CP studies at Belle II experiment

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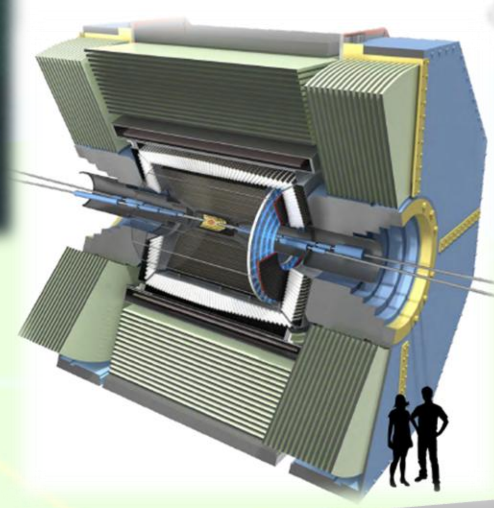


SM: successes and failures

The SM successes:

All particles have been observed

All symmetries have been confirmed and

The mechanism of symmetry breaking is established

All parameters have been measured

Essentially all experimental measurements are consistent with the SM predictions

BUT in the same time a lot of intrinsic problems

Inconsistencies at high energies (rad. corrections , UV divergences , Landau pole)

Still no unification of strong and electroweak interactions

Large number of free parameters

CP-violation is not completely understood

Flavor mixing and the number of generations is arbitrary

The origin of the mass spectrum in unclear

Most of open questions are addressed to the flavor sector

Flavor physics in the SM …

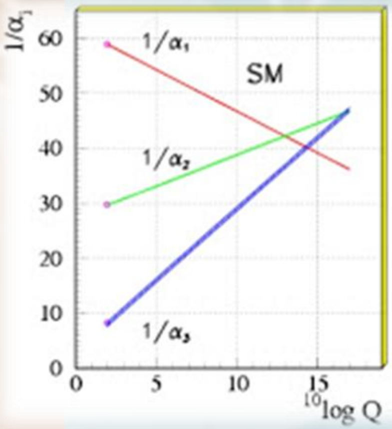
bosonic sector of the SM:

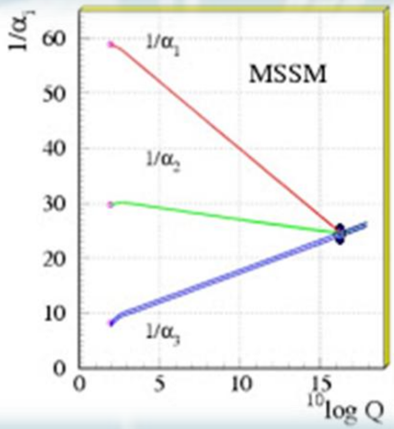
$$@1\text{GeV}: g' \sim 0.3,\quad g \sim 0.6,\ g_s \sim 0.6,\ \lambda \sim 1$$

5 free parameters:

one defines the scale

+ 4 dimensionless coupling constants





Ideally, we have to accept one scale parameter, and expect that dimensionless parameters are some geometrical constants; there is a hint that gauge constants are related to each other...

fermionic (flavor) sector (without neutrino):

3 Yukawa constants for charged leptons:

6 Yukawa constants for quarks

4 quark-mixing parameters

$$Y_t \sim 10^0,\quad Y_b \sim 10^{-2}, Y_c \sim 10^{-2},$$
$$Y_s \sim 10^{-3}, Y_u \sim 10^{-5}, Y_d \sim 10^{-5},$$
$$Y_\tau \sim 10^{-2}, Y_\mu \sim 10^{-3}, Y_e \sim 10^{-6},$$
$$|V_{ud}| \sim 1, |V_{us}| \sim 0.2, |V_{cb}| \sim 0.04,$$
$$|V_{ub}| \sim 0.004, \delta_{\text{KM}} \sim 1$$

This is a really miraculous part of the SM.
There is no idea

- **why do we have many (3) generations?**
- **why are these 13 constants such as they are?**
- **why is there a hierarchy & smallness structure?**
- **why is the mixing matrix almost unit, but not exactly?**

All these "W*hys?*": <u>The SM flavor puzzle</u>

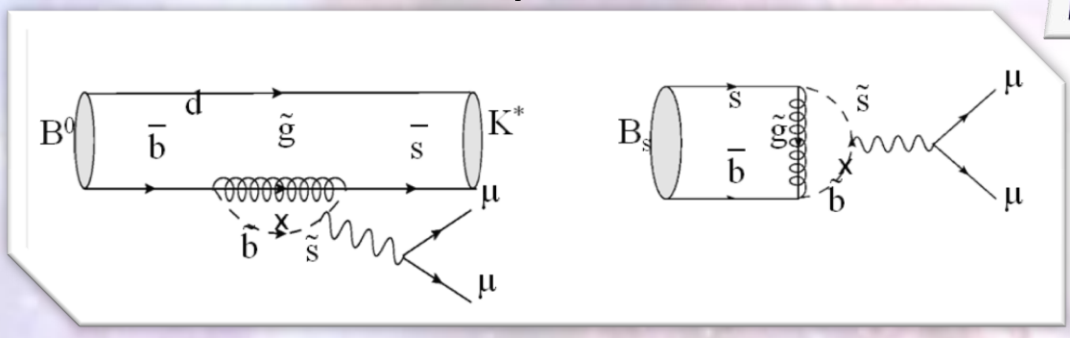
… and beyond

Beyond SM:

13 parameters are too many for a fundamental theory, but few to check consistency of the SM predictions for decay/oscillation/CP violation patterns:

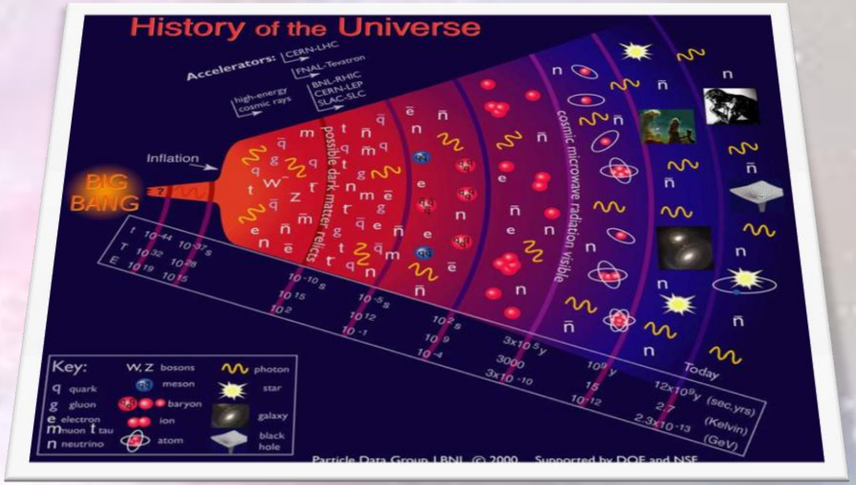
500 decays modes (Br's and UL's) for B
200 decays for D
40 decays for K (some with BR's ~ 10^{-12}!)

non-SM particles (even very heavy) run around in loops



Cosmology:

needs CP-violation



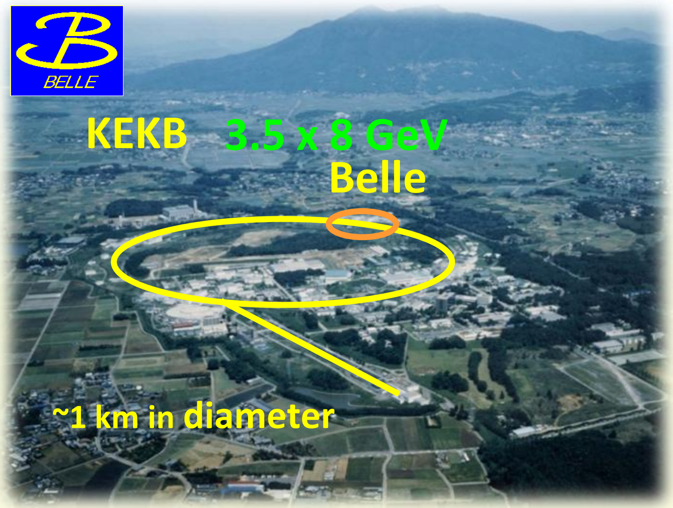
to produce baryonic asymmetry of the Universe; the only known source of CP violation is a flavor sector of the SM (though it is too small…)

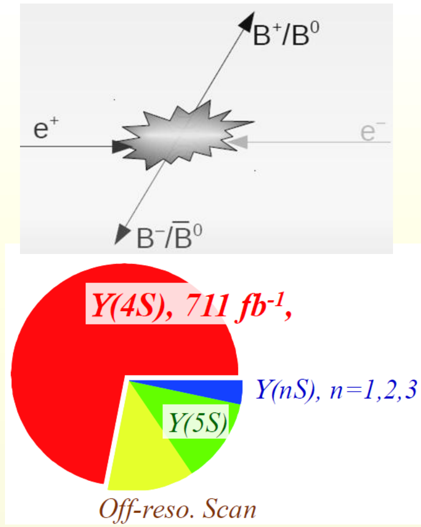
Flavor physics:
Beyond SM: measurements are sensitive to New particles
Cosmology: related to matter-antimatter asymmetry

Favor physics is in the heart of the poorly understood jungle at electroweak scale – the SM interactions

e^+e^- asymmetric B-factories

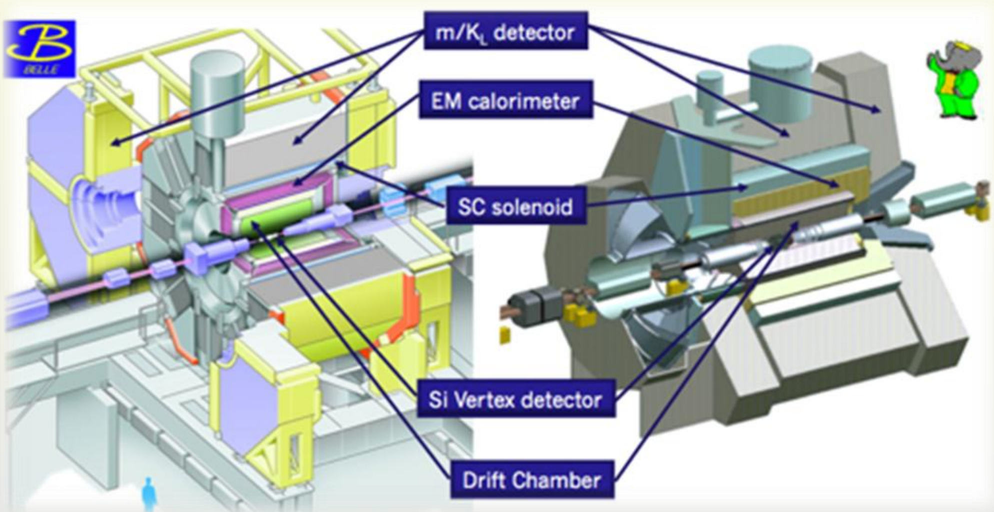
world highest luminosities

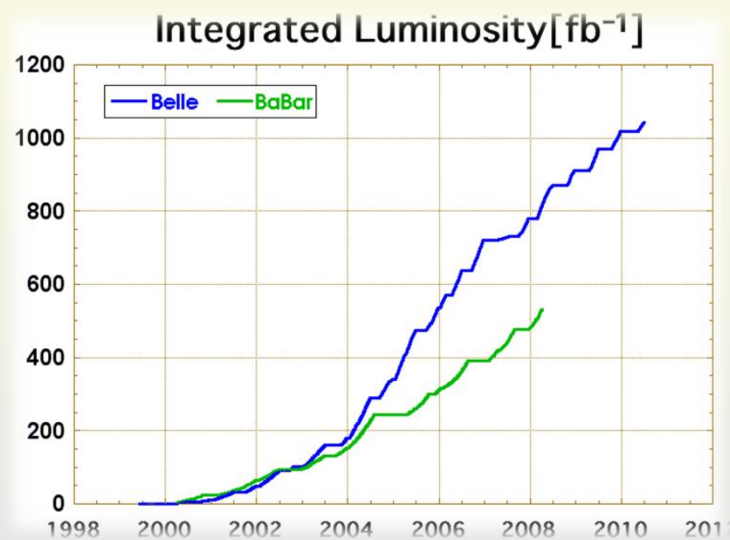




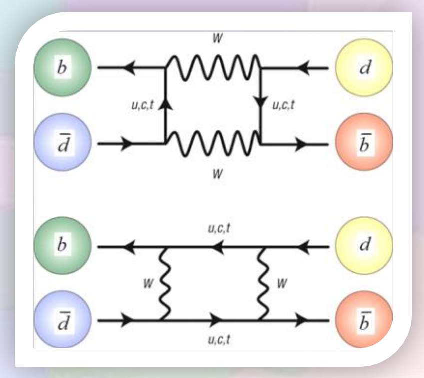
Completed data taking on June, 2010
to start SuperKEKB/Belle II upgrade

