Recent results and future prospects of the Belle II experiment

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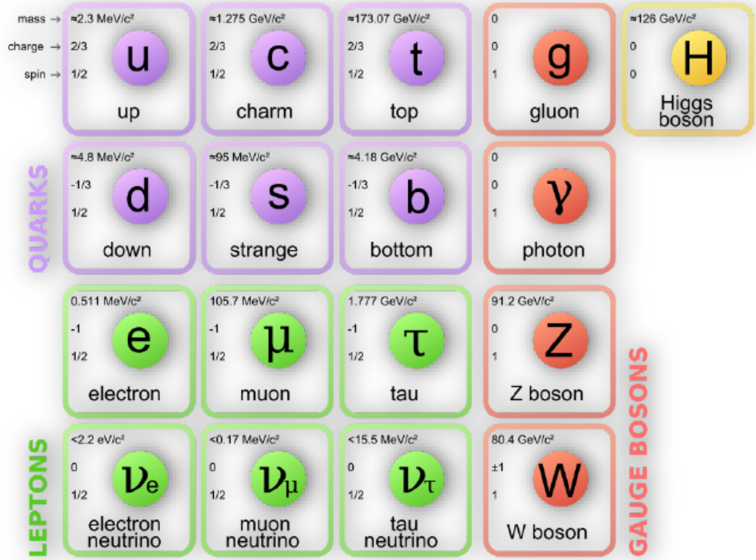
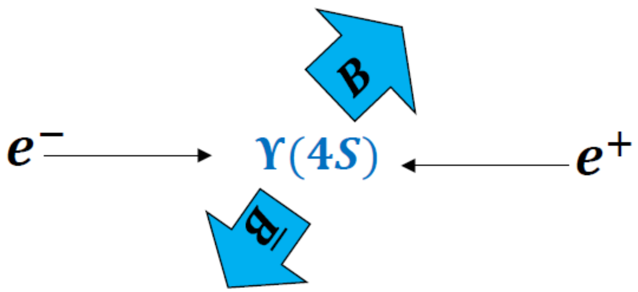
Asymmetric e^+e^- B Factories: Concept

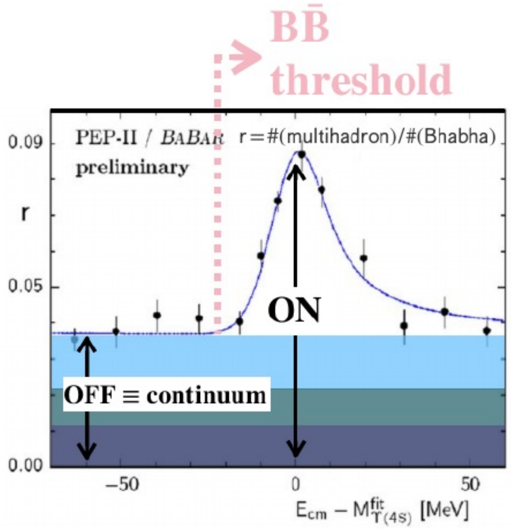


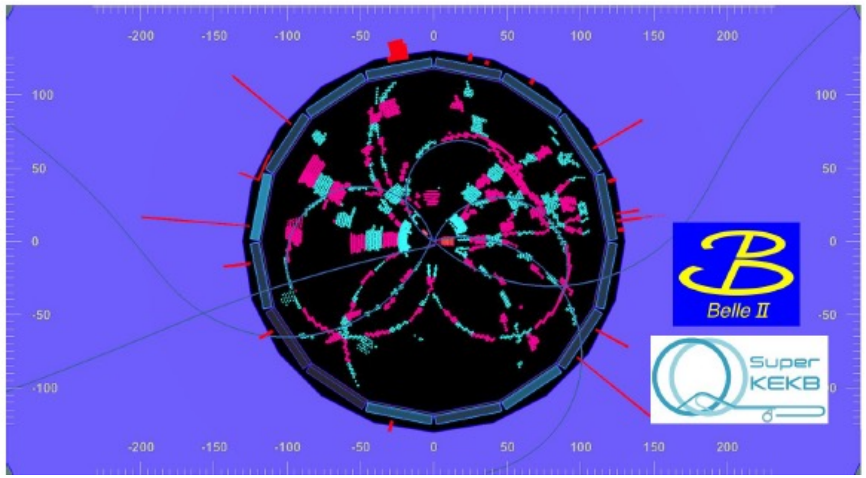


- Mass of B meson $(b\bar{q})$ is around 5~6 GeV.
  - B pairs can be generated plentifully using ~11 GeV $\Upsilon(4S)$ colliders
- Relatively lower energy → intensity up easily → intensity frontier
- First generation B factory
  - ARGUS/DORIS II at DESY 1982 – 1992
  - CLEO/CESR at Cornell 1979 – 2008 (including Cleo-c)
- Next, asymmetric B factory:
  - BaBar/PEP-II at SLAC 1999 – 2008
  - Belle/KEKB at KEK 1999 – 2010
- 2nd generation asymm. B factory: Belle II/SuperKEKB at KEK 2019 –

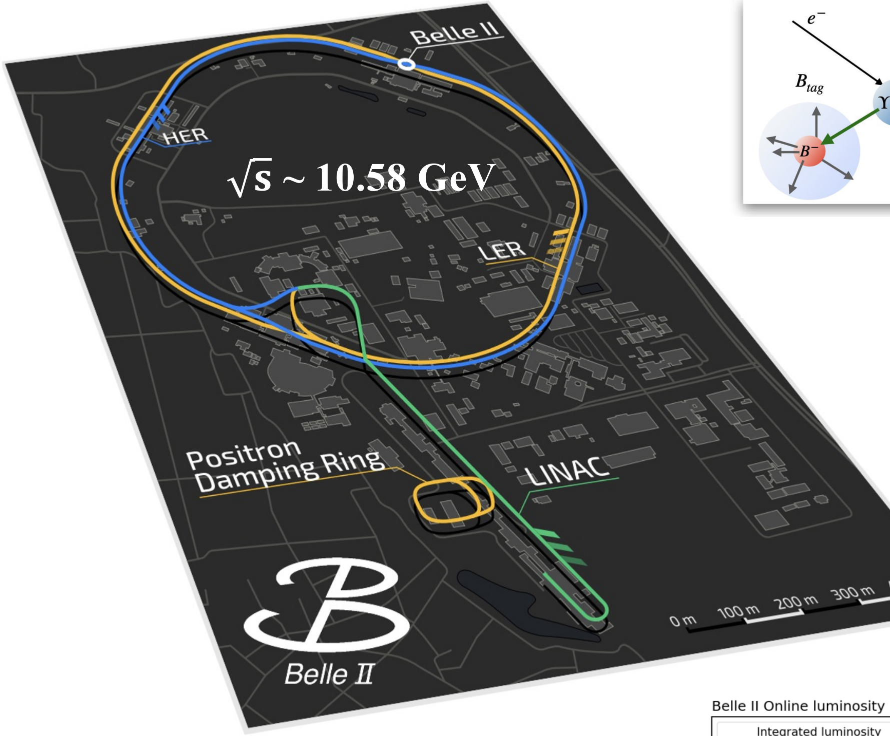
Advantages of an e^+e^- flavor factory

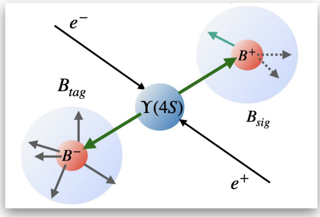
- Known initial kinematics and good hermeticity
  - possible to fully reconstruct events with invisible particles
- Clean environment (average 11 tracks per event)
  - efficient detection of neutrals (γ, π^0, η, ...)
- Run at the $\Upsilon(4S)$ mass just above $B\bar{B}$ threshold
  - Relatively low background
  - Data off-resonance provide control sample without $B\bar{B}$





SuperKEKB and Belle II





K_L and μ Detection

K_L^0 p resolution: 15 MeV

μ identification eff.: ~90%

Vertex Detector

vertex resolution: 15 μm

Central Drift Chamber

spatial resolution: 100 μm

dE/dx resolution: 5%

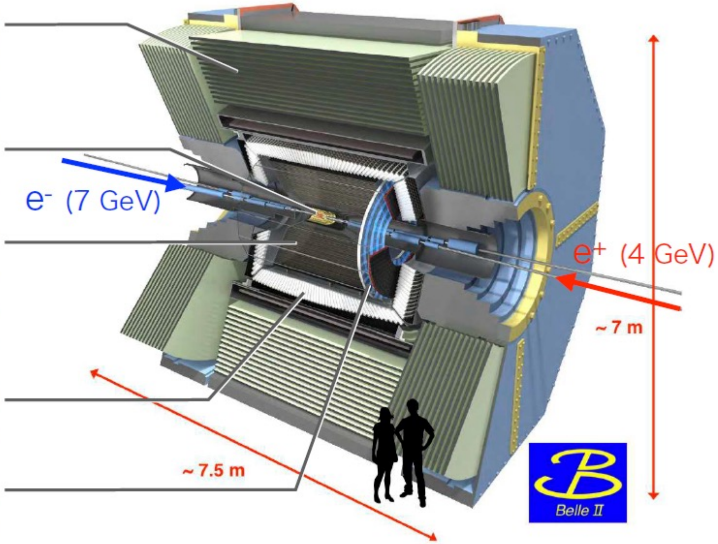
P_T resolution: 0.4%

EM Calorimeter, CsI(Tl)

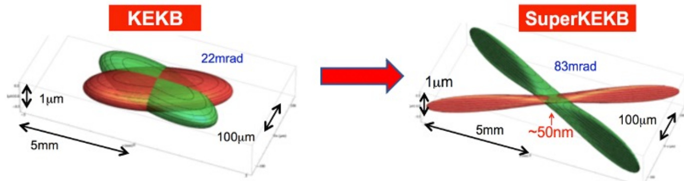
energy resolution: 1.6%-4%

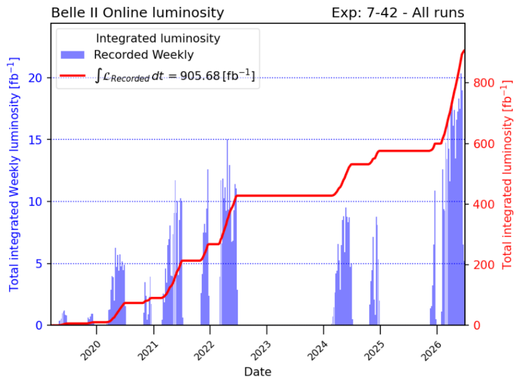
Particle Identification

K eff.: 90%, fake π rate: 5%



Nano-beam design: 30X peak luminosity of Belle



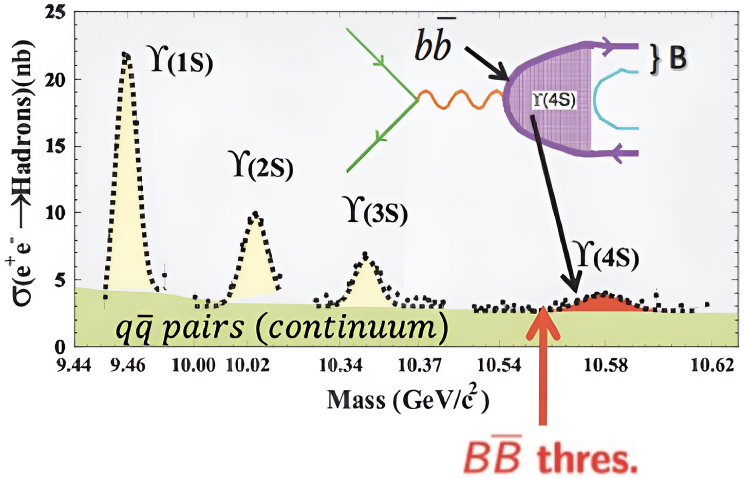


906 fb^{-1} data collected so far

- Targeting higher L_{inst}: $6 \times 10^{35}\ cm^{-2}\ s^{-1}$
- Ultimate goal: $\sim 50ab^{-1}$

Belle II physics

The Belle II Physics Book: [PTEP 2019 (2019) 12, 123C01]



$e^+e^- \to$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3

Belle II Physics Book, PTEP 2019, 123C01

Primarily a **B factory;** But not only B physics!

- Also, **tau, charm** factories
- Clean background for **spectroscopy** and searching for dark sector

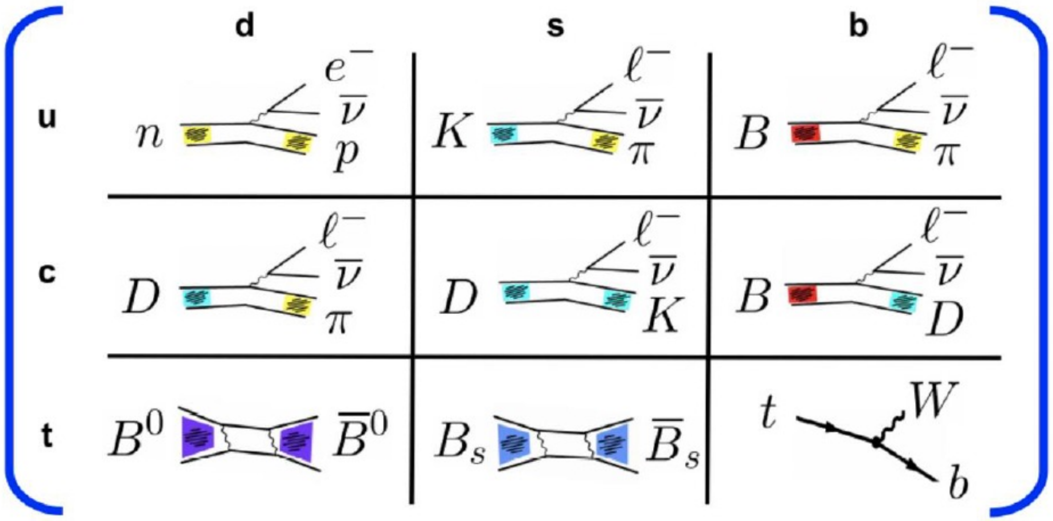
Various type of analyses:

- Lifetime, time-dependent measurement
- well-suited for decays with missing energy and missing mass

B decays

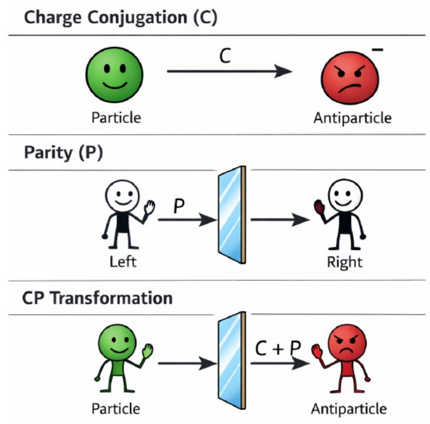
(CKM matrix)

V =



CP Violation and KM theory

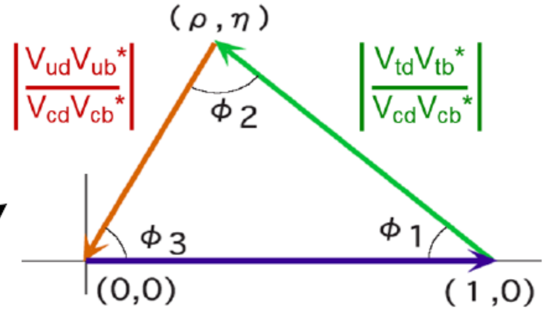
- CP violation: a key for the matter-antimatter asymmetry.
- Kobayashi-Maskawatheory (1973):
  - CP violation in the Standard Model (SM)
  - Complex phase in the quark mixing matrix



CKM (Cabibbo-Kobayashi-Maskawa) Matrix

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

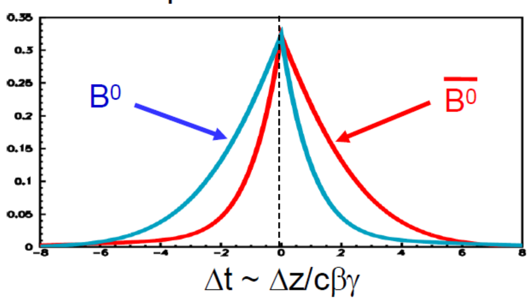
Triangles in the complex plane (from Unitarity)

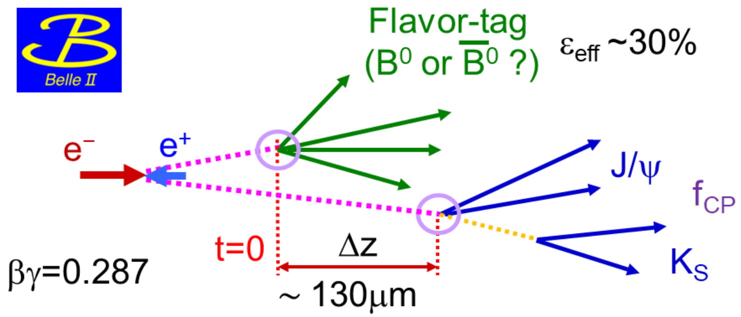


$\alpha = \phi_2 \quad \beta = \phi_1 \quad \gamma = \phi_3$

In B mesons, CP violation often appears as a decay time difference.

measure position instead of time

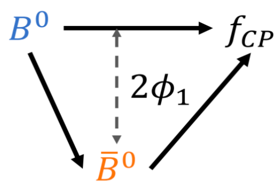




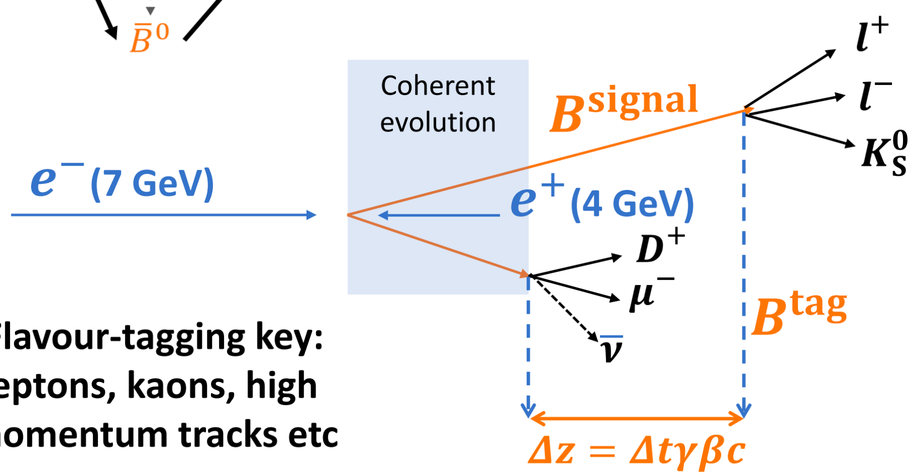
$\phi_1 = \beta$:Decay time dependent CPV in B decays

arXiv:2402.17260 [hep-ex]

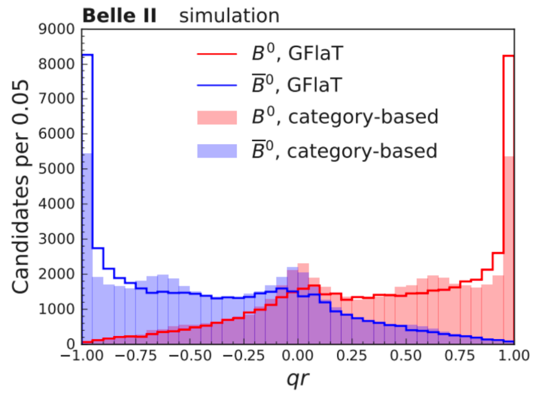
Flavour tagging improvements



$\propto \ |V_{td}|^2 e^{2i\phi_1}$

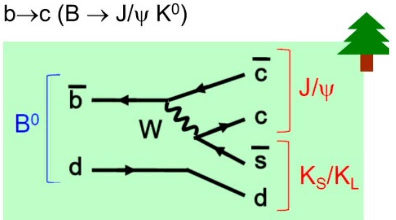


Flavour-tagging key: leptons, kaons, high momentum tracks etc

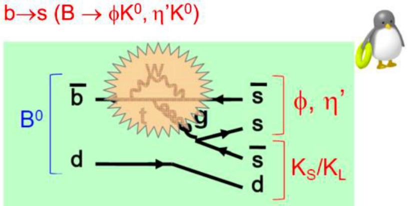


Graph-neural-network approach has improved our tagging by 18%
$\epsilon(1-2\omega) = 37.4\%$

b→c (B → J/ψ K⁰)



b→s (B → φK⁰, η'K⁰)



The SM predicts A = 0 and S = −η sin 2ϕ₁

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

Mixing-induced CPV

Direct CPV

CP Violation in B decays

Observation of time-dependent *CP* violation and measurement of the branching fraction of $B^0 \to J/\psi\, \pi^0$ decays, PRD 111, 012011 (2025)

Measurement of *CP* asymmetries in $B^0 \to K_S\, \pi^0 \gamma$ decays at Belle II, PRL 134, 011802 (2025)

Measurement of branching fractions, asymmetry, and isospin asymmetry for $B^0 \to \rho^0\gamma$ decays using Belle and Belle II data, Phys. Rev. D 111, L071103 (2025)

Measurement of the branching fraction, polarization, and time-dependent *CP* asymmetry in $B^0 \to \rho^+\rho^-$ decays and constraint on the CKM angle ϕ_2, PRD 111, 092001 (2025)

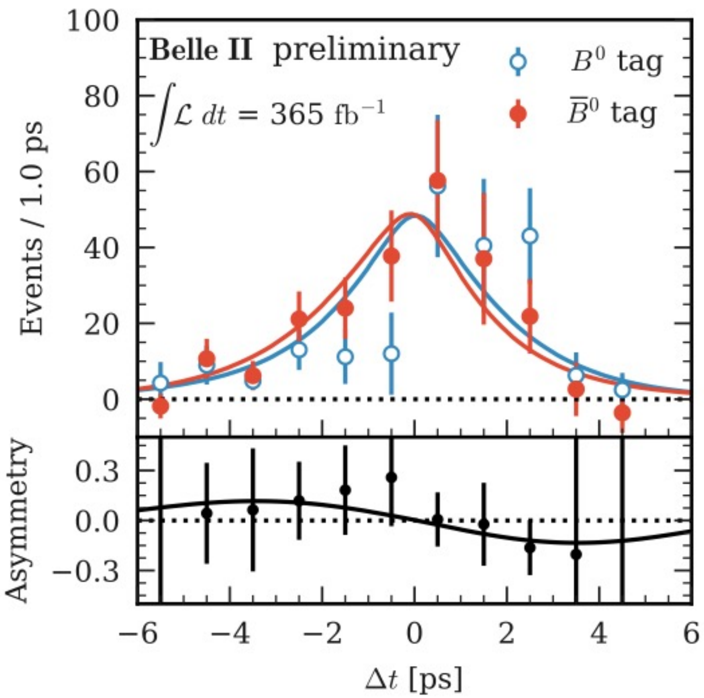
Measurement of the branching fraction and *CP*-violating asymmetry of the decay $B^0 \to \pi^0\pi^0$ using 387 million bottom-antibottom meson pairs in Belle II data, PRD 111, L071102 (2025)

Measurement of time-dependent *CP* asymmetries in $B^0 \to K_S\pi^+\pi^-\gamma$ decays at Belle and Belle II, arXiv: 2510.01331, to appear in JHEP

Search for CPV in $B^0 \to \rho^+\rho^-$

[PRD 111, 092001 (2025)]

- **much smaller loop contribution $\Longrightarrow$ dominates ϕ_2 precision**
- **two π^0's reconstruction needed $\Longrightarrow$ a channel suitable for Belle II**



$$S = -0.26 \pm 0.19 \pm 0.08$$

$$C = -0.02 \pm 0.12 \pm 0.05$$

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (2.89^{+0.37}_{-0.35}) \times 10^{-5}$$

$$f_L = 0.921^{+0.029}_{-0.029}$$

Mixing-induced CPV param.

