SUPER-WEAK FORCE AND NEUTRINO MASSES

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based on 1812.11189

WHFP, Lisbon, 17 January 2019

OUTLINE

1. Status of particle physics
2. $U(1)_Z$ extension of SM
3. UV behavior of the model

Status of particle physics: energy frontier

- LEP, LHC: SM describes final states of particle collisions precisely [see amazing ATLAS and CMS contributions Wednesday before lunch]

- SM is unstable

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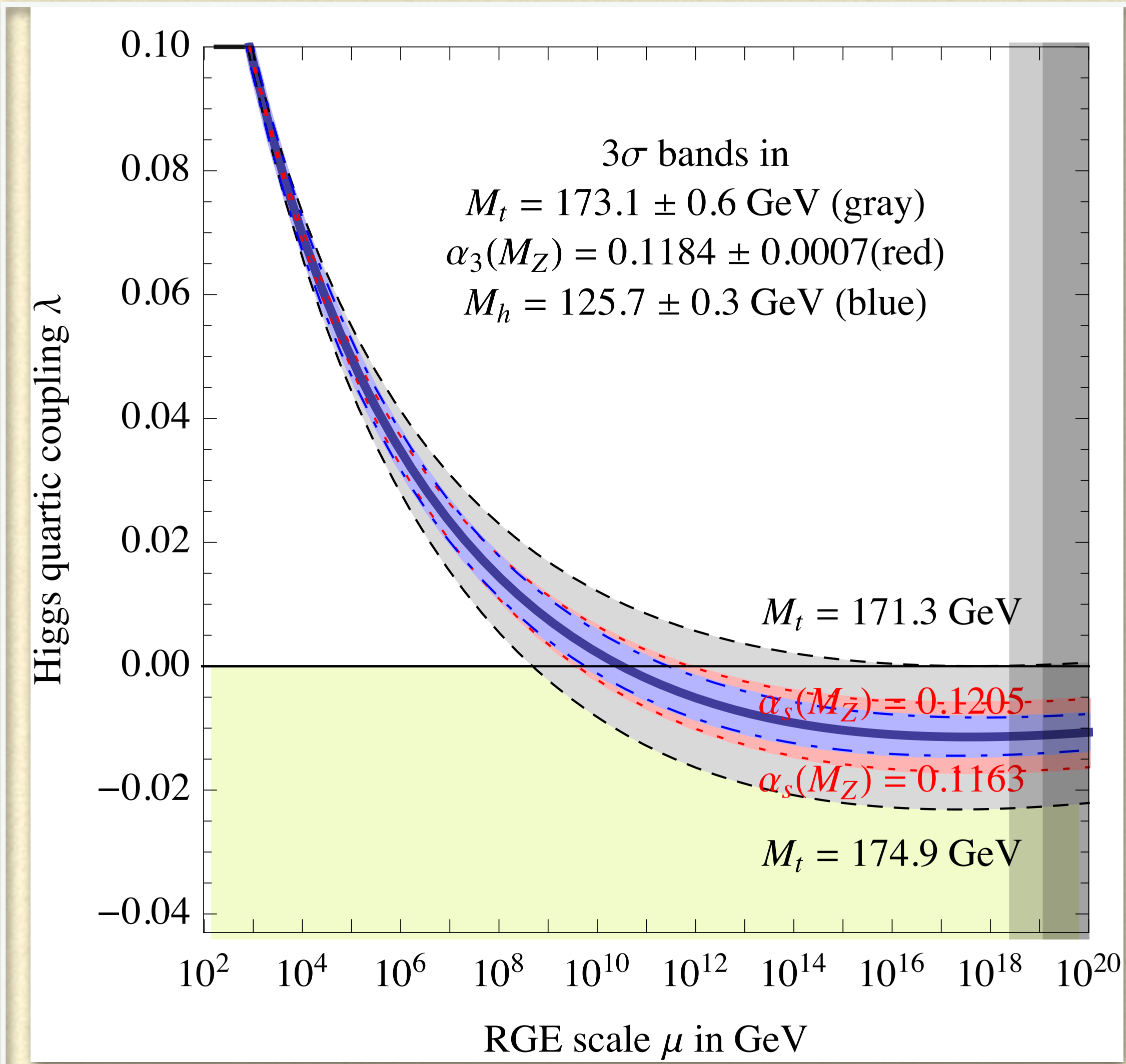

Degrassi et al., arXiv:1205.6497

Status of particle physics: energy frontier

- LEP, LHC: SM describes final states of particle collisions precisely
- SM is unstable
- No proven sign of new physics beyond SM at colliders* (only exclusion limits)

*There are some indications below discovery significance (such as lepton flavor non-universality in meson decays)

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- Universe at large scale described precisely by cosmological SM: ΛCDM ($\Omega_m = 0.3$) [Planck etc]

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- Neutrino flavours oscillate [excellent status report by Rondino]
- Existing baryon asymmetry cannot be explained by CP asymmetry in SM
- Inflation of the early, accelerated expansion of the present Universe [Planck, SNa1 etc]

Nature’s hide-and-seek

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Nature is neutral, which is closer to honest

Extension of SM
(theory built on observations, no predictions yet)

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- SM is highly efficient – let us stick to efficiency

the only exception of economical description is the relatively large number of arbitrary Yukawa couplings

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  - gauge and gravity anomaly cancellation and
  - gauge invariant Yukawa terms for neutrino mass generation

Fermions

- fermion fields:

$$\psi^f_{q,1} = \begin{pmatrix} U^f \\ D^f \end{pmatrix}_\mathrm{L} \qquad \psi^f_{q,2} = U^f_\mathrm{R}\,, \qquad \psi^f_{q,3} = D^f_\mathrm{R}$$

$$\psi^f_{l,1} = \begin{pmatrix} \nu^f \\ \ell^f \end{pmatrix}_\mathrm{L} \qquad \psi^f_{l,2} = \nu^f_\mathrm{R}\,, \qquad \psi^f_{l,3} = \ell^f_\mathrm{R}$$

where

$$\psi_{\mathrm{L/R}} \equiv \psi_{\mp} = \frac{1}{2}\left(1 \mp \gamma_5\right)\psi \equiv P_{\mathrm{L/R}}\psi$$

