Dark Matter searches at Belle II

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> on the behalf of the Belle II collaboration
SuperKEKB and Belle II

A second generation B-factory

Located at KEK Laboratory in Tsukuba, Japan.

SuperKEKB is an asymmetric $e^+e^-$ collider, operated mainly at the center of mass energy of 10.58 GeV ($= m_Y(4S)$).

A second generation B-factory:

• 40 times increase in instantaneous luminosity with respect to predecessor KEKB
  • 2x from higher beam current
  • 20x from final focus magnets

It will be the world highest luminosity ($L = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$).
The Belle II Experiment

Inside the detector

**Electromagnetic calorimeter (ECL):**
CsI(Tl) crystals, waveform sampling to measure time and energy (possible upgrade: pulse-shape).
Non-projective gaps between crystals

**K_{L} and muon detector (KLM):**
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

**Magnet:**
1.5 T superconducting

**Vertex detectors (VXD):**
2 layer DEPFET pixel detectors (PX)
4 layer double-sided silicon strip detectors (SVD)

**Central drift chamber (CDC):**
He(50%); C_{2}H_{6} (50%), small cells, fast electronics

**Particle Identification (PID):**
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cerenkov Counter (ARICH)

Belle vs Belle II
Better resolution, PID and capability to cope with higher background

TDR: arXiv:1011.0352
The Belle II Experiment

Time schedule

2018
First physics data (500 pb⁻¹).
Incomplete detector (1/8 VXD)
Commissioning data.

2019
Up to now ~10 fb⁻¹ collected
Will continue 7-9 month/years

~2027

Goal
Integrate up to 50 ab⁻¹
X50 dataset of its predecessor (Belle)
DM Searches

Motivations & Models

The absence of discoveries by the LHC or dark matter direct detection experiments as well as independent theoretical motivations motivate the interest for models with low-mass dark matter candidates.

A possible GeV and sub-GeV theoretical scenarios:

- Light-DM associated with new dark forces, weakly coupled to SM through a new light mediator X.

Different possible portals between Dark Sector and Standard Model depending on the mediator X:

- **Vector Portal** → Dark Photon A', Dark Z'
- **Pseudo-scalar Portal** → Axion Like Particles
- **Scalar Portal** → Dark Scalars, extended Higgs models
- **Neutrino Portal** → Sterile Neutrinos
The Belle II Experiment

Not just a B-factory

Although designed mainly for B-physics, Belle II has excellent features to explore the Dark Sector Physics:

• Clean environment with well defined initial state and low background level;
• Hermetic detector (>90% solid angle);
• Excellent PID capability;
• Dedicated triggers for low-multiplicity events (e.g. single photon trigger)

Belle II is very efficient in the reconstruction of recoiling system and missing energy final states

Probing DM at a collider

Perfect place to explore Dark Sector Physics in the ~ MeV - 10 GeV range

CNNP 2020 – Dark Matter searches at the Belle II experiment (M. Campajola)
Focus on analyses competitive with available Phase 2 (0.5 fb⁻¹) or early Phase 3 [ O(10-100 fb⁻¹) ] data sets:

- Invisible Z' (L_μ - L_τ)
- Axion-like particles
- Invisible dark photon
- Dark Higgsstrahlung
Z’ to invisible
Z’ to invisible

A bit of Theory

New light gauge boson Z’ coupling only to the 2\textsuperscript{nd} and 3\textsuperscript{rd} generation of leptons ($L_\mu - L_\tau$ model);

\[ \mathcal{L} = \sum_{\ell = \mu, \tau, \nu_{\mu, \tau}, \nu_{e, \ell}} \theta g' \tilde{\ell} \gamma^\mu Z'_\mu \ell \]

This model may explain:

- DM puzzle;
- $(g-2)_\mu$ anomaly;
- $B \rightarrow K(*)\mu\mu$, $R_K$, $R_{K^*}$ anomalies;

Looking for an invisibly decaying Z’ produced with a pair of muons.

- Z’ could decay to SM neutrinos or DM if kinematically accessible (e.g., sterile neutrinos, light Dirac fermions)

Shuve et al. (2014), \texttt{arXiv:1403.2727}
Altmannshofer et al. (2016) \texttt{arXiv 1609.04026}

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Z’ to invisible

Experimental signature

Looking for:
- A peak in the mass distribution of the recoiling system against $\mu\mu$ pair;
- Nothing else in the rest of event

Background:
- Everything with 2 particles identified as muons and missing momentum.
- Mainly from QED processes:
  $e^+e^- \rightarrow \mu^+\mu^- (\gamma)$;
  $e^+e^- \rightarrow \tau^+\tau^- (\gamma), (\tau \rightarrow \mu\nu\nu)$;
  $e^+e^- \rightarrow \mu^+\mu^- e^+e^-$;

Measurement performed with data collected during Phase 2. Only 276 pb$^{-1}$ usable due to trigger conditions for 2 track events.
**Z’ to invisible**

**g’ Upper Limit**

90% CL upper limit on the cross section and then translated in terms of the $g’$ coupling constant.

