The role of $|V_{cb}|$:

global UT fits & constraining |DF|=2 NP

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Luiz VALE SILVA (IFIC, UV – CSIC)

[CKMfitter 2023 update: see CKM 2023 @ Santiago]

[Charles, Descotes-Genon, Ligeti, Monteil, Papucci, Trabelsi, LVS, PRD 102, 056023 (2020), arXiv:2006.04824]

2023 Belle II Physics Week, 30/10/2023

Flavor in the quark sector

(Gauge couplings to fermions)

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

(Higgs self-interaction)

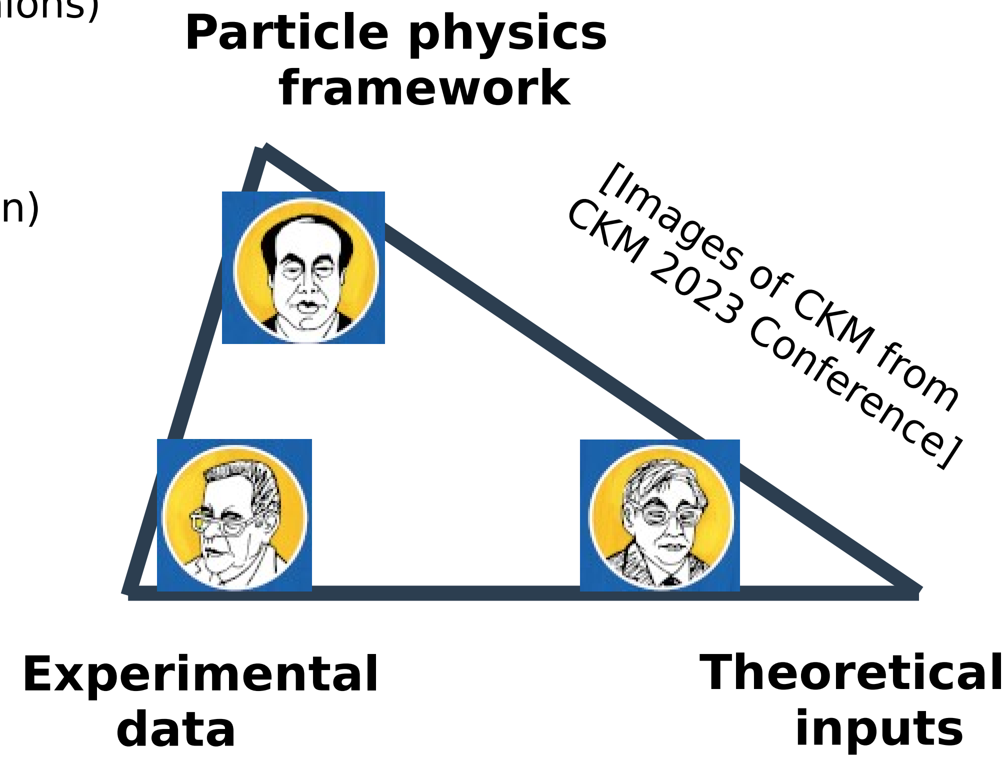
$$+ |D_\mu H|^2 - V(H)$$

(short-range weak interactions)

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

(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 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. <u>QCD inputs</u>)

The Cabibbo-Kobayashi-Maskawa matrix

15 June 1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

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

Universality of $\Delta S=0,1$ weak transitions; Cabibbo introduces a phenomenological mixing angle

first V_{cb}

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

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

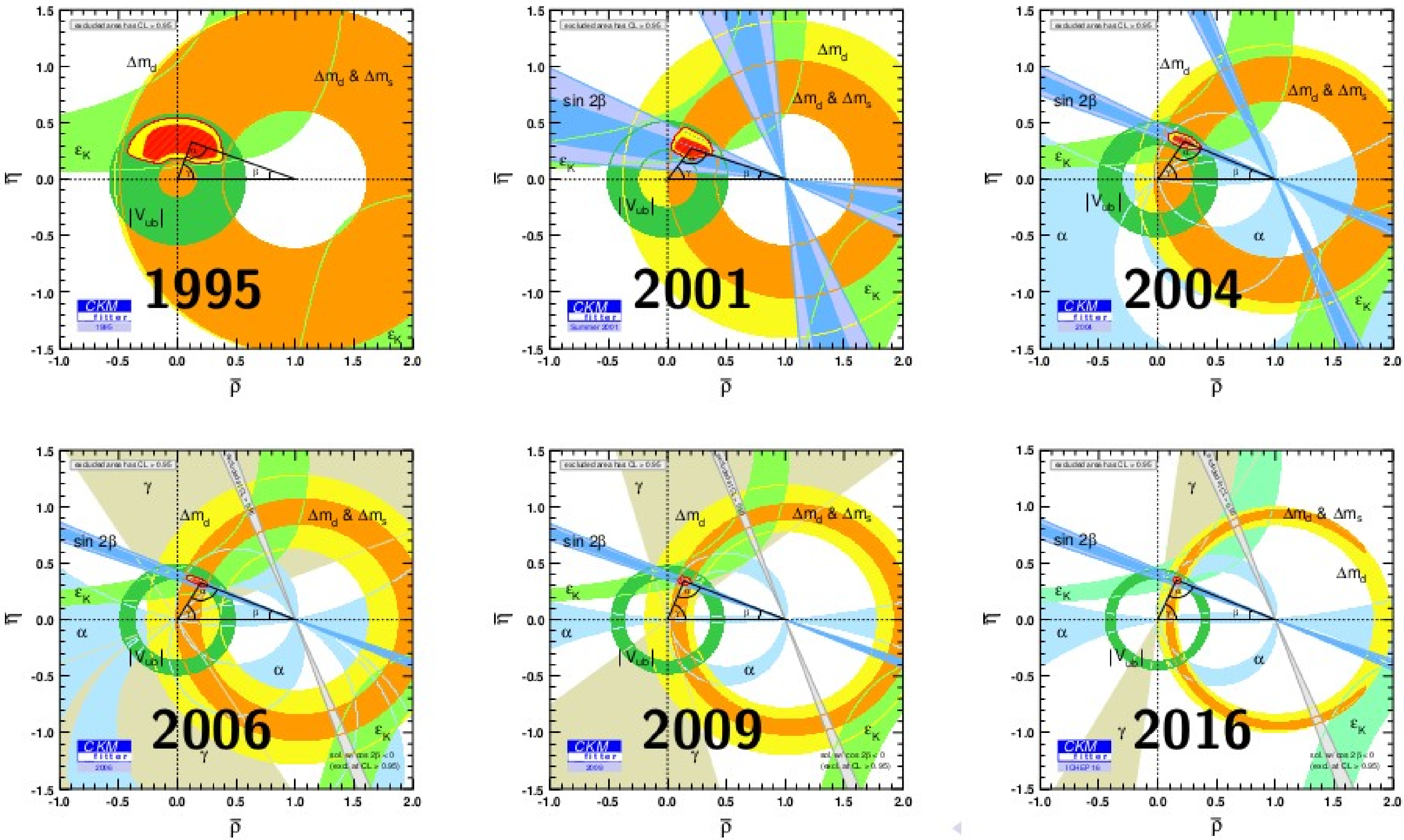
***CP*-Violation in the Renormalizable Theory of Weak Interaction**

Makoto KOBAYASHI and Toshihide MASKAWA
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

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, ...)



