Dark Matter Searches at B-Factories: BaBar, Belle and Belle II

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DARK MATTER SEARCH IN EXPERIMENTS
Three Frontiers

- **Energy Frontier possibilities**
  - Dark particles directly produced by the LHC collider, exploiting high beam energy.

- **Cosmic Frontier**
  - Dark particle searches in underground labs, etc.

- **Intensity Frontier**
  - Interaction mediators between SM particles and Light dark mater (LDM)
  - Mediators enter into various portals
Dark Sector Covered by e+ e- B-Factories

Dark matter mediators
- Scalar portal
  - Dark Higgs, scalars
- Pseudoscalar portal
  - Axions or ALPs
- Vector portal
  - Dark photon, $Z'$
- Neutrino portal
  - Sterile neutrino

BaBar, Belle, Belle II
Search signature depends on the dark mediator mass

- $ll\,(\gamma)$ (+ missing)
  - Visible: ALP $\rightarrow ff$
    minimal and non minimal dark photons
  - Invisible: dark photon, $Z'$

- $ll\,l'l'$
  - Visible: ALP $\rightarrow ff$, scalars, $\mu\mu\tau\tau,\tau\tau\tau\tau$
    non minimal dark photons

- Single $\gamma$
  - Invisible: dark photon, ALP $\rightarrow \chi\chi$, IDM, LLP

- $\gamma\gamma$
  - Visible: ALP $\rightarrow \gamma\gamma$

- Long lived particles (LLP)
  - $A'$, ALP $\rightarrow \chi\chi$, IDM, scalars

- B meson decays into dark particles
B FACTORIES - BASICS
• Mass of B meson is around 5~6 GeV.
  – B pairs can be generated plentifully using ~ 11 GeV colliders

• Relatively lower energy makes it feasible to increase the intensity → intensity frontier

• First generation B factory:
  – ARGUS/DORIS II at DESY
  – CLEO/CESR at Cornell

• Next, asymmetric B factory:
  – BaBar/PEP-II at SLAC
  – Belle/KEKB at KEK

• 2nd generation asymm. Belle II/SuperKEKB at KEK

• Detectors at B-Factories have versatile particle identification+ reconstruction abilities
  – Dark sector searches are also effective and gaining interests.
Two Asymmetric B Factories from 1999

- CP Violation in the B section confirmed.
- Precision measurement of the CKM matrix. X(3872) and exotic particles.
- 2008 Nobel Prize, Kobayashi and Maskawa
- 2017 Hoam Prize (Korea), Sookyung Choi
The Belle II Detector

**KL and muon detector:**
- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

**EM Calorimeter:**
- CsI(Tl), waveform sampling

**Particle Identification**
- Time-of-Propagation counter (barrel)
- Prox. focusing Aerogel RICH (forward)

**Central Drift Chamber**
- (He + C2H6) small cells, long lever arm

**Vertex Detector**
- 1 to 2 layers Si Pixels (DEPFET)
- 4 layers Si double sided strip DSSD

**Beryllium beam pipe**
- 2cm diameter

**Pixelated photo sensors in TOP/ARICH/KLM**
Front-end ASICs in many subsystems.

**With respect to Belle,**
- Vertexing and Tracking Improved
- Particle ID improved, and
- Better background insensitivity.

**Note:** higher event rate

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SuperKEKB Luminosity: Current Status

• After the SupepKEKB commission phases, physics runs started spring 2019.
• Spring/summer 2022 run ended June.
  – Peak luminosity at $L_{\text{peak}} = 4.7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, the current world record on June 22nd.
  – Current integrated luminosity at $\int L_{\text{recorded}} dt = 424 \text{fb}^{-1}$.
    (~ Babar, ~ ½ Belle)
• Long shutdown 1 (LS1) started 2022 summer for upgrades (see later slides).
• Run 2 starts coming fall/winter.
Merits of Dark Search at e+ e- B-Factories

- The search region can reach lighter dark particles (1 MeV – 1 GeV)
- Background is lower compared to hadron colliders.
- Closed detectors $\sim 4\pi$
  - Missing momentum and energy can be a signature of invisible particle(s)
- High efficiency of neutral particle findings
- Easy to find signatures. Full event interpretation possible.
  - Low multiplicity signatures possible
  - Dark particle signatures in B and $\tau$ decays available
  - Clean environment can compensate for lower production cross-section.
Z′ SEARCH
The $L_{\mu} - L_{\tau}$ Model

- A new gauge boson $Z'$ assumed to couple only the 2nd and 3rd generation leptons.
  - May contribute to muon g-2
  - May explain dark matter abundance

Search for signature of $e^+e^- \rightarrow l l Z'$

$Z' \rightarrow \text{invisible}, \mu\mu, \tau\tau$

Invisible: neutrino, dark matter $\chi$

Shuve and Yavin, Phys. Rev. D 89, 113004
Altmannshofer et al., JHEP 12 (2016), 106
Search for Invisible $Z'$: Belle II

- **Belle II**: $e^+e^- \rightarrow \mu^+\mu^-Z'$, $Z' \rightarrow$ invisible
  - Invisible: neutrino (vanilla), dark matter $\chi$
- Look for a narrow recoil mass peak ($Z'$ candidate) against a $\mu^+\mu^-$ pair.
  - Requires no other particles in the event
- Dominant background is radiative QED processes.

