Lepton Flavor Violation in charged leptons: the next challenge in flavor physics

Gino Isidori
[*Scuola Normale Superiore - Pisa & INFN - Frascati*]

- Introduction: the SM as an effective theory
- Flavor symmetry breaking in the quark sector
- Minimal Flavor Violation in the lepton sector
- Lepton Flavor symmetry breaking in GUTs
- LFV in explicit SUSY models
- Conclusions

Introduction: the SM as an effective theory

The effects of new physics below the electroweak 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 $d \leq 4$ compatible with the gauge symmetry]

most general parameterization of the new (heavy) degrees of freedom, as long as we perform low-energy experiments

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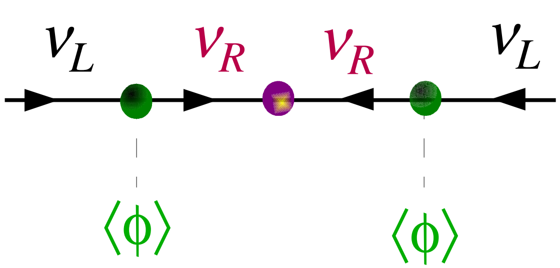
No neutrino masses (& mixing angles)

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

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

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

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



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

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

⬇

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

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

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Λ_{LN} cannot be the only scale of NP: new degrees of freedom in the TeV range are necessary to stabilize the Higgs sector $\Rightarrow$ NP within the reach of the LHC

↓

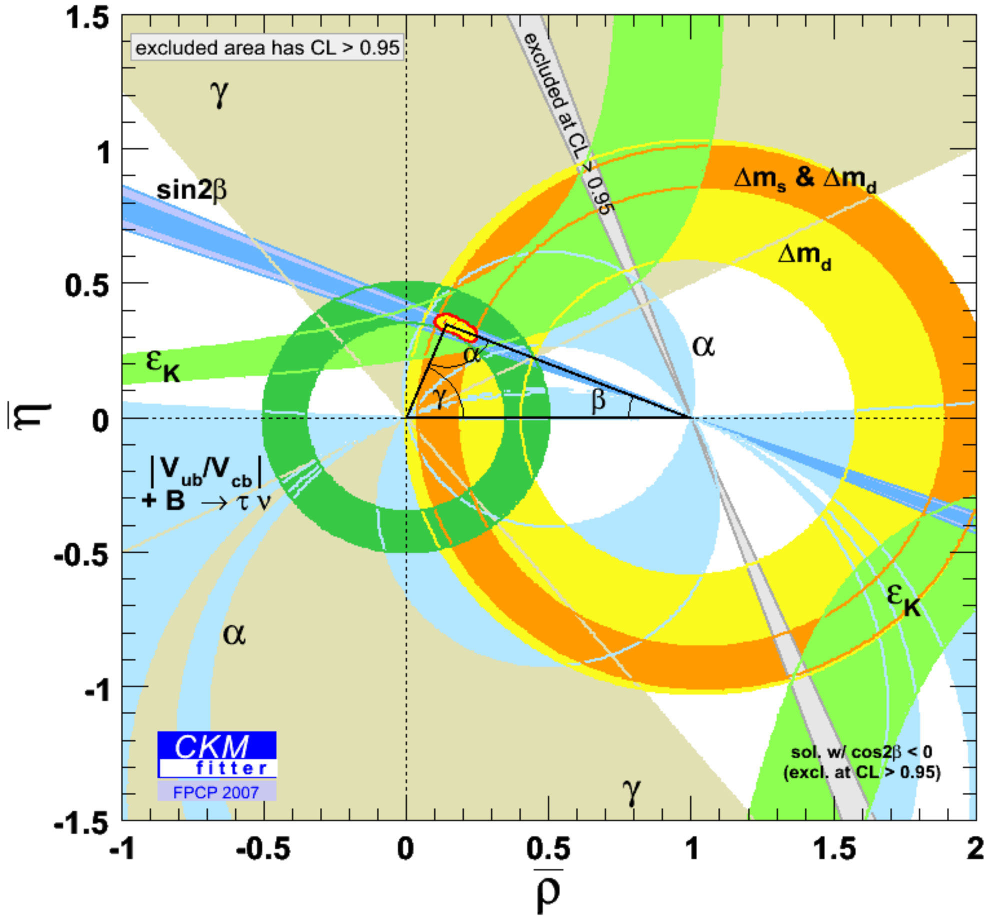
- $\Lambda_{\rm eff} \sim$ 1-10 TeV is the natural scale of NP for processes which do not violate the total barion or lepton number
- In the case of flavor-changing processes, this is possible only if flavor-changing couplings have a non-trivial (*minimal*) form (*the lesson of quark flavor physics*)

↓

some general conclusions about the size of LFV

Flavor symmetry breaking in the quark sector

The consistency of the various experimental constraints appearing in CKM fits and the absence of significant deviations from SM in rare decays, such as $B \to X_s \gamma \, (l^+ l^-)$, ... are a clear evidence that the SM is very successful in describing quark-flavor mixing.



New physics effects in quark-flavor mixing can only appear as small corrections to the leading CKM mechanism

Flavor symmetry breaking in the quark sector

The best way to quantify this success is to derive bounds on the scale of new physics:

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

contribution of the new heavy degrees of freedom

c_{NP}

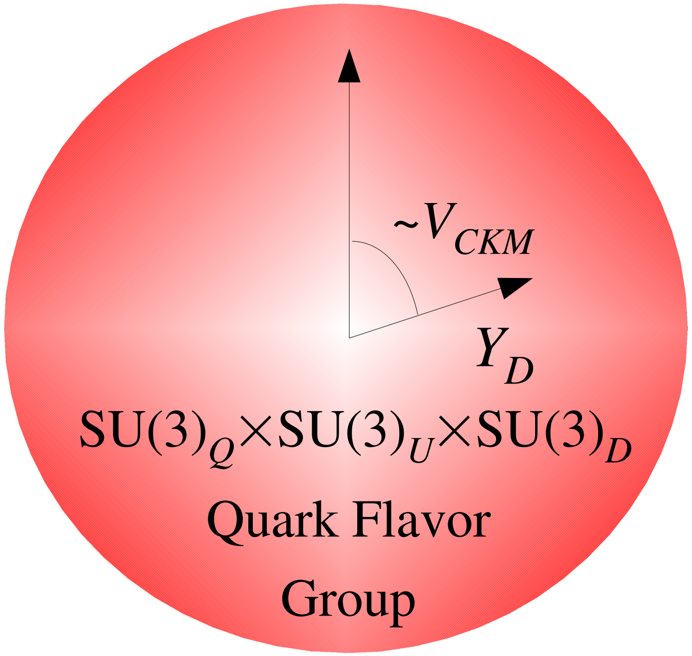
- ~ 1 — tree/strong + generic flavor → $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ — loop + generic flavor → $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ — tree/strong + MFV → $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\,\pi^2)$ — loop + MFV → $\Lambda \gtrsim 0.5$ TeV [K & B]

