Recent CKMfitter updates on global fits of the CKM matrix

Wenbin Qian

University of Chinese Academy of Sciences

On behalf of the *CKM*fitter Collaboration

CKM 2021

University of Melbourne, Australia (Online)

*CKM*fitter

- **Theorists + experimentalists performing a global analysis of measurements (inputs from HFLAV, FLAG) determining the CKM matrix parameters in the framework of the SM and some of extensions**

ckmfitter-l@in2p3.fr

Jérôme Charles	Theory	CPT Marseille (France)
Olivier Deschamps	LHCb	LPC Clermont-Ferrand (France)
Sébastien Descotes-Genon	Theory	LPT Orsay (France)
Stéphane Monteil	LHCb	LPC Clermont-Ferrand (France)
Jean Orloff	Theory	LPC Clermont-Ferrand (France)
Wenbin Qian	LHCb	University of Chinese Academy of Sciences (China)
Vincent Tisserand	LHCb/BABAR	LPC Clermont-Ferrand (France)
Karim Trabelsi	Belle/Belle II	LAL Orsay (France)
Philip Urquijo	Belle/Belle II	Melbourne Universiy (Australia)
Luiz Vale Silva	Theory	Univ. Sussex (UK)

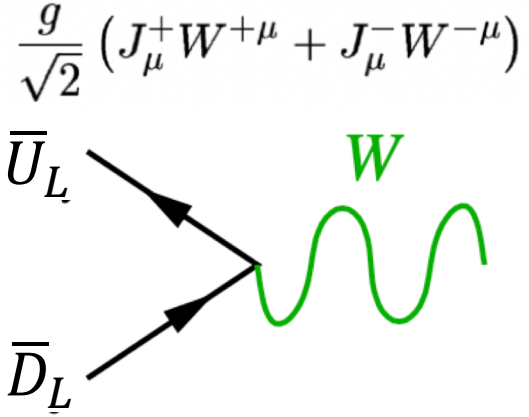
CKM matrix

- **Yukawa couplings not necessarily diagonalized in interaction eigenstates⟹ mass eigenstates different from interaction eigenstates**
- **Unitary matrix needed to diagonalize mass matrix**

$$J_\mu^+ = \bar{U}_L^I \gamma_\mu D_L^I + \bar{\nu}_L^I \gamma_\mu \ell_L^I,$$

$$J_\mu^+ = \bar{U}_L \gamma_\mu V_{CKM} D_L + \bar{\nu}_L \gamma_\mu \ell_L,$$

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

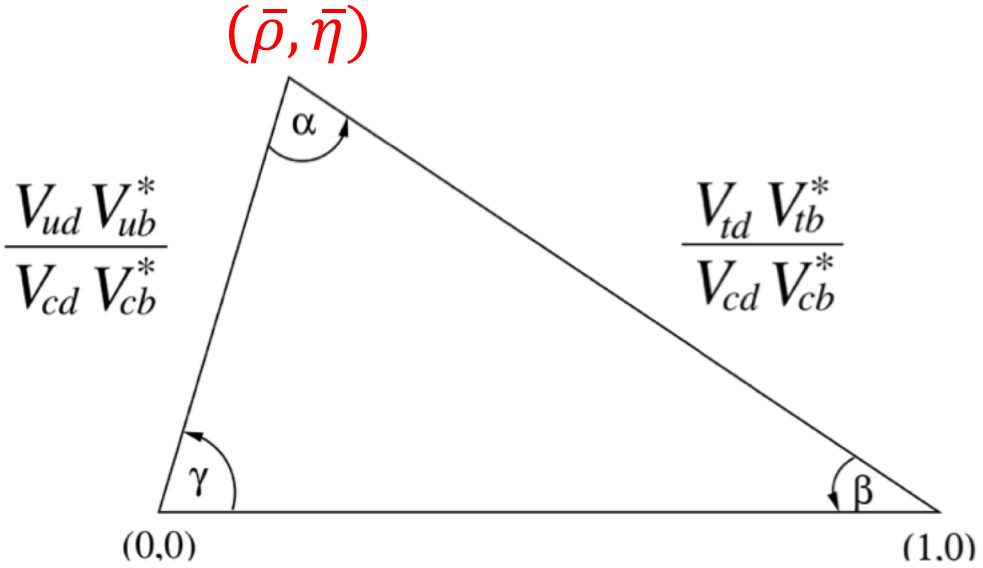


- **One complex phase (3 generations) for CP violation in SM**
- **Constraints from unitary conditions:**

$$\sum_{i \text{ or } j} V_{ij} V_{ij}^* = 1 \qquad \sum_i V_{ij} V_{ik}^* = 0 \qquad \sum_j V_{ij} V_{kj}^* = 0$$

Unitary triangle and parameter definition

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



- **Most popular one: similar size of three angles**
- **Closely related to B decays**

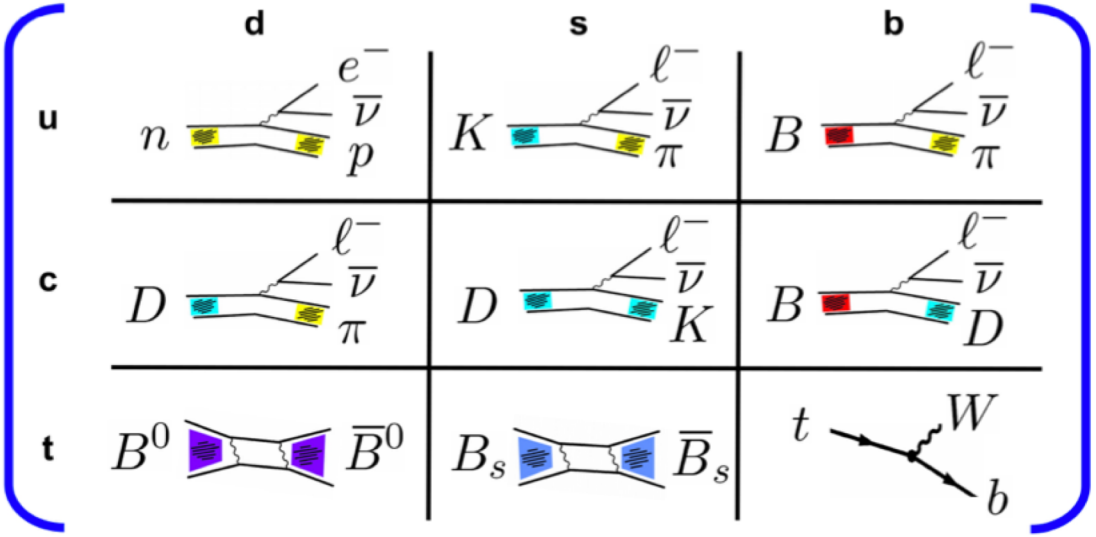
Wolfenstein parameterization:

$$\lambda^2 = \frac{V_{us}V_{us}^{*}}{V_{ud}V_{ud}^{*} + V_{us}V_{us}^{*}} \qquad A^2\lambda^4 = \frac{V_{cb}V_{cb}^{*}}{V_{ud}V_{ud}^{*} + V_{us}V_{us}^{*}} \qquad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}$$

X and y axis

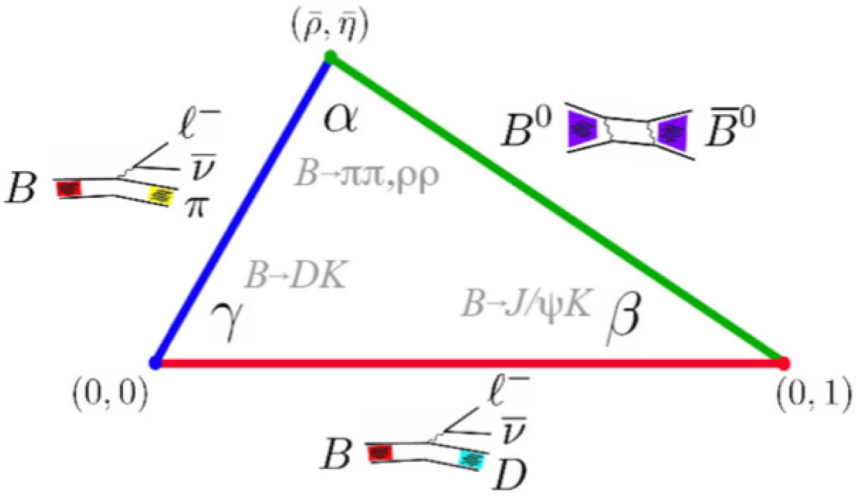
CKM observables (1)

