Neutrinos: A theory outlook from high to low energies

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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Horizon2020

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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}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

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

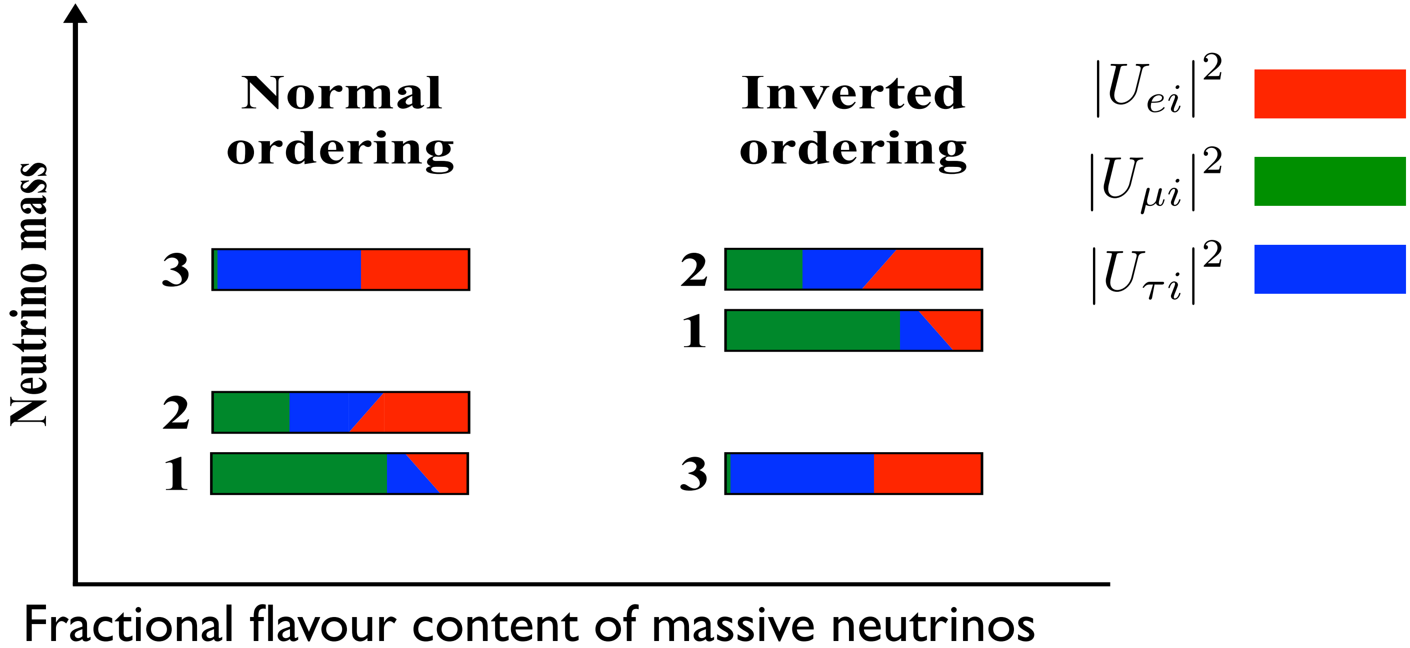
See I. Martinez-Soler's talk

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.



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

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

Measuring the masses requires:

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

Leptonic Mixing and CP-violation

The Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

CPV?

- θ_{23} maximal or close to maximal
- θ_{12} large but significantly different from maximal
- θ_{13} quite large: challenge to flavour models
- Mixings very different from those in the quark sector
- Possibly, large leptonic CPV. This is a fundamental question, possibly related to the origin of the baryon asymmetry and to the origin of the flavour structure.

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?

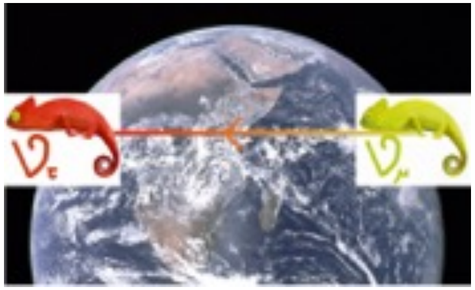
Very exciting experimental programme now and for the future.

	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

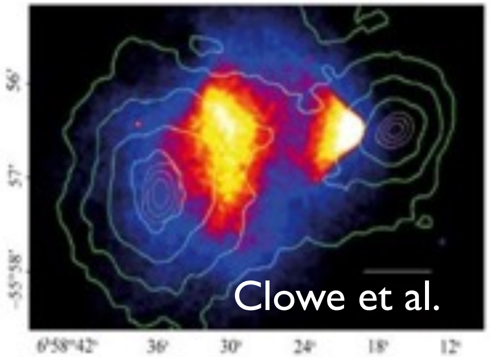
There is evidence that the Standard Model is incomplete: neutrinos play a key role.

Neutrino masses



Dark Matter

Baryon asymmetry



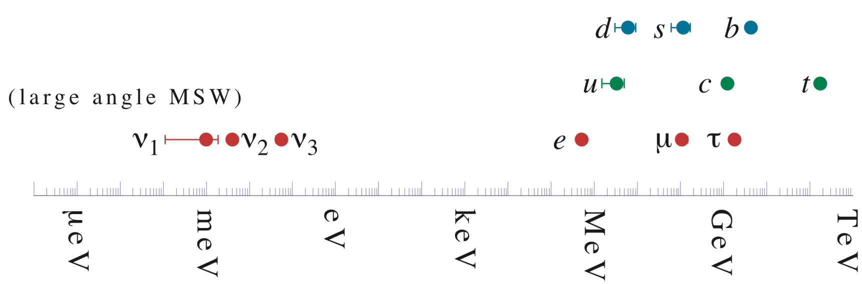
The ultimate goal is to understand

- 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?

Neutrino masses Beyond SM

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

Dirac Masses

If we introduce a right-handed neutrino, then an interaction with the Higgs boson emerges.

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.} \longrightarrow m_D = y_\nu v = V m_{\text{diag}} U^\dagger$$

This term is SU(2) invariant and respects lepton number.

