CP violation measurements at Belle II

Radek Žlebčík

June 10, 2021

Conference on

Flavor Physics and CP Violation

CHARLES UNIVERSITY

Belle II

CP violation for neutral B-mesons

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

$B^0(t_1)$ — Time evolution, $P_{B^0 \to B_{\rm CP}}(\Delta t)$ → $B^0_{\rm CP}(t_2)$

~~CP~~ | CP

$$\Delta t = t_2 - t_1$$

$\bar{B}^0(t_1)$ — Time evolution, $P_{\bar{B}^0 \to B_{\rm CP}}(\Delta t)$ → $B^0_{\rm CP}(t_2)$

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

Direct CPV

Mixing-induced CPV

Sin 2β and the Unitarity Triangle

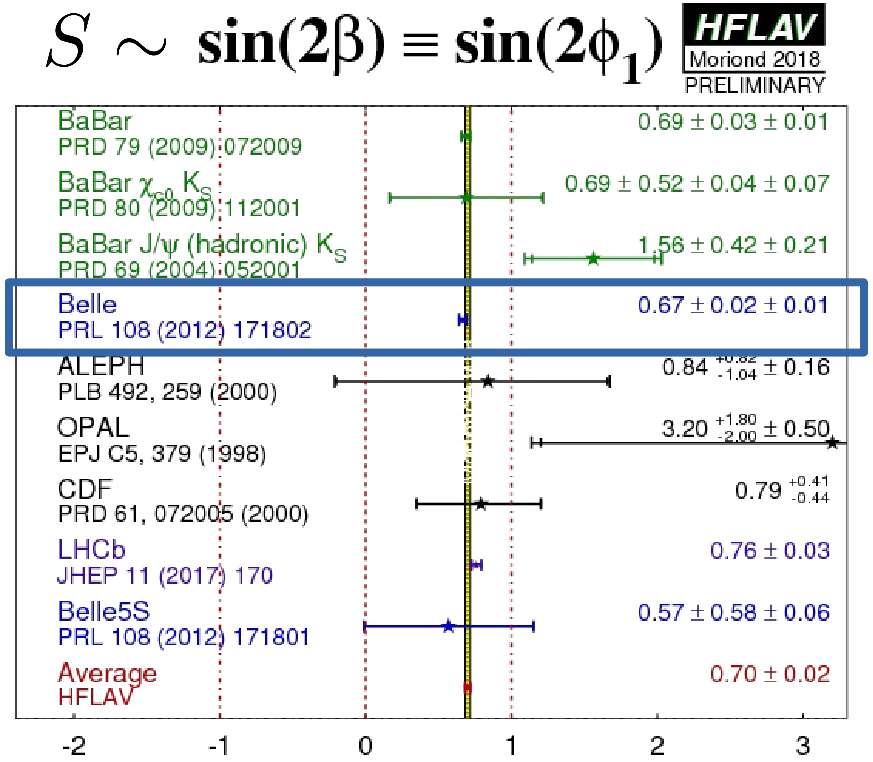
- Constructed from CKM matrix

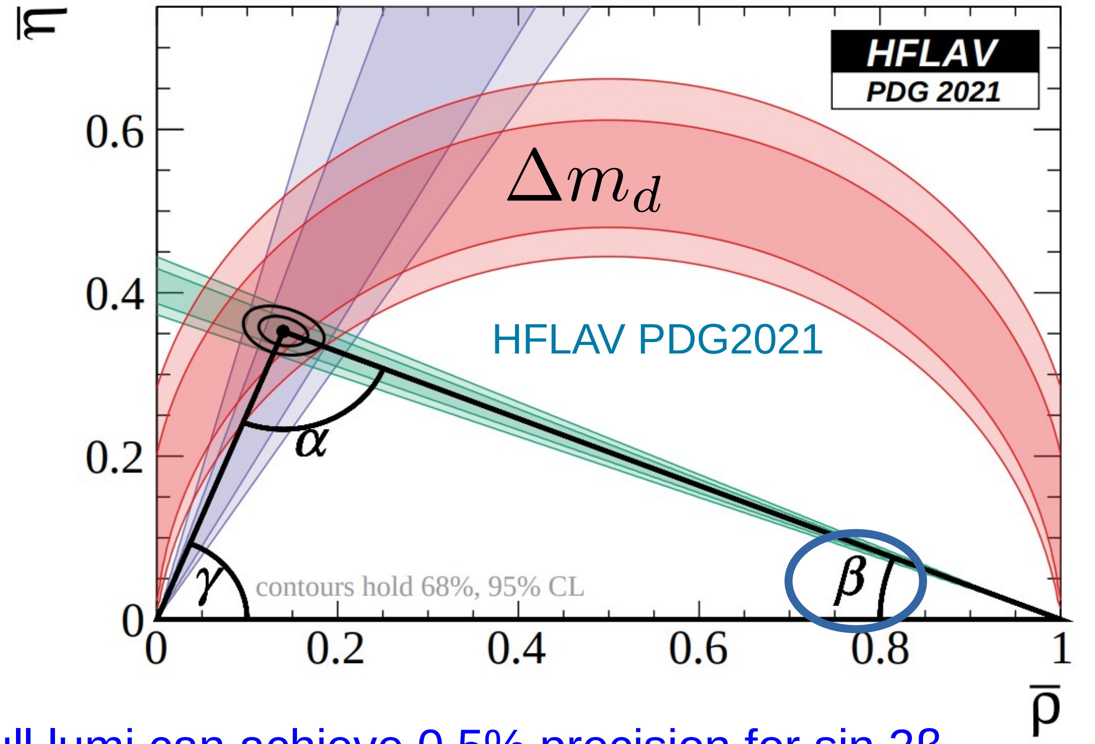
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

- Angles and sides are well-defined (physical) quantities

Hints for BSM physics

- Do the angles sum to 180°?
- Are sides consistent with angles?
- Do all processes indicate a consistent picture?





