Time-dependent CPV in the B decays at Belle II

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on behalf of the Belle II collaboration

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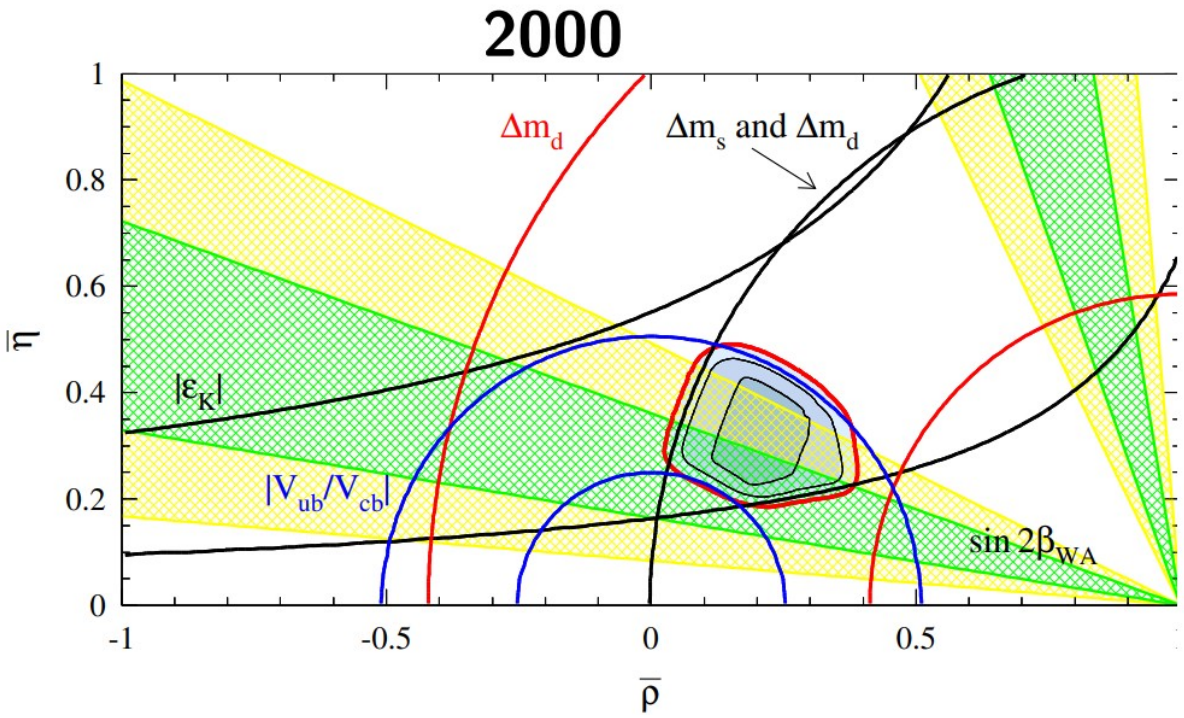
CHARLES UNIVERSITY

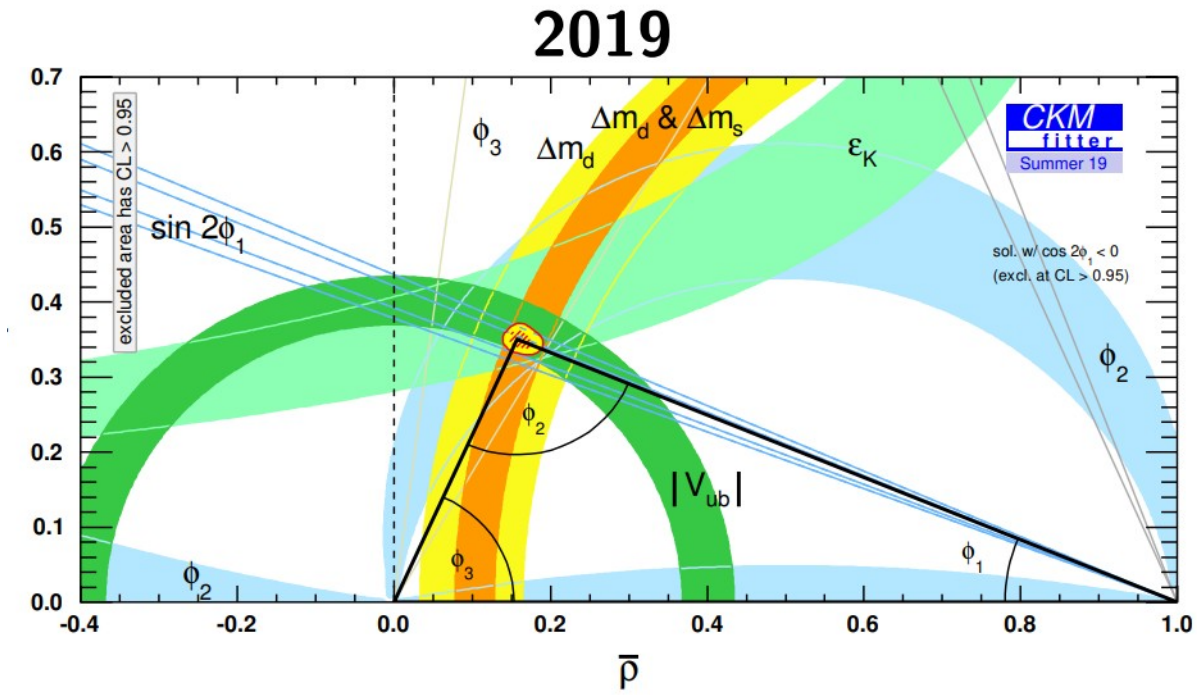
Belle II

Cape Canaveral

Unitarity triangle : 20 years of development

- UT constructed from CKM matrix has angles and sides which are well-defined (physical) quantities
- New Physics can cause inconsistency in the triangle parameters or inconsistency between tree-dominated and loop-dominated modes

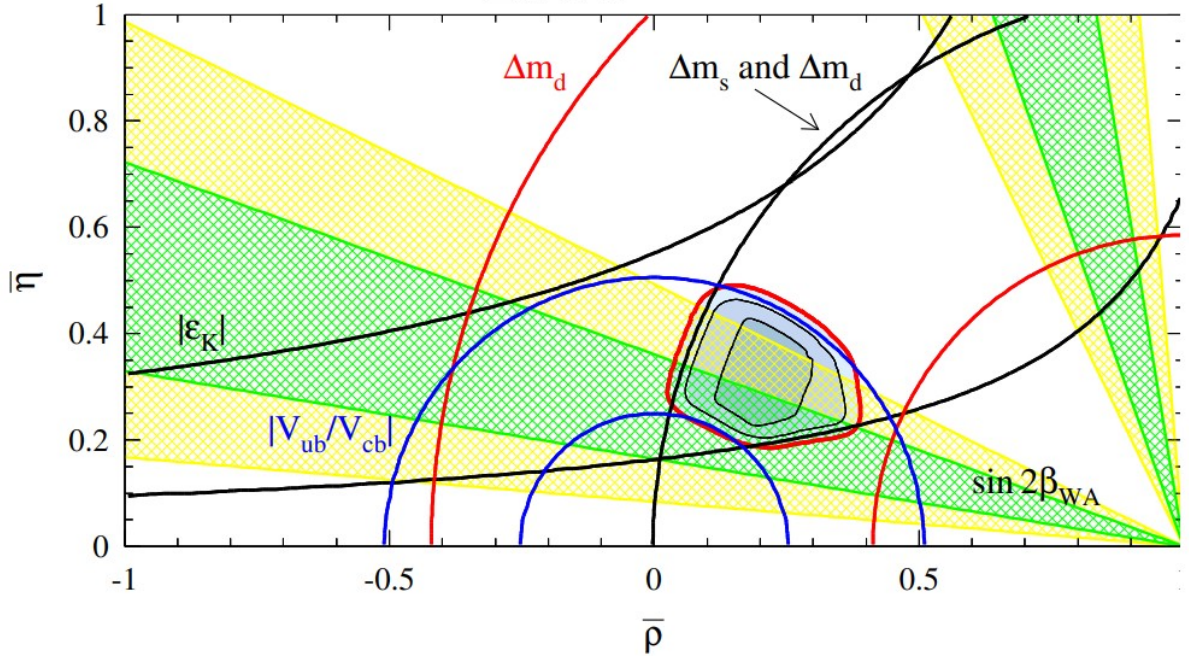




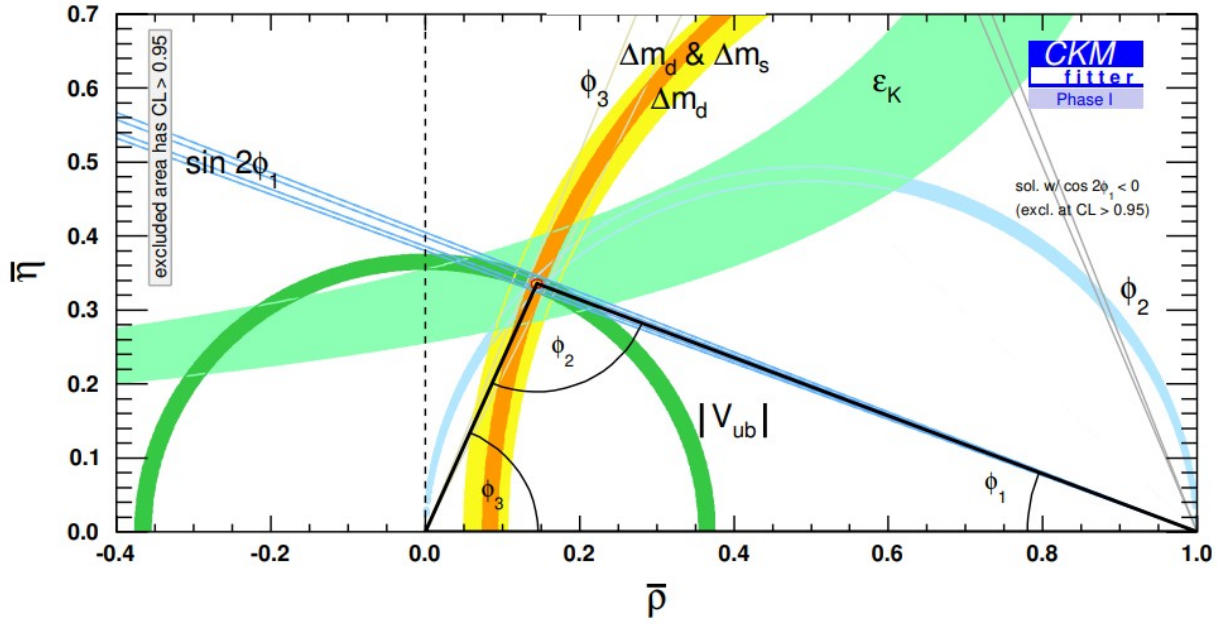
Unitarity triangle : in 15 years?

