Flavour Physics beyond the Standard Model

Gino Isidori
[*INFN, Frascati*]

- The two main open questions in flavour physics
- Fall and rise of "non-standard signals" in flavour physics
- News from the high-energy frontier (*the "natural" SUSY spectrum*)
- Future prospects (*the key role of LFV & EDMs*)
- Conclusions

The two main open questions in flavour physics

To a large extent, the origin of "flavour" is still a mystery...

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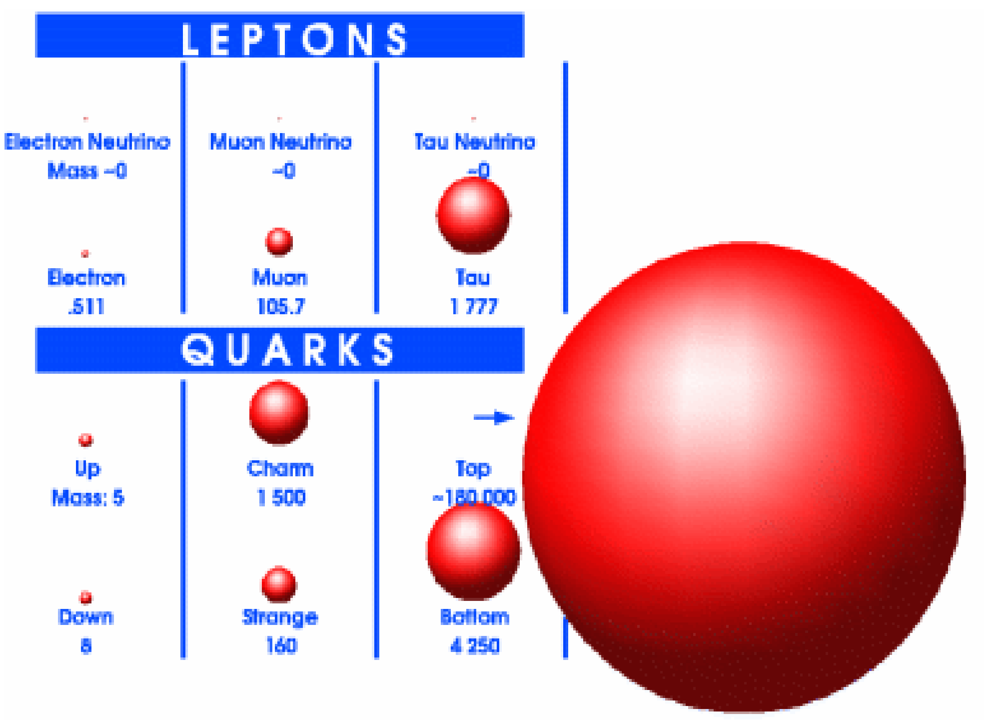
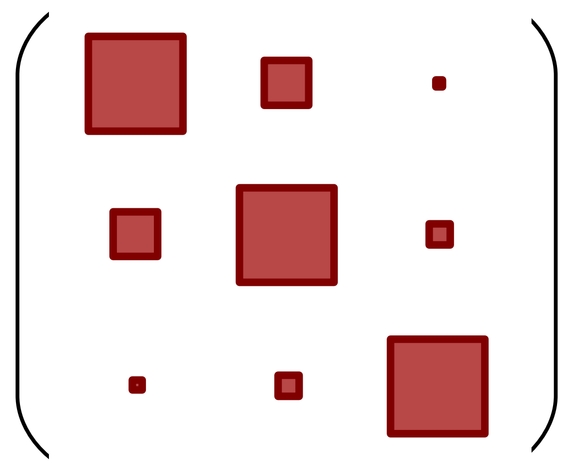
Our "ignorance" can be summarized by the following two open questions:

- *What determines the observed pattern of masses and mixing angles of quarks and leptons?*

- *Which are the sources of flavour symmetry breaking accessible at low energies?*



$V_{CKM} \sim$ 

The two main open questions in flavour physics

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Answers to this question are usually obtained by means of

- New (flavour) symmetries
- New dynamics (e.g. fermion profiles in extra dimensions)

Several plausible options on the market, with no outstanding case.

It is quite easy to reproduce the observed mass matrices in terms of a reduced number of free parameters, while it is difficult to avoid problems with FCNCs (without some amount of fine-tuning).

Hard to make progress without knowing the ultraviolet completion of the SM.

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- *Which are the sources of flavour symmetry breaking accessible at low energies?*
  [Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

Answering this question is more easy:

- It can be formulated independently of the UV completion of the theory.
- It is mainly a question of precision (both on the theory and on the experimental side).

⬇

Main goal of flavour-physics in the early LHC era

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High-Intensity Frontier

↕

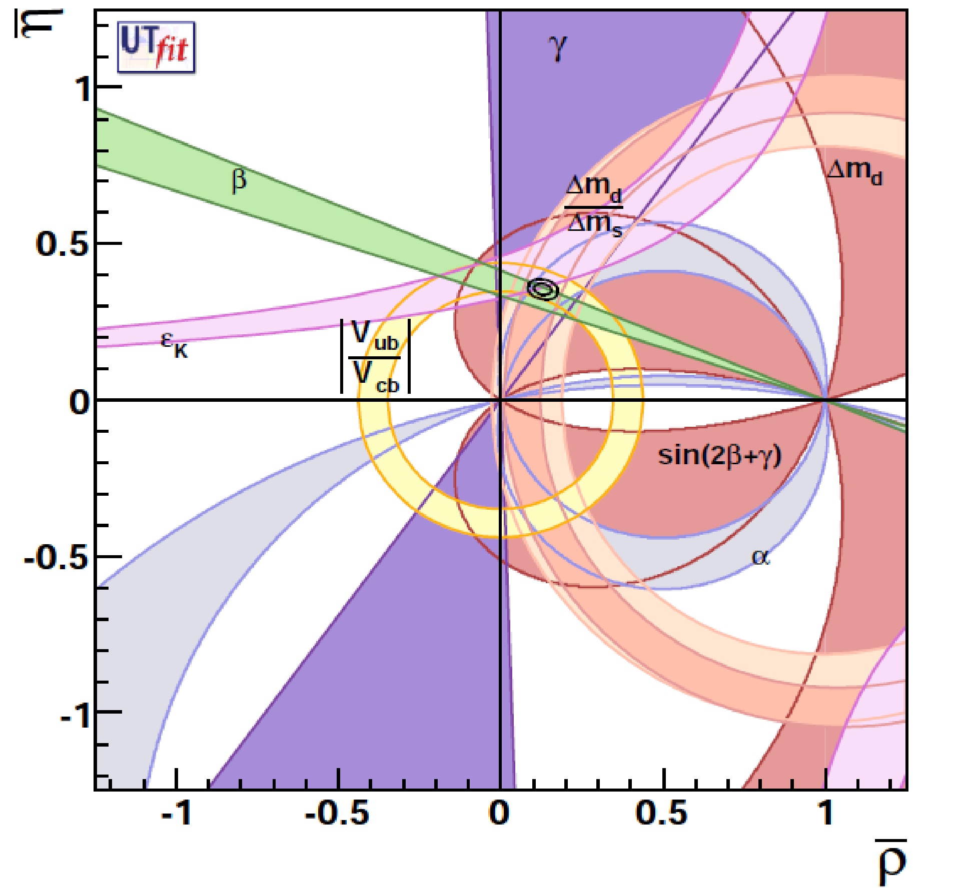
- *What determines the Fermi scale?*

- *Is there anything else beyond the SM Higgs at the TeV scale?*

High-Energy Frontier

Which are the sources of flavour symmetry breaking accessible at low energies?

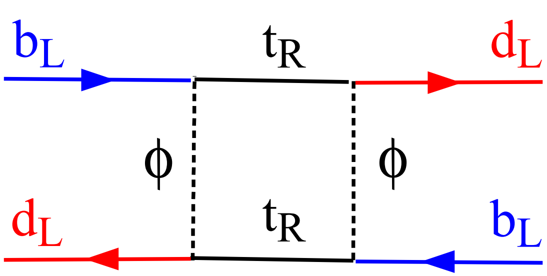
The measurements of quark flavor-violating observables show a remarkable overall success of the CKM picture



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

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

tiny SM contribution (Yukawa interaction)



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

Which are the sources of flavour symmetry breaking accessible at low energies?

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

G.I, Nir, Perez '10

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} ($\Lambda = 1$ 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; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	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}
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⬇

New flavor-breaking sources at the TeV scale (if any) are highly tuned

Which are the sources of flavour symmetry breaking accessible at low energies?

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

The problem is at least as severe in the lepton sector:

$$\frac{c_{\mu e}}{\Lambda^2}\, \bar{e}_L \sigma^{\mu\nu} \mu_R \phi F_{\mu\nu}$$

$$\Lambda > 2\times10^5\ \text{TeV} \times (c_{\mu e})^{1/2} \quad \text{from} \quad \text{BR}(\mu\to e\gamma)^{\rm exp} < 2.4\times10^{-12}$$

MEG '11

New flavor-breaking sources at the TeV scale (if any) are highly tuned

Which are the sources of flavour symmetry breaking accessible at low energies?

