Recent B-Physics results from Belle II

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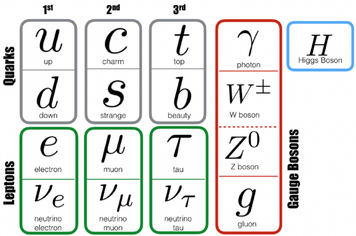
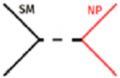
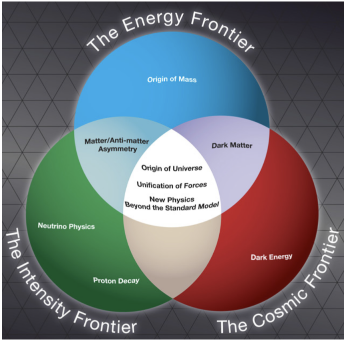
Physics Motivation

- Origin of particles generations and the role of flavor
- *CP* violation and matter-antimatter asymmetry

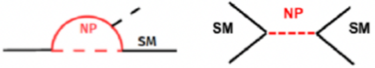


- Where to look for NP at colliders?
- Energy Frontier → direct search of new particles



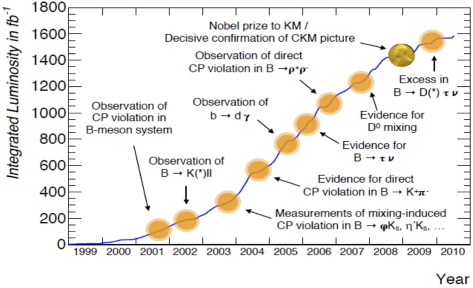


- Intensity Frontier → indirect search of new virtual particles and search for NP in high precision measurements by looking at deviation from SM



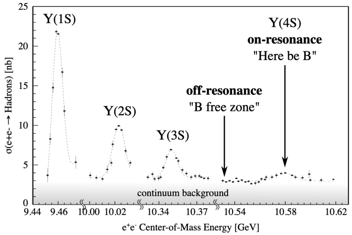
First generation B factories

- Belle at KEKB and BaBar at PEP-II
- High luminosities:
  - 711 fb^{-1} at Belle
  - 424 fb^{-1} at BaBar

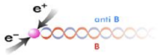


- Wide physics program
  - confirmation of KM mechanism, direct CPV in B decay
  - 2008 Nobel prize in Physics
- Rich legacy left for next generation experiments

- Asymmetric beam energies
  - boosted CMS to measure B decay time by decay length reconstruction
- Collision energy at $\Upsilon(4S)$ resonance



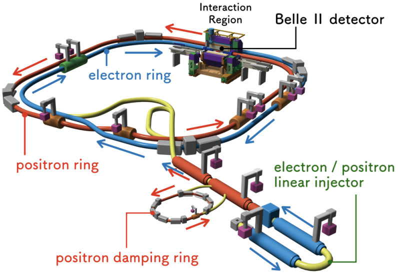
- Coherent production of $B^0\overline{B^0}$

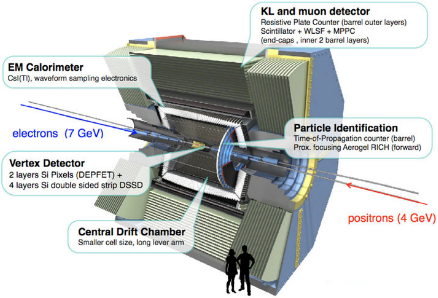


- Full reconstruction of one of the B's, tagging the flavor of the other B etc.

Belle II Experiment - Next generation B factory

- Belle II experiment is a leading Flavor Physics experiment at the Intensity Frontier



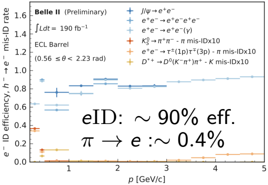


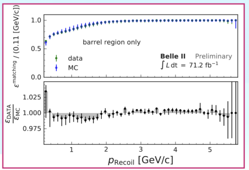
- Asymmetric e^+ (4 GeV) - e^- (7 GeV) collider with CM energy at $B\overline{B}$ threshold, 10.58 GeV
- Design luminosity $= 6 \times 10^{35}$ cm^{-2}s^{-1}
- World record $L_{\text{peak}} = 4.7 \times 10^{34}$ cm^{-2}s^{-1}

- Run I (2019 - 2022): Recorded 424 fb^{-1} of data: equivalent to BaBar and 1/2 of Belle data sample during Run I
- At $\Upsilon(4S)$ resonance: 362 fb^{-1}
- Recorded 532 fb^{-1} of data from Run I and Run II (2024a, 2024b)
- Aims to collect 50 ab^{-1} of data

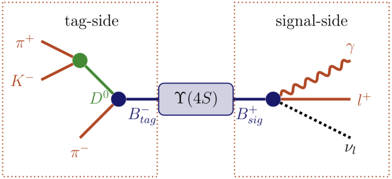
Advantages of Belle II

- Clean environment: Average 11 tracks per event compared to hundreds of tracks for hadron colliders

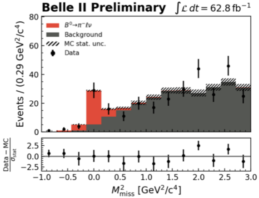


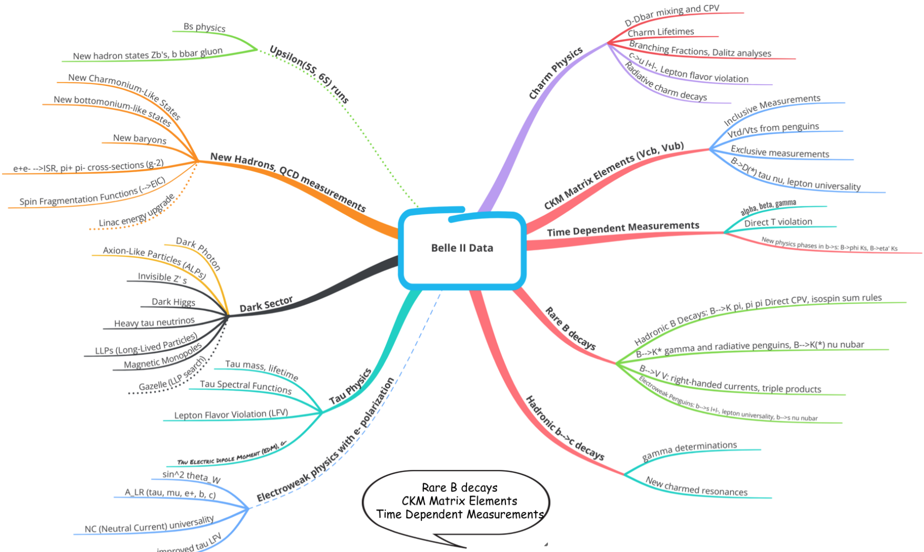


- Good particle identification and performance
- Similar sensitivity for μ and e
- High photon detection efficiency
- Good π^0 mass resolution



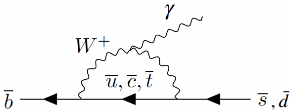
- Unique for B factories:
  - channels with π^0, γ, $\eta^{(\prime)}$, K_L ...
  - final states with one or more missing ν
- Dealing with missing energy:
  - fully reconstruct the partner B meson: full event interpretation
  - Identify invisible particle using, $M^2_{\mathrm{miss}} = (p_{e^+e^-} - p_{\mathrm{visible}})^2$

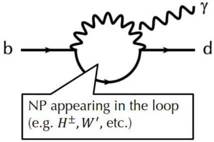



Belle II Data
Upsilon(5S, 6S) runs
Bs physics
New hadron states Zb's, b bbar gluon
New Hadrons, QCD measurements
New Charmonium-Like States
New bottomonium-like states
New baryons
e+e- -->ISR, pi+ pi- cross-sections (g-2)
Spin Fragmentation Functions (-->EIC)
Linac energy upgrade
Dark Sector
Dark Photon
Axion-Like Particles (ALPs)
Invisible Z' s
Dark Higgs
Heavy tau neutrinos
LLPs (Long-Lived Particles)
Magnetic Monopoles
Gazelle (LLP search)
Tau Physics
Tau mass, lifetime
Tau Spectral Functions
Lepton Flavor Violation (LFV)
Tau Electric Dipole Moment (EDM),
Electroweak physics with e- polarization
sin^2 theta_W
A_LR (tau, mu, e+, b, c)
NC (Neutral Current) universality
improved tau LFV
Charm Physics
D-Dbar mixing and CPV
Charm Lifetimes
Branching Fractions, Dalitz analyses
c->u l+l-, Lepton flavor violation
Radiative charm decays
CKM Matrix Elements (Vcb, Vub)
Inclusive Measurements
Vtd/Vts from penguins
Exclusive measurements
B->D(*) tau nu, lepton universality
Time Dependent Measurements
alpha, beta, gamma
Direct T violation
New physics phases in b->s: B->phi Ks, B->eta' Ks
Rare B decays
Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
B-->K* gamma and radiative penguins, B-->K(*) nu nubar
B-->V V: right-handed currents, triple products
Electroweak Penguins: b-->s l+l-, lepton universality, b-->s nu nubar
Hadronic b-->c decays
gamma determinations
New charmed resonances
Rare B decays
CKM Matrix Elements
Time Dependent Measurements

Rare B decays

- Involves $b \to s\gamma$ transition
- New particles can contribute to internal loop, altering $\mathcal{B}$ as well as other observables





- SM $\mathcal{B}$ predictions have large theoretical uncertainties ($\sim$ 20%) related to form factors [JHEP 04 (2017) 027]
- Observables;
  - Branching fraction, $\mathcal{B}$
  - CP Asymmetry

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B} \to \overline{K}^* \gamma) - \Gamma(B \to K^* \gamma)}{\Gamma(\overline{B} \to \overline{K}^* \gamma) + \Gamma(B \to K^* \gamma)}$$

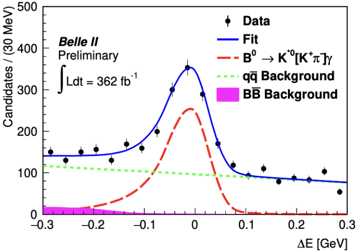
$$\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) - \mathcal{A}_{CP}(B^+ \to K^{*+}\gamma)$$

