Time-dependent CPV in the B decays at Belle II

Radek Žlebčík
on behalf of the Belle II collaboration

August 30, 2022
14th Conference on the Intersections of Particle and Nuclear Physics
Orlando, state Florida

CHARLES UNIVERSITY

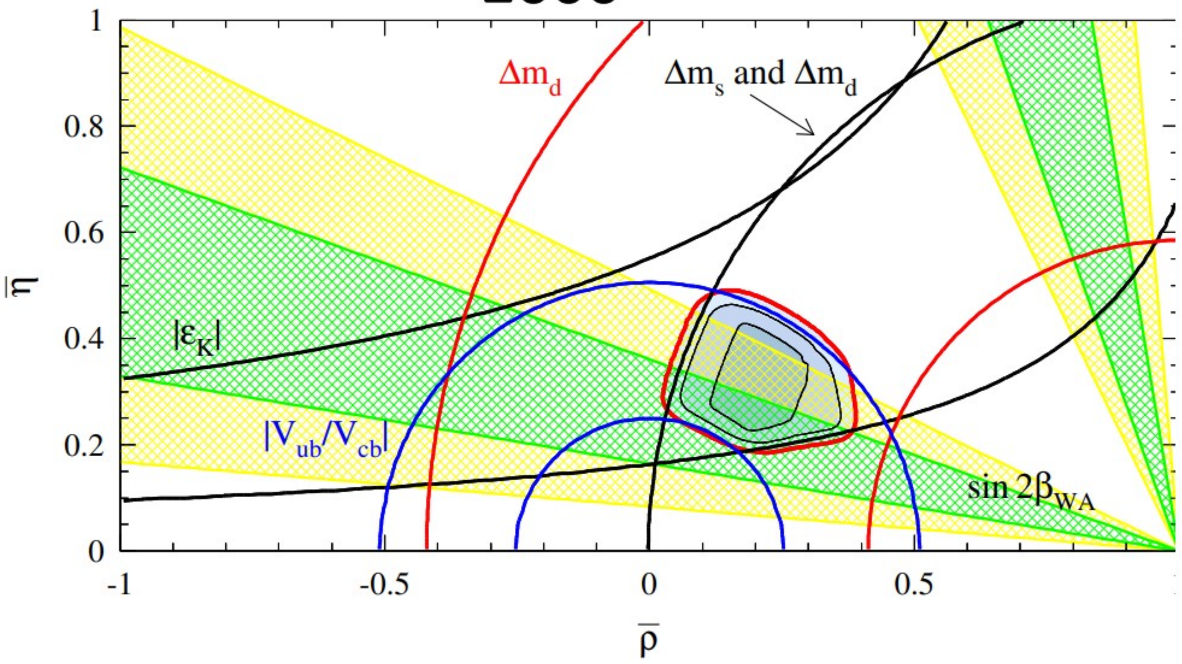
Belle II

Cape Canaveral

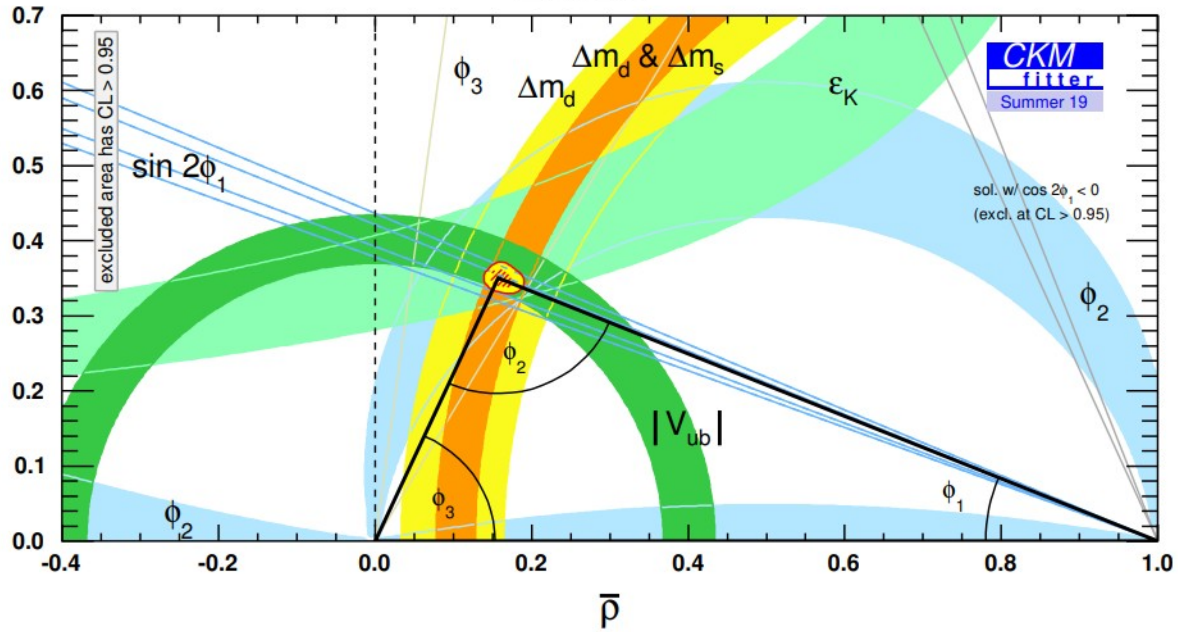
Unitarity triangle : 20 years of development