The good overall consistency of the experimental constraints appearing in the so-called CKM fits seems to indicate there is not much room for new sources of flavour symmetry breaking

⬇

Minimal Flavor Violation paradigm:

The $\boxed{\mathrm{U}(3)^5 = \mathrm{U}(3)_Q \times \mathrm{U}(3)_U \times \mathrm{U}(3)_D \times \mathrm{U}(3)_L \times \mathrm{U}(3)_E}$ <u>flavor symmetry</u> of the SM gauge sector is <u>broken only by the Yukawa couplings</u>: $Y_D \sim \bar{3}_Q \times 3_D$ $Y_U \sim \bar{3}_Q \times 3_U$ $Y_E \sim \bar{3}_L \times 3_E$

\+ *neutrino mass terms*

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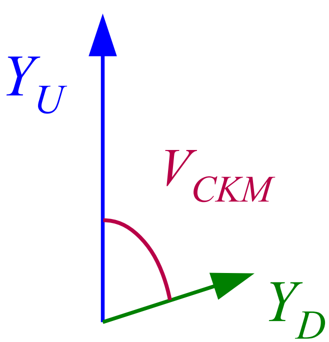
+ *neutrino mass terms*

Chivukula & Georgi, '89

D'Ambrosio, Giudice, G.I., Strumia, '02

Cirigliano, Grinstein, G.I., Wise, '05



- The CKM matrix controls all flavor-changing phenomena in the quark sector
- Small effects in quark flavor-changing processes even for TeV new-physics
- LFV connected to neutrino masses (*more freedom but also more uncertainties...*)

Which are the sources of flavour symmetry breaking accessible at low energies?

The good overall consistency of the experimental constraints appearing in the so-called CKM fits seems to indicate there is not much room for new sources of flavour symmetry breaking. However....

The MFV hypothesis is very unlikely to be exact.
Most likely, it is only an approximate low-energy property => important to search for possible deviations (even if tiny) from MFV predictions.

Even if MFV holds , it does not imply negligible effects in flavour physics (especially in the lepton sector !!)

On the other hand, it is clear that is not easy to firmly establish deviations from the SM => need for high precision and th.-clean observables...

This conclusion, which was already quite clear after LEP & various low-energy experiments, has been substantially reinforced by the first LHC results.

Fall and rise of "non-standard signals" in flavour physics

Before the summer we had well-motivated th. arguments (+ a few exp. hints) pointing to large deviations from the SM in selected B physics observables:

- Hope of large $B(B_s \to \mu\mu)$ from various SUSY models
- Hope and hints of large B_s mixing phase

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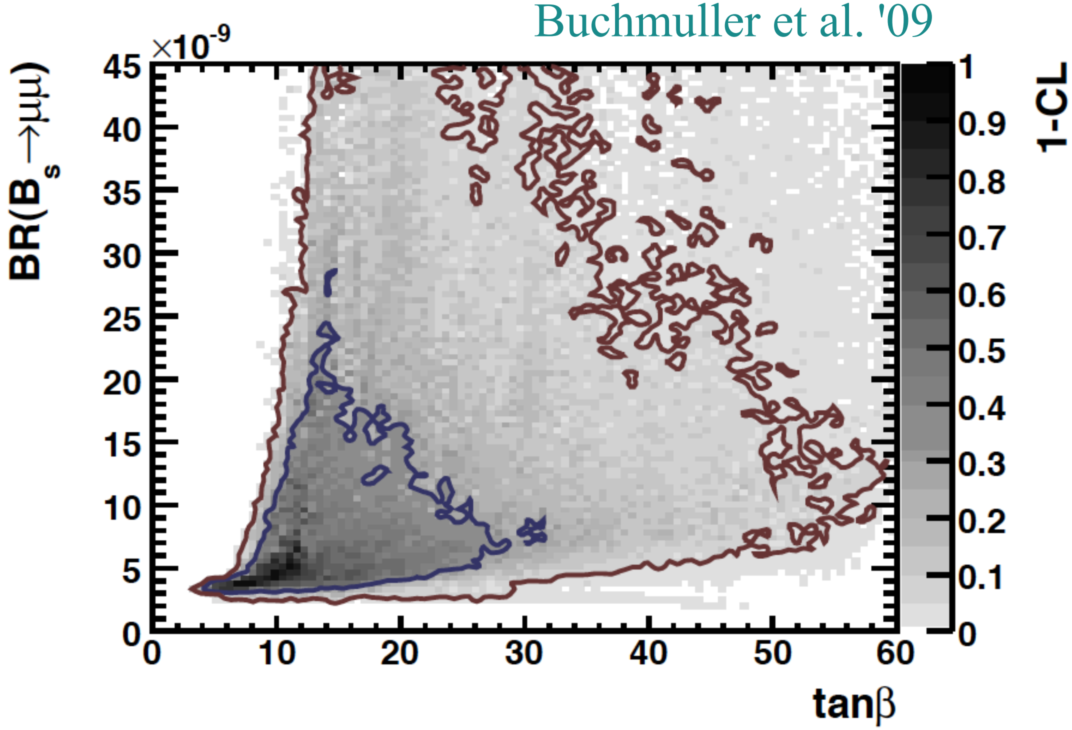
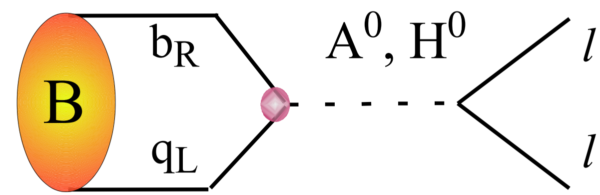
Buchmuller et al. '09





$$A(B \to ll)_H \sim \frac{m_b\, m_l}{M_A^{\,2}} \, \frac{\mu\, A_U}{\tilde{M}_q^{\,2}} \, \tan^3\beta$$

Possible large enhancement even in MFV, even in constrained MSSM, provided large μ and large $\tan\beta$

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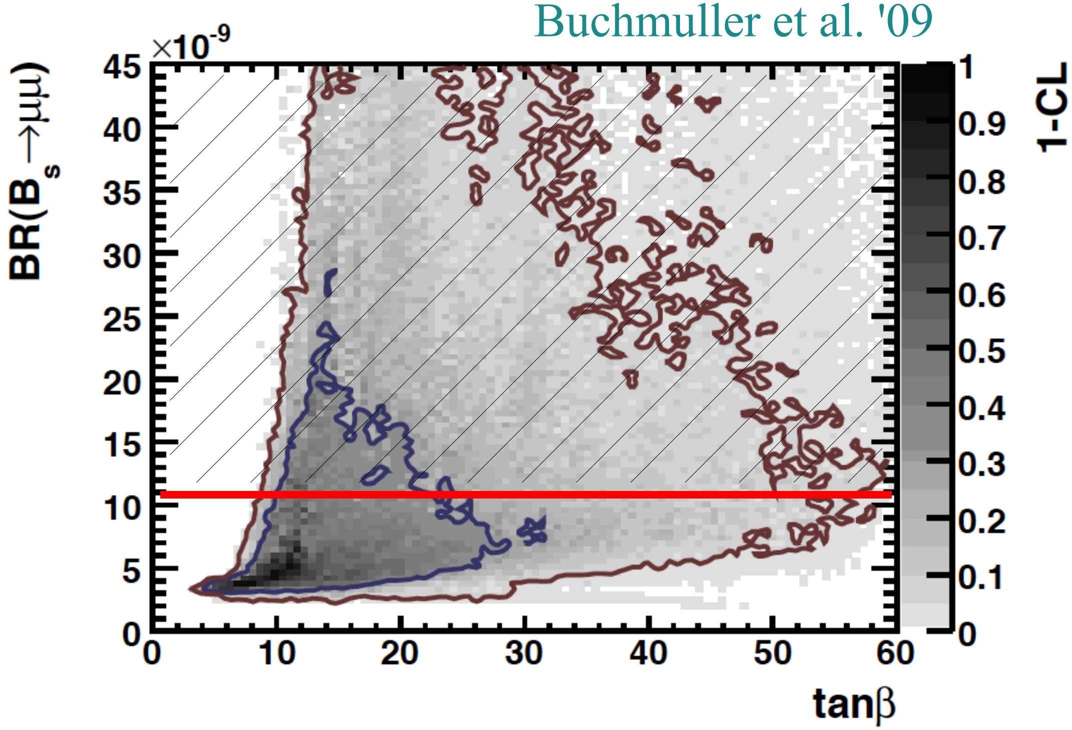
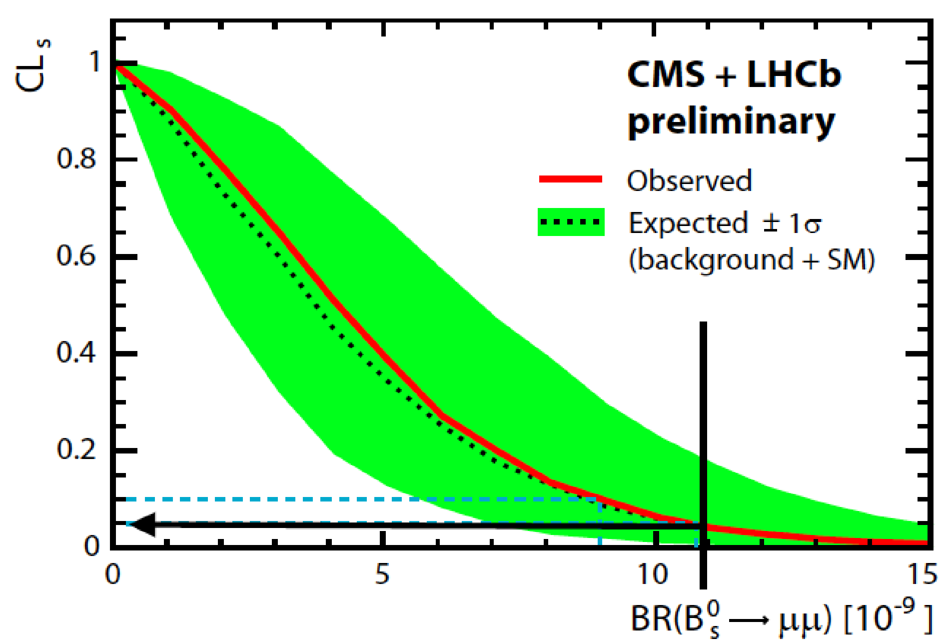


