Belle and Belle II

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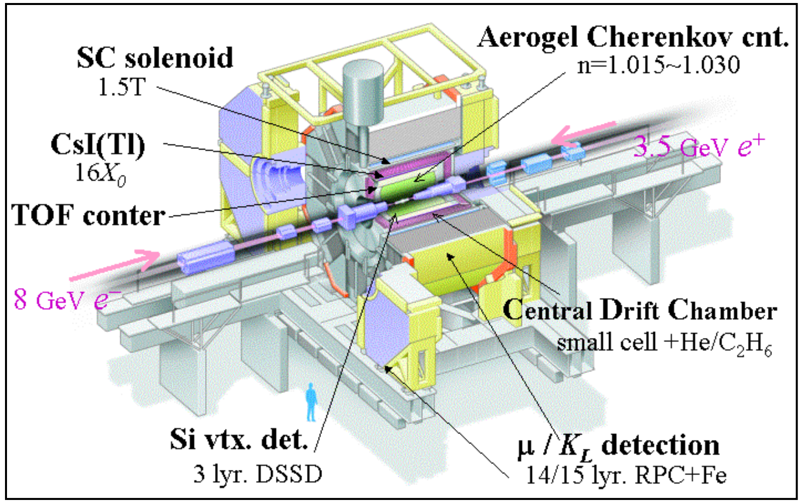
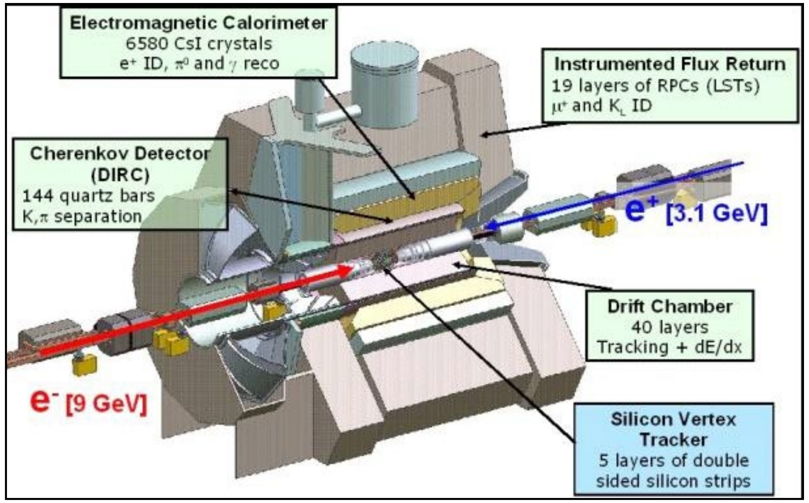
November 18, 2022
KSHEP 2022 Fall Meeting
Pusan National University

Two B Factories from 1999

Belle / KEKB



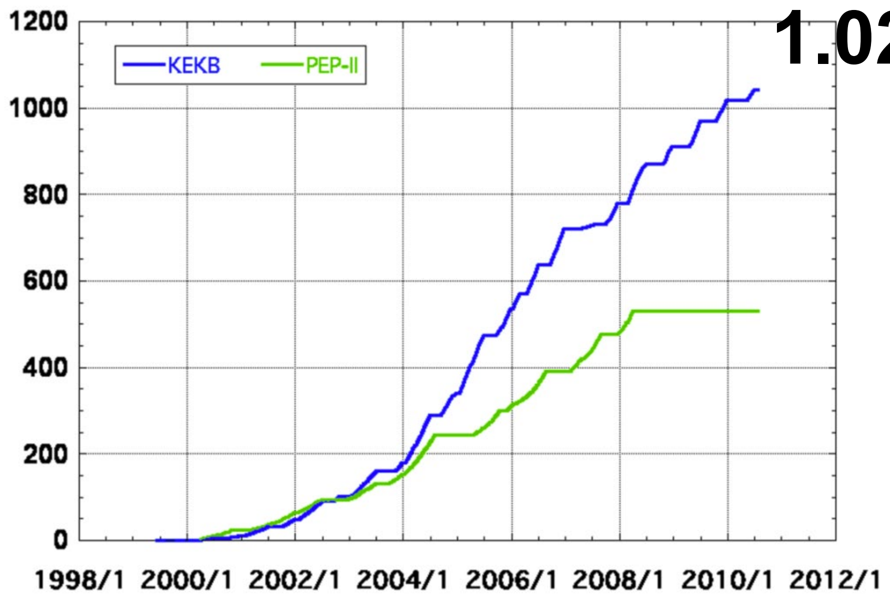
BABAR / PEP II



- 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)



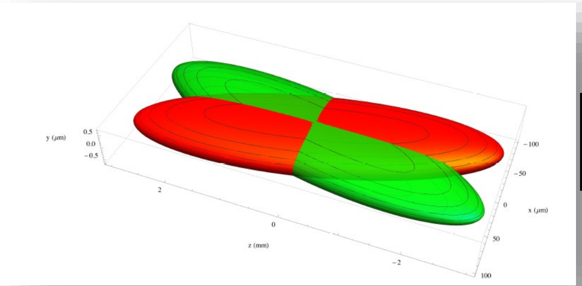
1.02 ab^{-1}

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

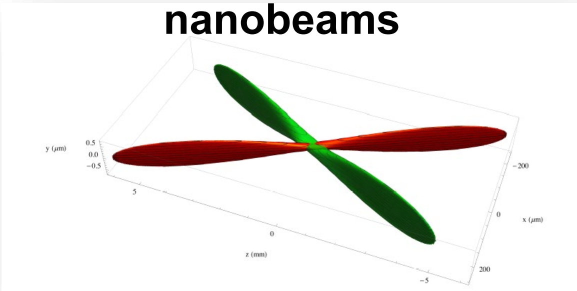
- Nano beam scheme + Crab waist optics
- Target: vertical beta function β_y^* 5.9 mm (KEKB) to 0.3 mm (SuperKEKB)
- Increase beam currents $I_{e\pm}$
- Increase beam-beam interaction ξ_y

