CKM matrix status in 2023

Luiz Vale Silva

University of Valencia

18 Sept. 2023

on behalf of the *CKM*fitter Collaboration
12th International Workshop on the CKM Unitarity Triangle

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101031558"

Outline

1. Introduction
2. Analysis and results

Outline

Flavor transitions in the quark sector

$$\mathcal{L}_{SM(NP)} \sim -\frac{1}{4}(F_{\mu\nu})^2 + i\bar{\psi}\not{D}\psi$$

Gauge couplings to fermions

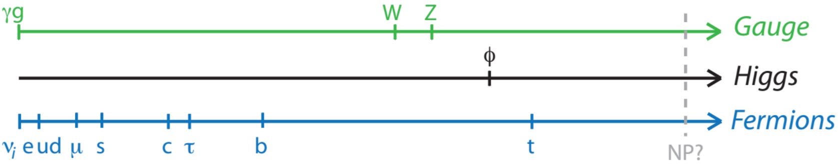
$$+ |D_\mu H|^2 - V(H)$$

Short-range *weak* interactions
Higgs self-interaction

$$+ \mathbf{Y} H\bar{\psi}\psi + \text{h.c.}$$

Structure of flavor:
Spectrum of fermion masses
CKM matrix

$$\left(+ \sum_{d>4} \frac{1}{\Lambda_{heavy}^{d-4}} C_k O_k^d \right)$$



→ Flavor transitions pattern is likely to change in the presence of NP

→ **Goal here is to test the SM, and possibly point out tensions**

The Cabibbo-Kobayashi-Maskawa matrix

15 June 1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

Universality of ΔS=0,1 weak transitions; Cabibbo introduces a phenomenological mixing angle

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \quad (13)$$

No CPV with 2 generations; KM consider a 3rd one, 1st CKM matrix in the literature

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

***CP*-Violation in the Renormalizable Theory of Weak Interaction**

Makoto Kobayashi and Toshihide Maskawa
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

CKM '23 in Santiago: O(100) talks devoted to its study during this week!

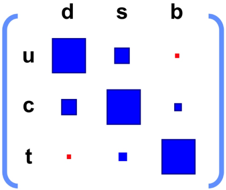
The CKM matrix

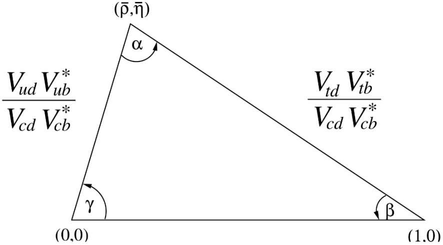
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

three mixing angles, one single CPV phase

$$V_{u\alpha} V^*_{u\beta} + V_{c\alpha} V^*_{c\beta} + V_{t\alpha} V^*_{t\beta} \overset{\alpha \neq \beta}{=} 0$$

V is measured to be hierarchical

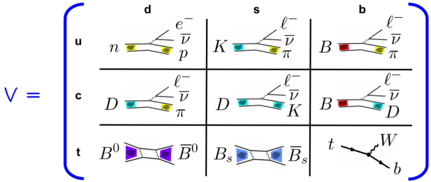


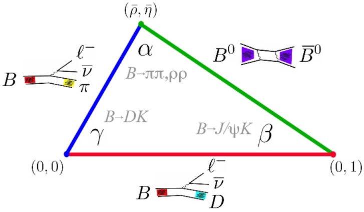


Rephasing invariant:

$$\frac{|V_{us}|}{(|V_{ud}|^2+|V_{us}|^2)^{1/2}} = \lambda \,, \quad \frac{|V_{cb}|}{(|V_{ud}|^2+|V_{us}|^2)^{1/2}} = A\lambda^2 \,, \quad -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} = \bar{\rho} + i\bar{\eta}$$

Tests of the CKM matrix





→ 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

Theoretical inputs

$\rightarrow$ Need to deal with **hadronic effects** inherent to the quark sector

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

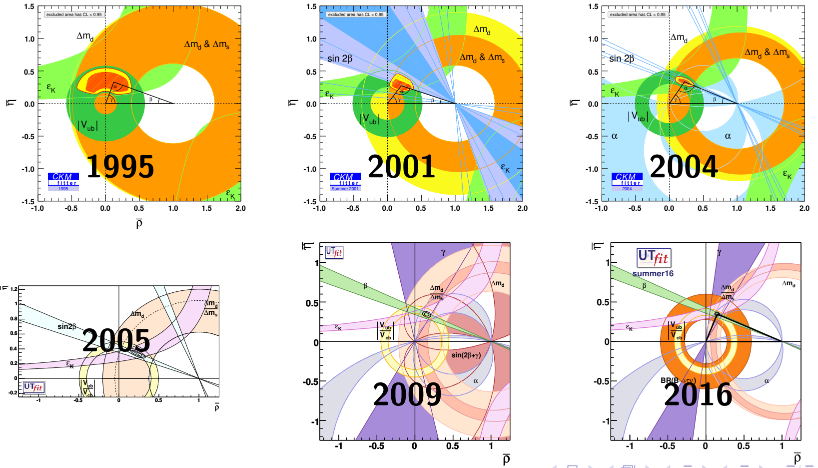
(semi-)leptonic decays	$\pi \to \ell\nu$, $K \to \pi\ell\nu$, etc.: decay constants, form factors Ex.: f_π, $f_+^{K\to\pi}(0)$ $-p_\mu f_\pi = \langle 0\|(\bar{d}\gamma_\mu\gamma_5 u)\|\pi(p)\rangle$, $f_+^{K\to\pi}(q^2)(p+p')_\mu + f_-^{K\to\pi}(q^2)(p-p')_\mu = \langle\pi(p')\|(\bar{s}\gamma_\mu P_L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

