Precise measurements of CP-violation in B decays at Belle II

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on behalf of the Belle II Collaboration

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and Leptons

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Unitarity Triangle from B Decays

- Quark interactions described by the CKM unitary matrix V_{CKM}

- Off-diagonal elements of $V^\dagger V = I$ can be represented by triangles in complex plane
  - Sides ~ Amplitudes ~ Branching fractions
  - Angles ~ Phases ~ CPV

- Most common triangle from $\Sigma_i V_{id} V_{ib}^*$, i=u,c,t (be aware that $\varphi_1 = \beta$, $\varphi_2 = \alpha$, $\varphi_3 = \gamma$!)

- All angles can be accessed at B-factories → BaBar (SLAC) and Belle (KEK) collected together about 1.5 ab^{-1} → precise determination of unitarity triangle
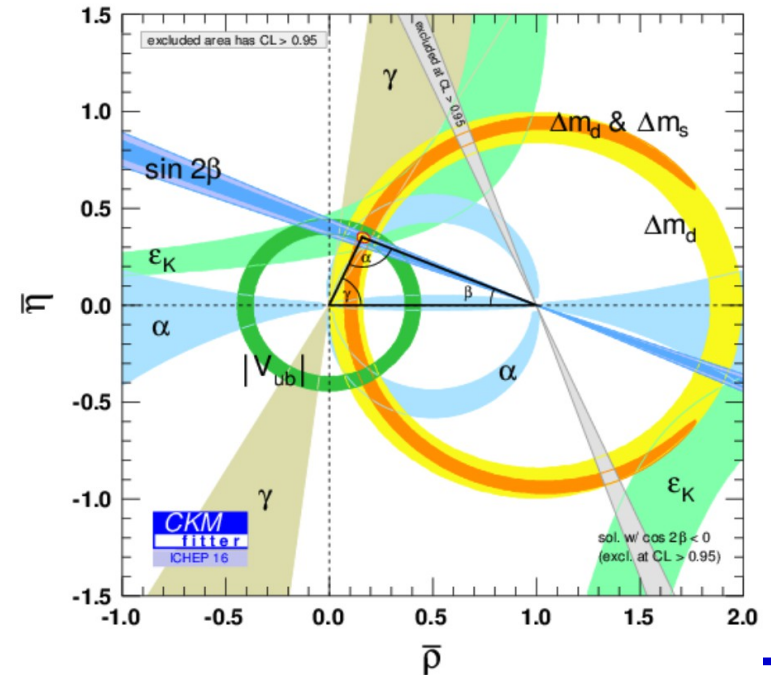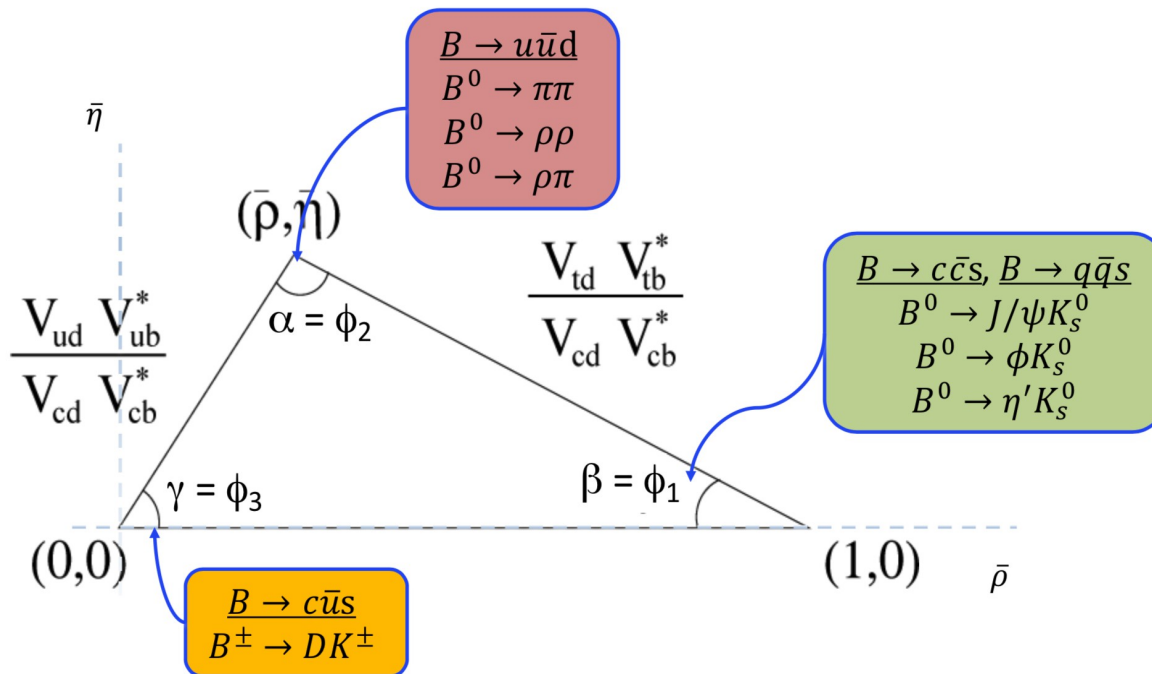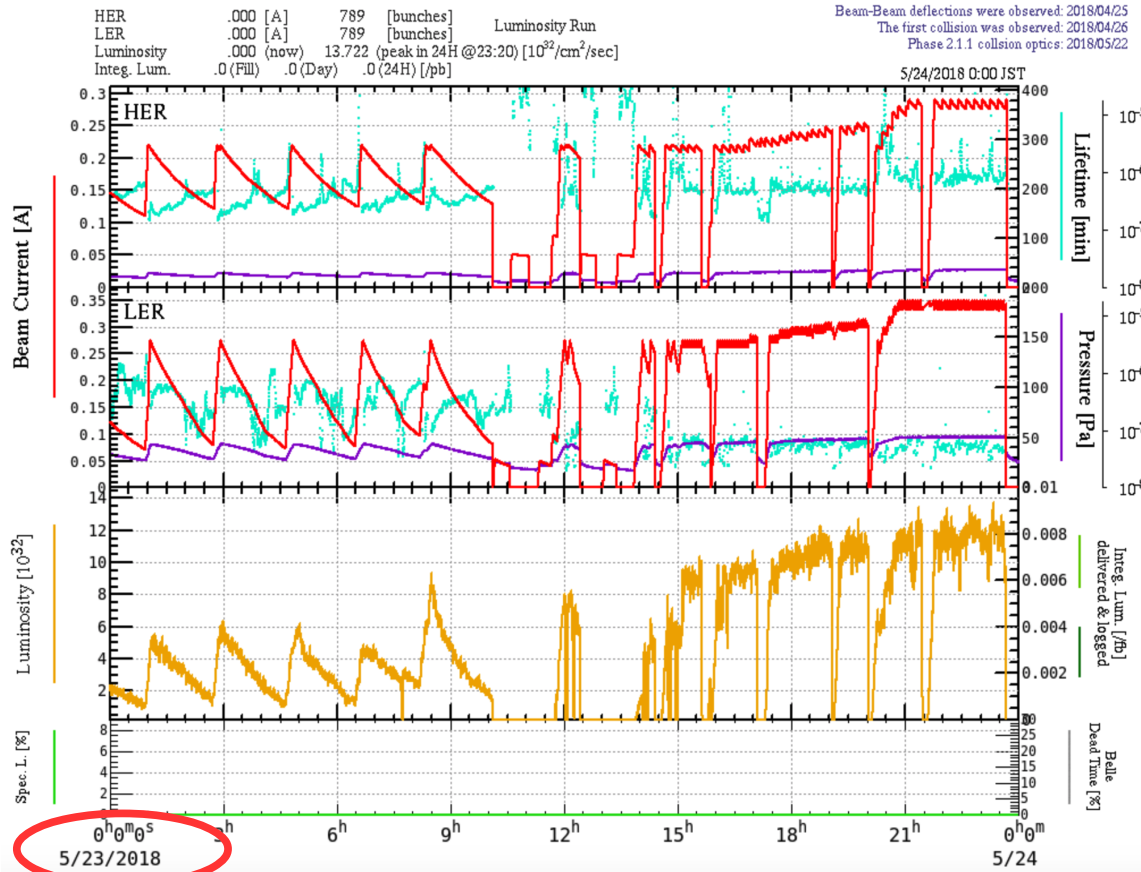
Belle II at SuperKEKB

