Charm and time-dependent CPV in B decays at Belle II

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on behalf of the Belle II collaboration

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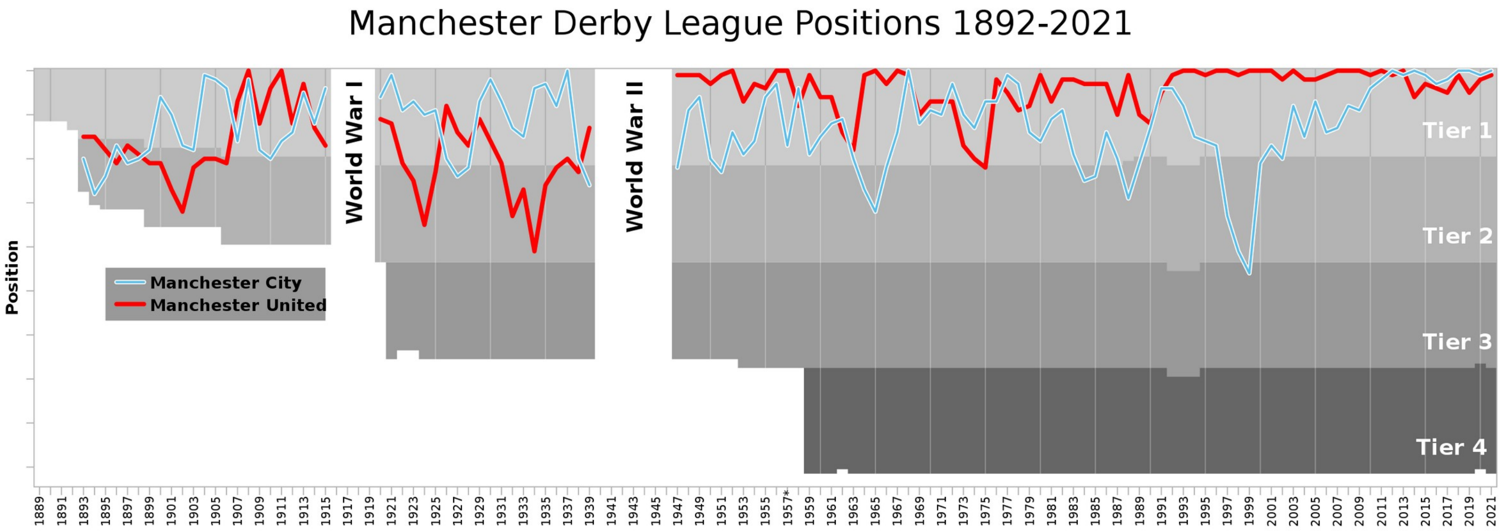
CHARLES
UNIVERSITY

Belle II

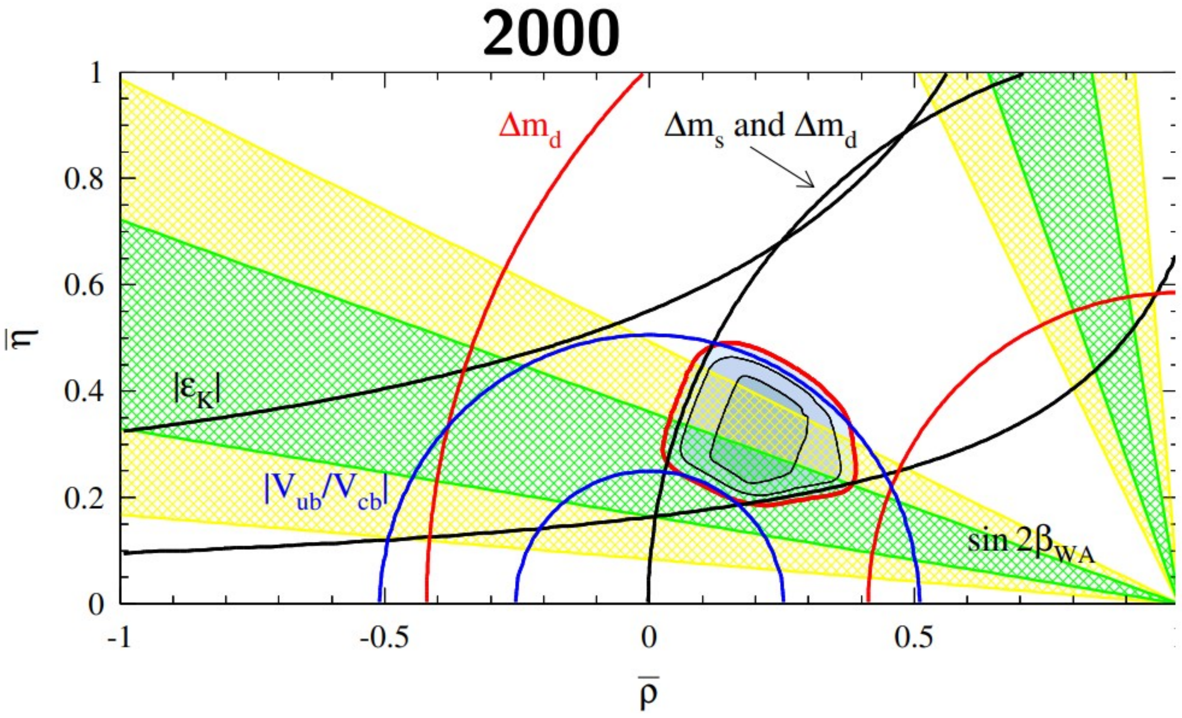


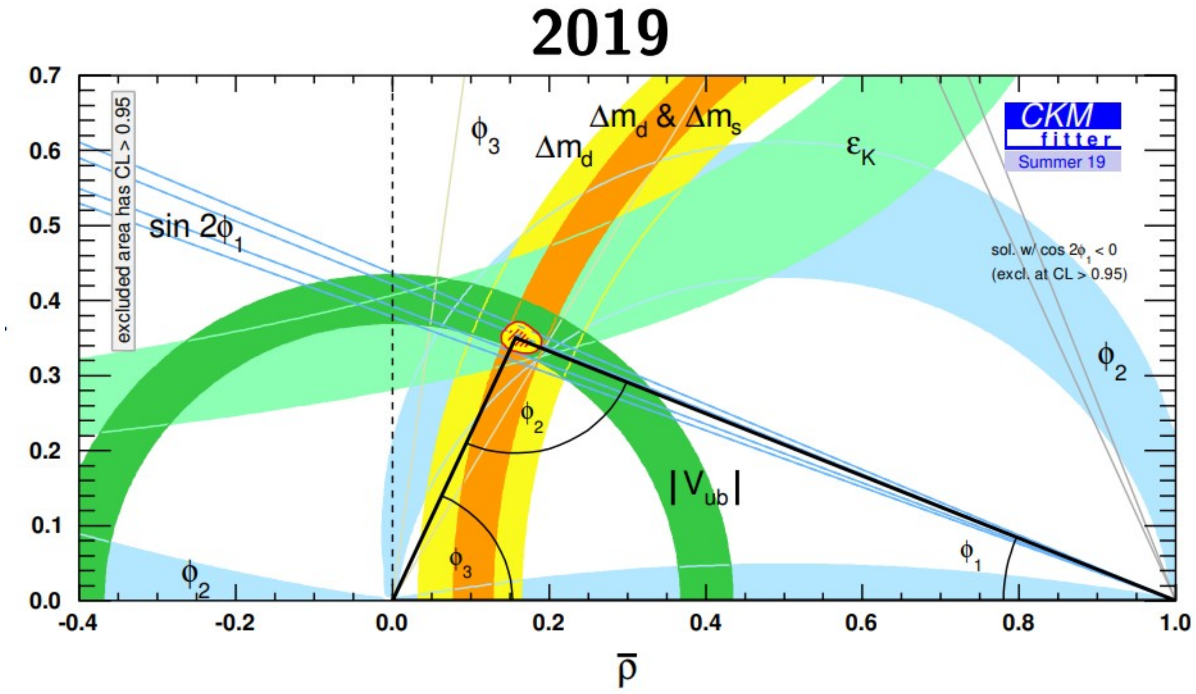
Review of the talk

1) $B\bar{B}$ oscillation frequency from early Belle II data (35 fb^{-1})
2) sin $2\phi_1$ estimate from early Belle II data (35 fb^{-1})
3) D-lifetime measurement (72 fb^{-1})

Unitarity triangle : 20 years of development

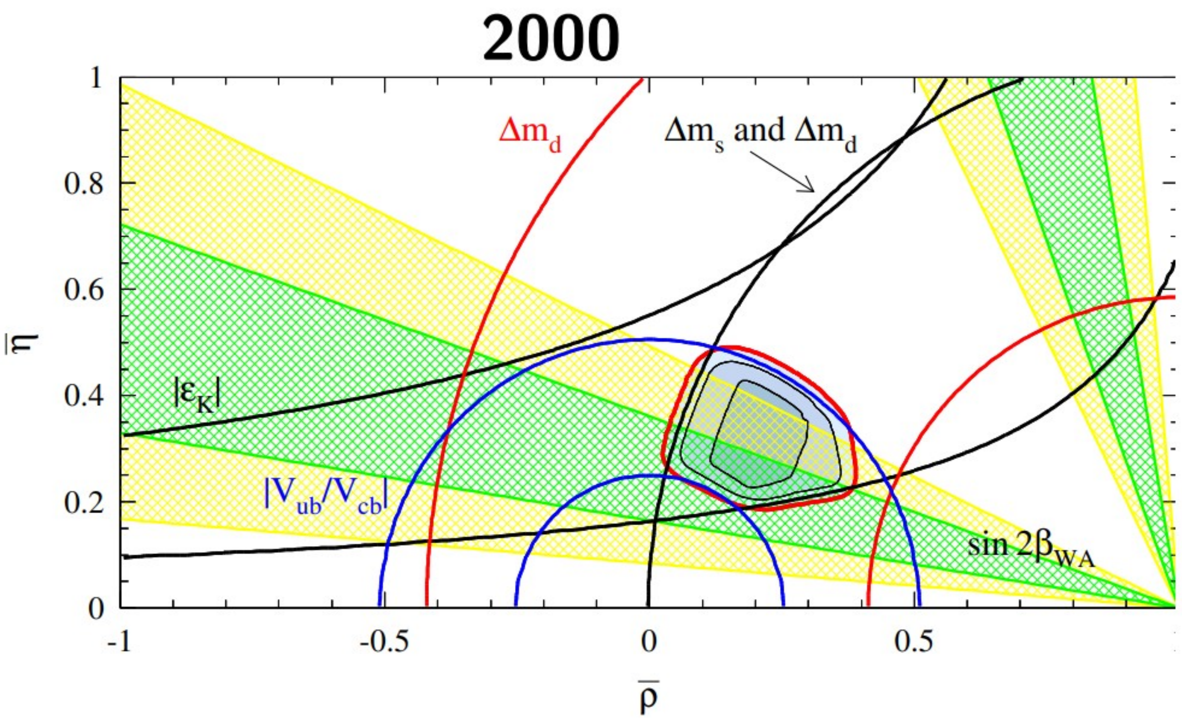
- Constructed from CKM matrix $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
- Angles and sides are well-defined (physical) quantities
- New Physics can cause inconsistency in the triangle parameters

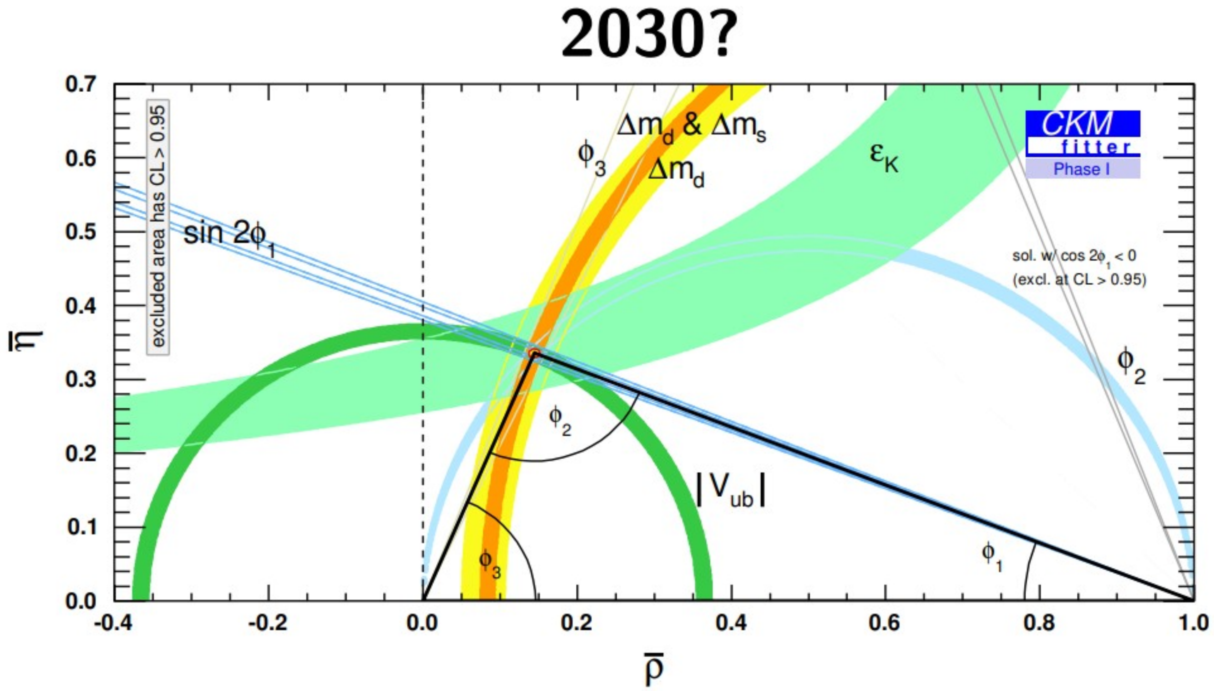




Unitarity triangle : in 10 years?

