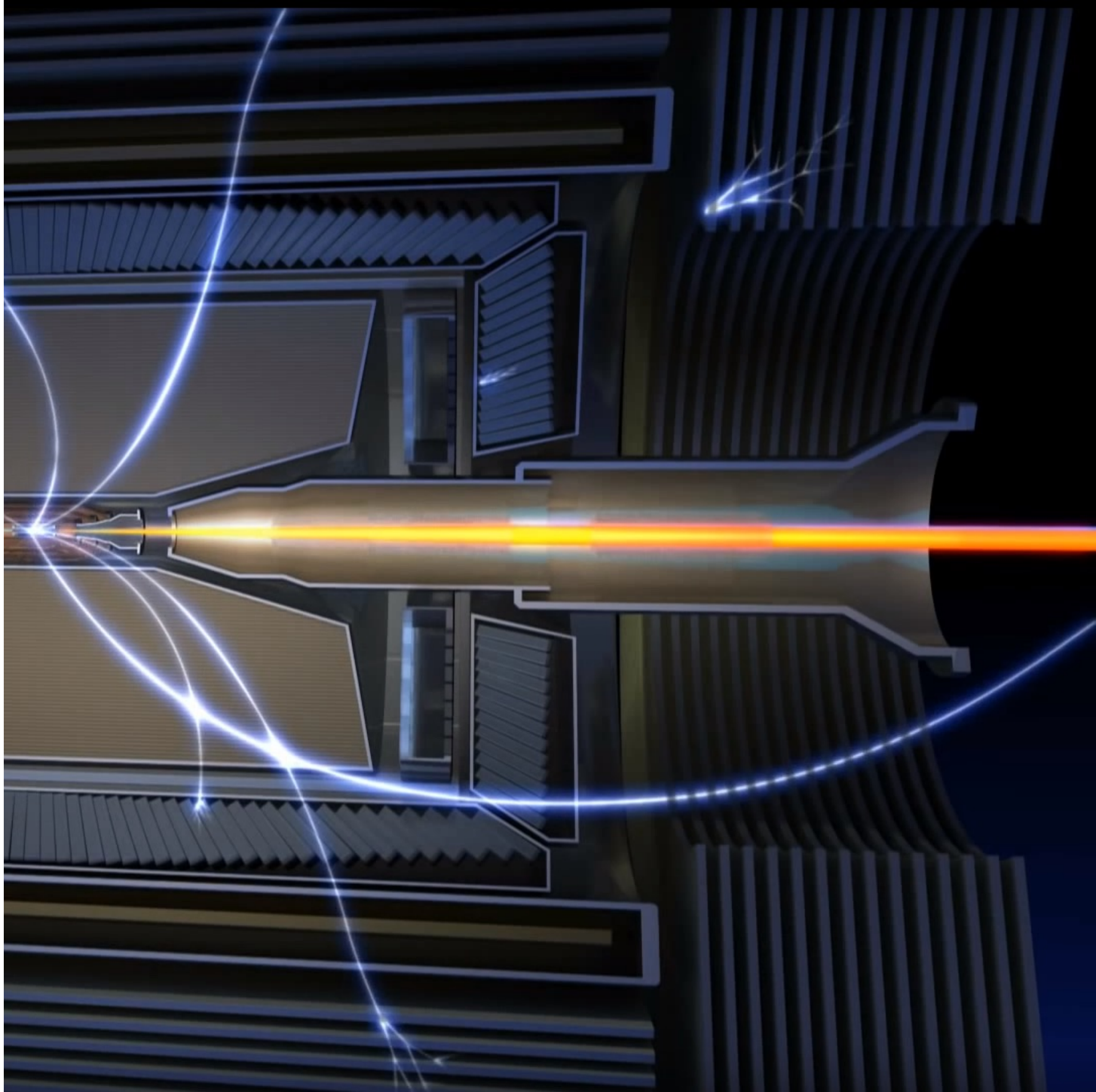
Dark sector physics at Belle II

Jan Strube (he/him)

On behalf of the Belle II collaboration

PNNL is operated by Battelle for the U.S. Department of Energy



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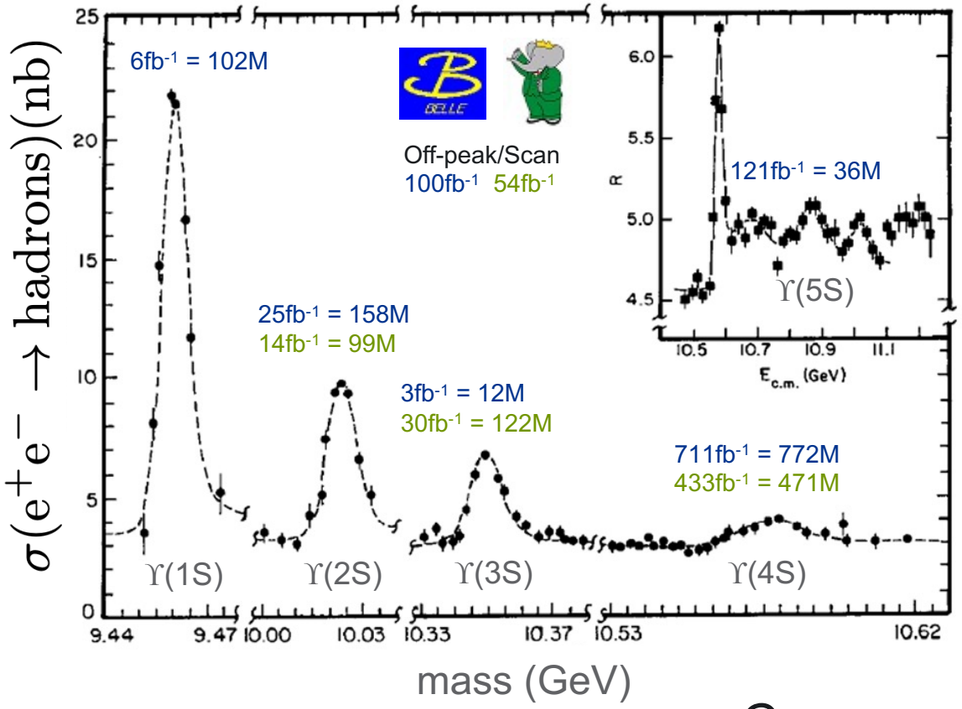
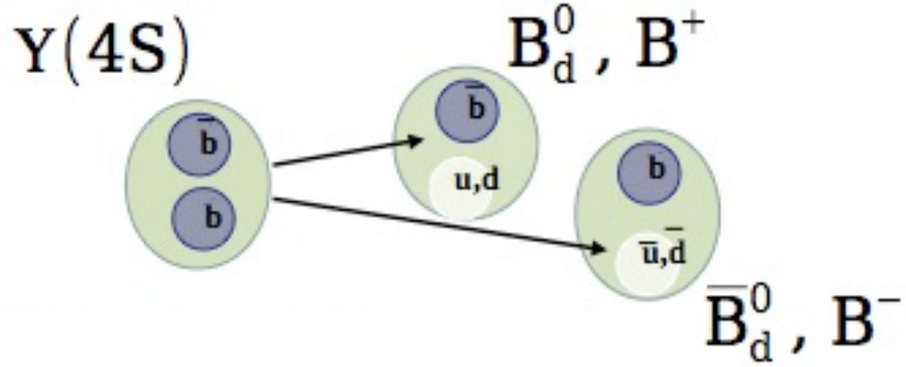
Introduction – Dark matter at Belle II

