Theory perspective on neutrino physics for the HTE factory

31 March 2023

ECFA WG1 HET Meeting

Silvia Pascoli

HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

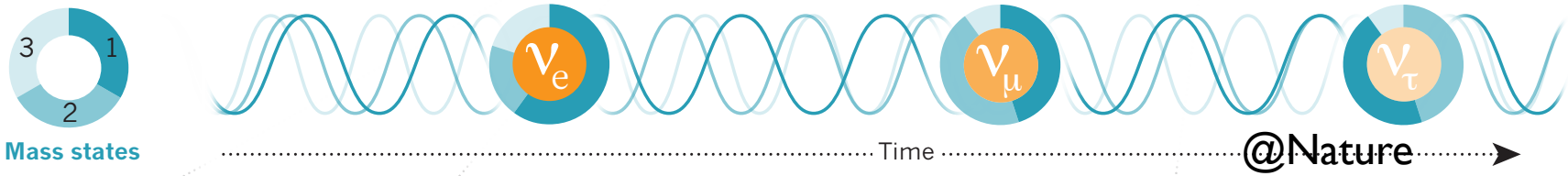
Horizon2020

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

INFN Istituto Nazionale di Fisica Nucleare

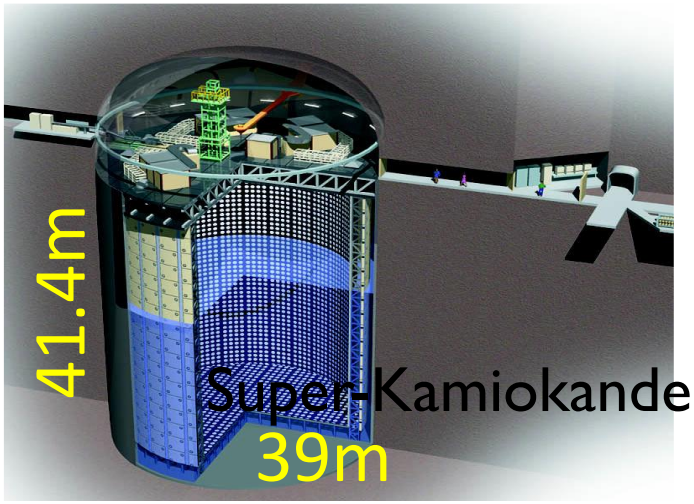
Neutrino oscillations

Neutrino oscillate and this implies neutrino masses and leptonic mixing.



@Nature

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i U_{\alpha 1} U^*_{\beta 1} e^{-i \frac{\Delta m^2_{i1}}{2E} L} \right|^2$$



Nobel Prize in Physics 2015

Current status of neutrino parameters: the era of very precise neutrino physics

with SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

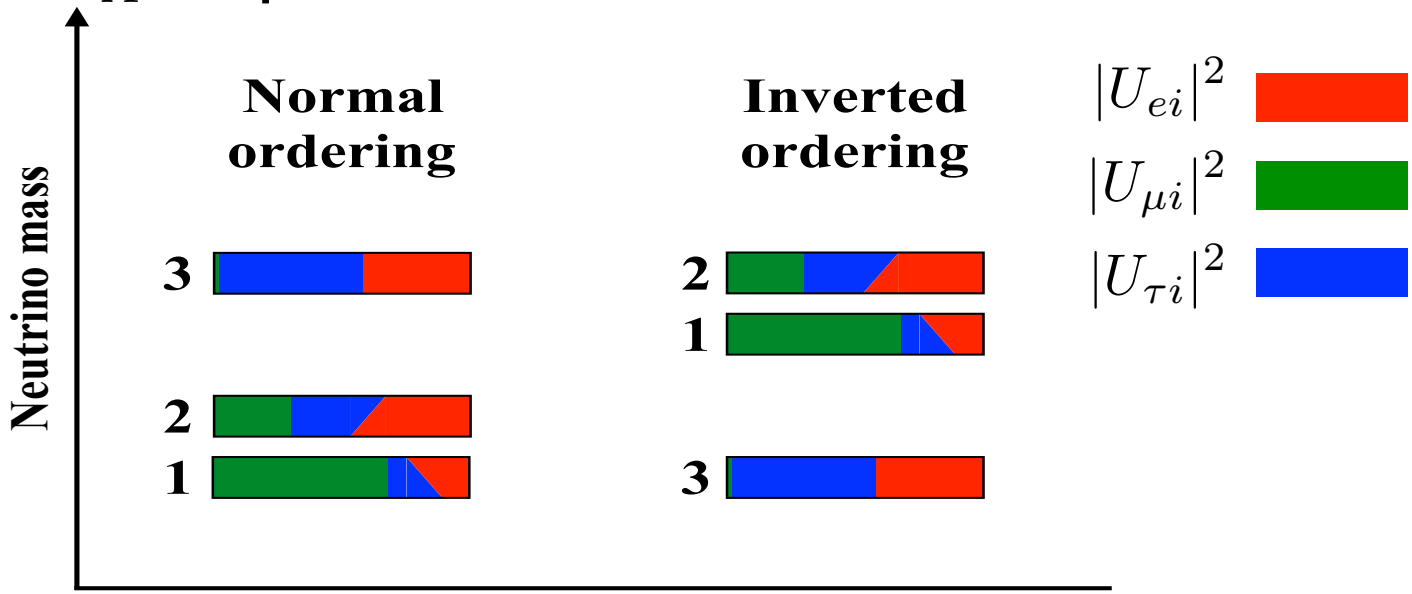
Esteban et al., 2007.14792, See also Capozzi et al., de Salas et al.

http://www.nu-fit.org/

- 2 mass squared differences
- 3 sizable mixing angles (one not too well known)
- mild hints of CPV (not robust)
- mild indications in favour of NO (?)

Neutrino masses

$\Delta m^2_{\rm s} \ll \Delta m^2_{\rm A}$ implies at least 3 massive neutrinos.



Fractional flavour content of massive neutrinos

$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm sol}}$$
$$m_3 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A}}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A} - \Delta m^2_{\rm sol}}$$
$$m_2 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A}}$$

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the mass ordering.

What do we still need to know?

1. **What is the nature of neutrinos?**

2. **What are the values of the masses?** Absolute scale and the ordering.

3. **Is there CP-violation?**

4. **What are the precise values of mixing angles?**

5. **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Non-unitarity? Other effects?

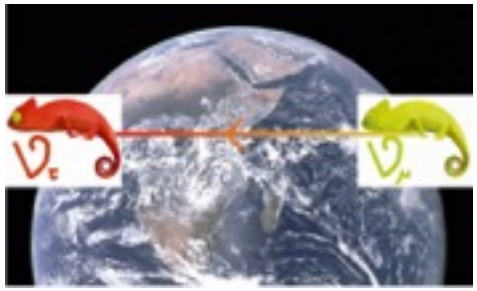
Very exciting experimental programme now and for the future.

	2020	2025	2030	2035
LBL osc.	T2K NOvA	LBNF-DUNE T2HK (T2HKK)		ESSnuSB?, nufactory?
SBL osc.	SBL reactor,… MicroBooNE SBN	LBNF-DUNE ND T2HK ND ???		
Other osc.	SK, Borexino, LBL detectors JUNO	DUNE HK		Theia???
Direct mass	KATRIN	Project 8, ECHO, Holmes		
DBD0nu	KamLAND-Zen GERDA CUORE LEGEND-200 NEXT-100	LEGEND-1000 CUPID, nEXO, NEXT-HD, PANDAX, DARWIN…		Next-next gen?
UHE	IceCube	IceCubeGen2 ORCA, KM3Net		

Evidence beyond the SM

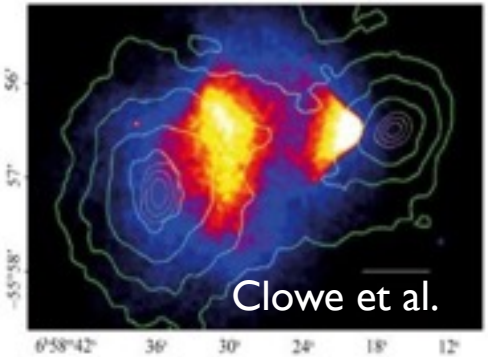
There is evidence that the Standard Model is incomplete: neutrinos play a key role.

Neutrino masses



Dark Matter

Baryon asymmetry



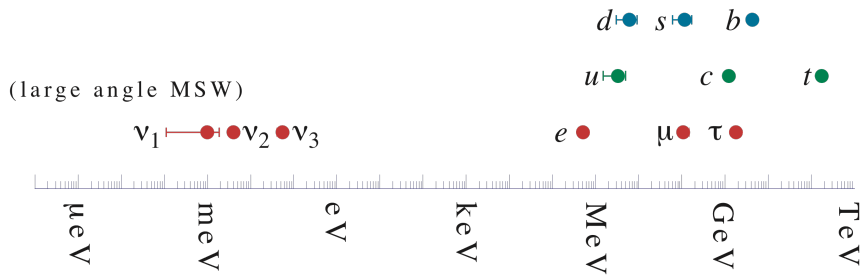
The ultimate goal is to understand

- where do neutrino masses come from?
- what is the origin of leptonic mixing?

Neutrinos: Open window on Physics BSM

Neutrinos give a new perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass?
and why are they so much lighter than the other fermions?
and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

Dirac Masses

In the SM, neutrinos do not acquire mass and mix.

Neutrino masses Beyond SM

If we introduce a right-handed neutrino, then an interaction with the Higgs boson is allowed. We need to impose L as a fundamental symmetry (BSM).

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.}$$

This conserves lepton number!

$$\downarrow$$

$$m_D = y_\nu v = V m_{\text{diag}} U^\dagger$$

$$y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$$

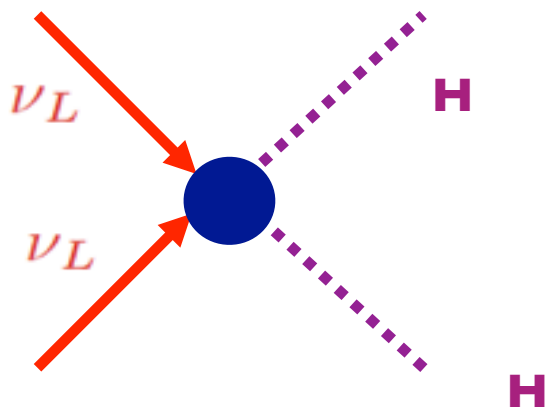
- why no Majorana mass term for RH neutrinos?
- why the coupling is so small????
- why the leptonic mixing angles are large?
- why neutrino masses have at most a mild hierarchy?

