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Belle II

Measurements of CP violation and hadronic B decays at Belle and Belle II

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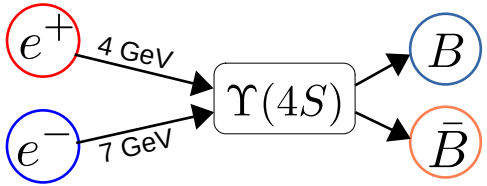
On behalf of the Belle II collaboration

Lepton-Photon 2025

Madison, Wisconsin, USA

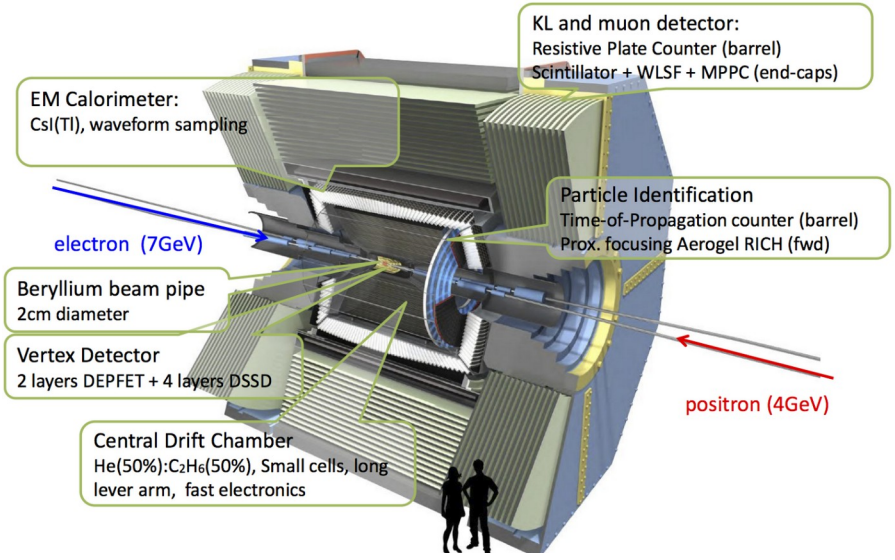
Belle (II) @ (Super)KEKB – B factories of 1st and 2nd generation

- **(Super)KEKB:** asymmetric e^+e^- collider operating nominally at $\Upsilon(4S) = 10.58$ GeV



(+ large number of D, τ !)

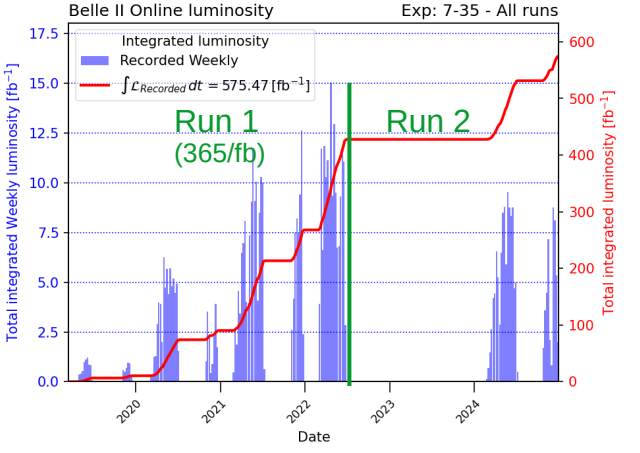
- **Belle (II):** general purpose spectrometer
  - → 4π coverage
  - → clean e^+e^- environment with known initial state
  - → good charged track reconstruction efficiency, excellent particle identification, (γ, π^0) reconstruction
  - → excellent vertexing ($\sigma \sim 60\,\mu$m for B,D vertices)



- **Belle** operated from 1999 to 2010, collected **711/fb @ Υ(4S)**

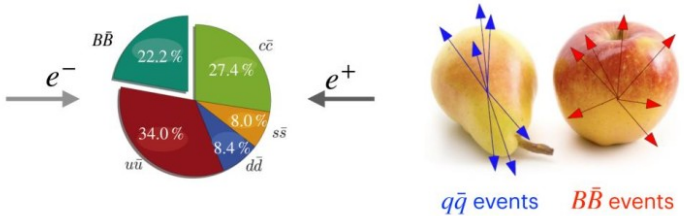
- **Belle II** started operation in 2019: a new detector which maintained or improved (e.g. vertexing) Belle performance characteristics despite much increased beam background levels, so far collected **~510/fb @ Υ(4S)**

  → goal to collect 50/ab!



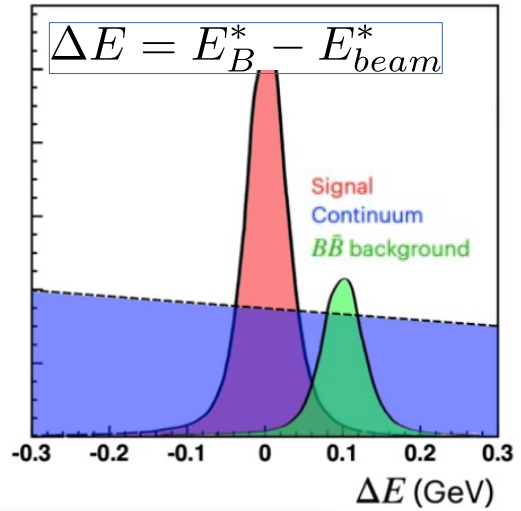
Analysis workflow @ Belle II

1. **Reconstruction**
   - combine final state particle candidates in kinematic fits to form *B* candidates
2. **Selection**
   - optimize event-shape multivariate classifier + particle ID criteria

