Flavor Physics

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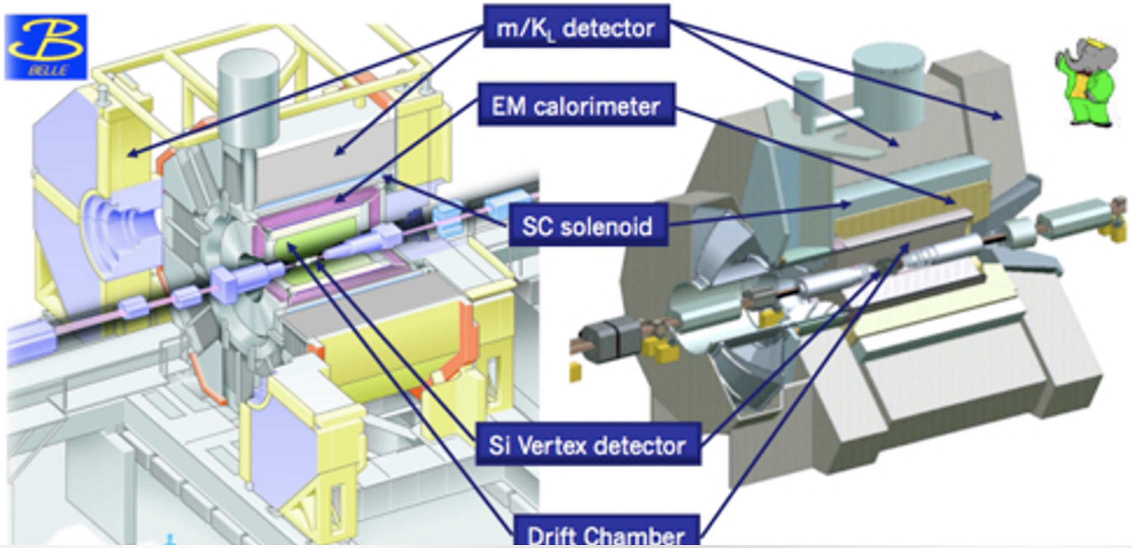
Lecture 4

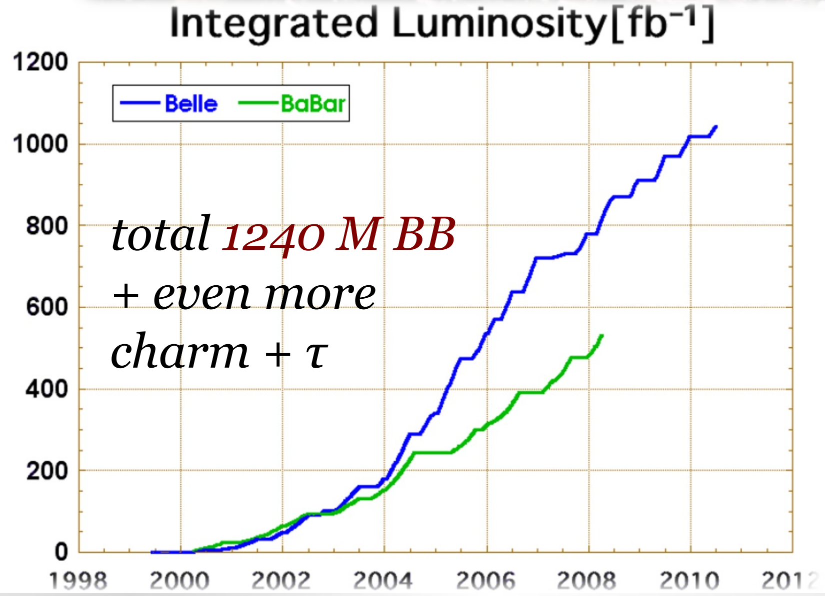
Results

Where we discuss why after 20 years of hard work that failed to observe New Physics we still not give up

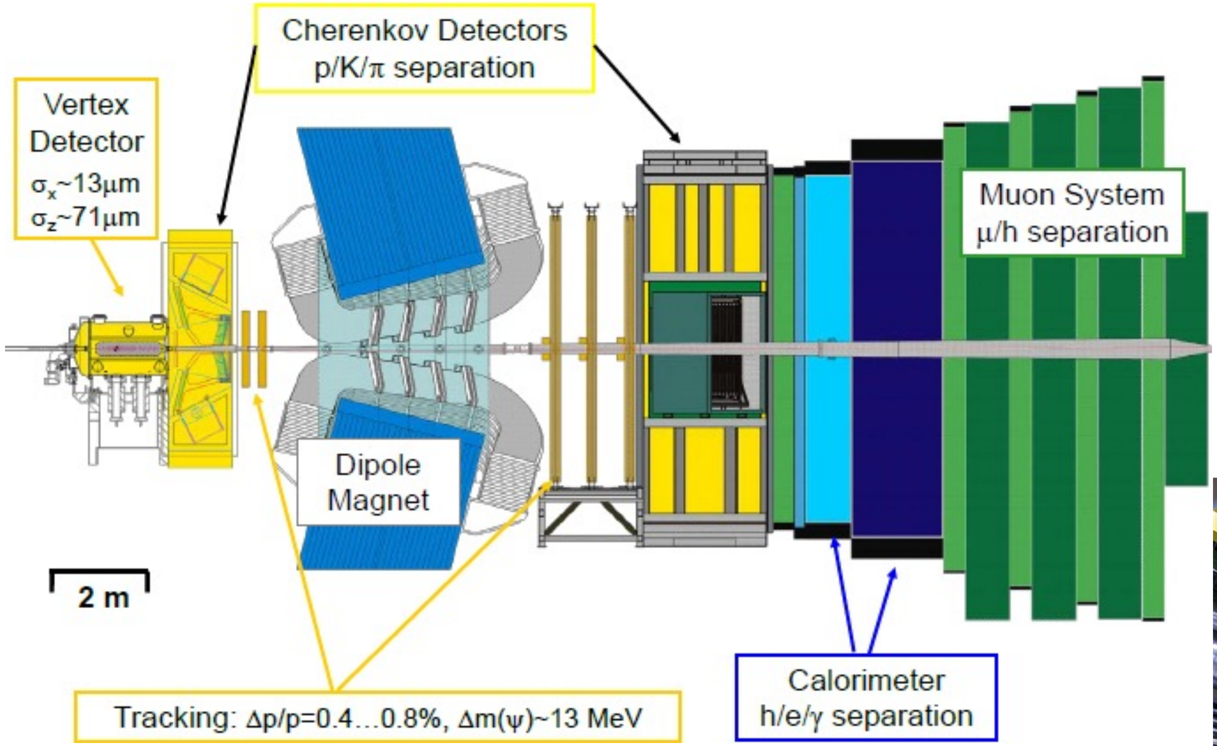
e⁺e⁻ Asymmetric B-factories

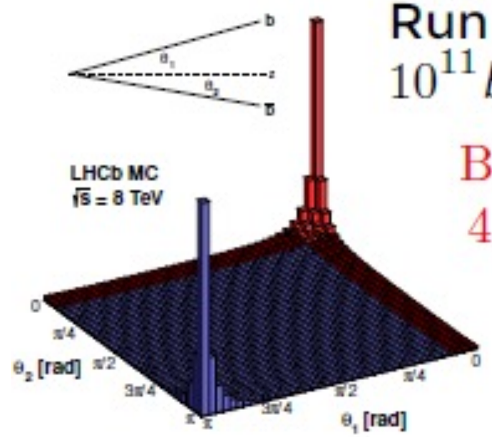
world highest luminosities





LHCb



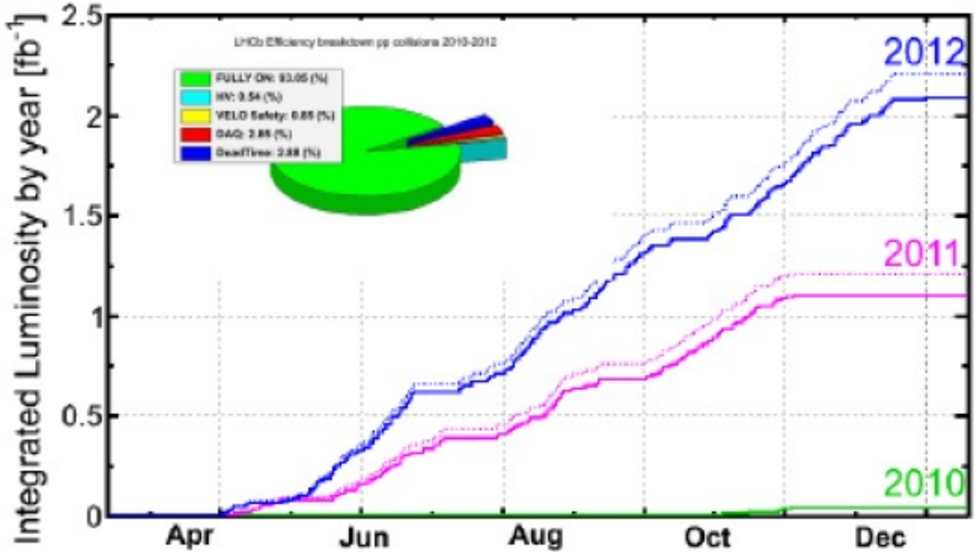


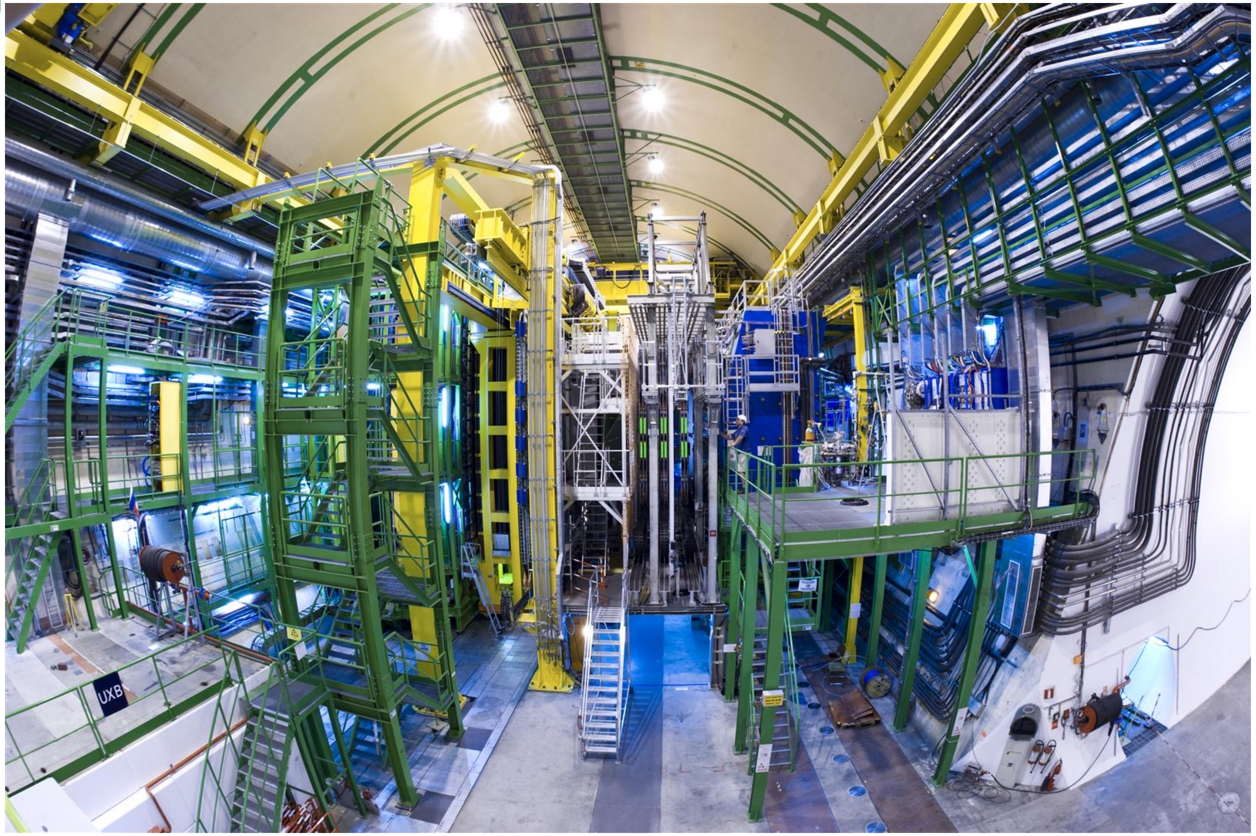
Run I: $3\,fb^{-1}$

10^{11} $b\bar{b}$ pairs

$\mathrm{B} : \Lambda_b : \mathrm{B}_s^0$

$4 : 2 : 1$





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 $\xrightarrow{1/20}$	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 $\xrightarrow{x2}$	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity ($10^{34} cm^{-2} s^{-1}$)	1.0	2.11 $\xrightarrow{x40}$	80

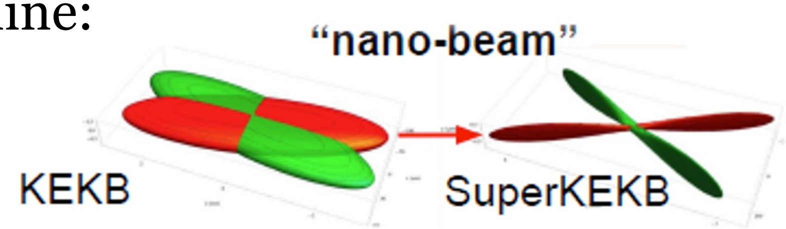
$$\boxed{L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)}$$

Main idea is to squeeze the beam up to nanometer size in the interaction point.

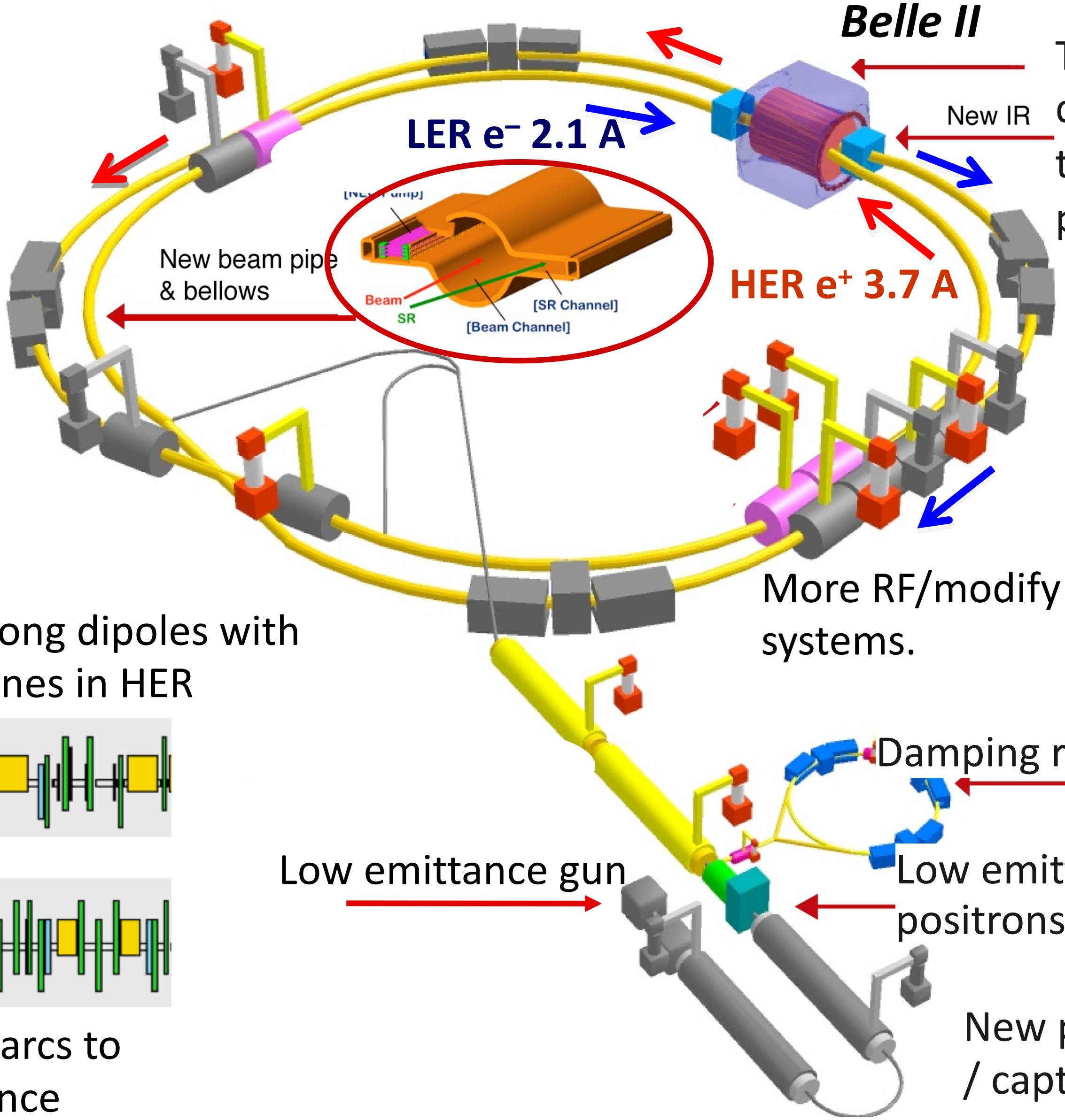
Just imagine:
Radius of accelerator ~ 1km,
Size of the beam ~10nm,
Position of the beam should be kept inside the vacuum tube ~ 1nm.

