Flavor Symmetries and CLFV

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Outline

- flavor symmetries (and beyond)
  - why flavor symmetries (and beyond)?
  - which ones?
  - what is their predictive power?
- CLFV
  - in models with extra dimension
  - in supersymmetric models
- continuous flavor symmetries and CLFV
- phenomenological imprints beyond CLFV

Flavor symmetries (and beyond)

Why?

- in the Standard Model of particle physics most free parameters are in the flavor sector

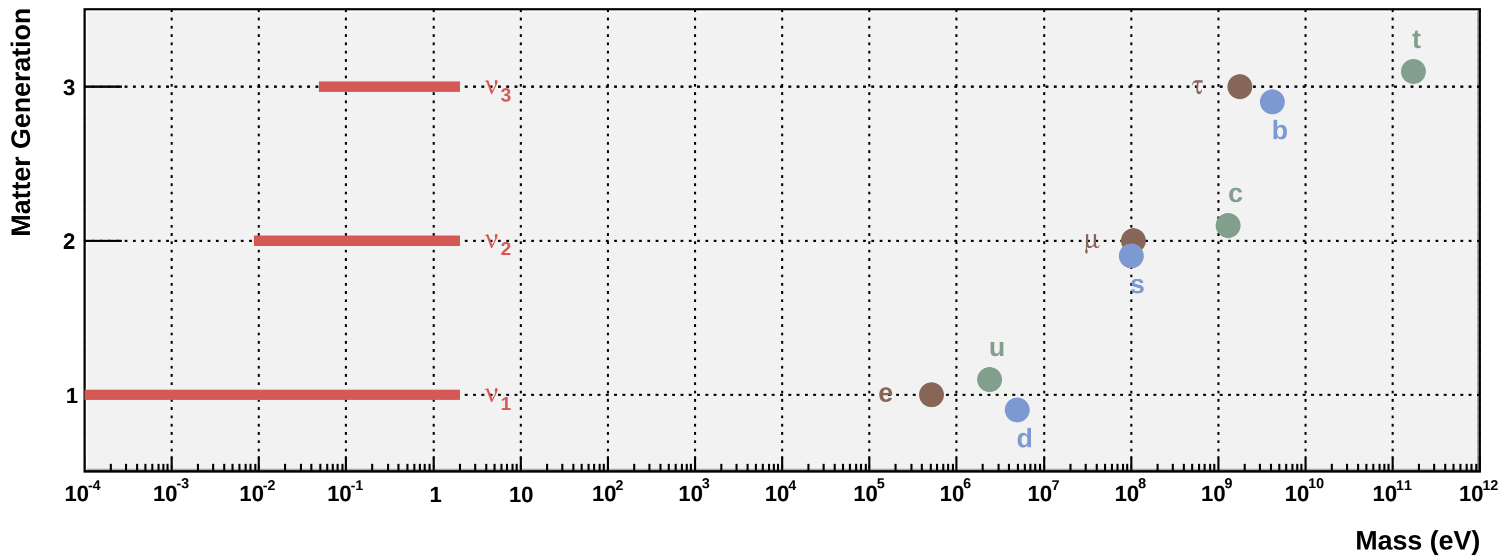
$$-\mathcal{L}_{\text{Yuk}} = y^e_{ij}\, \overline{L_i}\, H\, e_{R\,j} + y^u_{ij}\, \overline{Q_i}\, H^\star\, u_{R\,j} + y^d_{ij}\, \overline{Q_i}\, H\, d_{R\,j}$$

  and coming from the mechanism which gives mass to neutrinos, e.g. the type-I seesaw mechanism

$$-\mathcal{L}_\nu = y^\nu_{ij}\, \overline{L_i}\, H\, \nu_{R\,j} + \frac{1}{2}\, M_{ab}\, \overline{\nu^c_{R\,a}}\, \nu_{R\,b}$$

- they are needed to accommodate fermion masses and mixing

Why?



log scale

- three generations of elementary fermions
- strong mass hierarchy among charged fermions
- (possibly) much milder one among neutrinos

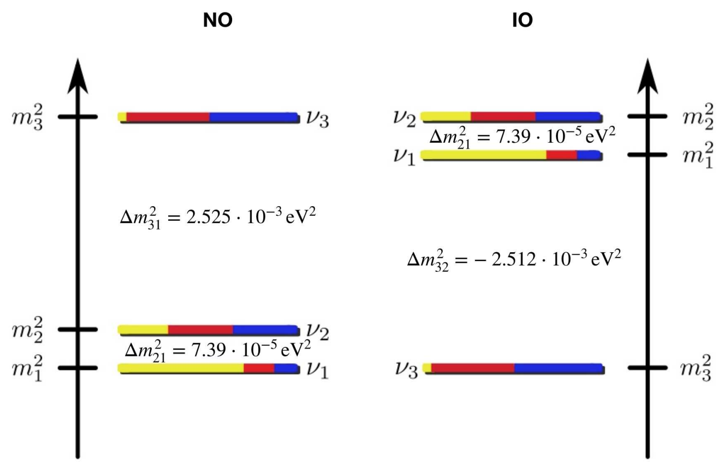
Why?

Summary of charged fermion masses (Xing et al. ('07))

	mass at M_Z	in units of heaviest mass
e	$(0.486570161 \pm 0.000000042)$ MeV	$\lambda^{4\div 5}$
μ	$(102.7181359 \pm 0.0000092)$ MeV	λ^2
τ	$1.74624^{+0.00020}_{-0.00019}$ GeV	1
u	$(1.27^{+0.50}_{-0.42})$ MeV	λ^8
c	(0.619 ± 0.084) GeV	λ^4
t	(171.7 ± 3.0) GeV	1
d	$(2.90^{+1.24}_{-1.19})$ MeV	λ^4
s	(55^{+16}_{-15}) MeV	λ^2
b	(2.89 ± 0.09) GeV	1

Why?

Summary of current knowledge about neutrino masses

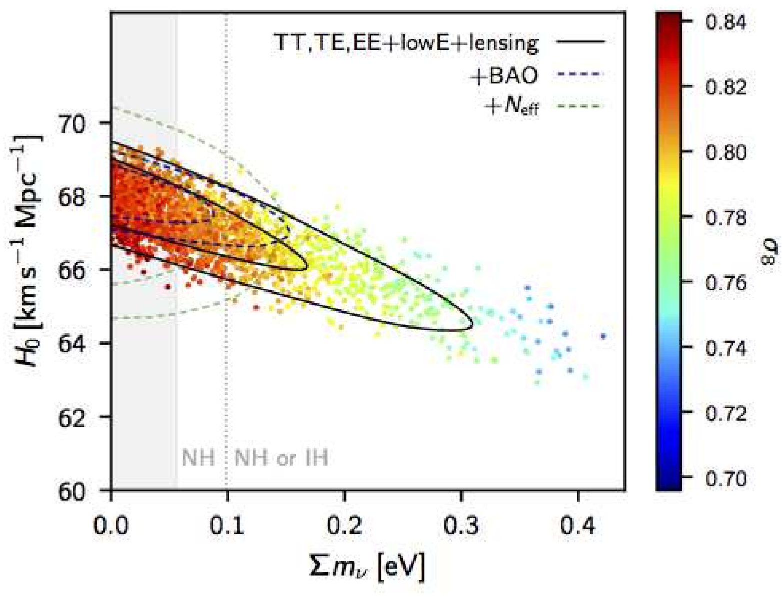


Their ordering is unknown, although NO seems preferred.

