# 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

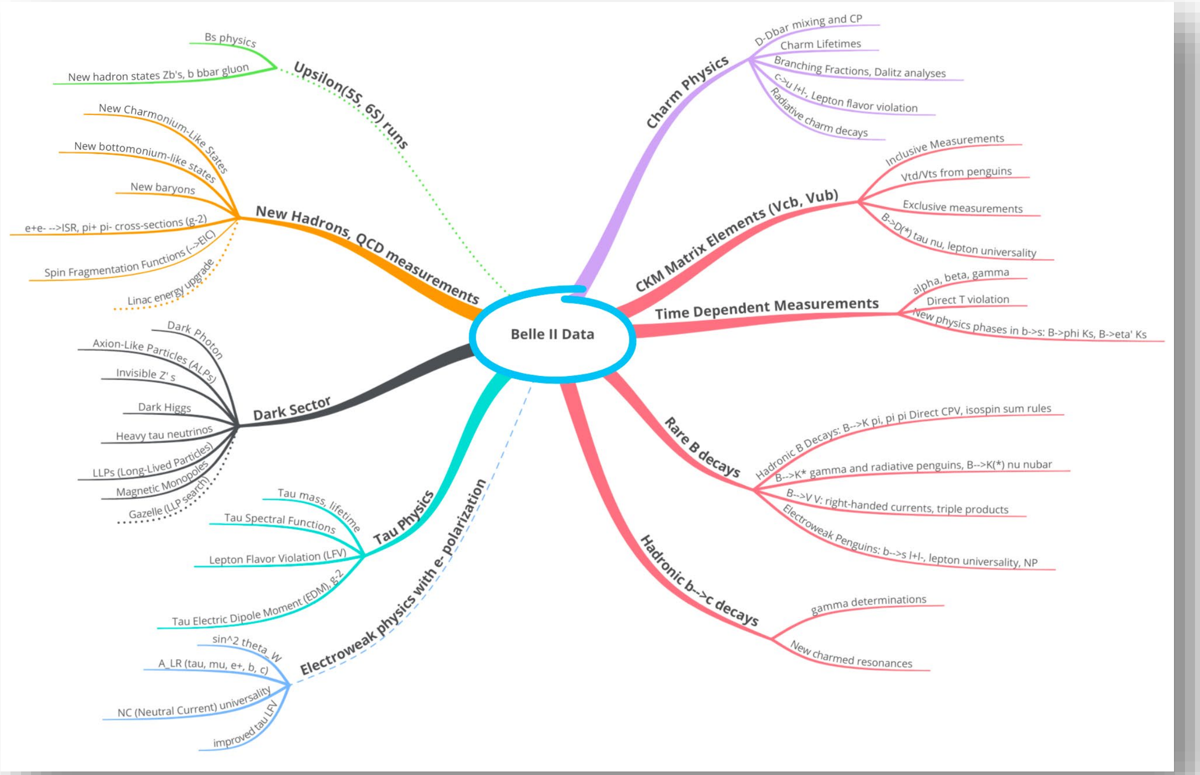
# Belle II Experiment in a Nutshell

- 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 $\gamma$, $\pi^0$, $K_L$.
- A hermetic detector:
  - Detection of neutrinos or invisibles as missing energy/momentum.
- Large continuum charm and $\tau$ samples in addition to B samples.
  - Detect both e and $\mu$ with similar performance.
  - For example, search for LFV $\tau$ 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
- $\tau$ physics
- Hadron spectroscopy
- Rare decays, FCNC
- New physics
  - Lepton flavor violation
  - Dark sector, long lived particles

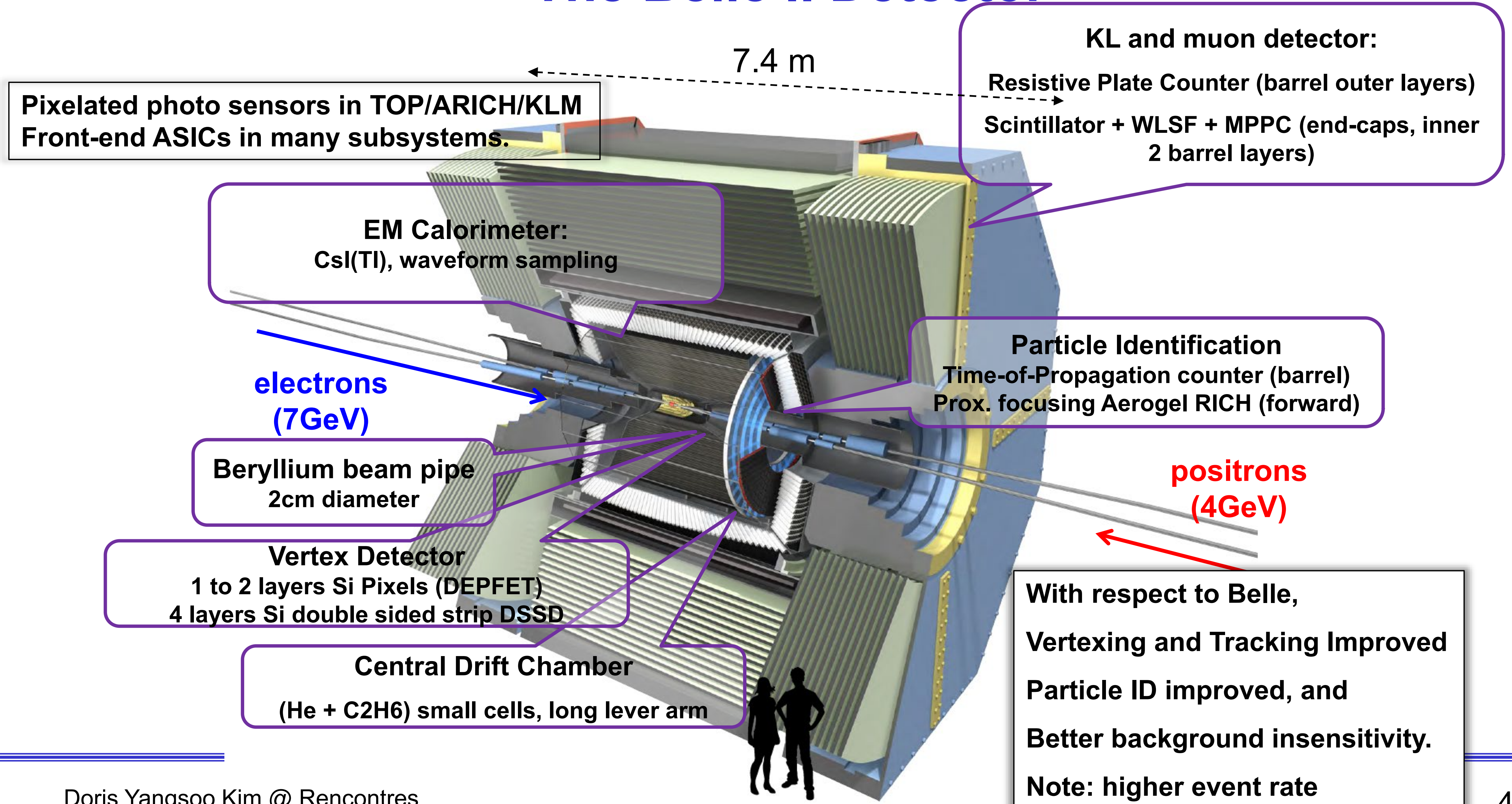



Belle II Physics Book, PTEP 2019, 123C01

**Paolo Rocchetti, Today, Parallel Session**

**Recent Belle II results related to flavor anomalies**

# The Belle II Detector




With respect to Belle,

Vertexing and Tracking Improved

Particle ID improved, and

Better background insensitivity.

