Current and expected precision in the determination of the CKM triangle

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Flavor in the quark sector

(Gauge couplings to fermions)

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

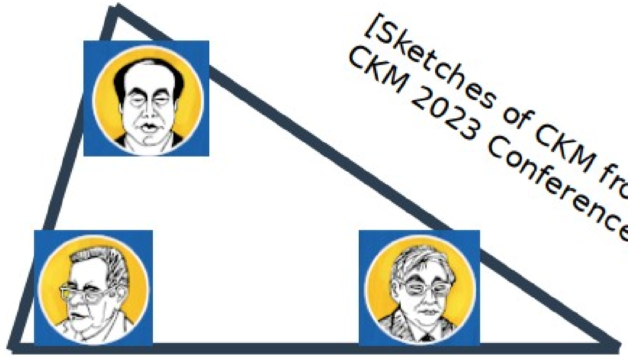
(Higgs self-interaction)

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

(short-range weak interactions)

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

(spectrum of fermion masses, CKM matrix)

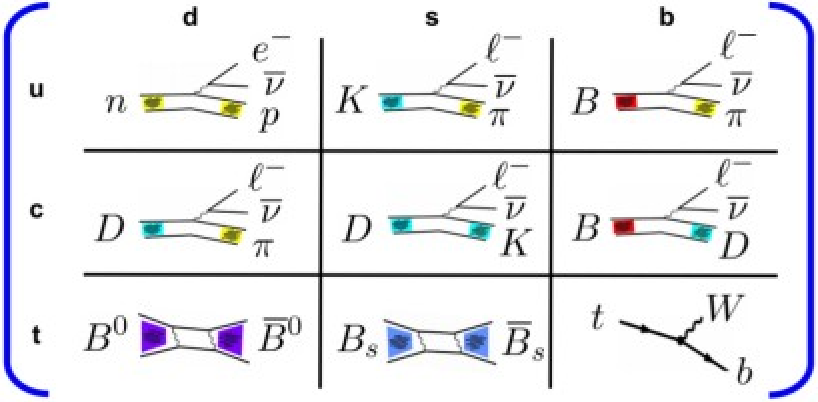


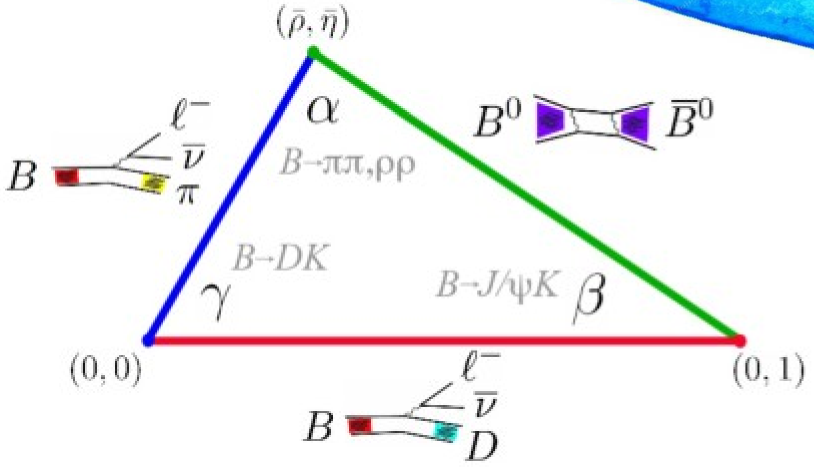
[Sketches of CKM from CKM 2023 Conference]

- Goal is **testing the SM**, and **possibly point out tensions**
- Many flavour observables enjoy the status of precision physics, thanks to progress in different fronts (e.g. QCD inputs)
- Flavor transitions pattern is likely to change in the presence of NP

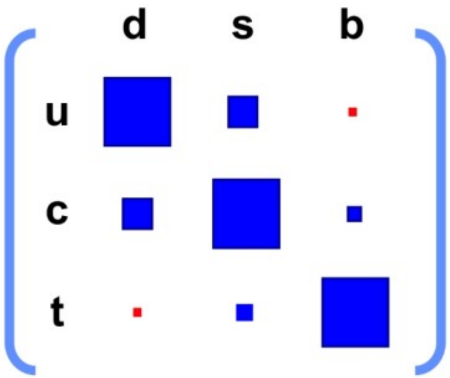
Measuring the CKM matrix

V =





- *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



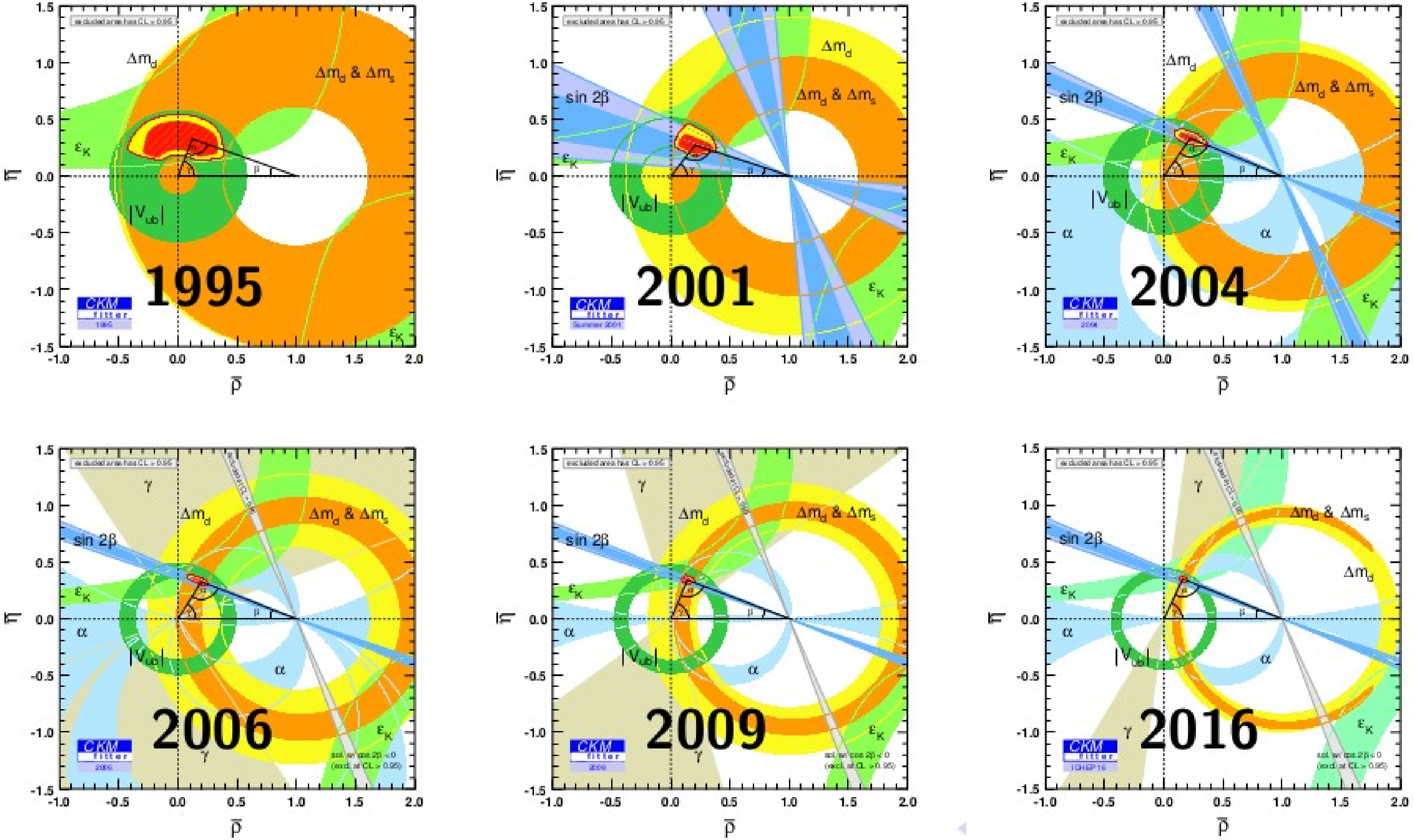
Theo. inputs: hadronic effects

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

$\rightarrow$ 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

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

Progress over the years



Inputs

[CKMfitter]

$$\mathcal{L} \overset{Rfit}{=} \mathcal{L}_{stat} \times \mathcal{L}_{theo}$$

$$\chi^2 = -2 \ln \mathcal{L}$$

$\mathcal{L}_{stat}$: exp. data

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

[LVS, 2405.08046]