- 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

2000



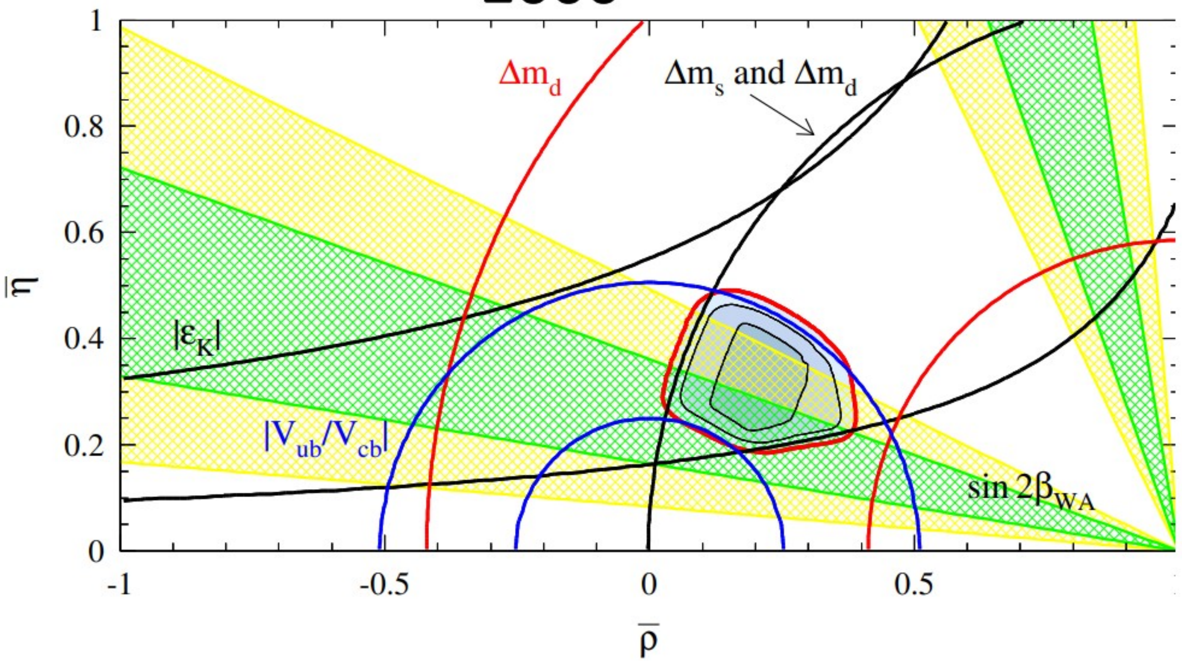
2019



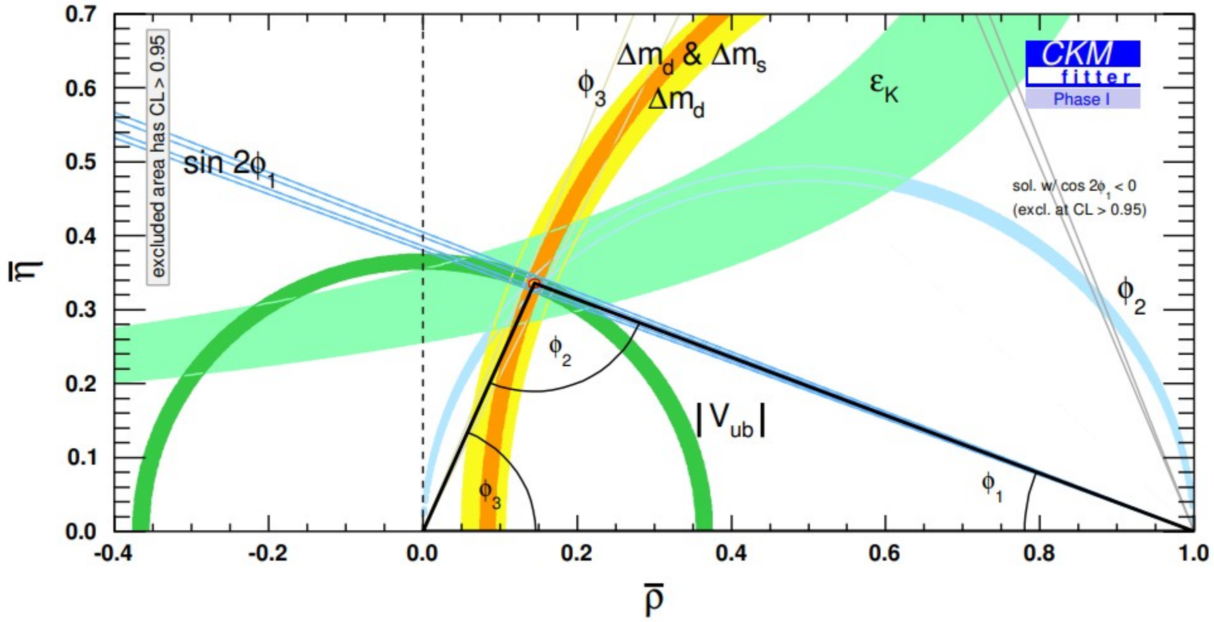
Unitarity triangle : in 10 years?

- 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



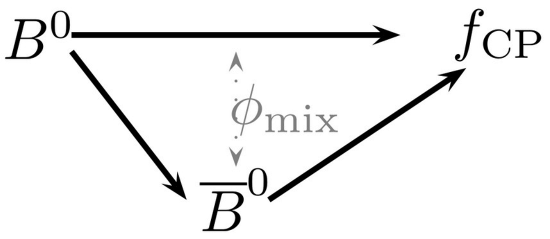
2030?



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

CP violation in interference of mixing and decay

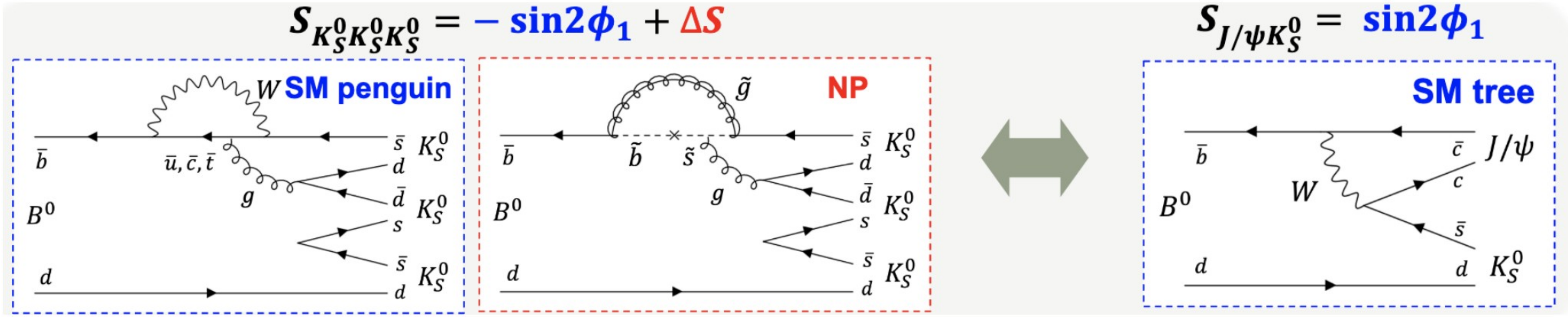
- The $|S| \sim \sin 2\phi_1$ measurable from the time-dependent asymmetry between $B^0 \to f_{CP}$ and $\overline{B}^0 \to f_{CP}$



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

Mixing-induced CPV

Direct CPV



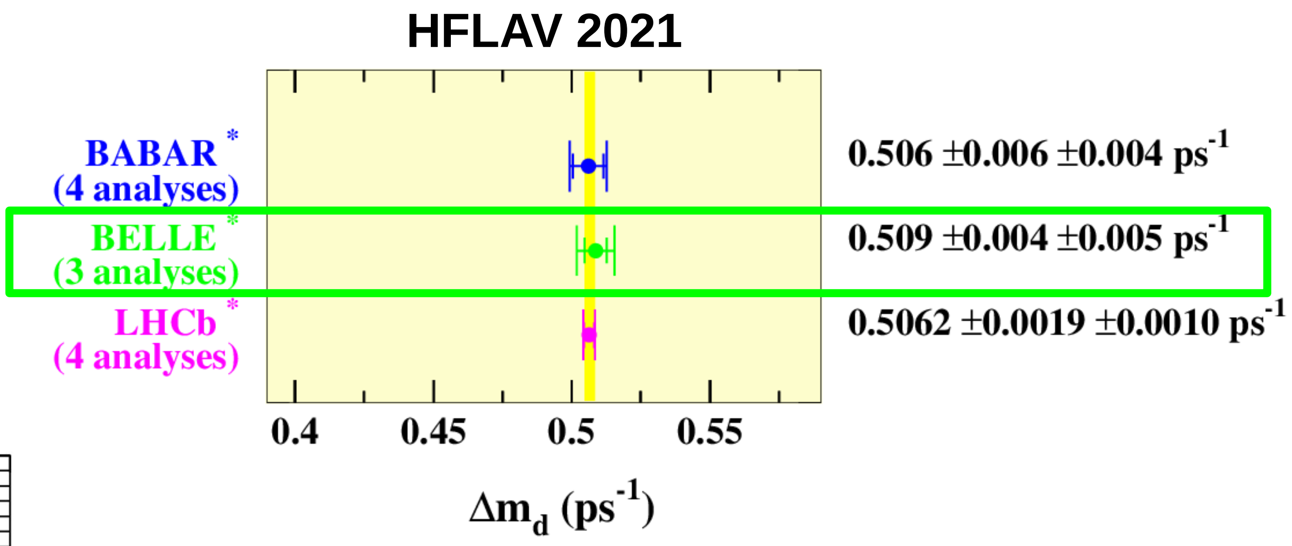
Workflow for time-dependent B measurements

