Recollections from more than 20 years of collaboration and friendship

(Contribution to HirschFest)

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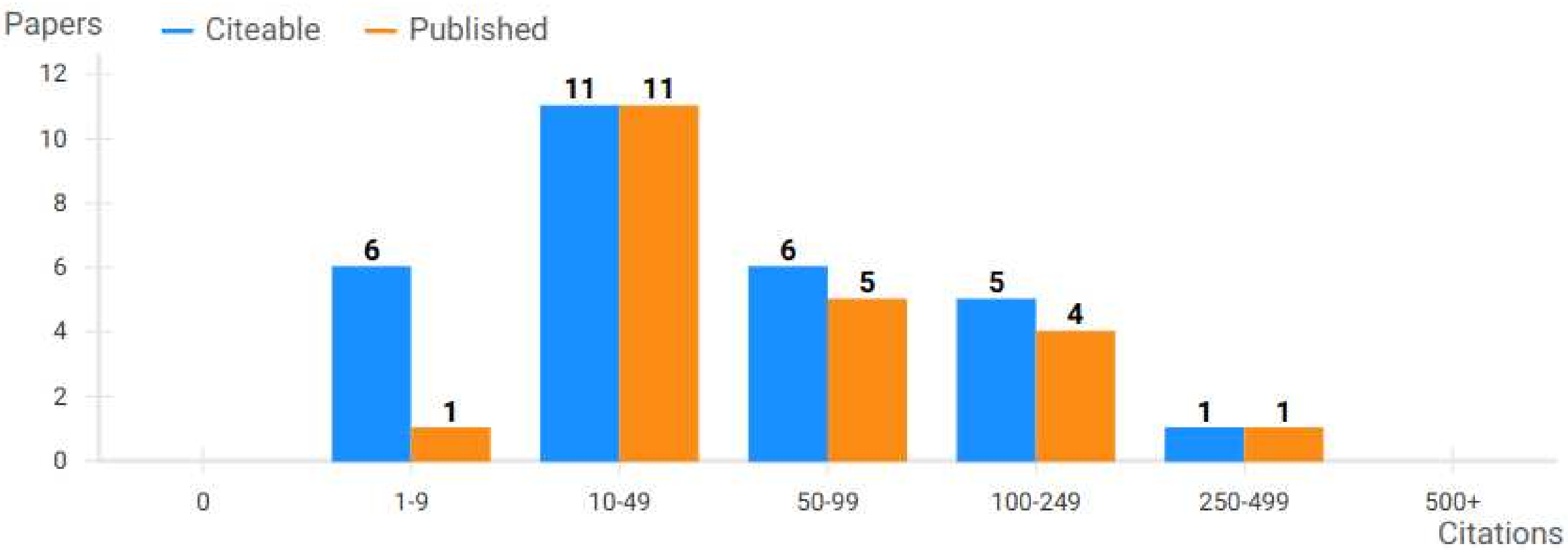
M. Hirsch & J.C.Romão papers

find a hirsch,m and a romao,j

Citation Summary

Exclude self-citations

	Citeable	Published
Papers	29	22
Citations	1,952	1,718
h-index	22	20
Citations/paper (avg)	67.3	78.1



Some of the topics we studied

- R-Parity Violation and neutrino masses masses
  - Bilinear R-Parity Violation
  - Spontaneous R-Parity Violation
- Testing R-Parity at the colliders
  - SUSY decays
  - Higgs decays
- Lepton Flavour Violation (LFV) and Dark Matter
  - Type I, II and III seesaw
  - Left-Right (LR) model
- Unification in GUT's
  - LR models with sliding scale

Broken R-Parity Models

$$R_P = (-1)^{2J+3B+L}$$

- BRpV: **Explicit R-Parity Violation**
  - Bilinear R-Parity Violation
  - Same particle content as the MSSM
- SRpV: **Spontaneously R-Parity Violation**
  - More Complicated Higgs Structure
  - Majoron J
  - Invisible Higgs Decay $h \to JJ$

Rich Phenomenology
Hierarchical Spectrum: No visible $\beta\beta_{0\nu}$

J.W.F. Valle, M. Diaz, M. Hirsch, W. Porod, A. Villanova del Moral, JCR, ...

Neutrino Masses from broken R-parity: The BRpV Model

- The superpotential of the BRpV model is

$$W^{\text{BRpV}} = W^{\text{MSSM}} + \varepsilon_{ab}\epsilon_i \widehat{L}_i^a \widehat{H}_2^b$$

- The superfield content is as in the MSSM.
- The last term in is the only R–parity violating term. The ϵ_i are parameters with units of mass
- The electroweak symmetry is broken when the two Higgs doublets H_d and H_u, and the neutral component of the slepton doublets $\widetilde{L}_i^0$ acquire vacuum expectation values.
- The scalar potential is

$$V^0_{\text{total}} = \sum_i \left| \frac{\partial W}{\partial z_i} \right|^2 + V_D + V_{\text{SB}}^{\text{MSSM}} + V_{\text{SB}}^{\text{BRpV}}$$

where z_i is any one of the scalar fields in the superpotential

Tree Level Neutrino Masses and Mixings

- The 7×7 neutralino/neutrino mass matrix $\boldsymbol{M}_N$ has two zero eigenvalues. Therefore two of the ν's remain massless at tree level.
- The values of the parameters ϵ_i needed to account for the neutrino masses and mixings are small compared with the electroweak scale.
- Using this we can approximately bring $\boldsymbol{M}_N$ to block diagonal form,

$$\boldsymbol{M}_N \simeq \begin{bmatrix} m_{\text{eff}} & 0 \\ 0 & \mathcal{M}_{\chi^0} \end{bmatrix}, m_{\text{eff}} = \frac{M_1 g^2 + M_2 g'^2}{4 \det(\mathcal{M}_{\chi^0})} \begin{bmatrix} \Lambda_e^2 & \Lambda_e \Lambda_\mu & \Lambda_e \Lambda_\tau \\ \Lambda_e \Lambda_\mu & \Lambda_\mu^2 & \Lambda_\mu \Lambda_\tau \\ \Lambda_e \Lambda_\tau & \Lambda_\mu \Lambda_\tau & \Lambda_\tau^2 \end{bmatrix}$$

