Measurements of CP violation and CKM matrix elements in B decays at Belle and Belle II

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Lake Louise Winter Institute (LLWI 2025)
Chateau Lake Louise, Canada
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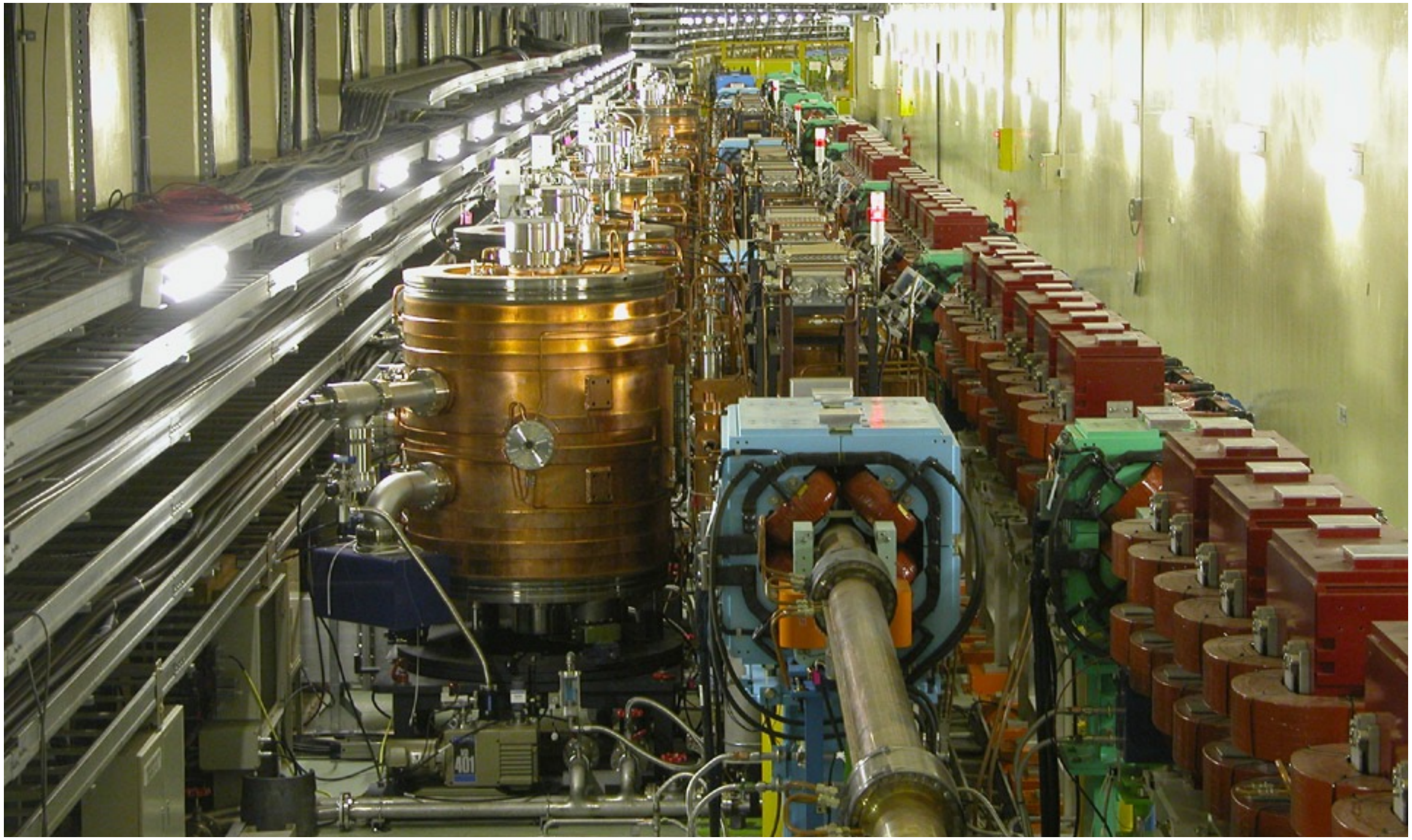
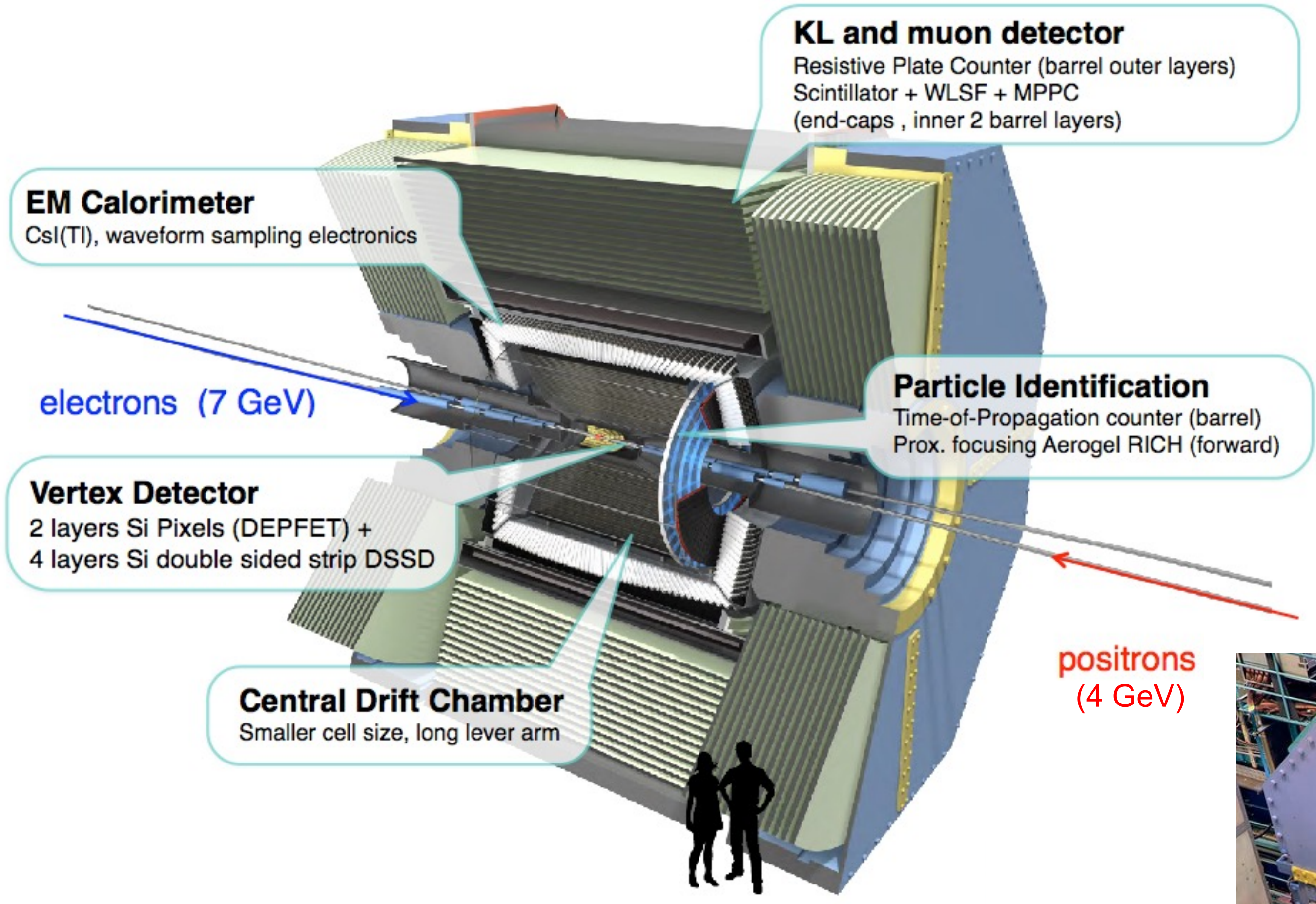
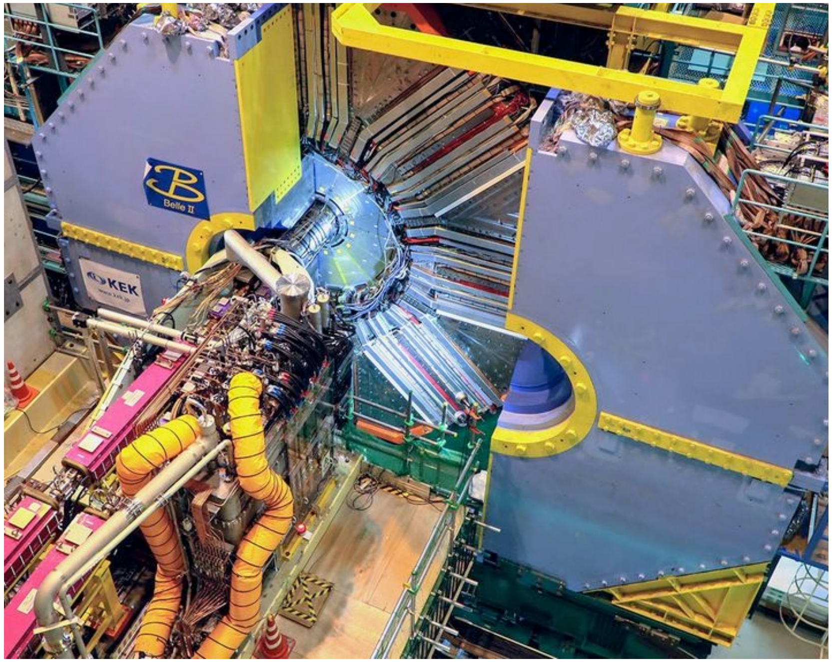


- the Belle II experiment
- the CKM unitarity triangle
- CP violation measurements
  - $B^0 \to \rho^+ \rho^-$
  - $B^0 \to \pi^0 \pi^0$
  - $B^0 \to \omega\omega$
  - $B^0 \to J/\psi\, \pi^0$
  - $B^0 \to K_S\, \pi^0 \gamma$
  - others
- CKM elements
  - $|V_{cb}|$
  - $|V_{ub}|$
- summary