G. Raven, LP '11



< 11×10^{-9} @ 95% CL

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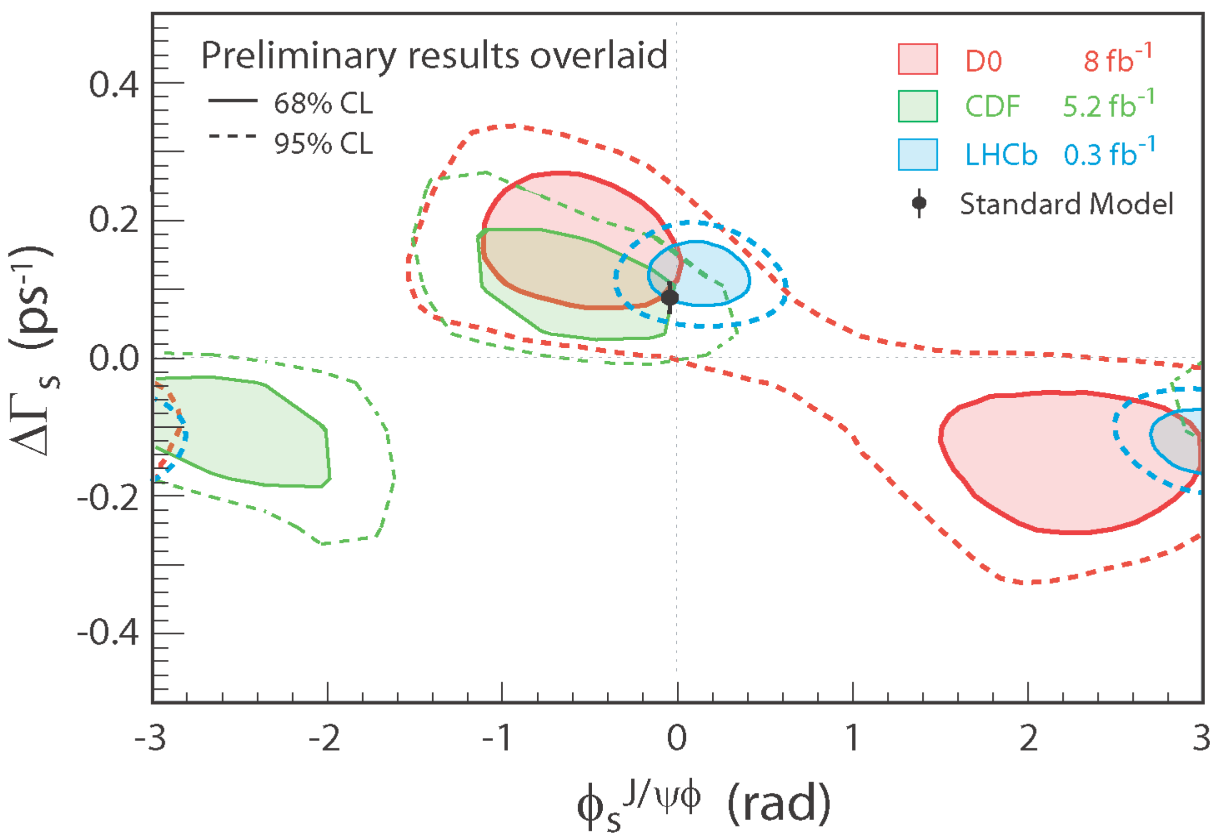

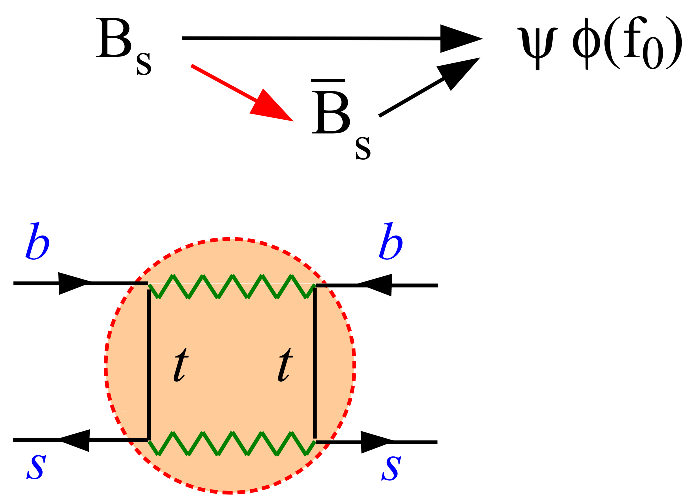

Tiny asymmetry if the phase is determined only by the Yukawa couplings

Fall and rise of "non-standard signals" in flavour physics

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- $BR(B_s \to \mu\mu)$
- B_s mixing phase

➡ *still very interesting, but high-precision is needed (no large effects)*

On the other hand, an old anomaly in the CKM fit [ε_K vs. $\sin(2\beta)$ tension] has been partially reinforced

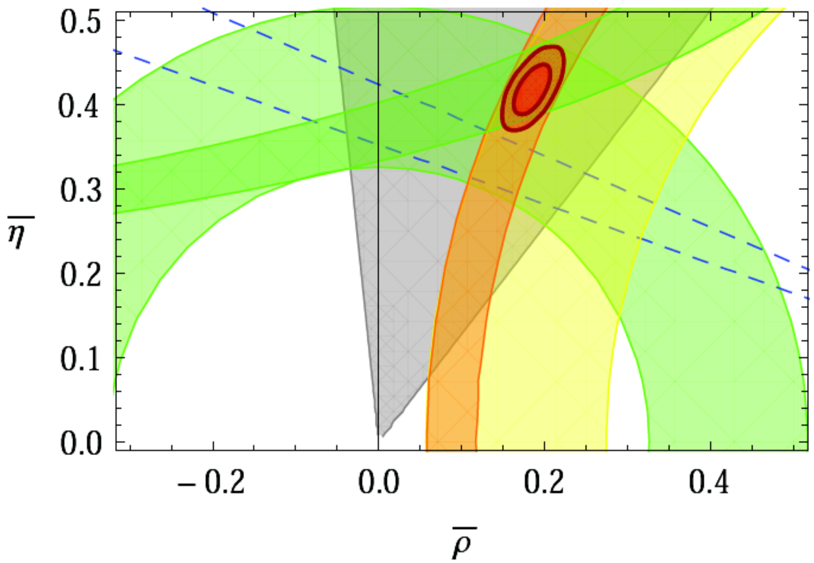
and a surprisingly large evidence of (direct) CP violation has been observed in the charm system [$\Delta a_{CP} = a_{KK} - a_{\pi\pi}$]

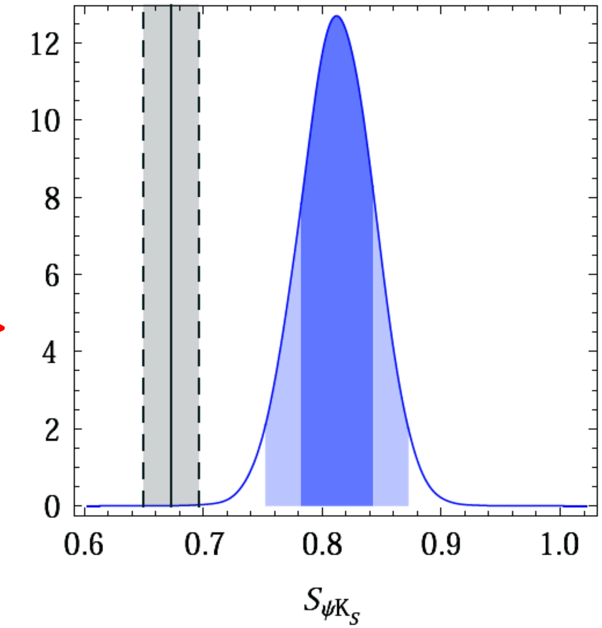
N.B.: both "anomalies" (if any...) are beyond MFV

The ε_K vs. $\sin(2\beta)$ tension in the CKM fit

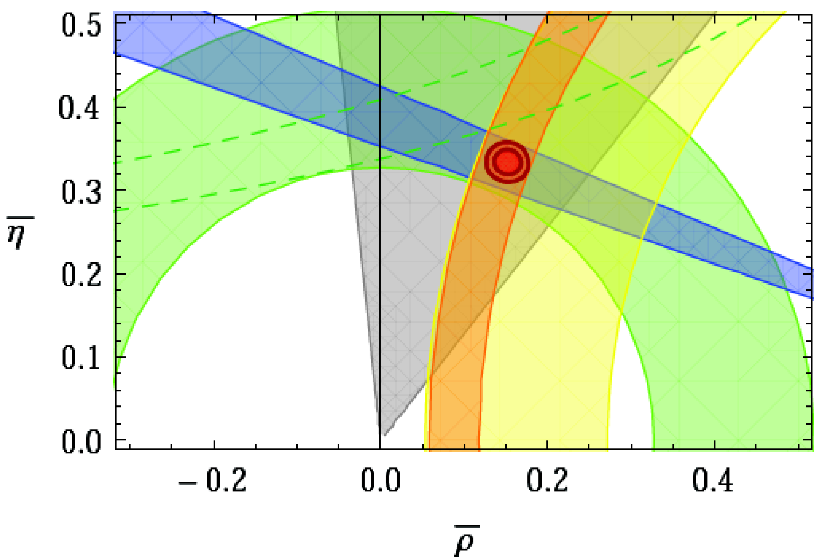
Barbieri *et al.* '11

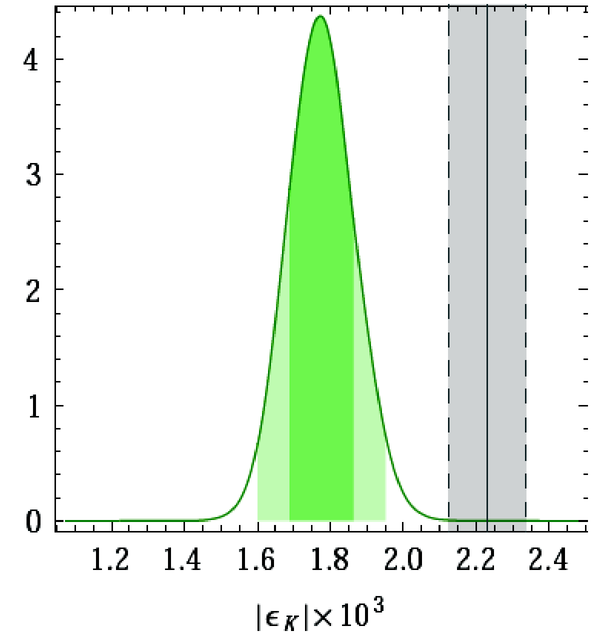
I. SM fit,
no $S_{\psi K}$
(no B-meson mixing phase, measured via $B\to\psi K$)