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

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

Progress over the years

$\rightarrow$ Long road for a better theoretical control (e.g., Lattice QCD), and more accurate data (LEP, KTeV, NA48, BaBar, Belle, CDF, DØ, LHCb, CMS, ...)



Outline

Statistical approach

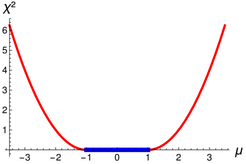
- ***CKM*fitter**: Frequentist statistics based on a χ^2 analysis
- χ^2_{min}: **goodness-of-fit** under SM (or NP), **estimators** for V_{CKM}
- $\Delta\chi^2$ (χ^2-distributed): **Confidence Level** (CL) intervals
- *Range* fit scheme (*R*fit) incorporates **theoretical uncertainties**

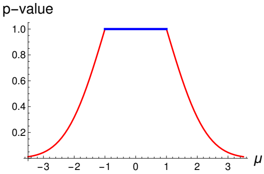
$$\mathcal{L} \overset{Rfit}{=} \mathcal{L}_{stat} \times \mathcal{L}_{theo},$$
$$\chi^2 = -2\,\ell\text{n}\,\mathcal{L}$$
$\mathcal{L}_{stat}$: exp. data

$\mathcal{L}_{theo}$: had. inputs

[cf. Charles, Descotes-G., Niess, LVS '17]

Example in 1D, $0 \pm 1_{stat} \pm 1_{theo}$ ($N_{dof} = 1$)





χ^2: flat bottom, quadratic walls

UTfit: Bayesian approach [Ciuchini et al. hep-ph/0012308] [See M. Bona on Tue @ 17h35]

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

black: no or slight change; **red**: substantial update since CKM'21

(color **does not** reflect the impact of the exp./theo. input!)

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)

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

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

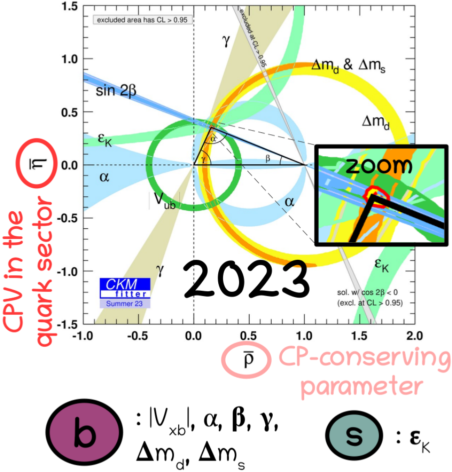
$\bar{\rho} = 0.1562^{+0.0112}_{-0.0040}$ (4.9% unc.)

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

68% C.L. intervals

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

B_d Unitary Triangle:



[For direct CPV in charm, see U. Nierste Today @ 15h45]

Overall results of the **UT**fit 2023 update

Summer update: **UT**fit official webpage

$A = 0.827 \pm 0.010$ (1.2% unc.)

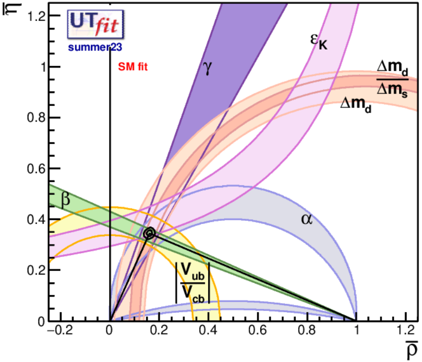
$\lambda = 0.2251 \pm 0.0008$ (0.4% unc.)

$\bar{\rho} = 0.160 \pm 0.009$ (5.6% unc.)

$\bar{\eta} = 0.346 \pm 0.009$ (2.6% unc.)

68% probability intervals

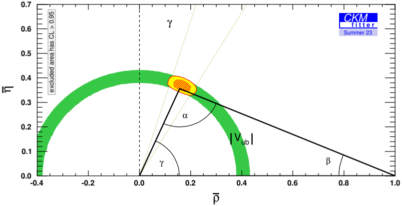
B_d Unitary Triangle:



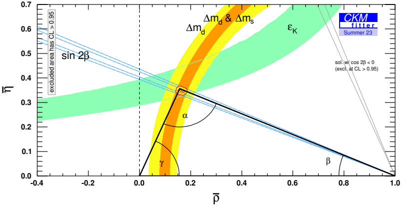
Consistent values for the Wolfenstein parameters between the fits
For *CKM*fitter and **UT**fit fits with **exactly** the same inputs,
see PDG's CKM reviews

*CKM*fitter: consistency among classes of obs.

