Neutrino windows to new physics

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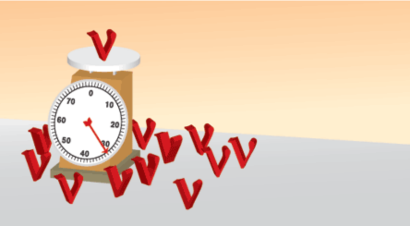
1st November 2019

Open questions of the SM

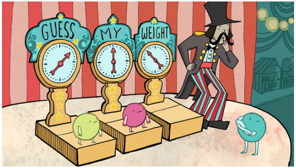
- Experimentally observed non-vanishing **neutrino masses**



Neutrino masses

- neutrino oscillation experiments have demonstrated that neutrinos are massive
- non-vanishing neutrino masses: one of few experimental evidences for physics beyond the SM
- neutrino mass scale not measured, only upper limit from sum of neutrino masses [Planck '18]

$$\sum_i m_i \lesssim 0.12 \ \text{eV}$$



Neutrino masses

- neutrinos are singlets of unbroken SM group $\rightarrow$ **two** possibilities to introduce mass term
- first option:

$$m_D \overline{\nu_L} \nu_R$$

Dirac mass term $\rightarrow$ add right-handed neutrinos to SM

Neutrino masses

- neutrinos are singlets of unbroken SM group$\rightarrow$ **two** possibilities to introduce mass term
- first option:

$$m_D \overline{\nu_L} \nu_R$$

Dirac mass term $\rightarrow$ add right-handed neutrinos to SM

- second option:

$$m_M \overline{\nu_L^c} \nu_L$$

Majorana mass term $\rightarrow$ breaks gauge invariance, need to introduce dimension-5-operator

$$\frac{\mathcal{O}^W}{\Lambda} = \frac{(\overline{L_L^c} \mathrm{i}\sigma_2 H)(H \mathrm{i}\sigma_2 L_L)}{\Lambda}$$

Neutrino masses

- expect that first sign of new physics comes from the EFT operator which is least suppressed by new physics scale Λ

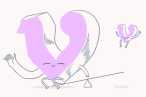
- the only dimension 5 operator build from SM fields

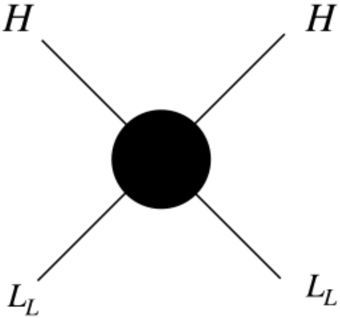
$$\frac{\mathcal{O}^W}{\Lambda} = \frac{(L^T H)(HL)}{\Lambda}$$

$\Rightarrow$ generates neutrino masses

Seesaw mechanism

several possibilities to generate this operator: **seesaw** mechanism





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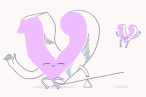
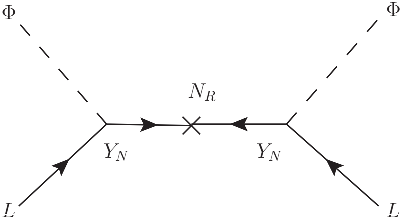


Type I seesaw



$$m_\nu = Y_N \frac{1}{M_N} Y_N^T v^2$$

Seesaw mechanism

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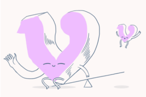
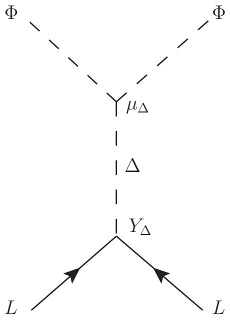


Type II seesaw

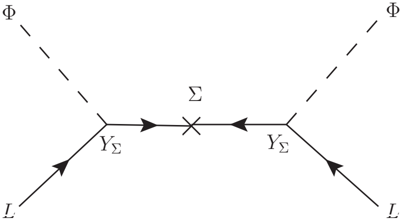


$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Seesaw mechanism

several possibilities to generate this operator: **seesaw** mechanism

Type III seesaw

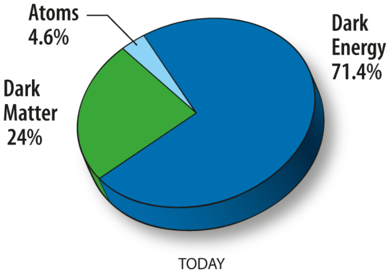


$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

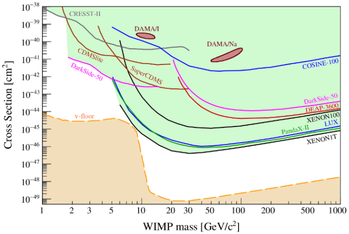
Open questions of the SM

- Experimentally observed non-vanishing **neutrino masses**
- Need for a **Dark Matter** candidate

Dark Matter

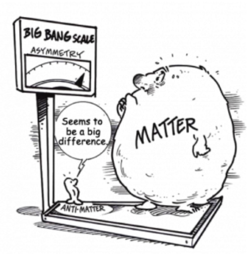


- large experimental effort to detect DM
  [Schumann '19]
- so far DM only observed via its gravitational interactions



Open questions of the SM

- Experimentally observed non-vanishing **neutrino masses**
- Need for a **Dark Matter** candidate
- Observed **baryon asymmetry of the Universe**



Baryon asymmetry of the Universe

- measured value of BAU [Planck '18]

$$Y_{\Delta B} = \left.\frac{n_B - n_{\bar{B}}}{s}\right|_0 \approx \left.\frac{n_B}{s}\right|_0 = (8.75 \pm 0.23) \cdot 10^{-11}$$

- Sakharov conditions for successfull baryogenesis: [Sakharov '67]
  - $\not{B}$ number violation
  - $\not{C}$, $\not{C}P$ violation
  - out of equilibrium processes
- Sakharov conditions satisfied in SM but the generated asymmetry is not enough the explain the observed value

Open questions of the SM

- Experimentally observed non-vanishing **neutrino masses**
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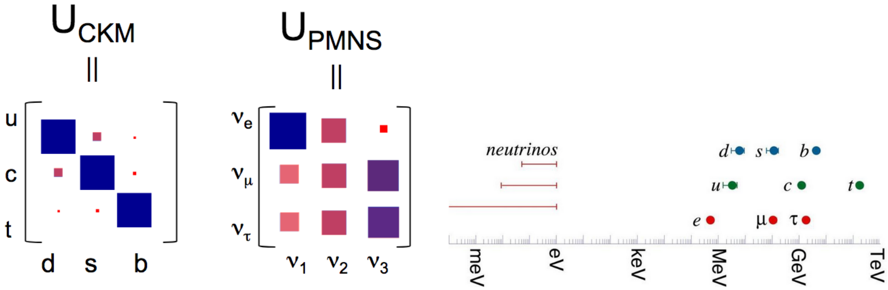
- Observed **baryon asymmetry of the Universe**
- measured fermion masses and mixings are very different: **flavour puzzle**