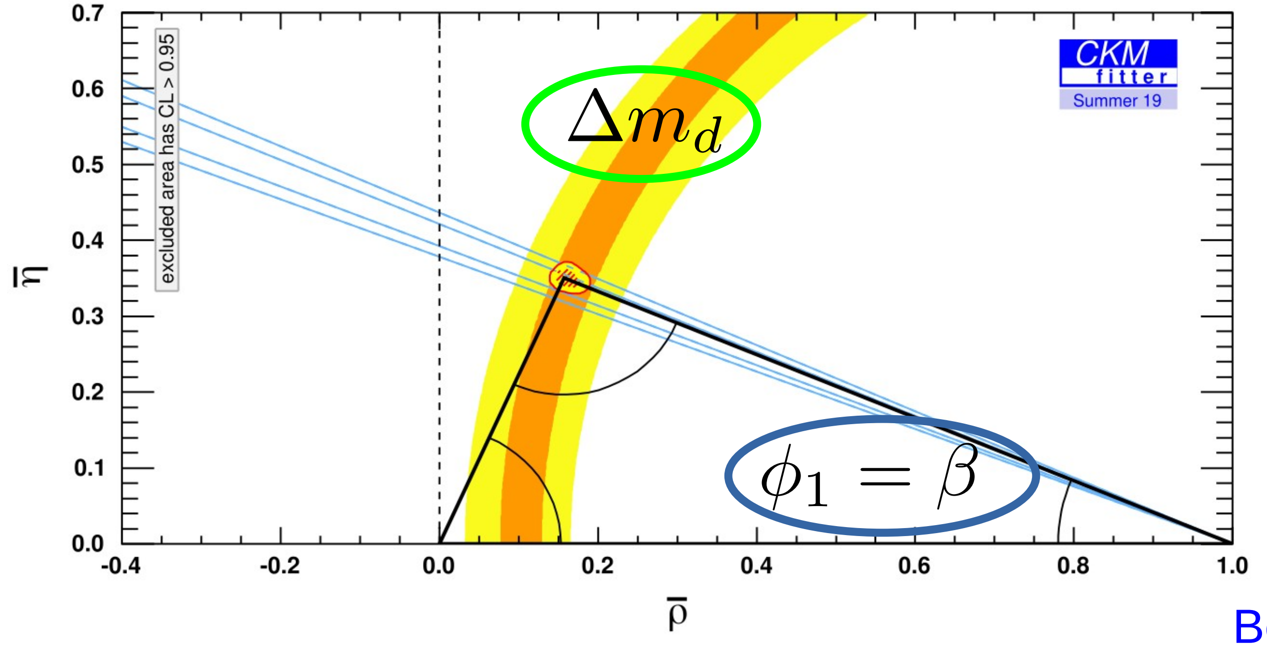
time, luminosity →

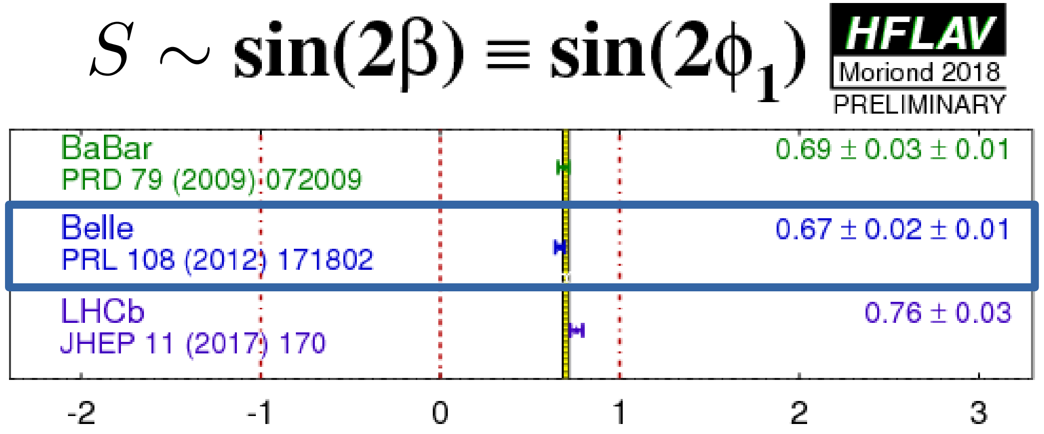
B^0-$\overline{B}^0$ oscillations Δm_d	CP violation in tree-decays sin 2β	CP violation in loop-decays sin 2β
LHCb dominated	Tie between LHCb and B-factories	Dominated by B-factories
Done	**$B^0 \rightarrow J/psi\ K_s$** **4-times less stat than Belle**	**$B^0 \rightarrow K_sK_sK_s$** **4-times less stat 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



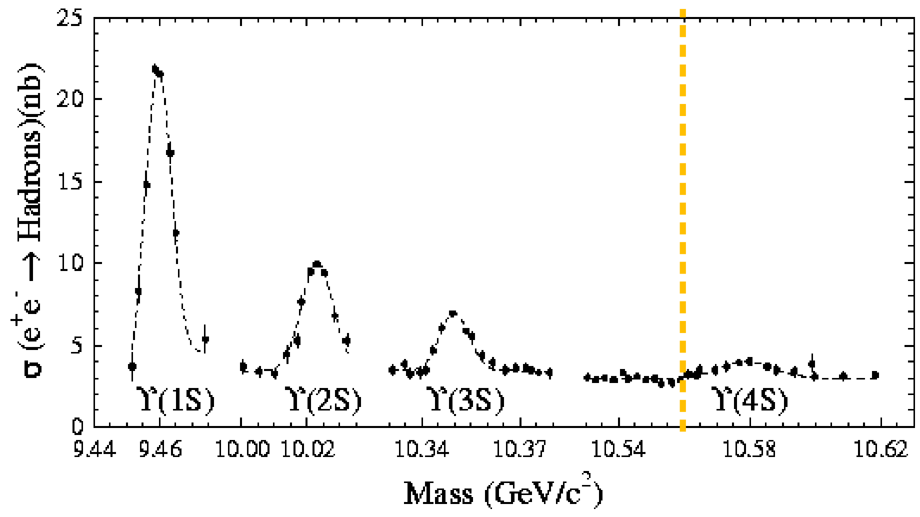




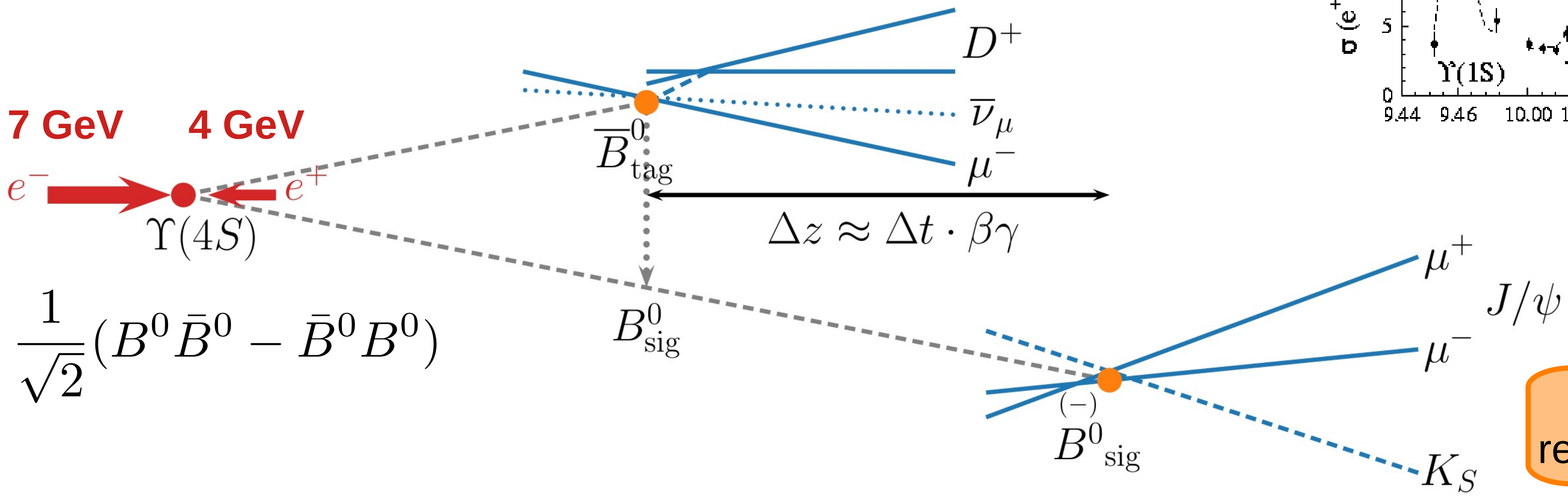
Belle II with full lumi can achieve 0.5% precision for sin 2β

Measuring time-dep. CPV at Belle II

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



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



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

Time-measurement ⇔ distance-measurement

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

Belle : $\Delta z \approx 200\,\mu m$

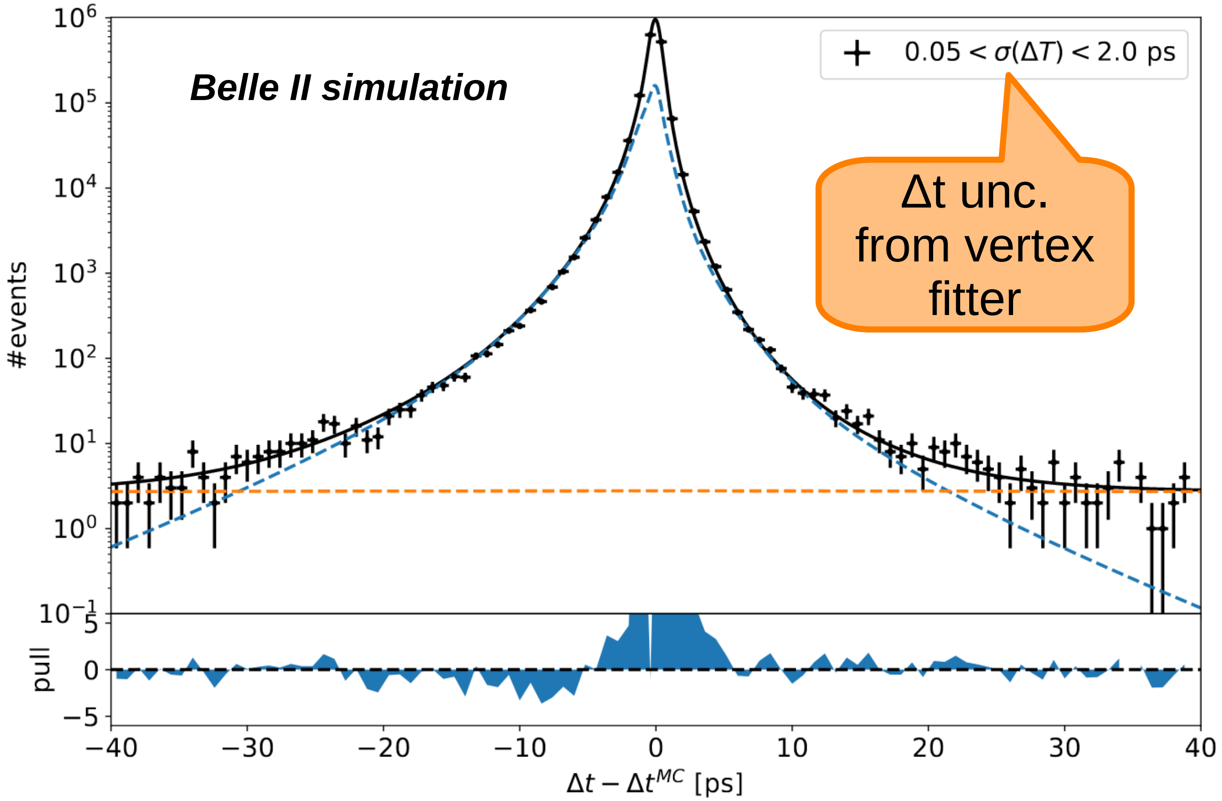
Fully reconstructed

From rest of event

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

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



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

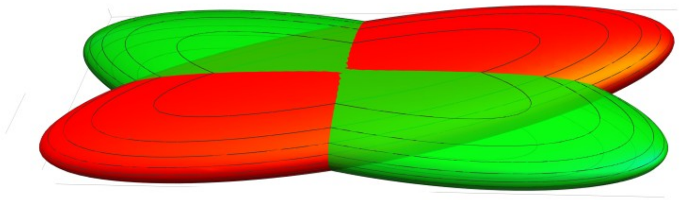
$$\begin{aligned}\mathcal{R}(\delta\Delta t;\sigma) = &(1-f_{\mathrm{tail}})\cdot G(\delta\Delta t;\mu_{\mathrm{main}}\cdot\sigma, s_{\mathrm{main}}\cdot\sigma)\\ &+(1-f_{\mathrm{exp}})\cdot f_{\mathrm{tail}}\cdot G(\delta\Delta t;\mu_{\mathrm{tail}}\cdot\sigma, s_{\mathrm{tail}}\cdot\sigma)\\ &+f_{\mathrm{tail}}\cdot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