Stopped in 2008





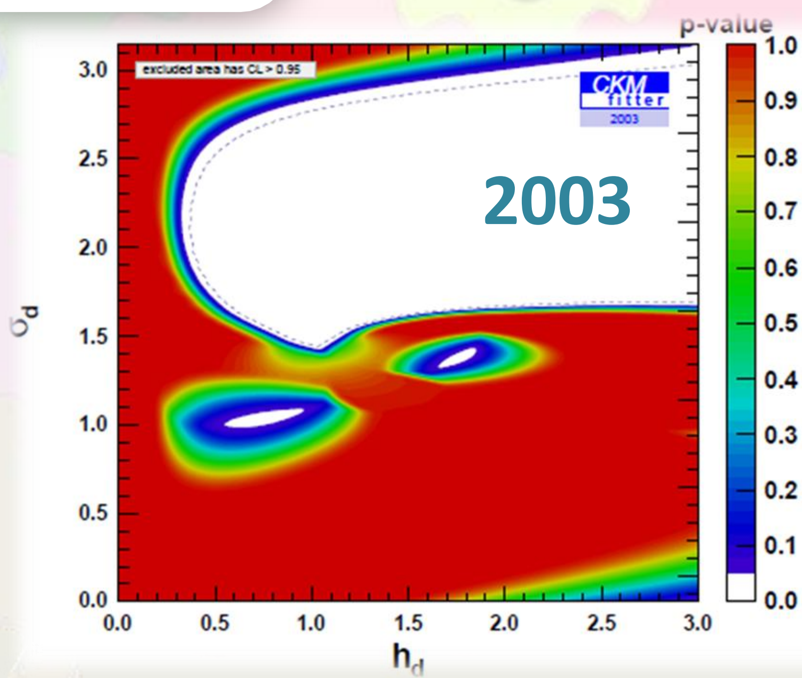
CP violation: enigmatic phenomenon & effective tool for New Physics searches

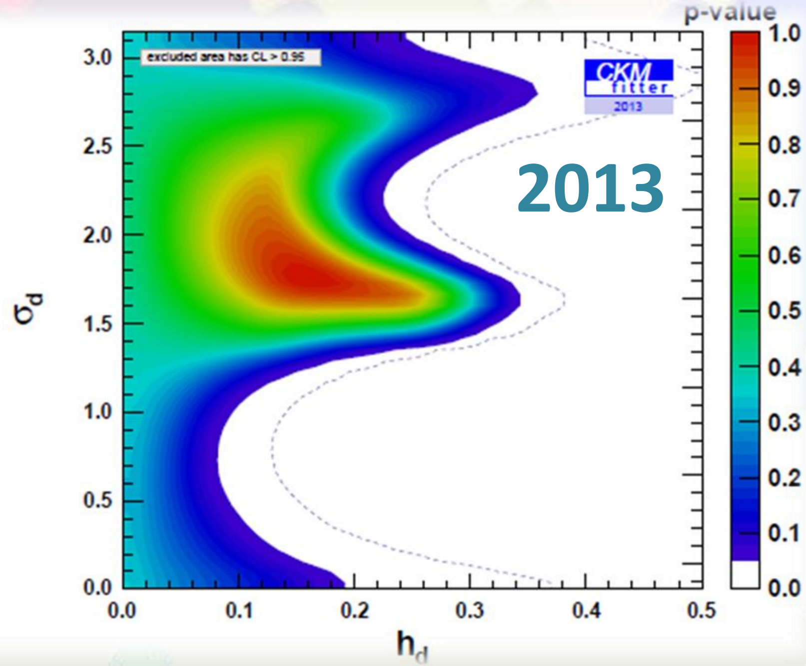


Before CP-studies at B-factories it was not known, if the SM is the main contributor to the $B^0\bar{B}^0$-mixing

$$\Delta m_d = \Delta m_d^{SM} \times (1 + h_d e^{2i\sigma})$$

NP





To continue study, SUPER B FACTORY NEEDED

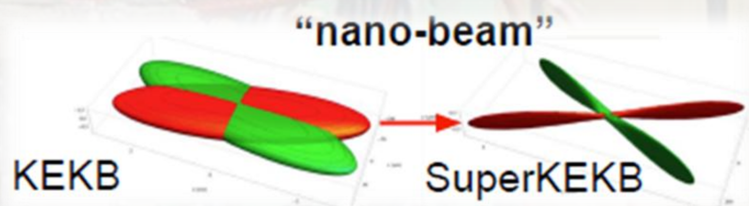
KEKB upgrade → SuperKEKB(nano-beam)

Parameter	KEKB Design	KEKB Achieved	SuperKEKB Design
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.0
β_y^* (mm)	10/10	5.9/5.9	0.27/0.30
β_x^* (mm)	330/330	1200/1200	32/25
ε_x (nm)	18/18	18/24	3.2/5.3
$\frac{\varepsilon_y}{\varepsilon_x}$ (%)	1	0.85/0.64	0.27/0.24
σ_y (μm)	1.9	0.94 (1/20 →)	0.048/0.062
ξ_y	0.052	0.129/0.090	0.09/0.081
σ_z (mm)	4	6/7	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19 (x2 →)	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity ($10^{34} cm^{-2} s^{-1}$)	1.0	2.11 (x40 →)	80

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

SuperKEKB is built in tunnel of KEKB but is almost entirely new machine:

- **× 20 smaller beam focus at interaction region**
- **Twice higher beam current**
- **First beam in 2016 → first collision in April 2018**

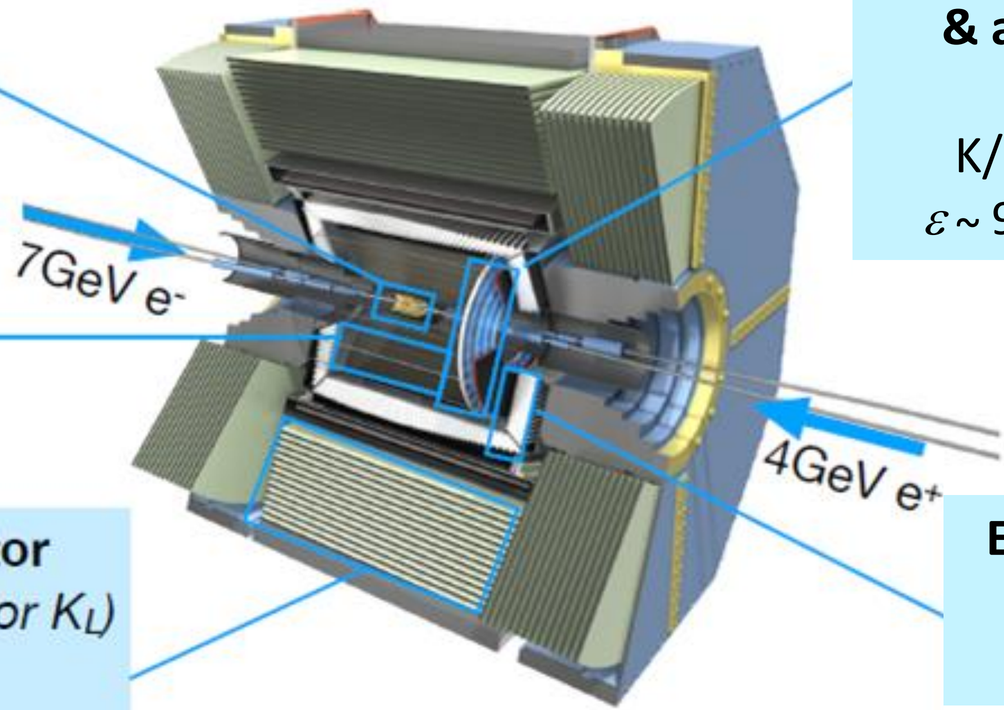


The Belle II detector

Vertex detector
Tracking
$\sigma_{z0} \sim 15\ \mu m$
(2x better than Belle)

Drift chamber
Tracking
$\sigma_{r\phi} \sim 100\ \mu m$
$\sigma_{dE/dx} \sim 5\%$

K_L and Muon detector
$\Delta\phi = \Delta\theta \sim$ *10-20 mrad (for K_L)*
μ/π separation:
$\varepsilon \sim 90\%$ @ 1.5% fake

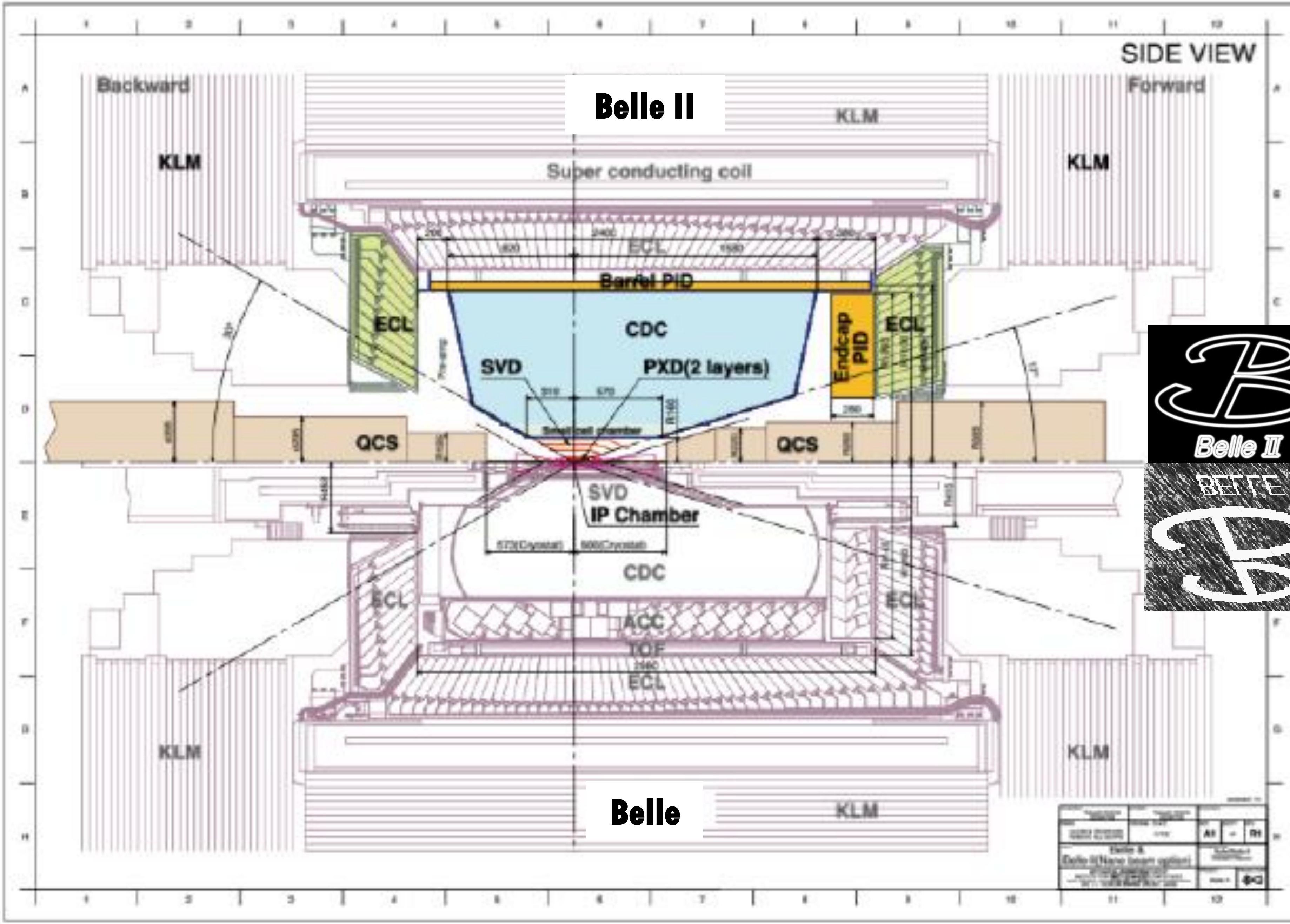


Time of propagation & aerogel RICH detectors
K/π separation
$\varepsilon \sim 90\%$ @ 5% fake

