CP violation at Belle II

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The Belle II experiment

- A multipurpose detector operating at the SuperKEKB energy-asymmetric e^+e^- collider, located at KEK in Tsukuba, Japan

- Latest in a series of experiments operating at collision energies near the $\Upsilon(4S)$ resonance. Aims to collect 50x larger samples than its predecessor Belle

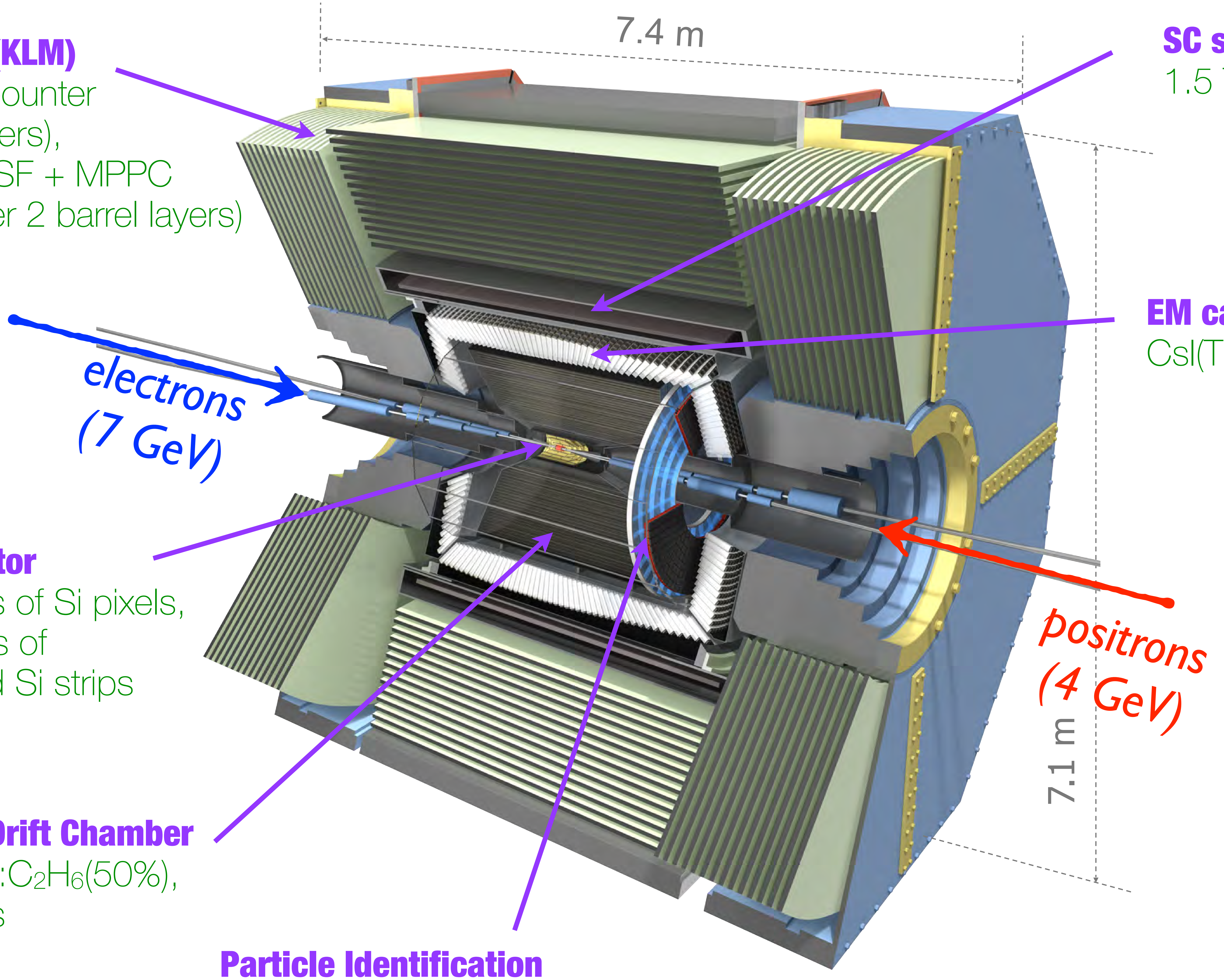
- Core physics program is precision measurements and searches for rare processes in weak decays of bottom mesons, but unique capabilities also in charm, τ, dark sector, hadron spectroscopy, soft QCD

[Prog. Theor. Exp. Phys. 2019 123C01, 2207.06307]

The Belle II detector

K_L & μ Detector (KLM)
Resistive Plate Counter (barrel outer layers),
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

SC solenoid
1.5 T B field



EM calorimeter
CsI(Tl) crystals

Vertex Detector
2 inner layers of Si pixels,
4 outer layers of double-sided Si strips