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

Trick of asymmetric beams

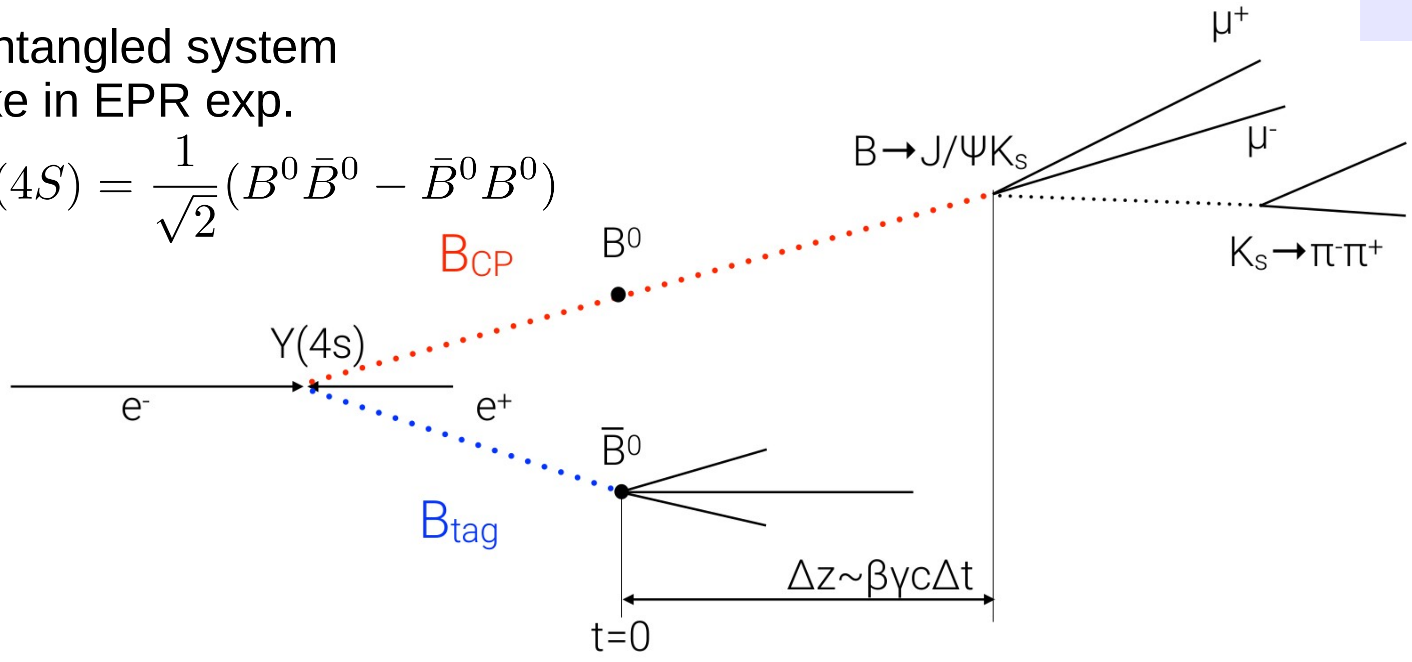
- $\Upsilon(4S)$ is a first $b\bar{b}$ resonance above $m_B + m_{\bar{B}}$
  → Bs nearly in rest in $\Upsilon(4S)$ frame

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})

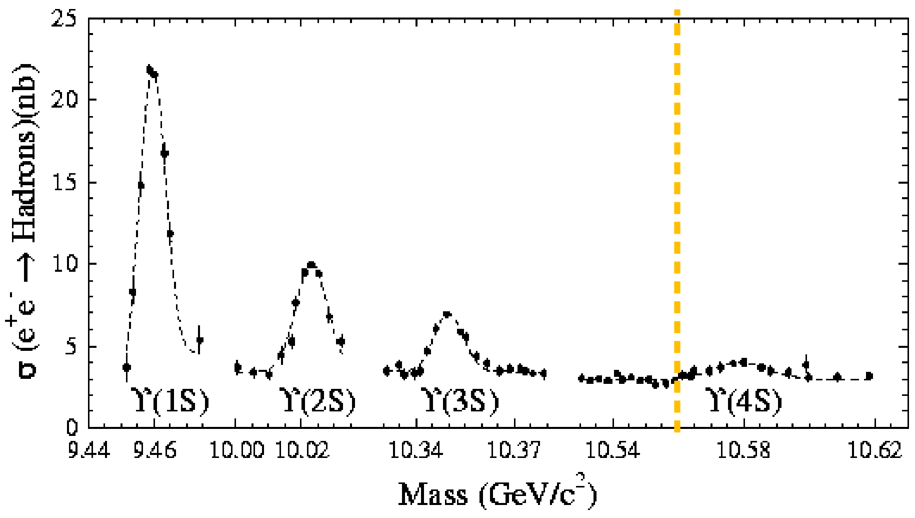
Entangled system
like in EPR exp.

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



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

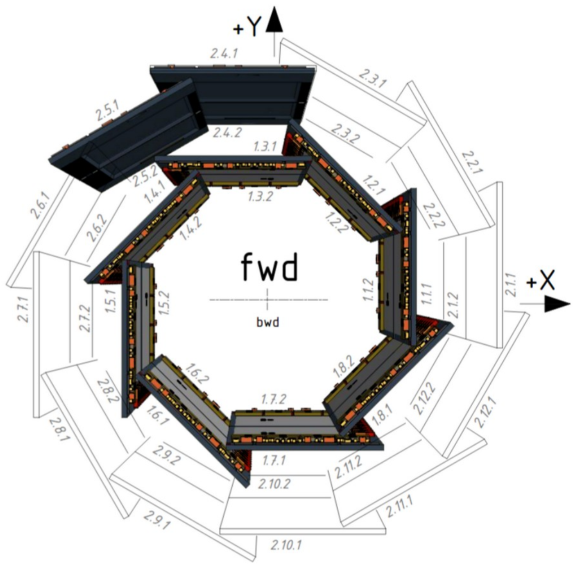
$B^0\bar{B}^0$ mass



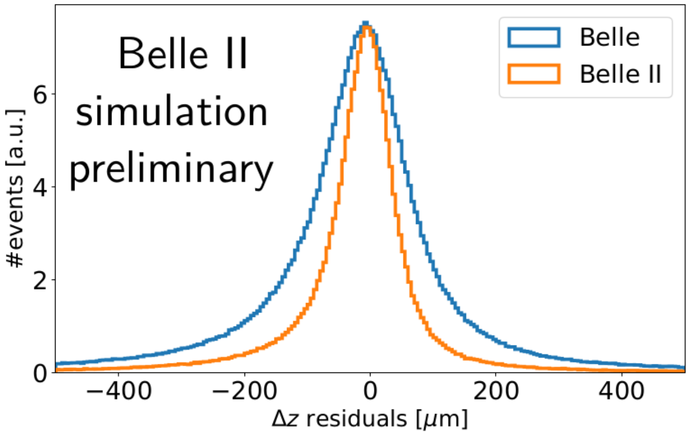
The Δt Measurement

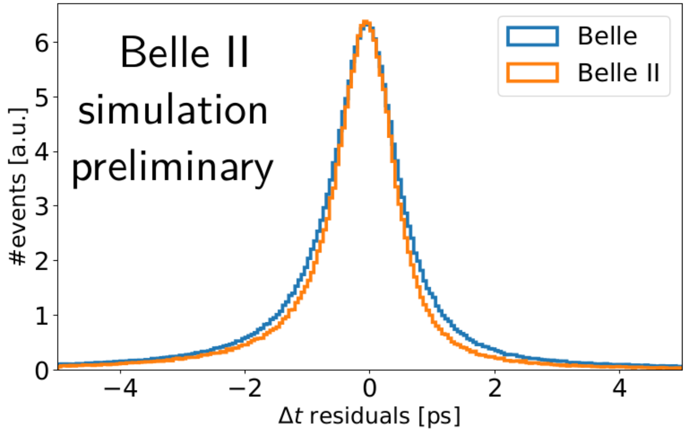
- At Belle II there is smaller boost, but better vertex resolution than at Belle
- We continuously measure the probability density for:
  - → Υ(4S) velocity (boost vector)
  - → Υ(4S) energy (CM energy)
  - → Υ(4S) vertex position (beam spot)

