From SUSY to the Coq au vin and Beyond

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UTfit

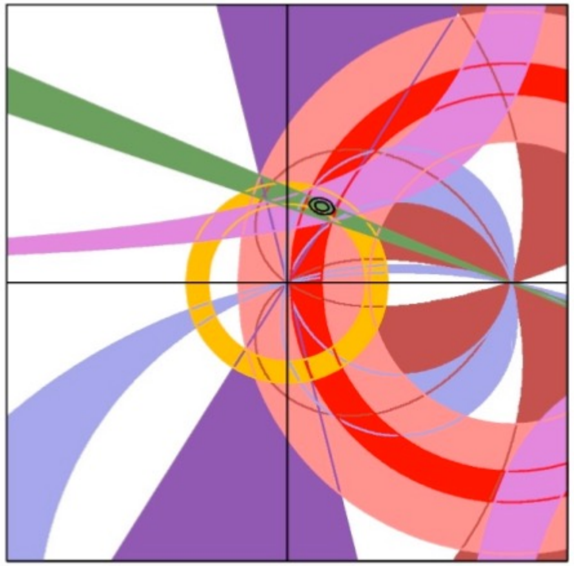
Extended Twisted Mass Collaboration

INFN Istituto Nazionale di Fisica Nucleare

Only for this session: From Max Planck to Antonio Masiero

PLAN OF THE TALK

- *The past: Susy around the corner*
- *Susy around the corner II*
- *Turning to pop-art*
- *The coq-au-vin and beyond*
- *Modern Times:Flavor in the SM*
- *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: Susy Around the Corner

CP Violating B Decays in the Standard Model and Supersymmetry

M Ciuchini, E Franco, G Martinelli, A Masiero, L Silvestrini

1) The Context: two body B decays
2) FCNC in the mass insertion approximations
3) Results

The context: M Ciuchini, E Franco, G M, L Silvestrini just finished a phenomenological study of two body non-leptonic B decays

The Hamiltonian

$\lambda_f = V_{fd} V^{\star}_{fb}$

$$\mathcal{H}_{eff}^{\Delta B=1} = \lambda_u \frac{G_F}{\sqrt{2}} \Big[\Big(C_1(\mu) \left(Q_1^u(\mu) - Q_1(\mu) \right) + C_2(\mu) \left(Q_2^u(\mu) - Q_2(\mu) \right) \Big) + \tau \vec{C}(\mu) \cdot \vec{Q}(\mu) \Big]$$

$$\begin{aligned}
Q_1^u &= (\bar{b}d)_{(V-A)} (\bar{u}u)_{(V-A)} \\
Q_2^u &= (\bar{b}u)_{(V-A)} (\bar{u}d)_{(V-A)} \\
Q_1 &= (\bar{b}d)_{(V-A)} (\bar{c}c)_{(V-A)} \\
Q_2 &= (\bar{b}c)_{(V-A)} (\bar{c}d)_{(V-A)} \\
Q_{3,5} &= (\bar{b}d)_{(V-A)} \sum_q (\bar{q}q)_{(V\mp A)} \\
Q_4 &= \sum_q (\bar{b}q)_{(V-A)} (\bar{q}d)_{(V-A)} \\
Q_6 &= -2 \sum_q (\bar{b}q)_{(S+P)} (\bar{q}d)_{(S-P)} \\
Q_{7,9} &= \frac{3}{2} (\bar{b}d)_{(V-A)} \sum_q e_q (\bar{q}q)_{(V\pm A)} \\
Q_8 &= -3 \sum_q e_q (\bar{b}q)_{(S+P)} (\bar{q}d)_{(S-P)} \\
Q_{10} &= \frac{3}{2} \sum_q e_q (\bar{b}q)_{(V-A)} (\bar{q}d)_{(V-A)}
\end{aligned}$$

The Wick Contractions

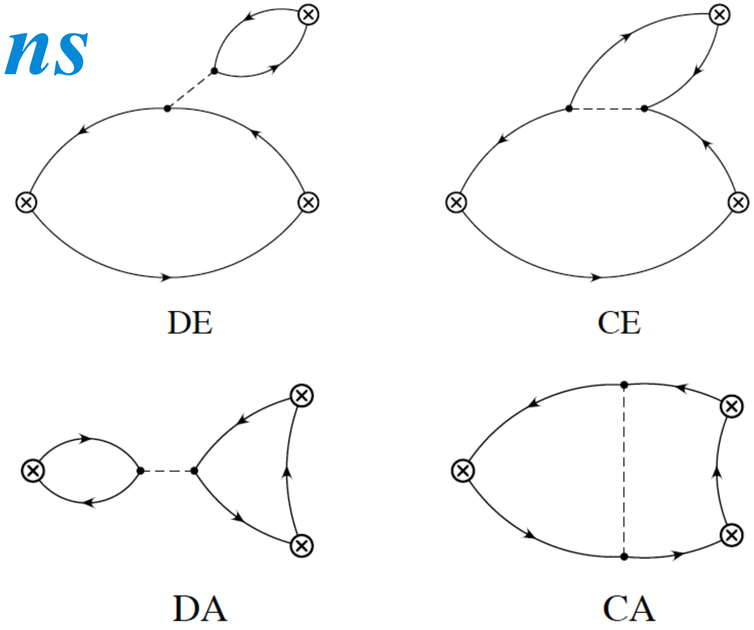


Figure 1: *Non-penguin diagrams. The dashed line represents the four-fermion operator.*

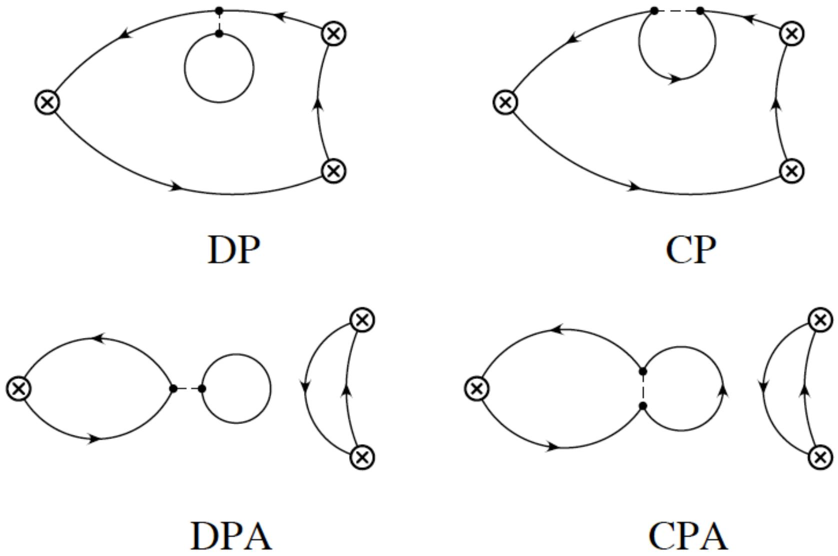


Figure 2: *Penguin diagrams.*

TABLES

Process	DE	$DE + CE$	$DE + CE+$ CA	$DE + CE+$ $CA + DE_{LR} + CE_{LR}$	$DE + CE+$ $DP + CP$	$DE + CE+$ $\overline{DP} + \overline{CP}$
$B_d^0 \to J/\psi K_S$	–	–	–	–	–	–
	-0.03	0.1	0.1	0.1	0.1	0.1
	-0.008	0.02	0.02	0.04	0.02	0.02
$B_d^0 \to \phi K_S$	–	–	–	–	–	–
	0.7	0.7	0.7	0.6	0.4	0.4
	0.2	0.2	0.2	0.1	0.1	0.09
$B_d^0 \to K_S \pi^0$	0.08	-0.06	-0.05	-0.02	-0.009	-0.01
	0.7	0.7	0.6	0.6	0.4	0.4
	0.2	0.2	0.2	0.1	0.1	0.09
$B_d^0 \to D_{CP}^0 \pi^0$	0.02	0.02	0.02	0.02	0.02	0.02
$B_d^0 \to \pi^0 \pi^0$	-0.6	0.9	-0.7	-2	6	4
	0.3	-0.07	0.4	-0.4	-0.07	-0.06
	0.06	-0.02	0.09	-0.1	-0.02	-0.02
$B_d^0 \to \pi^+ \pi^-$	-0.09	-0.1	-0.1	-0.3	-0.9	-0.8
	0.02	0.02	0.03	0.09	0.8	0.4
	0.005	0.006	0.008	0.02	0.2	0.1
$B_d^0 \to D^+ D^-$	0.03	0.04	0.05	0.1	0.3	0.2
	-0.007	-0.008	-0.01	-0.02	-0.02	-0.02
	-0.002	-0.002	-0.002	-0.005	-0.006	-0.005
$B_d^0 \to K^0 \bar{K}^0$	0	0	0	0	0	0.07
	-0.2	-0.2	-0.2	-0.2	-0.09	-0.08
	-0.06	-0.05	-0.05	-0.04	-0.02	-0.02
$B_d^0 \to K^+ K^-$	–	–	-0.2	-0.4	–	–
	–	–	0.04	0.1	–	–
	–	–	0.01	0.03	–	–
$B_d^0 \to D^0 \bar{D}^0$	–	–	–	–	–	–
	–	–	-0.01	-0.03	–	–
	–	–	-0.003	-0.006	–	–
$B_d^0 \to J/\psi \pi^0$	-0.04	0.1	0.1	0.3	0.1	0.1
	0.007	-0.02	-0.02	-0.03	-0.02	-0.02
	0.002	-0.005	-0.005	-0.008	-0.005	-0.005
$B_d^0 \to \phi \pi^0$	–	–	–	–	–	–
	-0.06	-0.1	-0.1	-0.1	-0.1	-0.1
	-0.01	-0.03	-0.03	-0.03	-0.03	-0.03

TABLE I. *Ratios of amplitudes for exclusive B decays. For each channel, whenever two terms with different CP phases contribute in the SM, we give the ratio r of the two amplitudes. For each channel, the second and third lines, where present, contain the ratios of SUSY to SM contributions for SUSY masses of 250 and 500 GeV respectively.*

Antonio came in with Susy: FCNC in the mass insertion approximation

i) SM predictions, however, are plagued by large uncertainties;
ii) A critical assessment of these uncertainties constitutes a major goal of this work;
iii) We discuss several possibilities of looking for signals of low-energy supersymmetry (SUSY) in CP violating B decays (in spite of i)).

As for the SUSY contribution we make use of the parameterization of the SUSY FCNC and CP quantities in the framework of the so-called mass insertion approximation [L.J. Hall, V.A. Kostelecky and S. Raby]

For the fermion and sfermion states, we choose a basis where all the couplings of these particles to neutral gauginos are flavour diagonal, while the FC arises from the non-diagonality of the sfermion propagators

$$\delta = \frac{\Delta}{m_{\tilde{q}}}$$

Where $m_{\tilde{q}}$ is an average sfermion mass and Δ denote off-diagonal terms in the sfermion mass matrices

Four different mass-insertions in the down-squark propagators give rise to b -> s or b -> d transitions:

$$\Delta_{LL}, \Delta_{RR}, \Delta_{LR}, \Delta_{RL}$$

Incl.	Excl.	$\phi^D_{\rm SM}$	$r_{\rm SM}$	$\phi^D_{\rm SUSY}$	r_{250}	r_{500}
$b \to c\bar{c}s$	$B \to J/\psi K_S$	0	–	ϕ_{23}	0.03 – 0.1	0.008 – 0.04
$b \to s\bar{s}s$	$B \to \phi K_S$	0	–	ϕ_{23}	0.4 – 0.7	0.09 – 0.2
$b \to u\bar{u}s$		Penguin 0				
	$B \to \pi^0 K_S$		0.009 – 0.08	ϕ_{23}	0.4 – 0.7	0.09 – 0.2
$b \to d\bar{d}s$		Tree γ				
$b \to c\bar{u}d$		0				
	$B \to D^0_{CP}\pi^0$		0.02	–	–	–
$b \to u\bar{c}d$		γ				
	$B \to D^+ D^-$	Tree 0	0.03 – 0.3		0.007 – 0.02	0.002 – 0.006
$b \to c\bar{c}d$				ϕ_{13}		
	$B \to J/\psi\pi^0$	Penguin β	0.04 – 0.3		0.007 – 0.03	0.002 – 0.008
	$B \to \phi\pi^0$	Penguin β	–		0.06 – 0.1	0.01 – 0.03
$b \to s\bar{s}d$				ϕ_{13}		
	$B \to K^0\bar{K}^0$	u-Penguin γ	0-0.07		0.08 – 0.2	0.02 – 0.06
$b \to u\bar{u}d$	$B \to \pi^+\pi^-$	Tree γ	0.09 – 0.9	ϕ_{13}	0.02 – 0.8	0.005 – 0.2
$b \to d\bar{d}d$	$B \to \pi^0\pi^0$	Penguin β	0.6 – 6	ϕ_{13}	0.06 – 0.4	0.02 – 0.1
	$B \to K^+K^-$	Tree γ	0.2 – 0.4		0.04 – 0.1	0.01 – 0.03
$b\bar{d} \to q\bar{q}$				ϕ_{13}		
	$B \to D^0\bar{D}^0$	Penguin β	only β		0.01 – 0.03	0.003 – 0.006

TABLE II. *CP phases for B decays.* ϕ^D_{SM} *denotes the decay phase in the SM; for each channel, when two amplitudes with different weak phases are present, one is given in the first row, the other in the last one and the ratio of the two in the* r_{SM} *column.* ϕ^D_{SUSY} *denotes the phase of the SUSY amplitude, and the ratio of the SUSY to SM contributions is given in the* r_{250} *and* r_{500} *columns for the corresponding SUSY masses.*

PAST: Susy Around the Corner II

ΔM_K and ε_K in SUSY at the Next-to-Leading order

The Hamiltonian

$$\mathcal{H}_{\rm eff}^{\Delta S=2} = \sum_{i=1}^{5} C_i\, Q_i + \sum_{i=1}^{3} \tilde{C}_i\, \tilde{Q}_i \qquad (2.2)$$

where

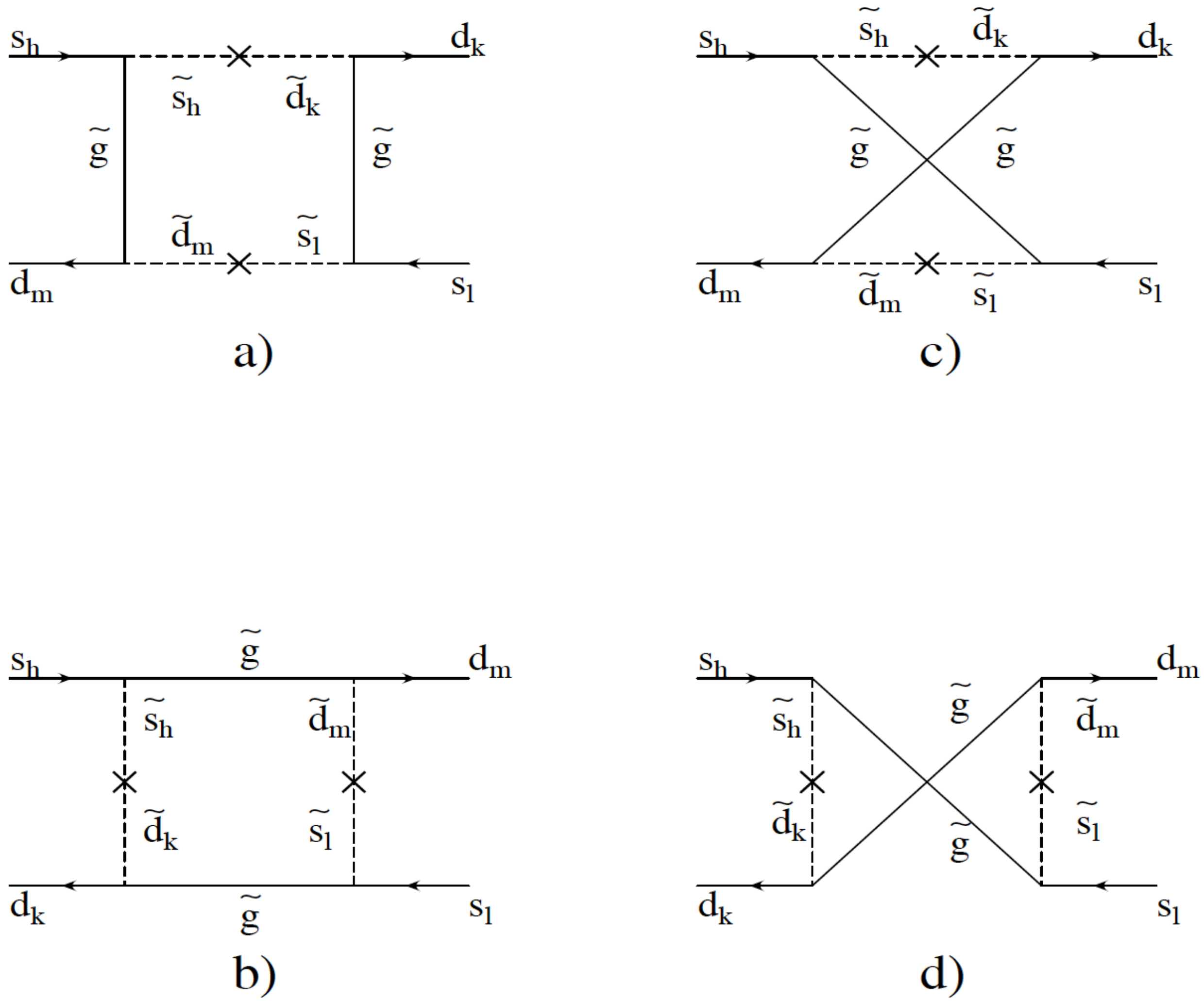
$$\begin{aligned} Q_1 &= \bar{d}_L^\alpha \gamma_\mu s_L^\alpha \bar{d}_L^\beta \gamma^\mu s_L^\beta \, , \\ Q_2 &= \bar{d}_R^\alpha s_L^\alpha \bar{d}_R^\beta s_L^\beta \, , \\ Q_3 &= \bar{d}_R^\alpha s_L^\beta \bar{d}_R^\beta s_L^\alpha \, , \\ Q_4 &= \bar{d}_R^\alpha s_L^\alpha \bar{d}_L^\beta s_R^\beta \, , \\ Q_5 &= \bar{d}_R^\alpha s_L^\beta \bar{d}_L^\beta s_R^\alpha \, , \end{aligned} \qquad (2.3)$$

LO QCD corrections
Important
Bagger et al.

and the operators $\tilde{Q}_{1,2,3}$ are obtained from the $Q_{1,2,3}$ by the exchange $L \leftrightarrow R$. Here $q_{R,L} = P_{R,L}\, q$, with $P_{R,L} = (1 \pm \gamma_5)/2$, and α and β are colour indices.

