Past, Present and Future in Flavor Physics, the Unitary Triangle Fit, Anomalies and all that

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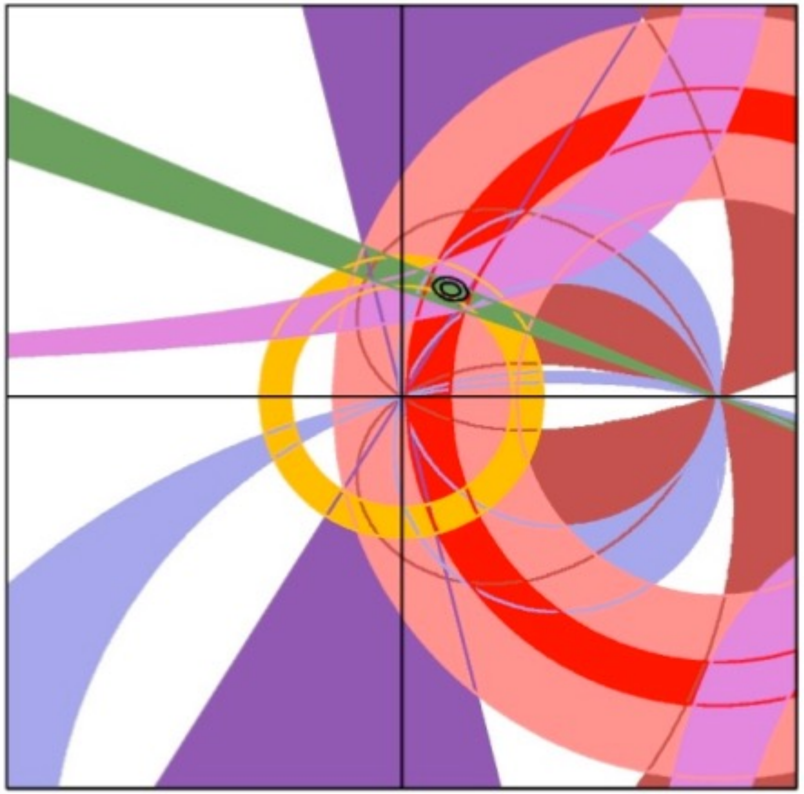
PLAN OF THE TALK



- *The lesson from the past*
- *Flavor in the SM*
- *Utfit Analysis, Tensions and unknown*
- *Flavor Beyond the SM*
- *Future directions, new/old ideas*
- *Conclusion*

Thanks to
R.Barbieri, M. Bona, A. Di Domenico, G. Isidori,V. Lubicz, C. Sachrajda, L. Silvestrini, S. Simula, L. Vittorio

PAST of Flavour Physics

***1963:* Cabibbo Angle**
***1964:* CP violation in K decays ***
***1970* GIM Mechanism**
***1973:* CP Violation needs at least three quark families (CKM) ***
***1975:* discovery of the tau lepton – 3rd lepton family ***
***1977:* discovery of the b quark - 3rd quark family**
***2003/4:* CP violation in B meson decays**

*** Nobel Prize**

PRESENT: the Standard Model and beyond

Vacuum Energy

Hierarchy

Vacuum Stability

$$\mathcal{L} = \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 +$$

Higgs meson 2012

$$(D_\mu H)^2 + \bar{\psi} \not{D} \psi + F_{\mu\nu}^2 + F_{\mu\nu}\tilde{F}_{\mu\nu}$$

Strong $\not{CP}$

neutral currents 1973

charm quark 1974

$$Y H \bar{\psi}\psi + \frac{1}{\Lambda}(\bar{L}H)^2 + \frac{1}{\Lambda^2}\sum_i C_i O_i + \ldots$$

Buchmuller&Wyler '88

Flavor puzzle

Neutrino Masses

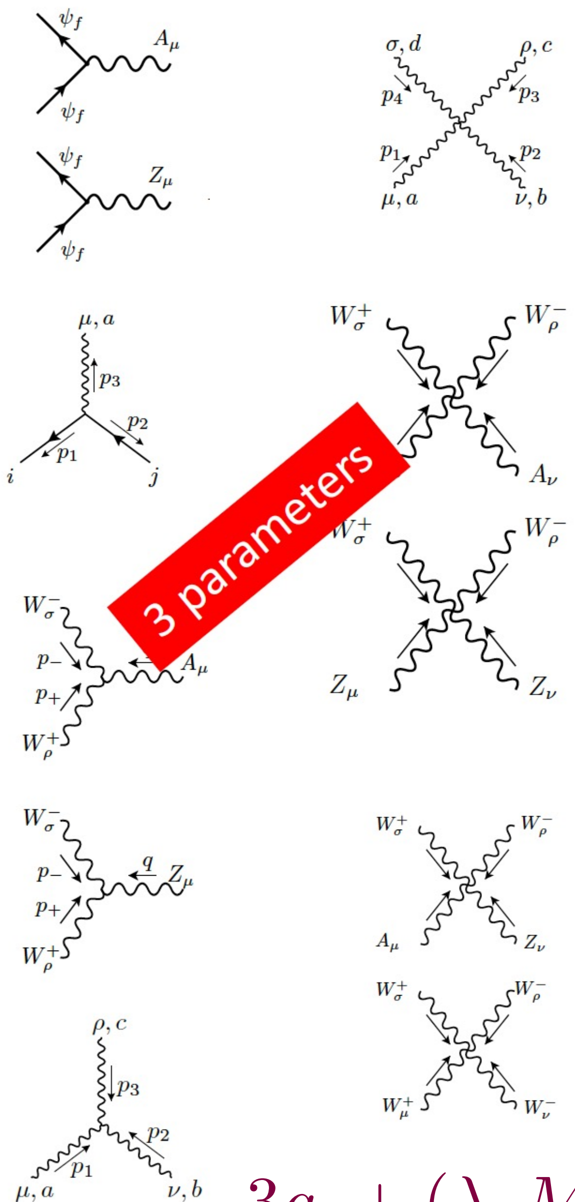
New Physics

Possible breaking of accidental symmetries

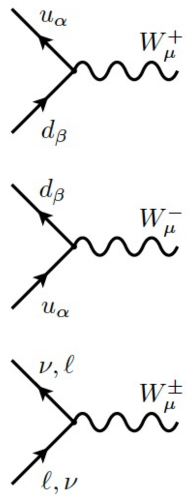
Only circled terms discussed in this talk

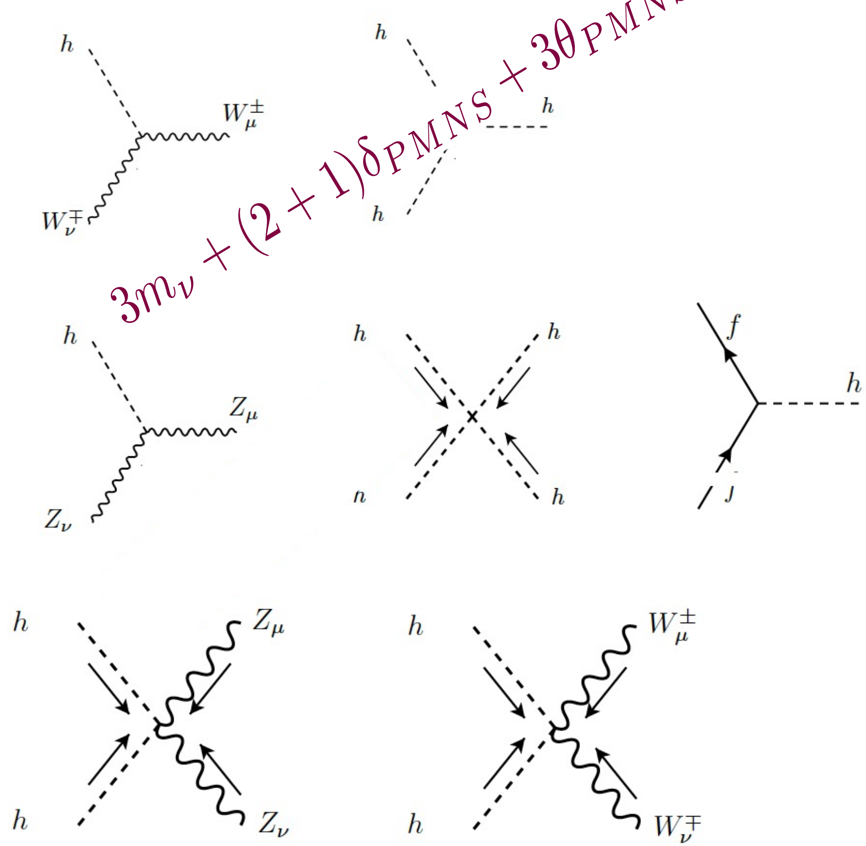
The Standard Model

$SU(3) \times SU(2) \times U(1)_Y$



Higgs + gauge principle





$3m_\nu + (2+1)\delta_{PMNS} + 3\theta_{PMNS} = 9$

from elegance to caos !!

If we are looking for the suspect that could be hiding some secret obviously the higgs is the one!

$$3g_i + (\lambda, M_H) + 6m_q + 3m_\ell + \delta + 3\theta_{CKM} + \theta_{QCD} = 19$$

The Weirdness of the Standard Model

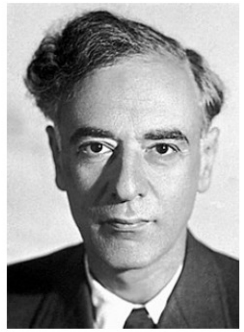
- Three families

$3m_\nu + (2+1)\delta_{PMNS} + 3\theta_{PMNS} = 9$

"who ordered that ?" I. Rabi

- Fundamental breaking of Parity

"space cannot be asymmetric!" L. Landau



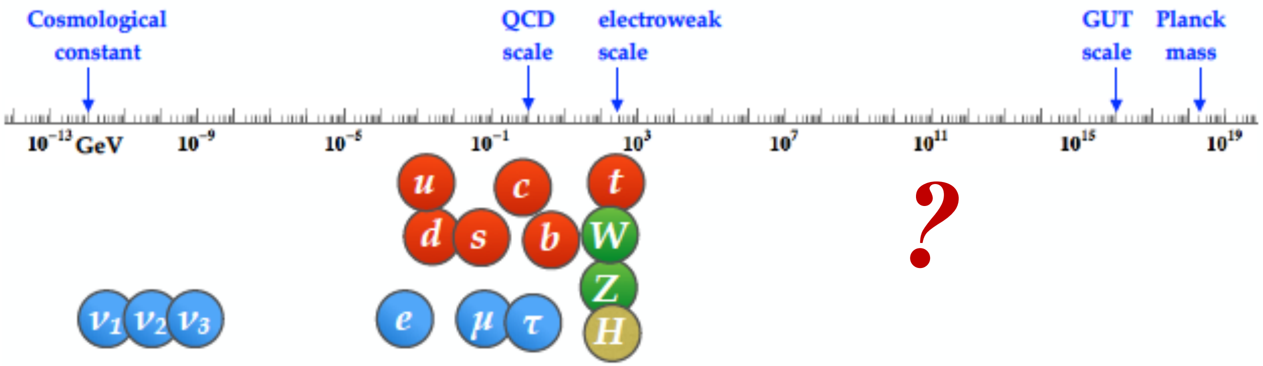
- Predictivity: 3 gauge couplings+ 16 higgs couplings (+ 7 higgs-neutrino) !
  + the coupling θ of strong CP violation

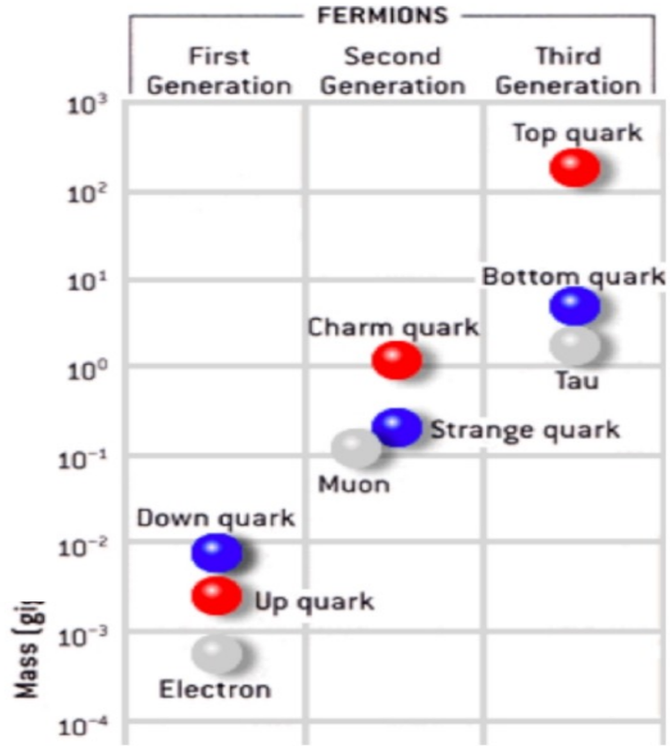
"has too many arbitrary features for [its] predictions to be taken very seriously" S. Weinberg '67

$$3g_i + (\lambda, M_H) + 6m_q + 3m_\ell + \delta + 3\theta_{CKM} + \theta_{QCD} = 19$$

Zupan

J. ZUPAN





$$m_\nu \leq 1\, eV$$

Illustration from a G. Isidori talk

Quark Masses from Lattice QCD

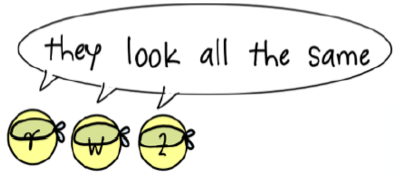
Input	Lattice/Exp
$m_u^{\overline{\rm MS}}(2\,\text{GeV})$	2.20(9) MeV
$m_d^{\overline{\rm MS}}(2\,\text{GeV})$	4.69(2) MeV
$m_s^{\overline{\rm MS}}(2\,\text{GeV})$	93.14(58) MeV
$m_c^{\overline{\rm MS}}(3\,\text{GeV})$	993(4) MeV
$m_c^{\overline{\rm MS}}(m_c^{\overline{\rm MS}})$	1277(5) MeV
$m_b^{\overline{\rm MS}}(m_b^{\overline{\rm MS}})$	4196(19) MeV
$m_t^{\overline{\rm MS}}(m_t^{\overline{\rm MS}})$ (GeV) to be updated	163.44(43)

Table 3 *Full lattice inputs. The values of the different quantities have been c taking the weighted average of the $N_f = 2+1$ and $N_f = 2+1+1$ FLAG nun*

Hints of NP structure: Flavor symmetries of the SM

- Standard Model (SM) gauge sector is *i* flavor blind and CP conserving

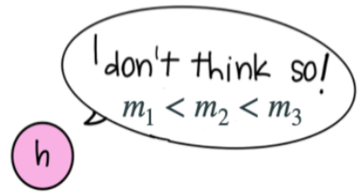
$$\mathcal{G}_F(\mathrm{SM}) = U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$



The Higgs introduces the only known non-gauge couplings

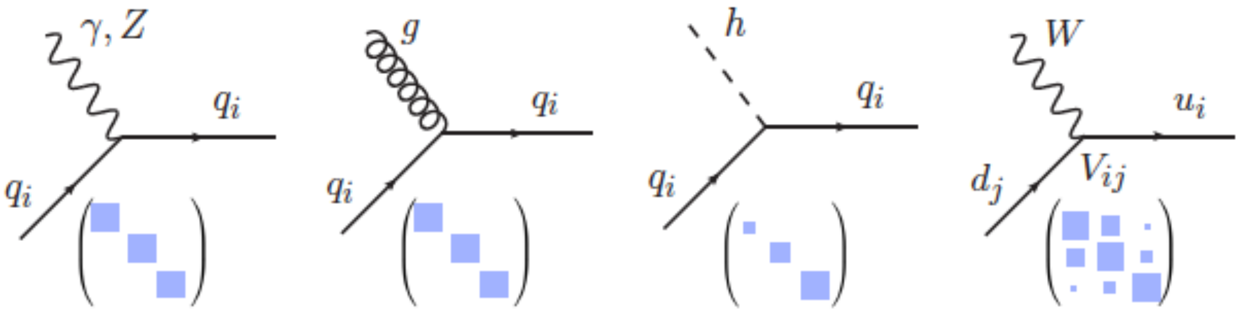
Turn on Yukawas

$$Y_{ij}\bar{\Psi}^i_L H \Psi^j_R$$



$$\mathcal{G}_F(\mathrm{SM}) = U(1)_B \times U(1)_L$$

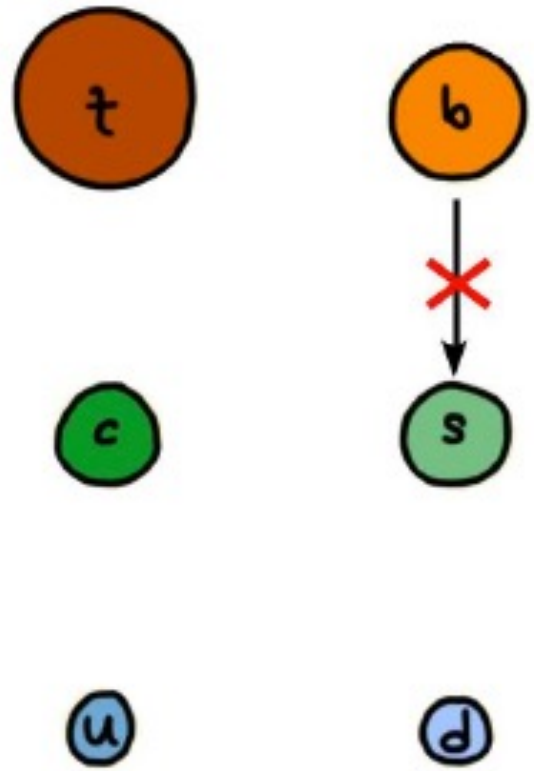
Higgs couplings are not flavor blind



courtesy of B.A. Stefanek

Absence of FCNC at tree level (& GIM suppression of FCNC @loop level)

Almost no CP violation at tree level



Tiny CP violation in K and D mesons due to small coupling between the third and the two first generations

Flavour Physics is extremely sensitive to New Physics (NP)

In competition with Electroweak Precision Measurements

The usual mantra

reasons to go beyond the SM(s):

"Experimental" evidence

1. Neutrino Masses
2. Dark Matter and Dark Energy
3. Matter-Antimatter Asymmetry

"Theoretical" evidence

1. SM instability (hierarchy, naturalness)
2. Flavour Physics (families, Yukawa couplings, CP violation for both quarks and leptons)
3.Unification of forces and quantization of gravity

Why Flavor Physics is so important:

It is sensitive to NP scales $\Lambda_{NP} \gg E_{collider}$
since FCNC are suppressed in the SM by loops and small $|V_{ij}|$

SM Flavor puzzle:
Why flavor parameters are so small and hierarchical? (and different from the neutrino sector)

NP Flavor puzzle:
If NP is at the TeV scale, why FCNC effects are so small that they have not be detected yet?

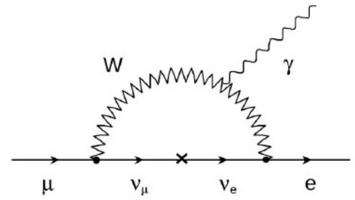
WHY RARE DECAYS ?