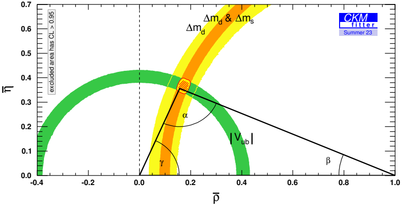
tree level



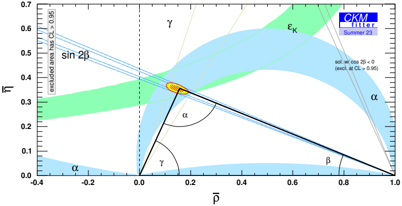
loop-induced



$\mathcal{CP}$−conserving

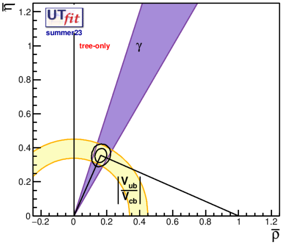


$\mathcal{CP}$−violating

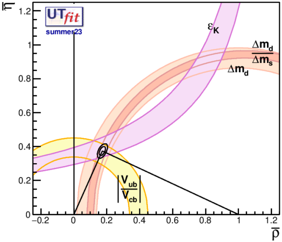


UTfit: consistency among classes of observables

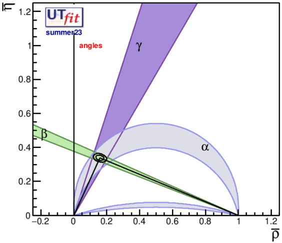
tree level



sides of B_d UT, ϵ_K



angles of B_d UT



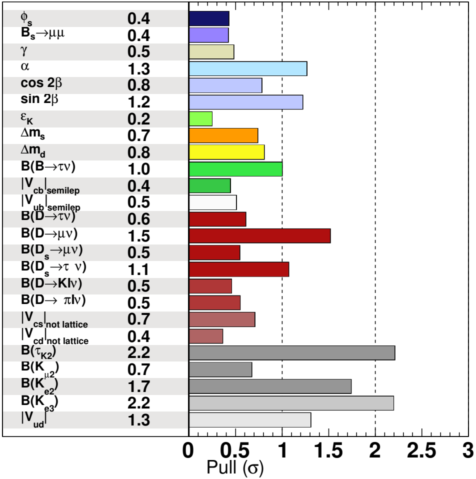
*CKM*fitter Pulls: individual tensions

$$pull_{\mathcal{O}_{exp}} = \sqrt{\chi^2_{min} - \chi^2_{min,!\mathcal{O}_{exp}}},$$
$$!\,\mathcal{O}_{exp}:\ \chi^2_{min}\ \text{w/o}\ \mathcal{O}_{exp}$$

→ If Gaussian uncs., uncorrelated random vars.: mean 0 and variance 1

→ Here, correlations are expected

→ Some large pulls in relation to the 1st row of the CKM matrix



First two generations: $|V_{ud}|$ and $|V_{us}|$ plane

→ $|V_{ud}|$ from nuclear transitions
*R*fit: add theo. uncs. linearly

[Hardy, Towner '20]

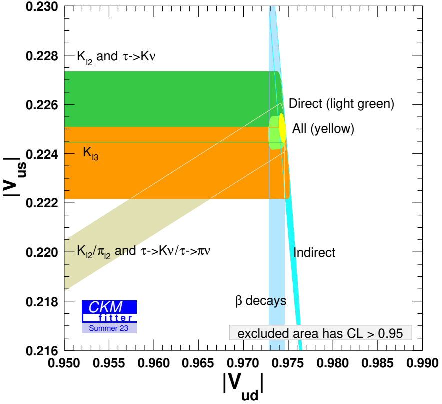
[See M. Gorshteyn on Thu @ 11h30]

→ $|V_{us}|$ from K, π, τ decays

[rad. correcs.: χPT, Cirigliano, Neufeld '11; RχT, Arroyo-U., Hernandez-T., Lopez-C., Roig, Rosell '21 '21]

[See M. Moulson on Wed @ 09h00]

→ Fair agreement among different classes of inputs, $K_{\ell 3}$ and τ_{K2} pulls of 2.2



$|V_{ud}|$: $\pm 0.006\%$ [ind.], $\pm 0.005\%$ [comb.]
$|V_{us}|$: $\pm 0.40\%$ [ind.], $\pm 0.10\%$ [comb.]

First two generations: $|V_{cd}|$ and $|V_{cs}|$ plane

$\rightarrow \mathcal{B}(D_s \rightarrow \tau\nu_\tau)$, $W \rightarrow c\bar{s}$

[BESIII 2303.12600; CMS 2201.07861]

[See T. Wang on Tuesday @ 09h30]

$\rightarrow f_+^{D\rightarrow\pi}(0)$: syst. $2\times$ smaller

'21, $f_+^{D\rightarrow\pi}(0) = 0.621 \pm 0.018 \pm 0.012$

'23, $f_+^{D\rightarrow\pi}(0) = 0.624 \pm 0.004 \pm 0.006$

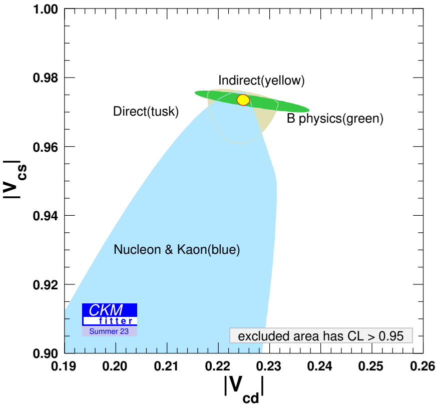
$\rightarrow f_+^{D\rightarrow K}(0)$: syst. $3\times$ smaller

