Search for New Physics via CP violation in B decays

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

Belle II

Alessandro Gaz

KMI, Nagoya University

Hints for New Physics in HF

Nagoya, November 15th 2018

Why look for CP violation

- The violation of the Charge-conjugation and Parity (CP) symmetry is a well established experimental fact;
- The Standard Model allows for the presence of CP violation thanks to a non-trivial complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix;

- All the phenomena we have observed so far at HEP experiments are consistent with this paradigm;
- But one fundamental question remains:

"How could the Universe, starting from a substantial matter/anti-matter equilibrium, become dominated by matter?"

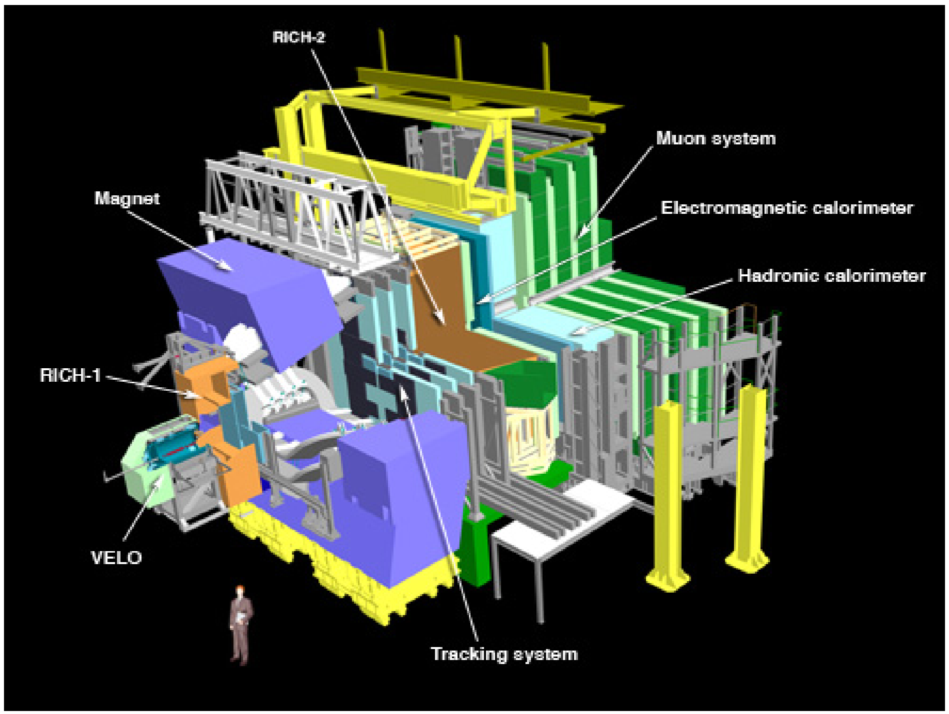
We need (more) CPV

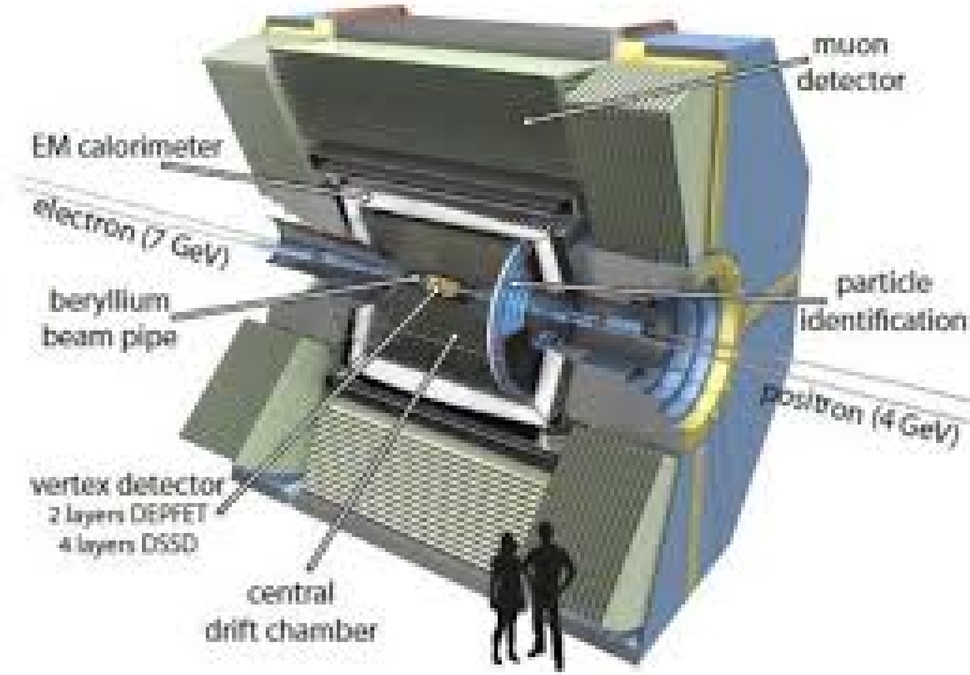
- How do we reach the observed level of matter dominance?
- Sakharov proposed three conditions that are necessary for baryogenesis:
  1) The baryonic number must be violated;
  2) The C and CP symmetries must be violated;
  3) The interactions must happen outside of thermal equilibrium;

- However… the amount of CP violation we have in the Standard Model is by far too small to explain the baryogenesis;
- We have to look for new sources of CP violation outside the Standard Model!
- This is one of the main motivations for the LHCb and Belle II Experiments.

Status of the Experiments

Two major players on the scene now:





> 9 fb^{-1} in Run1+Run2

(most results shown so far based on 3.0 fb^{-1})

Physics Run starts next March

Plan to accumulate 50 ab^{-1} in ~5 years.

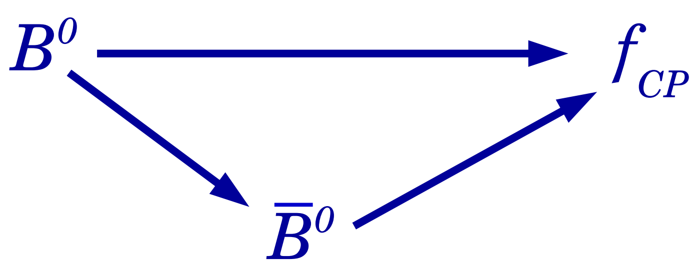
CP violation in B decays

There are three kinds of CP violation in B physics:

1) Direct CP violation:

$$P(B^0 \rightarrow f) \neq P(\overline{B}^0 \rightarrow \overline{f})$$

2) CP violation in the interference between mixing and decay:



3) CP violation in $B^0\overline{B}^0$ mixing (still unobserved):

$$P(B^0 \rightarrow \overline{B}^0) \neq P(\overline{B}^0 \rightarrow B^0)$$

Direct CP violation

$$P(B^0 \rightarrow f) \neq P(\bar{B}^0 \rightarrow \bar{f})$$

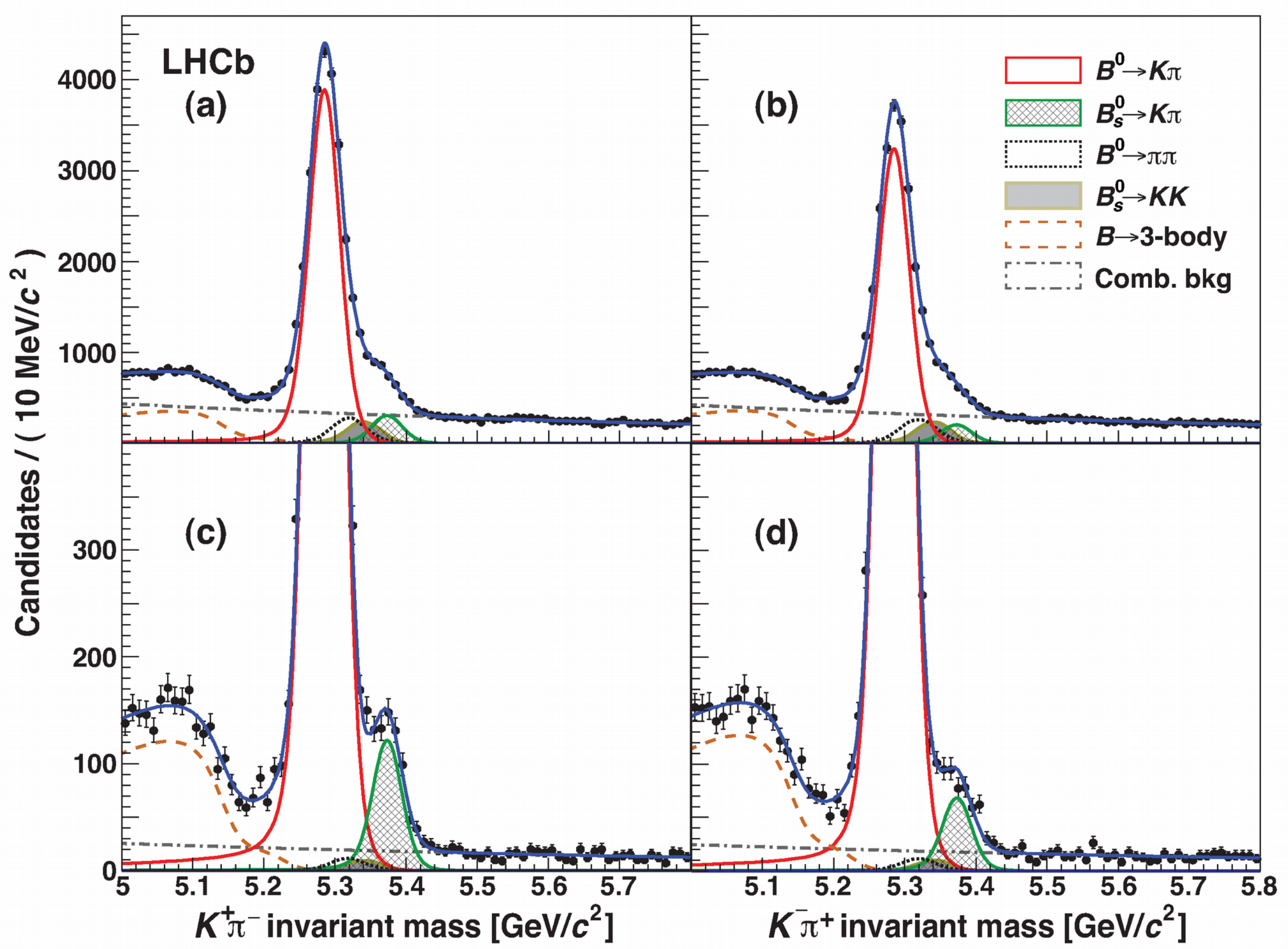
- Direct CP violation has been observed already in many B decay channels;
- It's easy to explain to students, but difficult to interpret in terms of the fundamental parameters of the Standard Model, as many amplitudes and strong phases can contribute.