CKM	Process	Observables				Non-perturbative theoretical inputs
$\lvert V_{ud}\rvert$	$0^+ \to 0^+\ \beta$	$\lvert V_{ud}\rvert_{\text{nucl}}$	=	$0.97373 \pm 0.00009 \pm 0.00053$	[14]	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 ± 0.00038	[38]	$f_+^{K\to\pi}(0) = 0.9675 \pm 0.0011 \pm 0.0023$
	$K \to e\nu_e$	$\mathcal{B}(K \to e\nu_e)$	=	$(1.582 \pm 0.007) \cdot 10^{-5}$	[39]	
	$K \to \mu\nu_\mu$	$\mathcal{B}(K \to \mu\nu_\mu)$	=	0.6356 ± 0.0011	[39]	$f_K = 155.57 \pm 0.17 \pm 0.57$ MeV
	$\tau \to K\nu_\tau$	$\mathcal{B}(\tau \to K\nu_\tau)$	=	$(0.6986 \pm 0.0085) \cdot 10^{-2}$	[19]	
$\lvert V_{us}/V_{ud}\rvert$	$K \to \mu\nu_\mu/\pi \to \mu\nu_\mu$	$\frac{\mathcal{B}(K\to\mu\nu_\mu)}{\mathcal{B}(\pi\to\mu\nu_\mu)}$	=	1.3367 ± 0.0028	[39]	$f_K/f_\pi = 1.1973 \pm 0.0007 \pm 0.0014$
	$\tau \to K\nu_\tau/\tau \to \pi\nu_\tau$	$\frac{\mathcal{B}(\tau\to K\nu_\tau)}{\mathcal{B}(\tau\to\pi\nu_\tau)}$	=	$(6.437 \pm 0.092) \cdot 10^{-2}$	[19]	
$\lvert V_{cd}\rvert$	νN	$\lvert V_{cd}\rvert_{\text{not lattice}}$	=	0.230 ± 0.011	[39]	
	$D \to \tau\nu_\tau$	$\mathcal{B}(D \to \tau\nu_\tau)$	=	$(1.20 \pm 0.27) \cdot 10^{-3}$	[19]	$f_{D_s}/f_D = 1.1782 \pm 0.0006 \pm 0.0033$
	$D \to \mu\nu_\mu$	$\mathcal{B}(D \to \mu\nu_\mu)$	=	$(3.77 \pm 0.17) \cdot 10^{-4}$	[19]	
	$D \to \pi\ell\nu_\ell$	$\lvert V_{cd}\rvert_{\text{SL}} f_+^{D\to\pi}(0)$	=	0.1426 ± 0.0018	[19]	$f_+^{D\to\pi}(0) = 0.624 \pm 0.004 \pm 0.006$
$\lvert V_{cs}\rvert$	$W \to c\bar{s}$	$\lvert V_{cs}\rvert_{\text{not lattice}}$	=	0.967 ± 0.011	[40]	
	$D_s \to \tau\nu_\tau$	$\mathcal{B}(D_s \to \tau\nu_\tau)$	=	$(5.32 \pm 0.10) \cdot 10^{-2}$	[18]	
	$D_s \to \mu\nu_\mu$	$\mathcal{B}(D_s \to \mu\nu_\mu)$	=	$(5.43 \pm 0.16) \cdot 10^{-3}$	[19]	$f_{D_s} = 249.23 \pm 0.27 \pm 0.65$ MeV
	$D \to K\ell\nu_\ell$	$\lvert V_{cs}\rvert_{\text{SL}} f_+^{D\to K}(0)$	=	0.7180 ± 0.0033	[19]	$f_+^{D\to K}(0) = 0.742 \pm 0.002 \pm 0.004$
$\lvert V_{ub}\rvert$	semileptonic B	$\lvert V_{ub}\rvert_{\text{SL}}$	=	$(3.86 \pm 0.07 \pm 0.12) \cdot 10^{-3}$	see text	form factors, shape functions
	$B \to \tau\nu_\tau$	$\mathcal{B}(B \to \tau\nu_\tau)$	=	$(1.09 \pm 0.24) \cdot 10^{-4}$	[19]	$f_{B_s}/f_B = 1.2118 \pm 0.0020 \pm 0.0058$
$\lvert V_{cb}\rvert$	semileptonic B	$\lvert V_{cb}\rvert_{\text{SL}}$	=	$(41.22 \pm 0.24 \pm 0.37) \cdot 10^{-3}$	see text	form factors, OPE matrix elements
$\lvert V_{ub}/V_{cb}\rvert$	semileptonic Λ_b	$\frac{\mathcal{B}(\Lambda_b\to p\mu\nu_\mu)_{q^2>15}}{\mathcal{B}(\Lambda_b\to\Lambda_c\mu\nu_\mu)_{q^2>7}}$	=	$(0.918 \pm 0.083) \cdot 10^{-2}$	[27]	$\frac{\zeta(\Lambda_b\to p\mu\nu_\mu)_{q^2>15}}{\zeta(\Lambda_b\to\Lambda_c\mu\nu_\mu)_{q^2>7}} = 1.471 \pm 0.096 \pm 0.290$
	semileptonic B_s	$\frac{\mathcal{B}(B_s\to K\mu\nu_\mu)_{q^2>7}}{\mathcal{B}(B_s\to D_s\mu\nu_\mu)}$	=	$(3.25 \pm 0.28) \cdot 10^{-3}$	[41]	$\frac{\zeta(B_s\to K\mu\nu_\mu)_{q^2>7}}{\zeta(B_s\to D_s\mu\nu_\mu)} = 0.363 \pm 0 \pm 0.065$
	inclusive	$\lvert V_{ub}/V_{cb}\rvert_{\text{incl}}$	=	$0.100 \pm 0.006 \pm 0.003$	[29]	
α	$B \to \pi\pi,\ \rho\pi,\ \rho\rho$	branching ratios, CP asymmetries			see text	isospin symmetry
β	$B \to (c\bar{c})K$	$\sin(2\beta)_{[c\bar{c}]}$	=	0.708 ± 0.011	[19]	subleading penguins neglected
γ	$B \to D^{(*)}K^{(*)}$	γ	=	$(65.9^{+3.3}_{-3.5})^{\text{o}}$	[19]	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	[19]	
$V_{tq}^* V_{tb}$	Δm_d	Δm_d	=	$0.5065 \pm 0.0019\ \text{ps}^{-1}$	[19]	$\hat{B}_{B_s}/\hat{B}_{B_d} = 1.007 \pm 0.010 \pm 0.014$
	Δm_s	Δm_s	=	$17.765 \pm 0.006\ \text{ps}^{-1}$	[42]	$\hat{B}_{B_s} = 1.313 \pm 0.012 \pm 0.030$
	$B_s \to \mu\mu$	$\mathcal{B}(B_s \to \mu\mu)$	=	$(3.45 \pm 0.29) \cdot 10^{-9}[\times(1-0.063)]$	[19]	$f_{B_s} = 228.75 \pm 0.69 \pm 1.87$ MeV
$V_{td}^* V_{ts}$ and	ε_K	$\lvert\varepsilon_K\rvert$	=	$(2.228 \pm 0.011) \cdot 10^{-3}$	[39]	$\hat{B}_K = 0.7567 \pm 0.0020 \pm 0.0123$
$V_{cd}^* V_{cs}$						$\kappa_\varepsilon = 0.940 \pm 0.013 \pm 0.023$

Current status of flavour

- A **single** phase must be responsible for CP violation across distinct flavour sectors
- Observables of very different natures

