Belle and Belle II

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KPS-DPF 2022 Meeting

Sungkyunkwan University

Belle II

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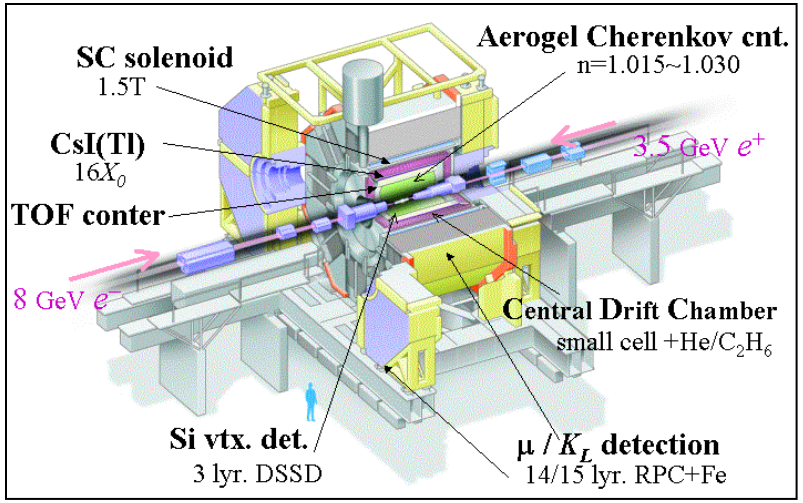
Soongsil University

연세대학교
YONSEI UNIVERSITY

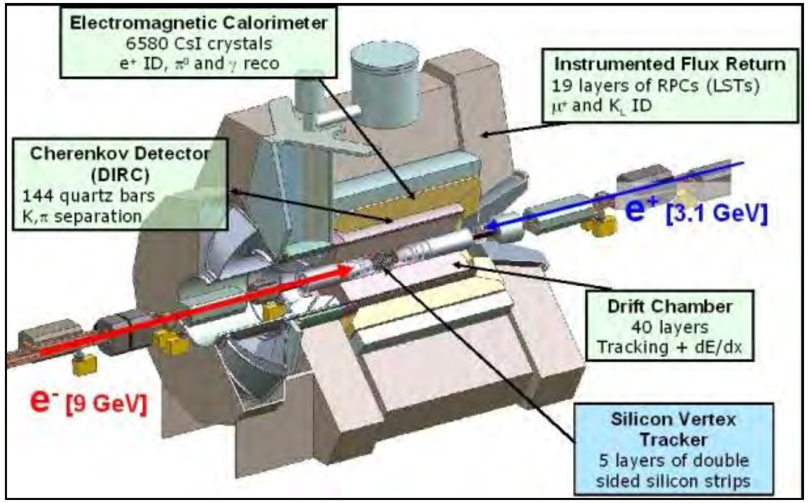
BELLE

Two B Factories from 1999

Belle / KEKB



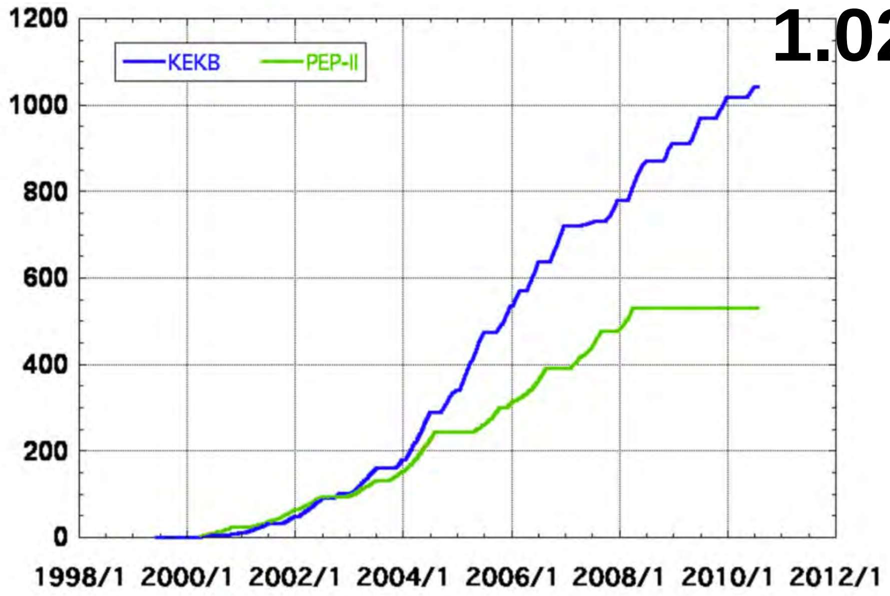
BABAR / PEP II



- CP Violation in the B section confirmed.
- Precision measurement of the CKM matrix. X(3872) and exotic particles.
- 2008 Nobel Prize, Kobayashi-Maskawa
- 2017 Hoam Prize (Korea), Sookyung Choi

Belle: Excellent Data Set

- The largest data samples at Υ(5s), Υ(4s), Υ(2s), Υ(1s)



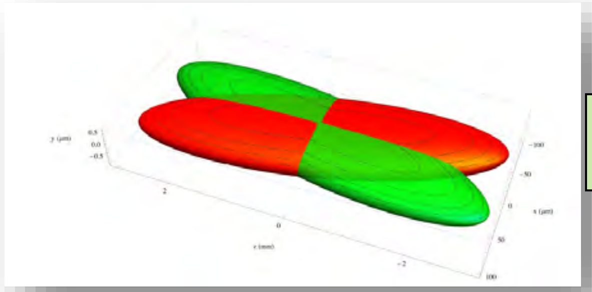
1.02 ab^{-1}

Energy	Size
Υ(5s)	121 fb^{-1}
Υ(4s)	711fb^{-1}
Υ(3s)	3 fb^{-1}
Υ(2s)	25 fb^{-1}
Υ(1s)	6 fb^{-1}
Off-resonance/ Scan	155 fb^{-1}

KEKB to SuperKEKB: Accomplished

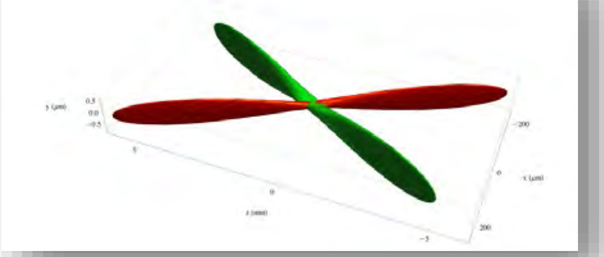
- Nano beam scheme + Crab waist optics
- Target: vertical beta function β_y^* 5.9 mm (KEKB) to 0.3 mm (SuperKEKB)
- Increase beam currents $I_{e\pm}$
- Increase beam-beam interaction ξ_y

KEKB beams



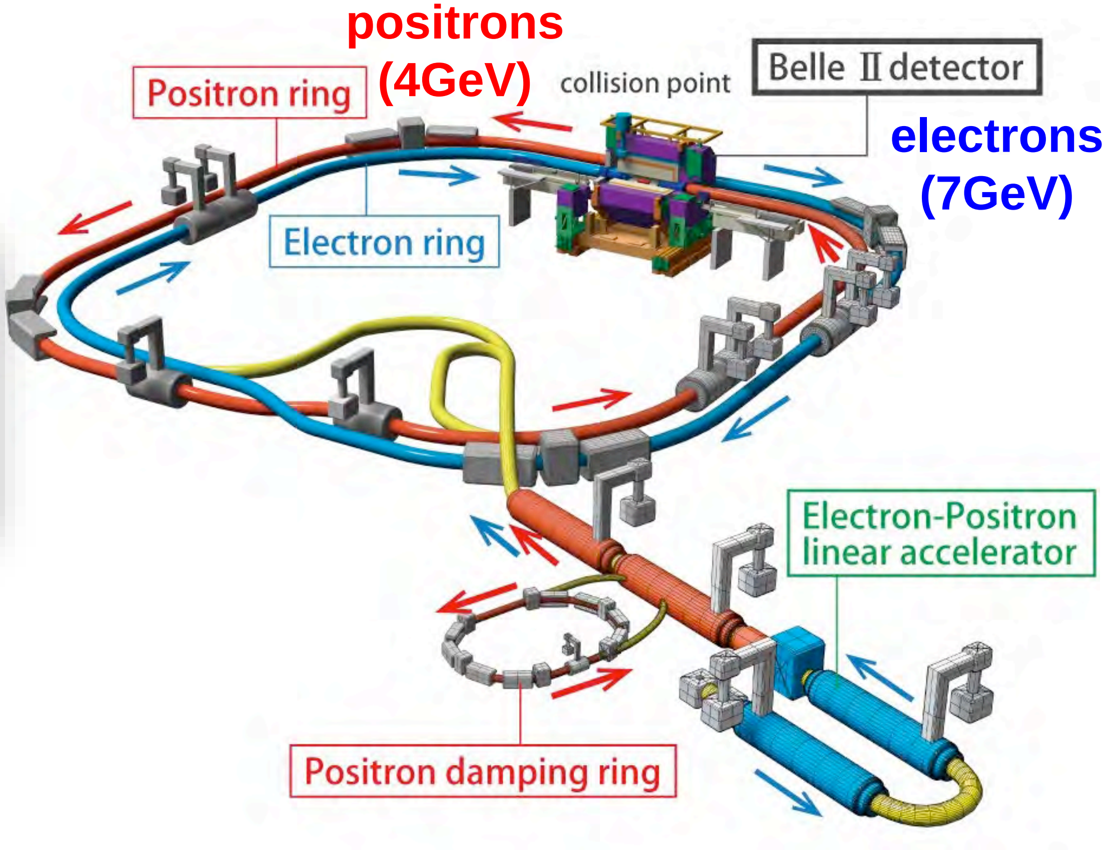
Beam crossing angle 22mrad

SuperKEKB nanobeams



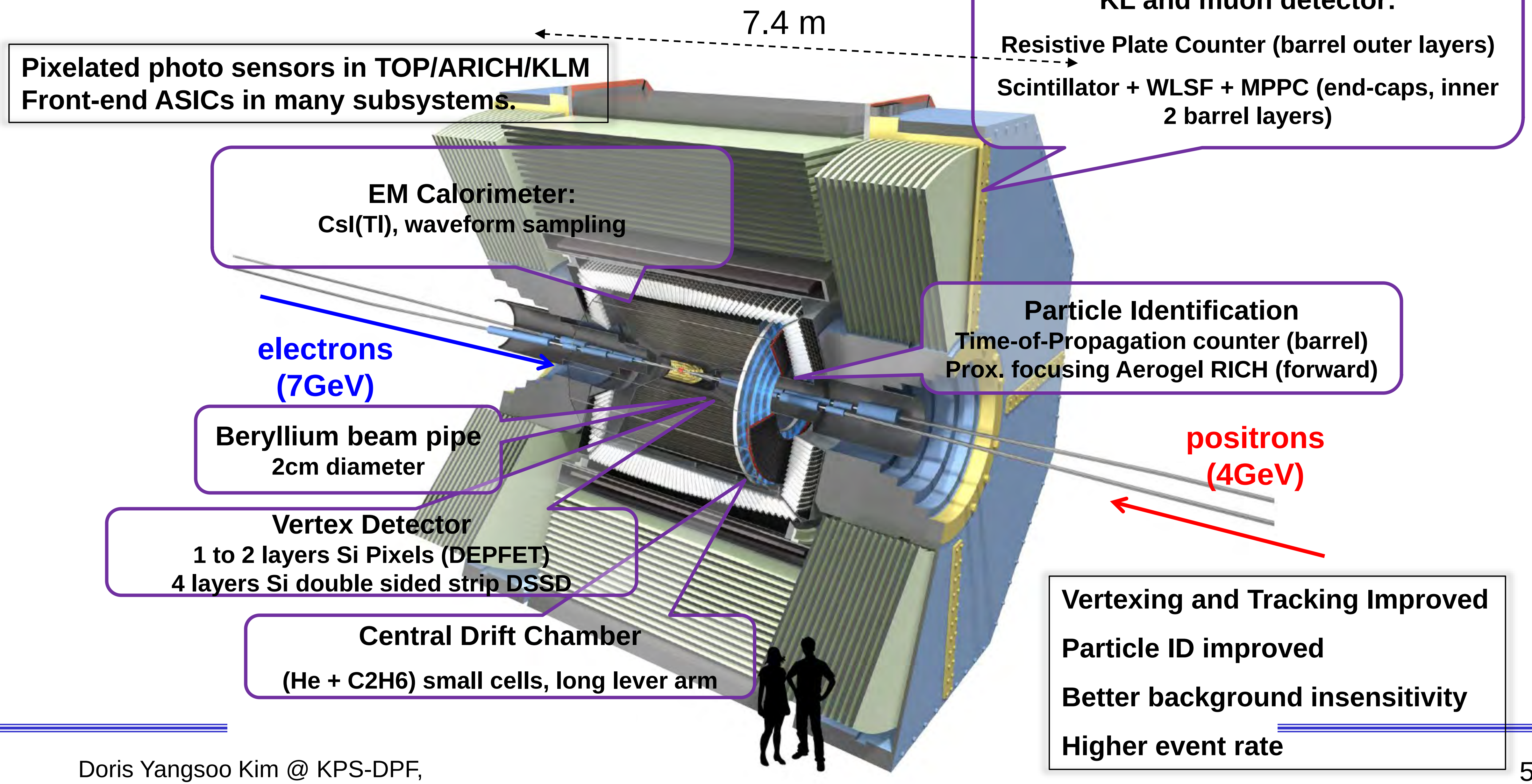
Beam crossing angle 83mrad

$$L = \frac{\gamma_{e\pm}}{2e\,r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\cdot\xi_{y,e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$



https://en.wikipedia.org/wiki/Beta_function_(accelerator_physics)

