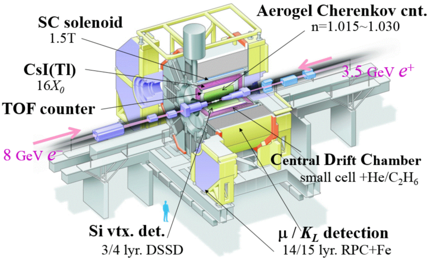
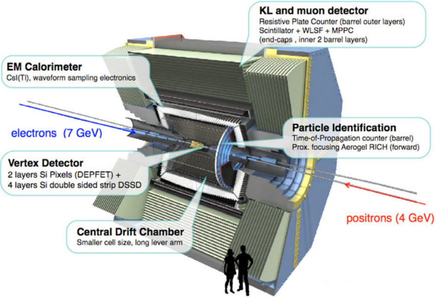
# $B$-Physics results from Belle & Belle II


**Seema Choudhury**
Iowa State University, USA
(on behalf of the Belle & Belle II Collaborations)


June 04 2024

# Belle & Belle II Detectors



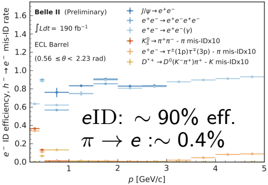




- Asymmetric $e^+$ (3.5 GeV) - $e^-$ (8 GeV) collider
- Collected total 1 ab$^{-1}$ of data
- Data taken from 1999 to 2010
- Collected 711 fb$^{-1}$ at $\Upsilon(4S)$ resonance

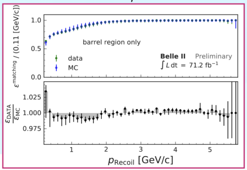
- Asymmetric $e^+$ (4 GeV) - $e^-$ (7 GeV) collider
- Recorded 424 fb$^{-1}$ of data: $\sim$ equivalent to BaBar and 1/2 of Belle data sample during Run I
- Data taken between 2019 - 2022
- Run I data at $\Upsilon(4S)$ resonance: 362 fb$^{-1}$
- Run II has started from early 2024
- Aims to collect many-ab$^{-1}$ of data

# Advantages of Belle & Belle II

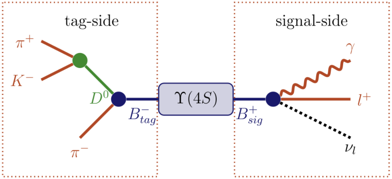
- Clean environment: Average 11 tracks per event compared to hundreds of tracks for hadron colliders



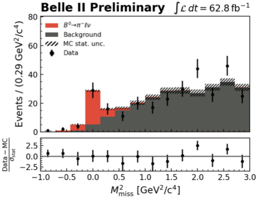

$\gamma$: $\sim 90\%$ eff.




- Good particle identification and performance
- Similar sensitivity for $\mu$ and $e$
- High photon detection efficiency
- Good $\pi^0$ mass resolution

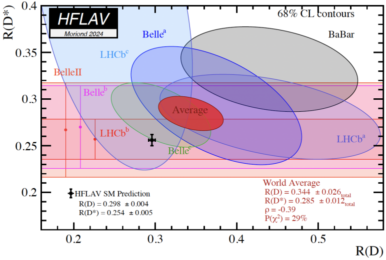



- Unique for $B$ factories:
  - channels with $\pi^0$, $\gamma$, $\eta^{(\prime)}$, $K_L$ ...
  - final states with one or more missing $\nu$
- Dealing with missing energy:
  - fully reconstruct the partner $B$ meson: full event interpretation
  - Identify invisible particle using, $M^2_{\mathrm{miss}}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



# Physics Programs

# Rare decays and Lepton flavor Universality


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

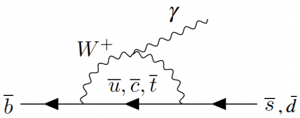
$$H = D, D^*, X, \pi, \ldots$$
$$\ell = e, \mu$$

(next decade?)

**New! Featured today**

"Traditional" modes

# $B \to K^*\gamma$ at Belle II [paper in preparation]




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

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

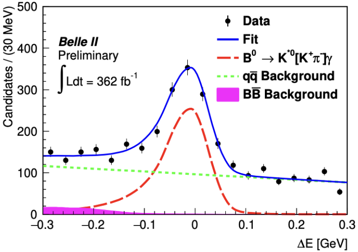
$$\boxed{\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) - \mathcal{A}_{CP}(B^+ \to K^{*+}\gamma)}$$

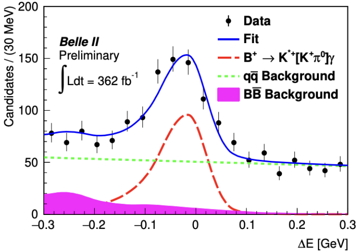
  - Isospin asymmetry

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

- $\mathcal{A}_{CP}$ and $\Delta_{0+}$ are theoretically clean due to cancellation of form factor contributions in ratio
- Belle [PRL 119 (2017) 191802] has observed evidence of isospin violation at $3.1\sigma$ using 711 $\text{fb}^{-1}$
- Used Run I data sample of Belle II
- Measured $\mathcal{A}_{CP}$, $\Delta\mathcal{A}_{CP}$, $\Delta_{0+}$ in addition to $\mathcal{B}$