Probability distribution

$$P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \Big\{ 1 + q \big[S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t) \big] \Big\},$$

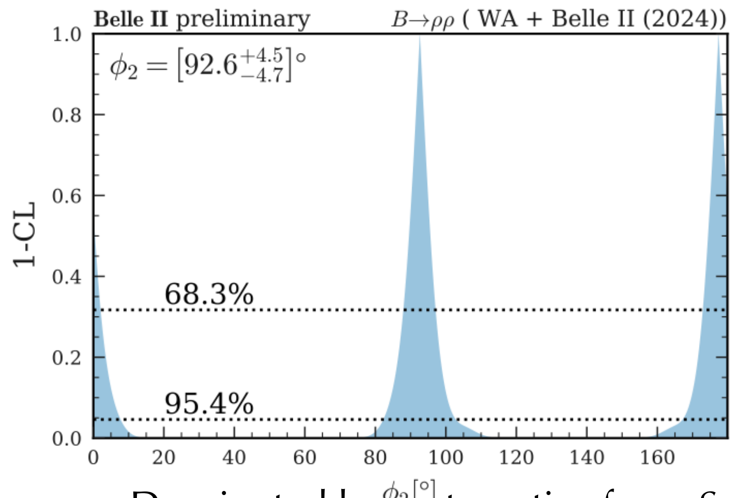
Direct CPV param.

Helicity angle distribution

Longitudinal polarisation fraction

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

Constraining ϕ_2:



Dominated by systematics from S

$B \to \rho\rho$ world average:
$\phi_2 = (91.5^{+4.5}_{-5.4})^\circ$

$B \to \rho\rho$ world average
+ Belle II $\rho^+\rho^-$ result
$\Rightarrow \boldsymbol{\phi_2 = (92.6^{+4.5}_{-4.8})^\circ}$

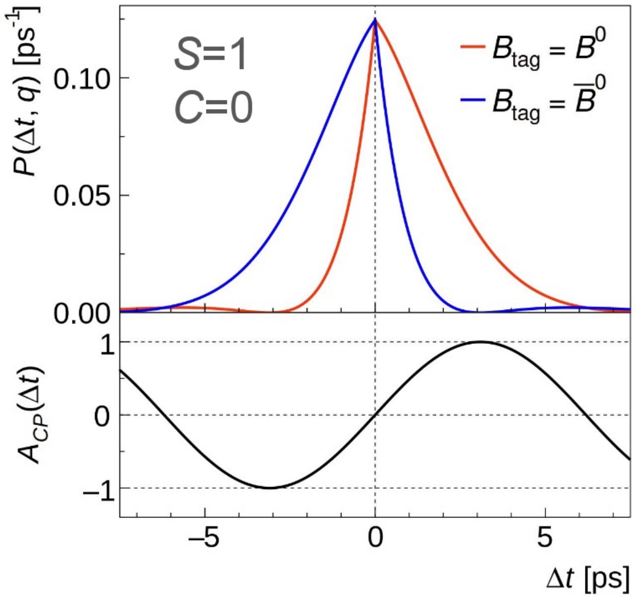
6%

First measurement of time-dependent CP violation in $B^0 \to \pi^0\pi^0$

$$\Gamma(B^0/\bar{B}^0(t) \to f_{CP}) \propto e^{-t/\tau_B}\left[1 + q\left(\underbrace{S\sin(\Delta m_d t)}_{\text{mixing-induced CPV}} - \underbrace{C\cos(\Delta m_d t)}_{\text{direct CPV}}\right)\right]$$

2606.20797
Submitted to NP

$$\mathcal{A}_{CP}(\Delta t) = \frac{\mathcal{P}(\Delta t,+1) - \mathcal{P}(\Delta t,-1)}{\mathcal{P}(\Delta t,+1) + \mathcal{P}(\Delta t,-1)} = S\sin\Delta m\Delta t - C\cos\Delta m\Delta t$$



$\Delta t = t_{CP} - t_{tag}$ from the two decay vertices

The Issue with $B^0 \to \pi^0\pi^0$

- $\sim 99\%$ of decays: vertexless 4γ final state
- No decay vertex $\Rightarrow$ no Δt
- $\Rightarrow$ standard time-dependent CPV analysis not possible with current samples

The New Idea

PHYS. REV. D 112, 032011 (2025)

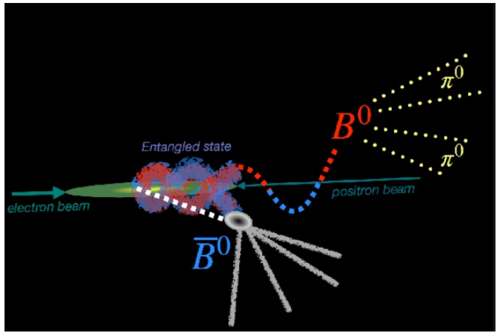
- Quantum entanglement of $B^0\bar{B}^0$ pairs links the two decays
- New approach: use only the tag-side decay time t_{tag}
- A time-dependent flavour asymmetry still arises:
  - reduced oscillation amplitude ($\sim -20\%$)
  - maximal asymmetry occurs at larger t_{tag}, where fewer B mesons remain

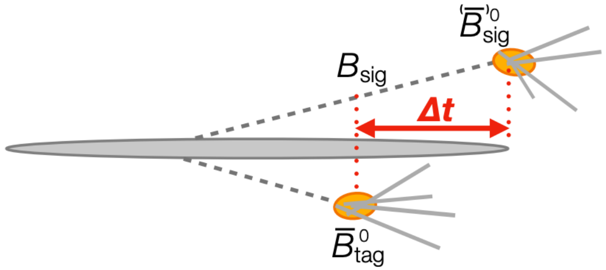
First measurement of time-dependent CP violation in $B^0 \to \pi^0\pi^0$

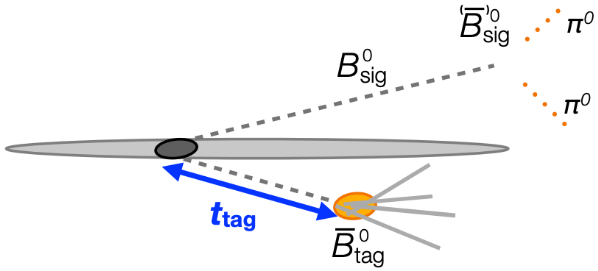
- Very small signal: $\sim$170 events
  - Dominated by continuum background ($\sim$130$\times$ larger)
  - Additional $B\bar{B}$ background of similar size
- Goal: extract signal, determine flavour, and measure decay time for B^0_{tag} and $\bar{B}^0_{\text{tag}}$
- No signal vertex (4γ final state) $\Rightarrow$ cannot measure decay time
- Use tag-side decay time t_{tag} instead

$$P(t_{\text{tag}}, q) \approx e^{-t_{\text{tag}}/\tau}\Big[1 - q\,D\Big(S_{\pi^0\pi^0}\sin[\Delta m(t_{\text{tag}} - \hat{t}\,)] + C_{\pi^0\pi^0}\cos[\Delta m(t_{\text{tag}} - \hat{t}\,)]\Big)\Big]$$

$$\hat{t} = \arctan(\Delta m\tau)/\Delta m \approx 1.294\,\text{ps}$$



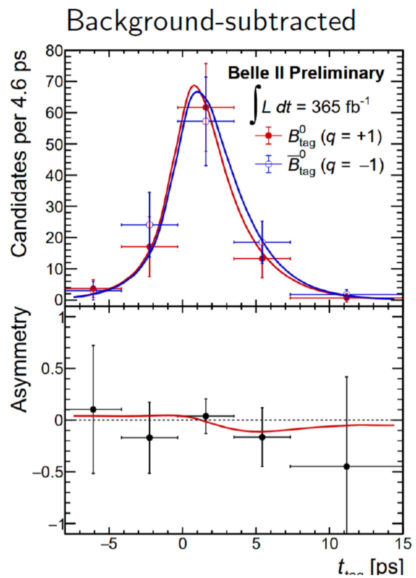




First measurement of time-dependent CP violation in $B^0 \to \pi^0\pi^0$

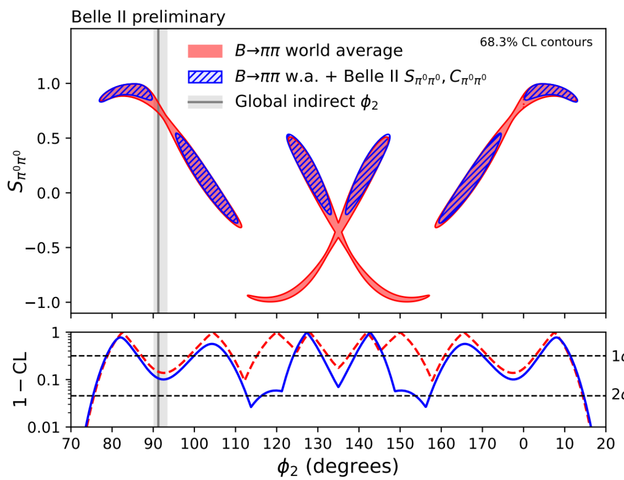
$$S_{00} = 0.61^{+0.75}_{-0.79}\,(\text{stat}) \pm 0.11\,(\text{syst})$$
$$C_{00} = 0.05 \pm 0.28\,(\text{stat}) \pm 0.07\,(\text{syst})$$

- C_{00} consistent with time-integrated $A_{CP} = 0.03 \pm 0.30$ within 0.5σ (considering overlapping events)
- Uncertainties consistent with expectations
- S compatible with theoretical expectation (~ 0.65)



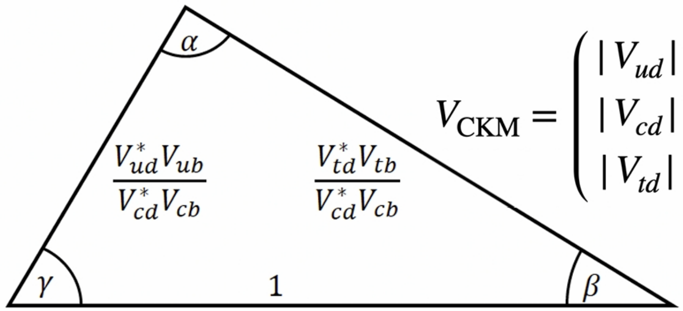
First measurement of mixing-induced CP violation in $B^0 \to \pi^0\pi^0$

Conventional time-dependent analysis:require a data set **twenty times** larger



Semileptonic decay: CKM matrix

- Important to constrain CKM unitarity triangle & test SM
- Determinations via inclusive or exclusive semileptonic B decays
- Long-standing “**Vxb-puzzle**”: discrepancy btw. inclusive and exclusive determinations



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

$$V_{\mathrm{CKM}} V_{\mathrm{CKM}}^{\dagger} = \mathbf{1}$$

Exclusive

$B \to \pi \ell \nu$, $B \to \rho \ell \nu$, $B \to D^{(*)} \ell \nu$, $\Lambda_b \to p \ell \nu$, etc.

$$\mathscr{B} \propto \left|V_{xb}\right|^2 f^2$$

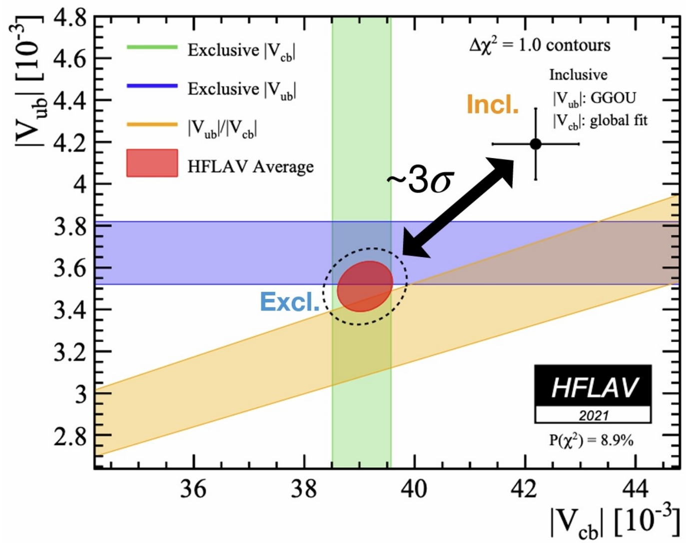
Form factor f (LCSR, LQCD)

Inclusive

$$B \to X_u \ell \nu, \ B \to X_c \ell \nu$$

$$\mathscr{B} \propto \left|V_{xb}\right|^2 \left[1 + \frac{c_5(\mu)\langle O_5 \rangle(\mu)}{m_b^2} + \frac{c_6(\mu)\langle O_6 \rangle(\mu)}{m_b^3} + O\left(m_b^4\right)\right] \qquad \left|V_{xb}\right| = \sqrt{\frac{\Delta \mathscr{B}}{\tau_B \cdot \Delta\Gamma}}$$

+ Shape Function / Fermi Motion (OPE)



$B^+ \to \mu^+\nu_\mu$

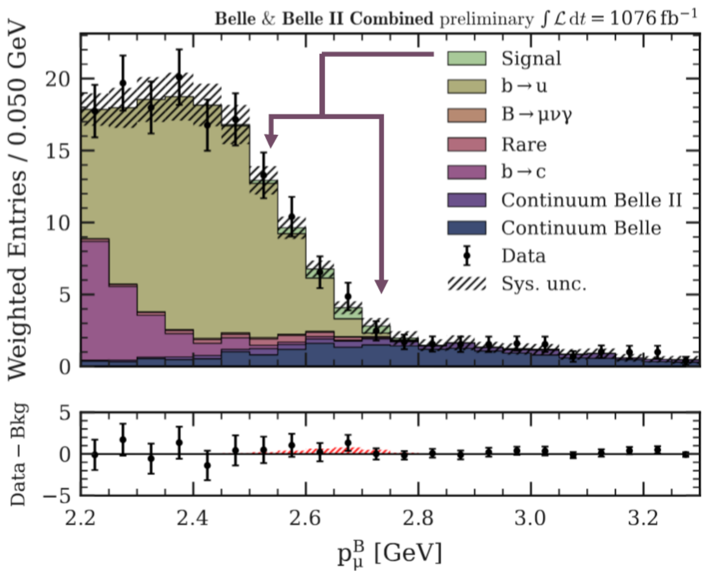
[arXiv:2602.09800]

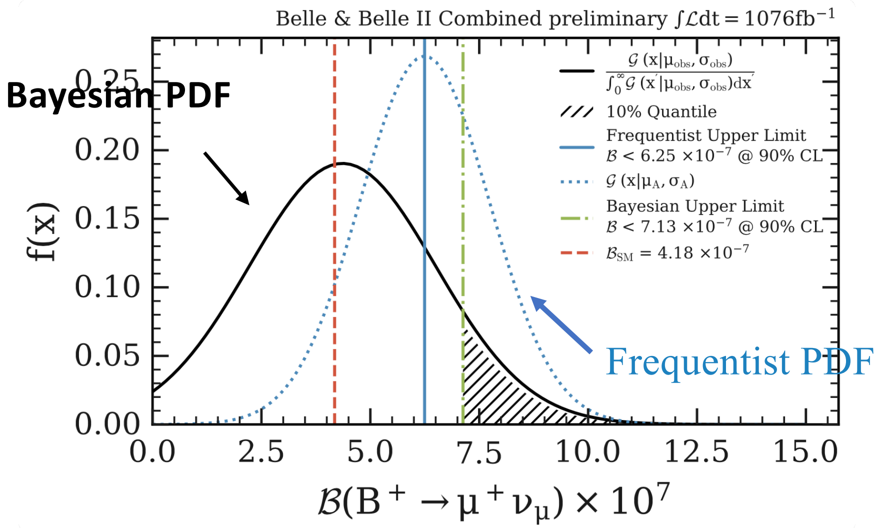
- SM branching fraction:

$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) = \frac{G_F^2 m_B m_\mu^2}{8\pi}\left(1 - \frac{m_\mu^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_{B^+},$$

- SM predicted: $B = (4.18 \pm 0.44)\times 10^{-7}$.
- Belle: $B = (5.3 \pm 2.0 \pm 0.9)\times 10^{-7}$ (2.8σ)

  (PRD 101 (2020) 032007)





- Belle + Belle II (1076/fb):
  - $B(B^+ \to \mu^+\nu_\mu) = (4.36 \pm 1.89 \pm 1.01)\times 10^{-7}$ (2.35σ)

$B(B^+ \to \mu^+\nu_\mu) < 7.13\times 10^{-7}$ (*Bayesian Upper Limit*)

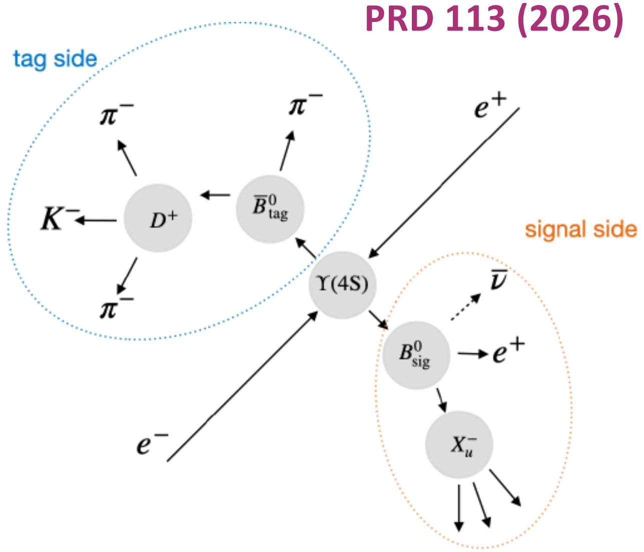
$B(B^+ \to \mu^+\nu_\mu) < 6.25\times 10^{-7}$ (*Frequentist Upper Limit*)

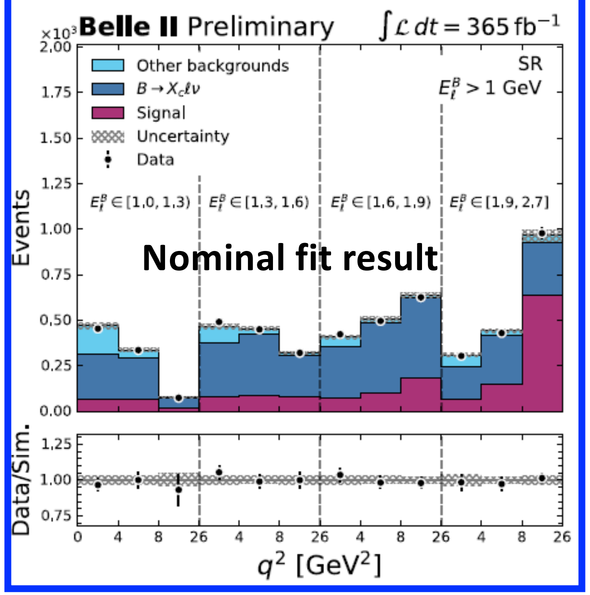
These are the most stringent limits to date.