- New generation B-factory, upgrade of KEKB

- Higher beam currents, reduced beam size

- Aim for 40x times KEKB peak luminosity
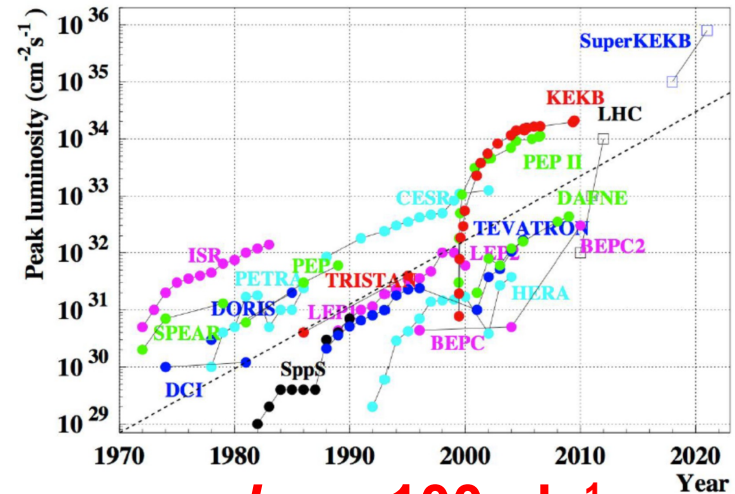
- First collisions in April 2018 (Phase2)!
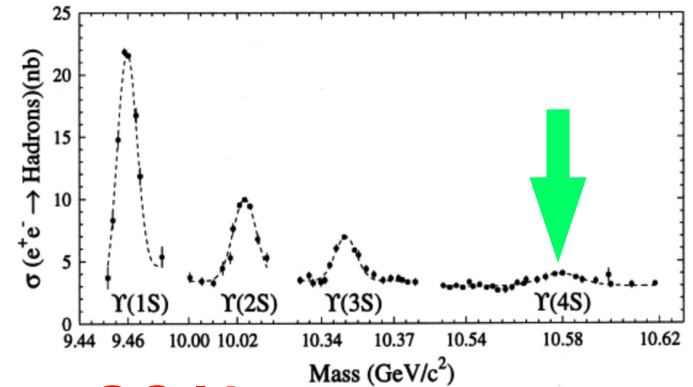
GOAL:

L_{int}: **50 ab^{-1} by 2025 (50 x KEKB)**

at Y(4S) CM energy

Already exceeded $L = 1.3 \times 10^{33}$ cm^{-2} s^{-1}

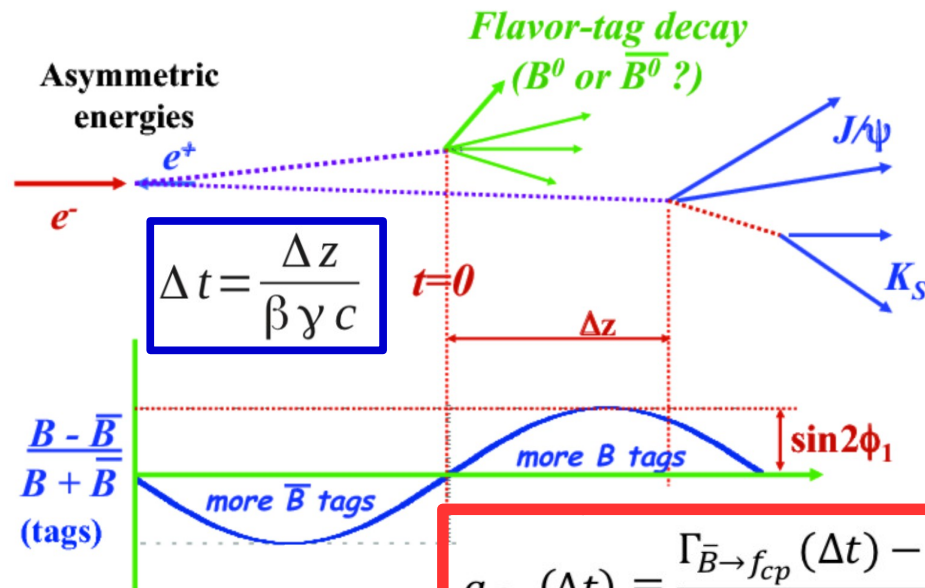L_{int} ~ 100 pb^{-1} (by yesterday)

Belle → Belle II

- Belle II is an upgrade of the Belle detector designed to improve performance, especially with new machine conditions, in particular:
    - Much higher background environment of SuperKEKB
    - Reduced CM boost w.r.t. Belle
- Highlights:
    - Vertex detector:
        - 2 layers of pixels
        - 4 DSSD layers with extended coverage
    - Particle-ID:
        - new TOP + ARICH (FWD)
    - Drift chamber:
        - smaller cell size, longer lever arm
    - K_L & muons:
   - Inner (barrel) and FWD RPCs replaced with scintillators
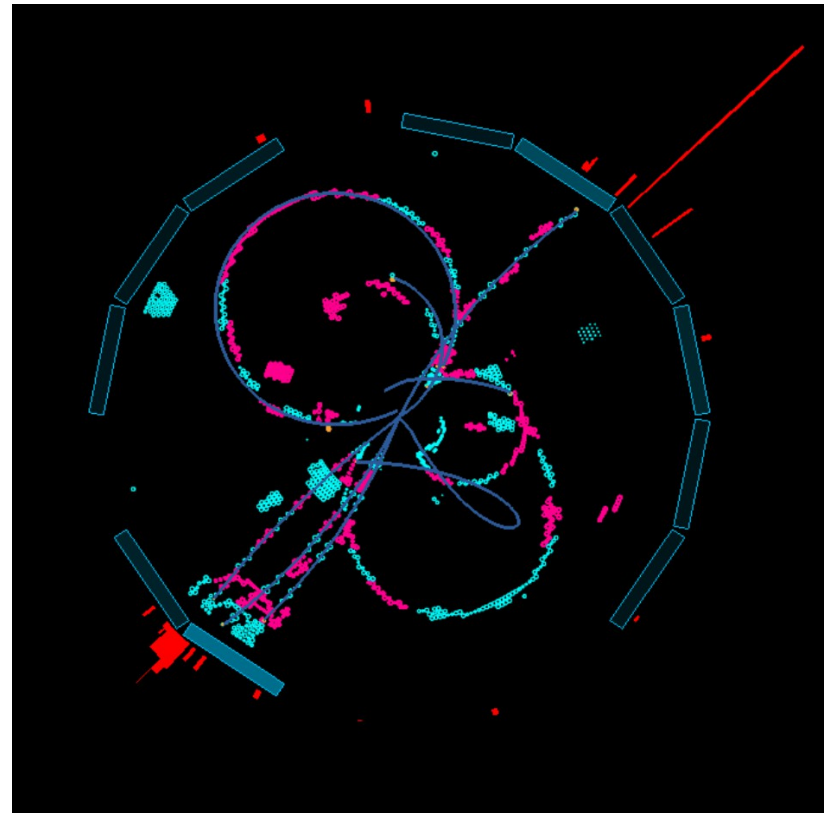
φ₁ and φ₂ at B-factories