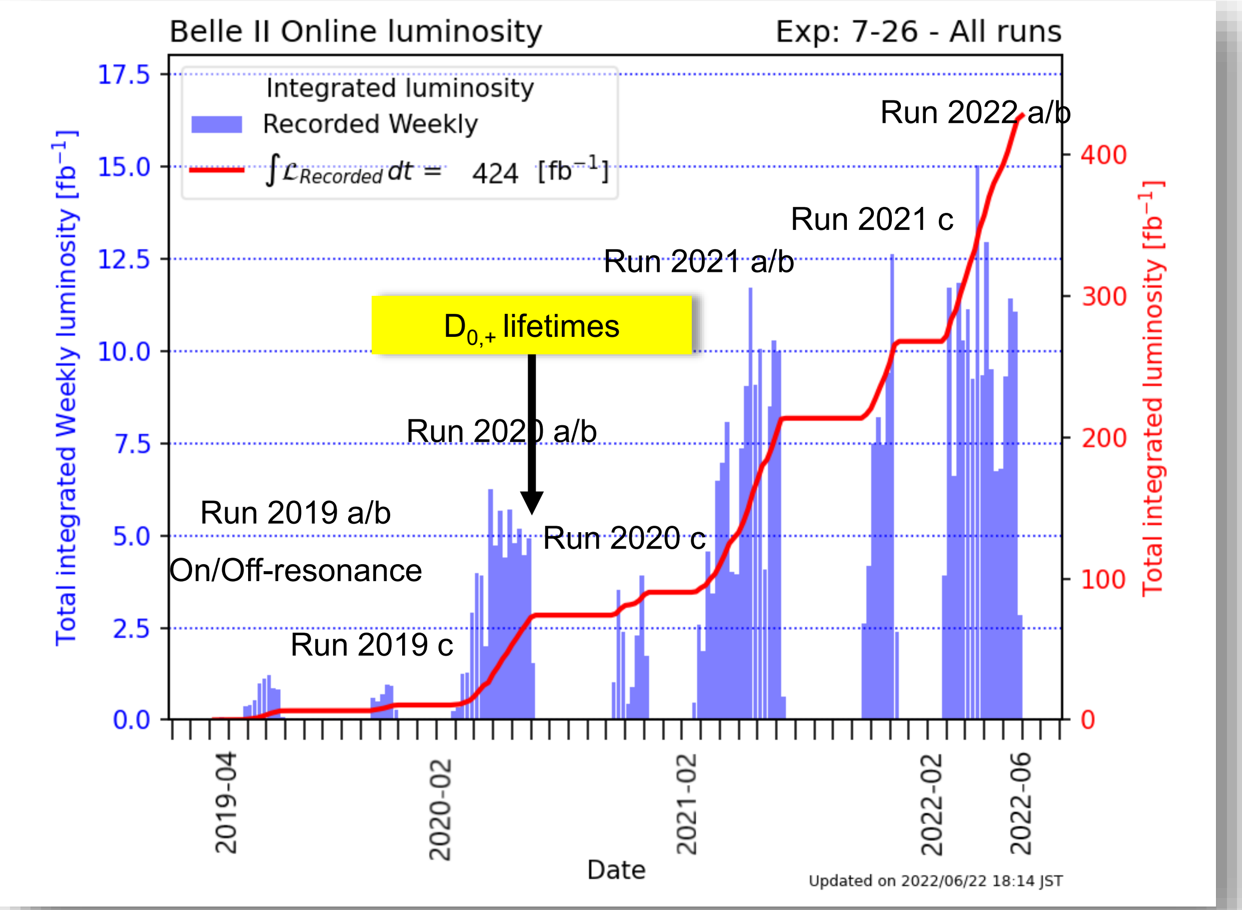
Note: higher event rate

# The Belle II Collaboration


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

# SuperKEKB Luminosity: Current Status

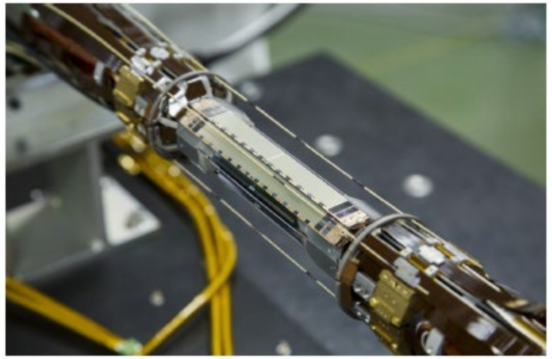
- After the SupepKEKB commission phases, physics runs started spring 2019.
- Spring/summer 2022 run ended June.
  - Peak luminosity at $\boldsymbol{L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}}$, the current world record on June 22nd.
  - Current integrated luminosity at $\int L_{recorded} dt = 424\, fb^{-1}$. (~ Babar, ~ ½ Belle)
- Long shutdown 1 (LS1) started 2022 summer for upgrades (see later slides).
- Run 2 starts coming fall/winter.




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

# Charm Particle Lifetime

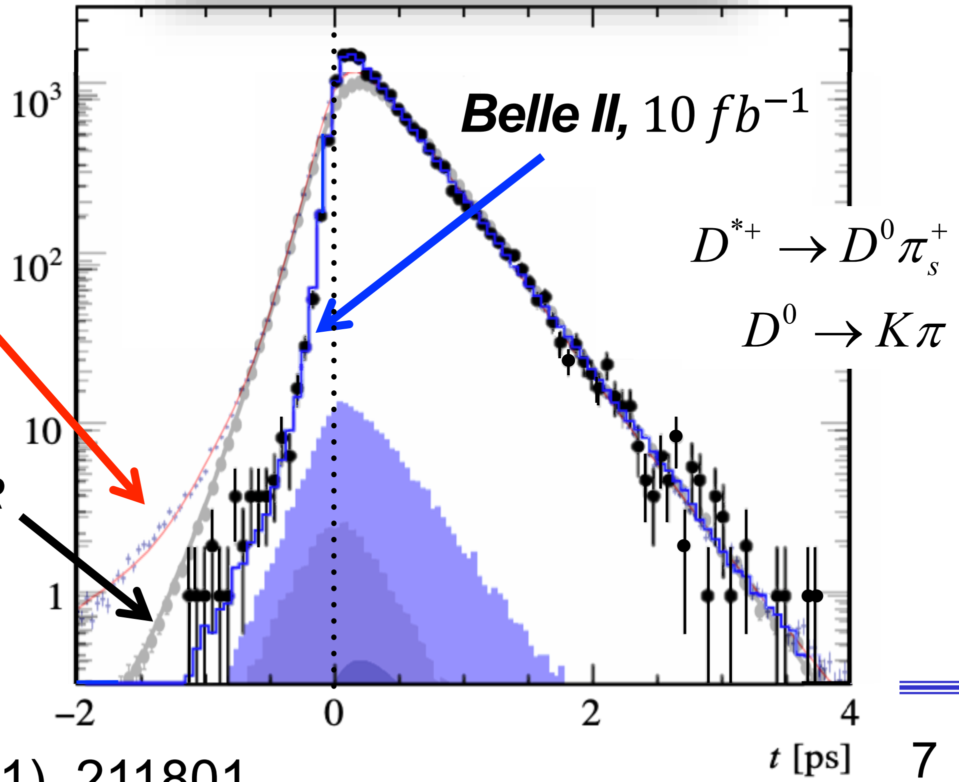
- Charm particles @ low-energy QCD calculation (non-perturbative and high order correction). The effective models do have uncertainties.
- Measurements of charm lifetimes can test the models.



Pixel detector radius ≈ 1.4 cm

**PXD v1**

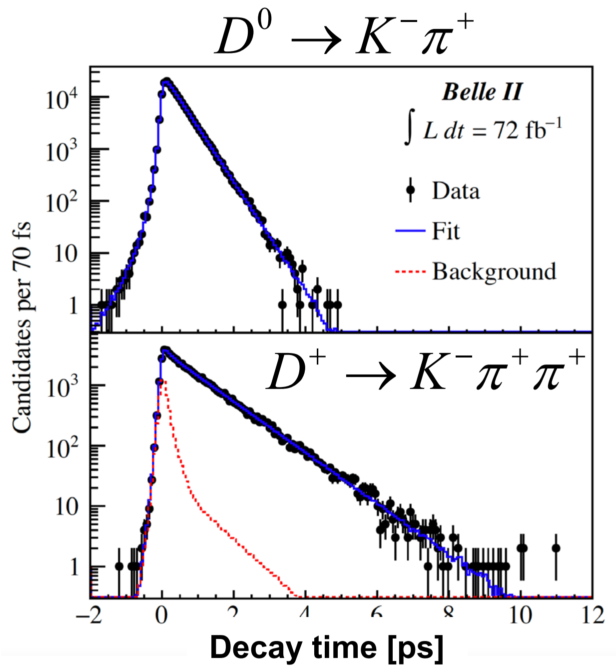
- At SuperKEKB, $\sigma_{c\bar{c}} \sim \sigma_{b\bar{b}}$. Large charm sample.
- $e^+ e^-$ collision gives clean environment. Less bias.
- Small interaction region and the new Belle II vertex detector give strong constraints and better resolutions.
  - Amount of $t < 0$: detector resolution
- A great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