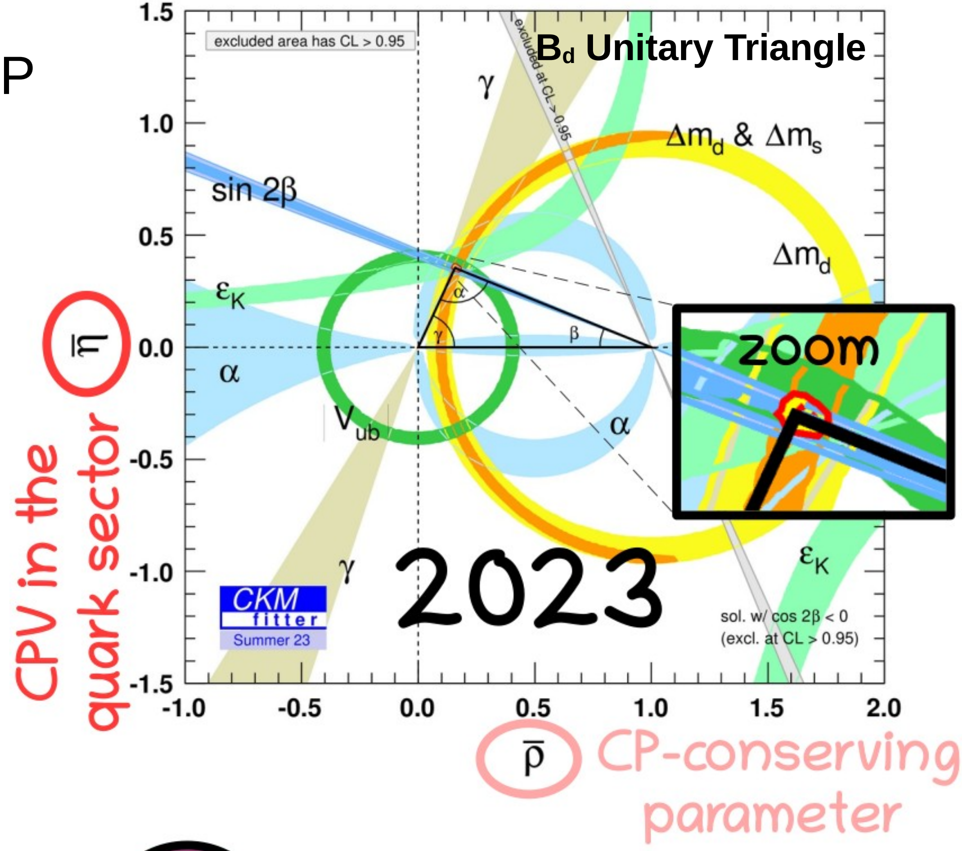
$$A = 0.8215^{+0.0047}_{-0.0082} \ (0.8\% \text{ unc.})$$

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

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

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

68% C.L. intervals



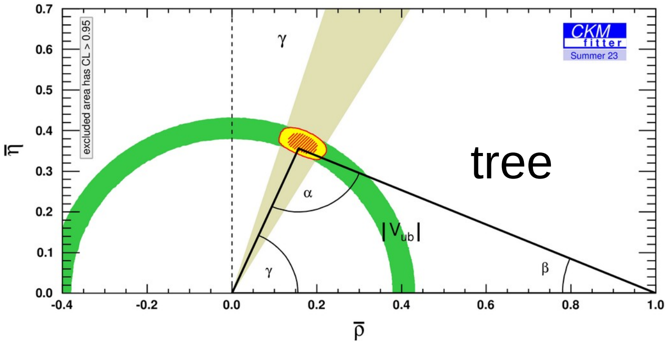
Rephasing invariant:

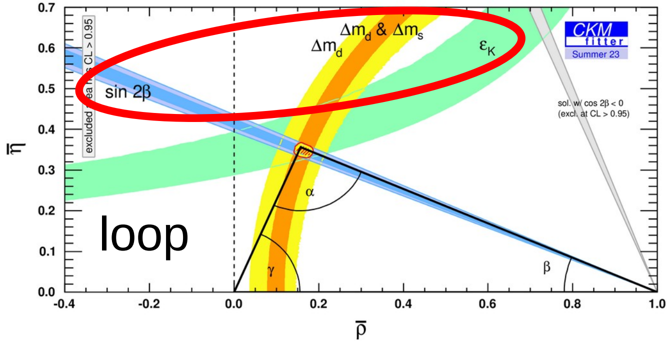
$$\frac{|V_{us}|}{(|V_{ud}|^2+|V_{us}|^2)^{1/2}} = \lambda, \quad \frac{|V_{cb}|}{(|V_{ud}|^2+|V_{us}|^2)^{1/2}} = A\lambda^2, \quad -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = \bar{\rho} + i\bar{\eta}$$

b : $|V_{xb}|$, α, β, γ, Δm_d, Δm_s

s : ε_K

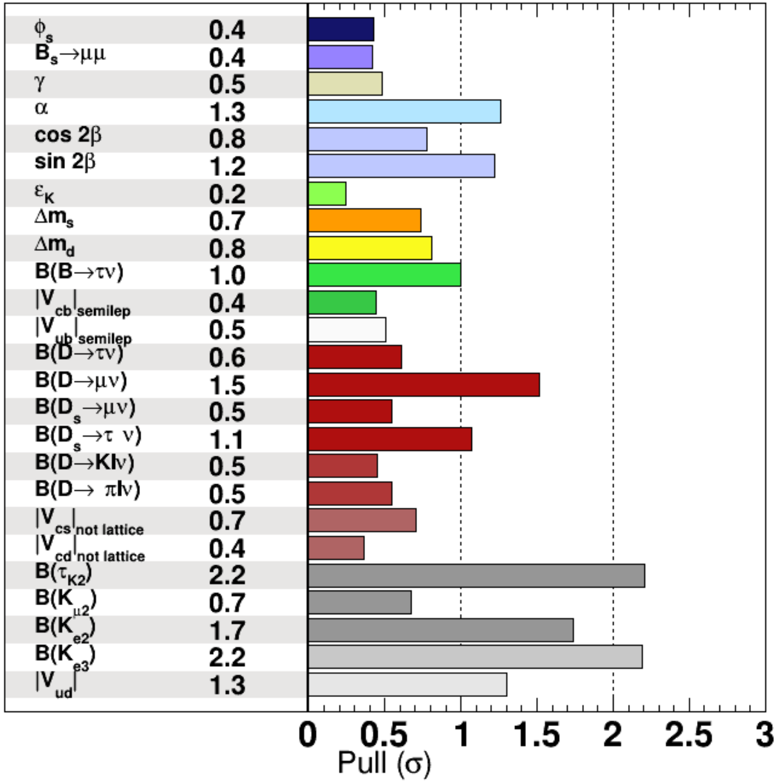
Consistency among observables





$$pull_{\mathcal{O}_{exp}} = \sqrt{\chi^2_{min} - \chi^2_{min,!\mathcal{O}_{exp}}}$$

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



- If NP in loop: extraction of ρ, η degraded
- Overall agreement w/ the SM, but some existing tensions

New era of flavour ahead

LHCb → | LHCb Upgrade I | LHCb Upgrade II

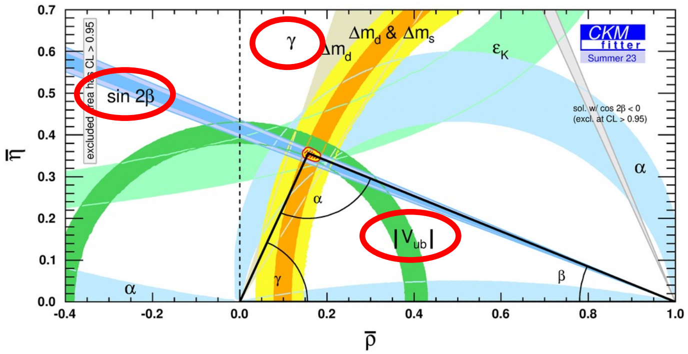
Run 1 - Run 2		Run 3		Run 4		Run 5		Run 6
$\mathcal{L}_{int} = 10\ fb^{-1}$ $\mathcal{L} = 4 \times 10^{32}\ cm^{-2}\,s^{-1}$	LS2 Injector Upgrades LHCb Upgrade I	$\mathcal{L} = 2 \times 10^{33}\ cm^{-2}\,s^{-1}$	LS3 HL-LHC ATLAS/ CMS Phase 2 Upgrades LHCb Upgrade Ib (Consolidation)	$\mathcal{L}_{int} \sim 50\ fb^{-1}$	LS4 LHCb Upgrade II	$\mathcal{L} = 1\text{-}2 \times 10^{34}\ cm^{-2}\,s^{-1}$	LS5	$\mathcal{L}_{int} \sim 300\ fb^{-1}$
2010 - 2018	2019 - 2022	2022 - 2025	2026 - 2028	2029 - 2032	2033 - 2034	2035 - 2038	2039	2040 – 20XX
		Increased Lumi by x 5 Limited to ~ 6 int. per bunch crossing		Limited to ~ 6 int. per bunch crossing		~ 40 int. per bunch crossing		~ 40 int. per bunch crossing

