$\mathcal{CP}$ Violation and the CKM matrix

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10th international workshop on the CKM Unitarity Triangle

On behalf of the ***CKM*fitter** Collaboration

Outline

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Flavor transitions in the quark sector

$$\mathcal{L}_{SM} \sim (F_{\mu\nu})^2 + \bar{\psi} \not{D} \psi$$

Gauge couplings to fermions

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

Short-range *weak* interactions
Higgs self-interaction

$$+ \mathbf{Y} H \bar{\psi} \psi$$

Structure of flavor:
Spectrum of fermion masses
CKM matrix

$\rightarrow$ Flavor transitions pattern is likely to change in presence of NP

$\rightarrow$ **Goal here is to test the SM, and possibly point out tensions**

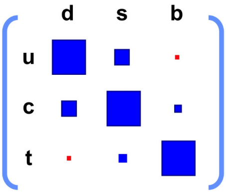
The CKM matrix

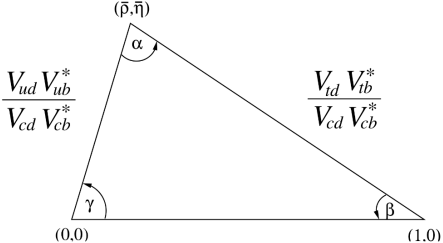
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

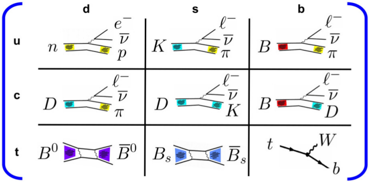


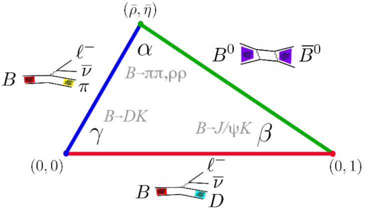


$$\frac{|V_{us}|}{(|V_{ud}|^2+|V_{us}|^2)^{1/2}} = \lambda\,, \quad \frac{|V_{cb}|}{(|V_{ud}|^2+|V_{us}|^2)^{1/2}} = A\lambda^2\,, \quad -\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}} = \bar{\rho} + i\bar{\eta}$$

Measuring the CKM matrix

V =





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

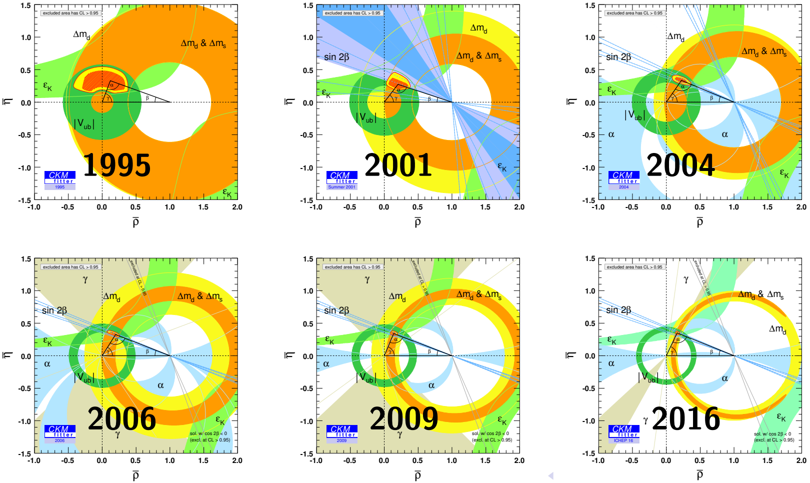
$\rightarrow$ Need to deal with **hadronic effects** inherent to the quark sector

Meson-mixing	$B_{(s)}\overline{B}_{(s)}$, $K\overline{K}$: bag-parameters $\widehat{B}_{B_s}$, $\widehat{B}_{B_s}/\widehat{B}_{B_d}$, $\widehat{B}_K$
(semi-)leptonic decays	$\pi \rightarrow \ell\nu$, $K \rightarrow \pi\ell\nu$, etc.: decay constants, form factors Ex.: f_π, $f_+^{K\rightarrow\pi}(0)$

$\rightarrow$ Lattice QCD: extractions of non-pert. parameters;
dominated by **systematic uncertainties**

Progress over the years

→ 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

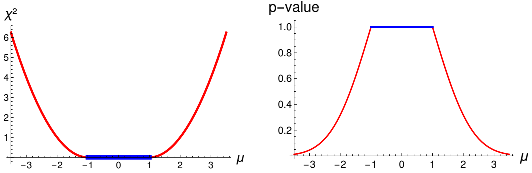
- ***CKM*fitter**: Frequentist statistics based on a χ^2 analysis
- χ^2_{min}: **goodness-of-fit** under SM (or NP), **estimators** for V_{CKM}
- $\Delta\chi^2$ (χ^2-distributed): **Confidence Level** (CL) intervals
- *Range* fit scheme (*R*fit) incorporates **theoretical uncertainties**
- Theo. inputs: published Lattice papers, **with error budgets**, different sources of syst. uncertainty are **combined linearly**, using FLAG reports as a guide to sort results

