

Belle II Highlights

Doris Yangsoo Kim
on behalf of the Belle II collaboration

August 8, 2023

30th Anniversary of the Rencontres du Vietnam:
Windows on the Universe
ICESE, Quy Nhon, Vietnam



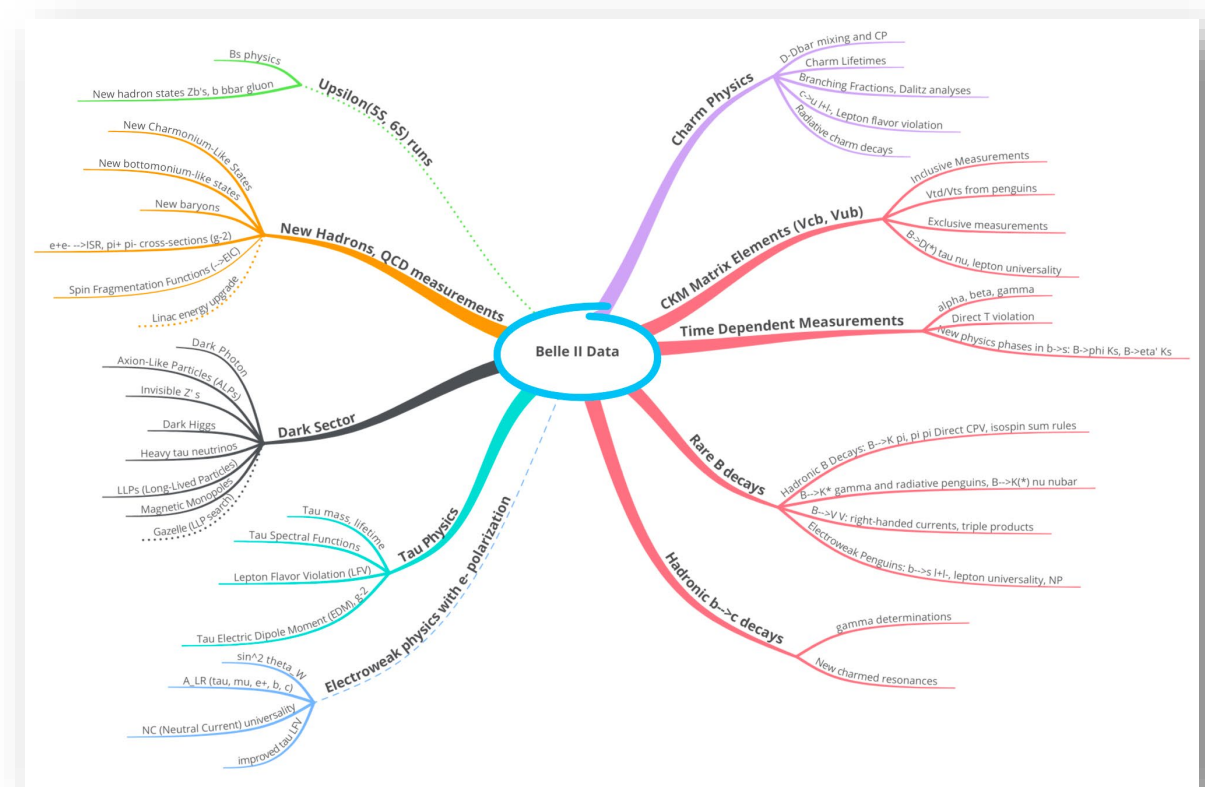
Belle II Experiment in a Nutshell

- 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.

Belle II Physics Prospects

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

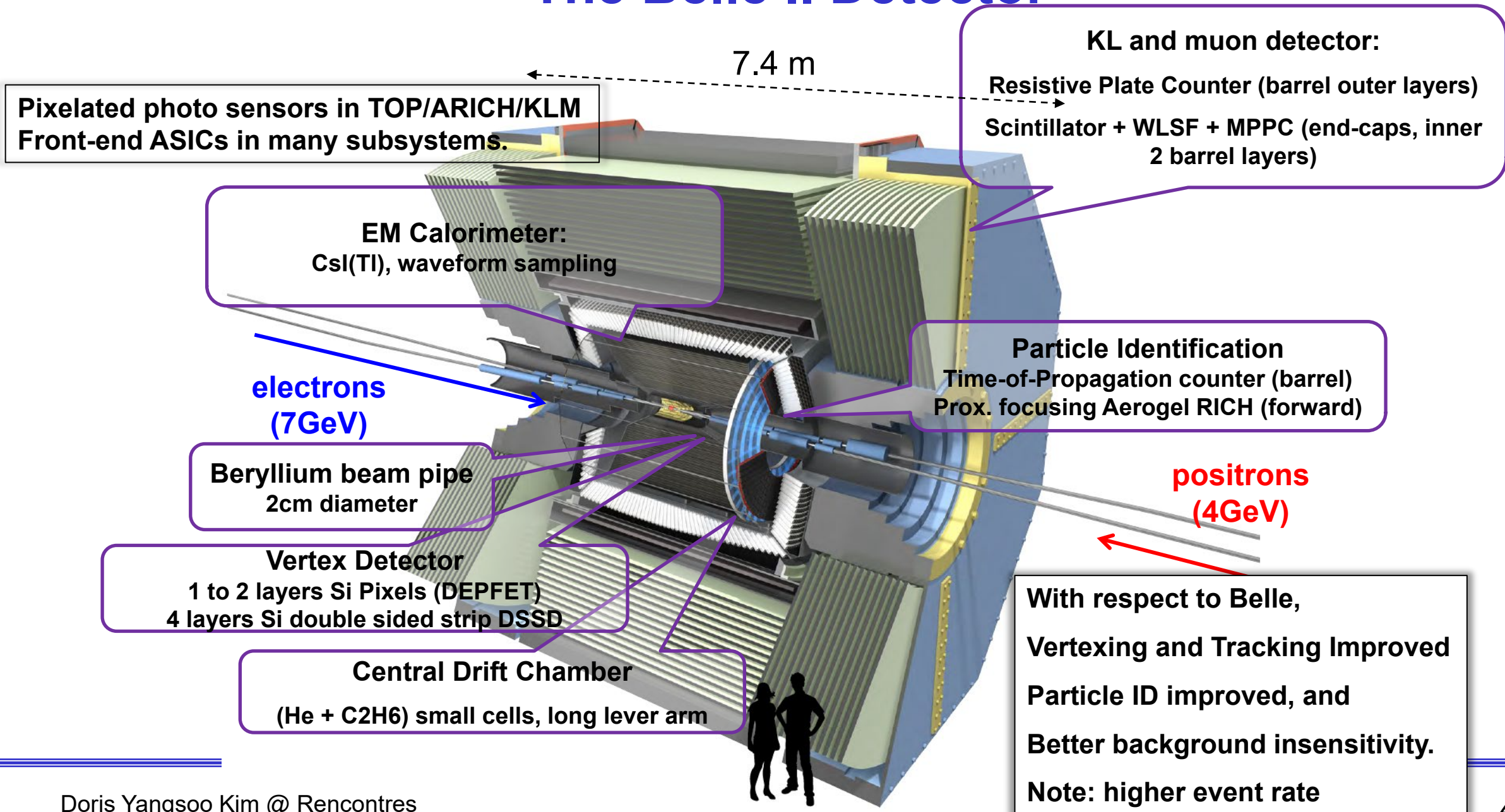
- Charm decays
- Next precision CKM matrix
 - Semileptonic B decays (CKM elements)
 - Hadronic B decays (angles and CPV)
 - Time dependent CP violation
- τ physics
- Hadron spectroscopy
- Rare decays, FCNC
- New physics
 - Lepton flavor violation
 - Dark sector, long lived particles



