Flavor Physics: from the past to the future we have to go through the present

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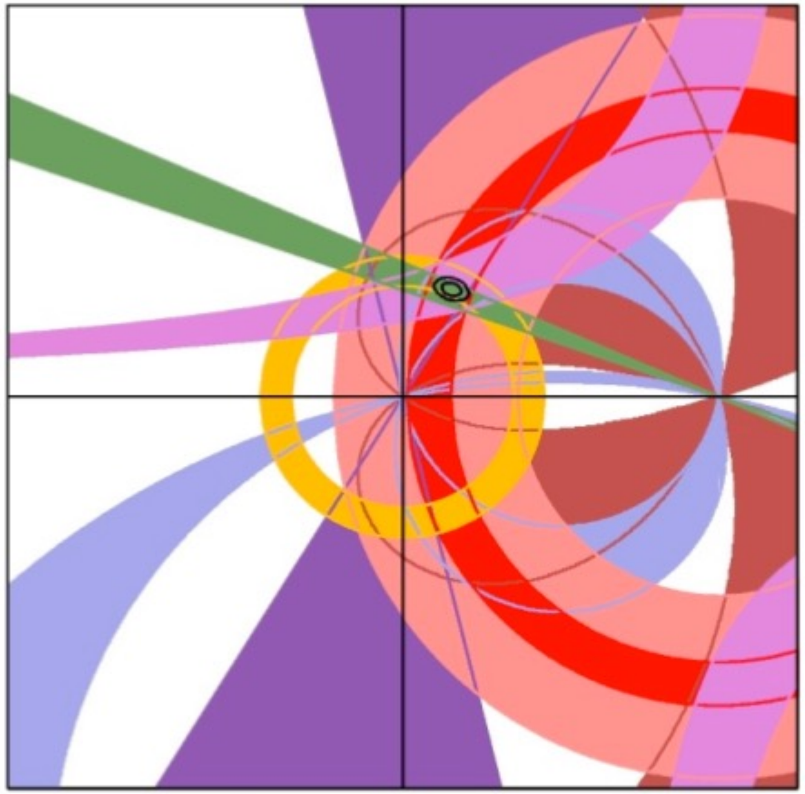
UTfit

Extended Twisted Mass Collaboration

INFN Istituto Nazionale di Fisica Nucleare

PLAN OF THE TALK

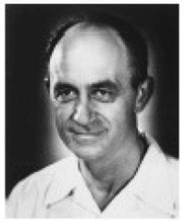


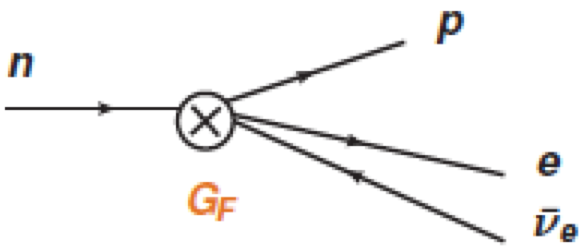
- *The lesson from the past*
- *Flavor in the SM*
- *Utfit Analysis, Tensions and unknown*
- *Flavor Beyond the SM*
- *Future directions, new/old ideas*
- *Conclusion*

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

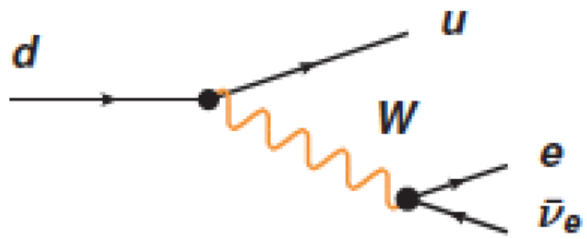
Historical example: β decay





Fermi constant

$G_F \simeq 1.17 \times 10^{-5}\ \mathrm{GeV}^{-2}$



W-boson exchange

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8 m_W^2}$$

Unitarization of the Fermi theory:
New Physics at 10^2 GeV (indirect evidence)

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***

Discoveries from Flavor Physics

CP Violation !!

- the tiny branching ratio of the decay $K_L \to \mu^+\mu^-$ led to the prediction of the charm quark to suppress FCNCs
  (Glashow, Iliopoulos, Maiani 1970)

$$\Gamma(K \to \mu\mu) \ll \Gamma(K \to \mu\nu)$$

- the measurement of the frequency of kaon anti-kaon oscillations allowed a successful prediction of the charm quark mass
  (Gaillard, Lee 1974)

$$\Delta m_K$$

(direct discovery of the charm quark in 1974 at SLAC and BNL)

- the observation of CP violation in kaon anti-kaon oscillations led to the prediction of the 3rd generation of quarks
  (Kobayashi, Maskawa 1973)

$$\varepsilon_K$$

- the measurement of the frequency of B - $\bar{B}$ oscillations allowed to predict the large top quark mass
  (various authors in the late 80's)

$$\Delta m_B$$

(direct discovery of the bottom quark in 1977 at Fermilab)

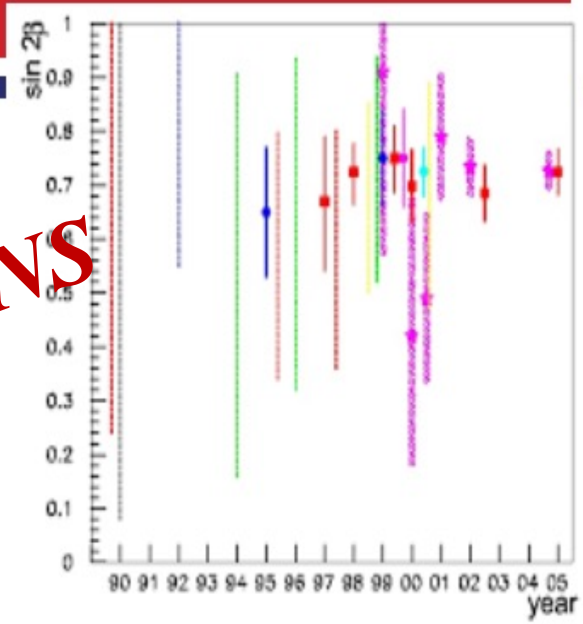
(direct discovery of the top quark in 1995 at Fermilab)

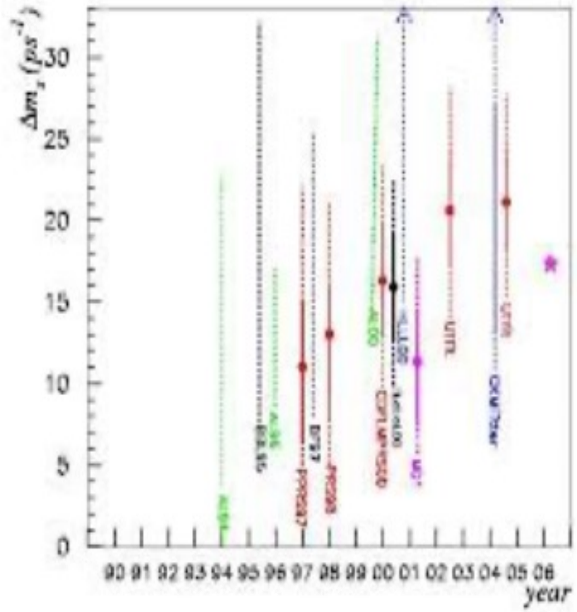
indirect evidence

30 years of UT fit

- Since early '90s, the UT framework has been established to probe CP violation in the flavor sector
  - sin2b (CPV in $B_d\bar{B}_d$ mixing) the reference quantity
  - very loose predictions once its value
  - jump in accuracy ~ '95, when the first full statistical analysis was attempted, strongly benefiting of the first determination of the top mass. The UT analysis was born, predicting a few still unknown quantities
    - $\sin 2\beta = 0.65 \pm 0.12$
  - In 2000, Rome and Orsay/Genova groups (running similar fits) joined forces. This was the beginning of the UTfit collaboration

PREDICTIONS





2000 CKM-TRIANGLE ANALYSIS
A Critical Review with Updated Experimental Inputs and Theoretical Parameters

M. Ciuchini[a], G. D'Agostini[b], E. Franco[b], V. Lubicz[a], G. Martinelli[b], F. Parodi[c], P. Roudeau[d] and A. Stocchi[d]

- Flavour, EW fit: m_t~170 GeV
- EW fit: m_H=100±30 GeV

Courtesy by M. Pierini

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

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

Buchmuller&Wyler '88

Flavor puzzle

Neutrino Masses

New Physics

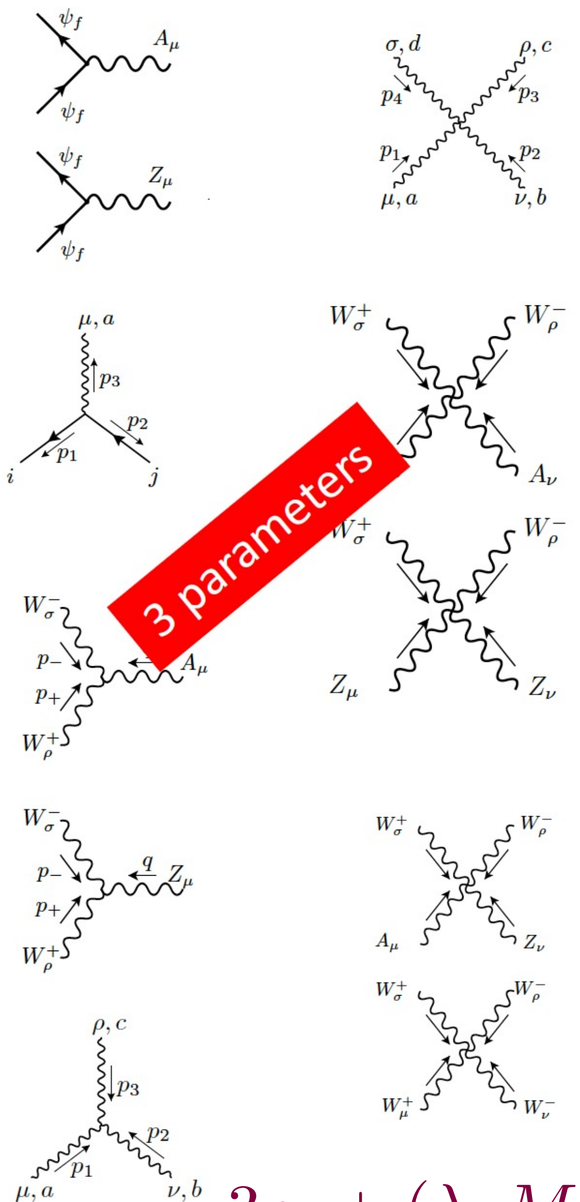
Possible breaking of accidental symmetries

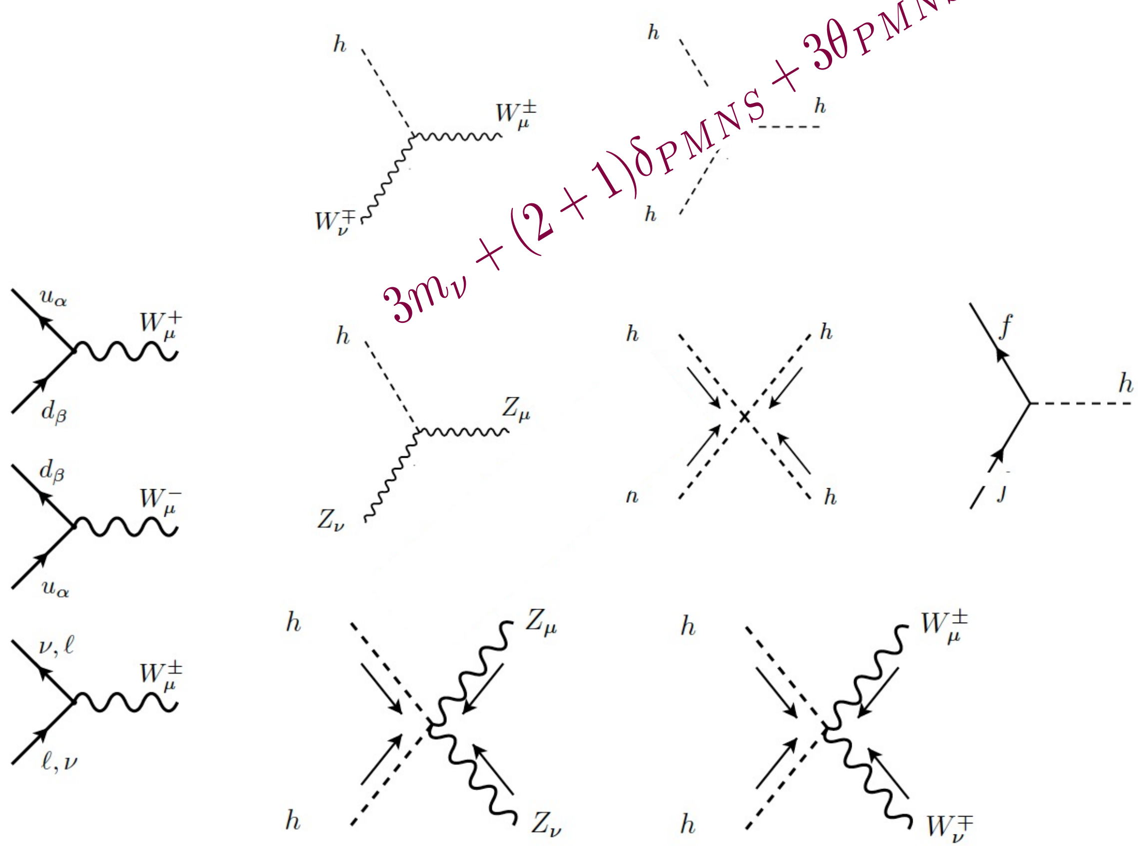
Only circled terms discussed in this talk

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

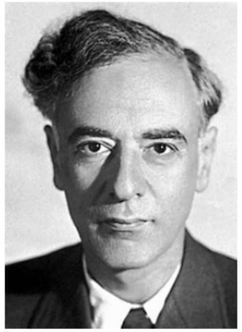
$3m_\nu + (2+1)\delta_{PMNS} + 3\theta_{PMNS} = 9$

- Three families

"who ordered that ?" I. Rabi

- Fundamental breaking of Parity

"space cannot be asymmetric!" L. Landau



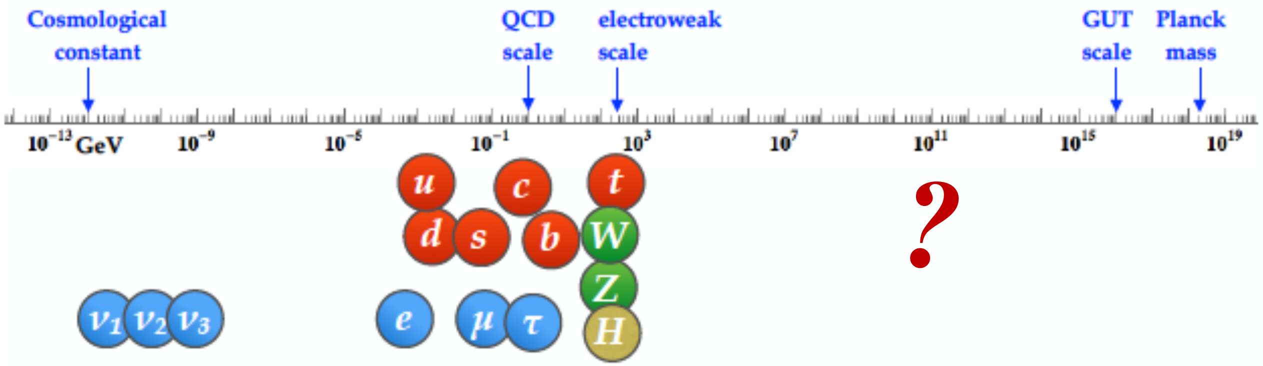
- Predictivity: 3 gauge couplings+ 16 higgs couplings (+ 7 higgs-neutrino) !
  + the coupling θ of strong CP violation

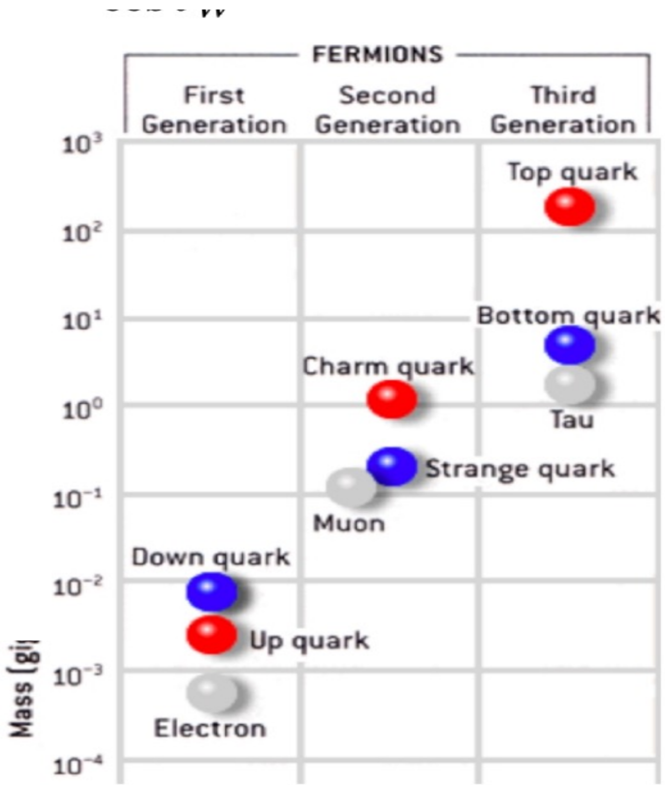
"has too many arbitrary features for [its] predictions to be taken very seriously" S. Weinberg '67

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

Zupan

J. Zupan





$m_\nu \leq 1\, eV$

Illustration from a G. Isidori talk

Quark Masses from Lattice QCD

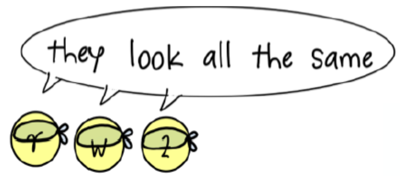
Input	Lattice/Exp
$m_u^{\overline{\rm MS}}(2\,\rm GeV)$	2.20(9) MeV
$m_d^{\overline{\rm MS}}(2\,\rm GeV)$	4.69(2) MeV
$m_s^{\overline{\rm MS}}(2\,\rm GeV)$	93.14(58) MeV
$m_c^{\overline{\rm MS}}(3\,\rm GeV)$	993(4) MeV
$m_c^{\overline{\rm MS}}(m_c^{\overline{\rm MS}})$	1277(5) MeV
$m_b^{\overline{\rm MS}}(m_b^{\overline{\rm MS}})$	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 flavor blind and CP conserving

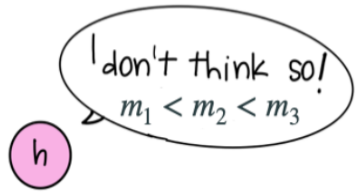
$$\mathcal{G}_F(\text{SM}) = U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$



The Higgs introduces the only known non-gauge couplings

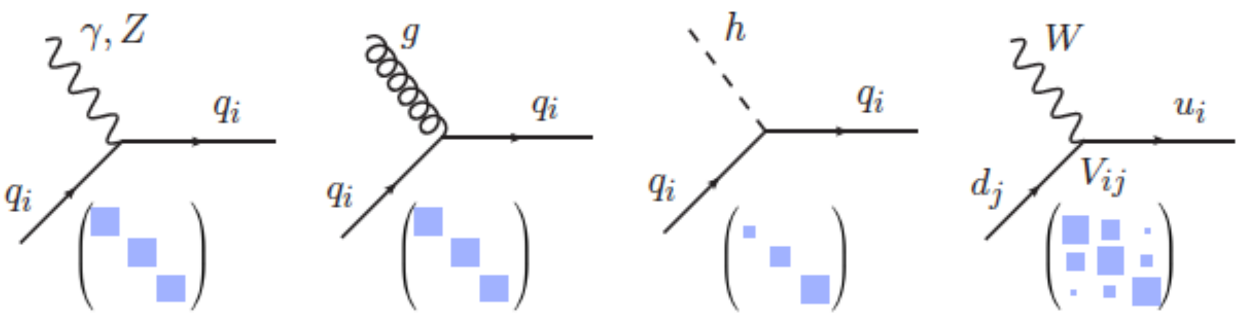
Turn on Yukawas

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



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

Higgs couplings are not flavor blind



courtesy of B.A. Stefan

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

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

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

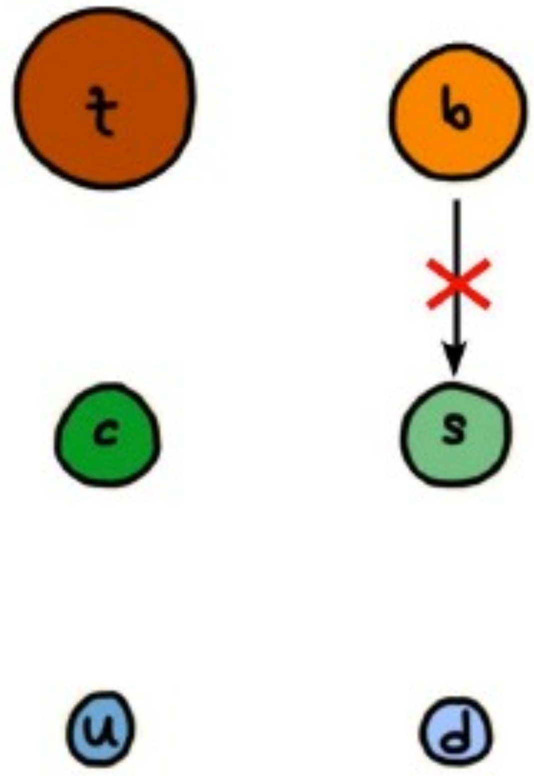
$$L_{CC}^{weak\,int} = \frac{g_W}{\sqrt{2}}\left(J_{\mu}^{-}W_{\mu}^{+} + h.c.\right)$$

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

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?

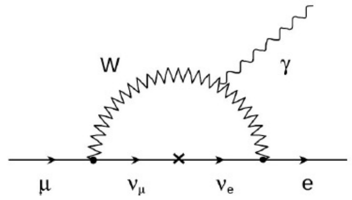
WHY RARE DECAYS ?

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

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

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

$q_i \to q_k + \gamma$

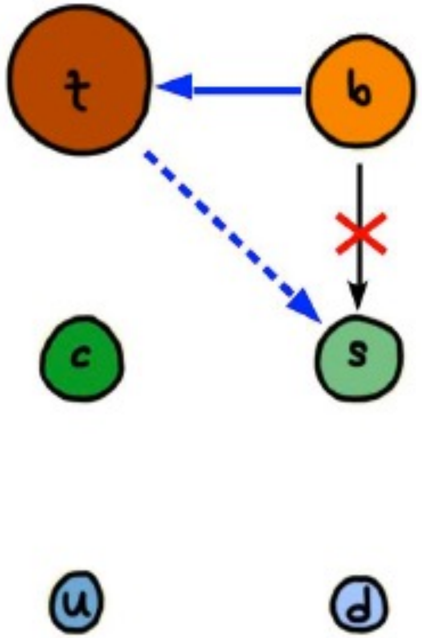
these decays occur only via loops and are suppressed by CKM because of GIM

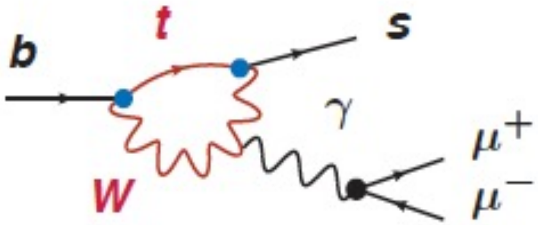
THUS THEY ARE SENSITIVE TO NEW PHYSICS

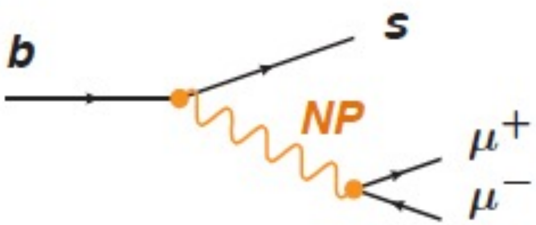
Flavor Changing Neutral Currents in the SM

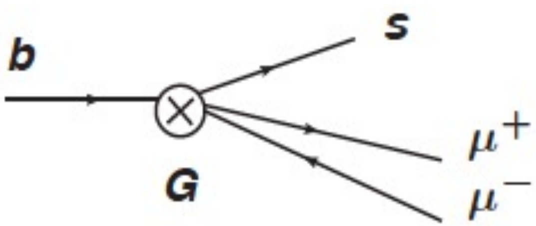
In the SM, flavor changing neutral currents (FCNCs) are absent at the tree level

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





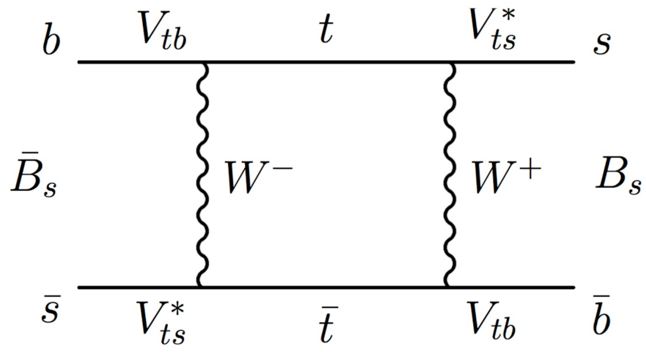




$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

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

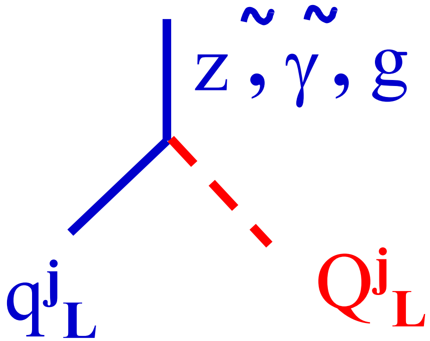
B^0 - $\overline{B}^0$ mixing



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



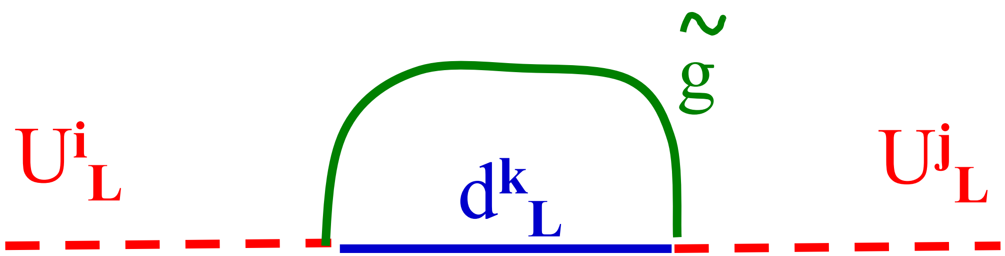
In general the mixing mass matrix of the SQuarks (SMM) is not diagonal in flavour space analogously to the quark case