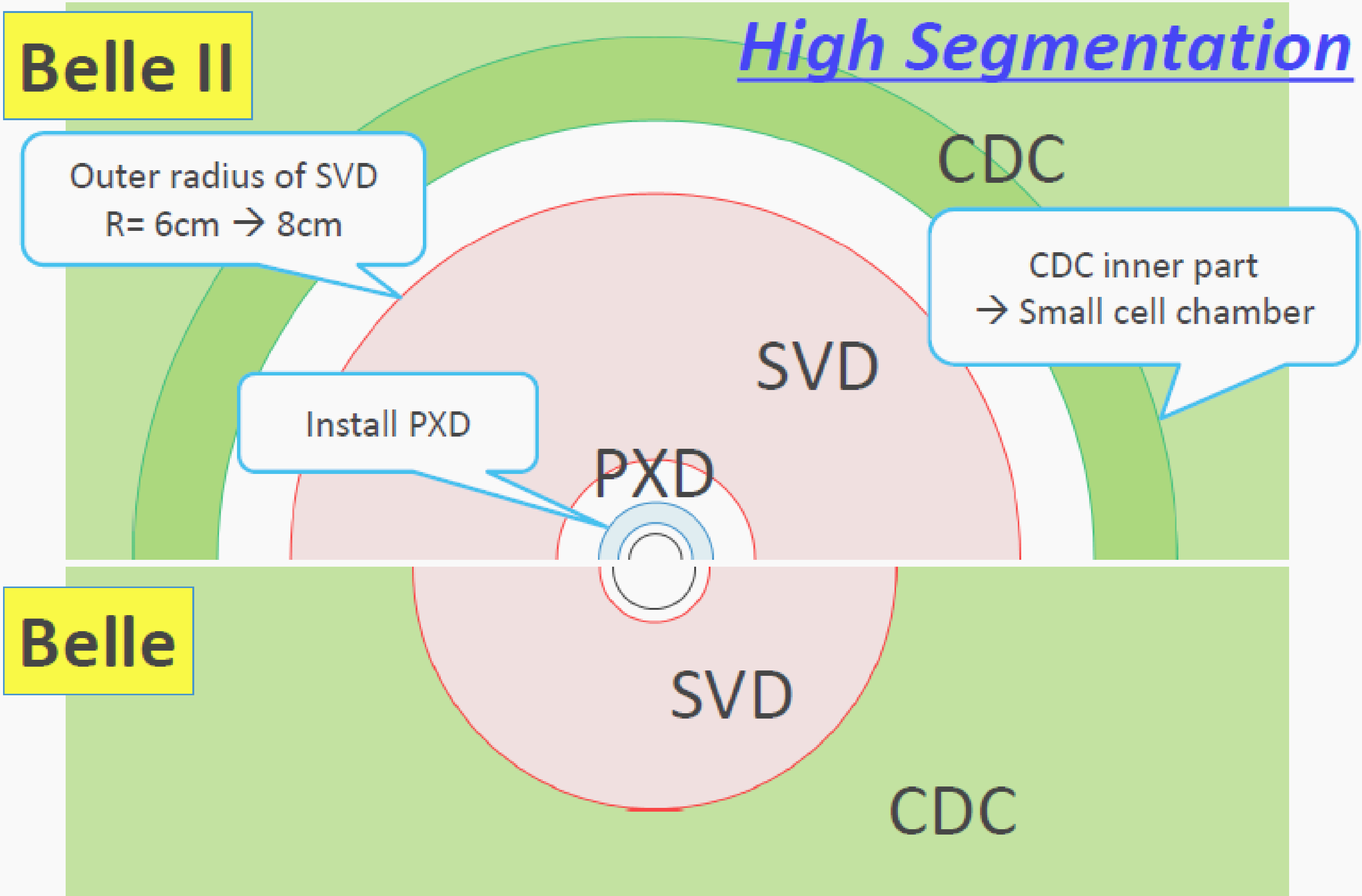
EM Calorimeter
$\sigma E/E \sim 2\%$ @
E =1 GeV

Belle II is an upgrade of the Belle detector: capable to work at much higher background environment
Highlights. *Vertex:* 2 layers of pixels, 4 layers of DS Si strips with extended coverage, *Drift chamber:* smaller cell size + longer lever arm, *PID:* new TOP + ARICH


Belle II
KEK

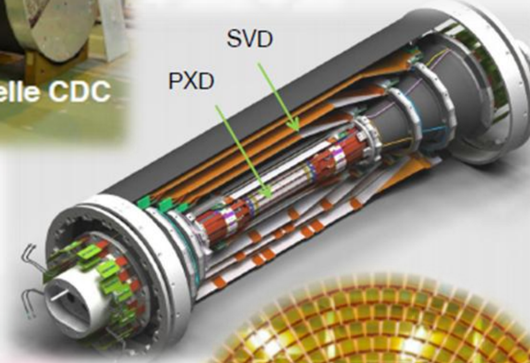

SIDE VIEW
Backward
Forward
Belle II
KLM
KLM
KLM
Super conducting coil
ECL
Barrel PID
CDC
ECL
ECL
Endcap PID
SVD
PXD(2 layers)
QCS
QCS
SVD
IP Chamber
CDC
ECL
ECL
ACC
TOF
ECL
KLM
KLM
Belle
KLM

Belle vs Belle II

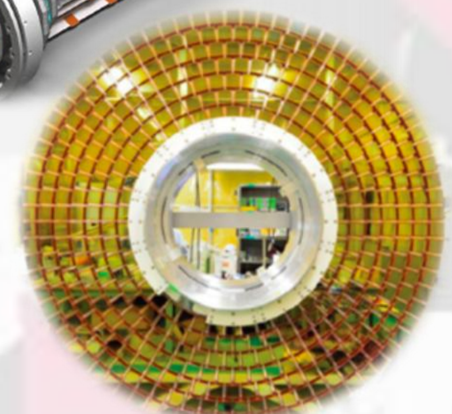


New Belle-II detector has many advantages for better CP violation studies

- ✓ ***Better tracking***
- ✓ ***Better vertexing***

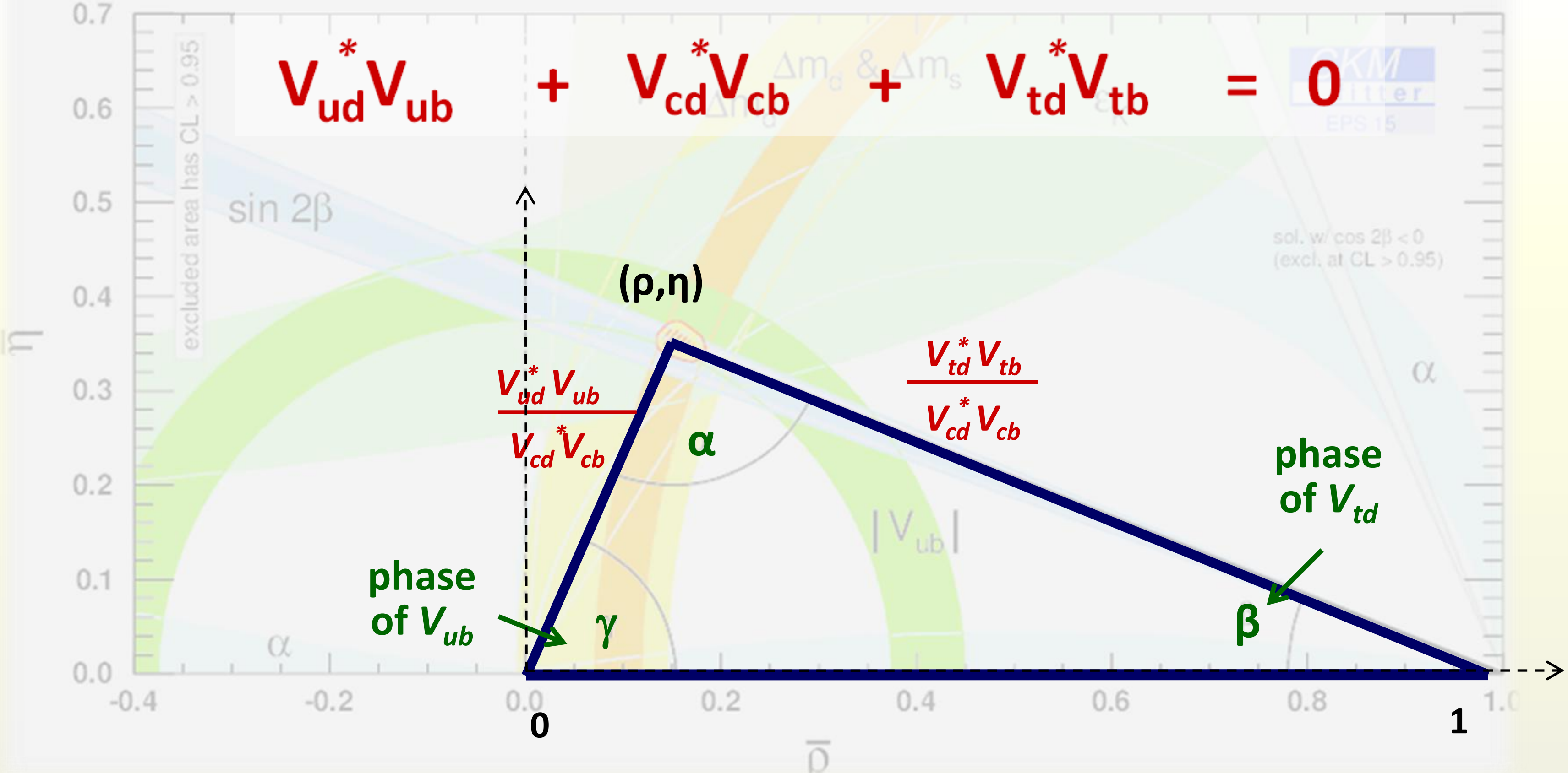


- ✓ ***Better particle identification***
- ✓ ***Better calorimeter resolution***



(in addition to the expected much larger data set)