Belle II Physics Book, PTEP 2019, 123C01

Paolo Rocchetti, Today, Parallel Session
Recent Belle II results related to flavor anomalies

The Belle II Detector

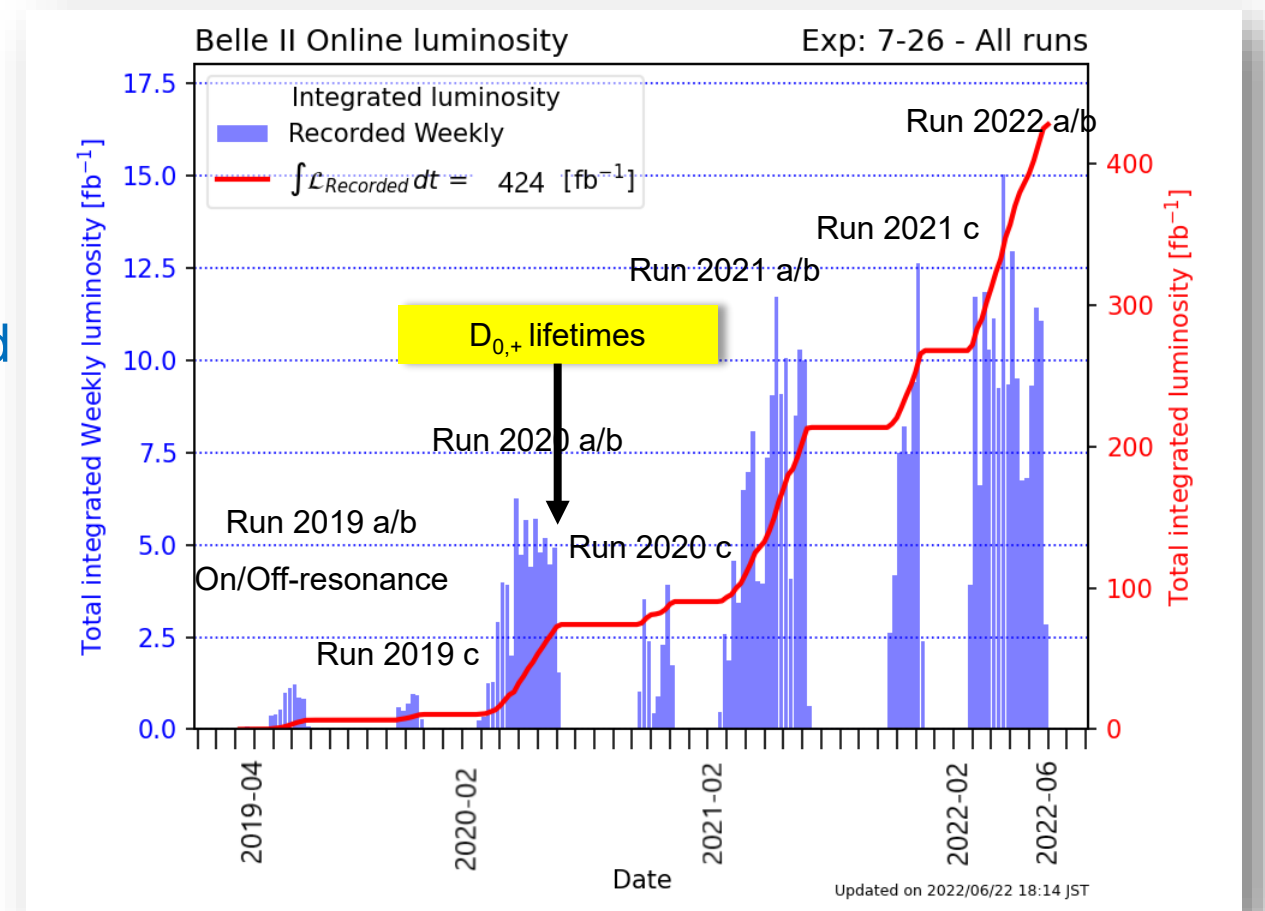


The Belle II Collaboration



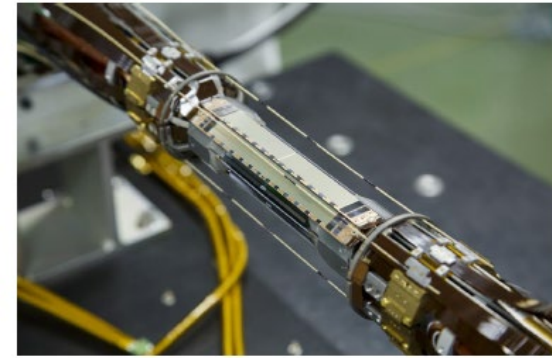
SuperKEKB Luminosity: Current Status

- After the SuperKEKB commission phases, physics runs started spring 2019.
- Spring/summer 2022 run ended June.
 - Peak luminosity at $L_{peak} = 4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, the current world record on June 22nd.
 - Current integrated luminosity at $\int L_{recorded} dt = 424 \text{ fb}^{-1}$. (~ Babar, ~ 1/2 Belle)
- Long shutdown 1 (LS1) started 2022 summer for upgrades (see later slides).
- Run 2 starts coming fall/winter.