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

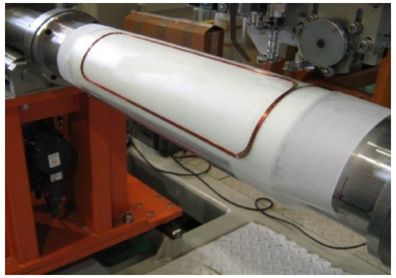
- × 20 smaller beam focus at interaction region
- Twice higher beam current
- First beam in 2016 → first collision in April 2018



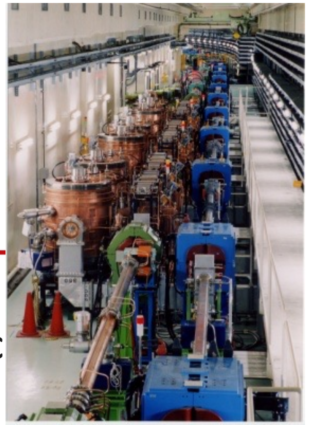
KEKB upgrade → SuperKEKB(nano-beam)



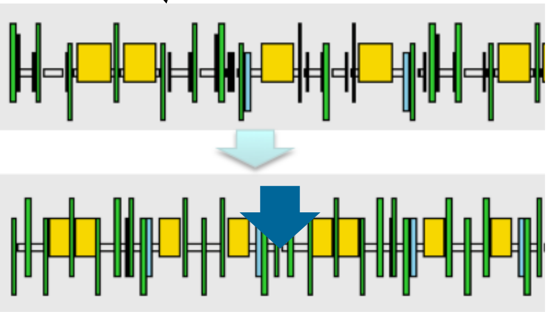
Two separate focusing quads/each 2 beams closer to IP; Superconducting / permanent magnets



More RF/modify RF systems.



Replace long dipoles with shorter ones in HER

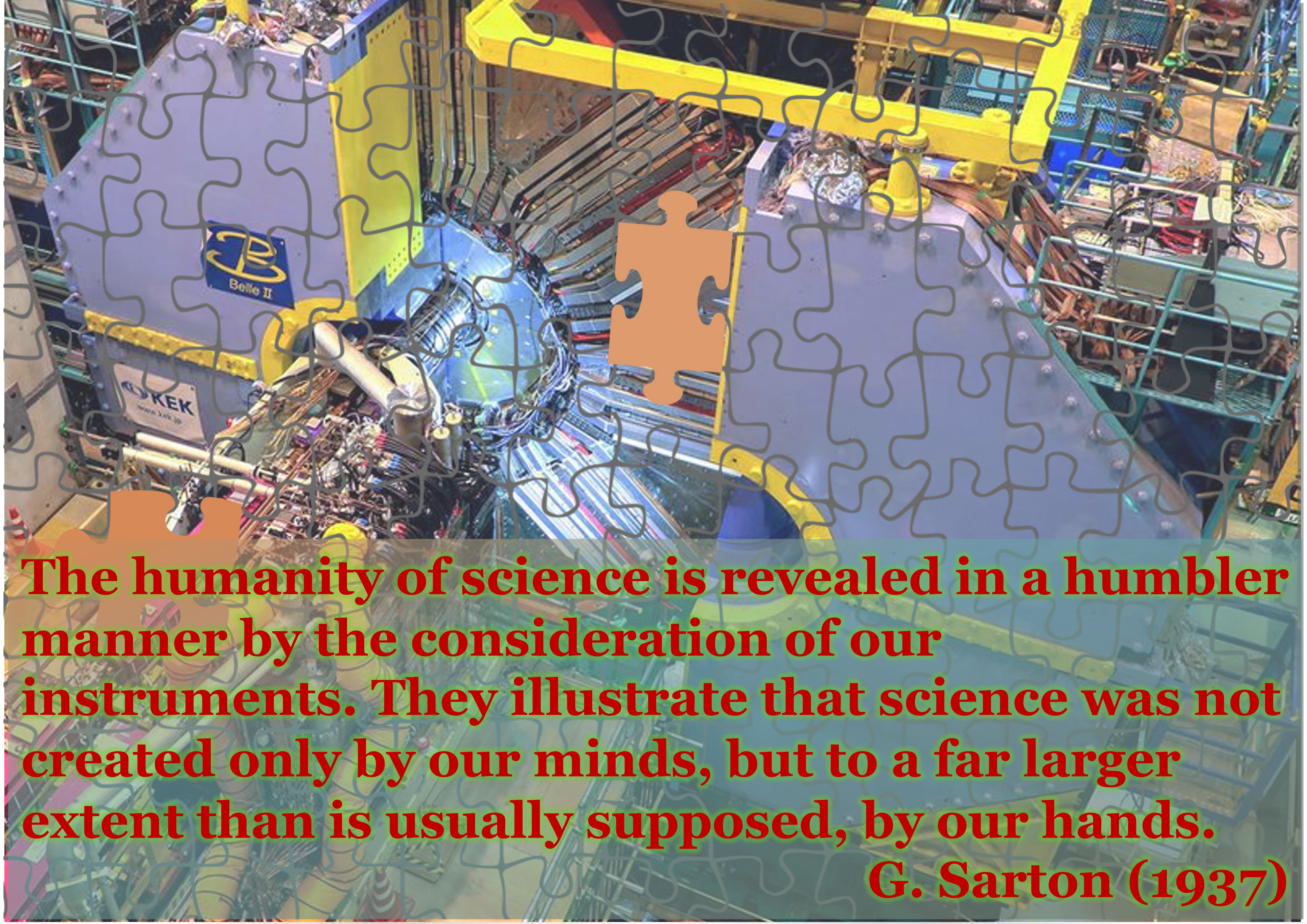


Redesign the HER arcs to reduce the emittance

Low emittance gun

Low emittanc positrons

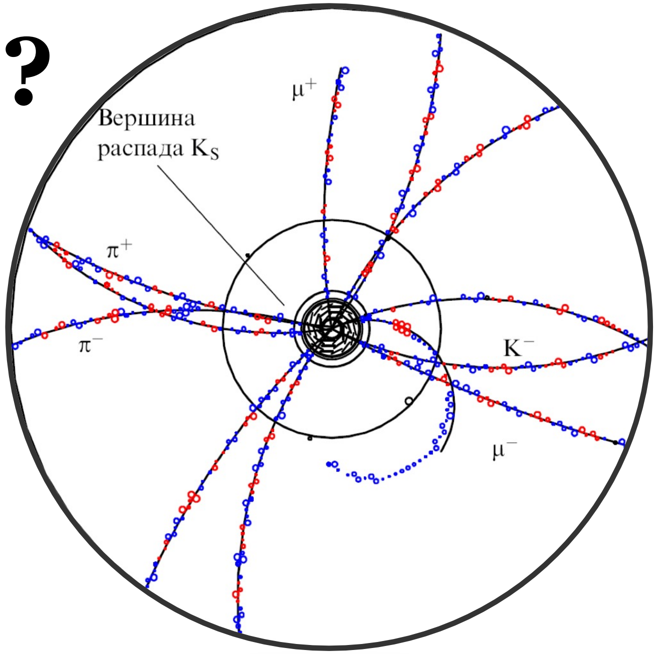
New positron target / capture section



The humanity of science is revealed in a humbler manner by the consideration of our instruments. They illustrate that science was not created only by our minds, but to a far larger extent than is usually supposed, by our hands.

G. Sarton (1937)

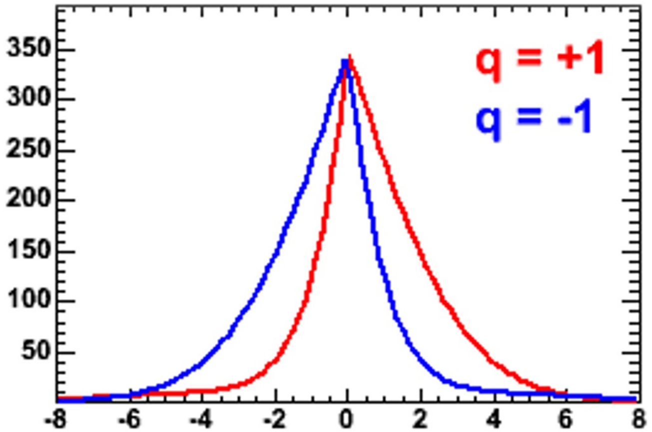
How to measure CPV at B-factories?

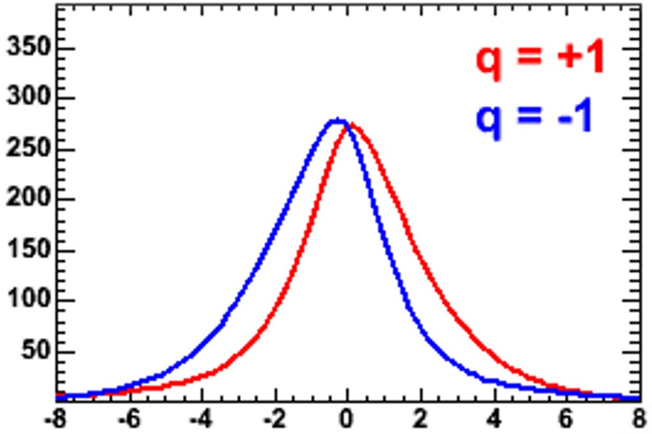


Reconstruct decay of one B-meson into CP eigenstate, e.g. $B \to J/\psi\, K_S$

Reconstruct the decay of the other B-meson to determine its flavor (“tag”). Partial reconstruction is sufficient

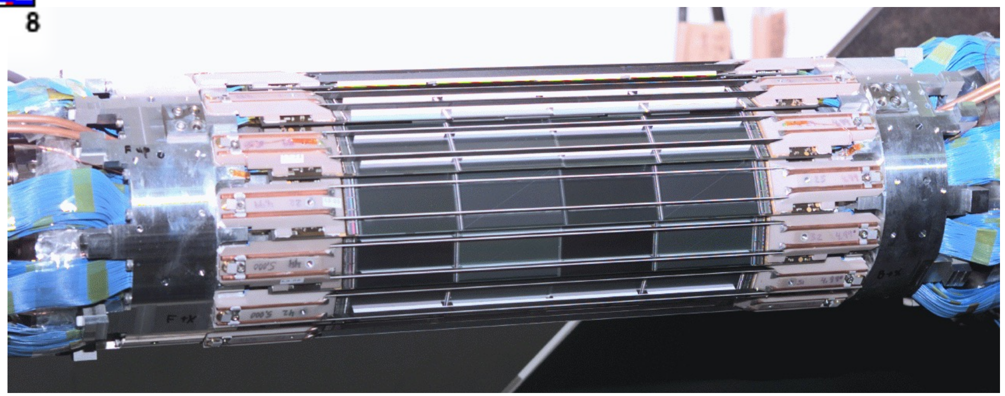
Measure the distance (L) between the two B meson decays vertices and convert to proper time $\Delta t = L/(\beta\gamma c)$





with real one the proper time is smeared by finite vertex detector resolution, while sometimes we the flavor is ascribed incorrectly…

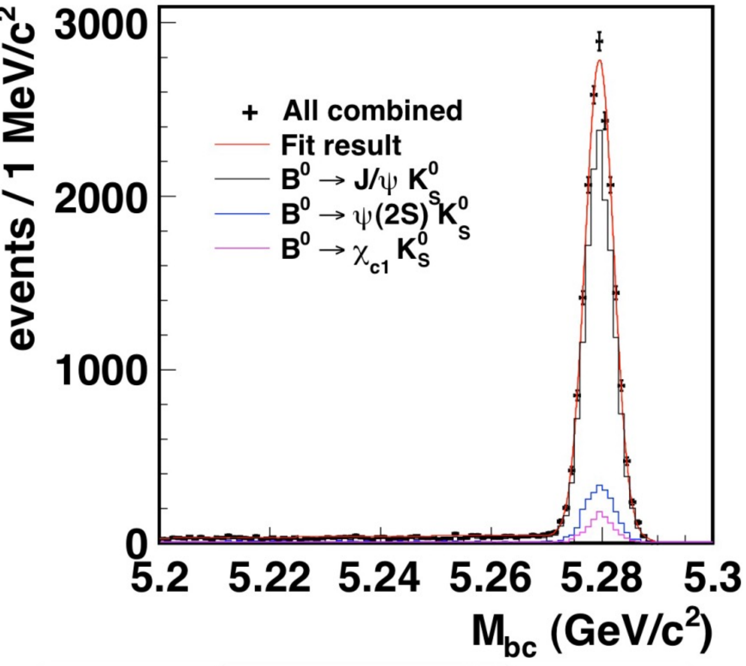
This is how CP violations looks with ideal detector…



Extract CP asymmetry from the measured Δt distributions for tagged B^0 and $\bar{B}^0$:

$$\mathbf{dN/d\Delta t \sim e^{-\Gamma|\Delta t|}\,[1 \pm \xi_{cp}\, A \sin(\Delta m\, \Delta t)]}$$

B→ charmonium K_S & K_L

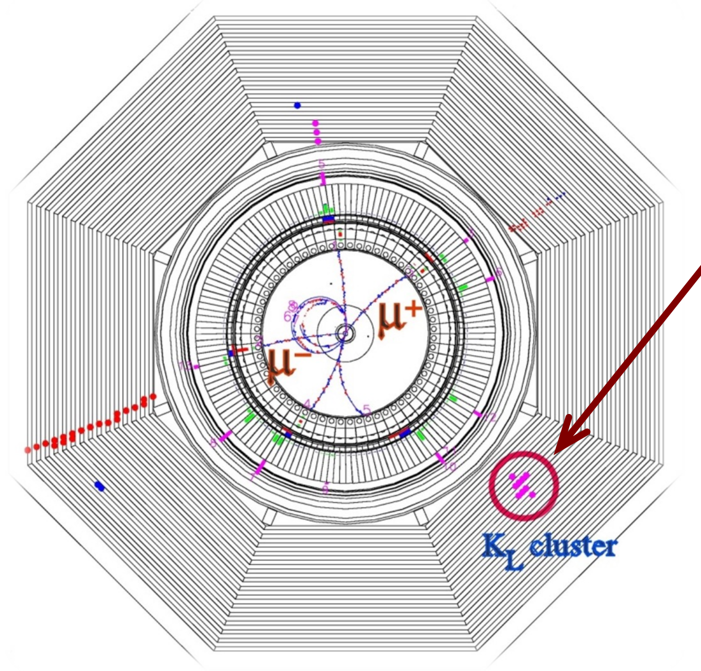


Use many other decays B to charmonium (η_c, χ_{c1}, ψ') + K_S to increase statistics:

- *have the same (odd) CP eigenvalue*
- *are equally theoretically clean (no penguin uncertainties)*
- *can be reconstructed with the similar high purity*

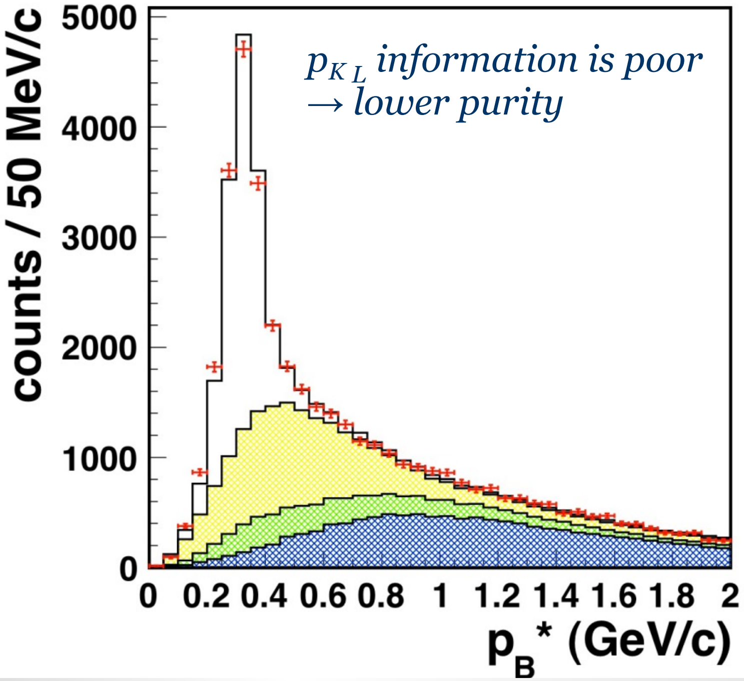
Because of known B-energy (= E_{beam}) almost no background

Important to check if the asymmetry flip the sign for the opposite CP eigenvalue



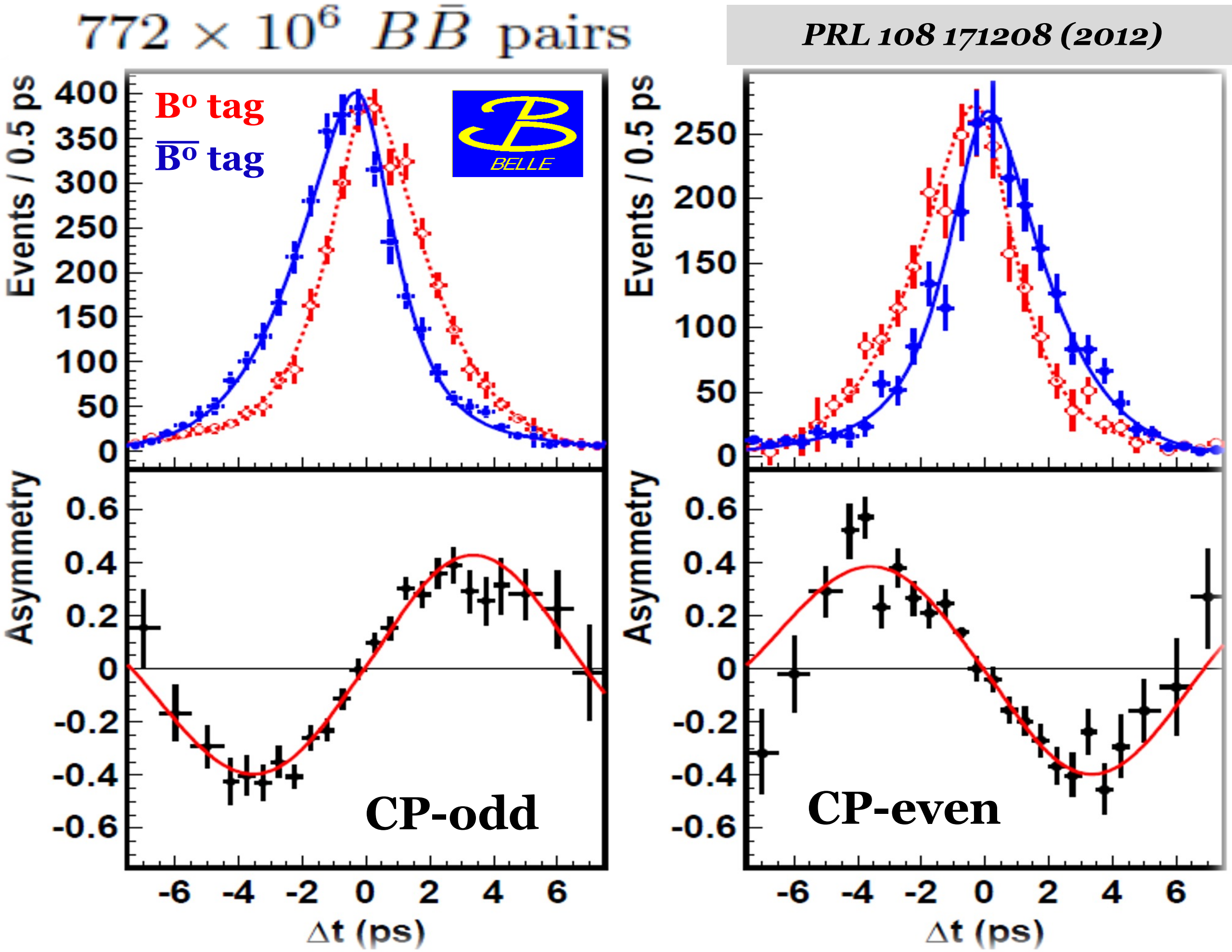
K_S is seen in tracker, but difficult to detect K_L:
cτ ~ 15m; only nuclear interactions.

Detect nuclear shower in iron: measure direction but not momentum.
Use known $J/\psi K_L$ energy = E_{beam} to calculate B momentum

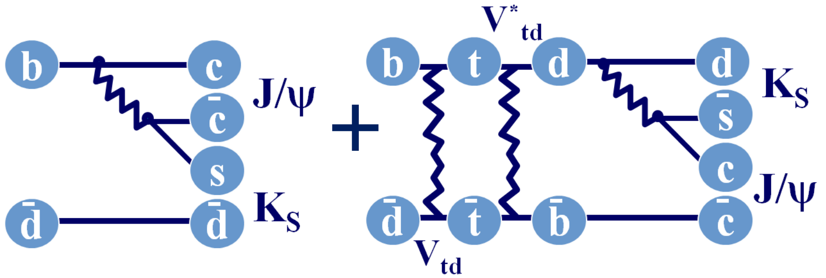


Precise measurement of sin(2β) in $B^o \to ccK^o$

PRL 108 171208 (2012)



$Y(4S) \to \bar{B}^o B^o \to f_{CP} f_{tag}$



Decay rate:

$$\frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1 + q\left[\mathcal{S}_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t)\right]\right\}$$

SM: S = –ξ sin(2β)

A = 0 (direct CPV)

sin(2β)

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

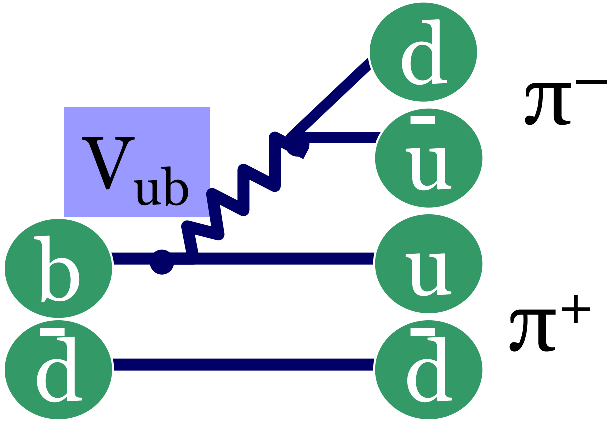
<u>Belle 2012</u>: $B \to ccK^o_S$ & $B \to J/\psi K^o_L$

sin(2β) = 0.667 ± 0.023 ± 0.012 (0.9°)

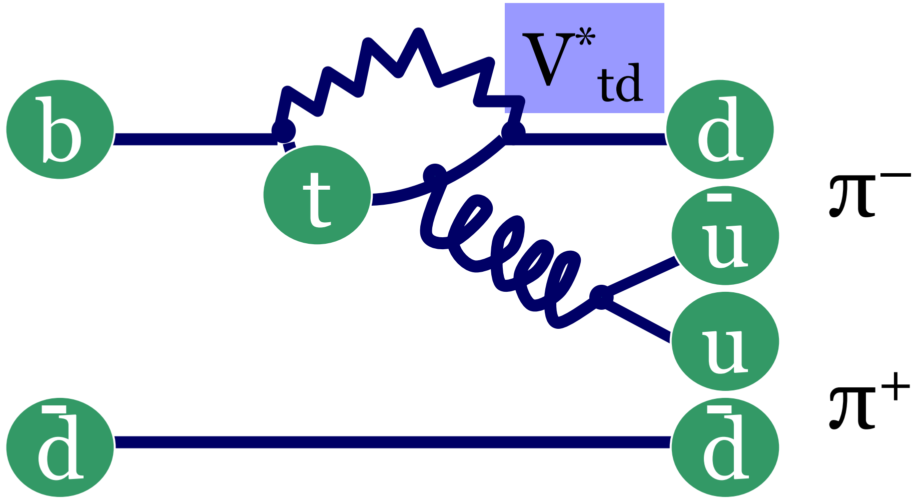
A_f = 0.006 ± 0.016 ± 0.012

$B^o \to \pi\,\pi$

$\alpha = \arg\left[-V_{ud}V_{ub}^*/(V_{td}V_{tb}^*)\right]$



$$\frac{\overline{A}}{A} = \frac{V_{ub}V_{ud}^*}{V_{ub}^*V_{ud}}$$



In this case the penguin diagram is not small and has different weak phase:

- The indirect CP violation ~ S sin(Δm t), where S ≠ sin 2α, but sin(2α + some not-negligible phase).
- There will be direct CP asymmetry ~ A cos(Δm t),

How to take into account this?

$B^0 \to \pi\pi$

The decay amplitudes $B \to \pi^+\pi^-$ ($\rho^+\rho^-$) are characterized by two different CKM terms:

a tree term (T) ~ $V_{ub}^* V_{ud}$ (dominant)

a penguin term (P) ~ $V_{tb}^* V_{td}$, (suppressed, but not small)

$$A_{CP}(\Delta t) = \frac{N(B^0 \to \pi^+\pi^-) - N(\overline{B}^0 \to \pi^+\pi^-)}{N(B^0 \to \pi^+\pi^-) + N(\overline{B}^0 \to \pi^+\pi^-)} = S\cdot\sin(\Delta m\Delta t) + \mathrm{A}\cdot\cos(\Delta m\Delta t)$$

Parameter S of indirect CPV:

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

δ – the relative strong phase between T and P amplitudes.

r < 1 – ratio of P to T amplitude

We can measure effective α (α_{eff}) shifted by extra angle

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

But we want α!

Additional inputs required.

Gronau-London idea

suggested long time ago (1990)

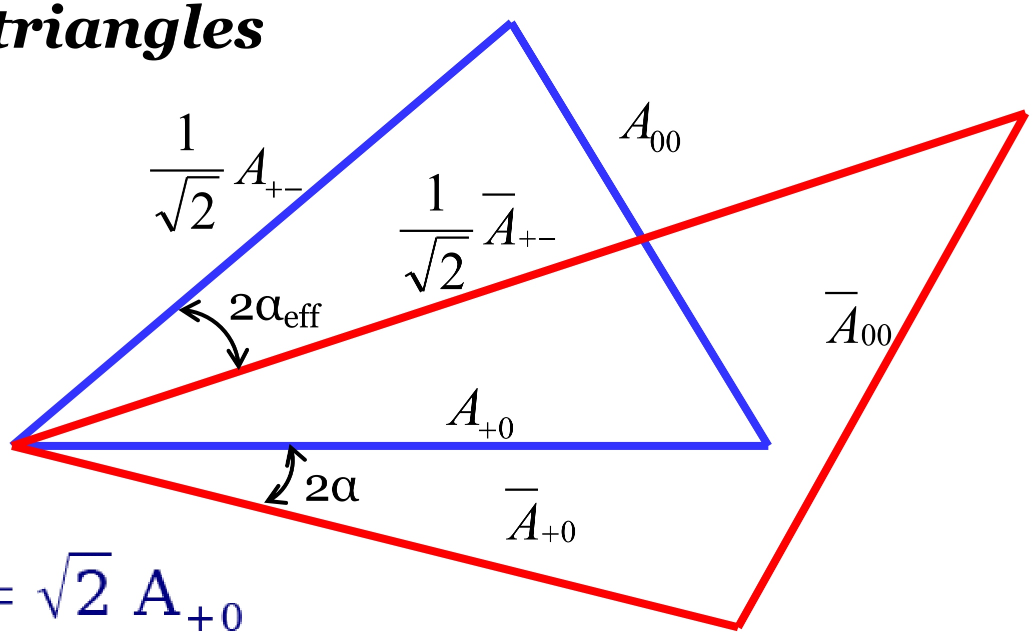
The cleanest method now available is the isospin analysis, proposed by M. Gronau and D. London.

We need to measure 6 BR's of B^0 to both $\pi^+\pi^-$ and $\pi^0\pi^0$, and B^+ (B^-) to $\pi^+\pi^0$ ($\pi^-\pi^0$).

