Dark Matter Search with Belle II

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OUTLINE OF THE TALK

• Belle II and SuperKEKB
• Highlights of Belle II dark searches
  No t channel, sorry …
• Perspectives & Summary
Peak luminosity trend

e^+e^- colliders

SuperKEKB

40 times higher luminosity

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

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

- Beam-beam parameter

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

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

- From KEKB to SuperKEKB
  - $\beta_y^* = 0.27/0.30 \text{ mm}$
  - $I_{+/} = 3.6/2.6 \text{ A}$

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

- Nano-Beam scheme

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

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**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: the past (2018)

Phase 2

Phase 2 finished July 2018
- Nano-beam scheme works!
- $L=5.5\times10^{33}$ cm$^{-2}$s$^{-1}$ achieved
- $L_{\text{int}} \approx 0.5$ 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 25\textsuperscript{th} 2018
Belle II & SuperKEKB Phase 2

Start of collisions: April 25th 2018

Effective bunch length: from KEKB to SuperKEKB Phase 2

Ordinary collision (KEKB)

Nano-Beam (SuperKEKB Phase2)

\[ \sigma = 4.5 \text{ mm} \]

\[ \sigma = 550 \mu\text{m} \]

Nano-beam scheme works!
Belle II performance snapshots

$k_S \rightarrow \pi\pi$

$\pi^0 \rightarrow \gamma\gamma$

$J/\psi \rightarrow e^+e^-$

$J/\psi \rightarrow \mu\mu$

$\mu_n\text{on}>0.001$

$\int L dt = 250 \text{ pb}^{-1}$

$\int L dt = \sim 5 \text{ pb}^{-1}$

$E_\gamma > 0.15 \text{ GeV}$

2 days after first collisions
From Phase 2 to Phase 3
From Phase 2 to Phase 3

Phase 3 = (almost) final setup for physics
→ 4 full layers of silicon strips
→ 1 + 1/6 full layers of pixel
→ full installation approx in 2020
From Phase 2 to Phase 3

Reach KEKB peak lumi
Reach Belle integrated lumi
From Phase 2 to Phase 3

- Phase 3 started on March 11
- Collisions recorded since March 25
- Unfortunately a fire accident at LINAC (with no serious consequences) slowed down operations
- $L_{\text{int}} \approx 100 \text{ pb}^{-1}$
What can we do at B-factories that we can't at the LHC in terms of DM searches?

- Clean, «energy conserving» environment
- 3d momentum conservation
- Easiness of tag & probe techniques
- Full Event Interpretation
- Less model dependency

- Low multiplicity signatures
- Missing energy channels
- Invisible particles
- Some fully neutral final states accessibility

- Cleanliness and luminosity sometimes compensate for cross section → competition
Dark Sector Candidates, Anomalies, and Search Techniques

- QCD Axion
- Ultralight Dark Matter
  - Pre-Inflationary Axion
  - Post-Inflationary Axion
- Hidden Sector Dark Matter
  - Hidden Thermal Relics / WIMPless DM
  - Asymmetric DM
  - Freeze-In DM
  - SIMPs / ELDERS
    - Beryllium-8
    - Muon g-2
    - Small-Scale Structure

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

WIMPs

Black Holes

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

Microlensing
Dark Sector Candidates, Anomalies, and Search Techniques

- zeV, aeV, feV, peV, neV, μeV, meV, eV, keV, MeV, GeV, TeV, PeV, 30M☉

- QCD Axion
- Ultralight Dark Matter
  - Pre-Inflationary Axion
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- Hidden Sector Dark Matter
  - Hidden Thermal Relics / WIMPless DM
  - Asymmetric DM
  - Freeze-In DM

- WIMPs
- Black Holes

- Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators
- Microlensing
Invisible dark photon: sensitivity

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

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

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

- $\alpha_D = 0.5$
- $3m_\chi = m_{A'}$
Visible dark photon: sensitivity
Axion Like Particles (ALPs): sensitivity

γ fusion

alp-strahlung

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

Only coupling to γ

\[ s^{1/2} = 10.58 \text{ GeV}, g_{\gamma\gamma} = 10^{-4} \text{ GeV}^{-1} \]

\[ g_{a\gamma\gamma} = 0 \]

\[ m_a \text{ [GeV]} \]

\[ g_{\gamma\gamma} \text{ [GeV}^{-1}] \]