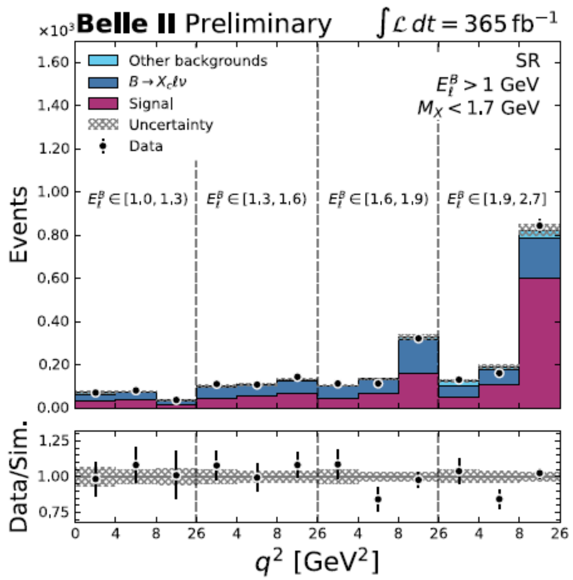
Inclusive $B \to X_u \ell \nu$

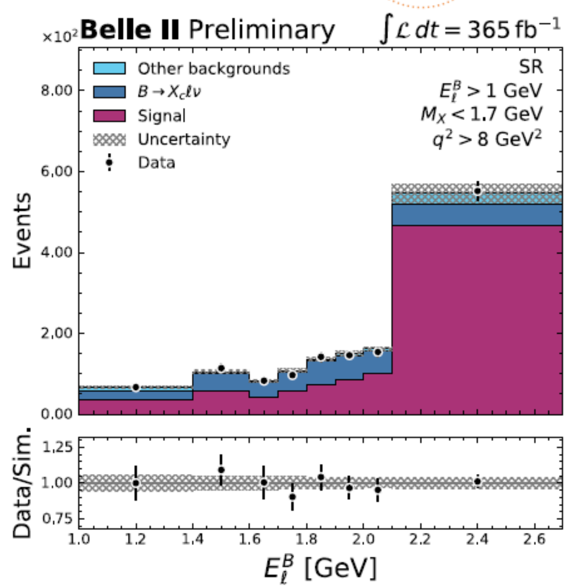
PRD 113 (2026) 032004

- **Reconstruct:** Combined signal lepton on the **signal side** with fully reconstructed hadronic B on **tag side**
- **Large backgrounds** from dominant $B \to X_c \ell \nu$ decays
  - Efficiently suppressed with MLP using different event shape variables
  - Normalization and shape mismodelling **corrected** using **control regions** in data
- **Extract signal** with 2D fit to lepton energy in B restframe E_ℓ^B & momentum transfer $q^2 = (p_\ell + p_\nu)^2$





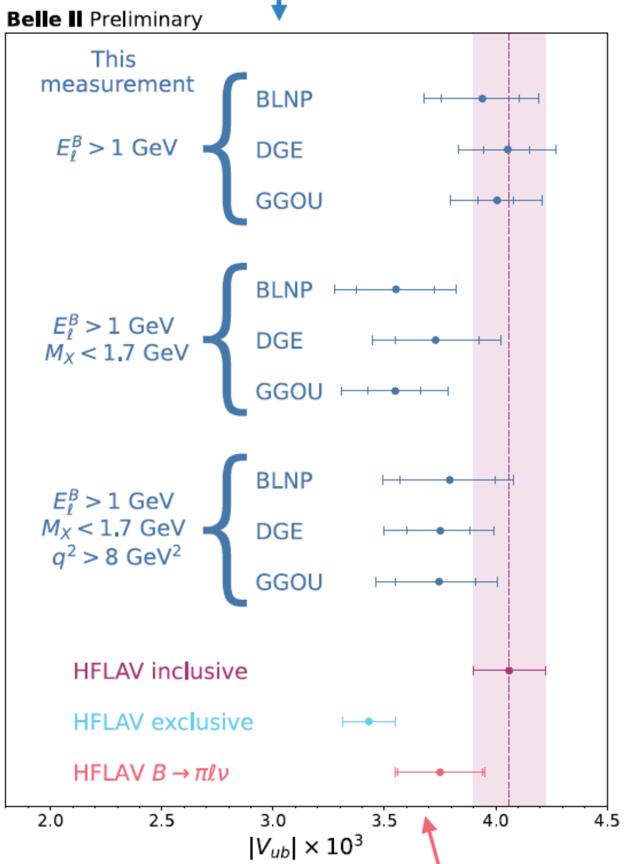




Inclusive $B \to X_u \ell \nu$

PRD 113 (2026) 032004

Predictions of the partial rate



Exclusive Average for $B \to \pi \ell \nu$:

$$|V_{ub}| = (3.75 \pm 0.06_{\rm exp} \pm 0.19_{\rm theo}) \times 10^{-3}$$

BLNP model: PRD72,073006; NPB 699,335

DGE model: JHEP 01 (2006) 097

GGOU model: JHEP 10 (2007) 058.

Determine $|V_{ub}|$ from the measured **partial branching fractions** in the 3 different phase space regions:

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell^+ \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u \ell^+ \nu_\ell)}}$$

Nominal result: $E_\ell^B > 1$ GeV with GGOU

$$\boxed{|V_{ub}| = (4.01 \pm 0.19^{+0.07}_{-0.08}) \times 10^{-3}}$$

Covering 87% of phase space

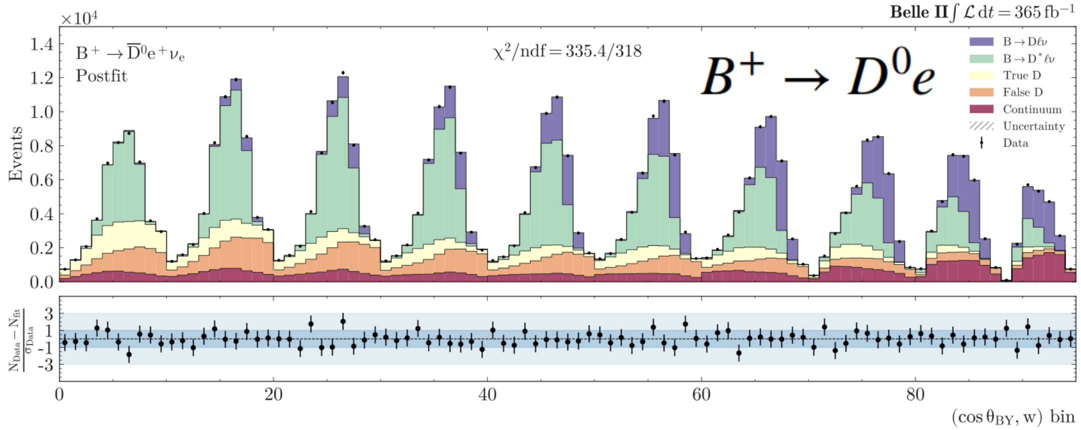
Dominant systematics:

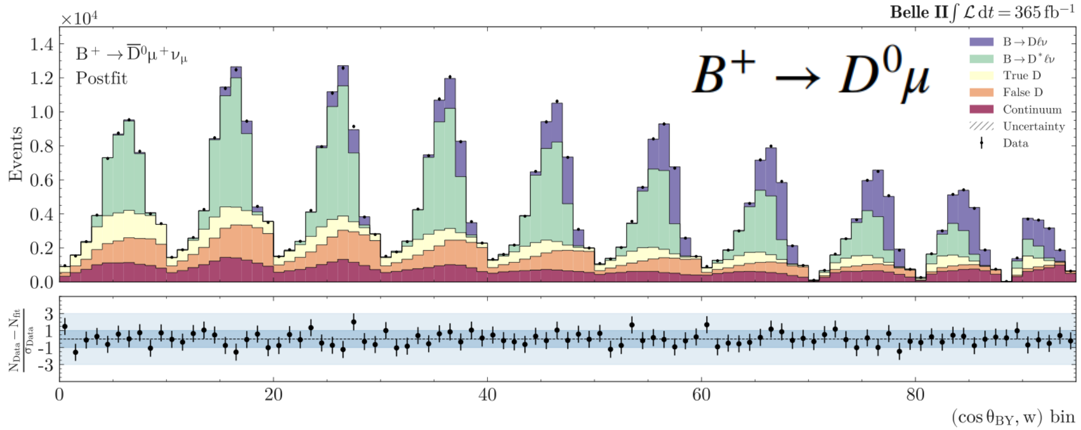
- $B \to X_u \ell \nu$ modelling: (m_b, a) where $a = f(m_b, \mu_\pi^2)$ in Kagan-Neubert scheme
- $B \to X_c \ell \nu$ composition differences between SR and CR
- X_u fragmentation modelling

Competitive with previous measurements!

$|V_{cb}|$ from untagged exclusive $B \to D\ell\nu_\ell$

Signal yields are extacted in 10 bins of w by fitting the simultaneously in the electron and muon channels and in the charged and neutral modes





$$w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

The recoil variable $w = v_B \cdot v_D$

$\cos\vartheta_{BY}$: the angle between the signal B and Dℓ system

PRD 112, 112009 (2025)

$$\mathcal{B}(B^0 \to D^- \ell^+ \nu_\ell) = (2.06 \pm 0.05(\mathrm{stat.}) \pm 0.10(\mathrm{syst.}))\,\%$$

$$\mathcal{B}(B^+ \to \bar{D}^0 \ell^+ \nu_\ell) = (2.31 \pm 0.04(\mathrm{stat.}) \pm 0.09(\mathrm{syst.}))\,\%$$

Extract by fitting values of $\Delta\mathcal{T}/\Delta w$ using BCL (Phys. Rev. D 82, 099902 (2010)) form factor parameterization.

$$|V_{cb}| = (39.2 \pm 0.4(\mathrm{stat.}) \pm 0.6(\mathrm{syst.}) \pm 0.5(\mathrm{th.})) \times 10^{-3}$$

- **Result in agreement with exclusive HFLAV average**
- **Most precise measurement using $B \to D\ell\nu_\ell$ decays**

Inclusive $B \to X_s \ell^+ l^-$

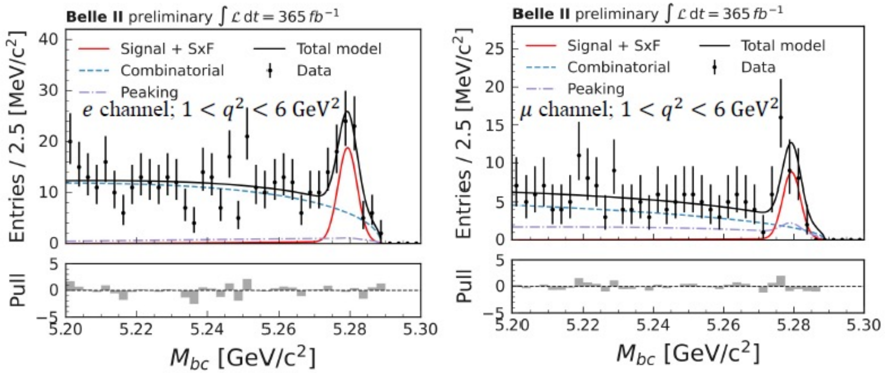
Partial branching fraction (BF) in $1 < q^2 < 6$ GeV₂

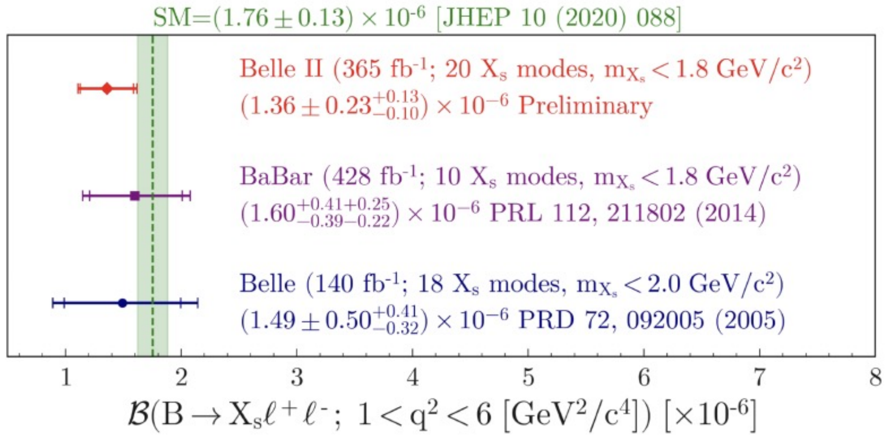
- Anomalies in *exclusive* measurements
  - ✓ $\mathcal{B}(B \to K^{(*)}\mu\mu)$ lower than SM in low-q^2 ($[1,6]$ GeV^2)
  - ✓ but large theory uncertainty ($\sim 20\%$) in $B \to K$ FF

- What about *inclusive*?
  - ✓ much less SM theory error ($\sim 7\%$)
  - ✓ $\mathcal{B}^{SM}(B \to X_s l^+ l^-) = 4.2 \times 10^{-6}$

- Run 1 Belle II data (365 fb^{-1})   Untagged analysis
- **Sum-of-Exclusive** method
  - ✓ X_s in 20 hadronic modes in $m_{X_s} < 1.8$ GeV/c^2.
  - ✓ visible fraction $\sim 71\%$ (incl. K_L^0) estimated with Pythia (Lund String mode[2])

- Signal extraction
  - ✓ by fitting to $M_{\rm bc} = \sqrt{E^2_{\rm beam} - p_B^2}$
  - ✓ peaking backgrounds from fake leptons – subtracted using data





$$\mathcal{B}(B \to X_s e^+ e^-) = (1.60 \pm 0.33^{+0.15}_{-0.11}) \times 10^{-6}$$

$$\mathcal{B}(B \to X_s \mu^+ \mu^-) = (1.13 \pm 0.33^{+0.11}_{-0.08}) \times 10^{-6}$$

$$\mathcal{B}(B \to X_s \ell^+ \ell^-) = (1.36 \pm 0.23^{+0.13}_{-0.10}) \times 10^{-6}$$

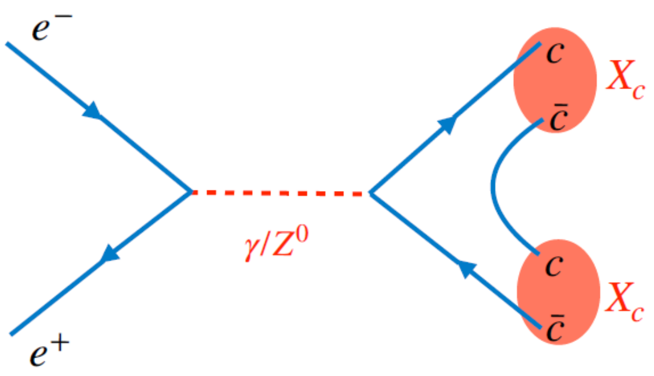
good agreement with SM, factor 2 improvement in precision

Charm

Charm production at Belle II

- At Belle II, e^+e^- mainly collide at 10.58 GeV to make $\Upsilon(4S)$ resonance mainly decaying into $B\bar{B}$.
- Meanwhile, **continuum processes $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) have large cross sections**.
- Two ways to produce charm samples: **1) $e^+e^- \to c\bar{c}$, and 2) $B \to$ charm decays**.

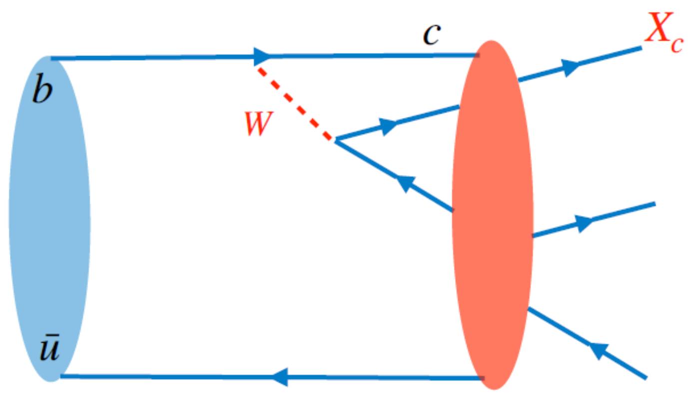
Two charmed hadrons produced from continuum



Large statistics but high level background

Only relative branching fractions can be measured
Absolute values obtained using external inputs

One or more charmed hadrons produced in B decays



Low statistics but very clean sample

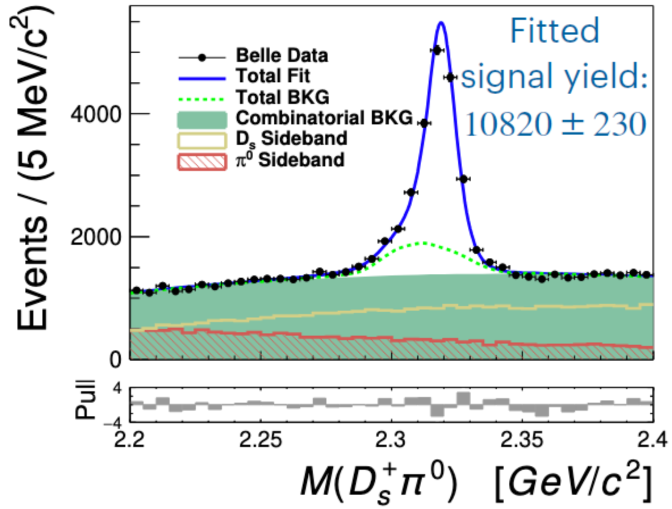
Absolute branching fractions can be obtained:
cross section of $B\bar{B}$ precisely measured

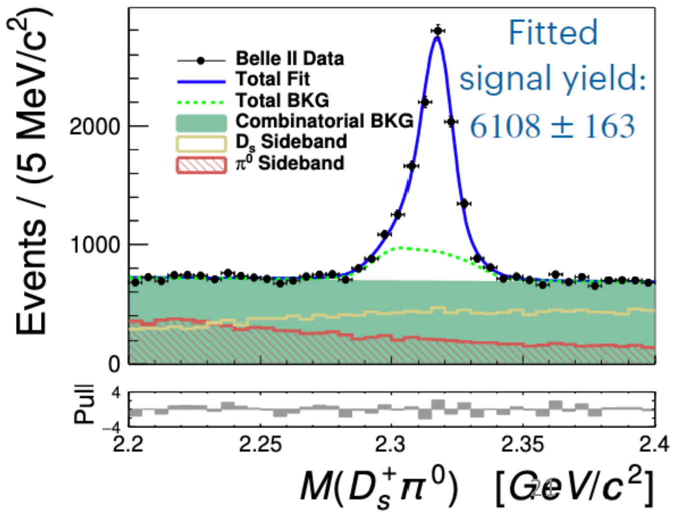
First observation of $D_{s0}^{*}(2317)^{+} \to D_s^{*+}\gamma$

PRL **136**, 241901
FEATURED IN PHYSICS

Motivation and analysis strategy

- Nature of $D_{s0}^{*}(2317)^{+}$ and $D_{s1}(2460)^{+}$ unclear: $c\bar{s}$ states, hadronic molecules, mixed configs, tetraquarks → motivate further studies
- Reconstruct $D_s^{+} \to \phi[\to K^{+}K^{-}]\pi^{+}$ and $D_s^{+} \to \bar{K}^{*0}[\to K^{-}\pi^{+}]K^{+}$ decays
  $D_{s0}^{*}(2317)^{+}$ candidates from $D_s^{*+}\gamma$ or $D_s^{+}\pi^{0}$ combinations
- $D_{s0}^{*}(2317)^{+} \to D_s^{+}\pi^{0}$ as normalization channel: yield obtained from an unbinned maximum-likelihood fit to $M(D_s^{+}\pi^{0})$ spectra
- Detailed study of background sources: use D_s and π^{0} sidebands
  Peaking background from a missing γ in $D_{s1}(2460)^{+} \to D_s^{*+}\pi^{0}$ decays