Flavour puzzle



striking hierarchy between fermion masses and mixing,
worsened by small neutrino masses

Open questions of the SM

- Experimentally observed non-vanishing **neutrino masses**
- Need for a **Dark Matter** candidate
- Observed **baryon asymmetry of the Universe**
- measured fermion masses and mixings are very different: **flavour puzzle**
- Higgs boson found but it is very light: **hierarchy problem**

Hierarchy problem

- at any energy scale μ, a physical parameter or set of physical parameters $\alpha_i(\mu)$ is allowed to be very small only if the replacement $\alpha_i(\mu) = 0$ would increase the symmetry of the system. -

[t'Hooft '80]

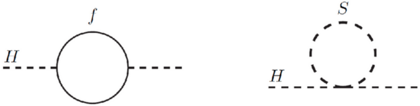
- example: fermion masses technically natural & protected by chiral symmetry

Hierarchy problem

- at any energy scale μ, a physical parameter or set of physical parameters $\alpha_i(\mu)$ is allowed to be very small only if the replacement $\alpha_i(\mu) = 0$ would increase the symmetry of the system. -

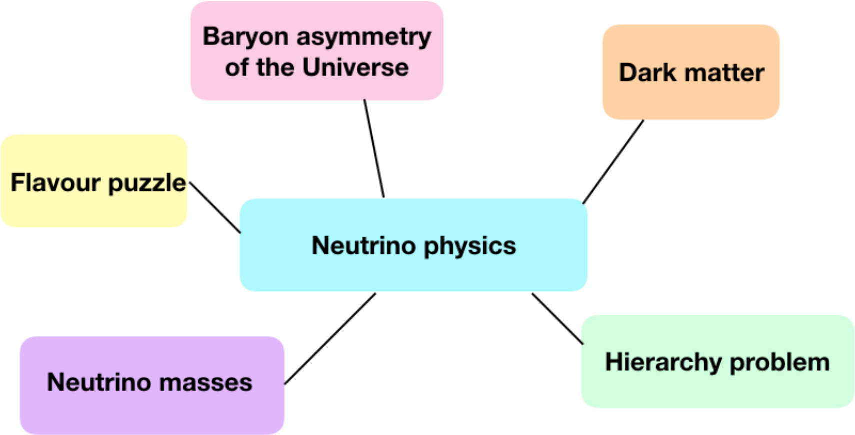
[t'Hooft '80]

- example: fermion masses technically natural & protected by chiral symmetry
- Higgs boson mass not protected by symmetry $\rightarrow$ sensitive through loop corrections to new physics scale
- unnatural that two contributions to an observable cancel to high accuracy

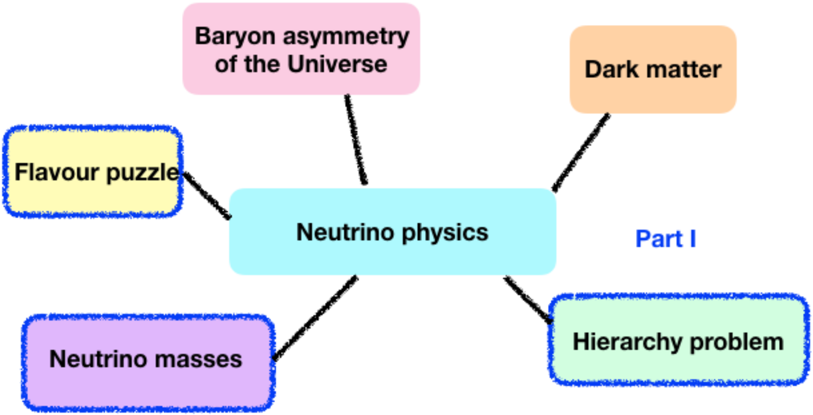


to **avoid** hierarchy problem $\Rightarrow$ NP at electroweak scale preferred

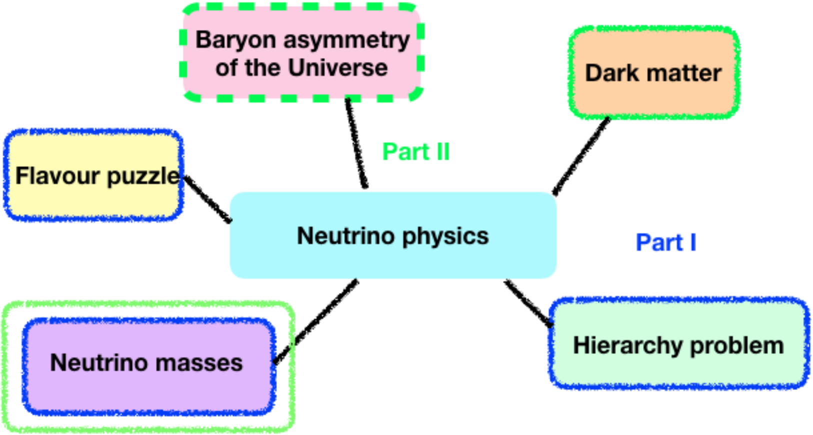
Neutrino windows to new physics



Neutrino windows to new physics

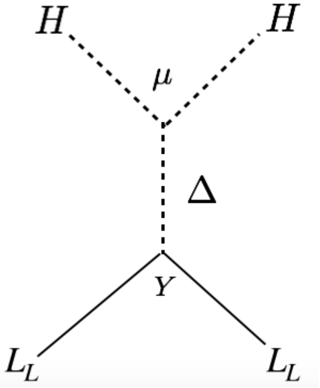


Neutrino windows to new physics



Type II seesaw [Schechter, Valle ’80; Lazarides, Shafi, Wetterich, ’81; Mohapatra, Senjanovi ’81; Wetterich ’81]

realise dimension 5 operator via type II seesaw



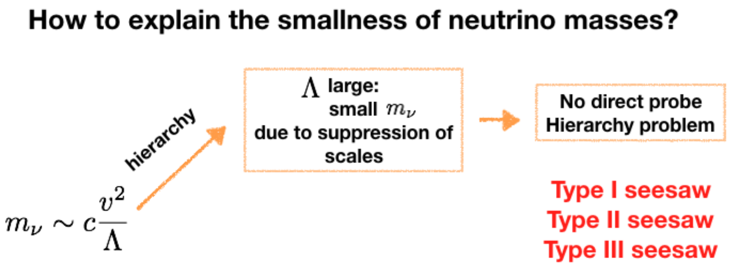
introduce $SU(2)_L$ scalar triplet with $Y = 1$