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

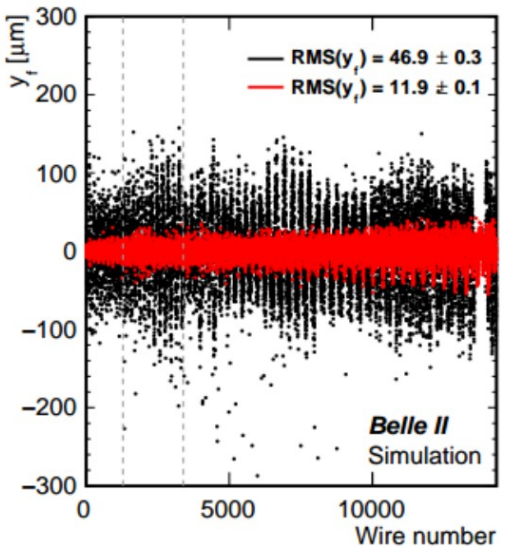
Boost vector magnitude

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

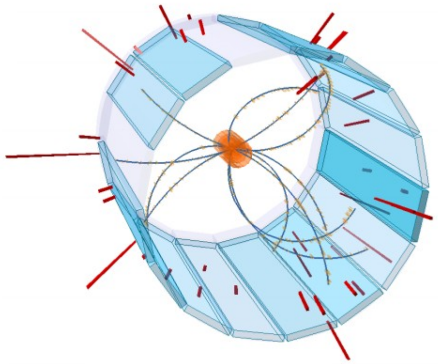
Tracker Alignment

- **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 has been included into the alignment
  → 60,000 parameters
  (for Pixel Detector, Strip Detector & Central Drift Chamber)