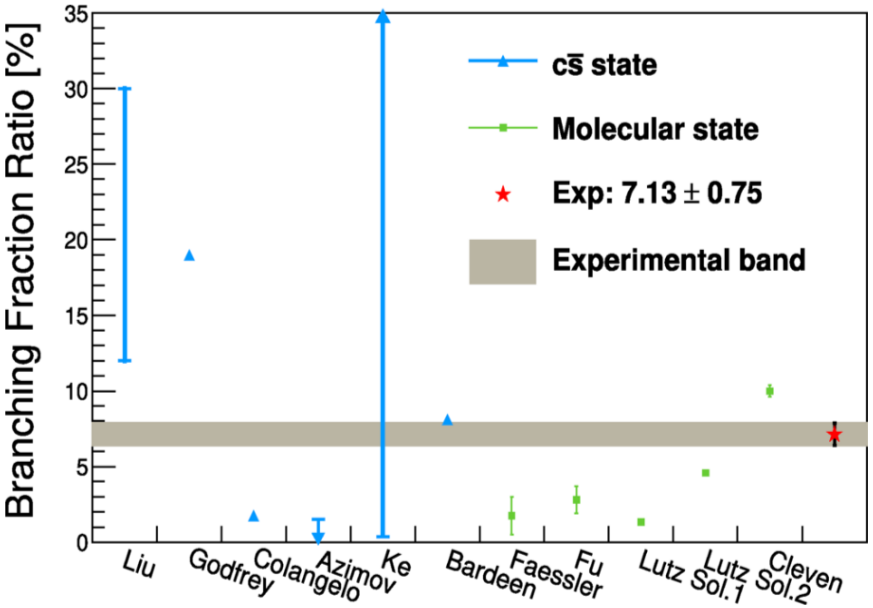
First observation of $D_{s0}^{*}(2317)^{+} \to D_s^{*+}\gamma$

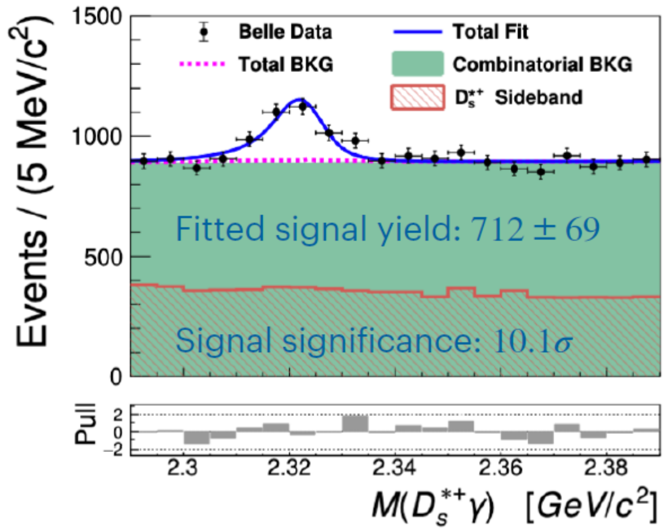
PRL **136**, 241901
FEATURED IN PHYSICS

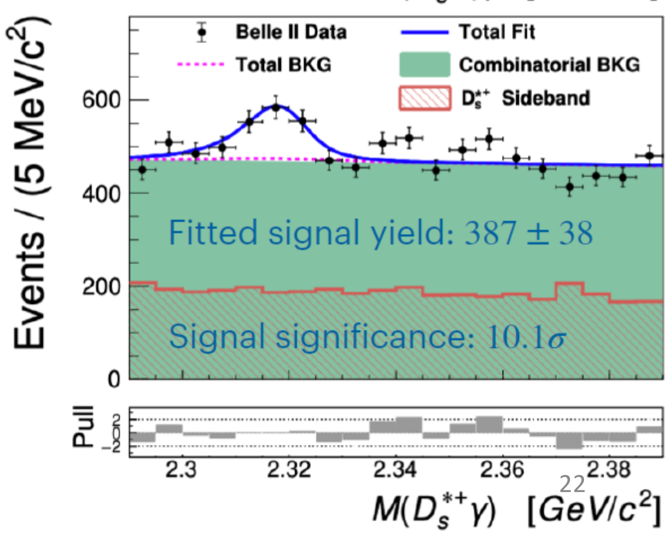
Results

First measurement of $R = \mathscr{B}(D_{s0}^{*+} \to D_s^{*+}\gamma)/\mathscr{B}(D_{s0}^{*+} \to D_s^{+}\pi^0)$ using a simultaneous unbinned maximum-likelihood fit to $M(D_s^{*+}\gamma)$ spectra

$$R = (7.14 \pm 0.70_{stat} \pm 0.23_{syst})\ \%$$







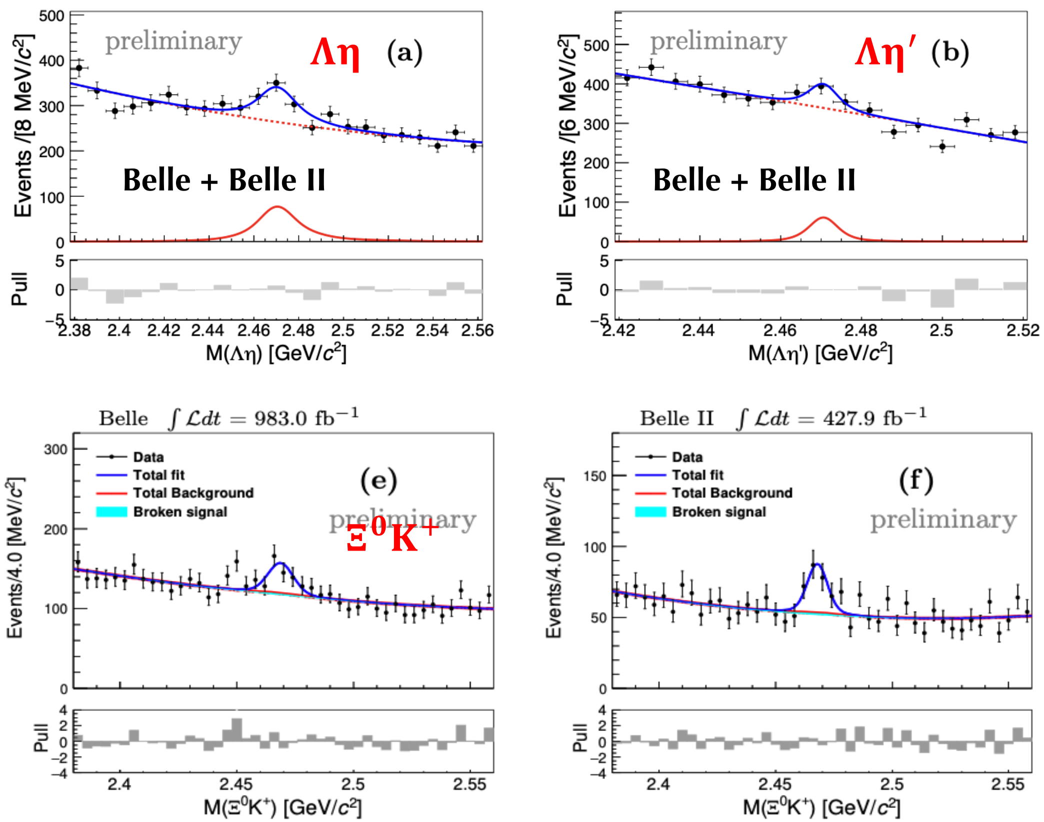
Above molecular predictions, below quark-model expectations: could be a mixed configuration

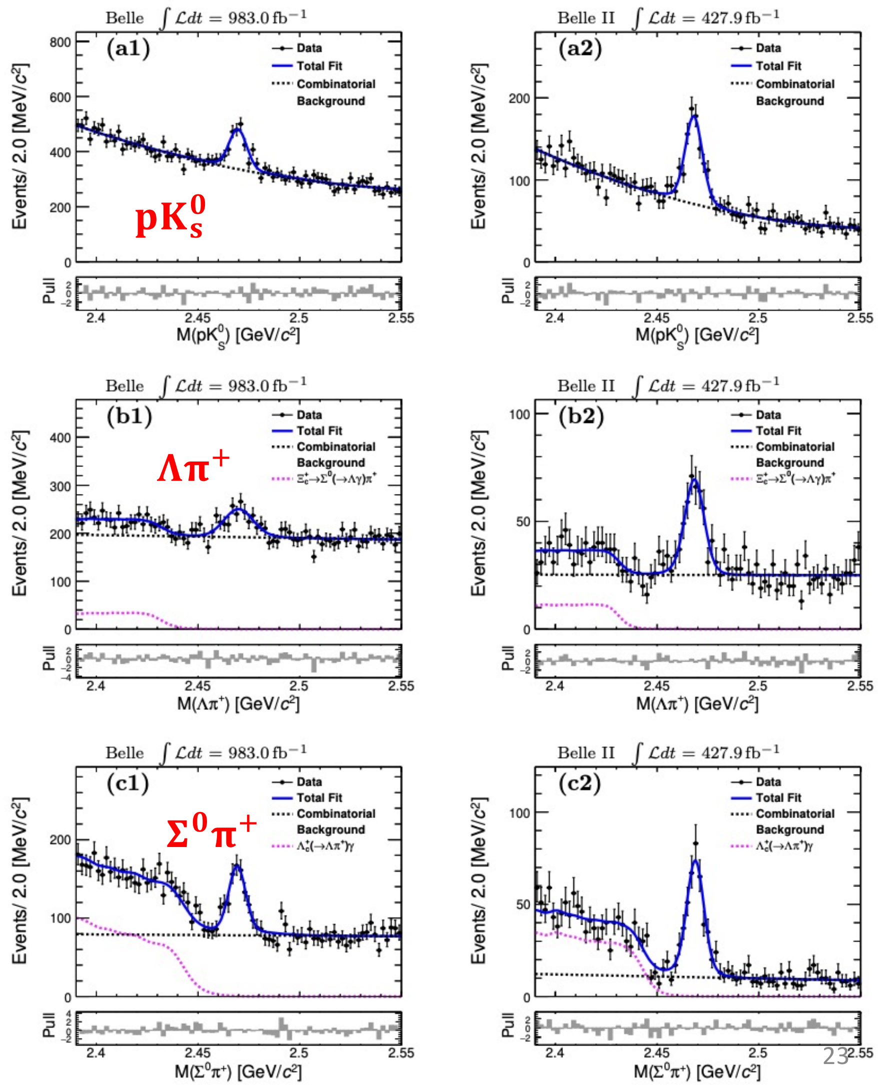
Ξ_c^+ and Ξ_c^0 decays

$e^+e^- \to \Xi_c^+/\Xi_c^0$ + anything

Reconstruct:

- $\Xi_c^0 \to \Lambda\eta$, $\Xi_c^0 \to \Lambda\eta'$ (singly Cabibbo-suppressed (SCS))
- $\Xi_c^+ \to \Xi^0 K^+$, $\Xi_c^+ \to pK_s^0$, $\Xi_c^+ \to \Lambda\pi^+$, $\Xi_c^+ \to \Sigma^0\pi^+$ (SCS)

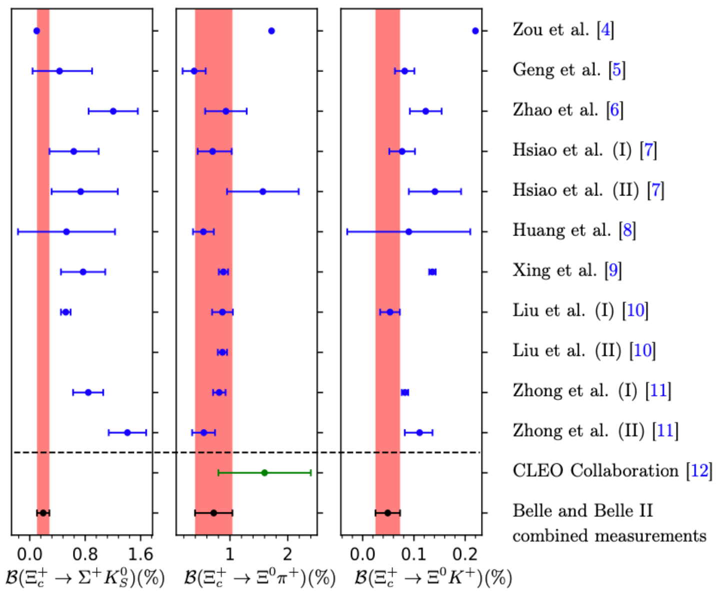




Branching fractions

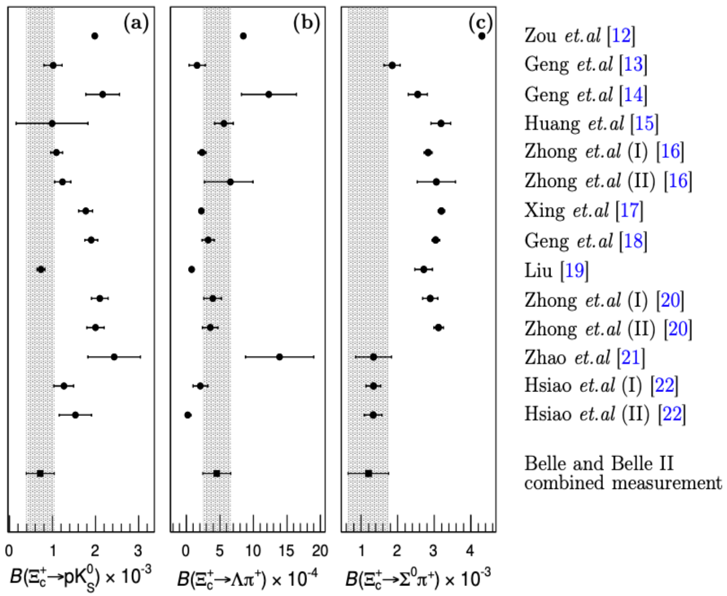
First or most precise measurements!

[JHEP 08 (2025) 195]



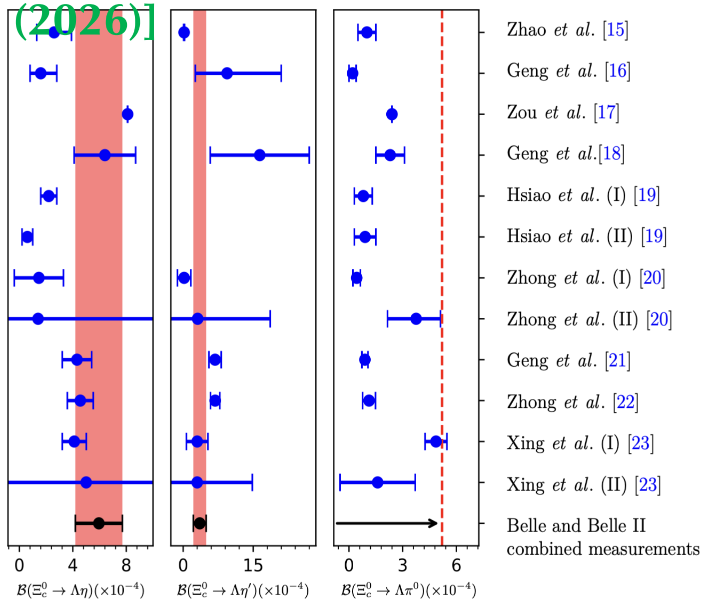
[4] the pole model (Pole), current algebra (CA)
[5-11] SU(3)$_F$ flavor symmetry

[JHEP 03 (2025) 061]



[12] Pole and CA
[13-22] SU(3)$_F$ flavor symmetry

[PRD 113, 032015 (2026)]



[15, 17-23] SU(3)$_F$ flavor symmetry
[16] Pole and CA
[22] Topological diagrammatic approach

Next steps: 1. Explore three-body decays;
2. Amplitude analyses to search for new intemediate states and identify J^P.

CP Violation in D decays

Measurement of the time-integrated *CP* asymmetry in $D^0 \to K_S K_S$ decays using Belle and Belle II data, PRD 111, 012015 (2025)

Search for *CP* violation in $D^+_{(s)} \to K_S K^- \pi^+ \pi^+$ decays using triple and quadruple products, JHEP 04 (2025) 036

Measurement of the *CP* asymmetry in $D^+ \to \pi^+ \pi^0$ decays at Belle II, PRD 112, L031101 (2025)

Measurement of the time-integrated CP asymmetry in $D^0 \to \pi^0 \pi^0$ decays at Belle II, PRD 112, 012006 (2025)

Measurement of the time-integrated *CP* asymmetry in $D^0 \to K_S K_S$ decays using opposite-side flavor tagging at Belle and Belle II, PRD 112, 012017 (2025)

Measurement of the *CP* asymmetry in $\boldsymbol{D^0} \to \pi^+\pi^-\pi^0$ decays at Belle II, 2510.21224, PRD 113, 052006 (2026)

CPV in $D \to \pi\pi$

- **$D^0 \to \pi^+\pi^-$:**
  - the only channel with > 3σ evidence of CPV in charm.
  - The SM generates CPV through interference of a tree-level and suppressed QCD loop amplitude ΔI = 1/2 (I = isospin) [*Pys. Rev.D 85, 114036 (2012)*].

- **$D^+ \to \pi^+\pi^0$:**
  - I= 2 and can be reached from the I= 1/2 initial state only via a ΔI = 3/2 transition.
  - Therefore, any observation will confirm New Physics.

- **$D^0 \to \pi^0\pi^0$:**
  - Can have I=0 or I=2 and hence can have nonzero direct CP asymmetries in SM.
  - Isospin sum rule:

$$R = \frac{a_{CP}(\pi^+\pi^-)}{1+\frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}}-\frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{a_{CP}(\pi^0\pi^0)}{1+\frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}}-\frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{a_{CP}(\pi^+\pi^0)}{1-\frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}}+\frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)}$$

  - $a_{CP} \neq 0$, $R=0$: CP violation from the ΔI= 3/2 amplitude (New Physics!!)
  - R = (0.93 ± 3.1) × 10^{-3}, uncertainty is dominated by the $\pi^0\pi^0$ mode *HFLAV*

CP asymmetry in $D^+ \to \pi^+\pi^0$

PRD 112, L031101 (2025)

- The physics variable that we are interested is $A_{CP}(D^+ \to \pi^+\pi^0) = \frac{\Gamma(D^+\to\pi^+\pi^0)-\Gamma(D^-\to\pi^-\pi^0)}{\Gamma(D^+\to\pi^+\pi^0)+\Gamma(D^-\to\pi^-\pi^0)}$
- But the variable easily accessed in exp is $A^{\pi\pi}_{raw} = \frac{N(D^+\to\pi^+\pi^0)-N(D^-\to\pi^-\pi^0)}{N(D^+\to\pi^+\pi^0)+N(D^-\to\pi^-\pi^0)}$
- $A^{\pi\pi}_{raw}$ is related by $A^{\pi\pi}_{CP} = A^{\pi\pi}_{raw} - \boxed{(A^D_{prod} + A^{\pi}_{\epsilon})} \to$ **nuisance asymmetries**

A^D_{prod}: forward-backward asymmetric production in e^+e^- collisions of charm hadrons, due to $\gamma^* - Z^0$ interference and higher-order QED effects, is an odd function of $\cos\theta_{CM}(D^\pm)$.

