Z’ analyses at Belle II

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DMNet International Symposium
Padova, 26-28 September 2023
Introduction
Dark Matter is one of the most compelling reasons for New Physics.

B-factories at $e^+e^-$ collider can access the mass range favored by light dark sector.

→ Possible sub-GeV scenario: DM weakly coupled to SM through a light mediator $X$:

1. Vector portal
   - Dark Photons, $Z'$ bosons

2. Pseudo-scalar portal
   - Axion Like Particles (ALPs)

3. Scalar portal
   - Dark higgs/Scalars

4. Neutrino portal
   - Sterile Neutrinos
Light Dark Matter at B-factories

- **Dark Matter** is one of the most compelling reasons for **New Physics**
- B-factories at $e^+e^-$ collider can access the mass range favored by **light dark sector**
  - Possible sub-GeV scenario: DM weakly coupled to SM through a **light mediator X**:

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  2. Pseudo-scalar portal: Axion Like Particles (ALPs)
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See L. Zani presentation
Light Dark Matter at B-factories

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2. Pseudo-scalar portal
   Axion Like Particles (ALPs)

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- B-factories at $e^+e^-$ collider can access the mass range favored by **light dark sector**
  → Possible sub-GeV scenario:
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This presentation
Light Dark Matter possible signatures

- Once produced, the mediator can have three different types of decays:
  1. Invisible decays
  2. Leptonic decays
  3. Hadronic decays
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Once produced, the mediator can have three different types of decays:

1. Invisible decays: $Z' \rightarrow \text{inv.}$
2. Leptonic decays: $Z' \rightarrow \mu\mu$
3. Hadronic decays: $Z' \rightarrow \tau\tau$

+ some reinterpretations
Signature-based

Advantages from the **low particle multiplicity** at lepton colliders + **hermetic detector:**

→ Belle II at SuperKEKB asymmetric e⁺e⁻ collider

  - running at 10.58 GeV, well-known **initial condition**
  - efficient reconstruction of **neutrals**
  - specific low-multiplicity **triggers** (not present at Belle)
  - excellent particle identification system

**Unprecedented luminosity**

\[4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}\]

○ Shutdown since 2022 to install two-layer pixel detector
○ 424 fb\(^{-1}\) collected to date
○ Data taking resume by end of 2023
Z' analyses at Belle II
The $L_\mu - L_\tau$ model

- New gauge boson $Z'$ coupling only to the 2nd and 3rd generation of leptons ($L_\mu$-$L_\tau$)\footnote{B.Shuve and I.Yavin (2014) Phys. Rev. D 89, 113004; Altmannshofer et al JHEP 1612 (2016) 106} may explain:
  - long-standing $(g-2)_\mu$ anomaly
  - dark matter abundance

\[\chi = \text{dark matter}\]

\[\text{invisible} \quad \mu\mu \quad \tau\tau\]

In Belle II we search for the processes:
\[e^+e^- \rightarrow \mu^+\mu^0Z'\]
Search for an invisible $Z'$

- Search for the process: $e^+e^- \rightarrow \mu^+\mu^- Z' \rightarrow \text{invisible}$
  - Two possible interpretations:
    1) Vanilla, $BF(Z' \rightarrow \nu\bar{\nu}) \sim 33-100\%$
    2) Full invisible, $BF(Z' \rightarrow xx) \sim 100\%$

- Look for a narrow peak in the recoil mass against a $\mu^+\mu^-$ pair in events where nothing else is detected

- Dominant background radiative QED processes:
  1) $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$
  2) $e^+e^- \rightarrow \tau^+\tau^- (\gamma)$ (especially with both $\tau \rightarrow \mu$)
  3) $e^+e^- \rightarrow \mu^+\mu^- (\gamma)$

- Final State Radiation properties of the emitted $Z'$ fed in a neural network trained for all $Z'$ masses simultaneously
Search for an invisible Z’

