Charged Lepton Flavor and Symmetry Physics Implications

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[*INFN, Frascati & CERN*]

- Introduction [*the key open questions in flavor physics*]
- What we learned so far
- Future prospects [*the key role of LFV and EDMs*]
- Conclusions

Introduction

All known phenomena in particle physics (*leaving aside cosmological observations*) can be described with good accuracy by a remarkably simple *effective* theory:

$$\mathscr{L}_{\mathrm{SM+\nu}} = \mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i) + \mathscr{L}_{\mathrm{Symm.\ Break.}}(\phi, A_a, \psi_i)$$

- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections (UV insensitive)
- Highly symmetric [*gauge + favor symmetries*]

- *Ad hoc*
- Necessary to describe data [*we couldn't live in a fully symmetric world...*]
- Not stable with respect to quantum corrections (UV sensitive)
- Origin of the flavor structure of the model [*and of all the problems of the model...*]

Introduction

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- *Natural*
- Experimentally tested with high accuracy

Elegant & stable,
but also a bit boring...

- *Ad hoc*
- Necessary to describe data [*we couldn't live in a fully symmetric world...*]

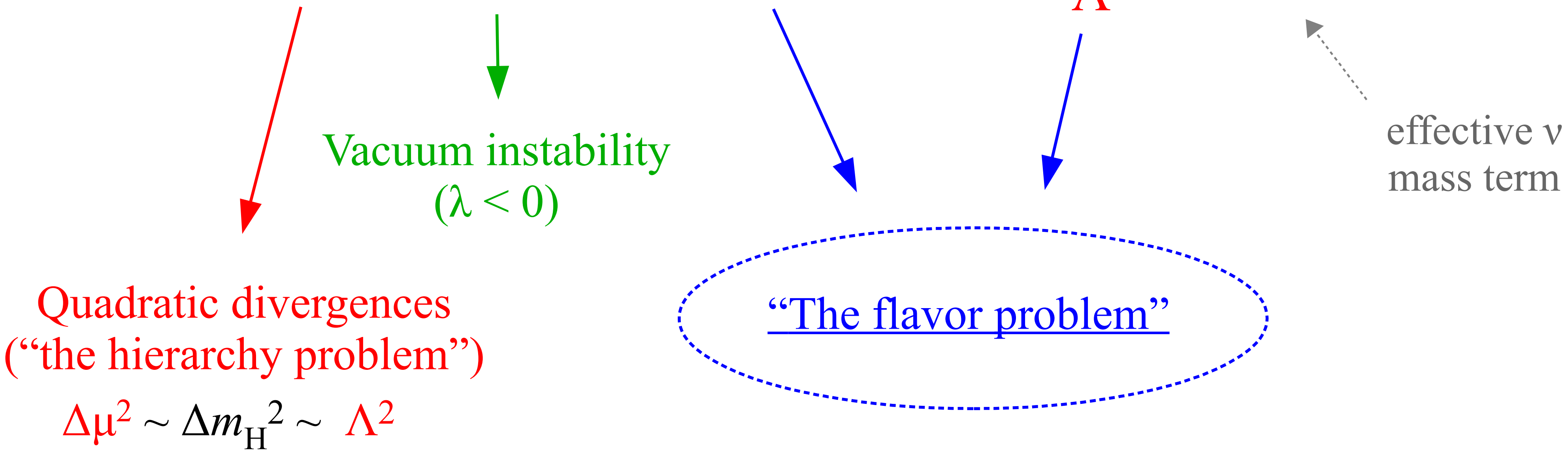
Ugly & unstable, but is what
makes nature interesting...!

The evidence of a new boson, compatible with the properties of the Higgs boson, indicates that the symmetry breaking sector has a <u>*minimal*</u> and <u>*weakly coupled*</u> structure:

$$\mathscr{L}_{\text{Symm. Break.}}(\phi, A_a, \psi_i\ ) = D\phi^+ D\phi - V(\phi)$$

...where all the “problems” are hidden in the Higgs potential:

$$V(\phi) = -\ \mu^2\, \phi^+\phi + \lambda\, (\phi^+\phi)^2 + Y^{ij}\, \psi_L{}^i\, \psi_R{}^j\, \phi + \frac{g^{ij}}{\Lambda}\, \psi_L{}^i \psi_L{}^{Tj}\, \phi\, \phi^T$$



Vacuum instability
($\lambda < 0$)

effective ν
mass term

Quadratic divergences
(“the hierarchy problem”)

$\Delta\mu^2 \sim \Delta m_H{}^2 \sim \Lambda^2$

“The flavor problem”

$$V(\phi) = - \mu^2 \phi^+\phi + \lambda\,(\phi^+\phi)^2 + \underbrace{Y^{ij}\,\psi_L^{\,i}\,\psi_R^{\,j}\,\phi + \frac{g^{ij}}{\Lambda}\,\psi_L^{\,i}\psi_L^{\,Tj}\,\phi\,\phi^T + \ldots}$$

- *General consideration:*

  Quark & Lepton flavor physics are a complementary (and necessary) ingredient to better understand the Higgs or, more generally, the symmetry-breaking sector of the theory.

- *Two key open questions:*
  - *What determines the observed pattern of masses and mixing angles of quarks and leptons?* [is there a rational behind the observed hierarchies?]
  - *Which are the sources of flavor symmetry breaking accessible at low energies?* [Is there anything else beside Yukawa couplings & the neutrino mass matrix that distinguishes the three families?]

What we learned so far

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

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

Answering the second 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).