Current status of flavour

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

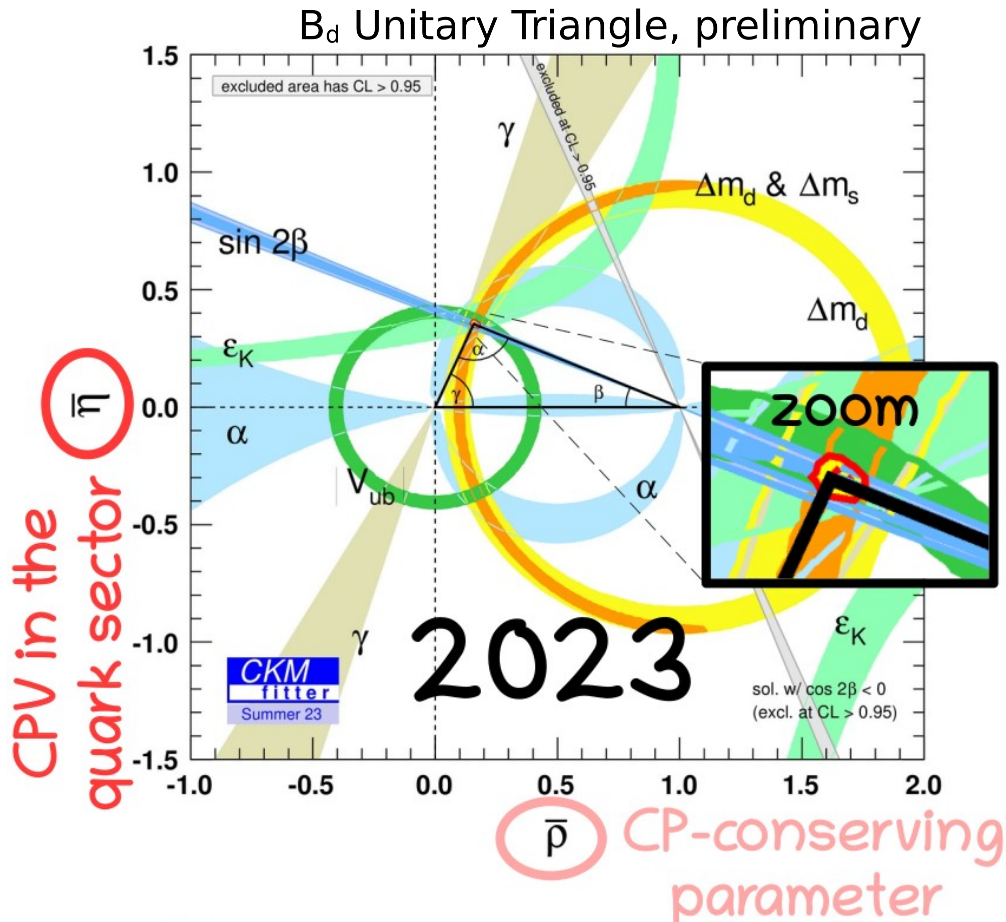
$$A = 0.8215\,^{+0.0047}_{-0.0082}\ (0.8\%\ \text{unc.})$$

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

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

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

68% C.L. intervals



b : $|V_{xb}|$, α, β, γ, Δm_d, Δm_s

s : ε_K

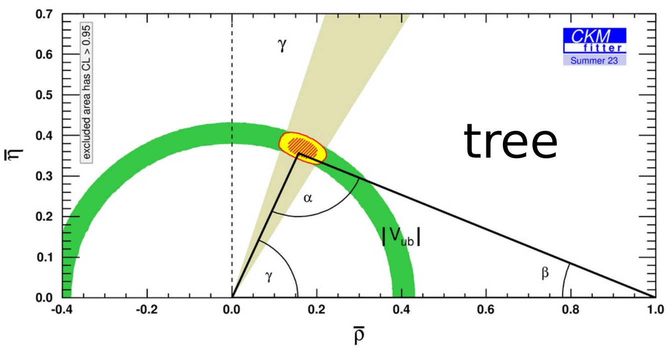
Rephasing invariant:

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

Consistency among observables

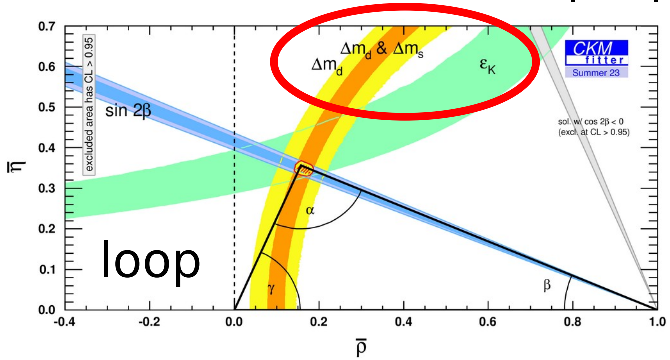
$$pull_{\mathcal{O}_{exp}} = \sqrt{\chi^2_{min} - \chi^2_{min,!\mathcal{O}_{exp}}}$$

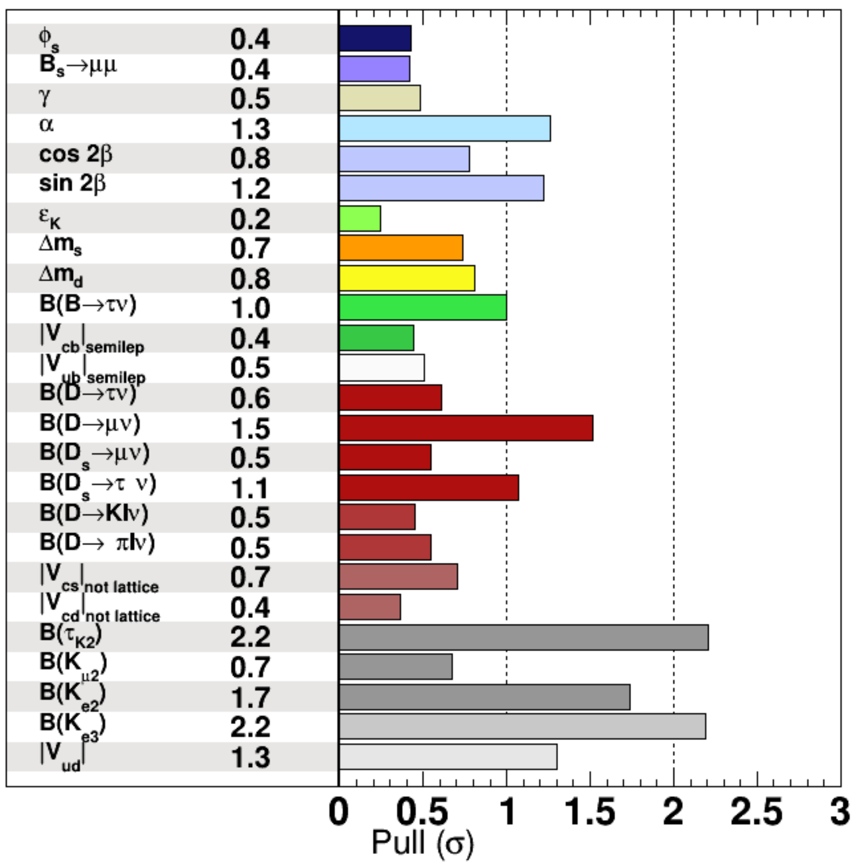
$$!\,\mathcal{O}_{exp}:\ \chi^2_{min}\ \text{w/o}\ \mathcal{O}_{exp}$$



