The lepton perspective on flavor

Gino Isidori
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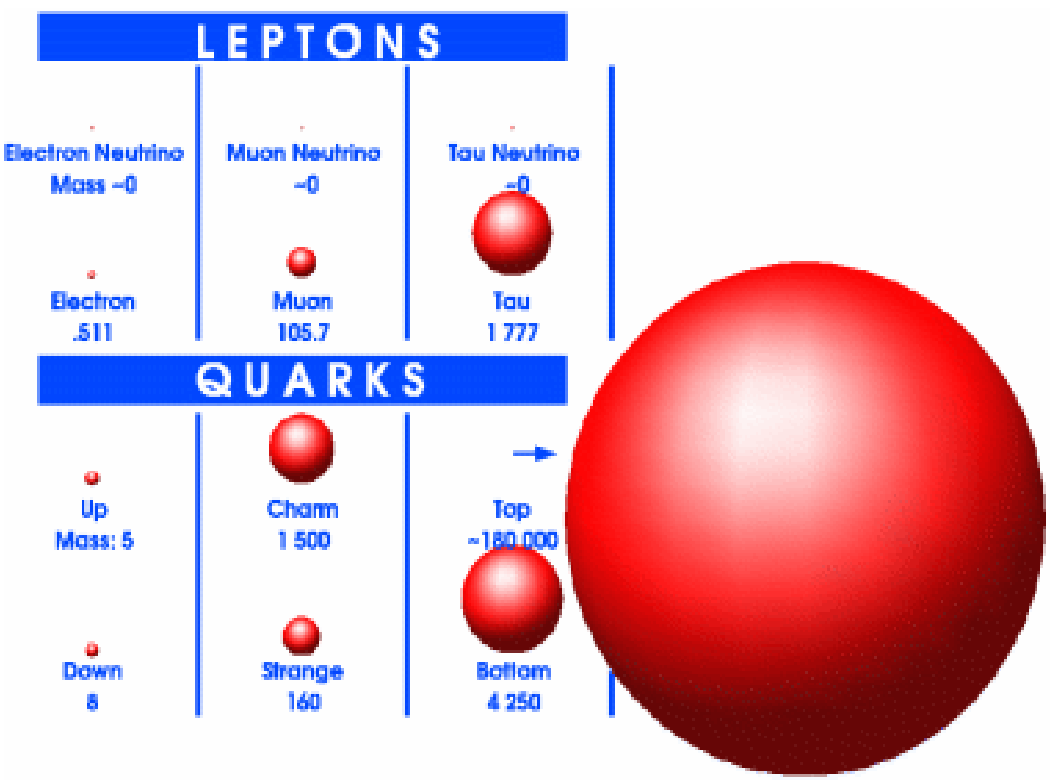
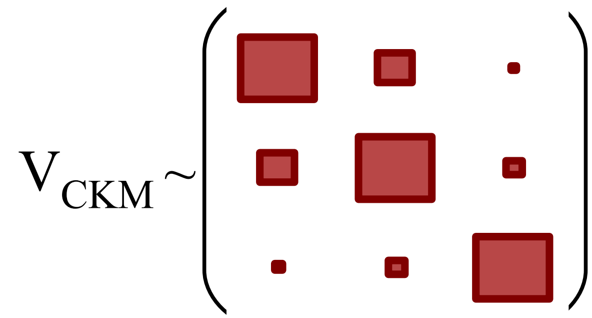
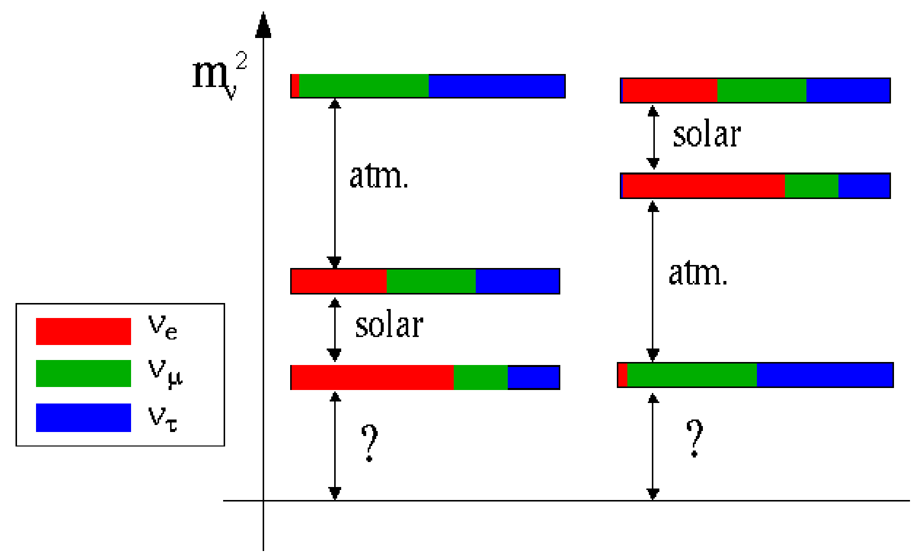
- Introduction [*anarchy vs. symmetry*]
  - *Prelude I:* $U(3)^3$ and $U(2)^3$ symmetries in the quark sector
  - *Prelude II:* $U(3)^3$ to $U(3)^5$ and LFU [*the charged-lepton perspective*]
  - *Prelude III:* Some open problems [*the neutrino perspective*]
- Dynamical Yukawa's from a Minimum Principle
- Gauging dynamical Yukawa's and B-physics anomalies
- Conclusions

Introduction [*anarchy vs. symmetry*]







Finding a rational explanation for the observed pattern of quark and lepton mass matrices (eigenvalues & mixing) is one of the key open problems in particle physics

Introduction [*anarchy vs. symmetry*]

Anarchy + Anthropic selection
"*Darwinism in physics...*"

New symmetries (& new dynamics)
"*The Galilean way...*"

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"*The Galilean way...*"

- A new way of thinking in particle physics, motivated by the hierarchy problem(s) in Λ_{cosmo} and -*maybe*- Λ_{EW}
  - *It works well for $m_{u,d}$*
  - *maybe also for m_t*
  - *appealing for ν mixing...*
  - *but what about CKM,*
  - *what about the other masses?*
- Many unanswered questions
- No clear direction for future searches

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New symmetries (& new dynamics)

"*The Galilean way...*"

- Main road of particle physics so far
  - *It works well in the Yukawa sector* (*less evident, but not excluded, in the neutrino case*)