Novelties:
Wilson coefficients computed at the NLO
Lattice matrix elements of extra operators

Feynman Diagrams in the mass-insertion approximation



Results

	NO QCD, VIA	LO, VIA	LO, Lattice B_i	NLO, Lattice B_i
x	$\sqrt{\lvert \mathrm{Re}(\delta^d_{12})^2_{LL} \rvert}$			
0.3	5.0×10^{-3}	5.7×10^{-3}	7.7×10^{-3}	7.7×10^{-3}
1.0	1.1×10^{-2}	1.2×10^{-2}	1.6×10^{-2}	1.6×10^{-2}
4.0	2.5×10^{-2}	2.9×10^{-2}	3.9×10^{-2}	3.9×10^{-2}
x	$\sqrt{\lvert \mathrm{Re}(\delta^d_{12})^2_{LR} \rvert}$ $(\lvert(\delta^d_{12})_{LR}\rvert \gg \lvert(\delta^d_{12})_{RL}\rvert)$			
0.3	1.1×10^{-3}	8.4×10^{-4}	1.1×10^{-3}	9.6×10^{-4}
1.0	1.2×10^{-3}	9.3×10^{-4}	1.2×10^{-3}	1.1×10^{-3}
4.0	1.8×10^{-3}	1.3×10^{-3}	1.6×10^{-3}	1.5×10^{-3}
x	$\sqrt{\lvert \mathrm{Re}(\delta^d_{12})^2_{LR} \rvert}$ $((\delta^d_{12})_{LR} = (\delta^d_{12})_{RL})$			
0.3	2.0×10^{-3}	1.4×10^{-3}	8.9×10^{-4}	6.7×10^{-4}
1.0	1.1×10^{-3}	9.7×10^{-4}	1.8×10^{-3}	3.0×10^{-3}
4.0	1.3×10^{-3}	1.0×10^{-3}	1.4×10^{-3}	1.3×10^{-3}
x	$\sqrt{\lvert \mathrm{Re}(\delta^d_{12})_{LL}(\delta^d_{12})_{RR} \rvert}$			
0.3	6.4×10^{-4}	3.9×10^{-4}	4.0×10^{-4}	3.3×10^{-4}
1.0	7.1×10^{-4}	4.4×10^{-4}	4.5×10^{-4}	3.7×10^{-4}
4.0	1.0×10^{-3}	6.1×10^{-4}	6.2×10^{-4}	5.2×10^{-4}

Table 2: Limits on $\mathrm{Re}\,(\delta_{ij})_{AB}\,(\delta_{ij})_{CD}$, with $A, B, C, D = (L, R)$, for an average squark mass $m_{\tilde{q}} = 200$ GeV and for different values of $x = m^2_{\tilde{g}}/m^2_{\tilde{q}}$.

Turning to pop-art

Two Body non-leptonic decays in the SM and Beyond (Moriond 2004)

Due to new graphics facilities
 at the beginning of the new millennium

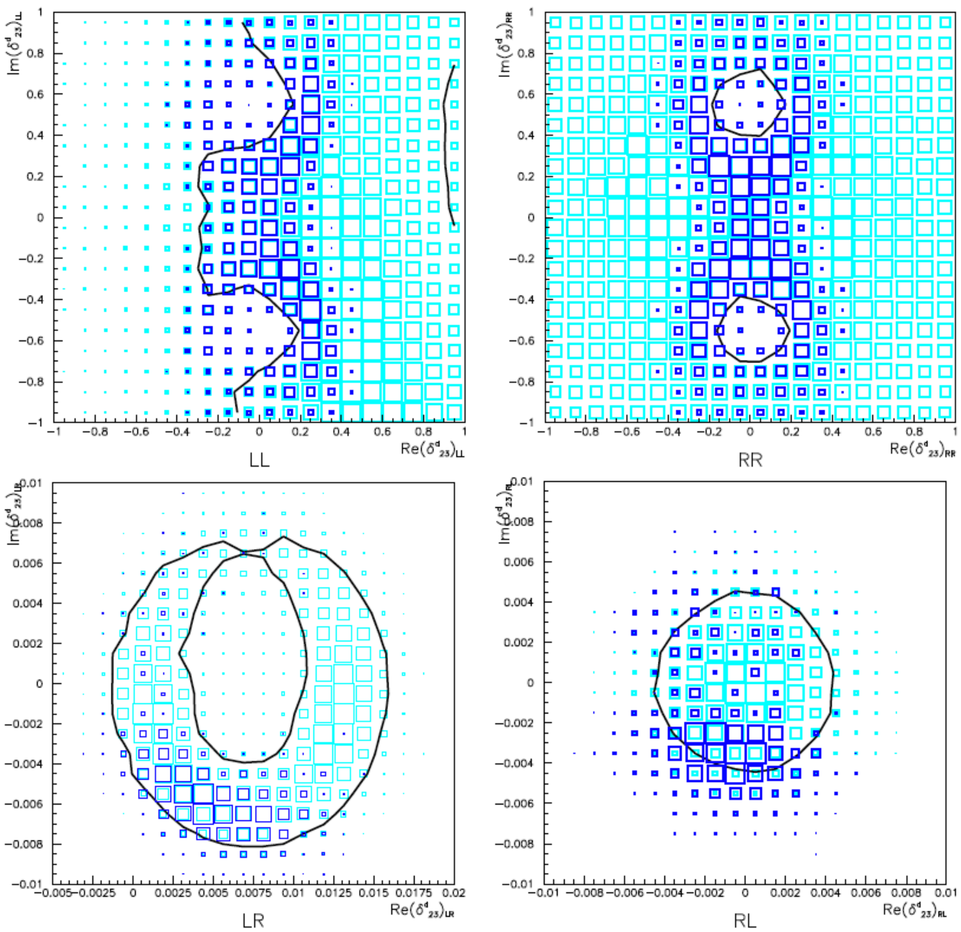


Figure 2: Allowed regions in the $\mathrm{Re}(\delta^d_{23})_{AB}$–$\mathrm{Im}(\delta^d_{23})_{AB}$ space for $AB = (LL, RR, LR, RL)$. The black line contains 68% of the weighted events. The darker regions are selected imposing $\Delta m_s < 20\ \mathrm{ps}^{-1}$ for LL and RR insertions and $S_{\phi K} < 0$ for LR and RL insertions.

Turning to pop-art

$B_d - \bar{B}_d$ mixing and the $B_d \to J/\psi K_s$ asymmetry in general SUSY models

D Becirevic, M Ciuchini,
E Franco, V. Gimenez,
G Martinelli, A Masiero,
M Papinutto, J Reyes and
L Silvestrini

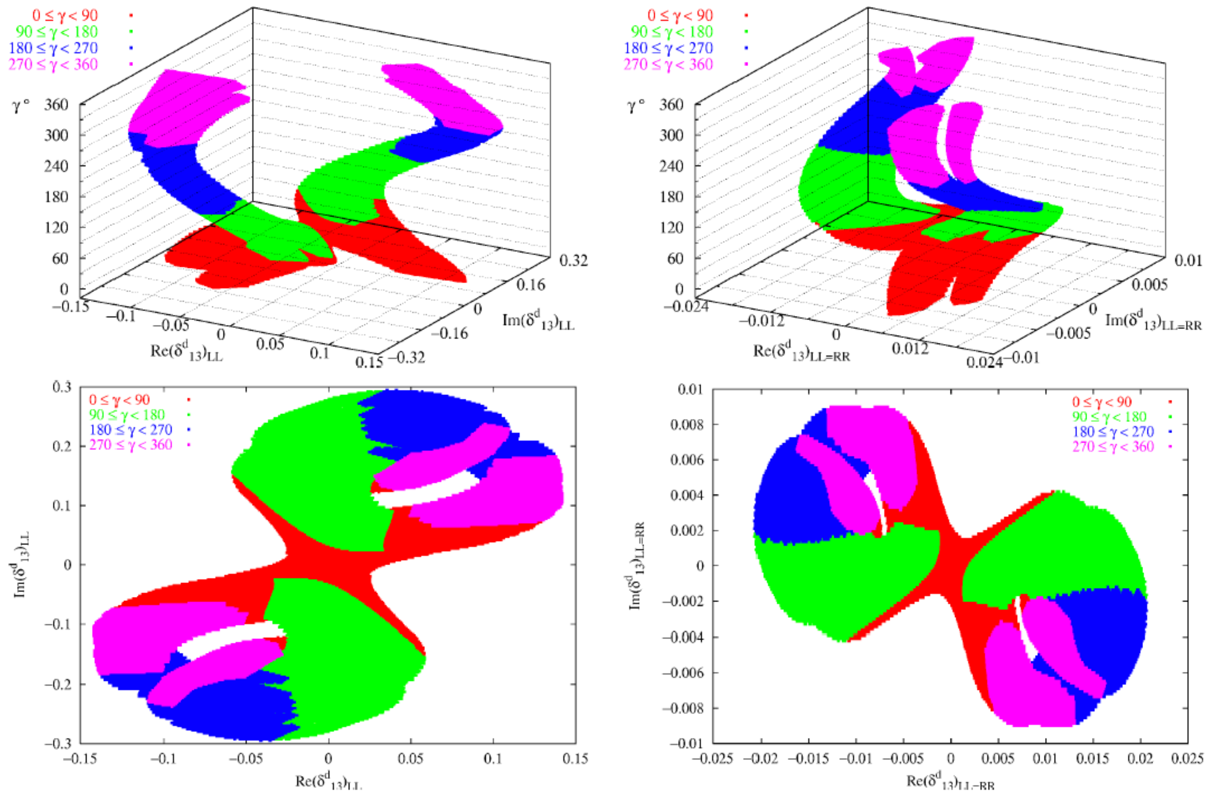


Figure 2: *Allowed regions in the* $(\gamma,\ Re(\delta^d_{13})_{LL},\ Im(\delta^d_{13})_{LL})$ *space with* $(\delta^d_{13})_{LL}$ *only (left) and* $(\delta^d_{13})_{LL} = (\delta^d_{13})_{RR}$ *(right). The two lower plots are the corresponding projections in the* $Re(\delta^d_{13})_{LL}$–$Im(\delta^d_{13})_{LL}$ *plane. Different colours denote values of* γ *belonging to different quadrants.*

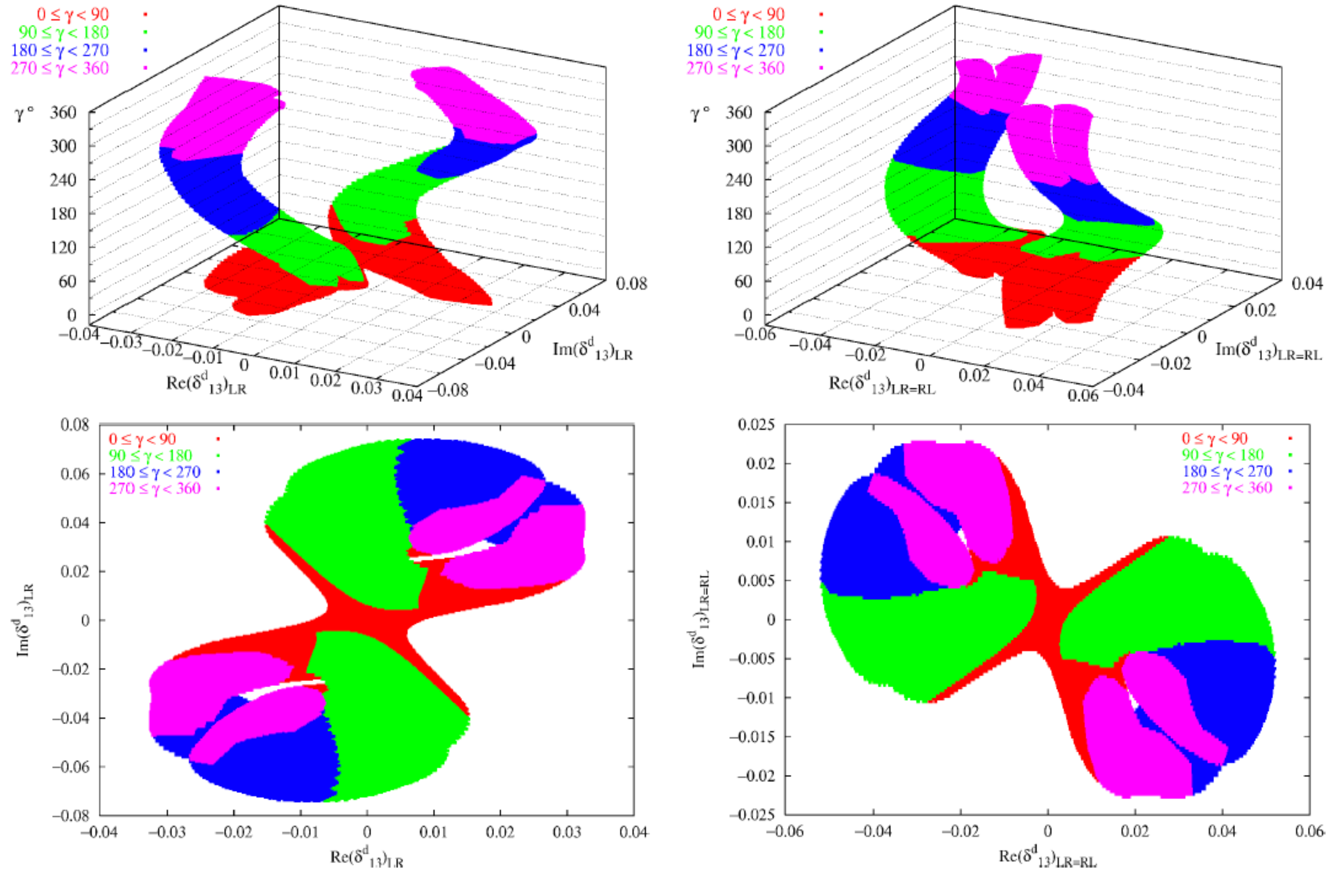


Figure 3: *Allowed regions in the* (γ, $\mathrm{Re}(\delta^d_{13})_{LR}$, $\mathrm{Im}(\delta^d_{13})_{LR}$) *space with* $(\delta^d_{13})_{LR}$ *only (left) and* $(\delta^d_{13})_{LR} = (\delta^d_{13})_{RL}$ *(right). The two lower plots are the corresponding projections in the* $\mathrm{Re}(\delta^d_{13})_{LR}$–$\mathrm{Im}(\delta^d_{13})_{LR}$ *plane. Different colours denote values of* γ *belonging to different quadrants.*

	$\lvert\mathrm{Re}(\delta^d_{13})_{LL}\rvert$			$\lvert\mathrm{Re}(\delta^d_{13})_{LL=RR}\rvert$		
x	TREE	LO	NLO	TREE	LO	NLO
0.25	4.9×10^{-2}	5.4×10^{-2}	6.2×10^{-2}	3.1×10^{-2}	2.0×10^{-2}	1.9×10^{-2}
1.0	1.1×10^{-1}	1.2×10^{-1}	1.4×10^{-1}	3.4×10^{-2}	2.2×10^{-2}	2.1×10^{-2}
4.0	6.0×10^{-1}	6.7×10^{-1}	7.0×10^{-1}	4.7×10^{-2}	3.0×10^{-2}	2.8×10^{-2}
	$\lvert\mathrm{Im}(\delta^d_{13})_{LL}\rvert$			$\lvert\mathrm{Im}(\delta^d_{13})_{LL=RR}\rvert$		
x	TREE	LO	NLO	TREE	LO	NLO
0.25	1.1×10^{-1}	1.2×10^{-1}	1.3×10^{-1}	1.3×10^{-2}	8.0×10^{-3}	8.0×10^{-3}
1.0	2.6×10^{-1}	2.8×10^{-1}	3.0×10^{-1}	1.5×10^{-2}	9.0×10^{-3}	9.0×10^{-3}
4.0	2.6×10^{-1}	2.9×10^{-1}	3.4×10^{-1}	2.0×10^{-2}	1.3×10^{-2}	1.2×10^{-2}
	$\lvert\mathrm{Re}(\delta^d_{13})_{LR}\rvert$			$\lvert\mathrm{Re}(\delta^d_{13})_{LR=RL}\rvert$		
x	TREE	LO	NLO	TREE	LO	NLO
0.25	3.4×10^{-2}	2.7×10^{-2}	3.0×10^{-2}	3.8×10^{-2}	2.7×10^{-2}	2.6×10^{-2}
1.0	3.9×10^{-2}	3.0×10^{-2}	3.3×10^{-2}	8.3×10^{-2}	5.4×10^{-2}	5.2×10^{-2}
4.0	5.3×10^{-2}	4.1×10^{-2}	4.5×10^{-2}	1.2×10^{-1}	2.5×10^{-1}	–
	$\lvert\mathrm{Im}(\delta^d_{13})_{LR}\rvert$			$\lvert\mathrm{Im}(\delta^d_{13})_{LR=RL}\rvert$		
x	TREE	LO	NLO	TREE	LO	NLO
0.25	7.6×10^{-2}	6.0×10^{-2}	6.6×10^{-2}	1.5×10^{-2}	9.0×10^{-3}	9.0×10^{-3}
1.0	8.7×10^{-2}	6.6×10^{-2}	7.4×10^{-2}	3.6×10^{-2}	2.4×10^{-2}	2.3×10^{-2}
4.0	1.2×10^{-1}	9.2×10^{-2}	1.0×10^{-1}	2.7×10^{-1}	5.7×10^{-1}	–