Search for New Physics in CP violation



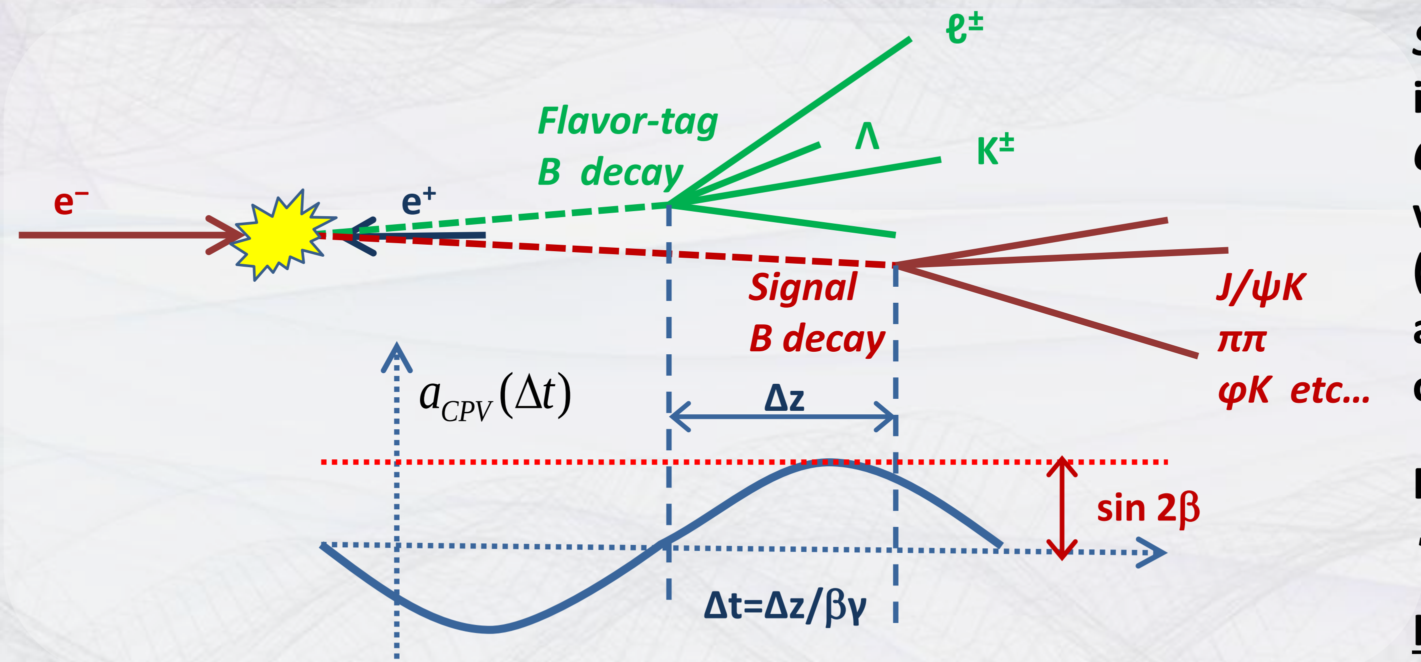
Consistency of Unitarity triangle = probe for NP at *O*(1TeV)

- UT Sides from Br's
- UT angles from CP violation

Measurement of CPV at B-factories

CPV asymmetry in the time-dependent rates for initial B/$\overline{\text{B}}$

$$a_{CPV}(\Delta t) = \frac{\Gamma_{\overline{B}\to\bar{f}}(\Delta t) - \Gamma_{B\to f}(\Delta t)}{\Gamma_{\overline{B}\to\bar{f}}(\Delta t) + \Gamma_{B\to f}(\Delta t)} = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)$$



S – parameter of indirect CP violation

C – direct CP violation parameter (non vanishing even after integration over Δt)

For $f = \bar{f} = J/\psi K_S^0$
$S = \sin 2\beta; \quad C = 0$

Important:

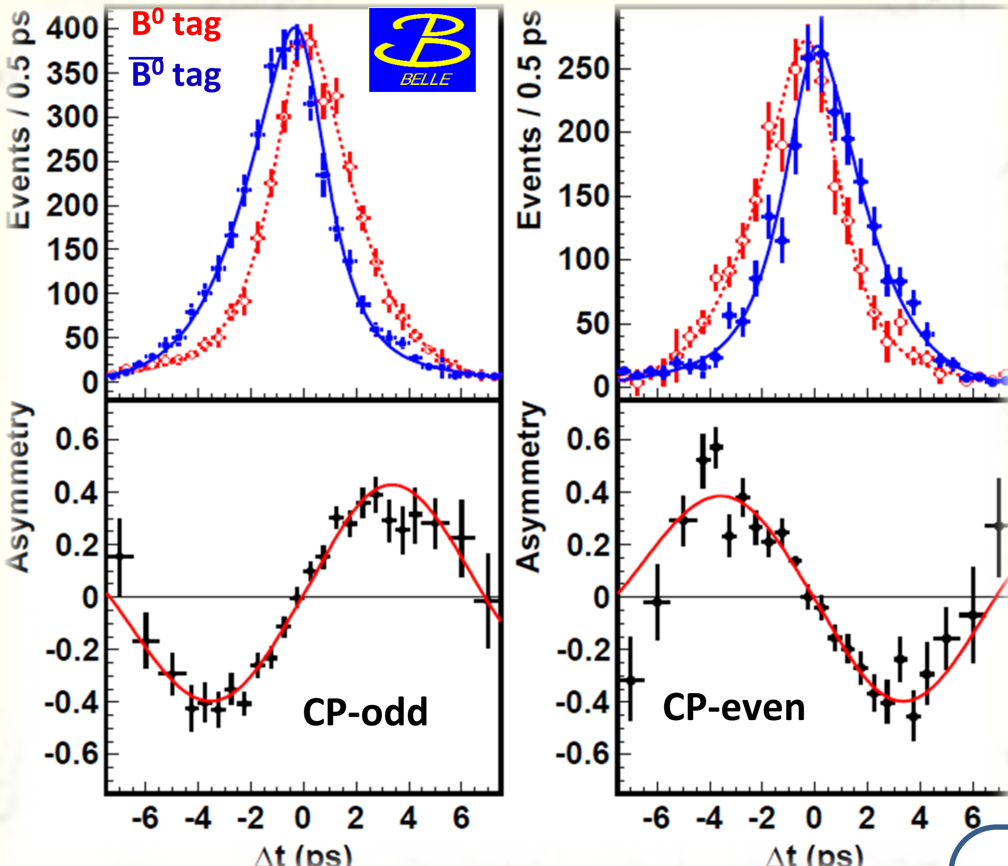
is provided by charged tracks from the second B ← Flavor tagging

β and γ are known from beam energies

Δt resolution is dominated by the resolution of z_{tag} – the tagging B-vertex (due to secondary tracks from D-decays) ← Both B-vertex finding

Precise measurement of sin(2β) in $B^0 \to c\bar{c}K^0$

Belle 2012 (0.8 ab^{-1}): $B \to c\bar{c}K^0_S$ & $B \to J/\psi K^0_L$

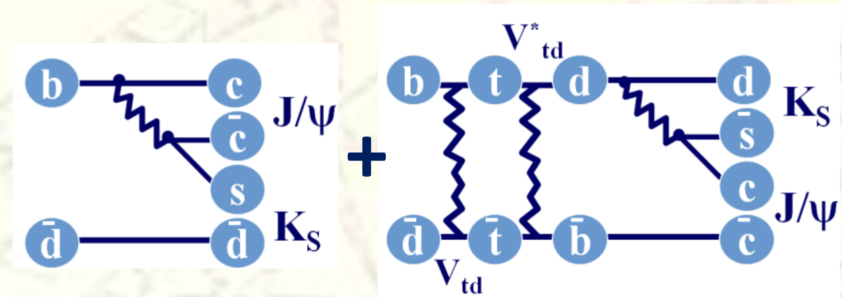


PRL 108 171208 (2012)

$\sin(2\beta) = 0.667 \pm 0.023 \pm 0.012\ (0.9^\circ)$

$A_f = 0.006 \pm 0.016 \pm 0.012$

$\Upsilon(4S) \to B^0\bar{B}^0 \to f_{CP} f_{tag}$



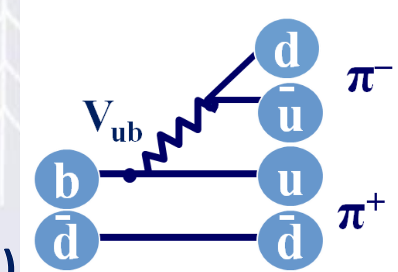
SM: $S = -\xi \sin(2\beta)$

$A = 0$ (direct CPV)

Belle II		sin(2β) LHCb	
5 ab^{-1}	50 ab^{-1}	8 fb^{-1} (2018)	50 fb^{-1}
0.4°	0.3°	0.6°	0.3°

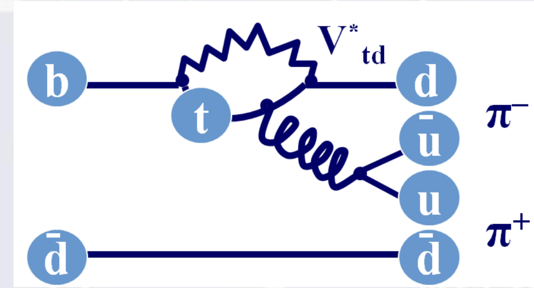
α measurements

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



The decay amplitudes $B \to \pi^+\pi^-(\rho^+\rho^-)$ include:

- tree term $T \sim V_{ub}^* V_{ud}$ (dominant)
- penguin term $P \sim V_{tb}^* V_{td}$ (suppressed, but not small)



Parameter S of indirect CPV related to effective $\alpha(\alpha_{eff})$ shifted by extra angle

$$S = \sin 2\alpha + 2r\cos\delta\sin(\alpha+\beta)\cos 2\alpha + O(r^2)$$

δ – the relative strong phase between T and P amplitudes
$r < 1$ – ratio of P to T amplitude

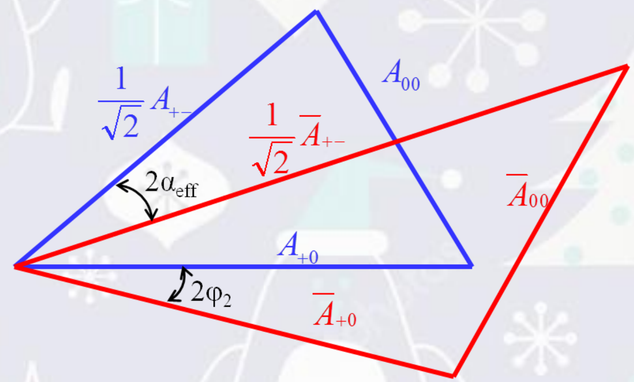
To extract α additional inputs required

$$S = \sqrt{1-C^2}\sin(2\alpha_{eff}) \qquad \alpha_{eff} = \alpha + \theta$$

The cleanest method is isospin analysis (Gronau and London)
We need to measure all 6 BR's of B^0 and B^+ to $\pi\pi$ decays: $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^+\pi^0$
Need neutral modes!