- B$\overline{\text{B}}$ mixing and decay amplitudes interfere → time-dependent CP asymmetry

- Need to measure Δt, hence decay vertex

- B$\overline{\text{B}}$ are produced threshold → Y(4S) → B$\overline{\text{B}}$ pairs at rest in the CM frame

- Asymmetric beam energies e⁺ = 4, e⁻ = 7 GeV

Tag side vertex fit

Belle II Simulation

Belle II
- Bias = 5.9 μm
- Resolution = 53 μm

Belle
- Bias = 29 μm
- Resolution = 89 μm

TagVz - GenTagVz / cm

Δt resolution

Belle II Simulation

Belle II
- Bias = -0.003 ps
- Resolution = 0.77 ps

Belle
- Bias = 0.20 ps
- Resolution = 0.92 ps

Δt - Gen. Δt / ps

$$\Delta t = \frac{\Delta z}{\beta \gamma c}$$
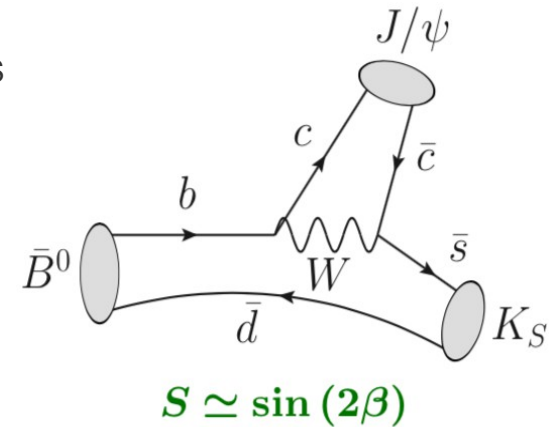
$$a_{f_{cp}}(\Delta t) \equiv \frac{\Gamma_{\overline{B} \to f_{cp}}(\Delta t) - \Gamma_{B \to f_{cp}}(\Delta t)}{\Gamma_{\overline{B} \to f_{cp}}(\Delta t) + \Gamma_{B \to f_{cp}}(\Delta t)} = S \sin(\Delta M \Delta t) - C \cos(\Delta M \Delta t)$$

- Resolution on Δt dominated by the resolution of the tagging B vertex fit
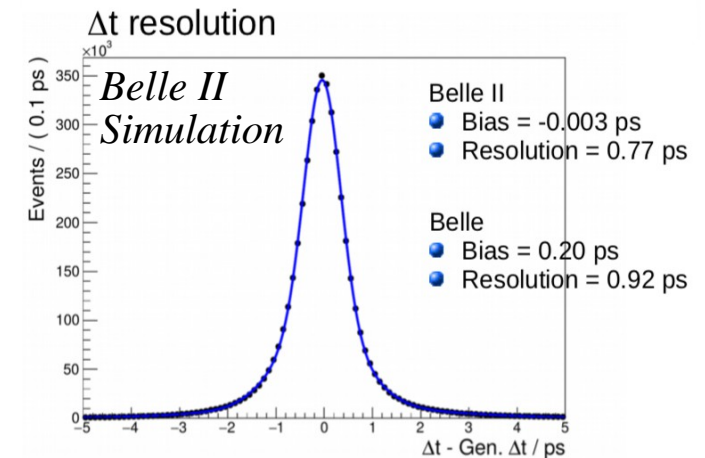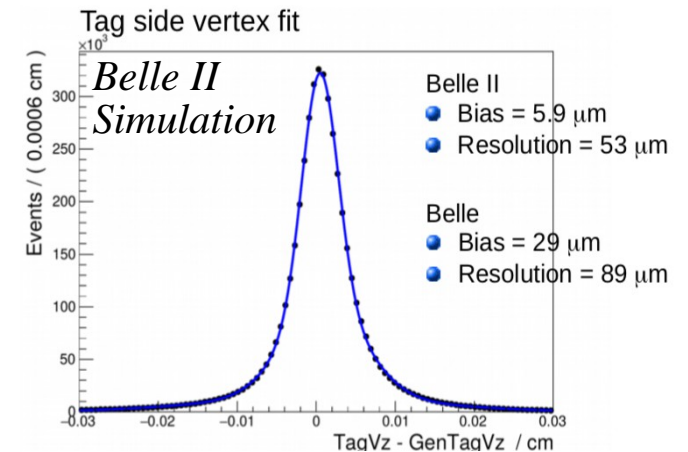
sin($2\varphi_1$) in b → c̄cs

- Tree dominated modes, golden channel B → J/ψ K$_S$

  - Theoretically clean process, $S = -\xi_f \sin(2\varphi_1)$, C~0

  - Clean experimental signature: 4 tracks

- Recent theoretical improvements in the calculation

  of penguin pollution

$S \simeq \sin(2\beta)$

Worst case scenario, same systematics as Belle

PRL 108 171802

With expected improvement due to better vertexing

Sample	Quantity	Value	Stat. ($\times 10^{-3}$)	Syst. (1) ($\times 10^{-3}$) Red.	Non-red.	Syst. (2) ($\times 10^{-3}$) Red.	Non-red.
				Belle (1 ab^{-1})			
$B \to J/\psi K_S$	S	+0.67	29	-	13	-	-
	$A \equiv -C$	-0.015	21	-	+45, -23	-	-
$b \to c\bar{c}s$	S	+0.667	23	-	12	-	-
	$A \equiv -C$	+0.006	16	-	12	-	-
				Belle II (50 ab^{-1})			
$B \to J/\psi K_S$	S	-	3.5	1.2	8.3	1.2	4.4
	$A \equiv -C$	-	2.5	0.7	+43, -22	0.7	+42, -11
$b \to c\bar{c}s$	S	-	2.7	2.6	7	2.6	3.6
	$A \equiv -C$	-	1.9	1.4	10.6	1.4	8.7

sin(2φ$_1$) in b → qq̄s: B^0 → φK^0

- Loop process, same weak phase as b → cc̄s

- Also sensitive to new physics

Δt resolution

Channel	Δt resolution (ps)
$\phi(K^+K^-)K_S^0(\pi^+\pi^-)$	0.75
$\phi(K^+K^-)K_S^0(\pi^0\pi^0)$	0.77
$\phi(\pi^+\pi^-\pi^0)K_S^0(\pi^+\pi^-)$	0.78

Expected sensitivity with 50 ab^{-1}

Channel	$\sigma(S)$	$\sigma(C)$
$\phi(K^+K^-)K_S^0(\pi^+\pi^-)$	0.025	0.017
$\phi(K^+K^-)K_S^0(\pi^0\pi^0)$	0.042	0.030
$\phi(\pi^+\pi^-\pi^0)K_S^0(\pi^+\pi^-)$	0.048	0.036
$K_S^0(\pi^+\pi^-)$ modes	0.019	0.014
$K_S^0(\pi^+\pi^-) + K_L^0(\pi^+\pi^-)$ modes	0.015	0.011