We may either

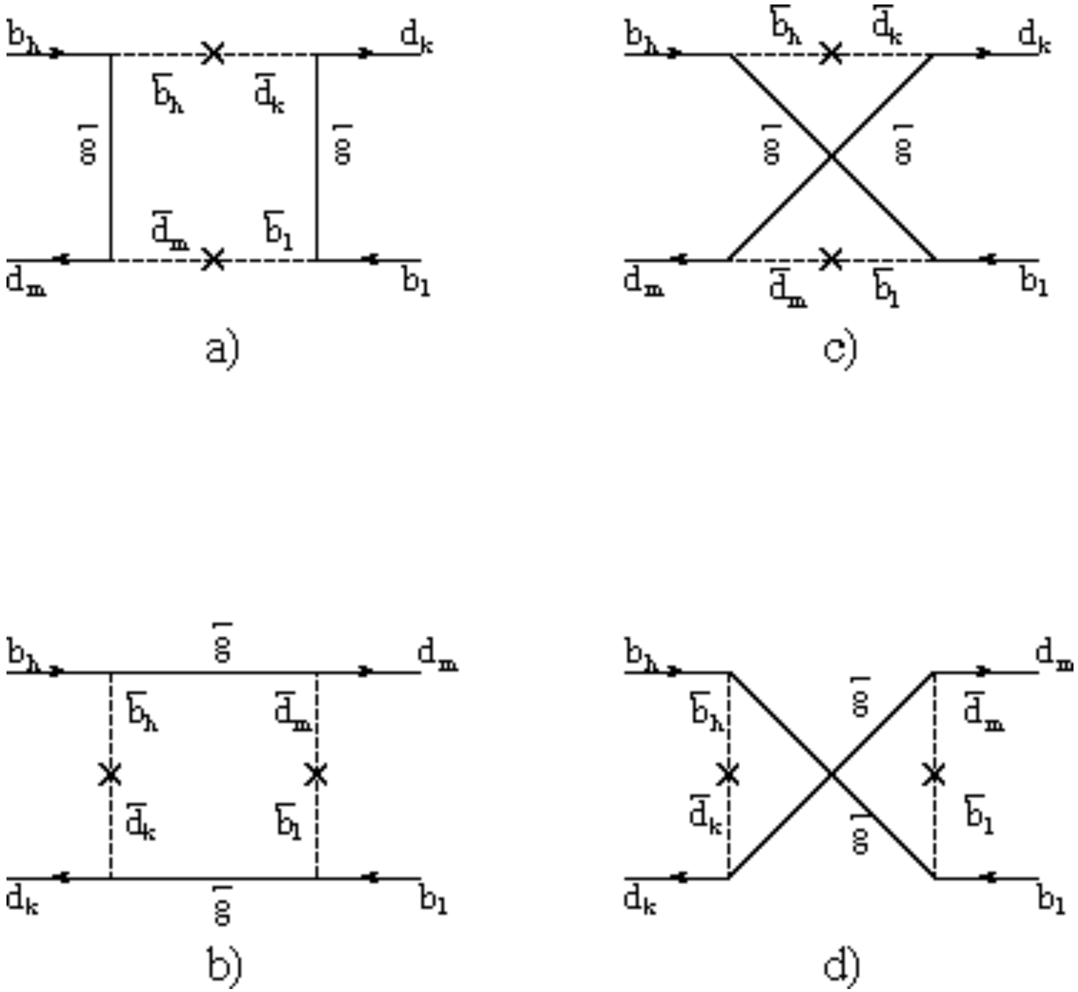
Diagonalize the SMM

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

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

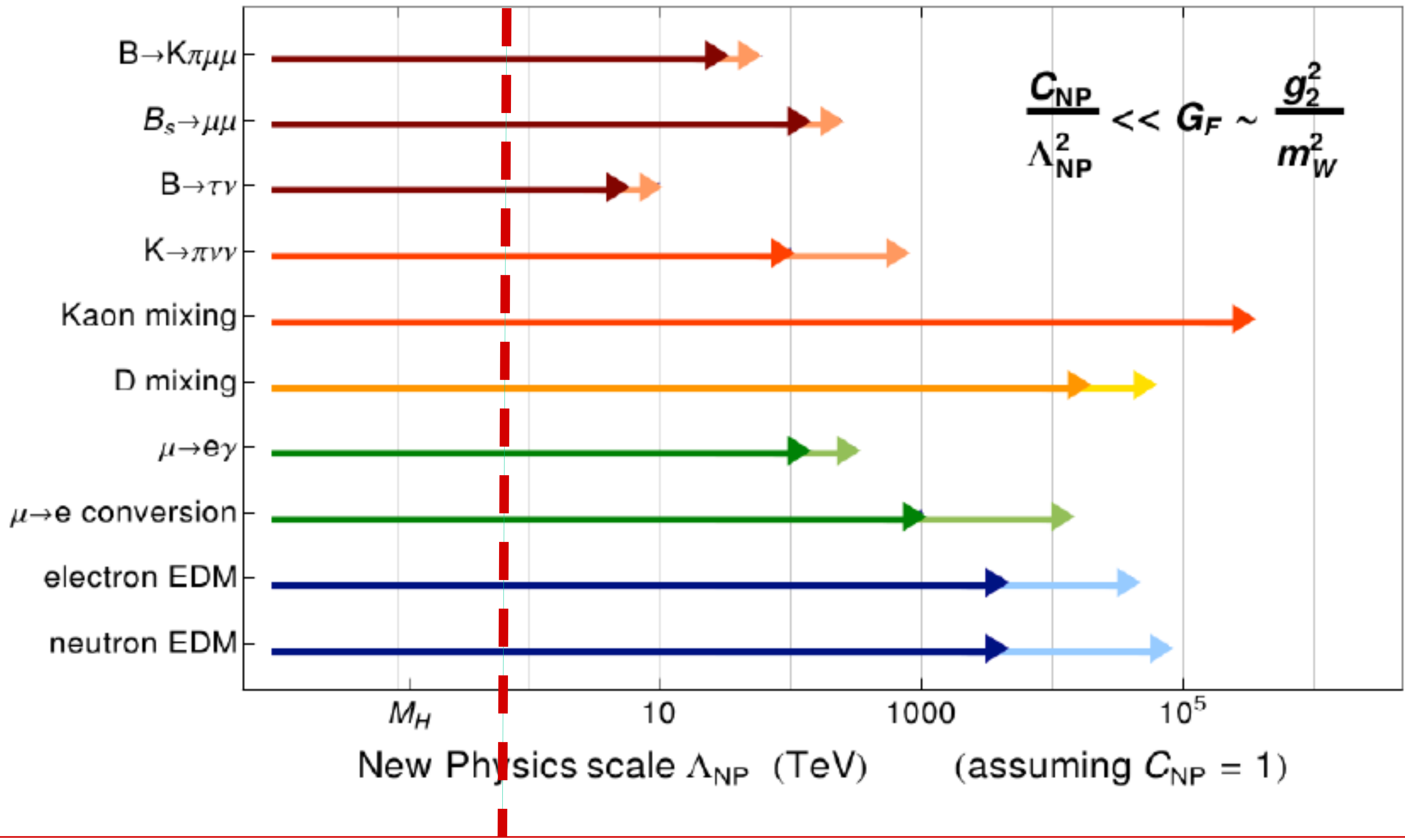


In the latter case the Squark Mass Matrix is not diagonal



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

Sensitivity to New Physics from Flavor

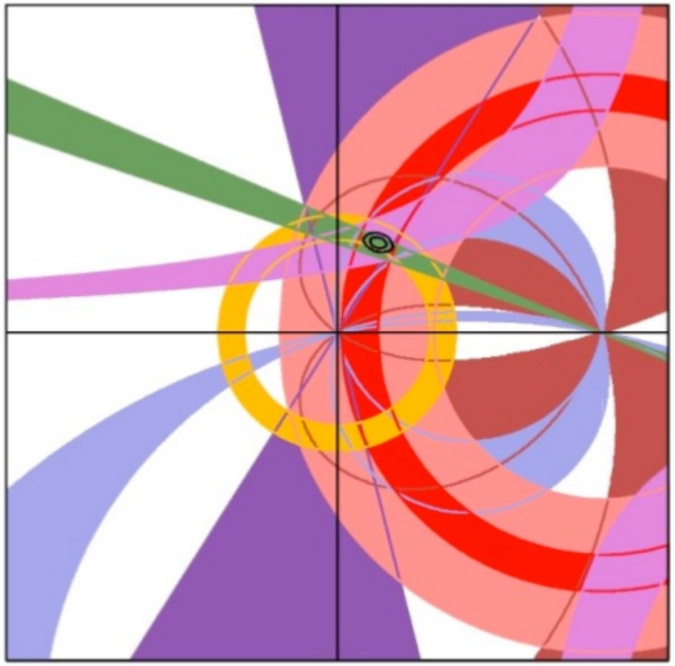


Approximate LHC direct reach

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

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

It is precision physics and we need precise lattice calculations

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. <u>CP violation;</u>

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

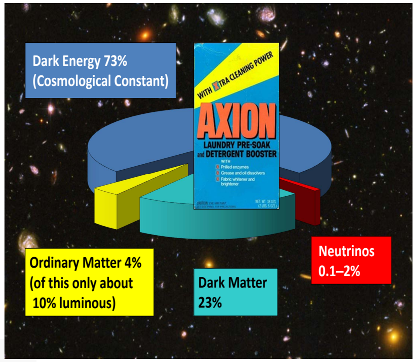
$$\mathcal{L}_\theta = \theta\, G^{\mu\nu a} \tilde{G}^a_{\mu\nu} \qquad \tilde{G}^a_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma} G^a_{\rho\sigma}$$

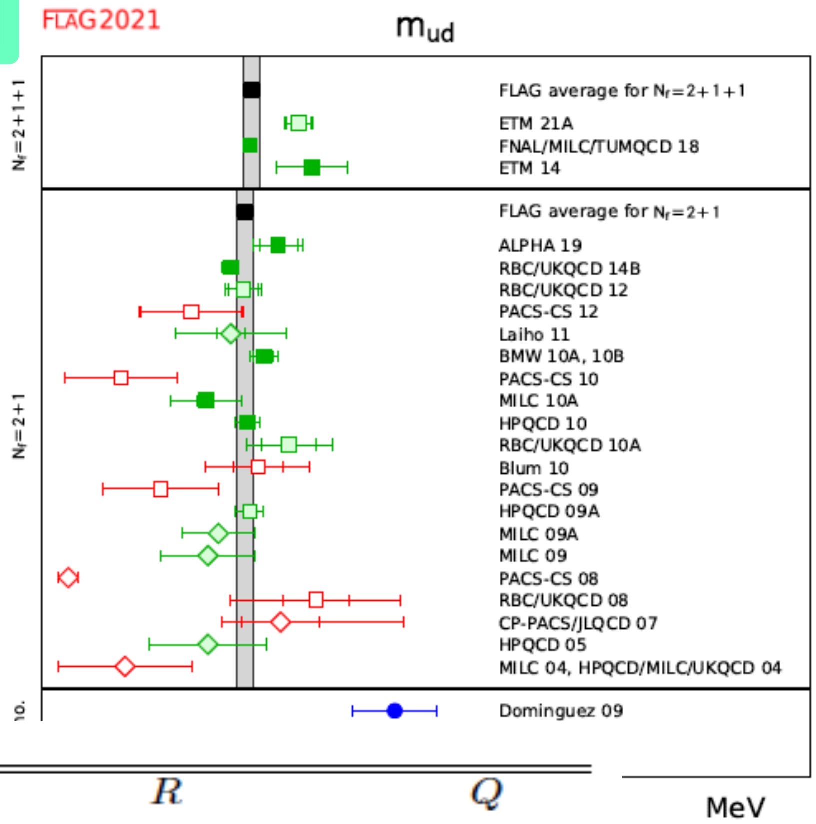
$$L_\theta \sim \theta\, \vec{E}^a \cdot \vec{B}^a$$

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

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

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



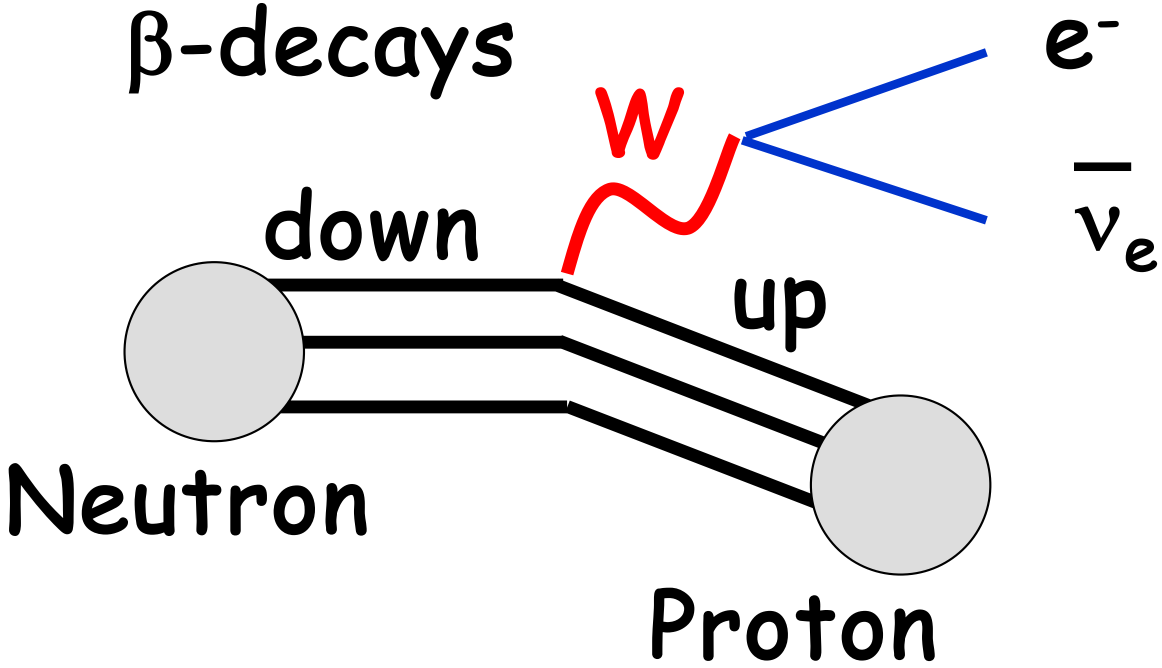


N_f	m_u	m_d	m_u/m_d	R	Q
2+1+1	2.14(8)	4.70(5)	0.465(24)	35.9(1.7)	22.5(0.5)
2+1	2.27(9)	4.67(9)	0.485(19)	38.1(1.5)	23.3(0.5)

Quark masses & Generation Mixing

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

β-decays



$|V_{ud}|$

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

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

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

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

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

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

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

(0.999)

updated values later

The Wolfenstein Parametrization

$1 - 1/2\,\lambda^2$	λ	$A\,\lambda^3(\rho - i\,\eta)$
$-\lambda$	$1 - 1/2\,\lambda^2$	$A\,\lambda^2$
$A\,\lambda^3 \times (1 - \rho - i\,\eta)$	$-A\,\lambda^2$	1

V_{ub}

$+ O(\lambda^4)$

It is really of $O(\lambda^3)$?

V_{td}

$\lambda \sim 0.2 \quad A \sim 0.8$

$\eta \sim 0.2 \quad \rho \sim 0.3$

$\sin\theta_{12} = \lambda$

$\sin\theta_{23} = A\,\lambda^2$

$\sin\theta_{13} = A\,\lambda^3(\rho - i\,\eta)$

The Unitarity Triangle Analysis

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

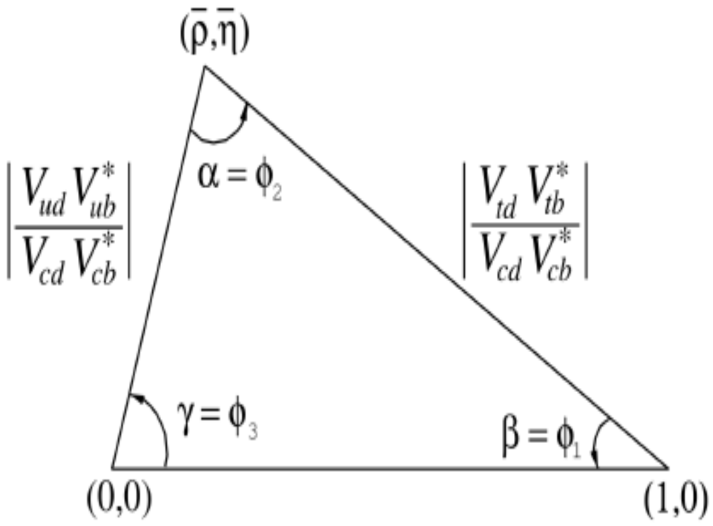
$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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



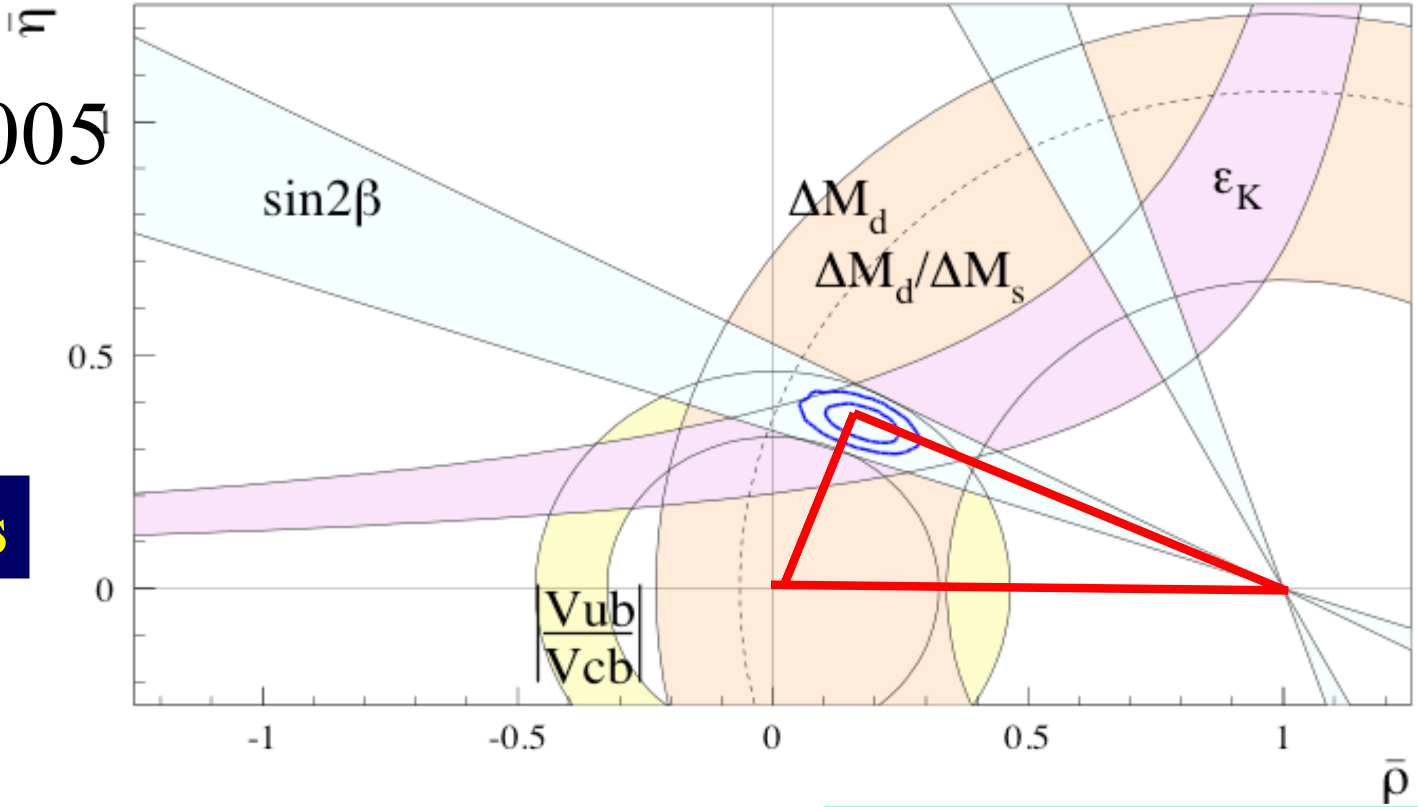
- By determining th... CKM matrix

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

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

Unitary Triangle SM

2005



semileptonic decays

Experimental co

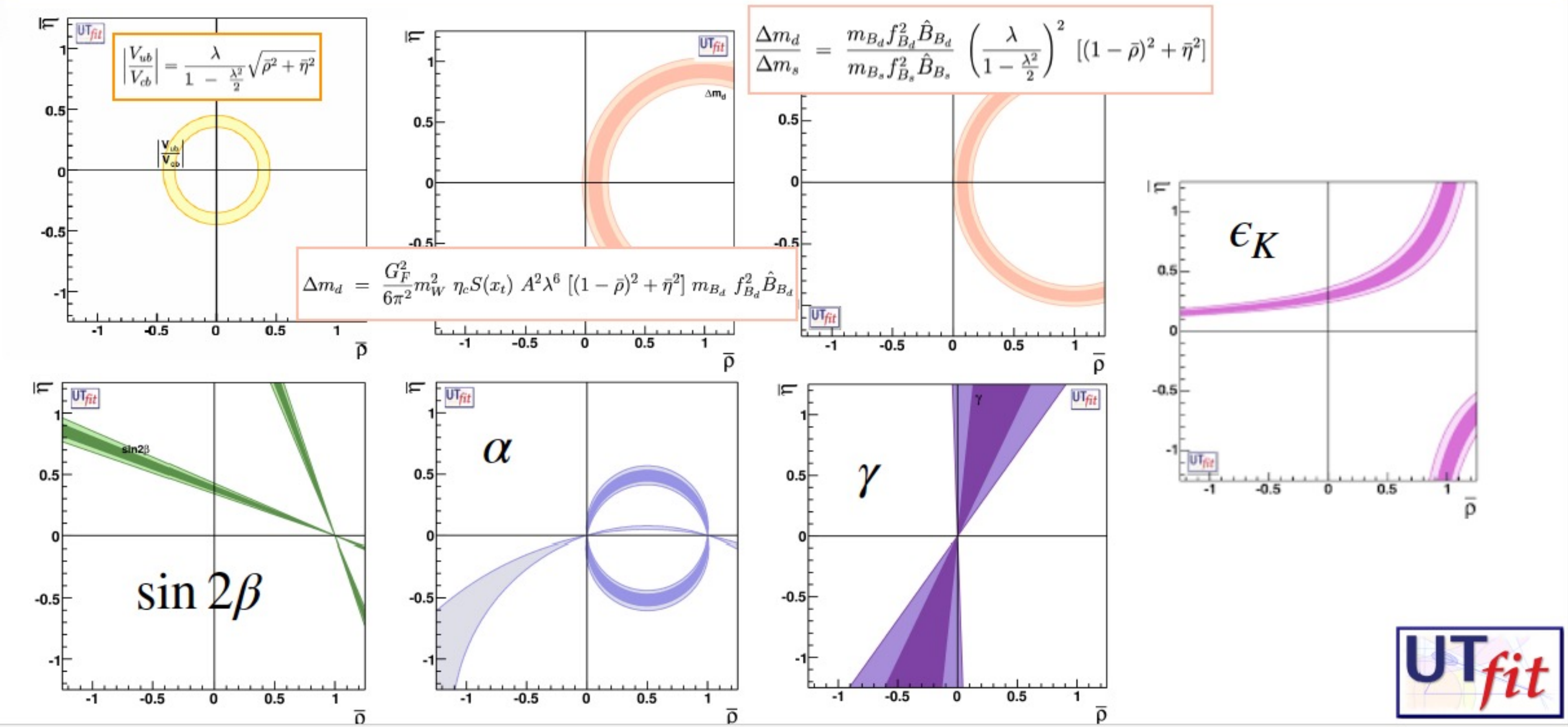
Meas.	$V_{CKM}\times$other	$(\bar\rho,\bar\eta)$
$\frac{b\to u}{b\to c}$	$\lvert V_{ub}/V_{cb}\rvert^2$	$\bar\rho^2+\bar\eta^2$
Δm_d	$\lvert V_{td}\rvert^2 f_{B_d}^2 B_{B_d}$	$(1-\bar\rho)^2+\bar\eta^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\left\lvert\frac{V_{td}}{V_{ts}}\right\rvert^2 \xi^2$	$(1-\bar\rho)^2+\bar\eta^2$
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

The extraordinary progress of the experimental measurements requires accurate theoretical predictions

Precision flavor physics requires the control of hadronic effects for which lattice QCD simulations are essential

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

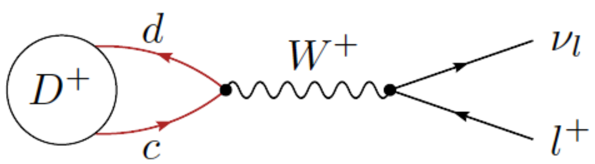
SM

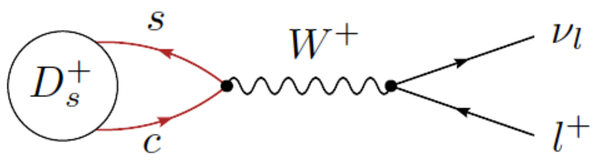
$$Q^{EXP} = \sum_i C^i_{SM}(M_W, m_t, \alpha_s)\langle F|\hat{O}_i|I\rangle + \sum_{i'} C^{i'}_{Beyond}(\tilde{m}_\beta, \alpha_s)\langle F|\hat{O}_{i'}|I\rangle$$

BSM

What can be computed and
What cannot be computed

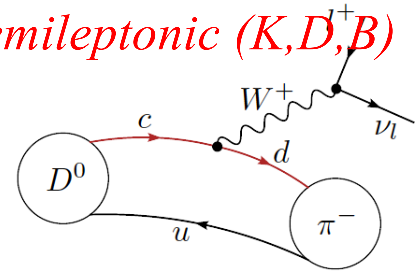
Leptonic (π,K,D,B)

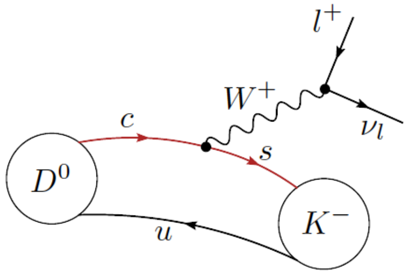


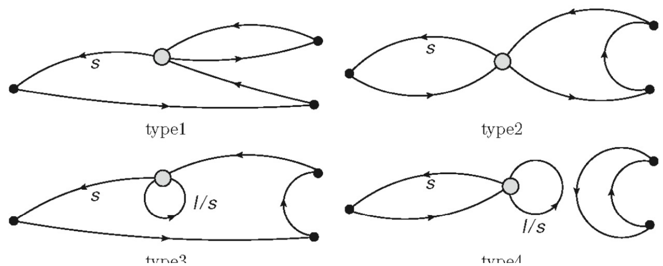


Non-leptonic
but only below the inelastic threshold
(may be also 3 body decays)

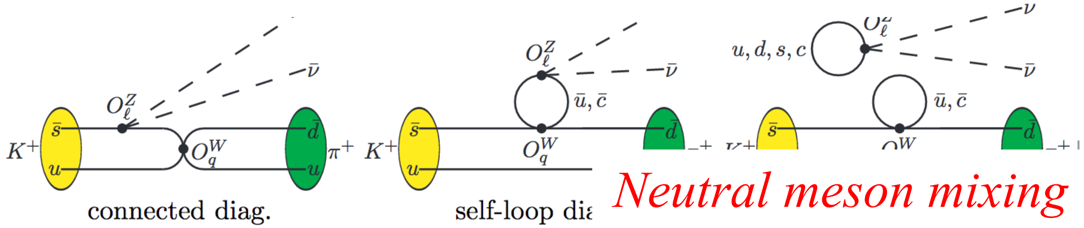
Semileptonic (K,D,B)



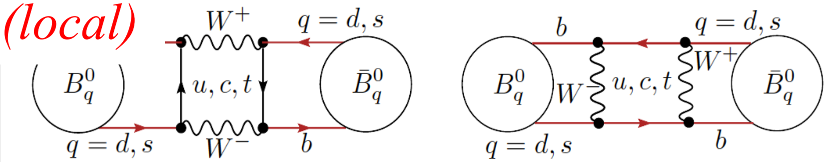




B -> ππ,Kπ, etc. No-> maybe !



Neutral meson mixing (local)



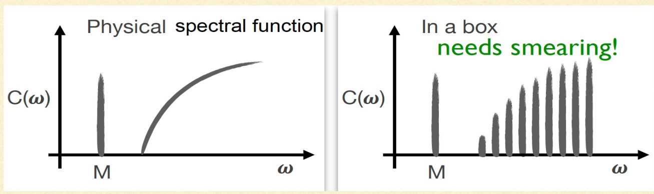
(some) Radiative and Rare *long distance effects*
(also K -> π l⁺l⁻)

INCLUSIVE DECAYS ON THE LATTICE

Inclusive processes impractical to treat directly on the lattice. Vacuum current correlators computed in euclidean space-time are related to $e^+e^- \to$ hadrons or τ decay via analyticity. In our case the correlators have to be computed in the B meson, but analytic continuation more complicated: two cuts, decay occurs only on a portion of the physical cut.

While the lattice calculation of the spectral density of hadronic correlators is an ***ill-posed problem***, the spectral density is accessible after smearing

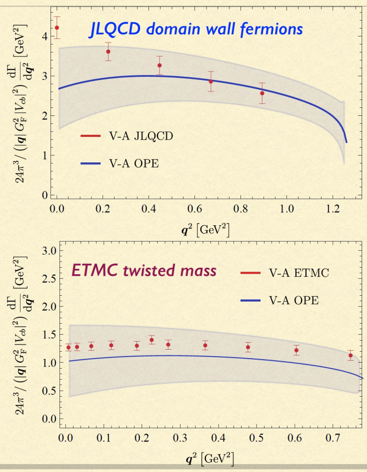
Hansen, Meyer, Robaina, Hansen, Lupo, Tantalo, Bailas, Hashimoto, Ishikawa



W. Jay @Snowmass workshop

PG, Hashimoto, Maechler, Panero, Sanfilippo, Simula, Smecca, Tantalo, 2

LATTICE vs OPE



m_b^{kin} (JLQCD)	2.70 ± 0.04
$\overline{m}_c(2\text{ GeV})$ (JLQCD)	1.10 ± 0.02
m_b^{kin} (ETMC)	2.39 ± 0.08
$\overline{m}_c(2\text{ GeV})$ (ETMC)	1.19 ± 0.04
μ_π^2	0.57 ± 0.15
ρ_D^3	0.22 ± 0.06
$\mu_G^2(m_b)$	0.37 ± 0.10
ρ_{LS}^3	-0.13 ± 0.10
$\alpha_s^{(4)}(2\text{ GeV})$	0.301 ± 0.006

OPE inputs from fits to exp data (physical m_b), HQE of meson masses on lattice

1704.06105, J.Phys.Conf.Ser. 1137 (2019) 1, 012005

We include $O(1/m_b^3)$ and $O(\alpha_s)$ terms

Hard scale $\sqrt{m_c^2 + \mathbf{q}^2} \sim 1 - 1.5\,\text{GeV}$

We do not expect OPE to work at high $|\mathbf{q}|$

Twisted boundary conditions allow for any value of $\vec{q}^2$

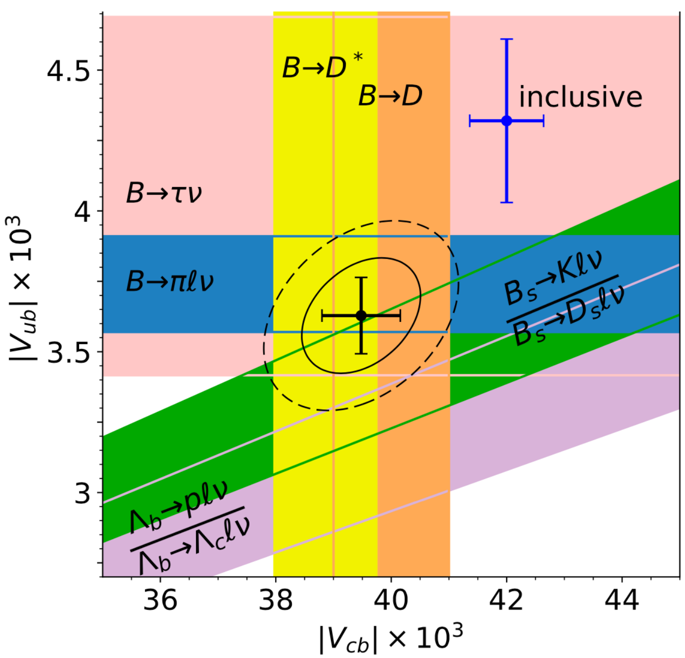
Smaller statistical uncertainties

What can be computed and What cannot be computed

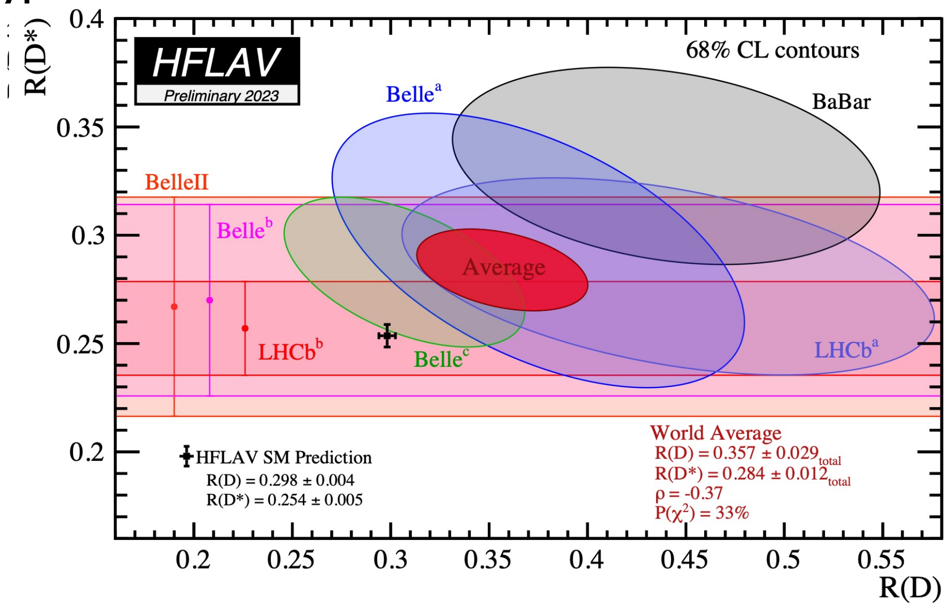
Tension(s) in $b \to c$ decays ? Charged Currents & Tree level

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

FLAG Review 2021 [EPJC '22 (2111.09849)]