(NuFIT ('18))

Their absolute scale is also unknown.

(Planck ('18))



Why?

- similarly, striking differences in fermion mixing among quarks and leptons are observed
- summary of current knowledge about lepton mixing

NuFIT 4.0 (2018)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{\rm CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$

Why?

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- summary of current knowledge about lepton mixing

(NuFIT ('18))

$$||U_{\text{PMNS}}|| \approx \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.29 & 0.59 & 0.75 \\ 0.49 & 0.59 & 0.64 \end{pmatrix} \quad \text{[NO]}$$

and hint for CP violation: $\delta \approx 215^\circ \ , \ \ \alpha =$? , $\ \beta =$?

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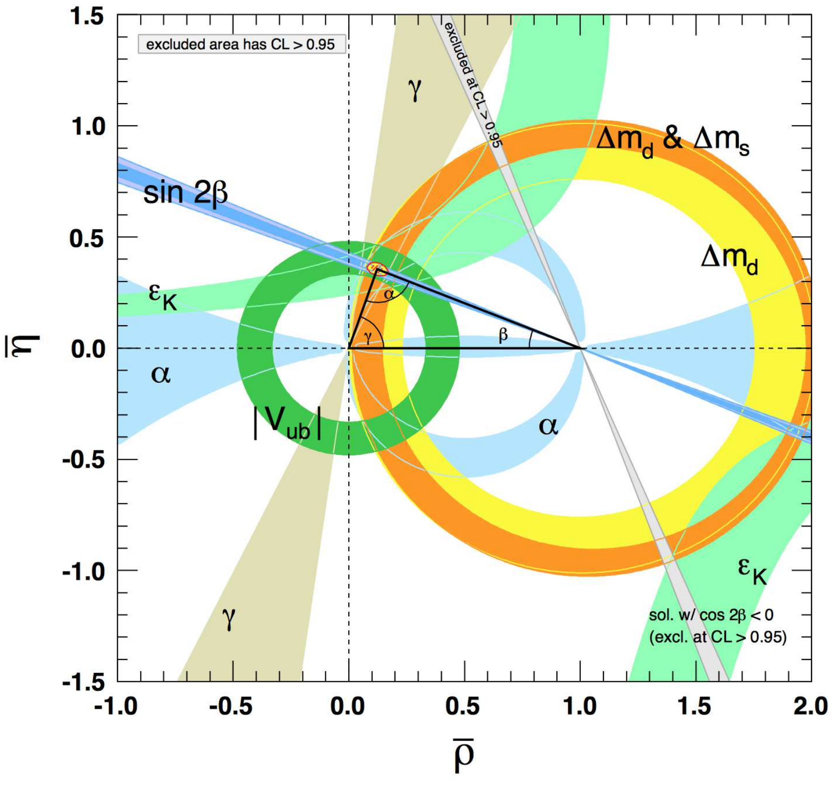
(PDG ('18))



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(PDG ('18))

$$||V_{\text{CKM}}|| \approx \begin{pmatrix} 0.97 & 0.22 & 3.7 \cdot 10^{-3} \\ 0.22 & 0.97 & 0.042 \\ 9.0 \cdot 10^{-3} & 0.041 & 0.999 \end{pmatrix}$$

and CP violation: $J_{\text{CP}} = 3.18 \cdot 10^{-5}$

Which ones?

G_f could be ...

- ... abelian or non-abelian
- ... continuous or discrete
- ... local or global
- ... spontaneously broken or explicitly
- ... broken arbitrarily or to non-trivial subgroups
- ... broken at low or high energies

Its maximal possible size depends on the gauge group,
e.g. in the Standard Model: $G_f \subset U(3)^5$.
in $SO(10)$: $G_f \subset U(3)$.

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Which ones?

You have (too) many choices ...

- permutation symmetries: S_N and A_N with $N \in \mathbb{N}$
- dihedral symmetries: D_n and D'_n with $n \in \mathbb{N}$
- further double-valued groups: T', O', I'
- subgroups of $SU(3)$: series of $\Delta(3\,n^2)$ and $\Delta(6\,n^2)$ groups with $n \in \mathbb{N}$, as well as finite number of Σ groups
- subgroups of $U(3)$ such as $\Sigma(81)$ and subgroups of the listed groups such as $T_7 \cong Z_7 \rtimes Z_3 \subset \Delta(147)$

NB: several isomorphisms among the groups,

e.g. $S_3 \cong D_3 \cong \Delta(6)$.

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- more experimental data: CLFV

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- more experimental data: CLFV

In the following, ...

- ... I will use non-trivial subgroups as additional constraint
- ... I will show results in different types of models for CLFV

Predictive power

I would like to focus on

explanations for lepton mixing

Two very successful approaches are:

- flavor symmetry G_f and its breaking as explanation
- flavor symmetry G_f and CP and its breaking as explanation

Predictive power

Flavor symmetry G_f and its breaking as explanation

(Lam ('07,'08), Blum/H/Lindner ('07))

$$G_f$$

$$\swarrow \qquad\qquad \searrow$$

charged leptons — neutrinos

$$G_e \qquad\qquad G_\nu$$

$$U_e \qquad\qquad U_\nu$$

$$\searrow \qquad\qquad \swarrow$$

$$U_{\text{PMNS}} = U_e^\dagger U_\nu$$

Note: Masses do not play a role in this approach.

Predictive power

You expect to fix

- the 3 lepton mixing angles
- the Dirac phase δ

up to permutations of rows and columns of the PMNS mixing matrix, since masses are not fixed.

Example for G_f for $\theta_{13} \neq 0$, $\theta_{23} \neq \frac{\pi}{4}$

(de Adelhart Toorop/Feruglio/H ('11))

- $G_f = \Delta(384)$
- $G_e = Z_3$
- $G_\nu = Z_2 \times Z_2$

Predictive power

(de Adelhart Toorop/Feruglio/H ('11))

$$||U_{\text{PMNS}}|| \approx \begin{pmatrix} 0.81 & 0.58 & 0.11 \\ 0.31 & 0.58 & 0.75 \\ 0.50 & 0.58 & 0.65 \end{pmatrix} \quad \text{and} \quad \sin\delta = 0$$

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NB: The value of θ_{13} is controlled by the choice of flavor symmetry.
The result $\sin\delta = 0$ instead is generic.

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The result $\sin\delta = 0$ instead is generic.

Non-trivial values of δ arise from the combination of flavor and CP symmetries.