Central Drift Chamber
He(50%):C_2H_6(50%),
56 layers

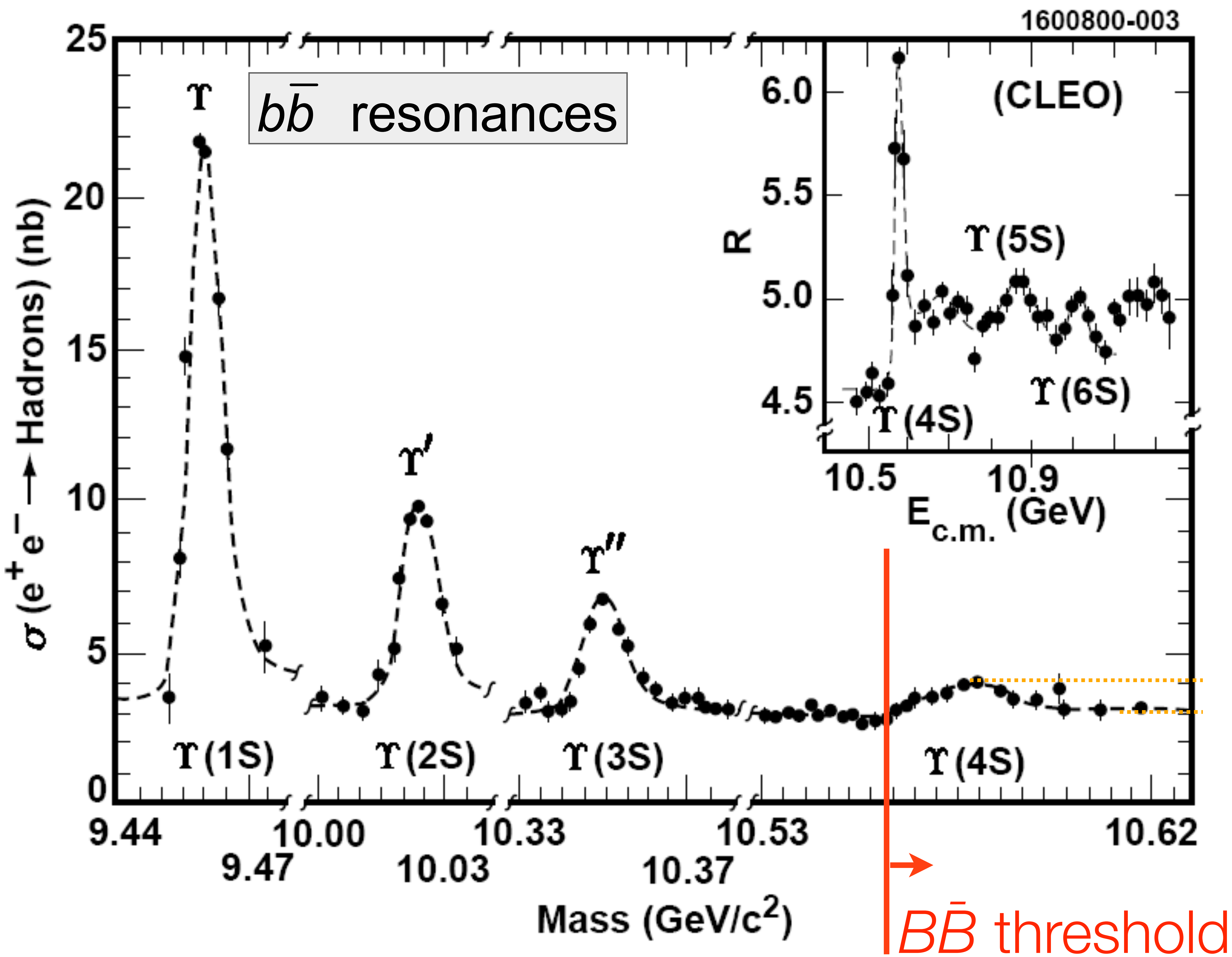
Particle Identification
Time-of-Propagation counter (TOP, barrel), Ionization loss in CDC (barrel),
Proximity focusing Aerogel Cherenkov Ring Imaging detector (forward)

- Hermetic detector
- Excellent vertexing , momentum and energy resolutions
- Efficient reconstruction of all final-state particles, including photons and neutral hadrons
- Good particle-identification capabilities