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↓

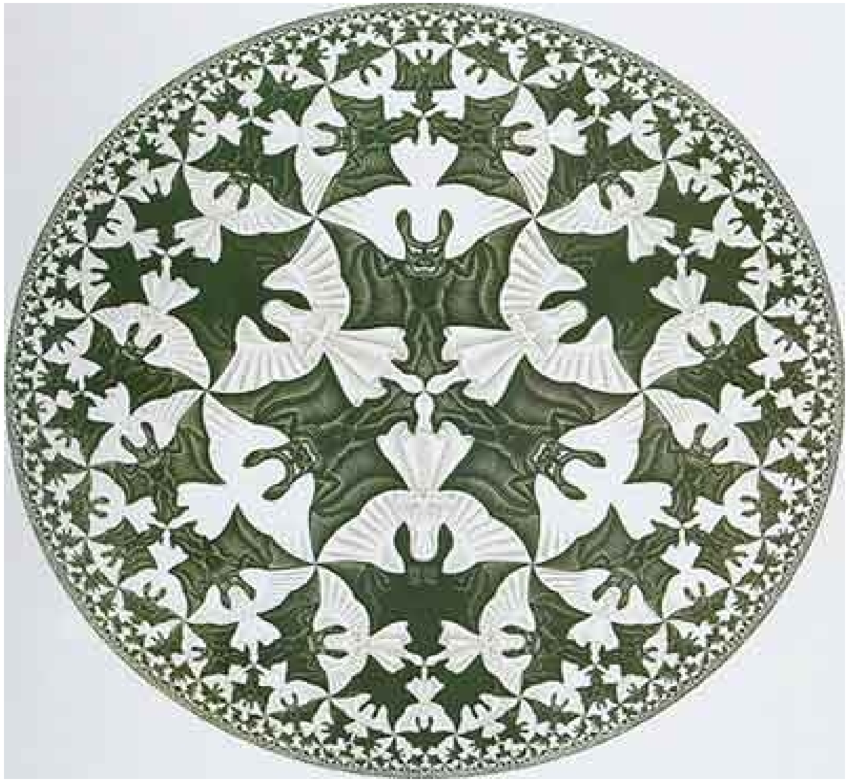
flavor symmetry for light generations
+ *large NP coupling of 3^rd^ gen.*

Interesting hypothesis that

- *fits well with all available data,*
- *could explain why we have not seen yet clear signals of NP,*
- *could possibly be tested in the near future...*

Prelude I:

U(3)^3 & U(2)^3 symmetries in the quark sector



U(3)^3 & U(2)^3 *symmetries in the quark sector*

$$\boxed{U(3)^3 = U(3)_Q \times U(3)_U \times U(3)_D}$$

- Largest flavor symmetry group compatible with the SM gauge symmetry
- MFV = minimal breaking of U(3)^3 by $(3,\underline{3})$ terms [*SM Yukawa couplings*]

Chivukula & Georgi, '89

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

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virtue

- Naturally small effects in FCNC observables assuming TeV-scale NP (*or even few TeV NP...*)

problems

- No explanation for *Y* hierarchies (masses and mixing angles)
- No explanation for small CPV flavor-conserving observables (edms)
- Enhanced hierarchy problem in explicit NP frameworks with key role for the 3rd generation (*particularly motivated nowadays...*)

U(3)^3 & U(2)^3 *symmetries in the quark sector*

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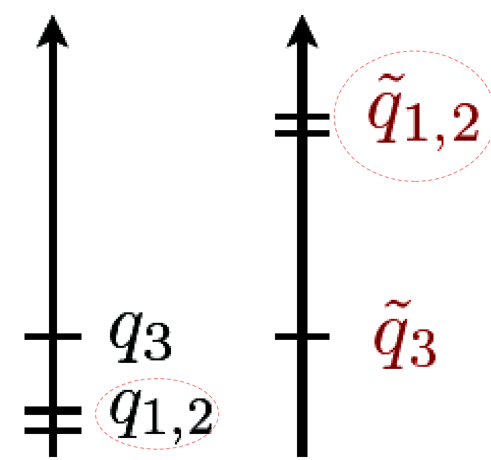
$$\boxed{U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D \text{ flavor symmetry}}$$

acting on 1st & 2nd generations

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

- The exact symmetry limit is good starting point for the SM quark spectrum ($m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$) $\rightarrow$ we only need small breakings terms
- The small breaking ensures small effects in rare processes
- In explicit NP models, this symmetry allows a large mass gap among NP states coupled to 3rd generation (*e.g. 3rd gen. squarks in natural SUSY*), and NP states coupled to 1st & 2nd gen.



A closer look to $U(2)^3$ & its (minimal) 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

Unbroken

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

$$2_Q \times 2_U$$

$$Y_u = y_t \left[\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right] \qquad Y_d = y_b \left[\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right] \qquad \left(M_{\text{squarks}} = \left[\begin{array}{c|c} m_h \times I & 0 \\ \hline 0 & m_3 \end{array}\right] \right)$$

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

$$\boxed{V \sim (2,1,1) \qquad O(\lambda^2 \sim 0.04)}$$

Leading breaking term:
connection 3rd gen. $\rightarrow$ light gen.

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

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

$\rightarrow$

$$(V_{ts}^2 + V_{td}^2)^{1/2} = (V_{cb}^2 + V_{ub}^2)^{1/2} = = O(\lambda^2)$$

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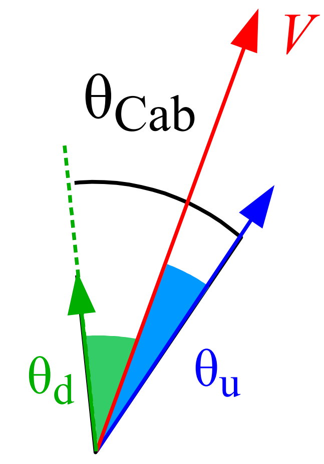

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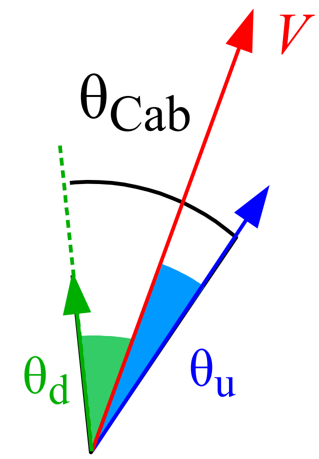
$$\Delta Y_u \sim (2,\underline{2},1) \qquad m_c,\, m_u,\, \theta_u \quad O(y_c \sim 0.006)$$

$$\Delta Y_d \sim (2,1,\underline{2}) \qquad m_s,\, m_d,\, \theta_d \quad O(y_s < 0.001)$$

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

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

A closer look to U(2)^3 *& its (minimal) breaking pattern:*



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$$\Delta Y_u \sim (2,\underline{2},1) \qquad m_c,\ m_u,\ \theta_u \quad O(y_c \sim 0.006)$$

$$\Delta Y_d \sim (2,1,\underline{2}) \qquad m_s,\ m_d,\ \theta_d \quad O(y_s < 0.001)$$

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

The assumption of a single (2,1,1) breaking term [*= a single spurion connecting the light generations to the third one*] ensures a MFV-like protection of FCNCs

The protection is as effective as MFV at large tanβ or general (non-linear) MFV, where $U(3)^3 \rightarrow U(2)^3 \mathrm{x} U(1)$

Feldmann, Mannel, '08
Kagan *et al*. '09

Prelude II:

From $U(2)^3$ & $U(2)^5$ and LFU [*the charged-lepton perspective*]

From U(3)^3 to U(2)^5 and LFU [*the charged-lepton perspective*]