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

CKM	Process	Observables			Theoretical inputs		
$\|V_{ud}\|$	$0^+ \to 0^+ \beta$	$\|V_{ud}\|_{\text{nucl}}$	=	$0.97420 \pm 0 \pm 0.00021$	Nuclear matrix elements		
$\|V_{us}\|$	$K \to \pi\ell\nu$	$\|V_{us}\|_{\text{SL}} f_+^{K\to\pi}(0)$	=	0.2165 ± 0.0004	$f_+^{K\to\pi}(0)$	=	$0.9681 \pm 0.0014 \pm 0.0022$
	$K \to e\nu$	$\mathcal{B}(K \to e\nu)$	=	$(1.582 \pm 0.007) \cdot 10^{-5}$	f_K	=	$155.6 \pm 0.2 \pm 0.6$ MeV
	$K \to \mu\nu$	$\mathcal{B}(K \to \mu\nu)$	=	0.6356 ± 0.0011			
	$\tau \to K\nu$	$\mathcal{B}(\tau \to K\nu)$	=	$(0.6960 \pm 0.0096) \cdot 10^{-2}$			
$\frac{\|V_{us}\|}{\|V_{ud}\|}$	$K \to \mu\nu / \pi \to \mu\nu$	$\frac{\mathcal{B}(K \to \mu\nu)}{\mathcal{B}(\pi \to \mu\nu)}$	=	1.3367 ± 0.0029	f_K/f_π	=	$1.1959 \pm 0.0007 \pm 0.0029$
	$\tau \to K\nu / \tau \to \pi\nu$	$\frac{\mathcal{B}(\tau \to K\nu)}{\mathcal{B}(\tau \to \pi\nu)}$	=	$(6.438 \pm 0.094) \cdot 10^{-2}$			
$\|V_{cd}\|$	νN	$\|V_{cd}\|_{\text{not lattice}}$	=	0.230 ± 0.011			
	$D \to \mu\nu$	$\mathcal{B}(D \to \mu\nu)$	=	$(3.74 \pm 0.17) \cdot 10^{-4}$	f_{D_s}/f_D	=	$1.175 \pm 0.001 \pm 0.004$
	$D \to \pi\ell\nu$	$\|V_{cd}\| f_+^{D\to\pi}(0)$	=	0.1426 ± 0.0019	$f_+^{D\to\pi}(0)$	=	$0.621 \pm 0.016 \pm 0.012$
$\|V_{cs}\|$	$W \to c\bar{s}$	$\|V_{cs}\|_{\text{not lattice}}$	=	$0.94^{+0.32}_{-0.26} \pm 0.13$			
	$D_s \to \tau\nu$	$\mathcal{B}(D_s \to \tau\nu)$	=	$(5.55 \pm 0.24) \cdot 10^{-2}$	f_{D_s}	=	$247.8 \pm 0.3 \pm 2.0$ MeV
	$D_s \to \mu\nu$	$\mathcal{B}(D_s \to \mu\nu)$	=	$(5.39 \pm 0.16) \cdot 10^{-3}$			
	$D \to K\ell\nu$	$\|V_{cs}\| f_+^{D\to K}(0)$	=	0.7226 ± 0.0034	$f_+^{D\to K}(0)$	=	$0.741 \pm 0.010 \pm 0.012$
$\|V_{ub}\|$	semileptonic B	$\|V_{ub}\|_{\text{SL}}$	=	$(3.98 \pm 0.08 \pm 0.22) \cdot 10^{-3}$	form factors, shape functions		
	$B \to \tau\nu$	$\mathcal{B}(B \to \tau\nu)$	=	$(1.08 \pm 0.21) \cdot 10^{-4}$	f_{B_s}/f_B	=	$1.205 \pm 0.004 \pm 0.006$
$\|V_{cb}\|$	semileptonic B	$\|V_{cb}\|_{\text{SL}}$	=	$(41.8 \pm 0.4 \pm 0.6) \cdot 10^{-3}$	form factors, OPE matrix elements		
$\|V_{ub}/V_{cb}\|$	semileptonic Λ_b	$\frac{\mathcal{B}(\Lambda_p \to p\mu^-\bar{\nu})_{q^2>15}}{\mathcal{B}(\Lambda_p \to \Lambda_c\mu^-\bar{\nu})_{q^2>7}}$	=	$(0.947 \pm 0.081) \cdot 10^{-2}$	$\frac{\zeta(\Lambda_p \to p\mu^-\bar{\nu})_{q^2>15}}{\zeta(\Lambda_p \to \Lambda_c\mu^-\bar{\nu})_{q^2>7}}$	=	$1.471 \pm 0.096 \pm 0.290$
α	$B \to \pi\pi,\ \rho\pi,\ \rho\rho$	branching ratios, CP asymmetries			isospin symmetry		
β	$B \to (c\bar{c})K$	$\sin(2\beta)_{[c\bar{c}]}$	=	0.699 ± 0.017	subleading penguins neglected		
$\cos(2\beta)$	$B^0 \to D^{(*)}h^0$	$\cos(2\beta)$	=	0.91 ± 0.25			
γ	$B \to D^{(*)}K^{(*)}$	inputs for the 3 methods			GGSZ, GLW, ADS methods		
ϕ_s	$B_s \to J/\psi(KK, \pi\pi)$	$(\phi_s)_{b\to c\bar{c}s}$	=	-0.021 ± 0.031			
$V_{tq}^* V_{tq'}$	Δm_d	Δm_d	=	0.5065 ± 0.0019 ps^{-1}	$\hat{B}_{B_s}/\hat{B}_{B_d}$	=	$1.007 \pm 0.013 \pm 0.014$
	Δm_s	Δm_s	=	17.757 ± 0.021 ps^{-1}	$\hat{B}_{B_s}$	=	$1.327 \pm 0.016 \pm 0.030$
	$B_s \to \mu\mu$	$\mathcal{B}(B_s \to \mu\mu)$	=	$(2.8^{+0.7}_{-0.6}) \cdot 10^{-9}[\times(1-0.063)]$	f_{B_s}	=	$226.0 \pm 1.3 \pm 2.0$ MeV
$V_{td}^* V_{ts}$ and $V_{cd}^* V_{cs}$	ε_K	$\|\varepsilon_K\|$	=	$(2.228 \pm 0.011) \cdot 10^{-3}$	$\hat{B}_K$	=	$0.7567 \pm 0.0021 \pm 0.0123$
					κ_ε	=	$0.940 \pm 0.013 \pm 0.023$

black: no change; **blue**: slight change; **red**: update since ICHEP'16

(colors **do not** reflect the impact of the exp./theo. input!)

