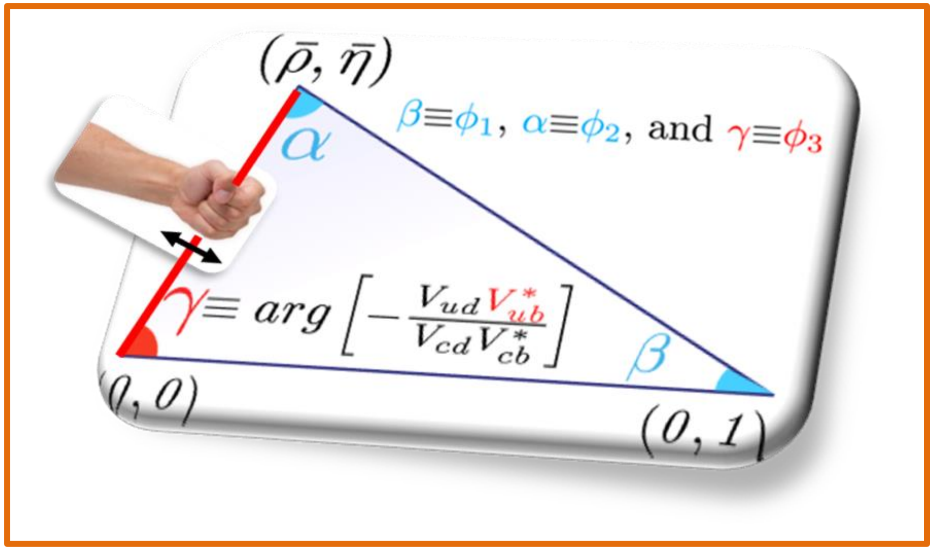
Heavy Flavour Physics: from CP violation to intensity frontiers, a new paradigm

V. Tisserand, LPC-Clermont Ferrand, France

Journées des 2 Infinis de l'IN2P3

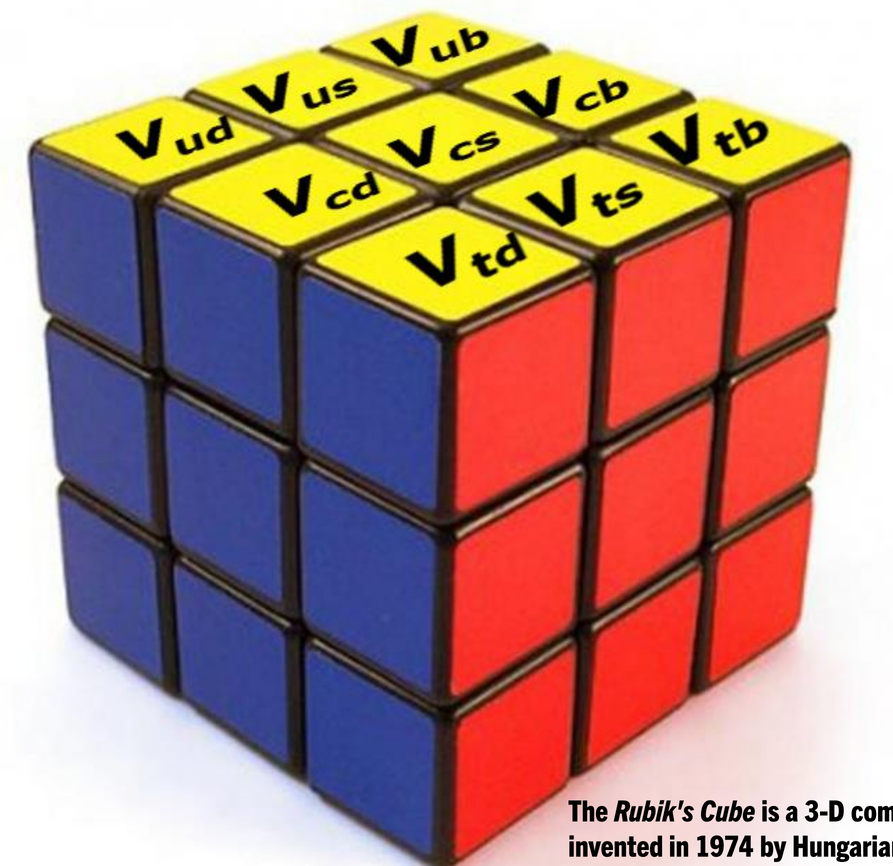
October 2023, Monday 30th - Tuesday 31st



cnrs IN2P3 Les deux infinis — LPC Laboratoire de Physique de Clermont — UCA Université Clermont Auvergne — INTENSITY frontier GDR-InF

Credits to C. Agapopoulou, J. Charles, O. Deschamps, G. Dujany, S. Monteil, I. Ripp Baudot,& L. Vale Silva.

The CKM MATRIX
Cabibbo-Kobayashi-Maskawa



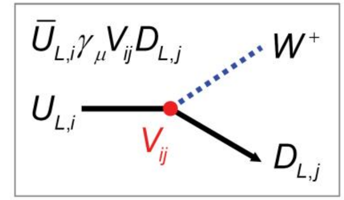
START OF DAY 2

The *Rubik's Cube* is a 3-D combination puzzle originally invented in 1974 by Hungarian sculptor and professor of architecture Ernő *Rubik*.

RECAP: the Standard Model (SM) & the Unitary CKM Matrix
➔ mixing of the 3 quarks families & CP violation

• the Higgs boson gives mass to elementary bosons & fermions (quarks, leptons) through Yukawa couplings, but there is not only that ! :

$$\mathcal{L}_{cc}^{\text{quarks}} = \frac{g}{2\sqrt{2}} W_\mu^\dagger \left[\sum_{ij} \bar{u}_i(q_2)\gamma^\mu(1-\gamma^5)V_{ij}d_j\right] + \text{h.c}$$



charged currents (EW) imply transitions between quark families : quarks decays [there are no neutral current changing flavour (FCNC) at tree level (i.e., GIM mechanism)].

V_{CKM} =

	d	s	b
u	$1-\lambda^2/2$	λ	$A\lambda^3(\rho-i\eta)$
c	$-\lambda$	$1-\lambda^2/2$	$A\lambda^2$
t	$A\lambda^3(1-\rho-i\eta)$	$-A\lambda^2$	1

$+ \mathcal{O}(\lambda^4)$ **($VV^\dagger$=1)**

• **strong hierarchy** in EW V_{ij} couplings for the 3 families (wrt diagonal couplings $\propto\lambda^N \approx (0.225)^N$:

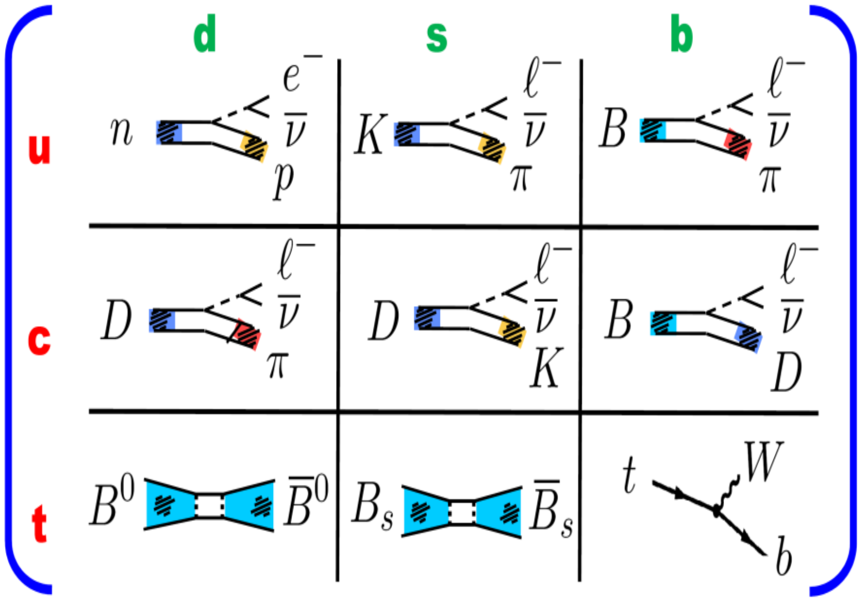
➔ **Cabibbo angle**).

• **KM** (Kobayashi-Maskawa) **mechanism :**

3 generations ➔ 4 params: A, λ, ρ & 1 complex part η which phase is the unique source of CPV in SM.

RECAP: the CKM Matrix, the unitary triangle & the very rich phenomenolgy of quark flavors

V_{CKM} =



➔4 parameters (A, λ, ρ & η) to be obtained/tested wrt. data: nucleons, K, D, $B_{(s)}$ & top quark physics.

➔ unitarity relation in B_d system (1rst line/3rd column):

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

Unitarity triangle in the $(\bar\rho,\bar\eta)$ complex plane:

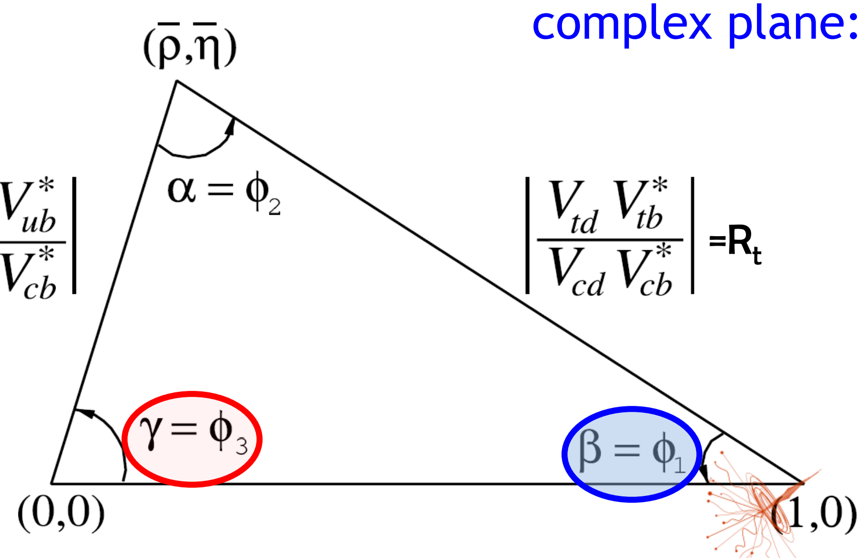
Parametrisation « à la Wolfenstein » phase invariant & valid at any orders in λ @ CKMfitter

(EPJ C41, 1-131, 2005) :

$$\bar\rho + i\bar\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

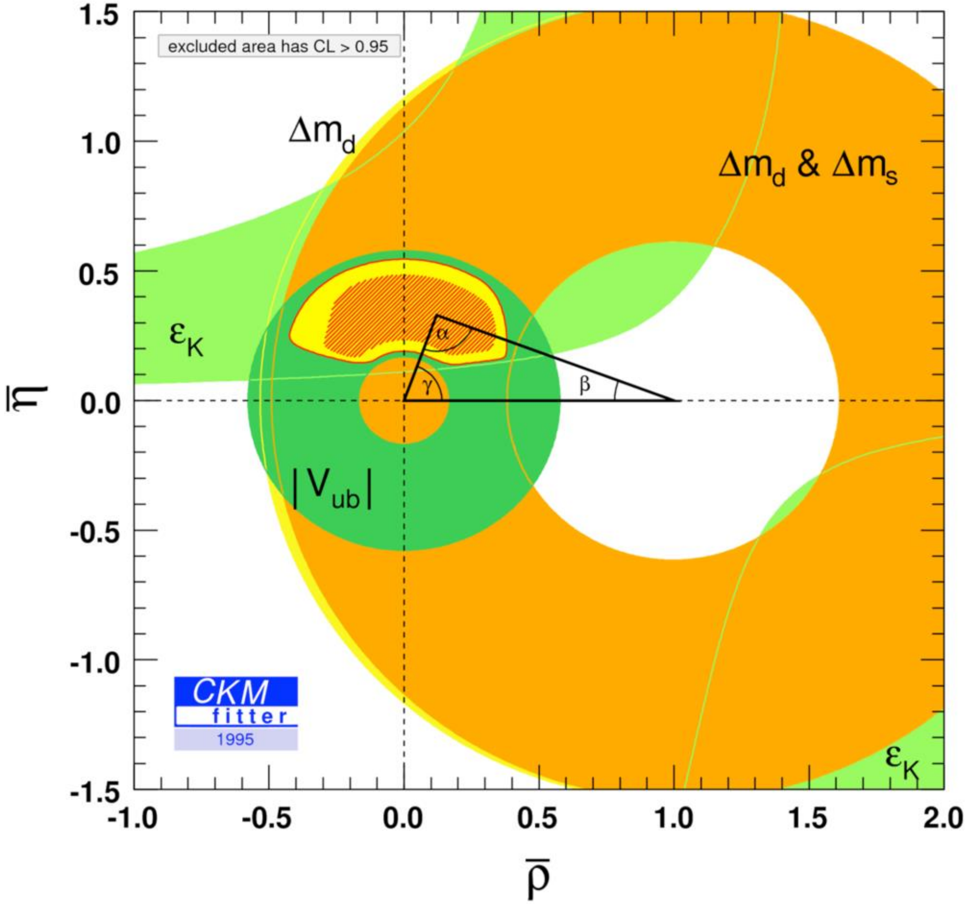
$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$

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



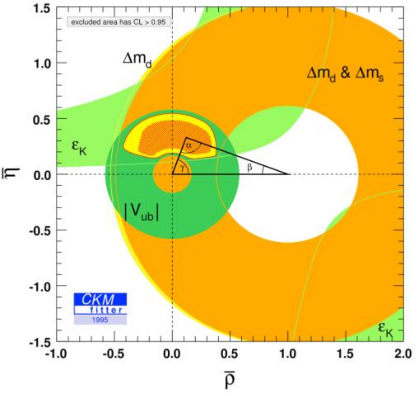
Last 25 years have seen tremendous progresses on CKM metrology

1995 after LEP

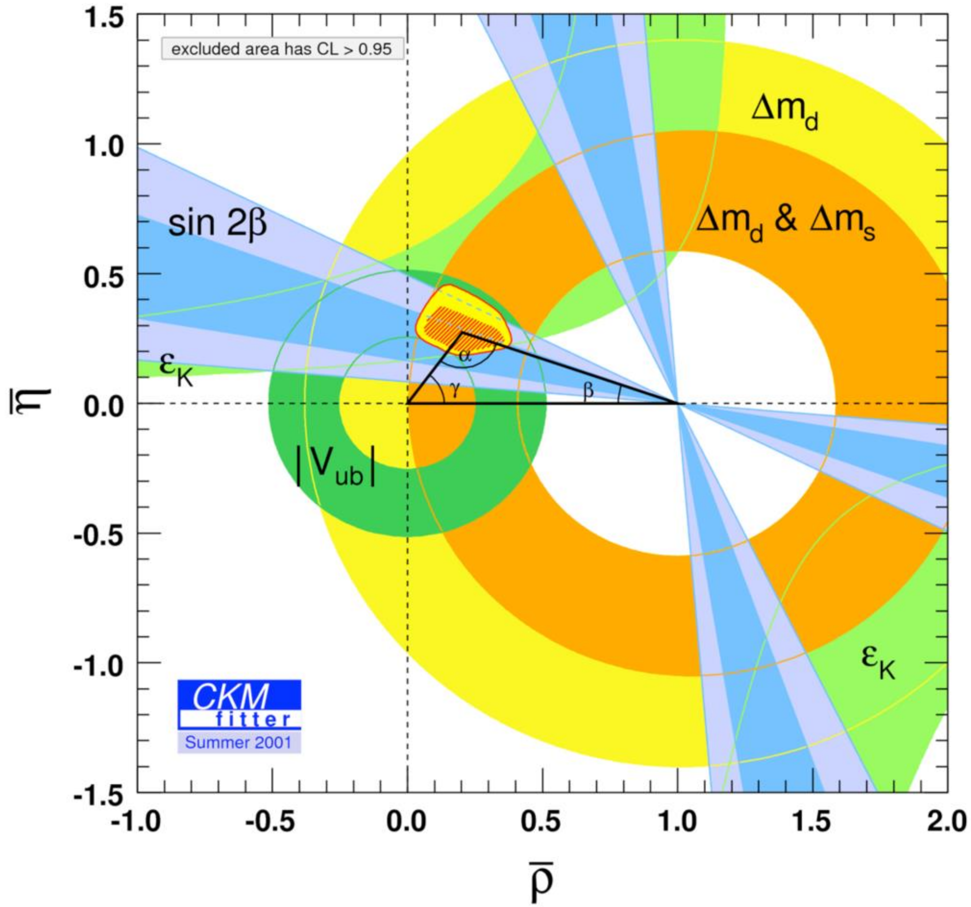


Last 25 years have seen tremendous progresses on CKM metrology

1995

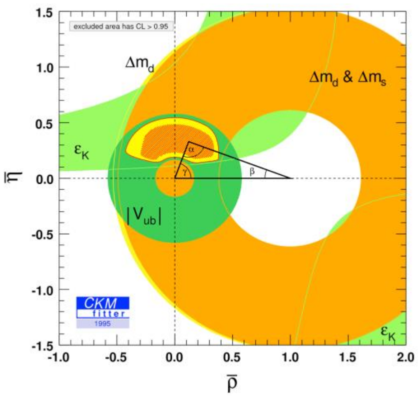


2001: B-factories at work

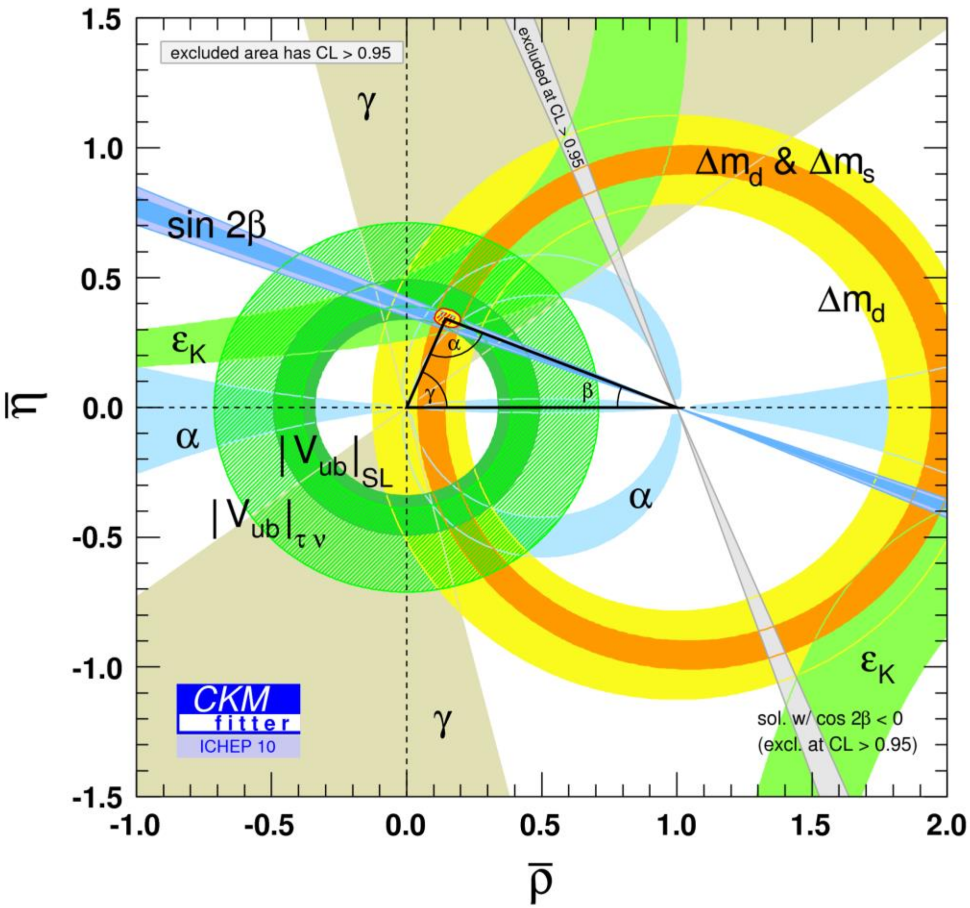


Last 25 years have seen tremendous progresses on CKM metrology

1995

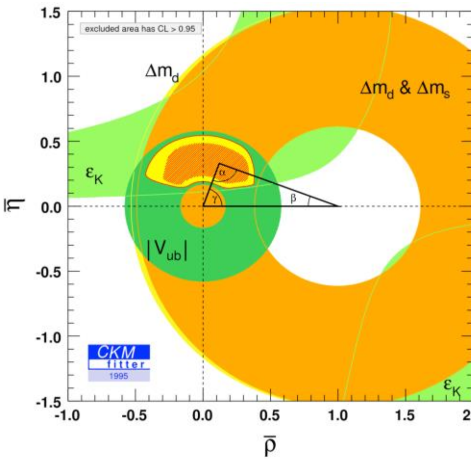


2010: B-factories legacy+CDF@TeVatron

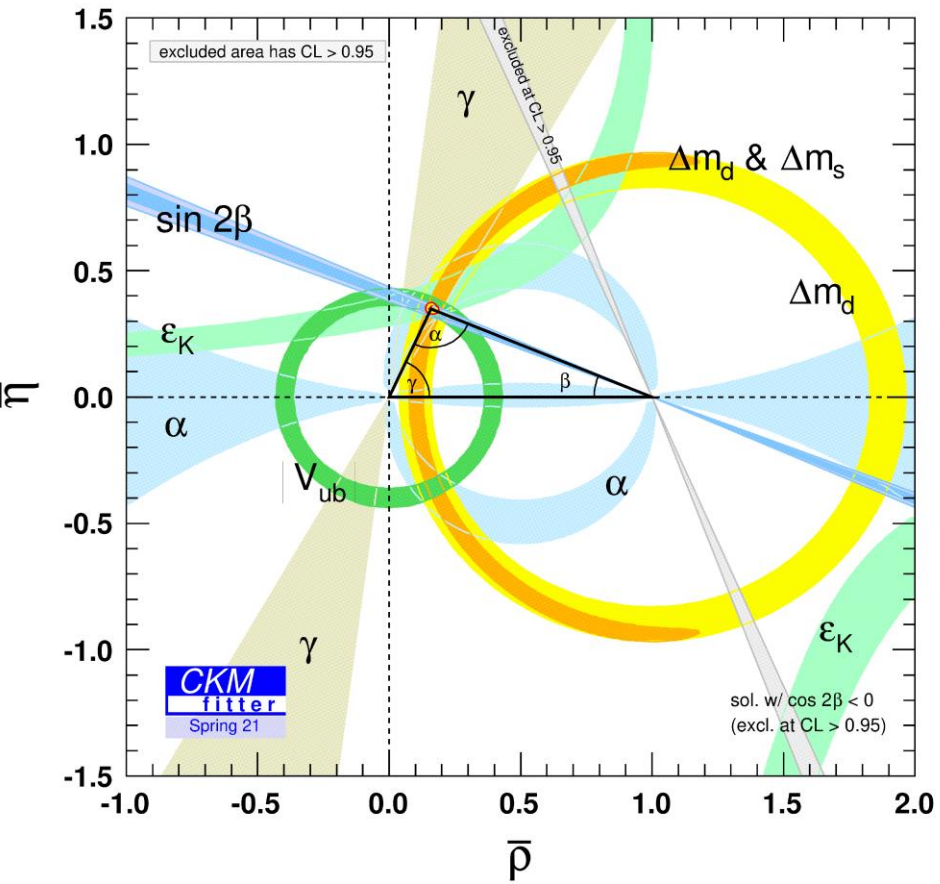


Last 25 years have seen tremendous progresses on CKM metrology

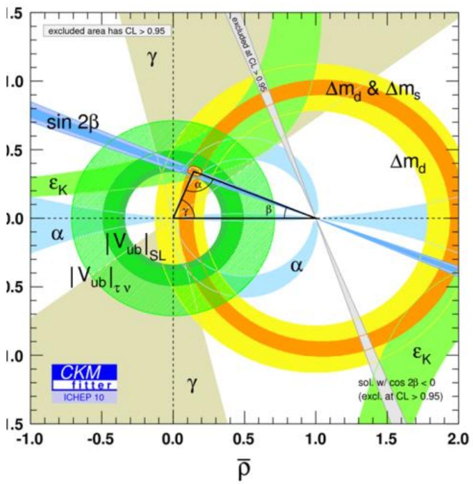
1995



Now after 10 years of LHCb



2010



Parametrisation of the CKM Matrix

With the mixing angles $\cos, \sin(\theta_{ij}) \equiv c_{ij}, s_{ij}$ the CKM matrix is the product of three 2x2 rotation matrices with one phase

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{23} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}.$$

Intermezzo: CKM metrology the UT & the PMNS Matrix & UT (CPV with neutrinos)

Pontecorvo ('57) solar neutrino problem : neutrinos oscillation! => explained by Sakata, Maki & Nakagawa ('62, **the Nagoya school** (+K.M.)) with a 3x3 unitary complex matrix!

