Belle II prospects for the mixing and CPV in B decays

B. Oberhof*

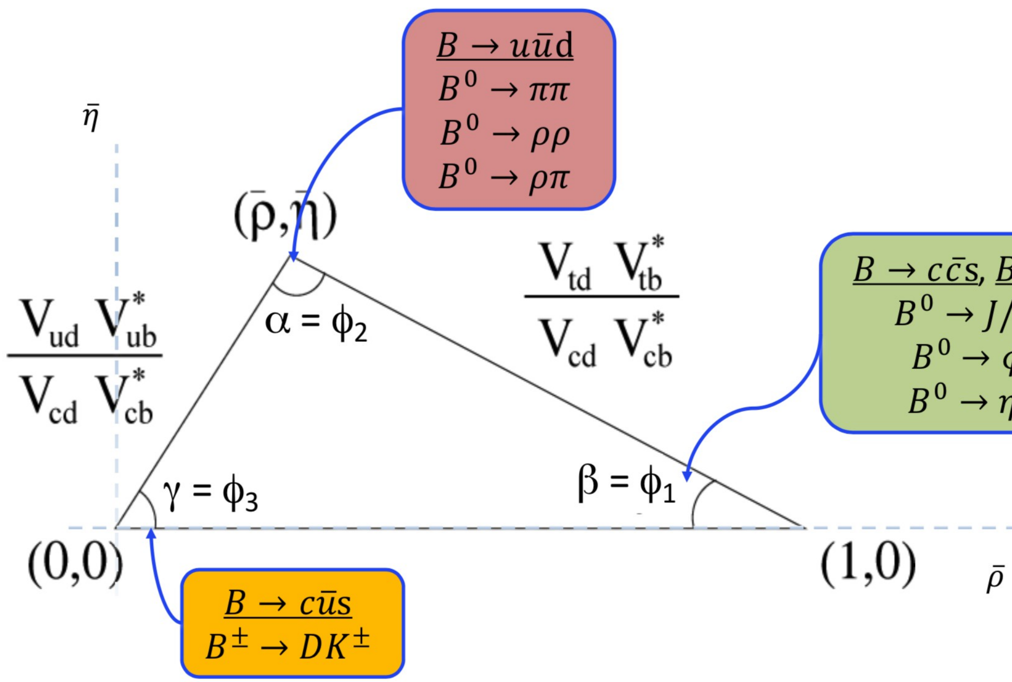
*LNF-INFN, Italy
on behalf of the Belle II Collaboration

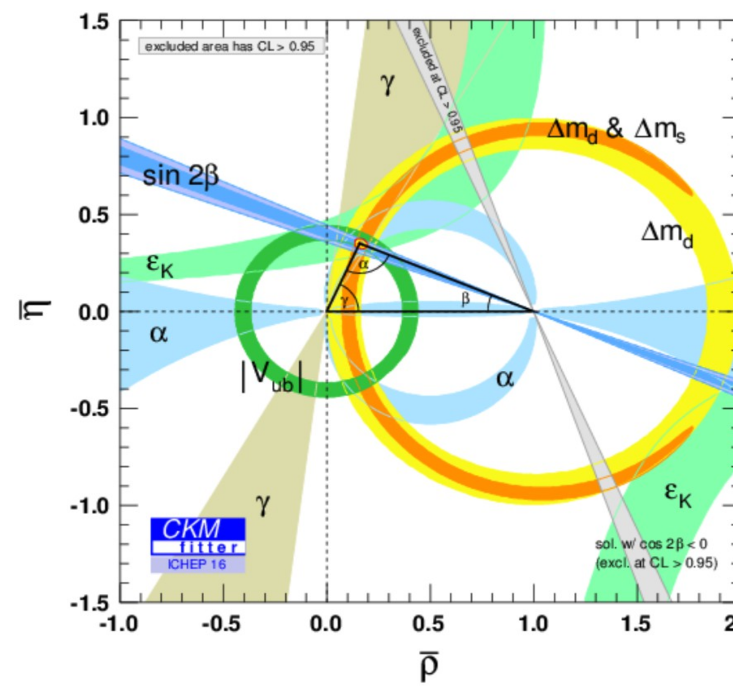
10th International Workshop on the CKM Unitarity Triangle

Heidelberg, Germany
September 19th, 2018

Unitarity Triangle from B Decays

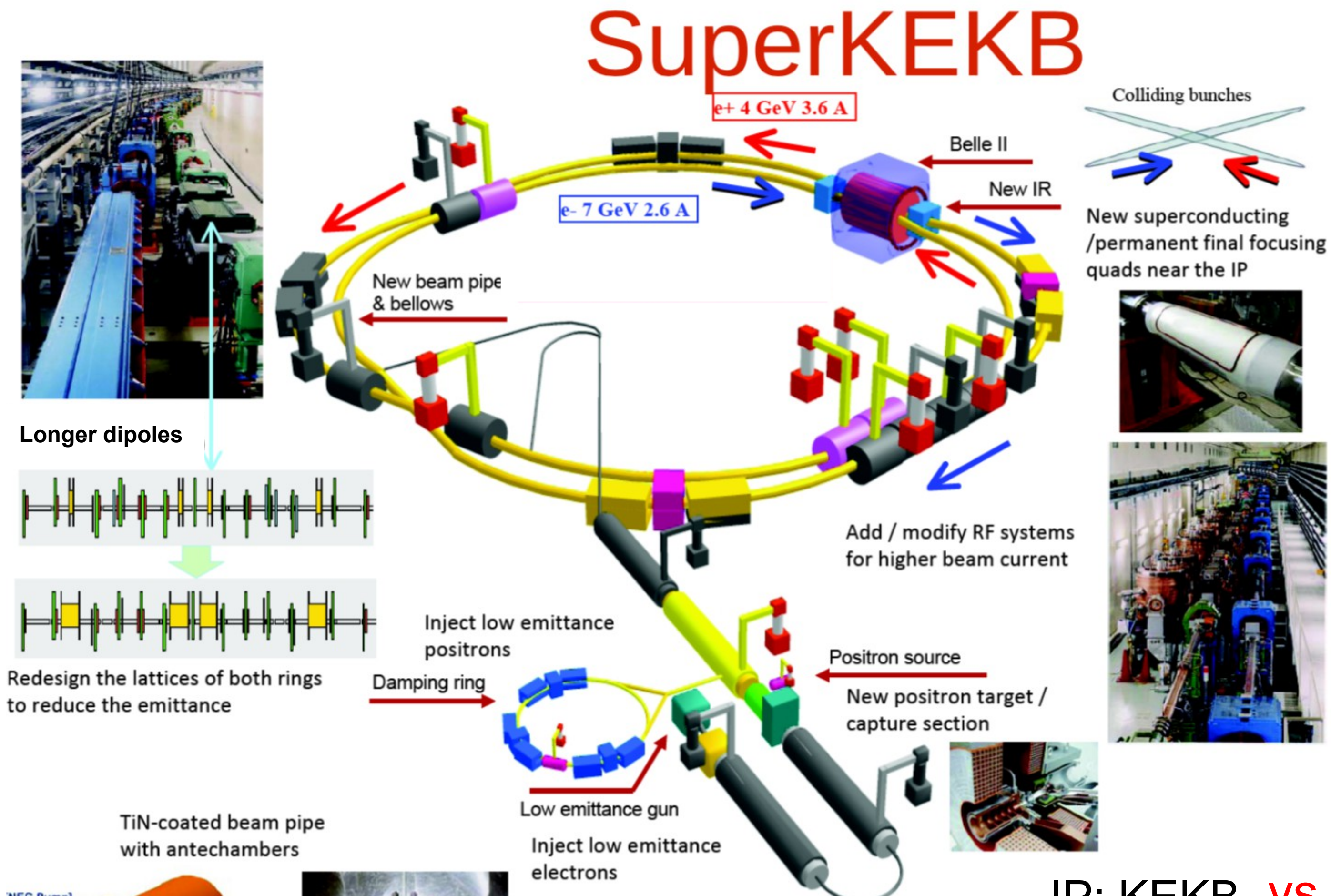
- Quark interactions described by the CKM unitary matrix V_{CKM}
- Off-diagonal elements of $V^{\dagger}V=I$ can be represented by triangles in complex plane
  - Sides ~ Amplitudes ~ Branching fractions
  - Angles ~ Phases ~ CPV
- Most common triangle from $\Sigma_i V_{id} V_{ib}^*$, i=u,c,t (be aware 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





Overview of SuperKEKB

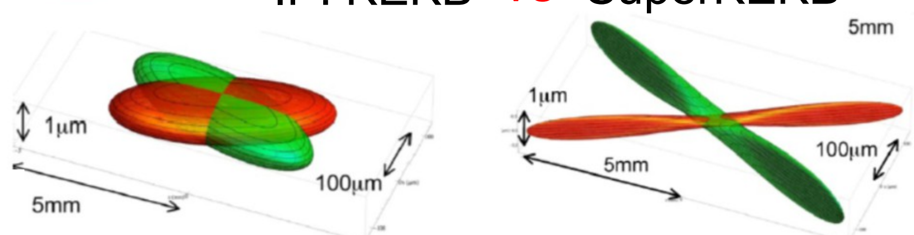
- New generation B-factory, upgrade of KEKB



Peak luminosity:
- KEKB =
2.11×10^{34} cm^{-2} s^{-1}
- SuperKEKB =
8.0×10^{35} cm^{-2} s^{-1}

