CP Violation sensitivity at the Belle II Experiment

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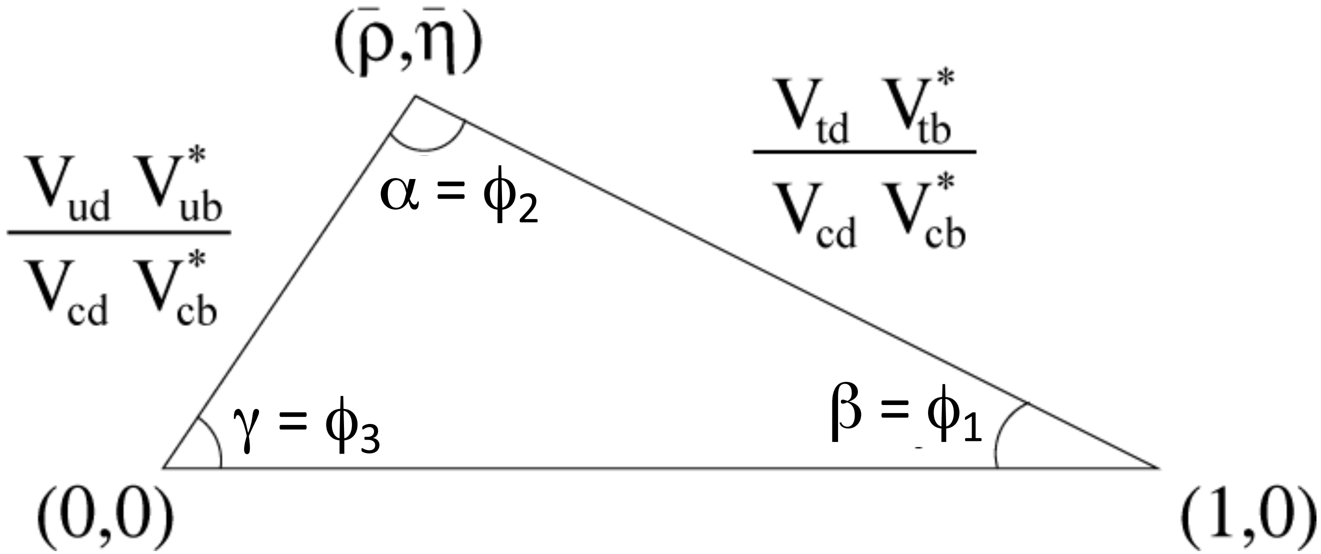
Outline

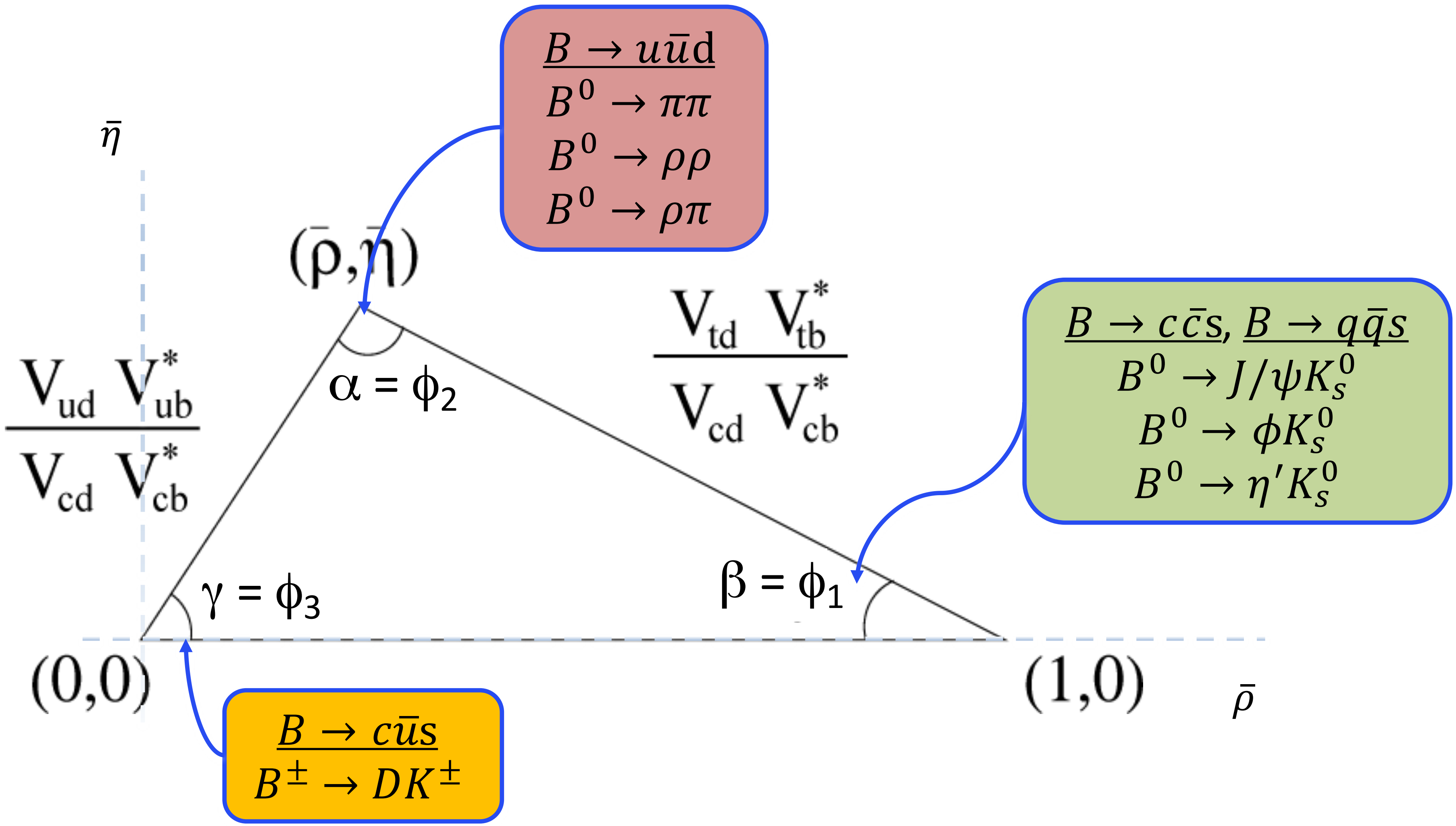
- Introduction on the Unitarity Triangle
- Super KEKB accelerator and Belle II detector
- CP Violation sensitivity Prospects at Belle-II
- Outlook and summary

