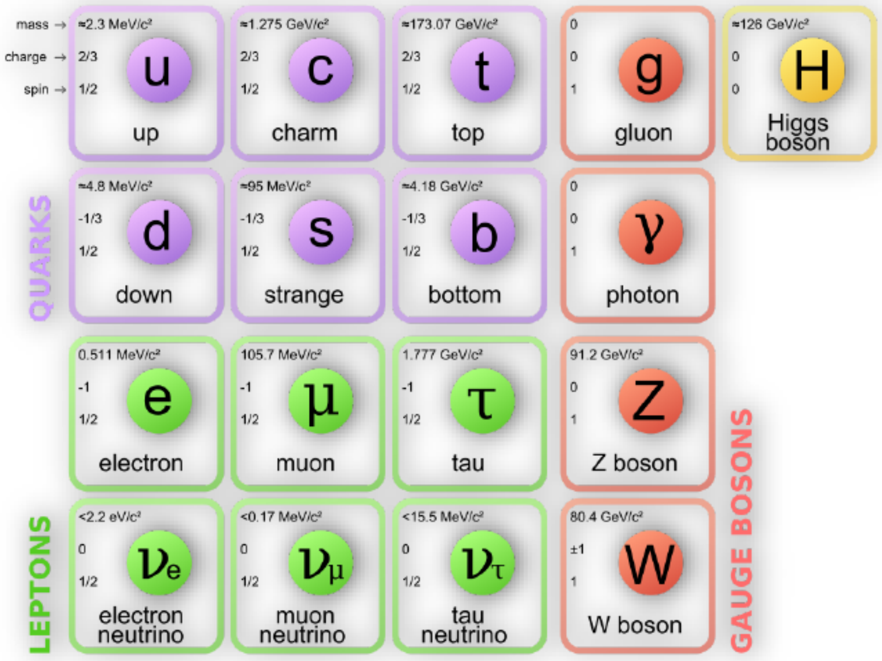
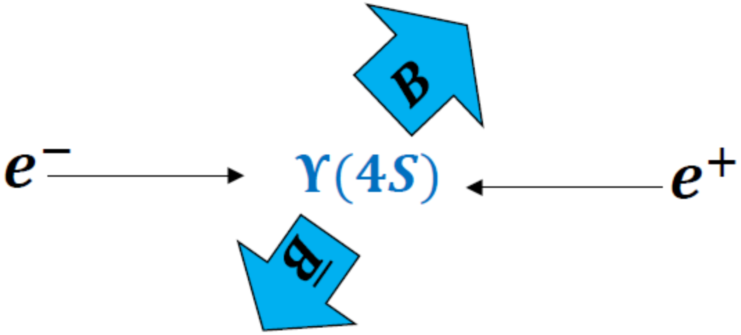
Recent results of B physics at Belle II

Chengping Shen (Fudan University)

The Shanghai Symposium on Particle Physics and Cosmology (SPCS 2026)

Asymmetric e^+e^- B Factories: Concept

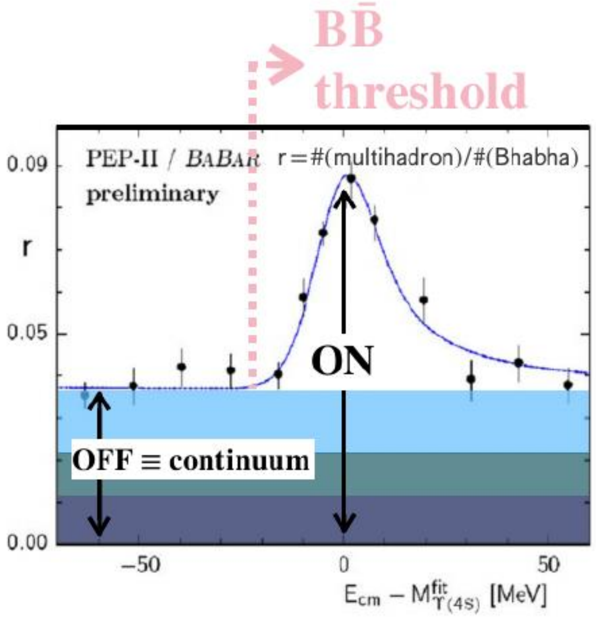


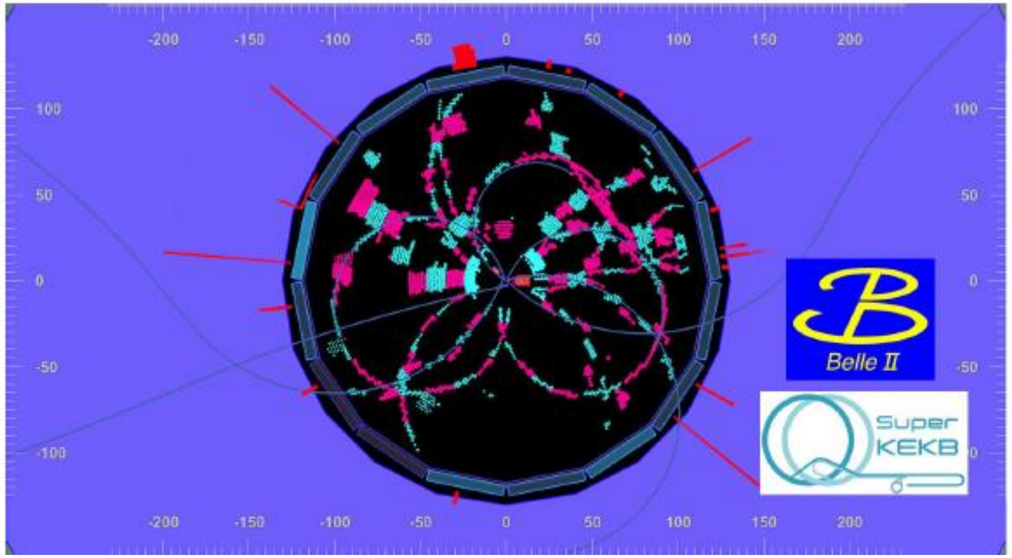


- Mass of B meson ($b\bar{q}$) is around 5~6 GeV.
  - B pairs can be generated plentifully using ~11 GeV $\Upsilon(4S)$ colliders
- Relatively lower energy → intensity up easily → intensity frontier
- First generation B factory
  - ARGUS/DORIS II at DESY 1982 – 1992
  - CLEO/CESR at Cornell 1979 – 2008 (including Cleo-c)
- Next, asymmetric B factory: one side flavor tag, the other side signal
  - BaBar/PEP-II at SLAC 1999 – 2008
  - Belle/KEKB at KEK 1999 – 2010
- 2nd generation asymm. B factory: Belle II/SuperKEKB at KEK 2019 –

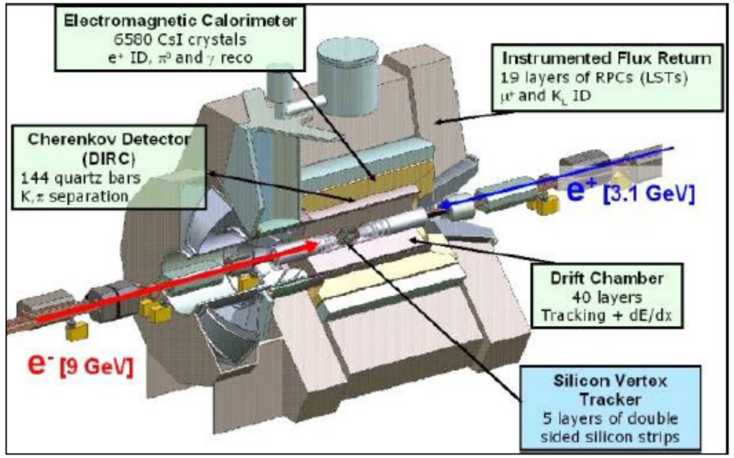
Advantages of an e^+e^- flavor factory

- Known initial kinematics and good hermeticity
  - possible to fully reconstruct events with invisible particles
- Clean environment (average 11 tracks per event)
  - efficient detection of neutrals (γ, π^0, η, ...)
- Run at the $\Upsilon(4S)$ mass just above $B\bar{B}$ threshold
  - Relatively low background
  - Data off-resonance provide control sample without $B\bar{B}$

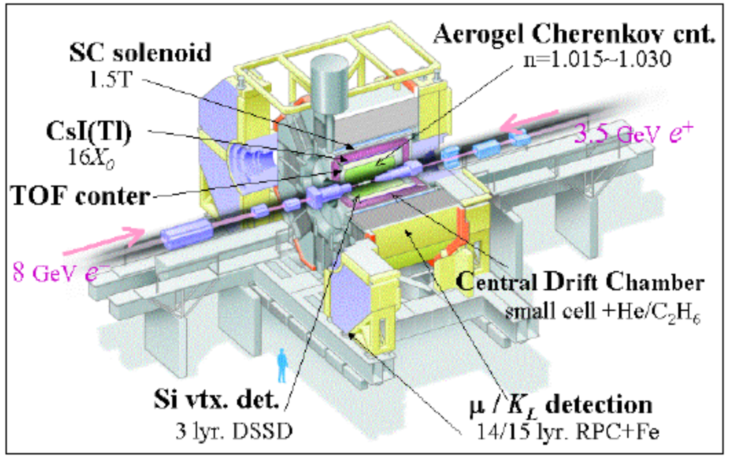




Excellent Results by Belle and BaBar

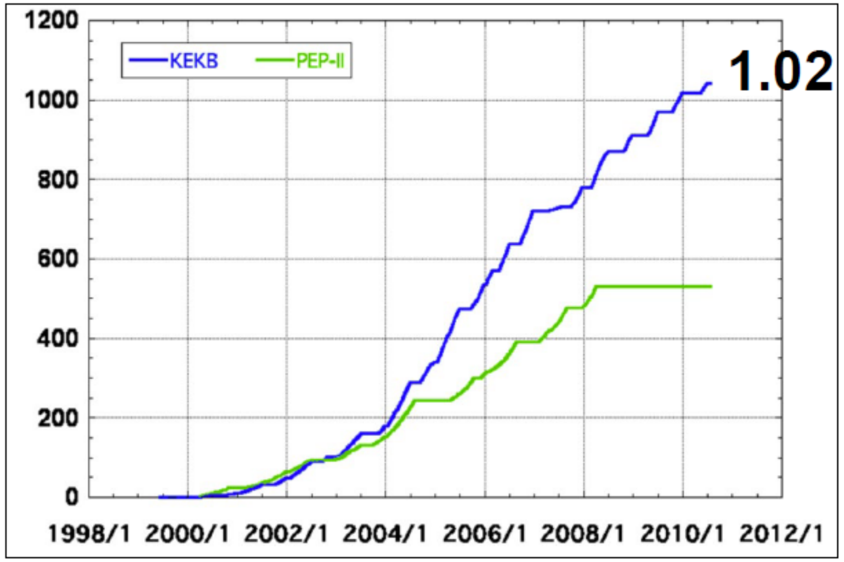


BABAR / PEP II



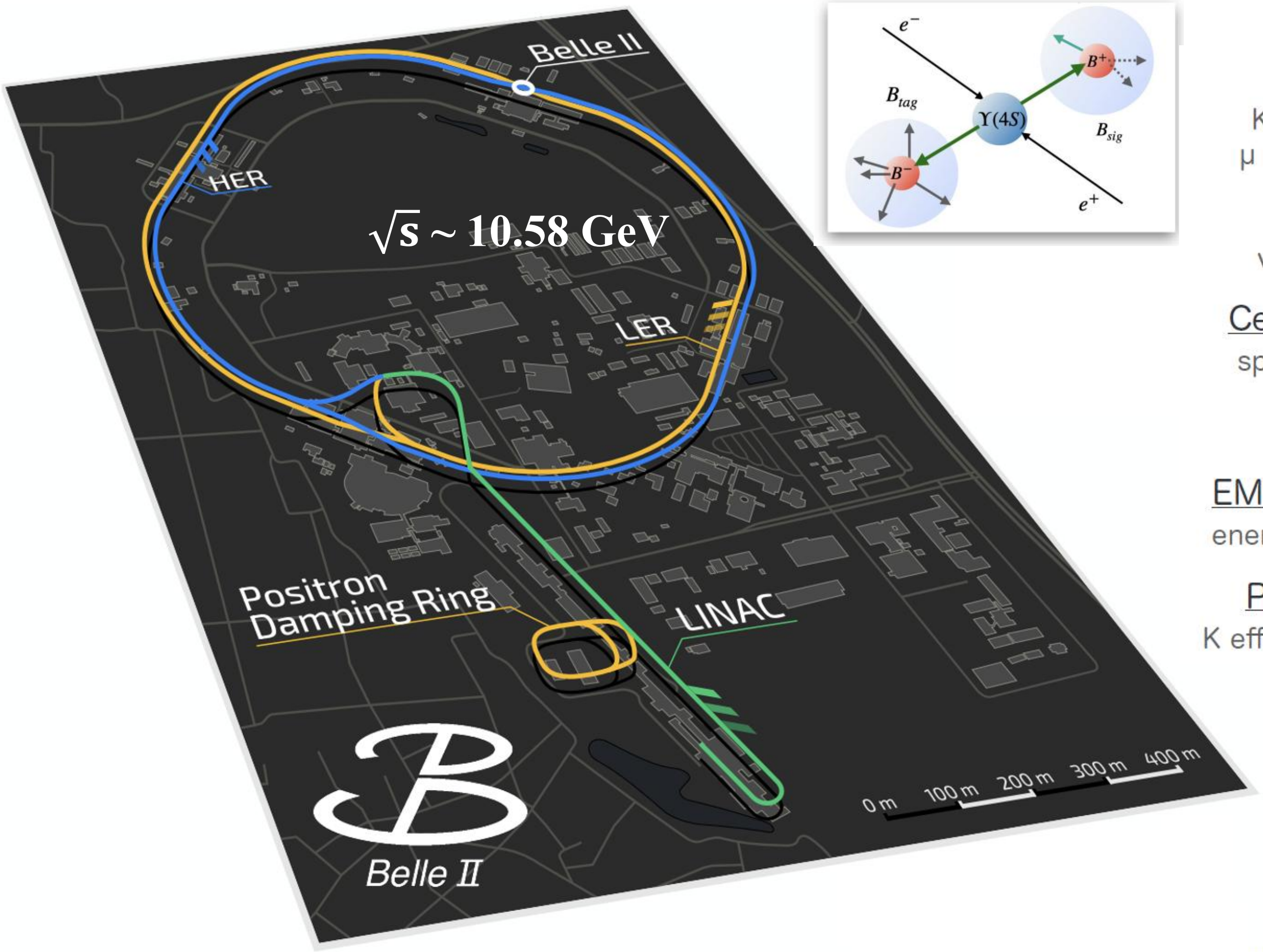
Belle / KEKB

- Two experiments confirmed CP violation in the b quark sector
  - based on the precision measurements of the CKM matrix
  - 2008 Nobel Prize for Prof. Kobayashi and Prof. Maskawa
- Discovery of X(3872) in 2003 by Belle, followed by other exotic particles
- Belle and BaBar, each published over 600 papers.
- Detectors at B-Factories show versatile physics analysis abilities



1.02 ab^{-1}

SuperKEKB and Belle II



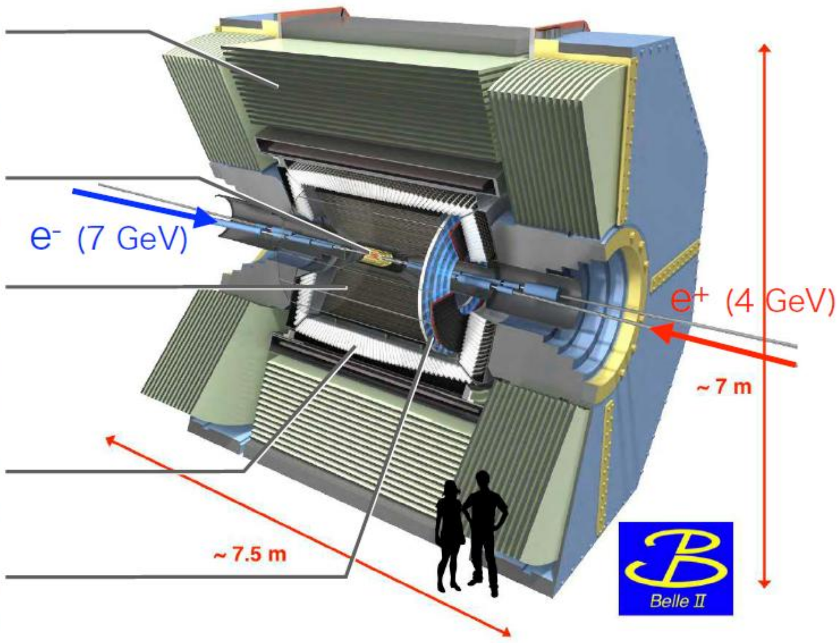
K$_L$ and μ Detection
K$_L^0$ p resolution: 15 MeV
μ identification eff.: ~90%

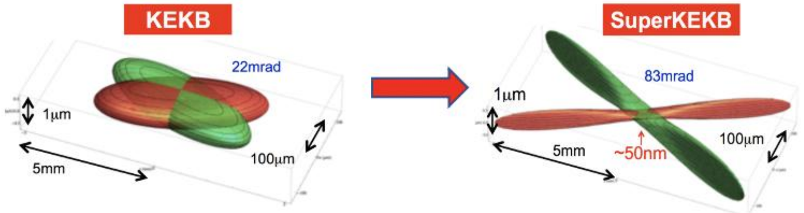
Vertex Detector
vertex resolution: 15 μm

Central Drift Chamber
spatial resolution: 100 μm
dE/dx resolution: 5%
P$_T$ resolution: 0.4%

EM Calorimeter, CsI(Tl)
energy resolution: 1.6%-4%

Particle Identification
K eff.: 90%, fake π rate: 5%





Nano-beam design: The target peak luminosity is much larger by squeezing beam sizes and enlarge beam currents.