- Constructed from CKM matrix
- Angles and sides are well-defined (physical) quantities
- New Physics can cause inconsistency in the triangle parameters

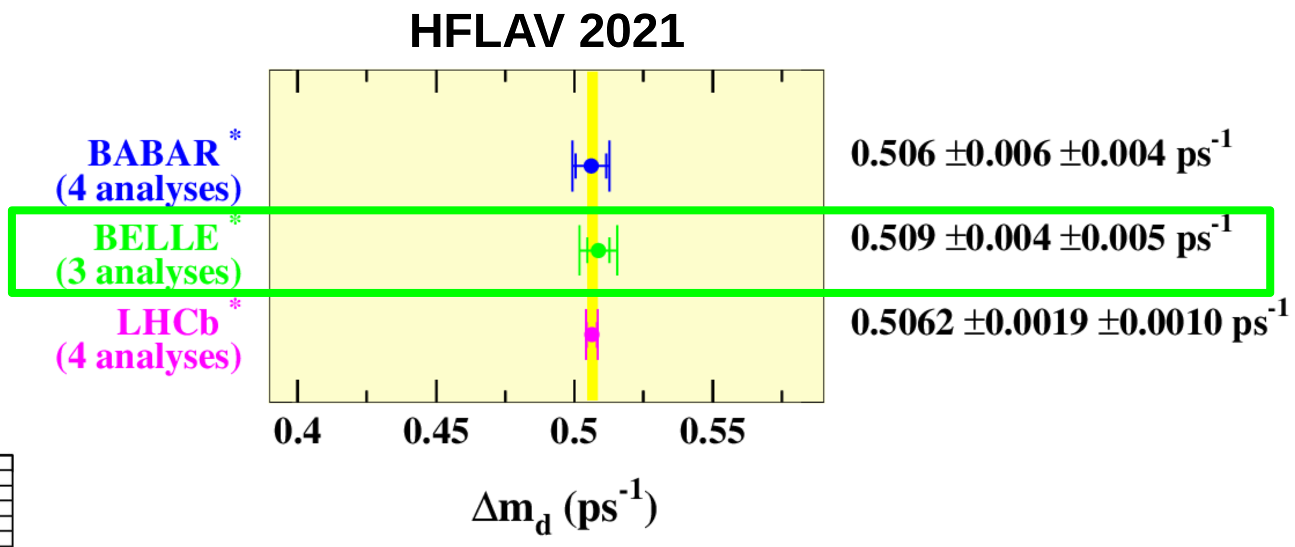


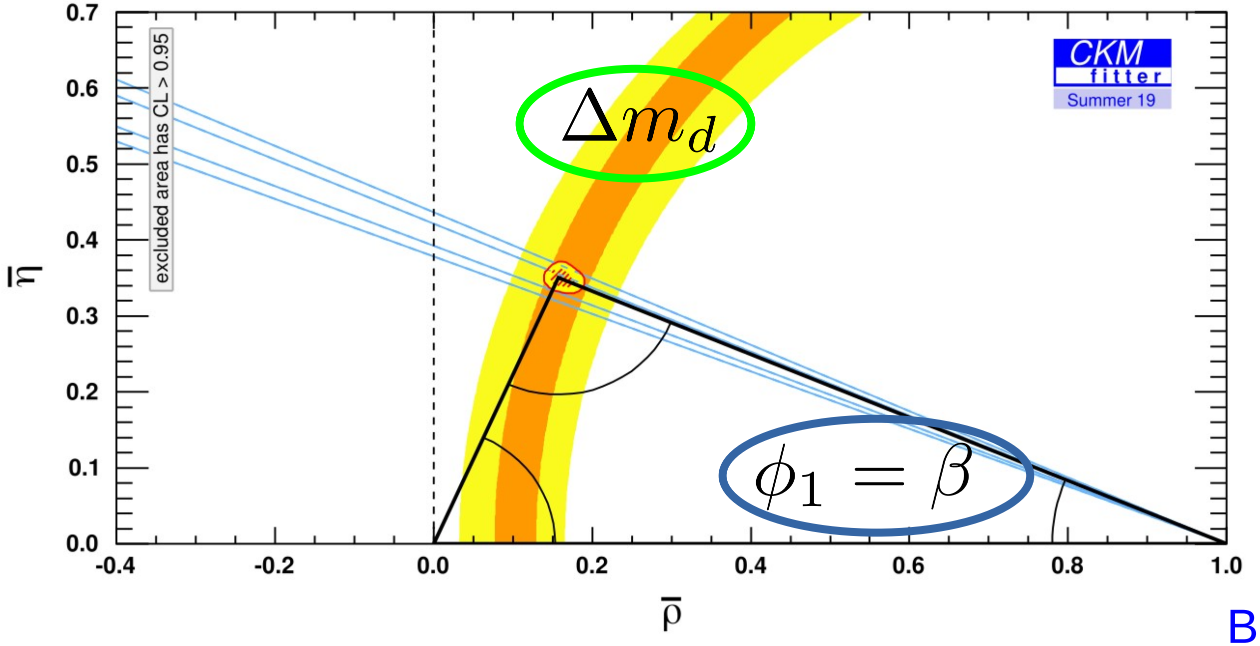


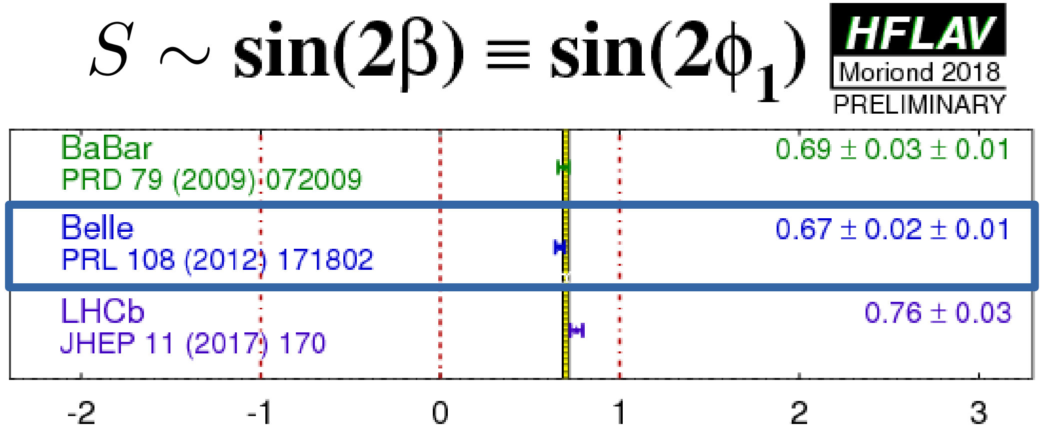
50 times larger Belle II data set will improve the precision to the sub-percent level

Sin $2\phi_1$= sin 2β and the $B^0\overline{B}^0$ oscillation frequency

- Most precise sin $2\phi_1$ estimate from the B-factories
- The oscillation frequency driven by the LHCb measurement







Belle II with full lumi can achieve 0.5% precision for sin 2β

CP violation in interference of mixing and decay

- The S~sin 2ϕ_1 measurable from the time-dependent asymmetry between $B^0 \to f_{CP}$ and $\overline{B}^0 \to f_{CP}$

$$\begin{tikzcd} B^0 \arrow[rr] \arrow[dr] & \phi_{\mathrm{mix}} & f_{\mathrm{CP}} \\ & \overline{B}^0 \arrow[ur] & \end{tikzcd}$$

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

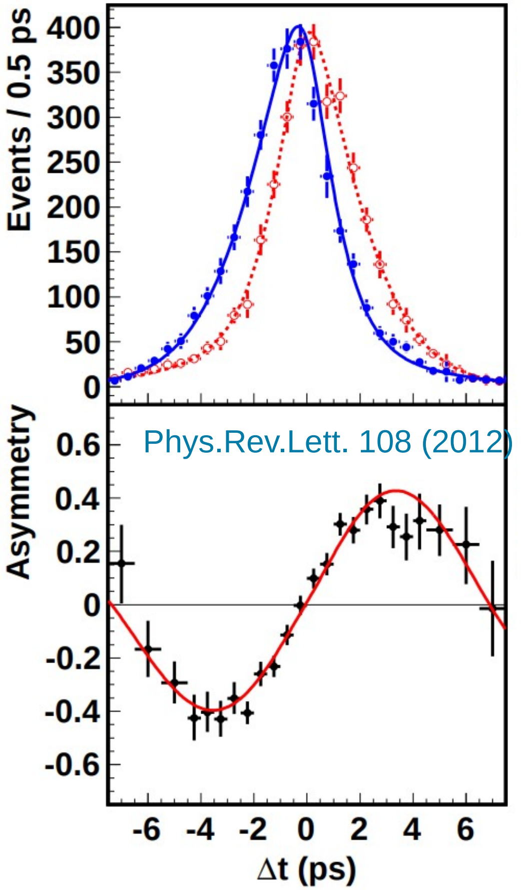
Mixing-induced CPV

Direct CPV

Two types of time-dependent CPV measurements

- **Tree-level** dominated decays like $B^0 \to J/\psi K_s$
  → most precise sin 2ϕ_1 measurement
- **Loop-induced** decays like $B^0 \to \phi K_s$, $B^0 \to \eta' K_s$
  → rare, window to new physics?