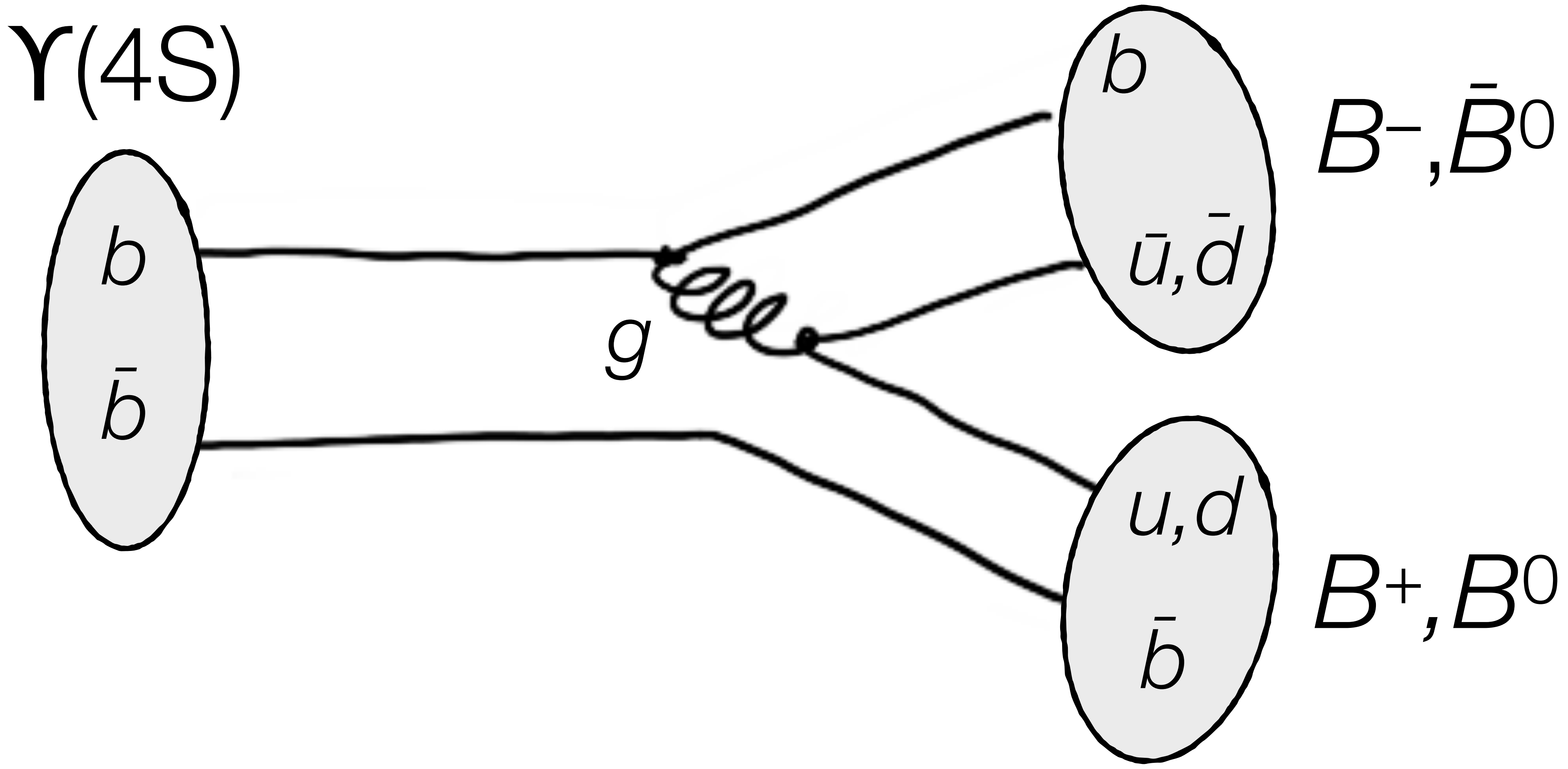
The Belle II collaboration

BNL is the US lead lab, manages the US operations on the experiment, contributes to offline computing, and to physics research

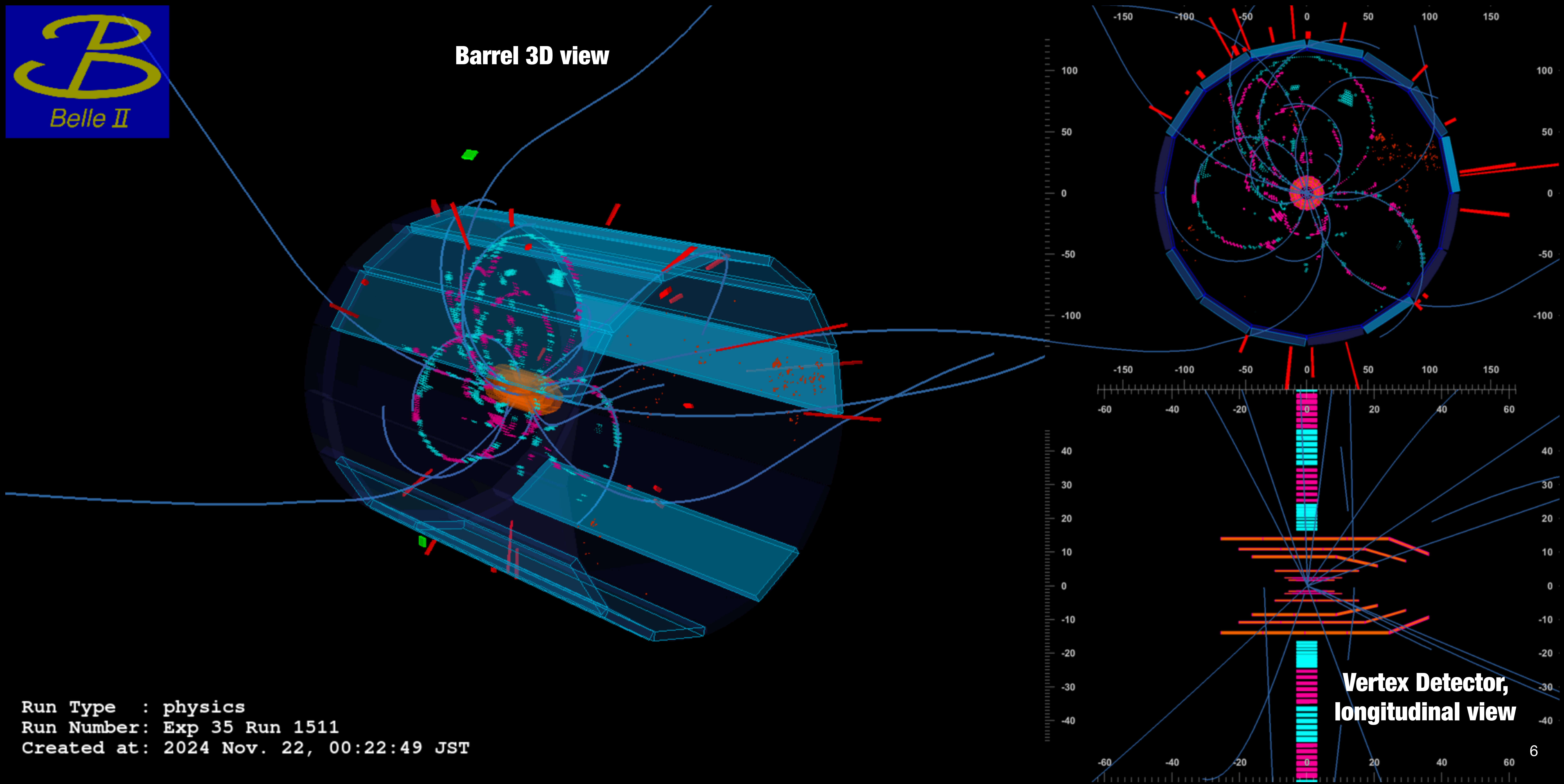
A beauty factory



- Bottomonium resonances (Υ mesons) are bound states of $b\bar{b}$ quarks
- The Υ(4S) state is just above the threshold for production of two B mesons: *i.e.*, decays to $B\bar{B}$ and no other particles are produced in the event