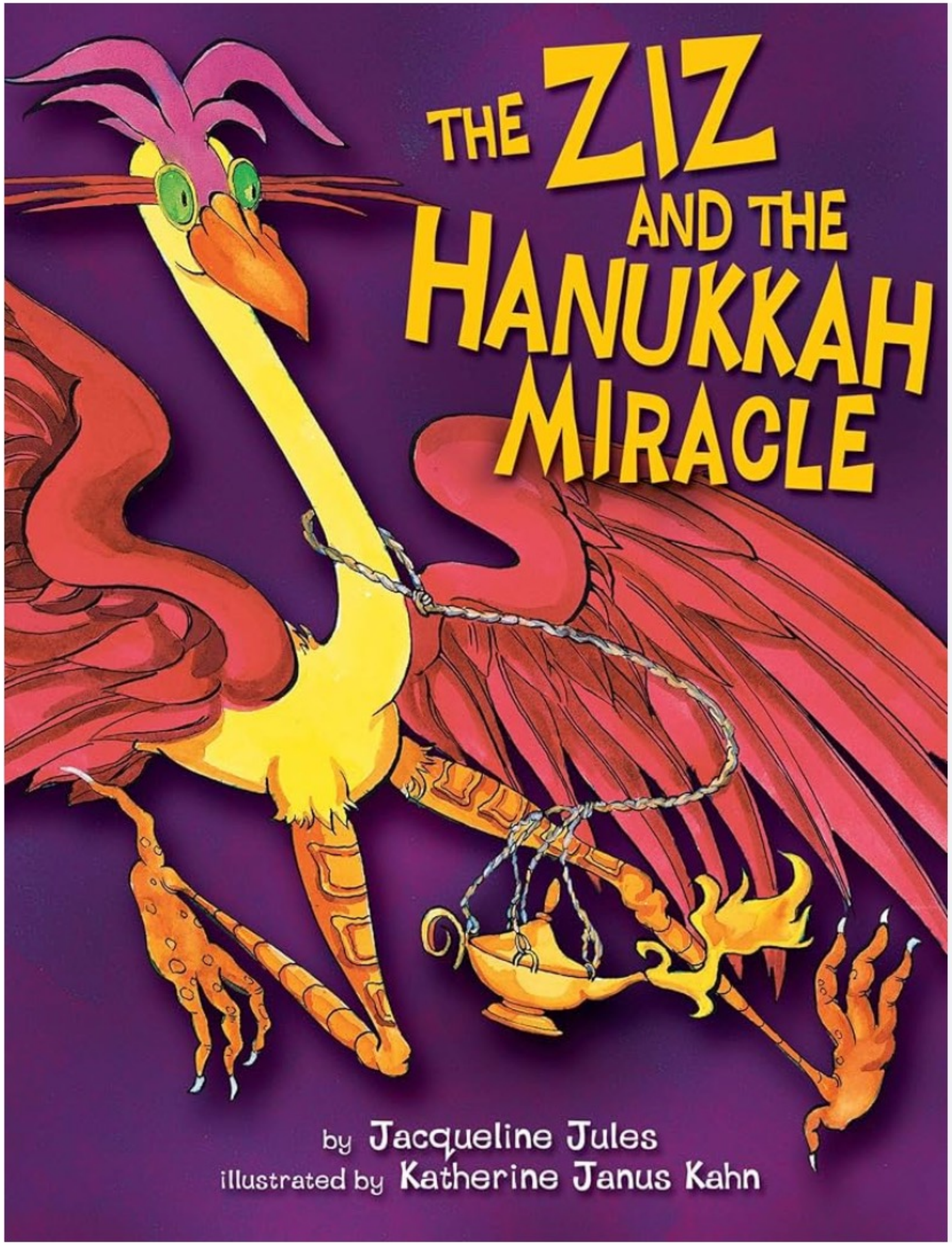
Table 2: *Maximum allowed values for* $\lvert Re\left(\delta^d_{ij}\right)_{AB}\rvert$ *and* $\lvert Im\left(\delta^d_{ij}\right)_{AB}\rvert$, *with* $A, B = (L, R)$, *for an average squark mass* $m_{\tilde{q}} = 500$ *GeV and for different values of* $x = m^2_{\tilde{g}}/m^2_{\tilde{q}}$. *We give the results in the following cases: i) with the tree level Wilson coefficients, namely without evolution from* M_S *to* m_b, *and VIA B parameters, denoted by TREE; ii) with LO evolution and VIA B parameters, denoted by LO; iii) with NLO evolution and lattice B parameters, denoted by NLO. The missing entries correspond to cases in which no constraint was found for* $\lvert\left(\delta^d_{ij}\right)_{AB}\rvert < 0.9$.

The coq-au-vin and beyond

We turned to new ideas/models for flavor physics

The ZIZ model:

Ziz in the mitology denotes a geant bird, like a gryphon, the most extraordinary creature of the sky



We were working very hard ...

Le modèle ZIZ (simplifié)

I proceed in the following way.
I write the up-quark mass matrix as

$$\begin{pmatrix} 0 & A\,au\,e3 & 0 \\ -A\,au\,e3 & e2\,S22\,su & e1\,(au\,ra23 + rs23\,su) \\ 0 & e1\,(-au\,ra23 + rs23\,su) & su \end{pmatrix}$$

and the down-quark mass matrix as

$$\begin{pmatrix} 0 & A\,ad\,e3 & 0 \\ -A\,ad\,e3 & e2\,S22\,sd & e1\,(ad\,ra23 + rs23\,sd) \\ 0 & e1\,(-ad\,ra23 + rs23\,sd) & sd \end{pmatrix}$$

I suppose that e1 ≳ e2 ≫ e3, with eventually e1^2 ~ e2.
Then I diagonalize at the second order in e3 and e1, and at the first order in e2. I drop the second order terms wherever possible (for example, I drop e1^2 corrections to m_top).
The diagonalization is done in three steps:
i) I diagonalize the (2,3) submatrix, using unitary matrices with one phase only. This means that the eigenvalues are still complex. For the moment I ignore these phases, I will fix them at the end of the game. The diagonalization is done at order e1^2 (where necessary).
ii) After the (2,3) rotation, I diagonalize the new (1,2) submatrix, with the same procedure as above. The diagonalization is done at order e3^2 (where necessary).
iii) After the (1,2) rotation, I diagonalize the new (1,3) submatrix, as done above.
iv) At this point I have the mass matrices in the diagonal form. Now I can impose that the eigenvalues are equal to the physical masses (I still have to remove the phases, but for the moment I don't care), and so I can fix six parameters out of eight.
v) The 3x3 quark rotation matrices are built by multiplying the three submatrices, and then expanding. Here I still have to work on the analytic expression.

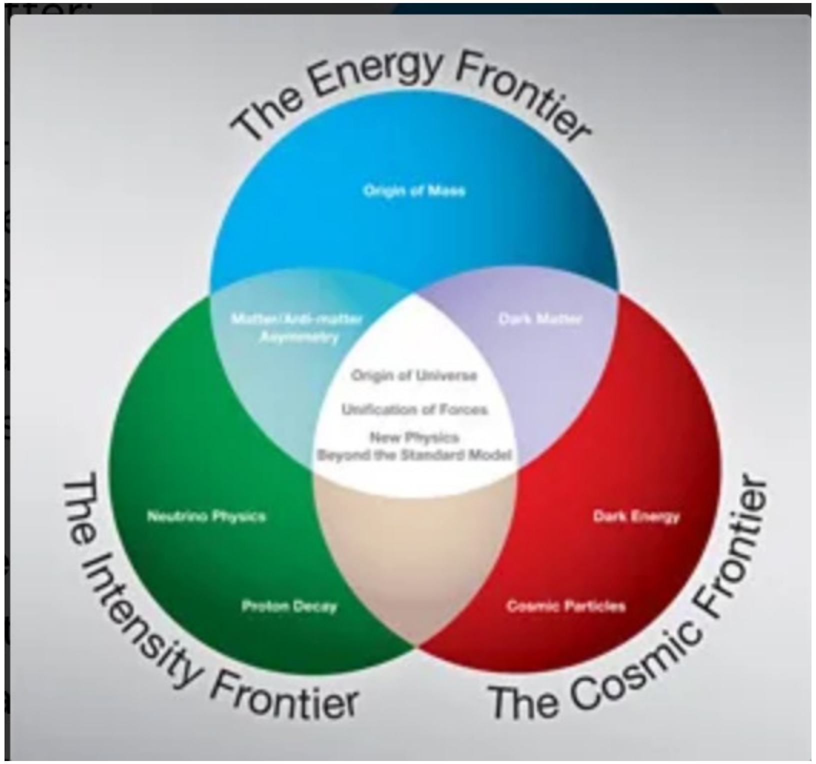
... even on Sunday ...

The coq-au-vin and beyond, namely from a gryphon to a chicken

The ZIZ model was plagued by too large FCNC effects incompatible with experimental findings

In spite of this accident our collaboration continued DaMESyFla

Together with R Contino, A Masiero, A Romanino, L Silvestrini, F Zwirner we got an ERC grant that allowed us to have exceptional post docs for 5 years



Modern times: Flavor in the Standard Model

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

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

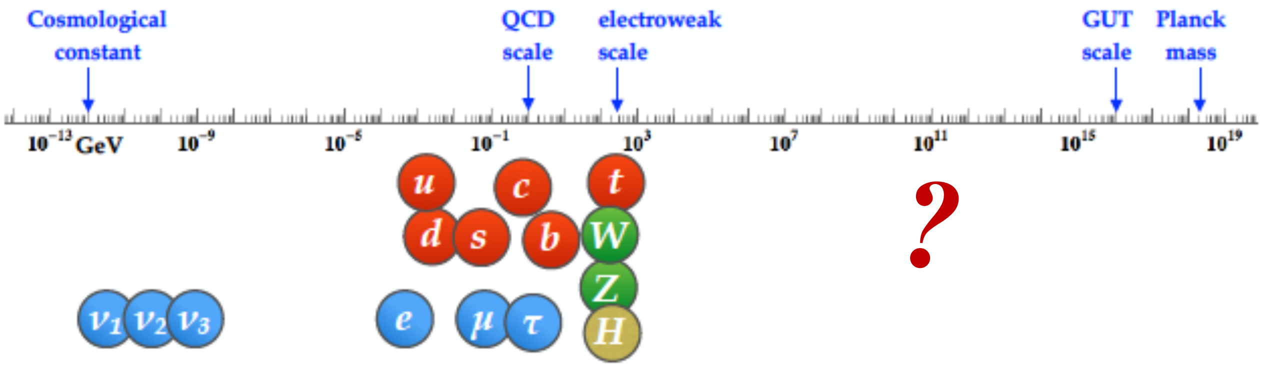
Neutrino Masses

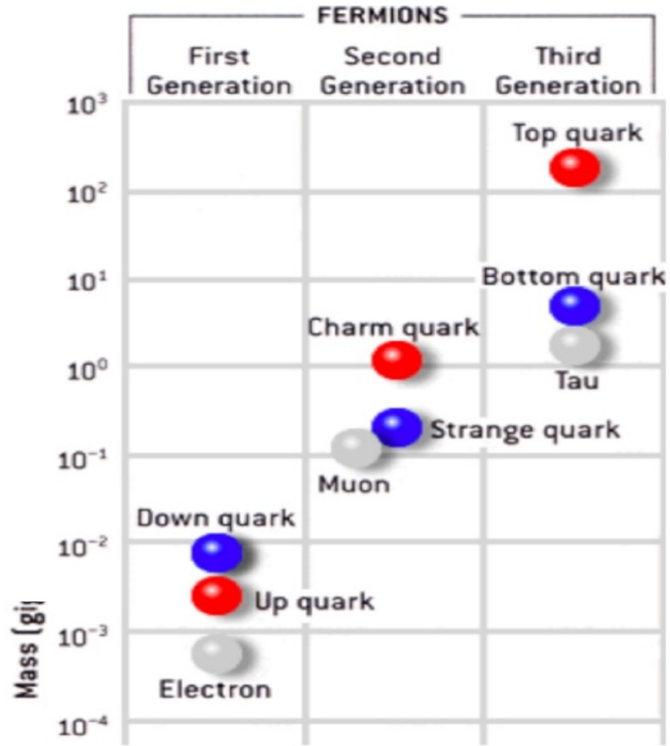
New Physics
Possible breaking of accidental symmetries

Only circled terms discussed in this talk

Zupan

J. Zupan





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

Illustration from a G. Isidori talk

Quark Masses from Lattice QCD

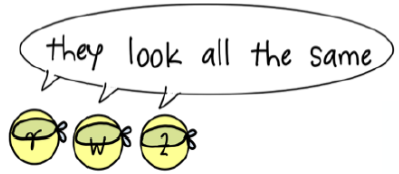
Input	Lattice/Exp
$m_u^{\overline{\rm MS}}(2\,{\rm GeV})$	2.20(9) MeV
$m_d^{\overline{\rm MS}}(2\,{\rm GeV})$	4.69(2) MeV
$m_s^{\overline{\rm MS}}(2\,{\rm GeV})$	93.14(58) MeV
$m_c^{\overline{\rm MS}}(3\,{\rm GeV})$	993(4) MeV
$m_c^{\overline{\rm MS}}(m_c^{\overline{\rm MS}})$	1277(5) MeV
$m_b^{\overline{\rm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

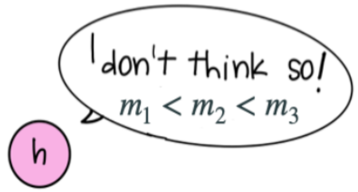
$$\mathcal{G}_F(\text{SM}) = U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$



The Higgs introduces the only known non-gauge couplings

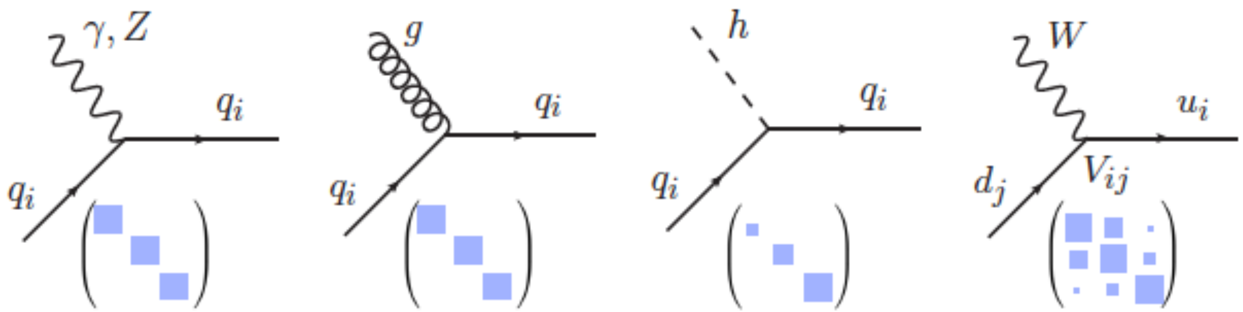
Turn on Yukawas

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



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

Higgs couplings are not flavor blind



courtesy of B.A. Stefanek

See talk by R. Barbieri

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

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

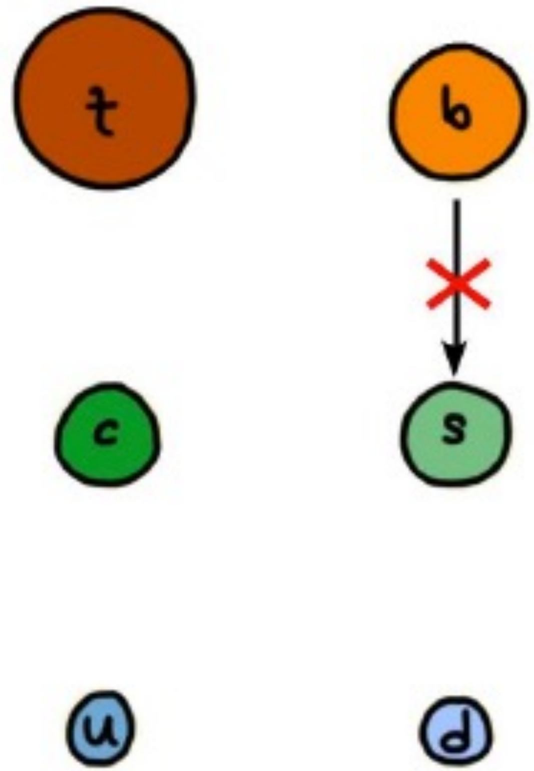
$$J_{\mu}^{Z} = 2J_{\mu}^{3} - 2\sin^2\theta_W J_{\mu}^{em}$$

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

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

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

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?