- Belle II will accumulate a unique data sample over the next decade
  - Clean environment of e^+e^- 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
  - Direct production
  - LFV decays
  - B decays

Physics at B factories



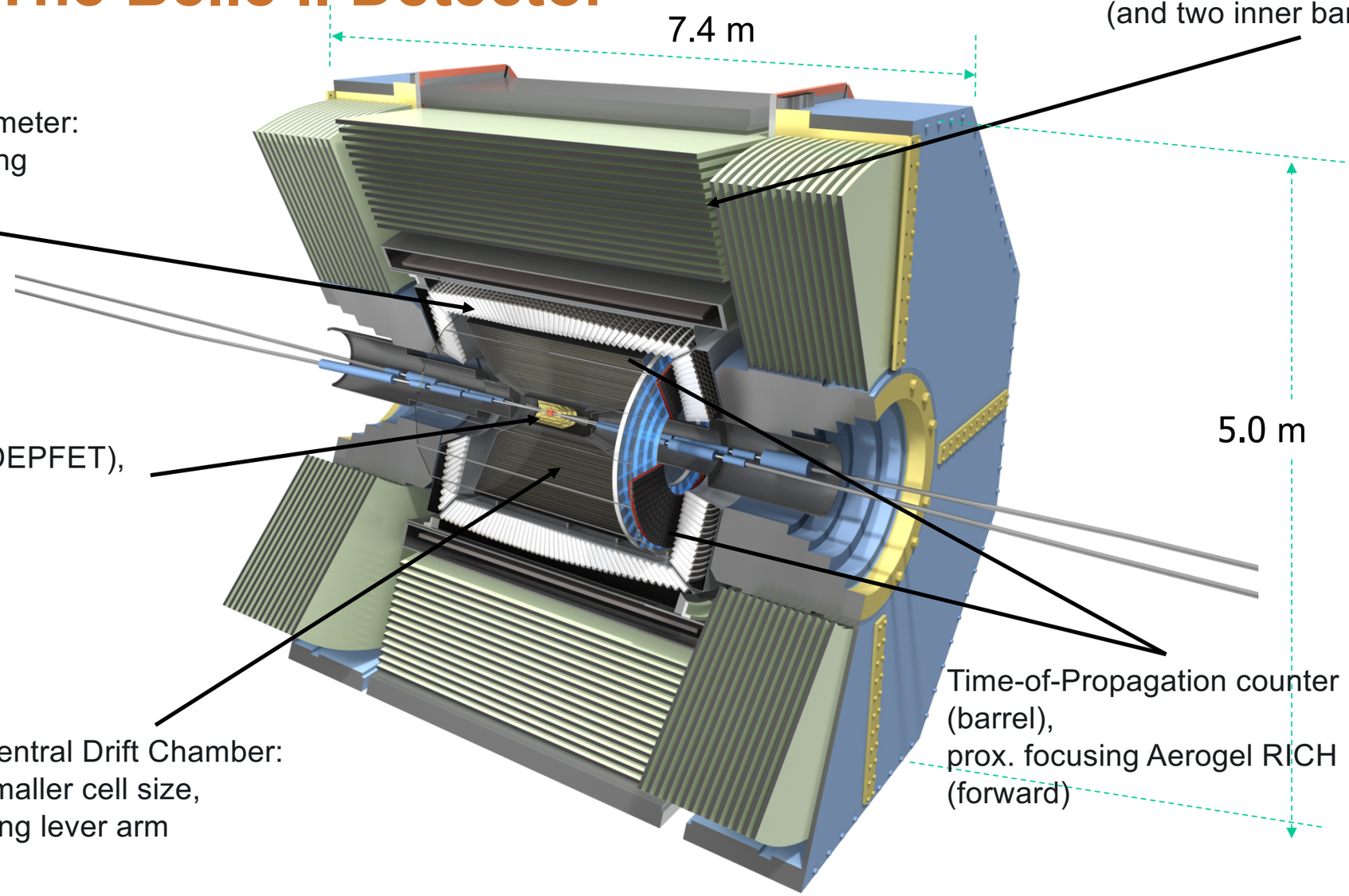


- Electron positron collision at Y(4S) resonance produces two B mesons
- Created in an L=1 coherent state

Cross sections

- $\sigma(e^+e^- \to b\bar{b}) = 1.1$ nb
- $\sigma(e^+e^- \to c\bar{c}) = 1.3$ nb
- $\sigma(e^+e^- \to s\bar{s}) = 0.4$ nb
- $\sigma(e^+e^- \to u\bar{u}) = 1.6$ nb
- $\sigma(e^+e^- \to d\bar{d}) = 0.4$ nb
- $\sigma(e^+e^- \to \tau^+\tau^-) = 0.9$ nb