Example event display

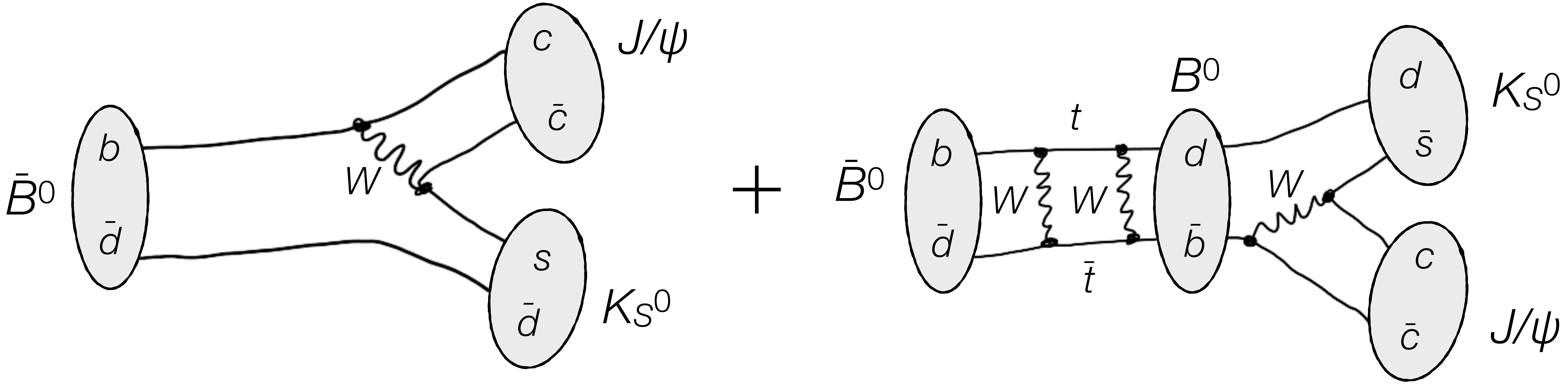


CP violation in *B* mesons

- In the standard model, *CP* violation arises from the phase of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix
- Need two interfering amplitudes to measure a phase difference. *B* decays offer many possibilities. For example, a direct decay and a decay preceded by B^0-$\bar{B}^0$ oscillation

$$V \approx \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\varphi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 \end{pmatrix} \end{array} \begin{array}{c} u \\ c \\ t \end{array}$$

$$\lambda \approx 0.22$$



$$\begin{tikzcd} B^0 \arrow[d, "\varphi_{\text{mixing}}"'] \arrow[dr, bend left, "\varphi_{\text{decay}}"] & \\ \bar{B}^0 \arrow[r, "-\varphi_{\text{decay}}"'] & J/\psi\, K_S^0 \end{tikzcd}$$

$$\varphi_{CP} = \varphi_{\text{mixing}} - 2\varphi_{\text{decay}}$$

$$= 2\arg\left(\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \equiv 2\beta$$

- Equivalent to a “double-slit experiment”: the two paths have a phase difference, φ_{CP}, which is the source of the *CP* violation

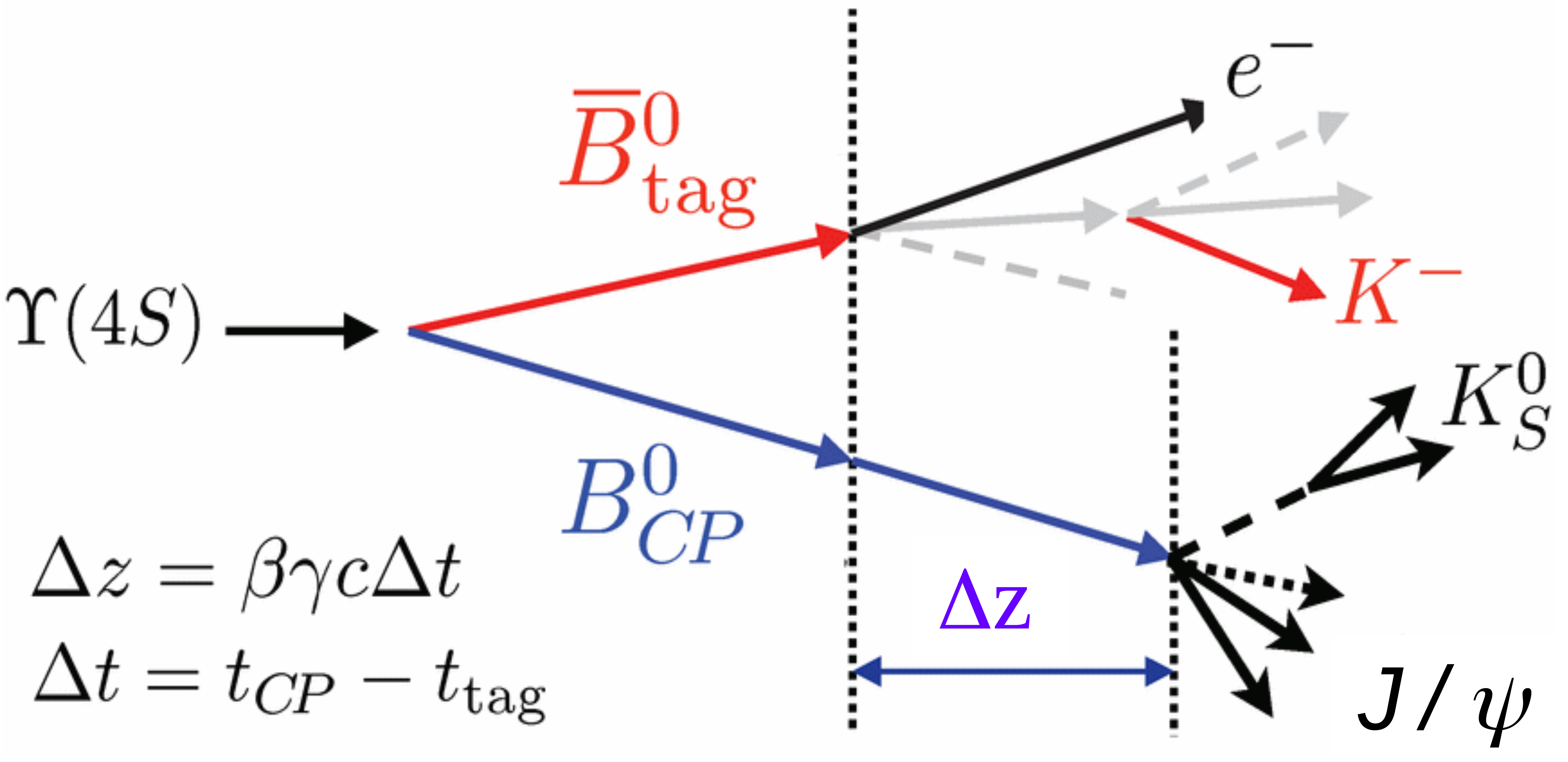
Quantum entangled state

- Neutral B meson pairs at the $\Upsilon(4S)$ are produced in an entangled quantum-mechanical state. Neither member of the entangled pair exists in a particular flavor state (B^0 or $\bar{B}^0$) until one of the two decays