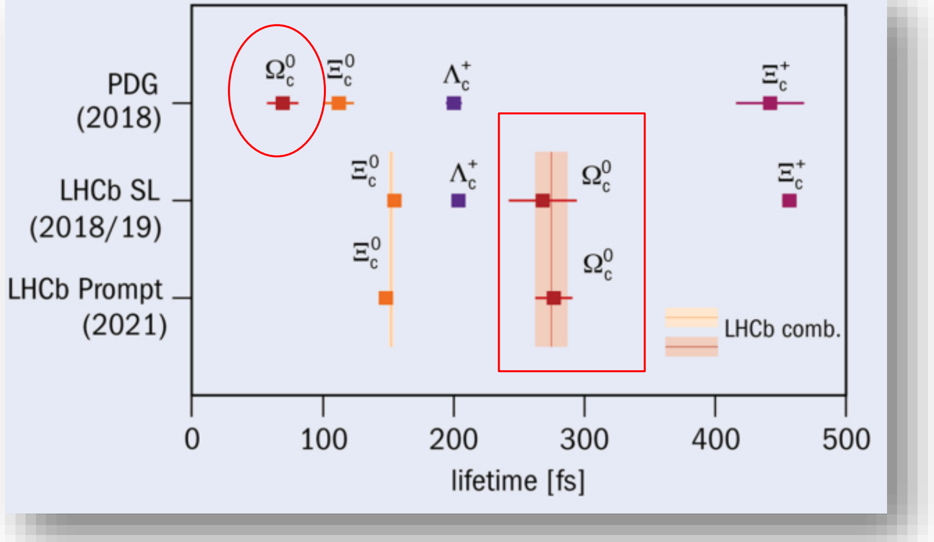



Phys. Rev. Lett. 127 (2021), 211801

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



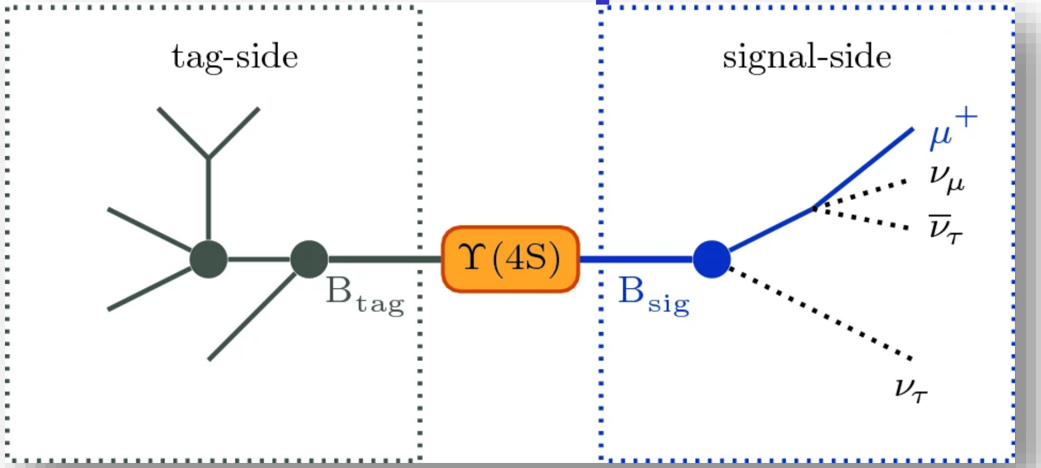

https://cerncourier.com/a/new-charmed-baryon-lifetime-hierarchy-cast-in-stone/



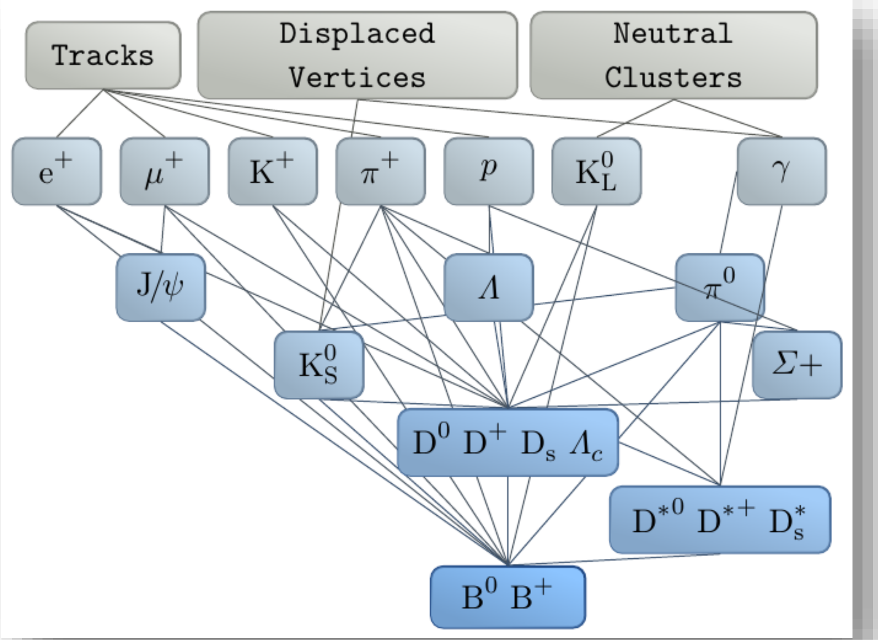

**Belle II $\Omega_c^0$ lifetime measurement confirms the LHCb result.**

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

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



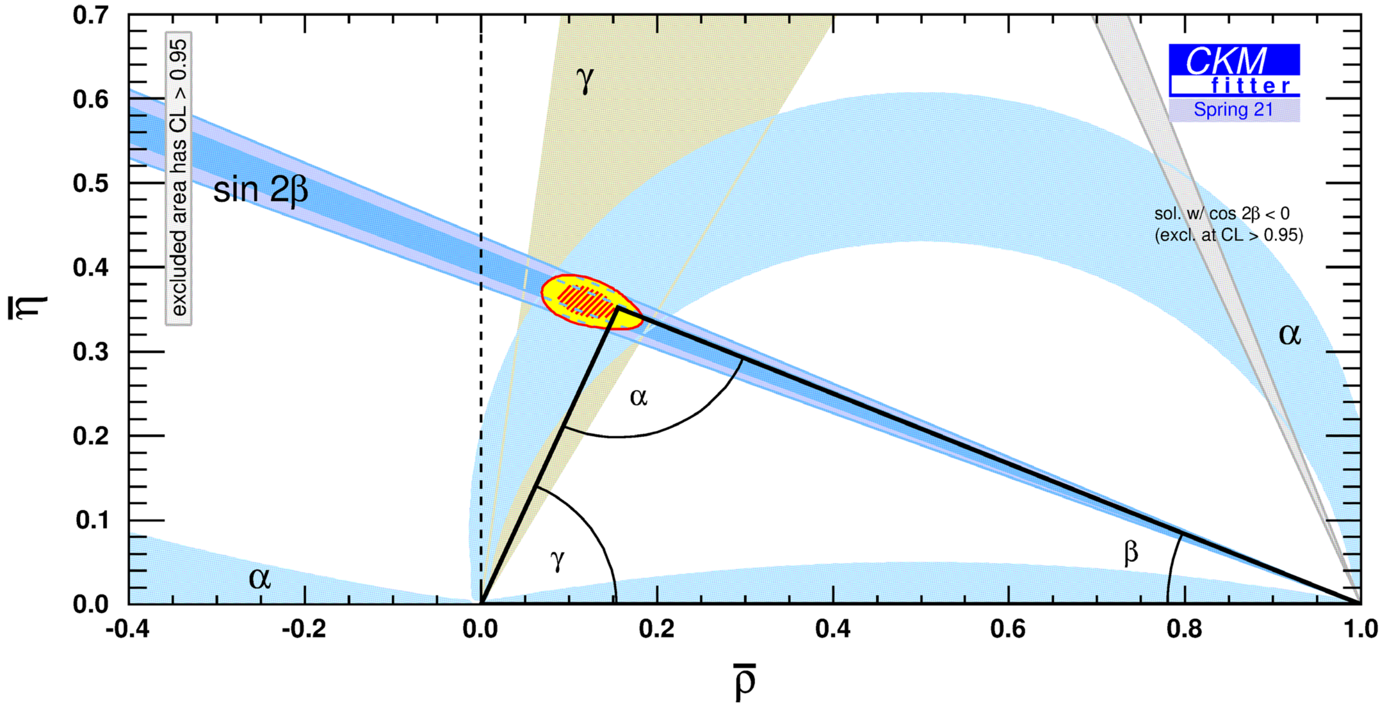

- Traditionally, at Upsilon(4s), one B (tag) is reconstructed first. The rest of the event is considered as a signal B.
  - B flavor tagging (page 11)
- An improved tool (FEI) was developed based on Boosted Decision Tree.
  T. Keck et al., Comput. Softw. Big Sci. 3, 6 (2019)
  - MVA based. $O(10^4)$ decay channels.
  - Max. tag side efficiency: $\varepsilon_{had} \approx 0.5\%$ and $\varepsilon_{SL} \approx 2\%$
  - ex) Paolo Rocchetti's talk. This talk page 13.