$A^{\pi^\pm}_{\epsilon}$: detection asymmetry of the low-momentum tagging pions.

use $D^+ \to \pi^+ K^0_S$ as a control mode to estimate this

$D^+ \to \pi^+ K^0_S$ $(Br = (1.562 \pm 0.031)\,\%$, Cabibbo-favored)

Control mode

$$\boxed{A^{\pi\pi}_{CP} = A^{\pi\pi}_{raw} - A^{\pi K_S}_{raw} + A_{K_S}}$$

Signal mode

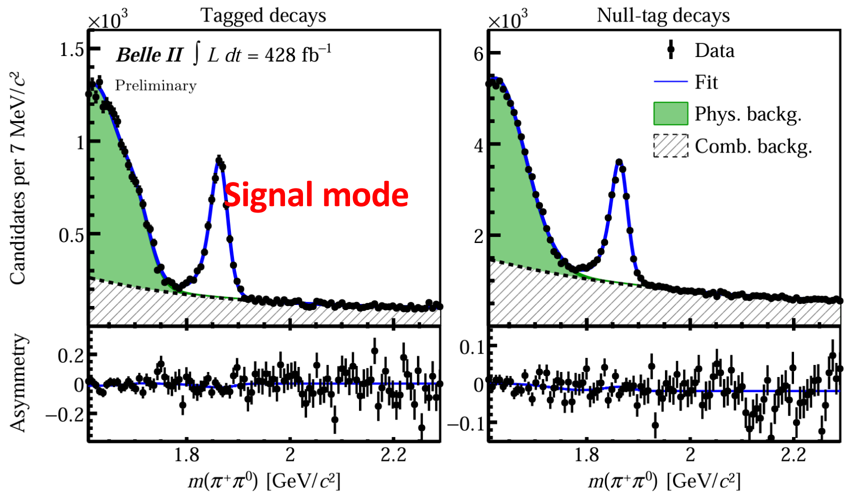
$$A^{\pi K_S}_{raw} = A_{K_S} + \boxed{A^D_{prod} + A^{\pi^\pm}_{\epsilon}}$$

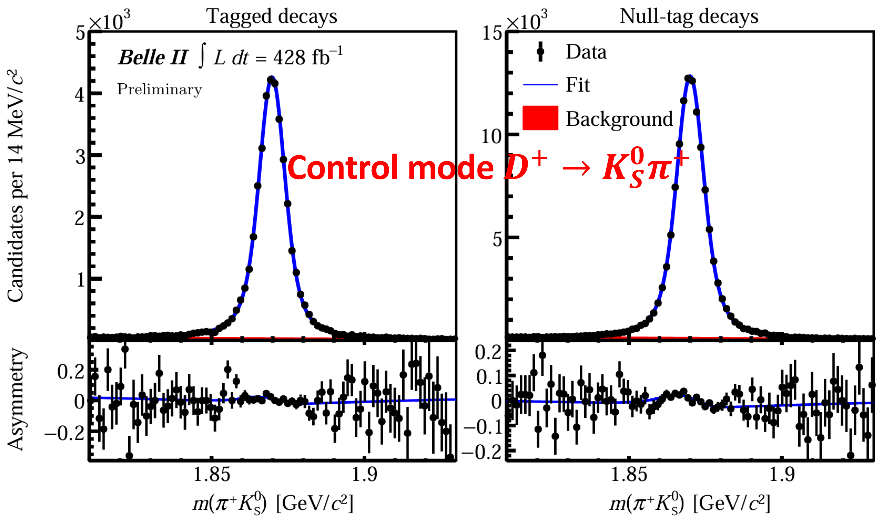
$\sim -0.4\,\%$

$A_{K^0_S}$: 1, CP-violation in the K^0-$\bar{K}^0$system.
2, different nuclear-interaction cross-sections for K^0 and $\bar{K}^0$ mesons with detector.

CP asymmetry in $D^+ \to \pi^+\pi^0$

PRD 112, L031101 (2025)





Signal mode

	Tagged	Null-tag
Yield	5130±110	18510±240
A_{raw}	(-2.9±1.8)%	(-0.4±1.0)%

Control mode

	Tagged	Null-tag
Yield	39630±300	123560±500
A_{raw}	(0.54±0.53)%	(0.33±0.30)%

- Using 428 /fb, Belle II obtain:

1. $A_{CP}(D^+ \to \pi^+\pi^0) = [-3.9 \pm 1.8(stat) \pm 0.2(syst)]\,\%$ for D^*-tagged sample;
2. $A_{CP}(D^+ \to \pi^+\pi^0) = [-1.1 \pm 1.0(stat) \pm 0.1(syst)]\,\%$ for null-tag sample.

- Combined:

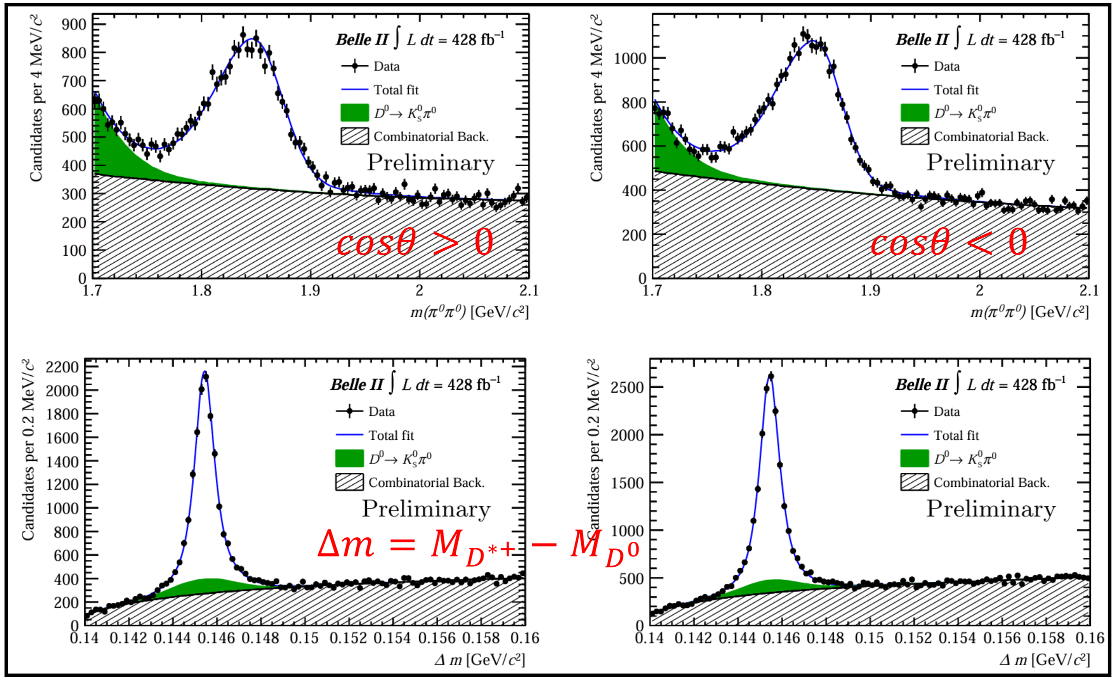
$$A_{CP}(D^+ \to \pi^+\pi^0) = [-1.8 \pm 0.9(stat) \pm 0.1(syst)]\,\%,$$

- ○ most precise measurement
- ○ improved precision compared to Belle's result: $(2.3 \pm 1.3 \pm 0.2)\%$ [*Phys. Rev. D 97, 011101 (2018)*]

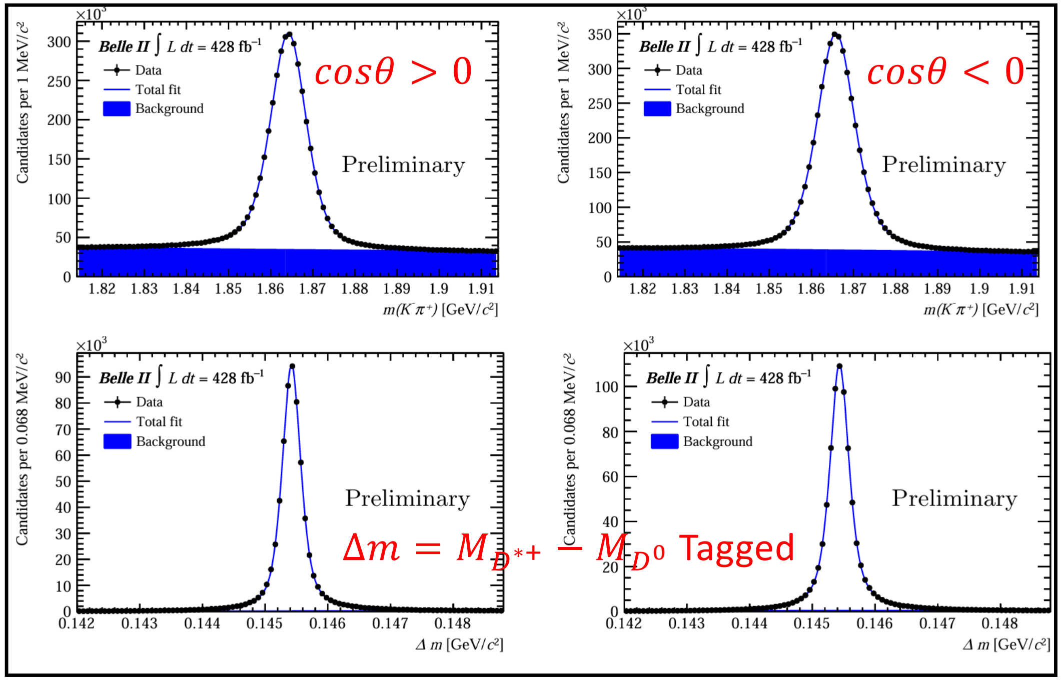
CP asymmetry in $D^0 \to \pi^0\pi^0$

PRD 112, 012006 (2025)

Signal mode



Control mode $D^0 \to K^-\pi^+$



- **A_{CP} ($D^0 \to \pi^0\pi^0$): (0.30 ± 0.72 ± 0.20) %**
  - 15% less precise than the Belle measurement: (0.030 ± 0.64 ± 0.10) % [*Phys. Rev. Lett. 112, 211601 (2014)*]

- **R= (1.5 ± 2.5) $\times$ 10^{-3}**, 20% improved precision.
  - The improved precision per luminosity due to Belle II's better reconstruction π^0 .

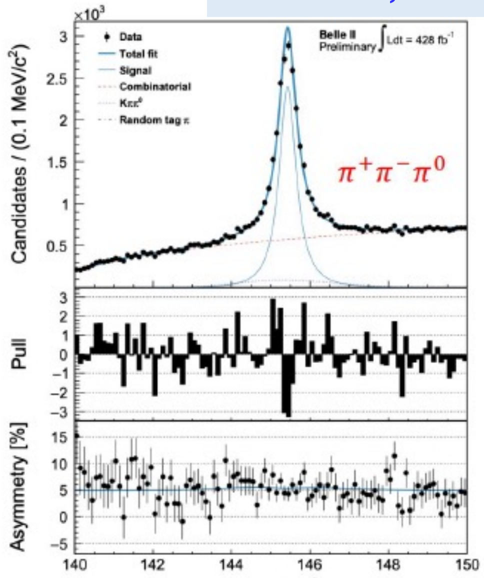
CP asymmetry in $D^0 \to \pi^+\pi^-\pi^0$

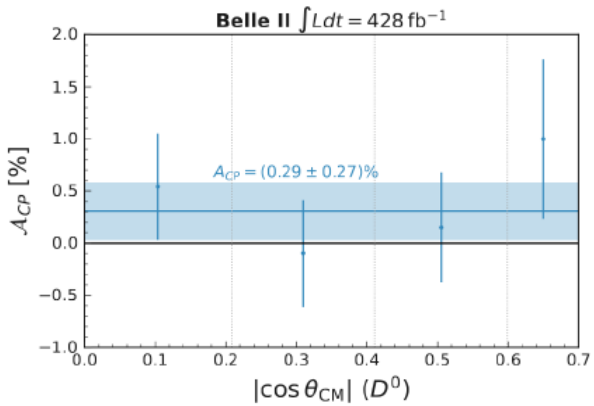
PRD 113, 052006 (2026)

- SCS three-body decay, interference of several amplitudes
- Signal: D^{*+} tagged sample for $D^0 \to \pi^+\pi^-\pi^0$.

$$\mathcal{A}_{\rm raw}^{\pi\pi\pi^0} \simeq \mathcal{A}_{CP} + \mathcal{A}_{\rm prod} + \mathcal{A}_{\varepsilon}^{\pi\pi\pi^0} + \mathcal{A}_{\varepsilon}^{\pi_{\rm tag}}$$

- Control mode: tagged and untagged $D^0 \to K^-\pi^+$
- Simultaneous fit to (Δm, $m(\pi^+\pi^-\pi^0)$) in 8 bins of $\cos\theta_{CM}$, averaged symmetrically around 0 to remove the production asymmetry
- A_{CP} ($D^0 \to \pi^+\pi^-\pi^0$): $(0.29 \pm 0.27 \pm 0.13)$ %
  - Most precise measurement till date
  - 34% more precise than BABAR with just 10% more statistics



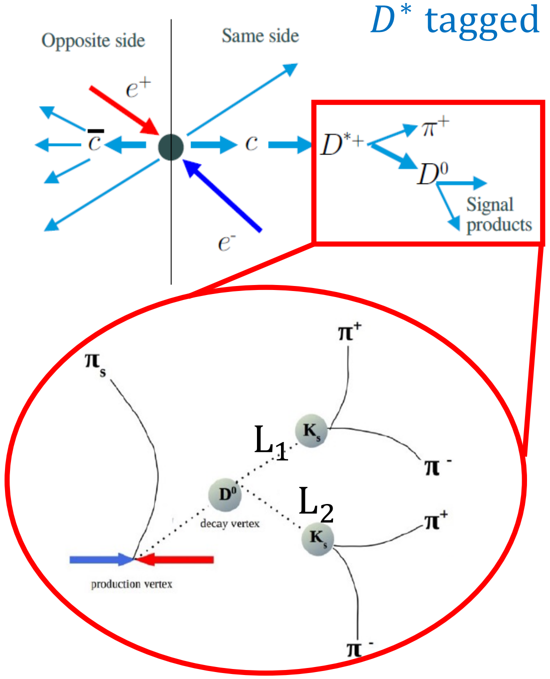


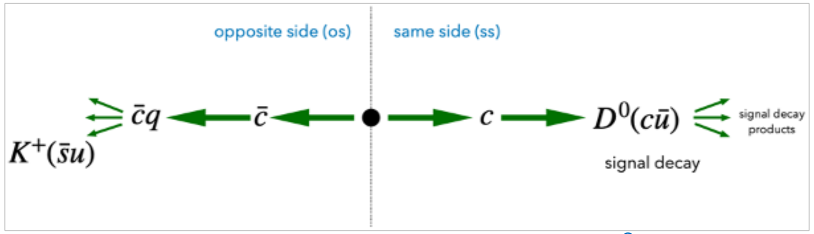
Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$

- Proceeds through color- and Cabibbo-suppressed transition
- Involves the interference between $c \to us\bar{s}$ and $c \to ud\bar{d}$ amplitudes
- Expected CP asymmetry of 1%
- World average:

  $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.9 \pm 1.0)\%$, is limited by statistics.
- Belle (980 fb^{-1}) + Belle II (428 fb^{-1}) data are used
- $A_{CP}(D^0 \to K_S^0 K_S^0) = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$
- Two independent measurements:
  - D^* tagged D^0 [Phys.Rev.D 111 (2025) 1, 012015]
    - Important definition: $S_{min}(K_S^0) = \log[\min(L_1/\sigma_{L_1}, L_2/\sigma_{L_2})]$
  - Opposite-side flavor tagged D^0 [Phys.Rev.D 112 (2025) 1, 012017]
    - Flavor $q = +1$ for D^0, $q = -1$ for $\bar{D}^0$
    - Dilution factor $r = 1 - 2\omega$ (ω is the mistag probability)

D^* tagged D^0





Opposite-side flavor tagged D^0

Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$ (D^* tagged D^0)

D^* tagged D^0

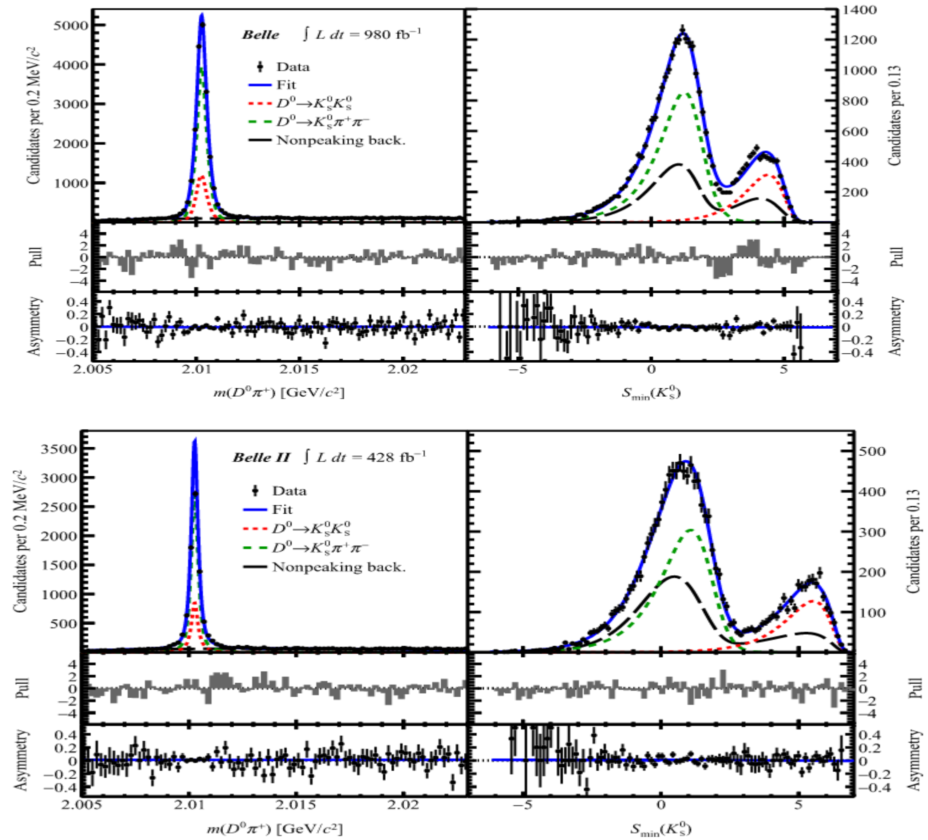
- Use $D^{*+} \to D^0 \pi^+$ to tag flavor
- Determine production and detection asymmetries using $D^0 \to K^+K^-$

$$A_{raw}^{K_S^0 K_S^0} = \frac{N(D^0 \to K_S^0 K_S^0) - N(\bar{D}^0 \to K_S^0 K_S^0)}{N(D^0 \to K_S^0 K_S^0) + N(\bar{D}^0 \to K_S^0 K_S^0)}$$
$$= A_{CP} + A_P^D + A_\epsilon^{\pi_s}$$

$$A_{CP}(D^0 \to K_S^0 K_S^0) = A_{raw}^{K_S^0 K_S^0} - A_{raw}^{K^+K^-} + A_{CP}(D^0 \to K^+K^-)$$

- Main background: $D^0 \to K_S^0 \pi^+ \pi^-$, separated by S_{min}
- 2D extended UML fit to $m(D^0\pi^+)$ and $S_{min}(K_S^0)$
- Belle: $A_{CP} = \left(-1.1 \pm 1.6(\text{stat.}) \pm 0.1(\text{syst.})\right)\%$
- Belle II: $A_{CP} = \left(-2.2 \pm 2.3(\text{stat.}) \pm 0.1(\text{syst.})\right)\%$
- Belle + Belle II: $A_{CP} = \left(-1.4 \pm 1.3(\text{stat.}) \pm 0.1(\text{syst.})\right)\%$

Phys.Rev.D 111 (2025) 012015



Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$ (Opposite-side flavor tagged D^0)

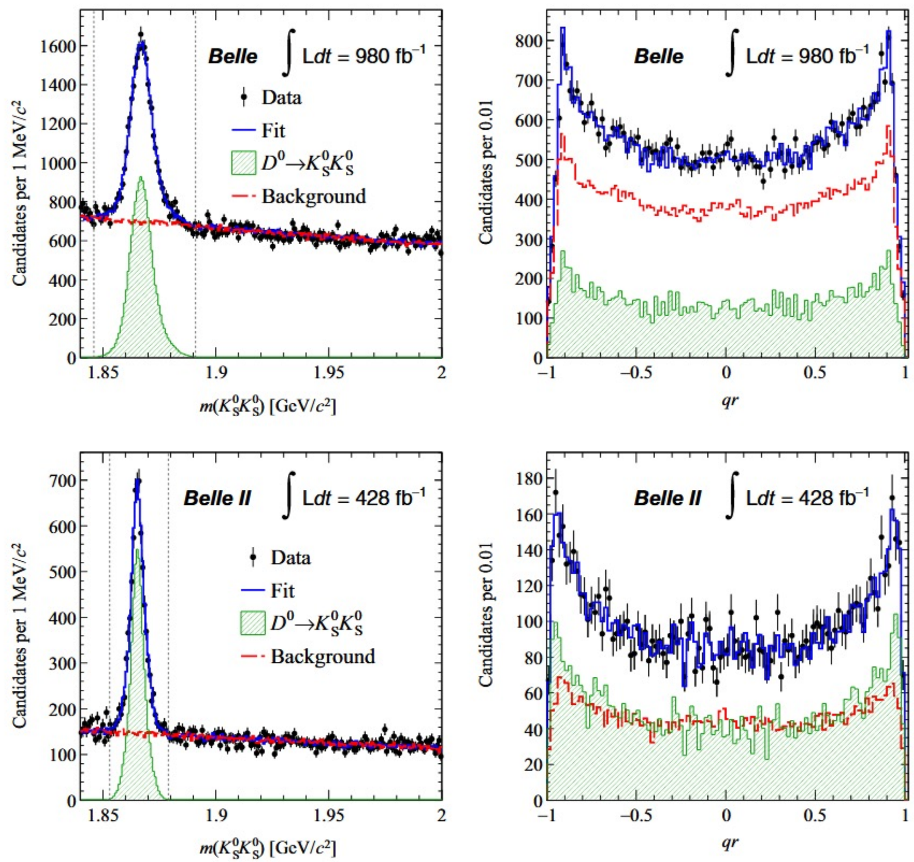
- Use information from the other tracks in the event to tag flavor
- Remove all the candidates in used in the D^* tagged measurement
- Background from partially reconstructed $D_s^+ \to K_S^0 K_S^0 \pi^+$ (peak at lower mass values)
- 2D extended UML fit to $m(K_S^0 K_S^0)$ and qr
- Belle: $A_{CP} = (2.5 \pm 2.7(\text{stat.}) \pm 0.4(\text{syst.}))\%$
- Belle II: $A_{CP} = (-0.1 \pm 3.0(\text{stat.}) \pm 0.3(\text{syst.}))\%$
- Belle + Belle II: $A_{CP} = (1.3 \pm 2.0(\text{stat.}) \pm 0.2(\text{syst.}))\%$
- Combined two tag methods:

$$A_{CP} = (-0.6 \pm 1.1(\text{stat.}) \pm 0.1(\text{syst.}))\%$$

The most precise determination to the date.