KEKB beams



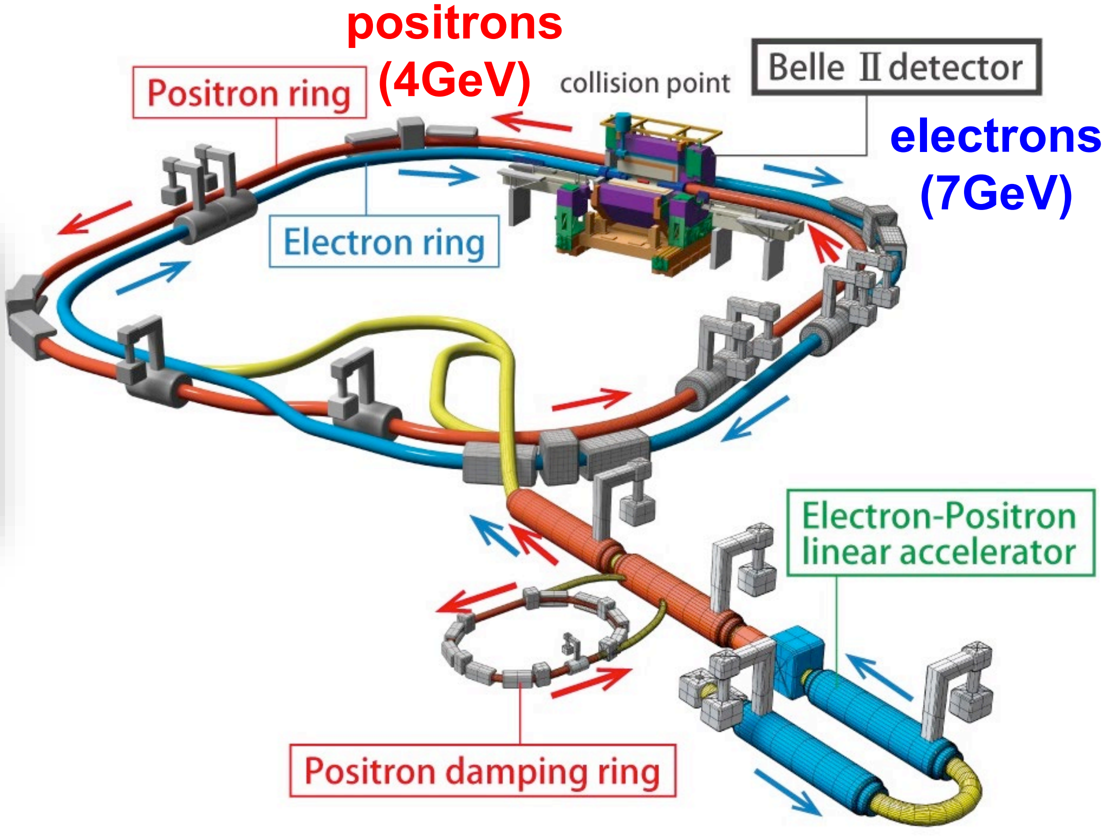
Beam crossing angle 22mrad

SuperKEKB nanobeams

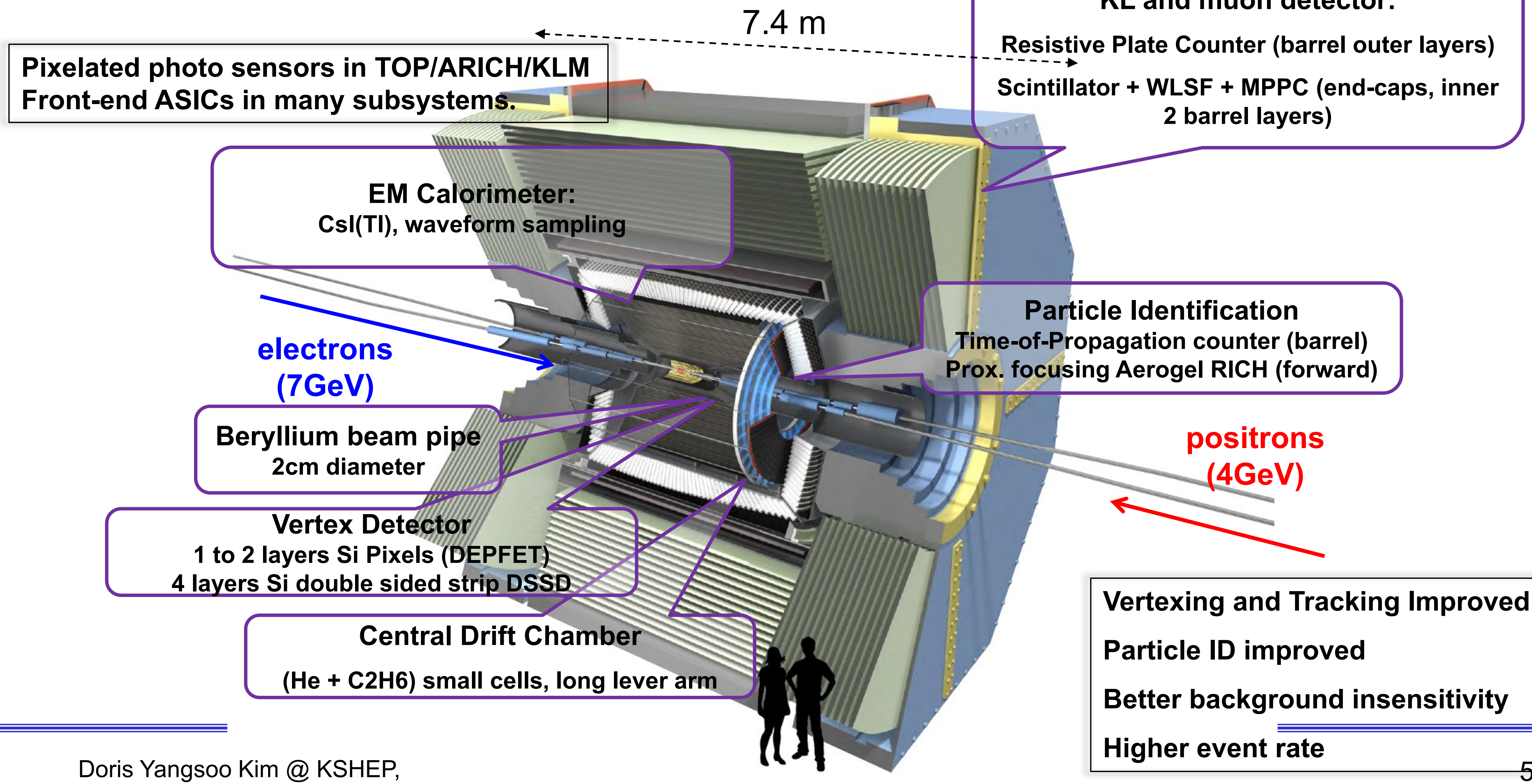


Beam crossing angle 83mrad

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



The Belle II Detector



Vertexing and Tracking Improved

Particle ID improved

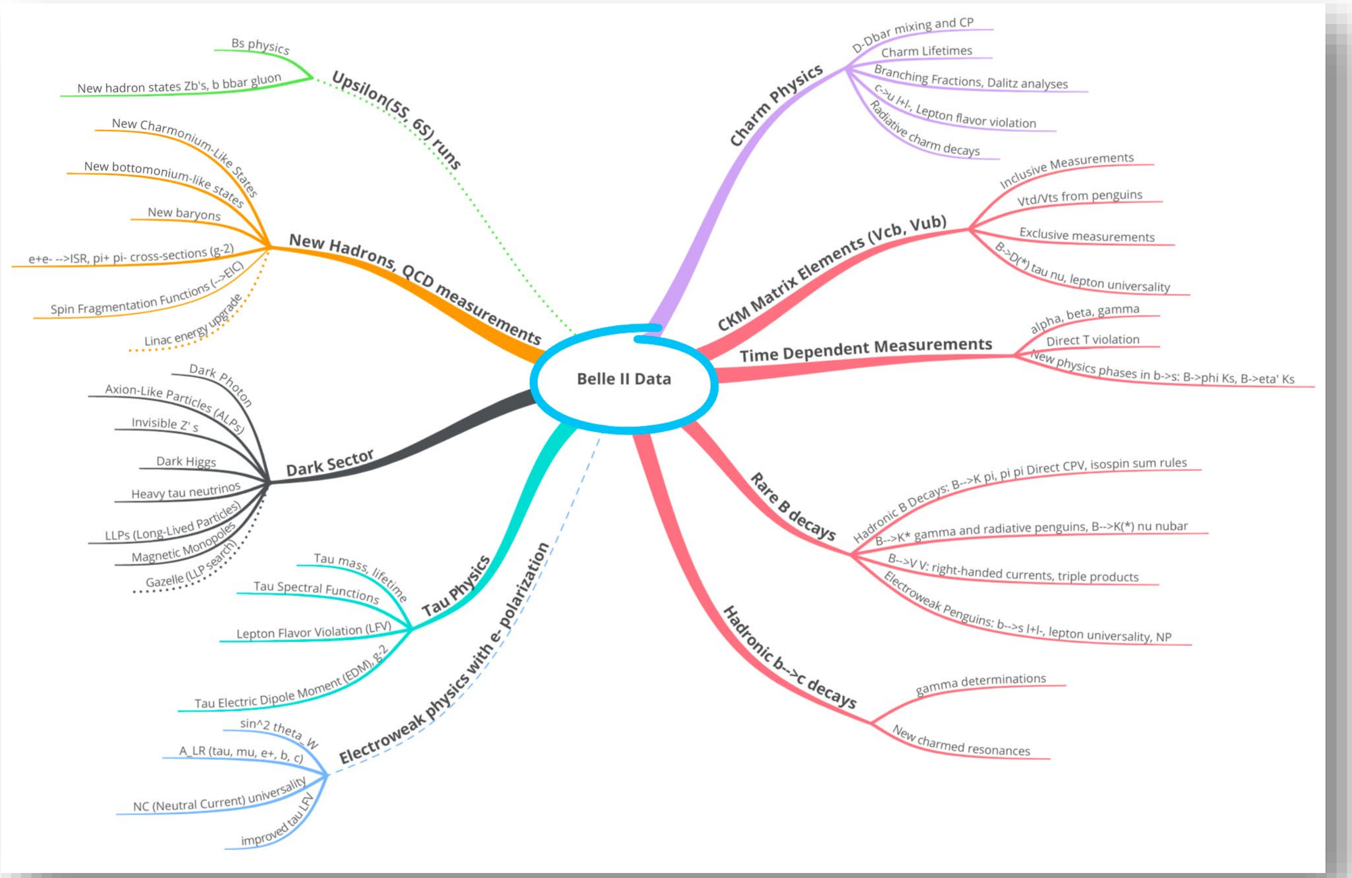
Better background insensitivity

Higher event rate

Belle II Physics Prospects

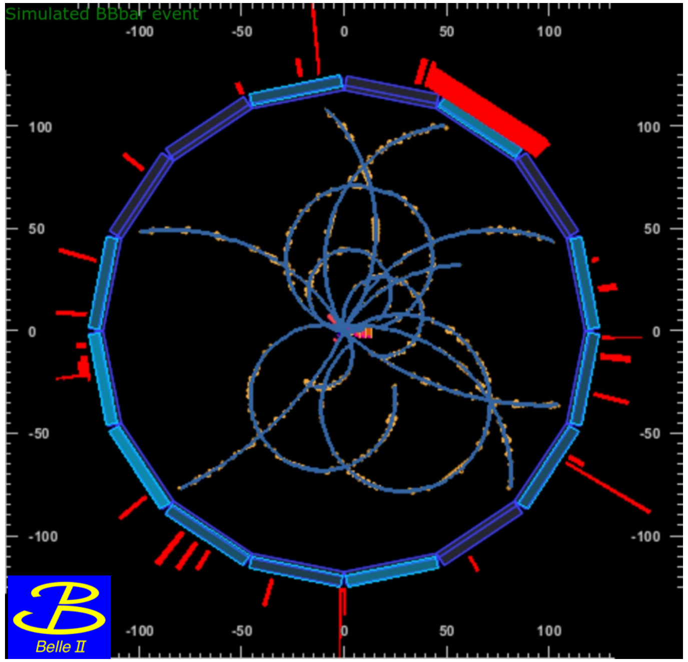
- Charm decays
- Next precision CKM matrix
  - Semileptonic B decays (CKM elements)
  - Hadronic B decays (angles and CPV)
  - Time dependent CP violation
- τ physics
- Hadron spectroscopy
- Rare decays, FCNC
- New physics
  - Lepton flavor violation
  - Dark sector, Long lived particles

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

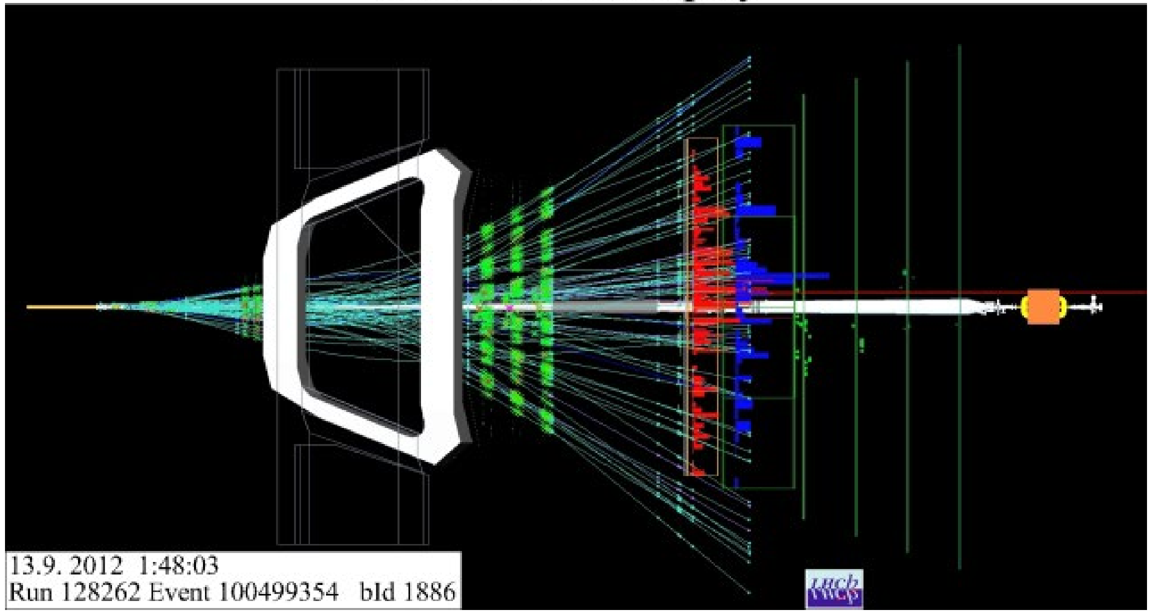


Belle (II) and LHCb

- 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.