Hierachial 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 $\alpha$ and $\gamma$ angles are much less than $\beta$.
- 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

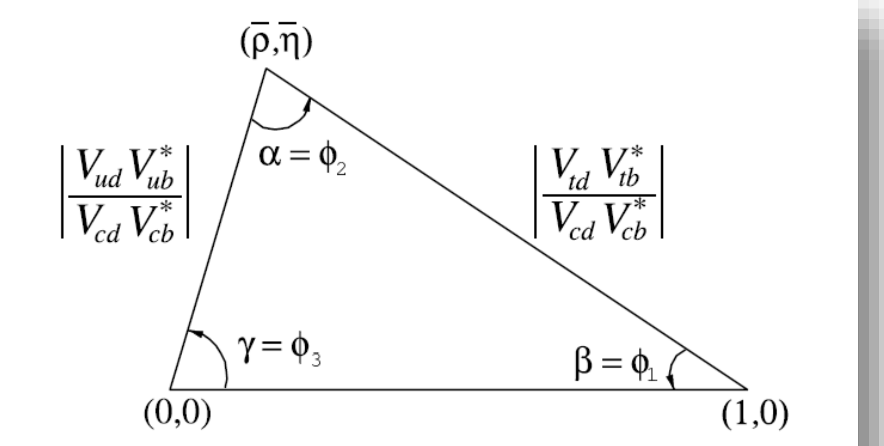
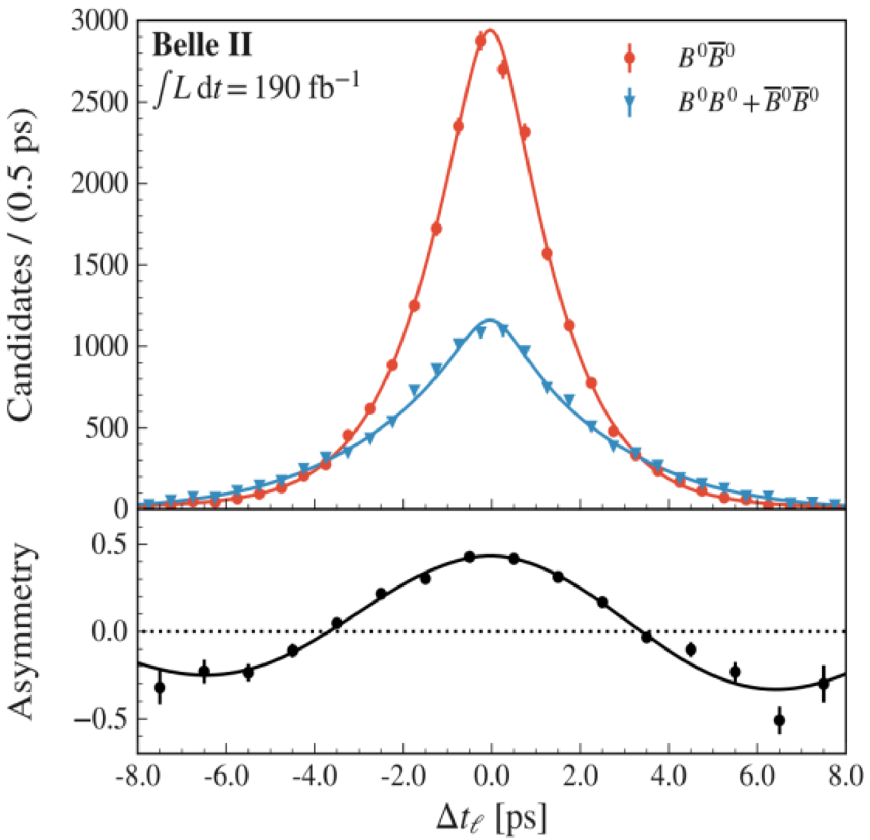
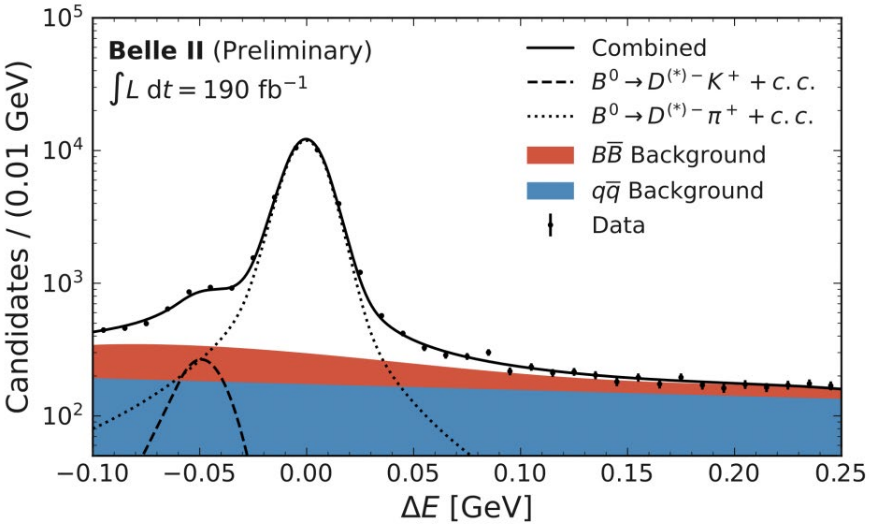



Figure 12.1: Sketch of the unitarity triangle.

# Time Dependent CPV and Mixing in B physics




- Belle II flavor tagging $\varepsilon_{\mathrm{eff}} = (30.0 \pm 1.2 \pm 0.4)\%$ 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.: $1.510 \pm 0.004$ ps |
| Belle II: $\Delta m_d = 0.516 \pm 0.008\,(stat) \pm 0.005\,(syst)\ \mathrm{ps}^{-1}$ | W. A.: $0.50665 \pm 0.0019\ \mathrm{ps}^{-1}$ |