Belle measurement: S$_{\phi K}$ = 0.9$_{-0.19}^{+0.9}$
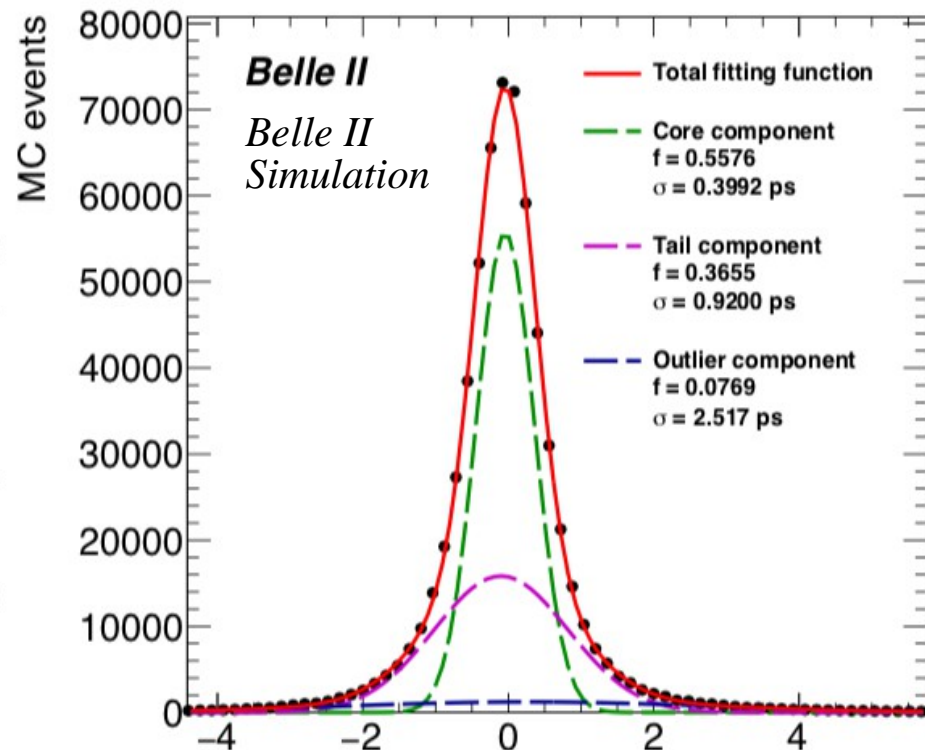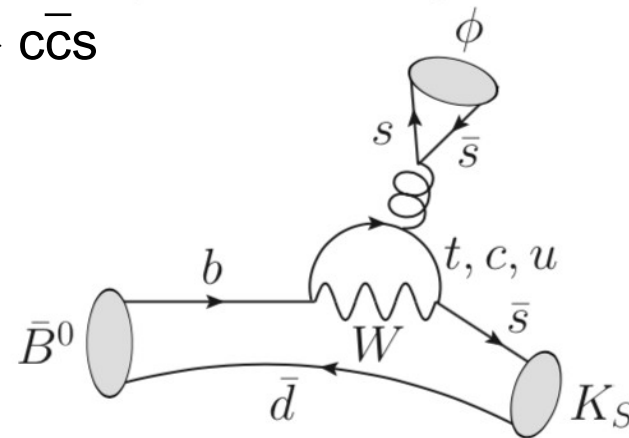
$\sin(2\varphi_1)$ in $b \rightarrow q\bar{q}s$: $B^0 \rightarrow \eta'K^0$

- Main issue for $B^0 \rightarrow \eta'K^0$, where $\eta' \rightarrow \eta\ \pi^+\pi^-$ is π^0 and η^0 reconstruction
- Mis-reconstruction leads to signal cross-feed
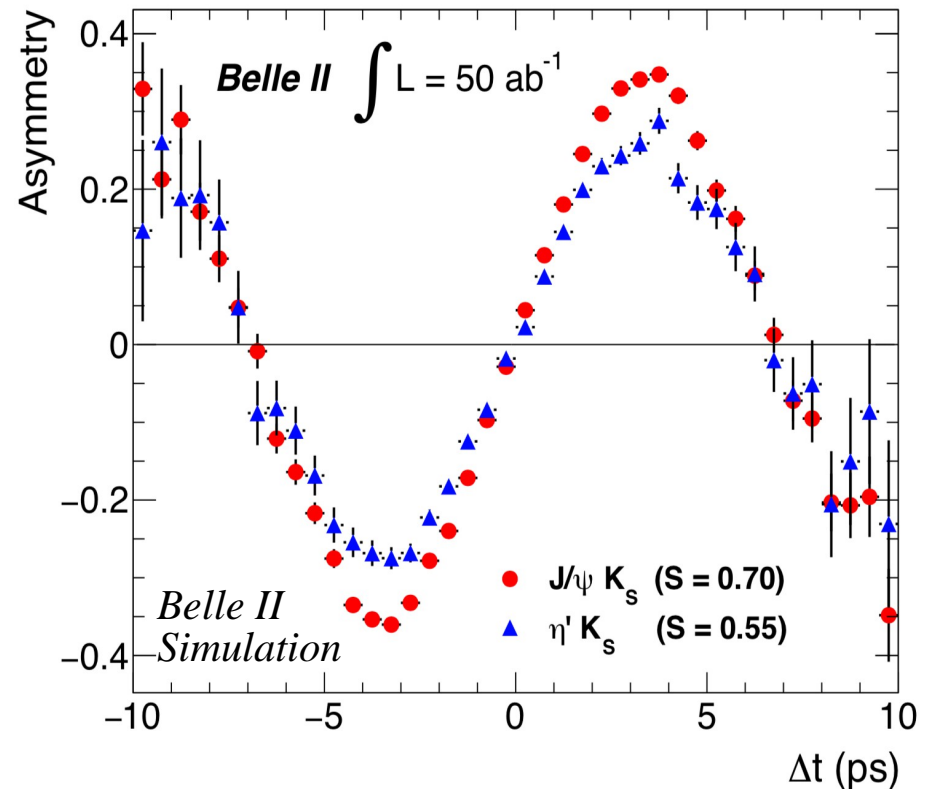- $B^0 \rightarrow \eta'K^0$ could be already systematically limited at $L \sim O(10)$ ab^{-1}

Δt resolution

Channel	True	SxF	All
$\eta'(\eta_{\gamma\gamma}\pi^\pm)K_S^{(\pm)}$	1.22 ps	2.87 ps	1.45 ps
$\eta'(\eta_{3\pi}\pi^\pm)K_S^{(\pm)}$	1.17 ps	2.36 ps	1.50 ps

Expected sensitivity with 50 ab^{-1}

Channel	$\sigma(S)$	$\sigma(C)$
$\eta'(\eta_{\gamma\gamma}\pi^\pm)K_S^\pm$	0.019	0.013
$\eta'(\eta_{3\pi}\pi^\pm)K_S^\pm$	0.035	0.025
K_S^0 modes	0.009	0.007
K_L^0 modes	0.025	0.016
$K_S^0 + K_L^0$ modes	0.0085	0.0063
Syst. (10^{-2})	1.8 (1.3)	-

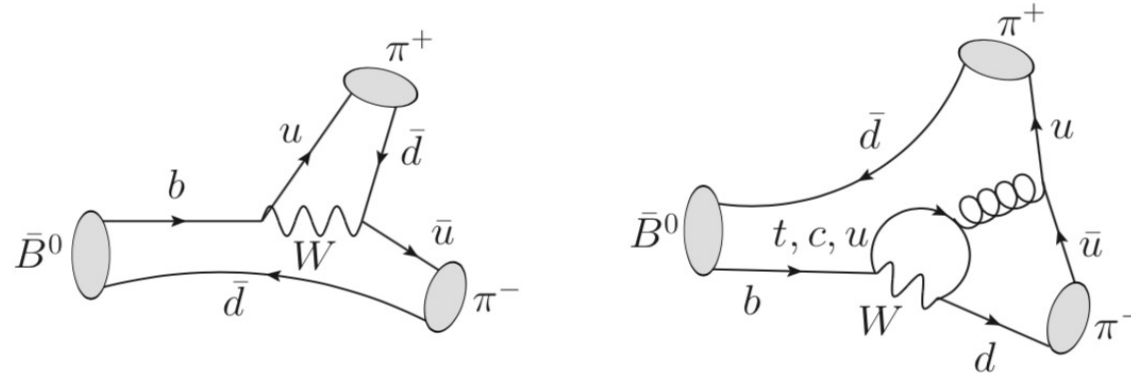Syst. Case 1 (Case 2)