Overall results of the 2018 update

Global fit remains excellent:

ICHEP'16: p-value $\sim 21\%$ $(1.3\sigma) \rightarrow$ **CKM'18**: p-value $\sim 51\%$ (0.7σ)

$$A = 0.8403\,^{+0.0056}_{-0.0201}\ (2\%\ \text{unc.})$$

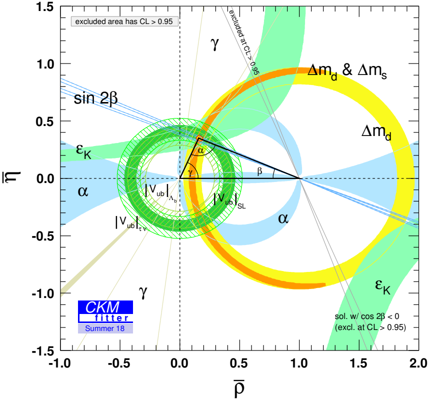
$$\lambda = 0.224747\,^{+0.000254}_{-0.000059}\ (0.07\%\ \text{unc.})$$

$$\bar{\rho} = 0.1577\,^{+0.0096}_{-0.0074}\ (5\%\ \text{unc.})$$

$$\bar{\eta} = 0.3493\,^{+0.0095}_{-0.0071}\ (2\%\ \text{unc.})$$

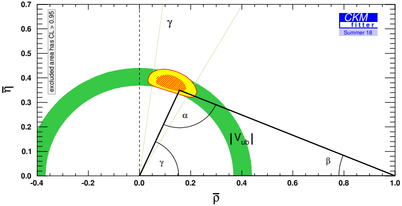
68% C.L. intervals

B_d Unitary Triangle:

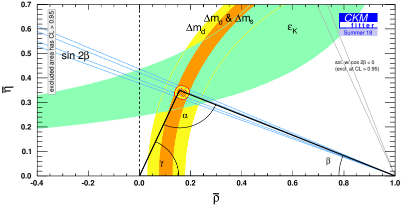


Consistency among classes of observables

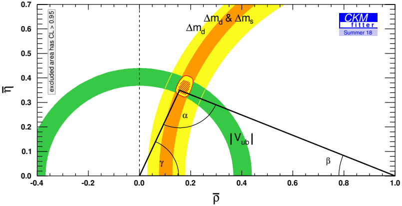
tree level



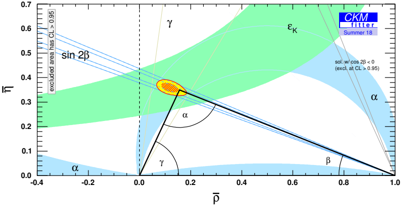
loop-induced



$\mathcal{CP}$−conserving



$\mathcal{CP}$−violating



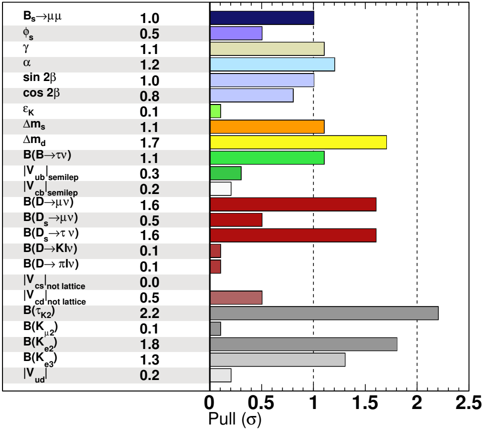
Pulls: individual tensions

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

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

→ Here, correlations are expected

→ No sector (e.g., K, D, B) particularly in tension



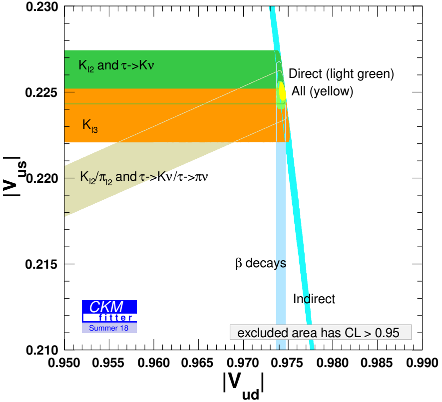
First two generations: $|V_{ud}|$ and $|V_{us}|$ plane

→ $|V_{ud}|$ from nuclear transitions

→ K, π, τ decays

→ **Good agreement** among different classes of inputs

→ Pull in $|V_{us}| f_+^{K\to\pi}(0)$ has decreased from 2.3σ to 1.3σ



V_{ud}: ±0.007% [ind.], ±0.004% [comb.]

V_{us}: ±0.3% [ind.], ±0.07% [comb.]

