Measurements of hadronic *B* decay rates at Belle and Belle II

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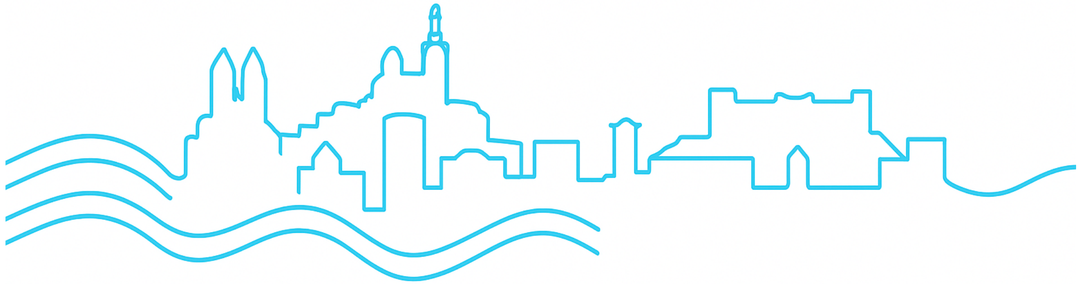
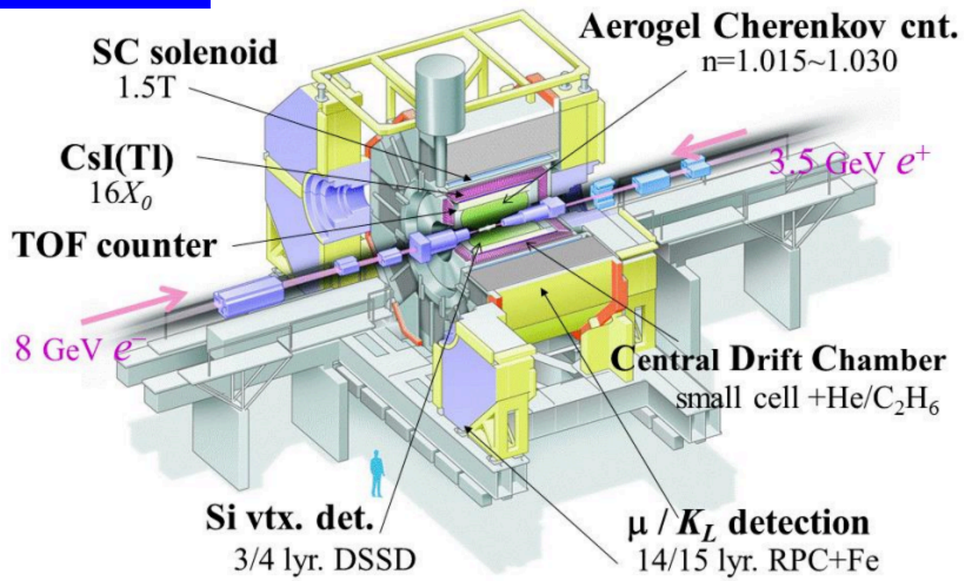
on behalf of the Belle II Collaboration

EPS-HEP 2025, Marseille
July 7-11, 2025



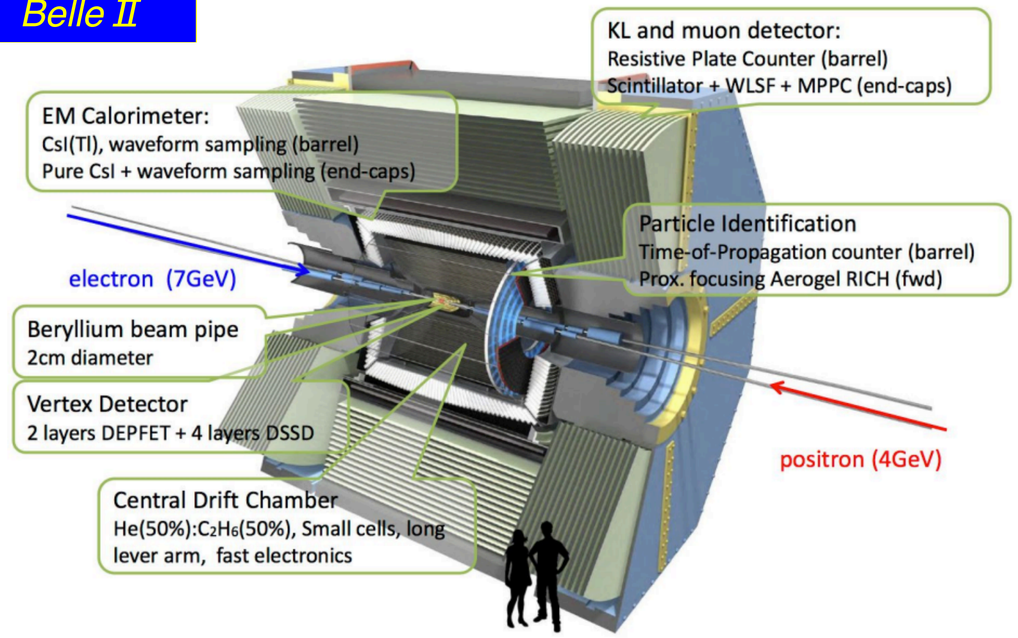
Belle and Belle II detectors

BELLE



- Operated from 1999 to 2010.
- Asymmetric e^+e^- collider at KEKB.
- Collected 1/ab of data, 711/fb at $\Upsilon(4S)$.