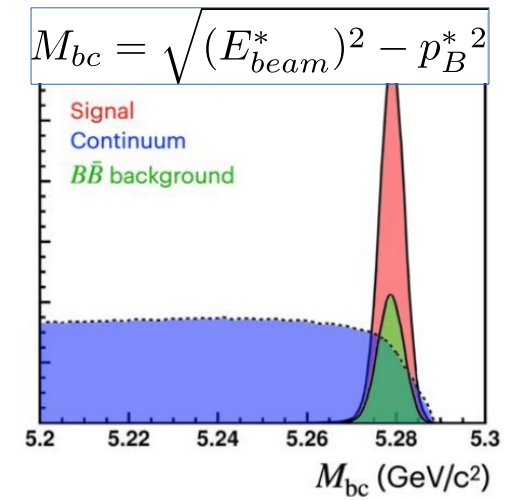


3. **Modelling + Fit**
   - extract models from simulation (+calibrate on data)
   - fit to data to extract physics quantities
4. **Systematic uncertainties**
   - toy studies + control modes

Challenges: small BR, high backgrounds, neutrals



Only $B\bar{B}$ in event
$E^*_B = E^*_{beam}$



Outline

- Belle and Belle II

- Time-dependent CP violation (TDCPV) at B factories

- recent measurements related to ϕ_2/α

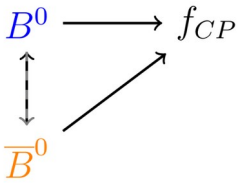
→ TDCPV in $B^0 \to \rho^+\rho^-$
→ $\mathcal{B}$ and A_{CP} in $B^0 \to \pi^0\pi^0$

- TDCPV in $B^0 \to K^0_s\pi^+\pi^-\gamma$ new

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

Time-dependent CP violation @ B factories

→ in decays of neutral B mesons to CP eigenstates interference between direct and mixed decay amplitude can lead to mixing-induced time-dependent CP violation

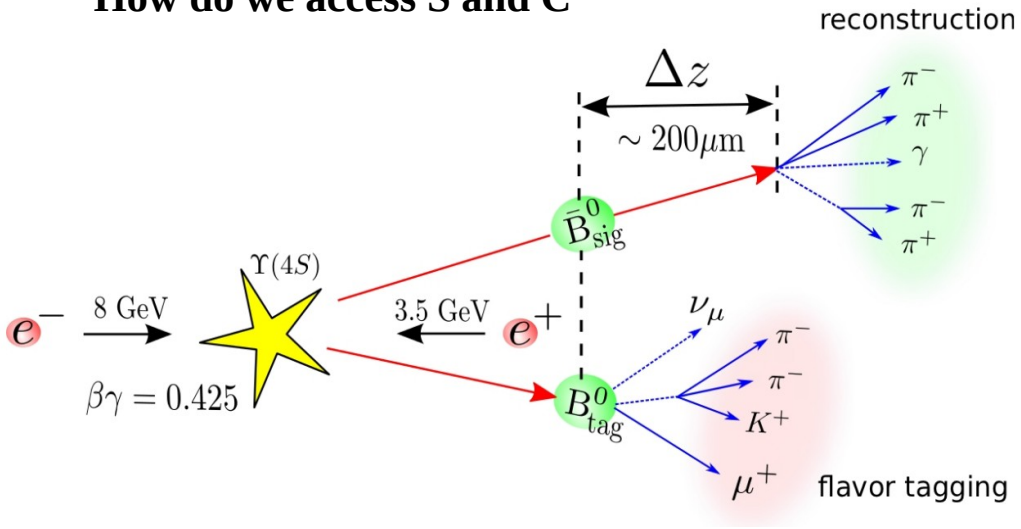


$$\mathcal{A}_{\mathrm{CP}}(\Delta t) = \frac{\Gamma(\bar{B}^0 \to f_{CP}\ )(\Delta t) - \Gamma(B^0 \to f_{CP}\ )(\Delta t)}{\Gamma(\bar{B}^0 \to f_{CP}\ )(\Delta t) + \Gamma(B^0 \to f_{CP}\ )(\Delta t)} = \boldsymbol{S} \cdot \sin(\Delta m_d \Delta t) - \boldsymbol{C} \cdot \cos(\Delta m_d \Delta t)$$

Mixing-induced CP violation

Direct CP violation

How do we access S and C



Quantum coherence
$B_{tag} \to B^0(\bar{B}^0)$ flavor specific at t
B_{sig} was $\bar{B}^0(B^0)$ at t

Mass of $\Upsilon(4S)$ just above $2M_B$
B pair ~ at rest in CMS

Asymmetric beam energy
$\Delta t = \Delta z / \beta\gamma c$

New flavor tagger at Belle II

→ based on graph-neural-net
→ eff. tagging efficiency:

30% (Belle) → **37%**

Phys. Rev. D 110, 012001

In each BB event we:
→ reconstruct signal decay (B_{sig})
→ determine flavor of B_{tag}
→ measure distance between decay vertices (Δt)

Determination of ϕ_2/α from $B \to \pi\pi$ / $\rho\rho$

→ least well measured angle of **CKM unitarity triangle** $\alpha \equiv \phi_2 = (84.1^{+3.7}_{-3.0})^\circ$