With less stringent assumptions on flavor (and residual) symmetries non-trivial CP violation can also be achieved, see e.g. ***Hernandez/Smirnov ('12)***.

Predictive power

Flavor symmetry G_f and CP and its breaking as explanation

(Feruglio/H/Ziegler ('12))

$$G_f \text{ and CP}$$

$$\swarrow \qquad\qquad\qquad \searrow$$

charged leptons | neutrinos

G_e | $G_\nu = Z_2 \times \text{CP}$

U_e | $U_\nu = \Omega_\nu R(\theta) K_\nu$

$$\searrow \qquad\qquad\qquad \swarrow$$

$$U_{\text{PMNS}} = U_e^\dagger \Omega_\nu R(\theta) K_\nu$$

Note: Masses do not play a role in this approach.

Predictive power

You expect to express

- the 3 lepton mixing angles
- all CP phases δ, α and β

in terms of one single real parameter θ and up to permutations of rows and columns of the PMNS mixing matrix, since one has one Z_2 only and masses are not fixed.

Example: study of $G_f = A_5$ with CP

(Di Iura/H/Meloni ('15))

- $G_f = A_5$ and CP
- $G_e = Z_2 \times Z_2$, Z_3 or Z_5
- $G_\nu = Z_2 \times$ CP

4 different mixing patterns with different characteristics

Predictive power

(Di Iura/H/Meloni ('15))

case II $\tan\varphi = 1/\phi$, $\phi = \frac{1}{2}\left(1+\sqrt{5}\right)$ and $\Phi = \frac{2\pi}{5}$

$$U_{\text{PMNS}} = \frac{1}{\sqrt{2}} \begin{pmatrix} -\sqrt{2}\,\cos\varphi & -\sqrt{2}\,\sin\varphi & 0 \\ -\,e^{-3\,i\,\Phi}\,\sin\varphi & e^{-3\,i\,\Phi}\,\cos\varphi & -e^{-7\,i\,\Phi/4} \\ -e^{-2\,i\,\Phi}\,\sin\varphi & e^{-2\,i\,\Phi}\,\cos\varphi & e^{-3\,i\,\Phi/4} \end{pmatrix} R_{13}(\theta)\;K_\nu$$

$$\sin^2\theta_{13} = \frac{1}{10}\left(5+\sqrt{5}\right)\sin^2\theta\;, \quad \sin^2\theta_{12} = \frac{2}{2+(3+\sqrt{5})\,\cos^2\theta}, \quad \sin^2\theta_{23} = \frac{1}{2}$$

and

$$|\sin\delta| = 1\;, \quad \sin\alpha = 0\;, \quad \sin\beta = 0$$

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$$\sin^2\theta_{13} \approx 0.0219\;, \quad \sin^2\theta_{12} \approx 0.283, \quad \sin^2\theta_{23} = \frac{1}{2}$$

and

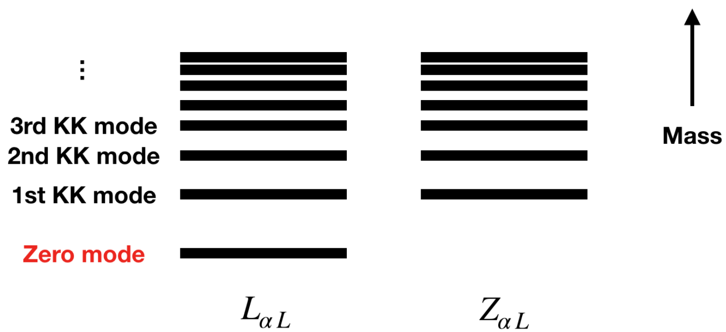
$$|\sin\delta| = 1 \;, \quad \sin\alpha = 0 \;, \quad \sin\beta = 0 \quad \text{for} \quad \theta \approx 0.175$$

CLFV

Extra dimension

Kaluza-Klein fermions ...

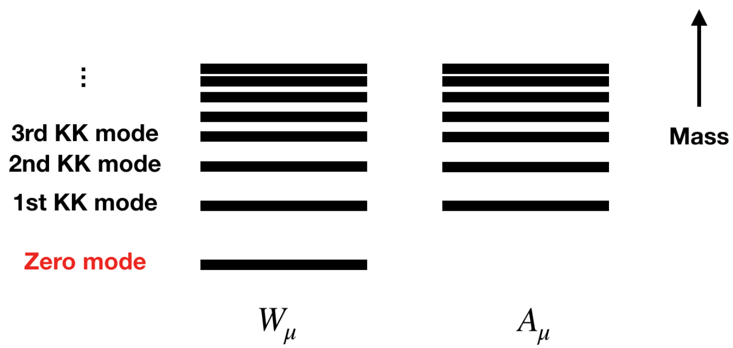
- ... usually also appear in three generations.



Extra dimension

Kaluza-Klein gauge bosons ...

- ... can be associated with Standard Model gauge group.
- ... can belong to new gauge interactions.



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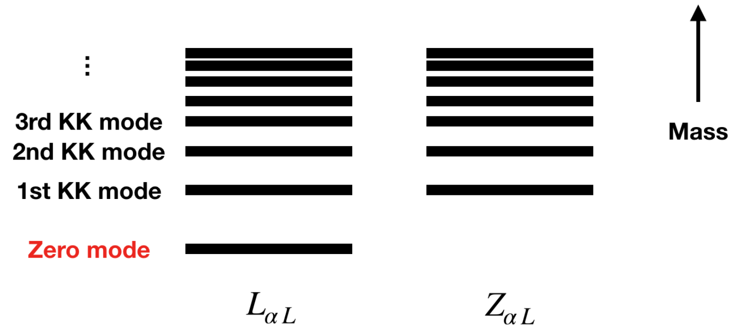
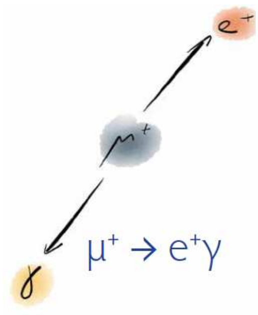
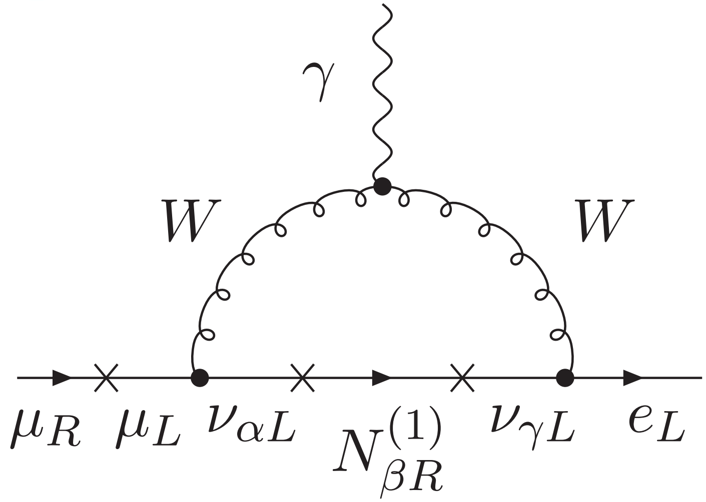
Kaluza-Klein particles ...