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




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

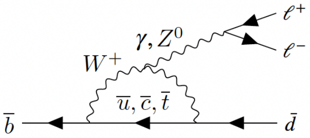
$$\mathcal{B}(B^0 \to K^{*0}\gamma) = (4.16 \pm 0.10 \pm 0.11) \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^{*+}\gamma) = (4.04 \pm 0.13 \pm 0.13) \times 10^{-5}$$
$$\mathcal{B}(B \to K^{*}\gamma) = (4.12 \pm 0.08 \pm 0.11) \times 10^{-5}$$

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

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

- Results are consistent with WA and SM
- Similar sensitivity to Belle [PRL 119 (2017) 191802] due to improved $\Delta E$ resolution and $K_S^0$ identification efficiency
- Dominant systematic for $\Delta_{0+}$ is $f^{+-} = \Gamma(\Upsilon(4S) \to B^+B^-)$ or $f^{00} = \Gamma(\Upsilon(4S) \to B^0\overline{B^0})$

- 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]

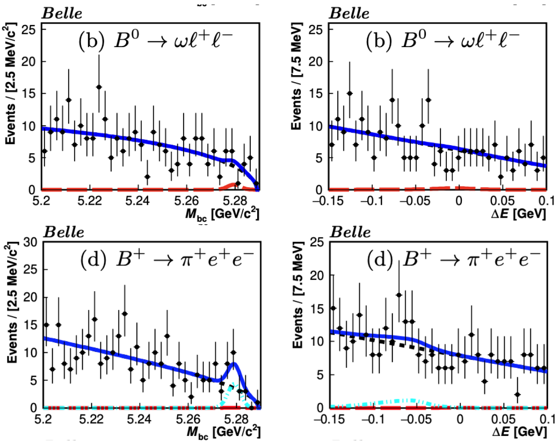
$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (1.78 \pm 0.23) \times 10^{-8}$$
$$\mathcal{B}(B^0 \to \rho^0\mu^+\mu^-) = (1.98 \pm 0.53) \times 10^{-8}$$
$$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-) = (2.11 \pm 0.52) \times 10^{-8}$$

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

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

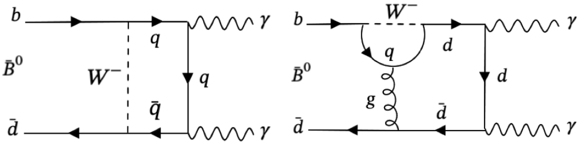
| channel | $\mathcal{B}^{\rm UL}$ $(10^{-8})$ |
|---|---|
| $B^0 \to \eta e^+ e^-$ | $< 10.5$ |
| $B^0 \to \eta \mu^+ \mu^-$ | $< 9.4$ |
| $B^0 \to \eta \ell^+ \ell^-$ | $< 4.8$ |
| $B^0 \to \omega e^+ e^-$ | $< 30.7$ |
| $B^0 \to \omega \mu^+ \mu^-$ | $< 24.9$ |
| $B^0 \to \omega \ell^+ \ell^-$ | $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

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



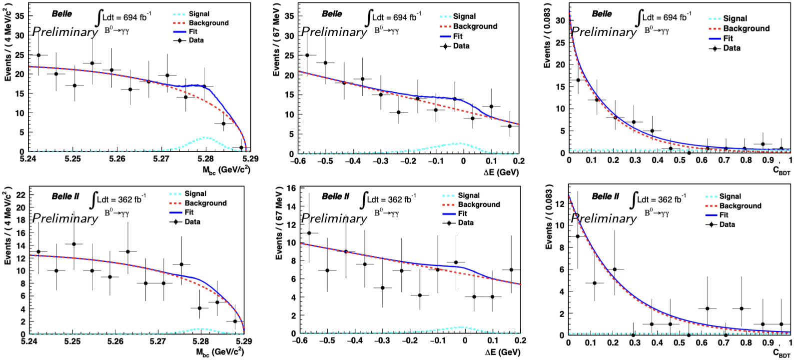

- World's best limits for $B^{\pm,0} \to (\eta, \omega, \pi^{\pm,0}, \rho^{\pm,0})ee$ and $B^{\pm,0} \to (\eta, \omega, \pi^0, \rho^{\pm})\mu\mu$
- World's first limits for $B^0 \to \omega \ell^+ \ell^-$, $B^+ \to \rho^+ \ell^+ \ell^-$, and $B^0 \to \rho^0 e^+ e^-$
- No LFU ($b \to d\mu^+\mu^- / b \to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

- No $b - d$ vertex
- 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
- 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 $M_{\mathrm{bc}}$, $\Delta E$, and $C'_{\mathrm{BDT}}$ (transformed BDT for continuum suppression) to extract signal yield

