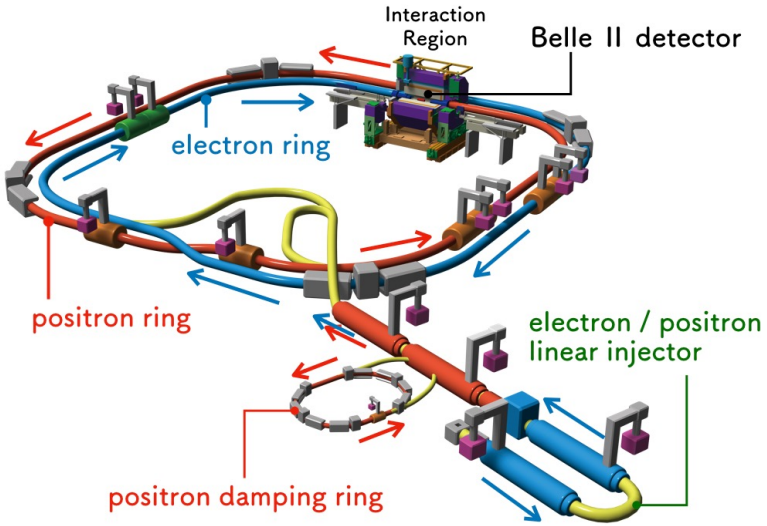
CP Violation and Charmless B Decays at Belle II

Chunhui Chen
Iowa State University
On behalf of the Belle II Collaboration
20th conference on Flavor Physics and CP violation
May 23-27, 2022

SuperKEKB and Belle II

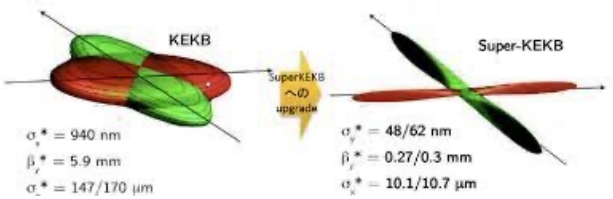


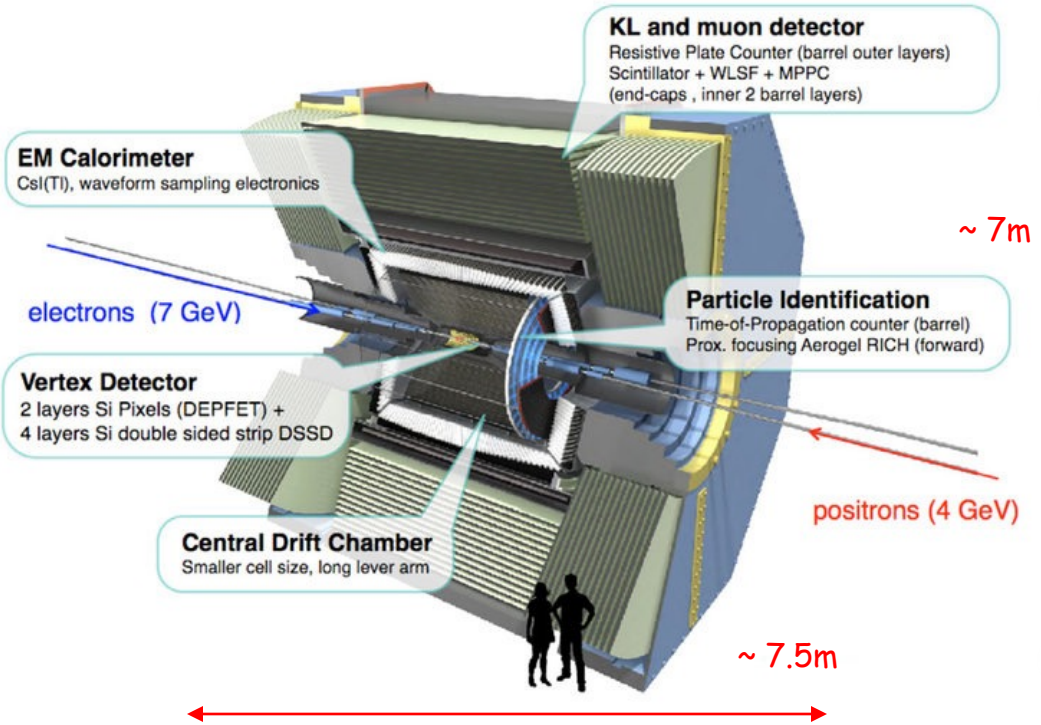
Asymmetric e^+e^- collider with CM energy at $\Upsilon(4S) = 10.58$ GeV resonance

$\Upsilon(4S) \to B^+B^-$ (~51.5%), $\Upsilon(4S) \to B^0\bar{B}^0$ (~48.5%)

Belle II is a general purpose 4π detector
Good charged tracking reconstruction efficiency, gamma reconstruction, and particle identification for kaon, pion, proton, electron, muon and K_L