$V =$



- $|V_{ud}|$: superallowed nuclear β decays
- $|V_{us}|$: $K \to \pi l \nu, K \to l \nu, \tau \to K \nu$ etc. + form factors, decay constants
- $|V_{cs}|, |V_{cd}|$: (semi-)leptonic charm decays + Lattice inputs
- $|V_{ub}|, |V_{cb}|$: (semi-)leptonic B decays + Lattice inputs
- $|V_{td}|, |V_{ts}|$: $\Delta m_d, \Delta m_s$ + bag parameters, decay constants

CKM observables (2)



- $\boldsymbol{\alpha}$: $\boldsymbol{B \to \pi\pi, B \to \rho\pi, B \to \rho\rho}$, isospin analyses
- $\boldsymbol{\beta}$: $\boldsymbol{B \to (\bar{c}c)K, B \to Dh^0}$, time-dependent CP violation
- $\boldsymbol{\gamma}$: $\boldsymbol{B \to DK}$, ADS/GLW/GGSZ
- $\boldsymbol{\phi_s}$: $\boldsymbol{B_s^0 \to (c\bar{c})(KK, \pi\pi)}$, time-dependent CP violation
- $-2\beta_s + \gamma$: $B_s \to D_s K$, not included yet
- $\boldsymbol{V_{td}^* V_{ts}}$ and $\boldsymbol{V_{cd}^* V_{cs}}$: $\boldsymbol{\epsilon_K}$ + lattice inputs

Statistical approach

- **Frequentist statistics based on a χ^2 analysis**
- **χ^2_{min}: indication of goodness-of-fit**
- **$\Delta\chi^2$: calculation of Confidence Level (CL) or p-values**
- ***Range* fit scheme (*R*fit): special treatment of theoretical uncertainties**

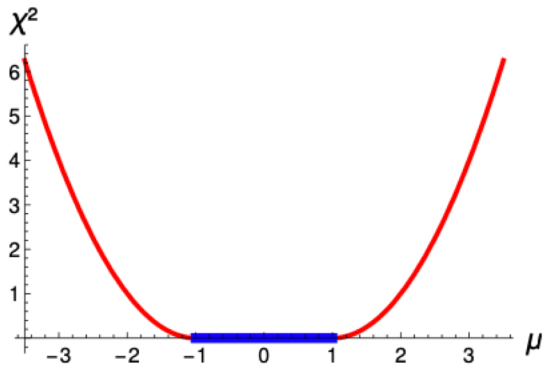
Theoretical inputs: mainly from Lattice papers (with error budgets); different systematic uncertainties combined linearly

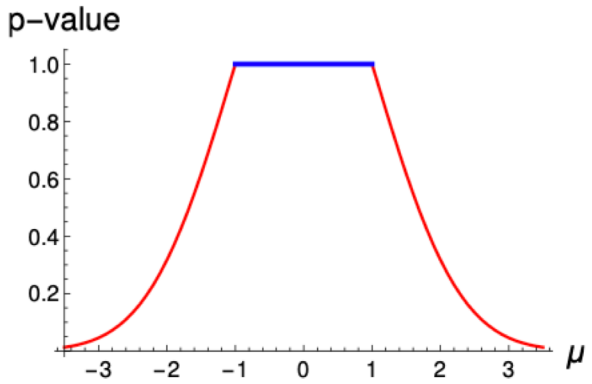
Example in 1D, $0 \pm 1_{stat} \pm 1_{theo}$ $(N_{dof} = 1)$

Treated as Gaussion

$\mathcal{L} = \mathcal{L}_{exp} \times \mathcal{L}_{theo}$

Treated as range





χ^2: flat bottom, quadratic walls

Charles, Descotes-Genon, Niess, Vale Silva 17

Recent updates on V_{ud}

- **Precision on $|V_{ud}|$ led by superallowed $0^+ \rightarrow 0^+$ nuclear β decays**
- **2020 survey by Hardy and Towner, including recent calculations for radiative corrections and new improved measurements**

NEW **Theoretical**

$$V_{ud} = 0.97373 \pm 0.00031$$

Our 2019 update (also from Hardy and Towner)

$$V_{ud} = 0.97418 \pm 0.00021$$

- **V_{ud} smaller by 0.00045, while uncertainties larger by 50%**
- **V_{ud} from our fits without direct measurements**

INDIRECT

$$V_{ud} = 0.97440 \pm 0.00006$$

- **Some tension seen if using new V_{ud} input directly without careful consideration**
- **Considering properly error budget from Hardy and Towner, in this update, we use**

