Recent Belle II results and projections

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on behalf of the Belle II collaboration

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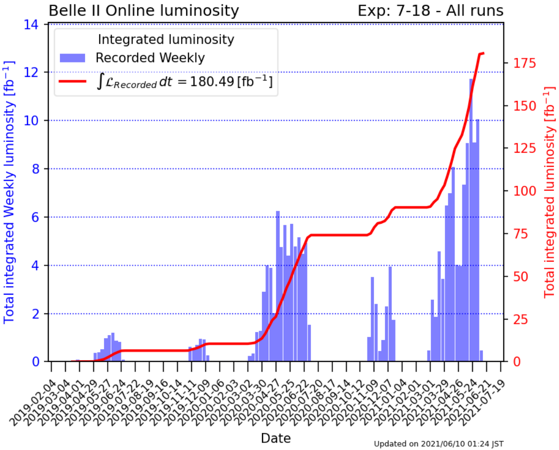
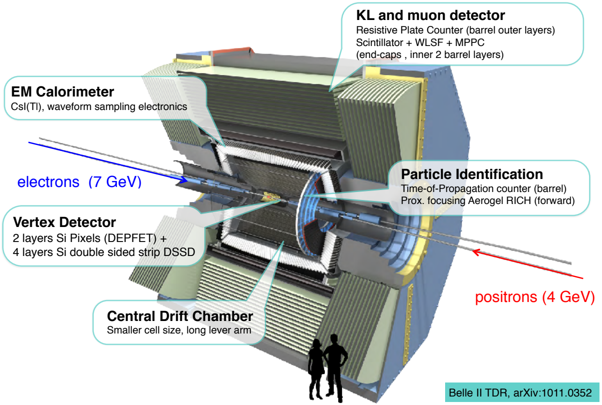
Introduction

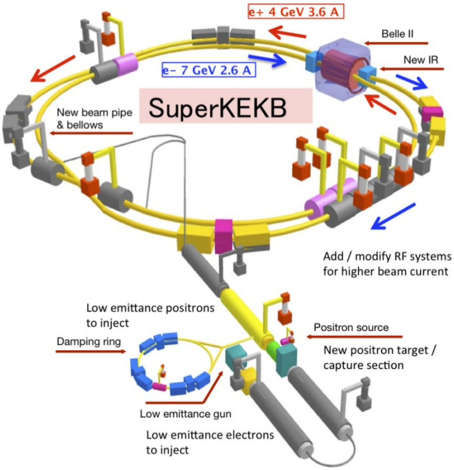


- data-taking started in 2018
- three journal publications
  - "Measurement of the integrated luminosity of the Phase 2 data of the Belle II experiment" (2020 Chinese Phys. C 44 021001)
  - "Search for an invisibly decaying Z' boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ + missing energy final states" (Phys. Rev. Lett. 124, 141801 (2020))
  - "Search for axion-like particles produced in e^+e^- collisions at Belle II" (Phys. Rev. Lett. 125, 161806 (2020))
- many performance studies + rediscovery analyses
- latest published analyses based on up to 72 fb^{-1}

The Belle II experiment

- asymmetric collision of e^+e^-
- center-of-mass energy mostly at $\Upsilon(4S)$ resonance
- $\Upsilon(4S) \to B^+B^-$ (∼51.5 %), $\Upsilon(4S) \to B^0\overline{B}^0$ (∼48.5 %)





Belle II TDR, arXiv:1011.0352

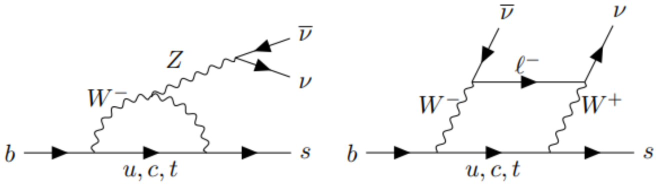
Benefits of Belle II

- e^+e^- collisions very clean compared to pp collisions
- low background environment allows reconstruction of final states containing photons from π^0, $\rho^\pm$, η
- excellent flavor tagging
- symmetric flavor production + (almost) no charged reconstruction asymmetry
- low track multiplicity and detector occupancy $\Rightarrow$ high reconstruction efficiency and very low trigger bias
- good vertex resolution thanks to Lorentz boost of e^+e^- system
- delivered luminosity via Bhabha scattering $\Rightarrow$ absolute branching fraction measurements
- initial state perfectly known $\Rightarrow$ analyses of missing mass
- production of large sample of charm mesons and τ leptons as well

