Dark sector physics with Belle II

Peter M. Lewis for the Belle II Collaboration
University of Hawaiʻi at Mānoa

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SuperKEKB

The super B-factory at KEK

- First-generation B-factory at Tsukuba, Japan:
  - KEKB: accelerator (world record luminosity)
  - Belle: detector
- Asymmetric-energy $10.57 \text{ GeV}$ electron-positron collider
- Instantaneous luminosity: $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ [40 times KEKB]
- Integrated luminosity: $50 \text{ ab}^{-1}$ [50 times KEKB]
  - “Nano-beam” scheme (right, showing positron and electron bunches crossing)
  - Doubled beam currents
- First collisions this spring! Exciting times!
Belle II

**Central beam pipe:** 2cm diameter, Beryllium with gold coating on inside

**Vertexing:** new 2 layers of pixels, 4 double-sided layers of silicon strips

**Tracking:** 14336-wire drift chamber

**PID:** time-of-flight (barrel) and proximity focusing aerogel (endcap) Cherenkov detectors

**EM calorimetry:** CsI(Tl) crystals

$K_{L}$ and $\mu$: scintillators (endcap and inner two layers of barrel) and RPCs (remainder of barrel)
Near-term operations

“Phase 2” run

- 2016: First beams (“Phase 1”)
- Current: global cosmic run
- This spring: “Phase 2”
  - Primary purpose: commission nano-beams
  - Target: KEKB instantaneous luminosity ($\leq 20\text{fb}^{-1}$ integrated)
  - Vertexing detectors absent
- But, with smart trigger design we can get competitive dark sector sensitivity:
  - New trigger modes
  - Flexible trigger firmware

Phase 2

Phase 3: final configuration
Event display from global Belle II cosmic run (last week)
Dark matter searches at Belle II

(Some) Phase 2 physics prospects

- **Vector** portal: dark photon $A'$ to invisible

- **Pseudoscalar** portal: axion-like particles $a$ (ALPs)
Dark matter searches at Belle II

(Some) Phase 2 physics prospects

- **Vector** portal: dark photon $A'$ to invisible

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

- **Pseudoscalar** portal: axion-like particles $a$ (ALPs)

  $e^+ \rightarrow a \rightarrow \gamma^* \rightarrow \gamma \rightarrow \chi_2$
Dark photon to invisible

A distinctive signature

- **Single photon** from initial state radiation
- SM photon mixes with massive dark photon $A'$
- If DM is light enough, $A'$ decays to invisible light DM particles
- **Signature:**
  - Single, mono-energetic, high-$E$ photon
  - Peak in recoil mass (dark photon mass)
Dark photon to invisible

A special trigger

- **Single-photon trigger:**
  - None in Belle
  - Only for short time in BaBar (53$\text{fb}^{-1}$)

- **Advantages over BaBar:**
  - More-hermetic calorimeter
    - Larger calorimeter coverage
    - Photons cannot escape between crystals due to a slight rotation in $\theta$ and $\phi$
  - Lower energy asymmetry

**Belle II Phase 2 run with single-photon trigger should be competitive**
Dark photon to invisible

Backgrounds

- ~No true physics backgrounds
- Missing particle backgrounds:
  - $e^+e^- \rightarrow \gamma\gamma$ (top)
  - Radiative Bhabha $e^+e^- \rightarrow e^+e^-\gamma$
- Final state particles get “lost” in cracks (top)
  - BaBar had no backwards endcap calorimeter and cracks between each crystal (bottom)
Dark photon to invisible

Phase 2 expectations

- **Single-photon trigger**
  - Exactly one cluster >1GeV, none other >300MeV
  - Rate dominated by $e^+e^- \rightarrow e^+e^-\gamma$
  - Single-photon trigger $\sim 0.5$kHz [of 8kHz max]
  - May be able to use in Phase 3

- **Handling backgrounds**
  - Peaking $e^+e^- \rightarrow \gamma\gamma(\gamma)$ dominates analysis (right)
  - The key: quantify photon efficiency

- **Key strength**
  - Low backgrounds $\rightarrow$ good sensitivity for **low-mass** dark photons

Belle II MC with 1.8GeV single-photon trigger
Dark photon to invisible: projected sensitivity

Disclaimer: relic density lines assume a standard cosmological history and that there is only a single component of dark matter, which only interacts via dark photon exchange.
Dark matter searches at Belle II

(Some) Phase 2 physics prospects

- **Vector** portal: dark photon $A'$ to invisible

- **Pseudoscalar** portal: axion-like particles $a$ (ALPs)
Axion-like particles

Three-photon final state

- ALPs couple to bosons
  - No relation between mass and coupling
  - Photon coupling $g_{a\gamma\gamma}$ targetable in Phase 2
- Signature
  - Three photons $> 0.1\text{GeV}$ in calorimeter
  - Pair of photons from $a\rightarrow\gamma\gamma$
  - Single recoil photon
- Search for $a$
  - Bump in invariant $\gamma\gamma$ mass spectrum
  - Multiplicity of three; we don’t know which photon is which

Simulated calorimeter event with reducible background
ALPs

Calorimeter signature

- Mass $m_a$ and coupling $g_{a\gamma\gamma}$ determine
  - Displacement from collision point ($r_D$)
  - Opening angle $\theta$ of decay photons
- Four signatures:
  - Resolved: prompt decay, large $\theta$
  - Merged: prompt decay, small $\theta$
  - Displaced: (ignore; indistinguishable from $e^+e^- \rightarrow \gamma\gamma$)
  - Invisible: decay outside Belle, single-photon final state
ALPs

Phase 2 considerations

● Backgrounds
  ○ $e^+e^- \rightarrow \gamma\gamma(\gamma)$ with 0 or 1 $\gamma$ from beam background
  ○ Resolved: $e^+e^- \rightarrow \pi^0\gamma, \eta\gamma, \eta'\gamma$

● Trigger
  ○ Resolved: relax $e^+e^- \rightarrow \gamma\gamma$ prescale in trigger
  ○ Invisible: single-photon trigger (also captures prompt $a \rightarrow$ invisible)
ALPs: projected sensitivity

Conclusions

Belle II dark sector

- Belle II has **unique** sensitivity to ALPs and dark photons, even in low-luminosity **Phase 2**:
  - Specially designed triggers
  - Lower background than BaBar
  - Complementary to searches at SHiP and LHC
- Other Phase 2 dark-sector searches could include:
  - Dark photon → pseudo-Dirac DM
  - Off-shell $A'$ decays
  - Magnetic monopoles with small magnetic charges (additional slides)
  - Muonic dark force with dark boson $Z'$: $e^+e^- \rightarrow \mu^+\mu^-Z', Z' \rightarrow$ invisible
- **Phase 3** (to final luminosity)
  - Can use Phase 2 trigger for early Phase 3 runs too
  - Dark photon coupling to leptons: $A' \rightarrow l^+l^-$
  - A lot more...
Thank you!
Magnetic monopoles

Another Phase 2 specialty

- Search for magnetons with small magnetic charge
- **Distinct signature** in drift chamber: seen on-end, tracks will be straight
- **Special trigger:**
  - Trigger on any track that crosses all cells of inner drift chamber
  - Trigger in Phase 3 may be too tight
- Detection efficiency is **high**: 40-97%, depending on magneton mass