Studies of Dark Sector particles at Belle

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Outline

• Searches for dark-sector
  ✓ motivations & opportunities at $e^+e^- B$-factories

• Recent results from Belle
  ✓ Dark-photon search via Higgsstrahlung
  ✓ Search for dark-boson in $\eta$ decays
  ✓ Search for $D^0$ decays to invisible final states

• Prospects with Belle II ⇒ *talk by T. Ferber*

PRL 114, 211801 (2015)
PRD 94, 092006 (2016)
PRD 95, 011102(R) (2017)
Astrophysical observation by, e.g. PAMELA, AMS, etc. have triggered light dark matter and dark sector scenarios.

The dark sector can be connected to SM via the so-called “portals”.

<table>
<thead>
<tr>
<th>Term</th>
<th>Portal</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H^+ H (A S + \lambda S^2) )</td>
<td>Higgs portal</td>
<td>(dim= 3, 4),</td>
</tr>
<tr>
<td>( \kappa F^Y_{\mu\nu} F^I_{\mu\nu} )</td>
<td>Vector portal</td>
<td>(dim= 4),</td>
</tr>
<tr>
<td>( Y_N \bar{L} H N )</td>
<td>Neutrino portal</td>
<td>(dim= 4),</td>
</tr>
<tr>
<td>( f^{-1}<em>a \bar{\psi} \gamma</em>\mu \gamma_5 \psi \partial_\mu a )</td>
<td>Axion portal</td>
<td>(dim= 5).</td>
</tr>
</tbody>
</table>
Dark photon & kinetic mixing – as a portal

- Dark photon, first proposed in P. Fayet, PL B95, 285 (1980)
- (Holdom, 1986) A boson $A'$ belonging to an additional $U(1)'$ would mix kinetically with $\gamma$

\[ \frac{1}{2} \epsilon F_{\mu\nu} F'^{\mu\nu} \]

- In general, one can express kinetic mixing as $\frac{1}{2} \epsilon F_{\mu\nu} F'^{\mu\nu}$
- $\epsilon$, the strength of the kinetic mixing, is supposed to be small, $(10^{-5} \sim 10^{-2})$.

- For $A'$ to acquire mass, an extended Higgs sector is required to break this $U(1)'$
What to look for with $B$-factories

![Diagram with Feynman diagrams]

**ISR**

**B decays**
What to look for with $B$-factories

\[ e^+e^- \rightarrow \gamma A'(\rightarrow \chi \bar{\chi}) \quad e^+e^- \rightarrow \gamma A'(\rightarrow \ell^+\ell^-) \]
\[ e^+e^- \rightarrow \Upsilon(nS) \rightarrow \gamma A^0 \]
\[ e^+e^- \rightarrow h'(\rightarrow A'A')A' \text{ with } A' \rightarrow \ell^+\ell^- \]

$B \rightarrow SS \rightarrow 2(\ell^+\ell^-)$
\[ B \rightarrow K^{(*)} S \rightarrow K^{(*)} \ell^+\ell^- \]
\[ B \rightarrow K^{(*)} h' \text{ with } h' \rightarrow A'A' \rightarrow 2(\ell^+\ell^-) \]
\[ B \rightarrow 2h' \rightarrow 4A' \rightarrow 4(\ell^+\ell^-) \]
\[ B \rightarrow A'A' \rightarrow 2(\ell^+\ell^-) \text{ through off-shell } h - h' \text{ mixing} \]

B decay modes from Batell, Pospelov, Ritz, PRD 83, 054005 (2011)
$\mathcal{L}_{\text{peak}} = 21.1 \text{ nb}^{-1}\text{s}^{-1}$

$e^- \rightarrow (\ast) \leftarrow e^+$

$8 \text{ GeV} \rightarrow 3.5 \text{ GeV}$
Search mode depends on $M_{h'}$ and $M_{A'}$