Agree with results from other experiments.

Phys.Rev.D 112 (2025) 012017



First measurement of $A_{cp}(\Xi_c^+ \to \Sigma^+ h^+ h^-)$ and $A_{cp}(\Lambda_c^+ \to p\, h^+ h^-)$ at Belle II

PRD 113, 032017 (2026)

Motivation and analysis strategy

- $\Xi_c^+ \to \Sigma^+ h^+ h^-$, $\Lambda_c^+ \to p h^+ h^-$ $(h = \pi, K)$: first-ever measurements A_{CP} in 3-body baryon decays. Test U-spin symmetry

SM expectations

$$\boxed{\begin{aligned} A_{CP}(\Xi_c^+ \to \Sigma^+\pi^+\pi^-) + A_{CP}(\Lambda_c^+ \to pK^+K^-) = 0 \\ A_{CP}(\Xi_c^+ \to \Sigma^+K^+K^-) + A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-) = 0 \end{aligned}}$$

Get A_{CP} from

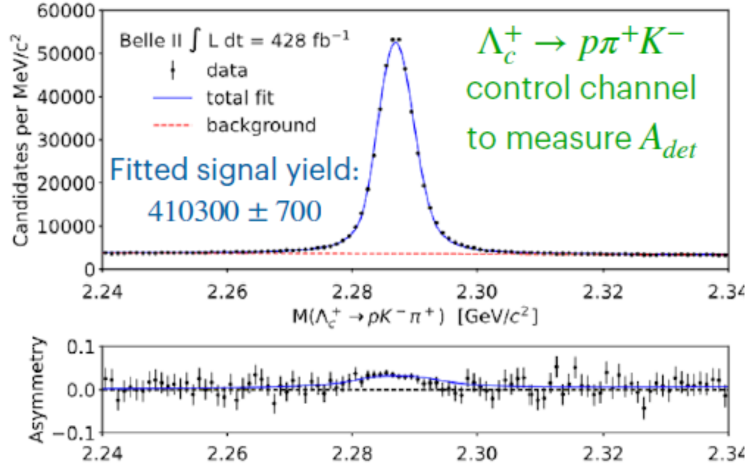
$$A_{raw}^{data} = A_{det} + A_{FB} + A_{CP}$$

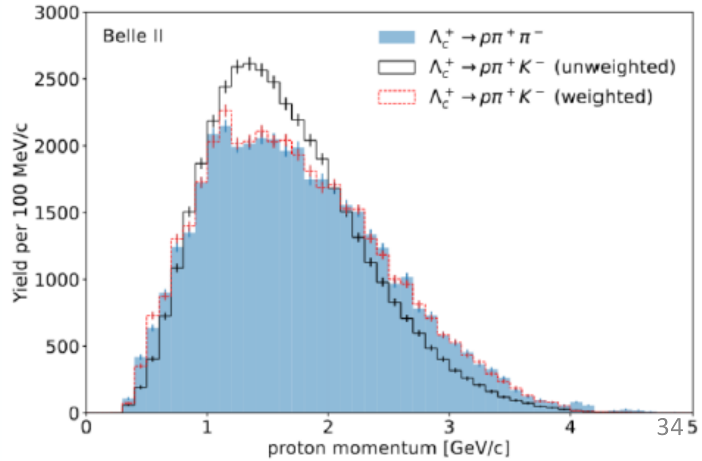
A_{raw}^{data}: what we measure

A_{det}: Measure detection asymmetry using control channels. Reweighing final states to mimic the signal ones.

A_{FB}: Cancel forward-backward asymmetry by averaging A_{raw}^{data} over opposite D production angles

A_{CP}: goal of the measurement





First measurement of $A_{cp}(\Xi_c^+ \to \Sigma^+ h^+ h^-)$ and $A_{cp}(\Lambda_c^+ \to p\, h^+ h^-)$ at Belle II

PRD 113, 032017 (2026)

Results

Signal yield extracted via unbinned maximum-likelihood fits to $M(\Xi_c^+)$ and $M(\Lambda_c^+)$; instrumental effects subtracted afterward

$$A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) = (3.7 \pm 6.6 \pm 0.6)\,\%$$

$$A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) = (9.5 \pm 6.8 \pm 0.5)\,\%$$

$$A_{CP}(\Lambda_c^+ \to p K^+ K^-) = (3.9 \pm 1.7 \pm 0.7)\,\%$$

$$A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) = (0.3 \pm 1.0 \pm 0.2)\,\%$$

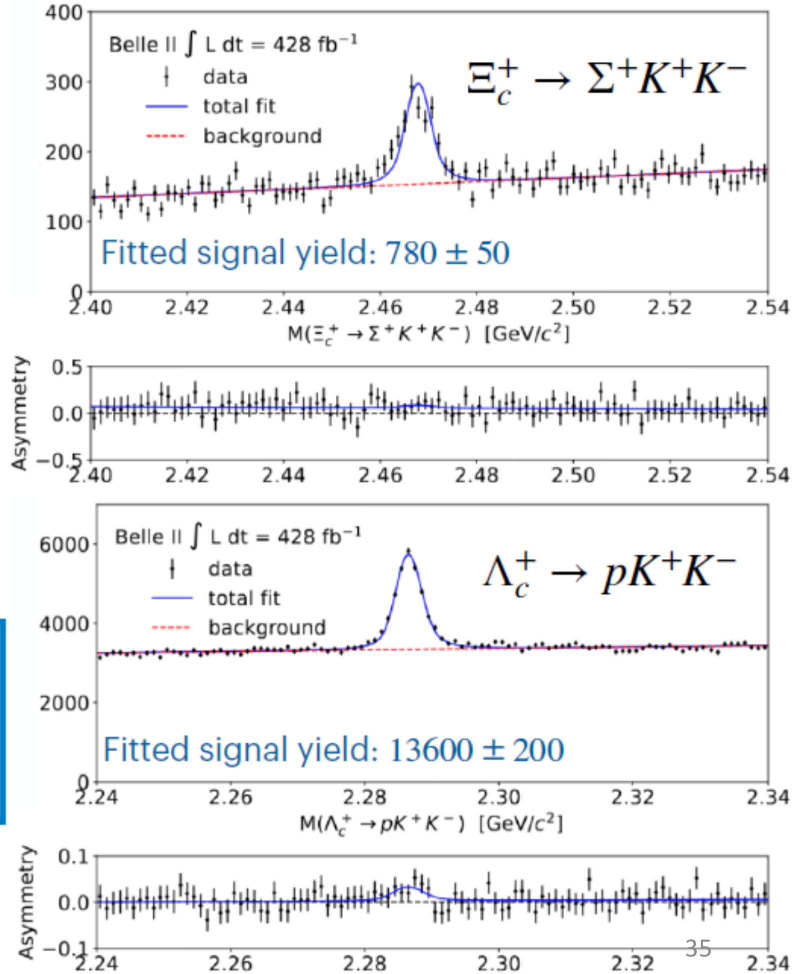
from which we get

$$A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) + A_{CP}(\Lambda_c^+ \to p K^+ K^-) = (13.4 \pm 7.0_{stat} \pm 0.9_{syst})\,\%$$

$$A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) + A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) = (4.0 \pm 6.6_{stat} \pm 0.7_{syst})\,\%$$

Statistically limited

Compatible with SM predictions

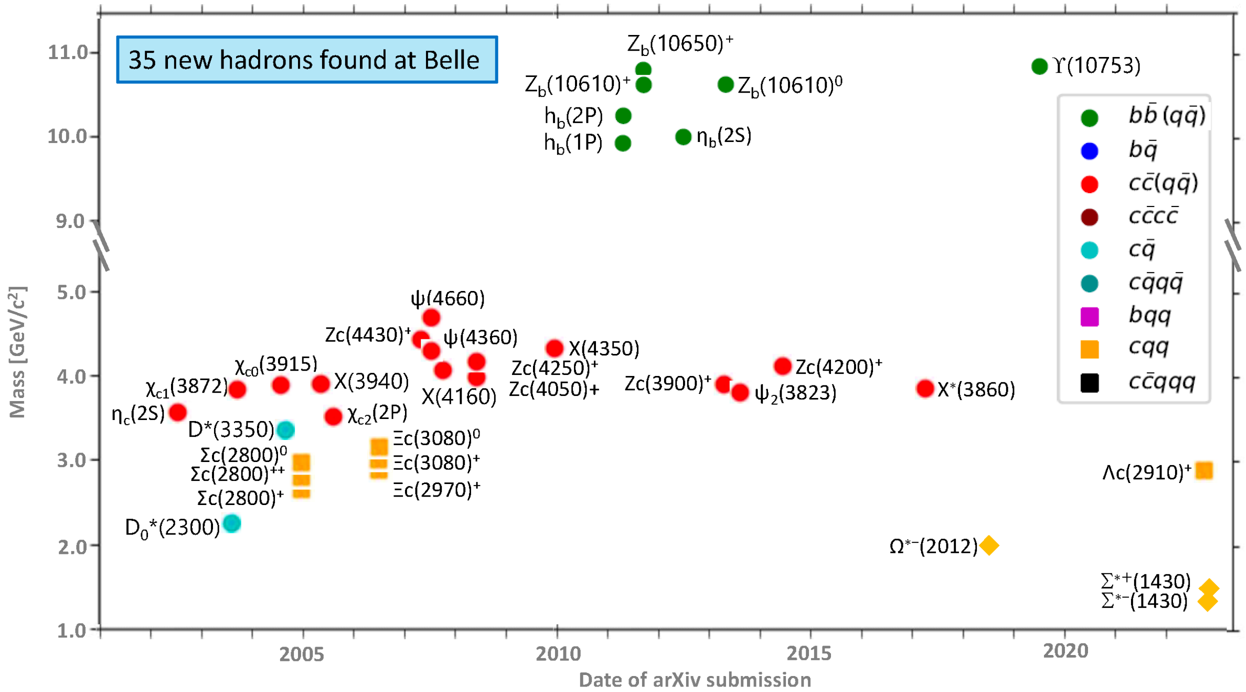


Charm CPV

Channel	A_{CP}	References
$D^0 \to \pi^0\pi^0$	$(+0.3\pm0.7\pm0.2)\%$	PRD 112, 012006 (2025)
$D^+ \to \pi^+\pi^0$	$(-1.8\pm0.9\pm0.1)\%$	PRD 112, L031101 (2025)
$D^0 \to \pi^+\pi^-\pi^0$	$(0.3\pm0.3\pm0.1)\%$	PRD 113, 052006 (2026)
$D^0 \to K_S^0 K_S^0$	$(-0.6\pm1.1\pm0.1)\%$	PRD 111, 012015 (2025), PRD 112, 012017 (2025)
$D^+, D_s^+ \to K_S^0 K^- \pi^+\pi^+$	$(+3.9\pm4.5\pm1.1)\%$, $(-0.2\pm2.5\pm1.1)\%$	JHEP 04 (2025) 036
$\Lambda_c^+ \to \Lambda K^+, \Sigma^0 K^+$	$(+2.1\pm2.6\pm0.1)\%$, $(+2.5\pm5.4\pm0.4)\%$	Sci. Bull. 68 (2023) 583
$\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$	$(+3.9\pm1.7\pm0.7)\%$, $(+0.3\pm1.0\pm0.2)\%$	PRD 113,032017 (2026)
$\Xi_c^+ \to \Sigma^+K^+K^-, \Sigma^+\pi^+\pi^-$	$(+3.7\pm6.6\pm0.6)\%$, $(+9.5\pm6.8\pm0.5)\%$	PRD 113, 032017 (2026)

Quarkoium and exotic states

New hadrons found at Belle(II)

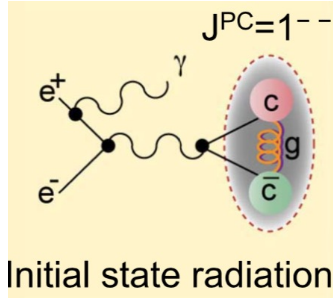


Belle II has been designed to make precise measurements of **weak interaction parameters, study exotic hadrons**, and search for **new phenomena** beyond the Standard Model of particle physics.

$e^+e^- \to h^+h^-J/\psi$ (h = π, K, p) via initial-state radiation (ISR) at Belle II

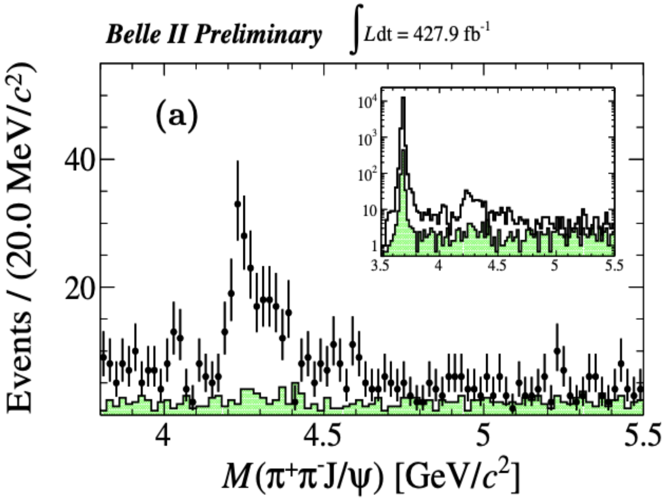
Adavantages of ISR:
- Allows to study energies below $E_{c.m.}$
- Wide energy range available
- Measure more precisely the line-shapes

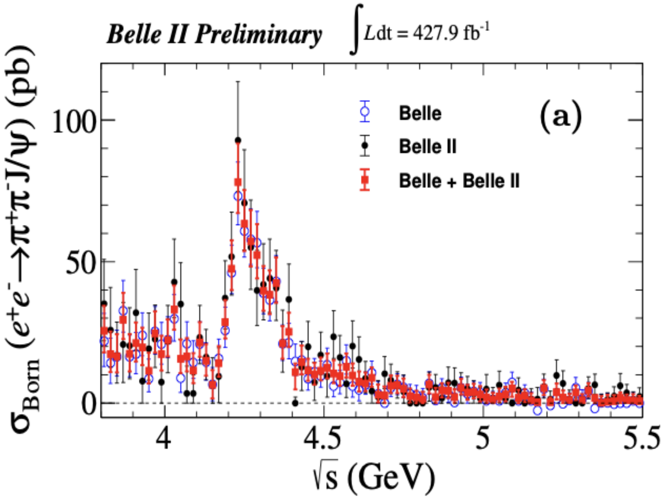
Disadvantages of ISR:
- The effective integrated luminosity decreases as the c.m. energy decreases
- The detection efficiency is also smaller

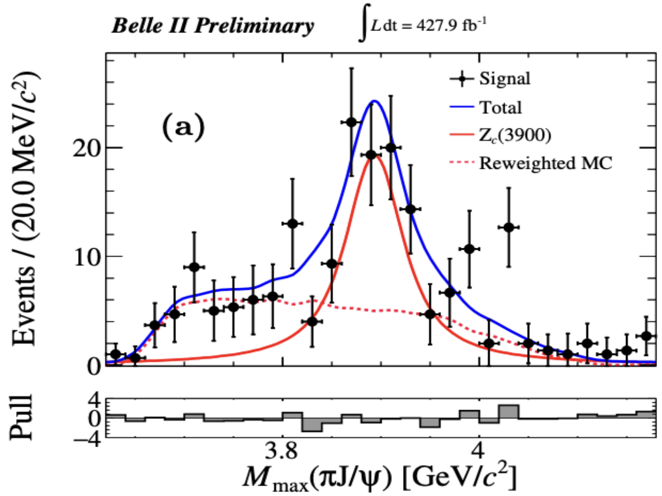


$e^+e^- \to \pi^+\pi^-J/\psi$ via ISR:

arXiv:2602.13569

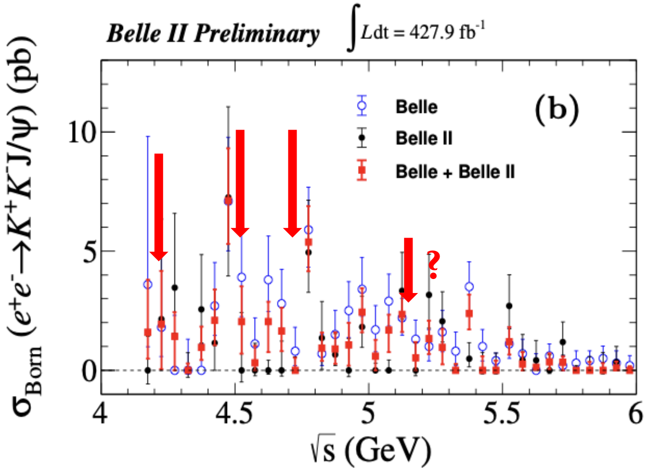




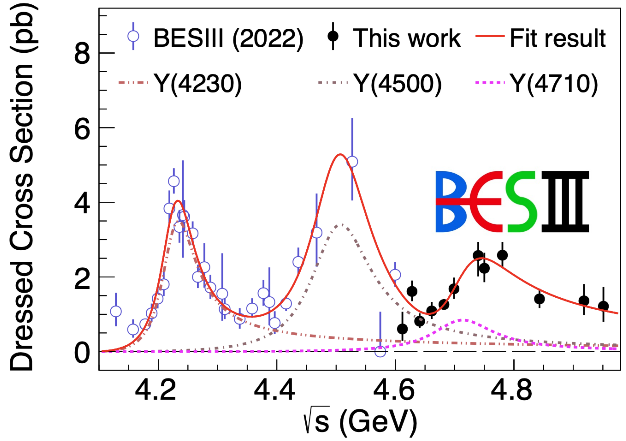


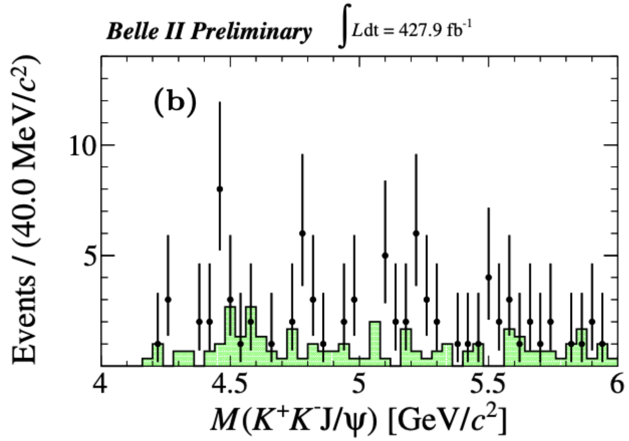
- **We can see the Y(4008) evidence and Y(4230/4320) signal.**
- **The significance of $Z_c(3900)$ is 5.3σ.**

$e^+e^- \to K^+K^-J/\psi$ via ISR:



PRL 131, 211902 (2023)

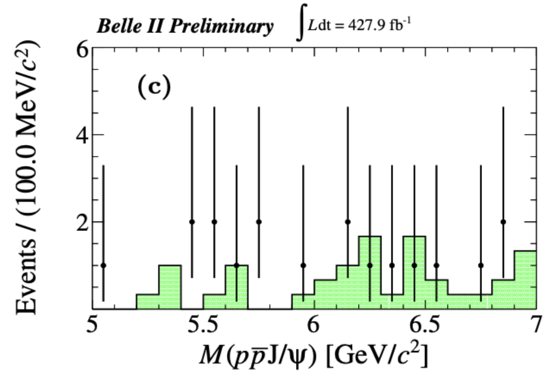


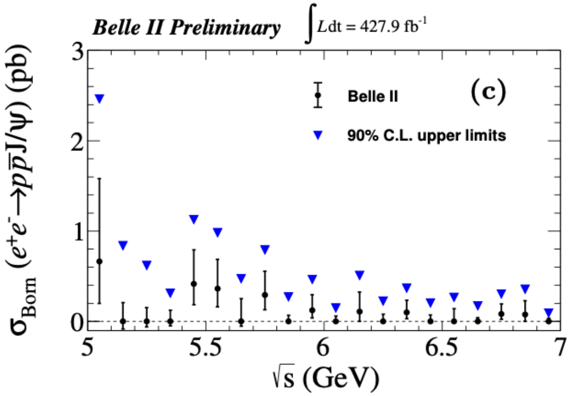


- **No clear signals were observed at Belle II.**
- **More data are needed.**

$e^+e^- \to p\bar{p}J/\psi$ via ISR:

The cross section for $e^+e^- \to P_c\bar{p}$ is estimated to be $\lesssim \mathcal{O}(0.1\ \text{pb})$ [arXiv: 2508.08694].