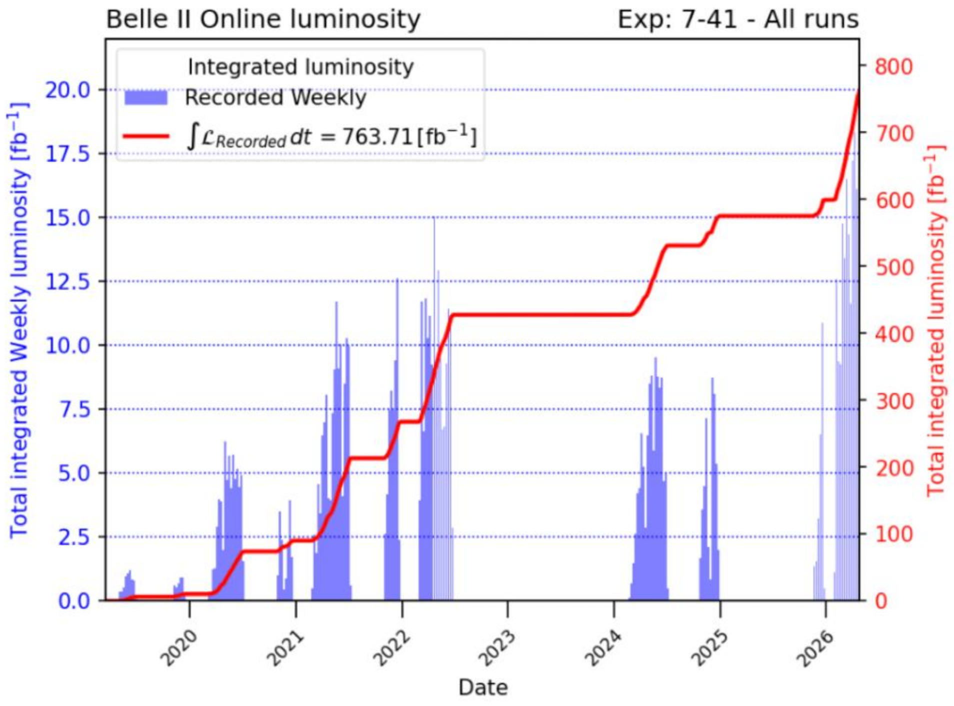
Belle and Belle II Datasets

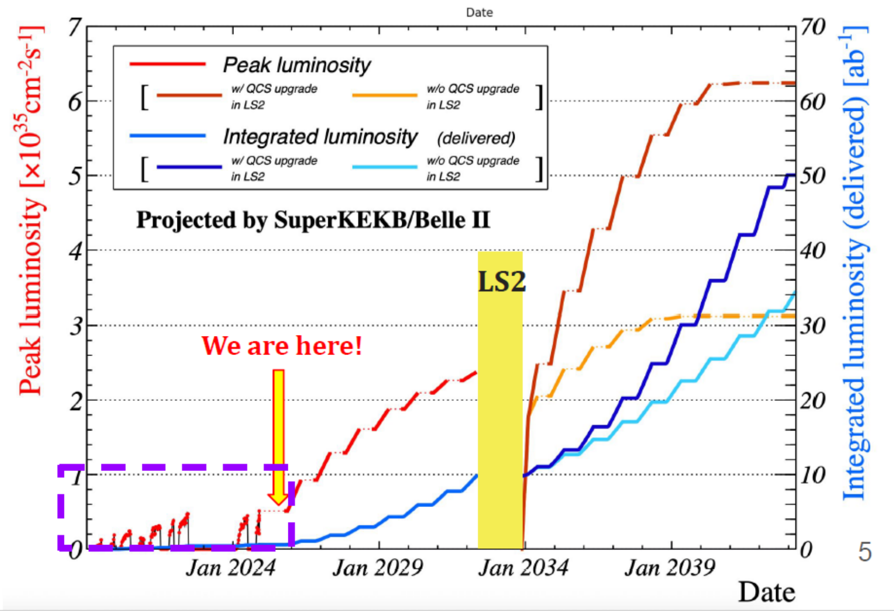
- **575 fb^{-1} data collected so far:**
  - 2019: **Run 1** data collection started (365 fb^{-1})
  - 2022.06: world record L_{inst}: **4.7 × 10^{34} cm^{-2} s^{-1}**
  - ~2023.12 **LS1,** New Collimator, 2-layer PXD, etc
  - 2024: start of **Run 2**
  - 2024.12.27 : new L_{inst} record (Belle II off) 5.2 × 10^{34} cm^{-2} s^{-1}
- Plenty of physics results with the data collected so far

- **LS2 planned for a major upgrade: 2032**
  - Targeting higher L_{inst}: 6 × 10^{35} cm^{-2} s^{-1}
  - Ultimate goal: ~ 50 ab^{-1}
  - Upgrade & Redesign of the **Interaction Region (IR)**
  - Window for upgrades of the Belle II detector

- **Belle (1999 - 2010)**

We have recorded >900/fb luminosity



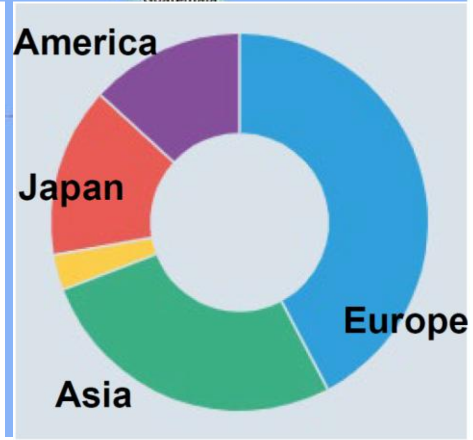


Belle II Collaboration

28 Institutes ~1200 members

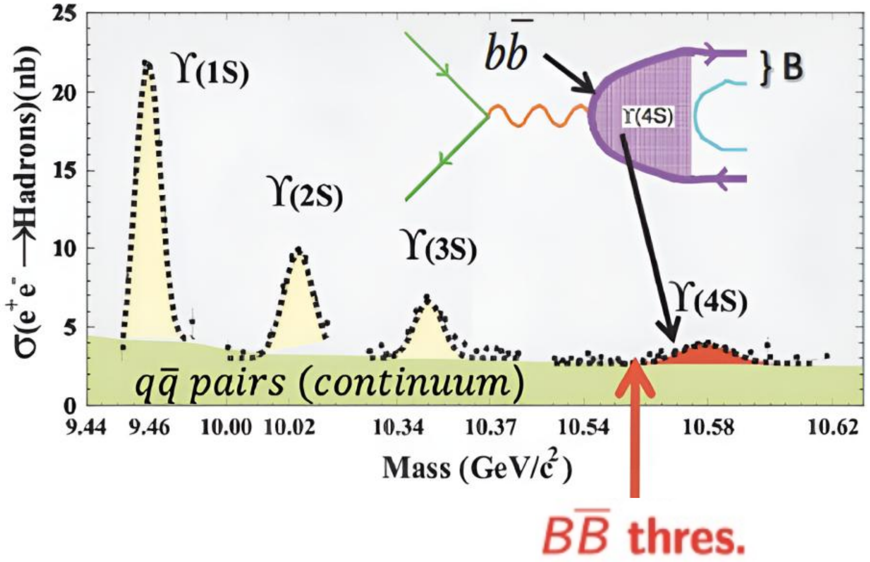
China

- Beihang: Beihang Univ.(BUAA)
- Fudan: Fudan Univ.
- HNU: Henan Normal University
- HUNNU: Hunan Normal University
- IHEP-China: Institute of High Energy Physics(IHEP)
- JLU: Jilin University
- LNNU: LiaoNing Normal University(LNNU)
- NNU: Nanjing Normal University
- Nankai: Nankai University
- SEU: Southeast University
- Shandong: Shandong University
- Soochow: Soochow University
- USTC: Univ. of Science and Technology of China(USTC)
- XJTU: Xi'an Jiaotong University
- ZZU: Zhengzhou University

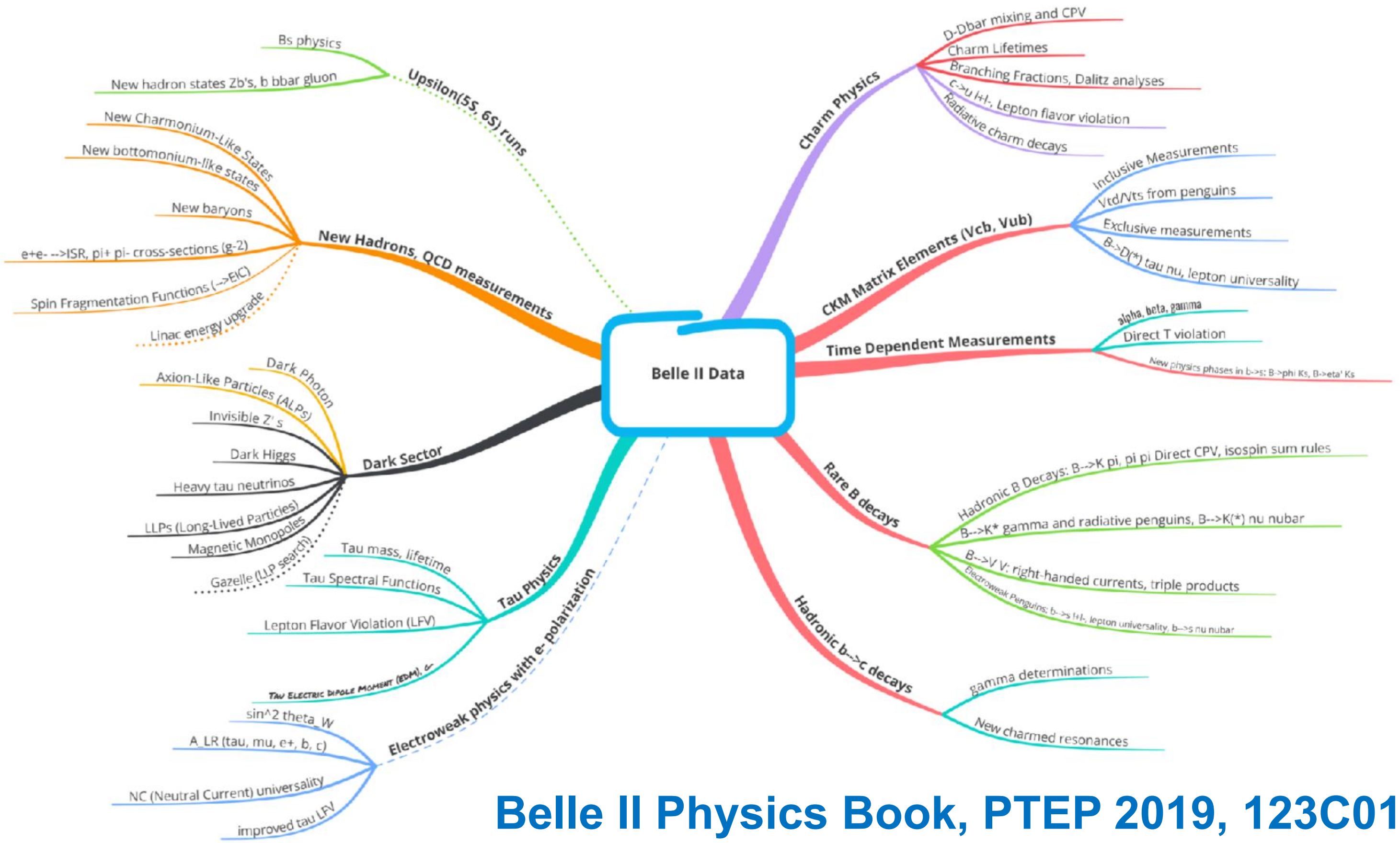


Belle II physics

The Belle II Physics Book: [PTEP 2019 (2019) 12, 123C01]



$e^+e^- \to$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3



Belle II Physics Book, PTEP 2019, 123C01

Primarily a **B factory;** But not only B physics!

- Also **tau, charm** factories
- Clean background for **spectroscopy** and searching for dark sector

Various type of analyses:

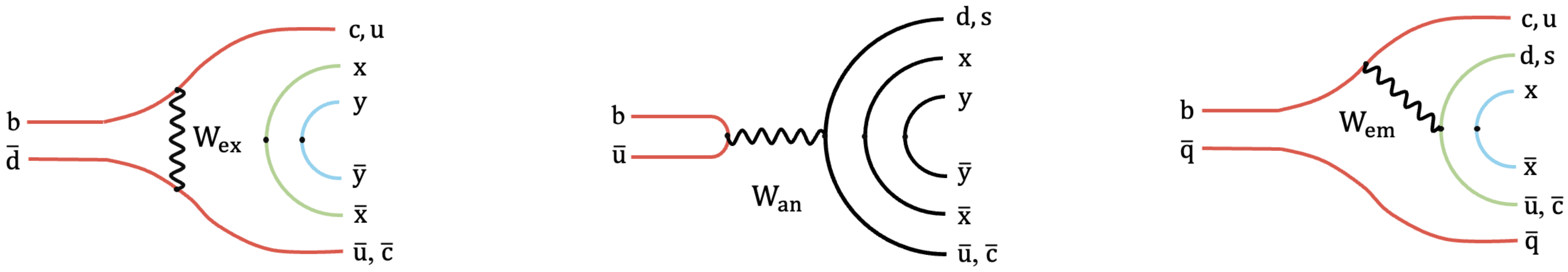
- Lifetime, time-dependent measurement
- well-suited for decays with missing energy and missing mass

Recent B results

Observation of the decay $B \to \Sigma_c(2455)\bar{\Xi}_c$

PRD 112, L051101 (2025)

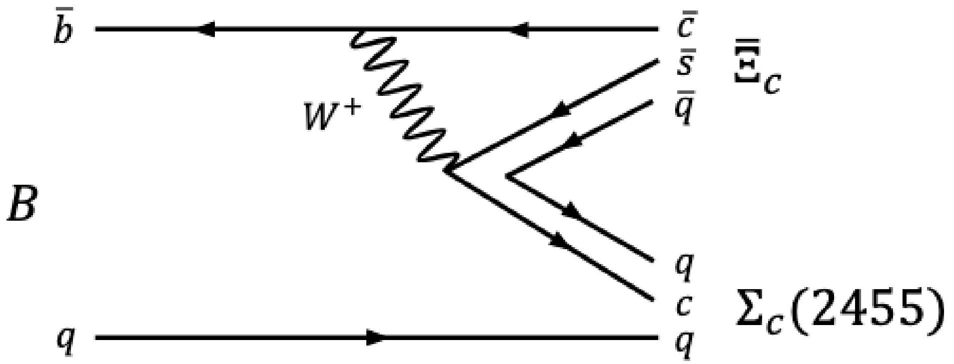
- The tree-level two-body baryonic B decays can proceed through W-exchange (W_{ex}), W-annihilation (W_{an}), and internal W-emission (W_{em}) diagrams.



W_{ex} and W_{an}: helicity suppressed W_{em}: nonfactorizable amplitude

- The decays $B \to \Sigma_c(2455)\bar{\Xi}_c$ proceed through a pure W_{em} diagram, providing a clean and ideal environment for studying nonfactorizable effects.

- The QCD sum rule predicts $\mathcal{B}(B \to \Sigma_c(2455)\bar{\Xi}_c) \sim 4 \times 10^{-3}$ [NPB 345 137 (1990)], while the diquark model estimates $\mathcal{B}(B \to \Sigma_c(2455)\bar{\Xi}_c)$ to be 30% – 70% of $\mathcal{B}(B \to \Lambda_c\bar{\Xi}_c) \sim 10^{-3}$ [ZPC 51 445 (1991)].

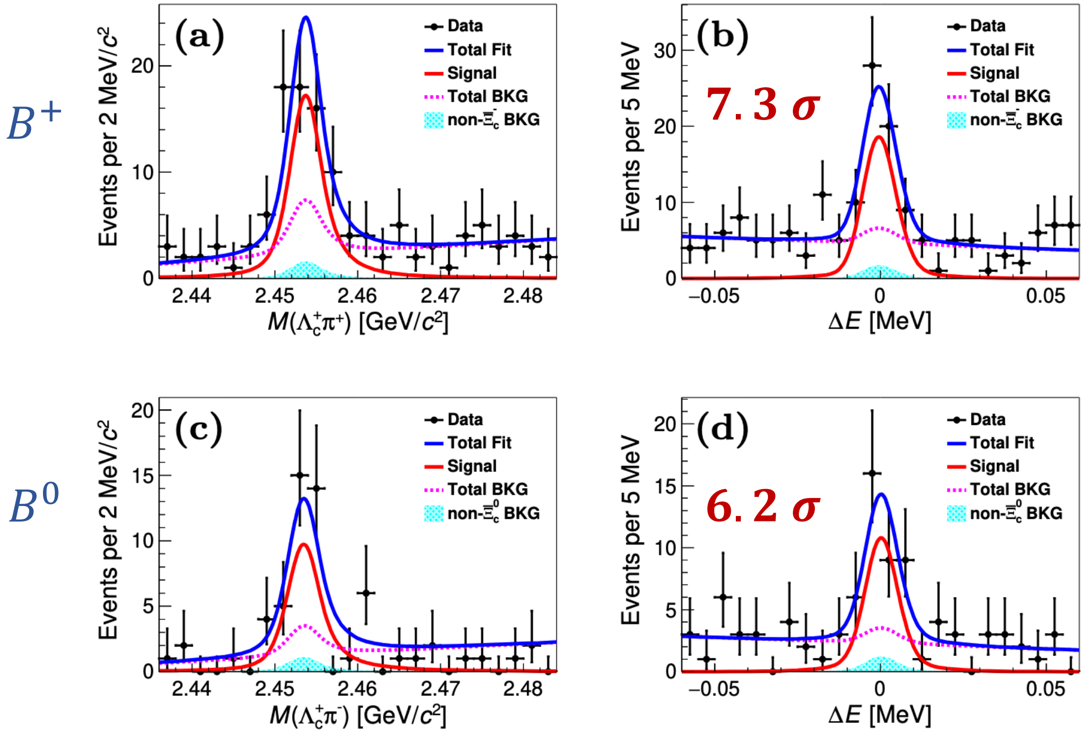


$\Sigma_c(2455)$: a sextet of flavor-symmetric states; $\bar{\Xi}_c$: an antitriplet of flavor-antisymmetric states

Observation of the decay $B \to \Sigma_c(2455)\bar{\Xi}_c$

PRD 112, L051101 (2025)

- We report the first observation of the decays $B^+ \to \Sigma_c(2455)^{++}\bar{\Xi}_c^-$ and $B^0 \to \Sigma_c(2455)^0\bar{\Xi}_c^0$, using the 772×10^6 and 387×10^6 $\Upsilon(4S)$ events collected by Belle and Belle II, respectively.
- We perform a 2D fit to the unbinned $M(\Lambda_c^+\pi^\pm)$ and ΔE distributions, simultaneously using four data sets: events from the signal and sideband regions of $M(\bar{\Xi}_c^{-,0})$.



$$\mathcal{B}(B^+ \to \Sigma_c(2455)^{++}\bar{\Xi}_c^-) = (5.74 \pm 1.11 \pm 0.42^{+2.47}_{-1.53}) \times 10^{-4}$$

$$\mathcal{B}(B^0 \to \Sigma_c(2455)^{0}\bar{\Xi}_c^0) = (4.83 \pm 1.12 \pm 0.37^{+0.72}_{-0.60}) \times 10^{-4}$$

- $\mathcal{B}(B \to \Sigma_c(2455)\bar{\Xi}_c)$ are larger than those of $B^+ \to \bar{\Sigma}_c(2455)^0 p$ and $B^0 \to \bar{\Sigma}_c(2455)^- p$:
  - Similar size of CKM matrix elements: $V_{bc} * V_{cs} \sim V_{bc} * V_{ud}$
  - Smaller phase-space

[Int. J. Mod. Phys. A 21(2006) 4209]

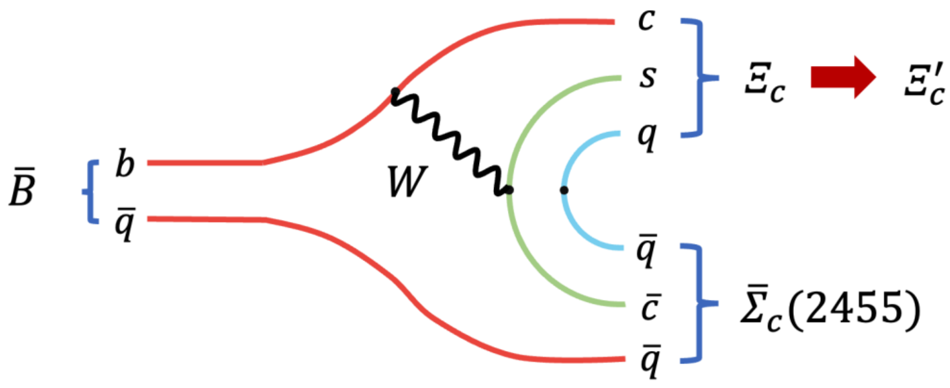
- One possible mechanism is that hard gluons are not necessarily required for double-charm decays.

Observation of the decay $B \to \Sigma_c(2455)\bar{\Xi}'_c$

arXiv:2606.12905

- The decay $B \to \Sigma_c(2455)\bar{\Xi}'_c$ proceeds through the same type of diagram as $B \to \Sigma_c(2455)\bar{\Xi}_c$ and are therefore expected to have a branching fraction of similar magnitude.