The Belle II Detector

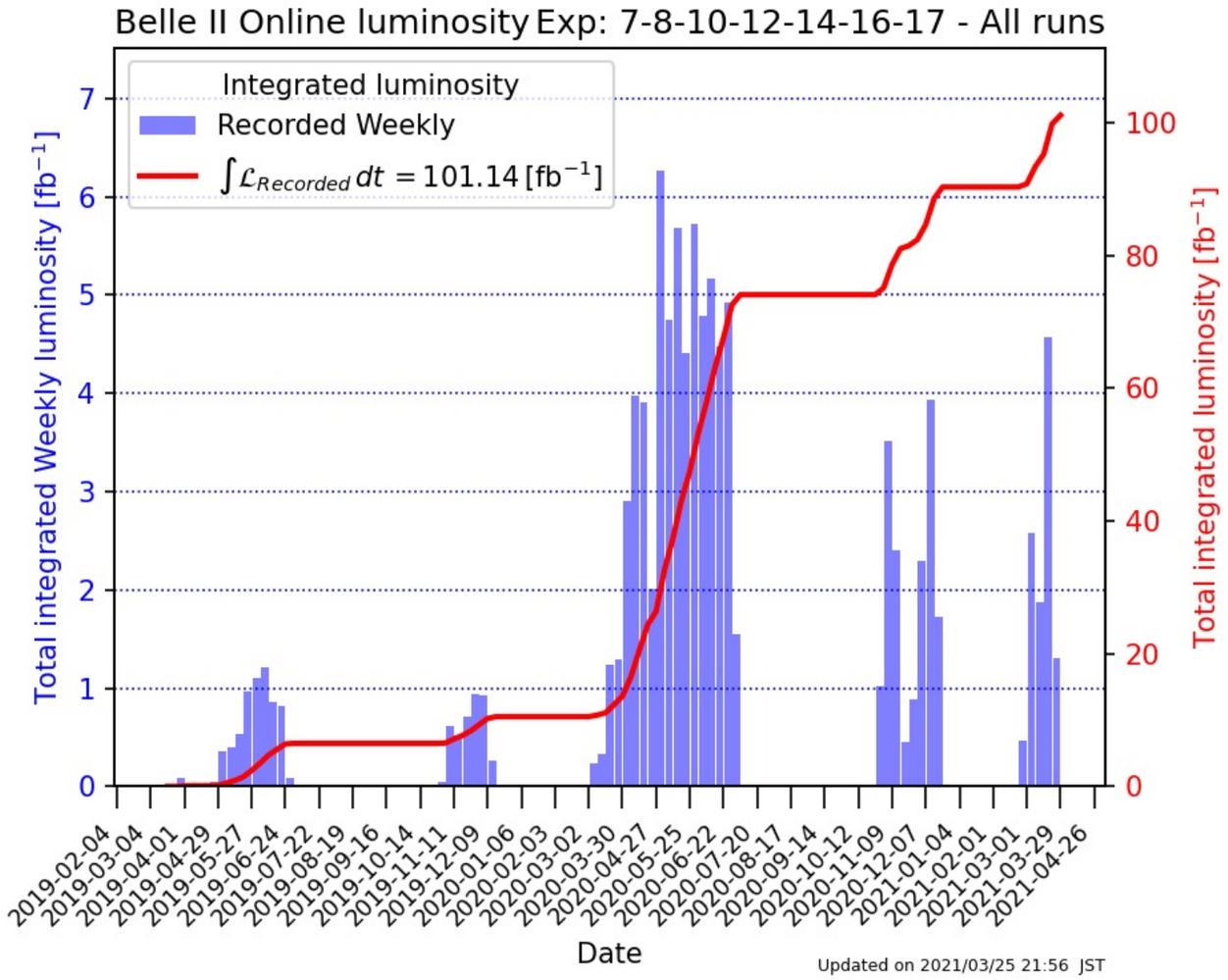


Belle II data sample

SuperKEKB performance

Instantaneous Luminosity world record broken on June 15, 2020:
2.22 x 10^{34} $cm^{-2}s^{-1}$

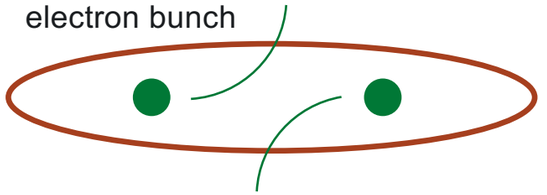
Data recorded:
passed 100 fb^{-1} on March 24th, 2021



Background sources

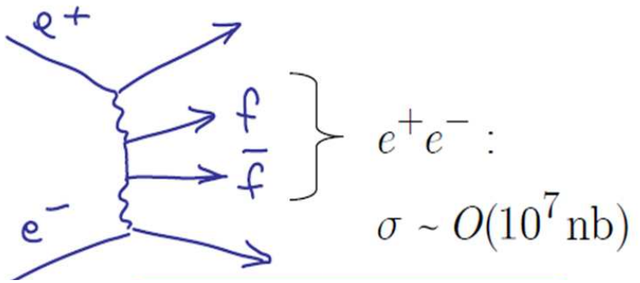
Touschek scattering

- Intra-bunch scattering
- rate ∝ (beam size)$^{-1}$, (Ebeam)$^{-3}$
- Most dangerous background at SuperKEKB
- Photons upstream hit nuclei and produce ~10^{11}/cm^2/year neutrons (1 MeV equivalent)