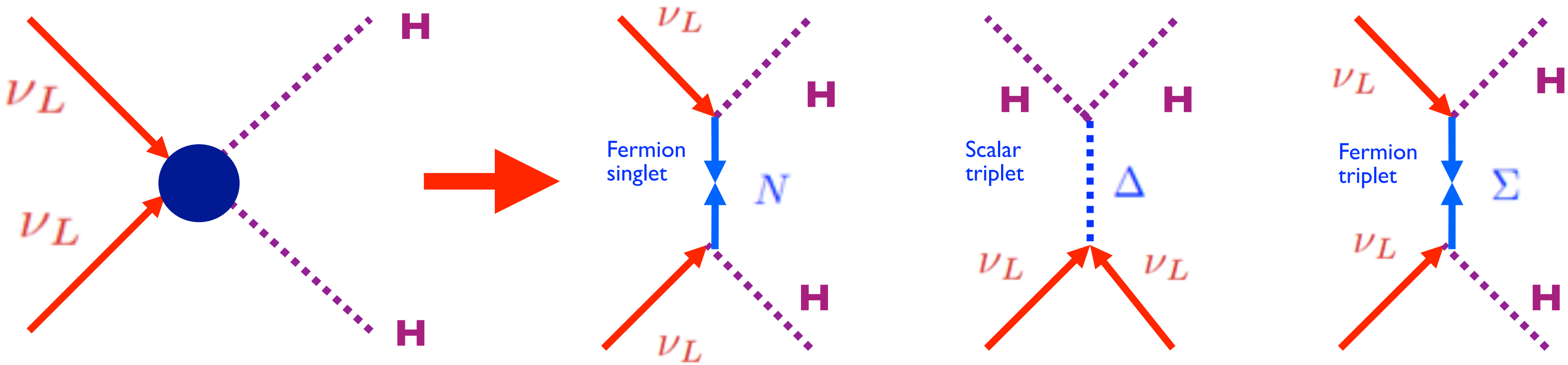
- why the coupling is so small??? $y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$
- why the leptonic mixing angles are large?
- why neutrino masses have at most a mild hierarchy?
- why no Majorana mass term for RH neutrinos? We need to impose L as a fundamental symmetry.

Majorana Masses

In order to have an SU(2) invariant Majorana 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



Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Ma, Mohapatra, Senjanovic, Magg, Wetterich, Lazarides, Shafi, Schecter, Valle, Hambye…

This term breaks lepton number and induces Majorana masses and Majorana neutrinos. It can be induced by a high energy theory (see-saw mechanism).

Neutrino masses BSM: "vanilla" see saw mechanism type I

Symmetry magazine

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

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

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

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

As a result, neutrinos can have naturally small masses and are Majorana particles.

For leptogenesis, see J. Turner's talk.

What is the new physics scale?

Are there new:

symmetries?

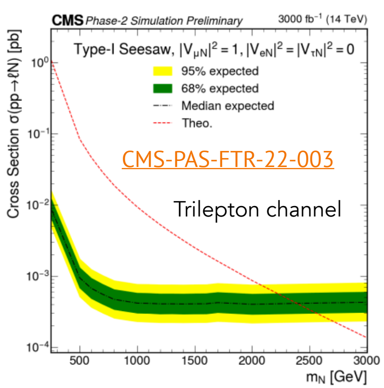
particles?

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...