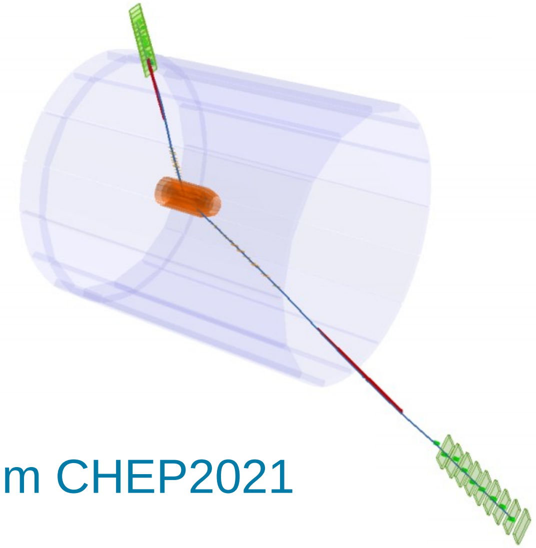
Monte Carlo



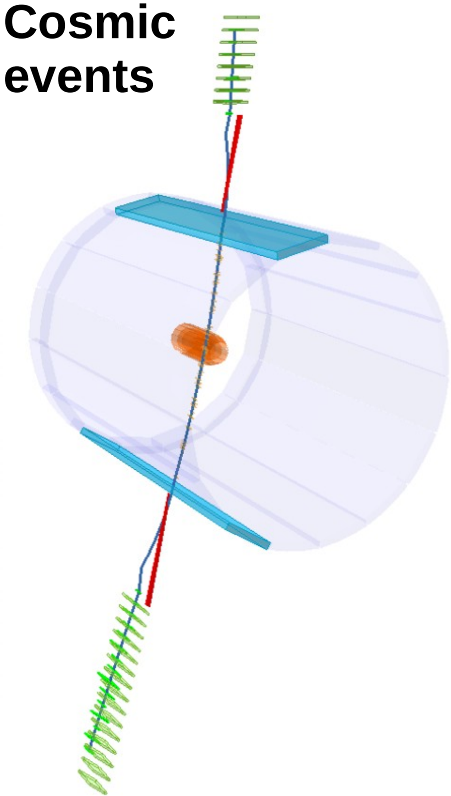
Hadronic events



Di-muon events

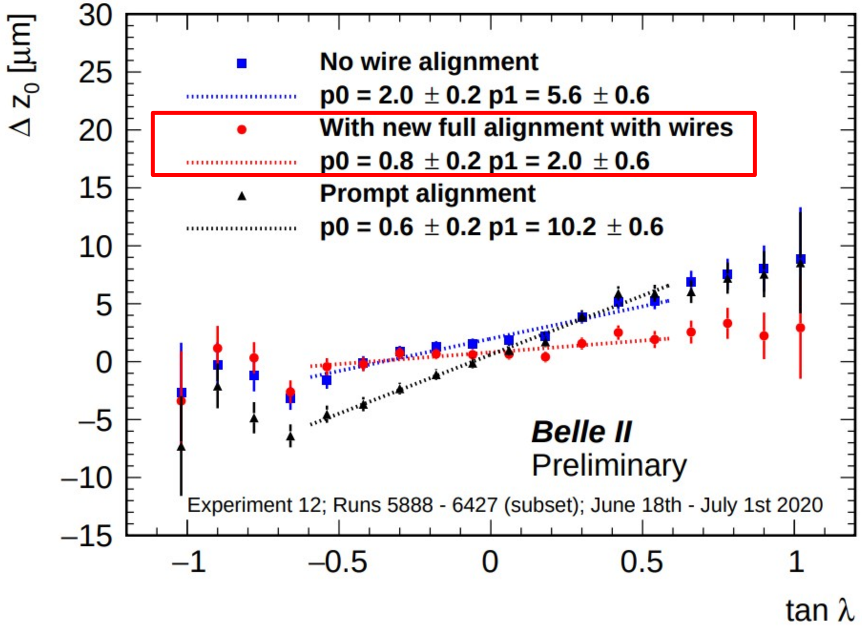


Cosmic events



See slides from CHEP2021

Data

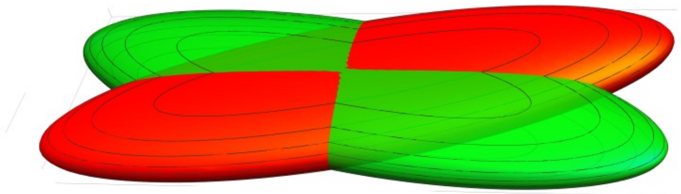


Beam spot constraint

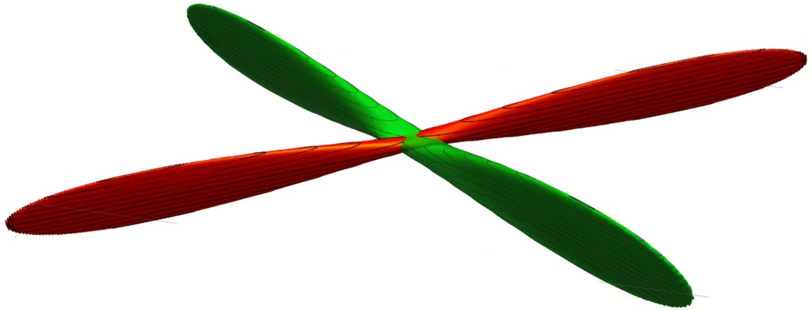
- At Belle II the much higher peak luminosity is achieved by so-called nano-beam scheme
- The small beam size can be used to better constraint the kinematics of the event (e.g. improving B_{tag} vertex precision and consequently Δt resolution)

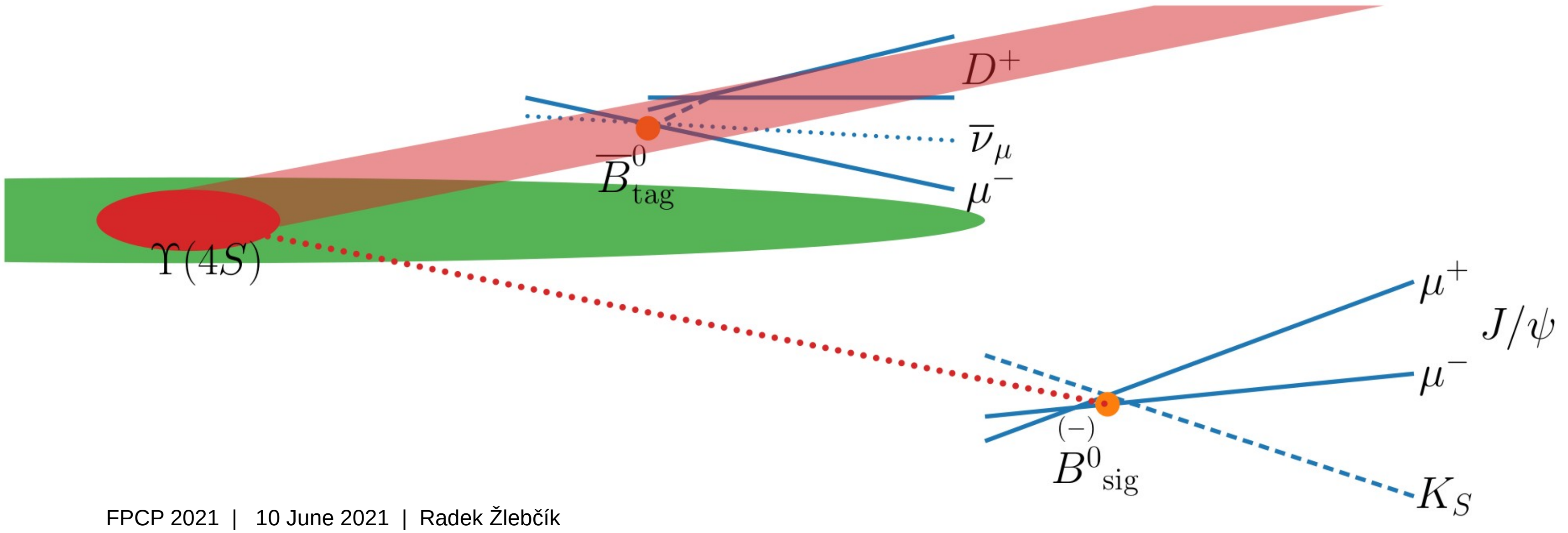
$$\sigma_{Y'} = 0.2\mu\text{m}, \sigma_{X'} = 10\mu\text{m}, \sigma_{Z'} = 240\mu\text{m}$$