$|V_{ub}|/|V_{cb}|$

meson-mixing, with $|V_{cb}|$





- **Overall agreement w/ the SM**, **but some existing tensions (e.g., incl. vs excl. $|V_{xb}|$)**

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

(individual inputs given in back up; see discussion in "SL b-Hadron Decays" PDG 2023 review)

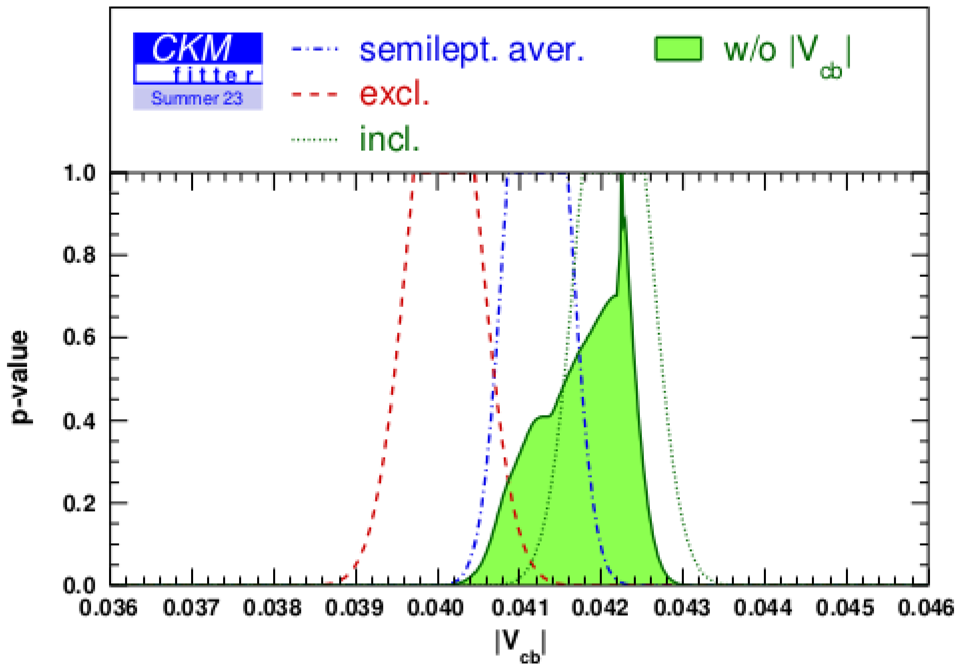
→ Excl. and incl. have similar error budgets

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

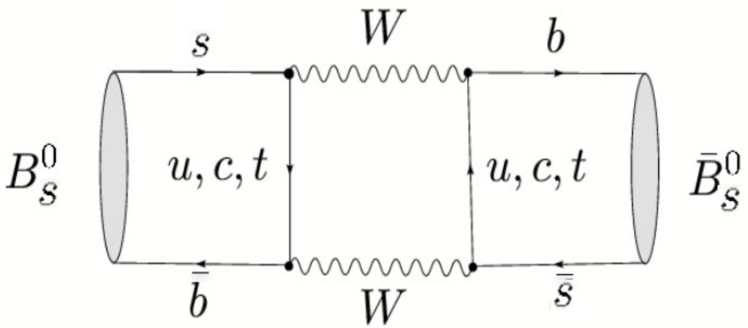


$|V_{cb}|$: $\pm 1.7\%$ [ind.], $\pm 0.9\%$ [comb.]

NP in B meson mixing

- **Address <u>present and future bounds</u> on NP in $|\Delta B|=2$, and discuss <u>future limitations</u>**

- **$|\Delta B|=2$: NP competes with suppressions in the SM (GIM/CKM), and enjoys the status of precision physics**



$V_{tb} V_{ts}^* \sim -V_{cb}$

- **Not discussing D meson mixing**

[K meson mixing: PRD 89, 033016 (2014), arxiv:1309.2293]

- **Combine projections for future data**: need global fit including "tree" and "loop" observables

[see e.g. CKMfitter]

NP in B meson mixing

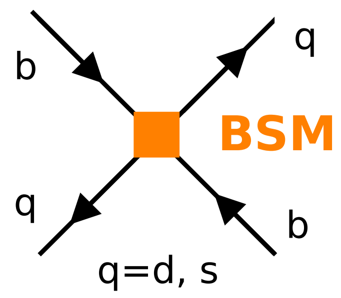
- **NP in |ΔB|=2:**
  h_d and h_s set sizes

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 |ΔF|=1:
    tree level in SM (γ, $|V_{ub}|$, $|V_{cb}|$, ...) free of NP
  - NP is short-distance
  - Unitarity of the CKM 3x3 matrix
  - Unrelated NP in B_d and B_s systems