First results ever for the $Z’$ to invisible decay.


**List of systematic uncertainties**

- Tracking: 4%
- Trigger: 6%
- LeptonID: 4%
- Luminosity: 0.7%
- Background suppression: 22%
- Muon yields (signal): 12.5%
- Background level: 2%

*If DM is kinematically accessible, $BR(Z'\rightarrow \text{inv}) \approx 1$ can be assumed.*

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Z’ to invisible

Results for a LFV Z’

Searching for a Lepton Flavour Violating Z’ that couples to $e\mu$;
Model independent search with same analysis selection criteria of
the Z’ to invisible search.

Submitted to PRL (same publication of the ‘Standard’ Z’)

For example see I. Galon et al. (2016) arXiv:1610.08060

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

\[ e^+ e^- \rightarrow \mu^+ \mu^- Z'; Z' \rightarrow \text{invisible} \]
Axion Like Particles
Axion Like Particles

A bit of theory

Axion Like Particles (ALPs) are pseudo-scalars particles ($a$) that couple to bosons.

\[ \mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \]

They can be Dark Matter candidates, Dark Sector mediators, and they appear in many BSM scenarios.

Focus on coupling to photons. Two possible production processes:

- **Photon fusion**
- **ALP-strahlung**

Exploring photon coupling $g_{a\gamma\gamma}$ in ALP-strahlung

No results at B-factories yet
First exploring photon coupling $g_{\gamma\gamma}$ in ALP-strahlung

Several topologies depending on $(m_a, g_{\gamma\gamma})$ parameters; ALPs can also decay to DM;

$$\tau \sim 1/g_{\gamma\gamma}^2 M_a^2$$

Final state:
- 3$\gamma$ that add up to the beam energy;
- Zero tracks;
- bump on di-photon mass;

Background:
- $e^+e^- \rightarrow \gamma\gamma(\gamma)$;
- $e^+e^- \rightarrow e^+e^- (\gamma)$;
- $e^+e^- \rightarrow P\gamma(\gamma)$, $P = \pi^0, \eta, \eta'$;

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Axion Like Particles

Expected sensitivity

*Belle II* can be competitive with Phase2 dataset (∼500pb⁻¹).

Measurement to be finalized very soon

*No systematics. Only (dominant) ee→γγ γ background included 135fb⁻¹ assumes no γγ trigger veto in the barrel*
Dark Photon
**Dark Photon to invisible**

**A bit of theory**

A possible extension of the SM includes a new massive gauge boson $A'$ of spin = 1 coupling to the SM through the kinetic mixing with strength $\varepsilon$, called **dark photon**.

\[
\mathcal{L} \supset \varepsilon g_D A'_\mu J_{\text{EM}}^\mu
\]

At $e^+e^-$ colliders: $e^+e^- \rightarrow \gamma_{\text{ISR}} A'$

Two basic scenarios depending on $A'$ vs DM masses relationship:

\[
m_x > \frac{1}{2} m_A' \rightarrow A' \text{ visible decays to SM particles;}
\]

\[
m_x < \frac{1}{2} m_A' \rightarrow A' \text{ invisible decays to LDM;}
\]

First exploring the invisible decay:

\[
e^+e^- \rightarrow \gamma_{\text{ISR}} A' \rightarrow \gamma_{\text{ISR}} \chi \bar{\chi}
\]
**Dark Photon to invisible**

**Analysis strategy**

**Signal Signature:**

- Only one mono-chromatic, high-E photon $\gamma_{ISR}$ in the detector.
- No tracks, no other good photons.
- Bump in the photon energy:

\[ E_\gamma = \frac{s - M^2_{A'}}{2\sqrt{s}} \text{ (on-shell)} \]

Needs a special **single photon trigger**

(not available in Belle, $\approx$ 10% of data in BaBar)

**Discriminant variables:** $E_{CMS}$ vs. polar angle of “single photon”

**SM backgrounds:**

- $ee \rightarrow \gamma\gamma(\gamma)$
- $ee \rightarrow ee(\gamma)$
- Cosmics
Dark Photon to Invisible

Expected Sensitivity

**Belle II expected sensitivity (preliminary)**

*From the Belle II Physics book, arXiv:1808.10567*

**BaBar limit, 50 fb-1**

**Belle II projection, 20 fb-1**

Very promising results even with early Phase 3 dataset (~ 20 fb⁻¹).