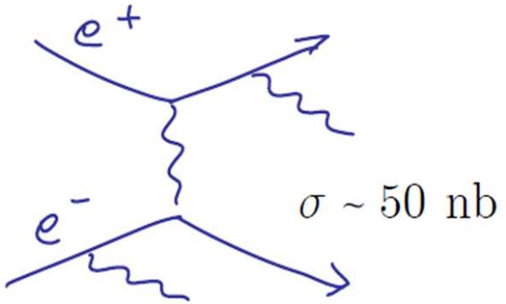
2-photon process

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

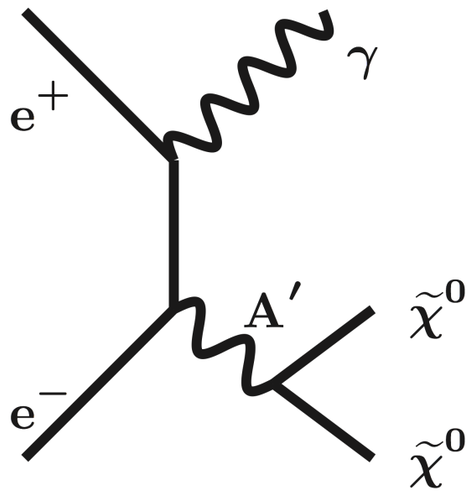


Radiative Bhabha

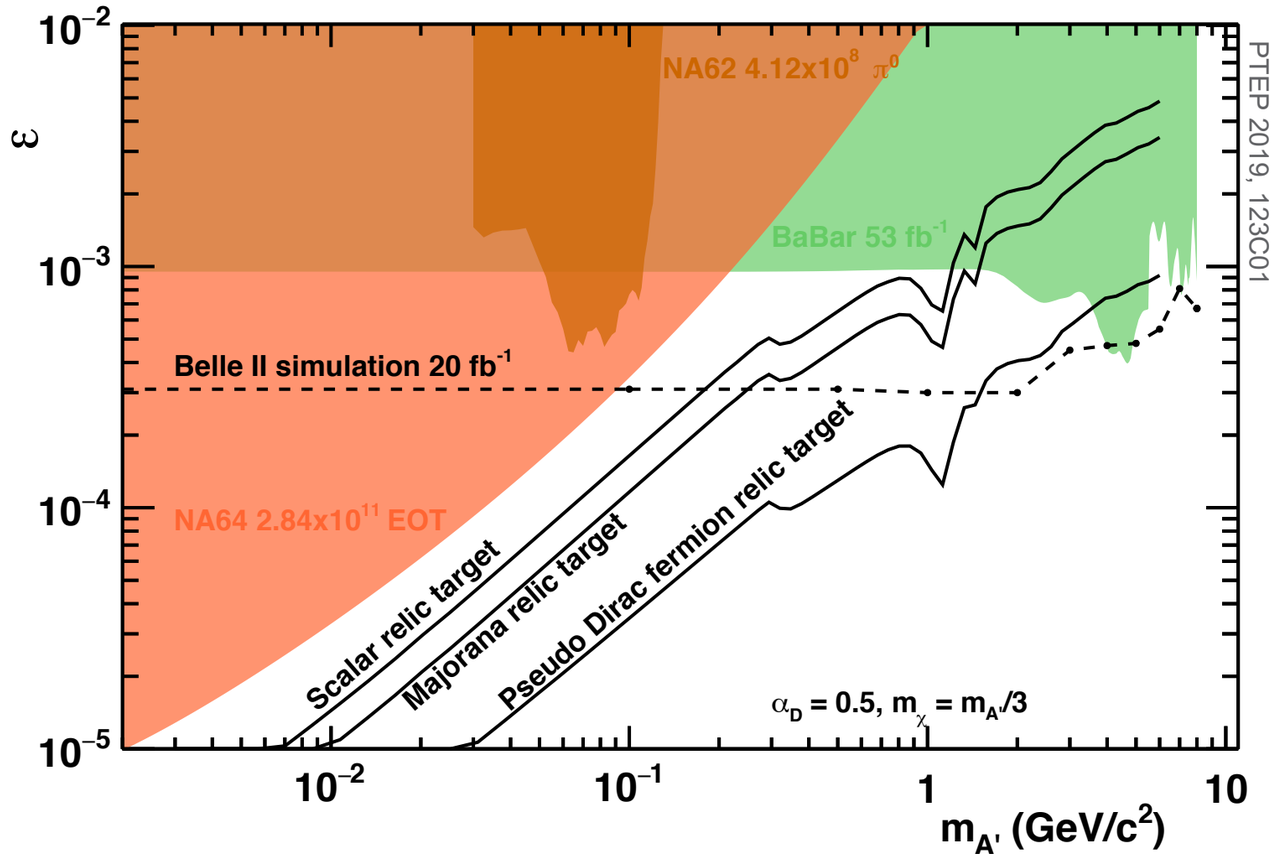
- Rate ∝ Luminosity (KEKB x 40)
- EM showers from outgoing beam
- Neutrons from photon



Invisible Dark Photon Search at Belle II

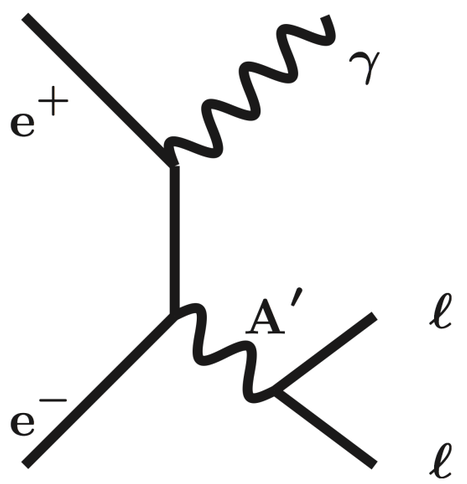


$$E_\gamma^* = \frac{\sqrt{s}}{2} - \frac{m_{A'}^2}{2\sqrt{s}}$$



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

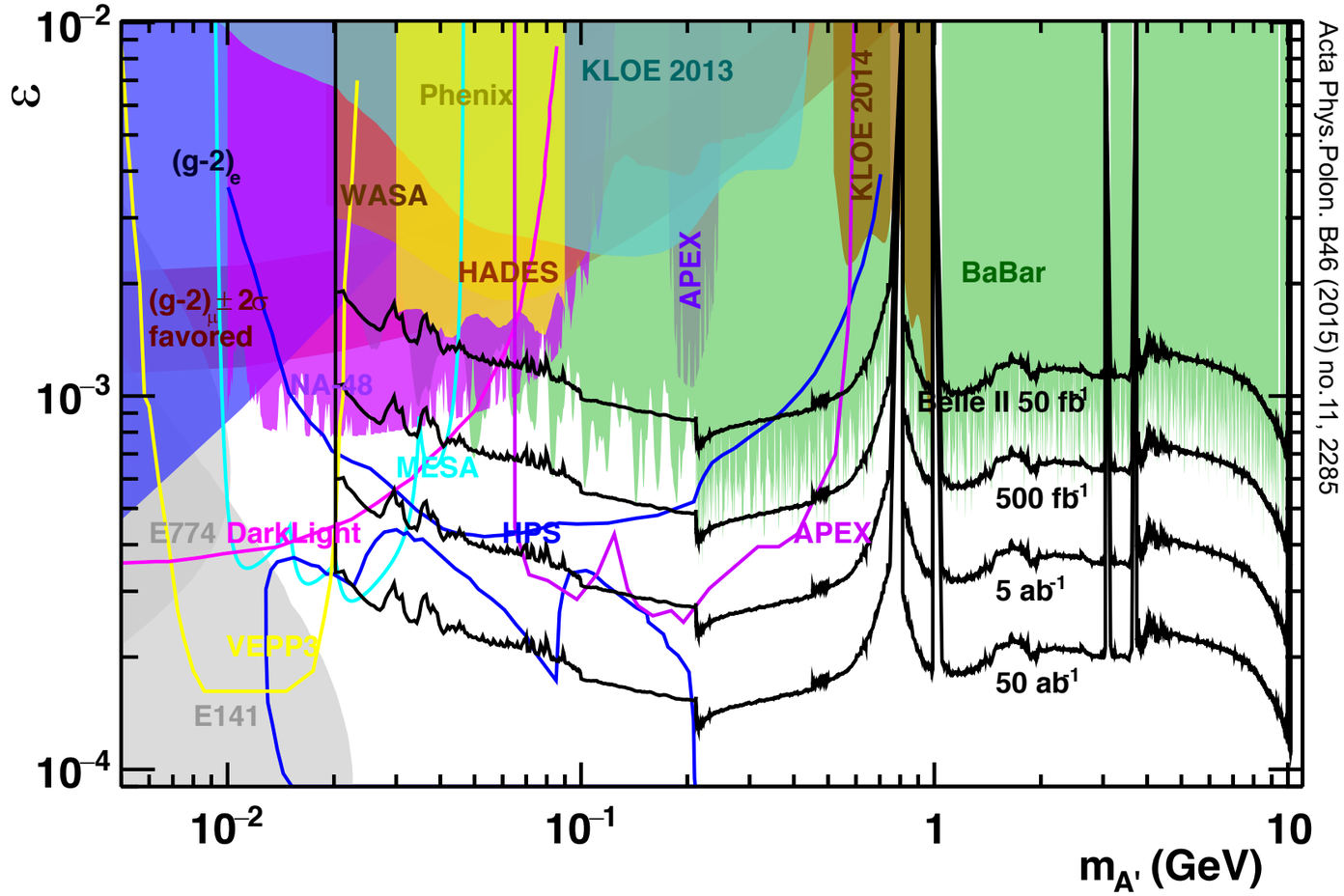
Visible Dark Photon Search at Belle II



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.)



