Outlook: future prospects in flavour physics
[*a personal perspective on NP searches in flavour physics*]

Gino Isidori [*INFN-Frascati*]

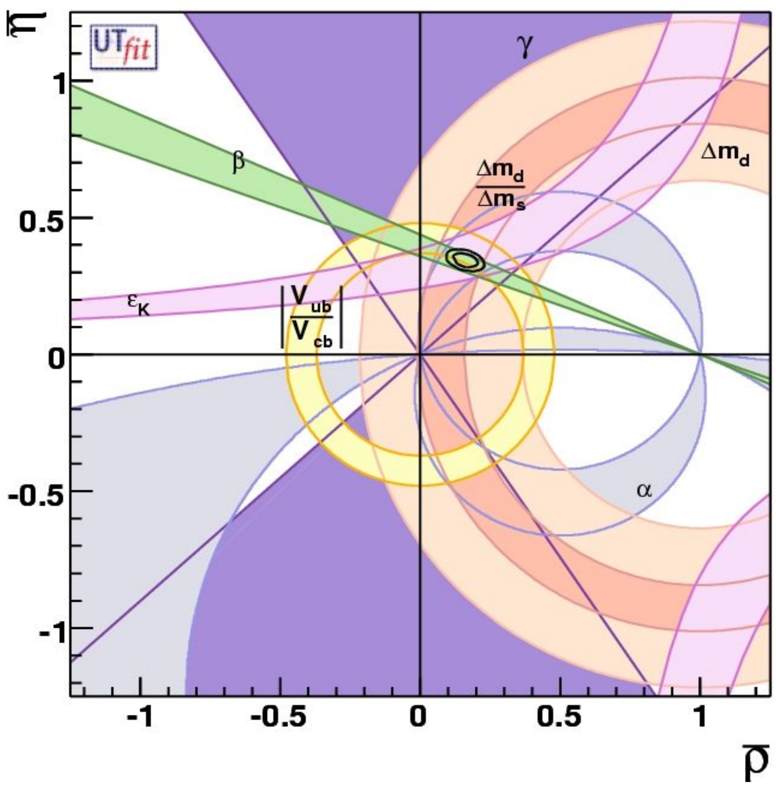
- Introduction
- The SM as an effective theory & the MFV hypothesis
- Flavour physics in the lepton sector
- Flavour physics in Grand Unified Theories
- Back to rare decays [$\mu \to e\gamma$ vs. $\tau \to \mu\gamma$; rare K decays]
- The large-tanβ scenario [rare B decays]
- Conclusions

Introduction

Despite the great success of B factories (both accelerators & detectors), so far the search for deviations form the SM in quark-flavour physics has been quite frustrating.

The situation is similar to the flavour-conserving electroweak sector (LEP physics):

- good knowledge of all the SM free parameters [quark masses & mixing angles]
- significant exp. tests of e.w. quantum corrections [boxes & penguins...]



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The situation is similar to the flavour-conserving electroweak sector (LEP physics):

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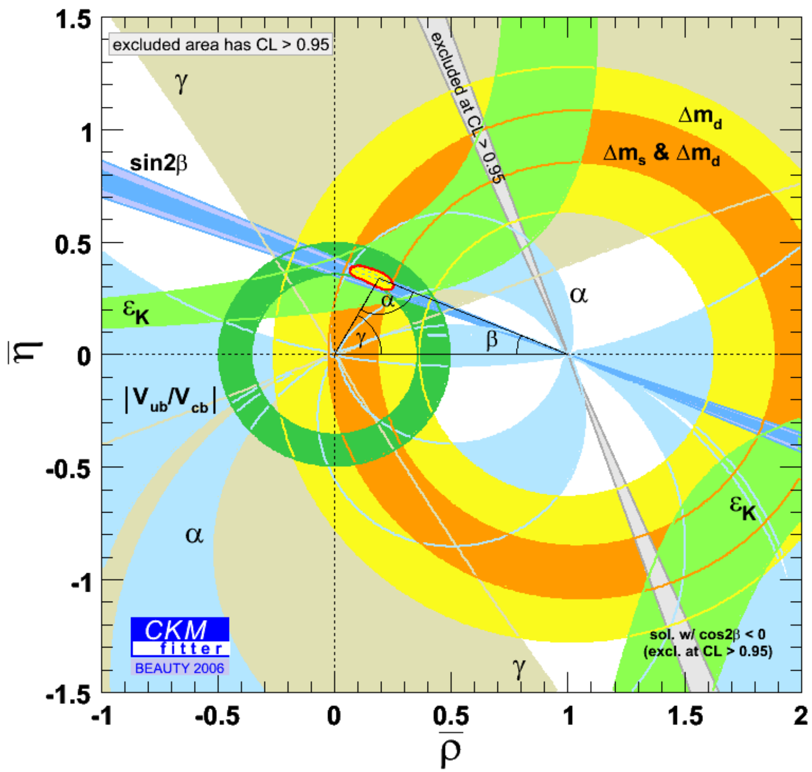
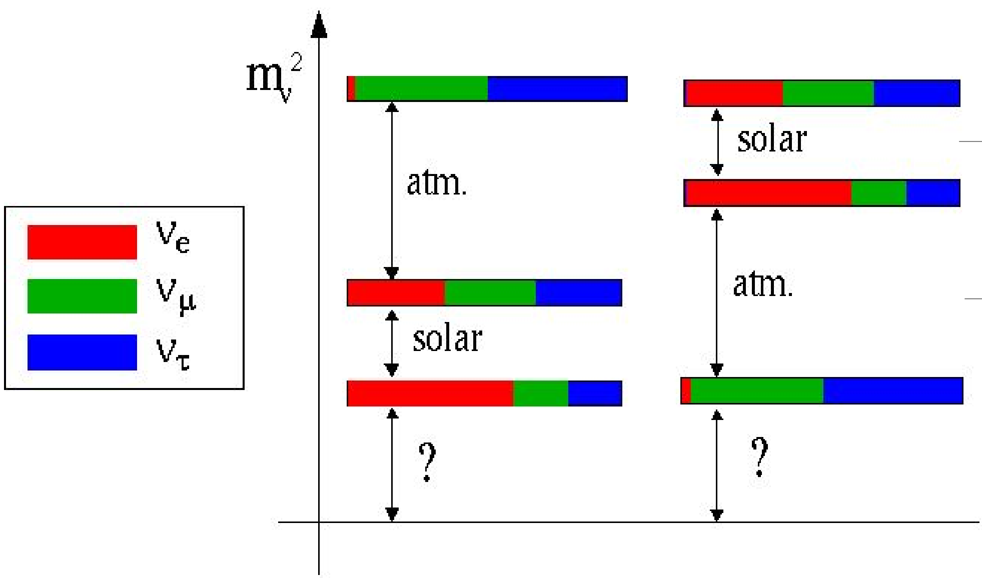
- significant exp. tests of e.w. quantum corrections [boxes & penguins...]
- but no deviations from the SM [indep. of graphical preferences & "statistical religions"...]

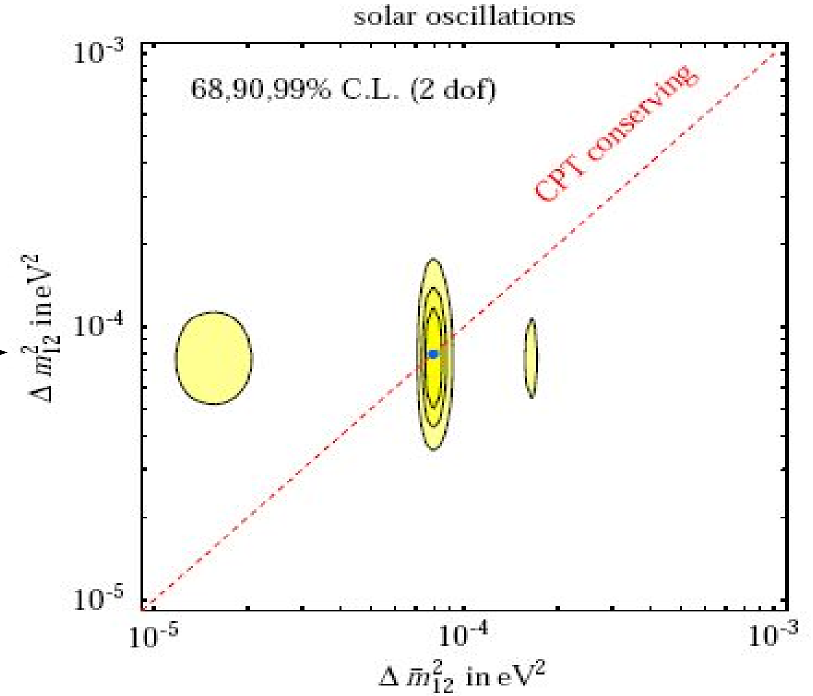


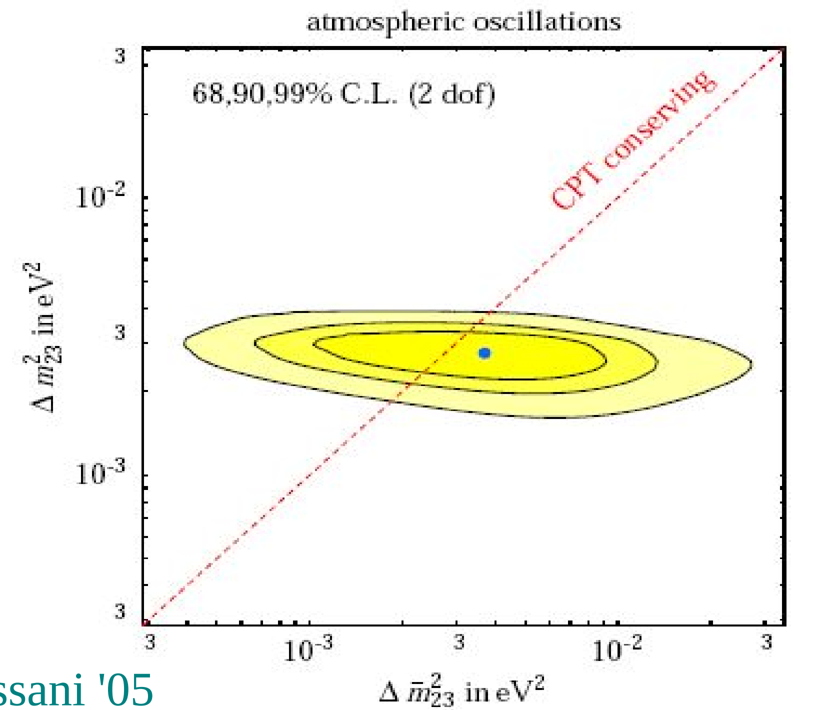
N.B.: This does not mean that we have not learned anything. Similarly to the e.w. precision tests, also flavour physics provides very significant constraints on New Physics.