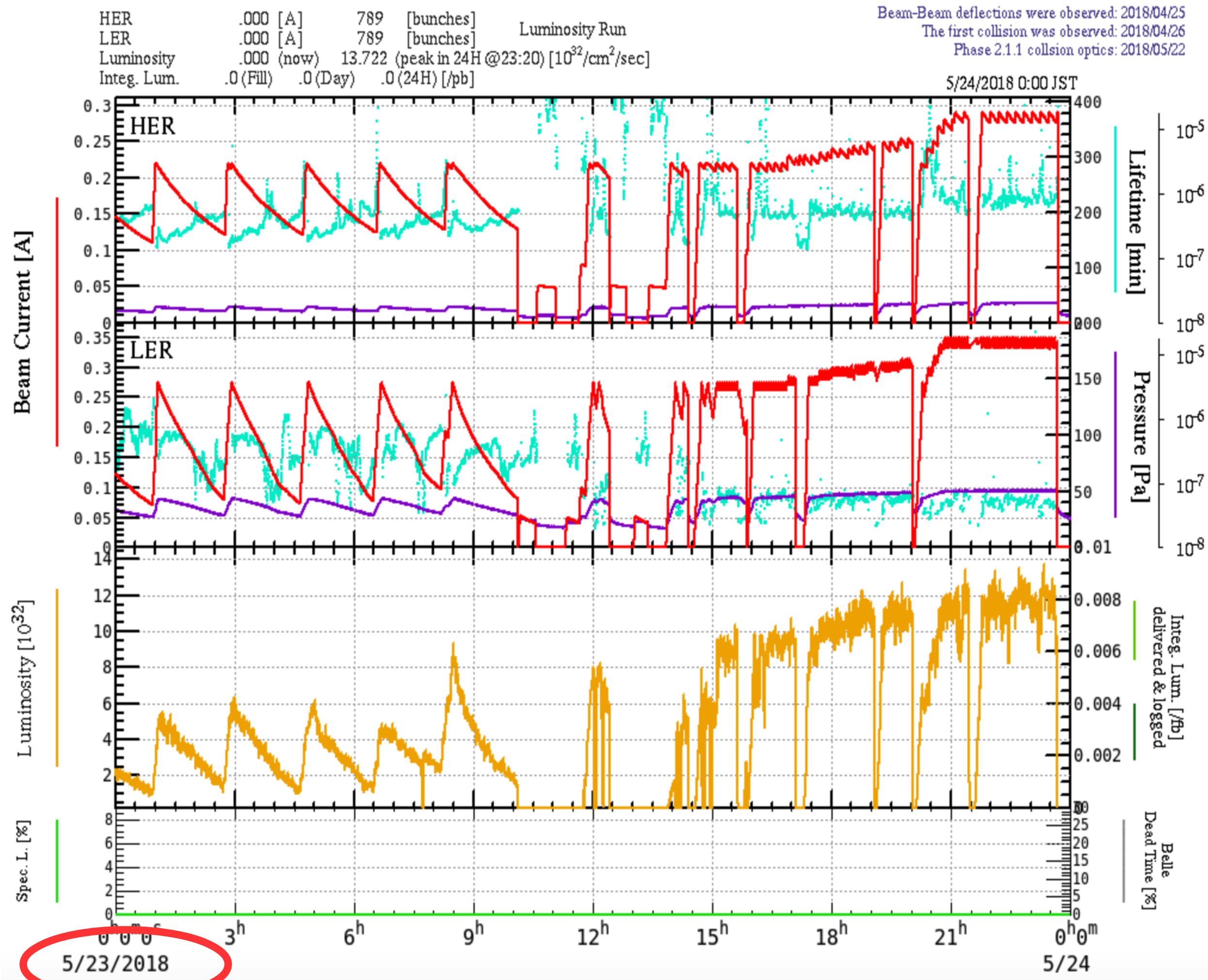
Beam Energies:
- KEKB =
8.0 / 3.5 GeV
- SuperKEKB =
7.0 / 4.0 GeV

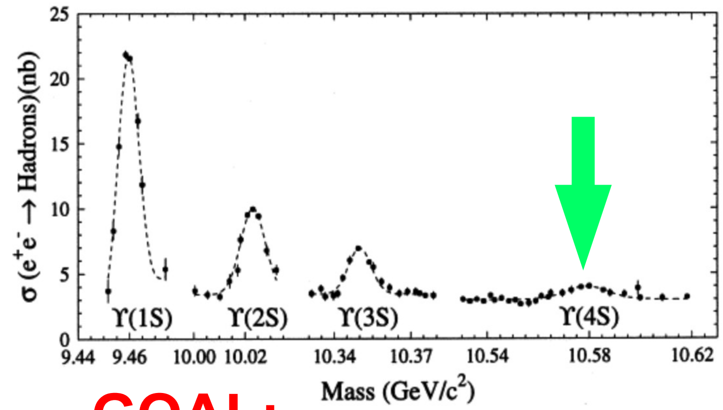
IP: KEKB vs SuperKEKB



SuperKEKB is working!

- First collisions in 26th April 2018 (with commissioning vertex detector)!

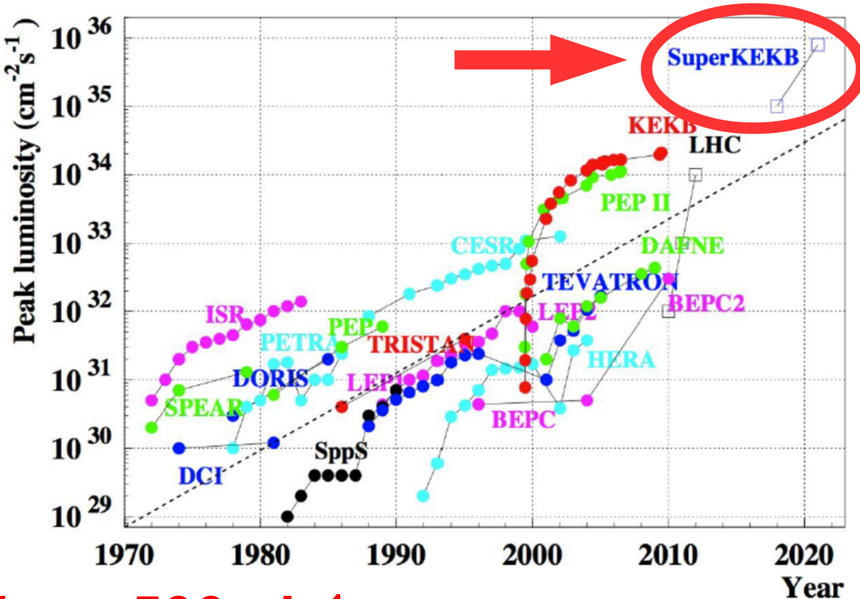




GOAL:

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

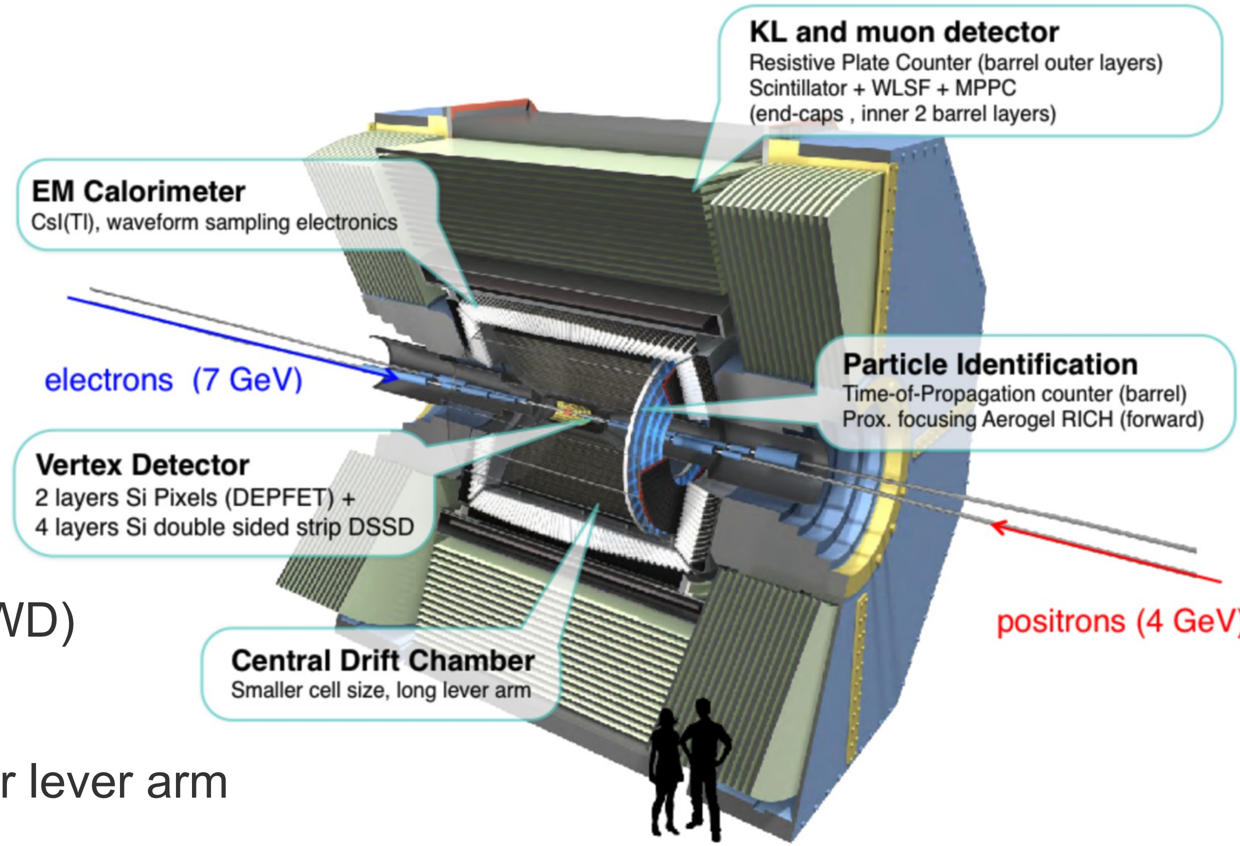
at Υ(4S) CM energy



Already exceeded $L = 2 \times 10^{33}$ cm^{-2} s^{-1} and L_{int} ~ 500 pb^{-1}

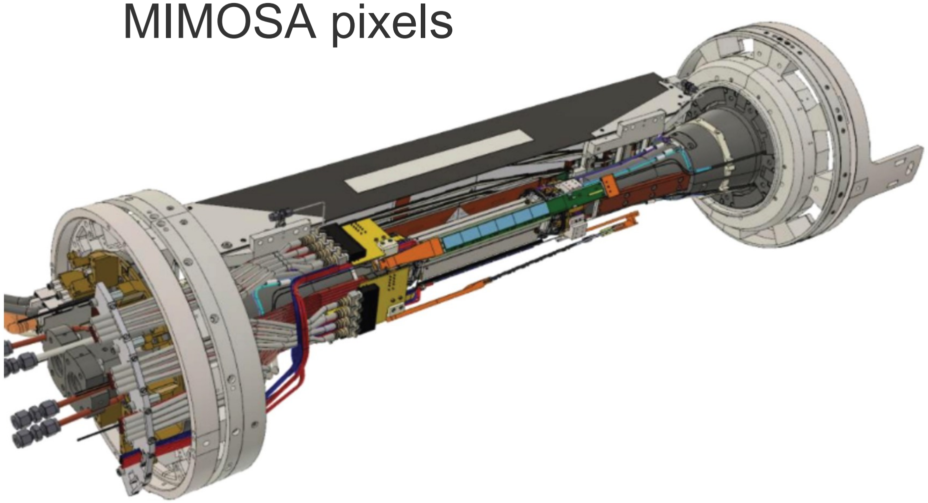
Belle → Belle II

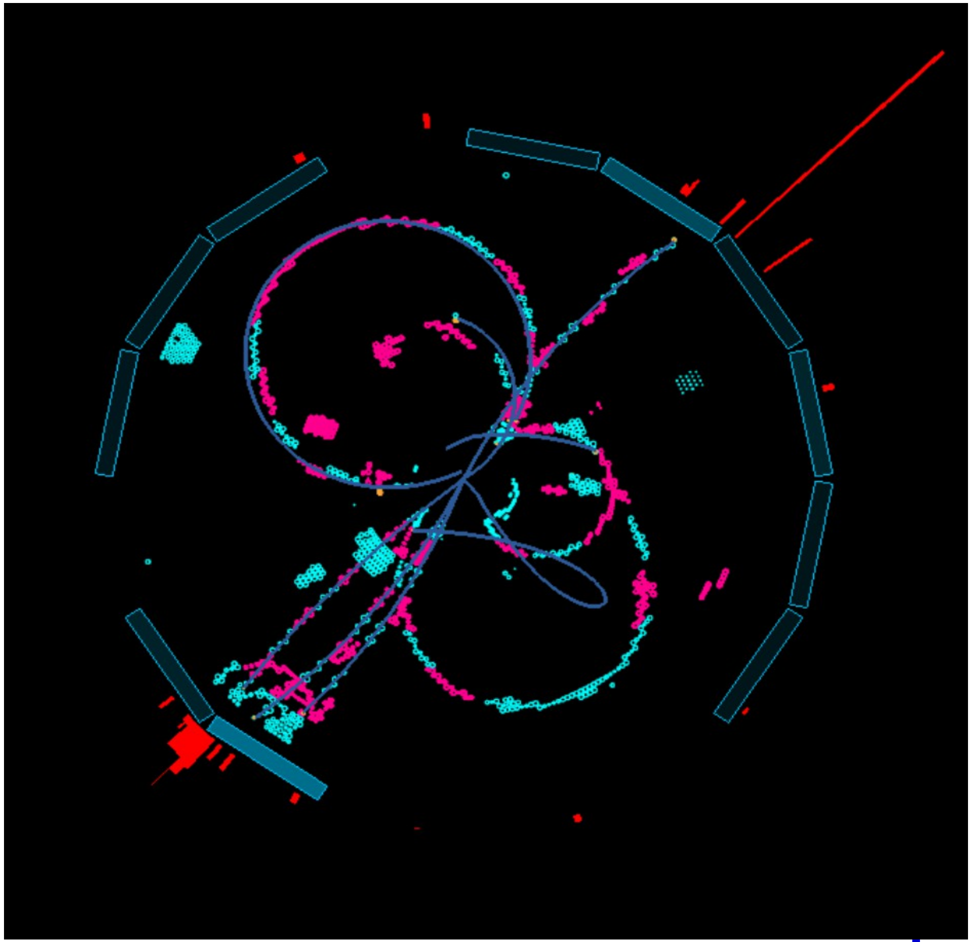
- Various upgrades in order to improve performance in new conditions:
  - Much higher beam-background environment of SuperKEKB
  - Reduced CM boost
- Highlights:
  - Vertex detector:
    - 2 layers of pixels
    - 4 DSSD layers with extended coverage
  - PID:
    - new TOP + ARICH (FWD)
  - Drift chamber:
    - smaller cell size, longer lever arm
  - K_L & muons:
    - Inner (barrel) and FWD RPCs replaced with scintillators



Belle II works!

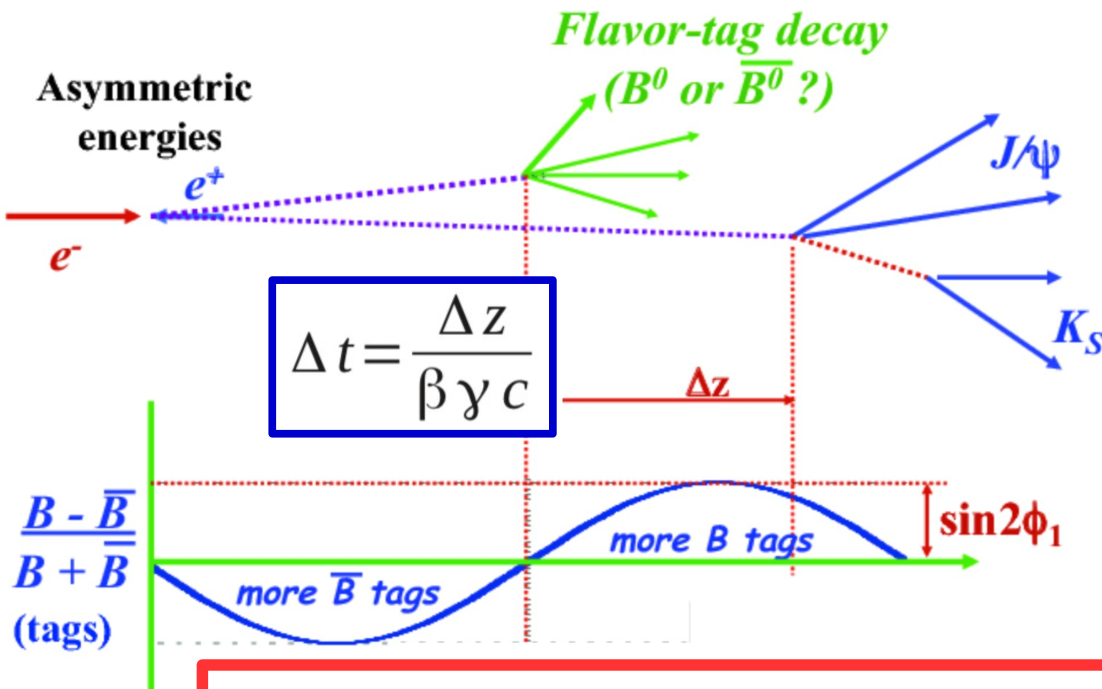
- Belle II has recorded its first collisions on April 26th and has continued taking data until July 17th with a commissioning vertex detector called BEAST-II in order to study beam-backgrounds close to the IP (Phase 2)
- 2 PXD and 4 DSSD ladders where the highest background is expected
- FANGS - FE-I4 based hybrid pixel to study Synchrotron Radiation
- CLAWS - for trickle injection bkg
- PLUME - double-sided high granularity MIMOSA pixels