LHCb Event Display

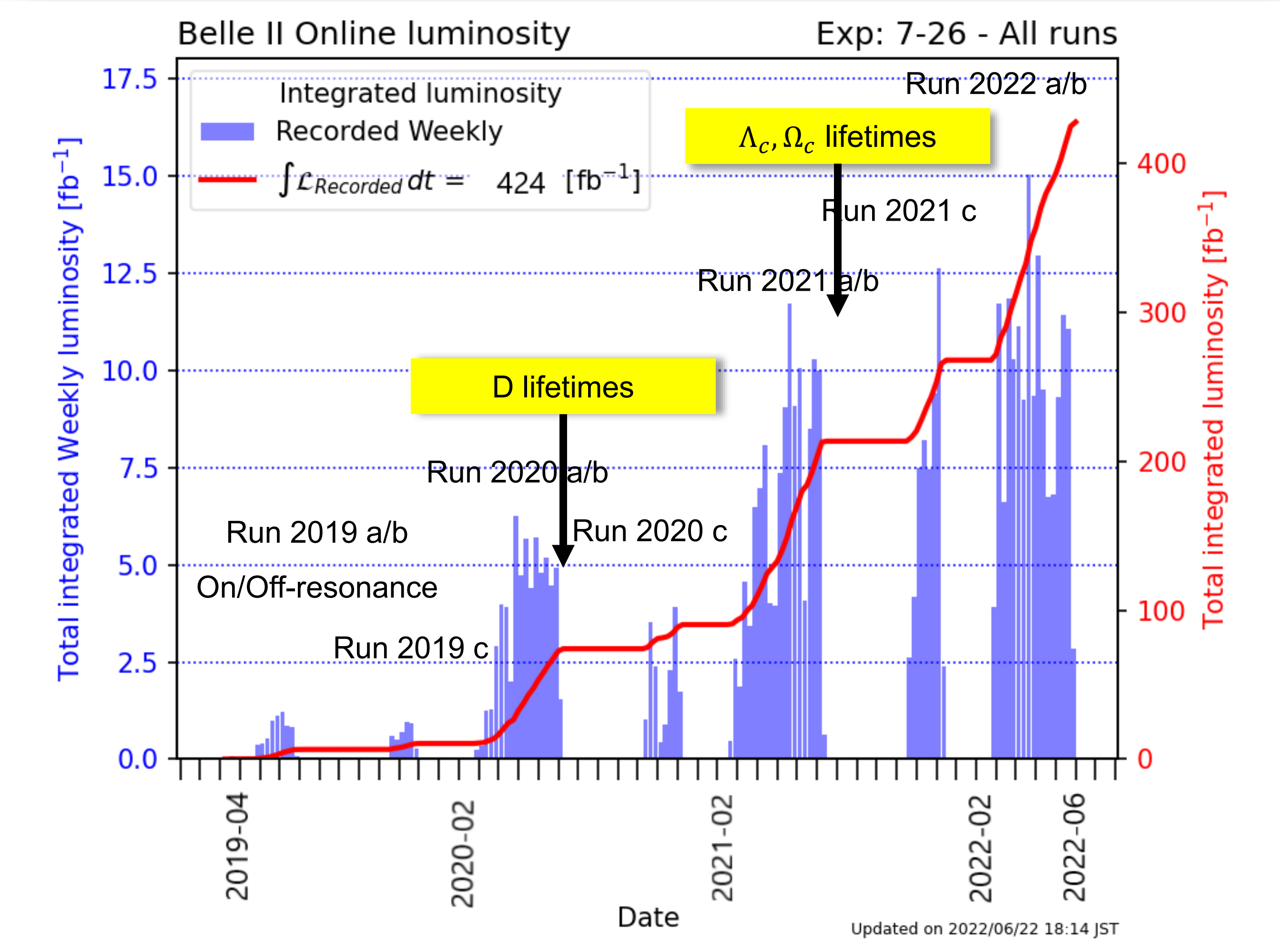


The Belle II Collaboration (This is not Belle!)

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

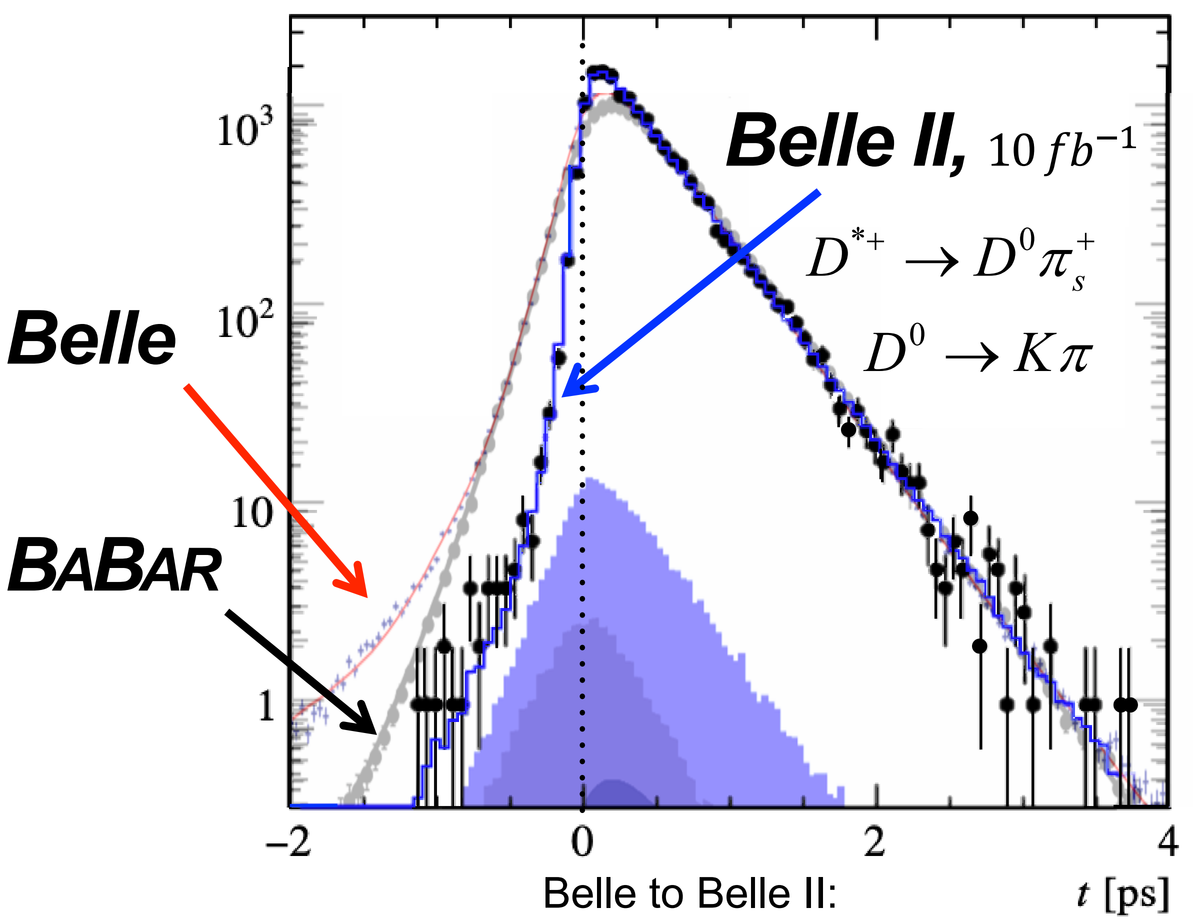
SuperKEKB Luminosity: Current Status

- 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 MPT, etc).



Charm Particle Lifetime

D^0 lifetime distribution comparison

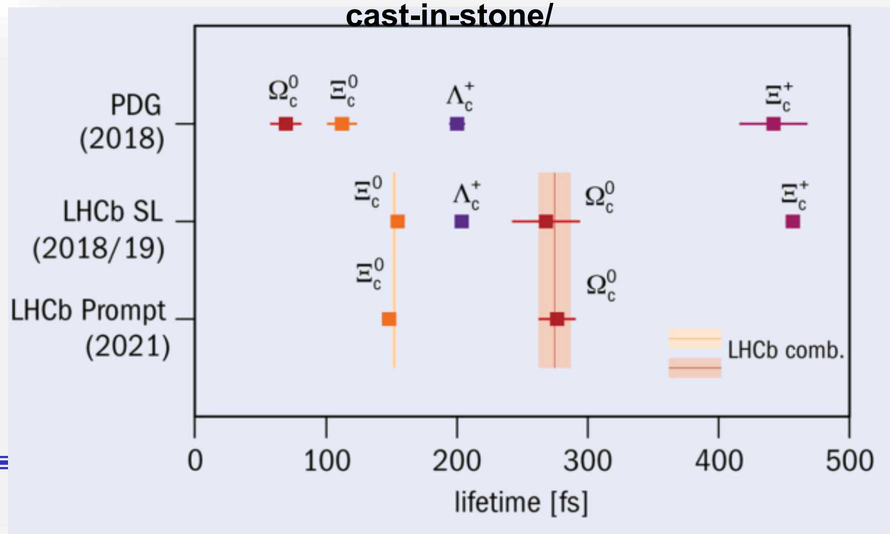


Belle to Belle II:
2 times better vertex resolution,
20 times smaller beam spot size