Belle measurement: $S_{\eta'K} = +0.68 \pm 0.07 \pm 0.03$

sin(2φ₂): isospin analysis in B → hh

- $\sin(2\varphi_2)$ can be extracted from time-dependent analysis of B → ππ, ρρ, πρ

- Tree and penguin contribution are comparable but additional weak and strong phases

- $S = \sin(2\varphi_{2,\,eff}), \quad \varphi_{2,\,eff} = \varphi_2 + \delta\varphi_{peng}$

- Disentangle the tree contribution and extract δα by isospin analysis

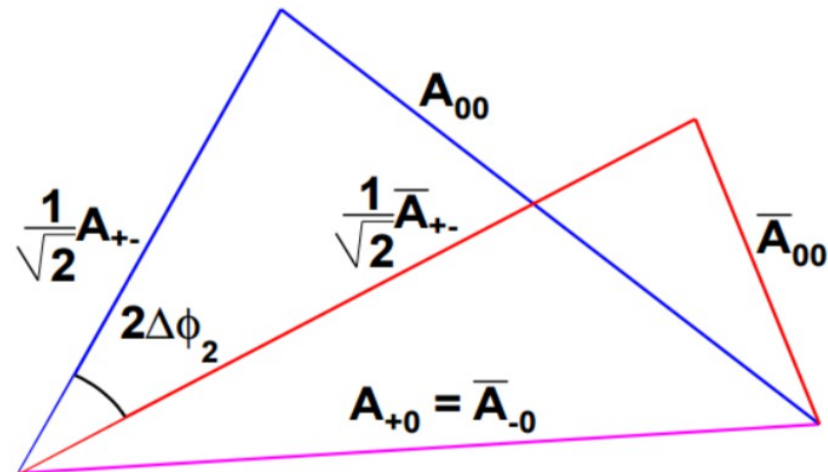$$A^{(i,j)} \equiv \mathcal{A}(B^{i+j} \to h^i h^j) \ (h = \pi, \rho \ / \ i, j = \pm, 0)$$

$$A^{+-}/\sqrt{2} + A^{00} = A^{+0}$$
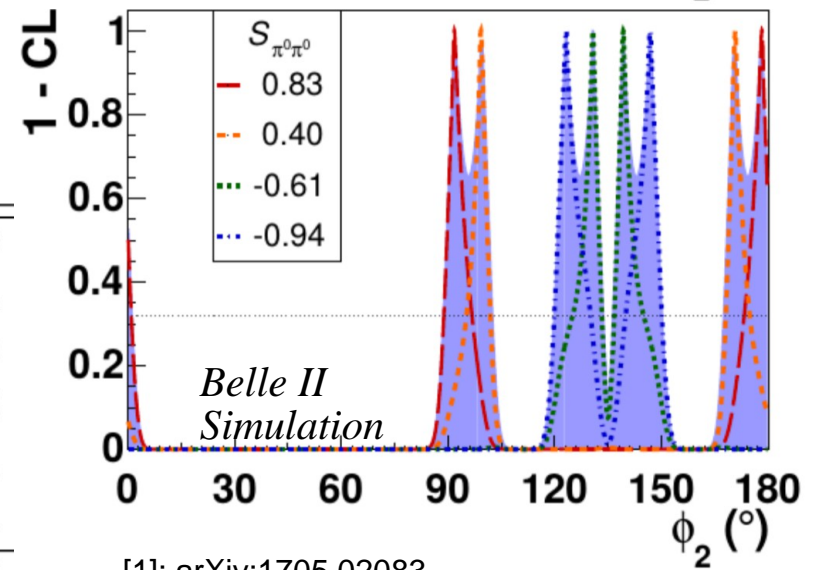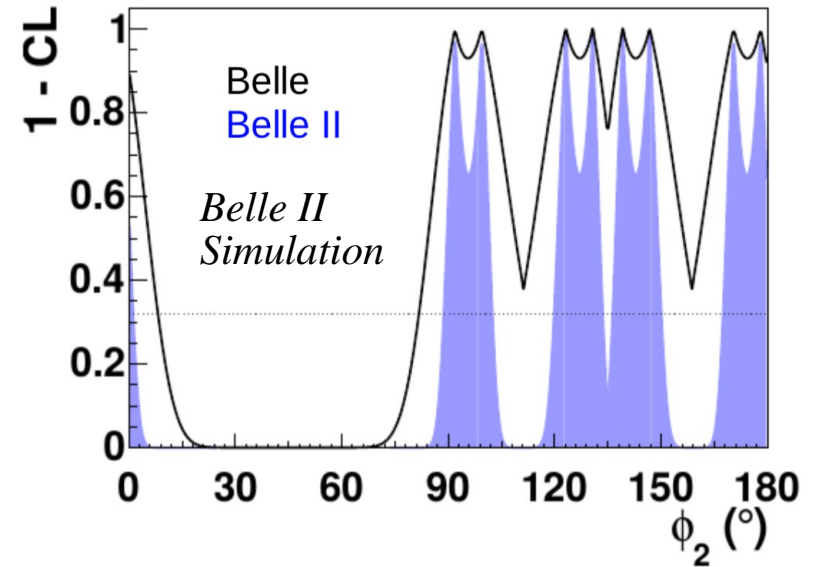
$$\bar{A}^{+-}/\sqrt{2} + \bar{A}^{00} = \bar{A}^{+0}$$

$$|A^{+0}| = |\bar{A}^{+0}|$$

M. Gronau and D. London, PRL 65 3381 (1990)

sin(2φ₂): B → ππ

- Up to date $S_{\pi^0\pi^0}$ has never been measured → **eightfold ambiguity on φ₂**

- We need the decay vertex, experimentally:

  - $B^0_{sig} \to \pi^0_{\gamma\gamma} (\to \gamma\gamma) \, \pi^0_{\gamma\gamma} (\to \gamma\gamma)$

  - $B^0_{sig} \to \pi^0_{dal} (\to e^+e^-\gamma) \, \pi^0_{\gamma\gamma} (\to \gamma\gamma)$

  - $B^0_{sig} \to \pi^0_{\gamma^*\gamma} (\to \gamma^* (\to e+e-) \gamma) \, \pi^0_{\gamma\gamma} (\to \gamma\gamma)$

- Photon conversion in the inner detector:

  - 3% of $B^0 \to \pi^0\pi^0$ events

  - ~ 5% including π^0 Dalitz decay

- Reconstruction efficiency is crucial!

	Value	Belle @ 0.8 ab^{-1}	Belle2 @ 50 ab^{-1}
$\mathcal{B}_{\pi^+\pi^-} [10^{-6}]$	5.04	$\pm 0.21 \pm 0.18$ [2]	$\pm 0.03 \pm 0.08$
$\mathcal{B}_{\pi^0\pi^0} [10^{-6}]$	1.31	$\pm 0.19 \pm 0.18$ [1]	$\pm 0.04 \pm 0.04$
$\mathcal{B}_{\pi^+\pi^0} [10^{-6}]$	5.86	$\pm 0.26 \pm 0.38$ [2]	$\pm 0.03 \pm 0.09$
$C_{\pi^+\pi^-}$	-0.33	$\pm 0.06 \pm 0.03$ [3]	$\pm 0.01 \pm 0.03$
$S_{\pi^+\pi^-}$	-0.64	$\pm 0.08 \pm 0.03$ [3]	$\pm 0.01 \pm 0.01$
$C_{\pi^0\pi^0}$	-0.14	$\pm 0.36 \pm 0.12$ [1]	$\pm 0.03 \pm 0.01$
$S_{\pi^0\pi^0}$	—	—	$\pm 0.29 \pm 0.03$