Beam spot constraint

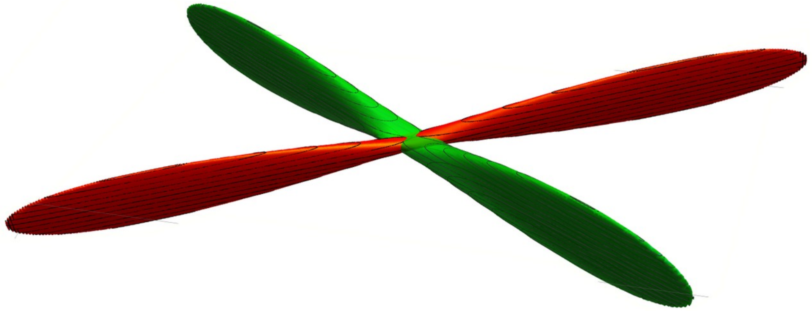
- At Belle II the much higher peak luminosity is achieved by so-called nano-beam scheme
- The small beam size can be used to better constrain the kinematics of the event (e.g. improving B_{tag} vertex precision and consequently Δt resolution)

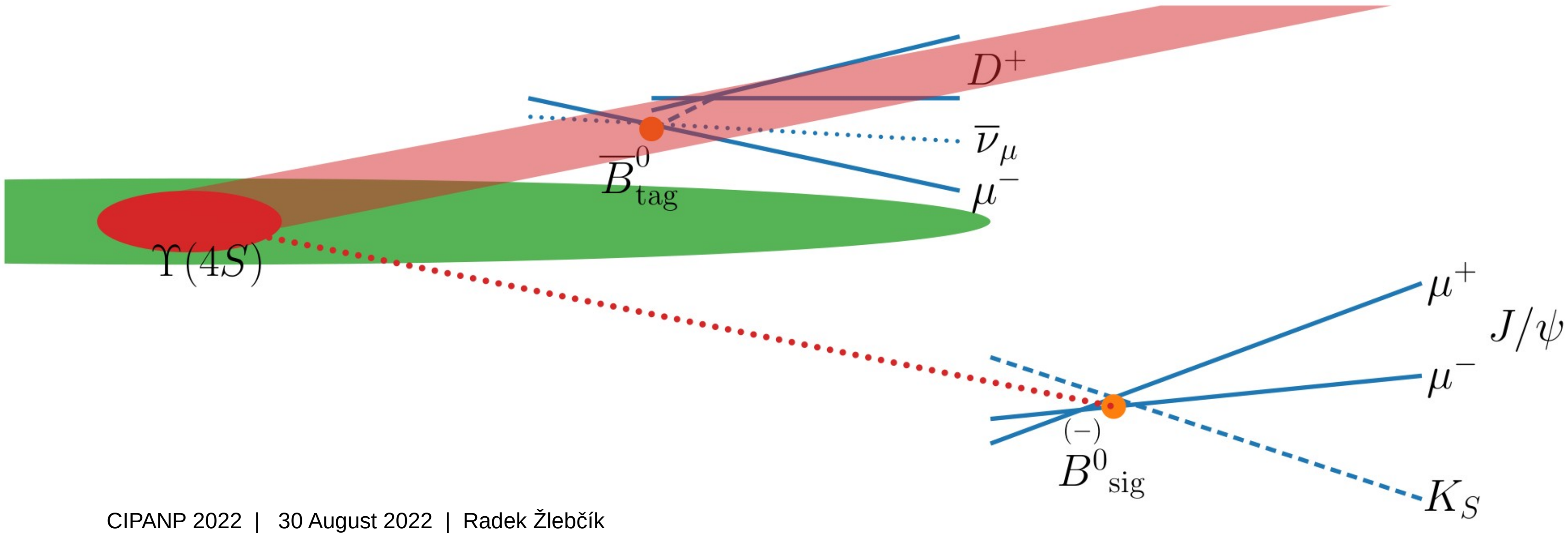
$$\sigma_{Y'} = 0.2\mu\text{m}, \sigma_{X'} = 13\mu\text{m}, \sigma_{Z'} = 320\mu\text{m}$$

Belle



Belle II



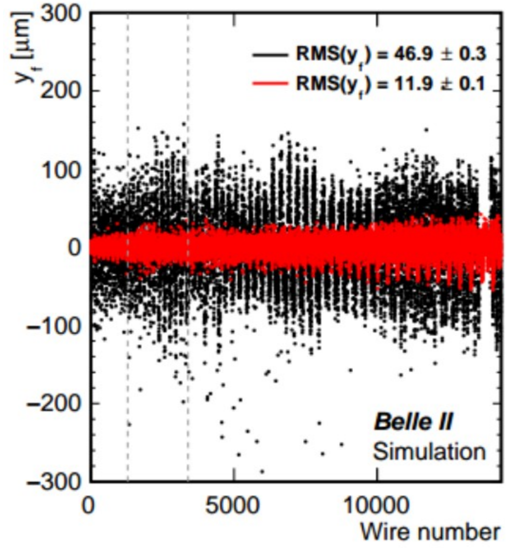


Beam spot calibration
- Based on ee→μμ events with high-stat
- Calibrated every ~30min
- All parameters of the 3D Gaussian PDF measured (3 sizes + 3 angles)

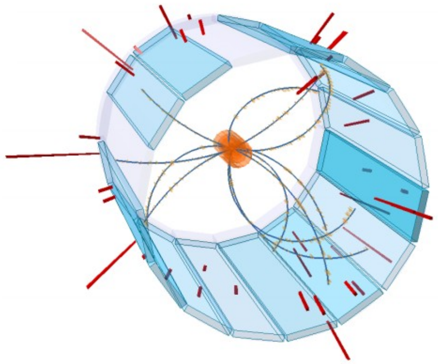
Tracker Alignment

- **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)