MFV = *Minimal Flavor Violation* hypothesis

The MFV hypothesis can be formulated in a general form as the assumption of a well-defined symmetry + symmetry-breaking structure in the flavor sector of the effective theory:

- Flavor symmetry:
  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$
  [global symmetry of the SM gauge sector]

- Symmetry-breaking terms:
  $Y_D \sim \bar{3}_Q \times 3_D \qquad Y_U \sim \bar{3}_Q \times 3_U$
  [quark Yukawa couplings]



$$\mathcal{L}_{\text{q-Yukawa}} = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R H_c + \text{h.c.}$$

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

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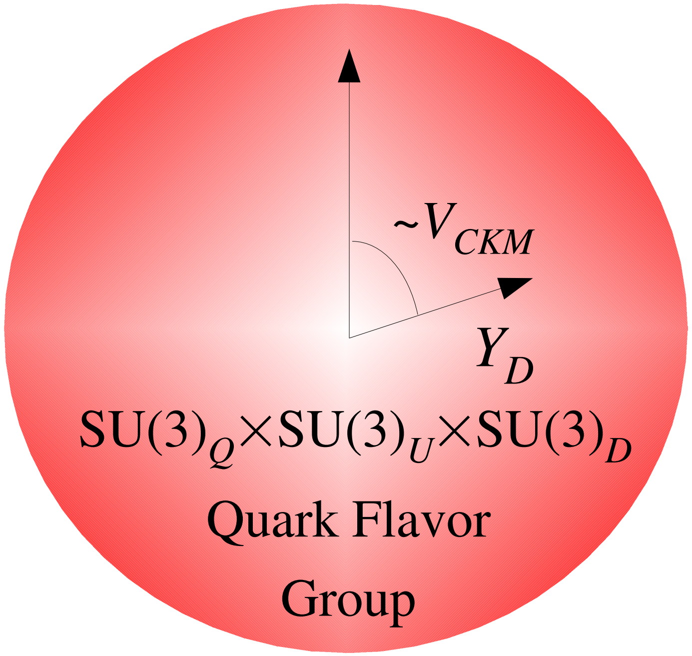

MFV = $Y_{U,D}$ are the only irreducible breaking sources of the flavor symmetry

⇓

New physics effects in flavor-changing processes naturally suppressed by the CKM matrix (as in SM) ⇒ Flavor observables do not exclude NP the TeV range.

Minimal Flavor Violation in the lepton sector

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

A severe lepton-FCNC problem exists:

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

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

However, in the lepton sector is not so easy to identify the irreducible sources of (lepton) flavor symmetry breaking.

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extra assumptions needed
in order to define an effective theory
approach similar to the quark sector

The game become interesting when these extra assumptions leads to predictions on other observables (in particular FCNCs) $\Rightarrow$ testable hypotheses about the irreducible sources of LF breaking independent from dynamical details

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

1st assumption (very natural)

Decoupling of the $U(1)_L$ breaking [Lepton Number] - associated to some high scale [$\Lambda_{LN} \gg$ TeV] - and the $SU(3)_{L_L}$ breaking [Lepton Flavor] $\Rightarrow$ small neutrino masses with *natural* [$g_\nu \sim O(1)$] flavor-violating couplings

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

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Decoupling of $U(1)_L$ and $SU(3)_{L_L}$ breaking $\Rightarrow$ $g_\nu \sim O(1)$, $\Lambda_{LN} \gg$ TeV

2nd assumption (more model dependent)

The effective neutrino couplings (masses + mixing) allow to determine completely the flavor-breaking structures

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

irreducible

[$g_\nu \sim 6$ of $SU(3)_{L_L}$]

no further assumption needed

$$m_\nu = (U_{PMNS}) \, m_\nu^{diag} \, U_{PMNS} \longleftrightarrow \frac{g_\nu v^2}{\Lambda_{LN}}$$

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reducible [see-saw type]

$g_\nu \propto Y_\nu^T M_R^{-1} Y_\nu$

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further ansatz needed → M_R flavor blind

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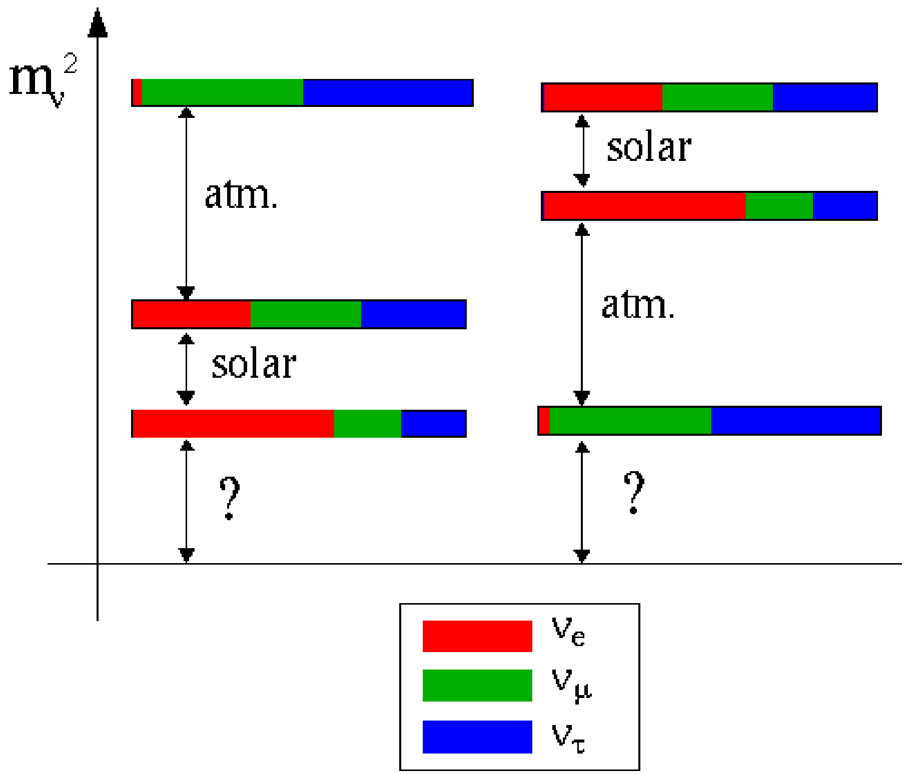
$$\frac{Y_\nu^T Y_\nu v^2}{M_R} \longleftrightarrow m_\nu = (U_{PMNS}) \, m_\nu^{diag} \, U_{PMNS} \longleftrightarrow \frac{g_\nu v^2}{\Lambda_{LN}}$$