[1]: arXiv:1705.02083
[2]: PRD 87(3) 031103
[3]: PRD 88(9) 092003

Belle II expectation: $\Delta\varphi_{2,\pi\pi} \sim 2°$ B. Oberhof - HQL 2018

sin($2\varphi_2$): B → ρρ

	Value	Belle @ 0.8 ab^{-1} Belle	Belle2 @ 50 ab^{-1} Belle II
$f_{L,\rho^+\rho^-}$	0.988	$\pm0.012 \pm 0.023$ [1]	$\pm0.002 \pm 0.003$
$f_{L,\rho^0\rho^0}$	0.21	$\pm0.20 \pm 0.15$ [2]	$\pm0.03 \pm 0.02$
$\mathcal{B}_{\rho^+\rho^-}$ [10^{-6}]	28.3	$\pm1.5 \pm 1.5$ [1]	$\pm0.19 \pm 0.4$
$\mathcal{B}_{\rho^0\rho^0}$ [10^{-6}]	1.02	$\pm0.30 \pm 0.15$ [2]	$\pm0.04 \pm 0.02$
$C_{\rho^+\rho^-}$	0.00	$\pm0.10 \pm 0.06$ [1]	$\pm0.01 \pm 0.01$
$S_{\rho^+\rho^-}$	-0.13	$\pm0.15 \pm 0.05$ [1]	$\pm0.02 \pm 0.01$

	Value	Belle @ 0.08 ab^{-1}	Belle2 @ 50 ab^{-1}
$f_{L,\rho^+\rho^0}$	0.95	$\pm0.11 \pm 0.02$ [3]	$\pm0.004 \pm 0.003$
$\mathcal{B}_{\rho^+\rho^0}$ [10^{-6}]	31.7	$\pm7.1 \pm 5.3$ [3]	$\pm0.3 \pm 0.5$

	Value	BaBar @ 0.5 ab^{-1}	Belle2 @ 50 ab^{-1}
$C_{\rho^0\rho^0}$	0.2	$\pm0.8 \pm 0.3$ [4]	$\pm0.08 \pm 0.01$
$S_{\rho^0\rho^0}$	0.3	$\pm0.7 \pm 0.2$ [4]	$\pm0.07 \pm 0.01$

[1] Phys. Rev. D78, 071104 (2008)
[2] Phys. Rev. Lett., 91, 221801 (2003)
[3] Phys. Rev. D93, 032010 (2016)
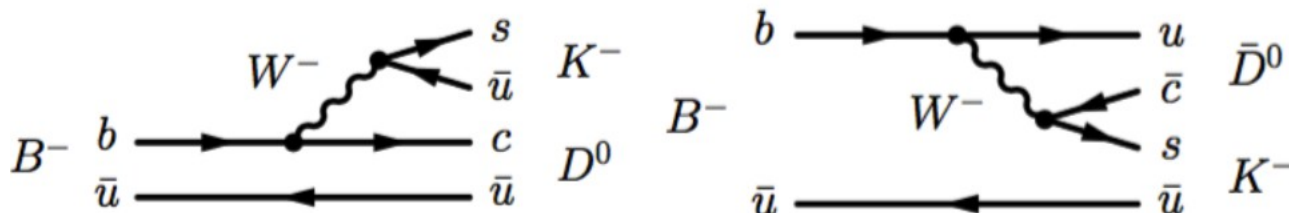[4] Add Phys. Rev. D89, n.11, 119903 (2014)

Belle II expectation: $\Delta\varphi_{2,\rho\rho} \sim 0.7°$

Combined: $\Delta\varphi_2 \sim 0.6°$
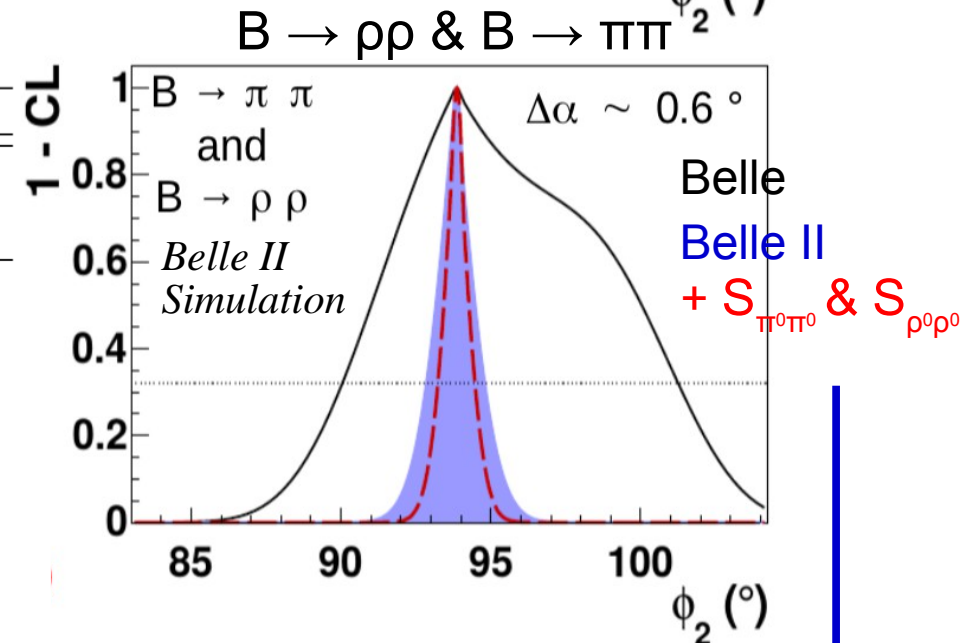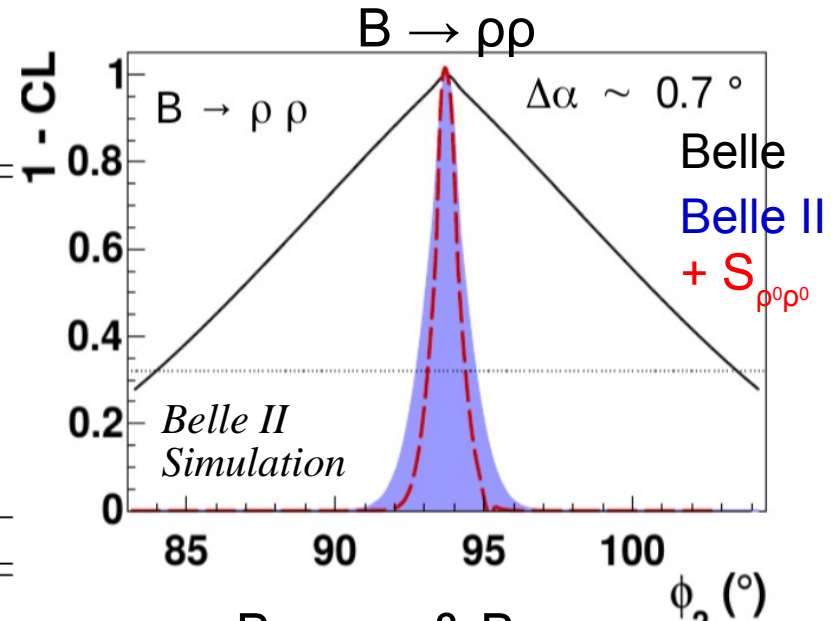
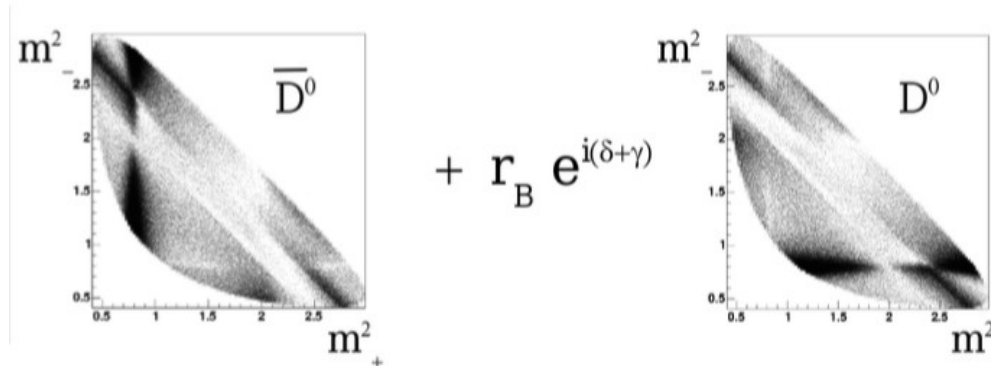# Measurement of φ₃ with B→D⁰ K