- UT constructed from CKM matrix has angles and sides which are well-defined (physical) quantities
- New Physics can cause inconsistency in the triangle parameters or inconsistency between tree-dominated and loop-dominated modes

2000



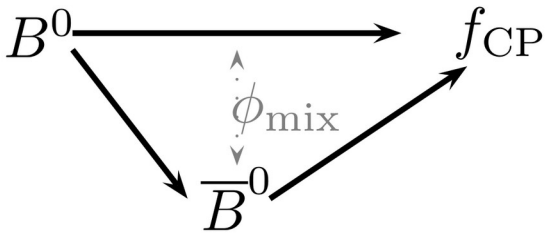
2035?



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

CP violation in interference of mixing and decay

- The |S|~sin $2\phi_1$ measurable from the time-dependent asymmetry between $B^0 \to f_{CP}$ and $\overline{B}^0 \to f_{CP}$

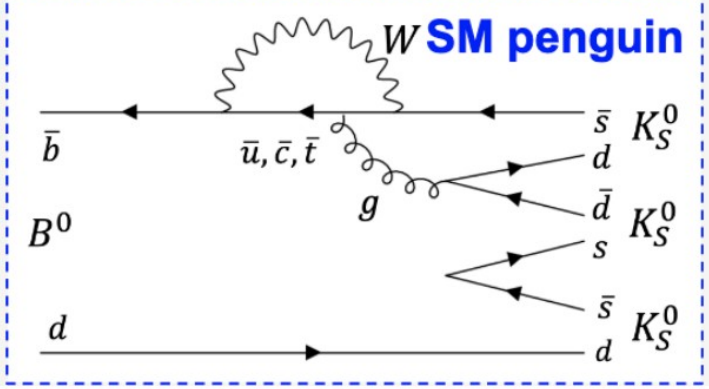


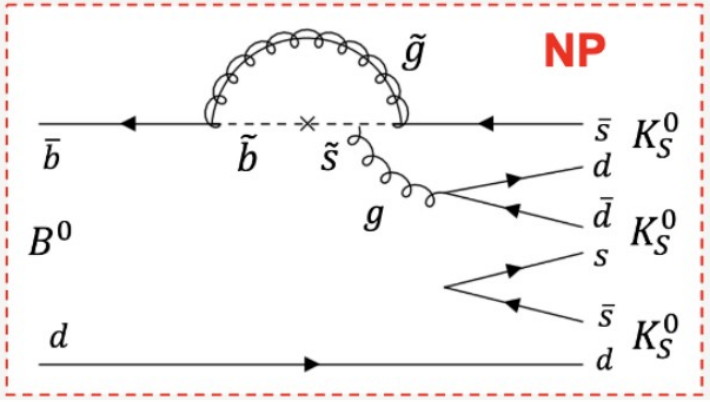
$$\mathcal{A}_{CP}(\Delta t) = \frac{\mathcal{B}(\bar{B}^0 \to f_{CP})(\Delta t) - \mathcal{B}(B^0 \to f_{CP})(\Delta t)}{\mathcal{B}(\bar{B}^0 \to f_{CP})(\Delta t) + \mathcal{B}(B^0 \to f_{CP})(\Delta t)} = S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)$$