II. SM,
no ε_K
(no K-meson mixing phase)





Similar results by CKMfitter & UTfit

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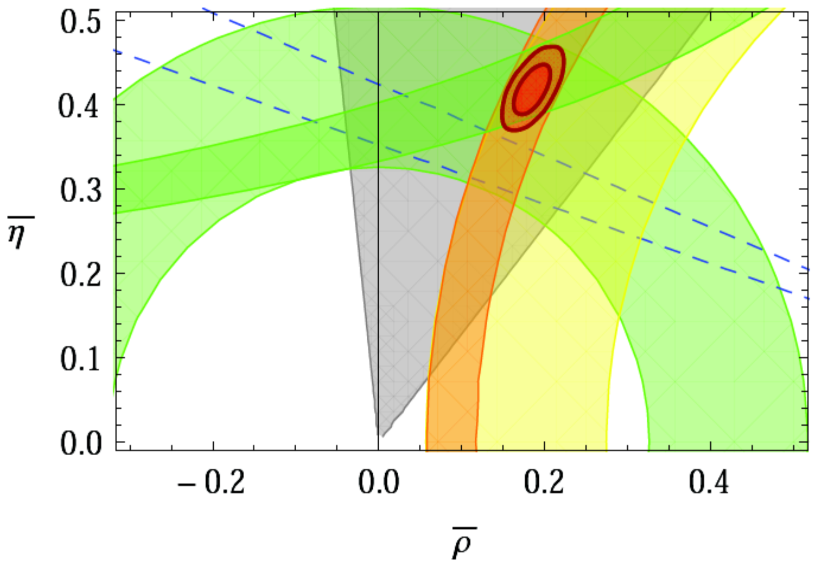

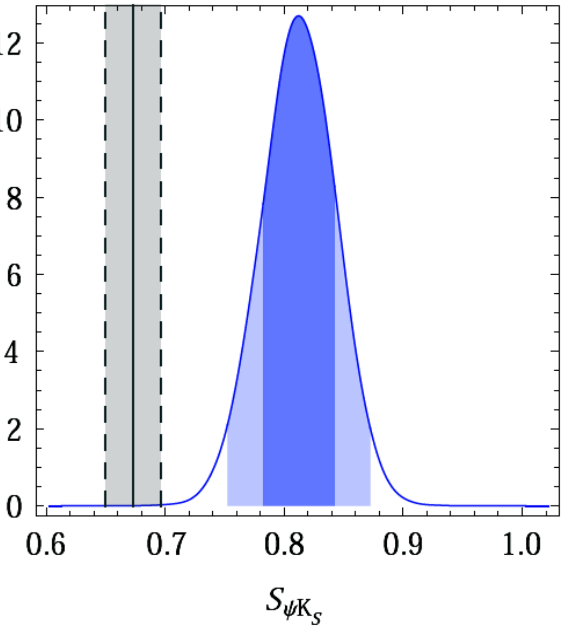

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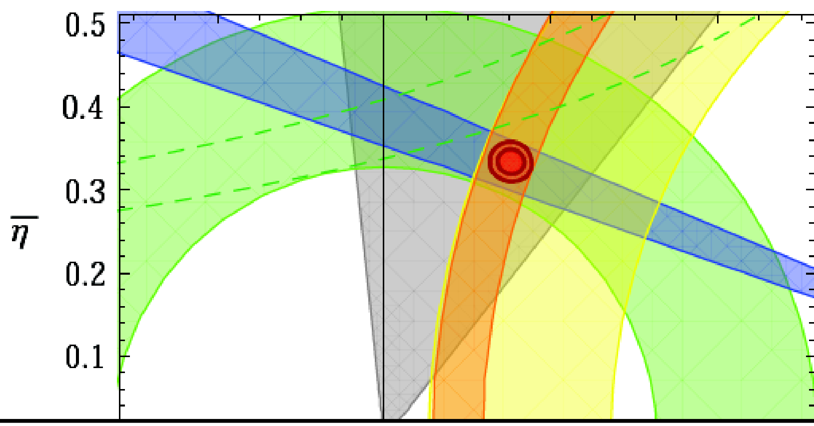

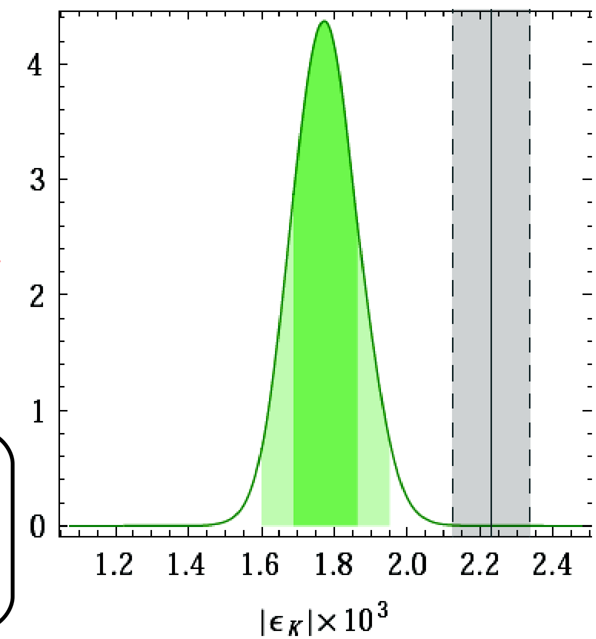

The "tension" has recently been reinforced by precise lattice data relevant to ε_K

CPV in Charm

The evidence of CPV in charm observed at LHCb is the news of the year! (*beside superluminal issues…*)

$$\Delta a_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-} = -(0.82 \pm 0.21 \pm 0.11)\%$$

Unambiguos evidence of direct CP violation:

$$a_{\rm CP}^{\rm (dir)} = \frac{\Gamma(\mathrm{D}\to\mathrm{PP}) - \Gamma(\overline{\mathrm{D}}\to\mathrm{PP})}{\Gamma(\mathrm{D}\to\mathrm{PP}) + \Gamma(\overline{\mathrm{D}}\to\mathrm{PP})}$$

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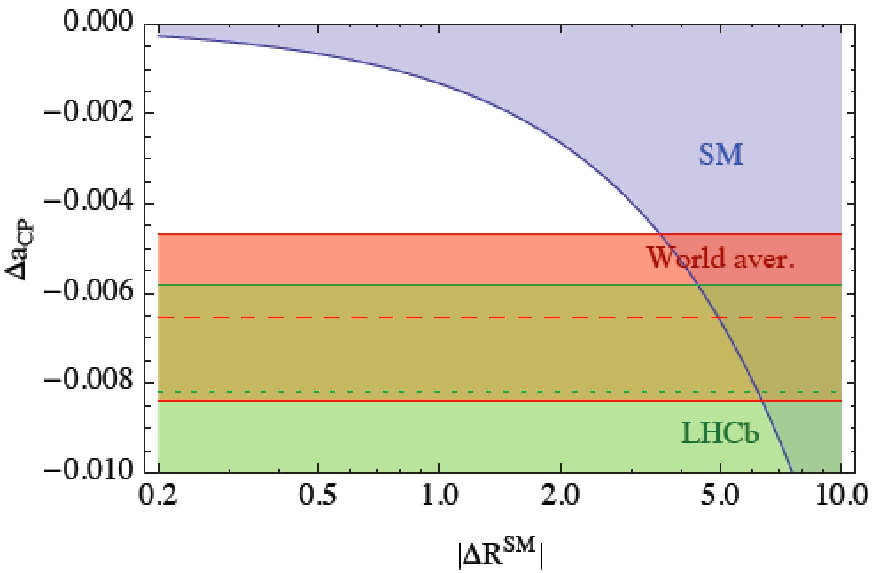
On general grounds, the charm system is quite complicated due to sizable non-perturbative effects (no hope to discover NP in CP-conserving observables). However, it can allow interesting null SM tests in CPV observables. Best example: CPV in D-D mixing above 0.1%.

The recently observed (direct) CPV asymm. is "border-line"...

$$\Delta a_{CP} \approx (0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}})$$

Model-independent suppression due to CKM strucutre

Ratio of "penguin" disconnedted/treel-level amplitudes (naivley expected < 1)



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...it is beyond the natural expectation within the SM [Grossman, Kagan, Nir '09]. However, it is not possible to proof is non-SM from first principles: it could be the result of large non-perturb. effects [Golden, Gristein, '89; Brod, Kagan & Zupan '11].

...it fits well within specific new-physics frameworks [G.I., Kamenik, Ligeti, Perez '11; Giudice, G.I, Paradisi, 12; Althmansofer *et al.* '12]: key information about the breaking of flavour symmetries in the right-handed up-type sector

News from the high-energy frontier (the “natural” SUSY spectrum)

In the meanwhile, the following two key messages arrived from the high-energy frontier:

- The Higgs boson is likely to be around 125 GeV (*in the “SUSY” region...*)
- No large signal of physics beyond the SM in pp collisions at 7 TeV.