Majorana Masses

In order to have an SU(2) invariant mass term for neutrinos, it is necessary to introduce a Dimension 5 operator (or to allow new scalar fields, e.g. a triplet):

$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

Weinberg operator, PRL 43



Only D=5 term allowed for the SM

This term breaks lepton number and induces Majorana masses and Majorana neutrinos.

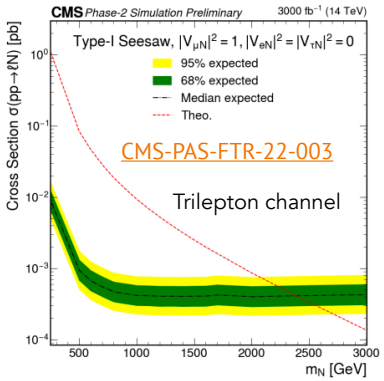
What is the new physics scale?

Are there new:
symmetries?
particles?
interactions?

New physics scale? Going to high energy

eV keV MeV GeV **TeV** **Intermediate scale** **GUT scale**

TeV see-saw I, see-saw II, see-saw III, extended-type seesaws, radiative models, extra-D, R-parity V SUSY...

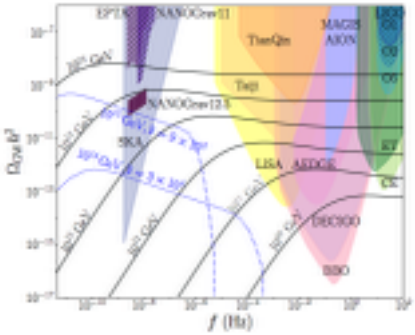


LHC searches

J. Xiao's talk at Neutrino2022

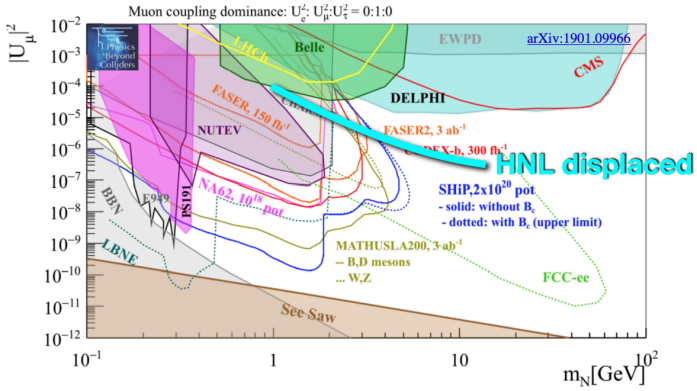
Leptogenesis

CLFV



GW

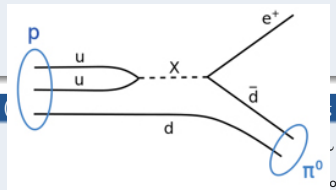
S. King et al., PRL 126 (2021)



Proton decay

T. Ohlsson's talk at Neutrino2022

JUNO (Jiangmen, China; under construction, data taking in 2023)



Hyper-Kamiokande (in 2027)

~ 8 × SK)

objectives.

DUNE (Illinois & South Dakota, USA)

- 68 kton liquid Argon detector
- Possibility to search for proton decay

ESSnuSB (Sweden)

- 0.5 Mton water-Cherenkov detector (~ 20 × SK)
- Excellent opportunity to search for proton decay

Going low in energy: Dark sectors

eV keV MeV GeV TeV Intermediate scale GUT scale

Low E See-saw models, NuMSM, extended see-saw…

Sterile nu oscillations

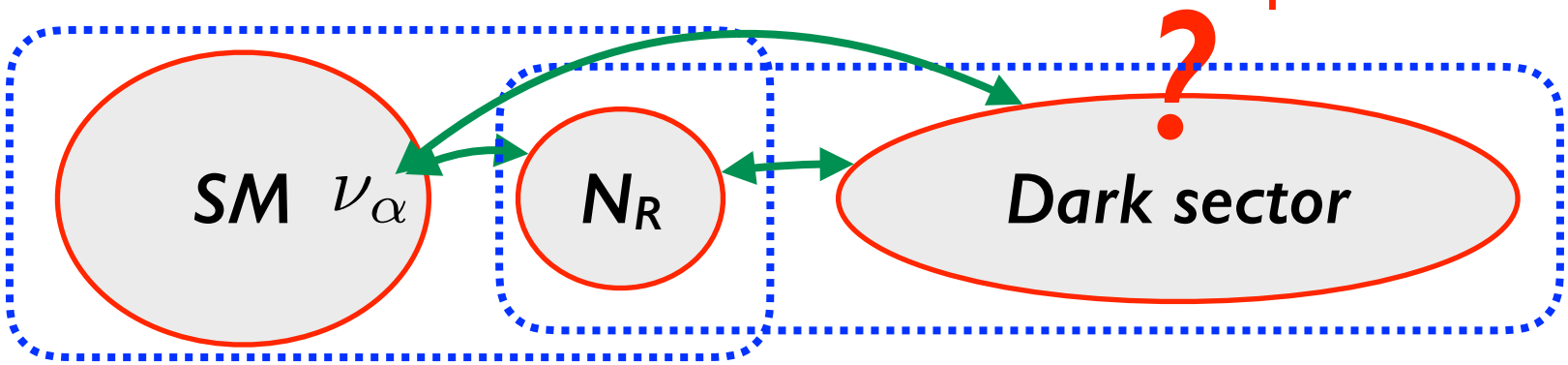
DM

Leptogenesis

HNL searches: peak, kinks, decays,

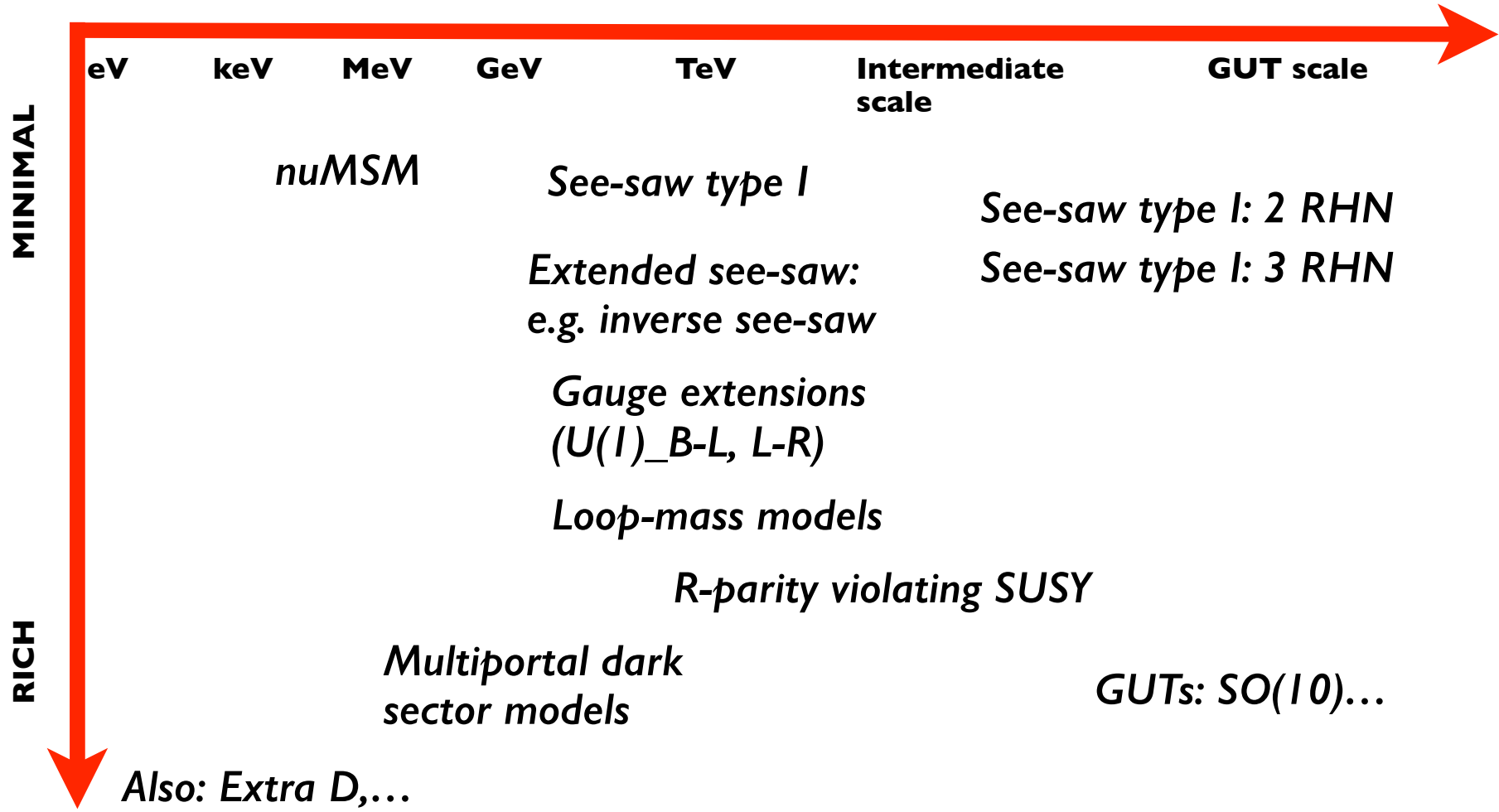
Neutrino play a unique role in searching for Dark Sectors.

$\bar{L} \cdot H N_R \quad (+ \ldots \overline{N_R} N_S)$ Neutrino portal



Have we seen already some glimpses??? If a signal in future, this would lead to a major change in the BSM paradigm.