So far, the other side of flavour physics (lepton-flavour physics) has definitely been more exiting...

The existence of physics beyond the SM and of new flavour-mixing structures has clearly been established by ν oscillations !







Strumia & Vissani '05

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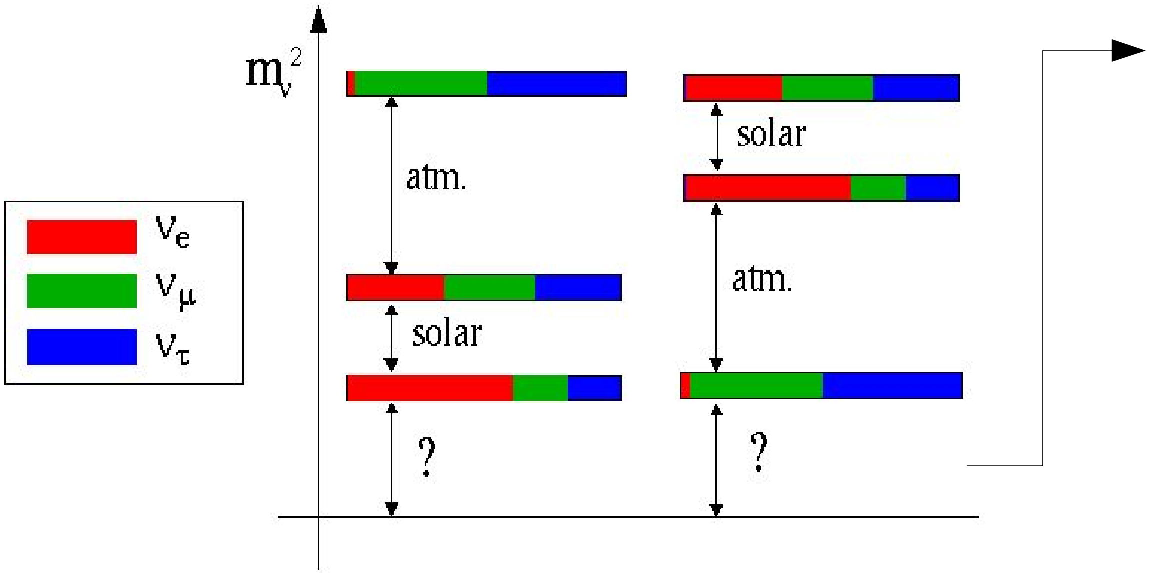
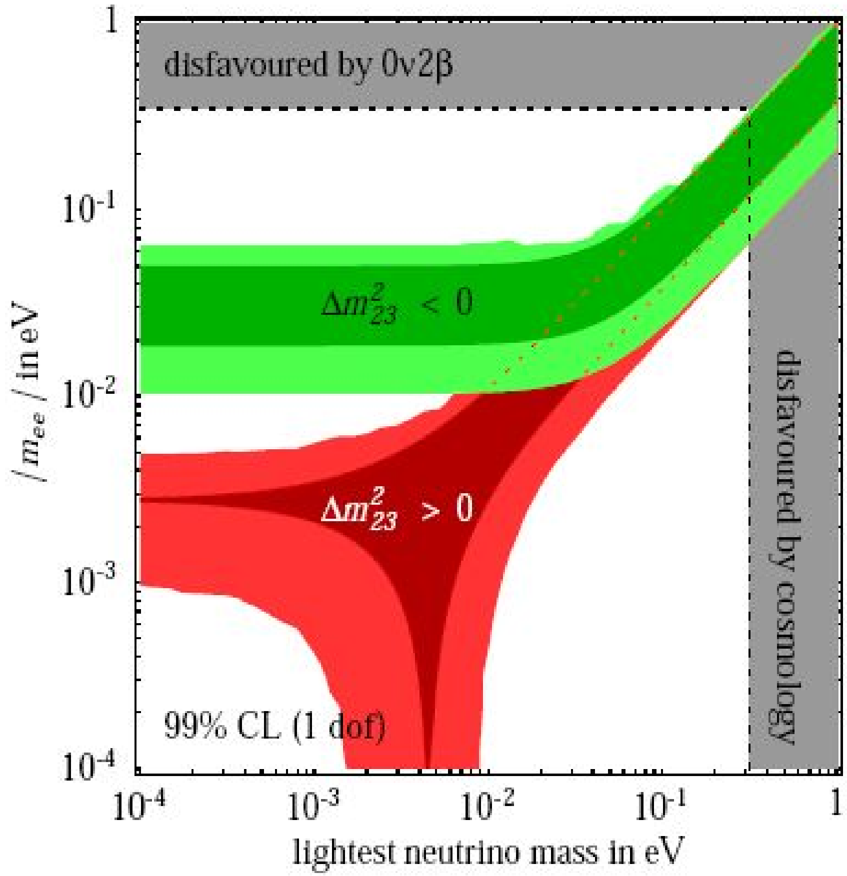


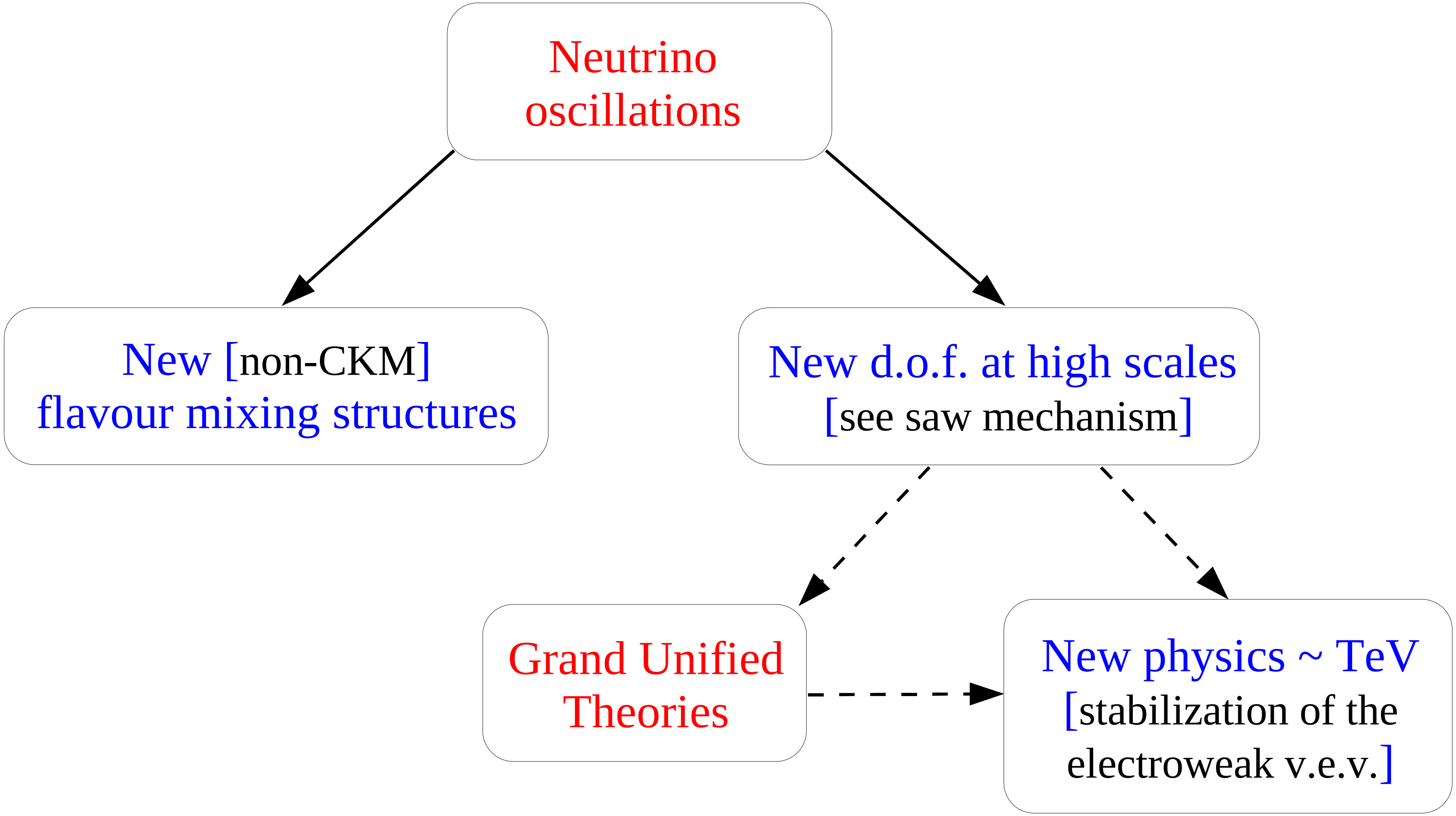


As I will discuss in the rest of this talk, the underlying mechanism at the origin of this phenomenon gives some realistic hopes to observe sizable non-standard effects also in quarks and charged-lepton rare decays