The PMNS Matrix

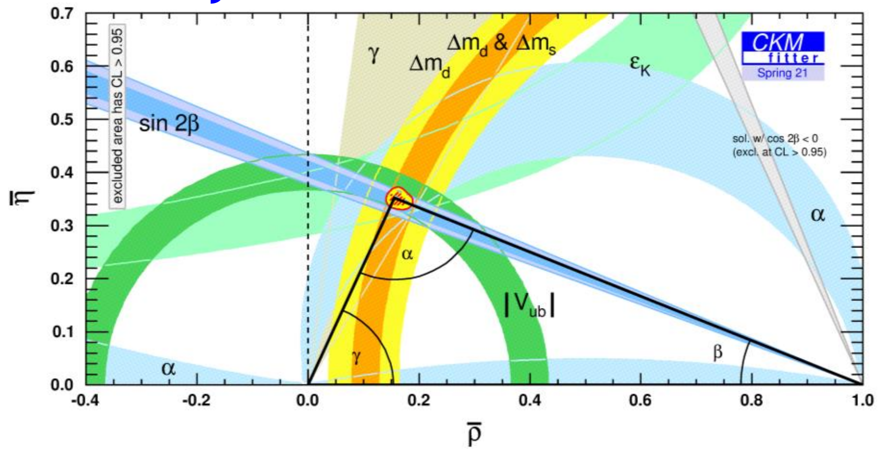
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

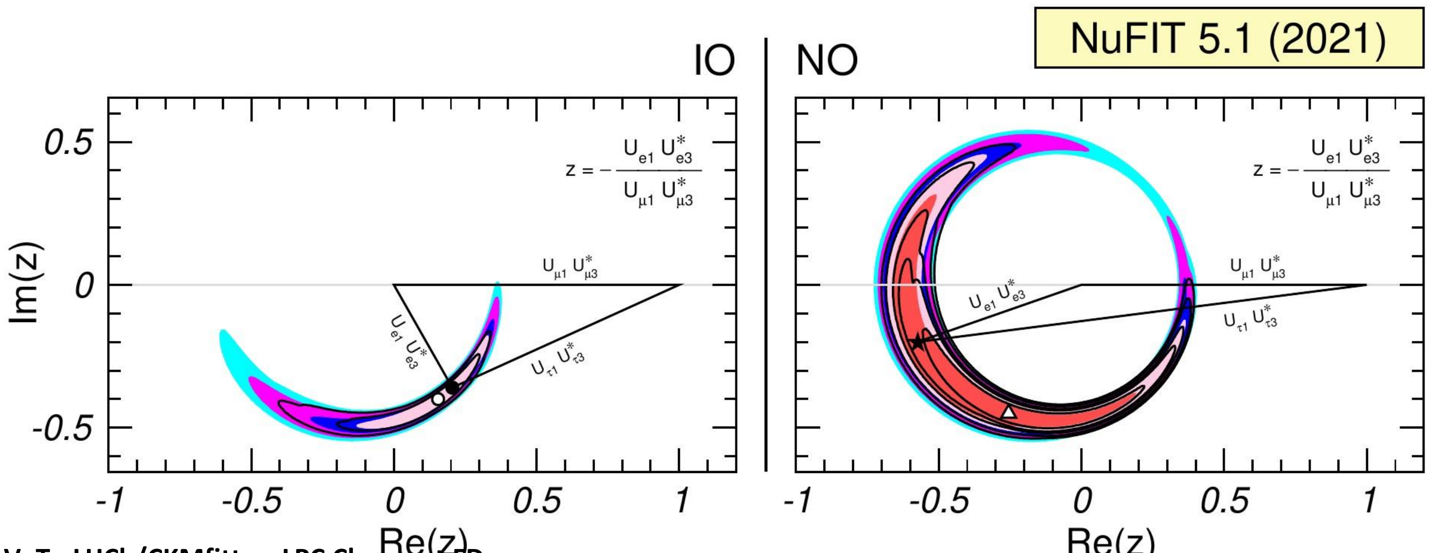
Intermezzo: CKM metrology the UT & the PMNS UT (CPV with neutrinos)

after 10 years of LHCb 2021



The other UT

Pontecorvo ('57) solar neutrino problem : neutrinos oscillation! => explained by Sakata, Maki & Nakagawa ('62, **the Nagoya school** (+K.M.)) with a 3x3 unitary complex matrix!



CKM metrology: where do we stand ?

Overall results of the *CKM*fitter 2023 update

The global fit remains excellent, **preliminary** results:

CKM'21: p-value $\sim$ 29% (1.1σ) $\rightarrow$ **CKM'23**: p-value $\sim$ 67% (0.4σ)

$$A = 0.8215^{+0.0047}_{-0.0082} \text{ (0.8\% unc.)}$$

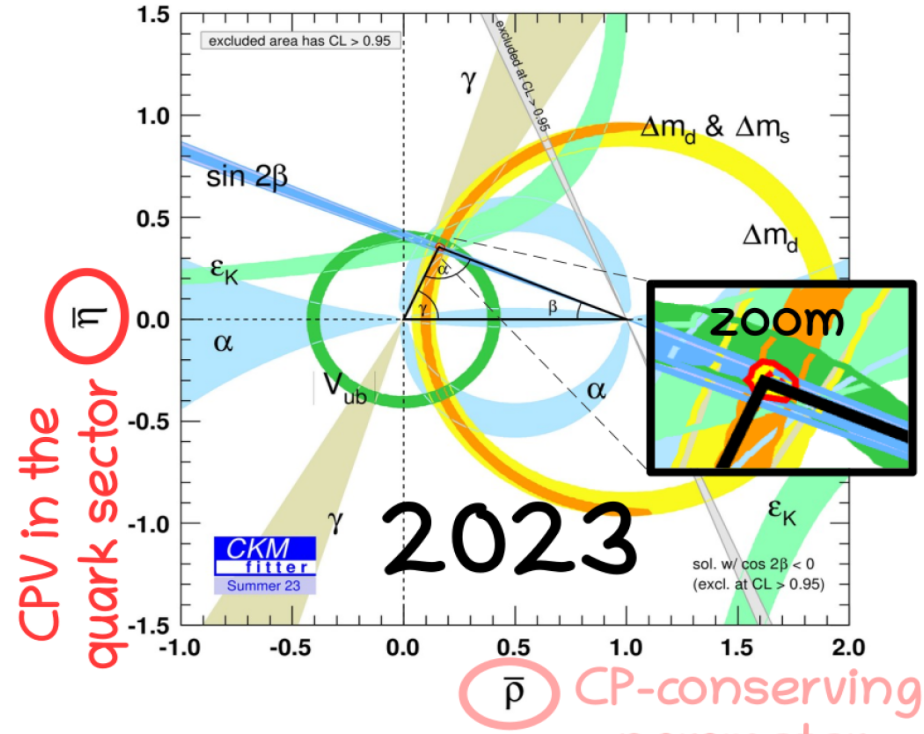
$$\lambda = 0.22498^{+0.00023}_{-0.00021} \text{ (0.1\% unc.)}$$

$$\bar{\rho} = 0.1562^{+0.0112}_{-0.0040} \text{ (4.9\% unc.)}$$

$$\bar{\eta} = 0.3551^{+0.0051}_{-0.0057} \text{ (1.5\% unc.)}$$

68% C.L. intervals

$\bar{\rho}, \bar{\eta}$: $\sim$ 20% more precise



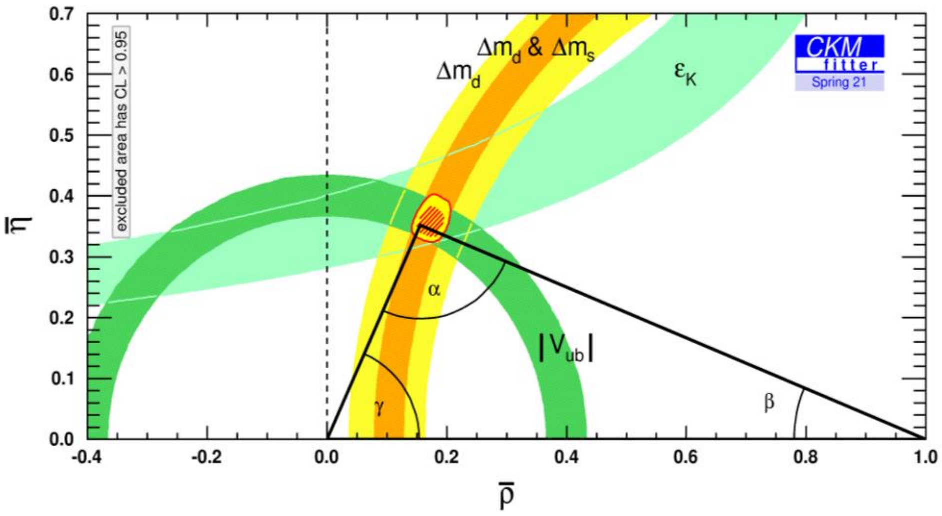
B_d Unitary Triangle:

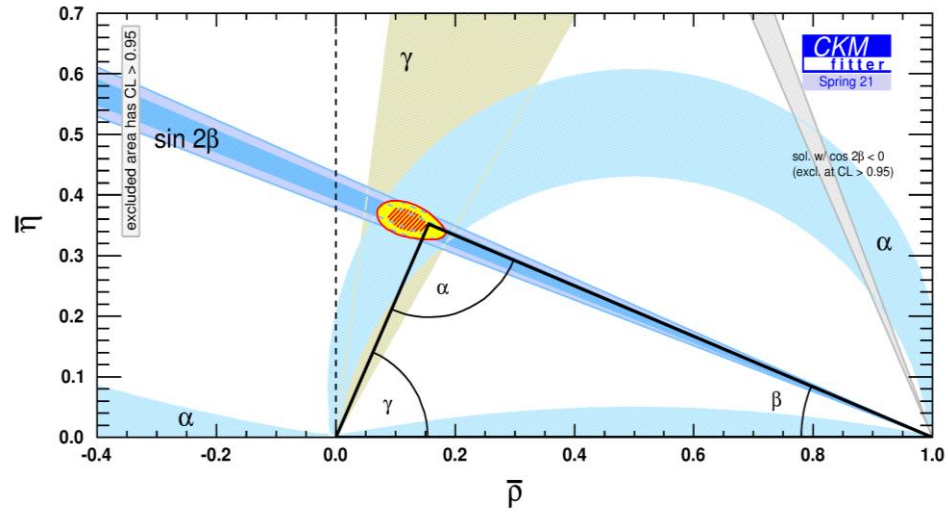
b : $|V_{xb}|$, α, β, γ, Δm_d, Δm_s

s : ε_K

L. Vale Silva @ CKM2023

CKM metrology: measuring the sides and the angles





Select only "clean" experimental observables, with either small theoretical uncertainties or well under control. For instance :

- **Sides measurement** rely on Lattice-QCD data for some non-perturbative quantities. Observables relying on penguin contamination knowledge are excluded (e.g., ε'_K)

- **Angles are measured** through interference and are generally theoretically clean observables. Extraction based on (broken) $SU(3)_F$ symmetry or non-perturbative QCD are excluded.

CKM global fit: the experimental and theoretical inputs

New in 2023

CKM	Process	Observables			Non-perturbative theoretical inputs		
$\|V_{ud}\|$	$0^+ \to 0^+ \ \beta$	$\|V_{ud}\|_{\text{nucl}}$	=	$0.97373 \pm 0.00009 \pm 0.00053$	Nuclear matrix elements		
$\|V_{us}\|$	$K \to \pi \ell \nu_\ell$	$\|V_{us}\|_{\text{SL}} f_+^{K\to\pi}(0)$	=	0.21635 ± 0.00038	$f_+^{K\to\pi}(0)$	=	$0.9675 \pm 0.0011 \pm 0.0023$
	$K \to e \nu_e$	$\mathcal{B}(K \to e\nu_e)$	=	$(1.582 \pm 0.007) \cdot 10^{-5}$			
	$K \to \mu \nu_\mu$	$\mathcal{B}(K \to \mu\nu_\mu)$	=	0.6356 ± 0.0011	f_K	=	$155.57 \pm 0.17 \pm 0.57$ MeV
	$\tau \to K \nu_\tau$	$\mathcal{B}(\tau \to K\nu_\tau)$	=	$(0.6986 \pm 0.0085) \cdot 10^{-2}$			
$\frac{\|V_{us}\|}{\|V_{ud}\|}$	$K \to \mu\nu_\mu / \pi \to \mu\nu_\mu$	$\frac{\mathcal{B}(K\to\mu\nu_\mu)}{\mathcal{B}(\pi\to\mu\nu_\mu)}$	=	1.3367 ± 0.0028	f_K/f_π	=	$1.1973 \pm 0.0007 \pm 0.0014$
	$\tau \to K\nu_\tau / \tau \to \pi\nu_\tau$	$\frac{\mathcal{B}(\tau\to K\nu_\tau)}{\mathcal{B}(\tau\to\pi\nu_\tau)}$	=	$(6.437 \pm 0.092) \cdot 10^{-2}$			
$\|V_{cd}\|$	νN	$\|V_{cd}\|_{\text{not lattice}}$	=	0.230 ± 0.011			
	$D \to \tau\nu_\tau$	$\mathcal{B}(D \to \tau\nu_\tau)$	=	$(1.20 \pm 0.27) \cdot 10^{-3}$			
	$D \to \mu\nu_\mu$	$\mathcal{B}(D \to \mu\nu_\mu)$	=	$(3.77 \pm 0.17) \cdot 10^{-4}$	f_{D_s}/f_D	=	$1.1782 \pm 0.0006 \pm 0.0033$
	$D \to \pi\ell\nu_\ell$	$\|V_{cd}\|_{\text{SL}} f_+^{D\to\pi}(0)$	=	0.1426 ± 0.0018	$f_+^{D\to\pi}(0)$	=	$0.624 \pm 0.004 \pm 0.006$
$\|V_{cs}\|$	$W \to c\bar{s}$	$\|V_{cs}\|_{\text{not lattice}}$	=	0.967 ± 0.011			
	$D_s \to \tau\nu_\tau$	$\mathcal{B}(D_s \to \tau\nu_\tau)$	=	$(5.32 \pm 0.10) \cdot 10^{-2}$			
	$D_s \to \mu\nu_\mu$	$\mathcal{B}(D_s \to \mu\nu_\mu)$	=	$(5.43 \pm 0.16) \cdot 10^{-3}$	f_{D_s}	=	$249.23 \pm 0.27 \pm 0.65$ MeV
	$D \to K\ell\nu_\ell$	$\|V_{cs}\|_{\text{SL}} f_+^{D\to K}(0)$	=	0.7180 ± 0.0033	$f_+^{D\to K}(0)$	=	$0.742 \pm 0.002 \pm 0.004$
$\|V_{ub}\|$	semileptonic B	$\|V_{ub}\|_{\text{SL}}$	=	$(3.86 \pm 0.07 \pm 0.12) \cdot 10^{-3}$	form factors, shape functions		
	$B \to \tau\nu_\tau$	$\mathcal{B}(B \to \tau\nu_\tau)$	=	$(1.09 \pm 0.24) \cdot 10^{-4}$	f_{B_s}/f_B	=	$1.2118 \pm 0.0020 \pm 0.0058$
$\|V_{cb}\|$	semileptonic B	$\|V_{cb}\|_{\text{SL}}$	=	$(41.22 \pm 0.24 \pm 0.37) \cdot 10^{-3}$	form factors, OPE matrix elements		
$\|V_{ub}/V_{cb}\|$	semileptonic Λ_b	$\frac{\gamma(\Lambda_b\to p\mu^-\bar{\nu}_\mu)_{q^2>15}}{\gamma(\Lambda_b\to\Lambda_c\mu^-\bar{\nu}_\mu)_{q^2>7}}$	=	$(0.918 \pm 0.083) \cdot 10^{-2}$	$\frac{\zeta(\Lambda_b\to p\mu^-\bar{\nu}_\mu)_{q^2>15}}{\zeta(\Lambda_b\to\Lambda_c\mu^-\bar{\nu}_\mu)_{q^2>7}}$	=	$1.471 \pm 0.096 \pm 0.290$
	semileptonic B_s	$\frac{\gamma(B_s\to K^+\mu^-\bar{\nu}_\mu)_{q^2>15}}{\gamma(B_s\to D_s^+\mu^-\bar{\nu}_\mu)_{q^2>7}}$	=	$(3.25 \pm 0.28) \cdot 10^{-3}$	$\frac{\zeta(B_s\to K^+\mu^-\bar{\nu}_\mu)_{q^2>7}}{\zeta(B_s\to D_s^+\mu^-\bar{\nu}_\mu)_{q^2>7}}$	=	$0.363 \pm 0.001 \pm 0.065$
	inclusive	$\|V_{ub}/V_{cb}\|_{\text{incl}}$	=	$0.100 \pm 0.006 \pm 0.003$			
α	$B \to \pi\pi,\ \rho\pi,\ \rho\rho$	branching ratios, CP asymmetries			isospin symmetry		
β	$B \to (c\bar{c})K$	$\sin(2\beta)_{[c\bar{c}]}$	=	0.708 ± 0.011	subleading penguins neglected		
	$B^0 \to D^{(*)}h^0$	$\cos(2\beta)$	=	0.91 ± 0.25			
γ	$B \to D^{(*)}K^{(*)}$	γ	=	$(65.9^{+3.3}_{-3.5})^\circ$	GGSZ, GLW, ADS methods		
ϕ_s	$B_s \to J/\psi(KK, \pi\pi)$	$(\phi_s)_{b\to c\bar{c}s}$	=	-0.039 ± 0.016			
$V_{tq}^* V_{tb}$	Δm_d	Δm_d	=	0.5065 ± 0.0019 ps^{-1}	$\hat{B}_{B_s}/\hat{B}_{B_d}$	=	$1.007 \pm 0.010 \pm 0.014$
	Δm_s	Δm_s	=	17.765 ± 0.006 ps^{-1}	$\hat{B}_{B_s}$	=	$1.313 \pm 0.012 \pm 0.030$
	$B_s \to \mu\mu$	$\mathcal{B}(B_s \to \mu\mu)$	=	$(3.45 \pm 0.29) \cdot 10^{-9} [\times(1 - 0.063)]$	f_{B_s}	=	$228.75 \pm 0.69 \pm 1.87$ MeV
$V_{td}^* V_{ts}$ and $V_{cd}^* V_{cs}$	ε_K	$\|\varepsilon_K\|$	=	$(2.228 \pm 0.011) \cdot 10^{-3}$	$\hat{B}_K$	=	$0.7567 \pm 0.0020 \pm 0.0123$
					κ_ε	=	$0.940 \pm 0.013 \pm 0.023$

CKM global fit: theoretical inputs, dealing with hadronic effects

→ Need to deal with **hadronic effects** inherent to the quark sector

→ Determine $\mathcal{L}^{eff}_{SM\,(NP)} \sim \sum_i C_i(\mu) \times O_i(\mu)$, where $\mu \sim \mathcal{O}(\text{few})$ GeV: C_i collects *short*-distance physics; O_i collects *long*-distance physics

(semi-)leptonic decays	$\pi \to \ell\nu$, $K \to \pi\ell\nu$, etc.★: decay constants, form factors Ex.: f_π, $f_+^{K\to\pi}(0)$ $-p_\mu f_\pi = \langle 0 \vert (\bar{d}\gamma_\mu\gamma_5 u) \vert \pi(p)\rangle$, $f_+^{K\to\pi}(q^2)(p+p')_\mu + f_-^{K\to\pi}(q^2)(p-p')_\mu = \langle \pi(p') \vert (\bar{s}\gamma_\mu P_L u) \vert K(p)\rangle$
Meson-mixing	$B_{(s)}\overline{B}_{(s)}$, $K\overline{K}$: bag-parameters $\widehat{B}_{B_s}$, $\widehat{B}_{B_s}/\widehat{B}_{B_d}$, $\widehat{B}_K$ $\frac{2}{3} m_K^2 f_K^2 B_K = \langle \overline{K} \vert (\bar{s}\gamma^\mu P_L d)\,(\bar{s}\gamma_\mu P_L d) \vert K\rangle$

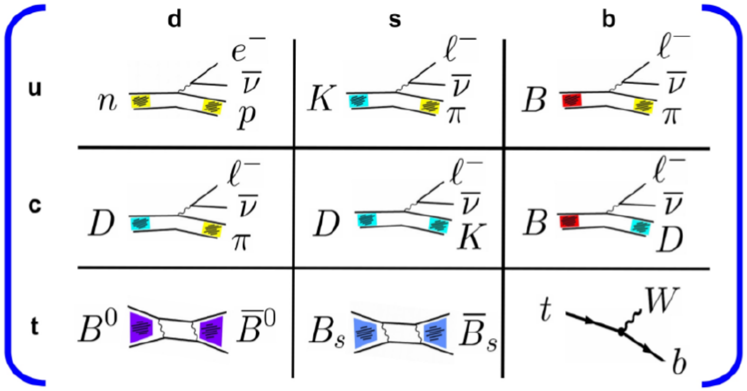
→ Lattice QCD: extractions of non-perturbative parameters; averages typically dominated by **systematic uncertainties**

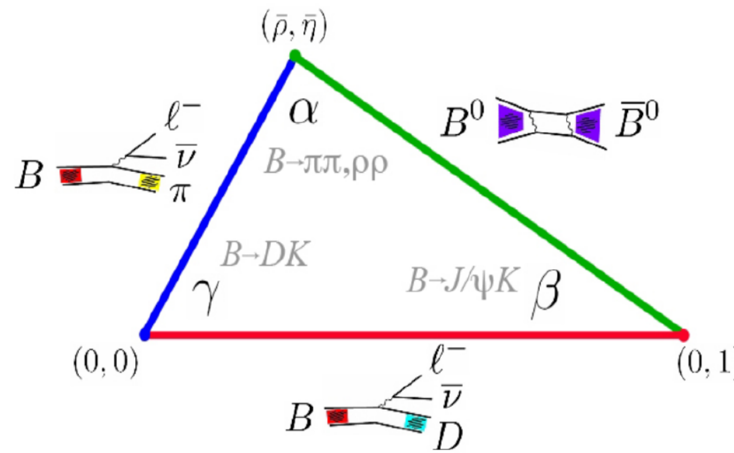
(fermion action, $a \to 0$, $L \to \infty$, mass extrapolations...)