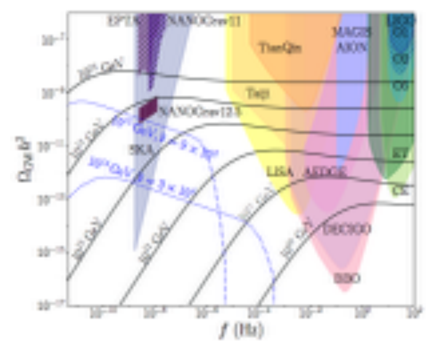
LHC searches

J. Xiao's talk at Neutrino2022

See J. Turner's talk

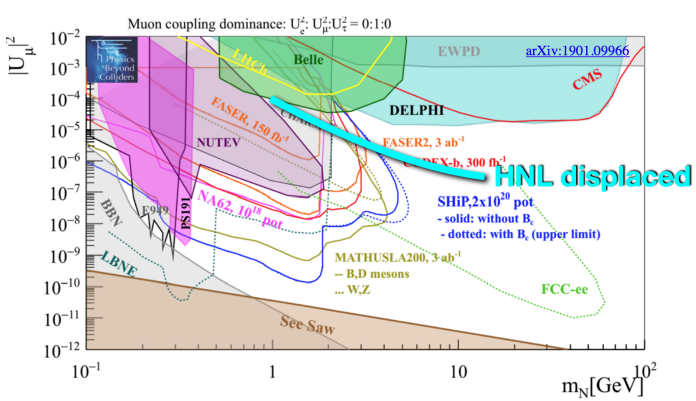
Leptogenesis

CLFV



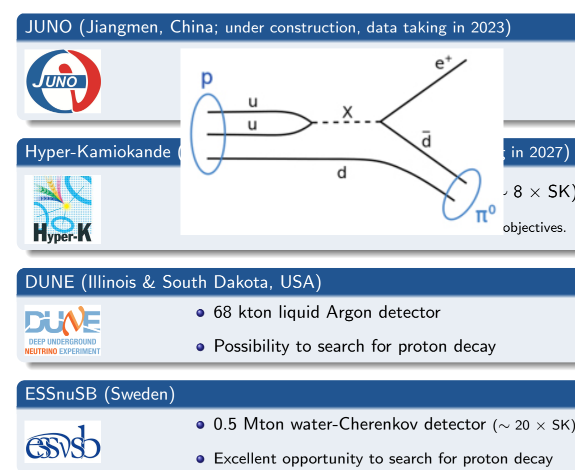
GW

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



Proton decay

T. Ohlsson's talk at Neutrino2022



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

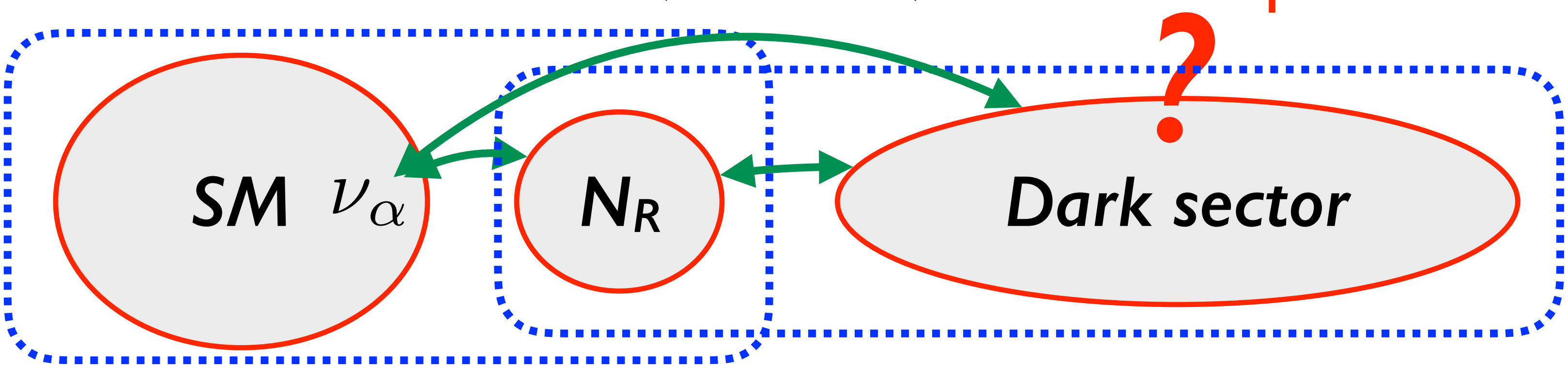
DM

Leptogenesis

HNL searches: peak, kinks, decays,

Neutrino play a unique role in searching for Dark Sectors.

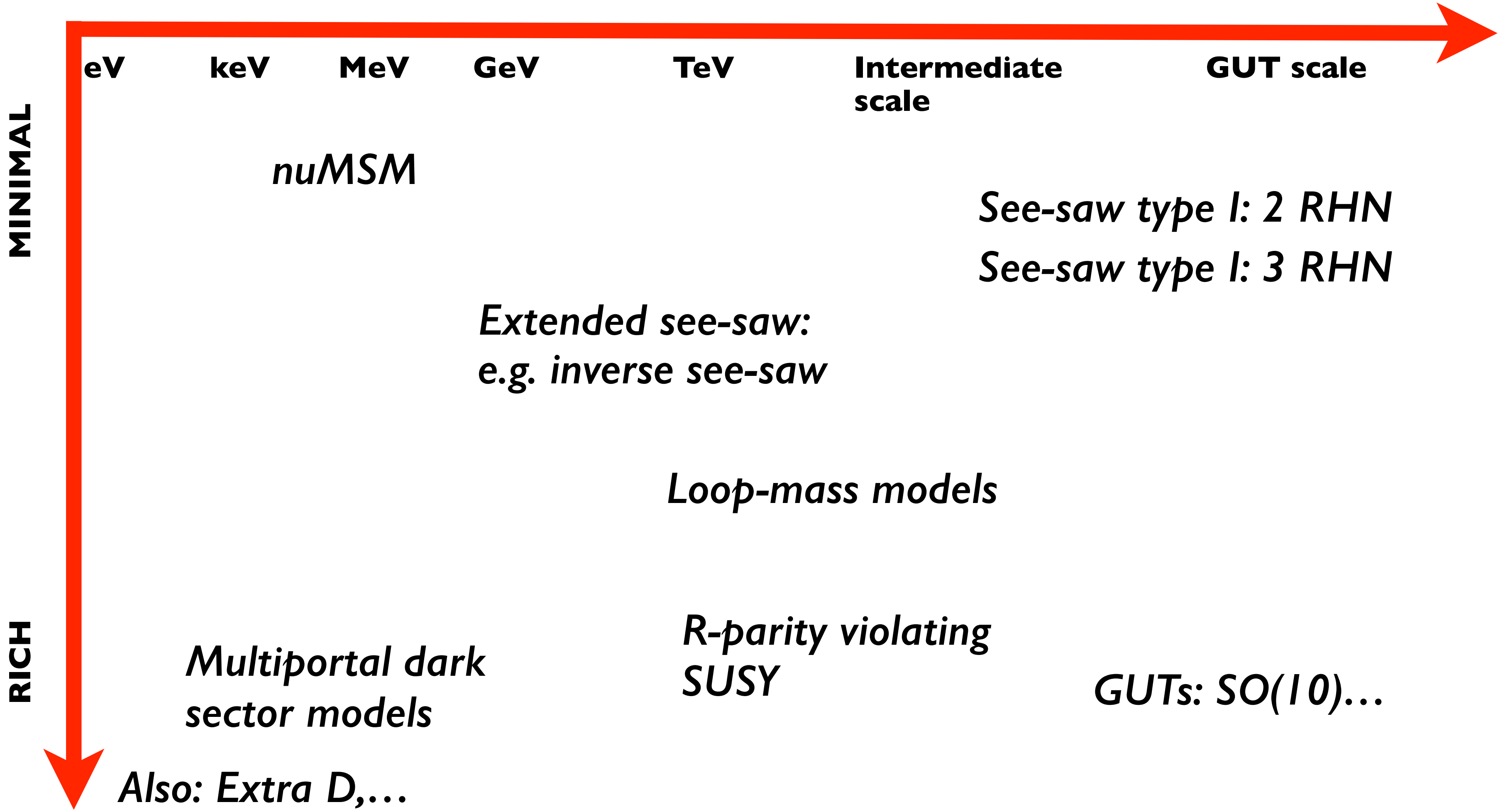
$\bar{L} \cdot H N_R \quad (+ ... \overline{N_R} N_S)$ Neutrino portal



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

See J Klaric's, A. Titov's talk

From minimality to richness



Two contrasting approaches can be taken:

Minimality: the fewest ingredients -> predictivity

Richness (theory-motivated): connections, new signatures

What is the new physics scale? Is it low???