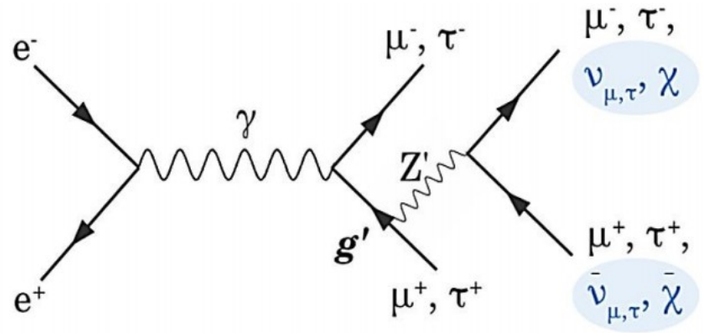
Detector signature: single photon + two tracks

$L_\mu - L_\tau$ model: search for an invisible Z'

$$\mathcal{L} = \sum_{\ell = \mu, \tau, \nu_{\mu,L}, \nu_{\tau,L}} \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell$$

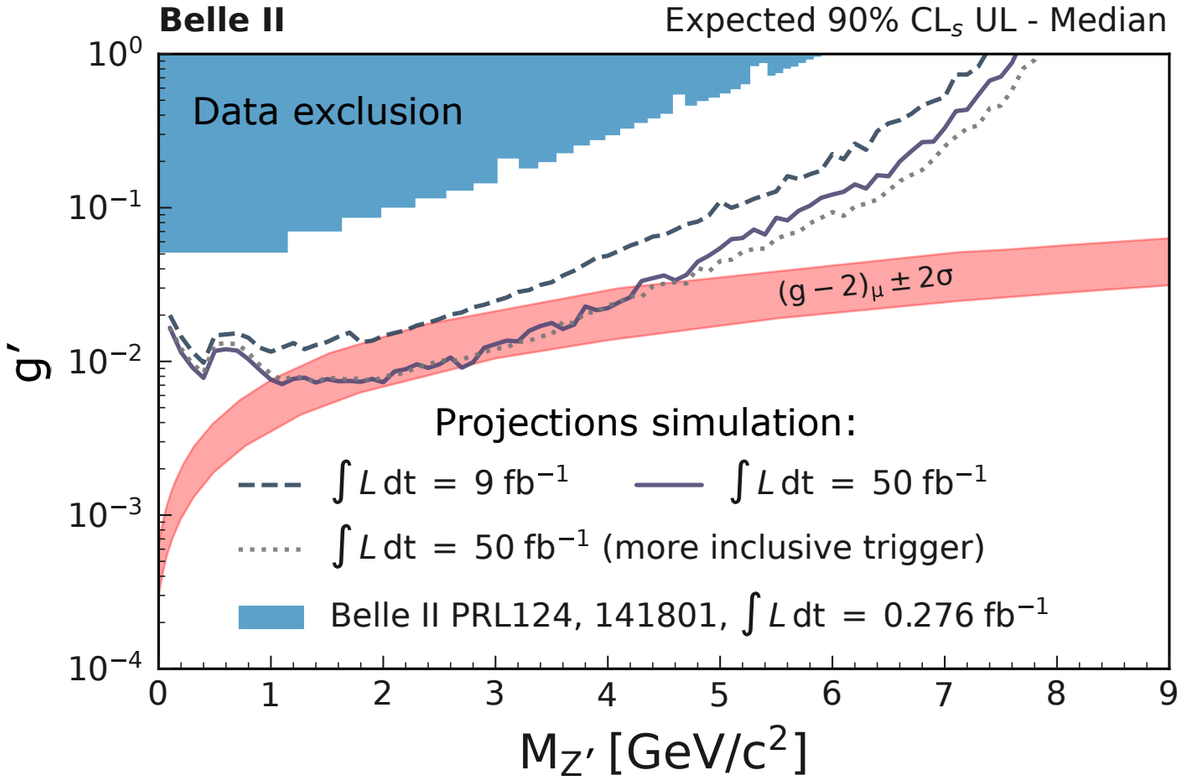
Could be related to: dark matter, g-2, R(K) and R(K*)

Shuve et al., arXiv:1403.2727



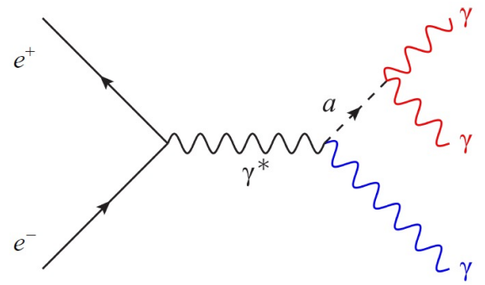
Search for a peak in the recoil mass, using 2018 pilot run data

