Dark Sector studies at Belle II: First results and prospects

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Luigi Corona ~ INFN and University of Pisa
✉ luigi.corona@pi.infn.it
● on behalf of the Belle II collaboration
Outline

- SuperKEKB and the Belle II experiment
- Dark Sector with Belle II
- Conclusions
SuperKEKB collider

- Second generation of B-factory, successor of KEKB (Tsukuba, Japan)
- $e^+/e^-$ asymmetric collider - $E^* \sim 10.58$ GeV ($M_{\Upsilon(4S)}$)
- highest world luminosity $\rightarrow$ Nano-beam scheme
  - Squeeze beams $\rightarrow$ increase probability of interaction
  - Higher currents and smaller beams than KEKB

**KEKB**

$I(A): \sim 1.6/1.2$
$\beta^*_y(mm) \sim 5.9/5.9$

**SuperKEKB**

$I(A): \sim 3.6/2.6 (x\ 2)$
$\beta^*_y(mm) \sim 0.27/0.3 (x\ 1/20)$

$x40$ higher luminosity than KEKB
Physics program

**Peak luminosity trend**

- **Flavor physics and SM Test:**
  - CKM parameters
  - CPV in $B$ decays
  - $B/D/\tau$ physics

- **BSM physics:**
  - rare or suppressed or forbidden processes in the SM

- **Search for:**
  - light Dark Sector

- **Peak luminosity** ($cm^{-2} s^{-1}$)
  - $8 \cdot 10^{35}$ cm$^{-2}$ s$^{-1}$

- **x40 higher luminosity than KEKB**
Belle II detector

- See Pavel Krokovny talk: 13/09, 9:00!

- **VerteX Detector (VXD):**
  - 2 layer DEPFET pixel detectors (PXD)***
  - 4 layer DSSD silicon vertex detectors (SVD)

- **Central Drift Chamber (CDC):**
  - He(50%)C₂H₆(50%)

- **Particle Identification:**
  - Time-of-Propagation (TOP) (barrel)
  - Aerogel Ring Cherenkov (ARICH) (FWD)

- **E.M. calorimeter (ECL):**
  - CsI(Tl) crystals

- **Kₑ and μ detector (KLM):**
  - Resistive Plate Chambers (RPC) (outer barrel)
  - Scintillators + SiPM (endcaps, inner barrel)

***second layer not complete

Belle II covering > 90% of 4π

Coordinate system

center of the ring

~ 7 m

~ 7.5 m

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SuperKEKB schedule

Phase 1 (2016):
• dedicated to machine commissioning, w/o detector

Phase 2 (Last year):
• commissioning data
• 500 pb\(^{-1}\) collected
• incomplete detector: ~1/8 of VXD in φ
• rediscoveries, Dark Sector physics

Phase 3:
• began on March 25\(^{\text{th}}, 2019\)
• 6.5 fb\(^{-1}\) collected
• goal: 50 ab\(^{-1}\) with the full detector (x50 data set than its predecessor)
Highlights from Phase 2

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

Good condition for dark searches:
- \[ e^+ e^- \rightarrow \gamma X \]
- \[ e^+ e^- \rightarrow \text{ALP} \gamma \rightarrow \gamma(\gamma\gamma) \]
- ...
Many astrophysical observations provide evidence for the existence of some kind of matter that interacts mostly gravitationally with the Standard Model (SM) particles: **Dark Matter**.

Possible GeV and sub-GeV theoretical scenarios: Light-DM weakly coupled with SM through a light Dark Sector mediator $X$.

Different possible portals between Dark Matter and SM depending on the mediator $X$:

- **Vector Portal** → Dark Photon $A'$, Dark $Z'$
- **Pseudo-scalar Portal** → Axion Like Particles (ALPs, axion)
- **Scalar Portal** → Dark Higgs / Dark Scalar
- **Neutrino Portal** → Sterile Neutrinos
Dark Sector Physics

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Search for Dark Matter

**Belle II**: search for events with missing energy, single/multi photons final state...

Analyses competitive with Phase 2 (500 pb$^{-1}$) or early Phase 3 data (20 fb$^{-1}$):

- Dark Photon to Invisible
- $Z'$ to invisible (L$\mu$ – L$\tau$ model)
- Axion-like particles

Legend:
- ● Dark Matter Candidates
- ○ Observed Anomalies

**Ref. arXiv:1707.04591**
Search for Dark Matter

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Dark photons $A'$

- Extension of the SM: → additional U(1)$'$ symmetry
- Massive dark photon that mixes with the photon with strenght $\varepsilon$

$$e\varepsilon J_{SM}^{\mu} A'_{\mu}$$

- $m_x > 0.5 m_{A'} \rightarrow A'$ visible decays to SM particles
- $m_x < 0.5 m_{A'} \rightarrow A'$ invisible decays to Light-DM particles