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)

U(1)'

$$\lambda_{\phi H} \phi^\dagger \phi \, H^\dagger H$$

$$\frac{\sin\chi}{2} X_{\mu\nu} B^{\mu\nu}$$

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

Scalar sector
dark scalar needed to break U(1)'

Gauge sector
Z' (dark photon, A')

Fermion sector
dark neutrinos charged under the U(1)'

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

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

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

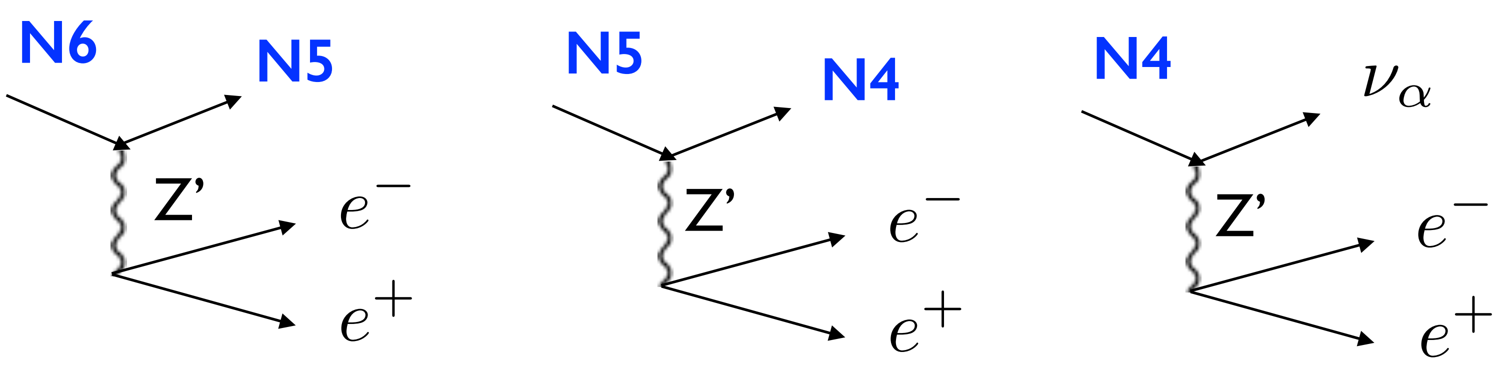
Z'/A' : mass $m_{Z'}$=1.25 GeV.

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.

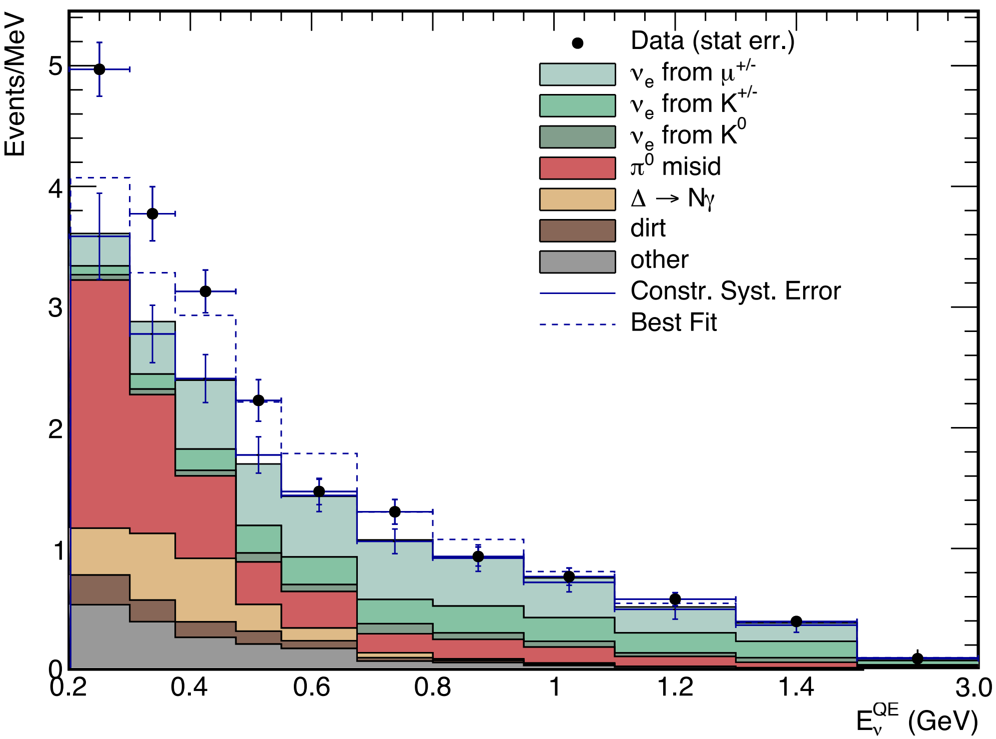
They decay via the new Z' into ee and neutrinos.

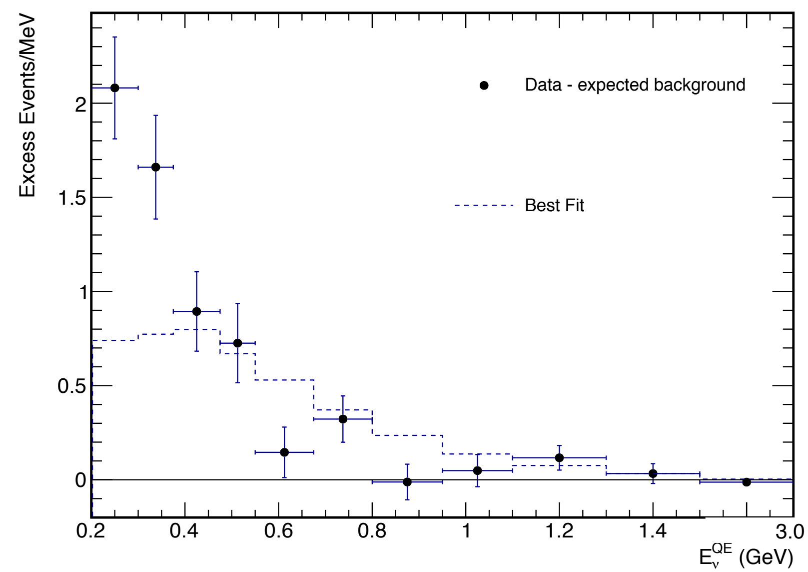


The decays are much faster than in the SM.

