Belle II Highlights

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on behalf of the Belle II collaboration

August 8, 2023

30th Anniversary of the Rencontres du Vietnam:
Windows on the Universe

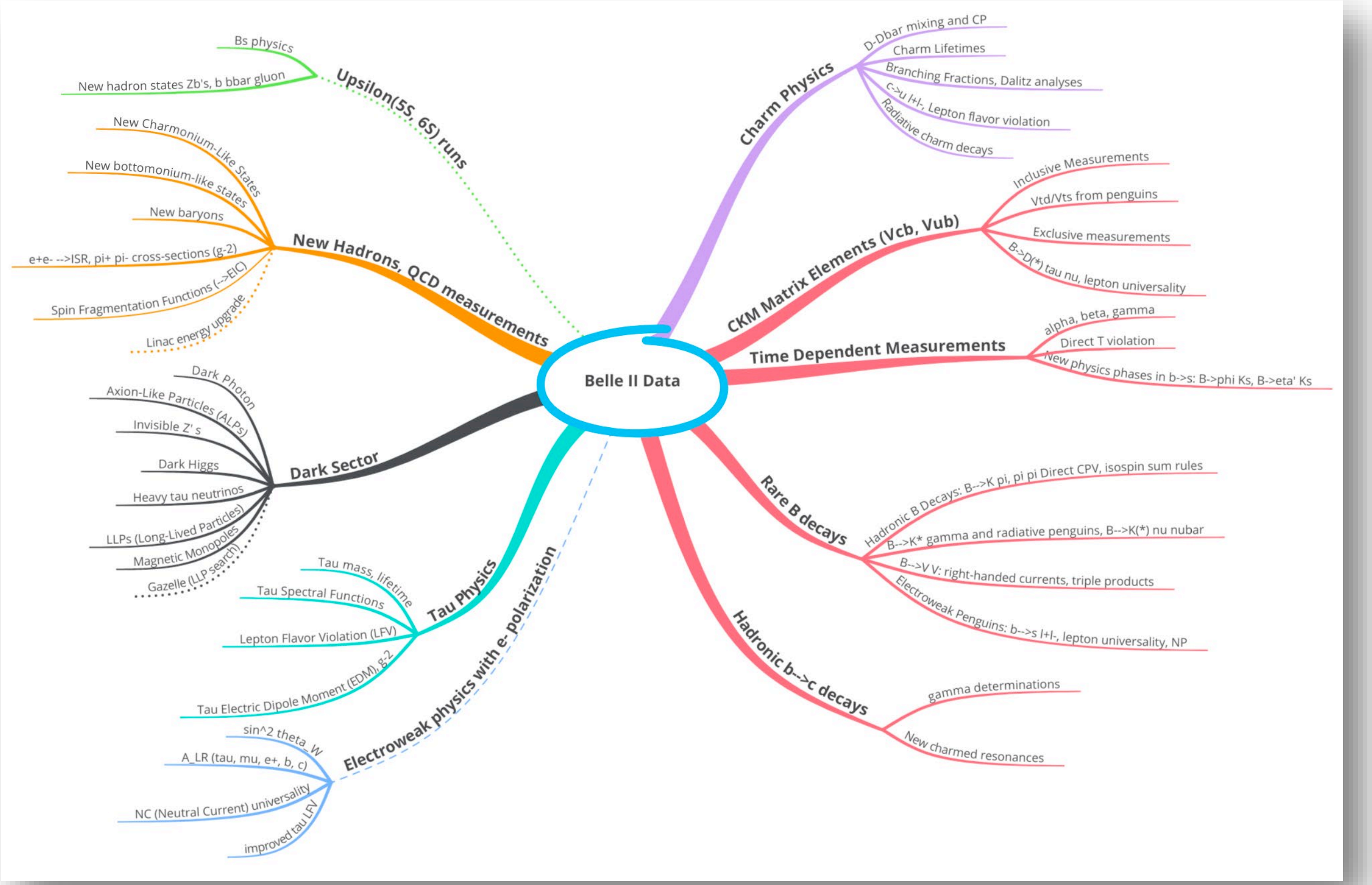
ICESE, Quy Nhon, Vietnam

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

- 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



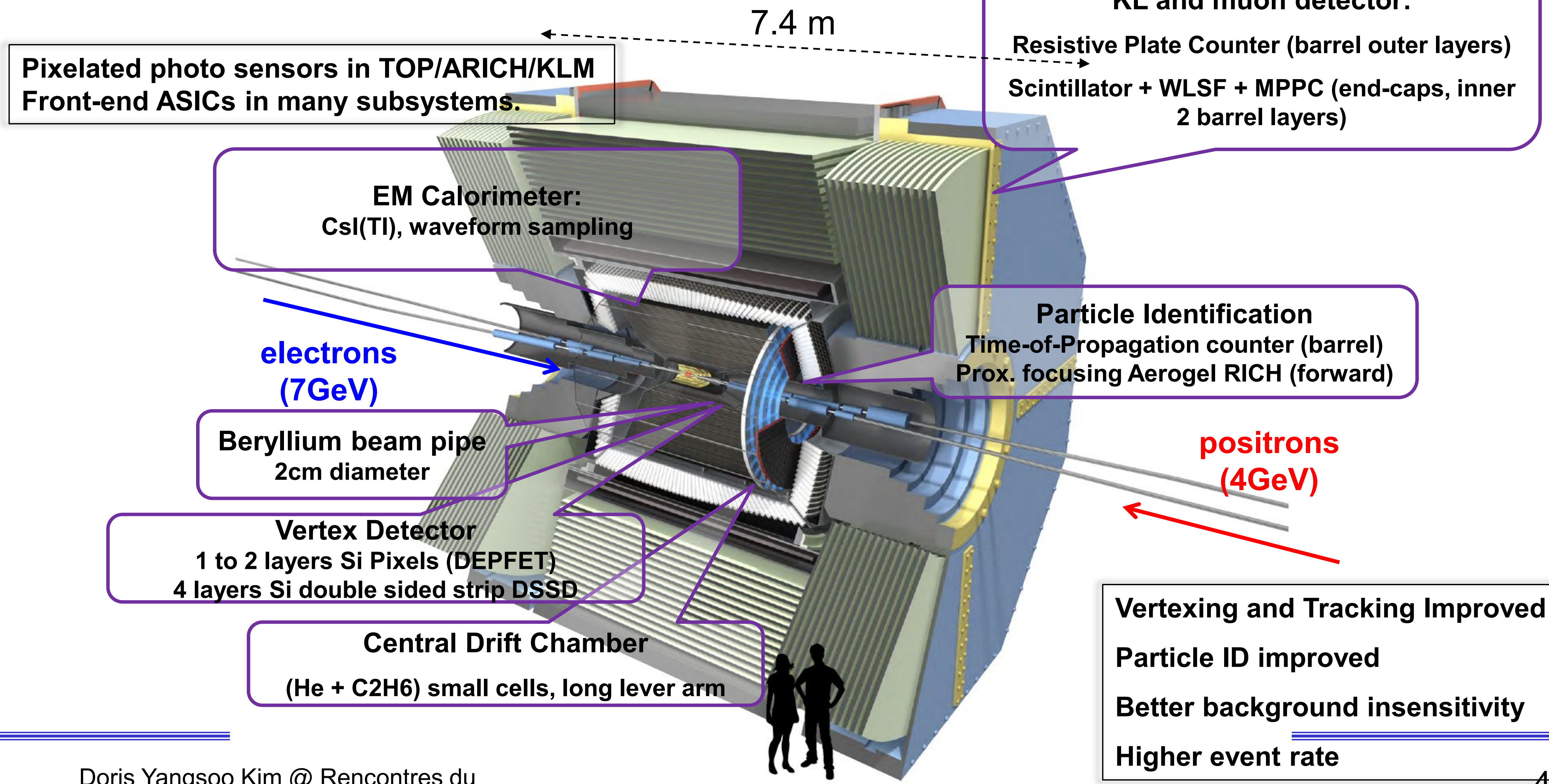
https://confluence.desy.de/display/BI/Snowmass+2021