Including the two SM lepton fields

$$\mathrm{U}(2)^3 \;\rightarrow\; \mathrm{U}(2)^5 = \mathrm{U}(2)^3 \times \mathrm{U}(2)_L \times \mathrm{U}(2)_E$$

$$Y_e = y_\tau \left[\begin{array}{c|c} \Delta Y_e & V_L \\ \hline 0 & 1 \end{array} \right]$$

V_L : unknown ($\leftrightarrow$ *ansatz on* m_ν)

ΔY_e : $O(y_\mu)$

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Renewed interest to this flavor symmetry (*and variations...*) generated by the recent *hints* of violations of Lepton Flavor Universality in B decays

- O(30%) LFU violation in $b \to c$ charged currents: τ vs. light leptons (μ, e)

$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \to D^* \tau \overline{\nu})_{\rm exp} / \mathcal{B}(B \to D^* \tau \overline{\nu})_{\rm SM}}{\mathcal{B}(B \to D^* \ell \overline{\nu})_{\rm exp} / \mathcal{B}(B \to D^* \ell \overline{\nu})_{\rm SM}} = 1.23 \pm 0.07$$

$$R_{D}^{\tau/\ell} = \frac{\mathcal{B}(B \to D \tau \overline{\nu})_{\rm exp} / \mathcal{B}(B \to D \tau \overline{\nu})_{\rm SM}}{\mathcal{B}(B \to D \ell \overline{\nu})_{\rm exp} / \mathcal{B}(B \to D \ell \overline{\nu})_{\rm SM}} = 1.34 \pm 0.17 \,,$$

- O(30%) LFU violation in $b \to s$ neutral currents: μ vs. e

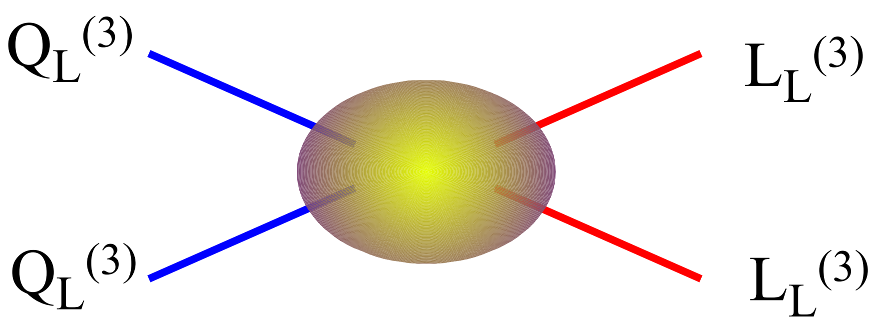
$$R_K^{\mu/e} = \left. \frac{\mathcal{B}(B \to K \mu \overline{\mu})_{\rm exp}}{\mathcal{B}(B \to K e \overline{e})_{\rm exp}} \right|_{q^2 \in [1,6]{\rm GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

From $U(3)^3$ to $U(2)^5$ and LFU [*the charged-lepton perspective*]

- Early to draw definite conclusions (*no single result exceeding* 3σ)...
- Interesting that $U(2)_Q \times U(2)_L$ models can provide a rational for the pattern of observed hints of LFU non-universality (taking into account the bounds from other low-energy processes)

Main idea:

- NP coupled mainly to 3rd generation (competing with SM tree-level) in bc ($=33_{CKM}$) → l_3 ν_3 [*data consistent with NP only in left-handed amplitudes*]



Glashow, Guadagnoli, Lane '14
Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
Barbieri, GI, Pattori, Senia '15

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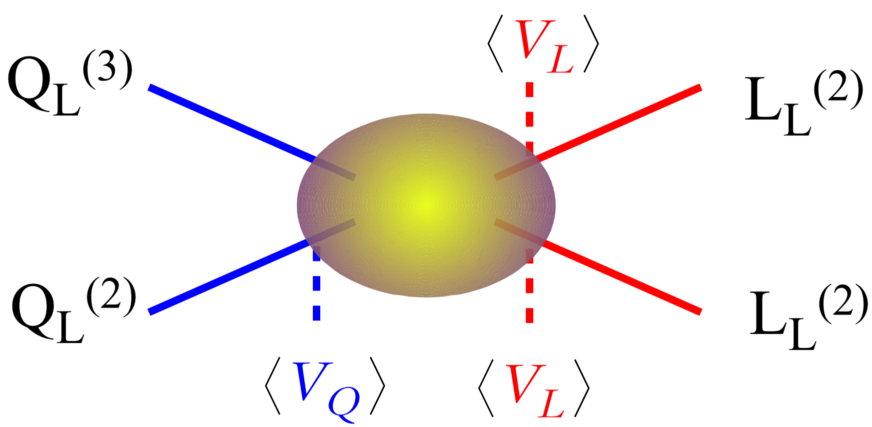
Main idea:

- NP coupled mainly to 3rd generation (competing with SM tree-level) in bc (=33_{CKM}) → $l_3\, \nu_3$ [*data consistent with NP only in left-handed amplitudes*]
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\, l_2$



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Prelude III:

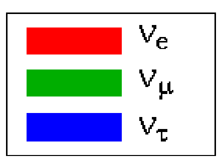
Some open problems [*the neutrino perspective*]

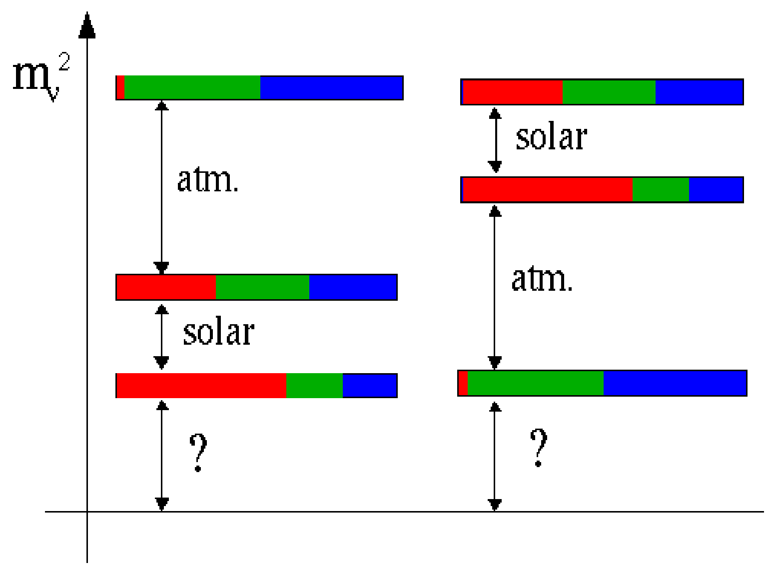
Open problems

I. A potential problem of the $U(2)^n$ approach and, more generally, of any approach attributing a special role to the hierarchies in the Yukawa sector, is the problem of neutrino masses (*under the hypothesis we are interested to describe in a unified way quark and lepton sectors*):

- Why neutrino mixing angles are not as small as in the quark sector? Why the mass hierarchies in the neutrino sector are not as large?