- A comparison between $\mathcal{B}(B \to \Sigma_c(2455)\bar{\Xi}'_c)$ and $\mathcal{B}(B \to \Sigma_c(2455)\bar{\Xi}_c)$ could provide insight into the underlying dynamics of B decays to charmed baryon pairs belonging to different SU(3)-flavor multiplets.



internal W-boson emission
nonfactorizable amplitude

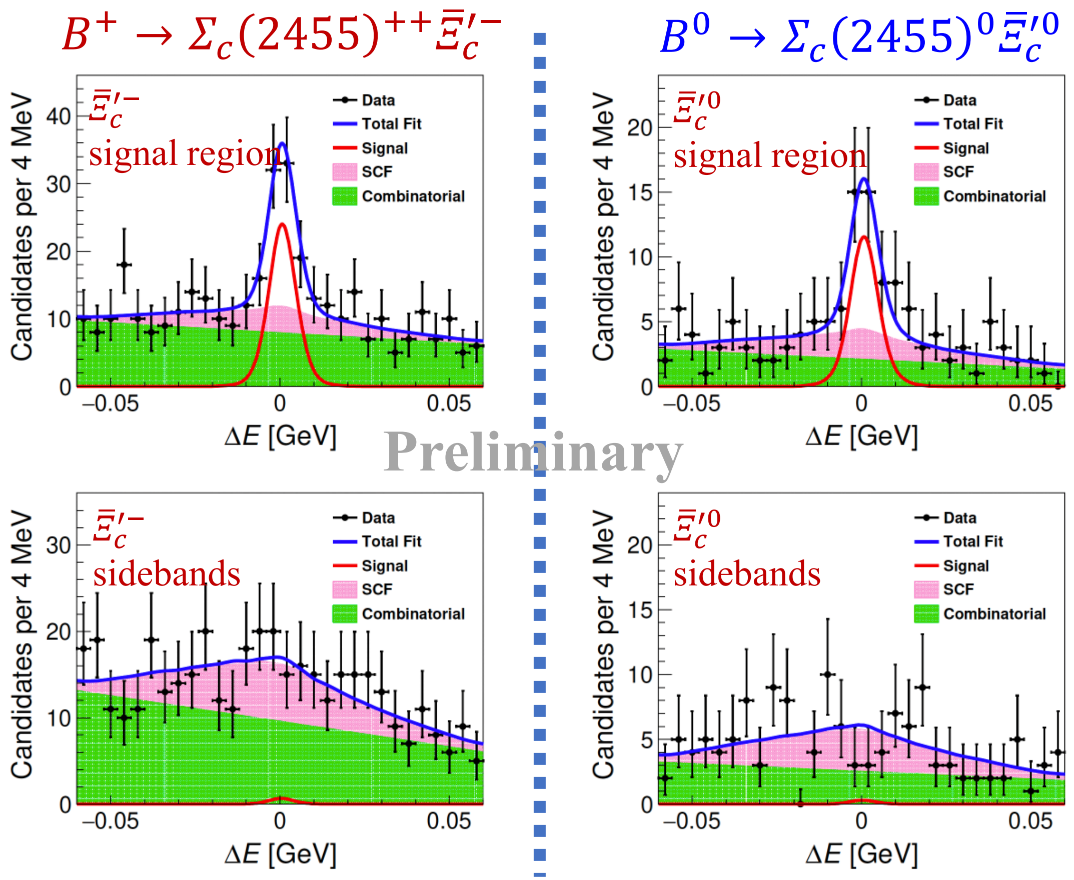
- Using 772×10^6 and 521×10^6 $\Upsilon(4S)$ events collected by Belle and Belle II detector, we present the first search for the decays $B^+ \to \Sigma_c(2455)^{++}\bar{\Xi}'^-_c$ and $B^0 \to \Sigma_c(2455)^0\bar{\Xi}'^0_c$.

- This is the first search for B-meson decays into a pair of charmed baryon-antibaryon states, each belonging to the SU(3)-flavor sextet.

Observation of the decay $B \to \Sigma_c(2455)\bar{\Xi}_c'$

arXiv:2606.12905

- To extract the signal yields, we perform a simultaneous unbinned maximum-likelihood fit to the ΔE distributions in the signal and sideband regions of $M(\gamma\bar{\Xi}_c)$ for the Belle and Belle II datasets.



- ✓ The observed signal significances exceed 6.4σ for the charged mode and 5.3σ for the neutral mode including systematic uncertainties.
- ✓ The measured branching fractions are

$$\mathcal{B}(B^+ \to \Sigma_c(2455)^{++}\bar{\Xi}_c'^-) = \left(1.68 \pm 0.31 \pm 0.12^{+1.49}_{-0.54}\right) \times 10^{-3}$$

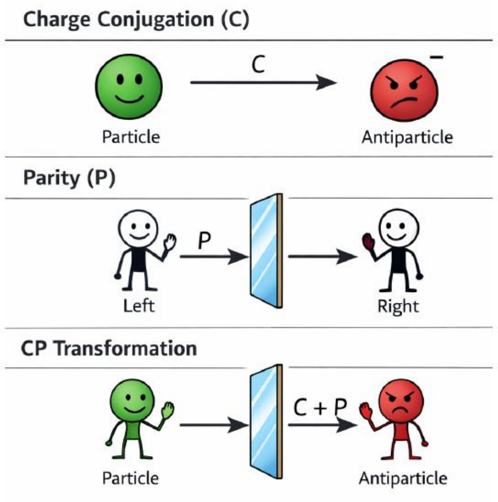
$$\mathcal{B}(B^0 \to \Sigma_c(2455)^0\bar{\Xi}_c'^0) = \left(1.28 \pm 0.32 \pm 0.10^{+0.30}_{-0.21}\right) \times 10^{-3}$$

Uncertainties are statistical, systematic, and from $\mathcal{B}(\bar{\Xi}_c \to X)$, respectively.

- ✓ The measured branching fractions are two to three times larger than those of $B^+ \to \Sigma_c(2455)^{++}\bar{\Xi}_c^-$ and $B^0 \to \Sigma_c(2455)^0\bar{\Xi}_c^0$, despite the smaller available phase space for these decays.

CP Violation and KM theory

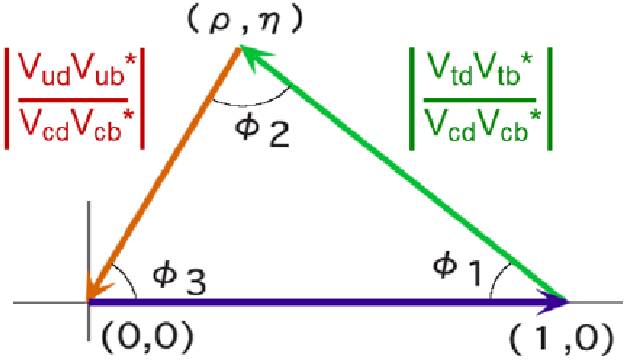
- CP violation: a key for the matter-antimatter asymmetry.
- Kobayashi-Maskawatheory (1973):
  - CP violation in the Standard Model (SM)
  - Complex phase in the quark mixing matrix



CKM (Cabibbo-Kobayashi-Maskawa) Matrix

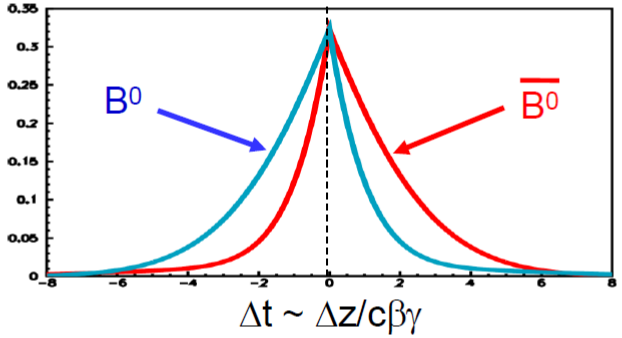
$$V=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

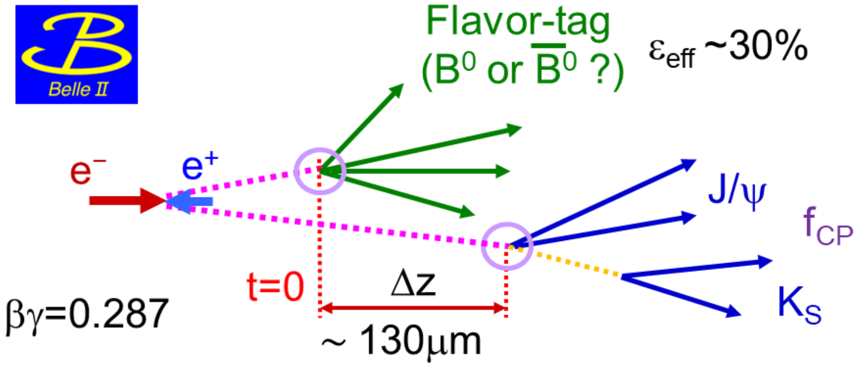
Triangles in the complex plane (from Unitarity)



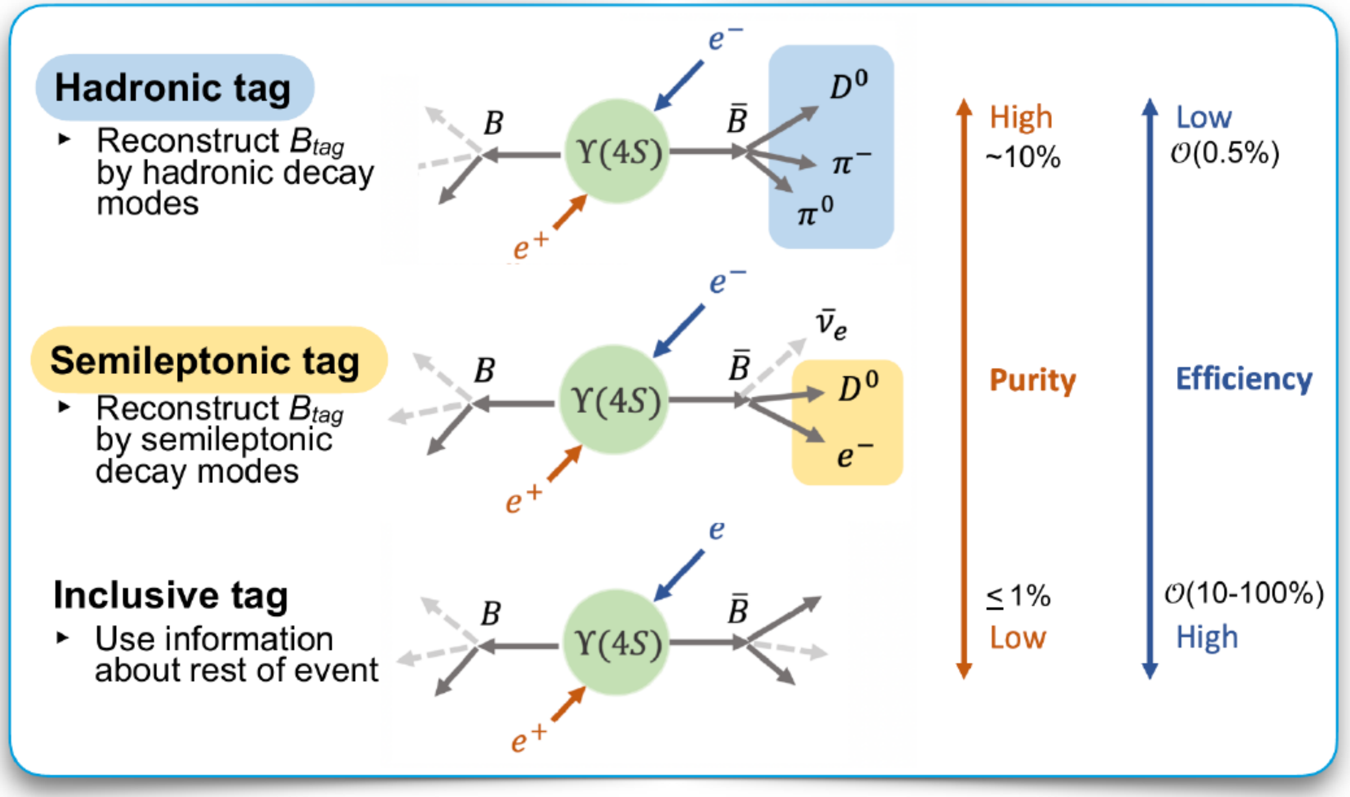
In B mesons, CP violation often appears as a decay time difference.

measure position instead of time





Three ways of B tagging

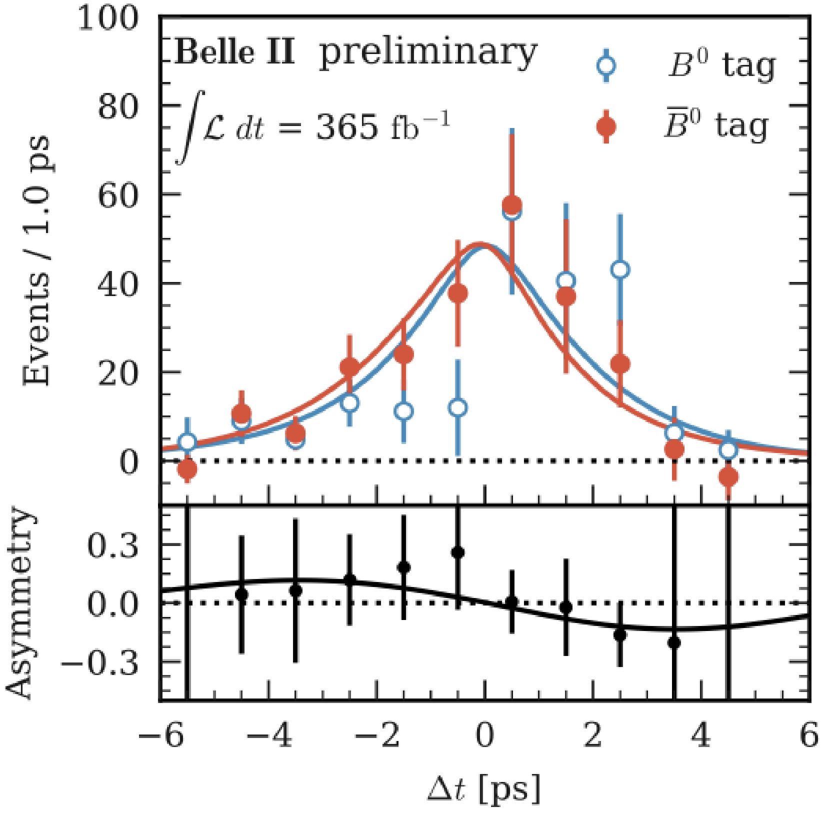


- **Tagging: Hadronic + Semileptonic**
- **Hadronic tagging and knowledge of initial state enables excellent E_{miss} reconstruction**
- **Inclusive ROE (Rest of Event) (× 10 - 20 efficiency, but large backgrounds); add some ML/AI (boosted decision trees) to help suppress the large backgrounds.**

Search for CPV in $B^0 \to \rho^+\rho^-$

[PRD 111, 092001 (2025)]

- **much smaller loop contribution $\Longrightarrow$ dominates ϕ_2 precision**
- **two π^0's reconstruction needed $\Longrightarrow$ a channel suitable for Belle II**



$S = -0.26 \pm 0.19 \pm 0.08$

$C = -0.02 \pm 0.12 \pm 0.05$

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (2.89^{+0.37}_{-0.35}) \times 10^{-5}$$

$$f_L = 0.921^{+0.029}_{-0.029}$$

Probability distribution

Mixing-induced CPV param.

$$P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 + q\big[S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\big]\Big\},$$

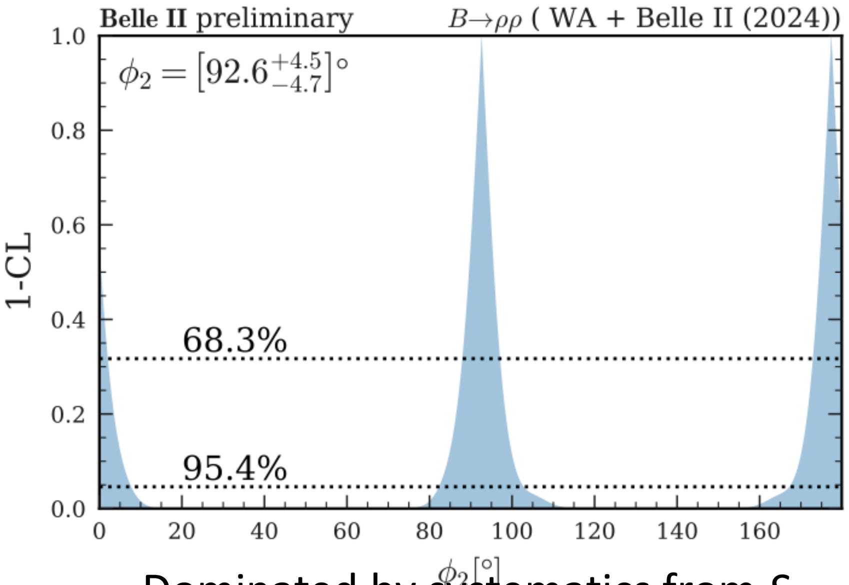
Direct CPV param.

Helicity angle distribution

Longitudinal polarisation fraction

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_{\rho^+}\, d\cos\theta_{\rho^-}} = \frac{9}{4}\Big[\frac{1}{4}(1-f_L)\sin^2\theta_{\rho^+}\sin^2\theta_{\rho^-} + f_L\cos^2\theta_{\rho^+}\cos^2\theta_{\rho^-}\Big],$$

Constraining ϕ_2:



Dominated by systematics from S

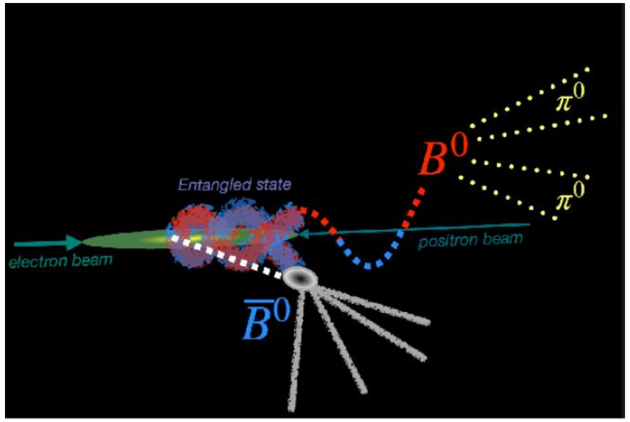
$B \to \rho\rho$ world average:
$\phi_2 = (91.5^{+4.5}_{-5.4})^\circ$

$B \to \rho\rho$ world average
+ Belle II $\rho^+\rho^-$ result
$\Rightarrow$ **$\phi_2 = (92.6^{+4.5}_{-4.8})^\circ$**

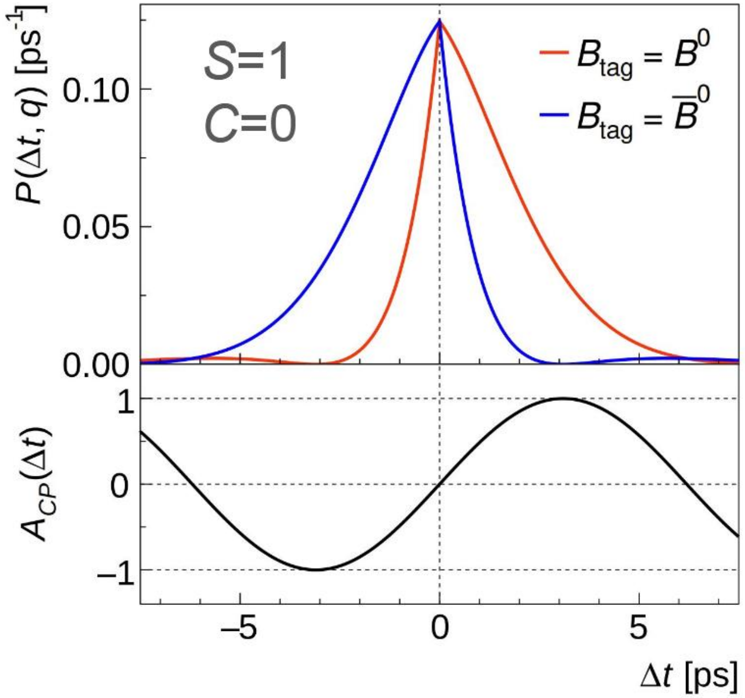
6%

First measurement of time-dependent CP violation in $B^0 \to \pi^0\pi^0$

$$\Gamma(B^0/\bar{B}^0(t) \to f_{CP}) \propto e^{-t/\tau_B}\left[1 + q\left(\underbrace{S\sin(\Delta m_d t)}_{\text{mixing-induced CPV}} - \underbrace{C\cos(\Delta m_d t)}_{\text{direct CPV}}\right)\right]$$



$$\mathcal{A}_{CP}(\Delta t) = \frac{\mathcal{P}(\Delta t, +1) - \mathcal{P}(\Delta t, -1)}{\mathcal{P}(\Delta t, +1) + \mathcal{P}(\Delta t, -1)} = S\sin\Delta m\Delta t - C\cos\Delta m\Delta t$$