Search for $B^+ \to K^+ \nu\overline{\nu}$ decays using an inclusive tagging method at Belle II

arXiv:2104.12624 (submitted to PRL)

- FCNC suppressed in standard model
- lower theoretical uncertainties in $b \to s\nu\overline{\nu}$ than in $b \to s\ell^+\ell^-$



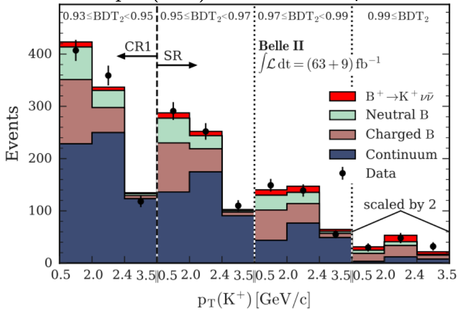
(a) Penguin diagram (b) Box diagram

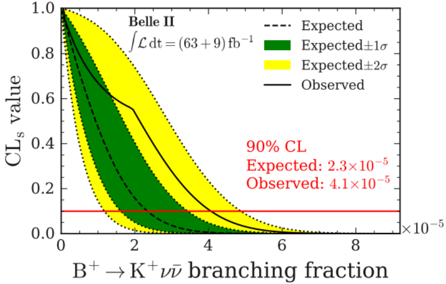
- challenge: two (undetectable) neutrinos in the final state
  - in the past: reconstruct second B-meson to constrain properties of signal B-meson
  - here: use inclusive tagging method $\Rightarrow$ four times higher signal reconstruction efficiency
- signal K^+: track with highest transverse momentum + ≥ 1 hit in pixel detector + PID wrt π
- remaining tracks and neutral clusters in calorimeter define rest of event $\Rightarrow$ missing momentum

Search for $B^+ \to K^+ \nu\bar{\nu}$ decays using an inclusive tagging method at Belle II

arXiv:2104.12624 (submitted to PRL)

- train BDT using equal number of candidates of each of the seven dominant background sources
  - other decays of charged and neutral B-mesons, u, d, s, and c continuum, $e^+e^- \to \tau^+\tau^-$
- event shape variables like Fox-Wolfram moment R_1 (momentum imbalance in event) most discriminating among 51 variables
- mismodelling of input variable distributions corrected via event weights, validated using off-resonance data
- fit in bins of p_T (K^+) and BDT output





Study of $B \to D^{(*)}h$ decays using 62.8 fb^{-1} of Belle II data arXiv:2104.03628

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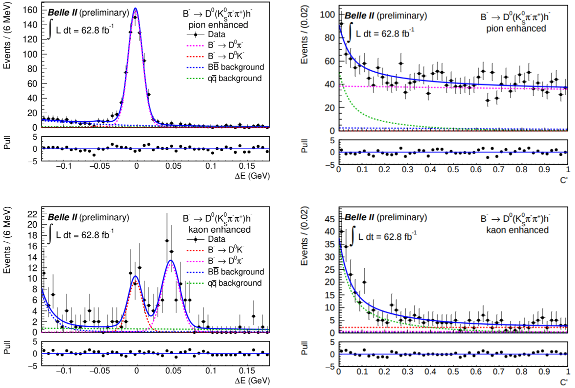
- $B^- \to D^0(\to K_S^0\pi^+\pi^-)K^-$ most sensitive $B \to Dh$ mode to determine CKM angle ϕ_3
- BDT to improve K_S^0 purity
- continuum suppression via BDT
- simultaneously fit $B \to Dh$ $(h = \pi, K)$ samples
- fit ΔE distribution to extract signal yields
- for $B^- \to D^0(\to K_S^0\pi^+\pi^-)K^-$ fit transformed BDT output as well
- measure ratios $R = \frac{\Gamma(B \to DK)}{\Gamma(B \to D\pi)}$

