Dark Matter searches in $e^+e^-$ annihilations & first results from Belle II

Next Frontiers in the Search for Dark Matter

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Outline

**Dark Matter searches in e+e- annihilations**

- Z' → invisible
- Y(1S) → γ invisible
- Y(1S) → invisible
- Invisible Dark photon A' → invisible
- Visible Dark photon A' → l+l-
- Axion Like Particles (ALPs)
- ALP-strahlung
- Higgs-strahlung

in this talk
Dark Matter searches in $e^+e^-$ annihilations

Collider Method: DM production at collider, model dependent
- Mainly operating at $\sqrt{s} = 10.58$ GeV
- Clean environment
- Known initial energy of the system

at the KEKB collider
KEK, Japan

at the PEP II collider
SLAC, USA
SuperKEKB

Next generation B-factory

40x KEKB integrated luminosity: 50 ab⁻¹
- from upgraded ring
  ×2 ↑ beam current
- from final focus magnets
  × 1/20 ↓ β* vertical beta-function at the IP
large crossing angle (83 mrad)
**Belle II**

**The detector**

- **Electromagnetic calorimeter**
  - CsI(Tl) crystals... new readout

- **1.5T magnet**

- **K_L** and muon (KLM) detectors
  - Resistive plate chambers + (new) scintillator w/ iron flux return

- **Dedicated triggers for Dark Matter searches**

- **e^+e^- collision**
  - @ $\sqrt{s} = 10.58$ GeV

- **Drift chamber tracking**
  - wires in 50:50 He:C_2H_6

- **7 GeV e^-**

- **4 GeV e^+**
Data schedule

- 2018: 500 pb\(^{-1}\).
  ▶ Commissioning data.
- 2019: \(~6.5\) fb\(^{-1}\) delivered.
- Expected in 2027: 50 ab\(^{-1}\).
Dark Matter searches at B-factories

\[ e^+e^- \text{collisions at } \sqrt{s} = 10.58 \text{ GeV} \]

*Light dark sector*

**Key:**
- Observed
- Theories

**QCD Axion**

**B-factories**

**WIMPs**

**Hidden / dark sector**

**Black holes**

**Higgs**

**G_{\mu} -2**

**Mass scale**

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Phenomenology

Renormalizable way of Dark Matter coupling to the SM

Vector portal → Dark photon

\[ \mathcal{L} \supset e V_\mu J^\mu_{SM} \]

Scalar portal (Higgs portal) → Dark Higgs/ Scalars

\[ \mathcal{L} \supset \lambda S^2 (H^\dagger H) \]

Pseudoscalar portal → Axion-Like Particle

dim 5 axion portal

\[ \mathcal{L} \supset \frac{\partial_\mu P}{f_A} \bar{f} \gamma^\mu \gamma^5 f \]

Neutrino portal → Sterile Neutrinos

\[ N (LH) \]
Phenomenology

Renormalizable way of Dark Matter coupling to the SM

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Dark sector

SM

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Visible

Invisible

Off-shell

Long-lived

SM

Dark matter mass, m_{DM}

Visible

m_{DM} = m_{Med} / 2

2m_e

Mediator mass, m_{med.}

SM

Portal

m_{DM} = m_{Med} / 2
\( Y(1S) \rightarrow \gamma \) invisible

**Theory**

- \( M_{\text{med.}} \) is very large \( \rightarrow \) can not be produced on-shell in B-factories
- DM particle is kinematically accessible

Limits on the branching fraction for \( Y(1S) \) decays

- Suppression scale of the effective operator parametrizing interactions DM with quarks

**BII – expected sensitivity for Belle II**

\[
\begin{align*}
\text{S1 & S2: Fermi} & & \text{S1 & S2: BII} \\
\text{F2 & F4: Fermi} & & \text{F2 & F4: BII} \\
\text{F1: ATLAS MonoJet} & & \text{F1 & F3: BII}
\end{align*}
\]
Y(1S) → γ invisible