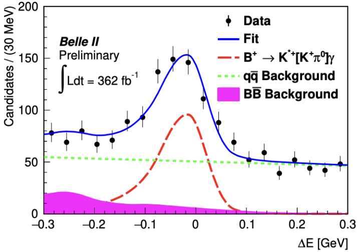
  - Isospin Asymmetry

$$\Delta_{0+} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$$

- $\mathcal{A}_{CP}$ and Δ_{0+} are theoretically clean due to cancellation of form factor contributions in ratio
- SM: $\mathcal{A}_{CP} =\sim 1\%$, $\Delta_{0+} = (4.9 \pm 2.6)\%$ [PRD 88 (2013) 094004]
- Belle [PRL 119 (2017) 191802] has observed evidence of isospin violation at 3.1σ using 711 fb^{-1}
- Used Run I data sample of Belle II
- Measured $\mathcal{A}_{CP}$, $\Delta\mathcal{A}_{CP}$, Δ_{0+} in addition to $\mathcal{B}$

$K^{*0} \to K^+\pi^-, K^0_S\pi^0$
$K^{*+} \to K^+\pi^0, K^0_S\pi^+$





- 2D fit of $M_{\rm bc}$ $\left(\sqrt{(E_{\rm beam}/c^2)^2 - (p_B/c)^2}\right)$ and ΔE $(E_B - E_{\rm beam})$ to extract signal

$$\mathcal{B}(B^0 \to K^{*0}\gamma) = (4.16 \pm 0.10 \pm 0.11) \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^{*+}\gamma) = (4.04 \pm 0.13 \pm 0.13) \times 10^{-5}$$
$$\mathcal{B}(B \to K^{*}\gamma) = (4.12 \pm 0.08 \pm 0.11) \times 10^{-5}$$

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (-3.2 \pm 2.4 \pm 0.4)\%$$
$$\mathcal{A}_{CP}(B^+ \to K^{*+}\gamma) = (-1.0 \pm 3.0 \pm 0.6)\%$$
$$\mathcal{A}_{CP}(B \to K^{*}\gamma) = (-2.3 \pm 1.9 \pm 0.3)\%$$

$$\Delta\mathcal{A}_{CP} = (2.2 \pm 3.8 \pm 0.7)\%$$
$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.0 \pm 1.1)\%$$

- Results are consistent with WA and SM

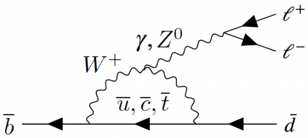
  SM: $\mathcal{A}_{CP} =\sim 1\%$, $\Delta_{0+} = (4.9 \pm 2.6)\%$

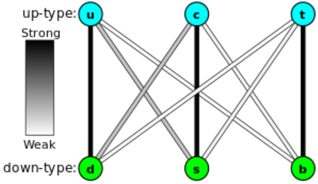
- Similar sensitivity to Belle [PRL 119 (2017) 191802] due to improved ΔE resolution and K^0_S identification efficiency

- Involves $b \to d\ell^+\ell^-$ transition
- $\mathcal{B}$ for $b \to d\ell^+\ell^-$ is more sensitive to new physics than $b \to s\ell^+\ell^-$ as SM $\mathcal{B}$ is suppressed by a factor of $|V_{td}/V_{ts}|^2 \sim 0.04$
- Typical $\mathcal{B}$ in SM is $\mathcal{O}(10^{-8})$ or smaller [PRD 86 (2012) 114025]
- LHCb [JHEP 10 (2015) 034, PLB 743 (2015) 46]

$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (1.78 \pm 0.23) \times 10^{-8}$$
$$\mathcal{B}(B^0 \to \rho^0\mu^+\mu^-) = (1.98 \pm 0.53) \times 10^{-8}$$
$$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-) = (2.11 \pm 0.52) \times 10^{-8}$$

- Search for e channels in addition to μ channels: tests LFU in $b \to d\ell^+\ell^-$
- Used 711 fb^{-1} data sample of Belle





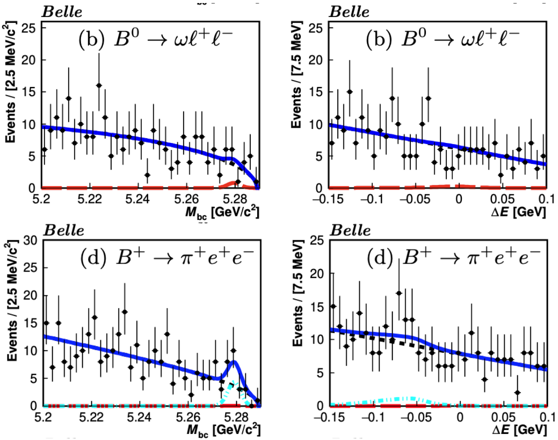
$$B^{\pm,0} \to (\eta, \omega, \pi^{\pm,0}, \rho^{\pm,0})ee$$
$$B^{\pm,0} \to (\eta, \omega, \pi^0, \rho^{\pm})\mu\mu$$

$B \to (\eta, \omega, \pi, \rho)\ell^+\ell^-$ at Belle

[arXiv:2404.08133]

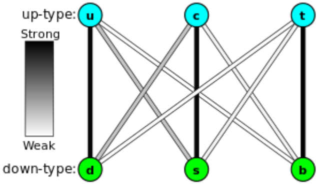
channel	$\mathcal{B}^{\rm UL}$ (10^{-8})
$B^0 \to \eta e^+ e^-$	< 10.5
$B^0 \to \eta \mu^+ \mu^-$	< 9.4
$B^0 \to \eta \ell^+ \ell^-$	< 4.8
$B^0 \to \omega e^+ e^-$	< 30.7
$B^0 \to \omega \mu^+ \mu^-$	< 24.9
$B^0 \to \omega \ell^+ \ell^-$	< 22.0
$B^0 \to \pi^0 e^+ e^-$	< 7.9
$B^0 \to \pi^0 \mu^+ \mu^-$	< 5.9
$B^0 \to \pi^0 \ell^+ \ell^-$	< 3.8
$B^+ \to \pi^+ e^+ e^-$	< 5.4
$B^0 \to \rho^0 e^+ e^-$	< 45.5
$B^+ \to \rho^+ e^+ e^-$	< 46.7
$B^+ \to \rho^+ \mu^+ \mu^-$	< 38.1
$B^+ \to \rho^+ \ell^+ \ell^-$	< 18.9

- 2D $M_{\rm bc}$ and ΔE fit to extract signal yield



- World's best limits for $B^{\pm,0} \to (\eta, \omega, \pi^{\pm,0}, \rho^{\pm,0})ee$ and $B^{\pm,0} \to (\eta, \omega, \pi^0, \rho^{\pm})\mu\mu$
- World's first limits for $B^0 \to \omega\ell^+\ell^-$, $B^+ \to \rho^+\ell^+\ell^-$, and $B^0 \to \rho^0 e^+ e^-$
- No LFU ($b \to d\mu^+\mu^- / b \to de^+e^-$) violation observed in $b \to d\ell^+\ell^-$ transitions

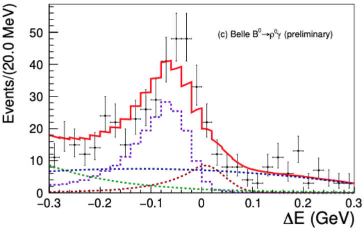
- $b \to d\gamma$ transition have one order of magnitude lower $\mathcal{B}$ compared to $b \to s\gamma$ processes and can be affected by NP independently

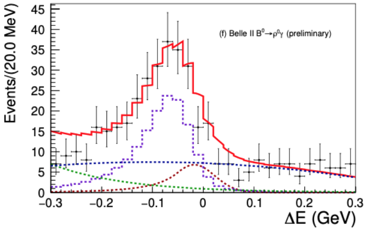


- $B \to \rho\gamma$ decay has been observed by the Belle [PRL 101 (2008) 200401] and BaBar [PRD 78 (2008) 112001]
- Current WA of $\Delta_{0+} = (30^{+16}_{-13})\%$ [PTEP 2022 (2022) 083C01] lies about 2σ away from the SM expectation of $(5.2 \pm 2.8)\%$ [PRD 88 (2013) 094004]]
- Used 711 fb^{-1} and 362 fb^{-1} data samples from Belle and Belle II
- Reconstructed $\rho^0 \to \pi^+\pi^-$ and $\rho^+ \to \pi^+\pi^0$ for B^0 and B^+
- Experimentally challenging due to the presence of $B \to K^*\gamma$ background
- $M_{K\pi}$: invariant mass of ρ recalculated based on hypothesis that one of the π^+ is a K^+
- $M_{K\pi}$ helps separate $K^*\gamma$ background better compared to $M_{\pi\pi}$

- Simultaneous 3D fitting on $M_{\rm bc}$, ΔE, and $M_{K\pi}$ with extended unbinned ML to 6 independent data sets: B^+, B^-, and $B^0 + \overline{B^0}$ in Belle and Belle II

signal + bkg, signal, continuum bkg,
generic B, $\mathrm{B} \to \mathrm{K}^*\gamma$





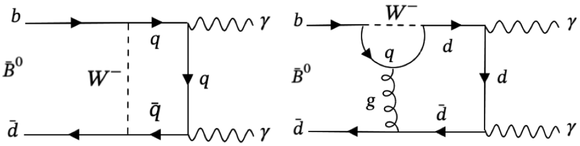
$$\mathcal{B}(B^+ \to \rho^+\gamma) = (13.1^{+2.0+1.3}_{-1.9-1.2}) \times 10^{-7}$$
$$\mathcal{B}(B^0 \to \rho^0\gamma) = (7.5 \pm 1.3^{+1.0}_{-0.8}) \times 10^{-7}$$
$$\mathcal{A}_{CP}(B^+ \to \rho^+\gamma) = (-8.2^{+15.3+1.4}_{-15.2-1.3})\%$$
$$\Delta_{0+}(B \to \rho\gamma) = (10.9^{+11.2+7.8}_{-11.7-7.3})\%$$

- Results are in agreement with SM
- Improved isospin asymmetry A_I results: consistent with the SM prediction

  SM: $\Delta_{0+} = (5.2 \pm 2.8)\%$

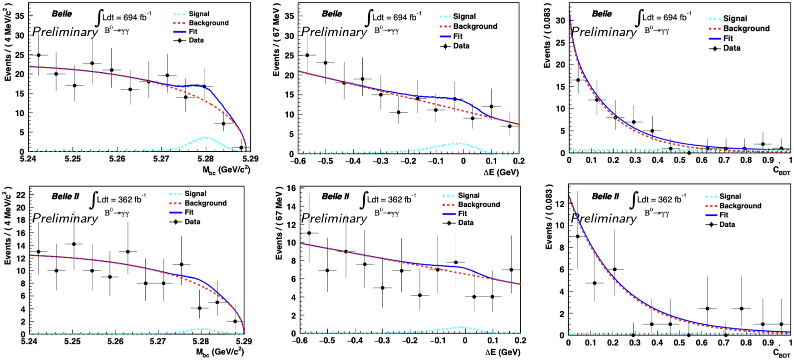
- Most precise measurement of observables for $B \to \rho\gamma$ to date