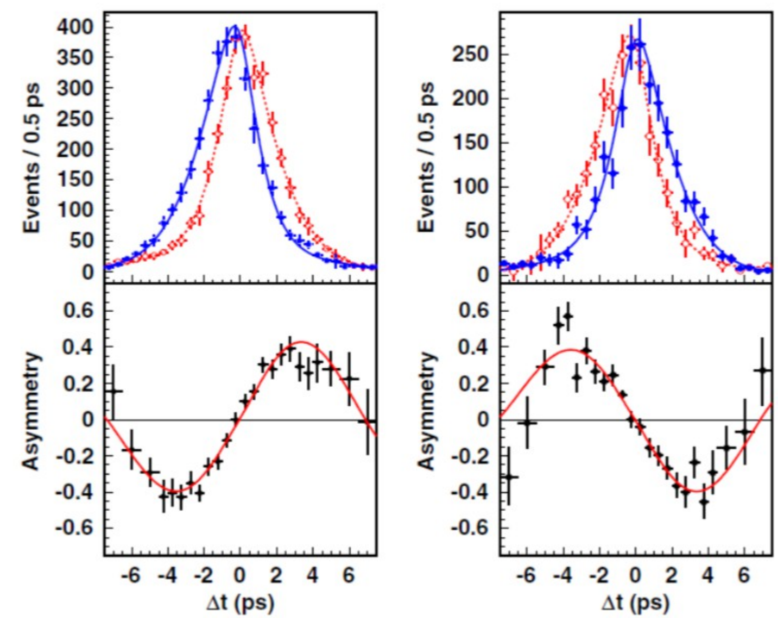




φ_1 and φ_2 at B-factories

- $B\bar{B}$ mixing and decay amplitudes interfere → time-dependent CP asymmetry
- The $B\bar{B}$ are produced in an entangled state, the flavor of the first decaying B (tag) defines the flavor of the other B (signal) at that time
- Need to measure Δt between tag B and signal B, hence a difference in Δz
- Y(4S) → $B\bar{B}$ pairs at rest in the CM frame → asymmetric beam energies



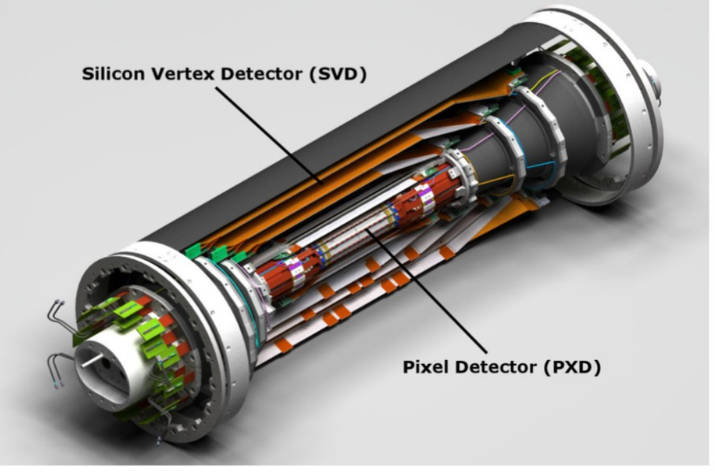


$$a_{f_{cp}}(\Delta t) \equiv \frac{\Gamma_{\bar{B}\to f_{cp}}(\Delta t) - \Gamma_{B\to f_{cp}}(\Delta t)}{\Gamma_{\bar{B}\to f_{cp}}(\Delta t) + \Gamma_{B\to f_{cp}}(\Delta t)} = S\sin(\Delta M \Delta t) - C\cos(\Delta M \Delta t)$$

$S = -\xi_f \sin 2\phi_1$ and $C \approx 0$

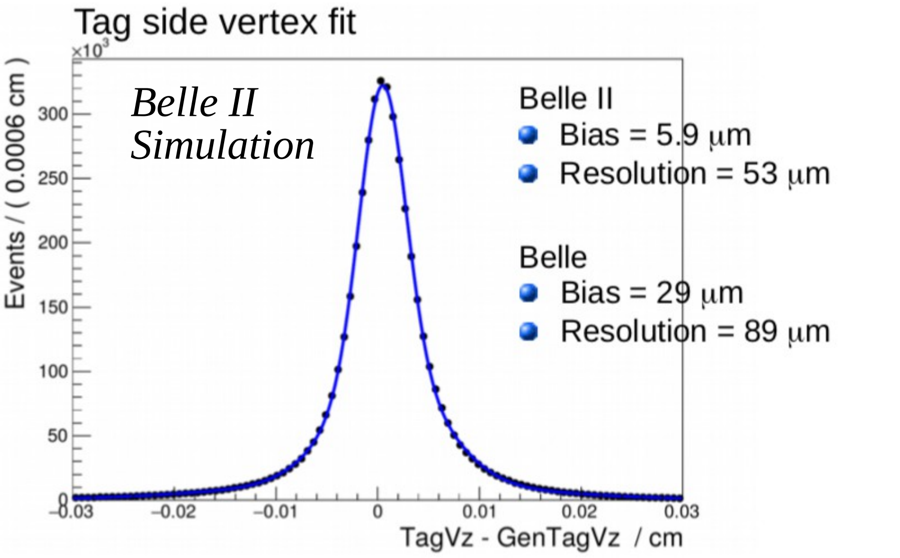
Systematics on φ_1 and φ_2

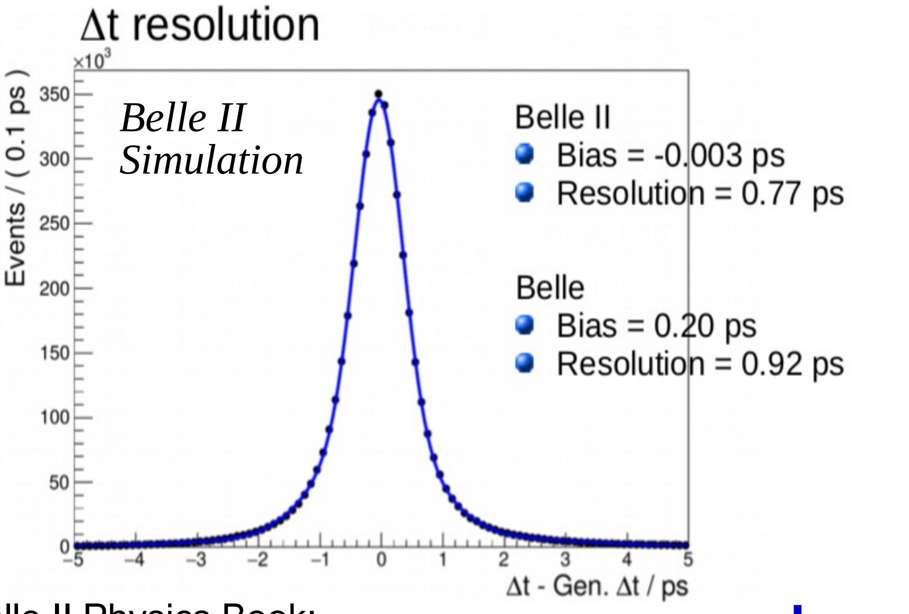
- Systematics are mainly limited by:
  - the resolution of the tagging B vertex fit and hence on Δt → inner pixel sensors high resolution in a noisy environment



  - the proper identification of the flavor of the non-signal B meson: Belle II uses a new inclusive flavor tagger technique which results in higher tagging efficiency

$\sim 35.8\%_{\text{Belle II}}$ vs $\sim 30.0\%_{\text{Belle}}$

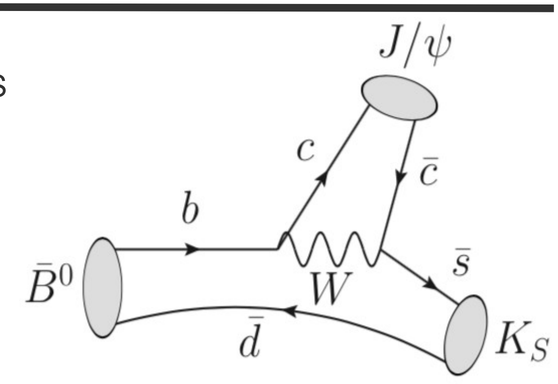




The Belle II Physics Book: https://arxiv.org/abs/1808.10567

$\sin(2\varphi_1)$ in $b \to c\bar{c}s$

- Tree dominated modes, golden channel $B \to J/\psi K_S$
  - Theoretically clean process, $S = -\xi_f \sin(2\varphi_1)$, $C \sim 0$
  - Clean experimental signature: 4 tracks
- Recent theoretical improvements in the calculation of penguin pollution



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

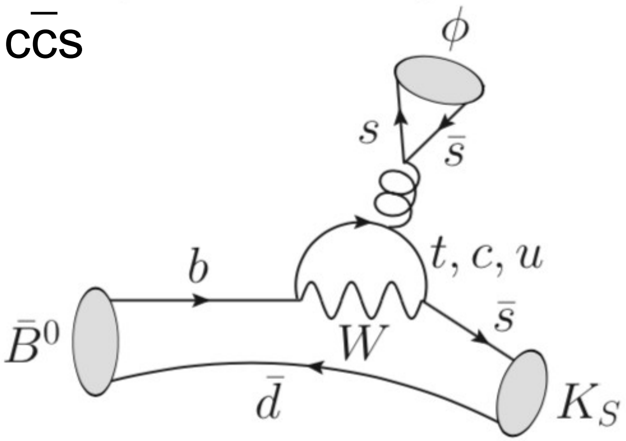
Worst case scenario, same systematics as Belle