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ (v_\Delta + \delta + i a_\delta)/\sqrt{2} & -\delta^+/\sqrt{2} \end{pmatrix}$$

Neutrino mass models

Majorana mass term

$$c\frac{\mathcal{O}^W}{\Lambda} = c\frac{(\overline{L_L^c}\mathrm{i}\sigma_2 H)(H\mathrm{i}\sigma_2 L_L)}{\Lambda}$$



Neutrino mass models

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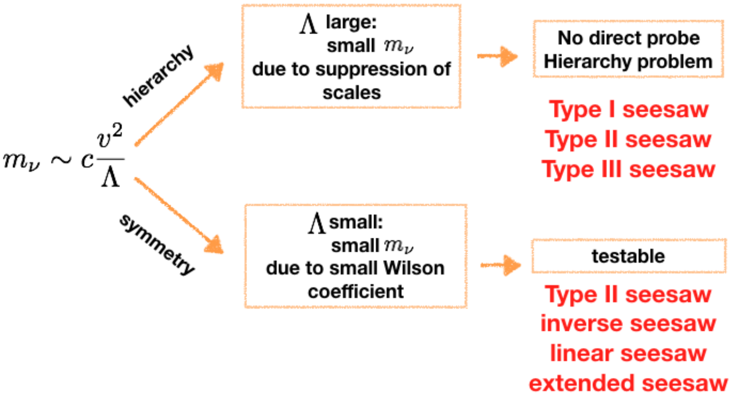
$$c\frac{\mathcal{O}^W}{\Lambda} = c\frac{(\overline{L_L^c}\mathrm{i}\sigma_2 H)(H\mathrm{i}\sigma_2 L_L)}{\Lambda}$$

How to explain the smallness of neutrino masses?



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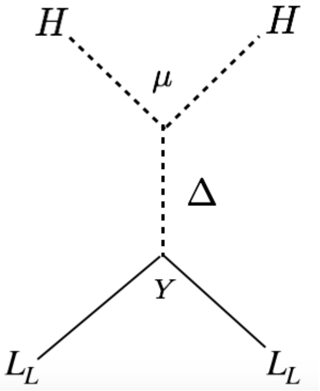


from $V \supset \mu H^T i\sigma_2 \Delta^\dagger H$ after EWSB: Δ obtains induced vev

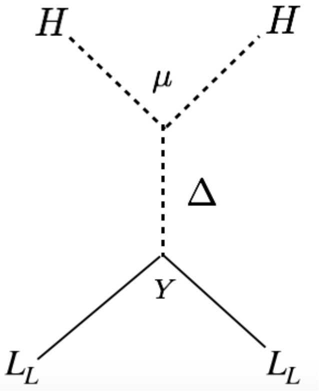
$$v_\Delta \simeq \frac{\mu}{\sqrt{2}} \frac{v^2}{M_\Delta^2},$$

neutrino masses from

$$-\mathcal{L}_{\text{type II}} = Y (L^c)^T i\sigma_2 \Delta L + \text{h.c.}$$

$$\Rightarrow m_\nu = \sqrt{2} Y v_\Delta = \mu \frac{Y v^2}{M_\Delta^2}$$

Type II seesaw [Schechter, Valle '80; Lazarides, Shafi, Wetterich, '81; Mohapatra, Senjanovi '81; Wetterich '81]



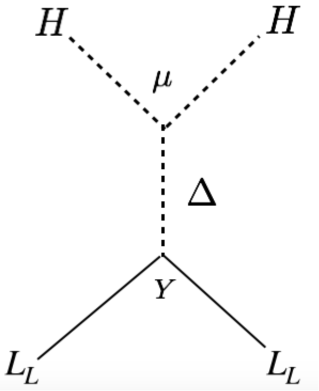
neutrino masses

$$m_\nu = \mu \frac{Yv^2}{M_\Delta^2}$$

explain smallness of neutrino masses via **hierarchy**:

$\mu \sim \mathcal{O}(v),\ Y \sim \mathcal{O}(0.01)$
$\rightarrow M_\Delta \sim \mathcal{O}(10^6 \text{ GeV})$

Type II seesaw [Schechter, Valle '80; Lazarides, Shafi, Wetterich, '81; Mohapatra, Senjanovi '81; Wetterich '81]



neutrino masses

$$m_\nu = \mu \frac{Yv^2}{M_\Delta^2}$$

explain smallness of neutrino masses via **symmetry**:
$M_\Delta \sim \mathcal{O}(100\text{ GeV}),\ Y \sim \mathcal{O}(0.01)$

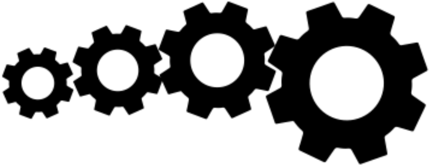
$$\rightarrow \mu \simeq 10\text{ keV}$$

$$\frac{\mu}{v} \lesssim \mathcal{O}(10^{-8})!!!$$

μ natural in t'Hooft sense

Generalized Type II seesaw

Based on *"Natural and Dynamical Neutrino Mass Mechanism at the LHC"*,
J. Gehrlein, D. Gonçalves, P. A. N. Machado and Y. F. Perez-Gonzalez,
Phys. Rev. D **98**, no. 3, 035045 (2018)
arXiv:1804.09184 [hep-ph].

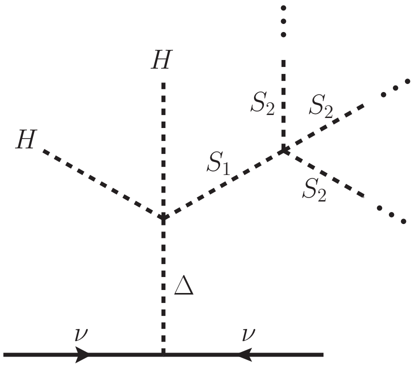


Generalized Type II seesaw [JG, Goncalves, Machado, Perez-Gonzalez '18]

Generate dynamically low lepton number breaking!