- When one B meson decays, its flavor is determined and the wavefunction of the other B collapses into the opposite flavor. Only from that point on, CP violation can be studied

Time-dependent *CP* violation at *B* factories

- Tag decay (B_{tag}) determines flavor of signal decay (B_{CP}) at time t_{tag}
- Asymmetric collision energy boosts the $B^0\bar{B}^0$ pair, giving access to the difference Δt between B_{CP} and B_{tag} decay times
- Measure *CP* violation through the asymmetry between $\bar{B}^0$ and B^0 tagged events as a function of Δt

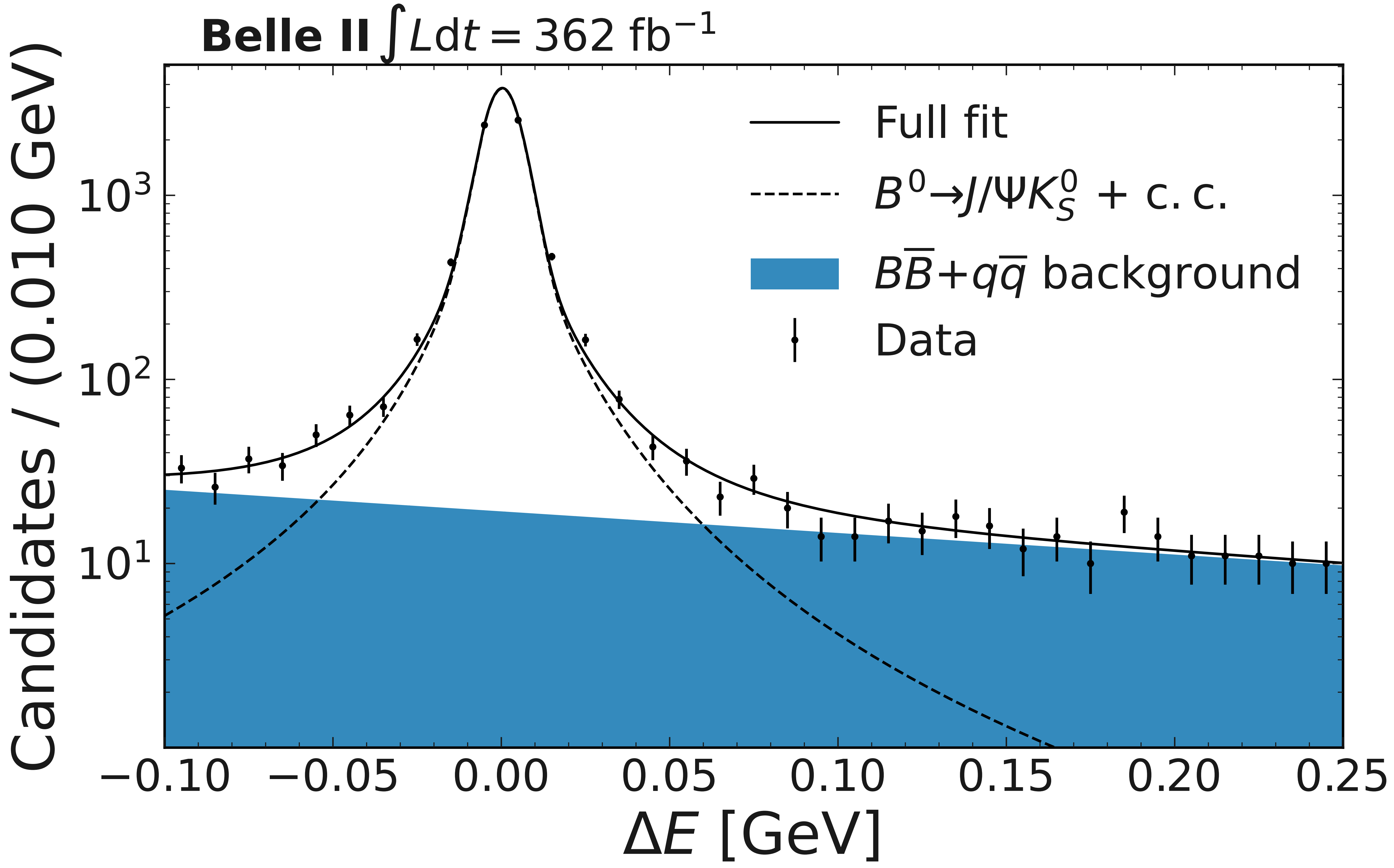


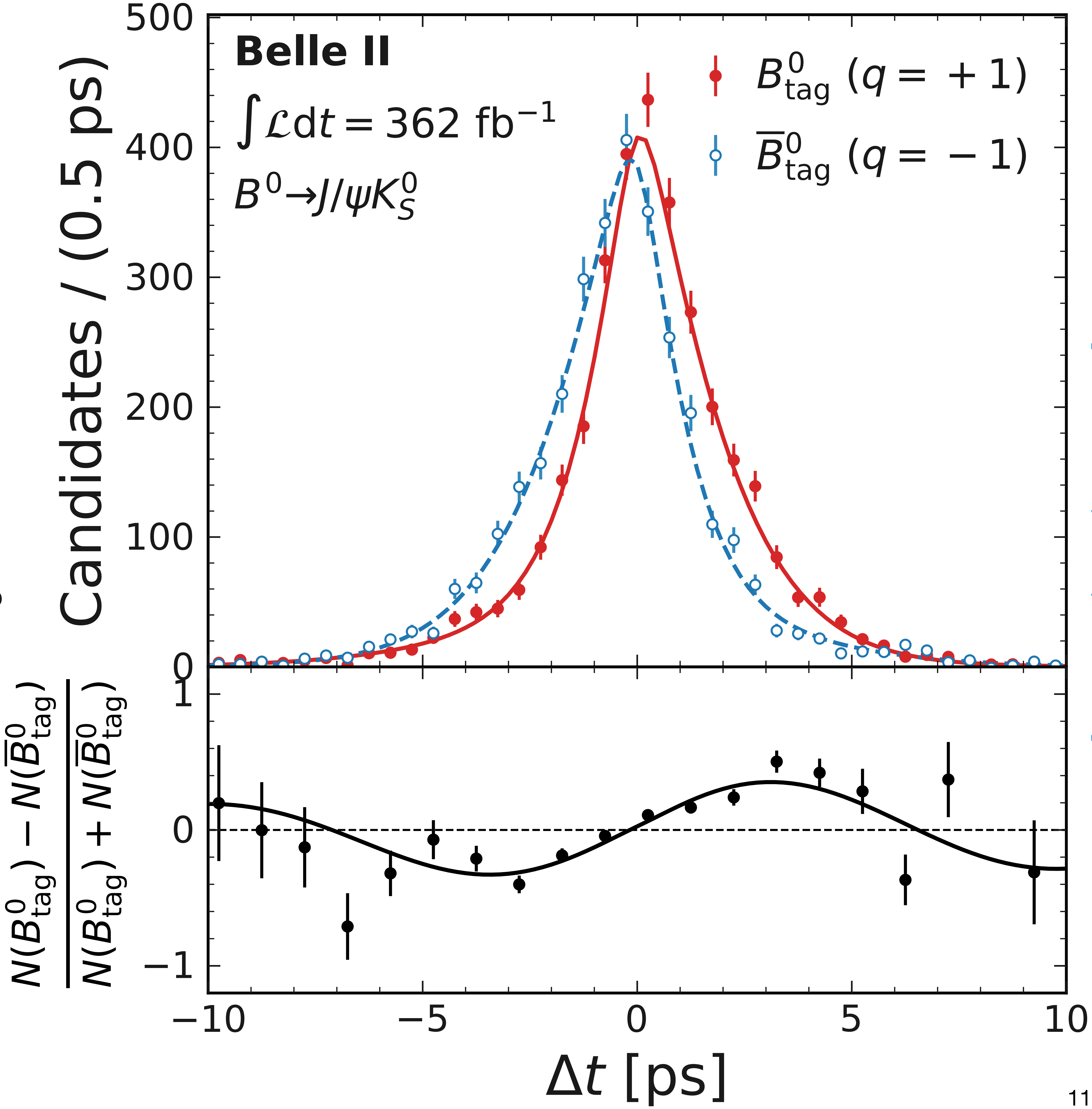
<Δz> ~ 130 μm at Belle II

$$A_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})} = S_{CP}\sin(\Delta m \Delta t) - C_{CP}\cos(\Delta m \Delta t)$$

For $B^0 \to J/\psi K_S^0$ decays: $S_{CP} = \sin 2\beta$, $C_{CP} = 0$

Measurement of sin2β at Belle II





[PRD 110 (2024) 012001]

$$S_{CP} = \quad 0.724 \pm 0.035(\mathrm{stat}) \pm 0.009(\mathrm{syst})$$
$$C_{CP} = -0.035 \pm 0.026(\mathrm{stat}) \pm 0.029(\mathrm{syst})$$