Sample	Quantity	Value	Stat. ($\times 10^{-3}$)	Syst. (1) ($\times 10^{-3}$) Red.	Syst. (1) ($\times 10^{-3}$) Non-red.	Syst. (2) ($\times 10^{-3}$) Red.	Syst. (2) ($\times 10^{-3}$) Non-red.
		Belle (1 ab^{-1}) PRL 108 171802					
$B \to J/\psi K_S$	$\mathcal{S}$	+0.67	29	-	13	-	-
	$\mathcal{A} \equiv -\mathcal{C}$	-0.015	21	-	+45, -23	-	-
$b \to c\bar{c}s$	$\mathcal{S}$	+0.667	23	-	12	-	-
	$\mathcal{A} \equiv -\mathcal{C}$	+0.006	16	-	12	-	-
		Belle II (50 ab^{-1})					
$B \to J/\psi K_S$	$\mathcal{S}$	-	3.5	1.2	8.3	1.2	4.4
	$\mathcal{A} \equiv -\mathcal{C}$	-	2.5	0.7	+43, -22	0.7	+42, -11
$b \to c\bar{c}s$	$\mathcal{S}$	-	2.7	2.6	7	2.6	3.6
	$\mathcal{A} \equiv -\mathcal{C}$	-	1.9	1.4	10.6	1.4	8.7

With expected improvement due to better vertexing

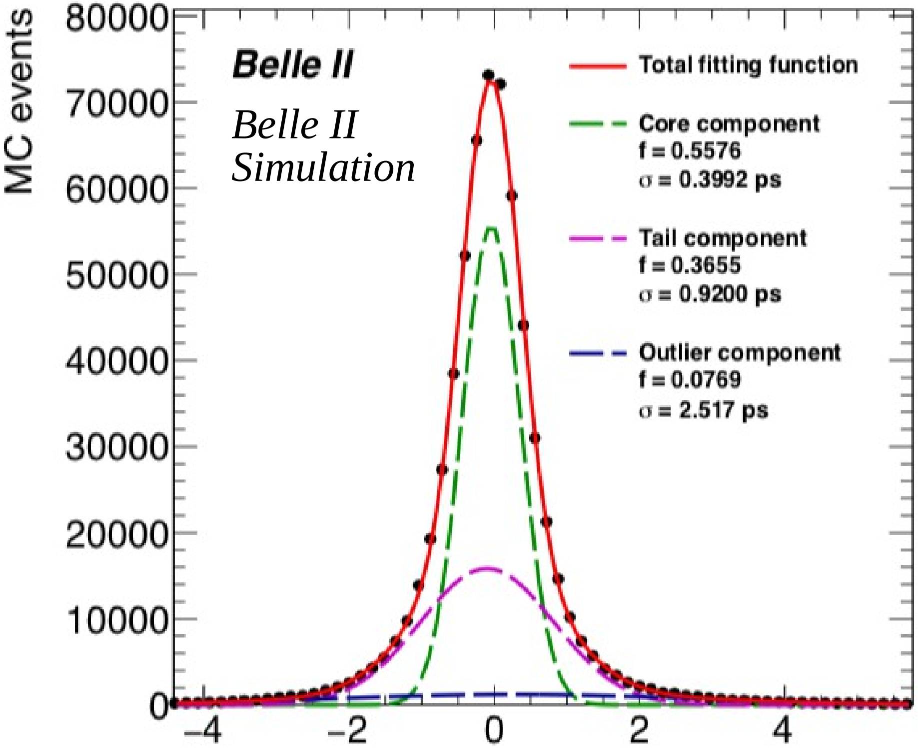
$\sin(2\varphi_1)$ in $b \to q\bar{q}s$: $B^0 \to \varphi K^0$

- Loop process, same weak phase as $b \to c\bar{c}s$
- Also sensitive to new physics



Δt resolution

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



Expected sensitivity with 50 ab^{-1}

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

Belle measurement: $S_{\varphi K} = 0.9^{+0.9}_{-0.19}$

$\sin(2\varphi_1)$ in $b \to q\bar{q}s$: $B^0 \to \eta' K^0$

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

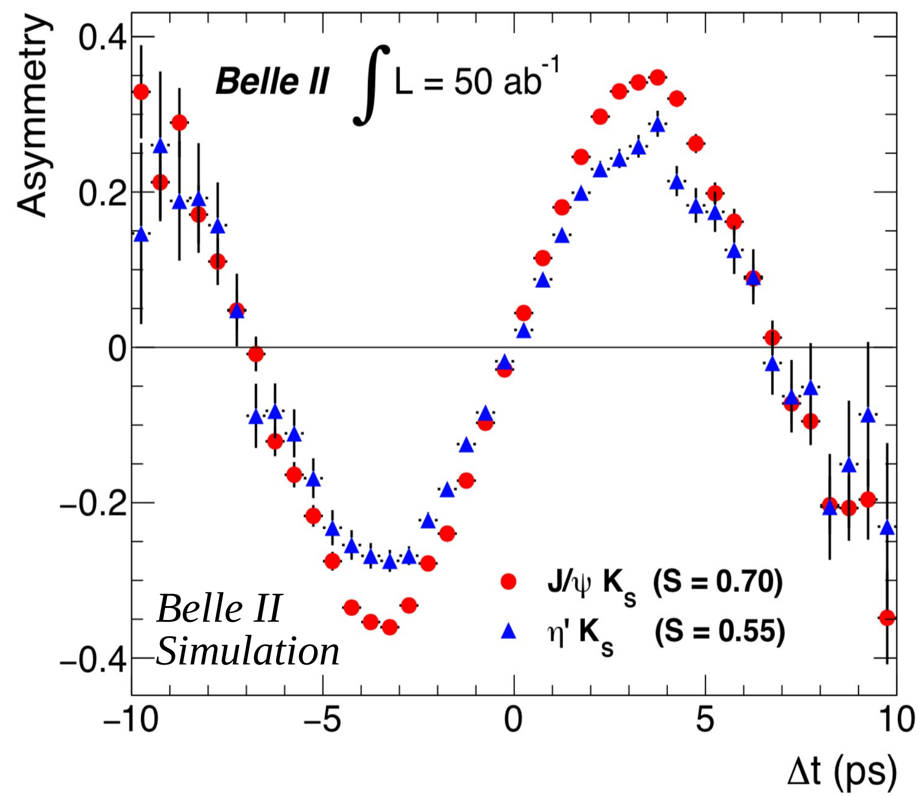
Δt resolution

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)	-

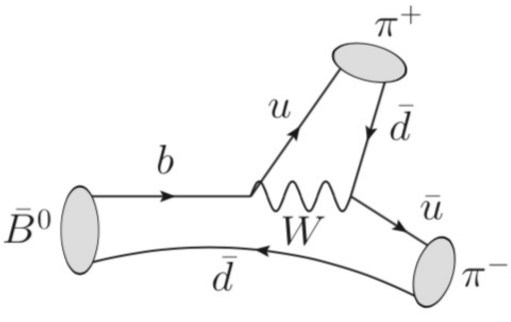
Syst. Case 1 (Case 2)

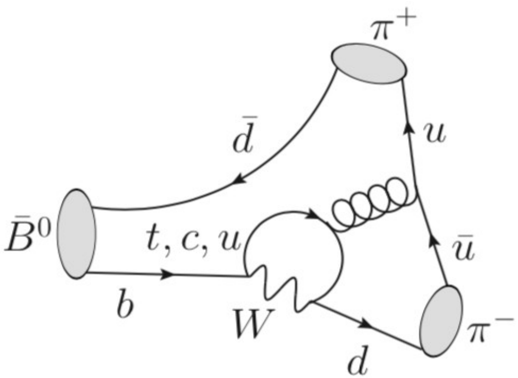


Belle measurement: $S_{\eta' K}$ = +0.68 ± 0.07 ± 0.03

sin(2φ_2): isospin analysis in B → hh

- sin(2φ_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$\varphi_{2,\,\mathrm{eff}}$), $\varphi_{2,\,\mathrm{eff}} = \varphi_2 + \delta\varphi_{\mathrm{peng}}$
- Disentangle the tree contribution and extract δφ by isospin analysis

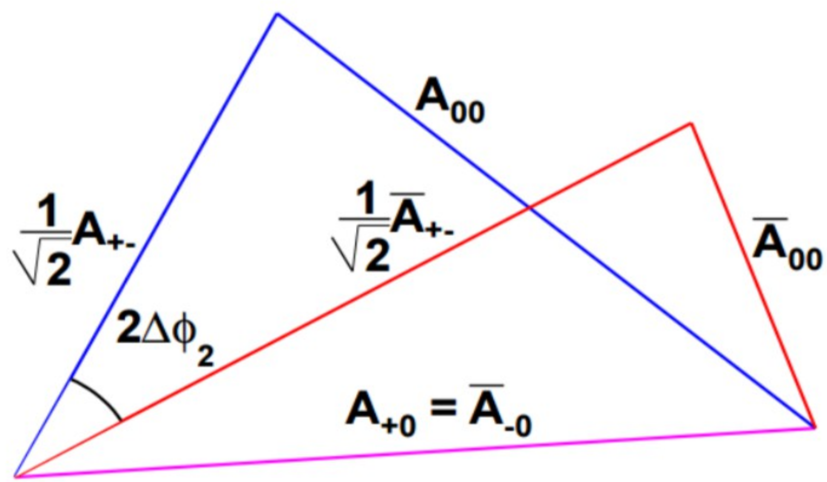
$$A^{(i,j)} \equiv \mathcal{A}(B^{i+j} \to h^i h^j)\ (h = \pi, \rho\ /\ i,j = \pm, 0)$$