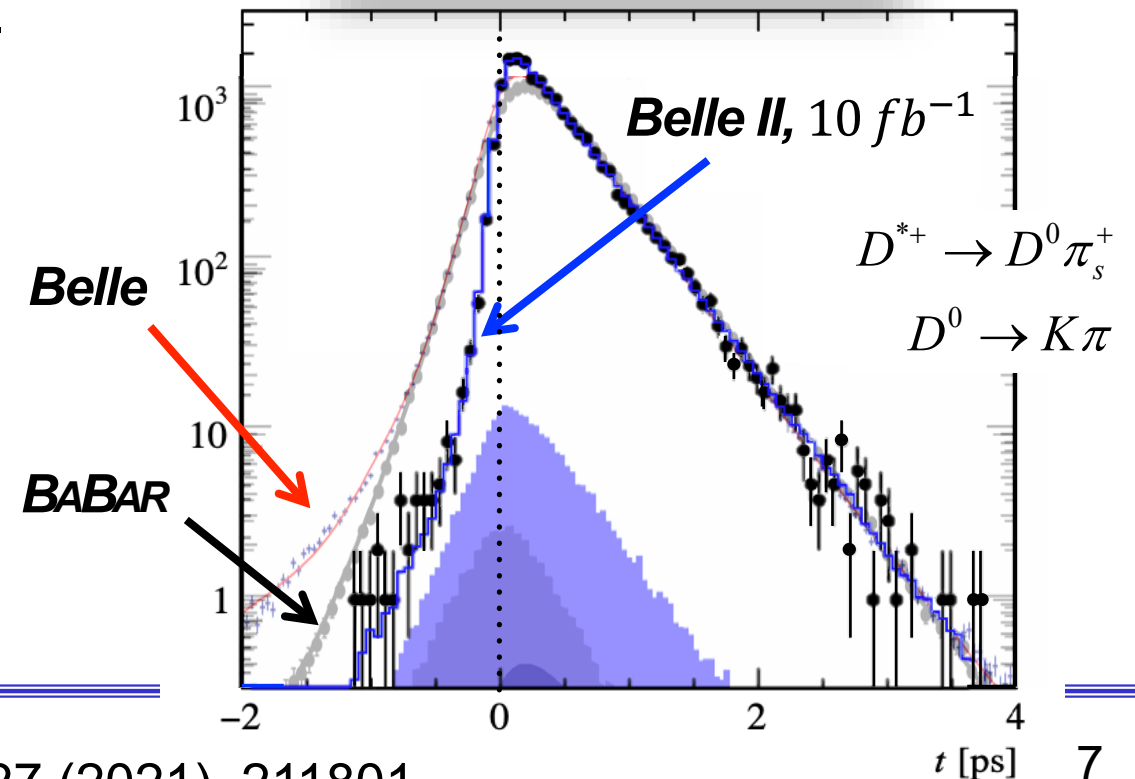
Charm Particle Lifetime

- 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.
- At SuperKEKB, $\sigma_{c\bar{c}} \sim \sigma_{b\bar{b}}$. Large charm sample.
- $e^+ e^-$ collision gives clean environment. Less bias.
- Small interaction region and the new Belle II vertex detector give strong constraints and better resolutions.
 - Amount of $t < 0$: detector resolution
- A great opportunity to measure the world best charm lifetimes.