Belle I legacy (CP=-1)

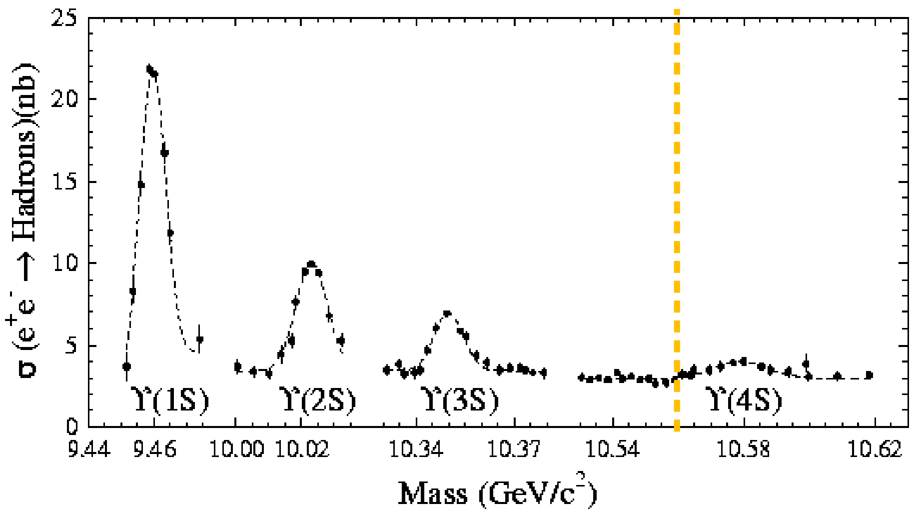


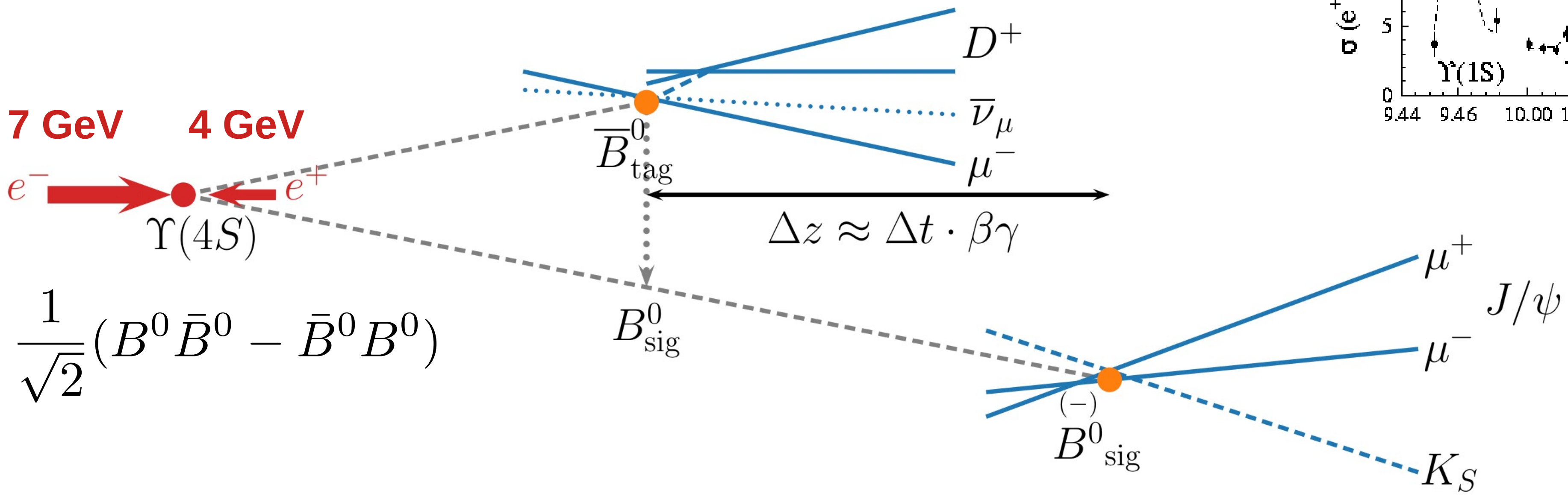
Phys.Rev.Lett. 108 (2012)

Measuring time-dep. CPV at Belle II

- Due to the asymmetric beam energies B-mesons fly in the direction of the e$^-$ beam with a maximal deviation of 12 deg

$B^0\bar{B}^0$ mass





$$\frac{1}{\sqrt{2}}(B^0\bar{B}^0 - \bar{B}^0B^0)$$

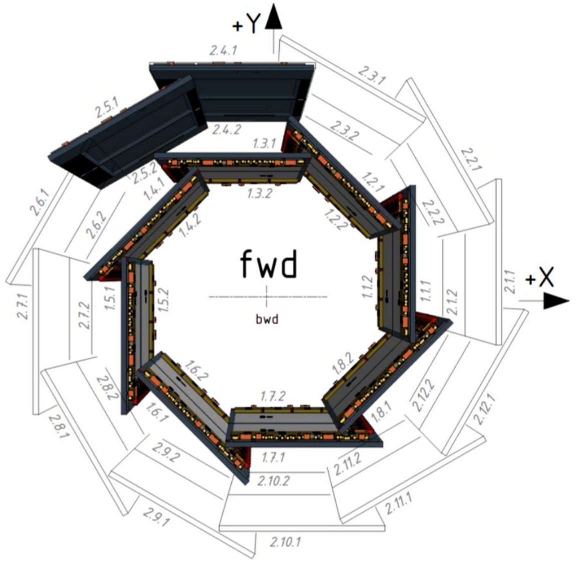
Belle II : $\Delta z \approx 130\,\mu\mathrm{m}$
Belle : $\Delta z \approx 200\,\mu\mathrm{m}$

Time-measurement ⇔ distance-measurement

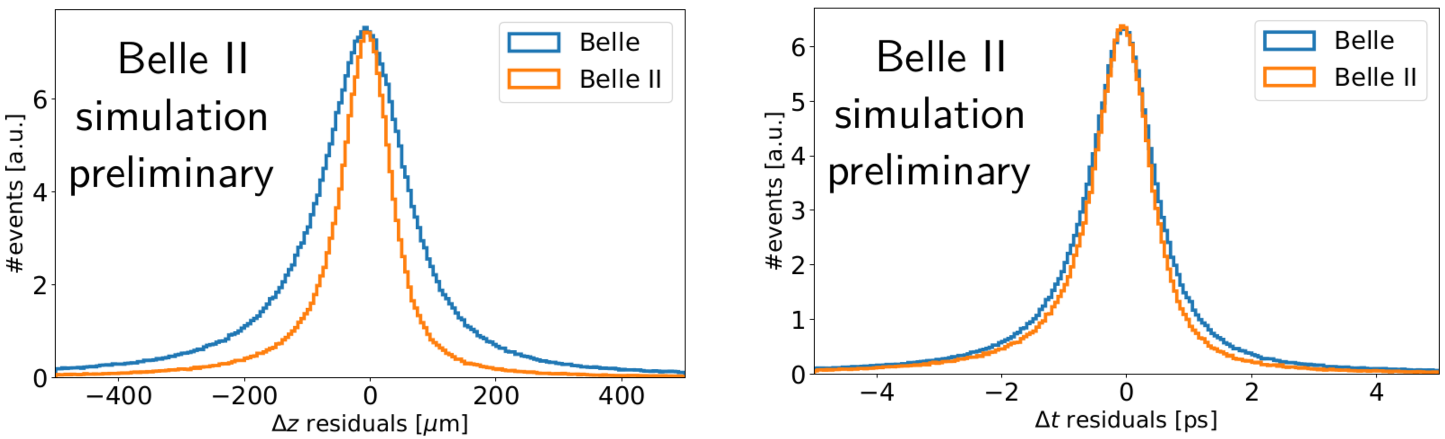
The Δt Measurement

- At Belle II there is smaller beam energy asymmetry, but better vertex resolution than at Belle
- From ee → μμ and hadronic B-meson decays we continuously measure:
  → ϒ(4S) velocity (boost vector)
  → ϒ(4S) energy (CM energy)
  → ϒ(4S) vertex position (beam spot)

Pixel Vertex Detector (PXD)



$$\beta\gamma = 0.43 \rightarrow \beta\gamma = 0.29$$



Difference of vertex positions

Boost vector direction

$$\Delta t = \frac{(\vec{v}_{\mathrm{CP}} - \vec{v}_{\mathrm{tag}}) \cdot \vec{n}_{\mathrm{boost}}}{\gamma^{*}\gamma\beta c}$$

Depends on collision energy

Boost vector magnitude

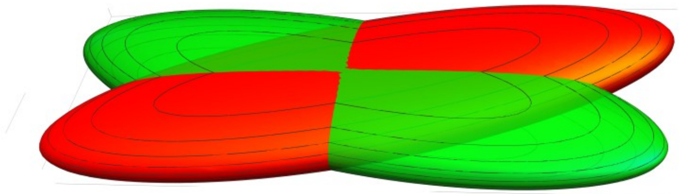
$\tau(B^0) \approx 1.5$ ps

Beam spot constraint

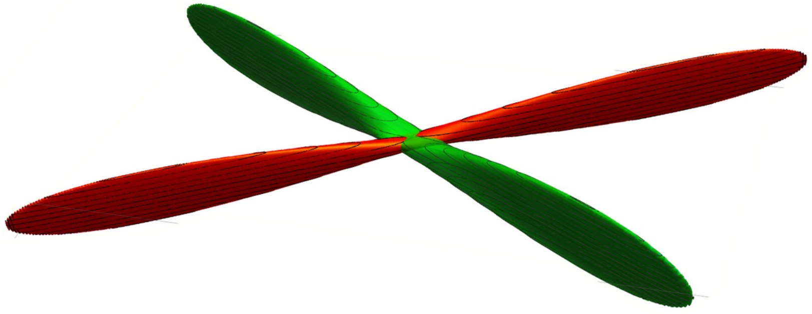
- At Belle II the much higher peak luminosity is achieved by so-called nano-beam scheme
- The small beam size can be used to better constrain the kinematics of the event (e.g. improving B_{tag} vertex precision and consequently Δt resolution)

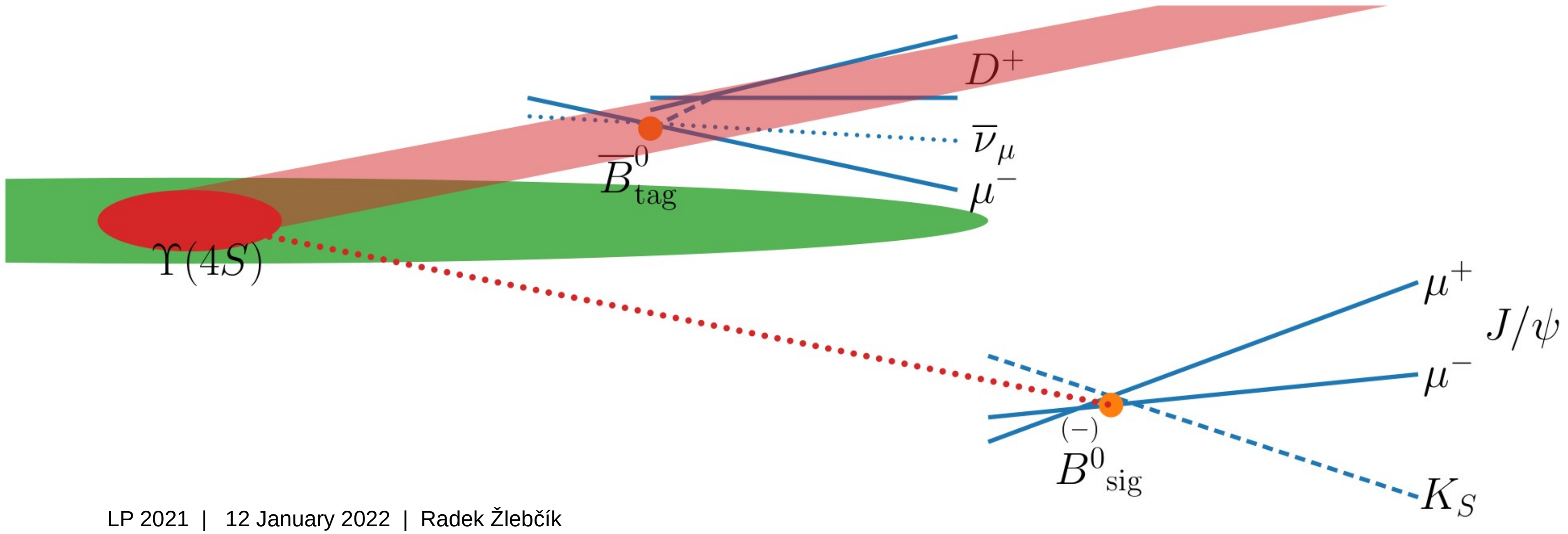
$$\sigma_{Y'} = 0.2\mu\mathrm{m}, \sigma_{X'} = 10\mu\mathrm{m}, \sigma_{Z'} = 240\mu\mathrm{m}$$