$\Delta t = t_{CP} - t_{tag}$ from the two decay vertices

The Issue with $B^0 \to \pi^0\pi^0$

- $\sim$ 99% of decays: vertexless 4γ final state
- No decay vertex $\Rightarrow$ no Δt
- $\Rightarrow$ standard time-dependent CPV analysis not possible with current samples

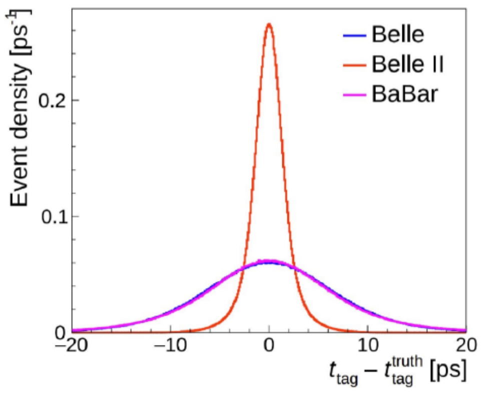
The New Idea

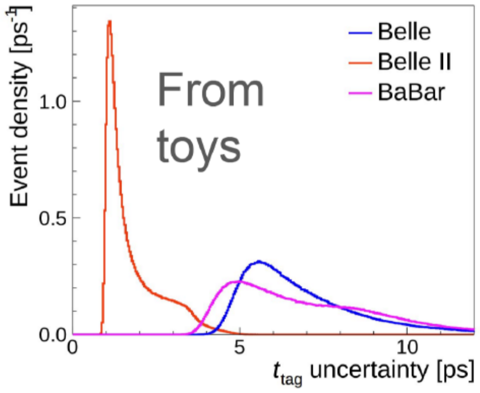
PHYS. REV. D 112, 032011 (2025)

- Quantum entanglement of $B^0\bar{B}^0$ pairs links the two decays
- New approach: use only the tag-side decay time t_{tag}
- A time-dependent flavour asymmetry still arises:
  - reduced oscillation amplitude ($\sim -20\%$)
  - maximal asymmetry occurs at larger t_{tag}, where fewer B mesons remain

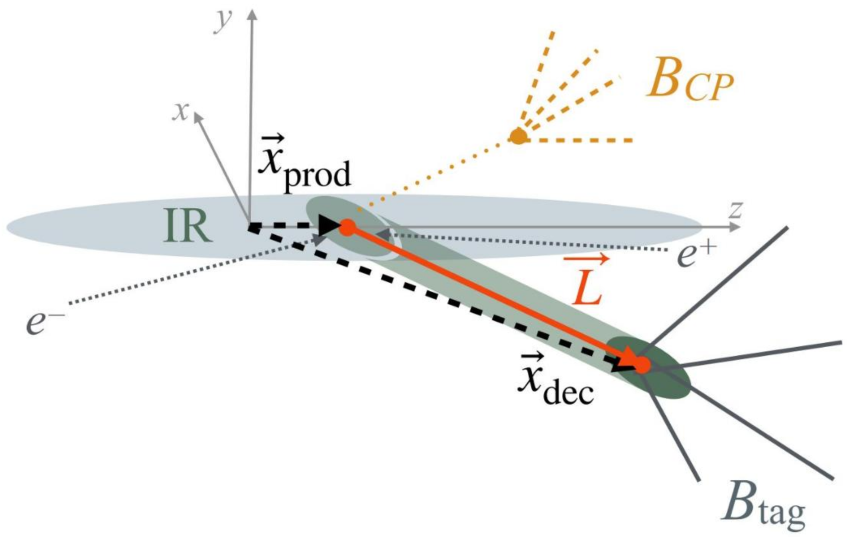
First measurement of time-dependent CP violation in $B^0 \to \pi^0\pi^0$

- Very small signal: $\sim$170 events
  - Dominated by continuum background ($\sim$130$\times$ larger)
  - Additional $B\bar{B}$ background of similar size
- Goal: extract signal, determine flavour, and measure decay time for B^0_{tag} and $\bar{B}^0_{\text{tag}}$
- No signal vertex (4γ final state) $\Rightarrow$ cannot measure decay time
- Use tag-side decay time t_{tag} instead



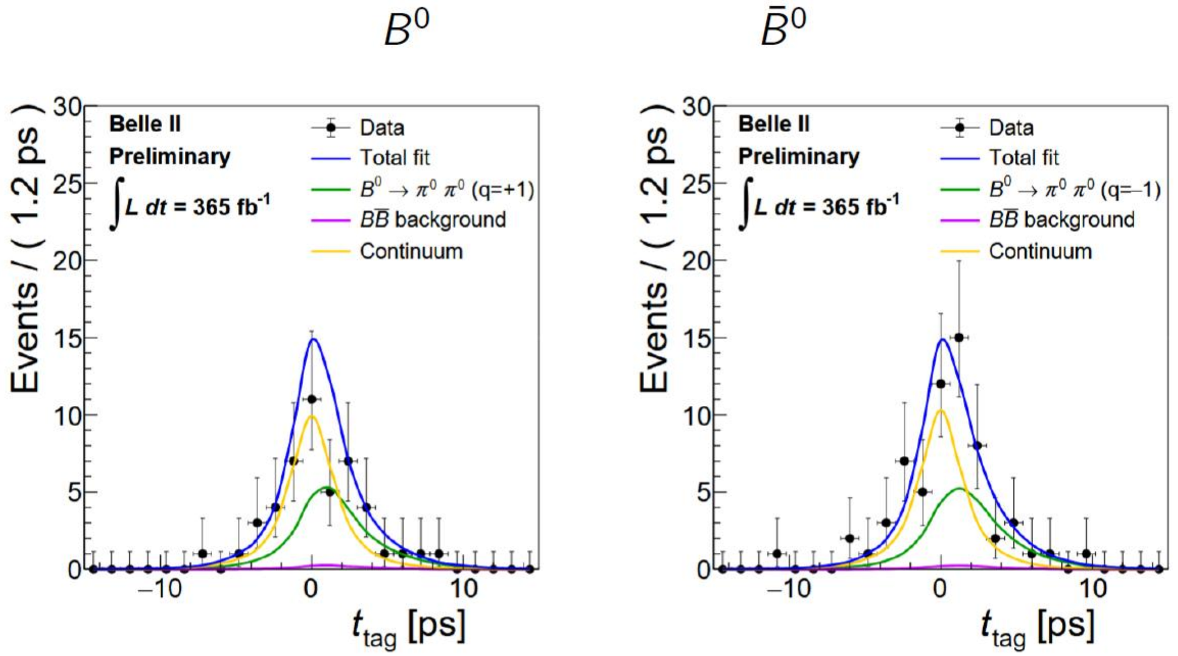


$$t_{\text{tag}} = m_B \frac{\vec{L} \cdot \vec{p}_{\text{tag}}}{|p_{\text{tag}}|^2}$$



Nanobeam and PXD gives Belle II useful (1.5 ps) t_{tag} resolution.
Belle/Babar 6 ps resolution hinders any S measurement

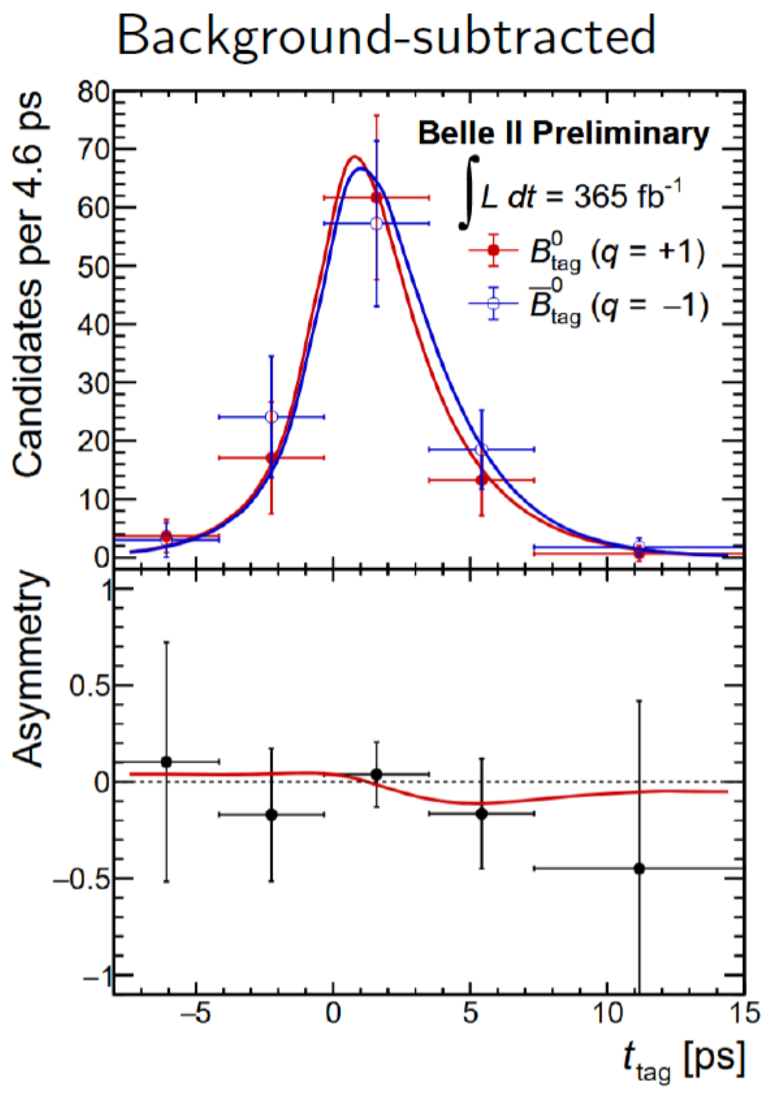
First measurement of time-dependent CP violation in $B^0 \to \pi^0\pi^0$



$$S_{00} = 0.61^{+0.75}_{-0.79}\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst})$$

$$C_{00} = 0.05 \pm 0.28\,(\mathrm{stat}) \pm 0.07\,(\mathrm{syst})$$

- C_{00} consistent with time-integrated $A_{CP} = 0.03 \pm 0.30$ within 0.5σ (considering overlapping events)
- Uncertainties consistent with expectations
- S compatible with theoretical expectation (~ 0.65)



First measurement of mixing-induced CP violation in $B^0 \to \pi^0\pi^0$

Time-dependent CP violation in $B^0 \to \gamma K_s^0 \pi\pi$

arXiv:2510.01331v2
accepted by JHEP

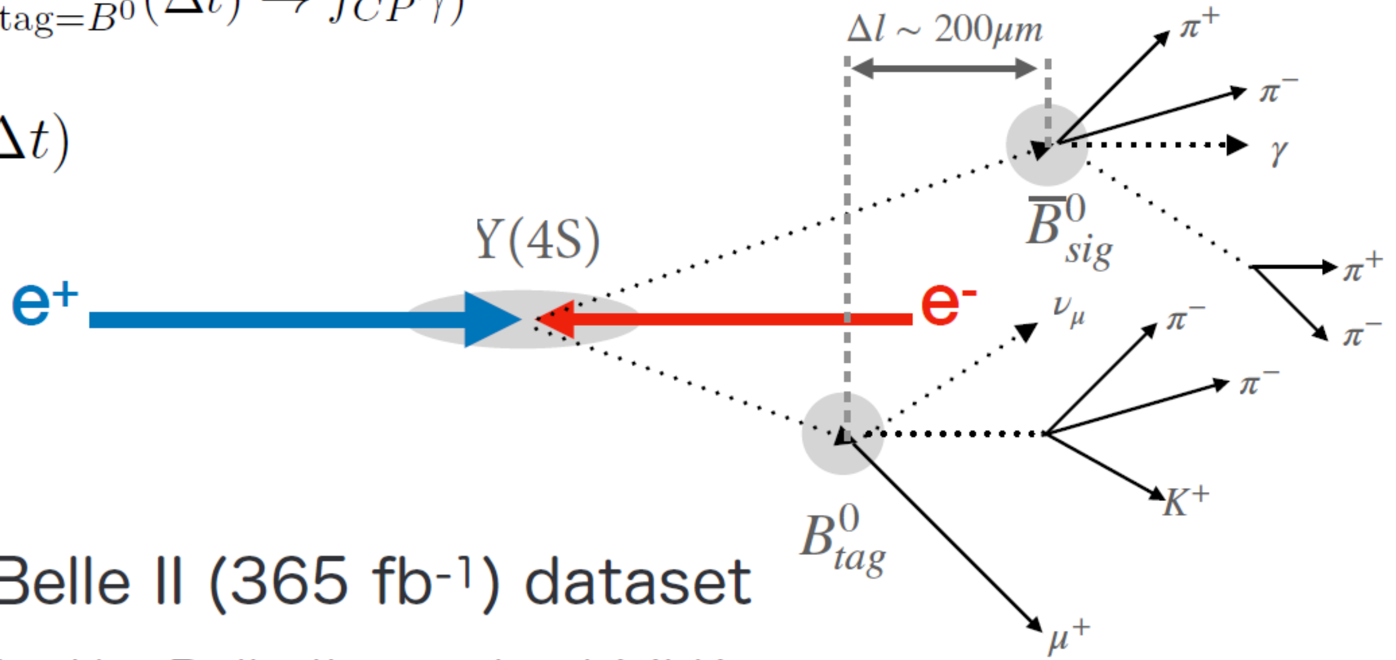
- In the SM, $S_{CP} \sim 0$ due to suppressed right-handed currents
- Sensitive to NP contributions in the loop

$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(B_{\mathrm{tag}=B^0}(\Delta t) \to f_{CP}\gamma) - \Gamma(B_{\mathrm{tag}=\bar{B}^0}(\Delta t) \to f_{CP}\gamma)}{\Gamma(B_{\mathrm{tag}=B^0}(\Delta t) \to f_{CP}\gamma) + \Gamma(B_{\mathrm{tag}=\bar{B}^0}(\Delta t) \to f_{CP}\gamma)}$$

$$= S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)$$

Mixing-induced CP violation

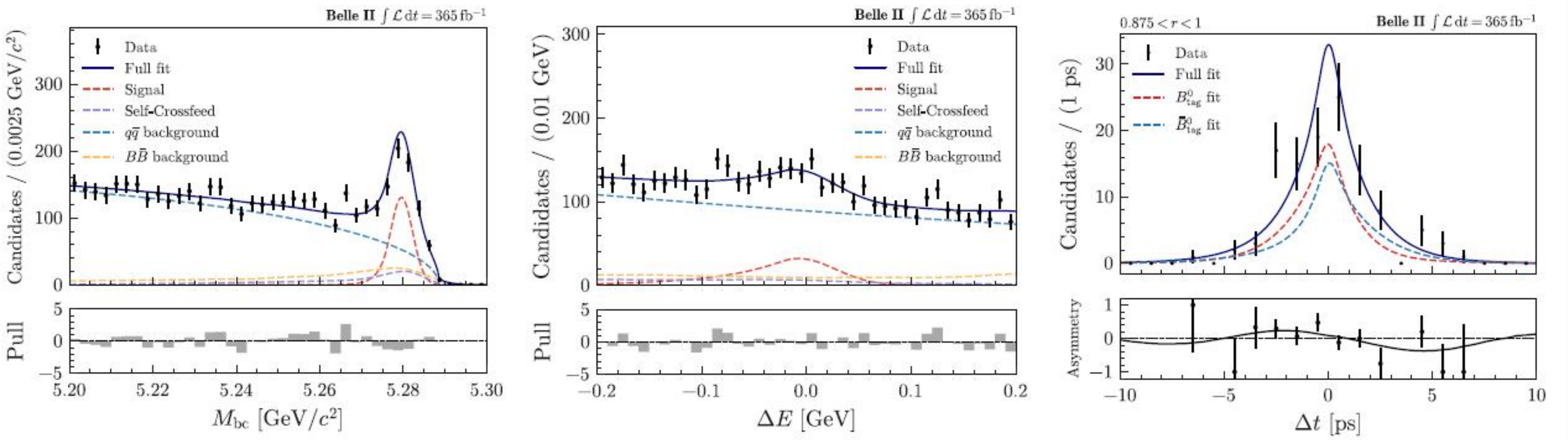
Direct CP violation



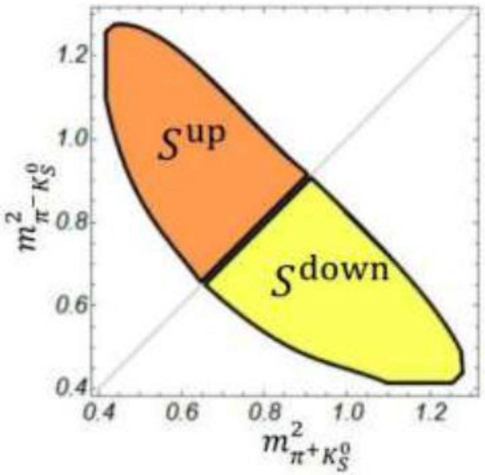
- Analyze full Belle (711 fb^{-1}) and Belle II (365 fb^{-1}) dataset
  - E_γ > 1.5 (1.4) GeV for Belle II (Belle), K_S: Belle II standard MVA
  - Continuum suppression via event shape, Vertexing and flavor tagging for Δt

Time-dependent CP violation in $B^0 \to \gamma K_s^0 \pi\pi$

- Time-dependent CP fit
  - Unbinned ML 3D fit
  - New observables S+, S-
    - Dalitz plane: S^{up}, S^{down}
    - Exploit $\pi^+ \leftrightarrow \pi^-$ symmetry of the Dalitz plane:
      even (symmetric) vs odd (antisymmetric) components
    e.g.) even-dominated: $K_S \rho^0 \gamma$,   odd-dominated: $K^{*\pm} \pi^\mp \gamma$



[arXiv:2510.01331v2](https://arxiv.org/abs/2510.01331v2)
accepted by JHEP



New observables:
- $S^+ = S^{up} + S^{down}$
- $S^- = S^{up} - S^{down}$

arXiv:1802.09433

Result: Most precise in S and C

$$C = -0.17 \pm 0.09 \pm 0.04$$
$$S = -0.29 \pm 0.11 \pm 0.05$$

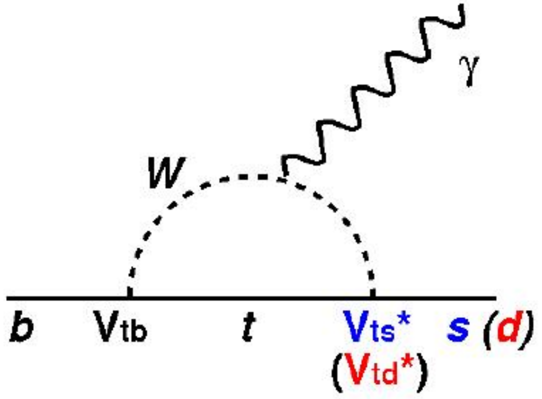
New approach

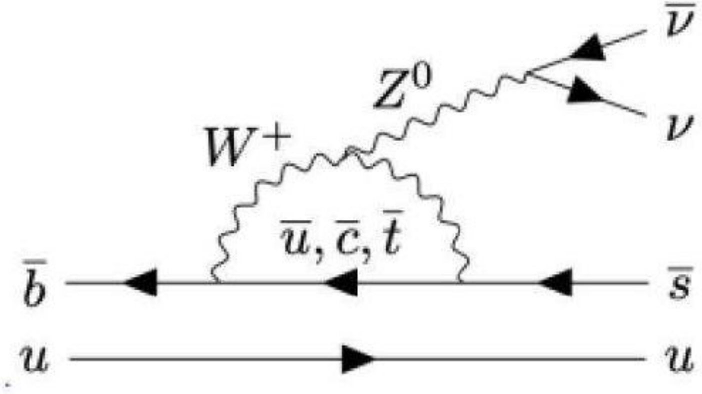
$$S^+ = -0.57 \pm 0.23 \pm 0.10$$
$$S^- = 0.31 \pm 0.24 \pm 0.05$$