'21, $f_+^{D\rightarrow K}(0) = 0.765 \pm 0.010 \pm 0.012$

'23, $f_+^{D\rightarrow K}(0) = 0.742 \pm 0.002 \pm 0.004$

[See E. Gamiz on Tuesday @ 10h00]

$\rightarrow$ Ind. inputs determine the extraction of $|V_{cd}|$, $|V_{cs}|$



$|V_{cd}|$: $\pm 0.10\%$ [ind./comb.]

$|V_{cs}|$: $\pm 0.006\%$ [ind./comb.]

$|V_{cb}|$ and $|V_{ub}|$ semi-leptonic extractions

similar theo. frameworks for **charmed** and **charmless** modes, but different tools for **inclusive** (OPE in $1/m_b^{\#}$, shape functions) and **exclusive** (HQET, Form Factors from Lattice QCD)

$|V_{cb}|$ and $|V_{ub}|$ semi-leptonic extractions

similar theo. frameworks for **charmed** and **charmless** modes, but different tools for **inclusive** (OPE in $1/m_b^\#$, shape functions) and **exclusive** (HQET, Form Factors from Lattice QCD)

→ Exclusive $|V_{cb}|$:

- $B \to D^* \ell \nu$, BGL: $|V_{cb}|_{B\to D^*} = (40.17 \pm 0.39 \pm 0.39) \times 10^{-3}$

[Belle '19 (untagged), BaBar '19 (untagged); preliminary Belle (tagged) & Belle II (untagged)]

[preliminary combination of lattice inputs]

[See M. Prim & R. Cheaib @ EPS-HEP; C. Schwanda on Tue @ 17h15]

- $B \to D \ell \nu$, BCL: $|V_{cb}|_{B\to D} = (40.00 \pm 0.93 \pm 0.37) \times 10^{-3}$

[HFLAV+FLAG 2021 combination]

$$\Rightarrow |V_{cb}|_{excl.} = (40.08 \pm 0.36 \pm 0.37) \times 10^{-3}$$

$|V_{cb}|$: excl. and incl. B-meson decays

→ Inclusive: $|V_{cb}|_{incl.} = (42.16 \pm 0.32 \pm 0.39) \times 10^{-3}$ (m_b^{kin})

[Fael, Schönwald, Steinhauser '20 '20 '20; Bordone, Capdevila, Gambino '21]

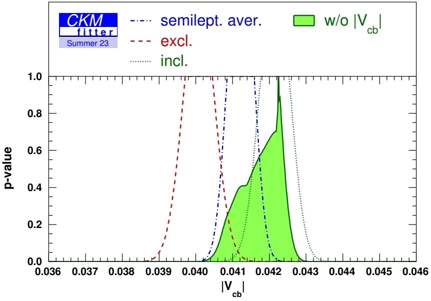
→ Excl. and incl. have similar error budgets

→ Our inputs for excl. and incl. differ by about 2σ

→ Similar averages:

'21, $|V_{cb}|_{\rm SL} = (41.15 \pm 0.34 \pm 0.45) \times 10^{-3}$

'23, $|V_{cb}|_{\rm SL} = (41.22 \pm 0.24 \pm 0.37) \times 10^{-3}$



$|V_{cb}|$: $\pm 1.7\%$ [ind.], $\pm 0.9\%$ [comb.]

$|V_{ub}|$: excl. and incl. B-meson decays

→ $B \to \pi \ell \nu$: $|V_{ub}|_{excl.} = (3.60 \pm 0.10 \pm 0.12) \times 10^{-3}$

[FLAG 2021+preliminary Belle II (tagged)]

→ GGOU+BLNP+DGE: $|V_{ub}|_{incl.} = (4.13 \pm 0.12 \pm 0.14) \times 10^{-3}$

[HFLAV 2021, including Belle '21 (tagged)]

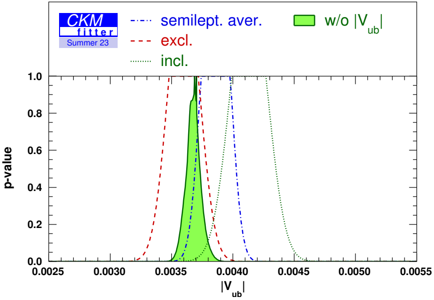
→ Excl. and incl. have similar error budgets

→ Our inputs for excl. and incl. are compatible at about 1σ

→ Decrease of the uncertainty:

'21, $|V_{ub}|_{\rm SL} = (3.88 \pm 0.08 \pm 0.21) \times 10^{-3}$

'23, $|V_{ub}|_{\rm SL} = (3.86 \pm 0.07 \pm 0.12) \times 10^{-3}$



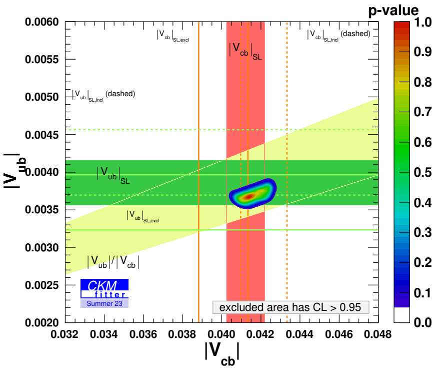
$|V_{ub}|$ ±2.1% [ind.] ±1.2% [comb.]