From minimality to richness

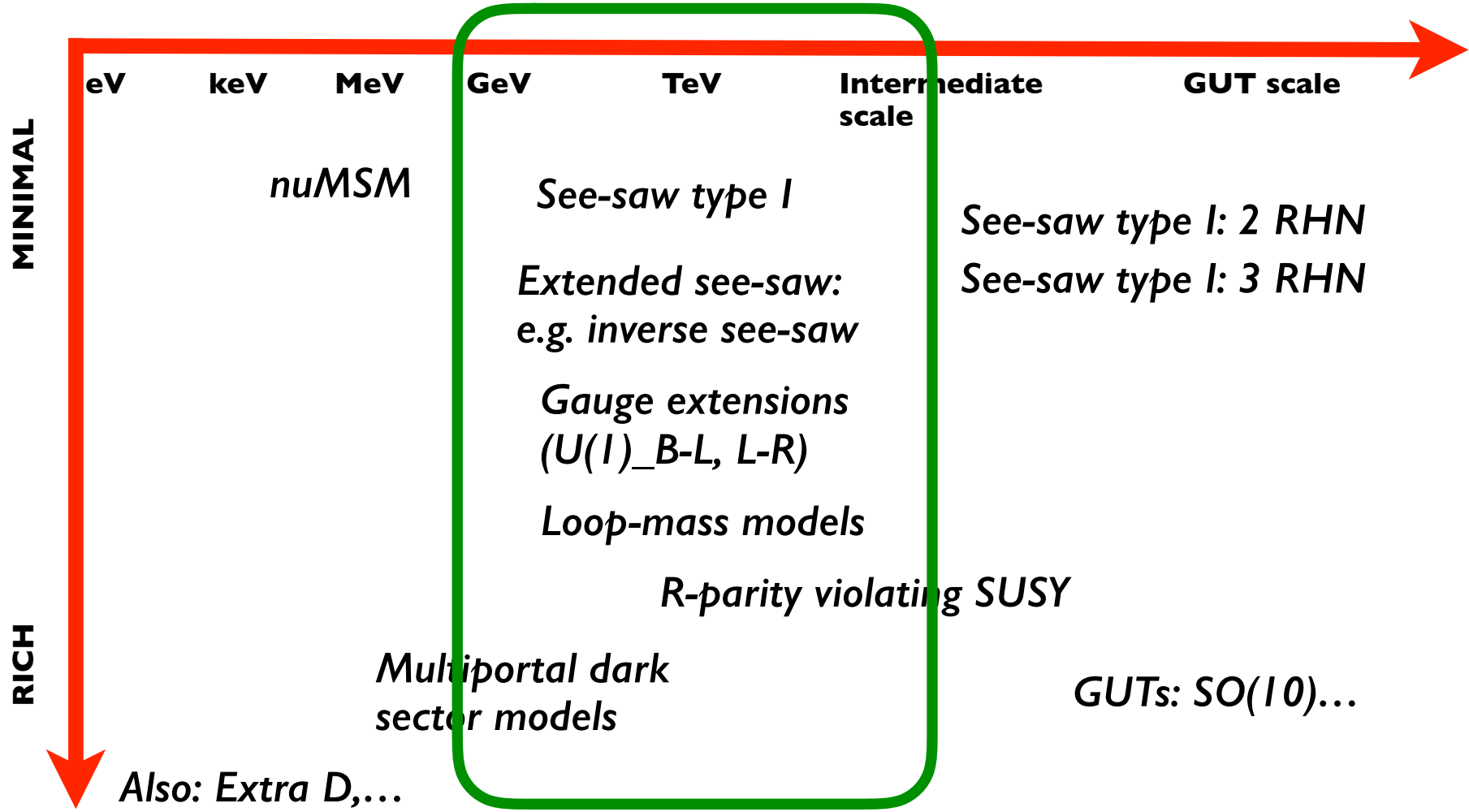


Two contrasting approaches can be taken:

Minimality: the fewest ingredients -> predictivity

Richness (theory-motivated): connections, new signatures

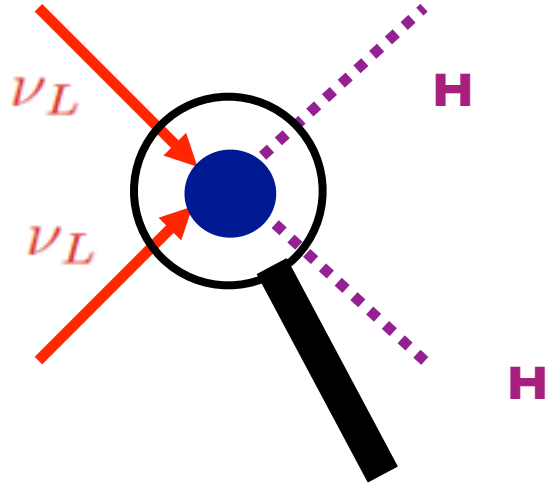
From minimality to richness



Two contrasting approaches can be taken:

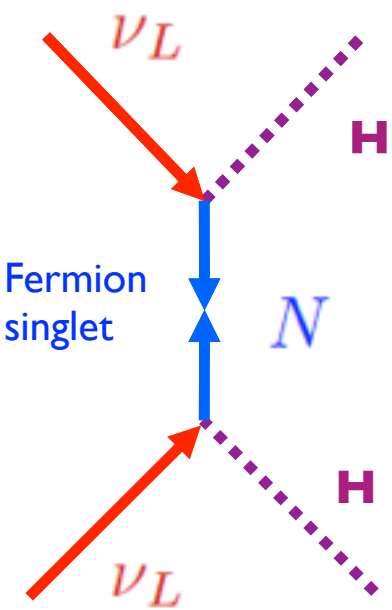
Minimality: the fewest ingredients -> predictivity

Richness (theory-motivated): connections, new signatures



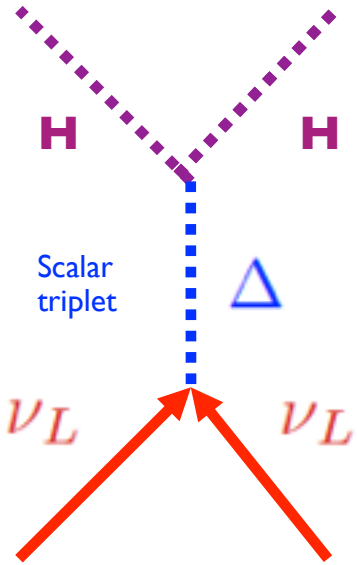
A **Majorana mass** can arise as the low energy realisation of a higher energy theory (new mass scale!).

See-saw Type I



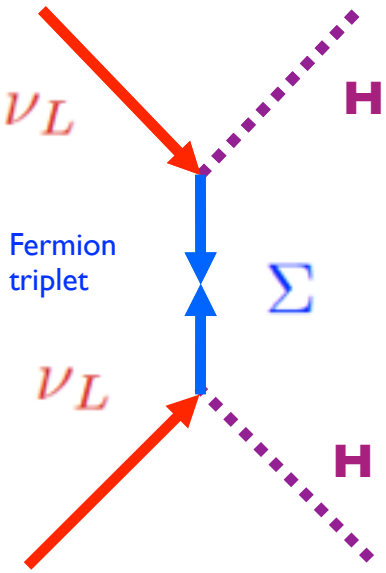
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic…

See-saw Type II



Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle…

See-saw Type III



Ma, Roy, Senjanovic, Hambye…

Most of the LNV models include new singlet fermions (sterile neutrinos) which generically mix with the light neutrinos:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U_{4\times 4} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Flavour state

Massive state

Nearly-sterile neutrino, commonly called sterile neutrino

$$\mathcal{L} = \cdots + \bar{\ell}_L U_{\ell 4} \gamma_\mu \nu_{4,L} W^\mu + \mathrm{NC} + \mathrm{h.c.}$$

Adding sterile neutrinos to the Standard Model is a minimal extension BSM.

- Theory remains anomaly free.

- Can give origin to neutrino masses and explain their smallness (at least in some cases).

- GUT theories embedding L-R symmetries, e.g. SU(4), SO(10),... predict their existence.

- There is no unique motivation for choosing one mass scale instead of another (except for a naturalness principle: setting their mass to zero restores the lepton number symmetry).

What are TeV models?
and how to test them?

See talks at ECFA WG1 SRCH Meeting on HNLs at HET colliders, 17 Feb 2023.

Vanilla see-saw type I models

Symmetry magazine

- Introduce a right handed neutrino **N**
- Couples to the Higgs and has a Majorana mass

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

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

$$m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

See-saw type I models can be embedded in GUT and explain the baryon asymmetry via leptogenesis.
HNL masses can go from eV to GUT scale.

Naive expectation for the HNL-neutrino mixing (that enters in the SM CC and controls production and decay of HNL):

$$\sin^2\theta \sim \frac{m_\nu}{M_N} \sim \frac{0.1\ \mathrm{eV}}{1\ \mathrm{TeV}} \sim 10^{-13}$$

Tiny values

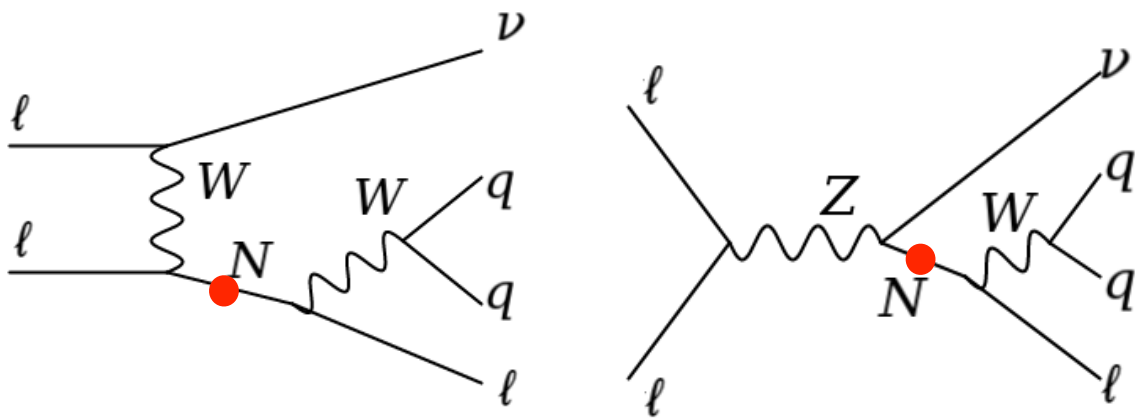
Pros:

- they explain "naturally" the smallness of masses
- they can be embedded in GUT theories!
- leptogenesis
- they can have many phenomenological signatures

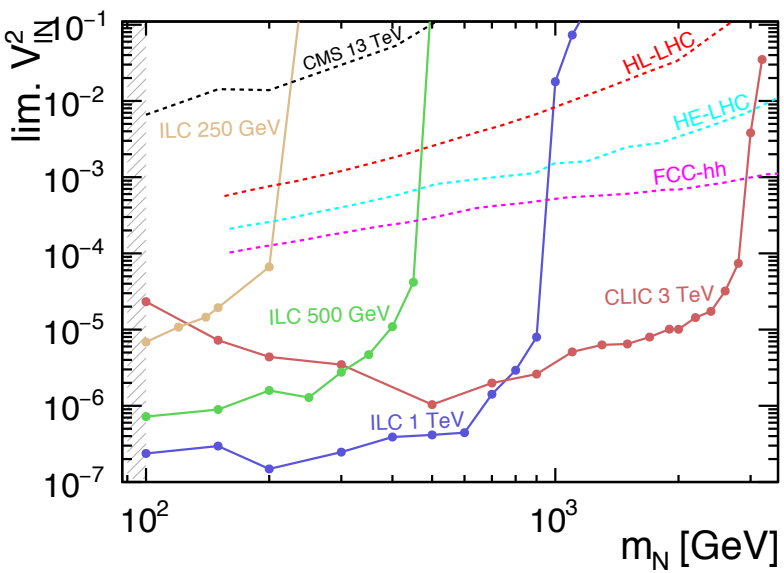
Cons:

- if M very heavy the new particles cannot be tested directly or the mixing with the new states is tiny
- many more parameters than measurable

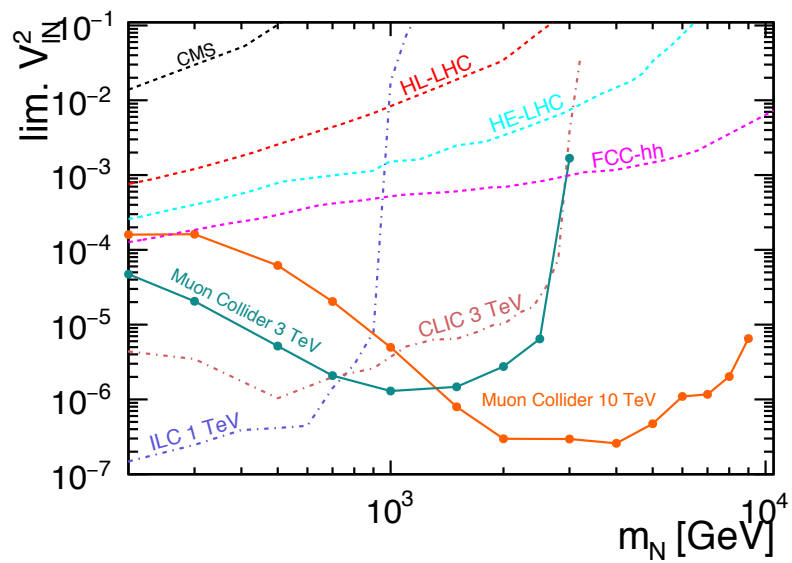
See-saw type I at colliders



Ns are produced and decay via mixing with neutrinos.



LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$



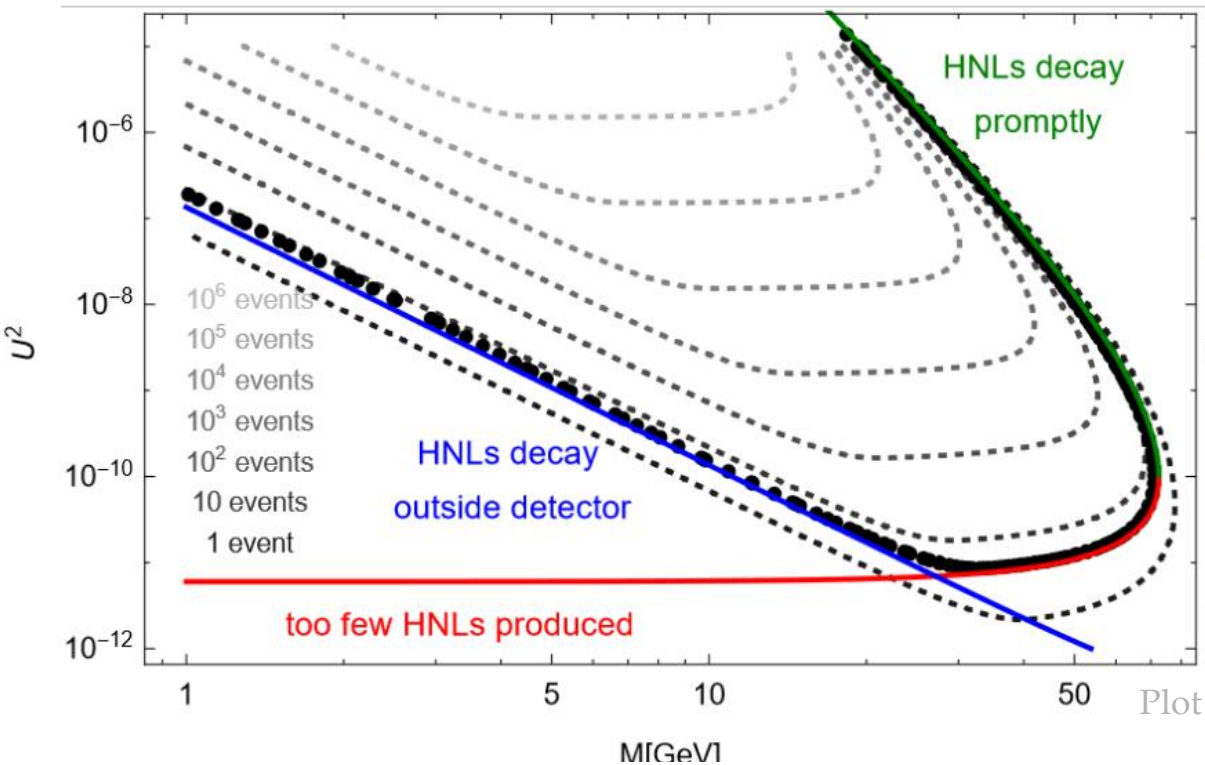
LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

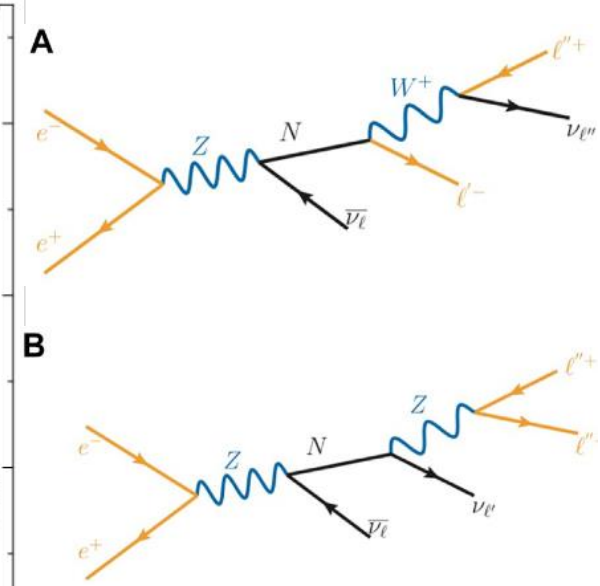
K. Mekala's talk

The decay rate scales as (for mN<MW)

$$\Gamma \sim g^4 U^2 \frac{m_N^5}{m_W^4}$$

and the decay length can be >>cm. Displaced vertices





proposed in Blondel et al 1411.5230

Plot and estimates from MaD 2210.17110

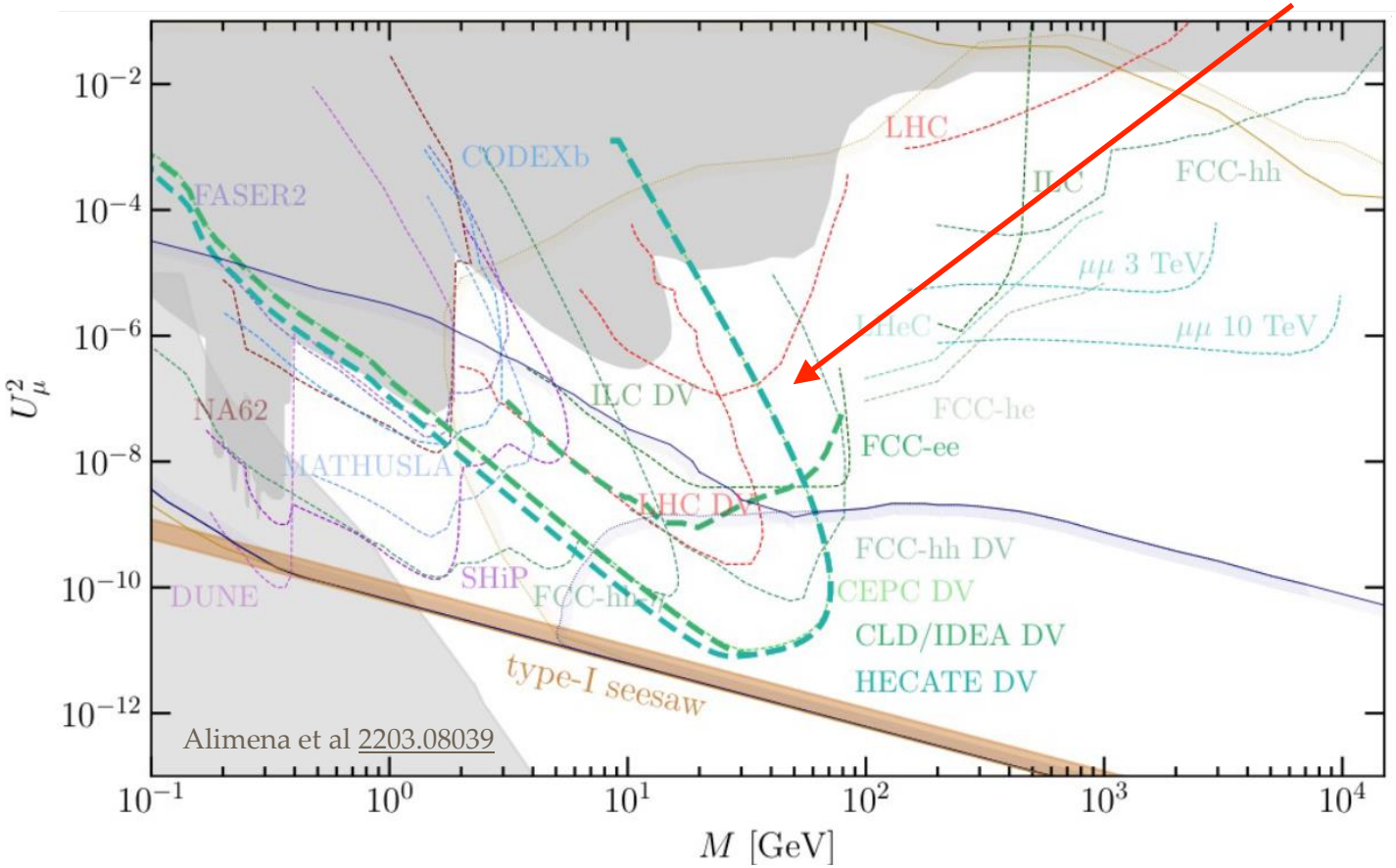
M. Drewes' talk

The decay rate scales as (for mN<MW)

$$\Gamma \sim g^4 U^2 \frac{m_N^5}{m_W^4}$$

and the decay length can be >>cm.

Displaced vertices



M. Drewes' talk

Symmetry-protected See-saw (inverse s-s etc)

Small neutrino masses can arise from the quasi-preservation of a symmetry (L number). Introduce two Ns: N1, N2.

$$m_\nu = \begin{pmatrix} 0 & Y v_H & \boxed{} \\ Y v_H & \boxed{} & \Lambda \\ \boxed{} & \Lambda & \boxed{} \end{pmatrix}$$

There is a preserved U(1)_L (L=1, N1=1, N2=-1) and neutrino masses are zero.