Disentangle α and θ from two triangles relying on isospin symmetry:

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

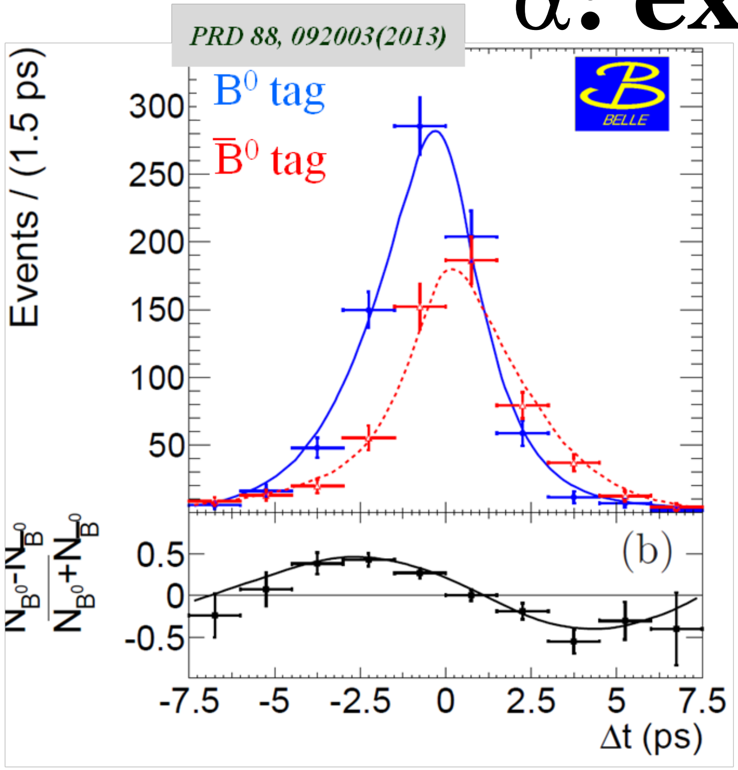
Isospin triangles



Isospin breaking:
- d and u charges different, $m_u \neq m_d$
- $\pi-\eta-\eta'$ and $\rho-\omega$ mixing

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

α: experimental results



$B^o \to \pi^+ \pi^-$

$S_{CP} = -0.64 \pm 0.06 \pm 0.03$

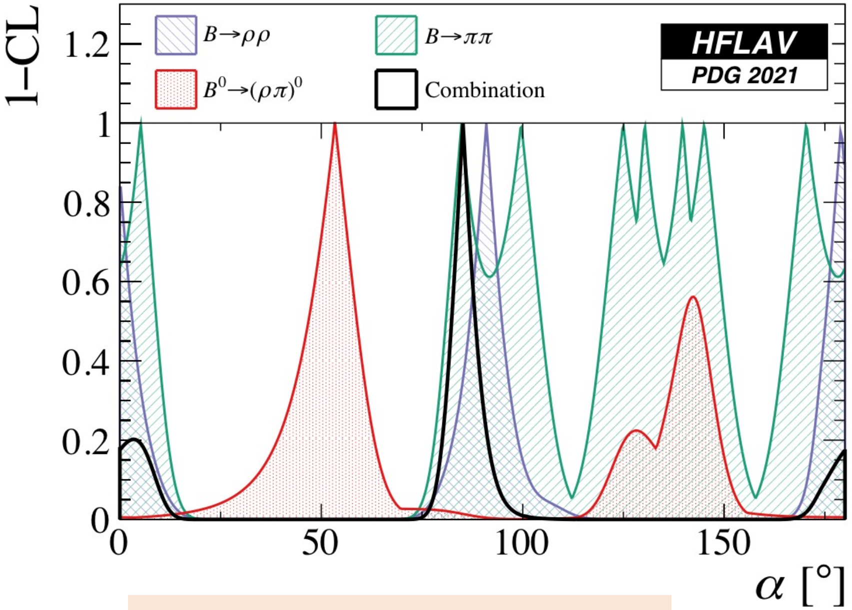
$A_{CP} = +0.33 \pm 0.06 \pm 0.03$

$B^o \to \rho^o \rho^o$

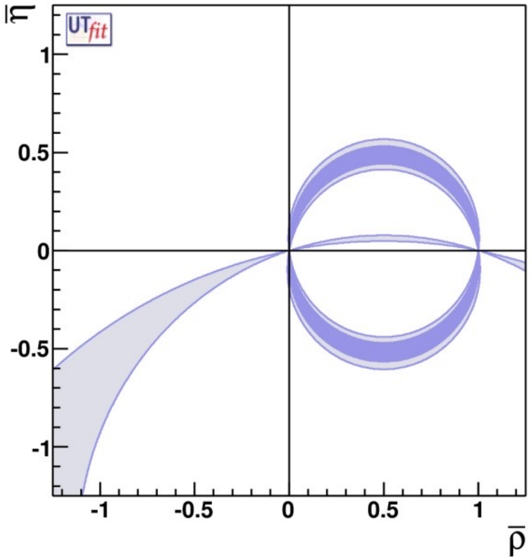
- angular analysis
- purely CP=+1 final state
- small Br, small penguin contribution

$B^o \to \rho^{\pm}\pi^{\pm}$

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



$\alpha = (85.2^{+4.8}_{-4.3})^\circ$



- Complicated analysis (especially for $\rho^o\rho^o$)
  - 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

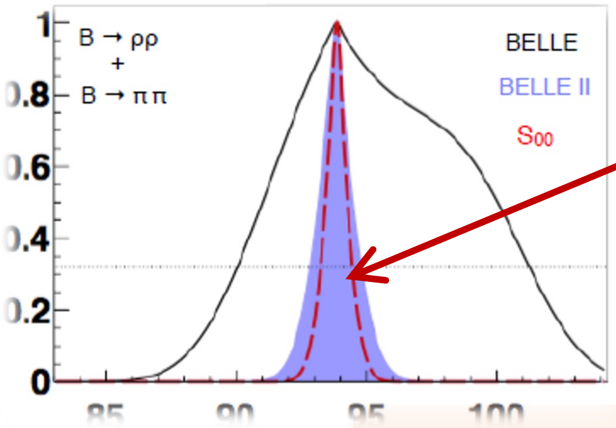
Inputs for isospin analysis

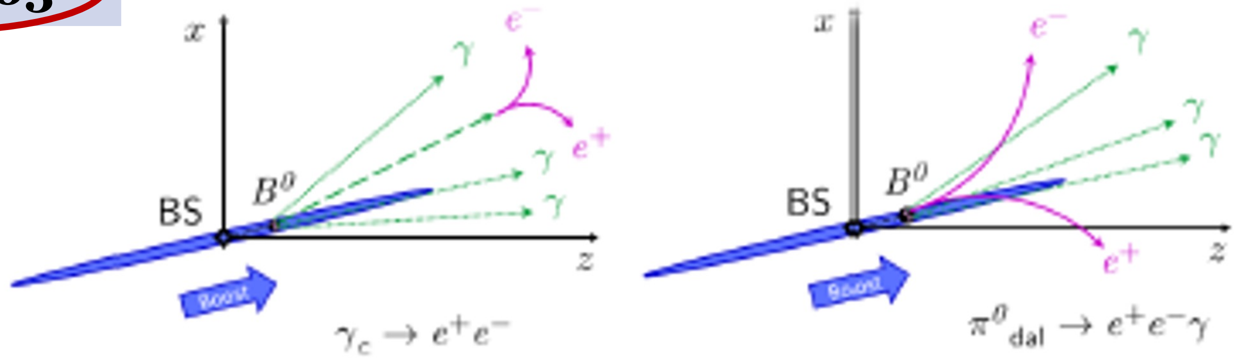
	Value	Belle 0.8 ab^{-1}	Belle-II 50 ab^{-1}
Br($\pi^+\pi^-$)	5.04	±0.21±0.18	±0.03±0.08
Br($\pi^0\pi^0$)	1.31	±0.19±0.18	±0.04±0.04
Br($\pi^+\pi^0$)	5.86	±0.26±0.38	±0.03±0.09
C($\pi^+\pi^-$)	–0.33	±0.06±0.03	±0.01±0.03
S($\pi^+\pi^-$)	–0.64	±0.08±0.03	±0.01±0.01
C($\pi^0\pi^0$)	–0.14	±0.36±0.12	±0.03±0.01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



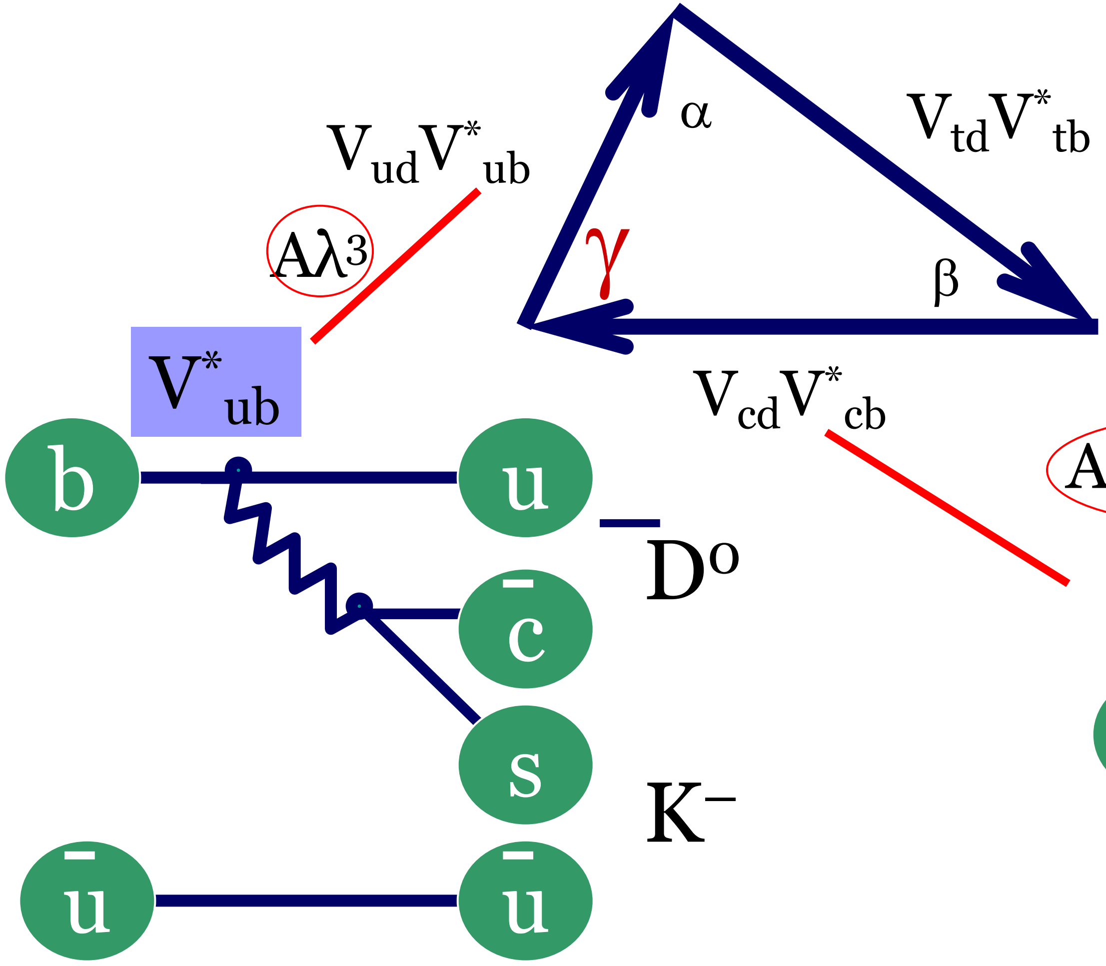


Expected errors at Belle II: 5 ab^{-1} to be 2°, 50 ab^{-1} to be 1°

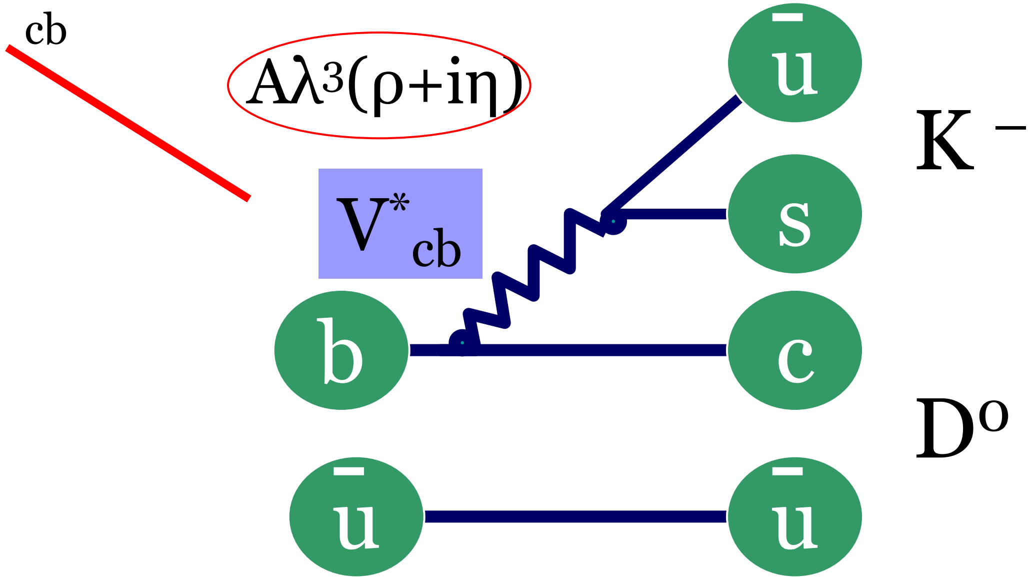
Direct CPV and γ

$B \to DK$

$$r_B = \frac{|A_{suppressed}|}{|A_{favoured}|} \sim \frac{|V_{ub}V^*_{cs}|}{|V_{cb}V^*_{us}|} \times [\text{color supp}] = 0.1\text{-}0.2$$