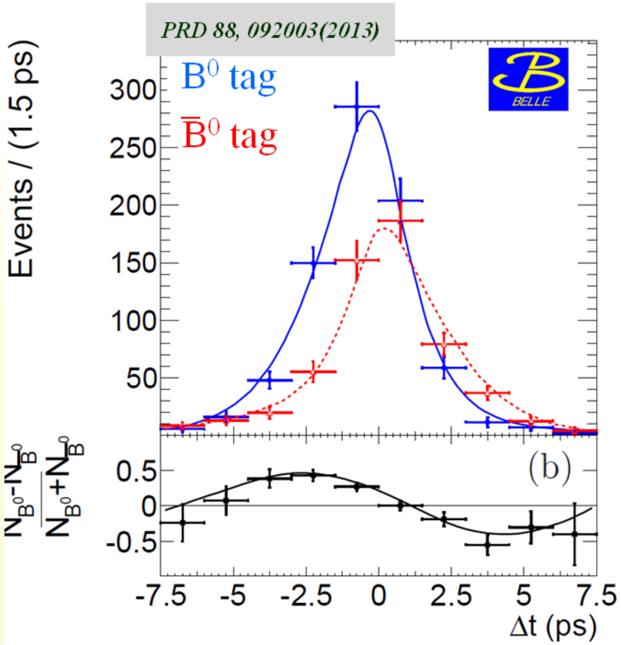
$$A_{+-} + \sqrt{2}\,A_{00} = \sqrt{2}\,A_{+0}$$
$$\overline{A}_{+-} + \sqrt{2}\,\overline{A}_{00} = \sqrt{2}\,\overline{A}_{+0}$$

$$A_{+-} = A(B^0 \to \pi^+\pi^-) = e^{-i\alpha}\,T^{+-} + P$$
$$\sqrt{2}\,A_{00} = \sqrt{2}\,A(B^0 \to \pi^0\pi^0) = e^{-i\alpha}\,T^{00} + P$$
$$\sqrt{2}\,A_{+0} = \sqrt{2}\,A(B^+ \to \pi^+\pi^0) = e^{-i\alpha}\,(T^{00} + T^{+-})$$



Isospin triangles

α: experimental results

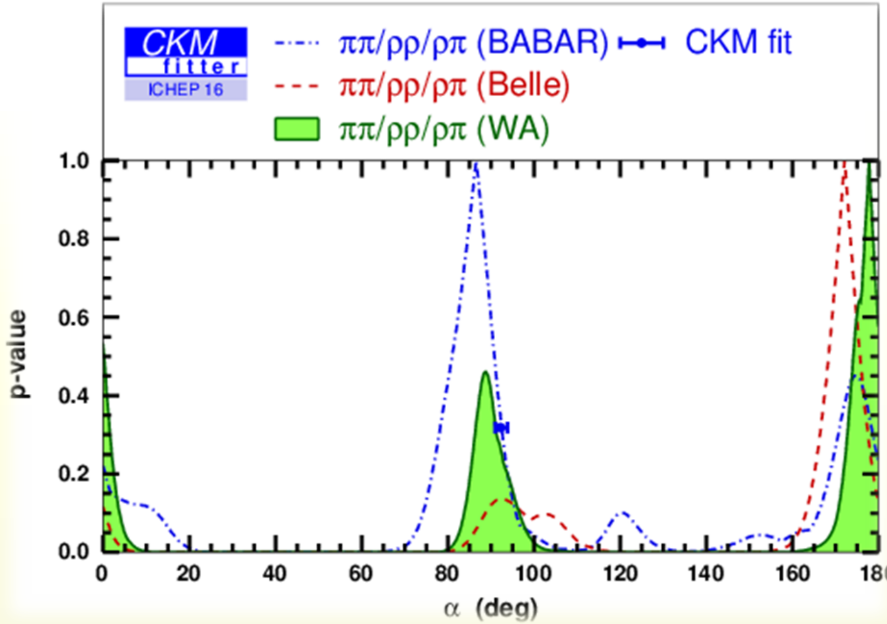


$B^0 \to \rho^0\rho^0$

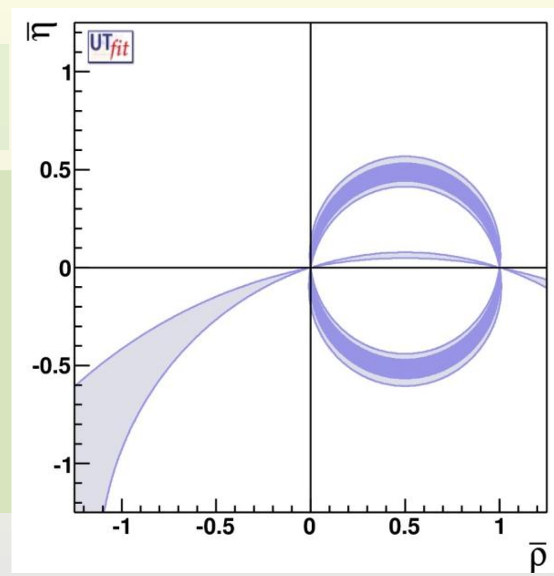
- angular analysis
- purely CP=+1 final state
- small Br, small penguin contribution

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

not CP eigenstate, but B^0 can decay to both $\rho^+\pi^-$ and $\rho^-\pi^+$



$$\alpha_{WA} = (88.8^{+2.3}_{-2.3})^\circ \bigcup (177.8^{+3.7}_{-4.9})^\circ$$



- Complicated analysis (especially for $\rho^0\rho^0$)
  - method was checked many times by Belle & BaBar
  - Belle & BaBar consistent results
- Statistics limited (not systematic)
- B factories only (a lot of neutrals in the final states)

α-measurements at Belle II

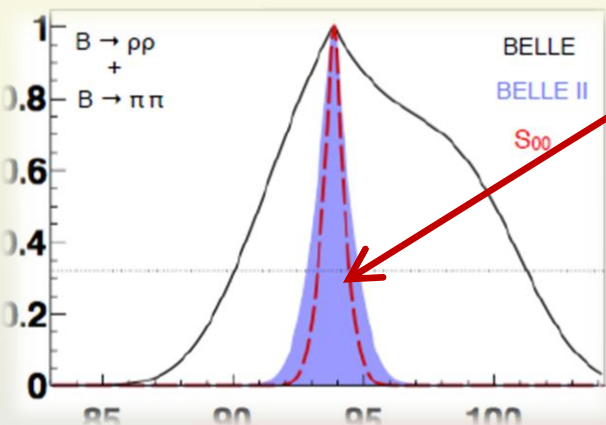
Inputs for isospin analysis

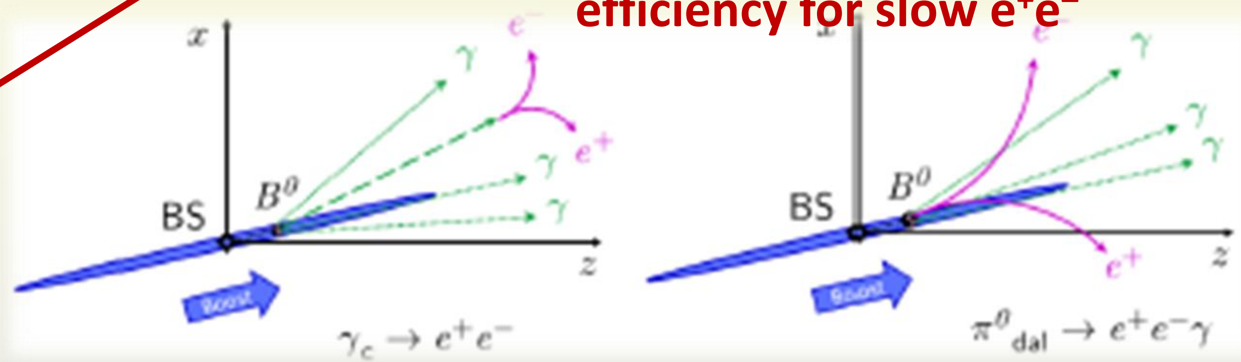
	Value	Belle 0.8 ab^{-1}	Belle-II 50 ab^{-1}
Br($\pi^+\pi^-$)	5.04	±0.21±0.18	±0.03±0.08
Br($\pi^0\pi^0$)	1.31	±0.19±0.18	±0.04±0.04
Br($\pi^+\pi^0$)	5.86	±0.26±0.38	±0.03±0.09
C($\pi^+\pi^-$)	−0.33	±0.06±0.03	±0.01±0.03
S($\pi^+\pi^-$)	−0.64	±0.08±0.03	±0.01±0.01
C($\pi^0\pi^0$)	−0.14	±0.36±0.12	±0.03±0.01
S($\pi^0\pi^0$)	?	–	±0.29±0.03

New constraint at Belle II
indirect CPV in $B^0 \to \pi^0\pi^0$

Need to reconstruct decay vertex of $B^0 \to \pi^0\pi^0$

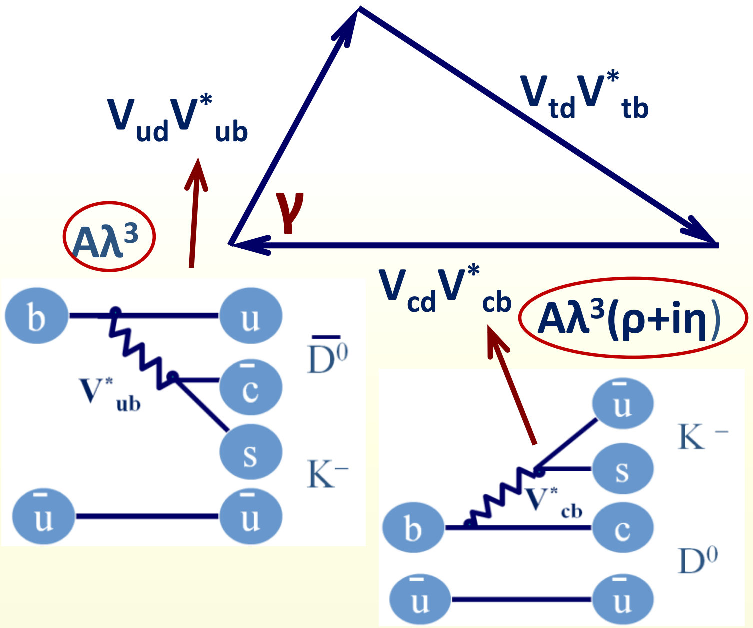
- Use converted photons and $\pi^0 \to \gamma e^+e^-$ decays (4 photons + π^0 Dalitz)
- More material budget for conversion wrt Belle
- Nice resolution & higher rec. efficiency for slow e^+e^-





Expected errors at Belle II: 5 ab^{-1} to be 2°, 50 ab^{-1} to be 1°

Direct CPV and angle γ

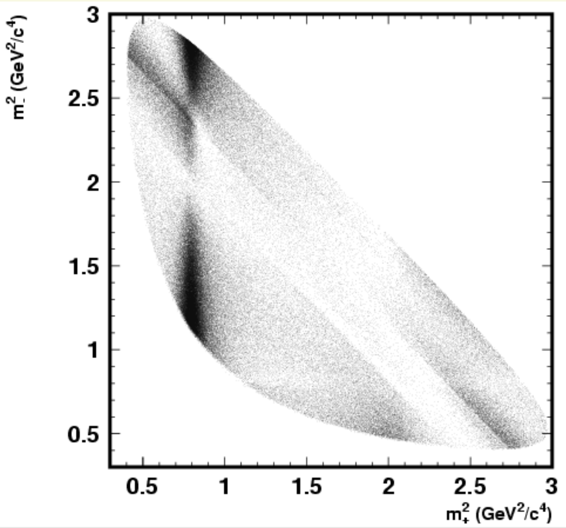


B→DK: the angle between two amplitudes is really γ, but the final states are different $D^0 \neq \overline{D^0}$

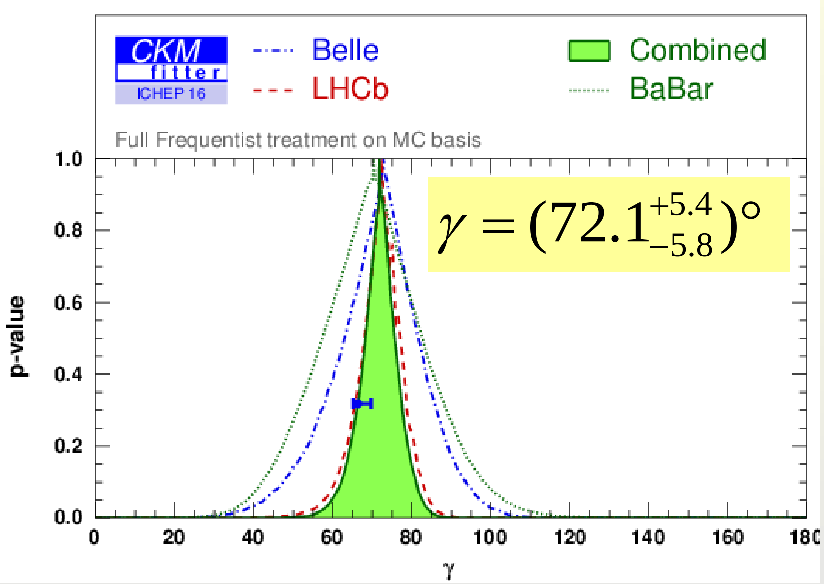
- **GLW method: use D^0 decays into two-body CP eigenstates, *e.g.* $D^0 \to K^+ K^-$**
- **GGSZ/Belle method: Dalitz analysis of 3-body final state, *e.g.* $D^0 \to K_S^0 \pi^+ \pi^-$**

