Dark matter search at Belle II

Enrico Graziani
INFN – Roma 3

on behalf of the Belle II Collaboration

OUTLINE OF THE TALK
✓ Light dark sector models
✓ Belle II and SuperKEKB
✓ An example: $L_\mu-L_\tau$ invisible $Z'$
✓ Results
✓ Perspectives & Summary
Peak luminosity trend

Very rich physics program

- **Flavour physics**
  - CKM matrix
  - CPV in B decays

- **BSM physics**
  - Rare decays
  - NP in loops in $b \rightarrow s\gamma$, $b \rightarrow sll$
  - $B \rightarrow D^{(*)}\tau\nu$
  - LFV in $\tau$ decays

- **New particles (quarkonium)**

- **Dark sector**

SuperKEKB

Final goal: $L = 50\text{ ab}^{-1}$
Dark matter hunt

LDM → Light Dark Matter Mediators → portals

The possibility of LDM make intensity machines genuine discovery machines
Searching for dark matter

Dark Sector Candidates, Anomalies, and Search Techniques

- Vector portal: Dark photon, $Z'$, ...
- Pseudoscalar portal: Axions, ALPs, ...
- Scalar portal: Dark Higgs, scalars
- Neutrino portal: Sterile neutrino

Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators

E. Graziani – Dark matter searches at Belle II - DMNet2023
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
From KEKB to SuperKEKB

- moderately increased beam currents
- Squeeze beams @IP by ~1/20

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From KEKB to SuperKEKB

- **Upgraded rings**
  - New e⁺ Damping Ring
  - Increased currents

- **Nano-beam scheme**
  - New Final Focus magnets (QCS)
  - Large crossing angle

**Final goal: 50 ab⁻¹**

- **Collected luminosity up to now: 2019-2022**
  - Integrated luminosity
  - Recorded Daily
  - $\int L_{\text{Recorded}} dt = 427.79 [fb^{-1}]$

  **~424 fb⁻¹ total**

- Total integrated daily luminosity [fb⁻¹]

- Current collected luminosity up to now: 2019-2022

- **Currently in shutdown LS1 since July 2022**

- **Restart run in December 2023**

- Peak luminosity world record: $4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Key factors for dark sector physics: trigger, high backgrounds, precise knowledge of acceptance/vetoes, PID
**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
- \( E_{\text{ECL}} > 1 \text{ GeV} \) trigger

**Single muon**
- CDC + KLM

**Single track**
- Neural based

**Single photon**
- \( E_{\gamma} > 0.5, 1, 2 \text{ GeV} \)

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**Displaced-vertex trigger**
- Under study

**Single \( \gamma \) trigger efficiency**

**Belle II** 2019

\[ \int L dt = 4.6 \text{ fb}^{-1} \]

1 GeV cluster trigger
What can we do at B-factories that we can't at the LHC?

• Closeness to the light region
• Clean, low background, «energy conserving» environment, closed kinematics
• 3d momentum conservation, as opposed to $p_T$
• Easiness of tag & probe techniques
• Full Event Interpretation

• Low multiplicity signatures
• Missing energy channels
• Invisible particles, often in closed kinematics regime
• Some fully neutral final states accessibility
• Dark sector signatures in B and $\tau$ decays

• Cleanliness and luminosity sometimes compensate for cross section $\rightarrow$ competition
Models are growing up ~ 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.

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**Search overview: models ↔ signatures ↔ topologies**

- **II (γ) (+missing)**
  - **Visible** minimal and non minimal dark photons, ALP→ff
  - **Invisible** dark photon, Z’

- **Single γ**
  - **Invisible** dark photon, ALP →χχ, iDM, LLP

- **VV**
  - **Visible** non minimal dark photons, ALP→ff, scalars, μμττ, ττττ

- **γγ**
  - **Visible** ALP → γγ

- **LLP**
  - long-lived particles
  - Hot topic

- **A’, ALP→χχ, iDM, scalars**

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Z’: L_\(\mu\) - L_\(\tau\) model

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

Shuve et al. (2014), arXiv 1408.2727
Altmannshofer et al. (2016) arXiv 1609.04026
Z': $L_\mu - L_\tau$ model

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Sterile $\nu$'s

Light Dirac fermions

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

Sterile neutrino abundance

Shuve et al. (2014), arXiv 1408.2727
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Annihilation

Direct detection

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Z’ to invisible: first Belle II physics result

Explored for the first time
\( e^+e^- \rightarrow \mu^+\mu^- + \text{missing energy} \)

Look for bumps in recoil mass against a \( \mu^+\mu^- \) pair

Main backgrounds:

\( e^+e^- \rightarrow \mu^+\mu^- (\gamma) \)
\( e^+e^- \rightarrow \tau^+\tau^- (\gamma), \tau^{\pm} \rightarrow \mu^{\pm}v\bar{v} \)
\( e^+e^- \rightarrow e^+e^- \mu^+\mu^- \)

FSR vs ISR + \( \tau \) decay
Z’ to invisible: first result

Pilot run physics results

First physics paper by Belle II
PRL 124 (2020), 141801

Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiency</td>
<td>6%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>4%</td>
</tr>
<tr>
<td>PID</td>
<td>4%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.5%</td>
</tr>
<tr>
<td>Background before τ suppression</td>
<td>2%</td>
</tr>
<tr>
<td>τ suppression (background)</td>
<td>22%</td>
</tr>
<tr>
<td>Discrepancy in μμ yield (signal)</td>
<td>12.5%</td>
</tr>
</tbody>
</table>

will decrease with new data
**Belle II dark sector search overview: results**

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

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

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

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

**In progress**

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

**LLP Dark Higgsstrahlung with IDM**
- $A'h' A' \rightarrow \chi_1\chi_2$, $h' \rightarrow \mu\mu, \pi\pi, kk$

**Invisible dark photon**
- $\gamma A' A' \rightarrow \chi\chi$
Belle II dark sector search overview: results

Fully invisible $Z'$

fully invisible $Z'$ as origin of $(g-2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/$c^2$

PRL 130, 231801 (2023)
Belle II dark sector search overview: projections

Belle II Simulation, $L_\mu - L_\tau$

Expected 90% CL UL

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

$Z' \rightarrow \text{invisible}$
Reinterpreted also as:

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

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

Probed for the first time masses above 6.5 GeV/$c^2$

World-leading limits!
Belle II dark sector search overview: results

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

First $g_s$ upper limit obtained from a dedicated search

To be submitted to PRD

Reinterpreted also as
- Muonphilic dark scalar $S \rightarrow (g-2)_\mu$
Belle II dark sector search overview: results

Axion like particles
ALP→γγ

Pilot run physics results

\[
\begin{align*}
    \text{Belle II (2018)} & \quad \int L dt = 445 \text{ pb}^{-1} \\
    g_{\text{AY}} [\text{GeV}^{-1}] & \quad m_a [\text{GeV}/c^2] \\
    g_{\text{AY}} = 0 & \quad \text{NA64, electron beam dumps, proton beam dumps, ee→γγ, ee→γ + inv.}
\end{align*}
\]

PRL 125, 161806 (2020)

see L. Zani’s talk
Belle II dark sector search overview: projections

Axion like particles
ALP → γγ

Belle II (2018) \( \int L dt = 445 \text{ pb}^{-1} \)

Belle II physics reach @ Snowmass

arXiv: 2207.06307v1
Belle II dark sector search overview: results

Dark Higgsstrahlung
A’h’ A’→μμ, h’ invisibile

Belle II ∫Ldt = 8.339 fb⁻¹

see L. Zani’s talk

PRL 130, 071804 (2023)
Belle II dark sector search overview: projections

**Dark Higgsstrahlung**

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

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**Belle II simulation**

$M_{h'} = 1$ GeV/$c^2$

- $\int L \, dt = 500$ fb$^{-1}$
- $\int L \, dt = 2$ ab$^{-1}$
- $\int L \, dt = 10$ ab$^{-1}$
- $\int L \, dt = 50$ ab$^{-1}$

90% CL UL

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Belle II physics reach @ Snowmass

arXiv: 2207.06307v1
Invisible $\alpha$ in $\tau$ decays

$\tau \rightarrow l \alpha \quad l = e, \mu$

Belle II dark sector search overview: results

LFV, possible ALP candidate

see L.Zani’s talk

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

LLP dark scalar in B decays

\[ B \rightarrow kS \quad S \rightarrow e^+e^- / \mu^{+}\mu^{-} / \pi^{+}\pi^{-} / K^{+}K^{-} \]

b→s transitions
Possible mixing with \( H_0 \)

LLP signature

Submitted to PRL
arXiv:2306.02830
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 $\epsilon$
- Couples to dark matter with strength $\alpha_D$
- Mass through Higgs or Stuckelberg mechanism

**Production cross section**

**Minimal dark photon**

**two basic scenarios depending on $A'$ vs $\chi$ DM mass relationship**

$\mathcal{M}_{A'} < 2\mathcal{M}_\chi \Rightarrow A'$ decays visibly to SM particles $(l, h)$