HL-LHC

- LHCb Upgrades [1812.07638]; Belle II [1808.10567]
- Phase I: LHCb-upgrade I 50/fb, & Belle II 50/ab
- Other later phases (more uncertain) left in back up

Experimental inputs

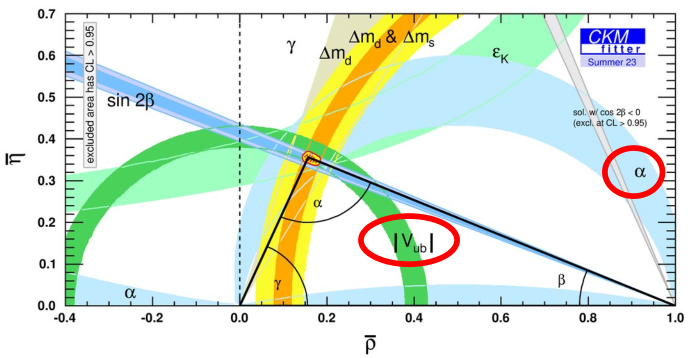
Quantity	Current (Rfit)	Unc. Phase I
$\sin(2\beta)_{[c\bar{c}]}$	0.011	0.005
γ	$3.4°$	$1°$
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert_{\Lambda_b}$	10 %	3 %
$(\phi_s)_{[b\to c\bar{c}s]}$	21 mrad	14 mrad



- Sizes of 1σ relative uncertainties [HL-LHC 1812.07638; Belle II 1808.10567]
- **Important role played by LHC in extracting quantities above**
- $|V_{ub}/V_{cb}|$: lattice determination of Λ_b form factors [Detmold, Lehner, Meinel ‘15]; extraction from B_s carries currently similar uncertainty (but larger)
- β and ϕ_s: penguin pollution, various estimates (QCDF, SU(3), etc.) w/ small central values and uncs. in the range $|\Delta\beta|\sim<1°$ [Boos, Mannel, Reuter ‘04; Ciuchini et al. ‘05; De Bruyn, Fleischer ‘14; Frings, Nierste, Wiebusch ‘15; ...]

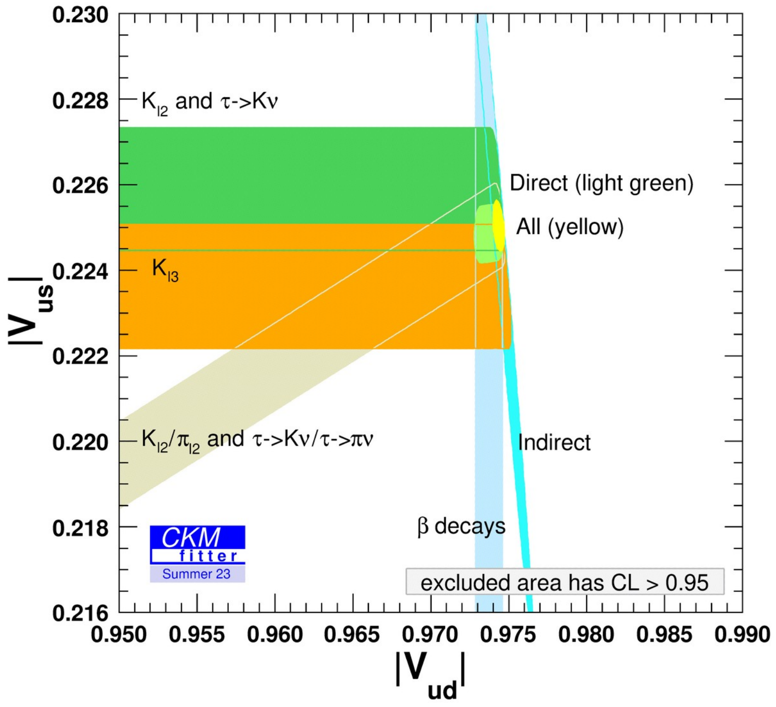
Other experimental inputs

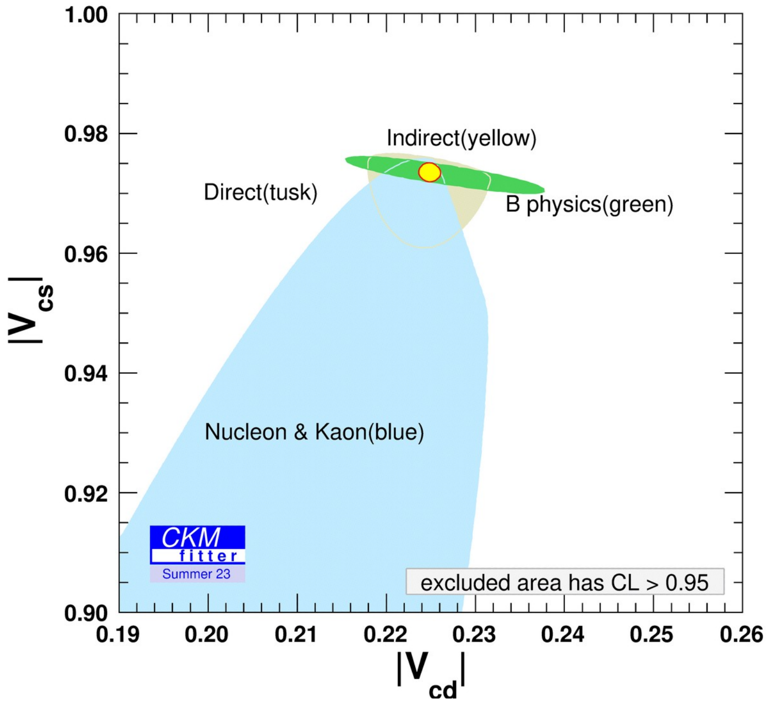
Quantity	Current (Rfit)	Unc. Phase I
$\lvert V_{ub}\rvert_{\mathrm{SL}}$	0.19	0.042
$\lvert V_{cb}\rvert_{\mathrm{SL}}$	0.61	0.60
α	3.7°	0.6°
$\mathcal{B}(B \to \tau\nu)$	22 %	5 %



- Sizes of 1σ relative uncertainties [**Belle II** 1808.10567]
- $|V_{ub}|$ and $|V_{cb}|$ exclusive: assumptions about lattice improvements; only exclusive extractions considered for projections ("Current" includes inclusive)
- α: limitation from neutral modes, main experimental improvement expected from Belle II; need to account for isospin breaking corrections [Charles, Deschamps, Descotes-G., Niess '17]
- Strangeness: presently small role in extracting ρ and η

Other experimental inputs

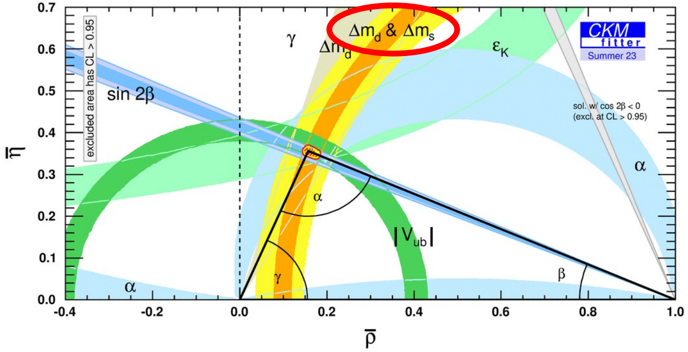




- $|V_{ud}|$, $|V_{us}|$: no expected exp. change from (semi-)leptonic decays, only from lattice inputs
- $|V_{cd}|$, $|V_{cs}|$: would need substantial exp (and theo) improvement from the charm sector

