Search for Dark Particles and Dark Sector at Belle

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Motivation

- Dark particles: originally considered as a new spin-1 boson for new physics beyond SM.
- This proposed “dark (hidden) sector” can be a part of dark matter.
- It would mix kinetically with the photon.

\[ \mathcal{L} = -\frac{1}{2} \epsilon F_{\mu \nu} F'_{\mu \nu} \quad \epsilon : \text{kinetic mixing parameter} \]

- \( A' \) is created on-shell in radiative \( e^+e^- \) collisions.
- \( A' \) can be short or long lived.
Standard Model & Dark Sector

\[
\begin{pmatrix}
u \\ d \\
\end{pmatrix}, \quad \begin{pmatrix}c \\ s \\
\end{pmatrix}, \quad \begin{pmatrix}t \\ b \end{pmatrix}
\]

\[g, W^\pm, Z^0, H^0\]

\[\gamma/Z^0 \text{ mixing} \quad \gamma \quad \gamma/A' \text{ mixing?}\]

\[A' \quad h'\]
Standard Model & Dark Sector

- One can also think a new boson couples to light quarks

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix}
\begin{pmatrix}
  c \\
  s
\end{pmatrix}
\begin{pmatrix}
  t \\
  b
\end{pmatrix}
\]

\[\mathcal{L} = \frac{1}{3} (g'U_0) \bar{q} \gamma^\mu q U'_\mu\]

\[gU': \text{ universal gauge coupling for quarks}\]

\[g, W^\pm, Z^0, H^0\]

\[\gamma/Z^0 \text{ mixing}\]

\[\gamma\]

\[\gamma/A' \text{ mixing?}\]
Present experimental sensitivity

- Dark gauge boson (dark photon): \( A' = \gamma' = A = U \)
- Expected to have small coupling to SM particles.
- Low mass of order MeV to GeV.

- An extended Higgs sector is required to break the new U(1)’ symmetry (dark Higgs: \( h' \)).
KEKB $e^+e^-$ Collider

3.5 GeV $e^+ \times 8.0$ GeV $e^-$
$e^+e^- \rightarrow \Upsilon(4S)$
with $\beta\gamma = 0.425$
22 mrad crossing angle

$L_{\text{peak}} = 2.1 \times 10^{34}/\text{cm}^2/\text{sec}$
$> 1 \text{ M BB pairs/day}$
Integrated $L = 1 \text{ ab}^{-1}$

Experiment: 1999 - 2010

Located in Tsukuba, Japan
Belle Detector

- $\gamma, \pi^0$ reconstruction
- $e^+e^-, K_L$ identification
- Electromagnetic Calorimeter
  CsI(Tl) 16X_0
- TOF counter
- $K/\pi$ separation
- 3.5 GeV $e^+$
- Central Drift Chamber
  momentum, $dE/dx$
  50-layers + He/C_2H_6
- $B$ vertex
  Si Vertex Detector
  4-layer DSSD
- $K/\pi$ separation
- Charged particle tracking
- Aerogel Cherenkov Counter
  $n = 1.015$~$1.030$
- 8.0 GeV $e^-$
- $K_L \mu$ detector
  14/15 layer RPC+Fe
- $K_L$ identification

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Search for $A'$ and $h'$ @ Belle

- Higgs-strahlung process ([PRD 79 111508 (2008)])
- $M_{h'} > 2M_{A'}$ and QED background is suppressed in this channel.

$$M_{h'} > 2M_{A'}$$

\[ \alpha_D : \text{dark sector coupling constant} \]
\[ \epsilon : \text{kinetic mixing parameter} \]

(excluding tau for leptons)

- 10 exclusive channels: $3(\ell^+\ell^-), 2(\ell^+\ell^-)(\pi^+\pi^-), (\ell^+\ell^-)2(\pi^+\pi^-)$, and $3(\pi^+\pi^-)$
- 3 inclusive channels for $m_X > 1.1$ GeV: $2(\ell^+\ell^-)X$

($X$: missing mass of the event)
Background Estimation

- Use same sign events: \( e^+e^- \rightarrow (\ell^+\ell^+)(\ell^-\ell^-)(\ell^+\ell^-) \)
- Order masses of lepton (hadron) pairs as \( m^1_{\ell\ell} > m^2_{\ell\ell} > m^3_{\ell\ell} \)
- Plot \( m^1_{\ell\ell} - m^3_{\ell\ell} \) vs. \( m^1_{\ell\ell} \)
- Select the region in invariant mass and predict the background using the same sign events

- Normalisation is from the side band same sign events
- Background estimated from counting same sign events

(I. Jaegle et al./Belle, (PRL 114, 211801 (2015)))
Belle results

Events consistent with background estimation.