The Belle II Experiment

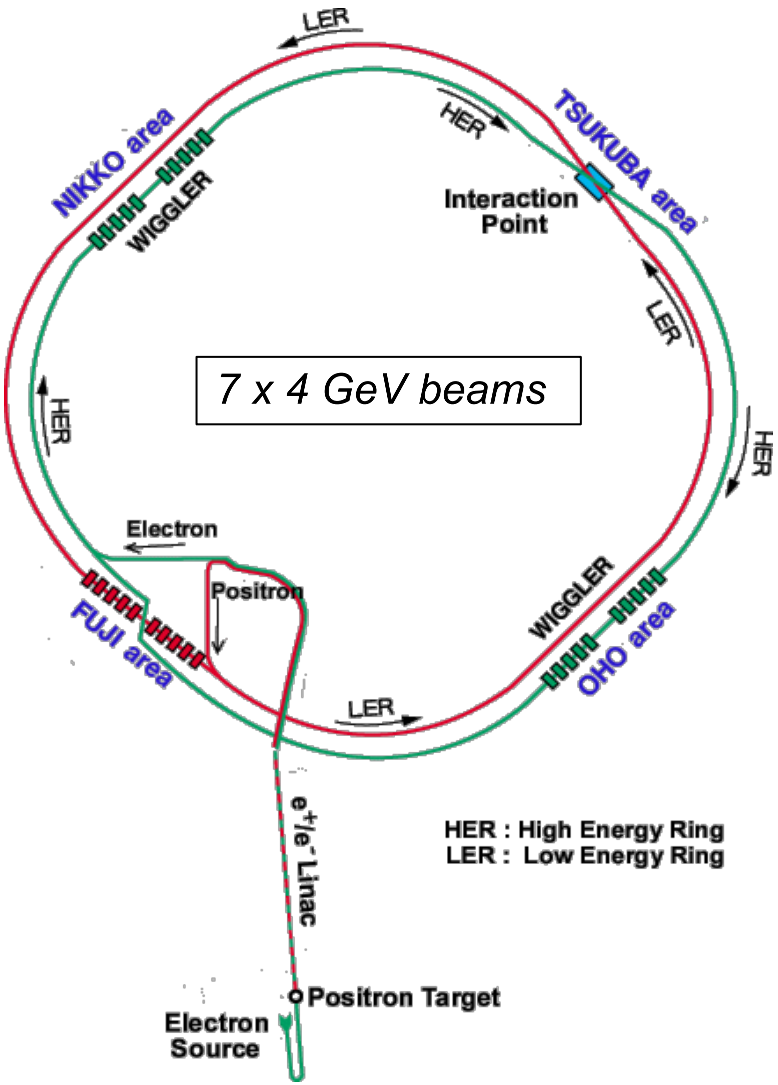


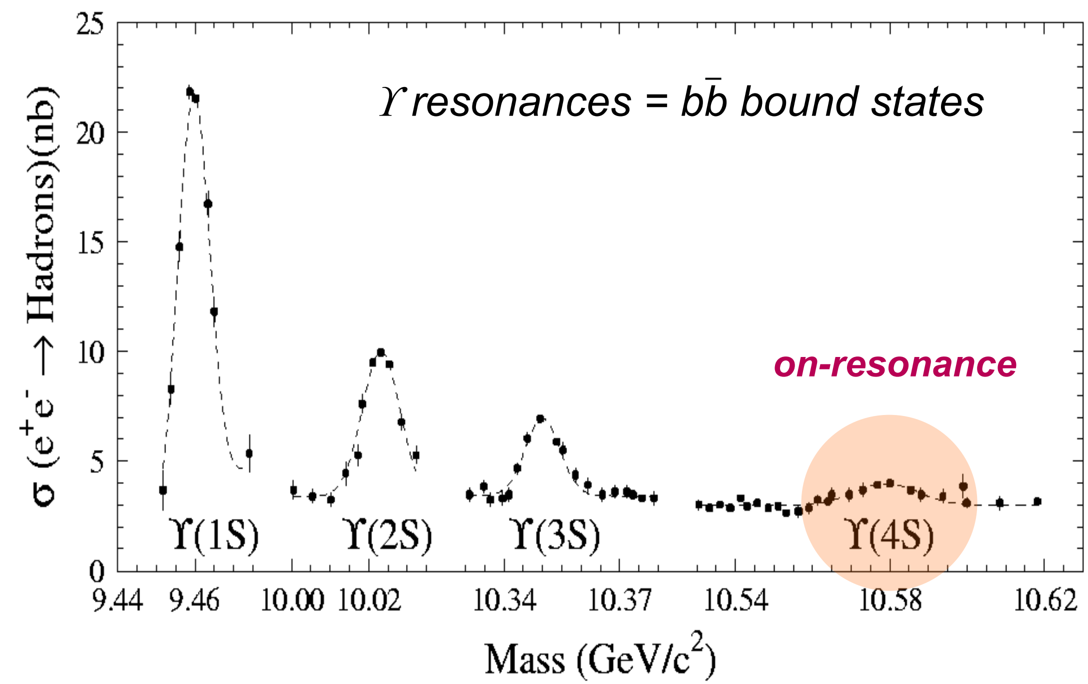
DEPFET pixels:	*Layer 1*	*r = 14 mm*
	Layer 2	*r = 22 mm*
double-sided strips:	*Layer 3*	*r = 39 mm*
	Layer 4	*r = 80 mm*
	Layer 5	*r = 104 mm*
	Layer 6	*r = 135 mm*



Super-KEKB runs at the Υ(4S) resonance

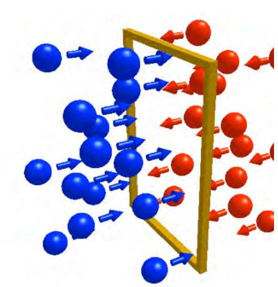
Super-KEKB collider:





At Υ(4S) resonance: ($\sqrt{s}$ = 10.579 GeV)

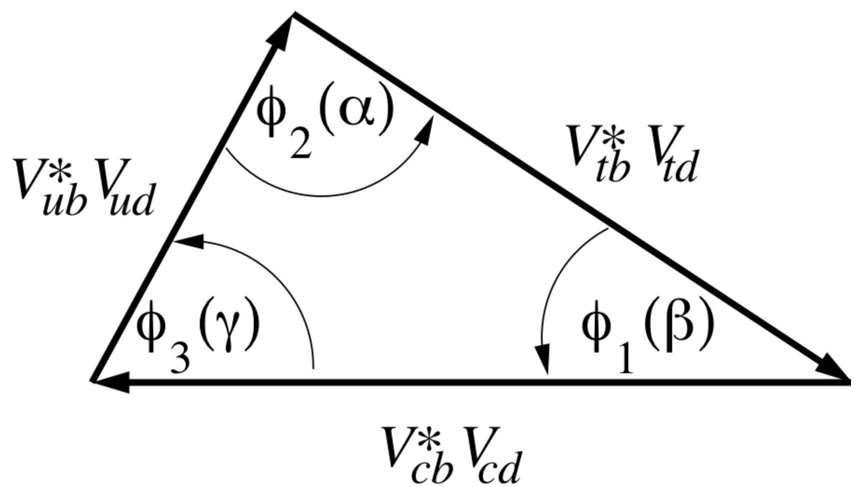
$\sigma(bb)$ = 1.1 nb
$\sigma(cc)$ = 1.3 nb
$\sigma(uu)$ = 1.4 nb
$\sigma(dd,ss)$ = 0.3 nb



CKM Matrix and Unitarity triangle

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$U^\dagger U = 1 \Rightarrow \left[\begin{array}{rl} V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} & = 0 \\ V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} & = 0 \\ V_{cd}^* V_{td} + V_{cs}^* V_{ts} + V_{cb}^* V_{tb} & = 0 \\ V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} & = 0 \\ V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} & = 0 \\ V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} & = 0 \end{array} \right.$$



$$\phi_1\ (\beta) = \arg\left(\frac{V_{cb}^* V_{cd}}{-V_{tb}^* V_{td}}\right) \qquad \phi_2\ (\alpha) = \arg\left(\frac{V_{tb}^* V_{td}}{-V_{ub}^* V_{ud}}\right) \qquad \phi_3\ (\gamma) = \arg\left(\frac{V_{ub}^* V_{ud}}{-V_{cb}^* V_{cd}}\right)$$

Belle II

CKM Unitarity triangle

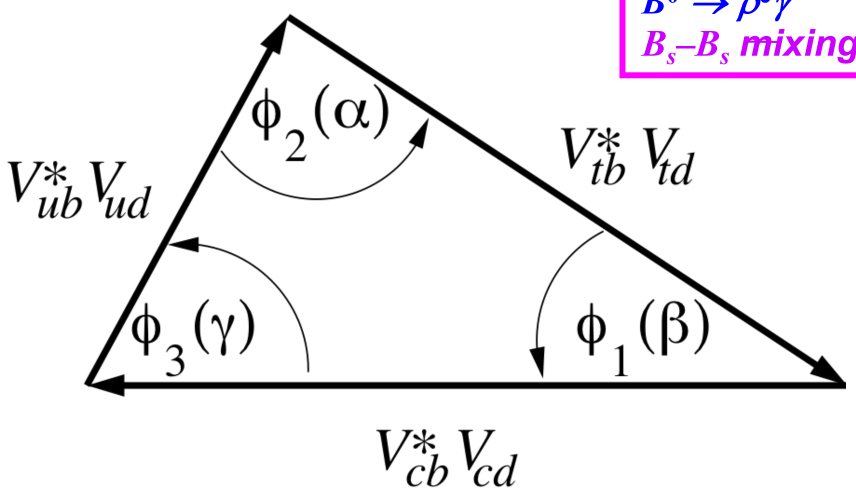
Belle
LHCb

$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$$

$B \to \pi^+\pi^- / \pi^+\pi^0 / \pi^0\pi^0$
$B \to \rho^+\rho^- / \rho^+\rho^0 / \rho^0\rho^0$
$B^0 \to \rho\,\pi$
$B^0 \to a_1(\rho\pi)^+\,\pi^-$