- promote lepton number to global symmetry:

  $l(L_L) = 1/2, \; l(\Delta) = -1$
  $\rightarrow \mu H^T i\sigma_2 \Delta^\dagger H$ forbidden



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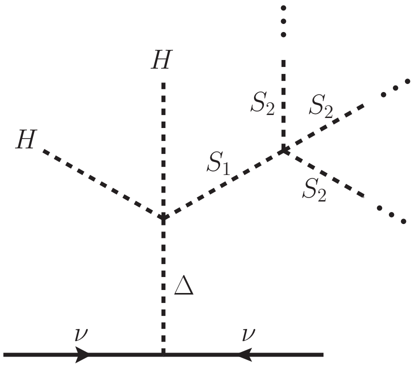
- introduce additional scalar singlet S_1 with $l(S_1) = +1$

  $\rightarrow$ vev of S_1 plays role of μ parameter



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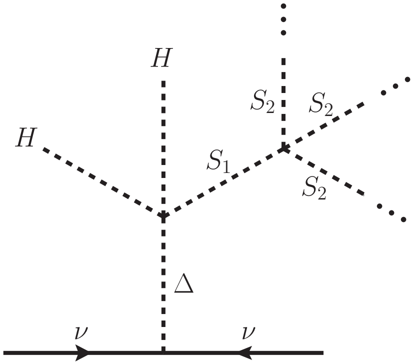
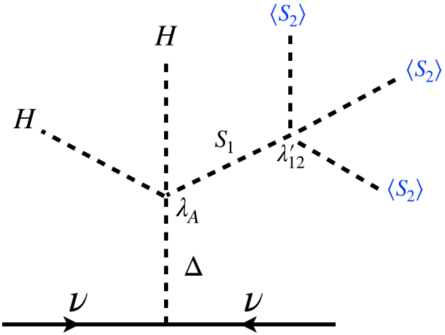
  $\rightarrow$ vev of S_1 plays role of μ parameter

- generalise seesaw mechanism in the scalar sector

  $\rightarrow$ introduce another scalar singlet S_2 with $l(S_2) = 1/3$

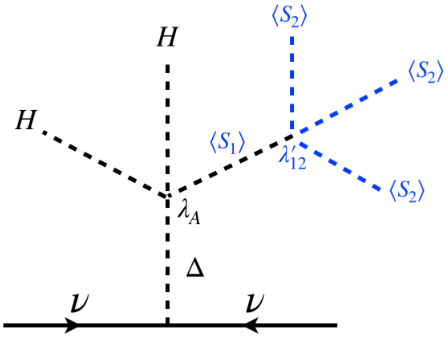


Generalized Type II seesaw [JG, Goncalves, Machado, Perez-Gonzalez '18]



- S_2 obtains vev

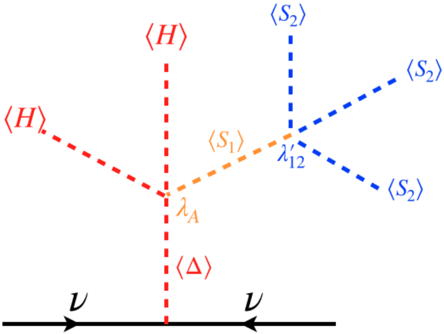
Generalized Type II seesaw [JG, Goncalves, Machado, Perez-Gonzalez '18]



- S_2 obtains vev $\to$ induces vev for S_1:

$$v_1 = \frac{\lambda'_{12} v_2^3}{3 M_1^2}$$

Generalized Type II seesaw [JG, Goncalves, Machado, Perez-Gonzalez '18]



- S_2 obtains vev $\to$ induces vev for S_1:

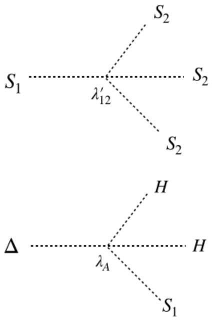
$$v_1 = \frac{\lambda'_{12} v_2^3}{3M_1^2}$$

- S_1 induces vev for Δ:

$$v_\Delta = \frac{\lambda_A v^2 v_1}{2M_\Delta^2}$$

Particle spectrum [JG, Goncalves, Machado, Perez-Gonzalez '18]

parameter	typical value
M_1	100 GeV
M_2	200 GeV
M_Δ	500 GeV
v_2	10 GeV
v_1	1 MeV
v_Δ	1 keV
λ_A	0.008
λ'_{12}	0.03
Y	0.001



Particle spectrum [JG, Goncalves, Machado, Perez-Gonzalez '18]

- 4 neutral scalars: h, δ_0, s_1, s_2
- singly charged scalar: δ^+
- doubly charged scalar: δ^{++}
- 2 massive pseudoscalars: a_1, a_δ
- longitudinal polarisation of Z boson
- massless Goldstone boson Majoron J

Mixing phenomenology [JG, Goncalves, Machado, Perez-Gonzalez '18]

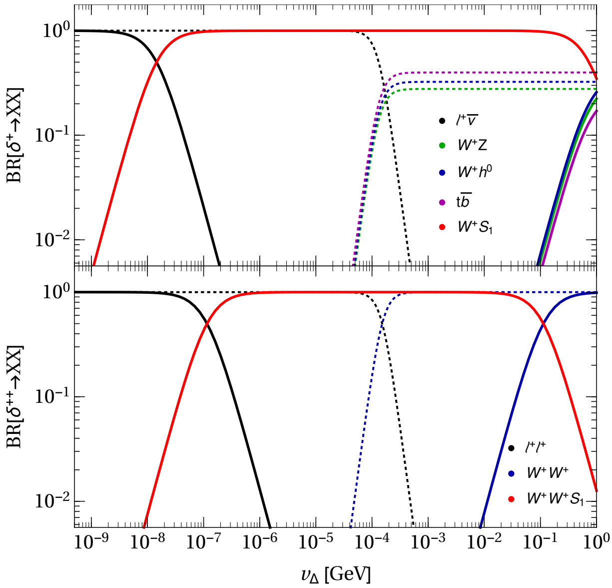
scalars	typical mixing	constraints
$h - s_2$	10^{-1}	$< 10^{-3}$ from EW precision observables&Higgs production/decay
$h - s_1$	10^{-5}	enables $s_1 \to ff$ decay
$\delta_0 - s_1$	10^{-3}	leads to deviations from usual type II seesaw pheno

Mixing phenomenology [JG, Goncalves, Machado, Perez-Gonzalez '18]