Belle



Belle II





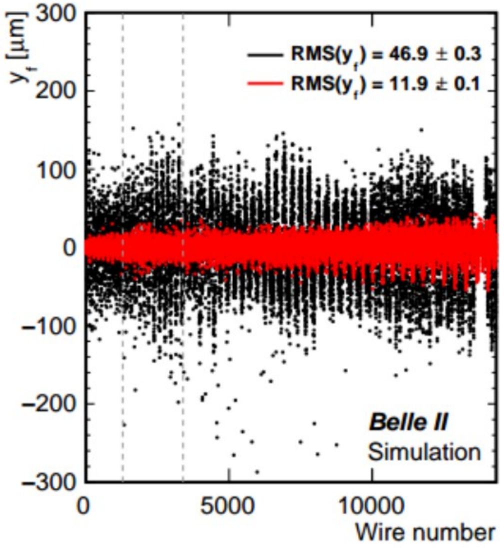
Beam spot calibration

- Based on ee → μμ events with high-stat
- Calibrated every ~30min
- All parameters of the 3D Gaussian PDF measured (3 sizes + 3 angles)

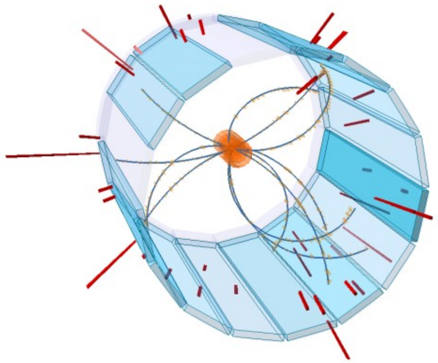
Tracker Alignment

- **Alignment** is a data driven method to determine positions of sensors/wires of the Tracker
  → Crucial for precise TD-CPV measurements
- Recently all the 14336 wires have been included into the alignment
  → 60,000 parameters
  (for Pixel Detector, Strip Detector & Central Drift Chamber)

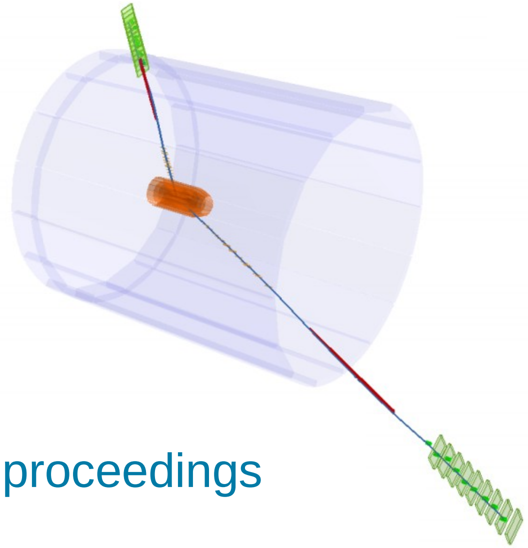
Monte Carlo



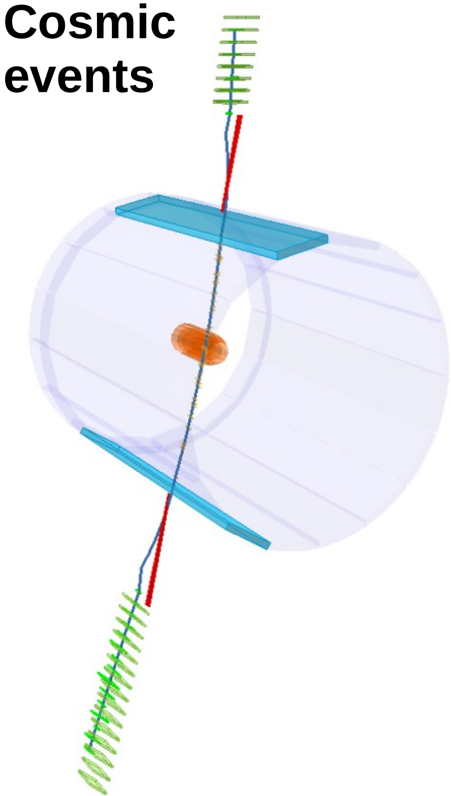
Hadronic events



Di-muon events



Cosmic events



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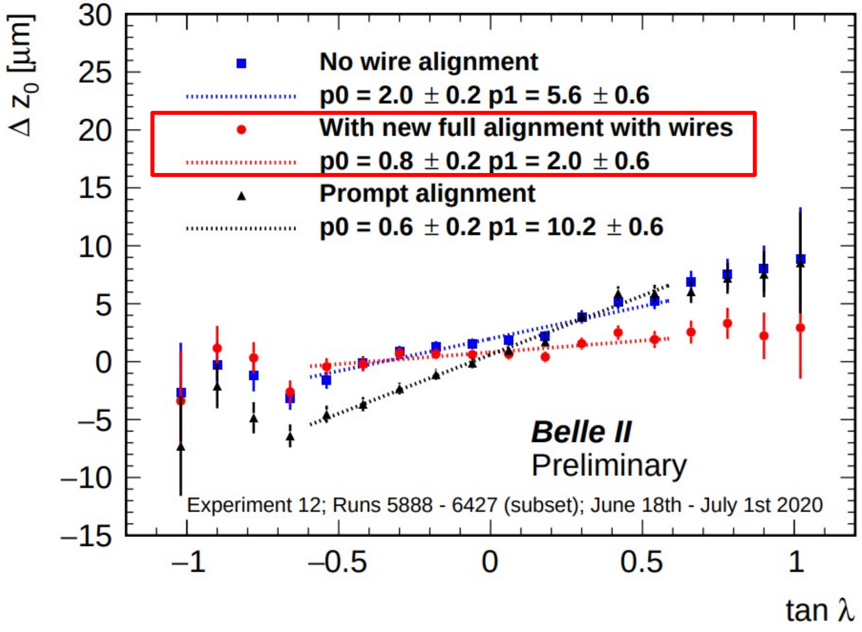
Data

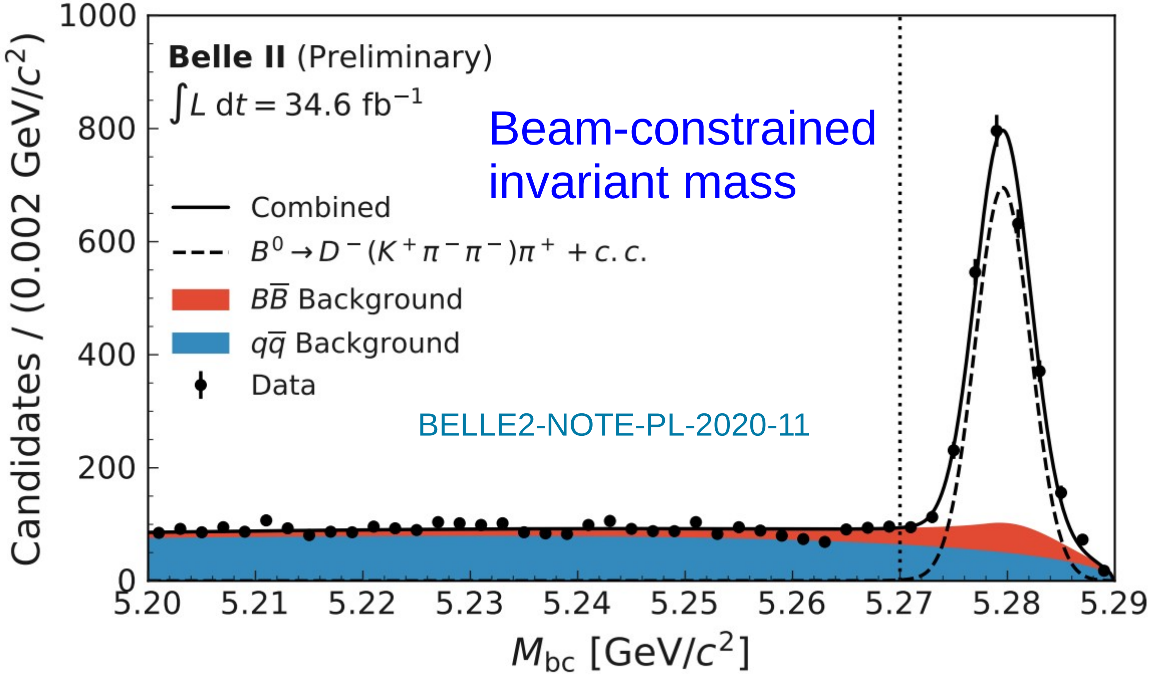


Mixing measurement: $B^0 \rightarrow D^- \pi^+$

PDG value:
$0.507 \pm 0.002\ \text{ps}^{-1}$

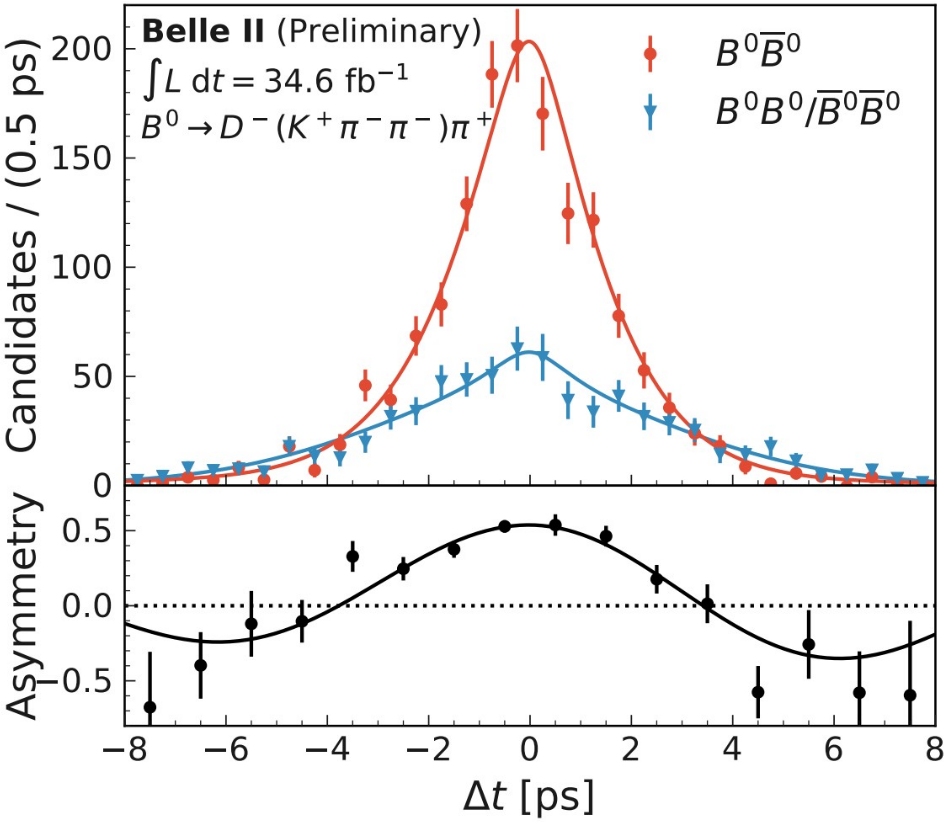
- At Belle measurement dominated by sys. unc. already with 140 fb^{-1}
  → Mixing measurement in hadronic B decays probes the TD analysis framework
- Both B mesons in the flavor eigenstate, one fully reconstructed

$$\Delta m_d = (0.531 \ \pm \ 0.046 \ (\text{stat.}) \ \pm \ 0.013 \ (\text{syst.})) \ \text{ps}^{-1}$$