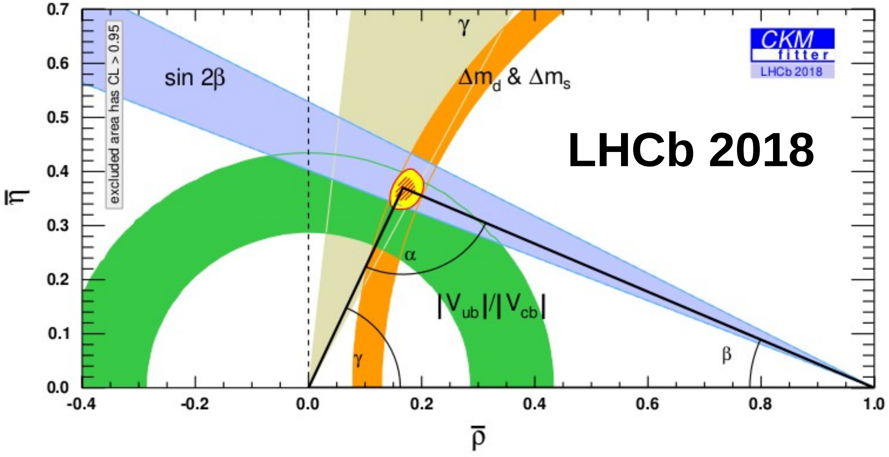
Lattice inputs

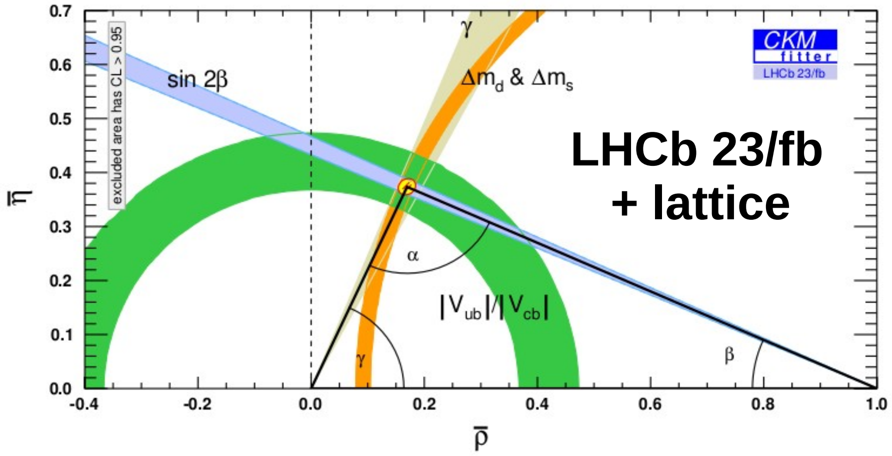
Quantity	Current (Rfit)	Unc. Phase I
f_K	0.5 %	0.3 %
$f_+^{K\to\pi}(0)$	0.4 %	0.1 %
f_{B_s}	1.1 %	0.5 %
B_{B_s}	3.2 %	0.8 %
f_{B_s}/f_{B_d}	0.6 %	0.4 %
B_{B_s}/B_{B_d}	2.4 %	0.5 %

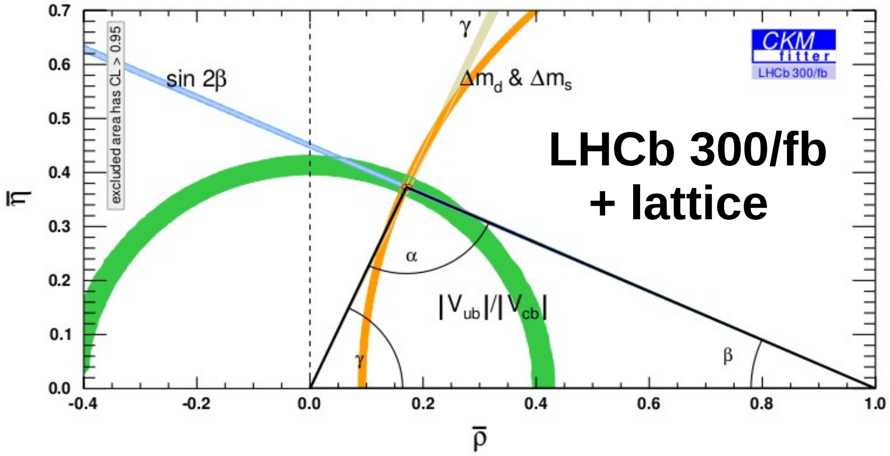


- Sizes of 1σ relative uncertainties [1812.07638]
- Ratios: better control of chiral extrapolations to light quark masses
- Isospin and QED corrections for leptonic and semileptonic decays: known and around 1% effect for K; will be needed for B (and D)

Impact of LHCb + lattice







[1808.08865]

Illustrative purpose: only including **LHCb**

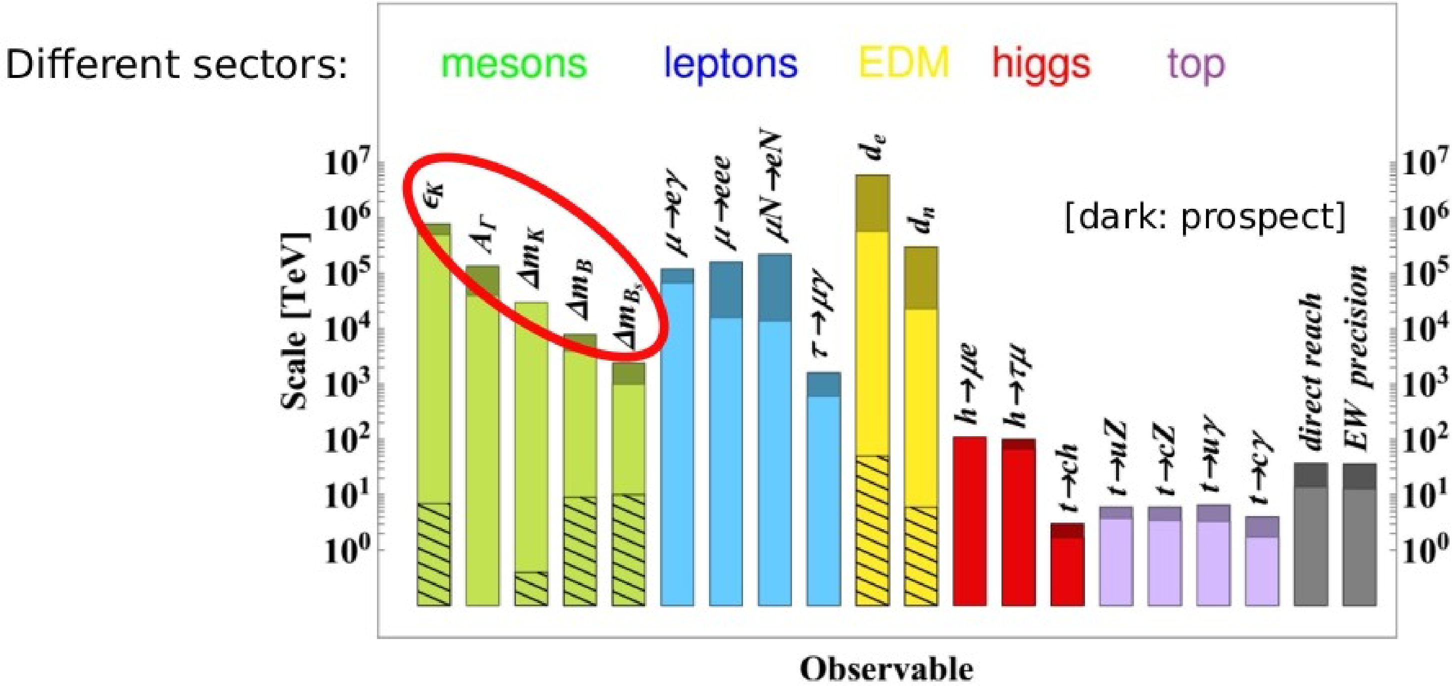
CKM metrology [Preliminary!]

Quantity	Current (Rfit)	Full agree	Unc. Phase I
A	1.8 %	1.9 %	1.4 %
λ	0.2 %	0.3 %	0.3 %
$\bar{\rho}$	10 %	9.3 %	3.9 %
$\bar{\eta}$	3.7 %	3.6 %	1.4 %

- Sizes of 2σ relative uncertainties
  - "Current" uncertainties follow Rfit scheme
  - "Full agree": central values adjusted to have perfect agreement among the constraints, and total theo. unc. treated as Gaussian
  - Future uncertainties treated as Gaussian
- A and λ extractions driven by $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$ inputs
- **Improvement of ρ, η by factor of 2-3**

Reach to New Physics (NP)

- Low-energy observables: probe <u>energies much beyond the reach of direct searches</u>
- The bounds on non-SM contributions shape NP candidates
- If deviation seen, possible NP manifestation!