$B^0 \to \rho^0\gamma$
B_s–B_s mixing

$B^0 \to \pi\,\ell^+\,\nu$
$B^0 \to X_u\,\ell\,\nu$
$B^+ \to \tau^+\,\nu$
$\Lambda_b \to p\,\ell^+\nu$



$B^- \to D^{(*)}{}_{CP}\,K^{(*)-}$
$B^0 \to D_{CP}\,K^{*0}$
$B^- \to D^{(*)}(K^+\pi^-)\,K^{(*)-}$
$B^- \to D^{(*)0}\,\pi^-$
$B^- \to D^{(*)}(K_S\,\pi^+\pi^-)\,K^{(*)-}$
$B^- \to D(\pi^0\pi^+\pi^-)\,K^-$
$B^- \to D(K_S\,K^+\pi)\,K^-$

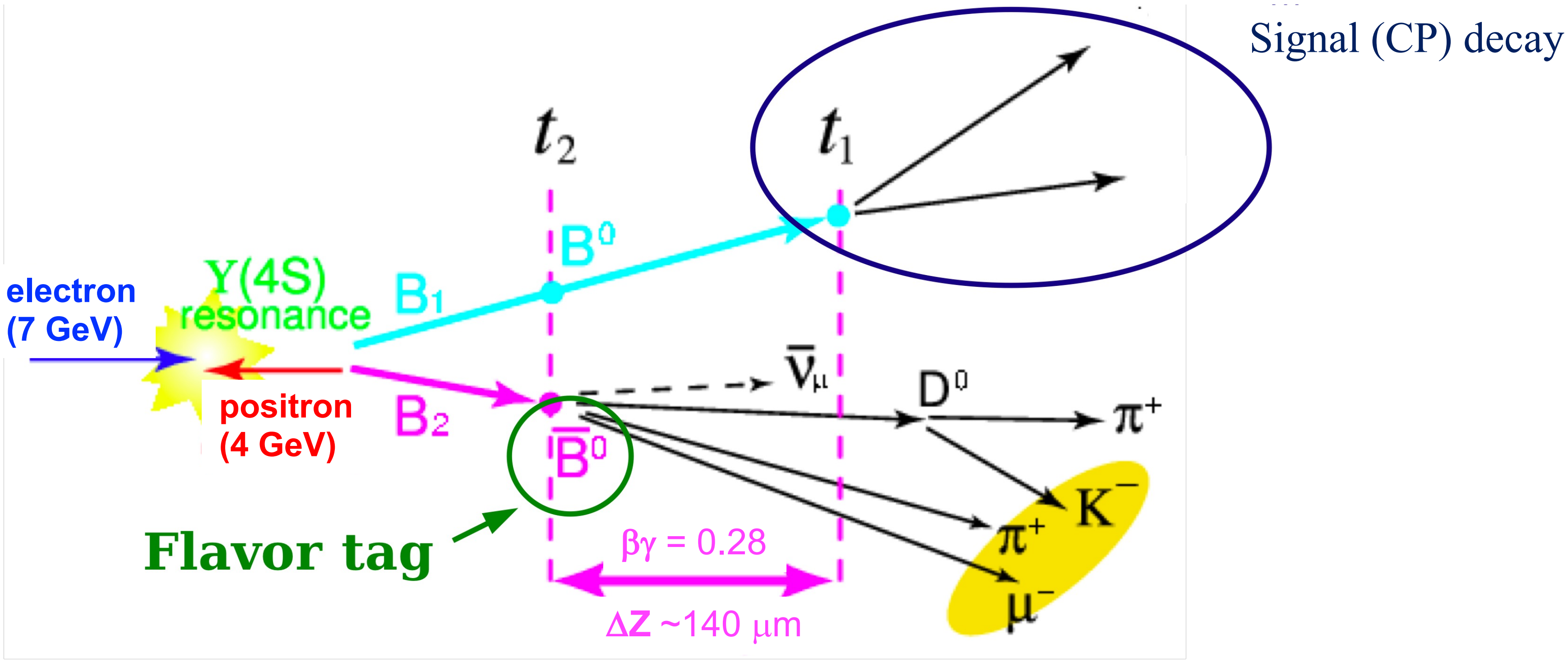
$B^0 \to D^{(*)}\ell\,\nu$
$B^0 \to X_c\,\ell\,\nu$ (ℓ energy, hadron mass moments)
$B^0 \to X_s\,\gamma$ (γ energy moments)

$B^0 \to J/\psi\,K_S$
$B^0 \to J/\psi\,K_L$
$B^0 \to \psi'\,K_S$
$B^0 \to \chi_c\,K_S$
$B^0 \to \eta_c\,K_S$
$B^0 \to D^{(*)}{}_{CP}\,h^0$
$B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$
$B^0 \to (K_SK_S/\rho^0/\omega)K_S$

$B^0 \to f$ decay time distribution:

Two B mesons are produced electromagnetically in an antisymmetric (C = –1) state:

$$\psi = \frac{1}{\sqrt{2}}\left(|B^0\rangle|\overline{B}^0\rangle - |\overline{B}^0\rangle|B^0\rangle\right)$$



$$\Delta z \sim c\beta\gamma\Delta t$$

For self-conjugate (CP eigenstate final state:

$$A(t) \equiv \frac{N(\overline{B}^0 \to f) - N(B^0 \to f)}{N(\overline{B}^0 \to f) + N(B^0 \to f)} = S\sin(\Delta M \Delta t) - C\cos(\Delta M \Delta t) \qquad S = \begin{cases} -\sin(2\phi_1 + \delta_1) \\ -\sin(2\phi_2 + \delta_2) \\ -\sin(2\phi_3 + \delta_3) \end{cases}$$

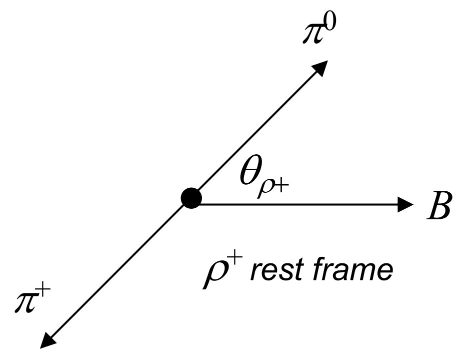
$B^0 \to \rho^+ \rho^-$

365 fb^{-1}, arXiv:2412.19624 (submitted to PRD)

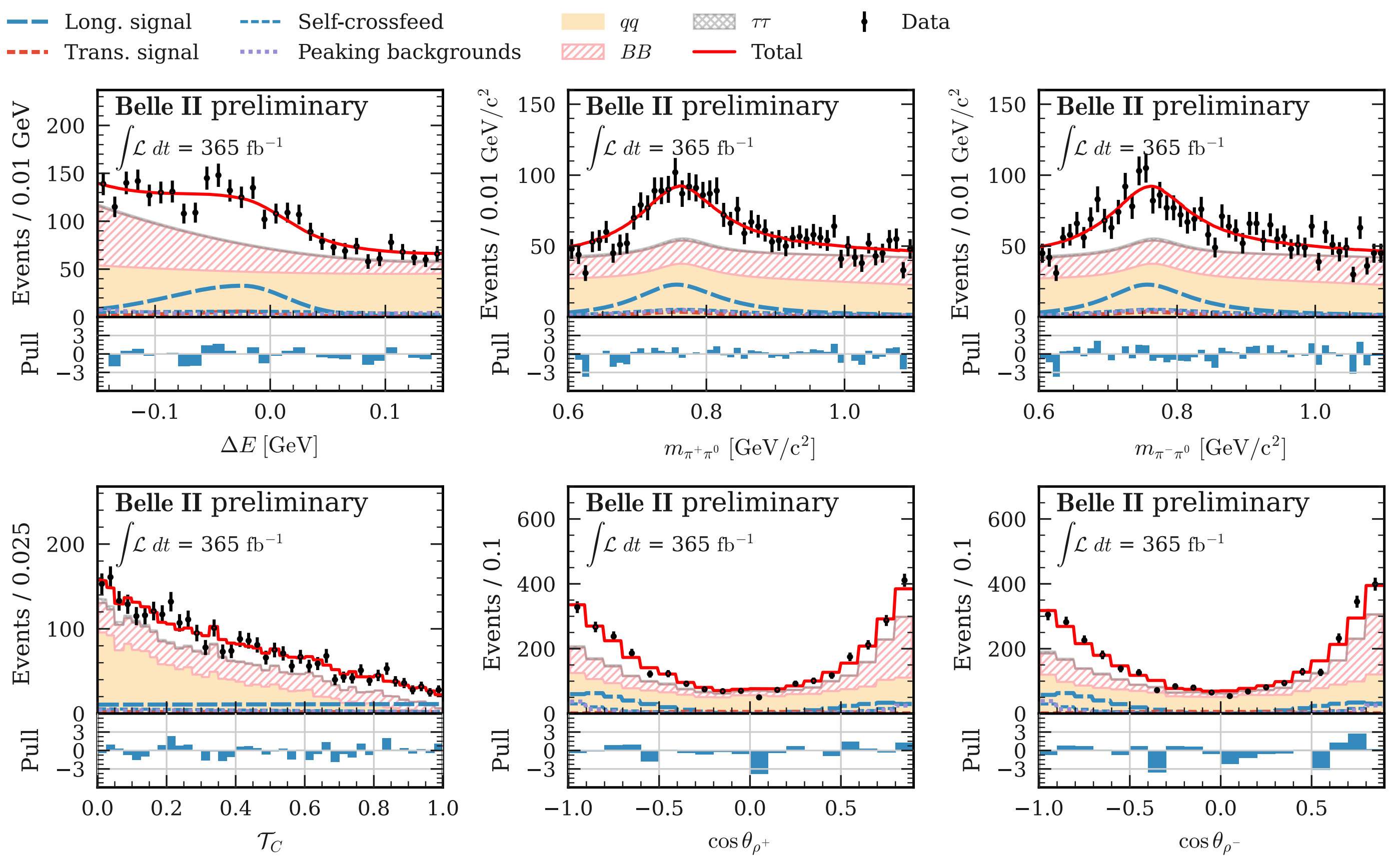
Two unbinned ML fits:

- fit to ΔE, $M(\pi^+\pi^0)$, $\cos\theta(\rho^+)$, BDT output $\mathcal{T}_C$ to determine branching fraction (from event yields) and fraction of longitudinal polarization (f_L)

$$\frac{d^2\Gamma}{d\cos\theta_{\rho^+}\, d\cos\theta_{\rho^-}} \propto f_L \cos^2\theta_{\rho^+} \cos^2\theta_{\rho^-} + \left(\frac{1-f_L}{4}\right) \sin^2\theta_{\rho^+} \sin^2\theta_{\rho^-}$$

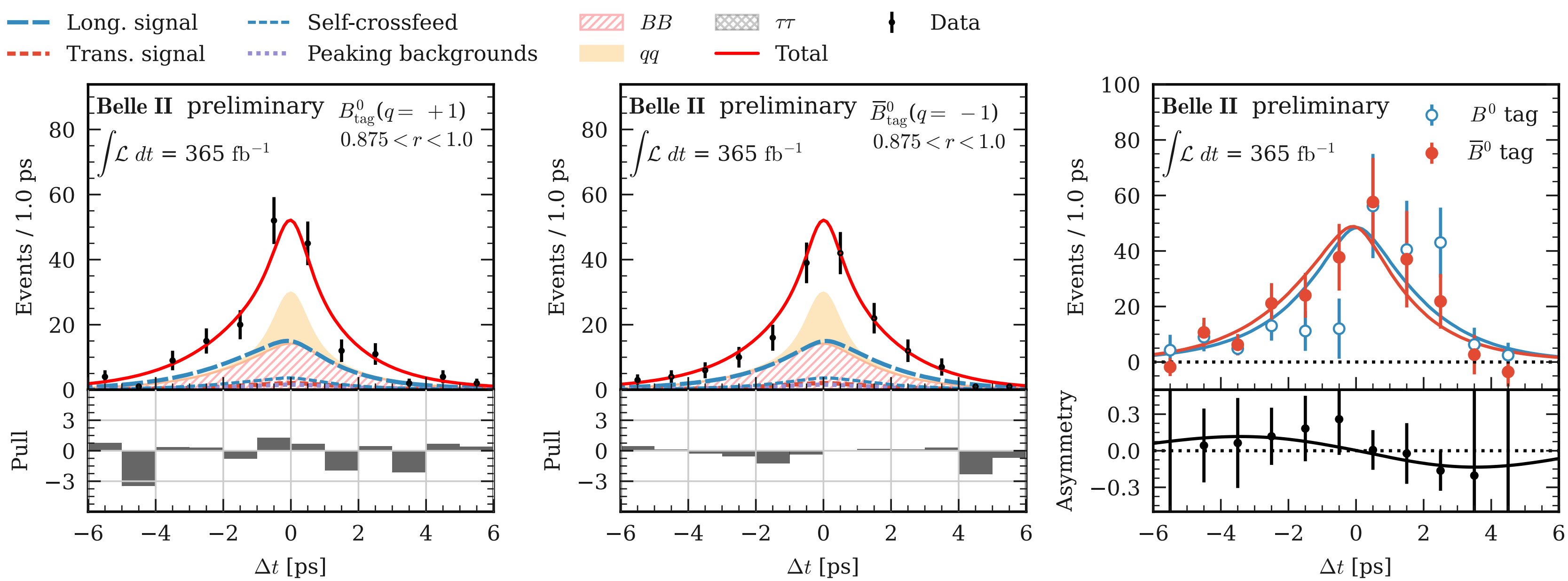


- fit to Δt, q (flavor tag) in 7 bins of r (tag quality) to determine S and C



$B^0 \to \rho^+ \rho^-$

365 fb^{-1}, arXiv:2412.19624 (submitted to PRD)



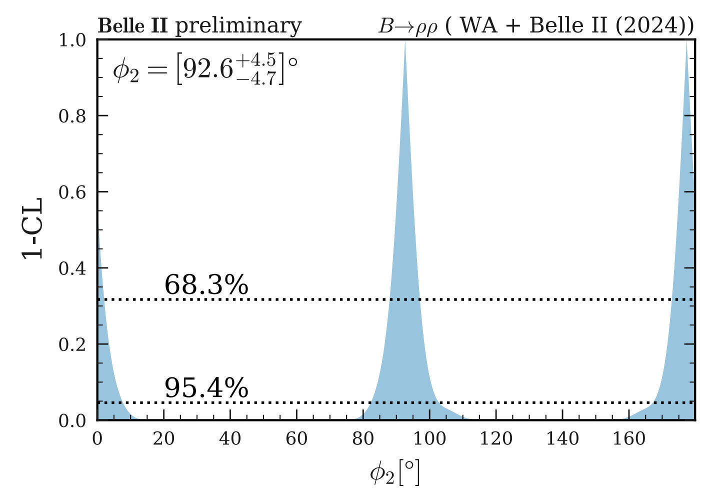
Results:

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (2.88\,^{+0.23}_{-0.22}\,^{+0.29}_{-0.27}) \times 10^{-5}$$

$$f_L = 0.921\,^{+0.024}_{-0.025}\,^{+0.017}_{-0.015})$$

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

$$C = -0.02 \pm 0.12\,^{+0.06}_{-0.05}$$



More precise than Babar (349 fb^{-1}), and less precise than Belle (711 fb^{-1})
Inputting these results into an isospin analysis, along with the measured branching fractions and S, C values for $B^0 \to \rho^0\rho^0$ and $B^+ \to \rho^+\rho^0$ gives:

$$\varphi_2 = (92.6\,^{+4.5}_{-4.7})^\circ$$

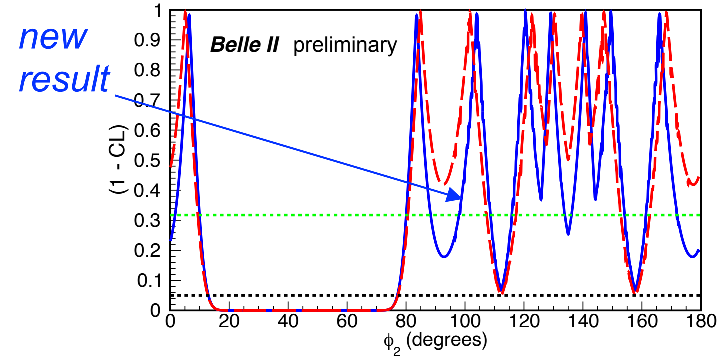
CKM Fitter 2023: $\varphi_2 = (86.2\,^{+3.9}_{-3.5})^\circ$

Other recent CPV analyses I

$B^0 \to \pi^0 \pi^0$ 365 fb^{-1} Belle II, 126 ± 20 signals

arXiv:2412.14260 (to appear in PRD)

Branching fraction,time-integrated CP asymmetry A_{CP} measured. Can perform the same isospin analysis as done for $B^0 \to \rho^+\rho^-$ to determine ϕ_2



$B^0 \to \omega\omega$ 711 fb^{-1} Belle, 60.3 ± 10.8 signals

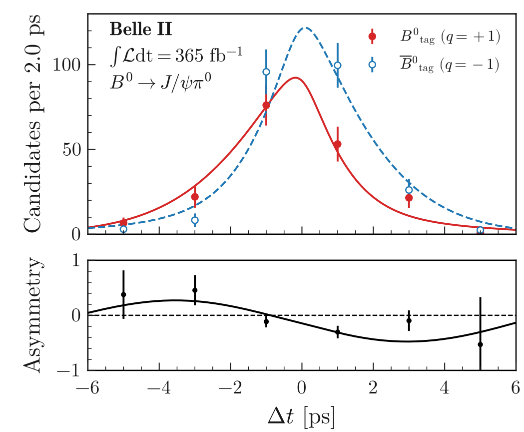
PRL 133, 081801 (2024)

First observation of this decay, and first measurement of fraction of longitudinal polarization (f_L) and CP asymmetry A_{CP}. Results for B and f_L disagree with LO pQCD but agree with NLO pQCD. This might explain the measured f_L for $B^0 \to \rho^0\rho^0$, which disagrees with LO pQCD. No CP violation observed.

$B^0 \to J/\psi\, \pi^0$ 365 fb^{-1}, 392 ± 24 signals

PRD 111, 012011 (2025)

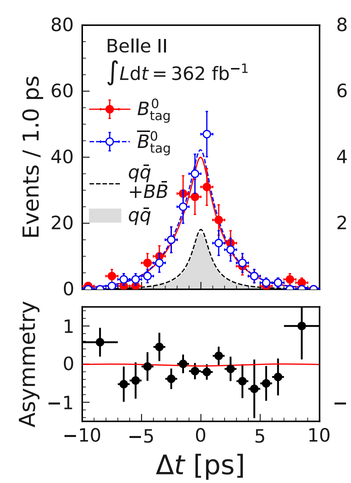
Branching fraction, CPV parameters S, C measured, first observation of CPV in this mode. C and S constrain penguin contribution to $B^0 \to J/\psi\, K_S$, which limits the precision on ϕ_1.