- φ_3 is the phase between $b \to u$ and $b \to c$

- The best methods to measure γ are based on the interference between $b \to \bar{c}us$ and $b \to u\bar{c}s$ amplitudes with $D^0/\bar{D}^0$ decaying to same final state


- Theoretically very clean, ambiguity on φ_3 is less than 1%

- Experimentally very challenging: CKM and color suppression

- Belle II technique: Dalitz-plot analysis of self-conjugate D decays (GGSZ)

- Different strong phases → have to be measured at charm factory (BES)

$$+ \; r_B \; e^{i(\delta + \gamma)}$$

Measurement of φ₃ with B→D⁰ K

- First sensitivity study of Belle II uses GGSZ analysis for $B^\pm \to (K_s\pi^+\pi^-) DK^\pm$

Belle II sensitivity expectation for
$B^\pm \to (K_s\pi^+\pi^-) DK^\pm$ with 50 ab⁻¹: $\Delta\varphi_3 \sim 3°$

Belle II Simulation

3° precision at 50ab⁻¹
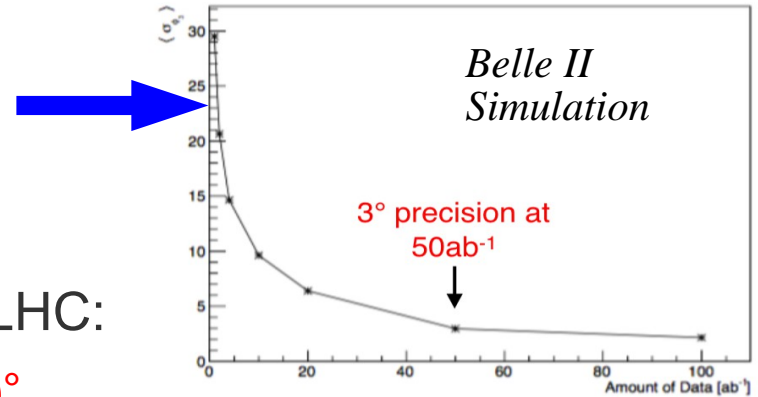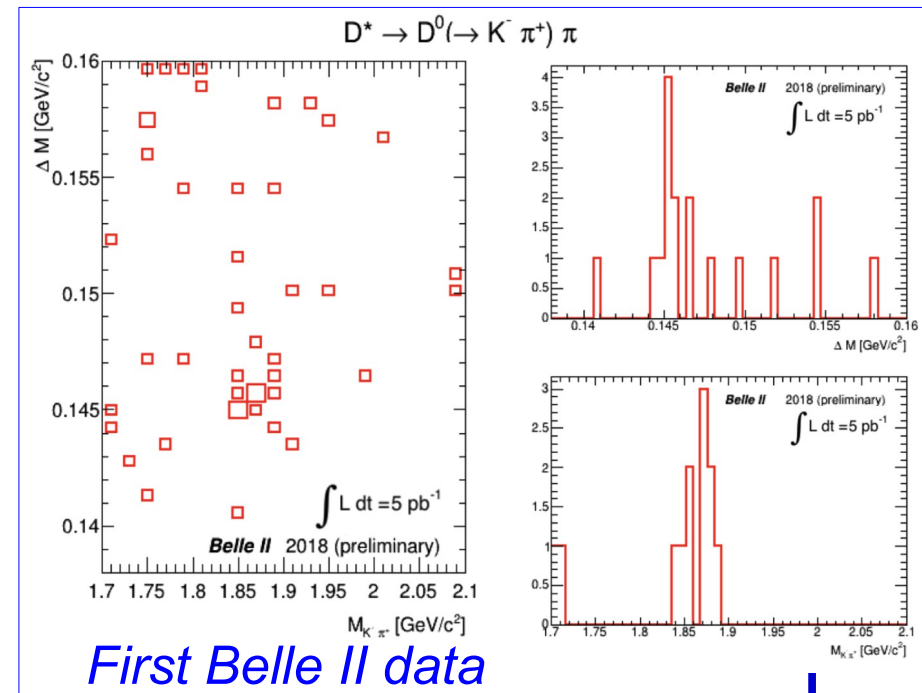
- Current measurement from B-factories and LHC:

Belle: $\varphi_3 = (78^{+15}_{-16})°$ LHCb: $\varphi_3 = (76.8^{+5.1}_{-5.7})°$

- Belle measurement used other D decay modes (ADS, GLW techniques)

- Best estimate for Belle II combines the different techniques

- Fundamental assumption: BES III will have collected ~10 fb⁻¹ at the ψ(3770)

Belle II sensitivity expectation
with 50 ab⁻¹: $\Delta\varphi_3 \sim 1.6°$
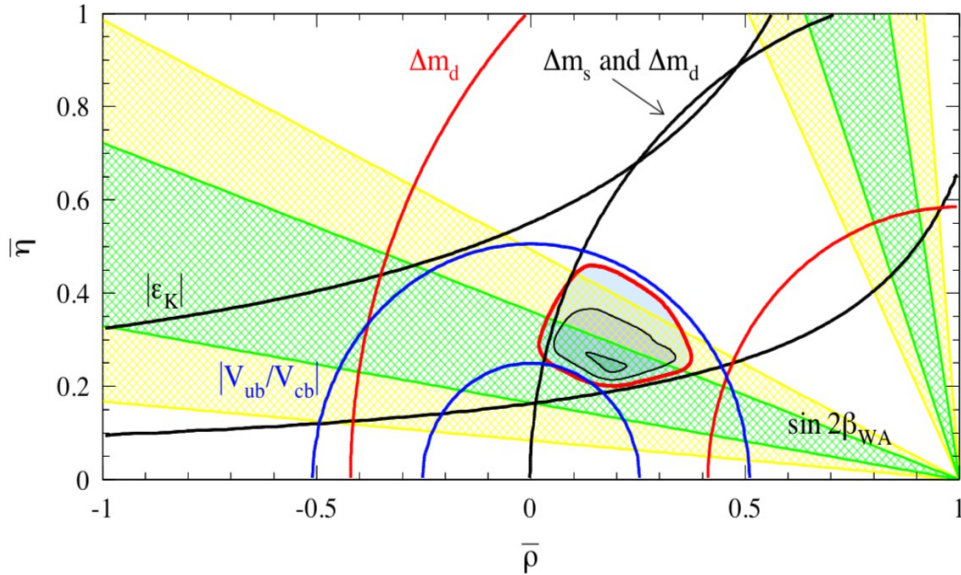