Mixing-induced CPV

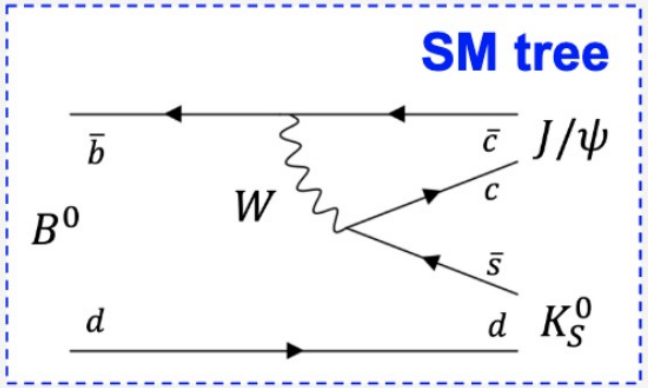
Direct CPV

$$S_{K_S^0 K_S^0 K_S^0} = -\sin 2\phi_1 + \Delta S$$

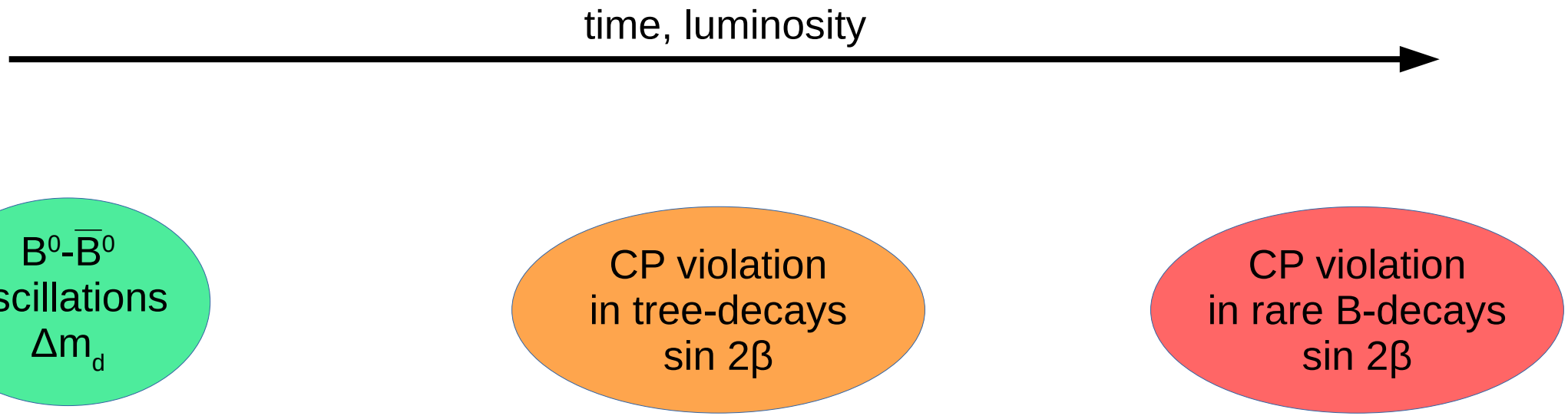




$$S_{J/\psi K_S^0} = \sin 2\phi_1$$



Workflow for time-dependent B measurements



LHCb dominated

Tie between LHCb and B-factories

Dominated by B-factories

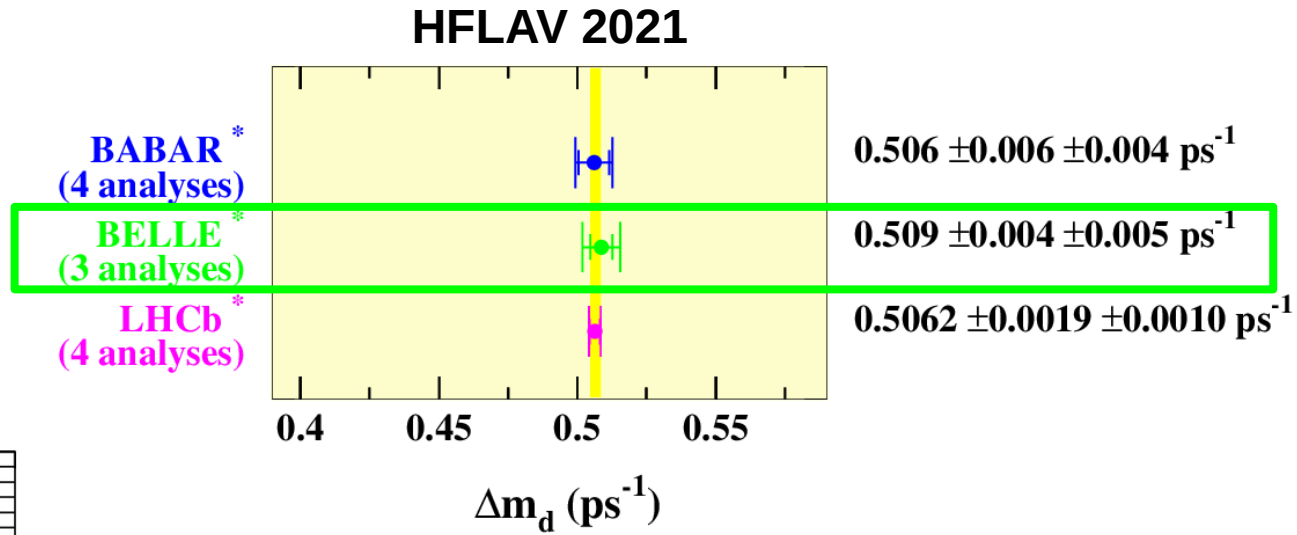
$B^0 \to D^{(*)-}\pi^+$
Done

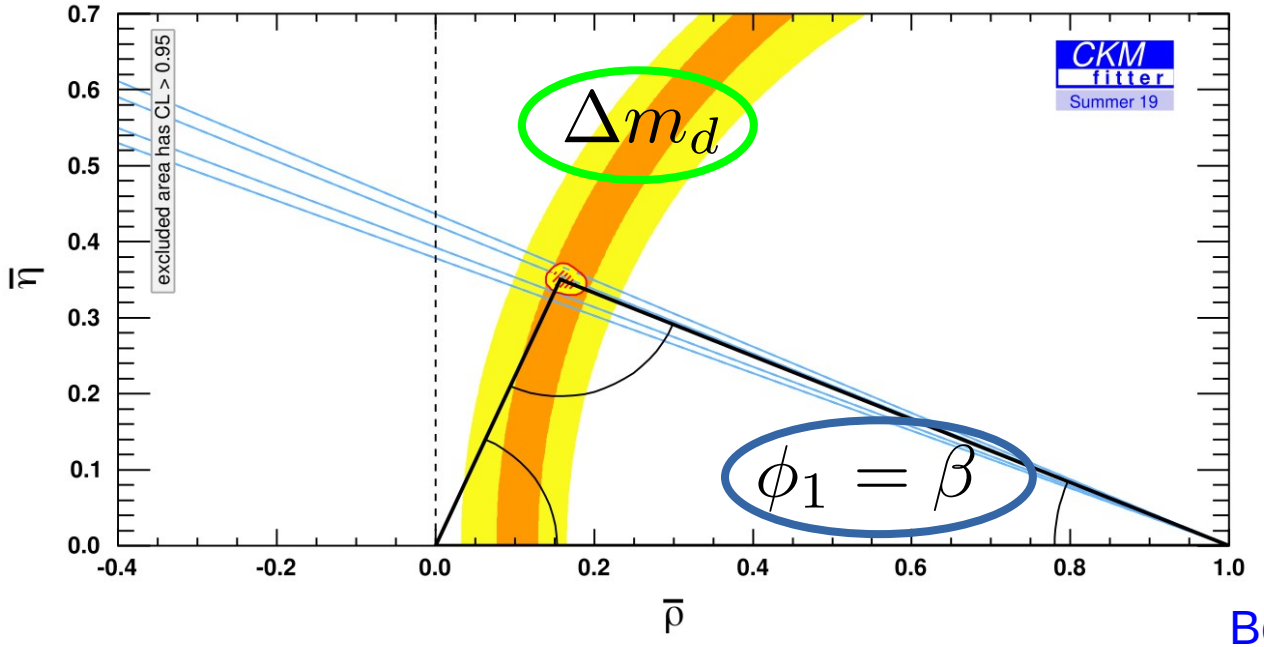
$B^0 \to J/\psi\, K_s$
4-times less stat than Belle

$B^0 \to K_s K_s K_s$
$B^0 \to K_s \pi^0$
4-times less stat than Belle

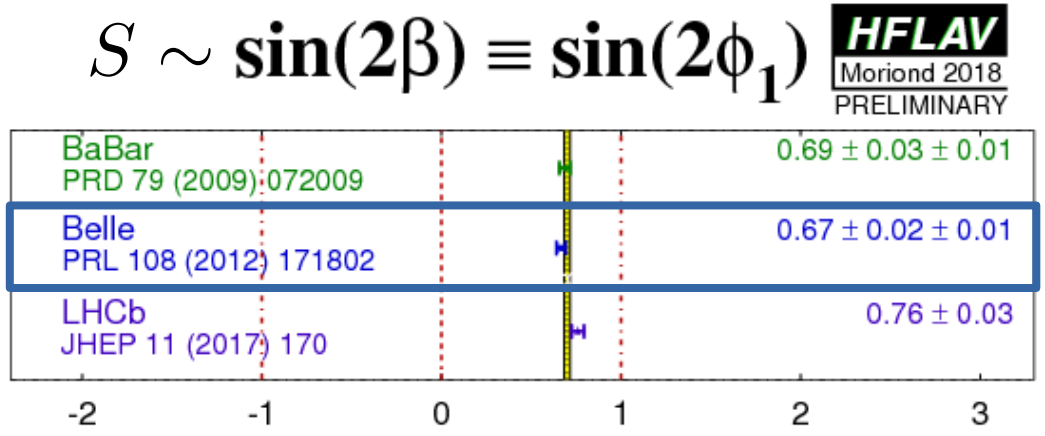
Sin $2\phi_1$= sin 2β and the $B^0\overline{B}^0$ osc. frequency Δm_d

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





$S \sim \sin(2\beta) \equiv \sin(2\phi_1)$

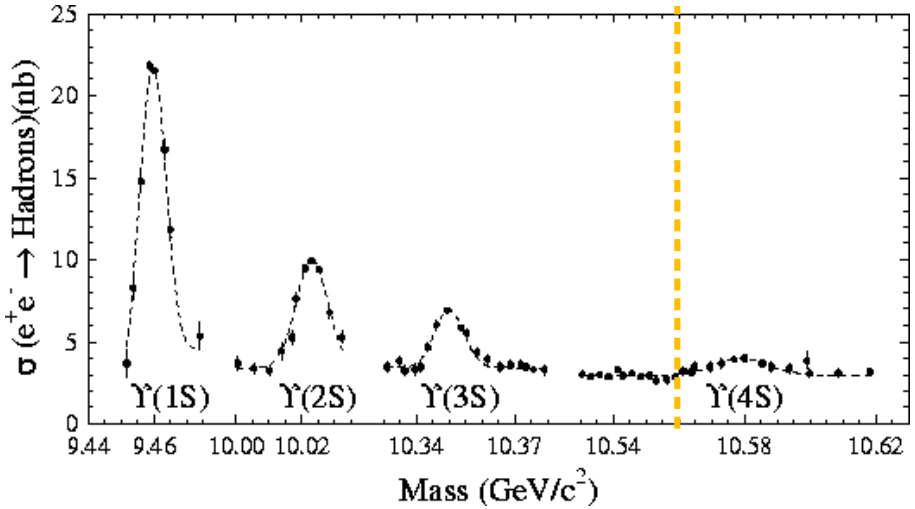


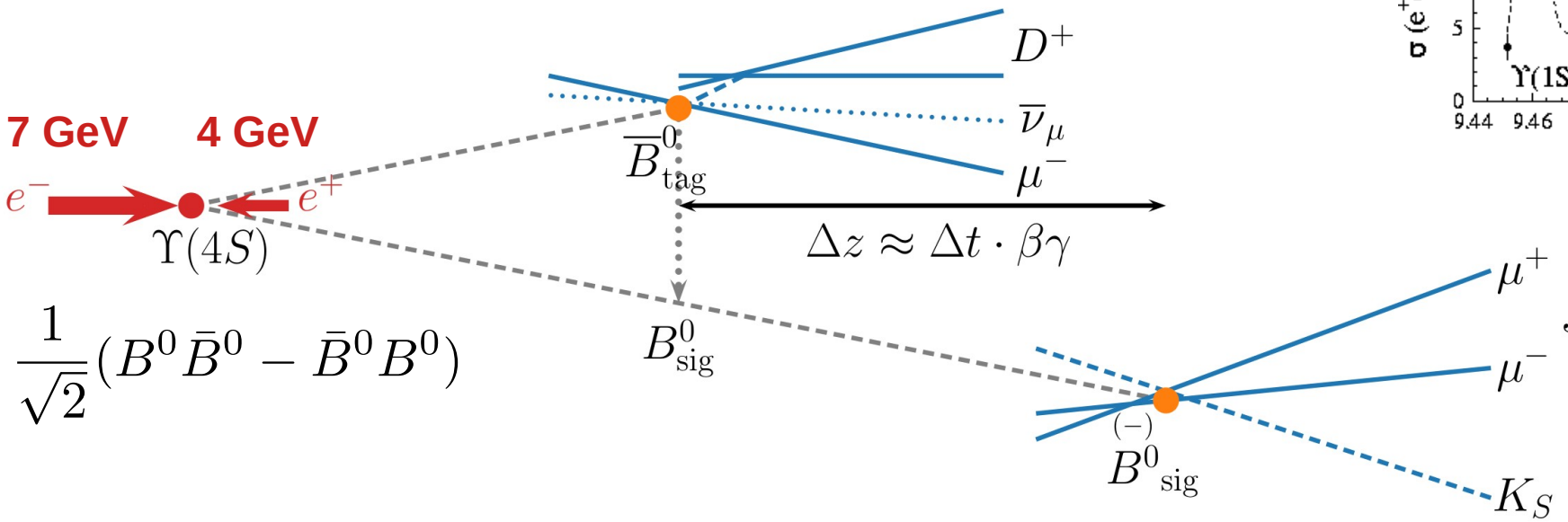
Belle II with full lumi can achieve 0.5% precision for sin 2β

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





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

Time-measurement ⟺ distance-measurement

Fully reconstructed

From rest of event

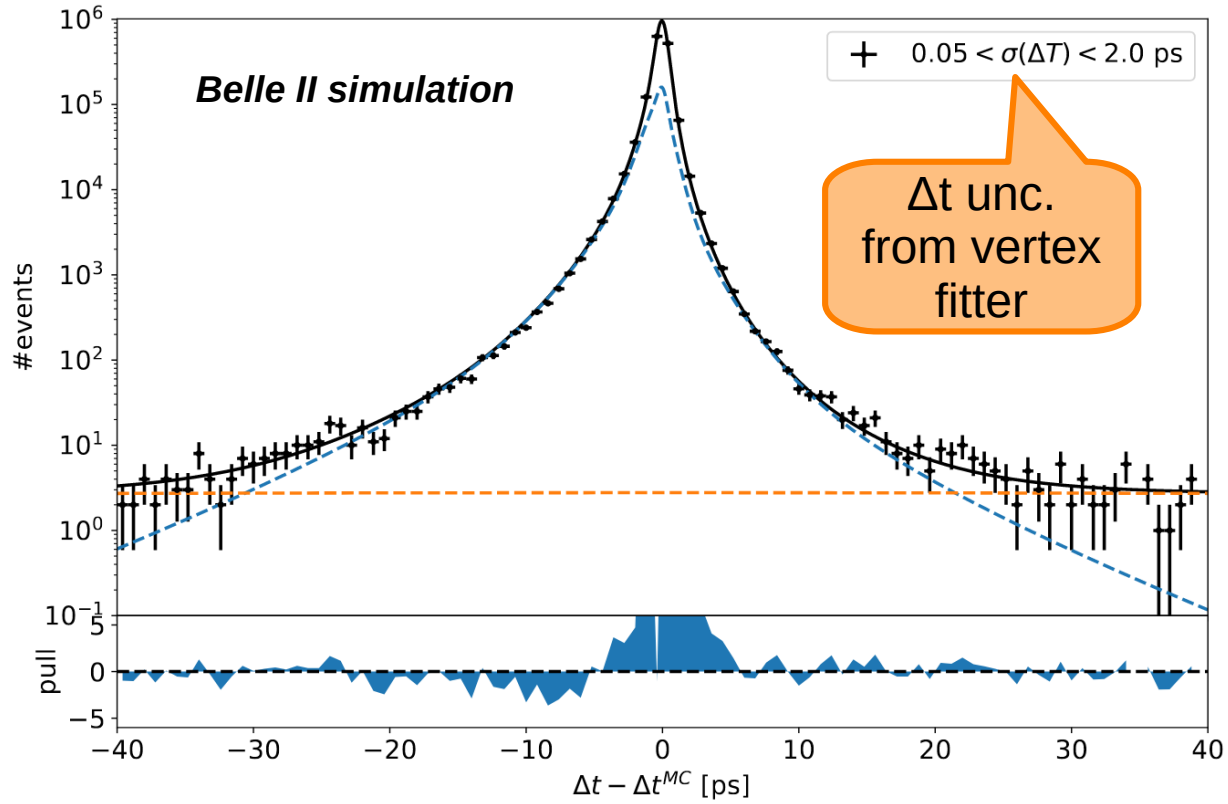
$$\Delta t = \frac{(\vec{v}_{\rm sig} - \vec{v}_{\rm tag}) \cdot \vec{n}_{\rm boost}}{\gamma\beta c}$$