- ... can induce, in particular, CLFV.







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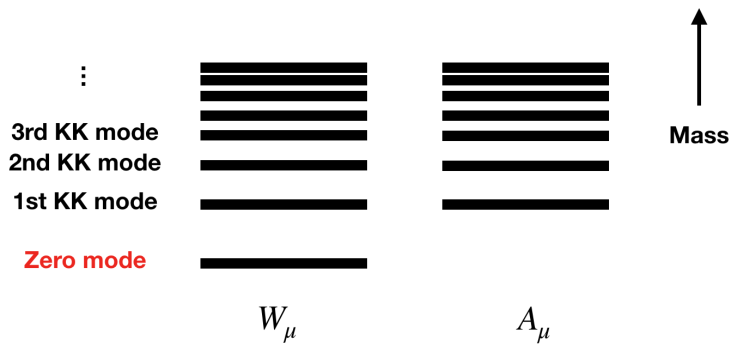

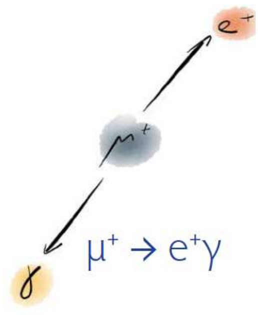

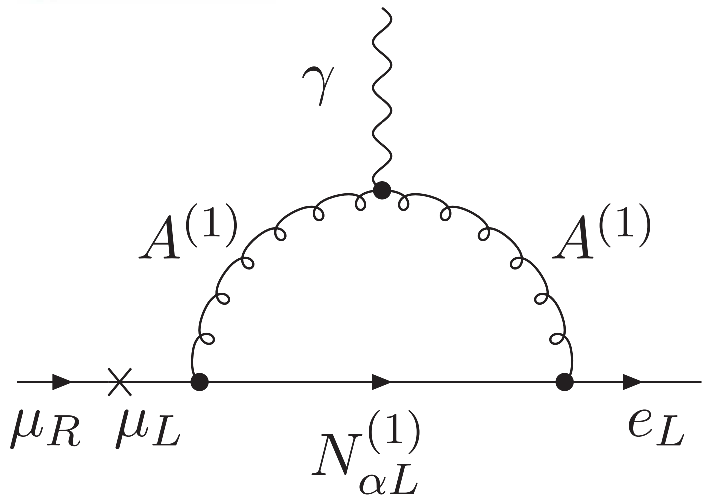

Extra dimension

(H/Serone ('11), H ('13))

- study 5D realization of holographic composite Higgs models (gauge-Higgs unified model with warped extra dimension)
- impose flavor symmetry $G_f = X \times Z_N$ (these correspond to the different colors in the plots)
- chosen symmetries can describe lepton mixing angles

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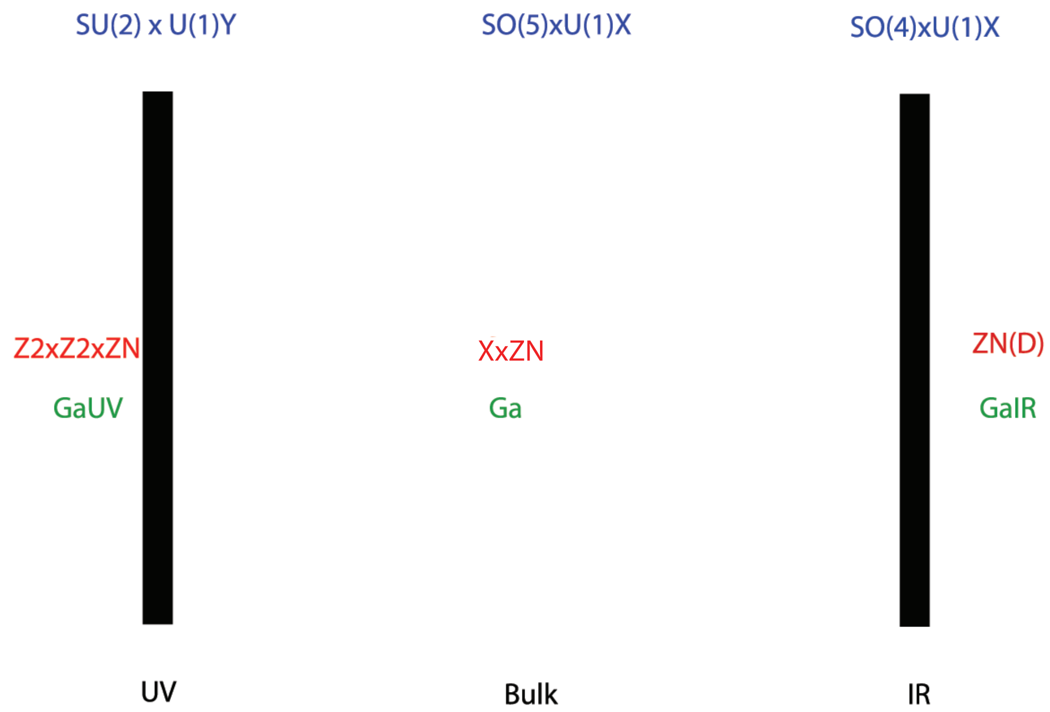


Extra dimension

(H/Serone ('11), H ('13))

- assume neutrinos are Majorana particles
- particle content ($X = 0$)

$$\xi_{l,\alpha} \sim (\mathbf{5}, \mathbf{3}, 1, \omega_3, \omega_3)\ ,\quad \xi_{e,\alpha} \sim (\mathbf{10}, \mathbf{1}, \omega_N^{n_\alpha}, \omega_3, \omega_3)\ ,\quad \xi_{\nu,\alpha} \sim (\mathbf{1}, \mathbf{3}, 1, \omega_3, 1)$$

with

$$\xi_{l,\alpha} = \begin{pmatrix} \left[\widetilde{L}_{1,\alpha L}\,(-+)\,,\ L_{\alpha L}\,(++)\right] \\ \\ \hat{\nu}_{\alpha L}\,(-+) \end{pmatrix},\qquad \xi_{e,\alpha} = \begin{pmatrix} x_{\alpha L}\,(+-) & \\ \widetilde{\nu}_{\alpha L}\,(+-) & Z_{\alpha L}\,(+-) \\ e_{\alpha L}\,(--) & \\ \left[\widetilde{L}_{2,\alpha L}\,(+-)\,,\ \hat{L}_{\alpha L}\,(+-)\right] & \end{pmatrix}$$

$$\xi_{\nu,\alpha} = \nu_{\alpha L}\,(--)$$

Extra dimension

(H/Serone ('11), H ('13))