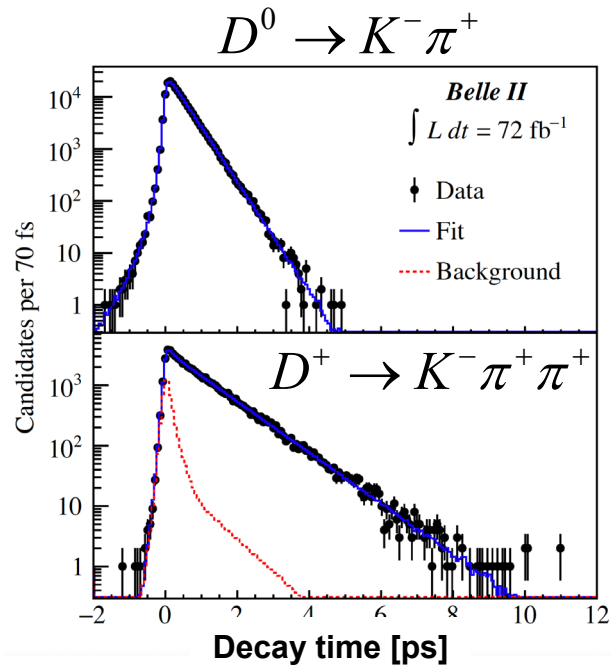


Pixel detector radius ≈ 1.4 cm

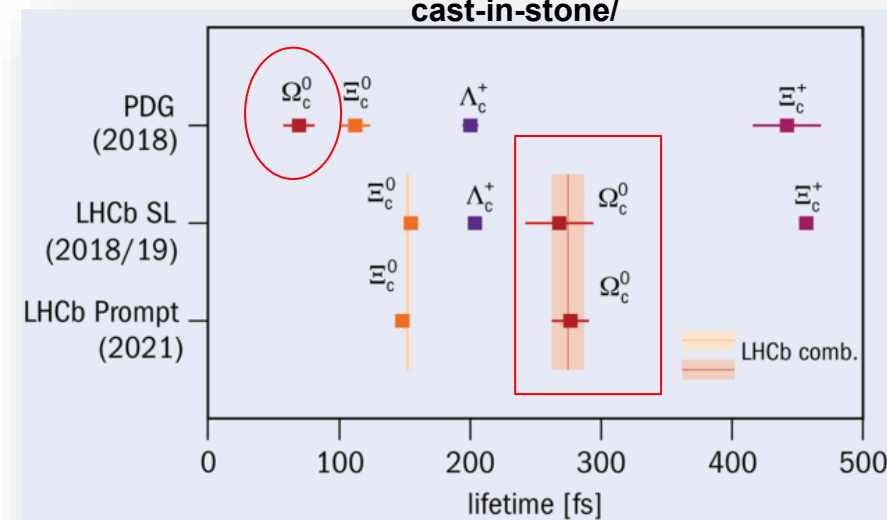
**PXD
v1**



$D^0, D^+, D_s^+, \Lambda_c^+, \Omega_c^0$ Lifetimes



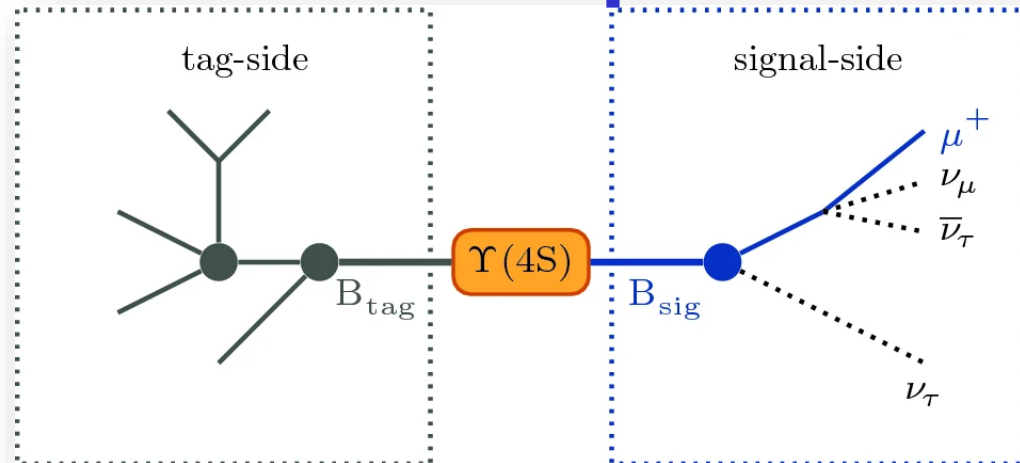
<https://cerncourier.com/a/new-charmed-baryon-lifetime-hierarchy-cast-in-stone/>



Belle II Ω_c^0 lifetime measurement confirms the LHCb result.

Mode	Belle II (fs)	Size	Previous WA (fs)	Ref.
D^0	$410.5 \pm 1.1 \pm 0.8$	72 fb^{-1}	410.1 ± 1.5	<u>Phys. Rev. Lett. 127 (2021), 211801</u>
D^+	$1030.4 \pm 4.7 \pm 3.1$		1040 ± 7	
D_s^+	$498.7 \pm 1.7^{+1.1}_{-0.8}$	207 fb^{-1}	504 ± 4	<u>arXiv: 2306.00365</u>
Λ_c^+	$203.2 \pm 0.9 \pm 0.8$		202.4 ± 3.1	<u>Phys. Rev. Lett. 130 (2023), 071802</u>
Ω_c^0	$243 \pm 48 \pm 11$		$268 \pm 24 \pm 10$ LHCb 69 ± 12 pre-LHCb	<u>Phys. Rev. D 127 (2023), L031103</u>

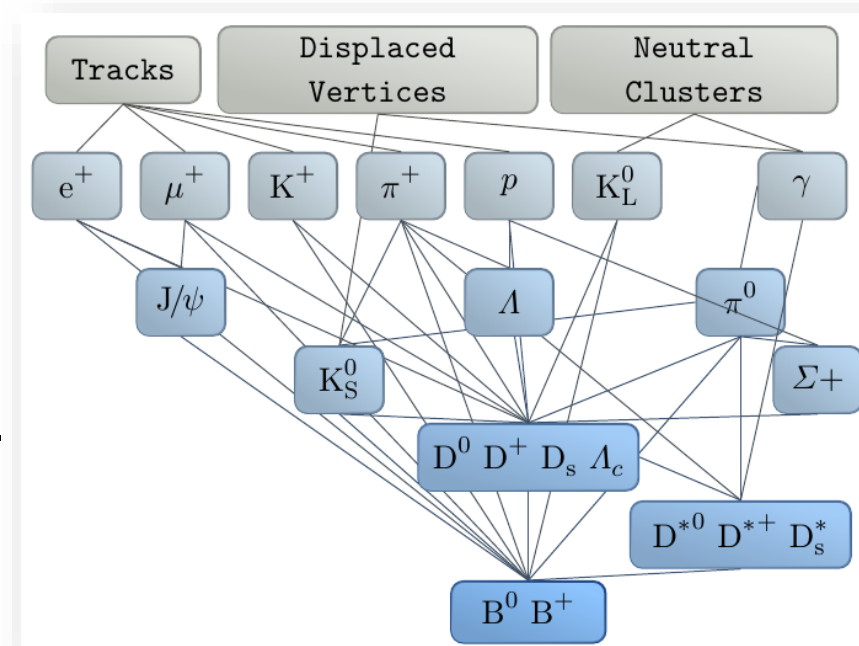
Full Event Interpretation for $B\bar{B}$ Reconstruction



- Traditionally, at Upsilon(4s), one B (tag) is reconstructed first. The rest of the event is considered as a signal B.
 - B flavor tagging (page 11)
- An improved tool (FEI) was 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: $\varepsilon_{\text{had}} \approx 0.5\%$ and $\varepsilon_{\text{SL}} \approx 2\%$
 - ex) Paolo Rocchetti's talk. This talk page 13.



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

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 New Physics searches.
 - Use semi-leptonic, leptonic decays of mesons.