- No direct interaction between b and d quark
- FCNC process through loop diagram as quark emits and reabsorbs a W^- boson



- $B^0 \to \gamma\gamma$ is suppressed by a factor of $|V_{td}^2|/|V_{ts}^2| \sim 0.04$ compared to $B_s \to \gamma\gamma$ decay, $\mathcal{B}(B_s \to \gamma\gamma)$ (SM) $\sim (2-37)\times 10^{-7}$ [JHEP 08 (2002) 054]
- SM $\mathcal{B} = (1.4^{+1.4}_{-0.8}) \times 10^{-8}$ [JHEP 12 (2020) 169], significant long distance contribution
- Best UL of $< 3.2 \times 10^{-7}$ by BaBar [PRD 83 (2011) 032006] at 90% CL with 426 fb^{-1} data
- Used 1.1 ab^{-1} of data sample: 694 fb^{-1} (Belle) + 362 fb^{-1} (Belle II)

- 3D simultaneous fit between Belle and Belle II using $M_{\rm bc}$, ΔE, and $C'_{\rm BDT}$ (transformed BDT for continuum suppression) to extract signal yield



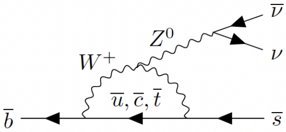
- $N_{\rm sig} = 11.0^{+6.5}_{-5.5}$ having a significance of 2.5σ

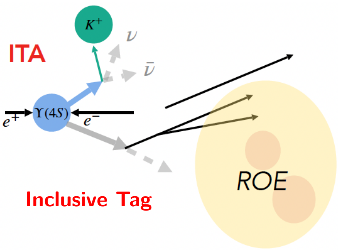
$$\mathcal{B}^{\rm UL}(B^0 \to \gamma\gamma) < 6.4 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

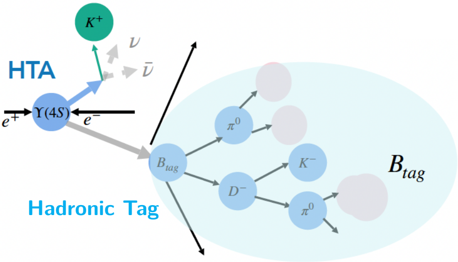
- Most stringent UL: 5× better than best limit from BaBar [PRD 83 (2011) 032006]
- Result is not too far from SM expectation

$B^+ \to K^+\nu\overline{\nu}$ at Belle II [PRD 109 (2024) 112006]

- $\mathcal{B}_{\rm SM}(B^+ \to K^+\nu\overline{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$ [PRD 107 (2023) 119903]
- Experimentally challenging due to two neutrinos
- Best limit of $< 1.6 \times 10^{-5}$ at 90% CL from BaBar [PRD 87 (2013) 112005]
- Used Run I data sample of Belle II

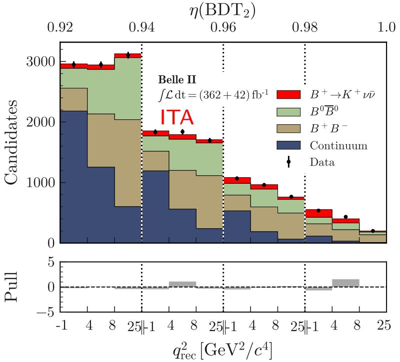


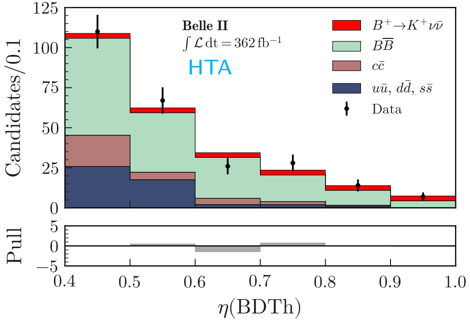




- ITA has low purity but high efficiency and HTA has high purity and low efficiency
  - ITA: signal efficiency = 8%; purity = 0.9%
  - HTA: signal efficiency = 0.4%; purity = 3.5%
- Parameter of interest: signal strength $= \mu = \dfrac{\mathcal{B}(B^+ \to K^+\nu\overline{\nu})}{\mathcal{B}_{\rm SM}(B^+ \to K^+\nu\overline{\nu})}$

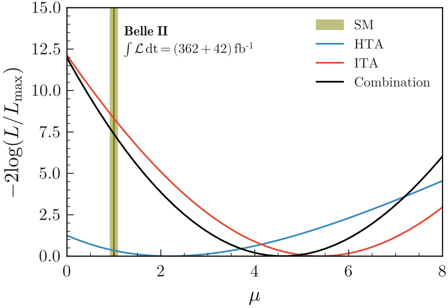
- Binned fit to extract μ:
  - ITA: Classifier 2 output [$\eta(\mathrm{BDT}_2)$] and q^2 [mass square of neutrino pair]
  - HTA: Classifier output [$\eta(\mathrm{BDTh})$]

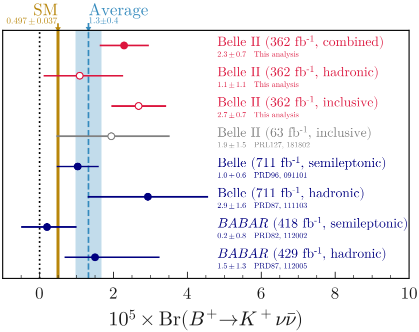




- $\mu = 5.4 \pm 1.0 \pm 1.1$
- $\mathcal{B} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$
- 3.5σ significance w.r.t bkg-only hypo
- 2.9σ departure from SM

- $\mu = 2.2^{+1.8+1.6}_{-1.7-1.1}$
- $\mathcal{B} = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$
- 1.1σ significance w.r.t bkg-only hypo
- 0.6σ departure from SM



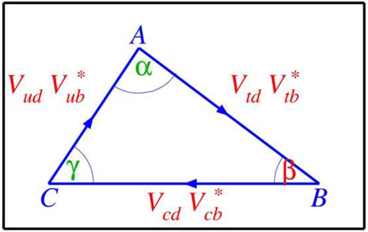


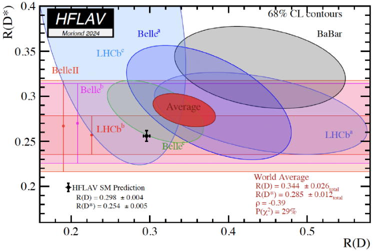
- Excluded common events from ITA sample
- Correlation between common systematic uncertainties are included

- $\mu = 4.6 \pm 1.0 \pm 0.9$
- $\mathcal{B} = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$
- 3.5σ significance w.r.t bkg-only hypo
- 2.7σ departure from SM

- First evidence of $B^+ \to K^+\nu\bar{\nu}$ process
- Results are in agreement with all previous measurements

Semileptonic B decays: CKM and Lepton Flavor Universality





$$R(H_{\tau/\ell}) = \frac{\mathcal{B}(B \to H\tau\nu)}{\mathcal{B}(B \to H\ell\nu)}$$

$H = D, D^*, X, \pi, \ldots$

$\ell = e, \mu$

"Traditional" modes (D, D^*)

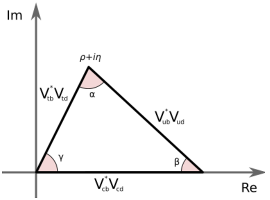
New! Featured today (X)

(next decade?) ($\pi, \ldots$)

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

- $|V_{ub}|$ is important to constrain CKM unitarity triangle and test SM

$$\mathcal{B} \propto |V_{ub}|^2 \times f,\ f = \text{form factor (LCSR, LQCD)}$$



- Long-standing V_{xb}-puzzle between inclusive and exclusive decays
- $|V_{ub}|$ for inclusive and exclusive differ by 2.5σ experimentally

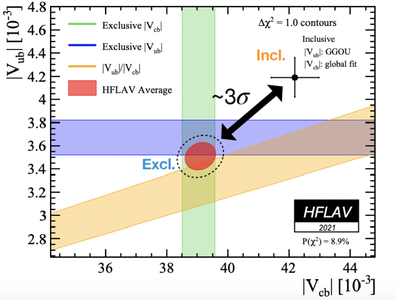
Exclusive : $B \to \pi\ell\nu,\ B \to \rho\ell\nu$

Inclusive: $B \to X_u\ell\nu$

- Used Run I data sample of Belle II
- Untagged analysis

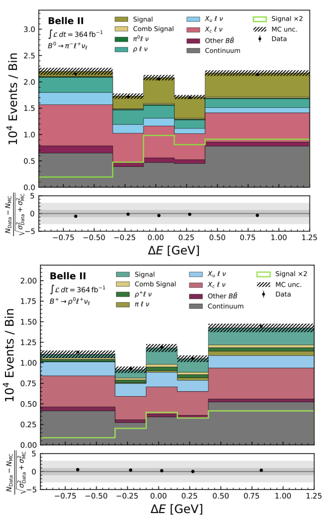
$$B^0 \to \pi^-\ell^+\nu_\ell$$
$$B^+ \to \rho^0\ell^+\nu_\ell$$

- Sum of measured exclusive $\mathcal{B}$ is $\sim 20\%$ of inclusive $\mathcal{B}(B \to X_u\ell\nu)$

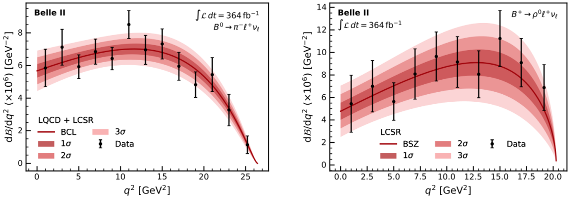


Untagged $|V_{ub}|$ at Belle II

[paper in preparation]



- Simultaneous $B^0 \to \pi^- \ell^+ \nu_\ell$ and $B^+ \to \rho^0 \ell^+ \nu_\ell$ signal yields extraction with binned 3D fit to $M_{\rm bc}$, ΔE, and $q^2 = (p_B - p_{\pi^-,\rho^0})^2$

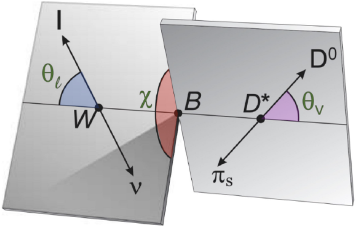


$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$

$$|V_{ub}|_{B\to\pi\ell\nu} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$$
$$|V_{ub}|_{B\to\rho\ell\nu} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$$