R [%]	$B^- \to D^0(\to K^-\pi^+)h^-$	$B^- \to D^0(\to K_S^0\pi^+\pi^-)h^-$	$\bar{B}^0 \to D^+h^-$
Belle II	$7.66 \pm 0.55\,^{+0.11}_{-0.08}$	$6.32 \pm 0.81\,^{+0.09}_{-0.11}$	$9.22 \pm 0.58 \pm 0.09$
LHCb	$7.77 \pm 0.04 \pm 0.07$	$7.77 \pm 0.04 \pm 0.07$	$8.22 \pm 0.11 \pm 0.25$

- good agreement with LHCb but more data needed



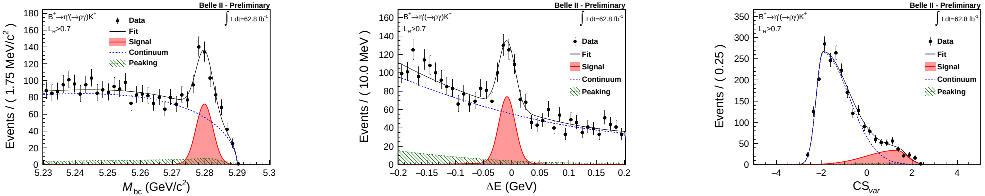
- significant cross-feed contribution but energy resolution improved with respect to Belle $\Rightarrow$ higher sensitivity

Measurement of the branching fractions of $B \to \eta' K$ decays using 2019/2020 Belle II data arXiv:2104.06224

- rare charmless hadronic B decay mediated via hadronic penguin diagram
  - possible to probe beyond standard model contributions with $\sin 2\beta$ measurement of $B^0 \to \eta' K_S^0$
- reconstruction via $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho(\to \pi^+\pi^-)\gamma$
  - high candidate multiplicity resolved via best B vertex probability
- continuum suppression validated on off-resonance data
- unbinned maximum likelihood fit to beam-constrained mass M_{bc}, energy difference ΔE, and BDT output

$$\mathcal{B}(B^+ \to \eta' K^+) = \left(63.4^{+3.4}_{-3.3}\,(\text{stat}) \pm 3.2\,(\text{syst})\right) \cdot 10^{-6} \qquad \text{world average} : (70.4 \pm 2.5) \cdot 10^{-6}$$

$$\mathcal{B}(B^0 \to \eta' K^0) = \left(59.9^{+5.8}_{-5.5}\,(\text{stat}) \pm 2.9\,(\text{syst})\right) \cdot 10^{-6} \qquad \text{world average} : (66 \pm 4) \cdot 10^{-6}$$



Results on the $K\pi$ puzzle

- significant difference between direct CP-violating asymmetries in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$
- large hadronic uncertainties
- isospin sum rule for $B \to K\pi$ decays

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

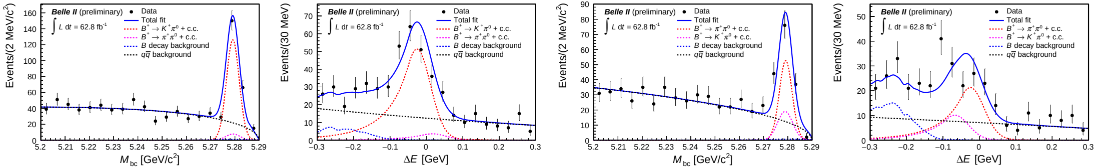
- null test of SM ($I_{K\pi} = 0$) in the limit of isospin symmetry and no electroweak penguin contributions
- "First search for direct CP-violating asymmetry in $B^0 \to K^0\pi^0$ decays at Belle II" (arXiv:2104.14871)
- "Measurements of branching fractions and direct CP-violating asymmetries in $B^+ \to K^+\pi^0$ and $\pi^+\pi^0$ decays using 2019 and 2020 Belle II data" (arXiv:2105.04111)
- fit of energy difference ΔE and modified beam-constrained mass M_{bc}
- BDT with 39 variables to suppress continuum background validated with $B^+ \to \overline{D}^0(\to K^+\pi^-)\pi^+$
  - BDT output optimized using $S/\sqrt{S+B}$