Rare decays are a manifestation of broken (accidental) symmetries e.g. of physics beyond the Standard Model

Proton decay — baryon and lepton number conservation

$\mu \to e + \gamma$ — lepton flavor number

$\nu_i \to \nu_k$ found !



$$\mathcal{B}(\mu \to e\gamma) \sim \alpha \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

Rare decays allowed in the SM

$q_i \to q_k + \nu\ \nu$

$q_i \to q_k + l^+ l^-$

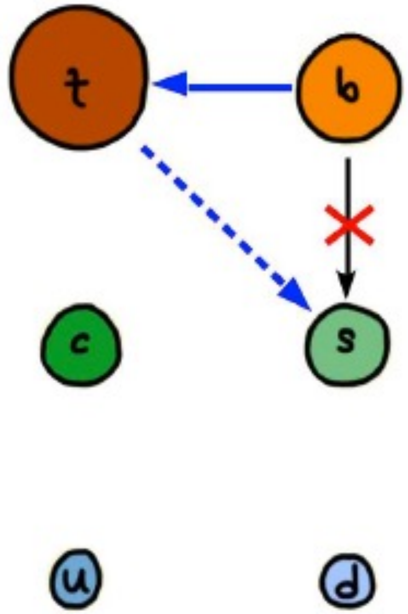
$q_i \to q_k + \gamma$

these decays occur only via loops and are suppressed by CKM because of GIM

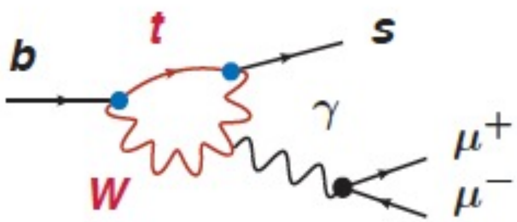
THUS THEY ARE SENSITIVE TO NEW PHYSICS

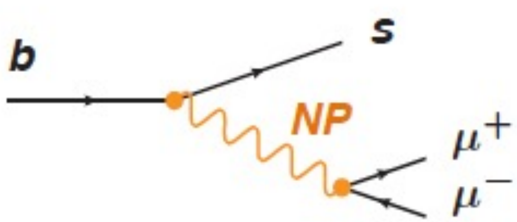
Flavor Changing Neutral Currents in the SM

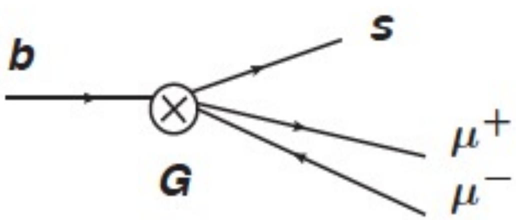
In the SM, flavor changing neutral currents (FCNCs) are absent at the tree level



FCNCs can arise at the loop level
they are suppressed by loop factors
and small CKM elements



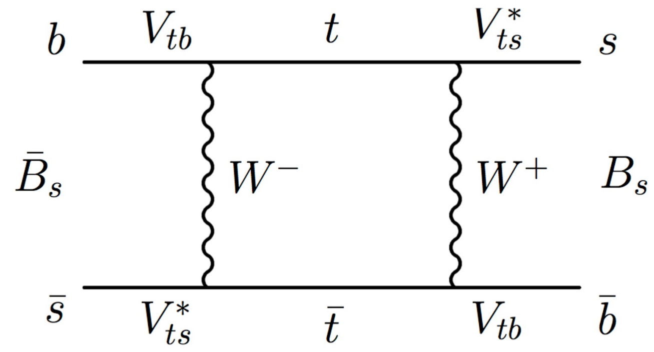




$$G \sim \frac{1}{16\pi^2}\frac{g^4}{m_W^2}\frac{m_t^2}{m_W^2}V_{tb}V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

→ measuring low energy flavor observables gives information on new physics flavor couplings and the new physics mass scale

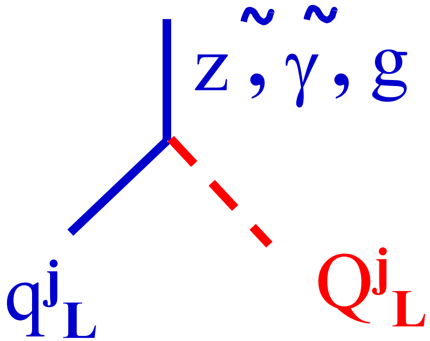
B^0 - $\overline{B^0}$ mixing



Standard Model CKM

$$\Delta m_{B_s} = \frac{G_F^2 M_W^2}{16\pi^2} A^2 \lambda^6 F_{tt}\left(\frac{m_t^2}{M_W^2}\right) \langle B_s| \left(\bar{s}\gamma_\mu(1-\gamma_5)b\right)^2 |\bar{B}_s\rangle$$

Hadronic matrix element



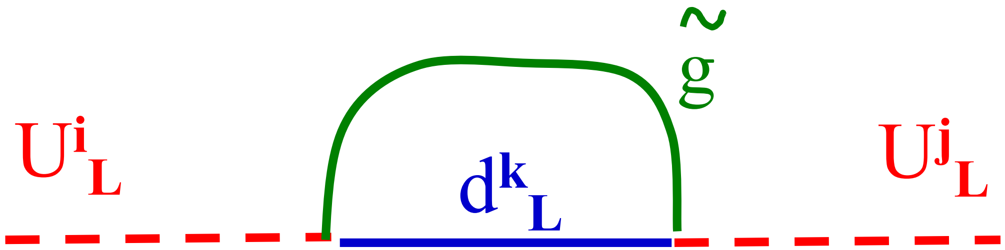
In general the mixing mass matrix of the SQuarks (SMM) is not diagonal in flavour space analogously to the quark case

We may either

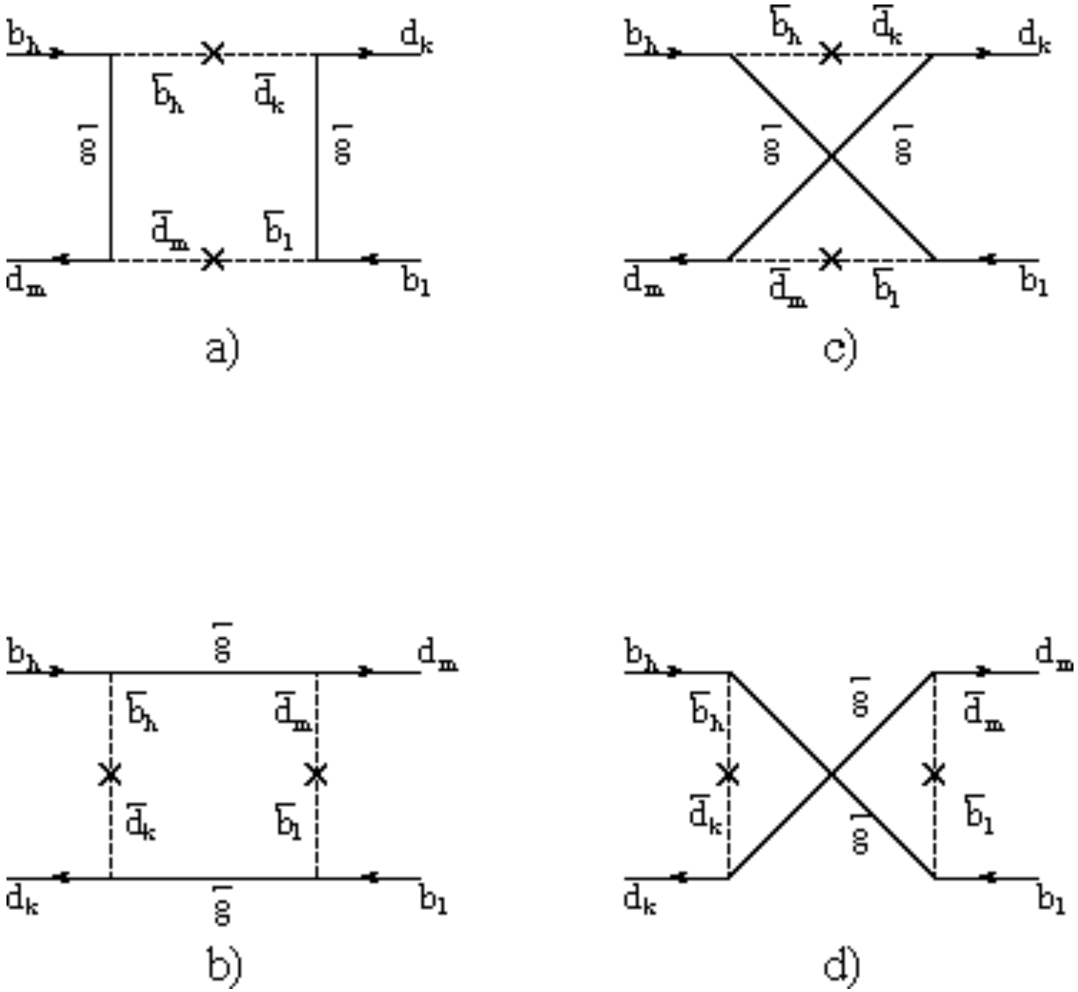
Diagonalize the SMM

or Rotate by the same Matrices the SUSY partners of the u- and d- like quarks

$(Q^j_L)' = U^{ij}_L Q^j_L$

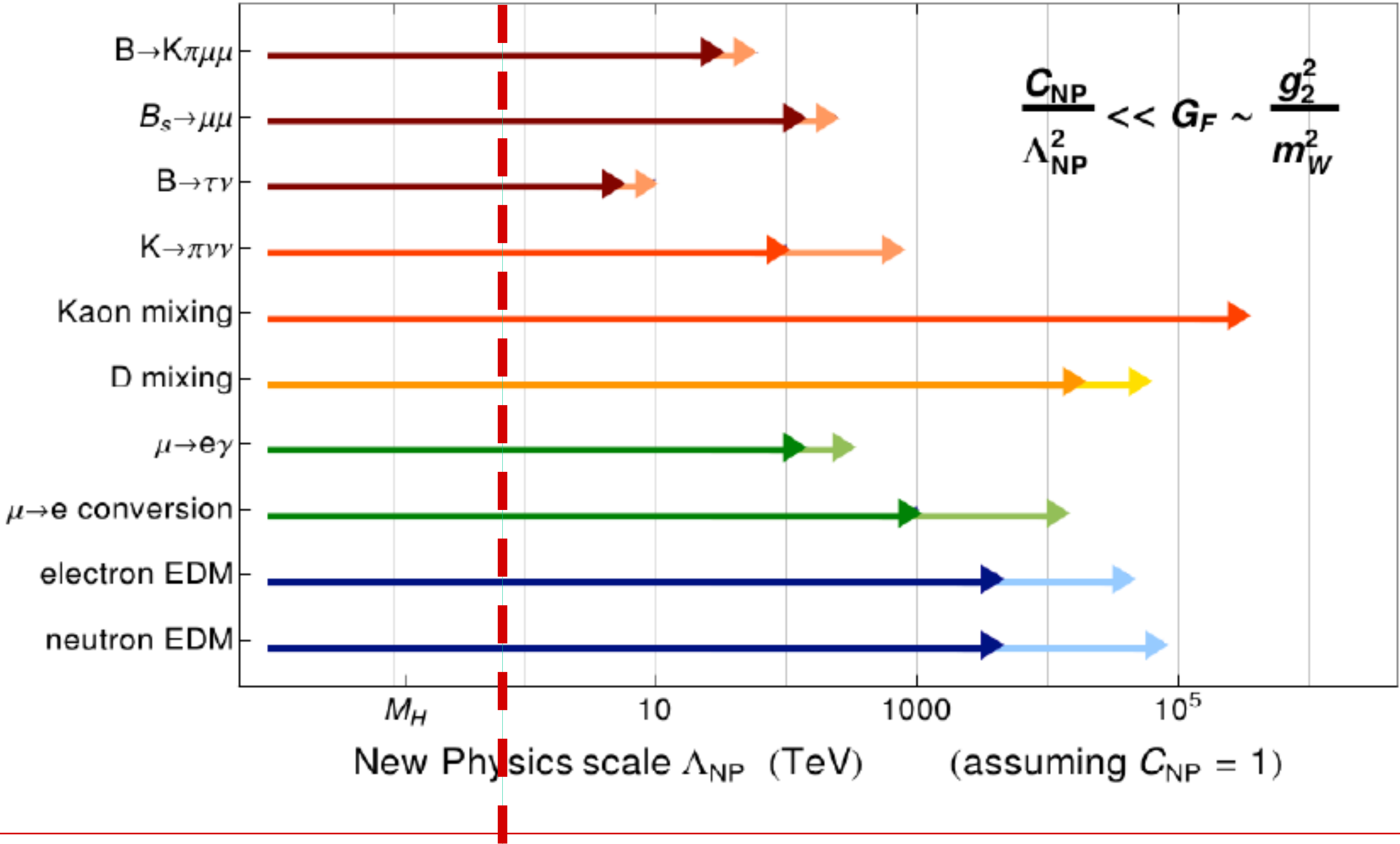


In the latter case the Squark Mass Matrix is not diagonal



$$(m^2{}_Q)_{ij} = m^2{}_{average}\, \mathbf{1}_{ij} + \Delta m_{ij}{}^2 \qquad \delta_{ij} = \Delta m_{ij}{}^2 / m^2{}_{average}$$

Sensitivity to New Physics from Flavor I

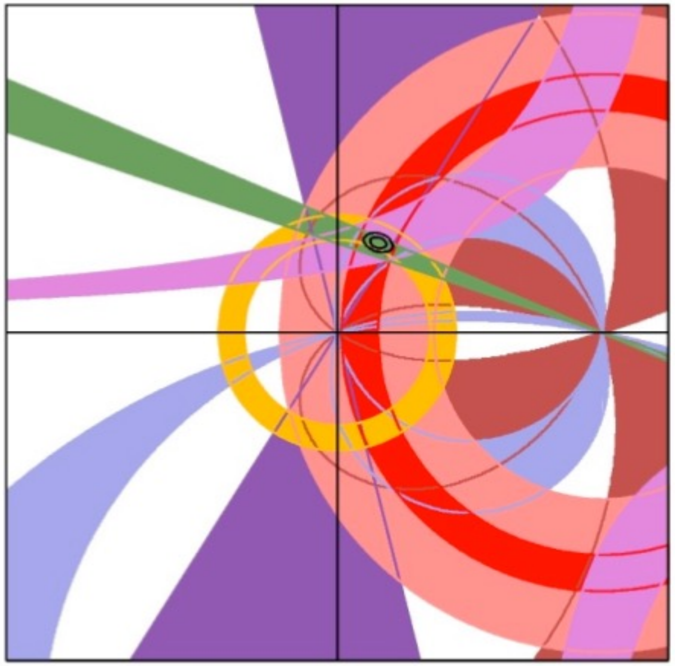


Approximate LHC direct reach

STANDARD MODEL UNITARITY TRIANGLE ANALYSIS

Tensions and Unknown

1. *Provides the best determination of the CKM parameters;*
2. *Tests the consistency of the SM (``direct'' vs ``indirect'' determinations) @ the quantum level;*
3. *Provides predictions for SM observables (in the past for example sin 2β and Δm_s)*
4. *It could lead to new discoveries (CP violation, Charm, !?)*
5. *The discovery potential of precision flavor physics should not be underestimated*



New UTfit Analysis of the Unitarity Triangle in the Cabibbo-Kobayashi-Maskawa scheme

It is by now precision physics and we need precise lattice calculations

Rend.Lincei Sci.Fis.Nat. 34 (2023) 37-57
arXiv:2212.03894

electromagnetic **neutral currents** **charged currents**

$$\mathcal{L}_{int} = -eA^\mu J_\mu^{em} - \frac{g_W}{2\cos\theta_W} Z^\mu J_\mu^Z - \frac{g_W}{2\sqrt{2}}[W^\mu (J^W)_\mu^\dagger + h.c.]$$

$$J_\mu^Z = 2J_\mu^3 - 2\sin^2\theta_W J_\mu^{em}$$

$$L_{CC}^{weak\,int} = \frac{g_W}{\sqrt{2}}(J_\mu^- W_\mu^+ + h.c.)$$

$$\rightarrow \quad \frac{g_W}{\sqrt{2}}(\bar{u}_L \mathbf{V}^{CKM} \gamma_\mu d_L W_\mu^+ + \ldots)$$

N(N-1)/2 angles and (N-1)(N-2) /2 phases

N=3 3 angles + 1 phase KM

the phase generates complex couplings i.e. CP violation;

6 masses +3 angles +1 phase = 10 parameters

V_{ud}	V_{us}	V_{ub}
V_{cd}	V_{cs}	V_{cb}
V_{tb}	V_{ts}	V_{tb}

$$L_{CC}^{weak\,int} = \frac{g_W}{\sqrt{2}}\left(J_\mu^- W_\mu^+ + h.c.\right)$$

$$\rightarrow \quad \frac{g_W}{\sqrt{2}}\left(\bar{u}_L \mathbf{V}^{CKM} \gamma_\mu d_L W_\mu^+ + \ldots\right)$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

STRONG CP VIOLATION

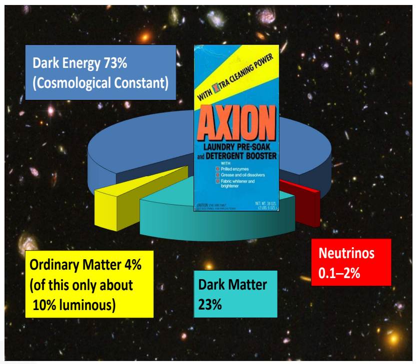
$$\mathcal{L}_\theta = \theta\, G^{\mu\nu a} \tilde{G}^a_{\mu\nu} \qquad \tilde{G}^a_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma} G^a_{\rho\sigma}$$

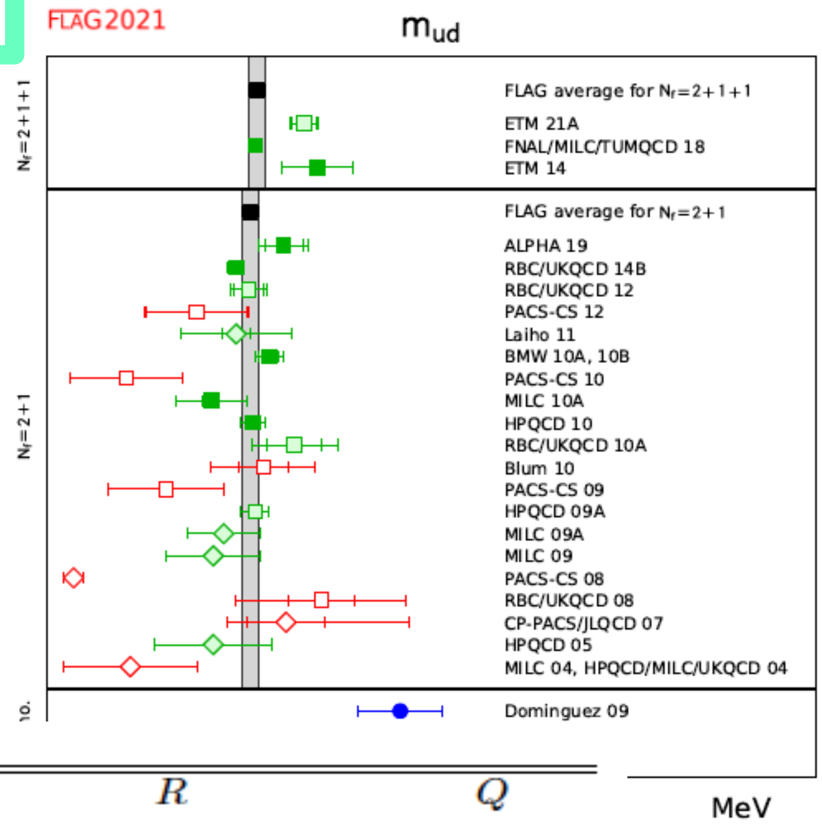
$$L_\theta \sim \theta\, \vec{E}^a \cdot \vec{B}^a$$

This term violates CP and gives a contribution to the electric dipole moment of the neutron

$$e_n < 3\ 10^{-26}\ e\ \mathrm{cm}$$

$\theta < 10^{-10}$ which is quite unnatural !!