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

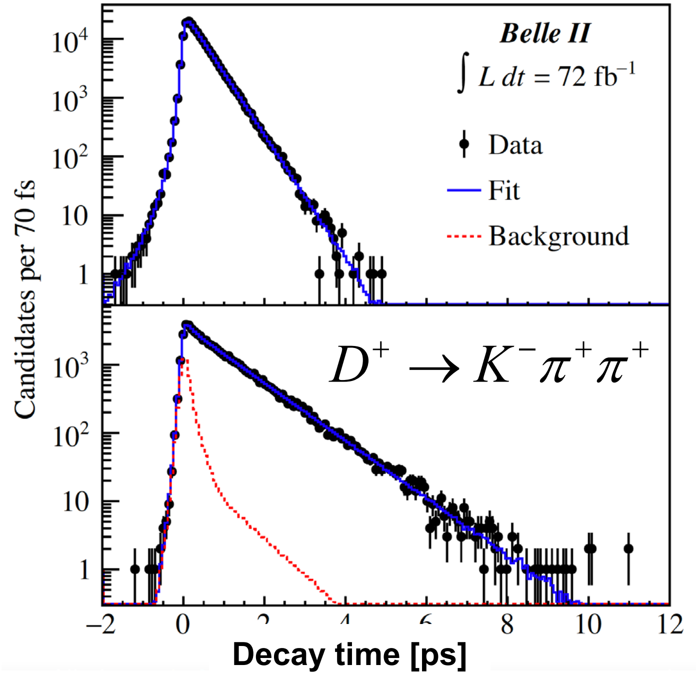
- Charm particles @ low-energy QCD calculation (non-perturbative and high order correction). The effective models do have uncertainties.
- Measurements of charm lifetimes can test the models.
- SuperKEKB gives a great opportunity to measure the world best charm lifetimes.

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

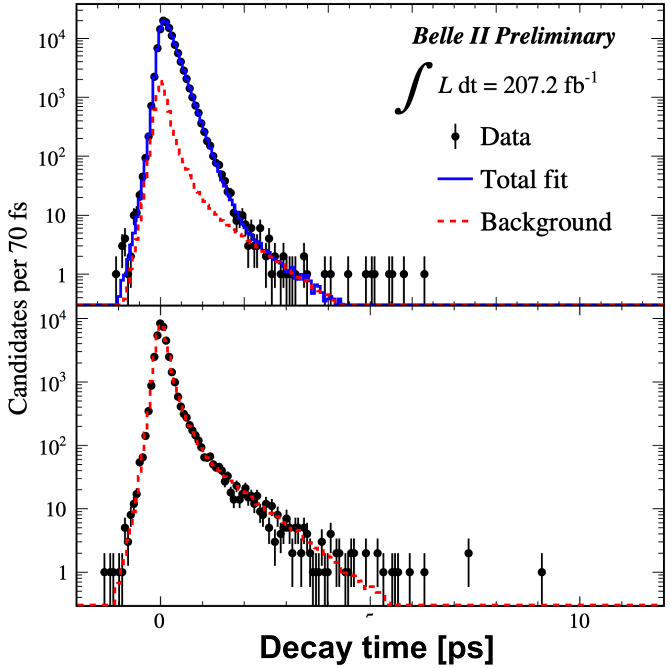


D^0, D^+, Λ_c^+, Ω_c^0 Lifetimes

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

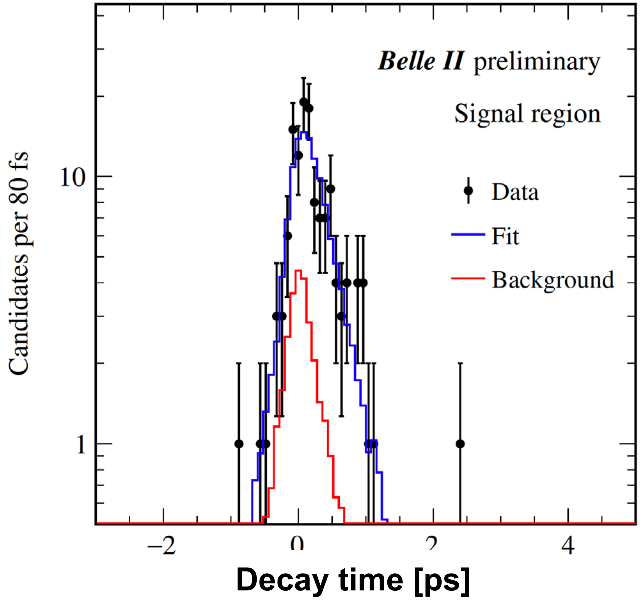


$\Lambda_c^+ \to p K^- \pi^+$



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

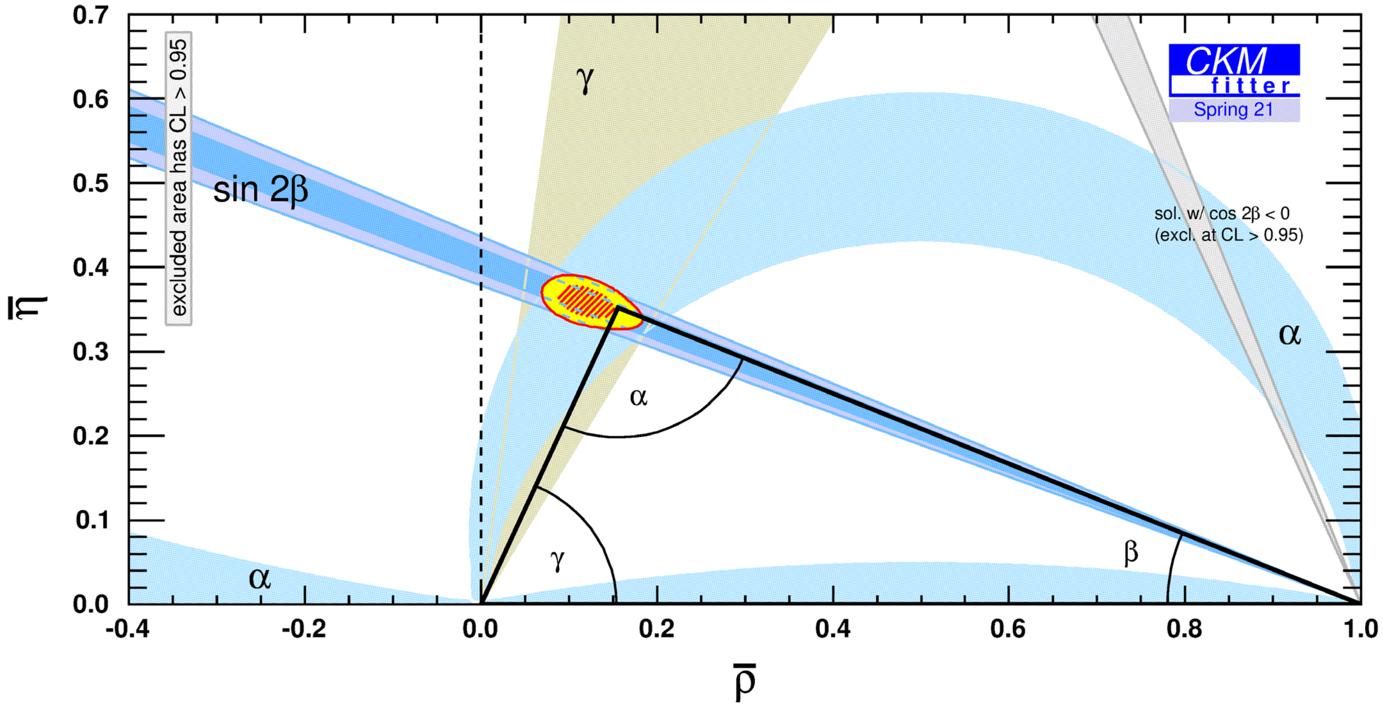
$\Omega^- \to \Lambda^0 K^-$, $\Lambda^0 \to p \pi^-$



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

Why CKM Matrix?

- Unitary triangle constraints are powerful test of the SM.
  - Precision on α and γ angles are much less than β.
- Predicting rare decays involves $V_{qq'}$. Needed for NP searches.
  - Use semi-leptonic, leptonic decays of mesons.