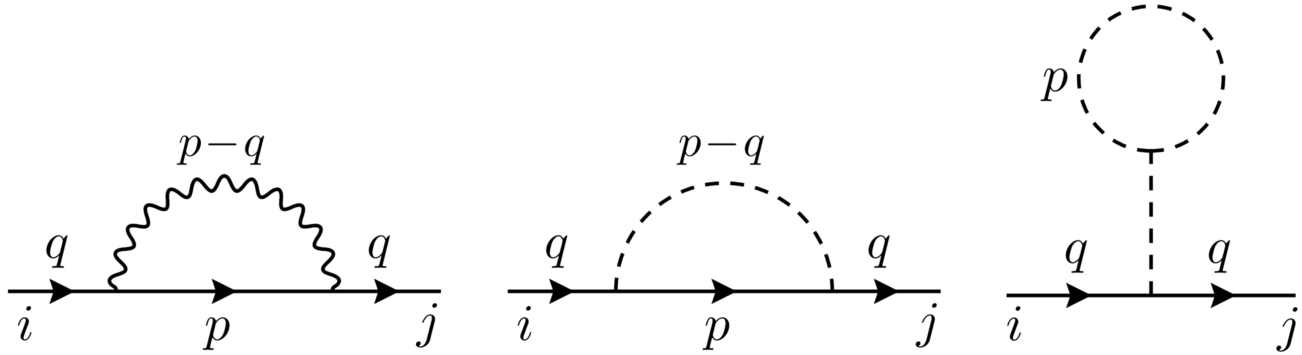
where $\mathcal{M}_{\chi^0}$ is the neutralino mass matrix and $\Lambda_i \equiv \mu v_i + v_d \epsilon_i$.

- It is clear from the the projective nature of m_{eff} that two of the ν's remain massless at tree level. The non zero neutrino mass is

$$m_\nu = \text{Tr}(m_{\text{eff}}) = \frac{M_1 g^2 + M_2 g'^2}{4 \det(\mathcal{M}_{\chi^0})} |\vec{\Lambda}|^2$$

One-Loop Neutrino Masses and Mixings

- The diagrams contributing to the self-energy include the exchange of gauge bosons as well of scalars.



- These diagrams can be calculated in a straightforward way. For instance the W diagram in the $\xi = 1$ gauge gives

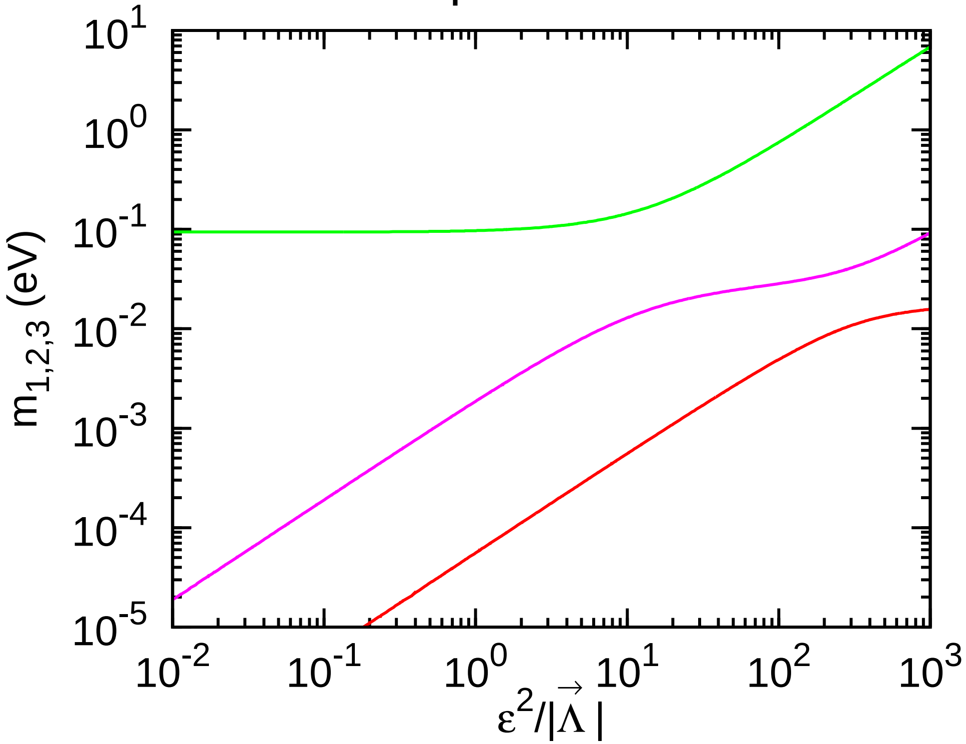
$$\Sigma^V_{ij} = -\frac{1}{16\pi^2}\sum_{k=1}^{5} 2\left(O^{\rm ncw}_{Ljk}O^{\rm cnw}_{Lki} + O^{\rm ncw}_{Rjk}O^{\rm cnw}_{Rki}\right) B_1(p^2, m_k^2, m_W^2)$$

$$\Pi^V_{ij} = -\frac{1}{16\pi^2}\sum_{k=1}^{5}(-4)\left(O^{\rm ncw}_{Ljk}O^{\rm cnw}_{Rki} + O^{\rm ncw}_{Rjk}O^{\rm cnw}_{Lki}\right) m_k\, B_0(p^2, m_k^2, m_W^2)$$

where B_0 and B_1 are the Passarino-Veltman functions, and $O^{\rm cnw}$, $O^{\rm ncw}$ are coupling matrices

Fitting the data

- The BRpV model produces a hierarchical mass spectrum



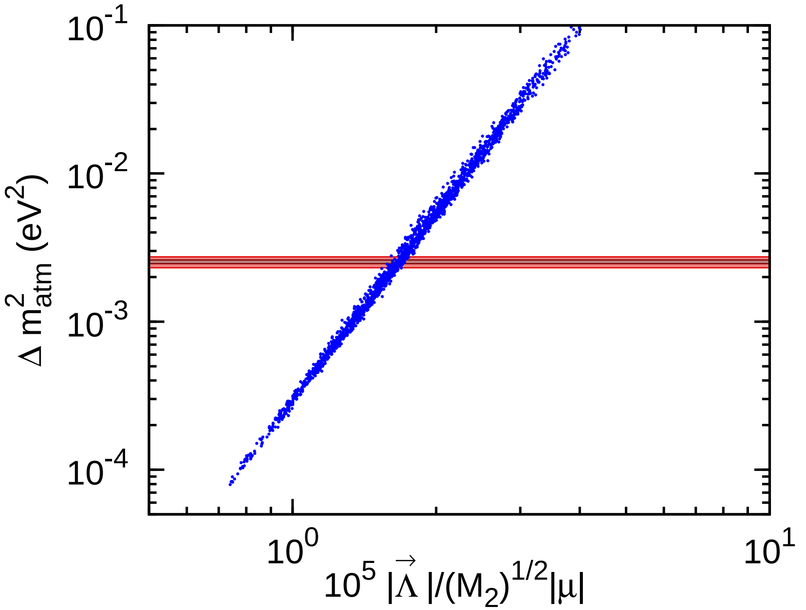
- The largest mass scale can be estimated by the tree level value
- The solar mass scale can be obtained at one-loop
- The correct mixing angles can be obtained by an appropriate choice of $|\vec{\Lambda}|$ and Λ_i such that