- assume neutrinos are Majorana particles
- mass mixing terms at IR brane

$$-\mathcal{L}_{\rm IR} = \left(\frac{R}{R'}\right)^4 \sum_{\alpha=e,\mu,\tau} \Big(m^l_{{\rm IR},\alpha} \left(\overline{\widetilde{L}}_{1,\alpha L} \widetilde{L}_{2,\alpha R} + \overline{L}_{\alpha L} \hat{L}_{\alpha R} \right) + m^\nu_{{\rm IR},\alpha} \overline{\hat{\nu}}_{\alpha L} \nu_{\alpha R} + h.c. \Big)$$

and Majorana mass terms for RH neutrinos at UV brane

$$-\mathcal{L}_{\rm UV} = \frac{1}{2} \overline{\nu^c_{\alpha R}} \mathcal{M}_{{\rm UV},\alpha\beta} \nu_{\beta R} + h.c.$$

are constrained by symmetries as well

Extra dimension

(H/Serone ('11), H ('13))

- assume neutrinos are Dirac particles
- crucial change in particle content

$$\xi_{l,\alpha} = \begin{pmatrix} \left[\widetilde{L}_{1,\alpha L}\,(-+)\,,\; L_{\alpha L}\,(++) \right] \\ \\ \hat{\nu}_{\alpha L}\,(+-) \end{pmatrix}$$

- also additional symmetries are slightly adjusted

Extra dimension

(H/Serone ('11), H ('13))

- assume neutrinos are Dirac particles
- mass mixing terms at IR brane

$$-\mathcal{L}_{\rm IR} = \left(\frac{R}{R'}\right)^4 \sum_{\alpha=e,\mu,\tau}^{3} m^l_{{\rm IR},\alpha} \left(\overline{\widetilde{L}}_{1,\alpha L}\widetilde{L}_{2,\alpha R} + \overline{L}_{\alpha L}\hat{L}_{\alpha R}\right) + h.c.$$

and mass mixing at UV brane

$$-\mathcal{L}_{\rm UV} = \overline{\hat{\nu}}_{\alpha L}\mathcal{M}_{{\rm UV},\alpha\beta}\nu_{\beta R} + h.c.$$

are constrained by symmetries as well

Extra dimension

(H/Serone ('11), H ('13))

- in addition to mass mixing terms there are

  boundary kinetic terms (BKTs)

  where the most important ones are

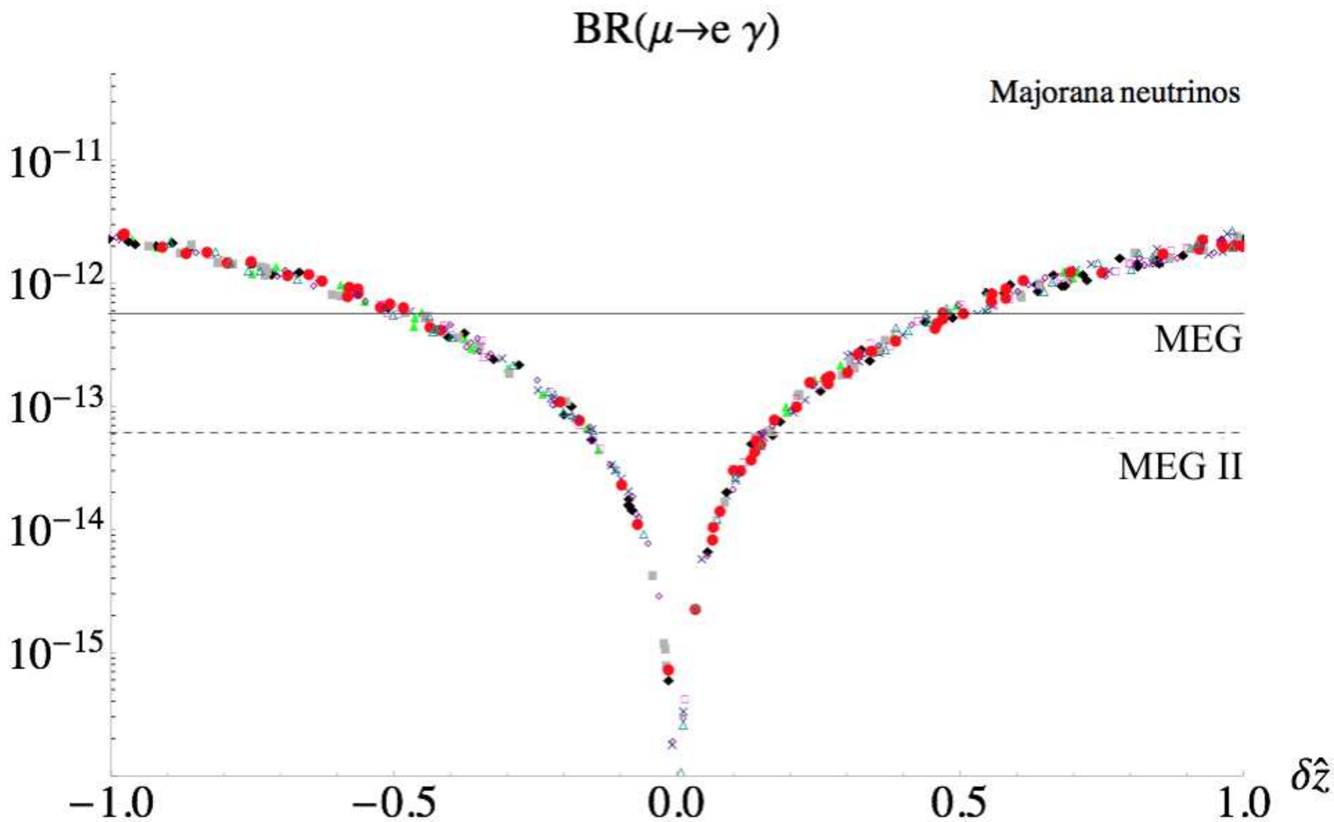
$$\mathcal{L}_{\rm BKT} = \bar{L}_L(x,R)(R\hat{Z}_l)i\not{D}L_L(x,R)\,.$$

  Also, these are constrained by the symmetries.