The Belle II Detector



Vertexing and Tracking Improved

Particle ID improved

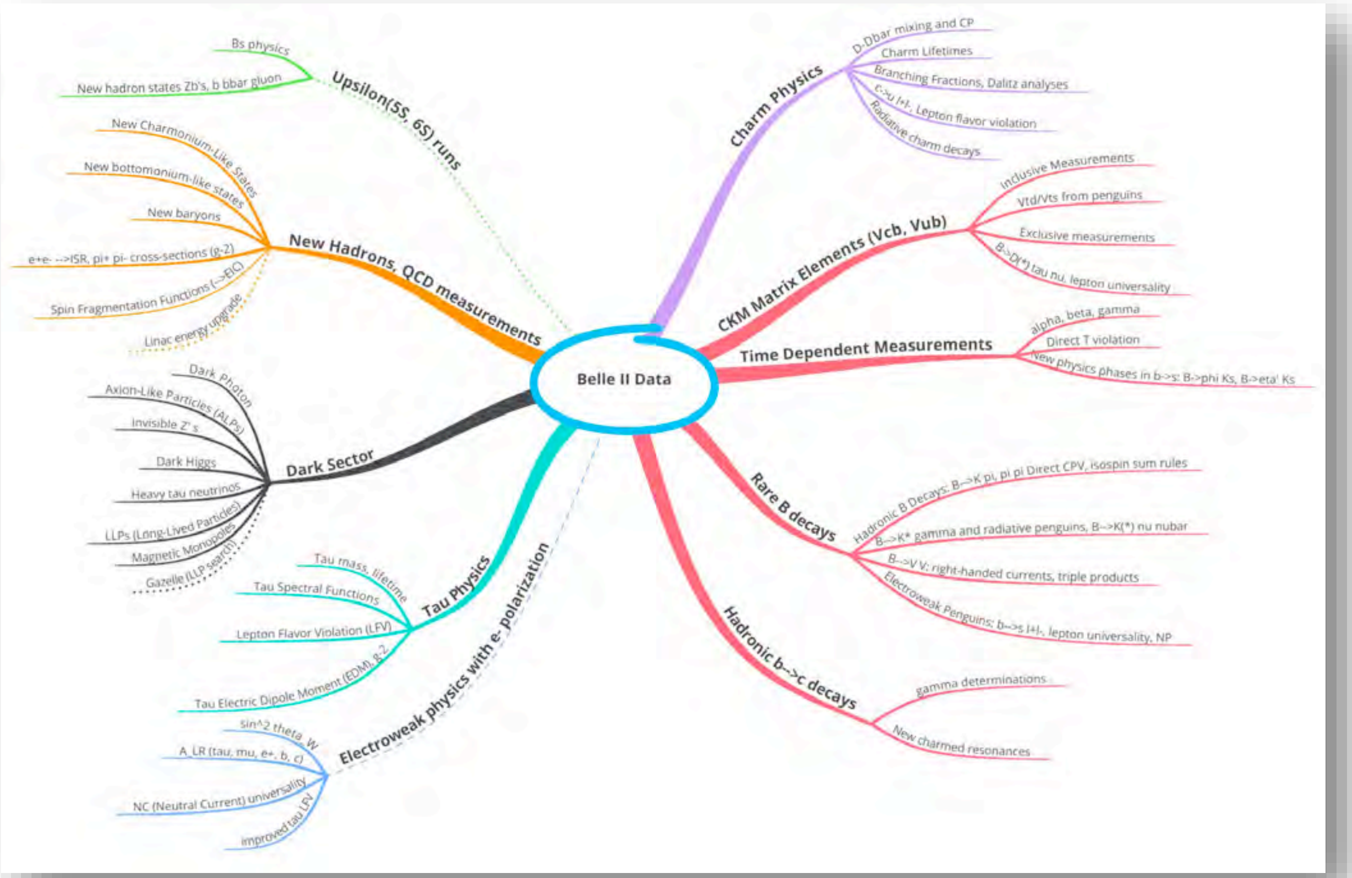
Better background insensitivity

Higher event rate

Belle II Physics Prospects

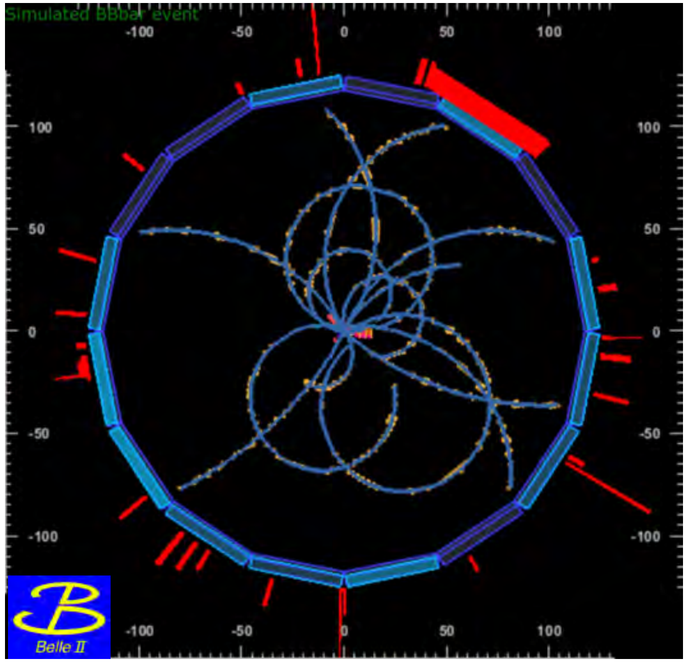
- Charm decays
- Next precision CKM matrix
  - Semileptonic B decays (CKM elements)
  - Hadronic B decays (angles and CPV)
  - Time dependent CP violation
- τ physics
- Hadron spectroscopy
- Rare decays, FCNC
- New physics
  - Lepton flavor violation
  - Dark sector, Long lived particles

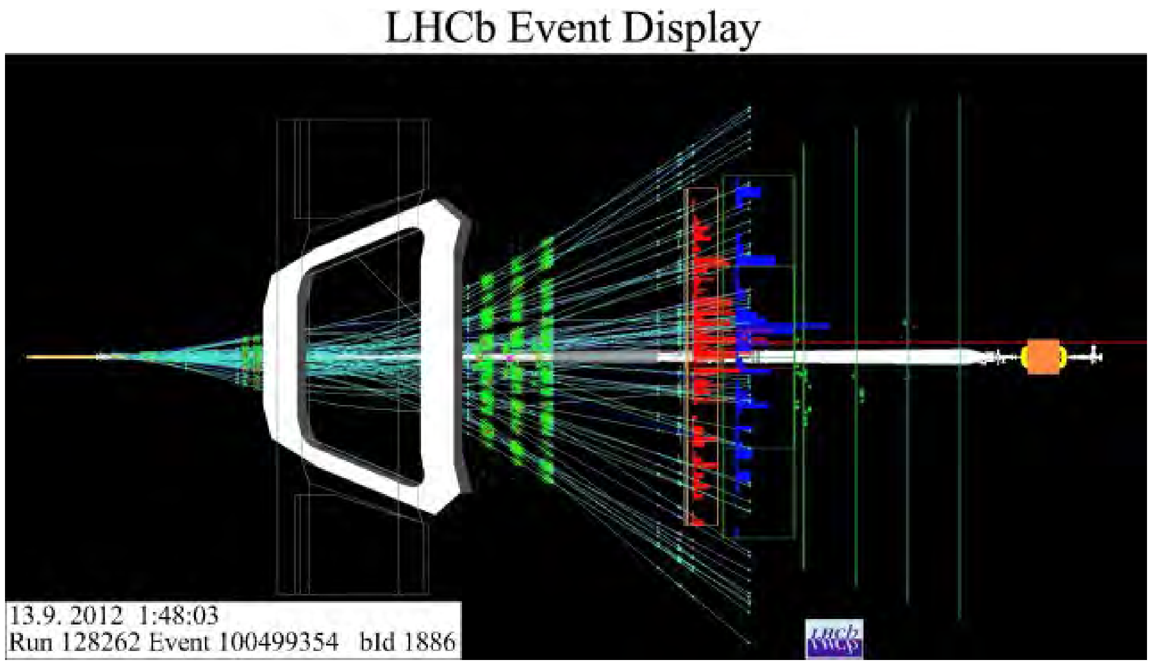
https://confluence.desy.de/display/BI/Snowmass+2021



Belle (II) and LHCb

- Belle (II) and LHCb have different systematics
  - Two experiments are required to establish NP.
  - LHCb: large $b\bar{b}$ cross-section (LHCb 1 fb^{-1} ~ Belle II 1 ab^{-1}). Good sensitivity and S/N with di-muon modes and charged tracks with a vertex.



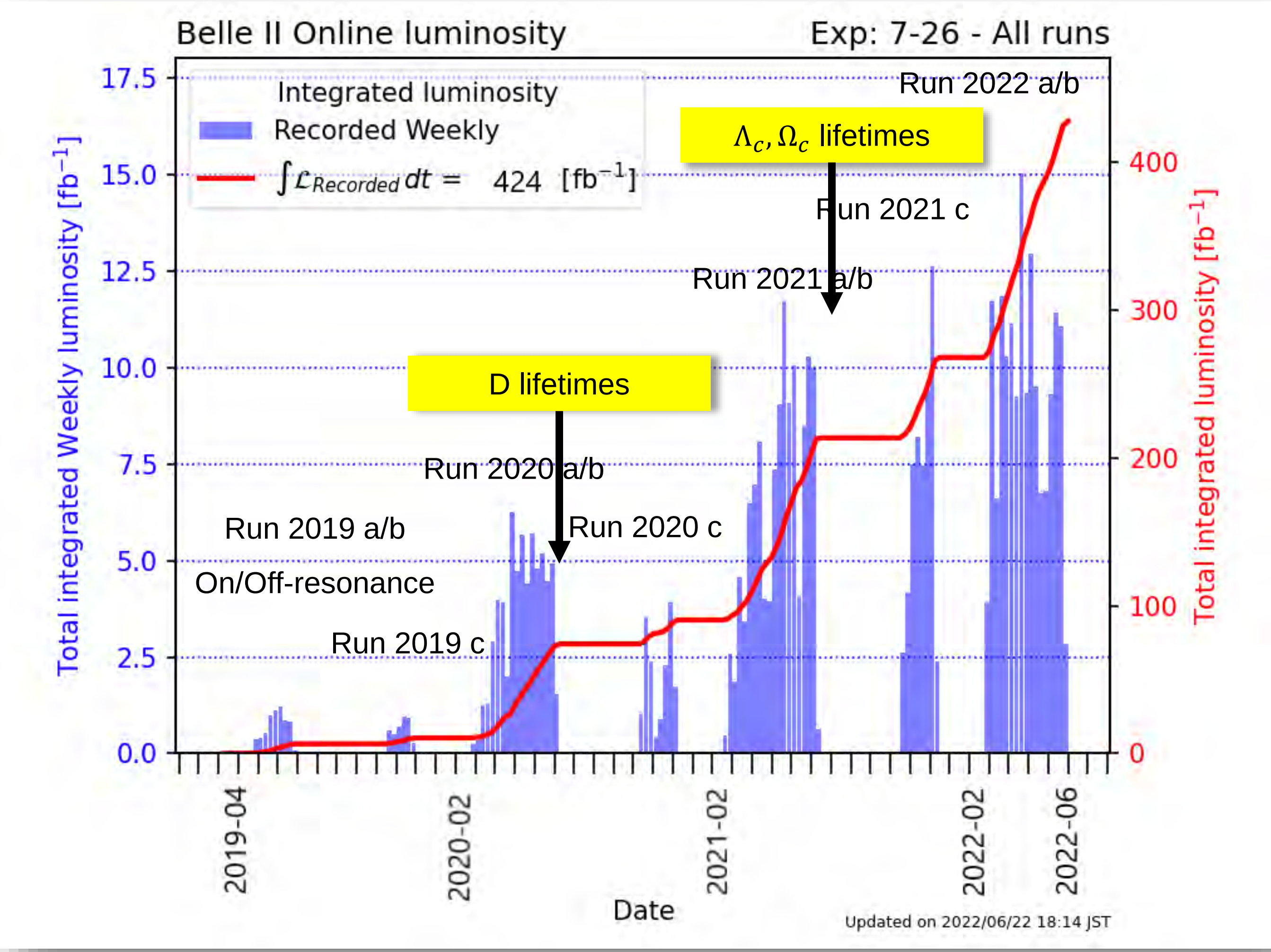


The Belle II Collaboration (This is not Belle!)

- As of December 2022, approximately
- 1,100 members, 120 institutes, 27 countries

SuperKEKB Luminosity: Current Status

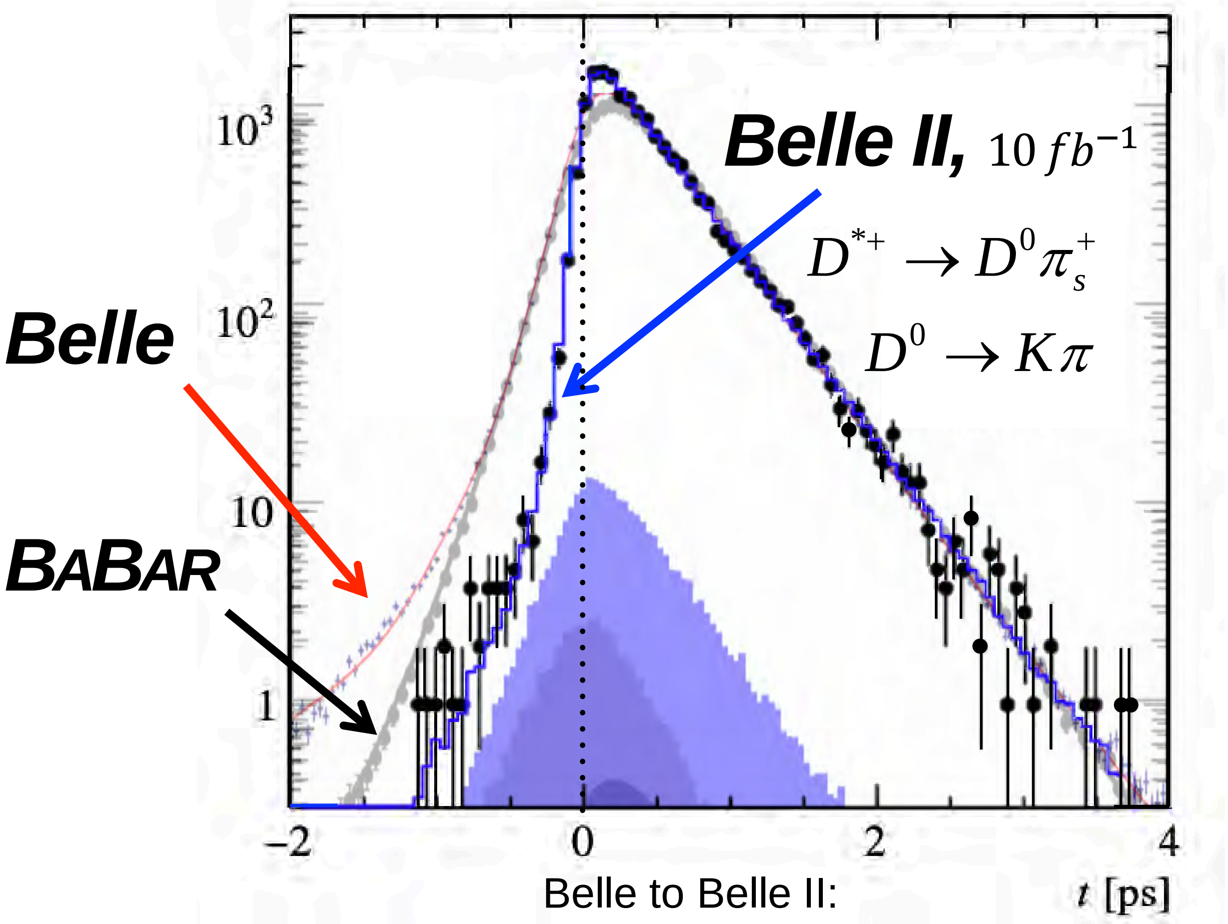
- After the commission phases, physics runs started spring 2019.
- Reclaimed the luminosity record June 2020! (Previously held by LHC.)
- Spring/summer 2022 run ended June.
  - Peak luminosity at $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the current world record on June 22nd.
  - Current integrated luminosity at $\int L_{recorded} dt = 424\ fb^{-1}$. (~ Babar, ~ ½ Belle)
- Long shutdown 1 (LS1) just started for upgrades (pixel, TOP PMT, etc).