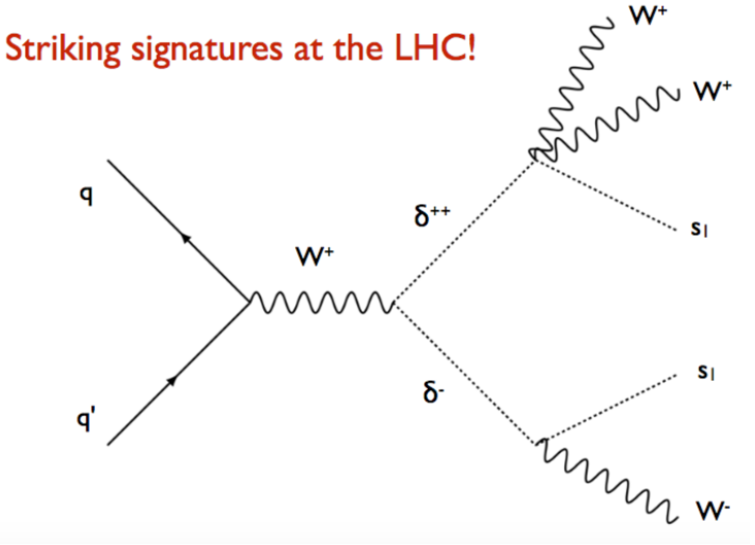
drastic deviations from usual type II seesaw phenomenology $\to$ new decay channels open up

scalar	Type II	Generalized type II	parameters
δ^{++}	$\ell^+\ell^+$, W^+W^+	$W^+W^+s_1$	$v_\Delta, \theta_{\delta 1}$
δ^+	$\ell^+\nu$, W^+Z, W^+h, $t\bar{b}$	W^+s_1	$v_\Delta, \theta_{\delta 1}$
δ_0	$\nu\nu$, W^+W^-, ZZ, hh	$h\,s_1$	$v_\Delta, \theta_{\delta 1}$
a_δ	$\nu\nu$, $t\bar{t}$, Zh	$Z\,s_1$	$v_\Delta, \theta_{\delta 1}$
s_1	not present	$\nu\nu$, $q\bar{q}$, W^+W^-, ZZ	$v_\Delta, \theta_{\delta 1}, \theta_{h1}$

Mixing phenomenology [JG, Goncalves, Machado, Perez-Gonzalez '18]



m_0=0.1 eV,
M_Δ=500 GeV,
M_1=100 GeV,
$\theta_{\delta 1}$=0.005

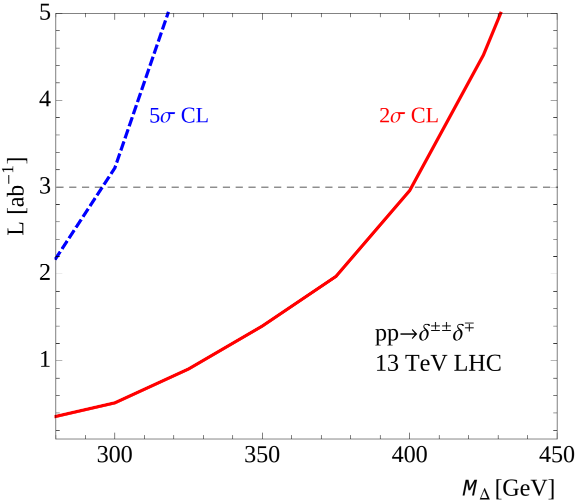

Striking signatures at the LHC!
q
q'
W+
δ++
δ-
W+
W+
s1
s1
W-

Collider phenomenology [JG, Goncalves, Machado, Perez-Gonzalez '18]

- analyse $pp \to \delta^{\pm}\delta^{\mp\mp}$ production at LHC with $\sqrt{s}$ = 13 TeV
- focusing on the trilepton plus missing energy, with same sign, same flavour leptons final signature

$$e^{\pm}e^{\pm}\mu^{\mp} + \text{MET}, \mu^{\pm}\mu^{\pm}e^{\mp} + \text{MET}$$

- following CMS analysis [1802.02965]

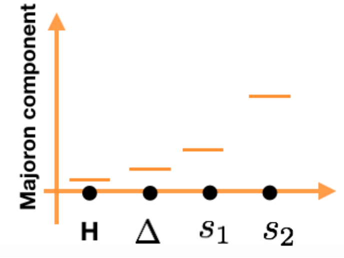


for $M_1 = 100$ GeV, $v_\Delta = 1$ keV

Majoron phenomenology [JG, Goncalves, Machado, Perez-Gonzalez '18]

Global lepton number is broken spontaneously: massless Majoron!

$$J \simeq \frac{1}{\ell_2 v_2}\left(\ell_1 v_1 a_1 + \ell_2 v_2 a_2 + \frac{1}{2} v_\Delta a_\delta - \frac{v_\Delta^2}{v} a\right)$$



Majoron phenomenology [JG, Goncalves, Machado, Perez-Gonzalez '18]

very suppressed couplings to SM

$$G_{Jff} = \frac{y_f}{\sqrt{2}} \frac{v_\Delta^2}{\ell_2 v_2 v} = \frac{1.6 \cdot 10^{-18}}{\ell_2} \frac{(m_f/\text{GeV})(v_\Delta/\text{keV})^2}{(v_2/10\ \text{GeV})},$$

$$G_{J\nu\nu} = \sqrt{2} y_\nu \frac{v_\Delta}{\ell_2 v_2} = \frac{5 \cdot 10^{-12}}{\ell_2} \frac{(m_\nu/0.1\ \text{eV})}{(v_2/10\ \text{GeV})}$$

$\rightarrow$ Majoron easily avoids experimental constraints:

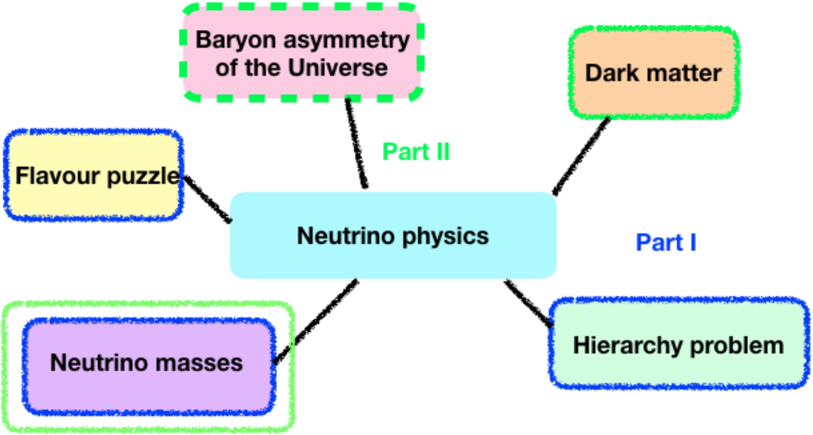
- neutrinoless double beta decay with Majoron emission: $G_{J\nu\nu} < (0.8 - 1.6) \times 10^{-5}$ [KamLAND-Zen '12]
- astrophysical bounds: $G_{Jee} < 4.3 \times 10^{-13}$ [PDG '16]

Summary

- dynamical realisation of type II seesaw pattern
- natural
- no arbitrary small parameters
- dynamical
- rich phenomenology:

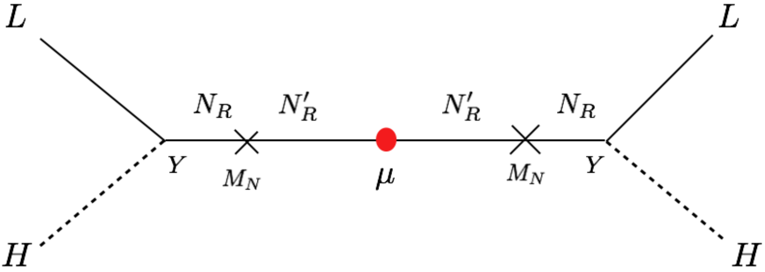
  massless Goldstone boson, deviation in Higgs observables, smoking gun at LHC - distinguishable from usual type II

Neutrino windows to new physics



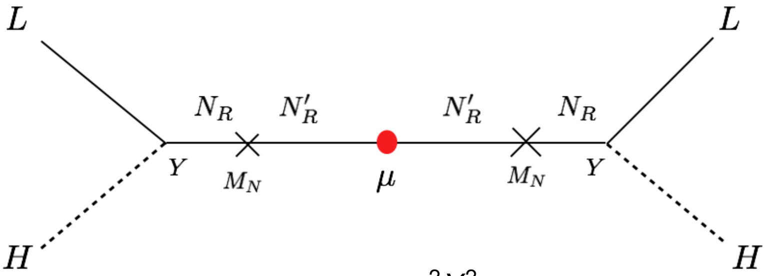
Inverse Seesaw [Mohapatra, Valle '86]

- variance of type I seesaw
- introduce two copies of right-handed neutrinos $N_R,\ N'_R$ with lepton number $L(N_R) = +1,\ L(N'_R) = -1$



$$-\mathcal{L}_{\text{ISS}} = \overline{L} Y \tilde{H} N_R + \overline{N_R^c} M_N N'_R + + \overline{(N'_R)^c}\, \mu N'_R + \text{ h.c.}$$

Inverse Seesaw [Mohapatra, Valle '86]



$$\rightarrow m_\nu \sim \mu \frac{v^2 Y^2}{M_N^2}$$

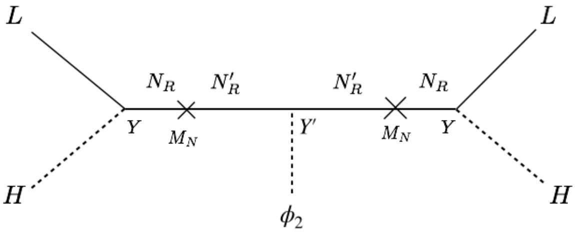
explain smallness of neutrino masses via **symmetry**:

$$M_N \sim \mathcal{O}(100\ \text{GeV}),\ Y \sim \mathcal{O}(0.01) \rightarrow \mu \sim \mathcal{O}(10\ \text{keV})$$

$$\mu/v \sim 10^{-8}!!!$$

Dynamical Inverse Seesaw

Based on *"Dark Matter and the elusive Z' in a dynamical Inverse Seesaw scenario"*,
V. De Romeri, E. Fernandez-Martinez, J. Gehrlein, P. A. N. Machado and V. Niro,
JHEP **1710** (2017) 169
arXiv:1707.08606 [hep-ph].

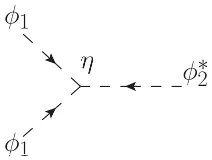


Dynamical Inverse Seesaw [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]

- Promote μ to a dynamical quantity by gauging $B-L$
- $B-L$ then spontaneously broken by

Particle	ϕ_1	ϕ_2
$U(1)_{B-L}$ charge	$+1$	$+2$

- scalar sector: $m_{\phi_1} \sim m_{\phi_2} \sim \mathcal{O}$ (TeV), $\langle\phi_1\rangle \sim$ TeV and induced vev $\langle\phi_2\rangle \sim \frac{\eta}{\sqrt{2}}\frac{\langle\phi_1\rangle}{m^2_{\phi_2}} \sim \mathcal{O}$(keV) via



η technically **natural** due to global symmetry in scalar sector

Dynamical Inverse Seesaw [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]

- anomaly cancellation calls for the introduction of additional fermions

	ISS			DM candidate		massless f.
Particle	ν_L	N_R	N'_R	χ_R	χ_L	ω_L
$U(1)_{B-L}$ charge	-1	-1	$+1$	$+5$	$+4$	$+4$
Multiplicity	3	3	3	1	1	1

$$-\mathcal{L}_\nu = \bar{L} Y_\nu \widetilde{H} N_R + \overline{N_R^c} M_N N'_R + \phi_2^* \overline{(N'_R)^c}\, Y'_N N'_R + \phi_2 \overline{N_R^c} Y_N N_R + \phi_1^* \overline{\chi_L}\, Y_\chi \chi_R + \text{ h.c.}$$

Dynamical Inverse Seesaw [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]

	ISS			DM candidate		massless f.
Particle	ν_L	N_R	N'_R	χ_R	χ_L	ω
$U(1)_{B-L}$ charge	-1	-1	$+1$	$+5$	$+4$	$+4$
Multiplicity	3	3	3	1	1	1

fermion mass matrix $(\nu_L^c, N_R, N'_R, \chi_L^c, \chi_R)$:

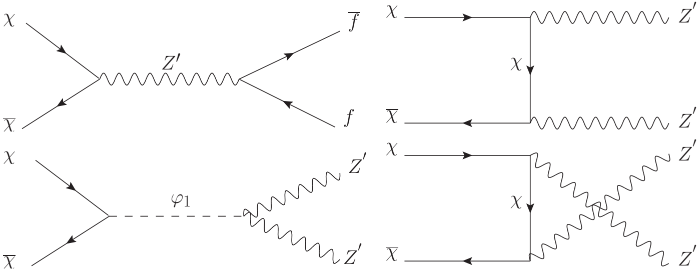
$$M = \left(\begin{array}{ccc|cc} 0 & Y_\nu \widetilde{H} & 0 & 0 & 0 \\ Y_\nu^T \widetilde{H}^\dagger & Y_N \phi_2 & M_N & 0 & 0 \\ 0 & M_N^T & Y'_N \phi_2^* & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & Y_\chi \phi_1^* \\ 0 & 0 & 0 & Y_\chi^T \phi_1 & 0 \end{array}\right)$$

Dark sector phenomenology [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]

- stable Dirac fermion $\chi = (\chi_L, \chi_R)$ mass at TeV scale: **DM** candidate
- massless fermion ω: contributes to number of relativistic degrees of freedom in the early Universe
- largest $B - L$ charge in dark sector $\rightarrow$ Z' couples dominantly to the dark sector (**elusive** Z')

Dark matter phenomenology [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]