Extra dimension

Model with Majorana neutrinos

(H/Serone ('11), H ('13))



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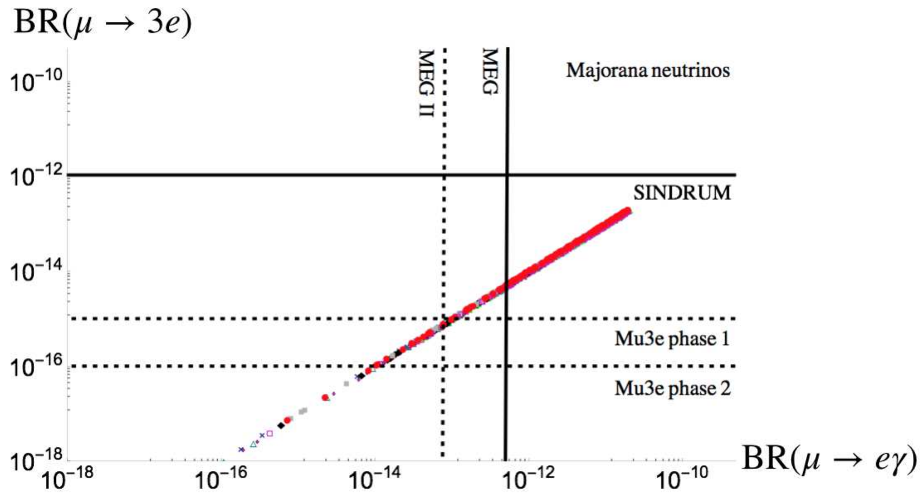

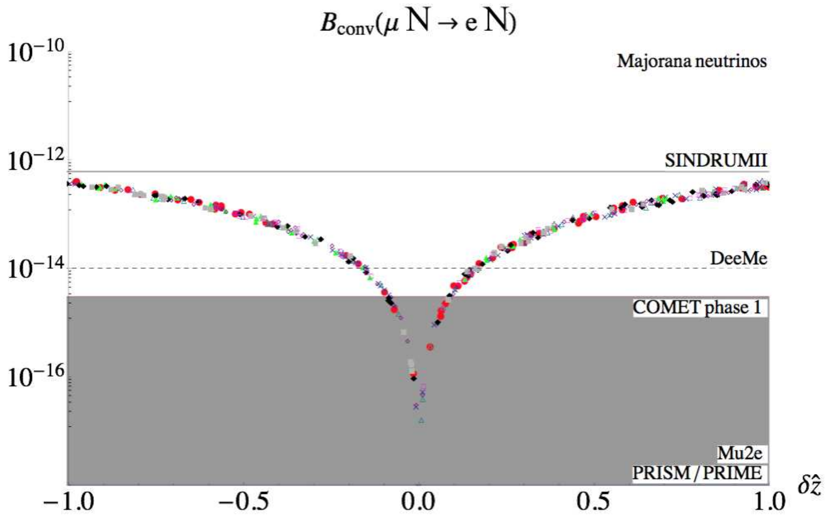

Extra dimension

Model with Dirac neutrinos

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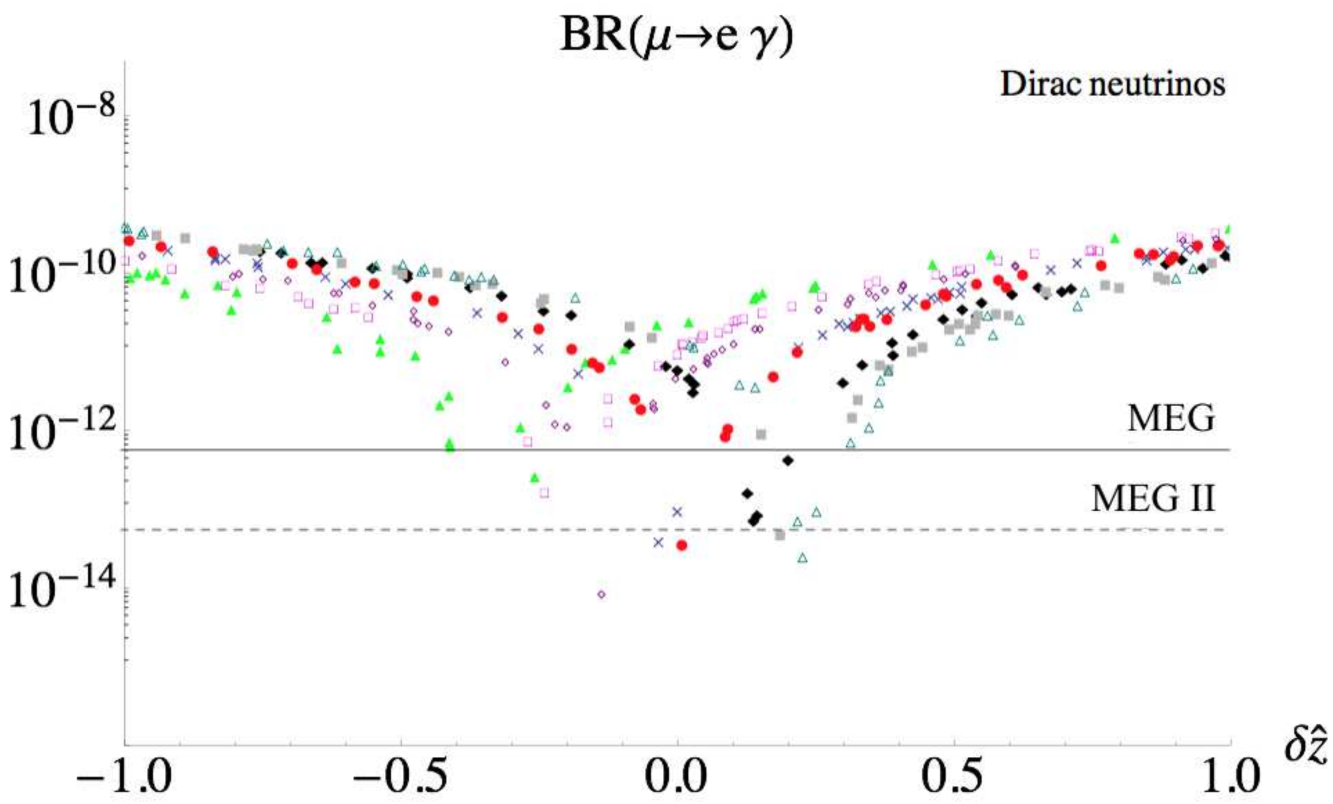