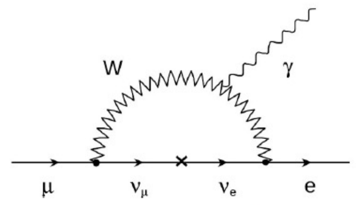
WHY RARE DECAYS ?

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

$q_i \to q_k + \nu \bar{\nu}$

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

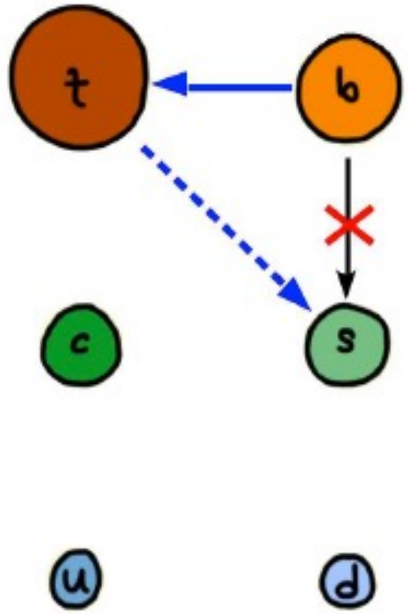
$q_i \to q_k + \gamma$

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

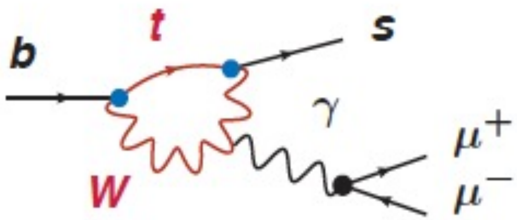
THUS THEY ARE SENSITIVE TO NEW PHYSICS

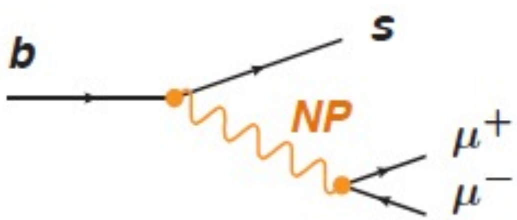
Flavor Changing Neutral Currents in the SM

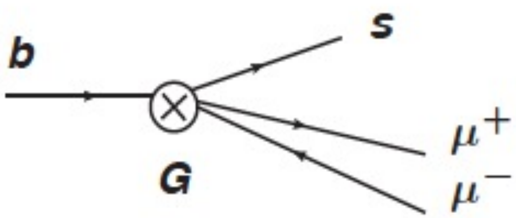
In the SM, flavor changing neutral currents (FCNCs) are absent at the tree level



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



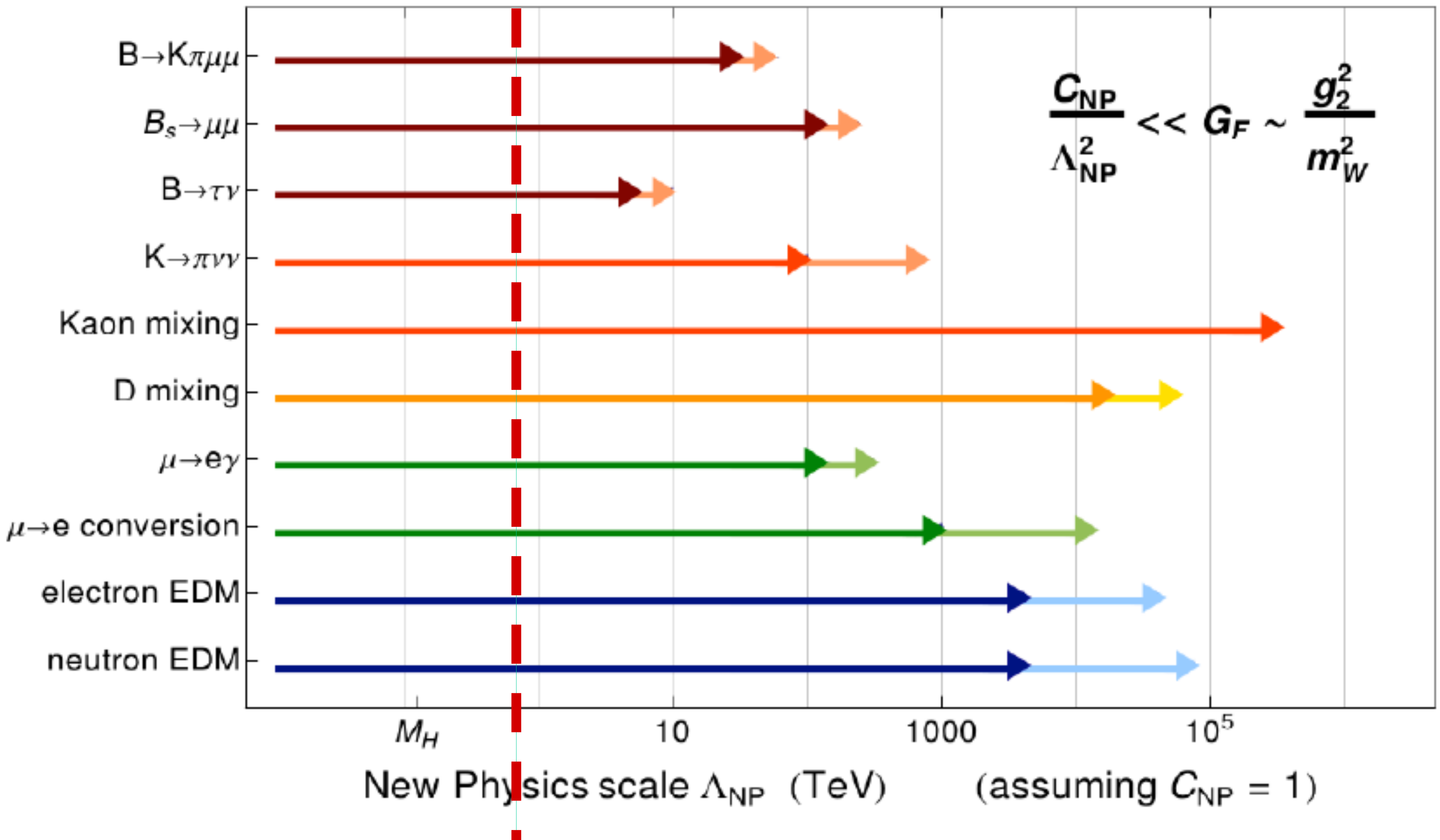




$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2}$$

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

Sensitivity to New Physics from Flavor I



Approximate LHC direct reach

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

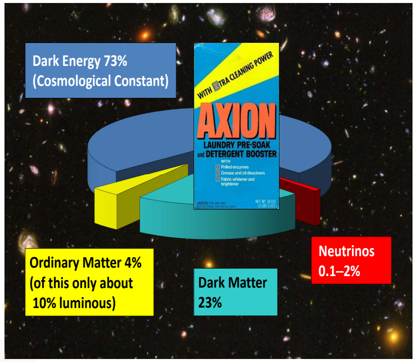
$$\mathcal{L}_\theta = \theta\, G^{\mu\nu a}\, \tilde{G}^a{}_{\mu\nu} \qquad \tilde{G}^a{}_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma}\, G^a{}_{\rho\sigma}$$

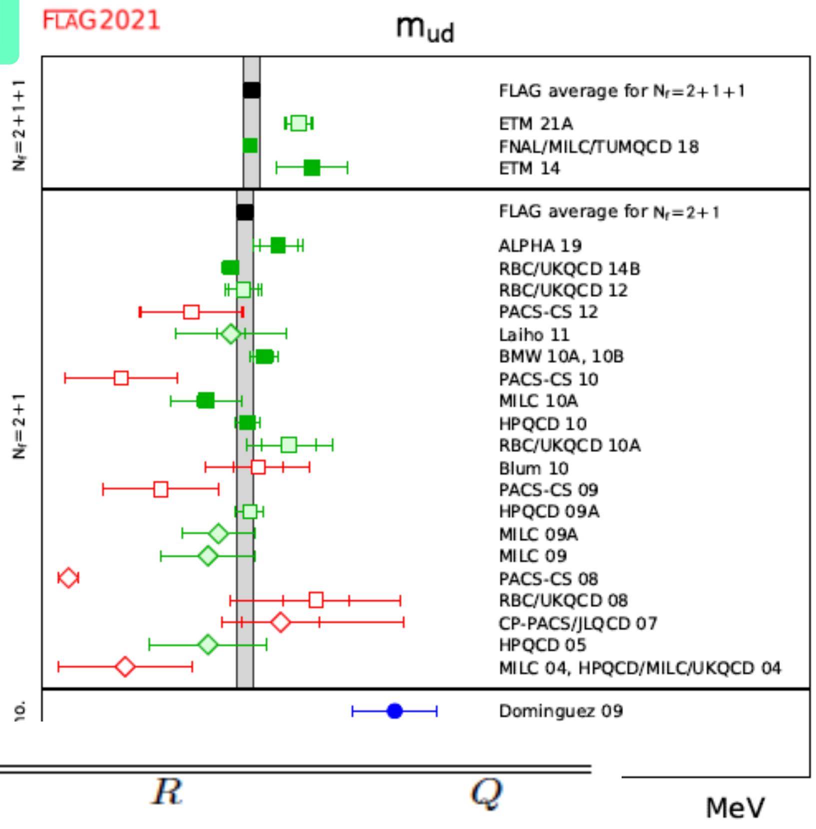
$$L_\theta \sim \theta\ \vec{E}^a \cdot \vec{B}^a$$

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

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

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



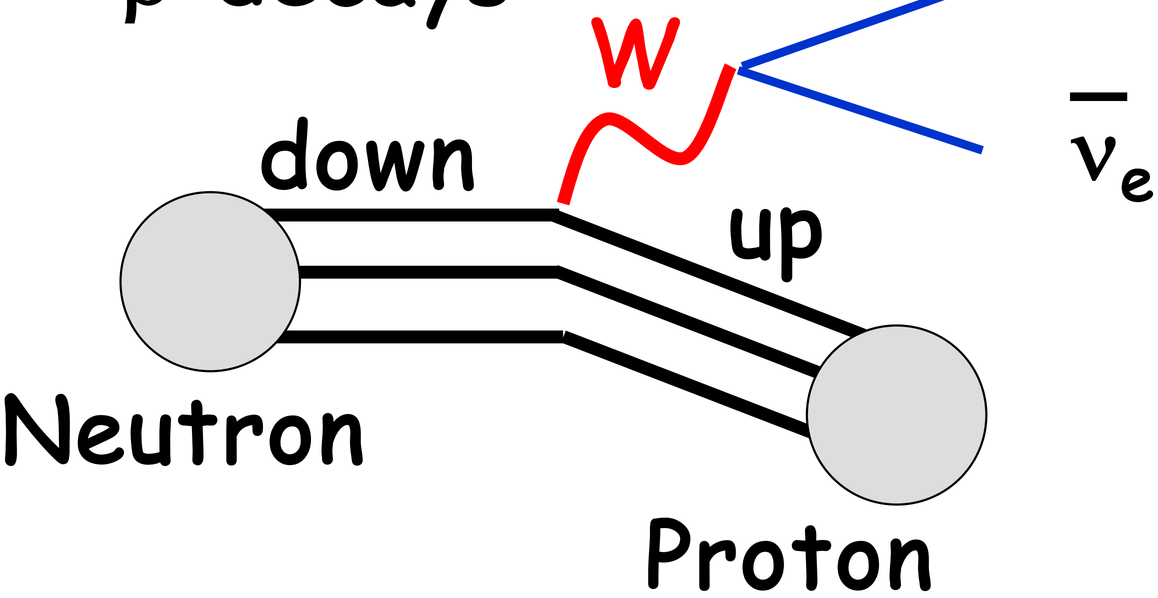


N_f	m_u	m_d	m_u/m_d	R	Q
2+1+1	2.14(8)	4.70(5)	0.465(24)	35.9(1.7)	22.5(0.5)
2+1	2.27(9)	4.67(9)	0.485(19)	38.1(1.5)	23.3(0.5)

Quark masses & Generation Mixing

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

β-decays



$|V_{ud}| = 0.9735(8)$
$|V_{us}| = 0.2196(23)$
$|V_{cd}| = 0.224(16)$
$|V_{cs}| = 0.970(9)(70)$
$|V_{cb}| = 0.0406(8)$
$|V_{ub}| = 0.00409(25)$
$|V_{tb}| = 0.99(29)$
(0.999)

$|V_{ud}|$

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

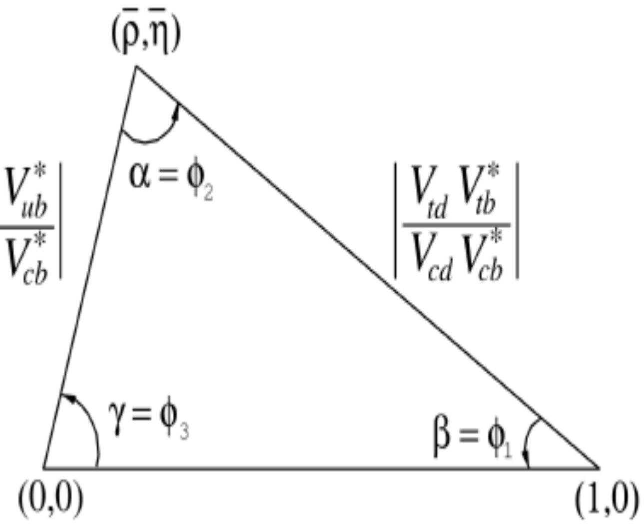
$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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



$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$ $\left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$