[European Strategy Update 2020, arXiv:1910.11775]

NP in B meson mixing

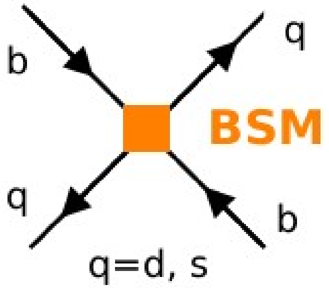
- **NP in $|\Delta B|=2$:**
  h_d and h_s set sizes

CKM (in presence of NP),
bag parameters,
↓ decay constants

$$M_{12} = M_{12}^{\mathrm{SM}} \times (1 + h\, e^{2i\sigma})$$

NP parameters

- **Assumptions**:
  - No NP in $|\Delta F|=1$:
    tree level in SM (γ, $|V_{ub}|$, $|V_{cb}|$, ...) free of NP
  - NP is short-distance [B-mesogenesis: Miró, Escudero, Nebot ‘24]
  - Unitarity of the CKM 3x3 matrix
  - Unrelated NP in B_d and B_s systems [See: PRD 89, 033016 (2014), arxiv:1309.2293]



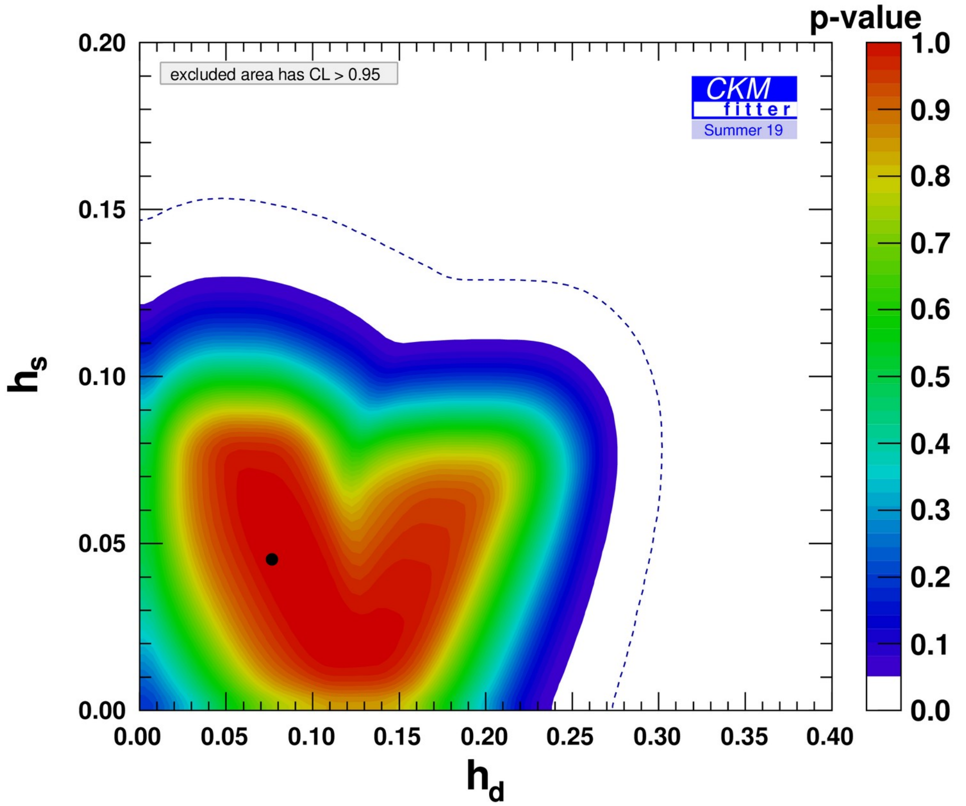
[CKM fits w/ NP: UTfit; Descotes-G., Falkowski, Fedele, Gonzalez-A., Virto '19; Biswas, Mukherjee, Nandi, Patra '23]

Status of NP in B meson mixing

- Status as of Summer '19: outdated, but conclusions should be similar
- Agreement with the SM (h_d=h_s=0) at ~1σ
- Allowed size for NP at the level of O(20%)!
- Extractions of ρ and η (Wolfenstein parm.) **degrade by factor ~3**

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

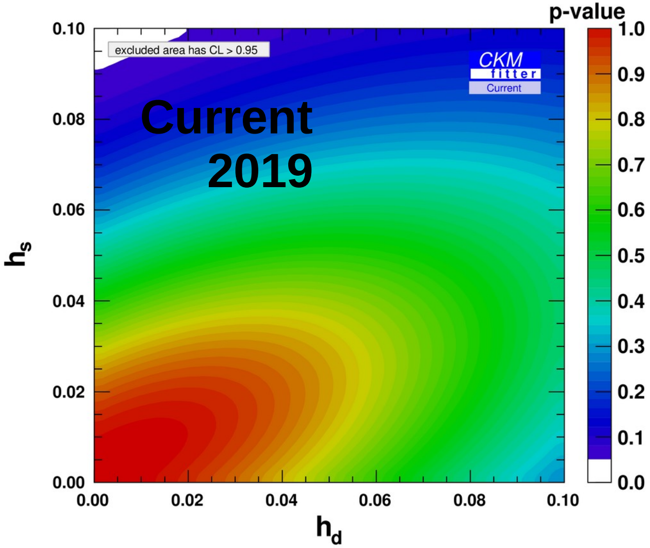
Black dot: best fit point; σ_d and σ_s are unconstrained

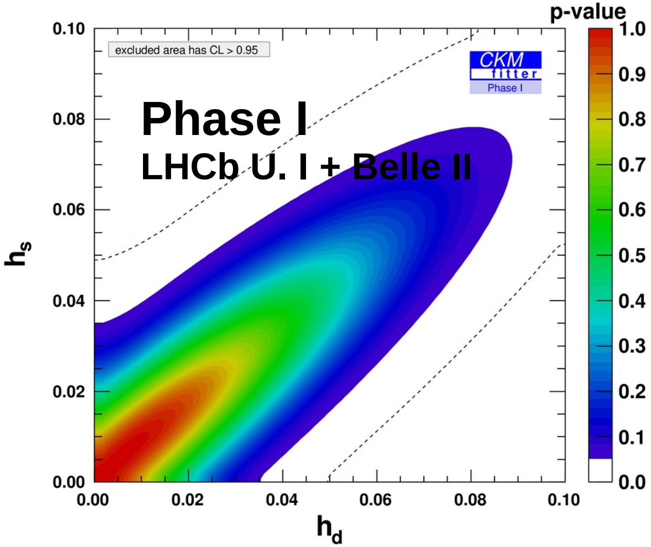


[See also: De Bruyn, Fleischer, Malami, van Vliet '23]

Future improvements

- SM reference: shift the central values
- Compared to Current, improvement by factor >3





Conclusions

- Global fit of a rich variety of processes sensitive to CP Violation and SM predictions in agreement
- We are then able to extract accurate values for the fundamental parameters describing the CKM matrix
- The mechanism of CP Violation in the SM (still) gives an accurate picture of nature: no clear indication of NP
- One example of the impact of NP: B meson mixing
- Exciting future prospects for Belle II, LHC, NA62,...

CKMfitter 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

THANKS!

BACK UP

Benchmarks for the future

- Phase I: LHCb-upgrade I 50/fb, & Belle II 50/ab
- Phase II: LHCb-upgrade II 300/fb, & Belle II upgrade 250/ab
- Phase III: Phase II + FCC-ee

FCC-ee: initial phase of FCC; operates at <u>different EW thresholds</u>:
5×10^{12} Z bosons, **10^8 WW pairs**, $>10^6$ Higgses, $>10^6$ tt pairs

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Particle species	B^0	B^+	B^0_s	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times10^9$)	310	310	75	65	1.5	600	170

[FCC Physics Opportunities, Conceptual Design Report]

[Flavour cases: EPJPlus 136, 837 arXiv:2106.01259,
and EPJPlus 136, 912 arXiv:2106.12168]

Experimental inputs: Phases II & III

Quantity	Current (Rfit)	Unc. Phase I	Unc. Phase II	Unc. Phase III
$\sin(2\beta)_{[c\bar{c}]}$	0.011	0.005	0.002	0.0008
γ	3.4°	1°	0.25°	0.20°
$\vert V_{ub}\vert/\vert V_{cb}\vert$	9 %	3 %	1 %	id
$(\phi_s)_{[b\to c\bar{c}s]}$	21 mrad	14 mrad	4 mrad	2 mrad
$\vert V_{ub}\vert_{\mathrm{SL}}$	0.19	0.042	0.032	id
$\vert V_{cb}\vert$	0.61	0.60	0.44	0.17
α	1.8°	0.6°	id	id
$\mathcal{B}(B\to\tau\nu)$	22 %	5 %	2 %	1 %

Lattice inputs: Phases II & III

Quantity	Current (Rfit)	Unc. Phase I	Unc. Phases II & III
f_K	0.5 %	0.3 %	id
$f_+^{K\to\pi}(0)$	0.4 %	0.1 %	id
f_{B_s}	1.1 %	0.5 %	id
B_{B_s}	3.2 %	0.8 %	0.6 %
f_{B_s}/f_{B_d}	0.6 %	0.4 %	id
B_{B_s}/B_{B_d}	2.4 %	0.5 %	0.3 %

CKM metrology [Preliminary!]