$M_{\text{recoil}} \sim M_{Z'}$
Search for Invisible $Z'$: Belle II

- **Belle II** 79.7 fb$^{-1}$. No excess found in the recoil mass ($Z'$ candidate).
- 90% CL upper limits on the cross-section and on $g'$
- $(g - 2)_\mu$ excluded from $0.8 < M(Z') < 5 \text{ GeV}/c^2$

Vanilla
*(decay to neutrinos)*

- $\nu_\tau - \nu_\tau$

Fully invisible $L_\mu - L_\tau$
*(100% decay to $\chi\bar{\chi}$)*

- $\nu_\tau - \nu_\tau$

$\chi\bar{\chi}$
Search for Invisible $Z'$: Belle

- **Belle preliminary** did the same search with the full sample.
- Comparison between Belle 977 fb$^{-1}$ and Belle II 79.7 fb$^{-1}$ shows the better sensitivity of Belle II.
Search in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$

- **Belle II**: Search for di-tau resonance in 4 lepton events.
  - Tau decays to one charged track + neutrals
- Dominant background from 4 leptons suppressed by $M$ (4 tracks) $< 9.5$ GeV/c²
- Also used is $X$ is radiated from one muon.
- Discrepancies between data and simulation are coming from non-simulated or unmodeled processes.

PRL 131, 121802 (2023)
Search in $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$

- Belle II 62.8 fb$^{-1}$. No excess found in the recoil mass.
- 90% CL upper limits on the cross-section

$$\sigma(e^+e^- \rightarrow X \rightarrow \tau^+\tau^-) \mu^+\mu^-) = \sigma(e^+e^- \rightarrow X \mu^+\mu^-)\sigma (X \rightarrow \tau^+\tau^-), \quad X = S, ALP, Z'$$

- Exclusion limits on the couplings for three dark particle models obtained.

$Z'$

Leptophilic scalar (S)

ALP

First prove for $M_S > 6.5 \text{ GeV}/c^2$

World leading limit

PRL 131, 121802 (2023)
Search in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

- **Belle II**: Search for di-muon resonance in 4 lepton events.
- Mass peak search in the candidate muon pair.
  - At least three muons identified.
  - Total charge zero, $M(4 \text{ tracks}) \sim \text{beam energy}$. No extra energy.
- Multi-layer Perceptron (MLP) based background suppression
  - Candidate mass peak and production mechanism considered.

Capdevilla et al., JHEP 04 (2022) 129
Search in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

- **Belle II** 178 fb$^{-1}$. No excess found.
- 90% CL upper limits on the process cross-section

$$\sigma(e^+e^- \rightarrow X \rightarrow \mu^+\mu^-\mu^+\mu^-) = \sigma(e^+e^- \rightarrow X\mu^+\mu^-) \sigma(X \rightarrow \mu^+\mu^-), \quad X = S, Z'$$
Search in $e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$

- **Belle II** 178 fb$^{-1}$. No excess found.
- Cross-section limits translated into upper limits on the coupling constant
  - $g'$ for the $L_{\mu} L_{\tau}$ model
  - $g_S$ for the muon-philic dark scalar S
DARK SCALAR/HIGGS SEARCH
Search in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$

- **Belle** on 626 fb$^{-1}$. Search for leptophilic dark scalar ($\phi_L$) in 2 tau (1-prong decay) + 2 lepton events.
  - This mode can affect muon (g-2) results.
- Lepton = muon or electron, $\xi$: coupling strength
- Major background is $e^+e^- \rightarrow \tau^+\tau^-$.
- Radiative Bhabha (photon to two muons) removed by cuts on missing energy and its angle.
- Boosted Decision Tree (GrandientBoostingClassifier, scikit) is used to suppress backgrounds.
Search in $e^+ e^- \rightarrow \tau^+ \tau^- l^+ l^-$

- 626 fb$^{-1}$ Belle sample
- 514 fb$^{-1}$ BaBar sample

- 90% CL limit on $\xi$ (flavor-independent coupling to leptons) and mass of the dark scalar shown.

