

# Dark sector physics at Belle II

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# Introduction – Dark matter at Belle II

- Belle II will accumulate a unique data sample over the next decade
  - Clean environment of e<sup>+</sup>e<sup>-</sup> collisions
  - Unique collision energy (among the currently running colliders)
- The Belle II detector is well designed to search for dark matter
  - Upgraded particle ID Improved constraints from recoil
  - Better hermeticity than BaBar
  - Special triggers for one- and three-photon signatures (under design)
  - Improved event reconstruction to increase the sensitivity to missing energy signatures
- Searches for dark matter in
  - B decays
  - LFV decays
  - Direct production





- Electron positron collision at Y(4S) resonance produces two B mesons
- Created in an L=1 coherent state



- $\sigma(e^+e^- \rightarrow b\overline{b}) = 1.1 \text{ nb}$
- $\sigma(e^+e^- \rightarrow c\overline{c}) = 1.3 \text{ nb}$
- $\sigma(e^+e^- \rightarrow s\overline{s}) = 0.4 \text{ nb}$

- $\sigma(e^+e^- \rightarrow u\overline{u}) = 1.6 \text{ nb}$
- $\sigma(e^+e^- \rightarrow d\overline{d}) = 0.4 \text{ nb}$
- $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.9 \text{ nb}$



## **Invisible Dark Photon Search at Belle II**



Detector signature: single photon + missing energy Background from  $e^+e^- \rightarrow \gamma\gamma$ 



# bible $(m_{A'} > 2 \ m_{\chi})$





Pacific

Northwest

Unlike dark matter, mediators from portal interactions can have sizable SM couplings.

See also SIMPs (Hochberg, Y., Kuflik, E.&Murayama, H. J. High Energ. Phys. (2016) 2016: 90. )







### **Belle II data sample**

### SuperKEKB performance

Instantaneous Luminosity world record broken on June 15, 2020: 2.22 x 10<sup>34</sup> cm<sup>-2</sup>s<sup>-1</sup>

Data recorded: > 100 fb<sup>-1</sup>



Updated on 2021/03/25 21:56 JST



# **Background sources**

### **Touschek scattering**

- Intra-bunch scattering
- rate  $\propto$  (beam size)<sup>-1</sup>, (Ebeam)<sup>-3</sup>
- Most dangerous background at SuperKEKB
- Photons upstream hit nuclei and produce ~10<sup>11</sup>/cm<sup>2</sup>/year neutrons (1 MeV equivalent)

### **2-photon process**

- Generated electron-positron pair might enter the detector
- 0.2% occupancy on PXD

### **Radiative Bhabha**

- Rate  $\propto$  Luminosity (KEKB x 40)
- EM showers from outgoing beam
- Neutrons from photon







 $\mathcal{L} = \sum_{\ell} \theta g' \bar{\ell} \gamma^{\mu} Z'_{\mu} \ell \quad \text{Could be related to: dark} \\ \text{matter, g-2, R(K) and R(K^*)}$ 

arXiv:1403.2727



 $\ell = \mu, \tau, \nu_{\mu,L}, \nu_{\tau,L}$ 

Search for a peak in the recoil mass, using 2018 pilot run data



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Outlook: Updated triggers Sensitivity to  $(g-2)_{\mu}$  band with data sample on tape



Tag

SL  $B^+$ 

SL  $B^0$ 

Hadronic  $B^+$ 

Hadronic  $B^0$ 

### Full event Reconstruction in Belle II arXiv:1807.08680

- Y(4S) decays to a pair of B mesons
- The detector covers nearly 4  $\pi$  $\rightarrow$  use the well-known collision energy and reconstruct one B meson to apply constraints on invisible decays of the other B meson  $B \rightarrow \mu \nu, B \rightarrow \tau \nu, B \rightarrow K(*) \nu \nu$

$\pi^+$ $\overline{D^0}$ $7$	$B_{\text{tag}}^{-}$ $(4S)$ $B_{\text{tag}}^{-}$
Belle II	u u
6%	
5%	×
8%	