Quantity	Current (Rfit)	Full agree	Unc. Phase I	Unc. Phase II	Unc. Phase III
A	0.8 %	0.9 %	0.7 %	0.7 %	0.5 %
λ	0.1 %	0.2 %	0.1 %	0.1 %	0.1 %
$\bar{\rho}$	4.9 %	4.6 %	1.9 %	0.9 %	0.7 %
$\bar{\eta}$	1.5 %	1.7 %	0.7 %	0.3 %	0.2 %

1σ

2σ

Quantity	Current (Rfit)	Full agree	Unc. Phase I	Unc. Phase II	Unc. Phase III
A	1.8 %	1.9 %	1.4 %	1.2 %	0.9 %
λ	0.2 %	0.3 %	0.3 %	0.3 %	0.3 %
$\bar{\rho}$	10 %	9.3 %	3.9 %	1.8 %	1.5 %
$\bar{\eta}$	3.7 %	3.6 %	1.4 %	0.7 %	0.4 %

Other projections are found in the CKMfitter webpage; see also CERN courier

Experimental and theoretical inputs

“Current”: 2019, used only for NP in |ΔB|=2

experimental

theory

	Central values	Uncertainties				Reference
		Current [28]	Phase I	Phase II	Phase III	Phases I–III
$\lvert V_{ud}\rvert$	0.97437	±0.00021	id	id	id	[28]
$\lvert V_{us}\rvert f_+^{K\to\pi}(0)$	0.2177	±0.0004	id	id	id	[28]
$\lvert V_{cd}\rvert$	0.2248	±0.0043	±0.003	id	id	[40,41]
$\lvert V_{cs}\rvert$	0.9735	±0.0094	id	id	id	[28,40,41]
Δm_d [ps^{-1}]	0.5065	±0.0019	id	id	id	[17]
Δm_s [ps^{-1}]	17.757	±0.021	id	id	id	[17]
$\lvert V_{cb}\rvert_{\rm SL}\times 10^3$	42.26	±0.58	±0.60	±0.44	id	[29]
$\lvert V_{cb}\rvert_{W\to cb}\times 10^3$		…	…	…	±0.17	[34–36]
$\lvert V_{ub}\rvert_{\rm SL}\times 10^3$	3.56	±0.22	±0.042	±0.032	id	[29]
$\lvert V_{ub}/V_{cb}\rvert$ (from Λ_b)	0.0842	±0.0050	±0.0025	±0.0008	id	[30]
$\mathcal{B}(B\to\tau\nu)\times 10^4$	0.83	±0.24	±0.04	±0.02	±0.009	[29,34]
$\mathcal{B}(B\to\mu\nu)\times 10^6$	0.37	…	±0.03	±0.02	id	[29]
$\sin 2\beta$	0.680	±0.017	±0.005	±0.002	±0.0008	[29,30,34]
$\alpha[^\circ]$ (mod 180°)	91.9	±4.4	±0.6	id	id	[29]
$\gamma[^\circ]$ (mod 180°)	66.7	±5.6	±1	±0.25	±0.20	[29,30,34]
β_s[rad] x(-2)	−0.035	±0.021	±0.014	±0.004	±0.002	[30,34]
$A_{\rm SL}^d\times 10^4$	−6	±19	±5	±2	±0.25	[14,17,34,37]
$A_{\rm SL}^s\times 10^5$	3	±300	±70	±30	±2.5	[14,17,34,37]
$\bar m_t$ [GeV]	165.30	±0.32	id	id	±0.020	[28,34]
$\alpha_s(m_Z)$	0.1185	±0.0011	id	id	±0.00003	[28,34]
$f_+^{K\to\pi}(0)$	0.9681	±0.0026	±0.0012	id	id	[30]
f_K [GeV]	0.1552	±0.0006	±0.0005	id	id	[30]
f_{B_s} [GeV]	0.2315	±0.0020	±0.0011	id	id	[30]
B_{B_s}	1.219	±0.034	±0.010	±0.007	id	[30]
f_{B_s}/f_{B_d}	1.204	±0.007	±0.005	id	id	[30]
B_{B_s}/B_{B_d}	1.054	±0.019	±0.005	±0.003	id	[30]
$\tilde B_{B_s}/\tilde B_{B_d}$	1.02	±0.05	±0.013	id	id	[30,42,43]
$\tilde B_{B_s}$	0.98	±0.12	±0.035	id	id	[30,42,43]
η_B	0.5522	±0.0022	id	id	id	[44]

[See for refs.: PRD 102, 056023 (2020), arXiv:2006.04824, and also EPJPlus 136, 837 arXiv:2106.01259, and EPJPlus 136, 912 arXiv:2106.12168]

- ***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

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

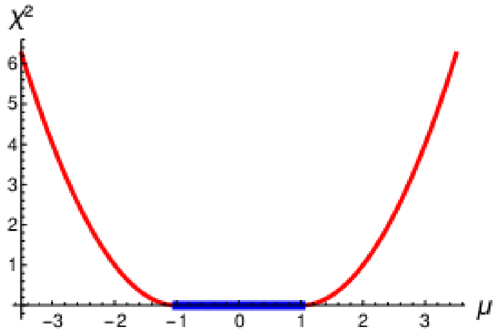
$\mathcal{L}_{stat}$: exp. data

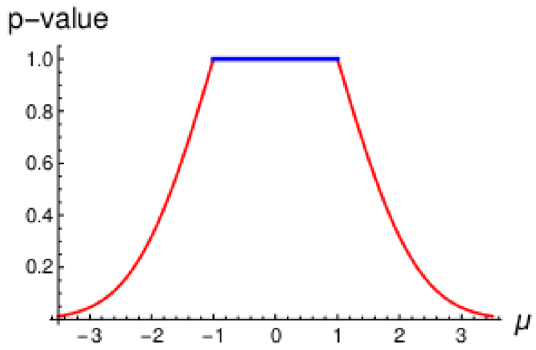
$\mathcal{L}_{theo}$: had. inputs

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

[Hoecker et al. '01, Charles et al. '04]