Beam-constrained invariant mass

BELLE2-NOTE-PL-2020-11



Results consistent with PDG, soon competitive with Belle/BaBar

CPV measurement: $B^0 \to J/\psi\ K_s$

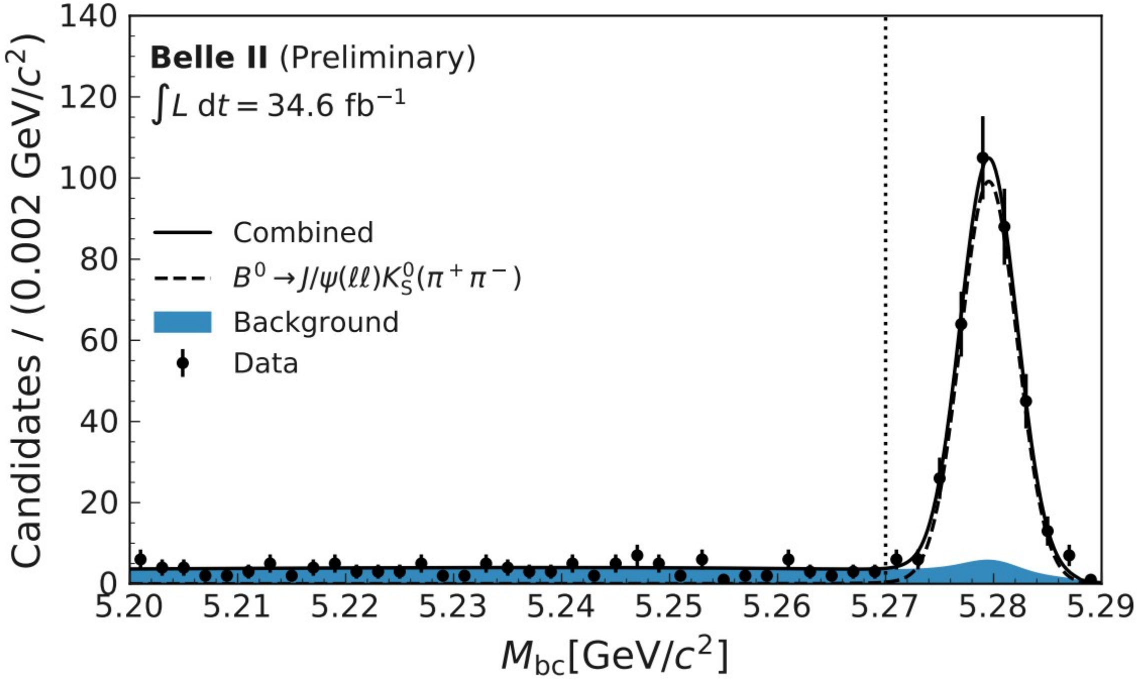
- Performed on 35 fb^{-1} of data
- Both J/ψ → μμ and J/ψ → ee analyzed

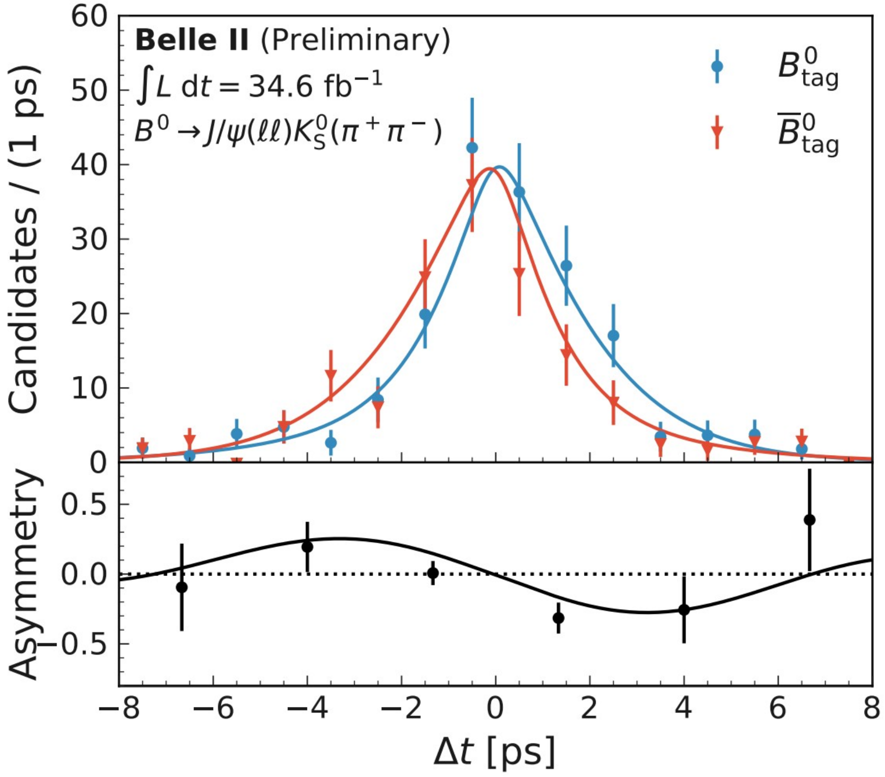
PDG value:

$$0.670 \pm 0.029(\mathrm{stat.}) \pm 0.013(\mathrm{sys.})$$

$$S_f = \sin 2\beta = 0.55 \pm 0.21(\mathrm{stat.}) \pm 0.04(\mathrm{sys.})$$

BELLE2-NOTE-PL-2020-11





First CPV measurement consistent with PDG, high-stat analysis in progress

D lifetime – Current status

- High precision measurement, crucial to probe beam spot & alignment calibration

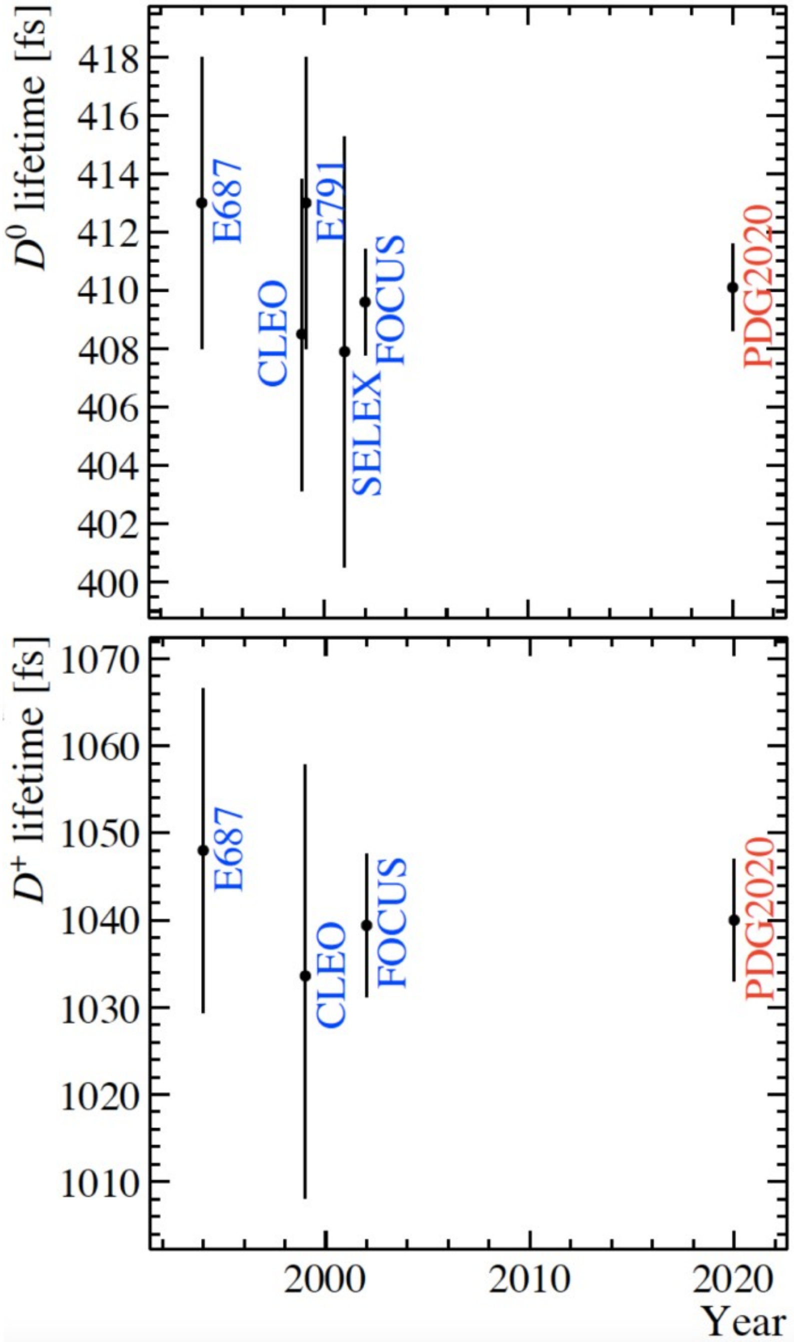
- **FOCUS** : most precise estimate from
  γ (180 GeV) + BeO
- **CLEO** : the only $e^+ e^-$ measurement,
  i.e. no results from LEP, BaBar or Belle

- The lifetime of other charm hadrons (D_s, Λ_C,Ξ_C, Ω_C) dominated by LHCb, all measured **wrt τ(D⁺)**

$$\tau(D_s^-) = 506.4 \pm 3.0(\text{stat}) \pm 1.7(\text{syst}) \boxed{\pm 1.7(\tau_{D+})} \text{ fs}$$

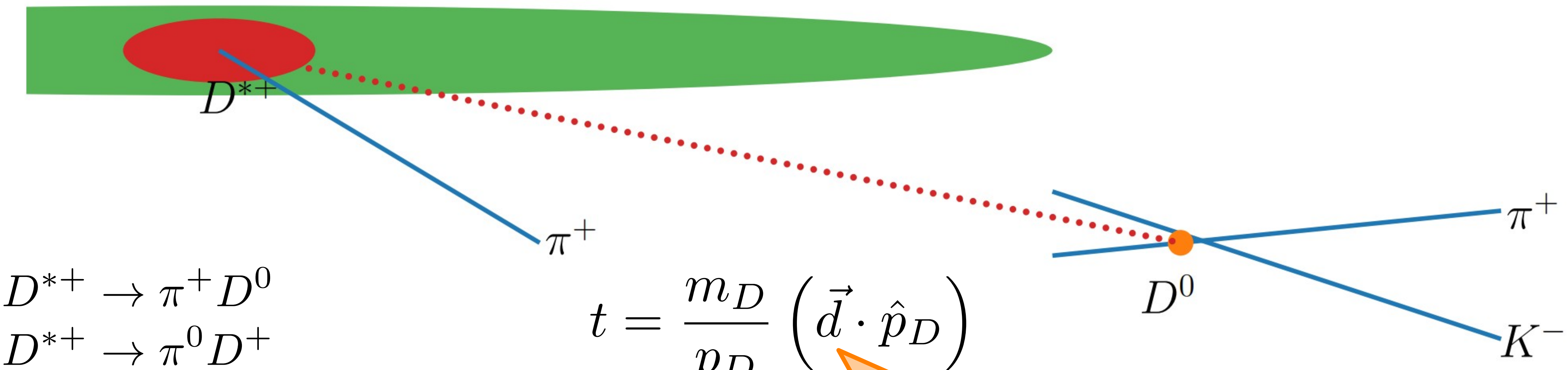
Phys.Rev.Lett. 119 (2017) 10

Belle II is also a charm-factory
with 1.3M $c\bar{c}$ events / 1 fb^{-1}



D lifetime measurement

- Measurement of D^0 and D^+ lifetimes performed with 72 fb^{-1} data
- D decay time computed from the distance between D* decay and D decay vertex



$$D^{*+} \to \pi^+ D^0$$
$$D^{*+} \to \pi^0 D^+$$

$$t = \frac{m_D}{p_D} \left(\vec{d} \cdot \hat{p}_D \right)$$

D-meson momentum

D-meson flight-distance vector

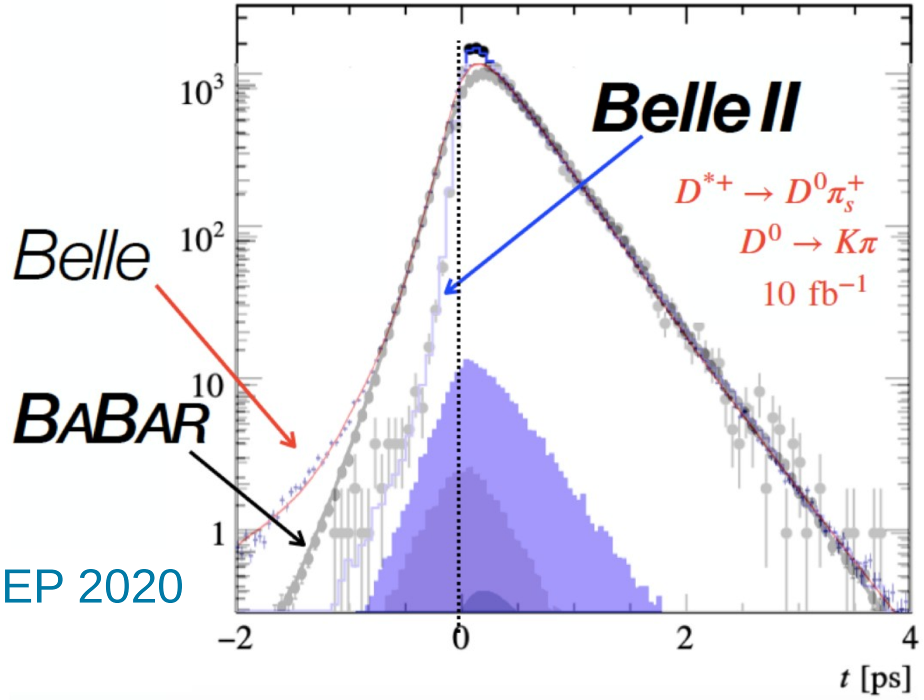
d(D^+) ~ 500 μm
d(D^0) ~ 200 μm

- Exploiting small transverse size of the beam spot (~0.2 um and 10 um)
- In contrast to B-mesons, the D flight direction is not collimated with the beam