Paolo Rocchetti, Today, Parallel Session

Recent Belle II results related to flavor anomalies

Belle II Physics Book, PTEP 2019, 123C01

The Belle II Detector



Vertexing and Tracking Improved

Particle ID improved

Better background insensitivity

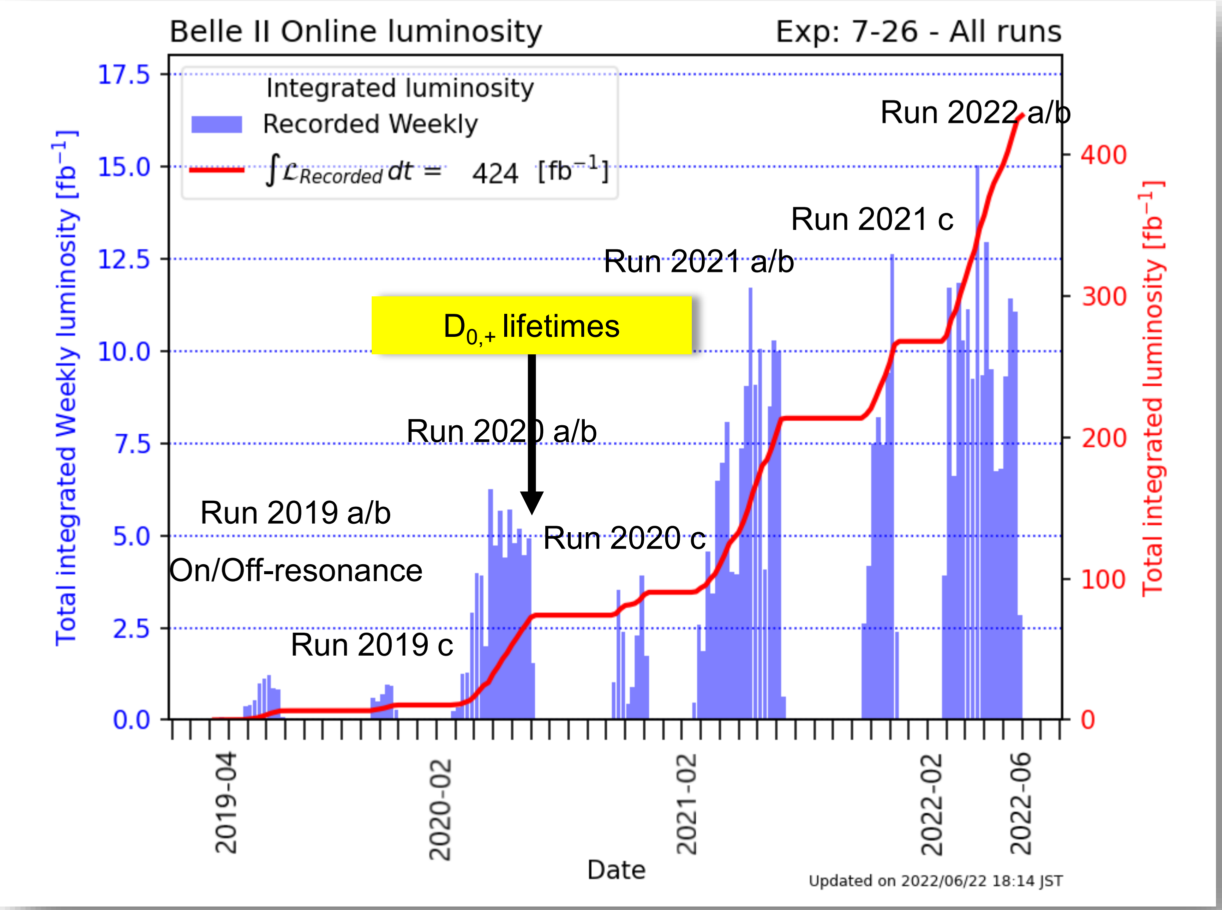
Higher event rate

The Belle II Collaboration

- As of July 2023, approximately
- 1,100 members, 120 institutes, 27 countries

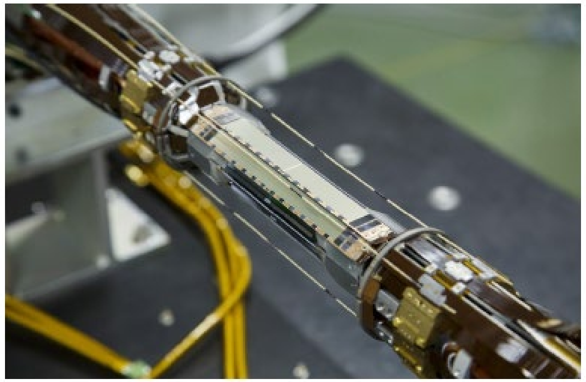
SuperKEKB Luminosity: Current Status

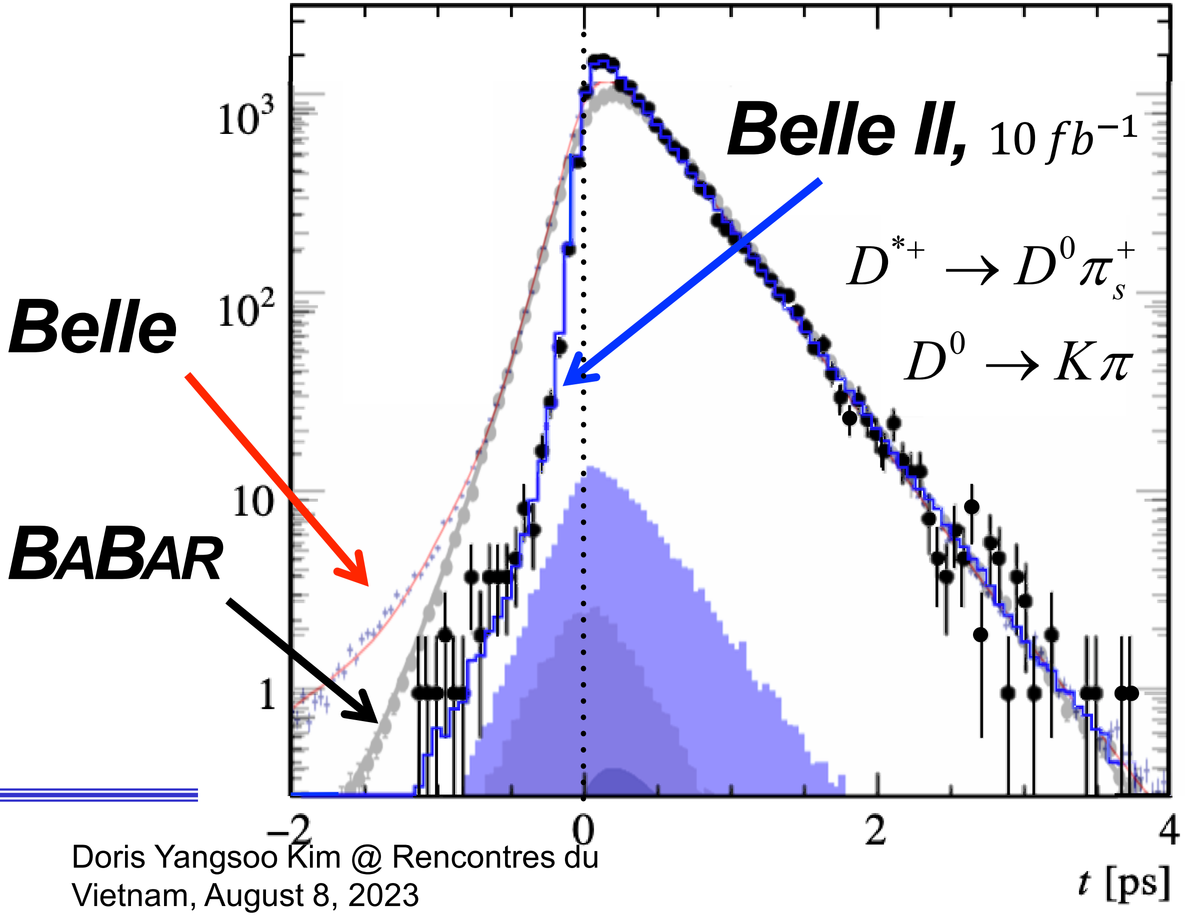
- After the SupepKEKB commission phases, physics runs started spring 2019.
- Reclaimed the luminosity record June 2020! (Previously held by LHC.)
- Spring/summer 2022 run ended June.
  - Peak luminosity at $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the current world record on June 22nd.
  - Current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