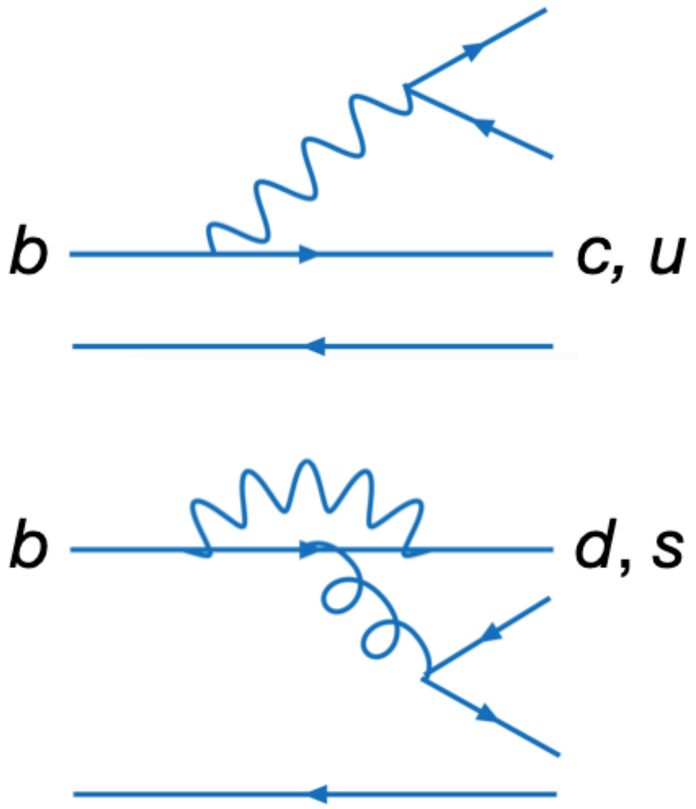
Belle II



- Start physics run in 2019.
- Asymmetric e^+e^- collider at SuperKEKB.
- World record instantaneous luminosity: **$5.1 \times 10^{34} cm^{-2} s^{-1}$**.
- Collected **576/fb** so far. ~486/fb at $\Upsilon(4S)$.
- Target: 50/ab data!

Hadronic B decays

$b \to c, u$ tree diagrams and $b \to d, s$ penguin diagrams.



Measure all three CKM angles:

- $\phi_1(\beta)$ via $B^0 \to J/\psi K_S^0, \eta(')K_S^0$ …
- $\phi_2(\alpha)$ via $B \to \rho\rho, B \to \pi\pi$ isospin analysis,
- $\phi_3(\gamma)$ via $B^\pm \to DK^\pm$ with different D decays,

and decay to baryons, decay to VV, etc.

In my talk:

- ϕ_3 combination,
- $B \to \pi^0\pi^0$ for ϕ_2,
- First observation of $B \to \omega\omega$,
- First observation of $B \to \Sigma_c(2455)\Xi_c$ decays,
- Search for BNV processes.

For time-dependent CPV results: see Oskar's talk.

Analysis workflow

~20% of hadronic events from e^+e^- are $B\bar{B}$.

10 tracks/clusters on average → easy to trigger on non-biasing variables (e.g. number of tracks).

Reconstruction: all final-state particles in signal B decay.

Main backgrounds: continuum process ($e^+e^- \to q\bar{q}$); mis-identification background in B decays.

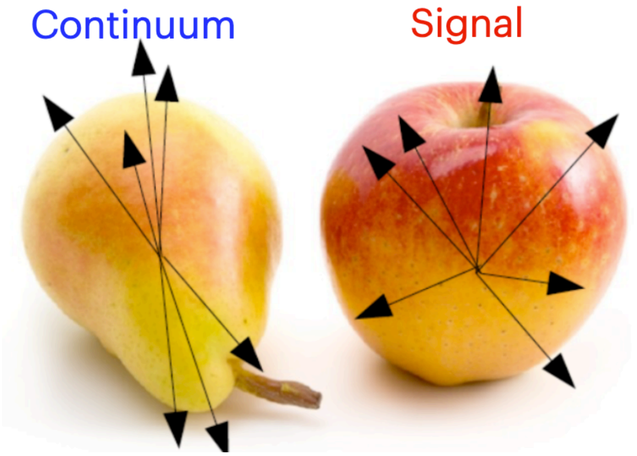
Selection: event-shape variables based classifier to suppress $q\bar{q}$ background; particle identification criteria.

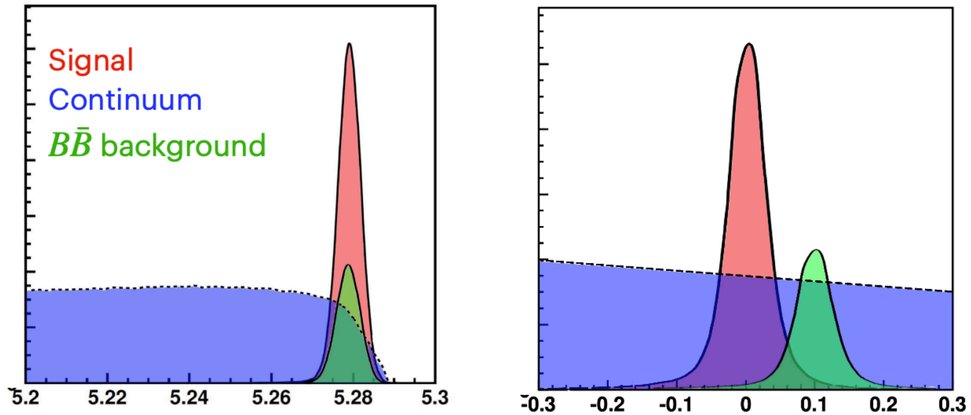
Fit: usually on ΔE, M_{bc},classifier output (C'), etc…

Systematic uncertainties: toy studies, control modes.

Validation & unblinding: validate the full analysis on a control channel; procedure frozen before opening box.