(ν_L can ν_R can also be Majorana neutrinos, embedded into *different* Dirac spinors)

Scalars

- Scalar for Φ complex $SU(2)_L$ doublet and χ complex singlet:

$$\mathcal{L}_{\phi,\chi} = [D_\mu^{(\phi)}\phi]^* D^{(\phi)\,\mu}\phi + [D_\mu^{(\chi)}\chi]^* D^{(\chi)\,\mu}\chi - V(\phi,\chi)$$

- with scalar potential

$$V(\phi,\chi) = V_0 - \mu_\phi^2|\phi|^2 - \mu_\chi^2|\chi|^2 + \left(|\phi|^2, |\chi|^2\right)\begin{pmatrix}\lambda_\phi & \frac{\lambda}{2} \\ \frac{\lambda}{2} & \lambda_\chi\end{pmatrix}\begin{pmatrix}|\phi|^2 \\ |\chi|^2\end{pmatrix}$$

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- After SSB, G → $SU(3)_c \times U(1)_{QED}$:

$$\phi = \frac{1}{\sqrt{2}}\,\mathrm{e}^{\mathrm{i}\boldsymbol{T}\cdot\boldsymbol{\xi}(x)/v}\begin{pmatrix}0\\ v+h'(x)\end{pmatrix} \;\&\; \chi(x) = \frac{1}{\sqrt{2}}\,\mathrm{e}^{\mathrm{i}\eta(x)/w}\left(w+s'(x)\right)$$

Fermion-scalar interactions

- Standard Yukawa terms:

$$\mathcal{L}_{\rm Y} = -\left[c_D\,(\bar{U},\,\bar{D})_{\rm L}\begin{pmatrix}\phi^{(+)}\\ \phi^{(0)}\end{pmatrix}D_{\rm R} + c_U\,(\bar{U},\,\bar{D})_{\rm L}\begin{pmatrix}\phi^{(0)\,*}\\ -\phi^{(+)\,*}\end{pmatrix}U_{\rm R} + c_\ell\,(\bar{\nu}_\ell,\,\bar{\ell})_{\rm L}\begin{pmatrix}\phi^{(+)}\\ \phi^{(0)}\end{pmatrix}\ell_{\rm R}\right] + \text{h.c.}$$

- lead to fermion masses after SSB:

$$\mathcal{L}_{\rm Y} = -\left(1+\frac{h(x)}{v}\right)\left[\bar{D}_{\rm L}\,M_D\,D_{\rm R} + \bar{U}_{\rm L}\,M_U\,U_{\rm R} + \bar{\ell}_{\rm L}\,M_\ell\,\ell_{\rm R}\right] + \text{h.c.}$$

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- Neutrino Yukawa terms $(z_\chi = -2z_{\nu_{\mathrm{R}}})$:

$$\mathcal{L}_{\mathrm{Y}}^{\nu} = -\sum_{i,j}\left((c_\nu)_{ij}\bar{L}_{i,\mathrm{L}}\cdot\tilde{\phi}\,\nu_{j,\mathrm{R}} + \frac{1}{2}(c_{\mathrm{R}})_{ij}\,\overline{\nu_{i,\mathrm{R}}^{c}}\nu_{j,\mathrm{R}}\,\chi\right) + \mathrm{h.c.}$$

After SSB neutrino mass terms appear

$$\mathcal{L}_{\rm Y}^{\nu} = -\frac{1}{2}\sum_{i,j}\left[\left(\overline{\nu_{\rm L}},\,\overline{\nu_{\rm R}^{c}}\right)_i M(h,s)_{ij}\begin{pmatrix}\nu_{\rm L}^{c}\\ \nu_{\rm R}\end{pmatrix}_j + {\rm h.c.}\right]$$

where

$$M(h,s)_{ij} = \begin{pmatrix} 0 & m_{\rm D}\left(1+\frac{h}{v}\right) \\ m_{\rm D}\left(1+\frac{h}{v}\right) & M_{\rm M}\left(1+\frac{s}{w}\right)\end{pmatrix}_{ij}$$

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but ν_{L} and ν_{R} have the same q-numbers,
can mix, leading to see-saw I

Effective light neutrino masses

If $m_i << M_j$, can integrate out the heavy neutrinos

$$\mathcal{L}^{\nu}_{\mathrm{dim}-5} = -\frac{1}{2}\sum_i m_{\mathrm{M},i}\left(1+\frac{h}{v}\right)^2\left(\overline{\nu'^{c}_{i,\mathrm{L}}}\nu'_{i,\mathrm{L}}+\mathrm{h.c.}\right)$$

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if m_i ~ O(100keV) and M_j ~ O(100GeV), then

$m_{M,i}$ ~ O(0.1eV)

Mixing in the neutral gauge sector

$$\begin{pmatrix} W_\mu^3 \\ B'_\mu \\ Z'_\mu \end{pmatrix} = \underline{M}(\sin\theta_{\mathrm{W}}, \sin\theta_{\mathrm{T}}) \begin{pmatrix} Z_\mu^0 \\ T_\mu \\ A_\mu \end{pmatrix}$$

- QED current remains unchanged:

$$\mathcal{L}_{\mathrm{QED}} = -eA_\mu J^\mu_{\mathrm{em}}\,, \quad J^\mu_{\mathrm{em}} = \sum_{f=1}^{3}\sum_{j=1}^{3} e_j \left(\overline{\psi}^f_{q,j}(x)\gamma^\mu\psi^f_{q,j}(x) + \overline{\psi}^f_{l,j}(x)\gamma^\mu\psi^f_{l,j}(x)\right)$$