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⬇

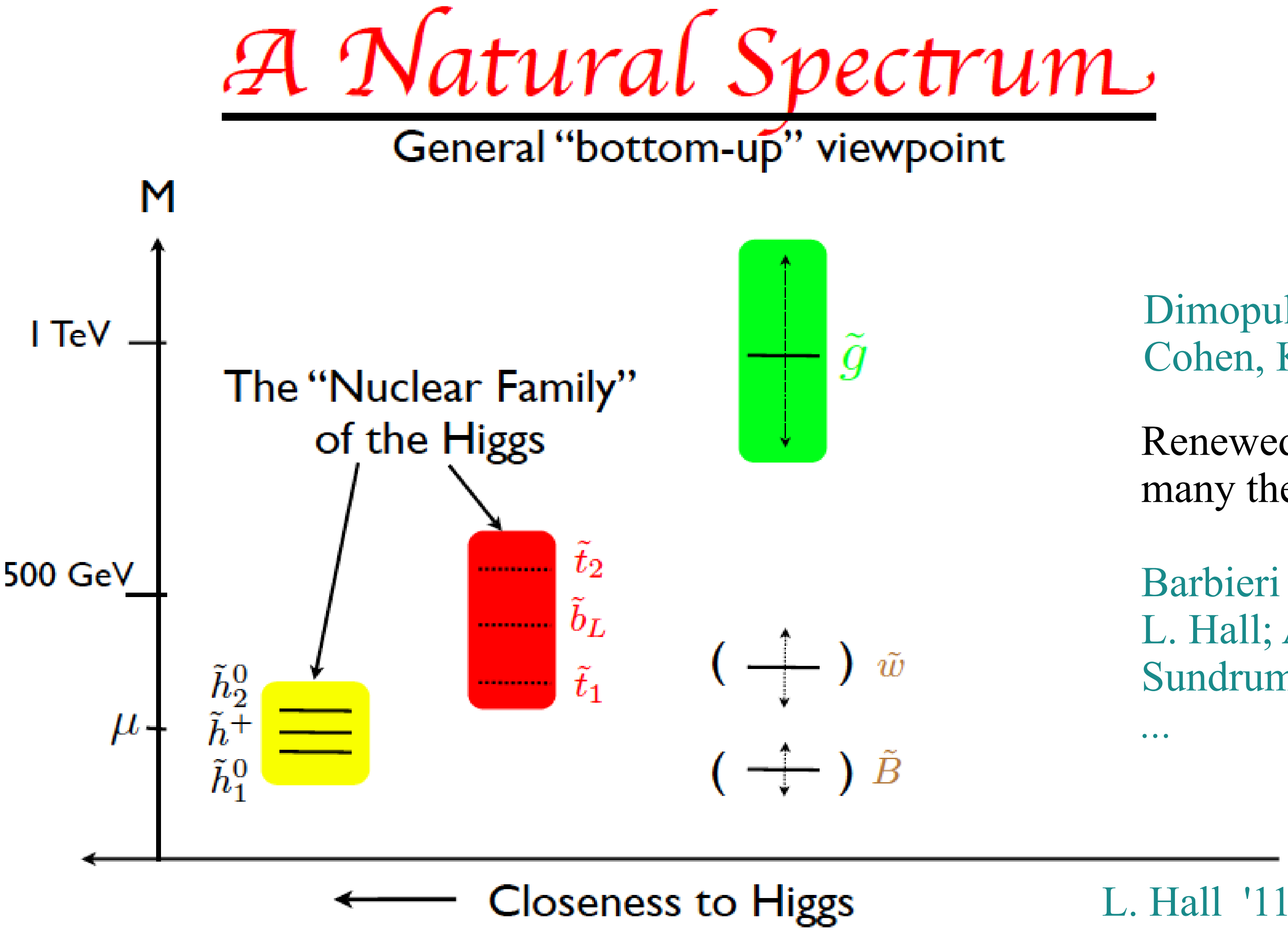
Supersymmetry remains a very good candidate (*shares of supersymmetry are definitely rising with respect to those of composite-Higgs models or extra-dimensions*): weakly coupled theory + light Higgs

But the SUSY spectrum cannot be (almost) degenerate, as in the most popular versions of the MSSM, and in MFV (otherwise too-large fine-tuning in m_h).

⬇

Supersymmetry with "split families" (3^{rd} gen. light, 1^{st} & 2^{nd} well above 1 TeV) is emerging as a very appealing possibility

News from the high-energy frontier (the “natural” SUSY spectrum)



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

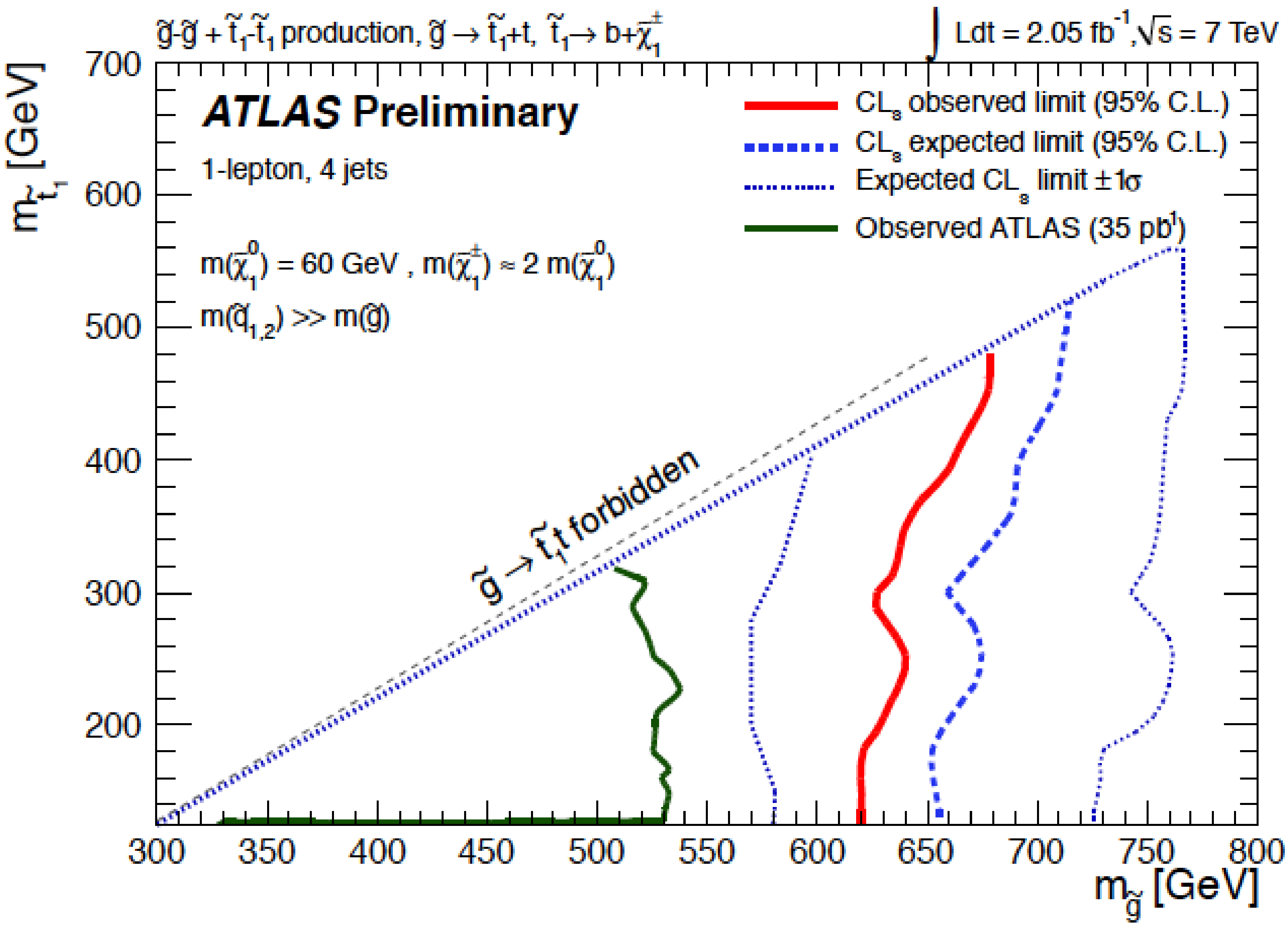
Renewed recent interest by many theorists:

Barbieri *et al.*,
L. Hall; Arkani-Hamed,
Sundrum *et al.*
...

L. Hall '11

- Only 3rd gen. squarks and Higgsinos need to be light to avoid tuning (in m_h)
- With heavy 1st & 2nd gen. squarks less “flavour problem” + easy to escape susy searches at LHC

<u>News from the high-energy frontier</u> (the “natural” SUSY spectrum)



▶ *News from the high-energy frontier* (the “natural” SUSY spectrum)

SUSY with split families does not fit well with the idea of MFV (at least in its minimal version), which would predict an almost degenerate squark spectrum (small splitting due to Yukawa couplings).

However, it offers an interesting prospects for

- solving some of the open problems of MFV
- addressing the existing anomalies in the quark sector (ε_K vs. $\sin(2\beta)$ tension & Δa_{CP})
- observing clear non-standard signals in other observables, most notably LFV in charged leptons and nuclear EDMs

⬇

Low-energy flavor physics is definitely non trivial

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)

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)

Both issues can be improved with "split-family susy" + flavor symmetry acting only on 1st & 2nd generations

Natural suppression for 1st & 2nd gen. edms of quarks and leptons

Partial explanation for *Y* hierarchies (3rd gen. Yukawas allowed by the flav. symmetry)

<u>MFV virtue</u> *<u>Split-family SUSY</u>*

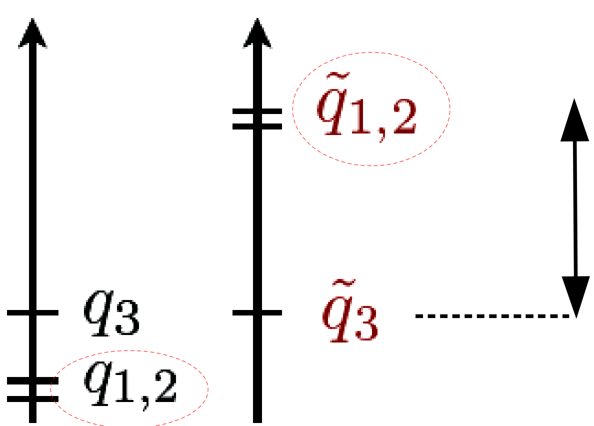
Naturally small effects in FCNC observables

Natural suppression for 1^{st} & 2^{nd} gen. edms of quarks and leptons

Partial explanation for *Y* hierarchies (with help of flav. symm.)