$D^* \to D^0(\to K^-\pi^+)\pi$
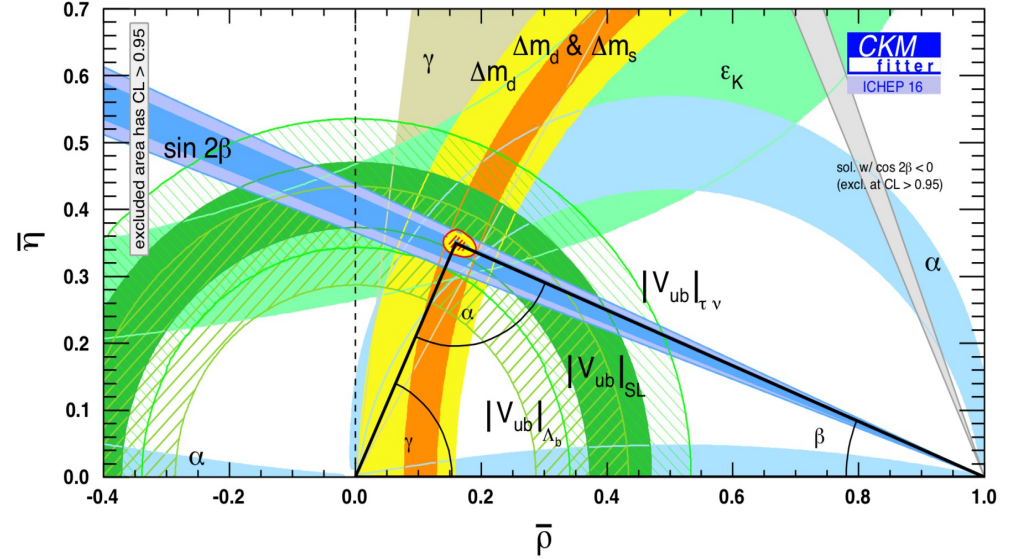
First Belle II data
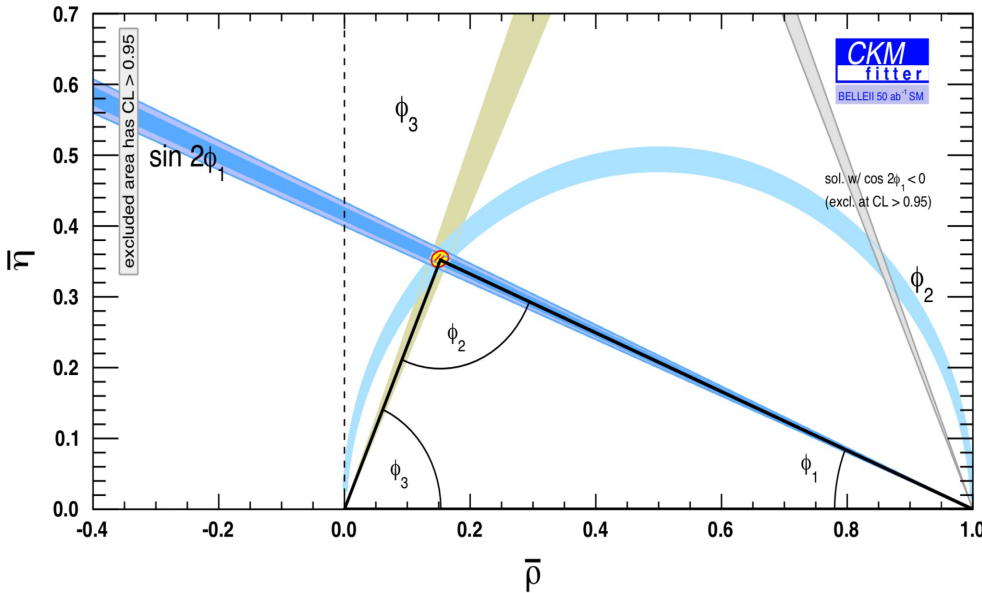
Pictorial Outlook

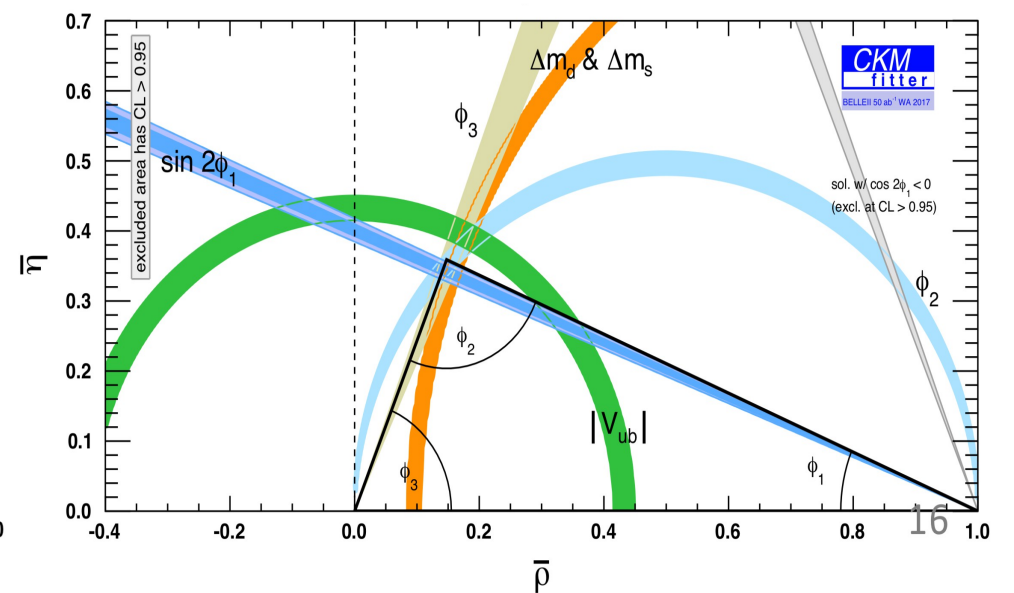Before B-factories   Eur.Phys.J.C21:225–259,2001

After B-factories

Belle II 50 ab^{-1} projection, CPV modes only

Belle II 50 ab^{-1} projection, all constraints

Summary

- Belle and BaBar have been very successful in testing the CKM paradigm

- Belle II and SuperKEKB represent a major upgrade B-factory

- Huge dataset along with improved detector performance will allow
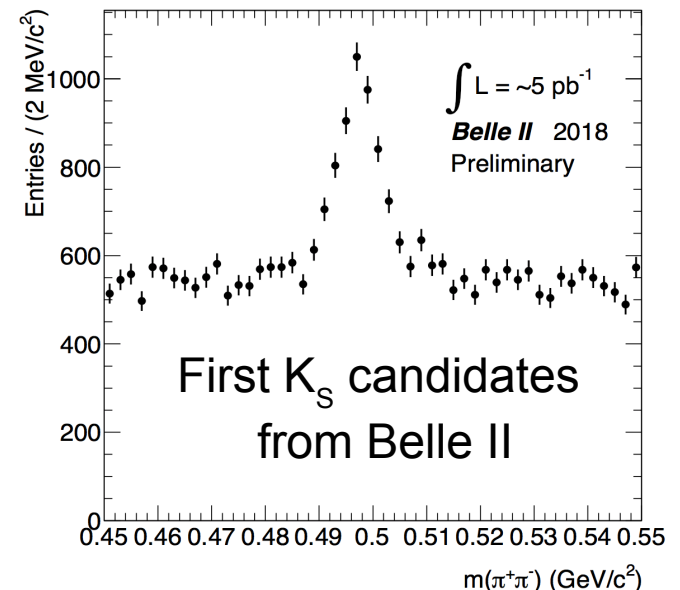
  to test CKM mechanism at 1% level

- $\sin(2\varphi_1)$: precision better than 1% using $c\bar{c}s$ modes

- $\sin(2\varphi_2)$: new inputs for isospin analysis, expected sensitivity $\delta\varphi_2 \sim 1°$

- φ_3: from $B \to DK$ decays $\delta\varphi_3 = 1.6°$ at 50 ab^{-1}

- Expected precision on $|V_{ub}|$

  from exclusive (inc.) semi-leptonic

  measurements around 1.3% (3%)

..the fun has just started!

First Belle II data!

$\int L = \sim 5$ pb^{-1}

Belle II 2018
Preliminary

First K_S candidates from Belle II

y-axis: Entries / (2 MeV/c^2)
x-axis: $m(\pi^+\pi^-)$ (GeV/c^2)

Thanks for your attention!