★ **etc. means: D→ Klν, B→ D$^{(*)}$lν / πlν**

CKM global fit: Testing the consistency

V =



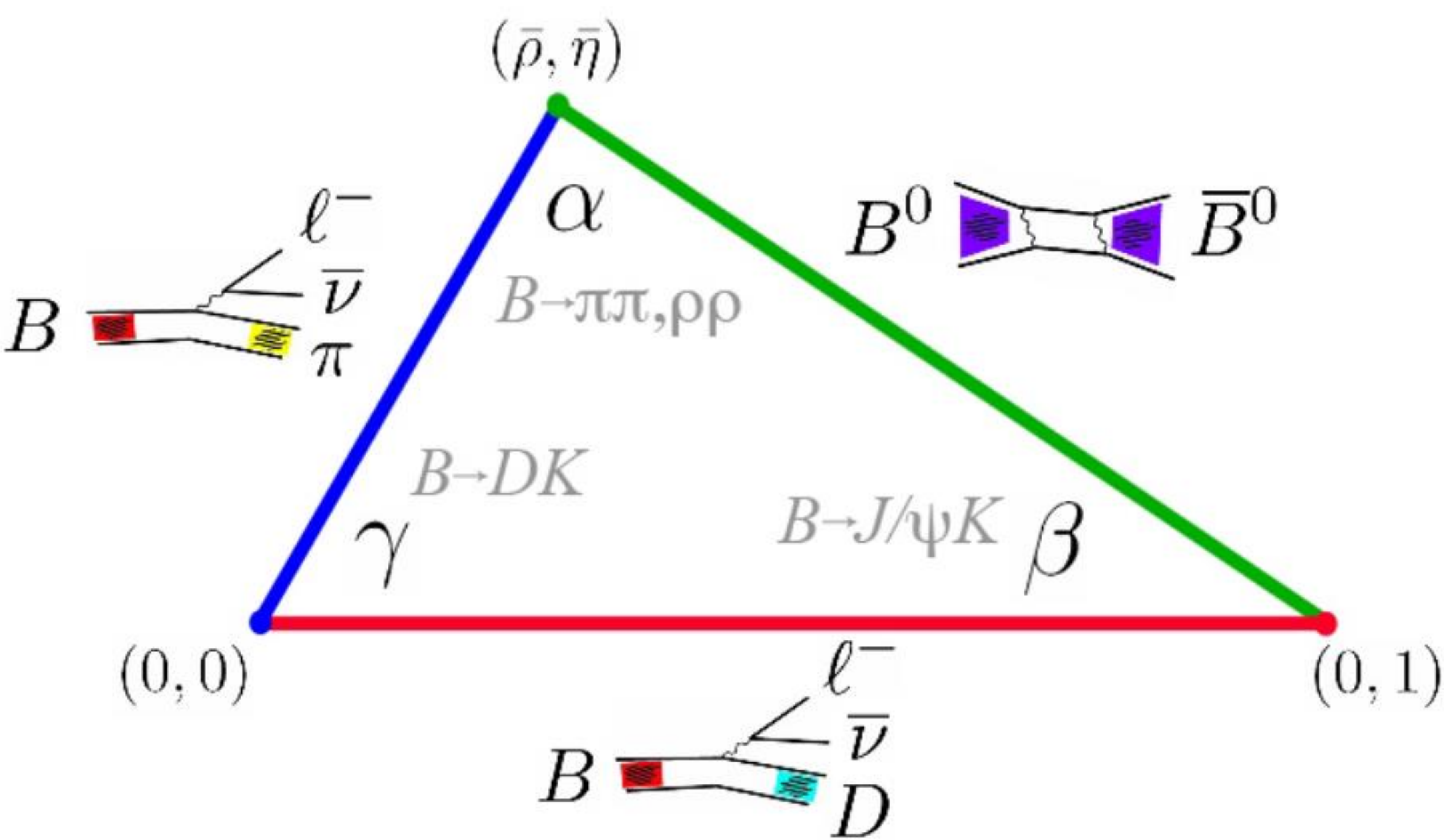


→ Double requirement: precision in meas. and theo. prediction

→ Observables with **very different properties** are available:

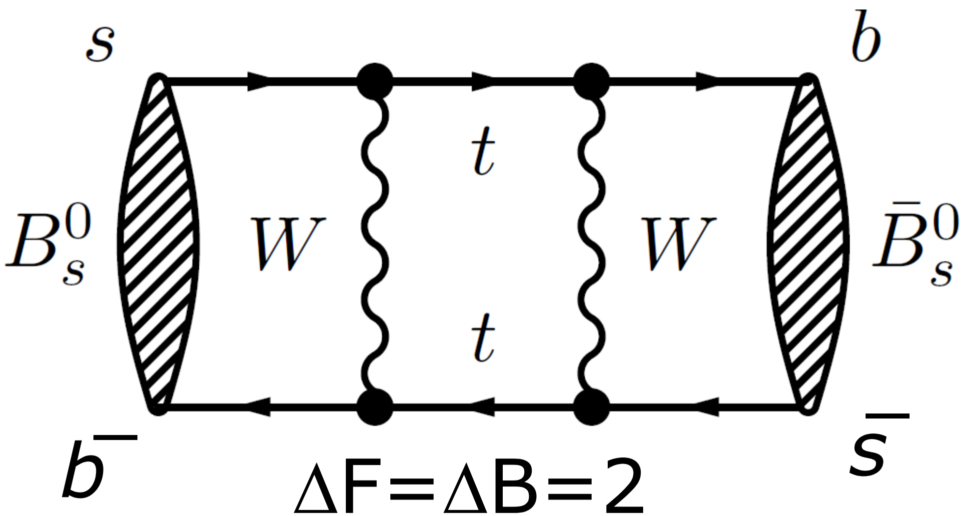
- *Tree*: e.g., $|V_{ub}|$
- *Loop*: e.g., Δm_d, Δm_s, ϵ_K, $\sin(2\beta)$
- *$\mathcal{CP}$-conserving*: e.g., $|V_{ub}|$, Δm_d, Δm_s
- *$\mathcal{CP}$-violating*: e.g., γ, ϵ_K, $\sin(2\beta)$
- *Exp. uncs.*: e.g., α, $\sin(2\beta)$, γ
- *Syst. uncs.*: e.g., $|V_{ub}|$, $|V_{cb}|$, ϵ_K, Δm_d, Δm_s

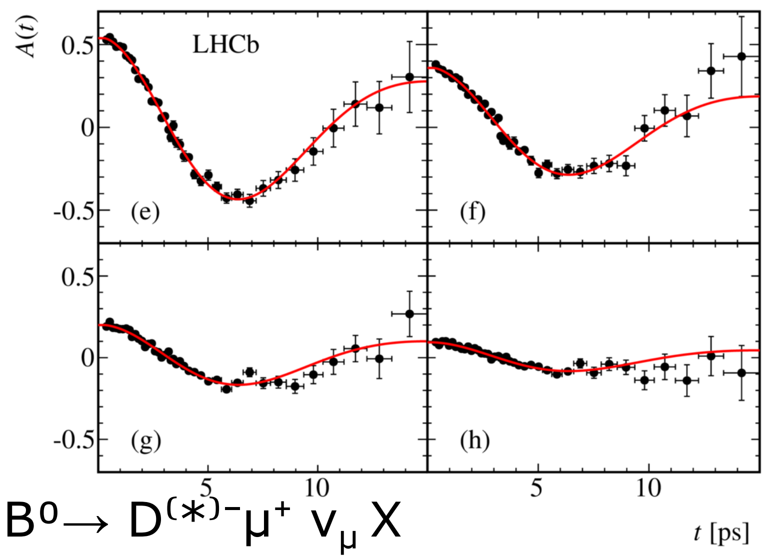
the sides:



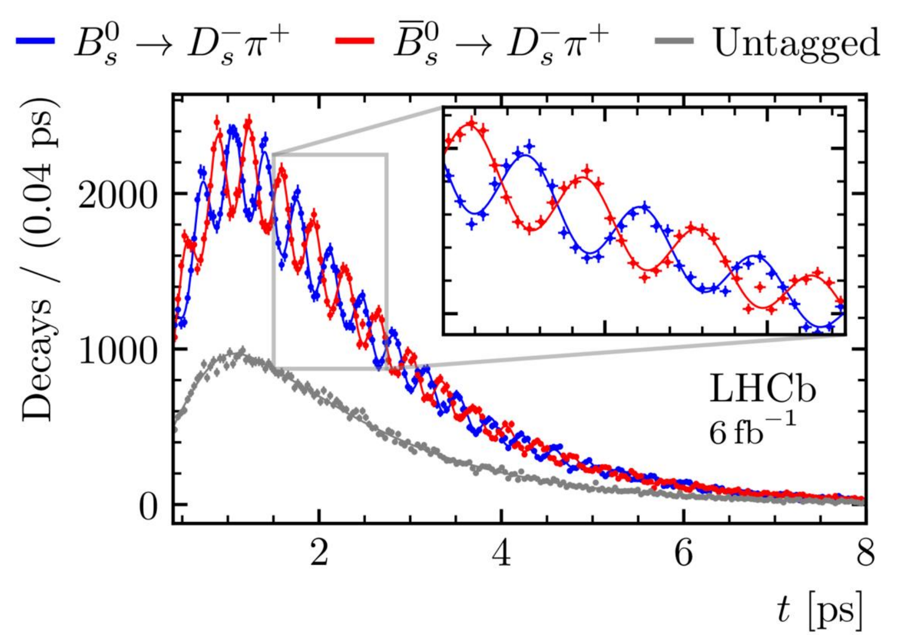
$(\bar{\rho}, \bar{\eta})$
α
B^0
$\overline{B}^0$
ℓ^-
$\overline{\nu}$
B
π
B→ππ,ρρ
B→DK
B→J/ψK
γ
β
(0, 0)
(0, 1)
ℓ^-
$\overline{\nu}$
B
D

CKM global fit, e.g.: the B^0 and Bs mixing parameters





$B^0 \to D^{(*)-} \mu^+ \nu_\mu X$



LHCb'2016 most precise meas.

$\Delta m_d = 505.0 \pm 2.3\ ns^{-1}$

LHCb'2022 most precise meas.

$\Delta m_s = 17.7683 \pm 0.0057\ ps^{-1}$

matter-antimatter oscillation at 2.8 10^3 GHz !!

CKM global fit, e.g.: the B^0 and Bs mixing parameters

HFLAV (WA) :

$$\begin{cases} \Delta m_d = 0.5065 \pm 0.0019 \ \text{ps}^{-1} \\ \Delta m_s = 17.765 \pm 0.004 \pm 0.004 \ \text{ps}^{-1} \end{cases}$$

➔ **uncertainty $\sigma(\Delta m_s)=0.3\%$ smaller than $\sigma(\Delta m_d)\approx 0.37\%$!**

$$\Delta m_s = G_F^2/(6\pi^2) m_{B_s} m_W^2 \eta_{Bs} S_0(x_t) f^2_{Bs} B_s \boxed{|V_{ts}V^*_{tb}|^2}$$

Very weak dependence $\bar{\rho}$ and $\bar{\eta}$

$$\xi = \frac{f_{Bs}\sqrt{Bs}}{f_{Bd}\sqrt{Bd}}$$

the $SU(3)_F$ breaking corrections (largest uncertainty)

➔ **Measurement of Δm_s reduces the uncertainties on $f^2_{B_d} B_d$ since ξ is better known from LQCD**

➔**Leads to improvement of the constraint from Δm_d measurement on $|V_{td}V^*_{tb}|^2$**

$$\Delta m_d = G_F^2/(6\pi^2) m_{B_d} m_W^2 \eta_{Bd} S_0(x_t) f^2_{Bd} B_d \boxed{|V_{td}V^*_{tb}|^2}$$

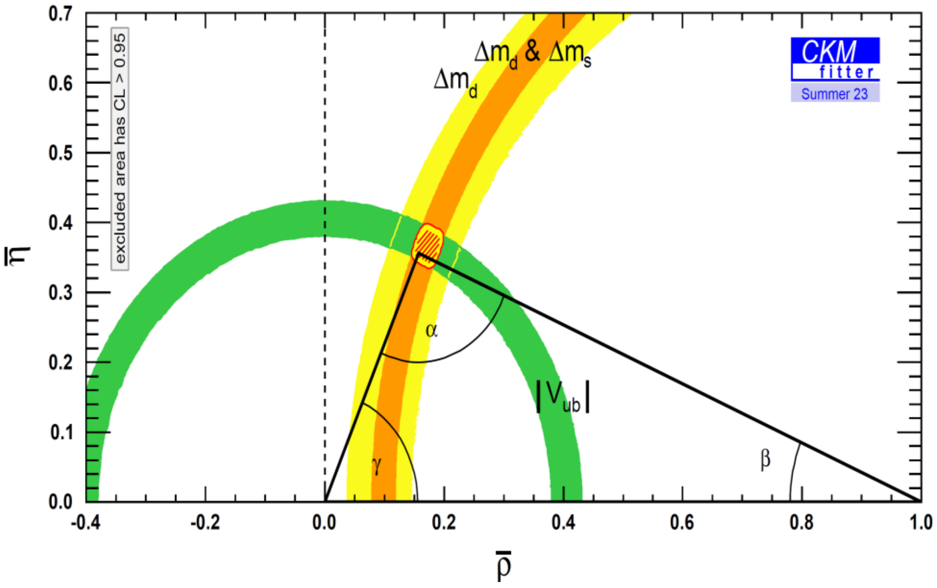
$$\propto \lambda^6 A^2[(1-\bar{\rho})^2+\bar{\eta}^2]$$

CKM global fit, e.g.: the B^0 and Bs mixing parameters

HFLAV (WA) :

$$\begin{cases} \Delta m_d = 0.5065 \pm 0.0019\ \mathrm{ps}^{-1} \\ \Delta m_s = 17.765 \pm 0.004 \pm 0.004\ \mathrm{ps}^{-1} \end{cases}$$

$$|V_{td}V^*_{tb}| = \lambda^6 A^2[(1-\bar{\rho})^2+\bar{\eta}^2]+\mathcal{O}(\lambda^{10})$$



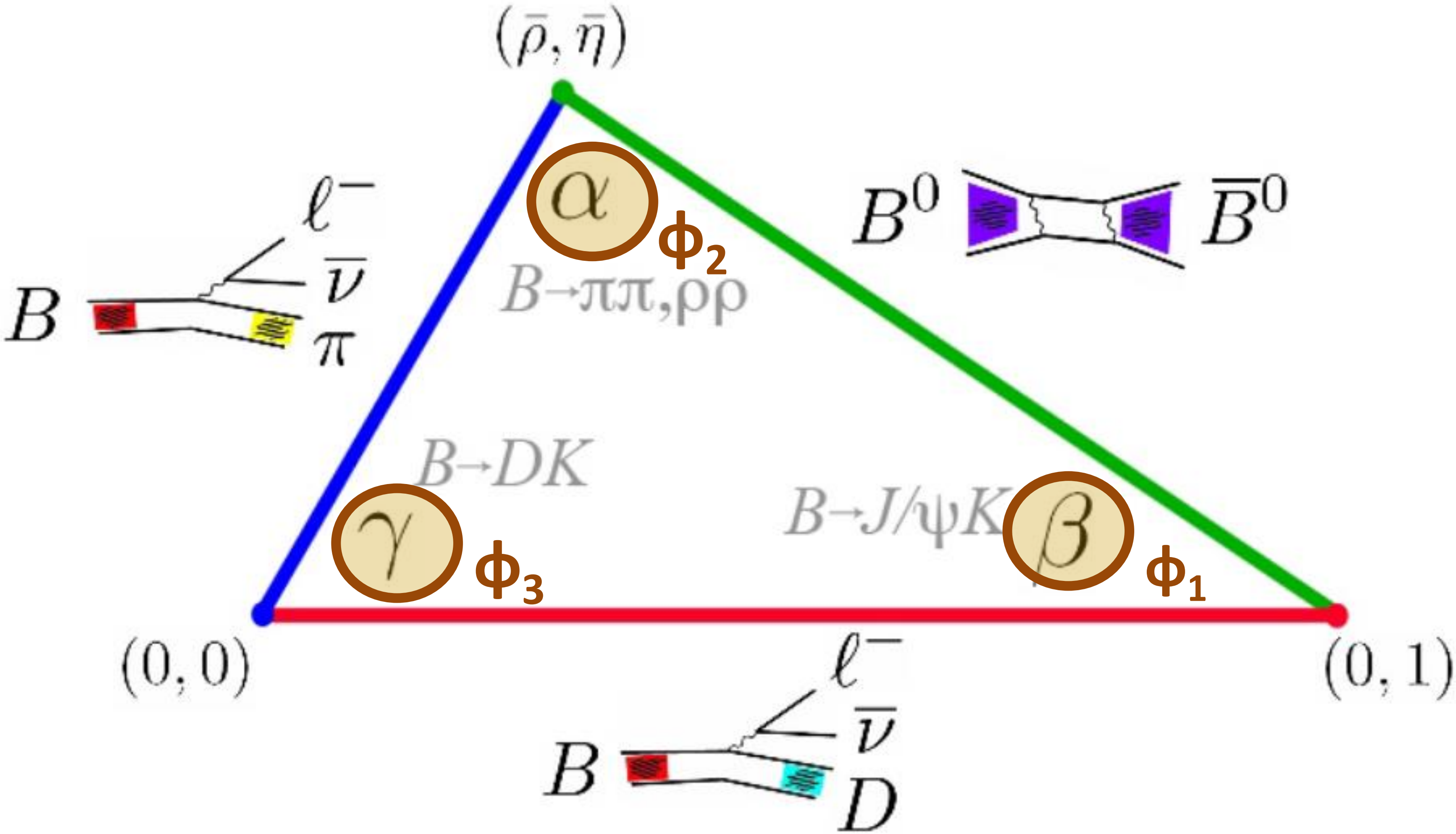
Global CKMfit:

$\Delta m_d\ [\mathrm{ps}^{-1}]$	$0.534\ ^{+0.033}_{-0.027}$	
$\Delta m_s\ [\mathrm{ps}^{-1}]$	$17.26\ ^{+0.63}_{-0.41}$	

Disclaimer:
Just talked about $|V_{t(d,s,b)}|$
won't talk here about the 6 other $|V_{ij}|$ elements : $|V_{ub}|$ (nor about $|V_{cb}|$, nor $|V_{u(d,s)}|$, $|V_{c(d,s)}|$ …)