2. Lepton Flavor Universality Violation



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

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

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

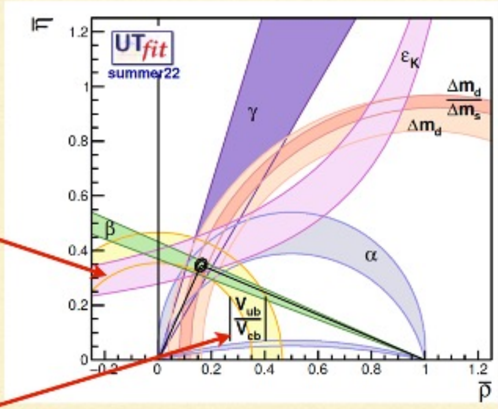
$$\varepsilon_K \approx x|V_{cb}|^4 + \ldots$$

and in the prediction of FCNC:

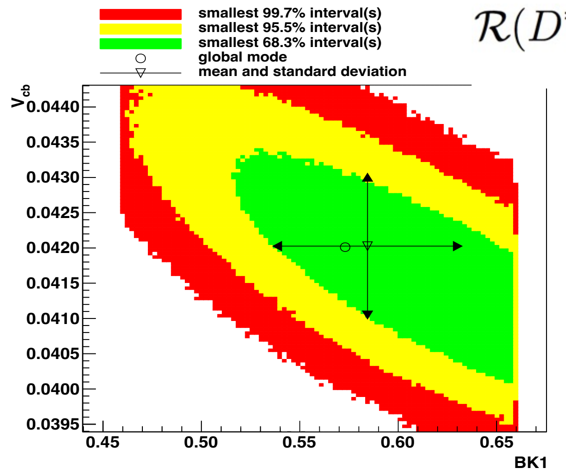
$$\propto |V_{tb}V_{ts}|^2 \simeq |V_{cb}|^2\left[1 + O(\lambda^2)\right]$$

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



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

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

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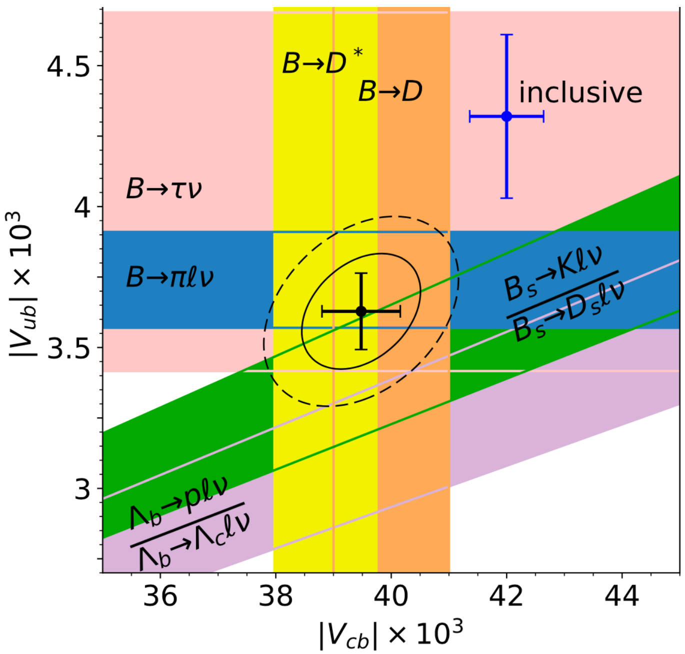

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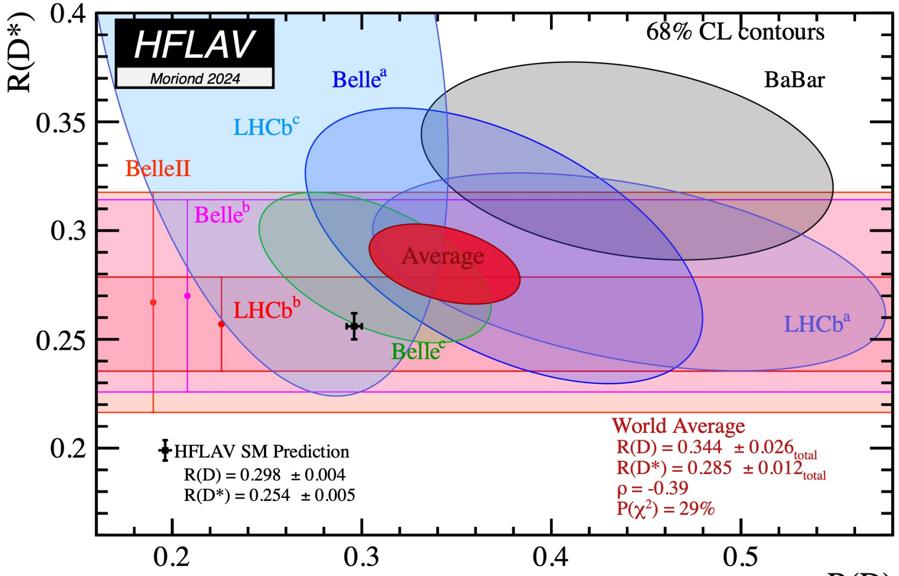
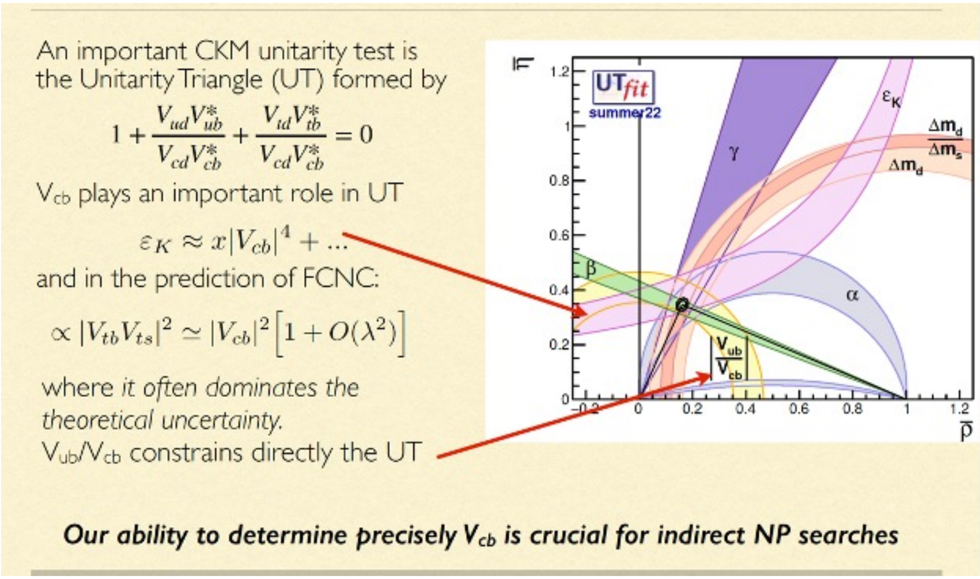
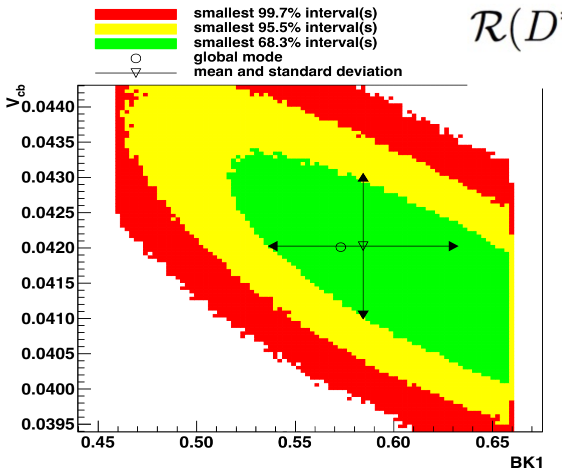


HFLAV Collaboration, PRD '23 [arXiv:2206.07501] (updated plot)

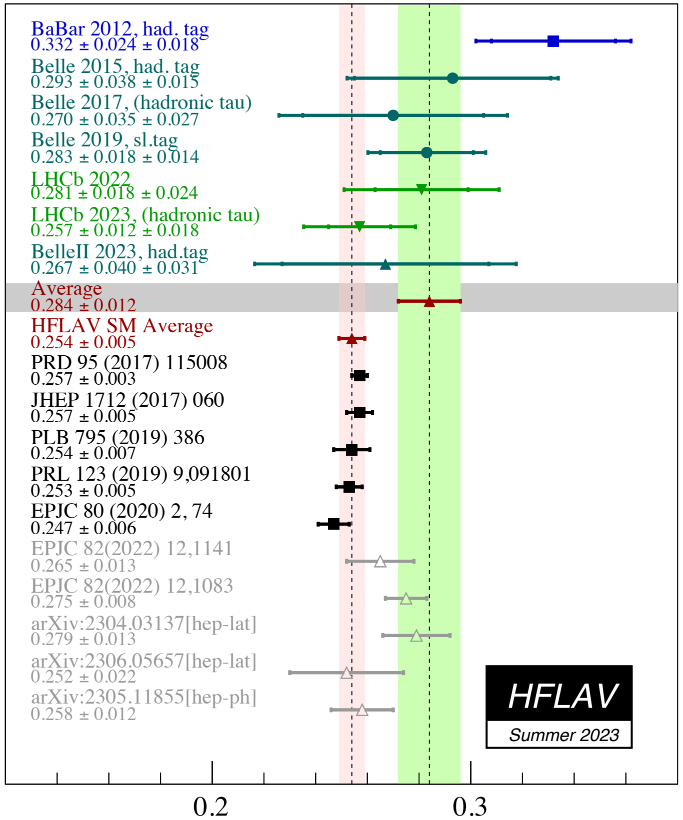
$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)},$$

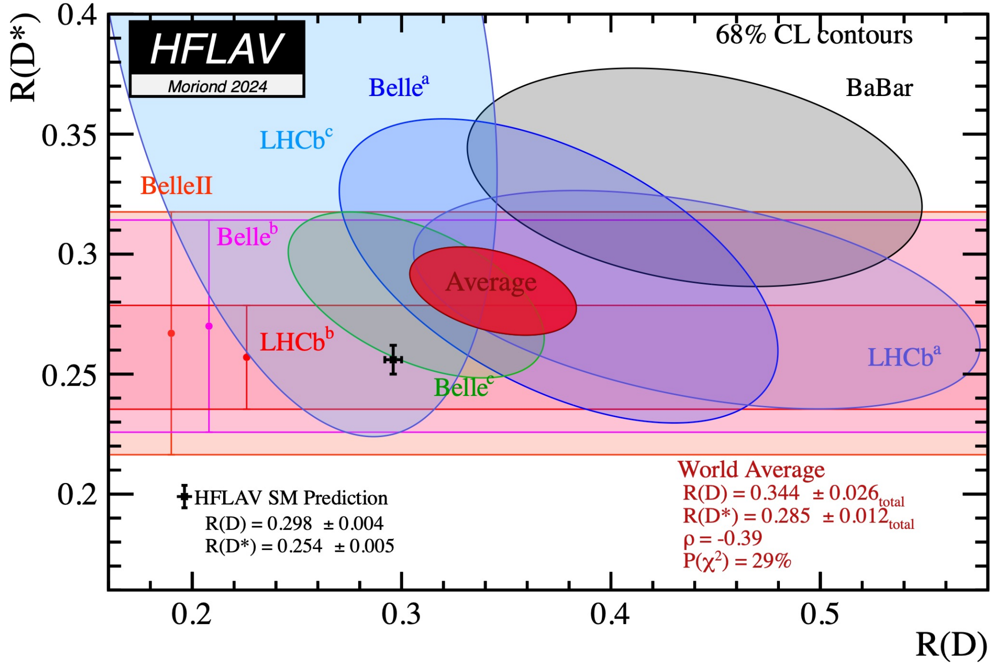
$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$



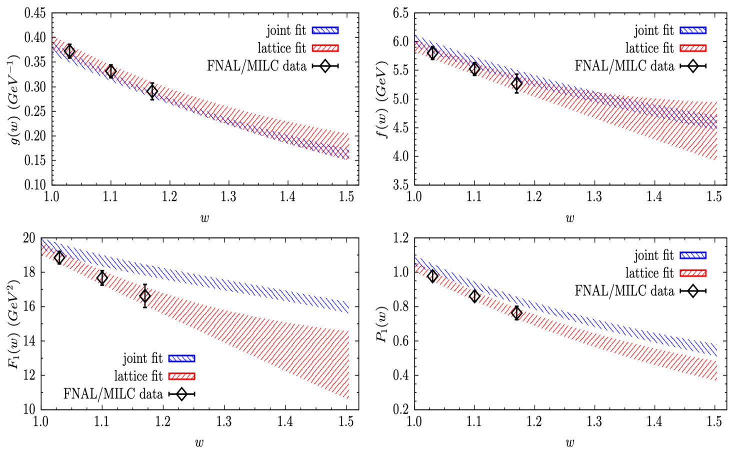


The tension strongly depends on the method used in the theoretical analysis





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



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

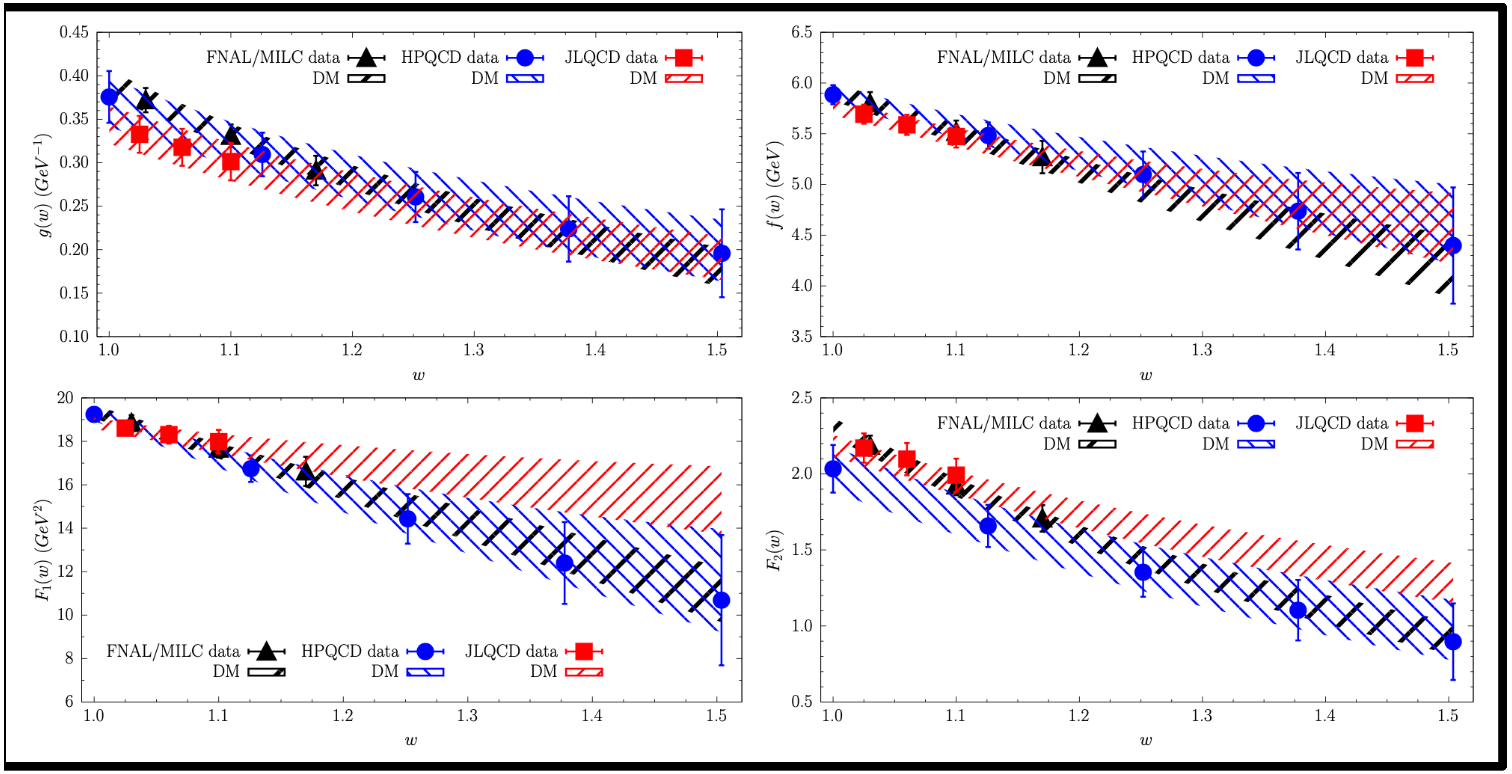
$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^* \tau \nu_\tau)}{\mathcal{B}(B \to D^* \ell \nu_\ell)}$$

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

$B \rightarrow D^* \ell \upsilon$

Teor.:	*Exp.:*
0.262(9)	0.284(12)

Compatibles @ 1.5σ



G. Martinelli, S. Simula, LV, arXiv:2310.03680

FNAL/MILC:
EPJC '22
(arXiv:2105.14019)

HPQCD:
arXiv:2304.03137

JLQCD:
PRD '24
arXiv:2306.05657

Important differences among different lattice calculations

i) The form factors from different lattice calculations are compatible among them at small recoil ($w \leq 1.2$);
ii) The band of the extrapolated values of F1(w) by JLQCD significantly differs from FNAL/MILC and differs from HPQCD

V_{cb} and V_{ub} ***Redundancy fundamental***

from FLAG 2021

$|V_{cb}|$ *(excl)* = $(39.44 \pm 0.63)\ 10^{-3}$

NEW $(40.6 \pm 0.46)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(42.16 \pm 0.50)\ 10^{-3}$

from Bordone et al.
arXiv:2107.00604

~ 3.2σ discrepancy

NEW $(3.64 \pm 0.16)\ 10^{-3}$

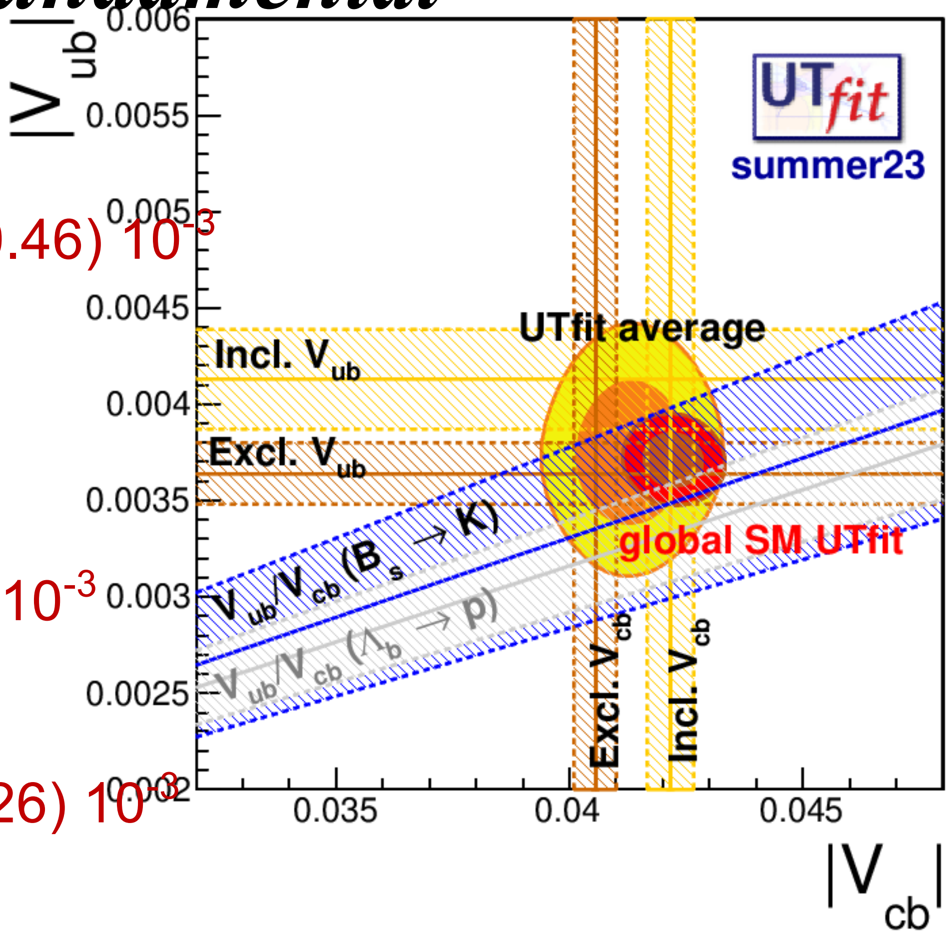
$|V_{ub}|$ *(excl)* = $(3.74 \pm 0.17)\ 10^{-3}$

$|V_{ub}|$ *(incl)* = $(4.32 \pm 0.29)\ 10^{-3}$

NEW $(4.13 \pm 0.26)\ 10^{-3}$

from GGOU HFLAV 2021
adding a flat uncertainty
covering the spread
of central values

~1.6σ discrepancy



From B_s to K at high q^2

$|V_{ub} / V_{cb}|$ *(LHCb)* = $(9.46 \pm 0.79)\ 10^{-2}$

NEW $(8.27 \pm 1.17)\ 10^{-2}$

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

From Λ_b, excluded following FLAG guidelines

From global SM fit $|V_{cb}| = (42.00 \pm 0.47)\ 10^{-3}$ $|V_{ub}| = (3.715 \pm 0.093)\ 10^{-3}$

Utfit Prediction Vcb= $(42.22 \pm 0.51)\ 10^{-3}$ *Vub*= $(3.70 \pm 0.11)\ 10^{-3}$

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 = $(8.27 \pm 1.17)\ 10^{-2}$
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= $(42.21 \pm 0.51)\ 10^{-3}$

Vub= $(3.70 \pm 0.09)\ 10^{-3}$

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

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

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

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

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

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

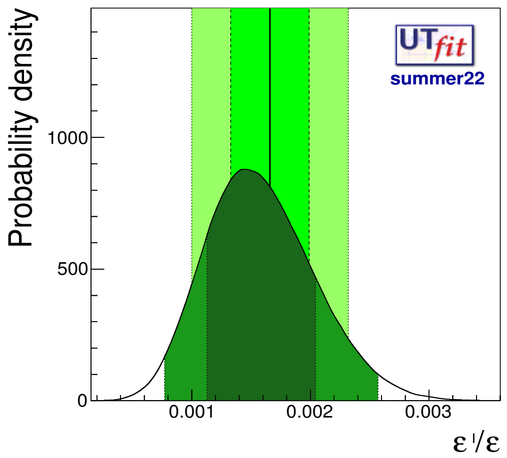
stat, sys, IB + EM

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}

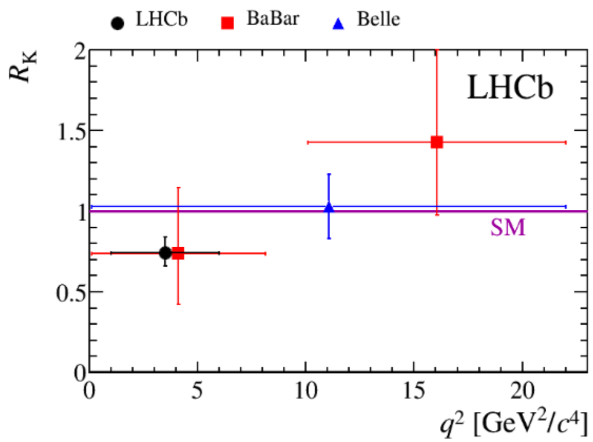


A second group should do this calculation!!

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

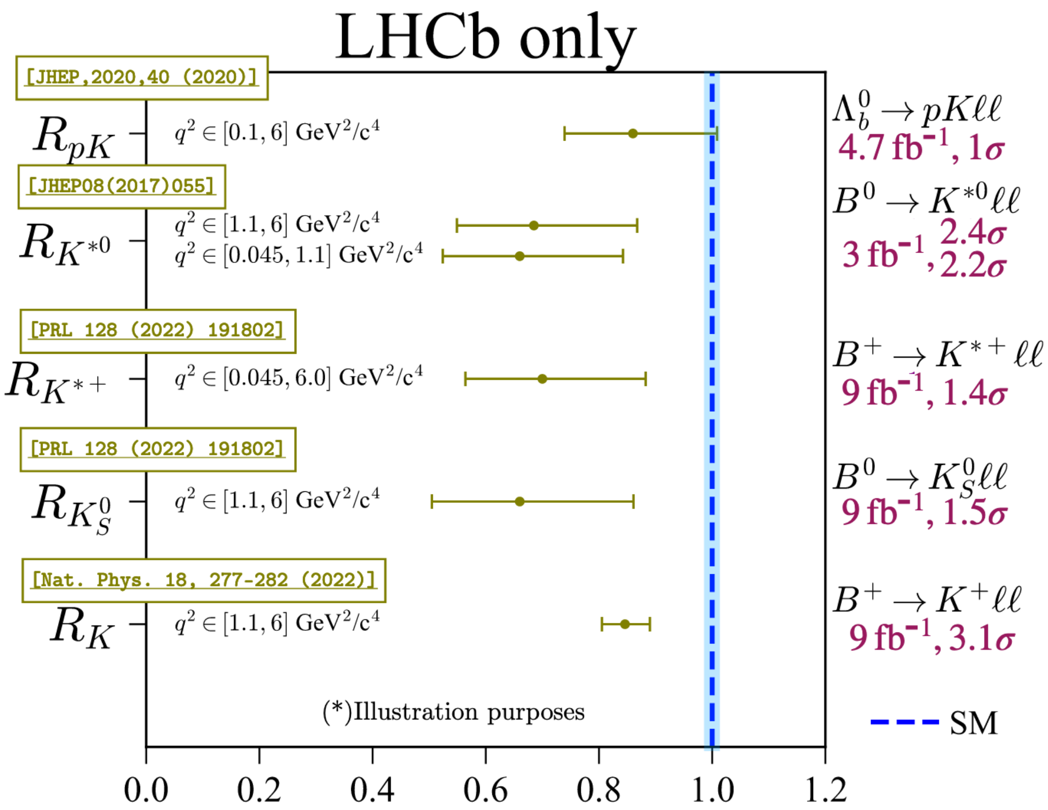
Analysis

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)

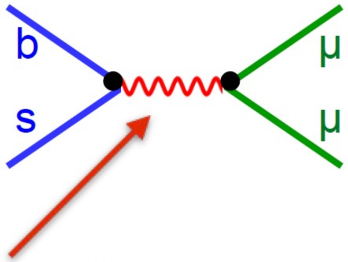
A EFT description

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

Harakiri!