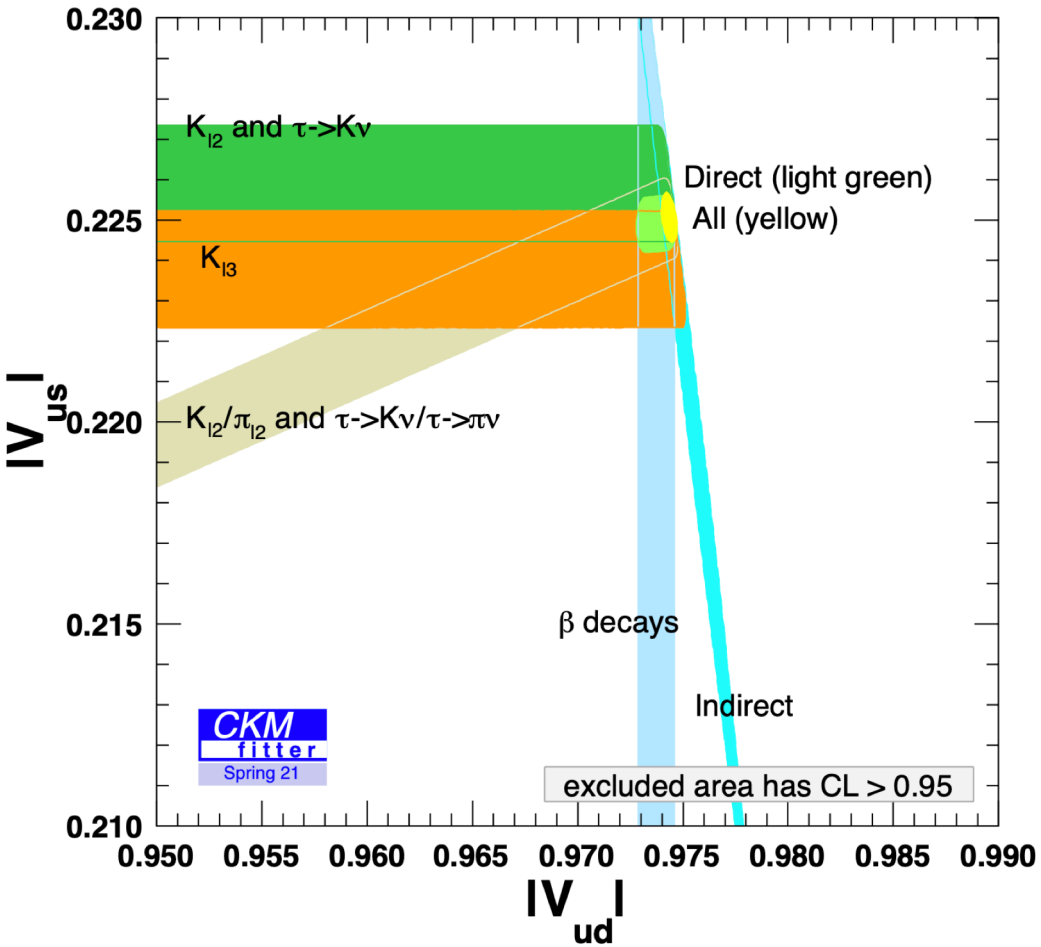
Our 2021 update

statistical **theoretical**

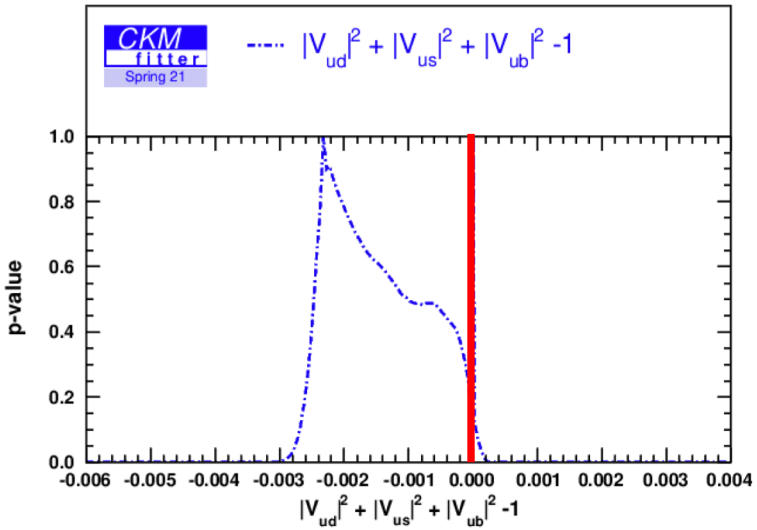
$$V_{ud} = 0.97373 \pm 0.00009 \pm 0.00053$$

Theoretical uncertainties summed up linearly

V_{ud} Vs V_{us}



- $|V_{us}|$ from $K \to l\nu, K \to \pi l\nu, \tau \to K\nu, \tau \to \pi\nu$ etc
- Still consistent with unitary $< 2\sigma$



$$V_{ud}V_{ud}^* + V_{us}V_{us}^* + V_{ub}V_{ub}^* - 1 = -0.00230^{+0.00218}_{-0.00023}\ (1\sigma)$$

$$-0.00230^{+0.00237}_{-0.00044}\ (2\sigma)$$

$$-0.00230^{+0.00242}_{-0.00065}\ (3\sigma)$$

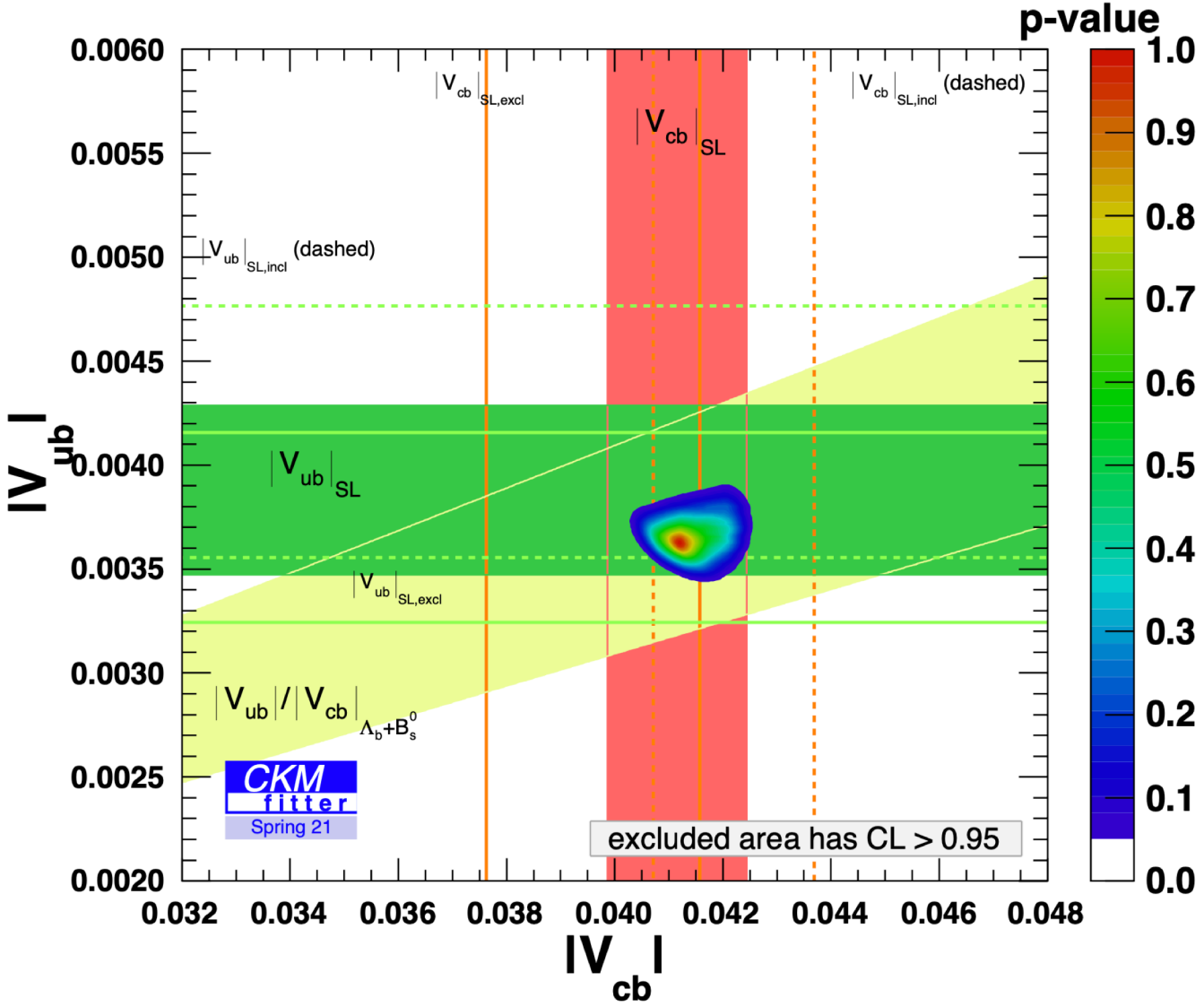
V_{ub} and V_{cb}

- Very small change on inclusive and exclusive V_{ub} and V_{cb} measurements

	Inclusive	Exclusive	Average
$V_{ub}(\times 10^{-3})$	$4.16 \pm 0.12 \pm 0.31$	$3.70 \pm 0.10 \pm 0.21$	$3.88 \pm 0.08 \pm 0.21$
$V_{cb}(\times 10^{-3})$	$42.2 \pm 0.4 \pm 0.5$	$39.6 \pm 0.6 \pm 0.5$	$41.15 \pm 0.34 \pm 0.45$