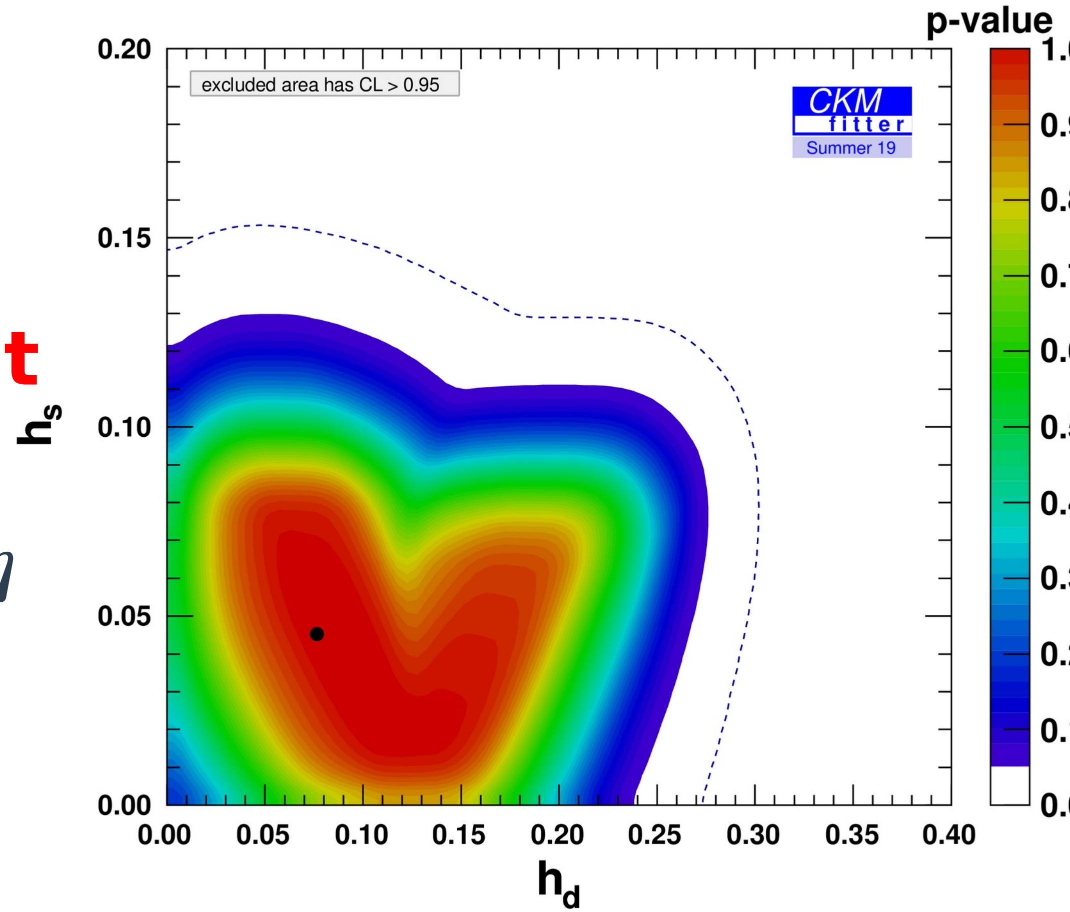
[See: PRD 89, 033016 (2014), arxiv:1309.2293]

- SMEFT: **four-quark operators** of different chiral structures

Present status of NP in B meson mixing

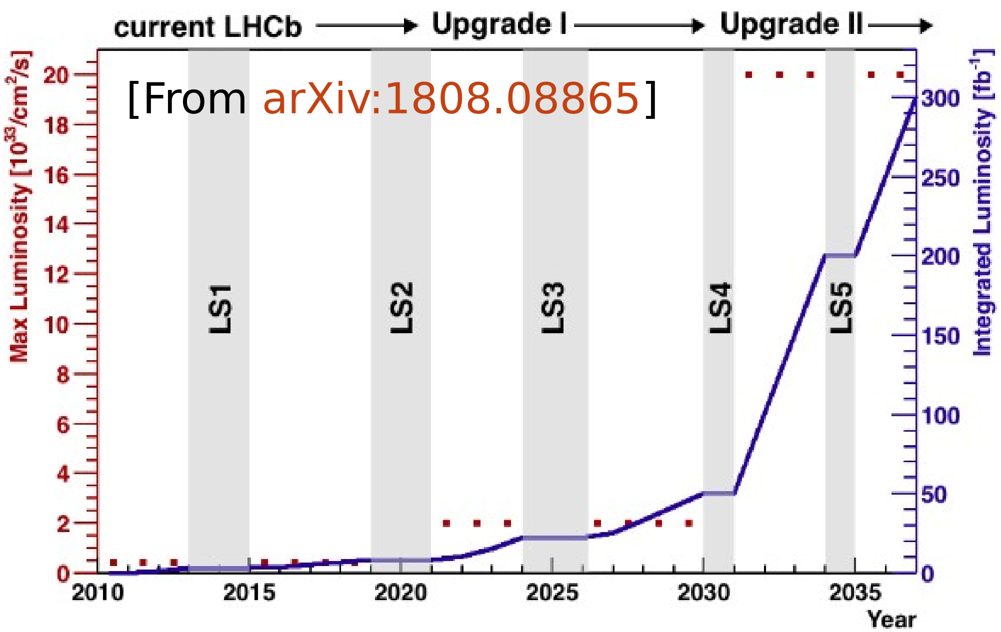
- **Agreement with the SM (h_d=h_s=0) at ~1σ**
- **Allowed size for NP at the level of O(20%)!**
- **Extractions of ρ and η** (Wolfenstein parm.) degrade by factor ~3

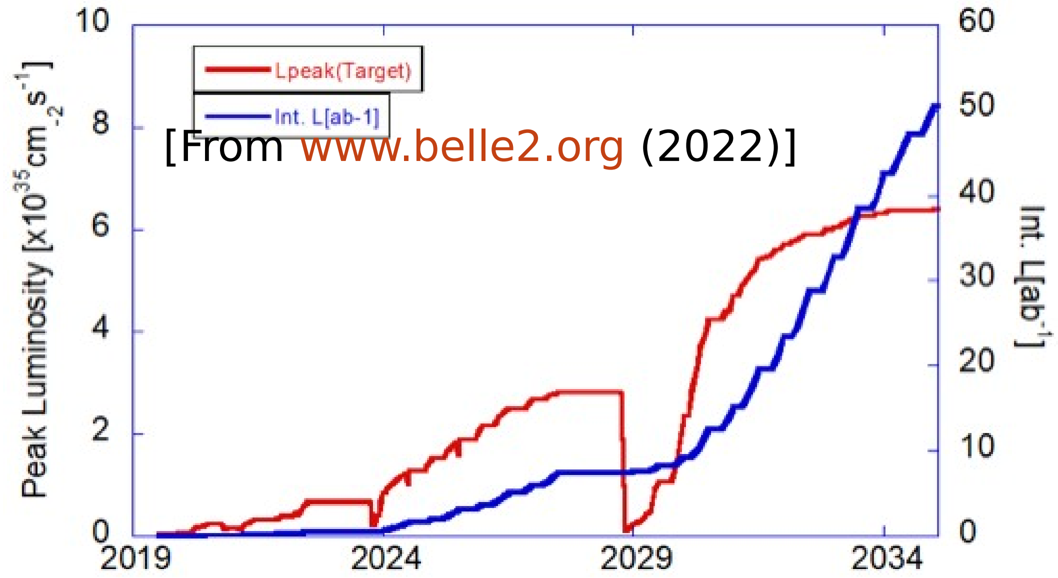
Status as of Summer '19



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

New era of flavour ahead





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

Experimental and theoretical inputs

[For projections, see e.g. Belle II Physics Book, 1808.10567]

[Full list of projections given in back up]

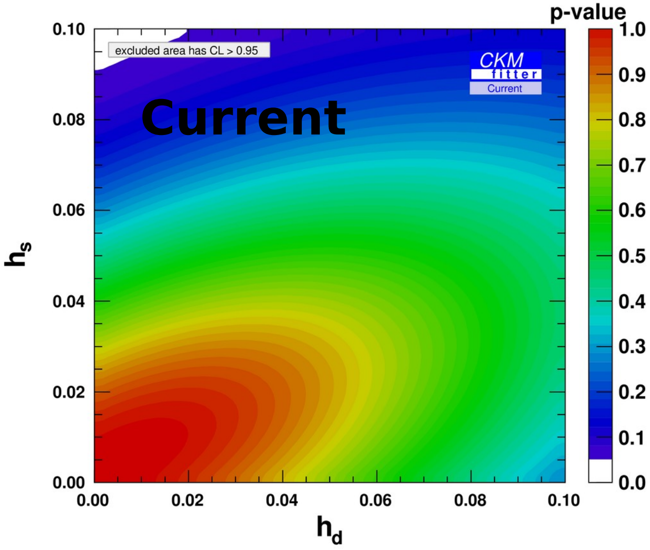
- **$|V_{ub}|_{SL}$ & $|V_{cb}|_{SL}$**: respectively 0.9% & 1.0% @ Phase II (Belle II U.)