$B^0 \rightarrow K^+\pi^-$

- The direct CP violation in B decays was discovered on the $B^0 \rightarrow K^+\pi^-$ decay channel;

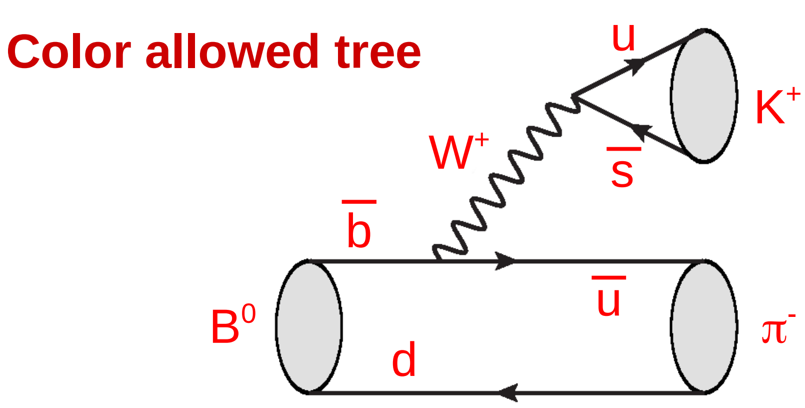
LHCb Collaboration,
PRL **110**, 221601 (2013)

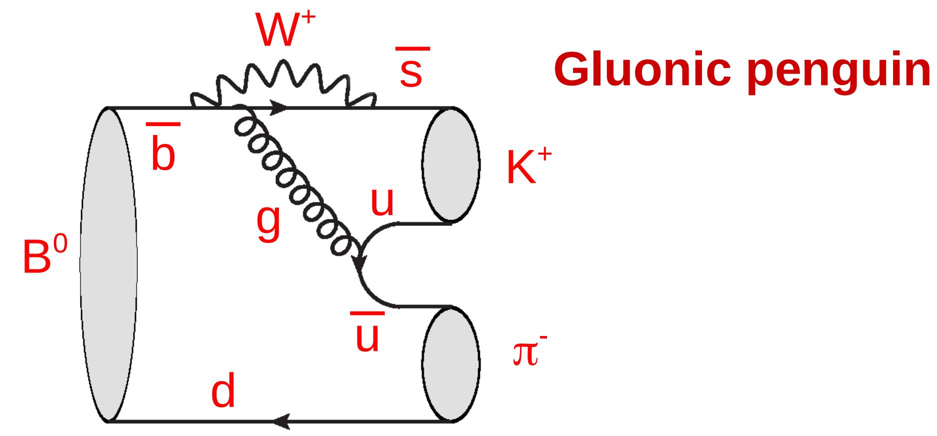
1.0 fb^{-1}



$$A_{CP} = -0.080 \pm 0.007\ (\text{stat}) \pm 0.003\ (\text{syst})$$

The Kπ "puzzle"





The "puzzle" arises from the fact that, by changing the spectator quark, we obtain the $B^+ \to K^+ \pi^0$ amplitudes. But these exhibit a very different value for the asymmetry:

$$A_{CP}\,(B^0 \to K^+ \pi^-) = (-0.082 \pm 0.006) \ \text{(World Average)}$$

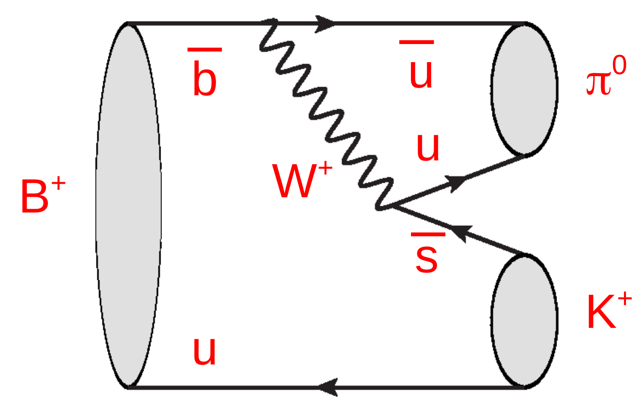
$$A_{CP}\,(B^+ \to K^+ \pi^0) = (+0.037 \pm 0.021) \ \text{(World Average)}$$

$$\Delta A_{CP}\,(B \to K\pi) = (+0.122 \pm 0.022)$$

The Kπ "puzzle"

Color suppressed tree

- The non-zero value of $\Delta A_{CP}(B \to K\pi)$ is not necessarily a sign of New Physics;
- Other amplitudes (that were expected to be negligible) contribute to the decays;



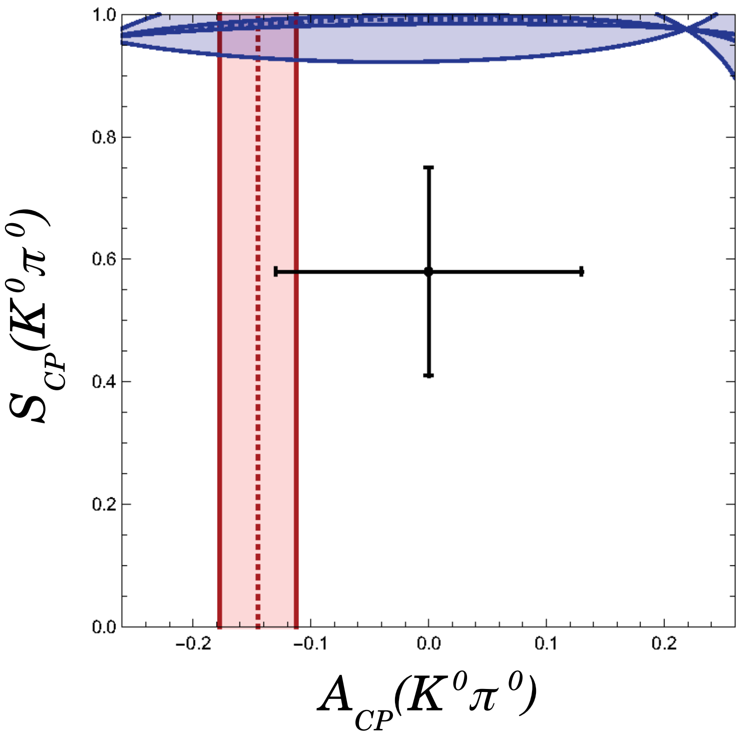
- To disentangle effects originating from suppressed amplitudes from New Physics, a wider combination of all the observables of the $B \to K\pi$ system must be taken into account:

Mode	$\mathcal{B}r[10^{-6}]$	A_{CP}^{f}	S_{CP}^{f}
$B_d^0 \to \pi^- K^+$	19.6 ± 0.5	-0.082 ± 0.006	–
$B_d^0 \to \pi^0 K^0$	9.9 ± 0.5	0.00 ± 0.13	0.58 ± 0.17
$B^+ \to \pi^+ K^0$	23.7 ± 0.8	-0.017 ± 0.016	–
$B^+ \to K^+ \pi^0$	12.9 ± 0.5	0.037 ± 0.021	–

The Kπ "puzzle"

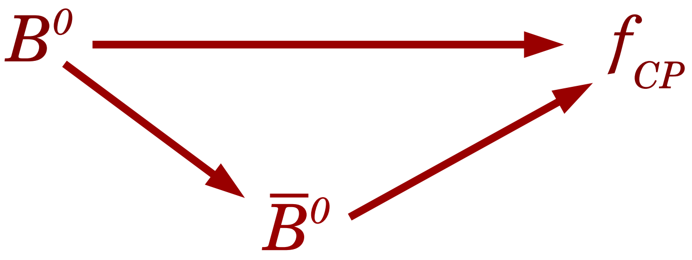
- Several tests or sum rules can be defined for the Kπ system;
- The observables of some modes can be used to predict those of a specific one;
- The precision of the test is (and will be) driven by $K^0\pi^0$;
- The current tension between data and predictions for the direct and time-dependent CP asymmetries is at the 2.2σ level;
- Strong motivation to improve these measurements further.