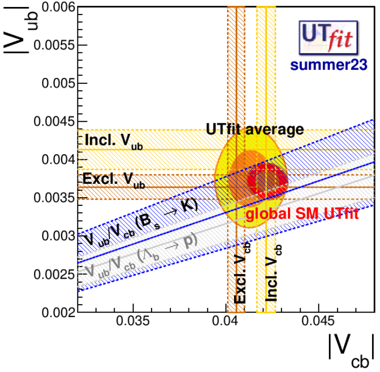
$|V_{ub}|$ and $|V_{cb}|$ plane

→ $|V_{ub}|/|V_{cb}|_{\rm incl} = 0.100 \pm 0.006 \pm 0.003$ (GGOU)

[preliminary Belle '23 (tagged)] [See L. Cao @ EPS-HEP; M. Prim on Tue @ 13h00]

→ $|V_{cb}|_{incl.}$ and $|V_{ub}|_{excl.}$ are preferred by their indirect extractions





α angle

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

$\rightarrow$ Isospin analysis constrains hadronic penguin and tree amplitudes

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

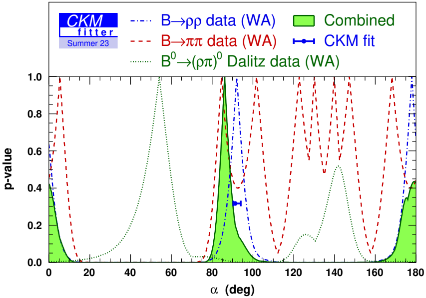
[See M. Dorigo on Tue @ 11h50]

As in previous editions:

$\rightarrow$ Average dominated by $B \rightarrow \pi\pi$ and $B \rightarrow \rho\rho$

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

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



CKM'18 edition	CKM'21 edition	CKM'23 edition
α [dir.] $(86.4^{+4.5}_{-4.3})^o \cup (-1.8^{+4.3}_{-5.1})^o$	α [dir.] $(86.4^{+4.3}_{-4.0})^o \cup (-1.6^{+4.1}_{-5.2})^o$	α [dir.] $(86.2^{+3.9}_{-3.5})^o \cup (-1.0^{+3.3}_{-4.9})^o$

β, γ, and β_s angles

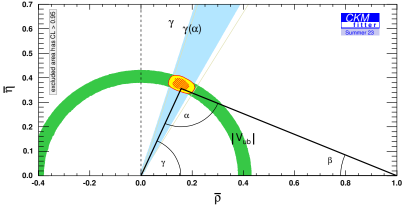
$\rightarrow$ Important change in $\sin(2\beta)$, following preliminary LHCb results from $\sin 2\beta = 0.699 \pm 0.017$ to $\sin 2\beta = 0.708 \pm 0.011$ [HFLAV]

[See T. Latham Today @ 15h55]

$\rightarrow$ γ: more accurate than α [dir.] [HFLAV]

$$\gamma[^{\circ}] = 65.9^{+3.3}_{-3.5} \text{ [dir.]}$$
$$\gamma[^{\circ}] = 66.29^{+0.72}_{-1.86} \text{ [ind.]}$$
$$\gamma[^{\circ}] = 66.23^{+0.60}_{-1.43} \text{ [comb.]}$$

[See e.g. S. Stanislaus Today @ 17h55, I. Mackay on Tue @ 09h40]



$\rightarrow$ $B_s \rightarrow J/\psi(KK, \pi\pi) \Rightarrow \phi_s^{c\bar{c}s}$: includes LHCb preliminary update from $\phi_s^{c\bar{c}s} = -0.057 \pm 0.021$, to $\phi_s^{c\bar{c}s} = -0.039 \pm 0.016$ [HFLAV]

[See M. M. Cruz T. Today @ 14h45]

$|\Delta F| = 2$ transitions

→ Precision SM observables: Δm_s, Δm_d, ϵ_K

[ϵ_K, higher order EW corrections: Brod, Kvedaraite, Polonsky '21, Brod, Kvedaraite, Polonsky, Youssef '22]

→ Lattice accuracy for the Bag Parameters around a few percent

Indirect extractions:

$$\hat{B}_K = 0.772^{+0.076}_{-0.057}(9\%),\ \frac{\hat{B}_{B_s}}{\hat{B}_{B_d}} = 1.061^{+0.044}_{-0.062}(5\%),\ \hat{B}_{B_s} = 1.303^{+0.051}_{-0.055}(4\%)$$

→ Consistent, but indirect $\hat{B}_K$, $\hat{B}_{B_s}/\hat{B}_{B_d}$ not competitive w/ LQCD

