Neutrino physics in gauged U(1) extensions of the standard model

Sho Iwamoto[1], Timo J. Kärkkäinen[1], Zoltán Péli[2]
and Zoltán Trócsányi[1,2]

[1] ELTE Eötvös Loránd university, Hungary
[2] University of Debrecen, Hungary
16 September 2021

Matter to the Deepest 2021

arXiv:hep-ph/2104.14571 (accepted for publication in PRD),
arXiv:hep-ph/2105.13360

Problems in the Standard Model

> Why neutrinos are massive?
> What is dark matter?
> Why is the electroweak vacuum metastable?
> What is the origin of cosmic inflation?
> Why is the matter-antimatter asymmetry larger than expected?

- $>$ Why neutrinos are massive?
  $\Rightarrow$ seesaw mechanism
- $>$ What is dark matter?
  $\Rightarrow$ keV scale sterile neutrinos
- $>$ Why is the electroweak vacuum metastable?
  $\Rightarrow$ it is stabilized by an extra scalar field
- $>$ What is the origin of cosmic inflation?
  $\Rightarrow$ two-field curvaton inflation
- $>$ Why is the matter-antimatter asymmetry larger than expected?
  $\Rightarrow$ resonant leptogenesis mechanism

Super-weak model answers these

Main paper: Trócsányi, 1812.11189

> Why neutrinos are massive?
  ⇒ seesaw mechanism
  Iwamoto, Kärkkäinen, Péli, Trócsányi, 2104.14571,
  Kärkkäinen, Trócsányi, 2105.13360 ⇒ This talk

> What is dark matter?
  ⇒ keV/MeV scale sterile neutrinos
  Iwamoto, Seller, Trócsányi, 2104.11248 ⇒ Károly Seller's talk

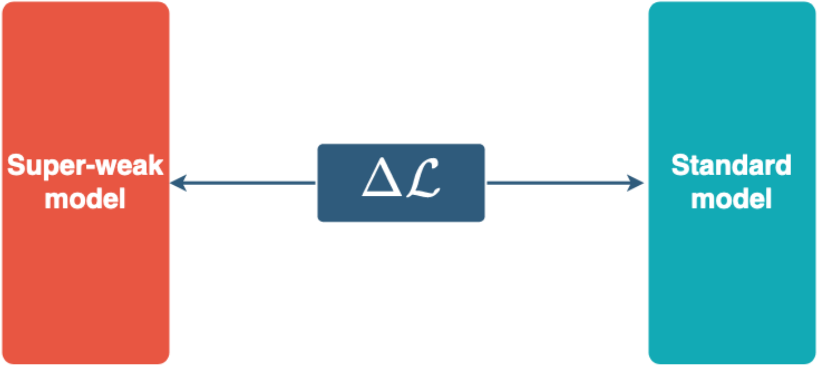
> Why is the electroweak vacuum metastable?
  ⇒ it is stabilized by an extra scalar field
  Péli, Trócsányi, 1902.02791

> What is the origin of cosmic inflation?
  ⇒ two-field curvaton inflation
  Nándori, Péli, Trócsányi, 1911.07082

> Why is the matter-antimatter asymmetry larger than expected?
  ⇒ resonant leptogenesis mechanism

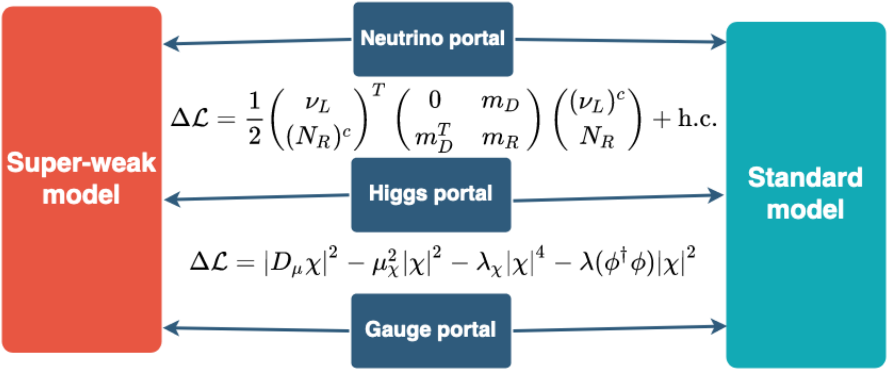
How to access physics beyond the SM?

Existence of dark matter, baryonic asymmetry of the universe, metastability of vacuum *et cetera* suggests that SM is incomplete.



New interactions should exist! Possible new particles must be either very heavy or must interact super-weakly, otherwise we would have seen notable deviations from SM predictions.

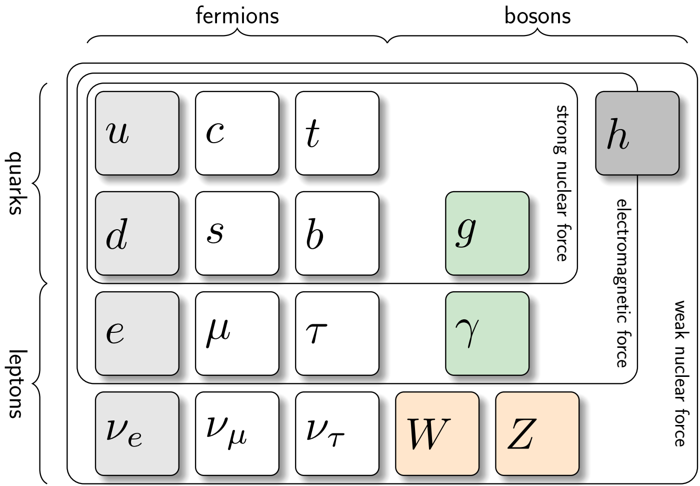
Pick your favourite?