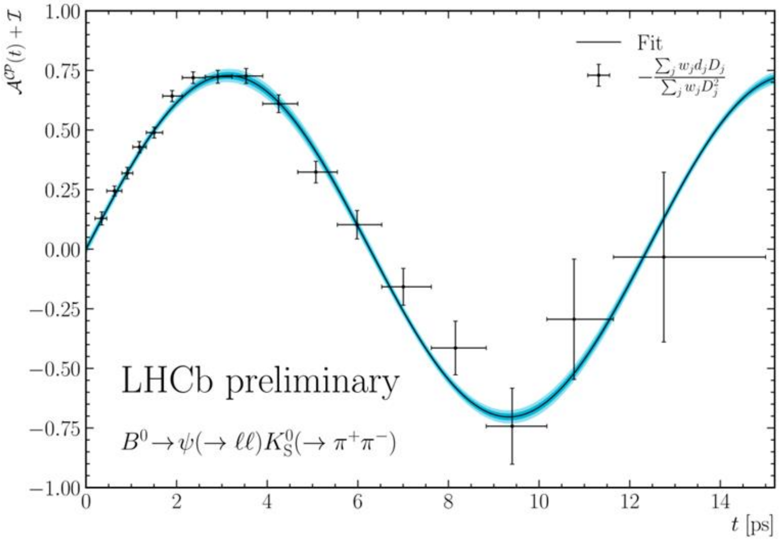
See: L. Vale Silva @ CKM2023

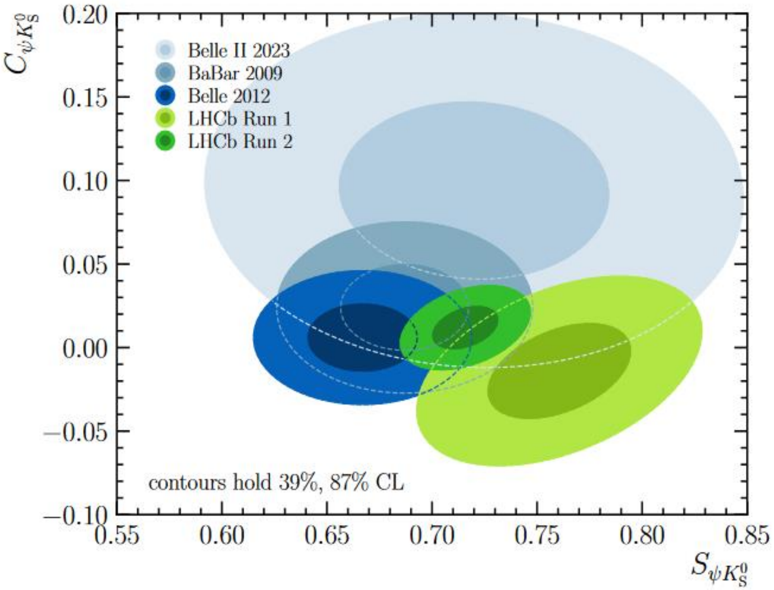
The angles

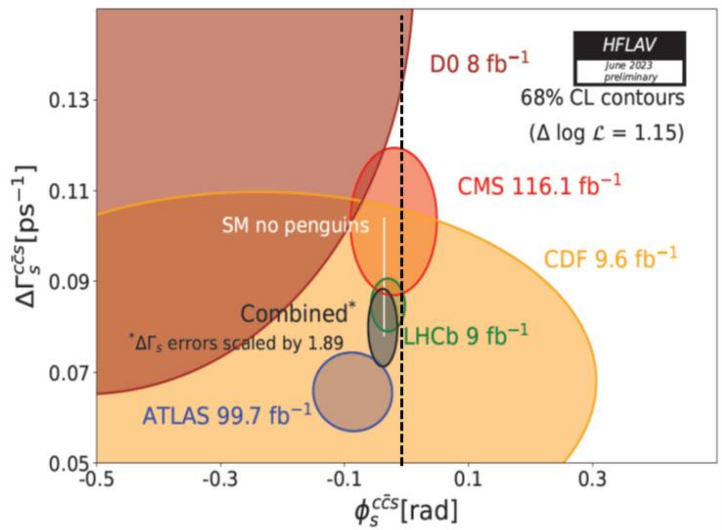


$(\bar{\rho}, \bar{\eta})$
α
ϕ_2
$B \to \pi\pi, \rho\rho$
B^0
$\overline{B}^0$
ℓ^-
$\overline{\nu}$
B
π
$B \to DK$
γ
ϕ_3
$B \to J/\psi K$
β
ϕ_1
$(0,0)$
$(0,1)$
ℓ^-
$\overline{\nu}$
B
D

CKM global fit: we have already seen the meas. Of $\sin(2\beta/\phi_1)$ and $\sin 2\beta_s$ ($-\sin\phi_s$)

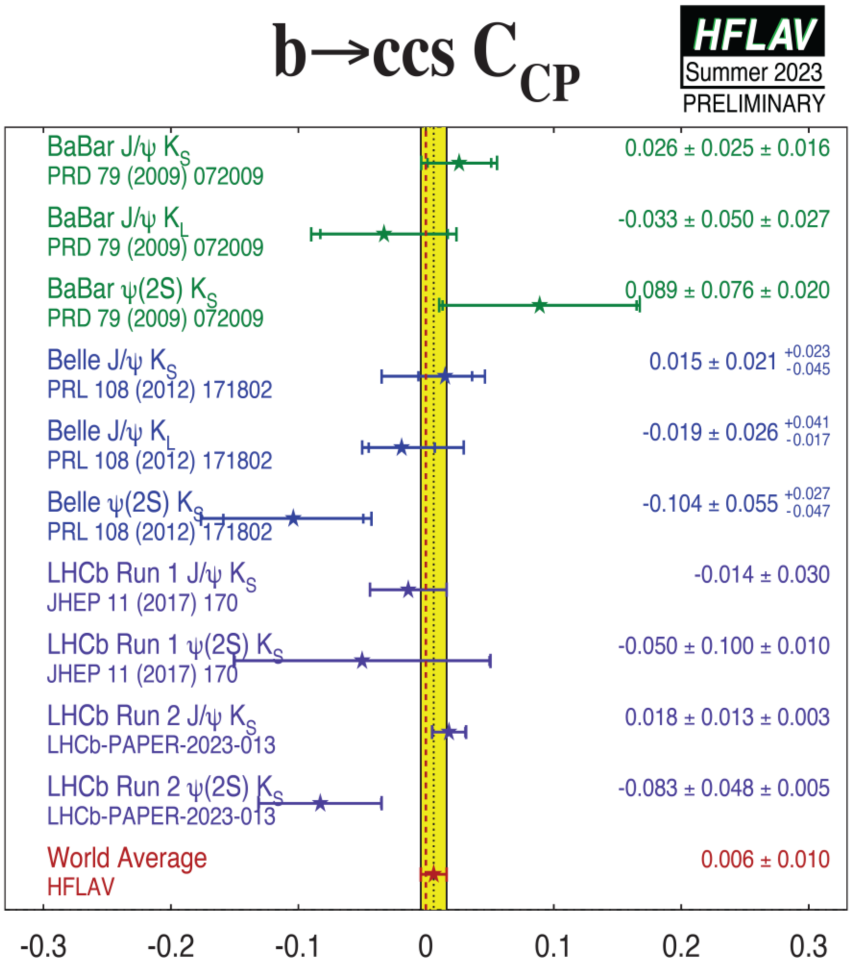






See for more details the LHCb CERN June 2023 Seminar: https://indico.cern.ch/event/1281612/

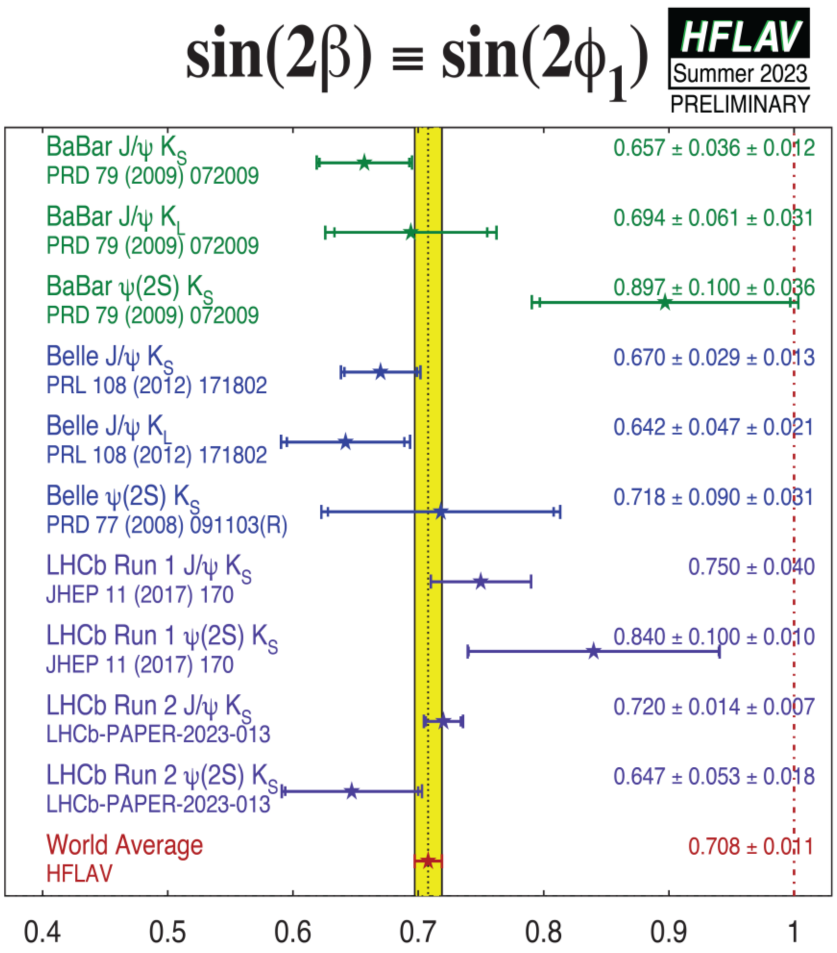
CKM global fit: we have already seen the meas. of $\sin(2\beta/\phi_1)$



NEW!!

NEW!!

NEW!!

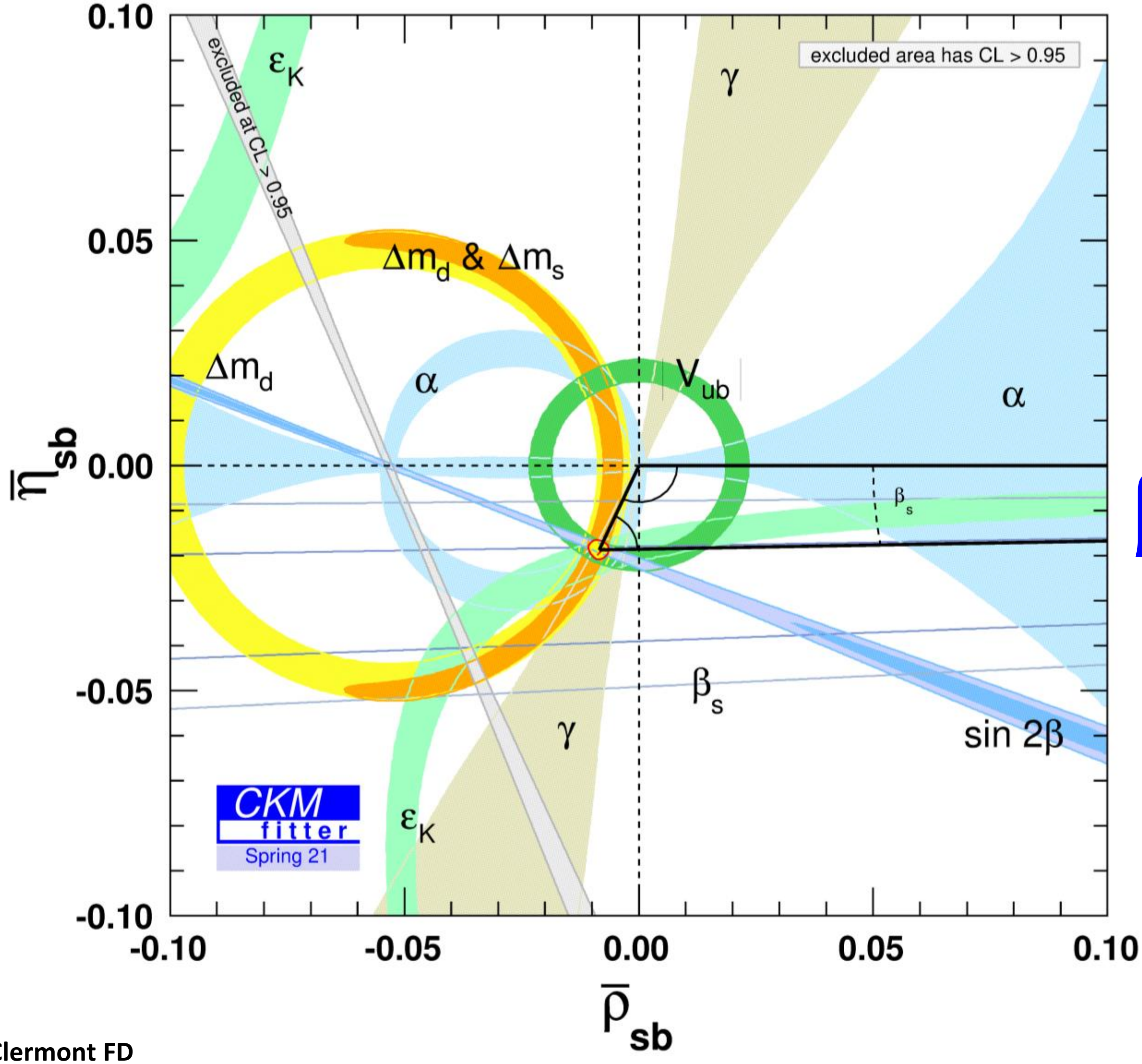


$\beta/\phi_1 = (22.54 \pm 0.31)°$

CKM global fit: $\sin 2\beta_s$ ($-\sin\phi_s$)

Unitarity condition from 2nd and 3rd columns:

$$V_{us}V^*_{ub}+V_{cs}V^*_{cb}+V_{ts}V^*_{tb}=0$$



β_s

CKM global fit: the angle α / ϕ_2

→ Branching ratios and $\mathcal{CP}$ asymmetries for $B \to \pi\pi, \rho\pi, \rho\rho$

→ Isospin analysis constrains hadronic penguin and tree amplitudes

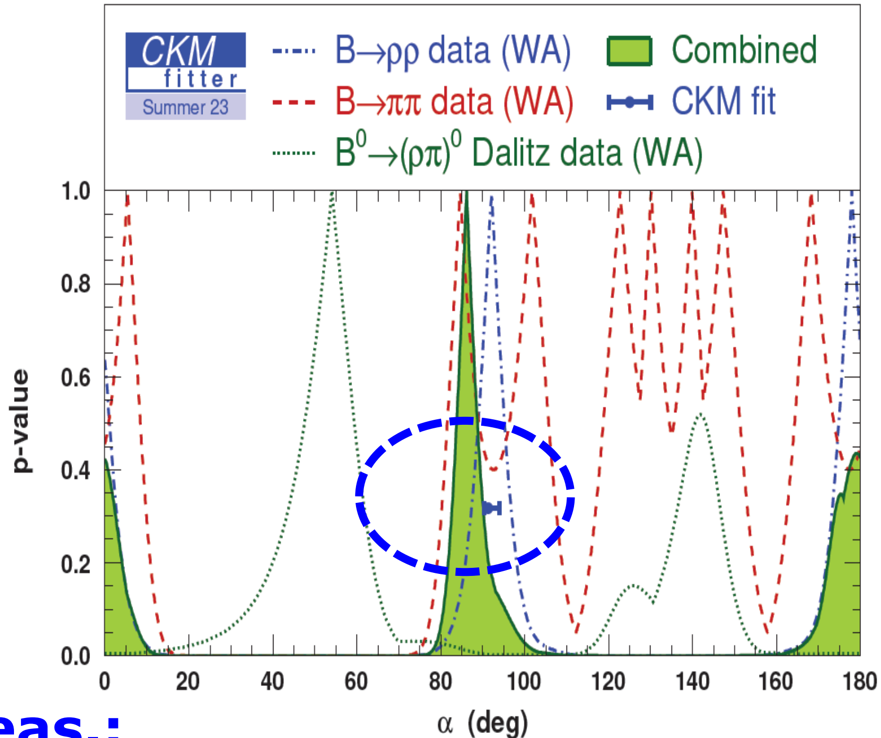
[$B^{0,+} \to \pi^{0,+}\pi^{0}, \rho^{+}\rho^{-,0}$ updates: Belle II] [Detailed discussion: Charles, Deschamps, Descotes-G., Niess '17]

As in previous editions:

→ Average dominated by $B \to \pi\pi$ and $B \to \rho\rho$

→ $B \to \pi\pi, \rho\rho$ agree w/ α [ind.]

→ $B \to \rho\pi$ is in tension [Charles+'17]



Global CKMfit+ meas.:

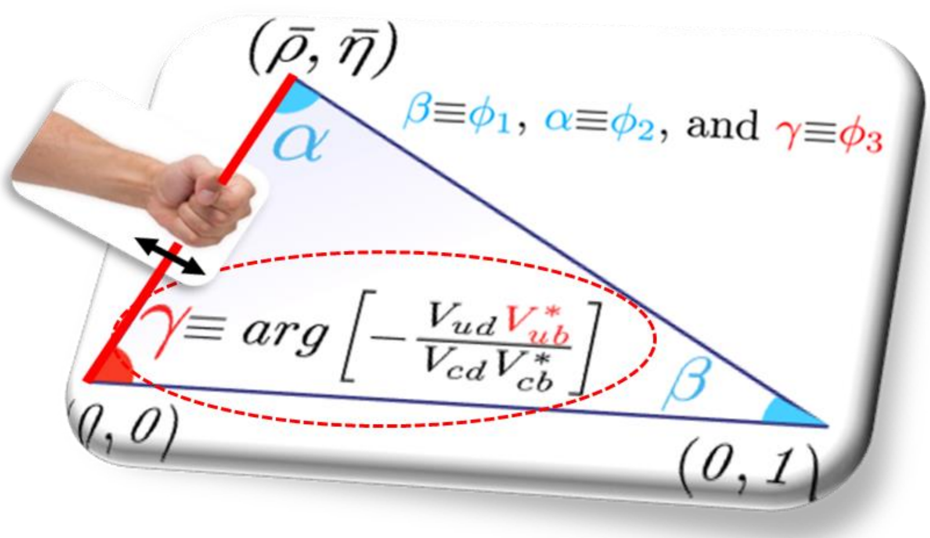
α [°]	$91.06^{+1.43}_{-0.75}$
α [°] (meas. not in the fit)	$91.28^{+2.73}_{-0.88}$
α [°] (dir. meas.)	$86.2^{+3.9}_{-3.5} \| - 1.0^{+3.3}_{-4.9}$

The CKM angle γ/ϕ_3 is special

It is a fundamental parameter of the SM related to the complex phase in the KM mechanism responsible for CP violation in quark sector.

In particular, γ/ϕ_3 is the phase of the complex number $(\bar{\rho}, \bar{\eta})$

Already ~12 years ago after the B factories BaBar@SLAC and Belle@KEK, we knew that!



M. Kobayashi & T. Masakwa, Nobel prize of physics 2008

The KM mechanism is the main source of CPV at EW scale (i.e. @ $m_{W/Z}$)
But there is still room for BSM physics

The usefulness of measuring accurately γ/ϕ_3

CKM angle γ is the least well known CKM constraint (although now only just (i.e., similar to α)) and remains a unique CPV parameter:

- **SM benchmark or standard candle of the CKM Matrix in SM – The only CKM angle accessible at tree level**

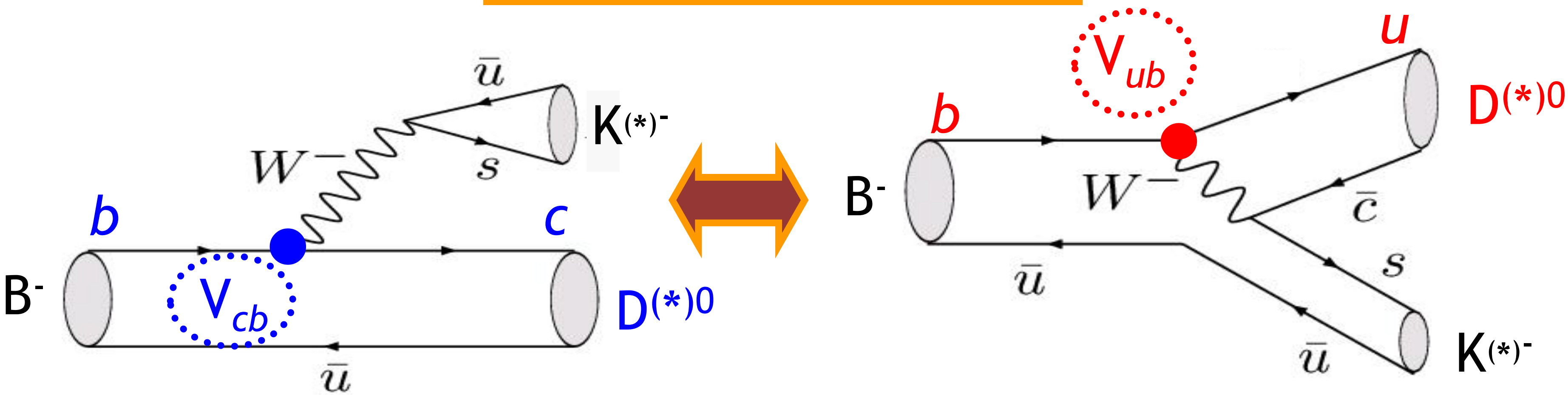
- **Probes NP scales extremely far beyond direct searches in ((N)M)FV NP scenarios:** $\Lambda_{NP}^{\gamma} \sim \mathcal{O}\left(10^3\ \mathrm{TeV}\right)$
  [arXiv:1101.0134]
  and at least 15-20 TeV in Model independent approach ! https://arxiv.org/pdf/1309.2293.pdf

➔ **Determination form tree B→DK decay theoretically extremely clean :** [arXiv:1308.5663] $\delta\gamma/\gamma \sim \mathcal{O}\left(10^{-7}\right)$

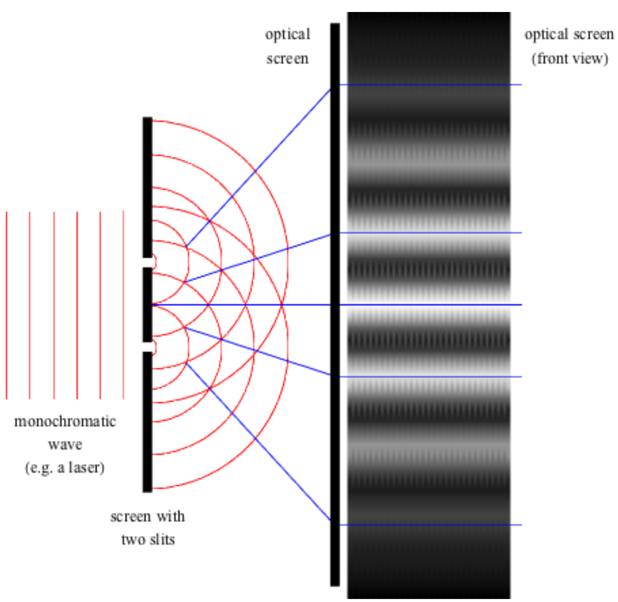
➔ **Use for "direct" vs "indirect" (i.e., "tree" vs "loop" processes) disagreement in global CKM fit consistency test : - Tree level decays test the SM and are robust to New Physics** ("standard candle for the SM KM coherence tests"): ⊥ **constraint to sin(2β), need ideally precision of about ~1° and below**
- Loops (B to charmless decays) test for physics beyond the SM but require a clean measurement as input & precise understanding of theory assumptions (SU(3) breaking, U-spin…).