Prog. Theor. Exp. Phys. 2022 083C01 (2022)
aka PDG 2022

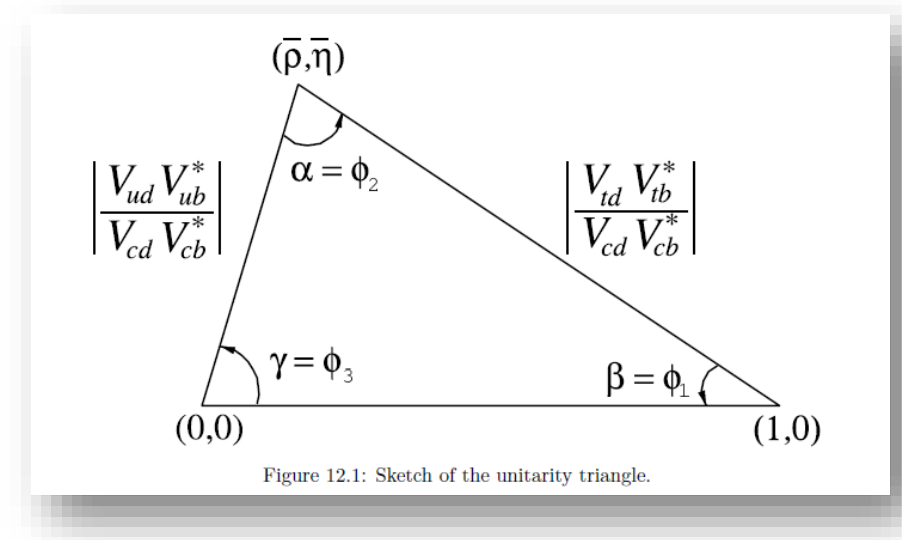
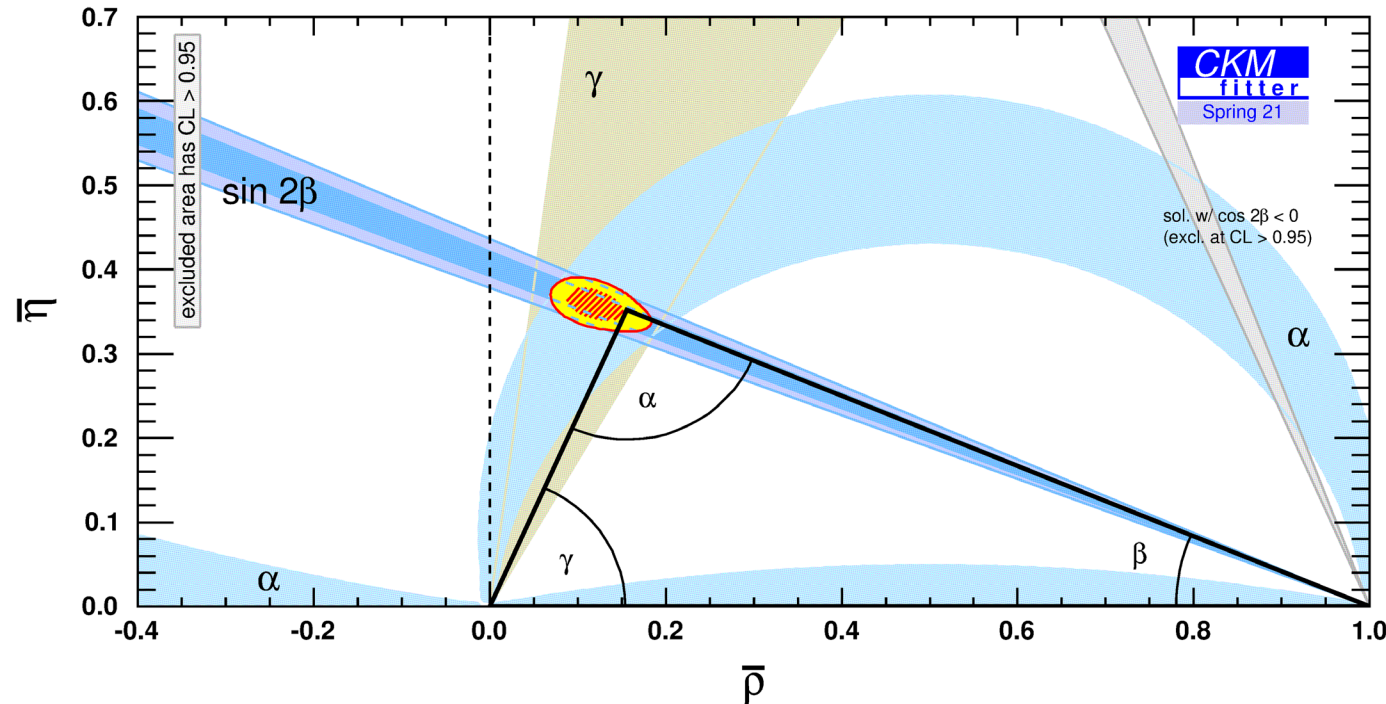
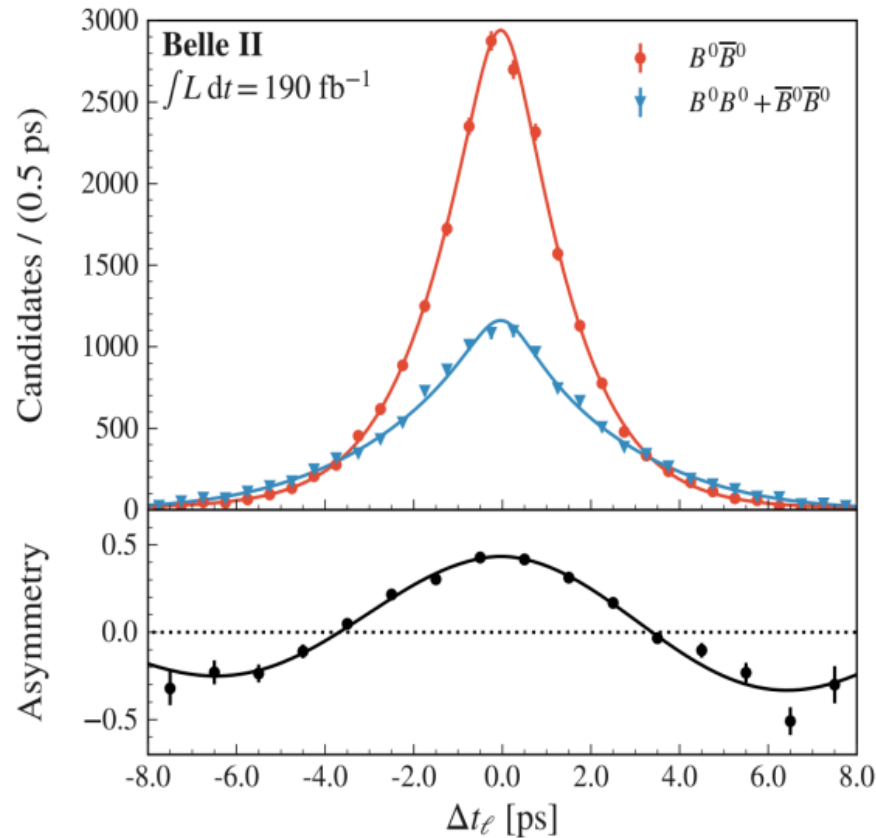
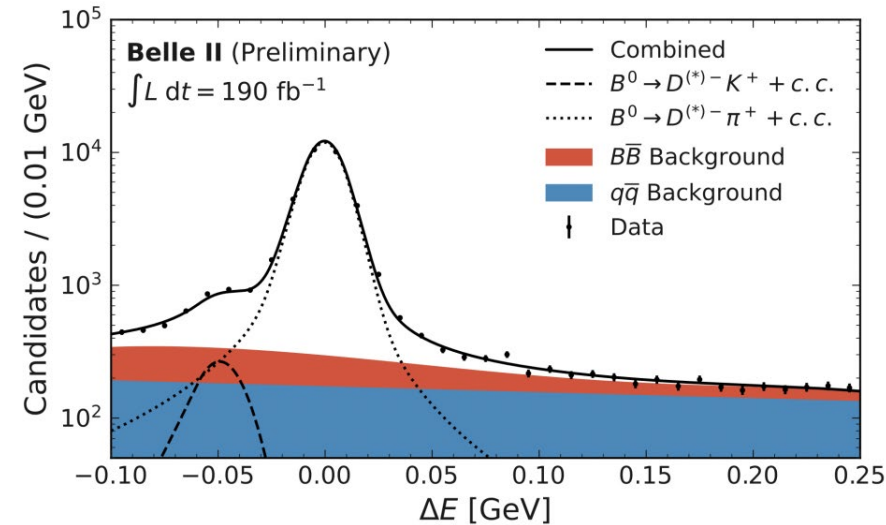