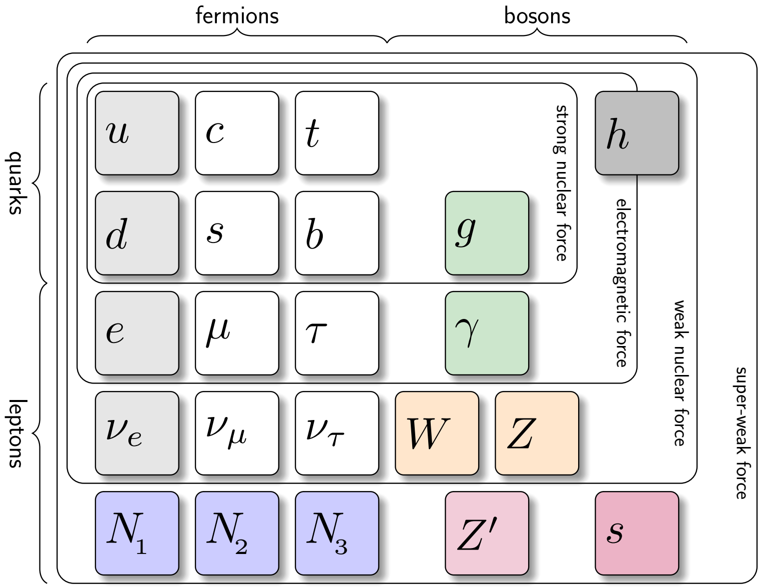


$$\Delta\mathcal{L} = \frac{1}{2}\begin{pmatrix}\nu_L \\ (N_R)^c\end{pmatrix}^T \begin{pmatrix}0 & m_D \\ m_D^T & m_R\end{pmatrix}\begin{pmatrix}(\nu_L)^c \\ N_R\end{pmatrix} + \text{h.c.}$$

$$\Delta\mathcal{L} = |D_\mu\chi|^2 - \mu_\chi^2|\chi|^2 - \lambda_\chi|\chi|^4 - \lambda(\phi^\dagger\phi)|\chi|^2$$

$$\Delta\mathcal{L} = -\frac{1}{4}Z^{\mu\nu}Z_{\mu\nu} - \frac{\varepsilon}{2}B_{\mu\nu}Z^{\mu\nu}$$


fermions
bosons
quarks
leptons
u
c
t
h
d
s
b
g
e
μ
τ
γ
ν_e
ν_μ
ν_τ
W
Z
strong nuclear force
electromagnetic force
weak nuclear force


fermions
bosons
quarks
leptons
u
c
t
h
d
s
b
g
e
μ
τ
γ
ν_e
ν_μ
ν_τ
W
Z
N_1
N_2
N_3
Z'
s
strong nuclear force
electromagnetic force
weak nuclear force
super-weak force

We choose all three simple portal extensions

$$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \otimes \mathrm{U}(1)_Z$$

Field	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_Z$
Q_L	**2**	$\frac{1}{6}$	$\frac{1}{6}$
u_R	**1**	$\frac{2}{3}$	$\frac{7}{6}$
d_R	**1**	$-\frac{1}{3}$	$-\frac{5}{6}$
L_L	**2**	$-\frac{1}{2}$	$-\frac{1}{2}$
ℓ_R	**1**	-1	$-\frac{3}{2}$
ϕ	**2**	$\frac{1}{2}$	1
N_R	**1**	0	$\frac{1}{2}$
χ	**1**	0	-1

SM

$+$

three sterile right-handed Majorana neutrinos

$+$

complex scalar singlet, which breaks the $\mathrm{U}(1)_Z$ symmetry and produces a massive gauge boson, Z'.

Chosen mass scales for the new particles

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_Z$$

$\Lambda_{\mathbf{EW}}$	New scalar s.
$\mathcal{O}(1)$ **GeV**	Neutrinos N_2 and N_3.
$\mathcal{O}(10)$ **MeV**	Z' and N_1.
$\mathcal{O}(10)$ **keV**	N_1.

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_Z$$

$\Lambda_{\mathbf{EW}}$	New scalar s.
$\mathcal{O}(1)$ **GeV**	Neutrinos N_2 and N_3.
$\mathcal{O}(10)$ **MeV**	Z' and N_1.
$\mathcal{O}(10)$ **keV**	N_1.

$$\mathcal{L}_{\text{gauge}} = \underbrace{-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}}_{U(1)_Y} \underbrace{-\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu}}_{U(1)_Z} - \underbrace{\frac{\varepsilon}{2}B_{\mu\nu}Z^{\mu\nu}}_{\text{kinetic mixing}} - \frac{1}{4}\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu} - \ldots$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{\varepsilon}{2}B_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu} - \dots$$