- By determining th

CKM matrix

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

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

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

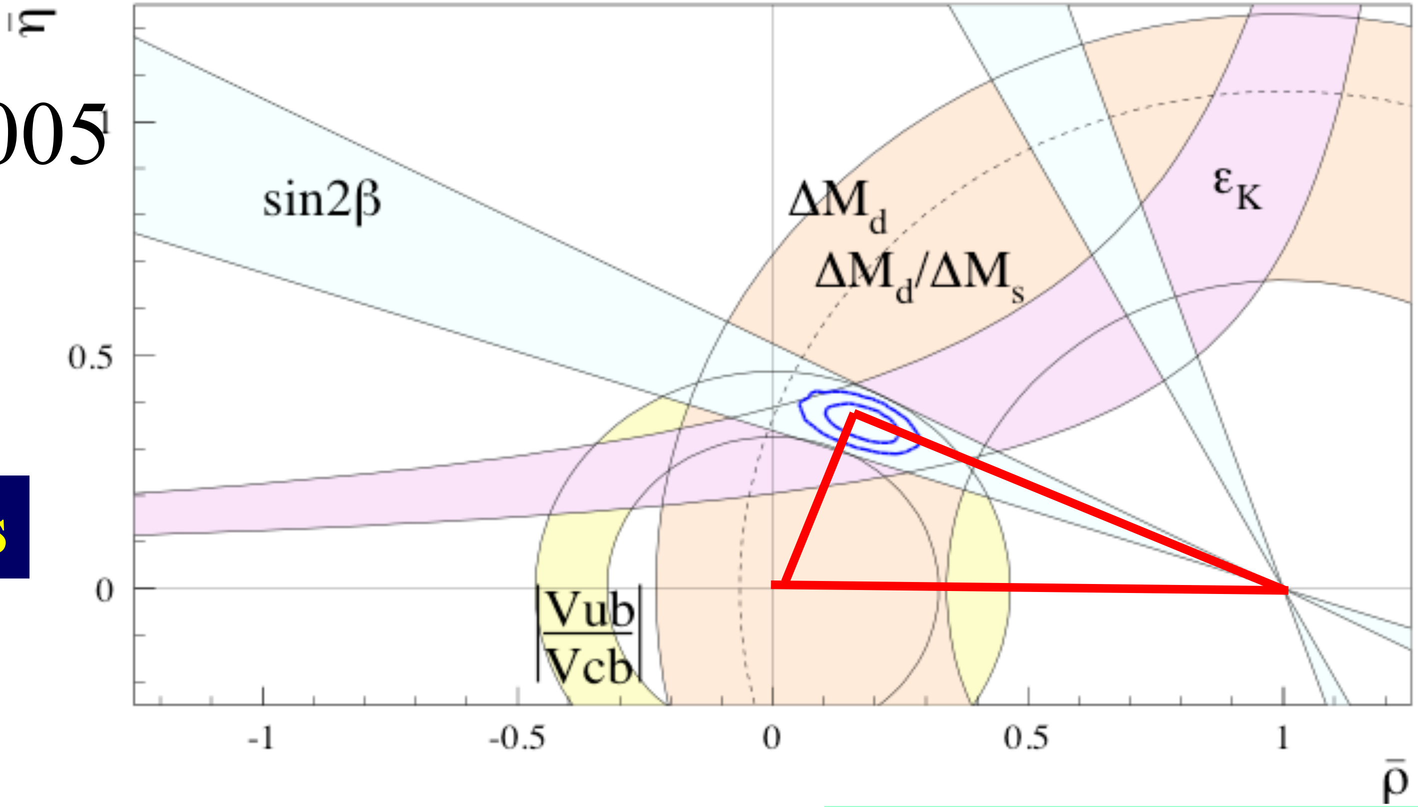
$$\delta_{13} = \gamma = \phi_3$$

CERN

UTfit

Unitary Triangle SM

2005



semileptonic decays

Experimental co

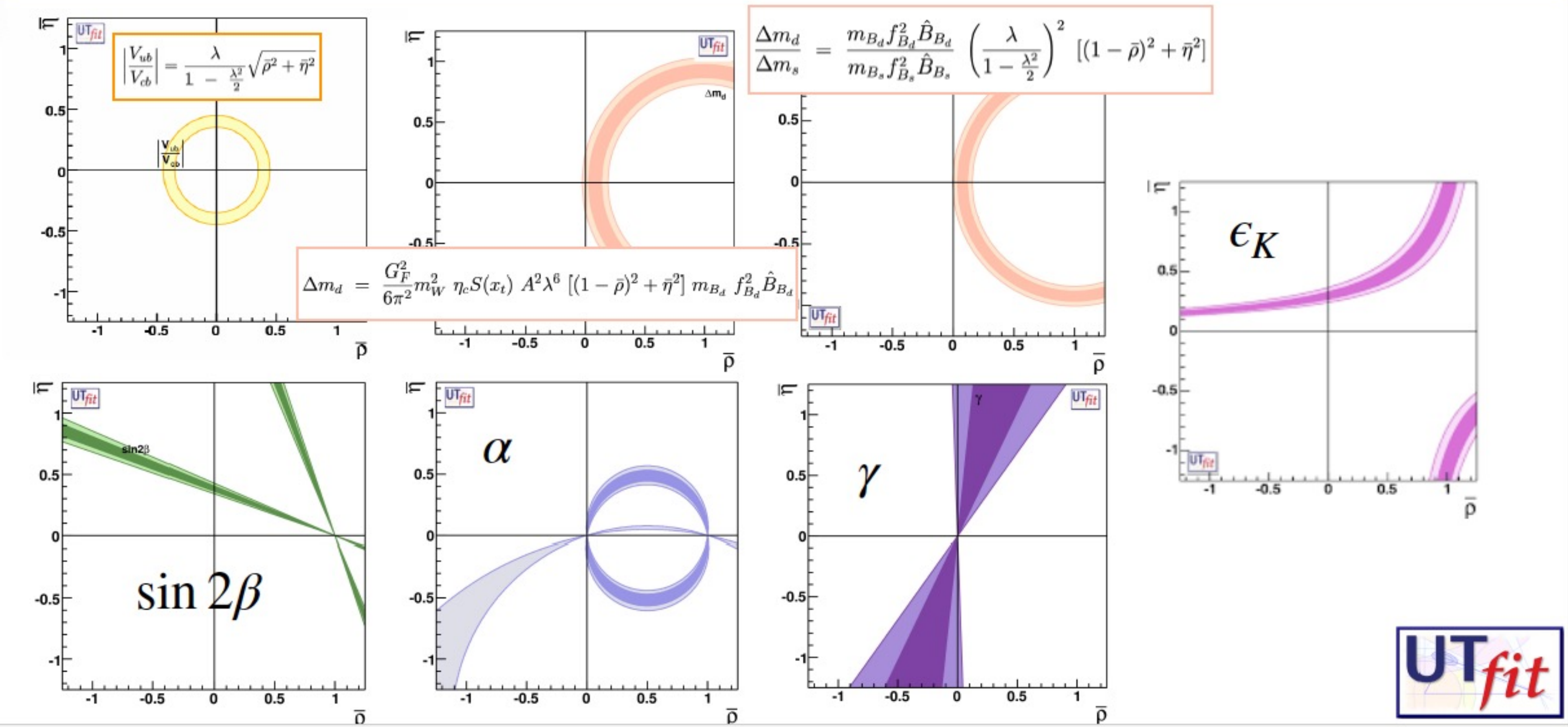
Meas.	$V_{CKM}\times$other	$(\bar{\rho},\bar{\eta})$
$\frac{b\to u}{b\to c}$	$\|V_{ub}/V_{cb}\|^2$	$\bar{\rho}^2+\bar{\eta}^2$
Δm_d	$\|V_{td}\|^2 f_{B_d}^2 B_{B_d}$	$(1-\bar{\rho})^2+\bar{\eta}^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\left\|\frac{V_{td}}{V_{ts}}\right\|^2 \xi^2$	$(1-\bar{\rho})^2+\bar{\eta}^2$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

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

UT constraints



<u>redundancy</u> 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

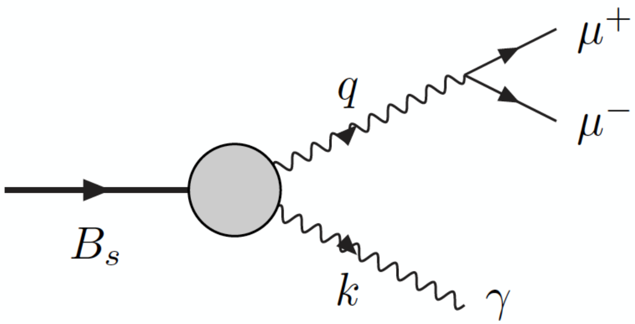
What can be computed and
What cannot be computed

small q^2 in the future

The $B_s \to \mu^+\mu^-\gamma$ Decay Rate at Large q^2

R.Frezzotti, **G.Gagliardi,** V.Lubicz, G.Martinelli, CTS, F.Sanfilippo, S.Simula, N.Tantalo, arXiv:2402.03262

- I use this interesting FCNC process to illustrate the elements which we are able to compute and to highlight the important theoretical issues which we are still working to resolve.
  - Preview: We can compute the dominant contribution, but are working to solve the problems which will enable an improved precision.



$x_\gamma = \frac{2E_\gamma}{m_{B_s}}$, E_γ is the energy of the real photon in rest frame of the B_s meson.

$$q^2 = m_{B_s}^2(1 - x_\gamma), \qquad 0 \le x_\gamma \le 1 - \frac{4m_\mu^2}{m_{B_s}^2}$$

- LHCb: $B(B_s \to \mu^+\mu^-\gamma)\,|_{\sqrt{q^2}>4.9\,\mathrm{GeV}} < 2.0 \times 10^{-9}$, arXiv:2108.09283/4

Courtesy of C.T. Sachrajda

The Effective b → s Hamiltonian

Charming penguins diagrams

$$\mathcal{H}_{\text{eff}}^{b\to s} = 2\sqrt{2}G_F V_{tb}V_{ts}^* \left[\sum_{i=1,2} C_i O_i^c + \sum_{i=3}^{6} C_i O_i + \frac{\alpha_{\text{em}}}{4\pi} \sum_{i=7}^{10} C_i O_i \right]$$

$$O_1^c = (\bar{s}_i \gamma^\mu P_L c_j)\,(\bar{c}_j \gamma_\mu P_L b_i) \qquad O_2^c = (\bar{s}\gamma^\mu P_L c)\,(\bar{c}\gamma_\mu P_L b)$$

$$\left(P_{L,R} = \frac{1}{2}(1 \mp \gamma^5) \right)$$

O_{3-6} are QCD Penguins with small Wilson Coefficients

Local form factors

$$O_7 = -\frac{m_b}{e}(\bar{s}\sigma^{\mu\nu} F_{\mu\nu} P_R b) \qquad O_8 = -\frac{g_s m_b}{4\pi\alpha_{\text{em}}}(\bar{s}\sigma^{\mu\nu} G_{\mu\nu} P_R b)$$

$F_{\mu\nu}$ and $G_{\mu\nu}$ are the QED and QCD Field Strength Tensors

$$O_9 = (\bar{s}\gamma^\mu P_L b)\,(\bar{\mu}\gamma_\mu \mu) \qquad O_{10} = (\bar{s}\gamma^\mu P_L b)\,(\bar{\mu}\gamma_\mu \gamma^5 \mu)$$

The amplitude is given by: $\mathcal{A} = \langle \gamma(k,\epsilon)\,\mu^+(p_1)\,\mu^-(p_2)\,|\, -\mathcal{H}_{\text{eff}}^{b\to s}\,|\, B_s(p)\,\rangle_{\text{QCD+QED}}$

$$= -e\frac{\alpha_{\text{em}}}{\sqrt{2}\pi} V_{tb} V_{ts}^* \epsilon_\mu^* \left[\sum_{i=1}^{9} C_i H_i^{\mu\nu} L_{V\nu} + C_{10}\left(H_{10}^{\mu\nu} L_{A\nu} - i\frac{f_{B_s}}{2} L_A^{\mu\nu} p_\nu \right) \right]$$

The $H^{\mu\nu}$ and L are hadronic and leptonic tensors respectively

Like the electromagnetic form factors Minkowski to Euclidean straightfoward

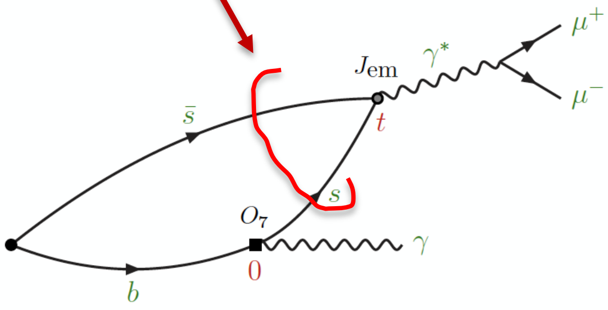
Contribution from "Semileptonic" Operators - F_V and F_A

$$H_9^{\mu\nu}(p\,.\,k) = H_{10}^{\mu\nu}(p\,.\,k) = i\int d^4y\langle\, 0\,|\, T\big[\,\bar{s}\,\gamma^\nu\, P_L\, b\,(0)\; J_{\text{em}}^\mu(y)\big]\,|\,\bar{B}_s(p)\,\rangle$$

$$= -\, i(g^{\mu\nu}\,(k\cdot q) - q^\mu k^\nu)\,\frac{F_A(q^2)}{2m_{B_s}} + \epsilon^{\mu\nu\rho\sigma}\,k_\rho\, q_\sigma\,\frac{F_V(q^2)}{2m_{B_s}}$$

- These form factors can be computed from Euclidean correlation functions (at accessible values of m_b).
- We choose $\mathbf{p} = \mathbf{0}$ and $\mathbf{k} = (0,0,k_z)$ and use twisted boundary conditions for k_z.
- With such a choice of kinematics: $\frac{1}{2k_z}\big(H_V^{12}(p,k) - H_V^{21}(p,k)\big) \to F_V(x_\gamma)$ and $\frac{i}{2E_\gamma}\big(H_A^{11}(p,k) + H_A^{22}(p,k)\big) \to F_A(x_\gamma)$.

intermediate light state propagates for t>0, continuation from Minkowski to Euclidean problematic



$\bar{\mathbf{F}}_{\mathbf{T}}$ (cont.)

- Large amount of effort is being devoted to developing techniques based on the spectral density representation,

M.Hansen, A.Lupo and N.Tantalo, arXiv:1903.06476
R.Frezzotti et al., arXiv:2306.07228

- For $t>0$ define $C_s(t,\mathbf{k}) = \langle\, 0\,|\, J^{\mu}_{{\rm em},s}(t,-\mathbf{k})\, J^{\nu}_{\bar{T}}(0)\,|\,B_s(\mathbf{0})\rangle \;=\; \int_{-\infty}^{\infty} dt'\,\delta(t'-t)\,C_s(t',-\mathbf{k})$

$$= \int_{-\infty}^{\infty} dt' \int_{-\infty}^{\infty} \frac{dE'}{2\pi}\, e^{iE'(t'-t)}\, C_s(t',-\mathbf{k}) = \int_{-\infty}^{\infty} \frac{dE'}{2\pi}\, e^{-iE't} \int d^4x'\, e^{ik'\cdot x'}\,\langle 0\,|\,J^{\mu}_{{\rm em},s}(x')\,J^{\nu}_{\bar{T}}(0)\,|\,B(\mathbf{0})\rangle \qquad \big(k'=(E',-\mathbf{k})\big)$$

$$= \int_{-\infty}^{\infty} \frac{dE'}{2\pi}\, e^{-iE't} \int d^4x'\,\langle 0\,|\,J^{\mu}_{{\rm em},s}(0)\, e^{-i(\hat{P}-k')\cdot x'}\, J_{\bar{T}}T^{\nu}(0)\,|\,B(\mathbf{0})\rangle = \int_{-\infty}^{\infty} \frac{dE'}{2\pi}\, e^{-iE't}\, \underbrace{\langle 0\,|\,J^{\mu}_{{\rm em},s}(0)\,(2\pi)^4\,\delta(\hat{P}-k')\,J^{\nu}_{\bar{T}}(0)\,|\,B(\mathbf{0})\rangle}_{\rho_s(E',\mathbf{k})}$$

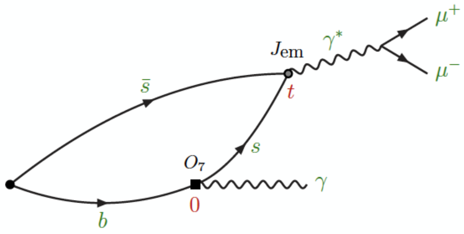
$$\equiv \int_{-\infty}^{\infty} \frac{dE'}{2\pi}\, e^{-iE't}\, \rho_s^{\mu\nu}(E',\mathbf{k})$$

- In Euclidean space $C_s(t,\mathbf{k}) = \int_{E^*}^{\infty} \frac{dE'}{2\pi}\, e^{-E't}\,\rho_s^{\mu\nu}(E',\mathbf{k})$.

other contributions Hansen, Meyer, Robaina; Hashimoto, Ishikawa et al.,; ….

$m_B - \omega$ is the energy of the lepton pair

$\bar{\mathbf{F}}_{\mathbf{T}}$ (cont.)



- For $t > 0$ define $C_s(t, \mathbf{k}) = \langle 0 \,|\, J^\mu_{{\rm em},s}(t, -\mathbf{k})\, J^\nu_T(0) \,|\, B_s(\mathbf{0})\rangle \;=\; \displaystyle\int_{E^*}^\infty \frac{dE'}{2\pi}\, e^{-iE't}\, \rho_s^{\mu\nu}(E', k)\,.$
- In Euclidean space $C_s(t, \mathbf{k}) \;=\; \displaystyle\int_{E^*}^\infty \frac{dE'}{2\pi}\, e^{-E't}\, \rho_s^{\mu\nu}(E', k)\,.$

- For the amplitude we require

$$H^{\mu\nu}_{\bar{T}_s}(m_B, \mathbf{k}) \;=\; i\int_0^\infty dt\; e^{i(m_B-\omega)t}\, C_s^{\mu\nu}(t, \mathbf{k}) \;=\; \lim_{\epsilon\to 0}\int_{E^*}^\infty \frac{dE'}{2\pi}\, \frac{\rho_s^{\mu\nu}(E', \mathbf{k})}{E' - (m_B - \omega) - i\epsilon}\,. \qquad (\omega = |\,\mathbf{k}\,|)$$

- The question is how (best) to extract the information about the spectral density, $\rho_s^{\mu\nu}(E, k)$, contained in the Euclidean correlation function in order to determine the amplitude (both the real and imaginary parts).

- We use the HLT method, in which computations are performed at several values of ϵ, and the kernel $\dfrac{1}{E' - (m_B - \omega) - i\epsilon}$ is approximated by a series of exponentials in time.

$$\frac{1}{E' - E - i\epsilon} \simeq \sum_{n=1}^{n_{\rm max}} g_n(E, \epsilon)\, e^{-anE'}$$ where the g_n are complex coefficients.

- Finally $H^{\mu\nu}_{\bar{T}_s}(m_B, \mathbf{k}) \;=\; \displaystyle\lim_{\epsilon\to 0}\int_{E^*}^\infty \frac{dE'}{2\pi}\, \frac{\rho_s^{\mu\nu}(E', \mathbf{k})}{E' - (m_B - \omega) - i\epsilon} \;=\; \lim_{\epsilon\to 0}\sum_{n=1}^{n_{\rm max}} g_n(m_B - \omega, \epsilon)\, C_s(an, \mathbf{k})$

$\bar{\mathbf{F}}_\mathbf{T}$ (cont.)

- Determining the g_n requires a balance between the systematic error due to the approximation of $1/(E' - E - i\epsilon)$ by a finite number of exponentials (in which the coefficients are large with alternating signs) and the statistical errors in the correlation functions $C_s(an, \mathbf{k})$.

- We have computed $\bar{F}_T$ at all four values of x_γ, at three of the five values of m_h $(m_h/m_c = 1, 1.5, 2.5)$ and on two of the gauge-field ensembles ($a = 0.0796(1)$ fm and $0.0569(1)$ fm).
    i) $\bar{F}_T$ only gives a very small contribution to the rate and is therefore not needed with great precision.
    ii) The spectral density method is computationally expensive.

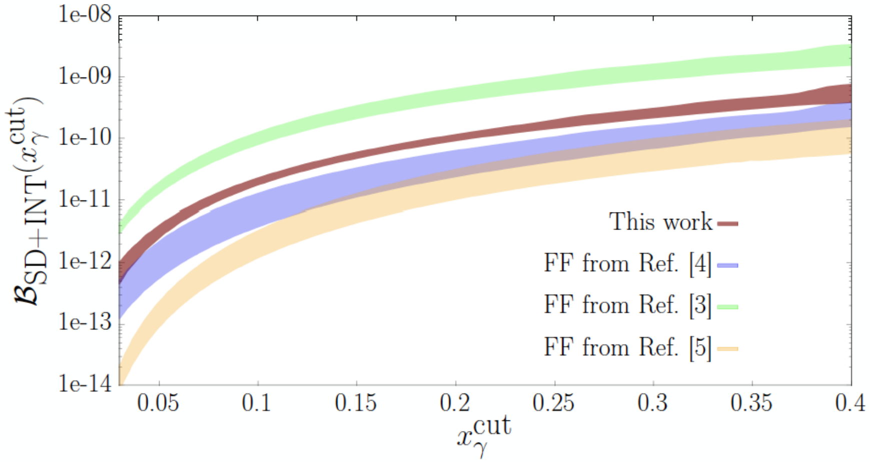
- An extrapolation in ϵ is required, as well as those in a and m_h.