https://confluence.desy.de/display/BI/Belle+II+Luminosity

Charm Particle Lifetime

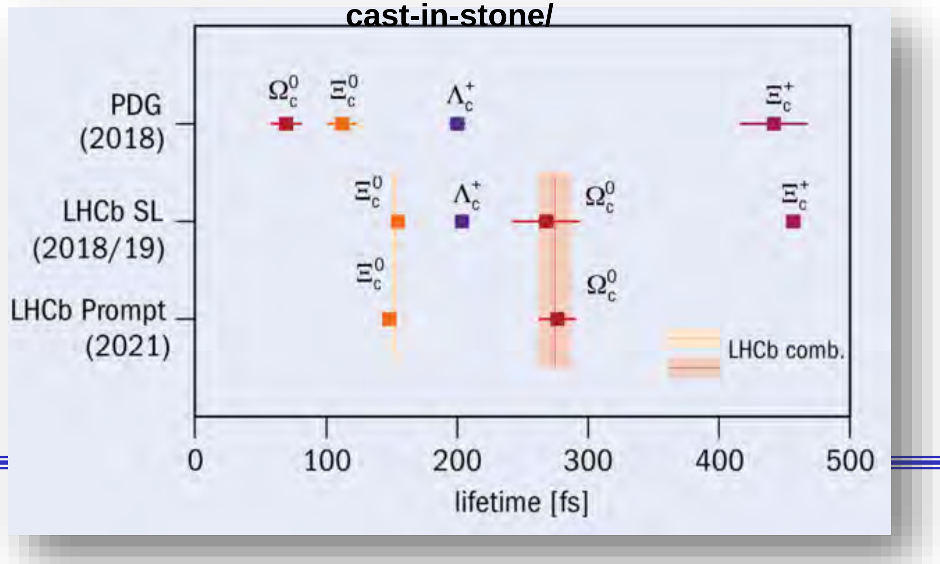
D^0 lifetime distribution comparison



Belle to Belle II:
2 times better vertex resolution,
20 times smaller beam spot size

- Charm particles @ low-energy QCD calculation (non-perturbative and high order correction). The effective models do have uncertainties.
- Measurements of charm lifetimes can test the models.
- SuperKEKB gives a great opportunity to measure the world best charm lifetimes.

https://cerncourier.com/a/new-charmed-baryon-lifetime-hierarchy-cast-in-stone/

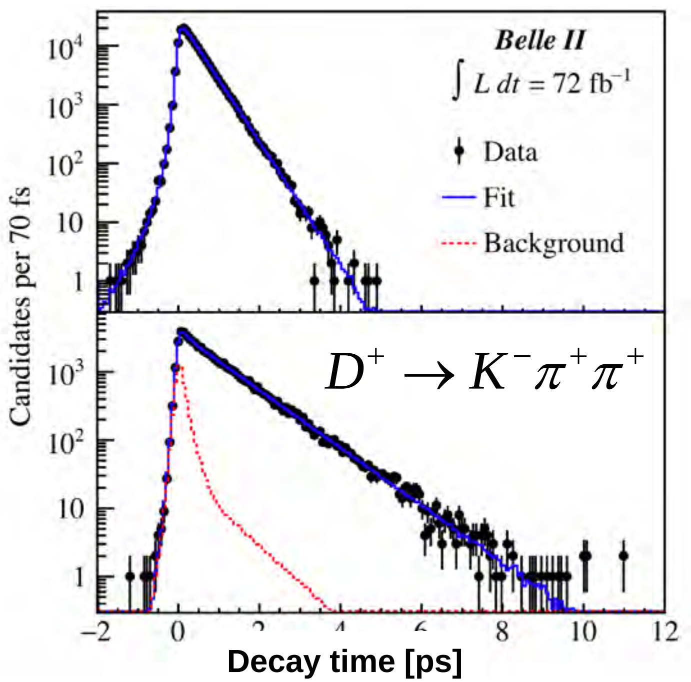


Phys. Rev. Lett. 127 (2021), 211801

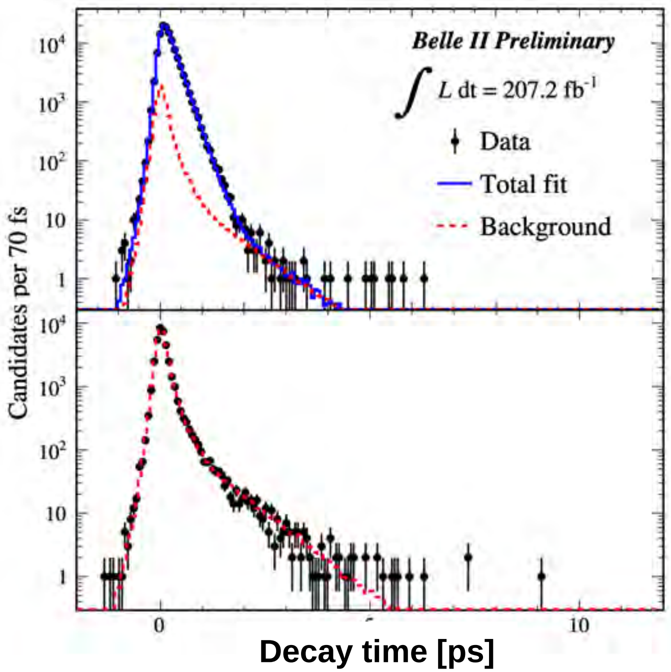
D^0, D^+, Λ_c^+, Ω_c^0 Lifetimes

$D^0 \to K^- \pi^+$

$D^+ \to K^- \pi^+ \pi^+$

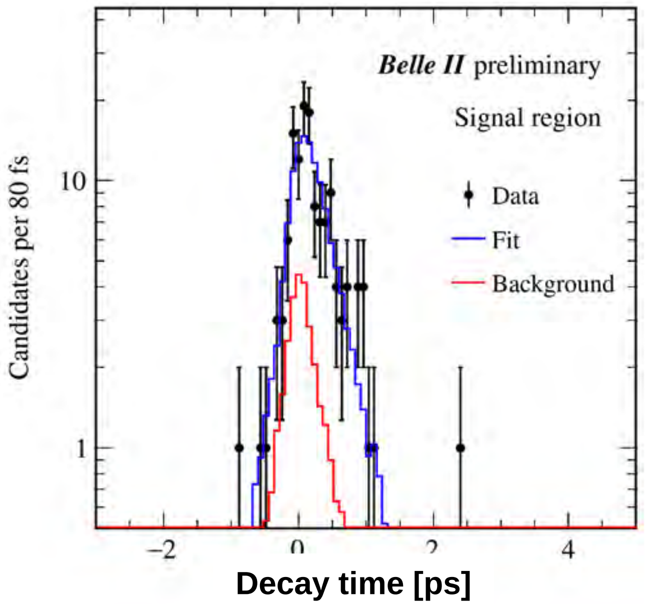


$\Lambda_c^+ \to p K^- \pi^+$



$\Omega_c^0 \to \Omega^- \pi^+,$

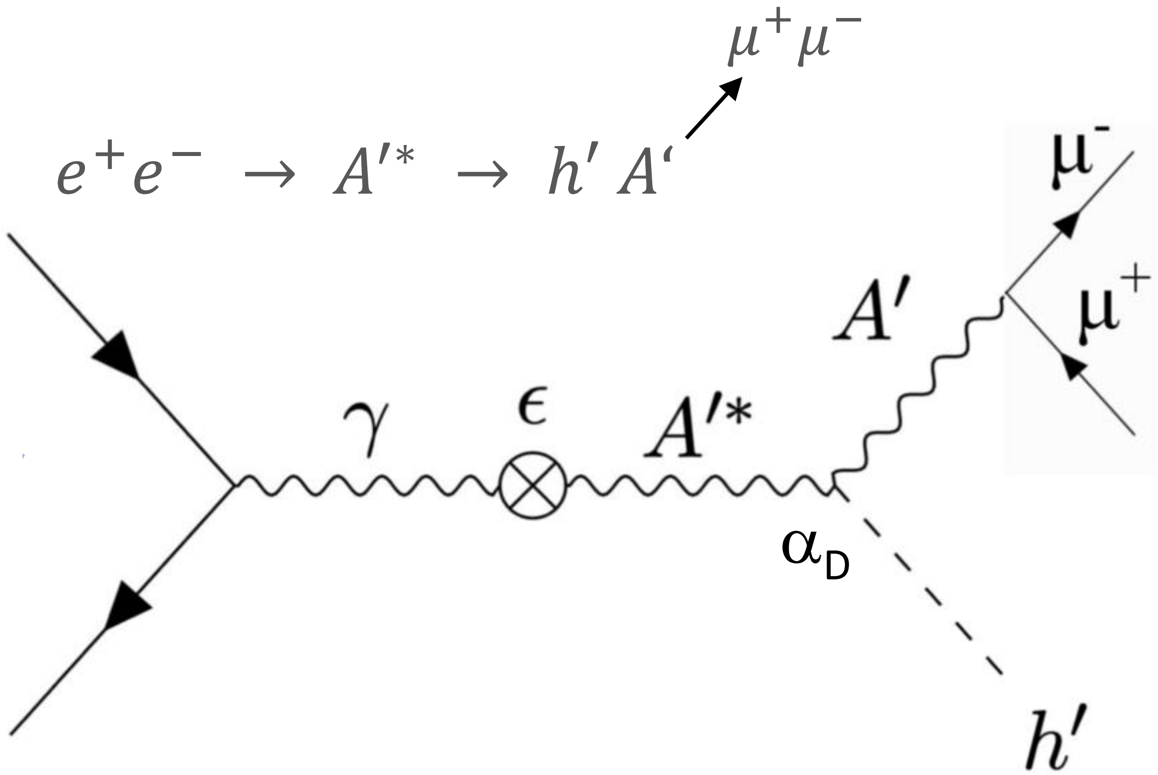
$\Omega^- \to \Lambda^0 K^-, \quad \Lambda^0 \to p \pi^-$



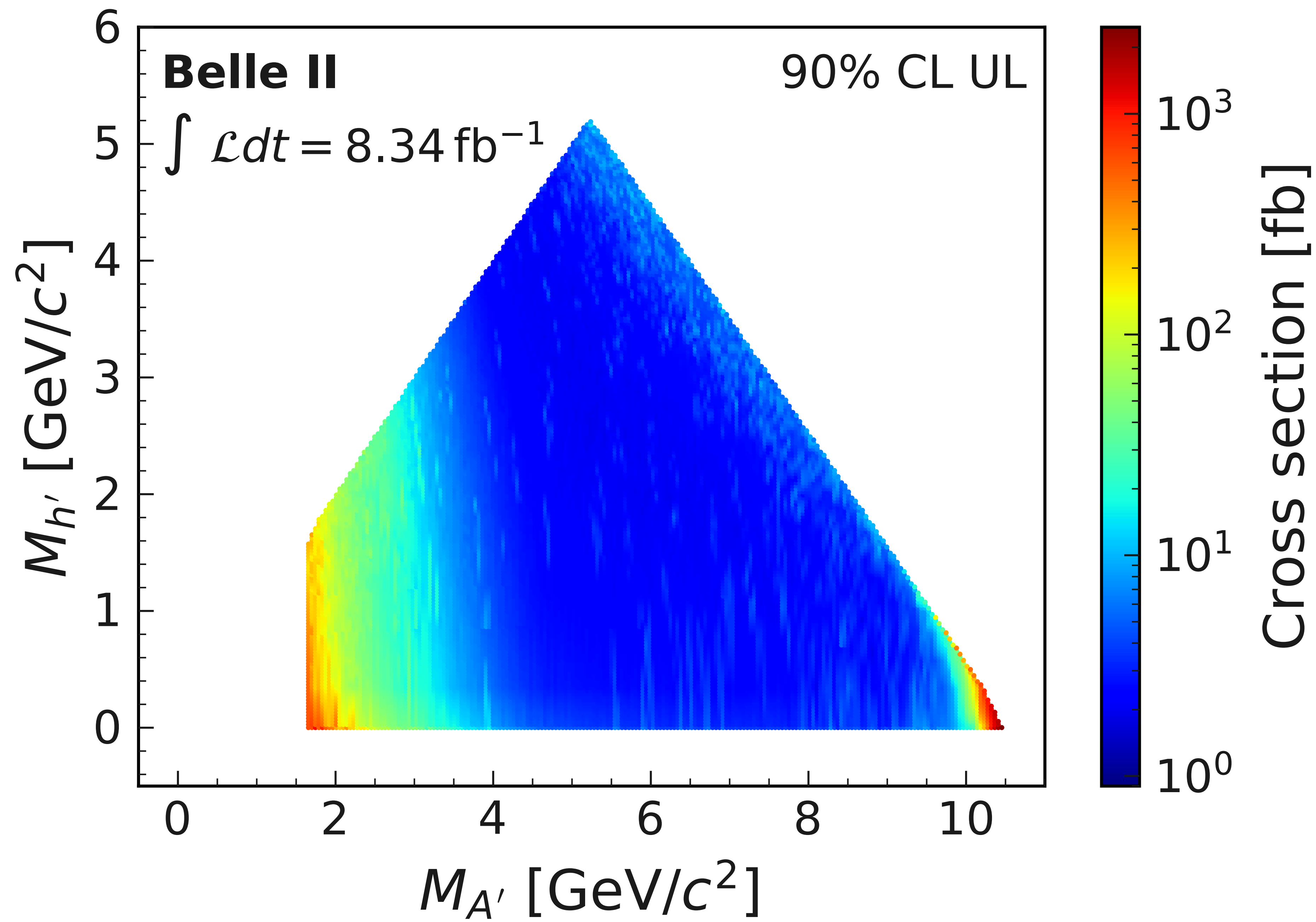
Mode	Belle II (fs)	Previous WA (fs)	Ref.
D^0	$410.5 \pm 1.1 \pm 0.8$	410.1 ± 1.5	Phys. Rev. Lett. 127 (2021), 211801
D^+	$1030.4 \pm 4.7 \pm 3.1$	1040 ± 7	
Λ_c^+	$203.2 \pm 0.9 \pm 0.8$	202.4 ± 3.1	arXiv: 2206.15227v1, PRL accepted
Ω_c^0	$243 \pm 48 \pm 11$	$268 \pm 24 \pm 10$ LHCb 69 ± 12 pre-LHCb	arXiv: 2208.08573, PRD accepted