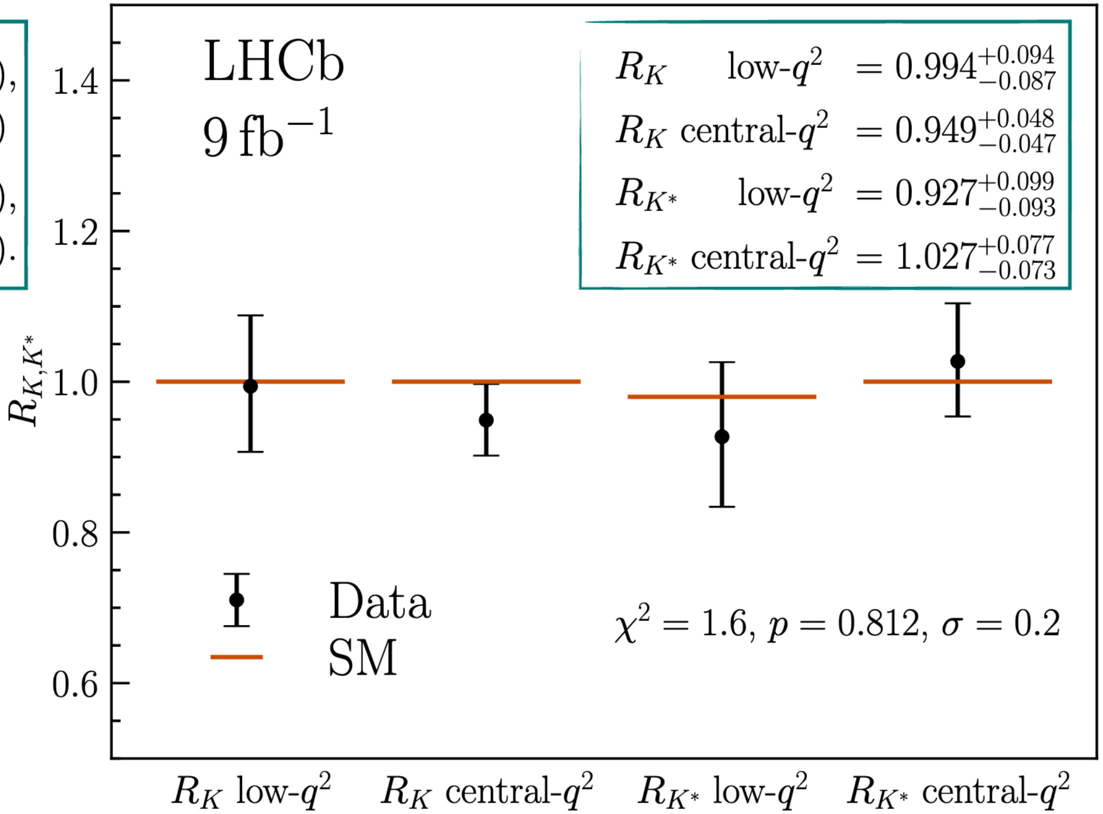
Results

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

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

- 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



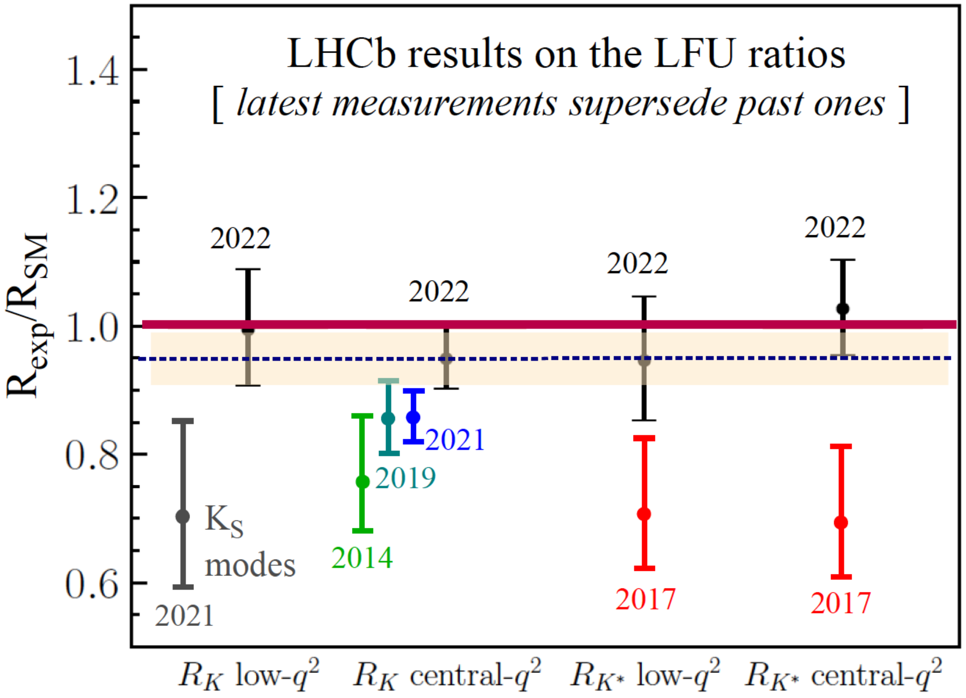
▶ Hints of non-universality in B-physics

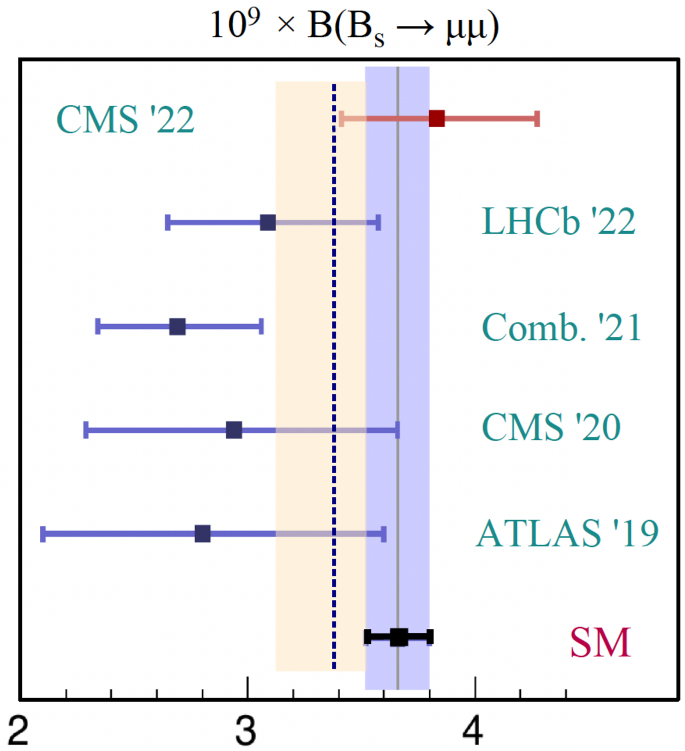
III. ~~LFU~~ anomaly in NC & BR($B_s \to \mu\mu$)

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

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

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

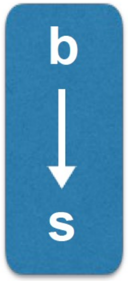


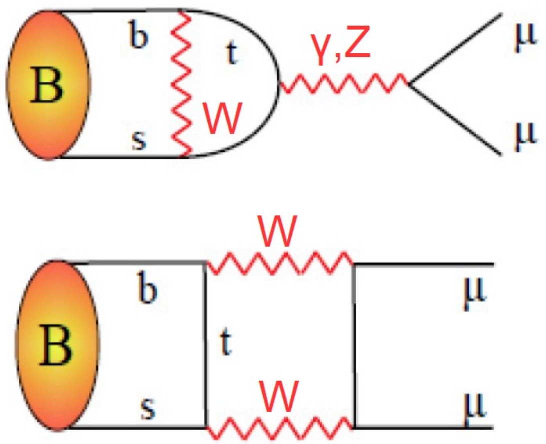


$$BR(B_s \to \mu\mu)_{exp} = (3.41 \pm 0.29) \times 10^{-9} \qquad 9\%$$

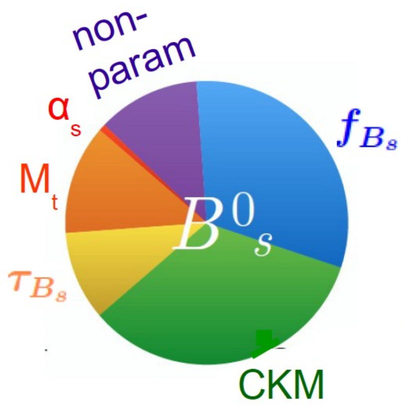
$$BR(B_s \to \mu\mu)_{SM} = (3.47 \pm 0.14) \times 10^{-9} \qquad 4\%$$

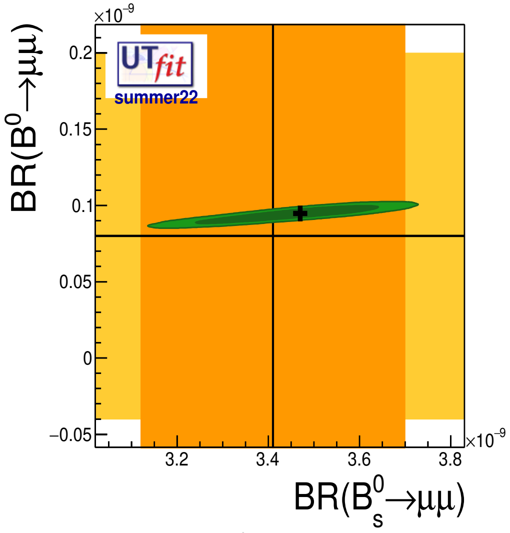
Bs→μμ SM prediction vs. measurement





Main uncertainties:





Theoretically very clean decay

$$BR(B_s \to \mu\mu) \simeq \frac{G_F^2\alpha^2}{16\pi^2} m_{B_s} f_{B_s}^2 m_\mu^2 \tau_{B_s} |V_{tb}^* V_{ts}|^2 |C_{10}^{SM}|^2 \sqrt{1 - 4\frac{m_\mu^2}{m_{B_s}^2}}$$

Only one hadronic parameter, f_{Bs}: $\langle 0|\bar{b}\gamma^\mu\gamma_5 s|B_s\rangle = iq^\mu f_{B_s}$ to be computed on the lattice

~2% hadronic uncertainty

$$BR(B_s \to \mu\mu)_{exp} = (3.41 \pm 0.29) \times 10^{-9} \qquad 9\%$$
$$BR(B_s \to \mu\mu)_{SM} = (3.47 \pm 0.14) \times 10^{-9} \qquad 4\%$$

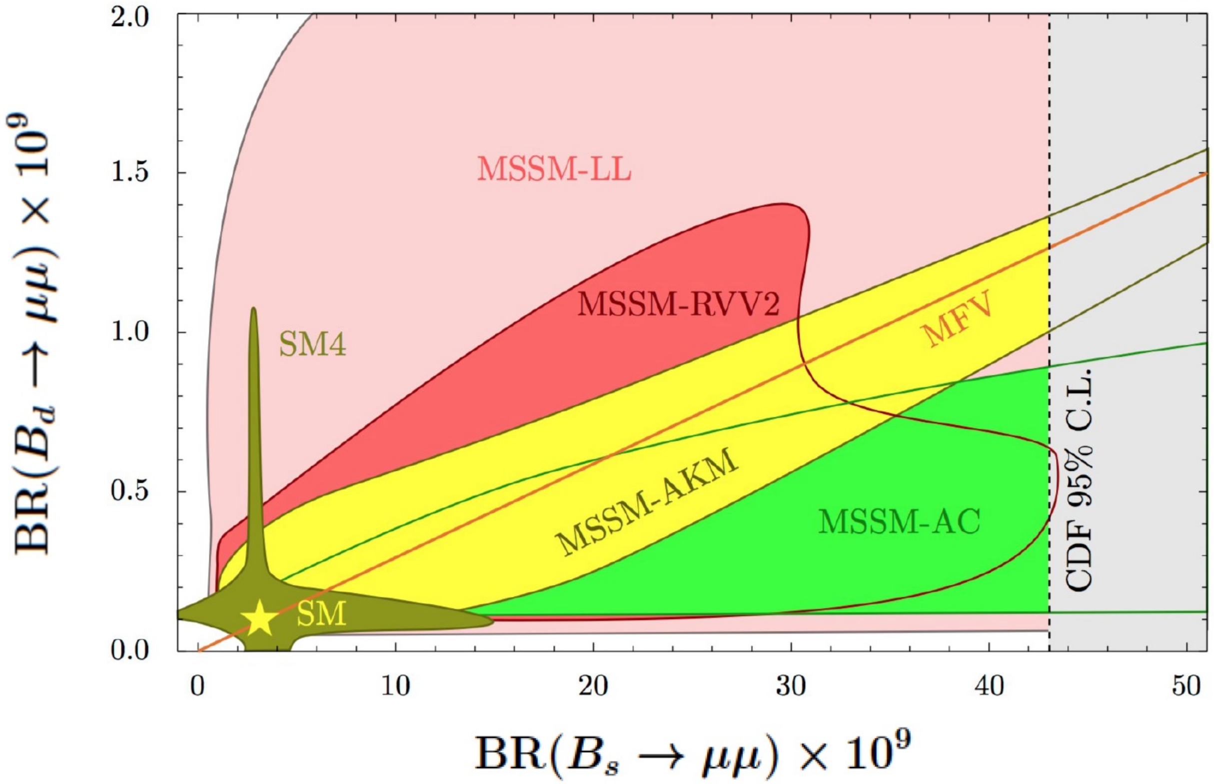
$$|V_{tb}^* V_{ts}|^2 \simeq |V_{cb}|^2 \left(1 + O(\lambda^2)\right)$$

Bs→μμ in NP theories

Generically, sizable NP effects are expected in Beyond the SM theories:

(cancelation of the helicity suppression, m_{μ}/m_{Bs})

Pre-LHC, 2011



Straub, 1107.0266

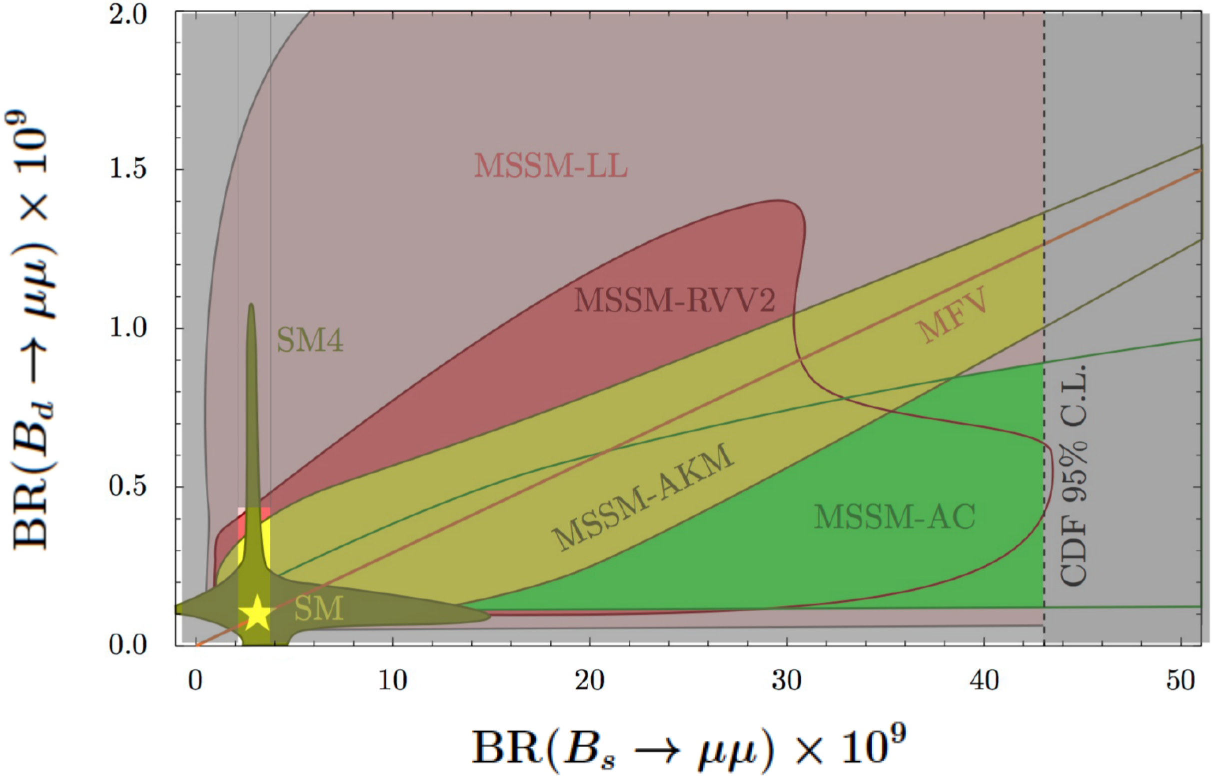
Bs⟶μμ in NP theories

Generically, sizable NP effects are expected in Beyond the SM theories:

(cancelation of the helicity suppression, m_μ/m_{Bs})

b ⟶ s

Now



Straub, 1107.0266

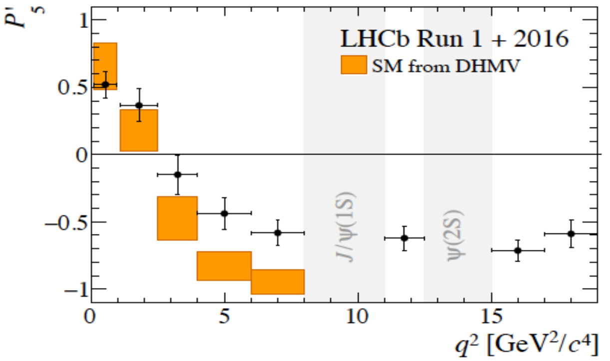
still

B anomalies in the post-R_K era

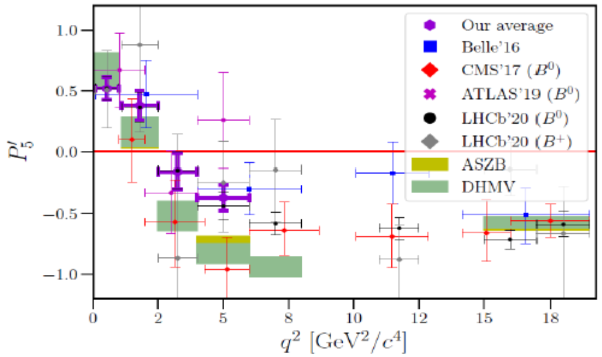
Nazila Mahmoudi *Corfu 2023*

Tension in the angular observables - 2020 updates

$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$: 2020 LHCb update with 4.7 fb^{-1}: $\sim 2.9\sigma$ local tension



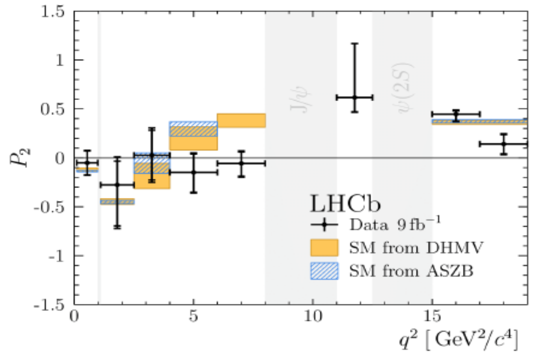
Phys. Rev. Lett. 125, 011802 (2020)

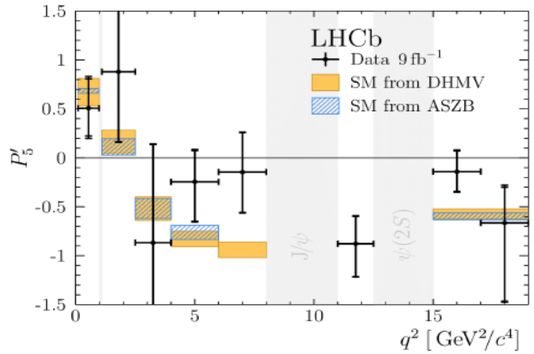


ATLAS-CONF-2017-023; CMS-PAS-BPH-15-008

anomalies hunters never surrender

First measurement of $B^+ \to K^{*+}\mu^+\mu^-$ angular observables using the full Run 1 and Run 2 dataset (9 fb^{-1}):





Phys. Rev. Lett. 126, 161802 (2021)

theoretical estimates of unnown amplitudes

The results confirm the global tension with respect to the ~~SM~~!

Comparison of one-operator NP fits:

All observables 2022 ($\chi^2_{\rm SM} = 253.3$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-0.95 ± 0.13	215.8	6.1σ
δC_9^e	0.82 ± 0.19	232.4	4.6σ
δC_9^μ	-0.92 ± 0.11	195.2	7.6σ
δC_{10}	0.08 ± 0.16	253.2	0.5σ
δC_{10}^e	-0.77 ± 0.18	230.6	4.8σ
δC_{10}^μ	0.43 ± 0.12	238.9	3.8σ
$\delta C_{\rm LL}^e$	0.42 ± 0.10	231.4	4.7σ
$\delta C_{\rm LL}^\mu$	-0.43 ± 0.07	213.6	6.3σ

All observables 2023 ($\chi^2_{\rm SM} = 231.3$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-0.96 ± 0.13	230.7	6.3σ
δC_9^e	0.21 ± 0.16	269.2	1.3σ
δC_9^μ	-0.69 ± 0.12	240.4	5.5σ
δC_{10}	0.15 ± 0.15	270.0	1.0σ
δC_{10}^e	-0.18 ± 0.14	269.3	1.3σ
δC_{10}^μ	0.16 ± 0.10	268.3	1.6σ
$\delta C_{\rm LL}$	-0.54 ± 0.12	249.1	4.7σ
$\delta C_{\rm LL}^e$	0.10 ± 0.08	269.2	1.3σ
$\delta C_{\rm LL}^\mu$	-0.23 ± 0.06	257.4	3.7σ

$\delta C_{\rm LL}^\ell$ basis corresponds to $\delta C_9^\ell = -\delta C_{10}^\ell$.

But … really a reliable estimate of uncertainties is missing and theory must be improved otherwise we will continue to generate anomalies out of our ingnorance

Known unknowns in B → K*μμ

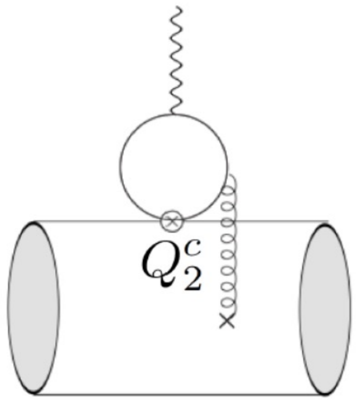
$$\mathrm{H}_V{}^\lambda = \frac{4iG_F m_B}{\sqrt{2}} \frac{e^2}{16\pi^2} \lambda_t \left\{ C_9^{\mathrm{eff}} \tilde{V}_{L\lambda} + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} C_7^{\mathrm{eff}} \tilde{T}_{L\lambda} - 16\pi^2 h_\lambda \right] \right\}$$

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

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

- dominated by

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



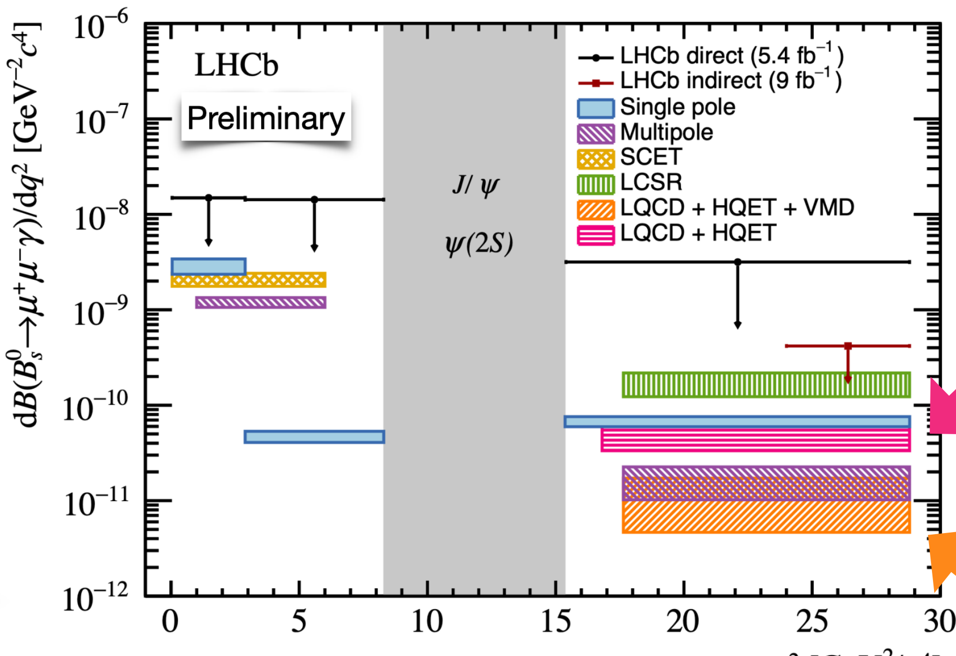
the charm pair can be close to the resonant region

Do we know how to compute them?

In general, no!

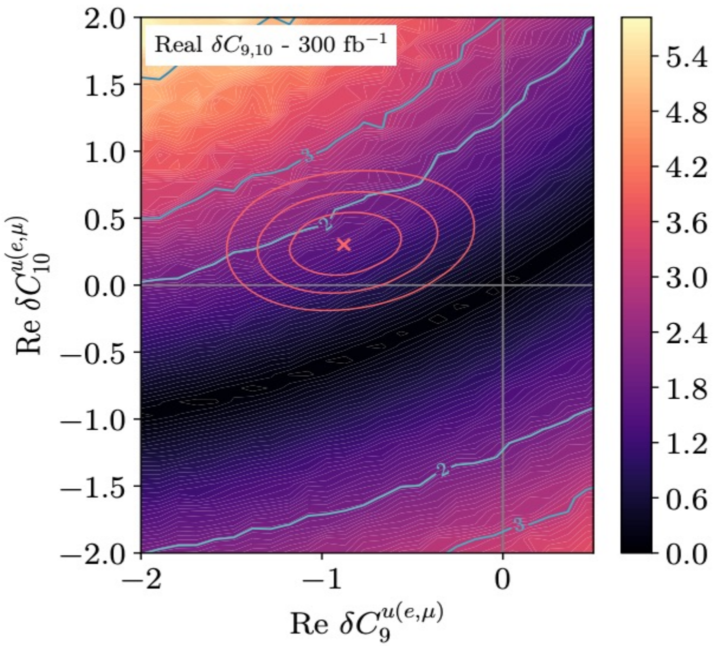
Look for complementary b $\rightarrow$ s transitions

$B_s \rightarrow \mu\mu\gamma$ @ high-q2: in this range the observables depend on the same short distance effects as those present in B $\rightarrow$ 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]

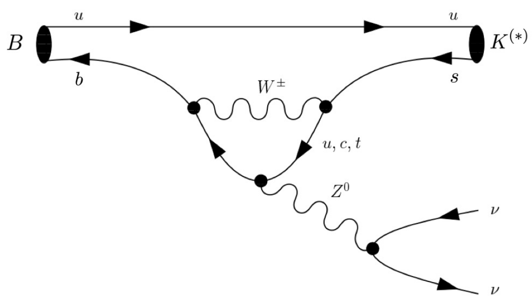
Look for complementary b → s transitions

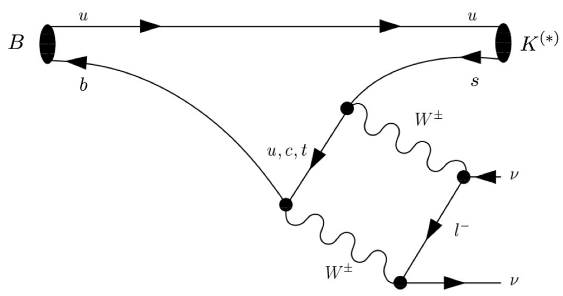
B → K$^{(*)}\upsilon\upsilon$: short distance contributions dominate

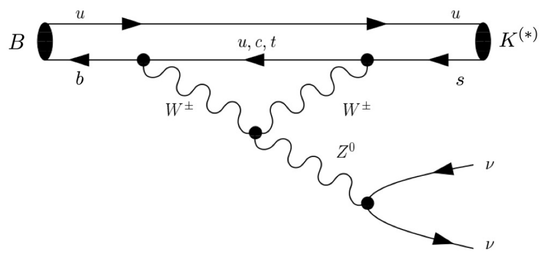
Main uncertainties

1. |Vcb|

2. Form factors







SM prediction *

$$\mathcal{B}\left(B^{\pm} \to K^{\pm}\nu\bar{\nu}\right) = (4.44 \pm 0.30) \times 10^{-6}$$

Jernej F. Kamenik(Frascati Christopher Smith(Karlsruhe U., TTP
Phys.Lett.B 680 (2009) 471-475 0908.1174 [hep-ph]

D. Becirevic, G. Piazza & O. Sumensari, EPJC ‘23 [arXiv:2301.06990]

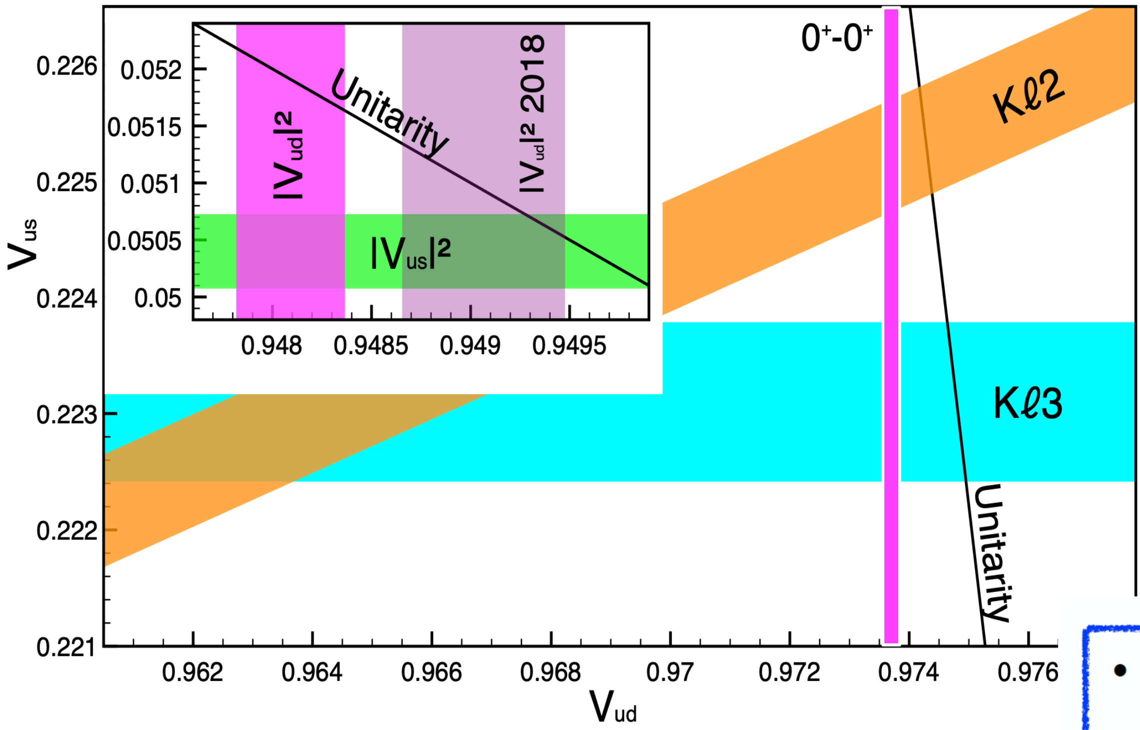
Phys.Lett.B 848 (2024) 138411 2309.02246 *

Tension in B → K$\upsilon\upsilon$: 2.8σ

$$\mathcal{B}\left(B^{+} \to K^{+}\nu\bar{\nu}\right)\Big|_{\mathrm{Belle-II}} = (2.4 \pm 0.7) \times 10^{-5}$$

Belle-II Collaboration, arXiv:2311.14647

Tensions with the unitarity of the first CKM row ?