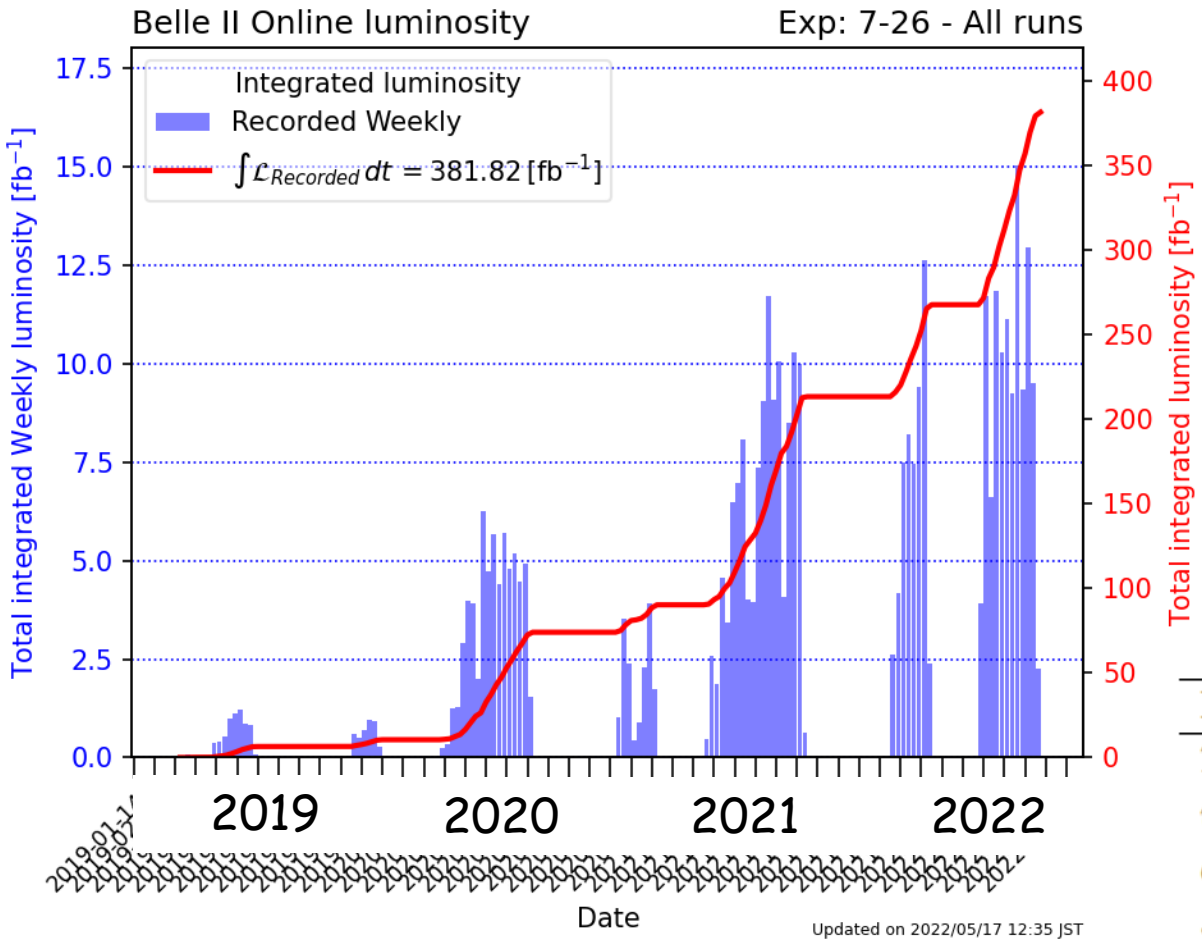
Design instantaneous luminosity: 6.5×10^{35}cm^{2}s^{-1}
30 times higher than its predecessor KEKB
Achieved: 4.14×10^{34}cm^{2}s^{-1}





L1 Trigger: CDC+ECL+TOP+KLM
Maximum L1 DAQ: 30kHz
Inclusive trigger: ~ 100% efficiency

Belle II Luminosity



Data taking efficiency ~ 90%

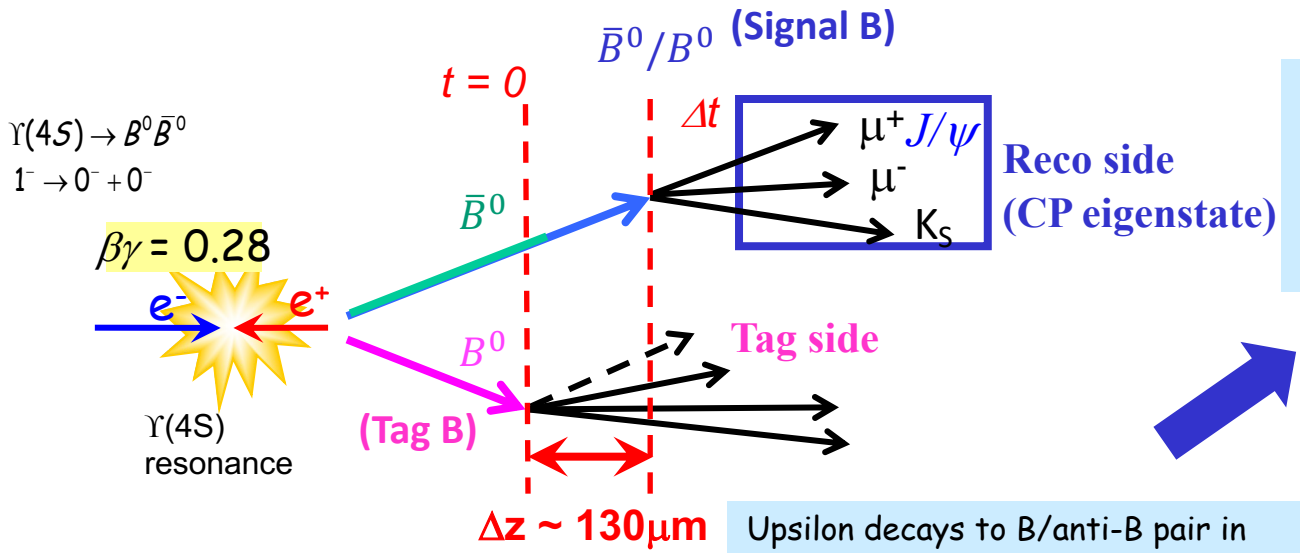
Recorded Lumi ~ 382 fb^{-1}
Expected total 50 ab^{-1}