D lifetime distribution

$$t = \frac{m_D}{p_D}\left(\vec{d}\cdot\hat{p}_D\right)$$

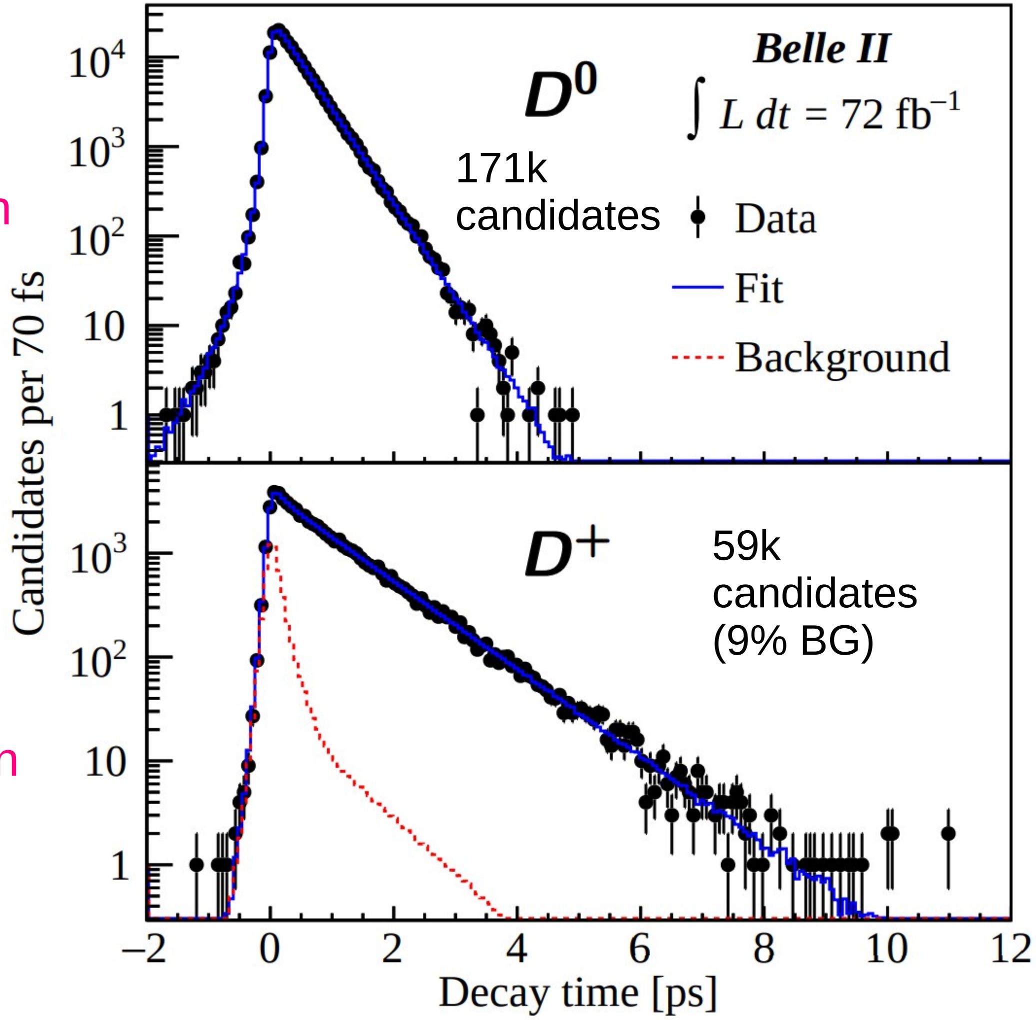
- Reconstructed D-lifetime can be negative due to the resolution effects
  → a tool to control the resolution
- Belle II profits from excellent vertex detector and small beam spot size



ICHEP 2020

~70 fs resolution

~60 fs resolution



2D unbinned ML fit to the (t, σ_t)

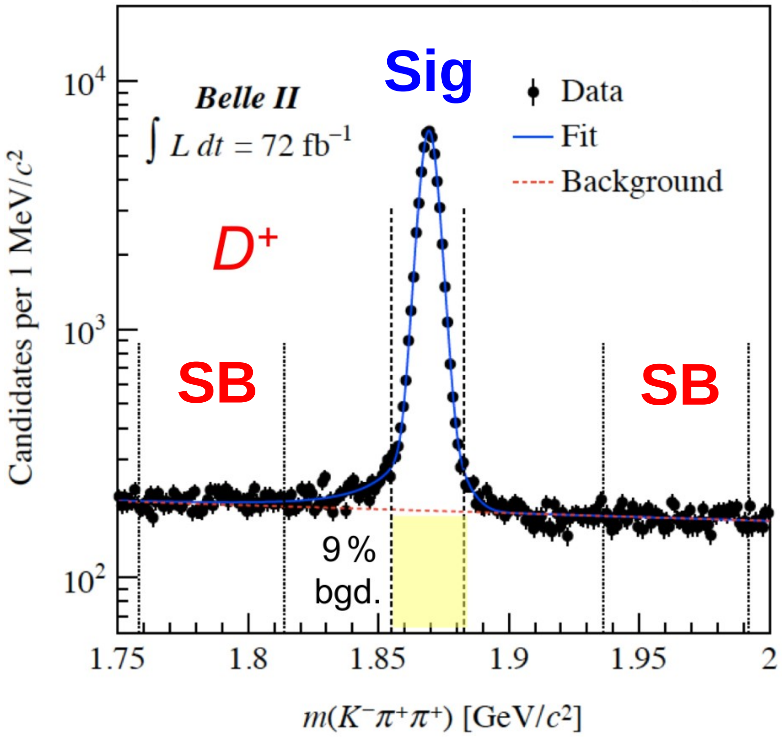
D lifetime : 2D (t,σ) ML fit

Simultaneous **Signal** & **Side Band** fit

$$\mathrm{PDF}_{\mathrm{Sig}}(t,\sigma) = (\mathrm{Sig}(t)\mathrm{Sig}(\sigma) + f\mathrm{BG}(t)\mathrm{BG}(\sigma)) \otimes R(\Delta t,\sigma)$$

$$\mathrm{PDF}_{\mathrm{SB}}(t,\sigma) = (\qquad\qquad\qquad\qquad\qquad\qquad \mathrm{BG}(t)\mathrm{BG}(\sigma)) \otimes R(\Delta t,\sigma)$$