- More searches on the Belle full sample continues for a while.
Search in $e^+ e^- \rightarrow \mu^+ \mu^- + \text{invisible } h'$

- **Belle II**: 8.34 fb$^{-1}$. Search for a peak in the dimuon mass (as $A'$) + 2nd peak in the recoil mass (as $h'$) in the system via the dark Higgs-strahlung process.
ALP SEARCH
Axion Like Particle (ALP)

- ALP: pseudo-scalars couple to bosons.
  - Difference to QCD axions: no relation between the coupling and the mass
- ALP-strahlung: to study photon coupling $g_{a\gamma\gamma}$
- $B \to K a$ decays: to study $g_{aw}$ couplings

### ALP strahlung

![ALP strahlung diagram](image1)

### Photon fusion

![Photon fusion diagram](image2)

### B decays

![B decays graph](image3)
Search for $e^+ e^- \rightarrow \gamma a, a \rightarrow \gamma \gamma$

- **Belle II** search: Required 3 clear, resolved photons as the signature.
- Total mass should be the center of mass energy.
- Used calorimeter trigger.
  - ECL efficiency almost 100%

For $m_a$ in [0.2, 6.85] GeV/C$^2$, diphoton invariant mass is fitted.
Search for $e^+ e^- \rightarrow \gamma a, a \rightarrow \gamma \gamma$

- **Belle II** 445 pb$^{-1}$ sample from 2018 pilot run.
- 95% CL upper limits on the signal cross section and coupling $g_{a \gamma \gamma}$

$$\sigma_a = \frac{g_{a \gamma \gamma}^2 \alpha_{QED}}{24} \left(1 - \frac{m_a^2}{s}\right)^3$$

World’s best limit around 500 MeV/c$^2$
Search for $B^\pm \rightarrow K^\pm a$, $a \rightarrow \gamma\gamma$

- **BaBar** results on 424 fb$^{-1}$ shown here: 90% CL limits on signal branching fraction and coupling.
- Cf) Belle II study on dark sector in B decays, arXiv:2306.02830, submitted to PRL.
Search for $\tau \rightarrow l \alpha$, $\alpha$ invisible

- **Belle II**: look for an invisible boson $\alpha$ in tau decays. $\alpha$ can be an ALP candidate.
- One tau (tag) decays into 3 charged pions. The other tau (signal) decays into one lepton and a missing particle signature (two-body decay. BG is 3-body).
- No significant excess in 62.8 fb$^{-1}$.
- 95% CL upper limits on BF ratios of $\text{BF}(\tau_{\text{sig}} \rightarrow \ell \alpha) / \text{BF}(\tau_{\text{SM}} \rightarrow \ell \nu \bar{\nu})$
  - $2 \sim 14$ tighter limit than the previous ARGUS result (1995) due to luminosity 120 times.
B MESOGENESIS
**B-Mesogenesis**

- Elor et al., PRD 99, 035031 (2019) & Elahi et al., PRD 105, 055024 (2022)
- Dark baryons produced in CPV decays of B mesons.
  - Can be a factor of baryogenesis and dark matter.
  - Example) $B^0 \rightarrow \Lambda + \psi_D$, $B^\pm \rightarrow p + \psi_D$ where $\psi_D$ are invisible.

**BaBar analysis**
- Tag B: Fully reconstructed B hadron decays
- Signal B: single SM baryon + missing mass
- BDT used to separate signal from backgrounds.
  - kinematic info from tag B, info on hadronic decays of tag B, neutral info from signal B, missing momentum, etc.
B-Mesogenesis

- **BaBar** Results on 398.5 fb⁻¹. No significant signal
- 90% CL limits on signal branching fraction
- Shaded regions: branching fraction prediction by B-mesogenesis
- The invisible particle can be interpreted as something else.

Green: expected signal at $m_{\psi_D} = 2$ GeV/c²

**BABAR** preliminary

**BABAR**

PRD 107, 092001 (2023), arXiv:2306.08490 (submitted to PRL)
Summary

- $e^+ e^-$ B-factories provide unique opportunities to study dark sector
  - BaBar and Belle spearheaded the search in this area.
- SuperKEKB has achieved $L_{peak} = 4.7 \times 10^{34} cm^{-2}s^{-1}$, the world record on June 22nd, 2022.
  - It is a super B factory and in the full mode for physics analysis.
- Analysis techniques are now incorporating the latest developments in machine learning. B/D decays and $\tau$ channels became a new search field.
  - Many new possibilities opened, both in theory and experiment
- This is a very exciting time to look for new physics beyond the Standard Model, especially in the Dark Sector.
Search for Invisible $Z'$

- **Belle II** 79.7 fb$^{-1}$. No excess found in the recoil mass ($Z'$ candidate).
- 90% CL upper limits on the cross-section and on $g'$

![Graph showing cross-section vs. $M_{Z'}$]
Search in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

• **Belle II**: Search for di-muon resonance in 4 lepton events.
• Multi-layer Perceptron (MLP) based background suppression
  – Candidate mass peak and production mechanism considered.