Belle Lumi ~ 1 ab^{-1}
Babar Lumi ~ 500 fb^{-1}

Physics process	Cross section [nb]
$\Upsilon(4S)$	1.110 ± 0.008
$u\bar{u}(\gamma)$	1.61
$d\bar{d}(\gamma)$	0.40
$s\bar{s}(\gamma)$	0.38
$c\bar{c}(\gamma)$	1.30

- Belle II has a broad and comprehensive physics program
  - ✓ CP violation in B meson decays is only one part of program
  - ✓ This talk only covers few selected recent analysis results

How to measure CP Violation



After a time Δt, the second B (call it signal B) decays into a CP or flavor eigenstate that is fully reconstructed

(Δt can be negative)

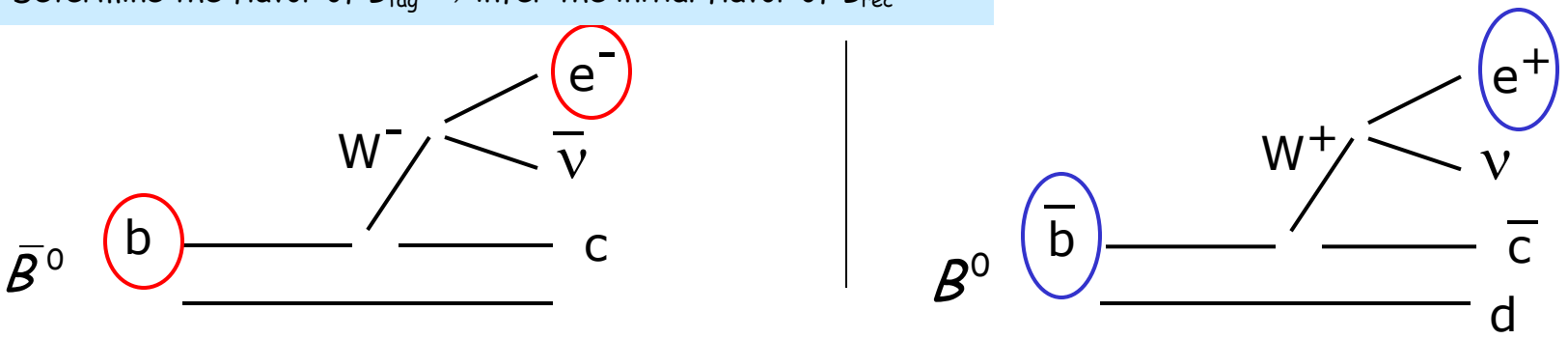
$$\Delta t = \frac{\Delta z}{\beta\gamma c}, \qquad \sigma(\Delta t) \sim 70\mu m$$

Upsilon decays to B/anti-B pair in coherent angular momentum state

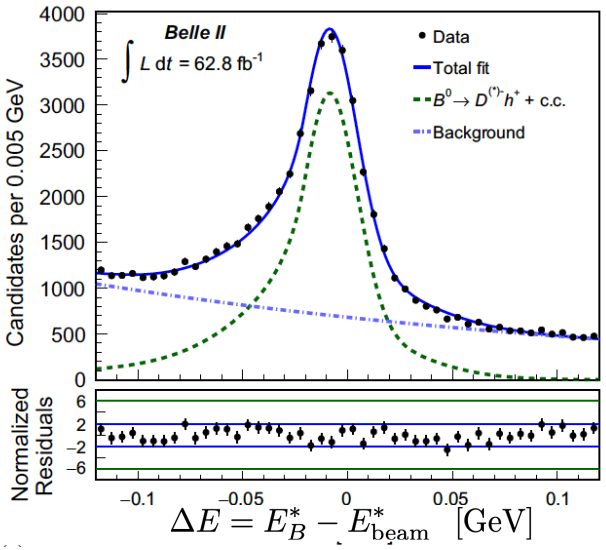
Electron and positron collide producing an Upsilon meson boosted in the lab frame

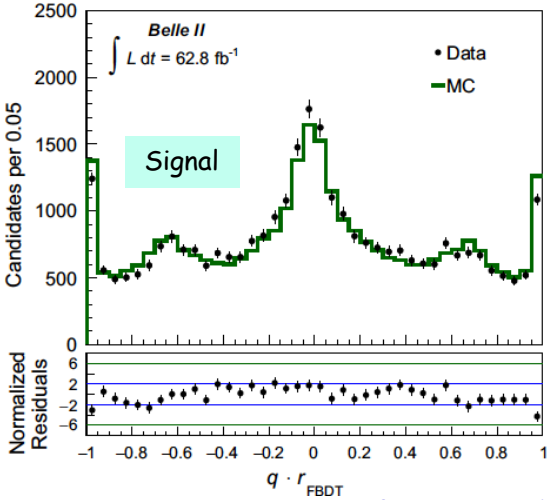
(same technique used for all time-dependent CP analyses)

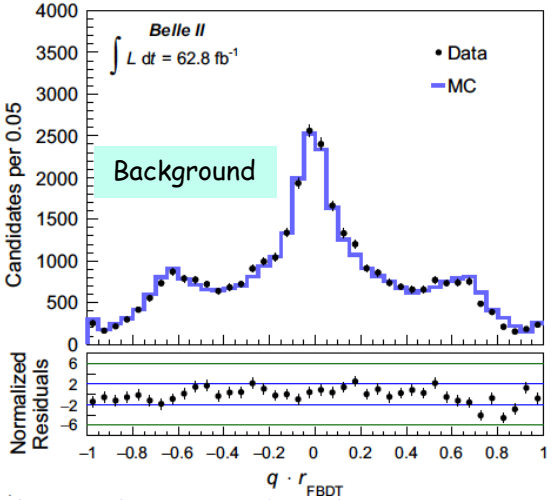
- Flavor tagging:
- $\Upsilon(4S)$ produces coherent $B\bar{B}$ pair, $B^0 \to$ flavor eigenstates ~ 100%
- Determine the flavor of $B_{tag} \Rightarrow$ infer the initial flavor of B_{rec}