Measuring γ/ϕ_3 in open-charm B-decays: $B^- \to \tilde{D}^{(*)0} K^{(*)-}$

Same final state $\tilde{D}^0 \equiv [D^0 / D^0]$



See Young's double slit experiment



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

Measuring γ/ϕ_3 in open-charm B-decays: $B^- \to \tilde{D}^{(*)0} K^{(*)-}$
Experimental aspects

➔ **measuring γ at tree level is difficult** (typical BFs $<10^{-6}$ and less, reconst. & selection efficiencies below %):

- **STATISTICS is THE NAME OF THE GAME** ⇒ efficient detection/ selection/ PID/ tracking/ vertexing and even neutrals
- **combining many measurements/methods + inputs** from charm factories (D parameters + mixing & CPV)

➔ **Many methods/modes to combine** for optimal & redundant determination of γ (+rigorous statistical treatment possibly matters !)

➔ **various charmed modes in B^0, B^+, B^0_s, Λ^0_b, B^+_c decays** are useful to understand/confirm possible sensitivity to BSM physics and its nature

✚ Very important experimental inputs from CLEO

CPV and strong phases at BESIII

Y. Gao
@ CKM 2023

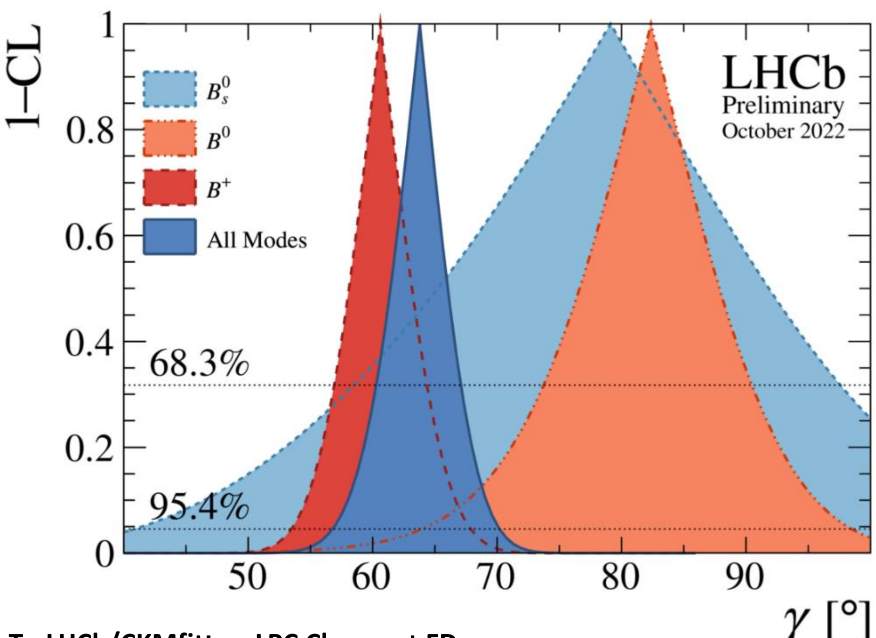
Measuring γ/ϕ_3 state of the art: world field yet dominated by LHCb

Update γ combination from LHCb measurements

$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^\circ$$

- Improvement of about 10%
- Good compatibility with unitarity fits

  $\gamma_{CKMFitter} = \left(65.5^{+1.1}_{-2.7}\right)^\circ$
- Tension between different B categories remains ($\sim 2\sigma$)



Approaching the 1° accuracy !

LHCb-CONF-2022-002 **[link] the LHCb fit combines dozens of LHCb papers**

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K_S^0 h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K_S^0 K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[39]	Run 1&2	As before
D decay	Observable(s)	Ref.	Dataset	Status since Ref. [14]
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]	Run 2	**New**
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]	Run 1	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]	Run 2	**New**
$D^0 \to h^+h^-$	ΔY	[43–46]	Run 1&2	As before
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[47]	Run 1	As before
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[48]	Run 1&2(*)	As before
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[49]	Run 1	As before
$D^0 \to K_S^0\pi^+\pi^-$	x, y	[50]	Run 1	As before
$D^0 \to K_S^0\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]	Run 1	As before
$D^0 \to K_S^0\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K_S^0\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]	Run 2	**New**

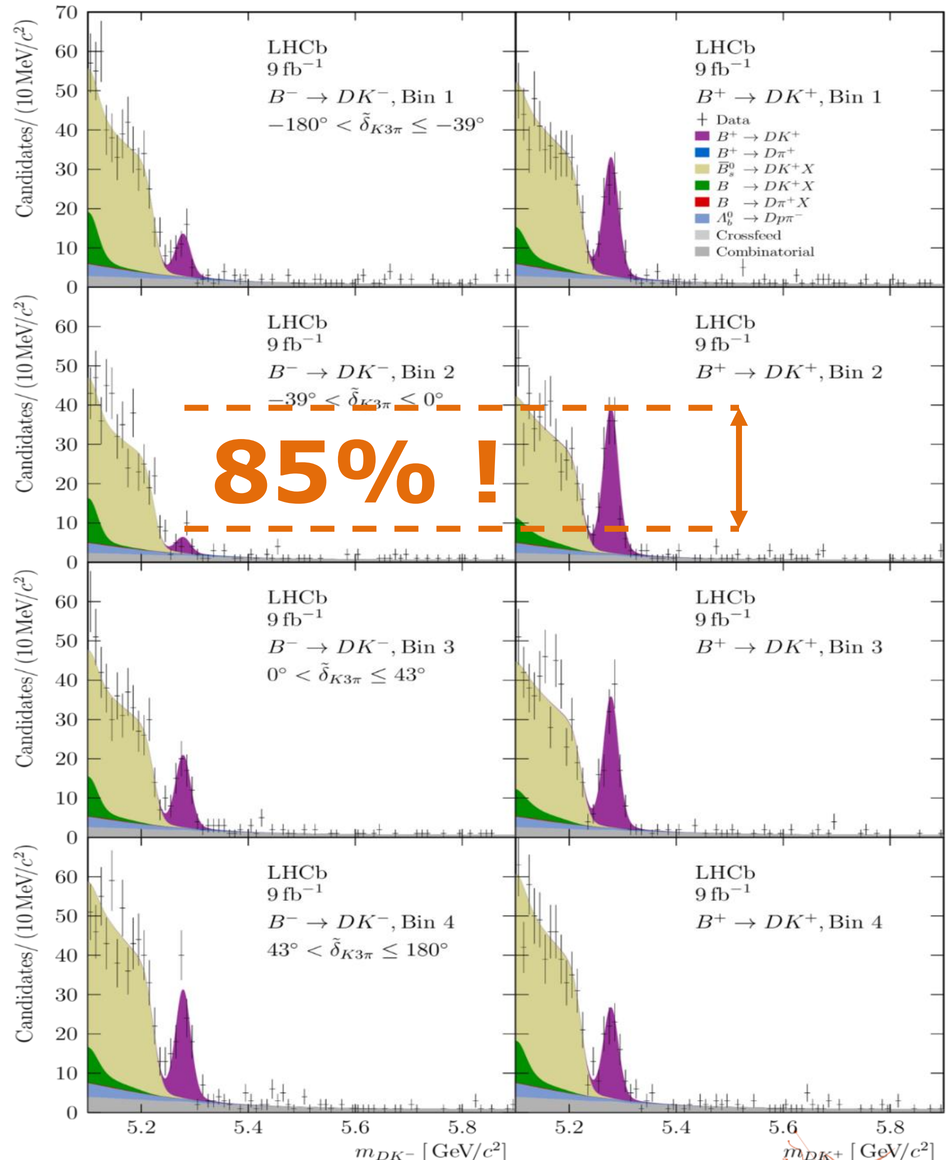
Recent measurements γ/ϕ_3 by LHCb

$B^\pm \to D^0 K^\pm$ with $D^0 \to K^\mp \pi^\pm \pi^\pm \pi^\mp$

- Binned approach based on Improved sensitivity to phase γ through binning D decay phase space [T. Evans et al. PLB 802 (2020)]
- Maximise the sensitivity: on second bin largest CPV ever observed!
- D decay hadronic parameters from CLEO-C and BESIII

$$\gamma = \left(54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.3}\right)^\circ$$

The former largest direct CPV observed is also by LHCb in March 2022 in B to hhh charmless decays [LINK]



B$^-$ B$^+$

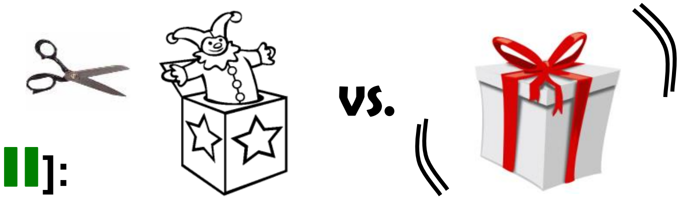
WHAT'S NEXT ?

Flavour Physics an open gate to Beyond the Standard Model ?

→New Physics(NP) can be discovered in complementary approaches
("bottom-up" : from data how to unfold the NP Lagragian ?)

☑ **Direct Search** [ATLAS/CMS] : production/observation of new particles @ $\mathcal{O}$(few TeV)

Special relativity $E=mc^2$ $\Rightarrow \sqrt{s} + \int\mathcal{L}.dt$



☑ **Indirect Search** [**LHCb/Belle II**]:

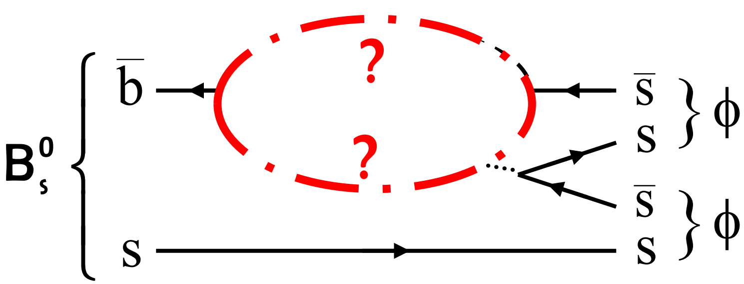
→ **K, D, $B_{d,u}$, Λ_B et B_s**

- Quantum corrections due to virtual effects ⇒ deviations wrt SM predictions
- Open gates to yet inaccessible energy scales at accelerators : $\Lambda_{NP} > 0.5\text{-}2\times10^4$ TeV
- NP@TeV: what Flavour physics « structure » explains the observed FCNC processes ?

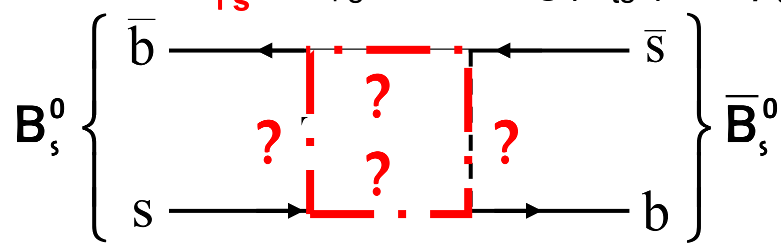
↪ Quantum mechanics $\Delta E.\Delta t \sim \hbar \Rightarrow \int\mathcal{L}.dt$ → accessing new couplings/phases in loops/boxes : CPV &/or rare decays

NP

$\Delta m_s \neq \Delta m_s^{SM} \propto |V_{ts}^2|$,
$\phi_s \neq \phi_s^{SM} = -\arg(V_{ts}^2) = 2\beta_s$



$B_s \to \phi\phi$ rare decay: "Penguin"



B_s–B_s oscillation: "Box"

LHCb Physics Program

Dedicated experiment for precision measurements for NP quest in CPV and rare decays de with all b (d) hadrons : B_d(40%), B_u(40%), B_s (10%), B_c (0.1%), b-baryons (10%)

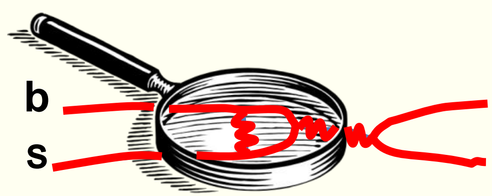
1) Precision CKM deviations/SM:

- UT coherence tests : angle γ many methods/modes+ trees/penguins
- Redundancy measurement of same parameters : NP sensitive or not
  [eg.: sin(2β) tree/penguins $B_d \to (J/\Psi K_S \Leftrightarrow \varphi K_S)$].

2) NP through new CP phases:

- B_s mixing phase $B_s \to J/\Psi\varphi$, $J/\Psi\pi\pi$, $J/\Psi KK$ +($J/\Psi\eta^{(\prime)}$, $\eta_c\varphi$, D_sD_s…)
- penguin with small CPV: $B_s \to \varphi\varphi$

3) NP in rares decays (|ΔF|=1 FCNC): asymmetries (A_{FB}, direct, time dep: C, S, …), angular/ampli. Analyse transversity/helicity structure of currents (V-A), polarization (RH γ ?), BFs >SM pred ? $B \to K^*\gamma$, $B_s \to \varphi\gamma$, $B \to K^* l^+ l^-$, $B_{(s)}/D \to \mu^+\mu^-$…

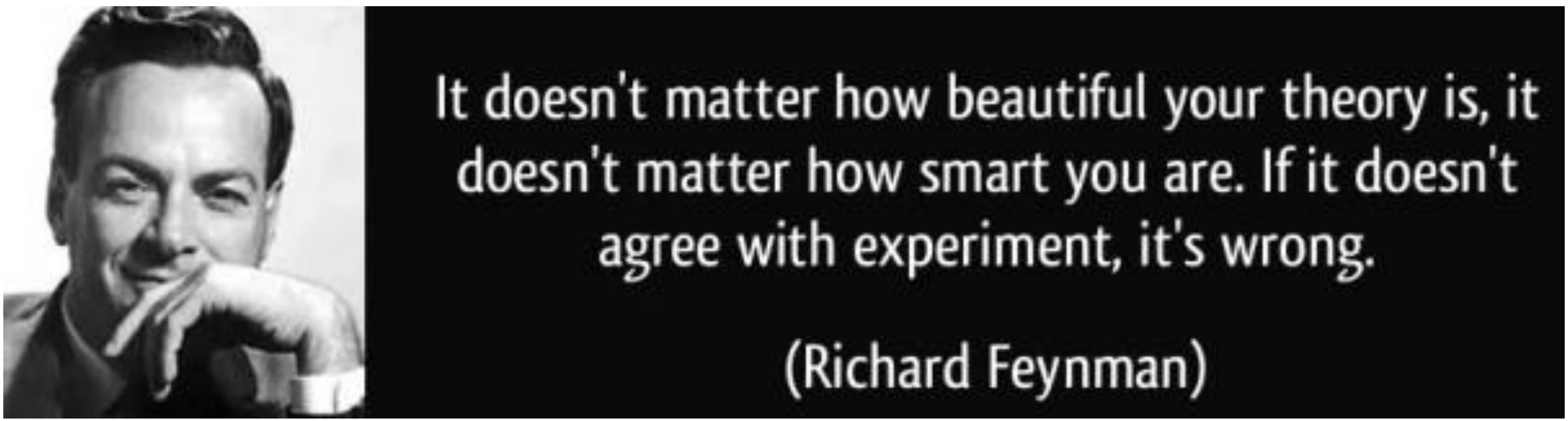


See also [Physics case for an LHCb Upgrade II]

Global coherence tests of CKM within/outside the SM

Now after ~10 years of LHCb

New physics or no New Physics yet seen ? When will we know ?



Global coherence tests of CKM within/outside the SM
Quasi-model-independent constraints on BSM in in the $B_{q=d,s}$ mixings

- Fix the apex by considering (model-dependence lies in particular in here) that four-fermions couplings are SM and 3x3 unitarity holds : main players are gamma and V_{ub} (V_{cb}).

$$|V_{ud}|,\ |V_{us}|,\ |V_{ub}|,\ |V_{cb}|,\ B^+ \to \tau^+\nu_\tau \text{ and } \gamma$$

- Model the BSM contributions in mixing as a complex number multiplying the SM mixing hamiltonian matrix elements

Assume that:

- tree-level processes are not affected by NP (SM4FC: $b \to q_i q_j q_k$ ($i \neq j \neq k$)) nor non-loop decays, eg: $B^+ \to \tau^+ \upsilon$ (implies 2HDM model).
- NP only affects the short distance physics in $\Delta B=2$ transitions.

Model independent parameterization:

$$\Delta_q = |\Delta_q| e^{i2\Phi_q^{NP}}$$

(use Cartesian coords.)

$$\langle B_q | \mathcal{H}_{\Delta B=2}^{SM+NP} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}_{\Delta B=2}^{SM} | \bar{B}_q \rangle \times (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q))$$

- SM $\Rightarrow \Delta_q = 1$
- other param.:

  $\Delta_q = r^2_q\, e^{2i\theta q} = 1 + h_q e^{2i\sigma q}$

- MFV (Yukawa)

  $\Rightarrow \Phi^{NP}_q = 0$ and $\Delta_d = \Delta_s$

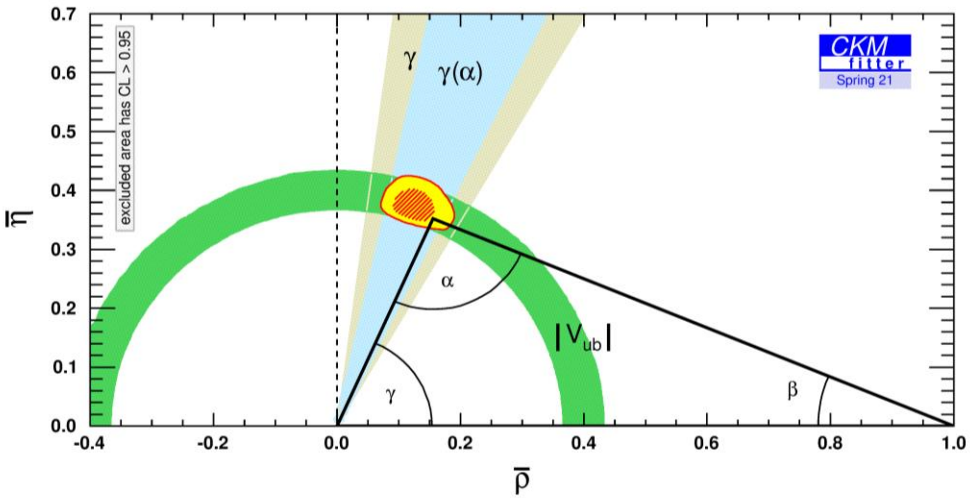
Global coherence tests of CKM within/outside the SM
Quasi-model-independent constraints on BSM in in the $B_{q=d,s}$ mixings

$$\langle B_q | \mathcal{H}^{SM+NP}_{\Delta B=2} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}^{SM}_{\Delta B=2} | \bar{B}_q \rangle \times (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q))$$