In this study, only $M_{h'} > 2M_{A'}$ is considered

$\Rightarrow h' \rightarrow A'A'$ is used

$\int L dt = 977 \text{ fb}^{-1}$

Look for 3 (or 2, for inclusive channels) lepton/hadron pairs ($e^+e^-$, $\mu^+\mu^-$, or $\pi^+\pi^-$)

- 10 exclusive channels: $3e^+3e^-, 3\mu^+3\mu^-, 2e^+2e^-+\mu^+\mu^-, 2\mu^+2\mu^-e^+e^-, 3\pi^+3\pi^-, 2\pi^+2\pi^-e^+e^-, 2\pi^+2\pi^-\mu^+\mu^-, 2e^+2e^-\pi^+\pi^-, 2\mu^+2\mu^-\pi^+\pi^-, e^+e^-\mu^+\mu^-\pi^+\pi^-$

- 3 inclusive channels for $m_A > 1.1 \text{ GeV}/c^2$: $2e^+2e^-\chi, 2\mu^+2\mu^-\chi, e^+e^-\mu^+\mu^-\chi$
- 19% of events due to $3(\pi^+\pi^-)$
- 74% due to $2(\pi^+\pi^-)X$
- no excess of signals in any channel
Limits on kinetic mixing parameters

- \( \epsilon \lesssim 8 \times 10^{-4} \) for \( \alpha_D = 1/137 \), \( M_{h'} < 8 \text{ GeV/c}^2 \), \( M_{A'} < 1 \text{ GeV/c}^2 \)
  - ✓ Compare with BaBar limits with 516 fb\(^{-1}\)  
  - PRL 108, 211801 (2012)
- first limits (by any experiment) on \( 3(\pi^+\pi^-) \) and \( 2(e^+e^-)X \)
- expect linear improvement with more data (almost background-free for many modes)
Search for $\eta \rightarrow U'(\rightarrow \pi^+\pi^-)\gamma$ at Belle

- Search for a dark vector boson $U'$ that couples to quarks ($U' \rightarrow \pi^+\pi^-$)
  - to constrain the baryonic fine structure constant $\alpha_{U'} \equiv g_{U'}^2/4\pi$,
  - where the interaction is given by $\mathcal{L} = (1/3)g_{U'}\bar{q}\gamma\mu qU'_\mu$
    
    à la S. Tulin, PRD 89, 114008 (2014)

- Use Belle data sample of 976 fb$^{-1}$
- To suppress combinatorial background, demand:
  - $\eta$ to come from $D^0 \rightarrow K_S^0 \eta$
  - $D^0$ to come from $D^{*+} \rightarrow D^0\pi^+$
Search for $\eta \rightarrow U'(\rightarrow \pi^+\pi^-)\gamma$ at Belle

- $\gamma$ selection
  - $E_\gamma > 60$ (100) MeV for barrel (endcap)
  - “E9/E25” $> 0.85$
- $K_S^0$ selection by neural net
- vertex $\chi^2$ cut for $\eta$ and mass-constraint
- $p_{D^*}^{cm} > 2.5, 2.6, 3.0$ GeV for $\sqrt{s}$ below, at, or above $\Upsilon(4S)$ resonance
Search for $\eta \rightarrow U'(\rightarrow \pi^+\pi^-)\gamma$ at Belle

- $N_\eta = 2974 \pm 90$ events by binned max. likelihood fit to $M(\pi^+\pi^-\gamma)$
- Cross-check by measuring the ratio

$$\frac{\mathcal{B}(\eta \rightarrow \pi^+\pi^-\gamma)}{\mathcal{B}(\eta \rightarrow \pi^+\pi^-\pi^0)} = 0.185 \pm 0.007$$

c.f. $0.184 \pm 0.004$ for W.A.
- Fit to $M(\pi^+\pi^-)$ after $\eta$ sideband subtraction