→ ϕ_2 can be determined from TDCPV in $B^0 \to \pi^+\pi^-/\rho^+\rho^-$
but due to sizable b→d penguin contribution

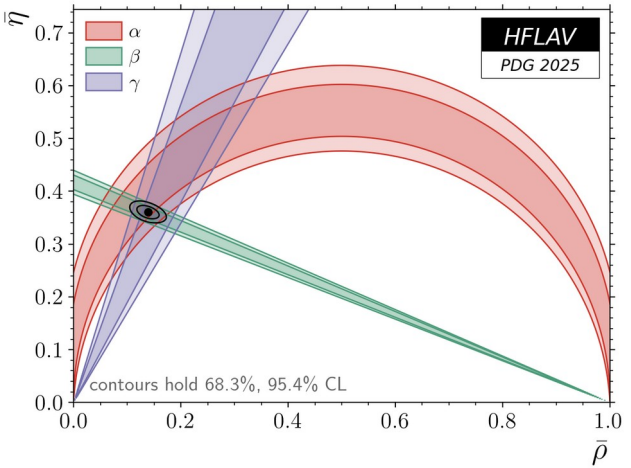
$$S \propto \sin(2\phi_2 + 2\Delta\phi_2)$$

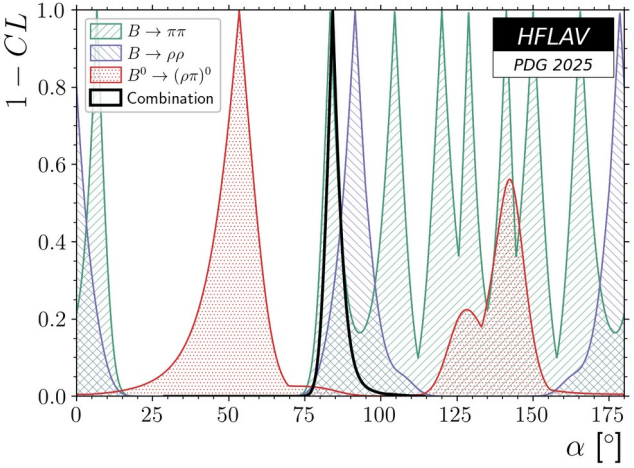
→ $\Delta\phi_2$ can be accessed based on the $\mathcal{B}$, $\mathcal{A}_{CP}$ of isospin related modes
($B^+ \to \pi^0\pi^+$, $B^0 \to \pi^0\pi^0$; $B^+ \to \rho^0\rho^+$, $B^0 \to \rho^0\rho^0$)

→ $\rho\rho$ less ambiguity in ϕ_2 due to smaller penguin contribution
+ possible to measure TDCPV in $\rho^0\rho^0$,
but need to determine fraction of longitudinal polarization f_L
($f_L = |H_0|^2/(|H_0|^2 + |H_+|^2 + |H_-|^2)$)

→ Challenging! low $\mathcal{B}$: $10^{-6} - 10^{-5}$ (+ large contributions from $q\bar{q}$ backgrounds!)

Several recent measurements @ Belle II providing new inputs for ϕ_2





TDCPV in $B^0 \to \rho^+\rho^-$ @ Belle II

PRD 111, 092001 (2025)

→ analysis in two steps: - determine $\mathcal{B}$ and f_L
- use obtained event weights for time-dependent CP fit

→ reconstruct $\rho^\pm \to \pi^\pm\pi^0$: two charged pions for vertex reconstruction (→ good Δt resolution)

→ large combinatorial backgrounds:
only pions, including neutral in final state
(large backgrounds at low photon energies)