First Belle II physics paper:
PRL 124 (2020) 141801



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

Search for Axion-like particles



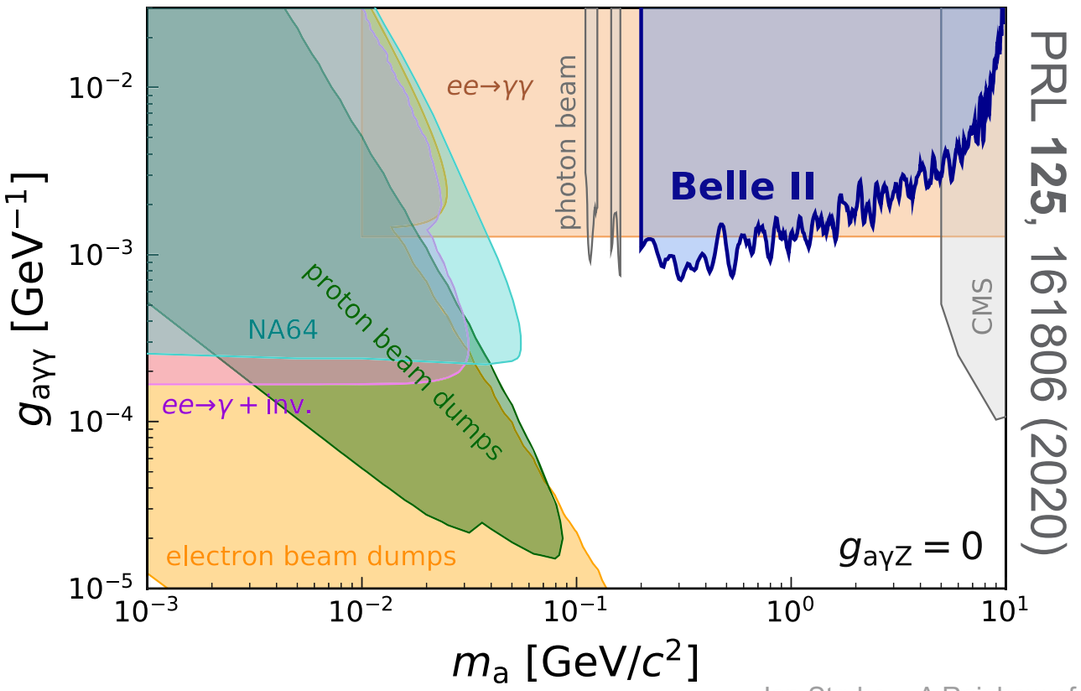
Belle II is sensitive to new propagators coupling to photons

$$\mathcal{L} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

We convert the cross section to a coupling using

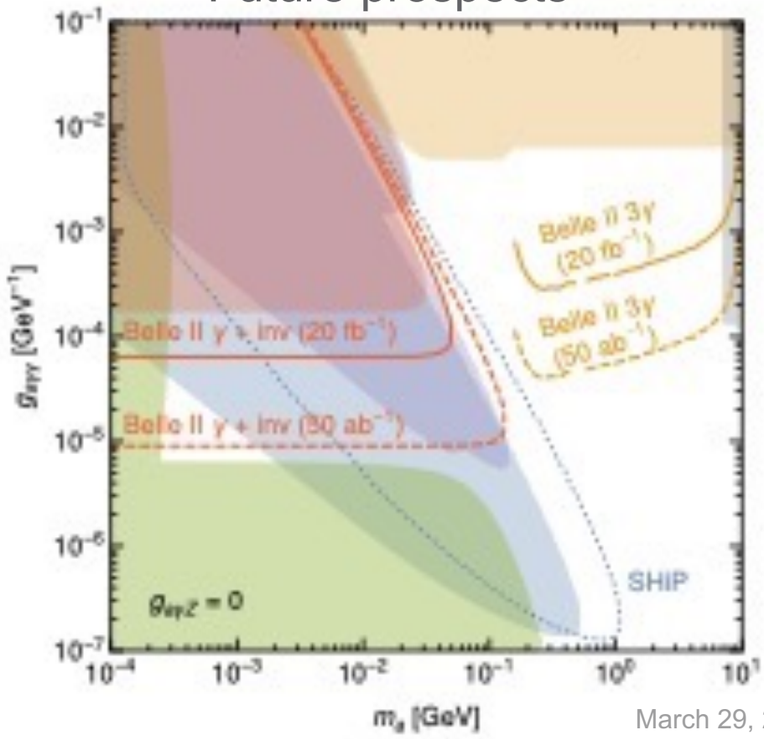
$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\mathrm{QED}}}{24} \left(1 - \frac{m_a^2}{s}\right)^3$$

Current status, using 445 pb^{-1} of 2018 data



PRL **125**, 161806 (2020)

Future prospects



JHEP03(2021)190

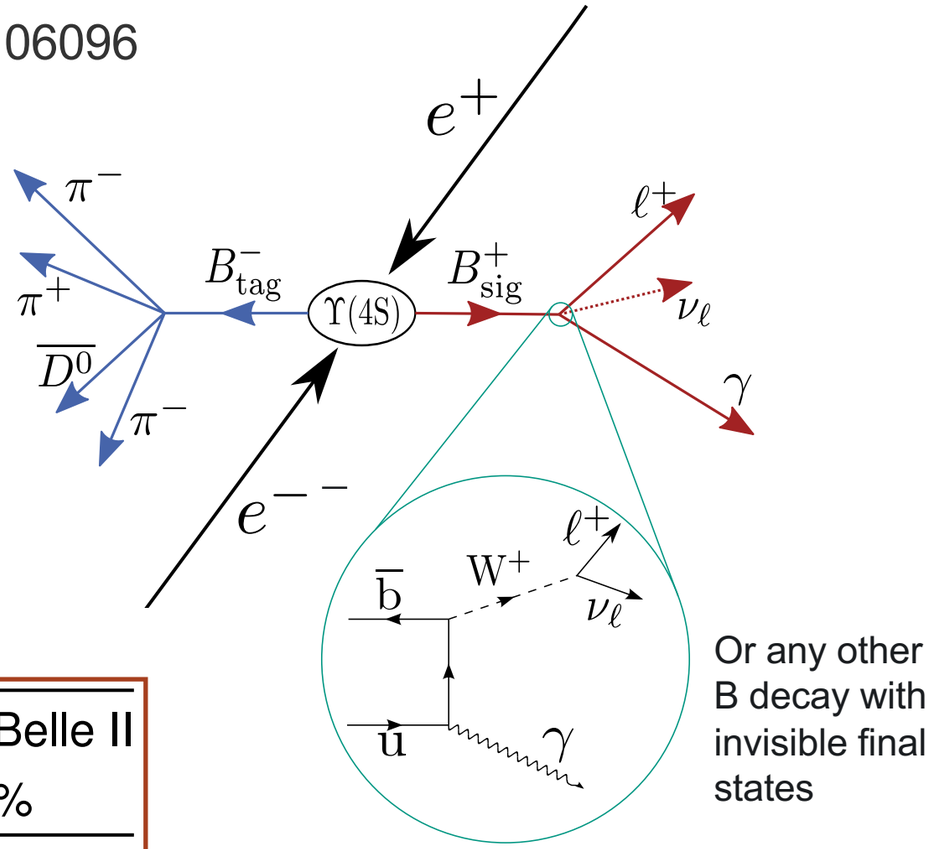
Full Event Interpretation in Belle II

Comput Softw Big Sci **3,** 6 (2019), arXiv:2008.06096

- Y(4S) decays to a pair of B mesons
- The detector covers nearly 4 π

→ use the well-known collision energy and reconstruct one B meson to apply constraints on invisible decays of the other B meson