The L-breaking terms can be taken to be small as they are technically natural:

$$m_\nu = \begin{pmatrix} 0 & Y v_H & \epsilon Y v_H \\ Y v_H & \mu' & \Lambda \\ \epsilon Y v_H & \Lambda & \mu \end{pmatrix}$$

ISS: $\Lambda \gg \mu'$

$$m_5 \simeq -m_4 \simeq \Lambda \ , \ m_5 - |m_4| = \mu'$$

$$U_{\alpha 5} \simeq U_{\alpha 4} \simeq \frac{m_D}{\sqrt{2}\Lambda}$$

$$m_{tree} \simeq -m_D^T M^{-1} m_D \simeq \frac{v^2}{2(\Lambda^2 - \mu'\mu)} \left(\mu Y_1^T Y_1 \right.$$

A pseudoDirac HNL.

Large mixing with nus.

ESS: $\Lambda \ll \mu'$

$$m_4 \simeq -\frac{\Lambda^2}{\mu'} \ , \ m_5 \simeq \mu'$$

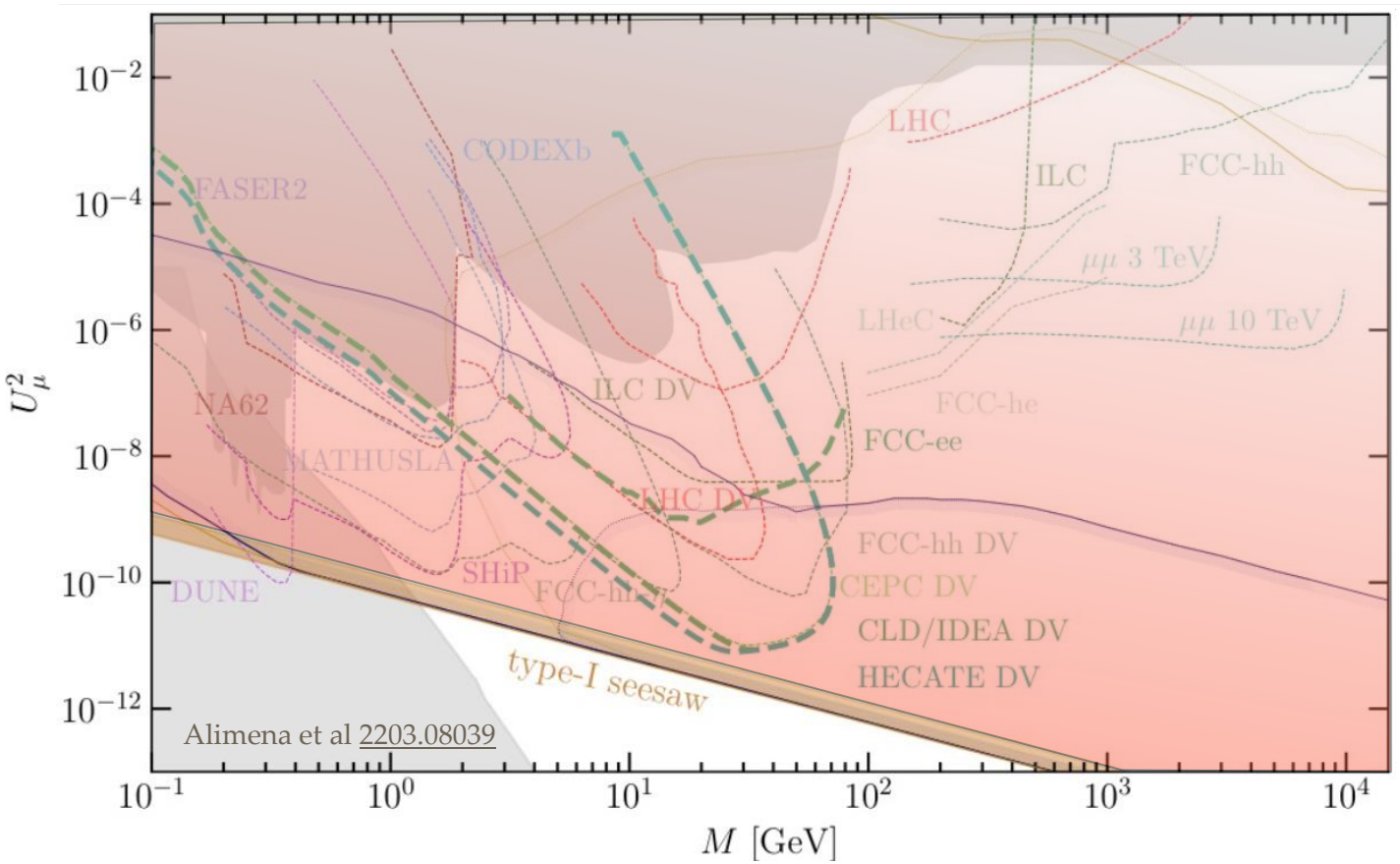
$$U_{\alpha 4} \simeq U_{\alpha 5} \sqrt{\frac{m_5}{|m_4|}} \simeq \frac{m_D}{\Lambda}$$

$$m_3 \simeq \frac{g'^2}{16\pi^2} \frac{m_D^2}{\Lambda^2} \mu' \mathcal{O}(1)$$

HNL see saw.

Large mixing with nus.

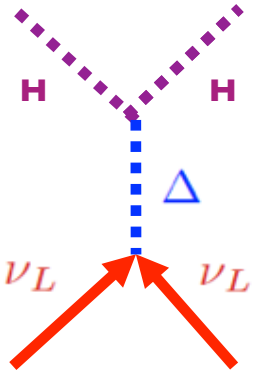
Larger mixing angles compared to the naive see-saw prediction are allowed and theoretically justified.



M. Drewes' talk

See-saw type II

We introduce a Higgs triplet which couples to the Higgs and left handed neutrinos. It has hypercharge 2.



$$\mathcal{L}_\Delta \propto y_\Delta L^T C^{-1} \sigma_i \Delta_i L + \text{h.c.}$$

with $$\Delta_i = \begin{pmatrix} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix}$$

Once the Higgs triplet gets a vev, Majorana neutrino masses arise:

$$\boxed{m_\nu \sim y_\Delta v_\Delta}$$

Type II seesaw

M. Nemevsek's talk

direct flavor relation with neutrino mass

involved phase space, limited experimental searches

See-saw type III

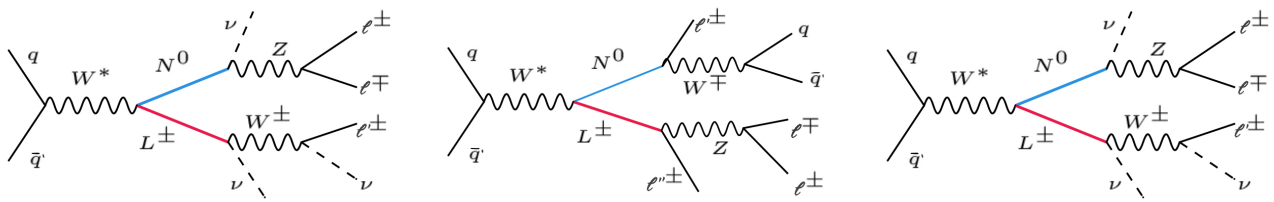
We introduce a fermionic triplet which has hypercharge 0.

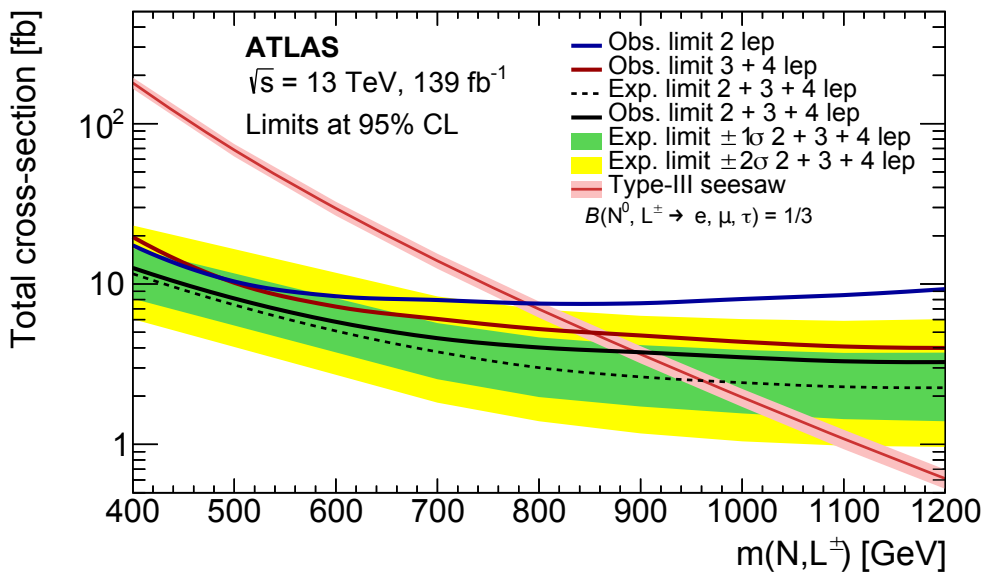
$$\mathcal{L}_T \propto y_T \bar{L} \sigma H \cdot T + \text{h.c.}$$