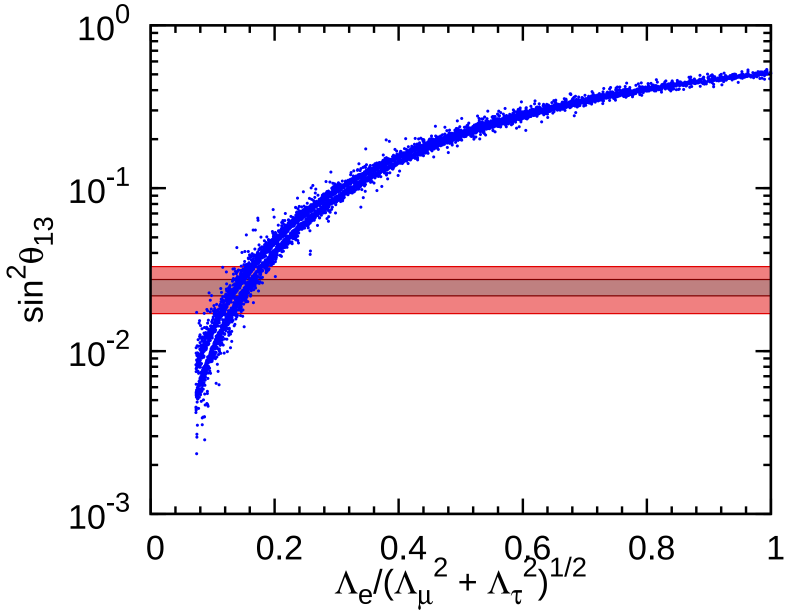
$$\Lambda_e \ll \Lambda_\mu, \Lambda_\tau$$

M. Hirsch, M. Diaz, W. Porod, JCR, J.W.F. Valle
Phys.Rev.D62:113008,2000

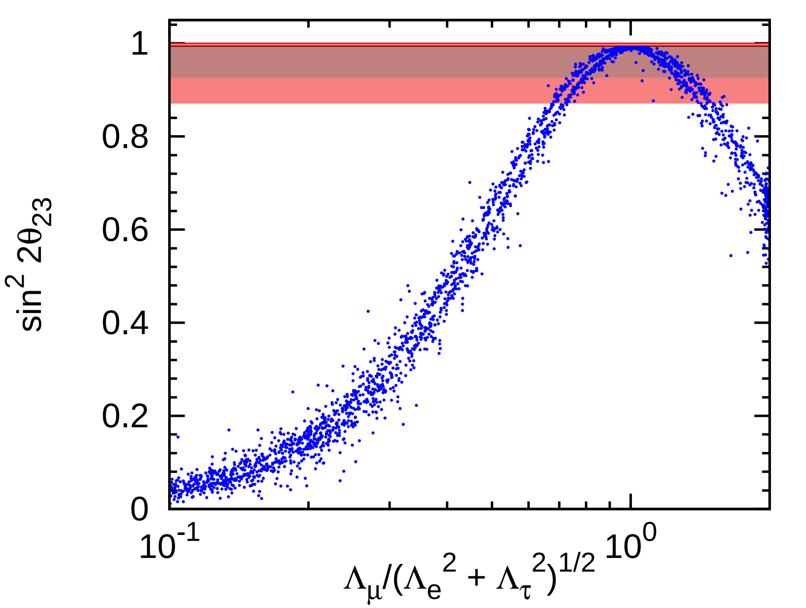
At the time BRpV was proposed the neutrino data was not very well known. It is interesting that with the present high precision data on neutrino physics, the model can still accommodate it.

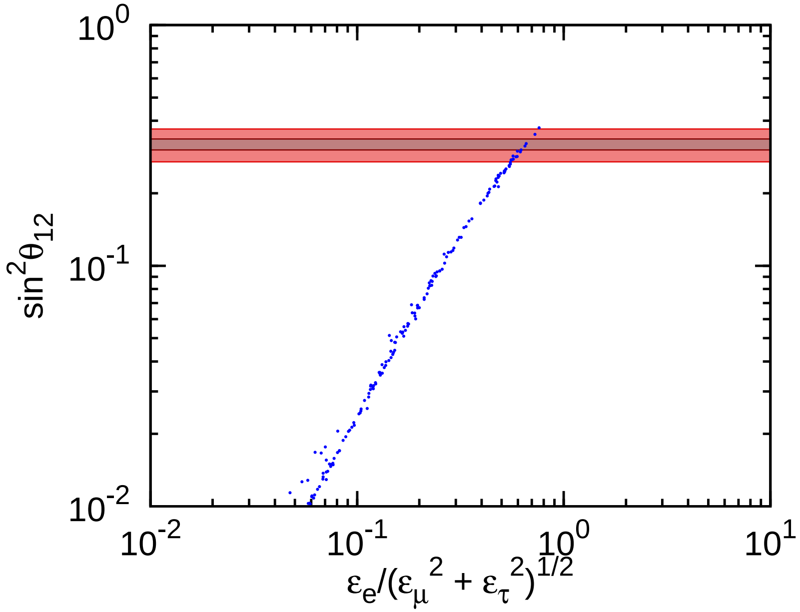
The mixings θ_{13}, θ_{23} and θ_{12} could be accommodated





J.W.F. Valle and JCR, Neutrinos in high energy and astroparticle physics (Wiley, 2015)





