Symmetries and symmetry-breaking in the flavor sector

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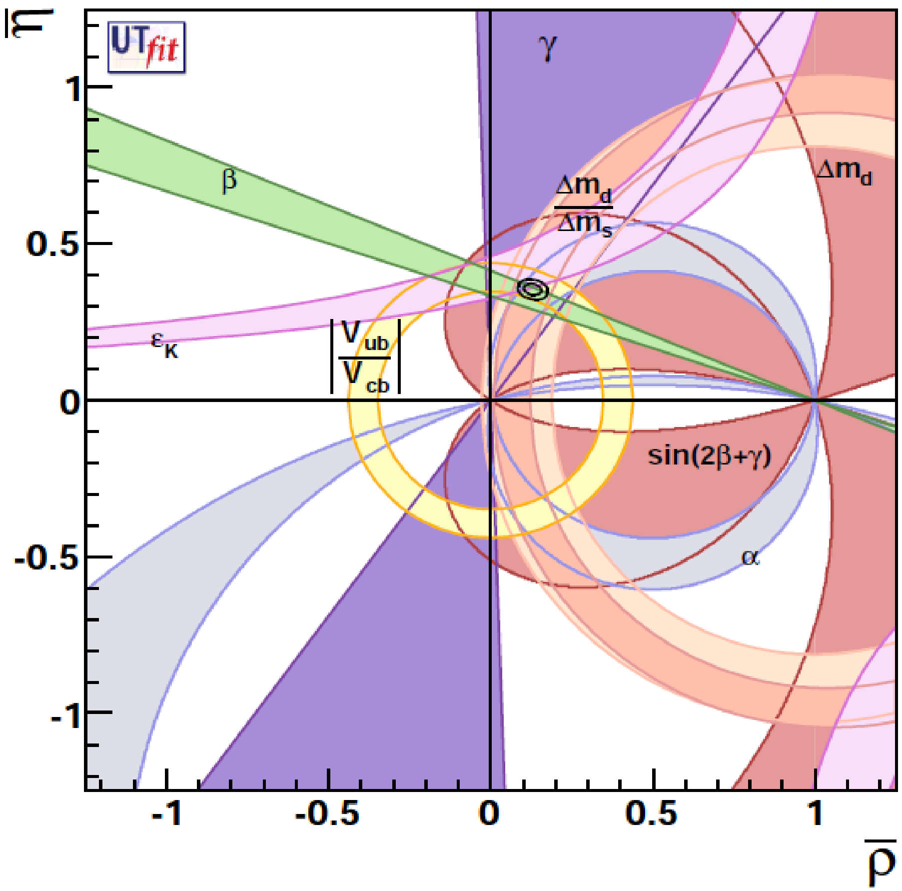
- The flavor problem
- From MFV to $U(2)^3$
- The $U(2)^3$ symmetry and its breaking pattern
- Phenomenological implications
- *A few words to thank Luciano...*

The flavor problem (or the embarrassing success of the GIM mechanism...)

- The measurements of quark flavor-violating observables show a remarkable overall success of the SM (and, particularly of the GIM mechanism).

This success is quite "embarrassing" if we assume there is some New Physics (NP) around the TeV scale...