Analysis

Y(2S) → Y(1S) π⁺π⁻

Bottonium transition with two soft pions

Dipion recoil mass:

\[ M_{\text{rec}}^2 = s + M_{\pi\pi}^2 - 2\sqrt{s} E^*_{\pi\pi}, \]

with \( M_{\pi\pi} \) is \([2M_\pi, (M_{Y(2S)} - M_{Y(1S)} )]\)

Mass scan point with \( M_{\text{med.}} = 2.946 \text{ Gev/c}^2 \)

Background estimation:

Continuum background

- studied with an off-resonance data set
- do not observe any significant peaking backgrounds

Y(1S) decay background (irreducible)

- Y(1S)→ ll (leptons) do not produce a peak at \( E_\gamma \) but at \( M_{\text{rec}} \)
- Y(1S)→ γ hh (hadrons) produce a peak at \( E_\gamma \) and \( M_{\text{rec}} \)
$\Upsilon(1S) \rightarrow \gamma$ invisible

Physics reach

Set limits on the branching fraction

conversion into a WIMP-nucleon scattering $\sigma$ limit

Used data:
Belle, 25 fb$^{-1}$
BaBar, 14.4 fb$^{-1}$
Dark photon

Theory

- Massive vector particle $A'$, mixes with the SM photon:
  \[ \mathcal{L} \supset \epsilon g_D A'_\mu J_{\text{EM}}^\mu \]

- Can decay to two leptons $A' \rightarrow l^+ l^-$
  Experimentally: search for a narrow peak in $l^+ l^-$ mass spectrum on top of large BG

\begin{align*}
\text{MadGraph} \\
g_\chi = g_e \\
M_\chi = 1 \text{ MeV/c}^2 \\
\epsilon = 1
\end{align*}
Dark photon
Theory

- Massive vector particle $A'$, mixes with the SM photon:
  \begin{equation}
  \mathcal{L} \supset \epsilon g_D A'_{\mu} J_{EM}^{\mu}
  \end{equation}

- Can decay to two leptons $A' \rightarrow l^+ l^-$
  Experimentally: search for a narrow peak in $l^+ l^-$ mass spectrum on top of large BG

- Can decay directly to light dark matter $A' \rightarrow \chi_1 \chi_2$
  Experimentally: negligible interaction with detector

- Experimentalist’s trick: require ISR photon
  \begin{equation}
  E_{\gamma_{\text{ISR}}} = \frac{s - m_{A'}^2}{2 \sqrt{s}}
  \end{equation}

Single photon trigger is required not available at Belle, and only 10% BaBar data
Dark photon

**Analysis**

- **First analysis:** \( ee \rightarrow \gamma A', A' \rightarrow \chi_1\chi_2 \)
- **One photon (no tracks, no other good photon clusters)**
- Bump search in recoil mass spectrum

**Main background sources:**

- \( ee \rightarrow ee\gamma(\gamma) \) and \( ee \rightarrow \gamma\gamma(\gamma) \)

- \( ee \rightarrow \gamma\gamma \), 1 \( \gamma \) in endcap gaps
- \( ee \rightarrow \gamma\gamma\gamma \), 1 \( \gamma \) in endcap gap, 1 \( \gamma \) out of ECL acc.

- \( ee \rightarrow ee\gamma \), both leptons out of tracking acceptance

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**Belle II Simulation**

- \( E_{e\gamma} \) in CMS (GeV)
- \( \theta_{\text{Lab}} \) (deg)
- Events/bin

**Event Details**

- \( ee \rightarrow \gamma\gamma \), 1 \( \gamma \) in ECL 90° gap, 1 \( \gamma \) out of ECL acc.
**Dark photon**

**Physics reach**

At **Belle II**:
- single photon trigger
- use KLM to detect escaped photons

The **Belle II** Physics book:
- BaBar 53 fb$^{-1}$ analysis: [PRL.119.131804](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.131804)
Z’ to invisible: $L_\mu - L_\tau$ model

**Theory**

- “Dark photon” → $Z'$ if non minimal
- Search is performed in flavour violating and flavour conserving modes
- Mediator coupling to muons and taus, not electrons ($L_\mu - L_\tau$)
- Abelian symmetry
- $Z' \rightarrow$ invisible:
  calculate a branching fraction and compare to theoretical prediction to find an indication of invisible DM

\[
\sigma \sim g'^2 (1 - M_{Z'}/\sqrt{s})
\]