M. Gorshteyn, talk @ CKM23 conference

Both theory and experiments demands a closer scrutiny of systematic errors

- Until ~2018, bands *did* intersect in the same region on the unitarity circle (< 2σ)
- *Main* changes since then:
  - V_{us} from Kl3 decreased (<V> increased with smaller uncertainty, 2+1+1 lattice QCD)
  - V_{ud} decreased (radiative corrections in nuclear & neutron increased with smaller uncertainty, dispersive)

$$\underbrace{|V_{ud}|^2}_{\sim 0.95} + \underbrace{|V_{us}|^2}_{\sim 0.05} + \underbrace{|V_{ub}|^2}_{\sim 10^{-5}} = 0.9985(6)_{V_{ud}}(4)_{V_{us}}$$

Courtesy of L. Vittorio

Determination of |Vud| e |Vus|

|Vud|

M. Gorshteyn, talk @ CKM23 conppference

- **Nuclear decays** 0^+-0^+ (es.: $^{14}O \rightarrow {}^{14}N$)

$$|V_{ud}^{0^+-0^+}| = 0.97370\,(1)_{exp,\,nucl}\,(3)_{NS}\,(1)_{RC}[3]_{total}$$

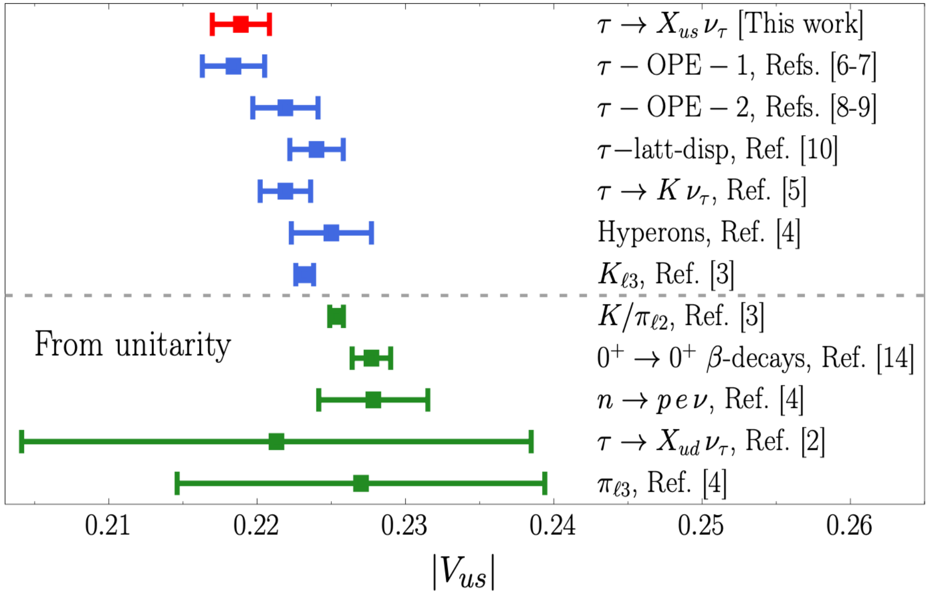
- **Neutron β decay**

$$|V_{ud}^{\mathrm{free\,n}}| = 0.9733\,(2)_{\tau_n}\,(3)_{g_A}\,(1)_{RC}[4]_{total}$$

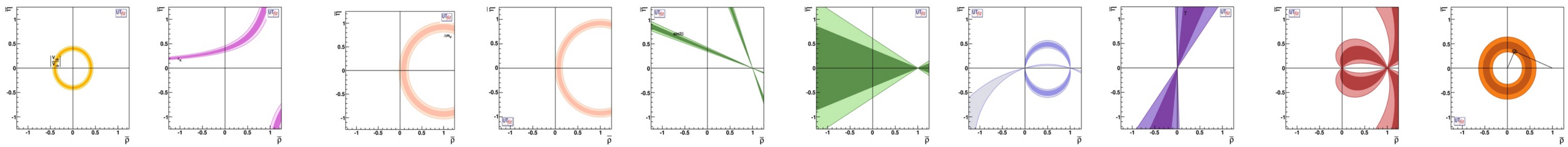
- $\pi^+ \rightarrow \pi^0 e^+ \nu$:

$$|V_{ud}^{\pi\ell 3}| = 0.9739\,(27)_{exp}\,(1)_{RC}$$

|Vus|



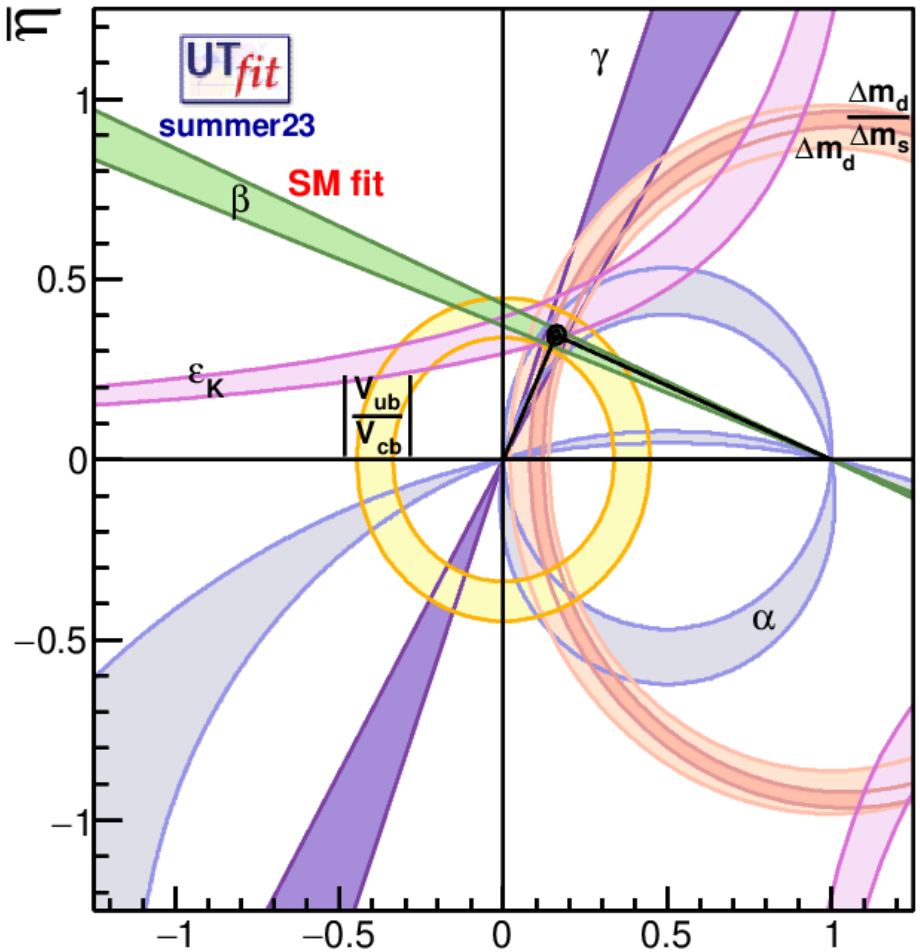
ETMC Collaboration [arXiv:2403.05404]



2023 results

$\bar{\rho} = 0.160 \pm 0.009 \quad \bar{\eta} = 0.345 \pm 0.011$

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



$\alpha = (92.4 \pm 1.4)^0$

$\sin 2\beta = 0.703 \pm 0.014$

$\beta = (22.46 \pm 0.68)^0$

$\gamma = (65.1 \pm 1.3)^0$

A = 0.828 ± 0.011

λ = 0.22519 ± 0.00083

2022

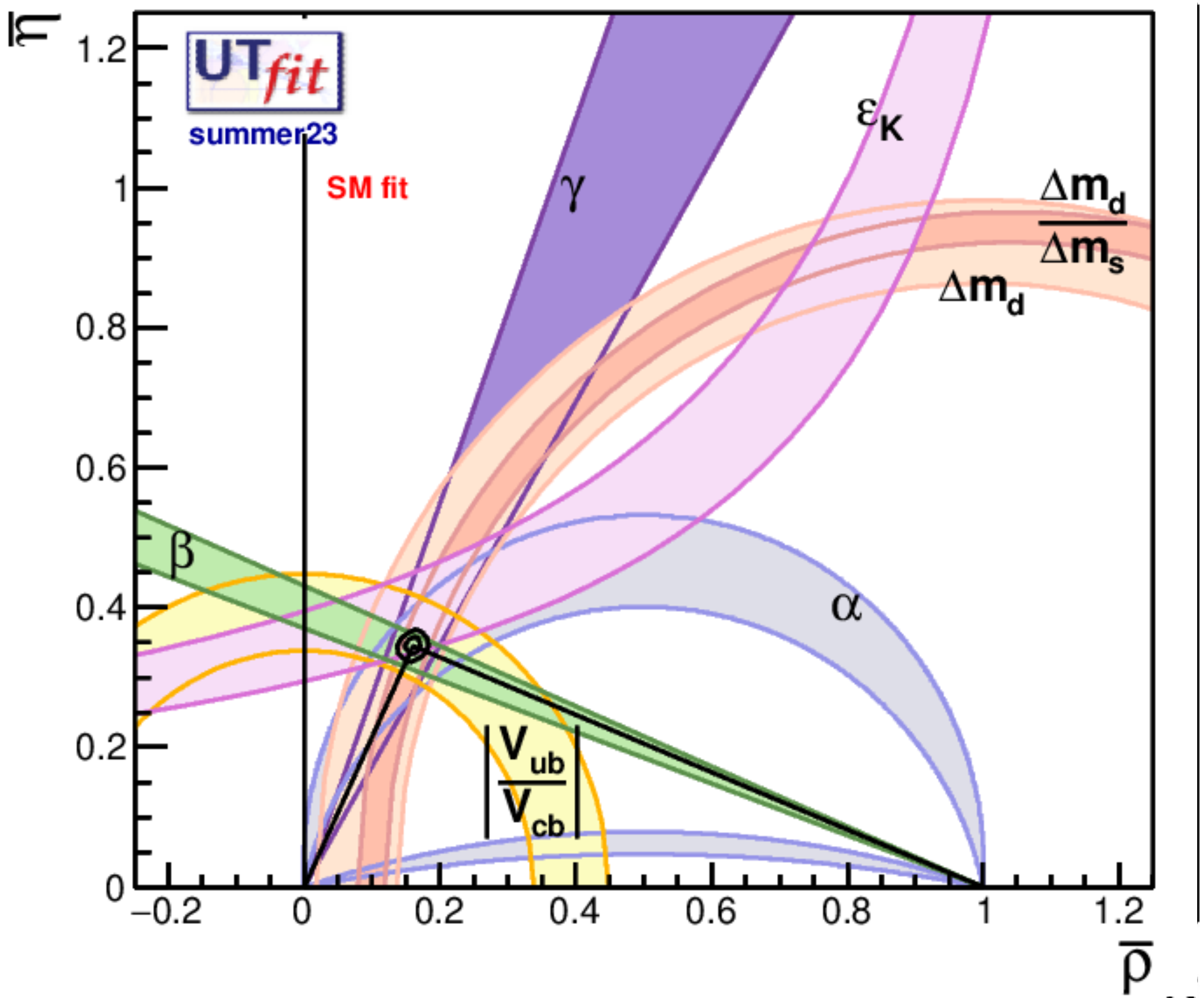
Consistence on an over constrained fit of the CKM parameters

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

Unitarity Triangle analysis in the SM:

2024 analysis in preparation

zoomed in..



levels @
95% Prob

~6%

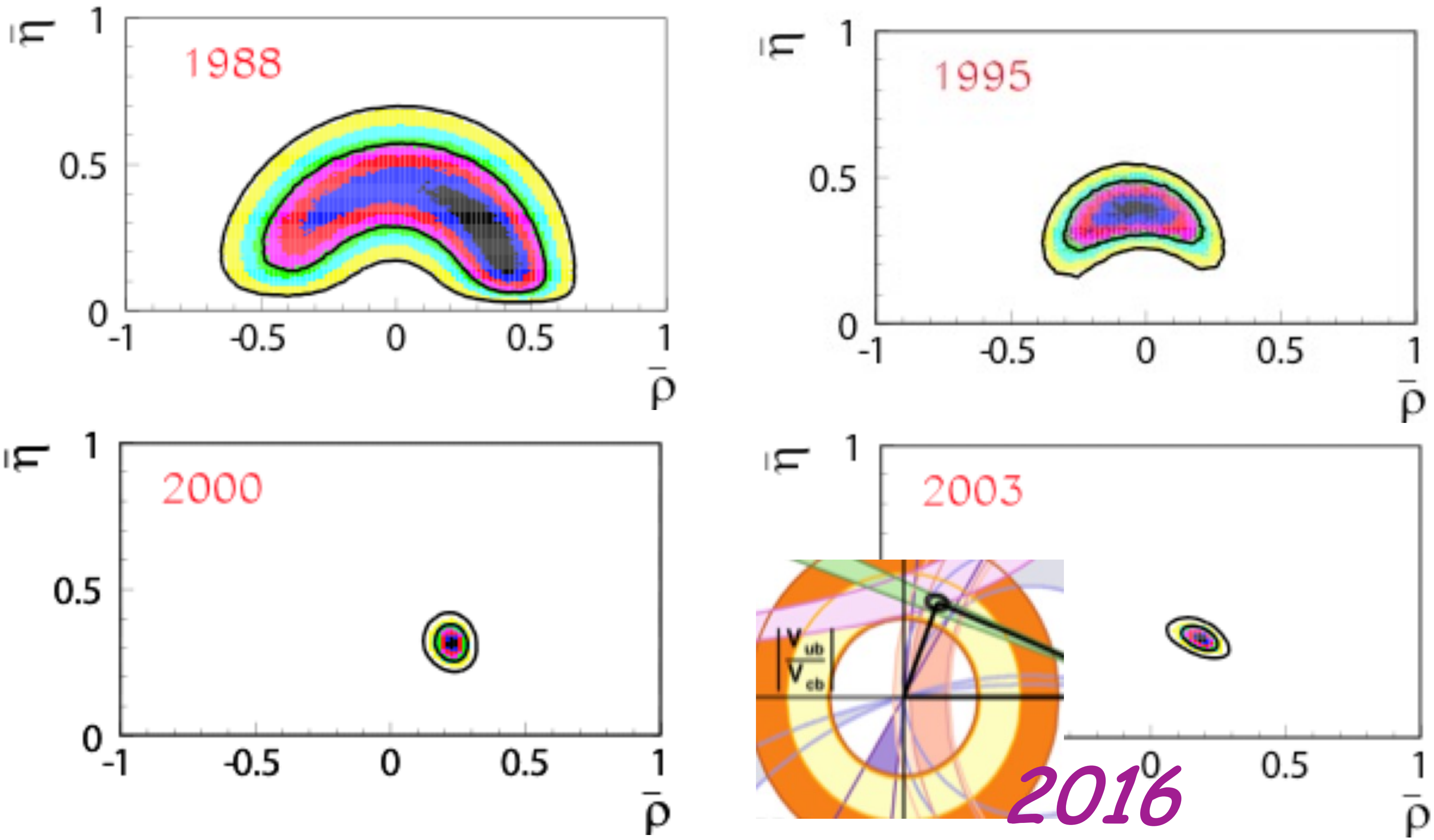
$\rho = 0.160 \pm 0.009$

$\eta = 0.345 \pm 0.011$

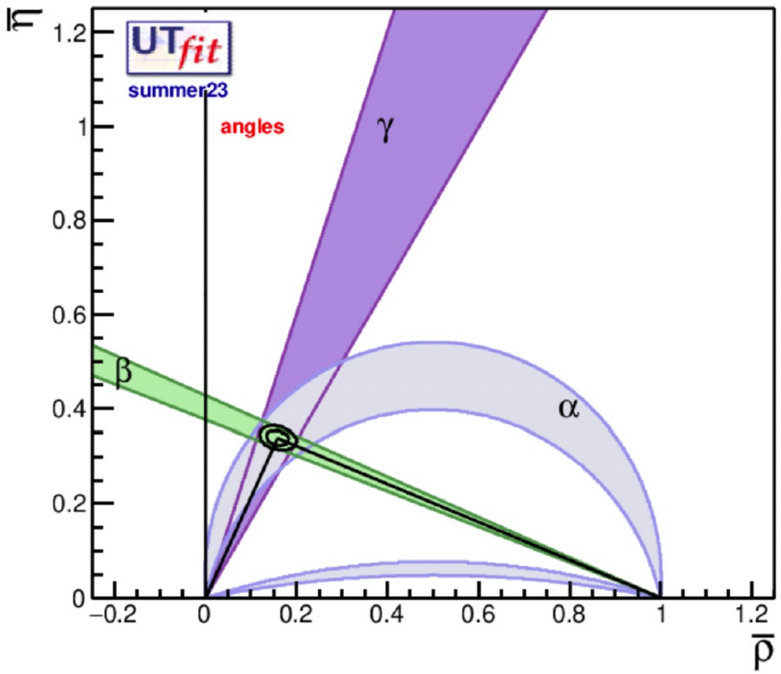
~3%

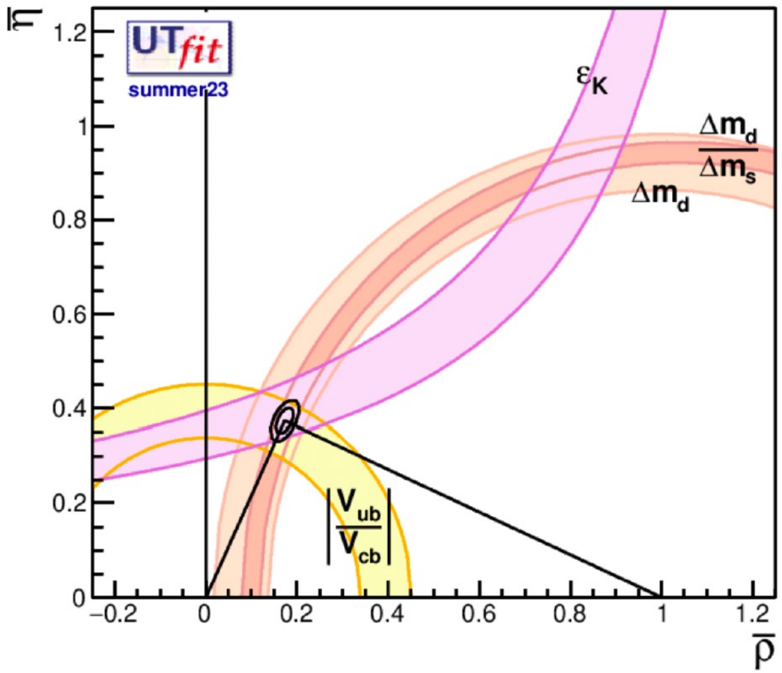
PROGRESS SINCE 1988

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



Standard Model Fit result



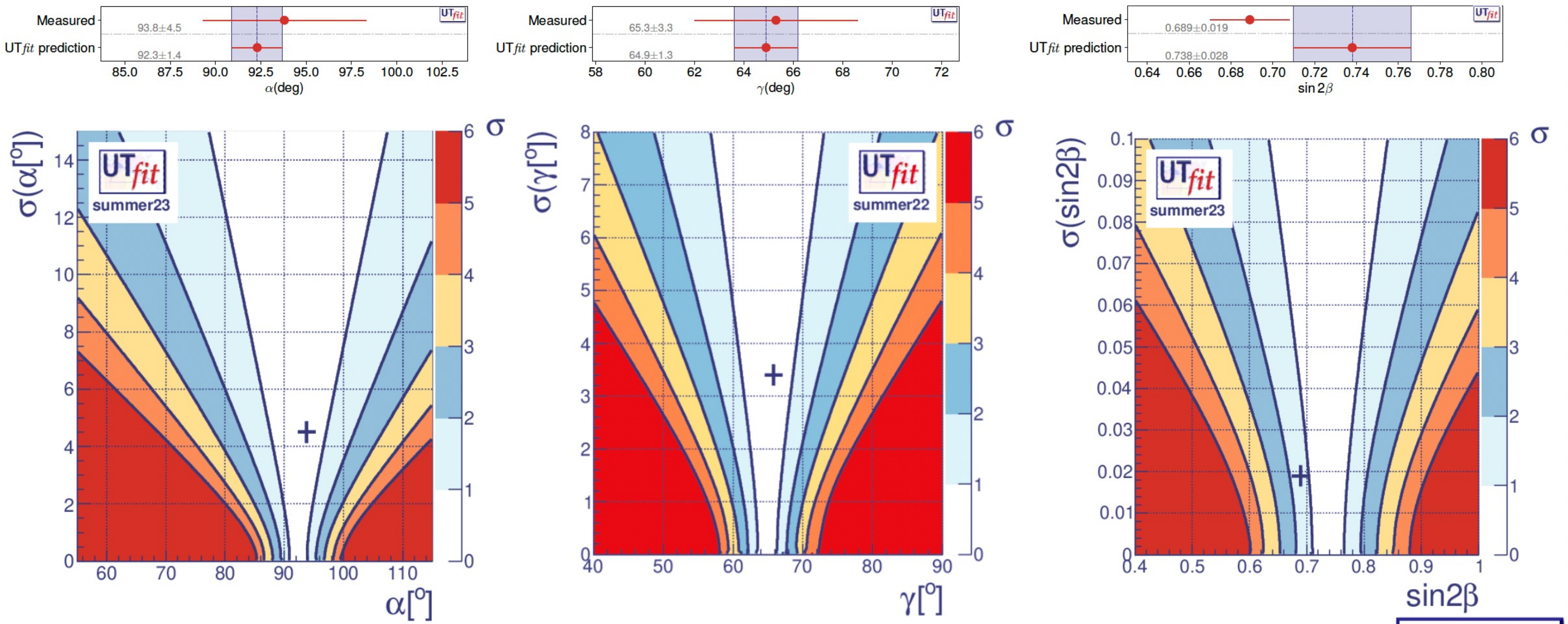


$$\bar{\rho} = 0.159 \pm 0.016$$
$$\bar{\eta} = 0.339 \pm 0.010$$

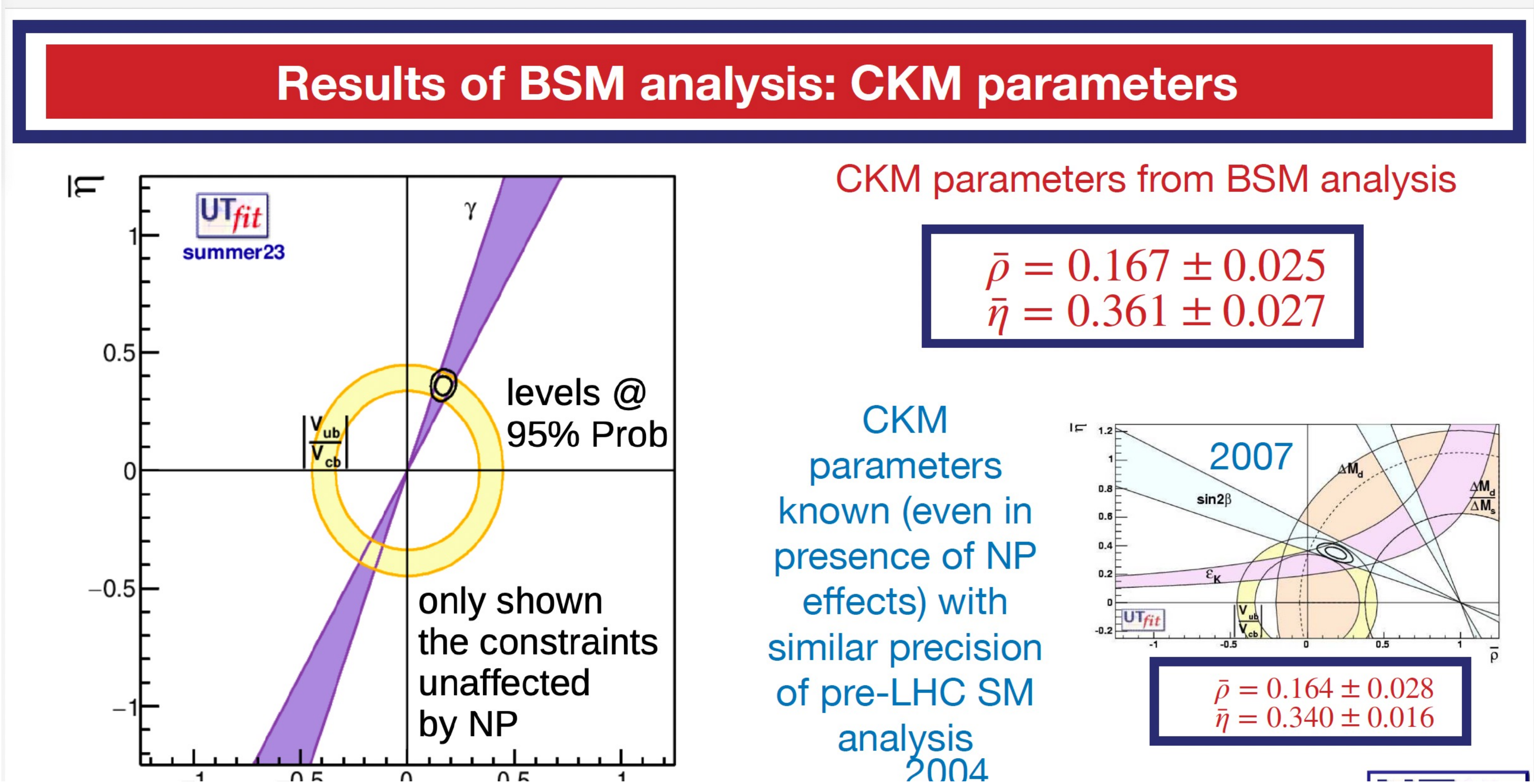
$$\bar{\rho} = 0.173 \pm 0.012$$
$$\bar{\eta} = 0.374 \pm 0.019$$

2023

Standard Model Fit compatibility



.... 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 m 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

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

- find out NP contributions to ΔF=2 transitions

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

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

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

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

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

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

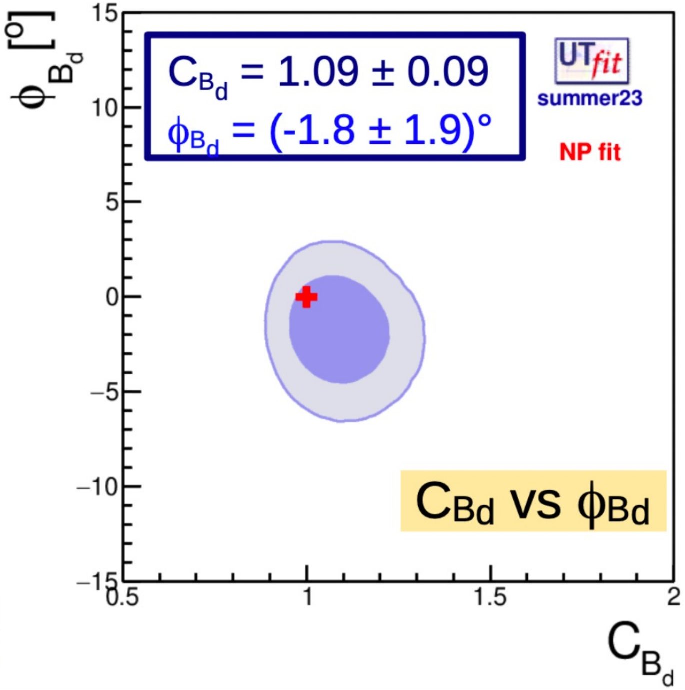
Results of BSM analysis: New Physics parameters

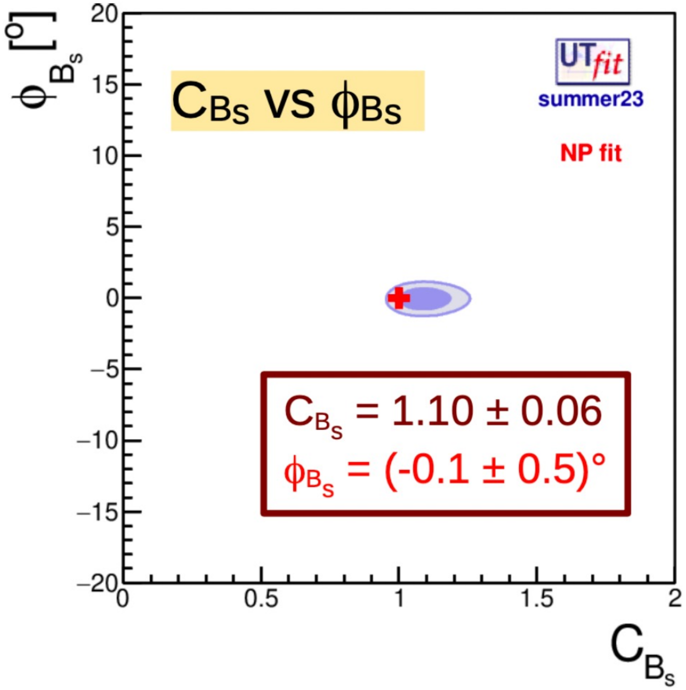
$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$

K system

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

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





Results of BSM analysis: New Physics parameters

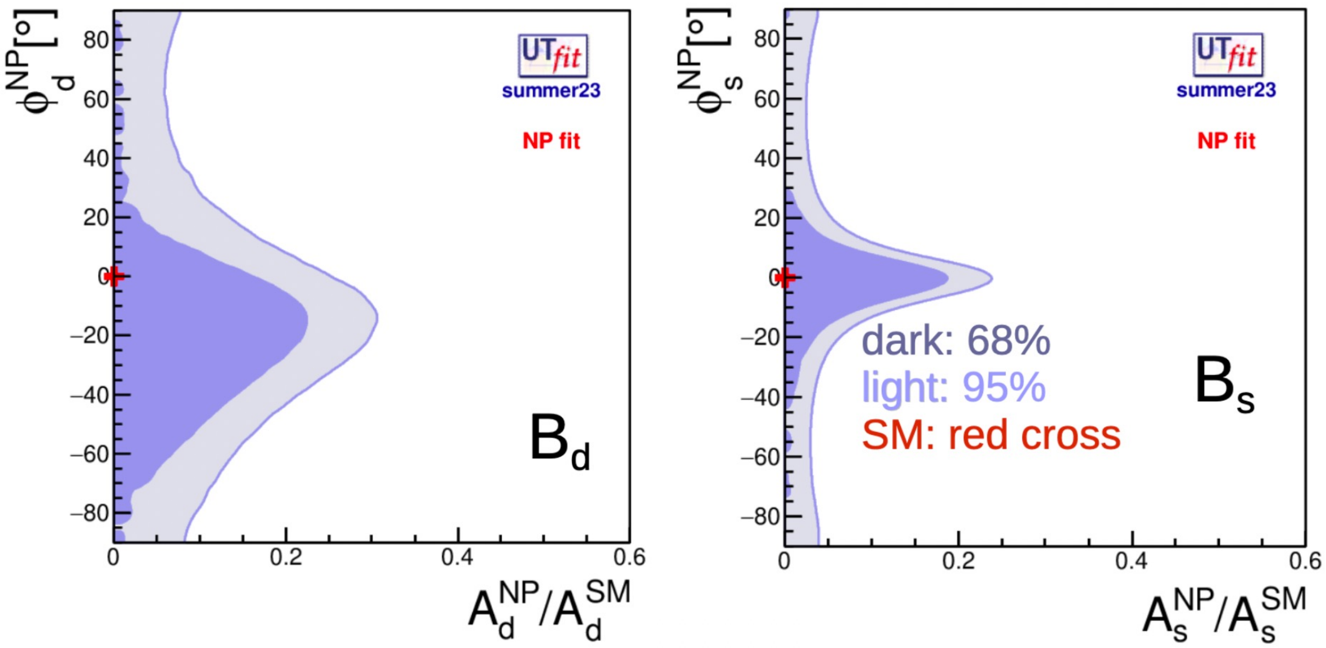
$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

The ratio of NP/SM amplitudes is:

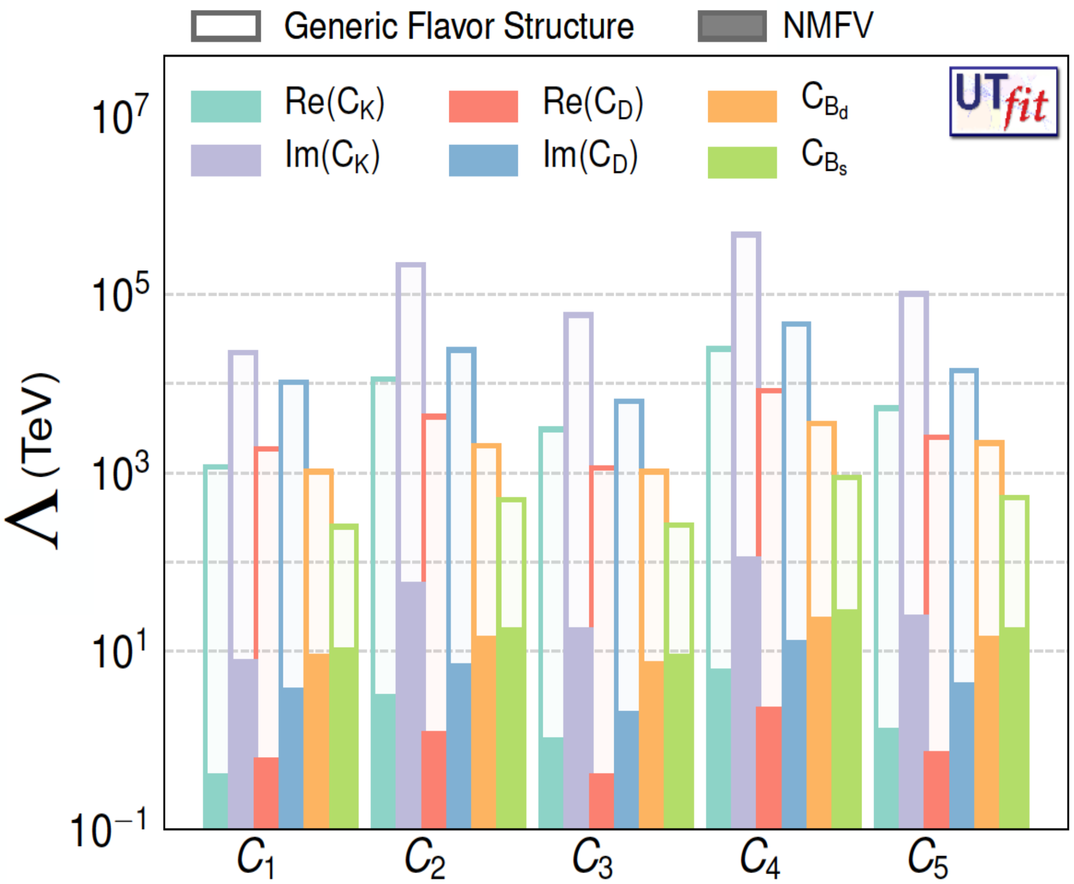
< 25% @68% prob. (35% @95%) in B_d mixing