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

$\rightarrow$ $\mathcal{B}(D_s \rightarrow \mu\nu)$:
average of HFLAV and BESIII

$\rightarrow$ $f_+^{D\rightarrow\pi}(0)$: syst. $4\times$ smaller

'16, $f_+^{D\rightarrow\pi}(0) = 0.666 \pm 0.020 \pm 0.048$

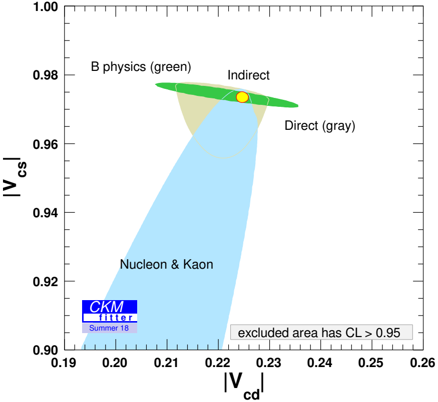
'18, $f_+^{D\rightarrow\pi}(0) = 0.621 \pm 0.016 \pm 0.012$

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

'16, $f_+^{D\rightarrow K}(0) = 0.747 \pm 0.011 \pm 0.034$

'18, $f_+^{D\rightarrow K}(0) = 0.741 \pm 0.010 \pm 0.012$

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



V_{cd}: $\pm 0.07\%$ [ind.], $\pm 0.07\%$ [comb.]

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

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

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

$\rightarrow$ Exclusive $|V_{cb}|$:

- Belle studies show tensions among **CLN**/**BGL** parameterizations
- Belle $B \to D^* \ell \nu$ combined (tagged and untagged), **BGL**:
  $|V_{cb}|_{B\to D^*} = (42.4 \pm 0.7(\mathrm{exp.}) \pm 1.1(\mathrm{LQCD}) \pm 0.2(\mathrm{EM})) \times 10^{-3}$

  [Fermilab-MILC'14'14, Grinstein+'17]

- Belle and Babar $B \to D \ell \nu$ combined, **BGL**:
  $|V_{cb}|_{B\to D} = (40.5 \pm 0.8(\mathrm{exp.}) \pm 0.6(\mathrm{LQCD}) \pm 0.2(\mathrm{EM})) \times 10^{-3}$

  [Fermilab-MILC'15, Bigi+'16]

$\Rightarrow |V_{cb}|_{excl.} = (41.2 \pm 0.6(\mathrm{exp.}) \pm 0.9(\mathrm{LQCD}) \pm 0.2(\mathrm{EM})) \times 10^{-3}$

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

→ Inclusive extraction: $|V_{cb}|_{incl.} = (42.2 \pm 0.4 \pm 0.6) \times 10^{-3}$ (m_b^{kin})

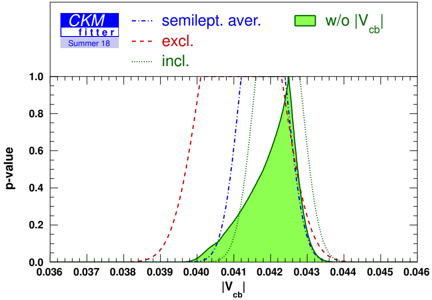
[Gambino+'07, HFLAV]

→ Our inputs for excl. and incl. are **compatible**

→ Average about 1σ **higher**:

'16, $|V_{cb}| = (41.0 \pm 0.3 \pm 0.7) \times 10^{-3}$

'18, $|V_{cb}| = (41.8 \pm 0.4 \pm 0.6) \times 10^{-3}$



V_{cb}: $\pm 1.7\%$ [ind.], $\pm 1.8\%$ [comb.]

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

→ $B \to \pi \ell \nu$: Simultaneous fit to Lattice and differential rates data:

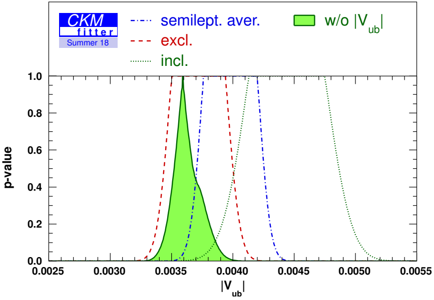
$|V_{ub}|_{excl.} = (3.72 \pm 0.09 \pm 0.22) \times 10^{-3}$ [Fermilab-MILC'15]

→ BLNP: $|V_{ub}|_{incl.} = (4.44 \pm 0.17 \pm 0.31) \times 10^{-3}$ [Neubert'05, HFLAV]

→ Average did not change:

$|V_{ub}|_{\mathrm{SL}} = (3.98 \pm 0.08 \pm 0.22) \times 10^{-3}$

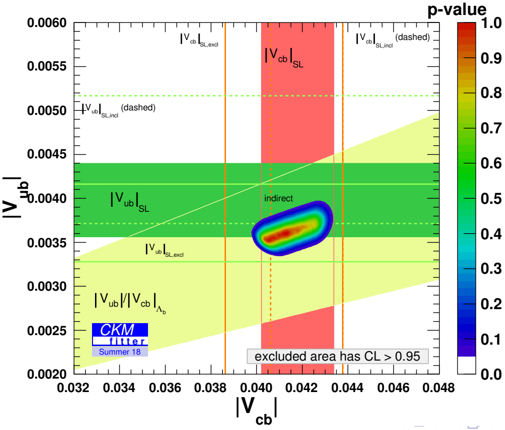
→ $|V_{ub}|_{excl.}$ **is still preferred** by the indirect extraction



V_{ub} $\pm 3.9\%$ [ind.] $\pm 2.0\%$ [comb.]