Neutrino oscillations

New [non-CKM] flavour mixing structures

New d.o.f. at high scales [see saw mechanism]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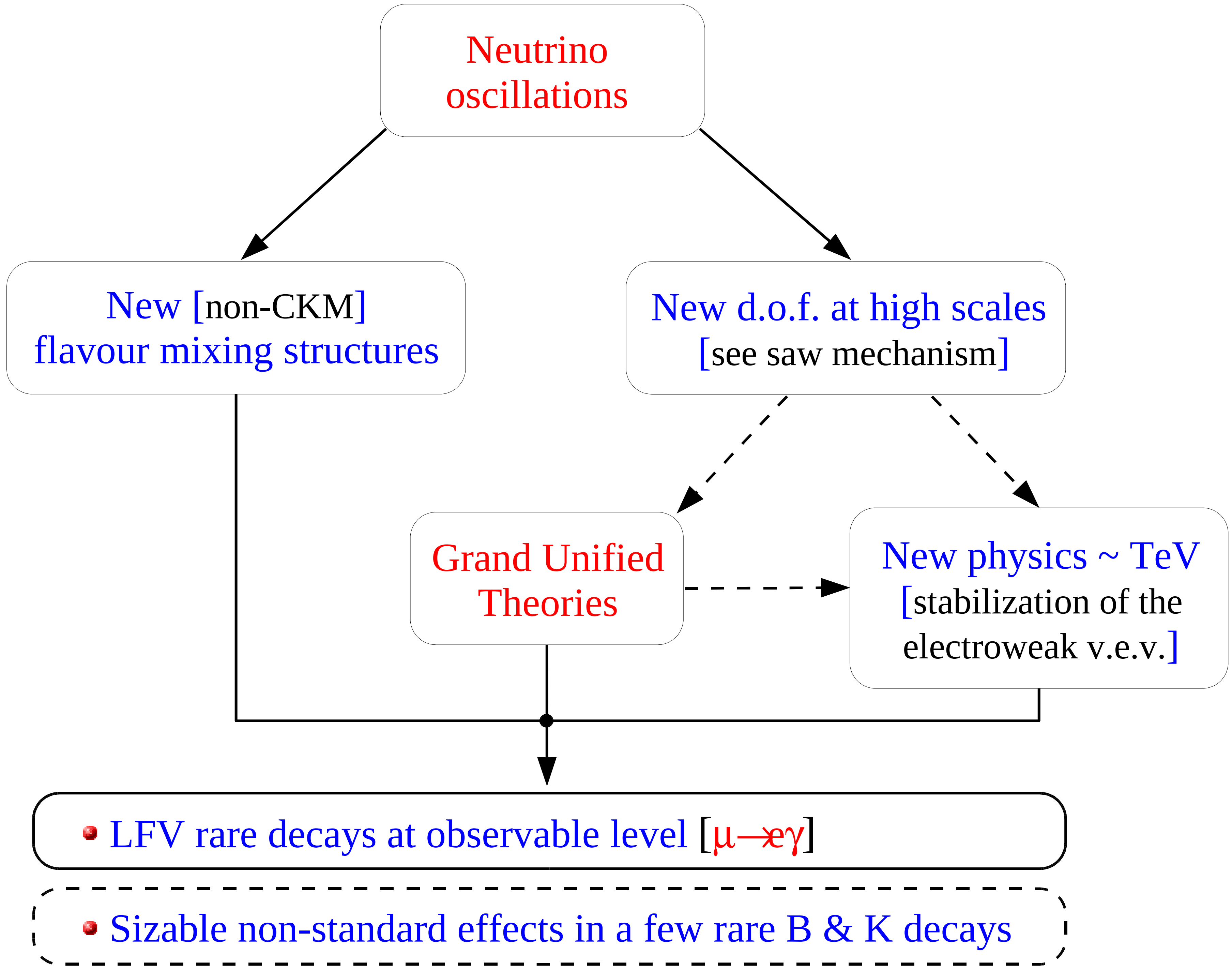
New physics ~ TeV [stabilization of the electroweak v.e.v.]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LFV rare decays at observable level [$\mu \to e\gamma$]
Sizable non-standard effects in a few rare B & K decays

The SM as an effective theory & the MFV hypothesis

The effects of new physics below the e.w. scale can be described in full generality by considering the SM as (the leading part) of an *effective field theory*:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm gauge}(A_k, \psi_i) + \mathcal{L}_{\rm Higgs}(\phi, A_k, \psi_i; Y, v) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\,d}(\phi, A_k, \psi_i)$$

$\mathcal{L}_{SM}$ = renormalizable part of $\mathcal{L}_{eff}$
[= all possible operators with d ≤ 4
compatible with the gauge symmetry]

most general parameterization
of the new (heavy) d.o.f.
as long as we perform
low-energy experiments

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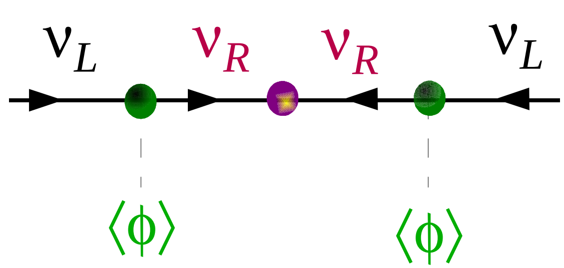
No neutrino masses (& mixing angles)

Neutrino oscillations provide the first evidence for a non-trivial term in this series

$$\frac{1}{\Lambda_{\rm LN}} (L_L{}^{\rm T})^i\, g_{LL}{}^{ik}\, L_L{}^k\, \phi^{\rm T} \phi$$

completely equivalent (but more general) of the usual see-saw mechanism [$M_{\nu_R} \sim \Lambda_{LN} \gg \langle\phi\rangle$]

$$(\nu_L{}^{\rm T})^i\, M_\nu{}^{ik}\, \nu_L{}^k$$



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The dim-5 operator responsible for neutrino masses is quite special since it violates *lepton number*

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$$\Downarrow$$

Natural to assume that this *symmetry of the pure SM Lagrangian* is broken at very high scales

- If $\Lambda_{\rm LN} \sim 10^{14}\text{-}10^{15}$ GeV some $g_{LL}^{\;ik}$ can be O(1) $\Rightarrow$ *natural* effective theory [no fine-tuning for the smallness of m_ν]
- Expected within known GUTs

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However, $\Lambda_{\rm LN}$ cannot be the only scale of NP [fine-tuning in the Higgs sector]

$\Rightarrow$ we also need $\Lambda \sim$ TeV to stabilize the $\Lambda_{\rm LN} \gg v$ hierarchy

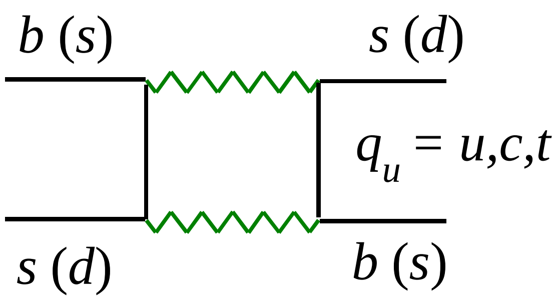
$\Lambda_{\rm eff} \sim$ 1-10 TeV should be the suppression scale of high. dim. ops. which preserves SM symm .

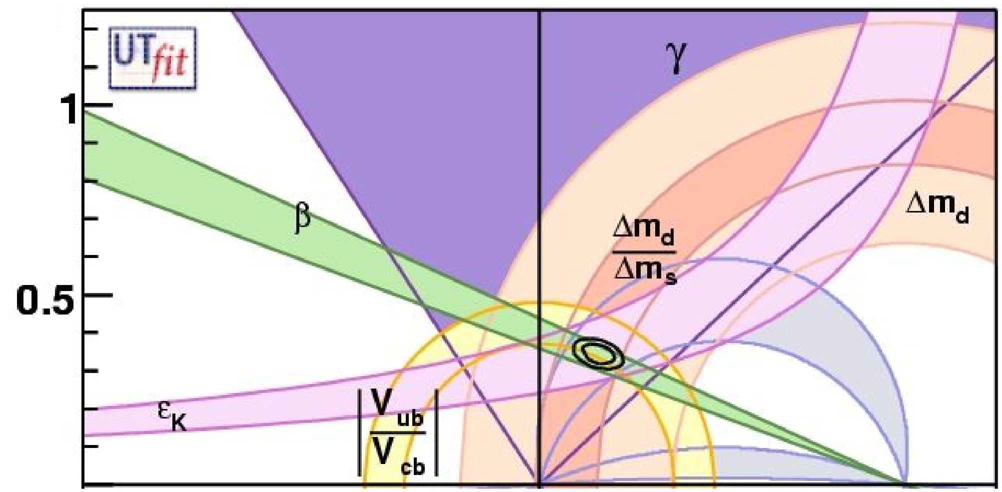
<u>*(quark) flavour problem*</u>

if $c_n \sim$ O(1) rare processes in the quark sector imply bounds on the effective NP scale well above the TeV

Most remarkable example of the quark flavour problem:
neutral-meson mixing [$\Delta F = 2$]

- No SM tree-level contribution
- Additional suppression within the SM because of CKM hierarchy





E.g.: $$M(B_d\text{-}\bar{B}_d) \sim c_{SM} \frac{(y_t V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{new} \frac{1}{\Lambda^2}$$

If $c_{new} \sim c_{SM} \sim 1$, in order to maintain the agreement between data and SM predictions:

$\Lambda > 10^4$ TeV for $O^{(6)} \sim (\bar{s}\, d)^2$ [K^0-$\bar{K}^0$ mixing]

$\Lambda > 10^3$ TeV for $O^{(6)} \sim (\bar{b}\, d)^2$ [B^0-$\bar{B}^0$ mixing]