These predictive M(L)FV schemes are useful working hypotheses to investigate some general properties of FCNC in the lepton sector [link between neutrino masses (& mixing) and lepton-flavor violating rare decays]

Much more freedom/uncertainty with respect to the quark case because of

- the overall scale
- the value of s_{13}, δ and the *spectrum ordering*:



Δm^2_{sol}	Δm^2_{atm}
$8.0\times10^{-5}\,eV^2$	$2.5\times10^{-3}\,eV^2$

$$U_{PMNS} \approx \begin{bmatrix} c & s & s_{13}\, e^{-i\delta} \\ -sc/\sqrt{2} & c/\sqrt{2} & 1/\sqrt{2} \\ s/\sqrt{2} & -c/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

$c = \cos\theta_{sol}$ $\quad s_{13} < 0.25$

$s = \sin\theta_{sol}$ $\quad 0 < \delta < 2\pi$

- the two scenarios

but some general phenomenological conclusions can still be obtained:

- If the scale of $U(1)_L$ breaking (M_R or Λ_{LN}) is sufficiently high, we should observe soon $\mu \to e\gamma$ [general conclusion, almost independent of the MLFV hypothesis]:

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

$$B(\mu \to e\gamma) \approx 10^{-13} \left[\frac{10\ \mathrm{TeV}}{\Lambda}\right]^4 \left[\frac{M_R}{10^{12}\ \mathrm{GeV}}\right]^2$$

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- The MLFV hypothesis implies a clear pattern for FCNC ratios

  $B(\tau \to \mu\gamma) : B(\tau \to e\gamma) : B(\mu \to e\gamma) \sim [\,500 - 10\,] : 1 : 1$ [dictated by PMNS & m_ν]

  According to this scaling, $\tau \to \mu\gamma$ is unlikely to be seen, especially if θ_{13} is large

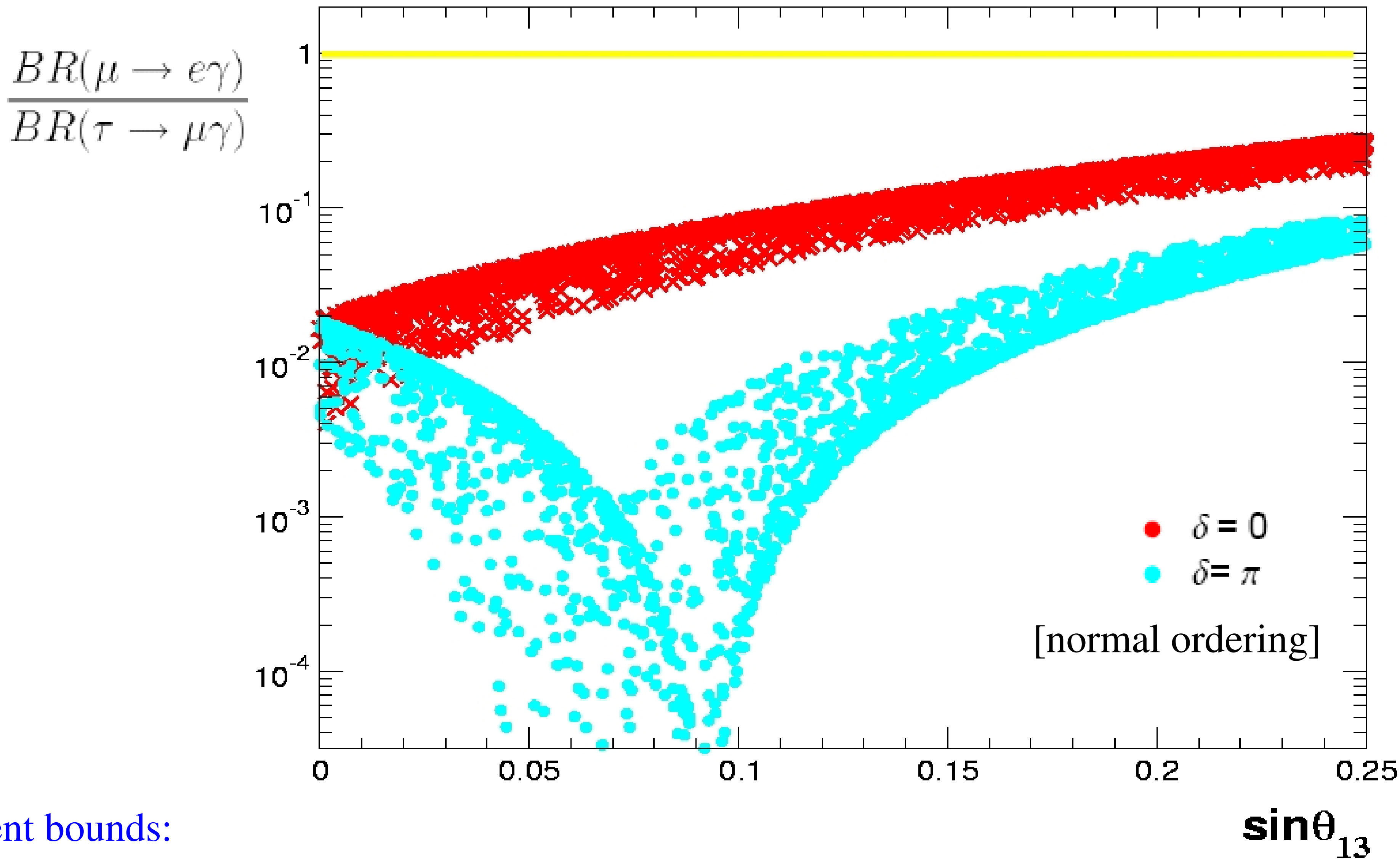
Relevant effective ops. for the radiative LFV decays:

$$\bar{L}_L^{\,i}\, Y_\nu^+ Y_\nu Y_e\, \sigma^{\mu\nu} e_R^{\,j} F^{\mu\nu}$$

or

$$\bar{L}_L^{\,i}\, g_\nu^+ g_\nu Y_e\, \sigma^{\mu\nu} e_R^{\,j} F^{\mu\nu}$$

N.B.: hierarchical structure quite similar in the two minimal schemes [with or without right-handed neutrinos]