Branching fractions and $\mathcal{A}_{CP}$ in $B^+ \to K^+\pi^0$ and $\pi^+\pi^0$ decays arXiv:2105.04111

- BDT rejects 99.3 %(99.6 %) of background at signal efficiency of 54.6 %(44.0 %) for $K^+\pi^0(\pi^+\pi^0)$
- in events with multiple candidates kinematic-fit quality used to select best candidate

$$\mathcal{P}^i_{\mathrm{j}}(M_{\mathrm{bc}},\Delta E) = \frac{1}{2}(1 - q_i \cdot \mathcal{A}_{\mathrm{raw}}) \times \mathcal{P}_{\mathrm{j}}(M_{\mathrm{bc}},\Delta E) \qquad \text{with} \quad \mathcal{A}_{\mathrm{raw}} = \frac{N_{B^-} - N_{B^+}}{N_{B^-} + N_{B^+}}$$

- simultaneous fit for $B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$ yields
  - fraction of signal and cross-feed constrained from simulation



Branching fractions and $\mathcal{A}_{CP}$ in $B^+ \to K^+\pi^0$ and $\pi^+\pi^0$ decays arXiv:2105.04111

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$$\mathcal{B}_{B^\pm\to h^\pm\pi^0} = \frac{N_{B^+\to h^+\pi^0}}{\varepsilon_{h^+\pi^0}\times\mathcal{R}^+_{\text{PID}}\times(1-\mathcal{A}_{\text{raw}})\times N_{B\bar{B}}} + \frac{N_{B^-\to h^-\pi^0}}{\varepsilon_{h^-\pi^0}\times\mathcal{R}^-_{\text{PID}}\times(1+\mathcal{A}_{\text{raw}})\times N_{B\bar{B}}}$$

- signal efficiency ε, data-MC PID ratio $\mathcal{R}_{\text{PID}}$, 35.8M $B\bar{B}$ pairs

$$\mathcal{B}(B^+\to K^+\pi^0) = [11.9^{+1.1}_{-1.0}\,(\text{stat}) \pm 1.6\,(\text{syst})]\cdot 10^{-6} \qquad \text{world average}: (12.9\pm 0.5)\cdot 10^{-6}$$

$$\mathcal{B}(B^+\to \pi^+\pi^0) = [5.5^{+1.0}_{-0.9}\,(\text{stat}) \pm 0.7\,(\text{syst})]\cdot 10^{-6} \qquad \text{world average}: (5.5\pm 0.4)\cdot 10^{-6}$$

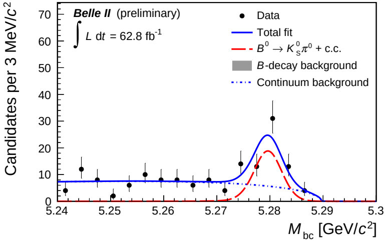
- largest systematic uncertainty from π^0 reconstruction efficiency
- account for detection asymmetry of $K^\pm/\pi^\pm$: $\mathcal{A}_{CP} = \mathcal{A}_{\text{raw}} - \mathcal{A}_{\text{det}}$
  - $\mathcal{A}(K) = \mathcal{A}(K\pi) - \mathcal{A}(K^0_S\pi) + \mathcal{A}(K^0_S)$ / $\mathcal{A}(\pi) = \mathcal{A}(K^0_S\pi) - \mathcal{A}(K^0_S)$
  - determined with $D^+\to K^0_S\pi^+$ and $\overline{D}^0\to K^+\pi^-$

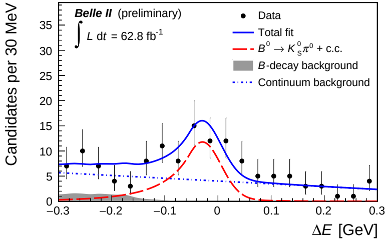
$$\mathcal{A}_{K^+\pi^0} = -0.09\pm 0.09\,(\text{stat})\pm 0.03\,(\text{syst})$$

$$\mathcal{A}_{\pi^+\pi^0} = -0.04\pm 0.17\,(\text{stat})\pm 0.06\,(\text{syst})$$