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

Belle : $\Delta z \approx 200\,\mu{\rm m}$

The Δt resolution function

- Knowledge of the Δt resolution is crucial for time-dependent measurements
- In most cases it is driven by tag-B meson
  → universality of the resolution function between processes



$$f_{\text{obs}}(\Delta t, \sigma) = f_{\text{phys}}(\Delta t) \otimes \mathcal{R}(\delta\Delta t, \sigma)$$

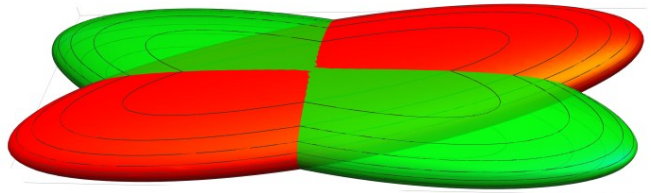
$$\begin{aligned}\mathcal{R}(\delta\Delta t;\sigma) =& (1 - f_{\text{tail}}) \cdot G(\delta\Delta t; \mu_{\text{main}} \cdot \sigma, s_{\text{main}} \cdot \sigma) \\ &+ (1 - f_{\text{exp}}) \cdot f_{\text{tail}} \cdot G(\delta\Delta t; \mu_{\text{tail}} \cdot \sigma, s_{\text{tail}} \cdot \sigma) \\ &+ f_{\text{tail}} \cdot f_{\text{exp}} \cdot G(\delta\Delta t; \mu_{\text{tail}} \cdot \sigma, s_{\text{tail}} \cdot \sigma) \\ &\otimes \left((1 - f_{\text{R}}) \exp_{-}(\delta\Delta t/c \cdot \sigma) + f_{\text{R}} \exp_{+}(-\delta\Delta t/c \cdot \sigma)\right)\end{aligned}$$

Beam spot constraint

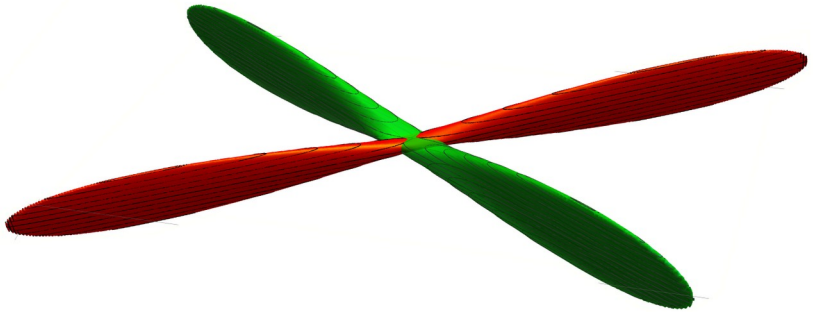
- At Belle II the much higher peak luminosity is achieved by so-called nano-beam scheme
- The small beam size can be used to better constrain the kinematics of the event (e.g. improving B_{tag} vertex precision and consequently Δt resolution)

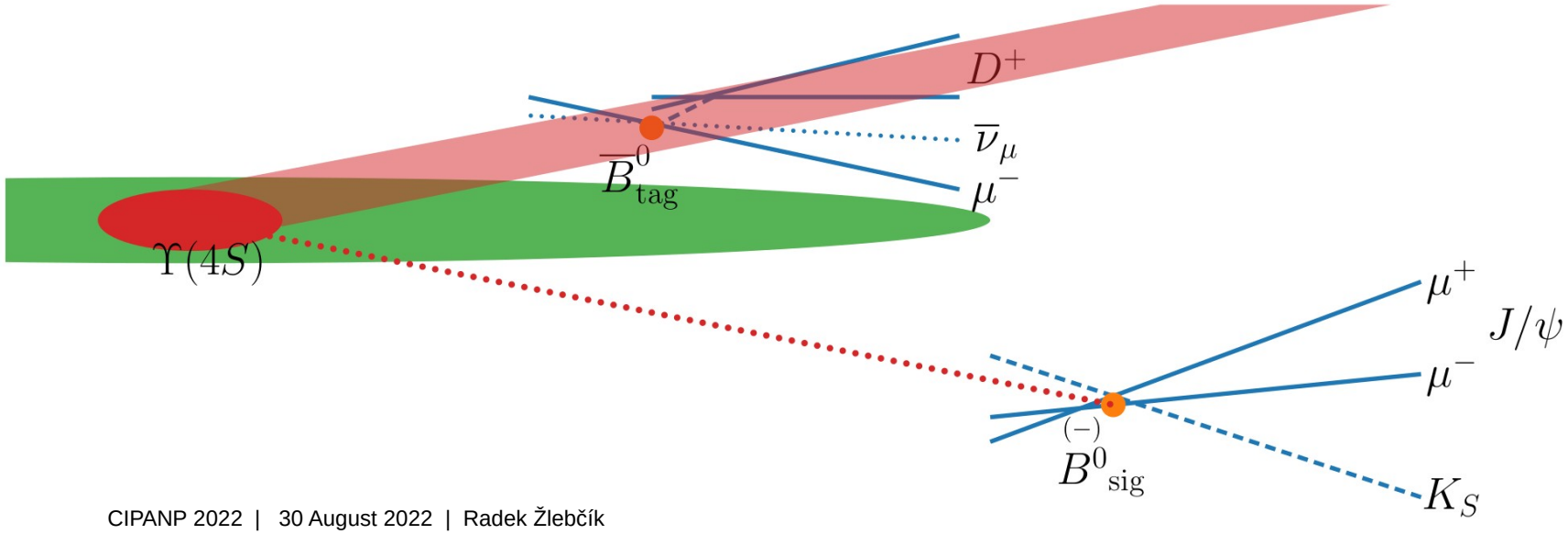
$$\sigma_{Y'} = 0.2\mu\mathrm{m}, \sigma_{X'} = 13\mu\mathrm{m}, \sigma_{Z'} = 320\mu\mathrm{m}$$

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)

Flavor tagging

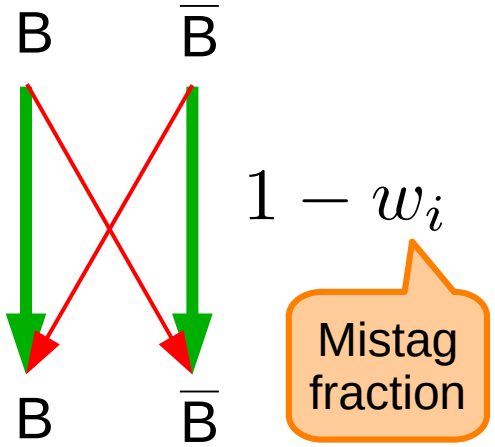
Eur. Phys. J. C 82, 283(2022)

- 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 BB/B$\overline{B}$ asymmetries in all |qr| bins

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

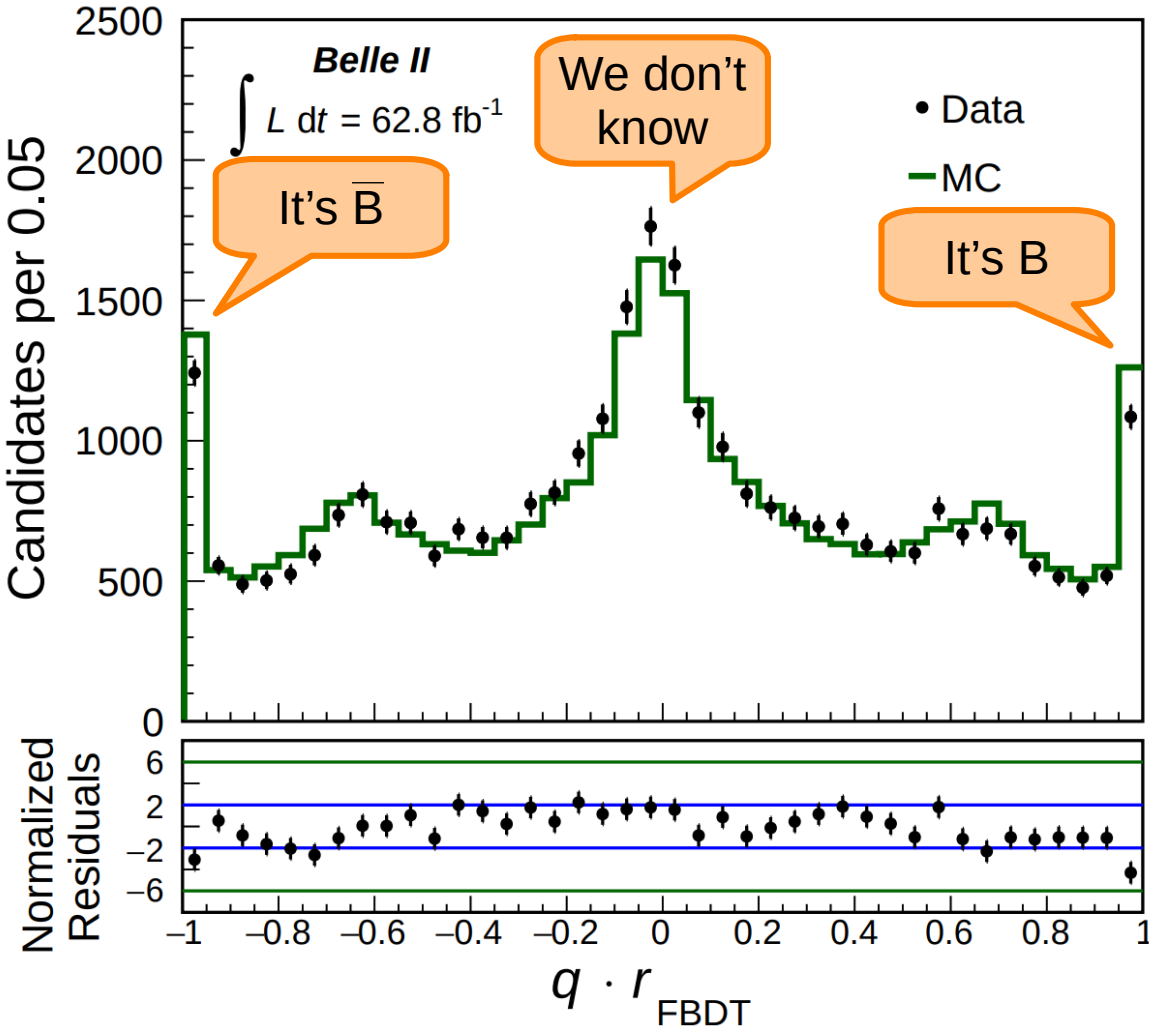
$$\varepsilon_{\text{eff}}^{\text{Belle}} = (30.1 \pm 0.4)\%$$