The Unitarity Triangle

- The weak interactions of quarks are described by the CKM unitary matrix (V_{CKM}).
- V_{CKM} is expressed by three rotation angles and one phase (phase≠0 ↔ CP violation in the quark sector).
- Unitarity relations are represented by six triangles in the complex plane.
- The B^0 Unitarity Triangle (UT) is shown here
  - ✓ Sides ~ Branching fractions and $B\bar{B}$ mixing
  - ✓ Angles ~ amounts of CPV



Observables from B decays

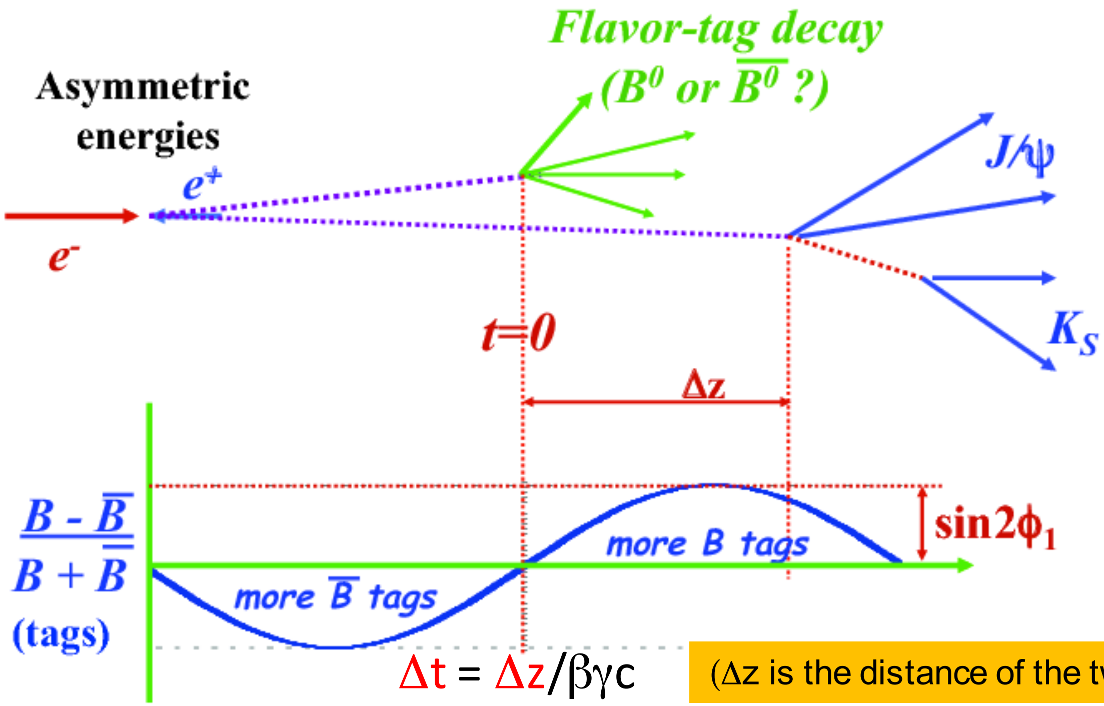


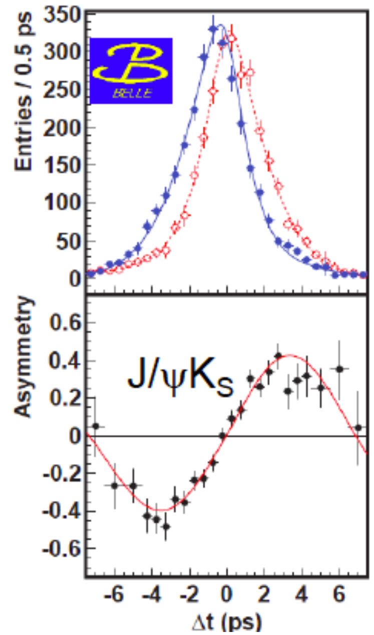
See Hulya Atmacan's talk on Sep. 1

Measurement of time dependent CP violation

- ϕ_1 is accessible through oscillations
- Resolution on Δt will be dominated by the resolution of the the tagging B vertex fit.