The model exhibits kinetic mixing between the U(1) gauge fields:

$$\Delta\mathcal{L} = -\frac{\varepsilon}{2}B_{\mu\nu}Z^{\mu\nu},$$
$$D'^{\mu} = \partial^{\mu} + ig_L\boldsymbol{\tau}\cdot\mathbf{W}^{\mu} + i(yg_yB_{\mu} + zg_zB'_{\mu})$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{\varepsilon}{2}B_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu} - \dots$$

The model exhibits kinetic mixing between the U(1) gauge fields:

$$\Delta\mathcal{L} = -\frac{\varepsilon}{2}B_{\mu\nu}Z^{\mu\nu},$$
$$D'^{\mu} = \partial^{\mu} + ig_L\boldsymbol{\tau}\cdot\mathbf{W}^{\mu} + i(yg_yB_{\mu} + zg_zB'_{\mu})$$

We can choose a basis where the mixing is absent, corresponding to covariant derivative

$$D^{\mu} = \partial^{\mu} + ig_L\boldsymbol{\tau}\cdot\mathbf{W}^{\mu} + i\left(yg_y \quad (z - y\eta)g'_z\right)\times(\cdots)$$
$$\eta = \frac{\varepsilon g_y}{g_z}, \quad g'_z = \frac{g_z}{\sqrt{1-\varepsilon^2}}$$

The neutral gauge bosons Z and Z' mix weakly

$$\begin{pmatrix} \hat{B}^{\mu} \\ W^{3\,\mu} \\ \hat{B}'^{\mu} \end{pmatrix} = \mathbf{R}(\theta_W, \theta_Z) \begin{pmatrix} A^{\mu} \\ Z^{\mu} \\ Z'^{\mu} \end{pmatrix},$$

where the $Z - Z'$ mixing angle is

$$\theta_Z = \theta_Z \left(g_y, g'_z, \frac{\langle \chi \rangle}{\langle h \rangle} \right) \ll 1,$$

suppressed due to small couplings.

$$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \otimes \mathrm{U}(1)_Z$$

$\Lambda_{\mathbf{EW}}$	New scalar s.
$\mathcal{O}(1)$ **GeV**	Neutrinos N_2 and N_3.
$\mathcal{O}(10)$ **MeV**	Z' and N_1.
$\mathcal{O}(10)$ **keV**	N_1.

$$\mathcal{L}_{\text{scalar}} = |D_\mu \phi|^2 + |D_\mu \chi|^2 - \mu_\phi^2 |\phi|^2 - \mu_\chi^2 |\chi|^2 - \lambda_\phi |\phi|^4 - \lambda_\chi |\chi|^4 - \lambda |\phi|^2 |\chi|^2,$$

Lagrangian:

$$\mathcal{L}_{\mathrm{scalar}} = |D_\mu\phi|^2 + |D_\mu\chi|^2 - \mu_\phi^2|\phi|^2 - \mu_\chi^2|\chi|^2 - \lambda_\phi|\phi|^4 - \lambda_\chi|\chi|^4 - \lambda|\phi|^2|\chi|^2,$$

Vacuum expectation values:

$$\langle\phi\rangle \equiv \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \quad \langle\chi\rangle \equiv \frac{w}{\sqrt{2}},$$

Lagrangian:

$$\mathcal{L}_{\text{scalar}} = |D_\mu\phi|^2+|D_\mu\chi|^2-\mu_\phi^2|\phi|^2-\mu_\chi^2|\chi|^2-\lambda_\phi|\phi|^4-\lambda_\chi|\chi|^4-\lambda|\phi|^2|\chi|^2,$$

Vacuum expectation values:

$$\langle\phi\rangle \equiv \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \quad \langle\chi\rangle \equiv \frac{w}{\sqrt{2}},$$

Eigenvalues of the scalar mass matrix are given by

$$m_{s,h} = \lambda_\phi v^2 + \lambda_\chi w^2 \pm \sqrt{(\lambda_\phi v^2 - \lambda_\chi w^2)^2 + \lambda^2 v^2 w^2}$$

RGE analysis and vacuum stability constrain $m_s \in [144, 598]$ GeV.

After spontaneous symmetry breaking, in R_ξ gauge

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} -i\sqrt{2}\sigma^+ \\ v + h' + i\sigma_\phi \end{pmatrix}, \quad \chi = \frac{1}{\sqrt{2}}(w + s' + i\sigma_\chi)$$

Mass eigenstates are h, s, σ_h and σ_s:

$$\begin{pmatrix} h \\ s \end{pmatrix} = \mathbf{Z}_S \begin{pmatrix} h' \\ s' \end{pmatrix}, \quad \begin{pmatrix} \sigma_Z \\ \sigma_{Z'} \end{pmatrix} = \mathbf{Z}_G \begin{pmatrix} \sigma_\phi \\ \sigma_\chi \end{pmatrix}$$

Goldstone mixing between σ_Z and $\sigma_{Z'}$ is given by a particularly simple form,

$$\boxed{\tan\theta_G = \frac{M_{Z'}}{M_Z}\tan\theta_Z},$$

double-suppressed by $Z - Z'$ mass ratio and mixing.

$$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \otimes \mathrm{U}(1)_Z$$

$\Lambda_{\mathbf{EW}}$	New scalar s.
$\mathcal{O}(1)$ **GeV**	Neutrinos N_2 and N_3.
$\mathcal{O}(10)$ **MeV**	Z' and N_1.
$\mathcal{O}(10)$ **keV**	N_1.