Flavor tagging performance at Belle II







Ref: European Physical Journal C 82, 283 (2022); arXiv:2110.00790 [hep-ex];

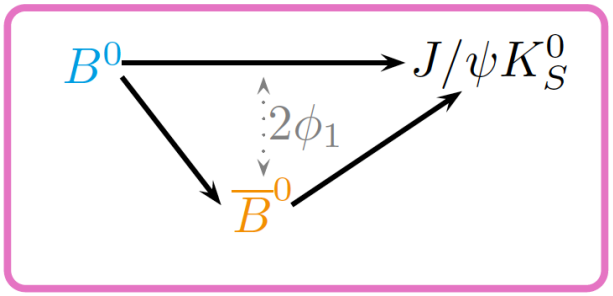
- Category based flavor tagging based on the BDT
- Calibrate using fully reconstructed flavor-eigenstate B^0 events: ~500 signal/fb^{-1}
- Time-integrated measurement

$$\epsilon_{\text{eff}} = (30.0 \pm 1.2(\text{stat.}) \pm 0.4(\text{syst.}))\% \quad \text{[BelleII]}$$
$$\epsilon_{\text{eff}} = (30.1 \pm 0.4)\% \quad \text{[Belle]}$$
$$\epsilon_{\text{eff}} = (31.2 \pm 0.3)\% \quad \text{[Babar]}$$

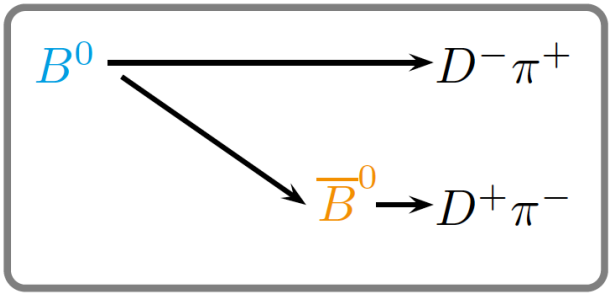
$$\epsilon = \frac{\epsilon_{B^0} + \epsilon_{\bar{B}^0}}{2} \qquad w = \frac{w_{B^0} + w_{\bar{B}^0}}{2}$$
$$\Delta\epsilon = \epsilon_{B^0} - \epsilon_{\bar{B}^0} \qquad \Delta w = w_{B^0} + w_{\bar{B}^0}$$
$$\mu = \Delta\epsilon/(2\epsilon)$$
$$\epsilon_{\text{eff}} = \sum_i \epsilon_{\text{eff,i}} = \sum_i \epsilon_i \cdot (1 - 2w_i)^2$$

- Sys error dominated by MC statistics
- Expect improvement of performance
  - ✓ Improve the current PID performance at Belle II

Time-dependent Analysis



CPV due to interference between mixing and decay



$B^0/\bar{B}^0$ Mixing

$$\mathcal{A}_{CP}(t) = \frac{N(B^0 \to f_{CP}) - N(\overline{B}^0 \to f_{CP})}{N(B^0 \to f_{CP}) + N(\overline{B}^0 \to f_{CP})}(t) = (S_{CP}\sin(\Delta m_d t) + A_{CP}\cos(\Delta m_d t))$$

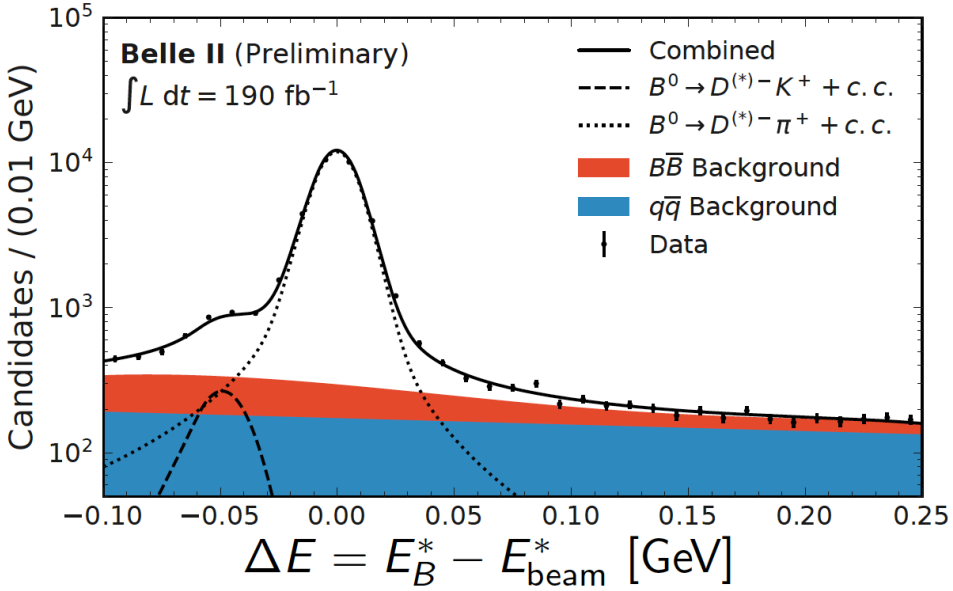
S: mix induced CP violating parameter, A: direct CP violating parameter