  [incl. vs excl. inputs and impact on extraction of NP in $|\Delta F|=2$: De Bruyn, Fleischer, Malami, van Vliet]

- Phases I and II uncs. for **Lattice QCD** (decay constants, bag parameters) < 1%

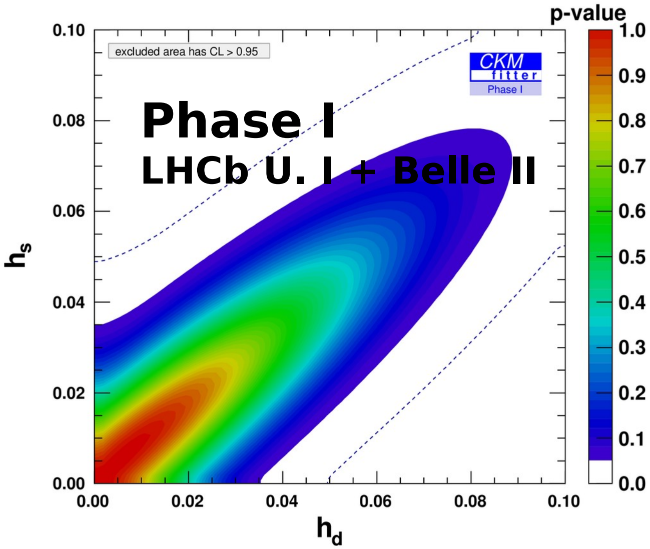
  Literature discusses Lattice QCD projections up to Phase II (QED effects included)

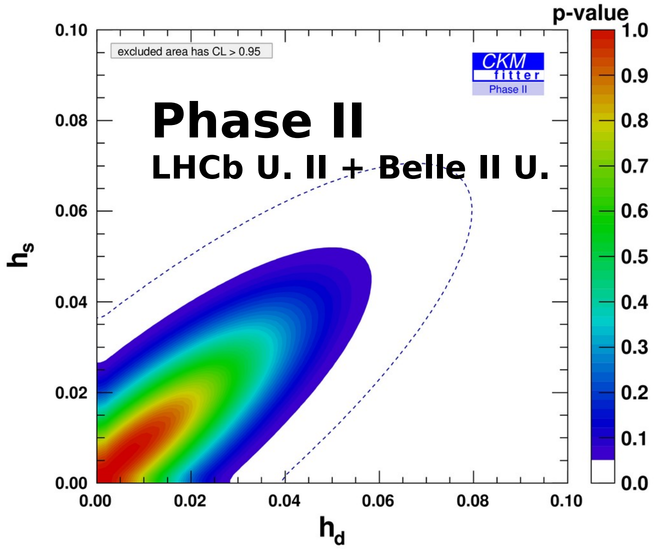
Future improvements



- SM reference: <u>shift the central values</u>
- Compared to Current, **improvement by factor >3 (5) at Phase I (II)**

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



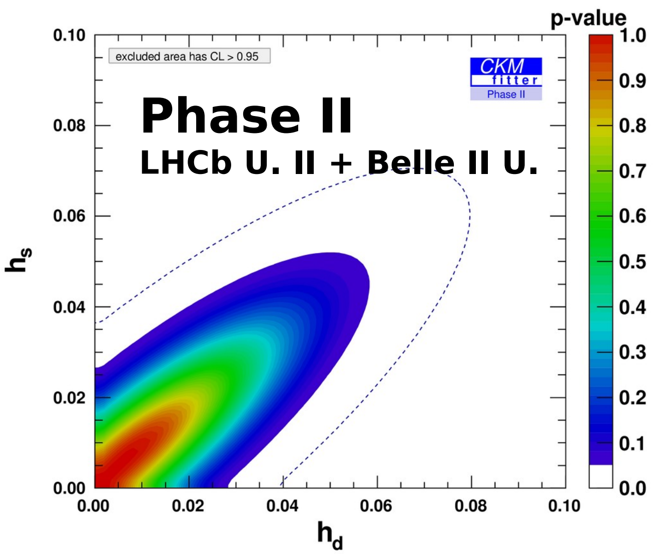


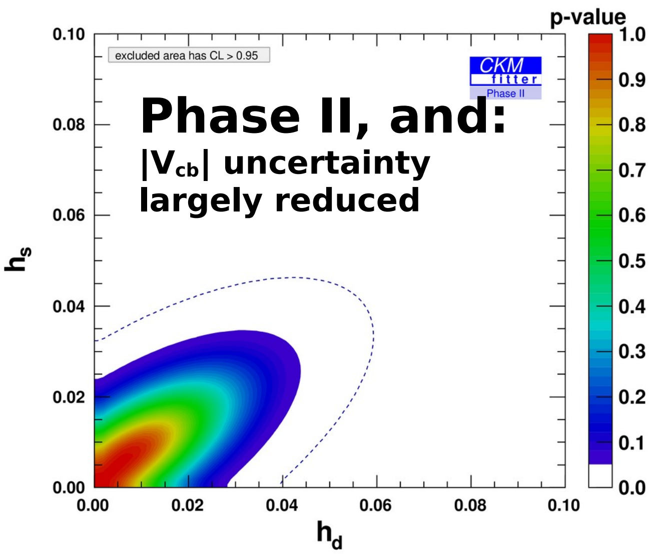
Bottlenecks

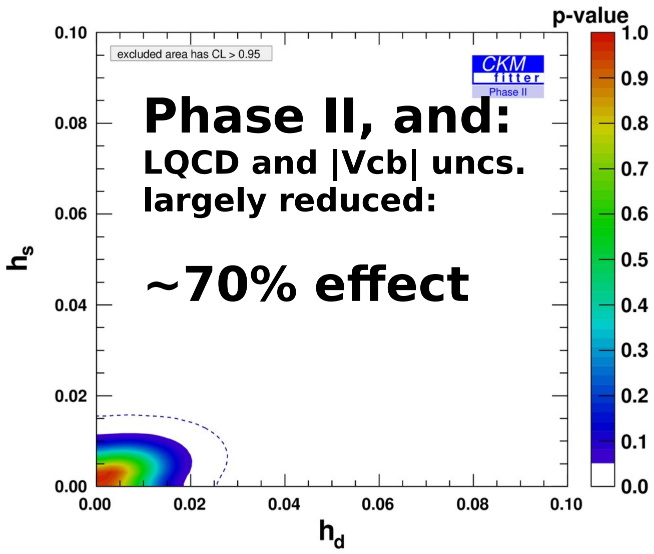
Necessary improvements beyond current expectations **for enhancing sensitivity to NP**:

[SD: Brod, Gorbahn, Stamou et al., in progress]

- **Lattice QCD** (also short-distance QCD corrections)
- **$|V_{cb}|$**, overall normalization (Wolfenstein parameter A)
- **Individual impacts on h_d and h_s**: improvements by O(20-30)%







Future reach to NP in B meson mixing

$$\frac{C_{ij}^2}{\Lambda^2}(\bar{q}_{i,L}\gamma_\mu q_{j,L})^2, \quad \Rightarrow \quad h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\frac{(4\pi)^2}{G_F\Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\left(\frac{4.5\ \text{TeV}}{\Lambda}\right)^2,$$

$$\sigma = \arg(C_{ij}\lambda_{ij}^{t*}),$$

- In the absence of suppressions: **NP scale >> TeV**
- Possible flavour and loop suppressions: **alleviate bounds on NP**

Couplings	NP loop order	Sensitivity for Summer 2019 [TeV]		Phase I Sensitivity [TeV]		Phase II Sensitivity [TeV]	
		B_d mixing	B_s mixing	B_d mixing	B_s mixing	B_d mixing	B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$	Tree level	9	13	17	18	20	21
(CKM-like)	One loop	0.7	1.0	1.3	1.4	1.6	1.7
$\lvert C_{ij}\rvert = 1$	Tree level	1×10^3	3×10^2	2×10^3	4×10^2	2×10^3	5×10^2
(No hierarchy)	One loop	80	20	2×10^2	30	2×10^2	40

Conclusions

- Flavour physics: crucial in **shaping the SM**, but also in looking for **candidates of NP**
- **V_{cb}: tests of CKM unitarity**
- $|\Delta B|=2$: only one flavour aspect of future experimental and theoretical progress
- Allowed NP in B meson mixing **still large**: bounds will largely improve
- Identified future limitations in Phase II:

LQCD and $|V_{cb}|$ → bounds on NP at 1-2% of SM

THANKS!

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

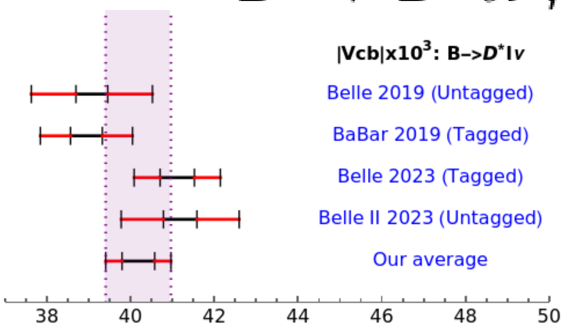
BACK UP!

CKMfitter 2023 inputs for $|V_{cb}|$

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

[Belle II untagged: 2310.01170]

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

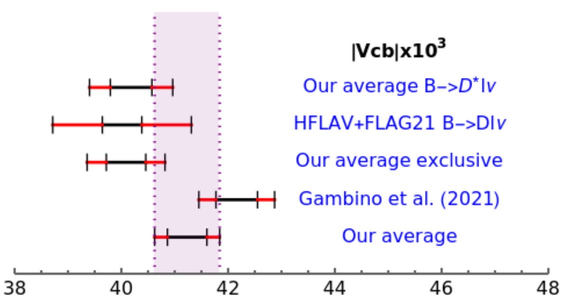


[Belle '19 (untagged), BaBar '19 (untagged); preliminary Belle (tagged) & Belle II (untagged)]

[preliminary combination of lattice inputs]

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

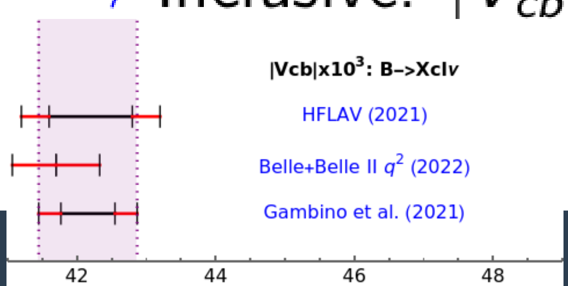
- $B \to D \ell \nu$, BCL: $|V_{cb}|_{B\to D} = (40.00 \pm 0.93 \pm 0.37) \times 10^{-3}$



[HFLAV+FLAG 2021 combination]

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

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



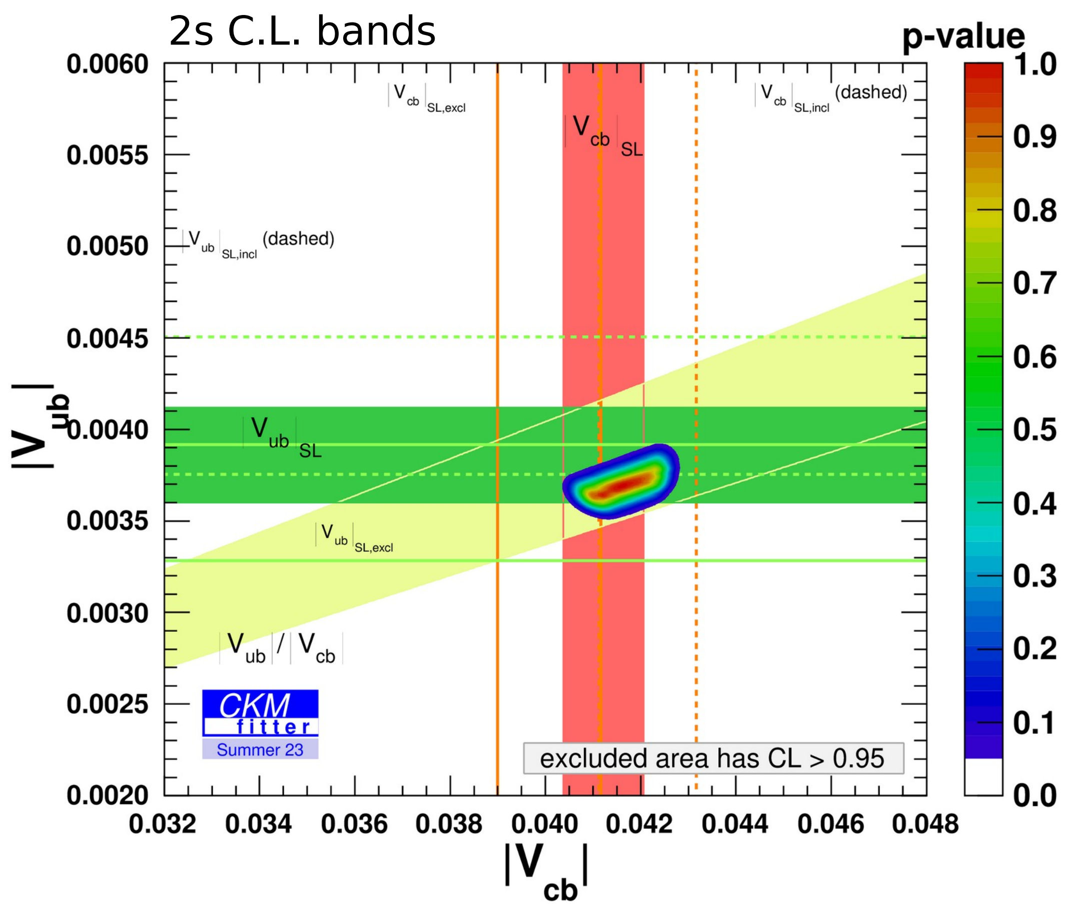
[Fael, Schönwald, Steinhauser '20 '20 '20; Bordone, Capdevila, Gambino '21]