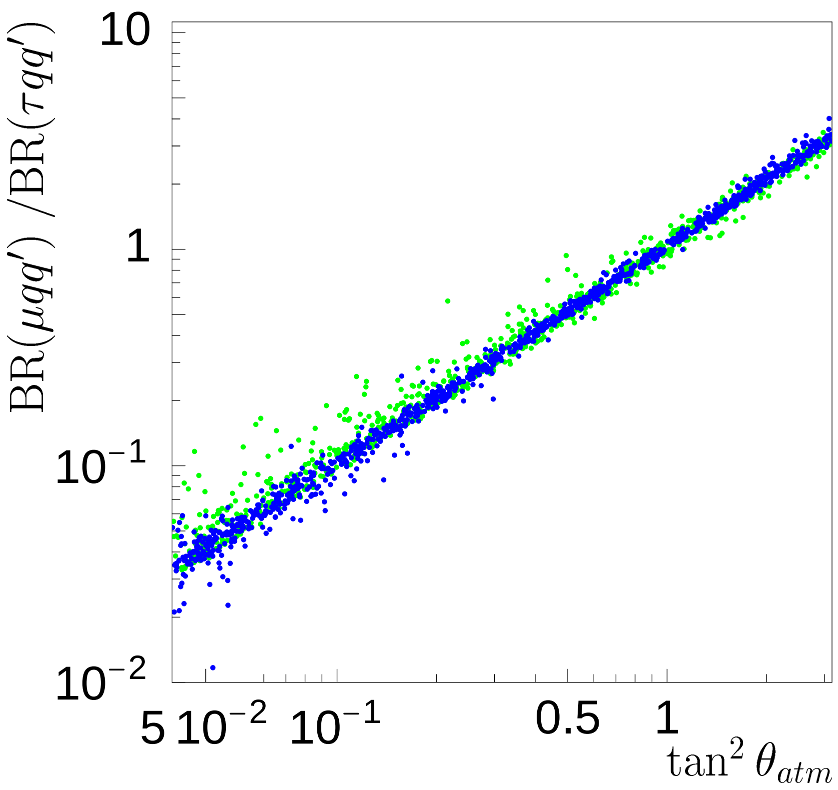
Testing BRpV via SUSY Decays

- LSP Decays: **(mSUGRA)**
  The fact that, in these models, the LSP decays through R–parity violating processes allows it to be either neutral or charged.
  - In most cases the LSP is the lightest neutralino, like in the MSSM.
  - For some regions of the parameter space the LSP can also be the scalar tau.
  - In both cases we have shown that despite the smallness of m_ν the LSP decays inside the detector.

- LSP Decays: **(non mSUGRA)**
  If we depart from mSUGRA then the LSP can be almost any particle. This gives complementary information.

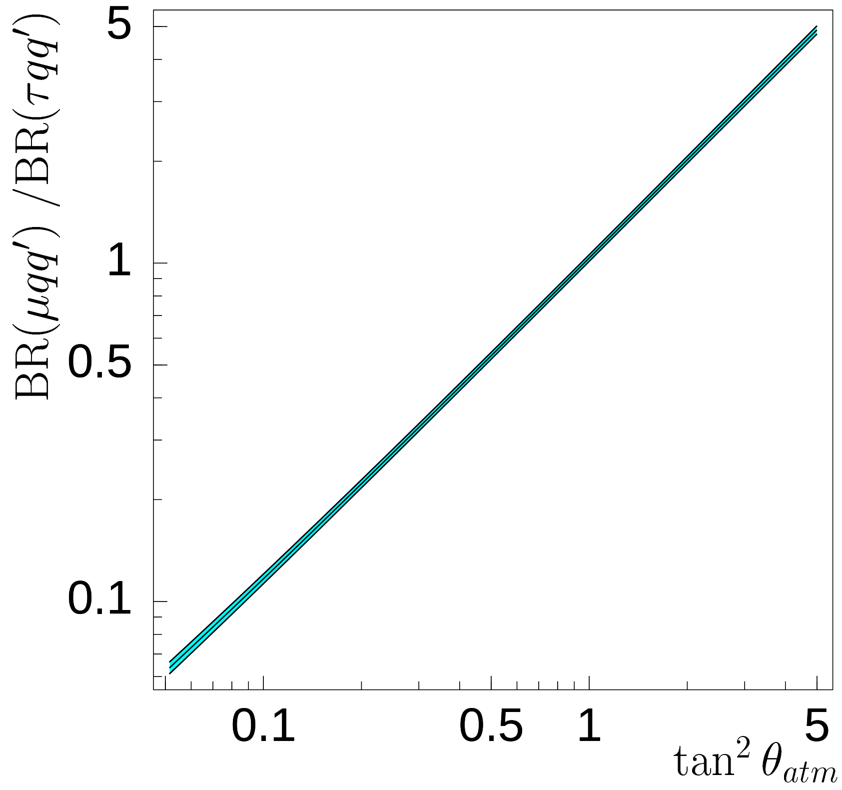
Example: Probing the Atmospheric Angle (old slide)

Before SUSY



W. Porod, M. Hirsch, JCR, J.W.F. Valle
Phys.Rev.D63:115004,2001

After SUSY



$M_2 = 120$ GeV, $\mu = 500$ GeV, $\tan\beta = 5$
$m_0 = 500$ GeV, $A = -500$ GeV.

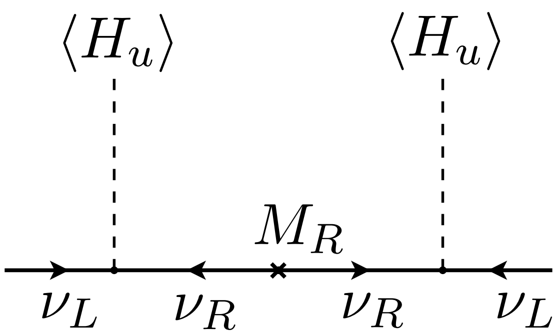
Seesaw models for neutrino masses: Type-I-II-III

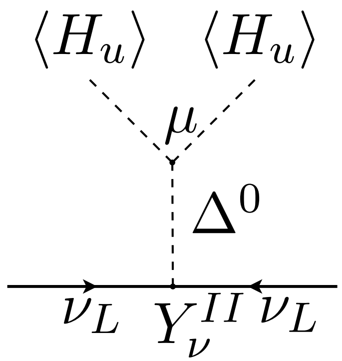
$$\mathcal{L} = \cdots + H_u \overline{\nu_L} Y_\nu^{\mathrm{I}} \nu_R - \frac{1}{2} \nu_R^T C^{-1} M_R \nu_R$$