CP violation in *B* mesons is a O(1) effect, compared to O(10^{-3}) in kaons

Discovery of *CP* violation outside the kaon sector

2001: Measurement of sin2β by Belle (KEK) and BaBar (SLAC)

VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Observation of Large *CP* Violation in the Neutral *B* Meson System

We present a measurement of the standard model CP violation parameter $\sin 2\phi_1$ based on a 29.1 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. One neutral B meson is fully reconstructed as a $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$, or $J/\psi K^{*0}$ decay and the flavor of the accompanying B meson is identified from its decay products. From the asymmetry in the distribution of the time intervals between the two B meson decay points, we determine $\sin 2\phi_1 = 0.99 \pm 0.14(\mathrm{stat}) \pm 0.06(\mathrm{syst})$. We conclude that we have observed CP violation in the neutral B meson system.

VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

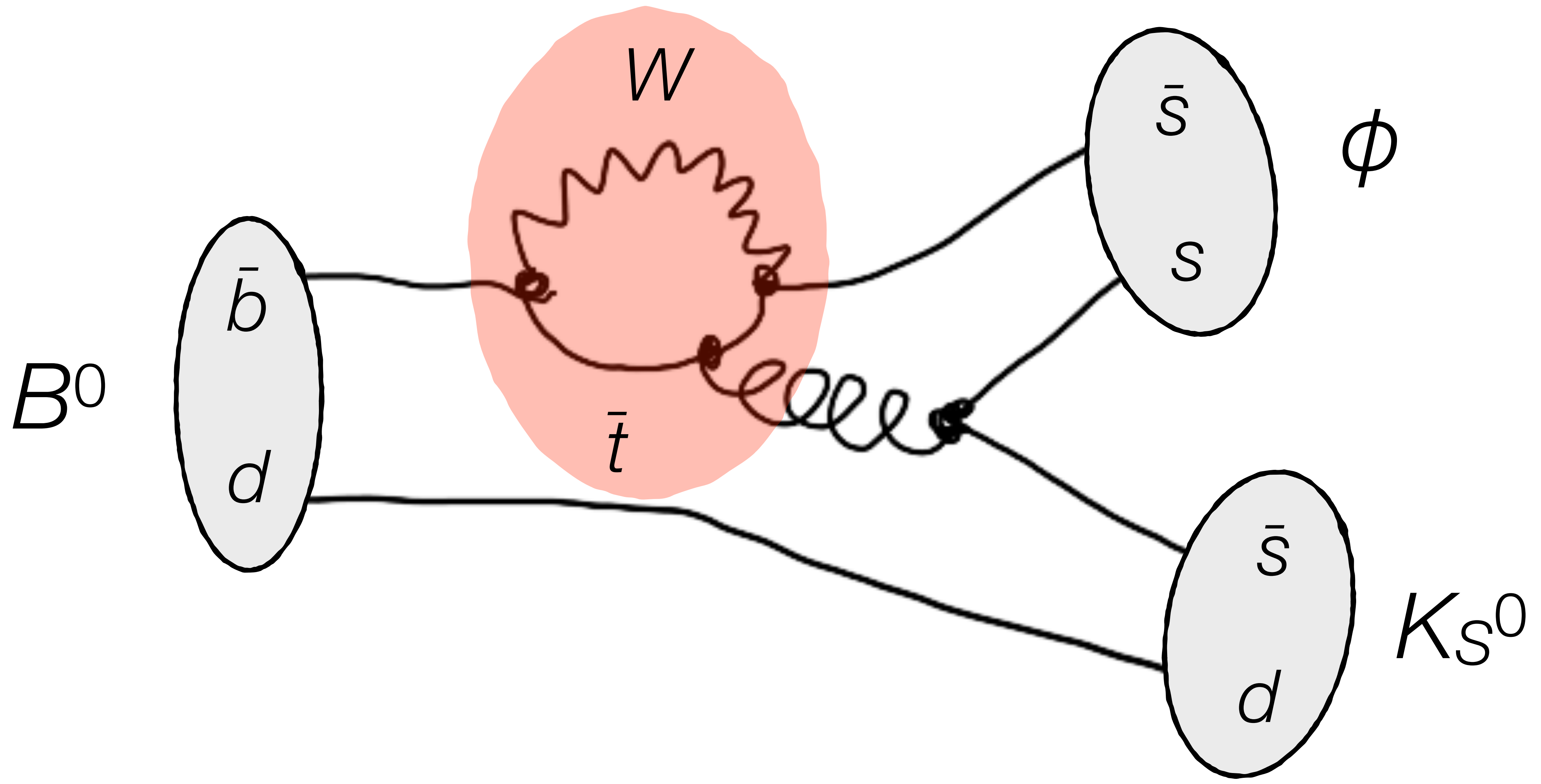
Observation of *CP* Violation in the B^0 Meson System