- relic density: main annihilation channels



Dark matter phenomenology [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]

- direct detection: cross section for coherent elastic scattering on a nucleon is

$$\sigma_\chi^{\rm DD} = \frac{\mu_{\chi \rm N}^2}{\pi} \left(\frac{9}{2} \frac{g_{\rm BL}^2}{M_{Z'}^2} \right)^2$$

- from experimental bound on spin-independent cross section lower bound on v_1: [LUX '17, XENON1T '17]

$$v_1 \ [\text{GeV}] > \left(\frac{2.2 \cdot 10^9}{\sigma_\chi^{\rm DD} \ [\text{pb}]} \right)^{1/4} \quad \Rightarrow m_\chi \gtrsim \text{TeV}$$

Dark matter phenomenology [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]

- indirect detection: main annihilation channels of χ via elusive Z'
- strongest bounds on [HESS '11, FermiLAT '15]

$$< \sigma v > (\chi\bar{\chi} \to \tau^+\tau^-) \lesssim 10^{-25}\,\text{cm}^3\text{s}^{-1} - 10^{-22}\,\text{cm}^3\text{s}^{-1}$$

for $m_\chi \approx 1 - 10$ TeV

- bound more than two orders of magnitude above typical results in the model (BR($\chi\bar{\chi} \to \tau^+\tau^- \approx 5\%$))

$\Rightarrow$ bounds from indirect detection subdominant

Dark fermion phenomenology [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]

- number of relativistic degrees of freedom in the early Universe, $N_{\rm eff}$

  measurement: $N_{\rm eff}^{exp} = 2.99 \pm 0.33$ [Planck '18]

- contribution from ω

$$\Delta N_{\rm eff} = \left(\frac{T_\omega^{\rm f.o.}}{T_\nu}\right)^4 = \left(\frac{11}{2g_\star(T_\omega^{\rm f.o.})}\right)^{4/3}$$

- typical value $T_\omega^{\rm f.o.} \sim 4$ GeV

$$\Rightarrow \Delta N_{\rm eff} \approx 0.026$$

Collider phenomenology [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]

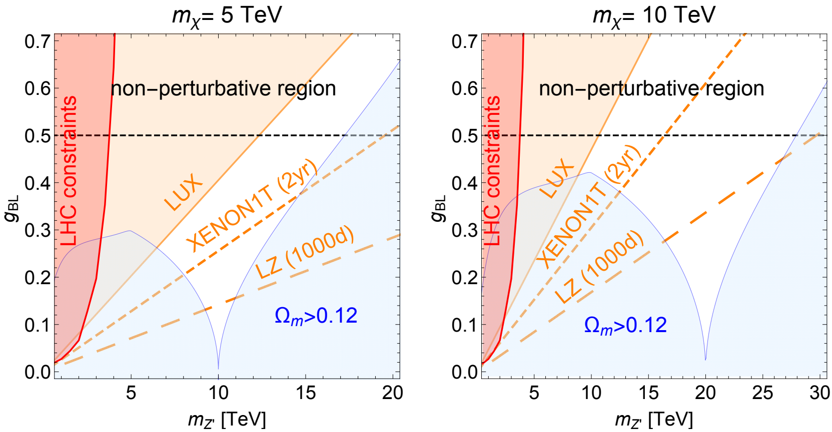
- Z' couples strongly to the dark sector

- $\mathrm{BR}(Z' \to \mathrm{inv}) \approx 70\%$, $\mathrm{BR}(Z' \to q\bar{q}) \approx 12\%$, $\mathrm{BR}(Z' \to \ell\bar{\ell}) \approx 18\%$

- recast constraints from LHC $Z' \to ee, \mu\mu$ resonant searches
  [CMS'16, ATLAS '16]

$$\sigma(pp \to Z' \to \ell\bar{\ell}) = \sum_q \frac{C_{qq}}{sM_{Z'}} \Gamma(Z' \to q\bar{q}) \mathrm{BR}(Z' \to \ell\bar{\ell})$$

Results [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]



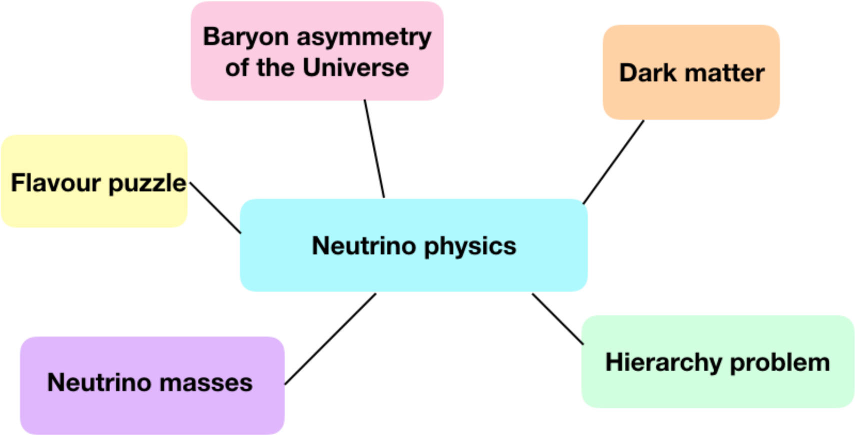
Summary and Conclusions

- promoted μ in ISS to a dynamical quantity by gauging $B - L$
- need for additional particles leads to interesting phenomenology
- additional Z' boson at the TeV scale
- dark sector with a DM candidate which can yield the correct relic density and passes the DM direct and indirect detection constraints
- massless fermion which contributes to $\Delta N_{\rm eff} \sim 0.02$

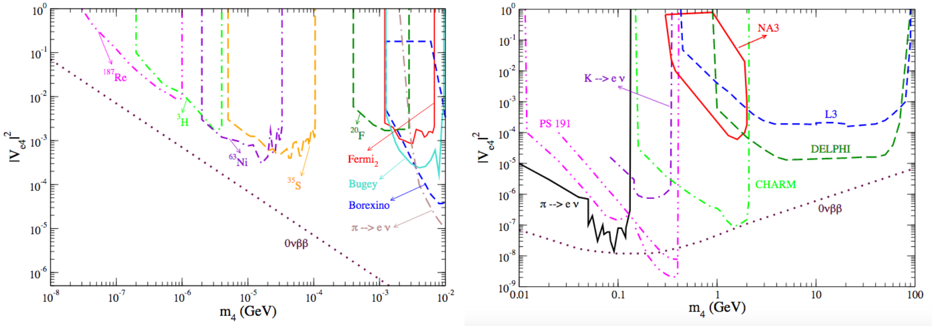
Neutrino windows to new physics

- neutrino physics: promising window to new physics extensions of the SM
- first step to build theories which can link various open questions of the SM at the same time
- exciting times ahead: more data from complementary avenues