$$-\mathcal{L}_Y^{\nu} = \underbrace{\frac{1}{2}\overline{\nu_R}\mathbf{Y}_N(\nu_R)^c\chi}_{\Rightarrow \text{ Majorana mass matrix}} + \underbrace{\overline{\nu_R}\mathbf{Y}_\nu\varepsilon_{\alpha\beta}L_{L\alpha}\phi_\beta}_{\Rightarrow \text{ Dirac mass matrix}} + \text{h.c.}$$

Neutrino sector - seesaw mechanism

Yukawa terms:

$$-\mathcal{L}_Y^\nu = \frac{1}{2}\overline{\nu_R}\mathbf{Y}_N(\nu_R)^c\chi + \overline{\nu_R}\mathbf{Y}_\nu\varepsilon_{\alpha\beta}L_{L\alpha}\phi_\beta + \text{h.c.}$$

$$-\mathcal{L}_m^\nu = \frac{1}{2}\begin{pmatrix}\nu_L \\ (\nu_R)^c\end{pmatrix}^T C\begin{pmatrix}\mathbf{0}_3 & \mathbf{M}_D^T \\ \mathbf{M}_D & \mathbf{M}_N\end{pmatrix}\begin{pmatrix}\nu_L \\ (\nu_R)^c\end{pmatrix}$$

$$\nu_L = \begin{pmatrix}\nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L}\end{pmatrix}, \quad \nu_R = \begin{pmatrix}N_{R1} \\ N_{R2} \\ N_{R3}\end{pmatrix}, \quad \mathbf{M}_D = \frac{v}{\sqrt{2}}\mathbf{Y}_\nu, \quad \mathbf{M}_N = \frac{w}{\sqrt{2}}\mathbf{Y}_N$$

$$\mathbf{M}_L = -\mathbf{M}_D\mathbf{M}_N^{-1}\mathbf{M}_D^\dagger + (\text{subleading terms}),$$

$$-\mathcal{L}_m^\nu = \frac{1}{2}\begin{pmatrix}\nu_L \\ (\nu_R)^c\end{pmatrix}^T C \begin{pmatrix}\mathbf{0}_3 & \mathbf{M}_D^T \\ \mathbf{M}_D & \mathbf{M}_N\end{pmatrix} \begin{pmatrix}\nu_L \\ (\nu_R)^c\end{pmatrix}$$

$$\mathbf{U}^T \begin{pmatrix}\mathbf{0}_3 & \mathbf{M}_D^T \\ \mathbf{M}_D & \mathbf{M}_N\end{pmatrix} \mathbf{U} = \mathrm{diag}(m_1, m_2, m_3, m_4, m_5, m_6)$$

$$\mathbf{U} = \begin{pmatrix}\mathbf{U}_L \\ \mathbf{U}_R^*\end{pmatrix}$$

$\mathbf{U}$ is unitary, but 3×6-matrices $\mathbf{U}_L$ and $\mathbf{U}_R$ are semiunitary:

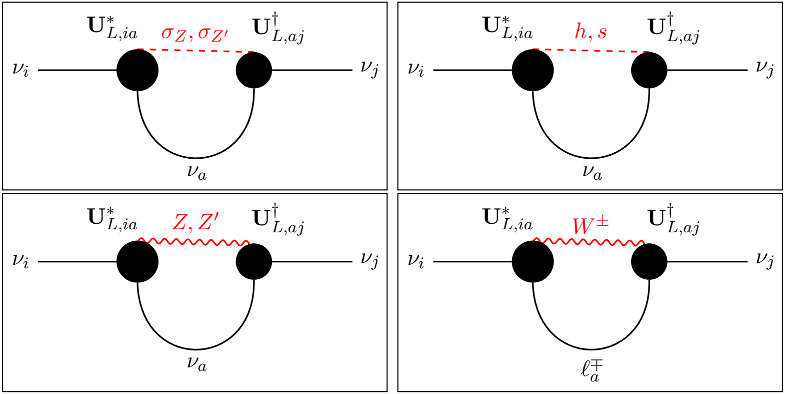
$$\mathbf{U}_L\mathbf{U}_L^\dagger = \mathbf{1}_3, \quad \mathbf{U}_R\mathbf{U}_R^\dagger = \mathbf{1}_3$$

$$\mathbf{U}_L^\dagger\mathbf{U}_L \neq \mathbf{1}_6, \quad \mathbf{U}_R^\dagger\mathbf{U}_R \neq \mathbf{1}_6$$

$$\mathbf{U}^\dagger\mathbf{U} = \mathbf{U}_L^\dagger\mathbf{U}_L + \mathbf{U}_R^T\mathbf{U}_R^* = \mathbf{1}_6$$