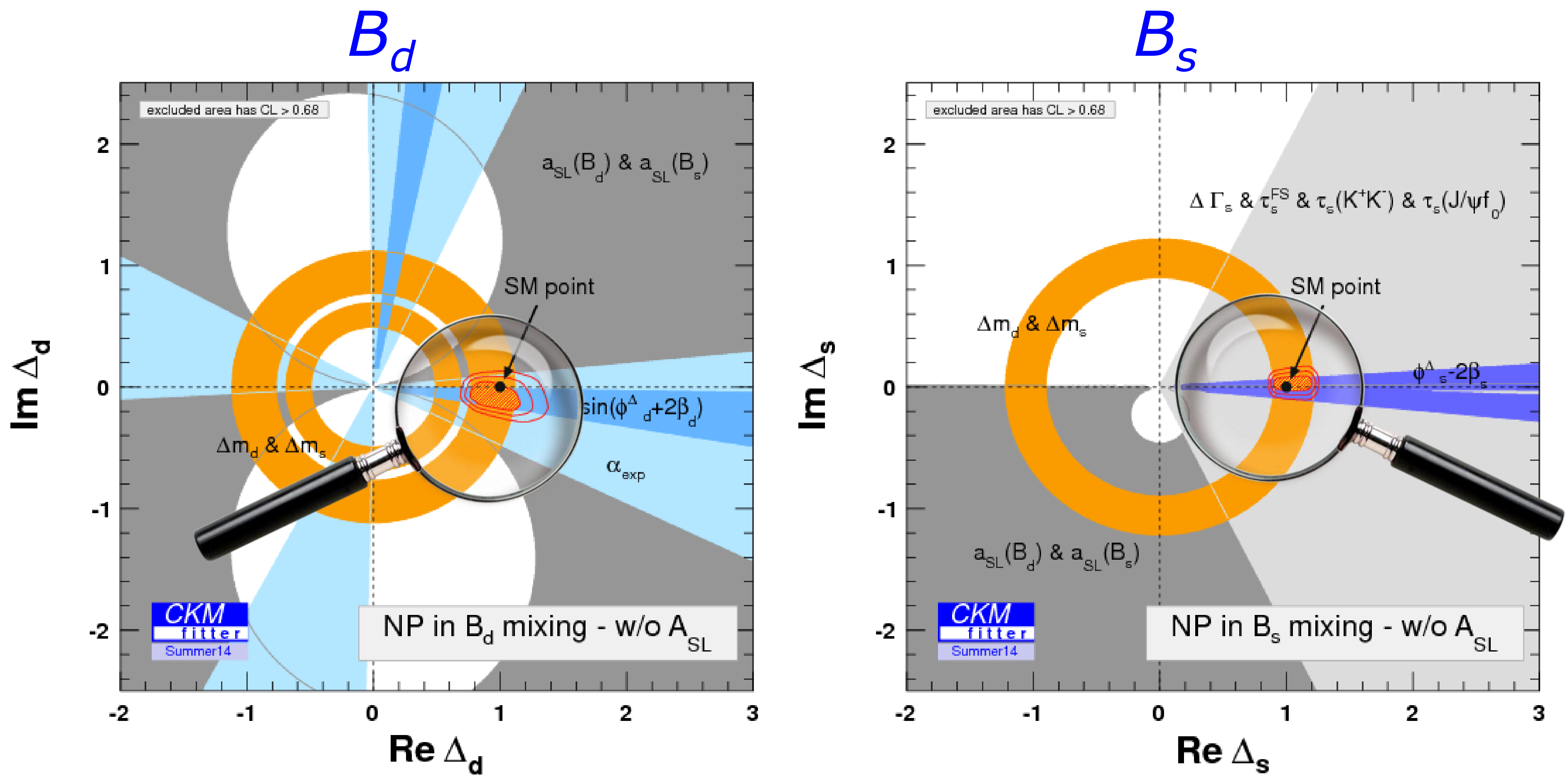
parameter		prediction in the presence of NP
Oscil.	Δm_q	$\lvert\Delta_q^{NP}\rvert \times \Delta m_q^{SM}$
Phases	2β	$2\beta^{SM} + \Phi_d^{NP}$
	$2\beta_s$	$2\beta_s^{SM} - \Phi_s^{NP}$
	2α	$2(\pi - \beta^{SM} - \gamma) - \Phi_d^{NP}$
	$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{SM} + \Phi_q^{NP}$
Asym SL	A^q_{SL}	$\frac{\Gamma_{12,q}}{M^{SM}_{12,q}} \times \frac{\sin(\Phi^{SM}_{12,q} + \Phi^{NP}_q)}{\lvert\Delta_q^{NP}\rvert}$
Lifetime diff.	$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi^{SM}_{12,q} + \Phi^{NP}_q)$

➔ **The SM parameters** (i.e., the unitarity triangle apex) **are fixed** by **4 CKM couplings, considered SM like**, and **the CKM angle γ** (directly measured and predicted):

$|V_{ub}|_{SL+\tau\nu}$, $|V_{cb}|$, $|V_{ud}|$, $|V_{us}|$, γ (standard candle), & $\gamma(\alpha) = \pi - \beta - \alpha$



Global coherence tests of CKM within/outside the SM
Quasi-model-independent constraints on BSM in in the $B_{q=d,s}$ mixings



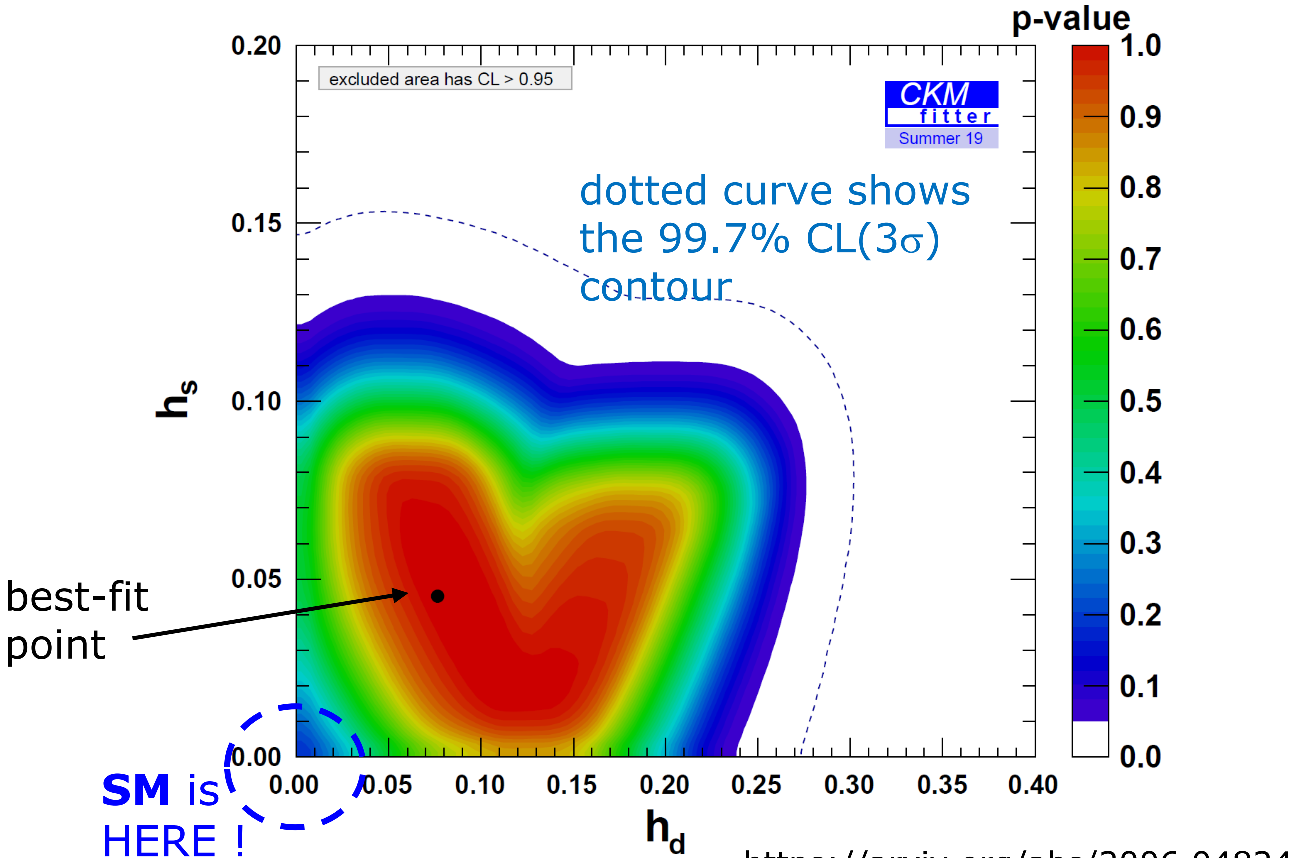
Sizeable NP is still allowed by the LHCb constraint in both B_d and B_s mixing

https://arxiv.org/pdf/1309.2293.pdf

Global coherence tests of CKM within/outside the SM
Quasi-model-independent constraints on BSM in in the $B_{q=d,s}$ mixings

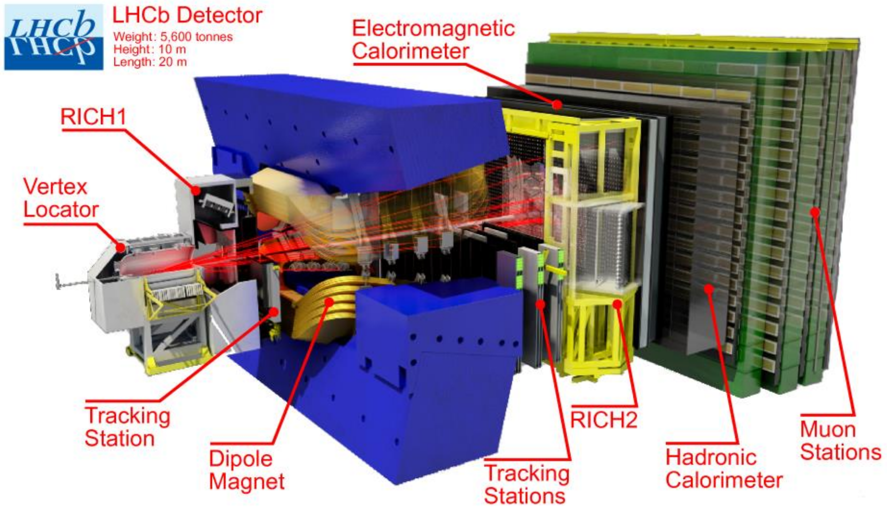
Another view can be obtained from a parameterisation of New Physics with modulus and phase, instead of cartesian model.

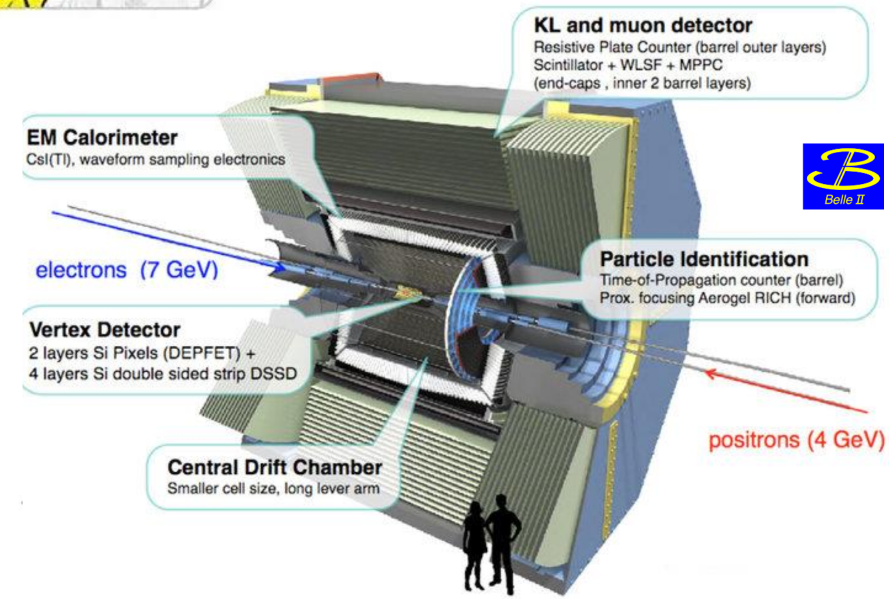
$$\mathrm{Re}(\Delta_q)+i\,\mathrm{Im}(\Delta_q)=r_q^2\, e^{i2\theta_q}=1+h_q e^{i\sigma_q}$$



https://arxiv.org/abs/2006.04824

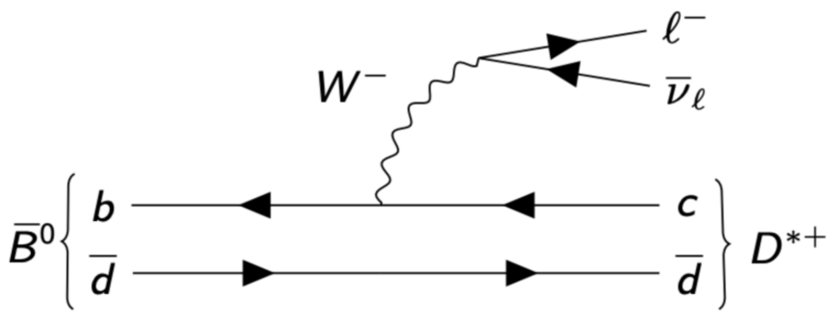
Do we have smoking guns, roads towards evidences of BSM Physics in quarks flavours ?

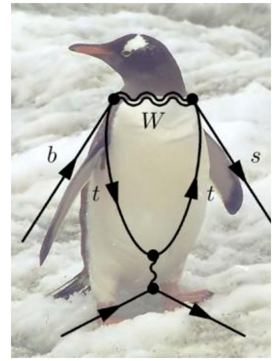




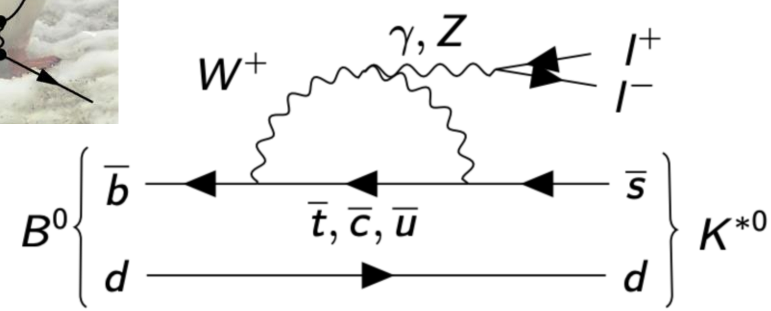
Evidences of BSM Physics in quarks flavours ?
RARE Flavour Changing Current

Charged





Neutral



Flavour Changing Charged Currents (FCCC)

- Tree-level semi-leptonic decays
- BR ~ 10%
- Neutrinos (missing energy) in the final state

Flavour Changing Neutral Currents (FCNC)

- Not allowed at tree-level in the SM **- very rare**
- Mediated by loops (penguins, box diagrams)
- BR < 10^{-6}

Evidences of BSM Physics in quarks flavours ? RARE Flavour Changing Current

- **Measuring the FCNC transitions, where NP is most likely to occur (especially in the b→sll (Bs) transitions that are least constrained by the data):**
- **OPE Development:**

Right handed part (suppressed in SM)

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_{i=1}^{10} \left(C_i(\mu) \times O_i(\mu) + \overbrace{C'_i(\mu) \times O'_i(\mu)} \right)$$

i=1,2	tree
i=3-6,8	g penguin
i=7	**γ penguin**
i=9,10	**EW penguin**

C_i : short distance Wilson coefficient (pert.)

O_i : long distance operator (non-pert.)

→NP can

modify the Wilson coefficents $C_i^{(\prime)}$

&/or

create new operators $O_i^{(\prime)}$

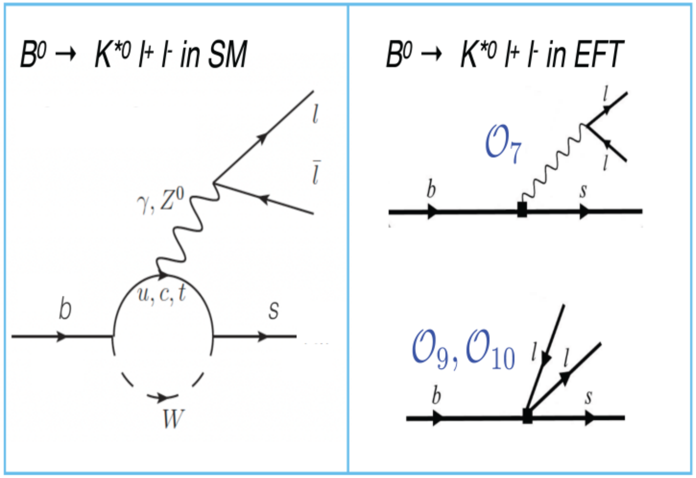
Evidences of BSM Physics in quarks flavours ? Let's repeat ourselves !!

- Model-independent approach: Effective Field Theory.
  - Operator Product Expansion.
  - Unknown field content of NP, but invariance and symmetry principles.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum \frac{C_n}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

NP scale

- B-physics: decouple heavy particles >> m_b.
  - Multi-scale: $m_{NP} >> m_{H,W,Z,top} >> m_b$.
  - OPE restricted to dim-6.



- $$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} V_{qb} V^*_{qq'} \sum_{i=1}^{10} \left(C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu) \right) \quad (\mu = m_b)$$

  left currents — right currents

  - Long distance operators $\mathcal{O}_i^{(')}$.

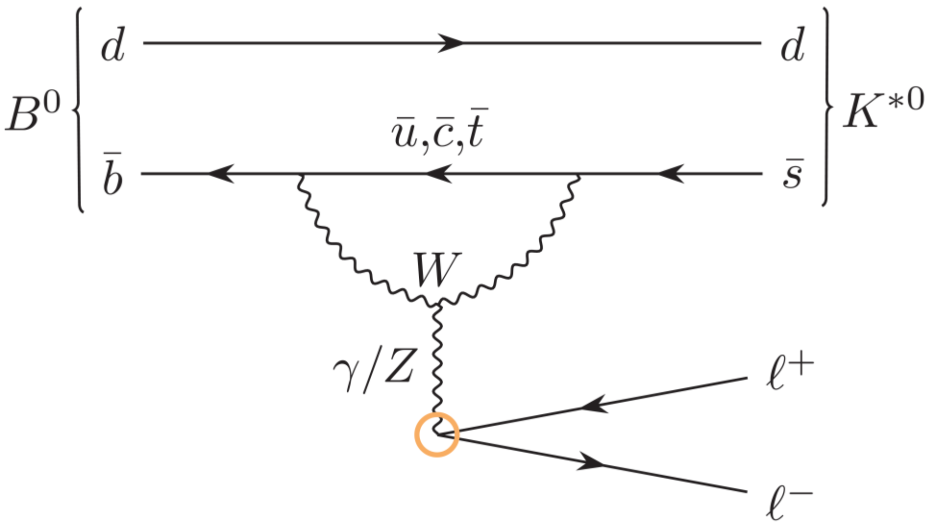
    Hadronic matrix elements still needed: main uncertainty.

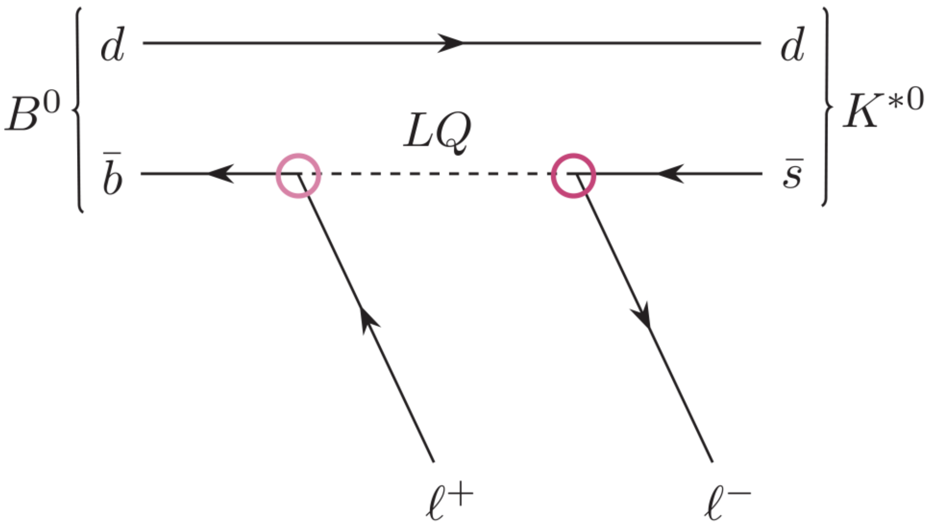
  - Short distance Wilson coefficients $C_i^{(')}$. $C_i = C_i^{SM} + C_i^{NP}$

    known — what we want to determine

Evidences of BSM Physics in quarks flavours ?
RARE Flavour Changing Current: example NP vs SM

$$b \to s\ell^+\ell^-$$





SM 🐧

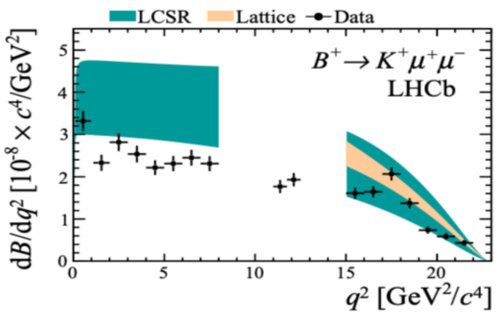
- loop-suppressed (FCNC)
- universal couplings guaranteed

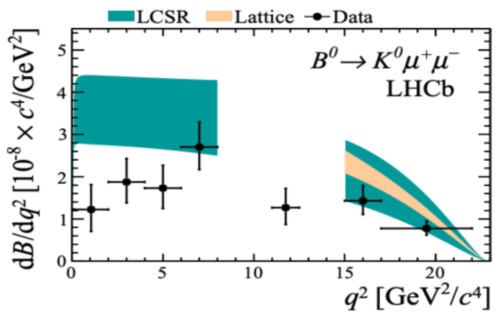
NP 🎄

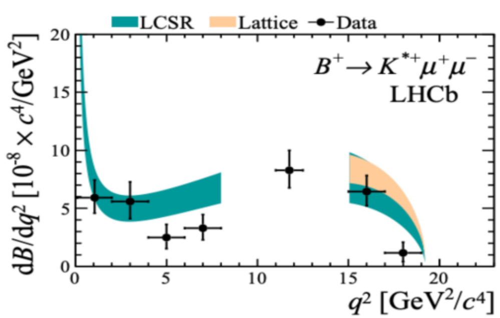
- can enter at tree-level
- universal couplings not guaranteed

$b \rightarrow s\mu^+\mu^-$ differential branching ratios

- Various $b \rightarrow s\mu^+\mu^-$ differential BRs measured by LHCb in the last years:

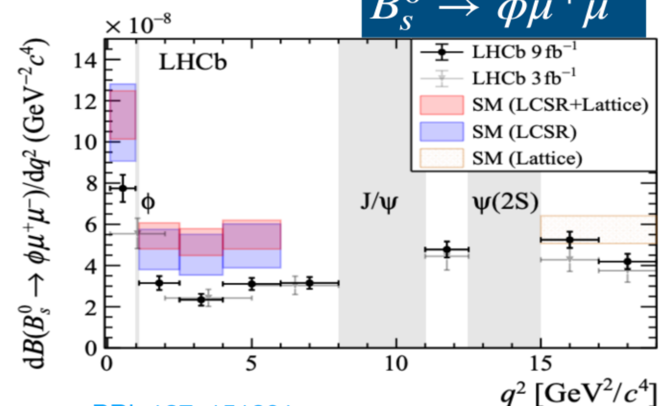






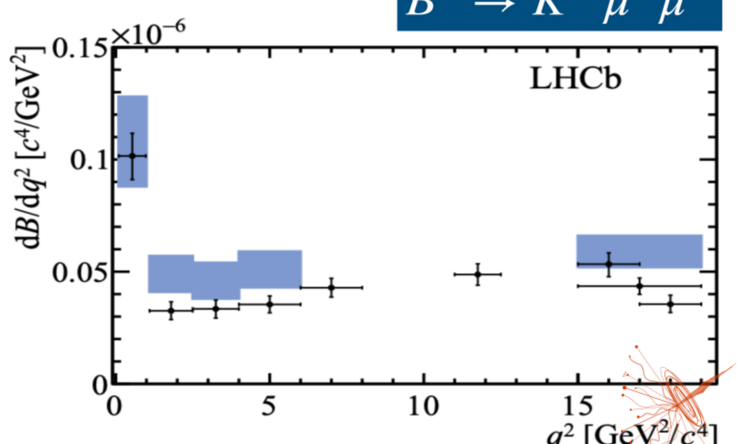
JHEP 06 (2014) 133

$B_s^0 \rightarrow \phi\mu^+\mu^-$



PRL 127, 151801

$B^0 \rightarrow K^{*0}\mu^+\mu^-$



JHEP 11 (2016) 047 JHEP 04 (2017) 142

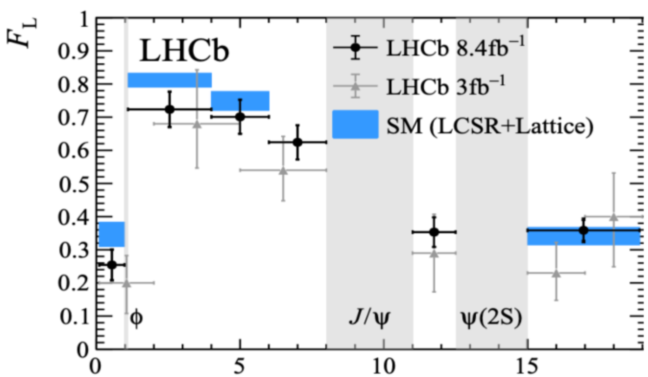
- Coherent trend for measured BRs < SM prediction
- But large theory uncertainties from form factors

Angular measurements

Access to various observables:

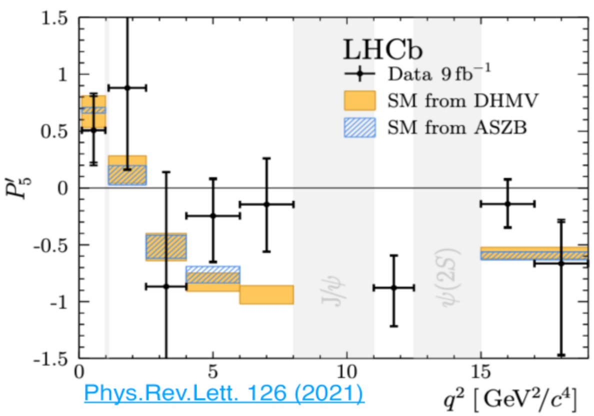
- Forward-backward asymmetry A_{FB}
- Longitudinal polarisation F_L
- Set of "clean" observables P_i to minimise hadronic uncertainties [JHEP 01 (2013), 48]

$B_s^0 \to \phi\mu^+\mu^-$



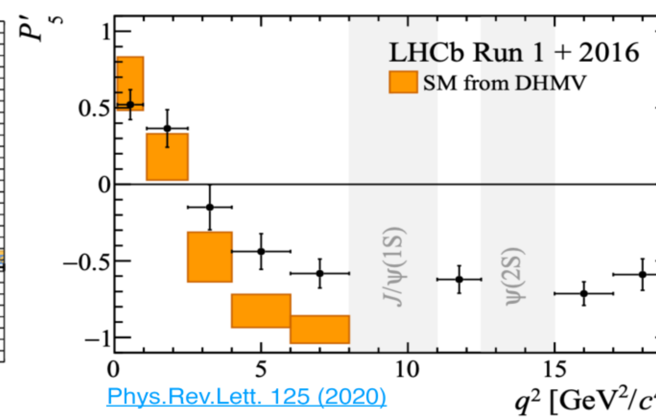
JHEP 11 (2021) 043

$B^+ \to K^{*+}\mu^+\mu^-$



Phys.Rev.Lett. 126 (2021)

$B^0 \to K^{*0}\mu^+\mu^-$



Phys.Rev.Lett. 125 (2020)

Tension seen in P'_5 in various modes and in certain q^2 bins

- Real NP effect or contribution from charm loops?

LFU tests in $b \to s\ell\ell$ decays

- Measurements of branching fraction ratio R_X:

$$R_X = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H\ell_1^+\ell_1^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H\ell_2^+\ell_2^-)}{dq^2} dq^2}$$

e.x $H_b = B^0$

e vs μ

$$R_{K^{*0}} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B^0 \to K^{*0}e^+e^-)}{dq^2} dq^2}$$

- Experimental challenges:
  - Different detector response for electrons than for muons
  - Background modelling
  - Corrections to simulation

Second lepton family (μ)

Versus

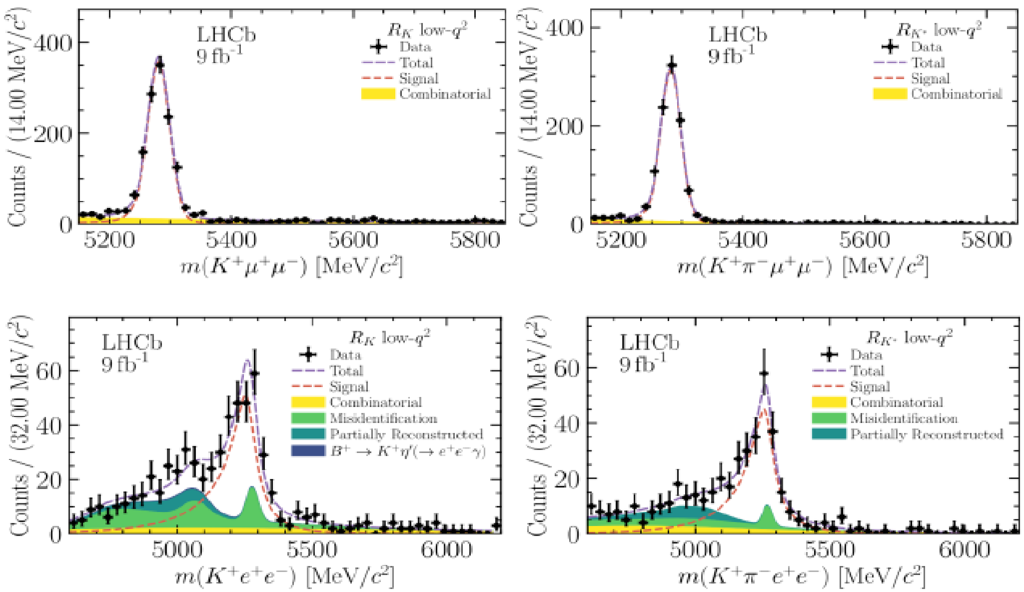
first lepton family (e)

Evidences of BSM Physics in quarks flavours ?
RARE Flavour Changing Current, anomaly ?

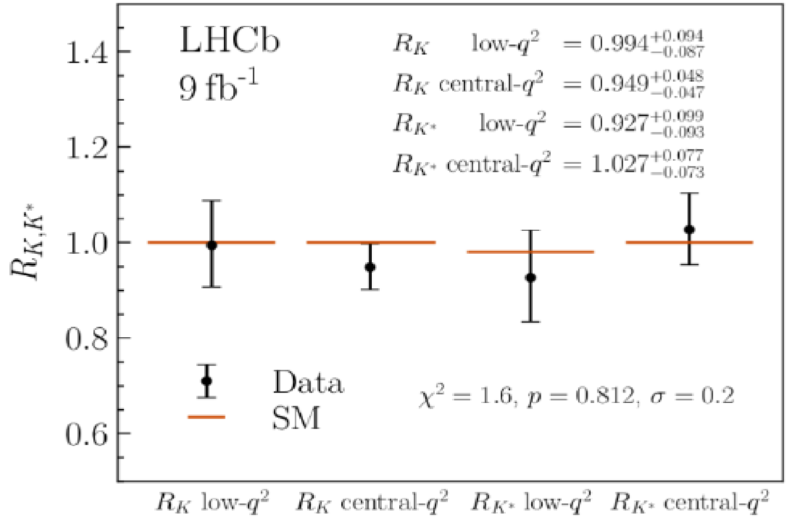
LFU tests in $b \to s\ell\ell$ decays

Both R_K and R_{K*} compatible with the SM

[arXiv:2212.09153] [arXiv:2212.09152]



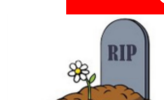
[arXiv:2212.09153] [arXiv:2212.09152]



Improvements with respect to previous publication [Nat. Phys. 18, 277-282 (2022)]**:**

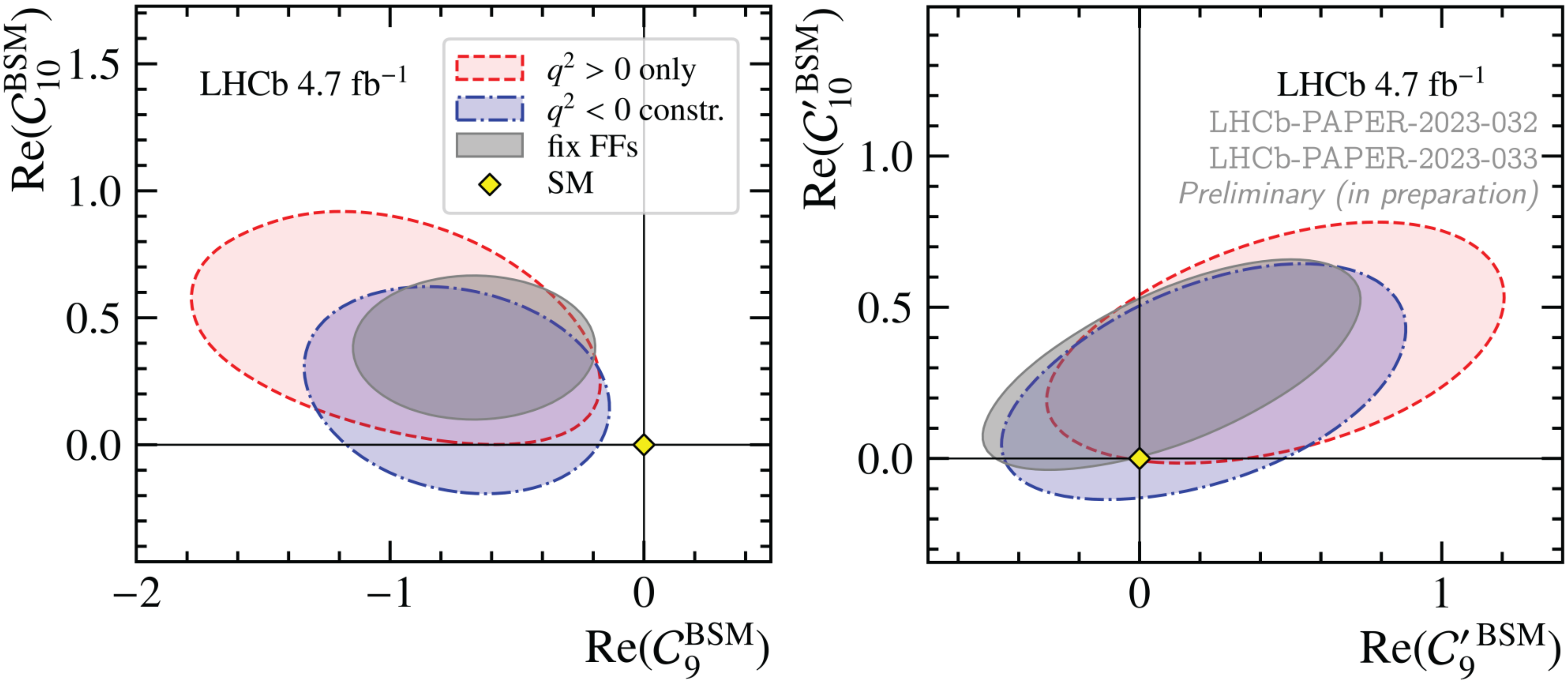
- Simultaneous fit & increased statistics
- Better understanding of $h \to e$ misID backgrounds:
  - Tigher PID requirements on electron modes
  - Residual misID component included in the fit

LHCb finally measure 1 with good precision ! Compatible with SM within 5%



Evidences of BSM Physics in quarks flavours ?
RARE Flavour Changing Current, NP in b→sll ?

Results: Wilson coefficients



Data — SM tension ~1.9 σ in C_9, up to 1.5 σ in C_{10}

Combined tension ~1.4 σ

17

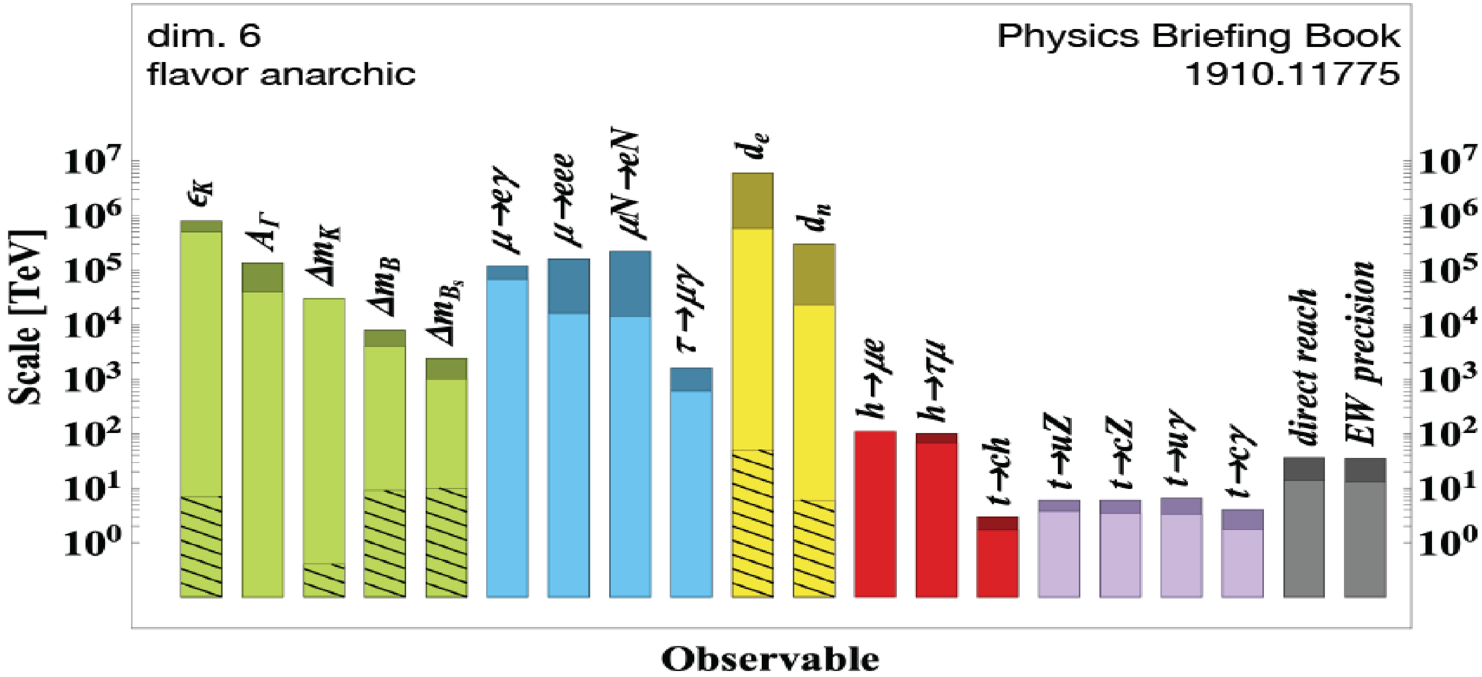
Evidences of BSM Physics in quarks flavours ? Including as well high P_T physics

Flavorful connections in the SMEFT

EFT≡Effective Field Theory

- SMEFT: $$\mathscr{L} = \mathscr{L}_{SM} + \sum_Q \frac{C_Q}{\Lambda_Q^{[Q]-4}} Q$$
  implies correlations between various observable sectors (important to build a *global* SMEFT likelihood, e.g. *smelli*)
- NP is expected to have some kind of flavor protection, e.g. MFV

hep-ph/0207036, 2005.05366, 2203.09561

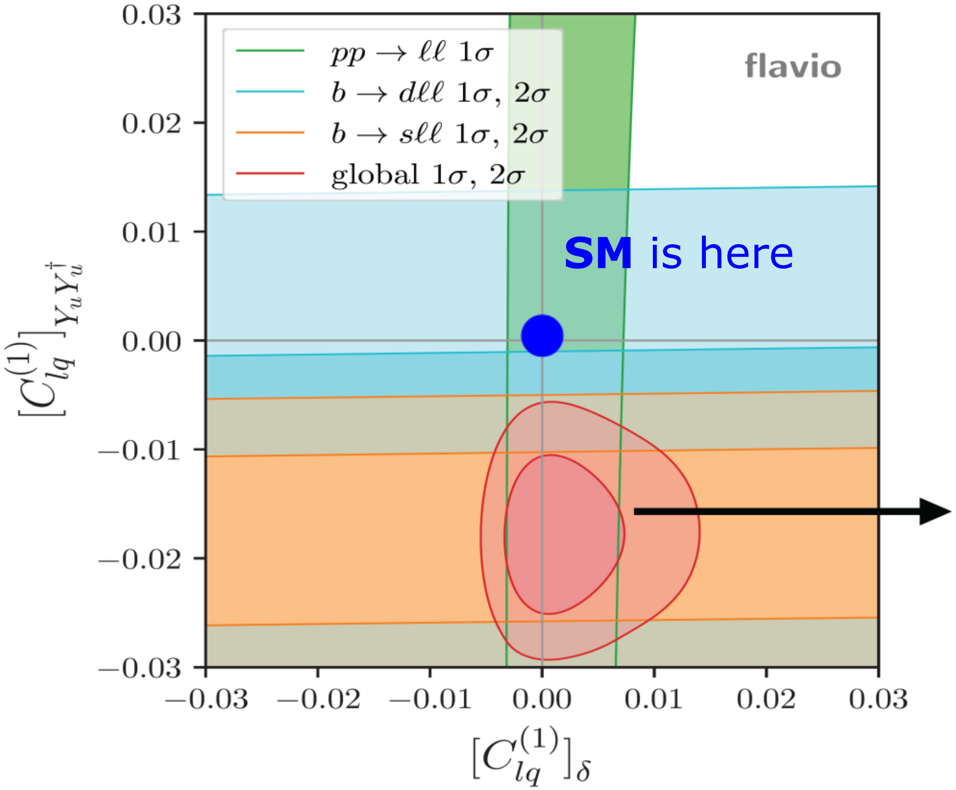


Evidences of BSM Physics in quarks flavours ?
Including as well high P_T physics

Flavorful connections in the SMEFT

Consider the $Q_{lq}^{(1)}$ operator:

$$[C_{lq}^{(1)}]_{st}(\bar{l}\gamma_\mu l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}$$

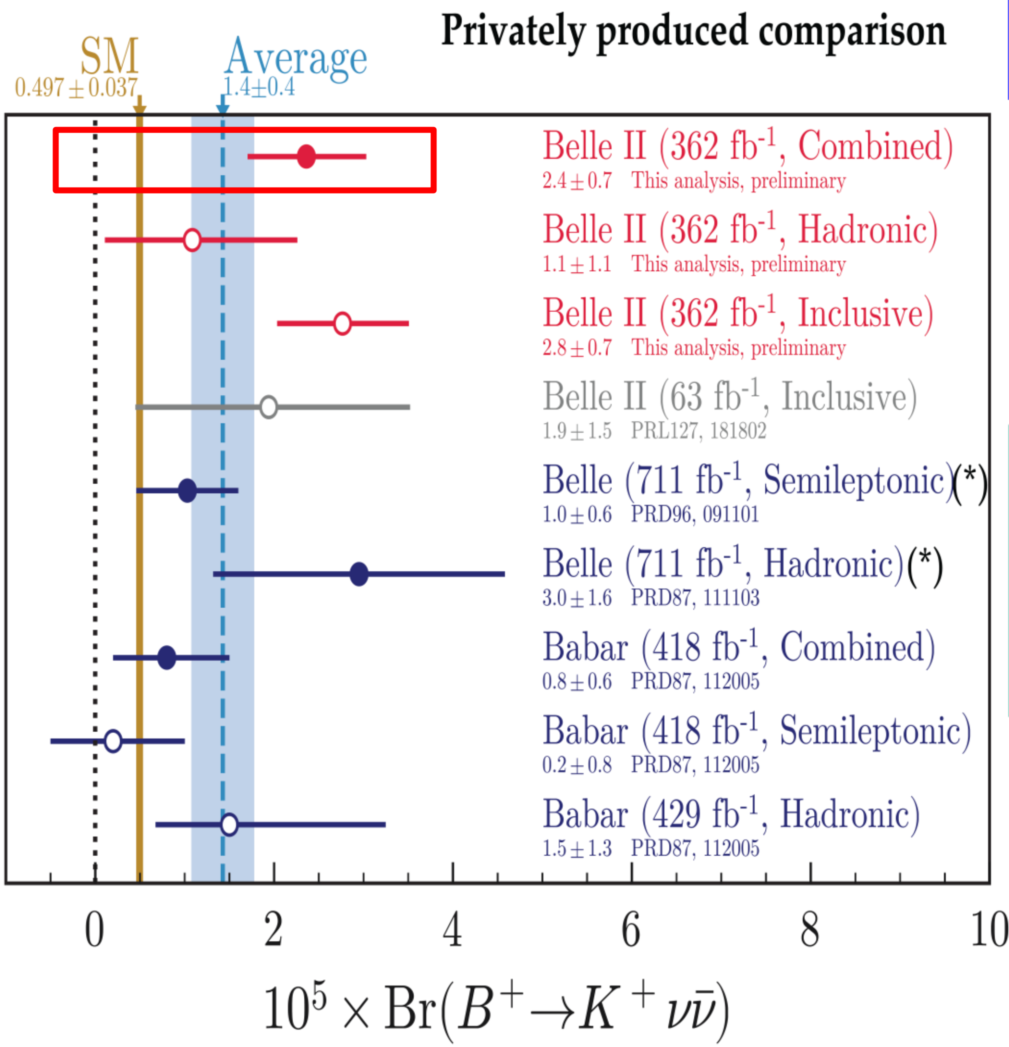


Presently dominated by $b \to s$

Improvements in $b \to d$ will allow to test flavorful BSM hypotheses

A. Greljo, J. Salko, AS, P. Stangl, 2212.10497
[see also 2209.04457]

Evidences of BSM Physics in quarks flavours ?
Belle II sees pure EW penguin $B^+ \to K^+ \nu \bar{\nu}$!!



