Searches for beyond-the-Standard-Model particles at Belle II

Christopher Hearty
University of British Columbia / IPP
June 4, 2019

CAP congress 2019
Outline

Focus on analyses possible with available (0.5 fb$^{-1}$) or short term (20 fb$^{-1}$) data sets, with a few interjections on longer term searches.

- Invisible decays of the dark photon
- Axion-like particles
- Invisible $Z'$
Quick summary of Belle II

• Located at the SuperKEKB e+e− collider at KEK. “Nano-beams” scheme should give 40× the luminosity of KEKB.

• Belle II is an extensive upgrade of Belle. New tracking, mostly new charged particle ID, new electronics for calorimeter.

• First colliding beam data (without vertex detectors) in Spring 2018 “Phase 2”. 0.5 fb−1 recorded.

• Currently commissioning with full detector. Expect 5 fb−1 by July 1, 100–200 fb−1 by summer 2020.
Dark sector

• The absence of discoveries by the LHC or dark matter direct detection experiments motivates interest in models with low-mass dark matter candidates.

• Simplest dark sector model has a (massive) dark photon $A'$ that mixes with strength $\epsilon$ with ordinary photon.

• Also includes dark matter particle $\chi$. Stable, neutral under SM forces. Carries dark charge, not electric charge.

The dark photon

- Can be created in $e^+e^-$ collision; will decay to dark matter if possible.

- On-shell $A' \Rightarrow$ signature is monoenergetic photon. Not sensitive to $m_\chi$ or $\chi/A'$ coupling.

\[
E^*_\gamma = E^*_\text{beam} - \frac{m^2_{A'}}{4E^*_\text{beam}}
\]

- Finite acceptance & imperfect detector: backgrounds from $e^+e^- \rightarrow \gamma \gamma (\gamma)$ and $e^+e^- \rightarrow e^+e^- \gamma (\gamma)$. Cosmics are not negligible.
• Simulated backgrounds, 40 fb$^{-1}$, excluding cosmics. Final sample is mostly $e^+e^- \rightarrow \gamma \gamma (\gamma)$ with $\geq 3\gamma$. 

\[ e^+e^- \rightarrow \gamma \gamma, \, 1\gamma \text{ in gap at 90°} \]

\[ e^+e^- \rightarrow \gamma \gamma \gamma, \, 1\gamma \text{ in barrel/endcap gap and 1 at } \theta^* \sim 0 \]

\[ \text{irreducible } e^+e^- \rightarrow e^+e^- \gamma \]
Goal with early dataset is the world’s best sensitivity.
- extrapolation to full 50 $\text{ab}^{-1}$ requires more work on photon inefficiency systematics.

If astronomical dark matter is due to the dark sector, parameters will lie along one of these lines.

How does Belle II improve on BaBar limits with a smaller dataset?

- BaBar calorimeter has (nearly) projective gaps; Belle II does not.

- Boost of center of mass is smaller and calorimeter is larger $\Rightarrow$ larger acceptance:

\[-0.94 < \cos \theta^* < 0.96 \quad \text{Belle II} \]
\[-0.92 < \cos \theta^* < 0.89 \quad \text{BaBar} \]
• Largest effect is at small mass / high photon energy. BaBar was not able to quantify the remaining peaking background from $e^+e^- \rightarrow \gamma\gamma$. We believe we have a program to do so on Belle II.

• What fraction of photons are missed by the calorimeter? What fraction are then also missed by the muon system?

\[ \text{Probability of } \gamma \text{ not interacting in 30 cm of CsI} = 3.4 \times 10^{-6}. \]
\[ \sim 9 \text{ beam-energy } \gamma \text{ per } fb^{-1}. \]
Use $e^+e^- \rightarrow \gamma\gamma$ control sample to measure probability that muon system detects photon as a function of energy leaking out of the back of the calorimeter.

- adjust MC (active detector size/efficiency, inactive material) to agree with data.

**Belle II simulation, 16 $fb^{-1}$; each bin = 1 calorimeter crystal**

- $0.7 < \text{Eleak} < 1.4 \text{ GeV}$
- $\text{Eleak} > 2.8 \text{ GeV}$

- gaps between muon system octants

- chimney for solenoid services
Search for a dark photon decaying to leptonic final states

- Final state is photon plus lepton pair. Large SM backgrounds, particularly in electron final state.

- Muon final state is dominant above threshold due to lower backgrounds.
Projected Belle II sensitivity for visible dark photon decays

- No real analysis yet; projected limits scaled from BaBar, assuming twice as good mass resolution.

Upper limit on $\varepsilon$ scales as luminosity $L^{0.25}$

Lifetime is non-negligible here; requires some work

BaBar collab., PRL 113, 201801 (2014), 514 fb$^{-1}$

Bertrand Echenard
C. Hearty
Search for invisible decays of the Z’

- Dark gauge boson may have direct couplings to SM (labeled Z’). Z’ that couples to 1st generation is strongly constrained, but not one that couples only to 2nd and 3rd generations.

- If $m_{Z'} < 2m_\mu$, decay is to neutrinos only. Also possible that decay to dark matter is dominant.

- BaBar searched for $4\mu^\pm$ final state, but no existing limits for invisible final state.


• Signature is $\mu^+\mu^-$ pair with a peak in the missing mass.