R. Fleischer, R. Jaarsma, K. Keri Vos
PL **B785**, 525 (2018)



Data point: experimental averages
Colored bands: predictions based on the other observables

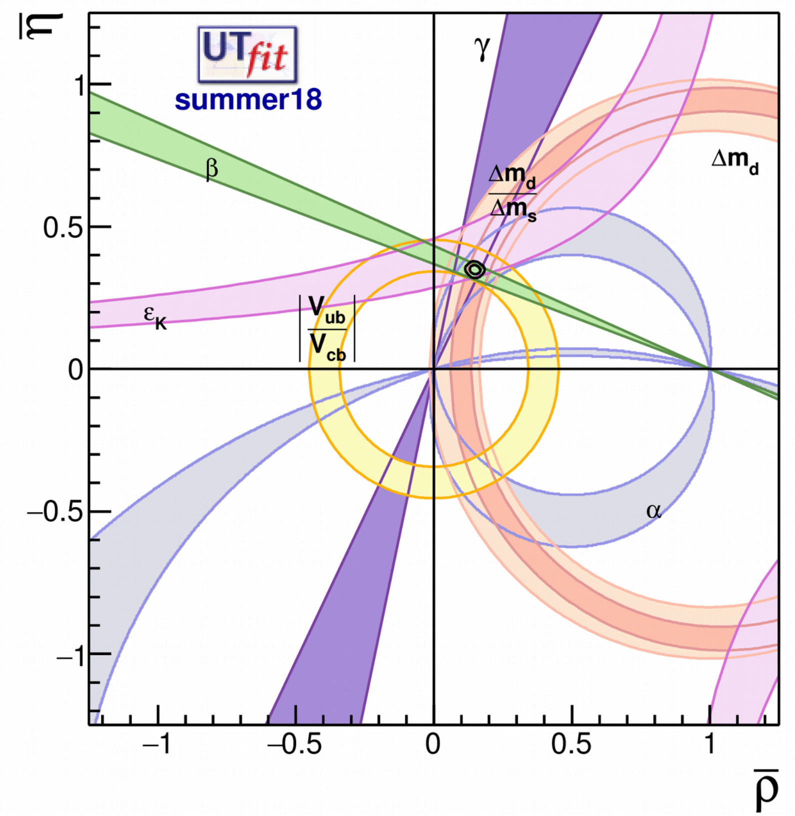
CP violation in the interference between mixing and decay



- This was the main motivation for building the B factories (and still a big part of the current Flavor Physics programme);
- Its interpretation allows a direct access to the fundamental parameters of the theory (elements of the CKM matrix).
- In general, theoretically very clean.

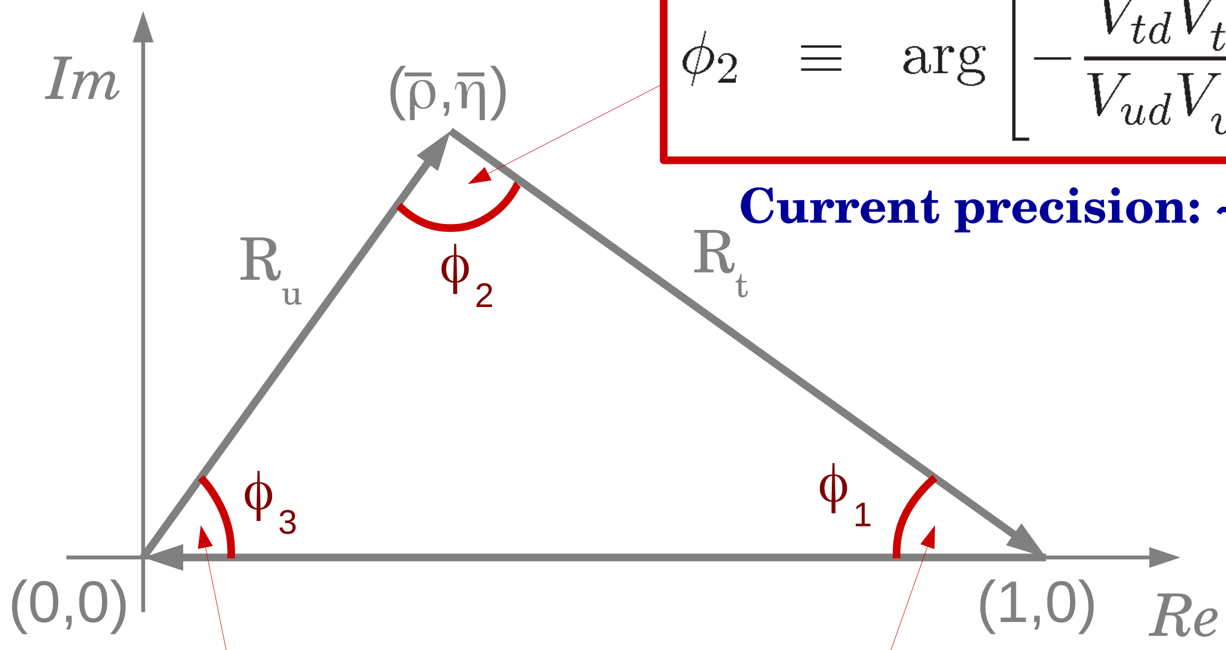
Motivations (1)

- The unitarity conditions on the CKM matrix define a triangle in the complex plane;
- Several observables (most of which from B physics) concur to define the position of the Unitarity Triangle (UT);
- The area of the triangle represents the "amount" of CP violation allowed by the CKM matrix;



- We can actually over-constrain the fit to the UT: as of now the agreement is fair, but there are some tensions at the ~2σ level;
- A possible way to New Physics: find some inconsistency in the UT, and demonstrate that the complex phase in the CKM matrix cannot be the only source of CP violation.

Current precision on the angles



$$\phi_2 \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

Current precision: ~5º

$$\phi_3 \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

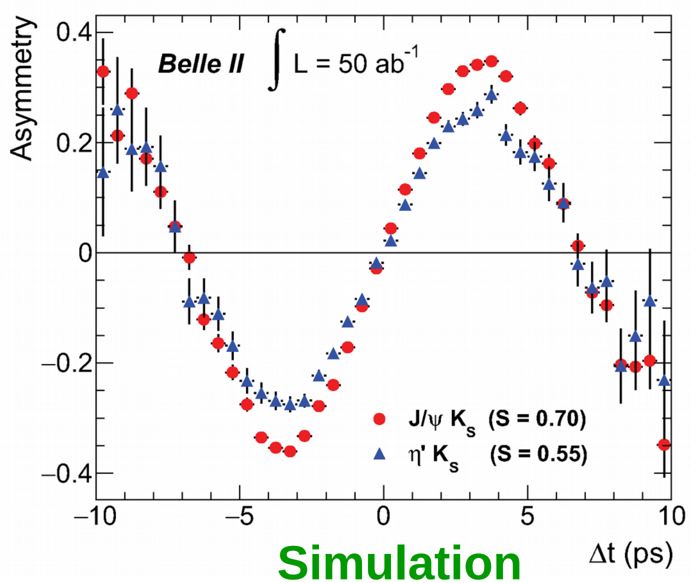
Current precision: ~5º

$$\phi_1 \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

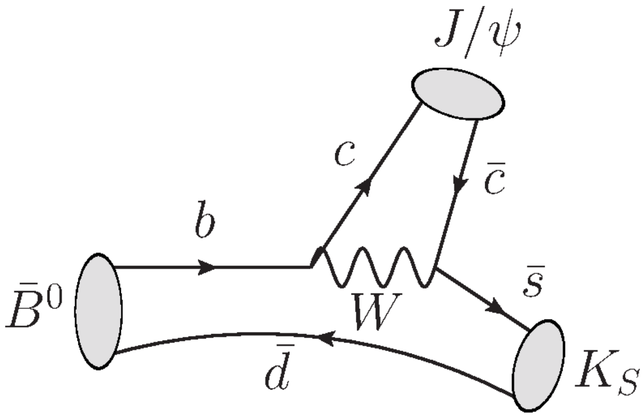
Current precision: ~0.7º

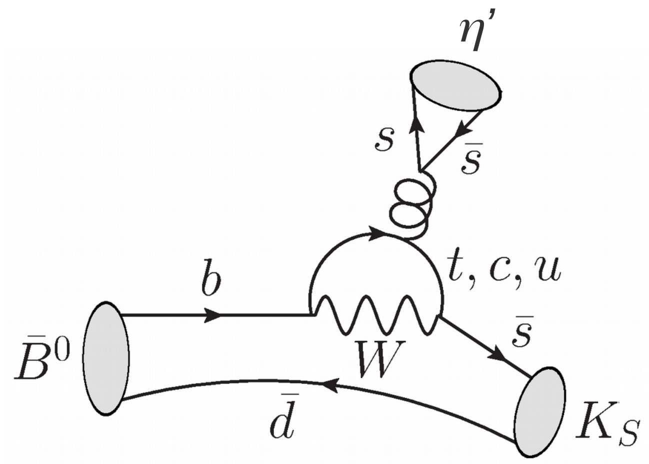
Motivations (2)

- Not only we can over-constrain the UT, we can over-constrain the measurement of the same angle;
- Example: time dependent analysis of both $B^0 \rightarrow J/\psi K^0$ and $B^0 \rightarrow \eta' K^0$ measures $\sin 2\phi_1$;
- $J/\psi K^0$ dominantly proceed through tree amplitudes, while $\eta' K^0$ is dominated by penguin amplitudes:



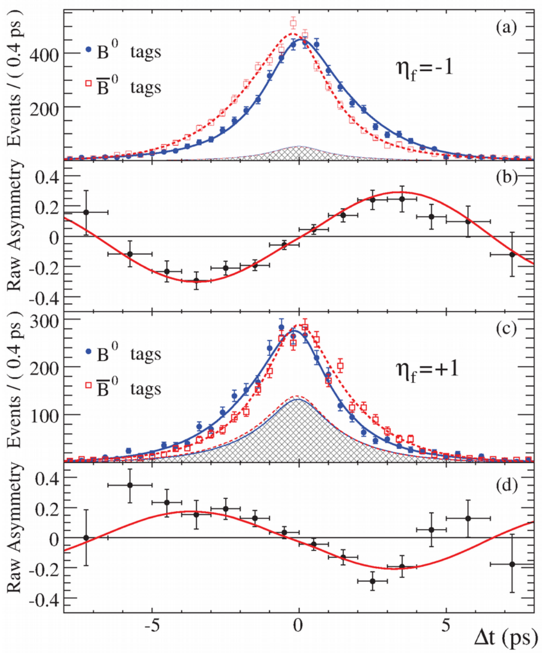
Simulation (dream scenario)