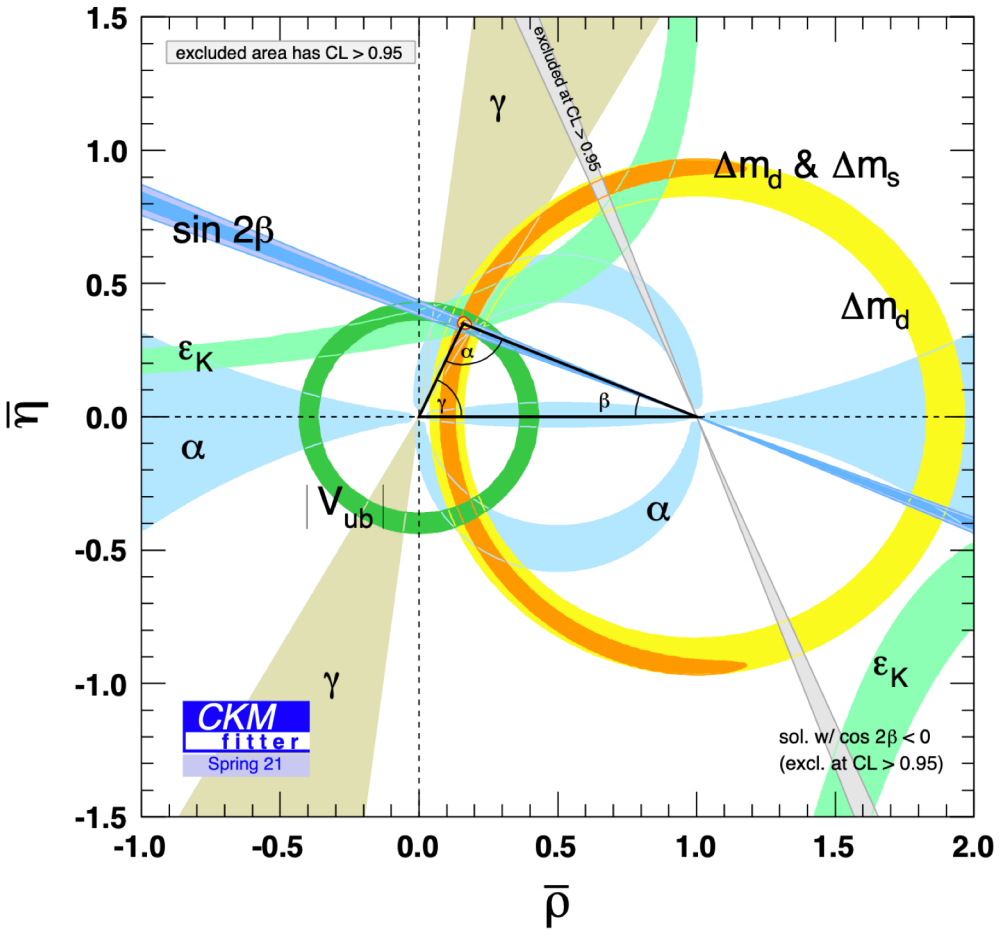
- New measurements of partial branching fractions of inclusive $B \to X_u l\nu$ decays with hadronic tagging (arXiv:2102.00020) included for V_{ub} inclusive
- V_{cb} exclusive: based on 2020 BGL refit with preliminary non-zero recoil FF ratio JLQCD inputs and new $D \to K\pi$ BF
- New ratio of $|V_{ub}|/|V_{cb}|$ from $B_s^0 \to K^+\mu^-\nu_\mu$ and $B_s^0 \to D_s^+\mu^-\nu_\mu$ (arXiv:1901.02561), only take high q^2 region which uses LQCD inputs (tension between high and low q^2)
- New $|V_{cb}|$ measurements from LHCb (arXiv:2001.03225) not used as knowledge of $B \to D^* l\nu$ required, care needed to consider larger correlations for $|V_{cb}|$ from these measurements

V_{ub} vs V_{cb}


p-value
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0060
0.0055
0.0050
0.0045
0.0040
0.0035
0.0030
0.0025
0.0020
0.032
0.034
0.036
0.038
0.040
0.042
0.044
0.046
0.048
|V_ub|
|V_cb|
|V_cb|_SL,excl
|V_cb|_SL
|V_cb|_SL,incl (dashed)
|V_ub|_SL,incl (dashed)
|V_ub|_SL
|V_ub|_SL,excl
|V_ub|/|V_cb|_Λb+Bs0
CKM fitter
Spring 21
excluded area has CL > 0.95

Current status

- **Inputs till spring 2021 (Moriond)**
- **χ^2 slightly increased compared to 2019 update，p-value ~ 29%**



Wolfenstein parameters:

$$A = 0.8132^{+0.0119}_{-0.0060}$$

$$\lambda = 0.25500^{+0.00024}_{-0.00022}$$

$$\bar{\rho} = 0.1566^{+0.0085}_{-0.0048}$$

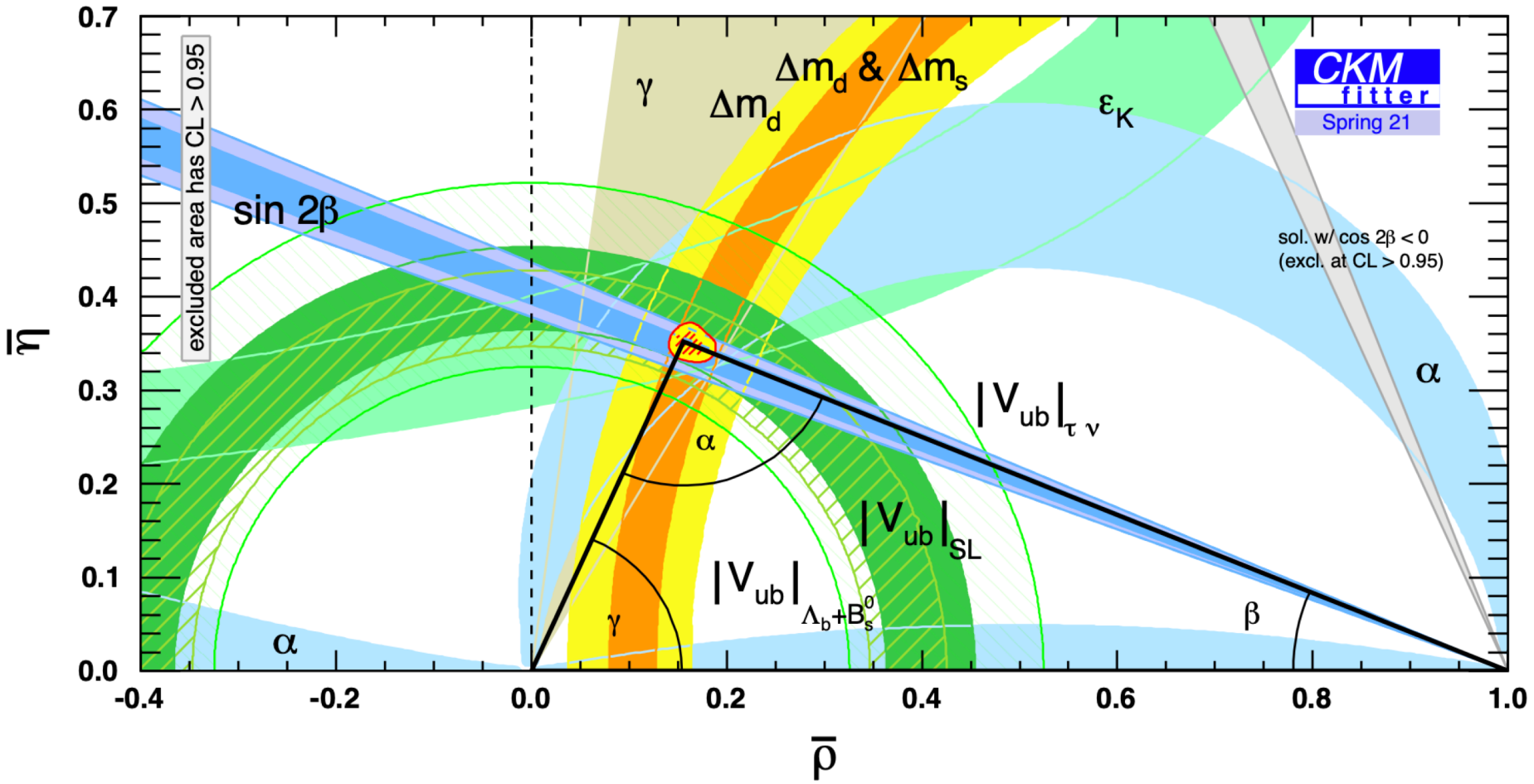
$$\bar{\eta} = 0.3475^{+0.0118}_{-0.0054}$$

Jarlskog invariant:

$$J = (3.044^{+0.068}_{-0.084}) \times 10^{-5}$$

@ 68% CL.