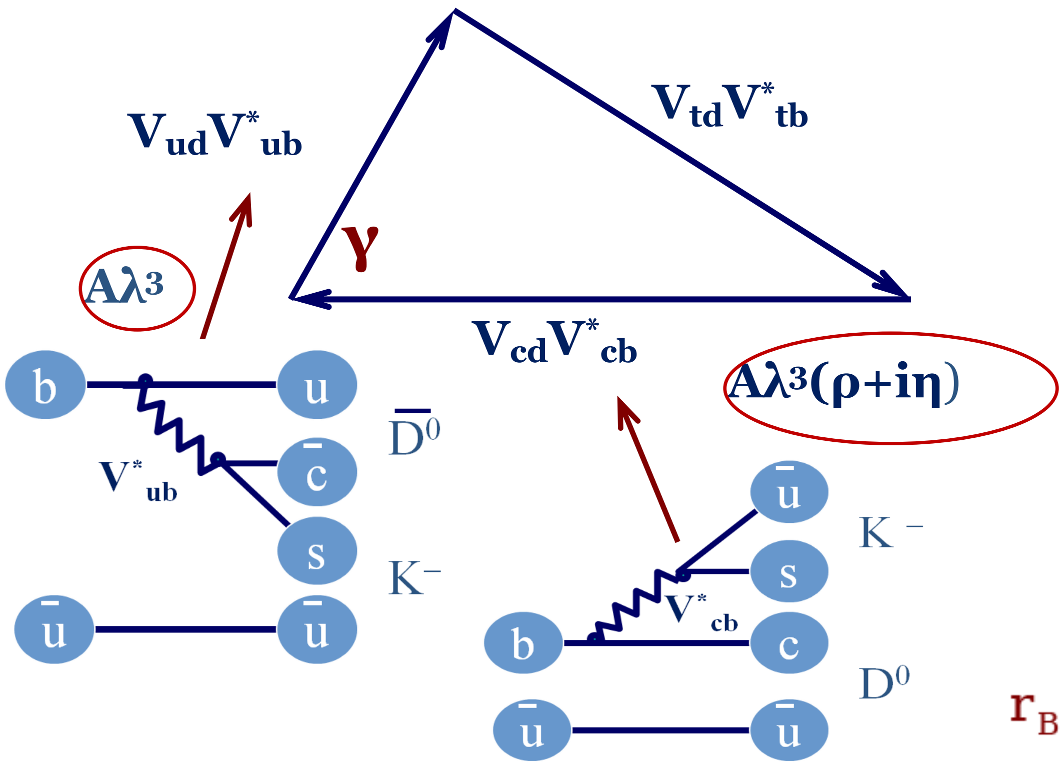


Color suppressed



Color allowed

Direct CPV and angle γ

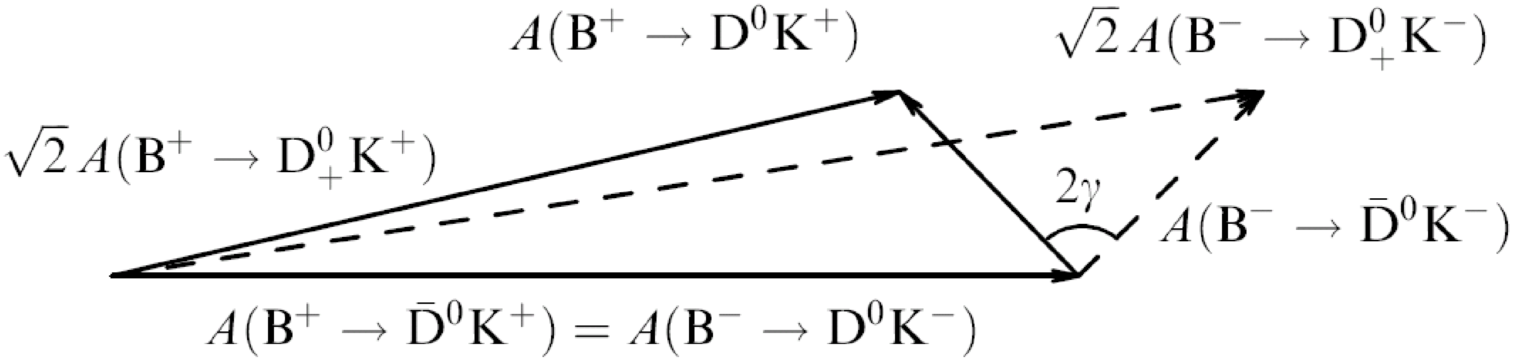


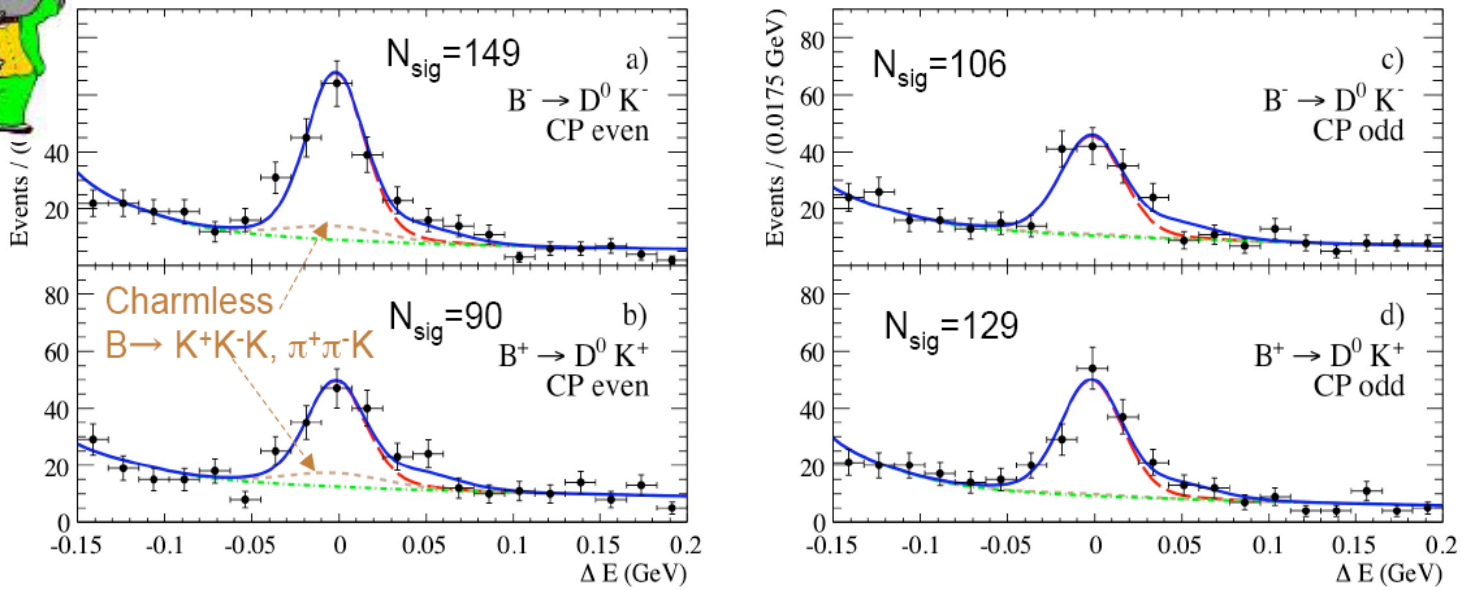
$B \to DK$: the angle between two amplitudes is really γ, but the final states are different $D^0 \neq \bar{D}^0$

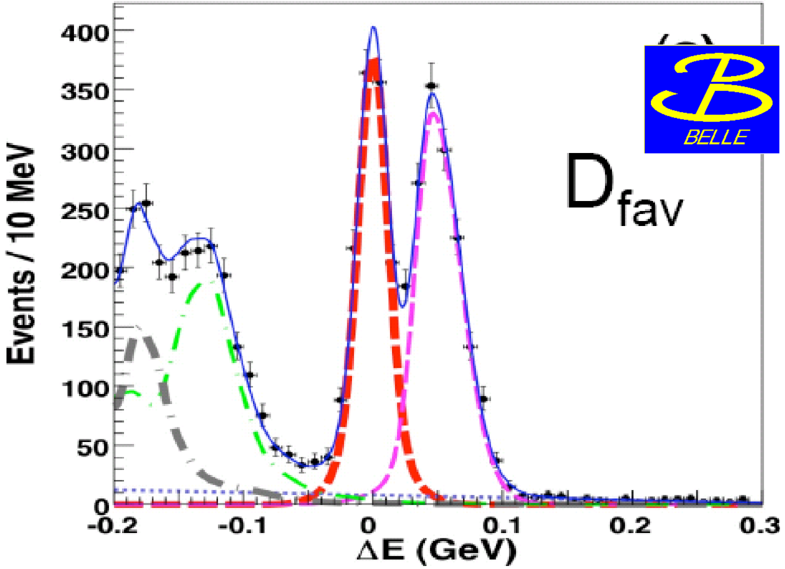
$$r_B = \frac{|A_{suppressed}|}{|A_{favoured}|} \sim \frac{|V_{ub}V^*_{cs}|}{|V_{cb}V^*_{us}|} \times [\text{color supp}] = 0.1\text{-}0.2$$

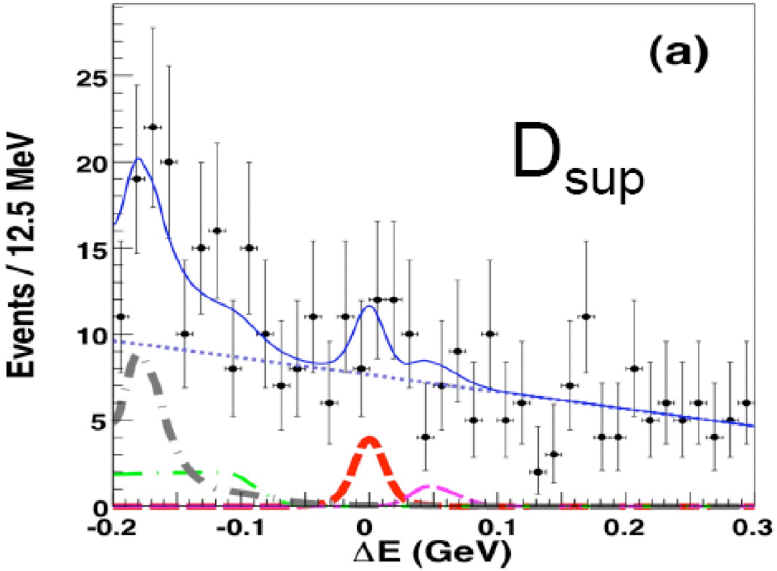
- GLW method: use D^0 decays into two-body CP eigenstates, *e.g.* $D^0 \to K^+K^-$
- ADS method: D^0 decays into final state typical for $\bar{D}^0$ *e.g.* $D^0 \to K^+\pi^-$
- Belle/GGSZ method: Dalitz analysis of 3-body final state, *e.g.* $D^0 \to K^0_S\pi^+\pi^-$

