Dark sector searches at Belle II

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OUTLINE OF THE TALK
✓ Light dark sector models
✓ Belle II searches
✓ Results
✓ Perspectives & Summary
Dark matter hunt with a light sector

**Light Dark Matter Mediators → portals**

**Vector portal**
- Dark photon, $Z'$, ...

**Pseudoscalar portal**
- QCD Axions, ALPs, ...

**Scalar portal**
- Dark Higgs, scalars

**Neutrino portal**
- Sterile neutrino

**Energy frontier**
Direct production of new particles - limited by beam energy (LHC – ATLAS, CMS)

**Cosmic frontier**
Direct effect search in (mostly) underground experiments
Light dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

- Probability of interaction of LDM detectors is negligible
  - Search for mediators
  - Search for missing energy signature
  - Search for both

Additional benefits:

- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, ...)
- Explanation of the (g-2)\(_\mu\) effect
- Explanation (with additional hypotheses) of some flavour anomalies (LHCb, Belle, ...)
- Some light mediators (not interacting with quarks) could escape direct search exclusion limits
**Belle II trigger**

**Dark sector physics**
- Low multiplicity signatures
- Huge backgrounds from beam, Bhabha, two-photon

Level 1 hardware-based combines info from CDC, ECL, KLM
- Tracks, clusters, muons
  - Two-track trigger
  - Three-track trigger
  - $E_{ECL} > 1 \text{ GeV}$ trigger

Single muon
- CDC + KLM

Single track
- Neural based
- Displaced-vertex trigger
  - Under study

Single photon
- $E_\gamma > 0.5, 1, 2 \text{ GeV}$
Models are growing up \sim exponentially (a warm thank’s to theoreticians to provide us so many ideas). They should be used both to exclude (or confirm!) and as wonderful excuses to search for signatures & topologies as model independently as possible.

Search overview: models $\leftrightarrow$ signatures $\leftrightarrow$ topologies

- **Visible minimal and non minimal dark photons, ALP$\rightarrow$ff**
- **Invisible dark photon, Z’**
- **Visible non minimal dark photons, ALP$\rightarrow$ff, scalars, $\mu\mu\tau\tau$, $\tau\tau\tau\tau$**
- **Invisible dark photon, ALP $\rightarrow$\chi\chi$, iDM, LLP**
- **Visible ALP $\rightarrow$ $\gamma\gamma$**
- **Single $\gamma$**
- **LLP long-lived particles**
- **A’, ALP$\rightarrow$\chi\chi$, iDM, scalars**

Invisible dark photon, $\text{ALP} \rightarrow \text{\gamma\gamma}$,

Visible minimal and non minimal dark photons, $\text{ALP} \rightarrow \text{ff}$,

Invisible dark photon, $\text{ALP} \rightarrow \text{\mu\mu\tau\tau}$,

Visible non minimal dark photons, $\text{ALP} \rightarrow \text{ff, scalars}$,

Invisible dark photon, $\text{ALP} \rightarrow \text{\chi\chi, iDM, LLP}$,

Visible dark photon, $Z’$,

Visible $\text{ALP} \rightarrow \text{\gamma\gamma}$,

Single $\gamma$,

LLP long-lived particles,

A’, $\text{ALP} \rightarrow \text{\chi\chi, iDM, scalars}$,

Hot topic
Belle II dark sector search overview: results

Published or publicly shown

- **$L_\mu$-$L_\tau$**
  - $Z' \rightarrow \text{invisible}$
  - $Z' \rightarrow \mu\mu$
  - $Z' \rightarrow \tau\tau$

- **Axion like particles**
  - ALP$\rightarrow\gamma\gamma$

- **Invisible $\alpha$ in $\tau$ decays**
  - $\tau \rightarrow l\alpha$

- **Dark Higgsstrahlung**
  - $A'h' \rightarrow \mu\mu, \ h' \rightarrow \text{invisible}$

- **Axion like particles**
  - $A'h' \rightarrow \chi_1\chi_2, \ h' \rightarrow \mu\mu, \pi\pi, \ kk$

- **Invisible dark photon**
  - $\gamma' \rightarrow A'h'$

**In progress**

Not covered today. Have a look at back up slides.