- The signal yield extraction is performed through a **two-dimensional fit**
  - exploit of the features in the $M^2_{\text{recoil}}$ vs. $\theta_{\text{recoil}}$ distribution
  - double the sensitivity with respect to the one-dimensional fit

From $\mu^+\mu^-\gamma\gamma$ background

- $\mu^+\mu^-\gamma\gamma$ background
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  - exploit of the features in the $M^2_{\text{recoil}}$ vs. $\theta_{\text{recoil}}$ distribution
  - double the sensitivity with respect to the one-dimensional fit
Search for an invisible Z’

- No excess found in 79.7 fb⁻¹
  - 90% CL upper limits on $\sigma(e^+e^-\rightarrow \mu^+\mu^-Z', Z'\rightarrow \text{invisible})$ and on $g'\rightarrow (g-2)_\mu$ favored region excluded for $0.8 < M(Z') < 5 \text{ GeV}/c^2$

Fully invisible $L_\mu - L_\tau$ vs $M_{Z'}$ [GeV/$c^2$]

Vanilla $L_\mu - L_\tau$ vs $M_{Z'}$ [GeV/$c^2$]
Search for a $\tau\tau$ resonance in $ee \to \mu\mu\tau\tau$ as a peak in the recoil against two muons

- Search for a di-tau resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ as a peak in the recoil against two muons.

- Reconstruct $\tau$ decays to one-charged particle ($+n\text{h}_0$) → select four-track events with at least two tracks identified as muons → $M(4\text{tracks}) < 9.5\text{ GeV}/c^2$ to suppress the four-lepton backgrounds that peak at them c.m. energy.

- Background suppression exploits features of kinematic variables in the signal ($X$ arising from a final state radiation, system recoiling against the 2 muons is a tau pair).

- Discrepancies between data and simulation due to contributions from non-simulated/unmodeled processes.

$e^+e^- \to 4l+\gamma_{\text{ISR}}$
Search for a $\tau\tau$ resonance in $ee \rightarrow \mu\mu\tau\tau$

- No significant excess observed in 62.8 fb$^{-1}$
  $\rightarrow$ 90% CL upper limits on the process cross-section
  $\sigma(e^+e^- \rightarrow (X \rightarrow \tau^+\tau^-) \mu^+\mu^-) = \sigma(e^+e^- \rightarrow X \mu^+\mu^-) B(X \rightarrow \tau^+\tau^-)$, with $X = S, \text{ALP}, Z'$

- Exclusion limits on the couplings for three different models ($Z'[2]$, leptophilic scalar ($S$)$^3$, and $\text{ALP}[4]$) are derived:

[References]
Search for a $\mu\mu$ resonance in $ee \to \mu\mu\mu\mu$

- Search for the process $e^+e^- \to \mu^+\mu^-X$, with $X \to \mu^+\mu^- (X = Z', S)$
  - Look for a peak in the opposite charge di-muon mass distribution in $e^+e^- \to \mu^+\mu^- \mu^+\mu^-$ events

- (L$_\mu$ - L$_\tau$) model used as benchmark and then performances are checked for the scalar case [5]

Scalar particle coupling to muons through Yukawa-like interaction

Mainly proposed as a way to solve the muon $(g-2)_\mu$ anomaly

$$\mathcal{L} \supset g_S S \bar{\mu}\mu$$

Coupling constant: induces a shift in

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{theory}}$$

If $m_S > 2m_\mu$ the only tree-level decay channel is $S \to \mu\mu$

($S \to \nu\bar{\nu}, \gamma\gamma$ also are possible at one loop level, but highly suppressed)
Search for a $\mu\mu$ resonance in $ee \rightarrow \mu\mu\mu\mu$

- Events selected have **4 charged particles**: 
  - zero charge 
  - at least **three identified as muons** 
  - $M(4\text{tracks}) \sim \sqrt{s}/c^2$ 
  - no extra energy

- Main SM background contributions:
  1) $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$
  2) $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$
  3) $e^+e^- \rightarrow \mu^+\mu^- (\gamma)$