$B^0 \to K_S \pi^0 \gamma$ 362 fb^{-1}, 556 ± 33 signals

PRL 134, 011802 (2024)

World's most precise measurement of CPV parameters S, C. Nonzero values would indicate right-handed currents (new physics). Measured values consistent with no CPV.

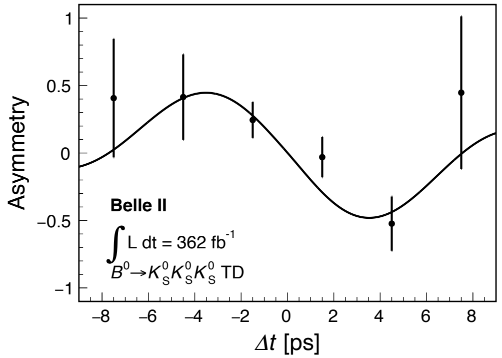


Other recent CPV analyses II

$B^0 \rightarrow K_S K_S K_S$

362 fb^{-1} Belle II, 220 ± 17 signals
PRD 109, 112020 (2024)

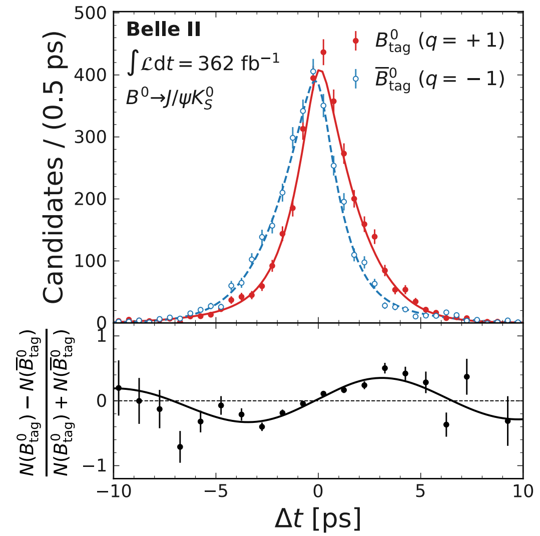
Challenging first measurement from Belle II: no tracks from B vertex. CP parameters S should be very close to sin2ϕ_1 (and is, but uncertainties are larger than Belle/Babar)



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

362 fb^{-1} Belle II, 392 ± 24 signals
PRD 110, 012011 (2024)

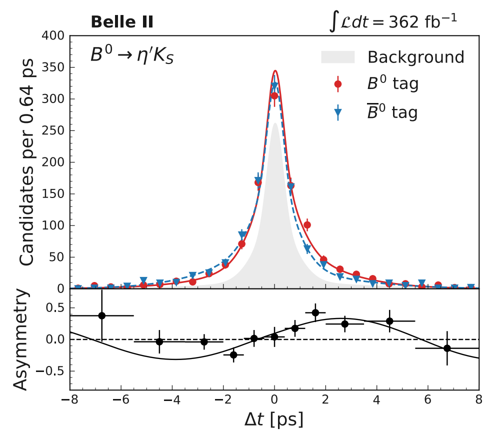
CPV parameters S, C measured using new graph-neural-network flavor tagger (18% improvement in effective tagging efficiency, 8% improvement in S precision). FIrst Belle II published result for sin2ϕ_1



$B^0 \rightarrow \eta' K_S$

362 fb^{-1}, 829 ± 35 signals
PRD 110, 112002 (2024)

b $\rightarrow$ sqqbar penguin-dominated decay, CPV parameter S should be very close to sin2ϕ_1 (and is, but uncertainties are larger than Belle/Babar)



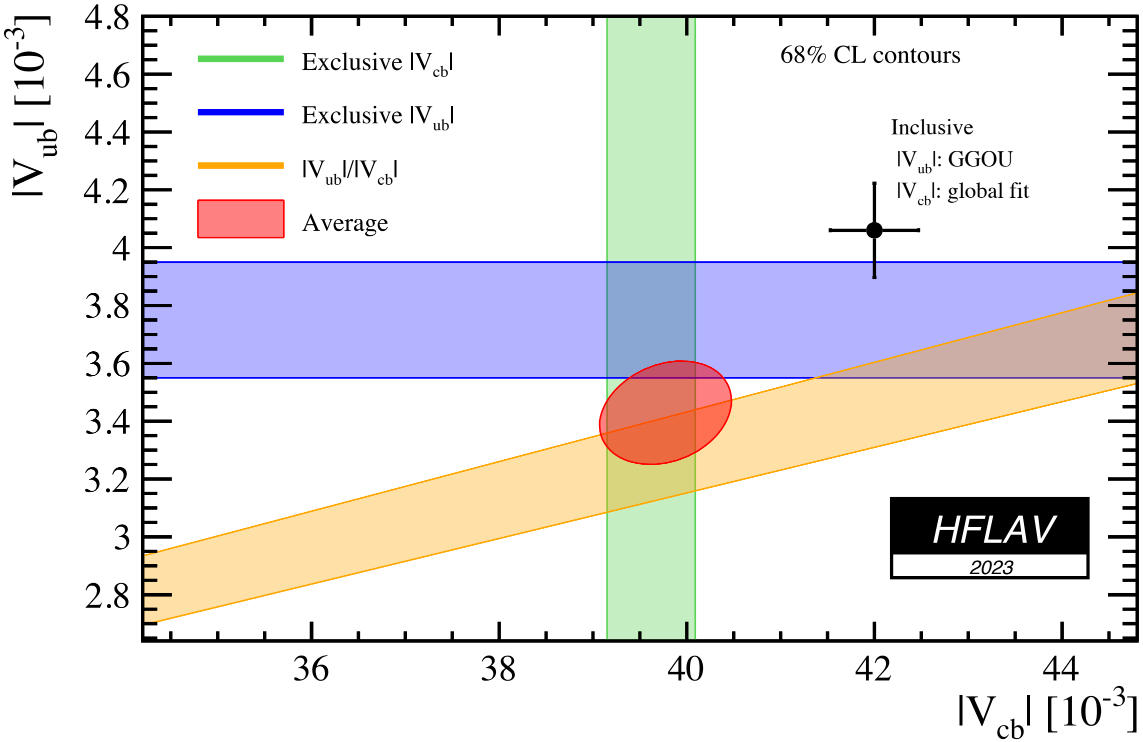
$B^0 \rightarrow \rho\, \gamma$

711 fb^{-1} + 365 fb^{-1}(Belle + Belle II), 213 ± 19 signals, arXiv:2407.08984 (submitted to PRD)

b $\rightarrow$ dγ penguin-dominated decay, measure CP asymmetry A_{CP} and isospin asymmetry

Inclusive vs. Exclusive $|V_{cb}|$, $|V_{ub}|$

Heavy Flavor Averaging Group (HFLAV), arXiv:2411.18639 (2024)



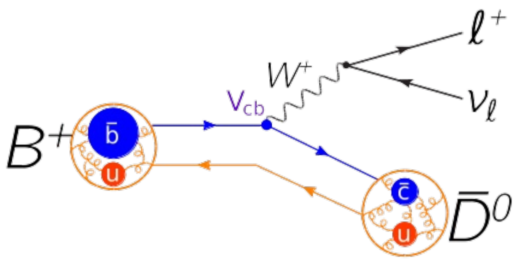
LHCb 2015 $\frac{\mathcal{B}(\Lambda_b \to p\mu^-\bar{\nu})}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\bar{\nu})}$:

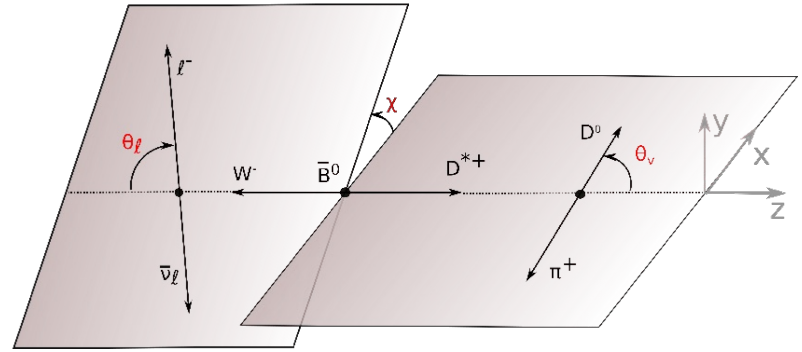
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.079 \pm 0.003 \pm 0.004$$

	Exclusive (x 10^{-3})	Inclusive (x 10^{-3})	Difference
$\lvert V_{cb}\rvert$	40.2 ± 0.6 ($D^*\ell\nu$, BGL form factor) 38.9 ± 0.7 ($D\ell\nu$, BGL form factor)	41.97 ± 0.48 (kinetic scheme, $M_X + E_\ell + q^2$ moments)	2.3σ, 3.6σ
$\lvert V_{ub}\rvert$	$3.75 \pm 0.06 \pm 0.19$ ($\pi\ell\nu$, BCL form factor + LQCD)	$4.06 \pm 0.12 \pm 0.11$ (GGOU kinetic scheme)	1.2σ

Belle + Belle II exclusive $|V_{cb}|$

Exclusive $|V_{cb}|$





$B^0 \to D^{*-}\ell^+\nu$ 711 fb^{-1} Belle

PRD 108, 012002 (2023);
PRL 133, 131801 (2024)