Figure 12.1: Sketch of the unitarity triangle.

Time Dependent CPV and Mixing in B physics



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



Belle II: $\tau_{B^0} = 1.499 \pm 0.013 \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ ps}$

W. A.: $1.510 \pm 0.004 \text{ ps}$

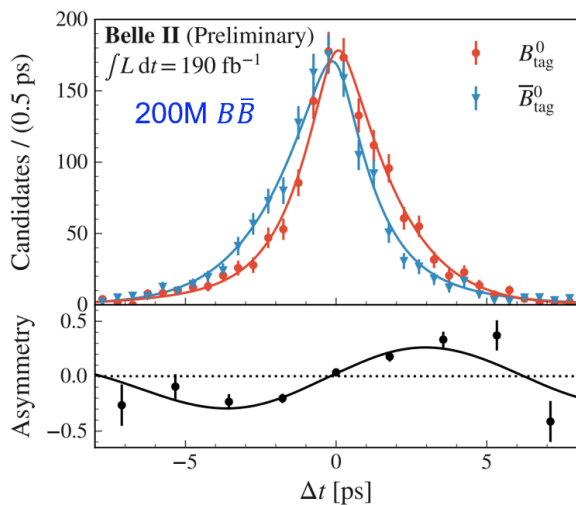
Belle II: $\Delta m_d = 0.516 \pm 0.008 \text{ (stat)} \pm 0.005 \text{ (syst)} \text{ ps}^{-1}$