Belle



Belle II





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

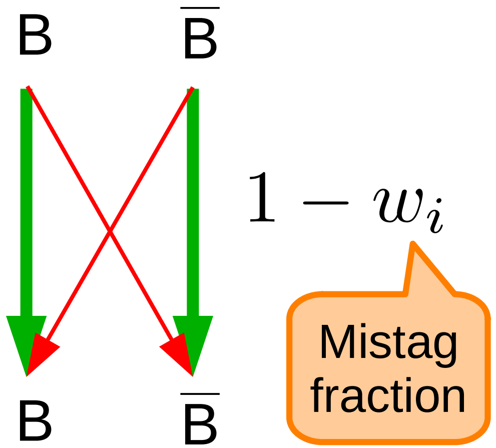
Flavor tagging

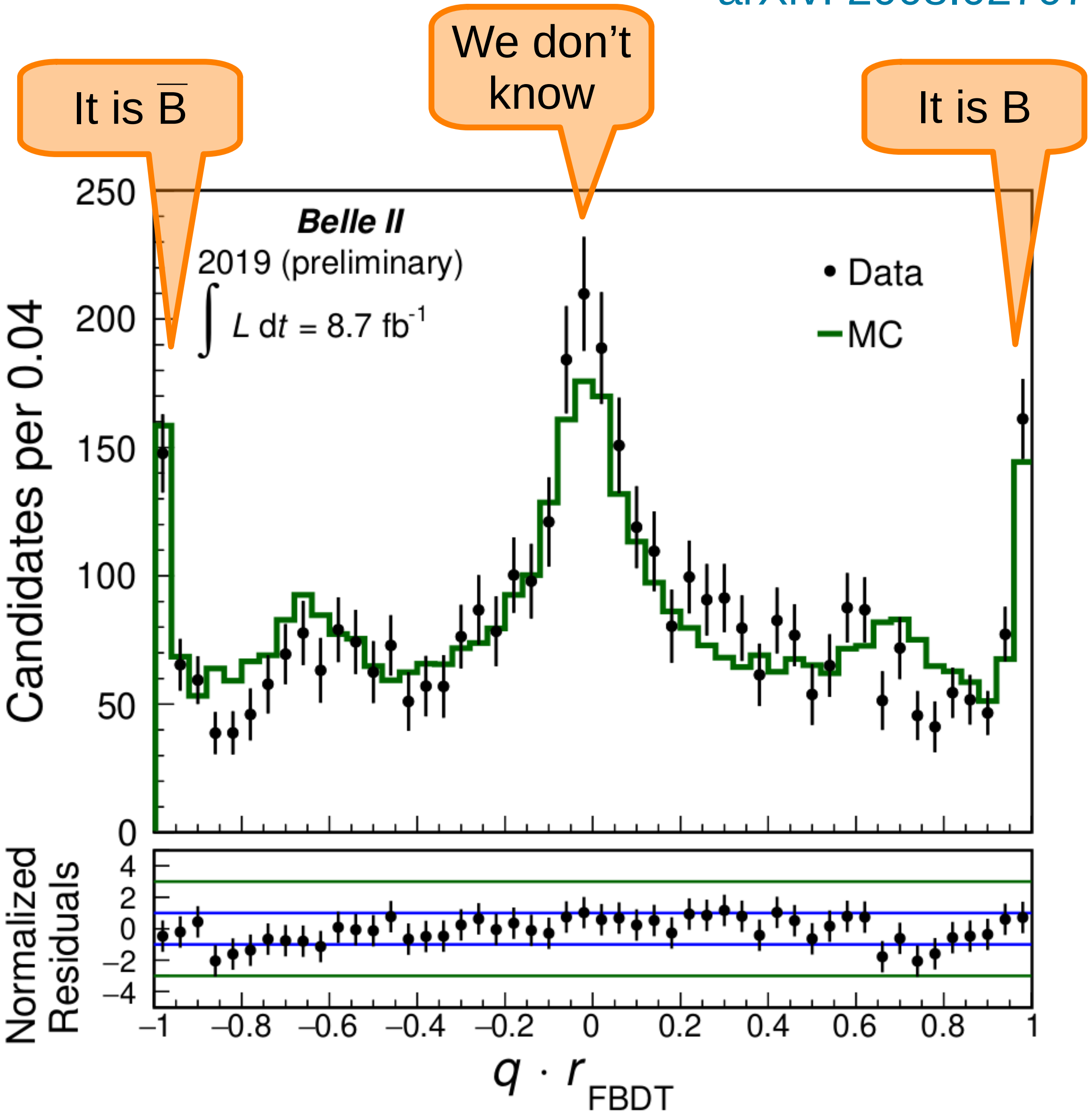
- Determination of the B_{tag} flavor using all the particles not belonging to signal B
- The |qr| is split into 7 bins to test the performance in hadronic B decays data
- The efficiency evaluated from $B\overline{B}/B\overline{B}$ asymmetries in all |qr| bins

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

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

$$\varepsilon_{\mathrm{eff}}^{\mathrm{Belle\,II}} = (33.8 \pm 3.9)\%$$





Dilution factor : $r_{\mathrm{FBDT}} \approx 1 - 2w$

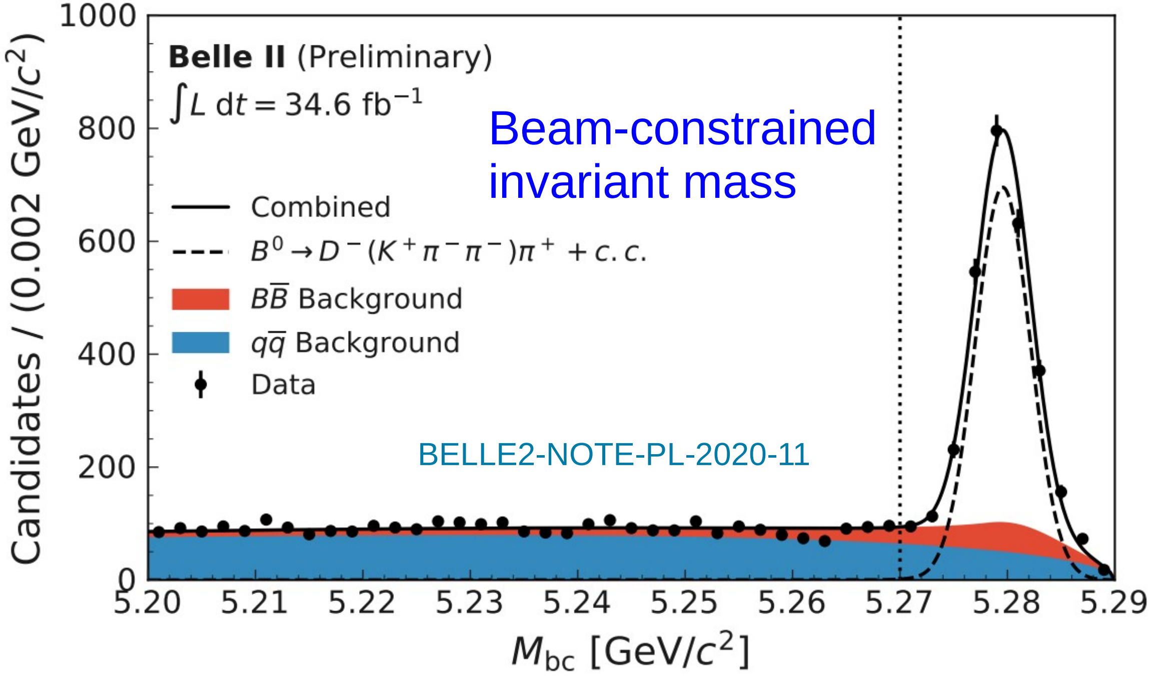
Flavor tag : $q = \pm 1$

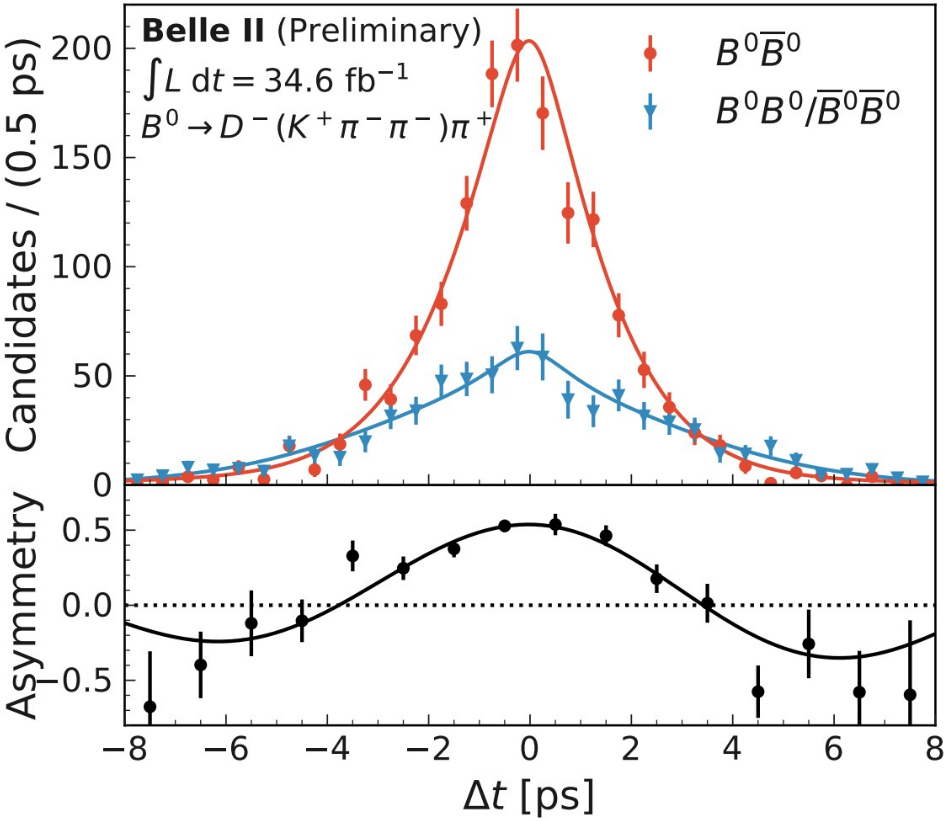
Mixing measurement: $B^0 \rightarrow D^- \pi^+$