Split family SUSY with a $U(2)^3 = U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}$ flavour symmetry

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11
[Pomarol, Tommasini, '96; Barbieri, Dvali, Hall, '96]



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

Exact symmetry is a good approximation
($m_u = m_d = m_s = m_c = 0$, $V_{CKM} = 1$) => only <u>small breaking</u>

MFV virtue

Split-family SUSY

Naturally small effects in FCNC observables

Natural suppression for 1^{st} & 2^{nd} gen. edms of quarks and leptons

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Split family SUSY with a $U(2)^3 = U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}$ flavour symmetry

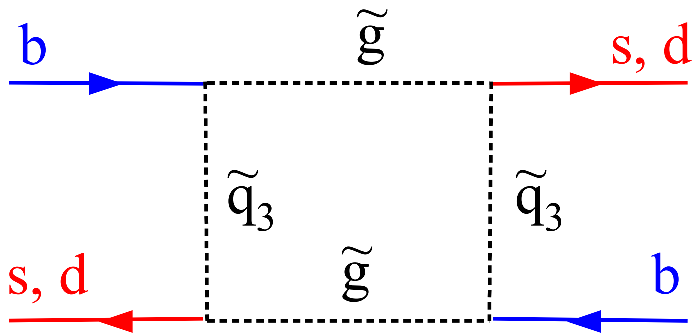
Split family SUSY with "disoriented A terms"

Giudice, G.I., Paradisi '12
[Nomura, Stolarski, '08-'09]

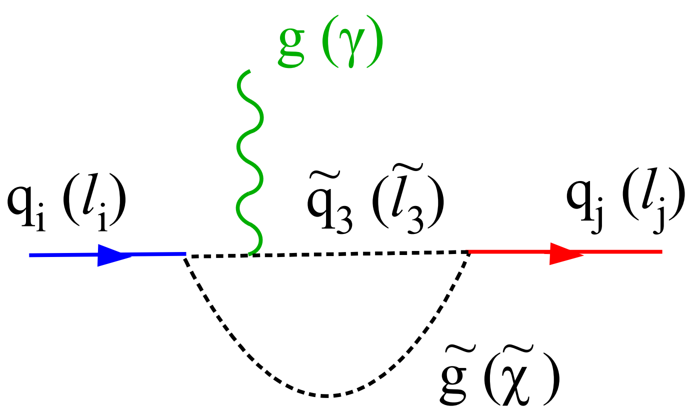
- The origin of flavor is all "confined" in the L-R mixing (Yukawas & A terms)
- Y & A are both proportional to quark & lepton masses, but are not perfectly aligned: potentially larger sources of flavour symmetry breaking, still compatible with existing bounds.

In both cases we expect interesting non-standard effects mediated by the exchange of the 3rd generation of squarks and leptons.

E.g.:



Possible solution of the "ε_K - sin(2β) tension"



Possible contribution to Δa_{CP} but also to LFV & edms

Split family SUSY with $U(2)^3$

Two clean predictions for the LHC:

I. Small non standard CPV in B_s mixing

$$S_{\psi\phi}^{U(2)} = 0.07 - 0.20$$

$$\left[\ S_{\psi\phi}^{SM} = 0.041 \pm 0.01\ \right]$$

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

II. Relatively "light" gluinos and 3rd generation squarks

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

Compatible with present
ATLAS & CMS data,
within their near-future reach

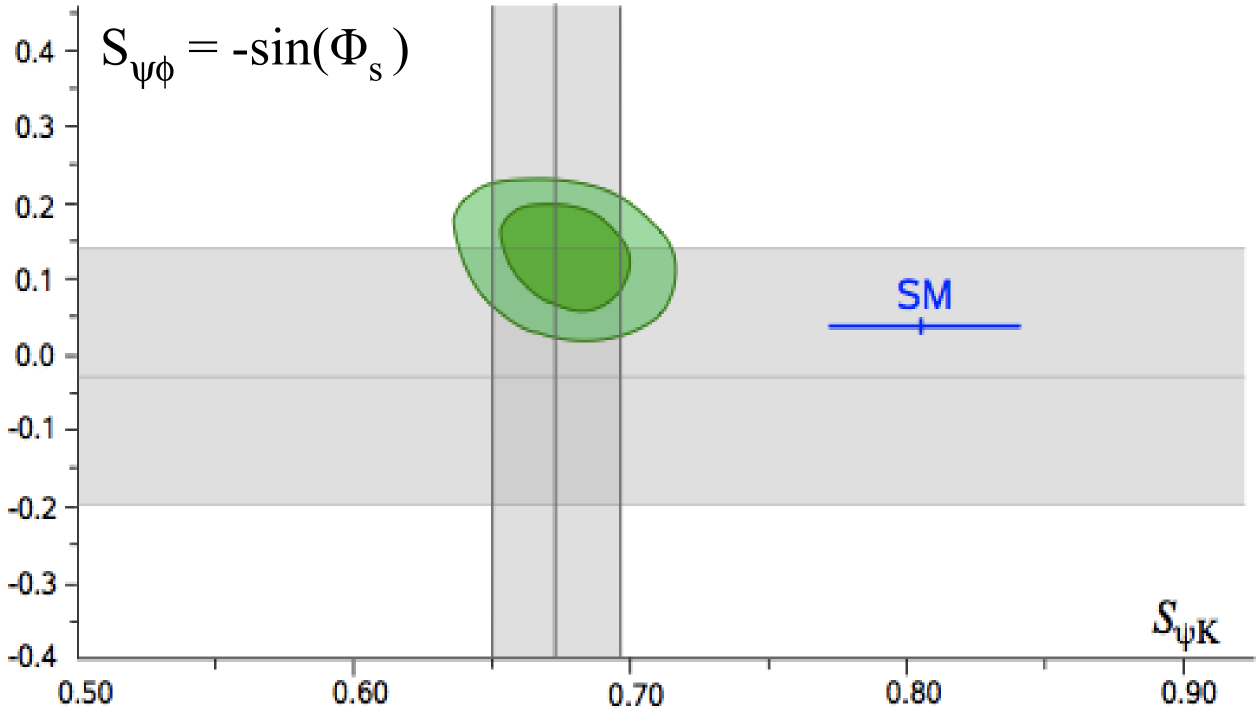
Split family SUSY with $U(2)^3$

Two clean predictions for the LHC:

I. Small non standard CPV in B_s mixing

$S^{U(2)}_{\psi\phi} = 0.07 - 0.20$

$S^{SM}_{\psi\phi} = 0.041 \pm 0.01$



1σ, prelim. LHCb result (LP2011)

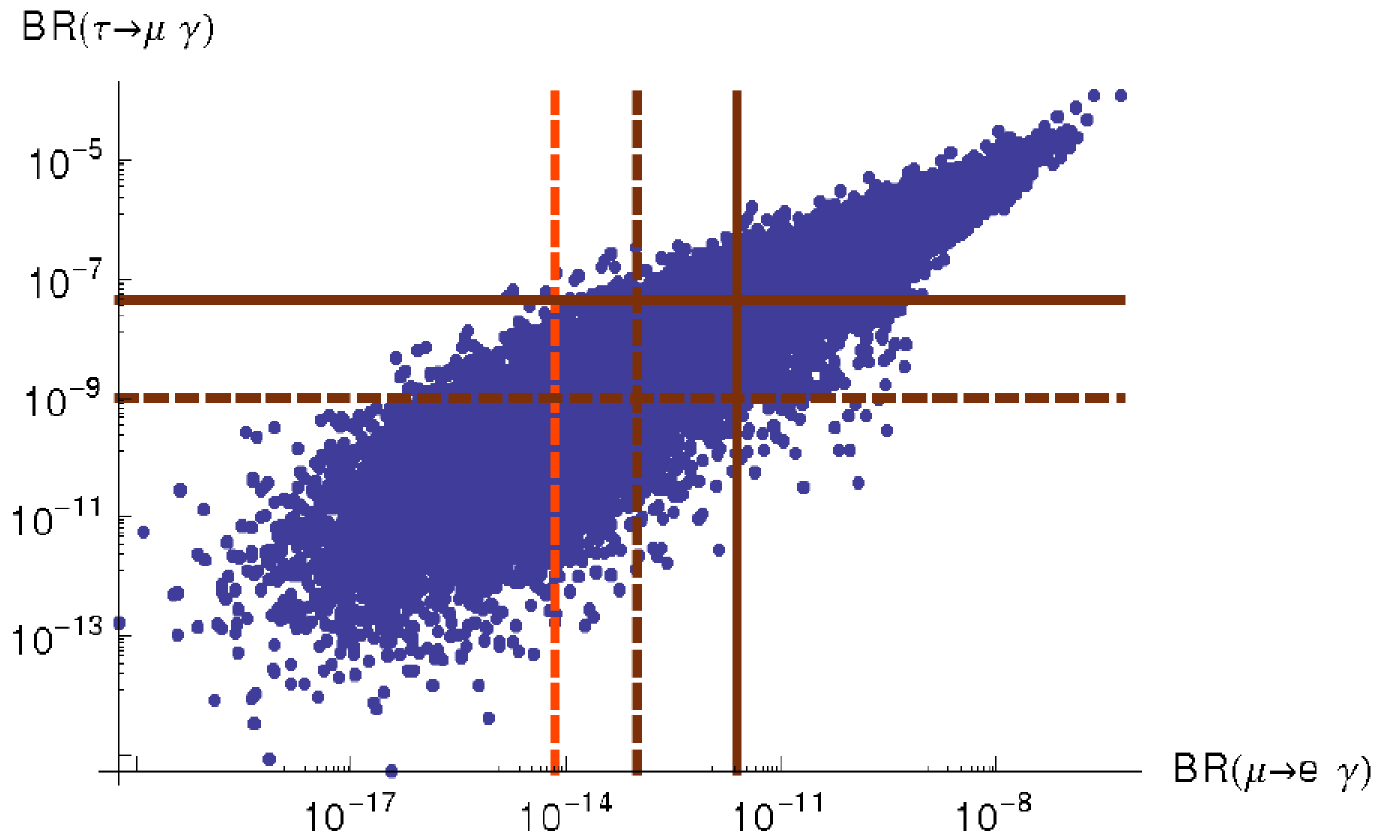
$-\Phi_s^{exp} = -0.03 \pm 0.16 \pm 0.07$

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

Representative example of the type of non-standard effects we should search for in the more "conservative" NP models.