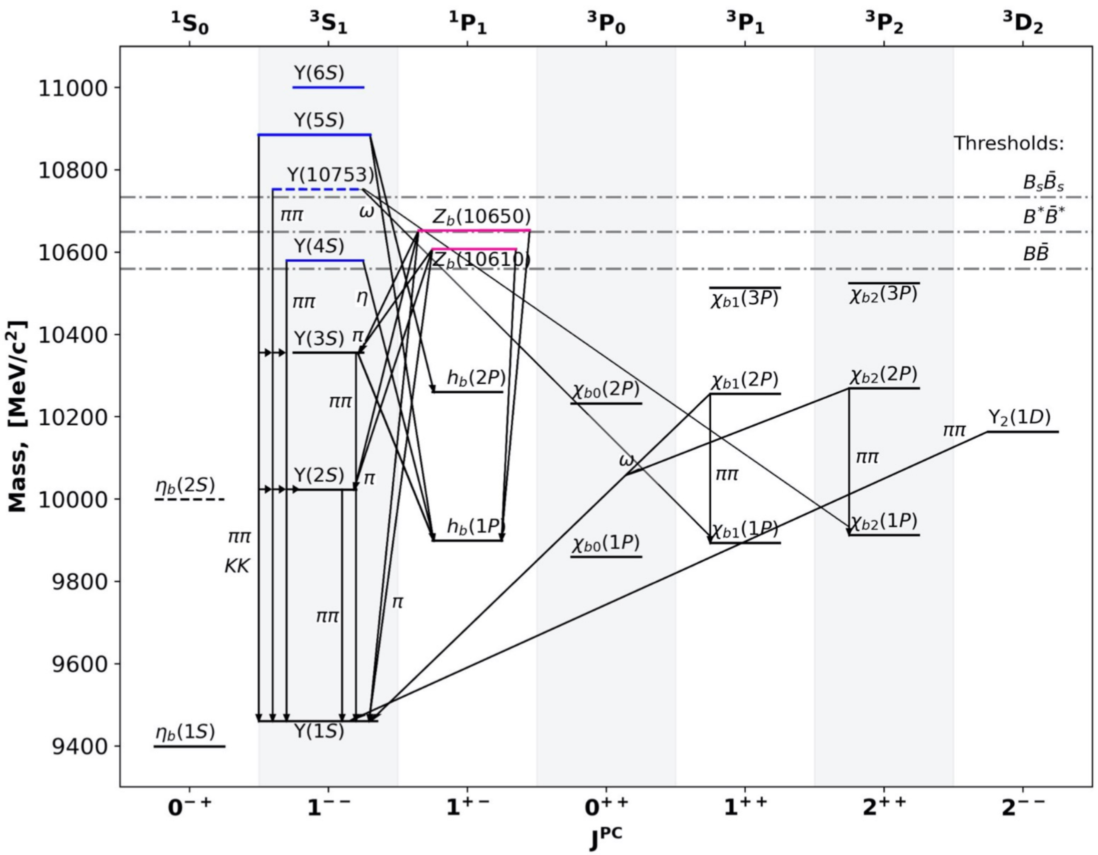


Bottomonium

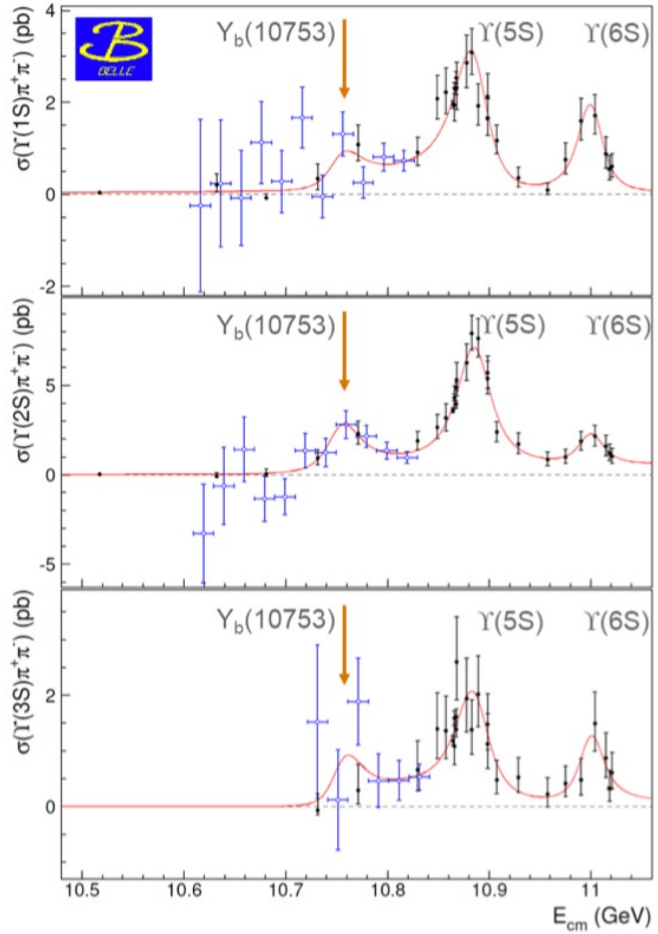
Conventional bottomonium (pure $b\bar{b}$ states)

Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)

Exotic charged states (Z_b^+)

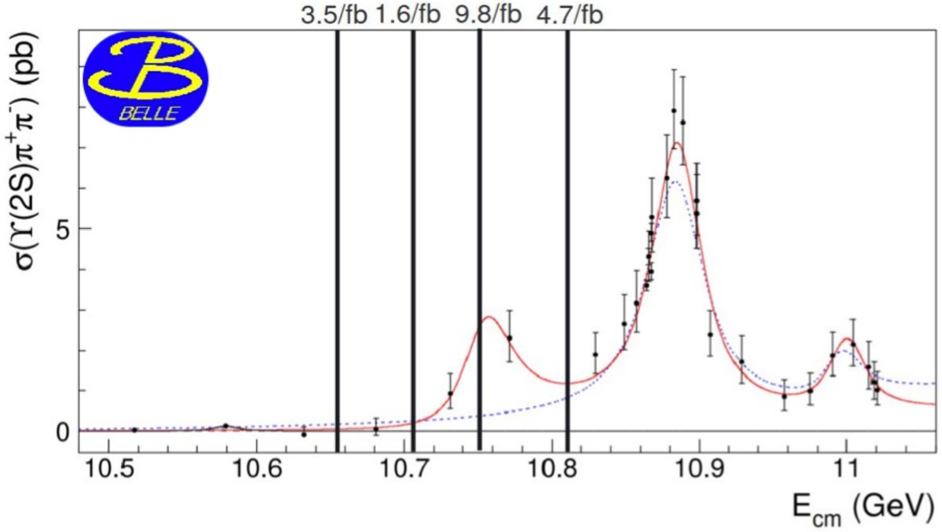


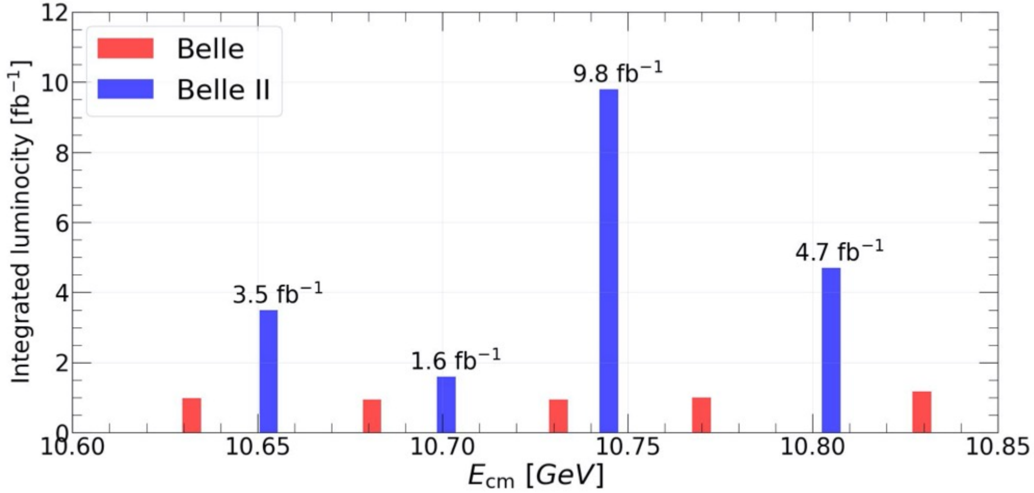
The Υ(10753) was first discovered in $\pi^+\pi^-\Upsilon(nS)$ final states using scan data by Belle [JHEP 10, 220 (2019)].



Belle II collected **19 fb^{-1} of unique data around $\sqrt{s}$ ~ 10.75 GeV** to study the nature of the Υ(10753).

Unique scan data near $\sqrt{s}$ = 10.75 GeV

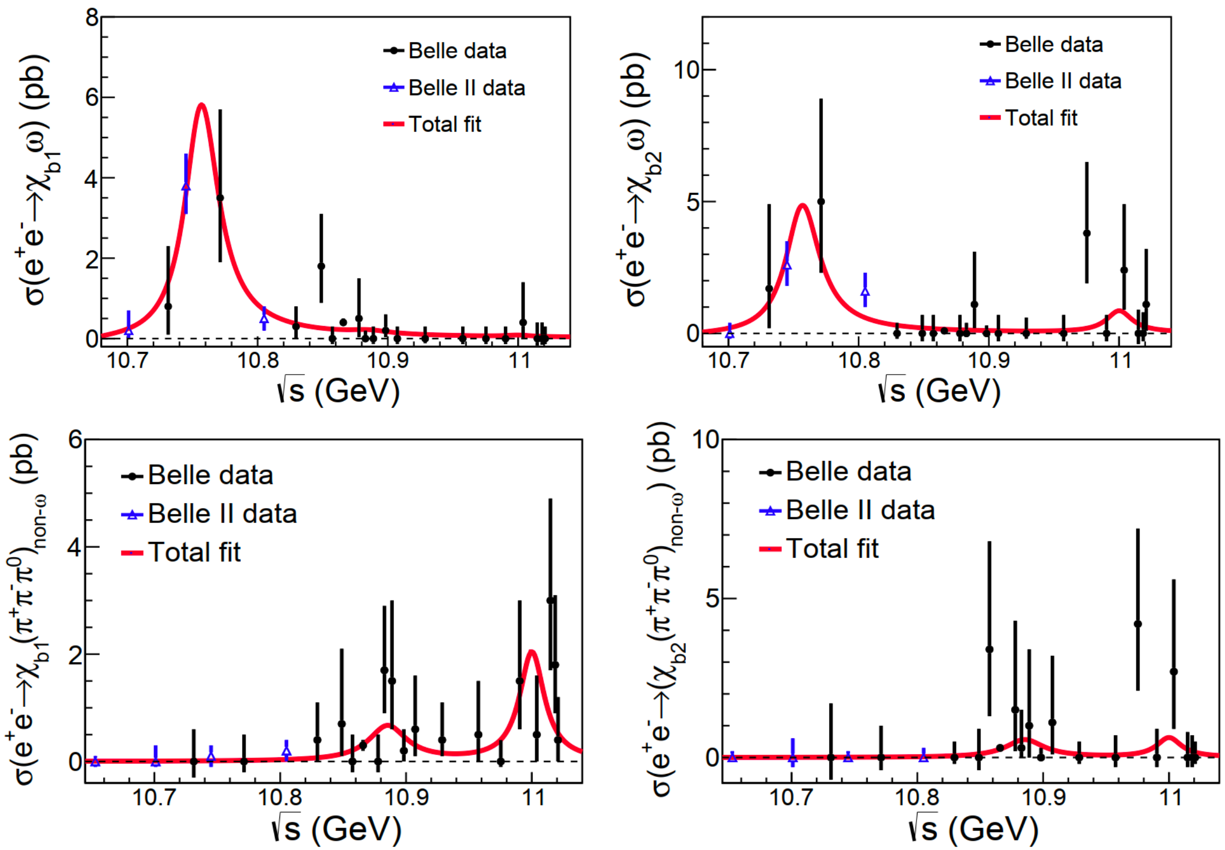




- In November 2021, Belle II collected 19 fb^{-1} of unique data at energies above the $\Upsilon(4S)$: four energy scan points around 10.75 GeV.
- Belle II collected the data in the gaps between Belle energy scan points.
- Physics goal: understand the nature of the $\Upsilon(10753)$ energy region.

$e^+e^- \to \omega\chi_{bJ}$ and $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ at Belle and Belle II

JHEP 04 (2026) 101



Υ(10753) mass	(10756.1 ± 4.3) MeV/c^2
Υ(10753) width	(32.2 ± 18.7) MeV

$$\frac{\sigma(e^+e^-\to\chi_{bJ}(1P)\omega)}{\sigma(e^+e^-\to\Upsilon(nS)\pi^+\pi^-)}$$

1.5 at $\sqrt{s}\sim10.75$ GeV

0.15 at $\sqrt{s}\sim10.867$ GeV

This may indicate the difference in the internal structures of Υ(10753) and Υ(10860).

$$\mathcal{B}(\Upsilon(10753)\to\chi_{b1}\,\omega)/\mathcal{B}(\Upsilon(10753)\to\chi_{b2}\,\omega)$$

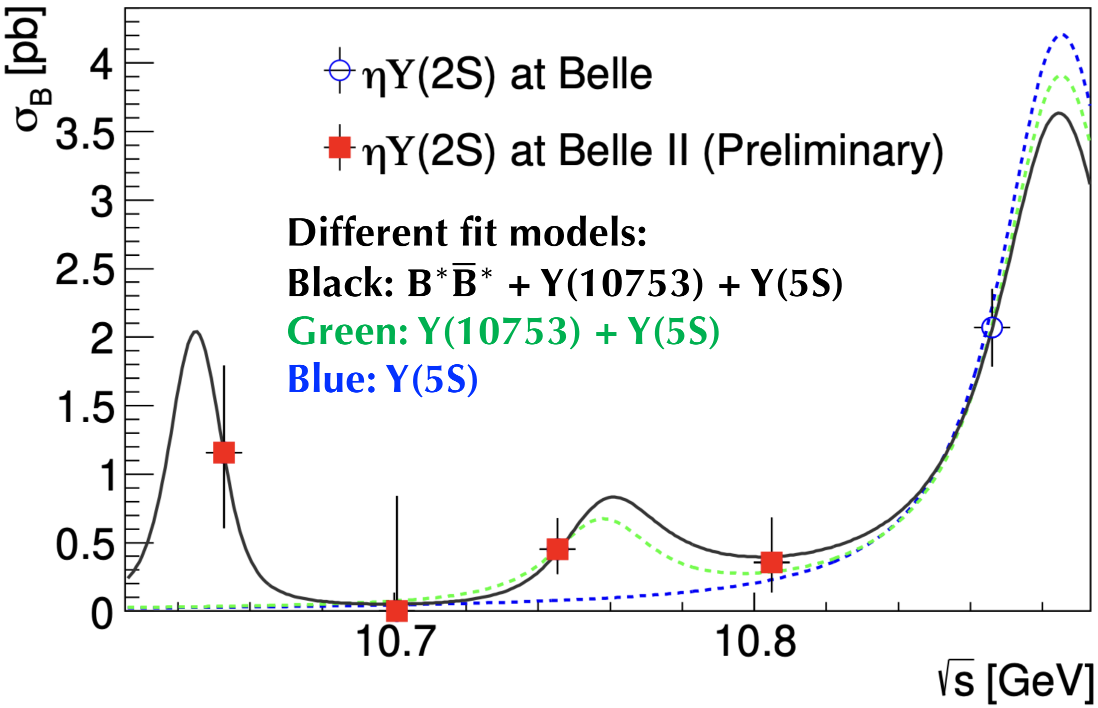
$$\Downarrow$$

$$1.13\pm0.38\pm0.34$$

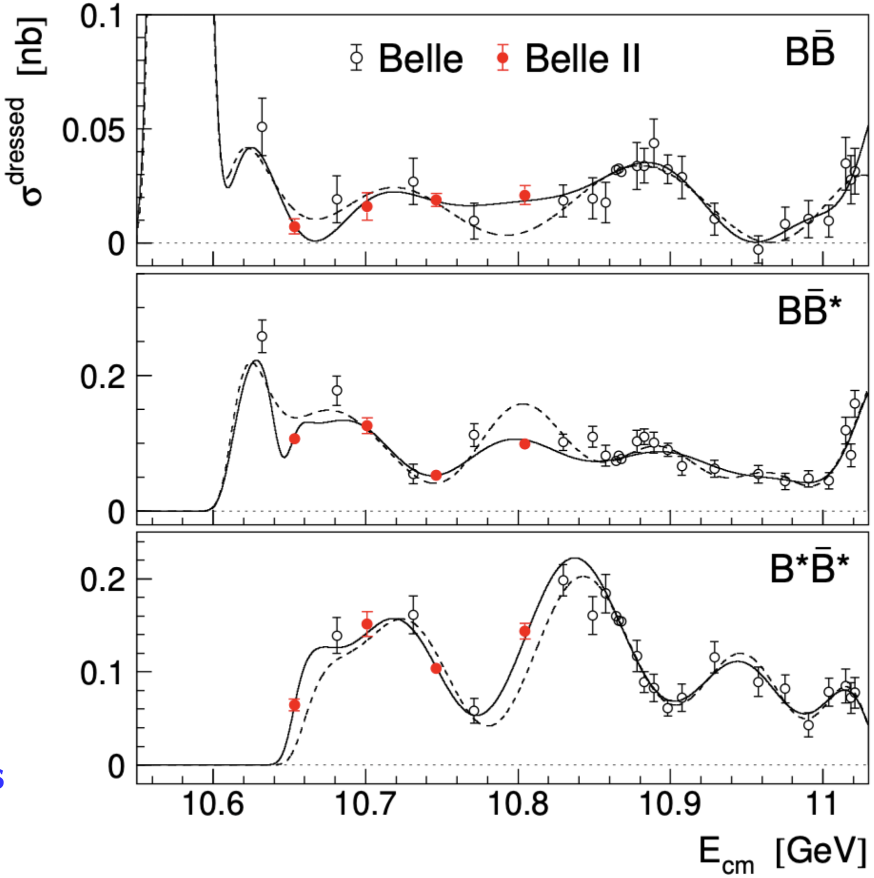
- The $(\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ excess maybe due the cascade decay of $\Upsilon(10860,11020)\to Z_b\pi\to\chi_{bJ}\rho\pi$ [PRD 90, 014036 (2014)].

$e^+e^- \to \eta\Upsilon(2S)$ and $e^+e^- \to B^{(*)}\bar{B}^{(*)}$

[arXiv:2509.01917]



[JHEP 10 (2024) 114]



- The Born cross section of $e^+e^- \to \eta\Upsilon(2S)$ around $B^*\bar{B}^*$ mass is relatively large.

The significance of $B^*\bar{B}^*$ bound state is larger than 3.2σ

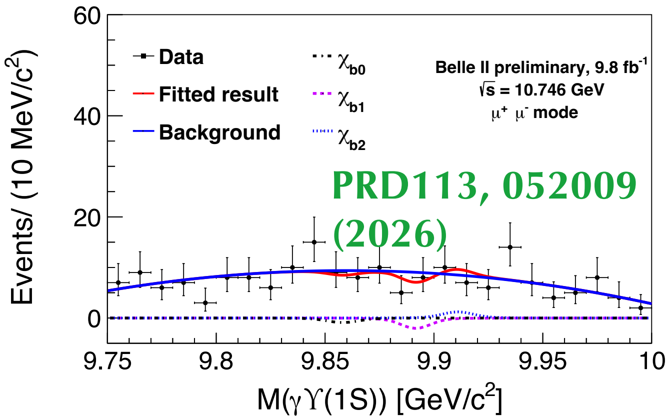
A new bottomonium-like state around $B^*\bar{B}^*$ threshold?

The $Y_b(10650)$ is predicted in Refs. [arXiv:2505.02742, arXiv:2508.11127, arXiv:2505.03647].