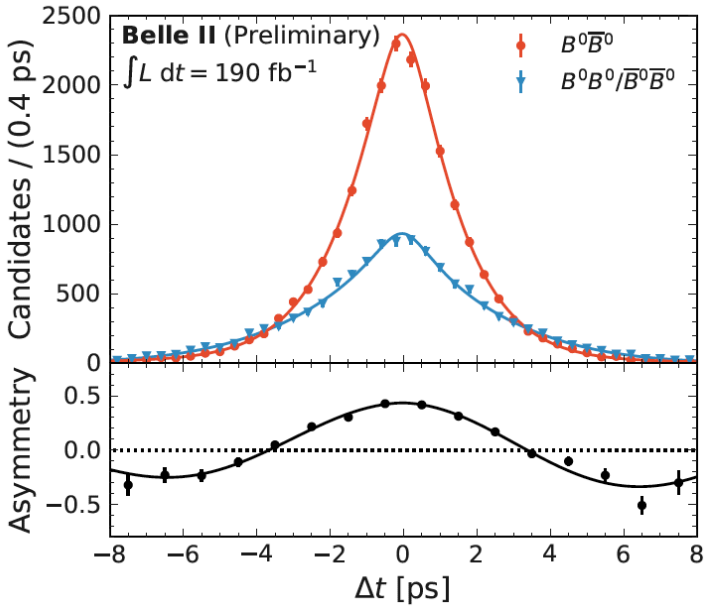
Precision Measurement of mixing parameter and lifetime is critical to time-dependent CPV measurements

$$\text{mix}(t) = \frac{N(B^0 \to B^0) - N(B^0 \to \overline{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \overline{B}^0)}(t) = \cos(\Delta m_d t)$$

- Vertex resolution for decay time measurement
- Flavor tagging calibration and validation

Mixing and Lifetime measurement





Also see: BELLE2-TALK-CONF-2022-031

- Using hadronic $B^0 \to D^{(*)-}\pi^+/K^+$ final states: ~ 40K signal yields
- Distinguish signal and background (bg) using ΔE and event-shape multivariate classifier
  - ✓ Subtract bg from sideband (sWeights) to obtain bg-free signal sample
  - ✓ Fit signal Δt distribution with wrong-tag fraction and vertex resolution model
- Result consistent with the world average

$$\tau_{B^0} = 1.499 \pm 0.013(\mathrm{stat.}) \pm 0.008(\mathrm{syst.})\ \mathrm{ps} \qquad \tau_{B^0} = 1.519 \pm 0.004\ \mathrm{ps} \quad [\mathrm{PDG}]$$

$$\Delta m_d = 0.516 \pm 0.008(\mathrm{stat.}) \pm 0.005(\mathrm{syst.})\ \mathrm{ps}^{-1} \qquad \Delta m_d = 0.5065 \pm 0.0019\ \mathrm{ps}^{-1} \quad [\mathrm{PDG}]$$

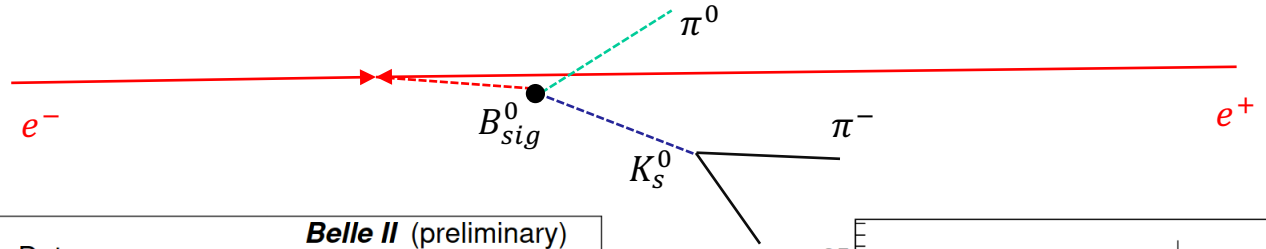
- Important milestone: we are ready for time-dependent analysis