Neutrino self-energy is a 6×6 matrix,

$$i\mathbf{\Sigma}(p) = \mathbf{A}_L(p^2)\not{p}P_L + \mathbf{A}_R(p^2)\not{p}P_R + \mathbf{B}_L(p^2)P_L + \mathbf{B}_R(p^2)P_R$$



$$\mathbf{\Sigma} \equiv \mathbf{U}_L^T(\mathbf{\Sigma}^Z + \mathbf{\Sigma}^{Z'} + \mathbf{\Sigma}^h + \mathbf{\Sigma}^s + \mathbf{\Sigma}^{\sigma_h} + \mathbf{\Sigma}^{\sigma_s} + \mathbf{\Sigma}^W)\mathbf{U}_L$$

$$\delta\mathbf{M}_L = \mathbf{U}_L^*\mathbf{B}_L(0)\mathbf{U}_L^\dagger$$

We generated neutrino interaction vertices via SARAH

Model file available online at arXiv and on PRD!

```
Model`Name = "U1XSM";
Model`NameLaTeX ="U(1)X extended Standard Model";
Model`Authors = "Sho Iwamoto, T. J. K\[ADoubleDot]rkk\[ADoubleDot]inen";
Model`Date = "2021-03-02";


(*--------------------------------------*)
(*   Particle Content*)
(*--------------------------------------*)

Gauge[[1]] = {B,   U[1], hypercharge, gYY,  False};
Gauge[[2]] = {WB, SU[2], left,        g2,   True};
Gauge[[3]] = {G,  SU[3], color,       g3,   False};
Gauge[[4]] = {Bp,  U[1], superweak,   gXX,  False};
```

`Mathematica` extension `SARAH` generates Feynman rules, beta functions, mass matrices *et cetera*.

We generated neutrino interaction vertices via SARAH

$$\boldsymbol{\Gamma}^{\mu}_{V\nu_i\nu_j} = -ie\gamma^{\mu}\Big(\boldsymbol{\Gamma}^{L}_{V\nu\nu}P_L + \boldsymbol{\Gamma}^{R}_{V\nu\nu}P_R\Big)_{ij}$$

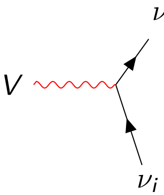
$$\boldsymbol{\Gamma}^{L}_{V\nu\nu} = C^{L}_{V\nu\nu}\mathbf{U}_L^{\dagger}\mathbf{U}_L - C^{R}_{V\nu\nu}\mathbf{U}_R^{T}\mathbf{U}_R^{*}$$

$$\boldsymbol{\Gamma}^{R}_{V\nu\nu} = -C^{L}_{V\nu\nu}\mathbf{U}_L^{T}\mathbf{U}_L^{*} + C^{R}_{V\nu\nu}\mathbf{U}_R^{\dagger}\mathbf{U}_R = -\Big(\boldsymbol{\Gamma}^{L}_{V\nu\nu}\Big)^{*}$$

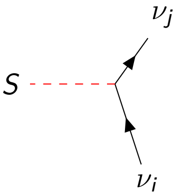
$$\boldsymbol{\Gamma}_{S_k/\sigma_k\,\nu_i\nu_j} = \Big(\boldsymbol{\Gamma}^{L}_{S_k/\sigma_k\,\nu\nu}P_L + \boldsymbol{\Gamma}^{R}_{S_k/\sigma_k\,\nu\nu}P_R\Big)_{ij}, \boldsymbol{\Gamma}^{R} = -(\boldsymbol{\Gamma}^{L})^{*}$$

$$\boldsymbol{\Gamma}^{L}_{S_k\nu\nu} = -i\left[\Big(\mathbf{M}\mathbf{U}_L^{\dagger}\mathbf{U}_L + \mathbf{U}_L^{T}\mathbf{U}_L^{*}\mathbf{M}\Big)\frac{(\mathbf{Z}_S)_{k1}}{v} + \mathbf{U}_R^{\dagger}\mathbf{M}_N\mathbf{U}_R^{*}\frac{(\mathbf{Z}_S)_{k2}}{w}\right]$$

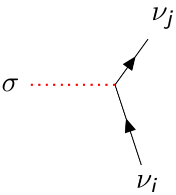
$$\boldsymbol{\Gamma}^{L}_{\sigma_k\nu\nu} = -\left[\Big(\mathbf{M}\mathbf{U}_L^{\dagger}\mathbf{U}_L + \mathbf{U}_L^{T}\mathbf{U}_L^{*}\mathbf{M}\Big)\frac{(\mathbf{Z}_G)_{k1}}{v} + \mathbf{U}_R^{\dagger}\mathbf{M}_N\mathbf{U}_R^{*}\frac{(\mathbf{Z}_G)_{k2}}{w}\right]$$



$$= -ie\gamma^{\mu}\left(\boldsymbol{\Gamma}^{L}_{V\nu\nu}P_L + \boldsymbol{\Gamma}^{R}_{V\nu\nu}P_R\right)_{ij}, \quad V = Z, Z'$$

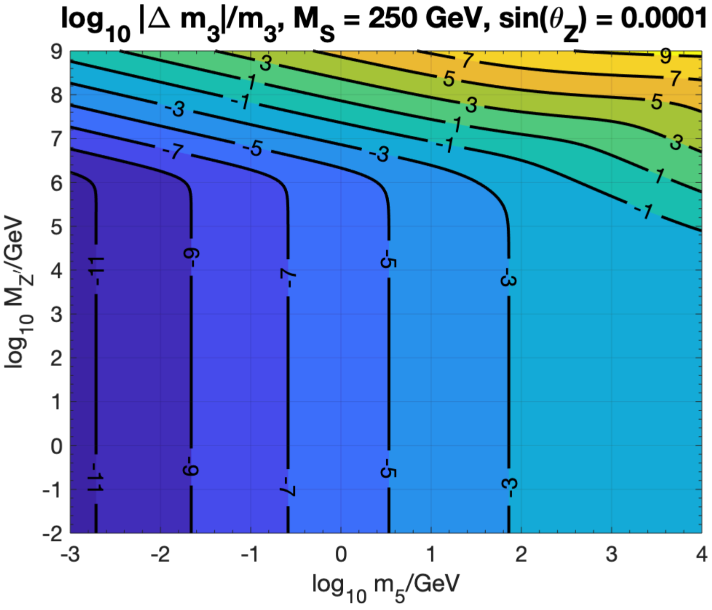


$$= \left(\boldsymbol{\Gamma}^{L}_{S\,\nu\nu}P_L + \boldsymbol{\Gamma}^{R}_{S\,\nu\nu}P_R\right)_{ij}, \quad S = h, s$$