Number of events observed after all selection criteria are applied.

(i. Jaegle et al./Belle, (PRL 114, 211801 (2015)))
Belle results - cont.

• Belle 977 fb\(^{-1}\) \(\text{(PRL 114, 211801 (2015))}\) and BaBar 520 fb\(^{-1}\) \(\text{(PRL 108 211801 (2012))}\)

• 90% CL upper limit on the product of \(\alpha_D\varepsilon^2\) vs. dark photon mass (top) and dark Higgs boson mass (below)
Dark vector gauge boson

- A new boson ($U'$) coupling to light quarks: S. Tulin, PRD 89, 11408 (2014)

The produced $\pi^0, \eta, \eta'$ from $e^+e^-$ collision can decay to a new boson and photon pair.

- Usually reconstructed light mesons suffer from combinatorial background.
- Suppress such background by looking at the exclusive decay of

  \[ \eta \rightarrow \pi^+\pi^-\gamma \text{ from } D^{*+} \rightarrow D^0\pi^+, \ D^0 \rightarrow K_S^0\eta \]
Reconstructed $\pi^+\pi^-\gamma$
- Clear peak from $\eta$ decay
- Combinatorial background and feed-down from $\pi^+\pi^-\pi^0$ seen.

- Fit is with low energy QCD (chiral perturbation + dispersive analysis)
- MC signal at 400 MeV overlaid
- No signature of $U'$ decays
Dark vector gauge boson

- E. Won et. al./Belle, PRD 94, 092006 (2016)

\[ \alpha_{U'} \equiv \frac{g_{U'}^2}{(4\pi)} \]

Upper limit on the coupling
- 95% C. L. by the Feldman-Cousins approach.

KLOE: model dependent (from A’)
Thick curves: current limits by total rate (no QCD contribution assumption)

Belle result: direct upper limit.
Other ongoing analyses

- Long lived dark photon search.

\[ e^+ e^- \rightarrow A' \rightarrow e^+ e^- \]

\[ c\tau = 1 - 10 \text{ cm} \]

- Invisible decays with photon conversion.

\[ e^+ e^- \rightarrow \chi \rightarrow \bar{\chi} \]

Single photon in the final state
- No such trigger in Belle.
- Photon conversion is under consideration.
Other ongoing analyses

• Search for a muonic dark force

\[ e^+e^- \rightarrow Z' \mu^+\mu^- \rightarrow \mu^+\mu^- \mu^+\mu^- \]

• The dark (scalar) Higgs h’’ boson

• Search for dark photon in B meson decays

\[ B^0 \rightarrow A' A', A' \rightarrow \ell^+\ell^- \text{ or } \pi^+\pi^- \]
Summary

• Studies on the dark sector represents an alternative to dark matter search efforts.

• $e^+e^-$ collider detector environment is sensitive to MeV - GeV ranges for proposed new dark particles: complementary to fixed-target experiment.

• We showed analyses at Belle for dark photon and dark boson.

• Prospects with Belle II data was presented in this conference as well (Dark Matter Detection session: July 5, 11:30 D. Neverov)
Belle results

3 entries per event in the plot  (I. Jaegle et al., (PRL 114, 211801 (2015))

- 19% of events due to $3(\pi^+\pi^-)$
- 74% of events due to $2(l^+l^-)X$
SuperKEKB & Belle II

- 40 time higher luminosity with new damping ring, new lattice, crab cavities, and nano beam.

- New detectors: pixel sensor, silicon strip, PID with quartz bar, and upgraded readout for all.
Belle II Schedule

- Commissioning (phase 1) of the main ring (without final quads) started Feb. 1, 2016, with a commissioning detector (not the real Belle II detector).
- Add final quads in summer 2016.
- Belle II: installation of the outer detector: spring/early summer 2016.
- Belle II (w/o the vertex detector) roll in autumn 2016, cosmic rays.

- Phase 2 commissioning autumn 2017 - spring 2018
- Install vertex detector summer 2018
- **Full detector operation autumn 2018 (phase 3)**
Sensitivity @ Belle II

- $e^+e^- \to \gamma A', A' \to \ell^+\ell^- (\ell = e \text{ or } \mu)$
- Predicted Belle II limits extrapolated from BaBar
- Improved low multiplicity trigger and better dimuon invariant mass resolution.
Sensitivity @ Belle II

- $e^+ e^- \rightarrow \gamma A', A' \rightarrow \chi \bar{\chi}$ (light dark matter R. Essig et al. arXiv:1309.5084)


- Assuming a single photon trigger in Belle II.