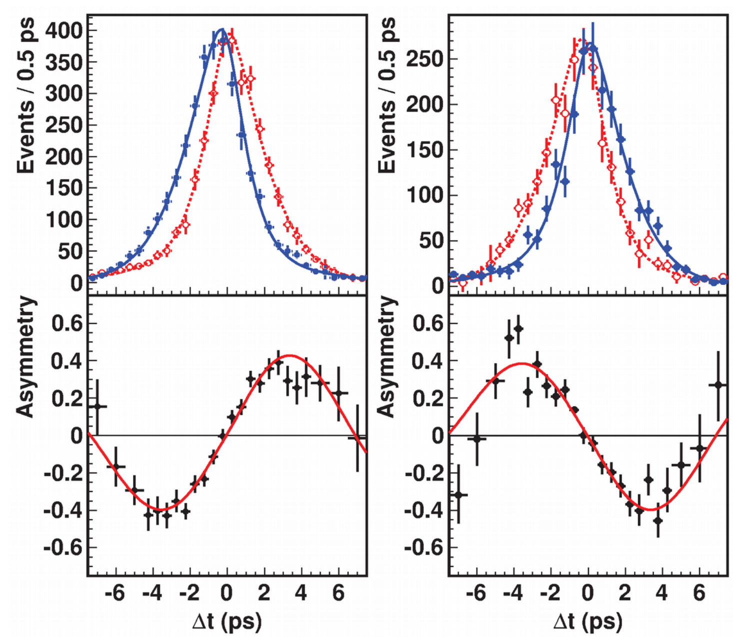


New Physics amplitudes can be competitive with the SM suppressed ones, and introduce new weak phases

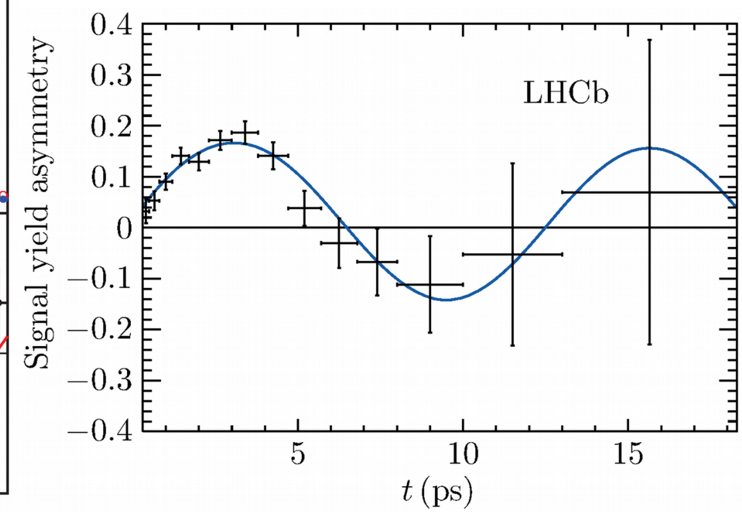
$\sin 2\phi_1$ from $B^0 \to J/\psi\, K^0$



BaBar Collaboration
PRD **79**, 072009 (2009)



Belle Collaboration
PRL **108**, 171802 (2012)



LHCb Collaboration
JHEP **11**, 170 (2017)

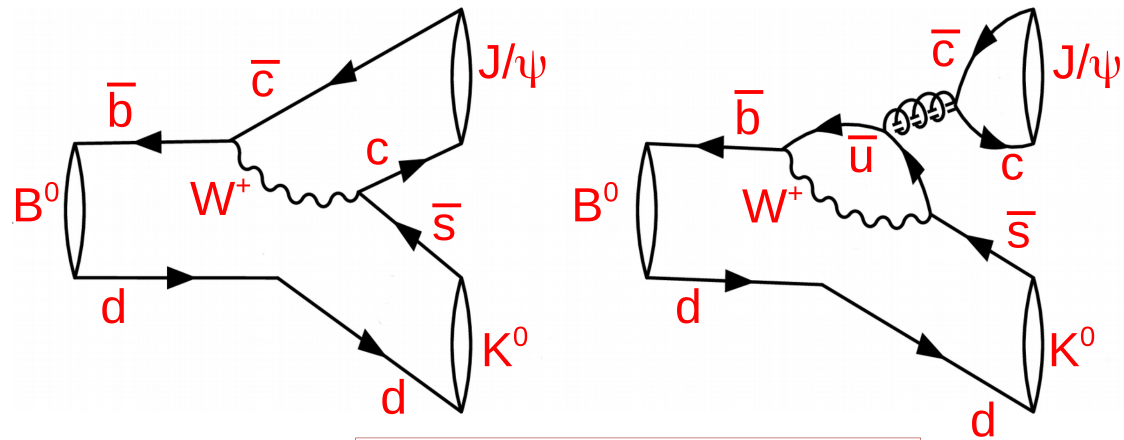
BaBar	Belle	LHCb
S = 0.687 ± 0.028 ± 0.012	S = 0.667 ± 0.023 ± 0.012	S = 0.760 ± 0.034
C = -A = 0.024 ± 0.020 ± 0.016	C = -A = -0.006 ± 0.016 ± 0.012	C = -A = -0.017 ± 0.029

The measurements will be systematics-dominated very soon:

- ➔ we need to control/improve the experimental uncertainties;
- ➔ effects from suppressed amplitudes can no longer be neglected.

“Penguin pollution” on $\sin 2\phi_1$

- Penguin diagrams carrying different weak phases contribute to these decays and can shift the measured value of the phase by as much as 1°;



see e.g.
K. De Bruyn, R. Fleisher
JHEP **1503**, 145 (2015)

- Those contributions cannot be reliably computed by QCD;
- Need a coherent plan to constrain these effects experimentally, measuring weak phases of SU(3) or U-spin related decays:

$B_d \to J/\psi\ K^0$ $\qquad$ $B_d \to J/\psi\ \pi^0$, $B_s \to J/\psi\ K^0$

$B_s \to J/\psi\ \phi$ $\qquad$ $B_s \to J/\psi\ K^{*0}$, $B_d \to J/\psi\ \rho^0$

Recent measurements from LHCb:
JHEP 1506, **131** (2015)
PLB 742, **38** (2015)

- This is a place where cooperation between LHCb and Belle II can be advantageous!

$\sin 2\phi_1$ from penguin dominated modes

- Several modes are theoretically very clean;
- The quantity $\Delta S_f = S_f - S_{J/\psi K0}$ can be predicted/constrained with quite small theoretical uncertainty:

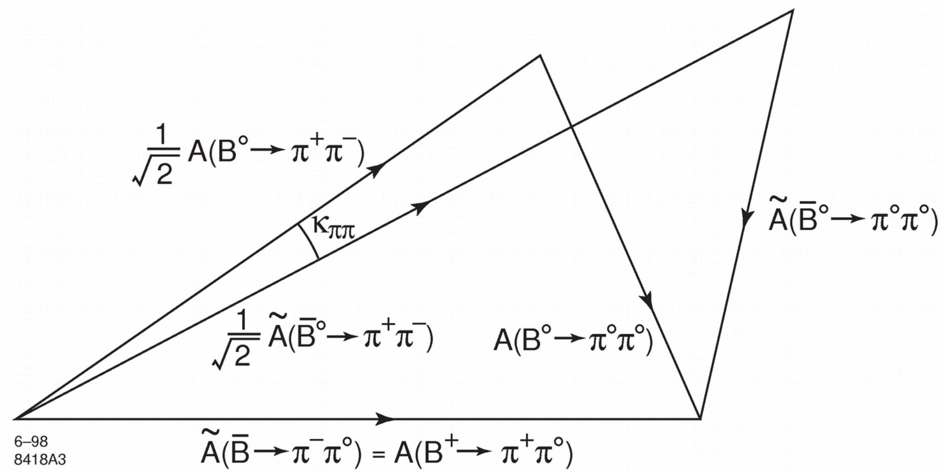
	Mode	QCDF [32]	QCDF (scan) [32]	$SU(3)$	Data
(★)	$\pi^0 K_S^0$	$0.07^{+0.05}_{-0.04}$	$[0.02, 0.15]$	$[-0.11, 0.12]$ [36]	$-0.11^{+0.17}_{-0.17}$
	$\rho^0 K_S^0$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.02]$		$-0.14^{+0.18}_{-0.21}$
★	$\eta' K_S^0$	$0.01^{+0.01}_{-0.01}$	$[0.00, 0.03]$	$(0 \pm 0.36) \times 2\cos(\phi_1)\sin\gamma$ [37]	-0.05 ± 0.06
	ηK_S^0	$0.10^{+0.11}_{-0.07}$	$[-1.67, 0.27]$		—
★	ϕK_S^0	$0.02^{+0.01}_{-0.01}$	$[0.01, 0.05]$	$(0 \pm 0.25) \times 2\cos(\phi_1)\sin\gamma$ [37]	$0.06^{+0.11}_{-0.13}$
	ωK_S^0	$0.13^{+0.08}_{-0.08}$	$[0.01, 0.21]$		$0.03^{+0.21}_{-0.21}$

The Belle II Physics Book, arXiv:1808.10567, submitted to PTEP

- Most promising modes: $\eta' K^0$, ϕK^0;
- The precision of the constraints will be increased by measurements of (for example) SU(3) related modes;
- These modes will be statistically dominated for a few more years!

Measurements of ϕ_2

- In principle ϕ_2 can be measured in the same way as ϕ_1;
- In practice the penguin pollution is so high that alternative methods should be used:
  - isospin analysis of $B \to \pi\pi$;
  - isospin analysis of $B \to \rho\rho$;
  - TD Dalitz plot analysis of $B^0 \to \pi^+\pi^-\pi^0$;
  - …



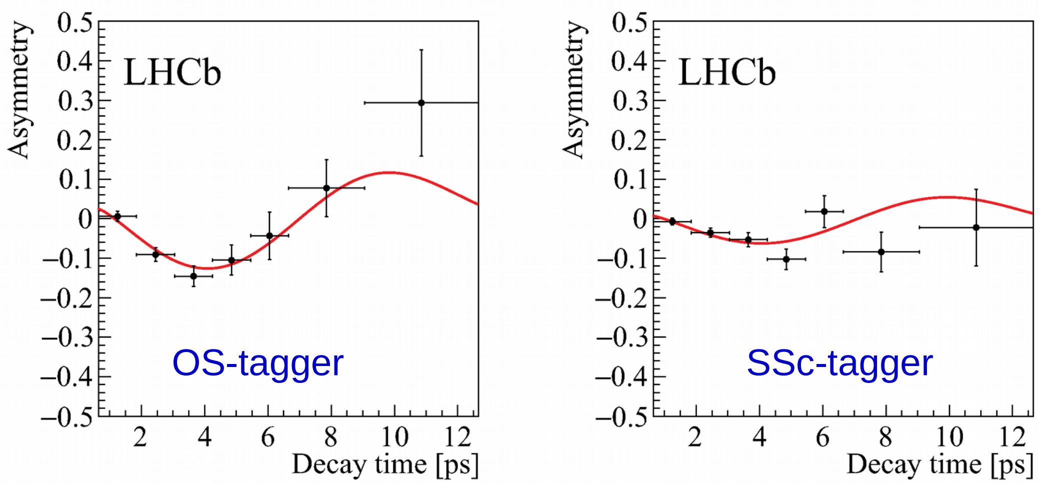
- Isospin analyses are affected by (8-fold) ambiguities;
- π^0's in the final states are unavoidable;
- Once more the name of the game is checking the consistency of the determination of ϕ_2 with the rest of the UT, and the consistency of the different methods.