59k $D^{*+} \rightarrow D^+(\rightarrow K^-\pi^+\pi^+)\pi_s^0$

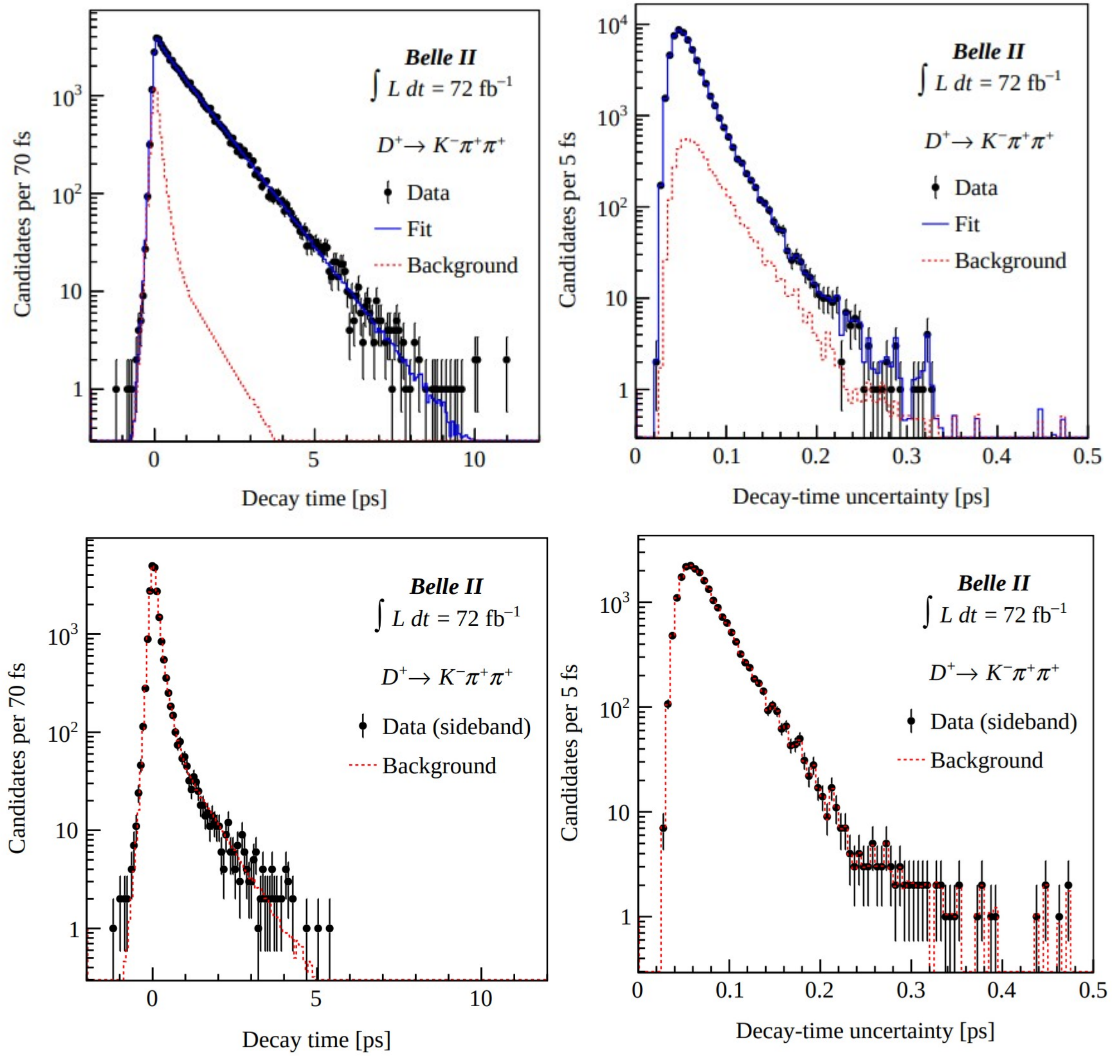


Decay time

Decay time uncertainty

Sig

SB



D lifetime results

- Results more precise than the world average

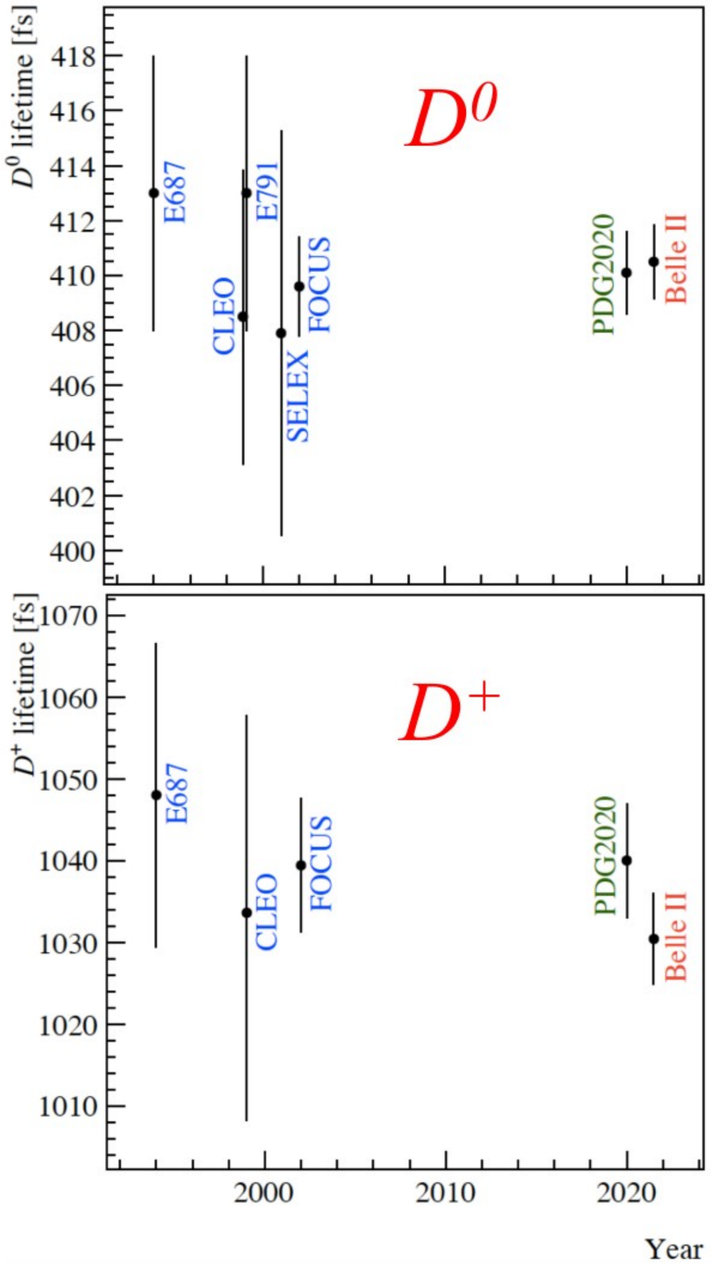
$$\tau(D^0) \;=\; 410.5 \pm 1.1 \pm 0.8 \text{ fs} \qquad (0.3\%)$$

$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1 \text{ fs} \qquad (0.5\%)$$

$$\tau(D^+)/\tau(D^0) = 2.510 \pm 0.015 \qquad (0.6\%)$$

Source	Uncertainty (fs)	
	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Input charm masses	0.01	0.03
Total systematic	0.8	3.1
Statistical	1.1	4.7

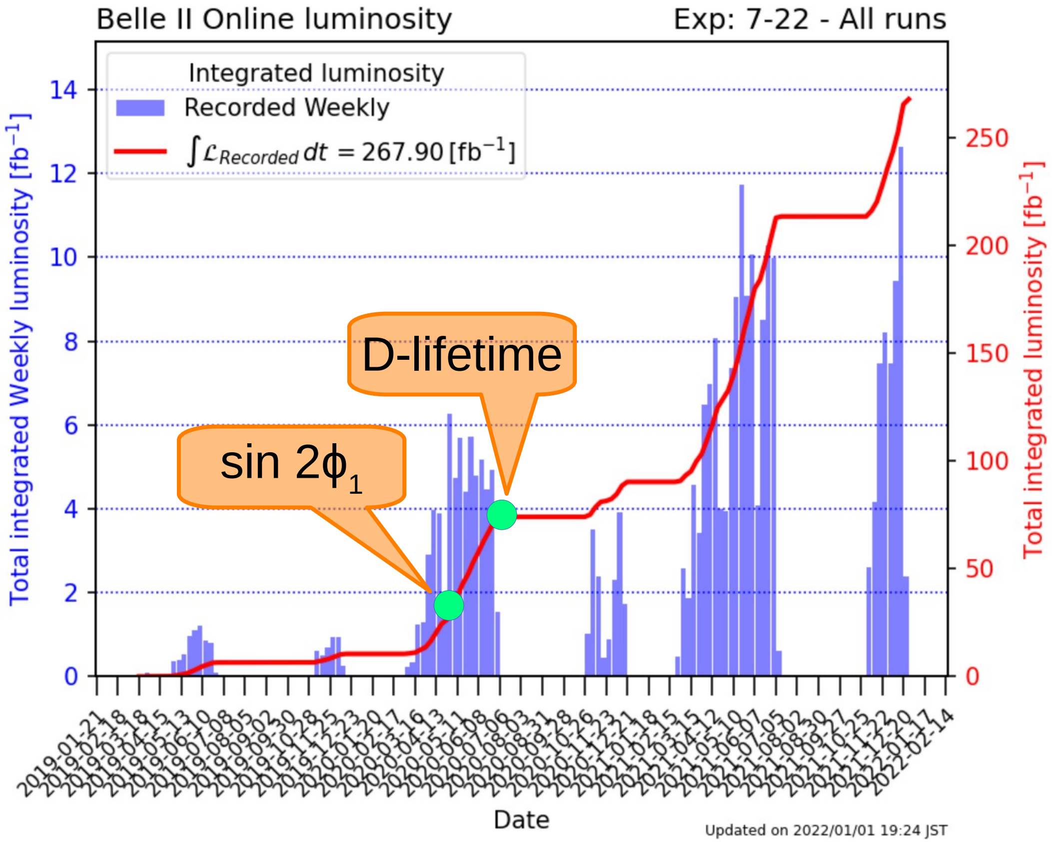
With 72 fb^{-1} the stat unc. still dominates



Phys. Rev. Lett. 127 (2021) 211801

Conclusions

- The TD-CPV measurement on 35 fb^{-1} of Belle II data shows better vertex resolution & comparable flavor tagging performance to Belle
  → road paved for high precision CPV results
- The world most precise D^+ & D^0 lifetime measurement with a permile-level uncertainty (on 72 fb^{-1} of Belle II data)
  → more charm lifetimes (D_s, Λ_c, Ω_c) on the way

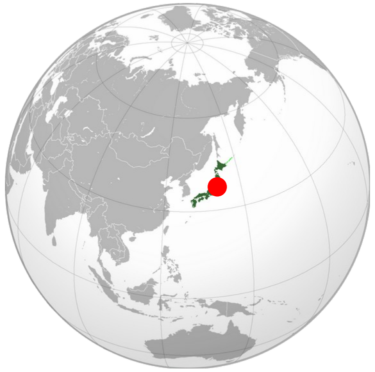


D-lifetime

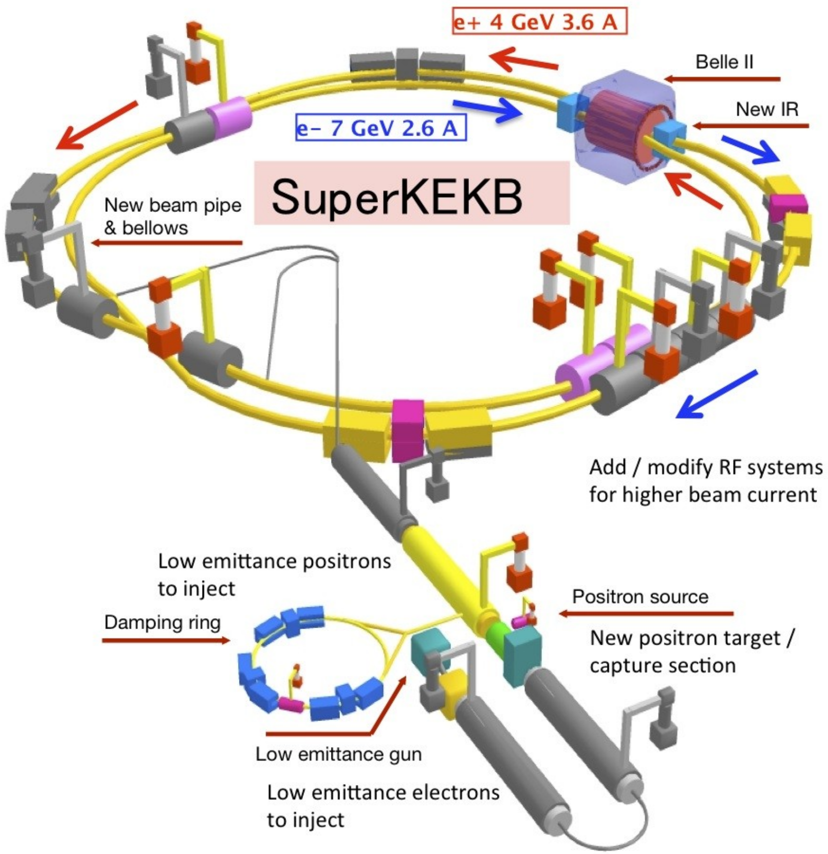
sin $2\phi_1$

https://confluence.desy.de/display/BI/Belle+II+Luminosity

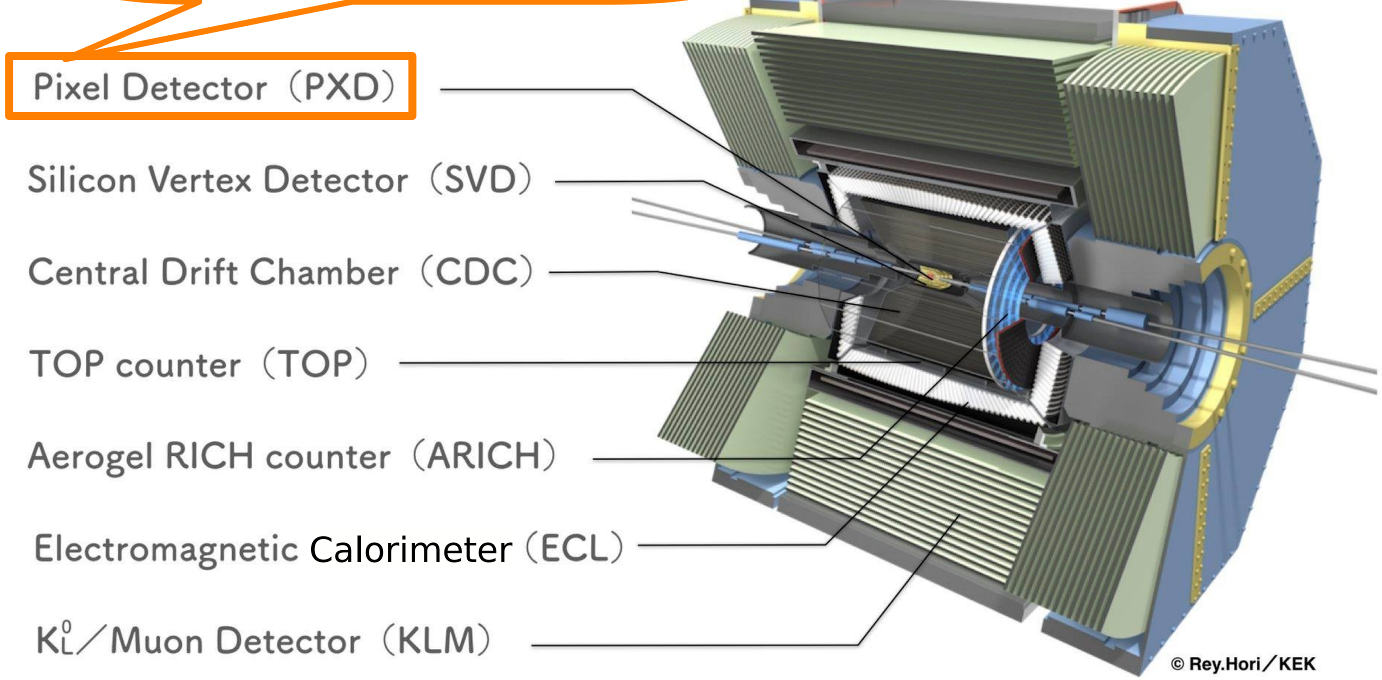
Belle2 & SuperKEKB



- The target luminosity $6*10^{35}$ cm^{-2} s^{-1} (50 ab^{-1} in total)
  (continuous injection allows long runs)



Crucial for Δt measurement



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CP violation for neutral B-mesons