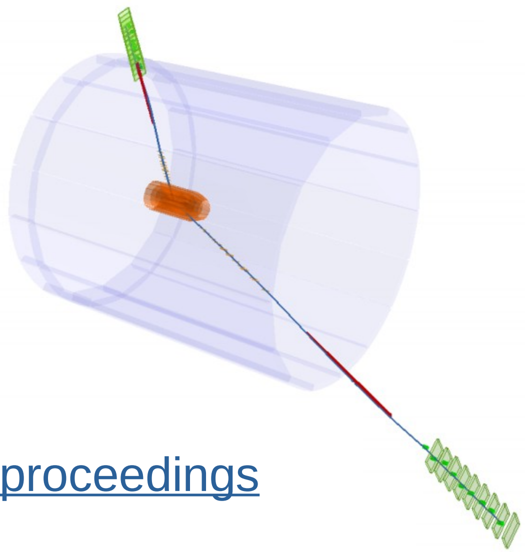
Monte Carlo



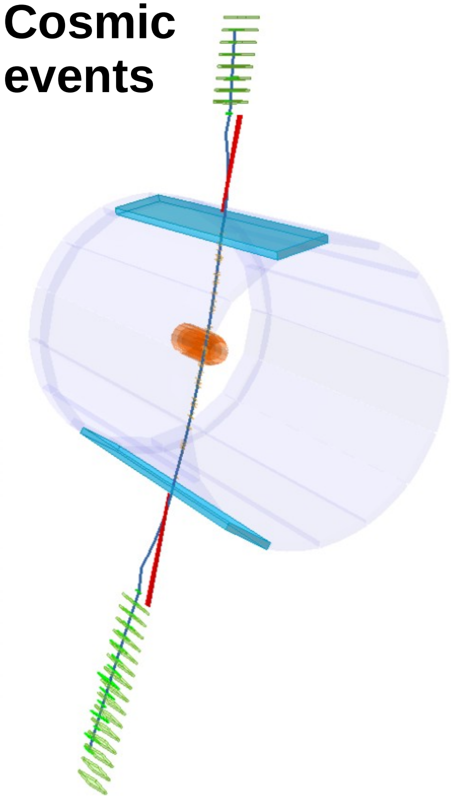
Hadronic events



Di-muon events

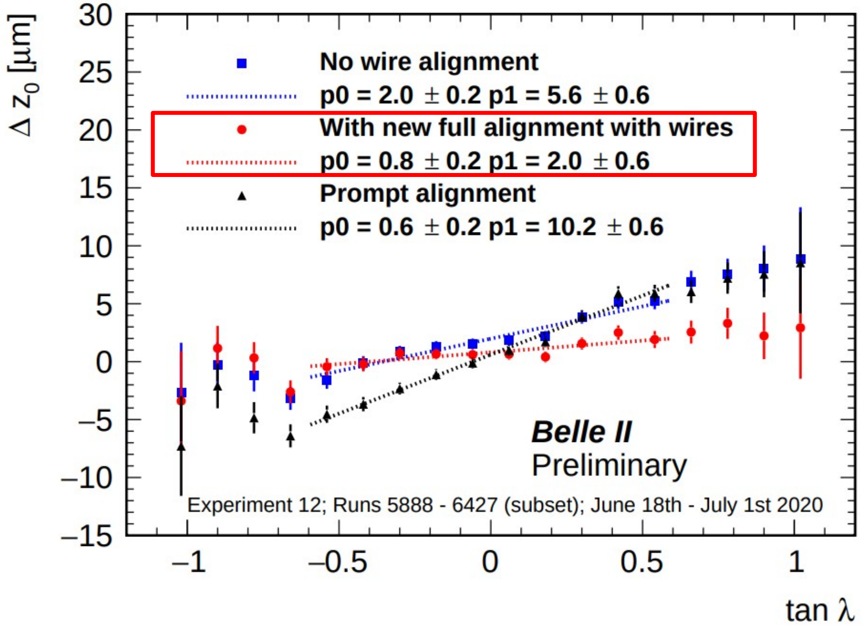


Cosmic events



[vCHEP 2021 proceedings]

Data



Flavor tagging

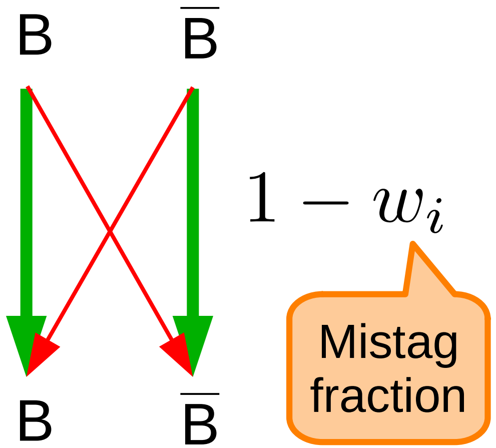
Eur. Phys. J. C 82, 283(2022)

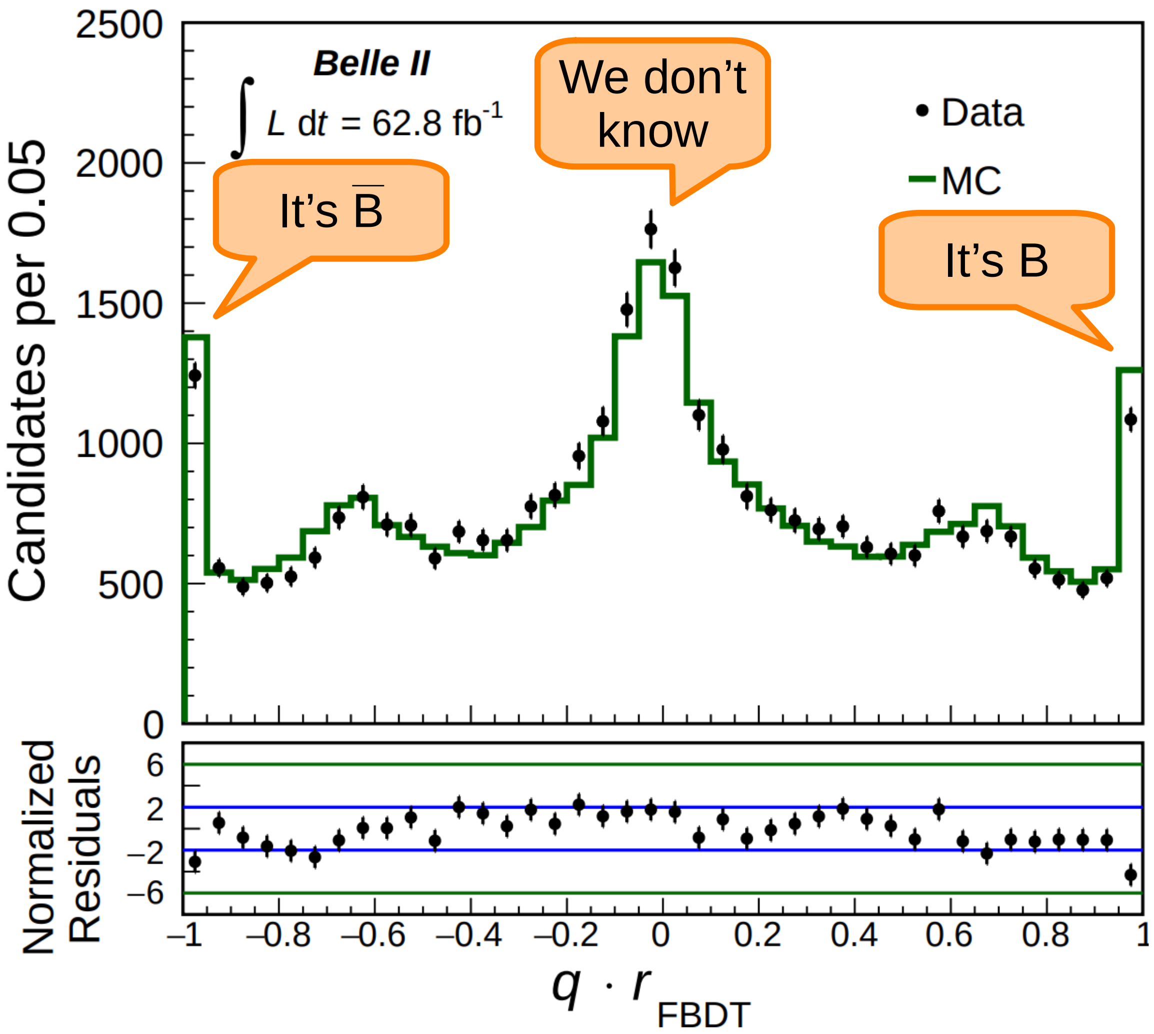
- Determination of the B_{tag} flavor using all the particles not belonging to signal B
- The |qr| is split into 7 bins to test the performance in hadronic B decays data
- The efficiency evaluated from $B\bar{B}/B\bar{B}$ asymmetries in all |qr| bins