→ employ BDT classifiers to reduce fake and beam-background photons

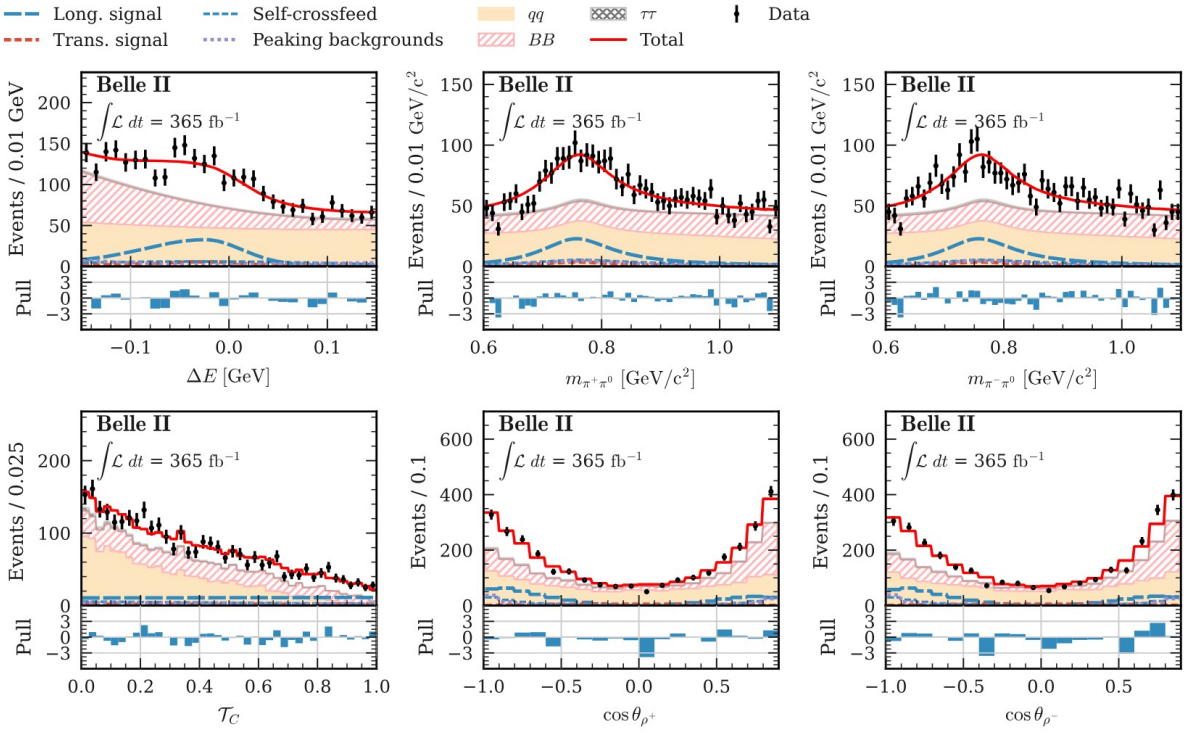
→ signal extraction by 6D ML fit in

$$\Delta E,\ m_{\pi^\pm\pi^0},\ \cos\theta_{\rho^\pm},\ \mathcal{T}_C$$

ρ helicity angle

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_{\rho^+}\, d\cos\theta_{\rho^-}} = \frac{9}{4}\left[\frac{1}{4}(1-f_L)\sin^2\theta_{\rho^+}\sin^2\theta_{\rho^-} + f_L\cos^2\theta_{\rho^+}\cos^2\theta_{\rho^-}\right]$$

$q\bar{q}$ background suppression variable



TDCPV in $B^0 \to \rho^+\rho^-$ @ Belle II

PRD 111, 092001 (2025)

→ distributions from previous fit used as event weights in Δt fit to B^0 and $\bar{B}^0$ tagged events to determine C and S

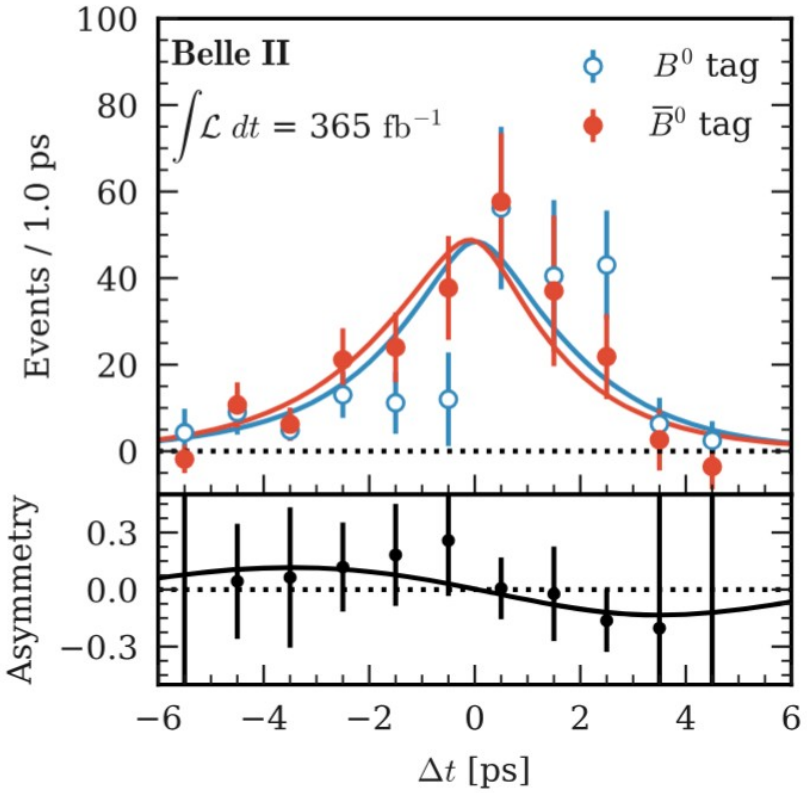
$$\mathcal{B} = (2.89^{+0.23+0.29}_{-0.22-0.27}) \times 10^{-5}$$

dominated by π^0 eff.

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

$$C_{CP} = -0.02 \pm 0.12^{+0.06}_{-0.05}$$

$$S_{CP} = -0.26 \pm 0.19 \pm 0.08$$



→ on par with world's best

→ combining these results with Belle/BaBar/LHCb results of isospin related $B \to \rho\rho$ modes we obtain

$$\phi_2 = (92.6^{+4.5}_{-4.7})°$$

Dominated by the uncertainties of $S_{\rho^+\rho^-}$ and $S_{\rho^0\rho^0}$

→ to be improved by future measurements!