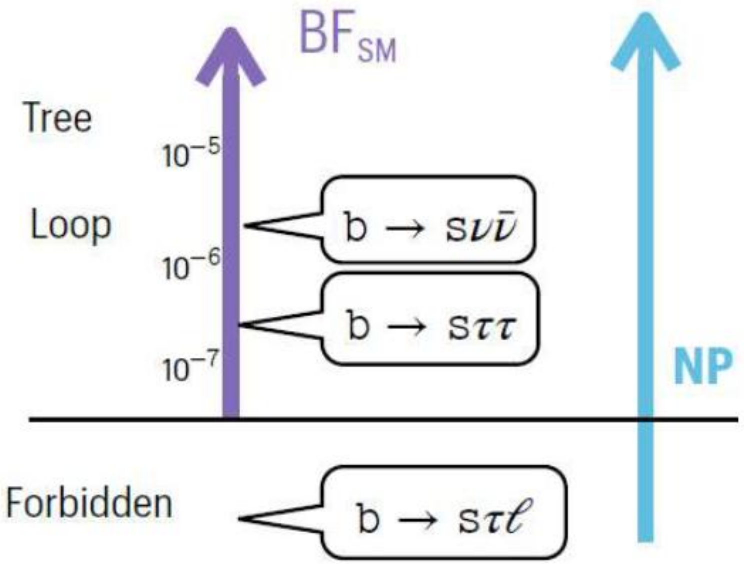
Statistically dominant,
Belle: vertex-detector misalignment,
Belle II: CP-fit validation bias

Electroweak Penguin Decays

- Flavor Changing Neutral Current (FCNC)
  - Forbidden at the tree level in the SM
  - Small branching fraction in the SM ($<10^{-5}$)
- Sensitive to New Physics (NP)
  - Heavy new particles can enter the loop
- Key channels: $b \to s\gamma$, $d\gamma$, $s\ell\ell$, $d\ell\ell$, $s\nu\nu$, …
- Precise theoretical prediction for the inclusive process
- The branching fraction of exclusive processes has large uncertainty, except for $b \to s\nu\nu$
- Many observables
  - Branching fractions, CP asymmetries, Angular distribution, Photon polarization



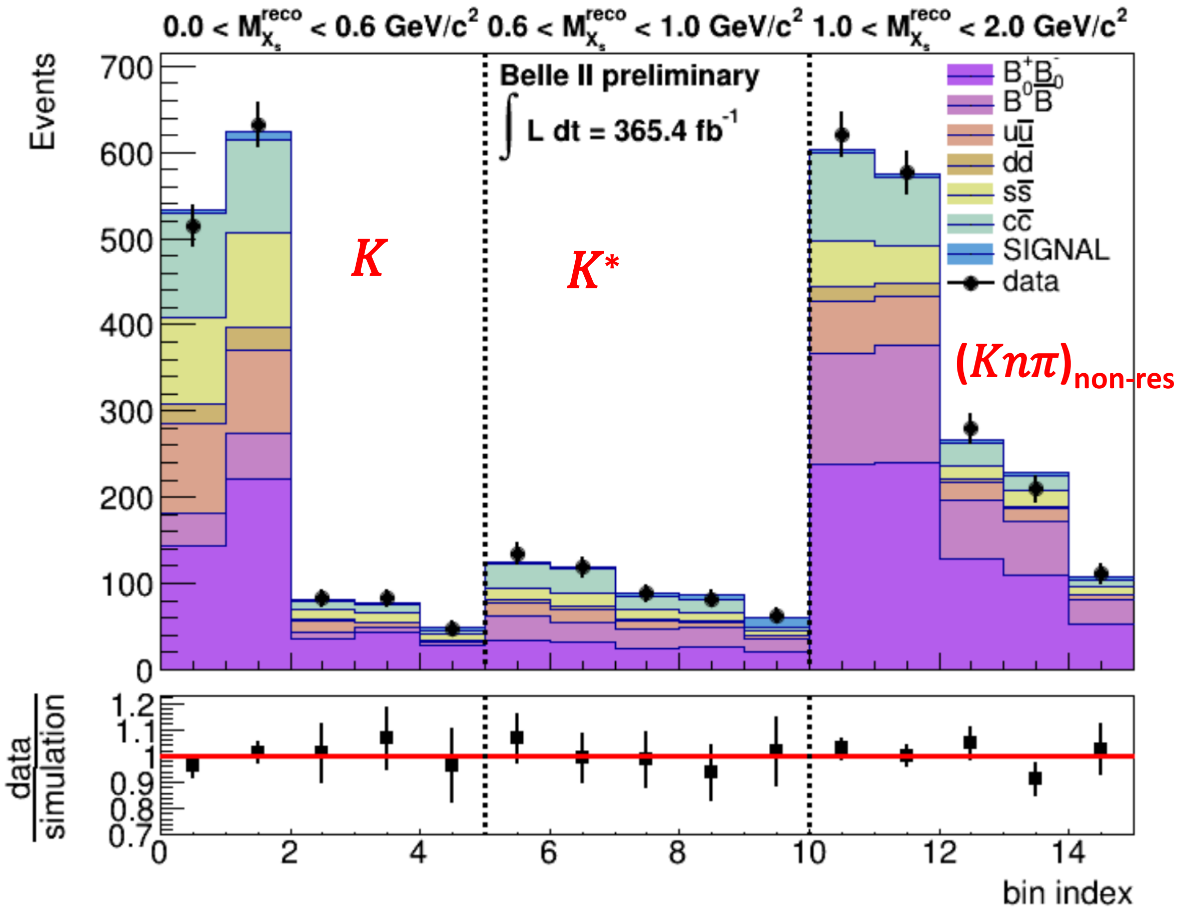


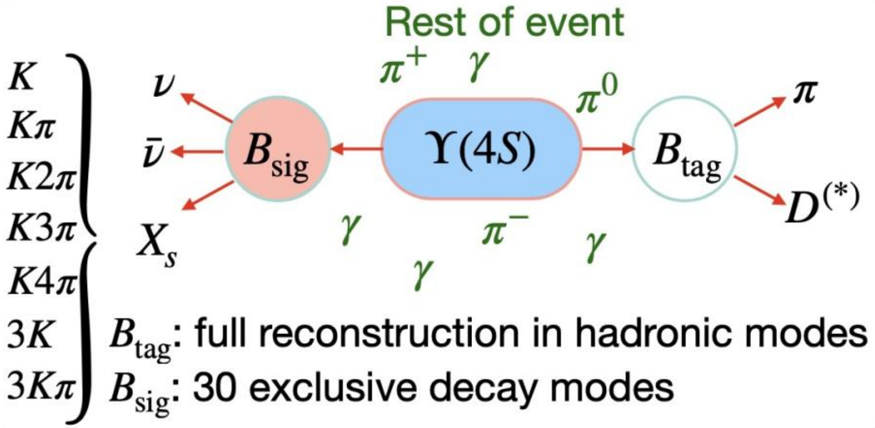


Inclusive $B \to X_s\nu\nu$ with hadronic tagging

- Probe flavor changing neutral currents (FCNC) in $b \to s\nu\nu$.
- The branching fraction for $B \to X_s\nu\nu$ is cleanly predicted to be $(2.9\pm0.3)\times10^{-5}$ in the SM [JHEP 02, 184 (2015)].

Maximum likelihood fit in $M_{X_S} \times \mathcal{O}_{BDT}$ with 3 × 5 bins:





			$\mathcal{B}$ $[10^{-5}]$		
M_{X_s} [GeV/c^2]	ϵ	N_{sig}	Central value	UL$_{obs}$	UL$_{exp}$
$[0, 0.6]$	0.29%	6^{+18+19}_{-17-16}	$0.3^{+0.8+0.9}_{-0.8-0.7}$	2.2	2.0
$[0.6, 1.0]$	0.12%	36^{+27+31}_{-26-26}	$3.5^{+2.6+3.1}_{-2.5-2.6}$	9.5	6.6
$[1.0, M_{X_s}^{max}]$	0.07%	24^{+44+62}_{-43-53}	$5.1^{+9.2+12.9}_{-8.8-11.0}$	31.2	26.7
Full range	0.10%	66^{+64+95}_{-62-81}	$8.8^{+8.5+12.6}_{-8.2-10.8}$	32.2	24.4

PRL 136, 231801 (2026)

Full range:

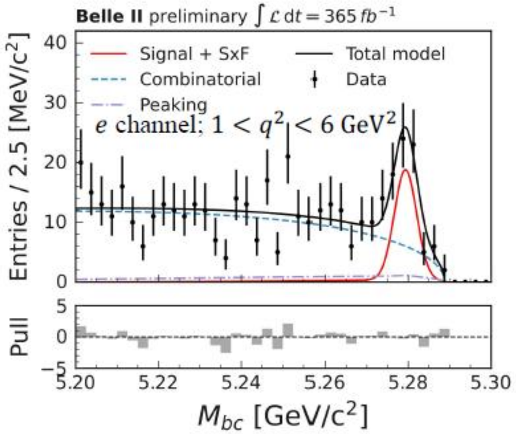
$$\mathcal{B}(B \to X_s\nu\bar{\nu}) < 3.6 \times 10^{-4}\ (90\,\%\ \text{CL})$$

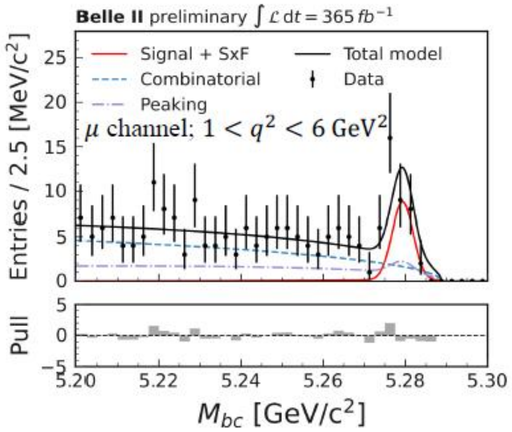
Most stringent upper limit on the inclusive rate

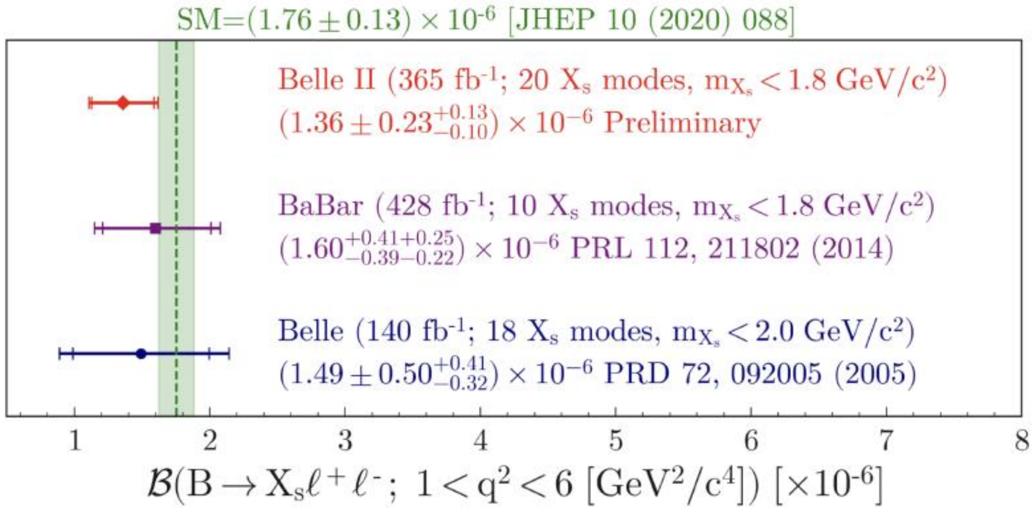
Inclusive $B \to X_s \ell^+ l^-$

Partial branching fraction (BF) in $1 < q^2 < 6$ GeV₂

- Anomalies in *exclusive* measurements
  - ✓ $\mathcal{B}(B \to K^{(*)}\mu\mu)$ lower than SM in low-q^2 ($[1,6]$ GeV^2)
  - ✓ but large theory uncertainty ($\sim 20\%$) in $B \to K$ FF
- What about *inclusive*?
  - ✓ much less SM theory error ($\sim 7\%$)
  - ✓ $\mathcal{B}^{SM}(B \to X_s l^+ l^-) = 4.2 \times 10^{-6}$
- Run 1 Belle II data ($365\ \mathrm{fb}^{-1}$) Untagged analysis
- **Sum-of-Exclusive** method
  - ✓ X_s in 20 hadronic modes in $m_{X_s} < 1.8\ \mathrm{GeV}/c^2$.
  - ✓ visible fraction $\sim 71\%$ (incl. K_L^0) estimated with Pythia (Lund String mode²)
- Signal extraction
  - ✓ by fitting to $M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - p_B^2}$
  - ✓ peaking backgrounds from fake leptons – subtracted using data







$$\mathcal{B}(B \to X_s e^+ e^-) = (1.60 \pm 0.33^{+0.15}_{-0.11}) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s \mu^+ \mu^-) = (1.13 \pm 0.33^{+0.11}_{-0.08}) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s \ell^+ \ell^-) = (1.36 \pm 0.23^{+0.13}_{-0.10}) \times 10^{-6}$$

good agreement with SM, factor 2 improvement in precision

$B^+ \to \mu^+ \nu_\mu$

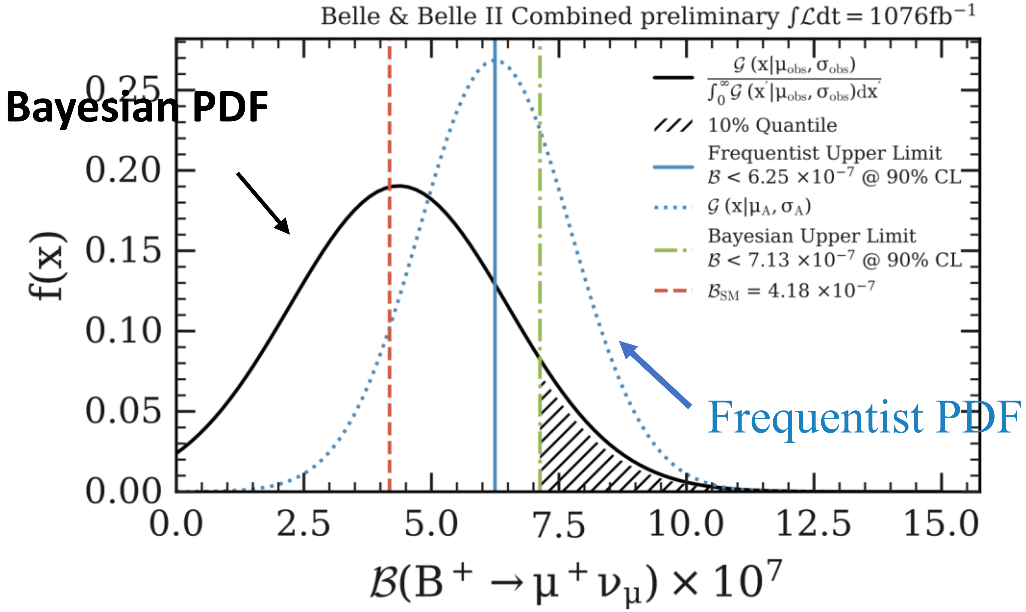
[arXiv:2602.09800](https://arxiv.org/abs/2602.09800)

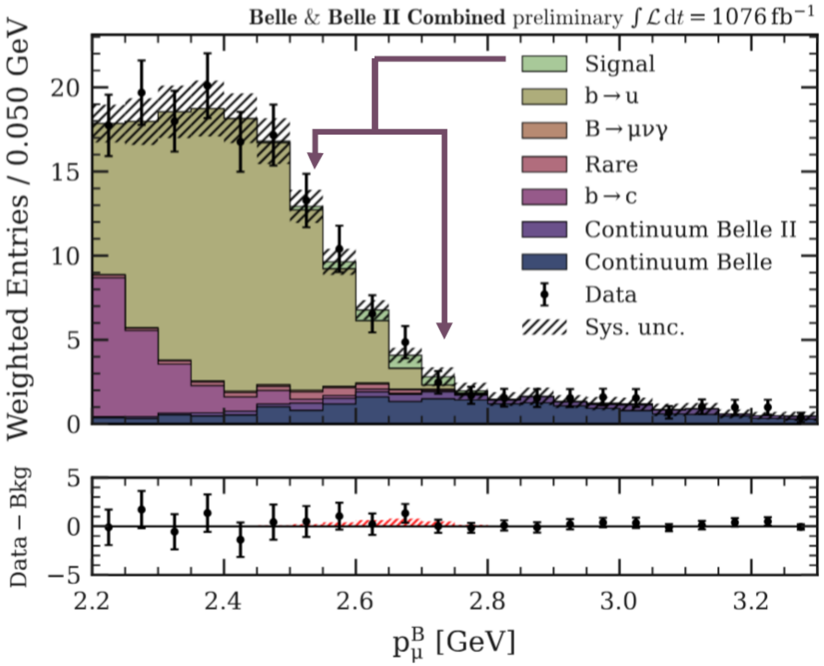
- SM branching fraction:

$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) = \frac{G_F^2 m_B m_\mu^2}{8\pi}\left(1 - \frac{m_\mu^2}{m_B^2}\right)^2 f_B^2 \left|V_{ub}\right|^2 \tau_{B^+} ,$$

- SM predicted: $B = (4.18 \pm 0.44) \times 10^{-7}$.
- Belle: $B = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7}$ (2.8σ)

  (PRD 101 (2020) 032007)





- Belle + Belle II (1076/fb):

An inclusive tagging approach

  - $B(B^+ \to \mu^+ \nu_\mu) = (4.36 \pm 1.89 \pm 1.01) \times 10^{-7}$ (2.35σ)

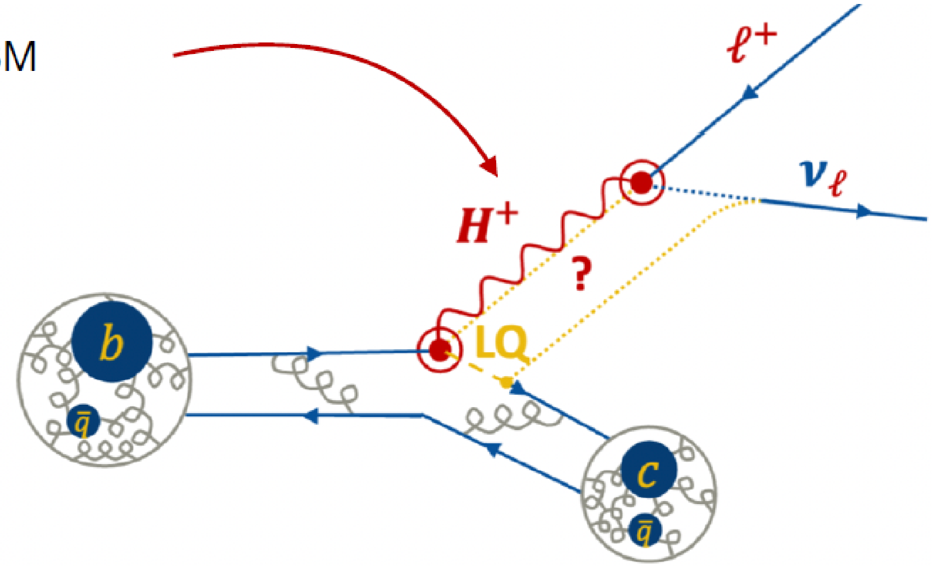
$B(B^+ \to \mu^+ \nu_\mu) < 7.13 \times 10^{-7}$ *(Bayesian Upper Limit)*

$B(B^+ \to \mu^+ \nu_\mu) < 6.25 \times 10^{-7}$ *(Frequentist Upper Limit)*

These are the most stringent limits to date.