References:
Invisible dark photon searching strategy

- Signal signature:
  - Single high-energetic ISR photon final state
  - Needs a single photon trigger (not available in Belle, \(\approx 10\%\) of data in BaBar)
  - Look for a bump in the variable:

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

- Selection criteria \(\rightarrow E_{\gamma}^{\text{LAB}} \text{ vs } \theta_{\gamma}^{\text{LAB}}\)

Simulated signal efficiency

\(\varepsilon = (30-40)\%\)
Invisible dark photon backgrounds

Sources of ECL inefficiency

Simulated background rates

- Main Backgrounds events:
  - $e^+e^- \rightarrow e^+e^-\gamma$
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$
Invisible dark photon backgrounds

Sources of ECL inefficiency

Simulated background rates

- **Main Backgrounds events:**
  - $e^+e^- \rightarrow e^+e^-\gamma$
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$

- **Peaking $e^+e^- \rightarrow \gamma\gamma(\gamma)$ dominates the analysis**
Projected upper limits on $\varepsilon$, invisible dark photon

\[ e^+e^- \rightarrow \gamma A', A' \rightarrow \text{invis.} \]

- Significantly better than BaBar (53 fb$^{-1}$) due to:
  - better hermeticity of the ECL
  - better efficiency of the KLM

BaBar 2017, 53 fb$^{-1}$  
arXiv:1702.03327

Belle II projection at  
- 20 fb$^{-1}$  
arXiv:1808.10567

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**Z’ to invisible: theory**

- Extension of the SM: additional $U(1)_{L_\mu - L_\tau}$ symmetry
  \[
  \mathcal{L} = \sum_\ell \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell
  \]

- Introduces a light vector boson $Z'$ with coupling $g'$ only with the 2\textsuperscript{nd} and 3\textsuperscript{rd} generation of leptons

- If kinematically accessible, $Z'$ could decay to DM

- May explain: $(g-2)_\mu$, abundance of DM in the Universe

- Invisible decay channel to be explored for the first time: $e^+e^- \rightarrow \mu^+\mu^- + \text{missing energy}$

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*Production cross section*

- Shuve et al. (2014), arXiv:1403.2727
- Altmannshofer et al. (2017) arXiv:1609.04026

**Computation with MadGraph5**
**Z’ to invisible search**

- **Signal signature:**
  - look for bumps in the recoil mass against a $\mu^+\mu^-$ pair
  - nothing in the rest of event

- **Main background events from QED processes:**
  - $e^+e^- \rightarrow \mu^+\mu^- (\gamma)$
  - $e^+e^- \rightarrow \tau^+\tau^- (\gamma), (\tau \rightarrow \mu \nu \nu)$
  - $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$

- **Only 276 pb$^{-1}$ used due to trigger conditions for two tracks events**

*No sensitivity to the parameter space region for $M_{Z'} > 8$ GeV/c$^2$*
If Dark Matter is kinematically accessible, it can be assumed $BR(Z' \to inv.) = 1$
Lepton Flavor Violating $Z'$

- Searching for a lepton flavor violating $Z'$ that couples to $e\mu$: $e^+e^- \rightarrow e^+\mu^- Z'$ ($Z' \rightarrow inv.$)
- Expected low background from SM processes
- No working model to test → Model independent approach
- Same selection criteria from flavor-conserving $Z'$ to invisible search used


$\epsilon \cdot \sigma$ upper limits
Axion-like particles (ALPs)

- Pseudo-scalar particles which couple to SM bosons
- No relation between mass and coupling → different from QCD axions
- \( m_a < \text{MeV} \) → excellent DM candidates
- \( m_a \sim \text{GeV} \) → mediator of interaction between SM and yet undiscovered DM particle
- Focus on coupling to photons → \(-\frac{g a}{4} a F_{\mu \nu} \tilde{F}^{\mu \nu}\)

- Two production processes possible:
  - Focus on ALP-strahlung
    - \( e^+ e^- \rightarrow \gamma + \text{inv.} \)
    - \( e^+ e^- \rightarrow 3 \gamma \)
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Sensitivity under study

\( s^{1/2} = 10.58 \text{ GeV}, g_{a\gamma\gamma} = 10^{-4} \text{ GeV}^{-1} \)
Axion-like particles: signal

Parameters \((m_a, g_{a\gamma\gamma})\) determine the displacement and the \(\theta\) angle between the \(2\gamma\)

- ALP lifetime: \(\tau \sim \frac{1}{m_a^2 g_{a\gamma\gamma}^2}\)

Four Signatures:

- Resolved: prompt decay, large \(\theta\)
- Merged: prompt decay, small \(\theta\)
- Invisible: \(a\) decays outside the detector or \(a\) decays to invisible particles, as DM particles
- Displaced: veto this region (indistinguishable from \(e^+e^- \rightarrow \gamma\gamma\))
Axion-like particles: sensitivity