- $\mathcal{B}$ results are consistent with WA
- $|V_{ub}|$ results are consistent with exclusive WA, HFLAV: $(3.67 \pm 0.09 \pm 0.12) \times 10^{-3}$
- $|V_{ub}|$ results are consistent with previous exclusive measurements [PRD 107 (2023) 052008, PRD 104 (2021) 034032], and theoretical uncertainty dominated

- Angular coefficiencts from differential decay rate of exclusive semileptonic $\overline{B} \to D^* \ell \overline{\nu}_\ell$
- $|V_{cb}|$ from angular coefficients of $\overline{B} \to D^* \ell \overline{\nu}_\ell$
- Angular coefficients also allow determination of form factors for $B \to D^*$ decay, test sensitive to BSM effects and LFU



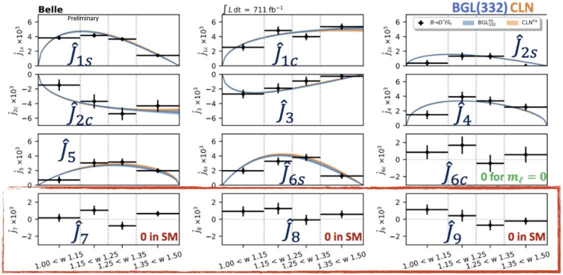
- Differential decay rate can be decomposed in a basis of angular functions with 12 coefficients, $\hat{J}_i$, all dependent on w

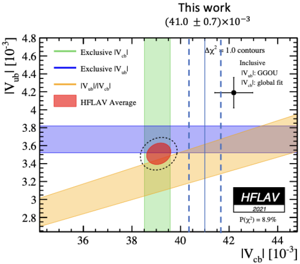
$$\frac{\mathrm{d}\Gamma(\bar{B} \to D^* \ell \bar{\nu}_\ell)}{\mathrm{d}w\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_V\,\mathrm{d}\chi} = \frac{2G_F^2 \eta_{EW}^2 |V_{cb}|^2 m_B^4 m_{D^*}}{2\pi^4} \times \Big(J_{1s}\sin^2\theta_V + J_{1c}\cos^2\theta_V + (J_{2s}\sin^2\theta_V + J_{2c}\cos^2\theta_V)\cos 2\theta_\ell + J_3 \sin^2\theta_V \sin^2\theta_\ell \cos 2\chi + J_4 \sin 2\theta_V \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_V \sin\theta_\ell \cos\chi + (J_{6s}\sin^2\theta_V + J_{6c}\cos^2\theta_V)\cos\theta_\ell + J_7 \sin 2\theta_V \sin\theta_\ell \sin\chi + J_8 \sin 2\theta_V \sin 2\theta_\ell \sin\chi + J_9 \sin^2\theta_V \sin^2\theta_\ell \sin 2\chi \Big).$$

Hadronic recoil energy $w = \dfrac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$

- Used full 711 fb^{-1} data sample of Belle
- Hadronic B tagging
- 12 $\hat{J}_i$ coefficients in 4 bins of w

$B^+ \to D^{*0}\ell^+\nu,\ D^{*0} \to D^+\pi^0$
$B^0 \to D^{*+}\ell^-\nu,\ D^{*+} \to D^0\pi^+$



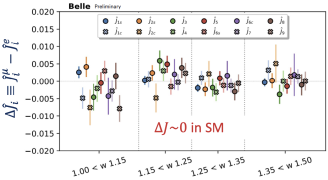


- Coefficients are in good agreement with the fit using BGL [NPB 461 (1996) 493, PRD 56 (1997) 6895] and CLN [NPB 530 (1998) 153] form-factor parametrizations
- Coefficients are consistent with the SM predictions

$$|V_{cb}| = (41.0 \pm 0.3 \pm 0.4 \pm 0.5) \times 10^{-3}\ \text{(BGL)}$$
$$|V_{cb}| = (40.9 \pm 0.3 \pm 0.4 \pm 0.4) \times 10^{-3}\ \text{(CLN)}$$

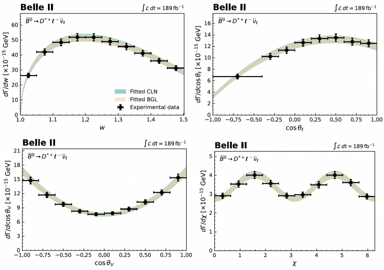
- Similar values of $|V_{cb}|$ using CLN and BGL form factors

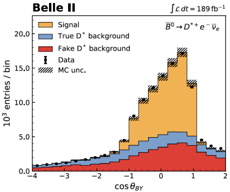
- Closing the gap with inclusive $|V_{cb}|$ measurement

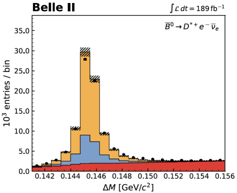


- No significant deviation from SM in LFU

- Reconstruct $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$, $D^{*+} \to D^0\pi^+$ and $D^0 \to K^-\pi^+$
- Used 189 fb^{-1} data sample of Belle II
- Extract signal yield with 2D fit to $\cos\theta_{BY}$ (angle between B and $D^*\ell$ system) and $\Delta M = M(D^{*+}) - M(D^0)$ in bins of $\cos\theta_\ell$, $\cos\theta_\nu$, χ, and w





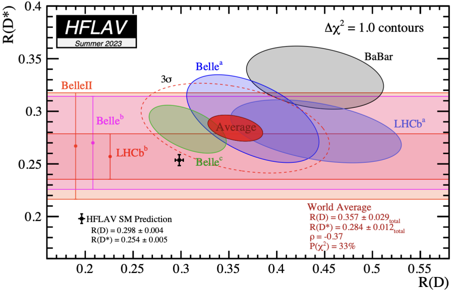


$$|V_{cb}|_{\rm BGL} = (40.57 \pm 0.31 \pm 0.95 \pm 0.58) \times 10^{-3}$$
$$|V_{cb}|_{\rm CLN} = (40.13 \pm 0.27 \pm 0.93 \pm 0.58) \times 10^{-3}$$

HFLAV:

$$|V_{cb}|_{\rm Excl.} = (39.10 \pm 0.50) \times 10^{-3}$$
$$|V_{cb}|_{\rm Incl.} = (42.19 \pm 0.78) \times 10^{-3}$$

- In agreement with WAs and $|V_{cb}|$ from angular coefficients at Belle
- Result limited by the slow-pion efficiency
- Closing the gap between inclusive and exclusive measurements
- $R_{e/\mu} = 0.998 \pm 0.009 \pm 0.020$, consistent with LFU

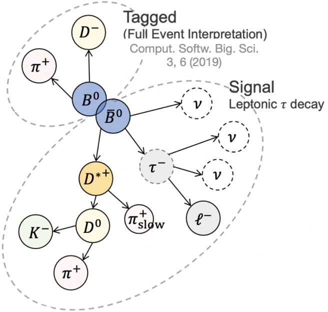


- Semileptonic decays provide theoretically clean probes to test LFU
- Long-standing tension between LFU-sensitive quantities $R(D) - R(D^*)$ and SM predictions

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

- 3.2σ deviation from SM expectations

- Used 189 fb^{-1} data sample of Belle II
- Tag-side B decays hadronically
- $D^{*+} \to D^0\pi^+$ and $D^+\pi^0$
  $D^{*0} \to D^0\pi^0$
- $D \to K\pi, K\pi\pi, K\pi\pi\pi, KK$
- Leptonic τ decays: $\tau^- \to e^-\overline{\nu}_e\nu_\tau$ and $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$



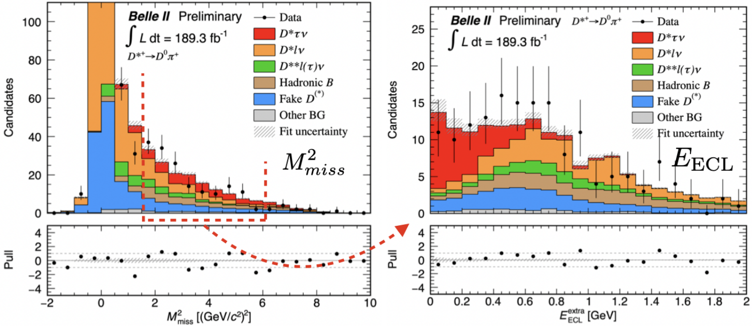
$R(D^*)$ Measurement

- Main challenge: Understand significant and poorly known $B \to D^{**}\ell\nu$ backgrounds
  - Data-driven validation of background and signal modelling based on studies of sideband regions
- 2D fit in the $M^2_{\rm miss} = (p_{e^+e^-} - p_{B_{\rm tag}} - p_{D^*} - p_\ell)^2$ and $E_{\rm ECL}$ (residual calorimetric energy)

Zoom of $M^2_{\rm miss}$ projection for $D^{*+} \to D^0\pi^+$ mode

Signal-enhanced projection

$1.5 < M^2_{\rm miss} < 6.0\ ({\rm GeV}/c^2)^2$



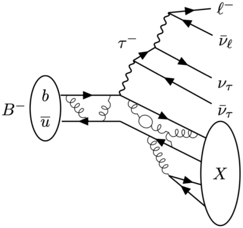
$$R(D^*) = 0.262^{+0.041+0.035}_{-0.039-0.032}$$

$R(D^*)\ ({\rm SM}) = 0.254 \pm 0.005$
$R(D^*)\ ({\rm HFLAV}) = 0.284 \pm 0.013$

- Result is consistent with SM and previous measurements
- Comparable precision to Belle inspite of smaller data sample due to improved B tagging algorithm

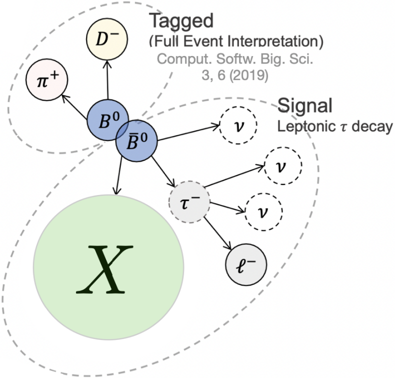
- Semileptonic $B \to X\tau(\ell)\nu$ is inclusive $b \to c\tau(\ell)\nu$ transition
- Test LFU in charged-current weak interaction by measuring tau-to-light-lepton ratio

$$R(X_{\tau/\ell}) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$$

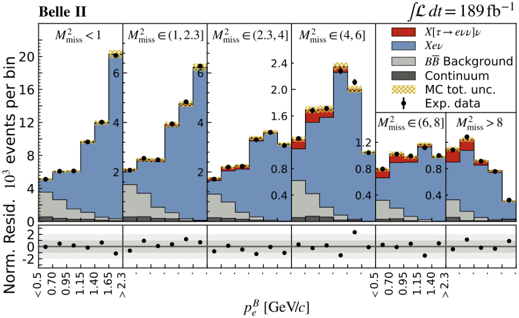


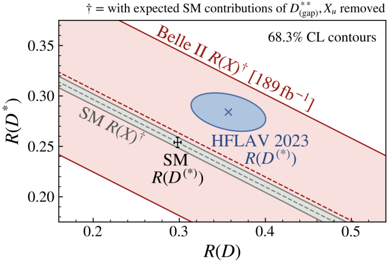
- Experimentally LFU in exclusive $B \to D^{(*)}\tau(\ell)\nu$ has a tension of 3.2σ