Neutral current interactions

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- current with Z^0 remains unchanged:

$$J^\mu_{Z^0} = \sum_{f=1}^{3} \sum_{j=1}^{3} \frac{T_3 - \sin^2\theta_W\, e_j}{\sin\theta_W \cos\theta_W} \Big(\overline{\psi}^f_{q,j}(x)\gamma^\mu \psi^f_{q,j}(x) + \overline{\psi}^f_{l,j}(x)\gamma^\mu \psi^f_{l,j}(x) \Big)$$

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- but mixes with new current of new couplings:

$$J^\mu_{\mathrm{T}} = \sum_{f=1}^{3}\sum_{j=1}^{3}\frac{\gamma'_Z r_j + \gamma'_{ZY} y_j}{\sin\theta_{\mathrm{W}}}\Big(\overline{\psi}^f_{q,j}(x)\gamma^\mu\psi^f_{q,j}(x) + \overline{\psi}^f_{l,j}(x)\gamma^\mu\psi^f_{l,j}(x)\Big)$$

Possible consequences with 5 new parameters

(new scalar mass, scalar & vector mixing, new VeV, ~coupling)

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- The second scalar together with the established BEH field may be the source of inflation.

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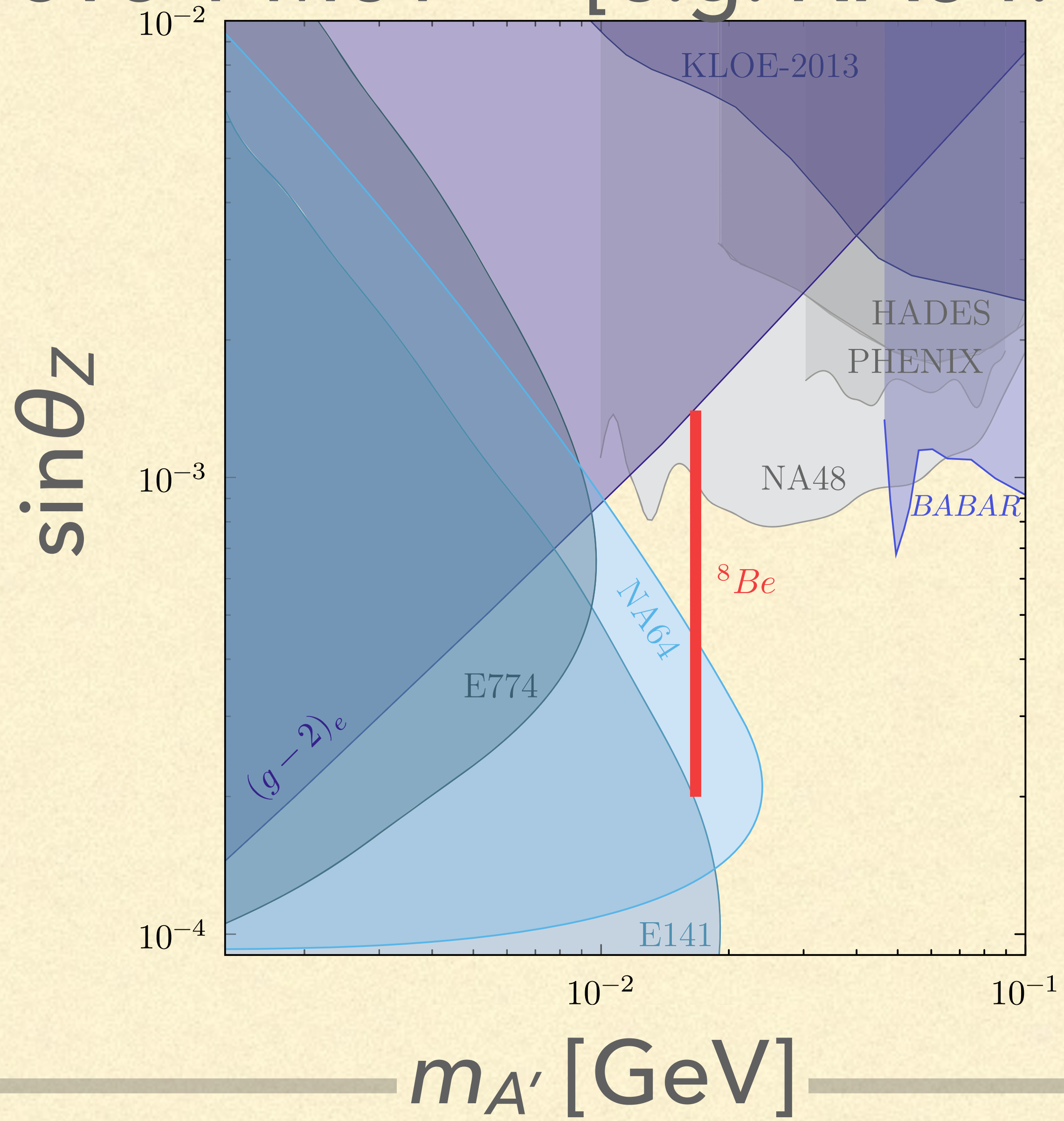
Answer is not immediate, extensive studies are needed

An immediate objection(?): such neutral gauge bosons are excluded

but these are searches for short-lived bosons of mass above 1 MeV [e.g. NA64: 1803.07748]