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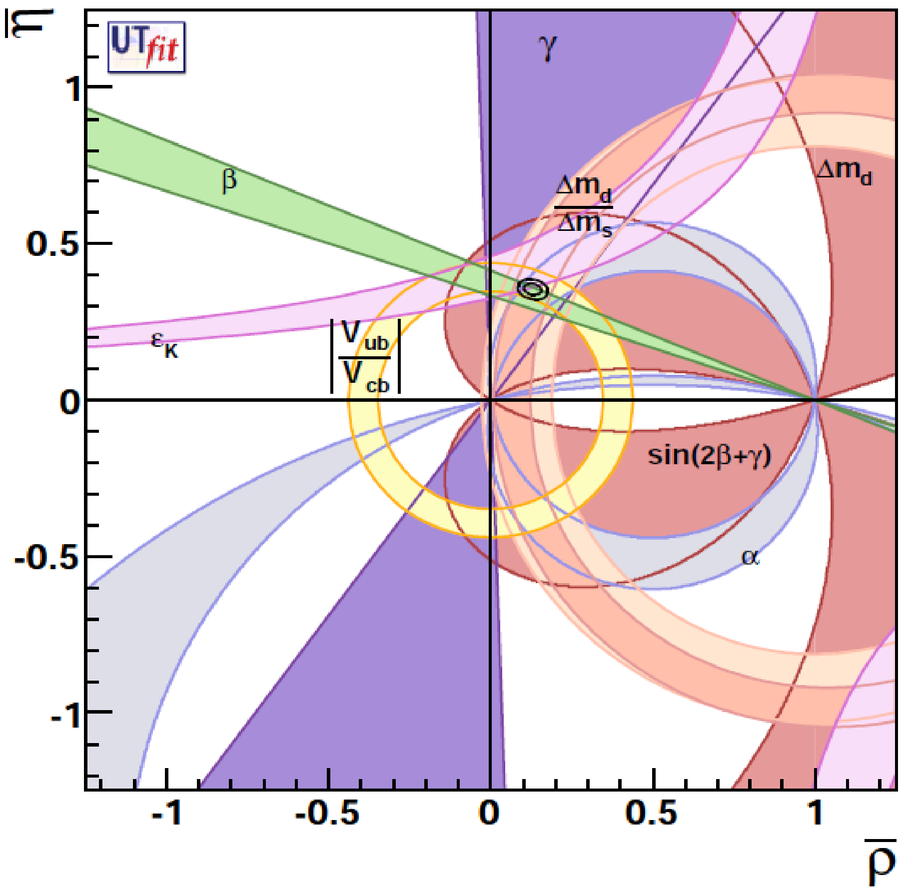
E.g.:

$$M(B_d\text{-}\bar{B}_d) \sim \frac{m_t^4 (V_{tb}^* V_{td})^2}{16\pi^2 m_w^2} + \frac{c_{NP}}{\Lambda_{NP}^2}$$

tiny SM contribution (GIM suppressed)

possible large contribution (if $\Lambda_{NP} \sim$ TeV and $c_{NP} \sim 1$), excluded by present data



The flavor problem

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{c_{ij}}{\Lambda^2} O_{ij}^{(6)}$$

G.I, Nir, Perez '10

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} (Λ = 1 TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\|q/p\|$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\|q/p\|$, ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

- New flavor-breaking sources of O(1) at the TeV scale are definitely excluded

The flavor problem

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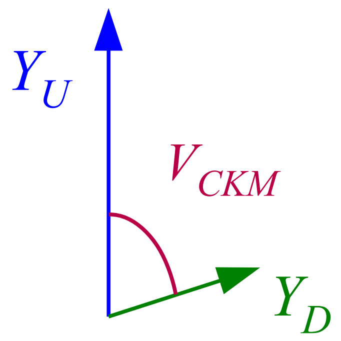
↓

Minimal Flavor Violation paradigm:

The $U(3)^3 = U(3)_Q \times U(3)_U \times U(3)_D$ quark-flavor symmetry of the SM gauge sector is broken only by the 2 quark Yukawa couplings: $Y_D \sim 3_Q \times \bar{3}_D$ $\quad Y_U \sim 3_Q \times \bar{3}_U$

↓



- The CKM matrix controls all flavor-changing phenomena in the quark sector also beyond SM
- Naturally small effects in the flavor-changing processes measured so far even for new-physics in the TeV range

From MFV to $U(2)^3$

MFV virtue

Naturally small effects in FCNC observables

MFV main open problems

No explanation for small CPV flavor-conserving observables (edms)

No explanation for *Y* hierarchies (masses and mixing angles)

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No explanation for small CPV flavor-conserving observables (edms)

No explanation for Y hierarchies (masses and mixing angles)

A solutions of both these problems is obtained in the context of supersymmetry introducing a horizontal U(2) flavor symmetry acting on the first two generations only (and suitably broken).

The so-called "effective susy" framework, with heavy first two generations of squarks

Dimopulos, Giudice, '95
Cohen, Kaplan, Nelson '96

Pomarol, Tommasini, '96
Barbieri, Dvali, Hall, '96
Barbieri, Hall, Romanino, 97

From MFV to $U(2)^3$

MFV virtue

Naturally small effects in FCNC observables

Effective susy with a U(2) flavour symmetry

Naturally small CPV flavor-conserving observables (edms)

Partial explanation for *Y* hierarchies ($|V_{td}/V_{ts}| = \vartheta_d = (m_d/m_s)^{1/2}$, ...)