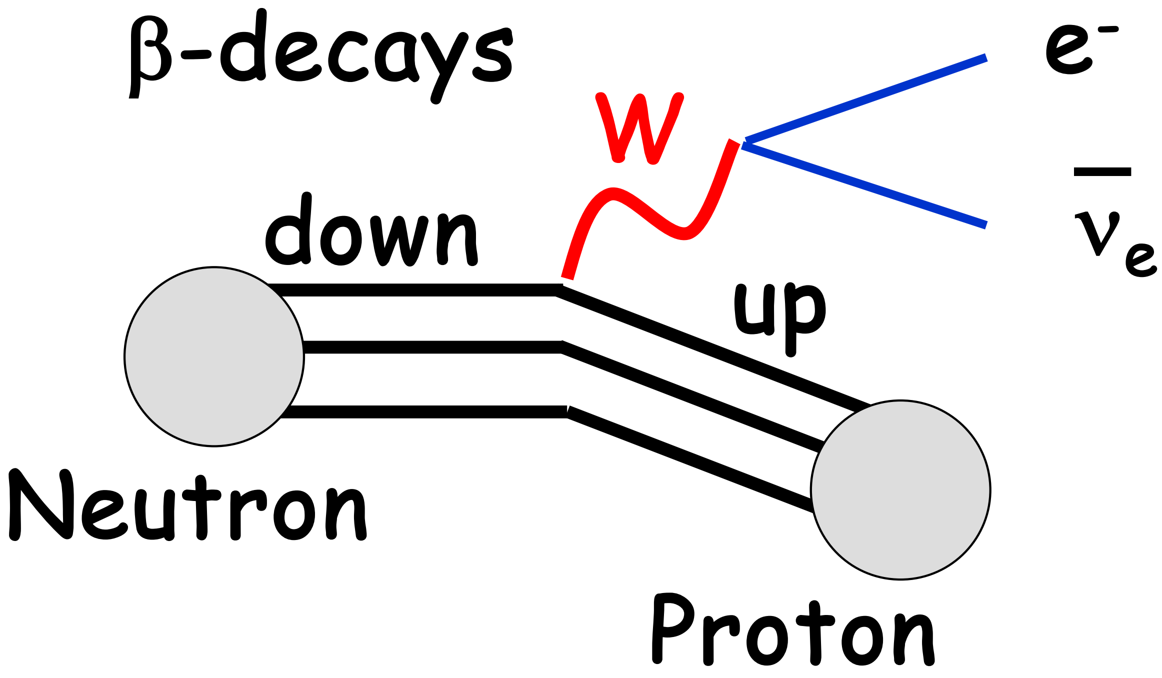




N_f	m_u	m_d	m_u/m_d	R	Q
2+1+1	2.14(8)	4.70(5)	0.465(24)	35.9(1.7)	22.5(0.5)
2+1	2.27(9)	4.67(9)	0.485(19)	38.1(1.5)	23.3(0.5)

Quark masses & Generation Mixing

V_{ud}	V_{us}	V_{ub}
V_{cd}	V_{cs}	V_{cb}
V_{td}	V_{ts}	V_{tb}



$|V_{ud}|$

$|V_{ud}| = 0.9735(8)$

$|V_{us}| = 0.2196(23)$

$|V_{cd}| = 0.224(16)$

$|V_{cs}| = 0.970(9)(70)$

$|V_{cb}| = 0.0406(8)$

$|V_{ub}| = 0.00409(25)$

$|V_{tb}| = 0.99(29)$

(0.999)

updated values later

The Unitarity Triangle Analysis

- Flavor-changing processes and CP violation in the SM ruled by 4 parameters in the 3x3 CKM (unitary) matrix

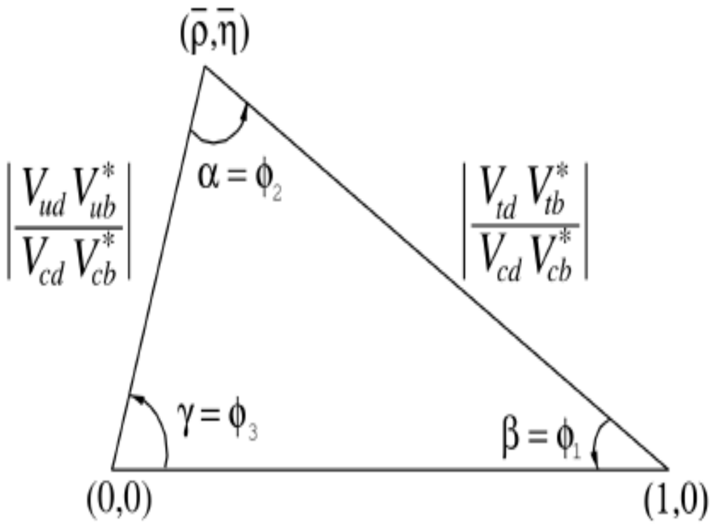
$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- $A, \lambda, \bar{\rho}$ and $\bar{\eta}$

$$\bar{\rho} = \rho(1-\lambda^2/2+\ldots) \quad \bar{\eta} = \eta(1-\lambda^2/2+\ldots)$$

- Small value sin of Cabibbo angle (λ) makes the CKM matrix close to diagonal

- Unitarity implies relations between elements, that can be represented as a triangle in a plane



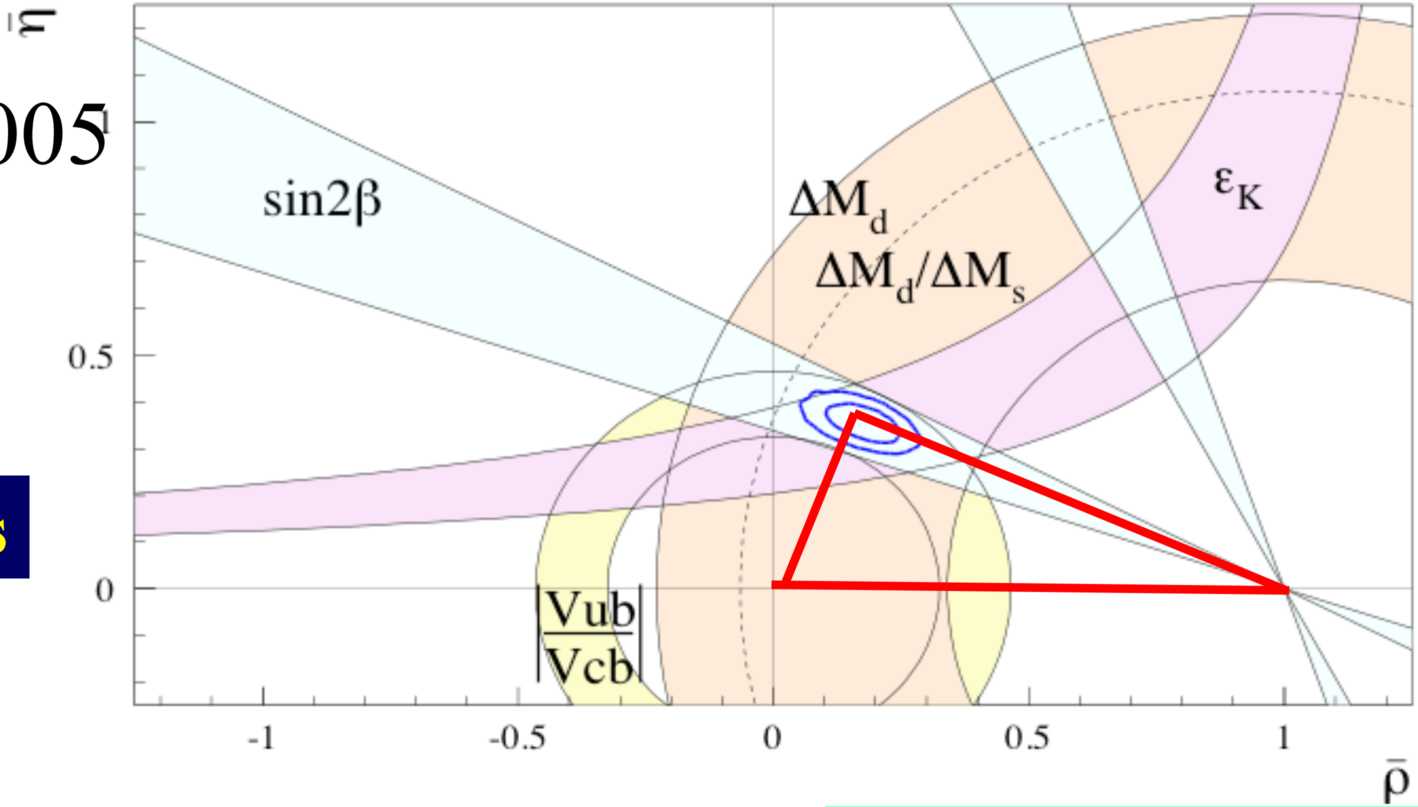
- By determining th
  CKM matrix

$\mathrm{Sin}\ \theta_{12} = \lambda$
$\mathrm{Sin}\ \theta_{23} = A\ \lambda^2$
$\mathrm{Sin}\ \theta_{13} = A\ \lambda^3(\rho - i\ \eta)$

$$\delta_{13} = \gamma = \phi_3$$

Unitary Triangle SM

2005



semileptonic decays

Experimental co

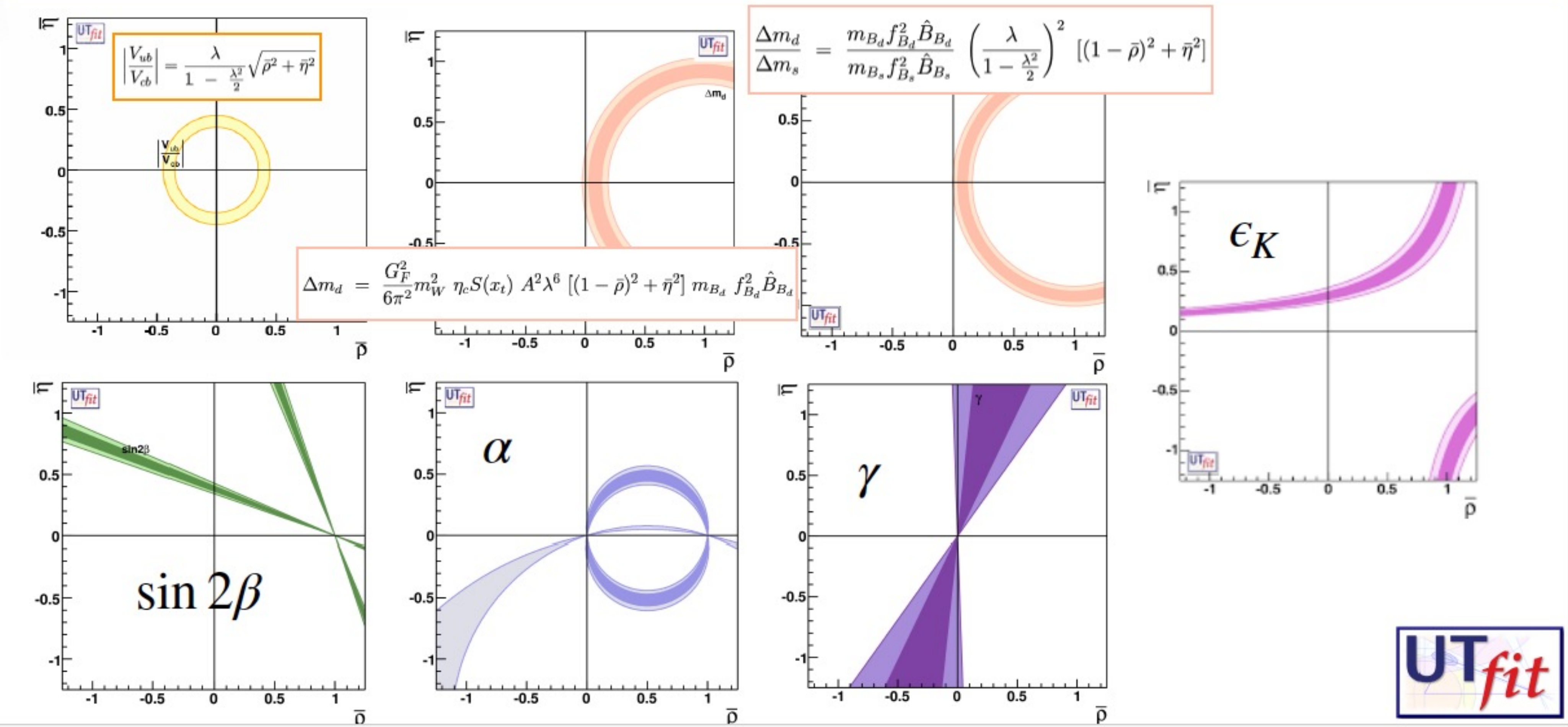
Meas.	$V_{CKM}\times$other	$(\bar{\rho}, \bar{\eta})$
$\frac{b\to u}{b\to c}$	$\lvert V_{ub}/V_{cb}\rvert^2$	$\bar{\rho}^2+\bar{\eta}^2$
Δm_d	$\lvert V_{td}\rvert^2 f_{B_d}^2 B_{B_d}$	$(1-\bar{\rho})^2+\bar{\eta}^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\left\lvert\frac{V_{td}}{V_{ts}}\right\rvert^2 \xi^2$	$(1-\bar{\rho})^2+\bar{\eta}^2$
ϵ_K	$f(A,\bar{\eta},\bar{\rho},B_K)$	$\propto \bar{\eta}(1-\bar{\rho})$
$A(J/\psi K^0)$	$sin2\beta$	$\frac{2\bar{\eta}(1-\bar{\rho})}{\sqrt{\bar{\eta}^2+(1-\bar{\rho})^2}}$

K^0 - $\overline{K}^0$ mixing

$B^0_{d,s}$ - $\overline{B}^0_{d,s}$ mixing

B_d

UT constraints



redundancy is the big strength of the UT analysis

one can remove a subset of inputs and still determine the CKM

one can exclude η=0 using only CP conserving processes

V_{cb} and V_{ub}

Latest inputs from arXiv:2310.03680

$|V_{cb}|$ *(excl)* = $(40.13 \pm 0.55)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(41.97 \pm 0.48)\ 10^{-3}$

from arXiv:2310.20324

from arXiv:2202.10285

$|V_{ub}|$ *(excl)* = $(3.57 \pm 0.23)\ 10^{-3}$

$|V_{ub}|$ *(incl)* = $(4.13 \pm 0.26)\ 10^{-3}$

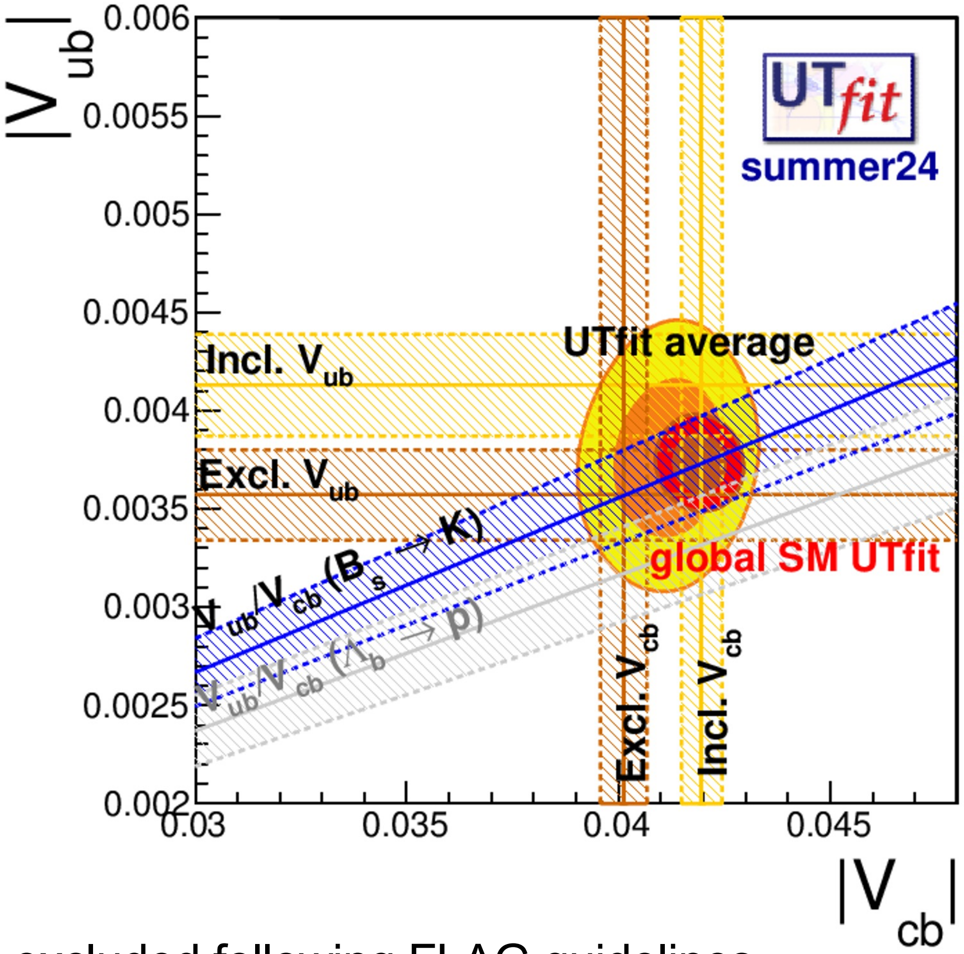
PDG 2024

from arXiv:2310.03680

$|V_{ub} / V_{cb}| = (8.7 \pm 0.9)\ 10^{-2}$

$|V_{ub} / V_{cb}|$ *(LHCb)* = $(7.9 \pm 0.6)\ 10^{-2}$

Λ_b, excluded following FLAG guidelines



$|V_{cb}|$ *(incl)* = $(42.00 \pm 0.47)\ 10^{-3}$
M. Fael et al. Eur.Phys.J.ST 233 (2024) 2, 325-346