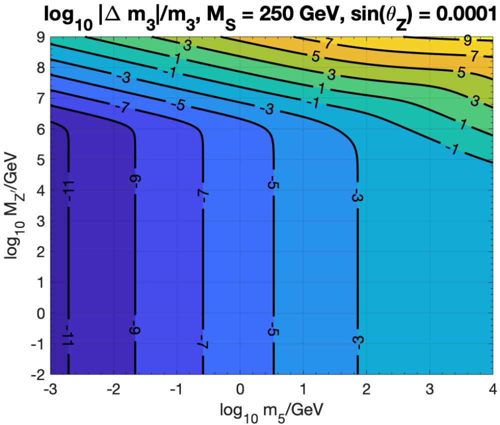


$$= \left(\boldsymbol{\Gamma}^{L}_{\sigma\,\nu\nu}P_L + \boldsymbol{\Gamma}^{R}_{\sigma\,\nu\nu}P_R\right)_{ij}, \quad \sigma = \sigma_Z, \sigma_{Z'}$$

Final result for one-loop correction



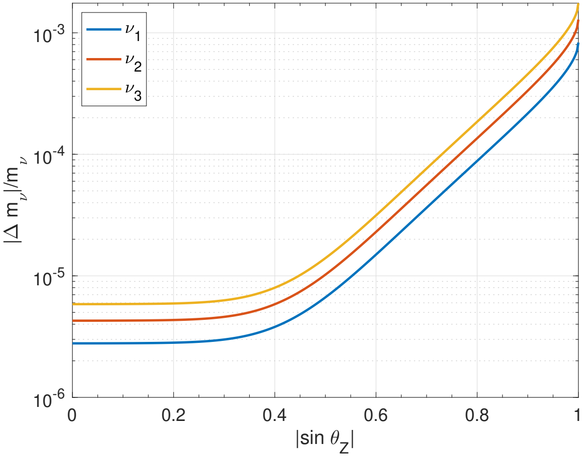
Final result for one-loop correction



$$\delta \mathbf{M}_L = \frac{1}{16\pi^2}\sum_{k=1,2}\left[3(\mathbf{Z}_G)^2_{k1}\frac{M^2_{V_k}}{v^2}\mathbf{F}(M^2_{V_k}) + (\mathbf{Z}_S)^2_{k1}\frac{M^2_{S_k}}{v^2}\mathbf{F}(M^2_{S_k})\right]$$

$$\mathbf{F}_{ij}(M^2) = \sum_{a=1}^{6}(\mathbf{U}_L^*)_{ia}(\mathbf{U}_L^\dagger)_{aj}\frac{m(\nu_a)^3}{M^2}\frac{\ln\frac{m(\nu_a)^2}{M^2}}{\frac{m(\nu_a)^2}{M^2}-1}$$

Relative correction to m_ν, with $M_{Z'} = 50$ MeV



We use the Casas-Ibarra parameterization, which allows us to input neutrino masses and PMNS matrix consistently

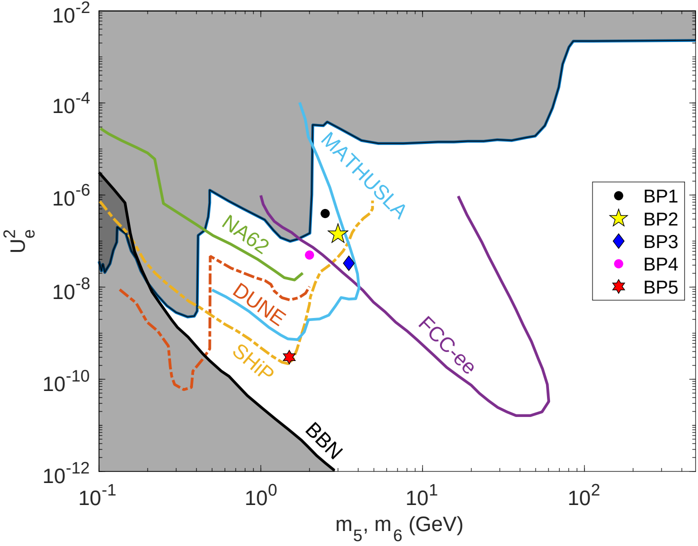
$$Y_\nu = \frac{\sqrt{2}}{v} U^*_{\mathrm{PMNS}} \sqrt{m_\nu^{\mathrm{diag}}} (-iR^T) \sqrt{m_R}, \quad R \in O(3)$$

$$U_{\nu \leftrightarrow N} = U_{\mathrm{PMNS}} \sqrt{m_\nu^{\mathrm{diag}}} iR^T \sqrt{m_R^{-1}}$$

The standard case $R = \mathbf{1}_3$ produces the expected active-sterile mixing, $|U^{ij}_{\nu \to N}| \approx \sqrt{m_\nu / m_R}$.