$$\left|\frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}}\right|^{1/2} \sim 1/6$$





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To extend the idea of large flavor symmetry group with small breaking to the neutrino sector we need to assume a different initial symmetry for Dirac and Majorna sectors (*or a different initial breaking of some larger flavor symmetry*)

Small parameters in the Neutrino (Majorana) mass matrix:

$$\zeta = \left| \frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}} \right|^{1/2} = 0.174 \pm 0.007 ,$$

$$s_{13} = |(U_{\rm PMNS})_{13}| = 0.15 \pm 0.02 ,$$

$$M_\nu^+ M_\nu \xrightarrow[\zeta,\, s_{13} \to 0]{} m_\nu^2\, I + \Delta m_{\rm atm}^2\, \Sigma$$

$$\Sigma \approx \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$$

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

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$$M_\nu^+ M_\nu \xrightarrow[\zeta,\, s_{13} \to 0]{} m_\nu^2\, I + \Delta m_{\rm atm}^2\, \Sigma \xrightarrow[\Delta m_{\rm atm}^2 \ll m_\nu^2]{\textit{and if}\ \ldots} m_\nu^2\, I$$

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O(3) symmetry

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II. Most important, both in $U(3)^n$ and in $U(2)^n$ the breaking terms are put in "by hands" (*non-dynamical spurion analysis*)

Explicit potentials

Feldmann *et al.* '09
Alonso, Gavela, *et al.* '11-'13
Nardi '11; Espinosa, Fong, Nardi '12
Alonso, Gavela, G.I., Maiani, '13

Gauging of $U(3)^n$ & $U(2)^n$

Albrecht, Feldmann, Mannel, '09
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Alonso, Fernandez Martinez *et al.* '16

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Stability of solutions corresponding to maximally unbroken subgroups

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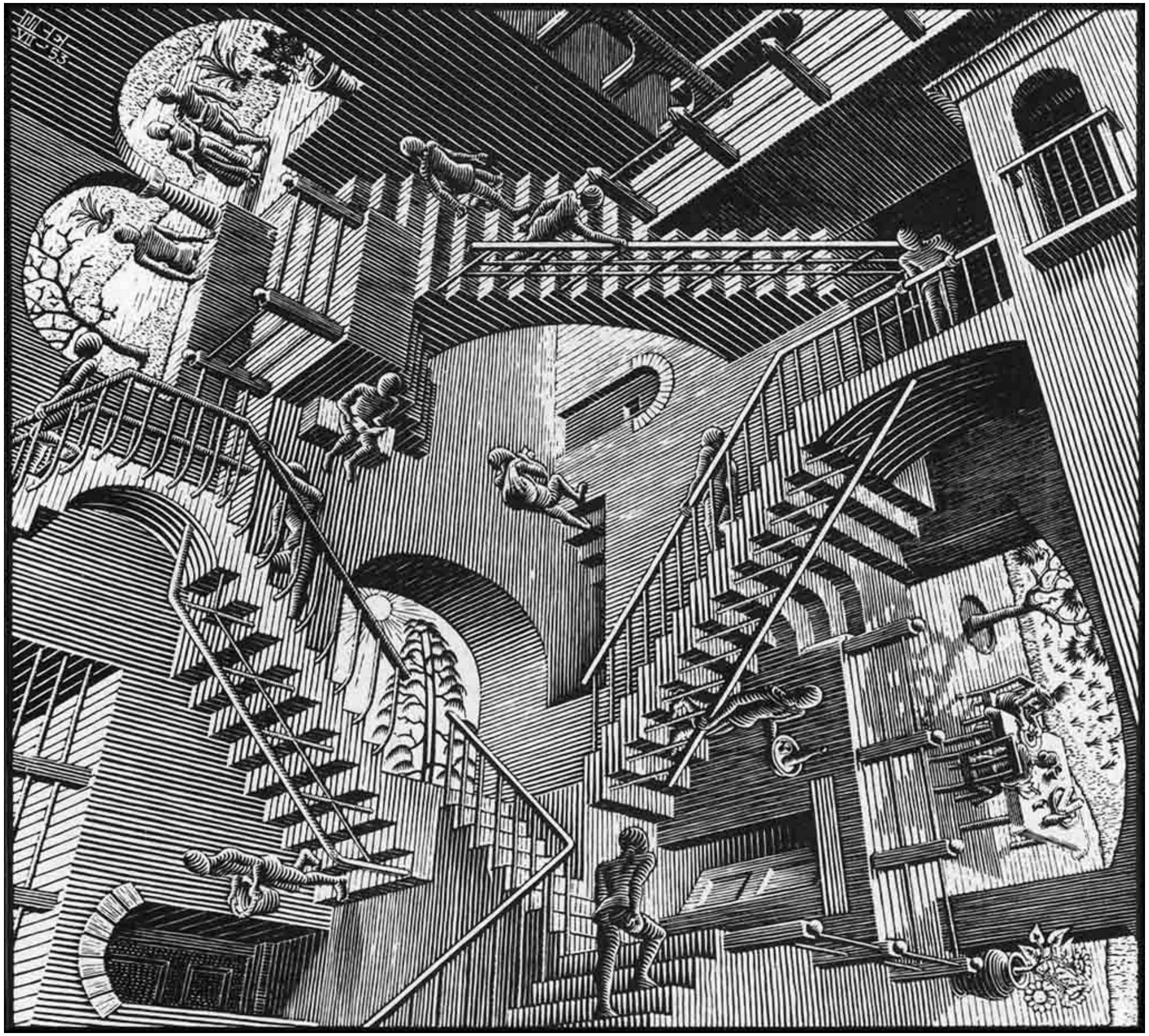
Dynamical Yukawa's from a Minimum Principle



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Let's consider first a type-I model:

- SM field content enlarged by 3 heavy right-handed neutrinos (N)
- Largest flavor symmetry compatible with SM gauge group + non-vanishing N masses [*ignoring flavor-conserving* U(1) *phases*]: $SU(3)^5 \times O(3)_N$

$$-\mathcal{L}_Y = \bar{q}_L \underline{Y_D} H D_R + \bar{q}_L \underline{Y_U} \tilde{H} U_R + \bar{\ell}_L \underline{Y_E} H E_R + \bar{\ell}_L \underline{Y_\nu} \tilde{H} N + \text{h.c.} + \frac{M}{2} N^T N$$

Let's then assume that both quark and lepton Yukawa couplings are *dynamical fields* of $SU(3)^5 \times O(3)_R$ and that their values are determined by a *minimization principle* (e.g. the potential minimum)

⬇

The "natural solutions" [*i.e. solution requiring no tuning in the parameters of the potential*] are the configurations preserving maximally unbroken subgroups.