- Used 189 fb^{-1} data sample of Belle II
- Tag-side B is fully reconstructed hadronically
- Hadronic system X is reconstructed using remaining tracks and energy deposits in the calorimeter
- Inclusive decay with τ is challenging due to larger background from less constrained X system



- 2D fit to p_ℓ^B (in the B_{sig} rest frame) and M^2_{miss} (mass squared for undetected neutrinos) to extract signal yield
- Simultaneous extraction of signal yields for $B \to X\tau\nu$ and $B \to X\ell\nu$





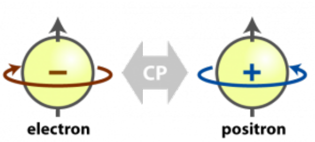
$$R(X_{\tau/e}) = 0.232 \pm 0.020 \pm 0.037$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027 \pm 0.050$$
$$R(X_{\tau/\ell}) = 0.228 \pm 0.016 \pm 0.036$$

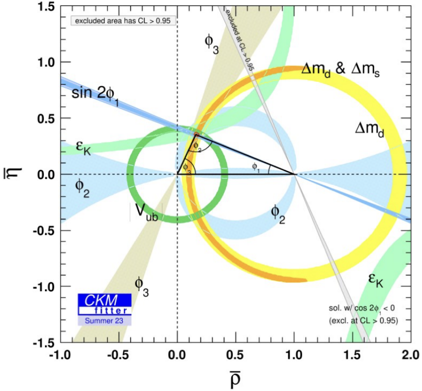
- $R(X_{\tau/\ell})$ result is consistent with SM predictions [JHEP 11 (2022) 007]

$$R(X_{\tau/\ell})(\text{SM}) = 0.223 \pm 0.005$$

- First measurement at B-factories with $\Upsilon(4S)$
- Result is also consistent with $R(D^{(*)})$

CP Violation and CKM Angles





Time dependent *CP* violation

- Flagship measurement for *B*-factories
- CP violation arises from irreducible complex phase in CKM matrix

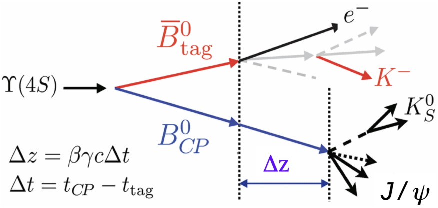
λ, A, ρ, η with $\lambda = 0.22$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$|V_{ub}| \times e^{-i\gamma}$

$|V_{td}| \times e^{-i\beta}$

- Measurement relies on ability to identify flavor of tag side *B*



<Δz> ~ 130 μm at Belle II

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

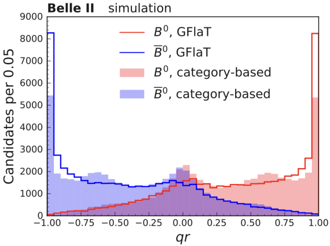
$$= S \cdot \sin(\Delta m_d \Delta t) - C \cdot \cos(\Delta m_d \Delta t)$$

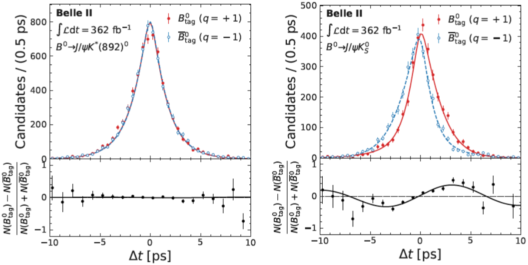
S: Mixing induced CP violation

C: Direct CP violation

- CKM angle ϕ_1 or β from mixing induced *CP* violation in $B^0 \to J/\psi K^0_S$ decay

- Used 362 fb^{-1} data sample of Belle II
- Graphical NN approach for flavor tagging → improved tagging efficiency by ∼ 18%
- $\varepsilon^{\mathrm{GFlaT}}_{\mathrm{tagging}} = (37.40 \pm 0.43 \pm 0.26)\%$ compared to $31.68 \pm 0.45\%$ for category-based
- Extract yields from ΔE and subtract Δt background from sideband (sPlot NIMA:555:356-369,2005)





$S = 0.724 \pm 0.035 \pm 0.009$

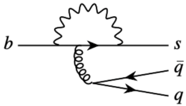
$C = -0.035 \pm 0.026 \pm 0.029$

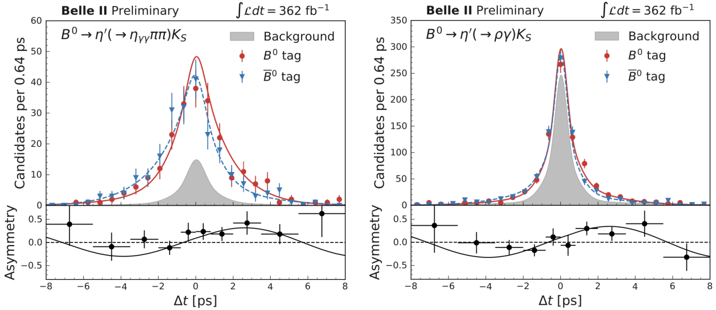
SM:
$S = \sin 2\phi_1$, $C = 0$

- Results are consistent with SM

- In agreement with measurements from BaBar [PRD 79 (2009) 072009], Belle [PRL 108 (2012) 171802], and LHCb [PRL 132 (2024) 021801]
- From S, the CKM angle $\phi_1 = (23.2 \pm 1.5 \pm 0.6)^\circ$

- Gluonic penguin with $b \to s q\bar{q}$ transition, $q = u, d$, or s
- Golden mode: Relatively large $\mathcal{B}$ and limited contribution from tree amplitudes
- In SM: $S \approx \sin 2\phi_1$ by 0.01 ± 0.01 and $C \approx 0$
- Used Run I data sample of Belle II
- Fit to $M_{\rm bc}$, ΔE, $C_{\rm BDT}$, Δt, and $q_{\rm tag}$ (tag-flavor)





$S = 0.67 \pm 0.10 \pm 0.04$

$C = -0.19 \pm 0.08 \pm 0.03$

- Results in agreement with WA

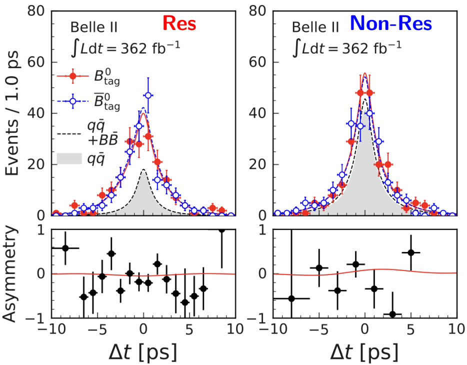
  HFLAV: $S = 0.63 \pm 0.06$ and $C = -0.05 \pm 0.04$

- Precision comparable with Belle [JHEP 10 (2014) 165] and BaBar [PRD 79 (2009) 052003] is spite of small data set

- Radiative penguin with $b \to s\gamma$ transition
- Used Run I data sample of Belle II
- Challenging to get B^0 vertex without prompt tracks

Res:
$M_{K_S^0\pi^0} \in (0.8, 1.0)$ GeV$/c^2$ *i.e.*, $K^{*0} \to K_S^0\pi^0$

Non-Res:
$M_{K_S^0\pi^0} \in (0.6, 0.8) \cup (1.0, 1.8)$ GeV$/c^2$



- $M_{\rm bc}$ and ΔE followed by Δt fit to extract signal yield

$S = 0.00^{+0.27}_{-0.26} \pm 0.03$

$C = 0.10 \pm 0.13 \pm 0.03$

$S = 0.04^{+0.45}_{-0.44} \pm 0.10$

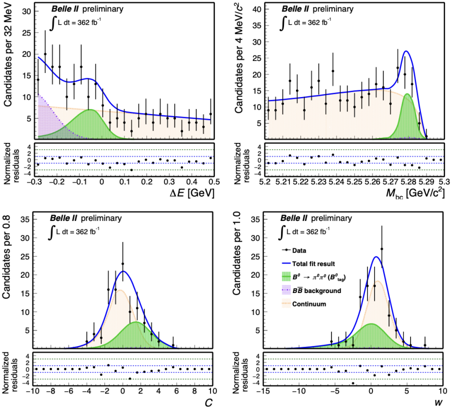
$C = -0.06 \pm 0.25 \pm 0.08$

HFLAV:
Res: $S = -0.16 \pm 0.22,\ C = -0.07 \pm 0.12$
NRes: $S = -0.15 \pm 0.20,\ C = -0.07 \pm 0.12$

- Improved precision compared to Belle [PRD 74 (2006) 111104] and BaBar [PRD 78 (2008) 071102]
- Results in agreement with WA and SM
- Results for S are most precise due to better K_S^0 identification

$B^0 \to \pi^0\pi^0$ at Belle II [paper in preparation]

- Tree-level $b \to u$ processes allow extraction of ϕ_2 or α (least known CKM angle)
- Theoretical $\mathcal{B}$ [PLB 794 (2008) 154, PRD 90 (2014) 014029] is $5\times$ smaller than experimental results as amplitude calculation is challenging involving low-energy, non-perturbative gluon exchanges
- Experimentally challenging: no tracks, γ trajectory and energy less precise than tracks
- Used Run I data sample of Belle II



- Fit to M_{bc}, ΔE, C, and w (wrong tag probability)

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.26 \pm 0.20 \pm 0.12) \times 10^{-6}$$

$$\mathcal{A}_{\mathrm{CP}}(B^0 \to \pi^0\pi^0) = 0.06 \pm 0.30 \pm 0.05$$

- Results in agreement with WA

  PDG: $\mathcal{A}_{\mathrm{CP}}(B^0 \to \pi^0\pi^0) = 0.33 \pm 0.22$

- Results have superior or comparable precision with Belle [PRD 96 (2017) 032007] and BaBar [PRD 87 (2013) 052009] in spite of small data set

Projections for Belle II

- Plans to collect 50 ab^{-1} by 2035

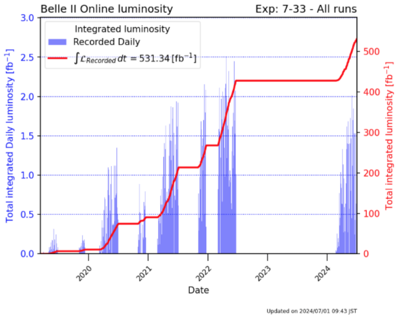
Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb

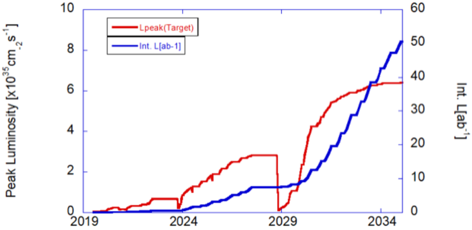
- High luminosity Belle II is perfect to search for Physics beyond the SM

Conclusions

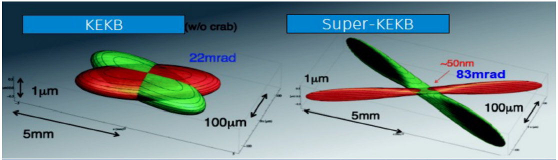
- Exploited full data of Belle or/and Run 1 data of Belle II
- Belle and Belle II have provided many world's leading measurements, best upper limits, and evidence
- Run II data taking of Belle II has started from early 2024: collecting quality physics data
- Waiting to enter 10^{35} luminosity era
- Many new results are on their way

A long way to go ... Stay tuned ...