Well motivated beyond flavor physics...
(hierarchy problem + non-observation of SUSY so far)

...not efficient as MFV in FCNC observables
(too large flavor-violating effects in the RH sector)

- Fine-tuning in the kaon system (ε_K & ε')
- Sizable non-standard CPV phases in $\Delta B=1$ obs.

From MFV to $U(2)^3$

MFV virtue

Naturally small effects in FCNC observables

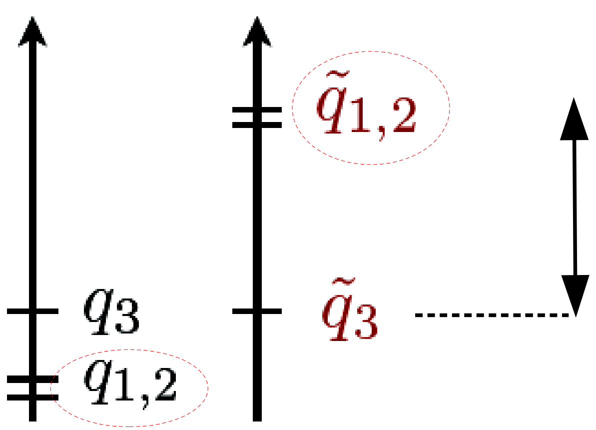
Effective susy with a U(2) flavour symmetry

Naturally small CPV flavor-conserving observables (edms)

Partial explanation for Y hierarchies

Effective susy with a $U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$ flavor symmetry

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11



Large mass gap (several TeV) not controlled by flavor symmetries (as opposite to MFV) and fine-tuning considerations

▶ *The $U(2)^3$ symmetry and its breaking pattern*

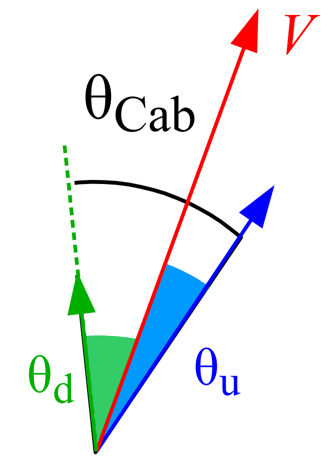
The symmetry is a good approximation to the SM quark spectrum (exact symmetry for $m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$), hence we only need to introduce small breaking terms

$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D \longrightarrow M_{\rm squarks} = \left[\begin{array}{c|c} m_{\rm heavy} & 0 \\ \hline 0 & m_3 \end{array}\right]$$

$$\downarrow$$

$$Y_u = y_t \left[\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right] \qquad Y_d = y_b \left[\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right]$$

The $U(2)^3$ symmetry and its breaking pattern



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The set of breaking terms necessary to reproduce the quark spectrum, while keeping small FCNCs beyond the SM are:

$V \sim (2,1,1)$	V_{cb} & V_{ts}	$O(\lambda^2 \sim 0.04)$
$\Delta Y_u \sim (2,2,1)$	m_c, m_u, θ_u	$O(y_c)$
$\Delta Y_d \sim (2,1,2)$	m_s, m_d, θ_d	$O(y_s)$

$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$$

$$Y_u = y_t \begin{bmatrix} \Delta Y_u & c_u V \\ 0 & 1 \end{bmatrix} \qquad Y_d = y_b \begin{bmatrix} \Delta Y_d & c_d V \\ 0 & 1 \end{bmatrix} \quad \rightarrow \quad \begin{aligned} |V_{us}| &\sim \theta_u - \theta_d \\ |V_{td}/V_{ts}| &= \theta_u \\ |V_{ub}/V_{cb}| &= \theta_d \end{aligned}$$

The $U(2)^3$ symmetry and its breaking pattern

The assumption of a single (2,1,1) breaking term
[*or a single breaking term connecting the light generations to the third one*]
ensures a GIM-like structure for FCNCs:

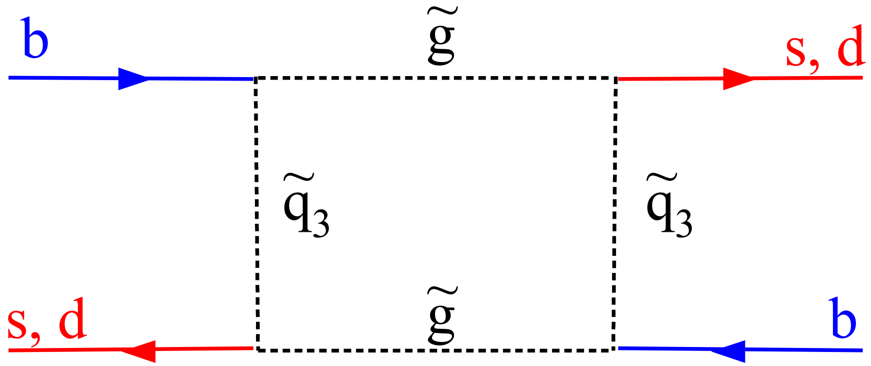
$$b_L \xrightarrow{V} d_L\ (s_L) \qquad \Rightarrow \qquad V_{td(s)}$$

$$s_L \xrightarrow{V^+} 3^{rd} \xrightarrow{V} d_L \qquad \Rightarrow \qquad V_{ts}^{*}V_{td}$$

The protection of FCNCs is robust even if we introduce additional (2,2,1) or (2,1,2) breaking terms (useful to explain light-quark mass ratios), provided they are sufficiently small

Phenomenological implications

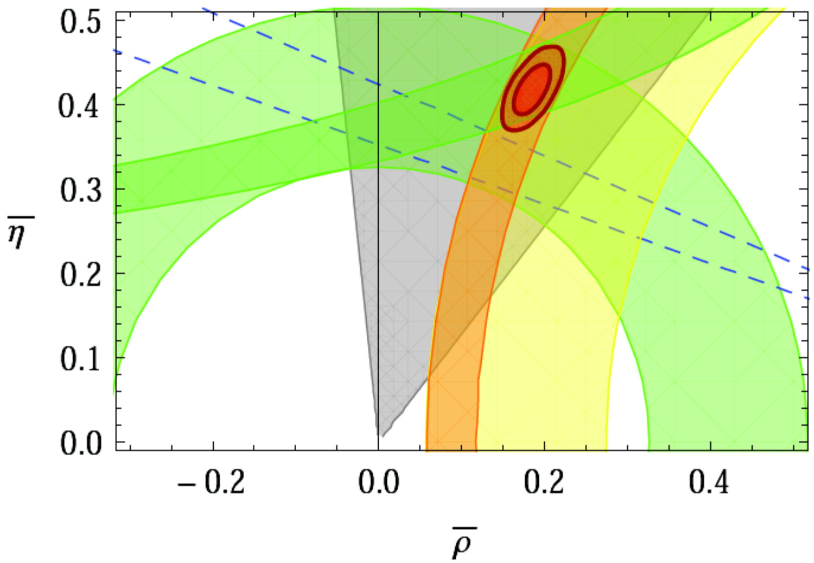
The leading and most clean deviations from the SM are expected in meson-anti-meson mixing, from gluino-box diagrams:

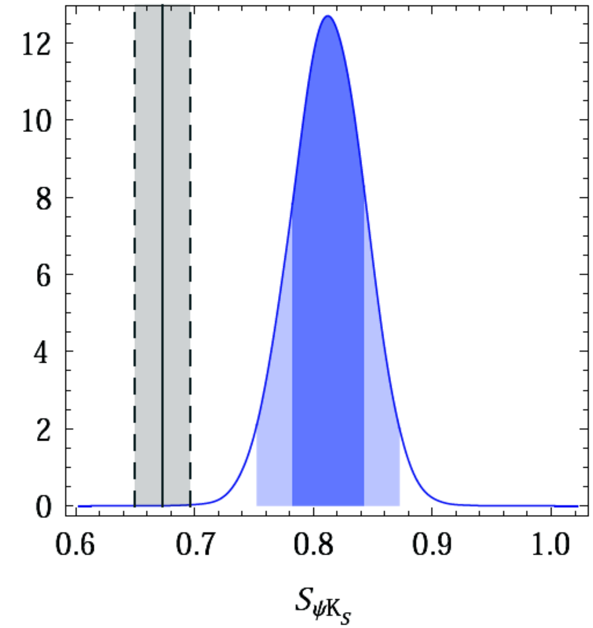


- Correction to K^0 mixing aligned in phase with the SM amplitude, with definite sign (constructive interference)
- New CPV appearing in $B_{s,d}$ mixing (in a universal way)