Feature in e^+e^- collider





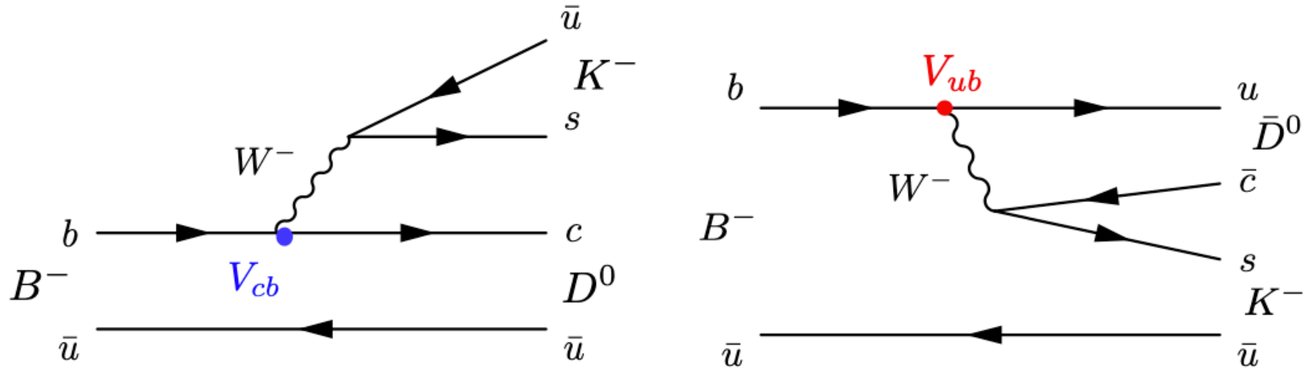
$M_{\mathrm{bc}} = \sqrt{s/4 - p_B^{*2}}$

$\Delta E = E_B^* - \sqrt{s}/2$

well-known knowledge of initial state

ϕ_3 combination

[JHEP 10(2024)143]



- Interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$, $D^0/\bar{D}^0 \to f$.
- Irreducible error in SM calculation $\sim 10^{-7}$ [JHEP 01 (2014) 051].
- W.A. $\phi_3 = (66.4^{+2.8}_{-3.0})^\circ$ [HFLAV], dominated by LHCb.

Belle/Belle II measured many different channels, via four methods.

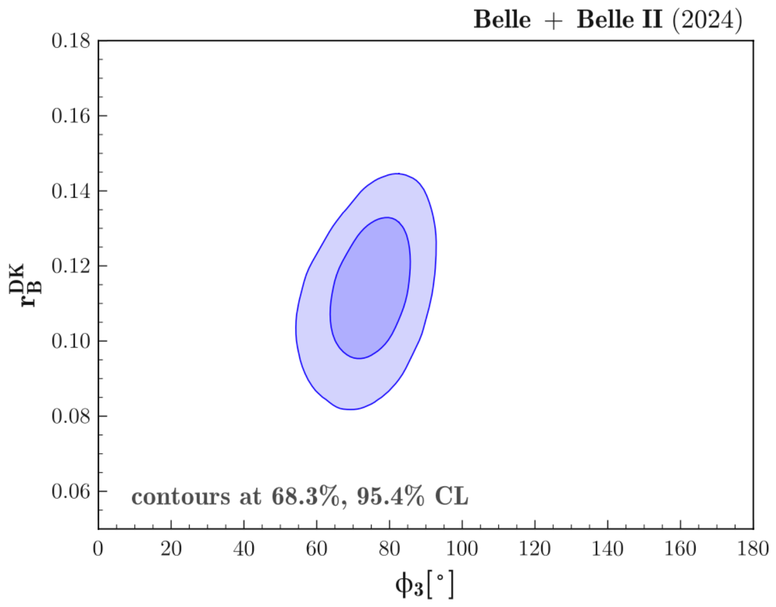
B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]	
$B^+ \to Dh^+$	$D \to K^0_S\pi^0, K^-K^+$	GLW	$711 + 189$	[JHEP 05 212 (2024)]
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	$711 + 0$	[PRL 106 231803 (2011), PRD 88 091104(2013)]
$B^+ \to Dh^+$	$D \to K^0_S K^-\pi^+$	GLS	$711 + 362$	[JHEP 09 146 (2023)]
$B^+ \to Dh^+$	$D \to K^0_S h^-h^+$	BPGGSZ (m.i.)	$711 + 128$	[JHEP 02 063 (2022)]
$B^+ \to Dh^+$	$D \to K^0_S\pi^-\pi^+\pi^0$	BPGGSZ (m.i.)	$711 + 0$	[JHEP 10 178 (2019)]
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D \to K^0_S\pi^0, K^0_S\phi, K^0_S\omega, K^-K^+, \pi^-\pi^+$	GLW	210+0	[PRD 73 051106 (2006)]
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D\gamma, D \to K^0_S\pi^-\pi^+$	BPGGSZ (m.d.)	$605 + 0$	[PRD 81 112002 (2010)]

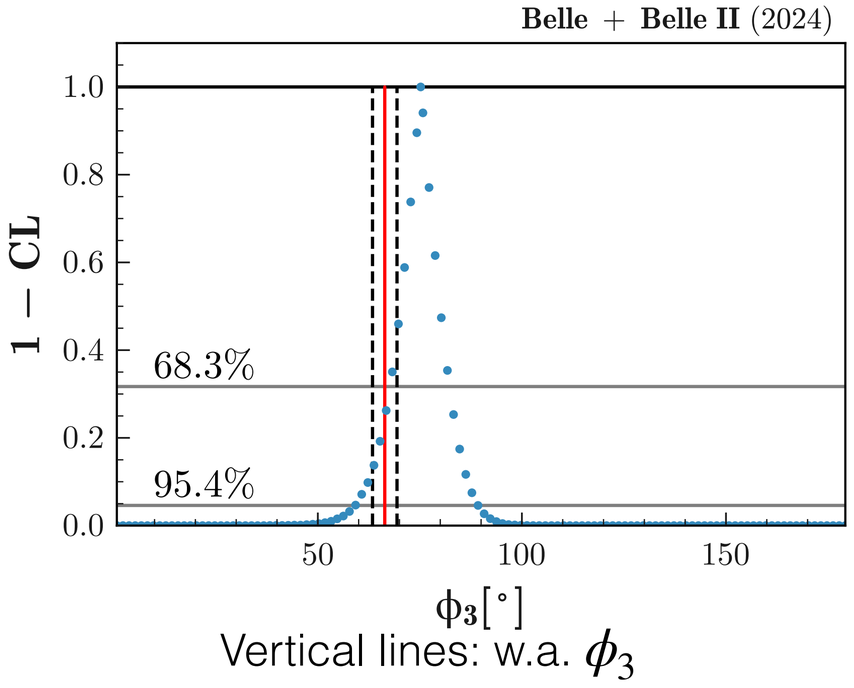
ϕ_3 combination

[JHEP 10(2024)143]

- 60 input observables and 16 parameters (including external inputs on D decay dynamics).
- P-value of the fit quality: 75%.

