologies not covered in this talk).

The search for light dark matter is competitive with BaBar already with 2018 data due to the more hermetic calorimeter.

Belle II Physics Book in preparation* (Belle II detector, simulation, software, analysis tools, physics program incl. dark sectors), to be submitted for publication in 2017.

Belle II physics data taking starts April 2018. Full detector (including VXD) starts end of 2018.

* https://confluence.desy.de/display/B2/B2TiP+ReportStatus
Entry #16

“CDC backward view after cabling.” This is CDC backward view on Jan 10th, 2016. After all cables, cooling pipe and dry air are connected.
BACKUP
**Belle II Beam Background**

- **Coulomb**
- **Bremsstrahlung**
- **Bhabha**
- **Two Photon**

- Degrades calorimeter resolution.
- Radiation damage.
- Pile-up and event size.
- Physics background.

![Graph showing average dose per crystal (Gy/year) vs. θ_ID for different beam backgrounds across the 12th campaign](image)
ALP coupling to two photons or Z bosons.
# Single Photon Triggers

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<td>0.2 nb</td>
<td>0.4 nb</td>
<td>1.6 nb</td>
</tr>
<tr>
<td>rate( @1/40 \text{ lumi.} ): 0.05 kHz</td>
<td>rate( @\text{final lumi.} ): 1.76 kHz</td>
<td></td>
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<tr>
<td>( 2 \text{ GeV}^* )</td>
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<td>( E^* &gt; 2 \text{ GeV} ) and ( ecl\text{bhabhaveto} ) and ( bhabhveto )</td>
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<td>2.9 nb</td>
<td>0.1 nb</td>
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<tr>
<td>rate( @1/40 \text{ lumi.} ): 0.08 kHz</td>
<td>rate( @\text{final lumi.} ): 2.80 kHz</td>
<td></td>
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*Both e have \( \theta^* > 1^\circ \) and one e has \( \theta^* < 1^\circ \).*
## ALP Triggers

<table>
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<th>Total (γγ)</th>
<th>Rate @ 1/40 lum.: 0.06 kHz</th>
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