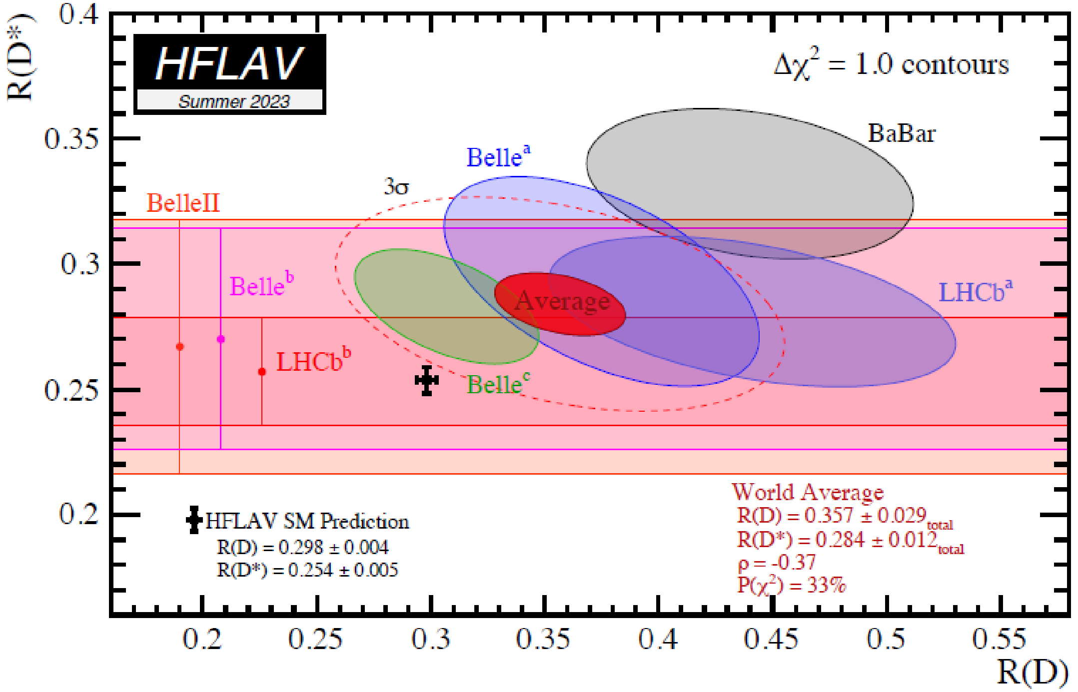
LFU in B decays

- Semileptonic decays also provide theoretically clean SM probes in Lepton Flavour Universality (LFU) tests.
- Differences in angular asymmetries for different lepton flavours are also sensitive to non-SM physics.
- Form factors and experimental uncertainties partially cancel in measurements of ratios of decay rates.



Long-standing tension between LFU-sensitive quantities $R(D^{(*)})$ and SM predictions!

$\sim 3.5\sigma$



Exclusive approach:

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} \qquad \ell = e, \mu$$

Complementary inclusive approach:

$$R(X_{\tau/\ell}) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)} \qquad \ell = e, \mu$$

Updated $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

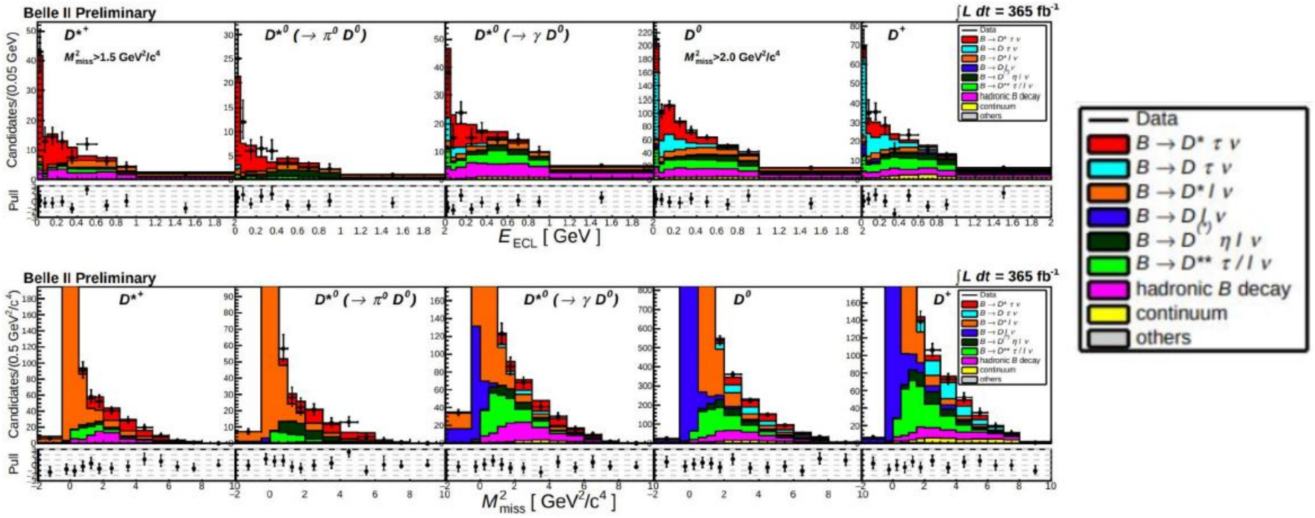
- Reconstruct 13 D decay modes, Hadronic tag
- 2D binned template likelihood fit, simultaneously in 5 channels (E_{ECL} and M_{miss}^2)

	D^{*+}	$D^{*}_{[D^0\pi^0]}{}^0$	$D^{*}_{[D^0\gamma]}{}^0$	D^0	D^+
$B \to D^*\tau\nu$	124 ± 10	64 ± 5	107 ± 8	380 ± 30	63 ± 5
$B \to D\tau\nu$	0 ± 0	2 ± 0	32 ± 4	340 ± 43	148 ± 19
$B \to D^*\ell\nu$	2899 ± 66	1417 ± 32	2598 ± 59	10638 ± 235	1624 ± 37
$B \to D\ell\nu$	4 ± 0	7 ± 0	215 ± 7	2882 ± 87	1226 ± 37
$B \to D^{**}\tau/(\ell)\nu$	60 ± 31	29 ± 24	191 ± 58	731 ± 134	294 ± 64
gap modes	21 ± 25	42 ± 15	53 ± 50	240 ± 94	90 ± 46
hadronic B decay	86 ± 25	4 ± 12	166 ± 38	469 ± 95	126 ± 25
continuum	3	2	33	181	84
other backgrounds	0	0	0	1	4
Total	3197	1567	3395	15862	3659

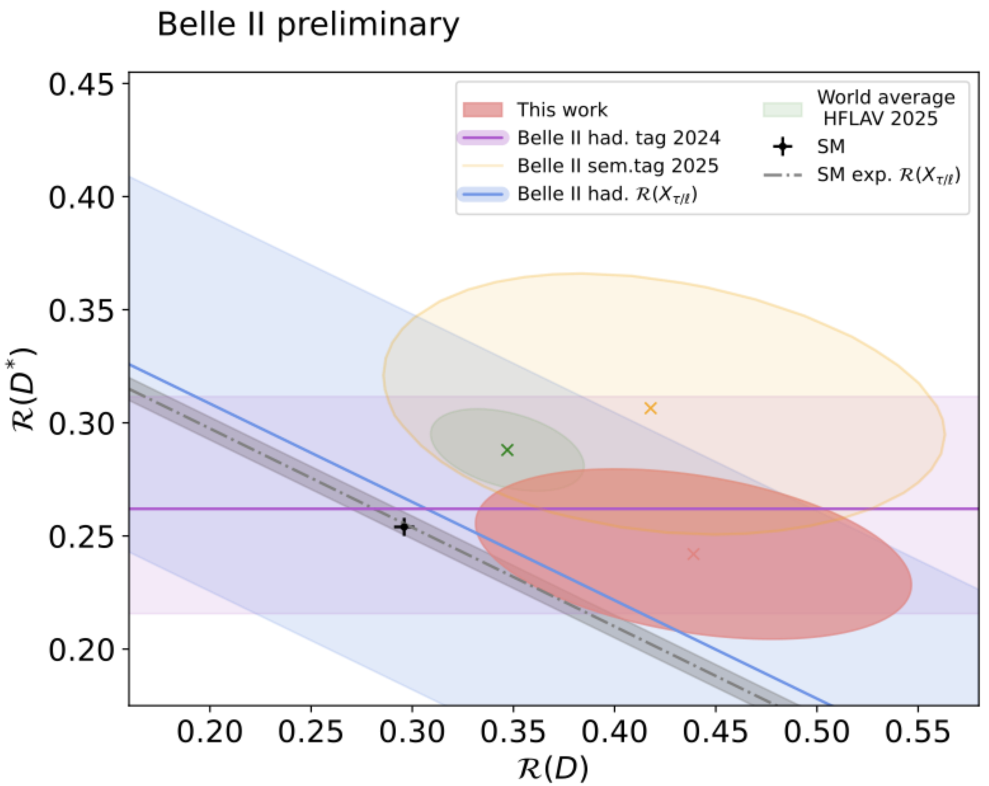
Signal

Normalization

Dominant backgrounds



$$\mathcal{R}(D^{(*)+}) = \frac{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\ell^-\bar{\nu}_\ell)}$$

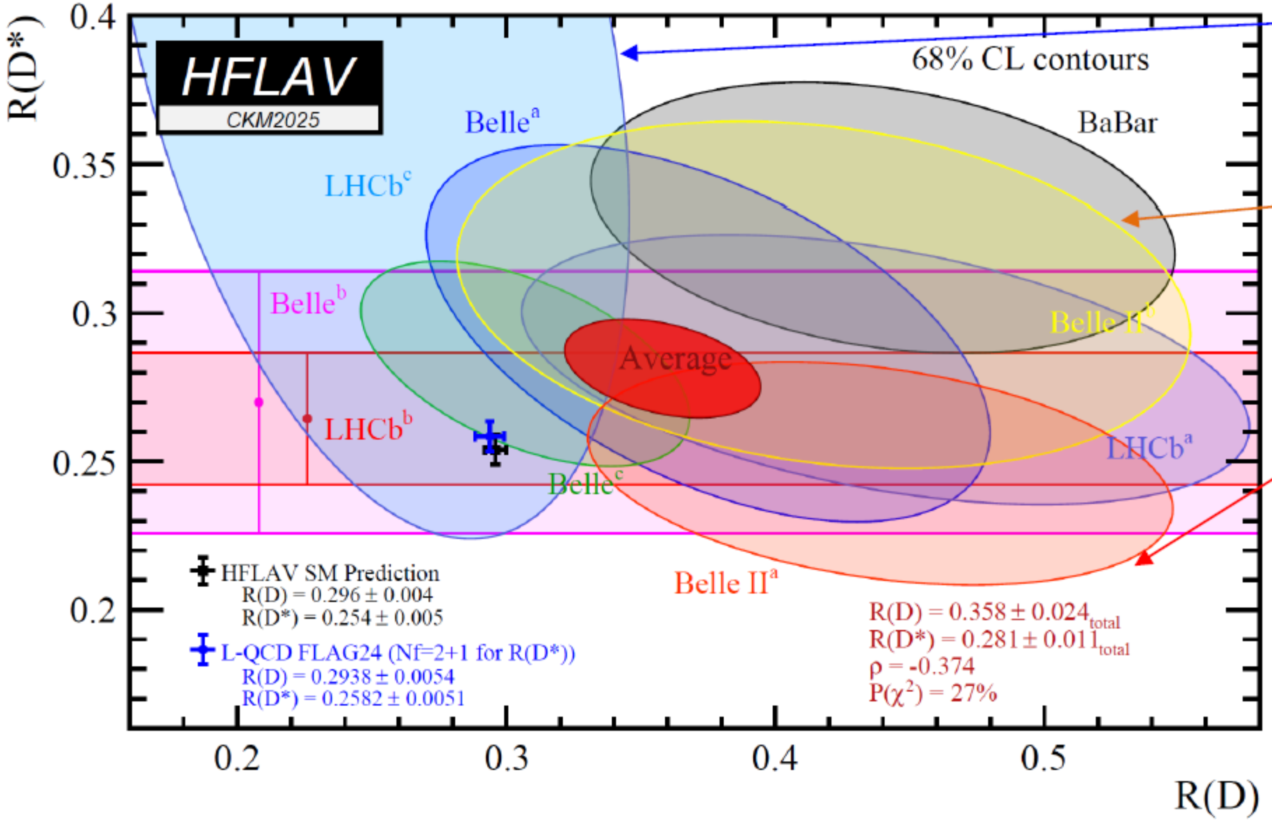


$$R(D^*) = 0.242 \pm 0.019(\text{stat}) \pm 0.016(\text{syst})$$
$$R(D) = 0.439 \pm 0.055(\text{stat}) \pm 0.045(\text{syst})$$

Consistent with SM expectation within 1.5σ

Most precise determination of $\mathcal{R}(D^{(*)})$ with hadronic tagging

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

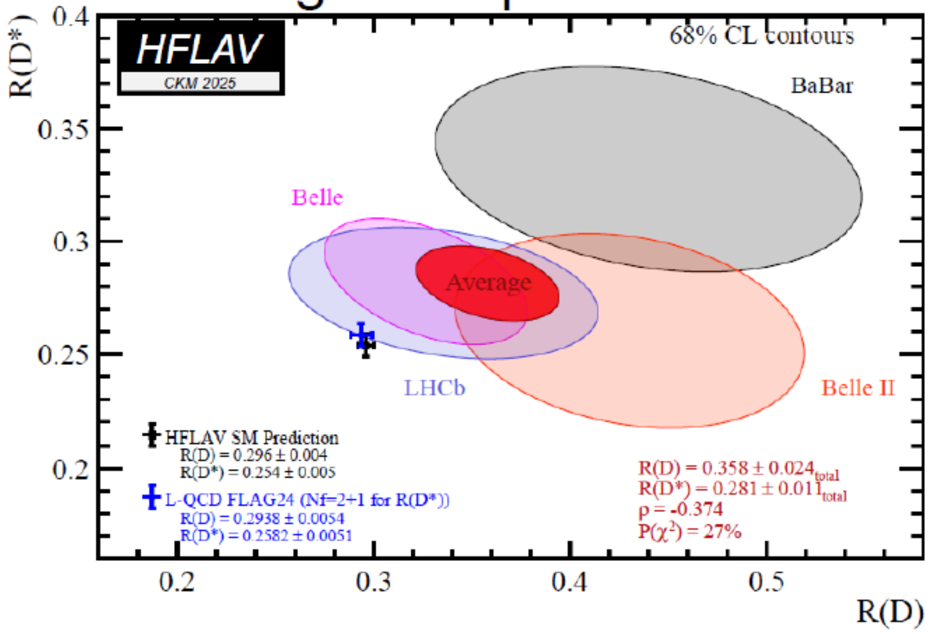


LHCb muonic τ decay

Belle II semi-leptonic tag leptonic τ decay

Belle II hadronic tag leptonic τ decay

average of experiments



3.8σ tension with SM prediction!

- R(D) tension with SM: 2.5σ
- R(D*) tension with SM: 2.3σ

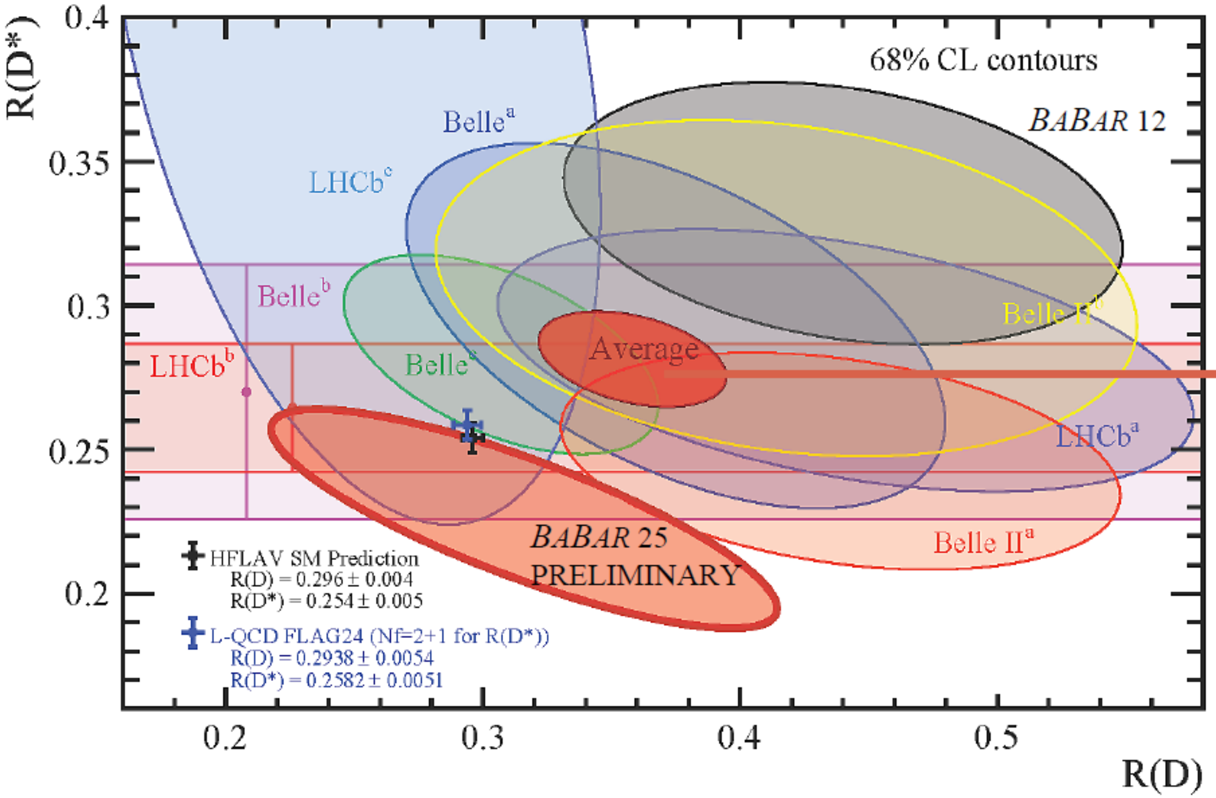
New inputs(?) from BABAR

Experiment	$R(D)$	$R(D^*)$	Correlation
BABAR 12 (hadronic tag)	0.440 ± 0.058 ± 0.042	0.332 ± 0.024 ± 0.018	-0.27
HFLAV (CKM 2025 average)	0.281 ± 0.011	0.358 ± 0.024	-0.374
BABAR 25 (leptonic tag) **PRELIMINARY**	0.316 ± 0.062 ± 0.019	0.226 ± 0.022 ± 0.012	-0.82

Systematics still under discussion:

- Normalization BFs
- D** modeling
- Limited MC for D**
- π^0 efficiency
- Fit/PDF shape modeling

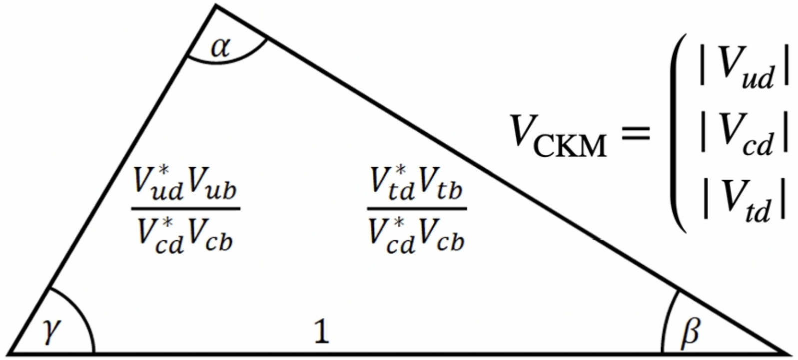
We await the final result and its finalized systematics.



