Dark Matter and ALP Searches at Belle II

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Dark Matter Searches with \( e^+ e^- \) Collisions

- Indirect evidence for dark matter ranging from galactic to cosmological scales.

- Intensity frontier B-Factories can explore direct production of MeV to GeV scale mediators between Standard Model and Dark Matter/Dark Sectors.

- Several advantages of \( e^+ e^- \) collision environment for Dark Matter searches:
  - Well-known initial conditions and hermetic detectors allows for precise determination of missing energy/momentum.
  - Minimal background from collision pile-up.
  - High detection efficiency of charged and neutral particles.

Image: https://chandra.harvard.edu/photo/2006/1e0657/1e0657.jpg
SuperKEKB Collider

- Asymmetric $e^+e^-$ collider at $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV).
- Nano-beams to boost instantaneous luminosity, targeting 40x increase relative KEKB.
- Design luminosity of $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$.
- Peak of $2.4 \times 10^{34}$ cm$^{-2}$s$^{-1}$ achieved in 2020 (world record).
- Continuous injection.
The Belle II Detector

**Electromagnetic calorimeter:**
CsI(Tl) crystals, crystal gaps offset from IP, waveform sampling electronics. Measures energy, time and pulse shape.

**Vertex Detectors:**
DEPFET pixel detector (2 layers)
Double-sided silicon strip detector (4 layers)

**Drift Chamber:**
He(50%):C₂H₆(50%), Larger size relative to Belle, smaller cells, new electronics.

**Charge Particle Identification:**
- **Barrel:** Time-of-Propagation counter
- **Backward Endcap:** Aerogel Ring-Imaging Cherenkov counter

**Magnet:**
1.5T superconducting

**K⁰/μ Detector:**
Inner Barrel/Endcaps: Scintillating Strips
Outer Barrel: Resistive Plate Counters
Belle II Integrated Luminosity

- First physics data arrived in 2018 with 0.5 fb$^{-1}$ commissioning run.
  - One octant of vertex detector installed.
- Steady operations throughout 2019/2020, current dataset is $\sim 74$ fb$^{-1}$.
  - Vertex detector installed.
- Specialized low multiplicity triggers for Dark Sector searches (eg. single photon), are enabled in entire dataset.
  - Belle did not have single photon trigger, and BaBar had only for $\sim 10\%$ of dataset.

**Single Photon Level 1 Triggers:**

- At least one photon with $E_{\text{CMS}} > 2$ GeV
- One $E_{\text{CMS}} > 1$ GeV photon in barrel + no other energetic photons
- One $E_{\text{CMS}} > 0.5$ GeV photon in central barrel + no other energetic photons
Search for Z’ and LFV Z’
**Search for Z’**

- Search for Z’ mediator which couples only to 2nd and 3rd generation leptons ($L_\mu - L_\tau$ model).

- Could address Dark Matter, $(g - 2)_\mu$ and $b \to s\mu^+\mu^-$ anomalies.

- Production at Belle II by final state radiation of muon, search channel: $e^+e^- \to \mu^+\mu^-Z', Z' \to$ Invisiable

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- Belle II signature:
  - $\Rightarrow$ Missing energy + dimuon pair.
  - $\Rightarrow$ Search for peak in recoil mass of muons.
  - Backgrounds:
    - $e^+e^- \to \mu^+\mu^-(\gamma)$: Do not reconstruct photon
    - $e^+e^- \to \tau^+\tau^-(\gamma)$: Neutrinos escape detector
    - $e^+e^- \to \mu^+\mu^-\mu^+\mu^-; e^+e^-$ not in acceptance

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Search for Z’ Results

• Search conducted with 0.276 fb\(^{-1}\) of commissioning data.

• No excess observed, Belle II is first experiment to set limits on Z’ coupling, g’, for Z’ → Invisible

• Published in: Phys. Rev. Lett. 124, 141801 (2020)
Search for Lepton Flavour Violating $Z'$

- $Z'$ with LFV $e - \mu$ coupling discussed in literature as Dark Matter candidate.

- Model independent search for $e^+ e^-\rightarrow e^\pm \mu^{\mp} + \text{missing energy}$ completed by Belle II.

- Belle II signature:
  
  $\rightarrow$ Missing energy + one muon and one electron.

- Search for peak in recoil mass of leptons.

- $e^\pm \mu^{\mp}$ final state allows for significant background suppression relative standard $Z'$ search.