γ from GLS and ADS methods





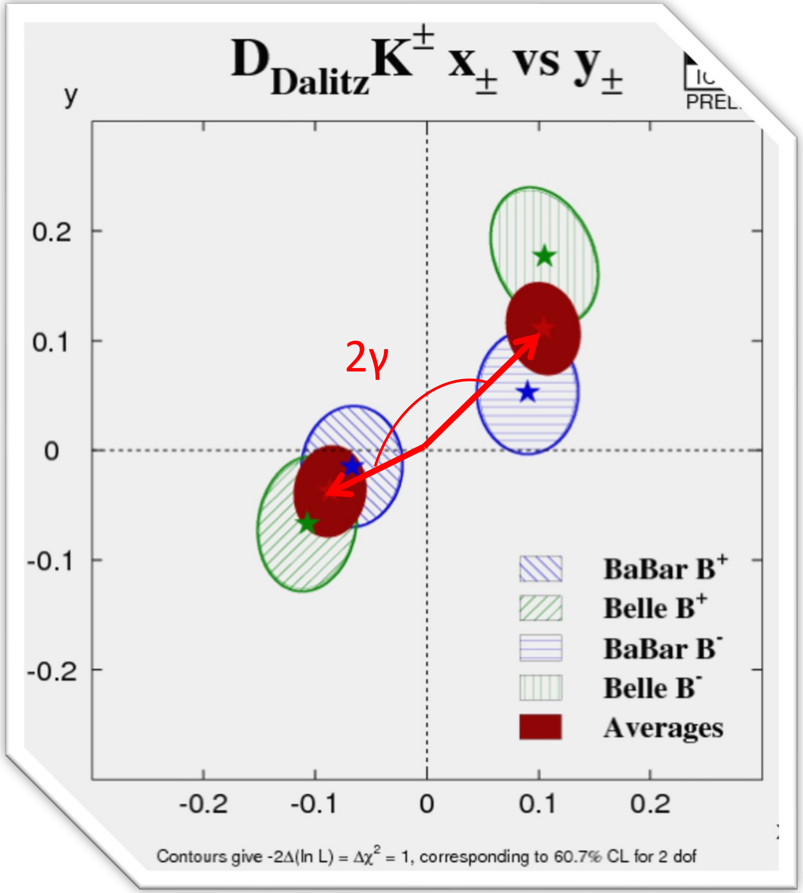


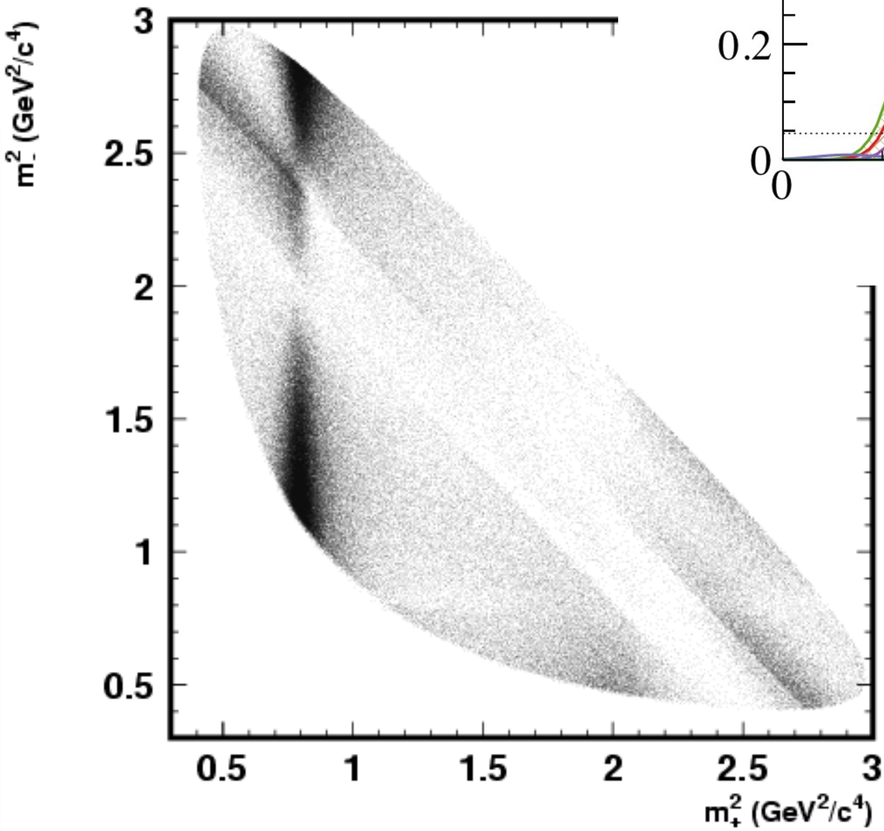


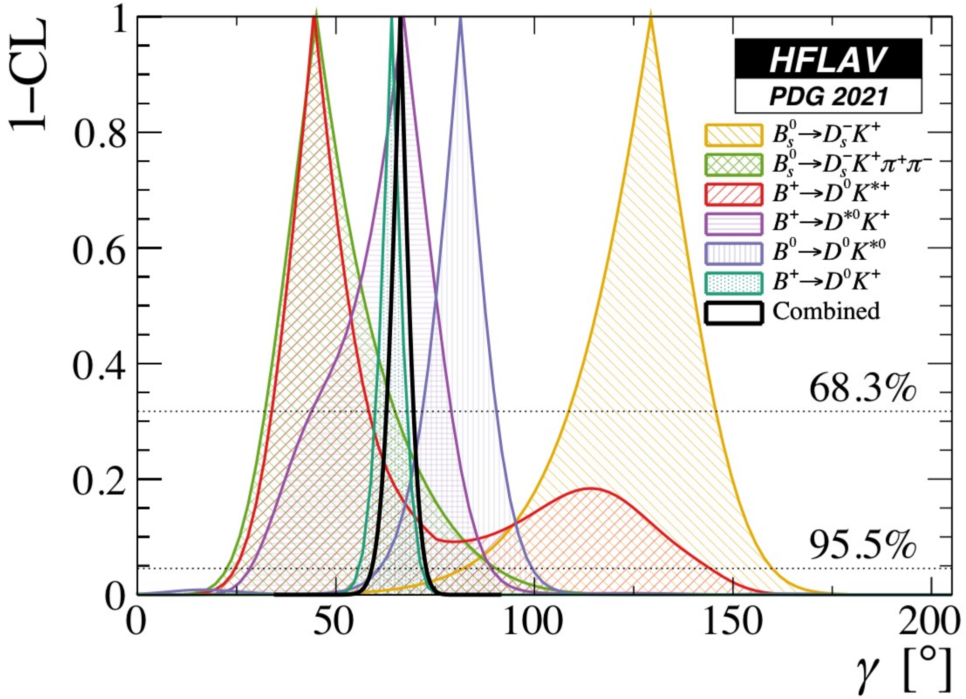
γ Belle/GGSZ method

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

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







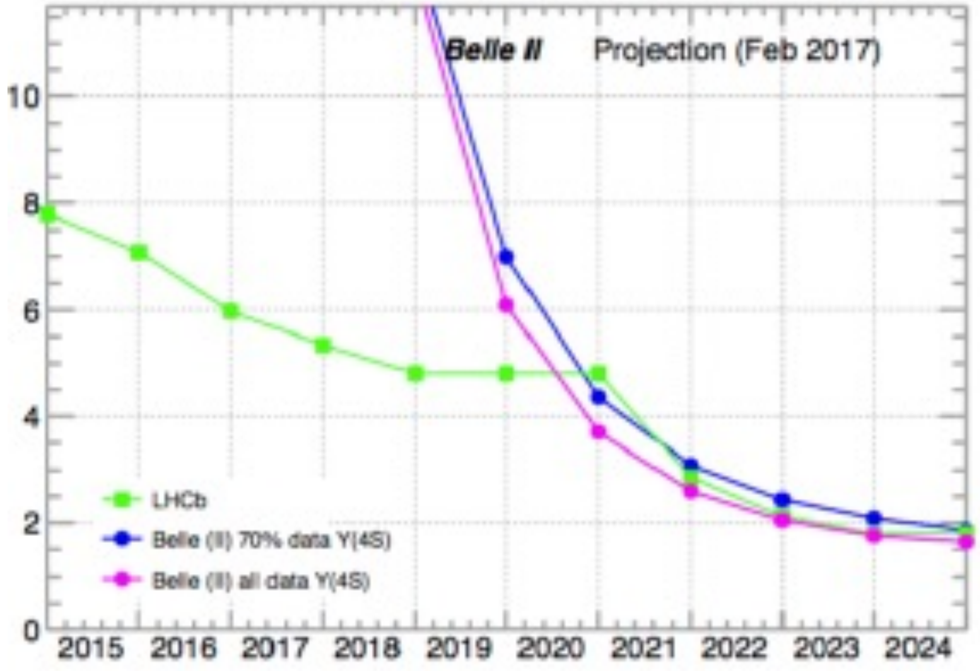
$$\gamma = (66.2^{+3.4}_{-3.6})^\circ$$

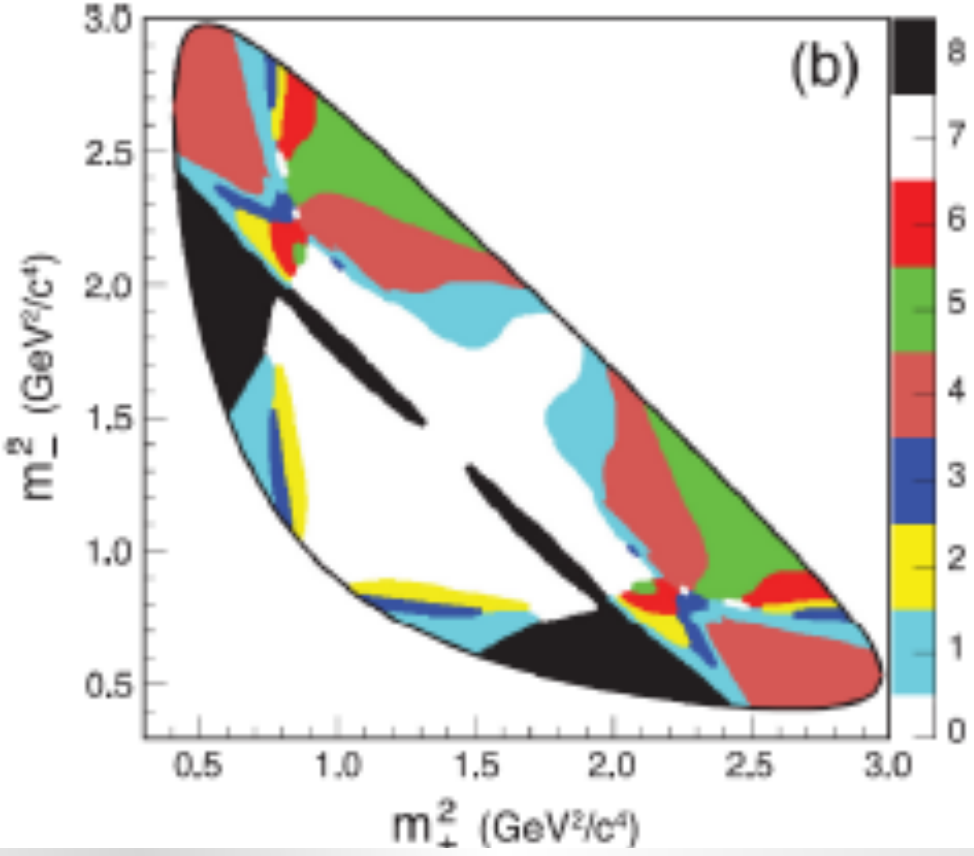
γ at Belle II and LHCb

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.

Sensitivity of Belle II and LHCb upgrade

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



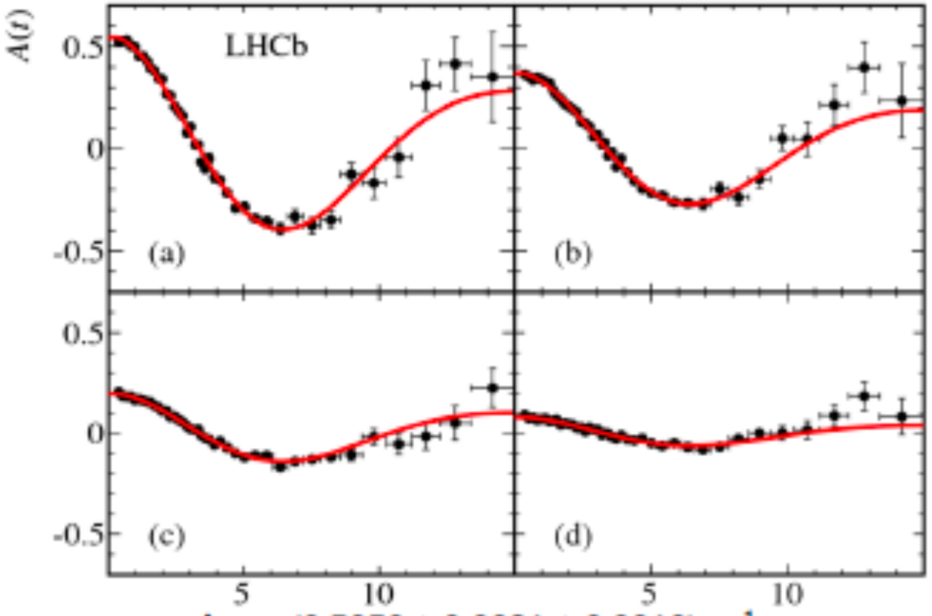


UT sides from B-Bbar mixing

World average based on many measurements

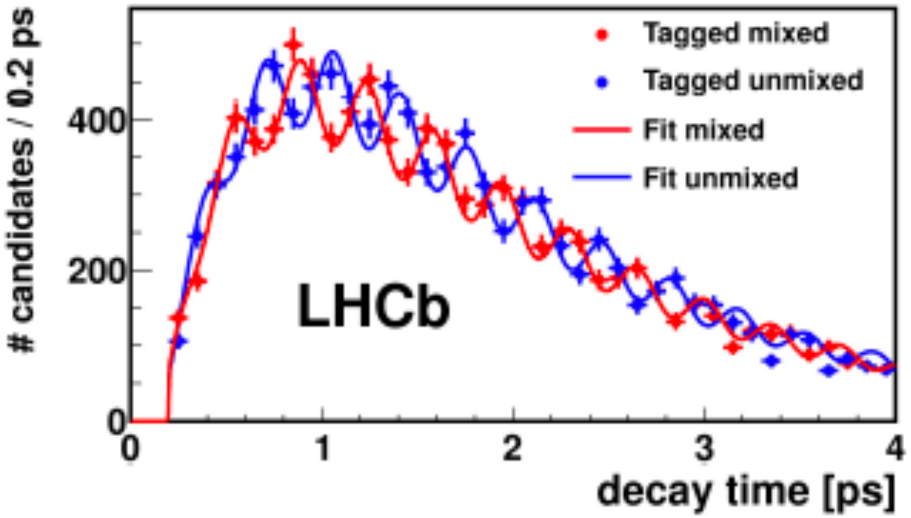
$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| \quad \& \quad \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

$P(\Delta t) = (1 \pm \cos(\Delta m t))e^{t}/2\tau$



$\Delta m_d = (0.5050 \pm 0.0021 \pm 0.0010)\ \mathrm{ps}^{-1}$

arXiv:1604.03475



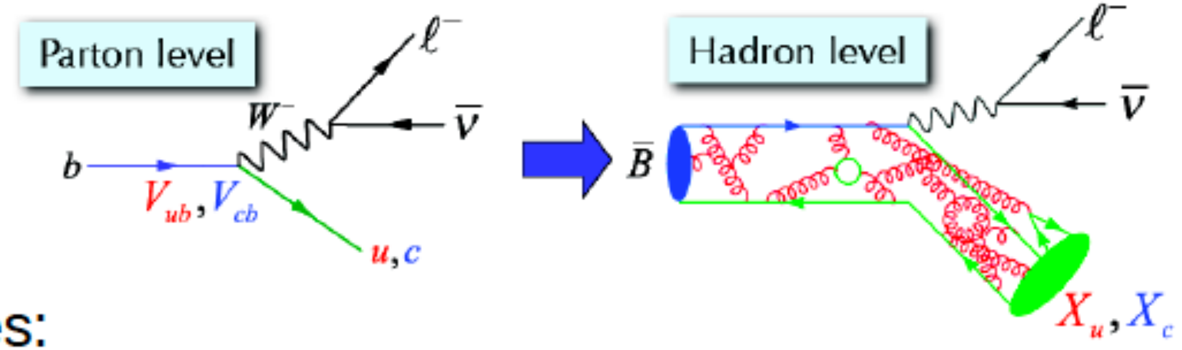
$\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\ \mathrm{ps}^{-1}$

NJP 15 (2013) 053021

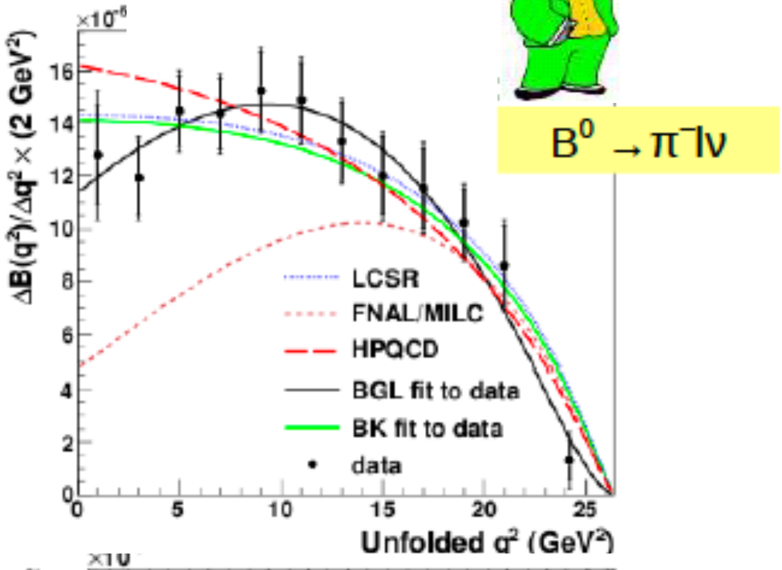
$$|V_{td}/V_{ts}| = 0.216 \pm 0.001 \pm 0.011$$

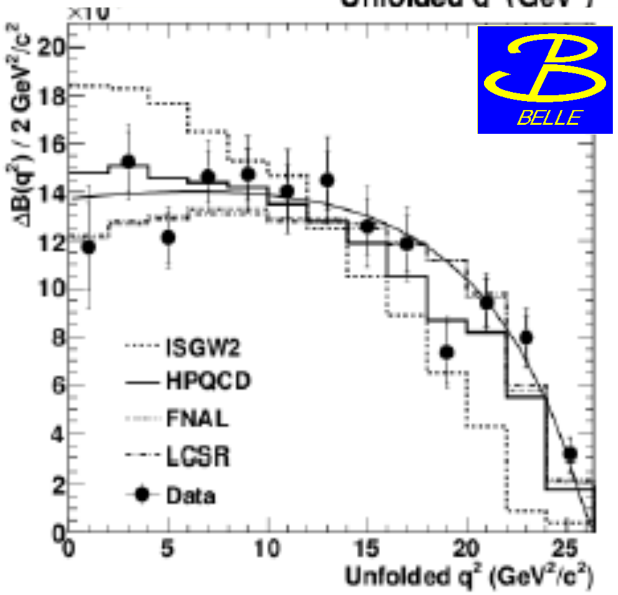
UT sides from B-Bbar mixing

$$R_u = \left| \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right|$$

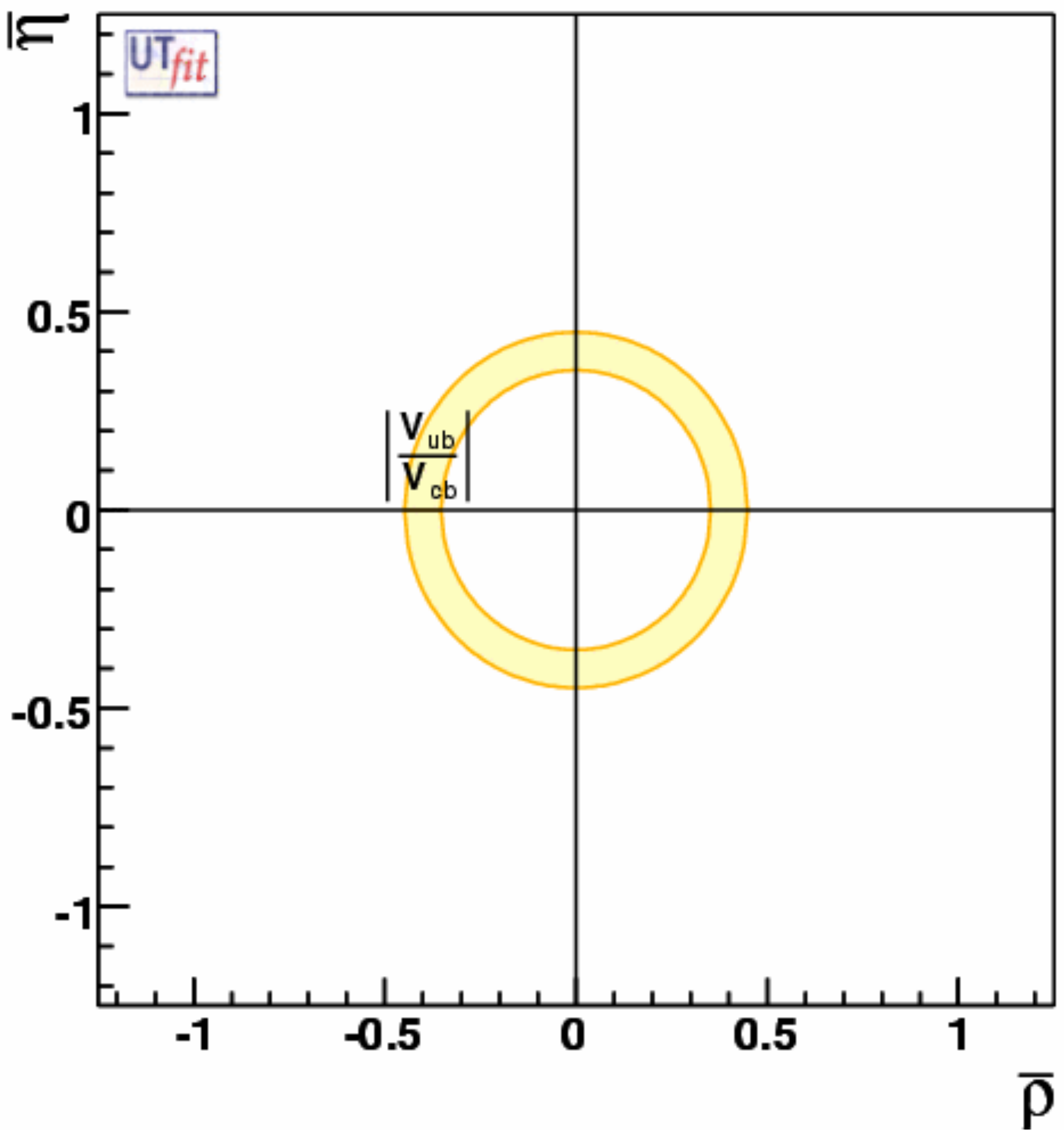


- Approaches:
  - exclusive semileptonic B decays, eg. $B^0 \to \pi^- e^+ \nu$
    - require knowledge of form factors
      - can be calculated in lattice QCD at kinematical limit
  - inclusive semileptonic B decays, eg. $B \to X_u e^+ \nu$
    - clean theory, based on Operator Product Expansion