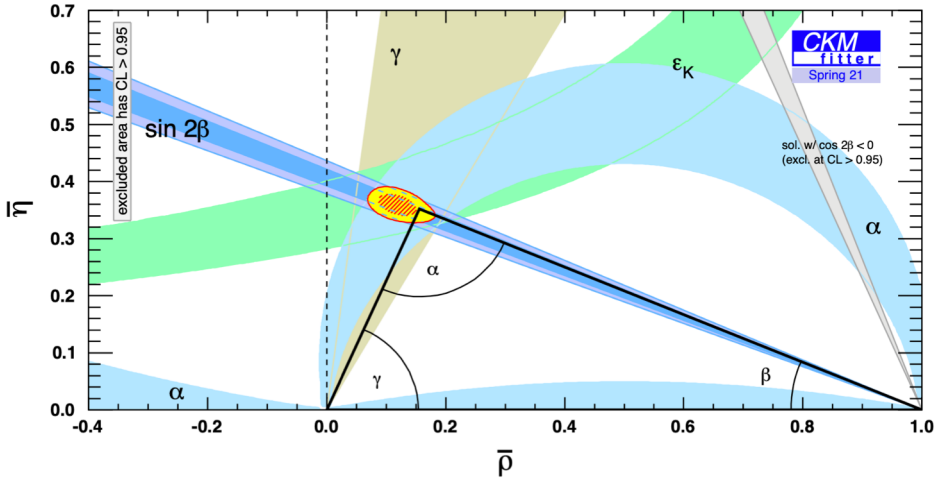
Zoomed version



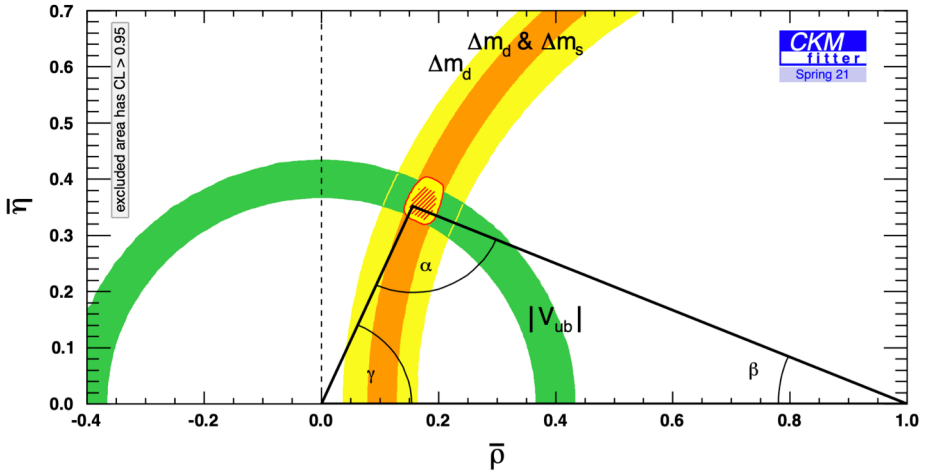
- **Different contributions for $|V_{ub}|$ from $B \to \tau\nu$, inclusive + exclusive semi-leptonic measurements and $|V_{ub}|/|V_{cb}|$ ratio measurements are explicitly shown**