The CP symmetric system in time t_2 is not CP symmetric at time t_1

$$\begin{tikzcd}
B^0(t_1) \arrow[rr, "\text{Time evolution}", "P_{B^0\to B_{\mathrm{CP}}}(\Delta t)"'] \arrow[d, leftrightarrow, "\cancel{\text{CP}}"] & & B^0_{\mathrm{CP}}(t_2) \arrow[d, leftrightarrow, "\text{CP}"] \\
\bar{B}^0(t_1) \arrow[rr, "\text{Time evolution}", "P_{\bar{B}^0\to B_{\mathrm{CP}}}(\Delta t)"'] & & B^0_{\mathrm{CP}}(t_2)
\end{tikzcd}$$

$$\Delta t = t_2 - t_1$$

$$A(\Delta t) = \frac{P_{\bar{B}^0\to B_{\mathrm{CP}}}(\Delta t) - P_{B^0\to B_{\mathrm{CP}}}(\Delta t)}{P_{\bar{B}^0\to B_{\mathrm{CP}}}(\Delta t) + P_{B^0\to B_{\mathrm{CP}}}(\Delta t)} = A\cos\Delta m\Delta t + S\sin\Delta m\Delta t$$

Direct CPV

Mixing-induced CPV

Trick of asymmetric beams

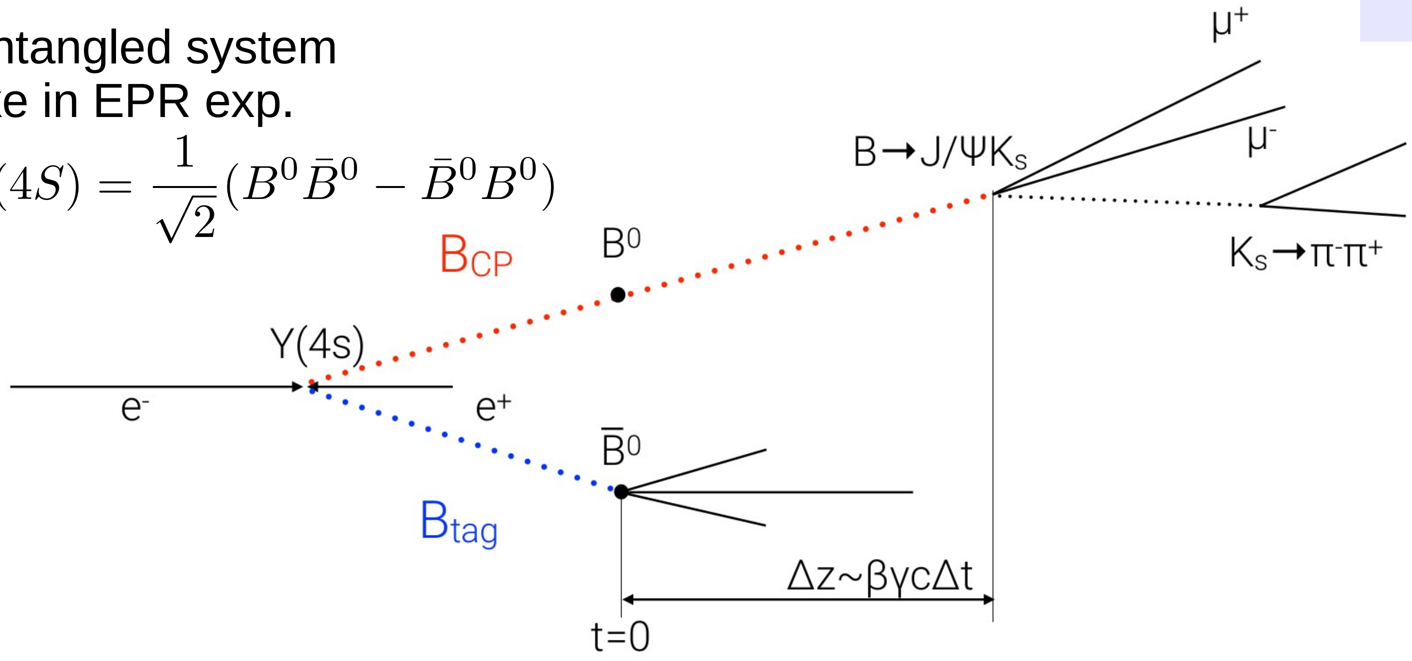
- Υ(4S) is a first $b\bar{b}$ resonance above $m_B + m_{\bar{B}}$
  → Bs nearly in rest in Υ(4S) frame

Time-measurement ⇔ distance-measurement

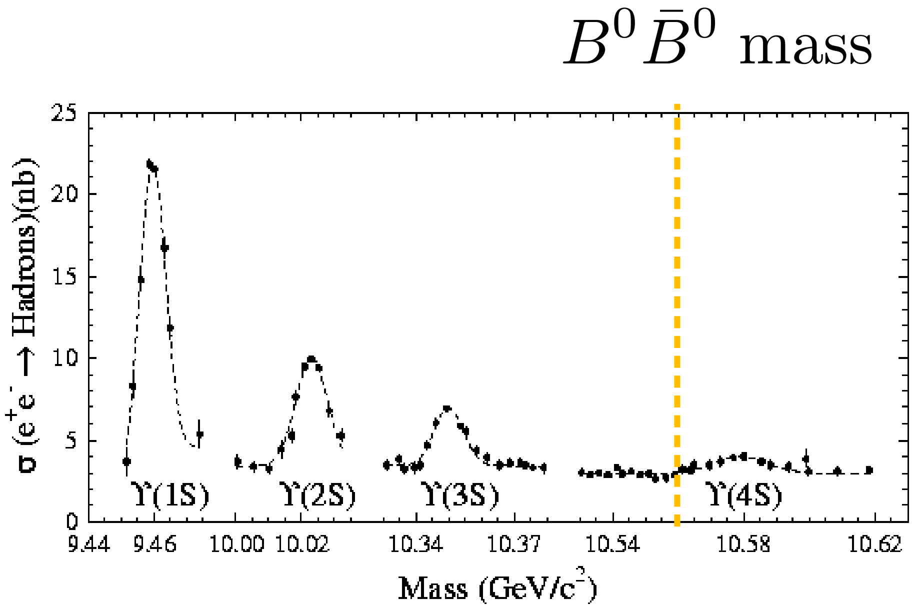
	e^- energy [GeV]	e^+ energy [GeV]	Lumi
BaBar	9.0	3.1	477 fb^{-1}
Belle	8.0	3.5	866 fb^{-1}
Belle II	7.0	4.0	50,000 fb^{-1} (50 ab^{-1})

Entangled system
like in EPR exp.

$$\Upsilon(4S) = \frac{1}{\sqrt{2}}(B^0\bar{B}^0 - \bar{B}^0B^0)$$



Belle II : $\Delta z \approx 130\,\mu\mathrm{m}$
Belle : $\Delta z \approx 200\,\mu\mathrm{m}$



Flavor tagging

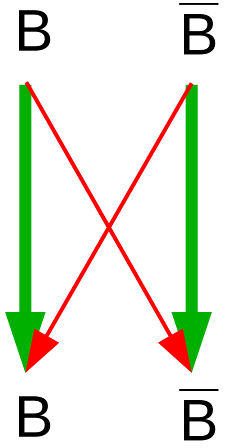
arXiv: 2110.00790

- Determination of the B$_{\text{tag}}$ flavor using all the particles not belonging to signal B
- The |qr| is split into 7 bins to test the performance in hadronic B decays data
- The efficiency evaluated from BB/B$\overline{\text{B}}$ asymmetries in all |qr| bins

$$\varepsilon_{\text{eff}} = \sum_{i \in |qr|\ \text{bins}} \epsilon_i (1 - 2w_i)^2$$

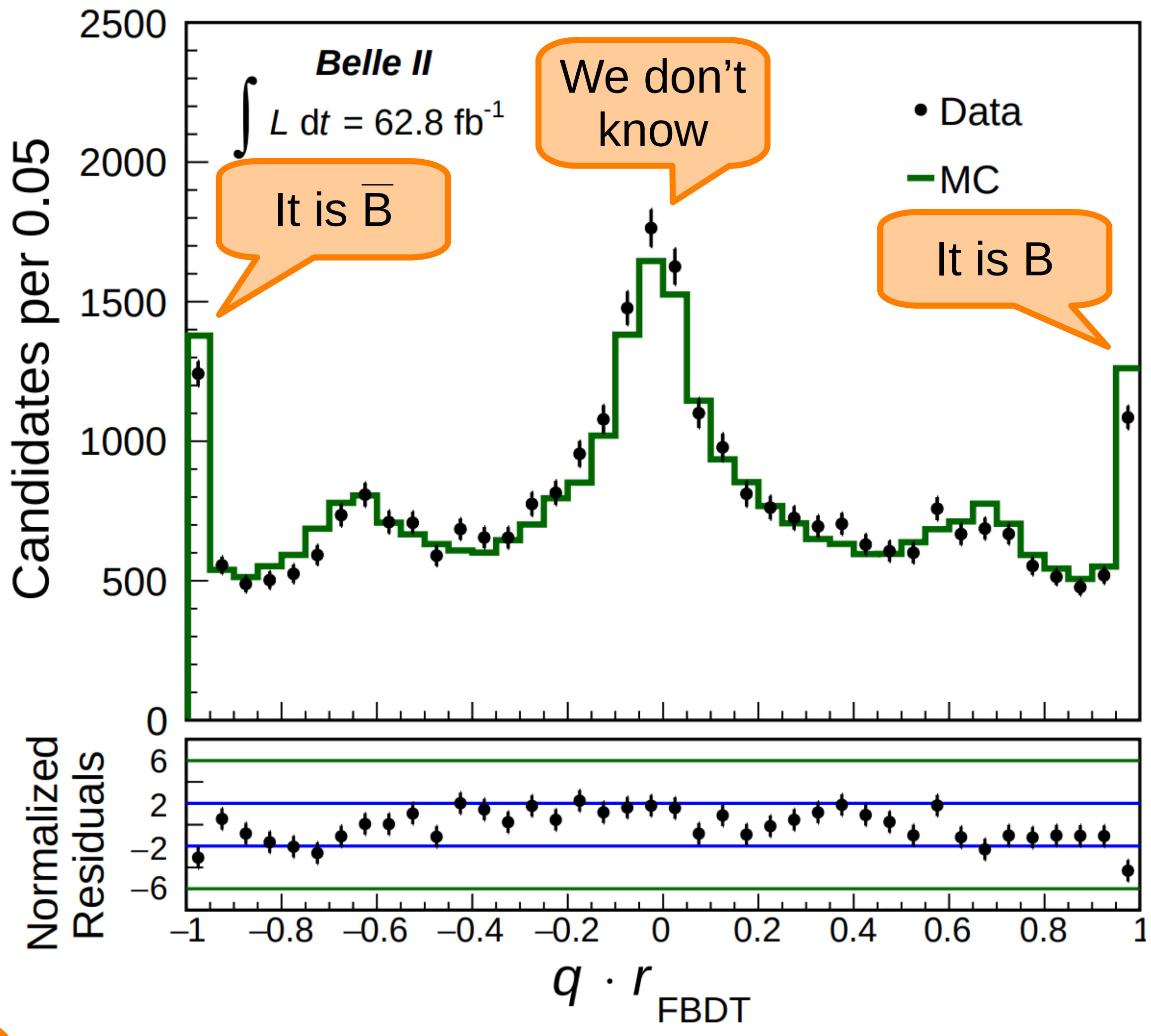
$$\varepsilon_{\text{eff}}^{\text{Belle}} = (30.1 \pm 0.4)\%$$

$$\varepsilon_{\text{eff}}^{\text{Belle II}} = (30.0 \pm 1.2)\%$$



$$1 - w_i$$

Mistag fraction



Dilution factor : $r_{\text{FBDT}} \approx 1 - 2w$
Flavor tag : $q = \pm 1$

Penguin-dominated processes

$$B^0 \to J/\psi K_\mathrm{S}$$

$$(\sin 2\beta)_\mathrm{PDG} = 0.70 \pm 0.02$$

⟺

$$B^0 \to (\phi, \eta')K_\mathrm{S}$$

$$(\sin 2\beta)_\mathrm{PDG} = 0.68 \pm 0.08$$

Tree channels & loop processes should give consistent β

→ New particle in loop can shift the SM phase