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

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

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



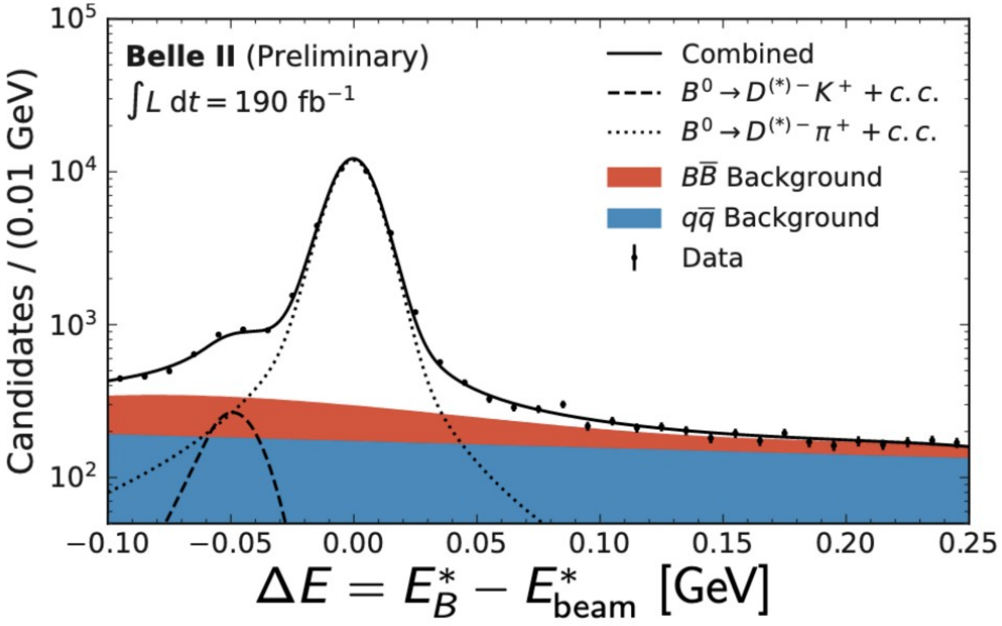


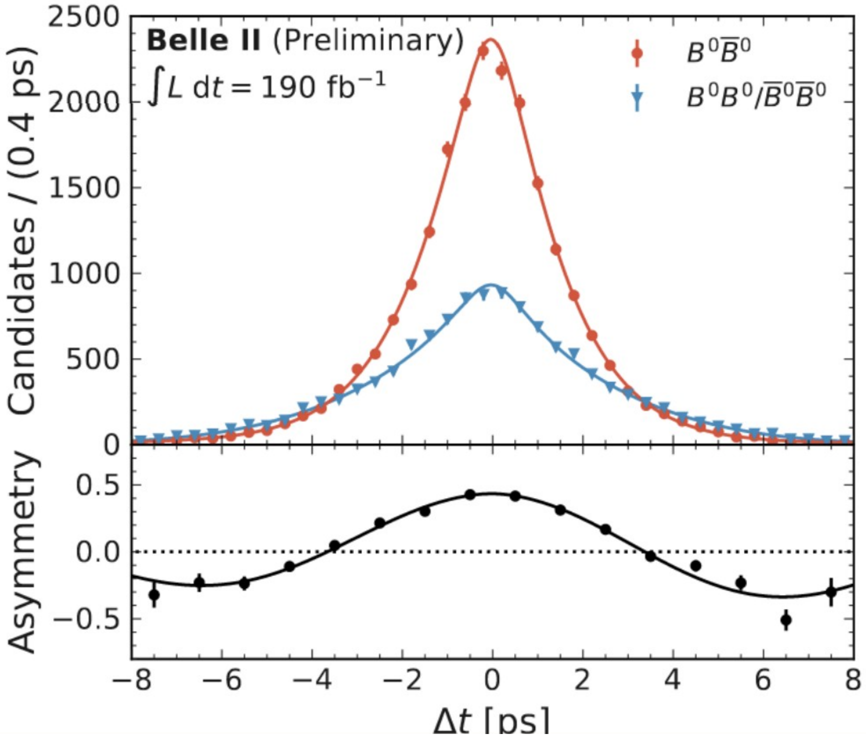
Dilution factor : $r_{\rm FBDT} \approx 1 - 2w$
Flavor tag : $q = \pm 1$

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

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
$q\overline{q}$ 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

Better than Belle / BaBar

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

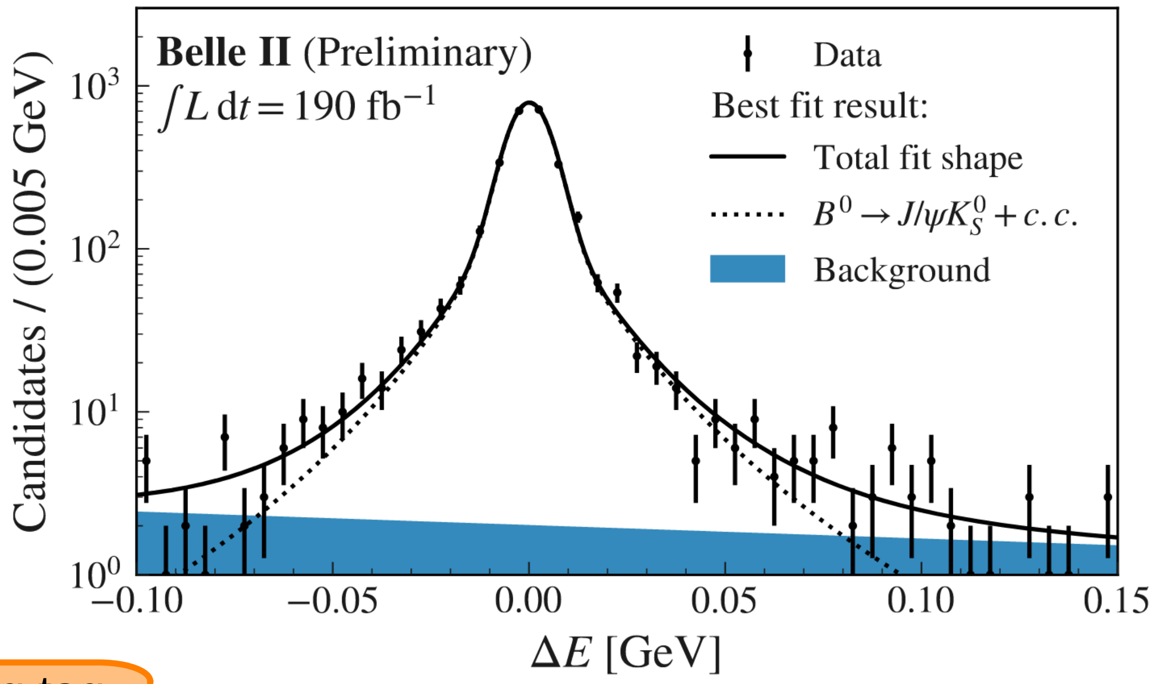
$$\Delta m_d = 1.516 \pm 0.008(\text{stat}) \pm 0.005(\text{syst})\ \text{ps}^{-1}$$

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

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

Efficiency q-asym.

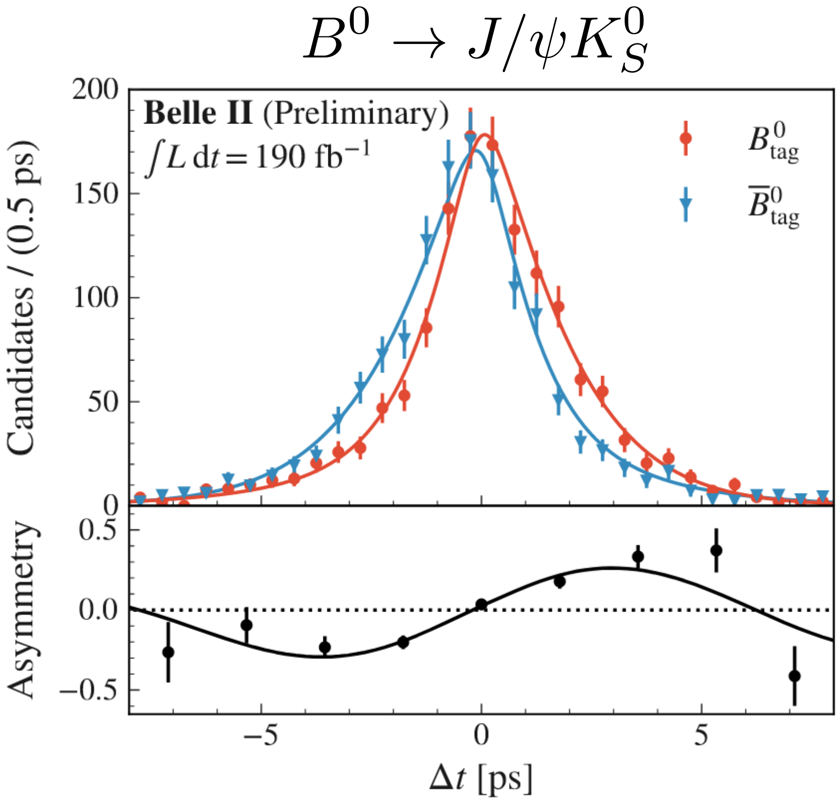
$$q = +1 \quad B_{\mathrm{tag}} = B^0$$
$$q = -1 \quad B_{\mathrm{tag}} = \bar{B}^0$$

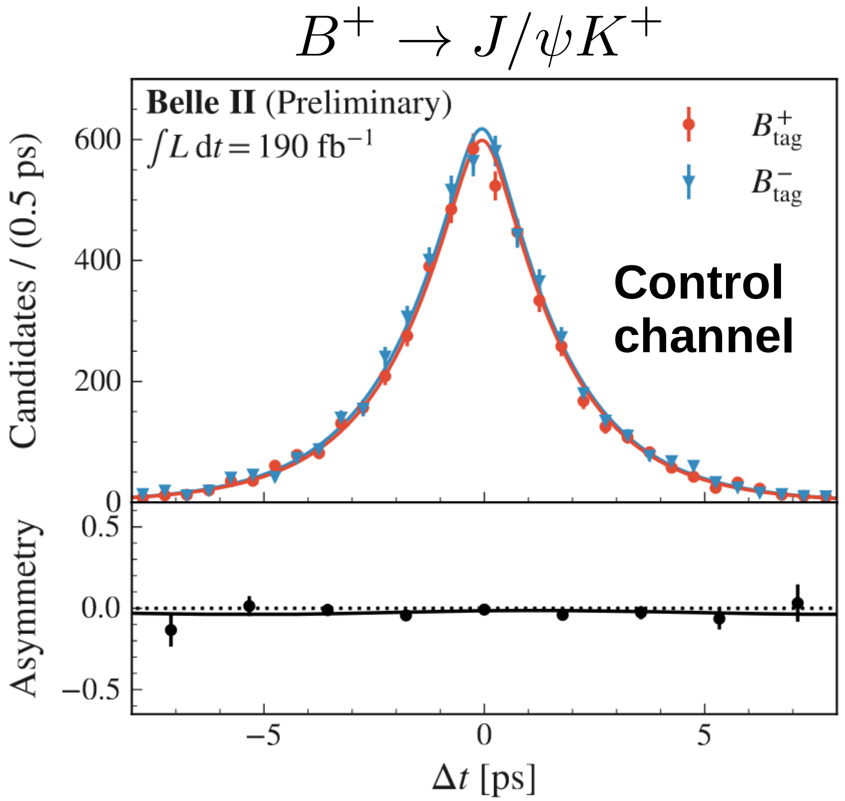
ICHEP 2022

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}	$p_{sig}(\%)$	$\varepsilon_{sig}(\%)$	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