Backup slides



	Energy (GeV) LER/HER	β_y^* (mm) LER/HER	ε_x (nm) LER/HER	ξ_y LER/HER	φ (mrad)	I_{beam} (A) LER/HER	Luminosity ($cm^{-2}s^{-1}$) x 10^{34}
KEKB Achieved	3.5/8.0	5.9/5.9	18/24	0.13/0.09	11	1.6/1.2	2.11
SuperKEKB	4.0/7.0	0.27/0.3	3.2/2.4	0.09/0.09	41.5	2.8/2.0	65

factor 20

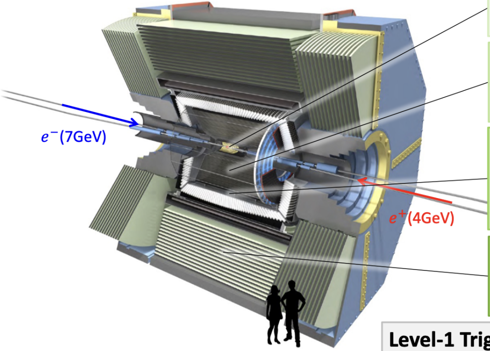
factor 1.5

Factor ~30 in the luminosity

- Design peak luminosity of 6.5×10^{35} cm^{-2}s^{-1} (30 times that of KEKB) to be achieved by;
  - reducing beam size by 20 times
  - increasing beam current by 1.5 times

Possible Belle II detector upgrade in LS2

Middle-term upgrade plan during LS2 (2028 or later)



Vertex detector

- Fully-pixelated CMOS DMAPS detector

Drift chamber

- New front-end electronics (less cross-talk, better radiation hardness, and less power)

Particle identification

Barrel: Time-Of-Propagation counters (TOP)

- Replace w/ life-extended PMTs
- New front-end electronics (less power)

K_L/μ detector (RPC + scintillator)

- Option 1: Replace RPC w/ scintillator
- Option 2: RPC avalanche mode operation

Level-1 Trigger

- Replace electronics with latest technology to allow more sophisticated ML algorithm and more data bandwidth

Table 3. Systematic uncertainties (%) for branching fraction measurements.

Source	$K^{*0}[K^+\pi^-]\gamma$	$K^{*0}[K_S^0\pi^0]\gamma$	$K^{*+}[K^+\pi^0]\gamma$	$K^{*+}[K_S^0\pi^+]\gamma$
B counting	1.5	1.5	1.5	1.5
$f^{\pm}/f^{00}$	1.6	1.6	1.6	1.6
γ selection	0.9	0.9	0.9	0.9
π^0 veto	0.7	0.7	0.7	0.7
η veto	0.2	0.2	0.2	0.2
Tracking efficiency	0.5	0.5	0.2	0.7
π^+ selection	0.2	–	–	0.2
K^+ selection	0.4	–	0.4	–
K_S^0 reconstruction	–	1.4	–	1.4
π^0 reconstruction	–	3.9	3.9	–
χ^2 requirement	0.2	1.0	0.2	1.0
CSBDT requirement	0.3	0.4	0.4	0.3
Best candidate selection	0.1	1.0	0.6	0.2
Fit bias	0.1	0.9	0.5	0.2
Signal PDF model	0.1	0.4	0.3	0.2
KDE PDF model	0.1	0.8	0.6	0.2
Simulation sample size	0.2	0.8	0.4	0.5
Self-crossfeed fraction	–	1.0	1.0	–
Total	2.6	5.4	4.9	3.2

Table 2. Systematic uncertainties (%) for $\mathcal{A}_{CP}$ measurements.

Source	$K^{*0}[K^+\pi^-]\gamma$	$K^{*+}[K^+\pi^0]\gamma$	$K^{*+}[K_S^0\pi^+]\gamma$
Fit bias	0.1	0.2	0.2
Signal PDF model	0.1	0.1	0.1
KDE PDF model	0.1	0.4	0.2
Best candidate selection	0.1	0.5	0.2
K^+ asymmetry	–	0.6	–
π^+ asymmetry	–	–	0.6
$K^+\pi^-$ asymmetry	0.3	–	–
Total	0.4	0.9	0.7

- Dominate systematics from number of $B\overline{B}$ events and $f^{\pm}$ or f^{00}
- A_{CP} measurement dominate uncertainty is coming from interaction of charged hadrons with detector material which give rise to asymmetries in track reconstruction efficiency

$b \to d\ell\ell$

- Used a classifier to suppress backgrounds from continuum ($e^+e^- \to q\bar{q}$, $q \in u, d, s, c$) and generic B ($B\overline{B}$)
- Peaking backgrounds are either vetoed or included in the fit of signal yield extraction

channel	background source
$B^0 \to \eta\mu\mu$	$B^0 \to \eta K\pi$
$B^0 \to \pi^0\mu\mu$	$B^0 \to \pi^0 K\pi$ & $B^0 \to \pi^0 KK$
$B^+ \to \pi^+ ee$	$B^+ \to K^+ ee$
$B^0 \to \rho^0 ee$	$J/\psi \to e$ & $K^* \to K \leftrightarrow e$
$B^+ \to \rho^+\mu\mu$	$J/\psi \to \mu$ & $K^* \to K \leftrightarrow \mu$, $\rho^+\overline{D^0}(K^+\pi^-)$

source	ηee	$\eta\mu\mu$	ωee	$\omega\mu\mu$	$\pi^0 ee$	$\pi^0\mu\mu$	$\pi^+ ee$	$\rho^0 ee$	$\rho^0\mu\mu$	$\rho^+ ee$	$\rho^+\mu\mu$
μ	–	0.6	–	0.6	–	0.6	–	–	0.6	–	0.6
e	0.8	–	0.8	–	0.8	–	0.8	0.8	–	0.8	–
π^+	1.0	1.0	1.0	1.0	–	–	0.5	1.0	1.0	0.5	0.5
π^0	2.3	2.3	2.3	2.3	2.3	2.3	–	–	–	2.3	2.3
γ	4.0	4.0	–	–	–	–	–	–	–	–	–
FastBDT	7.1	6.6	7.1	6.6	7.1	6.6	1.4	1.4	0.8	7.1	6.6
MC statistics	0.48	0.37	0.73	0.53	0.34	0.24	0.24	0.53	0.34	0.80	0.54
decay model	0.57	0.45	0.75	0.69	0.49	0.76	0.40	0.66	0.51	0.81	0.52
mass window	1.05	1.05	1.21	1.21	–	–	–	3.03	3.03	3.03	3.03
BCS	0.03	0.11	0.15	0.43	0.21	0.23	0.11	0.02	1.09	0.6	0.5
Tracking	0.7-1.4	0.7-1.4	1.4	1.4	0.7	0.7	1.05	1.4	1.4	1.05	1.05
PDF shape	0.04	0.04	0.43	0.07	0.10	0.09	0.50	0.20	0.06	0.34	0.32
$f^{+-/00}$	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45
$N_{B\overline{B}}$	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Total	9.35	8.95	8.37	7.91	8.07	7.64	3.56	4.80	4.76	8.75	8.29

TABLE XVII: Systematic uncertainties for $b \to d\ell\ell$ decay channels. The uncertainties are shown in %.

$b \to d\ell\ell$ results

channel	$\mathcal{B}^{\mathrm{UL}}(10^{-8})$	$\mathcal{B}\ (10^{-8})$
$B^0 \to \eta e^+ e^-$	< 10.5	$0.0^{+4.9}_{-3.4} \pm 0.1$
$B^0 \to \eta \mu^+ \mu^-$	< 9.4	$1.9^{+3.4}_{-2.5} \pm 0.2$
$B^0 \to \eta \ell^+ \ell^-$	< 4.8	$1.3^{+2.8}_{-2.2} \pm 0.1$
$B^0 \to \omega e^+ e^-$	< 30.7	$-2.1^{+26.5}_{-20.8} \pm 0.2$
$B^0 \to \omega \mu^+ \mu^-$	< 24.9	$7.7^{+10.8}_{-7.5} \pm 0.6$
$B^0 \to \omega \ell^+ \ell^-$	< 22.0	$6.4^{+10.7}_{-7.8} \pm 0.5$
$B^0 \to \pi^0 e^+ e^-$	< 7.9	$-5.8^{+3.6}_{-2.8} \pm 0.5$
$B^0 \to \pi^0 \mu^+ \mu^-$	< 5.9	$-0.4^{+3.5}_{-2.6} \pm 0.1$
$B^0 \to \pi^0 \ell^+ \ell^-$	< 3.8	$-2.3^{+2.1}_{-1.5} \pm 0.2$
$B^+ \to \pi^+ e^+ e^-$	< 5.4	$0.1^{+2.7}_{-1.8} \pm 0.1$
$B^0 \to \rho^0 e^+ e^-$	< 45.5	$23.6^{+14.6}_{-11.2} \pm 1.1$
$B^+ \to \rho^+ e^+ e^-$	< 46.7	$-38.2^{+24.5}_{-17.2} \pm 3.4$
$B^+ \to \rho^+ \mu^+ \mu^-$	< 38.1	$13.0^{+17.5}_{-13.3} \pm 1.1$
$B^+ \to \rho^+ \ell^+ \ell^-$	< 18.9	$2.5^{+14.6}_{-11.8} \pm 0.2$

$B \to \rho\gamma$ Systematics

Source	$\mathcal{B}_{\rho^+\gamma} \times 10^8$	$\mathcal{B}_{\rho^0\gamma} \times 10^8$	$A_{\rm I}$	A_{CP}
Particle detection	4.1	1.3	1.4%	0.5%
Selection criteria	9.0	3.4	4.0%	0.5%
Fixed fit parameters	1.1	2.7	1.8%	0.2%
Signal shape	4.7	3.0	3.1%	0.5%
Histogram PDFs	1.0	0.6	0.5%	0.1%
Peaking $K^*\gamma$ bkg	3.4	5.4	3.1%	0.1%
Other peaking $B\overline{B}$ bkgs	2.2	0.8	0.9%	0.2%
Peaking $B\overline{B}$ A_{CP}	0.1	<0.1	0.1%	1.0%
Number of $B\overline{B}$'s	1.7	1.4	0.3%	0.1%
$\tau_{B^\pm}/\tau_{B^0}$	0.1	<0.1	0.2%	<0.1%
f_{+-}/f_{00}	4.0	3.6	3.8%	<0.1%
Total	12.5	8.6	7.5%	1.4%

- Signal reconstruction by two back-to-back highly energetic photons, with $E_\gamma^* \in [1.4 - 3.4]$ GeV
- To reject background from Bhabha scattering or $e^+e^- \to \gamma\gamma$, timing requirement is applied
- Classifier is used to distinguish photon from K_L^0 showers
- Used classifiers to reject background from continuum, $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$

TABLE I. Summary of additive systematic uncertainties.