Split family SUSY with U(2)^3

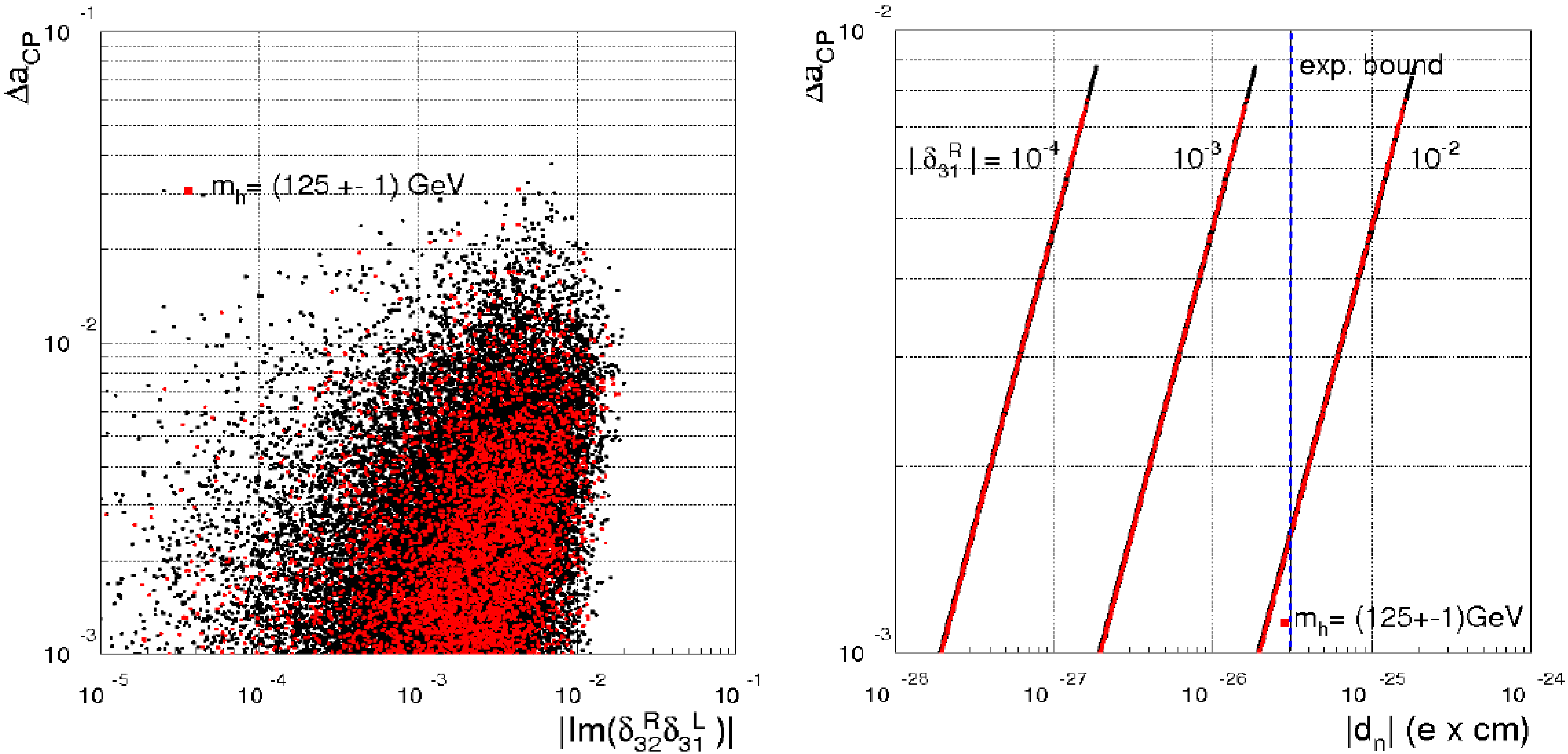
And potentially very clean signals also for MEG:



Blankenburg, G.I., Jones-Perez, work in prog.

Split family SUSY with "disoriented A terms"

Strong correlation between Δa_{CP} and d_n (neutron edm), which provide the strongest constraint on the model):



Giudice, G.I., Paradisi '12

Future prospects

General decomposition of flavour-violating observables:

$$A = A_0 \left[c_{SM} \frac{1}{M_W^{\,2}} + c_{NP} \frac{1}{\Lambda^2} \right]$$

trivial kinematical factors

(adimensional) effective couplings

This decomposition is very general: it holds for both for forbidden processes ($\tau\to\mu\gamma$, $\mu\to e\gamma$) and precision measurements

It is based only on the assumption that the new degrees of freedom respect the $SU(2)_L \times U(1)$ gauge symmetry

Future prospects

General decomposition of flavour-violating observables:

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- The sensitivity to the energy scale grows slowly with the statistics or the luminosity of the experiment ($\sigma \sim 1/N^{1/4}$)
- The interest of a given flavour obs. depends on the magnitude of c_{SM} vs. c_{NP} and on the theoretical error of c_{SM} => concentrate on clean & rare processes
- No way to disentangle Λ & c_{NP}, but the combined information which can be extracted is fully complementary to direct searches at high-p_T: flavour symmetry structure of NP

Future prospects (a personal view)

"Minimalistic" set of key flavour-physics observables:

- γ and V_{ub} (for a clean tree-level determination of the CKM matrix)
- Clean rare B & K decays, especially & $B_{s,d} \to l^+ l^-$ & $K \to \pi\nu\nu$
- Precise determination of CPV in B_s mixing
- Deeper study of CPV in charm
- Improved searches for LFV in charged leptons
- Improved searches for EDMs of both leptons and nuclei

LFV in charged leptons

After what we learned from neutrino physics, LFV in charged leptons is probably the most interesting search in the flavour sector:

Neutrino oscillations

New [non-CKM] flavour mixing structures

New d.o.f. at high scales [see saw mechanism]

$$m_\nu \sim Y_n^T \frac{v^2}{M_R} Y_n$$

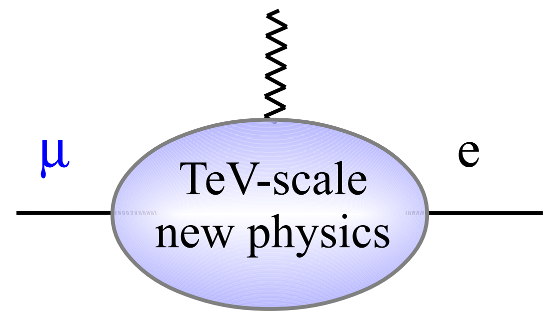
Grand Unified Theories

New physics ~ TeV [stabilization of the GUT/electroweak hierarchy]

LFV in charged leptons close to the present exp. bounds

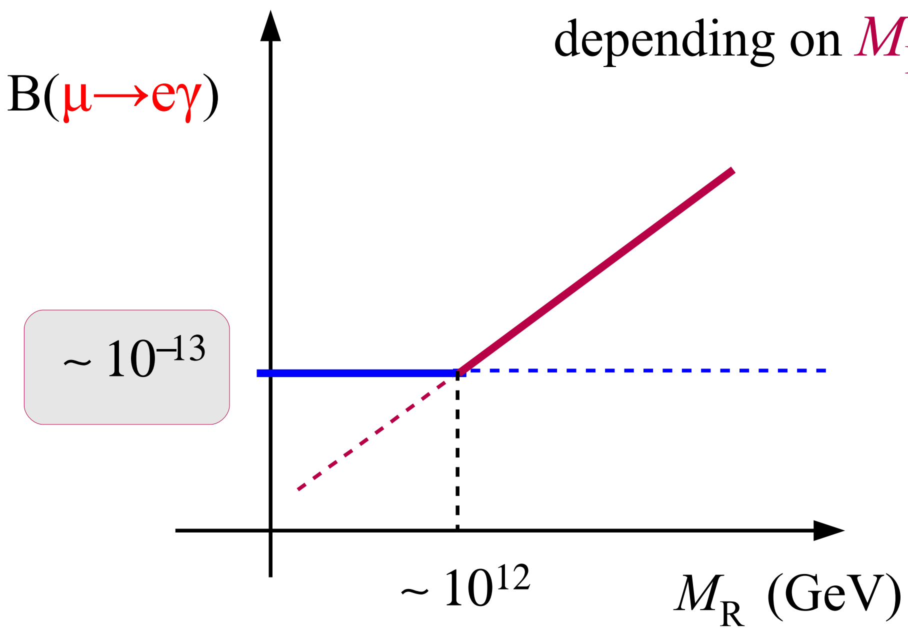
In non-GUT theories we can arbitrarily suppress LFV rates by lowering M_R (or the normalization of Y_n). This is not possible in GUT frameworks => contribution from quark Yukawas which are M_R-independent

$$A(\, l_i \text{->}\, l_j\, \gamma) = a\, [Y_e\, Y_n^{\,+} Y_n]_{ij} + b\;\, [Y_U^{\,+} Y_U\, Y_D\,]_{ij}$$