Branching fraction and Acp of $B^0 \to \pi^0\pi^0$

Phys. Rev. D 111, L071102

→ ϕ_2 from $B \to \pi\pi$ uncertainty dominated by $B^0 \to \pi^0\pi^0$ branching fraction and CP asymmetry

→ very challenging measurement due to solely 4 photons in the final state

→ signal swamped by large backgrounds
(mostly true π^0 combination from $q\bar{q}$ events)

→ still, **uniquely accessible @ Belle II**

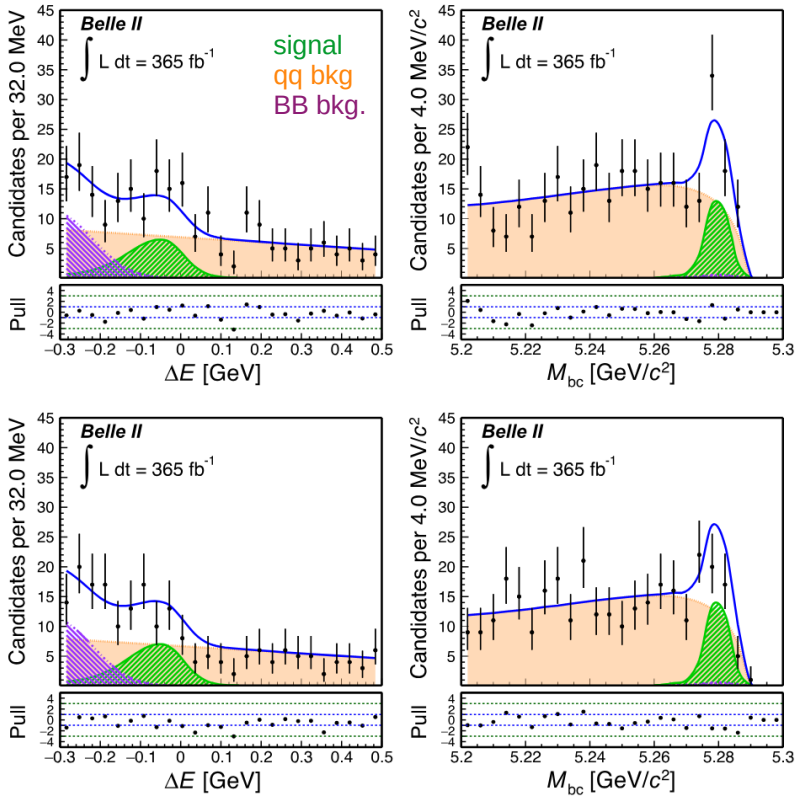
→ improved tagging, π^0 selection and fit configuration w.r.t. previous Belle II measurement

→ 4D fit is performed to extract $\mathcal{B}$ and time-integrated A_{CP}

$\Delta E, M_{bc}, C_t, w_t$

$q\bar{q}$ background suppression variable

wrong tag probability



Branching fraction and Acp of $B^0 \to \pi^0\pi^0$

Phys. Rev. D 111, L071102

From fit to 365/fb of Belle II data we obtain 125 +/- 20 signal events giving

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

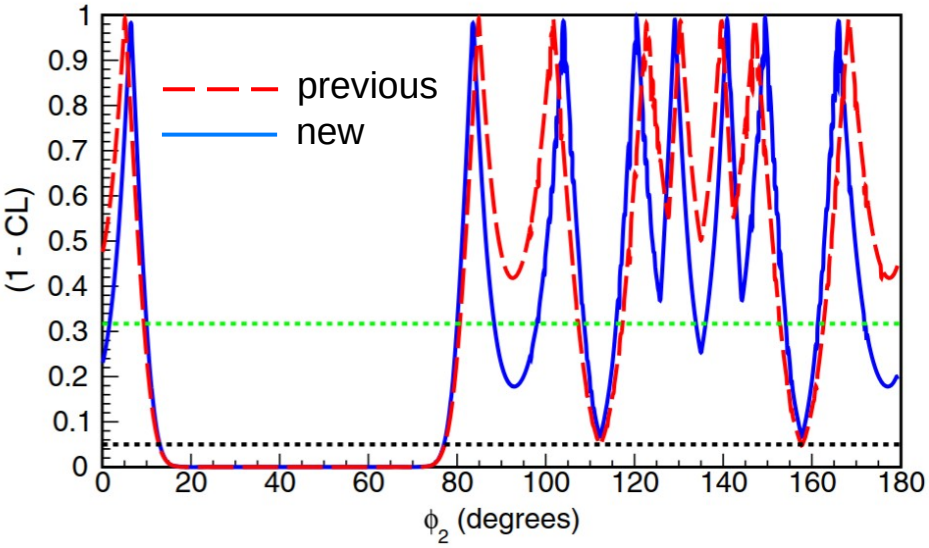
→ $\mathcal{B}$ systematics dominated by understanding of π^0 efficiency

→ on par with world's best, despite smaller data sample

→ we evaluate impact on ϕ_2 by combining results with isospin related $B \to \pi\pi$ measurements

→ 10° reduction of 68% CL exclusion interval

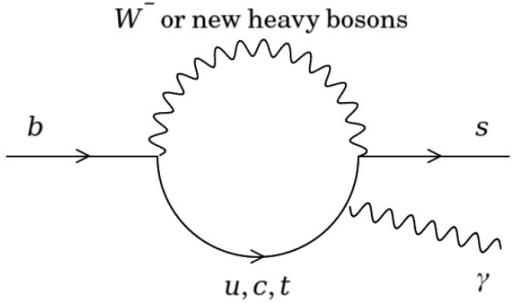
(30% fractional increase in ϕ_2 precision)



TDCPV in $B^0 \to K^0_S \pi^+ \pi^- \gamma$

New!

paper in preparation



→ $b \to s\gamma$ transition at the quark level

→ time-dependent CP asymmetry sensitive to photon polarization

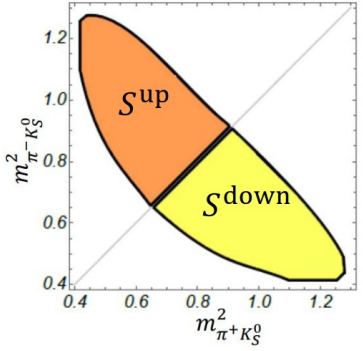
→ in the SM: $\mathcal{S} \sim 0$ due to suppressed right-handed currents