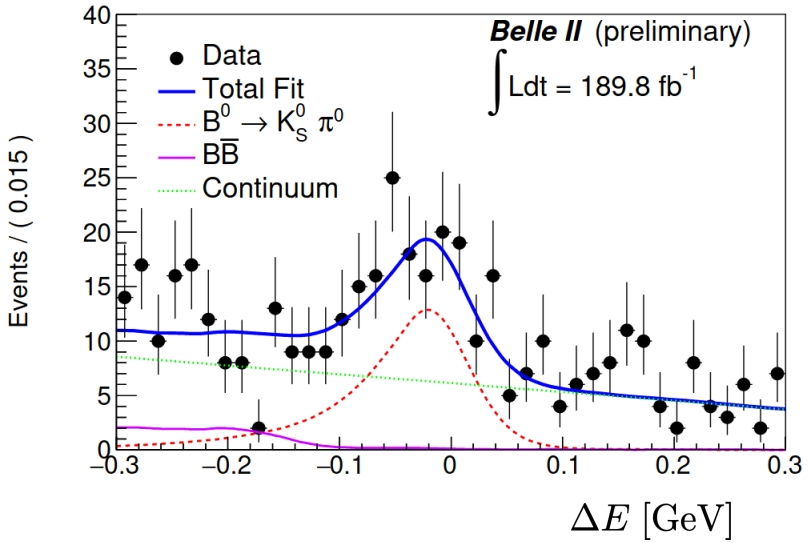
CP Violation of $B^0 \to K_s \pi^0$

- Test new physics based on isospin sum-rule

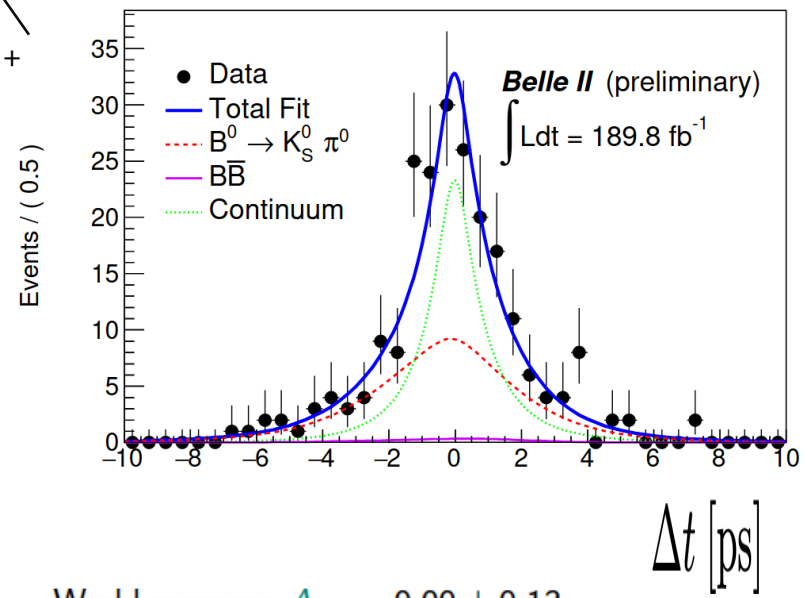
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- Uncertainty of $I_{K\pi} = 0$ test dominated by $A_{CP}(B^0 \to K_S\pi^0)$: only feasible at Belle II
- Time-dependent analysis needs good vertex measurement with beam spot constraint
  - ✓ Using $B^0 \to J/\psi K_S$ to calibrate Δt resolution and bias





$$A_{CP} = -0.41^{+0.30}_{-0.32}\,(\text{stat.}) \pm 0.09\,(\text{syst.})$$
$$\mathcal{B} = (11.0 \pm 1.2\,(\text{stat.}) \pm 1.0\,(\text{syst.})) \times 10^{-6}$$



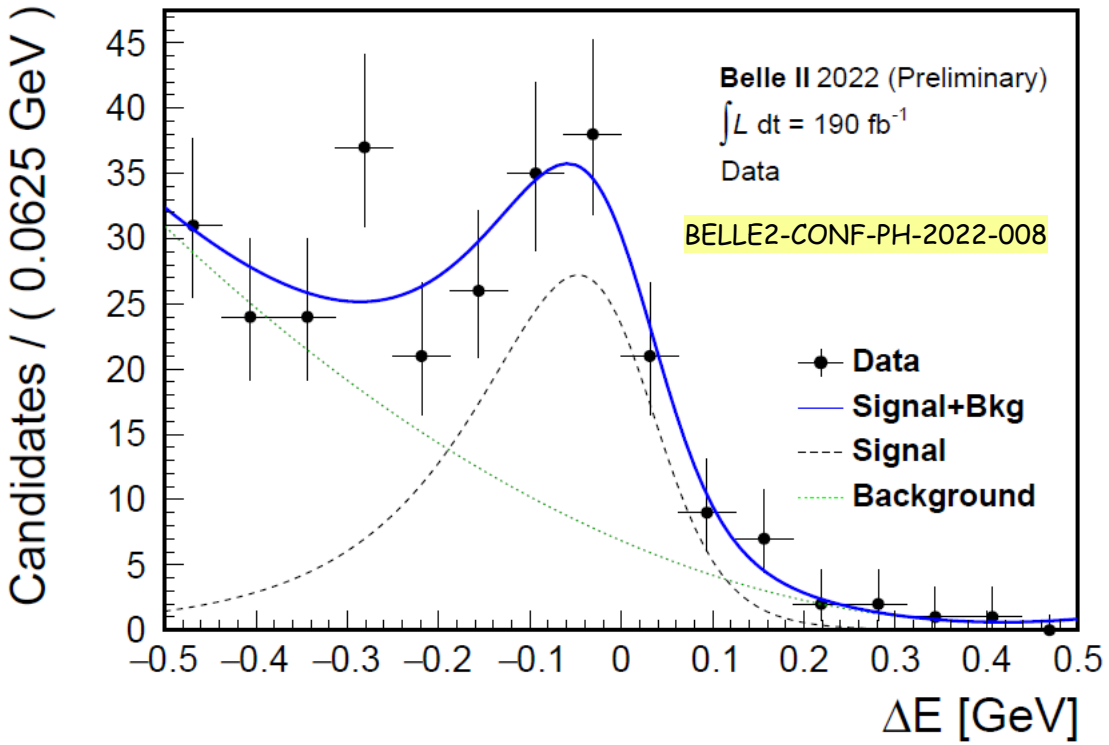
World average: $A_{CP} = 0.00 \pm 0.13$.

Also see: BELLE2-TALK-CONF-2022-031

Decay of $B^0 \to K_s \pi^0 \gamma$

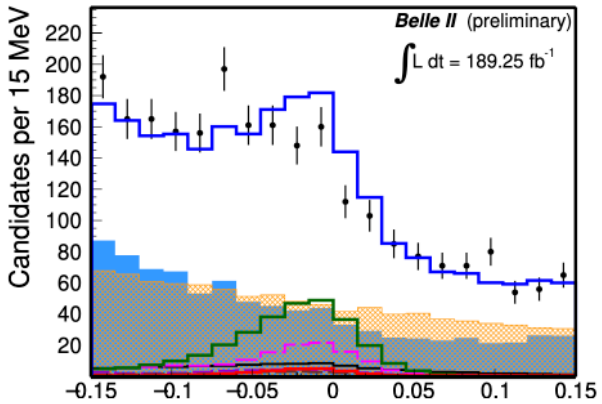
- No time-dependent CP asymmetry in the SM
  - ✓ Right (Left) handed photon in $B^0 \to K_s\pi^0\gamma$ ($\bar{B}^0 \to K_s\pi^0\gamma$)
- Possible non-zero CP asymmetry from NP contribution
- Similar challenge for time-dependent analysis as $B^0 \to K_s\pi^0$
  - ✓ Still on going
  - ✓ Branching fraction measurement compatible to the world average