arXiv:2207.00509
accepted to PRL

Dark Higgsstrahlung: $e^+e^- \rightarrow A'h'$

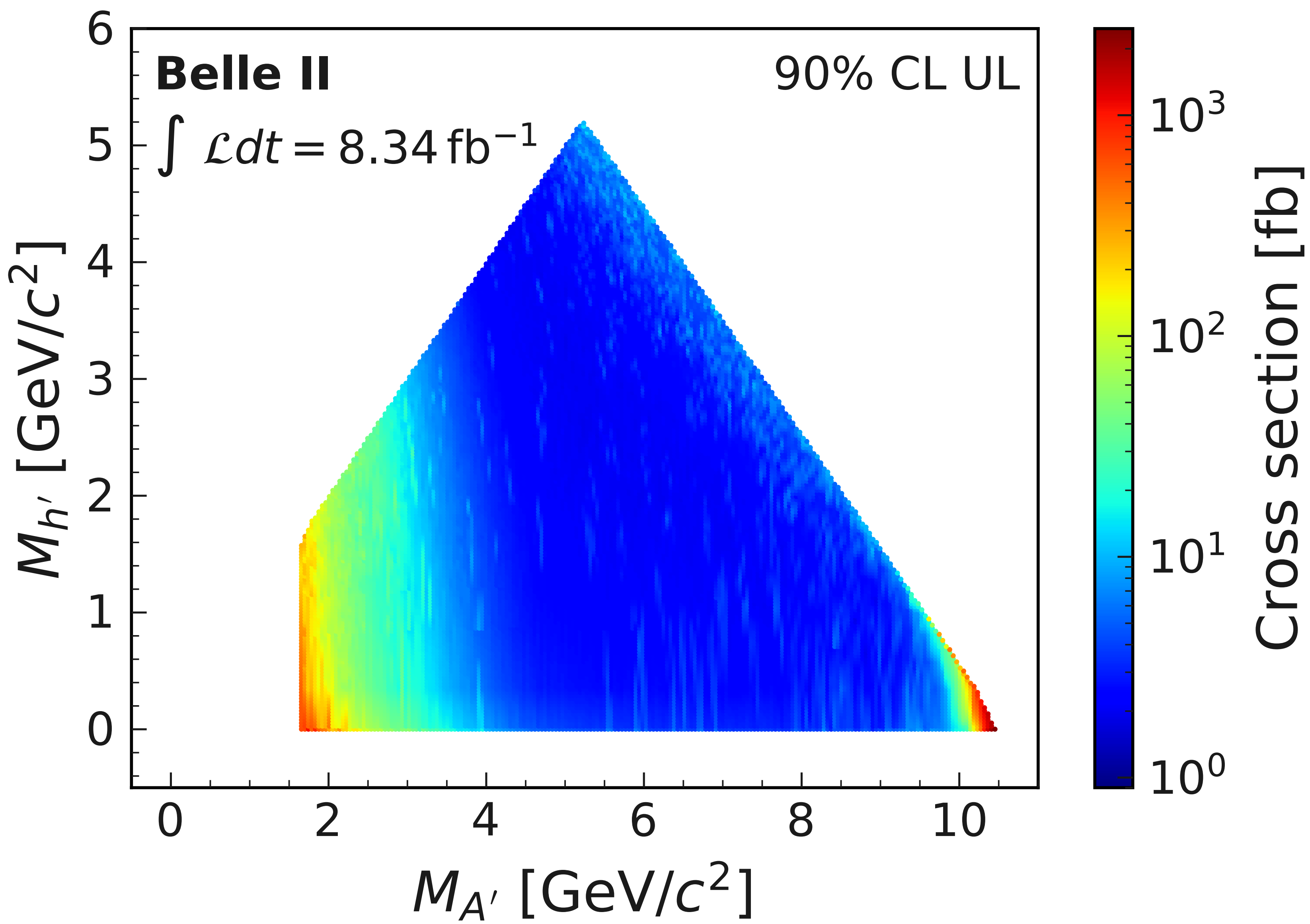


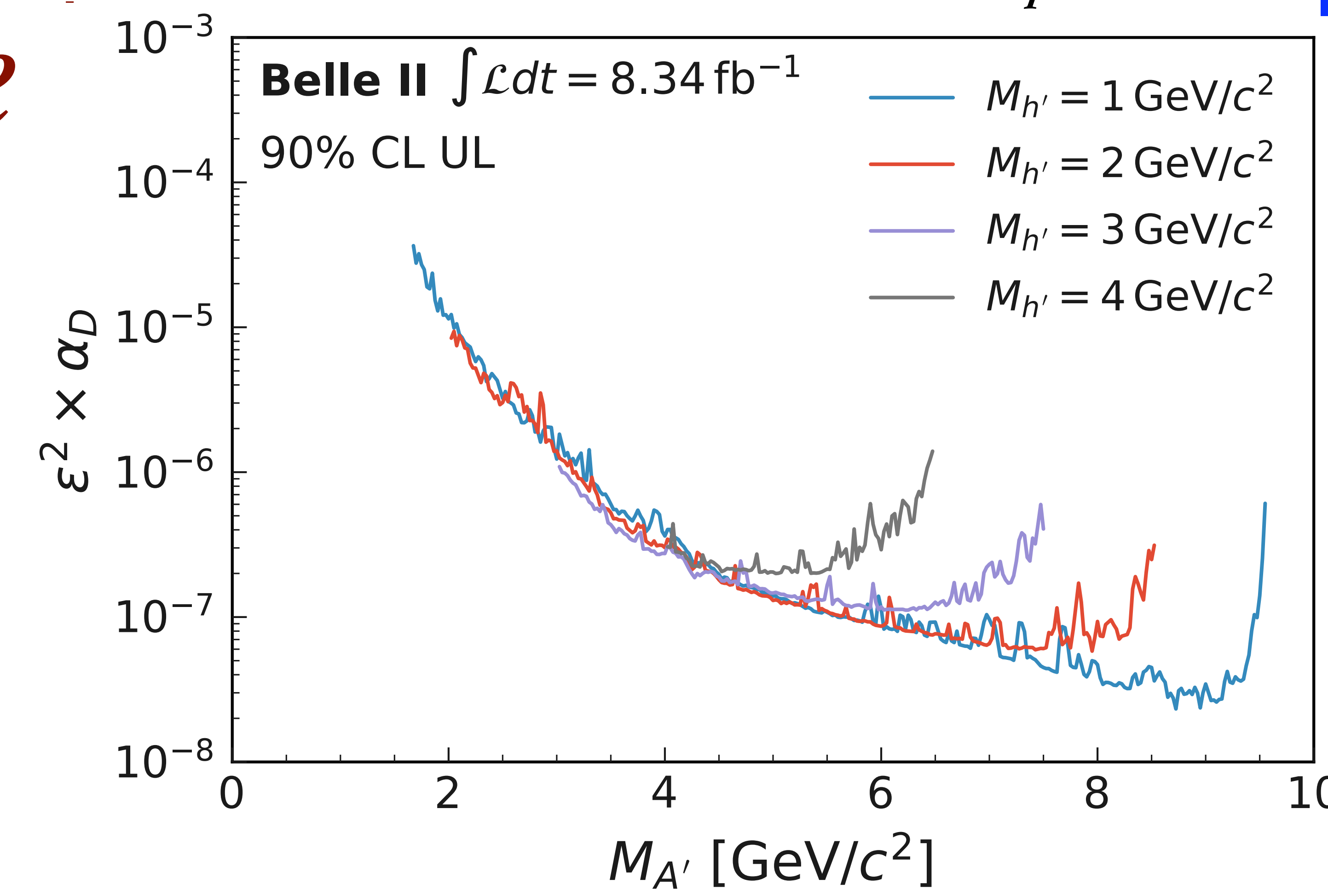
$e^+e^- \rightarrow \mu^+\mu^-$ + *missing energy*

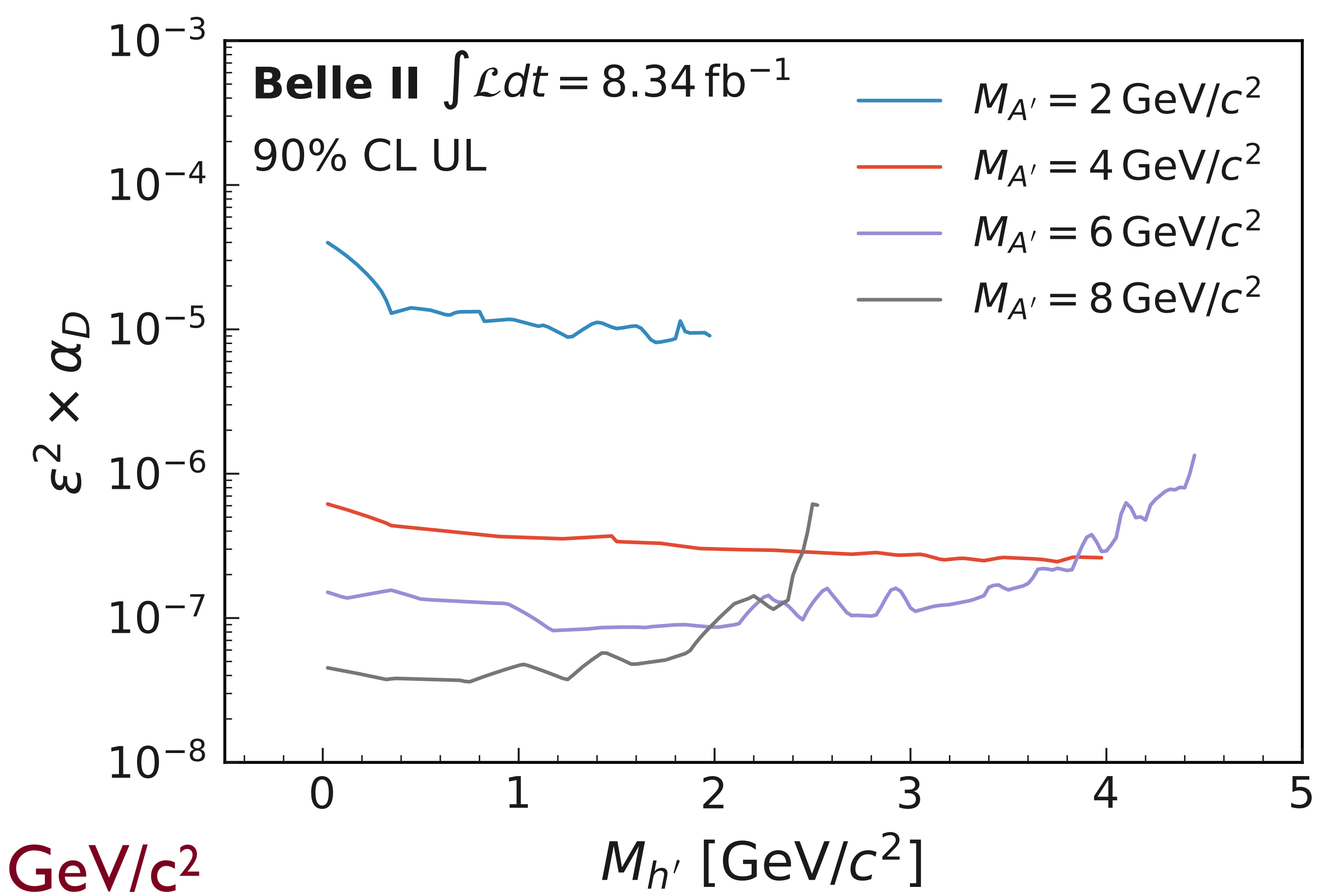


- No excess found
- upper limits on σ
- most sensitive for $4 < M_{A'} < 9.7$ GeV/c^2

Dark Higgsstrahlung: e







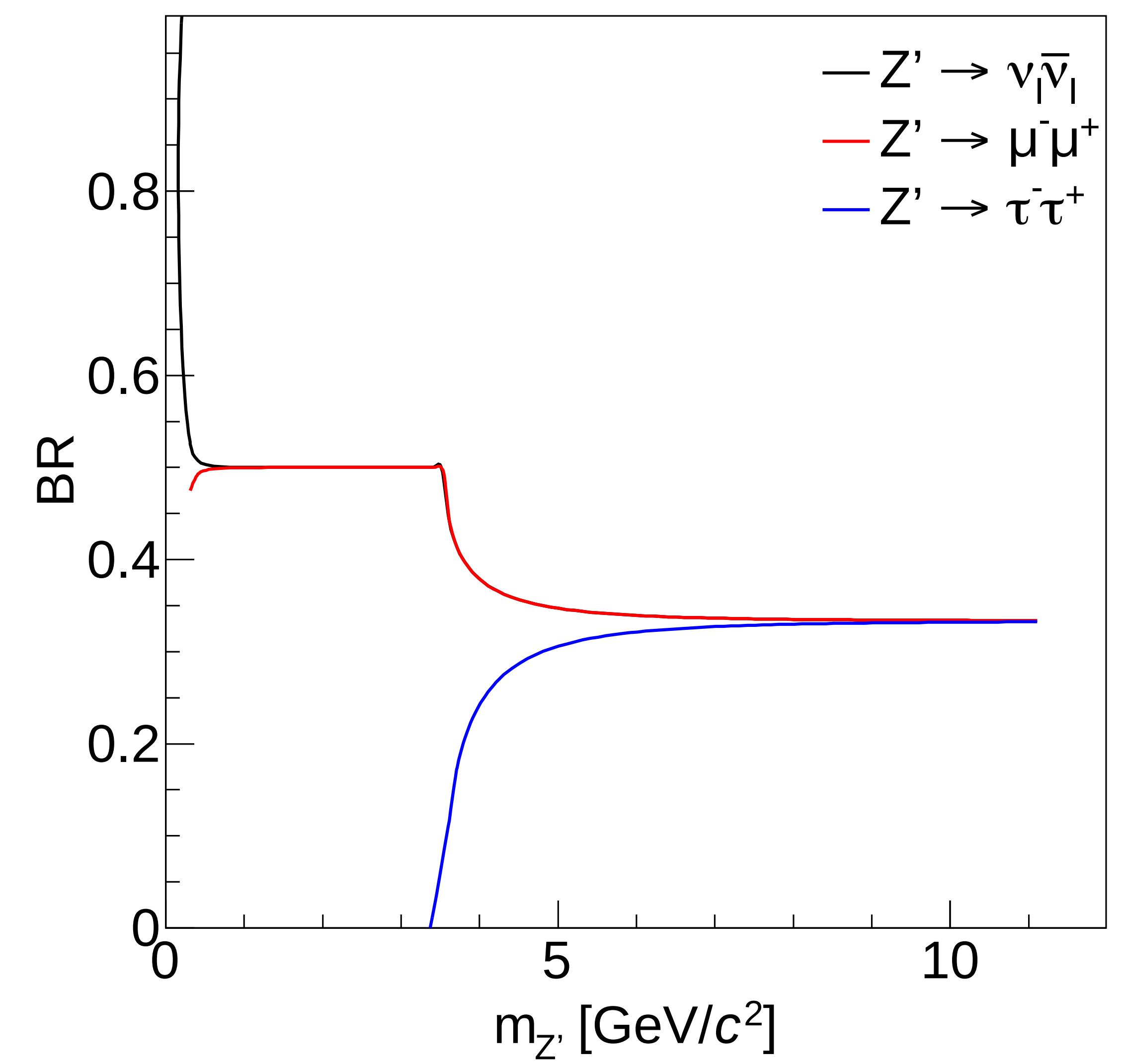
- No excess found
- upper limits on $\varepsilon^2\alpha_D$ as well
- most sensitive for 4 < $M_{A'}$ < 9.7 GeV/c²