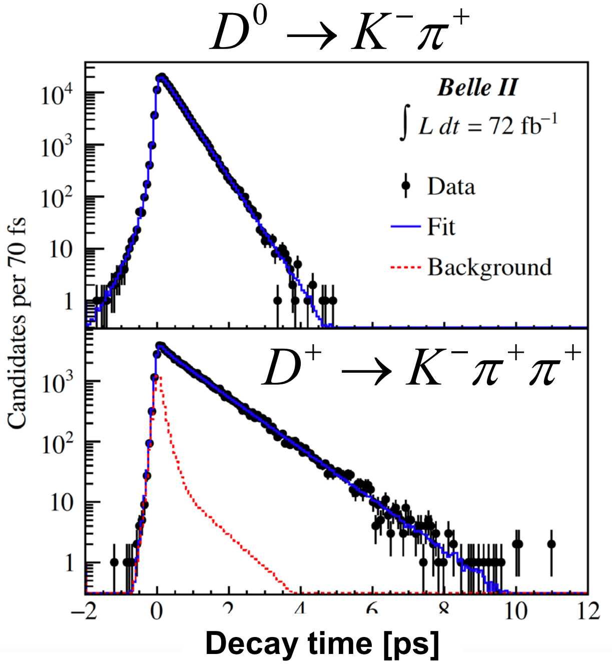




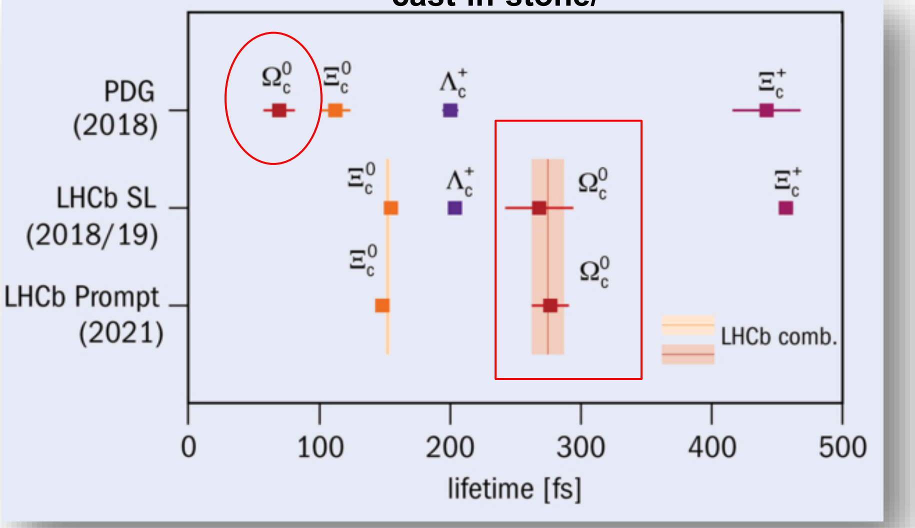
- At SuperKEKB, $\sigma_{c\bar{c}} \sim \sigma_{b\bar{b}}$. Large charm sample from continuum.
- $e^+ e^-$ collision gives clean environment. Less bias.
- Small interaction region and the new Belle II vertex detector give strong constraints and better resolutions.
- A great opportunity to measure the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

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

D^0, D^+, D_s^+, Λ_c^+, Ω_c^0 Lifetimes



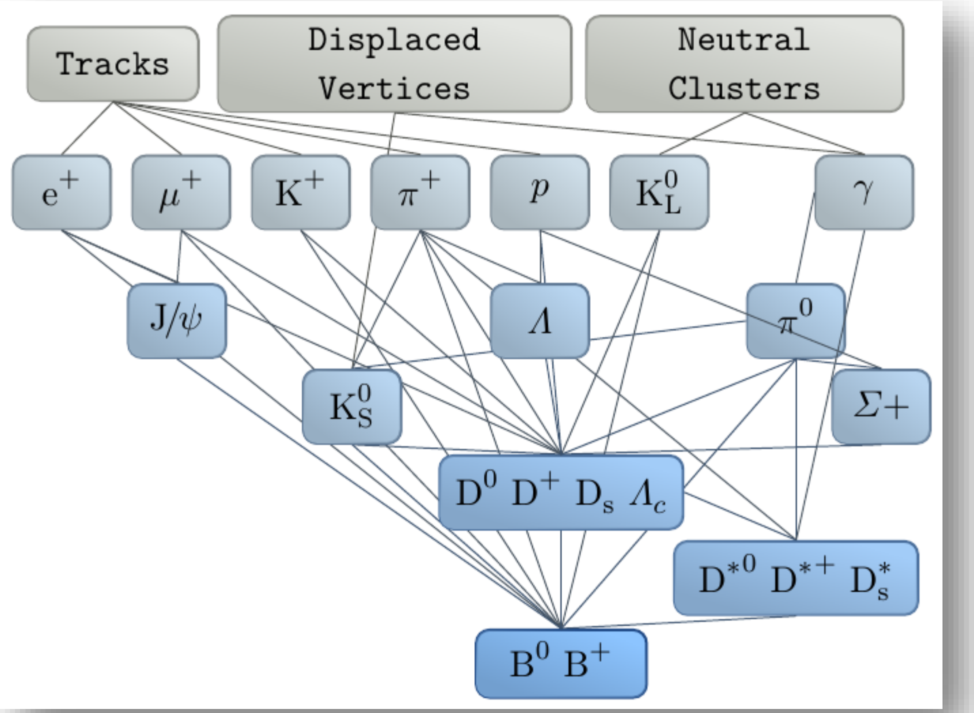
https://cerncourier.com/a/new-charmed-baryon-lifetime-hierarchy-cast-in-stone/



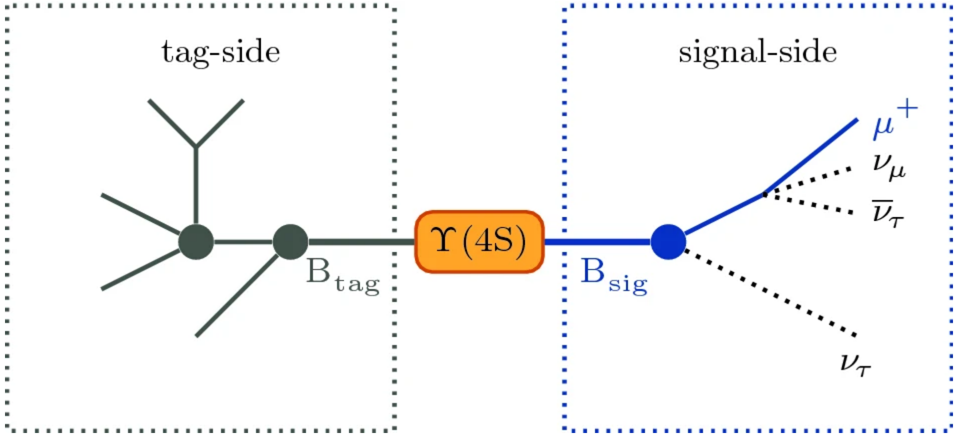
Belle II Ω_c^0 lifetime measurement confirms the LHCb result.

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	Phys. Rev. Lett. 127 (2021), 211801
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	arXiv: 2306.00365
Λ_c^+	$203.2 \pm 0.9 \pm 0.8$		202.4 ± 3.1	Phys. Rev. Lett. 130 (2023), 071802
Ω_c^0	$243 \pm 48 \pm 11$		$268 \pm 24 \pm 10$ LHCb 69 ± 12 pre-LHCb	Phys. Rev. D 127 (2023), L031103