Present bounds:

$BR(\mu \to e\gamma) < 1.2\times10^{-11}$ $BR(\tau \to \mu\gamma) < 0.5 \times 10^{-7}$ [Babar, Belle]

Expected sensitivities:

$BR(\mu \to e\gamma) \sim 10^{-13}$ [MEG] $BR(\tau \to \mu\gamma) \sim 10^{-9}$ [Super-B ?]

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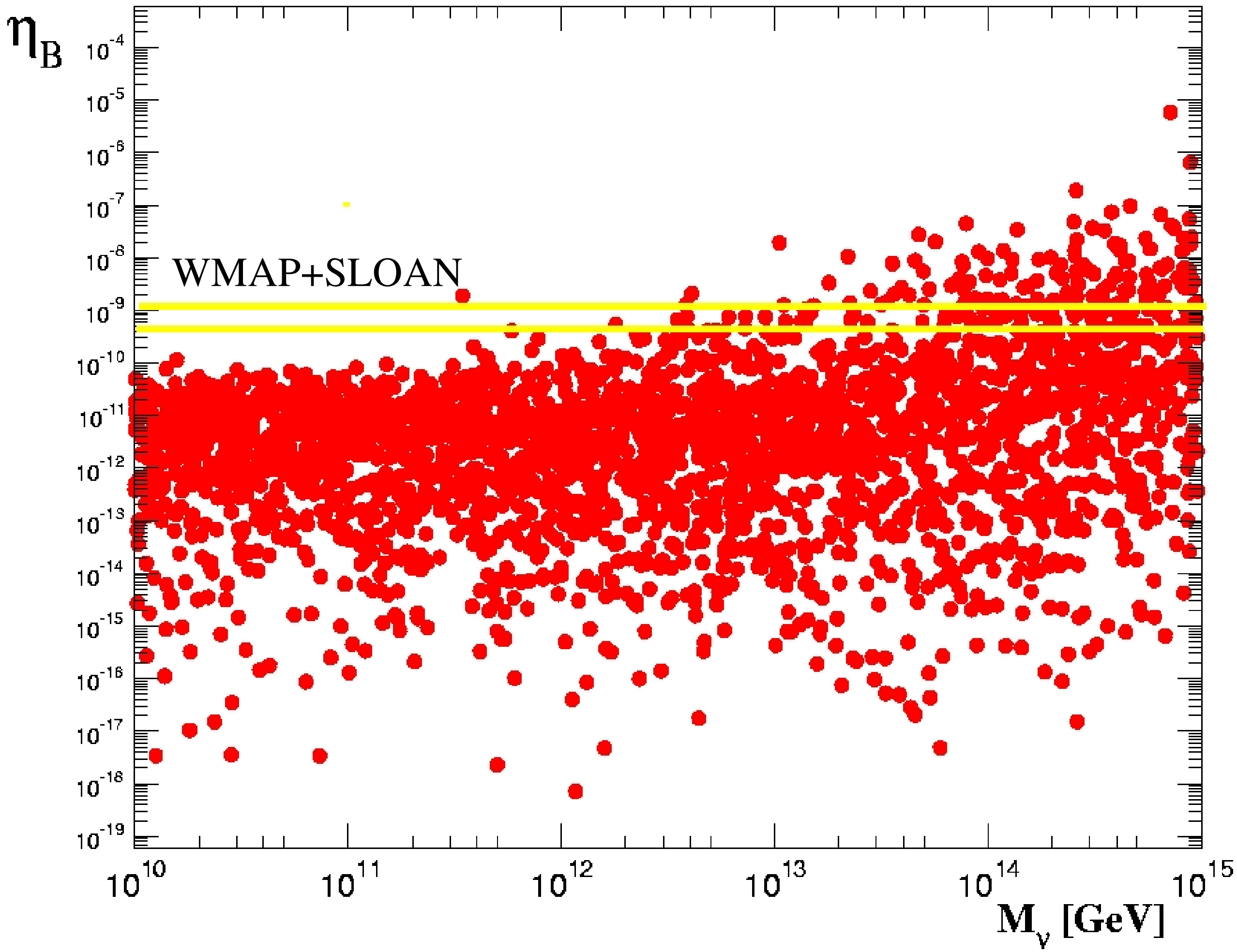
- In the case of degenerate M_R & with the inclusion of CPV phases in the Yukawas the observed matter-antimatter asymmetry of the universe can be generated via leptogenesis [for natural values of the free parameters, especially if M_R is high]

Cirigliano, GI, Porretti, '06
Branco et al. '06
De Simone, GI, Masina , Riotto, '08

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



Cirigliano, GI, Porretti, '06

No need to invoke non-trivial right-handed flavour structures and/or new CPV phase beyond the Yukawas to explain the matter-antimatter asymmetry: the MFV scheme is phenomenologically consistent

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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.