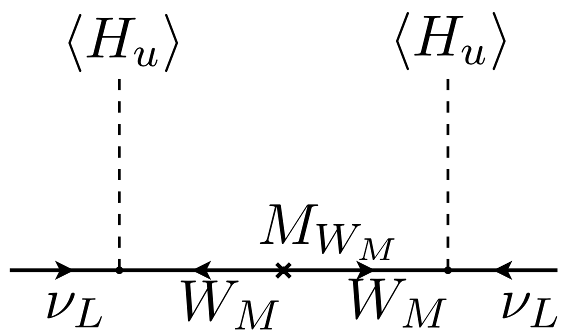
$$\mathcal{L} = \cdots - \frac{1}{2} Y_\nu^{\mathrm{II}} \overline{\nu_L^c} i\tau_2 \Delta_L \nu_L - \mu H_u^T \Delta_L H_u - M_\Delta^2 \Delta_L^\dagger \Delta_L$$

$$\mathcal{L} = \cdots + H_u \overline{W_M} Y_\nu^{\mathrm{III}} \nu_L - \frac{1}{2} W_M^T C^{-1} M_{W_M} W_M$$

type-I | type-II | type-III







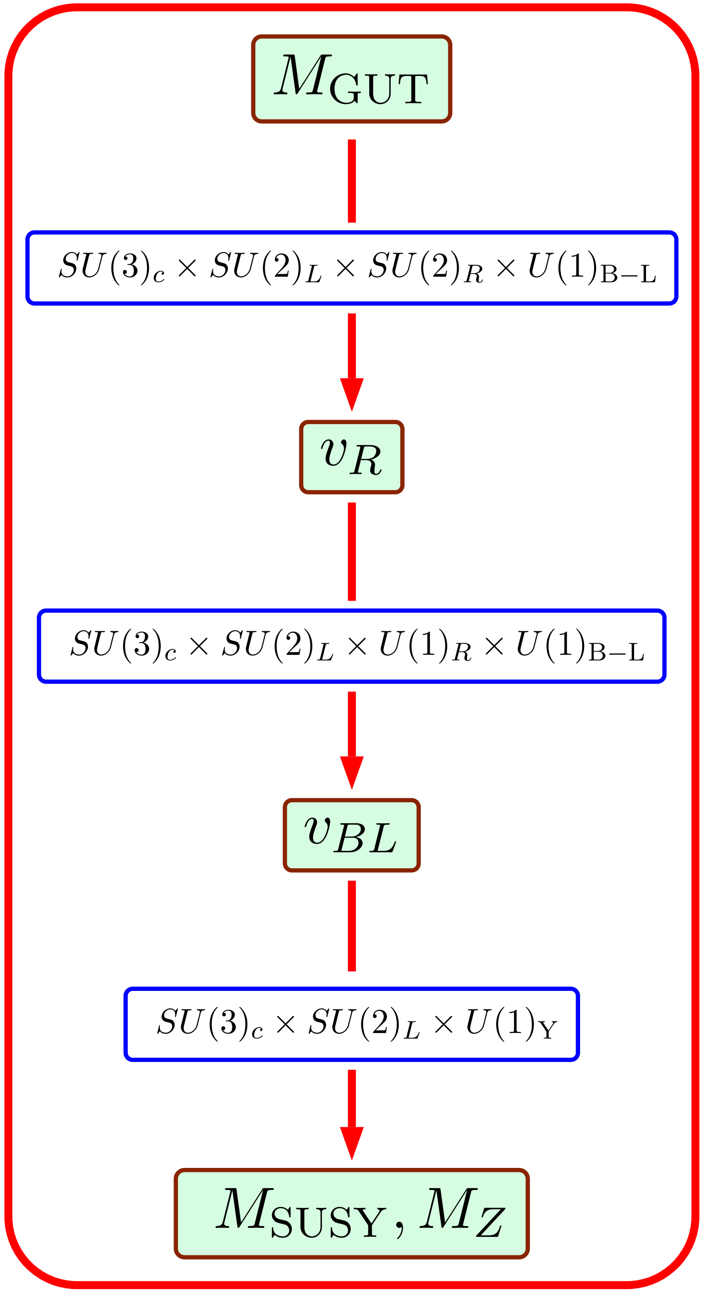
$$m_{\mathrm{eff}}^{\mathrm{I}} = -(vY_\nu) M_R^{-1} (vY_\nu)^T$$

$$m_{\mathrm{eff}}^{\mathrm{II}} = \frac{v^2 \mu Y_\nu^{\mathrm{II}}}{M_\Delta^2}$$

$$m_{\mathrm{eff}}^{\mathrm{III}} = -(vY_\nu^{\mathrm{III}}) M_{W_M}^{-1} (vY_\nu^{\mathrm{III}})^T$$

- Exchanged particle: Type-I-III: neutral fermion. Type-II: neutral scalar
- Type-I: gauge singlet. Type-II-III; gauge triplet ➡ Stronger running
- $m_\nu \sim 1$eV and $Y_\nu \sim \mathcal{O}(1)$ ➡ $M_{\mathrm{Seesaw}} \sim \mathcal{O}(10^{12-14})$GeV **Not directly observable**

Left-Right Model: breaking scales and neutrino mass



- Superpotential

$$\mathcal{W} = Y_L L \Phi L^c - f_c L^c \Delta^c L^c + \cdots$$

  - Y_L and f_c complex 3×3 matrices

- Lagrangian at $v_{BL} = \langle \Delta_c^0 \rangle$

$$\mathcal{L} = H_u \overline{\nu_L} Y_\nu^{\rm I} \nu_R - \frac{1}{2} \nu_R^T C^{-1} (f_c v_{BL}) \nu_R + \cdots$$

- Effective neutrino mass matrix (type-I)