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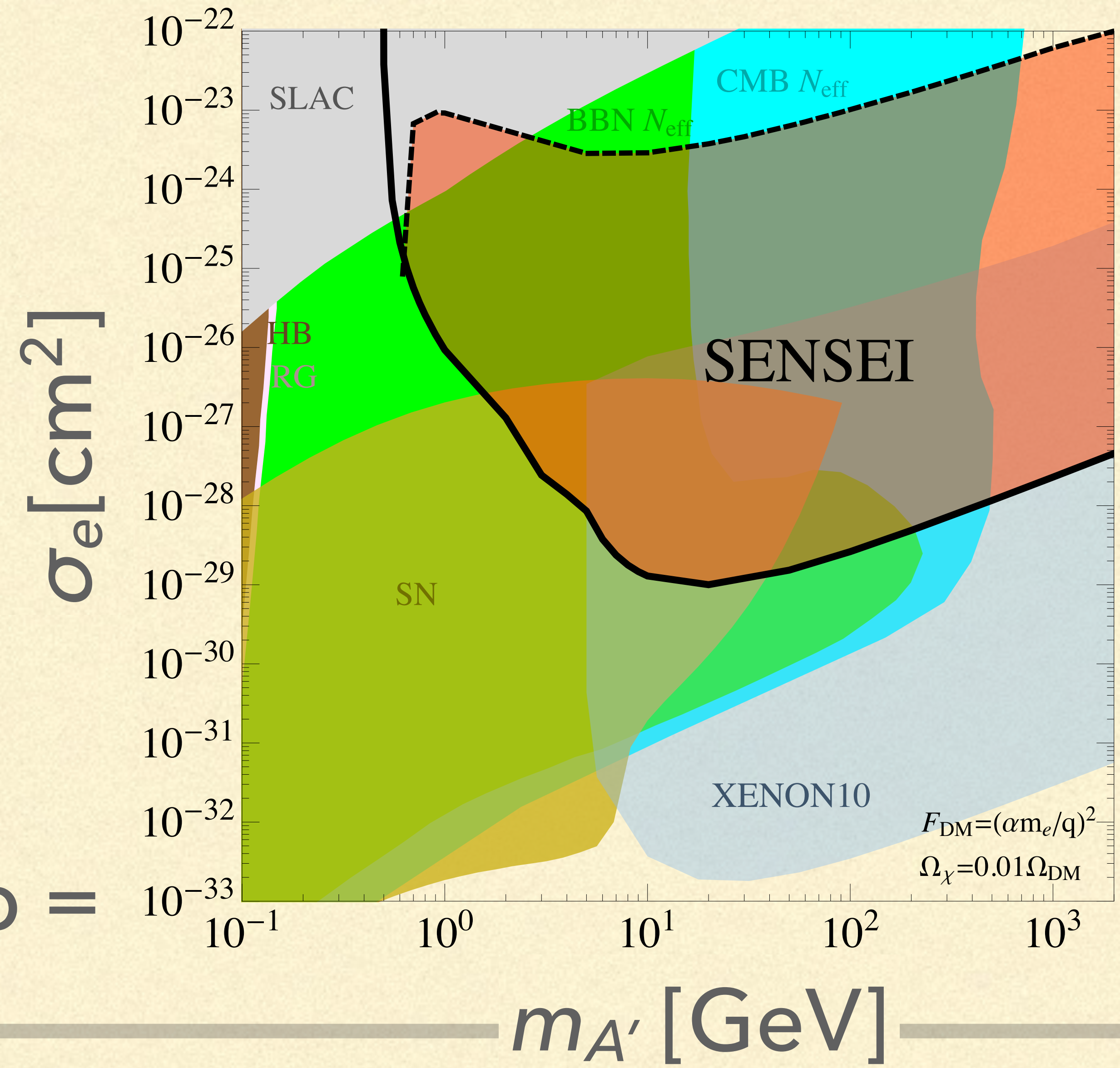
new searches will be sensitive to masses below 1 MeV
[e.g. SENSEI: 1804.00088]



1nb = 10^{-33}

An immediate example: contribution of the new gauge boson to a_μ

using the new neutral currents:

$$\Delta a_\mu = a_\mu^{(\mathrm{T+SM})} - a_\mu^{(\mathrm{SM})} = a_\mu^{(\mathrm{Z}^0)} - a_\mu^{(\mathrm{Z}^0)}(0,0) + a_\mu^{(\mathrm{T}^0)}$$

where

$$a_\mu^{(\mathrm{Z}^0)}(h_f,\theta_T) = \frac{G_\mathrm{F} m_\mu^2}{6\sqrt{2}\pi^2}\Big[2\sin\theta_\mathrm{W}(h_f\cos\theta_\mathrm{W}\sin\theta_T - \sin\theta_\mathrm{W}\cos\theta_T) \times \Big(2\sin\theta_\mathrm{W}(h_f\cos\theta_\mathrm{W}\sin\theta_T - \sin\theta_\mathrm{W}\cos\theta_T) + \cos\theta_T\Big) - \cos^2\theta_T\Big]$$