PDG value:
0.507 ± 0.002 ps^{-1}

- Measurement dominated by sys. unc. at Belle 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

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





Results consistent with PDG, soon competitive with Belle/BaBar

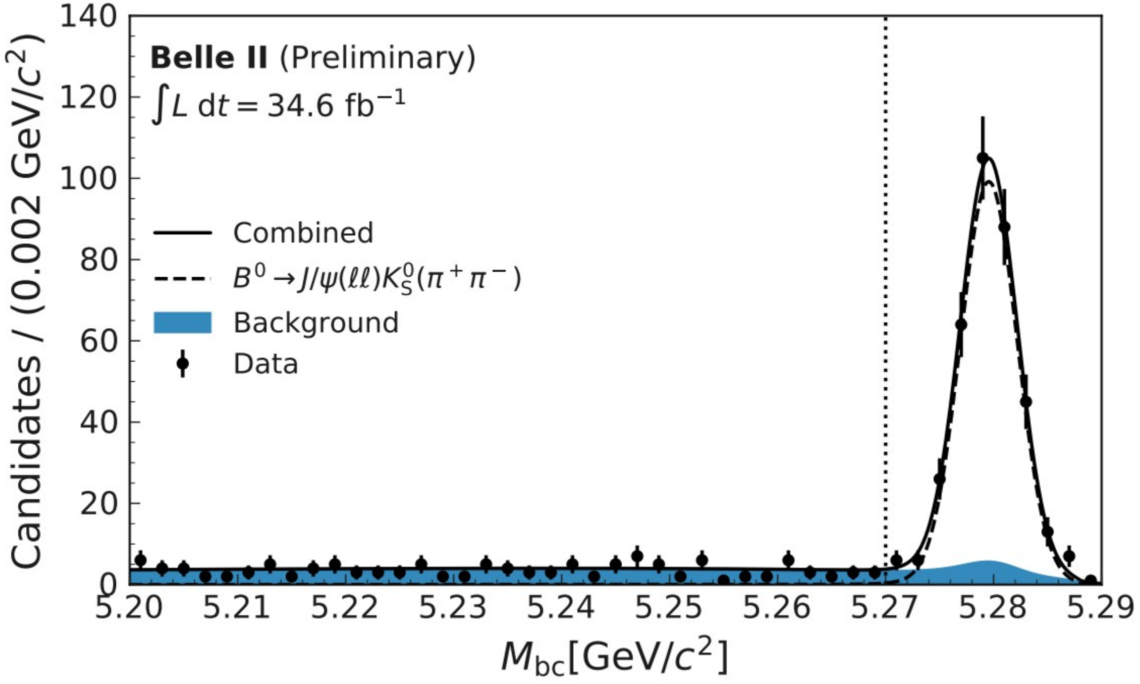
CPV measurement: $B^0 \to J/\psi\ K_s$

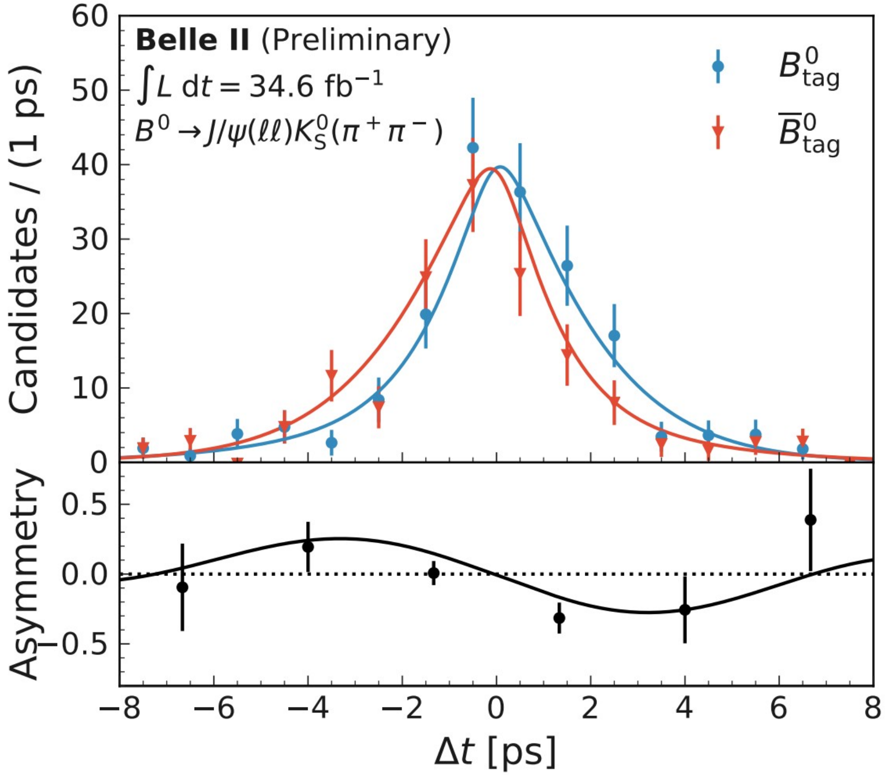
- Performed on 35 fb^{-1} of data
- Both $J/\psi \to \mu\mu$ and $J/\psi \to ee$ analyzed