- global shape: QCD-based $d\Gamma/ds$
- add $U'$ part with $\sigma_M \sim (1 \sim 2)$ MeV
Results for $\eta \rightarrow U'(\rightarrow \pi^{+}\pi^{-})\gamma$

\[
\alpha_{U'} = \frac{\alpha}{2} \left(1 - \frac{m_{U'}^2}{m_{\eta}^2}\right)^{-3} \left|\mathcal{F}(m_{U'}^2)\right|^{-2} \frac{1}{\mathcal{B}(U' \rightarrow \pi^{+}\pi^{-})} \times \left[\frac{\Gamma(\eta \rightarrow \pi^{+}\pi^{-}\gamma)}{\Gamma(\eta \rightarrow \gamma\gamma)}\right] \left[\frac{\Gamma(\eta \rightarrow U'\gamma \rightarrow \pi^{+}\pi^{-}\gamma)}{\Gamma(\eta \rightarrow \pi^{+}\pi^{-}\gamma)}\right],
\]

- First search for $U'$ in the $\pi^{+}\pi^{-}$ mode
- $\alpha_{U'} \lesssim (10^{-3} \sim 10^{-2})$ @ 95% CL.
  for $290 < m(U') < 520$ MeV/c$^2$
$D^0$ decays to invisible final states

- In SM, $D^0 \rightarrow \nu \bar{\nu}$ is helicity suppressed with $B \sim \mathcal{O}(10^{-30})$, but the rate could be enhanced via DM final states
- Belle uses ‘charm tagger’ method to collect inclusive $D^0$ samples for the search using $\int \mathcal{L} dt = 924 \text{ fb}^{-1}$

![Diagram of $D^0$ decay](image)

$$M_{D^0} \equiv M_{\text{miss}}(D_{\text{tag}}^* X_{\text{frag}} \pi^-) \quad N(D^0) = 0.7 \text{ M, inclusive}$$
$D^0$ decays to invisible final states

- Result of the first-ever search
  - $N_{\text{sig}} = -6.3^{+22.5}_{-21.0}$ from 2D fit to $(M_{D^0}, E_{\text{ECL}})$
  - $\mathcal{B}(D^0 \rightarrow \text{invisible}) < 9.4 \times 10^{-5}$ at 90% CL.
Closing words

• *B*-factory experiments are not merely good old CPV/CKM machines, but they probe much wider regions of physics.
  * e.g. exotic particles, heavy invisible particles, dark sector, etc.

• Dark photon searches at $e^+e^- B$-factories become available one by one.
  * Depending on the mass parameters of the dark sector, significant limits have been obtained in $\mathcal{O}(\text{GeV})$ region.
  * But there are many other modes which have yet to be explored.
  * Please stay tuned for Belle II
Back-up slides
Background

- estimated using “same-sign” pairs from $e^+e^- \rightarrow (\ell^+\ell^+)(\ell^+\ell^-)(\ell^-\ell^-)$
- Sort the pairs by invariant mass, $m_1 > m_2 > m_3$ then plot $m_1 - m_3$ vs. $m_1$
- For each $M_{\ell^+\ell^-}$ region, scale same-sign yield to $\ell^+\ell^-$ in the side-band, then extrapolate into the $M_{\ell^+\ell^-}$ signal region.

for 6π mode, with $m_1 = 2 \text{ GeV}/c^2$
Results – Limits on $B \times \sigma_{\text{Born}}$

\[ N_{\text{obs}} = \sigma_{\text{Born}} (1 + \delta) |1 - \Pi(s)|^2 \mathcal{L} \mathcal{B} \epsilon + N_{\text{bkg}} \]

- $(1 + \delta)$ from E.A. Kuraev and V.S. Fadin, Sov. J. Nucl. Phys. 41, 466 (1985)

- Limits are obtained from Bayesian method, using Markov Chain Monte Carlo$^1$
  - logarithmic prior for $\sigma_{\text{Born}}$
  - gaussian prior for other parameters

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Results – Limits on $\mathcal{B} \times \sigma_{\text{Born}}$

![Graph showing limits on $\mathcal{B} \times \sigma_{\text{Born}}$ for different mass squared values](image_url)
Control sample study

2D fit results for the control channel $D^0 \rightarrow K^- \pi^+$