Courtesy by M. Bona

V_{cb} and V_{ub}

Inputs to the global fit
from 2D à la D'Agostini averages

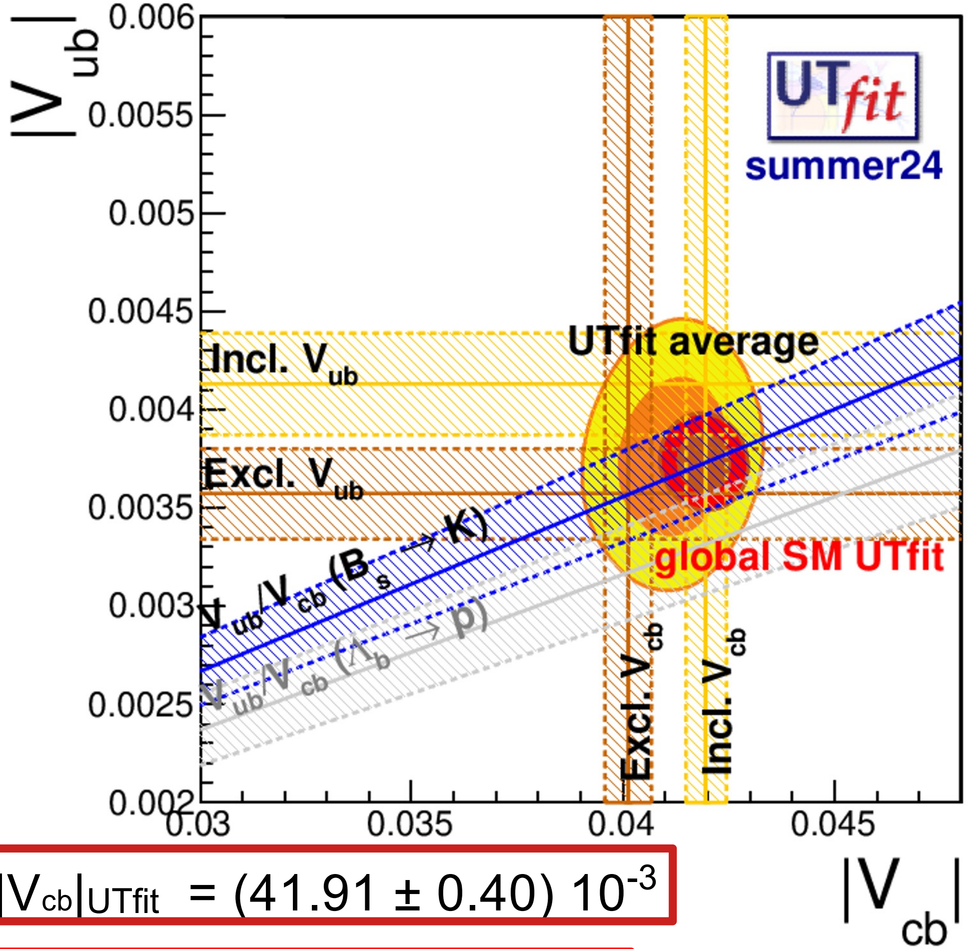
$|V_{cb}|_{UTfit}$ = (41.20 ± 0.74) 10^{-3}

$|V_{ub}|_{UTfit}$ = (3.84 ± 0.35) 10^{-3}

UTfit predictions:

$|V_{cb}|_{UTfit}$ = (42.19 ± 0.48) 10^{-3}

$|V_{ub}|_{UTfit}$ = (3.72 ± 0.10) 10^{-3}



UTfit full fit

$|V_{cb}|_{UTfit}$ = (41.91 ± 0.40) 10^{-3}

$|V_{ub}|_{UTfit}$ = (3.73 ± 0.09) 10^{-3}

New Analysis *(G.M., S.Simula, L.Vittorio 2310.03680)*

NEW EXCLUSIVE Vcb= $(39.92 \pm 0.64)\ 10^{-3}$ from B-> D*

$|V_{cb}|$ *(incl)* = $(41.97 \pm 0.48)\ 10^{-3}$
2.6 σ difference
Finauri & Gambino 2310.20324

$|V_{cb}|$ *(incl)* = $(41.69 \pm 0.63)\ 10^{-3}$
2.0 σ difference
F. Bernlochner etal. 2205.10274

NEW Vub/Vcb = $(8.7 \pm 0.9)\ 10^{-2}$
FLAG UNDERESTIMATES OF THE UNCERTAINTY
The larger error reduces the correlation between Vub nd Vcb

$\|V_{cb}\| \cdot 10^3$				
experiment	FNAL/MILC	HPQCD	JLQCD	Average
Belle '18 [19]	39.64 (74)	39.11 (81)	39.92 (74)	39.58 (98)
$\chi^2/(\text{d.o.f.})$	3.71	1.14	0.04	0.26
Belle '23 [13]	40.87 (115)	41.03 (125)	41.38 (134)	41.11 (138)
$\chi^2/(\text{d.o.f.})$	1.80	0.11	0.31	0.03
BelleII '23 [14]	39.35 (77)	39.98 (102)	40.20 (85)	39.79 (94)
$\chi^2/(\text{d.o.f.})$	0.63	0.09	0.42	0.29

Utfit Prediction Vcb= $(42.19 \pm 0.48)\ 10^{-3}$
Vub= $(3.72 \pm 0.10)\ 10^{-3}$

see also
e-Print: 2409.10492

determination of $|V_{cb}|$ from Γ

Martinelli, SS, Vittorio arXiv:2410.17974

determination of $|V_{cb}\,f(1)|$ using the total decay rate $\Gamma_{exp}(B \to D^* \ell \nu_\ell)$

$$\Gamma(B \to D^* \ell \nu_\ell) \to_{m_\ell=0} \frac{4\eta_{EW}^2 m_B m_{D^*}^2 G_F^2}{3(4\pi)^3} |V_{cb}\,f(1)|^2 \left[\widetilde{H}_{++} + \widetilde{H}_{--} + \widetilde{H}_{00}\right]$$

where $\Gamma_{exp} = 21.74\,(51) \cdot 10^{-15}$ GeV from PDG '24, while $\widetilde{H}_{++,--,00}$ can be calculated using the reduced FFs $\tilde{g}, \tilde{f}, \widetilde{F}_1$ obtained either from the ***exps+unitarity*** fit or from LQCD

	$\lvert V_{cb}\,f(1))\rvert \cdot 10^3$ GeV^{-1}	$\lvert V_{cb}\rvert \cdot 10^3$
Belle18	222.9 (8.5)	38.1 (1.5)
Belle23	234.2 (9.3)	40.1 (1.6)
BelleII23	236.5 (5.6)	40.5 (1.0)
Belle18 + Belle23 + BelleII23	231.8 (4.6)	39.7 (0.8)

using $f(1)|_{LQCD} = 5.845\,(50)$ GeV^{-1}

	$\lvert V_{cb}\,f(1)\rvert \cdot 10^3$ GeV^{-1}	$f(1)$ GeV^{-1}	$\lvert V_{cb}\rvert \cdot 10^3$
FNAL/MILC	253.2 (9.2)	5.951 (91)	42.6 (1.7)
HPQCD	253.4 (11.7)	5.885 (94)	43.1 (2.1)
JLQCD	231.3 (9.5)	5.776 (90)	40.0 (1.8)
LQCD	243.2 (5.9)	5.845 (50)	41.6 (1.1)

larger values due to the LQCD versus exp. **slope of $F_1(w)$**

bin-per-bin analysis of the same datasets within DM

$$|V_{cb}| \cdot 10^3 = 39.92\,(64)$$

Martinelli, SS, Vittorio arXiv:2310.03680

Bayesian inference based analysis

$$|V_{cb}| \cdot 10^3 = 40.42\,(71)$$

Bordone, Jüttner arXiv:2406.10074

UTfit **prediction** arXiv:2212.03894

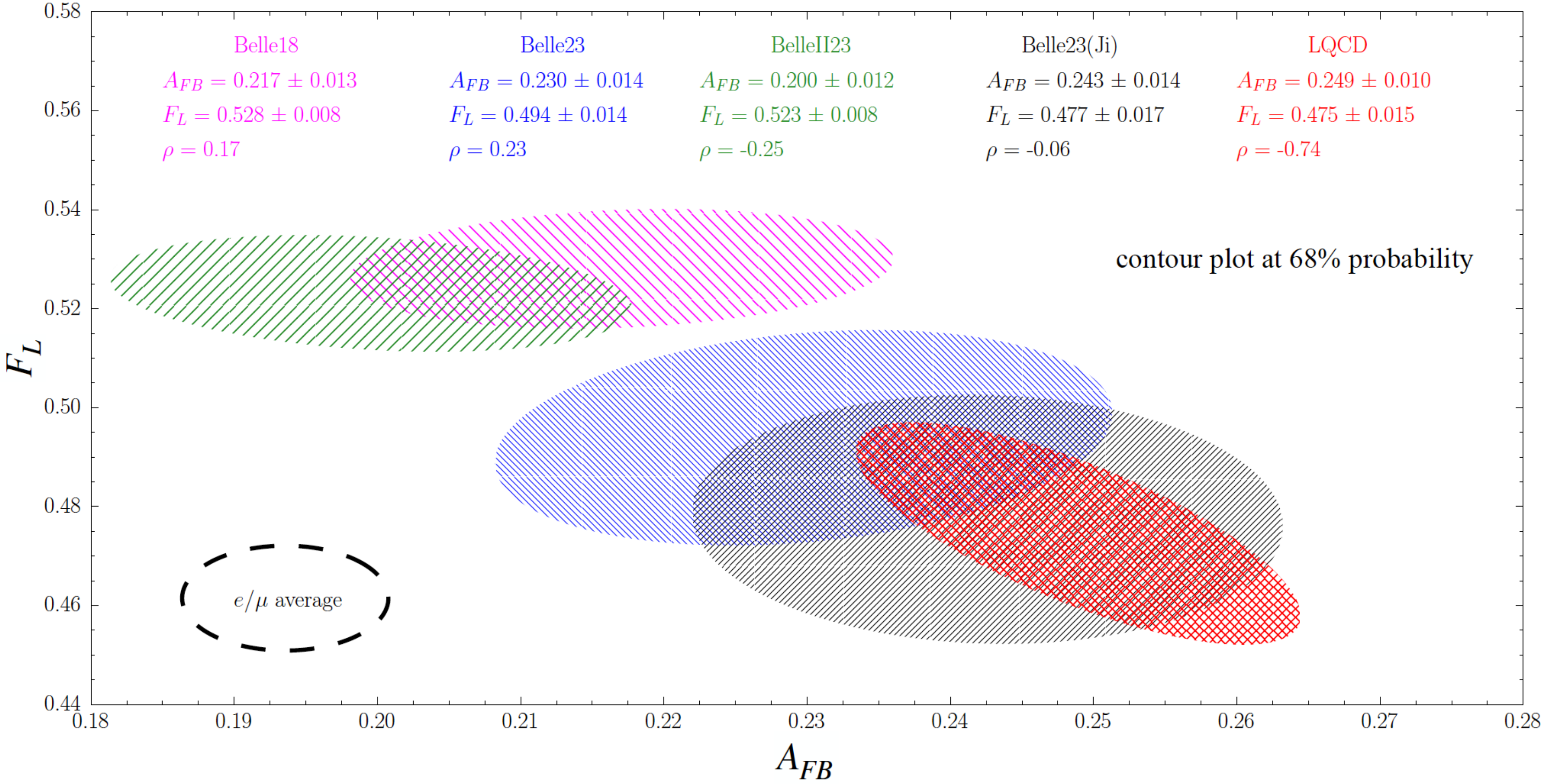
$$|V_{cb}| \cdot 10^3 = 42.19\,(48)$$

~ updated inclusive value (Fael et al. arXiv:2212.03894)

$$|V_{cb}| \cdot 10^3 = 42.00\,(47)$$

contour plots for light-lepton asymmetries

Martinelli, SS, Vittorio arXiv:2409.10492



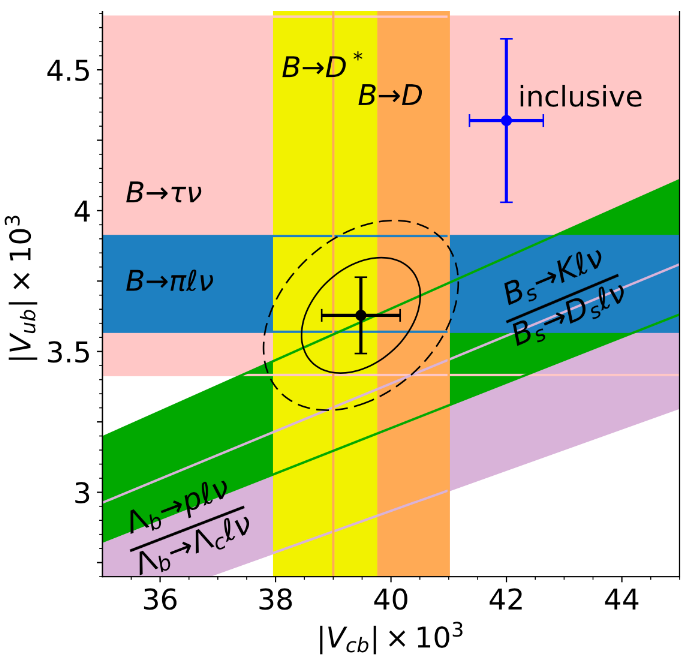
- relevant differences among the results corresponding to different datasets (cfr. Belle18, BelleII23 with Belle23)
- the SM LQCD predictions are consistent with the results from the Belle23 (or Belle23(Ji)) dataset, while the largest deviations occur with BelleII23

if Athens cries, Sparta does not laugh (G. Martinelli, talk @CERN '24)

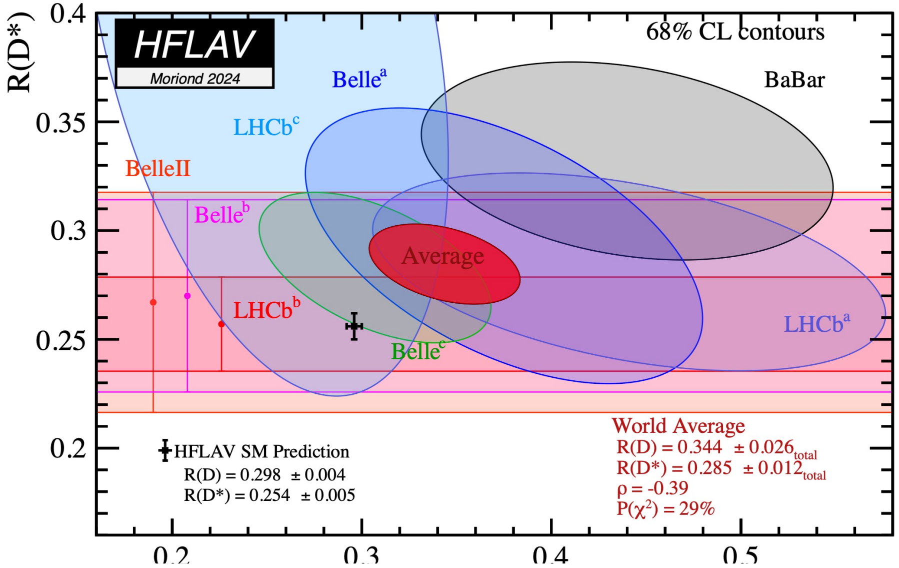
Tension(s) in $b \to c$ decays ? Charged Currents & Tree level

1. |Vcb| (and |Vub|) puzzle

FLAG Review 2021 [EPJC '22 (2111.09849)]



2. Lepton Flavor Universality Violation



HFLAV Collaboration, PRD '23 [arXiv:2206.07501] (updated plot)

$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)},$$

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$

An important CKM unitarity test is the Unitarity Triangle (UT) formed by

$$1 + \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

V_{cb} plays an important role in UT

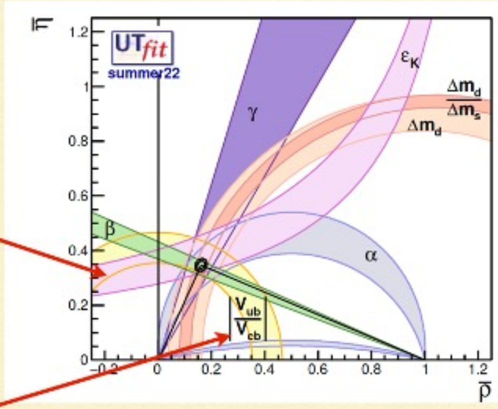
$$\varepsilon_K \approx x|V_{cb}|^4 + ...$$

and in the prediction of FCNC:

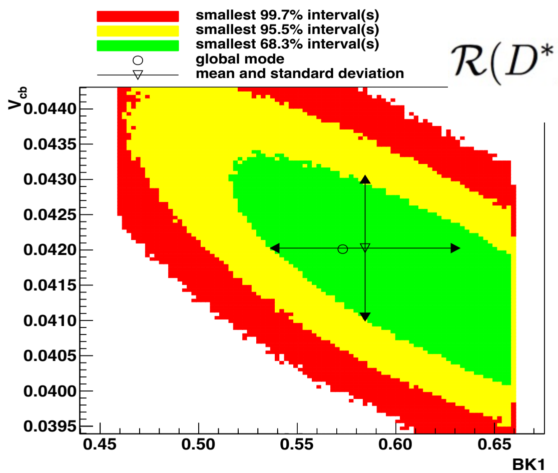
$$\propto |V_{tb}V_{ts}|^2 \simeq |V_{cb}|^2\left[1 + O(\lambda^2)\right]$$

where it often dominates the theoretical uncertainty.