The most pessimistic (but also most natural) wey out to this problem is the so-called MFV hypthesis:

flaovur mixing induced only by the Yukawas [also beyond SM]

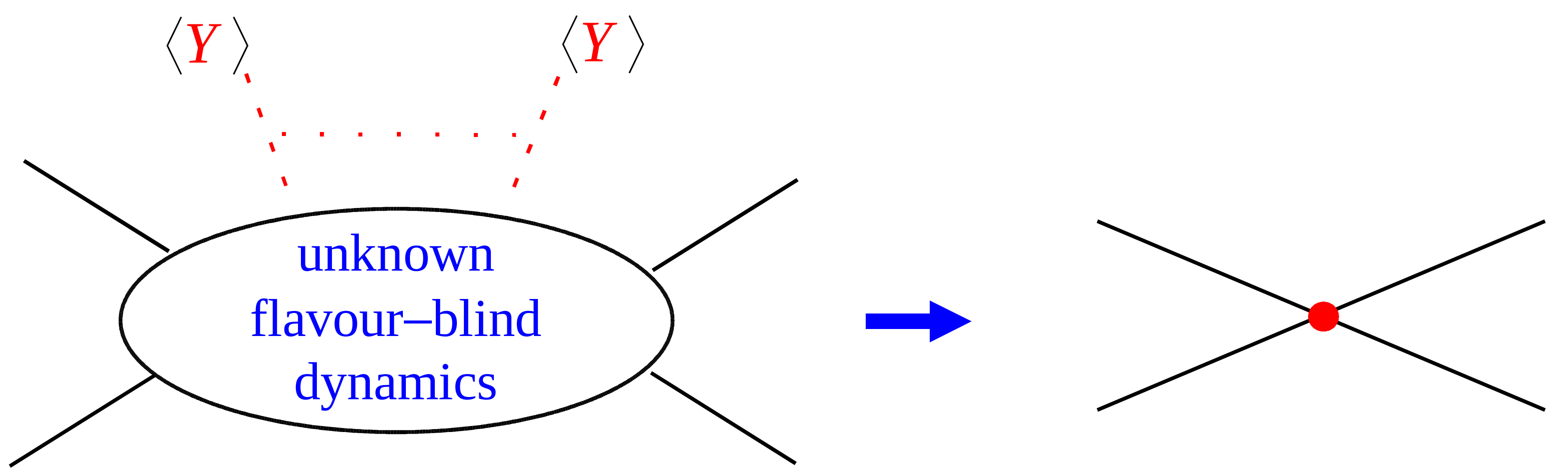
Buras et al. '01
D'Ambrosio et al. '02
(Chivuchula & Georgi '87
Hall & Randall, '90)

Λ_F Λ (~ TeV)

breaking of the *flavour symmetry* which gives origin to the Y

flavour-blind dynamics [non-SM degrees of freedom stabilizing the Higgs potential]

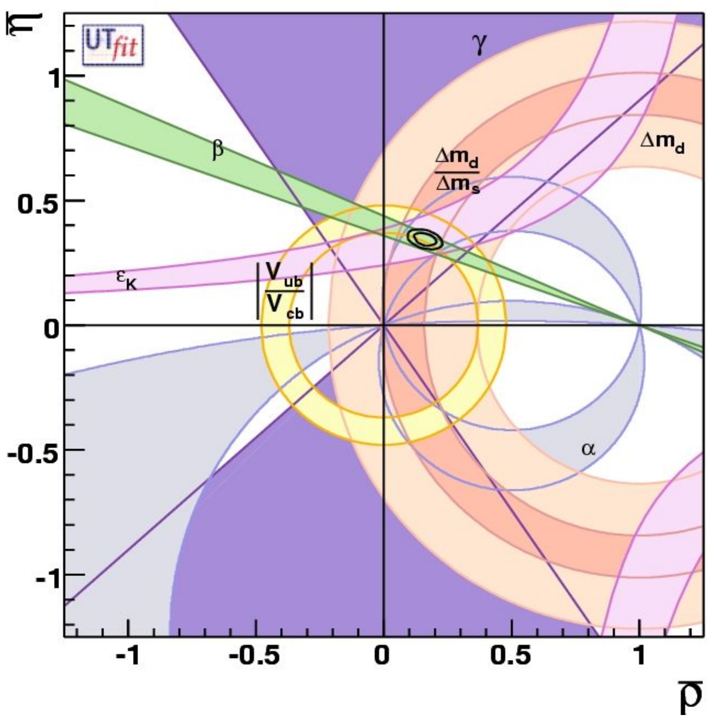
SM degrees of freedom



Within the MFV hypothesis:

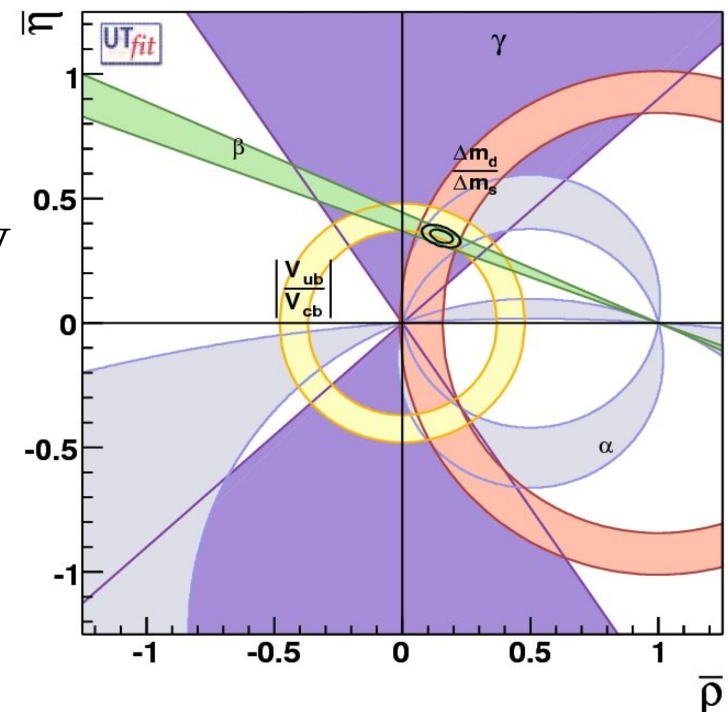
- All FCNC amplitudes with the same CKM structure as in the SM $\Rightarrow$ phase measurements [such as $a(B\to\psi K_S)$, $a(B\to\phi K_S)$, $\Delta M_{B_d}/\Delta M_{B_s}$] <u>not sensitive to NP</u>
- Only the flavour–independent magnitude of FCNC amplitudes can be modified by non–standard effects: typical size 10-30% <u>for electroweak s.d. amplitudes</u>

SM



SM
+
NP with MFV

Bona et al. '06



The MFV hypothesis is very *efficient* &in suppressing NP effects
& <u>the UT is definitely not the place to look for NP effects if MFV holds</u>

Flavour physics in the lepton sector

Do we need a MFV hypothesis also in the lepton sector ?

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A severe lepton-FCNC problem exists:

$$\mathscr{L}_{\rm eff} \subset \frac{c_{\mu e}}{\Lambda^2}\, \bar{e}_L \sigma^{\mu\nu} \mu_R\, \phi F_{\mu\nu} \quad \Rightarrow \quad \Lambda > 10^5\,\mathrm{TeV} \times (c_{\mu e})^{1/2}$$

from $\mathrm{BR}(\mu \to e\gamma)^{\rm exp} < 1.2\times 10^{-11}$

However, in the lepton sector is a not so easy to define which are the irreducible sources of (lepton) flavour symmetry breaking.

An interesting (and plausible) hypothesis is to assume that also in the lepton sector all flavour-violating interactions are generated by (left-right) Yukawa terms:

$$\bar{\nu}_R Y_\nu L_L \phi^T + M_R \nu_R^T \nu_R \longrightarrow m_\nu = \frac{Y_\nu^T Y_\nu v^2}{M_R} = U^* m_\nu^{\rm diag} U^+$$

flavour blind

PMNS matrix

This predictive M(L)FV scheme is a useful working hypothesis to investigate some general properties of FCNC in the lepton sector:

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

⬇

- If M_R is sufficiently high [high scale of the LN violation ⇒ large neutrino Yukawas], we should observe soon $\mu \to e\gamma$ [general conclusion indep. of the MLFV hypothesis]:

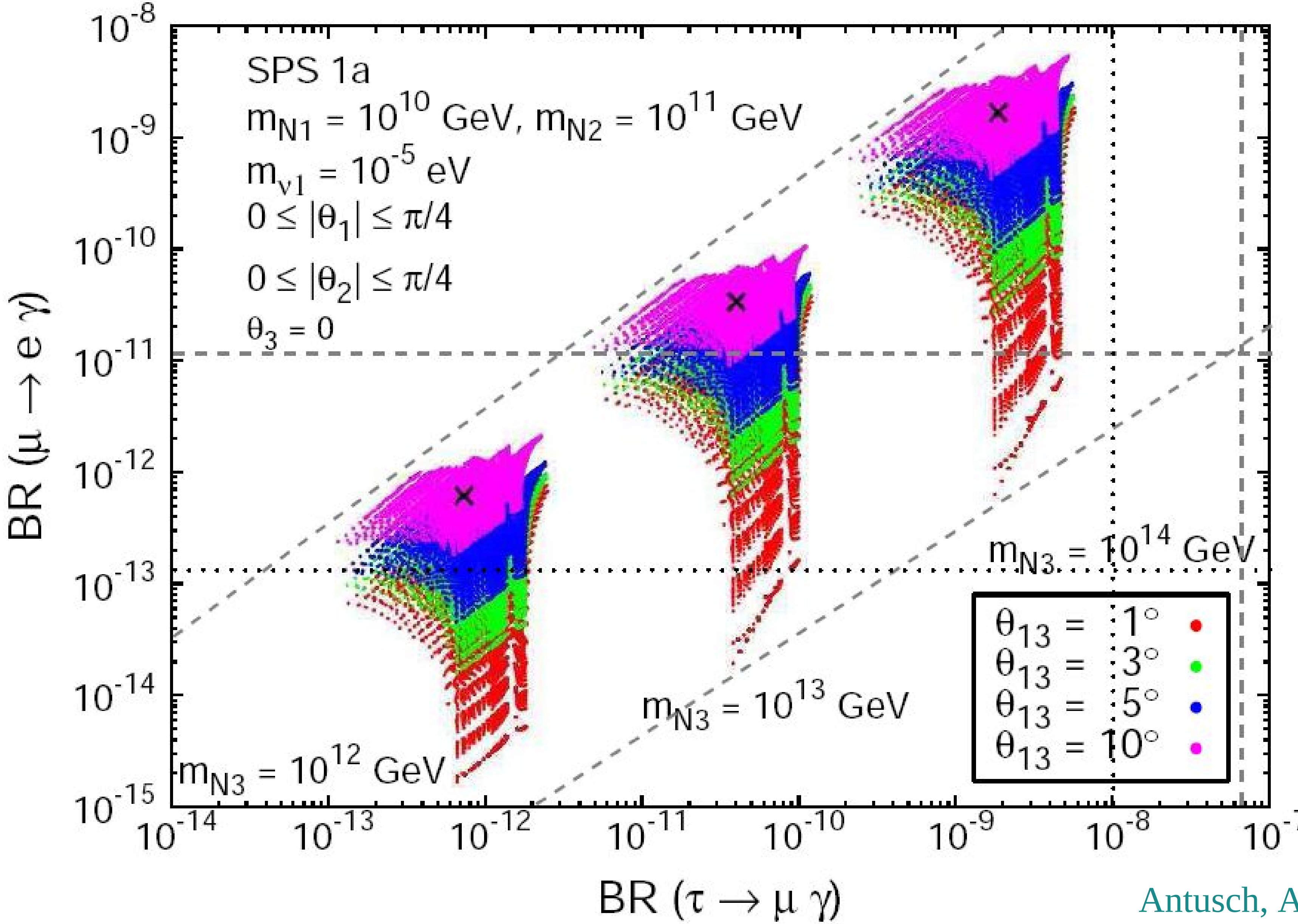
$$M_R \gtrsim 10^{12}\,\mathrm{GeV} \times (\Lambda / 10\ \mathrm{TeV})^2 \quad \Longleftrightarrow \quad B(\mu \to e\gamma) \gtrsim 10^{-13}$$

- The MLFV hypothesis implies a clear pattern for FCNC ratios

$B(\tau \to \mu\gamma) : B(\tau \to e\gamma) : B(\mu \to e\gamma) \sim [\ \lambda^{-4} \quad \lambda^{-2}\ ] : 1 : 1$ [dictated by PMNS & m_ν]

According to this scaling, $\tau \to \mu\gamma$ is unlikely to be seen, even at super-B

The LFV ratios within an explicit realization of this generic framework (up to minor differences) in the MSSM:



Antusch, Arganda, Herrero, Teixeira, '06

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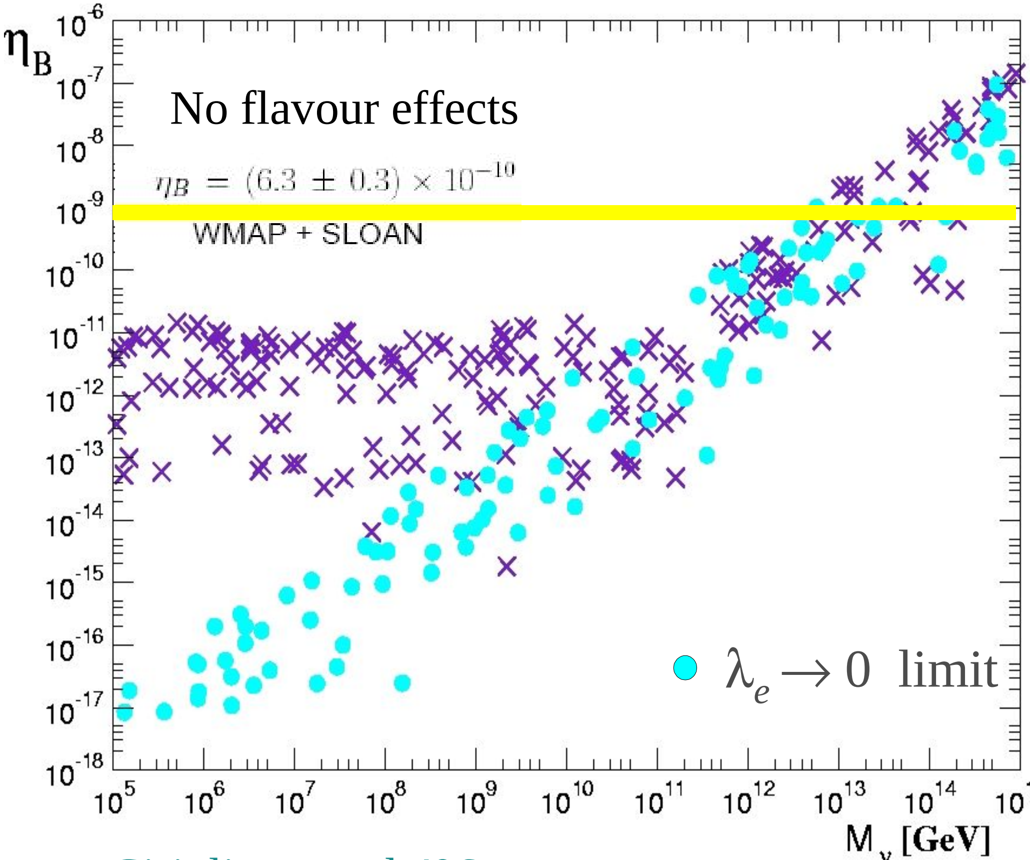
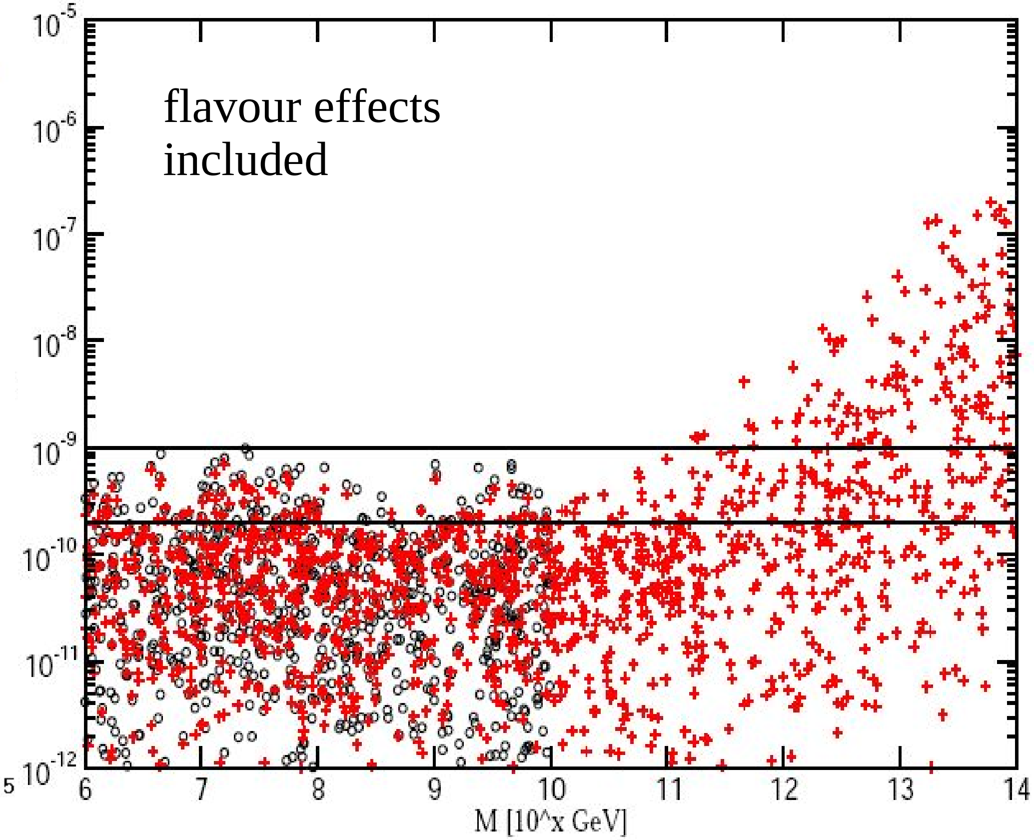
According to this scaling, $\tau \to \mu\gamma$ is unlikely to be seen, even at super-B

- <u>The observed matter-antimatter asymmetry of the universe can be generated via leptogenesis</u> [for very natural values of the free parameters, especially if M_R is high]

Cirigliano, GI, Porretti, '06
Branco, Buras, Jaeger, Uhlig, Weiler '06



Cirigliano et al. '06



Branco et al. '06

There is no need to invoke CP violation beyond the Yukawa couplings to explain the matter-antimatter asymmetry in the universe.

Flavour physics in Grand Unified Theories

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Flavour physics in Grand Unified Theories

Can we implement the (pessimistic) MFV hypothesis in a GUT framework ?

No ! [at least in the most pessimistic interpretation of MQFV+MLFV]:
within GUTs quarks & leptons are part of the same multiplets $\Rightarrow$ we cannot avoid some contamination between quark & flavour mixing terms.