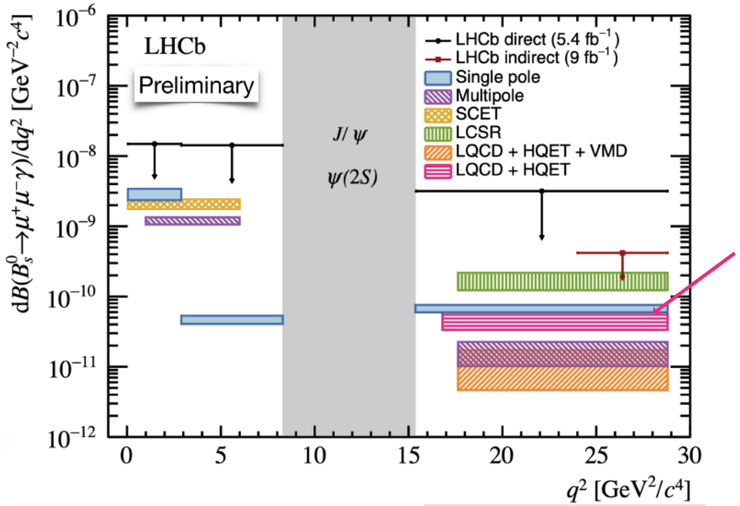
- Resulting error is $O(100\%)$ but $\bar{F}_T \ll F_{TV}, F_{TA}$. No clear x_γ dependence is observed in our data and we quote:

$$\mathrm{Re}\,\bar{F}_T^s(x_\gamma) = -\,0.019(19) \;\text{ and }\; \mathrm{Im}\,\bar{F}_T^s(x_\gamma) = 0.018(18)\,.$$

Comparison

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





Ref.[3] = T.Janowski, B.Pullin and R.Zwicky, arXiv:2106.13616, LCSR

Ref.[4]= A.Kozachuk, D.Melikhov and N.Nikitin, arXiv:1712.07926, relativistic dispersion relations

Ref.[5]= D.Guadagnoli, C.Normand, S.Simula and L.Vittorio, arXiv:2303.02174, VMD+quark model+lattice at charm

Discrepancy persists since rate dominated by F_V

- New LHCb update with direct detection of final state photon.

I.Bachiller, La Thuile 2024
LHCb, 2404.07648

- For $q^2 > 15\ \mathrm{GeV}^2$ the bound is about an order of magnitude higher than before.

From the May/June 2024 issue of the Cern Courier

b -> s transitions (appetite comes with eating)

THE EFFECTIVE WEAK HAMILTONIAN FOR $B \to K^{(*)}\ell\ell$ AND $B \to \ell\ell\gamma$ DECAYS

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\left\{\lambda_u\{C_1(O_1^{(c)} - O_1^{(u)}) + C_2(O_2^{(c)} - O_2^{(u)})\} + \lambda_t \sum_{i=1}^{10} C_i(\mu)O_i(\mu)\right\},$$

$\lambda_q = V_{qb}V^*_{qs}$

$$O_1^{(q)} = \left(\bar{s}^j\gamma^\mu P_L q^i\right)\left(\bar{q}^i\gamma_\mu P_L b^j\right), \qquad O_2^{(q)} = \left(\bar{s}^i\gamma^\mu P_L q^i\right)\left(\bar{q}^j\gamma_\mu P_L b^j\right)$$

$$O_3 = \left(\bar{s}\gamma^\mu P_L b\right)\sum_q\left(\bar{q}\gamma^\mu P_L q\right), \qquad O_4 = \left(\bar{s}^i\gamma^\mu P_L b^j\right)\sum_q\left(\bar{q}^j\gamma^\mu P_L q^i\right),$$

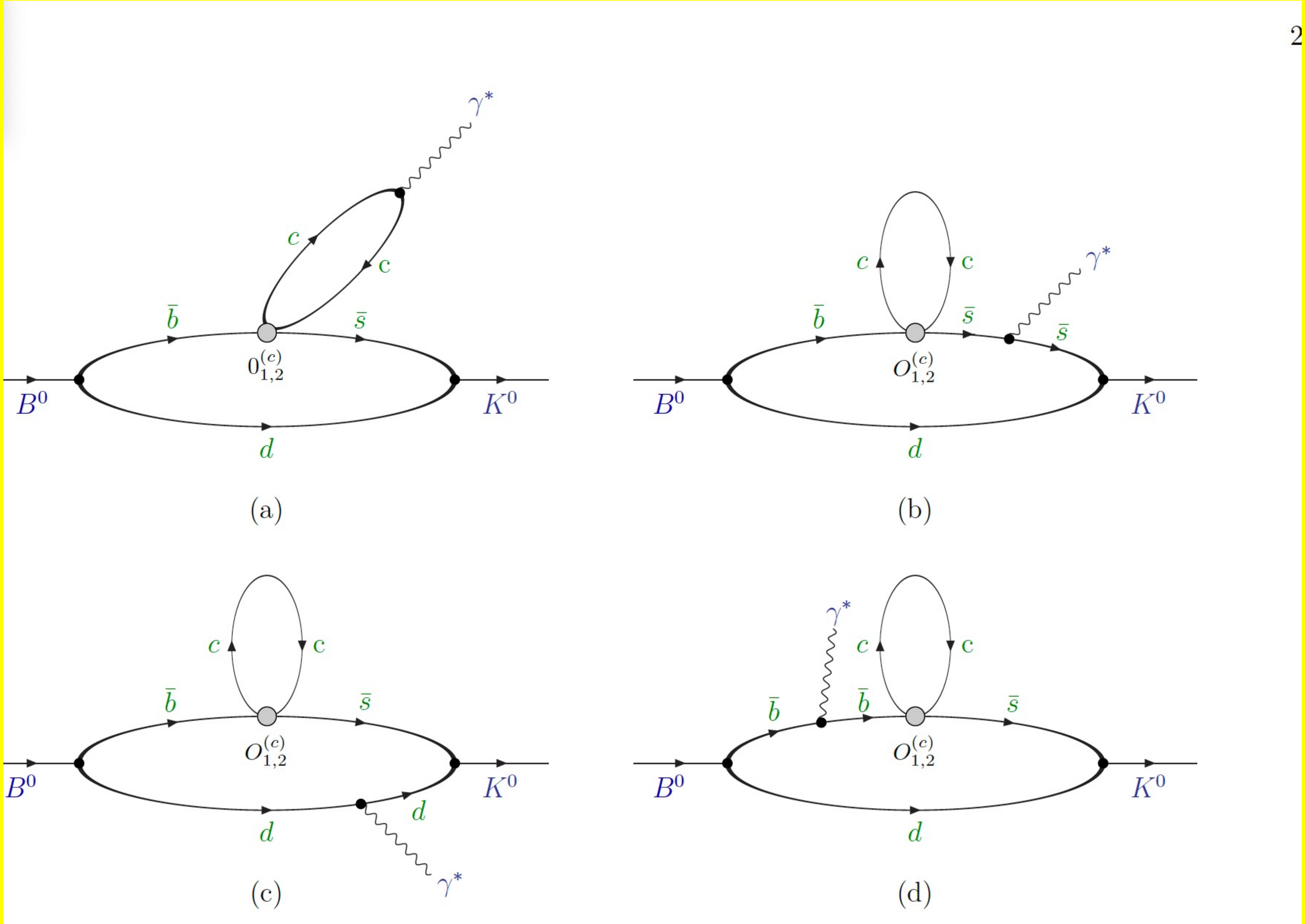
$$O_5 = \left(\bar{s}\gamma^\mu P_L b\right)\sum_q\left(\bar{q}\gamma^\mu P_R q\right), \qquad O_6 = \left(\bar{s}^i\gamma^\mu P_L b^j\right)\sum_q\left(\bar{q}^j\gamma^\mu P_R q^i\right);$$

$$O_7 = \frac{e}{(4\pi)^2}\, m_b\left(\bar{s}\sigma^{\mu\nu}P_R b\right)F_{\mu\nu}, \qquad O_8 = \frac{g_s}{(4\pi)^2}\, m_b\left(\bar{s}\sigma^{\mu\nu}T^a P_R b\right)G^a_{\mu\nu}$$

$$O_9 = \frac{e^2}{(4\pi)^2}\left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu \ell\right), \qquad O_{10} = \frac{e^2}{(4\pi)^2}\left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu\gamma^5 \ell\right)$$

$$\tilde{\mathcal{H}}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}V_{tb}V^*_{ts}\left\{C_1O_1^{(c)} + C_2O_2^{(c)} + C_7O_7 + C_8O_8 + C_9O_9 + C_{10}O_{10}\right\}$$

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

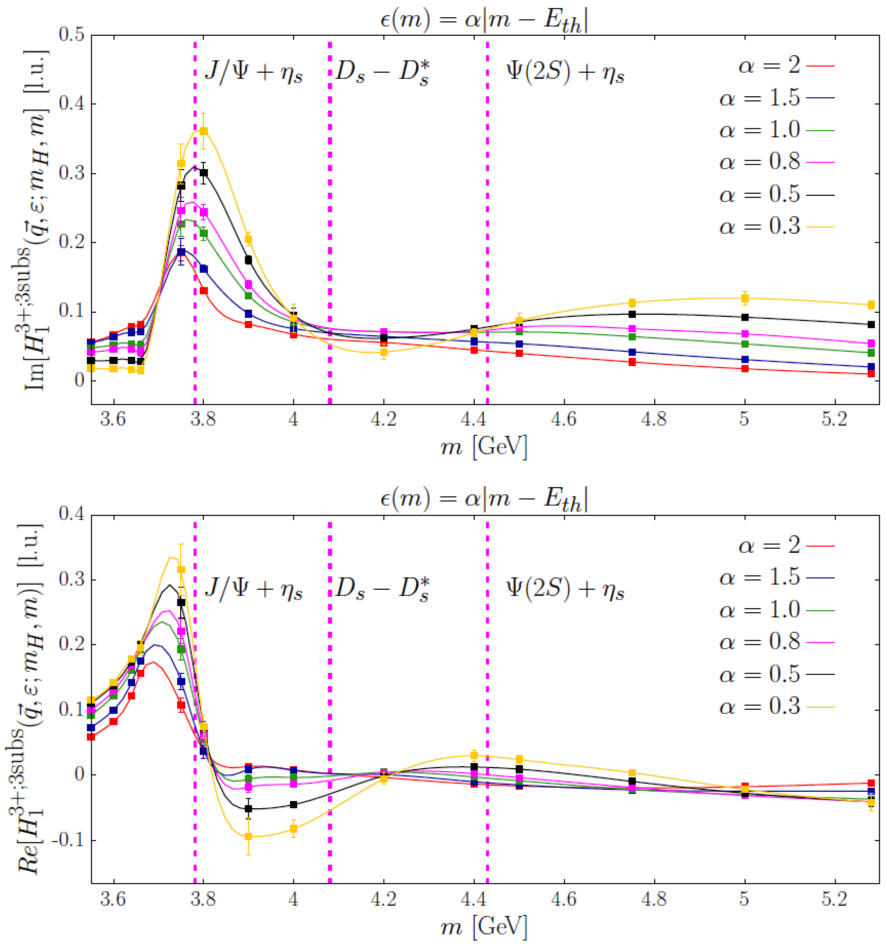
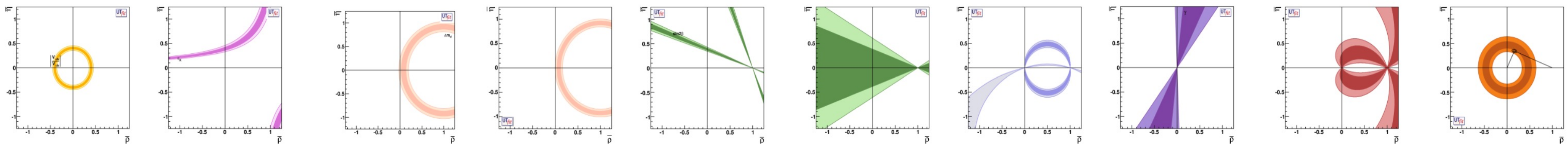


FIG. 12: The real (bottom) and imaginary (top) part of the smeared amplitude $H_1^{3+;3\mathrm{subs}}(\vec{q}, \varepsilon; m_H, m)$, as a function of m, for some of the simulated values of α in Eq. (140). The continuous lines correspond to spline interpolations of the lattice data.

This approach can be generalized to n-operators

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

Although it becames quite scaring (see Patella and Tantalo)

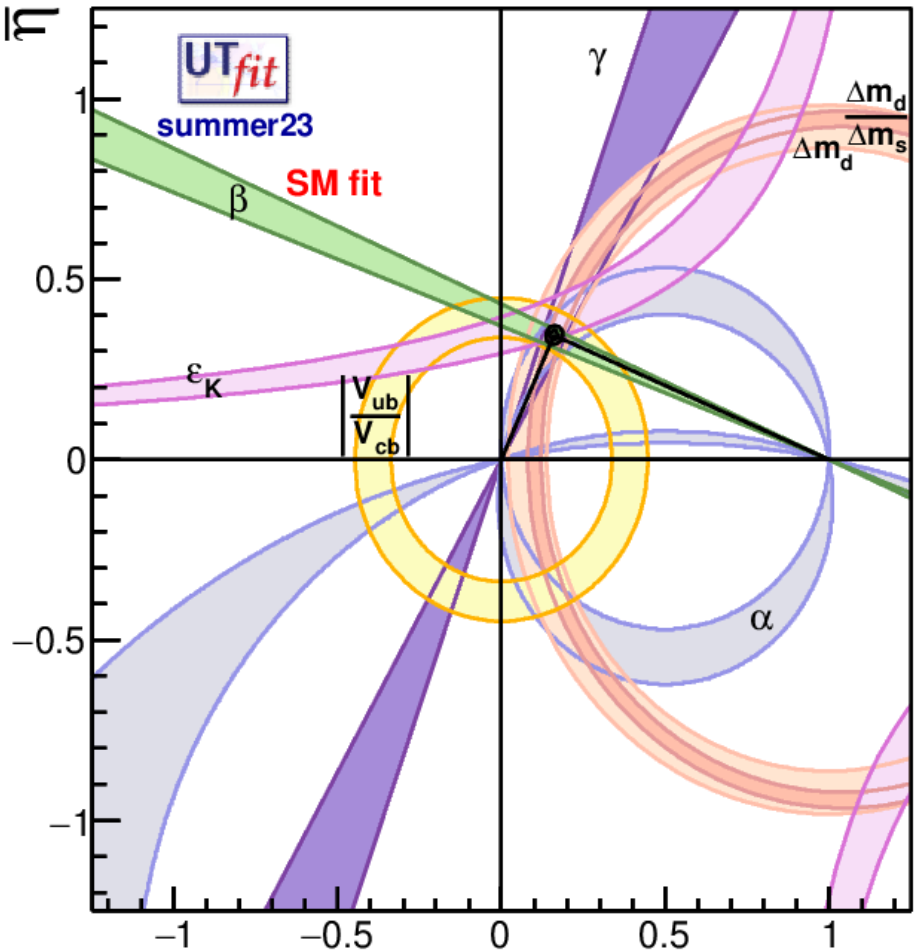


2023 results

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

To be updated

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

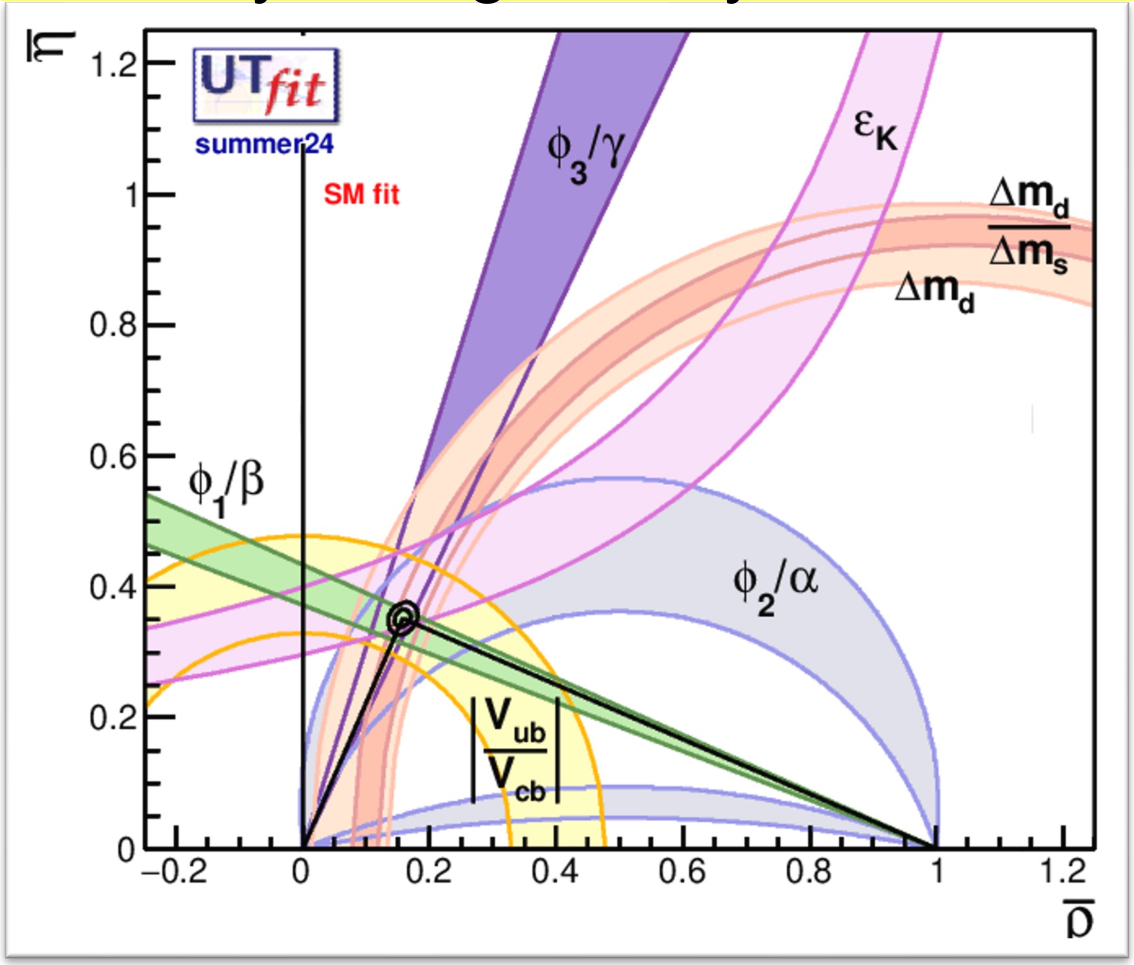


$\alpha = (92.4 \pm 1.4)^0$
$\sin 2\beta = 0.703 \pm 0.014$
$\beta = (22.46 \pm 0.68)^0$
$\gamma = (65.1 \pm 1.3)^0$
$A = 0.828 \pm 0.011$
$\lambda = 0.22519 \pm 0.00083$
2022