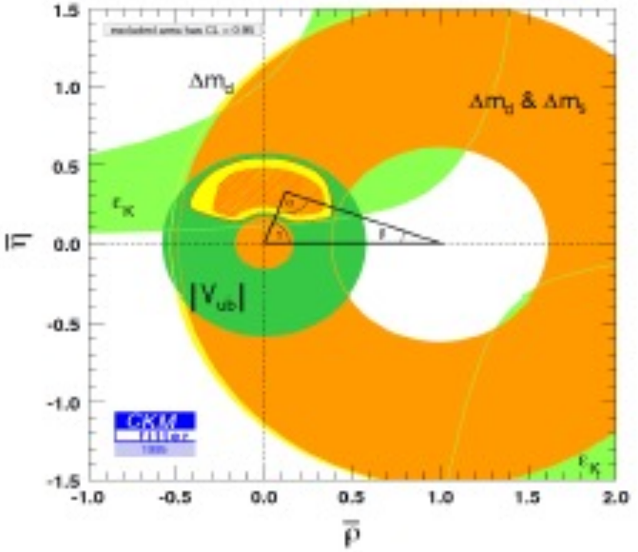




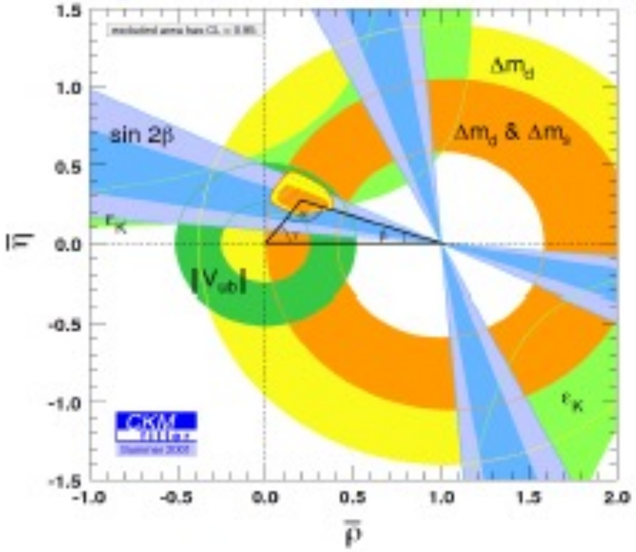
$$|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$$



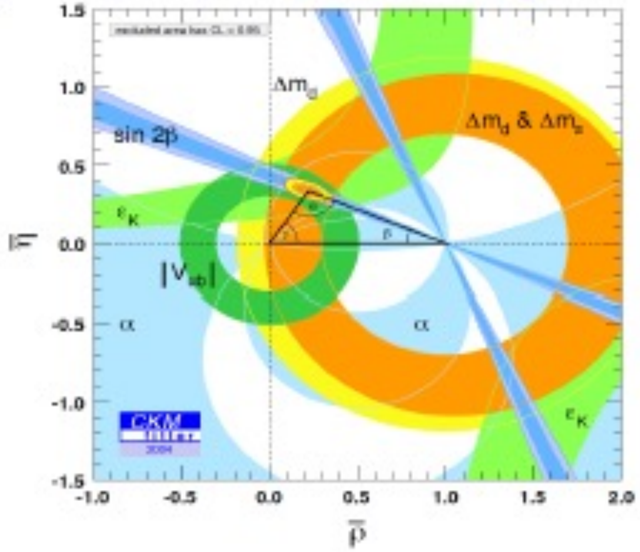
UTfit
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
$\bar{\eta}$
$\bar{\rho}$
$\left|\frac{V_{ub}}{V_{cb}}\right|$



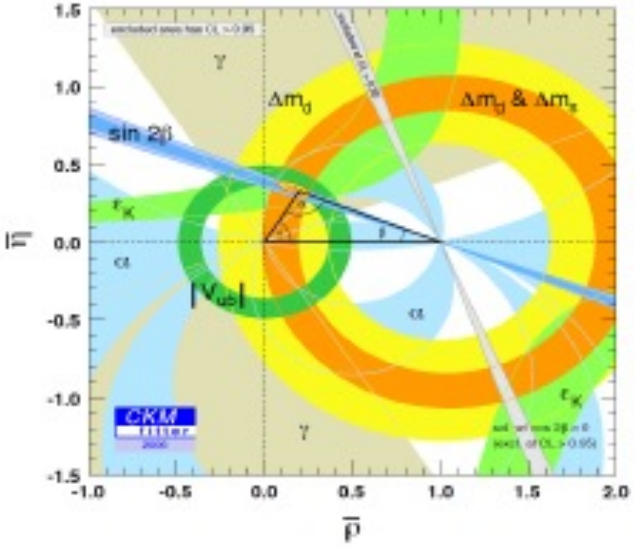
1995



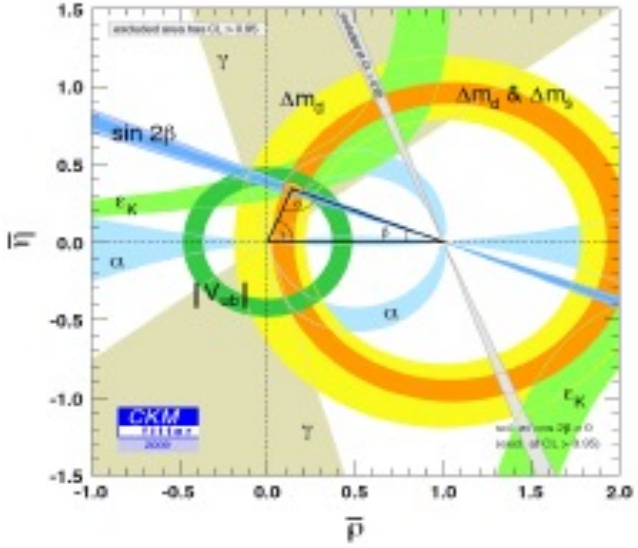
2001



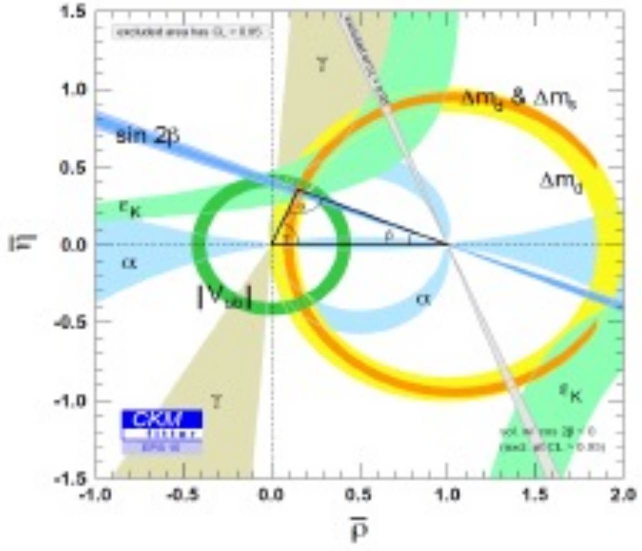
2004



2006



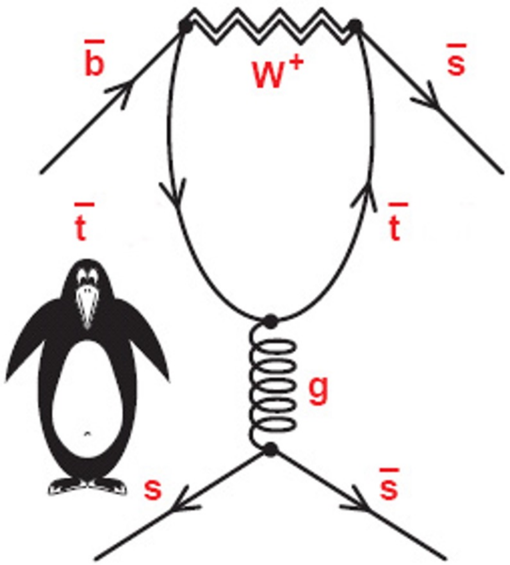
2009

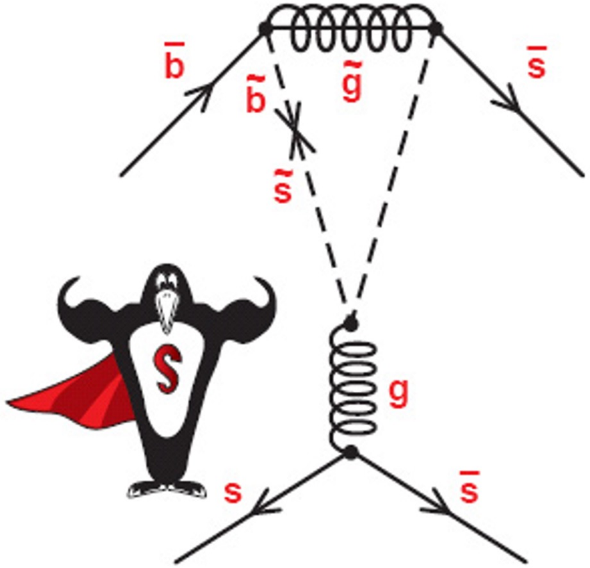


2015

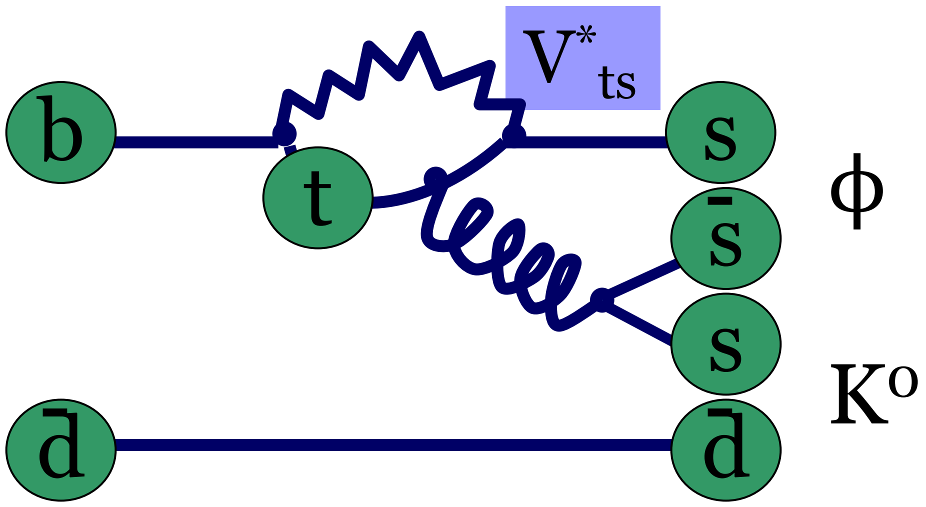
The curious name penguin goes back to a game of darts in a Geneva pub in the summer of 1977, involving theorists John Ellis, Mary K. Gaillard, Dimitri Nanopoulos and Serge Rudaz (all then at CERN) and experimentalist Melissa Franklin (then a Stanford student, now a Harvard professor). Somehow the telling of a joke about penguins evolved to the resolution that the loser of the dart game would use the word penguin in their next paper. It seems that Rudaz spelled Franklin at some point, beating Ellis (otherwise we might now have a detector named penguin); sure enough the seminal 1977 paper on loop diagrams in B decays [3] refers to such diagrams as penguins. This paper contains a whimsical acknowledgment to Franklin for "useful discussions" [4].

Search for Super-Penguins?





Testing loops!



CP asymmetry should be ~ sin2β

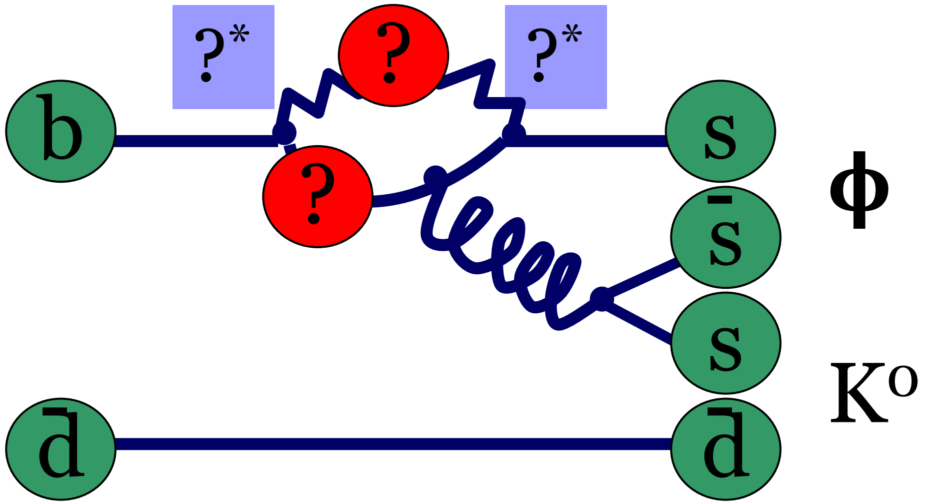
$$\frac{\bar{A}}{A} = \frac{V_{tb}V^*_{ts}}{V^*_{tb}V_{ts}} = \frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}$$

No tree contribution!

Theoretical uncertainty ~ 0.01-0.03 much smaller than the current exp errors!

All our previous measurements test new physics contribution to the box diagram and check the consistency with pure tree (where no big contribution from NP expected)

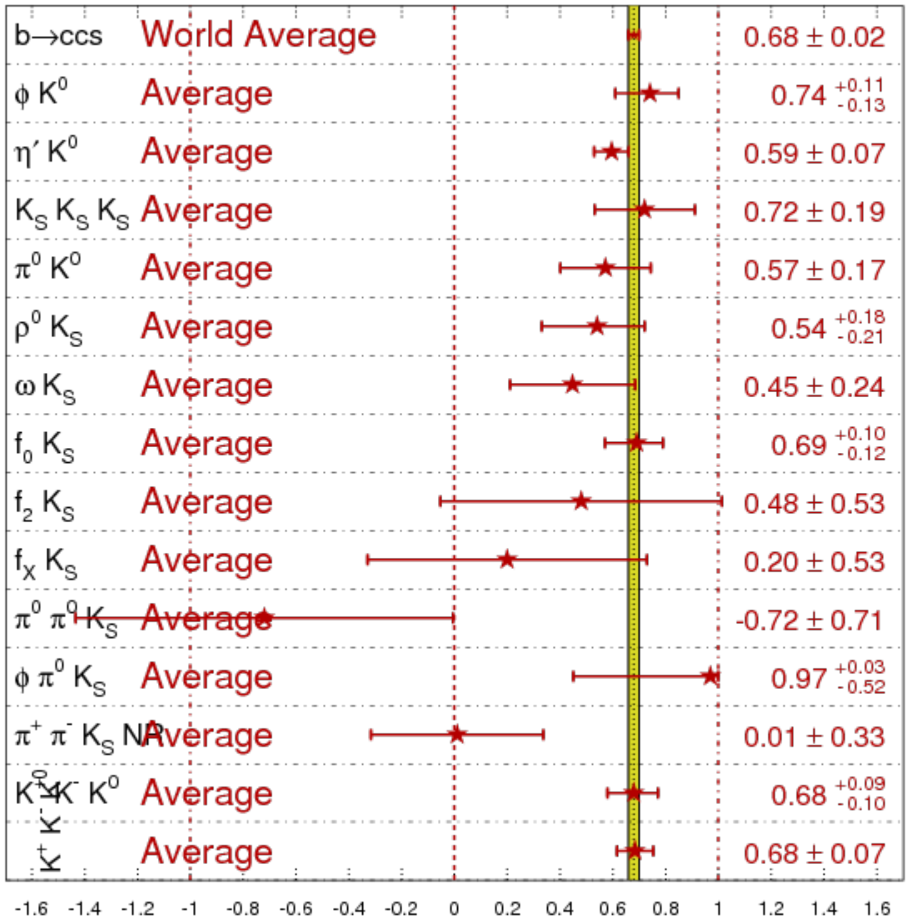
This one really give access to the loop. If any (heavy) particles (with extra to KM phases) are involved in the loop we can see the effect!



$\sin 2\varphi^{\text{eff}} \neq \sin 2\beta$

2006: exciting 3.5 σ discrepancy!