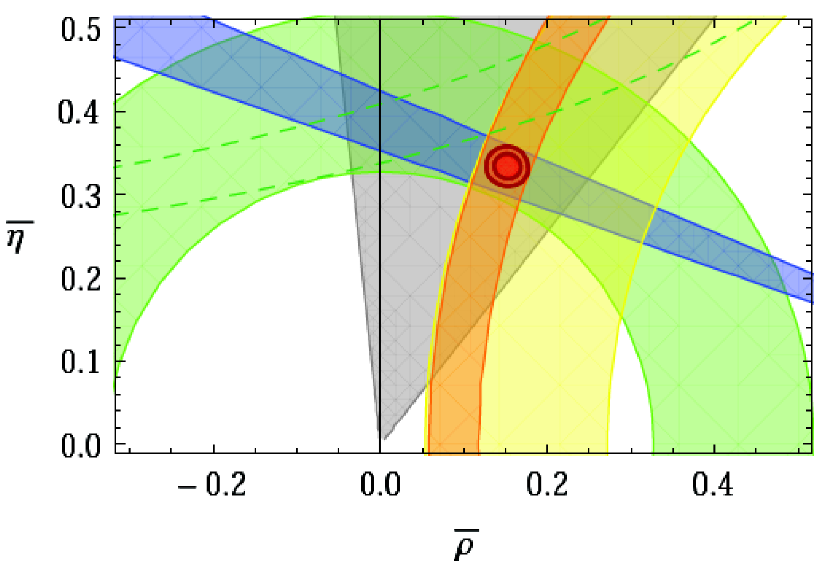
Despite the overall good consistency, the CKM fit within the SM shows some "tensions":