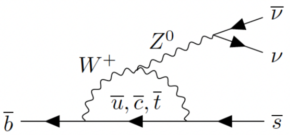


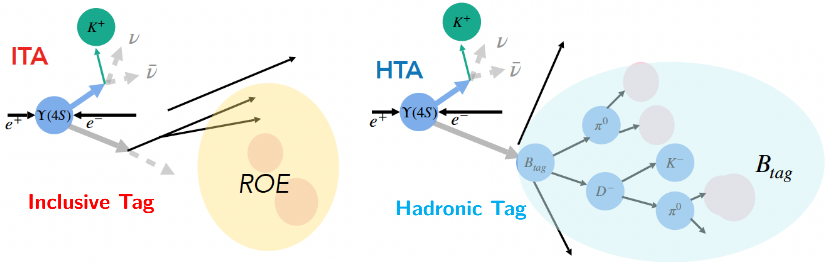

- $N_{\mathrm{sig}} = 11.0^{+6.5}_{-5.5}$ having a significance of $2.5\sigma$

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

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

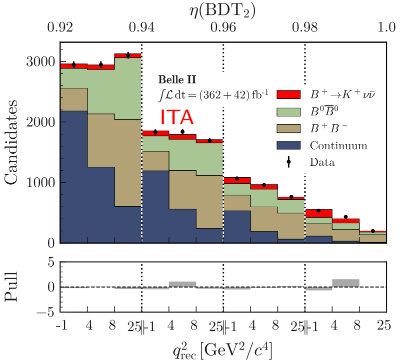
- $\mathcal{B}_{\rm SM}(B^+ \to K^+\nu\overline{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$ [PRD 107 (2023) 119903]
- Experimentally challenging due to two neutrinos
- Best limit of $< 1.6 \times 10^{-5}$ at 90% CL from BaBar [PRD 87 (2013) 112005]
- Used Run I data sample of Belle II

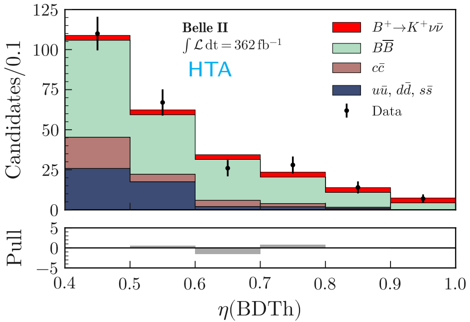



- ITA has low purity but high efficiency and HTA has high purity and low efficiency
  - ITA: signal efficiency = 8%; purity = 0.9%
  - HTA: signal efficiency = 0.4%; purity = 3.5%
- Parameter of interest: signal strength $= \mu = \dfrac{\mathcal{B}(B^+ \to K^+\nu\overline{\nu})}{\mathcal{B}_{\rm SM}(B^+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

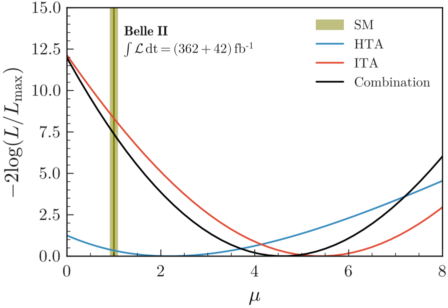
- Binned fit to extract $\mu$:
  - ITA: Classifier 2 output [$\eta(\mathrm{BDT}_2)$] and $q^2$ [mass square of neutrino pair]
  - HTA: Classifier output [$\eta(\mathrm{BDTh})$]

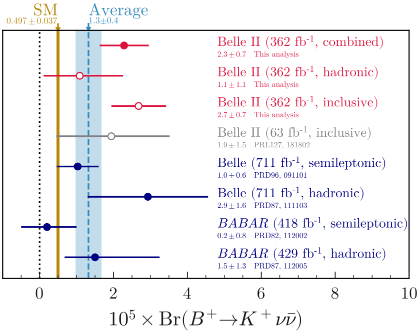



- $\mu = 5.4 \pm 1.0 \pm 1.1$
- $\mathcal{B} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$
- $3.5\sigma$ significance w.r.t bkg-only hypo
- $2.9\sigma$ departure from SM

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




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

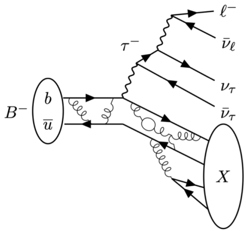
- $\mu = 4.6 \pm 1.0 \pm 0.9$
- $\mathcal{B} = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$
- $3.5\sigma$ significance w.r.t bkg-only hypo
- $2.7\sigma$ departure from SM

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

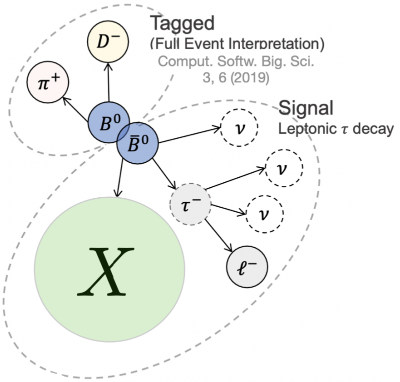
- Semileptonic $B \to X\tau(\ell)\nu$ is inclusive $b \to c\tau(\ell)\nu$ transition
- Test LFU in charged-current weak interaction by measuring tau-to-light-lepton ratio