Asymmetric B-factories @ Υ(4S)





(Δz is the distance of the two B decay vertices in the boost direction)

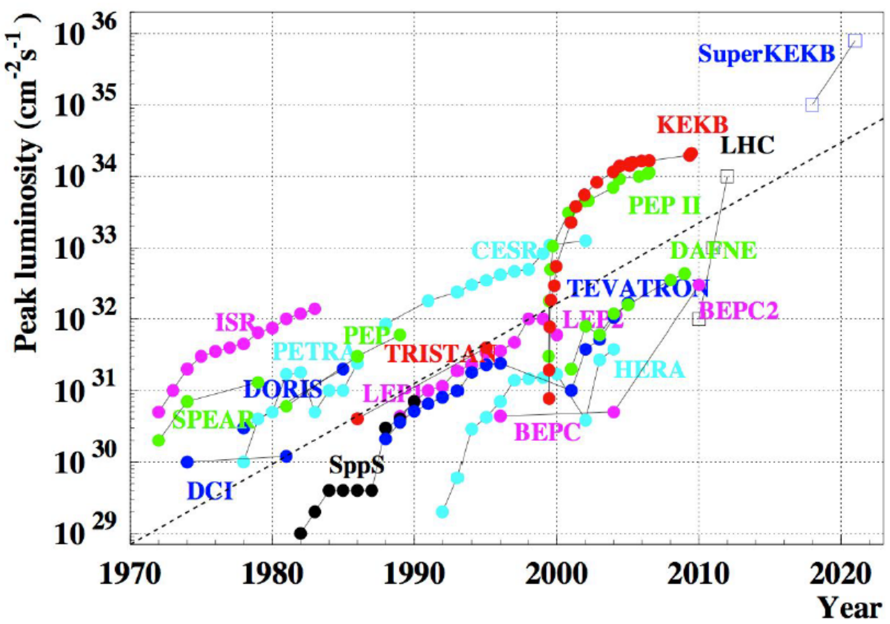
CPV asymmetry in the time-dependent rates for initial B meson decays to a CP eigenstate, f_{CP}

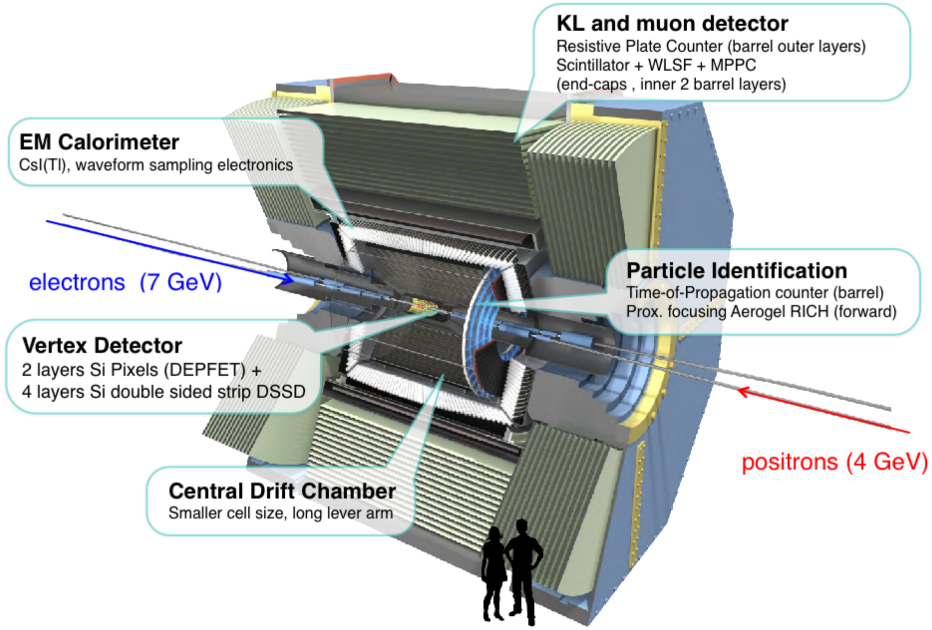
$$a_{f_{cp}}(\Delta t) \equiv \frac{\Gamma_{\bar{B}\to f_{cp}}(\Delta t) - \Gamma_{B\to f_{cp}}(\Delta t)}{\Gamma_{\bar{B}\to f_{cp}}(\Delta t) + \Gamma_{B\to f_{cp}}(\Delta t)} = S\sin(\Delta M \Delta t) - C\cos(\Delta M \Delta t)$$

S = $-\xi_f \sin 2\phi_1$ and C ≈ 0

Belle II Detector on SuperKEKB

Peak luminosity of SuperKEKB reach 40 times of KEKB!





- Reduction in the beam size by 1/20 at the IP.
- Doubling the beam currents.

Targets:
Peak luminosity: $8\times10^{35}cm^{-2}s^{-1}$
Integrated luminosity: **50ab^{-1} by 2024**

Many upgrades needed in order to increase the performance and cope with much more severe background conditions