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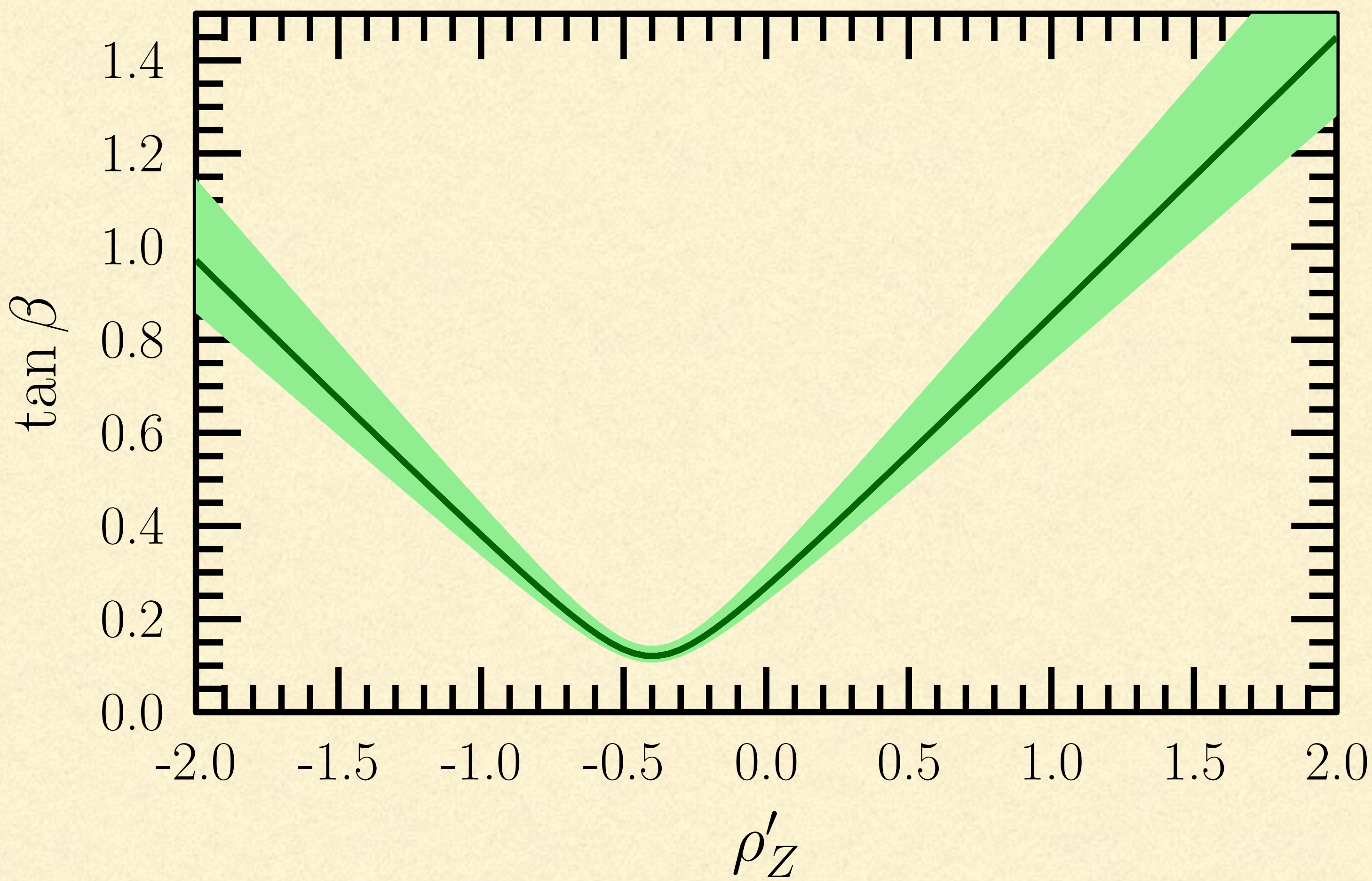
$$a_\mu^{(\mathrm{T+SM})} - a_\mu^{(\mathrm{SM})} = \frac{G_\mathrm{F} m_\mu^2}{6\sqrt{2}\pi^2}\frac{5{\rho'_Z}^2 + 4\rho'_Z + 1}{8\tan^2\beta} + \mathrm{O}(\theta_T) \qquad \rho'_Z = \frac{\gamma'_{ZY}}{\gamma'_Z}$$

experimentally: $a_\mu^{(\exp)} - a_\mu^{(\mathrm{SM})} = 268(76)\cdot 10^{-11}$



UV behavior (preliminary)

with Zoltán Péli

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- All β-functions derived at one loop (slightly differ for Dirac or Majorana neutrinos)
- Constrain scalar couplings by assuming that the new model remains stable up to M_{Pl}
- Among new couplings the flow is most sensitive to the largest neutrino Yukawa coupling (c_ν)

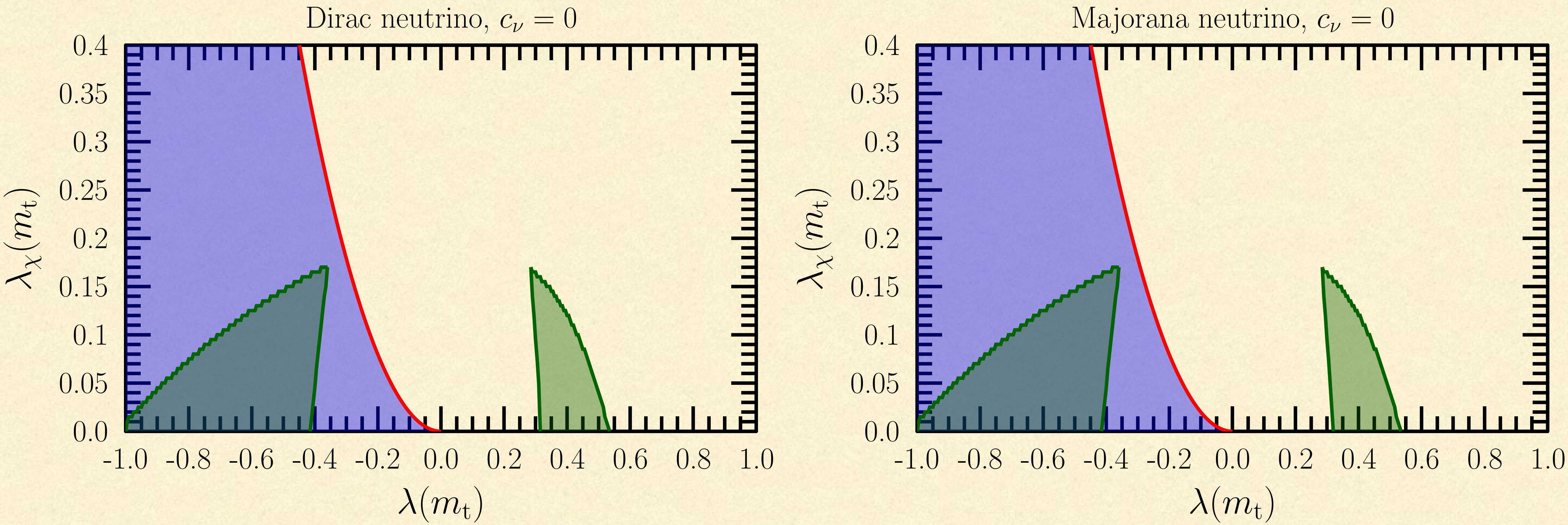
Initial values set at $m_{\rm t}$

$$g_Y(m_{\rm t}) = \sqrt{\frac{3}{5}} \times 0.4626\,, \quad g_{\rm L}(m_{\rm t}) = 0.6477\,, \quad g_3(m_{\rm t}) = 1.166\,,$$