Measure B^+/B^- asymmetry across Dalitz plot

$$A_\pm = f\left(m_+^2, m_-^2\right) + r_B e^{\pm i\gamma} e^{i\delta} f\left(m_-^2, m_+^2\right)$$

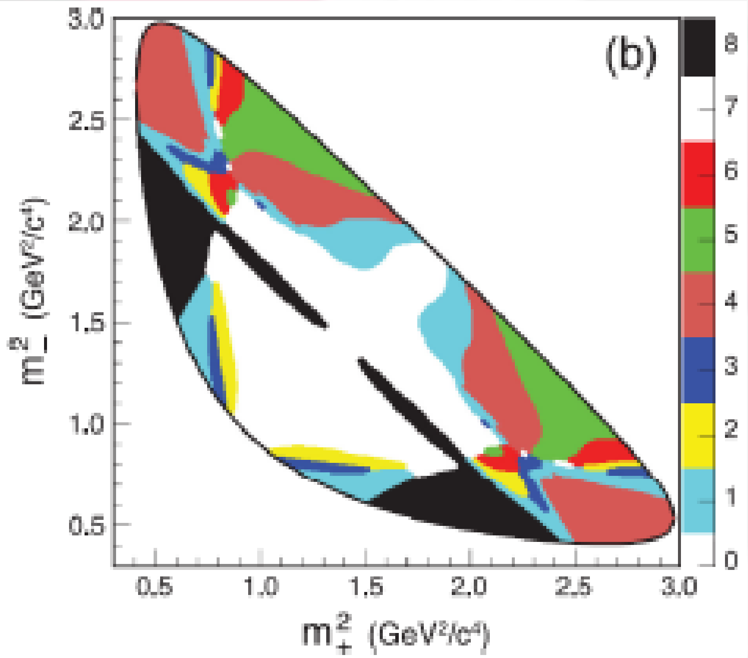


The accuracy of present measurements are limited by statistics.
The systematic and model uncertainties are much smaller.



γ at Belle II and LHCb

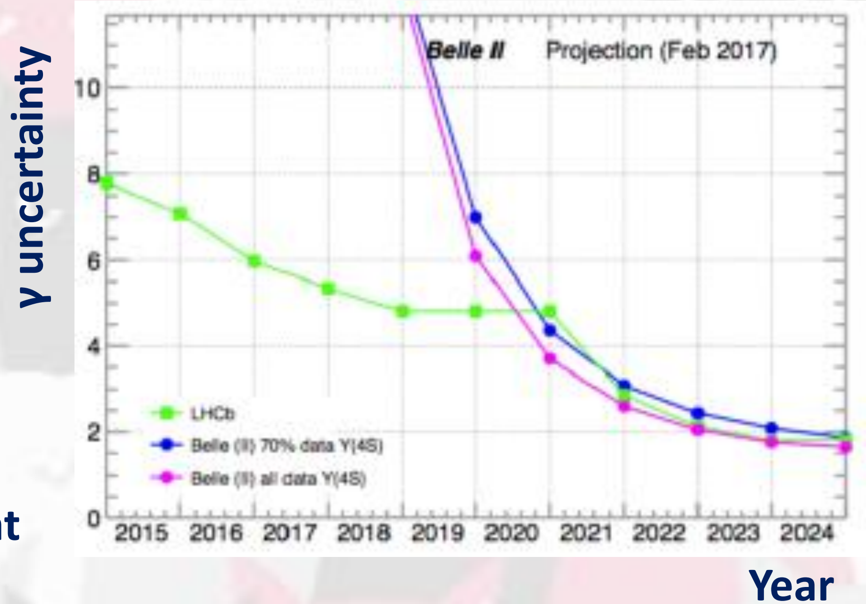
Continue in future with these two methods. But model uncertainties will become critical for Dalitz method with more data and reduced statistical errors. Propose to use $D^0 \to K_S^0 \pi^+ \pi^-$ binned plot from CP tagged data at charm-factory. Tried with CLEO data.

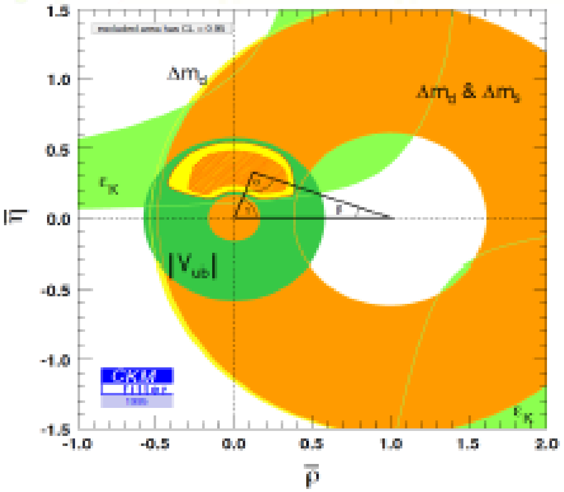


Extrapolation is done assuming BESIII data at ψ(3770) is ~ 10/fb

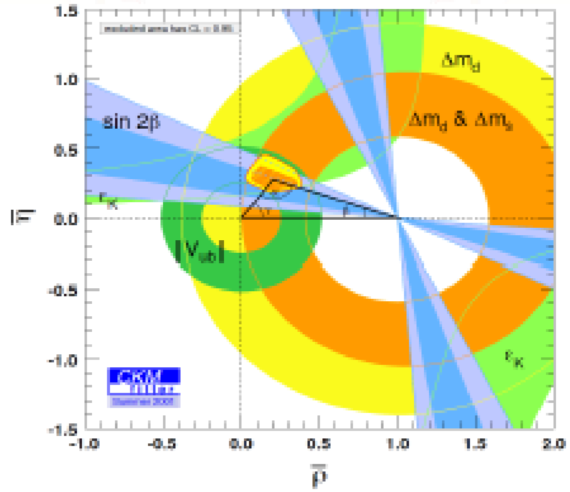
Sensitivity of Belle II and LHCb upgrade

	LHCb	Belle II
B→DK with D→hh	1.3°	2.0°
B→DK with $D \to K_S^0\pi\pi$	1.9°	2.0°
Total	**1.1°**	**1.5°**
Time dependent $B_s \to D_s K$	2.4°	