W. A.: $0.50665 \pm 0.0019 \text{ ps}^{-1}$

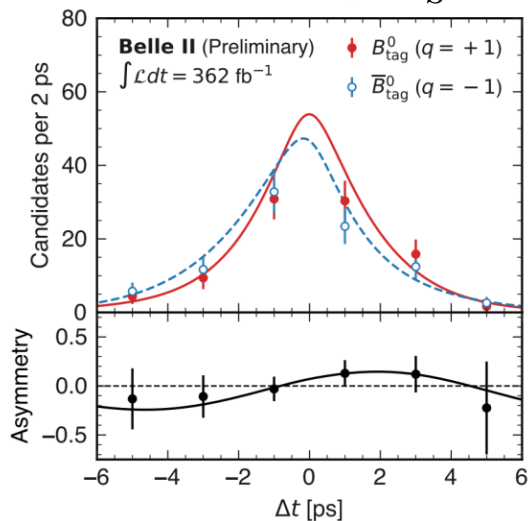
Next, $\sin 2\beta$

Proper time differences

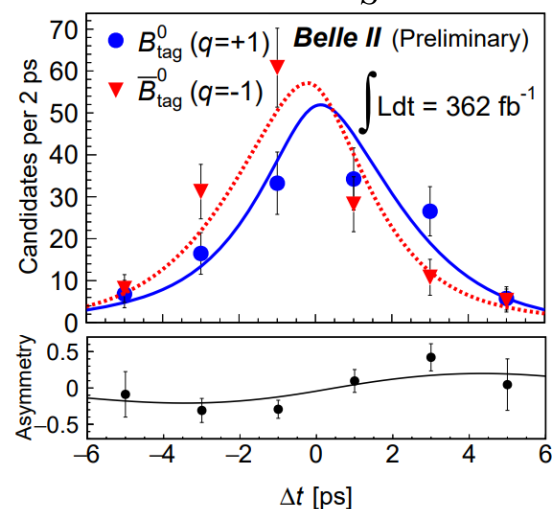
$$B^0 \rightarrow J/\psi K_S^0$$



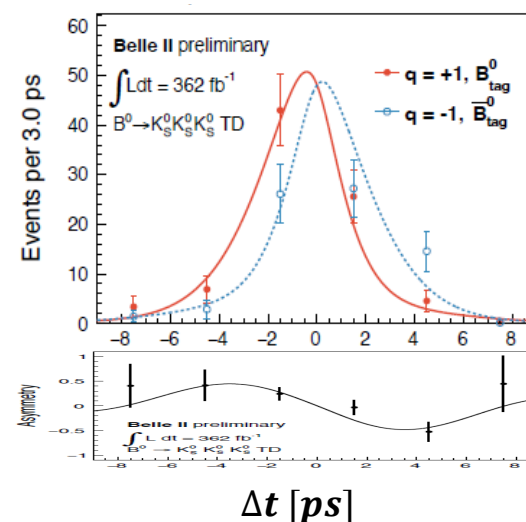
$$B^0 \rightarrow \phi K_S^0$$



$$B^0 \rightarrow K_S^0 \pi^0$$



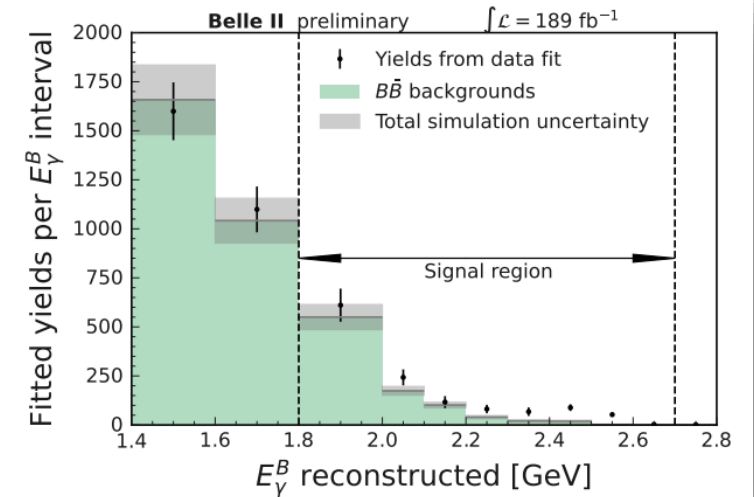
$$B^0 \rightarrow K_S^0 K_S^0 K_S^0$$



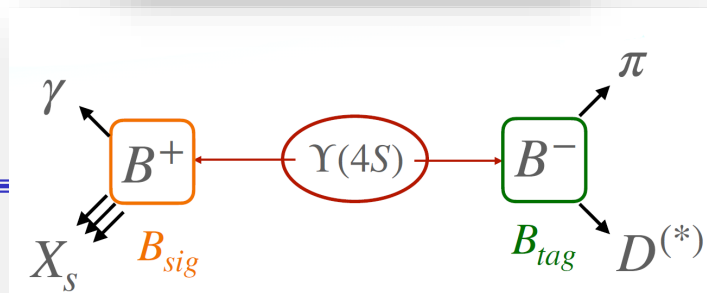
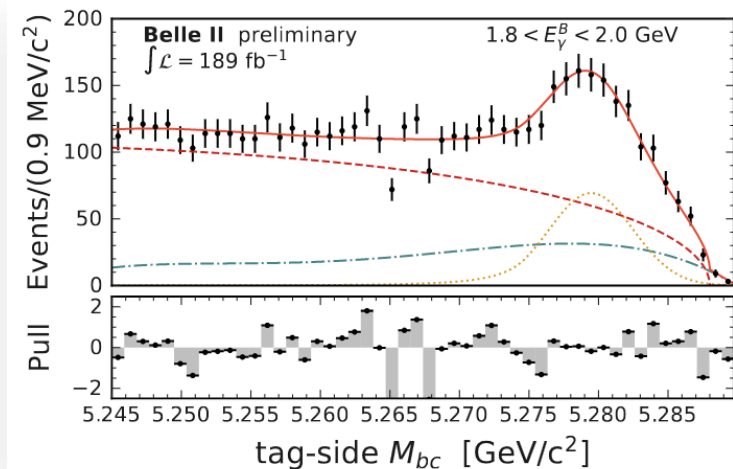
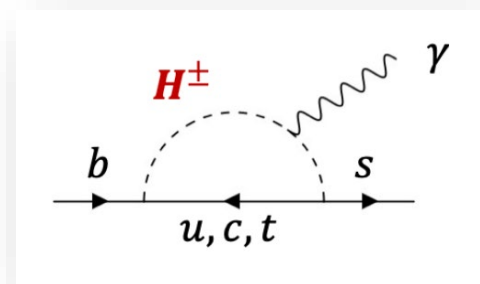
Type	Mode	$\sin 2\beta = S$	$A_{CP} = -C$	Ref.
$b \rightarrow c\bar{c}s$	$B^0 \rightarrow J/\psi K_S^0$	$0.720 \pm 0.062 \pm 0.016$	$0.094 \pm 0.044^{+0.042}_{-0.017}$	arXiv:2302.12898
$b \rightarrow s\bar{s}s$	$B^0 \rightarrow \phi K_S^0$	$0.54 \pm 0.25^{+0.06}_{-0.08}$	$0.31 \pm 0.20 \pm 0.05$	arXiv:2307.02802
$b \rightarrow d\bar{d}s$	$B^0 \rightarrow K_S^0 \pi^0$	$0.75^{+0.20}_{-0.23} \pm 0.04$	$0.04^{+0.15}_{-0.14} \pm 0.05$	arXiv:2305.07555
$b \rightarrow d\bar{d}s$	$B^0 \rightarrow K_S^0 K_S^0 K_S^0$	$-1.37^{+0.35}_{-0.45} \pm 0.03$	$0.07^{+0.15}_{-0.20} \pm 0.02$	Moriond 2023, arXiv:2209.09547

Fully Inclusive $B \rightarrow X_s \gamma$

- An effective way to search for NP in $b \rightarrow s \gamma$ channel. FCNC forbidden at tree level SM.
- 189 fb^{-1} sample fitted in bins of E_γ^B (photon energy in B_{sig} rest frame) simultaneous with B_{tag} mass
- FEI used. Tag side is B hadronic decays
- Signal photon background veto from π^0 and η . Further suppression by a BDT classifier. X_s candidate is isolated.
- Though efficiency is low at $< 1\%$.



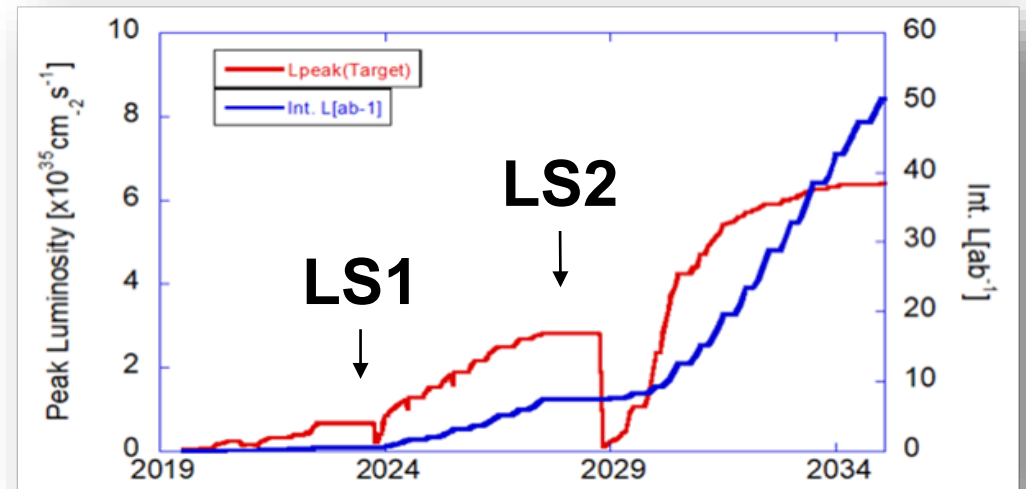
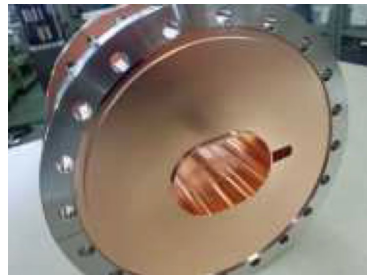
E_γ^B threshold (GeV)	$\mathcal{B}(B \rightarrow X_s \gamma)$ (10^{-4})
1.8	$3.54 \pm 0.78 \pm 0.83$
2.0	$3.06 \pm 0.56 \pm 0.47$
2.1	$2.49 \pm 0.46 \pm 0.35$