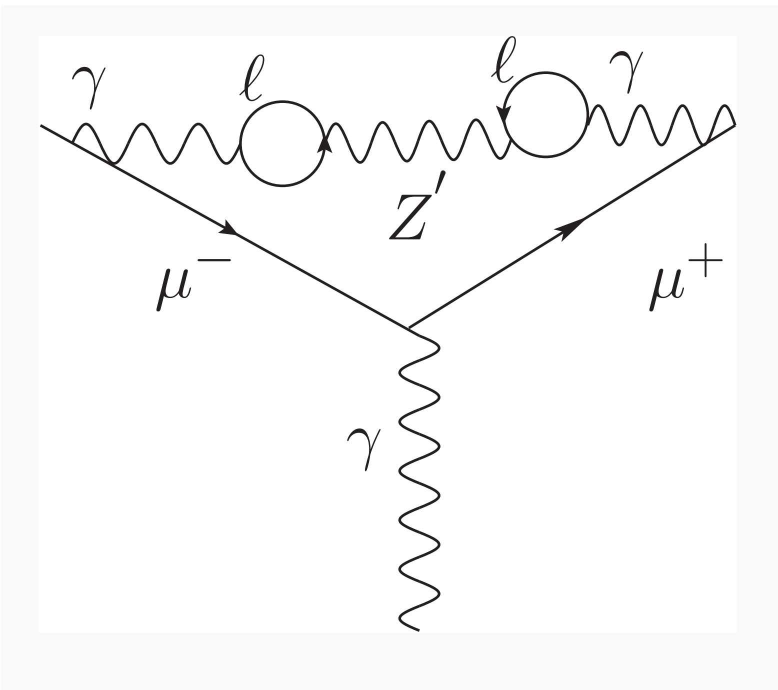
Leptophilic Z' search

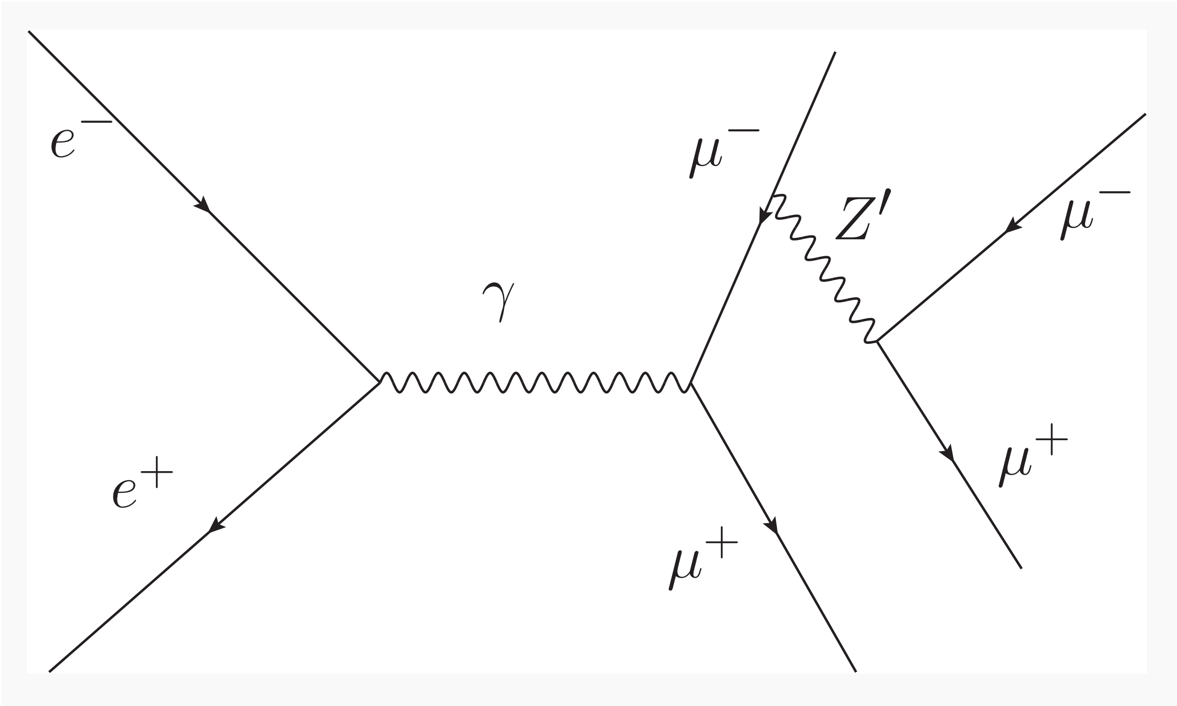
- $L_\mu - L_\tau$ model, initially motivated by $(g-2)_\mu$
- could also be a channel for sterile neutrinos as a dark matter candidate, as well as a potential sol. to $R_{K^{(*)}}$

- Search for $Z' \to \mu^+\mu^-$ (Belle)
- **Search for $Z' \to$ "invisible" (Belle II)**

  $Z' \to \tau^+\tau^-$ (Belle II)

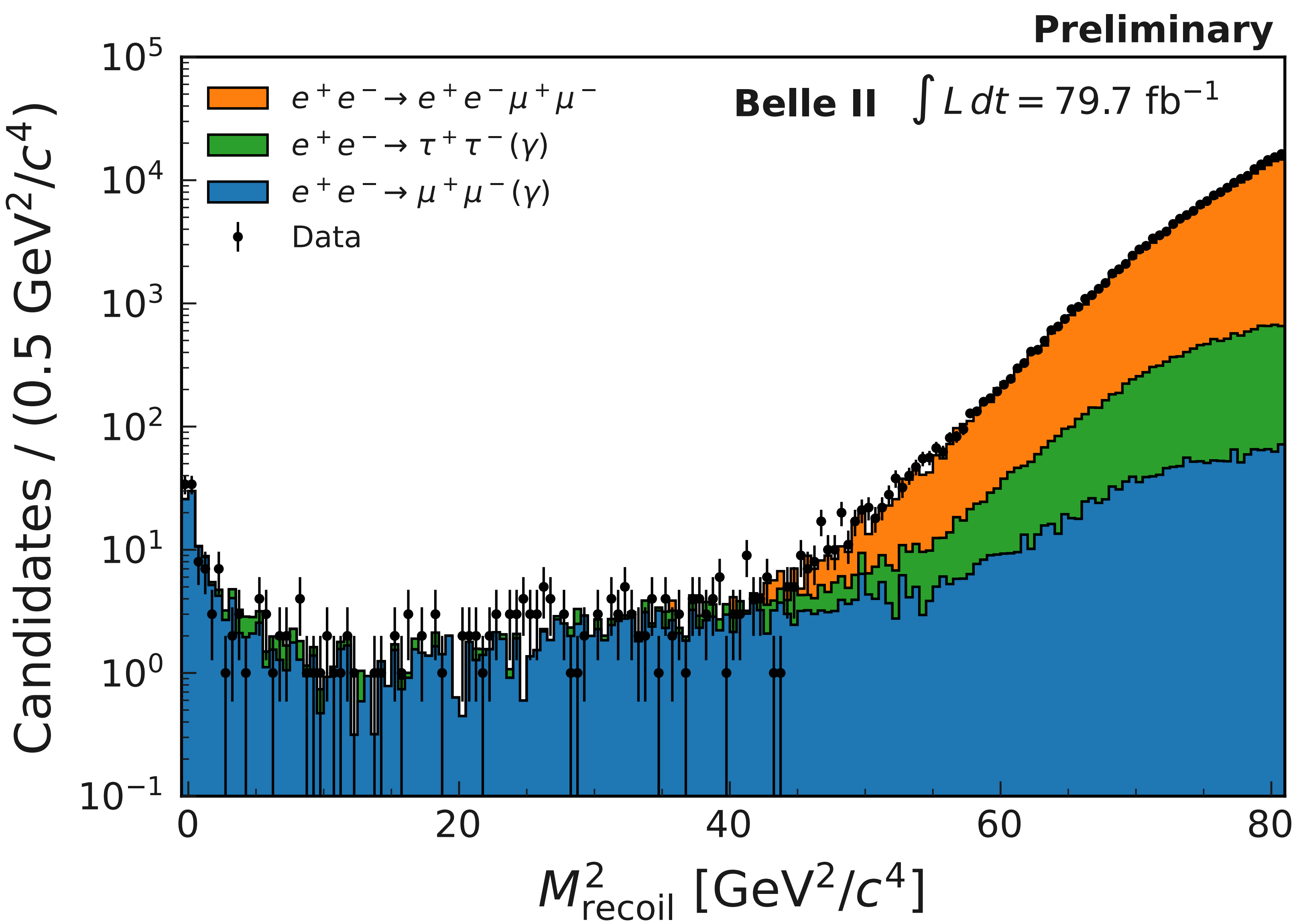


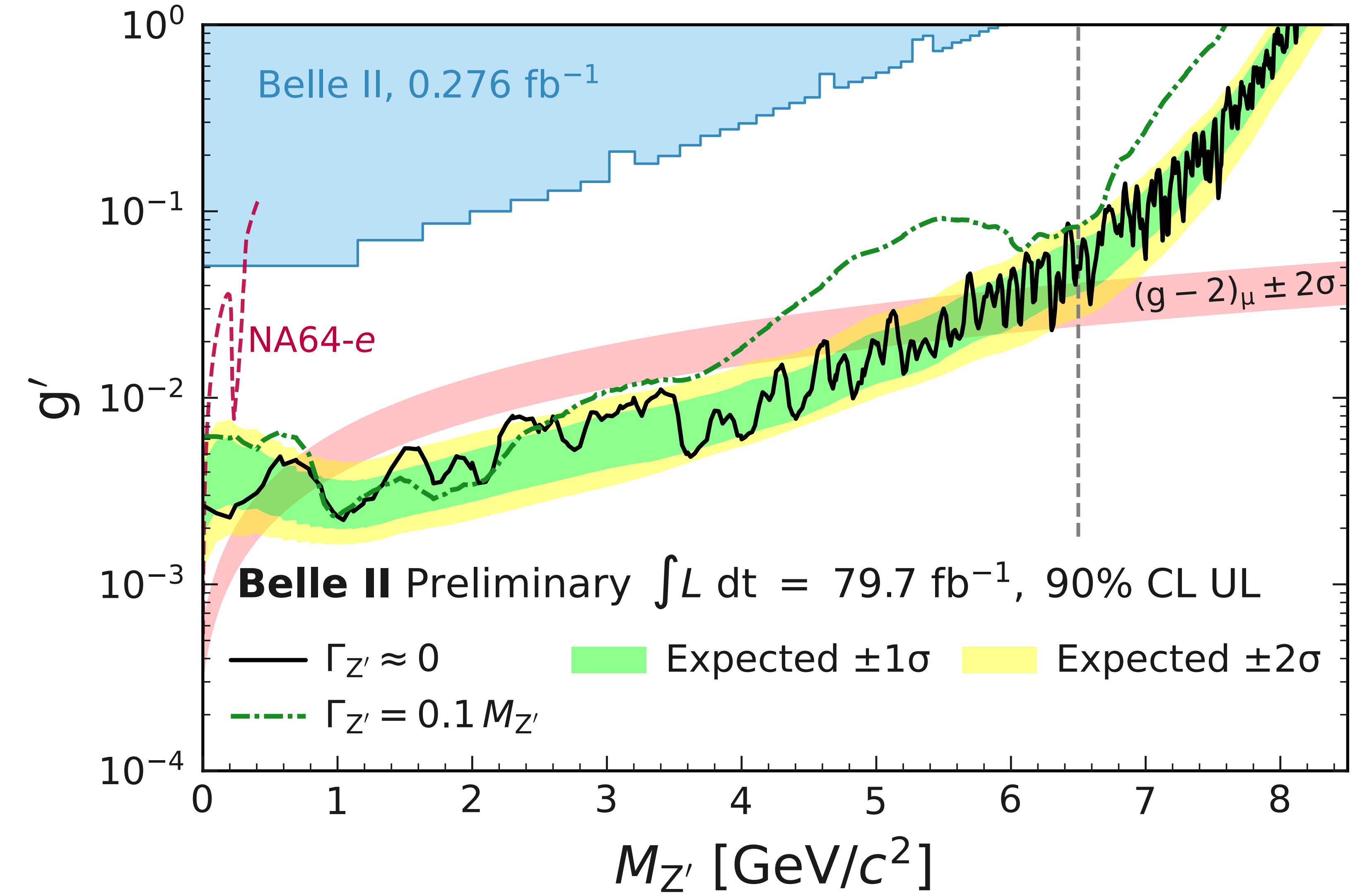




arXiv:2212.03066
submitted to PRL

Leptophilic Z' search (Belle II)

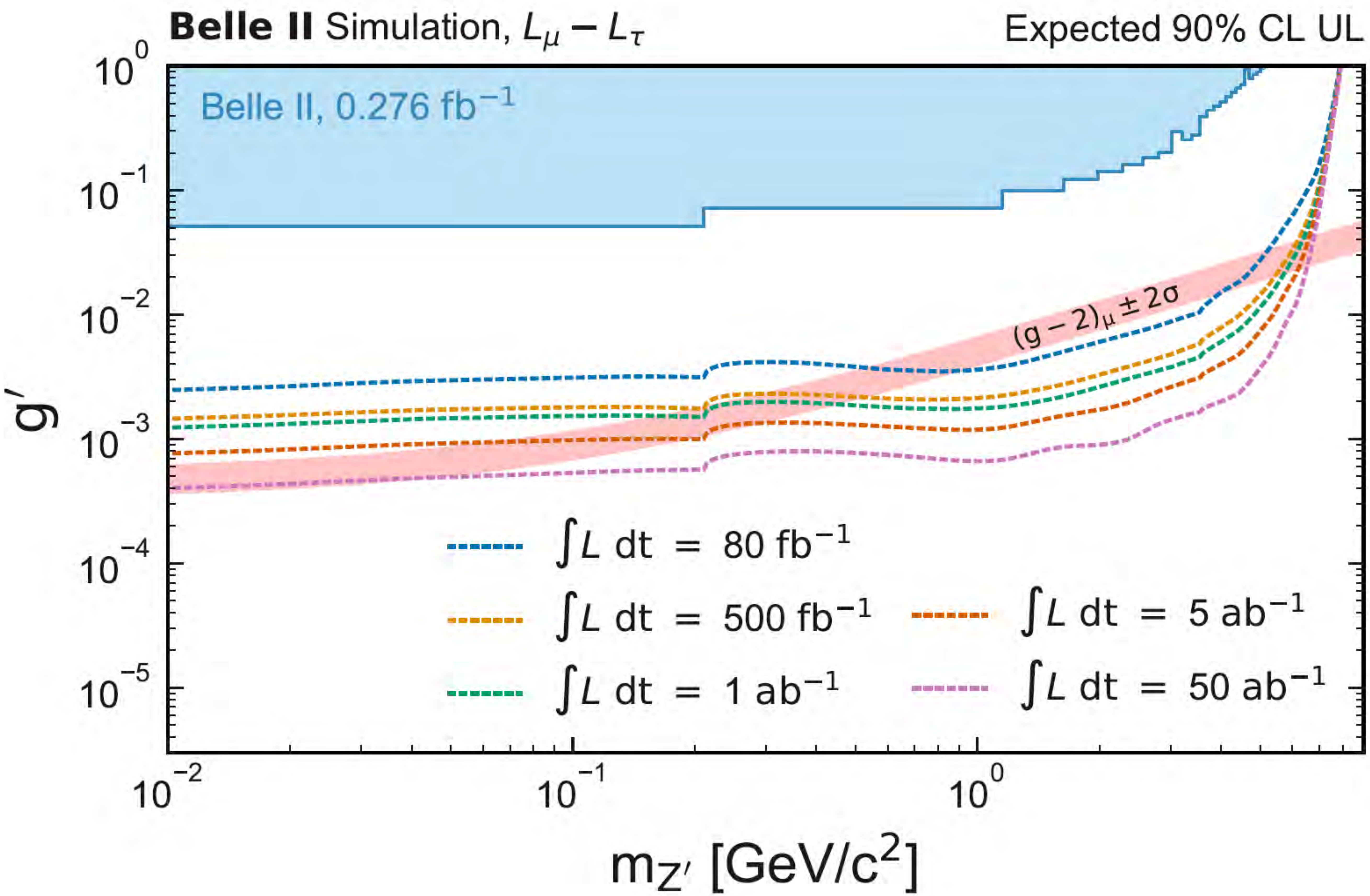




fully invisible Z' as origin of $(g-2)_\mu$ is excluded for $0.8 < M_{Z'} < 5.0$ GeV/c²

arXiv:2207.06307
(Belle II, Snowmass)