This average does not include the *BABAR* 25 preliminary result

Semileptonic decay: CKM matrix

- Important to constrain CKM unitarity triangle & test SM
- Determinations via **inclusive** or **exclusive** semileptonic B decays
- Long-standing "**Vxb-puzzle**": discrepancy btw. inclusive and exclusive determinations



$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix}$$

$$V_{\mathrm{CKM}} V_{\mathrm{CKM}}^\dagger = 1$$

Exclusive

$B \to \pi\ell\nu$, $B \to \rho\ell\nu$, $B \to D^{(*)}\ell\nu$, $\Lambda_b \to p\ell\nu$, etc.

$$\mathscr{B} \propto \left|V_{xb}\right|^2 f^2$$

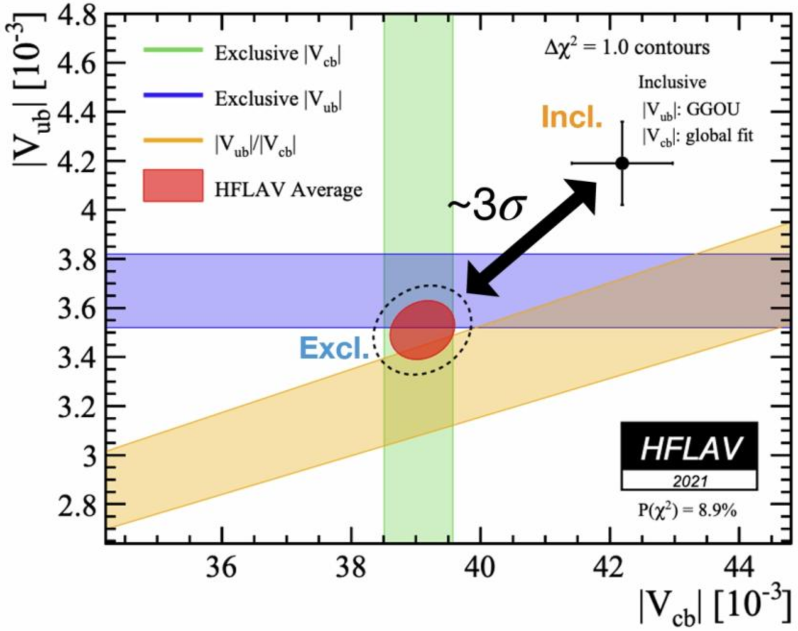
Form factor f (LCSR, LQCD)

Inclusive

$$B \to X_u\ell\nu,\ \ B \to X_c\ell\nu$$

$$\mathscr{B} \propto |V_{xb}|^2 \left[1 + \frac{c_5(\mu)\langle O_5\rangle(\mu)}{m_b^2} + \frac{c_6(\mu)\langle O_6\rangle(\mu)}{m_b^3} + O\left(m_b^4\right)\right] \qquad |V_{xb}| = \sqrt{\frac{\Delta\mathscr{B}}{\tau_B \cdot \Delta\Gamma}}$$

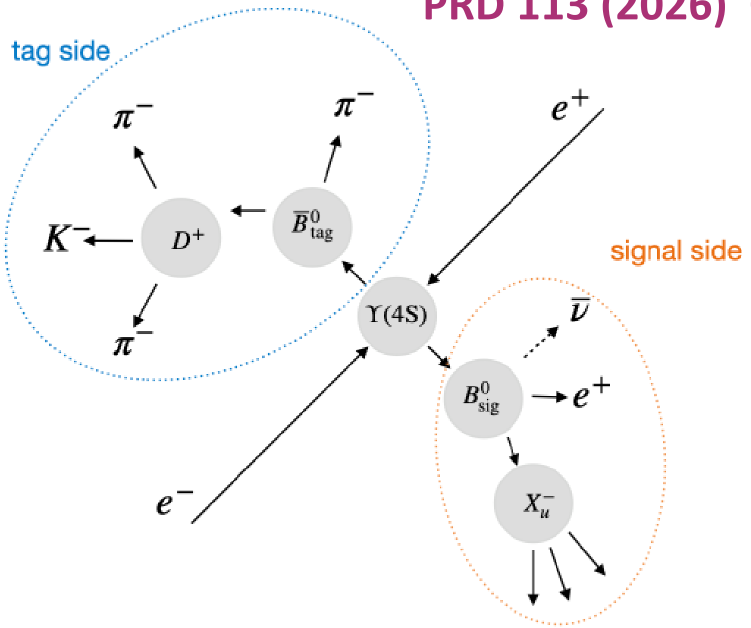
+ Shape Function / Fermi Motion (OPE)

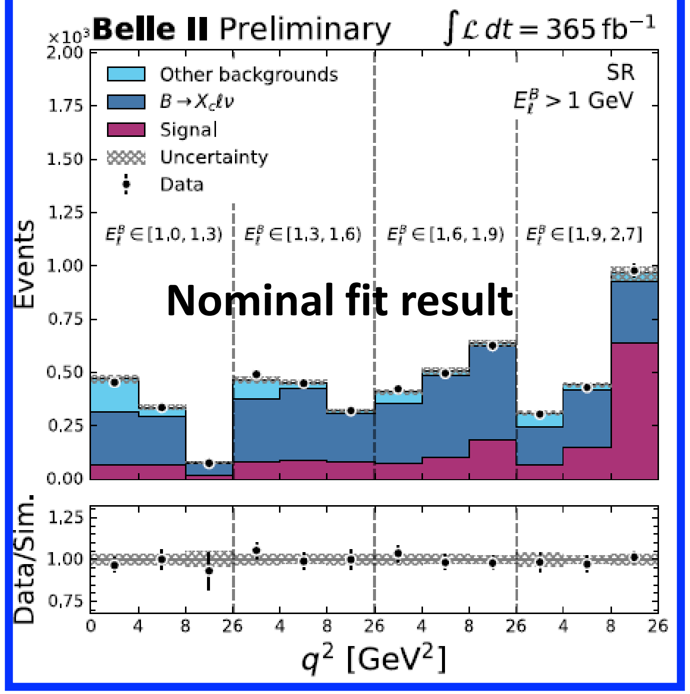


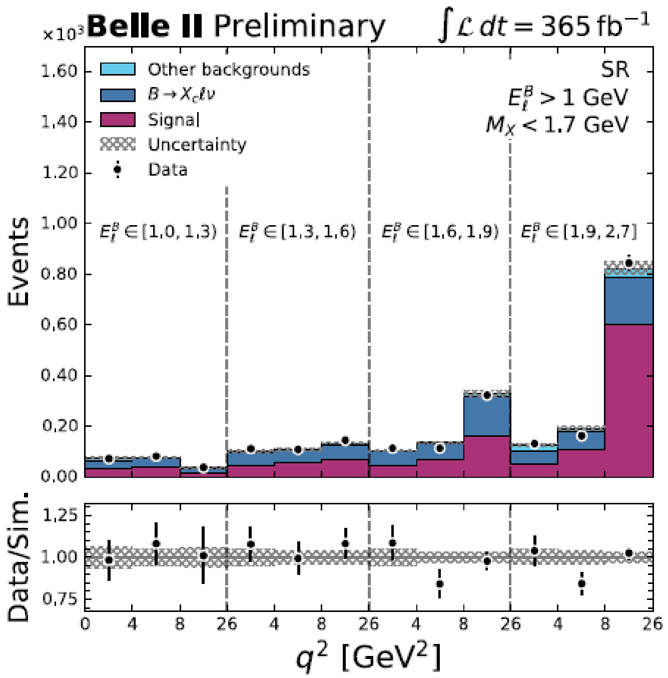
Inclusive $B \to X_u \ell \nu$

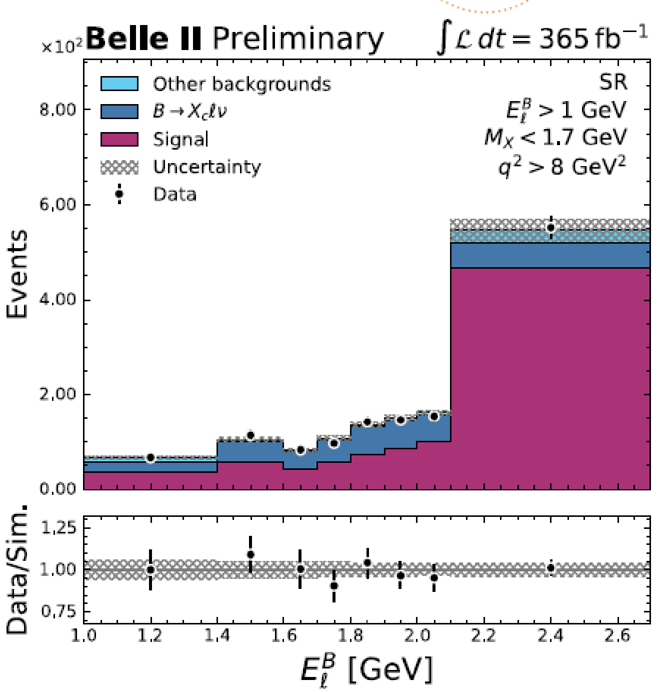
PRD 113 (2026) 032004

- **Reconstruct:** Combined signal lepton on the **signal side** with fully reconstructed hadronic B on **tag side**
- **Large backgrounds** from dominant $B \to X_c \ell \nu$ decays
  - Efficiently suppressed with MLP using different event shape variables
  - Normalization and shape mismodelling **corrected** using **control regions** in data
- **Extract signal** with 2D fit to lepton energy in B restframe E_ℓ^B & momentum transfer $q^2 = (p_\ell + p_\nu)^2$







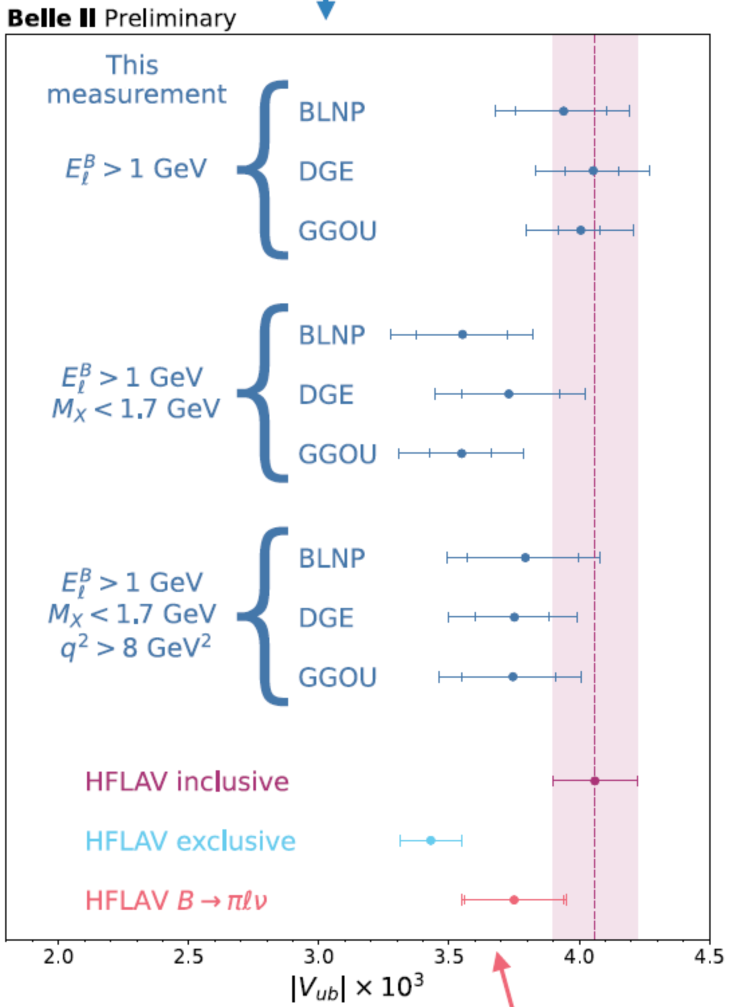


Inclusive $B \to X_u \ell \nu$

PRD 113 (2026) 032004

BLNP model: PRD72,073006; NPB 699,335
DGE model: JHEP 01 (2006) 097
GGOU model: JHEP 10 (2007) 058.

Predictions of the partial rate



Exclusive Average for $B \to \pi \ell \nu$:
$|V_{ub}| = (3.75 \pm 0.06_{\text{exp}} \pm 0.19_{\text{theo}}) \times 10^{-3}$

Determine $|V_{ub}|$ from the measured **partial branching fractions** in the 3 different phase space regions:

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell^+ \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u \ell^+ \nu_\ell)}}$$

Nominal result: $E_\ell^B > 1$ GeV with GGOU

$$\boxed{|V_{ub}| = (4.01 \pm 0.19^{+0.07}_{-0.08}) \times 10^{-3}}$$

Covering 87% of phase space

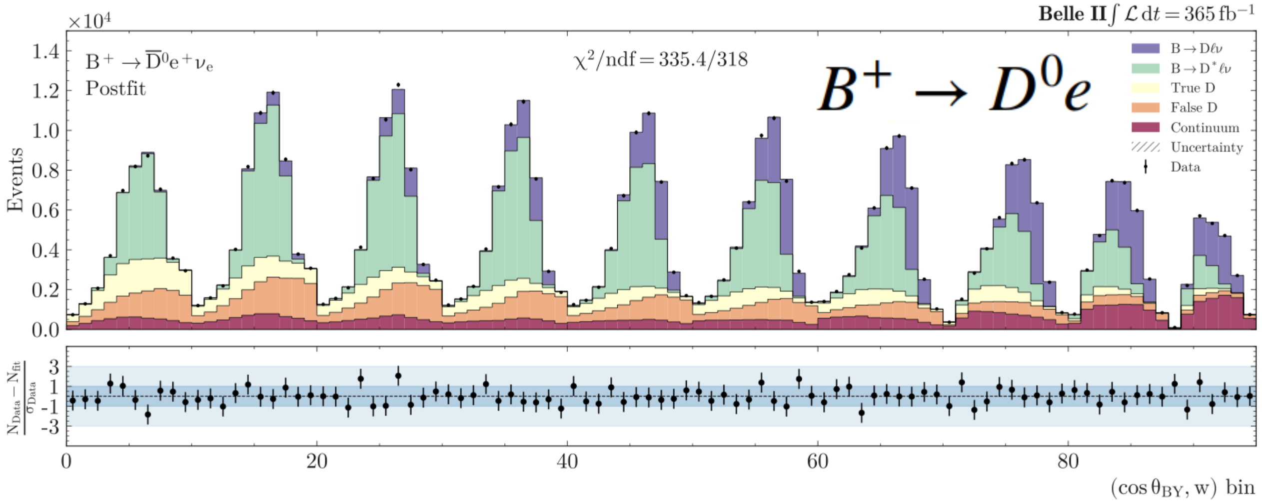
Dominant systematics:

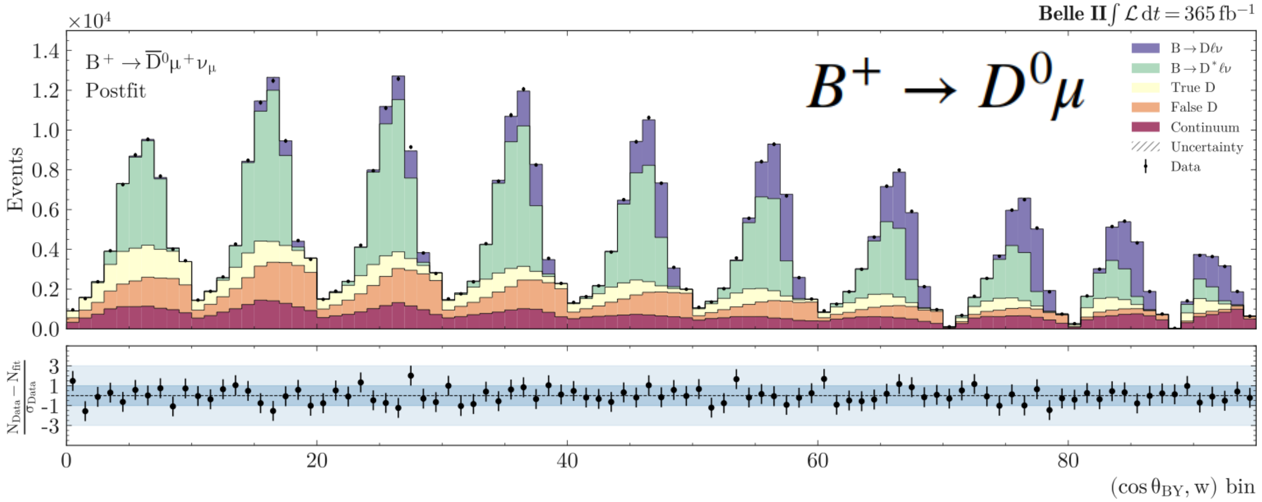
- $B \to X_u \ell \nu$ modelling: (m_b, a) where $a = f(m_b, \mu_\pi^2)$ in Kagan-Neubert scheme
- $B \to X_c \ell \nu$ composition differences between SR and CR
- X_u fragmentation modelling

Competitive with previous measurements!

$|V_{cb}|$ from untagged exclusive $B \to D\ell\nu_\ell$

Signal yields are extacted in 10 bins of w by fitting the simultaneously in the electron and muon channels and in the charged and neutral modes





$$w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

The recoil variable $w = v_B \cdot v_D$

$\cos\vartheta_{BY}$: the angle between the signal B and Dℓ system

PRD 112, 112009 (2025)

$$\mathcal{B}(B^0 \to D^- \ell^+ \nu_\ell) = (2.06 \pm 0.05(\text{stat.}) \pm 0.10(\text{syst.}))\,\%$$

$$\mathcal{B}(B^+ \to \bar{D}^0 \ell^+ \nu_\ell) = (2.31 \pm 0.04(\text{stat.}) \pm 0.09(\text{syst.}))\,\%$$

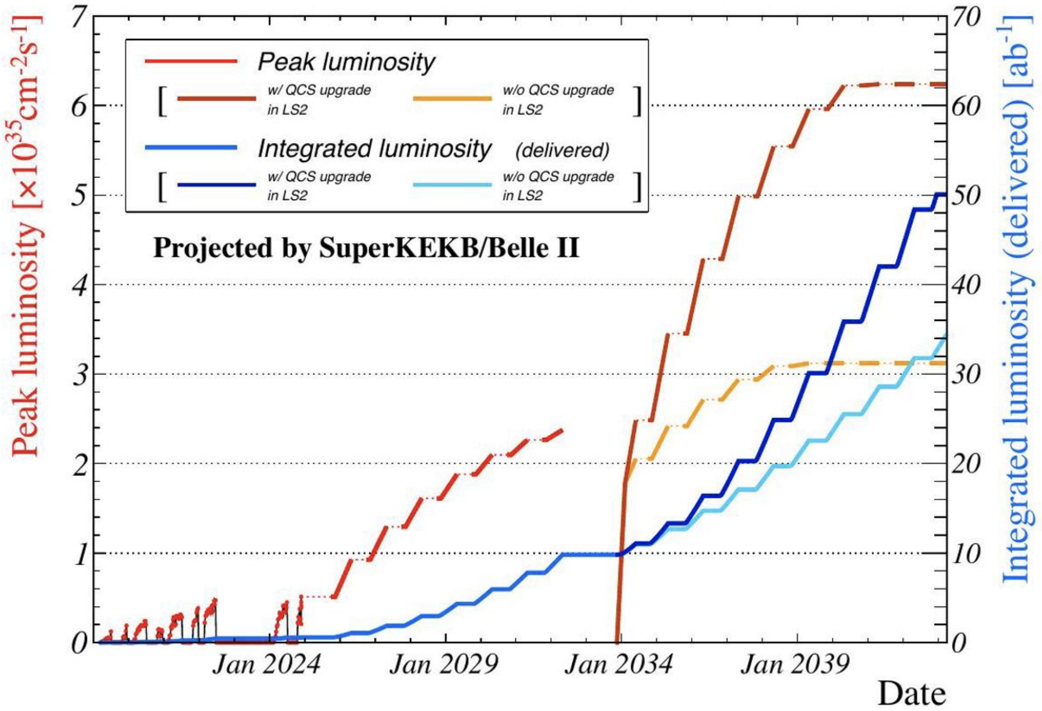
Extract by fitting values of $\Delta\mathcal{T}/\Delta w$ using BCL (Phys. Rev. D 82, 099902 (2010)) form factor parameterization.

$$|V_{cb}| = (39.2 \pm 0.4(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.5(\text{th.})) \times 10^{-3}$$

- **Result in agreement with exclusive HFLAV average**
- **Most precise measurement using $B \to D\ell\nu_\ell$ decays**

Future prospects

From https://www.belle2.org/research/luminosity/



- Until 2026, about 1 ab^{-1} data, comparable to Belle
- Until 2029, about 4 ab^{-1} data.