V_{ub}/V_{cb} constrains directly the UT

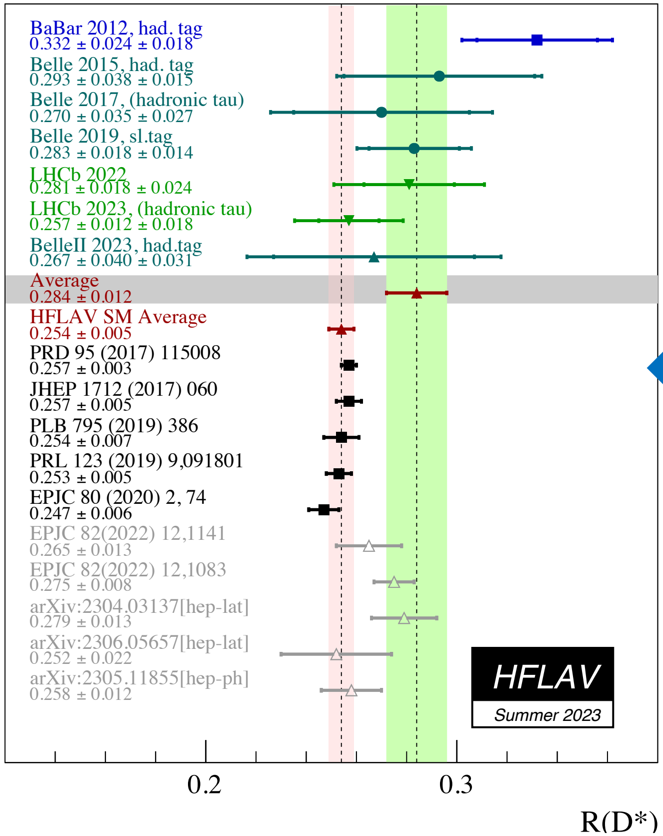


Our ability to determine precisely V_{cb} is crucial for indirect NP searches



$$BR(K^+ \to \pi^+\nu\bar{\nu}) \propto |V_{cb}|^2$$

The tension strongly depends on the method used in the theoretical analysis



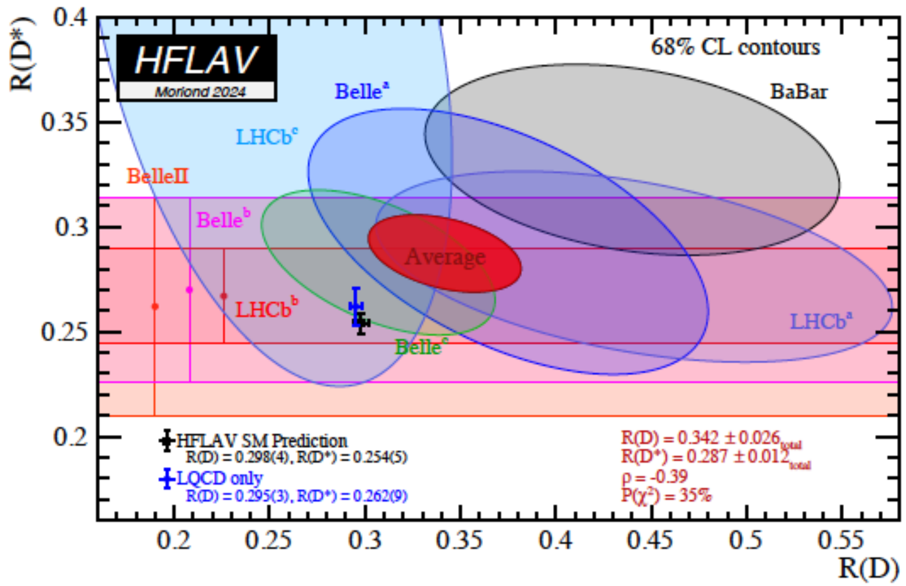
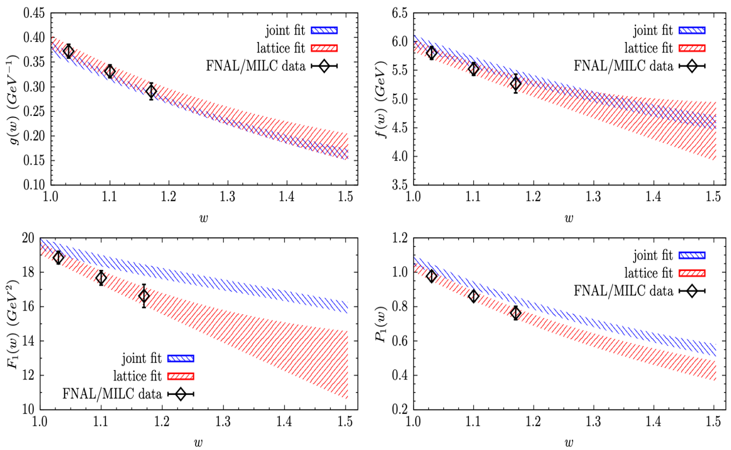


Figure 9. Measurements of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ listed in Table 3 and their two-dimensional average. Contours correspond to 68% CL for both the bands and the ellipses. The black and blue points with error bars are two recent SM predictions for $\mathcal{R}(D^*)$ and $\mathcal{R}(D)$. The SM prediction reported is based on the results summarized in Table 1. This prediction and the experimental average deviate from each other by about 3.3σ. The SM prediction based only on LQCD calculations is also reported, where $\mathcal{R}(D)$ is taken from FLAG [25], while $\mathcal{R}(D^*)$ is taken from Ref. [28]. The deviation from the experimental average and this prediction is about 2.5σ. The measurements are listed in Table 3.



joint fit:
BGL fit of LQCD points + Belle + BaBar exp. data

$|V_{cb}| \cdot 10^3 = 38.40 \pm 0.74$

$R(D^*) = 0.2483 \pm 0.0013$

lattice fit:
quadratic BGL fit of LQCD points only

$|V_{cb}| > |V_{cb}|^{\text{joint fit}}$?

$R(D^*) = 0.265 \pm 0.013$

simultaneous fit of the lattice points and experimental data to determine the shape of the FFs and to extract $|V_{cb}|$

*** slope differences between exp's and theory $\rightarrow$ bias on $|V_{cb}|^{\text{joint fit}}$? ***

Klaver S & Rotondo M,
doi 10.3390/sym16080964

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$

$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)},$$

Power corrections to the CP-violation parameter ε_K

M. Ciuchini[(a)], E. Franco[(b)], V. Lubicz[(c,a)],
G. Martinelli[(d,b)], L. Silvestrini[(b)], C. Tarantino[(c,a)]

$$\varepsilon_K^{exp} = 2.228 \pm 0.011) \cdot 10^{-3}$$

2021: an estimate from the 1/mc expansion of the effective Hamiltonian + UTfit

$$\varepsilon_K = 2.00\ (15) \times 10^{-3}$$

Computing the long-distance contributions to ε_K

Ziyuan Bai
Columbia University, USA
bzyhty@gmail.com

Norman Christ[* †]
Columbia University, USA
E-mail: nhc@phys.columbia.edu

RBC and UKQCD Collaborations

2015: a real exploratory calculation
no physical masses, no extrapolation to the continuum

$$|\varepsilon| = (1.806(41) + 0.891(11) + 0.209(6) + 0.112(13)) \times 10^{-3} = 3.019(45) \times 10^{-3}$$

$$tt \qquad ut_{SD} \qquad ut_{LD} \qquad \mathrm{Im}(A_0),$$

Final result for ε'

- Combining our new result for Im(A_0) and our 2015 result for Im(A_2), and again using expt. for the real parts, we find

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \mathrm{Re}\left\{\frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\right\}$$

$$= 0.00217(26)(62)(50)$$

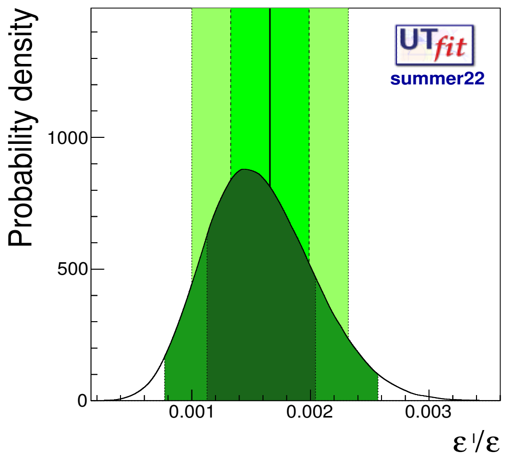
stat — sys — IB + EM

Consistent with experimental result:

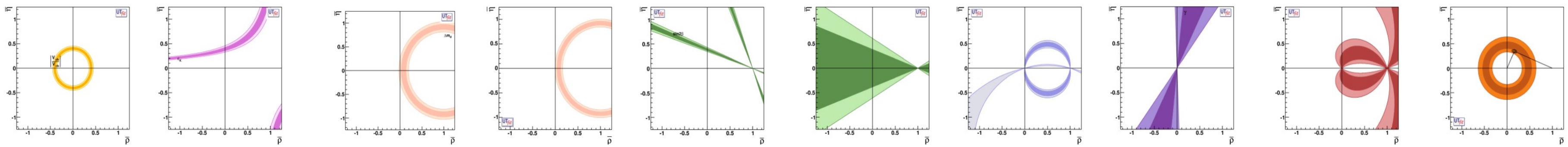
$$\mathrm{Re}(\epsilon'/\epsilon)_{\mathrm{expt}} = 0.00166(23)$$

RBC/UKQCD: e'/ e= 16.7 x10^{-4}

Utfit: e'/ e= 15.2(4.7) x10^{-4}



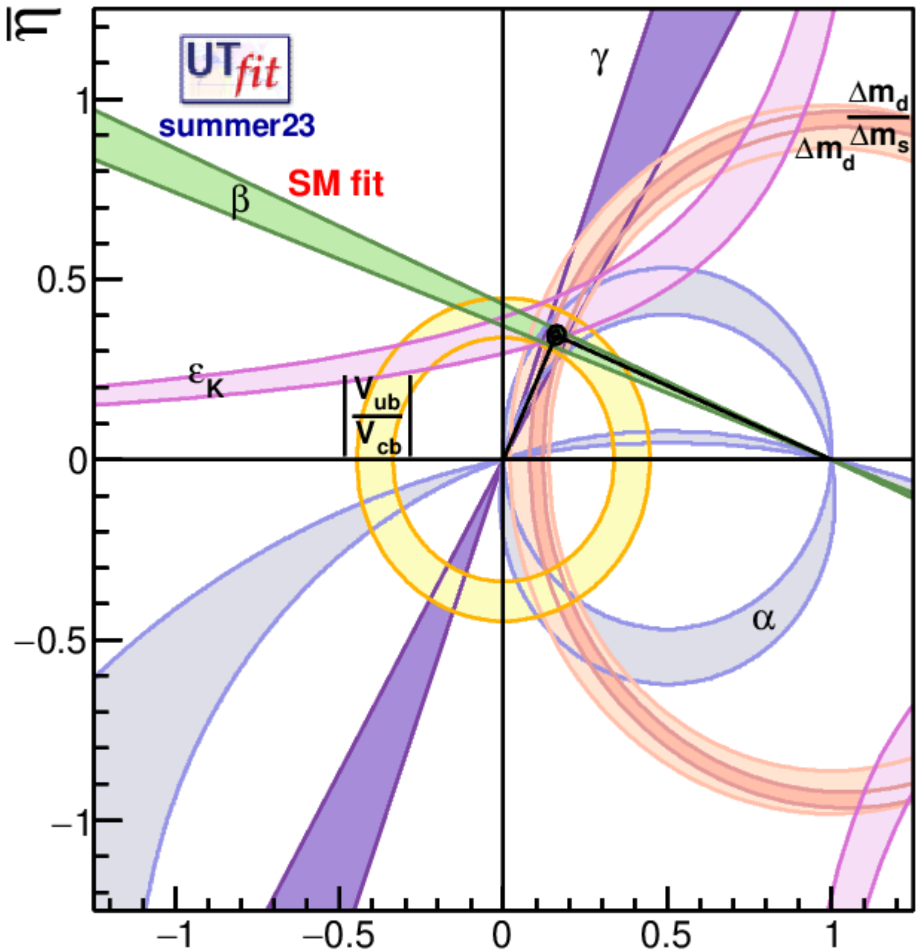
A second group should do this calculation!!



September 24

$\bar{\rho} = 0.158 \pm 0.009 \quad \bar{\eta} = 0.352 \pm 0.011$

In the hadronic sector, the SM CKM pattern represents the principal part of the flavor structure and of CP violation



$\alpha = (91.4 \pm 1.4)^0$

$\sin 2\beta = 0.763 \pm 0.030$

$\gamma = (65.6 \pm 1.4)^0$

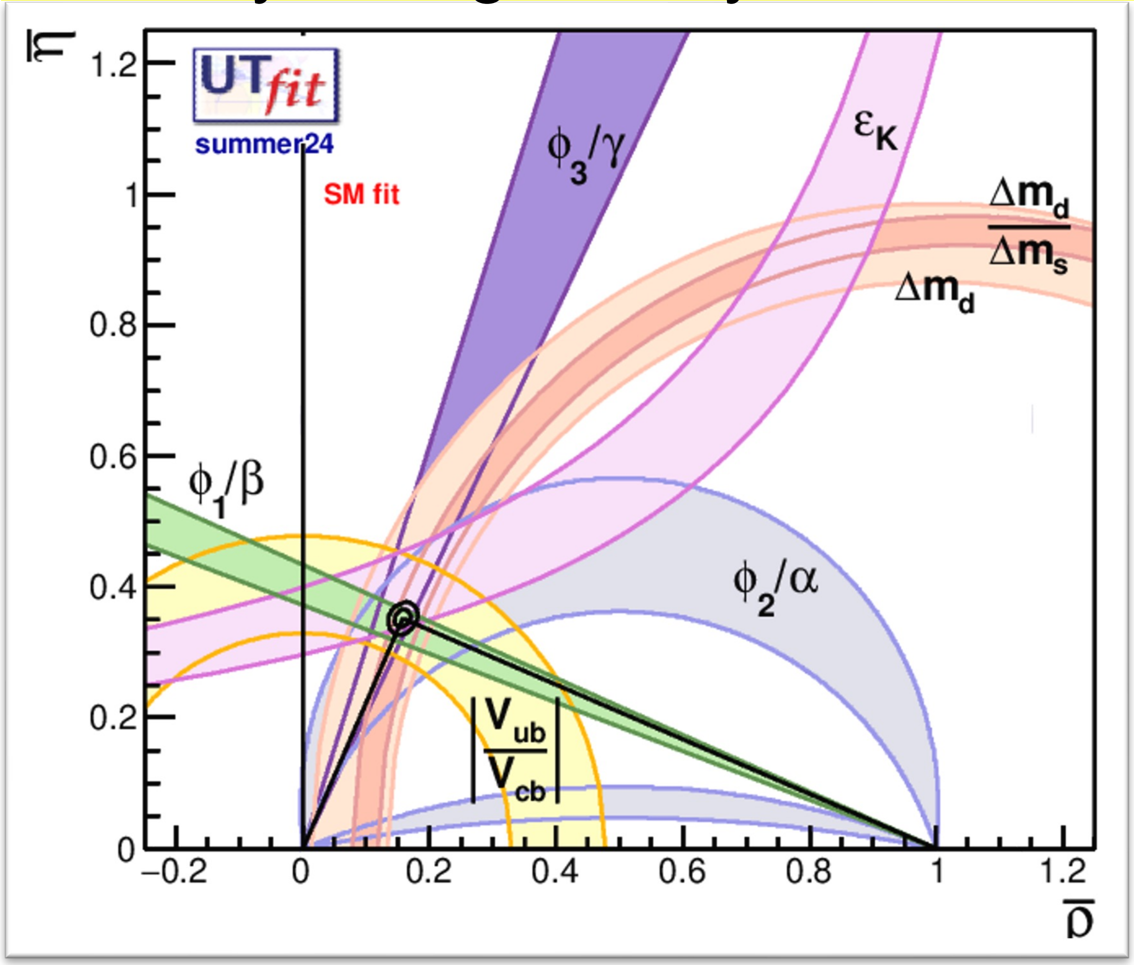
$A = 0.826 \pm 0.011$

$\lambda = 0.2250 \pm 0.0007$

Consistence on an over constrained fit of the CKM parameters

CKM matrix is the dominant source of flavour mixing and CP violation

Unitarity Triangle analysis in the SM:



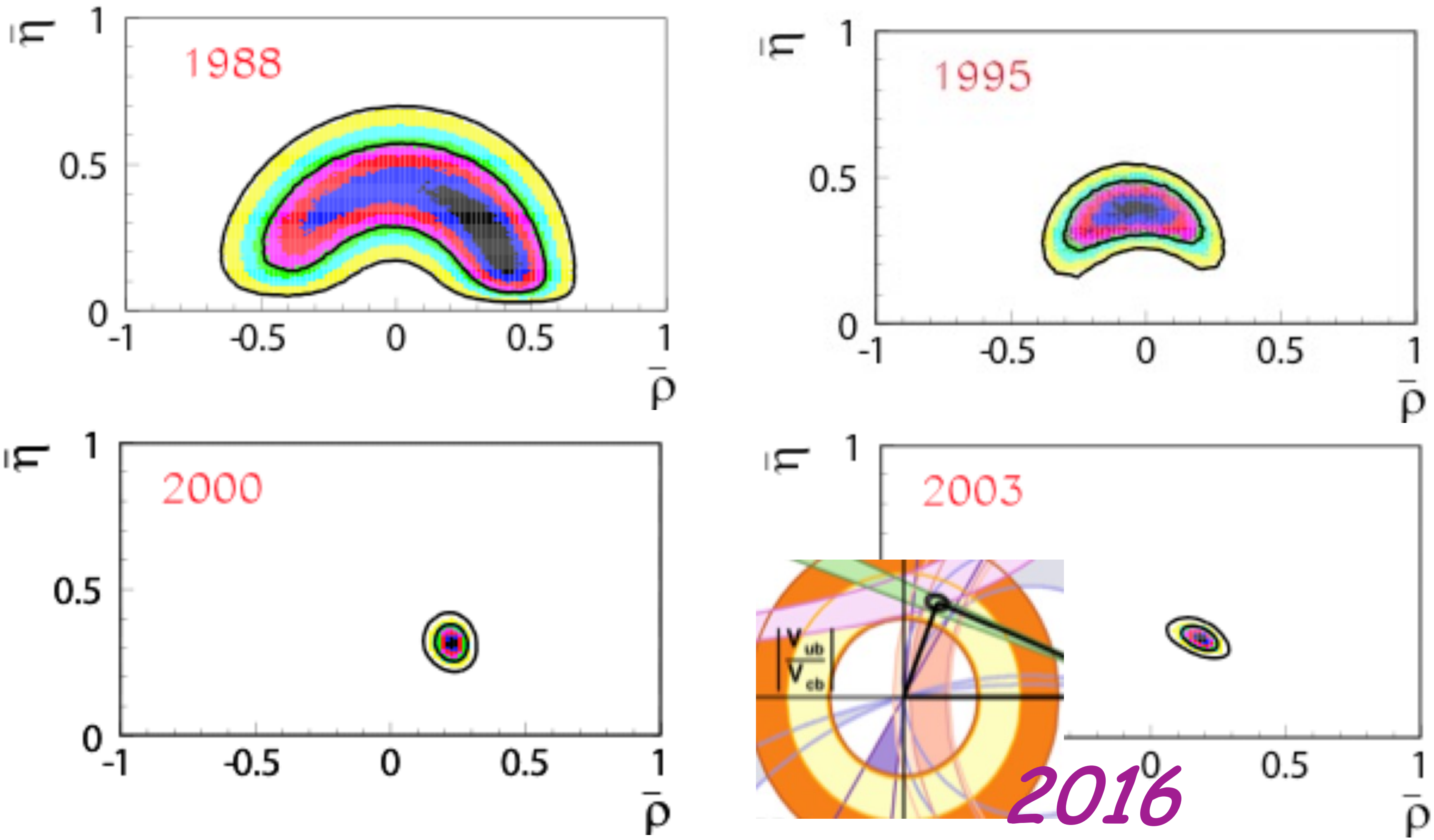
levels @
95% Prob

$\rho = 0.158 \pm 0.009$
$\eta = 0.352 \pm 0.010$

$\lambda = 0.2250 \pm 0.0007$
$A = 0.826 \pm 0.009$

PROGRESS SINCE 1988

Experimental progress so impressive that we can fit the hadronic matrix elements (in the SM)

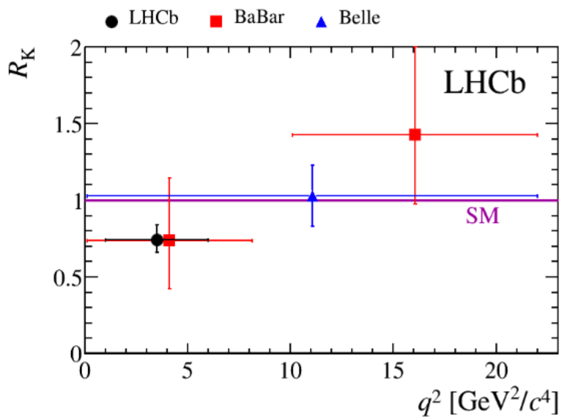


Tension(s) in $b \to s$ decays ?
Neutral Currents & Loop level

Reminder:

$R_K = B(B^+ \to K^+\mu^+\mu^-)/B(B^+ \to K^+e^+e^-)$

- Test of lepton universality : $R_K \sim 1$ in SM, with negligible theoretical uncertainties



LHCb, PRL 113 151601
Belle, PRL 103 171801
BaBar, PRD 86 032012

$$R_K(1 < q^2 < 6\ \mathrm{GeV}^2) = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

Old slide

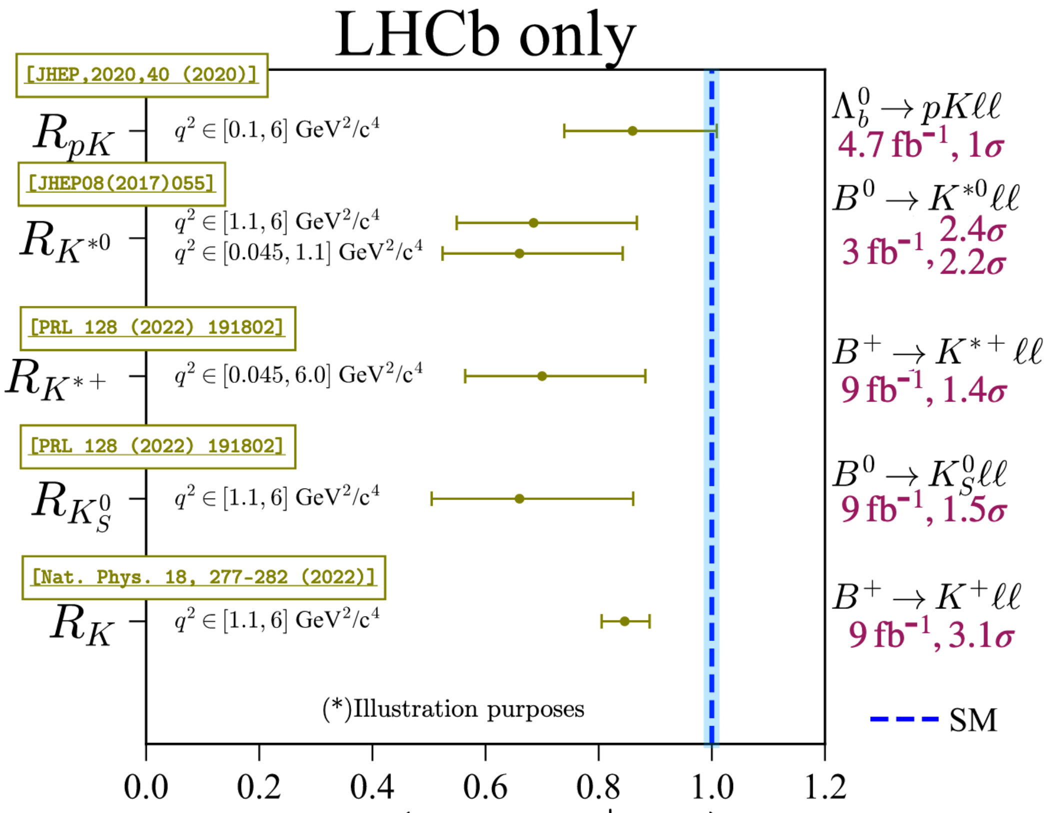
- Compatible with SM at 2.6σ
- Experimentally challenging
  - lower trigger efficiency for electrons, resolution deteriorated by bremsstrahlung
- Other modes suitable for same test: $B^0 \to K^{*0} l^+ l^-$, $B_s \to \phi\, l^+ l^-$, $\Lambda_B \to \Lambda\, l^+ l^-$

Excitement

Analysis

Lepton Flavour Universality (LFU) tests in $b \to s\ell^+\ell^-$

- Coherent pattern of tension to SM in LFU test with $b \to s\ell^+\ell^-$ transition:
- R_X ratio extremely well predicted in SM
  - Cancellation of hadronic uncertainties at 10^{-4}
  - $\mathcal{O}(1\%)$ QED correction [Eur.Phys.J.C 76 (2016) 8]
  - Statistically limited
- **Any departure from unity is a clear sign of New Physics**



$$R_X = \frac{\mathcal{B}(b \to s\mu^+\mu^-)}{\mathcal{B}(b \to se^+e^-)}$$

(*) Measurements from Belle not shown (larger statistical uncertainties)

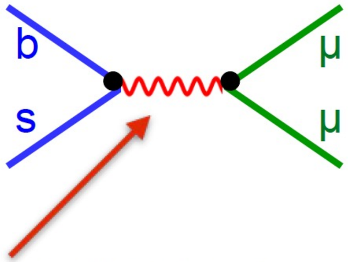
A EFT description

b ⟶ s

A relatively sizable New Physics effect...

~30% of the Standard Model contribution (arising at one loop)

...hinting towards a relatively low New Physics scale:



generic tree	$\frac{1}{\Lambda_{NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{NP} \simeq 35\ \text{TeV} \times (C_9^{NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{NP}^2} V_{tb}V_{ts}^* (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{NP} \simeq 7\ \text{TeV} \times (C_9^{NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{NP} \simeq 3\ \text{TeV} \times (C_9^{NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{NP}^2}\frac{1}{16\pi^2} V_{tb}V_{ts}^* (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{NP} \simeq 0.6\ \text{TeV} \times (C_9^{NP})^{-1/2}$

courtesy of Marco Ciuchini

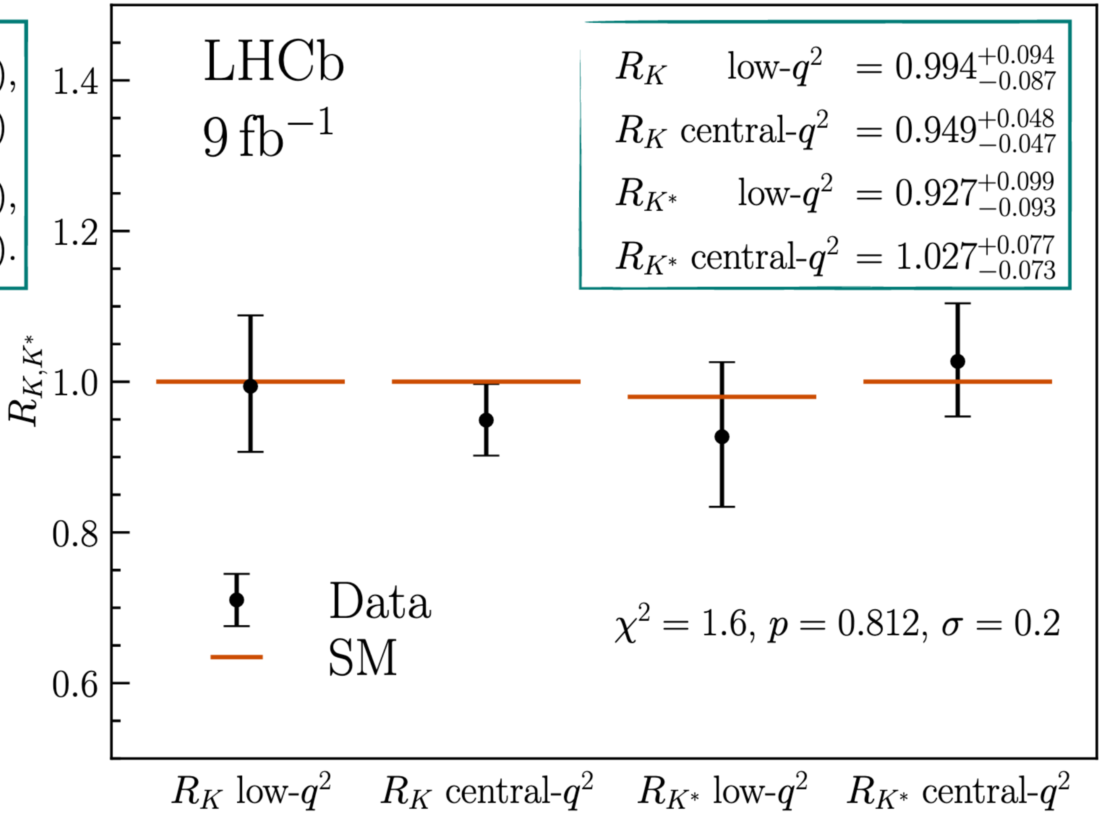
Harakiri!

Results

$$\text{low-}q^2 \begin{cases} R_K = 0.994\ ^{+0.090}_{-0.082}\ \text{(stat)}\ ^{+0.027}_{-0.029}\ \text{(syst)}, \\ R_{K^*} = 0.927\ ^{+0.093}_{-0.087}\ \text{(stat)}\ ^{+0.034}_{-0.033}\ \text{(syst)} \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949\ ^{+0.042}_{-0.041}\ \text{(stat)}\ ^{+0.023}_{-0.023}\ \text{(syst)}, \\ R_{K^*} = 1.027\ ^{+0.072}_{-0.068}\ \text{(stat)}\ ^{+0.027}_{-0.027}\ \text{(syst)}. \end{cases}$$

- Most precise and accurate LFU test in $b \to s\ell\ell$ transition
- Compatible with SM with a simple χ^2 test on 4 measurement at 0.2 σ



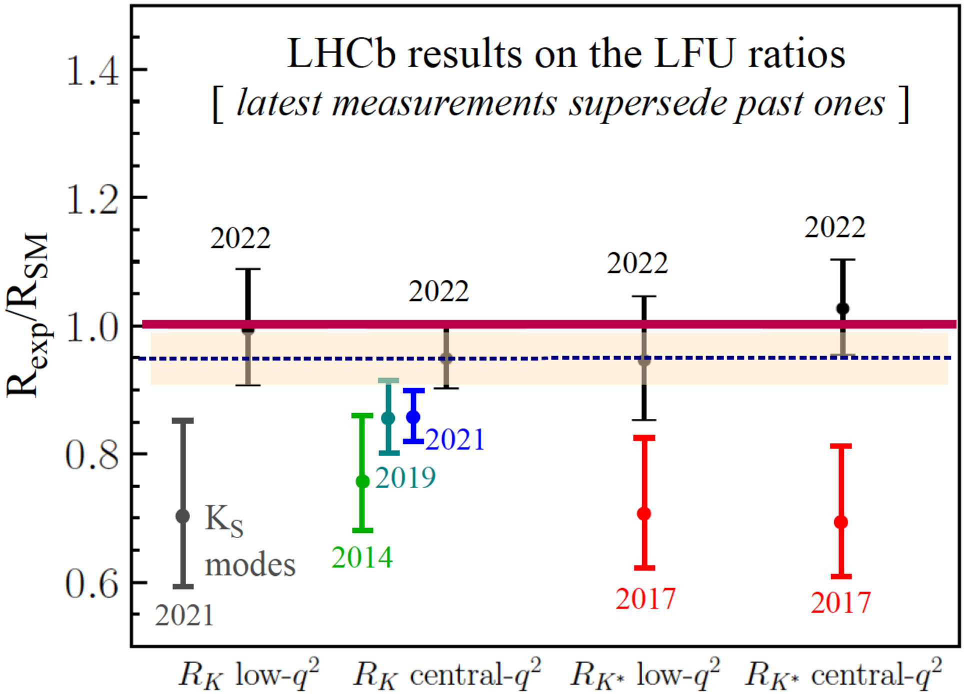
Hints of non-universality in B-physics

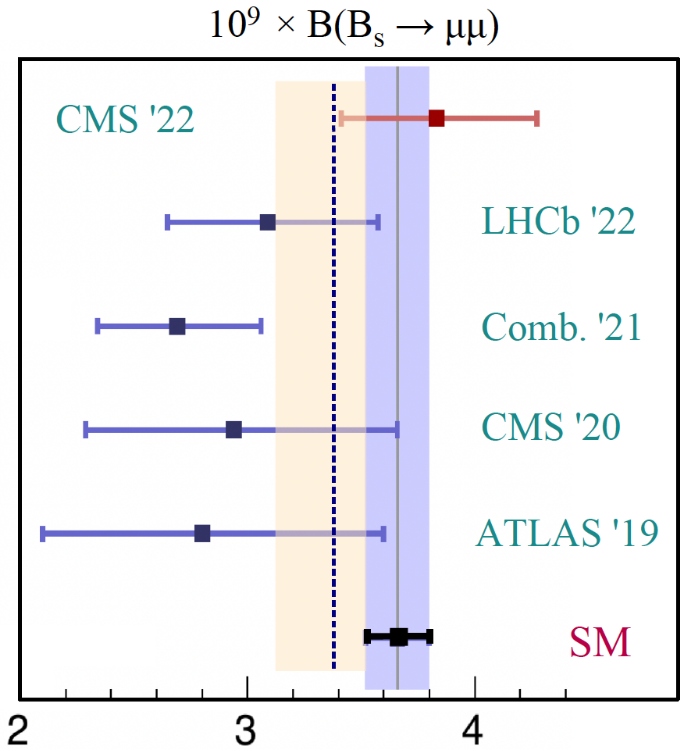
III. ~~LFU~~ anomaly in NC & BR($B_s \to \mu\mu$)

- Clean SM predictions
  (*LFU ratios + no long-distance in* $B_s \to \mu\mu$)
- ~~Highest significance till summer 2022~~

$$\text{low-}q^2 \begin{cases} R_K = 0.994\ ^{+0.090}_{-0.082}\ (\text{stat})\ ^{+0.027}_{-0.029}\ (\text{syst}), \\ R_{K^*} = 0.927\ ^{+0.093}_{-0.087}\ (\text{stat})\ ^{+0.034}_{-0.033}\ (\text{syst}) \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949\ ^{+0.042}_{-0.041}\ (\text{stat})\ ^{+0.023}_{-0.023}\ (\text{syst}), \\ R_{K^*} = 1.027\ ^{+0.072}_{-0.068}\ (\text{stat})\ ^{+0.027}_{-0.027}\ (\text{syst}). \end{cases}$$





$$BR(B_s \to \mu\mu)_{exp} = (3.41 \pm 0.29) \times 10^{-9} \qquad 9\%$$

$$BR(B_s \to \mu\mu)_{SM} = (3.47 \pm 0.14) \times 10^{-9} \qquad 4\%$$

Known unknowns in B → K*μμ

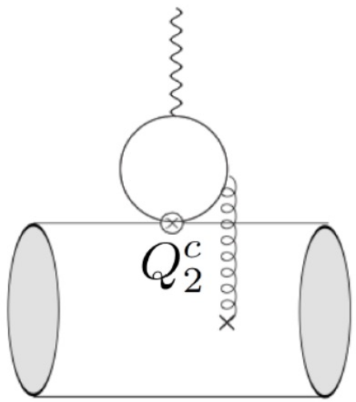
$$\mathrm{H}_V{}^\lambda = \frac{4iG_F m_B}{\sqrt{2}} \frac{e^2}{16\pi^2} \lambda_t \left\{ C_9^{\mathrm{eff}} \tilde{V}_{L\lambda} + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} C_7^{\mathrm{eff}} \tilde{T}_{L\lambda} - 16\pi^2 h_\lambda \right] \right\}$$

$$h_\lambda(q^2) = \frac{\epsilon_\mu^*(\lambda)}{m_B^2} \int d^4x e^{iqx} \langle \bar{K}^* | T\{ j^\mu_{\mathrm{em}}(x) \mathcal{H}^{\mathrm{had}}_{\mathrm{eff}}(0) \} | \bar{B} \rangle$$

Non-factorizable power-suppressed contributions of 4-quark operators to the matrix element

- dominated by

$$Q_1^c = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L),$$
$$Q_2^c = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L),$$



the charm pair can be close to the resonant region

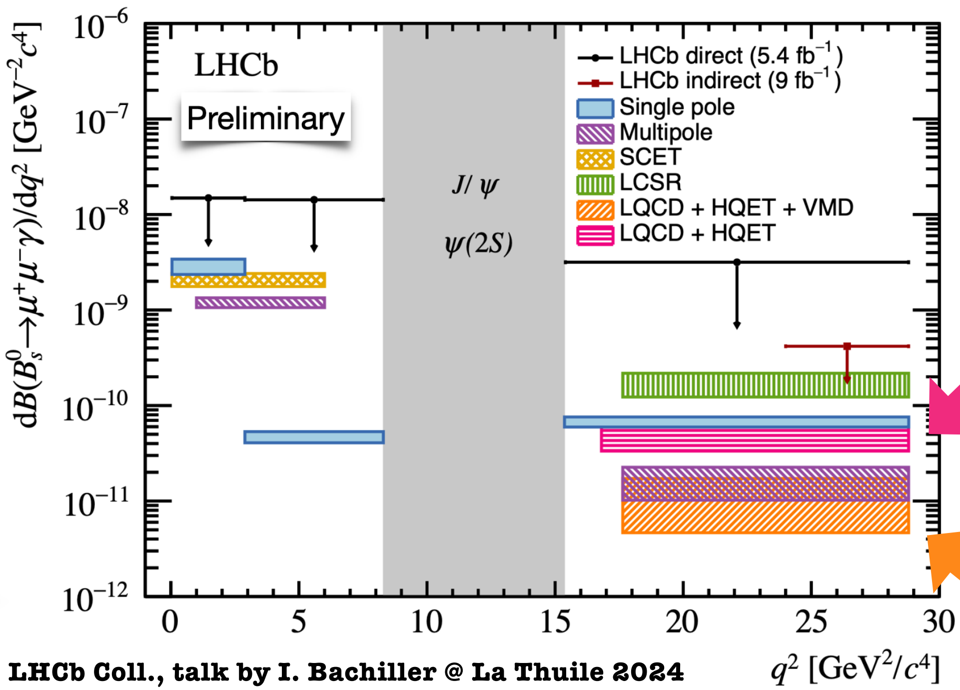
Do we know how to compute them?

In general, no!