To be published,
Prog. Theor. Exp. Phys. 2022 083C01 (2022)
aka PDG 2022

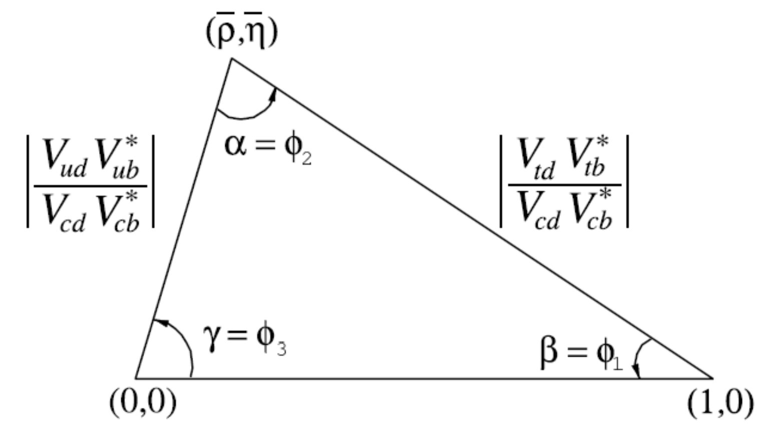
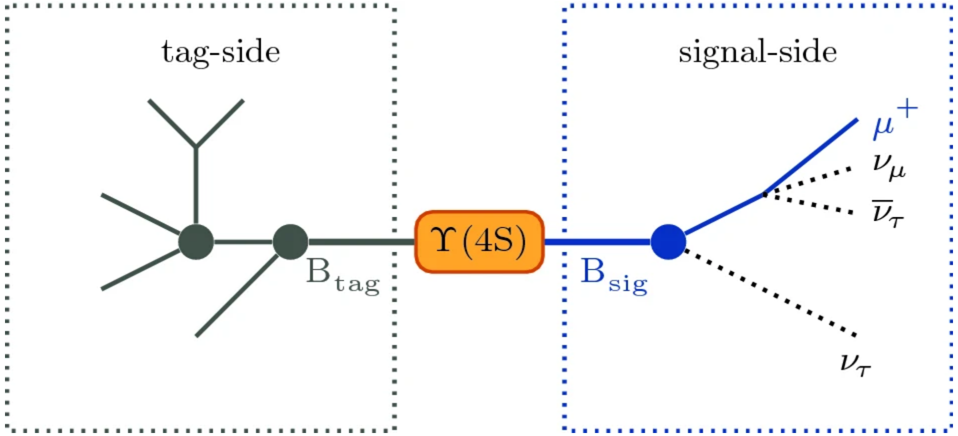
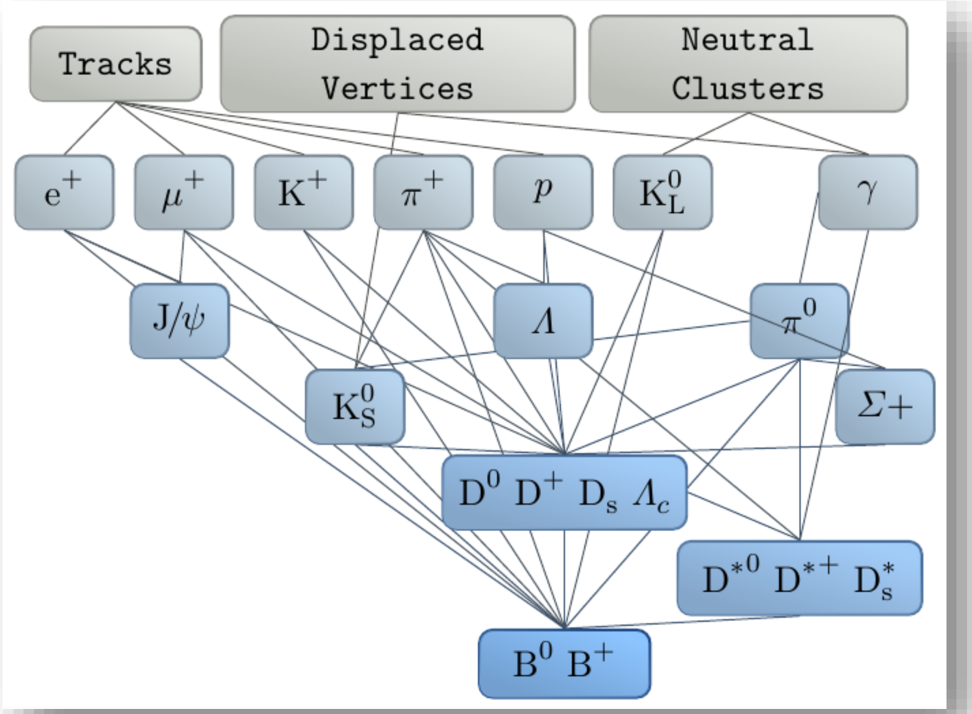


Figure 12.1: Sketch of the unitarity triangle.

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 $\varepsilon_{SL} \approx 2\%$

The CKM Matrix elements

- The ~ 3σ tension between inclusive and exclusive measurements in $|V_{cb}|, |V_{ub}|$ is still going on.
- Preliminary Belle II exclusive results, based on $190\ fb^{-1}$ samples.
  - The results are consistent with the previous measurements.

Matrix elem.	Signal B	Other B	Meas.	Ref.
$\lvert V_{cb}\rvert$	$B \to Dl\nu,\ (l = e, \mu)$	Untagged	$(38.53 \pm 1.15\ (stat.+sys.+theo.)) \times 10^{-3}$	ICHEP 2022
	$B^0 \to D^* l\nu,\ (l = e, \mu)$	Hadronic	$(38.2 \pm 2.8\ (stat.+sys.+theo.)) \times 10^{-3}$	Moriond 2022
$\lvert V_{ub}\rvert$	$B^0 \to \pi l\nu,\ (l = e, \mu)$	Untagged	$(3.54 \pm 0.12 \pm 0.15 \pm 0.16) \times 10^{-3}$	ICHEP 2022
	$B \to \pi e\nu$	hadronic	$(3.88 \pm 0.45(stat.+sys.+theo.)) \times 10^{-3}$	Moriond 2022

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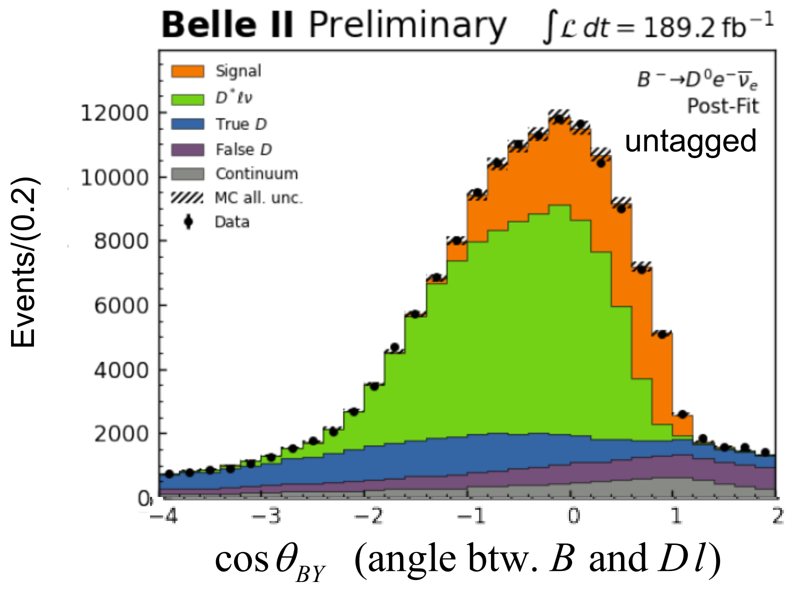
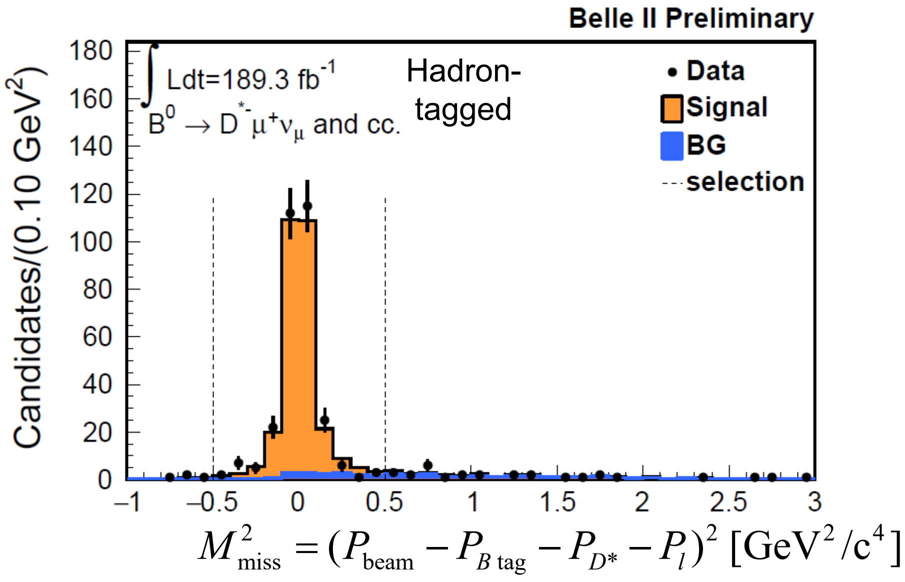
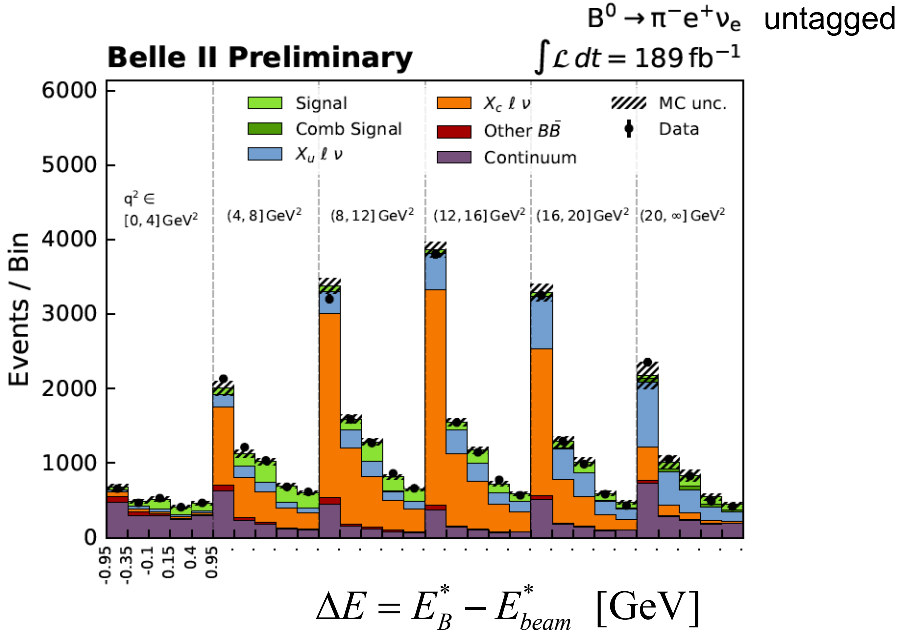
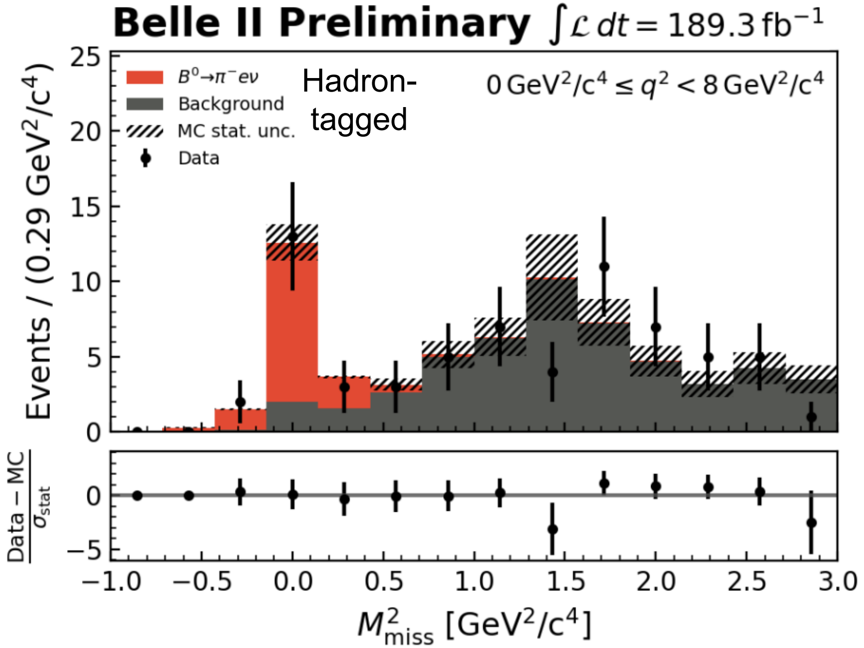
Signal Selection of SL modes