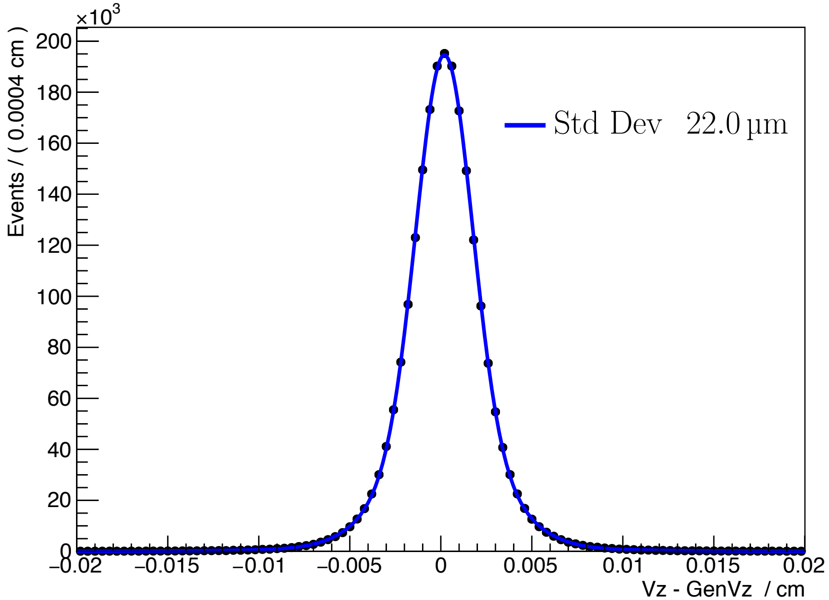
Main improvement in performance in two areas:
Tracking and vertex determination; Particle ID

More details can be found on Jake BENNETT's talk about the Belle II experiment

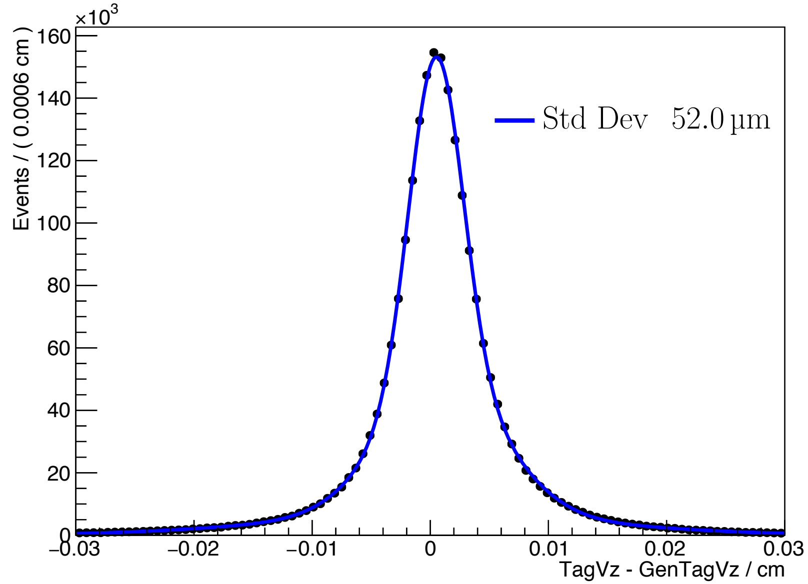
The Performance of Belle II detector(I)

Vertex fit

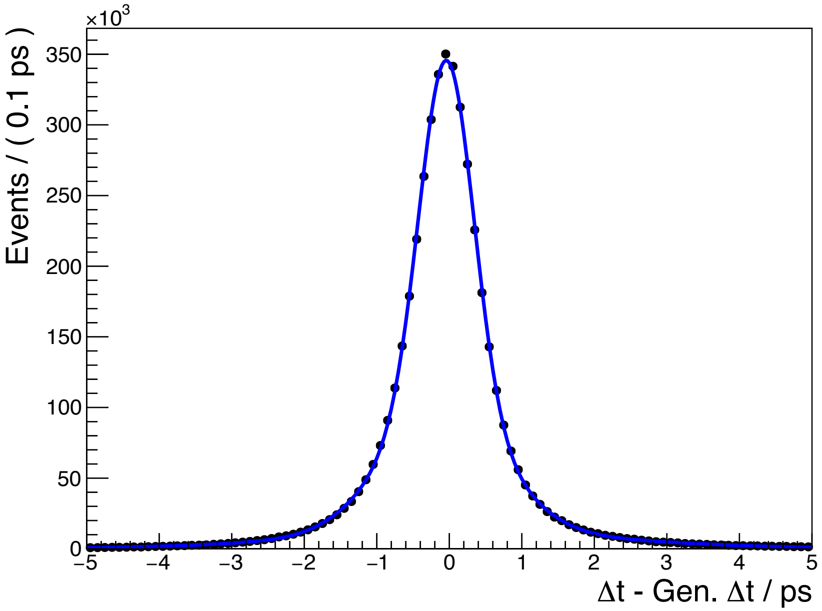
$J/\psi \to \mu^+\mu^-$ vertex fit residuals