Michel & Radicati, '69
Cabibbo & Maiani, '69

Dynamical Yukawa's from a Minimum Principle

The Michel-Radicati theorem (a sketch):

- $V = f\,[\, I_i(Y)\,]$ $I_i(Y)$=invariants of the group G built out of the Y's
- The space spanned by Y is infinite, but the manifold spanned by the I_i has boundaries, corresponding to the subgroups of G

E.g.: G=SU(3), I_1=Det(Y), I_2=Tr(Y^2) $\rightarrow$ $I_2 \geq (54\, I_1^{\,2})^{1/3}$

$I_2 = (54\, I_1^{\,2})^{1/3}$
only if Y invariant under SU(2)xU(1)

Dynamical Yukawa's from a Minimum Principle

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- The space spanned by Y is infinite, but the manifold spanned by the I_i has boundaries, corresponding to the subgroups of G
- Extrema of V characterized by $\partial V/\partial Y_j = \partial V/\partial I_i \times J_{ij} = 0$ where $J_{ij} = \partial I_i/\partial Y_j$
- Extrema of V (partially) independent from its structure if J has low rank → "natural extrema" corresponding to maximally unbroken subgroups.

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"natural solutions" associated to maximally unbroken subgroups:

I) $SU(3)_L \times SU(3)_R \xrightarrow{Y \sim 3\times\underline{3}} SU(3)_{L+R}$ or $SU(2)_L \times SU(2)_R \times U(1)$

II) $SU(3)_L \times O(3)_N \xrightarrow{Y \sim 3\times 3} O(3)_{L+N}$

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II) $SU(3)_L \times O(3)_N \xrightarrow{Y \sim 3\times 3} O(3)_{L+N}$

degenerate light ν's

"chiral" solution: $Y \sim \text{diag}(0,0,1)$

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Quarks: $SU(3)_Q \times SU(3)_U \times SU(3)_D \;\rightarrow\; SU(2)_Q \times SU(2)_U \times SU(2)_D \times U(1)_3$

"chiral" solution + $V_{CKM} = I$

Leptons: $SU(3)_E \times SU(3)_L \times O(3)_N \;\rightarrow\; SU(2)_E \times U(1)_{L+N}$

"chiral" charged leptons + degenerate light neutrinos
+ non-trivial PMNS [related to the orientation of O(3) in SU(3)]

Dynamical Yukawa's from a Minimum Principle

$$SU(3)^5$$

LR → $Y_{U,D,E} \propto \mathrm{diag}(0,0,1) \quad \begin{pmatrix} \text{unbroken} \\ SU(2)_L \times SU(2)_R \end{pmatrix}$

LL → $|M_\nu \propto Y_\nu Y_\nu^T| \propto \mathrm{diag}(1,1,1) \quad \begin{pmatrix} \text{unbroken} \\ O(3)_L \end{pmatrix}$

Two important comments:

- The assumption of seesaw of type-I can be relaxed
  [$O(3)_L$ "natural solution" also if $SU(3)_L$ is broken by $M_\nu \sim 6$ of $SU(3)_L$]

- The structure of the "initial" group can be made compatible with GUTs
  [e.g.: $SU(3)_{10} \times SU(3)_5 \times SU(3)_1$ in $SU(5)_{gauge}$]

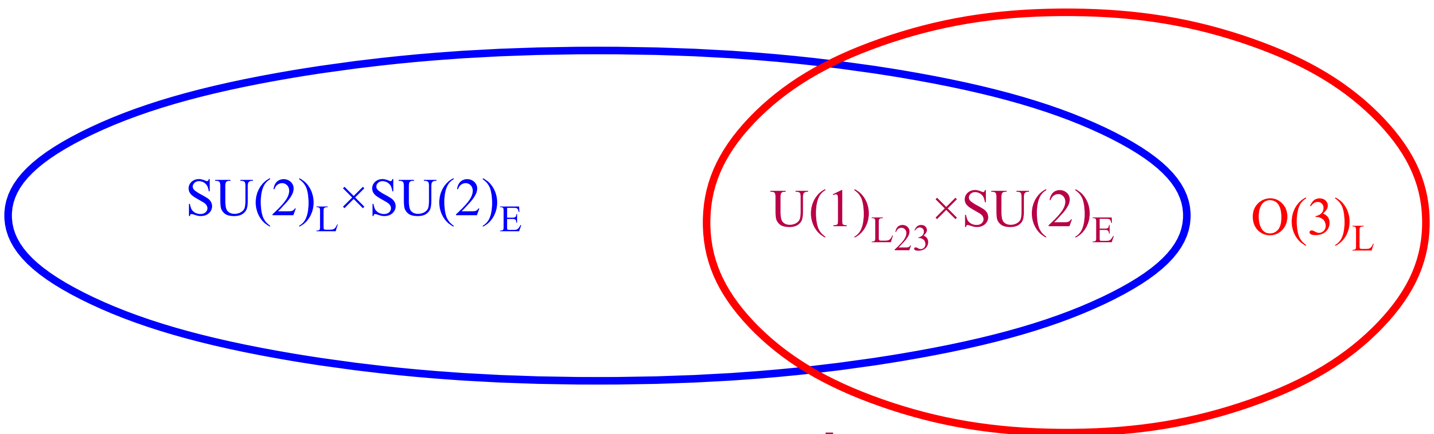
Dynamical Yukawa's from a Minimum Principle

$$SU(3)_L \times SU(3)_E$$

LR LL

$Y_E \propto \text{diag}(0,0,1)$ (unbroken $SU(2)_L \times SU(2)_E$)

$|M_\nu \propto Y_\nu Y_\nu^T| \propto \text{diag}(1,1,1)$ (unbroken $O(3)_L$)



Alonso, Gavela, G.I., Maiani, '13

A "natural orientation" of $O(3)_L$ vs. $U(2)_L$ preserving an unbroken $U(1)$ symmetry implies a $\pi/4$ mixing angle in the PMNS matrix.

Dynamical Yukawa's from a Minimum Principle

$$SU(3)_L \times SU(3)_E$$

LR LL

$$Y_E \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \left(\begin{array}{c} \text{unbroken} \\ SU(2)_L \times SU(2)_E \end{array}\right)$$

$$M_\nu \propto Y_\nu Y_\nu^T \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \left(\begin{array}{c} \text{unbroken} \\ O(3)_L \end{array}\right)$$

same basis

$$Y_\nu \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & -i\frac{1}{\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}} & i\frac{1}{\sqrt{2}} \end{pmatrix}$$

Residual $U(1)_{L_{23}}$ symmetry:

$$Y_\nu \to \exp(i\alpha\lambda'_3)\, Y_\nu\, \exp(-i\alpha\lambda_7)$$

$$\lambda'_3 = \mathrm{diag}(0,1,-1)$$

▶ *Dynamical Yukawa's from a Minimum Principle*

$$SU(3)_L \times SU(3)_E$$

LR LL

$$Y_E \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{pmatrix} \text{unbroken} \\ SU(2)_L \times SU(2)_E \end{pmatrix} \qquad M_\nu \propto Y_\nu Y_\nu^T \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \begin{pmatrix} \text{unbroken} \\ O(3)_L \end{pmatrix}$$

same basis

Sub-leading $U(2)_L$ breaking
resolving 1-2 degeneracy

$$\frac{m_\mu}{m_\tau} = O(\varepsilon) \qquad\qquad |s_{13}| \sim O(\varepsilon), \quad |s_{12}| \sim O(1)$$