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



$1 - w_i$

Mistag fraction



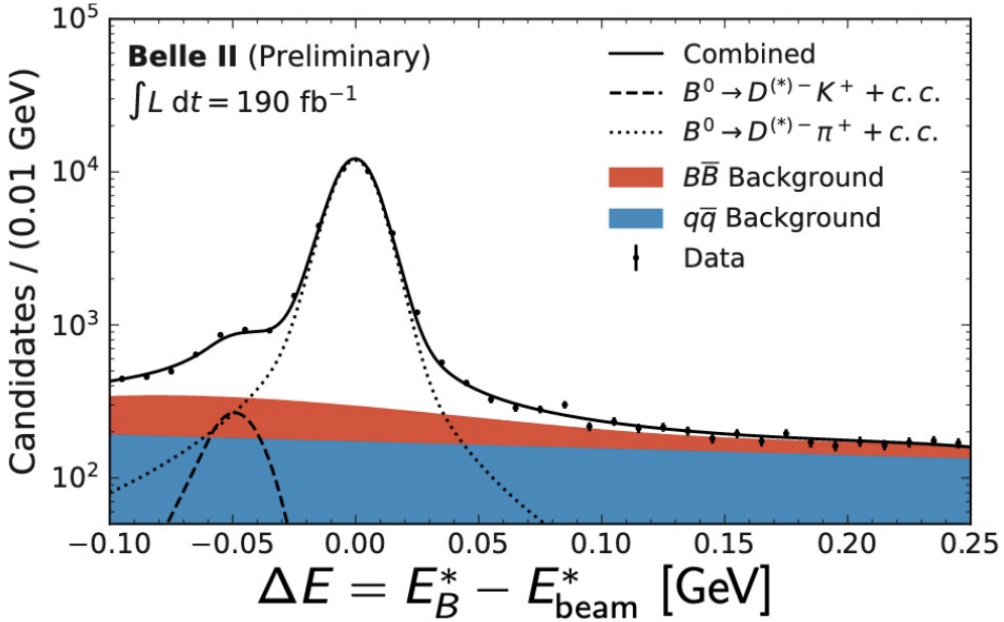
Dilution factor : $r_{\text{FBDT}} \approx 1 - 2w$

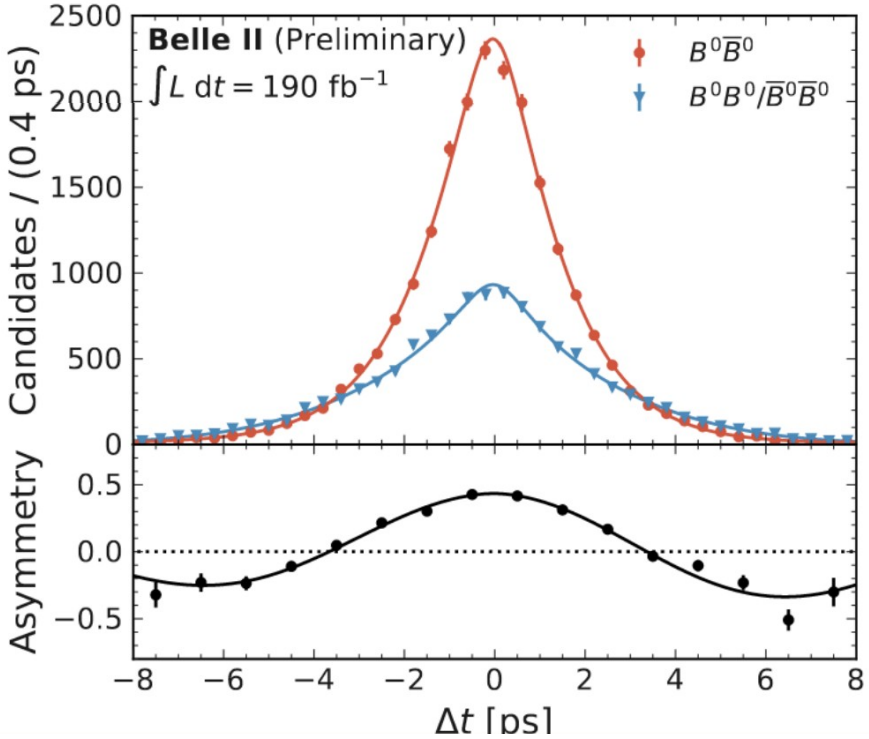
Flavor tag : $q = \pm 1$

Lifetime and mixing: $B^0 \to D^{(*)-} \pi^+$

- The Belle II measurement with 190 fb^{-1} follows the Belle measurement of 140 fb^{-1}
  → Mixing measurement in hadronic B decays probes the TD analysis framework
- Both B mesons are in the flavor eigenstate, one fully reconstructed
- Analysis of $B^0 \to D^{*-} l^+ \nu$ events in progress

33,317 +- 203 signal events





Data until July 2021

Moriond 2022

Lifetime and mixing: $B^0 \to D^{(*)-} \pi^+$: results

- Unbinned ML fit in Δt and σ
- Measurement still statistical limited
- Sys. unc. dominated by the resolution function, alignment and beam spot

Better than Belle / BaBar

$$\tau_{B^0} = 1.499 \pm 0.013(\text{stat}) \pm 0.008(\text{syst}) \text{ ps}$$

$$\Delta m_d = 1.516 \pm 0.008(\text{stat}) \pm 0.005(\text{syst}) \text{ ps}^{-1}$$

Source	τ_{B^0} [ps]	Δm_d [ps^{-1}]
Statistical	0.0130	0.0079
Resolution function	0.0063	0.0028
Alignment	0.0027	0.0024
Momentum scale	0.0002	0.0008
Analysis bias	0.0003	0.0011
Multiple candidates	0.0024	0.0009
Treatment of σ_t	0.0005	0.0010
$B^0 \to D^{(*)-} K^+$ fraction	0.0007	0.0002
$B\overline{B}$ ΔE shape	0.0004	0.0001
$q\bar{q}$ ΔE shape	0.0006	0.0000
C shapes	0.0000	0.0014
Beam spot	0.0021	0.0014
Boost vector	0.0003	0.0001
CoM energy	0.0007	0.0003
Total	0.0077	0.0046

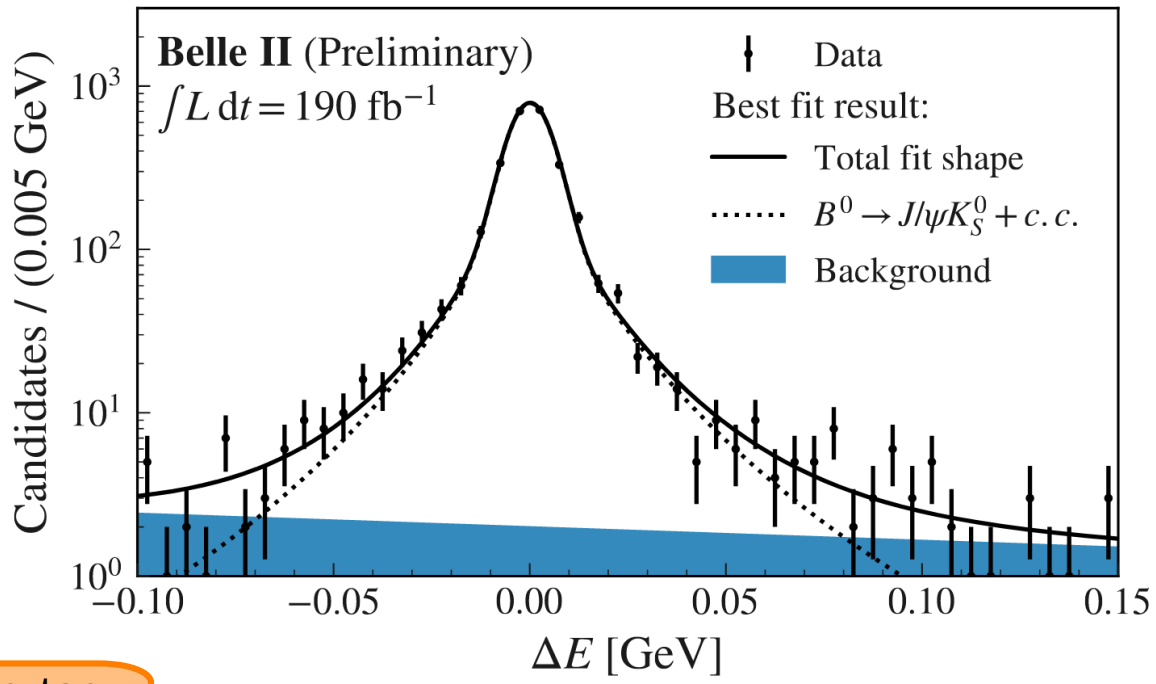
Δt resolution function & wrong tag info ready to be used in CPV measurements

Results consistent with PDG, ***competitive with Belle/BaBar***

CPV measurement: $B^0 \to J/\psi\, K^0_S$

- Golden channel for sin $2\phi_1$ measurement
- Both $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$ analyzed

1) Parameters of the Δt resolution function and flavor tagging obtained from $B^0 \to D^{(*)-}\pi^+$ analysis
2) ΔE distribution fitted
3) 2D fit of Δt, σ with only S, A free



Wrong tag fraction q-asym.