Control channel

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

PDG : S_{CP} = 0.699 ± 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

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	$^{+0.0418}_{-0.0173}$

Projection to Belle lumi ±0.013

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

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

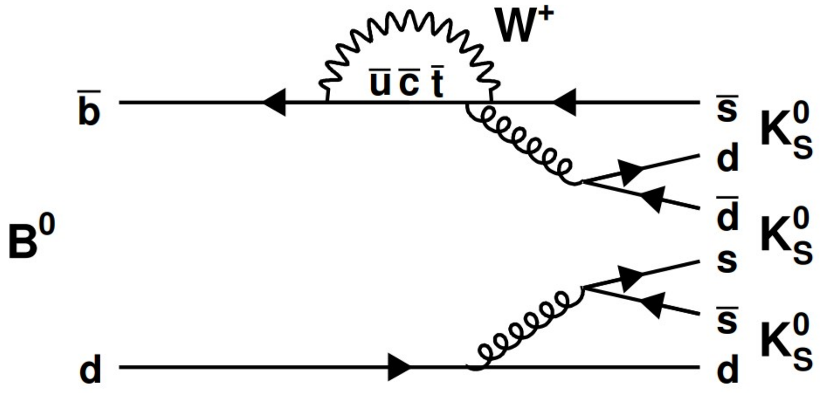
Belle I value:

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

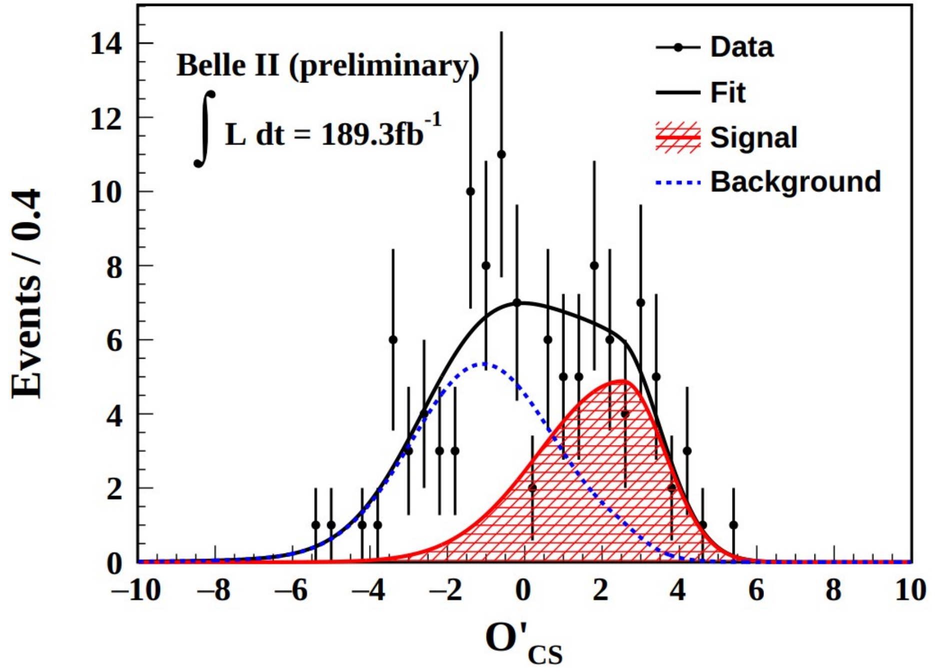
Sin 2ϕ_1 measured stat limited, similar sys. unc. as at Belle

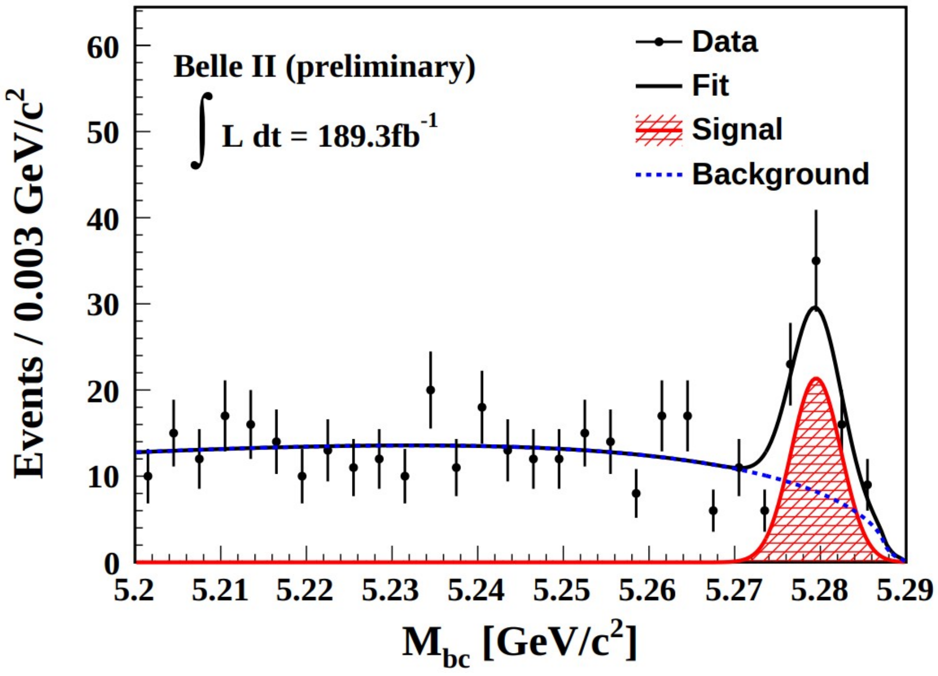
CP violation in $B^0 \to K^0_S K^0_S K^0_S$

- 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 $B^0 \to K^+ K^0_S K^0_S$



$\mathcal{B} = 6 \times 10^{-6}$





53 +- 8
signal events

ICHEP 2022

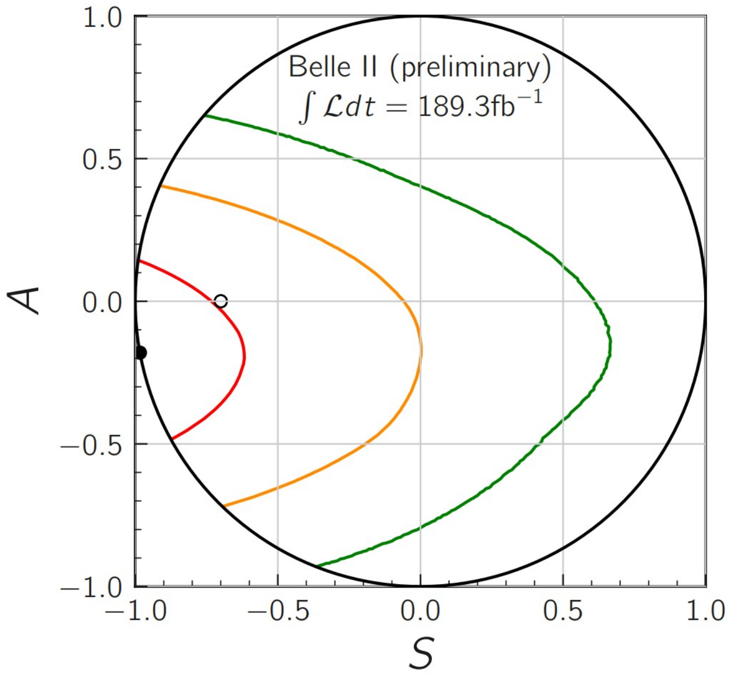
CP violation in $B^0 \to K^0_S K^0_S K^0_S$

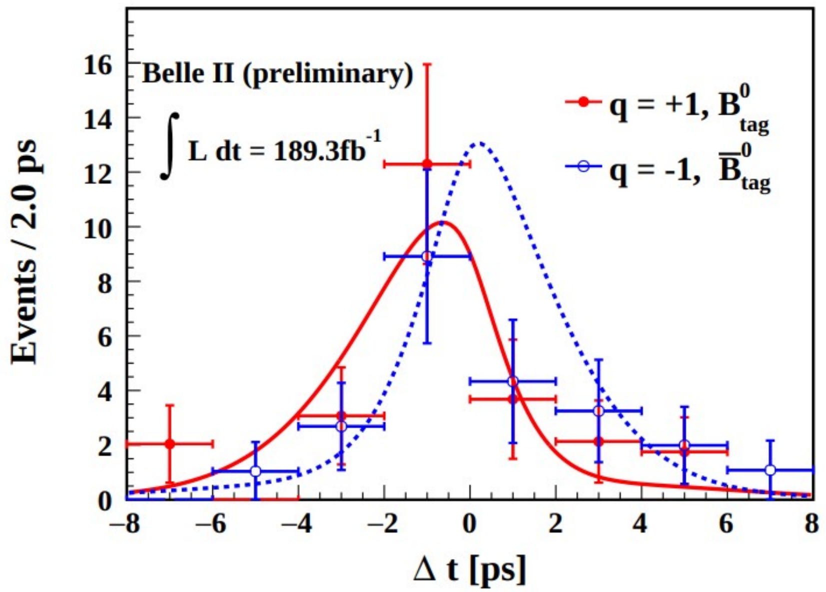
- In the fit S, A not restricted to physical limit $S^2 + A^2 < 1$ which can lead to situation, where f_{phys} is sometimes negative but f_{obs} always positive