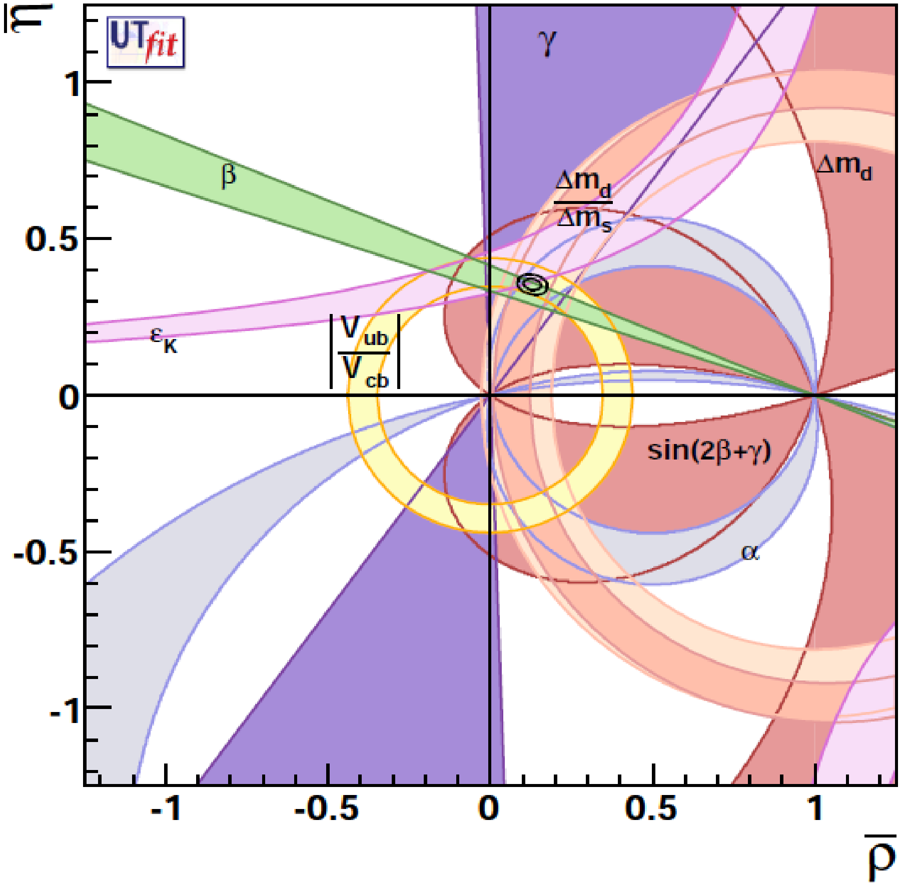
⬇

We learned a lot about the possible sources of flavor symmetry breaking from a series of high-precision measurements of flavor-changing processes performed in the recent past

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

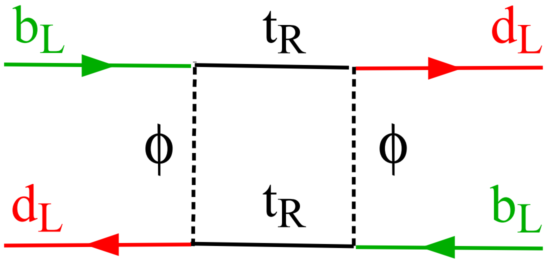
In the quark sector all measurements show a remarkable overall success of the CKM picture

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



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

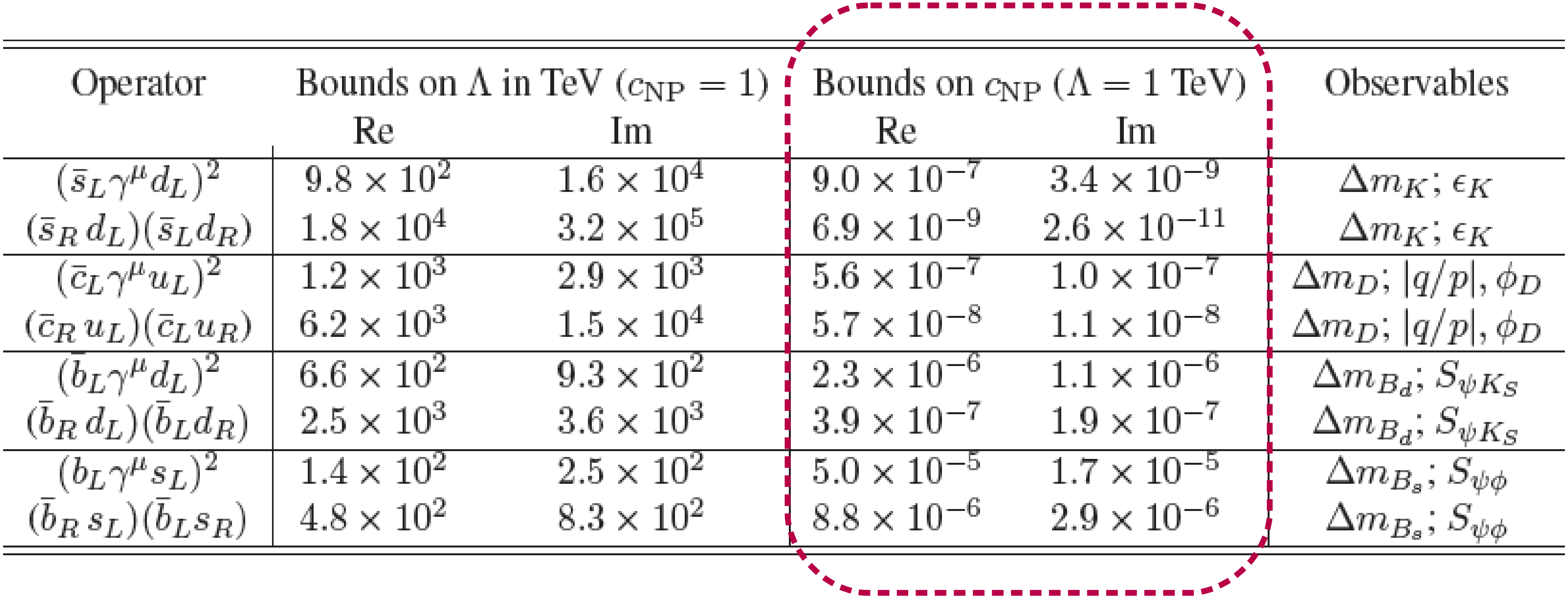
tiny SM contribution (Yukawa interaction)