Parameters	$\phi_3(^\circ)$	r_B^{DK}	$\delta_B^{DK}(^\circ)$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^\circ)$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^\circ)$
Best-fit value	75.2	0.115	137.8	0.0165	347.0	0.229	342
68.3% interval	[67.7, 82.3]	[0.102, 0.127]	[128.0, 146.3]	[0.0113, 0.0220]	[337.4, 355.7]	[0.162, 0.297]	[326,356]
95.4% interval	[59, 89]	[0.089, 0.138]	[116, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[306, 371]





Vertical lines: w.a. ϕ_3

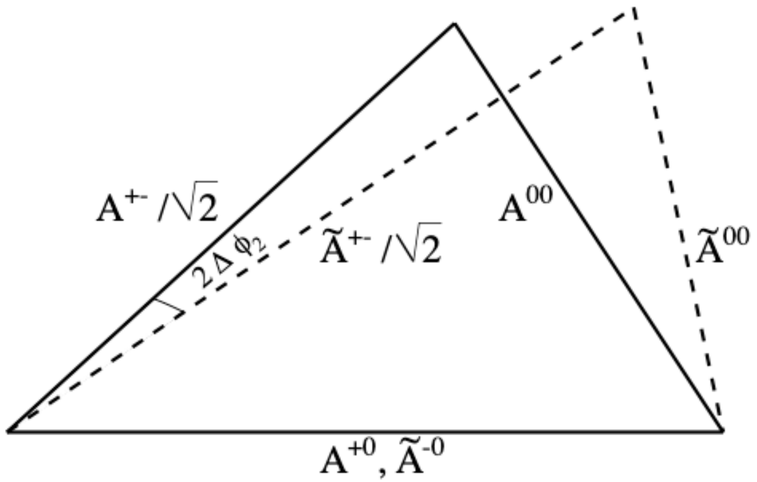
- ϕ_3 consists with w.a. within 1.1 σ.
- Expect precision 2.2/1.0° @ 10/50 ab^{-1}.

ϕ_2 results with $B \to \pi^0\pi^0$

[PRD 111, L071102 (2025)]

- The CKM angle with least precision at the moment:W.A. $\phi_2 = (84.1^{+4.5}_{-3.8})°$ [HFLAV].
- Determined using $B \to \rho\rho$, $B \to \pi\pi$ isospin analysis: using the $\mathcal{B}$ and A_{CP} to reduce hadronic uncertainties.

Check $\rho^+\rho^-$ result in Oskar's talk.



Gronau-London Isospin triangles

$B \to \pi^0\pi^0$ results w/ Run 1 data (362/fb)

- 4 γ in final state.
- Use graph-neural-network flavor tagger.
- By a four-dimensional fit on $\Delta E, M_{bc}, C_t, w_t$, measure $\mathcal{B}$ and time-integrated A_{CP}.

w_t: transformed from w (flavor tagger output) via probability integral transform.

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = \frac{N f_s}{2\,\varepsilon\, f^{00}\, N_{\Upsilon(4S)}\, \mathcal{B}(\pi^0 \to \gamma\gamma)^2},$$

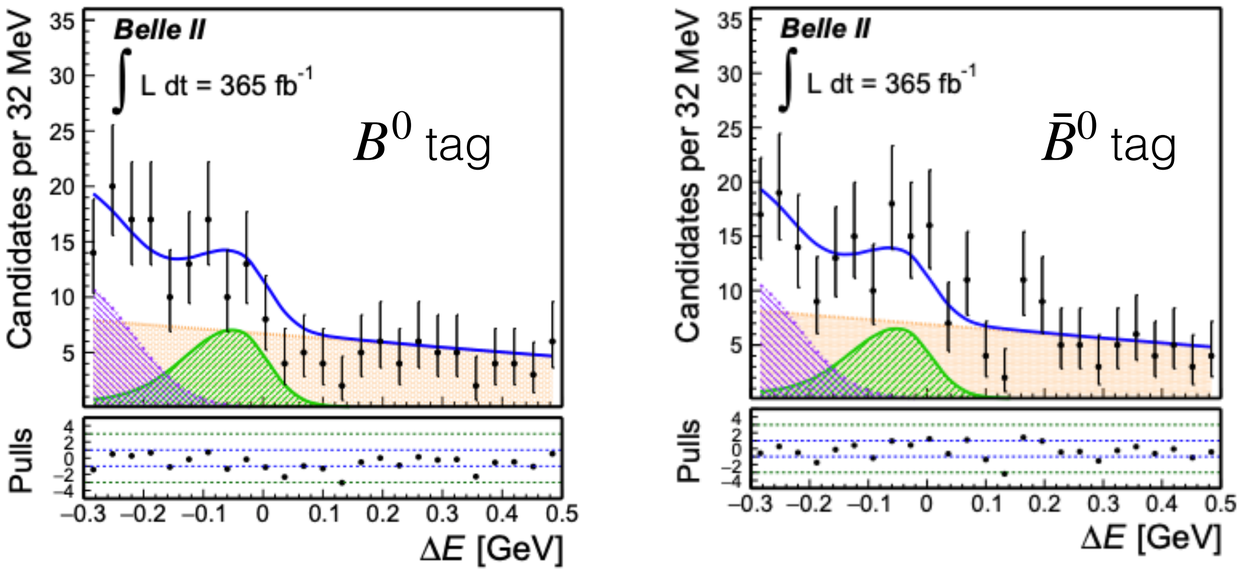
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = \frac{\Gamma(\overline{B}^0 \to \pi^0\pi^0) - \Gamma(B^0 \to \pi^0\pi^0)}{\Gamma(\overline{B}^0 \to \pi^0\pi^0) + \Gamma(B^0 \to \pi^0\pi^0)},$$