B → μν, B → τν, B → K(*)$\nu\nu$



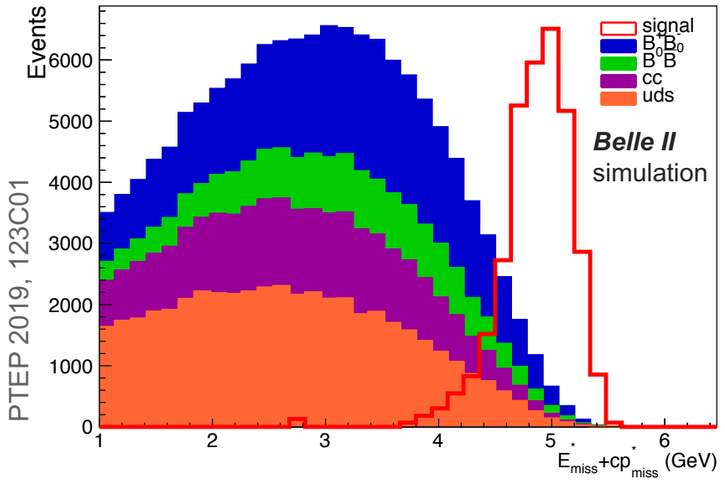
Or any other B decay with invisible final states

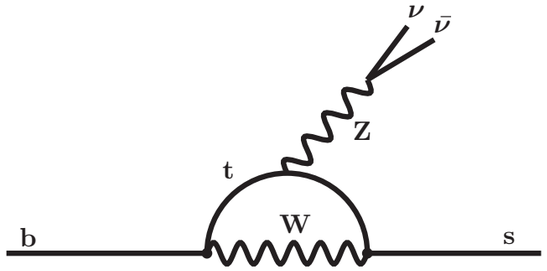
Tagging ϵ on MC

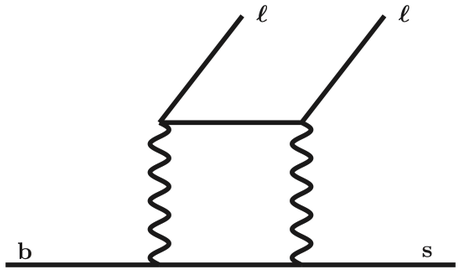
Tag	Belle	Belle w/ FEI	FEI Belle II
Hadronic B^+	0.28%	0.76%	0.66%
SL B^+	0.67%	1.80%	1.45%
Hadronic B^0	0.18%	0.46%	0.38%
SL B^0	0.63%	2.04%	1.94%

Incl. Belle II background

B → Kνν







Analysis is made possible by event reconstruction in a 4 π detector.

New physics coupling to third-generation leptons could enhance the decay while avoiding existing limits.

Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\mathrm{Backg.}}$ 711 fb^{-1} Belle	$N_{\mathrm{Sig-exp.}}$ 711 fb^{-1} Belle	$N_{\mathrm{Backg.}}$ 50 ab^{-1} Belle II	$N_{\mathrm{Sig-exp.}}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+\nu\bar{\nu}$	4.68	5.68	21	3.5	2960	245	20%	22%
$B^0 \to K^0_S\nu\bar{\nu}$	2.17	0.84	4	0.24	560	22	94%	94%
$B^+ \to K^{*+}\nu\bar{\nu}$	10.22	1.47	7	2.2	985	158	21%	22%
$B^0 \to K^{*0}\nu\bar{\nu}$	9.48	1.44	5	2.0	704	143	20%	22%
$B \to K^*\nu\bar{\nu}$ combined							15%	17%