Isospin analysis of B → ππ

- Observables:
  - branching fractions of: $B \to \pi^+\pi^0, \pi^+\pi^-, \pi^0\pi^0$;
  - direct (time independent) CP asymmetries: C^{+-}, C^{00};
  - time dependent CP asymmetry: S^{+-}.

LHCb Collaboration,
PRD **98**, 032004 (2018)

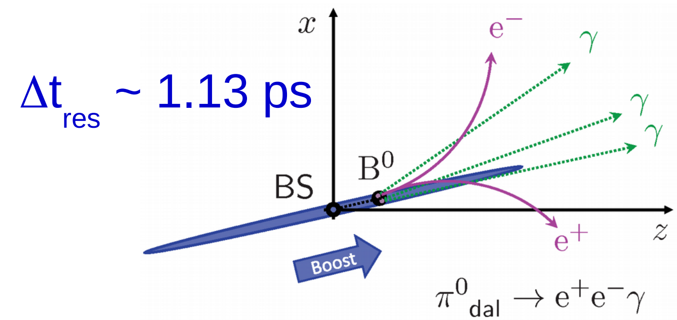
S = -0.63 ± 0.05 ± 0.01
C = -0.34 ± 0.06 ± 0.01

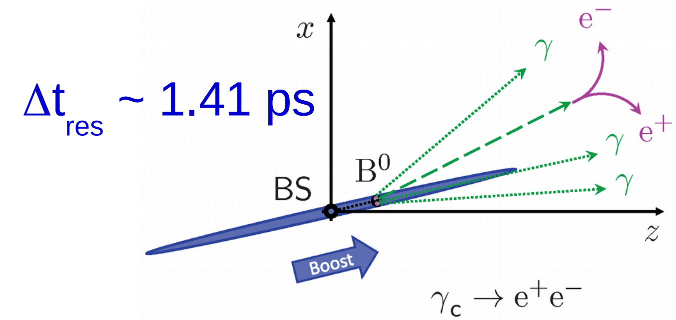


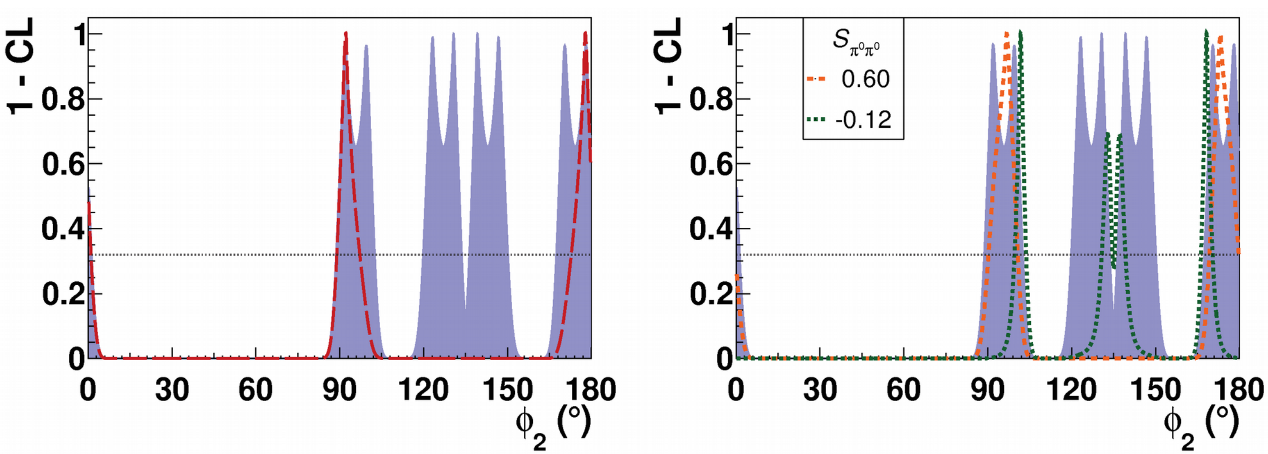
- In general, the isospin analysis is affected by an 8-fold ambiguity;
- By adding the time-dependent CP asymmetry of $B^0 \to \pi^0\pi^0$ S^{00}, the ambiguity would be reduced by a factor 2-4.

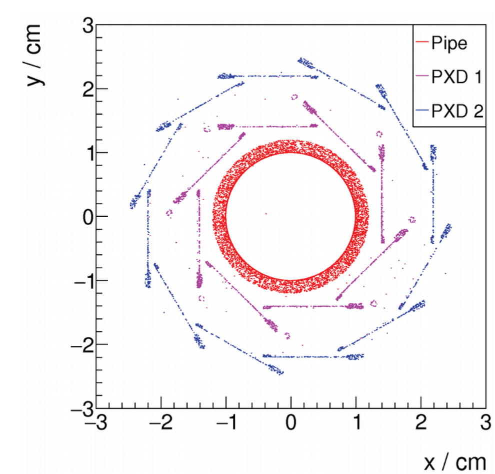
Time dependent $B^0 \to \pi^0\pi^0$

- Only at Belle II: TD CPV of $B^0 \to \pi^0 \pi^0$, exploiting π^0 Dalitz decays and γ conversions;
- Expect ~270 signal events with full dataset;
- Predicted error on S^{00} ~ 0.28;
- This would reduce the ambiguity on ϕ_2 by a factor 2 or 4 (depending on central value).







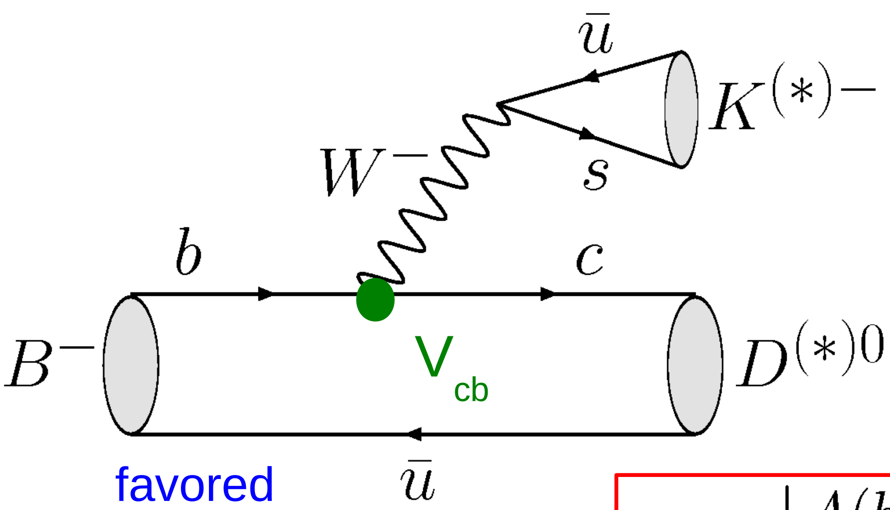


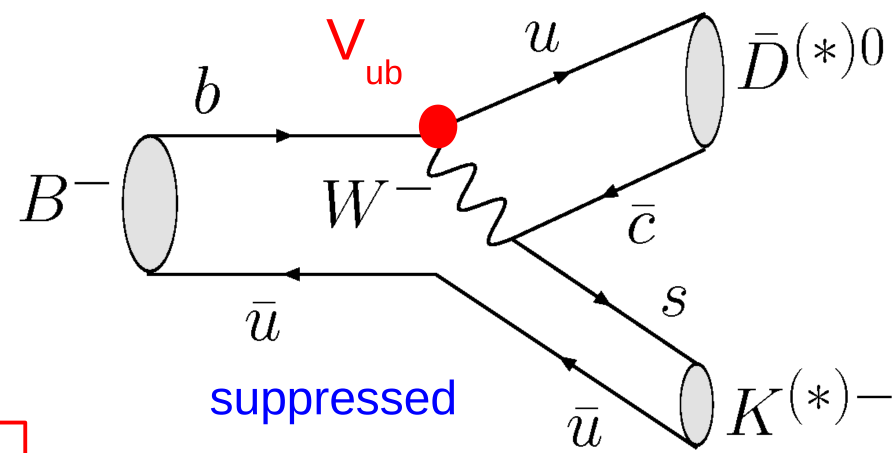
Filled area: extrapolation of Belle results to Belle II sensitivity.

Dashed line: same as above, but adding S^{00}.

Measurements of ϕ_3

- The first (and currently most precise) way to measure ϕ_3 relies on the interference between the color allowed/suppressed tree amplitudes:





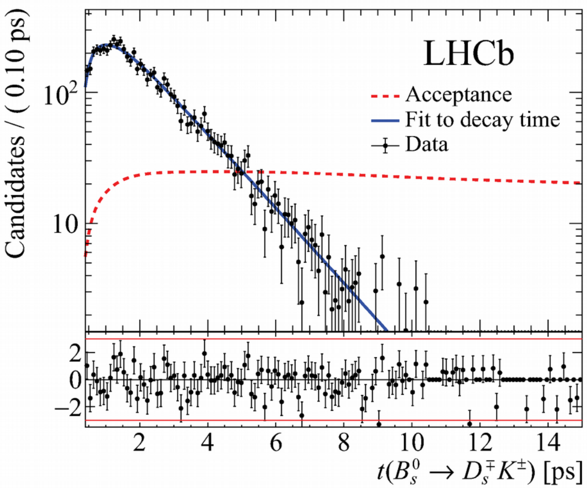
$$r_B = \left| \frac{A(b \to u)}{A(b \to c)} \right| \sim 0.15$$

- Other methods exploit the time dependent CP asymmetry of $B^0 \to D^-\pi^+$ and $B_s \to D_s^- K^+$ decays (where ϕ_3 is measured together with the mixing phases).