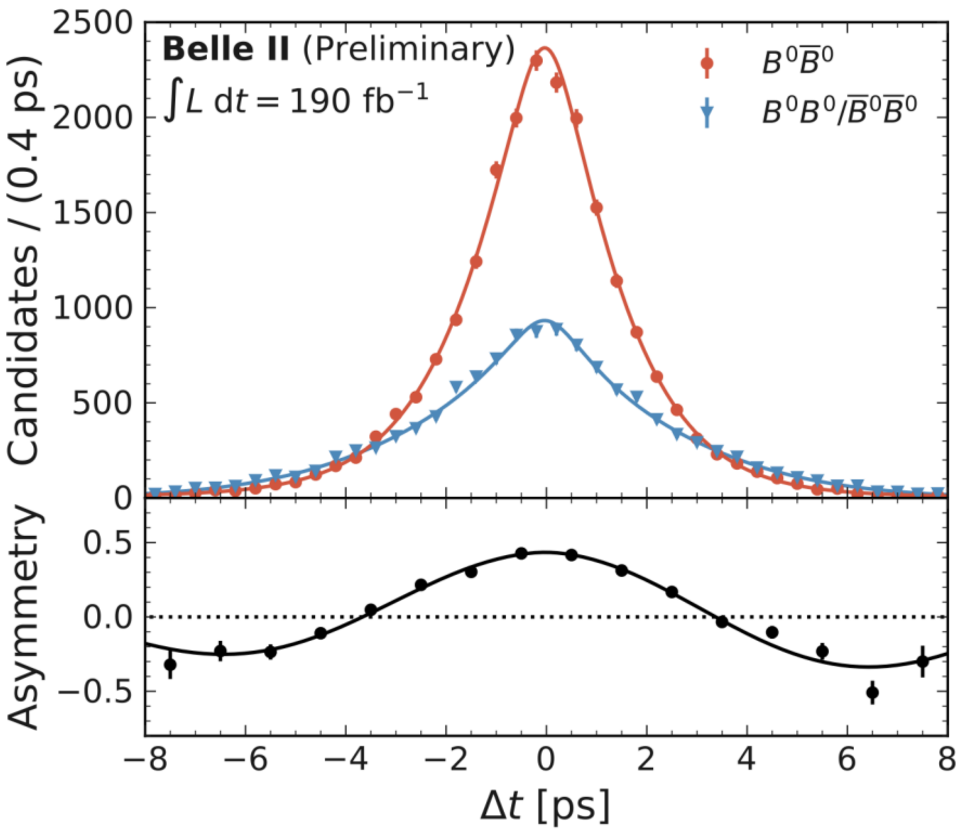




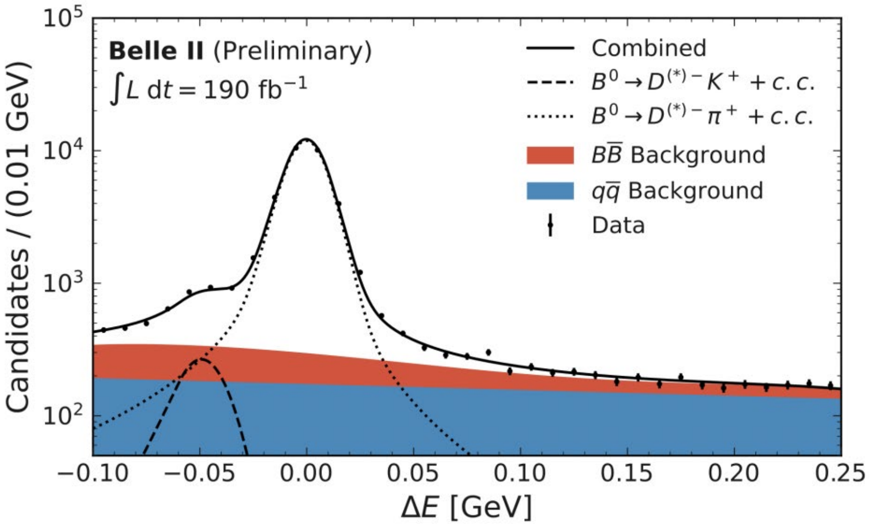




Time Dependent CPV and Mixing



- Belle II flavor tagging $\varepsilon_{eff} = (30.0 \pm 1.2 \pm 0.4)\%$ Eur. Phys. J. C 82, 283(2022) .
- The $190\ fb^{-1}$ sample was studied to extract B^0 lifetime and mixing frequency.
- 30k $B^0 \to D^{(*)-}h^+$ decays are used for this result.



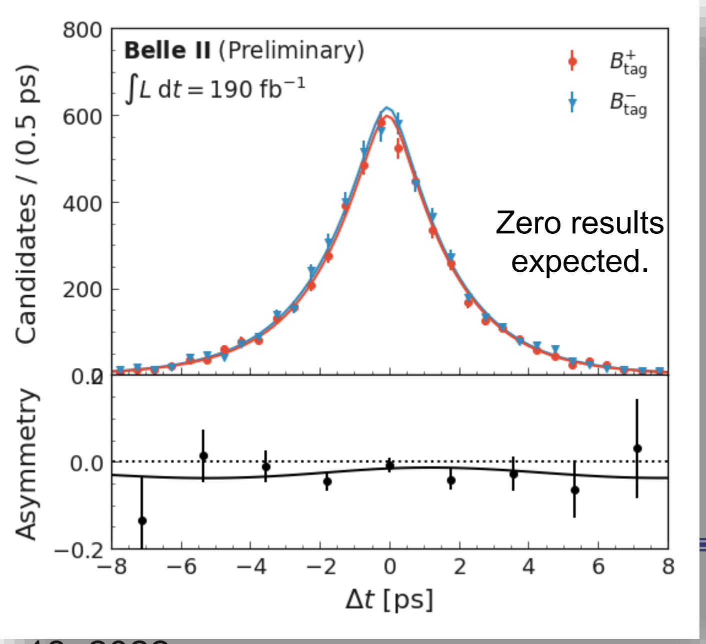
Belle II: $\tau_{B^0} = 1.499 \pm 0.013\,(stat) \pm 0.008\,(syst)$ ps W. A.: 1.510 ± 0.004 ps

Belle II: $\Delta m_d = 0.516 \pm 0.008\,(stat) \pm 0.005\,(syst)\ ps^{-1}$ W. A.: $0.50665 \pm 0.0019\ ps^{-1}$

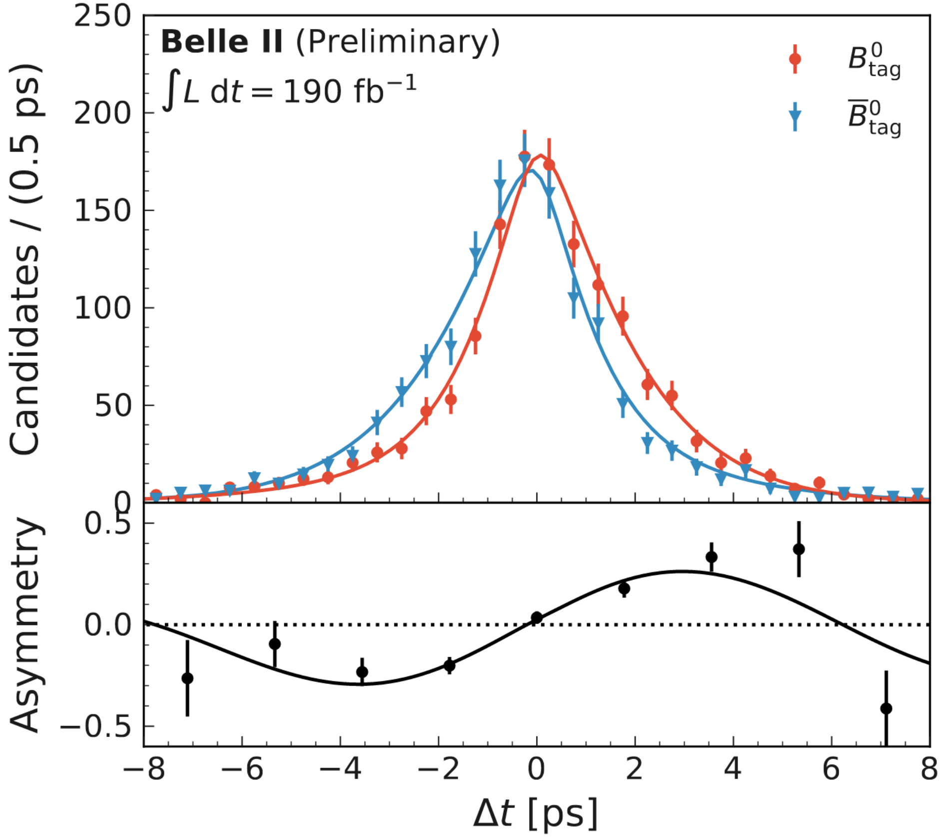
Next, Measure sin 2β

- Apply the strategy to the golden mode: $B^0 \to J/\psi\ K_S^0$. This tree mode should be precisely measured, to compare with the penguin decays.
- NP can appear in the penguin decays such as $B^0 \to K_S^0\ K_S^0\ K_S^0$.