Source	Belle (events)	Belle II (events)
Fit bias	$+0.14$	$+0.10$
PDF parameterization	$^{+0.56}_{-0.48}$	$^{+0.28}_{-0.32}$
Shape modeling	$+0.06$	$+0.04$
Total (sum in quadrature)	$^{+0.58}_{-0.48}$	$^{+0.30}_{-0.32}$

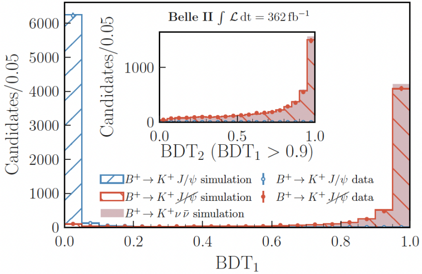
TABLE II. Summary of multiplicative systematic uncertainties.

Source	Belle (%)	Belle II (%)
Photon detection efficiency	4.0	2.7
MC statistics	0.4	0.3
Number of $B\bar{B}$ pairs	1.3	1.5
f^{00}	2.5	2.5
C_{BDT} requirement	0.4	0.9
π^0/η veto	0.4	0.6
Timing requirement efficiency	2.8	–
Total (sum in quadrature)	5.7	4.1

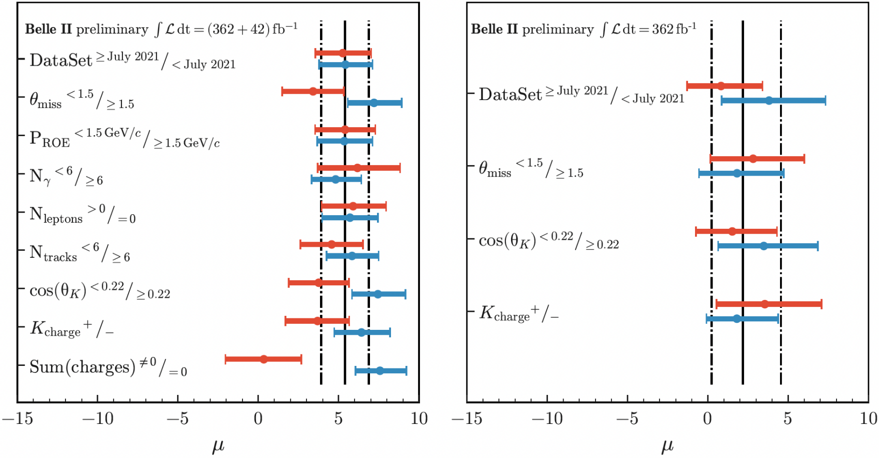
- Photon detection systematic is dominate, obtained using recoil technique in radiative Bhabha events $e^+e^- \to e^+e^-\gamma$ in Belle, and $e^+e^- \to \mu^+\mu^-\gamma$ in Belle II

$B^+ \to K^+\nu\overline{\nu}$ ITA result validation

- Trained two consecutive BDTs and signal efficiency was checked with $B^+ \to J/\psi K^+$ decays:
  - Remove J/ψ and correct K^+ kinematics to match $K^+\nu\overline{\nu}$

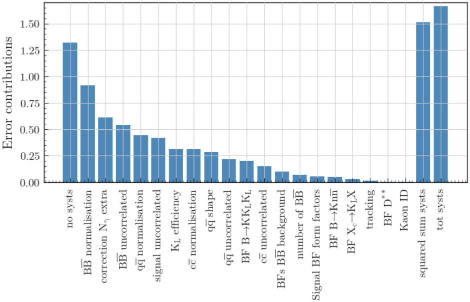


- Closure test with measurement of $\mathcal{B}(B^+ \to \pi^+ K_S^0) = (2.5 \pm 0.5) \times 10^{-5}$
  - Result is compatible with PDG value of $(2.38 \pm 0.08) \times 10^{-5}$
- Controlled background using
  - Off-resonance data for continuum background
  - Background from charmless hadronic B decays with K_L^0 or neutrons *i.e.*, $B^+ \to K^+K^0\overline{K^0}$, $B^+ \to K^+n\overline{n}$, and $B \to K^*\nu\overline{\nu}$, are considered.
    - $B^+ \to K^+K^0\overline{K^0}$ bkg is validated by reconstructing $B^+ \to K^+K_S^0K_S^0$ and $B^0 \to K_S^0K^+K^-$ decays
  - $B \to D(\to K^+X)\ell^-\nu_\ell$ background is studied by combining K^+ with other charged tracks in the event
  - Used pion-enhanced sideband for misidentification study



- A tension at 2.4σ is observed for the total charge split sample in the ITA. Several studies are conducted to investigate this tension, but they did not reveal any significant systematic effects.

Source	Correction	Uncertainty type	Uncertainty size	Impact on μ
Normalization of continuum and $B\bar{B}$ background	—	Global, 7 NP	50%	0.87
Leading B-decays branching fractions	—	Shape, 5 NP	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	20%	0.48
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	30%	0.02
Branching fraction for $B \to D^{(**)}$	—	Shape, 1 NP	50%	0.41
Branching fraction for $B^+ \to n\bar{n}K^+$	q^2 dependent $O(100\%)$	Shape, 1 NP	100%	0.20
Branching fraction for $D \to K_L X$	+30%	Shape, 1 NP	10%	0.14
Continuum background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1 NP	100% of correction	0.01
Integrated luminosity	—	Global, 1 NP	1%	< 0.01
Number of $B\bar{B}$	—	Global, 1 NP	1.5%	0.02
Off-resonance sample normalization	—	Global, 1 NP	5%	< 0.01
Track finding efficiency	—	Shape, 1 NP	0.3%	0.20
Signal kaon PID	p, θ dependent $O(10-100\%)$	Shape, 7 NP	$O(1\%)$	0.07
Photon energy scale	—	Shape, 1 NP	0.5%	0.07
Hadronic energy scale	−10%	Shape, 1 NP	10%	0.35
K^0_L efficiency in ECL	−17%	Shape, 1 NP	8%	0.21
Signal SM form factors	q^2 dependent $O(1\%)$	Shape, 3 NP	$O(1\%)$	0.02
Global signal efficiency	—	Global, 1 NP	3%	0.03
MC statistics	—	Shape, 156 NP	$O(1\%)$	0.52



$B^0 \to \pi^- \ell^+ \nu_\ell$ and $B^+ \to \rho^0 \ell^+ \nu_\ell$ at Belle II

- Background from $B \to X_c \ell \nu$ is suppressed by applying $p^*_\ell > 1.0$ or > 1.4 GeV/c^2 for $B^0 \to \pi^- \ell^+ \nu_\ell$ and $B^+ \to \rho^0 \ell^+ \nu_\ell$

$B^0 \to \pi^- \ell^+ \nu_\ell$													
Source	$q1$	$q2$	$q3$	$q4$	$q5$	$q6$	$q7$	$q8$	$q9$	$q10$	$q11$	$q12$	$q13$
Detector effects	2.0	0.9	1.1	1.0	1.0	1.1	1.1	1.0	0.9	1.2	2.3	4.1	5.8
Beam energy	0.6	0.8	0.7	0.8	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.7
Simulated sample size	4.7	3.8	3.3	3.2	3.2	2.9	3.8	3.7	4.0	4.5	5.9	8.0	13.6
BDT efficiency	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Physics constraints	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Signal model	0.1	0.1	0.2	0.1	0.0	0.2	0.2	0.4	0.3	0.8	0.9	0.2	4.9
ρ lineshape	0.1	0.1	0.3	0.3	0.2	0.1	0.3	0.1	0.3	0.1	0.2	0.2	0.6
Nonres. $B \to \pi\pi\ell\nu_\ell$	0.5	0.6	0.4	0.4	0.5	1.0	1.2	1.0	0.8	1.8	1.2	2.3	14.3
DFN parameters	0.8	0.4	1.5	1.6	1.4	1.7	1.2	0.1	0.7	1.2	2.9	3.5	3.7
$B \to X_u \ell \nu_\ell$ model	0.2	0.4	0.3	0.4	0.2	0.9	1.1	1.2	1.0	1.3	1.6	0.7	8.7
$B \to X_c \ell \nu_\ell$ model	1.4	2.0	1.7	1.3	1.3	1.4	1.8	1.6	1.3	1.4	1.1	0.5	1.7
Continuum	15.1	11.3	7.6	7.1	5.8	5.7	8.1	8.3	9.6	10.4	14.5	23.8	34.4
Total systematic	16.4	12.6	9.3	8.7	7.7	7.7	10.0	9.9	11.1	12.2	16.6	26.0	41.6
Statistical	11.0	8.8	7.9	7.0	7.5	6.4	7.9	7.7	9.1	10.7	9.6	14.6	22.6
Total	19.7	15.4	12.2	11.2	10.7	10.0	12.7	12.6	14.4	16.3	19.1	29.8	47.3