- Inclusion of ε'/ε [Bona et al. hep-ph/2212.03894]
- Study of D meson mixing [See R. Di Palma @ EPS-HEP]

[ϵ_K, dim.-8 operators: Ciuchini, Franco, Lubicz, Martinelli, Silvestrini, Tarantino '21]

Sensitivity to NP $|\Delta B| = 2$

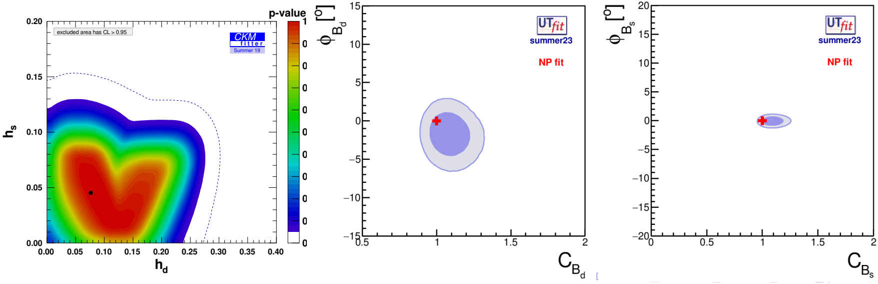
- $\rightarrow$ GIM mechanism suppresses SM [GIM in SMEFT: LVS hep-ph/2201.03038]
- $\rightarrow$ Extract possible NP contributions, $M_{12} = (M_{12})_{SM}\,(1 + he^{2i\sigma})$

[See E. Malami on Tue @ 09h00]

- $\rightarrow$ Main inputs: $\{\Delta m_d, \beta\}$, and $\{\Delta m_s, \beta_s\}$
- $\rightarrow$ In presence of NP, extraction of $\bar{\rho}$ and $\bar{\eta}$ degrades by about ~ 3

[Charles, Descotes-G., Ligeti, Monteil, Papucci, Trabelsi, LVS '20]

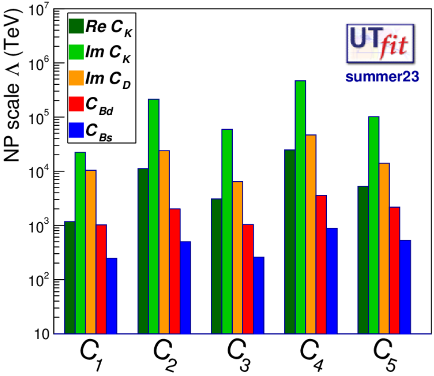
NP in B_d, B_s — NP in B_d — NP in B_s



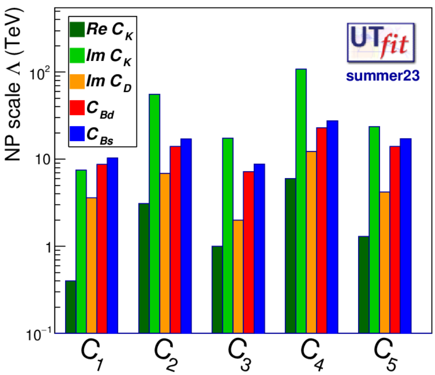
Sensitivity to NP $|\Delta F| = 2$

$\rightarrow$ Very high energy scales probed

Generic NP

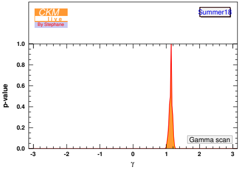


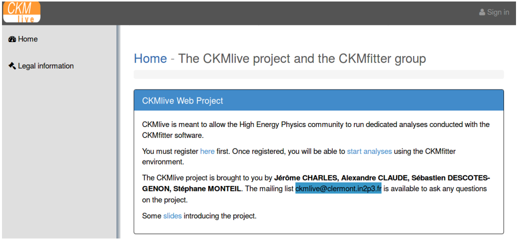
NMFV suppression



CKMlive web interface

- Run dedicated CKM SM fits from ***CKMfitter*** package @ CKMlive
- User chooses the set of observables, and the values of the theoretical and experimental inputs, plus fitting parameters





Conclusions

Global fits shown here:

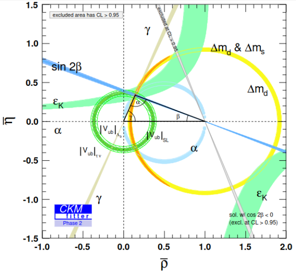
- SM framework: CKM mechanism for quark flavor transitions
- Theoretical inputs (mainly Lattice QCD)
- Experimental results (B factories, LHCb, etc.)

$\rightarrow$ Global fit of a **rich variety of processes sensitive to $\mathcal{CP}$ Violation and SM predictions in agreement**

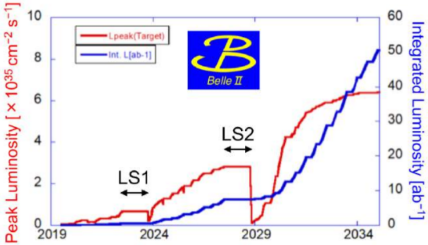
$\rightarrow$ We are then able to extract accurate values for parameters describing the CKM matrix: $\mathcal{O}(1\,\%)$ or much better

$\rightarrow$ The **mechanism of $\mathcal{CP}$ Violation in the SM** (still) gives an **accurate picture of nature**: *no clear indication of NP*

Conclusions



→ Exciting future prospects for Belle II, LHC, NA62,...