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

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

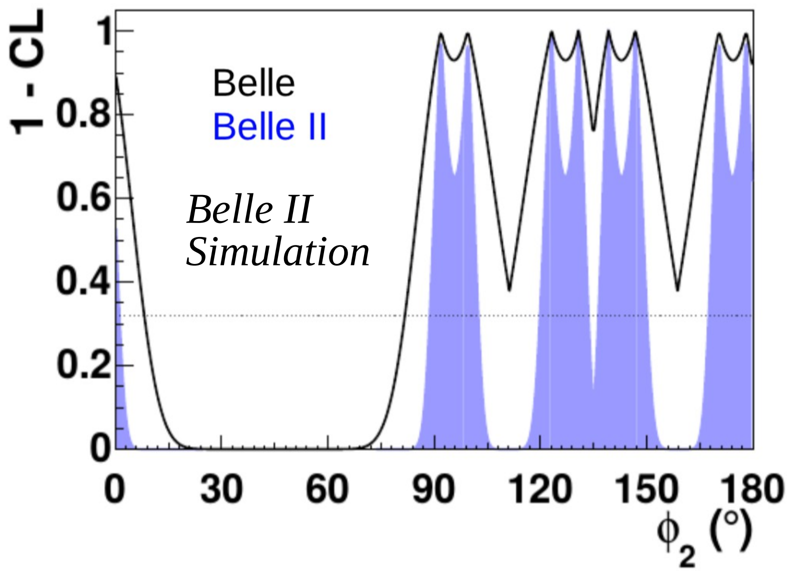
$$|A^{+0}| = |\bar{A}^{+0}|$$

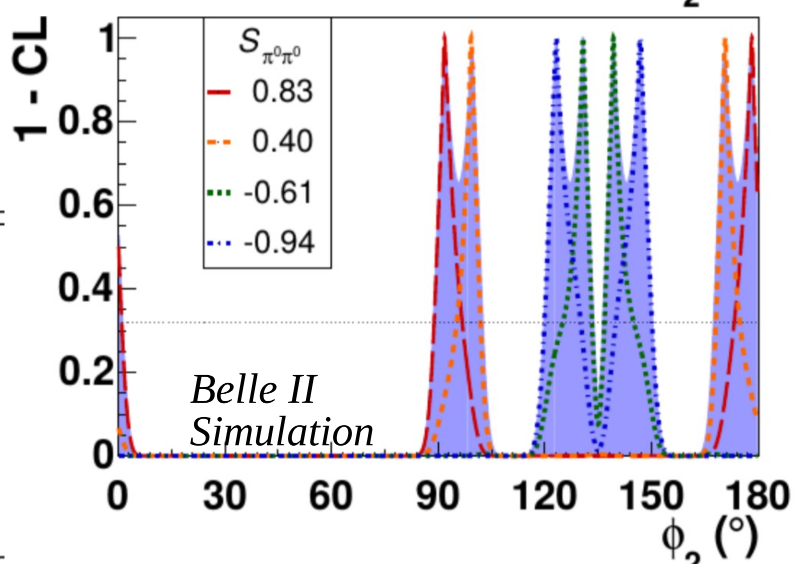
M. Gronau and D. London, PRL 65 3381 (1990)



$\sin(2\varphi_2)$: $B \to \pi\pi$

- Up to date $S_{\pi^0\pi^0}$ has never been measured → eightfold ambiguity on φ_2
- 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]	$\pm 0.03 \pm 0.01$
$S_{\pi^0\pi^0}$	—	—	$\pm 0.29 \pm 0.03$

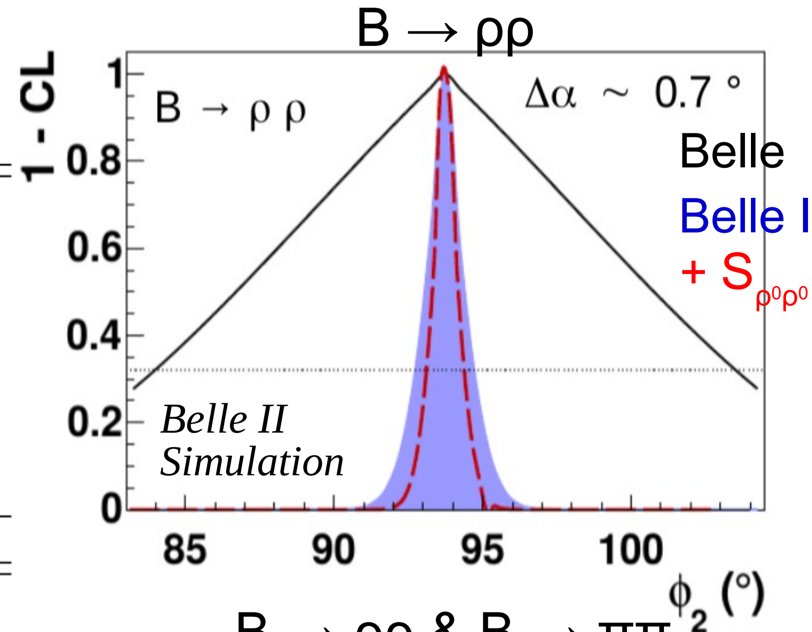
[1]: arXiv:1705.02083
[2]: PRD 87(3) 031103
[3]: PRD 88(9) 092003

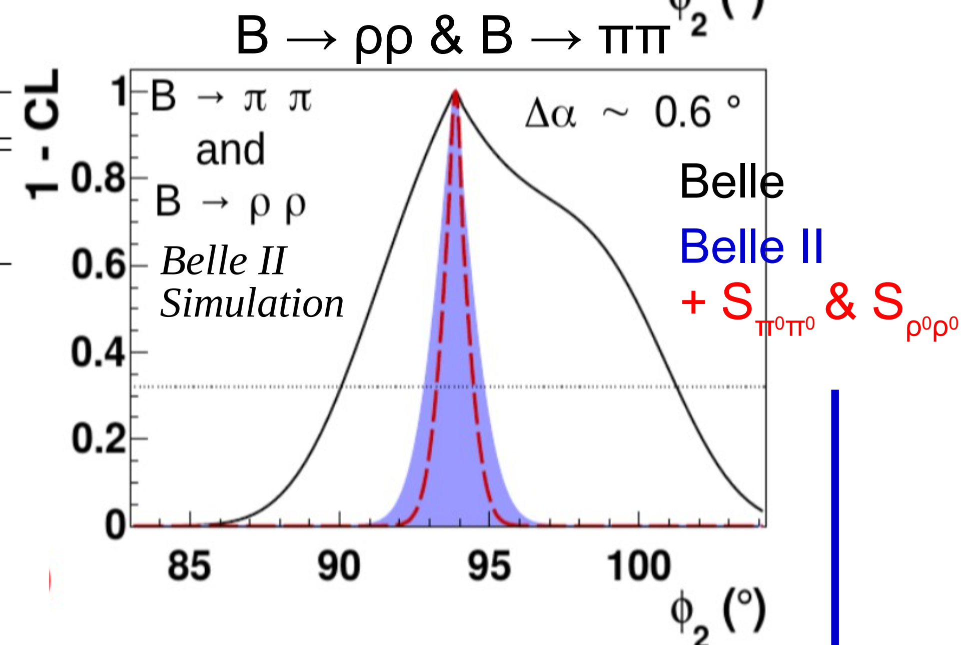
Belle II expectation: $\Delta\varphi_{2,\pi\pi} \sim 2°$

$\sin(2\varphi_2)$: $B \to \rho\rho$

	Value	Belle: Belle @ 0.8 ab^{-1}	Belle II: Belle2 @ 50 ab^{-1}
$f_{L,\rho^+\rho^-}$	0.988	$\pm 0.012 \pm 0.023$ [1]	$\pm 0.002 \pm 0.003$
$f_{L,\rho^0\rho^0}$	0.21	$\pm 0.20 \pm 0.15$ [2]	$\pm 0.03 \pm 0.02$
$\mathcal{B}_{\rho^+\rho^-}$ [10^{-6}]	28.3	$\pm 1.5 \pm 1.5$ [1]	$\pm 0.19 \pm 0.4$
$\mathcal{B}_{\rho^0\rho^0}$ [10^{-6}]	1.02	$\pm 0.30 \pm 0.15$ [2]	$\pm 0.04 \pm 0.02$
$C_{\rho^+\rho^-}$	0.00	$\pm 0.10 \pm 0.06$ [1]	$\pm 0.01 \pm 0.01$
$S_{\rho^+\rho^-}$	-0.13	$\pm 0.15 \pm 0.05$ [1]	$\pm 0.02 \pm 0.01$
	Value	Belle @ 0.08 ab^{-1}	Belle2 @ 50 ab^{-1}
$f_{L,\rho^+\rho^0}$	0.95	$\pm 0.11 \pm 0.02$ [3]	$\pm 0.004 \pm 0.003$
$\mathcal{B}_{\rho^+\rho^0}$ [10^{-6}]	31.7	$\pm 7.1 \pm 5.3$ [3]	$\pm 0.3 \pm 0.5$
	Value	BaBar @ 0.5 ab^{-1}	Belle2 @ 50 ab^{-1}
$C_{\rho^0\rho^0}$	0.2	$\pm 0.8 \pm 0.3$ [4]	$\pm 0.08 \pm 0.01$
$S_{\rho^0\rho^0}$	0.3	$\pm 0.7 \pm 0.2$ [4]	$\pm 0.07 \pm 0.01$

[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)