Extra dimension

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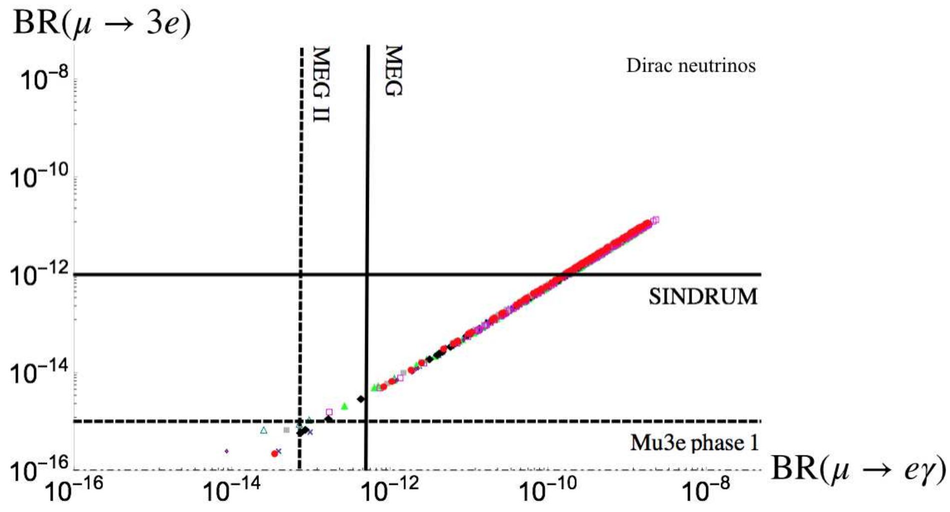
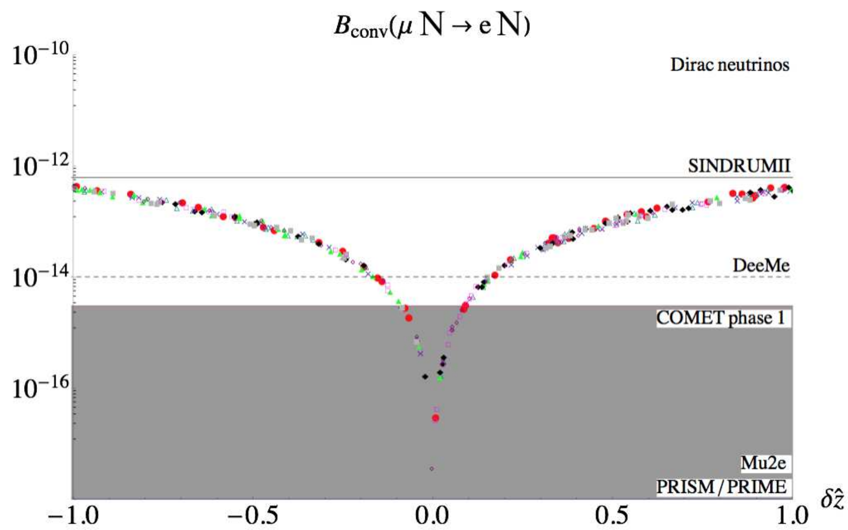
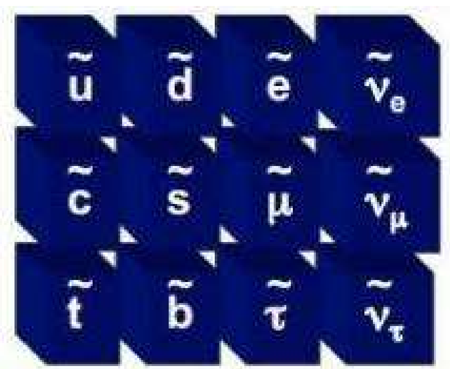




Supersymmetric models

Supersymmetric particles ...

- ... usually also appear in three generations.



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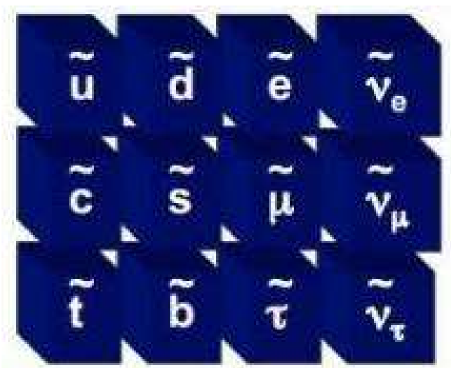
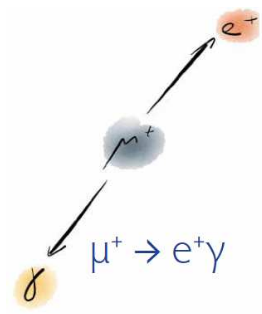
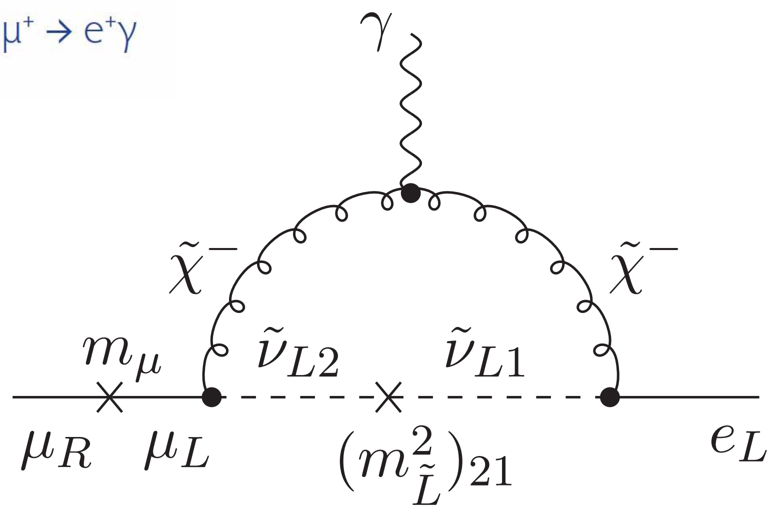






Supersymmetric models

(Lopez-Ibanez et al. ('19))

- impose flavor symmetry $G_f = A_5$ and CP on MSSM theory
- chosen symmetries can describe lepton mixing well

(Di Iura/H/Meloni ('15))

- assume soft SUSY breaking terms

$$\mathcal{L}_{\text{soft}} \supset (m^2_{\tilde{L}})_{ij} \, \tilde{L}_i^\dagger \, \tilde{L}_j$$

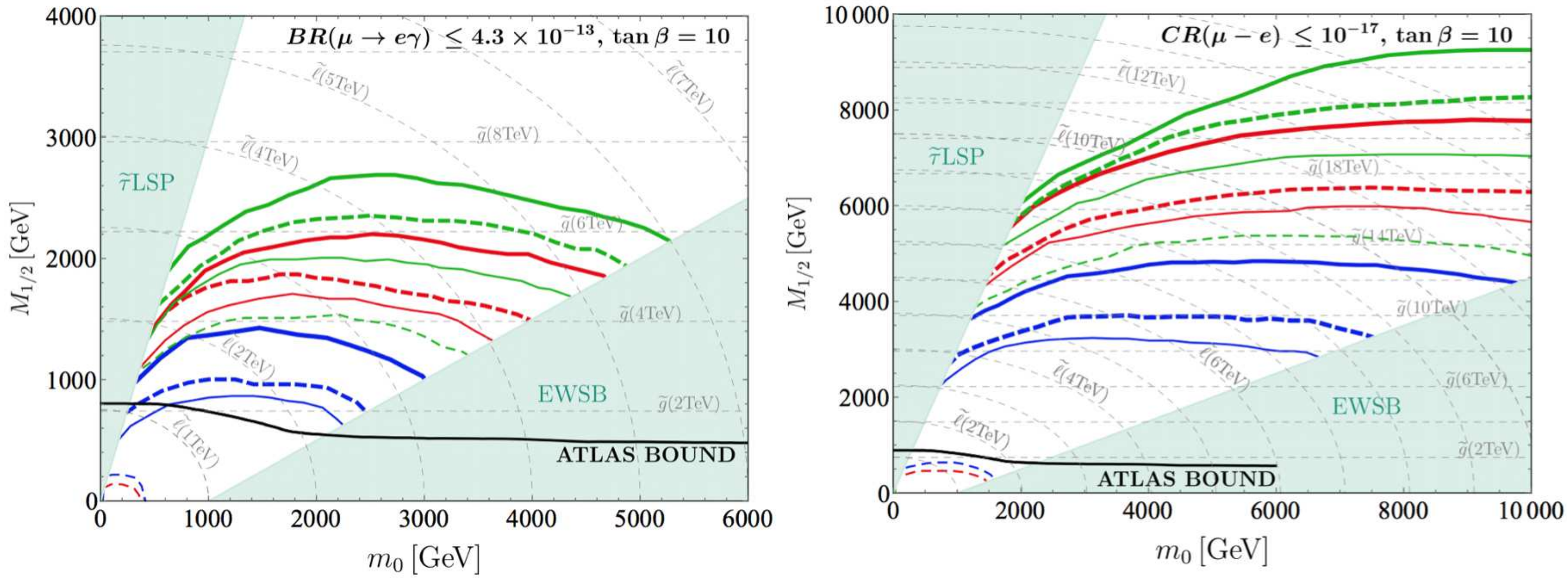
  are constrained by these symmetries as well