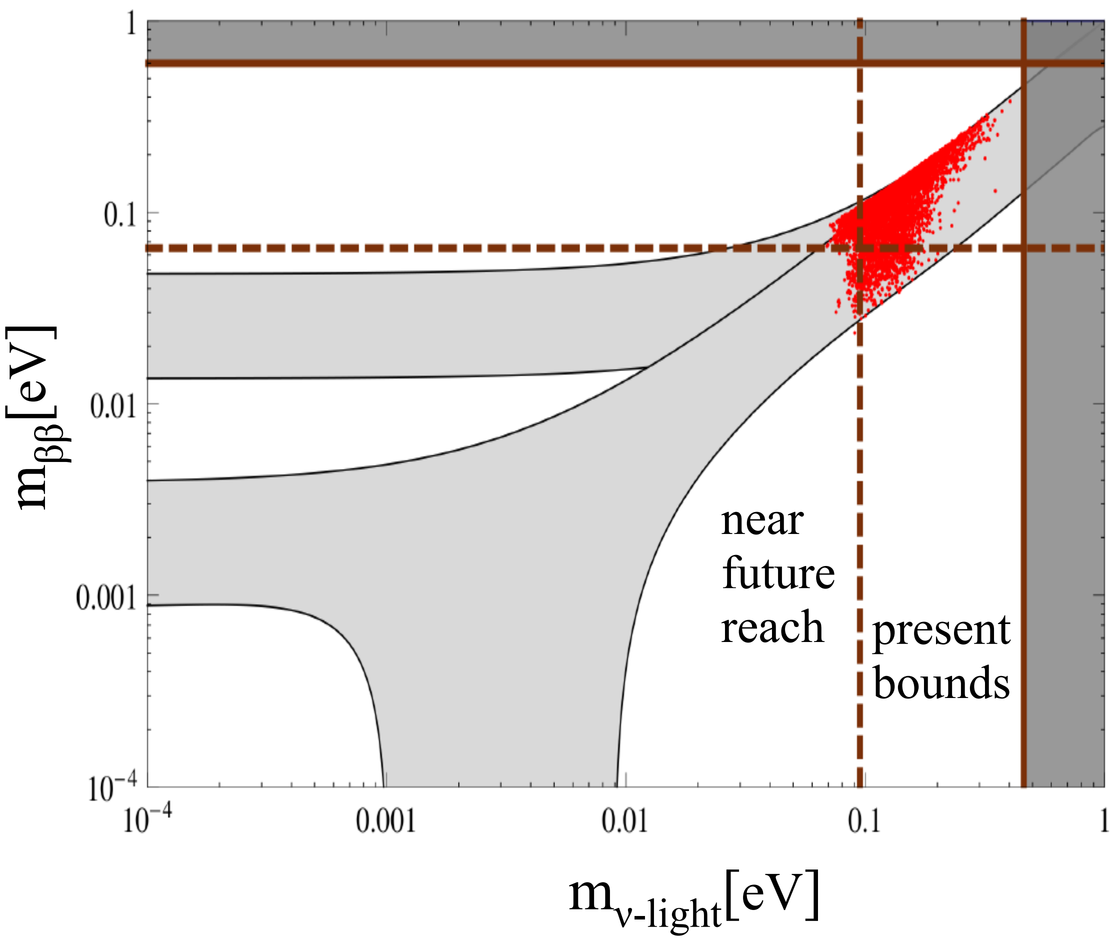
$$\frac{m_\mu}{m_\tau} \sim 0.06 < \frac{\Delta m_{atm}^2}{m_\nu^2} = O(\varepsilon) < |s_{13}| \sim 0.2$$

$$\boxed{\langle m_\nu \rangle \approx 0.1\ \text{eV}}$$

If all this is correct...

$SU(3)_L \times SU(3)_E$

LL



$$M_\nu \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \left(\begin{matrix}\text{unbroken} \\ O(3)_L\end{matrix}\right)$$

$+$

$$\frac{\Delta m_{atm}^{\ \ 2}}{m_\nu^{\ 2}} = O(\varepsilon)$$

$$\boxed{\langle m_\nu \rangle \approx 0.1 \text{ eV}}$$

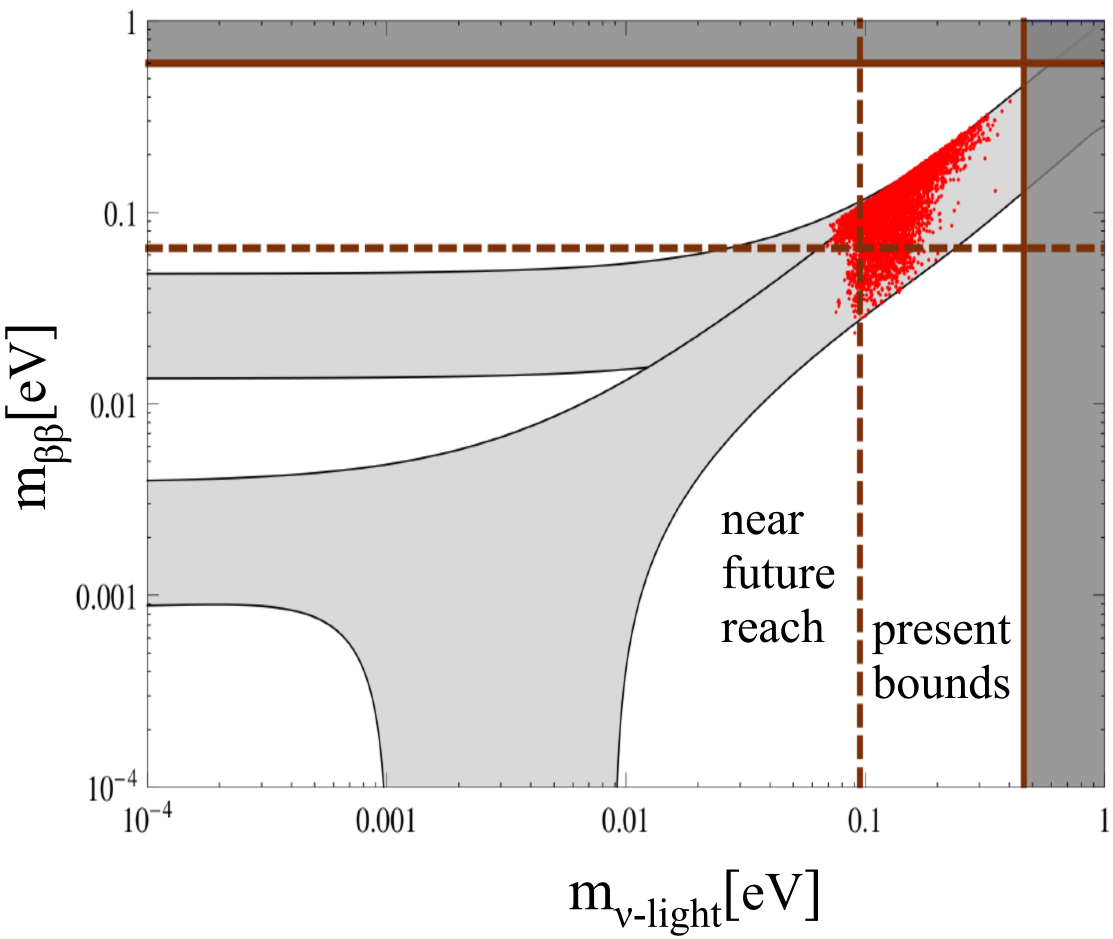
$$\Sigma m_\nu \gtrsim 0.25 \text{ eV}$$

….0ν2β decay experiments should be very close to observe a positive signal

If all this is correct...