$$m_\nu \simeq -y_T^T M_T^{-1} y_T v_H^2$$

Type III seesaw: trileptons and dileptons+jets

ATLAS 2202.02039





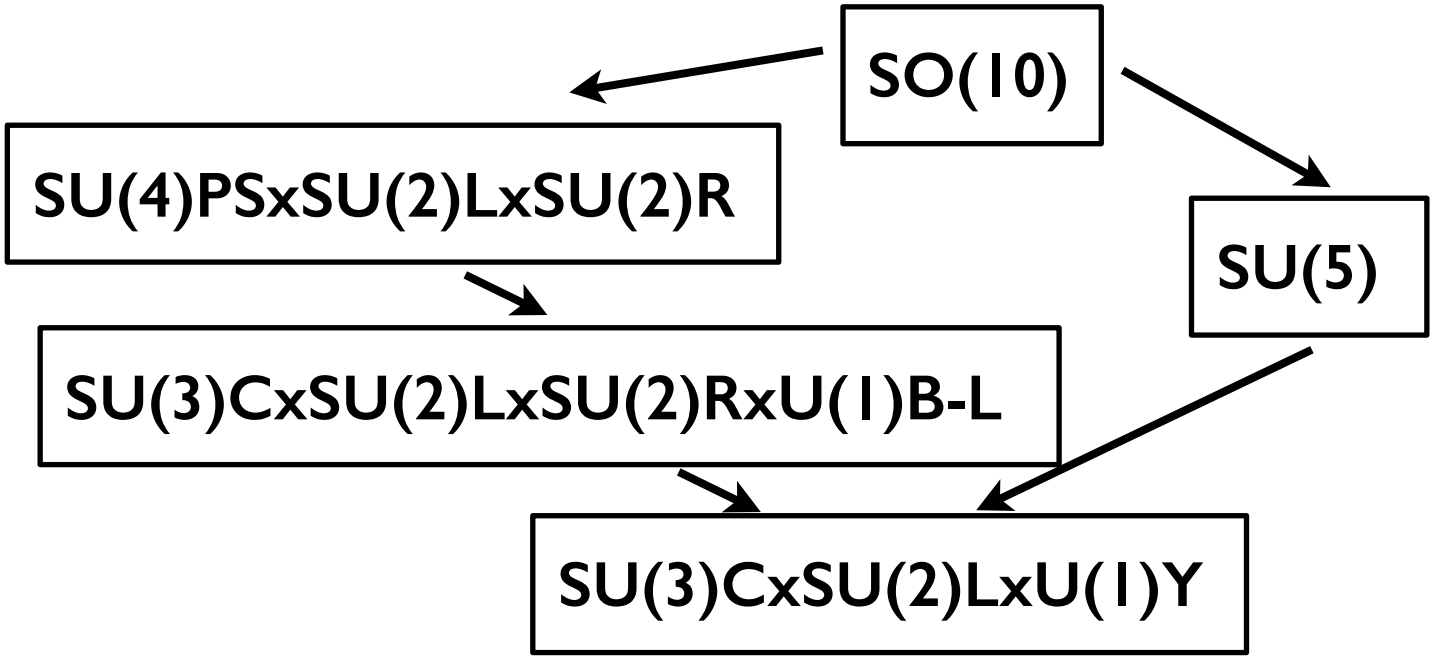
M. Nemevsek's talk

@Silvia Pascoli

Gauge models

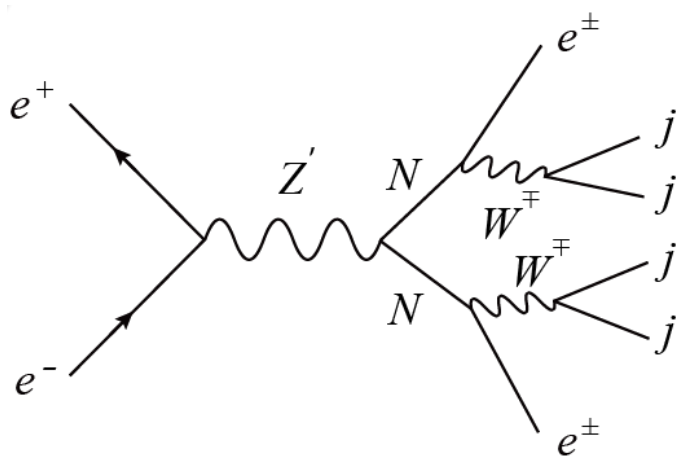
Gauge extensions of the SM at the TeV scale are possible:

- B-L: anomaly-free with Ns, typical remnant of GUT theories,
- combinations of Le, Lmu, Ltau, e.g. Lmu-Ltau;
- secluded U(1);
- L-R models: possible remnant of Pati-Salam, SO(10) models, can naturally embed NR.



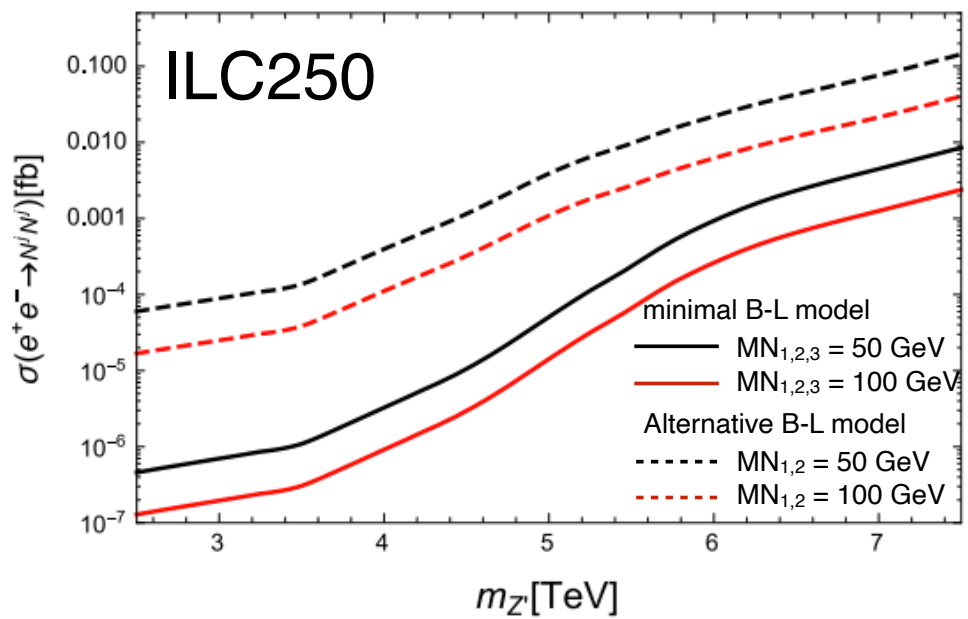
HNL production is not suppressed by the mixing angle but can proceed via large couplings. Decays can still be due to SM+mixing.

B-L extension: it contains a heavy Z' which couples with large couplings to HNLs.



s-channel via Z'

HL-LHC prospects limit for $U(1)_{B-L}$ model



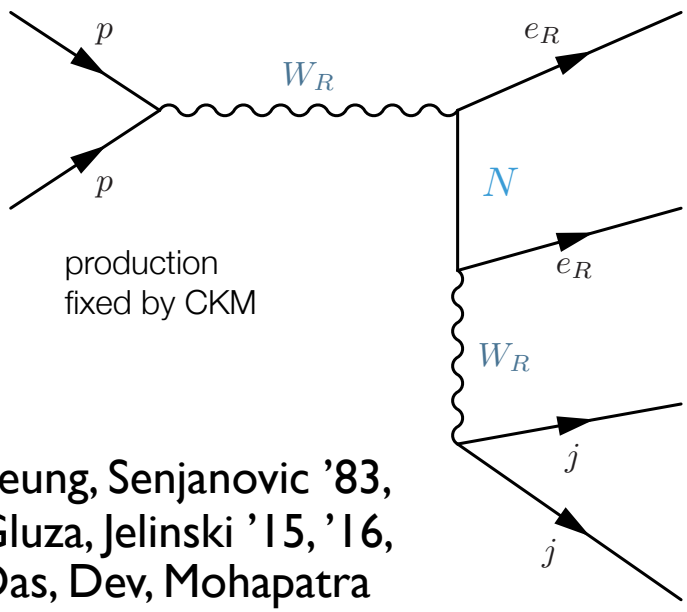
arXiV[1812.11931]

J. Nakajima's talk

$SU(2)_L \times SU(2)_R$ models have heavy R gauge bosons WR which can mediate the HNL production:

$$\mathcal{L}_Y \ni \overline{L}_L \left(Y\,\Phi + \tilde{Y}\,\tilde{\Phi} \right) L_R + Y_L L_L^T C \Delta_L L_L + Y_R L_R^T C \Delta_R L_R + \text{h.c.}$$

Seesaw $\quad M_\nu = -M_D^T M_N^{-1} M_D + M_L$

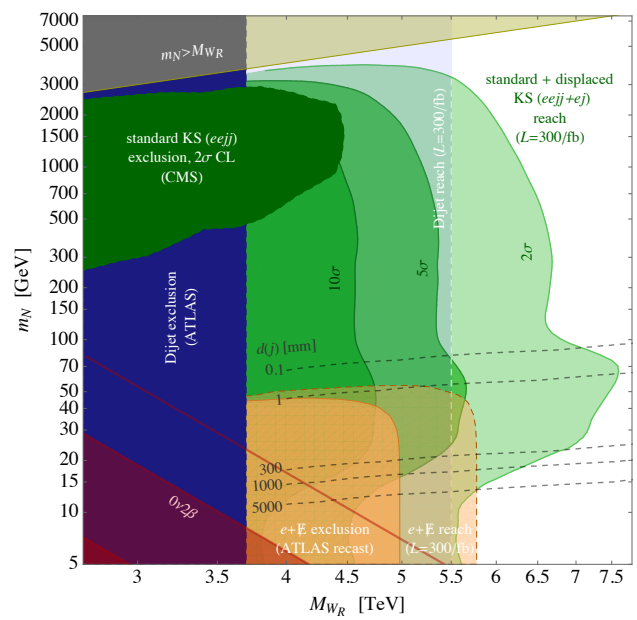


production
fixed by CKM

Leung, Senjanovic '83, Gluza, Jelinski '15, '16, Das, Dev, Mohapatra '17, Gobble et al., '20

Search overview $pp \to W_R \to \ell_R N$

MN, Nesti, Popara '18



standard prompt isolated mode

Ng et al.'15, Ruiz '17

merged neutrino jet $\ell\, j_N$

Mitra, Ruiz, Spannowsky '16

displaced jet $\ell\, j_N^d$

Cottin, Helo, Hirsch '18
Cottin, Helo, Hirsch, Silva '19

invisible: prompt $\ell + E_{miss}$

relevant for any light N search (SHIP, FASER, MATHUSLA, etc.)