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

- $\rightarrow$ LHCb: measurement of $\frac{\mathcal{B}(\Lambda_b^0 \to p\mu\bar{\nu})_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu\bar{\nu})_{q^2>7\,\mathrm{GeV}^2}}$
- $\rightarrow$ Our inputs for $|V_{cb}|_{excl.}$ and $|V_{cb}|_{incl.}$ are compatible
- $\rightarrow$ $|V_{ub}|_{excl.}$ is still preferred by the indirect extraction



α angle

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

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

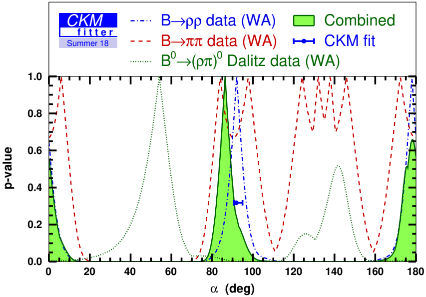
[$B \to \pi\pi$ update: Belle, LHCb] [Detailed discussion: Charles, Deschamps, Descotes-G., Niess '17]

As in previous editions:

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

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

$\rightarrow$ $B \to \rho\pi$ is in tension: possible origin discussed in [Charles+'17]

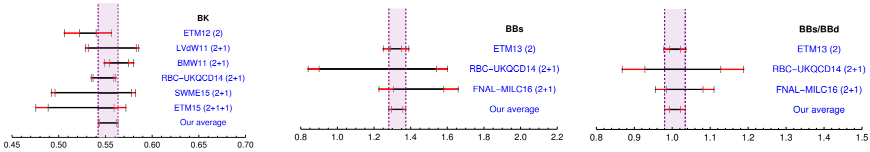


CKM'14 edition	ICHEP'16 edition	CKM'18 edition
α [dir.] $(87.7^{+3.5}_{-3.3})^o \cup (-1.1^{+3.8}_{-4.0})^o$	α [dir.] $(-2.2^{+3.7}_{-4.9})^o \cup (88.8^{+2.3}_{-2.3})^o$	α [dir.] $(86.4^{+4.5}_{-4.3})^o \cup (-1.8^{+4.3}_{-5.1})^o$
α [indir.] $(91.5^{+4.2}_{-1.3})^o$	α [indir.] $(92.1^{+1.5}_{-1.1})^o$	α [indir.] $(91.9^{+3.0}_{-1.2})^o$
α [comb.] $(91.0^{+2.3}_{-1.1})^o$	α [comb.] $(92.0^{+1.3}_{-1.1})^o$	α [comb.] $(91.6^{+1.7}_{-1.1})^o$

$|\Delta F| = 2$ transitions ($F = S, B$)

→ Observables: Δm_s, Δm_d, ϵ_K (*future prospect:* include ϵ'/ϵ)
→ Experimental accuracy below the percent level
→ Accuracy for the Bag Parameters around a few percent

$B_K^{\overline{\rm MS}}$ (2 GeV) $\hat{B}_{B_s}$ $\hat{B}_{B_s}/\hat{B}_{B_d}$



Educated *R*fit average; **black**: theoretical uncs., **red**: statistical uncs.
rescaling of uncertainties and averages follow our *R*fit scheme

Indirect extractions:

$$\hat{B}_K = 0.83\,^{+0.13}_{-0.19}(19\%),\ \frac{B_{B_s}}{B_{B_d}} = 1.143\,^{+0.056}_{-0.069}(5\%),\ B_{B_s} = 1.287\,^{+0.077}_{-0.072}(6\%)$$

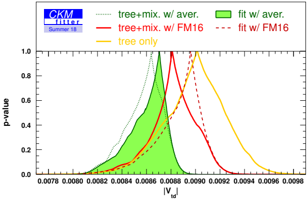
→ Fit results consistent, but mostly not competitive w/ LQCD

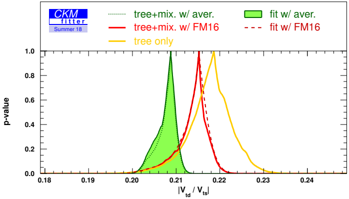
$|V_{td}|$, $|V_{ts}|$ extractions

Aver., CKM'18: $\hat{B}_{B_s} = 1.327(16)(30)$, $\hat{B}_{B_s}/\hat{B}_{B_d} = 1.007(13)(14)$

FNAL-MILC'16: $\hat{B}_{B_s} = 1.443(78)(138)$, $\hat{B}_{B_s}/\hat{B}_{B_d} = 1.033(29)(48)$

w.r.t. tree only,
p-v. $\in [0.4, 0.9]$





($|V_{ts}|$ extractions are similar and not shown)

$f_{B_q}\sqrt{\hat{B}^{(1)}_{B_q}}$ would lead to more accurate results for the "FM16" curves,
talk by A. El-Khadra

No clear tension among our different extractions

Rare B decays

- → SM under good theoretical control, w/ suppressed ratios
- → LHCb results w/ part of Run II, no official combination w/ CMS
- → Same values for branching ratios as for ICHEP'16

→ Predictions for rare B decays:

$\mathcal{B}(B_d \to e^+e^-)\ [10^{-15}] = 2.238\,^{+0.111}_{-0.097}$

$\mathcal{B}(B_d \to \mu^+\mu^-)\ [10^{-11}] = 9.54\,^{+0.46}_{-0.46}$

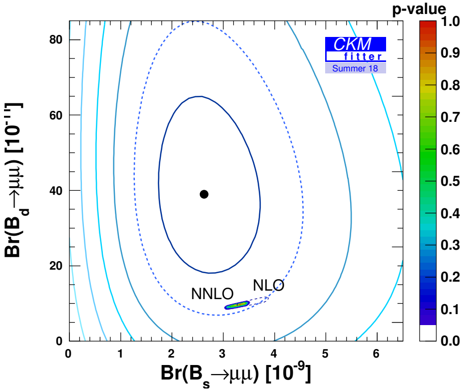
$\mathcal{B}(B_d \to \tau^+\tau^-)\ [10^{-8}] = 2.005\,^{+0.092}_{-0.095}$

$\mathcal{B}(B_s \to e^+e^-)\ [10^{-14}] = 7.63\,^{+0.34}_{-0.41}$

$\mathcal{B}(B_s \to \mu^+\mu^-)\ [10^{-9}]\ \text{(ind.)} = 3.25\,^{+0.15}_{-0.14}$

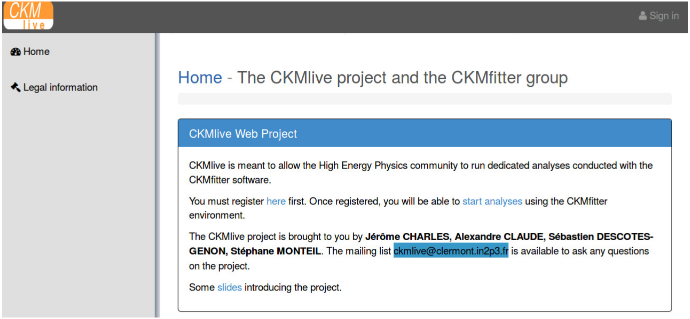
$\mathcal{B}(B_s \to \tau^+\tau^-)\ [10^{-7}] = 6.89\,^{+0.35}_{-0.29}$

[For $s \to d\nu\bar{\nu}$ rare K decays: *CKM*fitter Webpage]



Advertisement: CKMlive web interface

- Run dedicated CKM fits from ***CKM*fitter** 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, 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*

$\rightarrow$ Exciting future prospects for Belle II, LHC, NA62,...

*CKM*fitter Collaboration

MORE DETAILS @ CKMfitter

Jérôme Charles, Theory
Olivier Deschamps, LHCb
Sébastien Descotes-Genon, Theory
Heiko Lacker, ATLAS/BABAR
Stéphane Monteil, LHCb
José Ocariz, ATLAS/BABAR
Jean Orloff, Theory
Alejandro Perez, BABAR
Luis Pesantez, Belle/Belle II
Wenbin Qian, LHCb
Vincent Tisserand, LHCb/BABAR
Karim Trabelsi, Belle/Belle II
Philip Urquijo, Belle/Belle II
Luiz Vale Silva, Theory

THANKS!


CKM fitter

CKMFITTER

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Plots & Results
Specific Studies

Talks & Writeups
Publications

CKMfitter Group

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The CKMfitter group provides:

- A global analysis of measurements determining the CKM matrix parameters in the framework of the Standard Model and some of its extensions.
- Graphical and numerical constraints on CKM matrix elements, predictions on rare K and B meson decays, theoretical parameters, etc.
- The statistical treatment is based on Frequentist statistics and **Rfit** (Range fit) for the theoretical uncertainties.

Publications

Isospin analysis of charmless B-meson decays
arXiv:1705.02981 [hep-ph]

Disentangling weak and strong interactions in $B \to K^*(\to K\pi)\pi$ Dalitz-plot analyses
arXiv:1704.01596 [hep-ph]

Modelling theoretical uncertainties in phenomenological analyses for particle physics
arXiv:1611.04768 [hep-ph]

Tools

Perform your own flavour analyses online with CKMlive

Plots & Results

Preliminary results as of ICHEP 16
(updated Dec 2016)

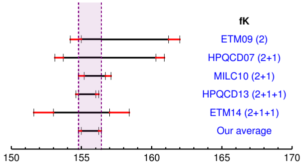
Specific Studies

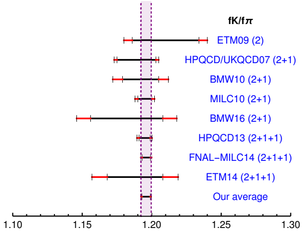
Prospective studies on $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$ rare kaon decays
(updated August 2015)