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

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

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



Operator	Bounds on Λ in TeV ($c_{\rm NP} = 1$)		Bounds on $c_{\rm NP}$ ($\Lambda = 1$ 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; $\lvert q/p\rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_R\, d_L)(\bar b_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar b_R\, s_L)(\bar b_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

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

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

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

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

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

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

MEG '11

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

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

The good overall consistency of the SM predictions for flavor-changing processes indicates there is not much room for new sources of flavor symmetry breaking close to the TeV scale, or that the scale of New Physics (NP) is very high

However, the constraints on the scale of NP become much less severe in realistic models where the mechanisms of flavor-mixing and fermion masses are linked together [e.g.: *Minimal Flavor Violation*, or *Partial Compositeness*]

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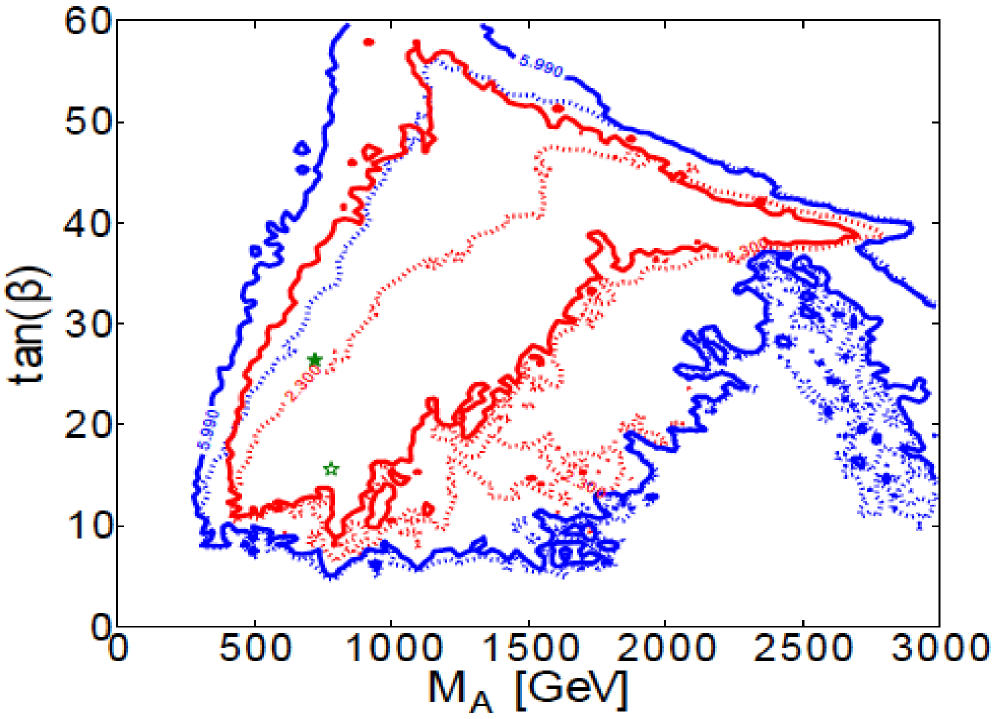
E.g.: Impact of the exp. bound on BR($B_s \to \mu^+\mu^-$) in the NUHM-MSSM

Buchmueller *et al*. '12



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⬇

In such models we do expect small but detectable deviations from the SM predictions in selected flavor-violating observables:

- Small/tiny corrections over leading SM amplitudes
- Rare/forbidden processes (such as LFV & EDMs)

We need more statistics on theoretically-clean observables to make progress

We have understood that the flavor structure of NP is highly non trivial,
but we have not yet identified this structure yet.

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

Two main roads:

Anarchy
+
Anthropic selection

(*"Chance & Necessity"* [J. Monod])

The symmetric way

(*"The book of nature is written in terms of circles, triangles and other geometrical figures..."* [G. Galilei])

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

Two main roads:

Anarchy
+
Anthropic selection

("*Chance & Necessity*" [J. Monod])

- Many unanswered questions:

  It works well for $m_{u,d}$
  maybe also for m_t *& ν mixing,*
  but what about CKM and the other masses? Why 3 generations?

  ….