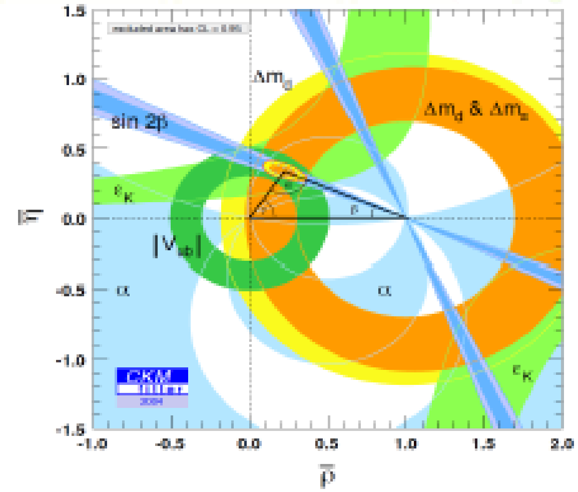




1995

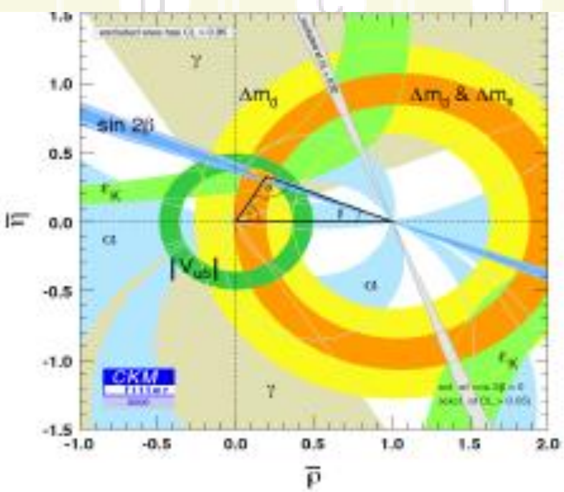


2001

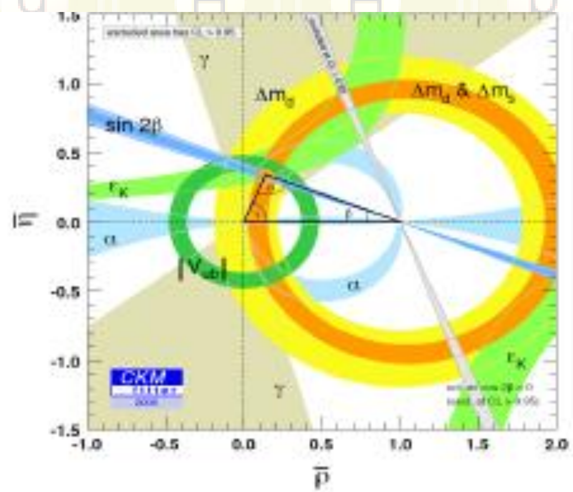


2004

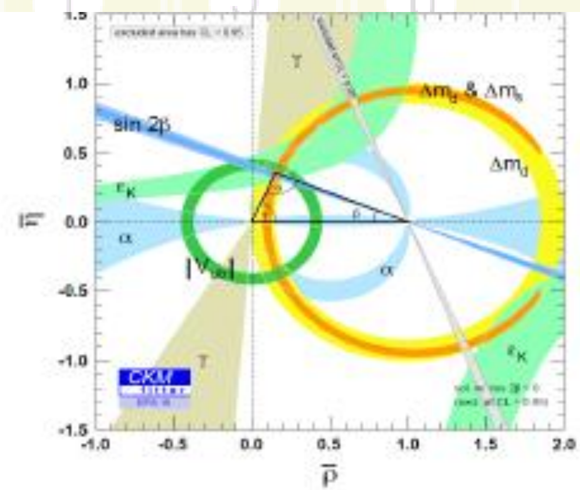
Unitarity triangle: two decades history



2006

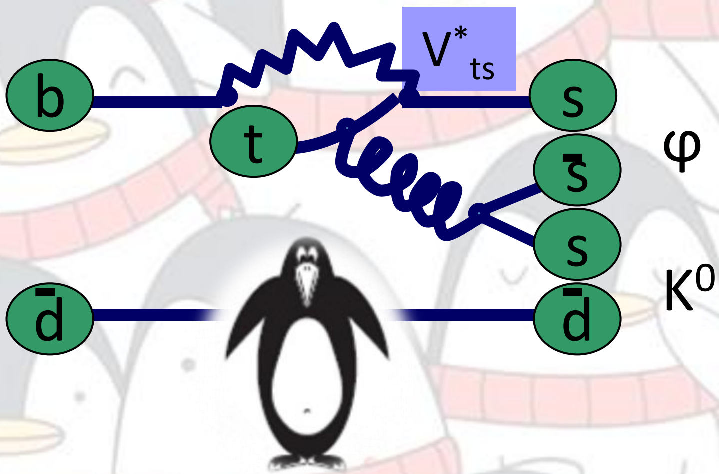


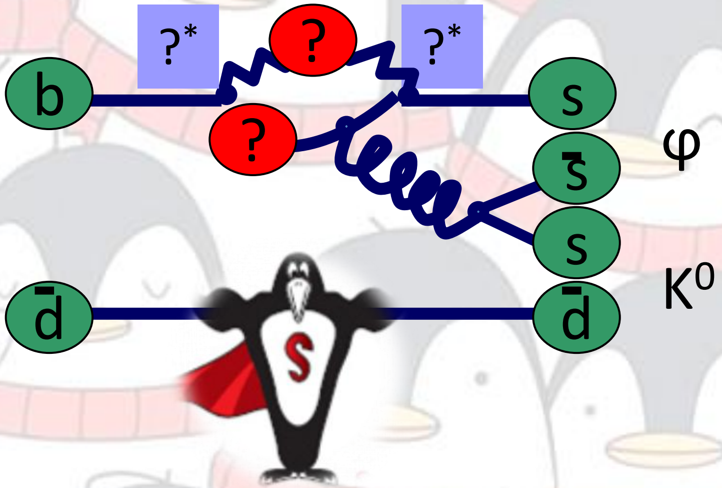
2009



2015

CP violation in hadronic penguin modes





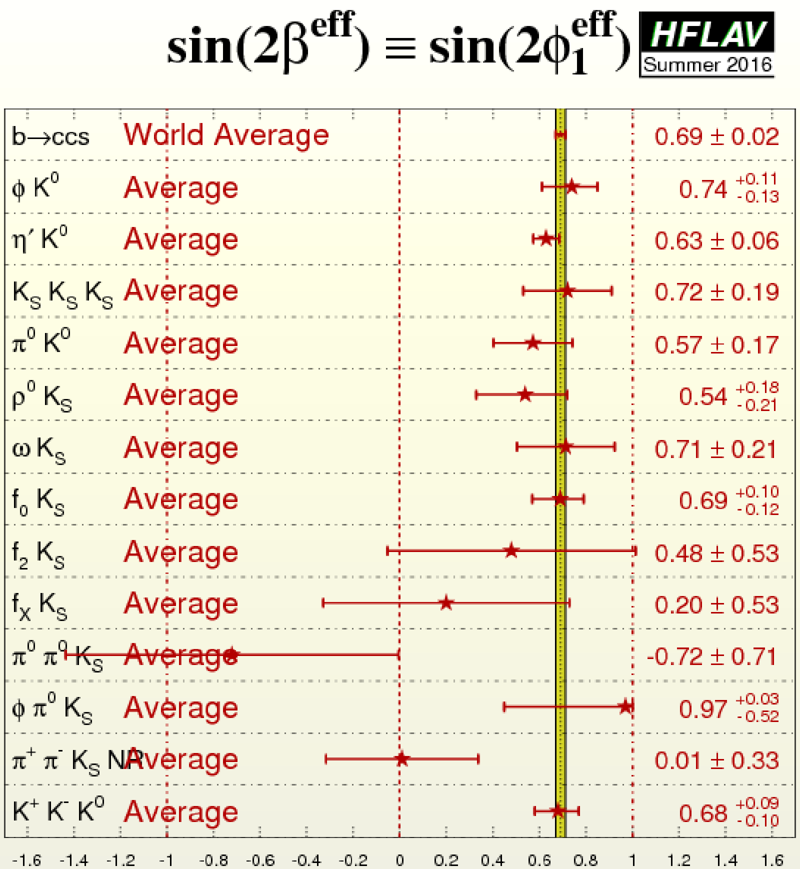
SM: No tree contribution!

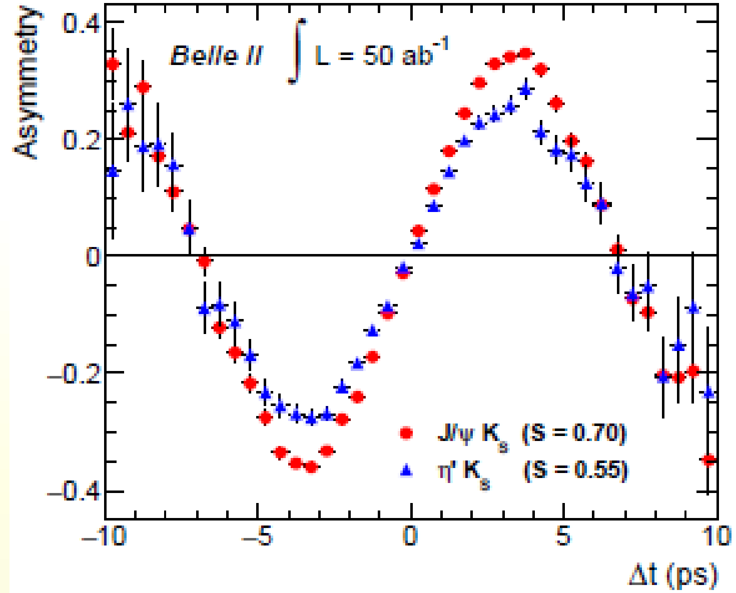
indirect CP asymmetry should be ≡ sin2β, direct asymmetry ≡ 0

Theoretical uncertainty $\sin 2\varphi^{eff} = \sin 2\beta + O(0.01\text{-}0.03)$ is much smaller than the current experimental errors!

NP: Any new heavy particles (*e.g.* SUSY) can enter loop (at the same order as SM) and change $\sin 2\varphi^{eff}$

$\sin 2\varphi^{eff}$ at Belle II



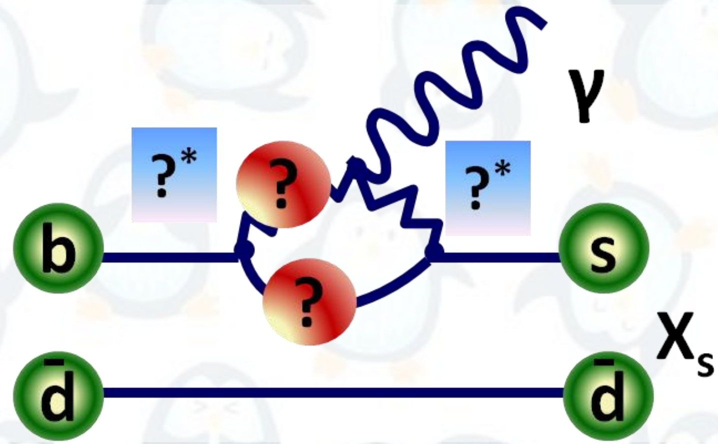


Indirect CPV as indication on NP for $J/\psi K^0$ and $\eta' K^0$ at Belle II 50/ab

Channel	σ(S)	σ(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
ϕ(all modes) $(K_S^0 + K_L^0)$	0.015	0.011
$\eta'(\eta_{\gamma\gamma}\pi^+\pi^-)\ K_S^0(\pi^+\pi^-)$	0.019	0.013
$\eta'(\eta_{3\pi}\pi^+\pi^-)\ K_S^0(\pi^+\pi^-)$	0.035	0.025
η(all modes) $(K_S^0 + K_L^0)$	0.0085	0.0063

Belle II will reach the statistical accuracy ~ theoretical uncertainty

CP violation in radiative penguin modes



SM: Definite prediction of photon helicity $B^0 \to X_s \gamma_R$; $\bar{B}^0 \to X_s \gamma_L$

The final states are different ➔ no time dependent CPV;

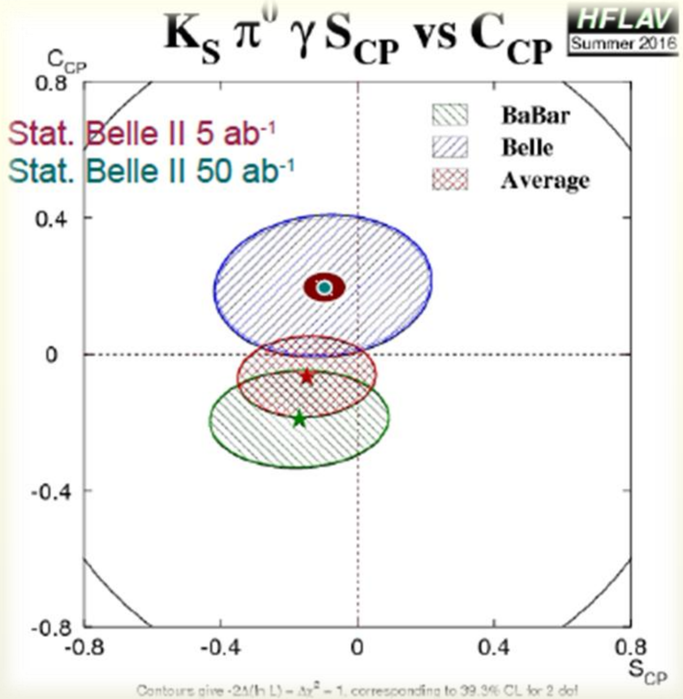
SM corrections are ~$m_s/m_b \approx 0.05$…

NP: New contribution with different Lorentz structure can result in sizable indirect CP violation

ICPV in radiative modes at Belle II

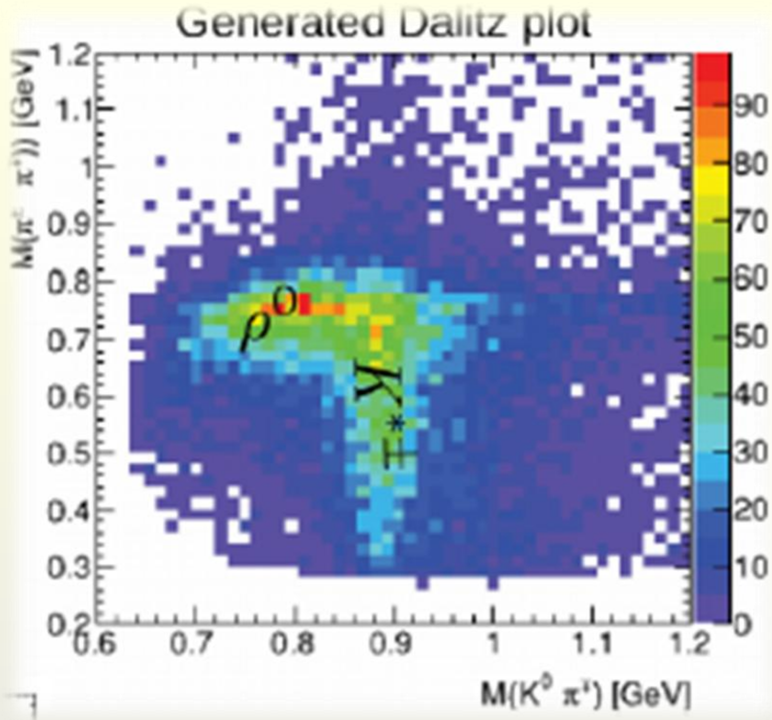
Need neutral mode

- $B \to (K_S \pi^0)\gamma$ decay vertex is provided by extrapolation of K_S vertex to IP (checked at Belle to work nicely)



Channel	σ(S)	σ(C)
$(K_S \pi^0)\gamma$ current accuracy	0.20	0.12
$(K_S \pi^0)\gamma$ Belle II 50/ab	0.032	0.022

- Also $B \to (K_S \pi^+\pi^-)\gamma$ with better vertexing can be used. However, this mode requires Dalitz analysis