189 fb^{-1} Belle II

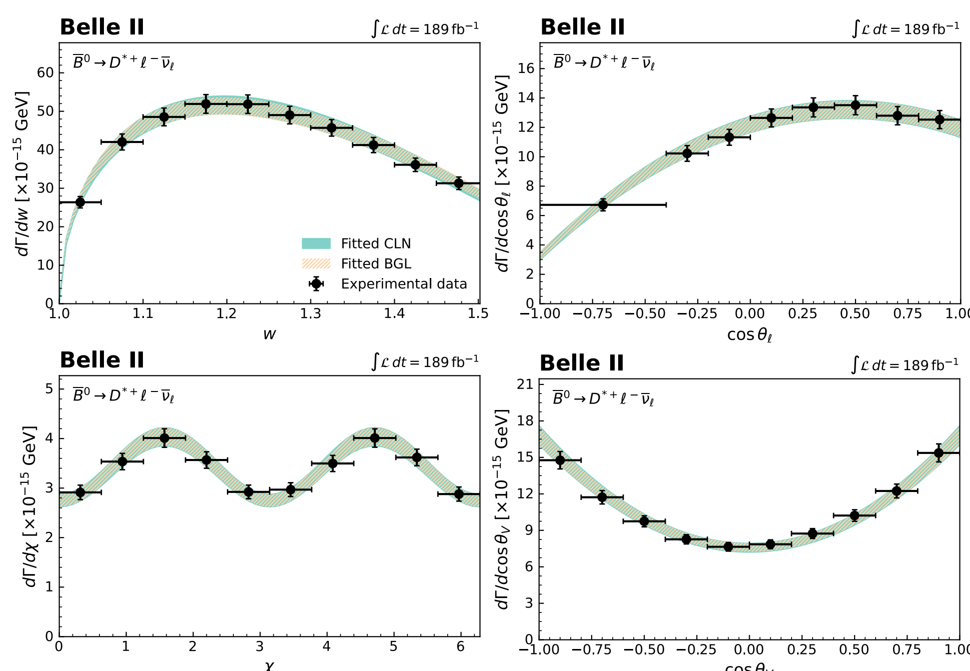
PRD 108, 092013 (2023)

$$w \equiv v_B \cdot v_D = \frac{M_B^2 + M_D^2 - q^2}{2 M_B M_D}$$

$q^2 = (P_B - P_D)^2$

Partial decay rates are measured in bins of w, $\cos\theta_\ell$, $\cos\theta_V$, χ, and these spectra are fit to BGL and CLN form factors.

Boyd, Grinstein, and Lebed, PRD 56, 6895 (1998)
Caprini, Lellouch, and Neubert, Nucl. Phys. B530, 153 (1998)
Also: take $\mathcal{F}(1) = 0.906 \pm 0.013$ from LQCD [FNAL MILC, PRD89, 114504 (2014)]



Results:

Belle

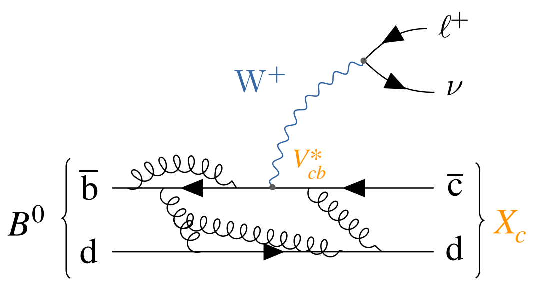
$$|V_{cb}|_{\mathrm{CLN}} = (40.2 \pm 0.9) \times 10^{-3}$$
$$|V_{cb}|_{\mathrm{BGL}} = (40.7 \pm 1.0) \times 10^{-3}$$

Belle II

$$|V_{cb}|_{\mathrm{CLN}} = (40.13 \pm 0.27 \pm 0.93 \pm 0.58) \times 10^{-3}$$
$$|V_{cb}|_{\mathrm{BGL}} = (40.57 \pm 0.31 \pm 0.95 \pm 0.58) \times 10^{-3}$$

Belle (II) inclusive $|V_{cb}|$

Gambino, Schwanda, PRD 89, 014022 (2014)
Alberto, Gambino, Nandi, JHEP 01 (2014) 147
Mannel, Turczyk, Uraltsev, JHEP 11 (2010) 109

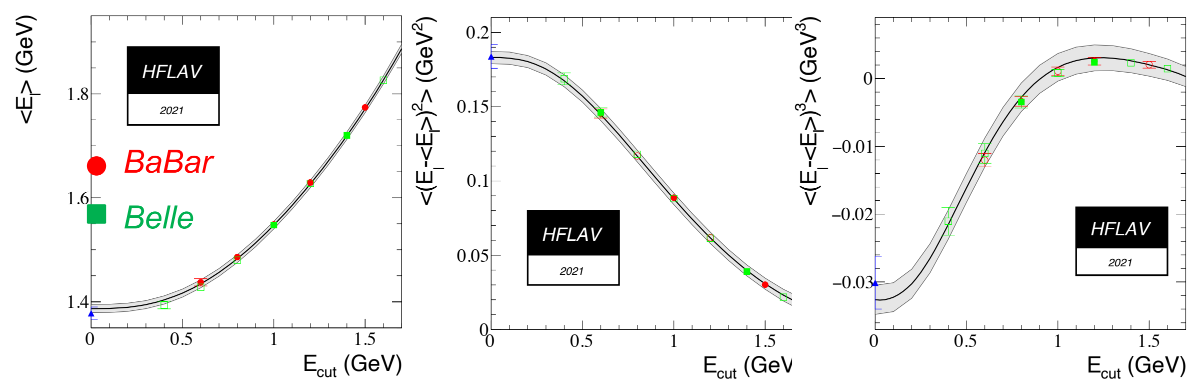


$B \to X_c l \nu$, where X_c denotes final state hadrons containing charm

- *Experimentally,* no specific final state is reconstructed. Statistics are high, but backgrounds are high
- *Theoretically,* one calculates a $b \to c$ transition, not a $\langle D^* | \mathcal{H} | B \rangle$ matrix element (parameterized by form factors).

Strategy: the inclusive $b \to cl\nu$ decay rate is calculated via the Heavy Quark Expansion. This is a double expansion in α_s and (Λ_{QCD}/m_b). The expansion depends on unknown B matrix elements of local operators. However, these matrix elements also determine moments of the lepton energy and recoil hadronic mass M_X in $B \to X l \nu$. These moments have been measured (Belle, BaBar, others), and thus one can fit the moments and the measured width for $B \to X l \nu$ to extract $|V_{cb}|$. To order $(1/m_b)^3$, there are 4 hadronic parameters (~matrix elements) fitted for; to $(1/m_b)^4$ there are 13.

$$\langle E_\ell^n \rangle = \frac{\int_{E_{cut}}^{E_{max}} dE_\ell \, (E_\ell)^n \, \frac{d\Gamma}{dE_\ell}}{\int_{E_{cut}}^{E_{max}} dE_\ell \, \frac{d\Gamma}{dE_\ell}}$$



New Strategy: Fael, Mannel, and Vos, JHEP 02 (2019) 177

Use q^2 moments (mass squared of $\ell\nu$ system)., which are "reparameterization invariant." These moments depend on a reduced set of nonperturbative HQE parameters: to order $(1/m_b)^4$ there are 8.

$$\langle (q^2)^n \rangle = \frac{1}{\Gamma_0} \int_{q^2_{cut}}^{q^2_{max}} dq^2 \, (q^2)^n \, \frac{d\Gamma}{dq^2} \qquad \left(\Gamma_0 = \frac{G_F^2 \, |V_{cb}|^2 \, m_b^5 \, A_{EW}}{192\pi^3} \right)$$

Belle II inclusive $|V_{cb}|$ via q^2 moments

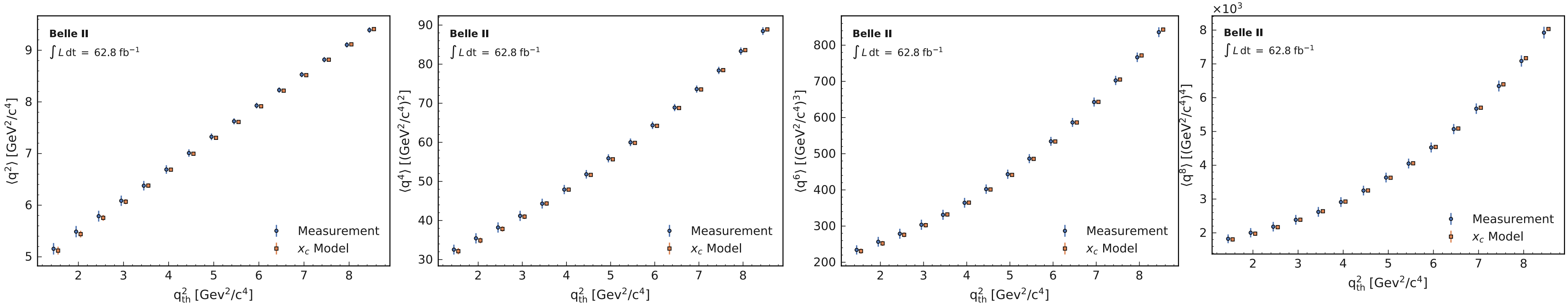
Two measurements of q^2 moments in $B \to X_c \, l \nu$: *711 fb^{-1} Belle,* *PRD 104, 112011 (2021)*
63 fb^{-1} Belle II, *PRD 107, 072002 (2023)*

Belle II mprovements w/r/t Belle:

- *q^2 threshold is lowered from **3.0 GeV^2** (58% of phase space) to **1.5 GeV^2** (77% of phase space).*
- *full reconstruction of tag side based on new boosted decision tree algorithm* [Keck et al., Comp. Software Big Sci. 3, 6 (2019)]*. ~10000 decay chains considered. effic. = 0.3-0.4%.*
- *q^2 resolution improved by performing a kinematic fit to the entire decay chain $e^+e^- \to BB \to B_{tag} X_c \ell \nu$, imposing $(P_{tag})^2 = m_B^2$ and $(P_{sig})^2 = m_B^2$.*

Results:

(background-subtracted by weighting events based on M_X)



Simultaneous fit of Belle and Belle II q^2 moments:

Bernlochner et al., JHEP 10 (2022) 068

$|V_{cb}|$ = (41.70 ± 0.69) x 10^{-3}

Compare to fit to E_ℓ and M_X moments:

Bordone et al., PLB 822, 136679 (2021)

$|V_{cb}|$ = (42.16 ± 0.51) x 10^{-3}

very close
⇒ consistent with exclusive values but central values still higher

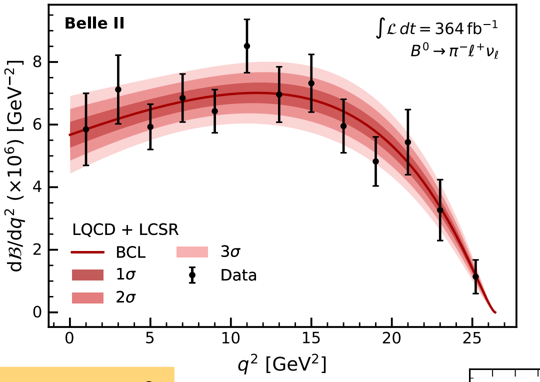
Belle (II) $|V_{ub}|$ analyses

$B^0 \to \pi^- \ell^+ \nu$, $B^+ \to \rho^0 \ell^+ \nu$

364 fb^{-1} Belle II
arXiv:2407.17403
(submitted to PRD)

$$\frac{d\Gamma(B\to\pi\ell\nu)}{dq^2} = \frac{G_F^2|\vec{p}_\pi|^3}{24\pi^3}|f_+(q^2)|^2|V_{ub}|^2$$

Take form factor $f_+(q^2)$ from LQCD [FLAG, EPJC 82 (2022) 869] and light cone sum rules [Leljak et al., JHEP 07 (2021) 36] . Fit partial branching fractions as a function of q^2.



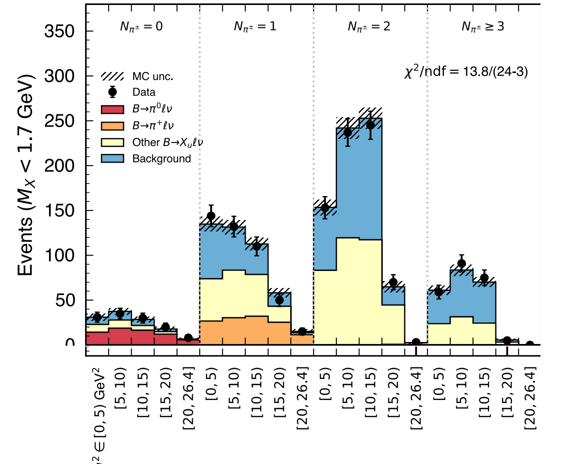
$|V_{ub}|$ = (3.73 ± 0.07 ± 0.07 ± 0.16) x 10^{-3}

$B^0 \to \pi^- \ell^+ \nu$, $B^+ \to X_u \ell^+ \nu$

711 fb^{-1} Belle
PRL 131, 211801 (2023)

Fully reconstruct the tag-side B. Classify signal side by number of π^+ reconstructed. FIt q^2 spectrum for both exclusive, inclusive signal yields. Take form factor $f_+(q^2)$ from LQCD [FLAG, EPJC 82 (2022) 869] ; take inclusive partial rate $\Delta\Gamma/|V_{ub}|$ from Gambino et al., JHEP 10 (2007) 058.

$|V_{ub}|_{\rm excl}$ = (3.78 ± 0.23 ± 0.16 ± 0.14) x 10^{-3}
$|V_{ub}|_{\rm incl}$ = (3.88 ± 0.20 ± 0.31 ± 0.09) x 10^{-3}



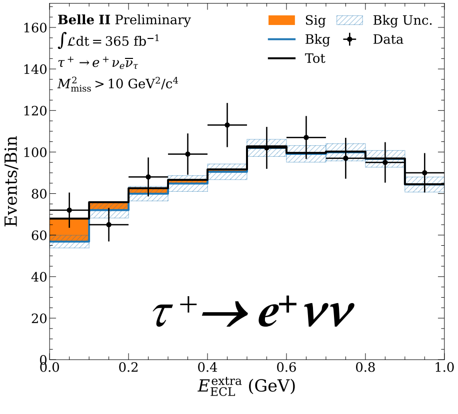
$B^+ \to \tau^+ \nu$

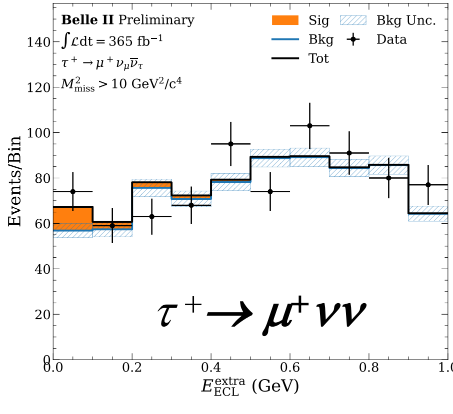
365 fb^{-1}, 90 ± 38 signals
arXiv:2502.04885 (submitted to PRD)

$$\mathcal{B}(B^+\to\tau^+\nu) = \frac{G_F^2 m_B m_\tau^2 \tau_B}{8\pi} f_B^2 |V_{ub}|^2 \left[1 - \left(\frac{m_\tau}{m_B}\right)^2\right]^2$$

Take f_B from LQCD [FLAG, arXiv:2411.04268 (2024)]. Fit distribution of extra energy deposited in ECAL for signal yield.

$|V_{ub}|$ = (4.41 $^{+0.74}_{-0.89}$) x 10^{-3}

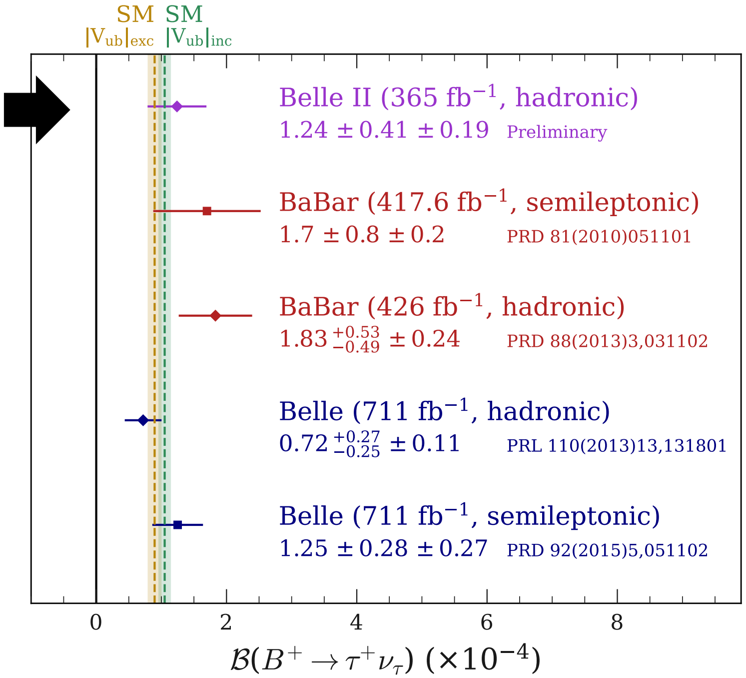




Summary

- The full Belle data set of 711 fb^{-1} continues to be analyzed, many relevant results for both CP violation and CKM matrix elements $|V_{cb}|$, $|V_{ub}|$.
- With ~400 fb^{-1} of Belle II data analyzed, many CP violation and $|V_{cb}|$, $|V_{ub}|$ measurements have been performed. Despite less data than Belle/Babar, Belle II sensitivity is competitive.This is due to an improved detector and reconstruction algorithms (full reconstruction of tag side, better flavor tagging, kinematic fitting, continuum suppression.
- Belle II is behind schedule in accumulating data. However, the SuperKEKB accelerator has set world records for instantaneous luminosity and daily/weekly integrated luminosity, and several improvements to the accelerator are planned.

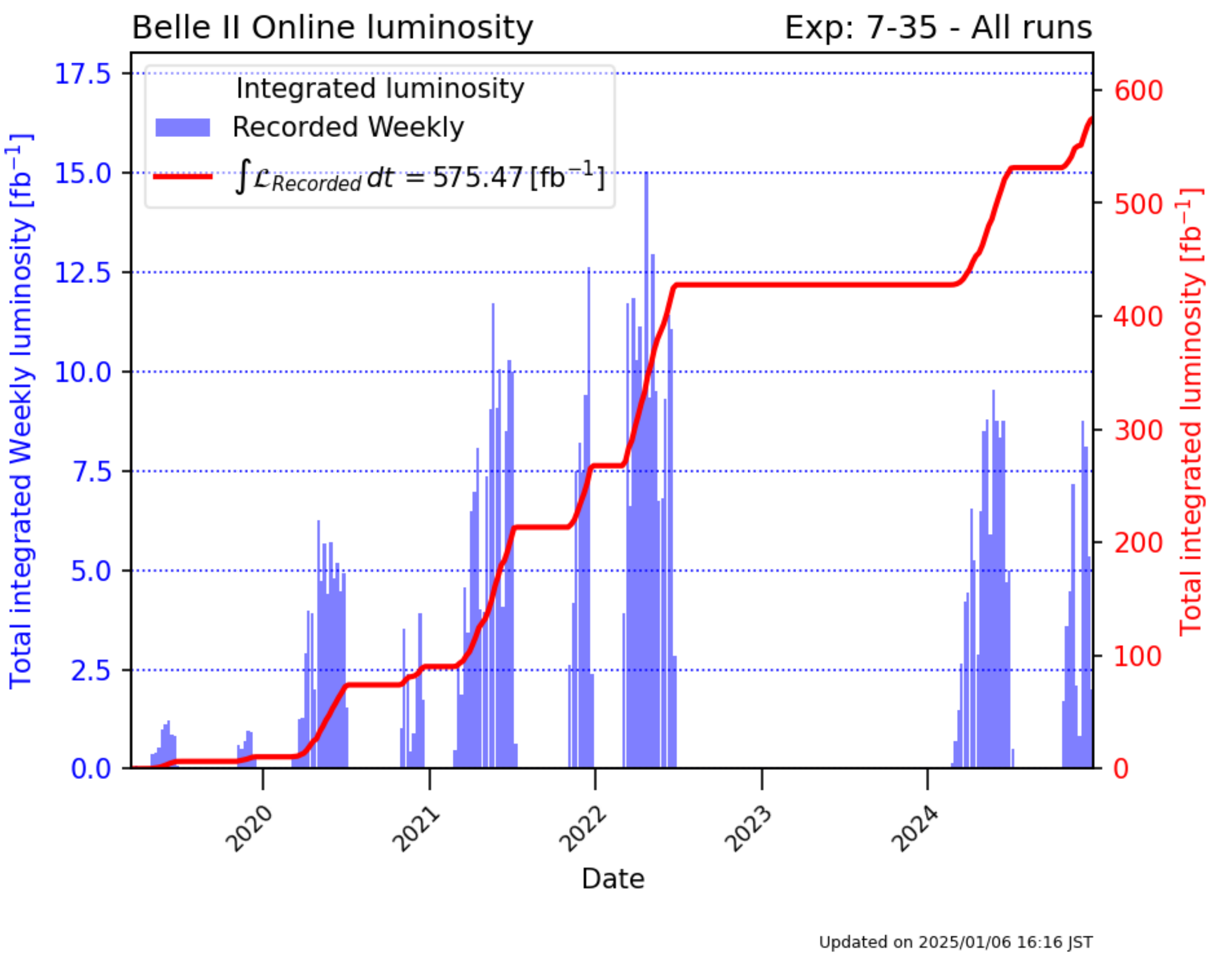
$B^+ \to \tau^+ \nu$ (365 fb^{-1})