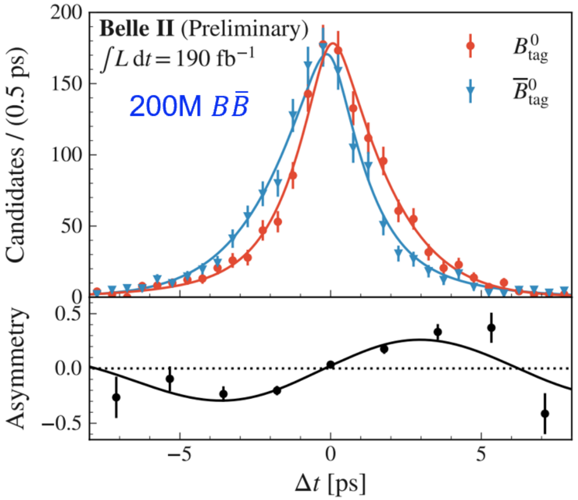


Phys. Rev. D 127 (2023), L091102

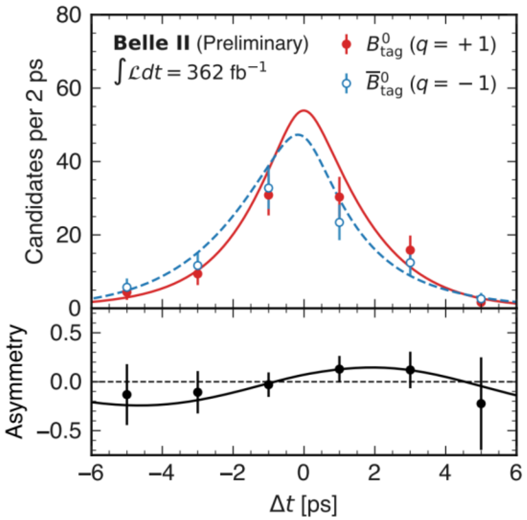
# Next, sin 2β

**Proper time differences**

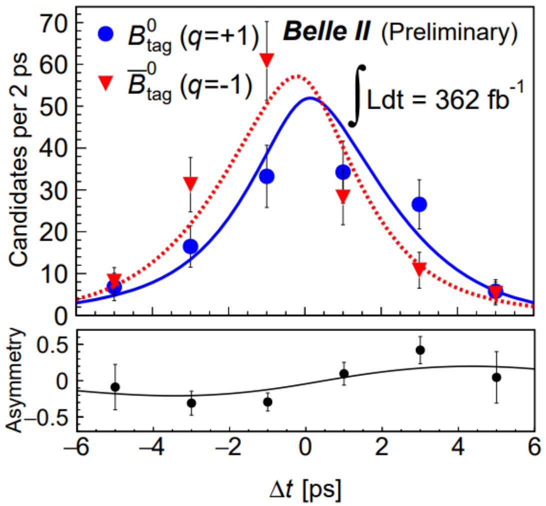
$B^0 \to J/\psi K_S^0$



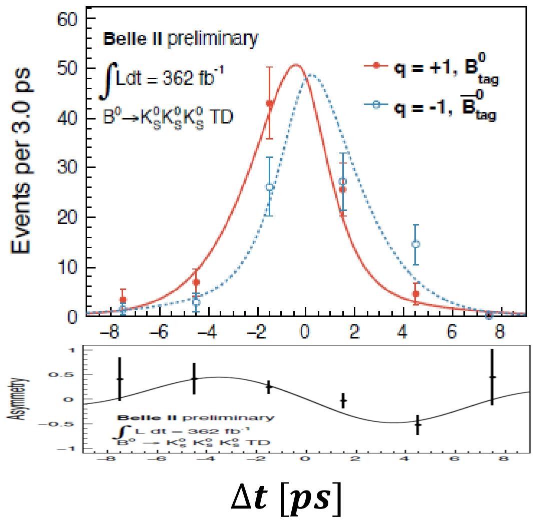

$B^0 \to \phi K_S^0$




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




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

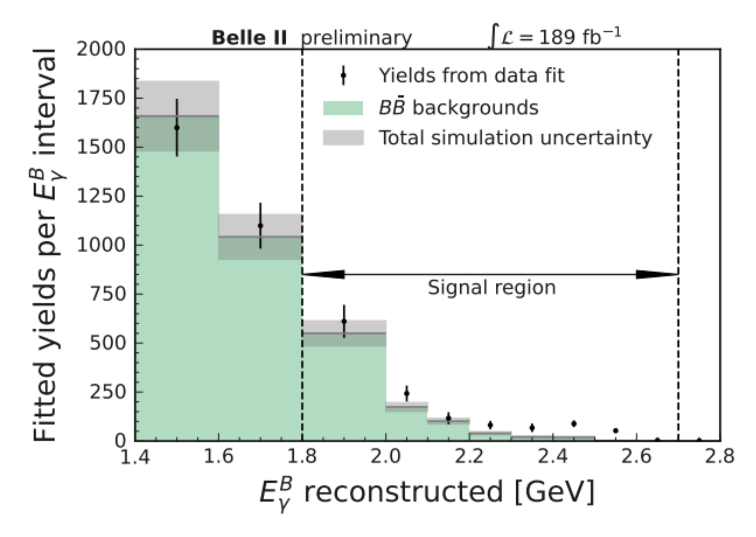


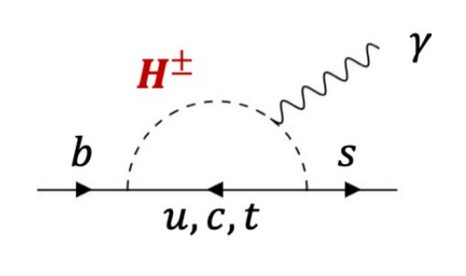

| Type | Mode | $sin2\beta = S$ | $A_{CP} = -C$ | Ref. |
|---|---|---|---|---|
| $b \to c\bar{c}s$ | $B^0 \to J/\psi K_S^0$ | $0.720 \pm 0.062 \pm 0.016$ | $0.094 \pm 0.044^{+0.042}_{-0.017}$ | arXiv:2302.12898 |
| $b \to s\bar{s}s$ | $B^0 \to \phi K_S^0$ | $0.54 \pm 0.25^{+0.06}_{-0.08}$ | $0.31 \pm 0.20 \pm 0.05$ | arXiv:2307.02802 |
| $b \to d\bar{d}s$ | $B^0 \to K_S^0 \pi^0$ | $0.75^{+0.20}_{-0.23} \pm 0.04$ | $0.04^{+0.15}_{-0.14} \pm 0.05$ | arXiv:2305.07555 |
| $b \to d\bar{d}s$ | $B^0 \to K_S^0 K_S^0 K_S^0$ | $-1.37^{+0.35}_{-0.45} \pm 0.03$ | $0.07^{+0.15}_{-0.20} \pm 0.02$ | Moriond 2023, arXiv:2209.09547 |

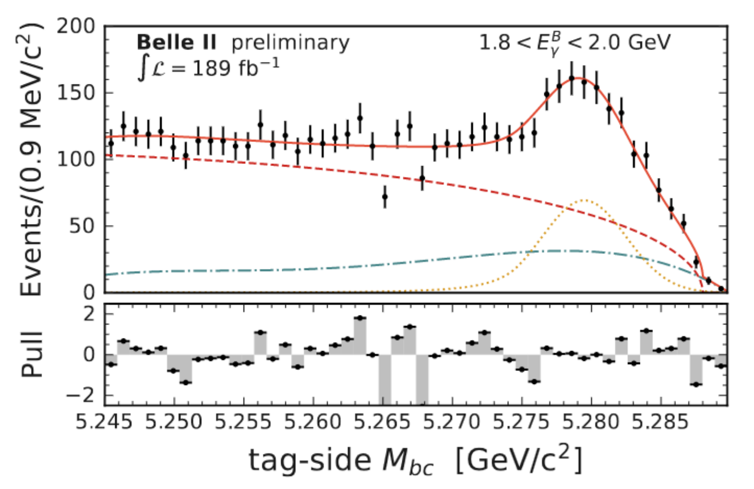
$\beta = \phi_1$

# Fully Inclusive $B \to X_s\gamma$

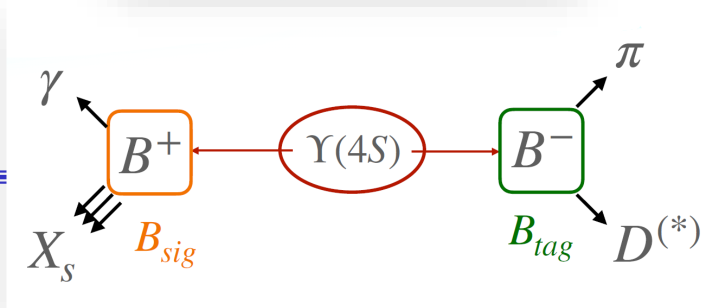
- An effective to way to search for NP in $b \to s\gamma$ channel. FCNC forbidden at tree level SM.
- $189\ fb^{-1}$ sample fitted in bins of $E_\gamma^B$ (photon energy in $B_{sig}$ rest frame) simultaneous with $B_{tag}$ mass
- FEI used. Tag side is B hadronic decays
- Signal photon background veto from pi0 and eta. Further suppression by a BDT classifier. $X_s$ candidate is isolated.
- Though efficiency is low at < 1%.




| $E_\gamma^B$ 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 | $2.49 \pm 0.46 \pm 0.35$ |

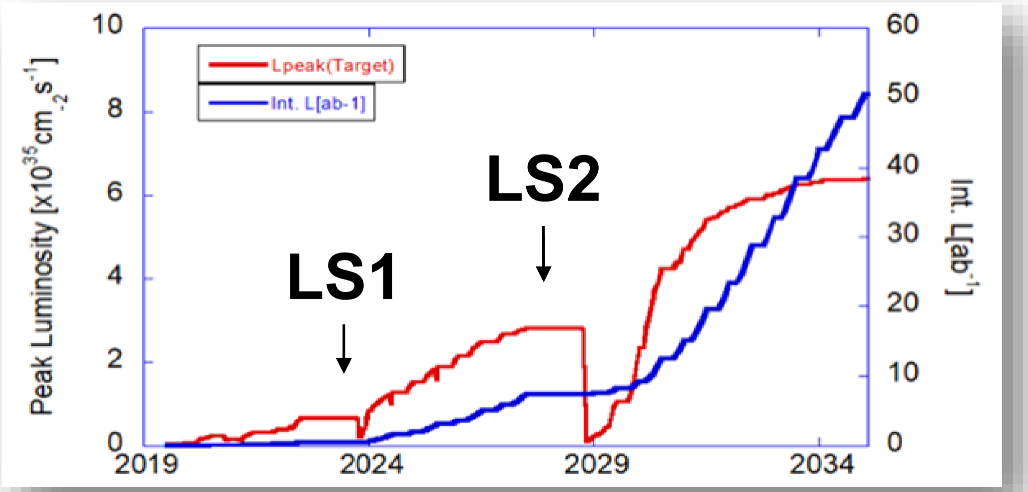


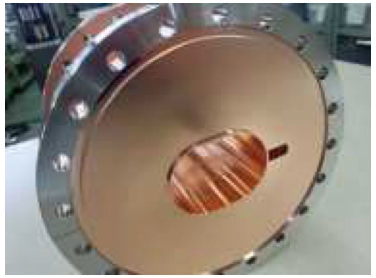

$$M_{bc} = \sqrt{(s/2)^2 - p_{tag}^2}$$

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

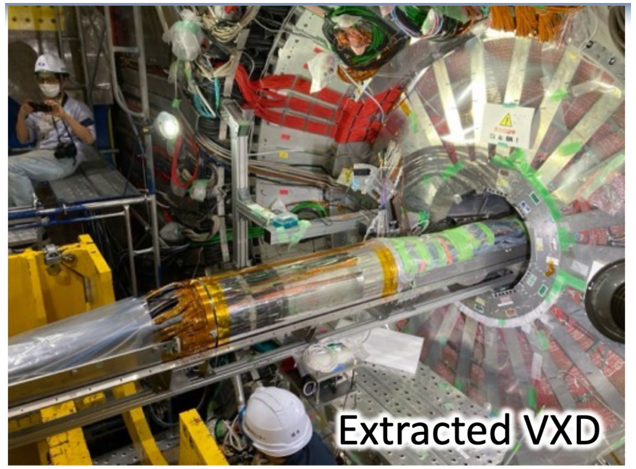


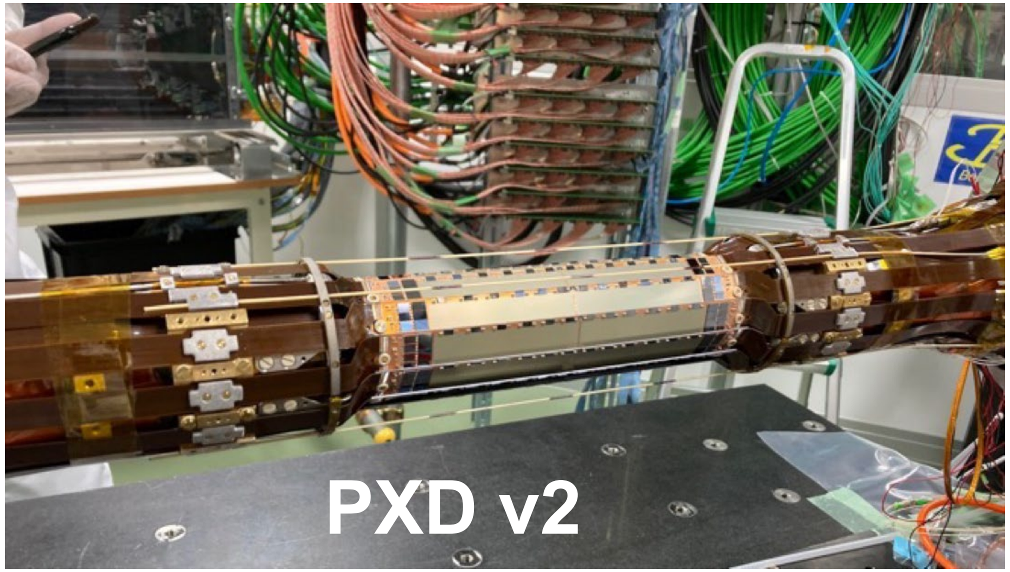
**For LS2 plan, <u>LP 2023 talk</u>**
**by L. Piilonen**