→ beyond SM contributions in loops could lead to interference between left- and right-handed current and non-zero value of $\mathcal{S}$

→ use full **Belle** (711 fb-1) and **Belle II** Run 1 (365 fb-1) datasets to measure $\mathcal{S}$ and $\mathcal{C}$

→ in addition measure two new observables proposed by Kou et al. [JHEP09(2019)034]

→ set additional constraint in C_7/C_7' plane



New observables:

- $S^+ = S^{up} + S^{down}$
- $S^- = S^{up} - S^{down}$

TDCPV in $B^0 \to K^0_s \pi^+ \pi^- \gamma$

new

paper in preparation

Belle II

Event selection

$\gamma : E_\gamma > 1.5\ (1.4)$ GeV for Belle II (Belle)

$K^0_s :$ MVA selector (flight length etc.)

Out of many intermediate resonances only
$B^0 \to K_{res}\gamma$ with $K_{res} \to K^0_s \rho^0$ are CP eigenstates
→ enhanced via:

$$m_{\pi^+\pi^-} \in [0.6, 0.9]\ \text{GeV}/c^2$$
$$m_{K_{res}} \in [0.9, 1.8]\ \text{GeV}/c^2$$

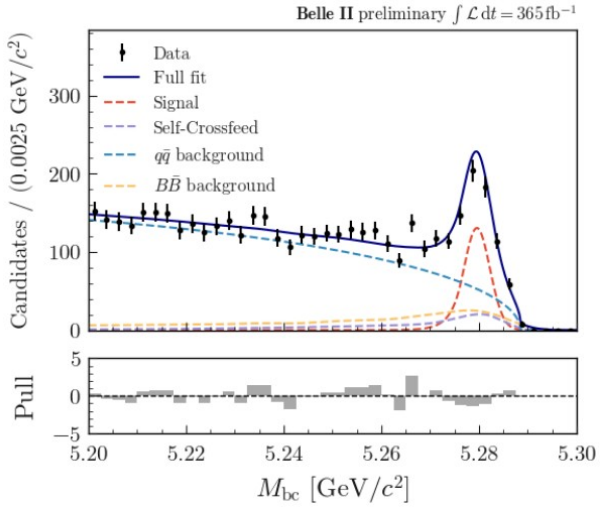
→ continuum suppression by standard MVAs based on event shape

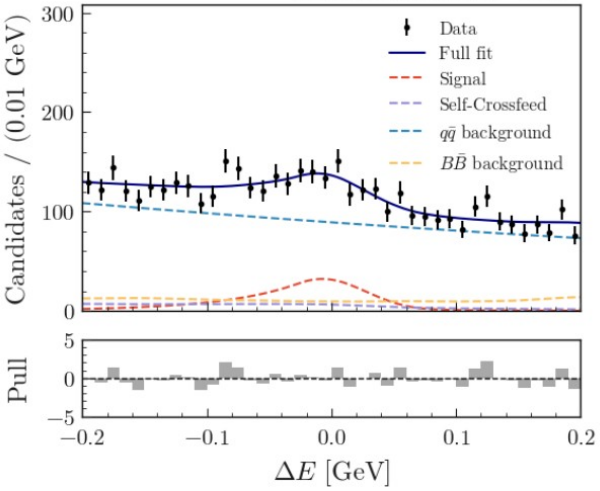
Vertexing and flavor tagging

→ prompt $\pi^+\pi^-$ used for B_{sig} vertex

→ standard Belle flavor tagging used for Belle (~30% eff.)
and GFlat algorithm for Belle II (~37% eff.)

→ Δt resolution function and tagging validated using $B^+ \to K^+\pi^+\pi^-\gamma$
and by performing B meson lifetime fit on signal channel





TDCPV in $B^0 \to K^0_s \pi^+ \pi^- \gamma$

new

paper in preparation

Belle II

Time-dependent CP fit

→ unbinned ML fit to $\Delta E, M_{bc},$ and Δt

→ separately for Belle and Belle II datasamples

Fit results

Belle + Belle II

$\mathcal{C} = -0.17 \pm 0.09 \pm 0.04$

$S = -0.29 \pm 0.11 \pm 0.05$

$S^+ = -0.57 \pm 0.23 \pm 0.10$

$S^- = 0.31 \pm 0.24 \pm 0.05$

Belle $\quad \mathcal{C} = -0.04 \pm 0.11 \pm 0.07$

$S = -0.18 \pm 0.17 \pm 0.08$

$(1\sigma$ from the SM)