(*) Belle reports upper limits only; branching fractions are estimated using published number of events and efficiency

Belle II

HEP-EPS Hamburg Aug 2023

$$\mu = 4.7 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$$

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = [2.4 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$$

$\mu \equiv$ signal strength wrt SM

- Combination improves the ITA-only precision by 10%
- 3.6 σ significance w.r.t background-only hypothesis
- 2.8 σ significance w.r.t SM signal hypothesis

  → first evidence of the $B^+ \to K^+ \nu\bar{\nu}$ process

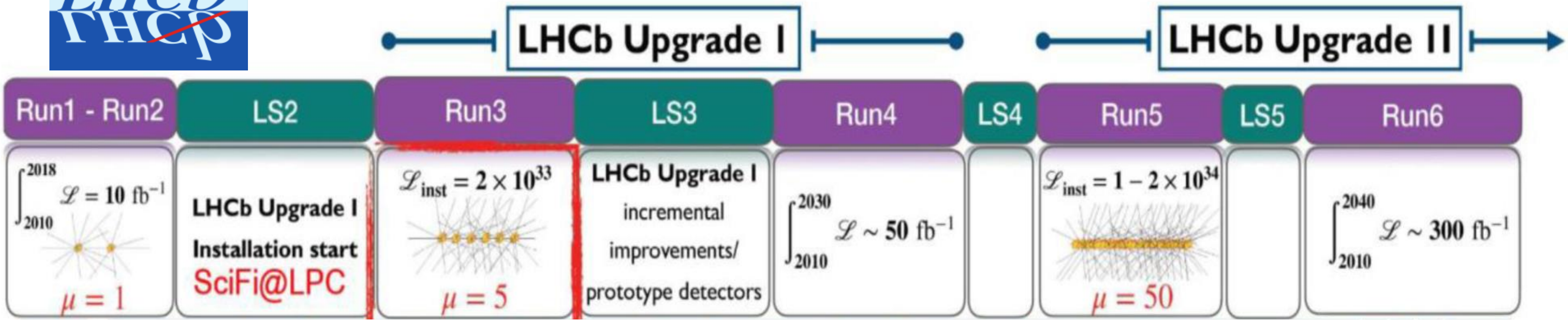
Overall compatibility is good: $\chi^2/ndf = 4.3/4$

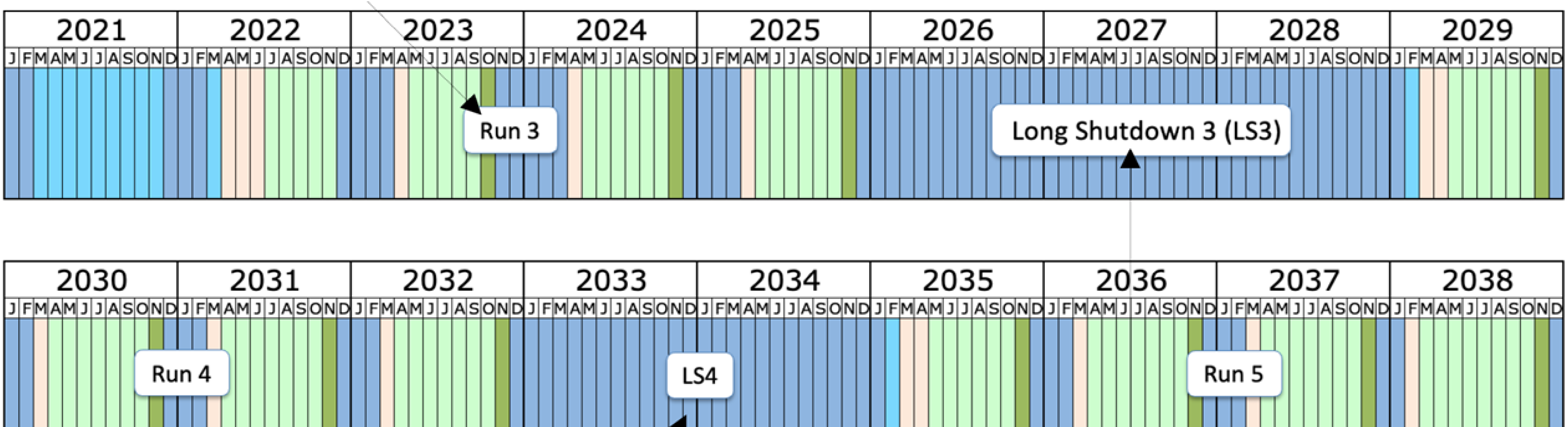
Evidences of BSM Physics in quarks flavours ?
Take HOME MESSAGE

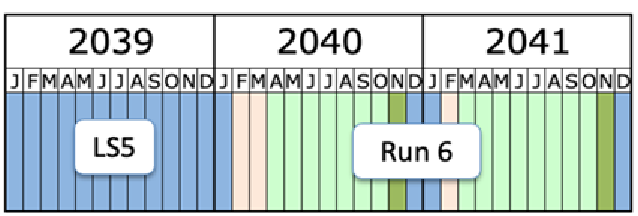
→ **Recent LHCb spectacular anomalies** **(i.e., $R_{K(*)}$ LFU) have shrunk, but there is still non negligible room for Beyond the Standard Model Physics in Heavy Flavour** (not talking about g-2 in muon decays and leptons/neutrinos)

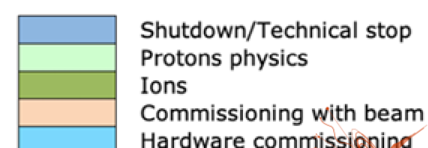
→ **LHCb and Belle II are expecting much much data: Intensity Frontier**

LOOKING FORWARD to the bright FUTURE









LOOKING FORWARD to the bright FUTURE

[This plot to be updated with actual numbers from 2022 & 2023]

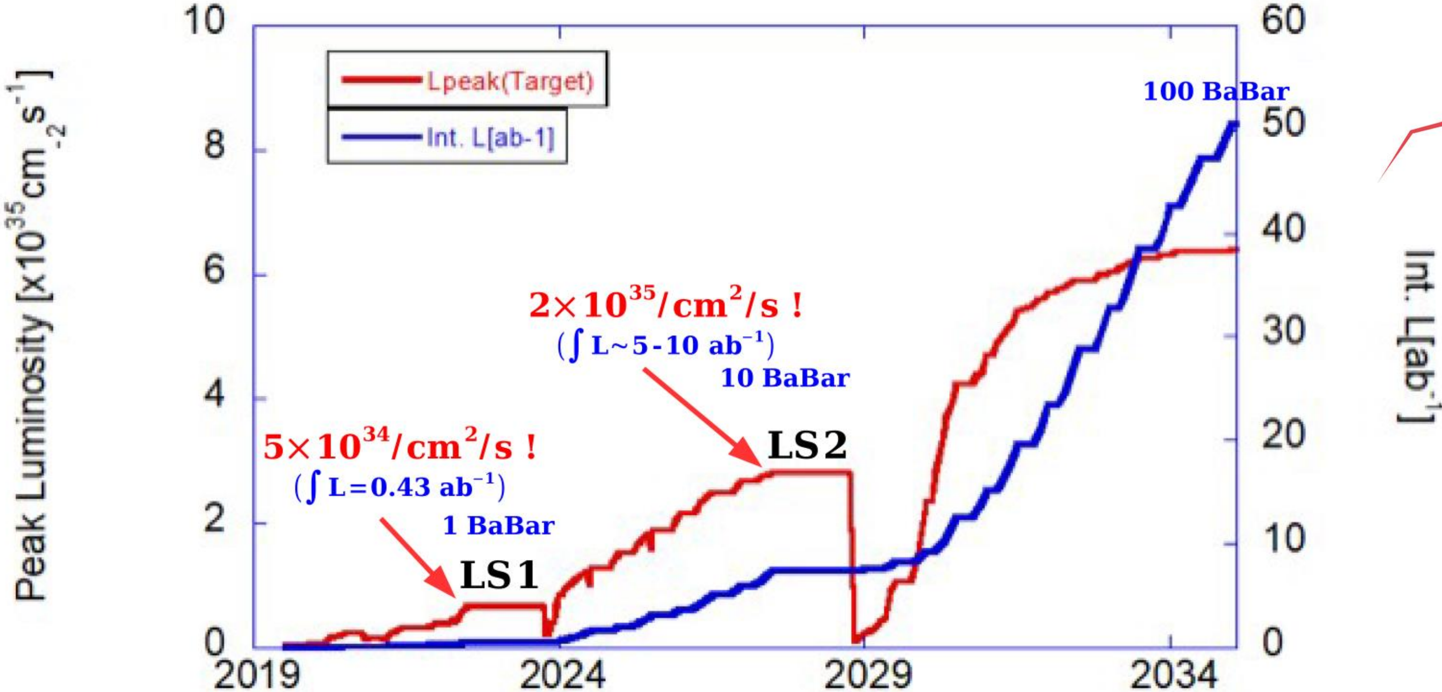
- Upgrade 1 designed to collect 50/fb, which we can collect by end of Run 4
- Opportunity to run for another 6 years
  [Assuming minimal commissioning time]
- Design Upgrade 2 detector to be able to accumulate maximum possible integrated luminosity
  - At least 300/fb by end of HL-LHC
  - Factor 6 increase in data → unprecedented sample and compelling physics programme

"The full physics potential of the LHC and the HL-LHC, including the study of flavour physics, ... should be exploited", European Strategy 2020

T. Gershon at the LHCb week Marseille Sept 23

LOOKING FORWARD to the bright FUTURE

Calendrier de Belle II



run 1 (→ juin 2022): luminosite integre $\sim$0.43 ab^{-1}, 4$-$5$\times10^{34}$/cm^2/s

PXD complet (2 couches) a installe durant LS1 (2022-2023)

(+beampipe + TOP PMTs)

run 2 (→ 2027): luminosite integre 5-10 ab^{-1}, 2$\times10^{35}$/cm^2/s

2027 : collider upgrade (QCS+RF) → installation upgraded detector

run 3 (→ > 2030): 50 ab^{-1}

K. Trabelsi @ CS IN2P3 27/10/2022

LOOKING FORWARD to the bright FUTURE

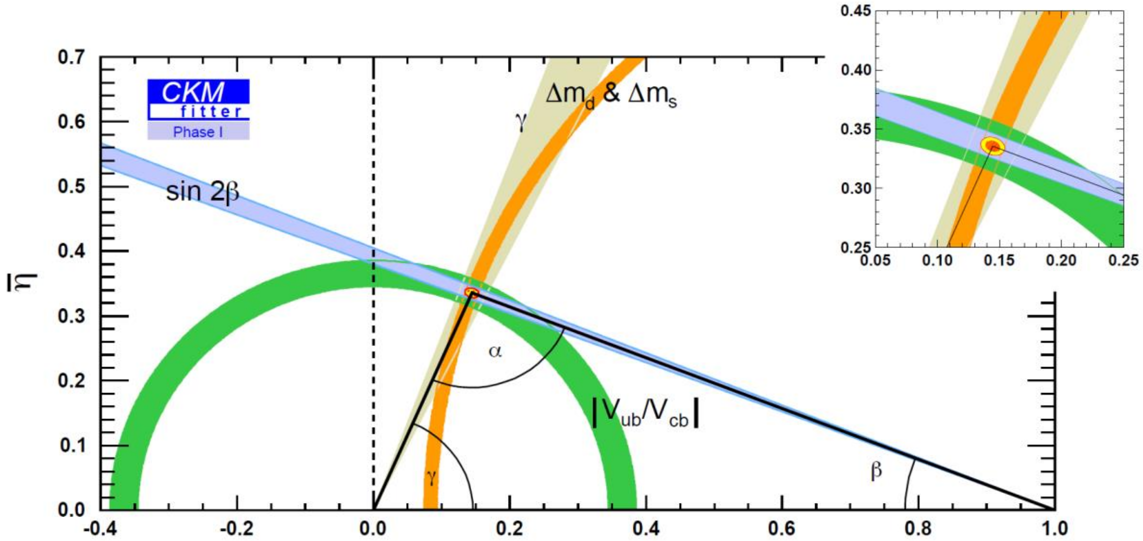
Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x\sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

See Physics case for an LHCb Upgrade II + the Belle II Physics book

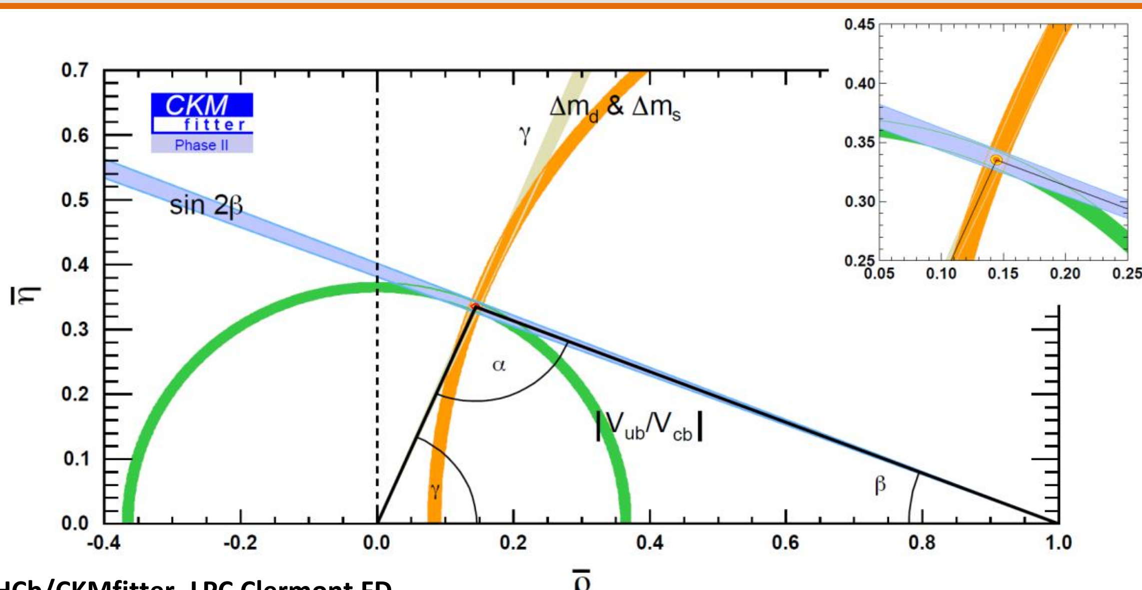
LOOKING FORWARD!

Phase I: LHCb at 23 fb^{-1}, CMS/ATLAS at 300 fb^{-1}, Belle II at 50 ab^{-1}.

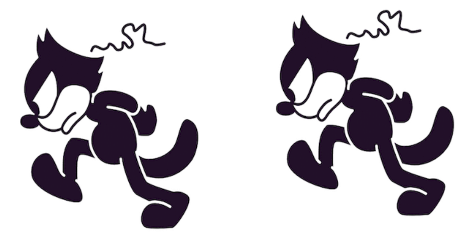


~in about 10 years

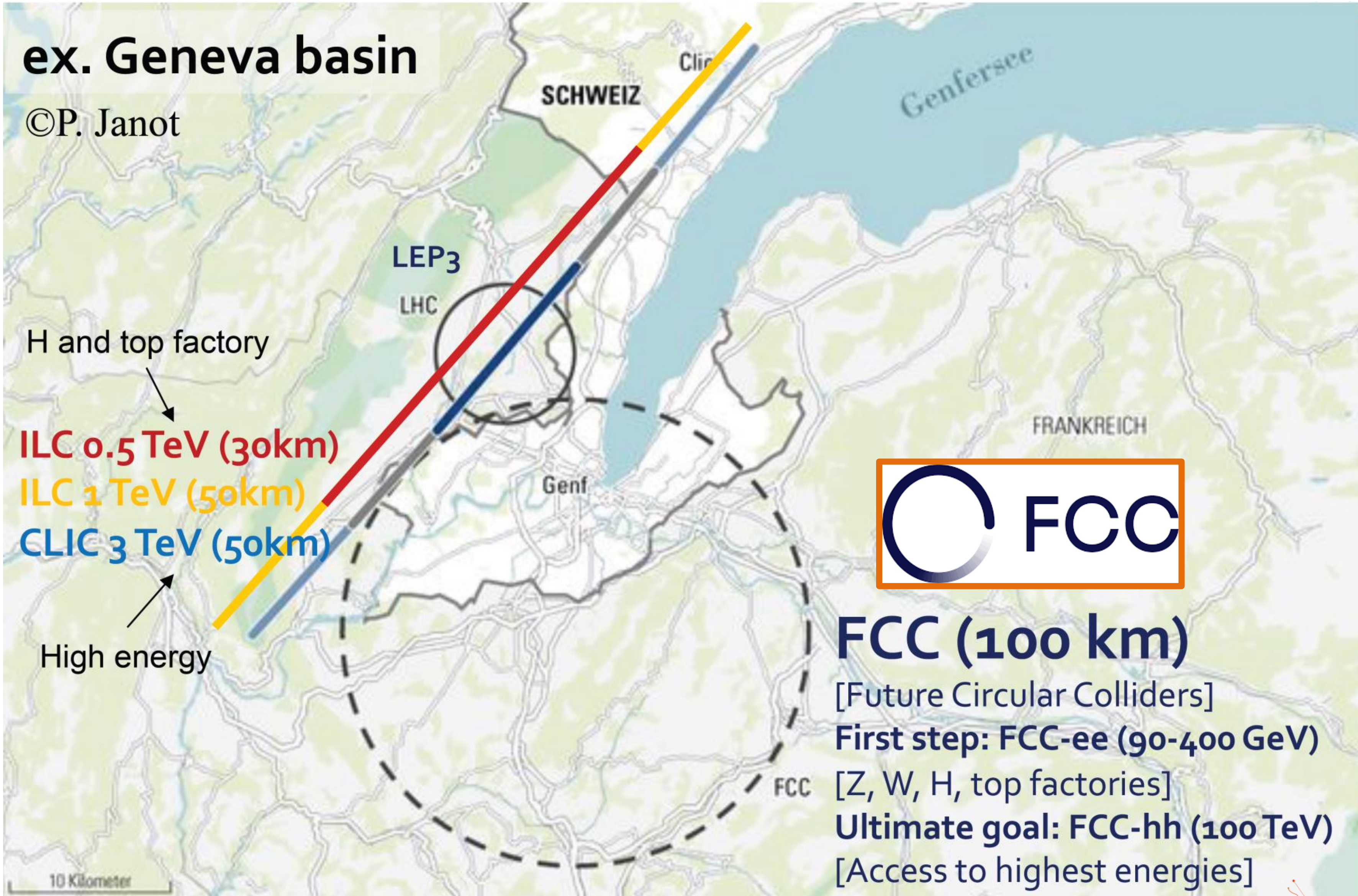
Phase II: LHCb at 300 fb^{-1}, CMS/ATLAS at 3000 fb^{-1}, and Belle II at 50 ab^{-1}.



~20 years



LOOKING FORWARD after 2040 !



Annecy ↓

https://fcc-cdr.web.cern.ch/

After 2045: FCC a GigaZ factory !

Eur. Phys. J. Plus (2021) 136:837
https://doi.org/10.1140/epjp/s13360-021-01814-0

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Check for updates

Heavy-quark opportunities and challenges at FCC-ee

Stéphane Monteil[1], Guy Wilkinson[2,a]

[1] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[2] Department of Physics, University of Oxford, Oxford, United Kingdom

Received: 7 May 2021 / Accepted: 28 July 2021

Abstract The abundant production of beauty and charm hadrons in the 5×10^{12} Z^0 decays expected at FCC-ee offers outstanding opportunities in flavour physics that in general exceed those available at Belle II and are complementary to the heavy-flavour programme of the LHC. A wide range of measurements will be possible in heavy-flavour spectroscopy, rare decays of heavy-flavoured particles and *CP*-violation studies, which will benefit from the low-background experimental environment, the high Lorentz boost and the availability of the full spectrum of hadron species. This essay first surveys the important questions in heavy-flavour physics and assesses the likely theoretical and experimental landscape at the turn-on of FCC-ee. From this certain, measurements are identified where the impact of FCC-ee will be particularly important. A full exploitation of the heavy-flavour potential of FCC-ee places specific constraints and challenges on detector design, which in some cases are in tension with those imposed by the other physics goals of the facility. These requirements and conflicts are discussed.

between 1989 and 1995, 18×10^6 Z bosons were collected at LEP@CERN, FCC aims for 5×10^{12} ! So LEP every few minutes of FCC operation!

At Z pole *qqbar* pairs:
- 15% are $b\bar{b}$ ➔ 750×10^9
- 12% are $c\bar{c}$ ➔ 600×10^9

Almost all triggerable and can be reconstructed (high eff'cy) in e+e- @Z (91.2GeV/c²) clean collisions !

A place for ultra-high heavy flavour precision and rares decays

It's every goodness & advantages from LHCb and from Belle II (very few drawbacks)!