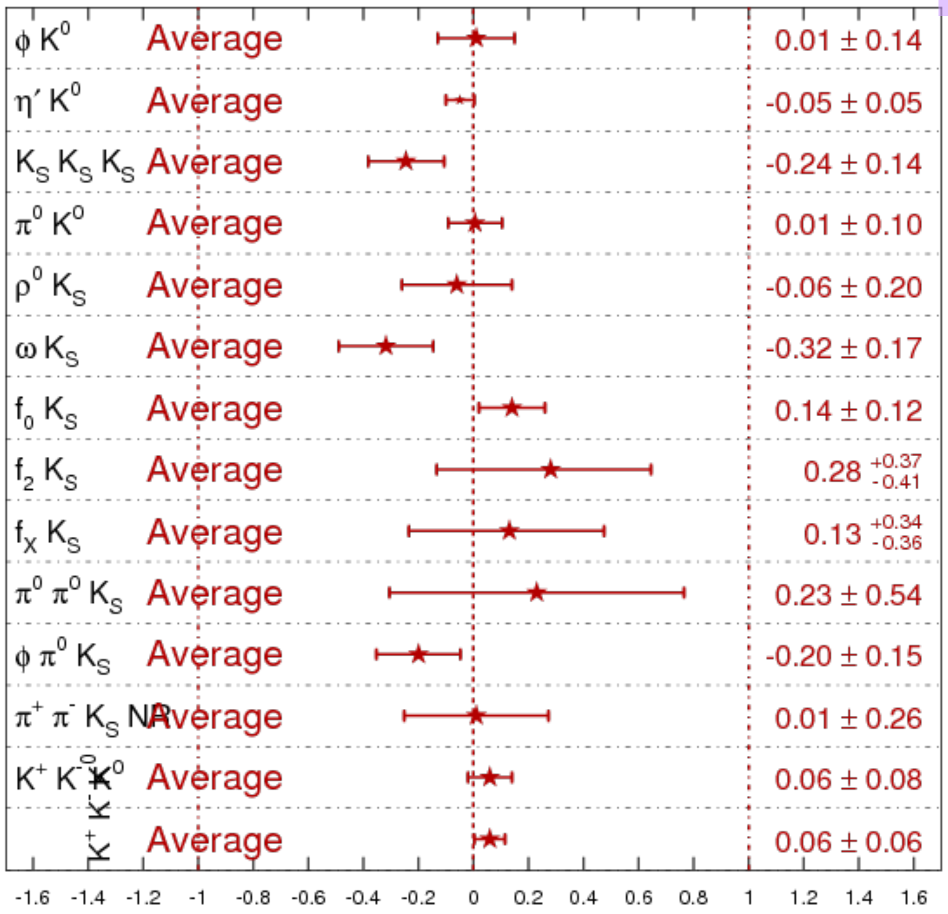
$\sin(2\beta^{\mathrm{eff}}) \equiv \sin(2\phi_1^{\mathrm{eff}})$



$\sin 2\beta = 0.68 \pm 0.02 \approx 0.68 \pm 0.07 = \sin 2\phi^{eff}$

$\mathbf{C_f = -A_f}$

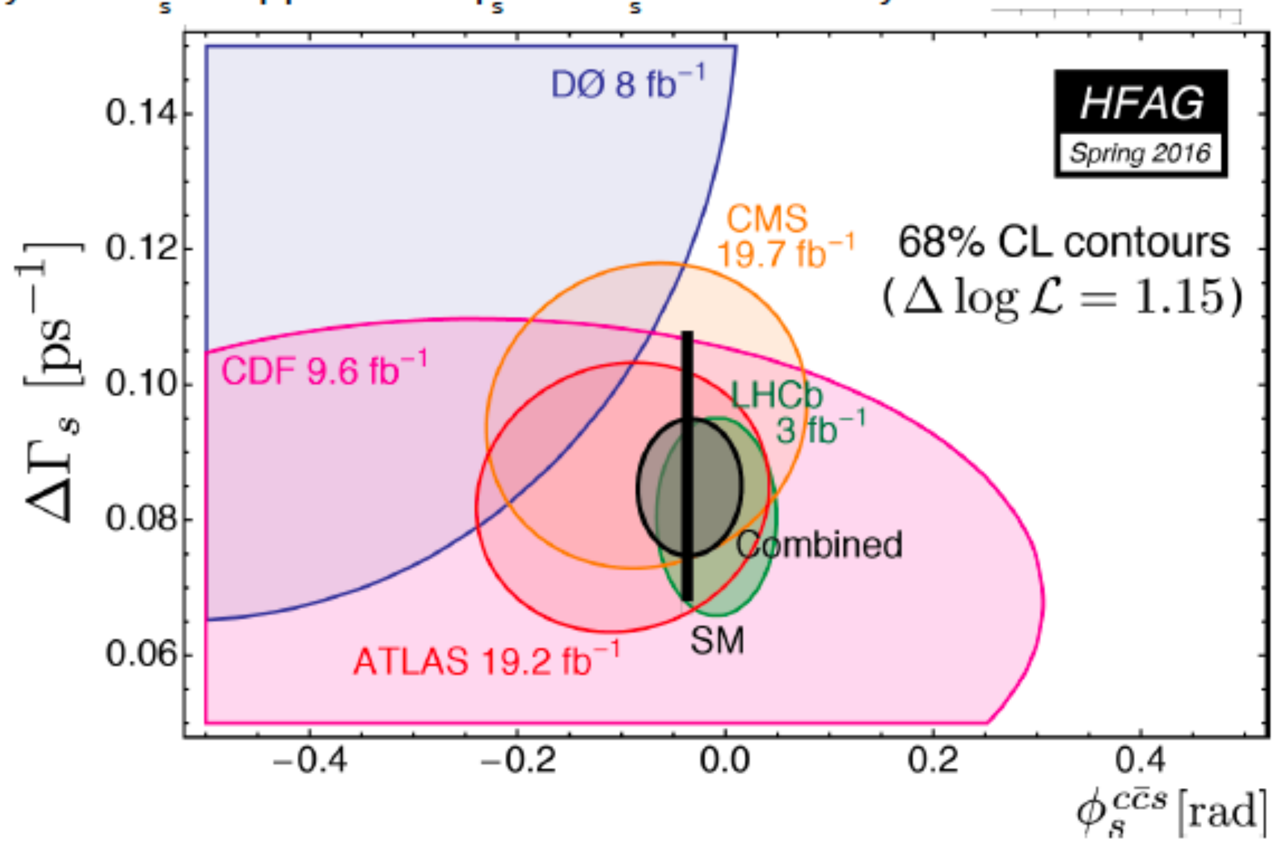
$A_{CP} \approx 0$



now: disappointing nice agreement

CP violation in $B_s^0 \to J/\psi\varphi$ & $J/\psi\pi\pi$

Analyses of $B_s^0 \to J/\psi\varphi$ measure φ_s and $\Delta\Gamma_s$ simultaneously

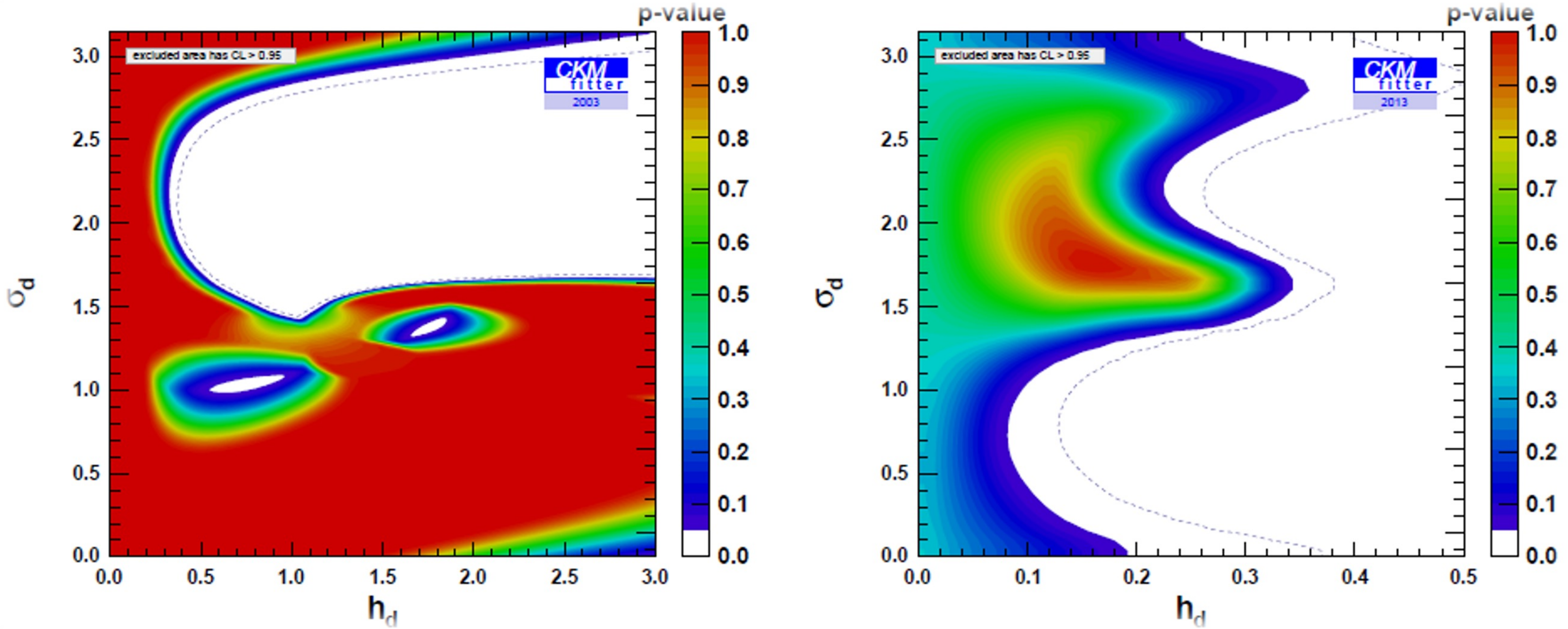


CP violation: enigmatic phenomenon & effective tool for New Physics searches

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

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

NP



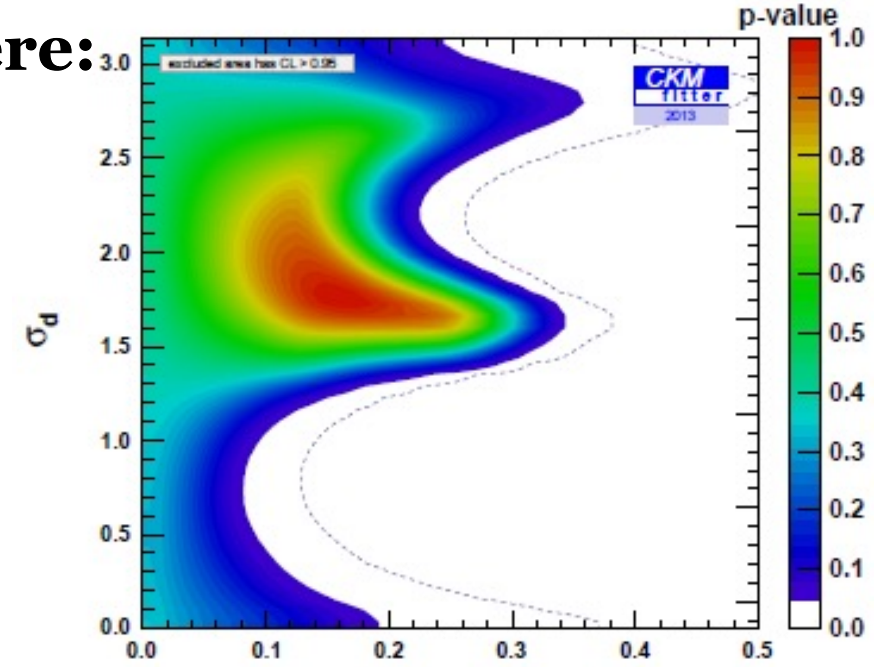
To continue study, SUPER B FACTORY NEEDED

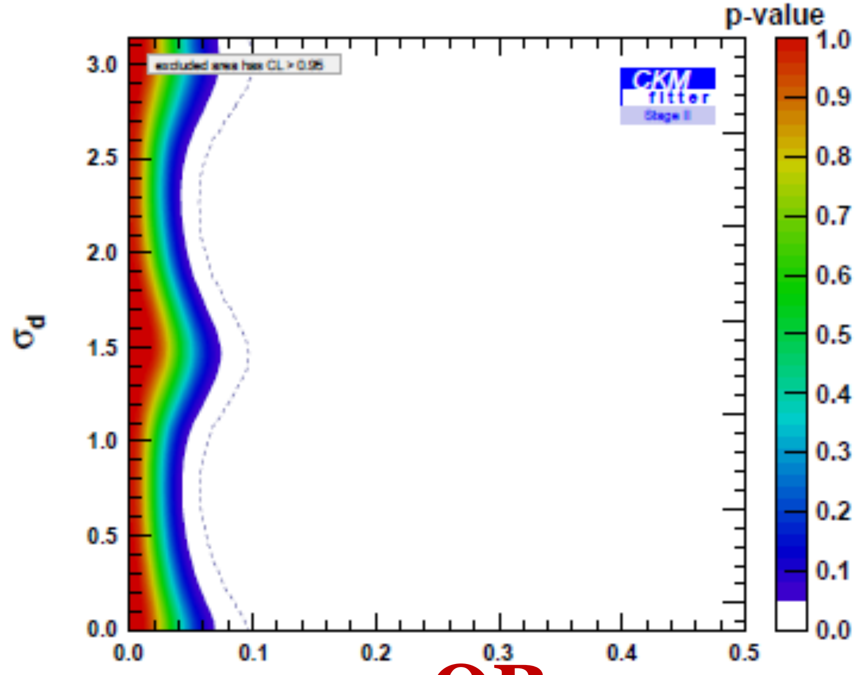
In 5-10 years:

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

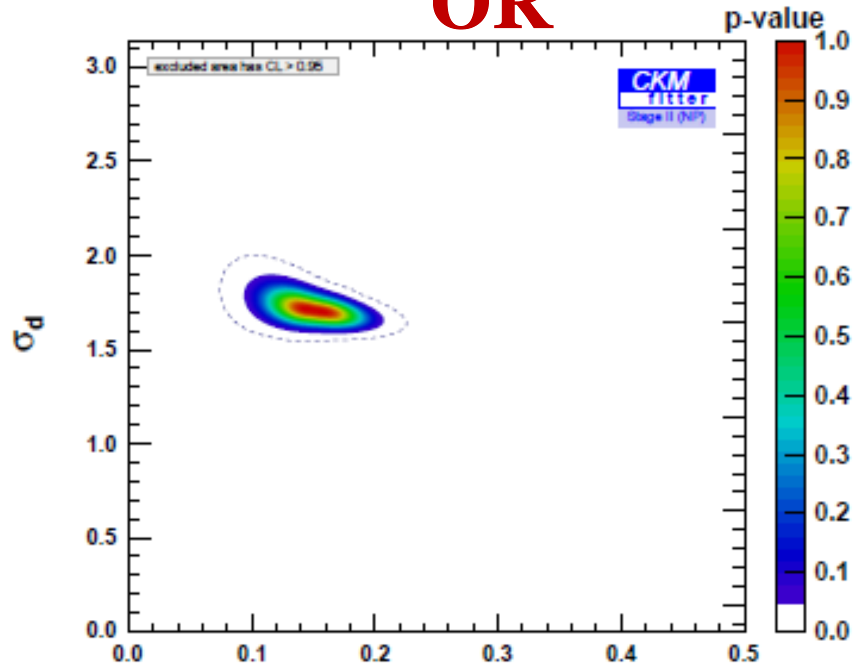
NP

Now we are here:





OR



Two scenario:

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