$SU(3)_L \times SU(3)_E$

LL



$$M_\nu \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \left(\begin{array}{c}\text{unbroken} \\ O(3)_L\end{array}\right)$$

$+$

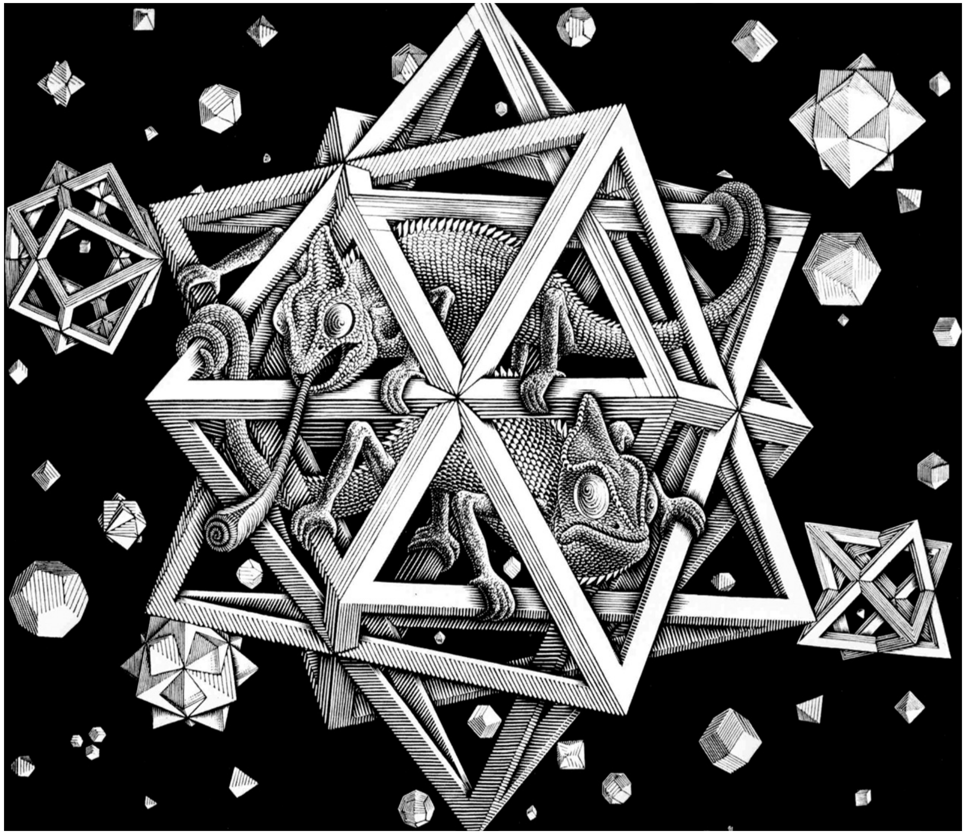
$$\frac{\Delta m_{atm}^{\;2}}{m_\nu^{\;2}} = O(\varepsilon)$$

$$\boxed{\langle m_\nu \rangle \approx 0.1 \text{ eV}}$$

$$\Sigma m_\nu \gtrsim 0.25 \text{ eV}$$

As you just heard... cosmological bounds on Σm_ν are challenging this picture, but the final word has not yet been spoken...

Gauging dynamical Yukawa's and B-physics anomalies



Gauging dynamical Yukawa's and B-physics anomalies

Natural to conceive a gauging of the flavor symmetry, in order to avoid Goldstone bosons → *massive "flavored" vector bosons*

The energy scale where the breaking of the flavor symmetry occurs is not fixed, these massive vectors could all be all be at high energies with no observables consequences.

However, *we cannot exclude some of them to be relatively light...* → possible implications in low-energy flavor-changing observables → *possible connection to B-physics anomalies*

Gauging dynamical Yukawa's and B-physics anomalies

Main idea: sequential SSB associated to different energy scales

Quark Sector

$SU(3)_Q \times SU(3)_U \times SU(3)_D$

$\downarrow$

$U(2)^3 \times U(1)_q$

natural minima

Lepton Sector

$SU(3)_L \times SU(3)_E \times O(3)_\nu$

$\downarrow$

$SU(2)_E \times U(1)_l$

Subsequent breaking
(perturbations)

$\downarrow$

SM spectrum

Energy

Gauging dynamical Yukawa's and B-physics anomalies

Main idea: sequential SSB associated to different energy scales

Energy

Quark Sector

$SU(3)_Q \times SU(3)_U \times SU(3)_D$

Lepton Sector

$SU(3)_L \times SU(3)_E \times O(3)_\nu$

natural minima

$U(2)^3 \times U(1)_q$

$SU(2)_E \times U(1)_l$

high-energy breaking
(1^{st}-2^{nd} mass splitting)

$U(1)_{q_3}$

$U(1)_{\mu\text{-}\tau}$

TeV scale dynamics

Two massive Z' @ TeV scale

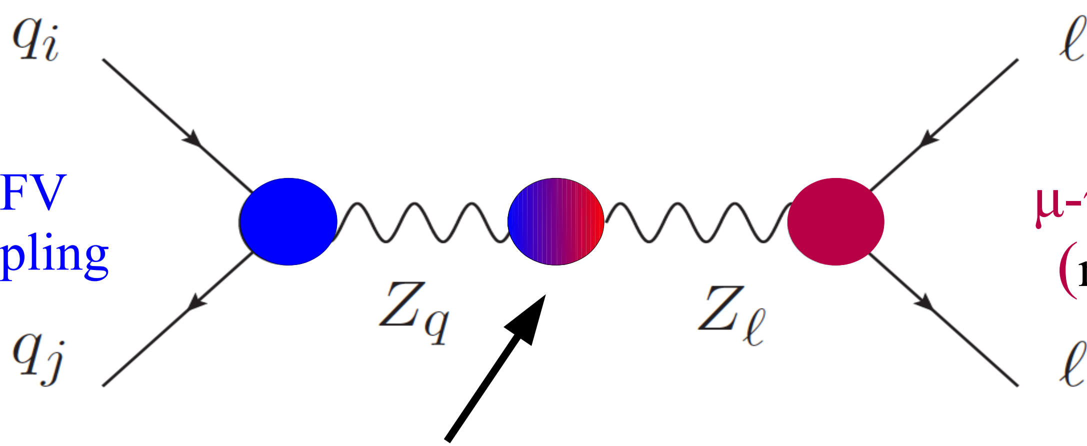
SM spectrum

Crivellin, Fuentes-Martin, G.I., Greljo, '16

Gauging dynamical Yukawa's and B-physics anomalies

The couplings of the two Z's are completely specified by the flavor symmetry up to overall-couplings (*which in turn are connected to their masses*)