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

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

Matter fields:

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

Maximal flavour group:

[allowed by the gauge interaction]

$$U(3)_\psi \times U(3)_\chi \times U(3)_N$$

The minimal GUT Yukawa interaction:

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

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

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- Y_D & Y_U (hence the CKM matrix) in the charged-lepton 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 [possible interesting effects in $3\to2$ transitions]

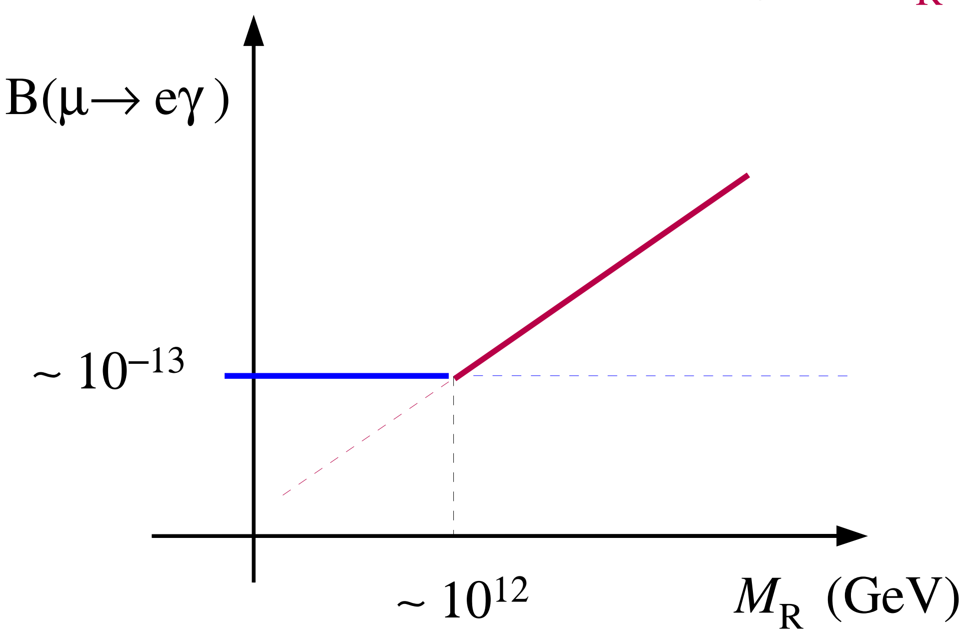
$\mu \to e\gamma$ vs. $\tau \to \mu(e)\,\gamma$

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:

$$A(l_i \to l_j \gamma) = a\,[Y_e Y_\nu^{+} Y_\nu]_{ij} + b\,[Y_U^{+} Y_U Y_D]_{ij}$$

Normalization depending on M_R

M_R independent



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

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

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PMNS mixing structure [MLFV],

dominant if $M_R > 10^{12}$ GeV $\Rightarrow$ $B(\mu \to e\gamma) \sim 10^{-13}\,(M_R/10^{12}\,\mathrm{GeV})\,(\Lambda/10\,\mathrm{TeV})^4$

CKM mixing structure [~ Barbieri-Hall-Strumia '95]

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The search for $\tau\to \mu(e)\,\gamma$ at B and super-B factories becomes very interesting $\Rightarrow$ best tool to discriminate the two scenarios :

$$B(\tau\to\mu\gamma):B(\tau\to e\gamma):B(\mu\to e\gamma) \sim \lambda^{-6}:\lambda^{-4}:1 \sim 10^4:500:1$$

$$B(\tau\to\mu\gamma):B(\tau\to e\gamma):B(\mu\to e\gamma) \sim [500\text{–}10]:1:1$$

LFV in SUSY models

The main features emerging from the general effective-theory approach are naturally realized within the popular (and well motivated) SUSY extensions of the SM.

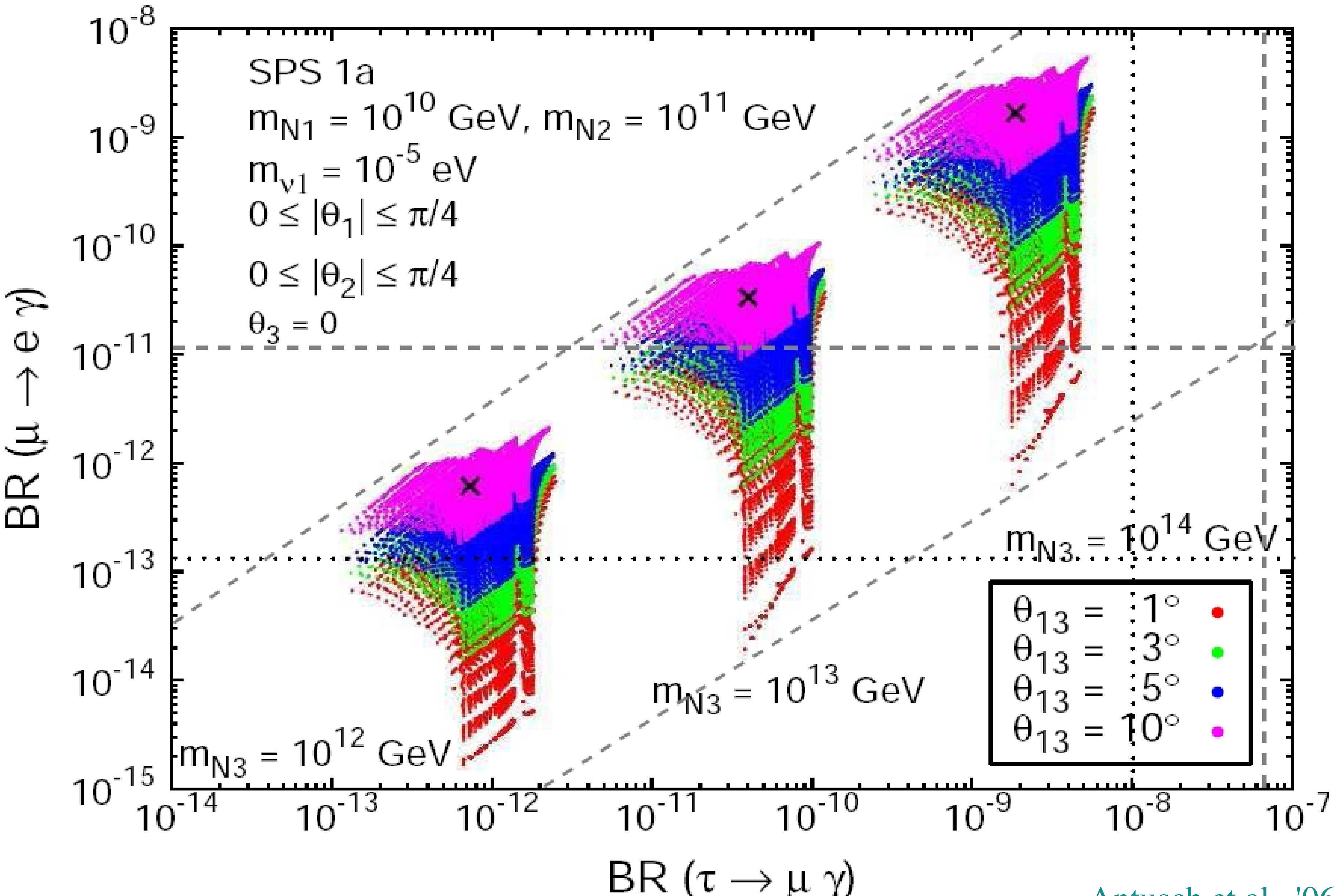
Two main scenarios [close correspondence with the general EFT approach]:

MSSM – GUT	MSSM + heavy N_R
Barbieri, Hall '94; Hisano *et al.* '95 Buchmuller *et al.* '99; Ellis *et al.* '00 Lavignac *et al.* '01; Masiero *et al.* '03 Ciuchini *et al.* '07 + many others	Borzumati, Masiero '86; Hisano *et al.* '95 Davidson, Ibarra '01; Masina, Savoy, '03 Petcov *et al.* '05; Calibbi *et al.* '05 Herrero *et al.* '05-'08 + many others

Two *special* [model-dependent] features:

- If the dynamical mechanism of supersymmetry breaking occurs below the GUT scale, we can conceive specific scenarios [gauge mediation] where quark and lepton flavor sectors decouple completely ⇒ no observable LFV rates
- Two Higgs doublets ⇒ key role played by $\tan\beta = \langle H_U \rangle / \langle H_D \rangle$ & possible sizable Higgs-mediated LFV amplitudes in τ decays.

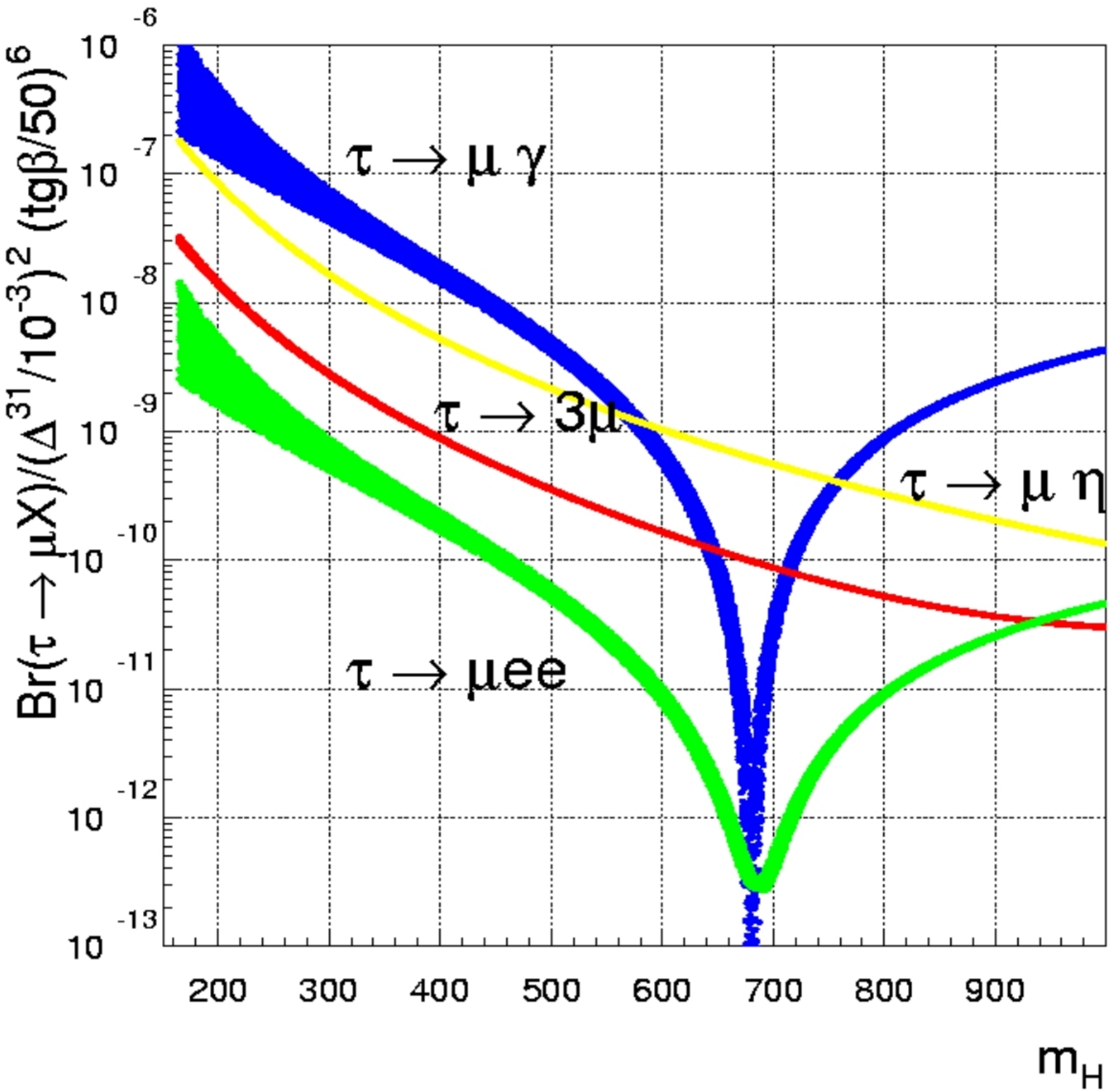
E.g. n.1: $\tau \to \mu\gamma$ vs. $\mu \to e\gamma$ in MSSM + heavy N_R [no GUT constraints]



Antusch et al. '06

E.g. n.2: Higgs-mediated $\tau \to \mu\gamma$ vs. non-radiative τ decays at large $\tan\beta$

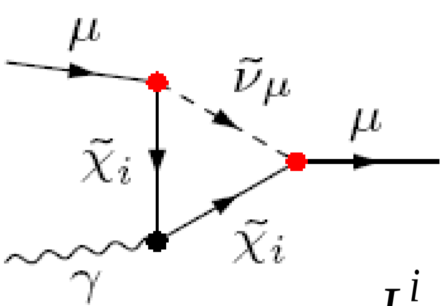
Even in the most favourable scenario for Higgs-mediated amplitudes (sparticles decoupling regime) the radiative mode is likely to dominate