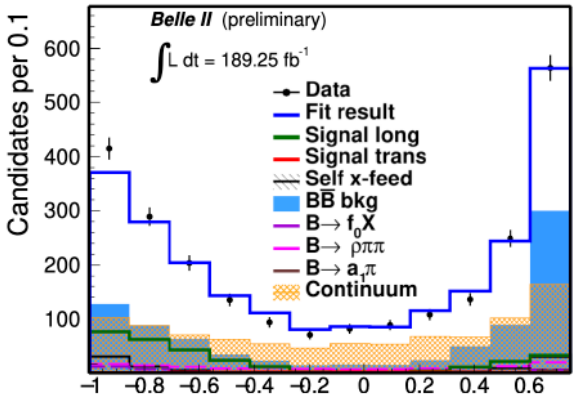
$$\mathcal{B} = (7.3 \pm 1.8(\text{stat.}) \pm 1.0(\text{syst.})) \times 10^{-6}$$
$$\mathcal{B} = (7.0 \pm 0.4) \times 10^{-6} \quad [\text{PDG}]$$

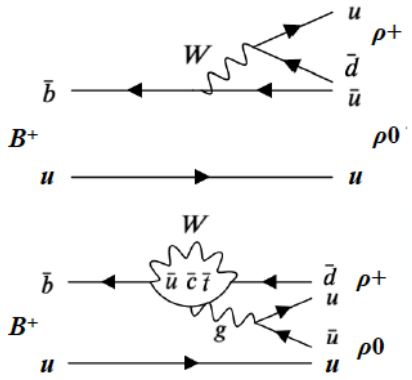


$B^+ \to \rho^+\rho^0\ (\rho^+ \to \pi^+\pi^0, \rho^0 \to \pi^+\pi^-)$

- Measure CKM angle ϕ_2/α using hadronic $B \to \rho\rho\ (\rho^0\rho^0, \rho^+\rho^-\rho^\pm\rho^0)$ final states
- Possible direct CP violation due to interference between tree and penguin diagram
- Measure longitudinal polarization f_L using angular distribution
  - ✓ Helicity angle distribution $\cos\Theta$: angle between π^+ momentum and opposite momentum of B^+ measured in ρ rest frame
- 6D template fit taking into account of correlation
  - ✓ M_{bc} , $\cos\Theta$, ΔE, $m(\pi^+\pi^-)$, $m(\pi^+\pi^0)$, event-shape multivariate classifier
  - ✓ Charge asymmetry of track reconstruction determined using $D^+ \to K_S\,\pi^+$