E.g.: $SU(5)_{\text{gauge}}$ -- the standard GUT prototype

Cirigliano, Grinstein, G.I., Wise, '06

Matter fields:

$$\Psi\,[\underline{5}] \subset L_L\,,\, d_R{}^c$$
$$\chi\,[10] \subset Q_L\,,\, u_R{}^c,\, e_R{}^c$$
$$N\,[1] \subset \nu_R$$

The minimal GUT Yukawa interaction:

$$\mathscr{L}_{\text{Y-GUT}} = Y_D\,\psi^T\chi\,H_{\underline{5}} + Y_U\,\chi^T\chi\,H_5 + Y_\nu\,N^T\psi\,H_5$$

Same Yukawa coupling for down quarks & charged lepton [bottom-tau unification]

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When constructing the effective operators which contribute to rare processes we cannot forbid the appearance of

- Y_D & Y_U (hence the CKM matrix) in the charged-lepton sector
- Y_ν (hence the PMNS matrix) in the quark sector

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$$m_\nu = \frac{Y_\nu^{\,T} Y_\nu\, v^2}{M_R}$$

Depending on the value of M_R [~ normalization of Y_ν] one of this two non-MFV effects is relevant

$M_R < 10^{12}$ GeV → Non-MFV in charged leptons [B($\tau \to \mu\gamma$)/B($\mu \to e\gamma$) enhancement]

$M_R > 10^{12}$ GeV → Non-MFV effects in the quark sector [especially rare K decays]

Back to rare decays

A) $\mu \to e\gamma$ vs. $\tau \to \mu(e)\,\gamma$

One of the most interesting consequences of flavour-mixing in GUTs is the fact that LFV rates cannot be arbitrarily suppressed by lowering M_{R}.

If there are new particles carrying lepton-flavour at the TeV scale (e.g. the sleptons) - even slightly above the TeV scale - then MEG should see $\mu \to e\gamma$:

$$\Lambda < 10\ \mathrm{TeV} \quad \Longrightarrow \quad B(\mu \to e\gamma) > 10^{-13} \quad \begin{cases} \sim Y_D Y_U^{+} Y_U & M_{\mathrm{R}} < 10^{12}\ \mathrm{GeV} \\ \sim Y_e Y_\nu^{+} Y_\nu & M_{\mathrm{R}} > 10^{12}\ \mathrm{GeV} \end{cases}$$

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In this framework the search for $\tau\to\mu(e)\,\gamma$ at B and super-B factories becomes also very interesting:

$$B(\tau\to\mu\gamma):B(\tau\to e\gamma):B(\mu\to e\gamma) \sim [\,\lambda^{-4}\ \ \lambda^{-2}\,]:1:1 \sim [500\text{–}10]:1:1 \qquad M_R \gg 10^{12}\ \text{GeV}$$

$$B(\tau\to\mu\gamma):B(\tau\to e\gamma):B(\mu\to e\gamma) \sim \lambda^{-6}:\lambda^{-4}:1 \sim 10^{4}:500:1 \qquad M_R \ll 10^{12}\ \text{GeV}$$

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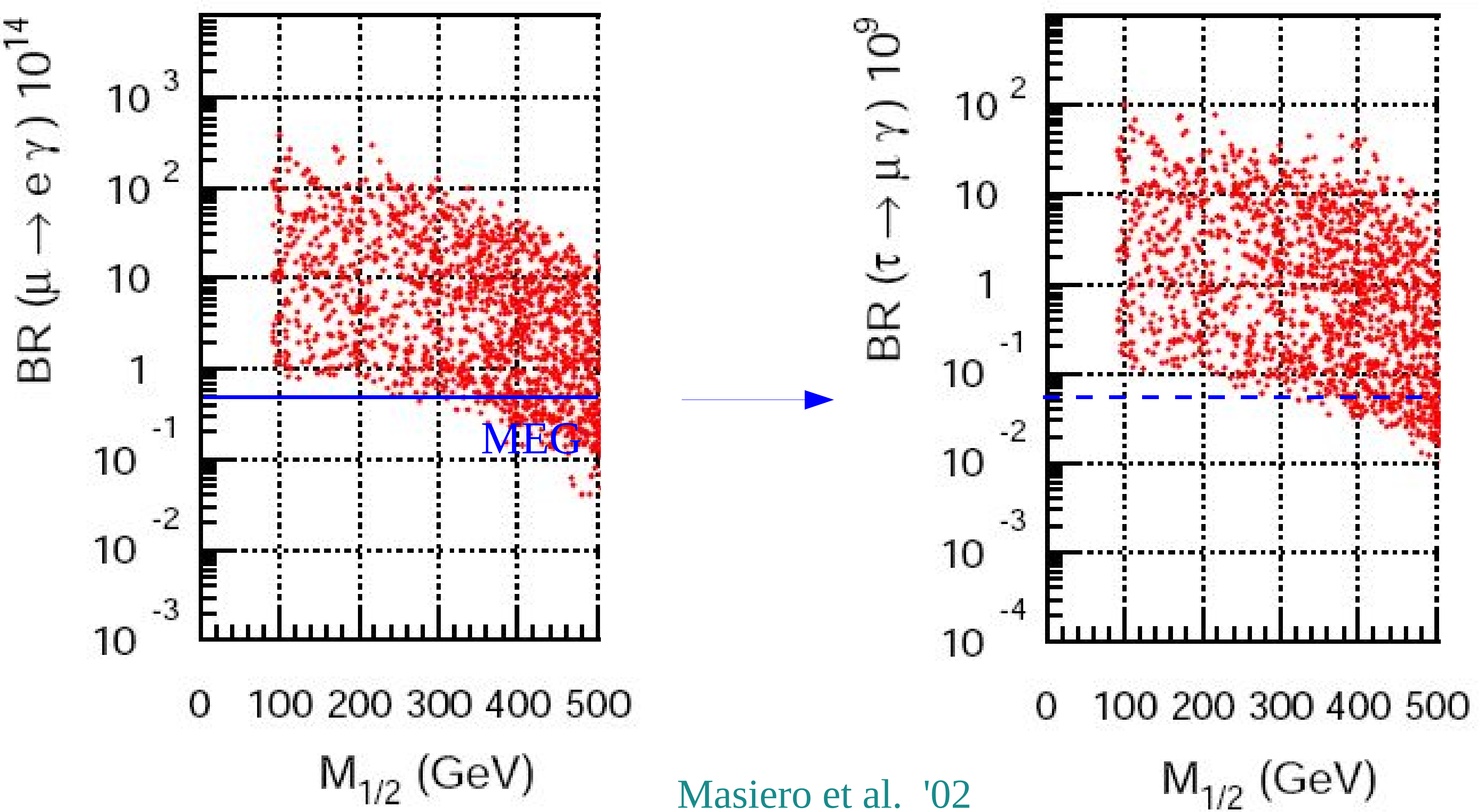
Explicit realization within the MSSM:



Masiero et al. '02

Back to rare decays

B) Rare quark decays

Deviations form MFV in $q_i \to q_j$ rare decays arise when

$$(Y_\nu^{+} Y_\nu)_{ij} \sim (Y_U^{+} Y_U)_{ij} = y_t^2 \, V_{ti}^{*} \, V_{tj}$$

CKM matrix

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CKM matrix

The smallest CKM combination appears in rare K decays ($V_{ts}^* V_{td} \sim \lambda^5$)

$\Rightarrow$ potentially O(1) non-SM effects in $K \to \pi\nu\nu$ & $K_L \to \pi^0 l^+ l^-$ with no (or negligible) effects in the B system

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N.B.:
- A similar conclusion is quite general and holds also in non-GUT scenarios [⇒ Cecilia's talk on Little Higgs models]
- Non-MFV effects in rare K decays (with no impact in B physics) could also be generated by the subleading non-minimal Yukawa structures which breaks the $Y_E = Y_D^T$ GUT relation for the light generations

The large tanβ scenario

So far I discussed general features which holds in most GUT models [SU(5) used as prototype]. However, specific GUT frameworks can have additional features with very interesting signatures in low-energy flavour physics. Most remarkable example: the large tanβ scenario, possible in any model with two light Higgs fields, particularly natural in $SO(10)_{gauge}$ [minimal group which allows to put all SM fermions + ν_R in the same (fundamental) representation] $\Rightarrow$ great impact in B physics

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$$\mathscr{L}_{\text{Yukawa}} = \bar{Q}_L Y_D D_R H_D + \bar{Q}_L Y_U U_R H_U + L_L Y_L E_R H_D + \text{h.c.}$$

Minimal choice: the Y are still the only (low-energy) sources of flavour symmetry breaking (CKM matrix only source of mixing)

$$Y_D = \text{diag}(y_d, y_s, y_b) \qquad Y_U = (V_{\text{ckm}})^+ \times \text{diag}(y_u, y_c, y_t)$$

$$y_u = m_u / \langle H_U \rangle \qquad y_d = m_d / \langle H_D \rangle = \tan\beta\, m_d / \langle H_U \rangle$$

But for $\tan\beta = O(m_t/m_b) \gg 1$ we can have both y_t & y_b of order

$$\mathscr{L}_{\text{Yukawa}} = \bar{Q}_L Y_D D_R H_D + \bar{Q}_L Y_U U_R H_U + L_L Y_L E_R H_D + \text{h.c.}$$

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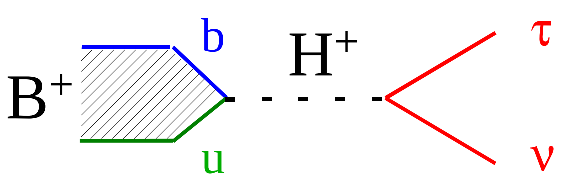
$$Y_D = \mathrm{diag}(y_d, y_s, y_b) \qquad Y_U = (V_{ckm})^+ \times \mathrm{diag}(y_u, y_c, y_t)$$

$$y_u = m_u / \langle H_U \rangle \qquad y_d = m_d / \langle H_D \rangle = \tan\beta \; m_d / \langle H_U \rangle$$