ϕ_2 results with $B \to \pi^0\pi^0$

[PRD 111, L071102 (2025)]

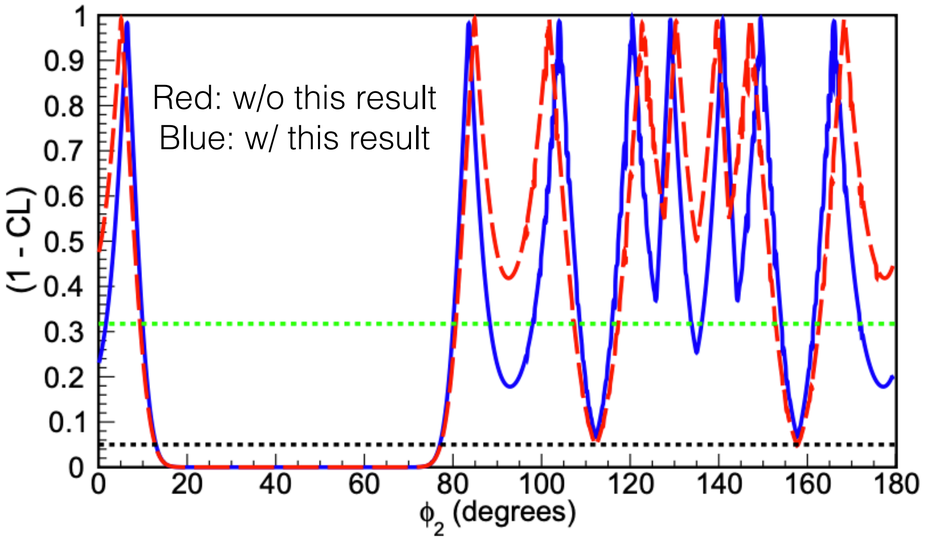
Using 362/fb, get 125 ± 20 signal yield.

- $\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.25 \pm 0.20 \pm 0.11) \times 10^{-6}$
- $A_{CP}(B^0 \to \pi^0\pi^0) = 0.03 \pm 0.30 \pm 0.04$



Clear impact on ϕ_2 from $\pi\pi$ system:

- Reduce interval @68% CL by 10°.
- 30% improvement on ϕ_2 precision.
- Check arXiv:2506.11196: a novel method to measure time-dependent CPV of $B \to \pi^0\pi^0$.

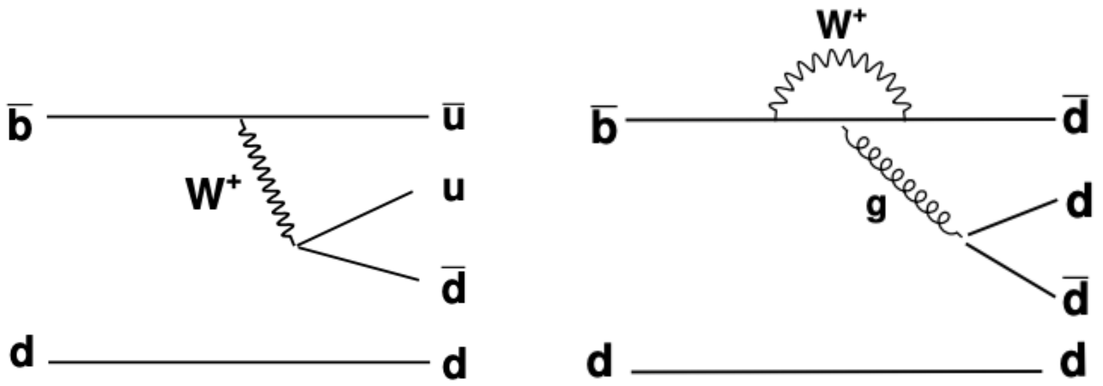


Eight solutions due to eight-fold ambiguity in isospin analysis.

$B^0 \to \omega\omega$

[PRL 133, 081801 (2024)]

- No observation before (only 4.4 σ from BaBar).
- For $B \to VV$ decay, f_L (longitudinal polarization) is interesting and sensitive to new physics.
- Possible A_{CP} from interference between tree and penguin diagrams, can contribute to ϕ_2.
- Multi theory predictions: $\mathcal{B}$ in range $(0.5 - 3) \times 10^{-6}$; f_L in range $(0.6 - 0.94)$; A_{CP} can be large as $-70\,\%$. [PRD 80, 114008 (2009); PRD 91, 054033 (2015); PRD 45, 193 (1992); PRD 73, 014024 (2006); PRD 96, 073004 (2017); CPC 45, 123103 (2022)]