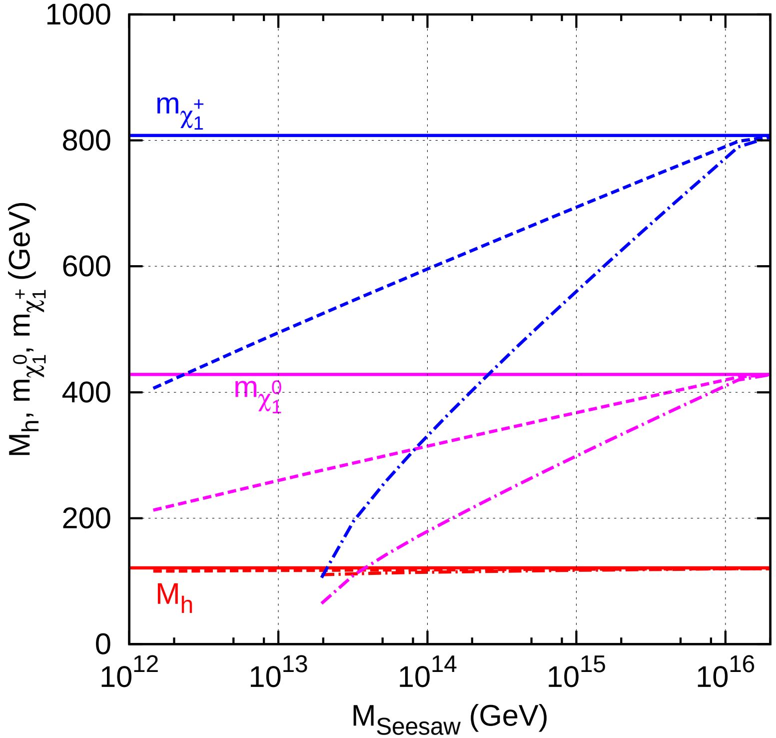
$$m_{\rm eff}^{\rm LR} = -(v Y_\nu)(f_c v_{BL})^{-1} (v Y_\nu)^T$$

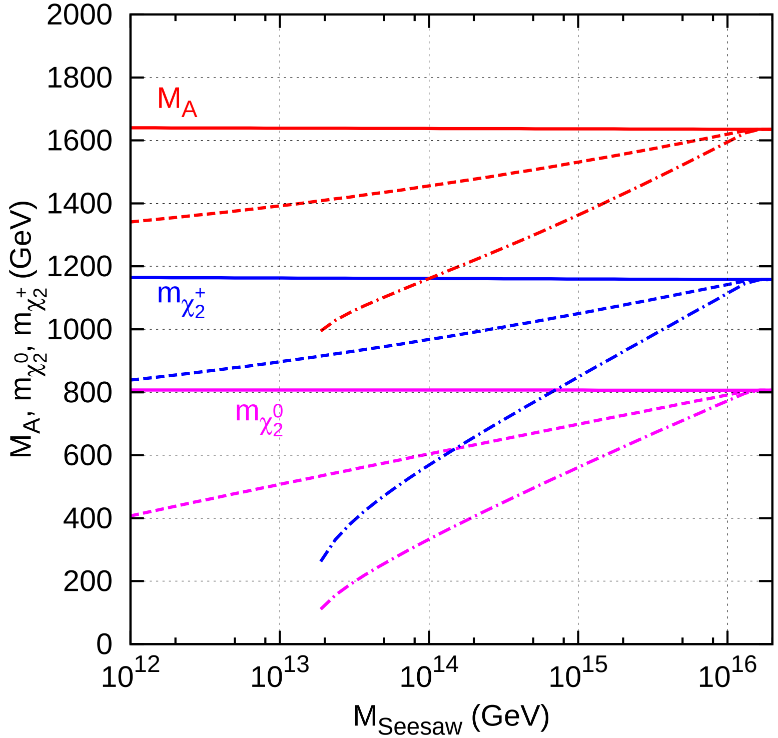
  - Y_ν fit $\to f_c = \mathbb{1}$, Y_ν arbitrary
  - f fit $\to Y_\nu = \mathbb{1}$, f_c arbitrary
  - Different imprints on RGE running

Effects of the heavy particles on the MSSM spectrum

- The appearance of particles with charges under the gauge group at scales between $M_{\rm Seesaw}$ and $M_{\rm GUT}$ leads to changes in the beta functions of the gauge couplings
- Example of spectra at $Q = 1$ TeV versus the seesaw scale
- SUSY parameters $m_0 = M_{1/2} = 1$ TeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$
- Type-I (full lines), type-II (dashed) and type-III (dash-dotted)

J.N. Esteves, JCR, M. Hirsch, F. Staub and W. Porod, Phys.Rev.D83,013003,2011





LFV in the slepton sector: Approximate formulas for $\Delta m_{L,E}$

Starting with universal (mSUGRA) boundary conditions @ M_{GUT}

Seesaw type-I-II-III

$$\Delta m^2_{L,ij} \simeq -\frac{a_k}{8\pi^2}\,(3m_0^2 + A_0^2)\left(Y_N^{k,\dagger} L Y_N^k\right)_{ij}, \qquad L = \ln\left(\frac{M_{\text{GUT}}}{M_{\text{N}}}\right)$$

$$\Delta m^2_{E,ij} \simeq 0 \qquad a_{\text{I}} = 1\,,\; a_{\text{II}} = 6 \text{ and } a_{\text{III}} = \frac{9}{5}$$

Left-Right Model

M_{GUT} → v_R

$$\Delta m_L^2 \simeq -\frac{1}{4\pi^2}\left(3 f f^\dagger + Y_L^{(k)} Y_L^{(k)\,\dagger}\right)(3m_0^2 + A_0^2)\ln\left(\frac{M_{\text{GUT}}}{v_R}\right)$$

$$\Delta m_E^2 \simeq -\frac{1}{4\pi^2}\left(3 f^\dagger f + Y_L^{(k)\,\dagger} Y_L^{(k)}\right)(3m_0^2 + A_0^2)\ln\left(\frac{M_{\text{GUT}}}{v_R}\right)$$

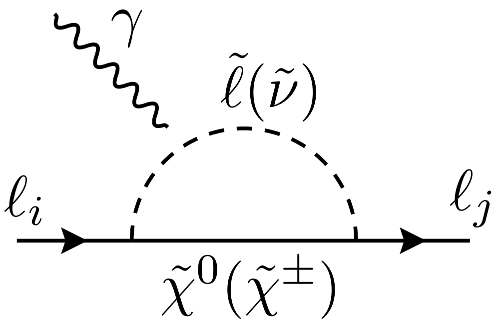
v_R → v_{BL}

$$\Delta m_L^2 \simeq -\frac{1}{8\pi^2} Y_\nu Y_\nu^\dagger \left(m_L^2|_{v_R} + A_e^2|_{v_R}\right)\ln\left(\frac{v_R}{v_{BL}}\right)$$

$$\Delta m_E^2 \simeq 0$$

Radiative lepton decays $l_i \to l_j\gamma$: Approximate formulas

- BR($l_i \to l_j\gamma$): (**MEG**...)



$$\mathcal{L}_{eff} = e\frac{m_i}{2}\bar{l}_i\sigma_{\mu\nu}F^{\mu\nu}(A_L^{ij}P_L + A_R^{ij}P_R)l_j + h.c.$$

$$\mathrm{BR}(l_i \to l_j\gamma) = \frac{48\pi^3\alpha}{G_F^2}\left(|A_L^{ij}|^2 + |A_R^{ij}|^2\right)\mathrm{BR}(l_i \to l_j\nu_i\bar{\nu}_j)$$