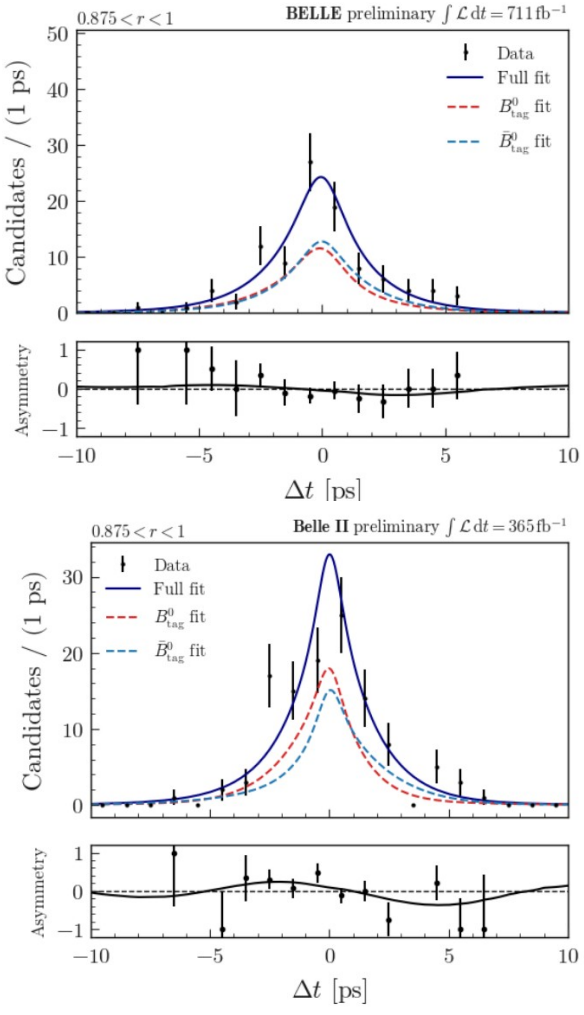
Belle II $\quad \mathcal{C} = -0.29 \pm 0.13 \pm 0.05$

$S = -0.36 \pm 0.16 \pm 0.06$

$(2.3\sigma$ from the SM)

→ most precise values of $S, \mathcal{C}$ to date

→ first determination of S^+, S^-

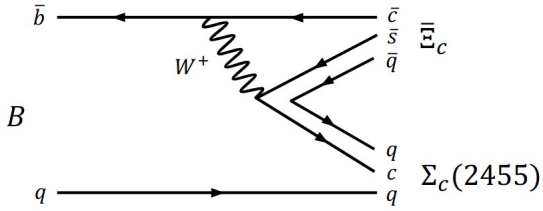


First observation of $B \to \bar{\Sigma}_c(2455)\Xi_c$

arXiv:2507.05094

Belle II

→ baryonic B decays are important system for studying production mechanisms of baryon-antibaryon pairs in non-perturbative QCD



→ inconclusive theory predictions

- 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: 711/bf + 365/fb

→ 2D fit to M($\Lambda_c^+\pi^+$), Δ E simultaneously to Belle and Belle II data in M(Ξ_c) signal and sideband regions

(→ treat potential non-Ξ_c peaking backgrounds)

$$\mathcal{B}(B^- \to \bar{\Sigma}_c(2455)^{--}\Xi_c^+) = (5.74 \pm 1.11 \pm 0.42^{+2.47}_{-1.53}) \times 10^{-4} \quad (7.3\sigma)$$

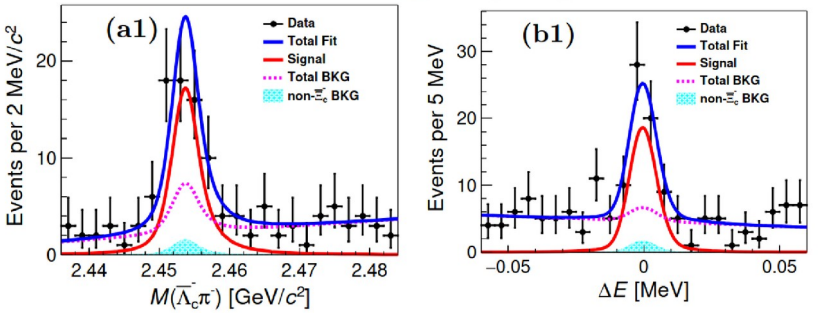
$$\mathcal{B}(\bar{B}^0 \to \bar{\Sigma}_c(2455)^0\Xi_c^0) = (4.83 \pm 1.12 \pm 0.37^{+0.72}_{-0.60}) \times 10^{-4} \quad (6.2\sigma)$$

First observations!

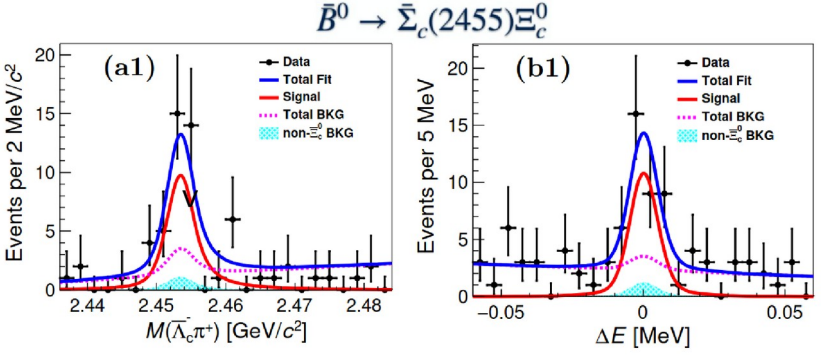
*3rd uncertainties are from cited Ξ_c's BR

→ almost 2 orders of magnitude larger than decays to singly charmed baryon pair!
(e.g. $B \to \Lambda_c p$ or $\Sigma_c(2455)p$)

$B^- \to \bar{\Sigma}_c(2455)^{--}\Xi_c^+$



$\bar{B}^0 \to \bar{\Sigma}_c(2455)\Xi_c^0$



Summary

Recent ϕ_2/α related measurements at Belle II

→ TDCPV in $B^0 \to \rho^+\rho^-$ PRD 111, 092001 (2025)

→ $\mathcal{B}$ and A_{CP} in $B^0 \to \pi^0\pi^0$ Phys. Rev. D 111, L071102

TDCPV in $B^0 \to K^0_s\pi^+\pi^-\gamma$ → **paper in preparation**

First observation of $B \to \bar{\Sigma}_c(2455)\Xi_c$ arXiv:2507.05094

- results competitve or better than Belle/BaBar although based on smaller datasamples

- expect more results on CPV and hadronic B decays to follow soon!