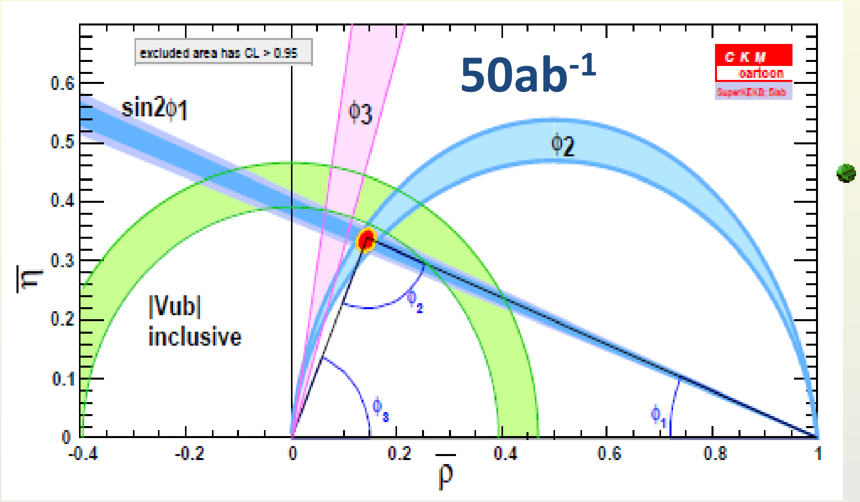


Summary I

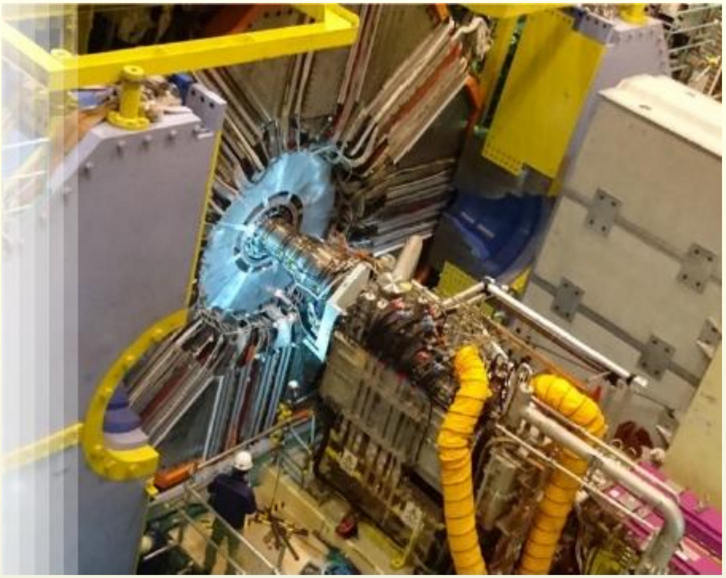
Physics beyond the Standard Model has successfully avoided detection up to now. But we are sure it is somewhere nearby.

Up to now the sensitivity of Flavor experiments to New Physics amplitude was ~10% of those from the SM; in 5-10 years it will be improved by an order of magnitude.

- **Rich physics program for Belle II**
- **Belle II is healthy and started data taking in 2018**
- **Belle II goal of 50/ab will provide great sensitivity and complimentarity to LHCb information in many areas of flavor, CPV and related fields**



- **We hope to observe something like THIS in 5-7 years**



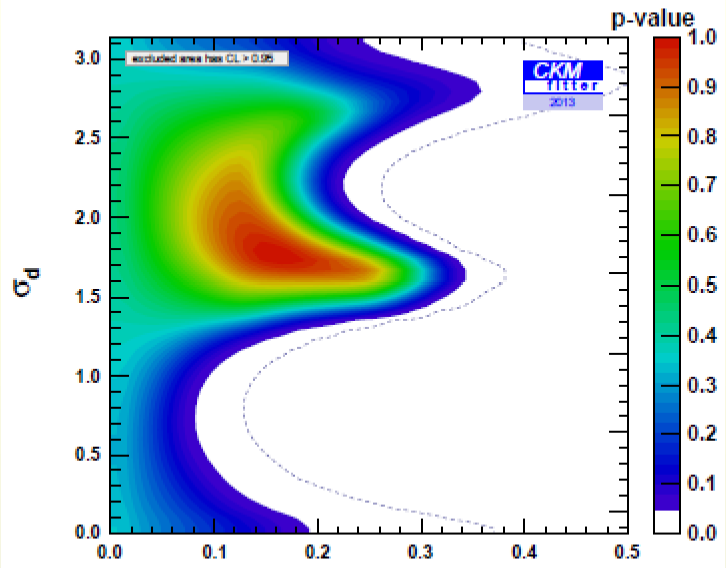
UT 2014		Belle II
α	4° (WA)	1°
β	0.8° (WA)	0.2°
γ	8.5° (WA) 14°(Belle)	1-1.5°

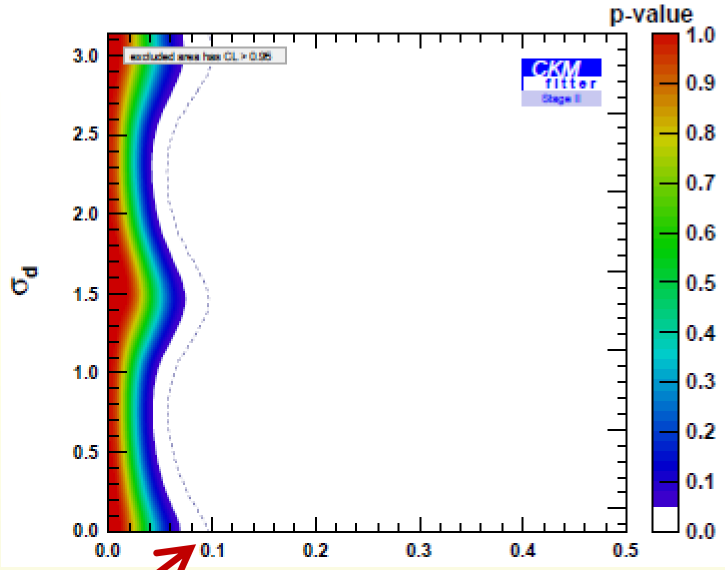
Summary II

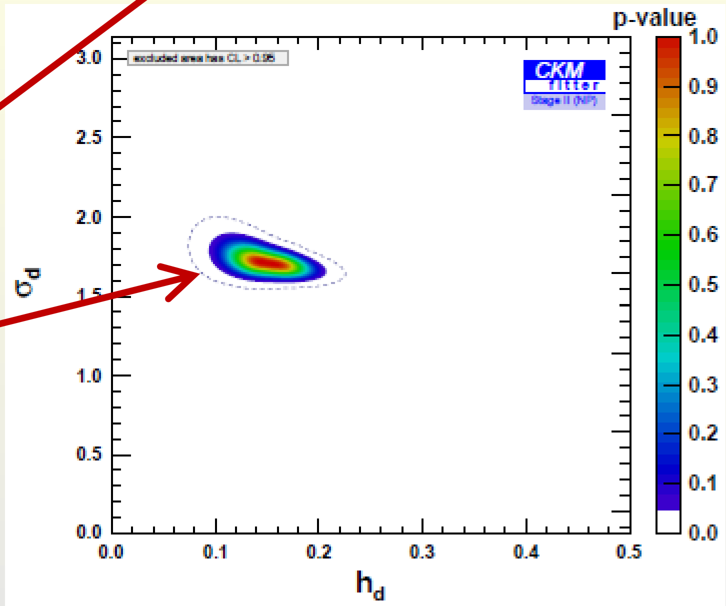
$$\Delta m_d = \Delta m_d^{SM} \times (1 + h_d e^{2i\sigma})$$

NP

Now we are here:







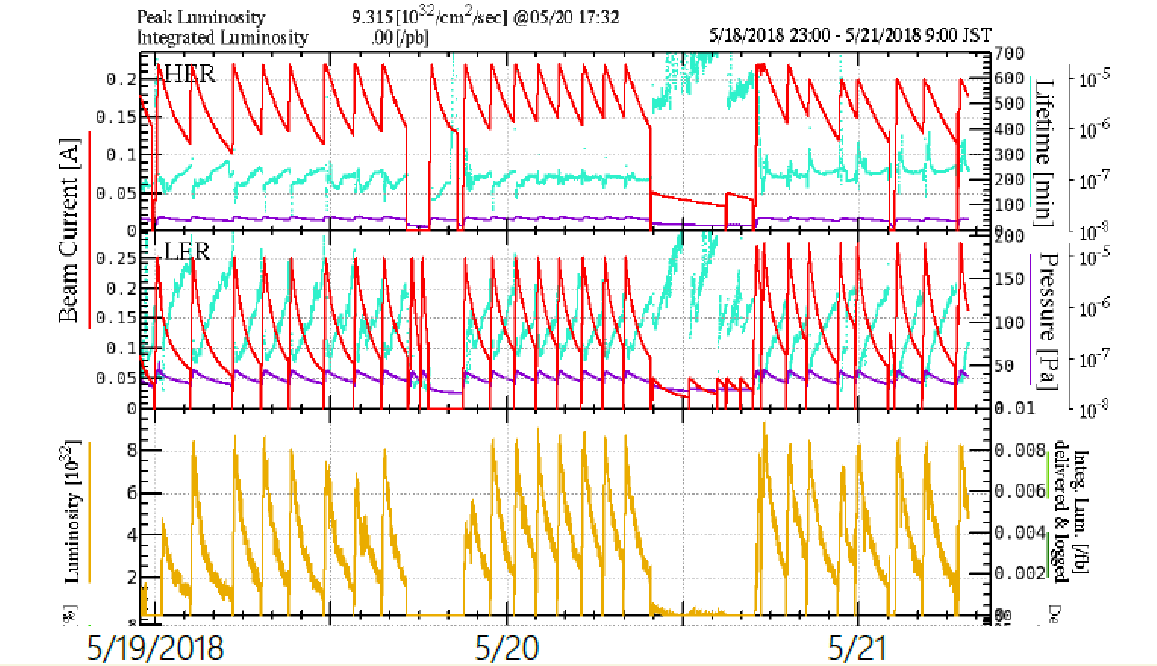
Two scenarios:

- **Improve UL by a factor of 5-10**
- **or observe something new!**

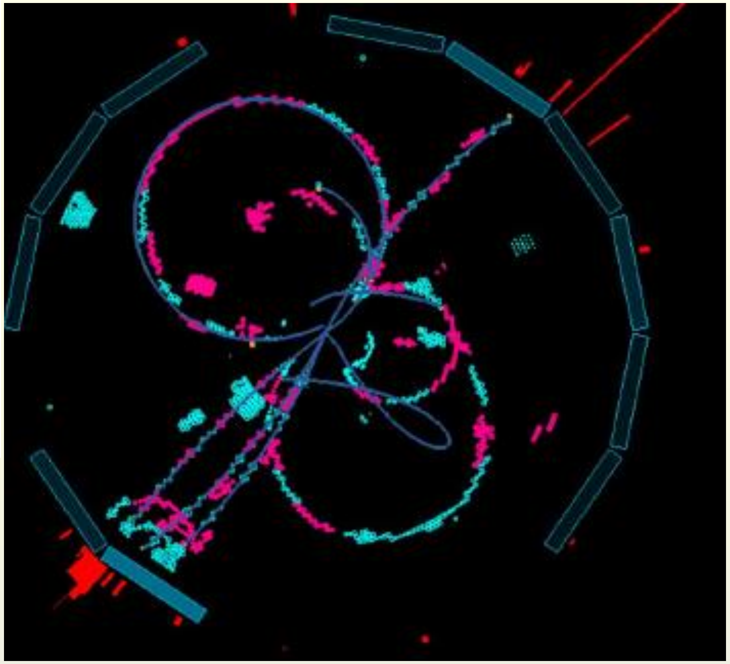
Summary III

Y. Ohnishi, Y. Funakoshi

L_{peak} = 9.3 x 10^{32} /cm²/s @ 5/20/2018



Belle II + SuperKEKB have successfully started operation



... the first hadronic event recorded at Belle II!

From January 2019 -- phase III: add vertex detector (Belle II full set) and perform long run for CP violation studies

T H A N K   Y O U !