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

•$\alpha \sim \alpha_W$ in case of loop coupling
•through weak interactions*

$\Lambda > 1.3\ 10^4$ TeV

•$\alpha \sim \alpha_W$ 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

$$Y_t \sim 1 \qquad Y_c \sim 10^{-2} \qquad Y_u \sim 10^{-5}$$

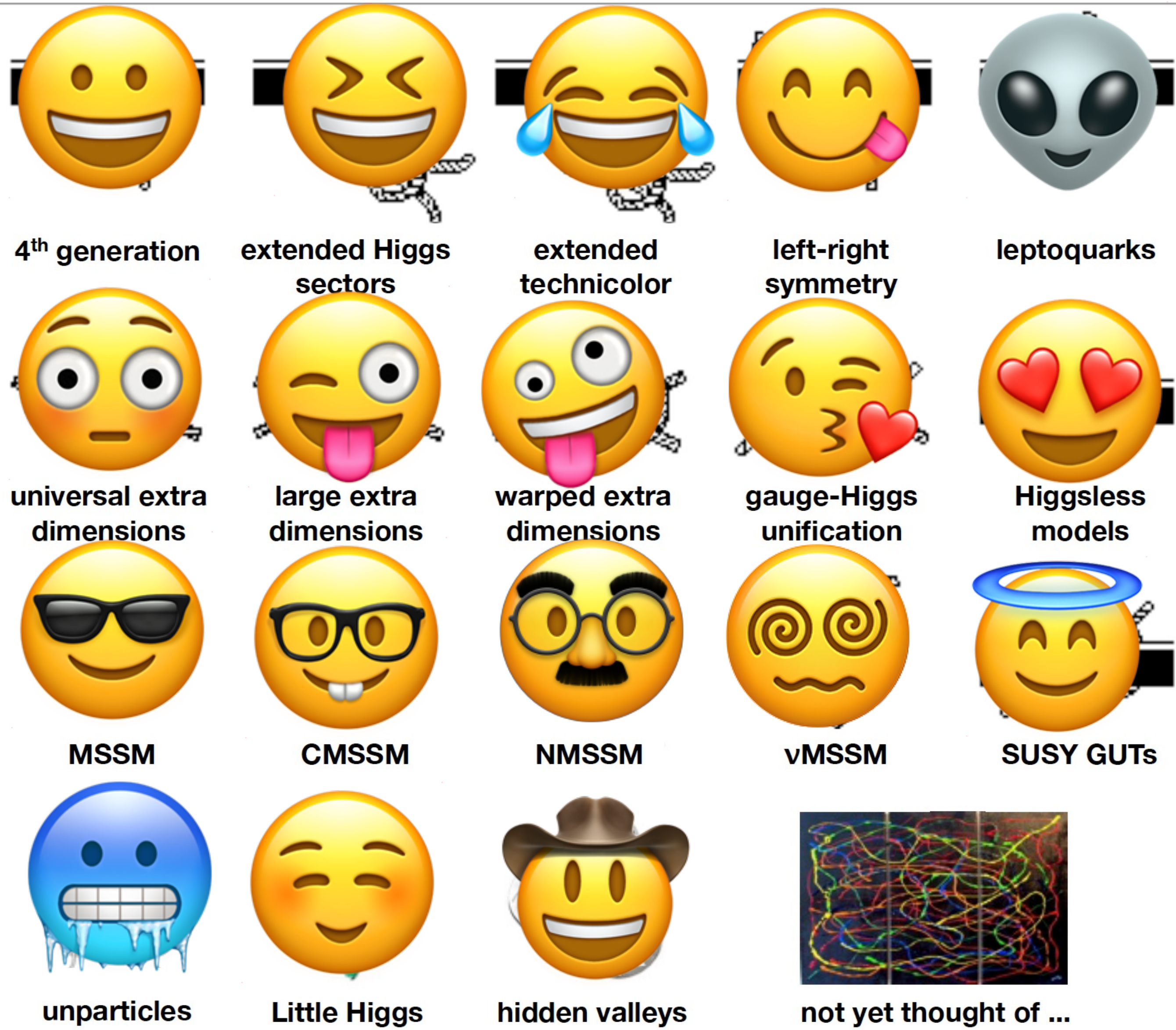
$$Y_b \sim 10^{-2} \qquad Y_s \sim 10^{-3} \qquad Y_d \sim 10^{-5}$$

$$Y_\tau \sim 10^{-2} \qquad Y_\mu \sim 10^{-3} \qquad Y_e \sim 10^{-6}$$

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

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

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

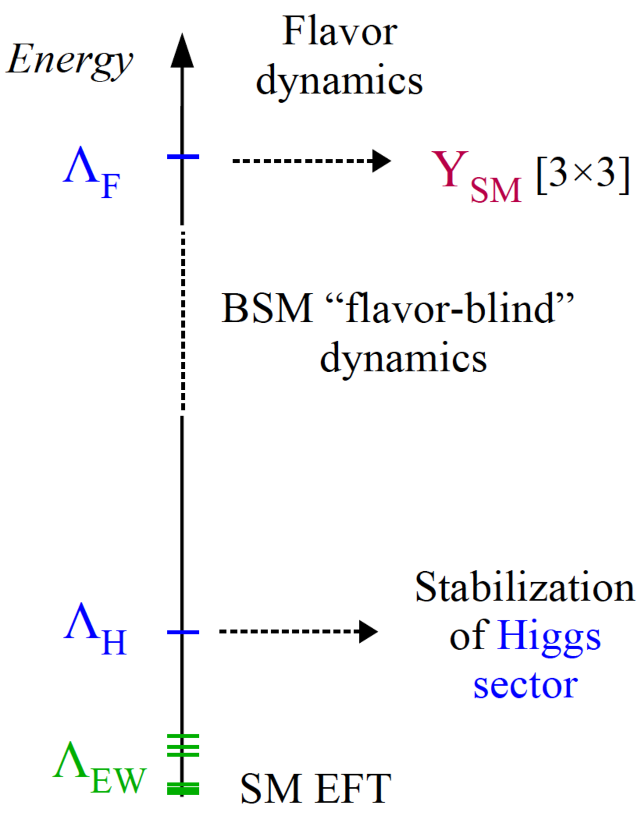


Let us discuss just an example to show the difficulties to construct a model that can survive the Utfit constraints

G. Isidori – Flavor non-universal interactions *Vienna – 23 Jan. 2024*

Flavor non-universal interactions

For a long time, the vast majority of model-building attempts to extend the SM was based on the *implicit* hypotheses of *flavor-universal* New Physics



- Concentrate on the Higgs hierarchy problem
- Postpone the flavor problem to higher scales

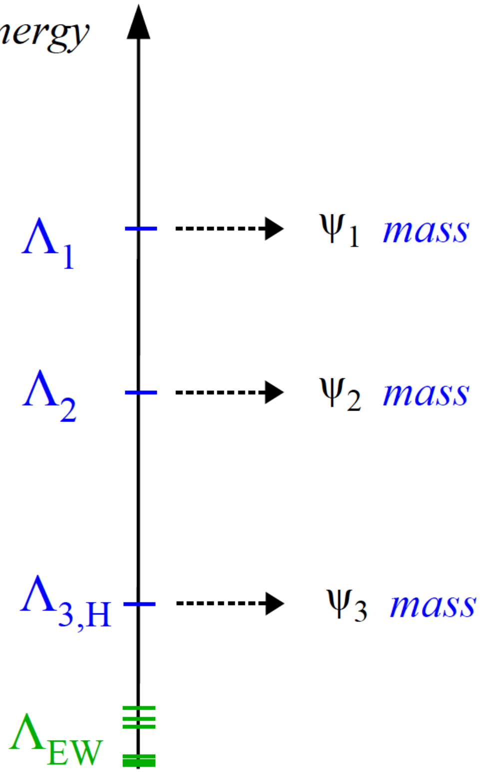
↕

The "MFV paradigm"
+
"Horizontal" flavor symmetries @ high scales

3 gen. = "identical copies" up to high energies

Flavor non-universal interactions

A more efficient paradigm to address both flavor puzzles (I+II), & *possibly* the Higgs hierarchy, is a *multi-scale* UV with *flavor non-universal* interactions



Dvali & Shifman '00
Panico & Pomarol '16
⋮
Bordone *et al.* '17
Allwicher, GI, Thomsen '20
Barbieri '21
Davighi & G.I. '23

Basic idea:

- 1st & 2nd generations have small masses (+ small coupling to NP) because these are generated by new dynamics at heavier scales
- *"flavor deconstruction"* of the SM gauge symmetry → flavor hierarchies emerge as accidental symmetries

⬇

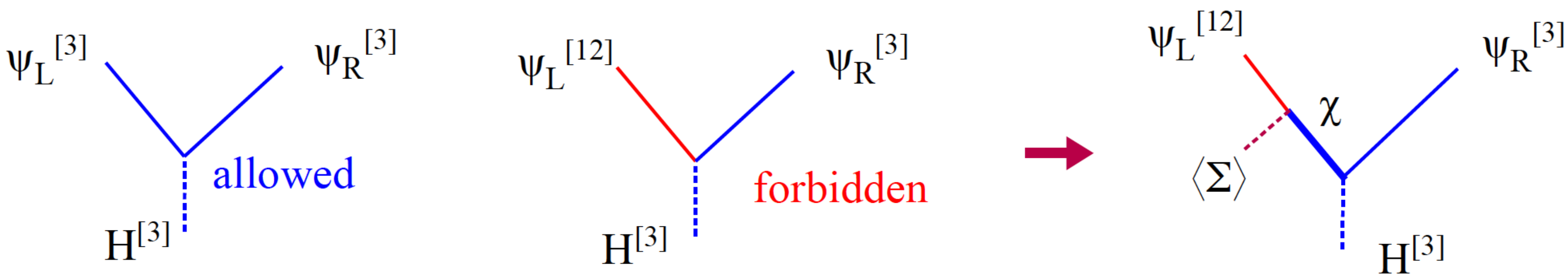
~~3 gen. = "identical copies" up to high energies~~

Flavor non-universal interactions

A more efficient paradigm to address both flavor puzzles (I+II), & *possibly* the Higgs hierarchy, is a ***multi-scale*** UV with ***flavor non-universal*** interactions

- *"flavor deconstruction"* of the SM gauge symmetries:

$$\text{E.g.:}\quad SU(3)_c\times SU(2)_L\times U(1)_Y^{[3]}\times U(1)_Y^{[12]} \xrightarrow{\langle\Sigma\rangle} SU(3)_c\times SU(2)_L\times U(1)_Y$$



$$V_{cb} \sim \frac{\langle\Sigma\rangle}{M_\chi}$$

Different schemes are at hands

Courtesy by R. Barbieri

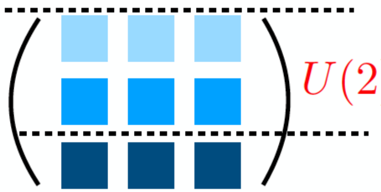
(approximate) symmetries of the Yukawa couplings

Charged fermion Yukawa couplings

$$Y \propto U_L^+ \begin{pmatrix} m_1/m_3 & 0 & 0 \\ 0 & m_2/m_3 & 0 \\ 0 & 0 & 1 \end{pmatrix} U_R \qquad m_1/m_3 << m_2/m_3 << 1 \qquad U_L^u (U_L^d)^+ = V_{CKM} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

1 IF $[U_L^{u,d}]_{i\neq j} \lesssim [V_{CKM}]_{i\neq j}$

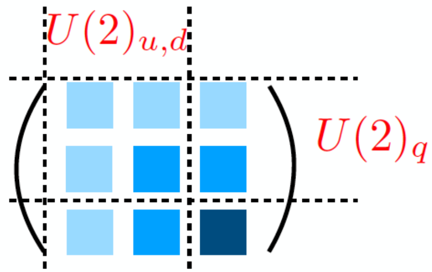
$Y^{u,d} \approx$



$\Rightarrow U(2)_q$

2 IF 1 + $[U_R^{u,d}]_{i\neq j} \lesssim [U_L^{u,d}]_{i\neq j}$

$Y^{u,d} \approx$



$\Rightarrow U(2)_q \times U(2)_u \times U(2)_d$

3 IF 2 + $[U_{L,R}^e]_{i\neq j} \lesssim [U_{L,R}^{u,d}]_{i\neq j}$

$\Rightarrow U(2)_q \times U(2)_u \times U(2)_d \times U(2)_l \times U(2)_e$

Can $U(2)^n$ emerge as an accidental symmetry?
What breaks it?

B, Isidori et al, 2011

One possibility

Minimal Flavour Deconstruction

B, Isidori, 2023

$$SU(3) \times SU(2) \times G_Y$$

$$G_Y = U(1)_Y^{[3]} \times U(1)_{B-L}^{[12]} \times U(1)_{T_{3R}}^{[2]} \times U(1)_{T_{3R}}^{[1]} \qquad H \overset{G_Y}{=} (-1/2, 0, 0, 0)$$

$$G_Y \xrightarrow{\sigma} U(1)_Y^{[3]} \times U(1)_{B-L}^{[12]} \times U(1)_{T_{3R}}^{[12]} \xrightarrow{\phi,\chi} U(1)_Y$$

$$\epsilon_\sigma = \frac{\langle\sigma\rangle}{\Lambda_{[12]}}\,, \qquad \epsilon_\phi = \frac{\langle\phi\rangle}{\Lambda_{[23]}}\,, \qquad \epsilon_\chi = \frac{\langle\chi^{q,l}\rangle}{\Lambda_{[23]}}$$

$$\begin{array}{c|c|c|c|c}
 & \multicolumn{2}{c|}{U(1)_{B-L}^{[12]}} & & \\
 & U(1)_{T_{3R}}^{[1]} & U(1)_{T_{3R}}^{[2]} & & \\
\hline
Y \sim & O(\epsilon_\sigma\epsilon_\phi) & O(\epsilon_\phi) & O(\epsilon_\chi) & U(1)_{B-L}^{[12]} \\
\hline
 & O(\epsilon_\sigma\epsilon_\phi\epsilon_\chi) & O(\epsilon_\phi\epsilon_\chi) & O(1) &
\end{array}$$

(Still EFT)

Can one construct an explicit 4d gauge theory without small Yukawa couplings?

(Where do the Λ's come from?)

But life is hard

Minimal Flavour Deconstruction in 4d

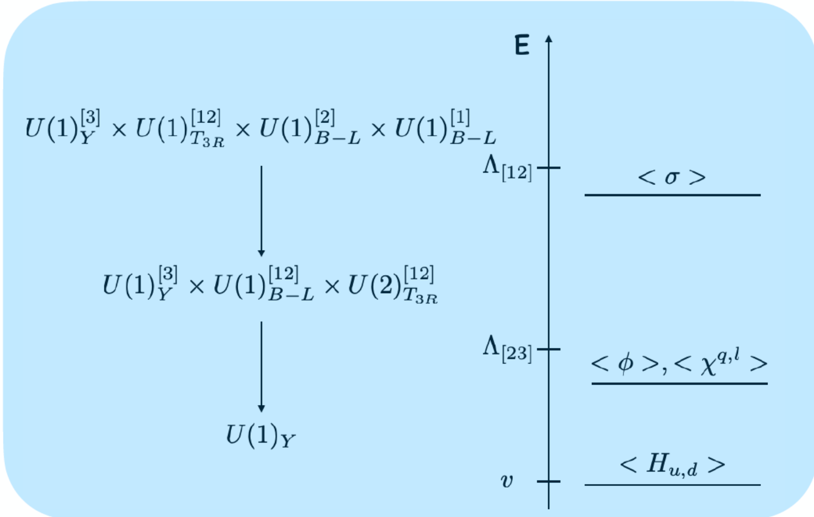
vev scale	Field	$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$	$SU(3)\times SU(2)$
v	$H_{u,d}$	$-1/2$	0	0	0	$(\mathbf{1},\mathbf{2})$
$O(10^{-1})\times\Lambda_{[23]}$	χ^q	$-1/6$	$1/3$	0	0	$(\mathbf{1},\mathbf{1})$
	χ^l	$1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
	ϕ	$1/2$	0	$-1/2$	0	$(\mathbf{1},\mathbf{1})$
$O(10^{-1})\times\Lambda_{[12]}$	σ	0	0	$1/2$	$-1/2$	$(\mathbf{1},\mathbf{1})$

$Z_2:\quad H_u\to u,\, H_d\to d, e$

$tan\beta = v_u/v_d = 10\div 30$

$V=\lambda(\chi^q)^3\chi^l$

Universal breaking of the gauge group



$$\epsilon_\sigma=\frac{\langle\sigma\rangle}{\Lambda_{[12]}}$$

$$\epsilon_\phi=\frac{\langle\phi\rangle}{\Lambda_{[23]}}\,,\qquad \epsilon_\chi=\frac{\langle\chi^{q,l}\rangle}{\Lambda_{[23]}}$$

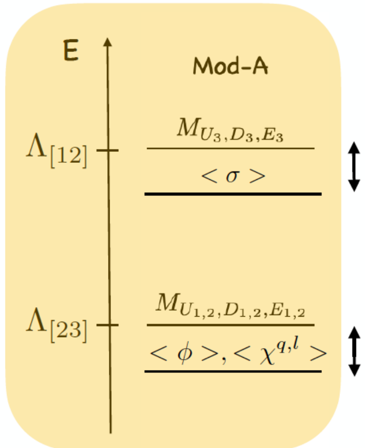
(Where do the Λ's come from?)

Model A

1st way for the Λ's

Vector-like fermions

		$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$	$SU(3)\times SU(2)$
light VL ($\alpha=1,2$)	U_α	$1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	D_α	$-1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	E_α	$-1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
heavy VL	U_3	0	$1/3$	$1/2$	0	$(\mathbf{3},\mathbf{1})$
	D_3	0	$1/3$	$-1/2$	0	$(\mathbf{3},\mathbf{1})$
	E_3	0	-1	$-1/2$	0	$(\mathbf{1},\mathbf{1})$



vector like Fermions will make happy some collegues

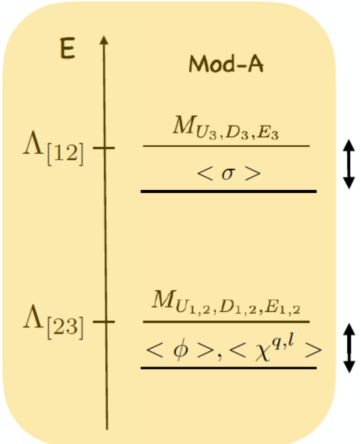
and some amout of fine tuning still necessary
some of the y ∽ 0.1 ; v2/v1 ∽ 10 etc.

Model A

1st way for the Λ's

Vector-like fermions

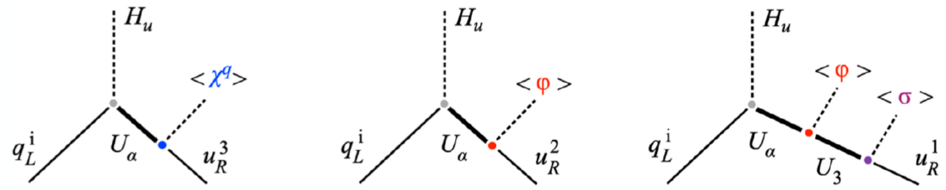
		$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$	$SU(3)\times SU(2)$
light VL ($\alpha=1,2$)	U_α	$1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	D_α	$-1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	E_α	$-1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
heavy VL	U_3	0	$1/3$	$1/2$	0	$(\mathbf{3},\mathbf{1})$
	D_3	0	$1/3$	$-1/2$	0	$(\mathbf{3},\mathbf{1})$
	E_3	0	-1	$-1/2$	0	$(\mathbf{1},\mathbf{1})$



Most general $d\leq 4$

$$\mathcal{L}_Y^u = (y_3^u\bar q_3 u_3 H_u + y_{i\alpha}^u \bar q_i U_\alpha H_u + y_\alpha^{\chi_u}\bar U_\alpha u_3\chi^q + y_{\alpha 2}^{\phi_u}\bar U_\alpha u_2\phi + y_{\alpha 3}^{\phi_u}\bar U_{R\alpha}U_{L3}\phi + \hat y_{\alpha 3}^{\phi_u}\bar U_{L\alpha}U_{R3}\phi + y_1^{\sigma_u}\bar U_3 u_1\sigma + \text{h.c.}) + M_{U_3}\bar U_3 U_3 + M_{U_\alpha}\bar U_\alpha U_\alpha$$

$Y_u \Rightarrow$



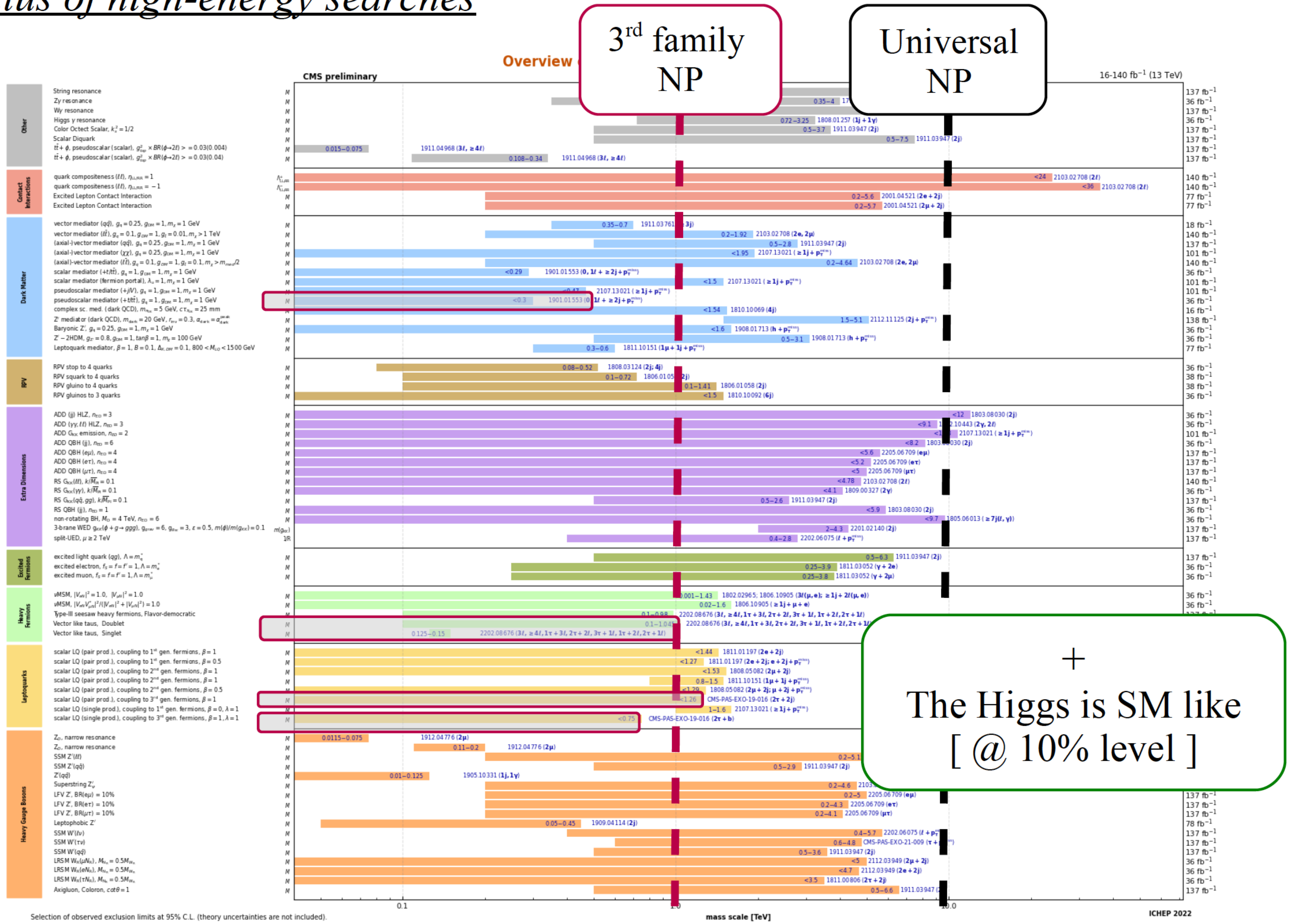
And similarly for $Y_{d,e}$

$$Y_u \approx \begin{pmatrix} y_{1\alpha}^u\hat y_{\alpha 3}^{\phi_u}y_1^{\sigma_u}\epsilon_\sigma\epsilon_\phi & y_{1\alpha}^u y_{\alpha 2}^{\phi_u}\epsilon_\phi & y_{12}^u y_2^{\chi_u}\epsilon_\chi \\ y_{2\alpha}^u\hat y_{\alpha 3}^{\phi_u}y_1^{\sigma_u}\epsilon_\sigma\epsilon_\phi & y_{2\alpha}^u y_{\alpha 2}^{\phi_u}\epsilon_\phi & y_{22}^u y_2^{\chi_u}\epsilon_\chi \\ \approx 0 & \approx 0 & y_3^u \end{pmatrix}$$

$\frac{v_2}{v_1}\approx 10 \qquad \epsilon_\chi\approx\epsilon_\phi\approx 5\cdot 10^{-2}$

$y's = 0.1\div 1 \qquad \epsilon_\sigma\approx 2\cdot 10^{-2}$

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...).

A definite goal: Precision in composite Higgs

What is the radius of Higgs compositeness, if any? $l_H = 1/m_*$

A two-parameter "theory"

$m_* = g_* f$

f

m_H

Giudice et al, 2007

H = pNGB

f = scale of symmetry breaking

m_* = scale of Higgs compositeness

Fine tuning = $(\frac{v}{f})^2 \quad v = 175 GeV$

An EFT approach

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{m_*^4}{g_*^2}\mathcal{L}_{res}\left(\frac{g_*\Phi^d}{m_*^d}, \frac{d_\mu}{m_*}, \frac{gA_\mu}{m_*}, \frac{\lambda_\Psi^i \Psi^i}{m_*^{3/2}}\right)$$

Giudice et al, 2007

Φ^d = Strong resonances of dim d (J=0,1/2,1,...) including H

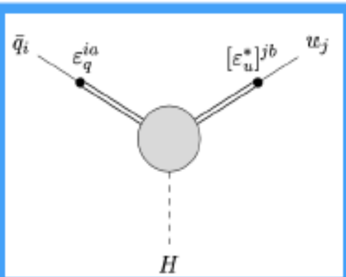
Ψ^i, A_μ = SM fields

λ_Ψ^i = flavour par.s, subject to suitable symmetries

Redi, Wyler 2011

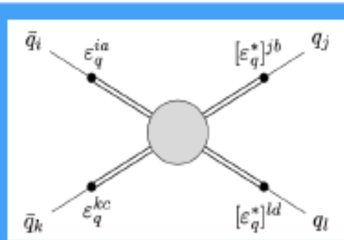
B, Buttazzo et al, 2013

Glioti et al, 2024



$Y_{ij}^u = g_* \varepsilon_q^{ia} c_{ab} [\varepsilon_u^*]^{jb}$.