Normalization depending on M_R

M_R independent

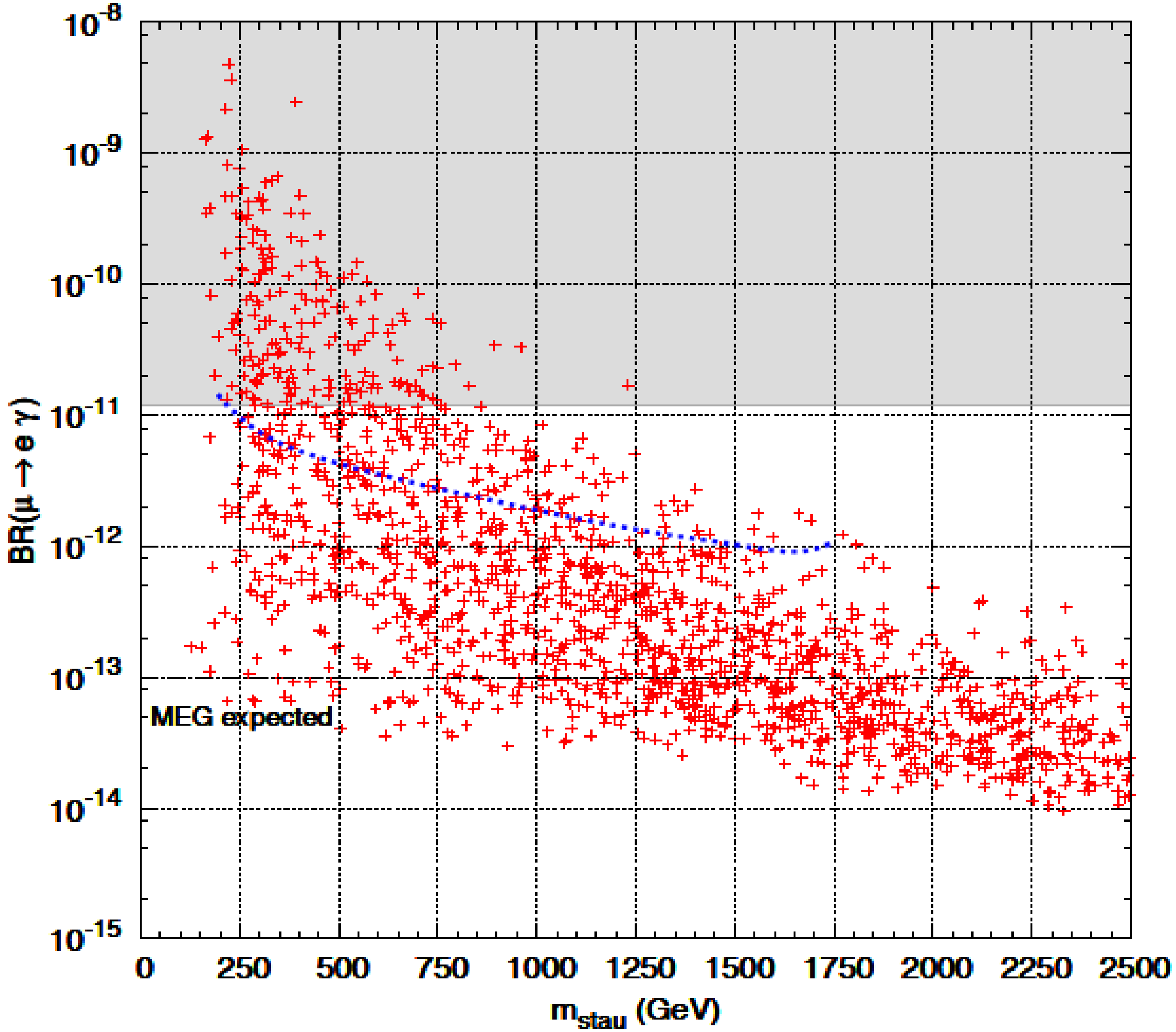


In GUT theories with new particles carrying lepton-flavor at the TeV scale (*e.g. the sleptons in the MSSM*)

MEG has high chances to see μ→eγ (*but remember that* $\Gamma \sim \Lambda^{-4}$)

Despite 10^{-12} - 10^{-13} is naturally the ball park for $\mu \rightarrow e\gamma$ in GUT models, O(1) numbers can make a dig difference

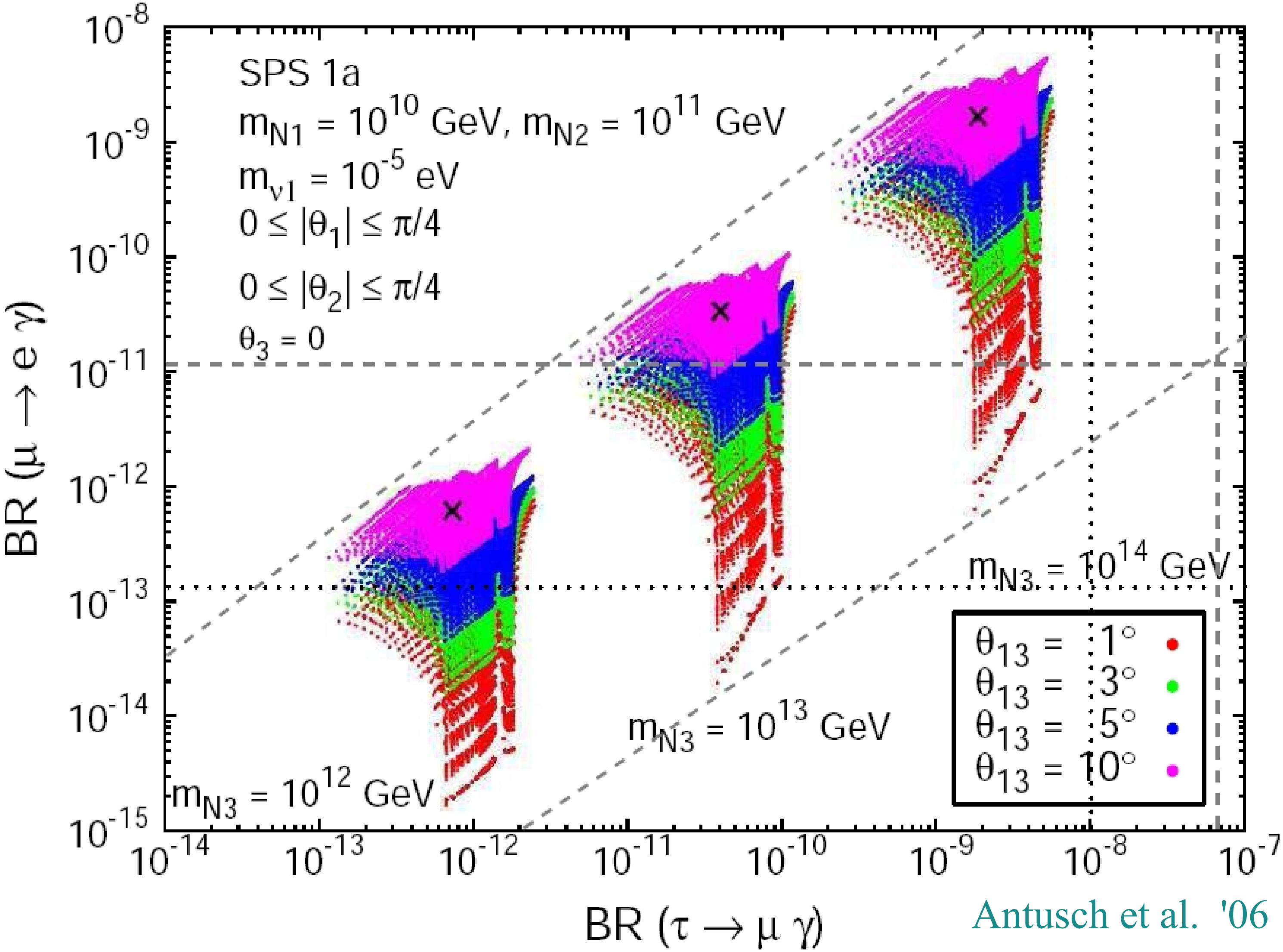
E.g.: SO(10) GUT with type-II see-saw



Calibbi et al. '09

In non-GUT models the uncertainty is even higher, but the recent evidence of non-vanishing θ_{13} is certainly a positive news.

E.g. : $\tau\to\mu\gamma$ vs. $\mu\to e\gamma$ in MSSM + heavy N_R [no GUT constraints]



Antusch et al. '06

Note that $B(\tau)/B(\mu) > 1$ but it cannot be arbitrarily large

if $B(\mu\to e\gamma) < 10^{-13}$ (not seen at MEG) little hopes to see $\tau\to\mu\gamma$ at SuperB

Conclusions

To a large extent, the origin of "flavour" is still a mystery...

...but we are making some progress:

- We have understood that large new sources of flavour symmetry breaking at the TeV scale are excluded

- The lack of large deviations from SM, even in suppressed observables, points toward protective flavour symmetry for 1^{st}-2^{nd} generations + weakly interacting NP at the TeV (coherent picture with e.w. precision tests + lack of large deviations at high-pT) => split-family SUSY emerging as a natural candidate

- In split family SUSY flavour physics some deviations from the SM in low-energy precisions observables are expected (flavour is not trivial!)

- Key tool to make progress in this field is to push forward the precision in the most clean observables: $\mu \to e\gamma$ and EDMs are excellent candidates => *full complementarity both between low-energy and high-pT physics and also between different low-energy facilities*