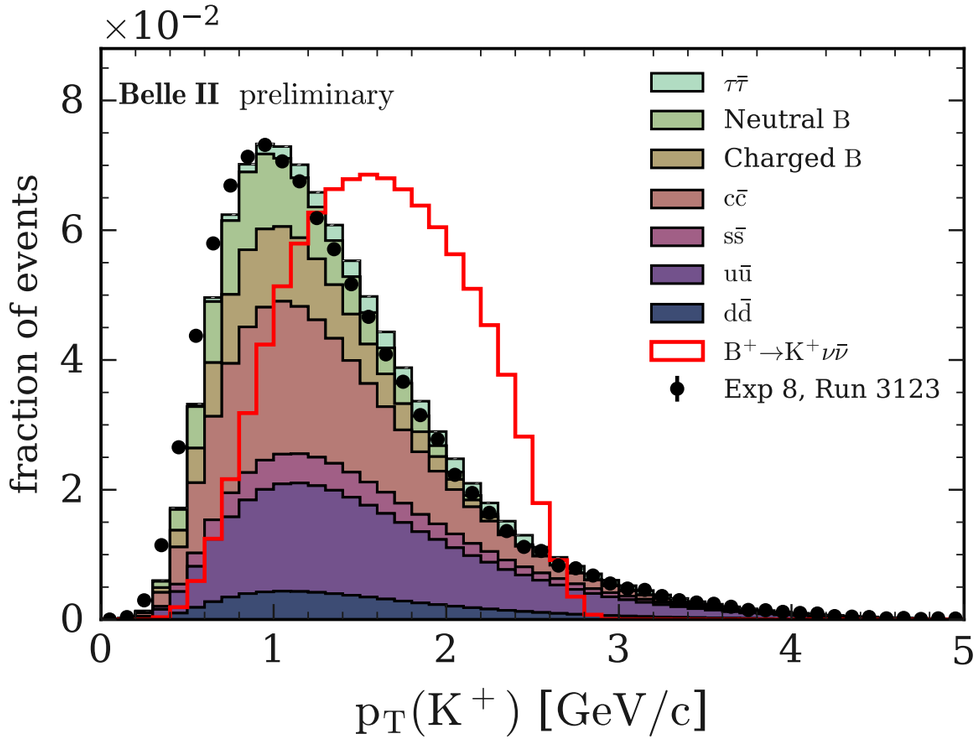
Current status of $K^+\nu\nu$

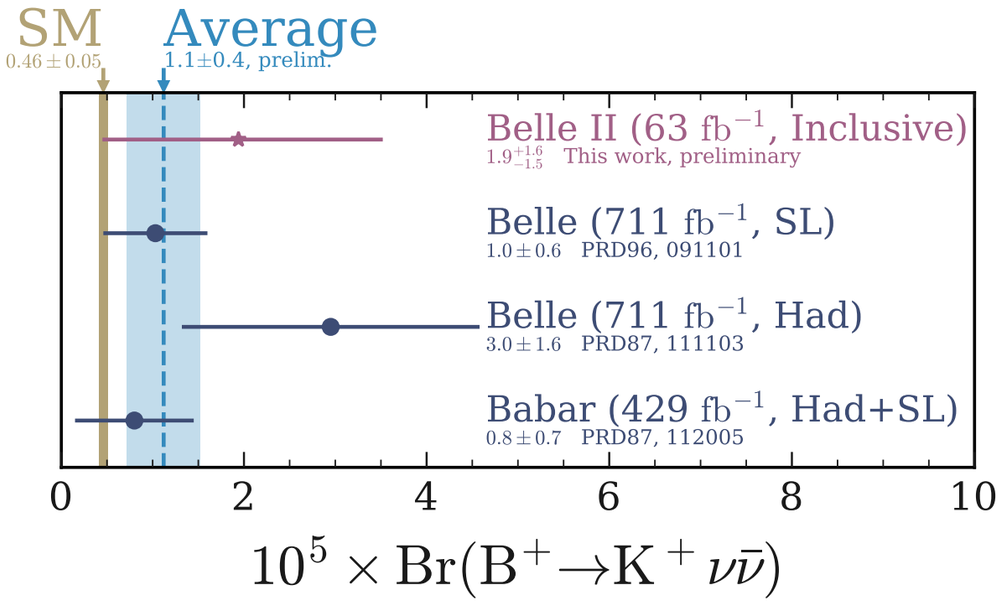
http://moriond.in2p3.fr/2021/EW/slides/3_flavour_10_dattola.pdf

- New idea: inclusive tagging
  - Select the track with the highest p_T
- 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

$\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})$ < 4.1 x 10^{-5} (90% CL)





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

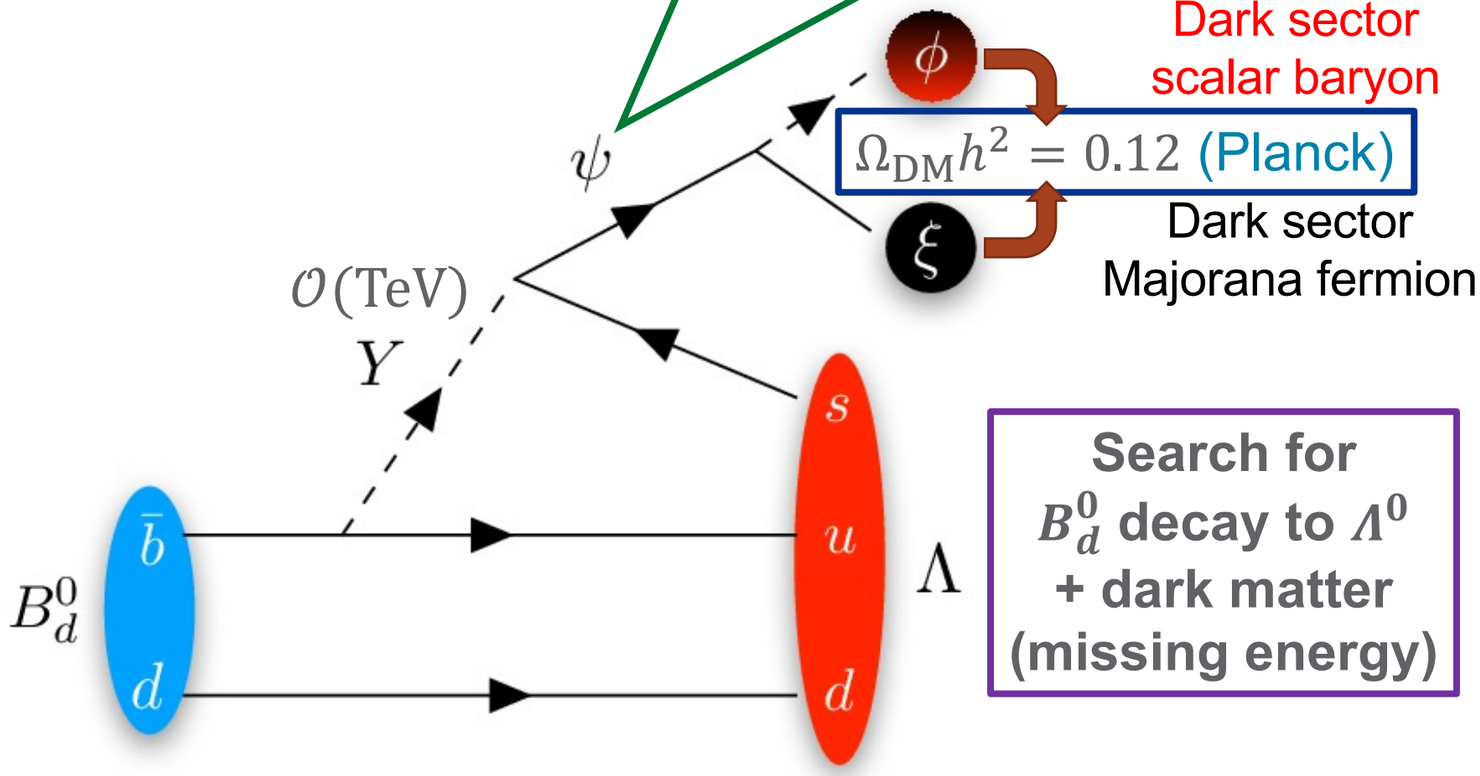
"Baryogenesis and Dark Matter from B Mesons"
Gilly Elor, Miguel Escudero, Ann E. Nelson
Phys. Rev. D 99, 035031 (2019)

Operator	Initial State	Final state	ΔM (MeV)
$\psi\, b\, u\, s$	B_d	$\psi + \Lambda\,(usd)$	4163.95
	B_s	$\psi + \Xi^0\,(uss)$	4025.03
	B^+	$\psi + \Sigma^+\,(uus)$	4089.95
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\psi\, b\, u\, d$	B_d	$\psi + n\,(udd)$	4340.07
	B_s	$\psi + \Lambda\,(uds)$	4251.21
	B^+	$\psi + p\,(duu)$	4341.05
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\psi\, b\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$	2807.76
	B_s	$\psi + \Omega_c\,(css)$	2671.69
	B^+	$\psi + \Xi_c^+\,(csu)$	2810.36
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2
$\psi\, b\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$	2853.60
	B_s	$\psi + \Xi_c^0\,(cds)$	2895.02
	B^+	$\psi + \Lambda_c\,(dcu)$	2992.86
	Λ_b	$\bar{\psi} + \overline{D}^0$	3754.7

← Initial focus

$1.5\ \mathrm{GeV} < M(\psi_{\rm DM})$

"Neutron stars exclude light dark baryons"
Phys. Rev. Lett. 121, 061802 (2018)



Dark sector scalar baryon

$\Omega_{\rm DM} h^2 = 0.12$ (Planck)

Dark sector Majorana fermion

Search for B_d^0 decay to Λ^0 + dark matter (missing energy)

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Summary

- 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
    - ✓ 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.

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Thank you for your attention