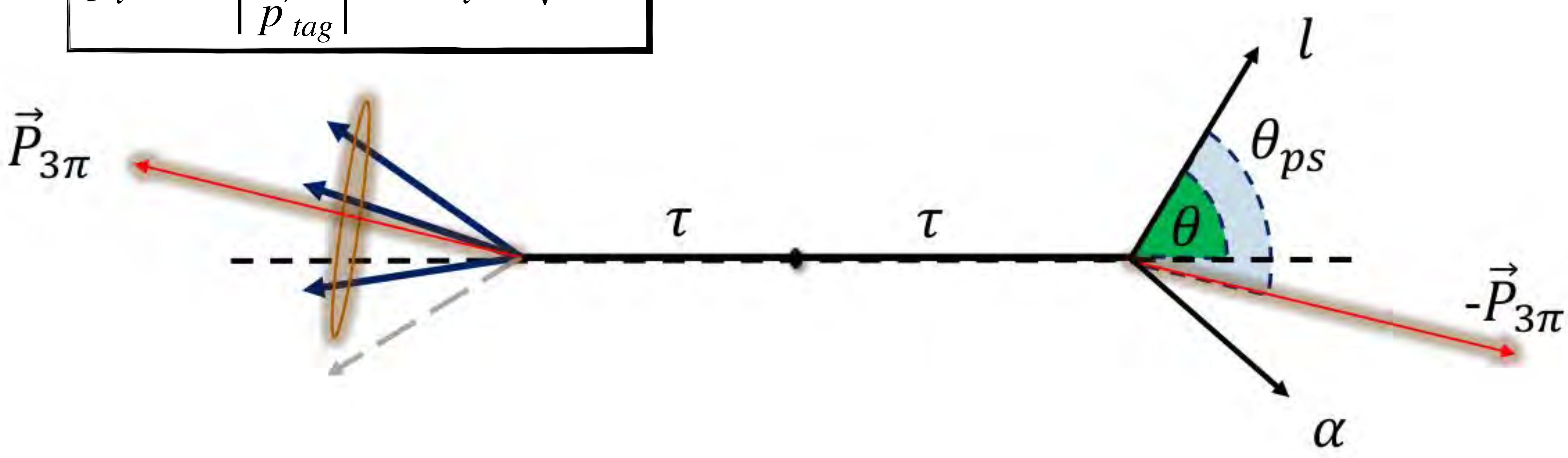
Leptophilic Z' search (Belle II *prospects*)



Search for $\tau \to \ell^+ \alpha$

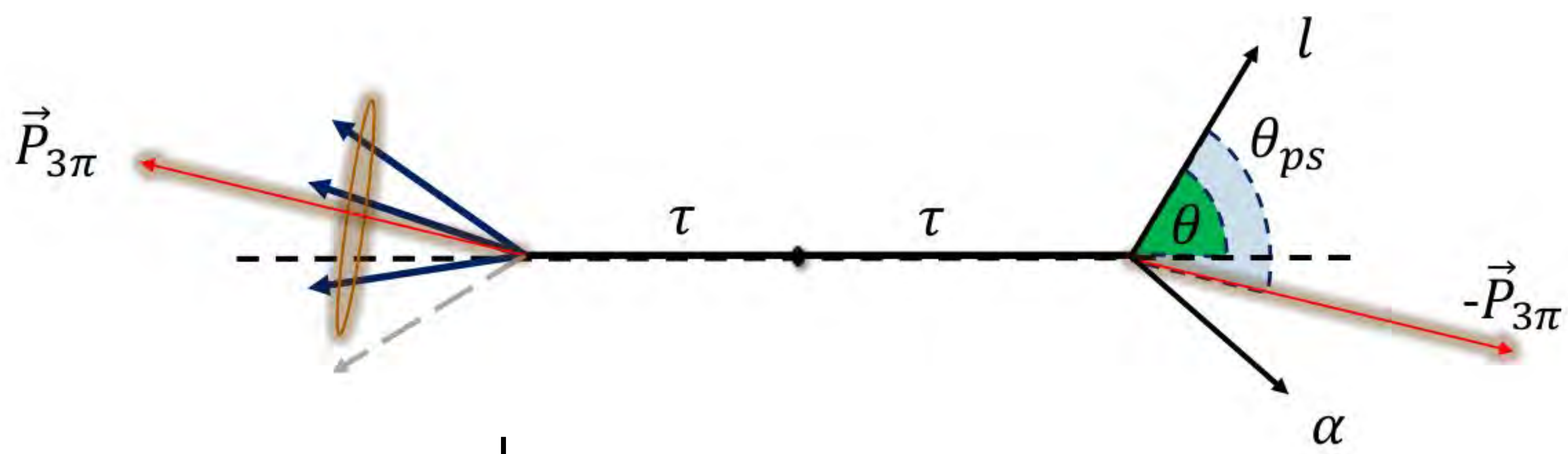
- for α being an ***invisible*** particle
- previous searches by Mark III (1985) and ARGUS (1995)
- event topology
  - ✓ 1-vs-3 (3-prong for tag side)
- τ pseudo-rest-frame by approx. $E_\tau^{\mathrm{CM}} \simeq \sqrt{s}/2$

$$\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}, \quad E_\tau \approx \sqrt{s}/2$$