M. Nemevsek's talk

Secluded U(1)

We consider a model in which we introduce a new U(1) gauge interaction under which the SM is neutral but new fermions are charged. In order to break the symmetry a new scalar is introduced.

$$\mathscr{L} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H)$$

Ballett et al., 1903.07589

$$- \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \overline{N} i \partial\!\!\!/ N + \overline{\nu_D} i D\!\!\!/ \nu_D$$

$$- \left[y_\nu^\alpha (\overline{L_\alpha} \cdot \widetilde{H}) N^c + \frac{\mu'}{2} \overline{N} N^c + y_N \overline{N} \nu_D^c \Phi + \text{h.c.} \right]$$

$$\mathscr{L} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H)$$

Ballett et al., 1903.07589

$$- \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \overline{N} i \partial\!\!\!/ N + \overline{\nu_D} i D\!\!\!/ \nu_D$$

$$- \left[y_\nu^\alpha (\overline{L_\alpha} \cdot \widetilde{H}) N^c + \frac{\mu'}{2} \overline{N} N^c + y_N \overline{N} \nu_D^c \Phi + \text{h.c.} \right]$$

After symmetry breaking, the theory contains:

- heavy neutral fermions which mix with the neutrinos;

$$\mathscr{L} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H)$$

Ballett et al., 1903.07589

$$- \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \overline{N} i \partial\!\!\!/ N + \overline{\nu_D} i D\!\!\!/ \nu_D - \frac{\sin\chi}{2} X_{\mu\nu} B^{\mu\nu}$$

$$- \left[y_\nu^\alpha (\overline{L_\alpha} \cdot \widetilde{H}) N^c + \frac{\mu'}{2} \overline{N} N^c + y_N \overline{N} \nu_D^c \Phi + \text{h.c.} \right]$$

After symmetry breaking, the theory contains:

- heavy neutral fermions which mix with the neutrinos;
- a dark photon, which generically mixes via a vector portal;

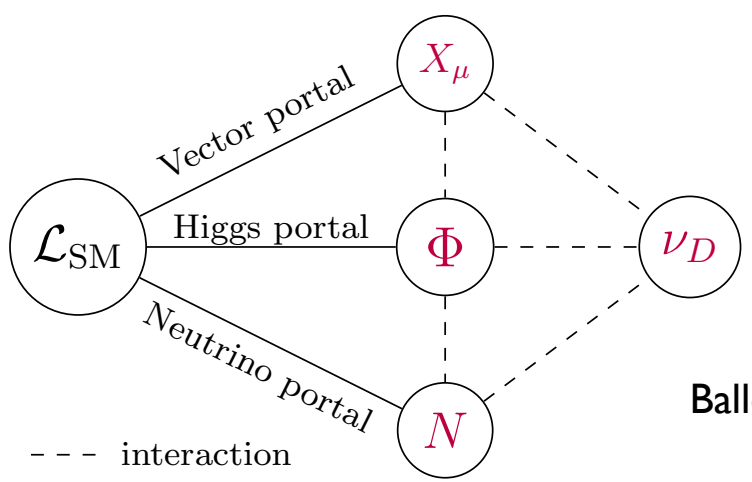
$$\lambda_{\Phi H}\, H^\dagger H\, |\Phi|^2$$

$$\mathscr{L} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H) - \frac{\sin\chi}{2} X_{\mu\nu} B^{\mu\nu}$$
$$- \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \overline{N} i \partial\!\!\!/ N + \overline{\nu_D} i D\!\!\!/ \nu_D$$
$$- \left[y_\nu^\alpha (\overline{L_\alpha} \cdot \widetilde{H}) N^c + \frac{\mu'}{2} \overline{N} N^c + y_N \overline{N} \nu_D^c \Phi + \text{h.c.} \right]$$

Ballett et al., 1903.07589

After symmetry breaking, the theory contains:

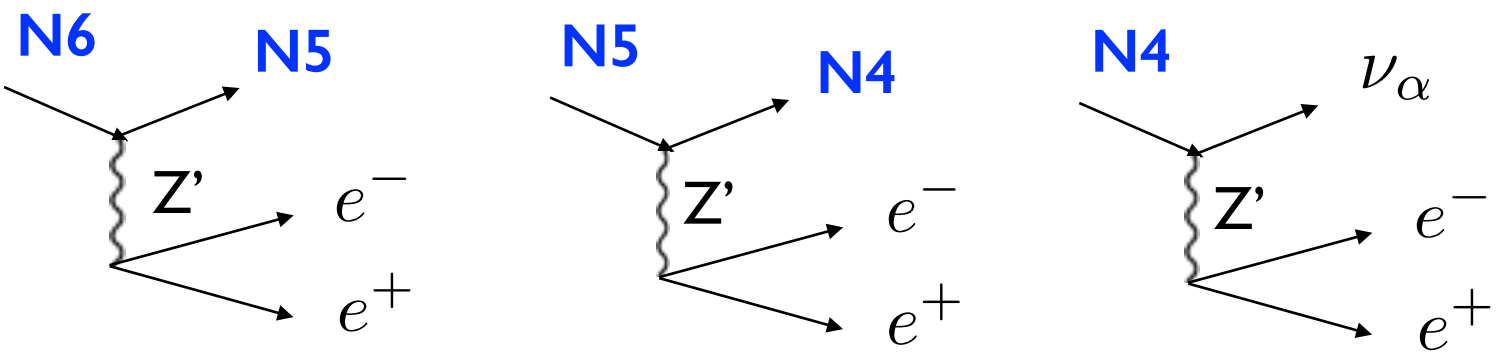
- heavy neutral fermions which mix with the neutrinos;
- a dark photon, which can mix via a vector portal;
- a massive scalar which generically mixes with the Higgs.



Ballett et al., 1903.07589

Ballett et al., PRD 99 (2019)

A typical signature are decay chains as the heavy N can decay into lighter N multiple times:



The decays can be much faster than in the SM + mixing.

Unique signature:

- if decays are fast this would lead to many leptons and/or jets;
- if (some of the) decays are slow, there could be multiple displaced vertices.

Searches of LNV or LFV models at future colliders

Lepton Number Violation

LNV is a key question in particle physics.
LN is an accidental symmetry of the SM. Its violation can be linked to the origin of neutrino masses, leptogenesis, phase transitions…

Leptogenesis in see-saw models

There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.18 \pm 0.06) \times 10^{-10}$$

Planck, 1502.01589, AA 594

In order to generate it dynamically in the Early Universe, the Sakharov's conditions need to be satisfied:

- B (or L) violation;
- C, CP violation;
- departure from thermal equilibrium.

- At T>M, N are in equilibrium:

$$N \leftrightarrow \ell H \qquad N \leftrightarrow \ell H \qquad N \leftrightarrow \ell H \qquad N \leftrightarrow \ell H \qquad N \leftrightarrow \ell H$$

- At T<M, N drops out of equilibrium:

$$N \to \ell H \qquad N \to \ell^c H^c \qquad N \to \ell H \qquad N \to \ell^c H^c \qquad N \to \ell^c H^c$$

- A lepton asymmetry can be generated if

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \ell^c H^c)$$

- $$\Delta L \xrightarrow{sphalerons} \Delta B$$

T

M

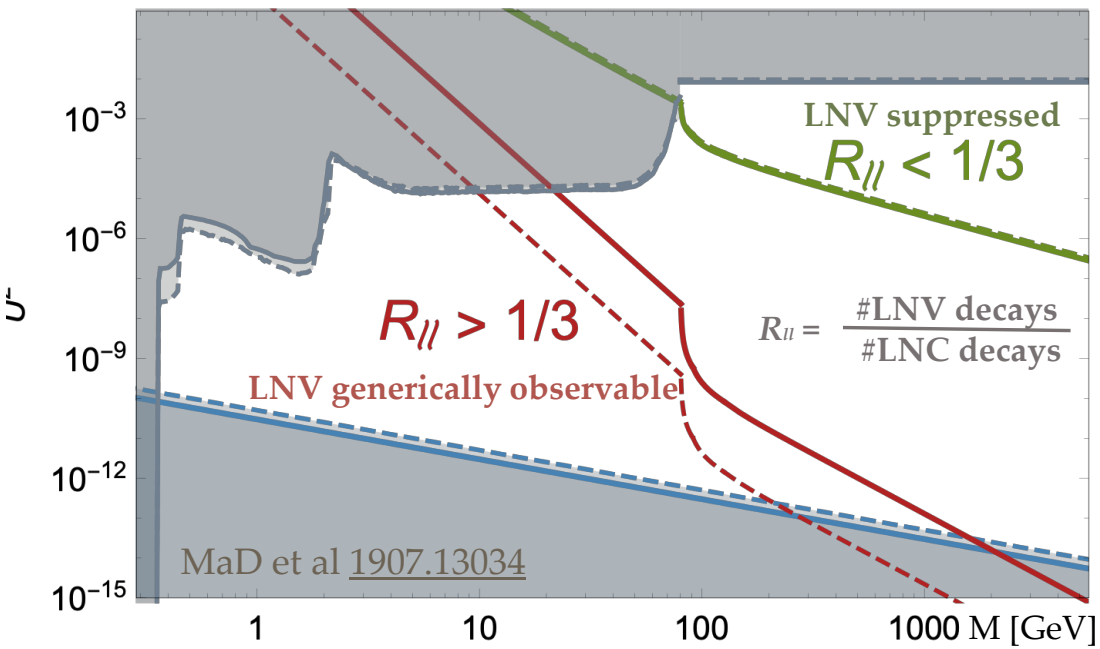
T=100 GeV

Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani PLB 384; Buchmuller, Plumacher, Annal. Phys. 315, ...

In see-saw type, LNV is strictly connected to neutrino masses and LNV al colliders is very suppressed:

$$\sin^2\theta \sim m_\nu / M_N$$

In extended see-saws, mixing can be larger but LNV (related to Δm_N) is still suppressed as two quasi-degenerate HNL can behave as a Dirac particle.



- **Quasi-degenerate HNLs kinematically indistinguishable**
- **behave like one particle with non-integer R_{ll}!**

e.g. Anamiati et al 1607.05641

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}$$

see talk by Jan Hajer

J. Hajer's and M. Drewes' talks

Signals can be enhanced in gauge or extended models.

Conclusions

Neutrinos are the most elusive and mysterious of the known particles.

Current status: precise knowledge of most of neutrino properties. Key questions open (nature, CPV) due to be answered in the next decade. Thriving experimental programme.

Neutrino masses only particle physics evidence BSM. What is the origin of neutrino masses?

Link with colliders Neutrino mass models at the TeV scale assume new particles and interactions that may be tested in (lepton) colliders. LNV is a key observable and directly linked with neutrino masses (and leptogenesis?).