Feynman diagrams of $B^0 \to \omega\omega$

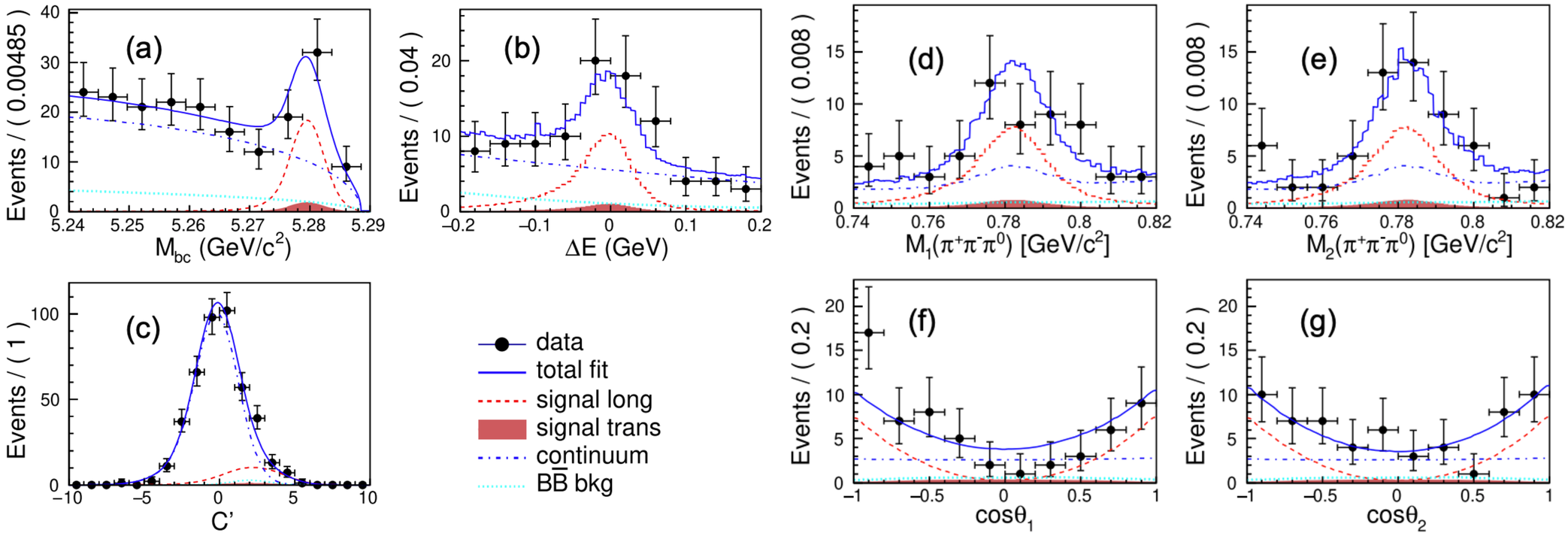
- Using Belle data sample (711/fb), measure $\mathcal{B}$, f_L and A_{CP}.
- Use flavor tagger to get tagged B's flavor.
- 7D fit to $\Delta E, M_{bc}, C', M_1(\pi^+\pi^-\pi^0), M_2(\pi^+\pi^-\pi^0), \cos(\theta_1), \cos(\theta_2)$ in each flavor bin.

Sensitive to non-ω

Sensitive to f_L

$B^0 \to \omega\omega$

[PRL 133, 081801 (2024)]

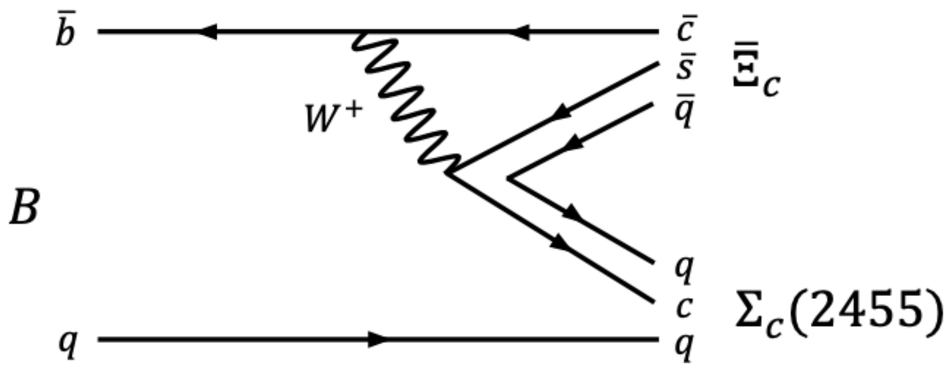


- First observation w/ 7.9 σ: $\mathscr{B} = (1.53 \pm 0.29 \pm 0.17) \times 10^{-6}$.
- First report: $f_L = 0.87 \pm 0.13 \pm 0.13$, $A_{CP} = -0.44 \pm 0.43 \pm 0.11$.
- $\mathscr{B}$ and f_L agree with next-to-leading-order perturbative QCD.
- $\mathscr{B}$ is higher than soft collinear effective theory's prediction.

First observation of $B \to \bar{\Sigma}_c(2455)\Xi_c$ decays

arXiv:2507.05094, submitted to PRD

- Baryonic *B* decays: a platform to study baryon-anti baryon production in non-perturbative QCD.
- Different theory prediction:
  - QCD sum rule : ~ 4×10^{-3} [Nucl. Phys. B 345, 137 (1990)]
  - di-quark model: O(10^{-4}) [Z. Phys. C 51, 445 (1991)]



- Use Belle and Belle II Run 1 data sample: 711/fb and 365/fb.
- 2D fit to ($M_{\bar{\Lambda}_c\pi}$, ΔE) on Belle and Belle II data simultaneously, on both $M_{\bar{\Xi}_c}$ signal and sideband regions.

[Signal channels]

$$\bar{\Lambda}_c^- \to \bar{p}K^+\pi^-/\bar{p}K_S^0(\to \pi^+\pi^-)$$
$$\bar{\Sigma}_c(2455)^{--} \to \bar{\Lambda}_c^-\pi^-$$
$$B^- \to \bar{\Sigma}_c(2455)^{--}\Xi_c^+$$
$$\Xi_c^+ \to \Xi^-\pi^+\pi^+/pK^-\pi^+$$
$$\Xi^- \to \Lambda\,(\to p\pi^-)\pi^-$$

$$\Lambda_c^- \to \bar{p}K^+\pi^-/\bar{p}K_S^0(\to \pi^+\pi^-)$$
$$\bar{\Sigma}_c(2455)^0 \to \bar{\Lambda}_c^-\pi^+$$
$$\bar{B}^0 \to \bar{\Sigma}_c(2455)^0\Xi_c^0$$
$$\Xi_c^0 \to \Xi^-\pi^+/\Lambda\,(\to p\pi^-)K^-\pi^+$$
$$\Xi^- \to \Lambda\,(\to p\pi^-)\pi^-$$