Computed with MadGraph5
Z’ to invisible: \( L_\mu - L_\tau \) model

Analysis

- \( ee \rightarrow \mu\mu Z' (Z' \rightarrow \text{invisible}) \)
- Bump hunt in recoil mass against \( \mu\mu \). Nothing in the rest of the event
- Kinematic fit of muons \( \rightarrow \) to select events recoil energy point to the barrel (best hermiticity)
- Dimuon trigger

Main background sources:
- \( ee \rightarrow \mu\mu(\gamma) \)
- \( ee \rightarrow \tau\tau(\gamma) \)
- \( ee \rightarrow ee\mu\mu \)

\[
M_{rec} = s + M_{\mu\mu}^2 - 2\sqrt{s}E^*_{\mu\mu}
\]

Simulated and reconstructed \( M_{Z'} \) in range \((0.1 – 10) \text{ GeV/c}^2\)
Z’ to invisible: \( L_\mu - L_\tau \) model

Physics reach

**Belle II** Preliminary - 2018

\[
\int Ldt = 276 \text{ pb}^{-1}
\]

\[ L_\mu L_\tau \]

\[ L_\mu L_\tau, \text{BF}(Z \rightarrow \chi \bar{\chi}) = 1 \]

\[ (g-2)_\mu \pm 2\sigma \]

\[ M_Z [\text{GeV/c}^2] \]

**Belle II MC**

Belle II 50 ab\(^{-1}\) projection

\[ \mu_{g-2} \pm 2\sigma \]

\[ M_Z [\text{GeV/c}^2] \]
Axion Like Particles (ALPs)

Theory

- Pseudo-scalar coupling to gauge bosons
- After EWSB:
  \[ \mathcal{L} \supset - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \]
- QED case: the coupling and the mass of the ALPs are independent
- ALPs at Belle II:
  - light ALPs \( m_a \approx 1 \text{ MeV}/c^2 \),
    \[ g_{a\gamma\gamma} \approx (10^{-5} - 10^{-6}) \text{ GeV}^{-1} \]
  - heavier ALPs \( m_a \approx (0.1 - 10) \) GeV/c^2
    \[ \text{Invisible: decays outside of the detector} \]
Axion Like Particles (ALPs)

Analysis

At higher masses, $m_a > 200 \text{ MeV}/c^2$

- Three photons within tracking acceptance: add up to beam energy
- Zero tracks
- Bump on di-photon mass

- The SM background: $ee \rightarrow \gamma\gamma$ ($\gamma$)
  - Does not peak in $\gamma\gamma$
  - Not a 2-body system: use angles & kinematics to suppress

At lower masses

- Two photons from ALPs are boosted: a cluster is reconstructed with one local maximum

Use the same technique to reconstruct merged $\pi^0$ meson

Searches for invisible and visible ALPs decays veto this region
Axion Like Particles (ALPs)

Physics reach

Belle II expected sensitivity

No systematics. Only (dominant) ee → γγ background included 135fb⁻¹ assumes no γγ trigger veto in the barrel

$g_{\alpha\gamma Z} = 0$
Summary

- Dark sector physics at $e^+e^-$ collider $\rightarrow$ excellent prospects even with very early data
- Only some of results are shown in this talk
- $\Upsilon(1S) \rightarrow \gamma$ invisible: more data are needed
- Single $\gamma$: dark photon decaying to stable dark matter
  Can improve limits from BaBar already with 20 $fb^{-1}$
- $\mu\mu Z'$: $L_\mu - L_\tau$ dark vector decaying to stable dark matter
  First $Z'$ $\rightarrow$ invisible analysis with early Belle II data
- $3\gamma$: ALP-strahlung, experimentally clean
  Can perform analysis with calibration collisions data (~500 $pb^{-1}$ 2018)
- $\sim 50$ $ab^{-1}$ of Belle II data is expected to be collected $\rightarrow$ unique opportunity to study Dark Matter in the regions not covered by other experiments
Belle II

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