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

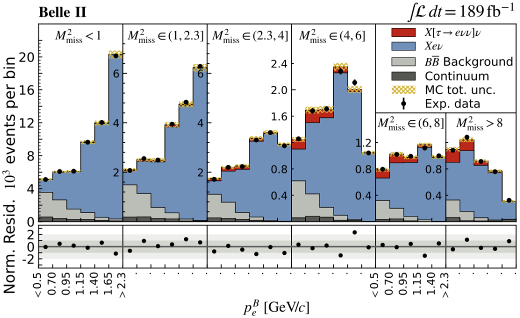
- Experimentally LFU in exclusive $B \to D^{(*)}\tau(\ell)\nu$ has a tension of $3.3\sigma$

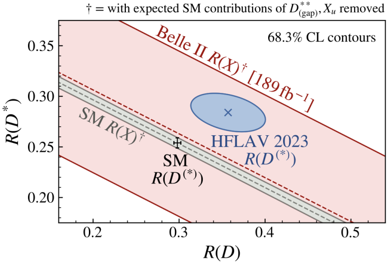



- Used 189 $\text{fb}^{-1}$ data sample of Belle II
- Tag-side $B$ is fully reconstructed hadronically
- Hadronic system $X$ is reconstructed using remaining tracks and energy deposits in the calorimeter
- Inclusive decay with $\tau$ is challenging due to larger background from less constrained $X$ system



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

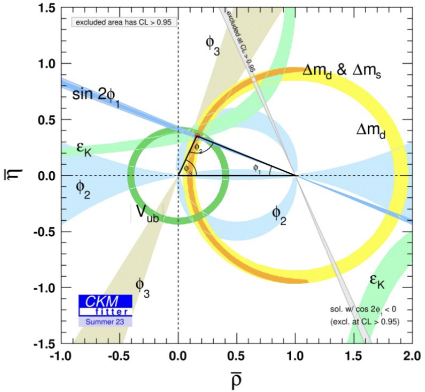



$$R(X_{\tau/e}) = 0.232 \pm 0.020 \pm 0.037$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027 \pm 0.050$$
$$R(X_{\tau/\ell}) = 0.228 \pm 0.016 \pm 0.036$$

- $R(X_{\tau/\ell})$ result is consistent with SM predictions of $0.223 \pm 0.005$ [JHEP 11 (2022) 007]
- First measurement at $B$-factories with $\Upsilon(4S)$
- Result is also consistent with $R(D^{(*)})$

# CKM and CP Violation

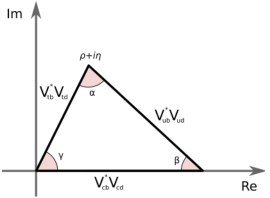


# $|V_{ub}|$ at Belle II [paper in preparation]

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

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

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




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

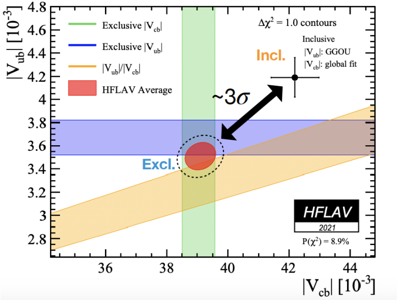
$$\boxed{\text{Exclusive}:\ B \to \pi\ell\nu,\ B \to \rho\ell\nu}$$

$$\boxed{\text{Inclusive}:\ B \to X_u\ell\nu}$$

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

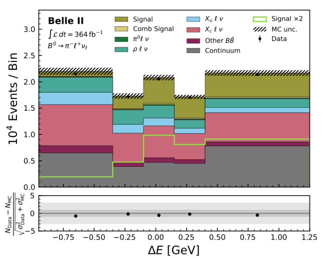
$$\boxed{\begin{array}{l} B^0 \to \pi^-\ell^+\nu_\ell \\ B^+ \to \rho^0\ell^+\nu_\ell \end{array}}$$

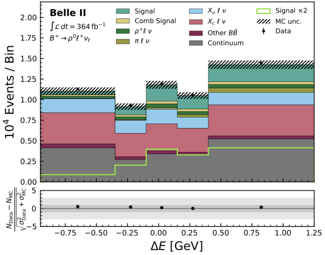
- Sum of measured exclusive $\mathcal{B}$ is $\sim 20\%$ of inclusive $\mathcal{B}(B \to X_u\ell\nu)$



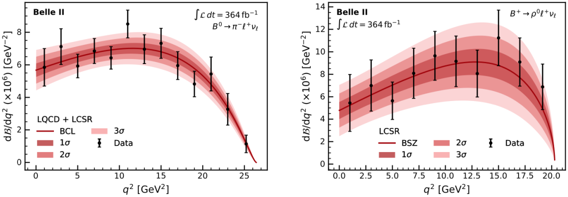
# $|V_{ub}|$ at Belle II

[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 $M_{\rm bc}$, $\Delta E$, and $q^2 = (p_B - p_{\pi^-,\rho^0})^2$

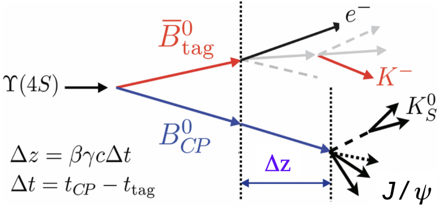



$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$

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

- $\mathcal{B}$ results are consistent with WA
- $|V_{ub}|$ results are consistent with previous exclusive measurements [PRD 107 (2023) 052008, PRD 104 (2021) 034032], and theoretical uncertainty dominated