Courtesy by L. Silvestrini

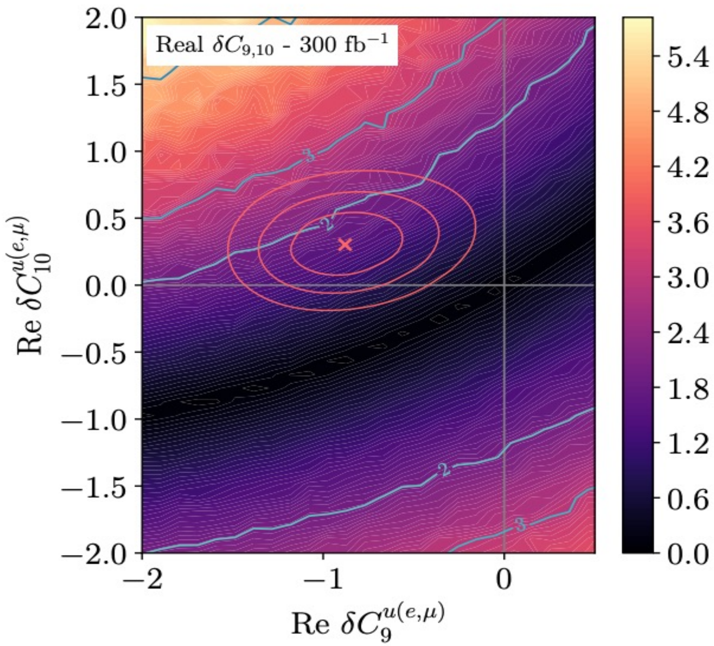
Look for complementary b → s transitions

$B_s \to \mu\mu\gamma$ @ high-q2: in this range the observables depend on the same short distance effects as those present in $B \to K(^*)\, l^+l^-$ but long distance contributions are espected to be rather small



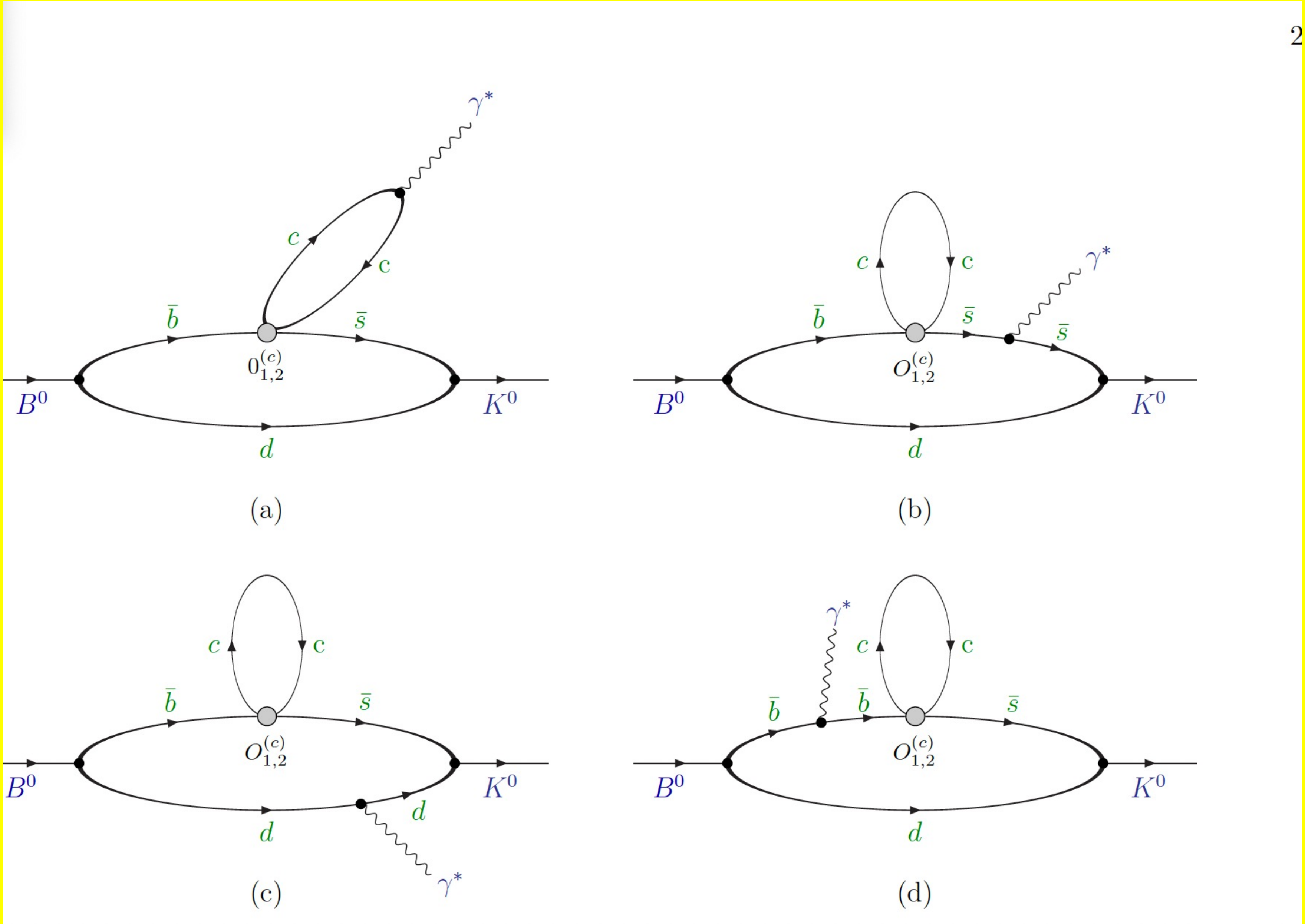
LHCb Coll., talk by I. Bachiller @ La Thuile 2024

Theoretical progresses:
First lattice calculation by the Rome-Southampton Collaboration
G. Gagliardi et al. (2402.03262)



Guadagnoli, Normand, Simula, Vittorio, JHEP '23 [2308.00034]

Charming Penguins Diagrams
(previously neglected)



Charming Penguins Diagrams:

HLT & R. Frezzotti et al Spectral-function determination of complex electroweak amplitudes with lattice QCD
Phys. Rev. D 108 (2023) 074510, [arXiv:2306.07228].

$B \to K \ell^+ \ell^-$

T-product of two ops

$$H^\nu_{1,2}(\vec{q}) = i \int d^4x \, e^{iq\cdot x} \, \langle K(\vec{p}_K)| \, T\left[J^\nu_{\rm em}(t,\vec{x}) \, O^{(c)}_{1,2}(0)\right] |B(\vec{0})\rangle$$

$$= i \left\{ \int_{-\infty}^0 dt \, \langle K(\vec{p}_K)| \, O^{(c)}_{1,2}(0) \, \tilde{J}^\nu_{\rm em}(t,\vec{q}) \, |B(\vec{0})\rangle + \int_0^\infty dt \, \langle K(\vec{p}_K)| \, \tilde{J}^\nu_{\rm em}(t,\vec{q}) \, O^{(c)}_{1,2}(0) \, |B(\vec{0})\rangle \right\}$$

$$H^{\nu+}_{1,2}(\vec{q}) = \int_{E^*}^\infty \frac{dE}{2\pi} \, \frac{\rho^{\nu+}_{1,2}(E,\vec{q})}{E - m_B - i\epsilon} \, .$$

$$\rho^{\nu+}_{1,2}(E,\vec{q}) = \langle K(-\vec{q})| \, J^\nu_{\rm em}(0) \, (2\pi)^3 \delta(\hat{\boldsymbol{P}}) \, (2\pi)\delta(\hat{H} - E) \, O_{1,2}(0) \, |B(\vec{0})\rangle \, .$$

Charming Penguins Diagrams:

$B \to \gamma \ell^+ \ell^-$

T-product of 3 ops
6 time orderings

$$H^{\mu\nu}_{1,2}(\vec{k}) = i \int dt \int d^3x \int dt_W \int d^3y \; \langle 0| T\left[J^\mu_\gamma(t,\vec{x})\, J^\nu_{\gamma^*}(0,\vec{y})\, O^{(c)}_{1,2}(t_W,\vec{0})\right] |\bar{B}_s(\vec{0})\rangle \; e^{ik\cdot x}\, e^{i\vec{k}\cdot\vec{y}}$$

$$H^{\mu\nu}_2(\vec{k}) = -\int_{E_1^*}^{\infty} \frac{dE_1}{2\pi} \int_{E_2^*}^{\infty} \frac{dE_2}{2\pi} \frac{\rho^{\mu\nu}_2(E_1,E_2,\vec{k})}{(E_2 - m_{\bar{B}_s} - i\epsilon)\,(E_2 + k_0 - m_{\bar{B}_s} - i\epsilon)}$$

$$\rho^{\mu\nu}_1(E_1,E_2,\vec{k}) = \langle 0|\, J^\mu_\gamma(0)\,(2\pi)^4\delta(\hat{\boldsymbol{P}} - \vec{k})\,\delta(\hat{H} - E_2)\, J^\nu_{\gamma^*}(0)\,(2\pi)^3\delta^{(3)}(\hat{\boldsymbol{P}})\,\delta(\hat{H} - E_1)\, O^{(c)}_{1,2}(0)\,|\bar{B}_s(\vec{0})\rangle$$

+ renormalisation of power divergences+ lattice mixing among operators + matching to the continuum Wilson coefficients of the effective Hamiltonian + the numerical calculation

we have a signal

G. Gagliardi et al.
in preparation

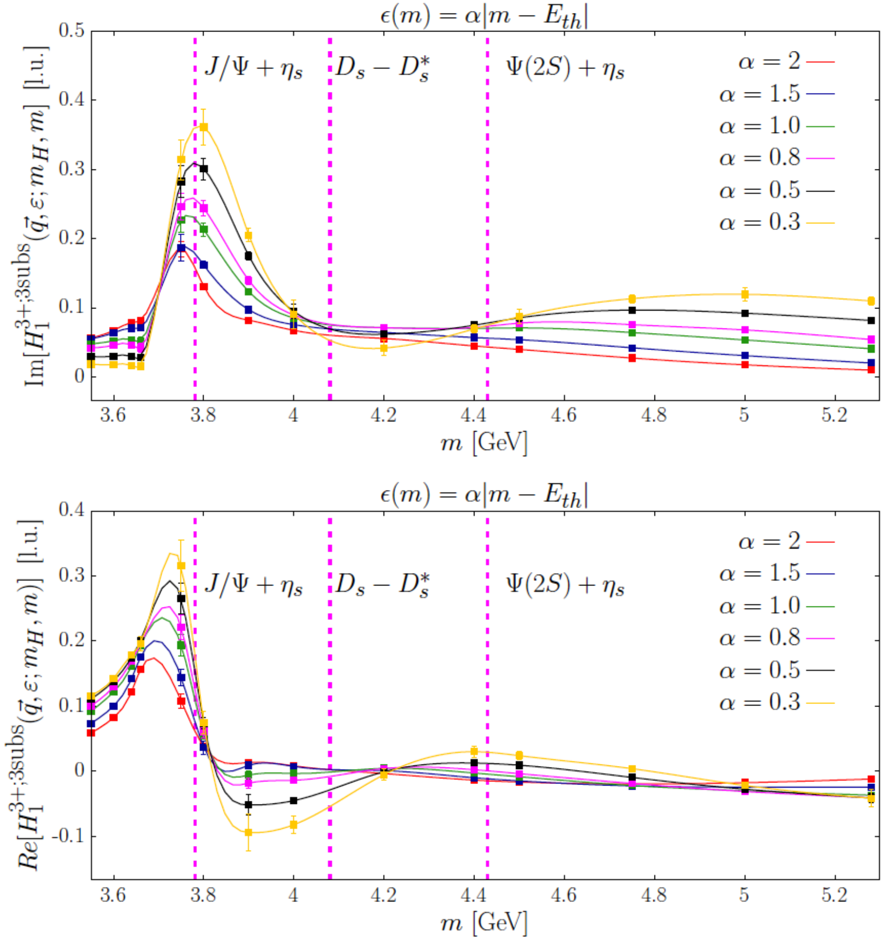


FIG. 12: The real (bottom) and imaginary (top) part of the smeared amplitude $H_1^{3+;3\mathrm{subs}}(\vec{q}, \varepsilon; m_H, m)$, as a function of m, for some of the simulated values of α in Eq. (140). The continuous lines correspond to spline interpolations of the lattice data.

This approach can be generalized to n-operators

$$H_P(k_1, k_2, \cdots, k_n) = (-i)^{n-1}(2\pi)^4\, \delta^{(4)}\Big(k_I - k_F - \sum_{i=1}^{n} k_i\Big) \Big\{ \prod_{i=1}^{n-1} \int \frac{d^4 p_i}{(2\pi)^4} \frac{(2\pi)^3 \delta^{(3)}(\vec{p}_i - \vec{\bar{k}}_{P_i})}{p_i^0 - \bar{k}^0_{P_i} - i\epsilon} \Big\} \rho_P(p_1, \cdots, p_{n-1})$$

Although it becames quite scaring (see Patella and Tantalo)

Anomalies or Theory/Exps Uncertainties ?

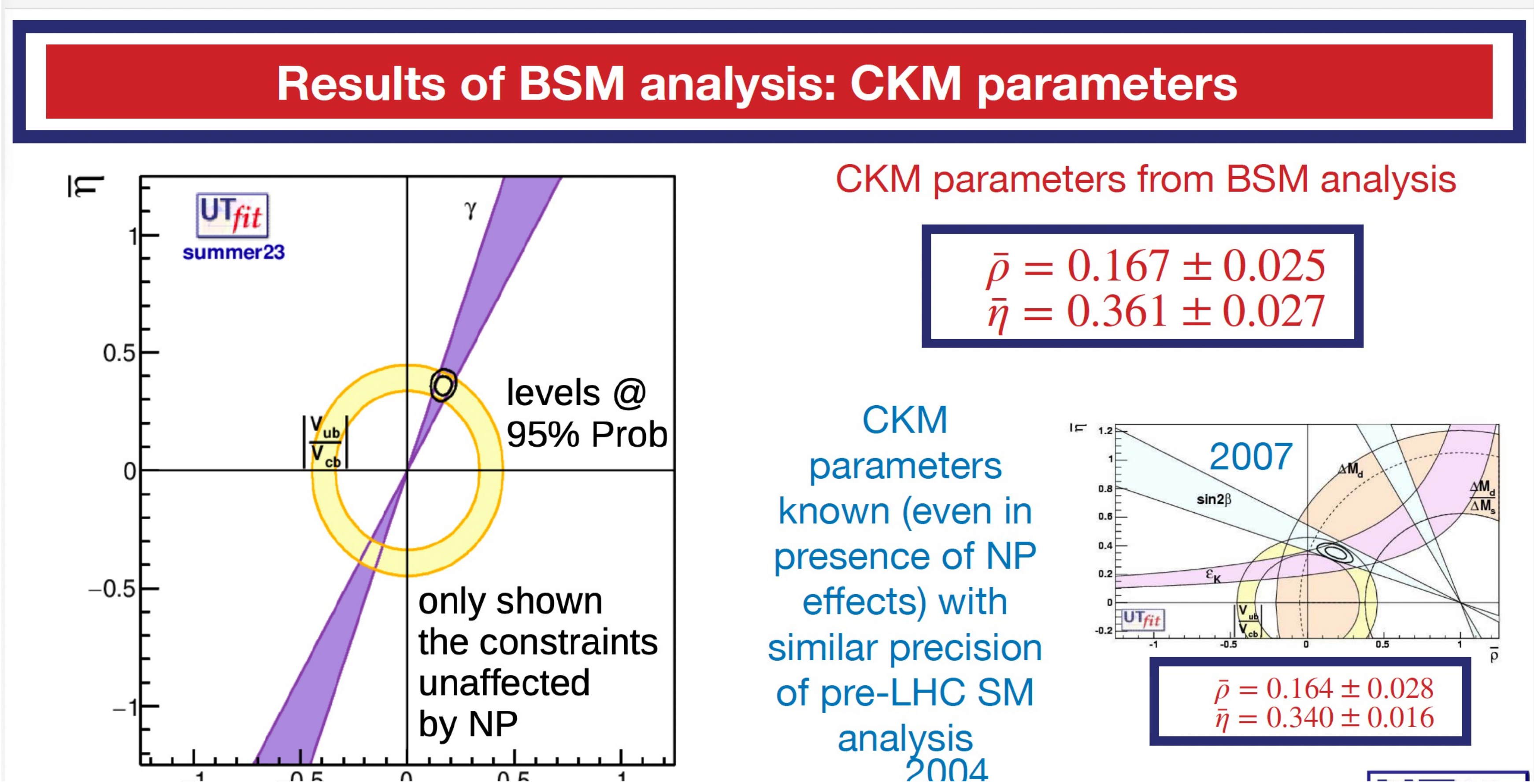
$|V_{cb}|$ $\quad$ $|V_{ub}|$

$|V_{ud}|$

P_5'

$B \to K\nu\bar{\nu}$


…. beyond
the Standard Model



1. The CKM phase is different from zero
2. The CKM phase is the dominant source of CP violation at low energy
3. No evidence for corrections to CKM
4. NP contributions to observed FCNC at most comparable (smaller) than the CKM ones
5. NP contributions very small in s-> d, c -> u , b -> d, b -> s

$$Q^{EXP} = V_{CKM}\langle F|\hat{O}|I\rangle$$

Constrains on NP from UTfit

$$Q^{EXP} = \sum_i C^i_{SM}(M_W, m_t, \alpha_s)\langle F|\hat{O}_i|I\rangle + \sum_{i'} C^{i'}_{Beyond}(\tilde{m}_\beta, \alpha_s)\langle F|\hat{O}_{i'}|I\rangle$$

UT generalization Beyond the Standard Model

- fit simultaneously for the CKM and the NP parameters (generalized UT analysis)

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

  - parameterize BSM effects in $\Delta F = 2$ Hamiltonian in model-independent
  - use all available experimental information

- find out NP contributions to $\Delta F=2$ transitions

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM}$$
$$A_{CP}^{B_d \to J/\psi K_s} = \sin 2(\beta + \phi_{B_d})$$
$$A_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_q\right)$$
$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$
$$A_{CP}^{B_s \to J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$
$$\Delta\Gamma^q / \Delta m_q = \mathrm{Re}\left(\Gamma_{12}^q / A_q\right)$$

CERN

UTfit

New local four-fermion operators are generated

$Q_1 = (\bar{b}_L{}^A \gamma_\mu d_L{}^A)(\bar{b}_L{}^B \gamma_\mu d_L{}^B)$ SM

$Q_2 = (\bar{b}_R{}^A d_L{}^A)(\bar{b}_R{}^B d_L{}^B)$

$Q_3 = (\bar{b}_R{}^A d_L{}^B)(\bar{b}_R{}^B d_L{}^A)$

$Q_4 = (\bar{b}_R{}^A d_L{}^A)(\bar{b}_L{}^B d_R{}^B)$

$Q_5 = (\bar{b}_R{}^A d_L{}^B)(\bar{b}_L{}^B d_R{}^A)$

+ those obtained by L $\leftrightarrow$ R

Similarly for the s quark e.g.