→ **Multi-Layer Perceptron (MLP)-based background suppression**
Signal over background discrimination relying on a few variables sensitive the signal features:

(a) Presence of a $\mu\mu$ resonance
(b) Production mechanism
Search for a $\mu\mu$ resonance in $ee \rightarrow \mu\mu\mu\mu$

Peak corresponding to the maximum muon pair momentum

→ transformed variables fed into MLP in order to reduce their change with the Z' mass

→ five separate MLPs in different $M(\mu\mu)$ intervals

→ selection optimized in each interval with a figure of merit

→ background rejection factor from 2 to 14
→ signal efficiency from 20% to 35%
Search for a $\mu\mu$ resonance in $ee \rightarrow \mu\mu\mu\mu$

- No significant excess observed in 178 fb$^{-1}$
- 90% CL upper limits on the process cross-section $\sigma(e^+e^- \rightarrow X \mu^+\mu^-) \times B(X \rightarrow \mu^+\mu^-)$, with $X = Z', S$
Search for a $\mu\mu$ resonance in $ee \rightarrow \mu\mu\mu\mu$

- No significant excess observed in 178 fb$^{-1}$
  - 90% CL upper limits on the process cross-section $\sigma (e^+e^- \rightarrow X \mu^+\mu^-) \times B(X \rightarrow \mu^+\mu^-)$, with $X = Z', S$
  - Cross section limits are translated into upper limits on the $g'$ coupling constant for the $L_\mu - L_\tau$ model and on the $g_S$ coupling constant for the muonphilic dark scalar $S$\cite{5}

First $g_S$ upper limit obtained from a dedicated search

Upper limits similar to those set from previous searches with much larger luminosity than ours

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Conclusion

- Belle II/SuperKEKB is a **unique environment** to search for **light dark matter or mediators**

- **Excellent sensitivity** for dark sector searches

- **World’s leading results** are obtained with a subset of the full available data

  - Search for invisible Z’
  - Search for visible Z’ to muons (+ muonphilic scalar)
  - Search for visible Z’ to taus (+ leptophilic scalar and ALP)

- 424 fb⁻¹ recorded to date, **more results with higher statistics and improved analyses will be produced**


Thank you!
Backup
SuperKEKB

Total beam current
1.5 x KEKB current

Vertical beam-beam parameter

Beta function at the IP
20 times smaller than KEKB

\[ L = \frac{y_{\pm}}{2\epsilon r_e} \left( \frac{I_{\pm}}{\beta^*} \right) \left( \frac{R_L}{R_{\xi y}} \right) \]
Search for a $\mu \mu$ resonance in $ee \to \mu \mu \mu \mu$: $J/\Psi$

- data/MC ratio is over 1 (but for very low masses)
- Modulations due to the different MLP ranges
- Visible features: $\rho$, $J/\Psi$, $\Upsilon(1S)$
Search for a $\mu\mu$ resonance in $ee \rightarrow \mu\mu\mu\mu$
Search for a $\mu\mu$ resonance in $ee \rightarrow \mu\mu\mu\mu$: muonphilic dark-scalar

We extended the $Z'$ search to the case of a muophilic dark scalar, $S$

- Scalar particle coupling through Yukawa-like interaction, only
- Mainly proposed as a way to solve the muon $(g-2)_\mu$ anomaly

$$\mathcal{L} \supset g_S S \overline{\mu} \mu$$

Coupling constant: induces a shift in

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{theory}}$$

- If $m_S > 2m_\mu$, the only tree-level decay channel is $S \rightarrow \mu\mu$
  ($S \rightarrow \nu\nu, \gamma\gamma$ also are possible at one loop level, but highly suppressed)

We reinterpreted our result in terms of the dark scalar $S$, keeping all the steps of the analysis completely unaltered

1) P. Harris, P. Schuster, J. Zupan, Snowmass White Paper: New flavors and rich structures in dark sectors
2) S. Gori, M. Williams, et al., Dark Sector Physics at High-Intensity Experiments
3) D. Forbes, C. Herwig, New Searches for Muonphilic Particles at Proton Beam Dump Spectrometers
4) R. Capdevilla, D. Curtin et al., Systematically testing singlet models for $(g - 2)_\mu$
Search for a $\mu\mu$ resonance in $ee \rightarrow \mu\mu\mu\mu$: muonphilic dark-scalar

Difference: $Z'$ is softly produced at low masses, $S$ have a hard momentum spectrum also in the low mass region.