Wrong tag fraction

$$P_{CP}(\Delta t,\ q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}\{1 - q\Delta w + q\mu(1-w) + [q(1-w) + \mu(1-q\Delta w)][S_{CP}\sin(\Delta m_d \Delta t) + A_{CP}\cos(\Delta m_d \Delta t)]\}$$

$q = +1 \quad B_{\mathrm{tag}} = B^0$
$q = -1 \quad B_{\mathrm{tag}} = \bar{B}^0$

Efficiency q-asym.

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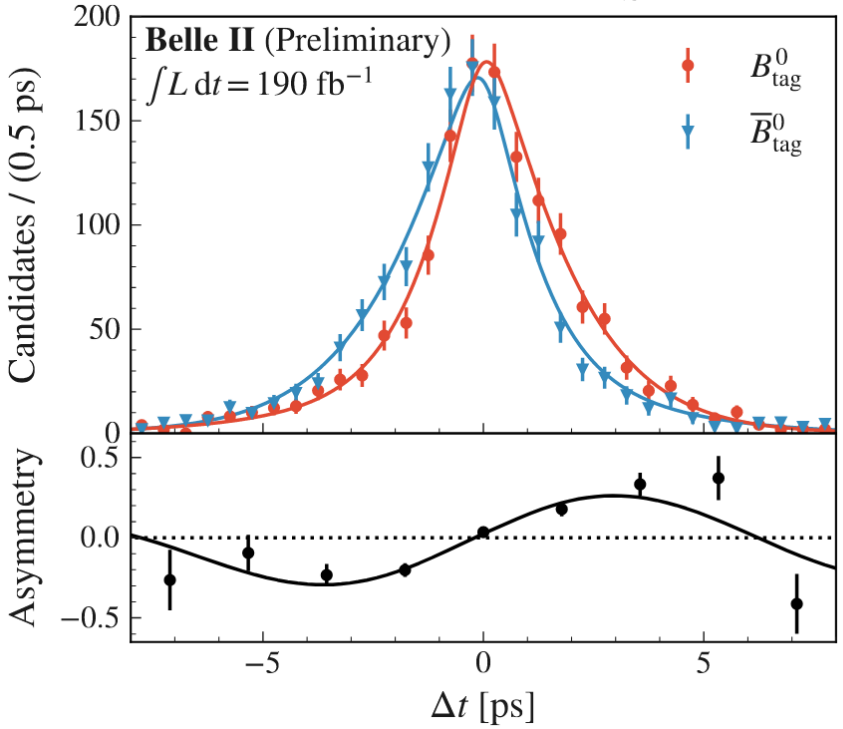
CPV measurement: $B^0 \to J/\psi\, K^0_S$

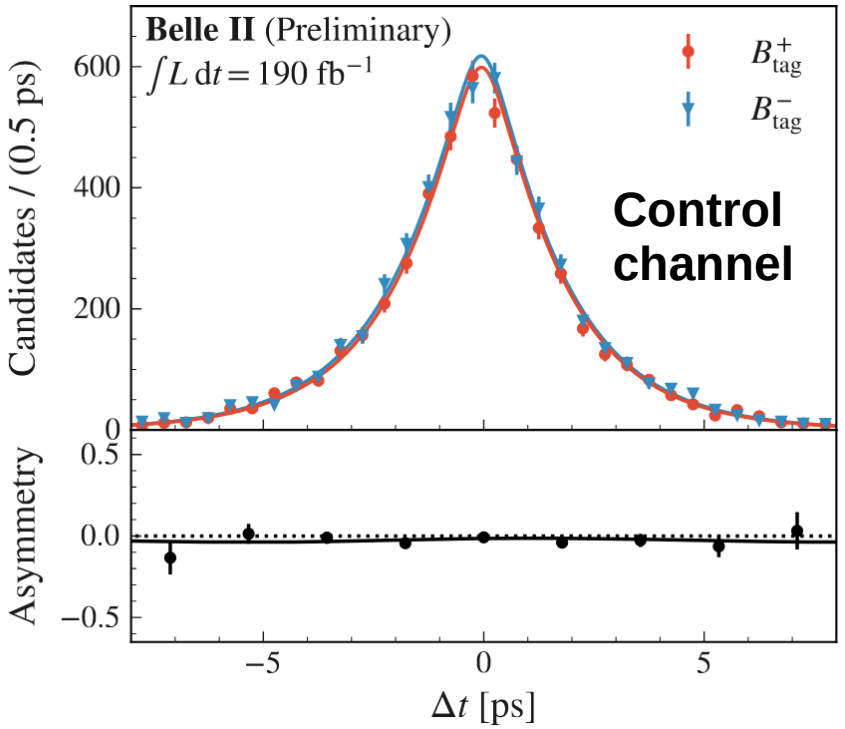
- The $J/\psi\, K^0_S$ sample has ~99% purity
- S, A for control mode compatible with 0
- Slight difference for A between e and μ

Sample	N_{evts}	$p_{\text{sig}}(\%)$	$\varepsilon_{\text{sig}}(\%)$	S_{CP}	A_{CP}
$B^0 \to J/\psi K^0_S$	2755	98.6	40.6	0.720 ± 0.062	0.094 ± 0.044
$B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S$	1615	99.2	47.6	0.776 ± 0.078	0.042 ± 0.057
$B^0 \to J/\psi(\to e^+e^-)K^0_S$	1140	98.0	33.6	0.676 ± 0.093	0.185 ± 0.068
$B^+ \to J/\psi K^+$	9973	98.1	40.3	0.016 ± 0.029	0.021 ± 0.021
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$	5760	99.0	46.6	-0.015 ± 0.039	0.008 ± 0.028
$B^+ \to J/\psi(\to e^+e^-)K^+$	4213	96.7	34.1	0.058 ± 0.045	0.040 ± 0.033

$B^0 \to J/\psi K^0_S$



$B^+ \to J/\psi K^+$



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

PDG : $S_{CP} = 0.699 \pm 0.017$

- S_{CP} value have twice larger stat uncertainty than at Belle due to 4times smaller sample
- In our convention, the syst. uncertainty incorporates res. fun. stat uncertainties from $B^0 \to D^{(*)-}\pi^+$ sample size

Projection to Belle lumi ±0.013

$$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$

$$A_{CP} = 0.094 \pm 0.044(\text{stat}) {}^{+0.042}_{-0.017}(\text{syst})$$

Belle I value:

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

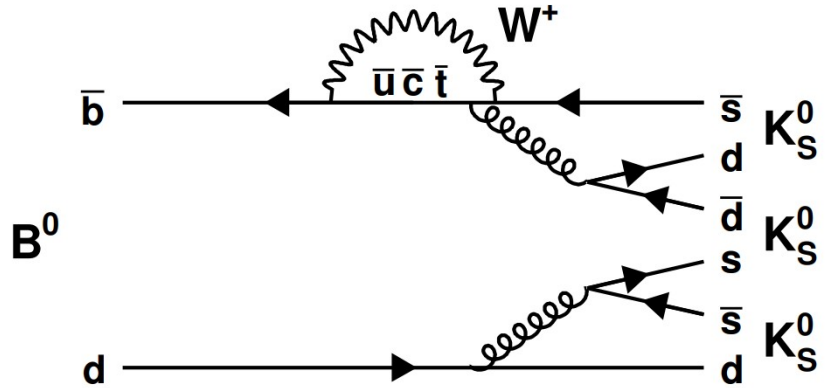
Scales like stat. unc

Source	$\sigma(S_{CP})$	$\sigma(A_{CP})$
Statistical	0.0622	0.0439
$B^0 \to D^{(*)-}\pi^+$ sample size	0.0111	0.0093
Analysis bias	0.0080	0.0020
Signal charge asymmetry	0.0027	0.0126
$w_6^+ = 0$ limit	0.0014	0.0001
Resolution function parametrization	0.0039	0.0008
τ_{B^0}, Δm_d	0.0007	0.0002
Alignment	0.0020	0.0042
Beam spot	0.0024	0.0020
Momentum scale	0.0005	0.0013
$\sigma_{\Delta t}$ binning	0.0050	0.0051
Multiple candidates	0.0005	0.0008
Tag-side interference	0.0020	$^{+0.0380}_{-0.000}$
Total systematic	0.0159	$^{+0.0418}_{-0.0173}$

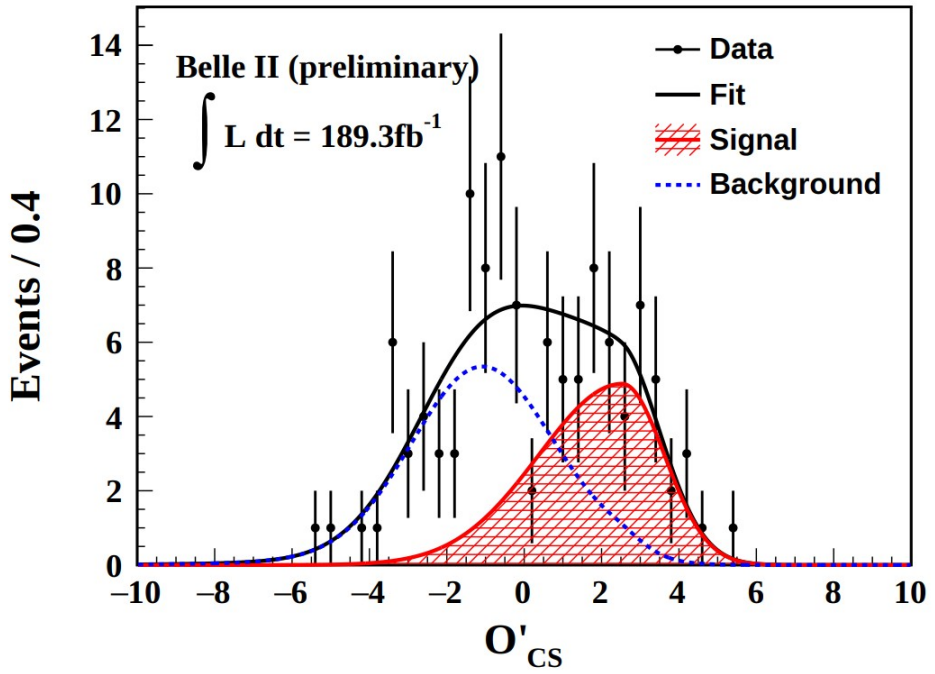
Sin $2\phi_1$ measured stat limited, similar sys. unc. as at Belle