MFV coupling



μ-τ coupling (no CLFV)

Mass mixing (ε) - *allowed by the symmetry of the system but not predicted*

$$C_9^\mu|_{\rm NP} \simeq -\left(\frac{g_q \Lambda_v}{M_{Z_2}}\right)\left(\frac{g_\ell \Lambda_v}{M_{Z_1}}\right) \times \varepsilon \longrightarrow$$

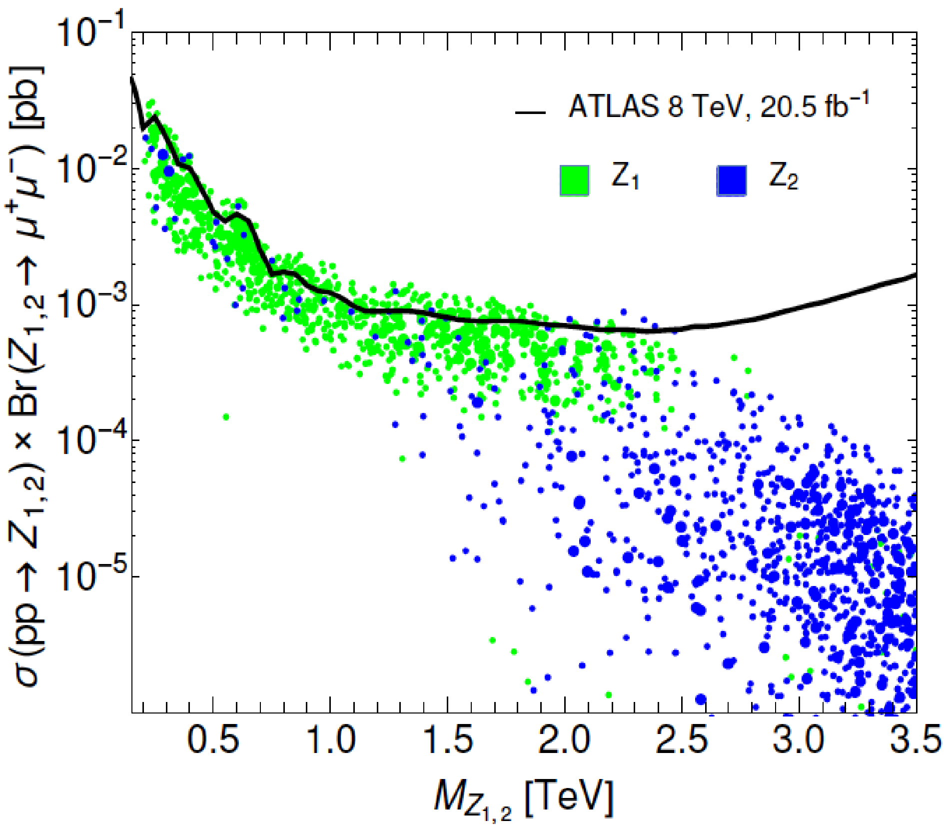
"solution" of B physics $b \to s$ anomalies for $\varepsilon \sim 0.1$

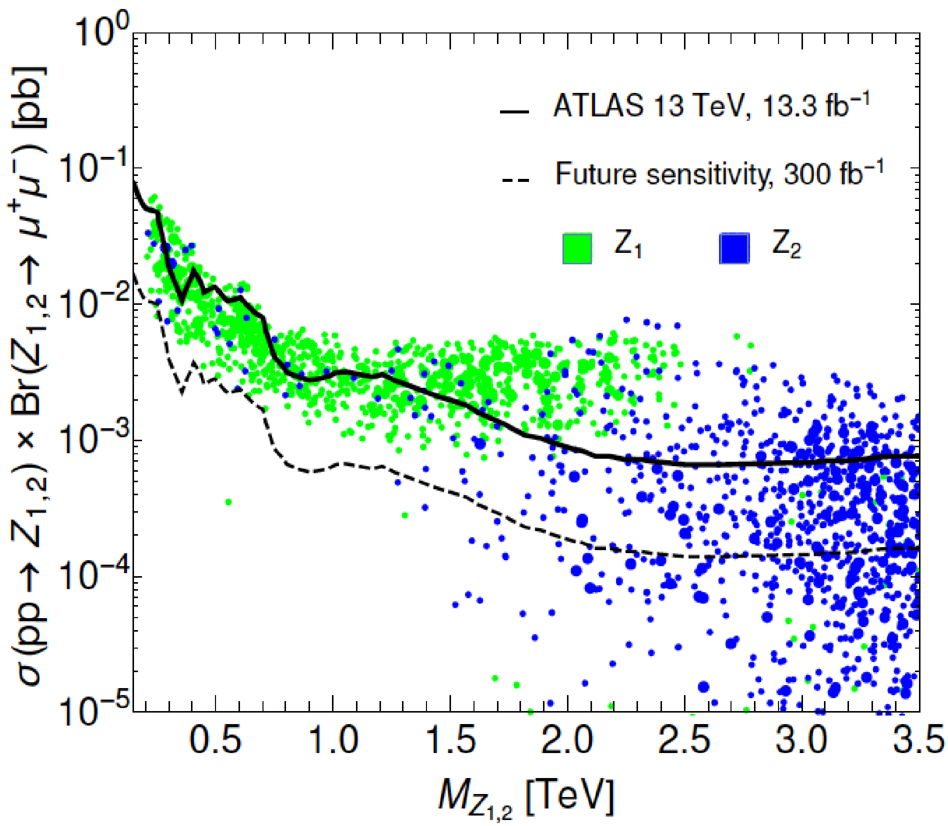
constrained by Bs mixing

constrained by $\sigma(\nu N \to \nu\mu\mu N)$

Gauging dynamical Yukawa's and B-physics anomalies

The couplings of the two Z's are completely specified by the flavor symmetry up to overall-couplings (*which in turn are connected to their masses*)
→ *highly constrained system* → parameter space relevant to B-physics anomalies can be tested at the LHC by ATLAS & CMS





Conclusions

- The "*lepton perspective*" is a key ingredient in addressing the flavor problem(s)

- The apparently different structure of quark and lepton mass matrices could be understood in terms of "natural solutions" of a large non-Abelian flavor symmetry broken by dynamical Yukawa fields → residual $SU(2)_L \times SU(2)_R$ chiral symmetry for Dirac masses + O(3) symmetry in the neutrino sector.

- Predictions of the un-perturbed solution:
  - Vanishing masses for first two generations of quarks & leptons + trivial CKM
  - Degenerate neutrinos + $\theta_{23}=\pi/4$, $\theta_{12}=O(1)$, $\theta_{13}=0$.

  (*excellent first-order approximation to the observed spectrum*)

- Decisive test of this hypothesis via $0\nu2\beta$ decay experiments

- In specific realization of the flavor symmetry-breaking mechanism, possible implications/connections with in LFU in B physics (*not guaranteed...!*)