- largest systematic uncertainty from detection asymmetry and background modeling

Branching fraction of $B^0 \to K^0\pi^0$ arXiv:2104.14871





- M_{bc}: double Gaussian + Argus distribution (phase-space driven continuum background model)
- ΔE: Crystal Ball model + linear function
- two-dimensional kernel distribution to account for non-signal B decays ($B^+ \to K^0\rho^+$, $B^+ \to K^{*+}\pi^0$)

$$\mathcal{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}\,(\text{stat}) \pm 1.2\,(\text{syst})] \cdot 10^{-6} \qquad \text{world average} : (9.9 \pm 0.5) \cdot 10^{-6}$$

- largest systematic uncertainty from π^0 reconstruction efficiency

CP-violating asymmetry of $B^0 \to K^0\pi^0$ arXiv:2104.14871

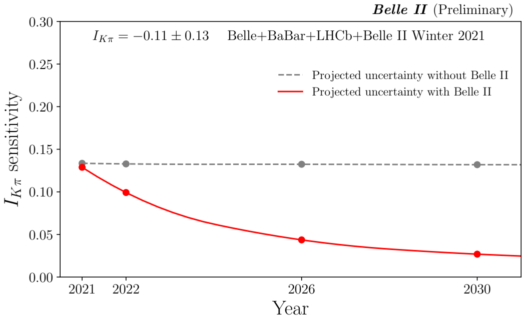
- constrain signal-to-background fraction to results from initial yield fit
- extend fit to quark flavor q

$$\mathcal{P}_{\text{sig}}(q) = \frac{1}{2}\Big(1 + q\cdot(1-2\omega_r)\cdot(1-2\chi_d)\mathcal{A}_{K^0\pi^0}\Big)$$

- $\chi_d = 0.1858 \pm 0.0010$ is time-integrated mixing parameter
- background assumed to be flavor-symmetric

$$\mathcal{A}_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}\,(\text{stat}) \pm 0.04\,(\text{syst})$$

- expect gain in signal efficiency and overall sensitivity by relaxing continuum suppression requirement and incorporate BDT output in fit



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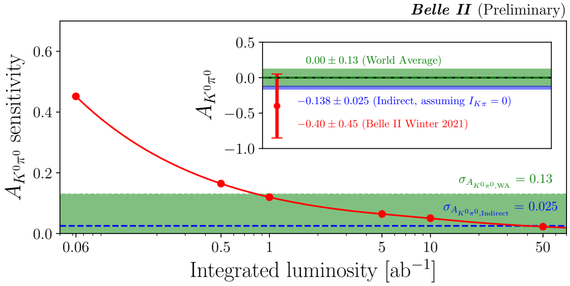
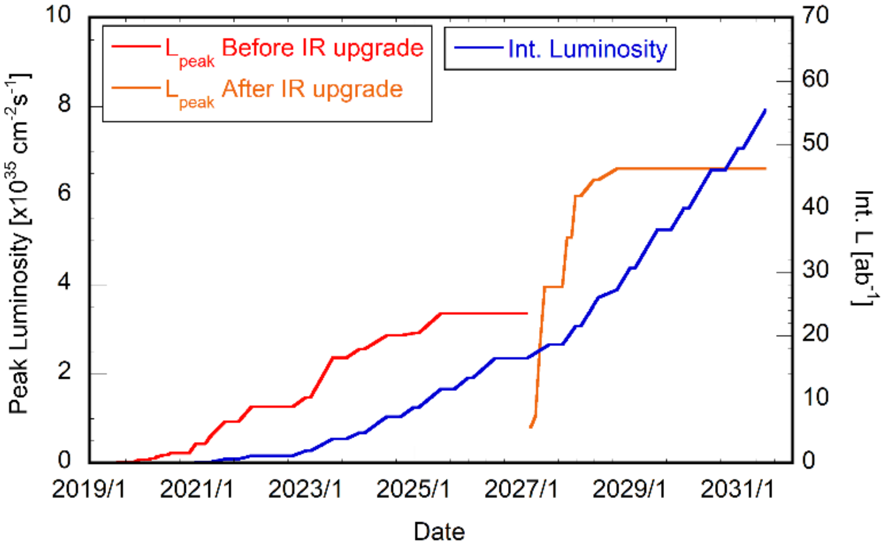