- Flagship measurement for $B$-factories



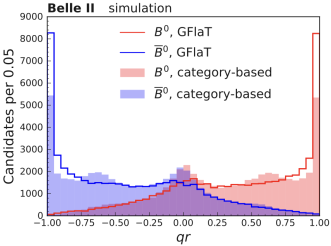

<Δz> ~ 130 μm at Belle II

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

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

Mixing induced CP violation

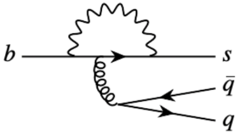
Direct CP violation

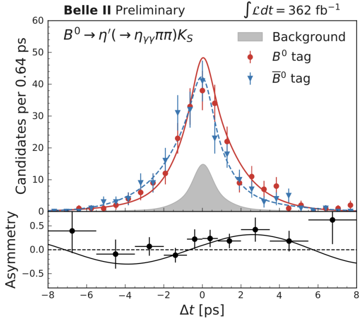


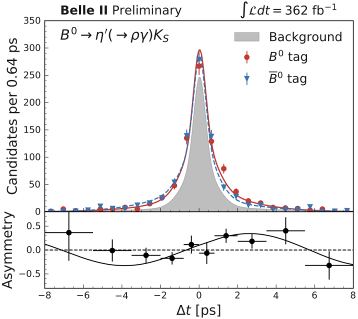

- Measurement relies on ability to identify flavor of tag side $B$
- Graphical neutral network approach for flavor tagging has improved the tagging efficiency by $\sim 18\%$ at Belle II [arXiv:2402.17260]

# $B^0 \to \eta' K_s^0$ at Belle II [arXiv:2402.03713]

- 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 $0.01 \pm 0.01$ and $C \approx 0$
- Used Run I data sample of Belle II
- Fit to $M_{\rm bc}$, $\Delta E$, $C_{\rm BDT}$, $\Delta t$, and $q_{\rm tag}$ (tag-flavor)



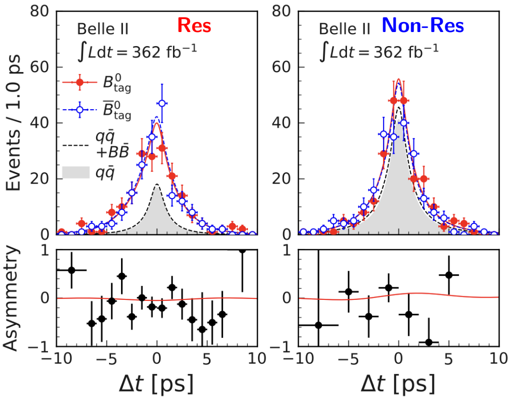

$$C = -0.19 \pm 0.08 \pm 0.03$$
$$S = 0.67 \pm 0.10 \pm 0.04$$

- Results in agreement with WA
- 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 $\Delta E$ followed by $\Delta t$ fit to extract signal yield

$S = 0.00^{+0.27}_{-0.26} \pm 0.03$
$C = 0.10 \pm 0.13 \pm 0.03$

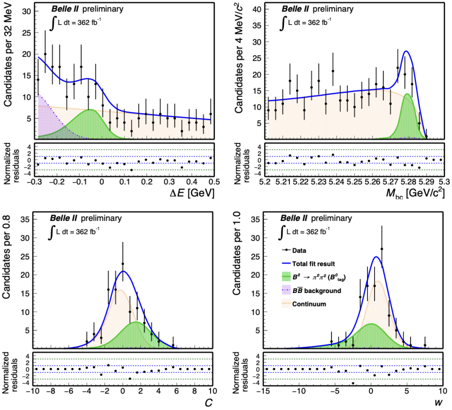
$S = 0.04^{+0.45}_{-0.44} \pm 0.10$
$C = -0.06 \pm 0.25 \pm 0.08$

- Results in agreement with WA and SM

- Results have improved precision compared to Belle [PRD 74 (2006) 111104] and BaBar [PRD 78 (2008) 071102]
- 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 $\phi_2$ or $\alpha$ (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, $\gamma$ trajectory and energy less precise than tracks
- Used Run I data sample of Belle II




- Fit to $M_{\rm bc}$, $\Delta E$, $C$, and $w$ (wrong tag probability)

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

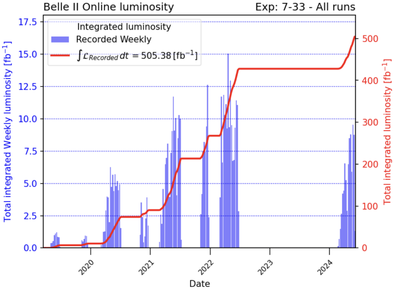
$$\boxed{\mathcal{A}_{\rm CP}(B^0 \to \pi^0\pi^0) = 0.06 \pm 0.30 \pm 0.05}$$

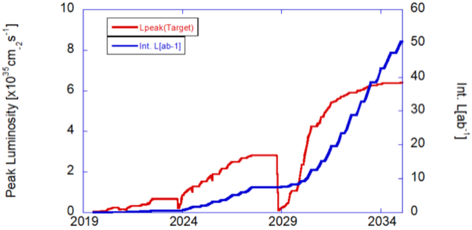
- Results in agreement with WA
- Results have superior or comparable precision with Belle [PRD 96 (2017) 032007] and BaBar [PRD 87 (2013) 052009] in spite of small data set

# 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

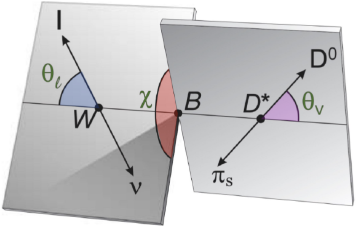
A long way to go ... Stay tuned ...