# 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







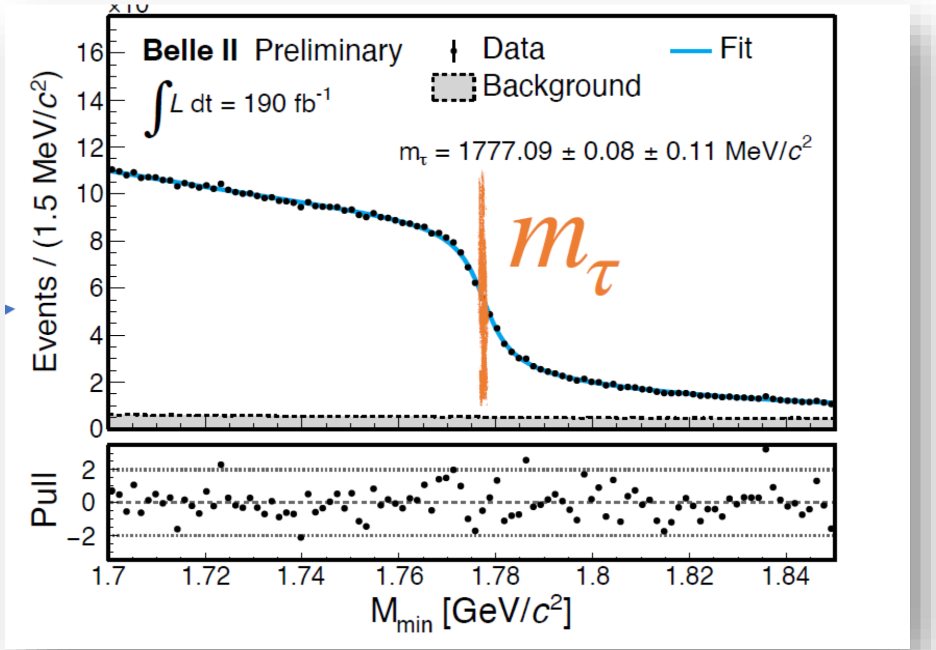
# Summary

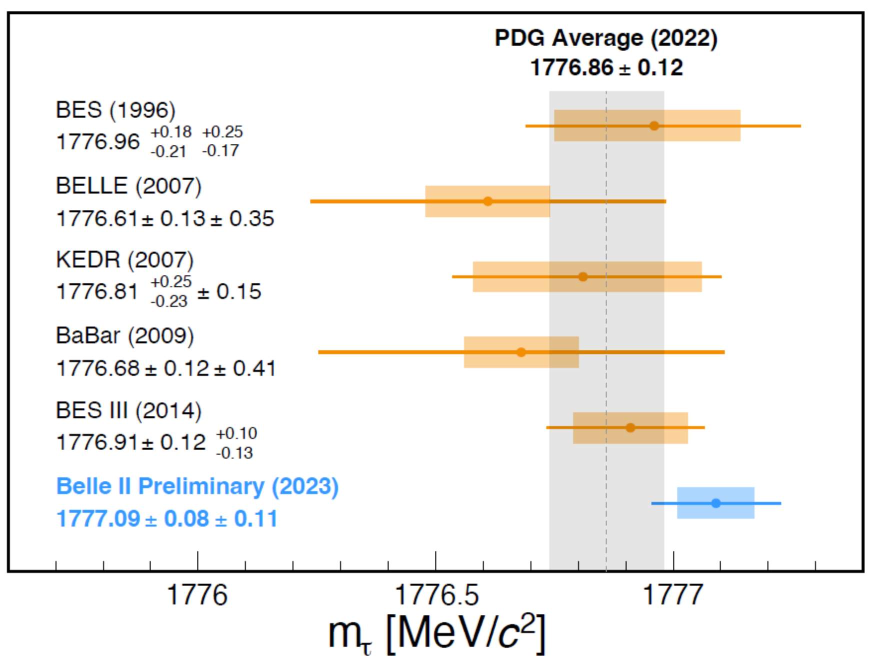
- SuperKEKB has achieved $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the world record on June 22nd, 2022.
  - It is a super B factory now.
- Belle II published world leading results in charm lifetime. D lifetime full set!
  - More updates are coming with the $424\ fb^{-1}$ sample.
- Belle II started 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.

# EXTRA

# $\tau$ Mass Measurement

- $\tau$ mass needed for lepton flavor universality test, BF measurements, and strong coupling measurements at $\tau$ mass.
- Belle II studied $190\ fb^{-1}$ of $e^+e^- \to \tau^+\tau^-, \tau^- \to \pi^-\pi^+\pi^-\nu_\tau$.
- Fit the threshold of $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \le m_\tau$
- Precision info of beam energy and track momentum scale is needed.



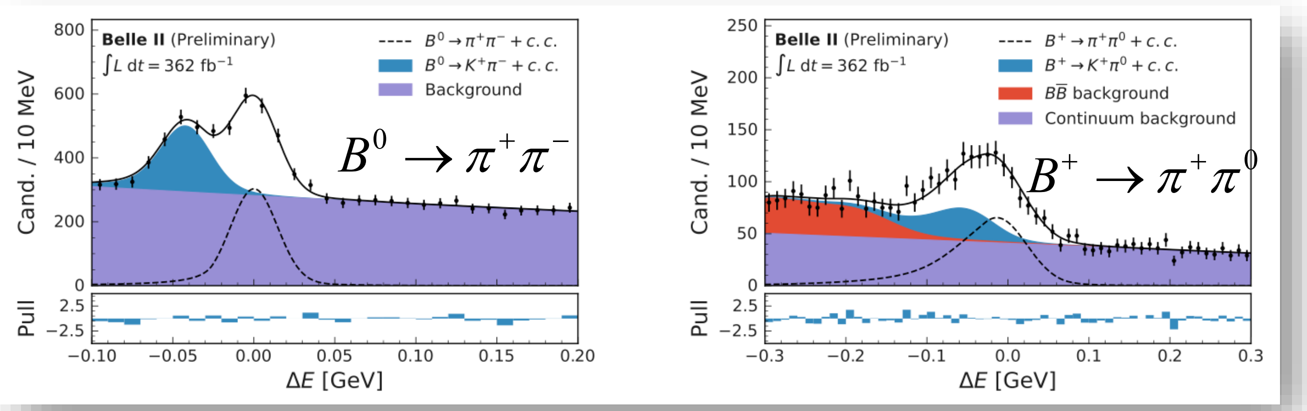


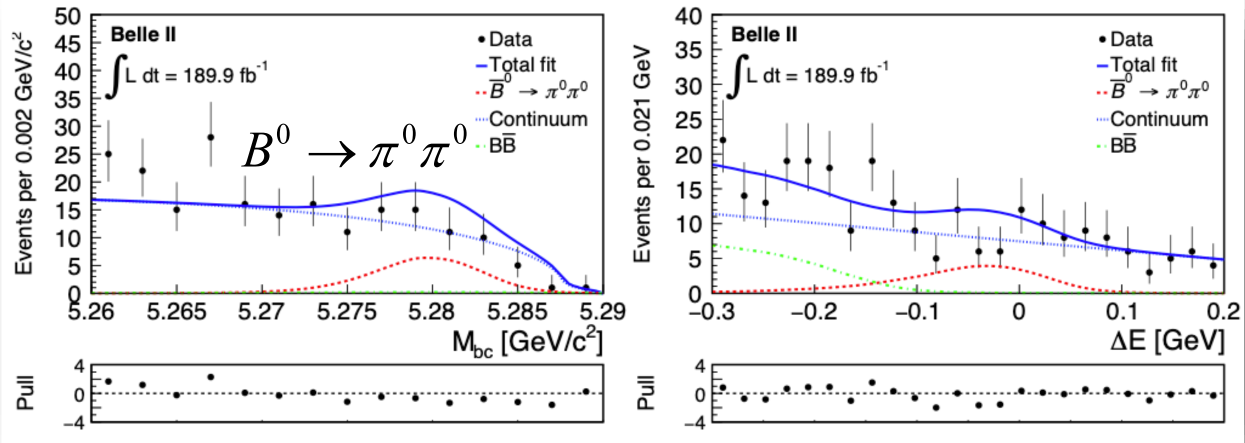

*: quantity in $e^+e^-$ CMS, arXiv:2305.19116, submitted to PRD

# $B \to \pi\pi$ Br and $A_{CP}$ Studies

- Belle II measures $B \to \rho\rho, \pi\pi$ properties with isospin analysis: *Br* and $A_{CP}$ used to reduce hadron uncertainties in CKM α (loop process).
- $B \to \rho\rho$: arXiv: 2206.12362, 2208.03554
- $B \to \pi\pi$: Moriond 2023, Phys. Rev. D 107, 112009 (2023)

| | |
|---|---|
| $362\,\text{fb}^{-1}$ | $Br(B^0 \to \pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$ |
| | $Br(B^+ \to \pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$ |
| | $A_{CP}(B^+ \to \pi^+\pi^0) = -0.081 \pm 0.54 \pm 0.008$ |
| $189.9\,\text{fb}^{-1}$ | $Br(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$ |
| | $A_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$ |