Fits from different subsets

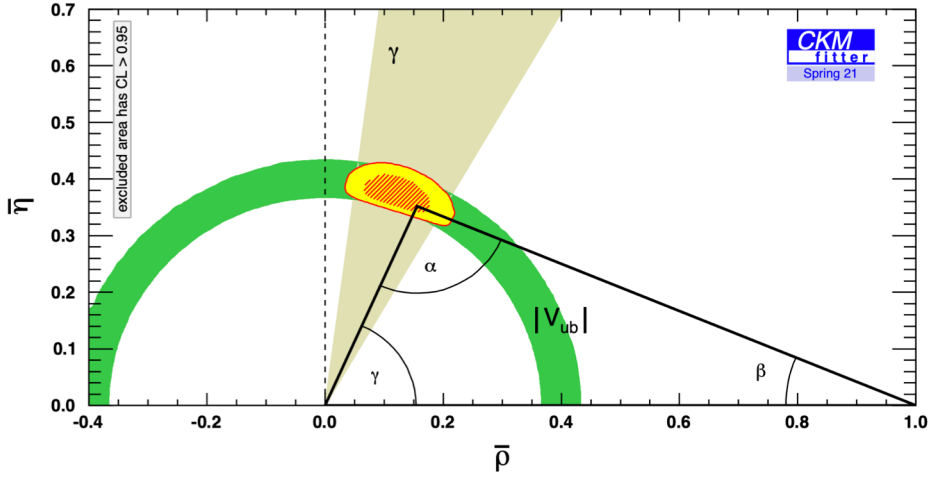
CP violating



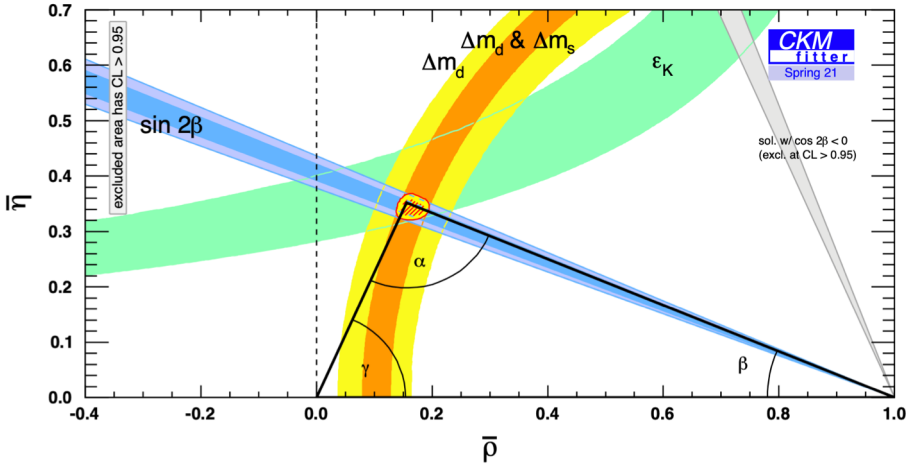
CP conserving



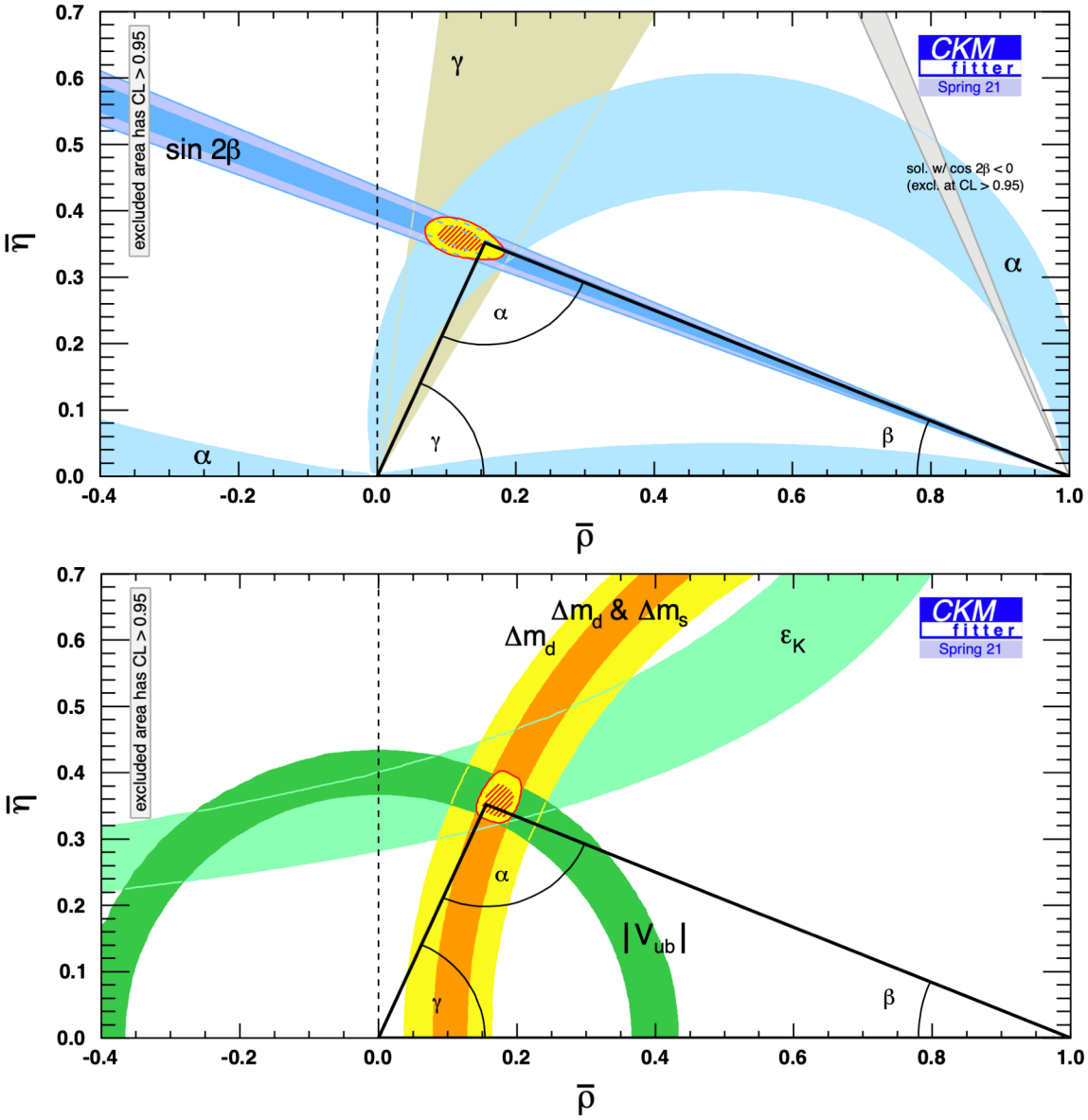
Tree



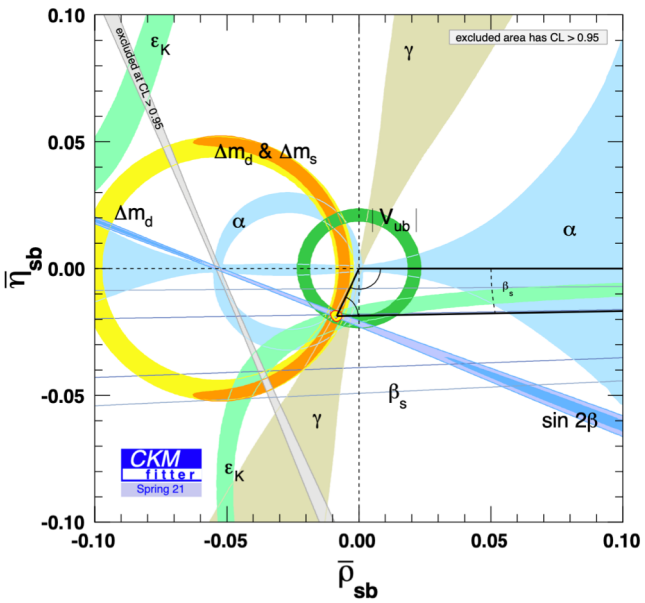
Loop

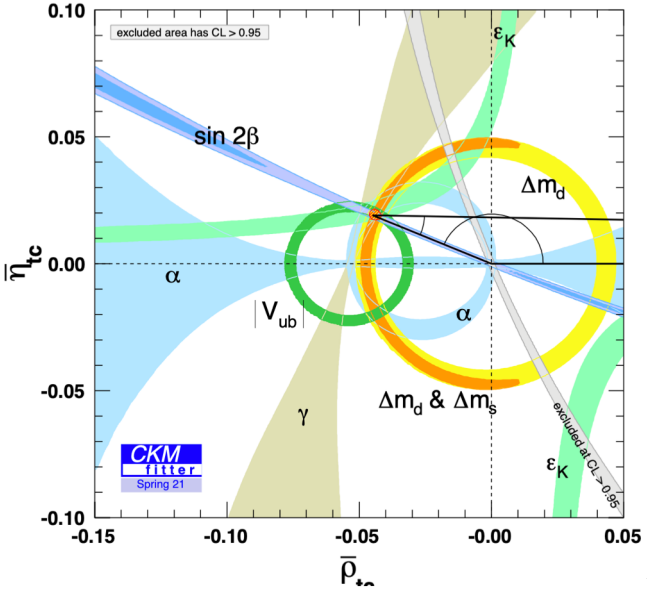


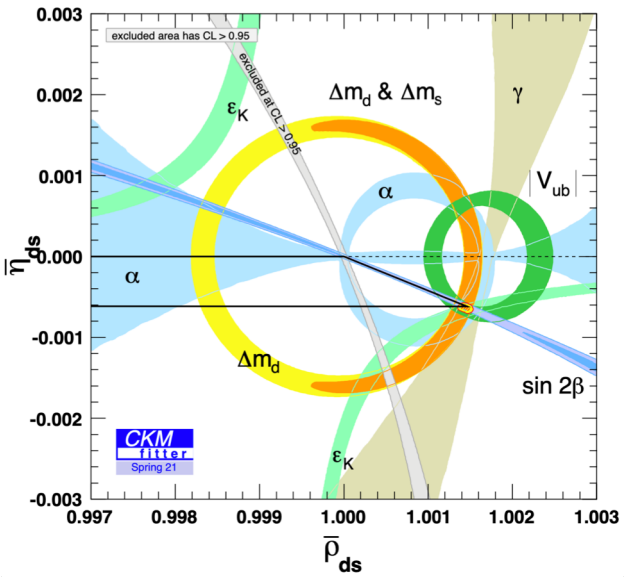
Angle vs magnitude

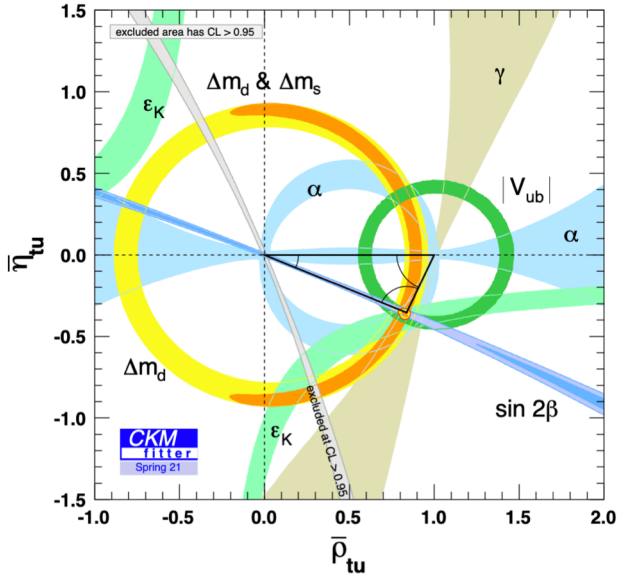


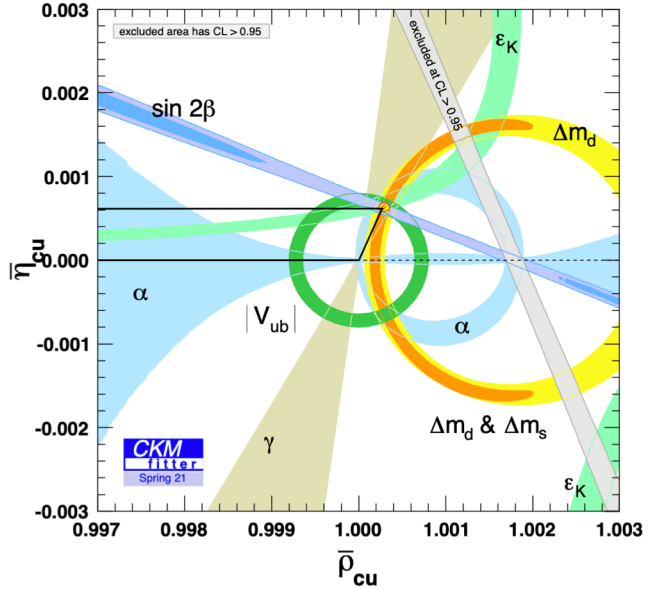