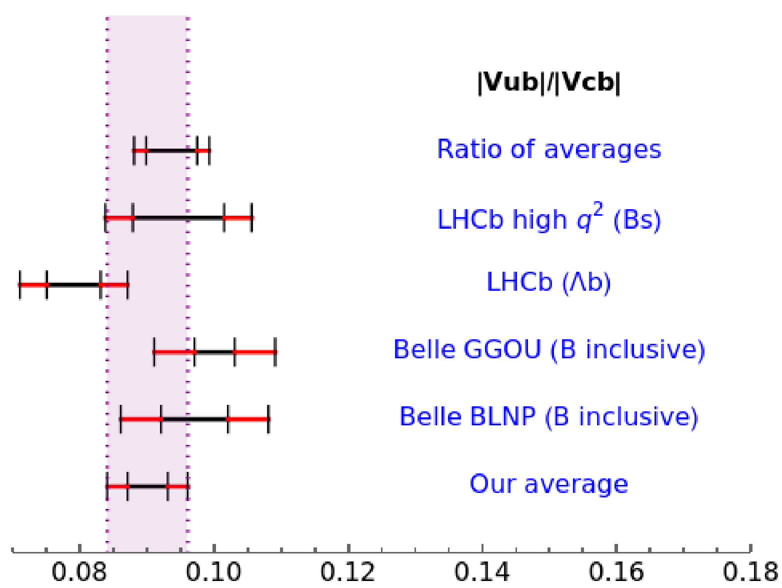
$|V_{ub}|$ and $|V_{cb}|$ plane

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





Experimental quantities vs. theoretical ones

Observables considered in the fit that are modified by NP in |ΔB|=2:

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

parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{\mathrm{NP}}\rvert \times \Delta m_q^{\mathrm{SM}}$
2β	$2\beta^{\mathrm{SM}} + \Phi_d^{\mathrm{NP}}$
$2\beta_s$	$2\beta_s^{\mathrm{SM}} - \Phi_s^{\mathrm{NP}}$
2α	$2(\pi - \beta^{\mathrm{SM}} - \gamma) - \Phi_d^{\mathrm{NP}}$
$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}}$
A_{SL}^q	$\frac{\Gamma_{12,q}}{M_{12,q}^{\mathrm{SM}}} \times \frac{\sin(\Phi_{12,q}^{\mathrm{SM}}+\Phi_q^{\mathrm{NP}})}{\lvert\Delta_q^{\mathrm{NP}}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})$

Experimental and theoretical inputs

	Central values	Uncertainties				Reference Phases I–III
		Current [28]	Phase I	Phase II	Phase III	
$\|V_{ud}\|$	0.97437	± 0.00021	id	id	id	[28]
$\|V_{us}\| f_+^{K\to\pi}(0)$	0.2177	± 0.0004	id	id	id	[28]
$\|V_{cd}\|$	0.2248	± 0.0043	± 0.003	id	id	[40,41]
$\|V_{cs}\|$	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]
$\|V_{cb}\|_{SL} \times 10^3$	42.26	± 0.58	± 0.60	± 0.44	id	[29]
$\|V_{cb}\|_{W\to cb} \times 10^3$		…	…	…	± 0.17	[34–36]
$\|V_{ub}\|_{SL} \times 10^3$	3.56	± 0.22	± 0.042	± 0.032	id	[29]
$\|V_{ub}/V_{cb}\|$ (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]	-0.035	± 0.021	± 0.014	± 0.004	± 0.002	[30,34]
$A_{SL}^d \times 10^4$	-6	± 19	± 5	± 2	± 0.25	[14,17,34,37]
$A_{SL}^s \times 10^5$	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]

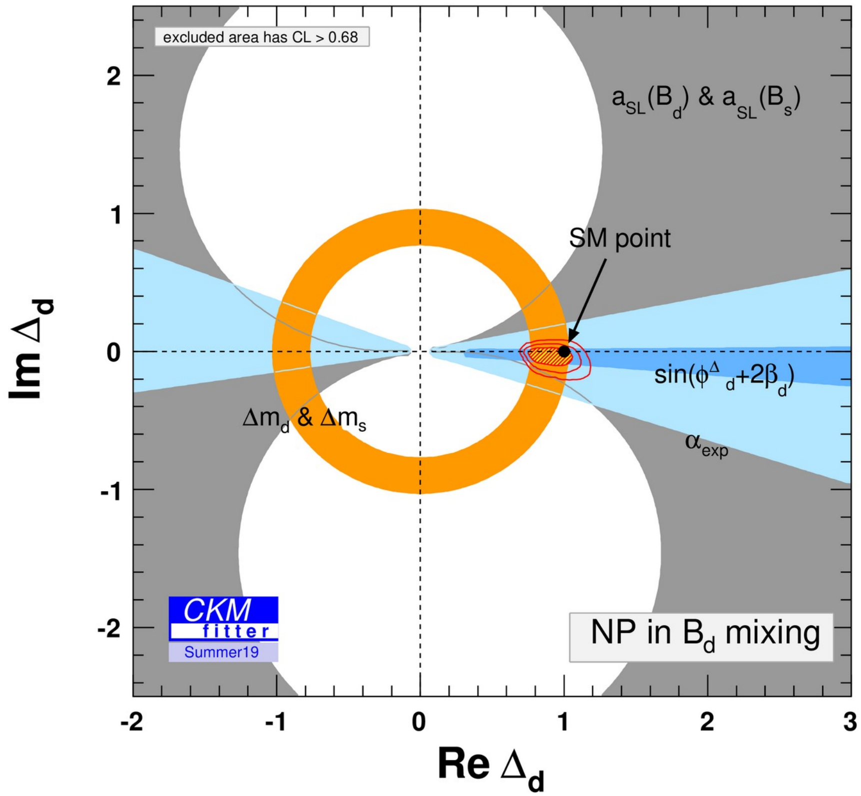
[See for refs.: PRD 102, 056023 (2020), arXiv:2006.04824
and also EPJPlus 136, 837 arXiv:2106.01259,
and EPJPlus 136, 912 arXiv:2106.12168]