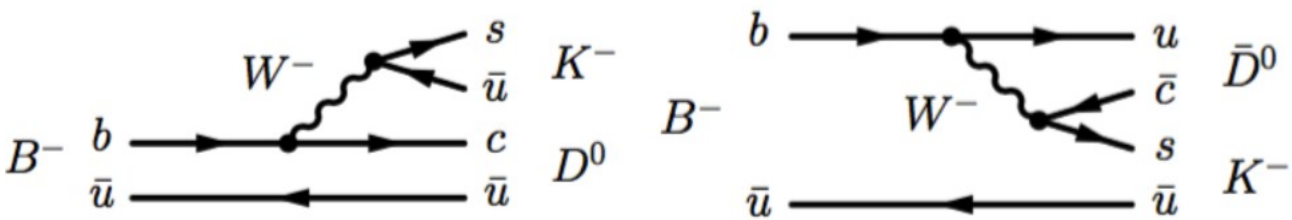


Belle II expectation: $\Delta\varphi_{2,\rho\rho} \sim 0.7°$

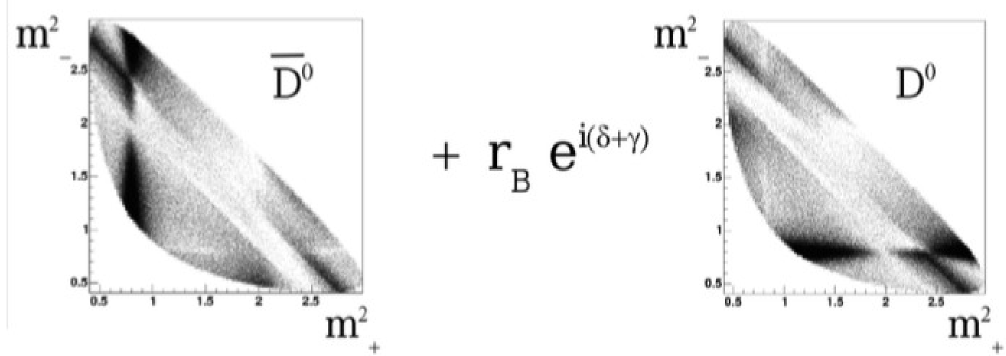
Combined: $\Delta\varphi_2 \sim 0.6°$

Measurement of φ_3 with $B \to D^0 K$

- φ_3 is the phase between $b \to u$ and $b \to c$
- The best methods to measure φ_3 are based on the interference between $b \to c\bar{u}s$ 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)

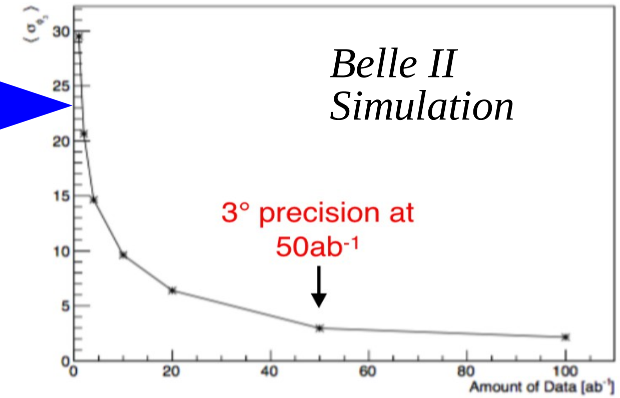


Measurement of φ_3 with $B^\pm \to D^0 K^\pm$

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

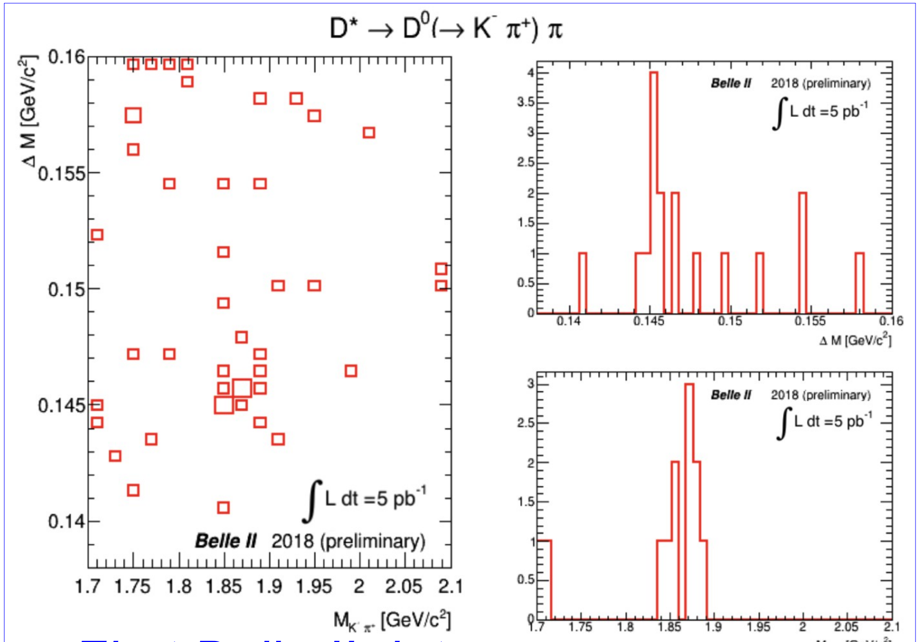
Belle II sensitivity expectation for

$B^\pm \to (K_s\pi^+\pi^-)_D K^\pm$ with 50 ab^{-1}: $\Delta\varphi_3 \sim 3°$



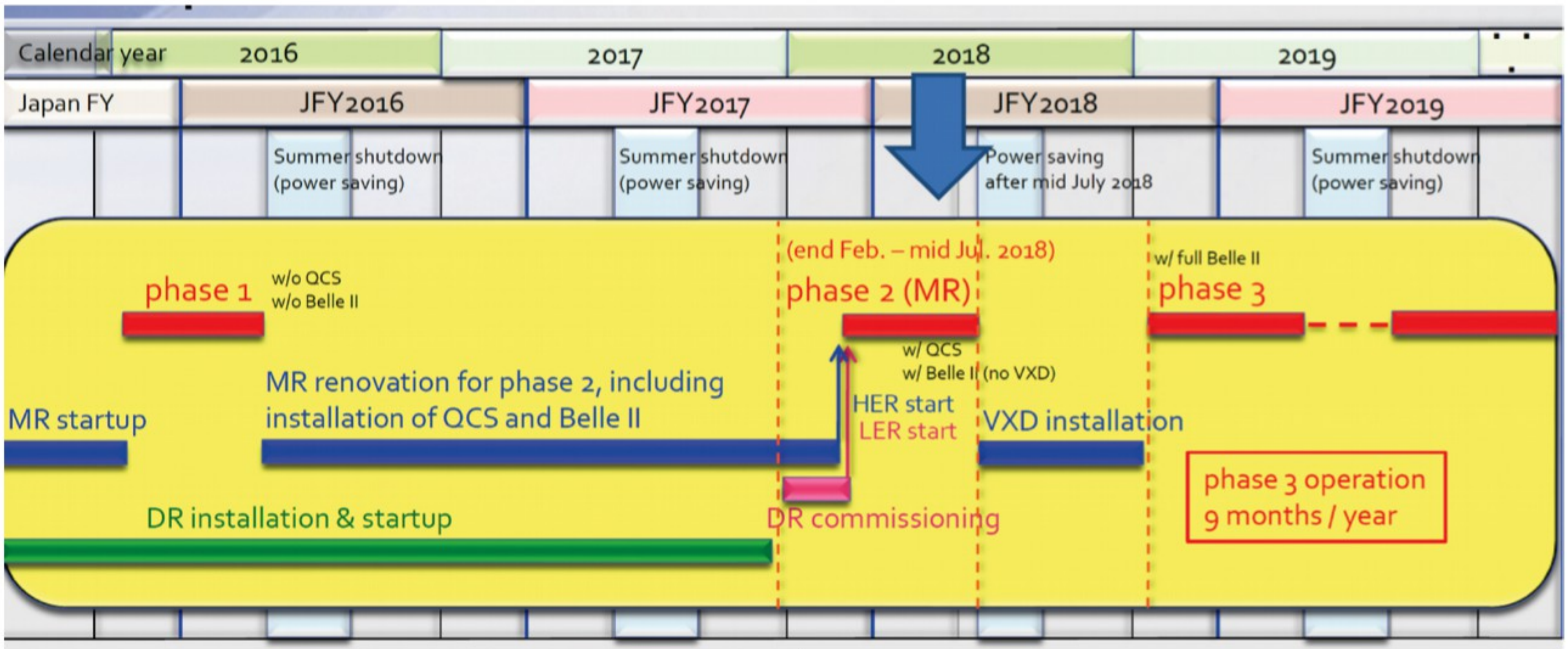
- Current measurement from B-factories and LHC:
  Belle: $\varphi_3 = (78^{+15}_{-16})°$ LHCb: $\varphi_3 = (76.8^{+5.1}_{-5.7})°$
- Belle measurement used other D decay modes (ADS, GLW techniques)
- Best estimate for Belle II combines the different techniques
- Fundamental assumption: BES III will have collected ~10 fb^{-1} at the $\psi(3770)$