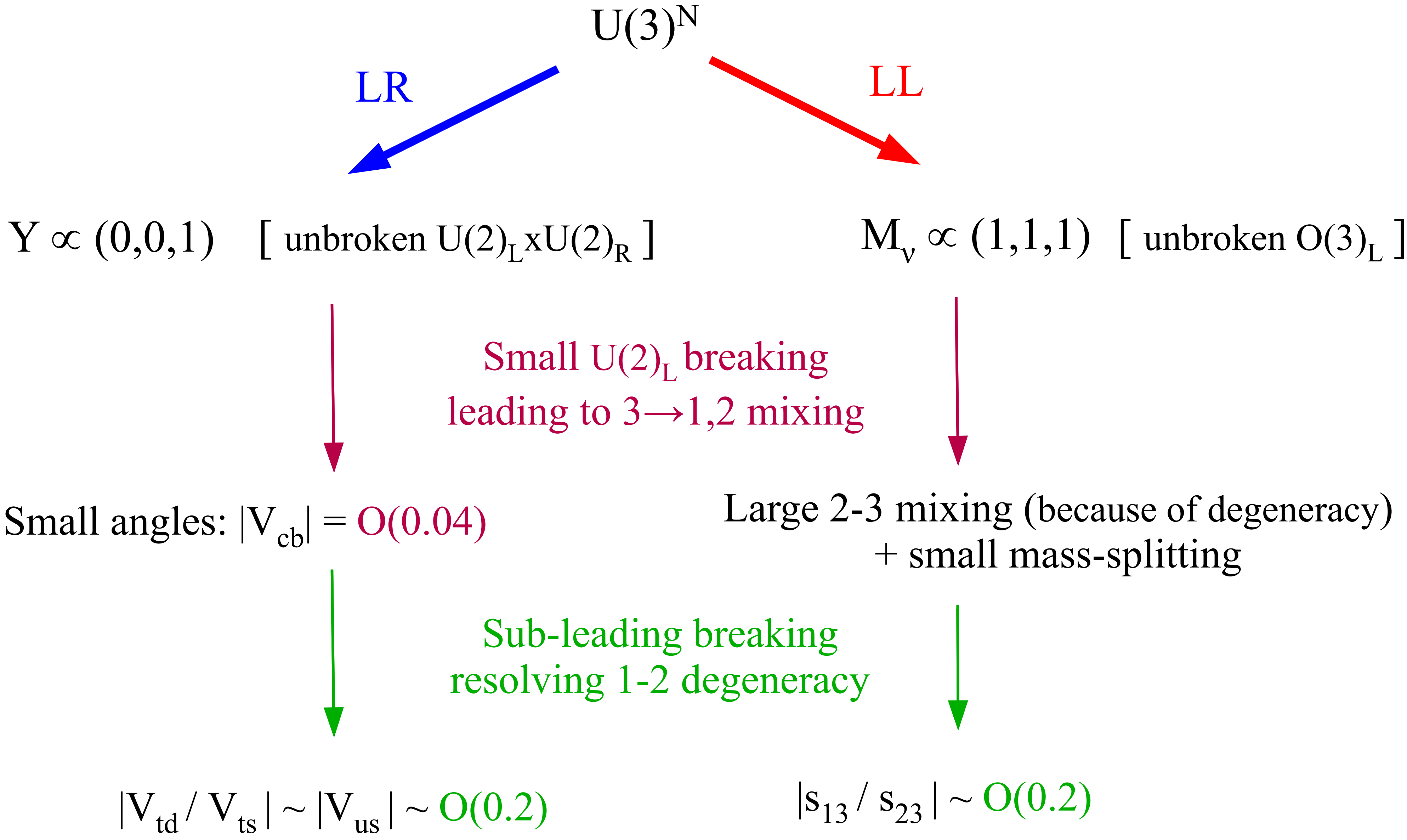
- No clear direction for future searches

The symmetric way

("*The book of nature is written in terms of circles, triangles and other geometrical figures…*" [G. Galilei])

- Main road of particle physics so far.
- It works well in the Yukawa sector (*several possible options*), less evident (but not excluded) in the neutrino case
- "large" flavor symm. + "small" breaking is the best way to explain the absence of NP signals so far [*and often implies visible NP signals with higher precision*].

The symmetric way [*a possible option*]



$U(3)^N$

LR

LL

$Y \propto (0,0,1)$ [unbroken $U(2)_L xU(2)_R$]

$M_\nu \propto (1,1,1)$ [unbroken $O(3)_L$]

Small $U(2)_L$ breaking
leading to 3→1,2 mixing

Small angles: $|V_{cb}| = O(0.04)$

Large 2-3 mixing (because of degeneracy)
+ small mass-splitting

Sub-leading breaking
resolving 1-2 degeneracy

$|V_{td} / V_{ts}| \sim |V_{us}| \sim O(0.2)$

$|s_{13} / s_{23}| \sim O(0.2)$

Future prospects

General decomposition of flavor-violating observables:

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

trivial kinematical factors

(dimension-less) effective couplings

This decomposition is very general.
It holds for both for forbidden processes ($\tau\rightarrow\mu\gamma$) 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 flavor-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 ($\sigma(\Lambda) \sim 1/N^{1/4}$)
- The interest of a given flavor obs. depends on the magnitude of c_{SM} vs. c_{NP} and on the theoretical error of c_{SM} => concentrate on clean & rare processes

In the quark sector, the present exp. accuracy ranges from 10% to 100% for loop-induced processes => we need to reach the few % level of precision (*in the few cases where the theory error is not dominant*)

Future prospects

"Minimalistic" list of the key (low-energy) quark flavor-violating observables:

- γ from tree ($B \to DK$, ...)
- $|V_{ub}|$ from exclusive semi-leptonic B decays

→ Clean (tree-level) determination of the main SM inputs [key ingredient to improve the precision of $\Delta F=2$ tests]

$B_{s,d} \to l^+l^-$	Higgs-mediated FCNCs [$\sigma(f_B) < 5\%$ (from lattice)]
CPV in B_s mix. [ϕ_s]	New CPV (SUSY, ...) [$\sigma(S_{\psi\varphi}) \sim 0.01$]
$B \to K^{(*)} l^+l^-, \nu\nu$	Non-standard FCNCs [$\sigma(A_{FB}) \lesssim 5\%$]
$B \to \tau\nu, \mu\nu$ (+D)	Scalar charged currents [$\sigma(f_B) \to 5\%$ (from lattice)]
$K \to \pi\nu\nu$	Best probe of non-MFV [$\sigma(BR) \lesssim 5\%$]
CPV in charm	Key window on up-type dynamics [more work on the th. side]

Future prospects

“Minimalistic” list of the key (low-energy) quark flavor-violating observables:

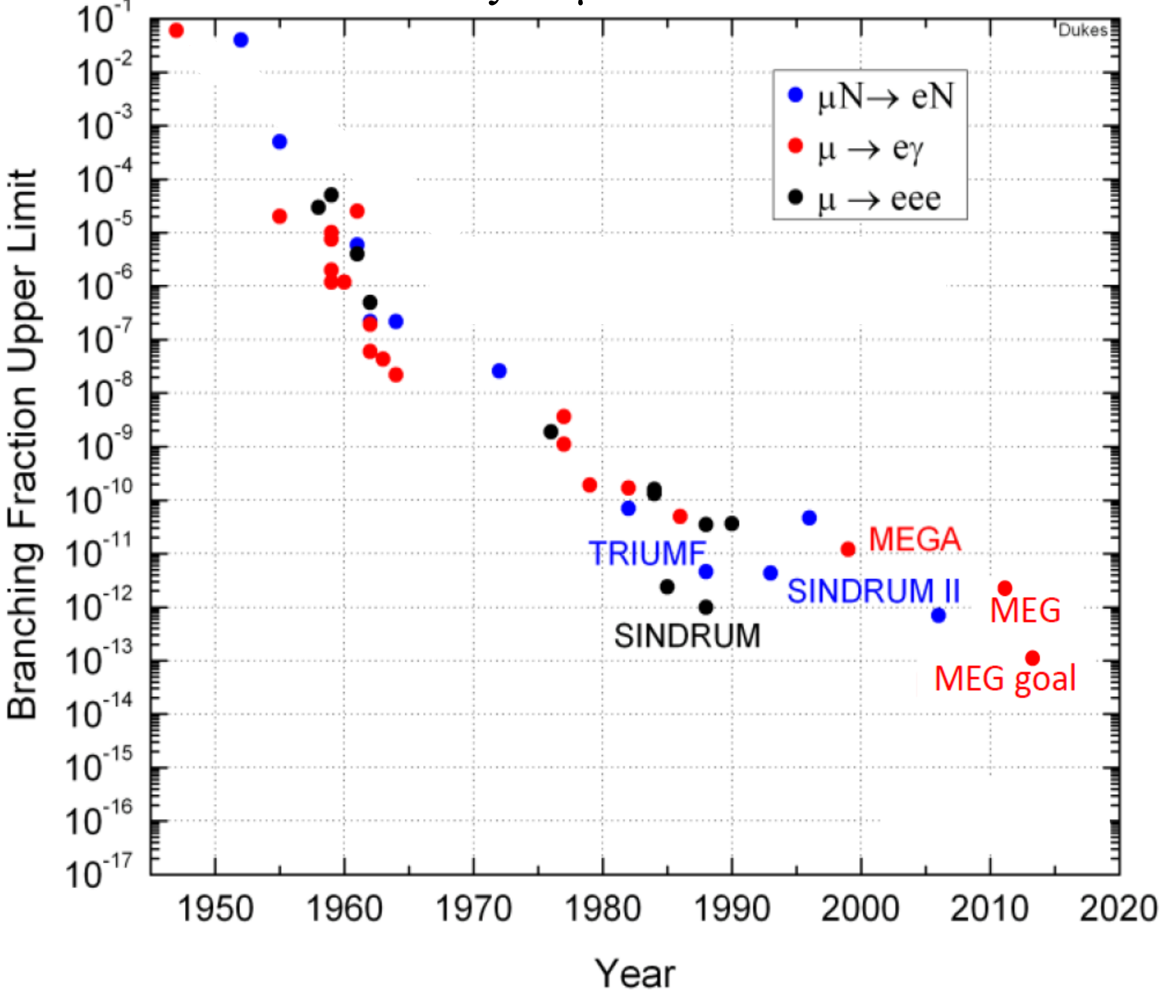
γ from tree ($B \to DK$, ...)	S-LHCb
$\lvert V_{ub} \rvert$ from exclusive semi-leptonic B decays	S-Bfactory [SuperKEKB & SuperB]
$B_{s,d} \to l^+l^-$	S-LHCb + ATLAS & CMS
CPV in B_s mix. [ϕ_s]	S-LHCb + ATLAS & CMS
$B \to K^{(*)} l^+l^-$, $\nu\nu$	S-LHCb / S-Bfactory
$B \to \tau\nu$, $\mu\nu$ (+D)	S-Bfactory
$K \to \pi\nu\nu$	Kaon beams [NA62, KOTO, ORKA]
CPV in charm	S-LHCb / S-Bfactory

The key role of LFV and EDMs

After what we learned from neutrino physics, LFV in charged leptons is probably the most interesting (*and potentially rewarding*) search in the flavor sector.

- Neutrino oscillations => Lepton Flavor Violation
- No problems of SM (and SM + ν) backgrounds
- LFV in charged leptons at "visible rates" if there are new particles carrying lepton flavor not too far from the TeV scale (*as in most realistic NP models*)

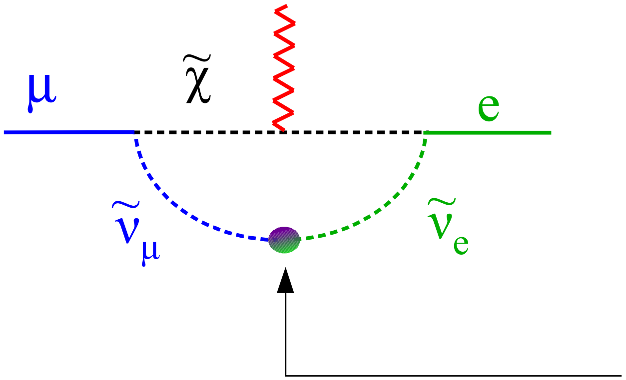
History of μ → e searches



The key role of LFV and EDMs

LFV in charged leptons at “visible rates” if there are new particles carrying lepton flavor not too far from the TeV scale:

E.g.: SUSY



$$(\delta_{LL})_{12} \sim \left[\begin{array}{ll} y_t^2 \;\; V_{13}V_{23}^* & [\textit{GUT}] \\ y_{\nu_3}^2 \; U_{13}U_{23}^* & [\textit{see-saw}] \end{array}\right.$$