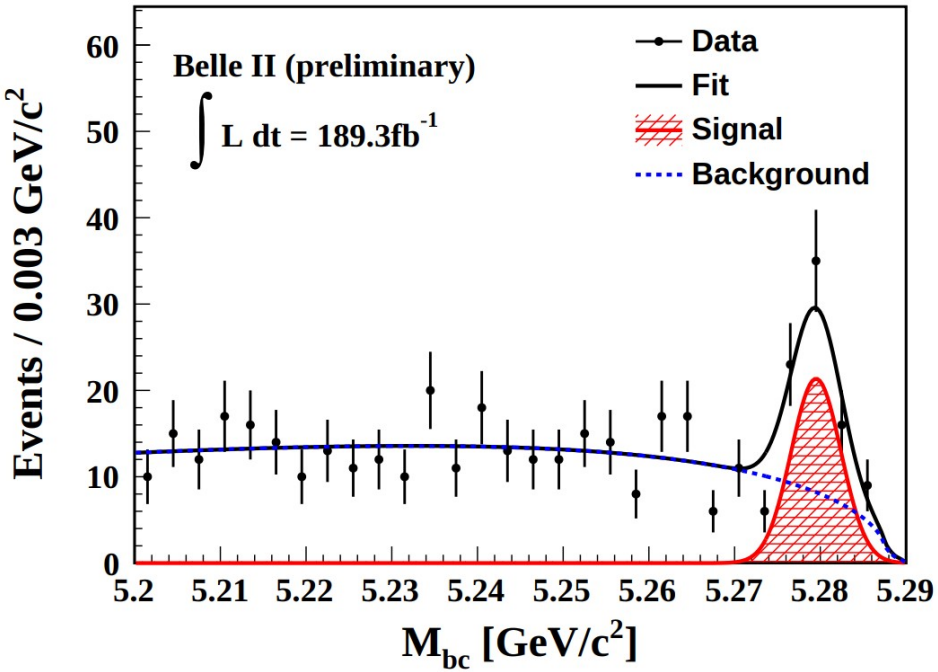
CP violation in $B^0 \to K^0_S K^0_S K^0_S$

- Challenging vertex reconstruction
- Two BDT classifiers
  - → to reduce fake K^0_S contribution
  - → to reduce continuum $q\bar{q}$ background
- Simultaneous fit to M_{bc}, M and O'_{CS}
- Validated in $B^+ \to K^+ K^0_S K^0_S$



B = 6 x 10^{-6}





53 +- 8
signal events

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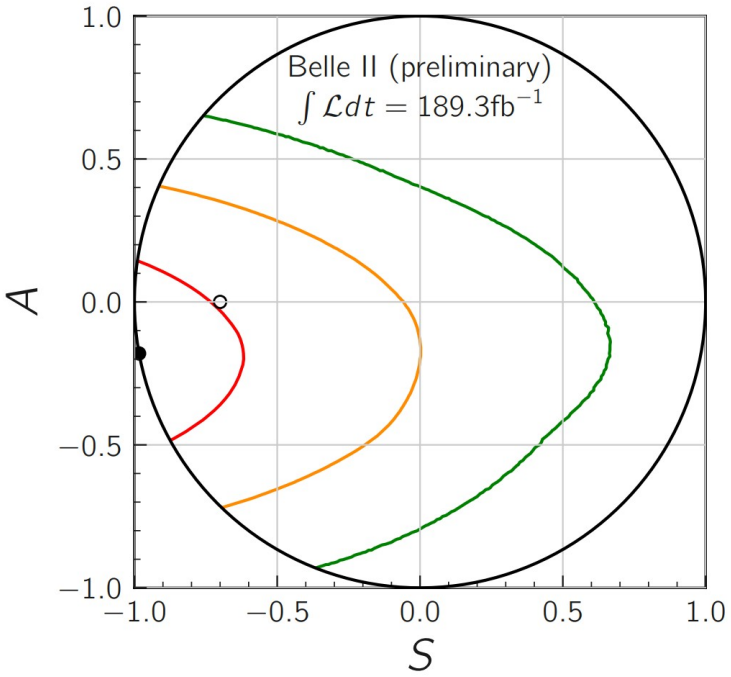
CP violation in $B^0 \to K^0_S K^0_S K^0_S$

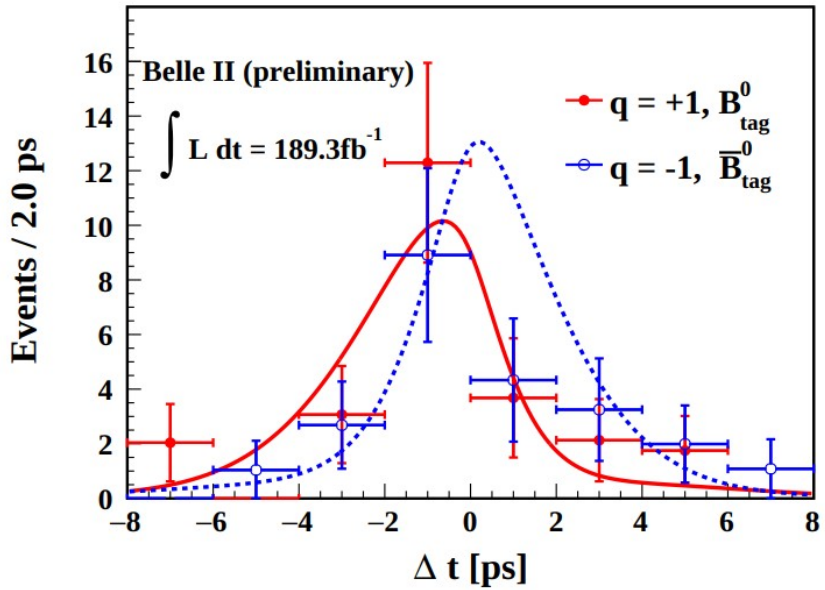
- In the fit S, A not restricted to physical limit $S^2 + A^2 < 1$ which can lead to situation, where f_{phys} is sometimes negative but f_{obs} always positive

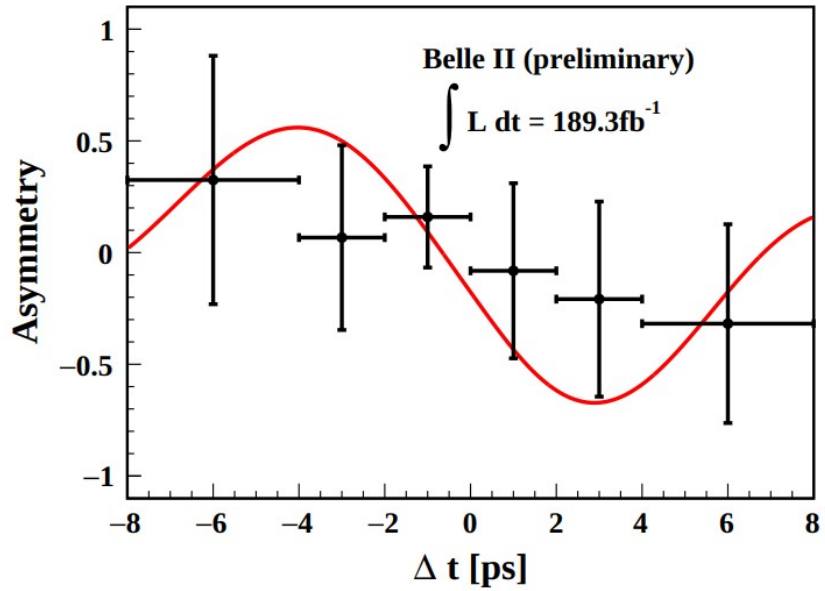
$$f_{\rm obs}(\Delta t, \sigma) = f_{\rm phys}(\Delta t) \otimes \mathcal{R}(\delta\Delta t, \sigma)$$

$$\mathcal{S} = -1.86\ ^{+0.91}_{-0.46}\ (\text{stat}) \pm 0.09\ (\text{syst})$$
$$\mathcal{A} = -0.22\ ^{+0.30}_{-0.27}\ (\text{stat}) \pm 0.04\ (\text{syst})$$

Belle
S = -0.71 ± 0.23 ± 0.05
A = -0.12 ± 0.16 ± 0.05







Direct CP violation in $B^0 \to K^0_s \pi^0$

Phys.Lett.B 627 (2005) 82

- From the iso-spin symmetry in the SM holds:

$$\mathcal{A}_{CP}(K^+\pi^-) + \mathcal{A}_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}(K^+\pi^0)\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}(K^0\pi^0)\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

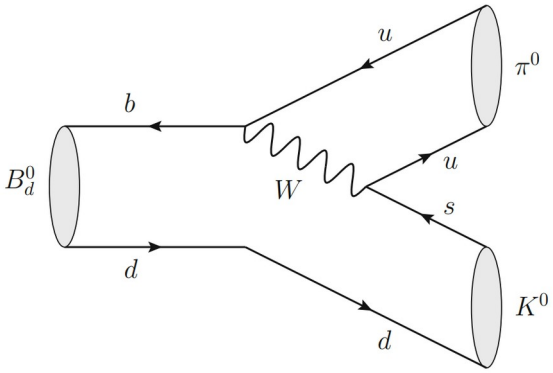
- The $A_{CP}(K^0\pi^0)$ is the most imprecise A_{CP} term in the equation