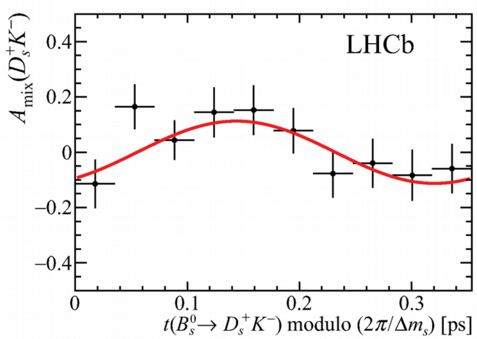
ϕ_3 from TD $B_s \to D_s^- K^+$

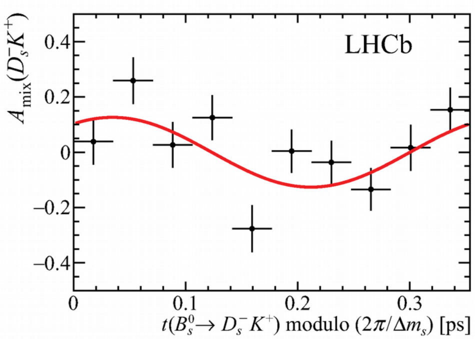
$$\frac{\Gamma(B_s(t)\to D_s^- K^+) - \Gamma(\overline{B}_s(t)\to D_s^- K^+)}{\Gamma(B_s(t)\to D_s^- K^+) + \Gamma(\overline{B}_s(t)\to D_s^- K^+)} = \frac{-C_f\cos(\Delta m_s t) + S_f \sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) + A_f^{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}$$

Parameter	Value
C_f	$0.730 \pm 0.142 \pm 0.045$
$A_f^{\Delta\Gamma}$	$0.387 \pm 0.277 \pm 0.153$
$A_{\overline{f}}^{\Delta\Gamma}$	$0.308 \pm 0.275 \pm 0.152$
S_f	$-0.519 \pm 0.202 \pm 0.070$
$S_{\overline{f}}$	$-0.489 \pm 0.196 \pm 0.068$



$$\gamma = (128\,^{+17}_{-22})^\circ$$
$$\delta = (358\,^{+13}_{-14})^\circ$$
$$r_{D_sK} = 0.37\,^{+0.10}_{-0.09}$$

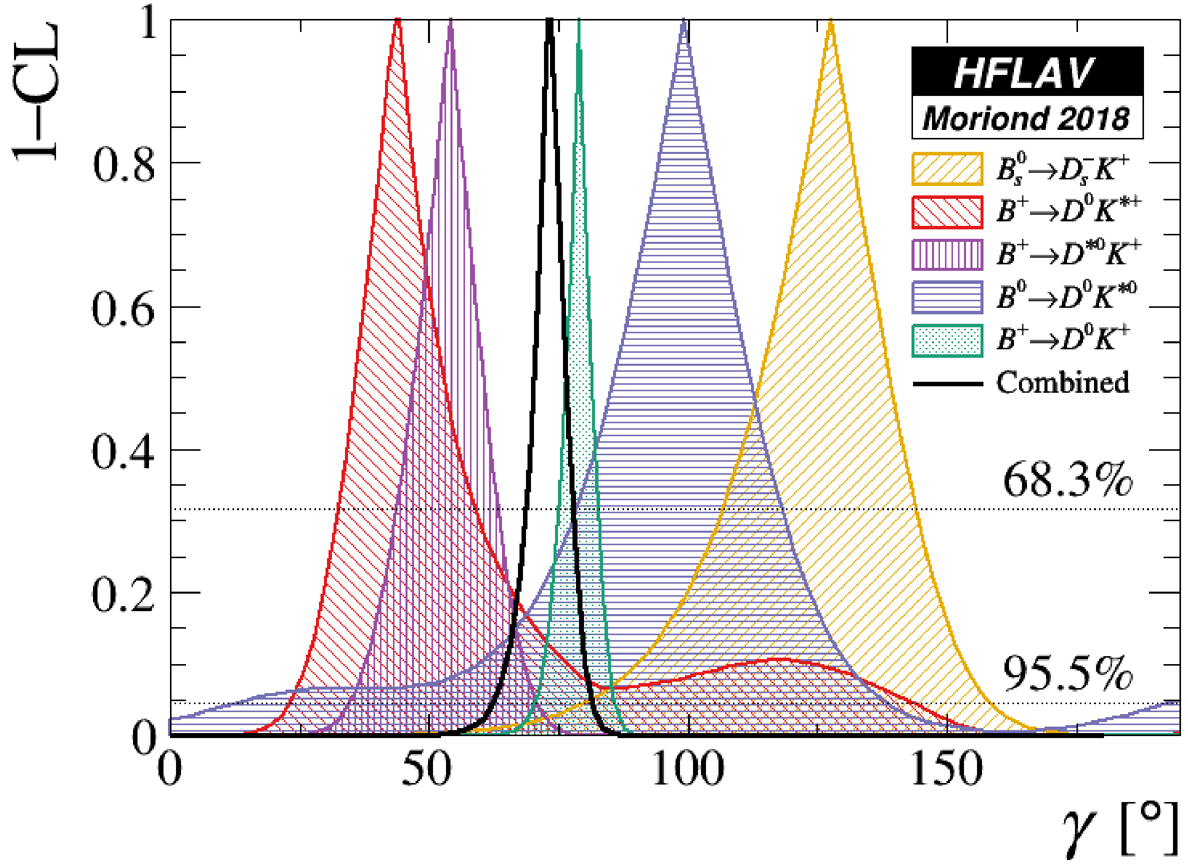




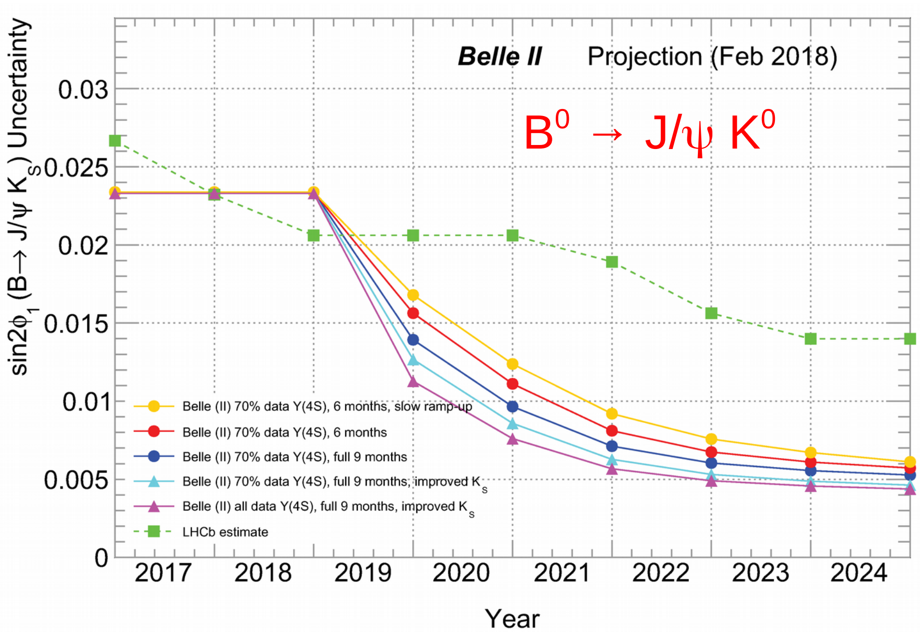
LHCb Collaboration,
JHEP **1803**, 059 (2018)