But for $\tan\beta = O(m_t / m_b) \gg 1$ we can have <u>both</u> y_t & y_b of order

Potentially observable non-standard effects in <u>helicity-suppressed</u> CC interactions

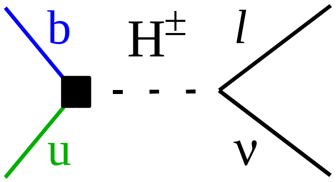
E.g.:



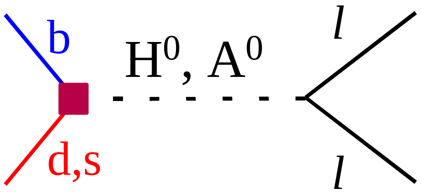
$$B_{2HDM} = B_{SM} \times [\, 1 - (\tan\beta \; m_B / M_H)^2]^2$$

G. Hou, '93

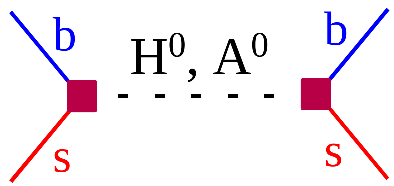
Four key players in the flavour sector (all in B physics):



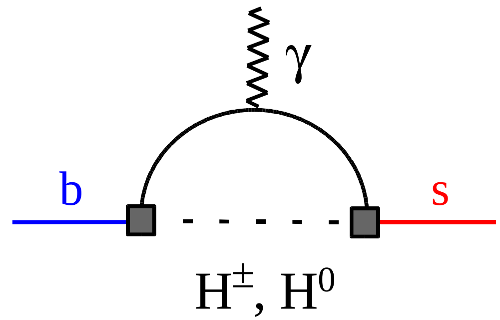
$B^{\pm} \to l^{\pm} \nu$



$B_{s,d} \to l^{+} l^{-}$



ΔM_{B_s}



$B \to X_s \gamma$

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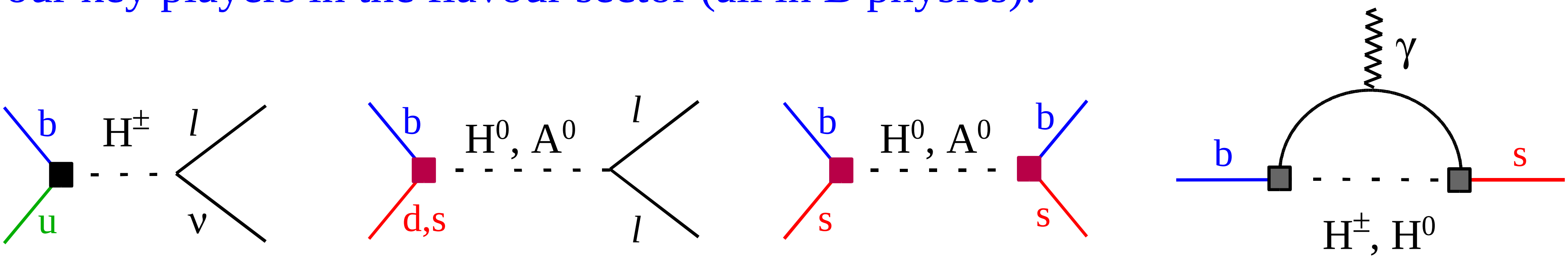


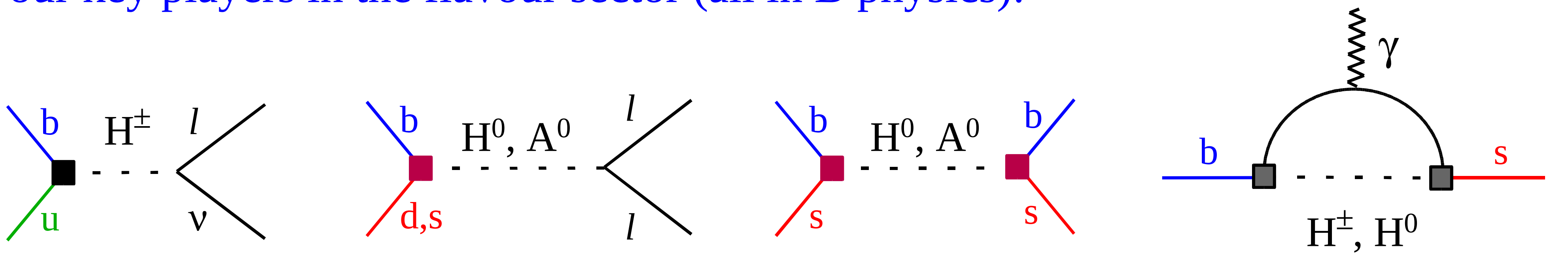
$B^\pm \to l^\pm \nu$	$B_{s,d} \to l^+ l^-$	ΔM_{B_s}	$B \to X_s \gamma$
↓	↓	↓	↓
~(10-50)% suppression	up to 100 × enhancement	~(0-20)% suppression	~(10-50)% enhancement

[qualitative general features for $M_H \sim 500$ GeV & $\tan\beta \sim 50$]

Despite several new free parameters, the framework exhibits a well defined pattern of enhancements & suppressions (consistent with present data)

The recent experimental infos on $B(B^\pm \to l^\pm \nu)$ [Belle & Babar] & ΔM_{B_s} [CDF], & the theoretical improvement on $B(B \to X_s \gamma)$ [Misiak et al. '06] finally allows us to start exploring this scenario more deeply

Four key players in the flavour sector (all in B physics):



$B^\pm \to l^\pm \nu$ $B_{s,d} \to l^+ l^-$ ΔM_{B_s} $B \to X_s \gamma$

The game becomes particularly interesing in the explicit realization of this scenario within the MSSM $\Rightarrow$ connection with flavour-conserving observables

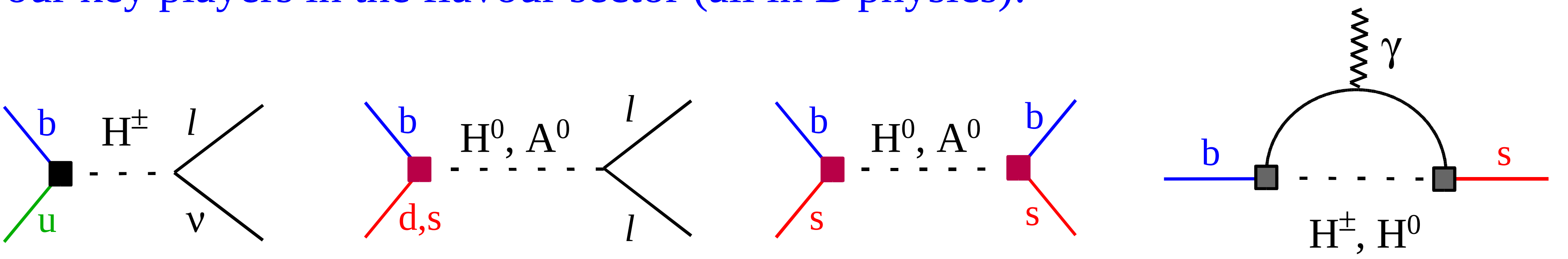
key parameters:

$$M_H \oplus \tan\beta \oplus [A_U, \mu, \tilde{m}_q]$$

$$(m_{h0})_{min} = f(A_U, \tan\beta, \tilde{m}_q)$$

$$(g-2)_\mu = f(\mu, \tan\beta, \tilde{m}_l)$$

Four key players in the flavour sector (all in B physics):



$B^\pm \to l^\pm \nu$ $B_{s,d} \to l^+ l^-$ ΔM_{B_s} $B \to X_s \gamma$

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key parameters:

$M_H \oplus \tan\beta \oplus [A_U, \mu, \tilde{m}_q]$

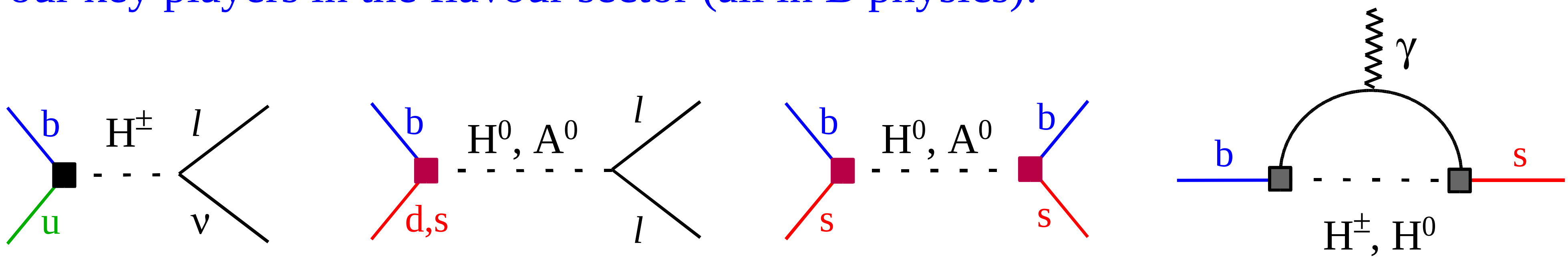
$(m_{h^0})_{min} = f(A_U, \tan\beta, \tilde{m}_q) \geq 115$ GeV

$(g-2)_\mu = f(\mu, \tan\beta, \tilde{m}_l)$

- large $\tan\beta$
- large $\tilde{m}_q$
- large $A_U/\tilde{m}_q$

Parameter region with the most interesting/consistent large-$\tan\beta$ effects in B physics

Four key players in the flavour sector (all in B physics):



$B^\pm \to l^\pm \nu$ $\quad B_{s,d} \to l^+ l^-$ $\quad \Delta M_{B_s}$ $\quad B \to X_s \gamma$