Paradisi '05

E.g. n.3: The link between $(g\text{-}2)_\mu$ and $\mu \to e\gamma$

Effective ops. contributing to $(g\text{-}2)_\mu$ and $\mu \to e\gamma$ are very similar:

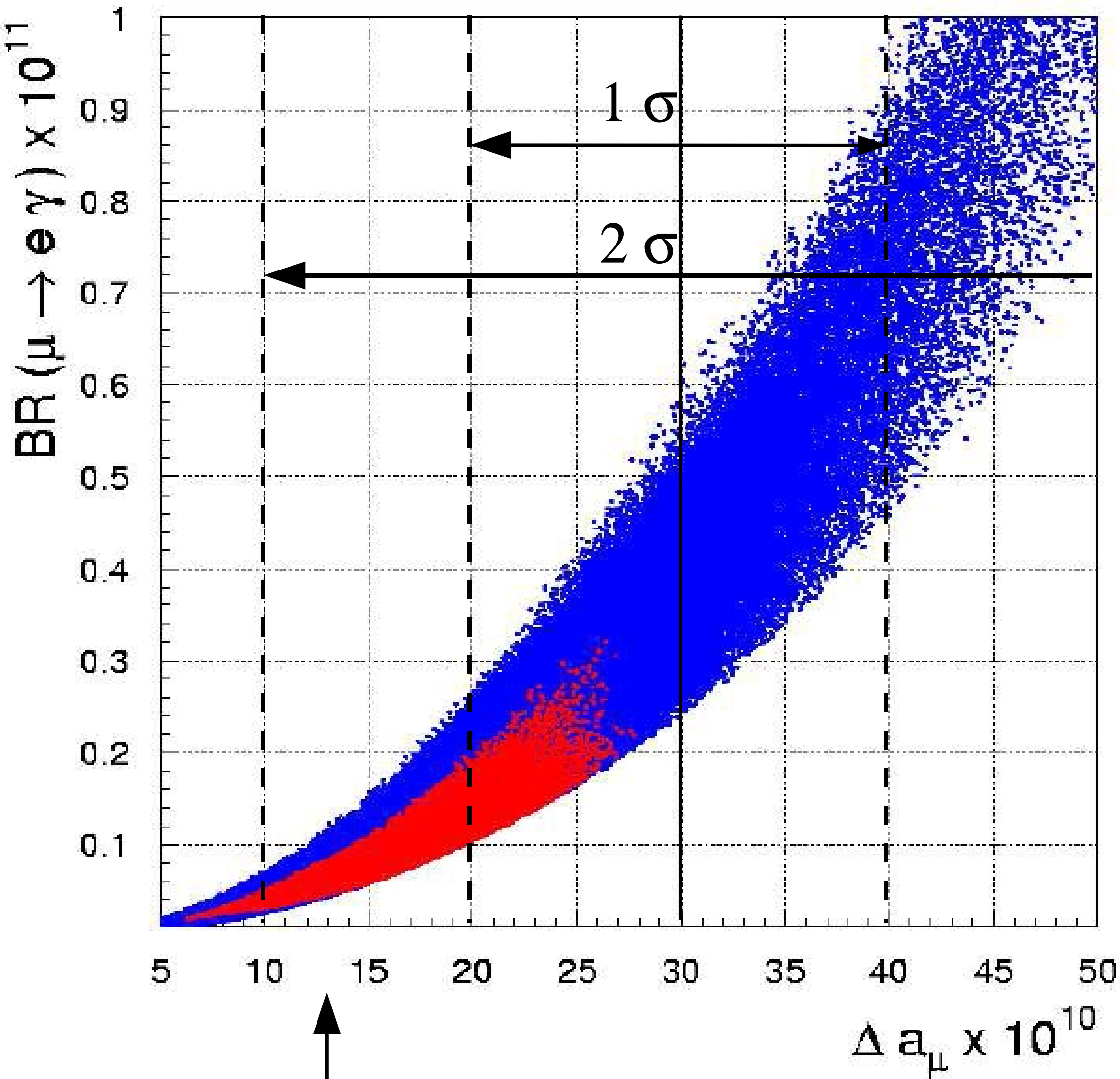


$$L_L^i \sigma^{\mu\nu} E_R^j \phi F_{\mu\nu}$$

(same tanb enhancement, same dep. on slepton masses) only the flavor structure distinguish them