Backup

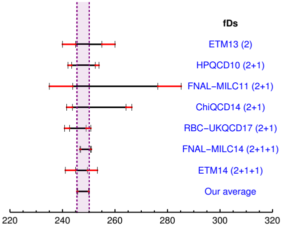
Lattice inputs, I: decay constants

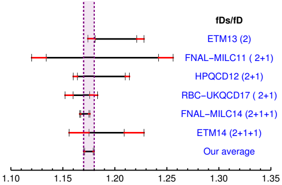
Light mesons



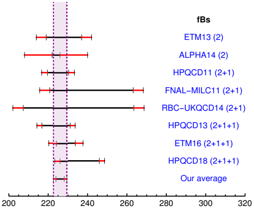


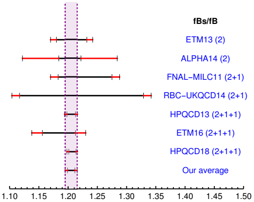
Charmed mesons





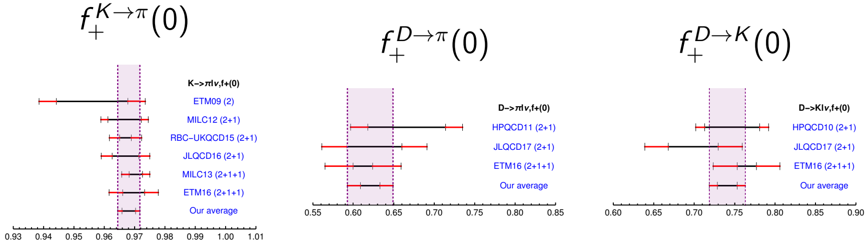
Beauty mesons





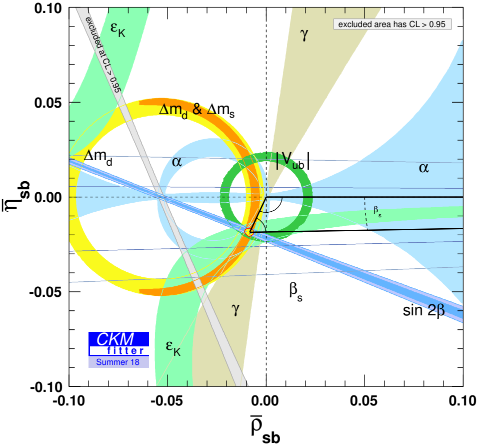
Educated *R*fit average; **black**: theoretical uncs., **red**: statistical uncs.

Lattice inputs, II: semileptonic form factors



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

Other triangles, I



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

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

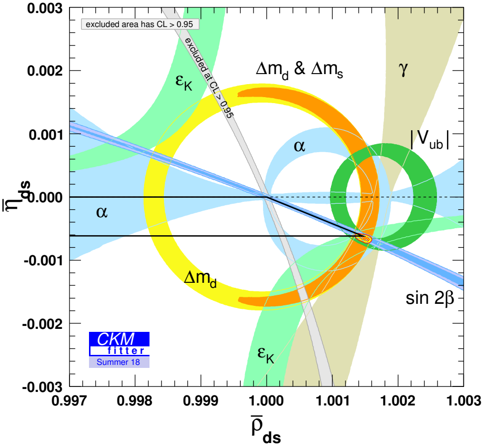
β_s easily visualized

$$\bar{\rho}_s = -0.00834\,^{+0.00035}_{-0.00056}$$

$$\bar{\eta}_s = -0.01861\,^{+0.00039}_{-0.00048}$$

68% C.L. intervals

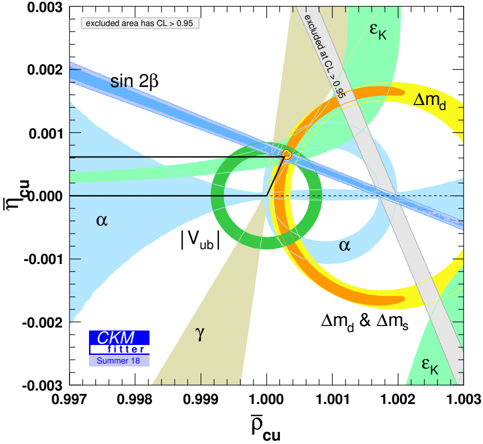
Other triangles, II



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

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

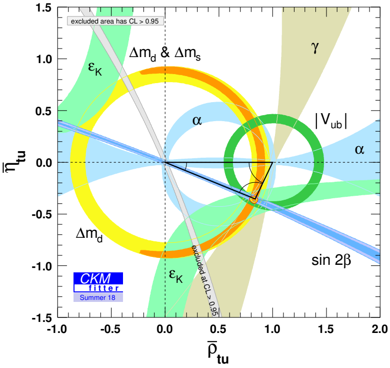
Other triangles, III



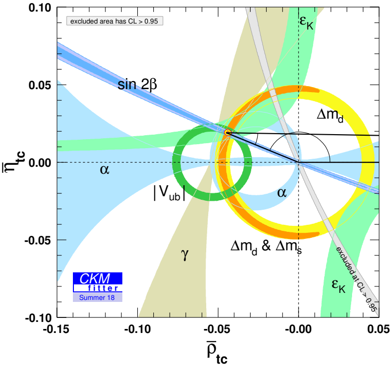
$$\bar{\rho}_{cu} + i\bar{\eta}_{cu} = -\frac{V_{cd}V_{ud}^*}{V_{cs}V_{us}^*}$$

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

Other triangles, IV

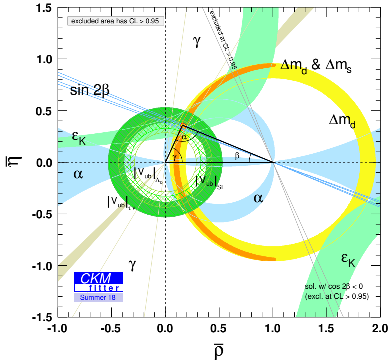


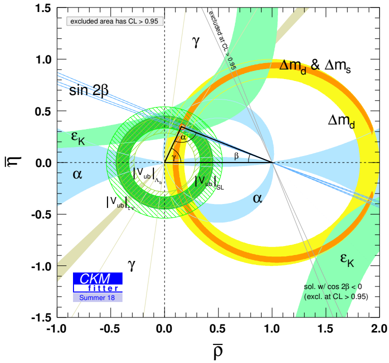
$$\bar{\rho}_{tu} + i\bar{\eta}_{tu} = -\frac{V_{td}V_{ud}^*}{V_{ts}V_{us}^*}$$
$$(\lambda^3, \lambda^3, \lambda^3)$$