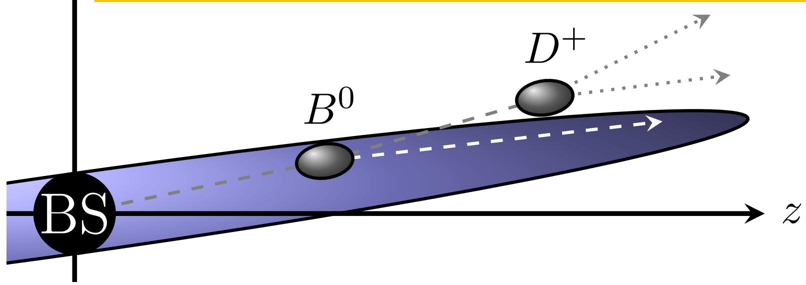
Tag side vertex fit residuals



Δt resolution = 0.77 ps



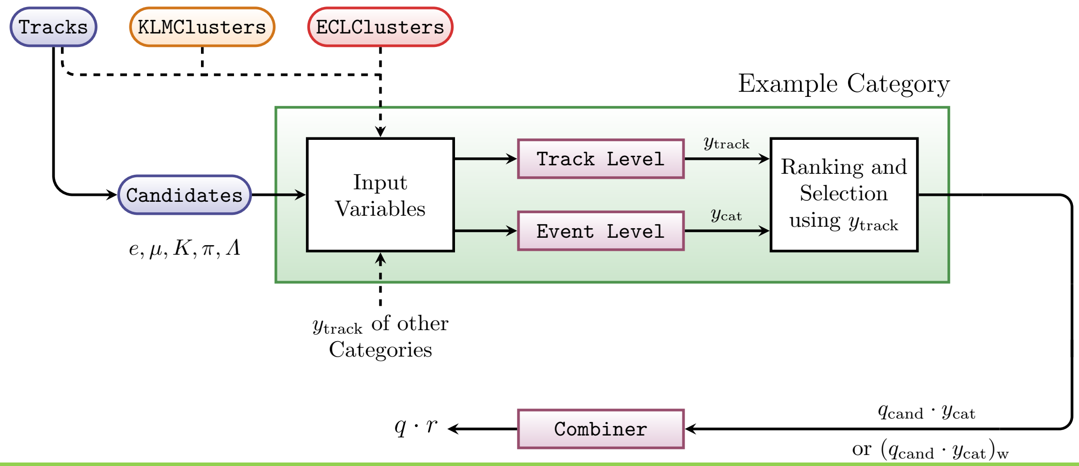
- The tag side vertex fit (RAVE Adaptive Vertex Fit algorithm)
  - ✓ Input all the tracks with at least one hit on the PXD
  - ✓ Not used for the fully reconstructed B
  - ✓ Not from K_S^0 decays
  - ✓ Tracks falling in the following ellipsoid have bigger weight than tracks decays from D in the final χ^2



The Performance of Belle II detector(II)

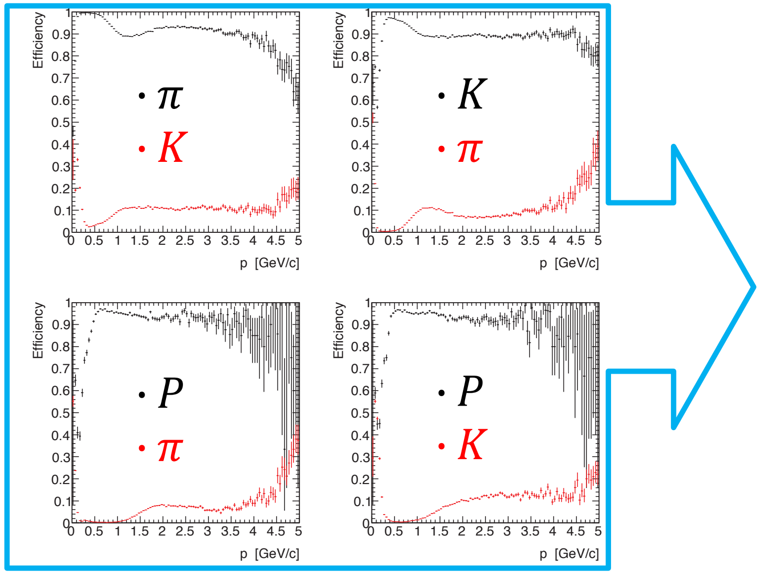
The global performance of the flavor tagger

q: flavor tag; r: flavor dilution fraction; they are the outputs of a multivariate



The FBDT combiner achieves a total effective efficiency of ε_{eff} = 35.8%

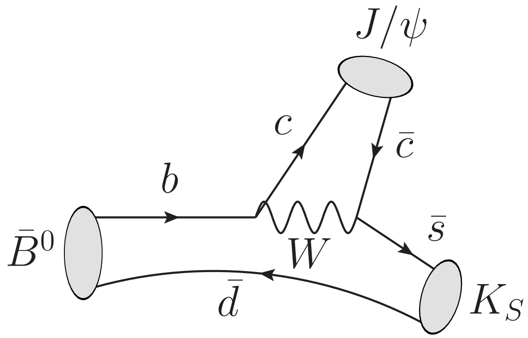
Combined charged PID performance of Belle II

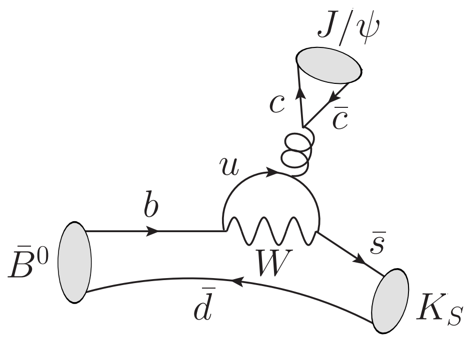


- Inclusive $c\bar{c}$ MC samples.
- Minimal track quality restrictions are applied
- $\mathcal{L}(\alpha{:}\beta) > 0.5$
- Black markers: selection eff. w/o background; red markers: fake rate
- Very good PID performance, especially in the low p region

ϕ_1 from $b \to c\bar{c}s$

Signal tree process | **Penguin pollution**





- $B^0 \to J/\psi K_S^0$ is the"golden mode" for extracting ϕ_1
  - ✓ The expected theoretical uncertainty is small
  - ✓ Experimental signature is clean (f = $J/\psi K_S^0$ is a CP eigenstate)
- Theoretical estimates of penguin pollution have been significantly improved in Phys. Rev. Lett., 115, 061802 (2015)