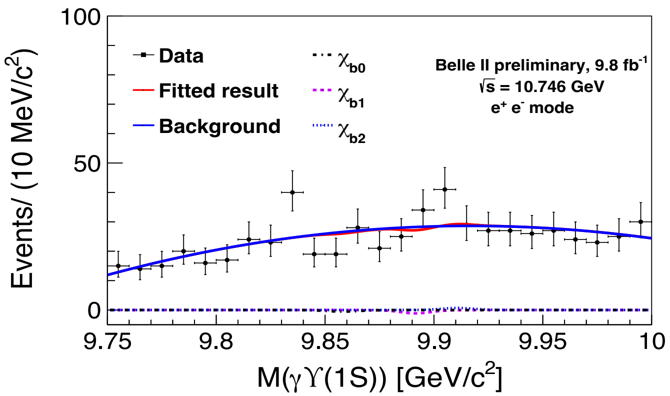
Rapid increase of $\sigma_{B^*\bar{B}^*}$ just above the threshold.

$e^+e^- \to \gamma\chi_{bJ}$ and $e^+e^- \to \pi^+\pi^-\Upsilon_J(1D)$

arXiv:2602.19807

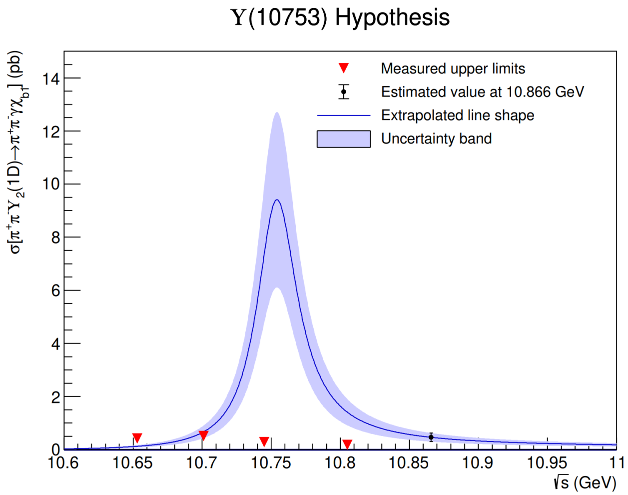


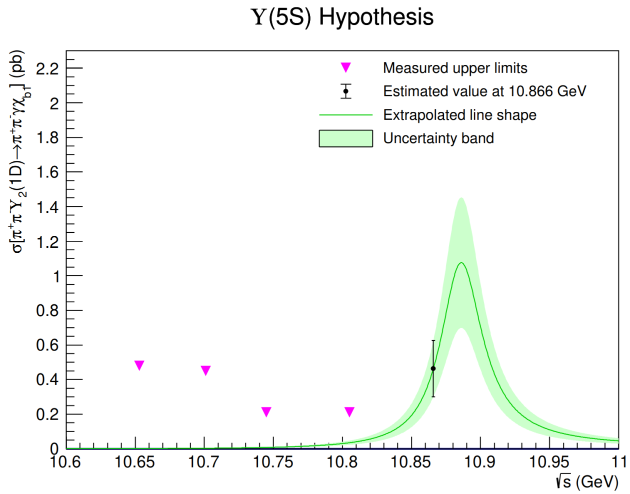
PRD113, 052009 (2026)



- No clear signal of $e^+e^- \to \gamma\chi_{bJ}$ can be seen.
- $\sigma^{UL}_{Born}(e^+e^- \to \gamma\chi_{b1})$ at 90% C.L. at $\sqrt{s}$ = 10.746 GeV is 0.25 pb, which is much smaller than the Born cross sections for $e^+e^- \to \omega\chi_{bJ}$ and $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$.

Inverted triangles: the 90% C.L. upper limits on the product $\sigma(e^+e^- \to \pi^+\pi^-\Upsilon_2(1D))\mathcal{B}(\Upsilon_2(1D) \to \gamma\chi_{b1})$ as a function of C.M. energy.

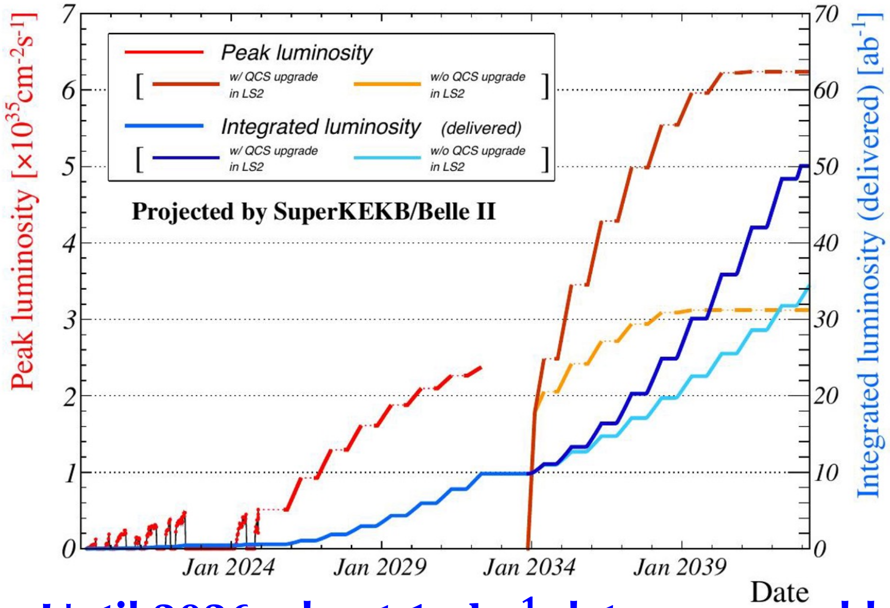




- A pronounced suppression in the coupling of the $\Upsilon(10753)$ resonance to $\Upsilon_J(1D)$ states via dipion transitions.
- The upper limits do not conflict with the $\Upsilon(10860)$ line shape.

Future prospects

From https://www.belle2.org/research/luminosity/



- **Until 2026, about 1 ab^{-1} data, comparable to Belle**
- **Until 2029, about 4 ab^{-1} data.**

During the long shutdown starting in 2032, upgrades are planned for the SuperKEKB accelerator and the Belle II detectors

From SNOWMASS2021 (https://arxiv.org/pdf/2203.10203)

Physics reach:

The goal of Belle II is to uncover new physics beyond the Standard Model.

- **Testing violations of lepton flavor conservation and universality and understanding their origins**
- **Checking the unitarity of the CKM matrix to high precision**
- **Identifying new weak (CP-violating) phases in the quark sector**
- **Probing the existence of dark-sector particles at MeV to GeV mass scales**
- **Reducing the uncertainty in the theory prediction for the muon g–2 anomaly**
- **Understanding the role of QCD in the production and binding of new hadronic states of matter**

Summary

- **Belle II: new data + upgraded detectors + new software tools**
  - **B CPV/semi-leptonic/rare, charm CPV/BF/α/spectrum $\Leftarrow$ $\gamma/\pi^0/K_s^0/\nu$ (recoiling/E_{ECL}/BDT) etc**
  - **Exotic states, τ physics, dark sectors $\Leftarrow$ special data at e^+e^- collider**

- **Only 1% of target luminosity collected so far. Until 2026, about 1 ab^{-1} data at Belle II. Stay tuned for more exciting results from Belle II.**

Thanks for your attention!

Backup slides

CKM matrix element

Exclusive: $B \to \pi l\nu, B \to \rho l\nu, B \to D^{(*)}l\nu, etc$

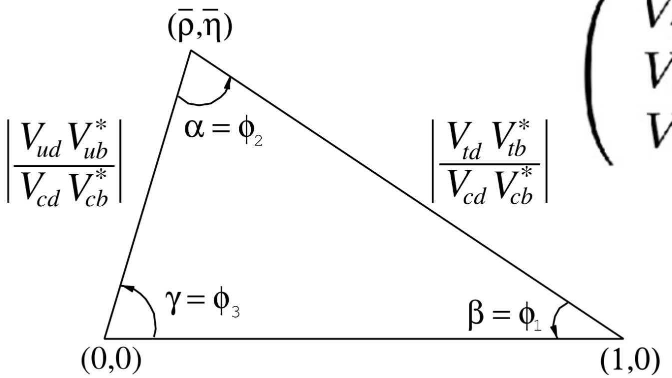
$\frac{dB}{dq^2} \propto |V_{xb}|^2 \times |FF(q^2)|^2$ Form factor from LCSR, LQCD

Inclusive: $B \to X_u l\nu, B \to X_c l\nu$

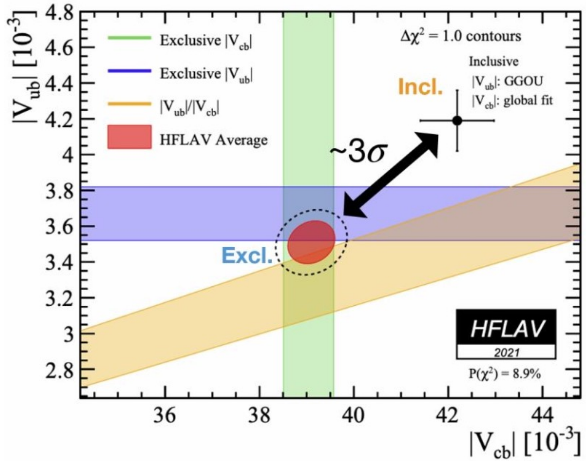
$\mathcal{B} \propto |V_{xb}|^2 \times \left[\Gamma(b \to q l \bar{\nu}_l) + \frac{1}{m_b} + \alpha_s + \cdots\right]$ From OPE

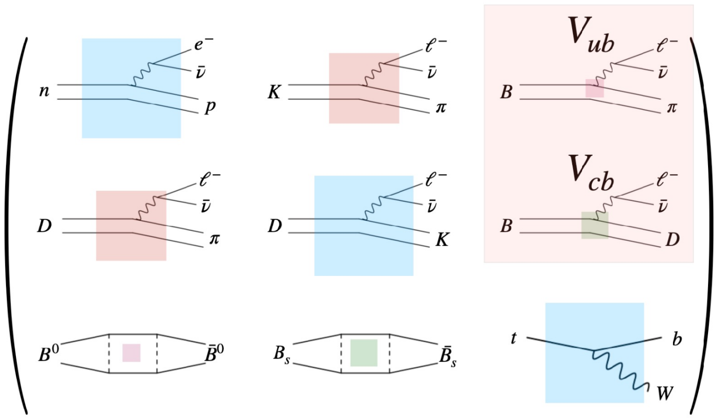
Belle II important task:

Constrain CKM unitarity triangle & test SM



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



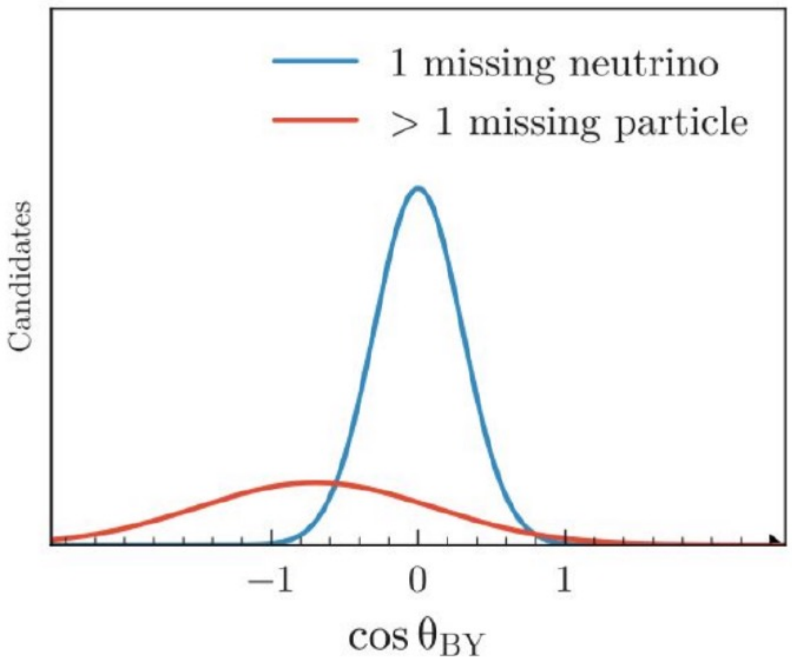


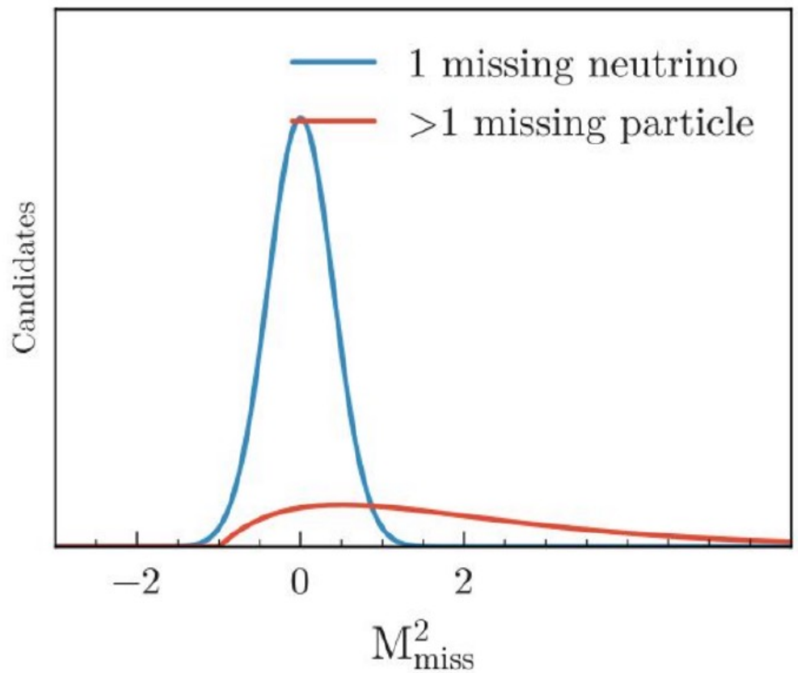
Several measurements carried out by Belle and Belle II:

$\lvert V_{cb}\rvert$	- Angular coefficients of $B \to D^* l\nu$	Belle: PRL 133, 131801 (2024)
$\lvert V_{ub}\rvert$	- $\lvert V_{ub}\rvert$ from $B \to (\pi, \rho) l\nu$ simultaneous analysis - Simultaneous inclusive and exclusive $\lvert V_{ub}\rvert$	New from Belle II Belle: PRL 131, 211801 (2023)
$\frac{\lvert V_{ub}\rvert}{\lvert V_{cb}\rvert}$	- Ratio of inclusive $b \to c$ and $b \to u$ decays	Belle: arXiv: 2311.00458

Common variables for $B \to (X)l\nu$ decays (only one neutrino missing)

- Leptonic system mass squared $q^2 = (p_l + p_\nu)^2$
- Recoil parameter $w = \frac{M_B^2 + M_X^2 - q^2}{2M_B M_X}$
- Missing mass squared M^2_{miss}
- $\cos\vartheta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - M_Y^2}{2|p_B^*||p_Y^*|}$, $Y = Xl$ system



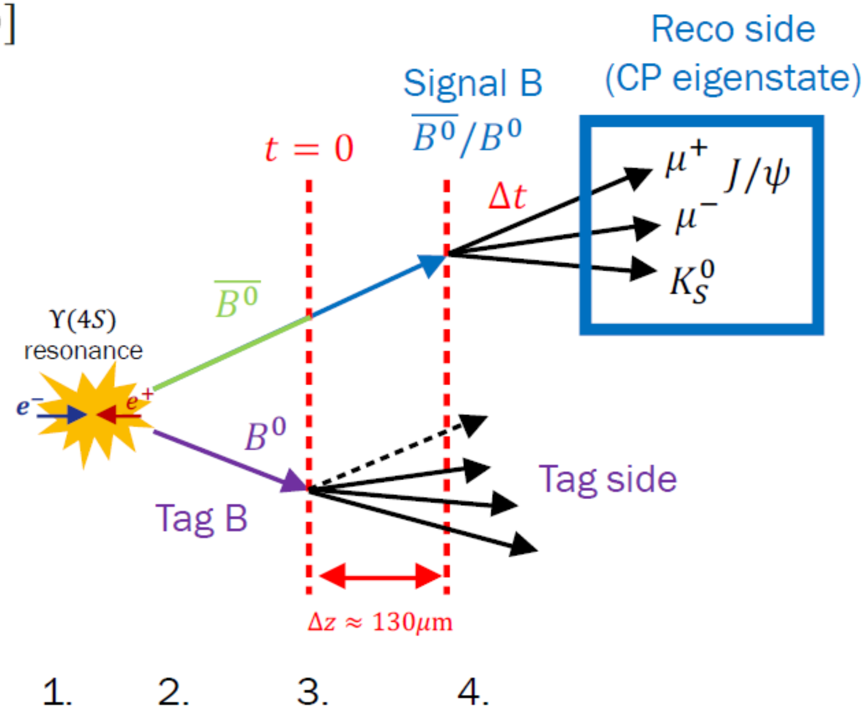


Measuring time-dependent CPV at Belle II

- $P(\Delta t, q) = \frac{e^{-\frac{|\Delta t|}{\tau_{B^0}}}}{4\tau_B^0}[1 + q[C\cos(m_d \Delta t) + S\sin(\Delta m_d \Delta t)]$
- General technique at Belle II for CPV analyses

1. $e^+e^- \rightarrow \Upsilon(4S)$, boosted in lab frame
2. The $\Upsilon(4S)$ produces an entangled $B^0\overline{B^0}$ pair
   - $1^{--} \rightarrow 0^- + 0^-$
3. At $t = 0$, one of the Bs decays, call it tag B
4. After a time Δt, the second B decays into a CP or flavor eigenstate that we fully reconstruct
   - If the signal B decays first, Δt is negative

- Resolution of Δt significantly influenced by Δz resolution from pixel detector

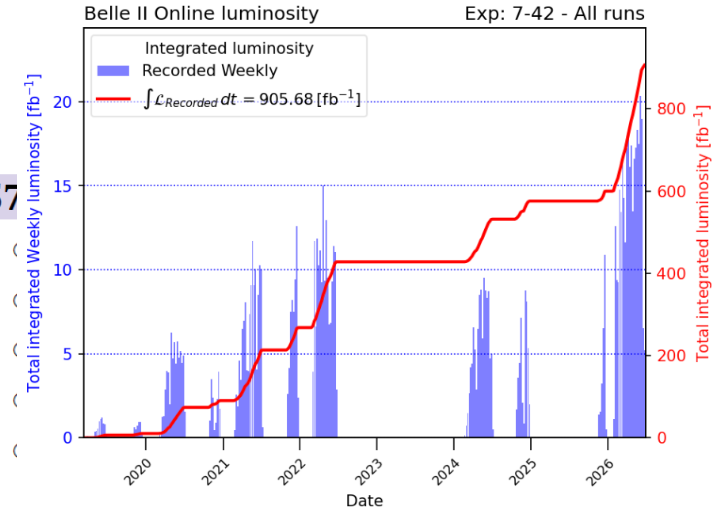


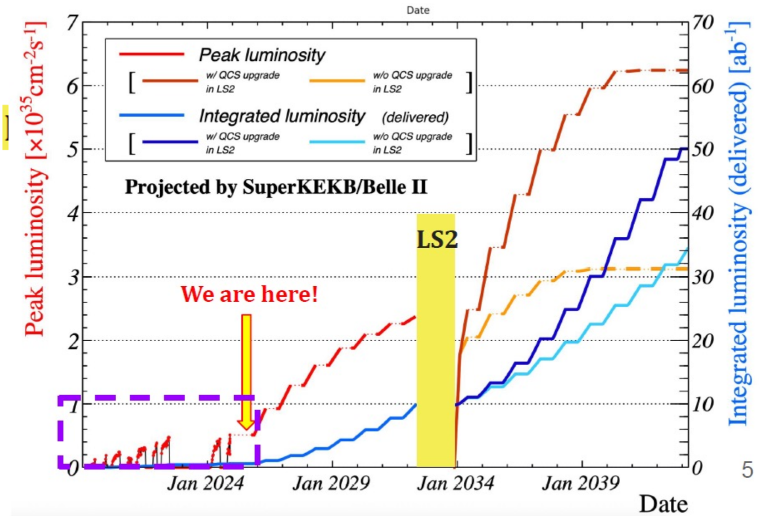
$$\Delta t = \frac{\Delta z}{\beta\gamma c}$$

Belle and Belle II Datasets

906 fb^{-1} data collected so far:

- 2019: Run 1 data collection started (365 fb^{-1})
- 2022.06: world record L_{inst}: 4.7×10^{34} cm^{-2} s^{-1}
- ~2023.12 LS1, New Collimator, 2-layer PXD, etc
- 2024: start of Run 2
- 2024.12.27: new L_{inst} record (Belle II off) 5.2×10^{34} cm^{-2} s^{-1}
- Plenty of physics results with the data collected so far
- LS2 planned for a major upgrade: 2032
- Targeting higher L_{inst}: 6×10^{35} cm^{-2} s^{-1}
- Ultimate goal: ~ 50 ab^{-1}
- Upgrade & Redesign of the Interaction Region (IR)
- Window for upgrades of the Belle II detector





- **Belle (1999 - 2010)**