Belle II γ + inv (20 fb⁻¹)
Belle II γ + inv (50 ab⁻¹)
LEP
Belle II 3γ (20 fb⁻¹)
Belle II 3γ (50 ab⁻¹)
SHiP
beam dump experiments

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Axion Like Particles (ALPs): sensitivity

Axion Like Particles (ALPs) are hypothetical particles that could be weakly coupled to photons. They are often considered in the context of dark matter searches. The sensitivity of Belle II to ALPs can be explored through various processes, such as the reaction $e^+ e^- \rightarrow \gamma \gamma$ and $e^+ e^- \rightarrow \gamma^{*} \gamma$.

The diagram illustrates the process of $\gamma$ fusion and alp-strahlung. With some assumptions on the trigger (no $\gamma \gamma$ veto in barrel), results expected with Phase 2 data are shown in the plot.

Results expected with Phase 2 data

- $s^{1/2} = 10.58$ GeV, $g_{\gamma\gamma} = 10^{-4}$ GeV$^{-1}$
- $e^+ e^- \rightarrow \gamma + \text{inv.}$
- Proton beam dumps
- Electron beam dumps
- HB stars
- SN1987A
- $g_{\alpha \gamma Z} = 0$
- Belle II 0.472 fb$^{-1}$
- Belle II 135 fb$^{-1}$
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- Couples only to the 2° and 3° lepton family
- Calls for LFU violation
- May explain $(g-2)_\mu$
- Invisible BR possibly enhanced by LDMA (sterile neutrinos, light Dirac fermions)
- Might solve $B \to K(\ast)\mu\mu, R_K, R_{K^\ast}$ anomalies

Shuve et al. (2014), arXiv 1408.2727
Altmannshofer et al. (2016) arXiv 1609.04026
**L_μ - L_τ: Z’ invisible decay**

- couples only to the 2° and 3° lepton family
- calls for LFU violation
- May explain (g-2)_μ
- Invisible BR possibly enhanced by LDMA (sterile neutrinos, light Dirac fermions)
- Might solve B→K(⁎)μμ, R_K, R_K⁎ anomalies

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**Very preliminary systematics, very conservative limits**

Z’ LFV

Z’→eμ ← t-channel
Z’→μτ

Visible + invisible
Invisible $Y(1S)$ decay searches in e+e- collisions

**BABAR vs. Belle vs. Belle II**

\[
\frac{BR(Y(1S) \to \nu \bar{\nu})}{BR(Y(1S) \to e^+e^-)} = \frac{27 G^2 M_{Y(1S)}^4}{64 \pi^2 \alpha^2} \left(-1 + \frac{4}{3} \sin^2 \theta_W\right)^2 = 4.14 \times 10^{-4}
\]

\[
BR(Y(1S) \to \nu \bar{\nu}) \approx 9.9 \times 10^{-6}
\]

- Low mass dark matter particles however might might play a role in the decays of $Y(1S)$, having $Y(1S) \to \chi \chi$ if kinematic allowed. [Phys. Rev. D 80, 115019, 2009]

- Also, new mediators ($Z', A^0, h^0$) or SUSY particles might enhance $Y(1S) \to \nu \bar{\nu}(y)$. [Phys. Rev. D 81, 054025, 2010]

- In absence of new physics enhancement, Belle2 should be able to observe the SM $Y(1S) \to \nu \bar{\nu}$

A signal of $Y(1S) \to \text{invisible}$ is an excess of events over the background in the $M_r$ distribution at a mass equivalent to that of the $Y(1S)$ (9.460 GeV/c²)

\[
M_r^2 = s + M_{\pi^+\pi^-}^2 - 2s E_{\pi^+\pi^-}^{CMS}
\]

Requires running at $Y(3S) \approx 200 \text{ fb}^{-1}$ with special low $p_T$ trigger
Translating $Y(1S) \rightarrow$ invisible search to dark matter limits