Other triangles





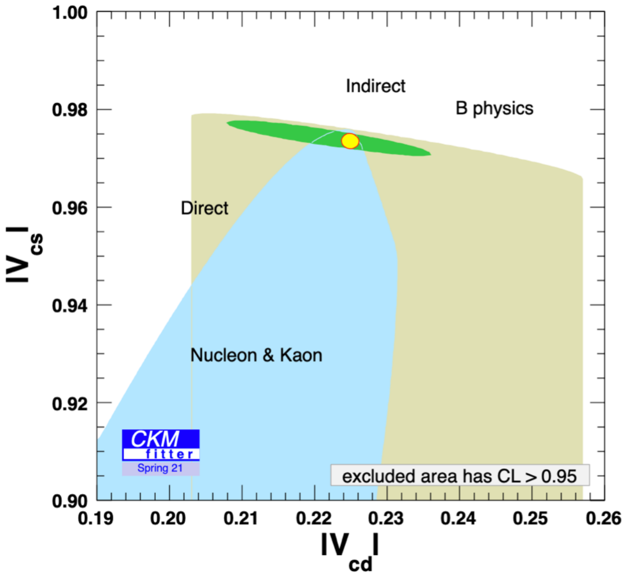


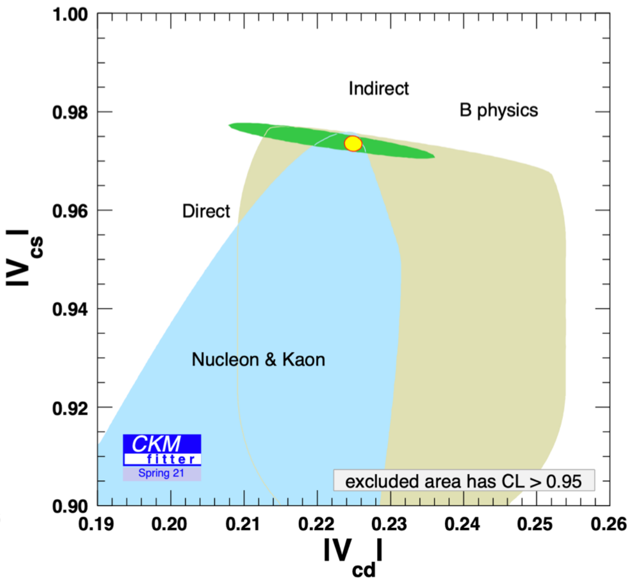


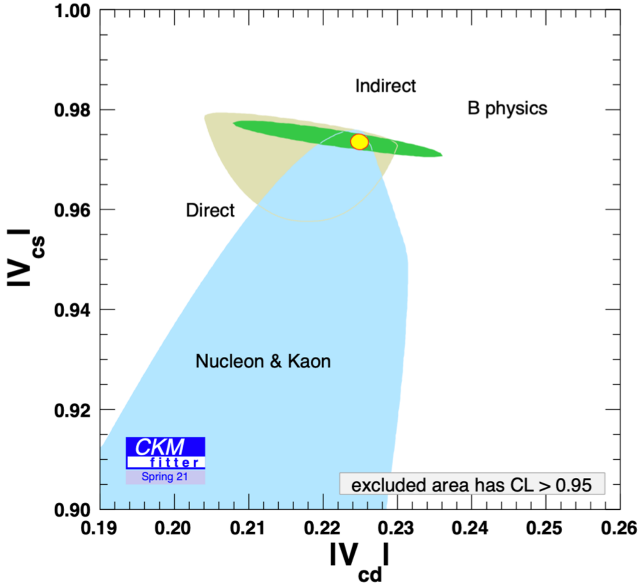


Consistency over all triangles

V_{cd} vs V_{cs}







$|V_{cd}|$: $\nu - N$ scattering

$|V_{cs}|$: W decay

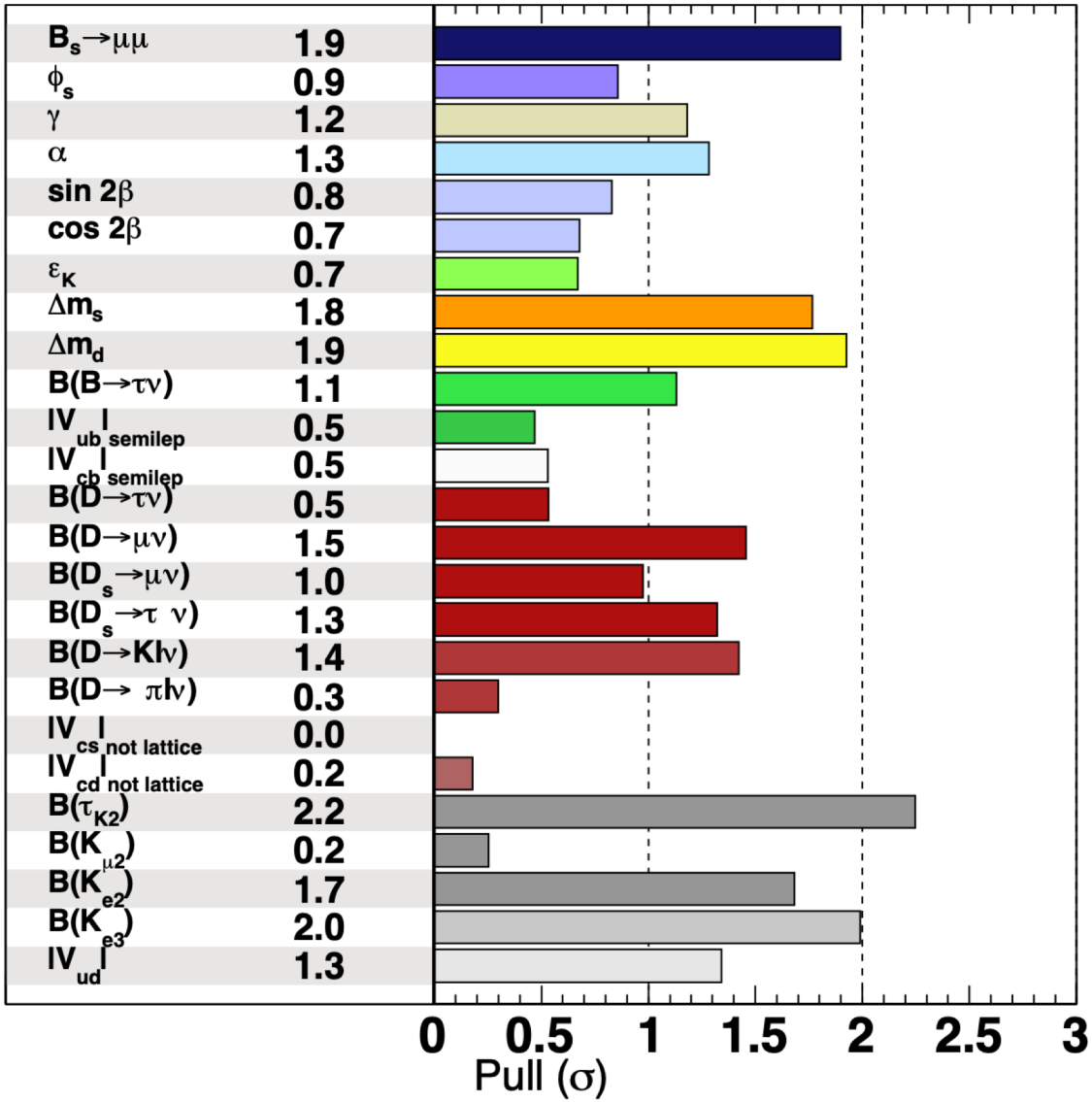
Semi-leptonic D decays

Leptonic D decays

Also other CKM elements + predictions for Br., ϕ_s etc.