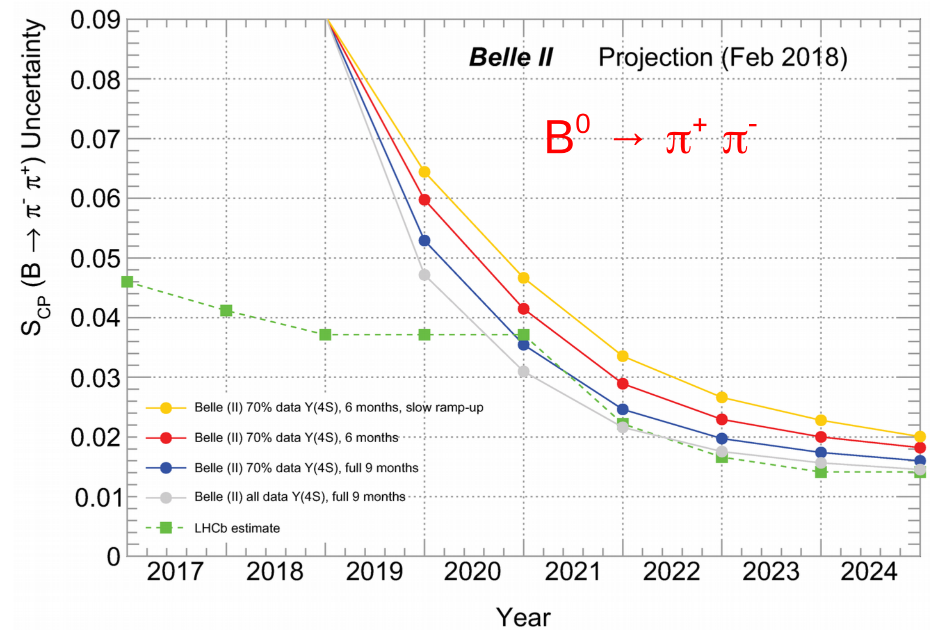
ϕ_3 status

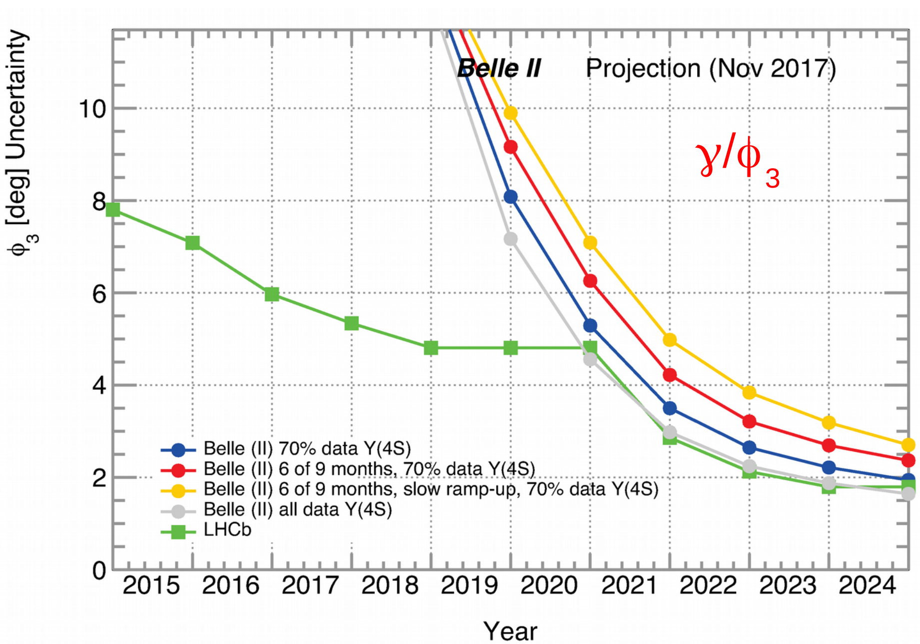
- LHCb is now leading the competition;
- Best sensitivity still coming from $B^+ \rightarrow D^0 K^+$;
- The compatibility of all the measurements is not fantastic, it could be due to statistical fluctuations …



Projections on the UT angles







Ultimate sensitivity:

$\phi_1/\beta \sim 0.2^o$

$\phi_2/\alpha \sim 1.0^o$

$\phi_3/\gamma \sim 1.0^o$

CP violation in B$\bar{B}$ mixing

$$P(B^0 \rightarrow \bar{B}^0) \neq P(\bar{B}^0 \rightarrow B^0)$$

- CP violation was discovered in the mixing of neutral K's;
- Still to be discovered in B$\bar{B}$ mixing, current limits one order of magnitude above SM predictions;
- Sizable improvement is expected in the near future.

Formalism

- Formalism of $B\bar{B}$ oscillations:

Time evolution of a $B^0\bar{B}^0$ system

$$i\frac{d}{dt}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix}$$

Mass eigenstates

$$|B_{H,L}\rangle = \frac{1}{\sqrt{2}}(p|B^0\rangle \mp q|\bar{B}^0\rangle)$$

If $|q/p| \neq 1$ the probability for a B^0 to oscillate to a $\bar{B}^0$ is different from the probability of a $\bar{B}^0$ going to B^0

- Experimentally we measure:

$$A_{SL} = \frac{\Gamma(\bar{B} \to B \to f) - \Gamma(B \to \bar{B} \to \bar{f})}{\Gamma(\bar{B} \to B \to f) + \Gamma(B \to \bar{B} \to \bar{f})} \approx 2\left(1 - \left|\frac{q}{p}\right|\right)$$

- The Standard Model predicts tiny CP violation in mixing:

$$\begin{aligned} A^d_{SL} &= (-4.1 \pm 0.6) \times 10^{-4} \\ A^s_{SL} &= (\ \ 1.9 \pm 0.3) \times 10^{-5} \end{aligned}$$

Experimental precision ~10^{-3}, still room for surprises…

A. Lenz, arXiv 1205.1444 [hep-ph]

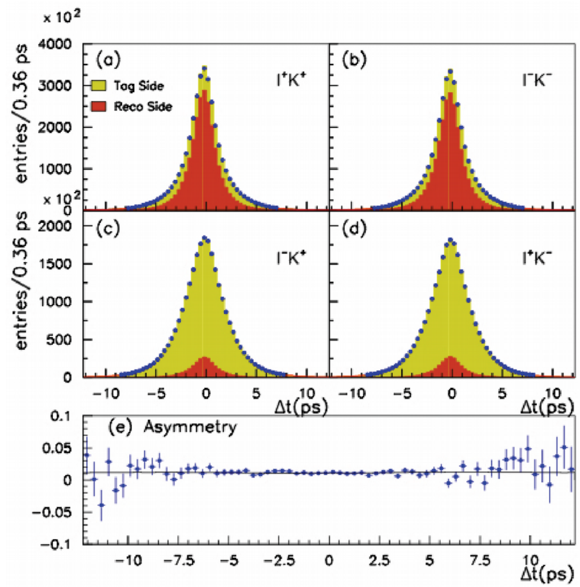
Experimental approach

Different strategies to measure A_{SL}:

1) Tag two B^0's (at B-factories and D0):

$$A_{SL} = \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)}$$

Can also tag B's using kaons.

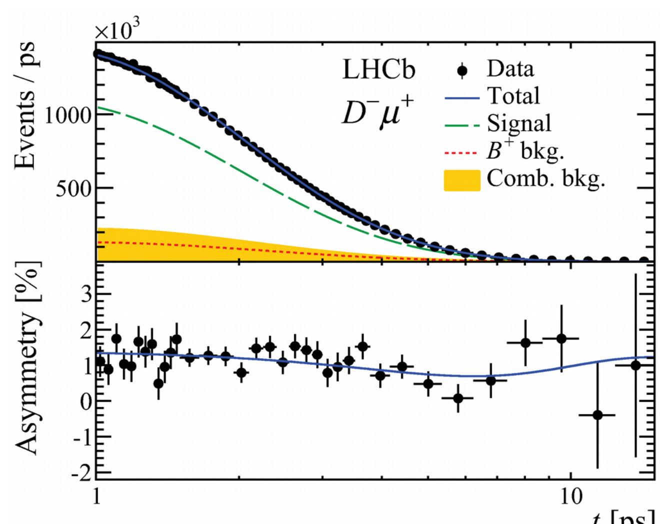


BaBar Collaboration, PRL **111**, 101802 (2013)

2) Untagged measurement (at LHCb):

$$\frac{N(B,t) - N(\bar{B},t)}{N(B,t) + N(\bar{B},t)} = \frac{A_{SL}}{2}\left[1 - \frac{\cos\Delta M t}{\cosh\frac{\Delta\Gamma t}{2}}\right]$$

Complications arising from the asymmetric production at a pp collider. For the B_s, the high oscillation frequency washes out the production asymmetry, so a time integrated approach is ok.



LHCb Collaboration, PRL **114**, 041601 (2014)

Current status

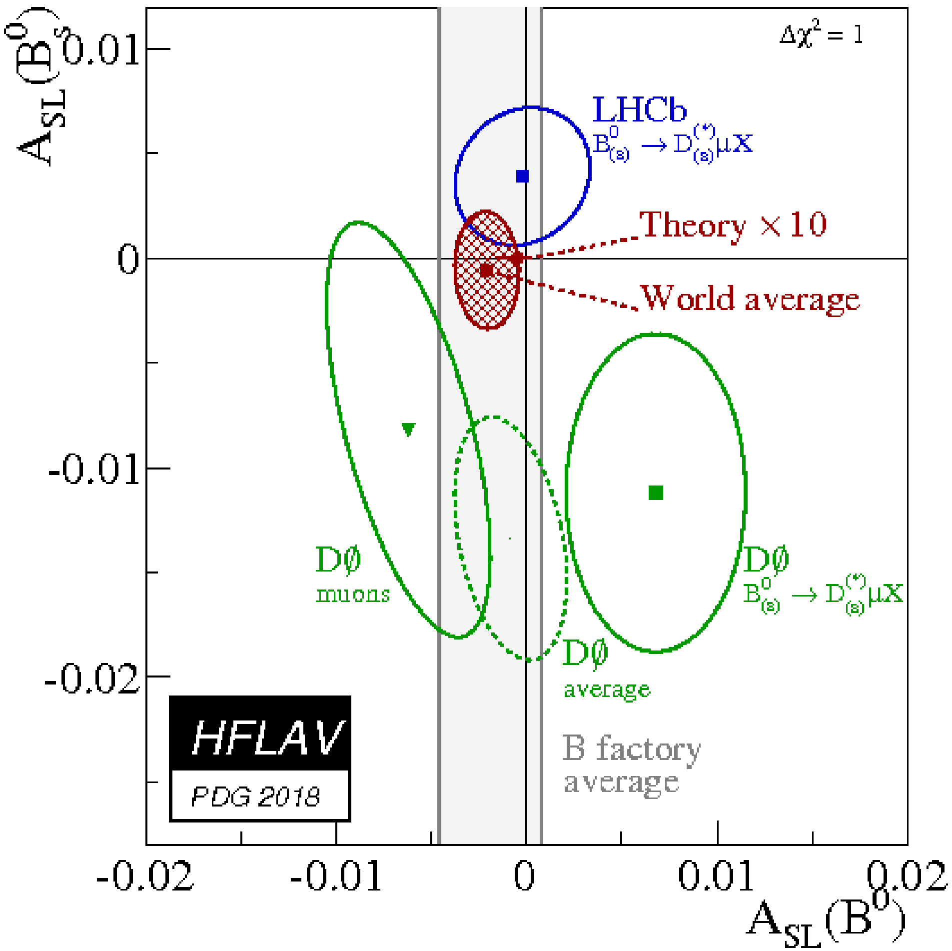
- Experimental status:

A^{d}_{SL}:

BaBar (*ll*):	(-0.39 ± 0.35 ± 0.19)%
BaBar ($D^*l\nu$):	(0.06 ± 0.17 ± 0.35)%
D0 ($D\mu X$):	(0.68 ± 0.45 ± 0.14)%
LHCb ($D\mu X$):	(-0.02 ± 0.19 ± 0.30)%