TDCPV in $B^0 \to \rho^+\rho^-$ - Systematics table

TABLE VI. Systematic uncertainties for $\mathcal{B}$ and f_L. Relative uncertainties are shown for $\mathcal{B}$.

Source	$\mathcal{B}$ [%]	$f_L[10^{-2}]$
Tracking	± 0.54	...
π^0 efficiency	± 7.67	...
PID	± 0.08	...
$\mathcal{T}_C$	± 2.87	...
MC sample size	± 0.24	± 0.2
Single candidate selection	± 0.55	± 0.3
SCF ratio	$^{+2.97}_{-2.45}$	$^{+0.2}_{-0.3}$
$\mathcal{B}$'s of peaking backgrounds	$^{+0.94}_{-0.98}$	± 0.1
$\tau^+\tau^-$ background yield	$^{+0.65}_{-0.69}$	± 0.0
Signal model	$^{+1.14}_{-2.02}$	± 0.2
$q\bar{q}$ model	$^{+0.49}_{-0.51}$	$^{+0.1}_{-0.2}$
$B\bar{B}$ model	$^{+1.00}_{-0.40}$	$^{+0.3}_{-0.1}$
$\tau^+\tau^-$ model	$^{+0.17}_{-0.26}$	$^{+0.0}_{-0.1}$
Peaking model	$^{+1.37}_{-1.01}$	$^{+0.3}_{-0.5}$
Interference	± 1.20	± 0.5
Data-MC mismodeling	$^{+3.51}_{-1.70}$	$^{+0.8}_{-0.3}$
Fit bias	± 1.03	± 1.2
f_{00}	$^{+1.67}_{-1.50}$	...
$N_{\Upsilon(4S)}$	± 1.45	...
Total systematic uncertainty	$^{+10.10}_{-9.51}$	$^{+1.7}_{-1.5}$
Statistical uncertainty	$^{+7.95}_{-7.61}$	$^{+2.4}_{-2.5}$

TABLE VII. Systematic uncertainties for S and C.

Source	$S[10^{-2}]$	$C[10^{-2}]$
$\mathcal{B}$'s of peaking backgrounds	$^{+0.6}_{-0.5}$	± 0.1
$\tau\tau$ background yield	± 0.9	$^{+0.0}_{-0.1}$
Data-MC mismodeling	$^{+0.6}_{-1.1}$	$^{+1.5}_{-0.6}$
Single candidate selection	± 1.3	± 1.9
SCF ratio	$^{+0.5}_{-0.4}$	$^{+0.7}_{-0.0}$
Signal model	$^{+1.1}_{-1.4}$	$^{+0.3}_{-0.4}$
$q\bar{q}$ model	$^{+2.2}_{-1.0}$	± 0.2
$B\bar{B}$ model	± 0.9	$^{+0.7}_{-0.5}$
$\tau^+\tau^-$ model	± 0.1	± 0.0
Peaking model	$^{+0.8}_{-0.4}$	$^{+0.2}_{-0.4}$
Fit bias	± 2.0	± 0.6
Interference	± 2.8	± 1.7
Resolution	$^{+3.4}_{-4.4}$	$^{+1.9}_{-1.4}$
Δt PDF for $q\bar{q}$ and $B\bar{B}$	$^{+3.8}_{-1.8}$	$^{+0.7}_{-0.1}$
Tag side interference	± 0.5	± 2.1
Wrong tag fraction	$^{+0.2}_{-0.3}$	± 0.5
Background CP violation	$^{+3.8}_{-3.6}$	$^{+4.2}_{-3.7}$
CP violation in TP signal	$^{+0.8}_{-0.2}$	$^{+0.2}_{-0.4}$
Tracking detector misalignment	± 1.4	± 0.5
τ_{B^0} and Δm_d	$^{+1.4}_{-1.6}$	± 0.3
Total systematic uncertainty	$^{+8.2}_{-7.8}$	$^{+6.1}_{-5.3}$
Statistical uncertainty	± 18.8	± 12.1

New Flavor Tagger algorithm - GFlaT

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→ Flavor tagging ($B^0/\bar{B}^0$) is based on the properties of final-state particle not used in B_{sig} reconstruction

e.g. lepton charge in $B^0 \to D\mu^{\oplus}\nu_\mu X$ or kaon charge in subsequent $D \to K^{\oplus}Y$

$\bar{B}^0 \to \bar{D}\mu^{\ominus}\bar{\nu}_\mu X$ $\bar{D} \to K^{\ominus}Y$

→ at Belle, based on multiple discriminants a multi-dimensional look-up table is used to determine B_{tag} flavor along with its quality (dilution factor)

→ at Belle II a novel algorithm, based on graph-neural-network is developed

→ it increases the effective tagging efficiency from ~**30%** → **37%**!

$q = -1 \to \bar{B}^0$ tag

$q = +1 \to B^0$ tag

$r \in [0, 1]$ - tag quality