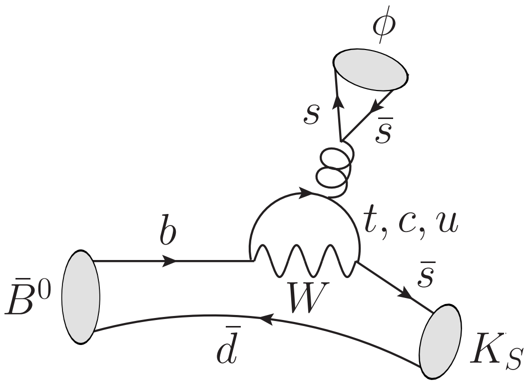
Current status from Belle | **Belle2 expected uncertainties @ 50 ab^{-1} (Precision better than 1%)**

Errors (10^{-3})	-	Value (10^0)	stat.	syst.	stat.	syst. reducible	syst.(case 1)	syst.(case 2)
$J/\psi K^0$	S	+0.67	29	13	3.5	1.2	8.2	4.4
	$\mathcal{A} \equiv -C$	-0.015	21	$^{+45}_{-23}$	2.5	0.7	$^{+43}_{-22}$	$^{+42}_{-11}$
$c\bar{c}s$	S	+0.667	23	12	2.7	2.6	7.0	3.6
	$\mathcal{A} \equiv -C$	-0.006	16	12	1.9	1.4	10.6	8.7

Case1: irreducible syst. same as Belle; Case2: irreducible syst. (vertexing)reduced by a factor 2 due to the new Pixel Vertex detector and improved tracking and alignment algorithms

ϕ_1 from $b \to q\bar{q}s$: $B^0 \to \phi K_s^0$

Penguin diagram



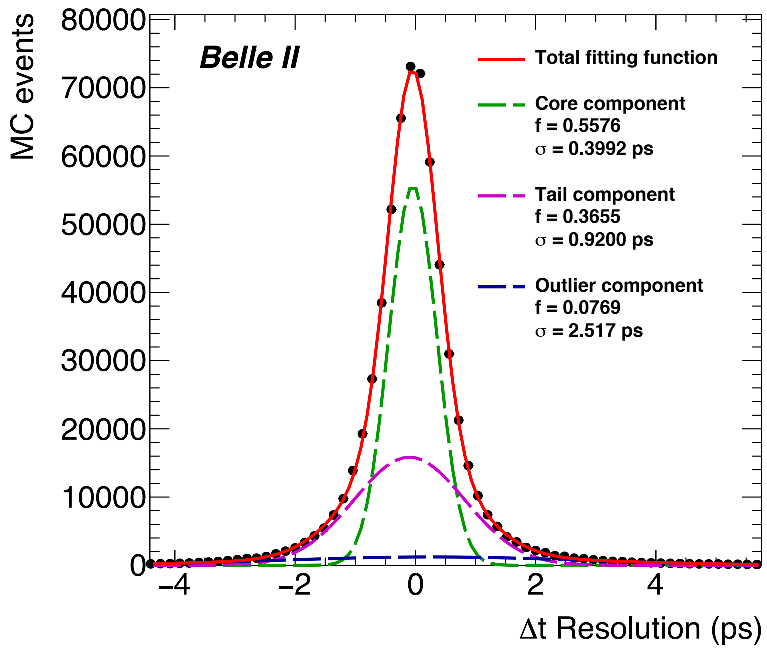
Best achievable Δt resolution of reference modes

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

Three-gaussian fit on the Δt resolution: $\sigma(\Delta t)$ ~0.75

Expected sensitivity @ 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



ϕ_1 from $b \to q\bar{q}s$: $B^0 \to \eta' K_s^0$

Best achievable Δt resolution of reference modes

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

Crucial aspect is π^0, η^0 reconstruction
Non negligible fraction of mis-reconstructed signal (SxF)

Belle: $S_{\eta' K_S^0} = +0.68 \pm 0.07 \pm 0.03$

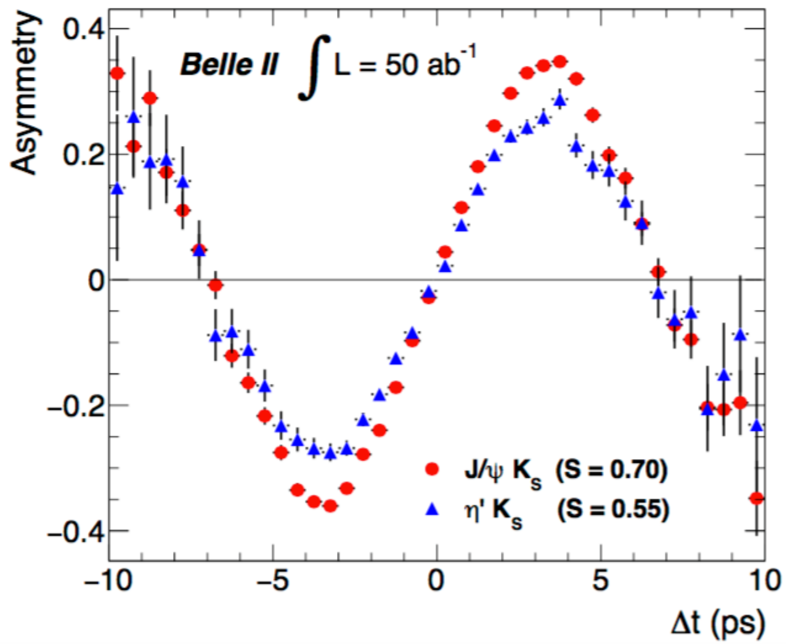
Expected sensitivity @ 50 ab^{-1}

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)