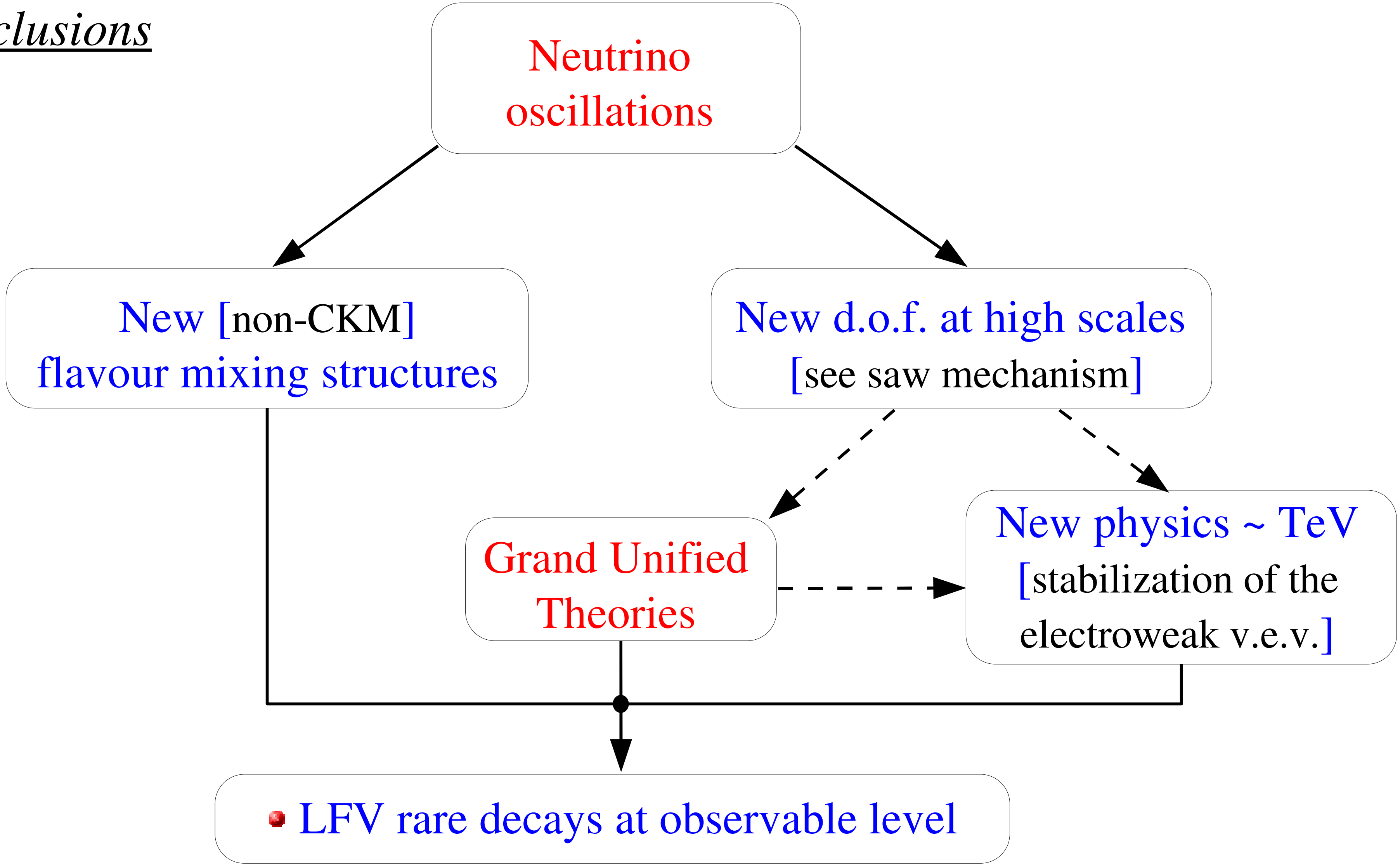
$M_R \sim 10^{12}$ GeV $\Rightarrow$ $(\delta_{LL})_{12} \sim 10^{-4}$

- No constraints from B physics
- With B physics constraints

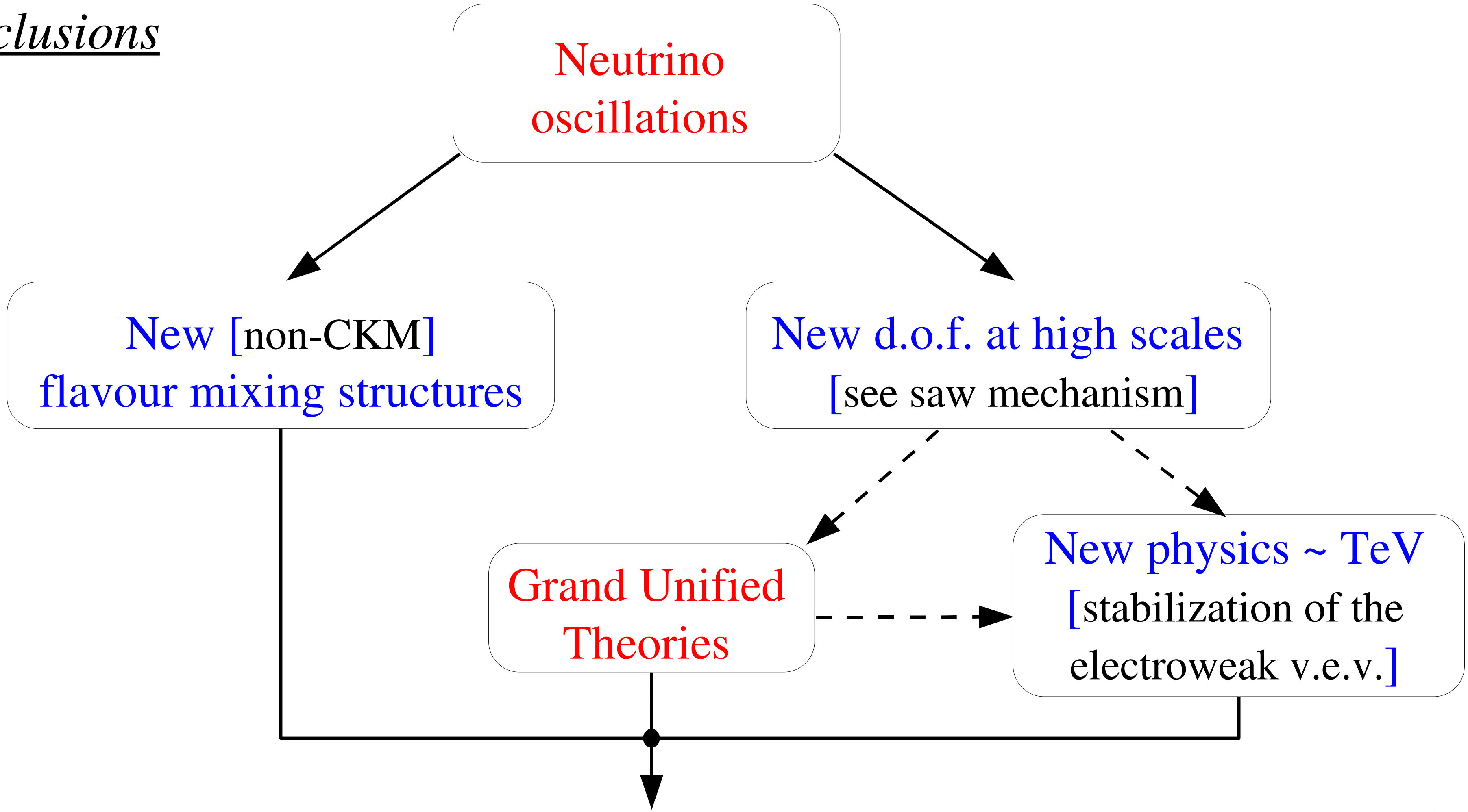


G.I., Mescia, Paradisi, Temes, '07

▶ *Conclusions*



Conclusions



Using a generic "minimalistic" EFT approach:

- $\mu \to e\gamma$ is likely to be seen at MEG [in most realistic scenarios]
- The observation of $\tau \to \mu\gamma$ at super-B is not guaranteed, but its search at the 10^{-9} level is a unique tool to discriminate GUT models