We present an updated measurement of time-dependent CP-violating asymmetries in neutral B decays with the *BABAR* detector at the PEP-II asymmetric B Factory at SLAC. This result uses an additional sample of $\Upsilon(4S)$ decays collected in 2001, bringing the data available to 32×10^6 $B\overline{B}$ pairs. We select events in which one neutral B meson is fully reconstructed in a final state containing charmonium and the flavor of the other neutral B meson is determined from its decay products. The amplitude of the CP-violating asymmetry, which in the standard model is proportional to $\sin 2\beta$, is derived from the decay time distributions in such events. The result $\sin 2\beta = 0.59 \pm 0.14(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ establishes CP violation in the B^0 meson system. We also determine $|\lambda| = 0.93 \pm 0.09(\mathrm{stat}) \pm 0.03(\mathrm{syst})$, consistent with no direct CP violation.

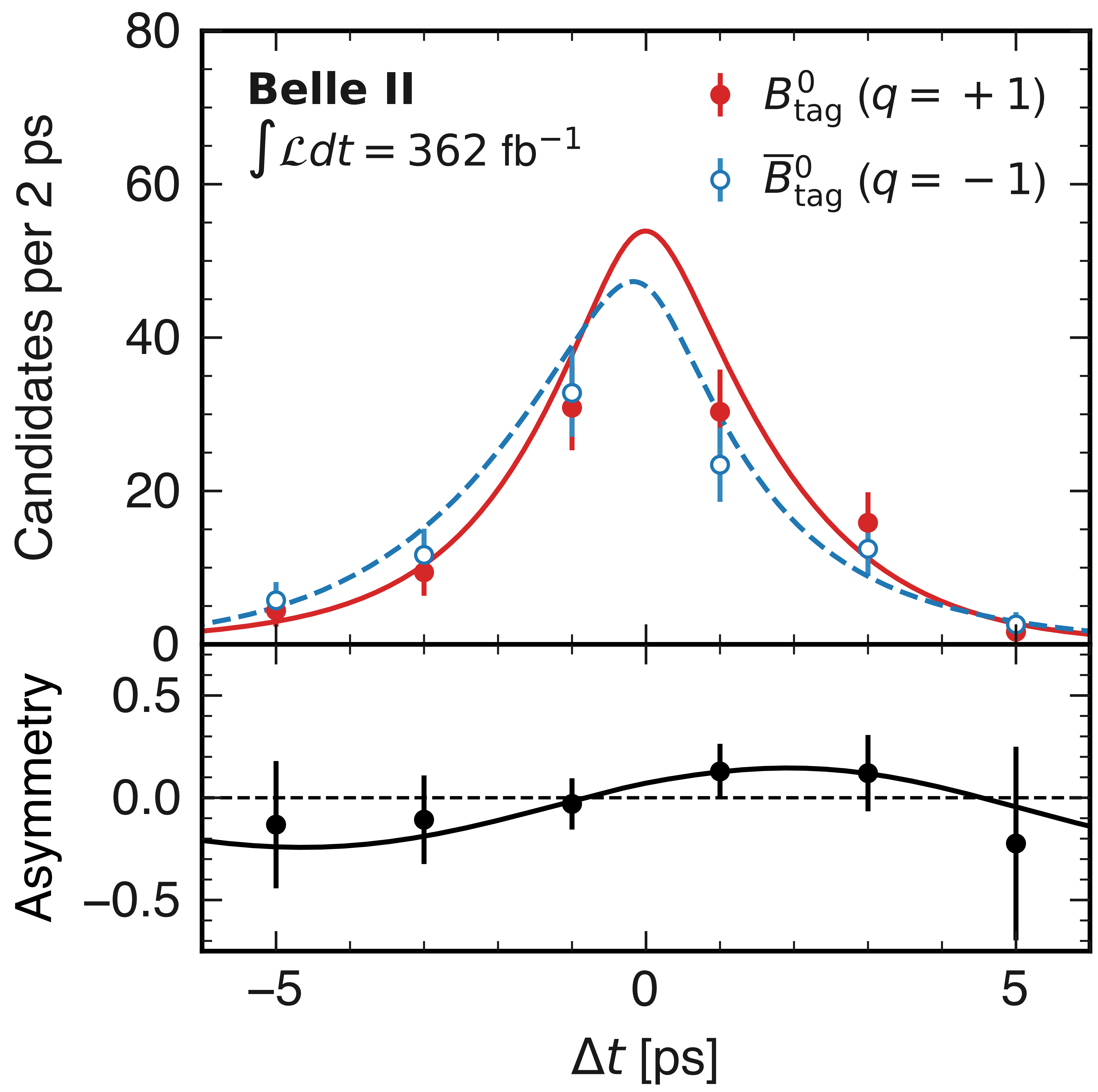
2008: Nobel prize to Kobayashi and Maskawa