- Focus on: \( e^+ e^- \rightarrow \gamma a, a \rightarrow \gamma \gamma \)

- Observable: Invariant mass of the two photons

- Main SM background:
  - \( e^+ e^- \rightarrow \gamma \gamma (\gamma) \)
  - \( e^+ e^- \rightarrow e^+ e^- (\gamma) \)
  - \( e^+ e^- \rightarrow P \gamma (\gamma), P = (\pi^0, \eta, \eta') \)

- Belle II expected limits
  - No systematics included
  - beam background assumed to be negligible

Belle II expected sensitivity (preliminary)

\[ g_{a\gamma \gamma} \] vs. \( m_a [\text{GeV/c}^2] \)
Conclusions

- The Belle II experiment, designed mainly for B-physics, has a broad and active program to explore the Dark Sector physics.

- 2018: successful SuperKEKB commissioning and collected ~0.5 fb\(^{-1}\) of data → b and charm physics rediscoveries, but also search for Dark Sector.

- 2019: phase 3 started this year on March 25\(^{th}\) → up to now 6.5 fb\(^{-1}\) collected.

- Many searches are ongoing, \(A'\), \(Z'\), ALPs, and there will be the possibility to explore many more Dark Sector models.
  - \(A' \rightarrow \text{inv.}\), expected sensitivity: \(\varepsilon \sim 2 \cdot 10^{-4}\) with \(L_{\text{int}} = 20\) fb\(^{-1}\), better than the current limits set by BaBar.
  - \(Z' \rightarrow \text{inv.}\), expected sensitivity: \(g' \sim 10^{-2} - 10^{-1}\) with Phase 2 data; with Phase 3: possibility to exclude the parameter region that explain \((g-2)_{\mu}\).
  - \(\text{ALPs, } a \rightarrow \gamma \gamma\), expected sensitivity: \(g_{a\gamma\gamma} \sim 10^{-3} - 10^{-2}\) with Phase 2 data, better than current limits.
Thank you
B-Factories

**B-factory**: asymmetric e+/e- collider (SuperKEKB: E(e-) = 7 GeV, E(e+) = 4 GeV) optimized for the production of B mesons (but also charm physics, tau physics...)

First generation of B-factories:
- BaBar at the PEP II collider (SLAC California)
- Belle at the KEKB collider (KEK, Japan)

Some features: well known initial state, high signal / noise ration, detector with high angular acceptance and composed of several subdetectors

\[
e^+e^- \rightarrow \Upsilon(4S)[bb] \quad (10.58 \text{ GeV/c}^2)
\]

B.R.\(\Upsilon(4S) \rightarrow \overline{B}B\) > 96%,

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section [nb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e^+e^- \rightarrow \mu^+\mu^-)</td>
<td>1.148 ± 0.005 (full angle)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow \tau^+\tau^-)</td>
<td>0.919 ± 0.003 (full angle)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow e^+e^-e^-)</td>
<td>294 ± 2 (10-170 deg)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow \gamma\gamma)</td>
<td>4.96 ± 0.02 (10-170 deg)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow e^+e^-e^+e^-)</td>
<td>39.74 ± 0.03 (full angle)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow e^+e^-e^+\mu^-)</td>
<td>18.87 ± 0.02 (full angle)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow uu(\gamma))</td>
<td>1.605 (full angle)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow dd(\gamma))</td>
<td>0.401 (full angle)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow ss(\gamma))</td>
<td>0.383 (full angle)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow cc(\gamma))</td>
<td>1.329 (full angle)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-)</td>
<td>0.5346 (full angle)</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}^0)</td>
<td>0.5654 (full angle)</td>
</tr>
</tbody>
</table>
Nano-beam scheme and luminosity

\[ \mathcal{L} = \frac{\gamma \pm}{2e r_e} \left( 1 + \frac{\sigma^*_y}{\sigma^*_x} \right) \left( \frac{I_{\pm} \xi_{y\pm}}{\beta^*_{y\pm}} \frac{R_L}{R_{\xi_y}} \right) \]

Ratio between the y and x dimension of the beam 0.01 – 0.02

<table>
<thead>
<tr>
<th>KEKB</th>
<th>E (GeV) LER/HER</th>
<th>(\beta^*_y) (mm) LER/HER</th>
<th>(\beta^*_x) (cm) LER/HER</th>
<th>(\phi) (mrad)</th>
<th>(I(A)) LER/HER</th>
<th>(L(\text{cm}^{-2}\text{s}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEKB</td>
<td>3.5/8.0</td>
<td>5.9/5.9</td>
<td>120/120</td>
<td>11</td>
<td>1.6/1.2</td>
<td>2.1 (\times 10^{34})</td>
</tr>
<tr>
<td>SuperKEKB</td>
<td>4.0/7.0</td>
<td>0.27/0.30 (\times 1/20)</td>
<td>3.2/2.5</td>
<td>41.5</td>
<td>3.6/2.6 (\times 2)</td>
<td>80 (\times 10^{34})</td>
</tr>
</tbody>
</table>
Phase 2 and Phase 3 VXD geometry (1/2)