First observation of $B \to \bar{\Sigma}_c(2455)\Xi_c$ decays

arXiv:2507.05094, submitted to PRD

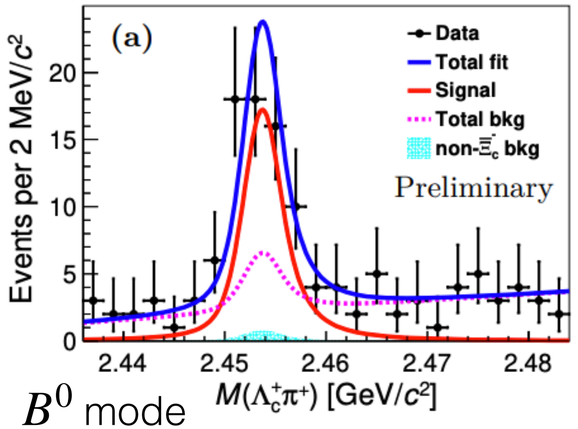
Preliminary

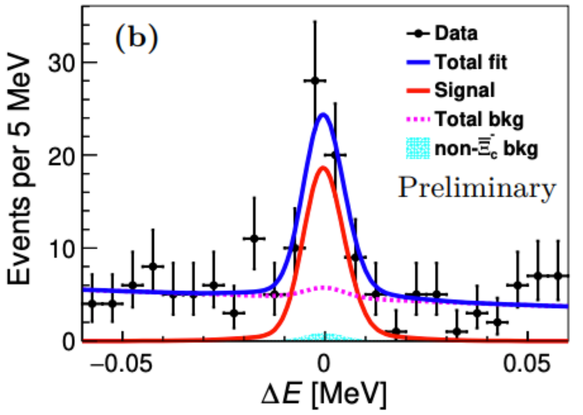
- Observe 52.8 ± 10.2 in B^- mode and 31.1 ± 7.2 in B^0 mode.
- First observation with 7.3 σ in B^- mode and 6.2 σ in B^0 mode.
- $\mathcal{B}(B^- \to \bar{\Sigma}_c(2455)^{--}\Xi_c^+) = (5.74 \pm 1.11 \pm 0.42^{+2.47}_{-1.53}) \times 10^{-4}$
- $\mathcal{B}(\bar{B}^0 \to \bar{\Sigma}_c(2455)^0\Xi_c^0) = (4.83 \pm 1.12 \pm 0.37^{+0.72}_{-0.60}) \times 10^{-4}$

*3rd uncertainties are from cited Ξ_c's BR

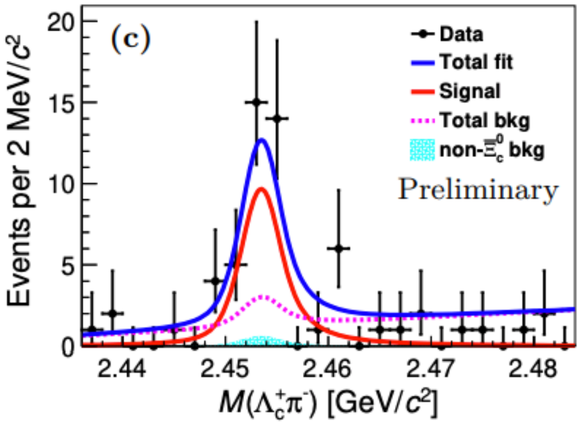
- An order of magnitude smaller than prediction w/ QCD sum rule, but consistent w/ di-quark model.
- $\mathcal{B}$ is 10 times larger than $B^+ \to \bar{\Sigma}_c(2455)^0 p$, $B^0 \to \bar{\Sigma}_c(2455)^- p$
  - ✦ Similar size of CKM matrix elements: $V_{bc} * V_{cs} \sim V_{bc} * V_{ud}$.
  - ✦ But no necessary to have 2 hard gluons [Int.J.Mod.Phys.A 21 (2006) 4209] (one possible mechanism)

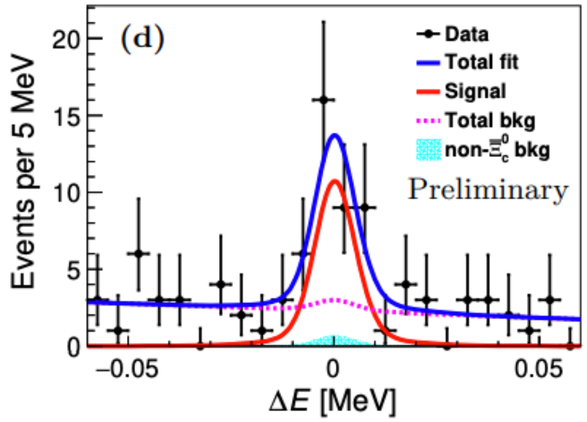
B^- mode





B^0 mode

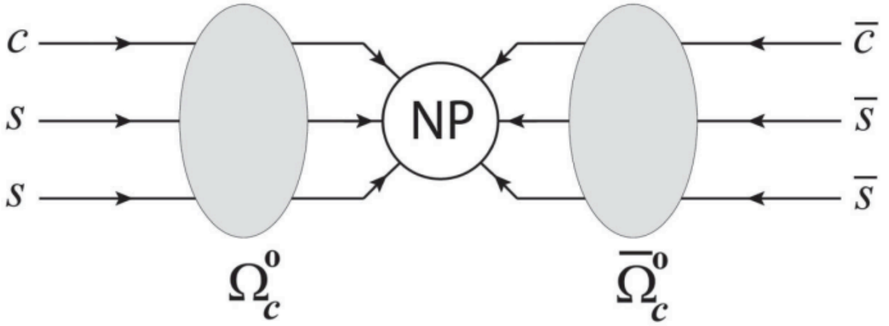




Search for BNV decay

[PRD 110, L 031102 (2024); PRL 133, 071802 (2024)]

- Baryon number violation (BNV), one of three necessary conditions for matter-antimatter asymmetry.
- No search on $B^- \to \bar{\Xi}_c^0 \bar{\Lambda}_c^-$, $B \to \bar{\Omega}_c^0 \bar{\Lambda}^0$ and $B \to \bar{\Omega}_c(2770)^0 \bar{\Lambda}^0$ yet, which can happen via : direct BNV or neutral baryon's oscillation.