THANKS!

[from M. Needham @ EPS-HEP]

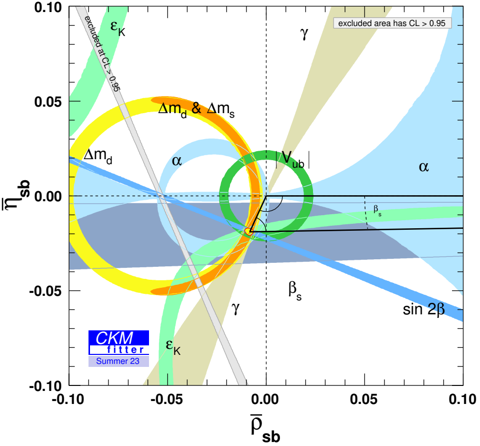
*CKM*fitter Collaboration

MORE DETAILS @ CKMfitter

Jérôme Charles, Theory
Olivier Deschamps, LHCb
Sébastien Descotes-Genon, Theory
Stéphane Monteil, LHCb
Jean Orloff, Theory
Wenbin Qian, LHCb/BESIII
Vincent Tisserand, LHCb/BABAR
Karim Trabelsi, Belle/Belle II
Philip Urquijo, Belle/Belle II
Luiz Vale Silva, Theory

Backup

Other triangles, I



$$\bar{\rho}_{bs} + i\bar{\eta}_{bs} = -\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*}$$

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

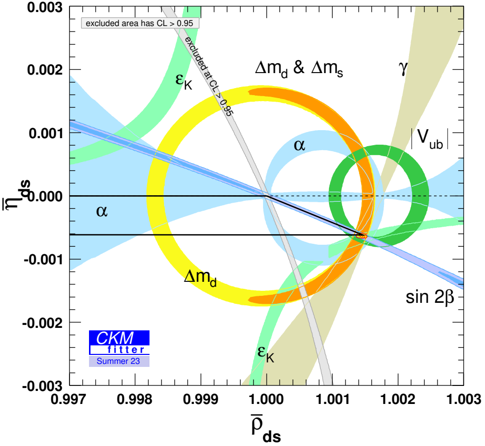
β_s easily visualized

$$\bar{\rho}_s = -0.00835^{+0.00027}_{-0.00044}$$

$$\bar{\eta}_s = -0.01896^{+0.00035}_{-0.00026}$$

68% C.L. intervals

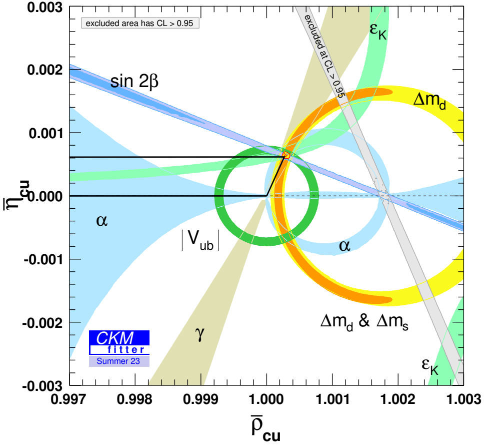
Other triangles, II



$$\bar{\rho}_{ds} + i\bar{\eta}_{ds} = -\frac{V_{ud}V_{us}^*}{V_{cd}V_{cs}^*}$$

$$(\lambda, \lambda, \lambda^5)$$

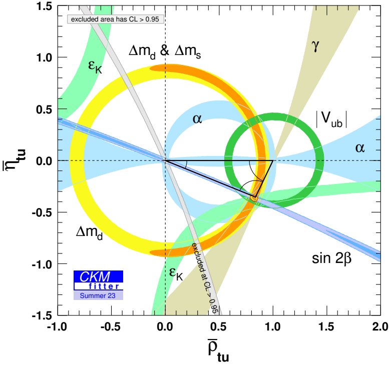
Other triangles, III



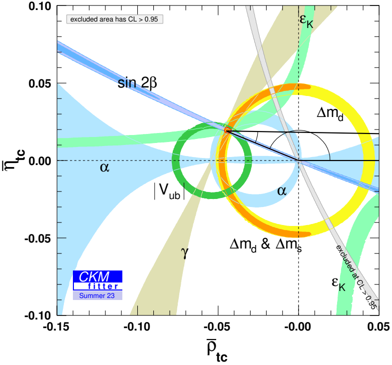
$$\bar{\rho}_{cu} + i\bar{\eta}_{cu} = -\frac{V_{cd}V_{ud}^*}{V_{cs}V_{us}^*}$$

$$(\lambda, \lambda, \lambda^5)$$

Other triangles, IV

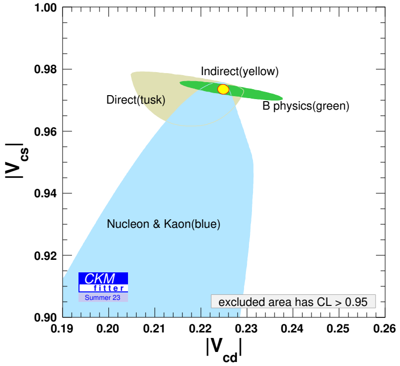


$$\bar{\rho}_{tu} + i\bar{\eta}_{tu} = -\frac{V_{td}V_{ud}^*}{V_{ts}V_{us}^*}$$
$$(\lambda^3, \lambda^3, \lambda^3)$$