Belle II sensitivity expectation with 50 ab^{-1}: $\Delta\varphi_3 \sim 1.6°$



First Belle II data

Current Schedule

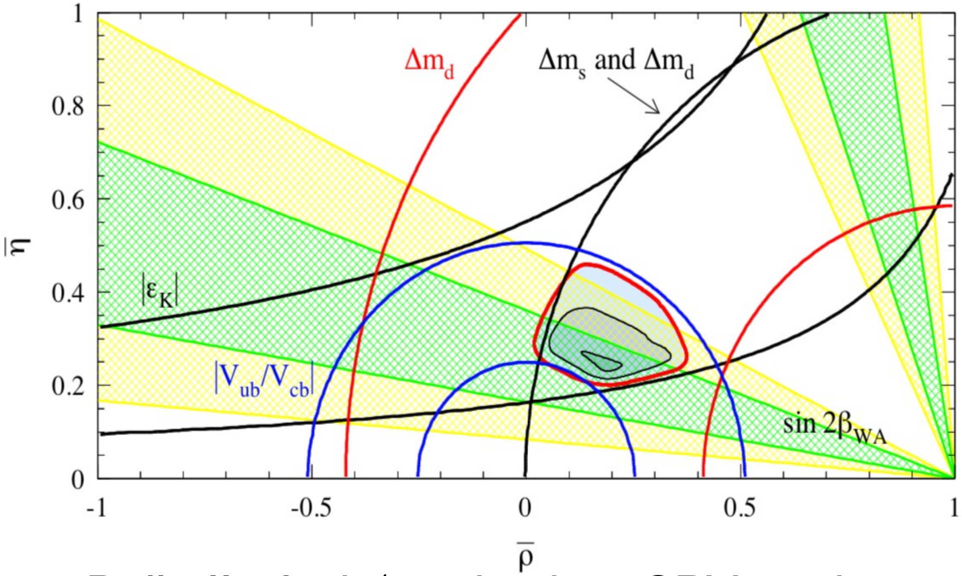


- Up to date Belle II has recorded ~500 pb^{-1} with partial (Phase 2) detector
- Commissioning has ended July 17th, we are now moving towards installation of the vertex detector in fall!
- Due to technical difficulties in the assembly, the second layer of the pixel detector will not be installed until 2020
- Physics run with increasing luminosity will start in February 2019 !

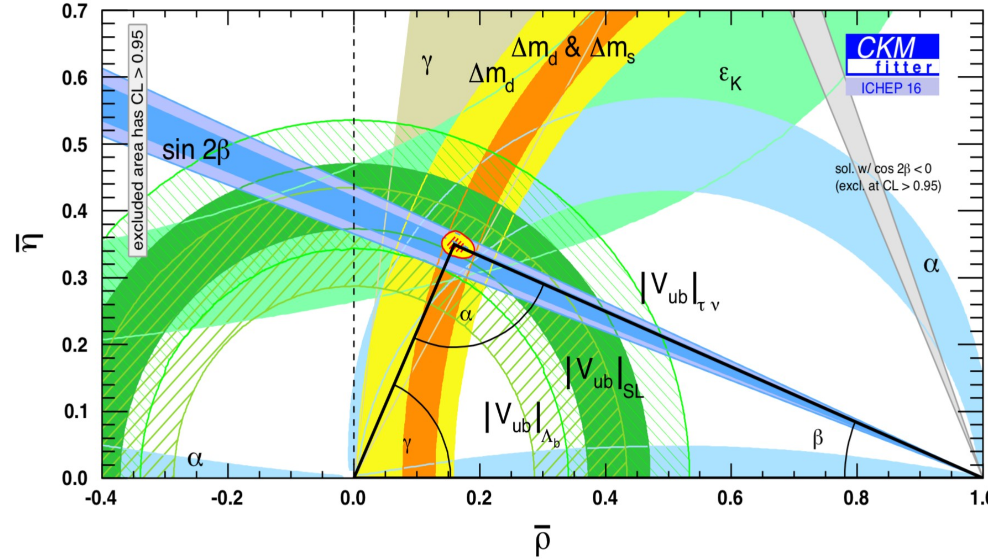
Pictorial Outlook

Before B-factories

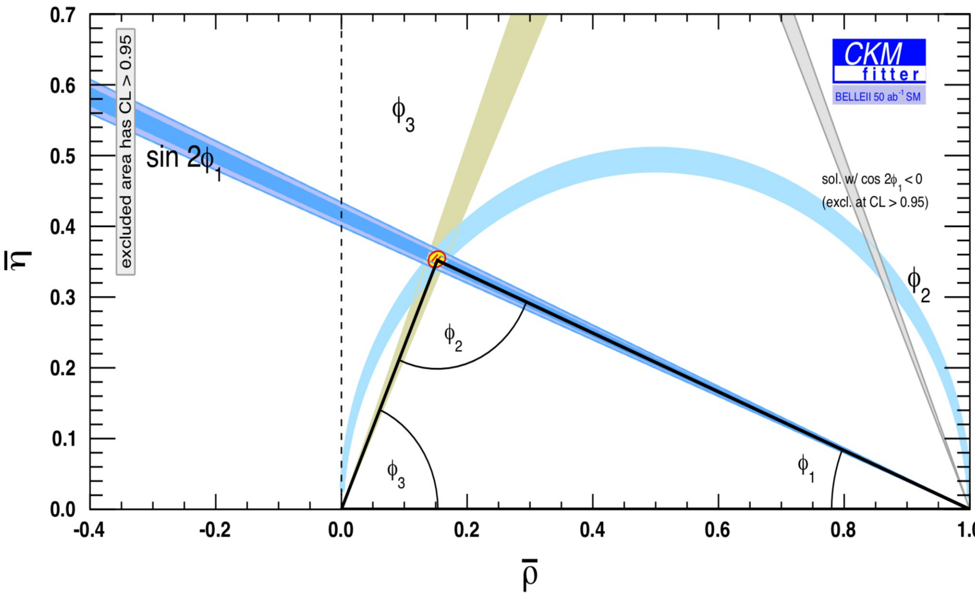
Eur.Phys.J.C21:225-259,2001



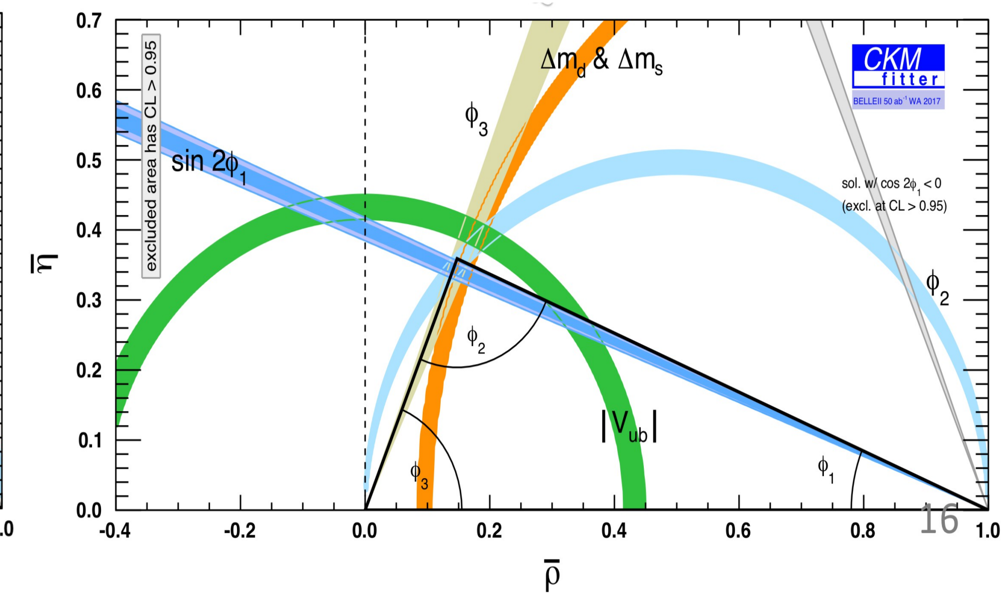
After B-factories



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



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



Conclusions

- 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

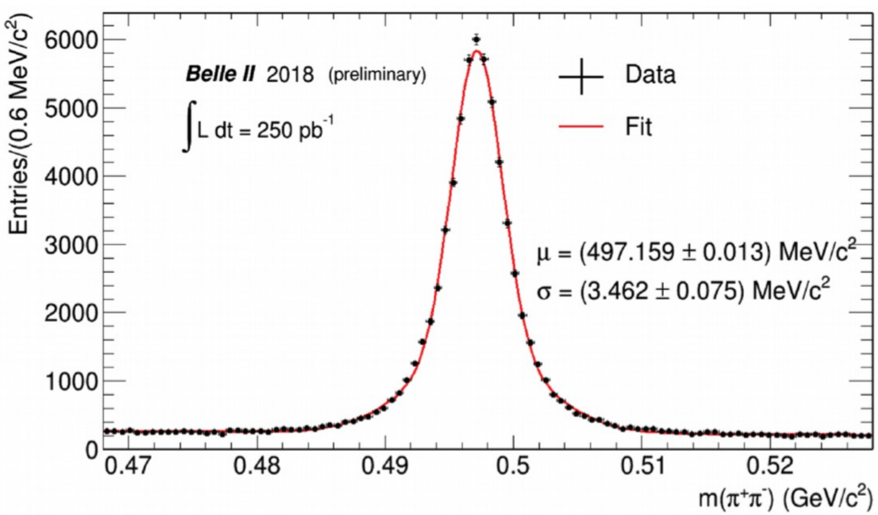
- $\sin(2\varphi_1)$: precision better than 1% using $c\bar{c}s$ modes
- $\sin(2\varphi_2)$: new inputs for isospin analysis, expected sensitivity $\delta\varphi_2 \sim 1°$
- φ_3: from $B \to DK$ decays $\delta\varphi_3 = 1.6°$ at 50 ab^{-1}
- Expected precision on $|V_{ub}|$

  from exclusive (inc.) semi-leptonic

  measurements around 1.3% (3%)

..the fun has just started!

First Belle II data!



First K_S candidates from Belle II

Thanks for your attention!