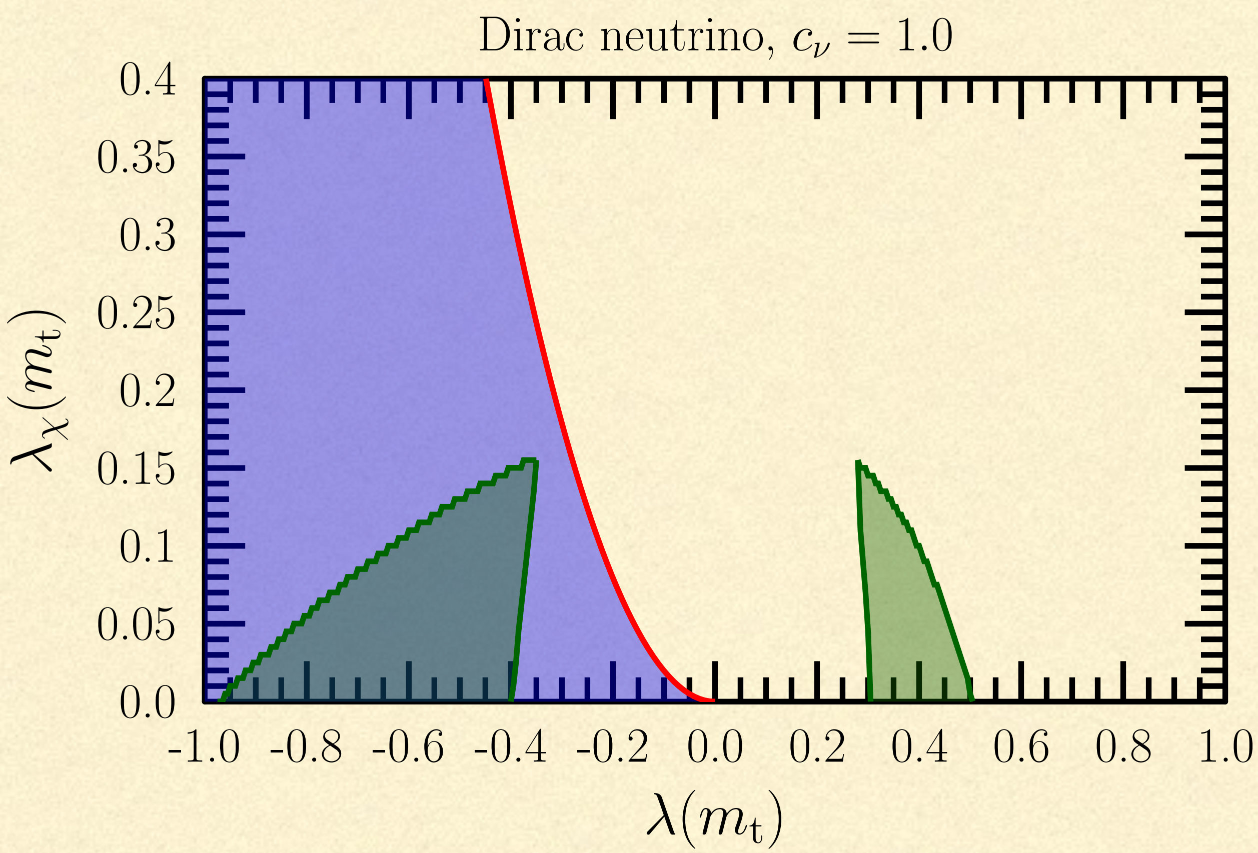
$$c_{\rm t}(m_{\rm t}) = 0.9379\,, \quad \mu_\phi(m_{\rm t}) = 131.5\,{\rm GeV}\,, \quad \lambda_\phi(m_{\rm t}) = 0.1259\,.$$

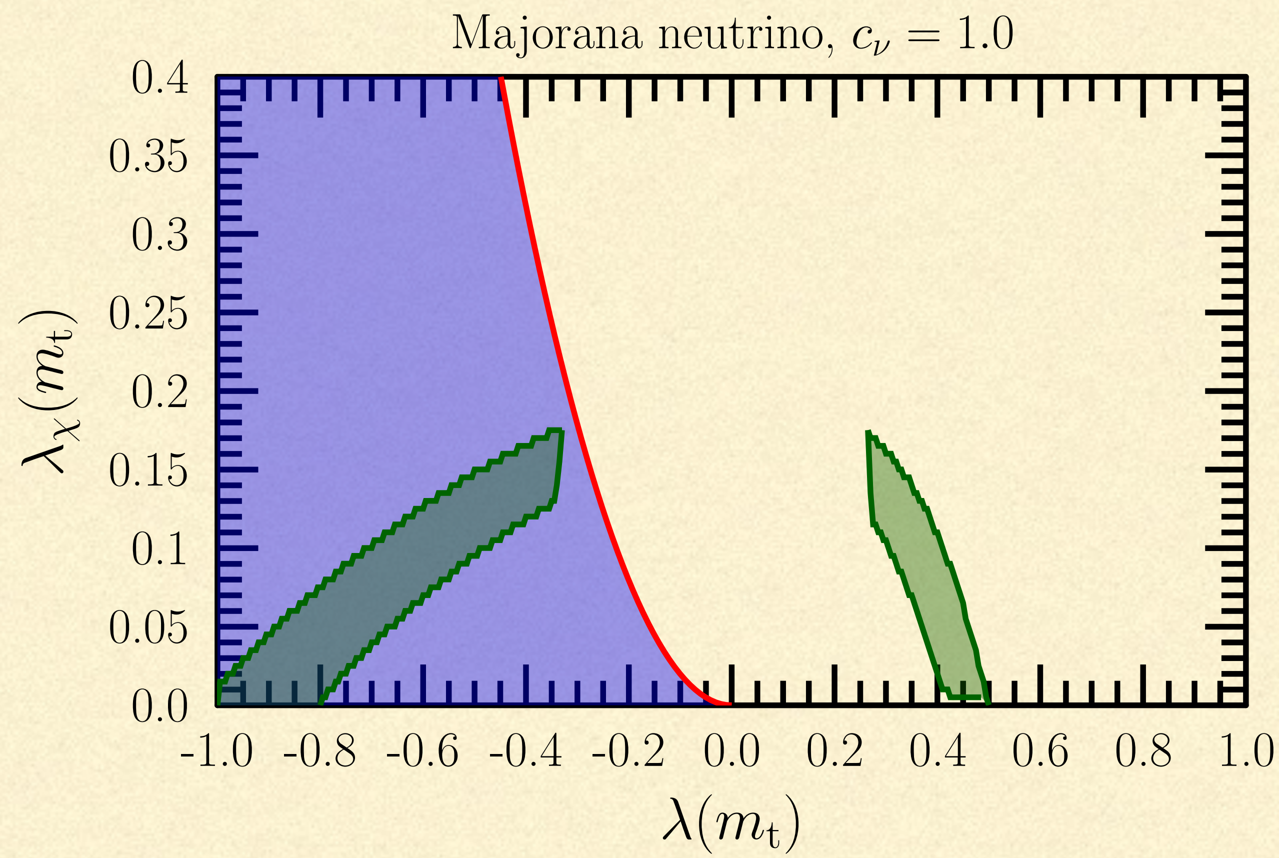
allowed regions at fixed values of the largest neutrino Yukawa coupling $c_{\rm v}$ for both Dirac and Majorana neutrinos