**Phase 2**

- CLAWS
- FANGS
- PLUME
- diamond sensors
- study and monitor the beam background levels
Phase 2 and Phase 3 VXD geometry (2/2)

- SVD L3,4,5,6 → Low material budget, precise hit time resolution ($\sigma \sim 3$ ns)
- PXD L1,2 → Low material budget, innermost layer at 1.4 cm
Dark Matter (DM): Introduction

- **Massive** → gravitational interaction with Standard Model (SM) matter
- **Dark** → does not interact with SM matter through any other interaction
- Many astrophysical observations in agreement with DM existence: flat galaxy rotation curves, gravitational lensing, galaxy velocity dispersion...

Flat galaxy rotation curves (first experimental evidence)

If DM exists as particles and interact with SM, although very weakly, it is possible to produce it in colliders
Kinetic mixing

- Extension of the SM: → additional U(1)' symmetry that mix with the photon

\[ A_{\mu} \rightarrow A_{\mu} - \varepsilon A_{\mu}' \]

- Off diagonal kinetic term

\[ -\frac{\varepsilon}{2} F_{\mu \nu} F'_{\mu \nu} \]

- \( \varepsilon \) is the strength of the kinetic mixing (\( \varepsilon \leq 10^{-2} \))

- After the redefinition of fields (\( A_{\mu} \rightarrow A_{\mu} - \varepsilon A_{\mu}' \)) the diagonal kinetic term is restored and the interaction term \( \varepsilon \varepsilon J_{SM}^\mu A_{\mu}' \) arises in the theory

- The symmetry U(1)' can be broken spontaneously by a dark Higgs mechanism that gives mass to the dark photon

References:
Other planned dark sector and exotic searches

- Visible dark photon decays
- Off-shell dark photon decays
- Muonic dark force: $e^+e^- \rightarrow \mu^+\mu Z'$, $Z' \rightarrow \mu^+\mu$
- Dark sector with Lepton Flavor Violation: $Z'$
- Dark scalar: $e^+e^- \rightarrow \tau^+\tau^- S$, $S \rightarrow l^+l^-$
- Magnetic monopoles with small magnetic charges
- Invisible $Y(1S)$ decays via $Y(3S) \rightarrow Y(1S)\pi^+\pi$ (Requires beam energies at $Y(3S)$)
- Dark Higgs/Higgstrahlung
- ...

For further details:
- The Belle II Physics Book arXiv:1808.10567

***Possible with Phase 2 data
Magnetic monopoles

Particle carrying magnetic charge

Distinct signature in drift chamber:

- Tracks are straight in (x,y) plane
- Tracks are curved in (r,z)

They need a dedicated tracking system

Detection efficiency is high: 40-97%, depending on magneton mass

Projected upper limits on $\varepsilon$, visible dark photon

$$e^+e^- \rightarrow \gamma A', A' \rightarrow l^+l^-$$

- Belle II is competitive only in Phase 3
- The Belle II Physics Book arXiv:1808.10567
ALPs expected limits

\[ a \rightarrow \gamma \gamma \]

\[ a \rightarrow \text{inv.} \]

\[ \text{LEP } e^+e^- \rightarrow \gamma \gamma \]

\[ \text{LEP } e^+e^- \rightarrow \text{inv.} \]

\[ \text{Belle II } \gamma + \text{inv} \]

\[ \text{LEP } \gamma + \text{inv} \]

\[ \text{BaBar } \gamma + \text{inv} \]

\[ \text{SHiP} \]

\[ \text{SN 1987A} \]

\[ \Omega h^2 = 0.12 \text{ via resonant freeze-out} \]

\[ m_\chi = 0.45 m_\text{Pl} \]

\[ m_\chi = 0.46 m_\text{Pl} \]

\[ m_\chi = 0.47 m_\text{Pl} \]

\[ m_\chi = 0.48 m_\text{Pl} \]

\[ m_\chi = 0.49 m_\text{Pl} \]
Projected upper limits on $g'$ with Phase 3 data

- Some possible factors of improvement: PID, vertex fit (full VXD), Multivariate Analysis

$\begin{align*}
12 \text{ fb}^{-1} & \\
59 \text{ fb}^{-1} & \\
135 \text{ fb}^{-1} & \\
135 \text{ fb}^{-1}, \text{ B/5} & \\
\end{align*}$

Same background or reduced by a factor 5
Highlights from Phase 3

- Results for early Phase 3 data:
  - based on 2.62 fb-1

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

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

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