The MiniBooNE low-E excess

MiniBooNE reports a low-E excess which has increased in significance in the past couple of years (~3σ -> 4.7σ -> 4.8σ).

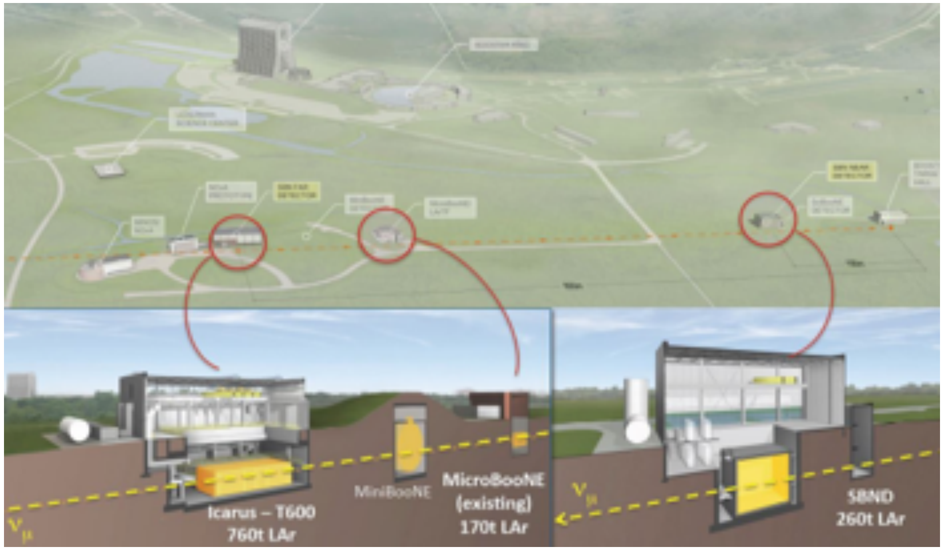




MiniBooNE Coll., PRL 121 (2018)

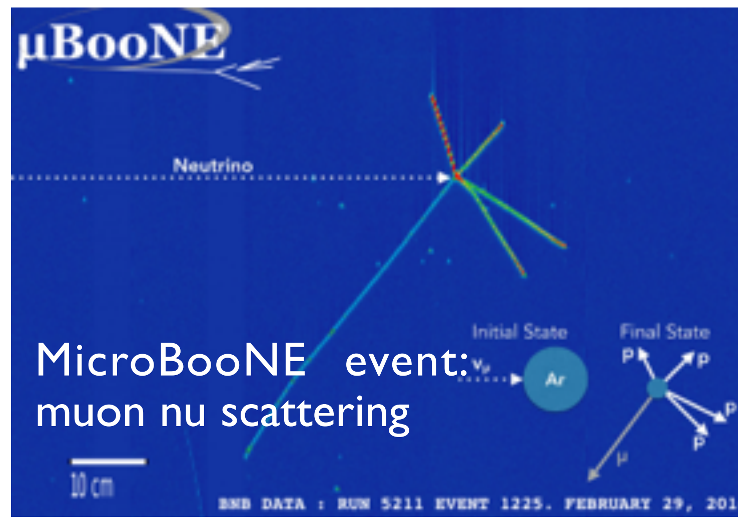
MicroBooNE and SBN at Fermilab

They use accelerator neutrinos with L~100-600m and E~700-800 MeV.



https://www.bo.infn.it/gruppo2/sbn-it/

MicroBooNE detector

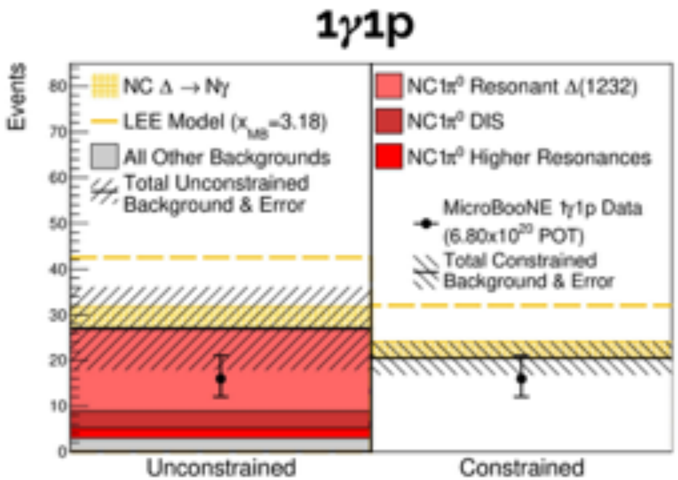


MicroBooNE event: muon nu scattering

Accelerator neutrino experiments should provide the definitive answer and can check both the appearance and disappearance channels.

First results from MicroBooNE.

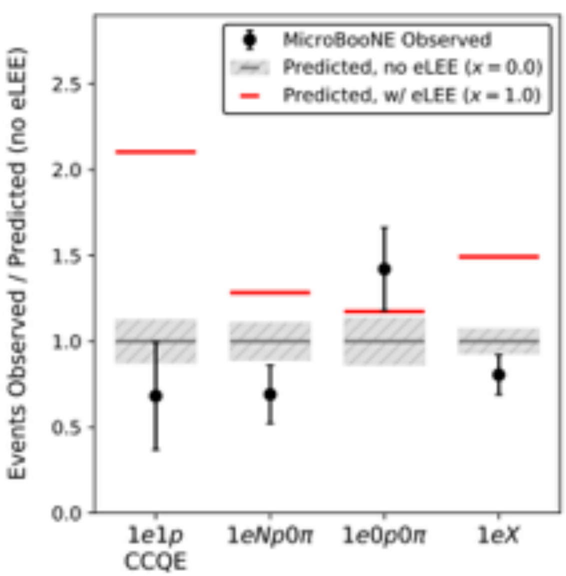
- Is the MiniBooNE LEE is due to SM photons?