In $e^+ e^- \rightarrow \mu^+ \mu^- X$ interactions $X$ can be:

- A vector: production occurs through a $s$-wave process
- A scalar: production occurs through a $p$-wave process

At low $S$ masses the $p$-wave suppression makes the scalar process grow slowly with the energy, while there is no suppression for vector processes.
Search for a $\mu\mu$ resonance in $ee \rightarrow \mu\mu\mu\mu$: muonphilic dark-scalar

**Belle II preliminary**

Harder $S$ spectrum compared to the $Z'$, $\mu D$ works better.

Differences in momentum spectrum decrease, and the MLP effect is dominant.
Search for a dark leptophilic scalar in $\tau$ decays at Belle

- Search for a narrow peak in $m_{ll}$ distribution
- Mass range probed in this analysis: $40\text{ MeV} < m(\Phi_l) < 6.5\text{ GeV}$
  - $\Phi_l \rightarrow e^+e^- \text{ for } m(\Phi_l) < 2m(\mu) \rightarrow$ low mass region
  - $\Phi_l \rightarrow \mu^+\mu^- \text{ for } m(\Phi_l) > 2m(\mu) \rightarrow$ high mass region

- **Strategy:**
  - $e^+e^- \rightarrow \tau^+\tau^- \Phi_l$ require 1-prong decay
  - 4 tracks with 0 net charge

- **Background:** $e^+e^- \rightarrow \tau^+\tau^-, e^+e^-/\mu^+\mu^-, q\bar{q}, B\bar{B}$
  - Define five BDT score to suppress backgrounds

- Maximum Likelihood fit to $m_{ll}$ distribution
  - Evaluate sensitivities to each mass point
Search for a long-lived (pseudo-)scalar particle in $b \rightarrow s$

- Search for **dark scalar** particles $S$ from $B$ decays in **rare $b \rightarrow s$ transitions**
  - $S$ could mix with SM Higgs with mixing angle $\theta_s$ (naturally long-lived for $\theta_s << 1$)
  - $M_S < M_B$, decays of $S$ into dark matter particles must be kinematically forbidden to provide the correct relic density

- Look for $S$ decays into SM final states in **8 exclusive channels**:
  - $B^+ \rightarrow K^+ S$
  - $B^0 \rightarrow K^0 (\rightarrow K^+\pi^-) S$

- **B-meson candidates** are reconstructed from prompt and displaced charged tracks
- **S candidates** are reconstructed from displaced oppositely-charged tracks pairs
- B-meson kinematics to reject combinatorial background
- **Signature**: bump hunt with extended max likelihood unbinned fits to the (*)reduced mass spectrum, separately for each channel and lifetime
Search for a long-lived (pseudo-)scalar particle in $b \to s$

- **No significant excess found in 189 fb$^{-1}$**
  - first model-independent 95% CL upper limits on $BF(B \to KS) \times BF(S \to x^+x^-)$
  - translate into model independent limits on $\sin \theta_s$ vs. $m_s$

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First limits on decay to hadrons

Results are also available for the pseudo-scalar (ALP) model

Submitted to PRL: https://arxiv.org/abs/2306.02830

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Search for a dark leptophilic scalar in $\tau$ decays at Belle

- No significant excess observed in 626 fb$^{-1}$ in all mass region
  - Low mass region
  - High mass region

- 90% CL UL on $\xi$ vs $m(\Phi_1)$
  - Comparable or more stringent limits than BaBar (Phys. Rev. Lett. 125, 181801)
  - Exclude a wide range of parameter space of the model favored by $(g-2)_\mu$