• Require $\vec{p}_{miss}$ to point into the calorimeter barrel. Reduce $\tau^+\tau^-$ background with kinematic distributions.
  - low $m_{Z^'}$ background is from $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$.

• Belle II can be competitive with 2018 data. Only 276 pb$^{-1}$ is usable due to low trigger efficiency for tracks.

Projected Belle II limits

range of parameters that would explain muon g-2. Will be challenging, even with 50 ab$^{-1}$
Axion-like particles

- Pseudo-scalars that couple to bosons. No strict relationship between coupling and mass.

- Focus on coupling to photons.

![Diagram of particle interactions]
• Different experimental signatures:

ALP is long lived: single photon analysis

• Three $\gamma$ signature: bump in invariant mass of $\gamma\gamma$.

• Large non-peaking background from $e^+e^- \rightarrow \gamma\gamma\gamma$.

• Largest peaking background is $e^+e^- \rightarrow \gamma\omega$, $\omega \rightarrow \pi^0\gamma$. Also $e^+e^- \rightarrow \gamma\pi^0$ and $e^+e^- \rightarrow \gamma\eta$.

Expected sensitivity

- No published results, so Belle II can be competitive with the 472 pb$^{-1}$ data from 2018.
• If ALP decays to dark matter, single $\gamma$ search is relevant. ALP mediation of SM / dark matter interaction could explain observed abundance if $m_a \approx 2m_\chi$. 

\[
\begin{align*}
\text{BaBar } \gamma + \text{inv} & \quad \text{LEP } \gamma + \text{inv} \\
\text{SN 1987A} & \\
\text{Belle II } \gamma + \text{inv (20 fb}^{-1}) & \\
\text{Belle II } \gamma + \text{inv (50 ab}^{-1}) & \\
\text{Qh}^2 = 0.12 \text{ via resonant freeze–out} \\
m_\chi = 0.45 \, m_a \\
m_\chi = 0.46 \, m_a \\
m_\chi = 0.47 \, m_a \\
m_\chi = 0.48 \, m_a \\
m_\chi = 0.49 \, m_a \\
g_{a\gamma Z} = 0
\end{align*}
\]
Searches for Axion-like particles in B decay

- ALP can be produced in radiative penguin B decays.
  - Sensitive to both $\gamma$ and $W^\pm$ couplings.

- Similar to $B \to K\pi^0$ analyses; will need a few ab$^{-1}$ to be competitive with Belle and BaBar data sets.
Longer term Belle II run plan

- Hope to surpass Belle integrated luminosity summer 2021 (depends on PXD installation).

- Full dataset by summer 2027.

---

**Plan is based on 8 months running per year**

- **Peak luminosity in early 2025**

- **50 ab^{-1} by summer 2027**

- **Phase 3 = real data taking**

- **long shut down in 2020 to install PXD**
Summary

• Searches for the direct production of low-mass new particles are a priority for the early running period of Belle II.

• Several topics are candidates for early publications. In particular, excellent calorimeter performance enables a competitive single photon analysis.

• Large number of other searches require more complex analyses or larger data sets.
Backup
Sources of detector inefficiency

- barrel/endcap gap
- 1.5mm structure at 90°
- active region of the detector
- backward gap for magnets/beam pipe
- forward gap for magnets/beam pipe
Nano-Beam Scheme

present KEKB (without crab)

SuperKEKB

1. Vertical beam size is much smaller: ~50 nm
2. Collision area is much smaller: ~0.5 mm
3. Even if bunch lengths are similar: ~10 mm

83 mrad crossing angle

22 mrad crossing angle

Collision area comparison:

KEKB
SuperKEKB

Top view
Side view

Longitudinal position (mm)
The Belle II detector

- Reusing solenoid, iron, part of muon system, calorimeter crystals. Remainder optimized for rates and high backgrounds.
Calorimeter performance in 2018 data

- Sufficient data to tune calorimeter performance.
  \[ \pi^0 \] reconstruction

  peak location good to 1% resolution within 2%

Comparison between calibration using Bhabhas and \( \gamma \gamma \) events
• \( \gamma \) control sample, \( e^+e^- \rightarrow \mu^+\mu^-\gamma \)

Ratio of observed to predicted energy

- Photon performance (Torben Ferber)
- Shower shapes example: Zernike MVA (all others in backup)
- MC normalized to data

Multivariate shower shape, MC and data

• Progress in hadron identification using new pulse-shape discrimination tools (Savino Longo)

K\(_L\) data (points) and MC

- Photons are selected using radiative muon pairs.
- Data and MC distributions for kaon-long sample peak near 0.0 indicating BDT is successfully classifying kaon-long candidate clusters as hadronic clusters.
- BDT distribution for photon candidates is shown on right. Peak at 1.0 indicates BDT is identifying photons as EM showers.

Additional details on BDT are in talk from physics session: https://kds.kek.jp/indico/event/28981/session/1/contribution/160

\( K_L \) data (points) and MC

\( \gamma \) from \( \mu\mu(\gamma) \)

\( m_{\phi}^{\text{calc}} \leq 1.06 \) GeV kaon-long candidates

\( \mu\mu\gamma \) MC
Soot in klystron gallery

- Fire was in accelerating structure test facility Nextef.
- Cleanup of klystron gallery took ~4 weeks.
• Path for cosmics to reach calorimeter without KLM or calorimeter vetos