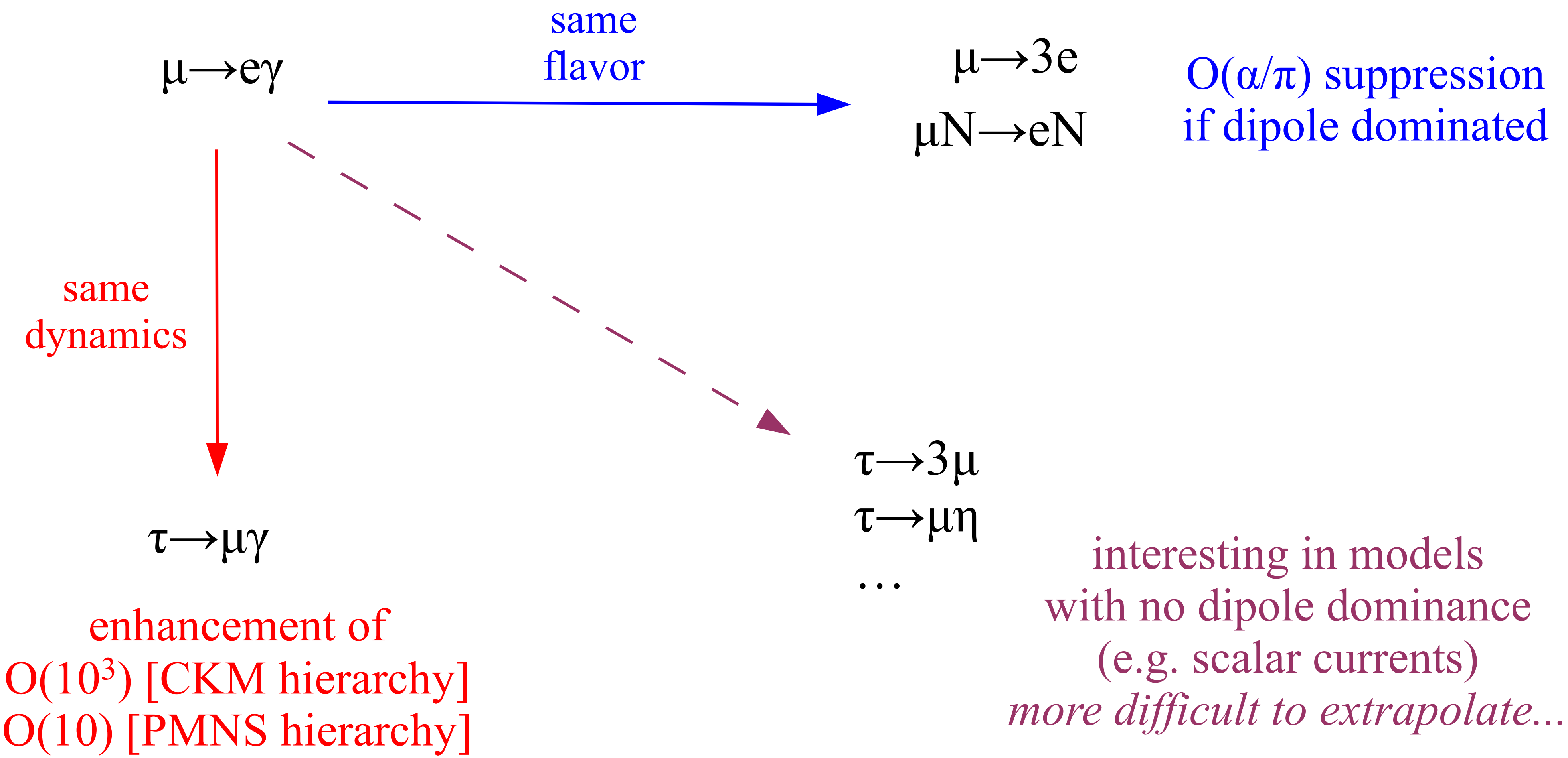
$$B(\mu \rightarrow e\gamma) \sim 10^{-13} \left[\frac{\tan\beta}{10}\right]^2 \left[\frac{0.5\ \text{TeV}}{\tilde{m}}\right]^4 \left[\frac{(\delta_{LL})_{12}}{10^{-4}}\right]^2$$

…and similar expressions holds in many other models:

=> MEG has realistic chances to see $\mu \rightarrow e\gamma$ (*but remember that* $\Gamma \sim \Lambda^{-4}$)

The key role of LFV and EDMs

The recent MEG bound, $BR(\mu\to e\gamma) < 2.4\times10^{-12}$, and its final sensitivity ($\sim10^{-13}$), can be taken as reference values to estimate potentially interesting levels for future LFV searches in different channels:



$\mu\to e\gamma$

same flavor

$\mu\to 3e$

$\mu N\to eN$

$O(\alpha/\pi)$ suppression if dipole dominated

same dynamics

$\tau\to\mu\gamma$

enhancement of $O(10^3)$ [CKM hierarchy] $O(10)$ [PMNS hierarchy]

$\tau\to 3\mu$

$\tau\to\mu\eta$

…

interesting in models with no dipole dominance (e.g. scalar currents)