End of the talk



Backup: Testing steriles [Atre, Han, Pascoli, Zhang '09]



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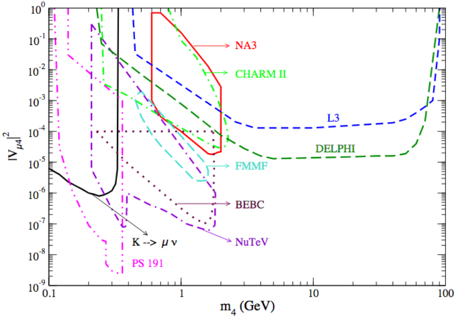
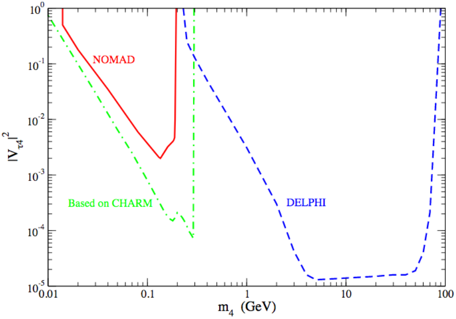
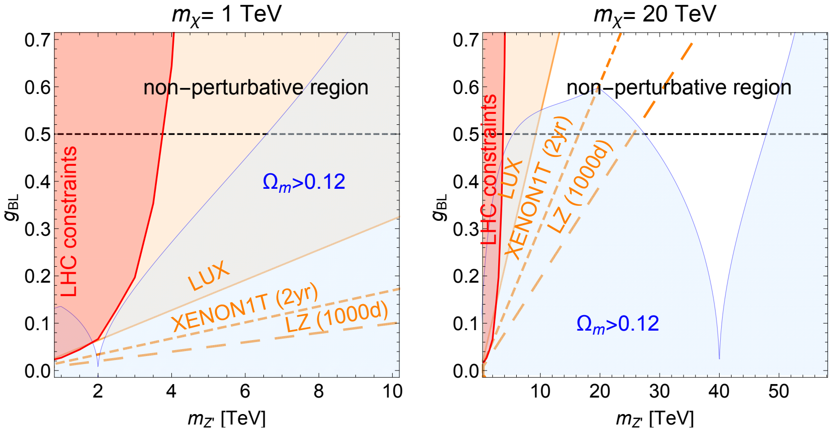




Backup: Results DISS [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]



Backup: Other seesaw mechanisms

- linear seesaw:

$$M = \begin{pmatrix} 0 & m_D & \epsilon \\ m_D^T & 0 & M_N \\ \epsilon & M_N^T & 0 \end{pmatrix}$$

$$m_\nu \sim \epsilon \frac{m_D}{M_N}$$

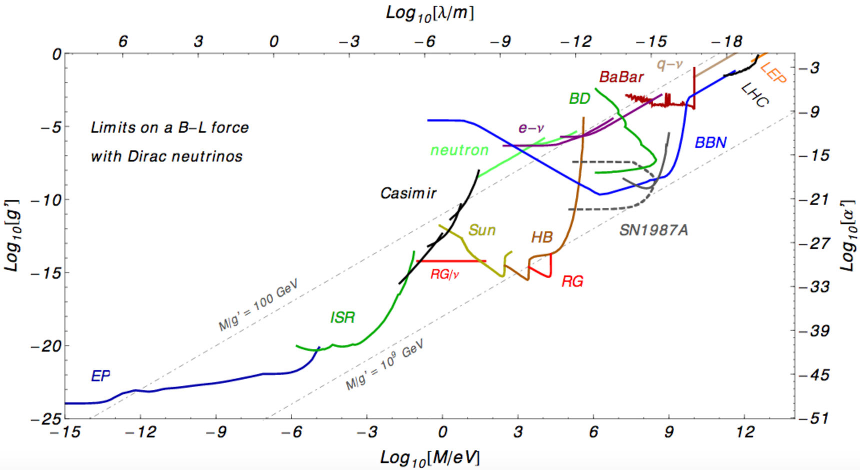
- extended seesaw:

$$M = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & \mathbf{M_R} & M_S^T \\ 0 & M_S & 0 \end{pmatrix}$$

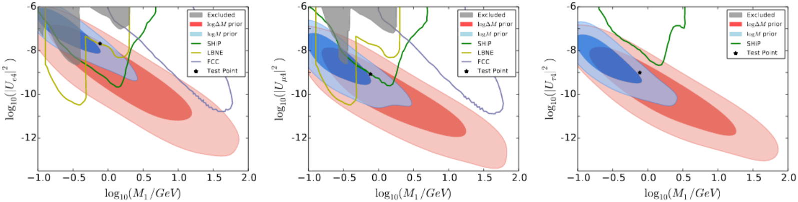
$$M_R \gg M_N > m_D$$

$$\to m_\nu \sim m_D M_R^{-1} M_S^T (M_S M_R^{-1} M_S^T)^{-1} M_S (M_R^{-1})^T m_D^T - m_D M_R^{-1} m_D^T$$

Backup: Z' mass [Heeck '14]



- baryogenesis via (low scale) leptogenesis mechanism possible in ISS [Hernandez et al '16, Abada et al '18]
- for $M_N \sim 0.1 - 100$ GeV: lepton asymmetry via freeze-in of the sterile states via their CP-violating oscillations



[Hernandez et al '16]

Backup: DISS, naturalness of η [De Romeri, Fernandez-Martinez, JG, Machado, Niro '17]

- there is a global symmetry in the scalar sector which is only broken by $\eta\phi_1^2\phi_2^*$
- gauged symmetry $C = B - L - X$ where X is DM number under which $\chi_{L/R}, \omega_L$ and ϕ_1 are charged
- SM fermions and ϕ_2 are just charged under $B - L$
- η is the only parameter which communicates between global $B - L$ and X symmetries

- CMS analysis used to search for sterile neutrinos [1802.02965]
- 3 observables: the trilepton mass system, minimum invariant mass of all opposite sign leptons, transverse mass
- background from $t\bar{t}$, DY, WZ, ZZ,...

Backup: n-step generalised seesaw [JG, Goncalves, Machado, Perez-Gonzalez '18]

- arbitrary number n of scalar singlets
- assume $M_i = M,\ \lambda'_{ij} = \lambda'$

$$v_j = \left(\frac{\lambda'}{3} \frac{v_n^2}{M^2} \right)^K v_n\ ,\ K = (3^{n-j} - 1)/2$$

- suppression ϵ^K, i.e. $\epsilon = 0.01, n = 3 \to v_1 \sim 10^{-8} v_3$