My take:
Most likely not.

MicroBooNE Coll., 2110.00409

- Is the MiniBooNE LEE is due to electrons?



Electrons would come from nu_e scattering, and would signal neutrino oscillations.

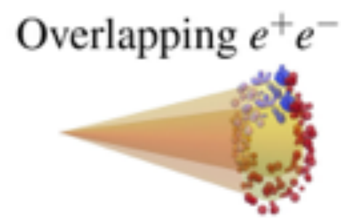
My take: Most likely not.

BSM explanations for MB LEE

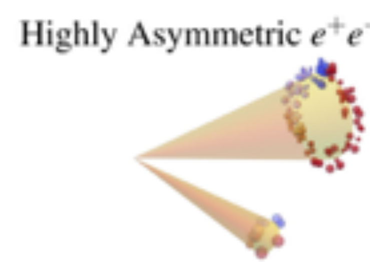
Due to the WC nature of MB, single electrons can be mimicked by photons and by electron-positron pairs (if overlapping or asymmetric).

Electrons? Or Photons? .....Or Neither?

Rich phenomenology developing in recent years around the possibility of the MiniBooNE excess being due to **e^+e^- pairs from decays of new exotic particles.**



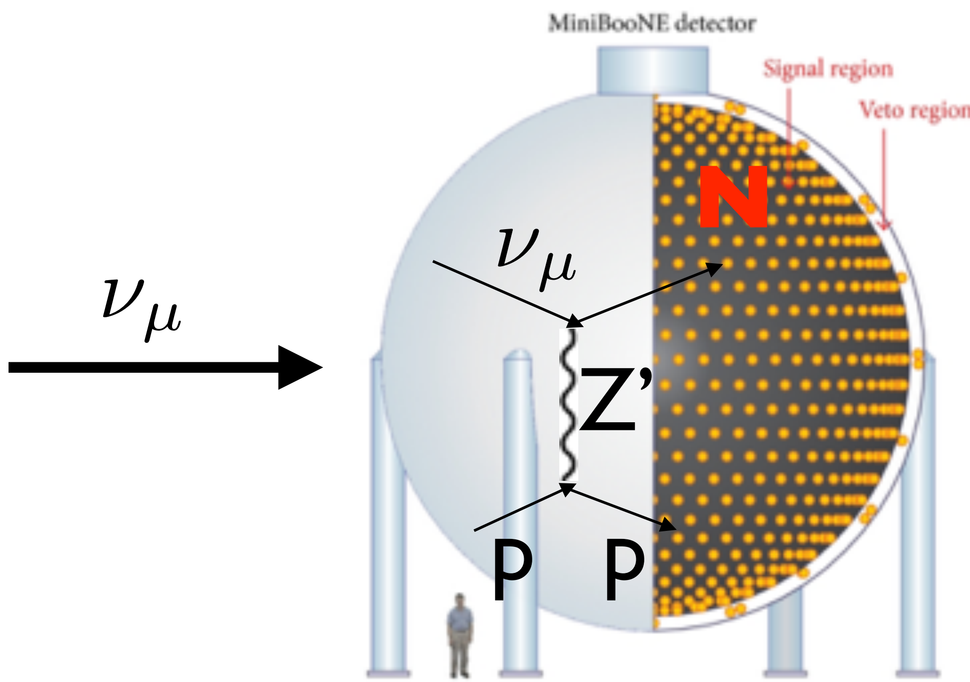
- Decays of **new dark gauge bosons** (Z')
  - E. Bertuzzo, S. Jana, P. A.N. Machado, R.Zukanovich Funchal Phys.Rev.Lett. 121 24, 241801(2018)
  - P. Ballett, S. Pascoli, M. RL Phys. Rev. D 99, 071701 (2019)
  - A. Abdullahi, M. Hostert, S.Pascoli Phys.Lett.B 820 136531(2021)
- General **Extended higgs sectors + Decay**
  - B. Dutta, S. Ghosh, T. Li Phys. Rev. D 102, 055017 (2020)
  - W. Abdallah, R. Gandhi, S. Roy Phys. Rev. D 104, 055028 (2021)
- Decays of **leptophilic axion-like** particles
  - C. V. Chang, C. Chen, S. Ho, S. Tseng Phys. Rev. D 104, 015030 (2021)