- Main background:
  
  $e^+ e^-\rightarrow \tau^+ \tau^-(\gamma)$

LFV Z’ Search Results

- Search conducted with 0.276 fb\(^{-1}\) of commissioning data.
- No excess observed, first experiment to set limits on cross-section for \(e^+e^- \rightarrow e^\pm\mu^\mp + \text{missing energy}\).
- Published in: *Phys. Rev. Lett.* 124, 141801 (2020)
Future Reach of Z’ Searches

- Full Belle II dataset is already over 200 times that used for first Z’ searches.
- Larger dataset and improvements in detector/trigger performance are predicted to already significantly extend sensitivity compared to initial search.

Update with current full dataset is in progress.
Search for Axion-Like Particles
Search for Axion-Like Particles

- Axion-Like Particles (ALPs) are pseudoscalars, $a$, which couple to Standard Model bosons via, $g_{a\gamma Z}$ and/or $g_{a\gamma\gamma}$. Belle II focus on $g_{a\gamma\gamma}$.

- ALPs with mass in the MeV-GeV range could be mediators to Dark Sectors and also could impact $(g - 2)_\mu$.

- Belle II search conducted using ALPstrahlung production channel:

\[
g_{a\gamma Z} e^+ e^- \rightarrow a \rightarrow \gamma \gamma^* \rightarrow \gamma \gamma \gamma
\]


Present analysis assumes prompt ALP decay
ALP Search

- Select fully neutral events consisting of 3 well-isolated photons with total invariant mass consistent with \(\sqrt{s}\).
- Search strategy optimized to maximize ALP sensitivity.
  - High ALP mass: Search \(M_{\text{recoil}}\) spectrum.
  - Low ALP mass: Search \(M_{\gamma\gamma}\) spectrum.
ALP Search Results

- Search conducted with $0.445 \text{ fb}^{-1}$ of commissioning data.
- No excess observed, limits set on ALP coupling to photons.

\[ \sigma_a = \frac{g_{\alpha \gamma \gamma}^2 \alpha_{\text{QED}}}{24} \left(1 - \frac{m_a^2}{s}\right)^3 \]
Extending ALP Searches at Belle II

• For ALP mass below ~0.2 GeV, ALPstrahlung channel limited. Photons from $a \rightarrow \gamma \gamma$ are merged in calorimeter.

• Photon fusion is an alternate production channel to search low mass region. Trigger is however challenging.

• At very low masses and small couplings ALP is long-lived, ALPstrahlung detector signature becomes single photon.

ALPstrahlung Detector Signature

$g_{\gamma \gamma}$

- Invisible
- Displaced
- Merged
- Resolved
- Completed

Detector signature is a single photon.

Photon Fusion ALP production

$e^+ e^-$

$\gamma$

$\gamma$

$e^-$

$e^-$

$e^+$

$e^+$

Single Photon Search
Single Photon Search

- Search for massive Dark Photon, $A'$, which mixes with Standard Model photon.
- Detector signature is a single initial-state radiation photon.

\[ e^+ e^- \rightarrow \mu^+ \mu^- \gamma \]

Belle II 2019
\[ \int L dt = 2.6 \text{ fb}^{-1} \]

0.5 GeV cluster trigger

Single photon trigger efficiency
\(~100\% \text{ above } 1 \text{ GeV}\)

- Single photon trigger is crucial:
  - Maintaining acceptable rate challenging due to beam-induced backgrounds
Projected Sensitivity


- Main backgrounds:
  
  \[ e^+e^- \rightarrow \gamma\gamma(\gamma) \]
  \[ e^+e^- \rightarrow e^+e^-(\gamma) \]

- Calorimeter coverage critical to suppress backgrounds.

- Belle II calorimeter features configuration where crystal gaps are offset from IP. Photons cannot escape between crystal boundaries.

  ➔ Significant improvement in background rejection. Belle II very competitive, even with smaller dataset.
Conclusions

• Intensity frontier B-Factories are a unique setting to search for direct production of MeV-GeV scale Dark Matter and Dark Sector mediators.

• Belle II has completed searches for Z' and axion-like particles using $< 0.5 \text{ fb}^{-1}$.


• Single photon search is in progress. L1 trigger efficiency measured to be $\sim 100\%$ above 1 GeV.

• Total dataset is now 74 fb$^{-1}$ and counting, many exciting updates ahead!
Thanks!
Extra Slides
$e^+e^- \rightarrow \tau^+\tau^-(\gamma)$ Suppression in Z' Search

- Missing energy in signal arises from Z' radiation off a final state muon.
- In background missing energy arises from both tracks due to neutrinos in tau decays.
- This difference allows the lepton kinematics to be used to suppress backgrounds from $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$.

![Plot](image.png)

**Belle II 2018 - Simulation**

Signal: $M_{Z'} = 3$ GeV/c$^2$