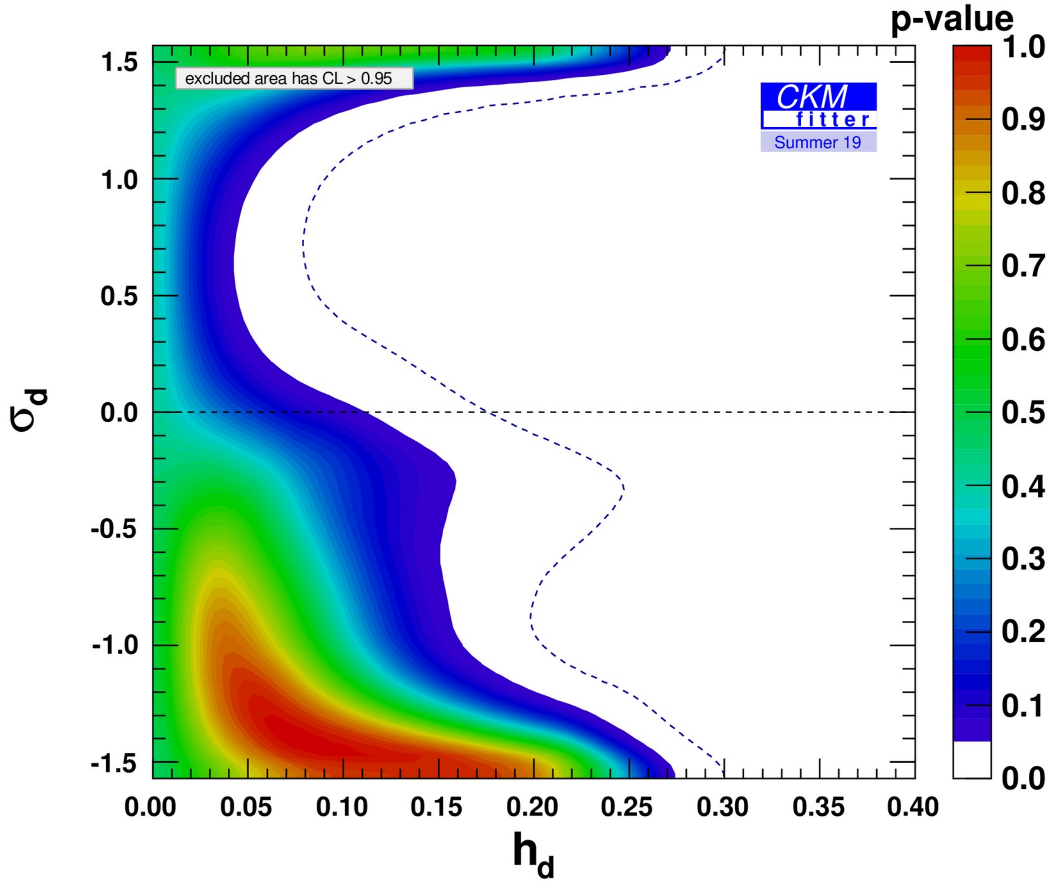
Example in 1D, $0 \pm 1_{stat} \pm 1_{theo}$ ($N_{dof} = 1$)

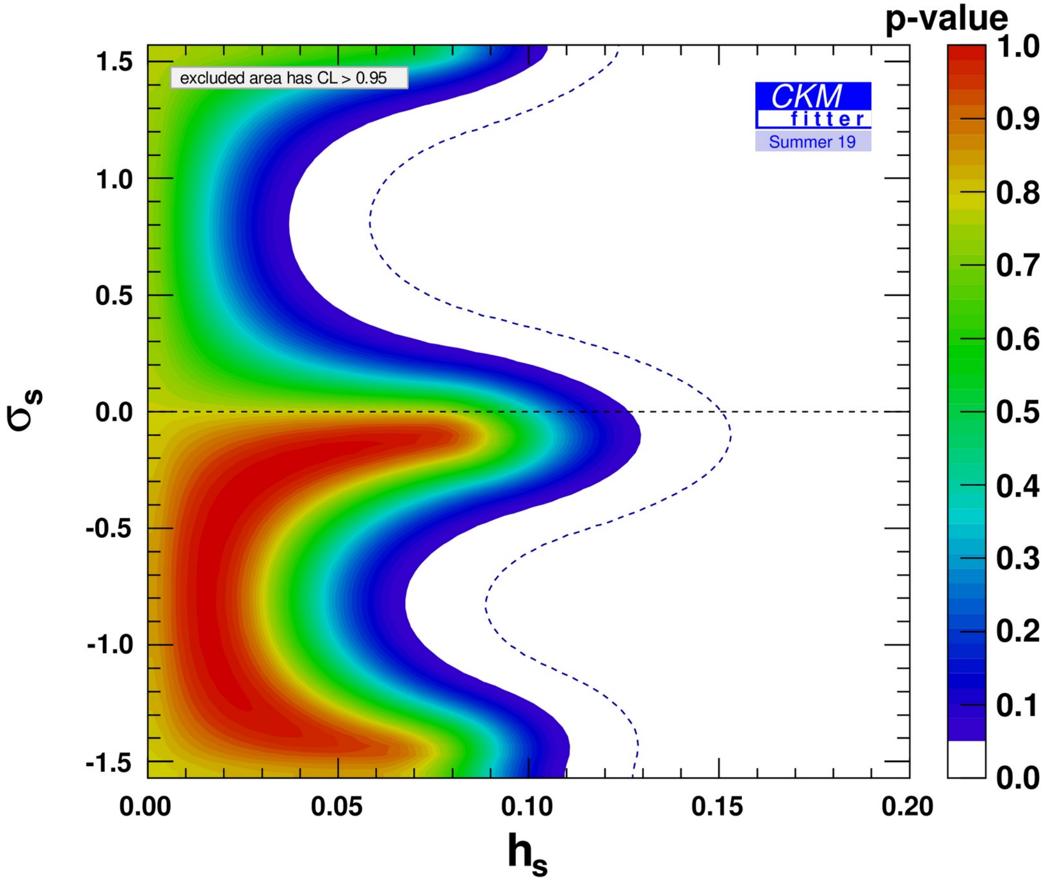




χ^2: flat bottom, quadratic walls

2019 status plots



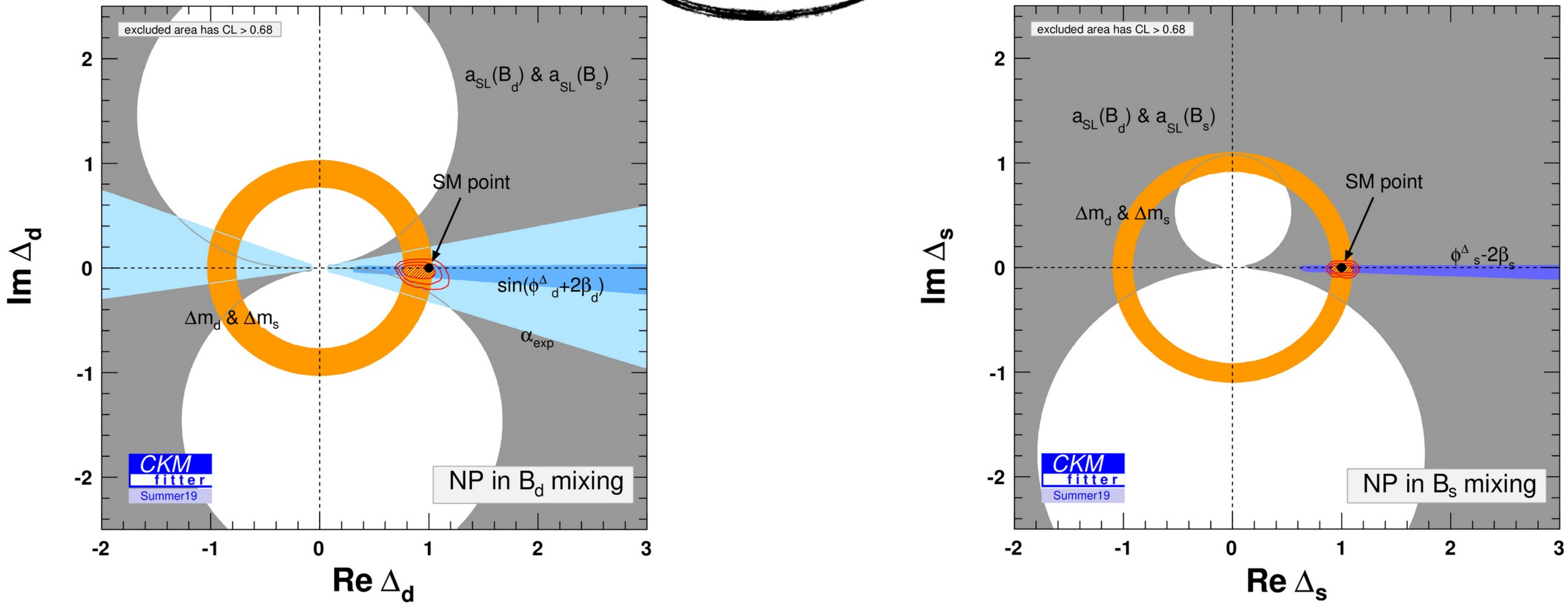


Different representation

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

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

Soares & Wolfenstein, PRD 47, 1021 (1993)
Deshpande, Dutta & Oh, PRL77, 4499 (1996)
Silva & Wolfenstein, PRD 55, 5331 (1997)
Cohen et al., PRL78, 2300 (1997)
Grossman, Nir & Worah, PLB 407, 307 (1997)



Future improvements

Sensitivities	Summer 2019	Phase I	Phase II	Phase III
h_d	0.26	0.073	0.049	0.038
h_s	0.12	0.065	0.044	0.031