Systematic uncertainty will be dominated

Time dependent CP asymmetries for the final states $J/\psi\ K_S$ (red dots) and $\eta' K_S$ (blue triangles), using $S_{J/\psi K_S^0}$ = 0.70 and $S_{\eta' K_S^0}$= 0.55 as inputs to the Monte Carlo



With the full integrated luminosity of 50 ab^{-1}, these two modes would be unambiguously distinguishable, signifying the existence of New Physics

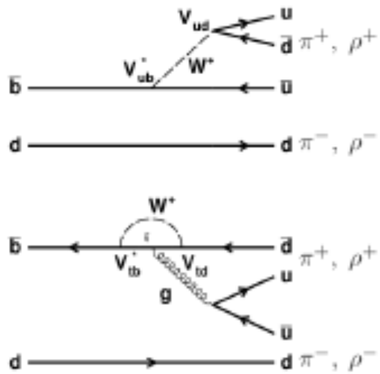
Outlook of ϕ_1 determination

Expected yields and uncertainties on the S and A parameters for the following channels with 50 ab^{-1} data, In the 4th and the last column we also give the present WA errors on each of the observables

Channel	Event yield	$\sigma(S)$	$\sigma(S)_{2017}$	$\sigma(A)$	$\sigma(A)_{2017}$
$J/\psi K^0$	1.4×10^6	0.0052	0.022	0.0050	0.021
ϕK^0	55900	0.015	0.12	0.011	0.14
$\eta' K^0$	272000	0.015	0.06	0.013	0.04
ωK_S^0	16700	0.025	0.21	0.019	0.14
$K_S^0 \pi^0 \gamma$	14000	0.032	0.20	0.022	0.12
$K_S^0 \pi^0$	56990	0.028	0.17	0.019	0.10

Measurement of ϕ_2

$$\phi_2 = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$



- access ϕ_2 via time-dependent CP asymmetry in:

$B^0 \to \pi\pi$
$B^0 \to \rho\rho$
$B^0 \to \rho\pi$

penguin contribution has to be controlled in analysis

$$S = \sin\left(2\phi_2^{eff}\right) \text{ with } \phi_2^{eff} = \phi_2 + \Delta\phi_2$$

$C \neq 0 \Rightarrow$ direct CP violation
from interference of tree and penguin

Existence of Non-negligible strong phase → Can not extract ϕ_2 directly

ϕ_2 from B→ππ

The B2TIP report: https://confluence.desy.de/display/BI/B2TiP+WebHome

Isospin analysis input in B→ππ

	Value	Belle @ 0.8 ab^{-1}	Belle2 @ 50 ab^{-1}
$\mathcal{B}_{\pi^+\pi^-}$ $[10^{-6}]$	5.04	$\pm0.21 \pm 0.18$ [2]	$\pm0.03 \pm 0.08$
$\mathcal{B}_{\pi^0\pi^0}$ $[10^{-6}]$	1.31	$\pm0.19 \pm 0.18$ [1]	$\pm0.04 \pm 0.04$
$\mathcal{B}_{\pi^+\pi^0}$ $[10^{-6}]$	5.86	$\pm0.26 \pm 0.38$ [2]	$\pm0.03 \pm 0.09$
$C_{\pi^+\pi^-}$	-0.33	$\pm0.06 \pm 0.03$ [3]	$\pm0.01 \pm 0.03$
$S_{\pi^+\pi^-}$	-0.64	$\pm0.08 \pm 0.03$ [3]	$\pm0.01 \pm 0.01$
$C_{\pi^0\pi^0}$	-0.14	$\pm0.36 \pm 0.12$ [1]	$\pm0.03 \pm 0.01$
$S_{\pi^0\pi^0}$	—	—	$\pm0.29 \pm 0.03$

[1]: arXiv:1705.02083

[2]: PRD 87(3) 031103

[2]: PRD 88(9) 092003

More details can be found about the estimating method can be found in arXiv:1608.06224

ϕ_2 from B→ρρ

The B2TIP report: https://confluence.desy.de/display/BI/B2TiP+WebHome

Isospin analysis input in B→ρρ

	Value	Belle @ 0.8 ab^{-1}	Belle2 @ 50 ab^{-1}
$f_{L,\rho^+\rho^-}$	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]	$\pm0.3 \pm 0.5$

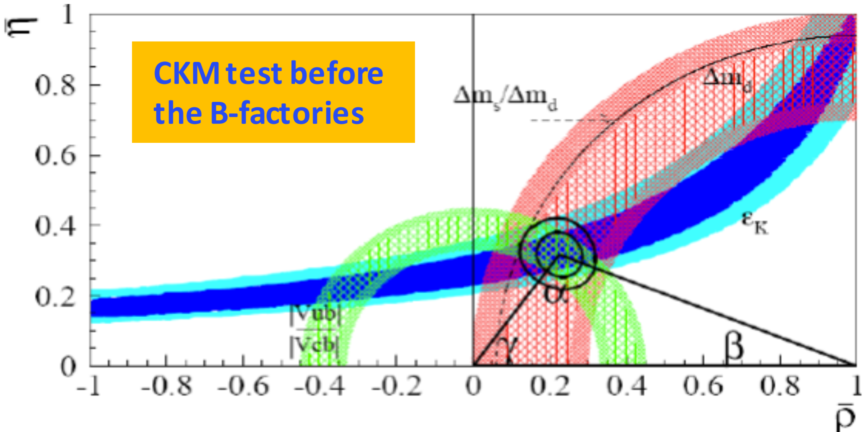
	Value	BaBar @ 0.5 ab^{-1}	Belle2 @ 50 ab^{-1}
$C_{\rho^0\rho^0}$	0.2	$\pm0.8 \pm 0.3$ [4]	$\pm0.08 \pm 0.01$
$S_{\rho^0\rho^0}$	0.3	$\pm0.7 \pm 0.2$ [4]	$\pm0.07 \pm 0.01$