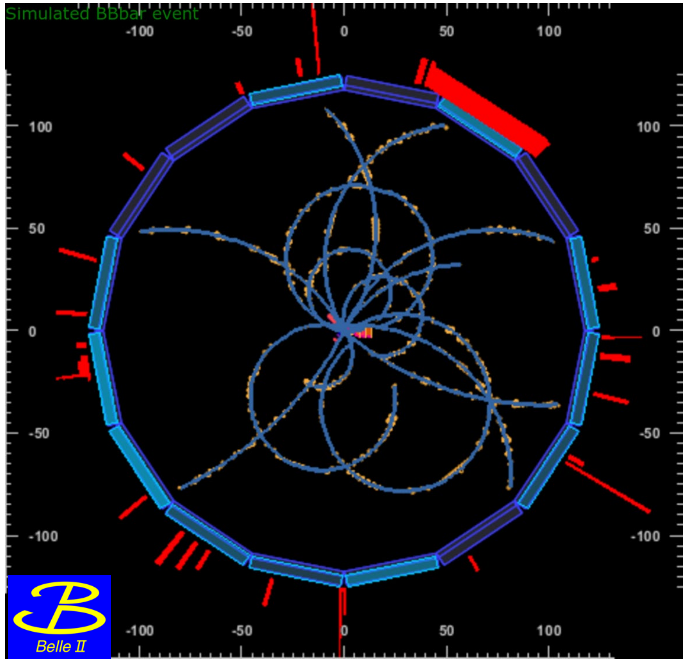
# Belle II & Related LP 2023 Physics Subjects

- Michele Veronesi "Recent Belle II results on time-dependent CP violation and charm physics"
- Xiaodong Shi "Recent Belle II results on hadronic B decays"
- Niharika Rout "Recent Belle II results on radiative and electroweak penguin decays"
- Kazuki Kojima "Recent Belle II results on semileptonic B-decays and tests of lepton-flavor universality"
- Savino Longo "Recent dark-sector and tau physics results at Belle II"
- Yang Li "Recent quarkonium results at Belle II"

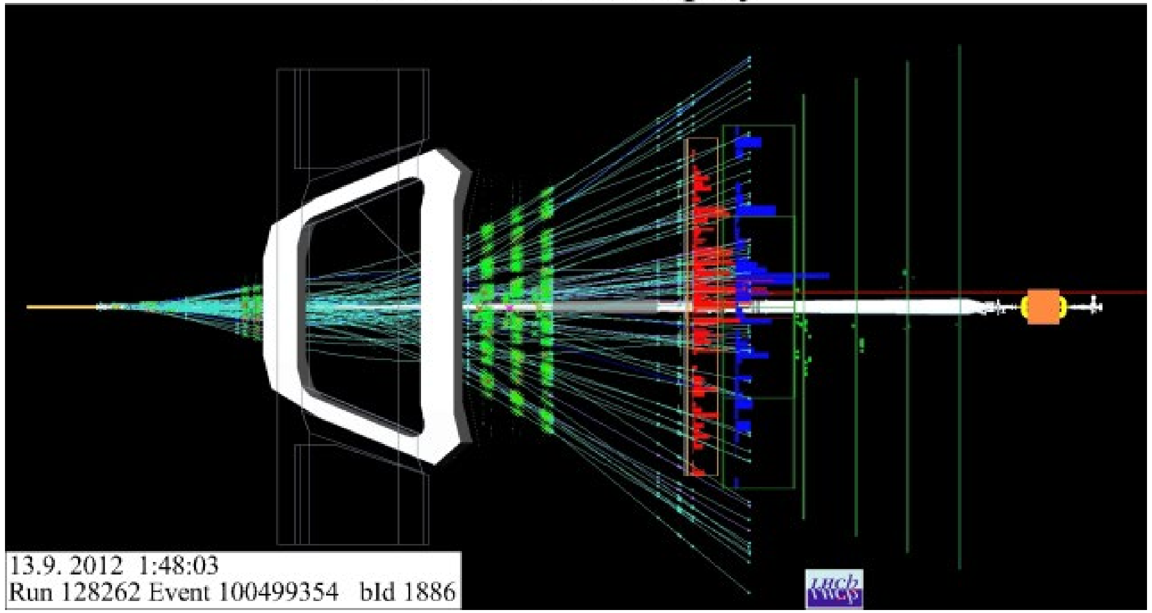
- Petar Rados "Belle II and LHCb Upgrade I performance"
- Yuehong Xie (Belle II & LHCb) "CP violation on heavy flavor physics"
- Chunhui Chen "Semileptonic b-hadron decays (Belle II / LHCb)"
- Changzheng Yuan (BESIII, Belle/Belle II, LHC exps.) "Heavy flavour spectroscopy"

# 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.



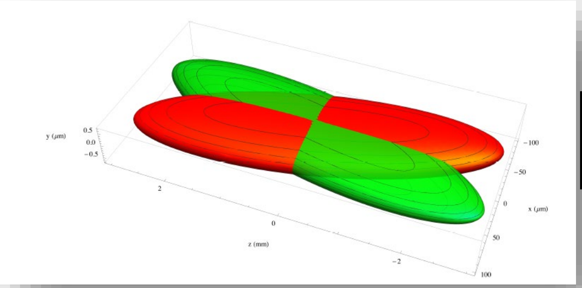

LHCb Event Display



# KEKB to SuperKEKB: Accomplished

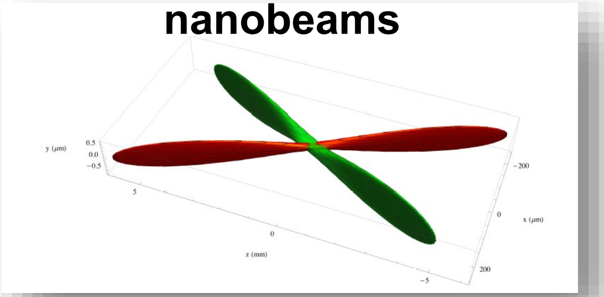
- Nano beam scheme + Crab waist optics
- Target: vertical beta function $\beta_y^*$ 5.9 mm (KEKB) to 0.3 mm (SuperKEKB)
- Increase beam currents $I_{e\pm}$
- Increase beam-beam interaction $\xi_y$