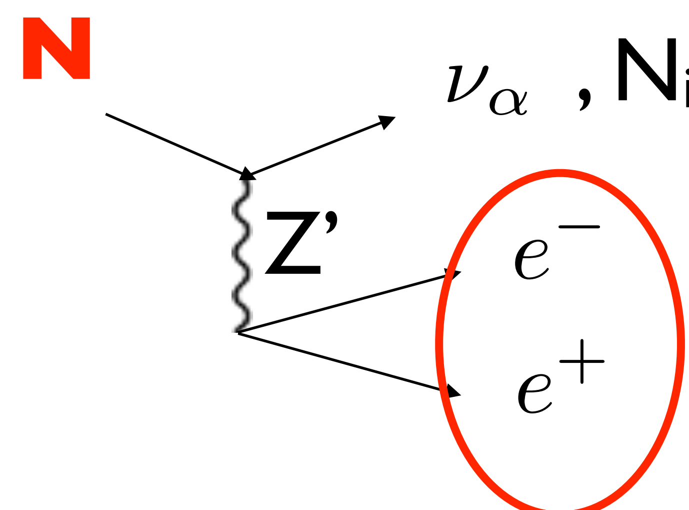


M. Ross-Lonergan's talk at Fermilab, 04/10/2021

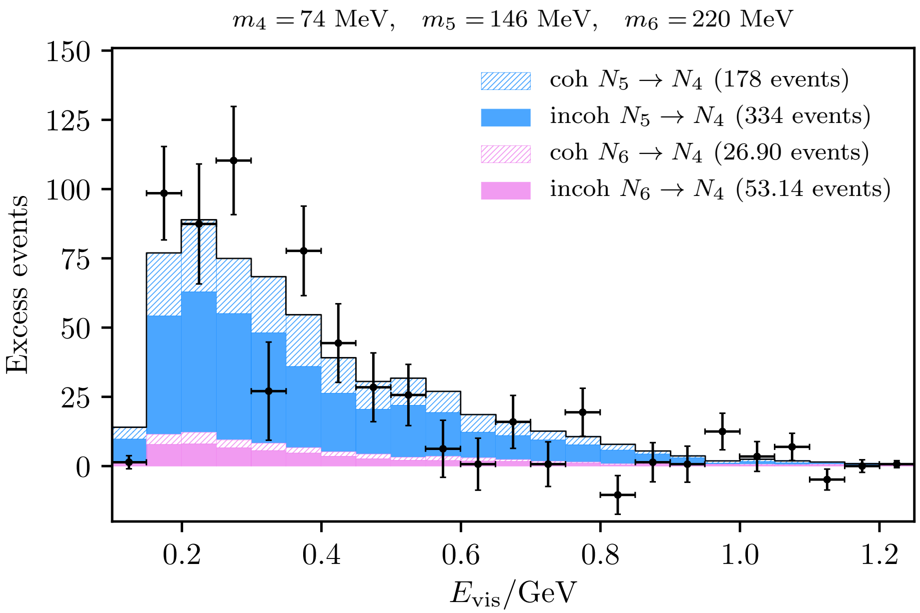
A viable explanation of the MiniBooNE low-E excess is provided by the up-scattering of an HNL N in the detector and its decay into ee nu.

It builds on a decay explanation of MiniBooNE by S. Gnineko, PRL 103 (2009). A similar analysis appeared at the same time but with light Z' by E. Bertuzzo et al., PRL 121 (2018).



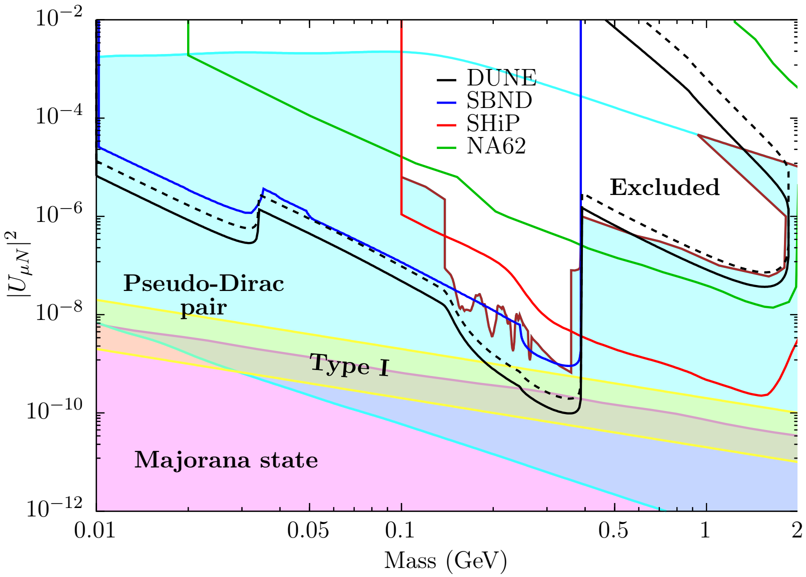


P. Ballett, S. Pascoli, M. Ross-Lonergan, PRD 99 (2019)



A. Abdullahi, M. Hostert, SP, 2007.11813

The N5, N6 produced in up scatterings of beam neutrinos decay in ee and missing energy mimicking the signal.



Ballett, Boschi, SP, 1905.00284

Bounds change if additional interactions are allowed, (HNL can decay invisibly or semivisibly).
Potentially, strong bounds from ND280 in T2K.

See V. Brdar et al., 2007.14411, C. Arguelles et al., 2205.12273

A host of other signatures

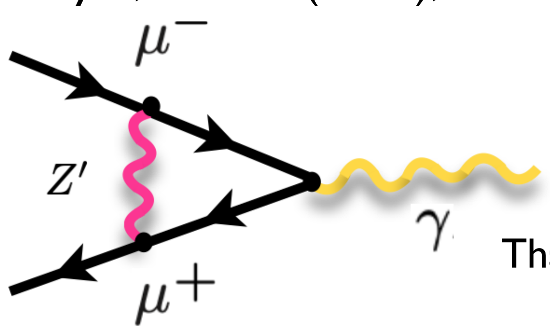
There is a longstanding discrepancy between the measured value of a_μ and the theoretical prediction, at 4.2 sigma.

See Keshavarzi, Marciano, Passera, Sirlin.