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



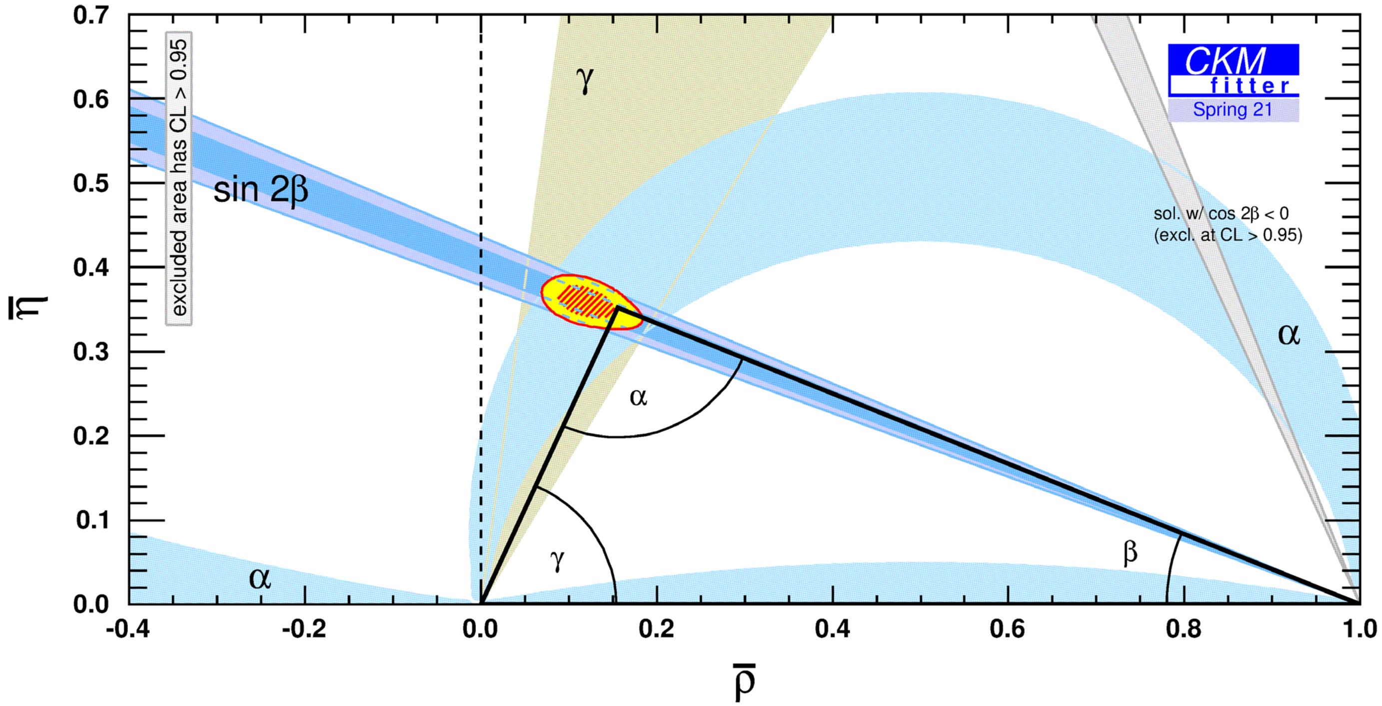
Hierachial reconstruction is performed to obtain B (tag) meson exclusively. Then use the Upsilon(4S) constraint to get the B (sig) meson.



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

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.



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

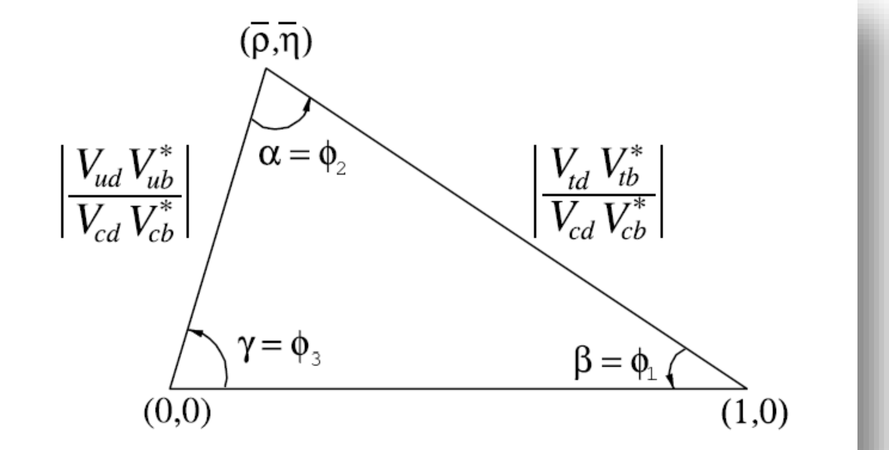
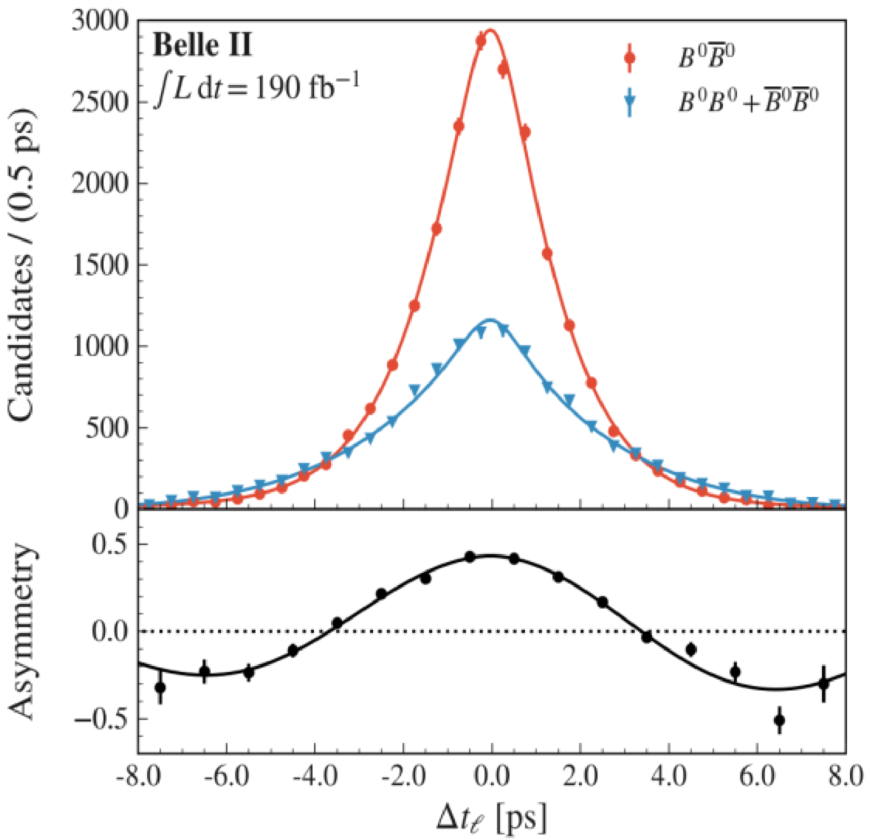
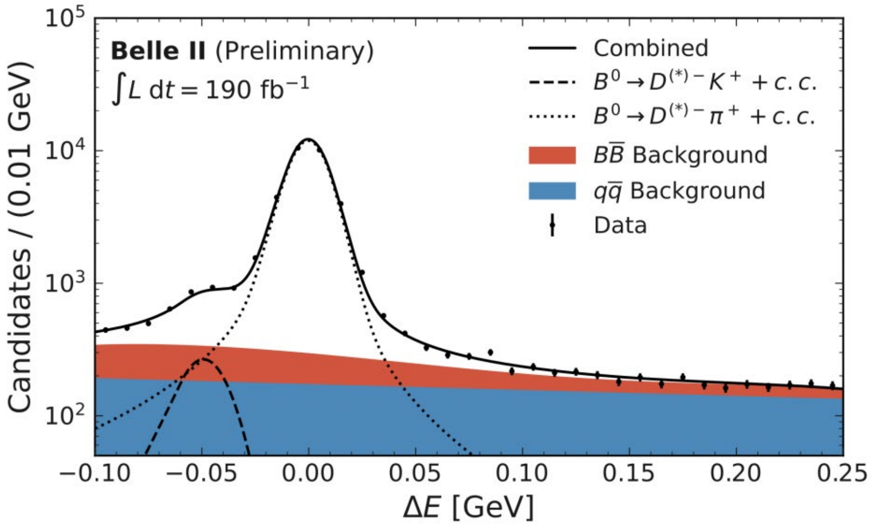


Figure 12.1: Sketch of the unitarity triangle.

Time Dependent CPV and Mixing in B physics



- Belle II flavor tagging $\varepsilon_{eff} = (30.0 \pm 1.2 \pm 0.4)\%$ 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.