- **LLP dark scalar in B decays**
  - $B \rightarrow kS \rightarrow ee, \mu\mu, \pi\pi, \ kk$

- **Invisible dark photon**
  - $\gamma' \rightarrow A'h'$

**Belle II dark sector search overview:**

[Results](#)
**Z': L_μ - L_τ model**

- Gauging $L_\mu - L_\tau$, the difference of leptonic $\mu$ and $\tau$ number
- A new gauge boson which couples only to the $2^\circ$ and $3^\circ$ lepton family
- Anomaly free (by construction)
- It may solve
  - dark matter puzzle
  - $(g-2)_\mu$
  - $B \to K(\ast)\mu\mu$, $R_K$, $R_{K^*}$ anomalies

Shuve et al. (2014), arXiv 1408.2727
Altmannshofer et al. (2016) arXiv 1609.04026
Belle II dark sector search overview: results

Reinterpreted also as
- Muonphilic dark scalar $S \rightarrow (g-2)_{\mu}$

- Discovery mode for $Z'$ and $S$
- Aggressive background suppression
- Exclusions on $Z' \sim$ Babar and Belle, with much less luminosity
- First limits on $S$ with a dedicated search

To be submitted to PRD
Belle II dark sector search overview: results

Reinterpreted also as
- Leptophilic dark scalar $S \rightarrow (g-2)_\mu$
- ALP with $\tau$ coupling

• Aggressive background suppression
• Look for peaks in the system recoiling against $\mu\mu$

PRL 131, 121802 (2023)
Belle II dark sector search overview: results

- Photon veto
- Aggressive background suppression
- Look for peaks in the system recoiling against $\mu\mu$

Fully invisible $Z'$ as origin of $(g-2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c$^2$
Belle II dark sector search overview: results

Axion like particles
ALP → γγ

Look for peaks in γγ mass or in the mass of the system recoiling against an isolated γ

PRL 125, 161806 (2020)
Look for a double peak in the $\mu\mu$ mass and in the system recoiling against $\mu\mu$. 

**Diagram:**

- $e^+e^- \rightarrow A'^* \rightarrow h' A'$
- $\gamma \rightarrow A'^*$
- $\alpha_D$
- $h'$
- $\mu^+\mu^-$
- $\mu^-$
- $\mu^+$

**Graphs:**

- Belle II
- $\int Ldt = 8.34 \text{ fb}^{-1}$
- $90\% \text{ CL UL}$
- $M_{h'}$ [GeV/c$^2$]
- $M_{A'}$ [GeV/c$^2$]
- $\varepsilon^2 \times \alpha_D$
Invisible $\alpha$ in $\tau$ decays
$\tau \rightarrow l\alpha \quad l = e, \mu$

$e^+e^- \rightarrow \tau^+\tau^-$

Pseudo-rest-frame from opposite (tag) $\tau \rightarrow \pi\pi\pi$

Invisible $\alpha$ in $\tau$ decays
$\tau \rightarrow l\alpha \quad l = e, \mu$

Pseudo-rest-frame from opposite (tag) $\tau \rightarrow \pi\pi\pi$

LFV, possible ALP candidate

**Belle II dark sector search overview: results**

PRL 130, 181803 (2023)
Belle II dark sector search overview: results

LLP dark scalar in $B$ decays
$B \rightarrow kS \quad S \rightarrow ee, \mu\mu, \pi\pi, kk$

$b \rightarrow s$ transitions
Possible mixing with $H_0$
LLP signature

$S \rightarrow e^+e^- / \mu^+\mu^- / \pi^+\pi^- / K^+K^-$

Submitted to PRL
arXiv:2306.02830
Dark sector searches in Belle II: future directions

- Align all the searches to the full pre-shutdown luminosity 424 fb$^{-1}$
- In most cases with improved analysis techniques: second generation searches
- We have already reasonable luminosity projections for some of the analyses (Snowmass)

- We need to enter the dark photon business: both visible and (especially) invisible

➢ My guess: LLP searches will have a considerable weight in the next years (especially with a new displaced-vtx trigger)
  Low SM background, open the possibility to explore small couplings

➢ Some searches are motivated more than others by the g-2 anomaly. Their future may depend on external inputs. My guess: the g-2 focus is moving (has moved?) in the theory field: dispersion relations vs lattice

- Luminosity will increase, background will increase as well
- Most of the searches have low multiplicity signatures → badly affected by machine background
- Best effort to keep the single-object (track, muon, photon) trigger lines in working conditions
- Display-vertex trigger needed (efficiency decreases abruptly with lifetime): in preparation

❖ We are eager of new dark models. Theorists never disappoint our expectations
Summary

• The persisting null results from new physics at LHC searches and in direct underground searches make the light dark sector scenario more and more attractive

• **Belle II** started a broad program of searches orthogonal/complementary to LHC