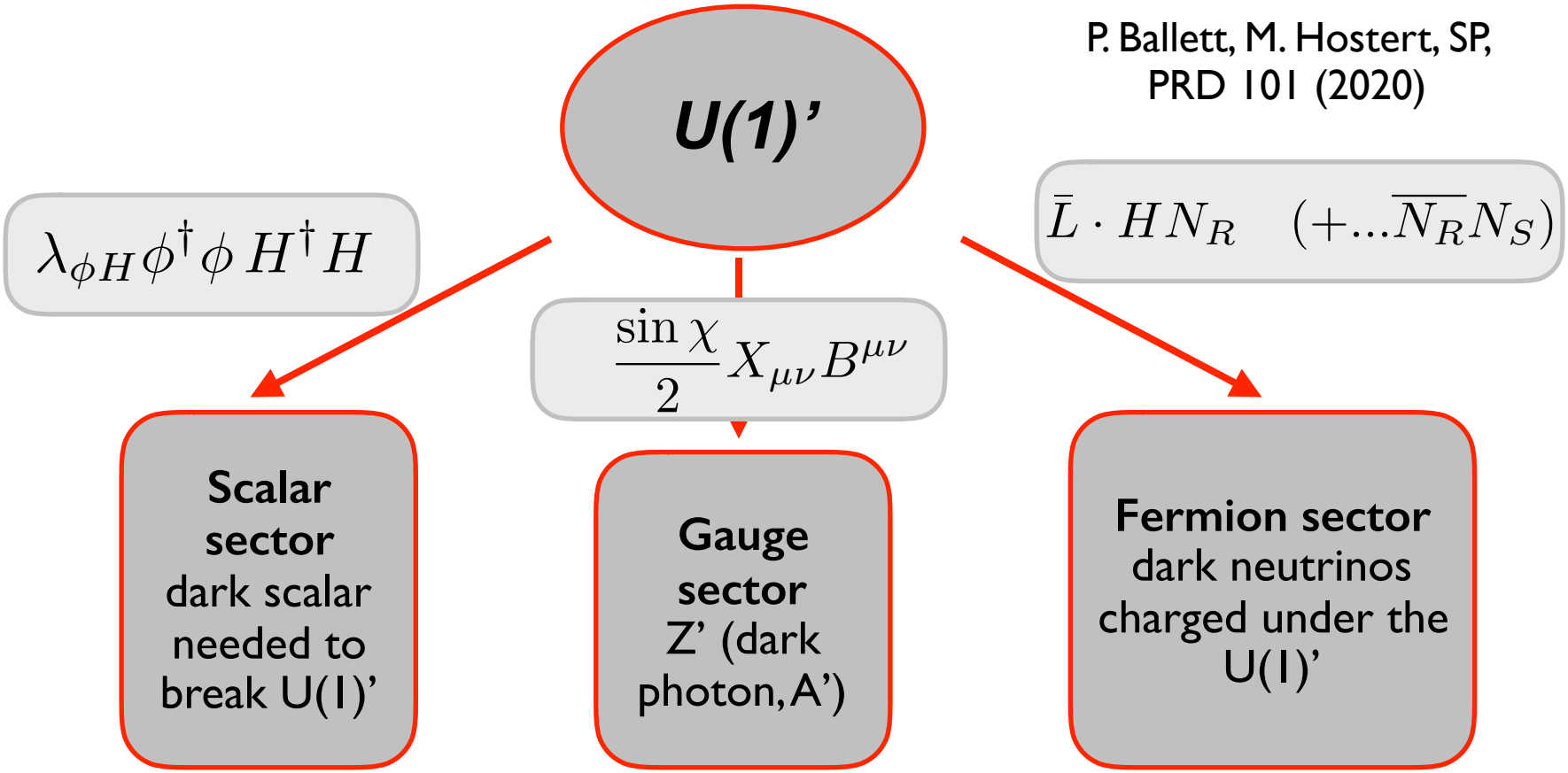
What is the new physics scale?

An application of rich dark sectors

A dark sector scenario

We extend the gauge sector via new U(1)'.

P. Ballett, M. Hostert, SP, PRD 101 (2020)



The phenomenology of this type of models can be very different from the standard case.

A specific 3-portal model

The Lagrangian is given by

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin\chi}{2} X_{\mu\nu} B^{\mu\nu}$$
$$+ \left(D_\mu \Phi\right)^\dagger \left(D^\mu \Phi\right) - V(\Phi) - \lambda_{\Phi H} \left|H\right|^2 \left|\Phi\right|^2$$
$$+ \overline{\widehat{\nu}_N} i \partial\!\!\!/ \widehat{\nu}_N + \overline{\widehat{\nu}_D} i D\!\!\!/_X \widehat{\nu}_D - \Big[(\overline{L} \widetilde{H}) Y \widehat{\nu}_N^c + \overline{\widehat{\nu}_N} Y_L \widehat{\nu}_{D_L}^c \Phi$$
$$+ \overline{\widehat{\nu}_N} Y_R \widehat{\nu}_{D_R} \Phi^* + \frac{1}{2} \overline{\widehat{\nu}_N} M_N \widehat{\nu}_N^c + \overline{\widehat{\nu}_{D_L}} M_X \widehat{\nu}_{D_R} + \text{h.c.} \Big]$$

A. Abdullahi, M. Hostert, SP, 2007.11813

The model is anomaly free thanks to the inclusion of two dark neutrinos with opposite charges. Other possibilities can also be considered (DM).

We focus on a scale of GeV: $v_\phi, m_{Z'} \sim \text{GeV}.$

New particles

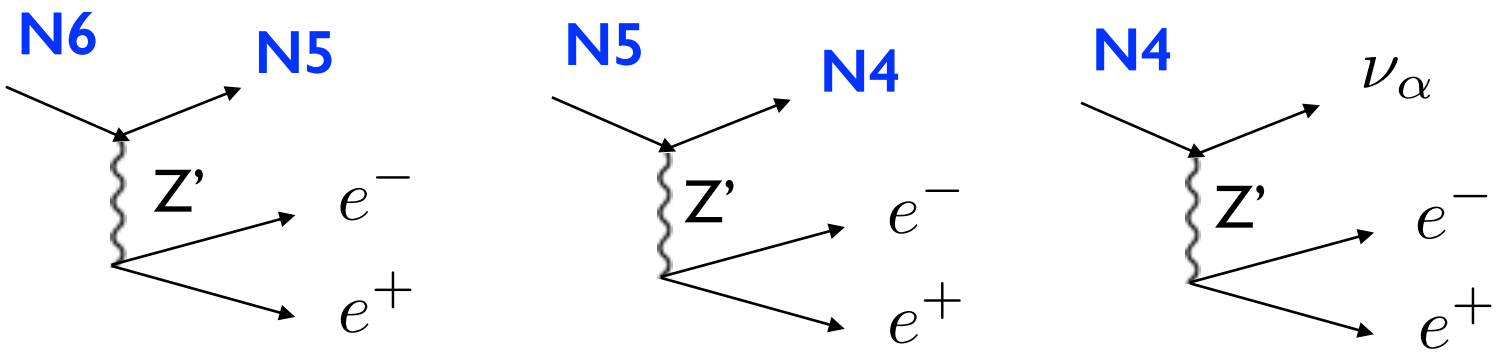
Z'/A' : mass $m_{Z'}$=1.25 GeV.

Z' decays predominantly into heavy neutrinos.

$\mathcal{B}(Z' \to N_i N_j)/\%$					
44	45	46	55	56	66
0.15	11	0.48	1.6	86	0.59

N6, N5, N4 : with 100s MeV masses.

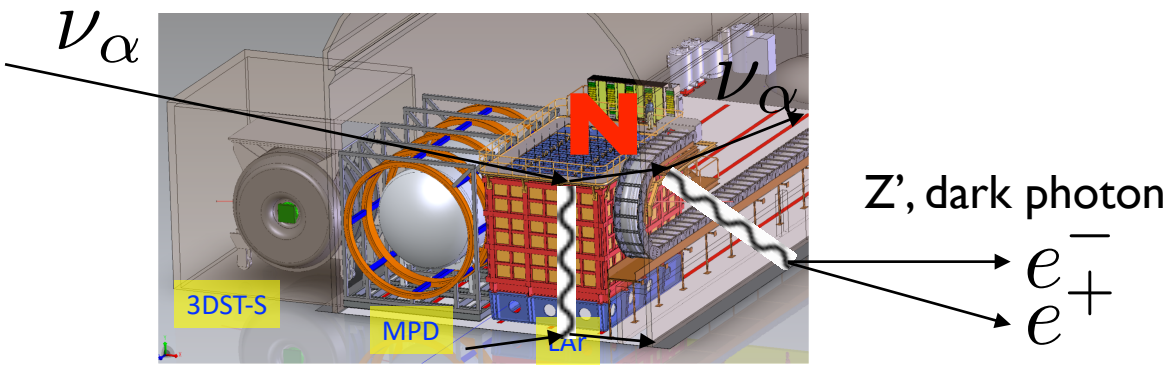
They decay via the new Z' into ee and neutrinos.



The decays are much faster than in the SM.

Unique signatures and future tests

The model has key signatures which can be tested.

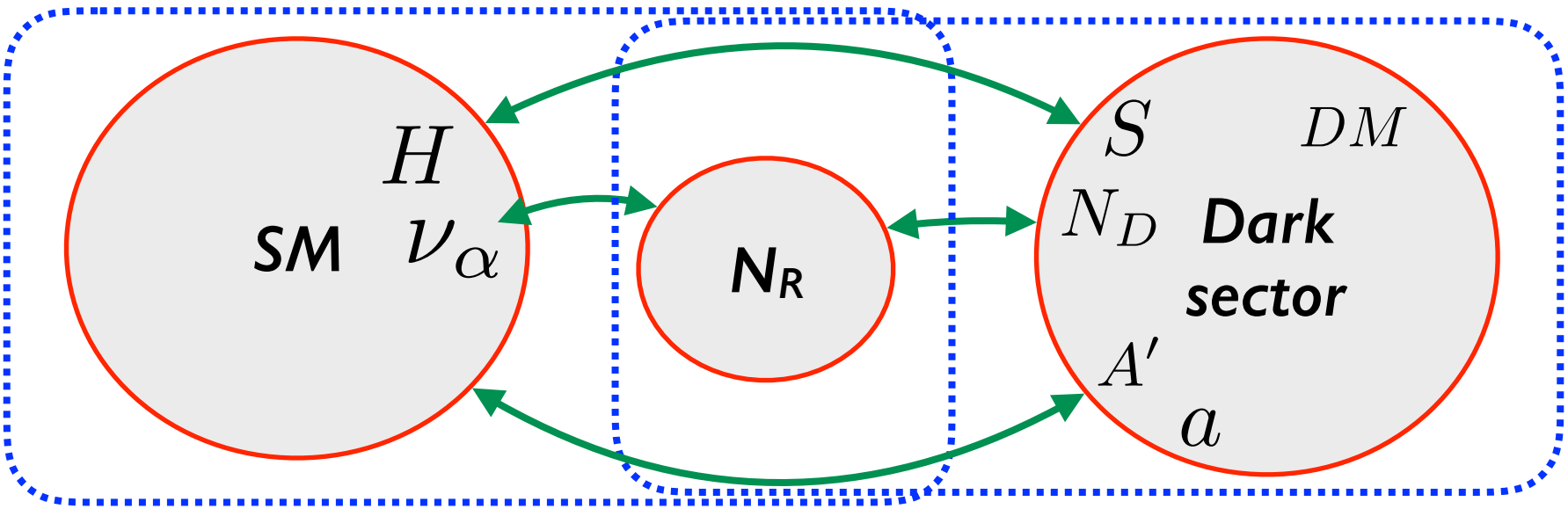


One can expect displaced vertices, decay chains and unique HNL and dark photon phenomenology (typically, semivisible decays):

- MicroBooNE, T2K ND, DUNE-ND;
- NA62&SHADOWS;
- Nu@LHC programme;
- NA64;
- BelleII and BESIII.

Neutrinos as a window to Dark sectors???

The dark or hidden sector indicate extensions of the SM that are below the electroweak scale.



Dark sectors can account for neutrino masses, the baryon asymmetry, dark matter.

This would be a major departure from "traditional" BSM thinking and open a very exciting experimental landscape.