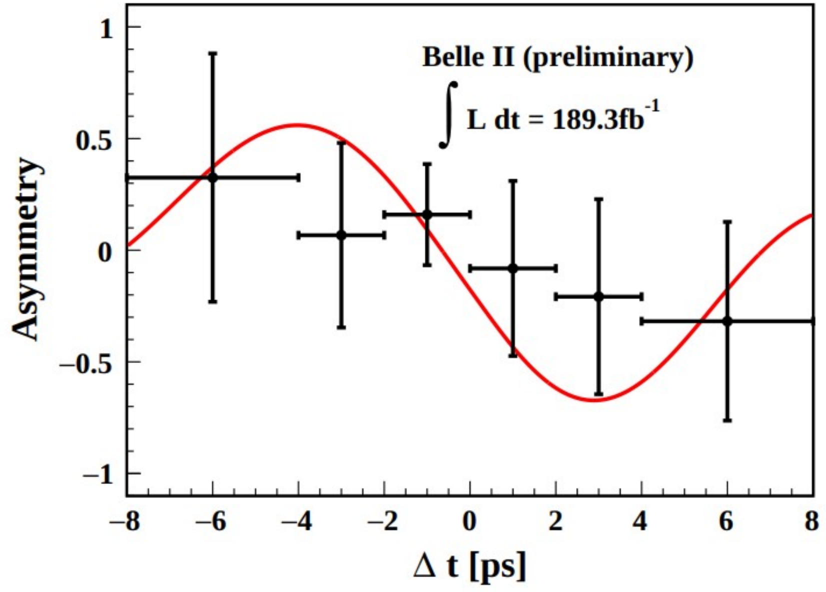
$$f_{\rm obs}(\Delta t, \sigma) = f_{\rm phys}(\Delta t) \otimes \mathcal{R}(\delta\Delta t, \sigma)$$

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

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:

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

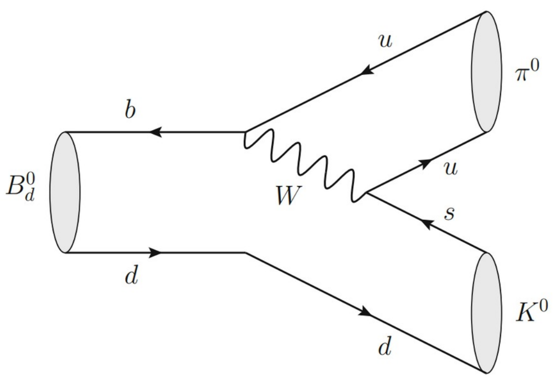
- The $A_{CP}(K^0\pi^0)$ is the most imprecise A_{CP} term in the equation

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

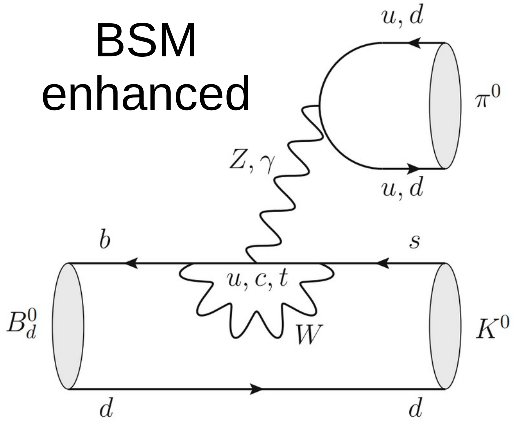
$$A_{CP} = -0.14 \pm 0.03$$

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

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



Color-suppressed tree

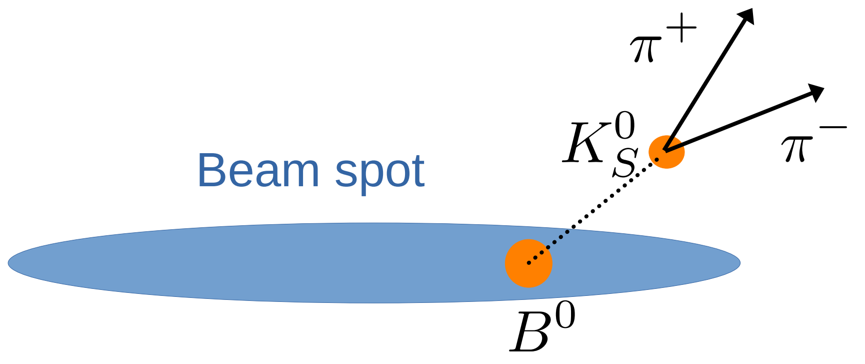


Color-allowed penguin

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

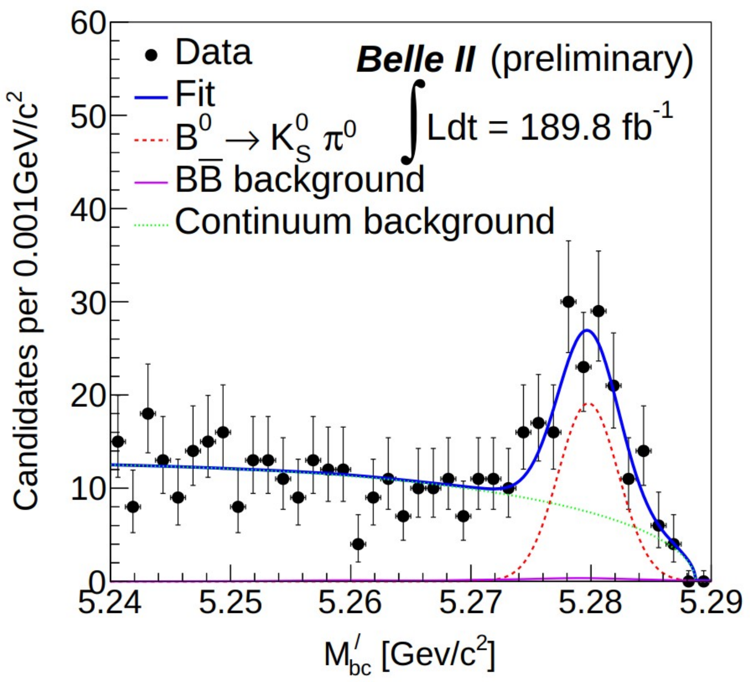
A($K^0\pi^0$) from iso-spin

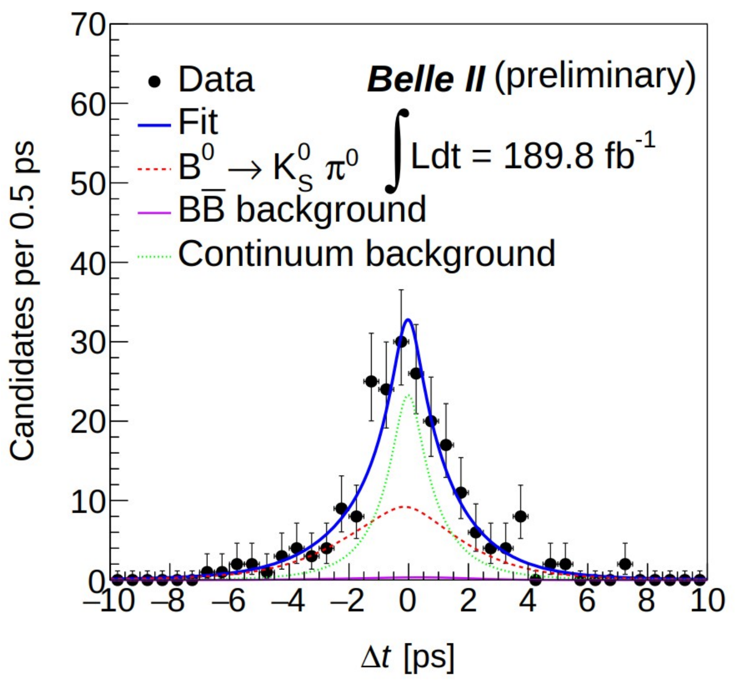
$$A_{CP} = -0.14 \pm 0.03$$

$$\mathcal{A}_{CP} = -0.41 \pm 0.32(\text{stat}) \pm 0.09(\text{syst})$$

$$\mathcal{B} = 11.0 \pm 1.2(\text{stat}) \pm 1.0(\text{syst}) \times 10^{-6}$$

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 $B\bar{B}$)
  → 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 $B^0 \to K^0_s \pi^0$