**KEKB beams**

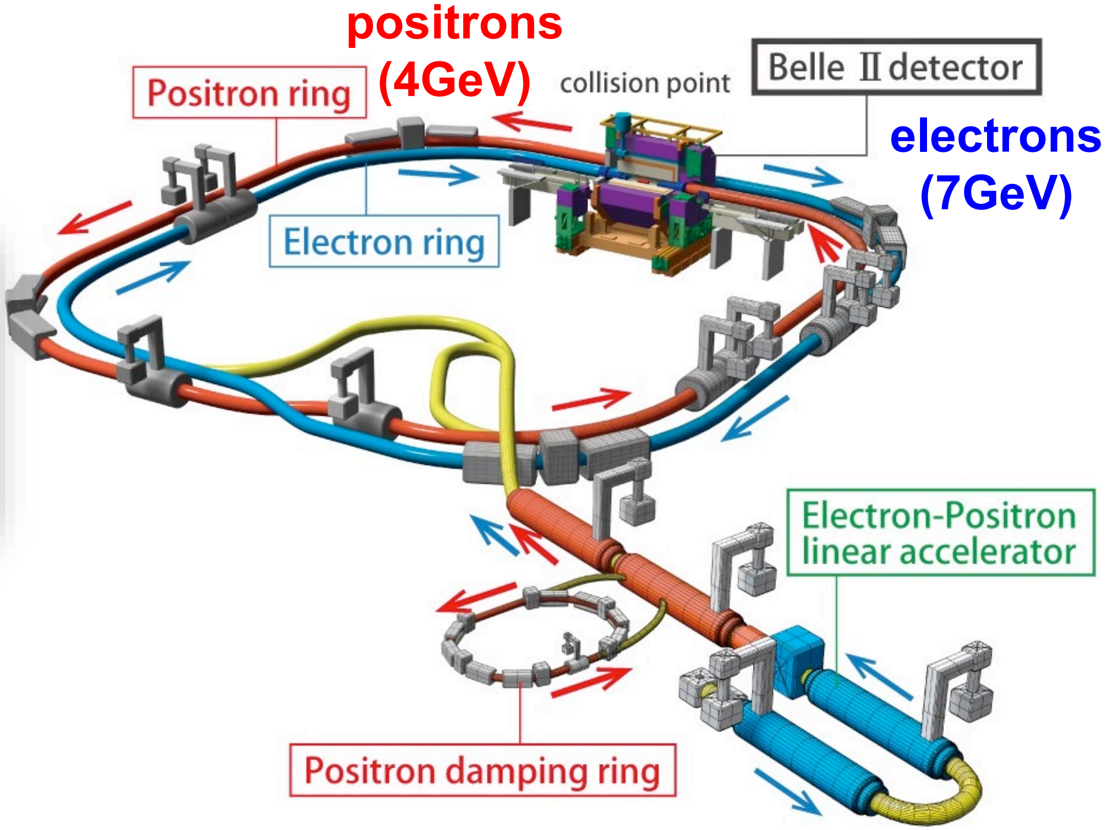


Beam crossing angle 22mrad

**SuperKEKB nanobeams**



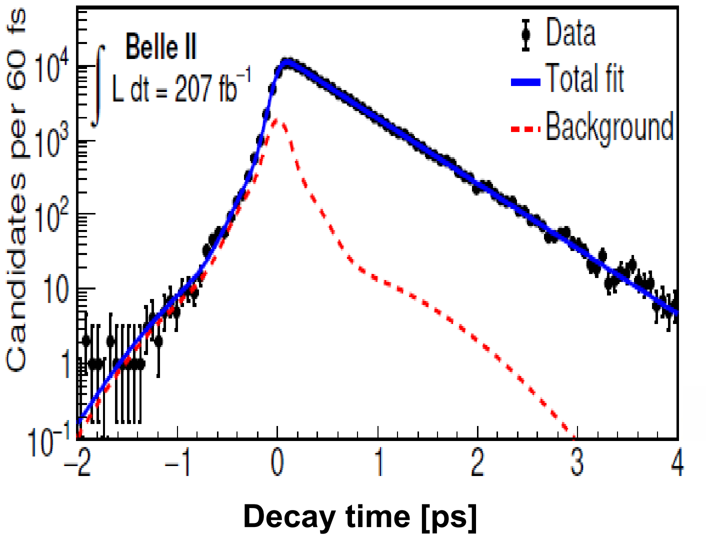
Beam crossing angle 83mrad



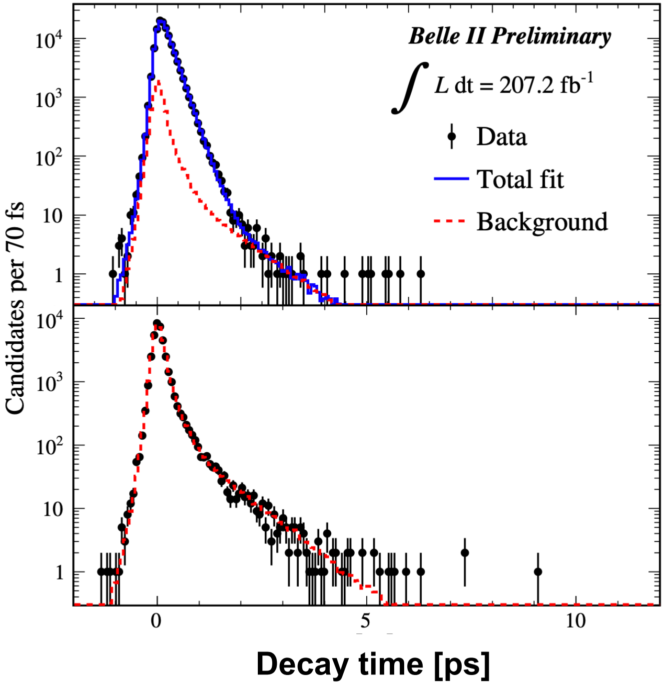

$$L = \frac{\gamma_{e\pm}}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\cdot\xi_{y,e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

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

$D_s^+ \to \phi\pi^+$

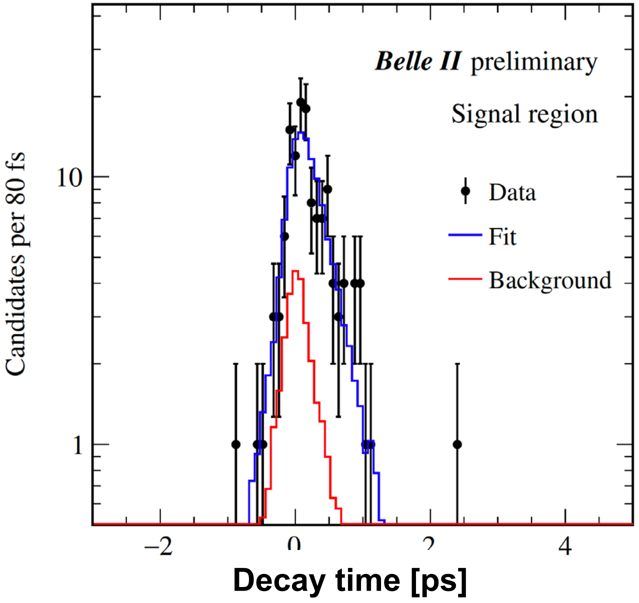



$\Lambda_c^+ \to pK^-\pi^+$




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

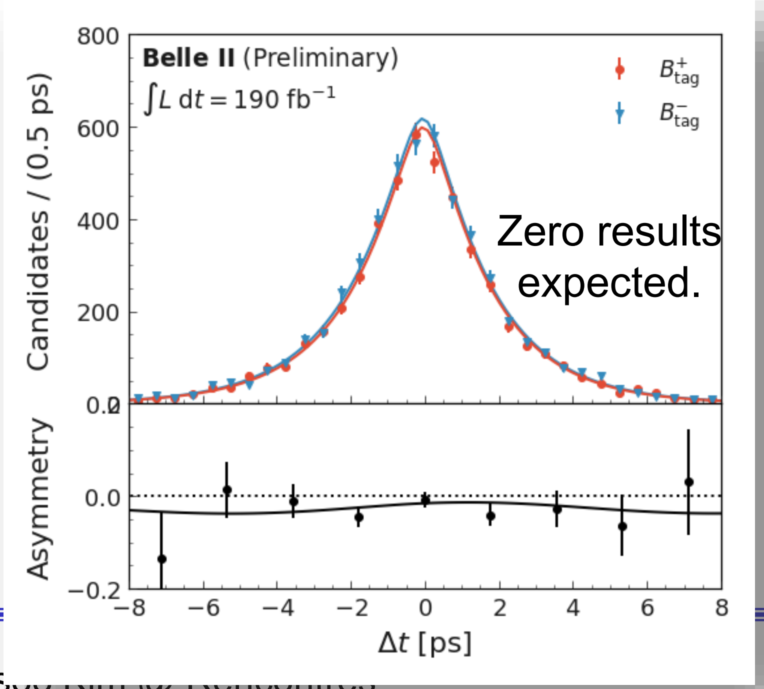
$\Omega^- \to \Lambda^0 K^-, \quad \Lambda^0 \to p\pi^-$



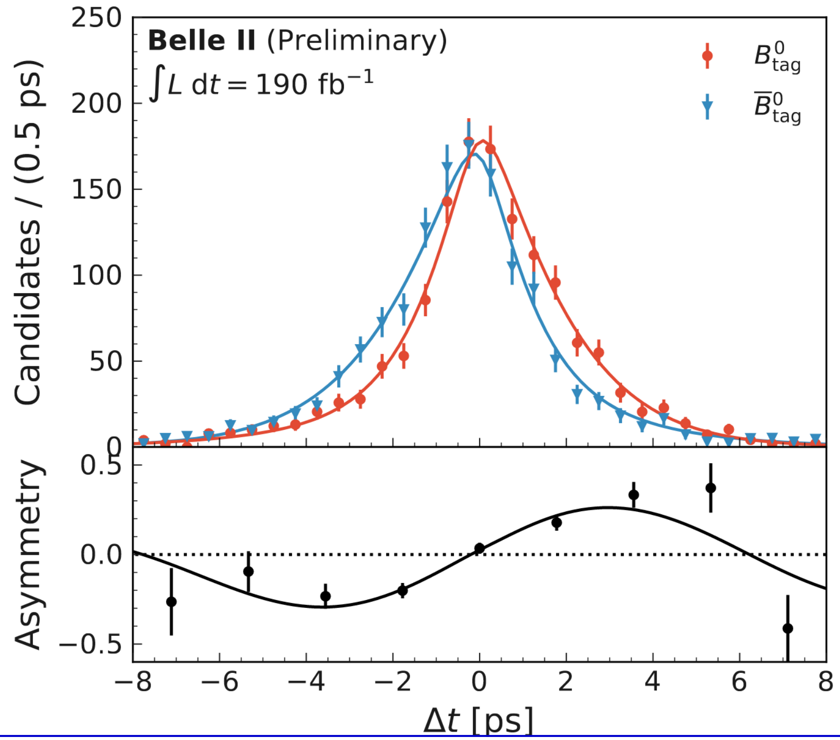
# Meanwhile, Validate sin 2β Method

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




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

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