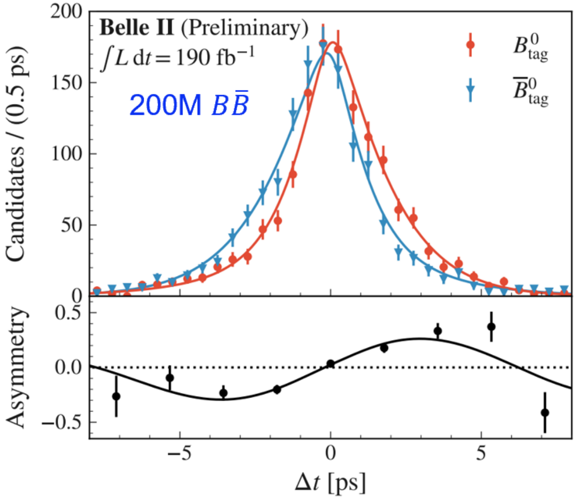
Belle II: $\tau_{B^0} = 1.499 \pm 0.013\,(stat) \pm 0.008\,(syst)$ ps W. A.: 1.510 ± 0.004 ps

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

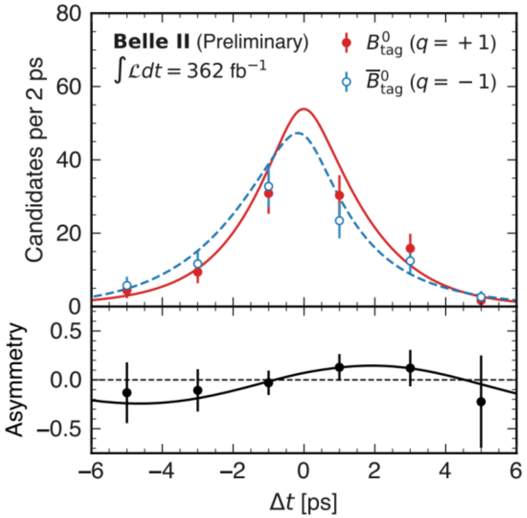
Phys. Rev. D 127 (2023), L091102

Next, sin 2β

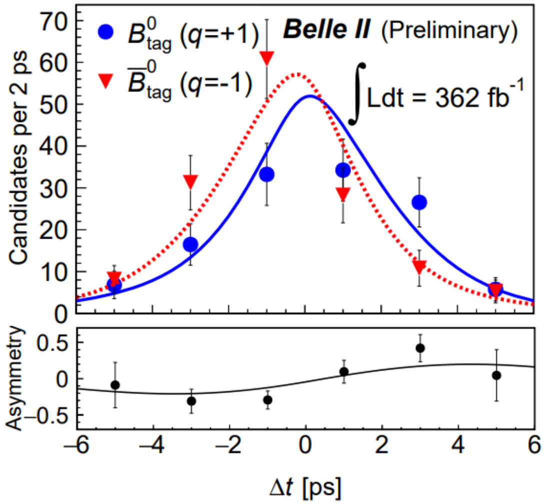
$B^0 \to J/\psi K_S^0$



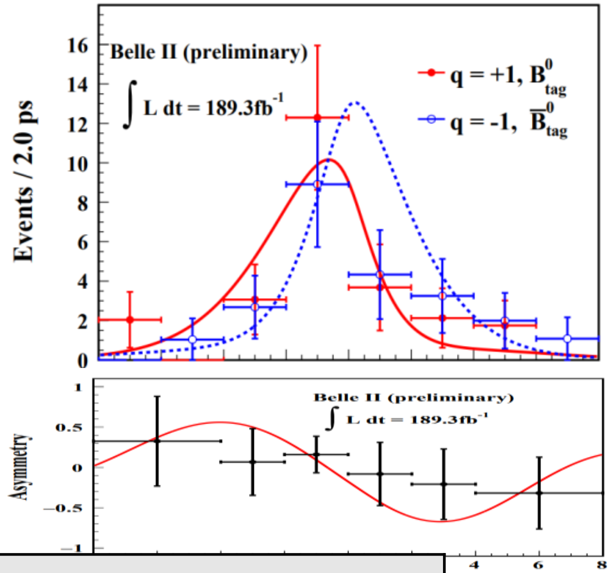
$B^0 \to \phi K_S^0$



$B^0 \to K_S^0 \pi^0$



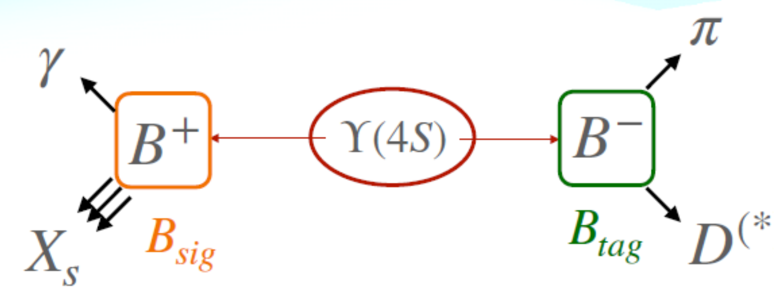
$B^0 \to K_S^0 K_S^0 K_S^0$



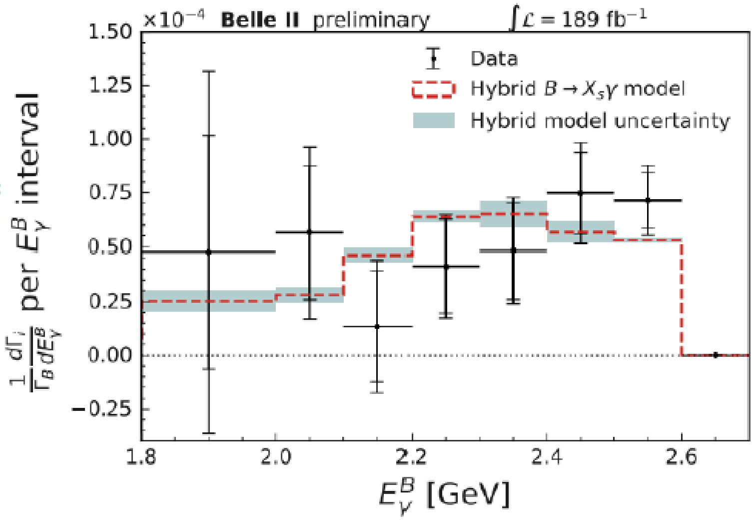
Type	Mode	$sin2\beta$	$A = -C$	Ref.
$b \to c\bar{c}s$	$B^0 \to J/\psi K_S^0$	$0.720 \pm 0.062 \pm 0.016$	$0.094 \pm 0.044^{+0.042}_{-0.017}$	arXiv:2302.12898
$b \to s\bar{s}s$	$B^0 \to \phi K_S^0$	$0.54 \pm 0.25^{+0.06}_{-0.08}$	$0.31 \pm 0.20 \pm 0.05$	arXiv:2307.02802
$b \to s\bar{d}d$	$B^0 \to K_S^0 \pi^0$	$0.74^{+0.20}_{-0.23} \pm 0.04$	$0.04^{+0.15}_{-0.14} \pm 0.05$	arXiv:2305.07555
$b \to s\bar{d}d$	$B^0 \to K_S^0 K_S^0 K_S^0$	$1.86^{+0.91}_{-0.46} \pm 0.09$	$-0.22^{+0.30}_{-0.27} \pm 0.04$	arXiv:2309.09547