more difficult to extrapolate…

✭ *The key role of LFV and EDMs*

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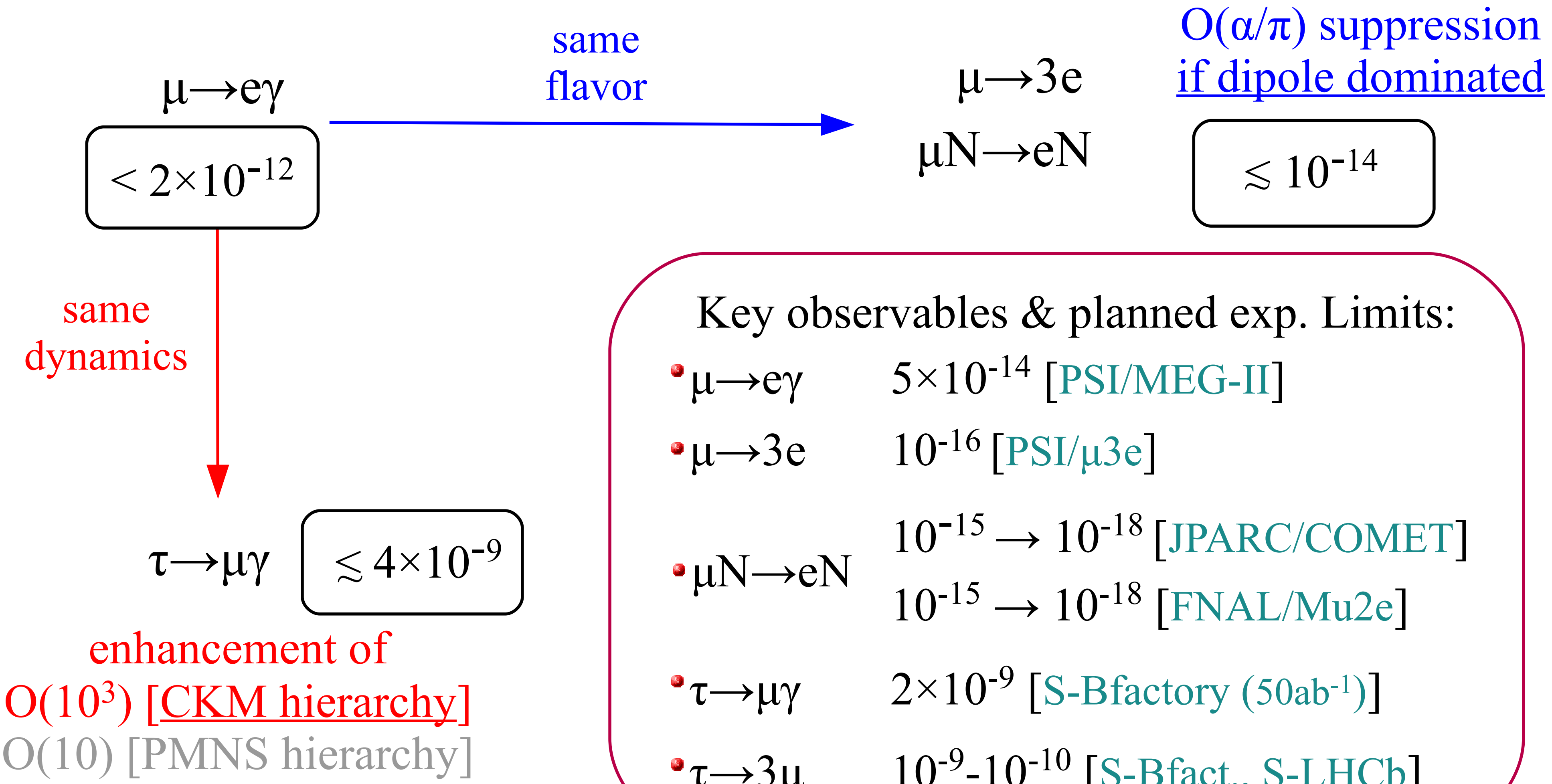


$\mu\to e\gamma$ $\boxed{< 2\times10^{-12}}$

same flavor

$\mu\to 3e$

$\mu N\to eN$

O(α/π) suppression if dipole dominated

$\boxed{\lesssim 10^{-14}}$

same dynamics

$\tau\to\mu\gamma$ $\boxed{\lesssim 4\times10^{-9}}$

enhancement of
O(10^3) [CKM hierarchy]
O(10) [PMNS hierarchy]

Key observables & planned exp. Limits:

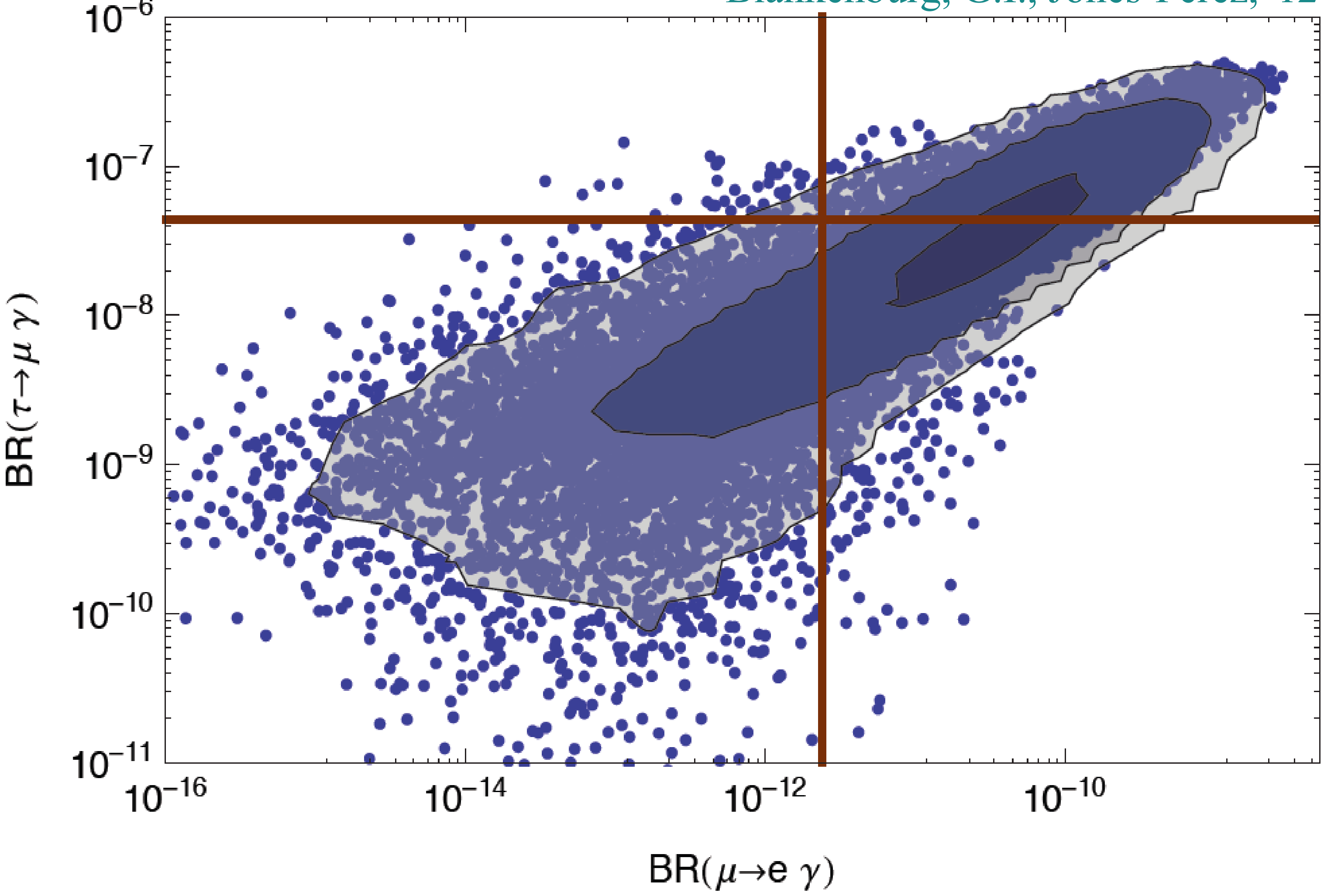
$\mu\to e\gamma$	5×10^{-14} [PSI/MEG-II]
$\mu\to 3e$	10^{-16} [PSI/μ3e]
$\mu N\to eN$	$10^{-15}\to10^{-18}$ [JPARC/COMET] $10^{-15}\to10^{-18}$ [FNAL/Mu2e]
$\tau\to\mu\gamma$	2×10^{-9} [S-Bfactory (50ab^{-1})]
$\tau\to 3\mu$	10^{-9}-10^{-10} [S-Bfact., S-LHCb]