Projected data-taking at Belle II



Conclusion

- early days of the experiment
- data set still small: results shown today based on 62.8 fb^{-1}
  - $\sim$120 fb^{-1} for summer publications
- new analysis ideas like in $B^+ \to K^+ \nu\overline{\nu}$
- unique analysis opportunities like in $B^0 \to K^0 \pi^0$
- systematic uncertainties dominated by statistical precision of control modes, *e.g.* π^0 efficiency
- stay tuned for new results in the near future

Backup

Prospects for charm physics

	Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb/BESIII	vs Belle	Anomaly	NP
●	$D^0 \to K_s \pi^+ \pi^-$	x, y,$\|q/p\|$	⋆⋆⋆	20	⋆⋆	⋆⋆⋆	-	⋆⋆
●	$D^0 \to K_S^0 K_S^0$	A_{CP}	⋆⋆	>50	⋆⋆⋆	⋆⋆⋆	⋆	⋆
●	$D^0 \to \pi^0 \pi^0$	A_{CP}	⋆⋆⋆	>50	⋆⋆⋆	⋆⋆	⋆	⋆
●	$D^+ \to \pi^+ \pi^0$	A_{CP}	⋆⋆	>50	⋆⋆⋆	⋆⋆	⋆	⋆⋆
●	$D_s \to \ell^+ \nu$	f_{D_s}	⋆⋆⋆	1-5	⋆⋆⋆	⋆	-	⋆⋆
●	$D^0 \to V \gamma$	A_{CP}	⋆	>50	⋆⋆	⋆⋆	⋆⋆	⋆⋆
●	$D^0 \to \gamma\gamma$	$Br.$	⋆	>50	⋆⋆	⋆⋆	⋆⋆	⋆⋆
●	$D^0 \to \nu\bar{\nu}$	$Br.$	⋆⋆⋆	>50	⋆⋆⋆	⋆⋆	⋆⋆⋆	⋆⋆⋆
●	$D \to \ell^+ \nu$	f_D	⋆⋆⋆	1-5	⋆	⋆	-	⋆⋆

Prospects for CPV measurements

	Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
●	$B \to J/\psi K_S^0$	ϕ_1	⋆⋆⋆	5-10	⋆⋆	⋆⋆	⋆	⋆
●	$B \to \phi K_S^0$	ϕ_1	⋆⋆	>50	⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \eta' K_S^0$	ϕ_1	⋆⋆	>50	⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \rho^\pm \rho^0$	ϕ_2	⋆⋆⋆	>50	⋆	⋆⋆⋆	⋆	⋆
●	$B \to J/\psi \pi^0$	ϕ_1	⋆⋆⋆	>50	⋆	⋆⋆⋆	-	-
●	$B \to \pi^0 \pi^0$	ϕ_2	⋆⋆	>50	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆
●	$B \to \pi^0 K_S^0$	S_{CP}	⋆⋆	>50	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆

Prospects for electro-weak penguins

Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to K^{(*)}\nu\nu$	$Br., F_L$	★★★	>50	★★★	★★★	★	★★
$B \to X_{s+d}\gamma$	A_{CP}	★★★	>50	★★★	★★★	★	★★
$B \to X_d\gamma$	A_{CP}	★★	>50	★★★	★★★	-	★★
$B \to K_S^0\pi^0\gamma$	$S_{K_S^0\pi^0\gamma}$	★★	>50	★★	★★★	★	★★★
$B \to \rho\gamma$	$S_{\rho\gamma}$	★★	>50	★★★	★★★	-	★★★
$B \to X_s\ell^+\ell^-$	$Br.$	★★★	>50	★★★	★★	★★	★★★
$B \to X_s\ell^+\ell^-$	R_{X_s}	★★★	>50	★★★	★★★	★★	★★★
$B \to K^{(*)}e^+e^-$	$R(K^{(*)})$	★★★	>50	★★	★★★	★★★	★★★
$B \to X_s\gamma$	$Br.$	★★	1-5	★★★	★	★	★★
$B_{d,(s)} \to \gamma\gamma$	$Br., A_{\text{CP}}$	★★	>50	★★	★★	-	★★
$B \to K^*e^+e^-$	P_5'	★★	>50	★★★	★★	★★★	★★★
$B \to K\tau\ell$	$Br.$	★★★	>50	★★	★★★	★★	★★★