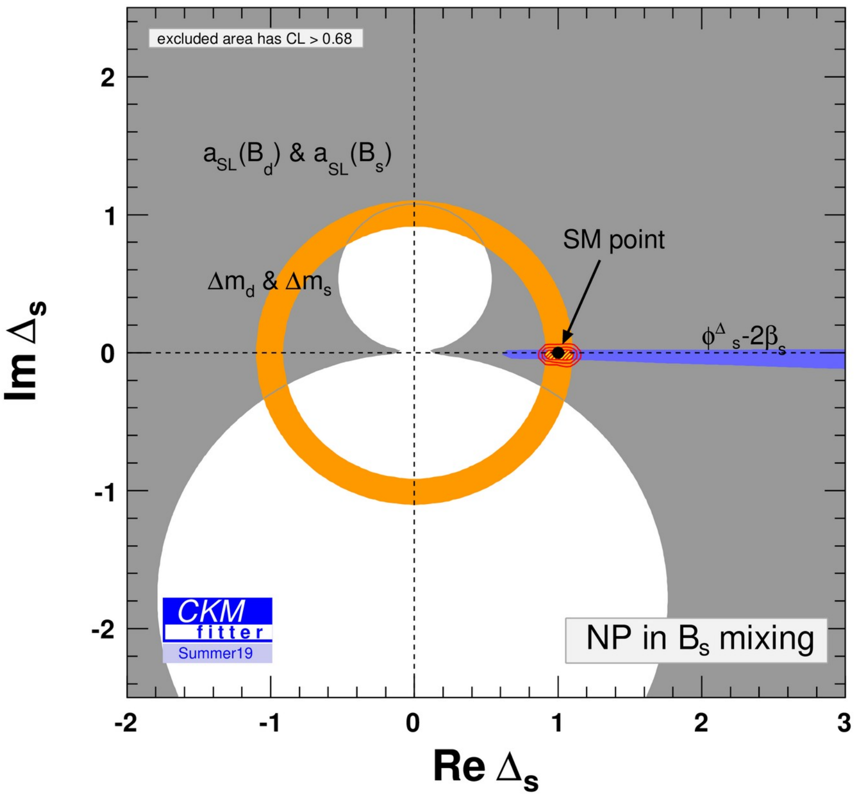
Different representation

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

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

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)





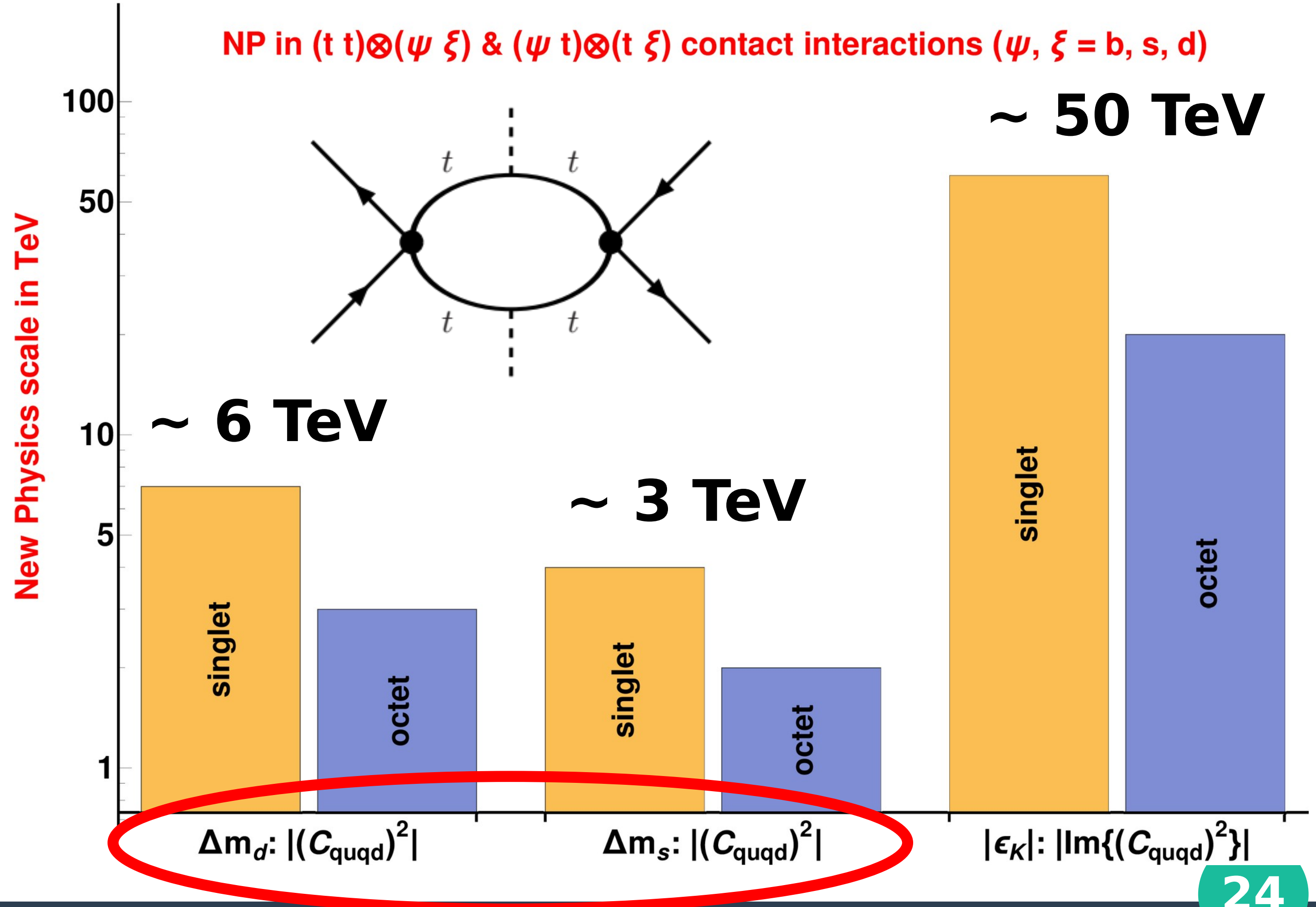
Current sensitivity to SMEFT dim.-8

|ΔF|=2 dim.-8: sensitivity to multi-TeV NP effects

- |ΔF|=2 dim.-6 operators: previous slide set bounds for (V-A)x(V-A)
- (|ΔF|=1 dim.-6)^2=(|ΔF|=2 dim.-8 operators)
- |ΔF|=1 quqd-operator does not change global fit analysis

NP bag parameters: [ETM ’15, HPQCD ’19]

[LVS, arXiv:2201.03038]



Discovery prospects

B meson mixing observables also provide potential **discovery for NP**