Scalar parameters allowed for stability



Scalar parameters allowed for stability with Majorana neutrinos





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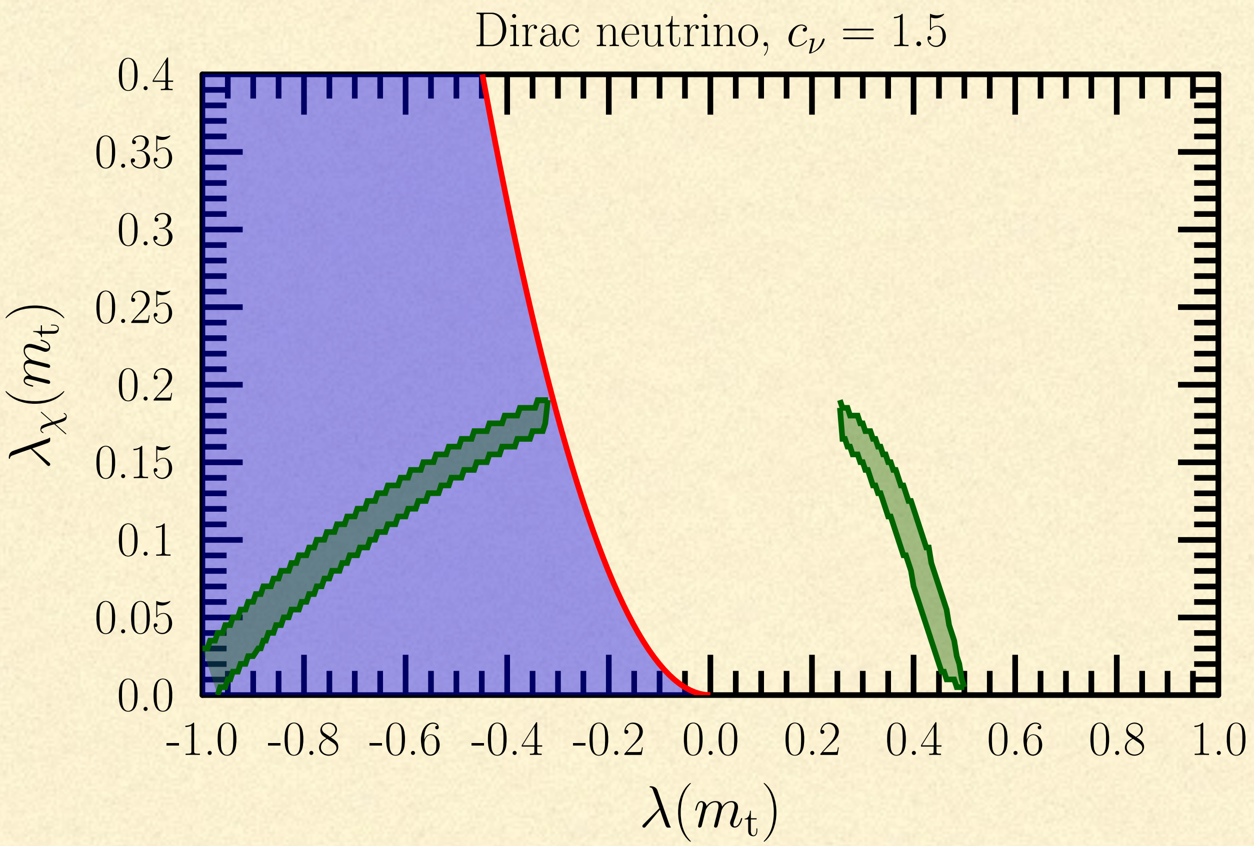