- For seesaw models: $A_L^{ij} \sim \frac{(\Delta m_{\tilde{L}}^2)_{ij}}{m_{SUSY}^4}$, $A_R^{ij} \sim \frac{(\Delta m_{\tilde{E}}^2)_{ij}}{m_{SUSY}^4}$
  - type-I-II-III ➞ only A_L
  - Left-Right model: In principle **both** A_L and A_R
  - Distinguish models: ➞ Positron polarization asymmetry(**MEG**)

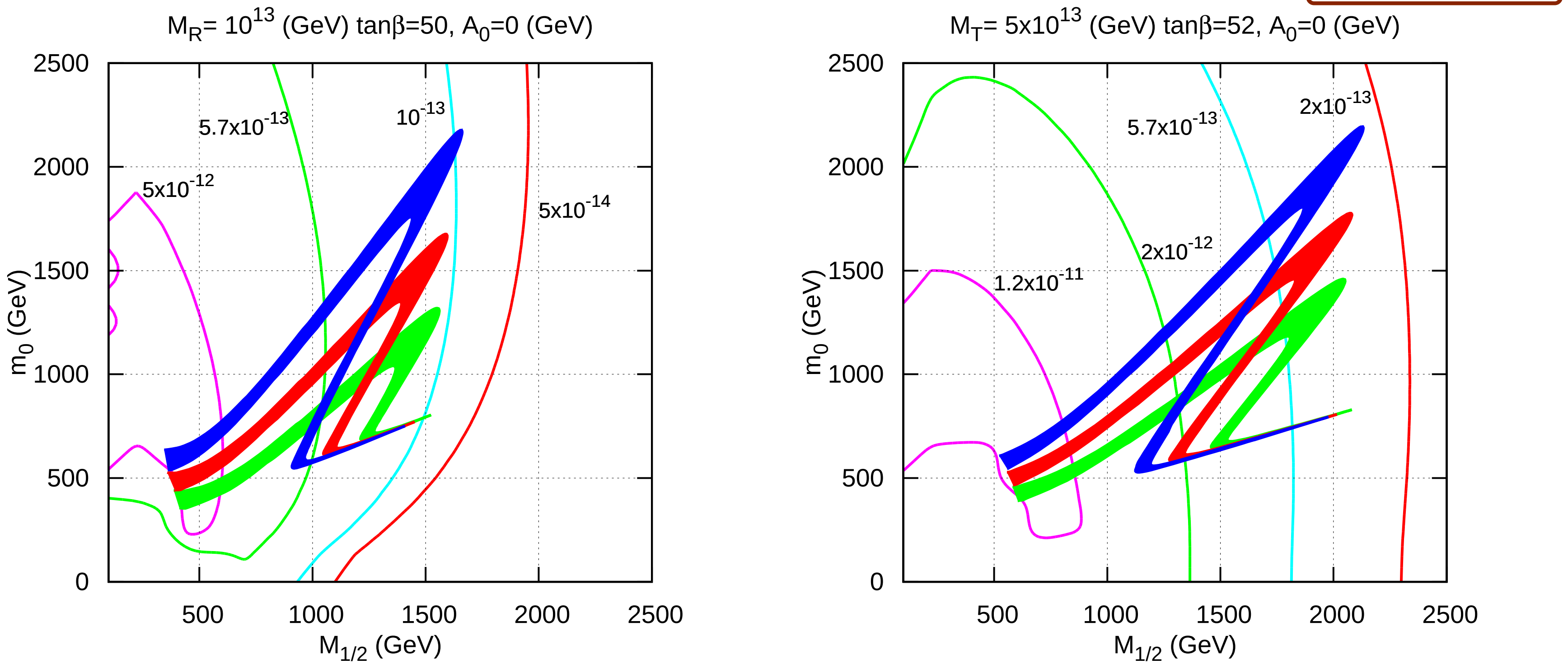
$$\mathcal{A}(\mu^+ \to e^+\gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2} = \begin{cases} 1 & \text{type-I-II-III} \\ \neq 1 & \text{LR} \end{cases}$$

Low-Energy LFV constraints in SUSY seesaw models: type-I,II

- Parameters: SUSY: $\{m_0,\ M_{1/2},\ A_0 = 0,\ \tan\beta = 10, 52,\ \text{sign}(\mu) = +\}$
- Seesaw: $M_R = 10^{13}$ GeV and $M_T = 5 \times 10^{13}$ GeV
- Dark matter region: WMAP (3σ), $0.081 \leq \Omega h^2 \leq 0.129$
- SPheno(W.Porod), SARAH(F.Staub)