$\mathcal{M}_{A'} > 2\mathcal{M}_\chi \Rightarrow A'$ decays $\approx100\%$ invisibly to DM particles

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Dark photon: luminosity projections

**Visible**

- painstaking accuracies
- Large acceptance
- KLM veto

**Invisible**

- Calorimeter with no projective cracks in $\phi$
- Larger acceptance
- KLM veto

**Belle II vs BaBar**

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

JHEP 04 (2021), arXiv:2012.08595

LLP signature

see L.Zani's talk
Belle II and SuperKEKB after shutdown

- Currently in shutdown LS1 since summer 2022
  - Accelerator upgrades: mitigate background and increase luminosity
  - Detector upgrades: two layer pixel detector installed

- Restart SuperKEKB in December 2023 and physics beginning of 2024

- Path to $2 \times 10^{35}$ cm$^{-2}$s$^{-1}$, but new interaction region to go beyond
  - Possible LS2 ~2027
  - Belle II upgrades under study

**Target scenario:** extrapolation from 2021 run including expected improvements.

**Base scenario:** conservative extrapolation of SuperKEKB parameters from 2021 run
Dark sector searches in Belle II: future directions

- Align all the searches to the full pre-shutdown luminosity $424 \text{ fb}^{-1}$
- 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 $g$-2 anomaly. Their future may depend by 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 $\rightarrow$ 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

see M.Laurenza’s talk

see L.Zani’s talk
SPARE SLIDES
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
Alternative DM scenario: light WIMPs ↔ light mediators

Light dark matter not ruled out if dark mediator(s) exist

WIMP paradigm: \( \sigma_{\text{ann}}(v/c) \approx 1 \text{ pb} \Rightarrow \Omega_{\text{DM}} \approx 0.25 \)

Electroweak mediators \( \Rightarrow \) Lee – Weimberg window

\[
\sigma(v/c) \propto \begin{cases} 
G_F^2 m_\chi^2 & \text{for } m_\chi \ll m_W \\
1/m_\chi^2 & \text{for } m_\chi \gg m_W 
\end{cases}
\]

\( \Rightarrow \) few GeV < \( m_\chi \) < few TeV

If annihilation via a light force carrier, \( \chi \) can be as light as few MeV

Possibility of Light New Physics, mostly with tiny couplings. Some models are minimal (but UV safe) and show diverse DM phenomenology
From KEKB to SuperKEKB

- New $e^+$ Damping Ring
- New Superconducting Final Focus (QCS)

**Beam current**

$$L = \frac{\gamma_{e^\pm}}{2e \gamma e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{I_{e^\pm}}{\beta_y^*} \right) \left( \frac{\xi_y^*}{\xi_y} \right)$$

**Beam-beam parameter**

$$\xi_{y\pm} = \frac{r_e}{2 \pi \gamma y \sigma_y^* (\sigma_x^* + \sigma_y^*)} R_{\xi y} \propto \frac{N_{e\pm} \beta_y^*}{\sigma_y^*} \sqrt{\frac{\beta_y^*}{\xi_y}}.$$

- Lumi. reduction factor (crossing angle) & Tune shift reduction factor (hour glass effect)
- 0.8 ~ 1 (short bunch)

- Vertical beta function@IP
- Beam size ratio@IP
- 1 ~ 2 % (flat beam)

**Nano-Beam scheme**

- $\sigma_x \sim 100 \mu m, \sigma_y \sim 2 \mu m$

... For a 30x increase in intensity you have to make the beam as thin as a few x100 atomic layers

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- $\beta_y^* = 0.30/0.30$ mm
- $I_{+/-} = 2.8/2.0$ A

(1) Smaller $\beta_y^*$
(2) Increase beam currents
(3) Increase $\xi_y$
Invisible dark photon: experimental signature

Only **one photon** in the detector

Needs a **single photon trigger**
*(not available in Belle, ≈ 10% of data in BaBar)*

Needs an excellent knowledge of the **detector acceptance**

\[ E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}} \]

Bump in recoil mass or photon energy

**Backgrounds**

- \( e^+e^- \rightarrow e^+e^-(\gamma) \) high \( M_{A'} \) region
- \( e^+e^- \rightarrow \gamma\gamma(\gamma) \) low \( M_{A'} \) region

**Cosmics**

\( e^+e^- \rightarrow \gamma\nu\nu \)

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Invisible dark photon: background

**ee→2γ and 3γ**
1γ in ECL 90° gap
1γ out of ECL acceptance

**ee→eeγ**
both electrons out of tracking acceptance

**Crucial usage of KLM to veto photons in ECL gaps**