Why Belle II is expected to perform better than BaBar?

- no ECL cracks pointing to the interaction regions
- smaller boost and larger calorimeter ⇒ larger acceptance
- KLM veto

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

General remarks

The dark photon mass could be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson $h'$ to the theory.

In a minimal scenario: a single dark photon $A'$ and a single dark Higgs boson $h'$.

The $h'$ could be produced in the Higgsstrahlung process, which is also sensitive to the dark sector coupling constant $\alpha_D$.

Different scenarios depending on the mass hypothesis.

Focus on $m_{h'} < m_{A'}$ case:
- 2 charged particle in the final state plus missing energy.
- First looking at muon final state.

Signal:
- A peak in the Recoil mass vs. Di-muon mass phase space.

Background:
- Everything with 2 particles identified as muons and missing momentum: $\mu\mu$, $\tau\tau$, $ee\mu\mu$, $\pi\gamma$
Dark Higgsstrahlung

Expected sensitivity

Belle II Expected Sensitivity (Preliminary) *

Very promising results even with early Phase 3 dataset (~10 fb⁻¹).

Still unconstrained region in $\epsilon^2 \alpha_D$.
Beyond the KLOE coverage.

90% C.L. UL on $\epsilon^2$ in Dark Photon searches lies in $\sim 5 \cdot 10^{-7}$ regime.

Probing non trivial regions with 10 fb⁻¹
Conclusions

• Although designed mainly for B-physics, the Belle II experiment has a broad and active program to explore the Dark Sector Physics;

• It started operations in 2018 (Phase 2). Successful commissioning of the machine and 0.5fb\(^{-1}\) of data collected;

• Phase 3 started physics data taking on March 2019. Up to now ~ 10 fb\(^{-1}\) collected.

• First result with early data are coming:
  • \textit{Z’ to invisible} search with the Phase 2 data close to publication.
  • ALPs search with Phase 2 data to be finalized very soon;
  • invisible \textit{A’}: good prospects even with early Phase 3 data;
  • Dark Higgsstrahlung:

Possibility to explore many more dark sector models;

For further details see:

Spare

Others Dark Sector searches

• Visible dark photon decays
• Off-shell dark photon decays
• Muonic dark force: $e^+ e^- \rightarrow \mu^+ \mu^- Z', Z' \rightarrow \mu^+ \mu^-$
• Magnetic monopoles with small magnetic charges
• Long-lived particles (LLPs)
Spare

Belle II performances snapshots

**Belle II 2018 (Preliminary)**

\[ \int L \ dt = 261 \text{pb}^{-1} \]

\[ \mu_{\text{EXP}} = 0.998 \pm 0.001 \]

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

Pull

![Graph showing data and fit for Belle II 2018 (Preliminary)]

**Belle II 2019 Preliminary**

\[ \int L \ dt = 2.62 \text{fb}^{-1} \]

\[ N_{\text{sig}} = 1608 \pm 54 \]

**Belle II 2019 Preliminary**

\[ J/\psi \rightarrow e^+e^- \]

Pull

![Graph showing candidates for Belle II 2019 Preliminary: J/\psi \rightarrow e^+e^- ]

**Belle II 2019 Preliminary**

\[ J/\psi \rightarrow \mu^+\mu^- \]

Pull

![Graph showing candidates for Belle II 2019 Preliminary: J/\psi \rightarrow \mu^+\mu^- ]

**Belle II 2019 Preliminary**

\[ \pi^0 \rightarrow \gamma\gamma \]

Pull

![Graph showing candidates for Belle II 2019 Preliminary: \pi^0 \rightarrow \gamma\gamma ]
Spare

$Z'$ to invisible

**Analysis cuts:**

- Require $p_{\text{rec}}$ to point into calorimeter barrel region (only for $M_{\text{rec}} < 3 \text{ GeV/c}^2$)
- Calorimeter-based particle identification ($E/p$)
- Reject events with additional energy $E > 0.4 \text{ GeV}$ or any $\pi^0$ candidates
- Reduce $\tau^+ \tau^-$ background with kinematic cuts on transverse momenta of $Z'$ (missing momentum) wrt max and min momentum muons;