Dark Sector Searches with Belle II

Enrico Graziani
INFN – Roma 3
on behalf of the Belle II Collaboration

OUTLINE OF THE TALK
• Belle II and SuperKEKB
• Search of the invisible dark photon
• Search of ALP
• Search of Z' (invisible)
• Search of magnetic monopoles
• Summary

SUSY2018
26th International Conference on Supersymmetry and Unification of Fundamental Interactions
Barcelona, July 23-27, 2018 susy2018.ifae.es
Peak luminosity trend

e+e- colliders

40 times higher luminosity

SuperKEKB

Very rich physics program

Flavour physics
- CKM matrix
- CPV in B decays

BSM physics
- Rare decays
- NP in loops in b→sγ, b→sll
- B →D(*)τν
- LFV in τ decays

New particles (quarkonium)

Dark sector
From KEKB to SuperKEKB

Beam current

Vertical beta function@IP

Beam size ratio@IP
1 ~ 2 % (flat beam)

Lorentz factor

Classical electron radius

Beam-beam parameter

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

1. Smaller $\beta_y^*$
2. Increase beam currents
3. Increase $\xi_y$

For a 40x increase in intensity you have to make the beam as thin as a few x100 atomic layers

$E^*y = 0.27/0.30 \text{ mm}$

$I_{+/-} = 3.6/2.6 \text{ A}$

$\sigma_x \sim 100 \mu \text{m, } \sigma_y \sim 2 \mu \text{m}$
**Belle II detector**

**Electromagnetic calorimeter (ECL):**
Csl(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

**Trigger:**
L1: < 30 kHz
HLT: < 10 kHz

**Vertex detectors (VXD):**
2 layer DEPFET pixel detectors (PXD)
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 II vs Belle**
better resolution, PID and capability to cope with higher background
Belle II data taking plan

**Phase 2**
- 1/8 of vertex detector
- Low backgrounds
- Pass-through HLT (software) trigger

**Good conditions for dark searches**

**Phase 3**
- $L \approx 50 \text{ ab}^{-1}$ with the full detector
Belle II data taking plan: today

Phase 2

Phase 2 finished July 17th 9 am
- Nano-beam scheme works!
- $L = 5.5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ achieved
- $L_{\text{int}} > 0.5 \text{ fb}^{-1}$ collected

- 1/8 of vertex detector
- Low backgrounds
- Pass-through HLT (software) trigger

- Tracking and clustering L1 trigger
- Bhabha veto L1 trigger
- Some single photon L1 trigger

Good conditions for dark searches
Belle II & SuperKEKB Phase 2

Start of collisions: April 25th
Belle II performance snapshots

\( k_S \rightarrow \pi \pi \)

\( J/\psi \rightarrow \mu \mu \)

\( \pi^0 \rightarrow \gamma \gamma \)

2 days after first collisions

\( \mu = (497.159 \pm 3.013) \text{ MeV/c}^2 \)

\( \sigma = (3.462 \pm 0.075) \text{ MeV/c}^2 \)
Dark photon: introduction

Some astrophysical observations suggest the possibility of the existence of a new light (GeV scale) hidden dark sector with a mediator \( A' \) (dark photon), weakly coupled to the Standard Model via kinetic mixing, and light dark matter.

At \( e^+e^- \) colliders

\( \chi \equiv \text{dark matter particle} \)

Two basic scenarios depending on \( A' \) vs matter mass relationship

\[
\begin{align*}
\text{m}_\chi > 1/2 \text{ m}_{A'} & \Rightarrow A' \text{ visible decays (SM particles)} \\
\text{m}_\chi < 1/2 \text{ m}_{A'} & \Rightarrow A' \text{ invisible decays to LDMA}
\end{align*}
\]

\( A' \rightarrow l^+l^- \)

\( A' \rightarrow \pi^+\pi^- \)

h' A' dark higgstrahlung

h' \rightarrow A'A', A'A' \rightarrow 6 \ l^\pm + \pi^\pm \ A'+\text{missing}

\( A' \rightarrow \chi \chi \)