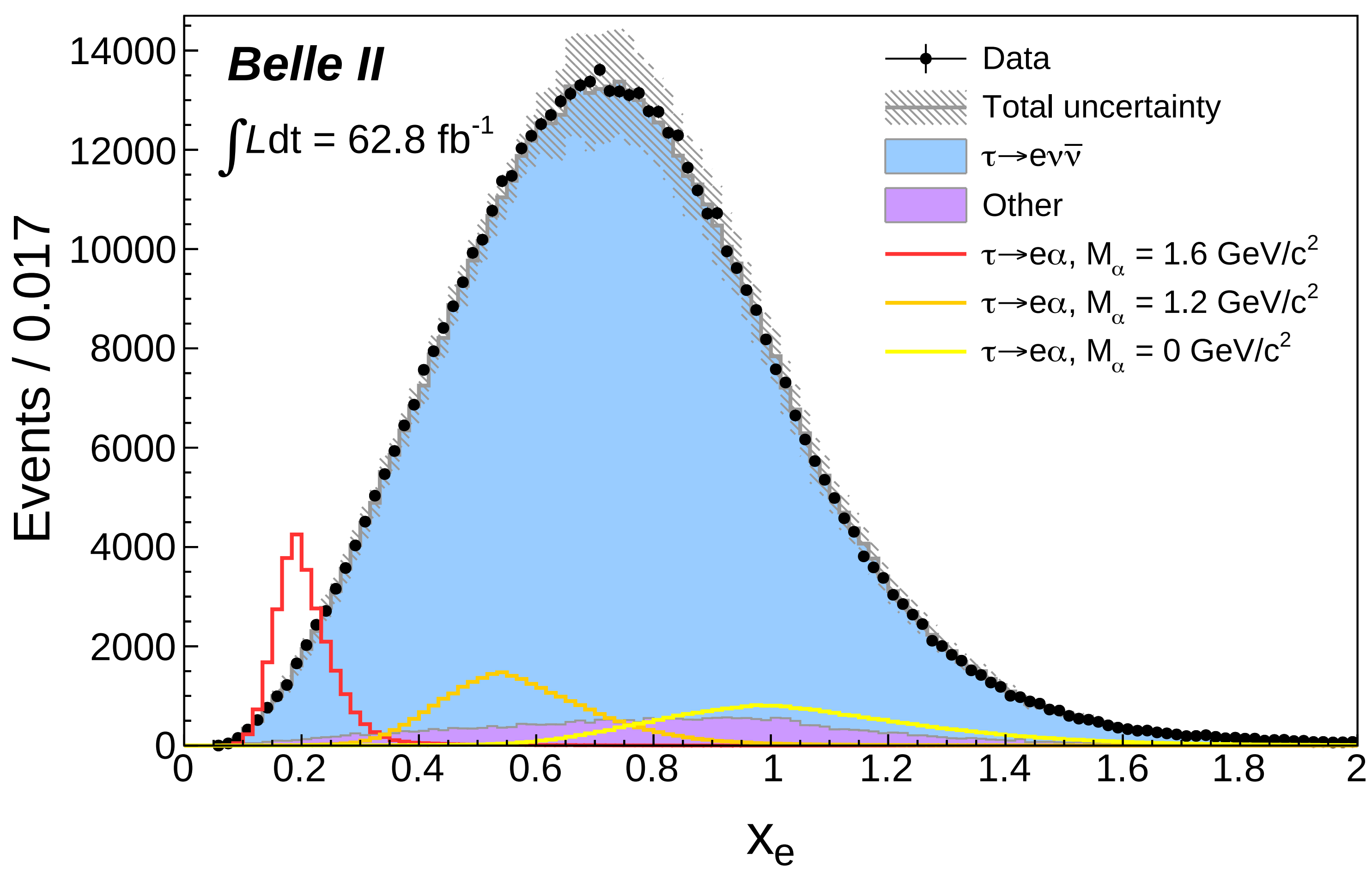
arXiv:2212.03634
submitted to PRL

Search for $\tau \to \ell^+ \alpha$

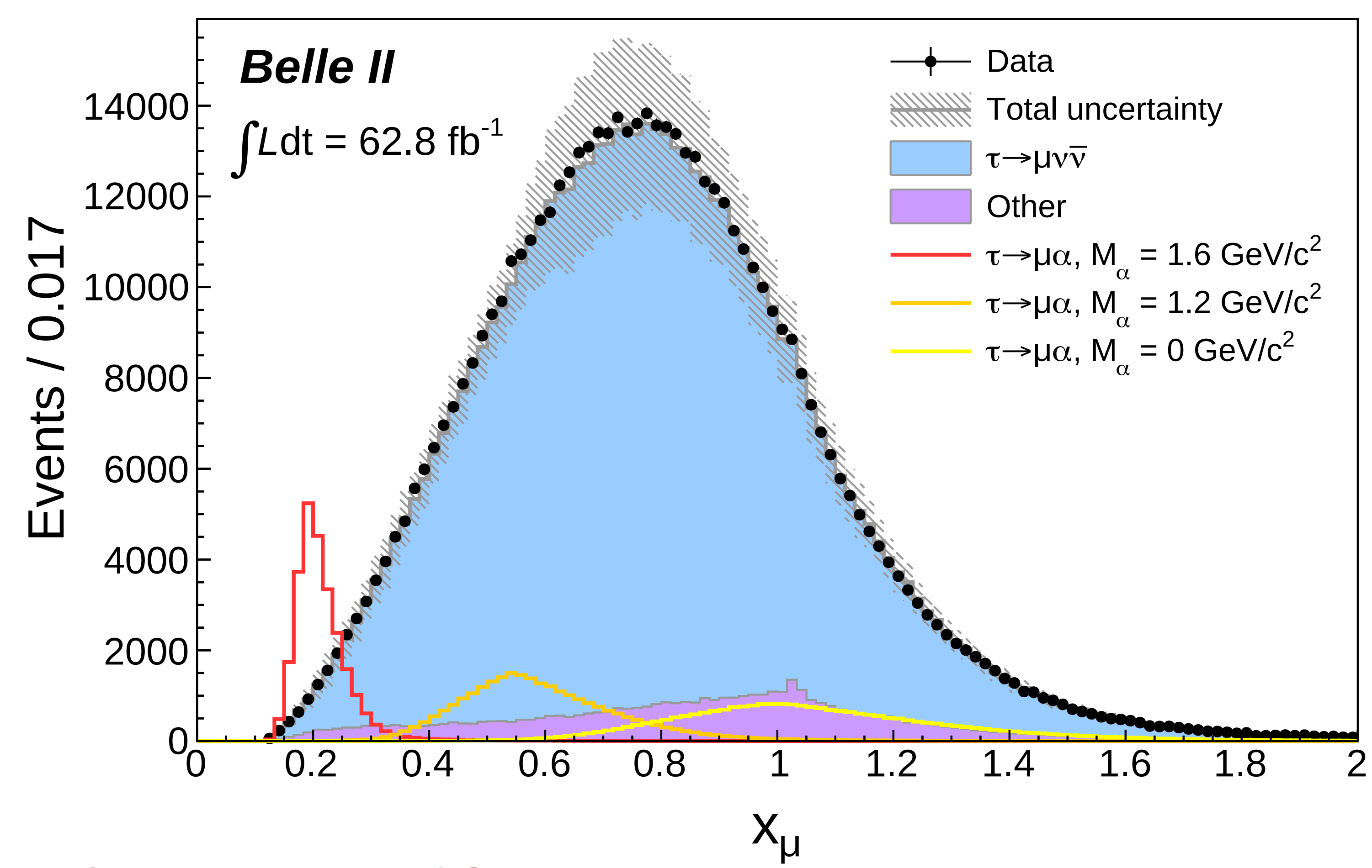


$$x_\ell \equiv \frac{E^*_\ell}{m_\tau c^2/2}$$

$\tau \to e^+\alpha$



$\tau \to \mu^+\alpha$

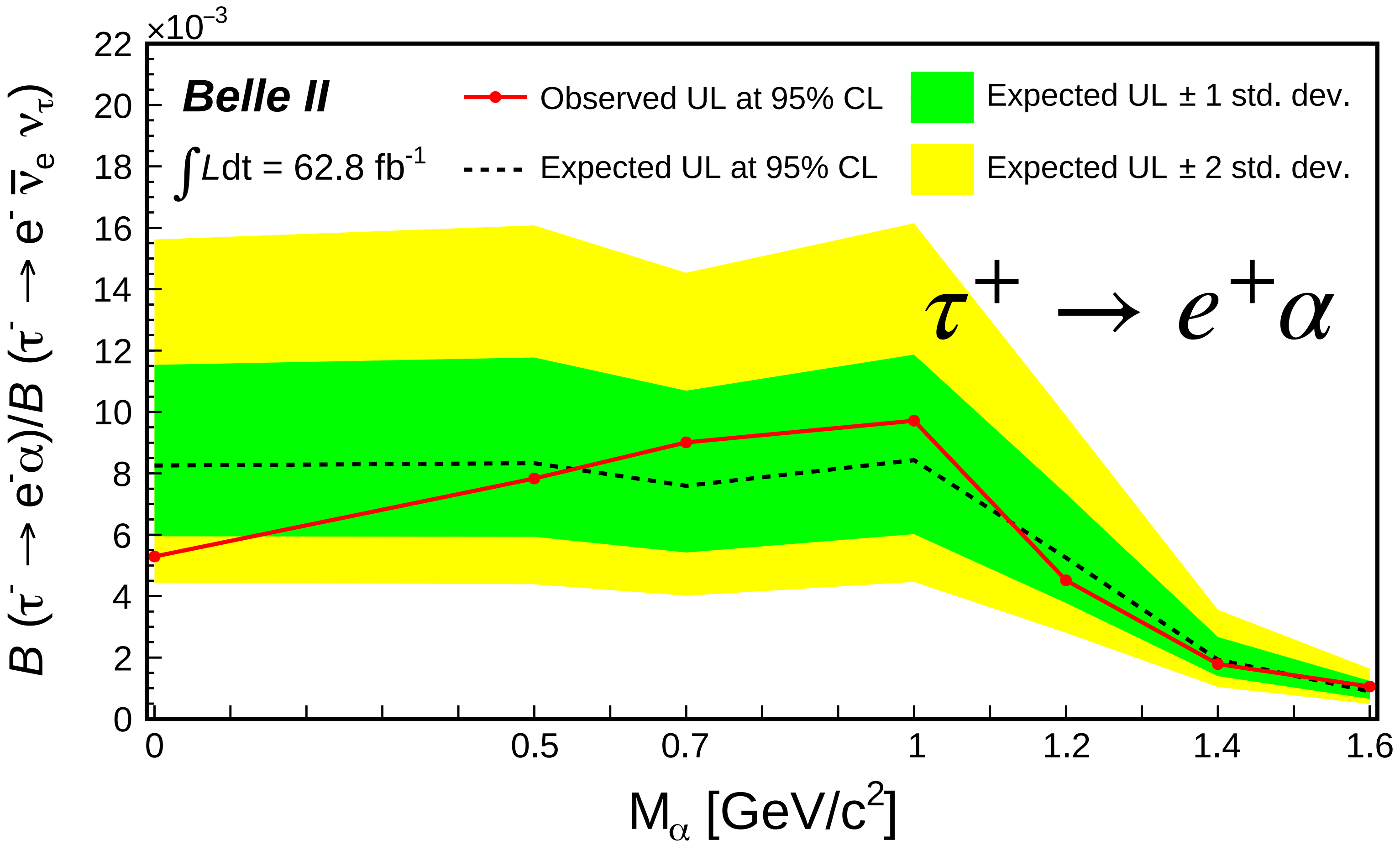


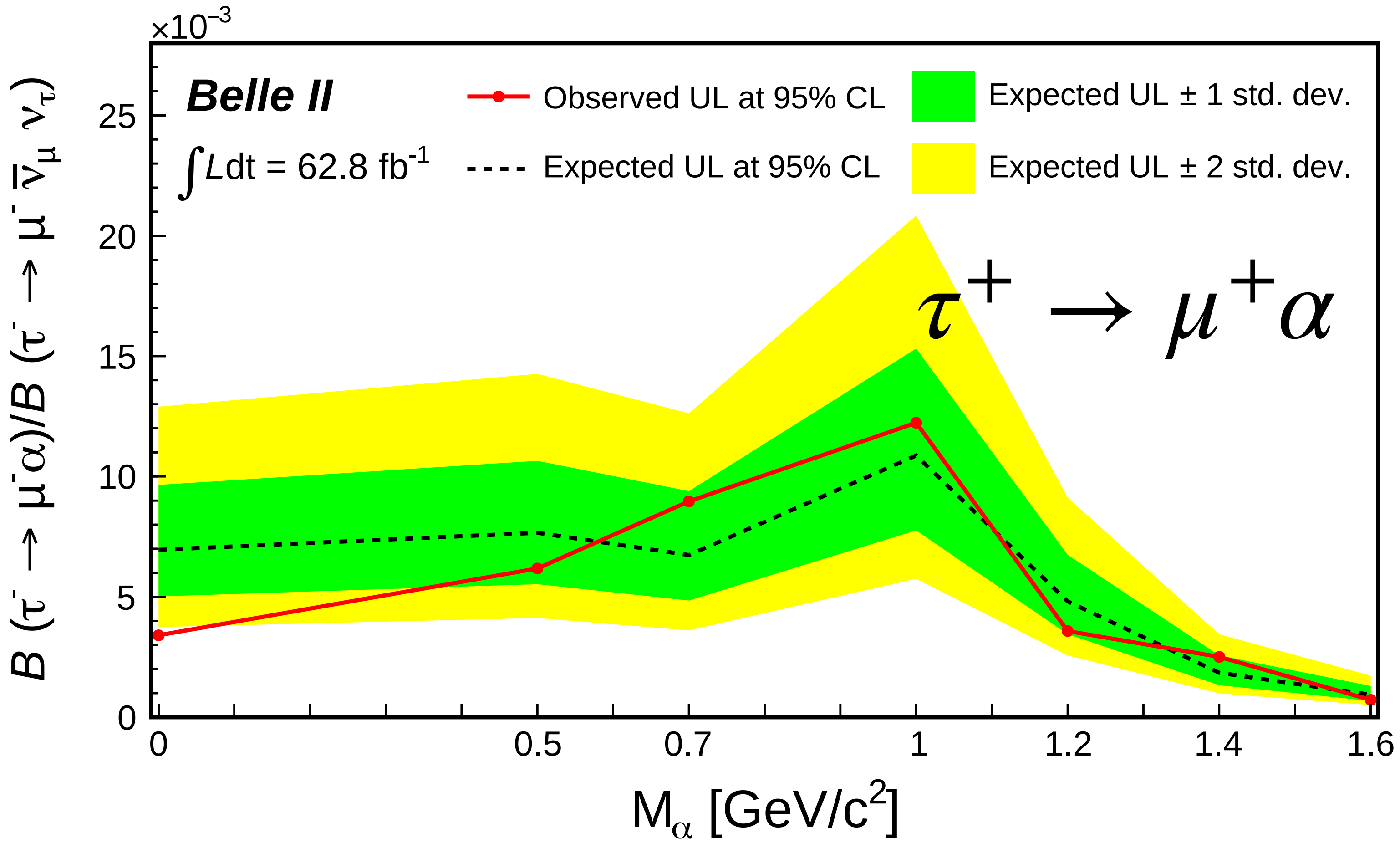
$\tau \to \ell\alpha$ shown for BF = 5%

Results for $\tau \to \ell^+\alpha$

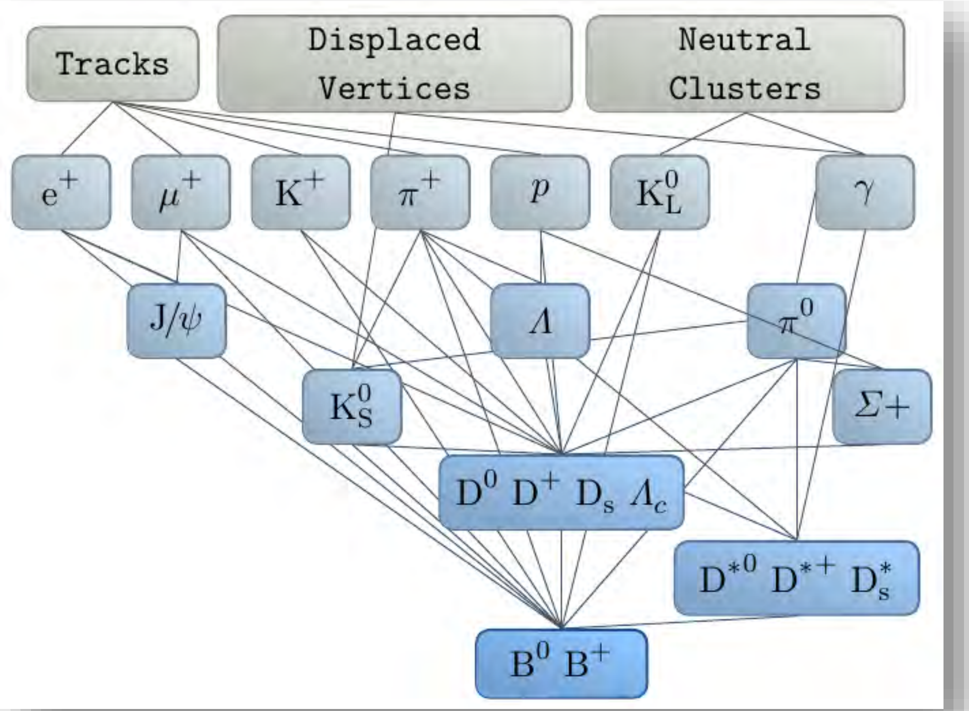
- We find no signal excess and set 95% CL upper limits on $\mathscr{B}(\tau \to \ell\alpha)/\mathscr{B}(\tau \to \ell\nu\bar{\nu})$

- Most stringent limits in these channels to date

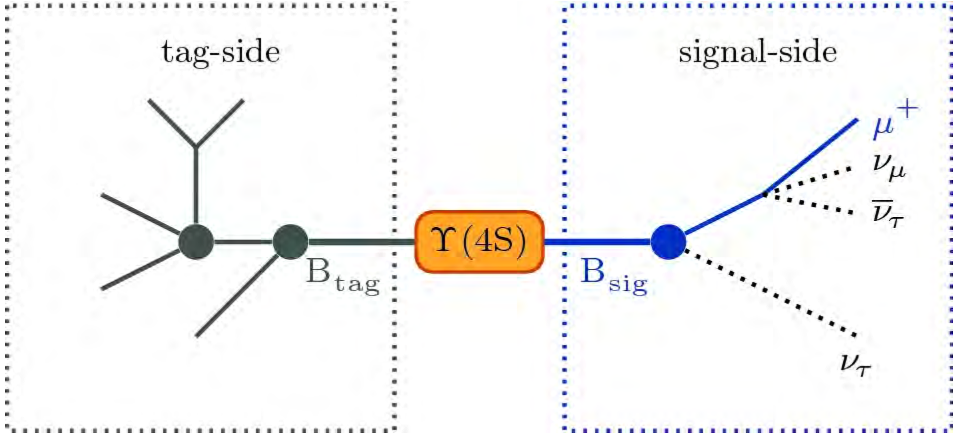




Full Event Interpretation



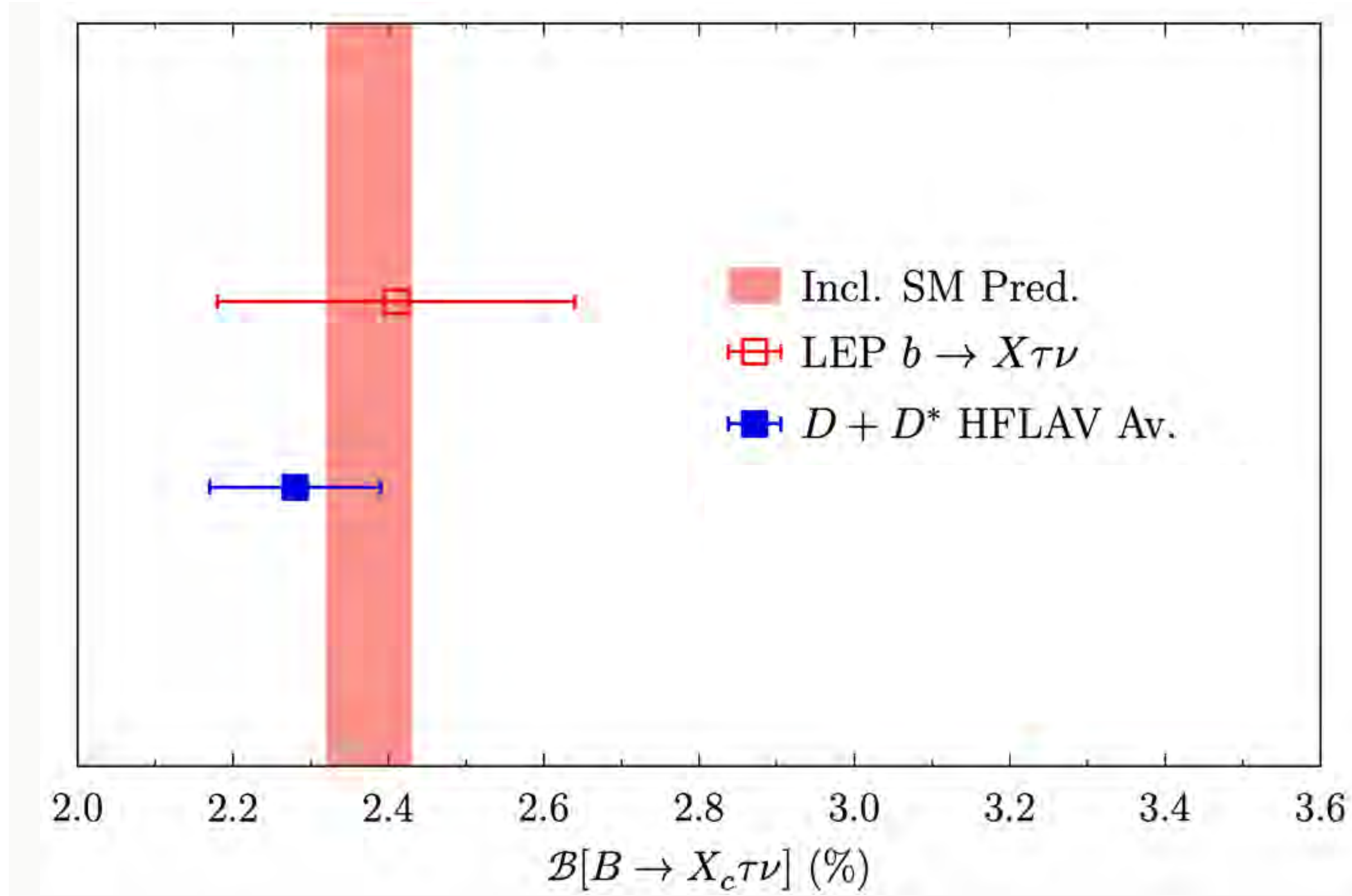
Hierachial reconstruction is performed to obtain B (tag) meson exclusively. Then use the Upsilon(4S) constraint to get the B (sig) meson.