$(\bar{s}_R{}^A d_L{}^A)(s_R{}^B d_L{}^B)$

$$\langle \bar{K}^0 | O_1(\mu) | K^0 \rangle = \frac{8}{3} M_K^2 f_K^2 B_1(\mu) ,$$

$$\langle \bar{K}^0 | O_2(\mu) | K^0 \rangle = -\frac{5}{3} \left(\frac{M_K}{m_s(\mu) + m_d(\mu)} \right)^2 M_K^2 f_K^2 B_2(\mu) ,$$

$$\langle \bar{K}^0 | O_3(\mu) | K^0 \rangle = \frac{1}{3} \left(\frac{M_K}{m_s(\mu) + m_d(\mu)} \right)^2 M_K^2 f_K^2 B_3(\mu) ,$$

$$\langle \bar{K}^0 | O_4(\mu) | K^0 \rangle = 2 \left(\frac{M_K}{m_s(\mu) + m_d(\mu)} \right)^2 M_K^2 f_K^2 B_4(\mu) ,$$

$$\langle \bar{K}^0 | O_5(\mu) | K^0 \rangle = \frac{2}{3} \left(\frac{M_K}{m_s(\mu) + m_d(\mu)} \right)^2 M_K^2 f_K^2 B_5(\mu) ,$$

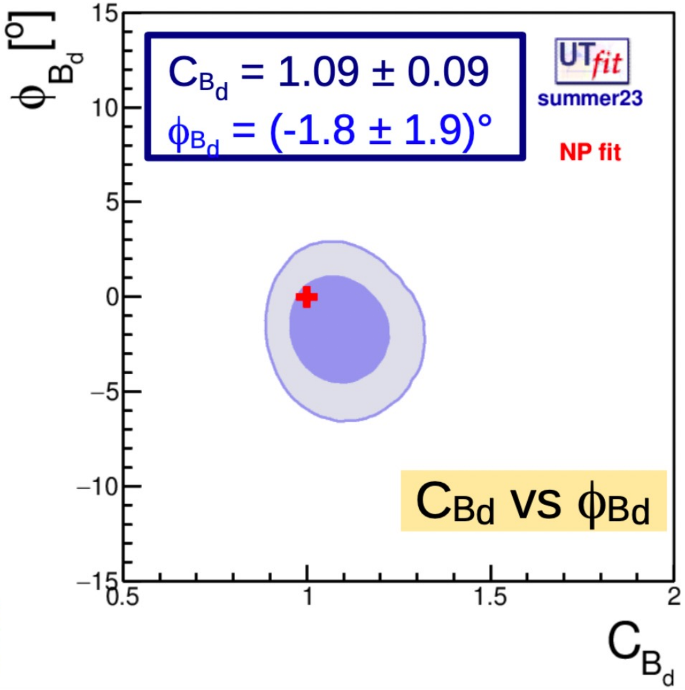
Results of BSM analysis: New Physics parameters

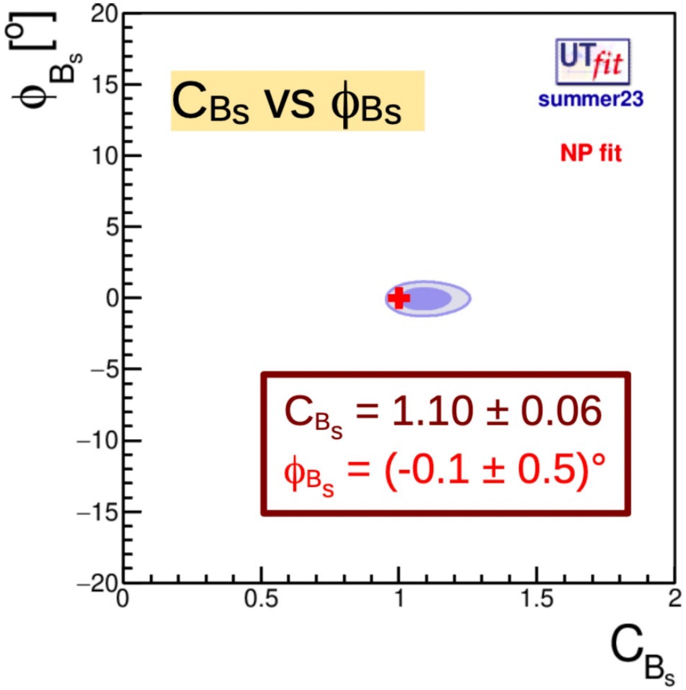
$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$

K system

$C_{\epsilon_K} = 1.09 \pm 0.10$

dark: 68%
light: 95%
SM: red cross



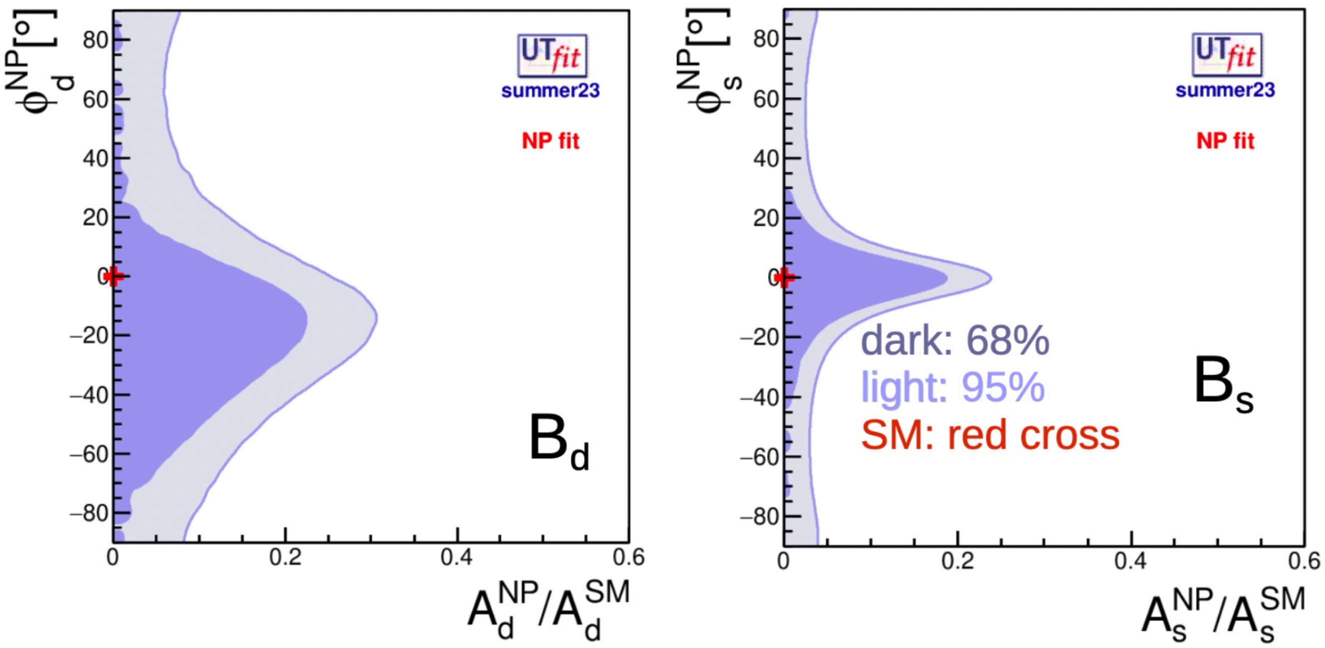


Results of BSM analysis: New Physics parameters

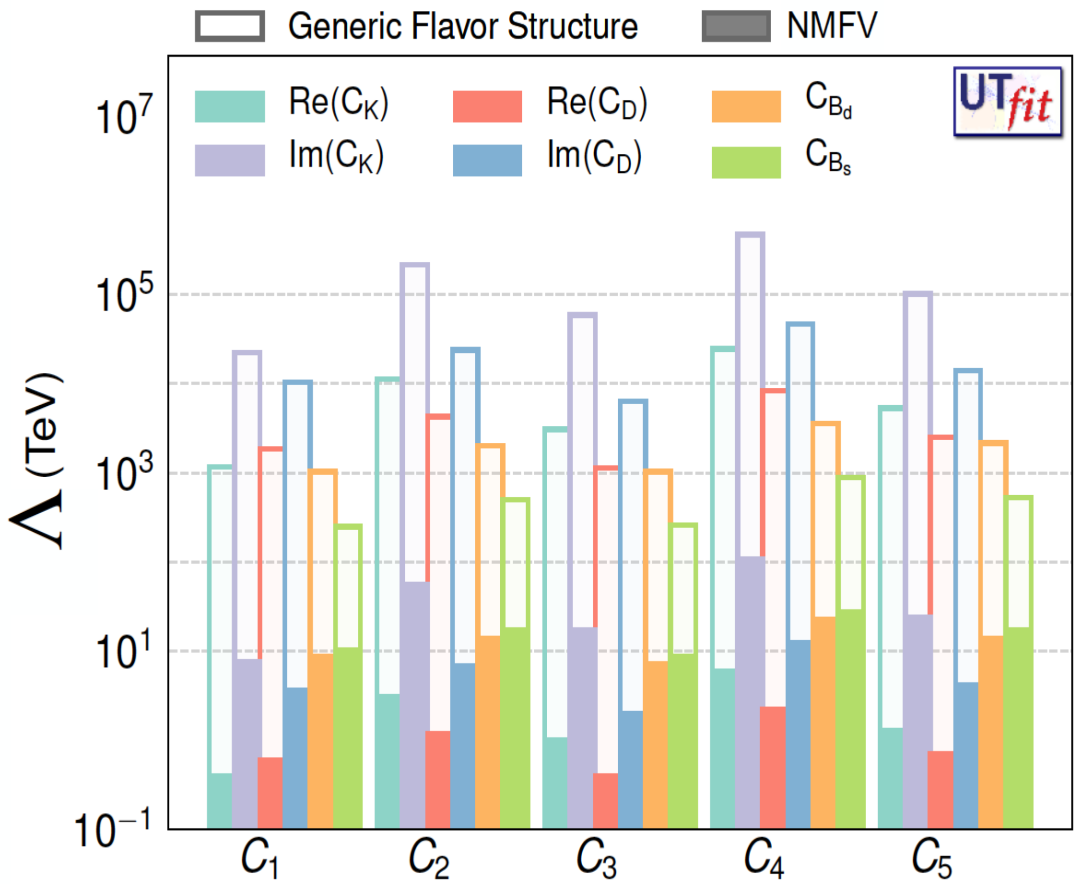
$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

The ratio of NP/SM amplitudes is:
< 25% @68% prob. (35% @95%) in B_d mixing
< 25% @68% prob. (30% @95%) in B_s mixing

dark: 68%
light: 95%
SM: red cross



Results of BSM analysis: probing New Physics Scale



$$\mathcal{H}_{\rm eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq}$$

$$Q_1^{q_iq_j} = \bar{q}_{jL}^{\alpha}\gamma_\mu q_{iL}^{\alpha}\bar{q}_{jL}^{\beta}\gamma^\mu q_{iL}^{\beta} ,$$

$$Q_2^{q_iq_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\bar{q}_{jR}^{\beta} q_{iL}^{\beta} ,$$

$$Q_3^{q_iq_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\bar{q}_{jR}^{\beta} q_{iL}^{\alpha} ,$$

$$Q_4^{q_iq_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\bar{q}_{jL}^{\beta} q_{iR}^{\beta} ,$$

$$Q_5^{q_iq_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\bar{q}_{jL}^{\beta} q_{iR}^{\alpha} .$$

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

- Generic: $C(\Lambda) = \alpha/\Lambda^2$ F_i~1, arbitrary phase
- NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ F_i~$|F_{SM}|$, arbitrary phase

- α ~ α_W in case of loop coupling
- through weak interactions*

$\Lambda > 1.3\ 10^4$ TeV

- α ~ α_W in case of loop coupling
- through weak interactions*

$\Lambda > 2.7$ TeV

1) NP must explain the strong hierarcy of the Fermion couplings/masses
2) If the scale of NP it is not too high it must suppresses FCNC processes at an accettable level

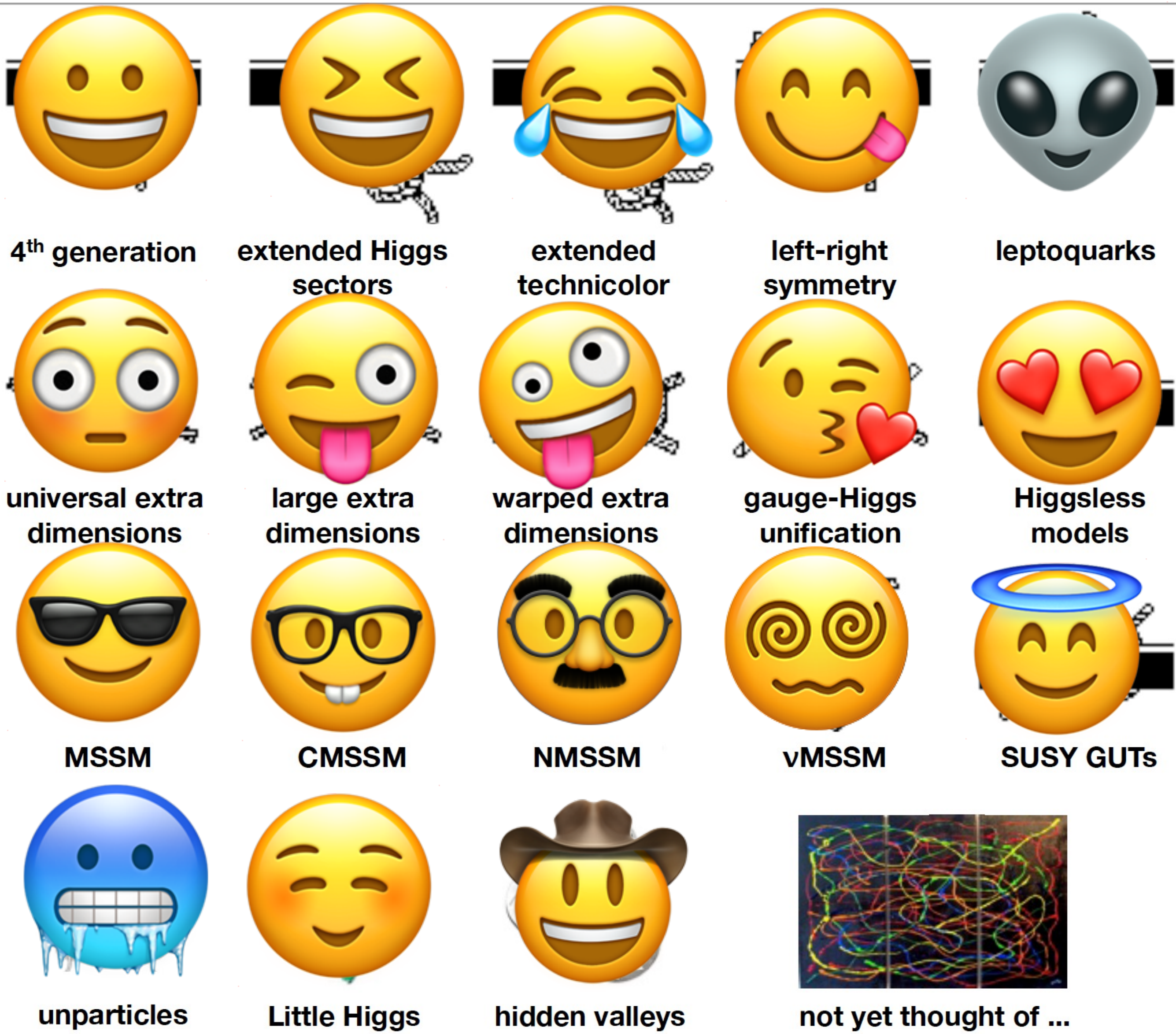
$$Y_t \sim 1 \qquad Y_c \sim 10^{-2} \qquad Y_u \sim 10^{-5}$$
$$Y_b \sim 10^{-2} \qquad Y_s \sim 10^{-3} \qquad Y_d \sim 10^{-5}$$
$$Y_\tau \sim 10^{-2} \qquad Y_\mu \sim 10^{-3} \qquad Y_e \sim 10^{-6}$$

$$|V_{us}| \sim 0.2 \qquad |V_{cb}| \sim 0.04 \qquad |V_{ub}| \sim 0.004 \qquad \delta \sim 1$$

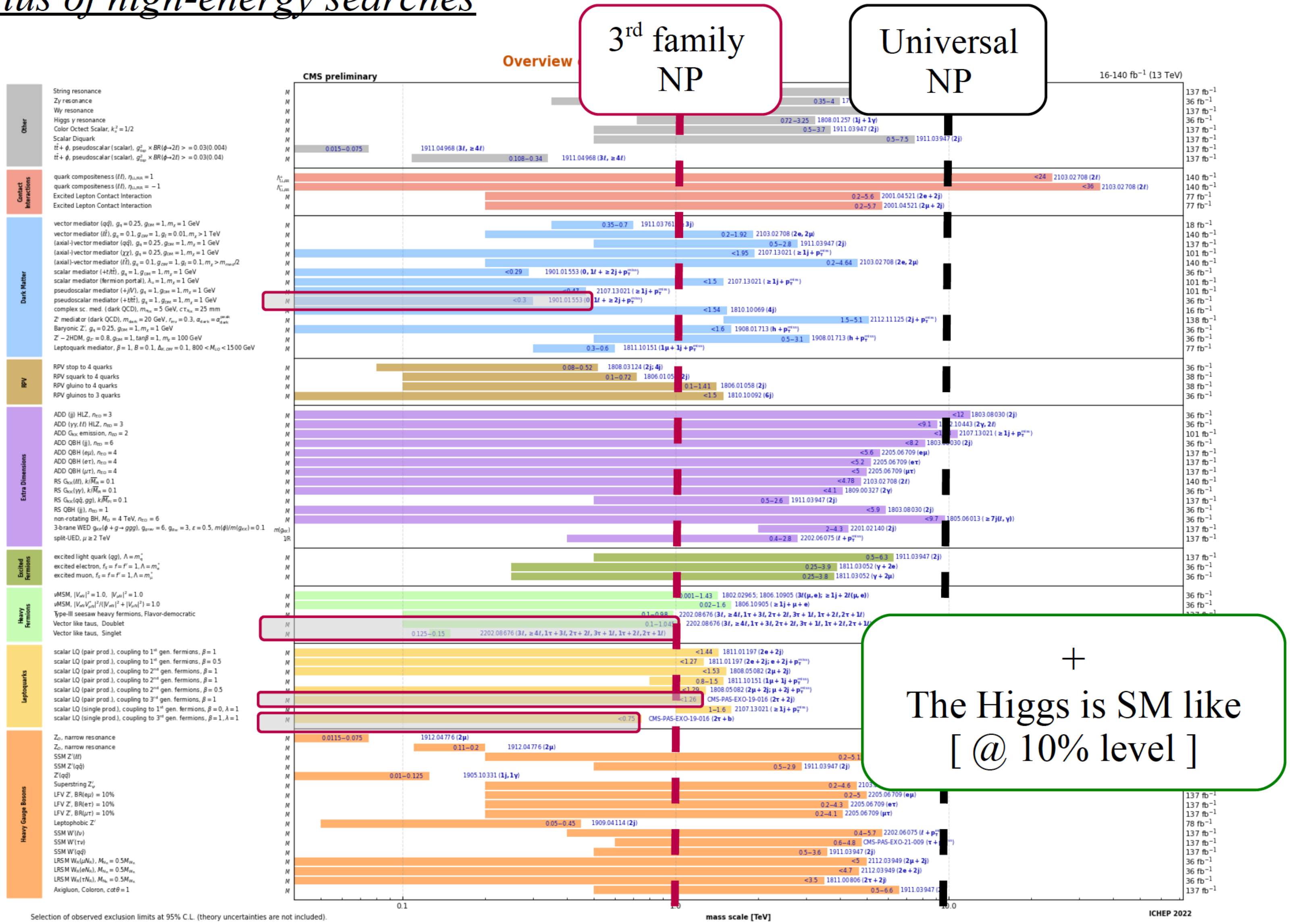
$$0.1 \sim \quad g' \,, \quad g \,, \quad g_s \,, \quad \lambda \quad \sim 1.$$

FUTURE, BSM: It is difficult to make predictions, especially about the future

It is time to leave you in the hands of R. Barbieri



Status of high-energy searches



If these ideas corrects, new non-standard effects should emerge soon both at low and at high energies (→ very interesting opportunities for run-3...).

absence says more than presence

FRANK HERBERT

(Dune)

THANKS FOR YOUR ATTENTION

INFN Istituto Nazionale di Fisica Nucleare

UTfit