The game becomes particularly interesing in the explicit realization of this scenario within the MSSM $\Rightarrow$ connection with flavour-conserving observables

key parameters:

$$M_H \oplus \tan\beta \oplus [A_U, \mu, \tilde{m}_q]$$

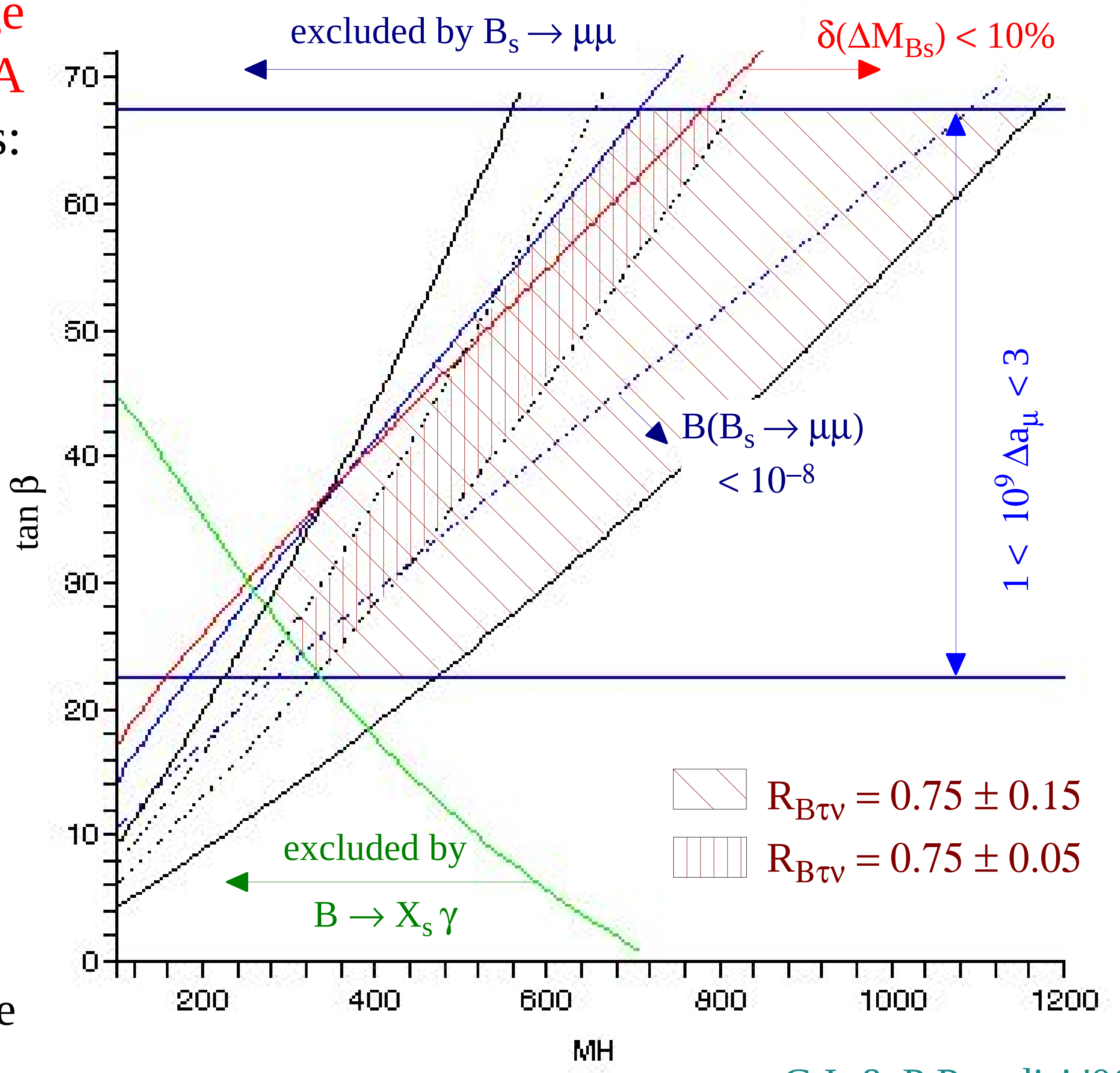
The present 3σ discrepancy between $(g-2)_\mu^{exp}$ and $(g-2)_\mu^{SM}$ provides the most significant evidence for $\tan\beta \gg 1$

$$(m_{h0})_{min} = f(A_U, \tan\beta, \tilde{m}_q)$$

$$(g-2)_\mu = f(\mu, \tan\beta, \tilde{m}_l) \approx (g-2)_\mu^{SM} + \delta \tan\beta \frac{\mu\, m_W}{\tilde{m}_l^2}$$

The MSSM scenario with large $\tan\beta$, heavy squarks & large A terms has several nice features:

- $O(10^{-9})$ contrib. to $(g-2)_\mu$
- (10-40)% suppress in $B(B\to\tau\nu)$
- Heavy $(m_{h0})_{min}$
- Small effects [possible tiny suppression] in ΔM_{B_s} with no fine-tuning
- Small effects [possible tiny enhancement] of $B \to X_s\gamma$ with no fine-tuning
- Possible large enhancement in $B \to \mu\mu$ [depending on the precise value of A_U]



G.I. & P.Paradisi '06

$\tilde{m}_q = 1$ TeV
$A_U = -2$ TeV $\mu = 1$ TeV

More exotic consequences of large tanβ :

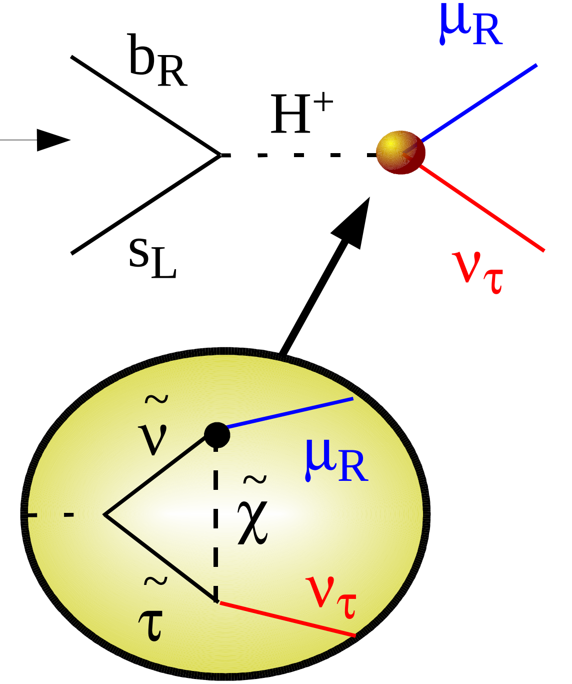
If the model has sizable sources of flavour symmetry breaking in the right-handed lepton sector (non-minimal LFV) ⇒ large violations of LF universality in $B(K) \to l\nu$

$$\Gamma(B \to \mu\nu)^{exp} = \Gamma(B \to \mu\nu_\mu) + \Gamma(B \to \mu\nu_e) + \Gamma(B \to \mu\nu_\tau)$$

≈ SM

≈ 0

scalar LFV amplitude



sizable one-loop eff. coupl. because of 3rd generation & large mixing in the lepton sector

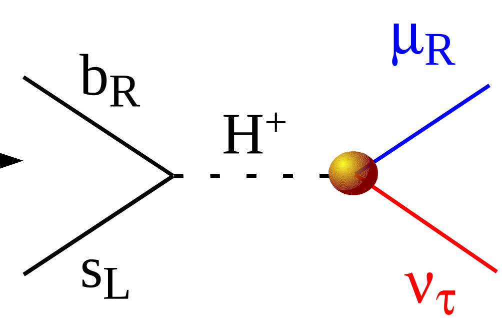
Masiero, Paradisi, Petronzio, '05

More exotic consequences of large $\tan\beta$:

If the model has sizable sources of flavour symmetry breaking in the right-handed lepton sector (non-minimal LFV) $\Rightarrow$ large violations of LF universality in $B(K) \to l\nu$

$$\Gamma(B \to \mu\nu)^{\rm exp} = \underbrace{\Gamma(B \to \mu\nu_\mu)}_{\approx\,\rm SM} + \underbrace{\Gamma(B \to \mu\nu_e)}_{\approx\,0} + \underbrace{\Gamma(B \to \mu\nu_\tau)}_{\text{scalar LFV amplitude}}$$

scalar LFV amplitude



Possible probe of this effect in the ratios:

$$R^B_{\mu\tau} = \frac{\Gamma(B^+ \to \mu^+\nu)}{\Gamma(B^+ \to \tau^+\nu)} \qquad R^B_{e\tau} = \frac{\Gamma(B^+ \to e^+\nu)}{\Gamma(B^+ \to \tau^+\nu)}$$

$$\Delta \sim 10\%\ (R^B_{\mu\tau})^{\rm SM} \qquad \sim 10^3 \times (R^B_{e\tau})^{\rm SM}$$

Interesting correlation with the same phenomenon in the Kaon system, which so far set the best upper limit

$$R^K_{\mu e} = \frac{\Gamma(K^+ \to \mu^+\nu)}{\Gamma(K^+ \to e^+\nu)} \longrightarrow \Delta \sim 1\%$$

Conclusions

One of the most interesting and promising directions in flavour physics is the exploration of the connections between quark & lepton flavour-breaking structures

In this perspective, the most useful experimental probes are the rare LFV decays:

- $\mu \to e\gamma$ should be seen at MEG in most realistic scenarios
- $\tau \to \mu\gamma$ very useful to discriminate different flavor-mixing models

On the quark side, the most interesting processes are a few rare (clean) decays involving leptons in the final state:

- $K \to \pi\nu\nu$ the most sensitive probes of possible (tiny) deviations from MFV
- $B \to \tau\nu$ & $B \to \mu\mu$ the golden modes to identify the large $\tan\beta$ scenario

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I really hope that in the next HQL conferences we'll have some exciting news from one of these channels !!