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:



levels @
95% Prob

ρ = 0.158 ± 0.009
η = 0.352 ± 0.010

λ = 0.2250 ± 0.0007

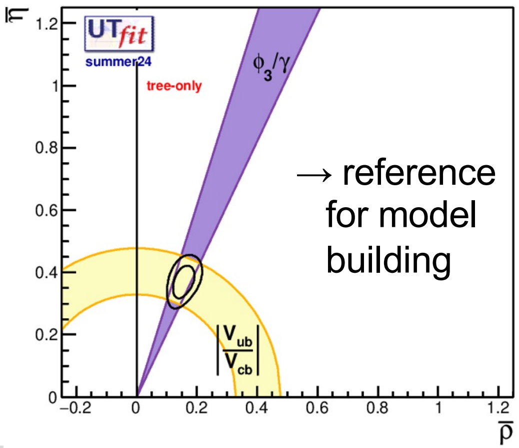
A= 0.826 ± 0.009

Some interesting configurations

"Tree only"

ρ = ±0.156 ± 0.024

η = ±0.372 ± 0.035

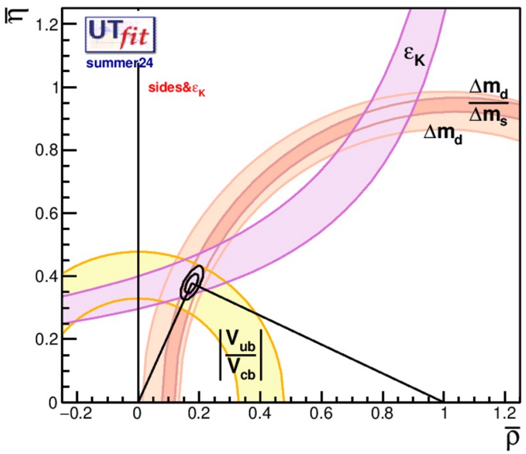


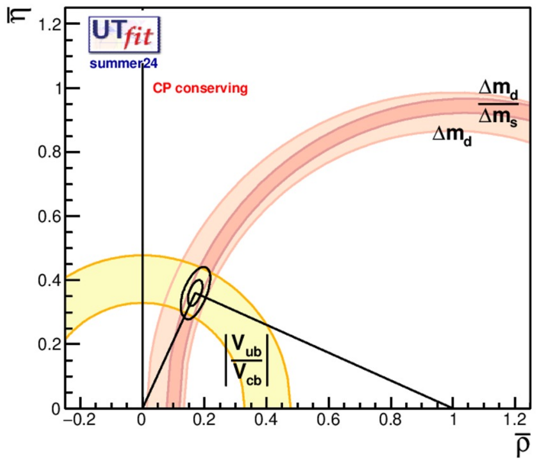
→ reference for model building

Sides and ε_K

ρ = 0.176 ± 0.015

η = 0.377 ± 0.022





CP conserving constraints

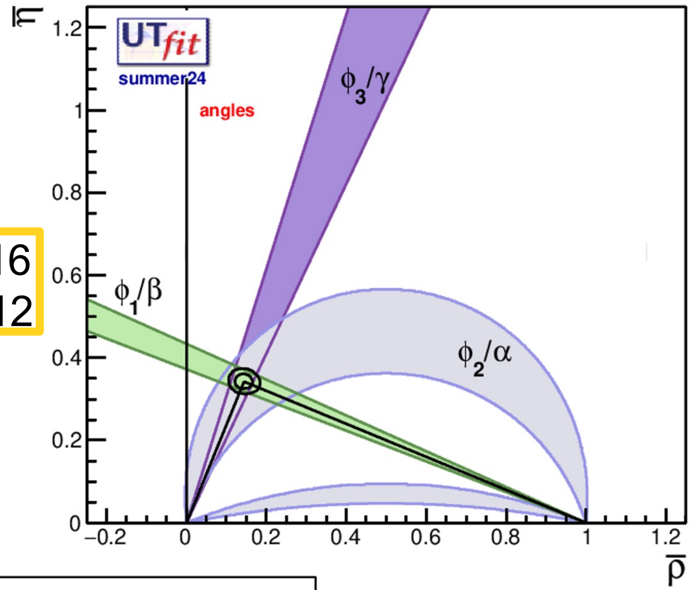
ρ = 0.170 ± 0.017

η = 0.361 ± 0.035

Angles only

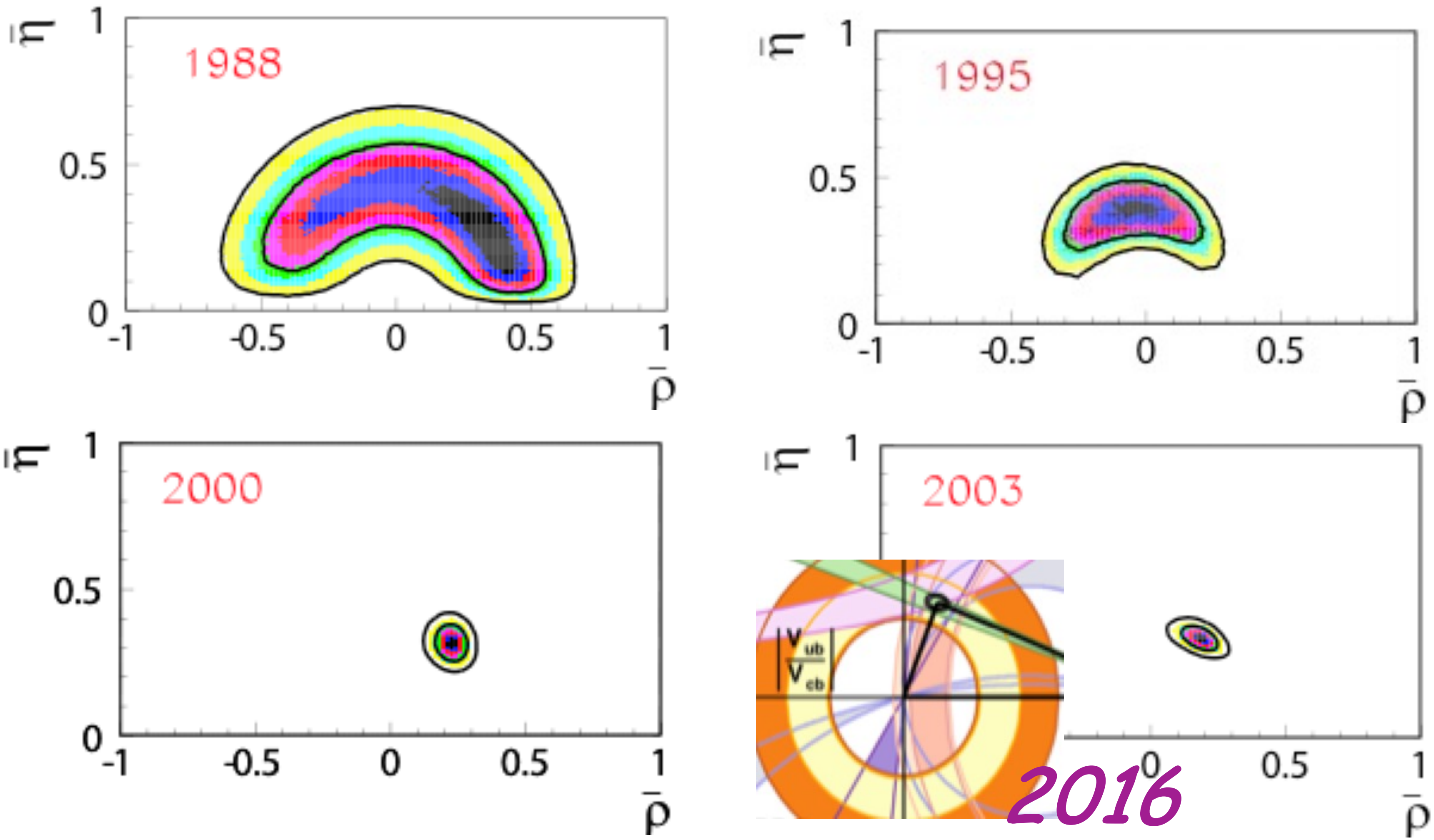
ρ = 0.144 ± 0.016

η = 0.343 ± 0.012

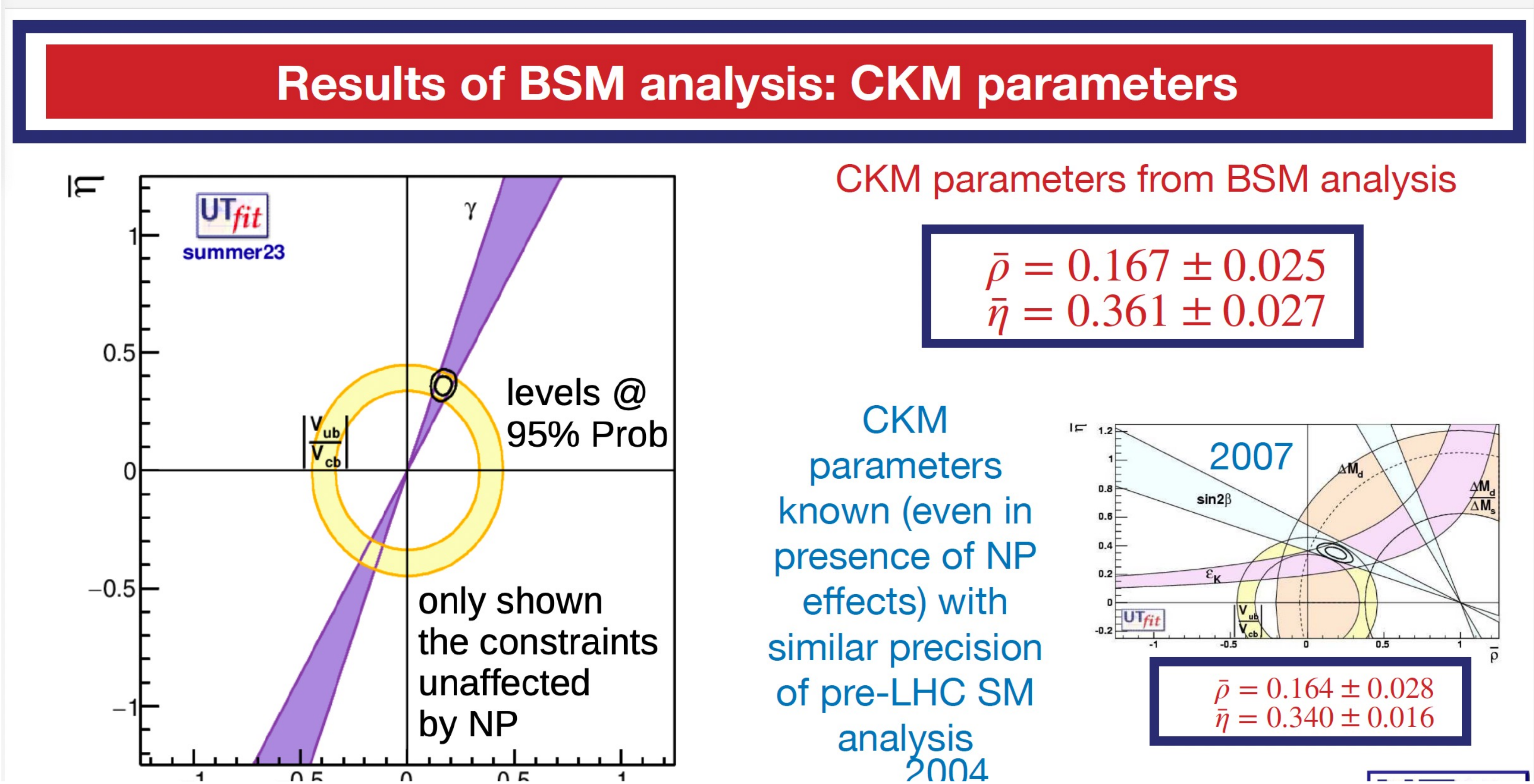


PROGRESS SINCE 1988

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




.... 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)
  - parameterize BSM effects in $\Delta F = 2$ Hamiltonian in model-independent
  - use all available experimental information
- find out NP contributions to ΔF=2 transitions

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

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

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.

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

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

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

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

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

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

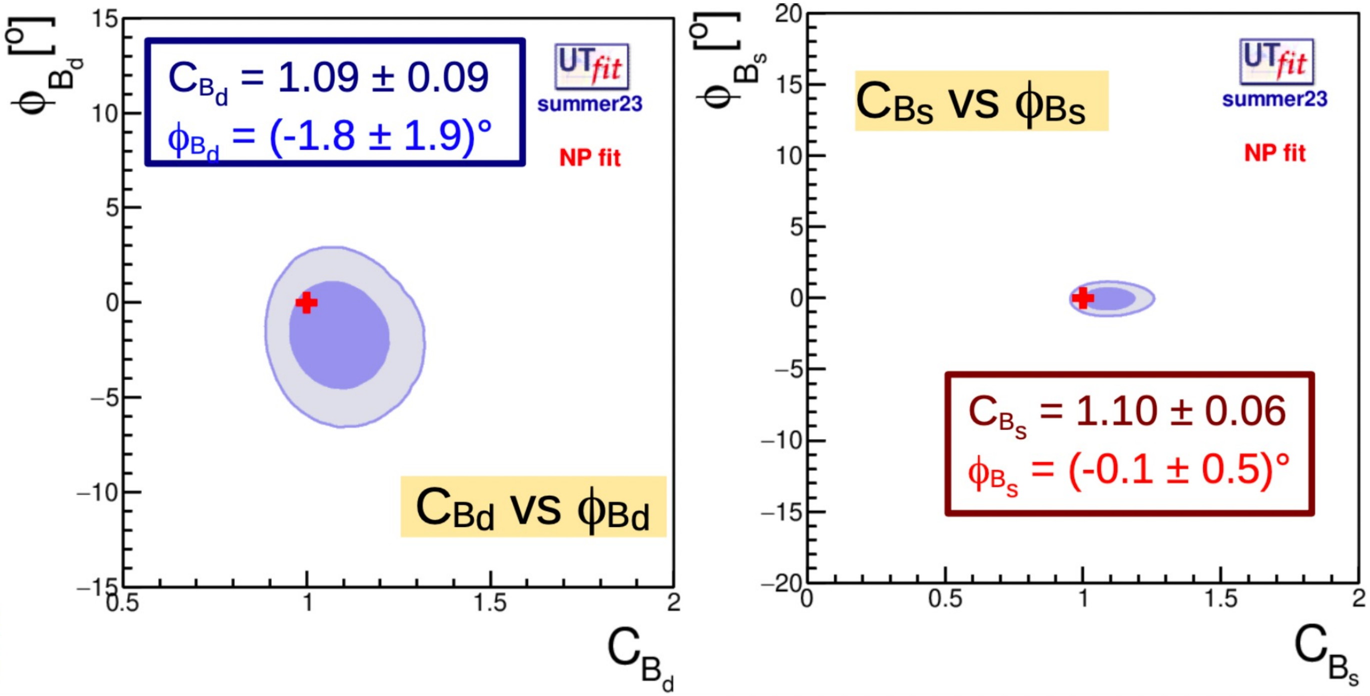
Results of BSM analysis: New Physics parameters

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

K system

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

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



Results of BSM analysis: New Physics parameters

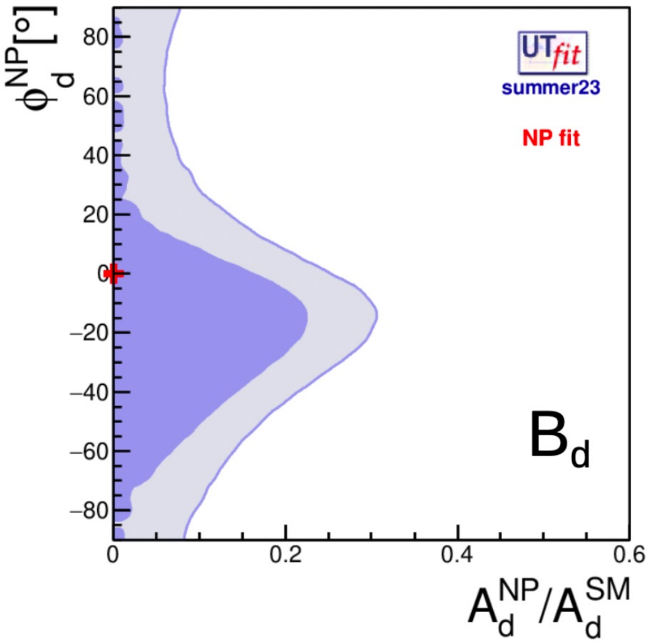
$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