**Backup slides**

- 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



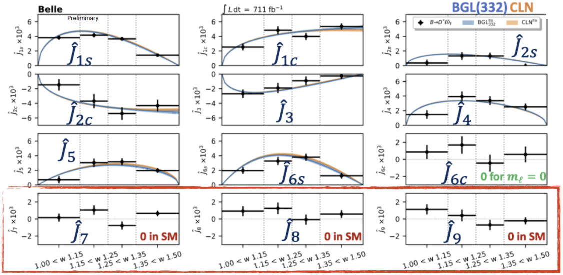

- Differential decay rate can be decomposed in a basis of angular functions with 12 coefficients, $\hat{J}_i$, all dependent on $w$

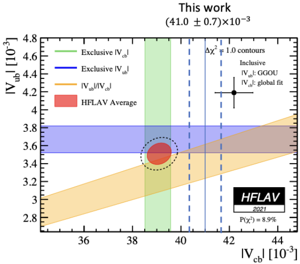
$$\frac{\mathrm{d}\Gamma(\bar{B} \to D^* \ell \bar{\nu}_\ell)}{\mathrm{d}w\, \mathrm{d}\cos\theta_\ell\, \mathrm{d}\cos\theta_V\, \mathrm{d}\chi} = \frac{2G_F^2 \eta_{EW}^2 |V_{cb}|^2 m_B^4 m_{D^*}}{2\pi^4} \times \Big( J_{1s}\sin^2\theta_V + J_{1c}\cos^2\theta_V + (J_{2s}\sin^2\theta_V + J_{2c}\cos^2\theta_V)\cos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

$$\text{Hadronic recoil energy } (w) = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

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

$$\boxed{\begin{array}{l} B^+ \to D^{*0}\ell^+\nu,\ D^{*0} \to D^+\pi^0 \\ B^0 \to D^{*+}\ell^-\nu,\ D^{*+} \to D^0\pi^+ \end{array}}$$



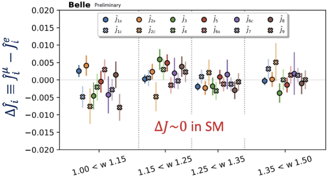




- Coefficients are in good agreement with the fit using BGL [NPB 461 (1996) 493, PRD 56 (1997) 6895] and CLN [NPB 530 (1998) 153] form-factor parametrizations
- Coefficients are consistent with the SM predictions

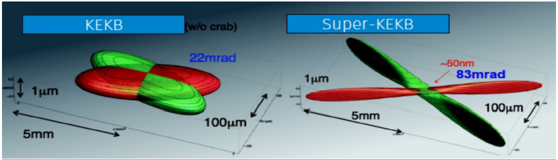
$$|V_{cb}| = (41.0 \pm 0.3 \pm 0.4 \pm 0.5) \times 10^{-3} \text{ (BGL)}$$
$$|V_{cb}| = (40.9 \pm 0.3 \pm 0.4 \pm 0.4) \times 10^{-3} \text{ (CLN)}$$

- 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




| | Energy (GeV) LER/HER | $\beta_y^*$ (mm) LER/HER | $\varepsilon_x$ (nm) LER/HER | $\xi_y$ LER/HER | $\varphi$ (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 $6.5 \times 10^{35}$ $cm^{-2}s^{-1}$ (30 times that of KEKB) to be achieved by;
  - reducing beam size by 20 times
  - increasing beam current by 1.5 times

# $B \to K^*\gamma$ at Belle II

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

| Source | $K^{*0}[K^+\pi^-]\gamma$ | $K^{*0}[K^0_S\pi^0]\gamma$ | $K^{*+}[K^+\pi^0]\gamma$ | $K^{*+}[K^0_S\pi^+]\gamma$ |
|---|---|---|---|---|
| $B$ counting | 1.5 | 1.5 | 1.5 | 1.5 |
| $f^{\pm}/f^{00}$ | 1.6 | 1.6 | 1.6 | 1.6 |
| $\gamma$ selection | 0.9 | 0.9 | 0.9 | 0.9 |
| $\pi^0$ veto | 0.7 | 0.7 | 0.7 | 0.7 |
| $\eta$ veto | 0.2 | 0.2 | 0.2 | 0.2 |
| Tracking efficiency | 0.5 | 0.5 | 0.2 | 0.7 |
| $\pi^+$ selection | 0.2 | – | – | 0.2 |
| $K^+$ selection | 0.4 | – | 0.4 | – |
| $K^0_S$ reconstruction | – | 1.4 | – | 1.4 |
| $\pi^0$ reconstruction | – | 3.9 | 3.9 | – |
| $\chi^2$ 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 | $K^{*0}[K^+\pi^-]\gamma$ | $K^{*+}[K^+\pi^0]\gamma$ | $K^{*+}[K^0_S\pi^+]\gamma$ |
|---|---|---|---|
| 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 | – |
| $\pi^+$ 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 $f^{00}$
- $A_{\mathrm{CP}}$ measurement dominate uncertainty is coming from interaction of charged hadrons with detector material which give rise to asymmetries in track reconstruction efficiency