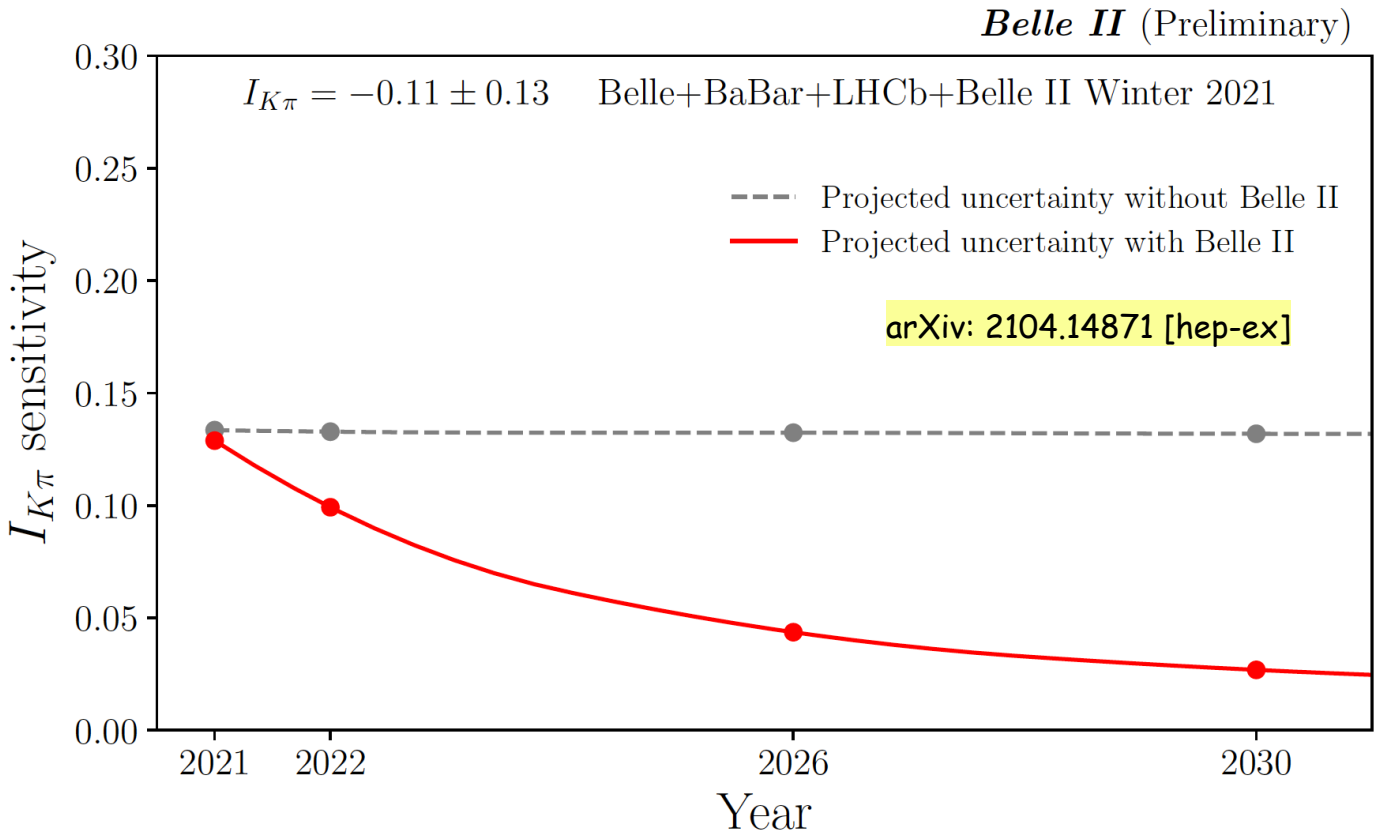
Also see: BELLE2-TALK-CONF-2022-031

$$A_{CP} = -0.069 \pm 0.068\ (\text{stat.}) \pm 0.060\ (\text{syst.})$$
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = \left(23.2^{+2.2}_{-2.1}\ (\text{stat.}) \pm 2.7\ (\text{syst.})\right) \times 10^{-6}$$
$$f_L = 0.943^{+0.035}_{-0.033}\ (\text{stat.}) \pm 0.027\ (\text{syst.})$$

World average: $A_{CP} = -0.05 \pm 0.05$

Conclusion and Prospects

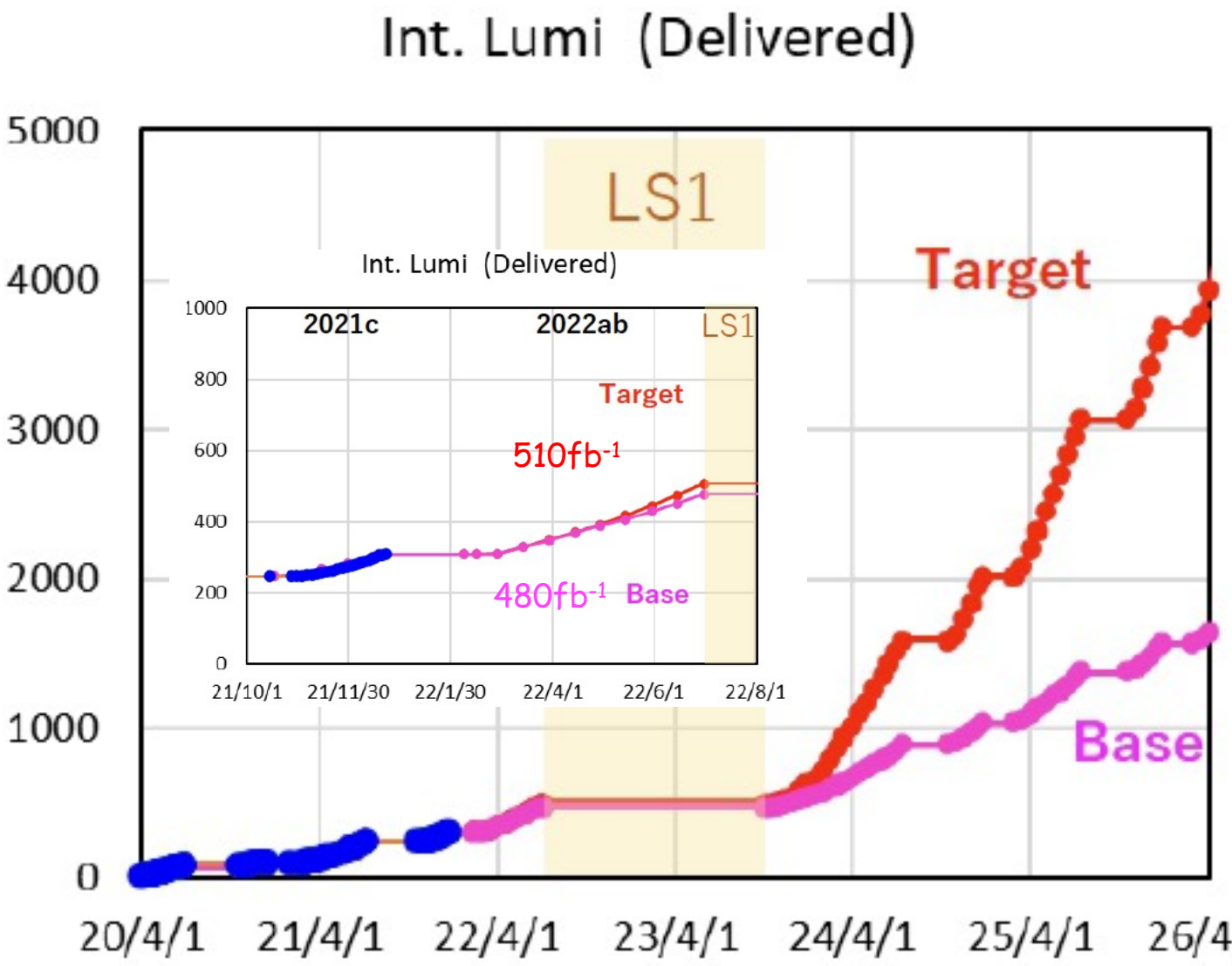
- A few selected recent results from Belle II
  - ✓ Measurement precisions are limited by the data sample
- Demonstrate key ingredients for Time-dependent analysis for CPV
- Expect exciting physics results and reach from Belle II in the future



Projection corresponding to the luminosity plan from LHCb and Belle II

Backup

Short-term SuperKEKB Plan



Long Shutdown (LS) 1 staring summer 2022 to fall 2023 to replace VXD

LS2 shutdown under discussion for machine improvement between 2026-27