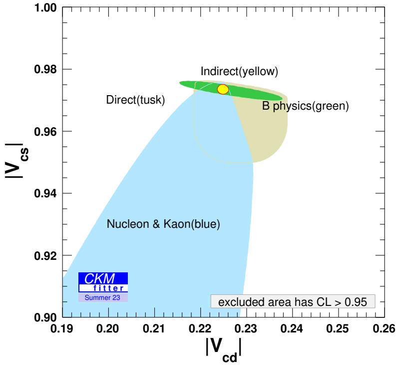


$$\bar{\rho}_{tc} + i\bar{\eta}_{tc} = -\frac{V_{td}V_{cd}^*}{V_{ts}V_{cs}^*}$$
$$(\lambda^4, \lambda^2, \lambda^2)$$

Progress in $|V_{cd}|$ and $|V_{cs}|$ plane



Leptonic

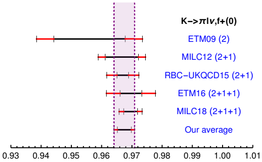


Semi-leptonic

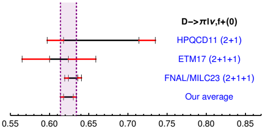
*CKM*fitter Lattice inputs, I: SL form factors

Theo. inputs: published Lattice papers, **with error budgets**, different sources of syst. uncertainty are **combined linearly**, using FLAG reports as a guide to sort results

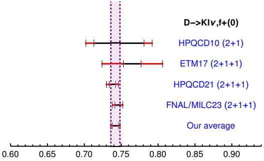
$f_+^{K\to\pi}(0)$



$f_+^{D\to\pi}(0)$



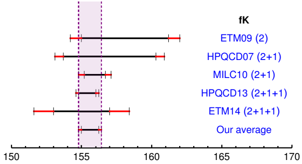
$f_+^{D\to K}(0)$

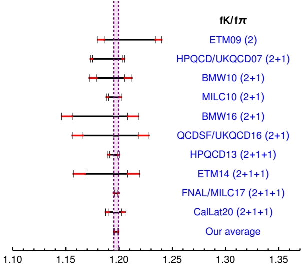


Educated *R*fit average; **black**: theoretical uncs., **red**: statistical uncs.

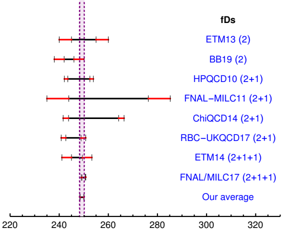
*CKM*fitter Lattice inputs, II: decay constants

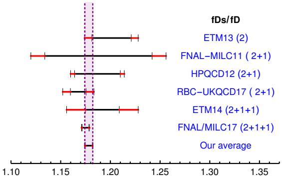
Light mesons



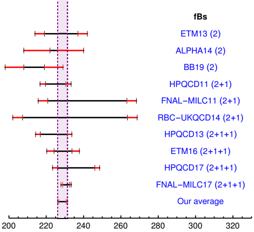


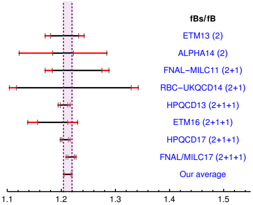
Charmed mesons





Beauty mesons

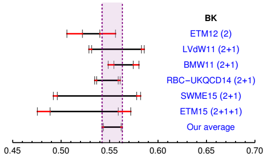




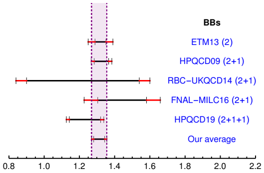
Educated *R*fit average; **black**: theoretical uncs., **red**: statistical uncs.

*CKM*fitter Lattice inputs, III: bag parameters

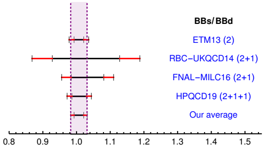
$B_K^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV})$



$\hat{B}_{B_s}$



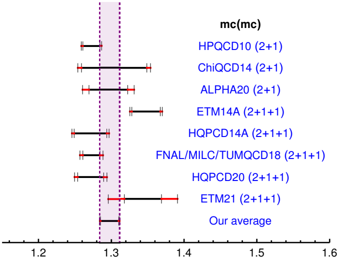
$\hat{B}_{B_s}/\hat{B}_{B_d}$



Educated *R*fit average; **black**: theoretical uncs., **red**: statistical uncs.

*CKM*fitter Lattice inputs, IV: light quark masses

$\overline{m}_c(\overline{m}_c)$



α angle

→ Review of the topic: [Charles, Deschamps, Descotes-Genon, Niess '17]
→ Isospin triangular relations are well satisfied
→ $\pi\pi$: α exhibits a 8 mirror solution