$A(K^0\pi^0)$ from iso-spin

$$A_{CP} = -0.14 \pm 0.03$$

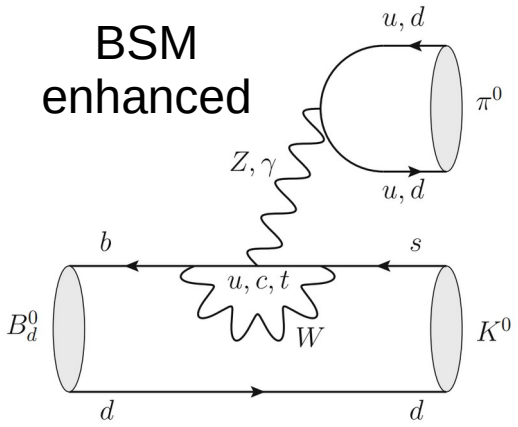
$A(K^0\pi^0)$ from Belle & BaBar

$$A_{CP} = 0.01 \pm 0.10$$



Color-suppressed tree

BSM enhanced

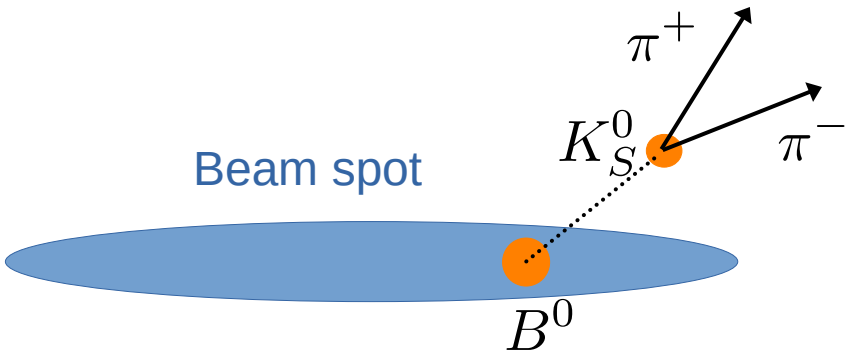


Color-allowed penguin

Eur.Phys.J.C 78 (2018) 11, 943

Direct CP violation in $B^0 \to K^0_S \pi^0$

- The $B^0 \to K^0_S \pi^0$ only accessible at e^+e^- B factories
- Main challenge is the decay vertex reconstruction
- BR and A_{CP} obtained from 4D fit in M_{bc}, ΔE, Δt, O_{CS}
  → S_{CP} fixed to 0.67, i.e. average from Belle

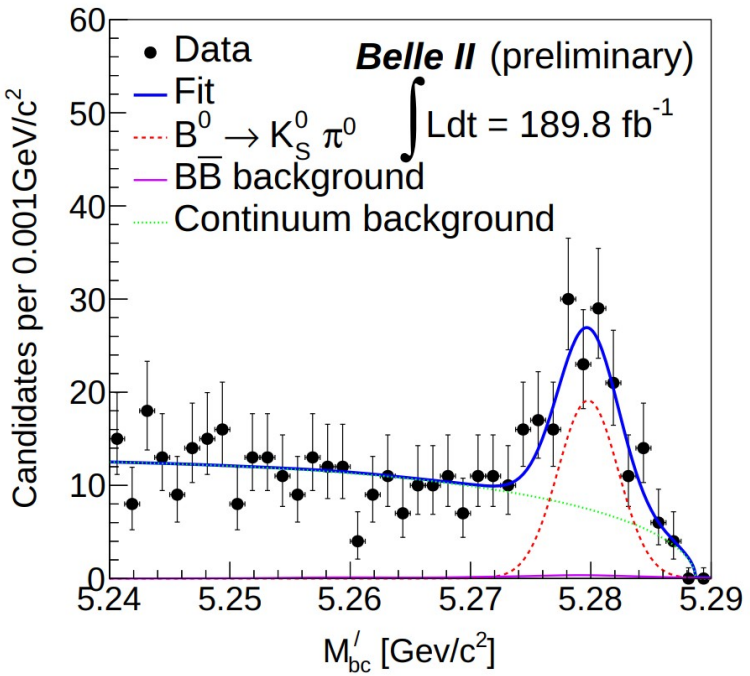


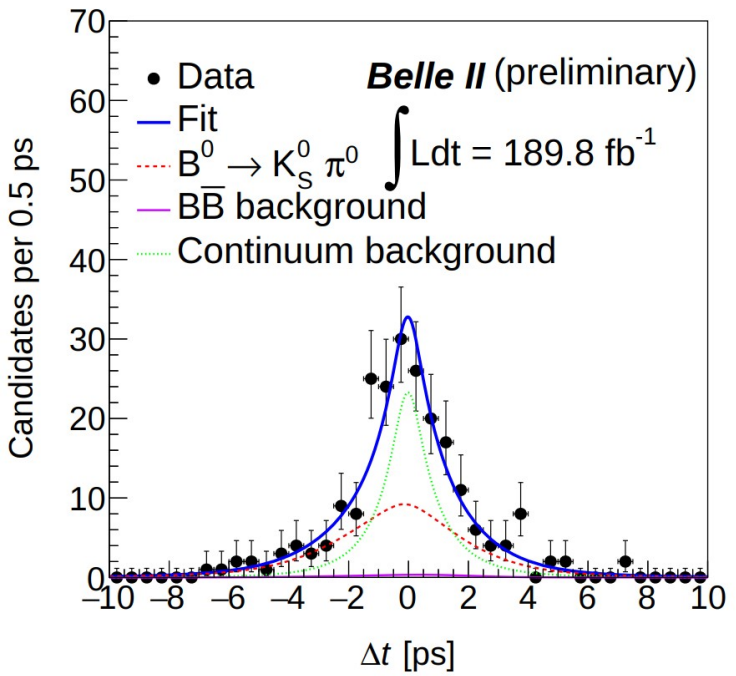
135 +- 16 signal events

A($K^0\pi^0$) from iso-spin

$$A_{CP} = -0.14 \pm 0.03$$

$$\mathcal{A}_{CP} = -0.41 \pm 0.32(\text{stat}) \pm 0.09(\text{syst})$$
$$\mathcal{B} = 11.0 \pm 1.2(\text{stat}) \pm 1.0(\text{syst}) \times 10^{-6}$$





arXiv:2206.07453

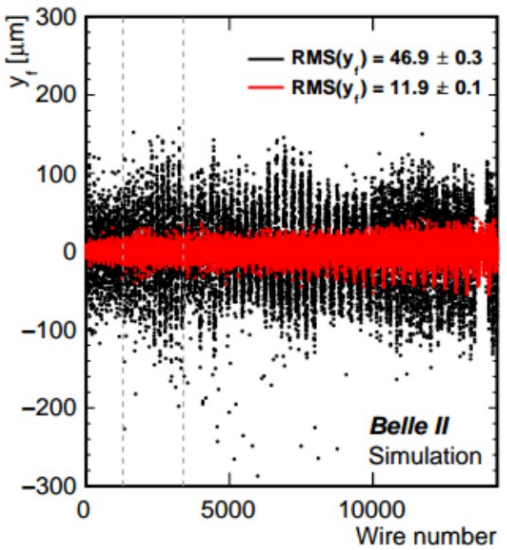
Conclusions

- Belle II searches for new physics in loop-dominated B^0 decays as well as by (over)constraining SM CKM parameters
- Time-dependent measurements profits from better vertex resolution and better knowledge of the interaction region compared to Belle
- Several time-dependent analyses performed Moriond 2022 dataset (190 fb^{-1}, i.e 200M $B\overline{B}$)
  - → B^0 lifetime and B^0-B^0 mixing
  - → sin $2\phi_1$ from $B^0 \to J/\psi\, K^0_S$
  - → sin $2\phi_1$ from $B^0 \to K^0_S\, K^0_S\, K^0_S$
  - → A_{CP} in $B^0 \to K^0_S\, \pi^0$

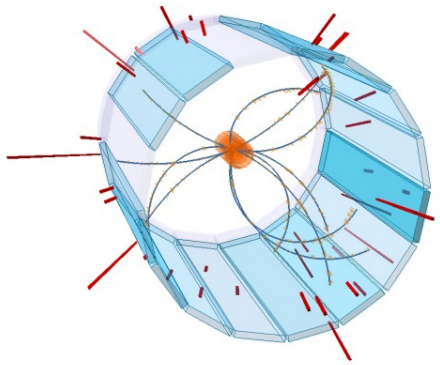
Tracker Alignment

- **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)

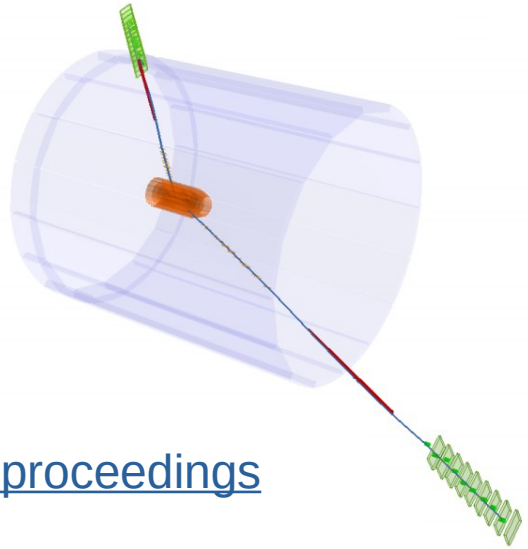
Monte Carlo



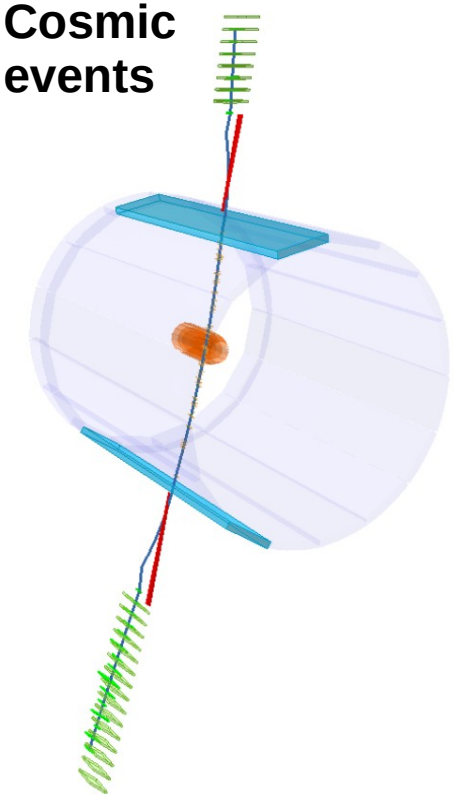
Hadronic events



Di-muon events



Cosmic events



[vCHEP 2021 proceedings]

Data