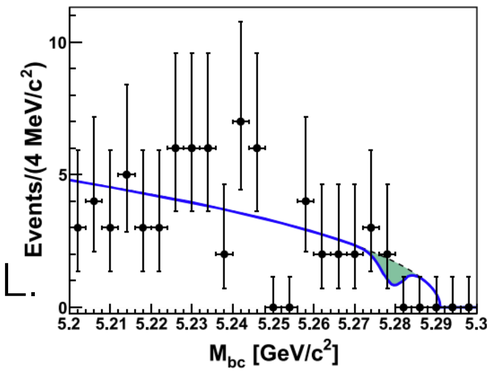


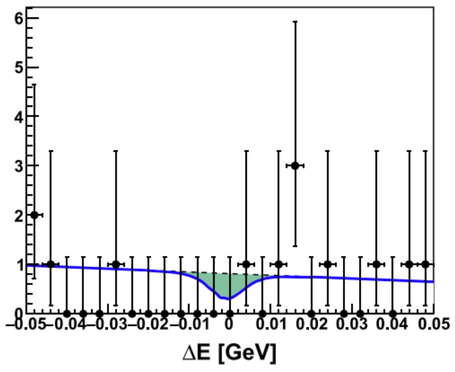
- First search using Belle data sample (711/fb).
- No signal observed.

$\mathcal{B}(B^- \to \bar{\Xi}_c^0 \bar{\Lambda}_c^-)/\mathcal{B}(B^- \to \Xi_c^0 \bar{\Lambda}_c^-) = 2.7\,\%$ @ 95 % C.L.

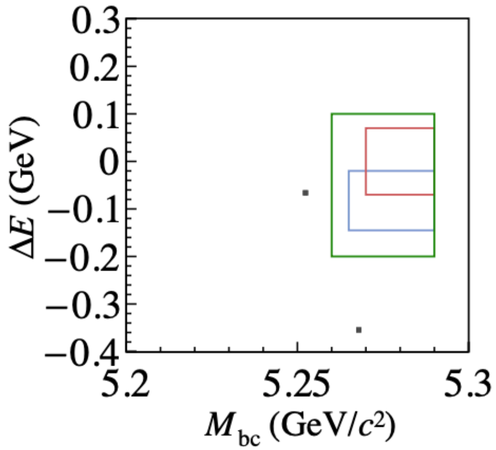
Quantity ($\times \mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)$)	Upper limit (at 95% CL)
$\mathcal{B}(B \to \bar{\Lambda}^0 \Omega_c^0)$	9.7×10^{-8}
$\mathcal{B}(B \to \bar{\Lambda}^0 \Omega_c(2770)^0)$	31.2×10^{-8}
$\mathcal{B}(B \to \bar{\Lambda}^0 \bar{\Omega}_c^0)$	9.5×10^{-8}
$\mathcal{B}(B \to \bar{\Lambda}^0 \bar{\Omega}_c(2770)^0)$	10.0×10^{-8}

SM processes are also searched.





No signal for $B^- \to \bar{\Xi}_c^0 \bar{\Lambda}_c^-$ search.



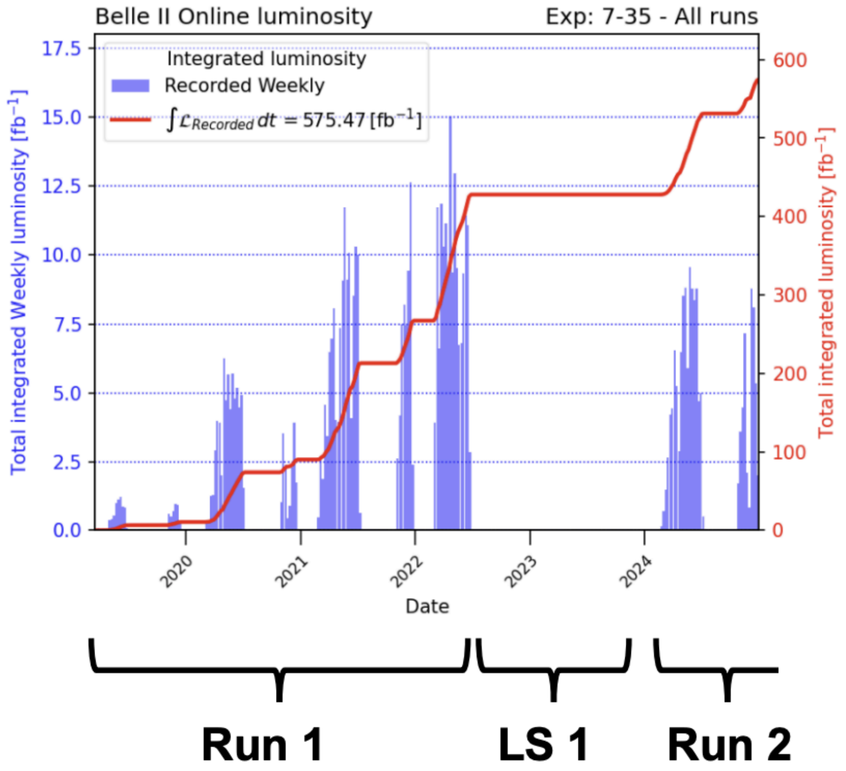
Signal regions for $B \to \bar{\Omega}_c^0 \bar{\Lambda}^0$ (red); $B \to \bar{\Omega}_c(2770)^0 \bar{\Lambda}^0$ (blue).

Summary

With Belle (711/fb) and Belle II Run 1 data (362/fb):

- ϕ_3 combination from Belle and Belle II.
- $\mathcal{B}$ and A_{CP} in $B \to \pi^0\pi^0$. Improve ϕ_2's precision.
- First observation of $B^0 \to \omega\omega$ and measurement of f_L and A_{CP}.
- First observation of $B^- \to \bar{\Sigma}_c(2455)^{--}\Xi_c^+$ and $\bar{B}^0 \to \bar{\Sigma}_c(2455)^0\Xi_c^0$.
- First search of BNV processes: $B^- \to \bar{\Xi}_c^0\bar{\Lambda}_c^-$, $B \to \bar{\Omega}_c^0\bar{\Lambda}^0$ and $B \to \bar{\Omega}_c(2770)^0\bar{\Lambda}^0$.

More results coming from Belle II! Stay tuned!



Merci!