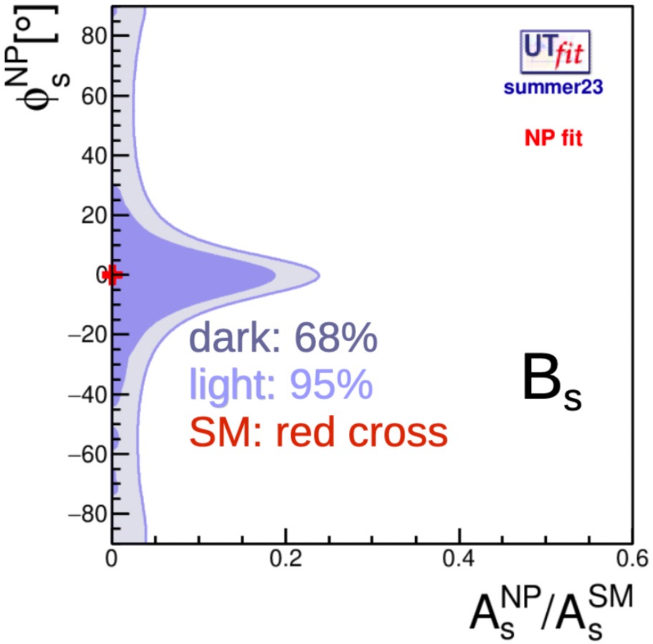
The ratio of NP/SM amplitudes is:

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

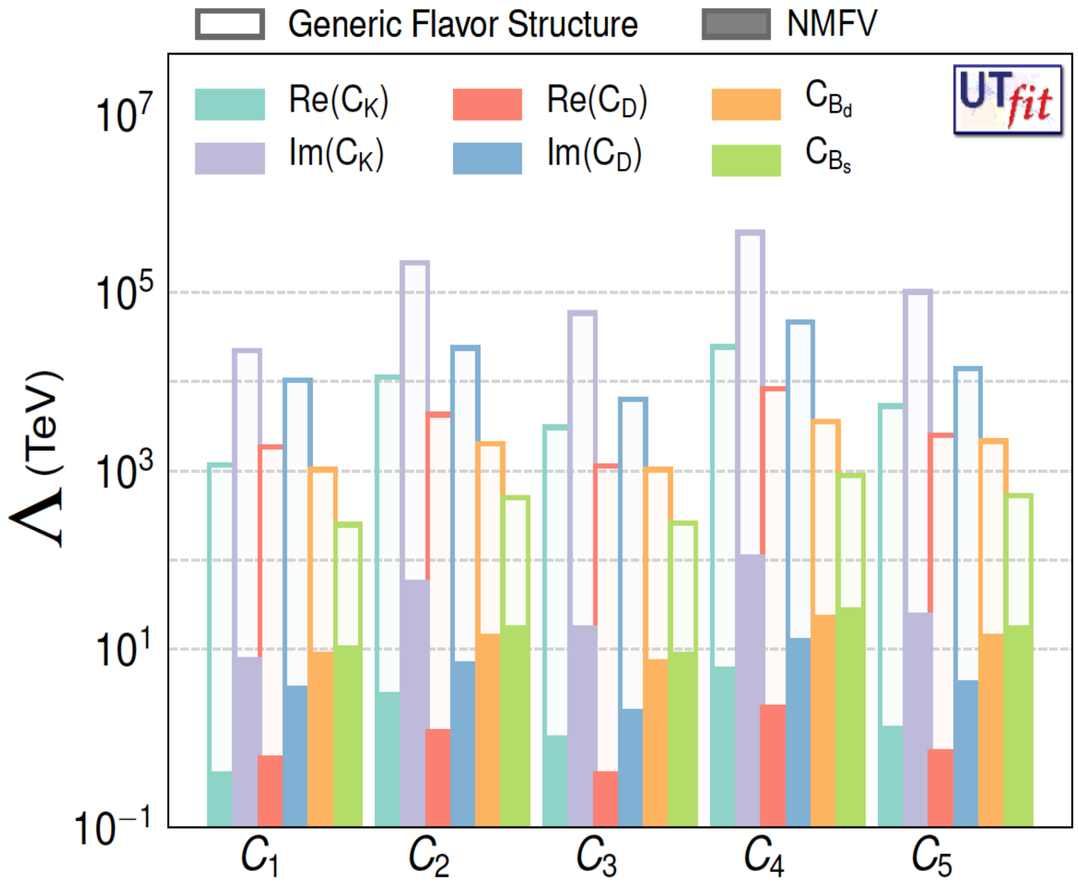
< 25% @68% prob. (30% @95%) in B_s mixing

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





Results of BSM analysis: probing New Physics Scale



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

$$\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}_{jL}^{\alpha}\gamma_\mu q_{iL}^{\alpha}\bar{q}_{jL}^{\beta}\gamma^\mu q_{iL}^{\beta}\,, \\
Q_2^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\bar{q}_{jR}^{\beta} q_{iL}^{\beta}\,, \\
Q_3^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\bar{q}_{jR}^{\beta} q_{iL}^{\alpha}\,, \\
Q_4^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\bar{q}_{jL}^{\beta} q_{iR}^{\beta}\,, \\
Q_5^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\bar{q}_{jL}^{\beta} q_{iR}^{\alpha}\,.
\end{aligned}$$

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

- 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

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

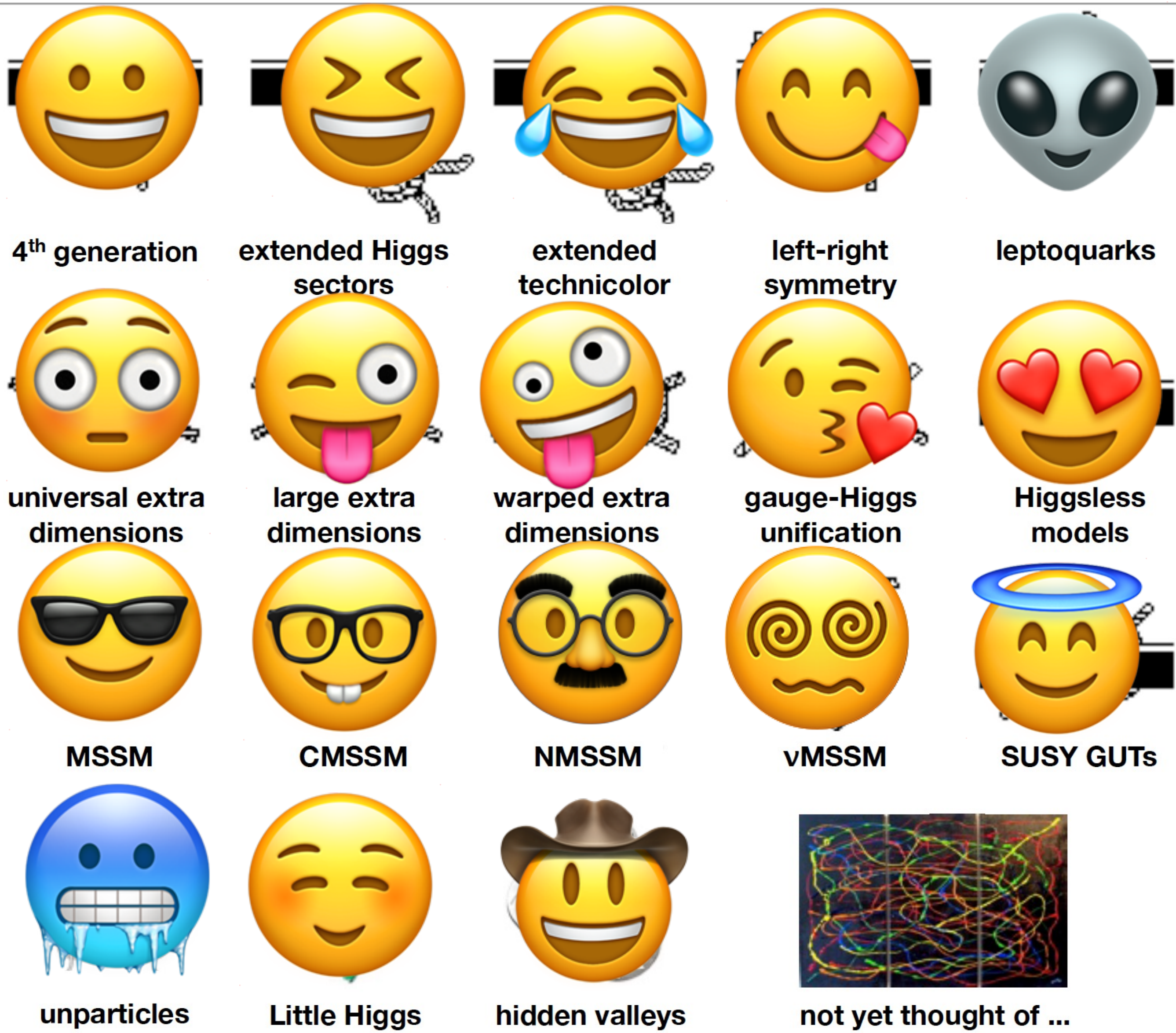
$$Y_b \sim 10^{-2} \qquad Y_s \sim 10^{-3} \qquad Y_d \sim 10^{-5}$$

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

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

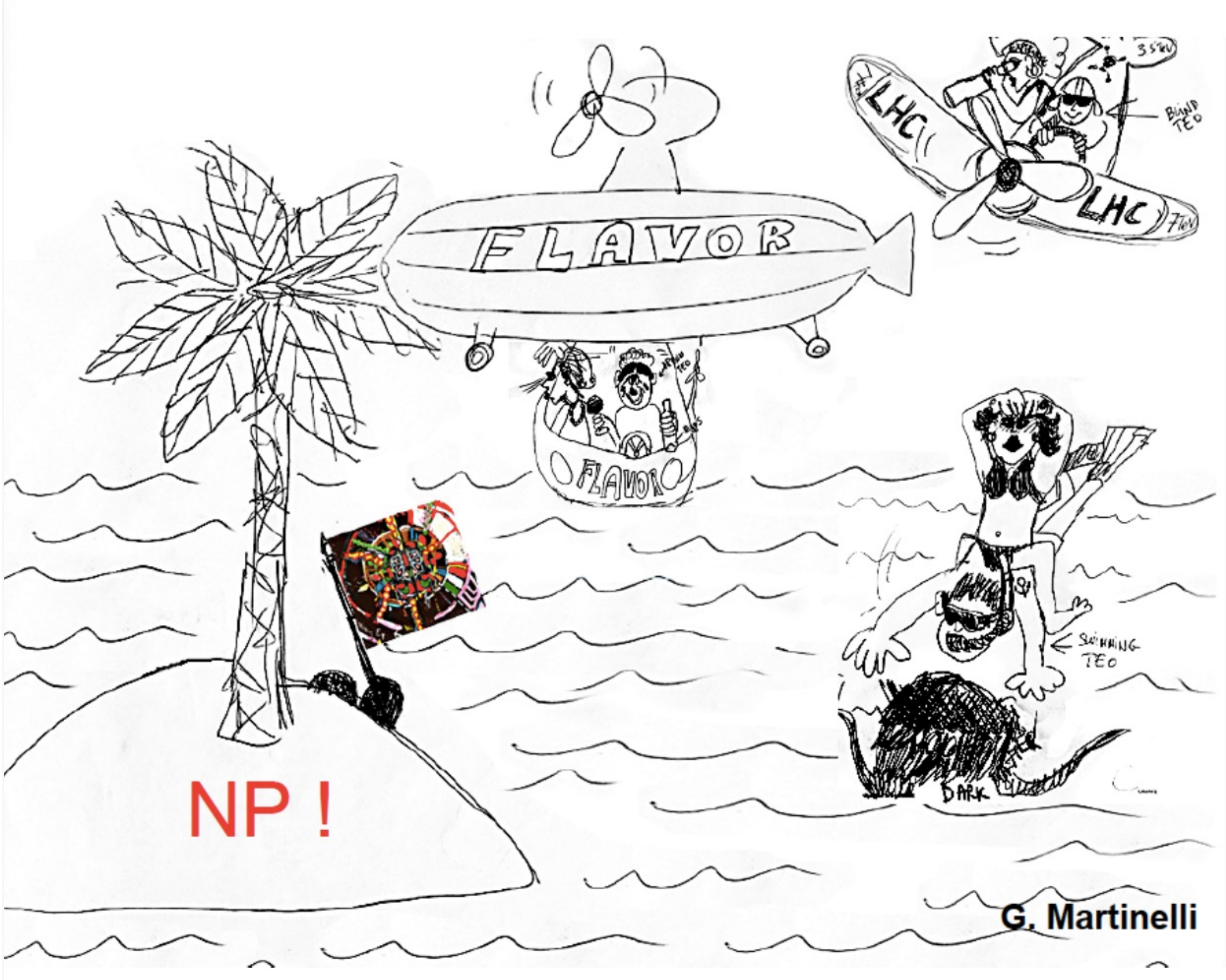
$$0.1 \sim \quad g' \,, \quad g \,, \quad g_s \,, \quad \lambda \quad \sim 1.$$

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

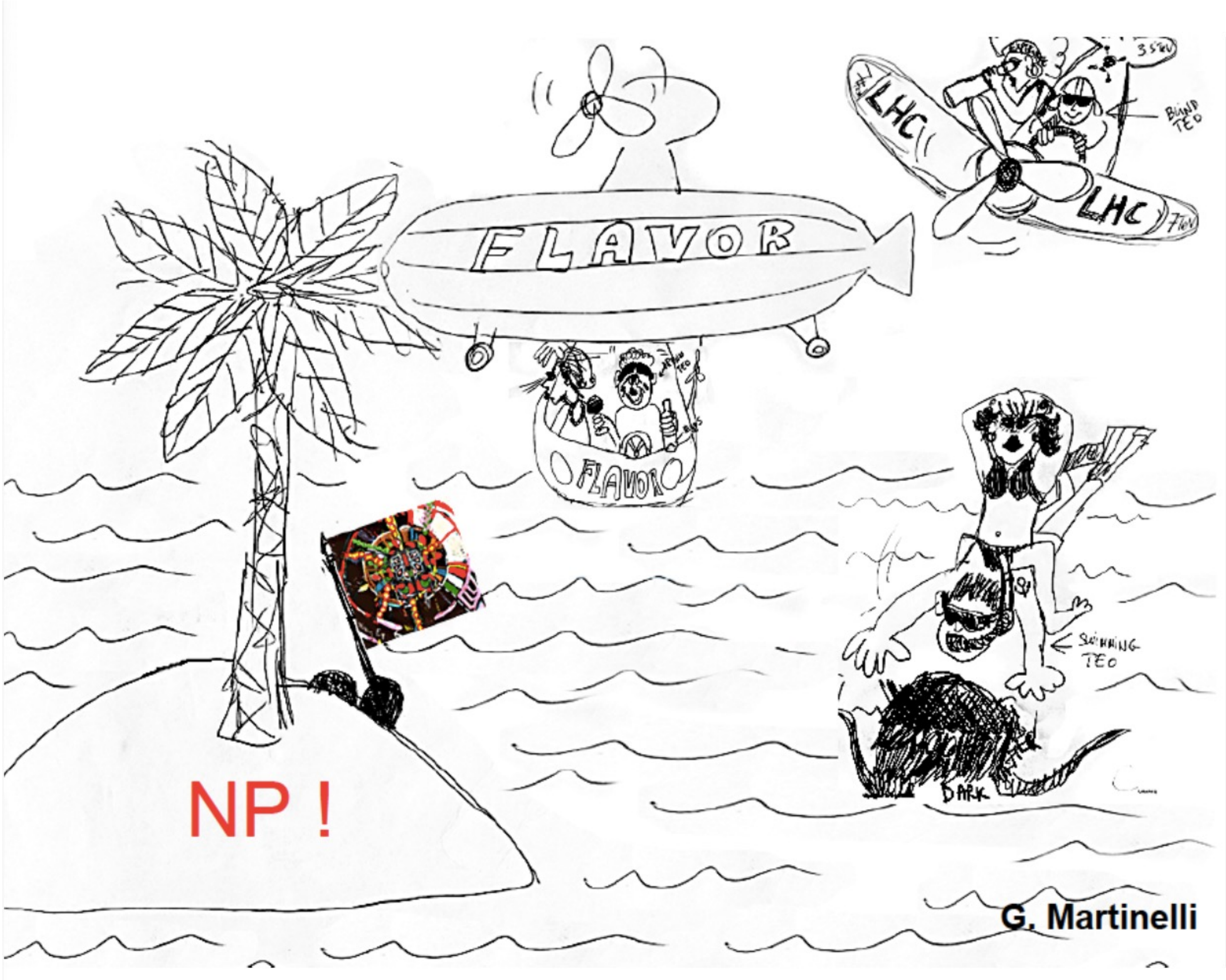


See Barbieri

This figure not only summarizes the three aspects of research in fundamental physics: the energy frontier, the intensity frontier and the cosmological frontier …



… but also, and above all, my relationship with Antonio, made of extreme scientific respect, great affection and deep friendship



absence says more than presence

FRANK HERBERT

(Dune)

THANKS FOR YOUR ATTENTION

Istituto Nazionale di Fisica Nucleare