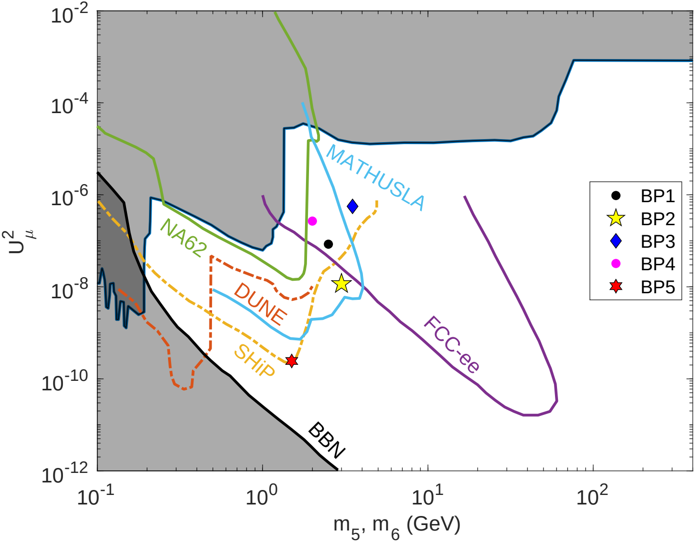
However since R is a general orthogonal matrix, benchmarks corresponding to large mixing can be generated by parameterizing R as Euler rotation matrix and scanning over the possible values.

Experimental constraints for GeV-scale sterile neutrinos



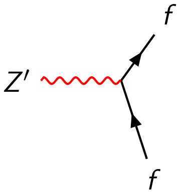
$$U_e^2 = \sum_{i=4}^{6} |U_{ei}|^2$$

Experimental constraints for GeV-scale sterile neutrinos



$$U_\mu^2 = \sum_{i=4}^{6} |U_{\mu i}|^2$$

Z' interactions



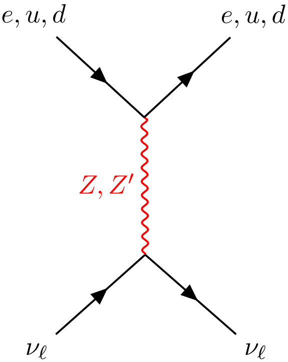
$$= -ie\gamma^{\mu}(C^{R}_{Z'ff}P_R + C^{L}_{Z'ff}P_L)$$

The couplings have the form

$$eC^{L,R}_{Z'ff} = (Q_1 g'_y + Q_2 g'_z)\cos\theta_Z + (Q_3 + Q_4 \sin^2\theta_W)g_L \frac{\sin\theta_Z}{\cos\theta_W}$$

where $Q_1, Q_2, Q_3, Q_4 \in \mathbb{Q}$ are different for different fermions and chiralities.

Nonstandard interactions



We integrate out the Z' boson to obtain effective nonrenormalizable dimension-6 operator.

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\varepsilon^{ff}_{\ell\ell'}(\overline{\nu_\ell}\gamma^\mu P_L\nu_\ell)(\bar{f}\gamma_\mu P_L f)$$

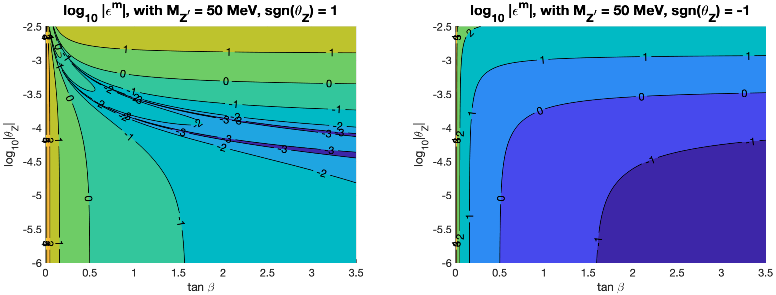
$$\varepsilon^{m,X}_{\ell\ell} = \frac{v^2}{2M^2_{Z'}}eC^L_{Z'\nu\nu}eC^X_{Z'ff}$$

$$\varepsilon^m_{\ell\ell} = \underbrace{\varepsilon^e_{\ell\ell} + 2\varepsilon^u_{\ell\ell} + \varepsilon^d_{\ell\ell}}_{=0} + \frac{N_n}{N_e}(\varepsilon^u_{\ell\ell} + 2\varepsilon^d_{\ell\ell})$$

Sum over the fermions $f = e, u, d$ and chiralities $X = L, R$.