$\sin 2\beta$ validation from $B^0 \to J/\psi K^+$



$\sin 2\beta$ results from $B^0 \to J/\psi K_S^0$



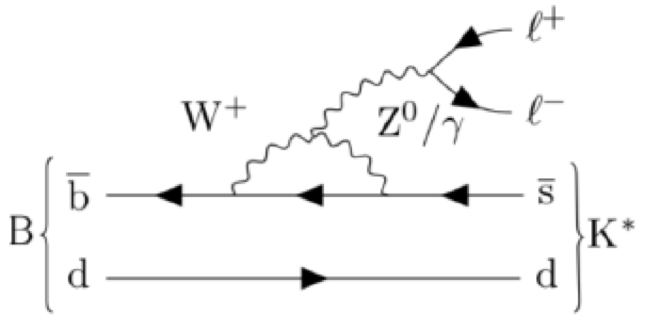
$$S_{CP}(\approx \sin 2\beta) = 0.720 \pm 0.062\ (stat) \pm 0.016\ (syst)$$

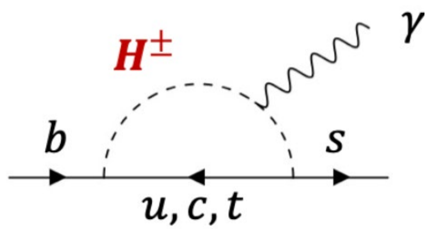
$$A_{CP} = 0.094 \pm 0.044\ (stat)^{+0.042}_{-0.017}\ (syst)$$

Rare B decays: Overview

- FCNC $b \to s$ transitions are suppressed in the SM. A good place to look for NP.
  - The 10 to 30% uncertainty in the SM BR (10^{-5} to 10^{-7}) can be supplemented by ratios, asymmetries, and angular distributions.
- A decay channel involving leptons is an excellent place to test LFU or LFV.
  - Belle II have similar detector performances between electron and muon.
- The results from the initial physics sample are shown here.

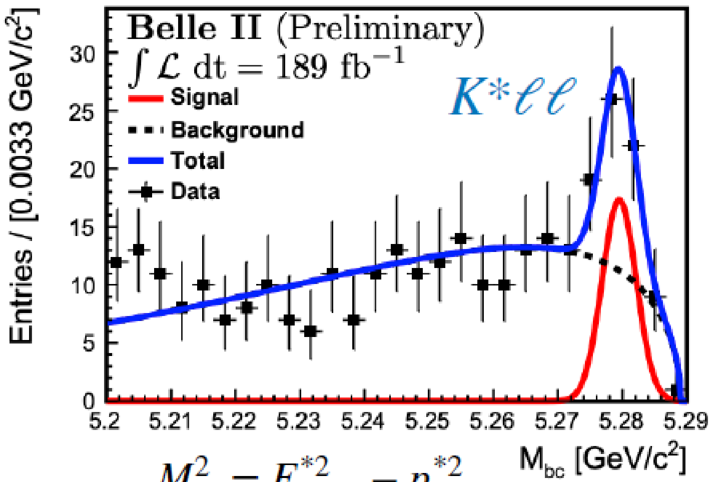
$B^+ \to K^* ll$



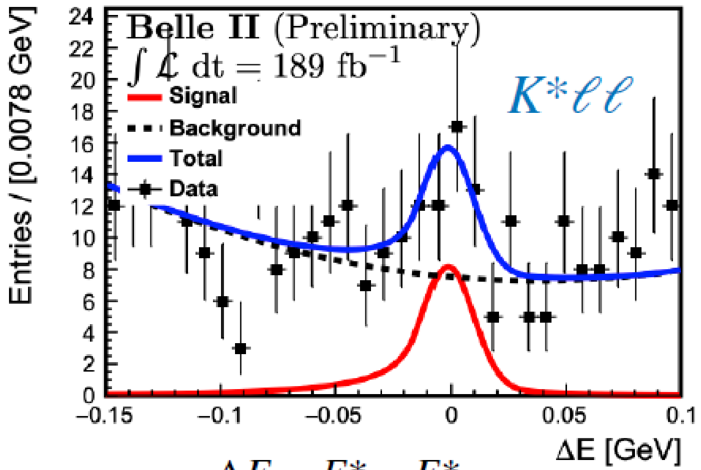


- R_{K^*} measurements have a 2-3 σ discrepancies between e and μ.
- The first Belle II report on $190\ fb^{-1}$ sample.
- Background suppressed by BDT, and veto on J/ψ, ψ(2S) mass.
- 2D fit to M_{bc} and ΔE.

Modes	Belle II	WA
$B \to K^* \mu^+\mu^-$	$(1.19 \pm 0.31^{+008}_{-0.07}) \times 10^{-6}$	$(1.06 \pm 0.09) \times 10^{-6}$
$B \to K^* e^+e^-$	$(1.42 \pm 0.48 \pm 0.09) \times 10^{-6}$	$(1.19 \pm 0.20) \times 10^{-6}$
$B \to K^* l^+l^-$	$(1.25 \pm 0.30^{+008}_{-0.07}) \times 10^{-6}$	$(1.05 \pm 0.10) \times 10^{-6}$



$M_{bc}^2 = E_{beam}^{*2} - p_B^{*2}$



$\Delta E = E_B^* - E_{beam}^*$

arXiv: 2206.05946

$B^+ \to K^+ \nu\bar{\nu}$ with Inclusive Tagging

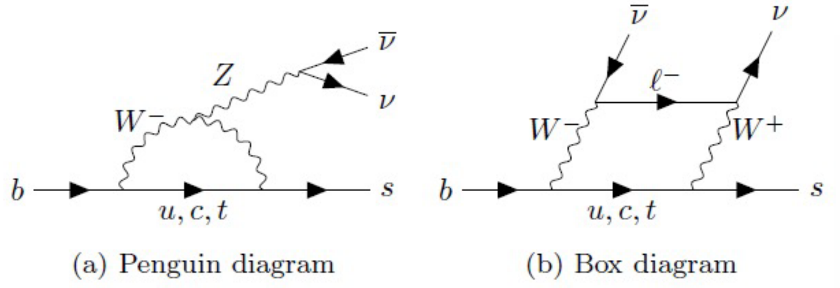
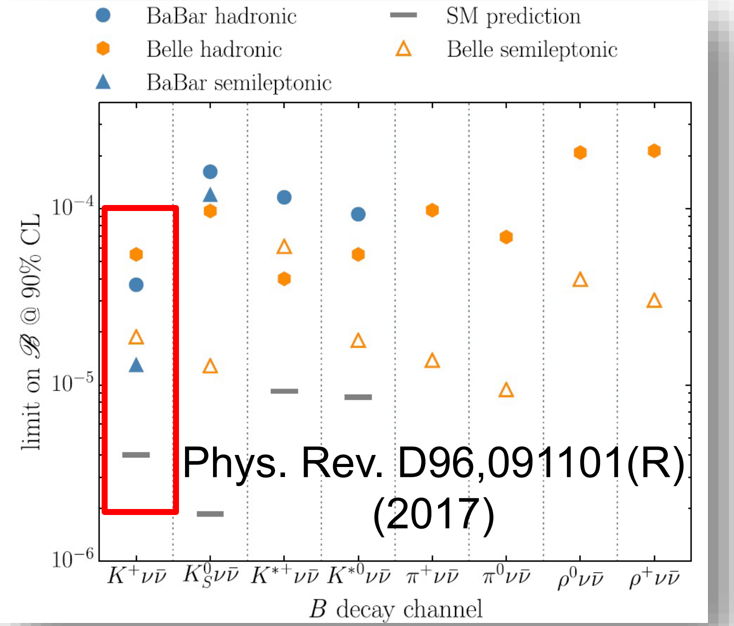
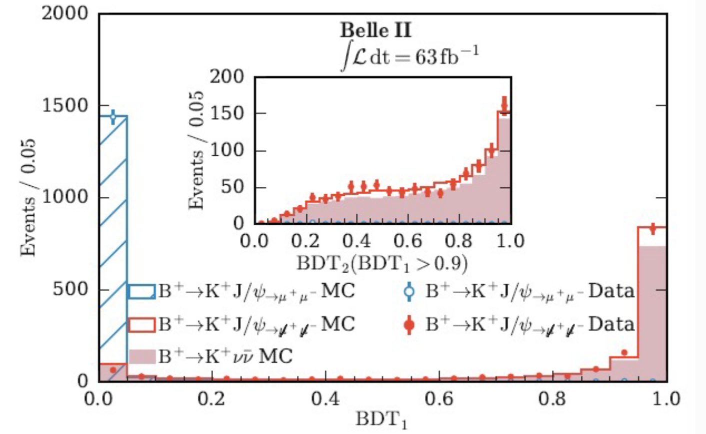
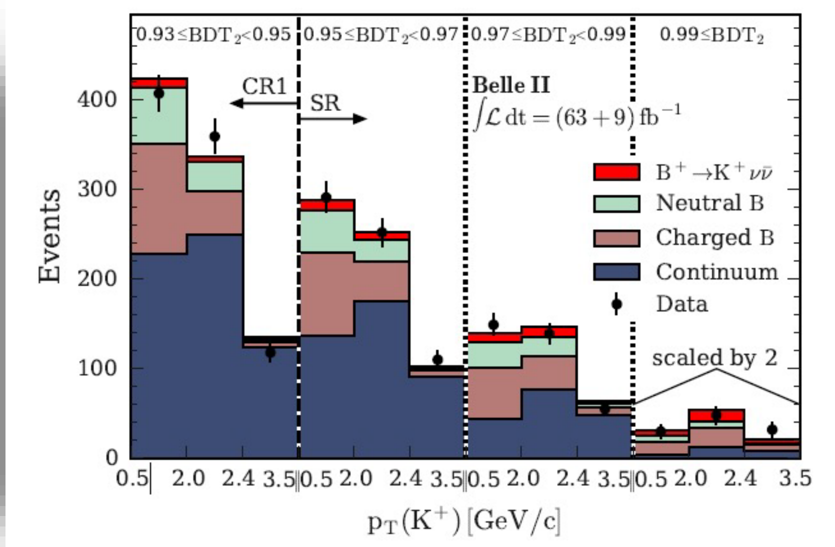


FIG. 1: Lowest-order quark-level diagrams for the $b \to s\nu\bar{\nu}$ transition in the SM.