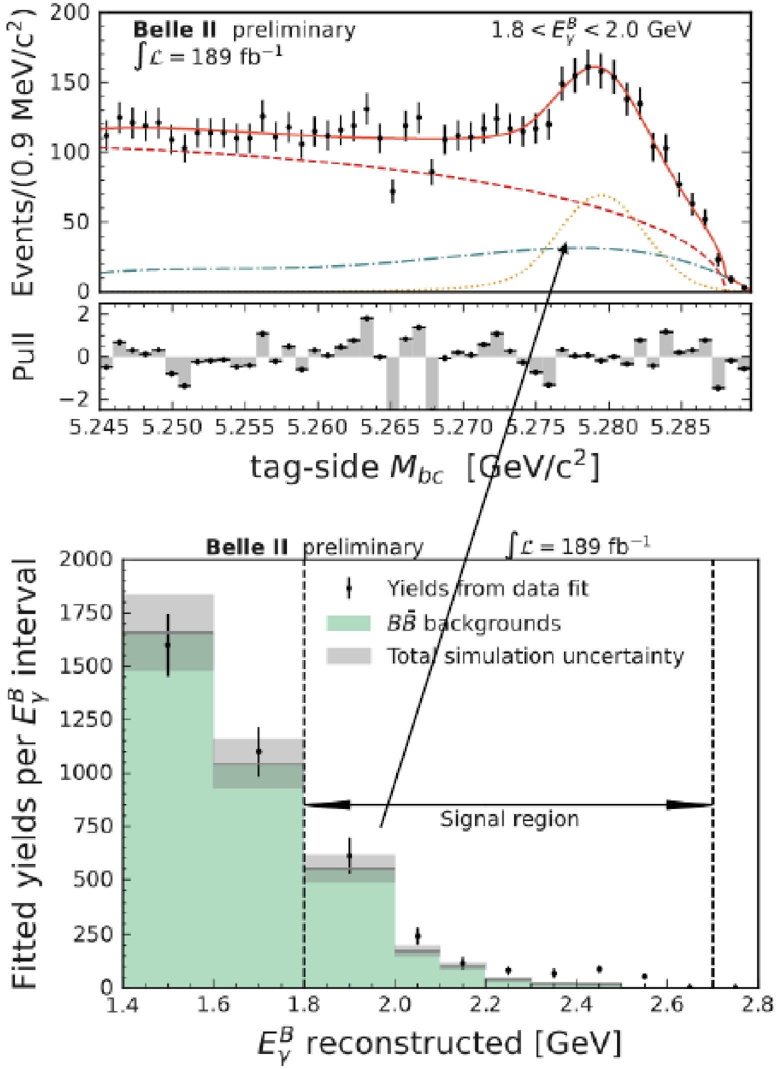
Fully Inclusive $B \to X_s\gamma$

- An effective to way to search for NP in $b \to s\gamma$ channel.
- $189\ fb^{-1}$ sample in bins of E_γ^B (photon energy in B rest frame)
- Tag side is hadronic B
- Background veto from pi0 and eta. Further suppressed by BDT cllasifier. X_s candidate is isolated.
- Though efficiency is low at < 1%.



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

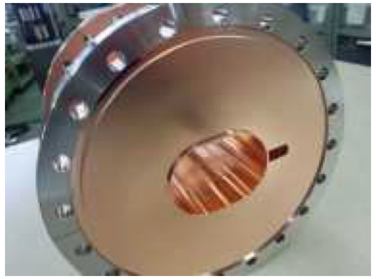


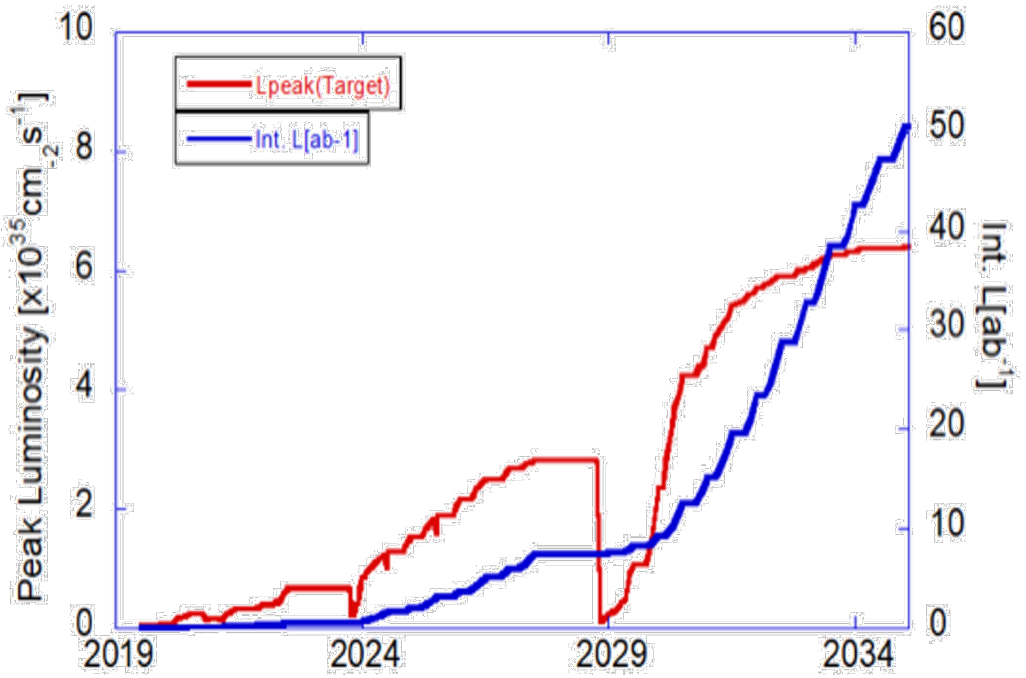


arXiv: 2210.10220

SuperKEKB Upgrade during LS1

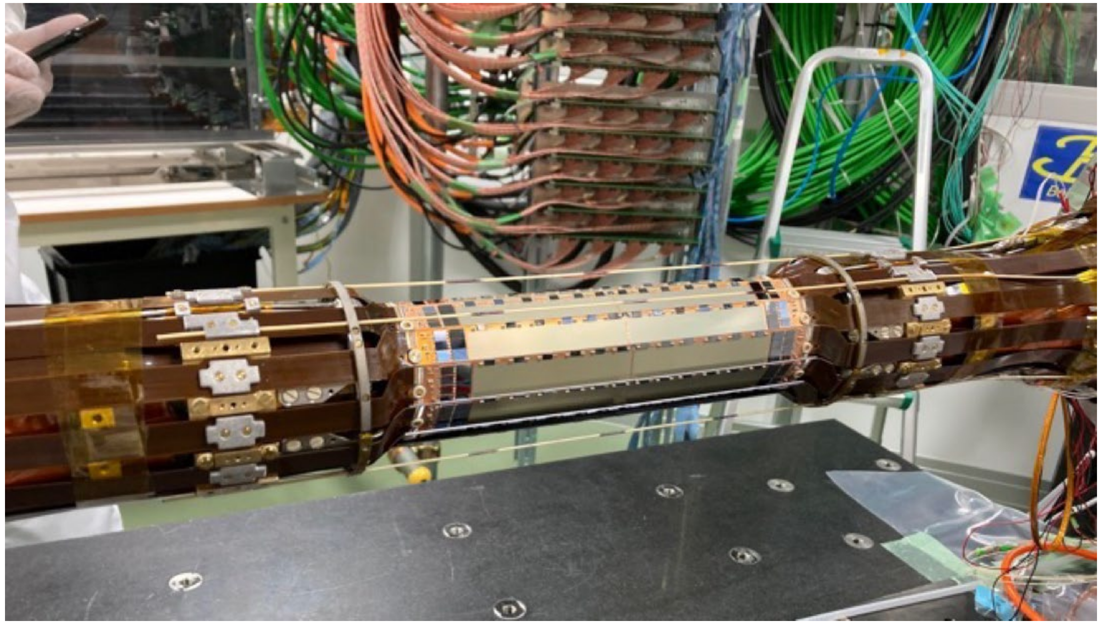
- The sudden beam loss mitgation strategy.
- Reducing beamline neutrons by additional shielding around final-focus magnets and endcaps
- Collimators: harder material, non-linear to decrease beam halo
- For stability and increase in currents, RF cavity being replaced.
- Injector area: faster kicker magnet,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





Belle II Upgrade during LS1

- Two layer pixel detector
- TOP PMT replaced for increased lifespan and robustness
- DAQ upgrade to PCIe40
- Improved gas distribution, gain stability, and monitoring for drift chamber



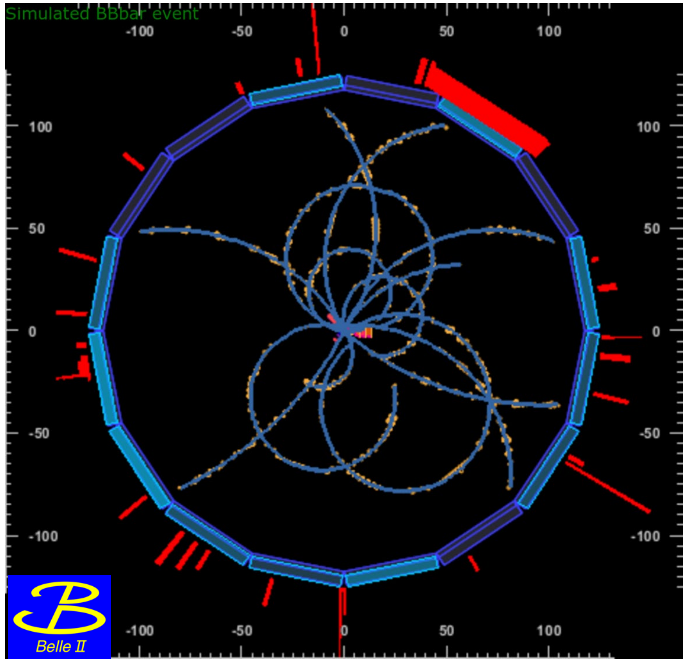
Summary

- 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 B physics.
  - Only a few selected topics are shown here.
- During 2020 - 2022, 6 papers published.
- In 2023, 9 papers published, 5 papers submitted, more in the pipeline.
  - Detailed reports at Moriond 2023, LP 2023
- This is a very exciting time to do flavor physics, looking for physics beyond the Standard Model.