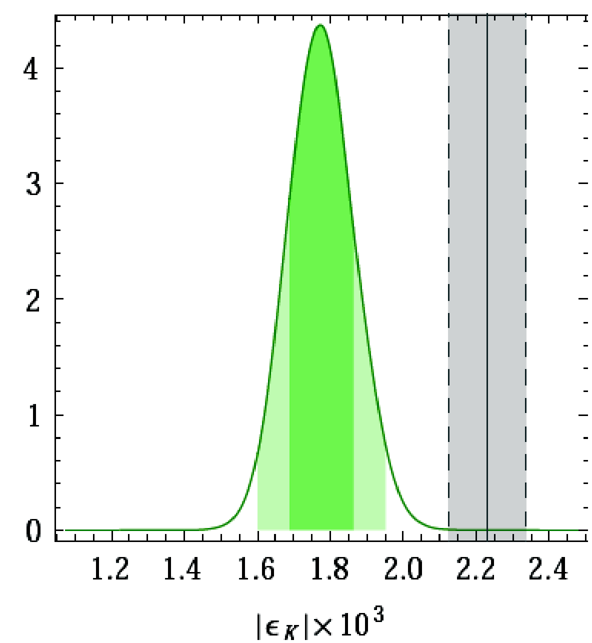
I. SM fit, no $S_{\Psi K}$





II. SM, no ε_K





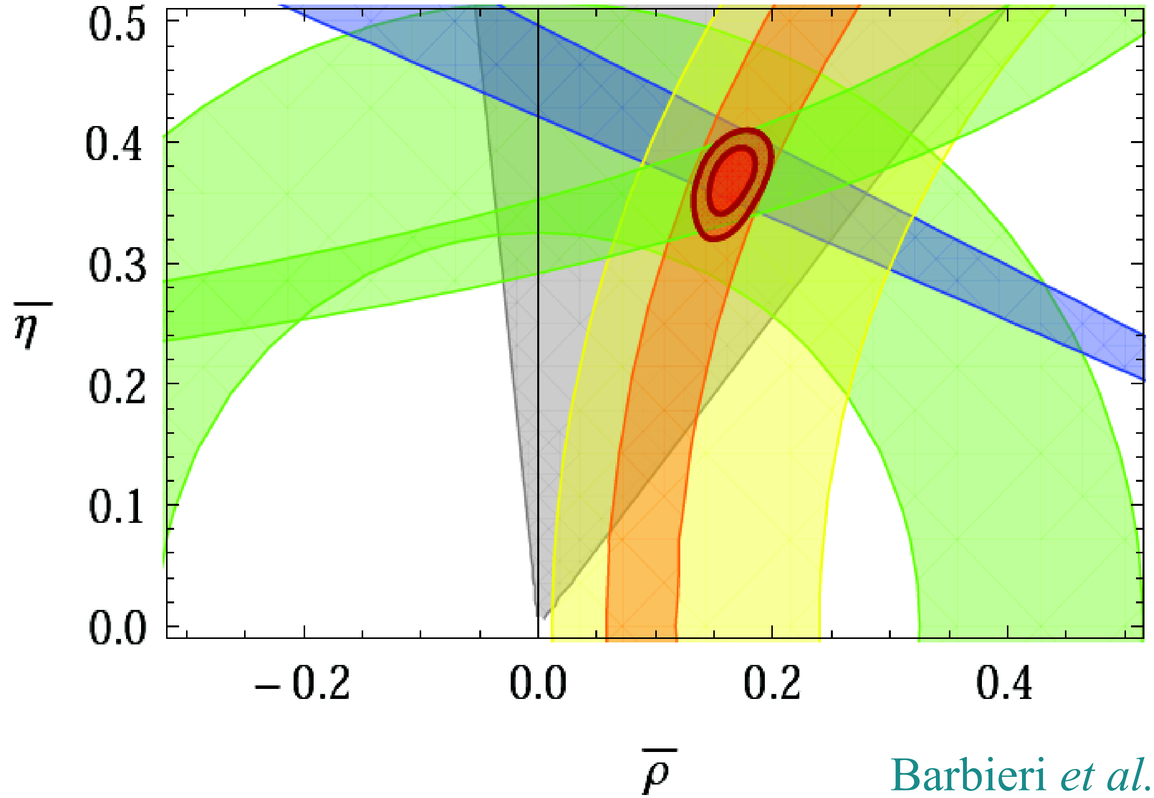
Similar results by CKMfitter & UTfit

Phenomenological implications

The situation improves substantially if we include the U(2)^3 SUSY corrections

$(\chi^2/N_{\mathrm{dof}})_{\mathrm{SM}} = 10/5$

$(\chi^2/N_{\mathrm{dof}})_{\mathrm{SUSY}} = 0.7/2$

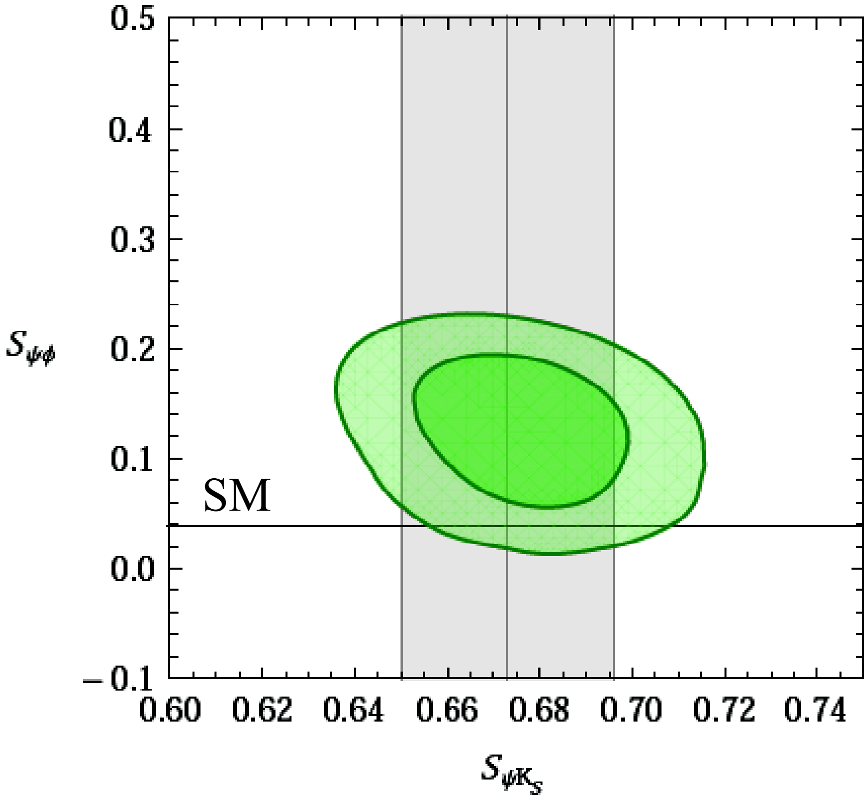


Barbieri *et al.* '11

Phenomenological implications

Two clean predictions for the LHC:

I. Small non standard CPV in B_s mixing



Compatible with the recent LHCb data, possibly within their near-future reach

II. Relatively “light” gluinos and 3rd generation squarks

$$m_{\tilde{g}},\ m_{\tilde{q}_3} < 1.0,\ 1.5\ \text{TeV}$$

Compatible with the most recent bounds from ATLAS & CMS, but within their near-future reach