PDG value:
$$0.670 \pm 0.029(\text{stat.}) \pm 0.013(\text{sys.})$$

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

BELLE2-NOTE-PL-2020-11





First CPV measurement consistent with PDG, more data needed

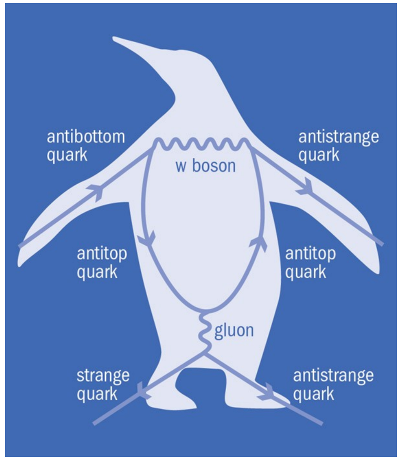
Penguin-dominated processes

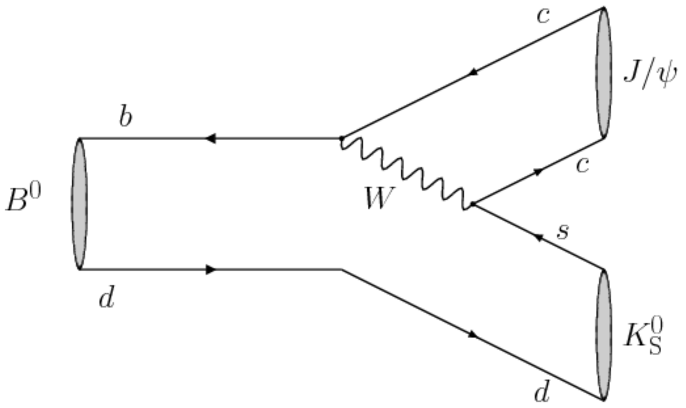
$$B^0 \to J/\psi K_S$$
$$(\sin 2\beta)_{\mathrm{PDG}} = 0.70 \pm 0.02$$

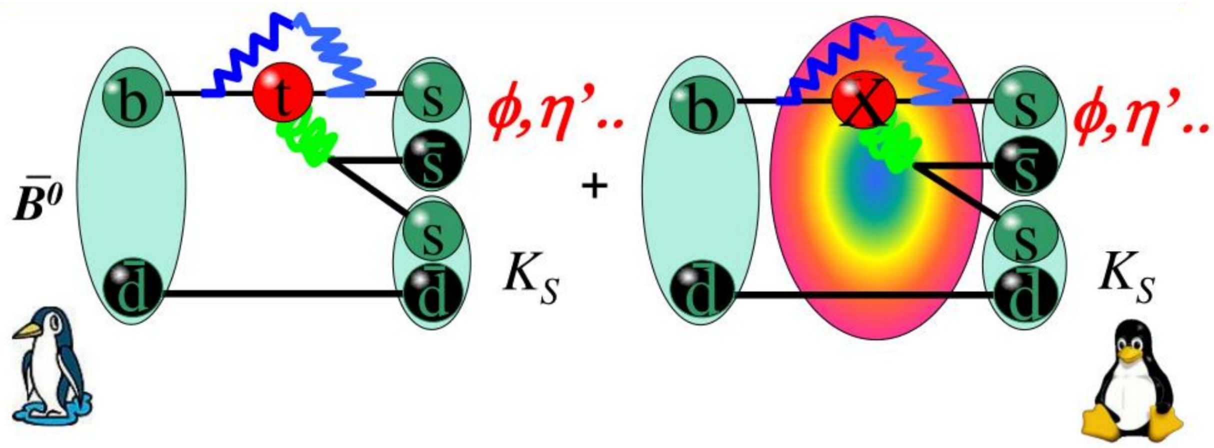
$$B^0 \to (\phi, \eta')K_S$$
$$(\sin 2\beta)_{\mathrm{PDG}} = 0.68 \pm 0.08$$

Tree channels & loop processes should give consistent β

→ New particle in loop can shift the SM phase







Time-integrated $B^0 \to \eta' K_s$ and $B^0 \to \phi K_s$

- Belle II performed the time-integrated analyses of the $b \to s$ penguin decay channels
  → work on the time-dependent CPV analyses

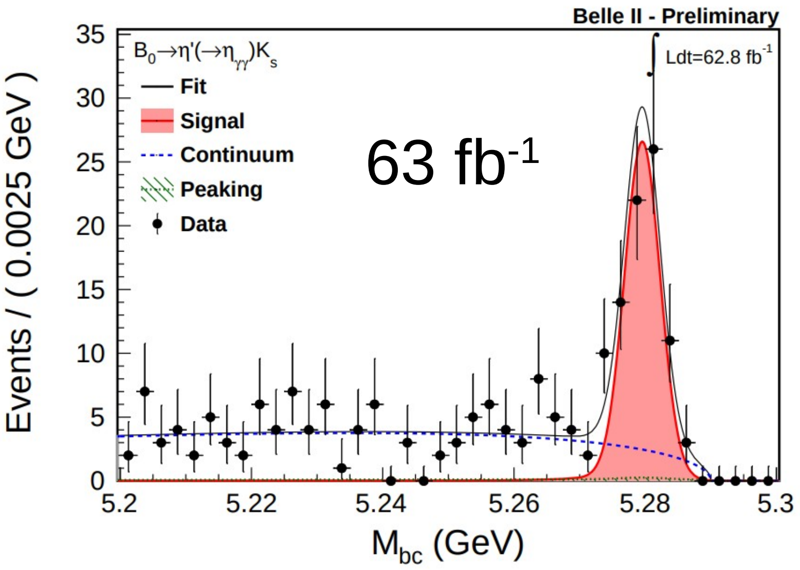
arXiv: 2104.06224

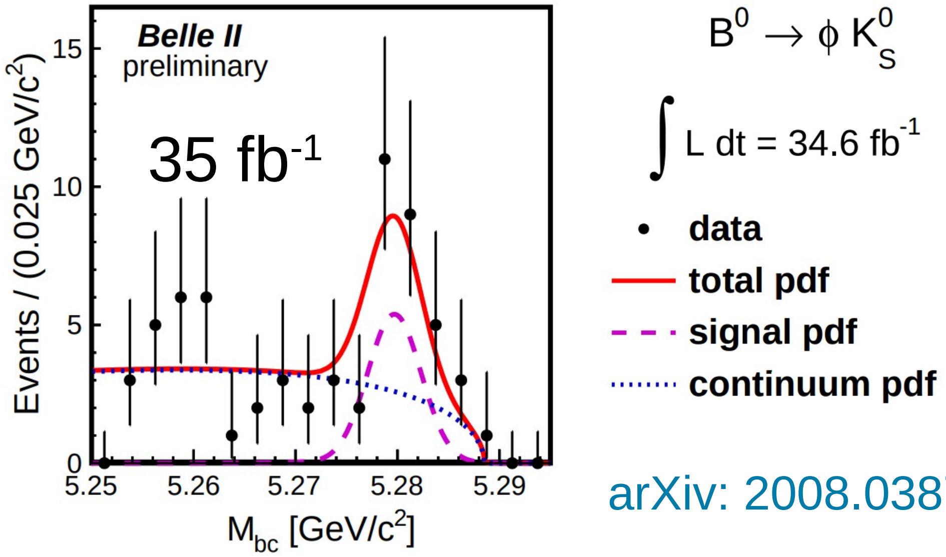
	BR
$B^0 \to (\eta' \to \eta\pi^+\pi^-)K_s^0$	$(65 \pm 8 \pm 7)10^{-6}$
$B^0 \to (\eta' \to \rho\gamma)K_s^0$	$(67 \pm 9 \pm 8)10^{-6}$