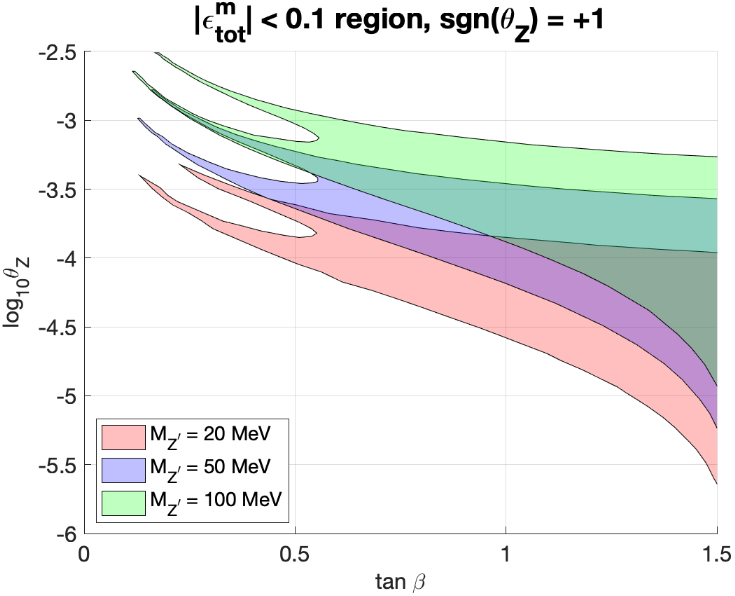
$$\varepsilon^m_{\ell\ell} = -\frac{v^2}{8M^2_{Z'}}\frac{N_n}{N_e}\left(g'_y\cos\theta_Z - \frac{g_L\sin\theta_Z}{\cos\theta_W}\right)\left((g'_y - g'_z)\cos\theta_Z - \frac{g_L\sin\theta_Z}{\cos\theta_W}\right)$$

NSI constraints for the gauge sector



Effective NSI for neutrino oscillation is suppressed by active-sterile mixing: $|\varepsilon^{\text{eff}}| \sim |\varepsilon U_{\nu\leftrightarrow N}|$.

MeV scale Z' boson constrains neutral gauge boson mixing

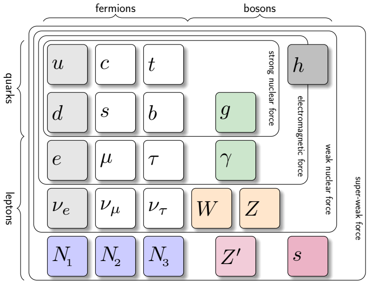


Conclusions

- Super-weak model is an economical U(1) extension of the standard model, adding only sterile neutrinos, complex singlet scalar and a massive neutral vector boson.
- New neutrino interactions are manifested via nonstandard interactions and active-sterile mixing.
- Higher order corrections to neutrino masses are small.

- Super-weak model is an economical U(1) extension of the standard model, adding only sterile neutrinos, complex singlet scalar and a massive neutral vector boson.
- New neutrino interactions are manifested via nonstandard interactions and active-sterile mixing.
- Higher order corrections to neutrino masses are small.

Thank you!



Backup slides

$$\begin{pmatrix} \hat{B}^{\mu} \\ W^{3\,\mu} \\ \hat{B}'^{\mu} \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\cos\theta_Z \sin\theta_W & -\sin\theta_Z \sin\theta_W \\ \sin\theta_W & \cos\theta_Z \cos\theta_W & \cos\theta_W \sin\theta_Z \\ 0 & -\sin\theta_Z & \cos\theta_Z \end{pmatrix} \begin{pmatrix} A^{\mu} \\ Z^{\mu} \\ Z'^{\mu} \end{pmatrix},$$

$$\tan(2\theta_Z) = \frac{2\kappa}{1-\kappa^2-\tau^2}$$

$$\kappa = \cos\theta_W(\gamma'_y - 2\gamma'_z), \quad \tau = 2\cos\theta_W \gamma'_z \tan\beta \ll 1$$

$$\gamma'_y = \frac{\varepsilon g_y}{g_L\sqrt{1-\varepsilon^2}}, \quad \gamma'_z = \frac{g'_z}{g_L} \ll 1$$

$$M_Z = \frac{M_W}{\cos\theta_W}\left(1+\mathcal{O}(\kappa^2)\right) \quad M_{Z'} = \frac{M_W}{\cos\theta_W}\tau\left(1+\mathcal{O}(\kappa^2)\right) \ll M_Z$$

$$\Rightarrow \tau \approx M_{Z'}/M_Z$$

Goldstone and scalar mixing

After spontaneous symmetry breaking, in R_ξ gauge

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} -i\sqrt{2}\sigma^+ \\ v + h' + i\sigma_\phi \end{pmatrix}, \quad \chi = \frac{1}{\sqrt{2}}(w + s' + i\sigma_\chi)$$

Mass eigenstates are h, s, σ_h and σ_s:

$$\begin{pmatrix} h \\ s \end{pmatrix} = \mathbf{Z}_S \begin{pmatrix} h' \\ s' \end{pmatrix} \equiv \begin{pmatrix} \cos\theta_S & -\sin\theta_S \\ \sin\theta_S & \cos\theta_S \end{pmatrix} \begin{pmatrix} h' \\ s' \end{pmatrix}$$

$$\begin{pmatrix} \sigma_Z \\ \sigma_{Z'} \end{pmatrix} = \mathbf{Z}_G \begin{pmatrix} \sigma_\phi \\ \sigma_\chi \end{pmatrix} \equiv \begin{pmatrix} \cos\theta_G & -\sin\theta_G \\ \sin\theta_G & \cos\theta_G \end{pmatrix} \begin{pmatrix} \sigma_\phi \\ \sigma_\chi \end{pmatrix}$$

Goldstone mixing between σ_Z and $\sigma_{Z'}$ is given by

$$\sin\theta_G = \frac{\tau \sin\theta_Z}{\sqrt{(\cos\theta_Z - \kappa\sin\theta_Z)^2 + (\tau\sin\theta_Z)^2}}$$