[1]: PRD 93(3) 032010, [2]: Add PRD 89 no.11 119903,
[3]: PRL 91 221801, [4]: PRD 78 071104

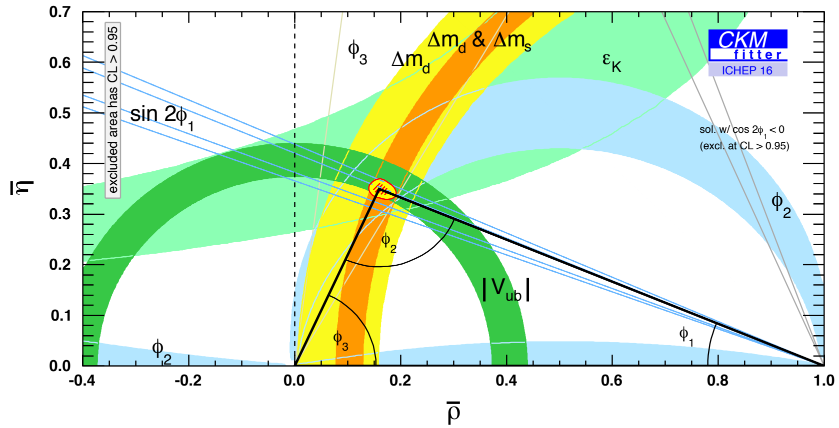
f_L: fractions of longitudinally polarized events

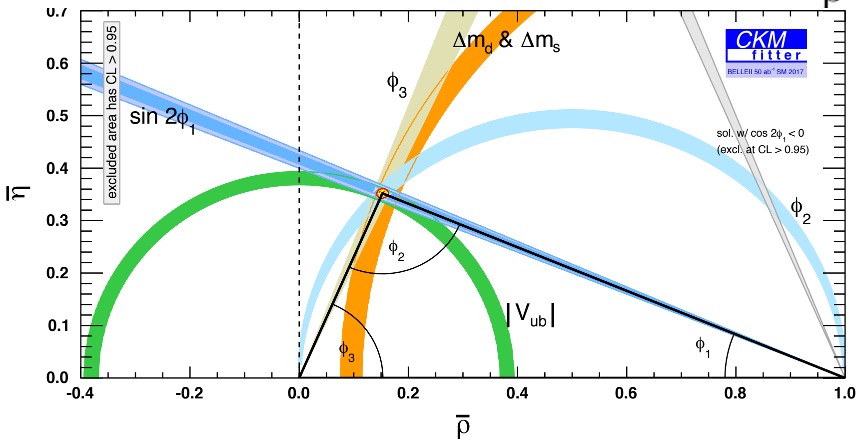
Outlook

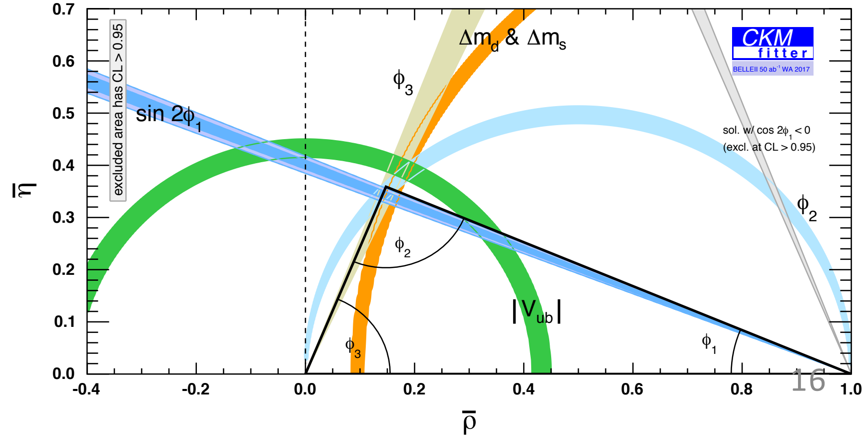
- Two key scenarios (SM-like central values and World average (ca. 2016) central values) are considered corresponding to 50 ab^{-1} data.
- All of the measurements on Belle II will greatly benefit from the accelator and detector improvements



Latest UT fit (ICHEP 2016)







Summary

- Belle has been a successful B factory, especially for CPV.
- Major upgrades of KEKB and Belle.
- CKM mechanism will be tested at 1% level on Belle II.
- Some flavor variables still to be measured precisely → therefore a lot of room for discoveries at Belle II!

Expected sensitivity on Belle II @ 50 ab^{-1}

Channel	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.0052	0.0050
ϕK^0	0.015	0.011
$\eta' K^0$	0.015	0.013
ωK^0_S	0.025	0.019
$K^0_S \pi^0 \gamma$	0.032	0.022
$K^0_S \pi^0$	0.028	0.019
$\pi^+\pi^-$	0.014	0.032
$\pi^0\pi^0$	0.032	0.29
$\rho^+\rho^-$	0.022	0.014
$\rho^0\rho^0$	0.071	0.081

Backup slides

Measurement of time dependent CP violation

time dependent indirect CP violation from interference of decay **without** mixing and decay **with** mixing