Prospects for hadronic B physics measurements

	Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
●	$B \to \pi^0 K^0$	A_{CP}, $I_{K\pi}$	★★	>50	★★★	★★★	★★★	★★
●	$B \to \rho K$	A_{CP}, $I_{K\rho}$	★	>50	★★	★★★	-	★★
●	$B \to \ell\nu\gamma$	λ_B	★★	>50(10)	★★★	★★★	★	★★
●	$B \to \rho K^*$	f_L	★★	>50	★★	★★	-	★★★
●	$B \to K^+K^-/\pi^+\pi^-$	$Br.$, A_{CP}	★★	>50	★	★★★	★★	★★
●	$B \to K\pi\pi, KKK$	A_{CP}	★★	>50	★★	★	★★★	★
●	$B_s \to K^0\overline{K}^0$	Lifetime	★	>5	★★	★★★	-	★★

Prospects for lepton flavor violation measurements

Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb/BESIII	vs Belle	Anomaly	NP
$\tau \to \mu\gamma$	$Br.$	★★★	>50	★★★	★★★	★	★★★
$\tau \to \ell\ell\ell$	$Br.$	★★★	>50	★★★	★★★	★	★★★
$\tau \to K^0_S\pi\nu$	$\lvert\Im(\eta_s)\rvert$	★★★	>50	★★★	★★★	★★	★★
$e^+e^- \to \gamma A'(\to \text{invisible})$	σ	★★★	>50	★★★	★★★	★	★★★
$e^+e^- \to \gamma A'(\to \ell^+\ell^-)$	σ	★★★	>50	★★★	★★★	★	★★★
$e^+e^- \to \gamma a'(\to \gamma^+\gamma^-)$	σ	★★★	>50	★★★	★★★	★	★★★
$\Upsilon(1S) \to$ invisible	★★★	$Br.$	>50	★★★	★★★	★	★★★
$\chi_{b0}(1P) \to \tau\tau$	★★★	$Br.$	>50	★★★	★★★	★	★★★
π form factor	$g-2$	★★	-	★★★	★★	★★	★★★
ISR $e^+e^- \to \pi\pi$ g-2	$g-2$	★★	-	★★★	★★★	★★	★★★

Prospects for semi-leptonic measurements

Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to \pi \ell \nu_\ell$	$\lvert V_{ub}\rvert$	$\star\star\star$	10-20	$\star\star\star$	$\star\star\star$	$\star\star$	$\star$
$B \to X_u \ell \nu_\ell$	$\lvert V_{ub}\rvert$	$\star\star$	2-10	$\star\star\star$	$\star\star$	$\star\star\star$	$\star$
$B \to \tau \nu$	$Br.$	$\star\star\star$	>50 (2)	$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$B \to \mu \nu$	$Br.$	$\star\star\star$	>50 (5)	$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$B \to D^{(*)} \ell \nu_\ell$	$\lvert V_{cb}\rvert$	$\star\star\star$	1-10	$\star\star\star$	$\star\star$	$\star\star$	$\star$
$B \to X_c \ell \nu_\ell$	$\lvert V_{cb}\rvert$	$\star\star\star$	1-5	$\star\star\star$	$\star\star$	$\star\star$	$\star\star$
$B \to D^{(*)} \tau \nu_\tau$	$R(D^{(*)})$	$\star\star\star$	5-10	$\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$
$B \to D^{(*)} \tau \nu_\tau$	P_τ	$\star\star\star$	15-20	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star\star$
$B \to D^{**} \ell \nu_\ell$	$Br.$	$\star$	-	$\star\star$	$\star\star\star$	$\star\star$	-