![Background peak graph](image1)

![Signal graph](image2)
Search for $e^+ e^- \rightarrow \gamma a, a \rightarrow \gamma \gamma$

- **Belle II** search: Required 3 clear, resolved photons as the signature.
- Total mass should be the center of mass energy.
- Used calorimeter trigger.
  - ECL efficiency almost 100%

for $m_a$ in [0.2, 6.85] GeV/C^2, diphoton invariant mass is fitted.

for $m_a$ in [6.85, 9.7] GeV/C^2, recoil invariant mass ($\sim$ single photon mass) is fitted.

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PRL 125, 161806 (2020)
Search for $B^\pm \to K^\pm \alpha, \alpha \to \gamma \gamma$

- **BaBar**: look for two photon mass peak originated from B decays.
- Train separated boosted decision trees to suppress backgrounds.

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PRL 128, 131802 (2022), arXiv:2111.01800
Search for $\tau \rightarrow l \alpha$, $\alpha$ invisible

- **Belle II**: look for an invisible boson $\alpha$ in tau decays. $\alpha$ can be an ALP candidate.
- One tau (tag) decays into 3 charged pions. The other tau (signal) decays into one lepton and a missing particle signature.
- The observable is the normalized lepton energy in the tau pseudo rest frame:

$$x_\ell \equiv \frac{E_\ell^*}{m_\tau c^2 / 2}$$

![Graphs showing Belle II results for electron and muon modes](image)

**Belle II**

- **Electron Mode**
  - $L_{\ell e} = 62.8$ fb$^{-1}$
  - Data, Total uncertainty, $\tau \rightarrow e\nu\alpha, M_\alpha = 1.6$ GeV/c$^2$, $\tau \rightarrow e\mu\alpha, M_\alpha = 1.2$ GeV/c$^2$, $\tau \rightarrow e\mu\alpha, M_\alpha = 0$ GeV/c$^2$

- **Muon Mode**
  - $L_{\mu\tau} = 62.8$ fb$^{-1}$
  - Data, Total uncertainty, $\tau \rightarrow \mu\nu\alpha, M_\alpha = 1.6$ GeV/c$^2$, $\tau \rightarrow \mu\mu\alpha, M_\alpha = 1.2$ GeV/c$^2$, $\tau \rightarrow \mu\mu\alpha, M_\alpha = 0$ GeV/c$^2$
Belle II Physics Prospects

- Charm decays
- Next precision CKM matrix
  - Semileptonic B decays (CKM elements)
  - Hadronic B decays (angles and CPV)
  - Time dependent CP violation
- \( \tau \) physics
- Hadron spectroscopy
- Rare decays, FCNC
- New physics
  - Lepton flavor violation
  - Dark sector, long lived particles

https://confluence.desy.de/display/BI/Snowmass+2021

Belle II Physics Book, PTEP 2019, 123C01
KEKB to SuperKEKB: Accomplished

- Nano beam scheme + Crab waist optics
- Target: vertical beta function $\beta_y^*$ 5.9 mm (KEKB) to 0.3 mm (SuperKEKB)
- Increase beam currents $I_{e\pm}$
- Increase beam-beam interaction $\xi_y$

\[ L = \frac{y_{e\pm}}{2e r_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{I_{e\pm} \cdot \xi_y, e\pm}{\beta_y^*} \right) \left( \frac{R_L}{R_{\xi_y}} \right) \]

Beam crossing angle 22mrad
Beam crossing angle 83mrad

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Belle II Experiment in a Nutshell

- HEP experiments have seen huge accomplishments during the last decades.
  - CPV/CKM, discovery of XYZ/tetra/penta particles, discovery of Higgs, etc.
  - Next major theme: New Physics, requiring more precision and larger samples.
- Belle II/SuperKEKB is the upgrade of Belle/KEK.
- Upsilon(4S) decays into $B\bar{B}$ meson pairs, coherently with no additional fragments.
  - Full event reconstruction tagging possible
- Direct detection of neutrals such as $\gamma$, $\pi^0$, $K_L$.
- A hermetic detector:
  - Detection of neutrinos or invisibles as missing energy/momentum.
- Large continuum charm and $\tau$ samples in addition to $B$ samples.
  - Detect both $e$ and $\mu$ with similar performance.
  - For example, search for LFV $\tau$ decays at $O(10^{-9})$ possible.
Belle II and LHCb

- Belle II and LHCb have different systematics
  - Two experiments are required to establish NP.
  - LHCb: large $b\bar{b}$ cross-section (LHCb 1 fb$^{-1}$ ~ Belle II 1 ab$^{-1}$). Good sensitivity and S/N with di-muon modes and charged tracks with a vertex.