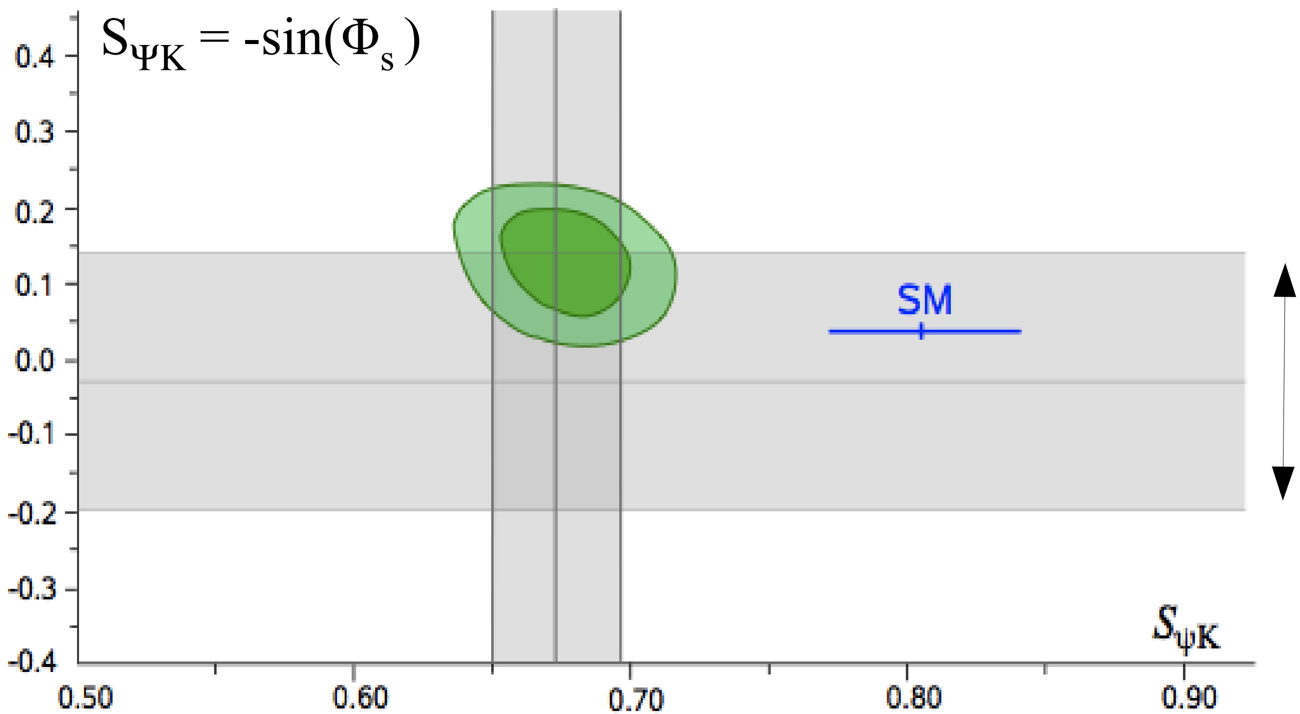
Phenomenological implications

Two clean predictions for the LHC:

I. Small non standard CPV in B_s mixing

$$S_{\Psi K}^{SM} = 0.041 \pm 0.002$$

$$S_{\Psi K}^{U(2)} = 0.12 \pm 0.05$$



1σ, prelim. LHCb result (LP2011)

$$-\Phi_s^{exp} = -0.03 \pm 0.16 \pm 0.07$$

Not easy to distinguish form the SM, but not impossible...

A few words to thank Luciano...

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But maybe not everybody is aware of the fact he is also a great teacher...

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Twenty-one years ago, during my last year as undergraduate student in physics, I dared to ask the diploma thesis to Luciano.

I had very little ideas of what particle physics is, and was a bit scared to ask the thesis to him. But after following Luciano's course on Theoretical Physics I had no doubt this was the right thing to do.

The course ended several days late, with a program ranging from QED to the path integral formulation of QFT, including a set of special lectures on SSB held by Goldstone himself (*probably these days these are three separate courses...*)... definitely the most exciting course in physics I ever attended !

(incidentally, only two of us showed up at the first call for the exam...)

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- the passion for comparing theory and data;
- the interest to work in different fields of physics;
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Many thanks and Happy Birthday Luciano!