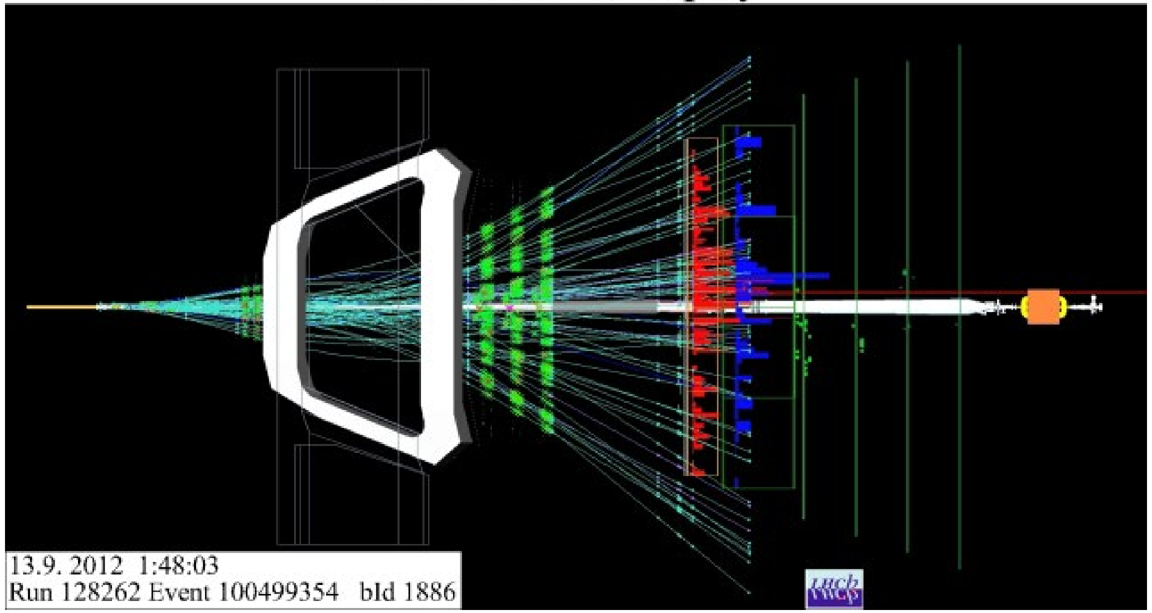
EXTRA

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.



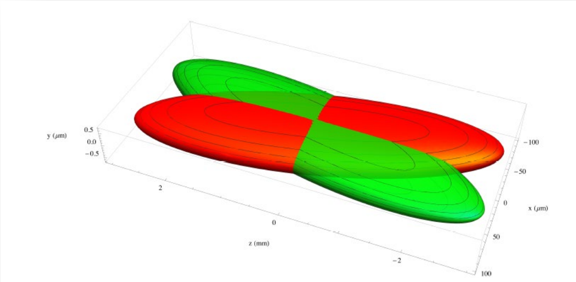
LHCb Event Display



KEKB to SuperKEKB: Accomplished

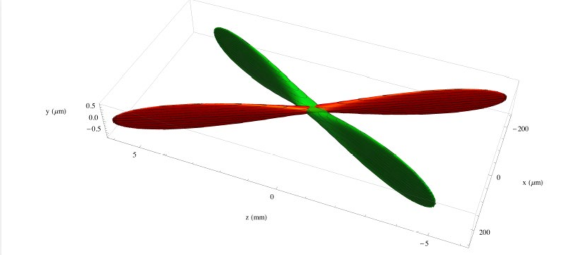
- Nano beam scheme + Crab waist optics
- Target: vertical beta function β_y^* 5.9 mm (KEKB) to 0.3 mm (SuperKEKB)
- Increase beam currents $I_{e\pm}$
- Increase beam-beam interaction ξ_y