During the long shutdown starting in 2032, upgrades are planned for the SuperKEKB accelerator and the Belle II detectors

From SNOWMASS2021 (https://arxiv.org/pdf/2203.10203)

Physics reach：

The goal of Belle II is to uncover new physics beyond the Standard Model.

- Testing violations of lepton flavor conservation and universality and understanding their origins
- Checking the unitarity of the CKM matrix to high precision
- Identifying new weak (CP-violating) phases in the quark sector
- Probing the existence of dark-sector particles at MeV to GeV mass scales
- Reducing the uncertainty in the theory prediction for the muon g−2 anomaly
- Understanding the role of QCD in the production and binding of new hadronic states of matter

Summary

Belle II is presently increasing its instantaneous luminosity, perfect for precision measurement of B decays and probing Standard Model assumptions

- **B hadronic decays, CPV in B decays, Electroweak Penguin Decays, B (semi-)leptonic decays, …..**
  - **Some are special at e^+e^- collider**

- **Only ~2% of target luminosity collected so far. Until 2026, about 1 ab^{-1} data at Belle II. Stay tuned for more exciting results from Belle II.**

Thanks for your attention!

Backup slides

CP Violation in B decays

Observation of time-dependent *CP* violation and measurement of the branching fraction of $B^0 \to J/\psi\ \pi^0$ decays, PRD 111, 012011 (2025)

Measurement of *CP* asymmetries in $B^0 \to K_S\ \pi^0\ \gamma$ decays at Belle II, PRL 134, 011802 (2025)

Measurement of branching fractions, asymmetry, and isospin asymmetry for $B^0 \to \rho^0 \gamma$ decays using Belle and Belle II data, Phys. Rev. D 111, L071103 (2025)

Measurement of the branching fraction, polarization, and time-dependent *CP* asymmetry in $B^0 \to \rho^+ \rho^-$ decays and constraint on the CKM angle ϕ_2, PRD 111, 092001 (2025)

Measurement of the branching fraction and *CP*-violating asymmetry of the decay $B^0 \to \pi^0 \pi^0$ using 387 million bottom-antibottom meson pairs in Belle II data, PRD 111, L071102 (2025)

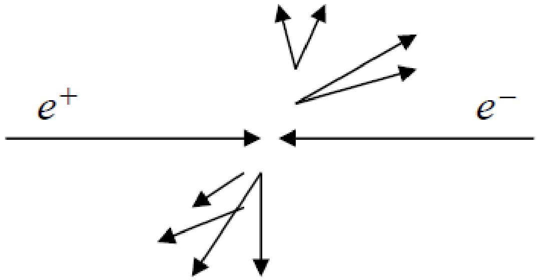
Measurement of time-dependent *CP* asymmetries in $B^0 \to K_S \pi^+ \pi^- \gamma$ decays at Belle and Belle II, arXiv: 2510.01331, to appear in JHEP

Usual method to extract signal yield

To select signal candidates, we kinematically constrain the event via the tag-side B decay. Three ways:

To select signal candidates, we kinematically constrain the event via the tag-side B decay. Three ways:

hadronic tagging: fully reconstruct tag side ⇒ backgrounds are low and B momentum well-determined. O(10^4) decay chains consituting 36 hadronic B decays are reconstructed using a series of boosted decision tree (BDT) classifiers [Keck et al., Comp. Soft. for Big Science 3, 6 (2019)]. *But efficiency is small: 0.1-0.5%*



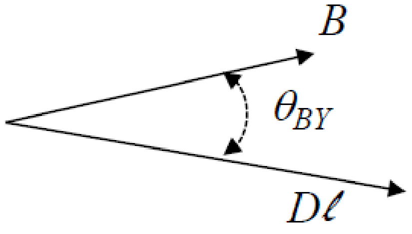
$$P_{(\text{signal } B)} = P_{e^+e^-} - P_{(\text{tag } B)}$$

$$\Rightarrow \text{ for } B \to D\ell\nu : \begin{cases} P_\nu = P_{(\text{signal } B)} - P_D - P_\ell \\ m_\nu^2 = \left(P_{(\text{signal } B)} - P_D - P_\ell\right)^2 \end{cases}$$

semileptonic tagging: reconstruct a well-identified lepton on tag side. Backgrounds are larger, B_{sig} momentum not known so less precise kinematic constraints, but efficiency is larger: 1-2%

$$\text{for } B \to D\ell\nu, \text{ where } Y \equiv D\ell \text{ system :}$$

$$\cos\theta_{BY} = \frac{2E_B E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$



inclusive tagging: tag-side B inferred ***after*** *reconstructing signal B decay; serves as a consistency check (efficiency ~100%)*

CKM matrix element

Exclusive: $B \to \pi l\nu, B \to \rho l\nu, B \to D^{(*)} l\nu, etc$

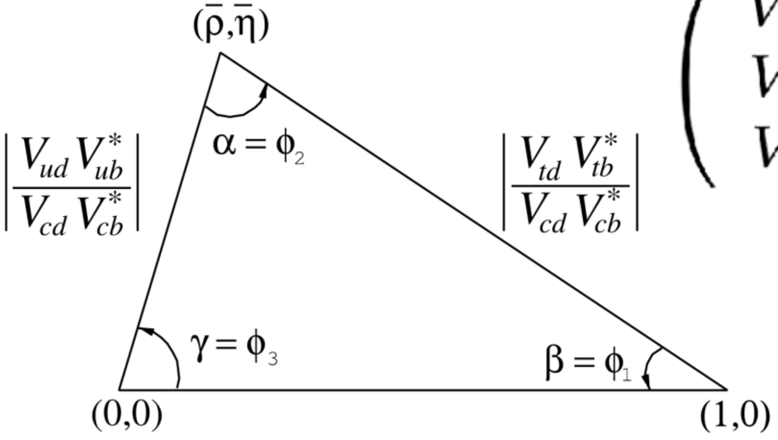
$\frac{dB}{dq^2} \propto |V_{xb}|^2 \times |FF(q^2)|^2$ Form factor from LCSR, LQCD

Inclusive: $B \to X_u l\nu, B \to X_c l\nu$

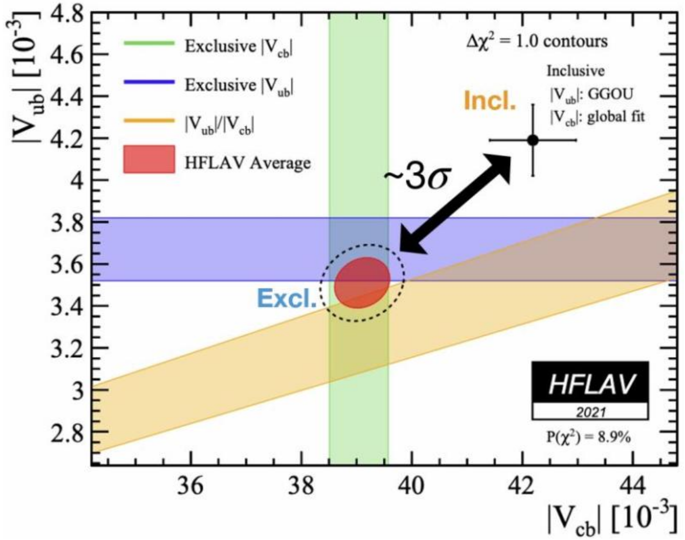
$\mathcal{B} \propto |V_{xb}|^2 \times \left[\Gamma(b \to q l \bar{\nu}_l) + \frac{1}{m_b} + \alpha_s + \cdots\right]$ From OPE

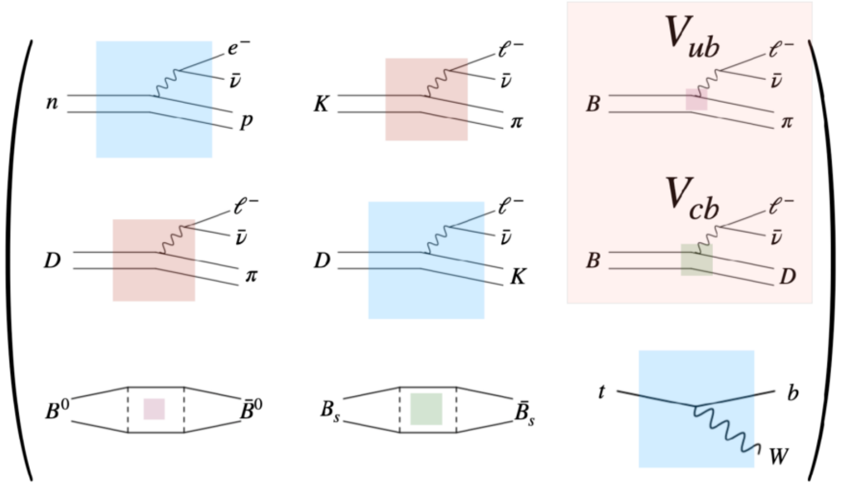
Belle II important task:

Constrain CKM unitarity triangle & test SM



$$\begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & \boxed{V_{cb}} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$





Several measurements carried out by Belle and Belle II:

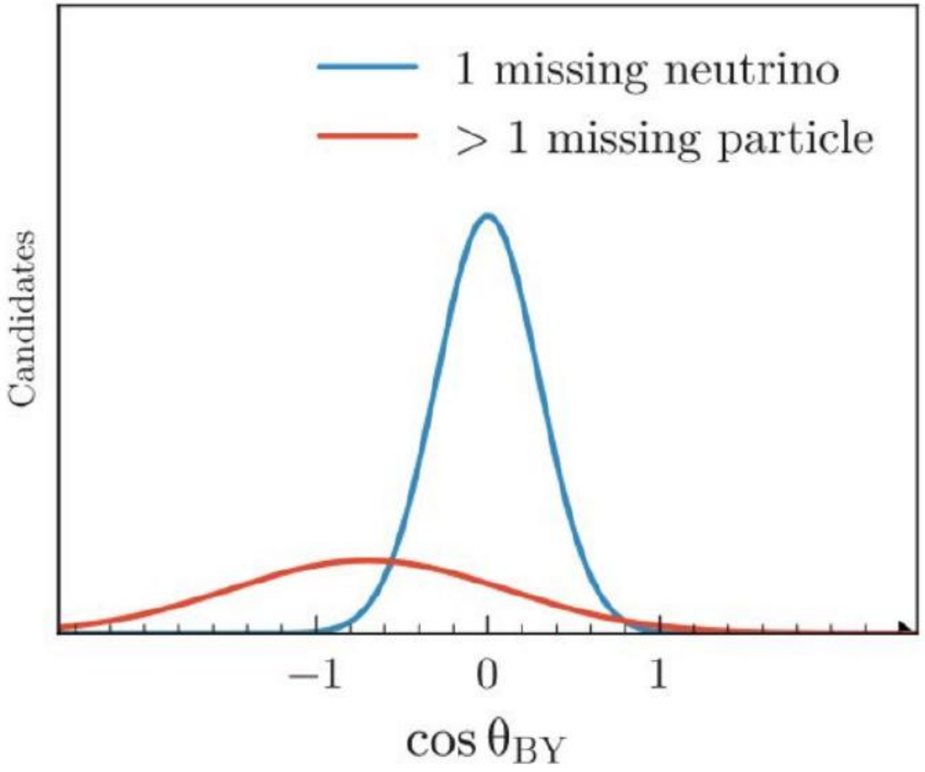
$|V_{cb}|$ - Angular coefficients of $B \to D^* l\nu$ **Belle: PRL 133, 131801 (2024)**

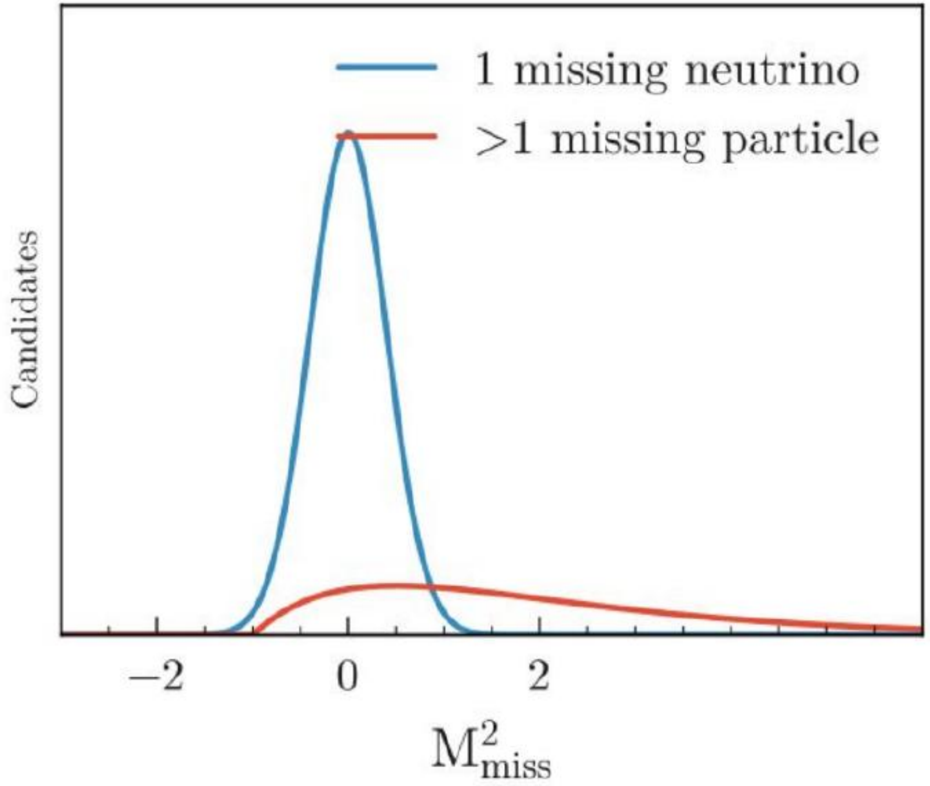
$|V_{ub}|$ - $|V_{ub}|$ from $B \to (\pi,\rho) l\nu$ simultaneous analysis New from Belle II
- Simultaneous inclusive and exclusive $|V_{ub}|$ **Belle: PRL 131, 211801 (2023)**

$\frac{|V_{ub}|}{|V_{cb}|}$ - Ratio of inclusive $b \to c$ and $b \to u$ decays **Belle: arXiv: 2311.00458**

Common variables for $B \to (X)l\nu$ decays (only one neutrino missing)

- Leptonic system mass squared $q^2 = (p_l + p_\nu)^2$
- Recoil parameter $w = \frac{M_B^2 + M_X^2 - q^2}{2M_B M_X}$
- Missing mass squared M^2_{miss}
- $\cos\vartheta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - M_Y^2}{2|p_B^*||p_Y^*|}$, $Y = Xl$ system



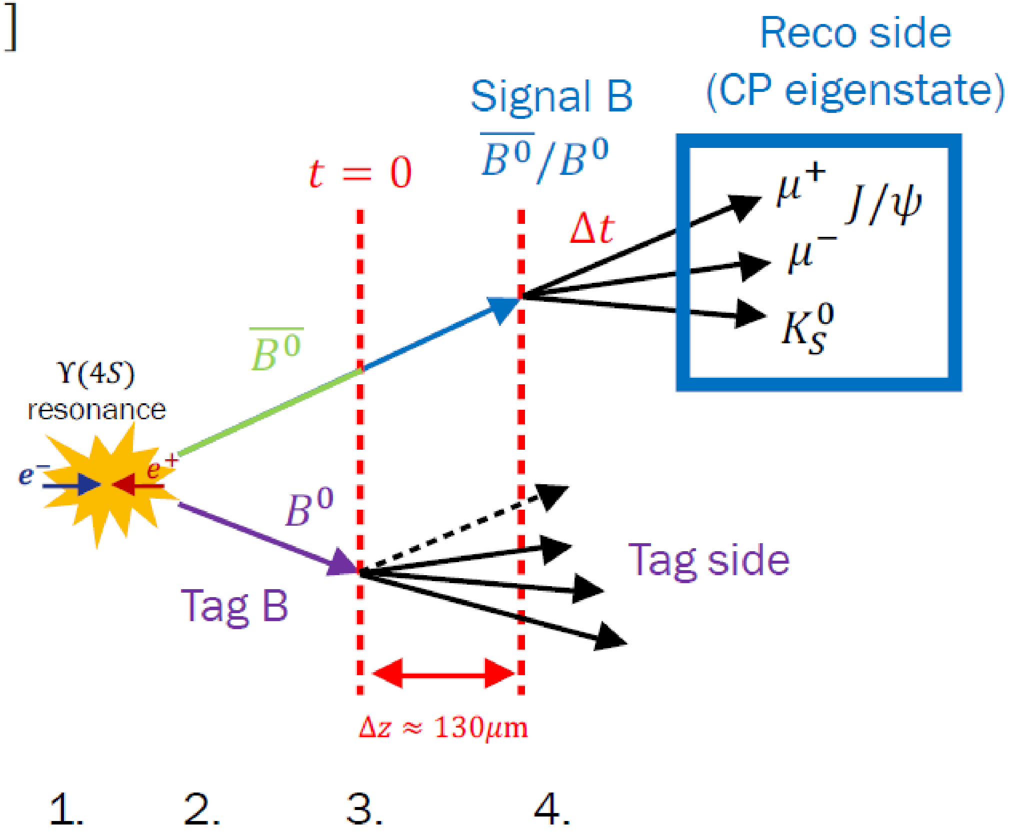


Measuring time-dependent CPV at Belle II

- $P(\Delta t, q) = \frac{e^{-\frac{|\Delta t|}{\tau_{B^0}}}}{4\tau_B^0}[1 + q[C\cos(m_d \Delta t) + S\sin(\Delta m_d \Delta t)]$
- General technique at Belle II for CPV analyses

1. $e^+e^- \to \Upsilon(4S)$, boosted in lab frame
2. The $\Upsilon(4S)$ produces an entangled $B^0\overline{B^0}$ pair
   - $1^{--} \to 0^- + 0^-$
3. At $t = 0$, one of the Bs decays, call it tag B
4. After a time Δt, the second B decays into a CP or flavor eigenstate that we fully reconstruct
   - If the signal B decays first, Δt is negative

- Resolution of Δt significantly influenced by Δz resolution from pixel detector



$$\Delta t = \frac{\Delta z}{\beta\gamma c}$$