E.g.



$$\mathcal{L}^{4q} = \frac{g_*^2}{m_*^2} c_{abcd} \varepsilon_q^{ia} [\varepsilon_q^*]^{jb} \varepsilon_q^{kc} [\varepsilon_q^*]^{ld} \bar{q}^i \gamma_\mu q^j \bar{q}^k \gamma^\mu q^l$$

$$\epsilon_f^{ia} = \frac{\lambda_f^{ia}}{g_*}$$

$$c_{ab}, c_{abcd} = \mathcal{O}(1)$$

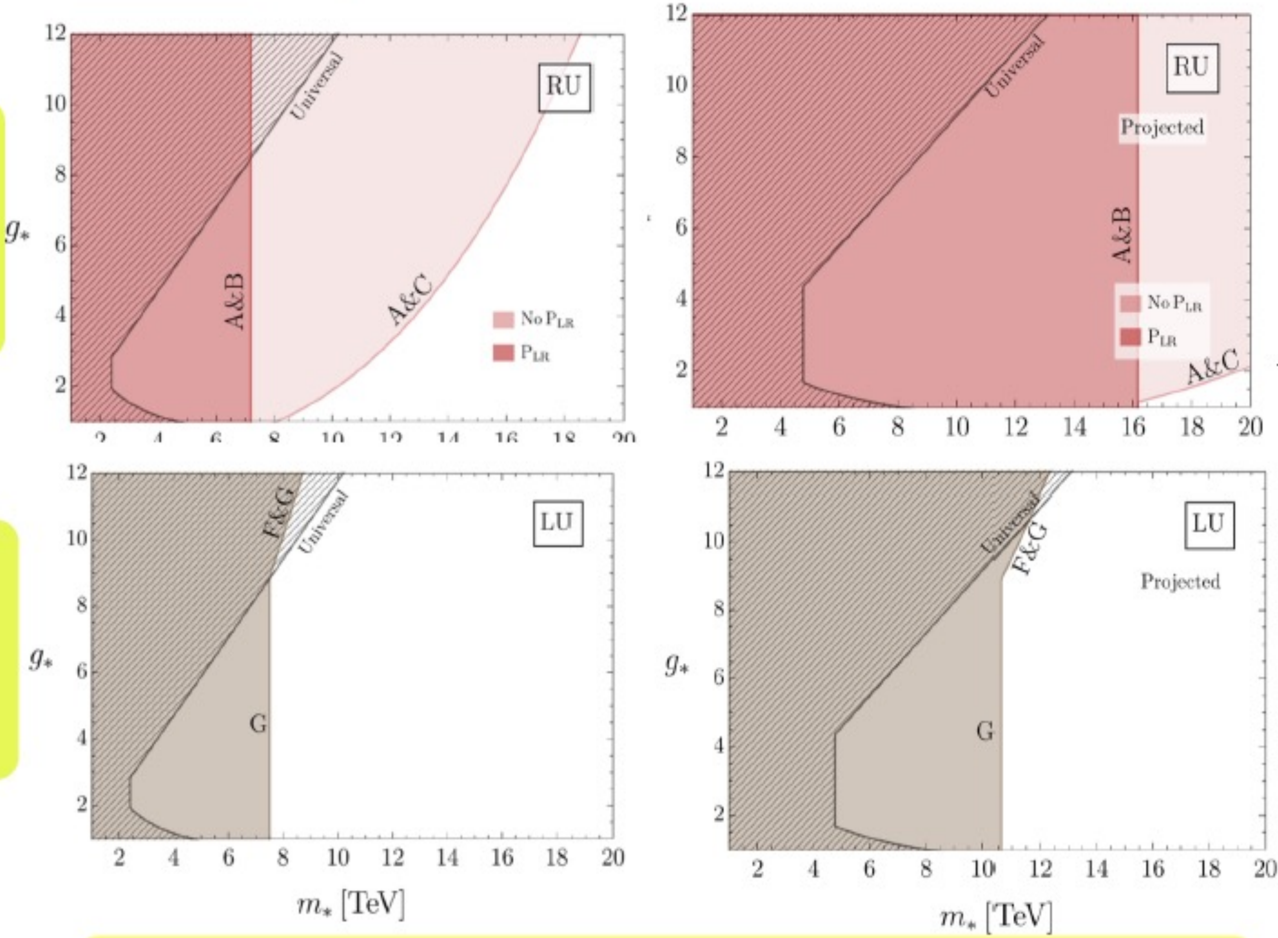
If $\epsilon_{11} << \epsilon_{22} << \epsilon_{33}$ "anarchy" $\Rightarrow m_* \gtrsim 10^{2\div 3} TeV (g_*/4\pi)$

Summary of excluded/sensitivity regions

Glioti et al, 2024

Right Univ = λ^i_Ψ respecting $U(3)_u \times U(3)_d$

Left Univ = λ^i_Ψ respecting $U(3)_q$



Label	Observable
A	$pp \to jj$
B	$\Delta F = 2\,(B_d)$
C	$B_s \to \mu^+\mu^-$
D	nEDM
E	$B^0 \to K^{*0}e^+e^-\ (C_7')$
F	$B \to X_s\gamma\ (C_7)$
G	W-coupling

Mid-term prospect: $m_* > (11 \div 20) TeV$ for any g_*

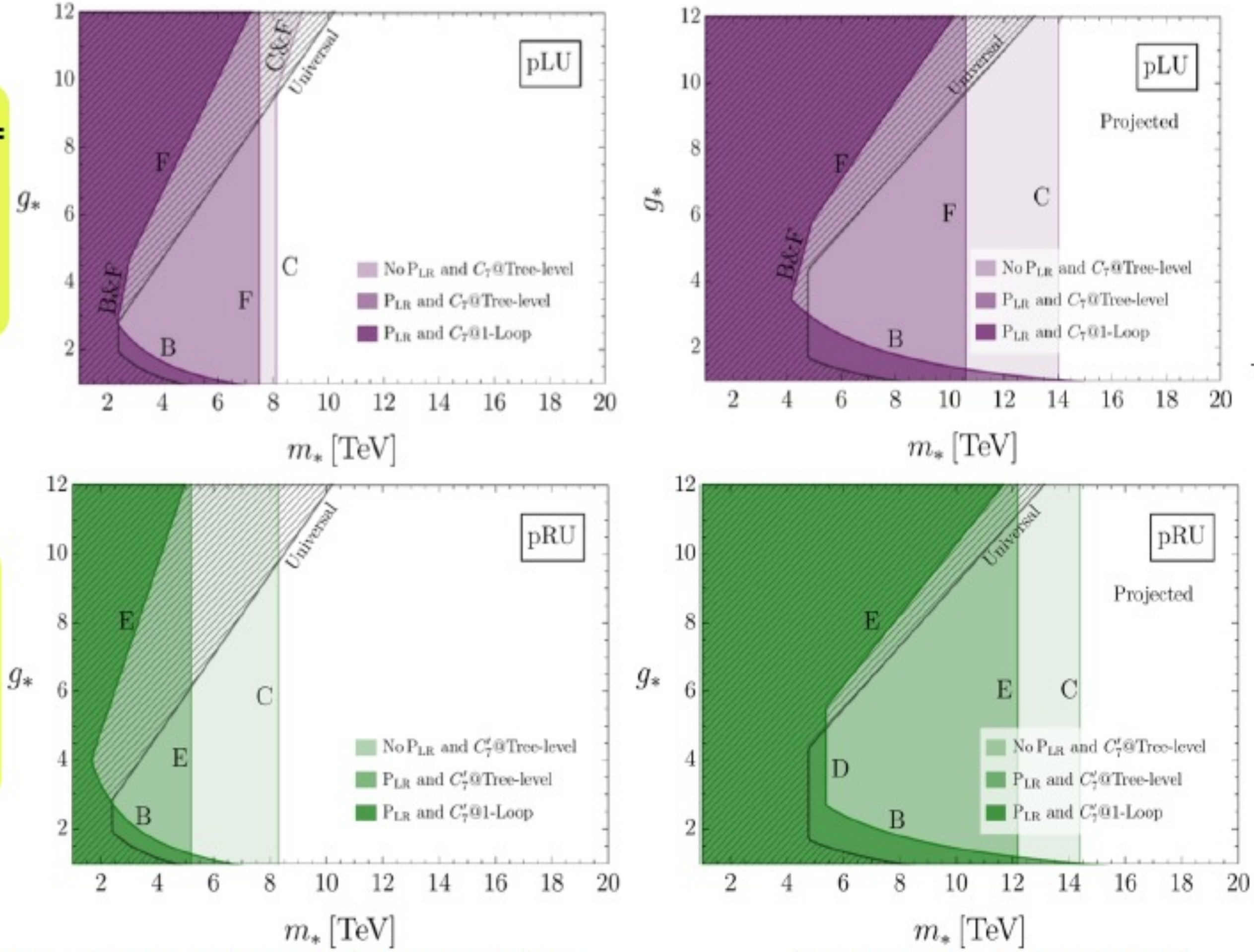
(Quarks only)

Summary of excluded/sensitivity regions

Glioti et al, 2024

partial Left Univ = λ^i_Ψ respecting $U(2)_q$

part. Right Univ = λ^i_Ψ respecting $U(2)_u \times U(2)_d$



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E	$B^0 \to K^{*0} e^+ e^-\ (C_7'$
F	$B \to X_s \gamma\ (C_7)$
G	W-coupling

Universal = flavour-less EW observables

Projected = "mid-term"

(Quarks only)

absence says more than presence

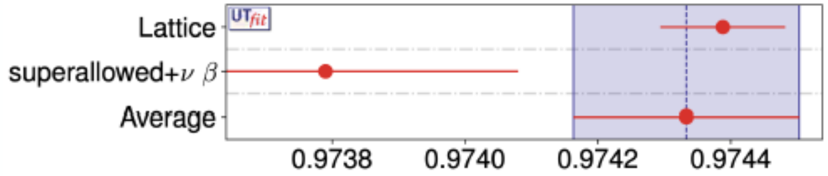
FRANK HERBERT

(Dune)

THANKS FOR YOUR ATTENTION

What's new for EPS23

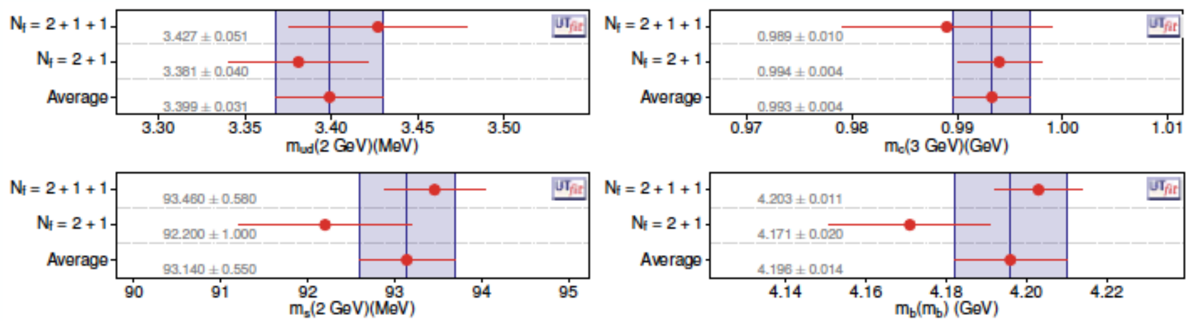
- Theory updates:
  - New V_{ud} extraction from neutron decays, following V. Cirigliano et al. arXiv:2306.03138



  - New lattice values for masses
  - New lattice form factors for exclusive $b \to q\ell\nu$

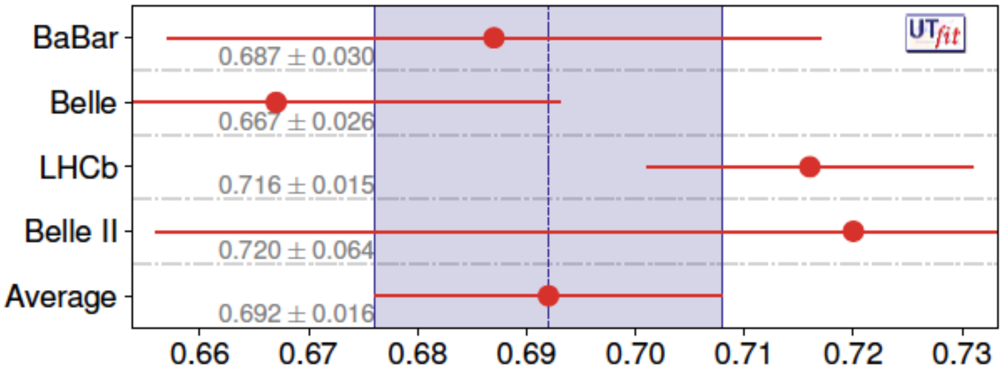
All masses computed in $\overline{\mathrm{MS}}$ and averaged with PDG scale factors

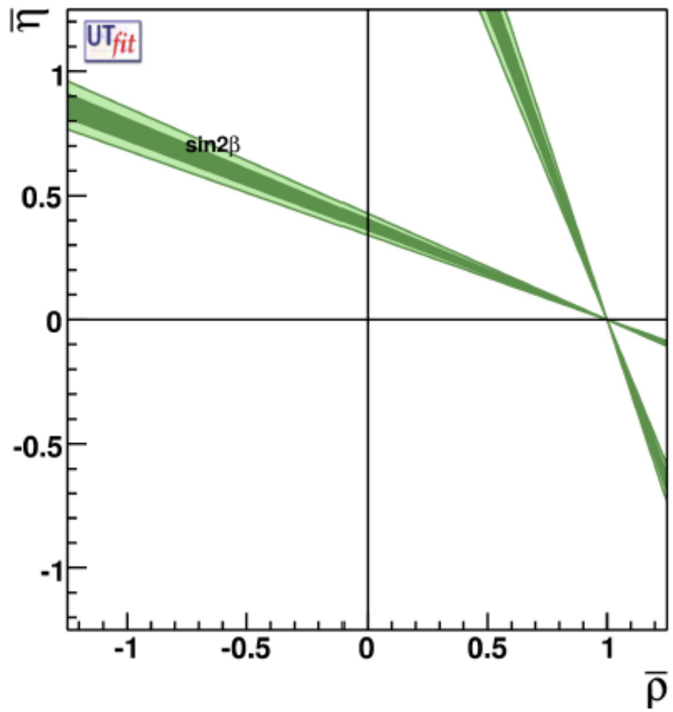
- Experiment updates:
  - New sin2β by LHCb
  - New γ by LHCb
  - New α
- …



What's new for EPS23: $sin(2\beta)$

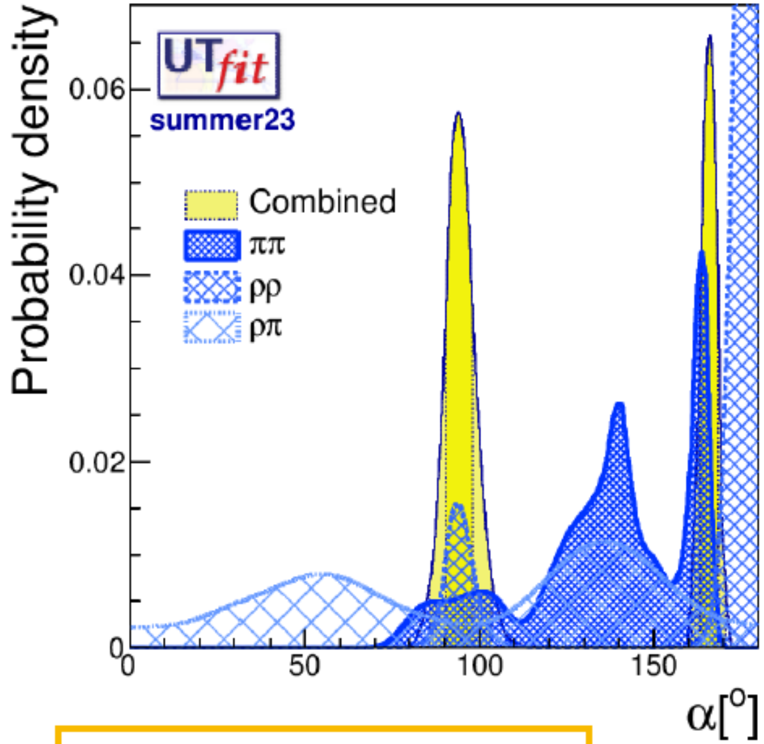
- Averaged charmonium values
- New sin2β from LHCb
- Average including correction due to Cabibbo-suppressed penguin contribution:
  - Most recent estimate $\Delta(\sin 2\beta) = -0.1 \pm 0.1$
  - Theoretical uncertainty comparable to experimental error





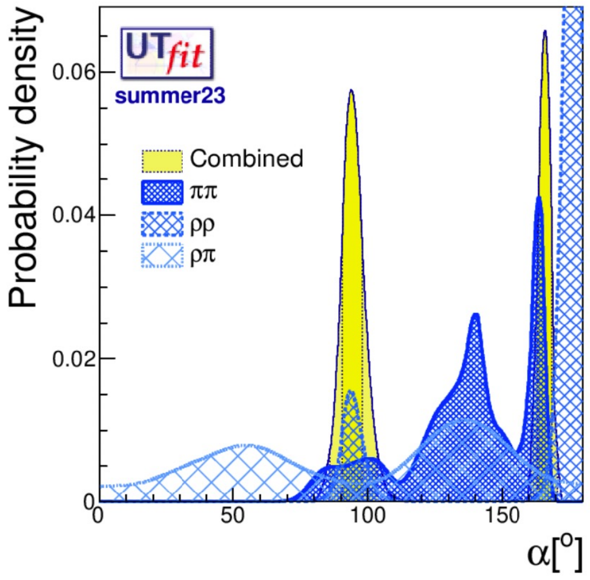
What's new for EPS23

- Updated the bound on α with
  - Bounds from ππ and ρρ derived from PDG averages (including PDG rescaling of the error)
  - Bound from ρπ derived from same inputs used by HFLAV
- As usual, main difference wrt other combinations is in the treatment of the multiple solutions
  - Profiling vs marginalization: in our case, multiple overlapping solutions counts more than a single solution when integrating out the other quantities (T, P, and strong phases)

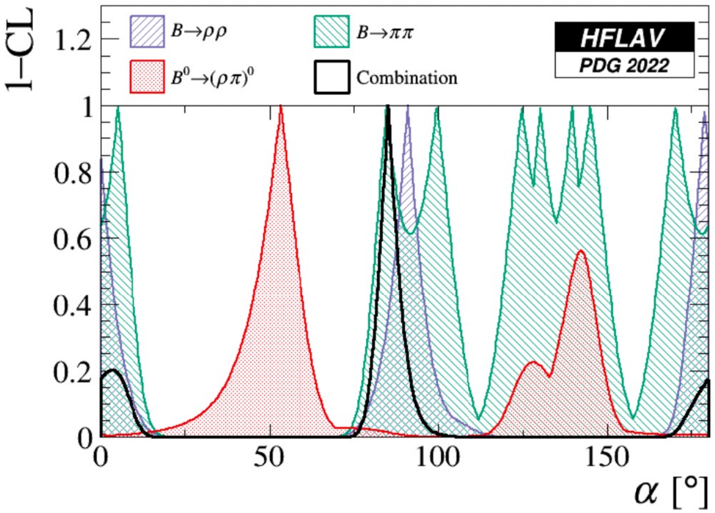


$$\alpha = (93.8 \pm 4.5)^o$$

More on α



$\alpha^{exp} = 93.8° \pm 4.5°$



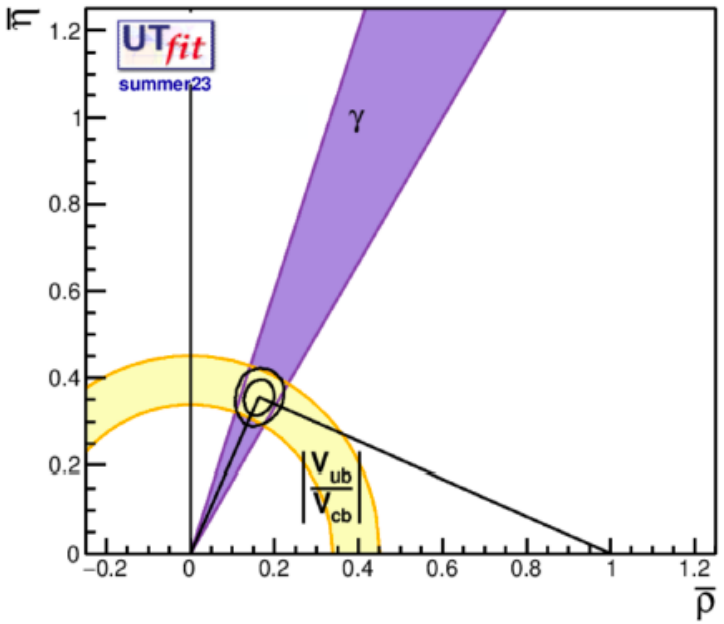
$\alpha_{HFLAV} = 85.5 \pm 4.6$

Inputs are slighly different from what HFLAV because for the BR averages we use the PDG (with the error inflation if there is a tension), while HFLAV would use their averages without error inflation.
So the pipi BR inputs are slightly different.   We also use the updated rhopi.

HFLAV
It seems that the reason why the combination falls on the pipi solution on the left of the rhorho peak (while the right solution would be just as probable and even not distinguishable) is due to the small bump from the rhopi distribution which instead goes to zero for the pipi solution on the right.

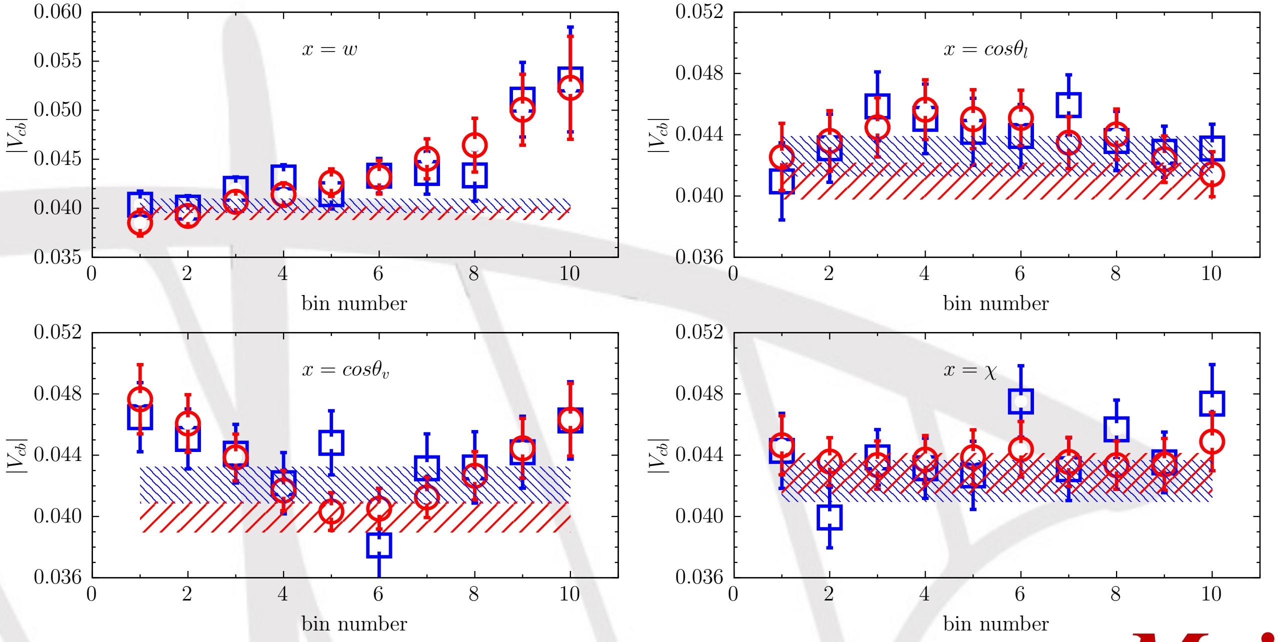
What's new for EPS23

- Determination combining all $D^{(*)}K^{(*)}$ modes
  - Simultaneous extraction of γ and $D\bar{D}$ mixing parameters (which enter the BSM analysis)
  - ~~Details are given in dedicated talk by R. Di Palma on Friday~~
- Tree-level determination
  - Baseline determination of CP violation in the SM, assuming BSM effects enter only at loop
  - With $|V_{ub}/V_{cb}|$, allows for a robust fit of the CKM parameters in the SM, even in presence of new physics



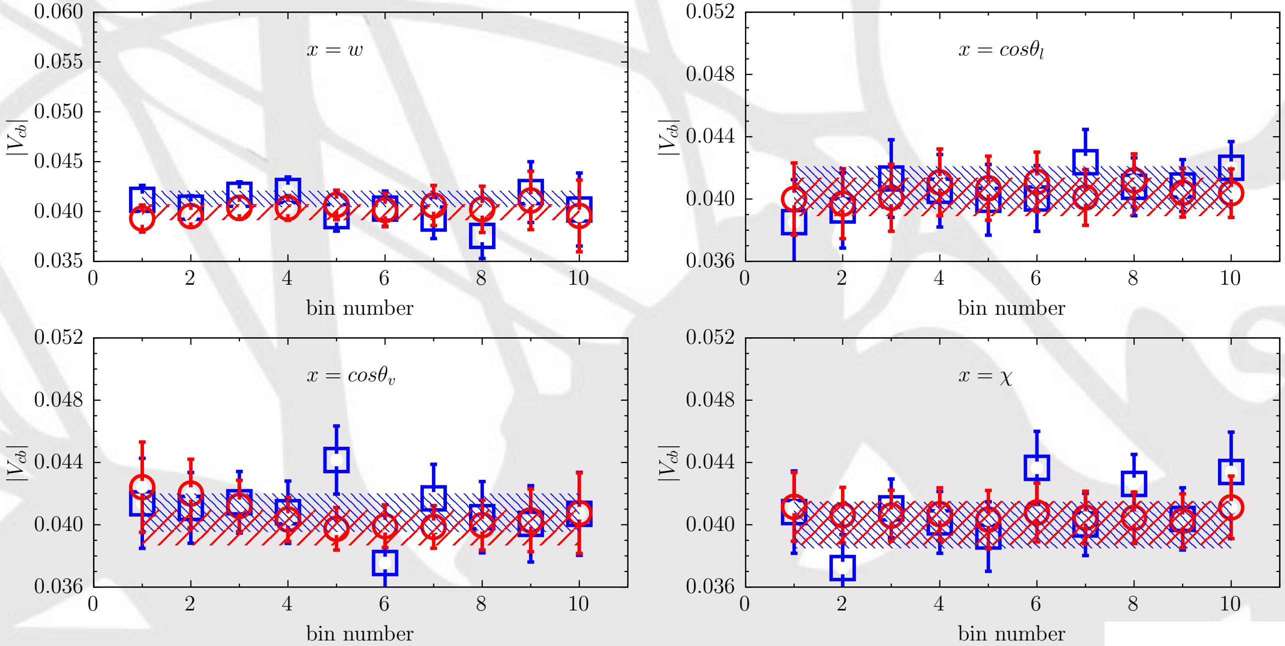
$$\bar{\rho} = \pm 0.163 \pm 0.024$$
$$\bar{\eta} = \pm 0.356 \pm 0.027$$

See talk by G. D'Ambrosio



FNAL/MILC

Mainly due to $F_1(w)$



JLQCD

GM,S. Simula,L.Vittorio

compatibility plots

A way to "measure" the agreement of a single measurement with the indirect determination from the fit using all the other inputs: test for the SM description of the flavour physics

2022

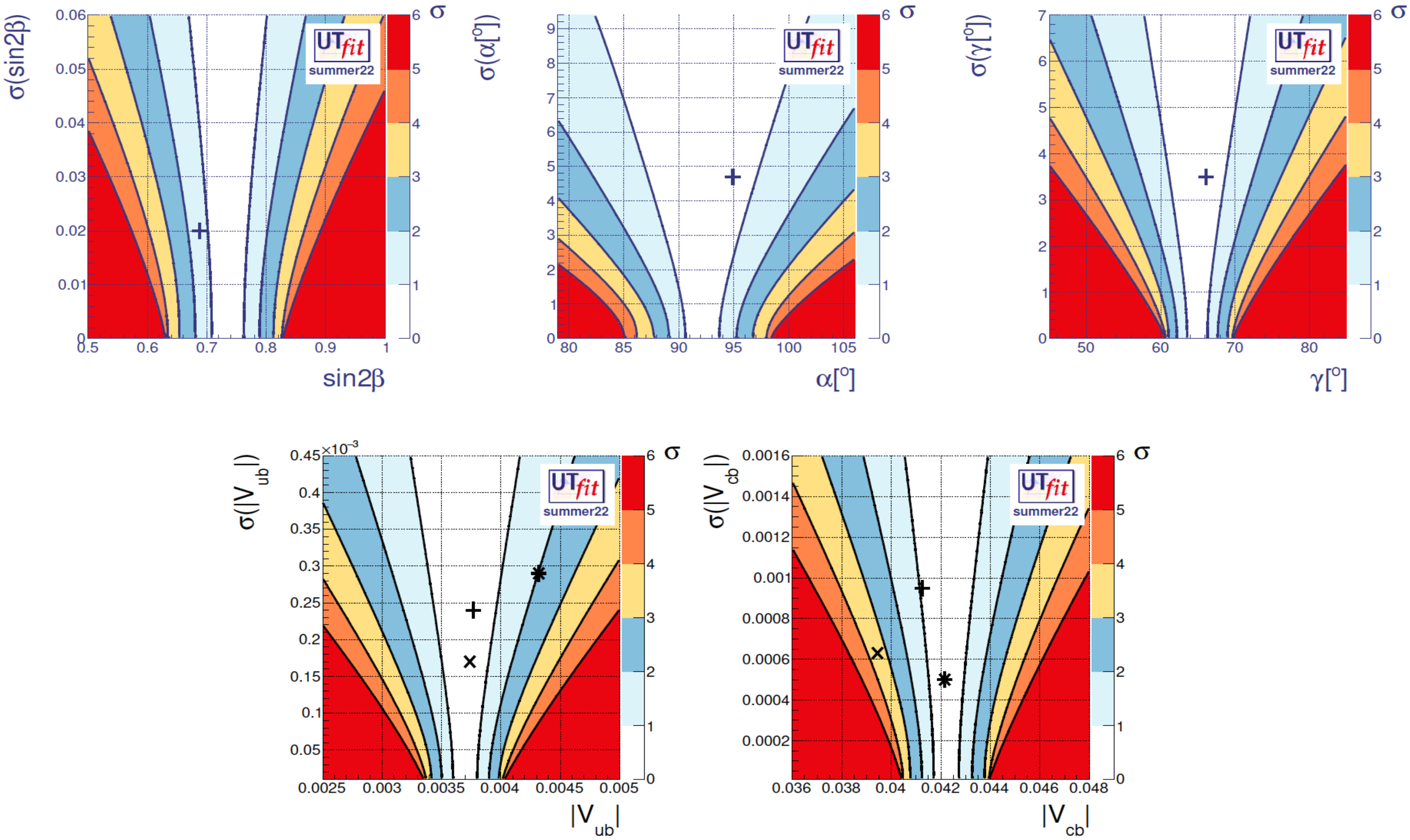


FIG. 5. *Pull plots (see text) for* $\sin 2\beta$ *(top-left),* α *(top-centre),* γ *(top-right),* $|V_{ub}|$ *(bottom-left) and* $|V_{cb}|$ *(bottom-right) inputs. The crosses represent the input values reported in Table I. In the case of* $|V_{ub}|$ *and* $|V_{cb}|$ *the x and the * represent the values extracted from exclusive and inclusive semileptonic decays respectively.*

State-of-the-art of the semileptonic B → {D(*),π} decays

Two critical issues

- V_{cb}

  - **exclusive/inclusive $|V_{cb}|$ puzzle:**

  exclusive (FLAG '21): $|V_{cb}|(BGL) \cdot 10^3 = 39.36\ (68)$

  inclusive (HFLAV '21): $|V_{cb}| \cdot 10^3 = 42.19\ (78)$

  difference of ~ 2.7 σ

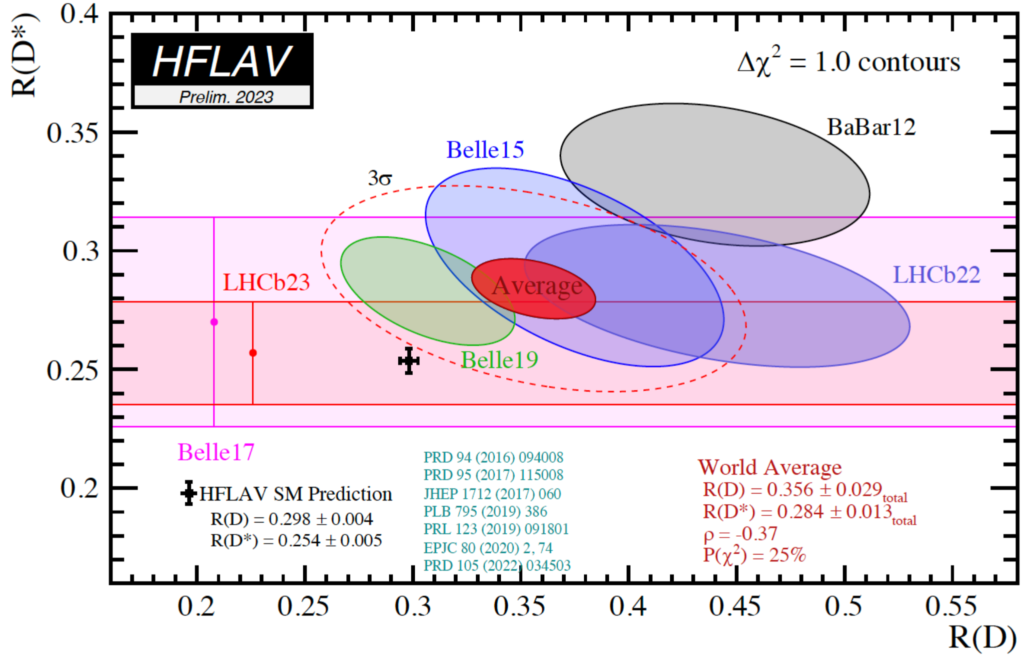
  $|V_{cb}| \cdot 10^3 = 42.16\ (50)$

  (Bordone et al. 2107.00604)