KEKB beams



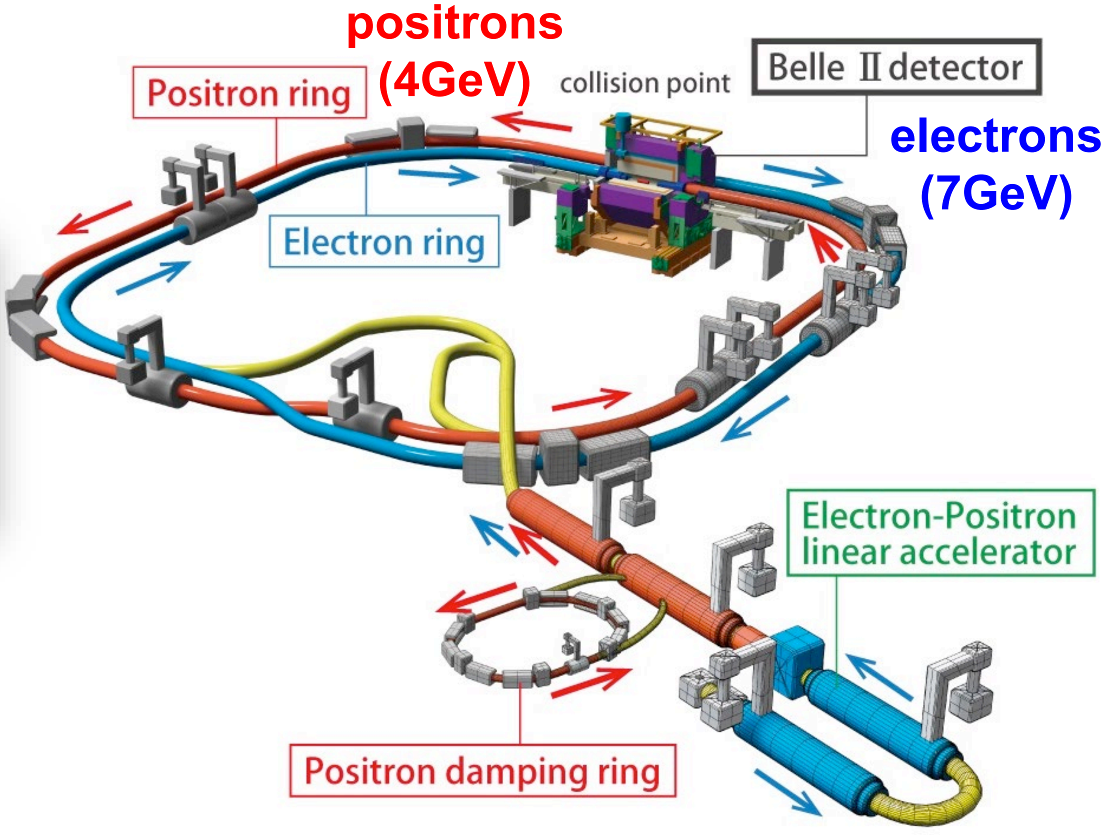
Beam crossing angle 22mrad

SuperKEKB nanobeams



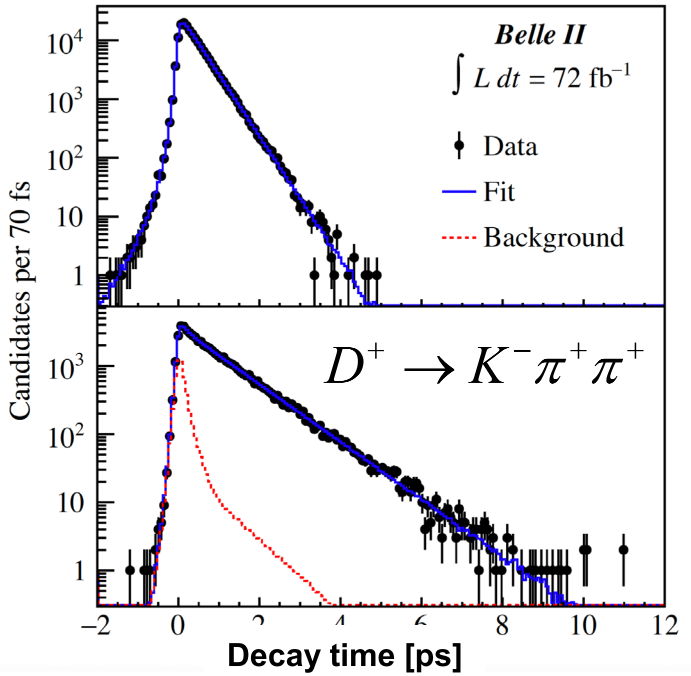
Beam crossing angle 83mrad

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

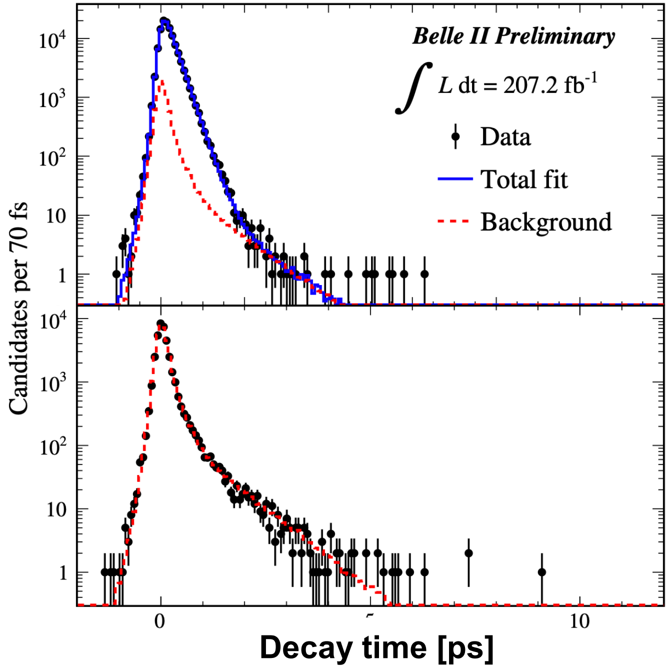


D^0, D^+, Λ_c^+, Ω_c^0, D_s Lifetimes

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

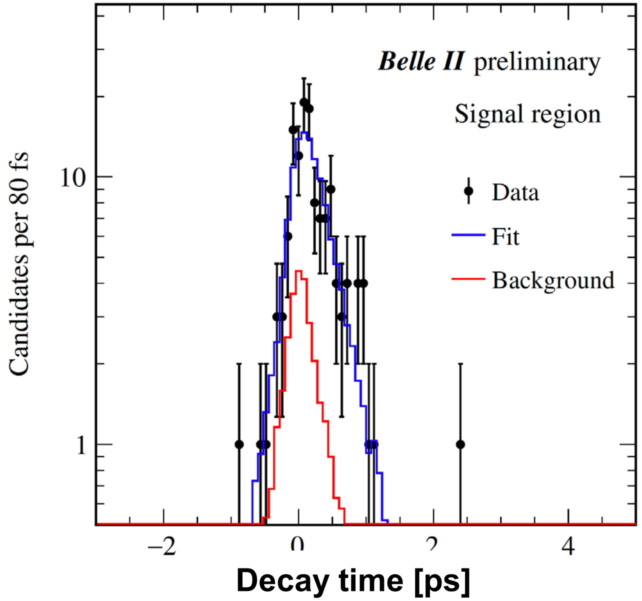


$\Lambda_c^+ \to pK^-\pi^+$



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

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



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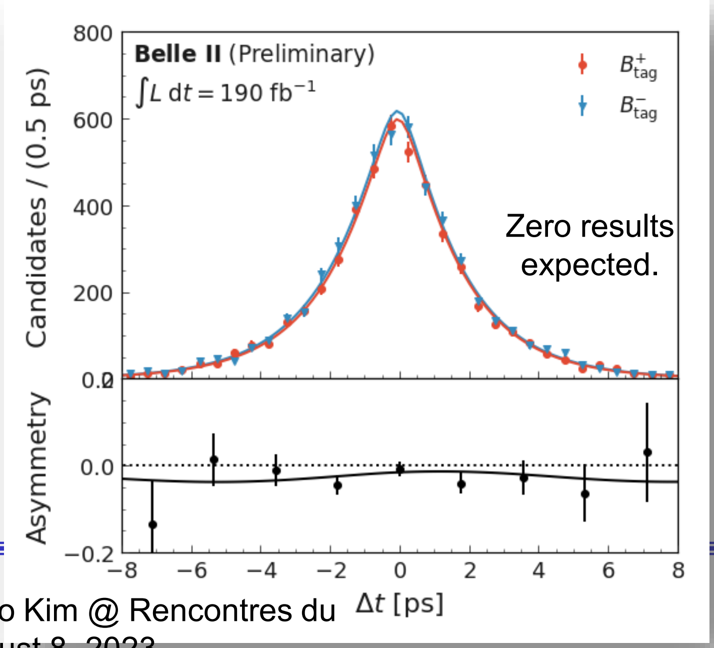
D^0	$410.5 \pm 1.1 \pm 0.8$	410.1 ± 1.5	Phys. Rev. Lett. 127 (2021), 211801
D^+	$1030.4 \pm 4.7 \pm 3.1$	1040 ± 7	
Λ_c^+	$203.2 \pm 0.9 \pm 0.8$	202.4 ± 3.1	arXiv: 2206.15227v1, PRL accepted
Ω_c^0	$243 \pm 48 \pm 11$	$268 \pm 24 \pm 10$ LHCb 69 ± 12 pre-LHCb	ICHEP 2022 preliminary

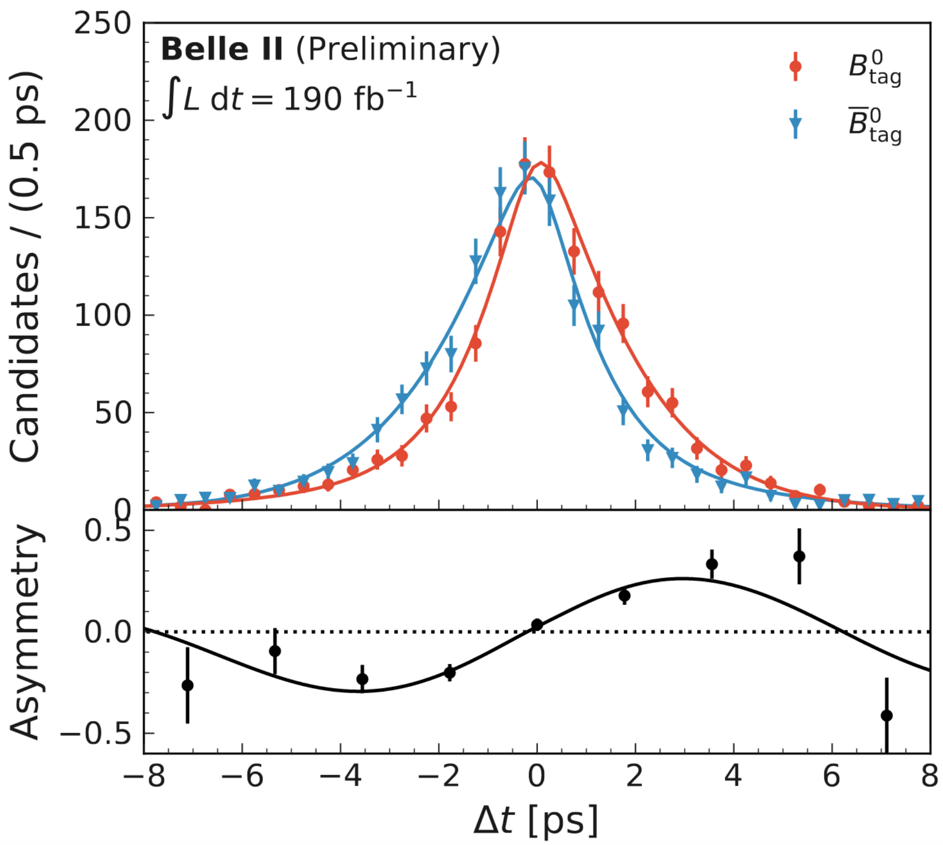
Next, Test sin 2β Method

- 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 $B^0 \to J/\psi K_S^0$



$$S_{CP}(\approx \sin 2\beta) = 0.720 \pm 0.062\,(stat) \pm 0.016\,(syst)$$
$$A_{CP} = 0.094 \pm 0.044\,(stat)^{+0.042}_{-0.017}\,(syst)$$