$$M_{bc} = \sqrt{(s/2)^2 - p_{tag}^2}$$

SuperKEKB Upgrade during LS1

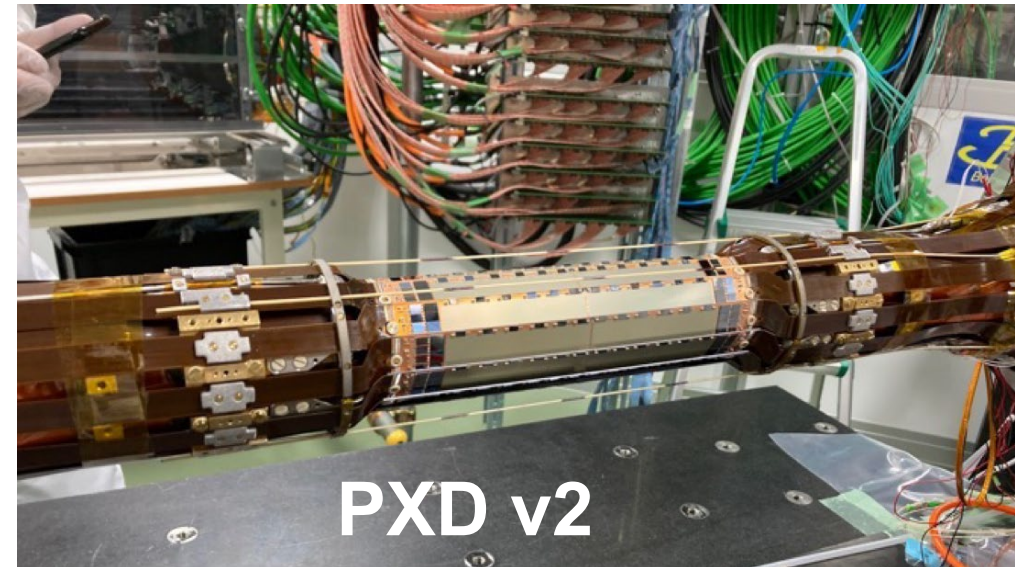
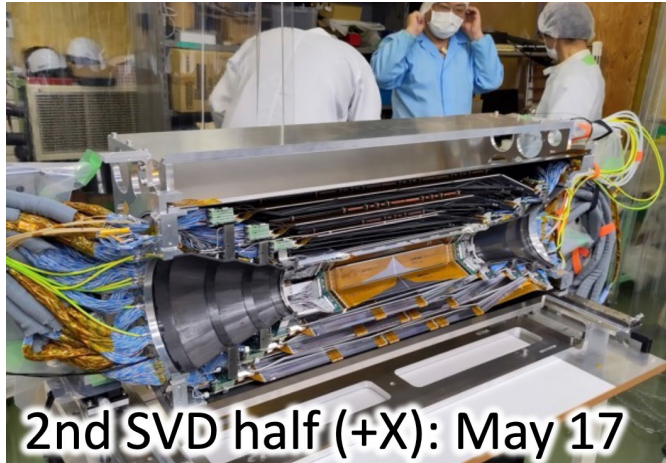
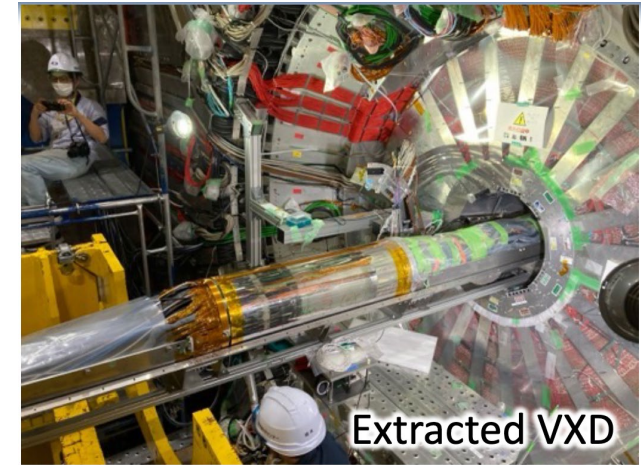
- The sudden beam loss mitigation strategy.
- Reducing beamline neutrons by additional shielding around final-focus magnets and endcaps
- Collimators: harder material, non-linear to decrease beam halo
- For stability and increase in currents, RF cavity being replaced.
- Injector area: faster kicker magnet, new focusing magnet, new large-aperture beam pipe



For LS2 plan, LP 2023 talk
by L. Pilonen

Belle II Upgrade during LS1

- One layer → two layer pixel detector (PXD)
- TOP PMT replaced for increased lifespan and robustness
- DAQ upgrade to PCIe40
- Improved gas distribution, gain stability, and monitoring for drift chamber



Summary

- 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 published world leading results in charm lifetime. D lifetime full set!
 - More updates are coming with the $424 fb^{-1}$ sample.
- Belle II started producing results on many interesting physics from B and other sectors.
 - Only a few selected topics are shown here.
 - Detailed reports at Moriond 2023, LP 2023
 - For published and submitted papers,
<https://confluence.desy.de/display/BI/Journal+Publications>
- This is a very exciting time to do flavor physics, looking for physics beyond the Standard Model.