Dark matter searches at Belle II.

Sam Cunliffe
Rencontres de Blois, 05.06.2019
SuperKEKB

- Reason for the second iteration of the project: **upgraded accelerator**.
- A factor **40** increase in instantaneous luminosity
  - \( \times 2 \) from upgraded ring (higher beam current)
  - \( \times 20 \beta^* \) from final focus magnets.
Final focus magnets

February 2018
Belle II

The detector

e^+e^- collision @ √s = 10.58 GeV
Belle II

The detector

Electromagnetic calorimeter
CsI(Tl) crystals… new readout

magnet
1.5T

new (larger)
Drift chamber tracking
wires in 50:50 He:C₂H₆

Kₗ and muon detectors
Resistive plate chambers + (new) scintillator w/ iron flux return

Dedicated triggers for low-multiplicity.
First collisions of 2019

25 March
Recent milestone

Delivered integrated luminosity [pb⁻¹]

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<th>Date</th>
<th>Luminosity [pb⁻¹]</th>
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Super KEKB
Data schedule

• Last year: 500 pb\(^{-1}\).
  ▶ Commissioning data.

• Up to now this year: ~2.5 fb\(^{-1}\) *delivered*.

• Lifetime data set: 50 ab\(^{-1}\).
Tracking and clustering
Radiative dimuon events in first data

\[ ee \rightarrow \mu\mu\gamma \]

**Belle II** 2018 (Preliminary)

\[ \int L \, dt = 261 \text{ pb}^{-1} \]

\[ \mu_{\text{fit}} = 0.998 \pm 0.001 \]
Dark matter
Dark matter

• It’s dark.
• It exists...
Dark matter

- It’s dark.
- It exists...

QCD Axion

Hidden / dark sector

WIMPs

Higgs

Black holes

Key:

Observed

Theories

Mass scale

meV, eV, keV, MeV, GeV, TeV, $30M_{\odot}$
Axion-like particle

Theory

- After EWSB, four terms:

\[ \mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4} a F_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu} \]

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

Theory

• After EWSB, four terms:

\[ \mathcal{L} \supset -\frac{g_{\alpha\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{\alpha\gamma Z}}{4} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{\alpha Z Z}}{4} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{\alpha W W}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu} \]

\[ s^{1/2} = 10.58 \text{ GeV}, \quad g_{\alpha\gamma\gamma} = 10^{-4} \text{ GeV}^{-1} \]
ALPs @ Belle II

3γ analysis

• ALP-strahlung is much easier experimentally.
  ▶ Do this first.

• 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.
Physics reach

No systematics.
Only (dominant) $ee \rightarrow yyy$ background included
135 fb$^{-1}$ assumes no $yy$ trigger veto in the barrel
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 directly to dark matter final state. Experimentally invisible $A' \rightarrow \chi_1 \chi_2$

- Can decay to two leptons $A' \rightarrow l^+ l^-$

- Experimentalist’s trick: require ISR photon.

$$E_{\gamma_{\text{ISR}}} = \frac{s - m_{A'}^2}{2\sqrt{s}}$$
Dark photon

Analysis

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

- Backgrounds
  - Cosmics
  - Beam interactions
  - $ee \rightarrow eey(\gamma)$
  - $ee \rightarrow \gamma\gamma(\gamma)$

*Belle II* simulation

signal only
Dark photon

Backgrounds

90° plate

endcap gaps

Belle II simulation

$E_{CMS}$ (GeV)

$\theta_0^{lab}$ (deg)

Events / bin

$10^0$

$10^1$

$10^2$
Dark photon

Backgrounds

-ee → eeγ, leptons out of acceptance
-ee → γγ, endcap gaps
-ee → 3γ, endcap gaps

Belle II simulation

90° plate
endcap gaps
Dark photon

Physics reach

The Belle II Physics book
arXiv:1808.10567
BaBar’s analysis
PRL.119.131804
Z’

- “Dark photon” → Z’ if non minimal.
- Mediator coupling to muons and taus, not electrons (L_μ - L_τ)
- ee → μμZ’ (Z’ → invisible)
- Bump hunt in recoil mass against μμ. Nothing in the rest of the event.
Summary

• Next generation e⁺e⁻ collider. Belle II taking data now.
• Dark sector physics → good prospects even with very early data.
• 3γ: ALP-strahlung and decaying to two photons.
  ▶ Experimentally clean.
  ▶ Can perform analysis with calibration collisions data (~500 pb⁻¹ 2018).
• Single γ: dark photon decaying to stable dark matter.
  ▶ Can improve limits from BaBar with 20 fb⁻¹.
• µµZ’: Lµ - Lτ dark vector decaying to stable dark matter.
  ▶ First analysis with early data.
Contact

DESY. Deutsches Elektronen-Synchrotron
Sam Cunliffe
sam.cunliffe@desy.de
orcid: 0000-0003-0167-8641

www.desy.de