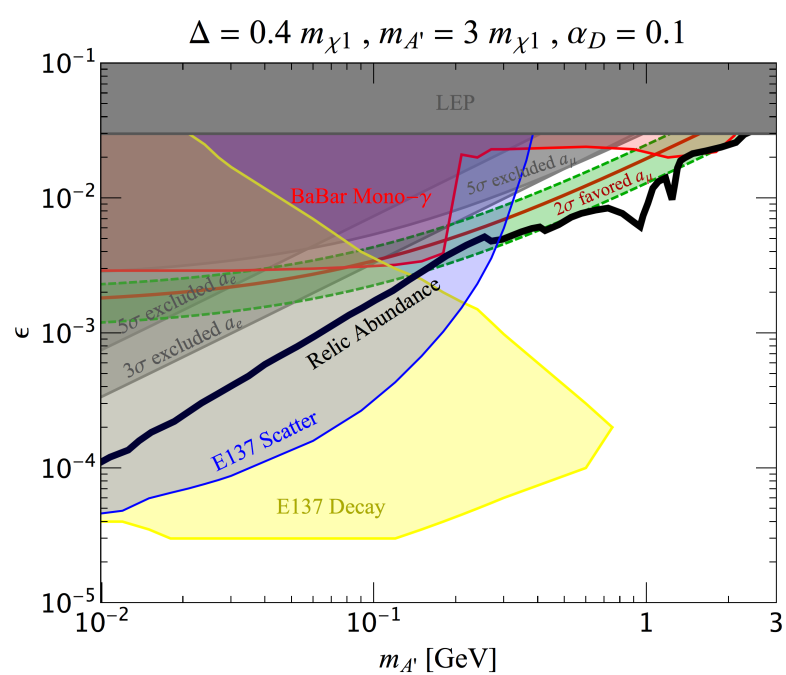
$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (274 \pm 73) \times 10^{-11}$$

Kinetic mixing and light Z' can explain the anomaly,…

P. Fayet, PRD75 (2007), M. Pospelov, PRD80 (2009)



Thanks to A. Abdullahi



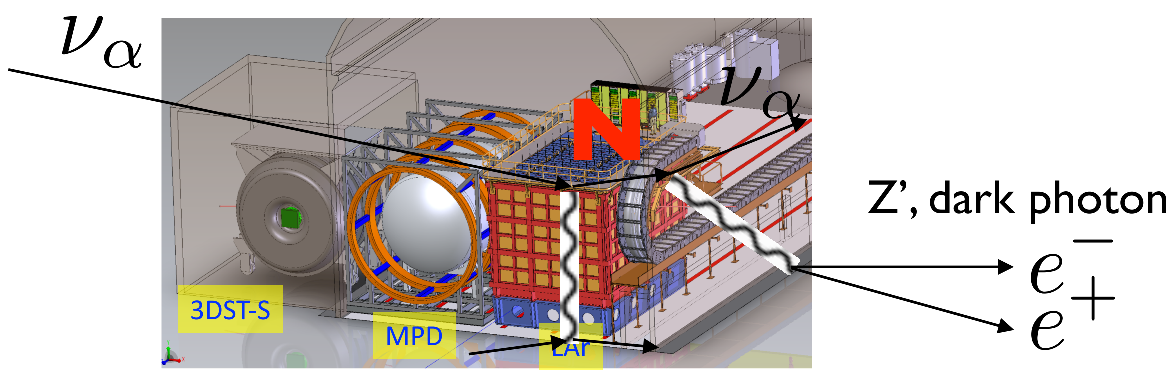
as far as Z' decays mainly semi-visibly (Z'->N N and N decay fast).

A. Abdullahi, M. Hostert, SP, 2007.11813

G. Mohlabeng, PRD99 (2019)

Unique signatures and future tests

The model has key signatures which can be tested.

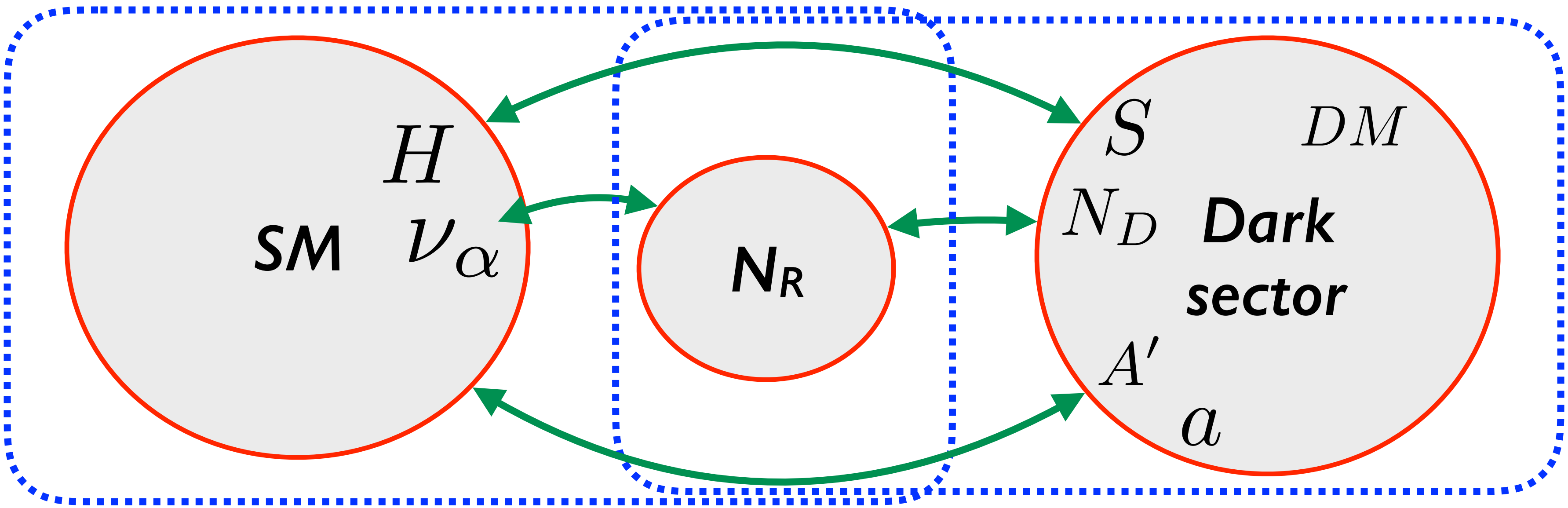


One can expect displaced vertices, decay chains and unique HNL and dark photon phenomenology (typically, semivisible decays):

- 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.

Conclusions

Neutrinos are the most elusive and mysterious of the known particles. Neutrino masses only particle physics evidence BSM.

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.

Surprises in store? MiniBooNE LEE remains a puzzle. New MicroBooNE results point away from sterile neutrinos. Neutrino4 and BEST anomalies?

Are neutrinos pointing towards a new understanding of particles: dark sector?