Access to light dark matter particles

Invisible dark photon: experimental signature

Only one photon in the detector. Needs a single photon trigger (not available in Belle, \approx 10\% of data in BaBar)

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

Bump in recoil mass or photon energy

Backgrounds
\[ e^+e^- \rightarrow e^+e^-\gamma(\gamma), e^+e^- \rightarrow \gamma\gamma(\gamma) \]

<table>
<thead>
<tr>
<th>Trigger logic</th>
<th>L1 rate at full luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>E &gt; 1 GeV</td>
<td>4 kHz (barrel)</td>
</tr>
<tr>
<td>+ 2nd cluster E &lt; 300 MeV</td>
<td>7 kHz (endcaps)</td>
</tr>
<tr>
<td>E &gt; 2 GeV</td>
<td>5 kHz (barrel)</td>
</tr>
<tr>
<td>+ Bhabba &amp; γγ vetoes</td>
<td></td>
</tr>
</tbody>
</table>

Limited mainly by acceptance

Probably not sustainable in deep Phase 3, where some prescaling or threshold adjustment will be needed
Invisible dark photon: backgrounds

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

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

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

**ee → 2γ**
1γ in ECL BWD or FWD gap

**ee → 3γ**
1γ in ECL BWD gap
1γ out of ECL acceptance
Invisible dark photon: sensitivity

![Graph showing the sensitivity of Belle II calorimeter compared to other experiments]

- Belle II calorimeter has no projective cracks in $\phi$
- Lower trigger threshold wrt BaBar

Mathematical expression:

$$y = \varepsilon^2 \alpha_D \left( \frac{m_\chi}{m_{A'}} \right)^4$$

Parameters:

- $\alpha_D = 0.5$
- $3m_\chi = m_{A'}$
Visible dark photon: sensitivity

Competitive only in Phase 3

E. Graziani – Dark Sector Searches with Belle II – SUSY2018
Axion Like Particles (ALPs)

- Pseudo-scalars particles which couple to bosons.
- Differently from QCD axions, no relation between mass and coupling.
- Focus on coupling to photons: $g_{a\gamma\gamma}$
- Alp-strahlung + photon fusion production mechanisms
- $\tau \sim 1 / g_{a\gamma\gamma}^2 m_a^3$
- No results at B factories yet

$$W \sim \frac{1}{g_{a\gamma\gamma}} \frac{2}{m_a^3}$$

Photon fusion sensitivity under study

3 $\gamma$ topology
Axion Like Particles (ALPs): signal

3 $\gamma$ topology, but...

ALP decays outside of the detector or decays into invisible particles: Single photon final state.

ALPs can also decay to DM $\rightarrow$ single photon topology

Two of the photons overlap or merge.

Three resolved, high energetic photons.

The searches for invisible and visible ALP decays veto this region.
Axion Like Particles (ALPs): sensitivity

Only coupling to $\gamma$

With coupling to $Z$

$g_{\gamma Z} = 0$

$g_{\gamma Z} = -2 \tan \theta_W g_{\gamma \gamma}$
L_\mu - L_\tau: Z' invisible decay

- A new gauge boson Z' which couples only to the 2° and 3° lepton family
- May explain (g-2)_\mu
- Invisible decay channel to be explored for the first time
- Invisible decay channel BR possibly enhanced by the presence of kinematically accessible dark matter (e.g. sterile neutrinos)
- Sometimes invoked to explain EDGES results

Invisible Branching Ratios

Branching ratios to SM v's:
- M_{Z'} < 2 M_\mu \rightarrow \Gamma(Z' \rightarrow \text{inv.}) = 1
- 2 M_\mu < M_{Z'} < 2 M_\tau \rightarrow \Gamma(Z' \rightarrow \text{inv.}) \sim 1/2
- M_{Z'} > 2 M_\tau \rightarrow \Gamma(Z' \rightarrow \text{inv.}) \sim 1/3

If LDMA kinematically available \rightarrow \approx 1
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

Main backgrounds:

\[ e^+e^- \rightarrow \mu^+\mu^- (\gamma) \]
\[ e^+e^- \rightarrow \tau^+\tau^- (\gamma), \tau^\pm \rightarrow \mu^\pm\nu\nu \]
\[ e^+e^- \rightarrow e^+e^- \mu^+\mu^- \]
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair.