Extrapolation based on ArXiv: 1511.03728, 1404.6599
• Belle II Phase2 finished in July 2018
• Early data taking mostly devoted to commissioning
• \( L_{\text{int}} \approx 0.5 \text{ fb}^{-1} \), with \( L_{\text{MAX}} = 5.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \)
• Resonances, b-physics and charm physics «rediscovered»
• Belle II Phase III (complete detector) just started
• \( L_{\text{int}} \approx 100 \text{ pb}^{-1} \) before the fire incident
• Hopefully \( \approx 10 \div 20 \text{ fb}^{-1} \) by summer conferences

- Invisible dark photon search
- ALP search
- Z’ to invisible search
- Z’ LFV search
- Y(1S) to invisible

Still to be started: dark searches in flavour physics

\[ \begin{align*}
B \to K^+ A, & \ A \to \gamma \gamma \\
Y(1S) \to \gamma A, & \ A \to gg \\
B \to X_c \mu \nu Z' \\
\end{align*} \]

Not even mentioned
- Magnetic monopoles
- muonic dark force
- dark Higgs
- dark Higgstrahlung
- dark scalars
- inelastic dark matter
- dark search in \( \tau \) decays
- long-lived particles
- ...

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SPARE SLIDES
Invisible dark photon: sensitivity

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

Lower trigger threshold wrt BaBar
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

- $\chi \equiv$ dark matter particle

Two basic scenarios depending on $A'$ vs matter mass relationship

- $m_\chi > 1/2 m_{A'} \Rightarrow A'$ visible decays (SM particles)
- $m_\chi < 1/2 m_{A'} \Rightarrow A'$ invisible decays to LDMA

$A' \rightarrow l^+l^-$

$A' \rightarrow \pi^+\pi^-, h^+h^-$

$h' \Rightarrow A'A', A'A'A' \rightarrow 6 l^\pm + \pi^\pm$

$A' \rightarrow \chi\overline{\chi}$

Access to light dark matter particles
Invisible dark photon: backgrounds

\[ ee \rightarrow 2\gamma \text{ and } 3\gamma \]
1\(\gamma\) in ECL 90° gap
1\(\gamma\) out of ECL acceptance

\[ ee \rightarrow e\gamma \]
both electrons out of tracking acceptance

\[ ee \rightarrow 3\gamma \]
1\(\gamma\) in ECL BWD gap
1\(\gamma\) out of ECL acceptance

Crucial usage of KLM to veto photons in ECL gaps
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.

$\varepsilon \approx 20 \div 40\%$

Three resolved, high energetic photons.

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

Only coupling to $\gamma$

$g_{\alpha\gamma} = 0$

ALP $\rightarrow$ DM decay

$\Omega h^2 = 0.12$ via resonant freeze-out
Possible (big) factors of improvement beyond luminosity:

- PID (up to 7 on $\tau$ bkg)
- Resolution (VXD)
- Vertex fit $\rightarrow$ $\tau$ rejection
- MVA vs linear cut analysis
- See also previous slide for assumptions on systematics

same background or background reduced by factors 3 and 5
**L_μ - L_τ, Z’ invisible decay sensitivity**

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

**Main backgrounds:**

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

**Alternative model under search**

**LFV Z’ (eμ coupling)**

\[
e^+e^- \rightarrow e^+\mu^- Z' \ ; Z' \rightarrow \text{invisible} \\
e^+e^- \rightarrow e^+\mu^- Z' \ ; Z' \rightarrow e^+\mu^- \text{ (no SM background expected)}
\]

**Z’ → visible decay (muonic dark force)**

\[
e^+e^- \rightarrow \mu^+\mu^- Z' \ ; Z' \rightarrow \mu^+\mu^- \text{ will be competitive in Phase 3 (due to BaBar result)}
\]
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: $e^+ e^- \rightarrow \tau^+ \tau^- (\gamma)$, $\tau^\pm \rightarrow \mu^\pm, e^\pm \nu\nu$

\[ e^+ e^- \rightarrow e^+ \mu^- Z'; Z' \rightarrow e^+ \mu^- + \text{c.c.} \]

no SM background
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)

$$z(s) = z_0 + \frac{p_z}{p_T} s + \frac{gBm}{2p_T^2} s^2$$

Projected sensitivity

BELLE II MC