PDG value: $(66 \pm 4)10^{-6}$

$$\mathrm{BR}(B^0 \to \phi K_s^0) = (5.9 \pm 1.8 \pm 0.7)\,10^{-6}$$

PDG value: $(7.3 \pm 0.7)\,10^{-6}$





arXiv: 2008.03873

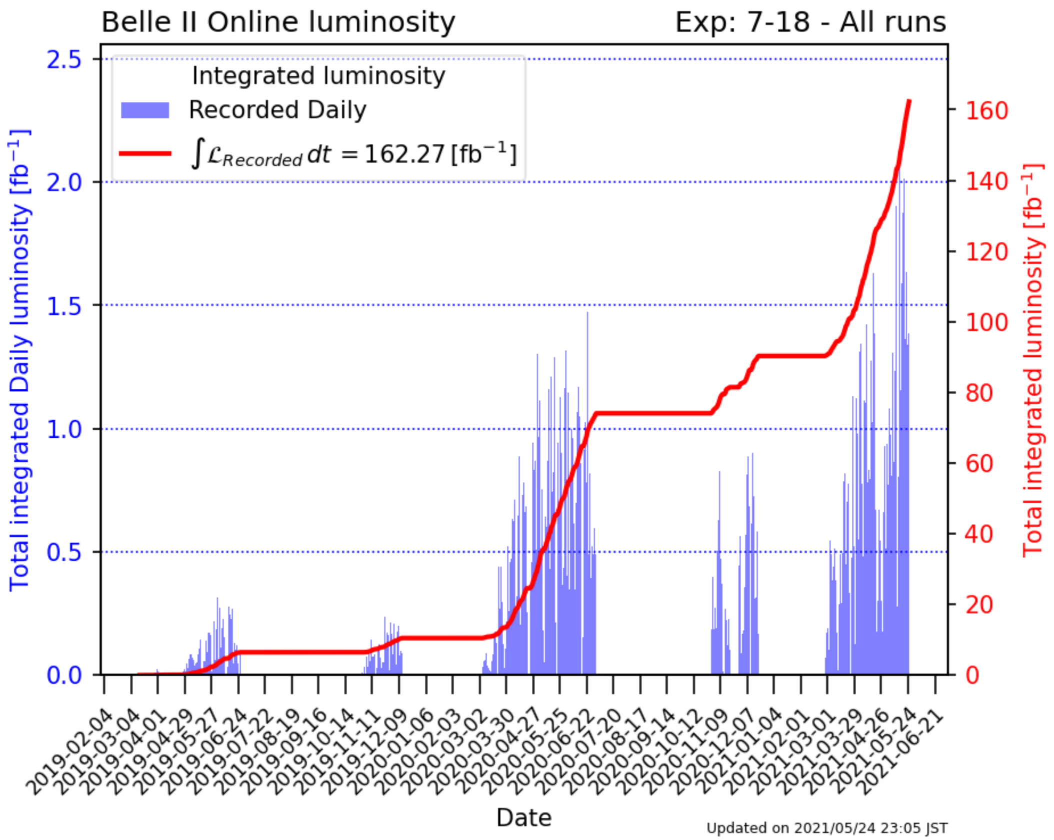
Observed branching fractions compatible with the world average

Conclusions

- The analysis of 35 fb^{-1} of Belle II data shows better vertex resolution & comparable flavor tagging performance to Belle
  → First CPV analysis in the B^0 decays

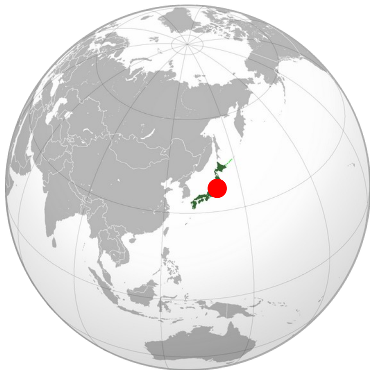
- First time-integrated analysis of the rare penguin $B^0 \to (\eta', \phi) K_s$ performed
  → first step towards CPV measurement in the $b \to s$ decays

- With increasing data statistics the systematic unc. more and more matter
  → Detector alignment
  → Beam Spot
  → Flavor tagging

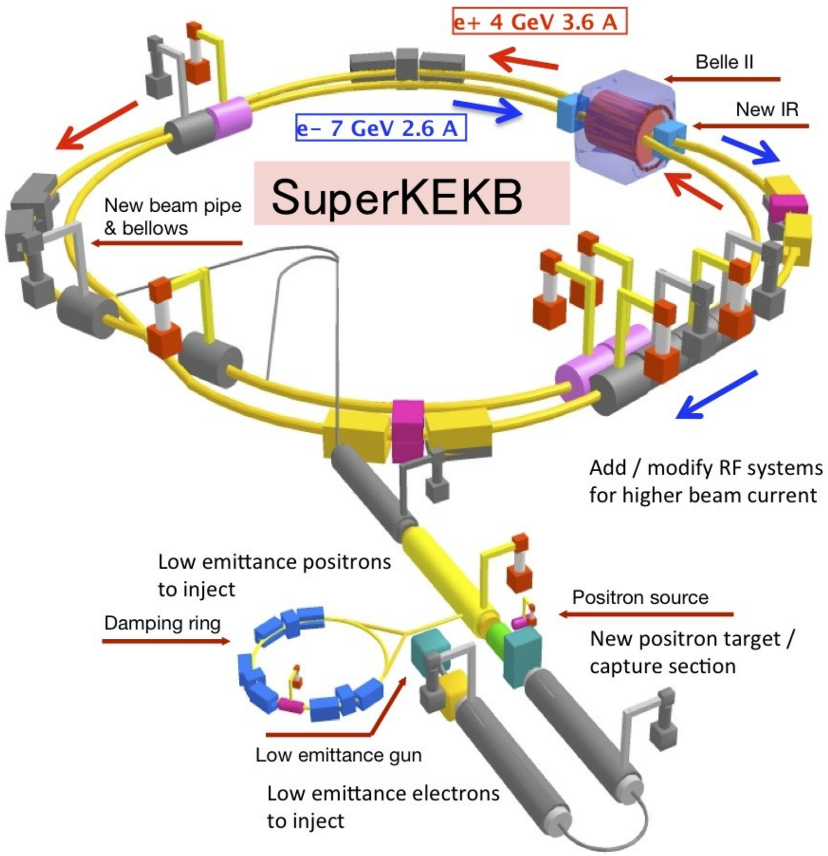


https://confluence.desy.de/display/BI/Belle+II+Luminosity

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