Main backgrounds:

\[ e^+ e^- \rightarrow \mu^+\mu^- (\gamma) \]
\[ e^+ e^- \rightarrow \tau^+\tau^- (\gamma), \tau^\pm \rightarrow \mu^\pm \nu\nu \]
\[ e^+ e^- \rightarrow e^+ e^- \mu^+\mu^- \]

$Z' \rightarrow$ visible decay (muonic dark force)

\[ e^+ e^- \rightarrow \mu^+\mu^- Z'; Z' \rightarrow \mu^+\mu^- \] will be competitive in Phase 3 (due to BaBar result)
Look for bumps in recoil mass against a \( \mu^+\mu^- \) pair

Main backgrounds:
\[
\begin{align*}
e^+e^- &\rightarrow \mu^+\mu^- (\gamma) \\
e^+e^- &\rightarrow \tau^+\tau^- (\gamma), \tau^\pm \rightarrow \mu^\pm \nu \nu \\
e^+e^- &\rightarrow e^+e^- \mu^+\mu^- 
\end{align*}
\]

Additional possibility

**LFV Z’ (e\(\mu\) coupling)**
\[
\begin{align*}
e^+e^- &\rightarrow e^+\mu^- Z’ ; Z’ \rightarrow \text{invisible} \\
e^+e^- &\rightarrow e^+\mu^- Z’ ; Z’ \rightarrow e^+\mu^- (\text{no SM background})
\end{align*}
\]

**Z’ \rightarrow \text{visible decay (muonic dark force)**
\[
e^+e^- \rightarrow \mu^+\mu^- Z’ ; Z’ \rightarrow \mu^+\mu^- \text{ will be competitive in Phase 3 (due to BaBar result)}
\]
Magnetic monopoles

- Particle carrying magnetic charge
- Recent searches for magnetic charges $g > 68.5e$
- Small charges $g < 10e$ are not excluded
- Weaker ionisation due to absence of $1/\beta^2$ factor for magnetic charges
- Tracks are straight in XY and curved in RZ
- They need a dedicated tracking (parabolas rather than helices)

\[ z(s) = z_0 + \frac{p_z}{p_T} s + \frac{g B m}{2p_T^2} s^2 \]
Summary

• Belle II Phase2 finished one week ago
• Early data taking mostly devoted to commissioning
• $L_{\text{int}} > 0.5 \text{ fb}^{-1}$, with $L_{\text{MAX}} = 5.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
• Hardware L1 trigger extensively studied (both tracks and neutrals)
• Resonances, b-physics and charm physics «rediscovered»

Some dark sector searches may lead to interesting new limits even with small data sets

- Invisible dark photon search
- ALP search
- Z' to invisible search
- Z' LFV search
- Magnetic monopoles search

They will be performed in the next months, aiming at more sensitive results in (the beginning of) Phase 3

Phase 3 (full detector, higher luminosity) will start in February 2019
SPARE SLIDES
Invisible dark photon: sensitivity

Belle II calorimeter has no projective cracks in $\phi$

Lower trigger threshold wrt BaBar
Axion Like Particles (ALPs): sensitivity

ALP $\rightarrow$ DM decay

![Graph showing ALP → DM decay sensitivity](image-url)
Z’ LFV: invisible + visible

What if symmetries of SM are not kept in the Dark Sector?

What if DM violates Lepton Flavour?

One can imagine, for example, $e\mu$ coupling

$$e^+e^- \rightarrow e^+\mu^-Z' ; Z' \rightarrow \text{invisible}$$

Dominant background: $e^+e^- \rightarrow \tau^+\tau^- (\gamma) , \tau^\pm \rightarrow \mu^\pm, e^\pm \nu\nu$

$$e^+e^- \rightarrow e^+\mu^-Z' ; Z' \rightarrow e^+\mu^- + c.c.$$  
no SM background