	Direct	Indirect
$\lvert V_{cs}\rvert$	$0.97508^{+0.00082}_{-0.00668}$	$0.97358^{+0.00015}_{-0.00026}$
$\lvert V_{cd}\rvert$	0.2220 ± 0.0038	0.22483 ± 0.00030

Pull



$$\text{Pull} = \sqrt{\chi^2_{\text{min}} - \chi^2_{\text{min,!obser.}}}$$

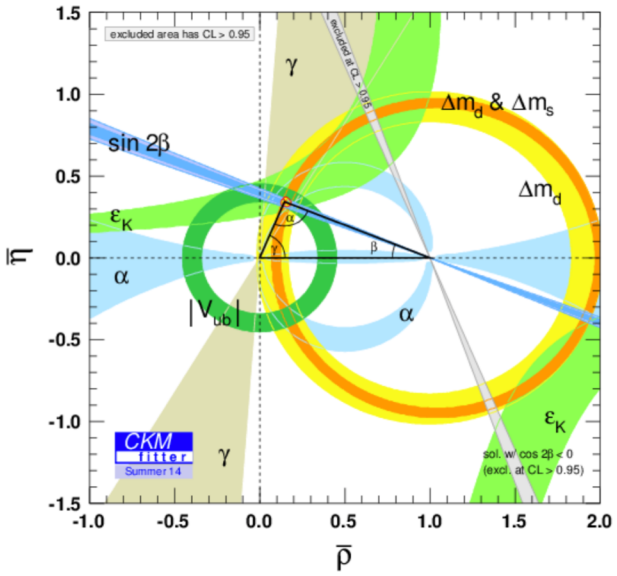
No clear discrepancy seen

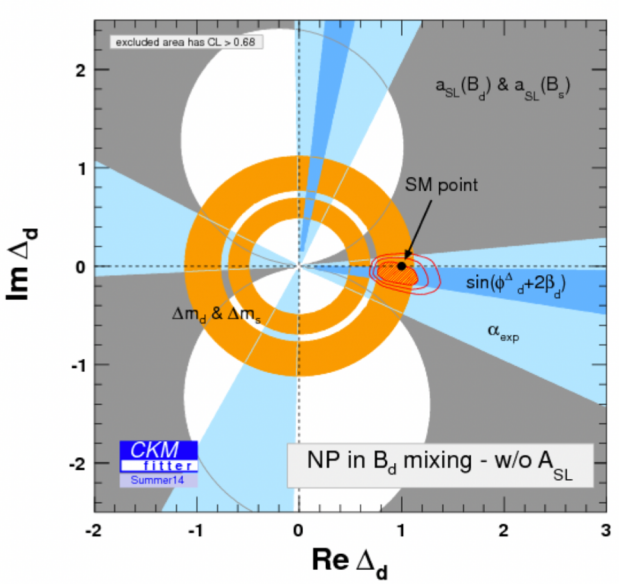
Some pull = 0 due to Rfit treatment of systematic uncertainties (theory)

CKMlive

- CKMlive: run dedicated analyses with the CKMfitter software
- Your inputs: set of related observables, theoretical and experimental inputs, fitting parameters and relations between them
- Outputs:

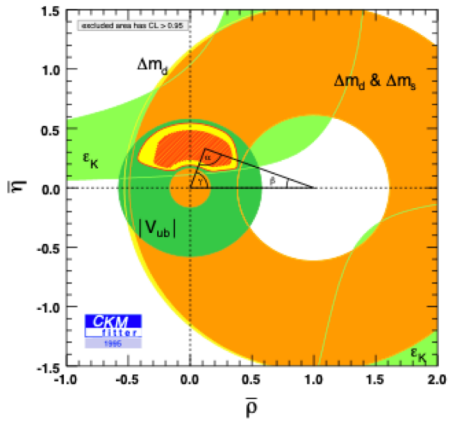
$$M_{12}^{q} = M_{12}^{SM,q} \cdot \Delta_q$$



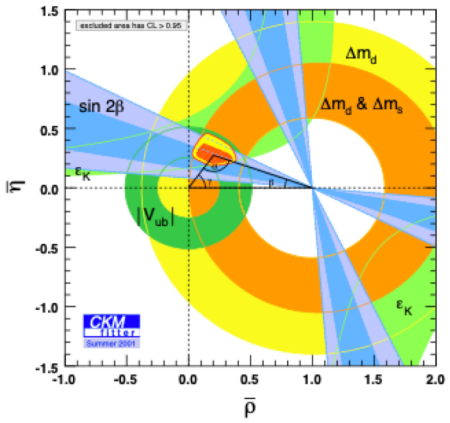


- Supports: ckmlive@clermont.in2p3.fr for questions; tutorial available

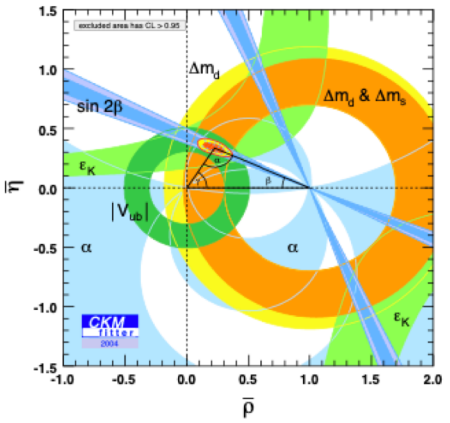
CKM status over years



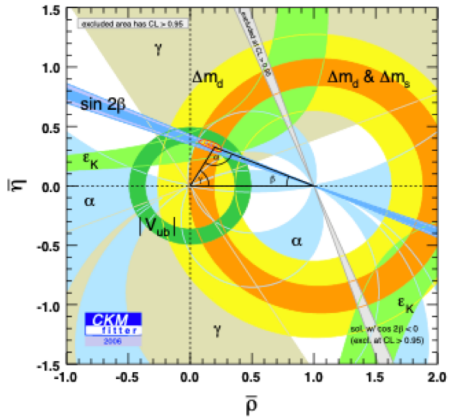
1995



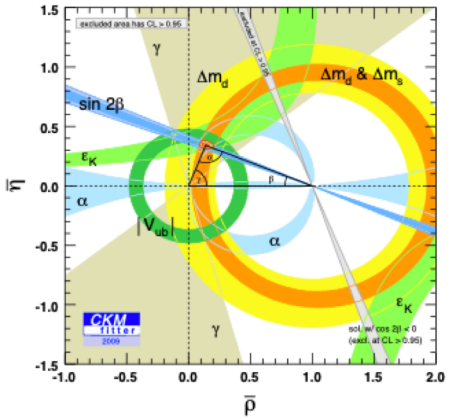
2001



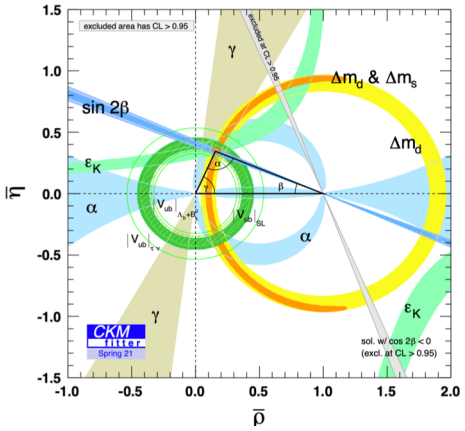
2004



2006



2009



2021

Thank you for your attention

Recent updates on V_{ud}

- **Precision on $|V_{ud}|$ led by superallowed $0^+ \rightarrow 0^+$ nuclear β decays**
- **2020 survey by Hardy and Towner, including recent calculations for radiative corrections:**

$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

Δ_R^V: process independent radiative correction

Reference	$\Delta_R^V(\%)$	
Marciano and Sirlin [186] 2006	2.361 ± 0.038	**OLD**
Seng *et al.* [187,188] 2018/19	2.467 ± 0.022	
Czarnecki, Marciano and Sirlin [189] 2019	2.426 ± 0.032	**Two new cal.**
Adopted value	2.454 ± 0.019	**NEW (averaged)**

δ_{NS} shifted G_V^2 to smaller values by 0.09%

Recent updates on V_{ud}

- **Precision on $|V_{ud}|$ led by superallowed $0^+ \rightarrow 0^+$ nuclear β decays**
- **2020 survey by Hardy and Towner, including recent calculations for radiative corrections:**

$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

$\mathcal{F}t$ merely changes

Uncertainties on $\mathcal{F}t$ larger (2.6 times) due to new theoretical terms in δ_{NS}