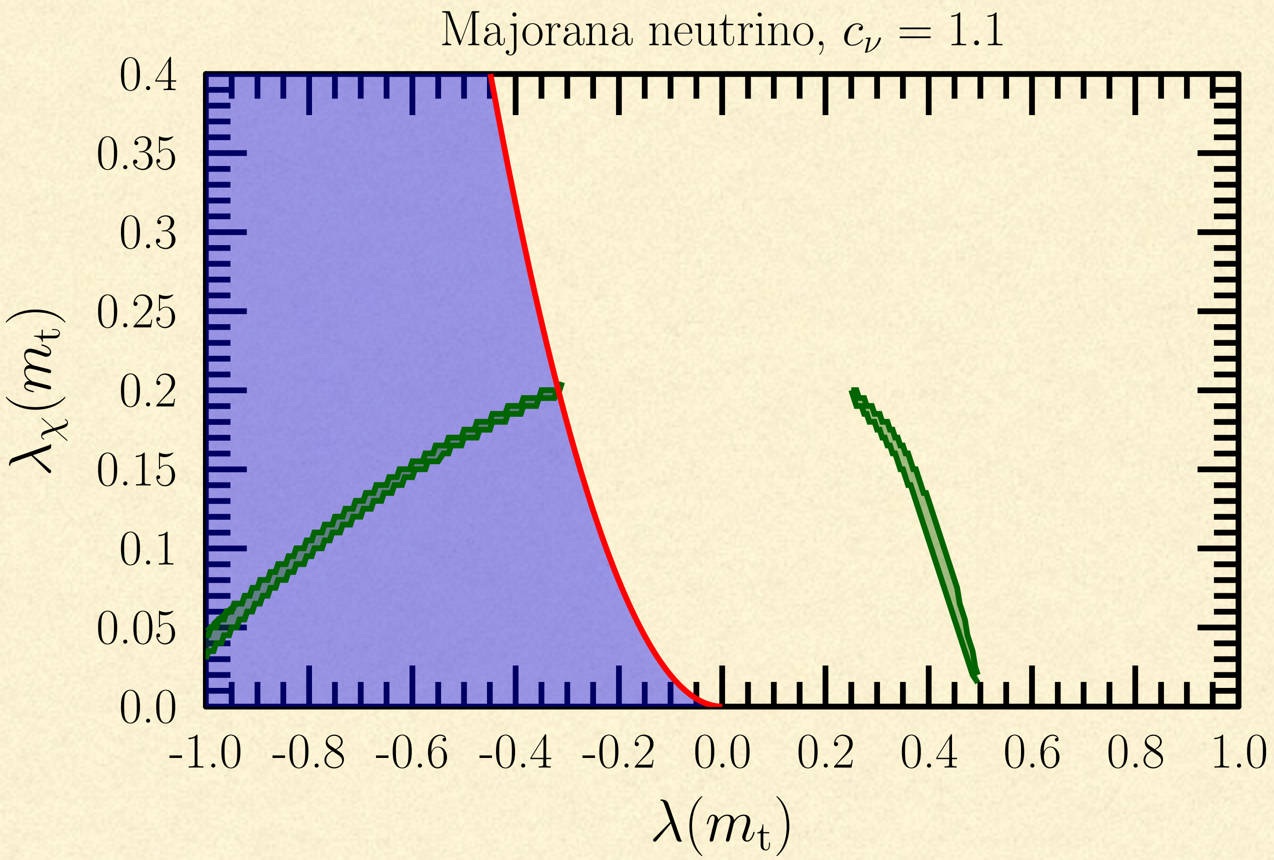

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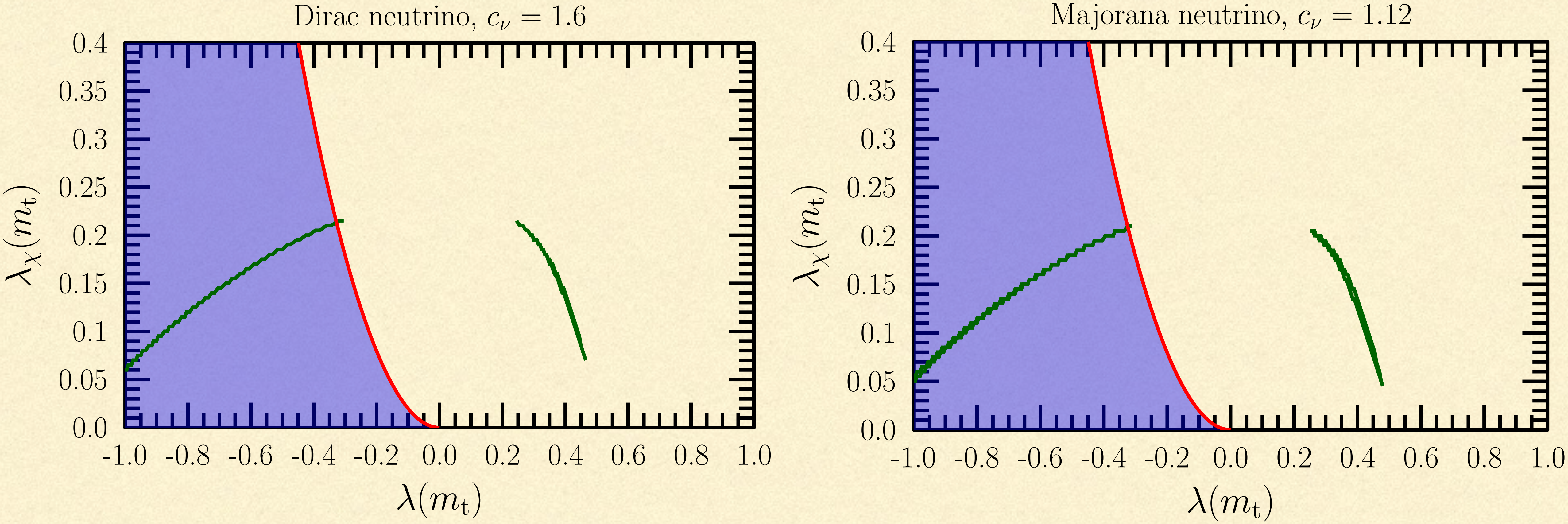

The parameter space vanishes rapidly above $c_\nu = 1$

The parameter space disappears completely for $c_t = 1$

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- $U(1)_Z$ extension has the potential of explaining all known results
- Anomaly cancellation and neutrino mass generation mechanism are used to fix the Z-charges up to reasonable assumptions
- Parameter space can be constrained from and should be confronted with existing experimental results