J.N. Esteves, S. Kaneko, JCR, M. Hirsch, and W. Porod, Phys.Rev.D80,095003,2009

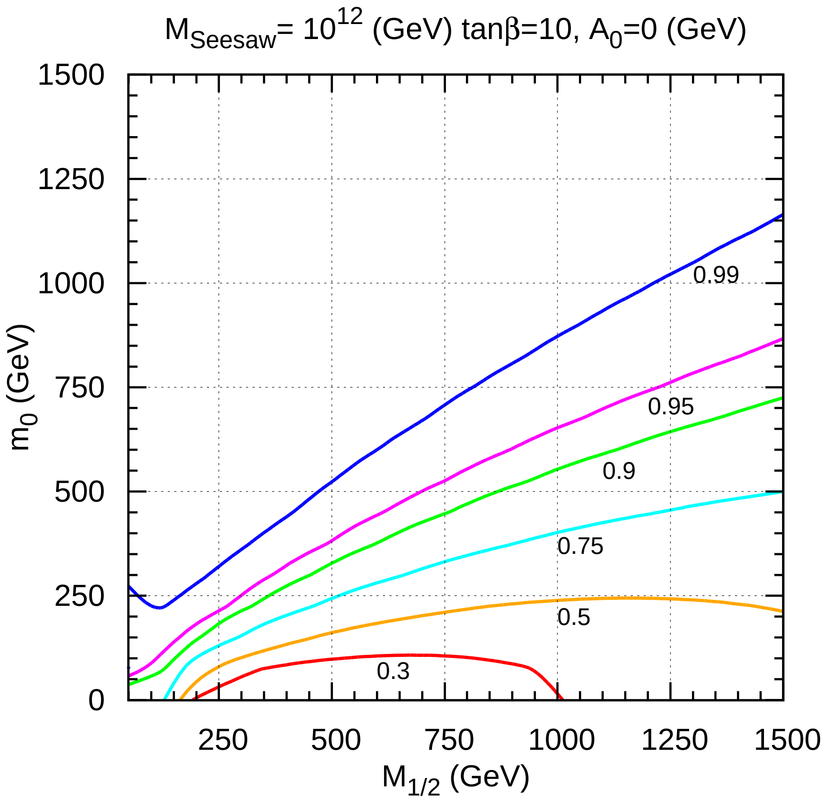
Higgs funnel

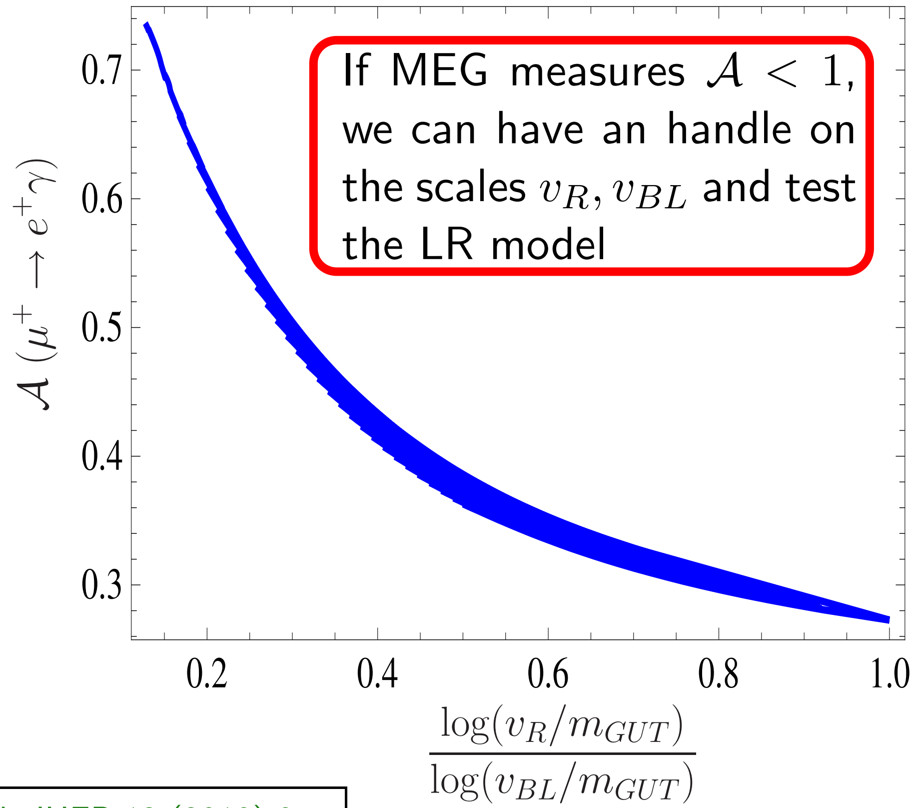


- $m_{top} = 169.1$ GeV (blue), 171.2 GeV (red), 173.3 GeV (green)
- Superimposed the contour lines for the $Br(\mu \to e\gamma)$. With the present bound of 4.2×10^{-13} most of parameter space shown is excluded

A low-energy observable for Left-Right model: $\mathcal{A}(\mu^+ \to e^+\gamma)$

- Positron polarization asymmetry: $\mathcal{A}(\mu^+ \to e^+\gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}$
- In seesaw type-I-II-III: $\mathcal{A}(\mu^+ \to e^+\gamma) = 1$, as $A_R \simeq 0$
- Parameters:
  - SUSY: SPS3 $\{m_0 = 90, M_{1/2} = 400, A_0 = 0, \tan\beta = 10, \text{sign}(\mu) = +\}$
  - LR: $v_{BL} = 10^{15}$ GeV, $v_R \in [10^{14}, 10^{15}]$ GeV, Y_ν fit





J.N. Esteves, JCR, M. Hirsch, A. Vicente and W. Porod, JHEP 12 (2010) 077

After Martin: Answering the question Why only 1 Higgs Boson?

❐ Number of particles with Spin 1

Fixed by the choice of Symmetry Group $\mathbf{SU(3)} \times \mathbf{SU(2)} \times \mathbf{U(1)}$

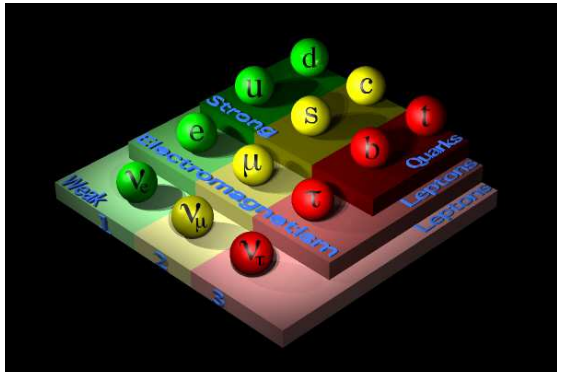
Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

❐ Number of Particles with Spin $\frac{1}{2}$

There is no principle. Fixed by experiment



❐ Number of particles with Spin 0

There is no principle. **Therefore should be fixed by experiment!**

NHDM: Many chalenges

- Theory
  - Perturbative Unitarity
  - Bounded From Below
  - Precision observables
  - CP violation and EDM constraints
  - Contributions to $b \to s\gamma$
  - Many parameters: Symmetry constrained models
  - Dark Matter
  - Flavor changing neutral interactions (FCNI)
  - ...
- Experiment
  - Confronting LHC data
  - Confronting the new limits on the EDM
  - Checking flavor constraints
  - ...

Also lots of fun in the last 10 years ...

Students and postdocs of the collaboration Valencia–Lisbon

These are the students and postdocs that I have shared with Martin:

- Albert Villanova del Moral
- Solveig Skadhauge
- Cyril Hugonie
- João N. Esteves
- Satoru Kaneko
- Thomas Kernreiter
- Avelino Vicente
- Carolina Arbelaez
- Renato M. Fonseca

Afterword

- It has been a lot of fun to work all these years with Martin
- We have established a very strong link between the Valencia and Lisbon groups, with the exchange of many students.
- I hope that the next years will be as rewarding as the ones that have elapsed.

Thank you Martin

Multi-Higgs Workshops