INVISIBLE Z' AND UPSILON(1S) WITH BELLE II
Super B-factory, located in Tsukuba, Japan

asymmetric $e^+e^-$ collider ($e^-$ at 7GeV, $e^+$ at 4GeV)

commissioning run from Feb to Jul 2018, regular operations started in Mar 2019

operated at 10.58 GeV ($= m_{\Upsilon(4S)}$)

design luminosity $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$
during last year’s commissioning run, 0.5 fb\(^{-1}\) collected
aim is to collect 50 times more data than Belle (i.e. 50 ab\(^{-1}\))
rich physics program: \(B\) and \(D\) physics, quarkonium
and low mass dark sector
DARK Z’

- extend SM by adding a $U(1)'$ group
- new massive gauge boson $Z'$ couples only to fermions of 2$^{\text{nd}}$ and 3$^{\text{rd}}$ generation
- $Z'$ coupled to $L_\mu$-$L_\tau$ via $g'$
- focus on invisible $Z'$ decay produced with a pair of muons
- invisible decay channel to be explored for the first time

\[
\begin{align*}
M_{Z'} < 2M_\mu & \implies BF[Z' \to \text{invisible}] = 1, \\
2M_\mu < M_{Z'} < 2M_\tau & \implies BF[Z' \to \text{invisible}] \simeq 1/2, \\
M_{Z'} > 2M_\tau & \implies BF[Z' \to \text{invisible}] \simeq 1/3. \\
\end{align*}
\]

if $M_{Z'} > 2M_\chi$

$BF(Z' \to \chi\bar{\chi}) = 1$

★ may solve dark matter puzzle (mediator between SM and DS)
★ may explain $(g-2)_\mu$
DARK Z'

Belle 2 DATA
event display
run # 3236
Event #493624
M\_Z\' candidate 2 GeV/c\(^2\)
DARK SECTOR WITH BELLE II

DARK Z'

- reconstruct recoil mass w.r.t. the two muons
- look for a bump in mass spectrum
- consider several mass hypothesis for $Z'$
- consider main backgrounds ($\mu^+\mu^-, \tau^+\tau^-, e^+e^-\mu^+\mu^-$)
- systematic effects include trigger, tracking and PID

$$M_r^2 = s + M_{\mu^+\mu^-}^2 - 2\sqrt{s}E_{\mu^+\mu^-}^{CMS}$$

analysis under internal review → unblinding
PRL paper in preparation to be submitted soon
**UPSILON (1S) TO INVISIBLE**

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

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

- Low mass dark matter particles however might play a role in the decays of $Y(1S)$, having $Y(1S) \rightarrow \chi\chi$ if kinematically allowed, *Phys. Rev. D 80:115019 (2009)*
- Also, new mediators ($Z', A^0, h^0$) or SUSY particles might enhance $Y(1S) \rightarrow \nu\nu(\gamma)$, *Phys. Rev. D 81:054025 (2010)*
- In absence of new physics enhancement, Belle II should be able to observe the SM $Y(1S) \rightarrow \nu\nu$

<table>
<thead>
<tr>
<th>L/\text{fb}^{-1}</th>
<th>N(Y(4S))</th>
<th>N(Y(4S)\rightarrow Y(1S)\pi\pi)</th>
<th>N(Y(3S))</th>
<th>N(Y(3S)\rightarrow Y(1S)\pi\pi)</th>
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<tbody>
<tr>
<td>50</td>
<td>54,300,000</td>
<td>4453</td>
<td>189,650,000</td>
<td>8,287,705</td>
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<td>100</td>
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<td>379,300,000</td>
<td>16,575,410</td>
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<tr>
<td>300</td>
<td>325,800,000</td>
<td>26716</td>
<td>1,137,900,000</td>
<td>49,726,230</td>
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</tbody>
</table>

\[
M_r^2 = s + M_{\pi^+\pi^-}^2 - 2\sqrt{s}E_{\pi^+\pi^-}^{CMS}
\]
DARK SECTOR WITH BELLE II

UPSILON (1S) TO INVISIBLE

- peaking bkg events due to $Y(1S)$ decay leptons out of detector acceptance (→ fake signal event)
- estimate different contributions with MC control sample
- select invisible candidates with PID, track and InvM criteria

**Number of peaking bkg events**

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{pbkg,\mu\mu}$</td>
<td>10581</td>
</tr>
<tr>
<td>$N_{pbkg,\tau\mu\mu}$</td>
<td>486</td>
</tr>
<tr>
<td>$N_{pbkg,ee}$</td>
<td>5894</td>
</tr>
<tr>
<td>$N_{pbkg,\tau\tauee}$</td>
<td>272</td>
</tr>
<tr>
<td>$N_{pbkg,\tau\tau\pi}$</td>
<td>48</td>
</tr>
</tbody>
</table>

$N_{exp} = 17281 \pm 131.457$

![Recoil mass plot](image)
UPSILON (1S) TO INVISIBLE

- reduce peaking and non-peaking bkg with MVA study
- FastBDT with signal=$\Upsilon(1S)\rightarrow\nu\nu$ and bkg=gen, cont
- features include $n\text{Tracks}_{ROE}, E_{\pi^+\pi^-}, E_{\gamma,\text{max}},...$
- extract signal yield with double gaussian fit
- preliminary cross section limit

\[BR(\Upsilon(1S) \rightarrow \text{inv}) < 3.74 \times 10^{-5}\]

\[BR(\Upsilon(1S) \rightarrow \text{inv}) < 3 \times 10^{-4}\]
WHAT ABOUT A DARK HIGGS?

- extend SM by adding a $U(1)$ group
- new minimal model includes dark photon ($U$ boson), coupled to SM $\gamma$ via kinetic mixing parameter $\varepsilon$
- introduce in analogy to SM a spontaneous symmetry breaking mechanism of $U(1)$ with new particle, dark Higgs $h'$
- $e^+e^- \rightarrow Uh'$ (Higgs-Strahlung), distinguish different signatures according to mass hypothesis
  - $m_{h'} > 2m_U$, $h'$ decays to $U$ pair, six charged particle final state, investigated by BaBar and Belle
  - $m_{h'} < m_U$, $h'$ has large lifetime to escape detection, 2 charged particle final state plus missing energy, only investigated by KLOE

![Diagram showing exclusion limits for $\alpha_D \varepsilon^2$](image)

Fig. 5. 90% CL upper limits in $\alpha_D \varepsilon^2$ for the on-peak sample (left plot) and off-peak sample (right plot).
CONCLUSION

- Belle II successfully running
- different low mass DS analysis: Dark Z', Y(1S), Dark Higgs...
- new techniques will allow to (hopefully) see the invisible
- important to explore alternatives
THANK YOU FOR YOUR ATTENTION!
BACKUP
BELLE II ECL

- Belle II ECL has no projective cracks in $\Phi$
- excellent to measure charge asymmetries
- not optimal for uniform photon efficiency