- $R_{D(*)}$

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

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

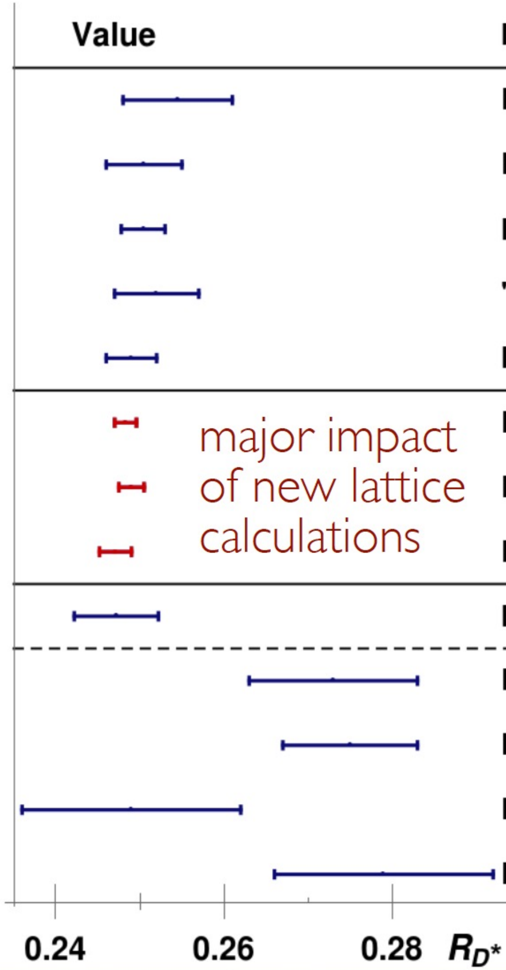


HFLAV Collaboration, PRD '23 [arXiv:2206.07501] (updated plot)

2022

3.2σ tension

Overview over predictions for $R(D^*)$

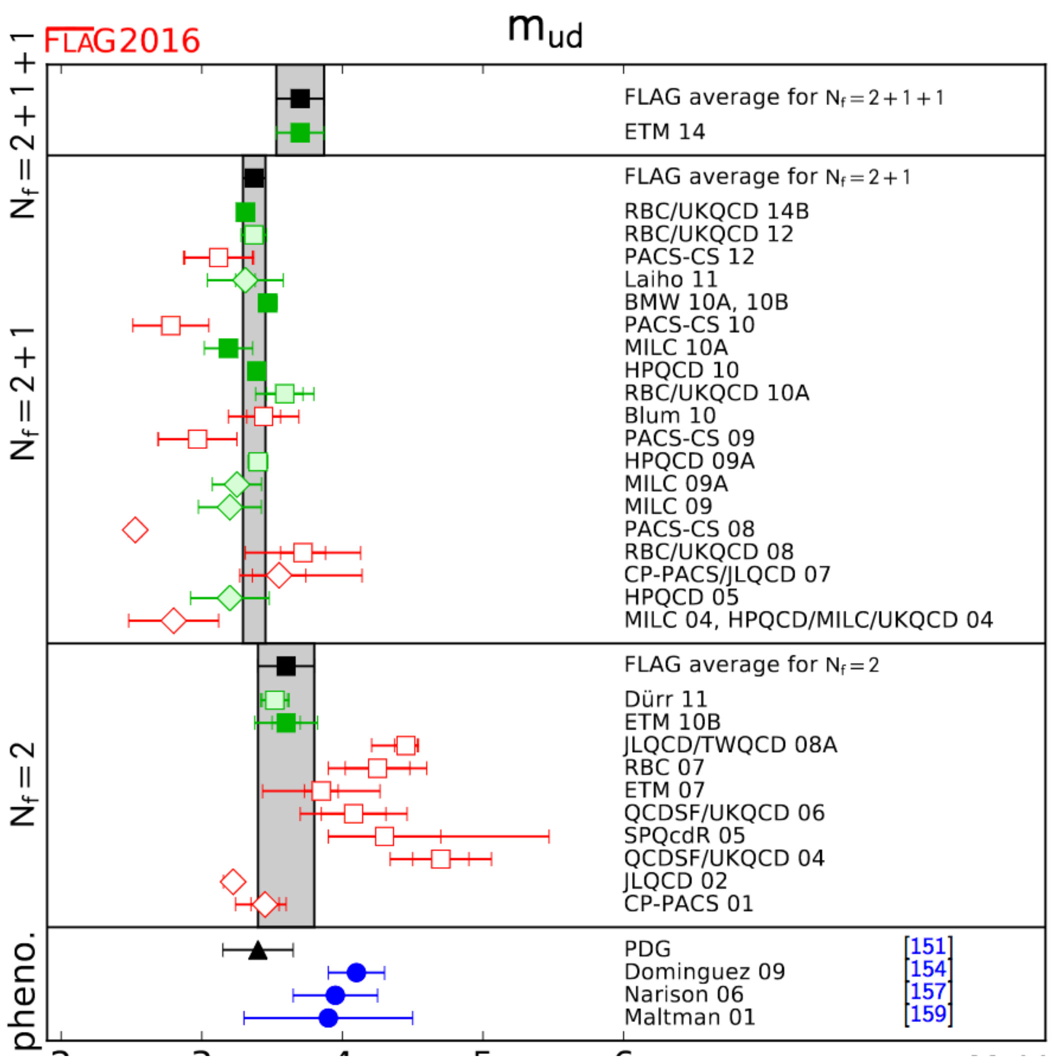


Method	Input Theo	Input Exp	Reference
BGL	Lattice, HQET	Belle'17'18	Gambino et al.'19
BGL	Lattice, HQET	Belle'18	Jaiswal et al.'20
HQET@$1/m_c^2,\alpha_s$	Lattice, LCSR, QCDSR	Belle'17'18	Bordone et al.'20
"Average"			HFLAV'21
HQET$_{RC}$@$1/m^2,\alpha_s^{(2)}$	Belle'17'18	Lattice	Bernlochner et al.'22
BGL	Lattice	Belle'18, Babar'19	Vaquero et al.'21v2
BGL	Lattice	Belle'18	JLQCD prel. (MJ)
BGL	Lattice	Belle'18	Davies, Harrison'23
HQET@$1/m_c^2,\alpha_s$	Lattice, LCSR, QCDSR	---	Bordone et al.'20
BGL	Lattice	---	Vaquero et al.'21v2
DM	Lattice	---	Martinelli et al. FNAL/MILC
BGL	Lattice	---	JLQCD prel. (MJ)
BGL	Lattice	---	Davies, Harrison'23

FNAL 0.275 \pm 0.008
JLQCD 0.248 \pm 0.008
HPQCD 0.276 \pm 0.009

Predictions based only on Fermilab & HPQCD lead to larg[e] agreement with exp, mostly because of the suppression at high w of the denominator.
I see no reason not to use experimental data for a SM test, especially in presence of tensions in lattice data.

Courtesy by Gambino ***EXP 0.284 \pm 0.013***

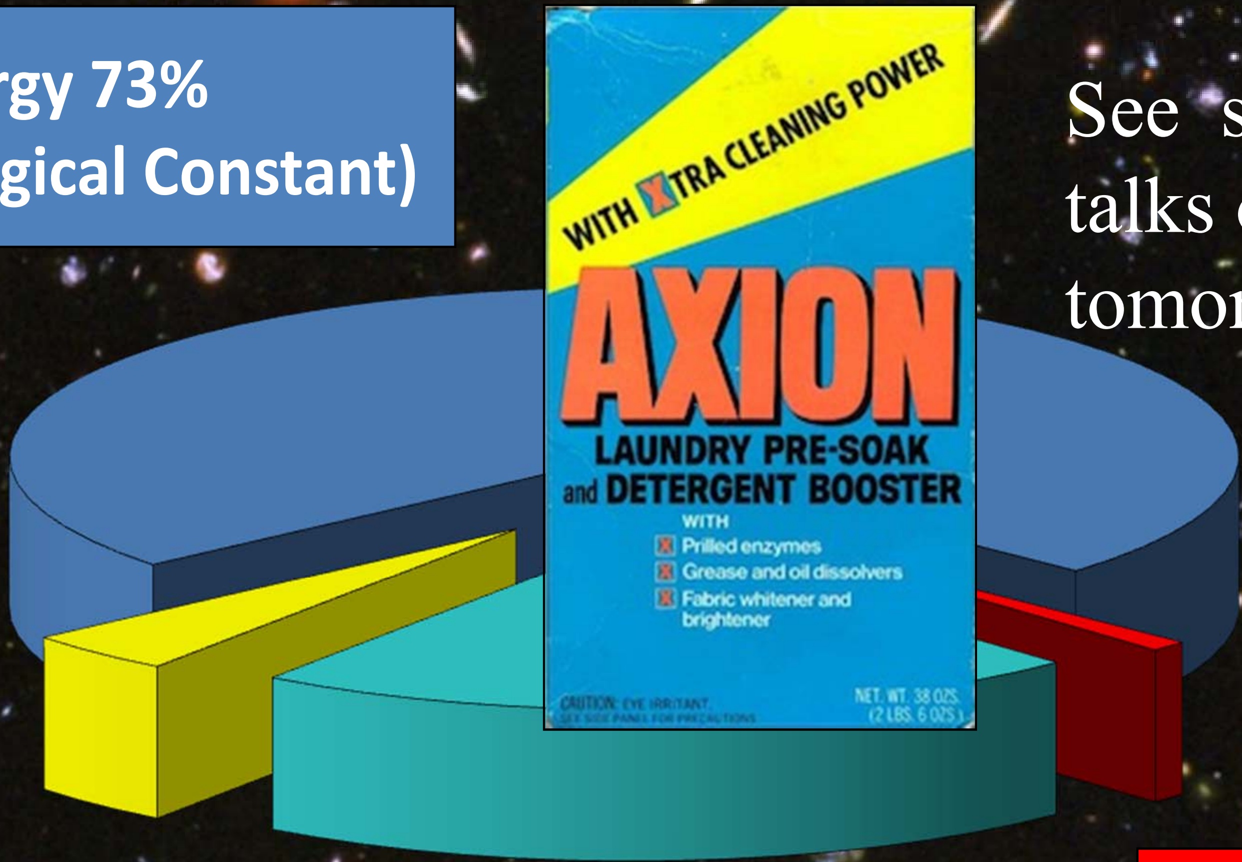


N_f	m_u	m_d	m_u/m_d	R	Q
2+1+1	2.36(24)	5.03(26)	0.470(56)	35.6(5.1)	22.2 (1.6)
2+1	2.16(9)(7)	4.68(14)(7)	0.46(2)(2)	35.0(1.9)(1.8)	22.5(6)(6)
2	2.40(23)	4.80(23)	0.50(4)	40.7(3.7)(2.2)	24.3(1.4)(0.6)

Raffelt

See several talks on axions tomorrow

Dark Energy 73%
(Cosmological Constant)



Ordinary Matter 4%
(of this only about 10% luminous)

Dark Matter
23%

Neutrinos
0.1–2%

B meson real photon emissions

Factorization at leading power in an expansion of the decay amplitude in Λ_{QCD}/E_γ and Λ_{QCD}/mb has been established to all orders in the strong coupling α_s. In this approximation, the branching fraction depends only on the leading-twist B-meson light-cone distribution amplitude (LCDA) $\phi_+(\omega, \mu)$

More precisely, it is proportional to $1/\lambda_B$, the most important LCDA parameter in exclusive decays, is uncertain by a large factor ranging from 200 MeV favoured by non-leptonic decays to 460 MeV from QCD sum rules.

The radiative leptonic decay has therefore been suggested as a measurement of λ_B

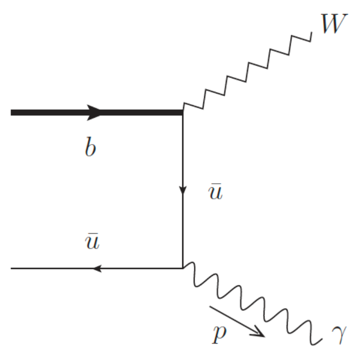


Figure 1. Leading contribution to $B \to \gamma \ell \nu_\ell$.

For large photon energies the form factors can be written as [9]

$$F_V(E_\gamma) = \frac{e_u f_B m_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma, \mu) + \xi(E_\gamma) + \Delta\xi(E_\gamma)\,,$$
$$F_A(E_\gamma) = \frac{e_u f_B m_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma, \mu) + \xi(E_\gamma) - \Delta\xi(E_\gamma)\,. \tag{2.7}$$

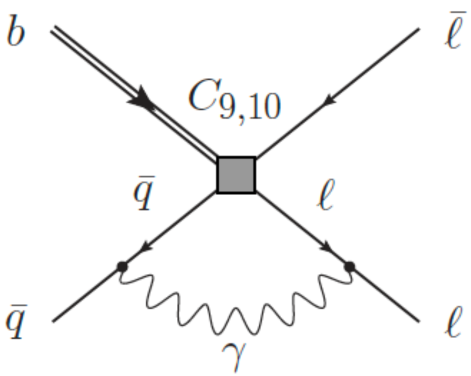
The first term is equal in both expressions and represents the leading-power contribution in the heavy-quark expansion (HQE). It originates only from photon emission from the light spectator quark in B meson (Fig. 1). In the above, f_B is the decay constant of B meson, and the quantity λ_B is the first inverse moment of the B-meson LCDA,

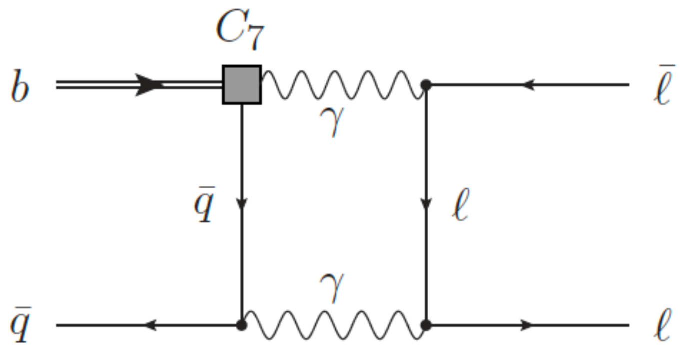
$$\frac{1}{\lambda_B(\mu)} = \int_0^\infty \frac{d\omega}{\omega}\, \phi_+(\omega, \mu)\,. \tag{2.8}$$

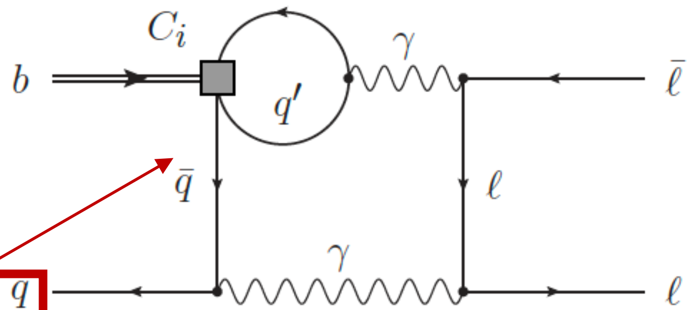
Further applications in decays of heavy neutral B mesons: Virtual corrections (some questions still open)

Enhanced electromagnetic correction to the rare B-meson decay $B_{s,d} \to \mu^+\mu^-$

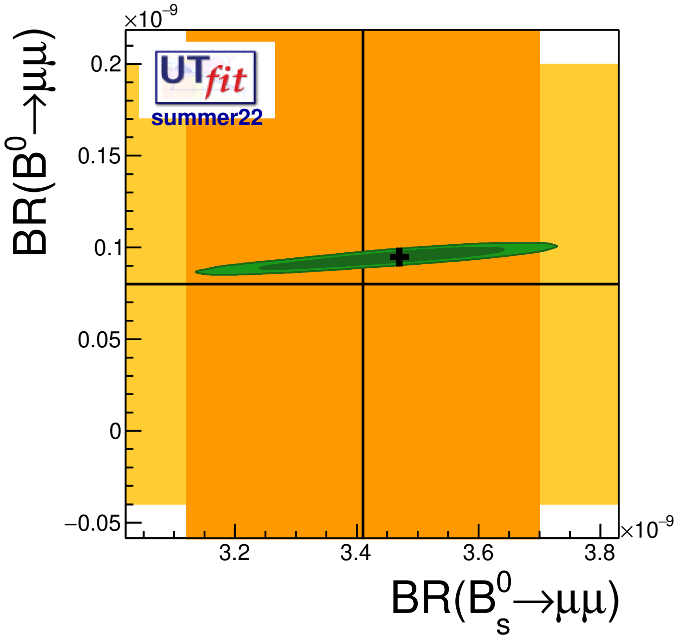
Martin Beneke,[1] Christoph Bobeth,[1,2] and Robert Szafron[1]







is this really reabsorbed in the coefficient of O_9?



Further applications in decays of heavy neutral B mesons: real corrections (some questions still open)

$B_s^0 \to \mu^+\mu^-\gamma$ from $B_s^0 \to \mu^+\mu^-$

Francesco Dettori[a], Diego Guadagnoli[b] and Méril Reboud[b,c]

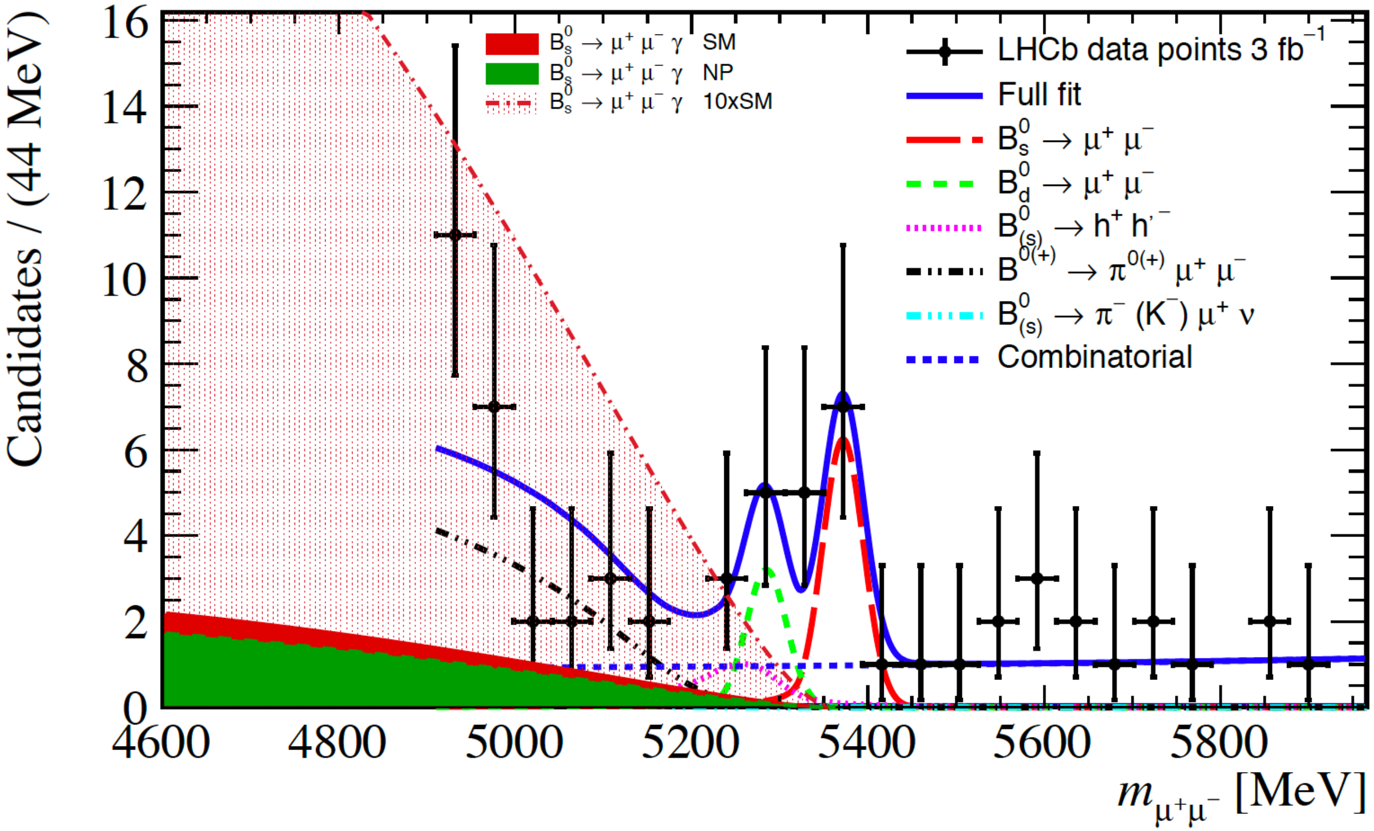
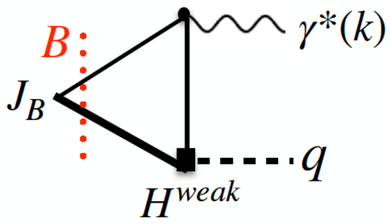
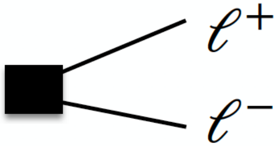


Figure 3: Dimuon invariant mass distribution from LHCb's measurement of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ [52] overlayed with the contribution expected from $B_s^0 \to \mu^+\mu^-\gamma$ decays (ISR only). Assumes flat efficiency versus $m_{\mu^+\mu^-}$. The line denoted as '$B_s^0 \to \mu^+\mu^-\gamma$ NP' refers to the $V-A$ case with $\delta C_9 = -12\%\, C_9^{\rm SM}$ (see also Fig. 2). The two filled curves are not stacked onto each other.

Particle(s) from weak vertex with momenta q



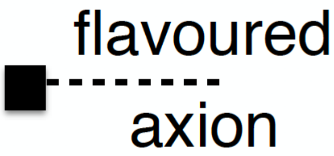
- **FCNC** Qb= Qq (need long distance in addition) : $F(q^2, k^2)$



Hweak ~ O9,10 : $B_{d,s} \to \ell^+\ell^-\gamma$ $\quad F(q^2) = F(q^2,0)$

Bobeth's talk

Hweak ~ O7 : $B_{d,s} \to \ell^+\ell^-\gamma$ $\quad F^*(k^2) = F(0,k^2)$



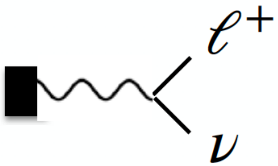
Hweak ~ $\bar{q}\gamma_\mu b_L \partial^\mu a$: $B_{d,s} \to \ell^+\ell^- a$ $\quad F(m_a^2, k^2) \to F^*(k^2)$

Ziegler's talk

or dark photon, scalar DM, …

Xin-Yu Tuo et al. arXiv:2103.11331
G. Gagliardi et al. arXiv:2202.03833 [hep-lat]

- **FCCC** Qb ≠ Qq :



Hweak ~ $V_{ub}\, \bar{u}\gamma_\mu b_L \ell \gamma^\mu \nu_L$: $B_u \to \ell^+\nu\gamma$

- Physics: helicity suppression of $B \to f_i \bar{f}_j$ relieved in radiative decay!

$B_s \to \mu^+\mu^-\gamma$ at large q^2 from lattice QCD

Giuseppe Gagliardi, INFN Sezione di Roma Tre

In collaboration with:
R. Frezzotti, V. Lubicz, G. Martinelli, C.T. Sachrajda,
F. Sanfilippo, S. Simula, N. Tantalo

[pre-print: arXiv:2402.03262]

Why $B_s \to \mu^+\mu^-\gamma$ at large q^2 ?

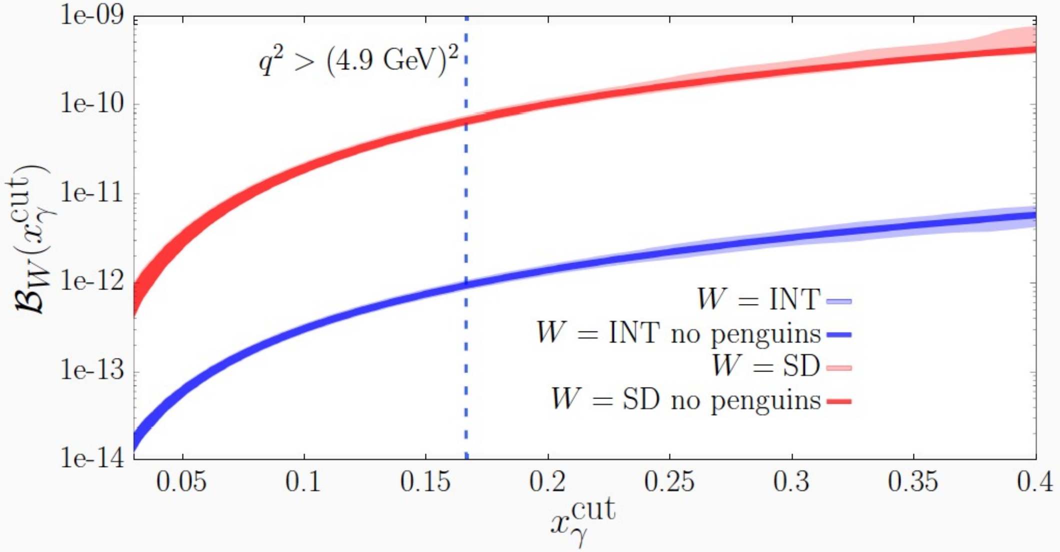
- The $B_s \to \mu^+\mu^-\gamma$ decay allows for a new test of the SM predictions in $b \to s$ FCNC transitions.
- Despite the $\mathcal{O}(\alpha_{\rm em})$-suppression w.r.t. the widely studied $B_s \to \mu^+\mu^-$, removal of helicity-suppression makes the two decay rates comparable in magnitude.
- At very high $\sqrt{q^2}$ = invariant mass of the $\mu^+\mu^-$, the contributions from penguin operators appearing in the weak effective-theory, which are difficult to compute on the lattice, are suppressed [Guadagnoli, Reboud, Zwicky, JHEP '17] ✓.

In this talk I will present the first, ($\simeq$) first-principles lattice QCD calculation of the $B_s \to \mu^+\mu^-\gamma$ decay rate for $q^2 \gtrsim (4.2~\mathrm{GeV})^2$.

The branching fractions

$$\mathcal{B}(x_\gamma^{\rm cut}) = \int_0^{x_\gamma^{\rm cut}} {\rm d}x_\gamma \, \frac{{\rm d}\mathcal{B}}{{\rm d}x_\gamma} \qquad\qquad x_\gamma^{\rm cut} \equiv 1 - \frac{q^2_{\rm cut}}{m^2_{B_s}}$$

- $E_\gamma^{\rm cut} = x_\gamma^{\rm cut} m_{B_s}/2$ is the upper-bound on the measured photon energy.

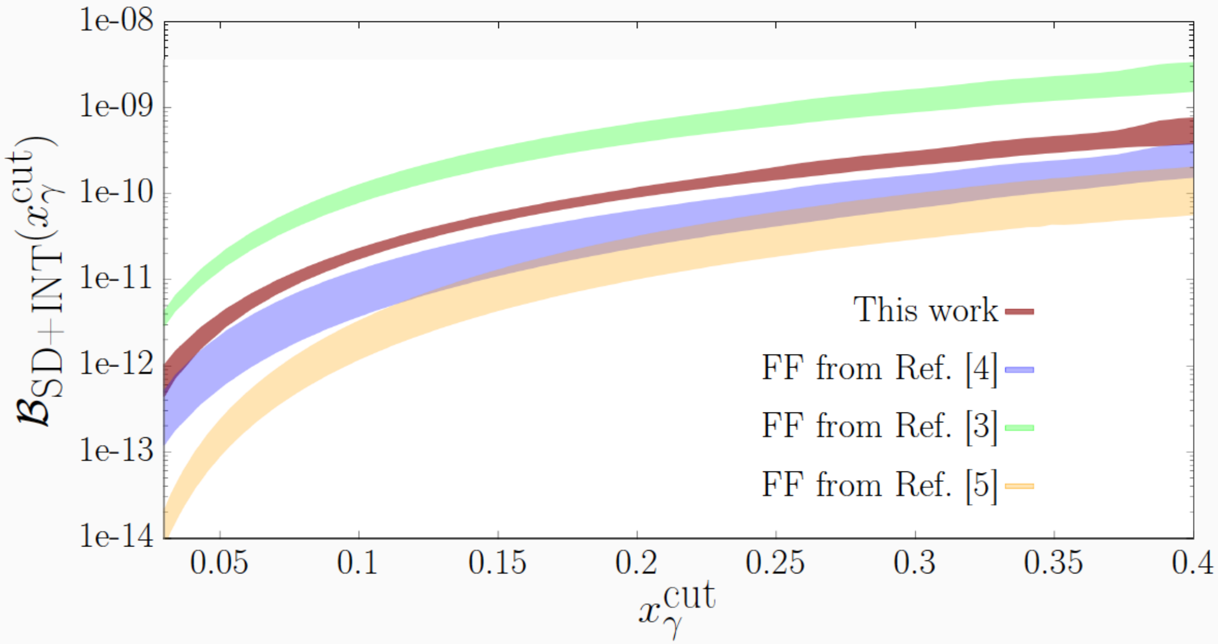


- SD contribution dominated by vector form factor F_V. Tensor form-factor contributions suppressed by small Wilson coefficient $C_7 \ll C_9, C_{10}$.
- At $x_\gamma^{\rm cut} \sim 0.4$ our estimate of charming-penguins uncertainties is around 30% [previous works quoted few percent uncertainties].

Comparison with current LHCb upper-bound for $x_\gamma^{\rm cut} \sim 0.166$.

$$\mathcal{B}_{\rm SD}^{\rm LHCb}(0.166) < 2 \times 10^{-9}\,, \qquad \mathcal{B}_{\rm SD}(0.166) = 6.9(9) \times 10^{-11} \qquad \text{[This work]}$$

Comparison with previous works



- Ref. [3] = Janowski, Pullin , Zwicky , JHEP '21 , light-cone sum rules.
- Ref. [4] = Kozachuk, Melikhov, Nikitin , PRD '18 , relativistic dispersion relations.
- Ref. [5] = Guadagnoli, Normand, Simula, Vittorio, JHEP '23, VMD/Lattice.

Differences with earlier estimates can be traced back to the fact that our determination of F_V (which gives the dominant contribution to the branching) is larger (smaller) than the one of Refs. [4-5] (Ref. [3]) by a factor of about $1.5 - 2$.

Conclusions

- We have presented a first-principles lattice calculation of the form factors F_V, F_A, F_{TV}, F_{TA} entering the $\bar{B}_s \to \mu^+\mu^-\gamma$ decay, in the electroquenched approximation.
- Systematic errors have been controlled thanks to the use of gauge configurations produced by the ETM Collaboration, which correspond to four values of the lattice spacing $a \in [0.057 : 0.09]$ fm, and through the use of five different heavy-strange masses $m_{H_s} \in [m_{D_s} : 2m_{D_s}]$.
- Presently our result for the branching fractions have uncertainties ranging from $\sim 15\%$ at $\sqrt{q^2_{\text{cut}}} = 4.9$ GeV to $\sim 30\%$ at $\sqrt{q^2_{\text{cut}}} = 4.2$ GeV.
- At small q^2_{cut} uncertainty dominated by the charming-penguins which we included using a phenomenological parameterization.

Outlook:

- Evaluate electro-unquenching effects.
- Evaluate charming-penguins contributions from first-principles.
- Simulate on finer lattice spacings to be able to reach higher m_{H_s} and reduce the impact of the mass-extrapolation.