- 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 | $\eta ee$ | $\eta\mu\mu$ | $\omega ee$ | $\omega\mu\mu$ | $\pi^0 ee$ | $\pi^0\mu\mu$ | $\pi^+ ee$ | $\rho^0 ee$ | $\rho^0\mu\mu$ | $\rho^+ ee$ | $\rho^+\mu\mu$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\mu$ | – | 0.6 | – | 0.6 | – | 0.6 | – | – | 0.6 | – | 0.6 |
| e | 0.8 | – | 0.8 | – | 0.8 | – | 0.8 | 0.8 | – | 0.8 | – |
| $\pi^+$ | 1.0 | 1.0 | 1.0 | 1.0 | – | – | 0.5 | 1.0 | 1.0 | 0.5 | 0.5 |
| $\pi^0$ | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | – | – | – | 2.3 | 2.3 |
| $\gamma$ | 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 | $\mathcal{B}^{\mathrm{UL}}(10^{-8})$ | $\mathcal{B}\ (10^{-8})$ |
|---|---|---|
| $B^0 \to \eta e^+ e^-$ | $< 10.5$ | $0.0^{+4.9}_{-3.4} \pm 0.1$ |
| $B^0 \to \eta \mu^+ \mu^-$ | $< 9.4$ | $1.9^{+3.4}_{-2.5} \pm 0.2$ |
| $B^0 \to \eta \ell^+ \ell^-$ | $< 4.8$ | $1.3^{+2.8}_{-2.2} \pm 0.1$ |
| | | |
| $B^0 \to \omega e^+ e^-$ | $< 30.7$ | $-2.1^{+26.5}_{-20.8} \pm 0.2$ |
| $B^0 \to \omega \mu^+ \mu^-$ | $< 24.9$ | $7.7^{+10.8}_{-7.5} \pm 0.6$ |
| $B^0 \to \omega \ell^+ \ell^-$ | $< 22.0$ | $6.4^{+10.7}_{-7.8} \pm 0.5$ |
| | | |
| $B^0 \to \pi^0 e^+ e^-$ | $< 7.9$ | $-5.8^{+3.6}_{-2.8} \pm 0.5$ |
| $B^0 \to \pi^0 \mu^+ \mu^-$ | $< 5.9$ | $-0.4^{+3.5}_{-2.6} \pm 0.1$ |
| $B^0 \to \pi^0 \ell^+ \ell^-$ | $< 3.8$ | $-2.3^{+2.1}_{-1.5} \pm 0.2$ |
| | | |
| $B^+ \to \pi^+ e^+ e^-$ | $< 5.4$ | $0.1^{+2.7}_{-1.8} \pm 0.1$ |
| | | |
| $B^0 \to \rho^0 e^+ e^-$ | $< 45.5$ | $23.6^{+14.6}_{-11.2} \pm 1.1$ |
| | | |
| $B^+ \to \rho^+ e^+ e^-$ | $< 46.7$ | $-38.2^{+24.5}_{-17.2} \pm 3.4$ |
| $B^+ \to \rho^+ \mu^+ \mu^-$ | $< 38.1$ | $13.0^{+17.5}_{-13.3} \pm 1.1$ |
| $B^+ \to \rho^+ \ell^+ \ell^-$ | $< 18.9$ | $2.5^{+14.6}_{-11.8} \pm 0.2$ |

# $B^0 \to \gamma\gamma$ at Belle & Belle II

- 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 $K^0_L$ 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 |
| $C_{\mathrm{BDT}}$ requirement | 0.4 | 0.9 |
| $\pi^0/\eta$ veto | 0.4 | 0.6 |
| Timing requirement efficiency | 2.8 | – |
| Total (sum in quadrature) | 5.7 | 4.1 |

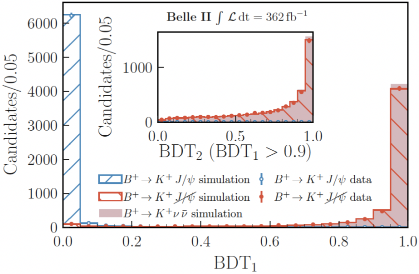
- Photon detection systematic is dominate, obtained using recoil technique in radiative Bhabha events $e^+e^- \to e^+e^-\gamma$ in Belle, and $e^+e^- \to \mu^+\mu^-\gamma$ in Belle II

# $B \to K\nu\bar{\nu}$ at Belle II

- ITA: low purity (0.8%) and high efficiency (8%)
- HTA: high purity (3.5%) and low efficiency (0.4%)
- Inclusive properties of tag-$B$ is used to suppress bkg from signal side
- Background suppression:
  - ITA: 2 consecutive classifiers to suppress continuum and generic $B$ backgrounds
  - HTA: 1 classifier to suppress continuum and generic $B$ backgrounds