A^{s}_{SL}:

D0 ($D_s\mu X$):	(-1.12 ± 0.74 ± 0.17)%
LHCb ($D_s\mu X$):	(0.39 ± 0.26 ± 0.20)%



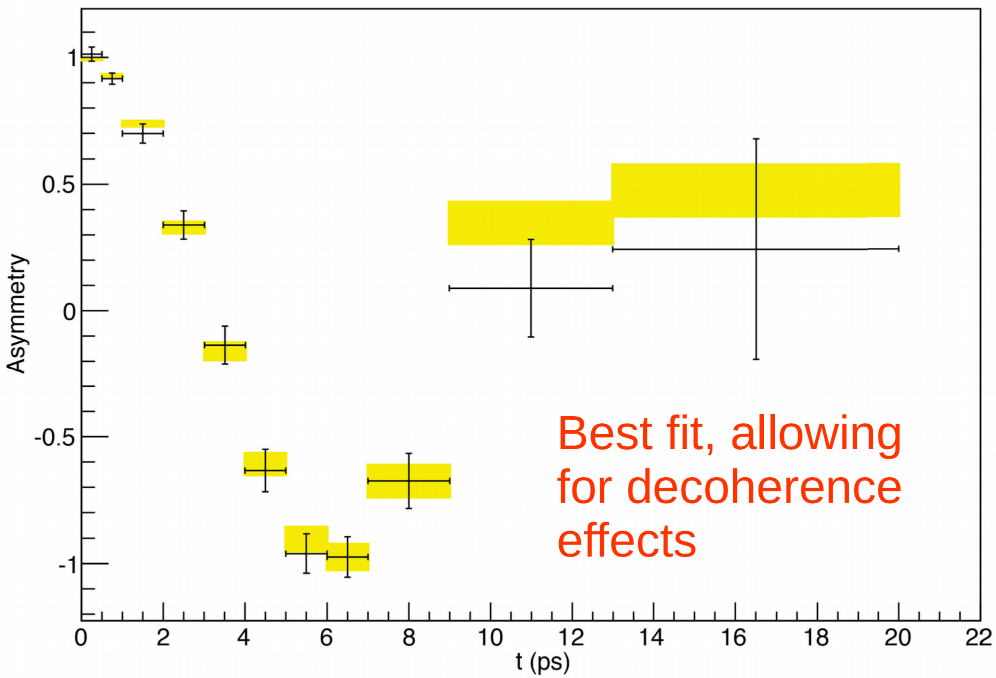
- The next years will be interesting: still margin for improvement (many systematics depend on statistics of control samples).

Decoherence in $B\bar{B}$ mixing

- General assumption: the time evolution of a coherent $B^0\bar{B}^0$ system does not depend on the rest of the Universe;
- This has verified at Belle with high accuracy (using 152 x 10^6 $B\bar{B}$'s);
- Strong motivation to look for effects of decoherence with a much larger sample;
- Quantity of interest:

$$\mathcal{A}_{\Delta m}(t) = \frac{\Gamma^{(OF)}(t) - \Gamma^{(SF)}(t)}{\Gamma^{(OF)}(t) + \Gamma^{(SF)}(t)}$$

$A = (1.5 \pm 8.4) \times 10^{-3}$



F. Benatti et al., EPJ **C77**, 651 (2017), using Belle data from PRL 99, 131802 (2007)

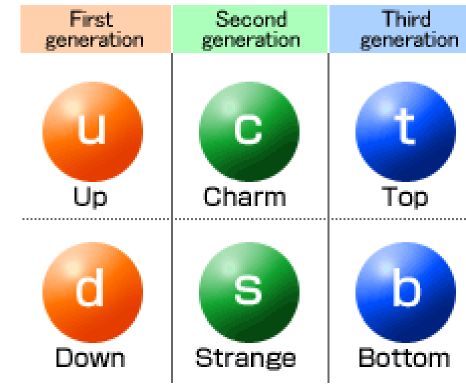
Conclusions

- CP violation is a fundamental ingredient for the evolution of our Universe;
- Only a small amount of it is allowed in the Standard Model, which, after many years of Flavor Physics, keeps standing strong;
- Improving existing approaches and probing new ideas might lead us to New Physics;
- The next few years will be crucial!

Backup slides

The CKM Matrix

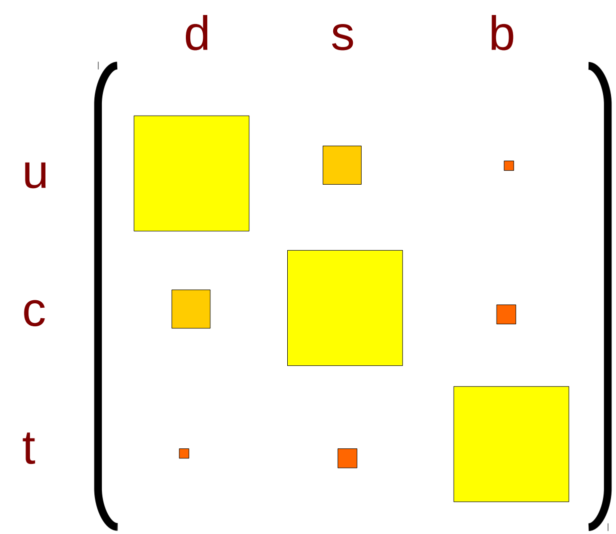
- The CKM Matrix can be parameterized as:



$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

λ: expansion parameter, aka Cabibbo angle, λ ~ 0.22

- Strong hierarchical structure: the coupling between quarks of different generations is suppressed;
- There can be a weak phase, affecting only the smallest elements of the Matrix, at first order;



- This weak phase is the origin of all CP Violating phenomena we have observed so far in the quark sector.

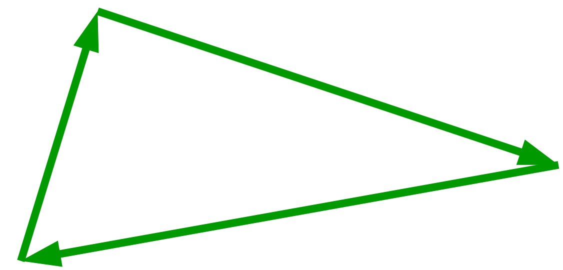
The Unitarity Triangle(s)

Six (only three are independent) of the unitarity conditions of the CKM Matrix define triangles on the complex plane:

$$V_{CKM}V_{CKM}^{\dagger} = \mathbb{1}$$

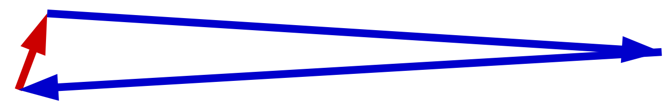
1) $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

$O(\lambda^3)$ $O(\lambda^3)$ $O(\lambda^3)$



2) $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$

$O(\lambda^4)$ $O(\lambda^2)$ $O(\lambda^2)$



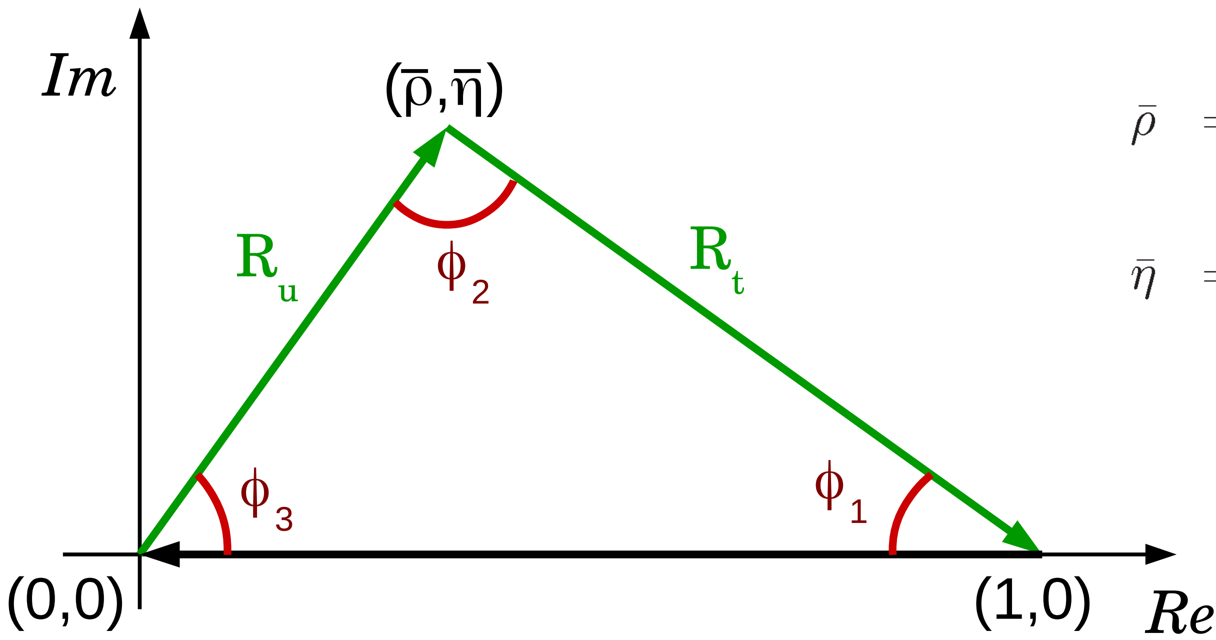
3) $V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$

$O(\lambda)$ $O(\lambda)$ $O(\lambda^5)$

The Unitarity Triangle

- Dividing 1) by $V_{cd}V^{*}_{cb}$, we obtain: $$\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}} + 1 + \frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}} = 0$$

  which defines the standard CKM Unitarity Triangle:



$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2}\right)$$

$$\bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2}\right)$$

- We can (over)constrain the position of the apex (ρ, η), by performing independent measurements of the magnitude of the sides R_u and R_t, and of the angles ϕ_1, ϕ_2, and ϕ_3.