Boosted Decision Tree Outputs



- The Belle II measurement at $63\ fb^{-1}$ is comparable to the previous Babar/Belle measurements.
- Next step: $424\ fb^{-1}$ sample, hadronic/semileptonic taggings, more channels (K*, K_S)

Babar	$< 1.6 \times 10^{-5}$ (90% C.L.)	Phys. Rev. D87,112005 (2013)
Belle	$< 1.9 \times 10^{-5}$ (90% C.L.)	Phys. Rev. D96,091101(R) (2017)
Belle II	$< 4.1 \times 10^{-5}$ (90% C.L.)	Phys. Rev. Lett. 127, 181802 (2021)

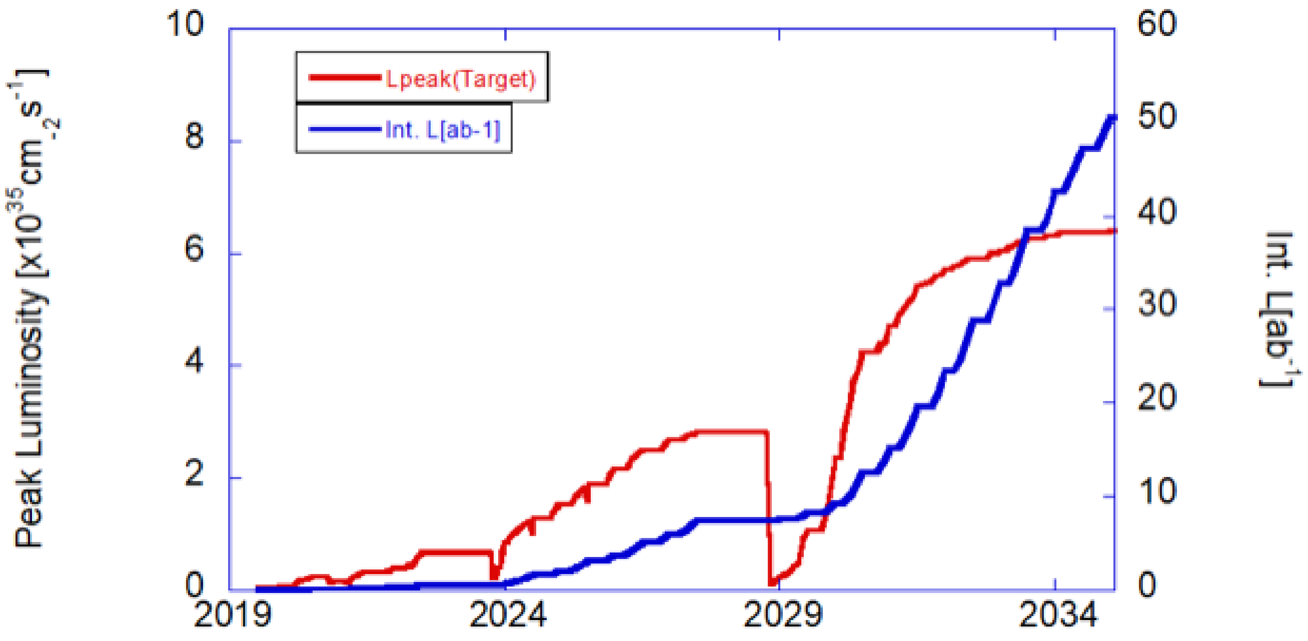
Summary I

- SuperKEKB has achieved $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the world record on June 22nd, 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

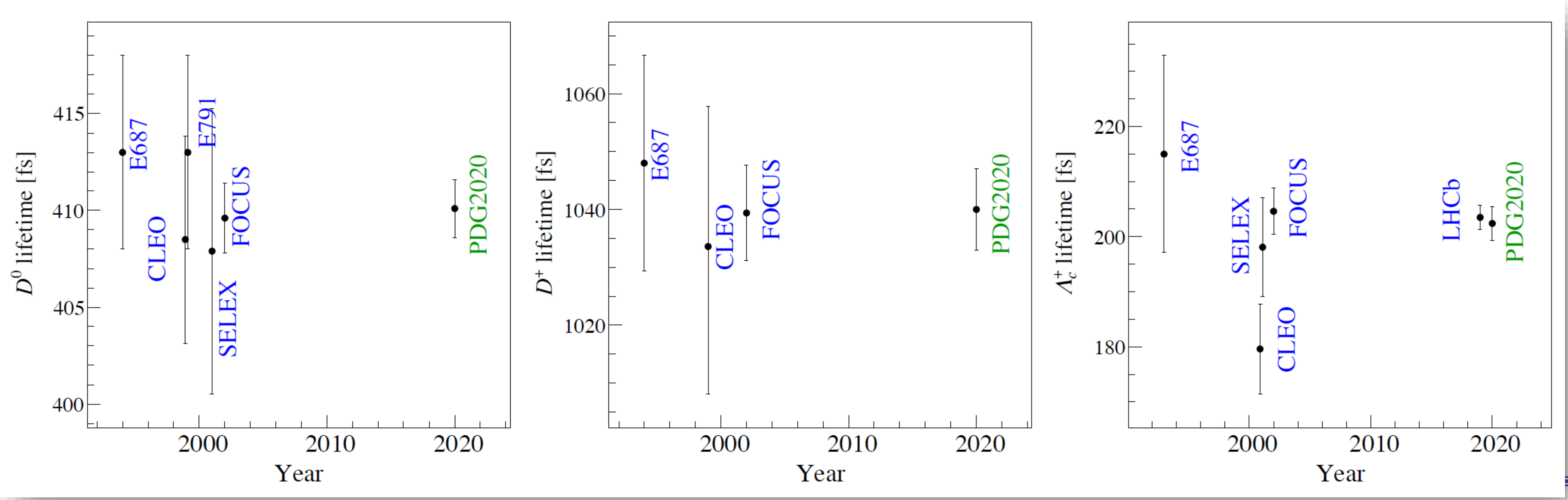
Belle II Experiment in a Nutshell

- 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.



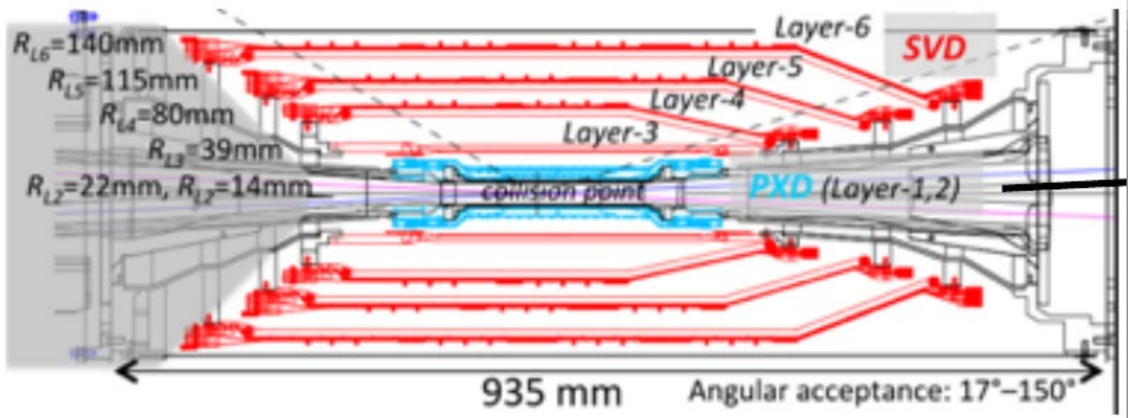
Belle II Vertex Detector

Inner most vertex detector consists of

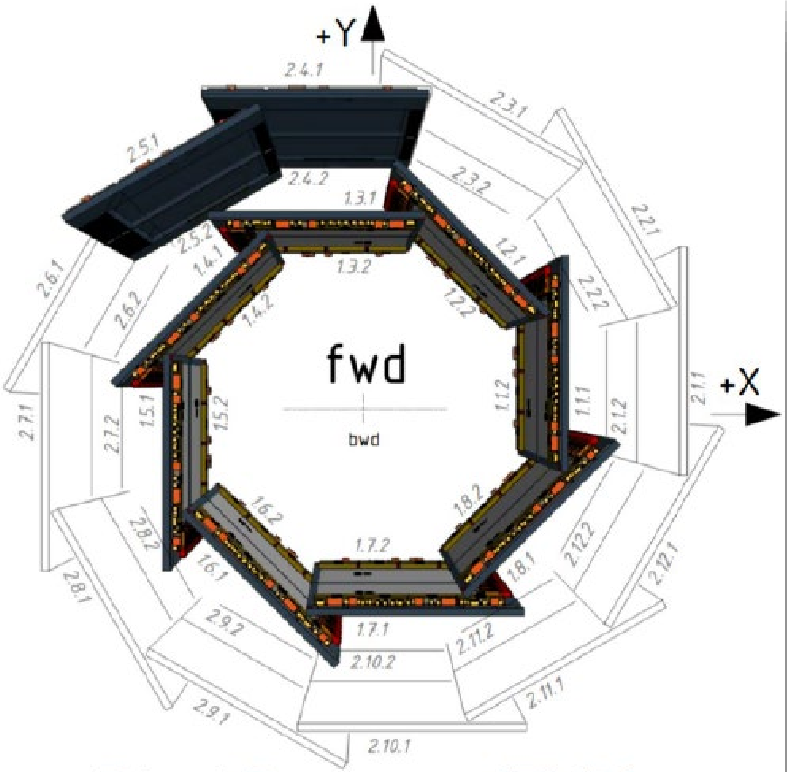
- 1 DEPFET layer (2nd layer will be completed in 2023) and 4 DSSD layers
- Resulting in two times better vertex resolution, improved efficiency for slow pions and Ks's, and better tracking against beam backgrounds w.r.t. Belle.

Alignment is crucial for lifetime measurements.

- Checked thoroughly during analysis.



Silicon Vertex Detector (SVD)



Pixel Detector (PXD)