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

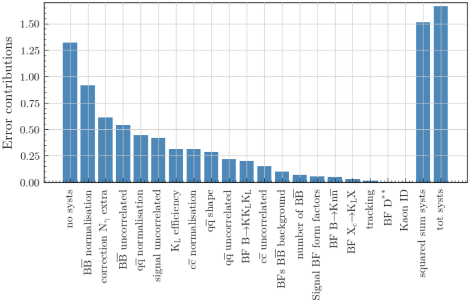
- Trained two consecutive BDTs and signal efficiency was checked with $B^+ \to J/\psi K^+$ decays:
  - Remove $J/\psi$ and correct $K^+$ kinematics to match $K^+\nu\overline{\nu}$




- 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

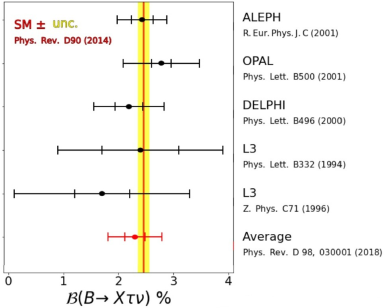
# $B \to K\nu\bar{\nu}$ at Belle II

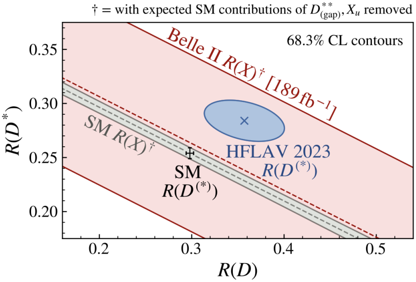
| Source | Correction | Uncertainty type | Uncertainty size | Impact on $\mu$ |
|---|---|---|---|---|
| Normalization of continuum and $B\bar{B}$ background | — | Global, 7 NP | 50% | 0.87 |
| Leading $B$-decays branching fractions | — | Shape, 5 NP | $O(1\%)$ | 0.22 |
| Branching fraction for $B^+ \to K^+ K_L^0 K_L^0$ | $q^2$ dependent $O(100\%)$ | Shape, 1 NP | 20% | 0.48 |
| $p$-wave component for $B^+ \to K^+ K_S^0 K_L^0$ | $q^2$ 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 | $p, \theta$ 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 |
| $K_L^0$ 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 |



# $R(X_{\tau/\ell})$ at Belle II

- Main backgrounds from hadrons misidentiied as leptons and leptons originating from charmed hadrons
  - Suppressed $\mu$ fakes from $\pi$ 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 $p_\ell^B$ sample



# $R(X_{\tau/\ell})$ at Belle II

| Source | Uncertainty [%] | | |
|---|---|---|---|
| | $e$ | $\mu$ | $\ell$ |
| 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

# $B^0 \to \pi^- \ell^+ \nu_\ell$ 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 |
| $\rho$ 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 |
| $\rho$ 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$^{-1}$)

# $B^0 \to \eta' K^0_S$, $B^0 \to K^0_S\pi^0\gamma$, 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 |
| $C_{\mathrm{BDT}}$ mismodeling | 0.004 | 0.010 |
| Signal and background modeling | 0.020 | 0.014 |
| Observable correlations | 0.008 | 0.001 |
| $\Delta t$ resolution fixed parameters | 0.005 | 0.009 |
| $\Delta t$ resolution model | 0.004 | 0.019 |
| Flavor tagging | 0.007 | 0.004 |
| $\tau_{B^0}$ and $\Delta m_d$ | $< 0.001$ | 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 $\Upsilon(4S)$ 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 | $\pm0.017$ | $\pm0.015$ | $\pm0.083$ | $\pm0.047$ |
| Vertex measurement | $\pm0.021$ | $\pm0.009$ | $\pm0.023$ | $\pm0.036$ |
| Flavor tagging | $\pm0.005$ | $^{+0.012}_{-0.009}$ | $^{+0.008}_{-0.009}$ | $^{+0.013}_{-0.009}$ |
| Signal modeling | $\pm0.003$ | $\pm0.003$ | $\pm0.032$ | $\pm0.013$ |
| $\Delta t$ resolution function | $\pm0.014$ | $\pm0.009$ | $\pm0.031$ | $\pm0.013$ |
| $\tau_{B^0}$ and $\Delta m_d$ | $< 0.001$ | $< 0.001$ | $\pm0.003$ | $< 0.001$ |
| $B\bar{B}$ background asym. | $^{+0.007}_{-0.008}$ | $\pm0.011$ | $^{+0.030}_{-0.026}$ | $^{+0.049}_{-0.051}$ |
| Tag-side interference | $< 0.001$ | $-0.002$ | $+0.001$ | $+0.001$ |
| Total | $\pm0.032$ | $^{+0.026}_{-0.025}$ | $^{+0.102}_{-0.100}$ | $\pm0.080$ |

| Source | $\mathcal{B}$ | $\mathcal{A}_{CP}$ |
|---|---|---|
| $\pi^0$ 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