		Belle W/ FEI	Belle
	0.66%	0.76%	0.28%
×	1.45%	1.80%	0.67%
	0.38%	0.46%	0.18%
	1.94%	2.04%	0.63%
J			

Tagging  $\epsilon$  on MC

Incl. Belle II background





## **Search for Axion-like particles**

Belle II is sensitive to new propagators coupling to photons  $\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{\Lambda} a F_{\mu\nu} \tilde{F}^{\mu\nu}$ 

We convert the cross section to a coupling using

$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\text{QED}}}{24} \left(1 - \frac{g_{a\gamma\gamma}^2 \alpha_{\text{QED}}}{24}\right) \left(1 - \frac{g_{a\gamma\gamma}^2 \alpha_{\text{QED}}}{$$

 $e^+$ 











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iency	$N_{\rm Backg.}$	$N_{\rm Sig-exp.}$	$N_{\rm Backg.}$	$N_{\rm Sig-exp.}$	Statistica	Total $=$	λ] <b>τ</b>		٦.7	λτ	λ.Τ	λτ	<u>O + + • + • 1</u>	
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	5	2.0	704	143	20%	22%	<b>0</b>	0.00	$\angle 1$	<b>5.0</b>	2900	Z40	2070	ZZ/0
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n], Phys. Rev. D 87, no. 11, 111103 (2013) [arXiv:1303.3719 [hep-ex]].

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# **Current status of K**<sup>+</sup>*vv*

- New idea: inclusive tagging
  - Select the highest track with the highest p<sub>T</sub>
- Signal efficiency increases to ~4%
- We apply a multivariate classifier on the rest of the event to reduce background
- Competitive measurement with a fraction of the data  $Br(B^+ \rightarrow K^+ \nu \bar{\nu}) < 4.1 \times 10^{-5} (90\% \text{ CL})$





 $n+ \nu + -$ 

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"Baryogenesis and Dark Matter from B Mesons" Gilly Elor, Miguel Escudero, Ann E. Nelson *Phys. Rev. D* 99, 035031 (2019)



# Search for $B_d^0 \to \Lambda^0 \psi_{\rm DM}$

- Generic backgrounds from:
  - $B^0/B^+$  events:  $e^+e^- \to Y(4S) \to B\overline{B}$
  - Continuum:  $e^+e^- \rightarrow q\bar{q} \ (q = u, d, s, c)$
- Rare  $B^0/B^+$  decays MC samples
- $\mathcal{B}(B_d^0 \to \Lambda^0 \psi_{\rm DM} + \text{mesons}) \in [2 \times 10^{-4}, 0.1]$ 
  - Upper limit: Inclusive *B* decays
  - Lower limit: A<sup>q</sup><sub>SL</sub> world averages
- Signal side:  $B_d^0 \to \Lambda^0 \psi_{\rm DM}$ 
  - Reconstruct:  $\Lambda^0 \rightarrow p\pi^-$
  - Benchmark  $M(\psi_{\rm DM}) = 3.3 \text{ GeV}$
  - 1.5 GeV  $< M(\psi_{\rm DM}) \lesssim 4.2$  GeV
- Tag side:  $B_d^0 \rightarrow$  hadronic decays  $B_d^0$ 
  - Full Event Interpretation (FEI)
  - Multivariate classifiers (MVCs)





- Dark sector searches are increasingly moving to lower energies.
- Belle II will make important contributions to the search(es) for a dark sector.
  - The accelerator will accumulate a unique data sample
  - The detector has unique capabilities compared to previous experiments
    - $\checkmark$  Improved triggers and reconstruction compared to Belle
    - ✓ Improved hermeticity compared to BaBar
- The collaboration is starting to exploit the data and first physics analysis related to dark sector searches have been published.
  - Axion-like particles
  - Invisible Z'
- We have lots more in the pipeline, but we're always looking for new ideas. If you have a model that you think Belle II might be sensitive to, please get in touch.



# Thank you