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

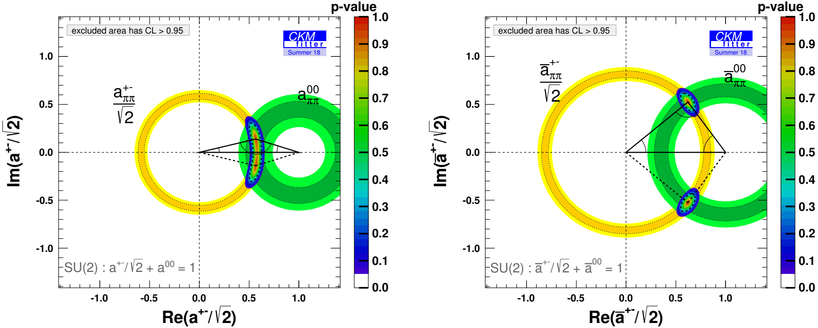
Inclusive vs. exclusive





α angle

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



Other angles

→ Slight change in $\sin(2\beta)$, following LHCb'17 results [LHCb'17, HFLAV]

→ **First evidence for** $\cos(2\beta) > 0$ (@ 3.7σ) [BaBar, Belle: arXiv:1804.06152]

Time-dependent Dalitz plot $B^0 \to [K_S^0 \pi^+ \pi^-]_{D^{(*)}} h^0$, $h^0 \in \{\pi^0, \eta, \omega\}$

Excludes trigonometric ambiguities in β on its own

Pull for $\cos(2\beta)_{exp}$ of 0.8

→ γ: same as for ICHEP'16 (LHCb update not included)

$\gamma[^{\rm o}] = 72.1^{+5.4}_{-5.7}$ [dir.], $\gamma[^{\rm o}] = 65.64^{+0.97}_{-3.42}$ [ind.], $\gamma[^{\rm o}] = 65.81^{+0.99}_{-1.66}$ [comb.]

→ $B_s \to J/\psi(KK, \pi\pi) \Rightarrow \phi_s^{c\bar{c}s}$: several updates from LHCb

from $\phi_s^{c\bar{c}s} = -0.030 \pm 0.033$, to $\phi_s^{c\bar{c}s} = -0.021 \pm 0.031$ [HFLAV]

Tests of unitarity

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2-1 = -0.00082^{+0.00085}_{-0.00014}(\mathrm{CL} \equiv 1\ \sigma)$$
$$|V_{cd}|^2+|V_{cs}|^2+|V_{cb}|^2-1 = -0.0007^{+0.0026}_{-0.0117}(\mathrm{CL} \equiv 1\ \sigma)$$

(V_{tb} is not determined directly with a competitive accuracy)

Tree level only fit

Global fit of observables dominated by tree level in the SM

p-value $\sim$ 43% (0.8σ)

$$A = 0.8396\,^{+0.0080}_{-0.0298}\,, \quad \lambda = 0.224756\,^{+0.000163}_{-0.000065}$$
$$\bar{\rho} = 0.123\,^{+0.023}_{-0.023}\,, \quad \bar{\eta} = 0.375\,^{+0.022}_{-0.017}$$

68% C.L. intervals

Comments on some specific inputs

$\rightarrow$ Different averaging procedure, hadron collider result:

$\alpha_s = 0.1181 \pm 0 \pm 0.011$ [PDG]

$\rightarrow$ m_{top}^{pole}: in lack of a global average from more recent data, we consider the average by ATLAS, CDF, CMS and D0

[hep-ex:1403.4427, iJES: in situ jet energy scale]

$$m_{top}^{pole} = 173.34 \pm 0.36(\text{stat} + \text{iJES}) \pm 0.67(\text{syst}) \text{ GeV}$$

$\rightarrow$ Other (perturbative) theo. inputs:

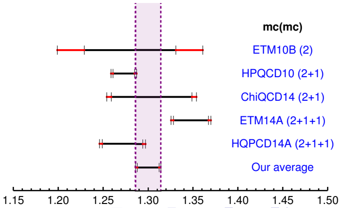
$\eta_{\text{NLO}}^{K,tt} = 0.5765 \pm 0 \pm 0.0065$ [Buras+'90, Herrlich+'94'96]

$\eta_{\text{NNLO}}^{K,ct} = 0.497 \pm 0 \pm 0.047$ [Brod+'10'12]

$\eta_{\text{NNLO}}^{K,cc} = 1.87 \pm 0 \pm 0.76$ [Brod+'10'12]

$\eta_{\text{NLO}}^{B} = 0.5510 \pm 0 \pm 0.0022$ [Buchalla+'96]

$\overline{m}_c(m_c)$



Averaging lattice results

Collecting lattice results

- follow FLAG to exclude limited results
- supplement with more recent published results with error budget

Splitting error estimates into stat and syst

- Stat : essentially related to size of gauge conf
- Syst : fermion action, $a \to 0$, $L \to \infty$, mass extrapolations...

added linearly using error budget

"Educated Rfit" used to combine the results

- no correlations assumed
- product of (Gaussian + Rfit) likelihoods for central value
- product of Gaussian (stat) likelihoods for stat uncertainty
- syst uncertainty of the combination = most precise method
  - the present state of art cannot allow us to reach a better theoretical accuracy than the best of all estimates
  - best estimate should not be penalized by less precise methods