Next step for Belle II: *CP* violation in suppressed decays

- Gluonic-penguin decays are suppressed in the standard model and can be more significantly affected by the possible presence of new massive particles



New massive particles could generate additional loop diagrams introducing *CP*-violation effects that differ from those of the tree-level $B^0 \to J/\psi K_S{}^0$ decay



[PRD 108 (2023) 072012]

$$S_{CP} = \quad 0.54 \pm 0.26(\mathrm{stat})\ {}^{+\,0.06}_{-\,0.08}(\mathrm{syst})$$

$$C_{CP} = -0.31 \pm 0.20(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

Beyond B mesons… CP violation in charm

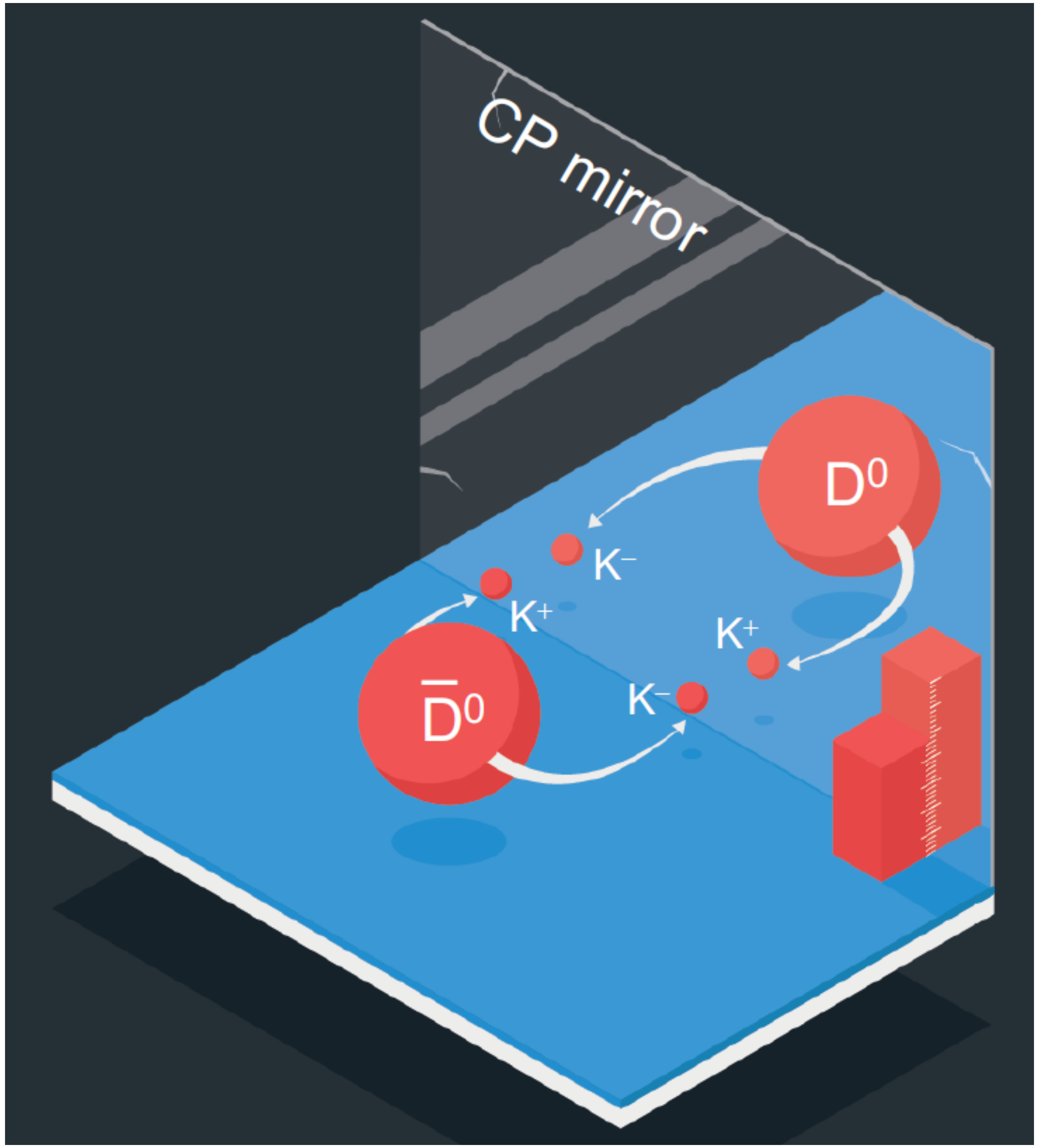
[PRL 122 (2019) 211803]

- Charm decays give unique sensitivity to new physics coupling to up-type quarks (complementary to K and $B_{(s)}$ decays)

- CP violation observed for the first time in 2019 at LHCb, in D^0 meson ($c\bar{u}$) decays to pairs of charged kaons or pions

  - Effects are O(10^{-3}). Unclear if consistent or not with the standard model, due to large theoretical uncertainties

- Need to explore more final states and cleaner modes. Huge program of measurements, many of which possible only at Belle II



Concluding remarks

- The discoveries we are celebrating today began a long program of measurements in the quark-flavor sector, which has since confirmed the CKM mechanism within ~10% precision

- Still, a long way lies ahead: in the next two decades, BNL's efforts in Belle II will contribute to precisely measuring suppressed processes in *B* and charm decays, with the potential to discover new sources of *CP* violation