- Traditionally, at Upsilon(4s), one B (tag) is reconstructed first. The rest of the event is considered as a signal B. arXiv.org: 2008.02707
- An improved tool (FEI) is developed based on Boosted Decision Tree. T. Keck et al., Comput. Softw. Big Sci. 3, 6 (2019)
- MVA based. $O(10^4)$ decay channels.
- Max. tag side efficiency: $\varepsilon_{had} \approx 0.5\%$ and $\varepsilon_{SL} \approx 2\%$

LFU test with inclusive $B \to X\ell\nu$

- ***inclusive*** study — complementary to ***exclusive*** studies
- one of the unique and high-profile goals of Belle II
- last measured by LEP (!)
- very challenging — larger bkgd. & much less constrained
- precise modeling of $B \to X\ell\nu$ is critical



- $R(X_{c,\tau/\ell})_{\mathbf{SM}} = \mathbf{0.223 \pm 0.004}$

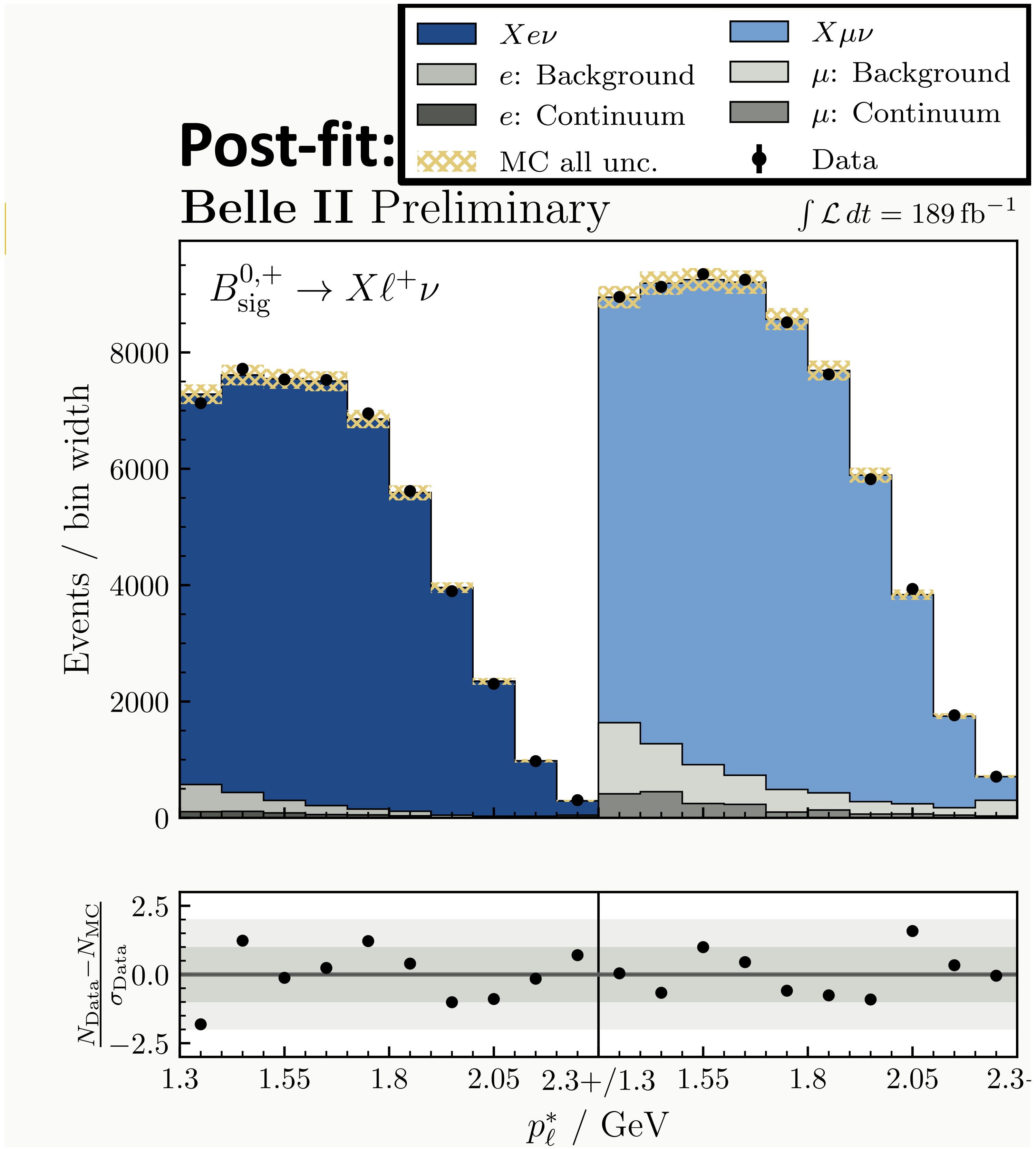
  Phys. Rev. D 92, 054018 (2015)

- $R(X_{e/\mu})_{\mathbf{SM}} = \mathbf{1.006 \pm 0.001}$

  K. Vos, M. Rahimi, in progress

LFU test with inclusive $B \to X\ell\nu$

Post-fit:



$$R(X_{e/\mu}) = \frac{N_{Xe\nu} \cdot \epsilon_{X\mu\nu}}{N_{X\mu\nu} \cdot \epsilon_{Xe\nu}} \quad \text{with}$$

$$\epsilon_{X\ell\nu} = \frac{N^{\ell}_{sel} \cdot (\epsilon^{data}_{B\,tag} / \epsilon^{MC}_{B\,tag})}{2 \cdot N_{BB} \cdot BR(B \to X\ell\nu)}$$

$$R(X_{e/\mu})^{p^*_\ell > 1.3} = 1.033 \pm 0.010 \pm 0.020$$

Source of uncertainty	Lepton ID	$X_c\ell\nu$ BFs	$X_c\ell\nu$ FFs	Statistical	Total
Rel. unc. of $R(X_{e/\mu})$	1.8%	0.1%	0.2%	1.0%	2.2%

compatible within 0.6σ with exclusive Belle measurement:

$R(D^*_{e/\mu}) = 1.01 \pm 0.01 \pm 0.03$ [PRD 100, 052007 (2019)]

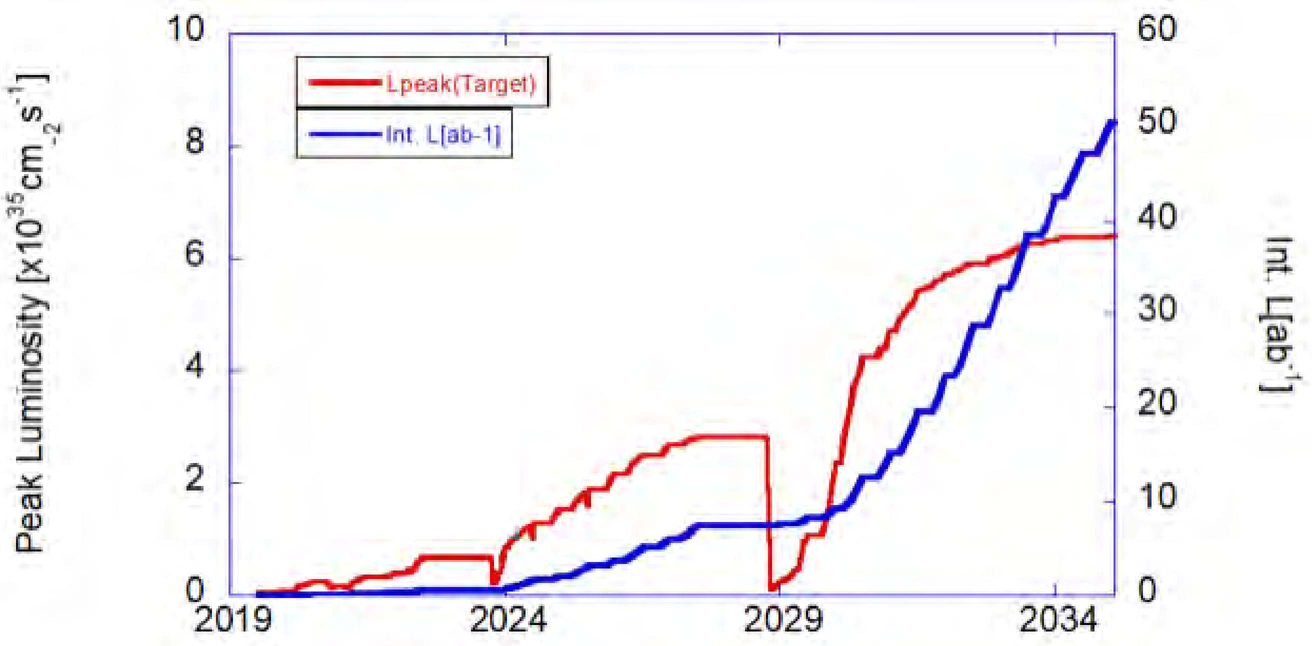
Summary I

- SuperKEKB has achieved $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the world record on June 22^{nd}, 2022.
  - It is a super B factory now.

- Belle II has started producing new results with the initial sample, including a world leading results in charm lifetime.
  - More updates are coming with the $424\ fb^{-1}$ sample!
  - Planning to merge Belle and Belle II data and analysis flow.

- Even in 2022, 26 new results from Belle and Belle II.
  - Only a few selected topics are shown here.
  - Further reports shown at ICHEP 2022, Moriond 2022.

Summary: For the future



LS1: New pixel detector, replacement of MCP-PMT for TOP, DAQ replaced by faster PCIe40 cards, etc.

- Belle II is in the first long shutdown period (LS1).
- Planning to resume the run late next year.
- Another long shutdown is being considered to increase luminosity.
- 50 ab^{-1} will be collected total.
- This is a very exciting time to do flavor physics, looking for physics beyond the Standard Model.

EXTRA

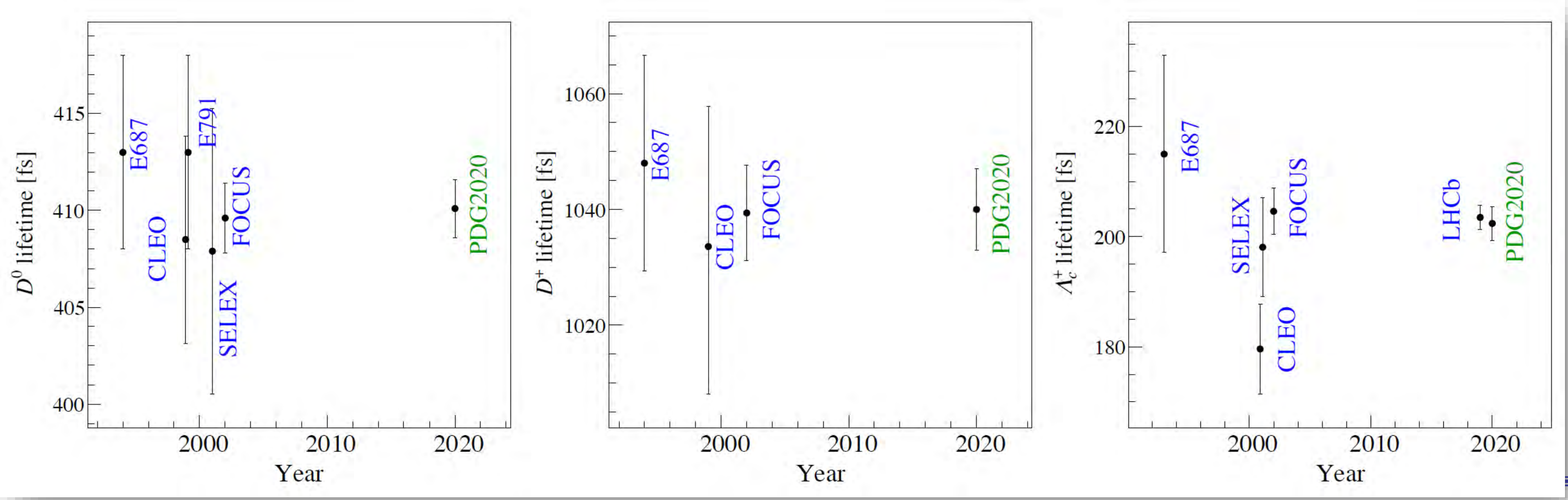
Belle II Experiment in a Nutshell

- HEP experiments have seen huge accomplishments during the last decades.
  - CPV/CKM, discovery of XYZ/tetra/penta particles, discovery of Higgs, etc.
  - Next major theme: New Physics, requiring more precision and larger samples.
- Belle II/SuperKEKB is the upgrade of Belle/KEK.
- Upsilon(4S) decays into $B\,\bar{B}$ meson pairs, coherently with no additional fragments.
  - Full event reconstruction tagging possible
- Direct detection of neutrals such as γ, π^0, K_L.
- A hermetic detector:
  - Detection of neutrinos or invisibles as missing energy/momentum.
- Large continuum charm and τ samples in addition to B samples.
  - Detect both e and μ with similar performance.
  - For example, search for LFV τ decays at $O(10^{-9})$ possible.

A Brief History of Charm Lifetime Measurements

Previously, charm particle lifetimes are dominated by

- D0 and D+
  - FOCUS (photon beam), SELEX (hyperon beam), CLEO (e+e-)
- Charm baryons
  - Dominated by LHCb, but its measurements are relative to D+ lifetime.



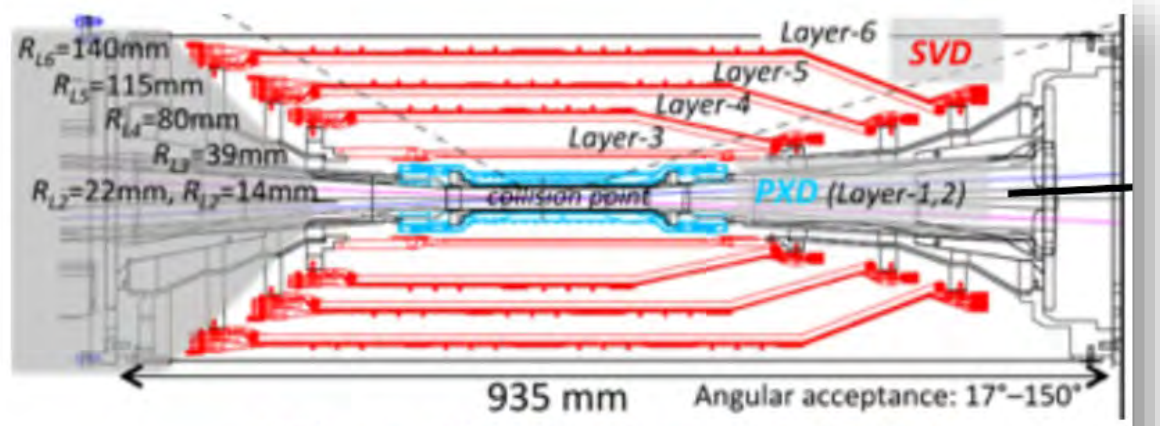
Belle II Vertex Detector

Inner most vertex detector consists of

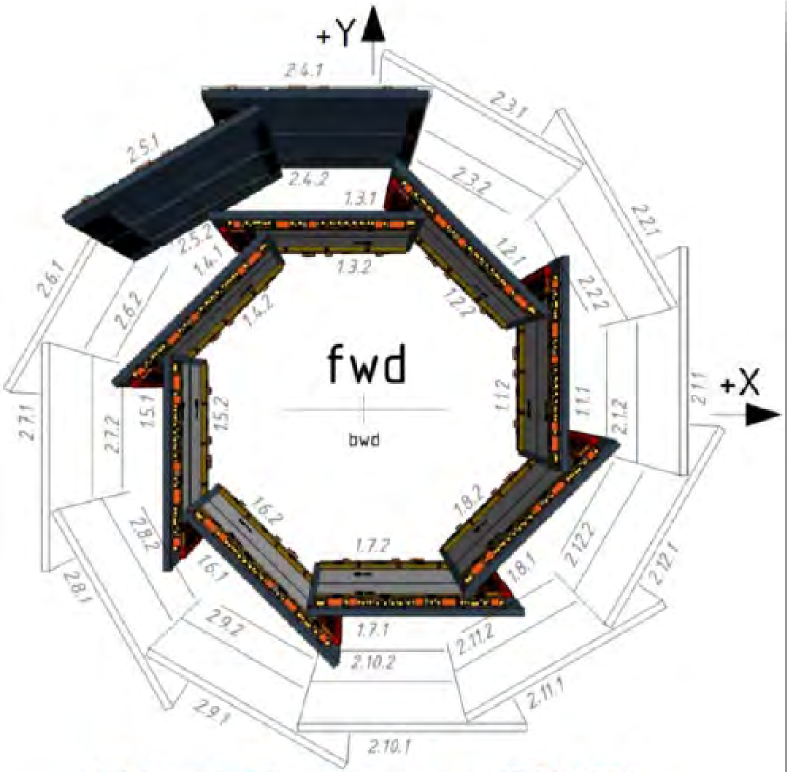
- 1 DEPFET layer (2nd layer will be completed in 2023) and 4 DSSD layers
- Resulting in two times better vertex resolution, improved efficiency for slow pions and Ks's, and better tracking against beam backgrounds w.r.t. Belle.

Alignment is crucial for lifetime measurements.

- Checked thoroughly during analysis.



Silicon Vertex Detector (SVD)



Pixel Detector (PXD)