✭ *The key role of LFV and EDMs*

...and there is no doubt that if MEG will see a positive signal, then all other LFV searches would be extremely important to understand the nature of the effect.

E.g.: SUSY with minimally broken $U(3)^5$

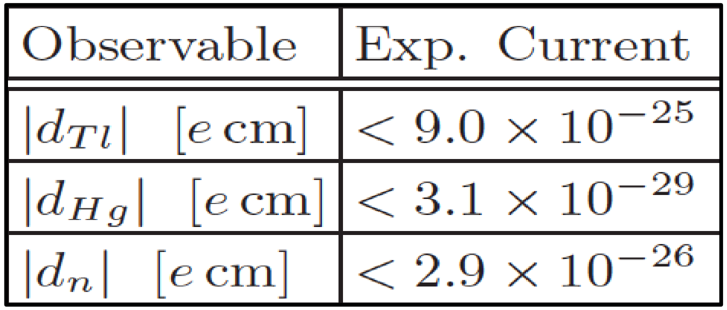
Blankenburg, G.I., Jones-Perez, '12



The key role of LFV and EDMs

The search for Electric Dipole Moments of fundamental particles (n, e, μ, … *and, more generally, atoms or heavy nuclei*), share the three main virtues of LFV searches:

- We know CP is not an exact symmetry of nature => non-vanishing EDMs
- Virtually no problems of SM backgrounds
  accidental” SM suppression: $d_n^{SM} < 10^{-32}\, e$ cm
- EDMs close to the present bounds (especially for the n case) in several realistic models (e.g. SUSY) with new CPV phases around the TeV scale



Observable	Exp. Current
$\lvert d_{Tl}\rvert$ [e cm]	$< 9.0 \times 10^{-25}$
$\lvert d_{Hg}\rvert$ [e cm]	$< 3.1 \times 10^{-29}$
$\lvert d_n\rvert$ [e cm]	$< 2.9 \times 10^{-26}$

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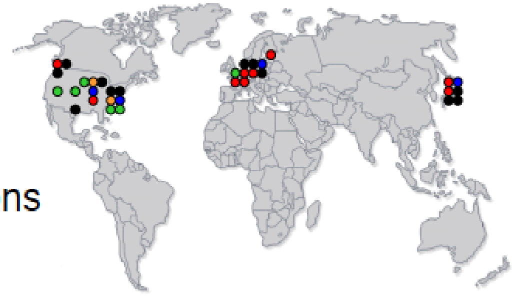
Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- Neutrons ~200
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC
- Molecules ~50
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma
- Atoms ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



- Ions-Muons ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC
- Solids ~10
  - GGG@Indiana
  - ferroelectrics@Yale

world-wide effort in trying to improve the limits by ~ 1 order of magnitude

Conclusions

- The success of the SM in describing flavor-changing processes of both quarks and charged leptons implies that large new sources of flavor symmetry breaking at the TeV scale are excluded. However, the two key questions about "the origin of flavor" are still open.

- This success fits well with the idea of a

mildly broken flavor symmetry + weakly interacting NP
+ little hierarchy around the TeV scale

(*coherent picture with e.w. precision tests + light Higgs + lack of deviations from SM at high-pT*). According to this picture, deviations from the SM are within the reach of future experiments in flavor physics.

- The key tool to make progress in this field is to push forward the precision in the most clean observables (key role of LFV & EDMs):
  - full complementarity between low-energy and high-pT physics
  - full complementarity among the different low-energy facilities [ambitious "single-goal" experiments should definitely be supported]

Additional material

Top-10 list of key flavor-changing measurements [a (motivated) personal choice]

$B(\mu \to e\gamma)$	SES $< 10^{-13}$
$B(\mu N \to eN)$	SES $< 10^{-16}$
$B(\tau \to \mu\gamma)$	SES $< 10^{-9}$
$B(B_s \to \mu^+\mu^-)$	$\sigma_{rel} < 5\%$
ϕ_s	$\sigma < 0.01$
$B(K^+ \to \pi^+\nu\nu)$ or $B(K_L \to \pi^0\nu\nu)$	$\sigma_{rel} < 5\%$
$B(B^+ \to l^+\nu)$	$\sigma_{rel} < 5\%$
$a_{CP}(D \to \pi\pi\gamma)$	$\sigma < 0.005$
$\|V_{ub}\|$	$\sigma_{rel} < 5\%$
γ_{CKM}	$\sigma < 1^o$

N.B.: the observables are not listed in order of importance