• **Will lead the world sensitivity in most of them**
BACKUP SLIDES
Key factors for dark sector physics: trigger, high backgrounds, precise knowledge of acceptance/vetoes, PID.
• Gauging $L_\mu - L_\tau$, the difference of leptonic $\mu$ and $\tau$ number
• A new gauge boson which couples only to the $2^\circ$ and $3^\circ$ lepton family
• Anomaly free (by construction)
• It may solve
  ➢ dark matter puzzle
  ➢ $(g-2)_\mu$
  ➢ $B \to K(\ast)\mu\mu, R_K, R_{K^*}$ anomalies

Sterile $\nu$'s
Light Dirac fermions

Shuve et al. (2014), arXiv 1408.2727
Altmannshofer et al. (2016) arXiv 1609.04026

Sterile neutrino abundance
Z': $L_\mu - L_\tau$ model

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  - **dark matter puzzle**
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Altmannshofer et al. (2016) arXiv 1609.04026

**Annihilation**

**Direct detection**

E. Graziani – Dark sector searches at Belle II - Brookhaven Forum 2023
Belle II dark sector search overview: projections

Lμ - Lτ
Z' → invisible

Belle II Simulation, $L_{μ} - L_{τ}$

Expected 90% CL UL

Belle II, 0.276 fb$^{-1}$

$g'$

$\int L \ dt = 80 \text{ fb}^{-1}$
$\int L \ dt = 500 \text{ fb}^{-1}$
$\int L \ dt = 5 \text{ ab}^{-1}$
$\int L \ dt = 1 \text{ ab}^{-1}$
$\int L \ dt = 50 \text{ ab}^{-1}$

$m_{Z'} \ [\text{GeV/c}^2]$
Belle II dark sector search overview: projections

Axion like particles
ALP → γγ

Belle II (2018) ∫ L dt = 445 pb⁻¹

Belle II physics reach @ Snowmass
arXiv: 2207.06307v1
Dark Higgsstrahlung

$A' h' \rightarrow \mu\mu$, $h'$ invisibile

Belle II dark sector search overview: projections

Belle II simulation $M_{h'} = 1 \text{ GeV/c}^2$

90% CL UL

$\epsilon^2 \times \alpha_D$

$M_{A'}$ [GeV/c$^2$]

$\epsilon^2 \times \alpha_D$

$M_{A'}$ [GeV/c$^2$]

$\epsilon^2 \times \alpha_D$

$M_{A'}$ [GeV/c$^2$]

Belle II physics reach @ Snowmass

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Belle II dark sector search overview: projections

LLP dark scalar in B decays

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LLP signature

$S \to e^+e^- / \mu^+\mu^- / \pi^+\pi^- / K^+ K^-$

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Dark matter hunt: «classical» approach

Intensity / precision frontier

New virtual particles in loops/trees transitions, deviation from SM expectations (B factories, LHCb)

If NP found in direct searches, it is reasonable to expect NP effects in B, D, tau decays

Energy frontier

Direct production of new particles - limited by beam energy (LHC – ATLAS, CMS)

Cosmic frontier

Direct effect search in (mostly) underground experiments

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In progress Belle II dark searches
Dark photon: introduction

- Paradigm of the vector portal extension of the SM
- QED inspired: $U(1)' \rightarrow$ new spin 1 gauge boson $A'$
- Couples to SM hypercharge $Y$ through kinetic mixing $\varepsilon$
- Couples to dark matter with strength $\alpha_D$
- Mass through Higgs or Stuckelberg mechanism

![Diagram](image)

**Minimal dark photon**

**Production cross section**

Production cross section

<table>
<thead>
<tr>
<th>$\varepsilon = 1$</th>
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$\sigma_{e^+e^- \rightarrow \gamma A'}$ (nb)

- $m_{A'} < 2m_\chi \Rightarrow A'$ decays visibly to SM particles ($l, h$)
- $m_{A'} > 2m_\chi \Rightarrow A'$ decays $\approx 100\%$ invisibly to DM particles

Belle II vs BaBar
✓ Calorimeter with no projective cracks in $\phi$
✓ Larger acceptance
✓ KLM veto

Belle II physics reach @ Snowmass

arXiv: 2207.06307v1
Inelastic dark matter with dark Higgs

- Dark photon $A'$ and dark Higgs $h'$
- Two dark matter states $\chi_1$ and $\chi_2$ with a small mass splitting
- $\chi_1$ is stable $\rightarrow$ dark matter candidate
- $\chi_2$ is generally long-lived
- $h'$ is generally long-lived and mixes with SM $H_0$
- Signature: up to two displaced vertices

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JHEP 04 (2021), arXiv:2012.08595