- consider different (minimal) scenarios for neutrino masses
  (these correspond to the differently colored lines in the plots)

Supersymmetric models

CLFV signals can probe soft masses larger than direct searches

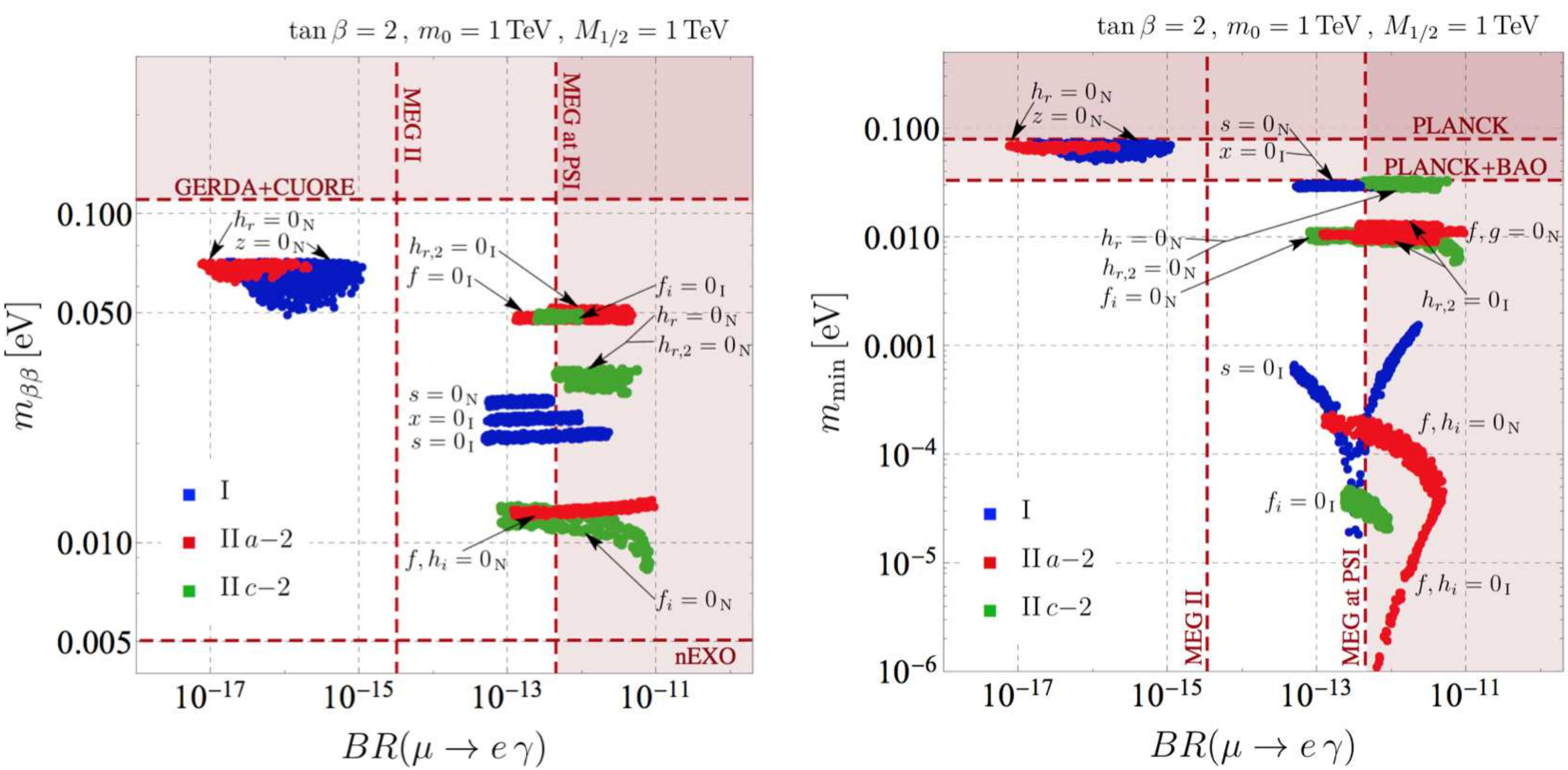
(Lopez-Ibanez et al. ('19))



Supersymmetric models

Correlations between CLFV signals and neutrino masses arise

(Lopez-Ibanez et al. ('19))



Continuous flavor symmetries and CLFV

Some examples

- models with $SU(3)$ flavor symmetry,
  see e.g. ***Antusch/King/Malinsky ('07), Calibbi/Jones-Perez/Vives ('08)***
- models with so-called minimal flavor violation can also be considered in this category,
  flavor symmetry $U(3)^5$ or alike is broken by spurions
- flavor symmetry can also be abelian,
  see e.g. ***Calibbi et al. ('12)***

Phenomenological imprints beyond CLFV

Examples of studied signals

- neutrinoless double beta decay,
  see e.g. ***King/Neder ('14), Ding/King/Neder ('14), H/Molinaro ('16)***
- generation of baryon asymmetry through unflavored and flavored leptogenesis in scenarios with flavor and CP symmetries,
  see e.g. ***H/Molinaro ('16), Mohapatra/Nishi ('15), Chen/Ding/King ('16)***
- anomalous magnetic moment and electric dipole moment of charged leptons,
  see e.g. ***Feruglio et al. ('08), Dimou/King/Luhn ('15)***
- possible explanation of (some) B physics anomalies,
  see e.g. ***de Medeiros Varzielas/Hiller ('15)***

Conclusions

- discrete non-abelian flavor symmetries (and CP) and their breaking can lead to a good description of lepton mixing angles and allow for predictions of the leptonic CP phase(s)
- in theories beyond the Standard Model such symmetries also constrain the signal strength of CLFV processes (models with extra dimension and supersymmetric models)
- such symmetries can leave further phenomenological imprints, e.g. by predicting neutrinoless double beta decay or the electric dipole moment of charged leptons

Thank you for your attention.