- Goal is to ultimately accumulate 50 ab^{-1}
- However: a large amount of physics will be done with ~5-10 ab^{-1}, perhaps uncovering new physics

Extra

Performance to date



Peak instantaneous luminosity:
5.1 x 10^{34} cm^{-2} s^{-1}
(new world record in 2024)

Integrated luminosity: 573 fb^{-1}

495 fb^{-1} *recorded at Υ(4S), which decays to BB ~1/3 of the time*

59 fb^{-1} *recorded 60 MeV below Υ(4S), for background studies*

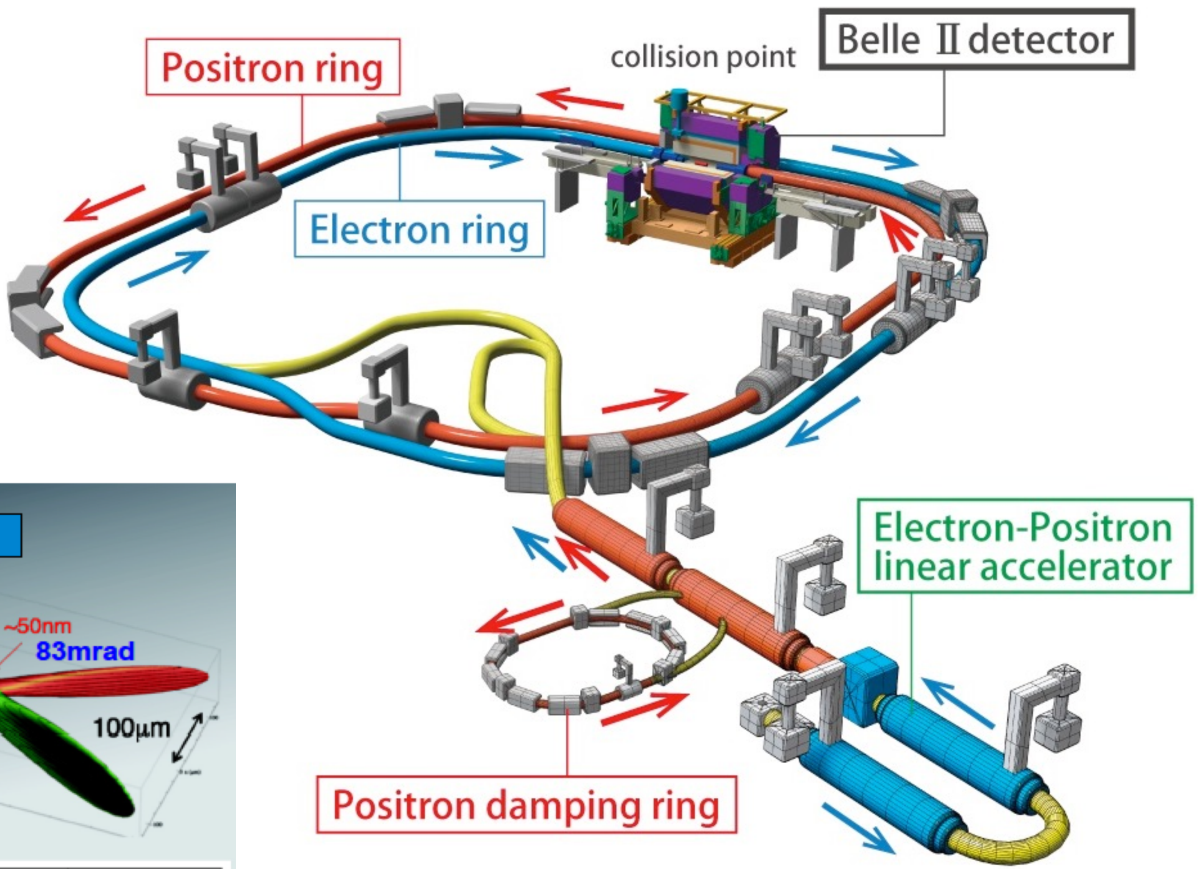
19 fb^{-1} *recorded at 10.75 GeV for exotic hadron searches*

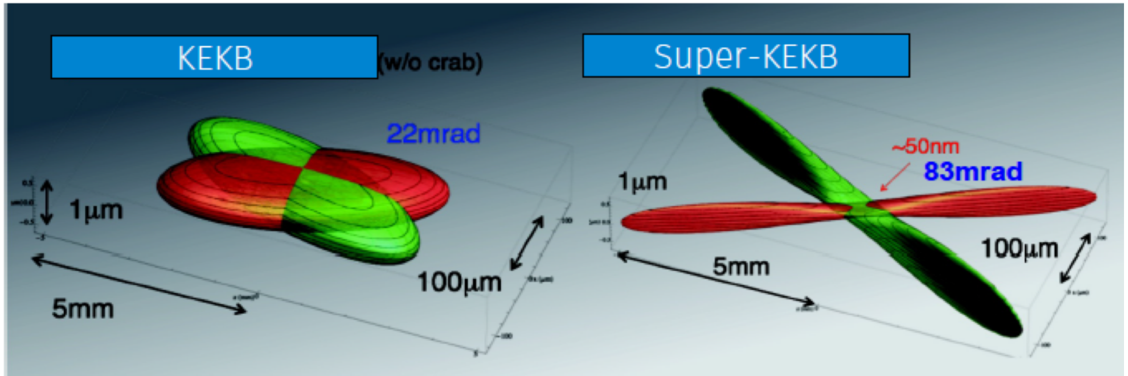
Major accelerator upgrade (KEKB → SuperKEKB)

e^+e^- collider running at the Upsilon(4S) [and Upsilon (5S)] resonances with 7 GeV (e^-) on 4 GeV(e^+) beams.
New e^+ damping ring, new e^+ storage ring, new IR optics, Superconducting FF, new RF

beam size:
100 μm(H) x 2 μm(V)
→ 10 μm(H) x 59 nm(V)

Belle-II Goal:
30 x Belle = ~6 x 10^{35}

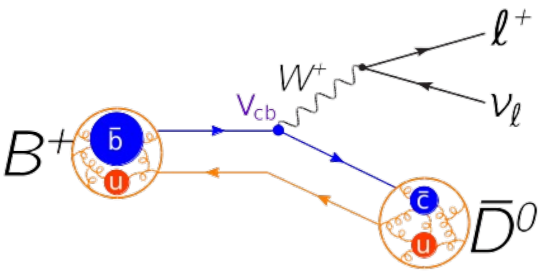




	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20 factor 2-3

Exlusive $|V_{cb}|$ from $B \to D^{(*)} l \nu$



$$w \equiv v_B \cdot v_D = \frac{M_B^2 + M_D^2 - q^2}{2 M_B M_D}$$

$B \to D l \nu$ decay rate:

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3} M_D^3 (M_B + M_D)^2 (w^2 - 1)^{3/2} |V_{cb}|^2 \eta_{EW}^2 G^2(w)$$

form factor

Caprini, Lelouch, Neubert:

$$G(w \to z) = G(1)\left[1 - 8\rho^2 z + (51\rho^2 - 10) z^2 - (252\rho^2 - 84) z^3\right]$$

$$\text{where } z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$$

$B \to D^* l \nu$ decay rate:

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3} M_{D^*}^3 (M_B - M_{D^*})^2 \sqrt{w^2 - 1}\,(w+1)^2 |V_{cb}|^2 \eta_{EW}^2 F^2(w)$$

form factor

$$F^2(w) = h_{A_1}^2(w) \left\{ 2\left[\frac{1 - 2wr + r^2}{(1-r)^2}\right]\left[1 + R_1^2(w)(w-1)\right] + \left[1 + (1 - R_2(w))\frac{w-1}{1-r}\right]^2 \right\}$$

$$\text{where } r = M_{D^*}/M_B$$

Caprini, Lelouch, Neubert:

$$h_{A_1}(z) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15) z^2 - (231\rho^2 - 91) z^3\right]$$
$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$
$$R_2(w) = R_2(1) - 0.11(w-1) + 0.06(w-1)^2$$