$B^+ \to \rho^0 \ell^+ \nu_\ell$										
Source	$q1$	$q2$	$q3$	$q4$	$q5$	$q6$	$q7$	$q8$	$q9$	$q10$
Detector effects	2.8	2.0	1.6	1.1	1.7	1.9	2.4	1.4	1.4	1.6
Beam energy	2.1	1.9	1.9	1.5	1.3	1.1	1.0	0.9	0.8	0.5
Simulated sample size	14.1	7.8	7.4	6.3	6.3	5.2	6.4	5.6	6.2	7.3
BDT efficiency	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Physics constraints	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Signal model	0.7	0.2	0.2	0.2	0.3	0.4	0.5	0.3	1.8	2.4
ρ lineshape	1.7	1.6	2.0	1.0	1.9	1.8	1.4	0.9	1.6	1.7
Nonres. $B \to \pi\pi\ell\nu_\ell$	5.6	6.3	6.7	8.6	9.3	10.7	10.1	7.0	7.8	11.8
DFN parameters	3.6	5.5	4.1	3.5	1.1	1.2	2.7	1.7	1.9	2.3
$B \to X_u \ell \nu_\ell$ model	1.7	3.0	3.8	5.0	5.8	6.1	6.3	1.9	7.2	12.4
$B \to X_c \ell \nu_\ell$ model	1.8	1.9	1.7	1.1	1.4	1.7	0.9	0.9	1.9	2.6
Continuum	31.5	24.3	17.0	19.6	13.2	14.8	16.0	16.6	15.2	18.7
Total systematic	35.6	27.5	21.0	23.5	18.8	20.5	21.6	19.4	20.2	27.0
Statistical	30.0	17.5	20.8	14.4	12.4	13.6	14.1	10.4	12.2	11.8
Total	46.6	32.6	29.6	27.6	22.6	24.6	25.8	22.0	23.6	29.5

- Continuum reweighting is dominate systematic and limited by off-resonance sample size (42 fb^{-1})

TABLE VI. Fractional contributions to the uncertainties of the CLN form factors from a fit to the $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decay. The uncertainties originating from tracking efficiency, the number of B^0 mesons, the B^0 lifetime, and the charm branching fractions only affect the overall normalization but do not contribute to the parameters related to the shape.

	ρ^2	$R_1(1)$	$R_2(1)$	$\|V_{cb}\|$
Statistical	3.0	4.1	2.8	0.7
Background subtraction	1.4	2.2	1.2	0.3
Size of simulated samples	1.2	1.7	1.1	0.3
Lepton ID efficiency	0.2	1.6	0.1	0.3
Slow pion efficiency	1.0	0.9	0.8	1.5
Tracking of K, π, ℓ				0.4
$N_{B\bar{B}}$				0.8
f_{+0}				1.3
$\mathcal{B}(D^{*+} \to D^0\pi^+)$				0.4
$\mathcal{B}(D^0 \to K^-\pi^+)$				0.4
B^0 lifetime				0.1
Signal modeling	2.6	2.6	2.0	0.5
Total	4.5	5.9	3.9	2.4

- Dominated systematic uncertainty from slow-pion efficiency determined using $B^0 \to D^{*-}\pi^+$ decay

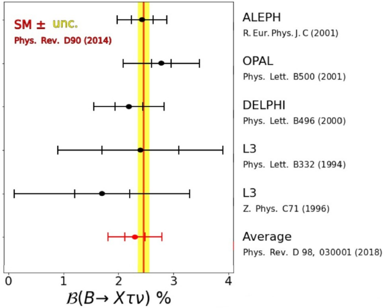
- BGL (Boyd-Grinstein-Lebed) utilize dispersive bounds and expand the helicity-basis form factors with a conformal parameter
- CLN (Caprini-Lellouch-Neubert) uses dispersive bounds and quark-model input to reduce the number of parameters required to describe the form factors

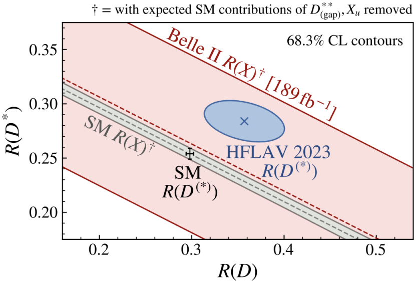
Table VIII. Summary of systematic uncertainties on $R(D^*)$.

Source	Uncertainty
PDF shapes	$^{+9.1\%}_{-8.3\%}$
Simulation sample size	$^{+7.5\%}_{-7.5\%}$
$\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell$ branching fractions	$^{+4.8\%}_{-3.5\%}$
Fixed backgrounds	$^{+2.7\%}_{-2.3\%}$
Hadronic B decay branching fractions	$^{+2.1\%}_{-2.1\%}$
Reconstruction efficiency	$^{+2.0\%}_{-2.0\%}$
Kernel density estimation	$^{+2.0\%}_{-0.8\%}$
Form factors	$^{+0.5\%}_{-0.1\%}$
Peaking background in ΔM_{D^*}	$^{+0.4\%}_{-0.4\%}$
$\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell$ branching fractions	$^{+0.2\%}_{-0.2\%}$
$R(D^*)$ fit method	$^{+0.1\%}_{-0.1\%}$
Total systematic uncertainty	$^{+13.5\%}_{-12.3\%}$

- Dominate systematic:

- Main backgrounds from hadrons misidentiied as leptons and leptons originating from charmed hadrons
  - Suppressed μ fakes from π or K by rejecting $\omega \to \pi^+\pi^-\pi^0$, $K^{*0} \to \pi^- K^+$, $D^0 \to K^-\pi^-\pi^+\pi^+$, $D^+ \to \pi^+\pi^+\pi^- + [\pi^0 \text{ or } \pi^+\pi^-]$, and $D^+ \to K^-\pi^+\pi^+(\pi^0)$
  - $B \to X_c \to \ell$ background modelling: reweight $B \to X\tau(\ell)\nu$ events by taking exp-to-sim ratio in M_X bin using high p_ℓ^B sample





Source	Uncertainty [%]		
	e	μ	ℓ
Experimental sample size	8.8	12.0	7.1
Simulation sample size	6.7	10.6	5.7
Tracking efficiency	2.9	3.3	3.0
Lepton identification	2.8	5.2	2.4
$X_c\ell\nu$ reweighting	7.3	6.8	7.1
$B\overline{B}$ background reweighting	5.8	11.5	5.7
$X\ell\nu$ branching fractions	7.0	10.0	7.7
$X\tau\nu$ branching fractions	1.0	1.0	1.0
$X_c\tau(\ell)\nu$ form factors	7.4	8.9	7.8
Total	18.1	25.6	17.3

- Dominated systematic uncertainties are experimental and simulated sample sizes as normalization
- Control sample reweighting procedure: $B\overline{B}$ background shapes uncertainties are associated with simulation reweighting

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

Table I. Systematic and statistical uncertainties on ε_{tag} for $B^0 \to D^{(*)-}\pi^+$ and, S and C for $B^0 \to J/\psi K_S^0$.

Source	ε_{tag} [%]	S	C
Detector alignment	0.08	0.005	0.003
Interaction region	0.16	0.002	0.002
Beam energy	0.03	$<$ 0.001	0.001
ΔE-fit background model	0.11	0.001	0.001
ΔE-fit signal model	0.08	0.003	0.006
sWeight background subtraction	0.24	0.001	0.001
Fixed resolution-function parameters	0.07	0.004	0.004
τ and Δm_d	0.06	0.001	$<$ 0.001
$\sigma_{\Delta t}$ binning	0.04	$<$ 0.001	$<$ 0.001
Δt-fit bias	0.09	0.002	0.005
CP violation in B_{tag} decay		$<$ 0.001	0.027
$B^0 \to D^{(*)-}\pi^+$ sample size		0.004	0.007
Total systematic uncertainty	0.36	0.009	0.029
Statistical uncertainty	0.43	0.035	0.026

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$B^0 \to \eta' K^0_S$, $B^0 \to K^0_S \pi^0 \gamma$, and $B^0 \to \pi^0 \pi^0$

Table II: Summary of systematic uncertainties for $C_{\eta' K^0_S}$ and $S_{\eta' K^0_S}$.

Source	$C_{\eta' K^0_S}$	$S_{\eta' K^0_S}$
Signal and continuum yields	< 0.001	0.002
SxF and $B\bar{B}$ yields	< 0.001	0.006
$C_{\rm BDT}$ mismodeling	0.004	0.010
Signal and background modeling	0.020	0.014
Observable correlations	0.008	0.001
Δt resolution fixed parameters	0.005	0.009
Δt resolution model	0.004	0.019
Flavor tagging	0.007	0.004
τ_{B^0} and Δm_d	< 0.001	0.002
Fit bias	0.003	0.002
Tracker misalignment	0.004	0.006
Momentum scale	0.001	0.001
Beam spot	0.002	0.002
B-meson motion in the Υ(4S) frame	< 0.001	0.017
Tag-side interference	0.005	0.011
$B\bar{B}$ background asymmetry	0.008	0.006
Candidate selection	0.007	0.009
Total	0.027	0.037

	$K^{*0}\gamma$		$K^0_S\pi^0\gamma$	
Source	S	C	S	C
E and p scales	±0.017	±0.015	±0.083	±0.047
Vertex measurement	±0.021	±0.009	±0.023	±0.036
Flavor tagging	±0.005	$^{+0.012}_{-0.009}$	$^{+0.008}_{-0.009}$	$^{+0.013}_{-0.009}$
Signal modeling	±0.003	±0.003	±0.032	±0.013
Δt resolution function	±0.014	±0.009	±0.031	±0.013
τ_{B^0} and Δm_d	< 0.001	< 0.001	±0.003	< 0.001
$B\bar{B}$ background asym.	$^{+0.007}_{-0.008}$	±0.011	$^{+0.030}_{-0.026}$	$^{+0.049}_{-0.051}$
Tag-side interference	< 0.001	-0.002	$+0.001$	$+0.001$
Total	±0.032	$^{+0.026}_{-0.025}$	$^{+0.102}_{-0.100}$	±0.080

Source	$\mathcal{B}$	$\mathcal{A}_{CP}$
π^0 efficiency	8.6 %	n/a
$\Upsilon(4S)$ branching fractions $(1 + f^{+-}/f^{00})$	2.5 %	n/a
Continuum-suppression efficiency	1.9 %	n/a
$B\bar{B}$-background model	1.7 %	0.034
Sample size $N_{B\bar{B}}$	1.5 %	n/a
Signal model	1.2 %	0.021
Continuum-background model	0.9 %	0.025
Wrong-tag probability calibration	n/a	0.008
Total systematic uncertainty	9.6 %	0.048
Statistical uncertainty	15.9 %	0.303

- For $B^0 \to K^0_S \pi^0 \gamma$ dominate systematic from vertex measurement: as main challenge was to find B^0 vertex without prompt tracks
  - Used $K^0_S \to \pi^+\pi^-$ information and beamspot constraint