Searching for BSM in the DUNE ND

21 June 2023

DUNE-ND Coll. meeting
IC London

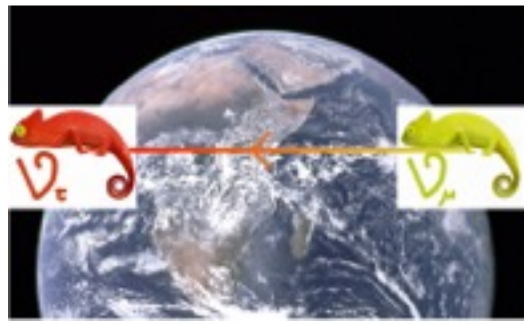
Silvia Pascoli
University of Bologna, INFN

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos
Horizon2020
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
INFN
Istituto Nazionale di Fisica Nucleare

Evidence beyond the SM

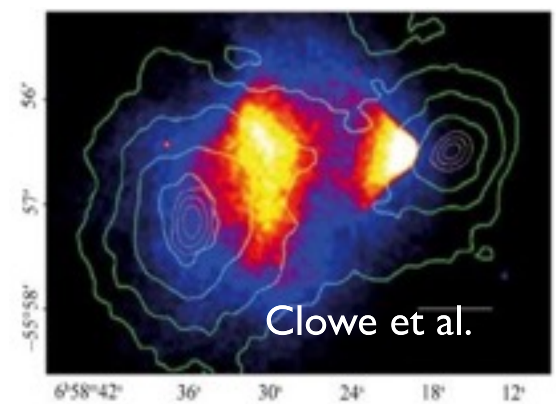
There is evidence that the Standard Model is incomplete.

Neutrino masses



Dark Matter

Baryon asymmetry



@Symmetry magazine

What is the new physics scale?

Are there new:
symmetries?
particles?
interactions?

New physics scale: High Energy frontier and above

eV keV MeV GeV TeV Intermediate scale GUT scale

At TeV SUSY MSSM, split SUSY, Composite Higgs, Technicolor….

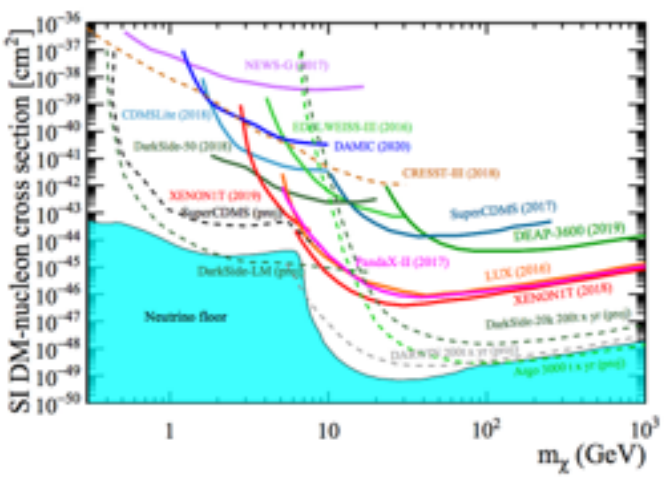
GUT theories

LHC new particle searches

CLFV

Leptogenesis/EW baryogenesis

LLP searches WIMPs



Proton decay

Neutrino masses via see-saw Type I

Leptogenesis

GW

Despite intense searches in colliders, flavour and DM exp, no hints of TeV new physics have been found.

Going low in energy: Dark sectors

A change of paradigm might be needed: new physics may be light but hidden because too weakly interacting (dark or hidden sectors).

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

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

Sterile nu oscillations

light DM

Leptogenesis

HNL searches: peak, kinks, decays,

Recently, a strong theoretical effort has been done together with a blooming of experimental opportunities at the intensity frontier. DUNE ND inscribes in this thriving context.

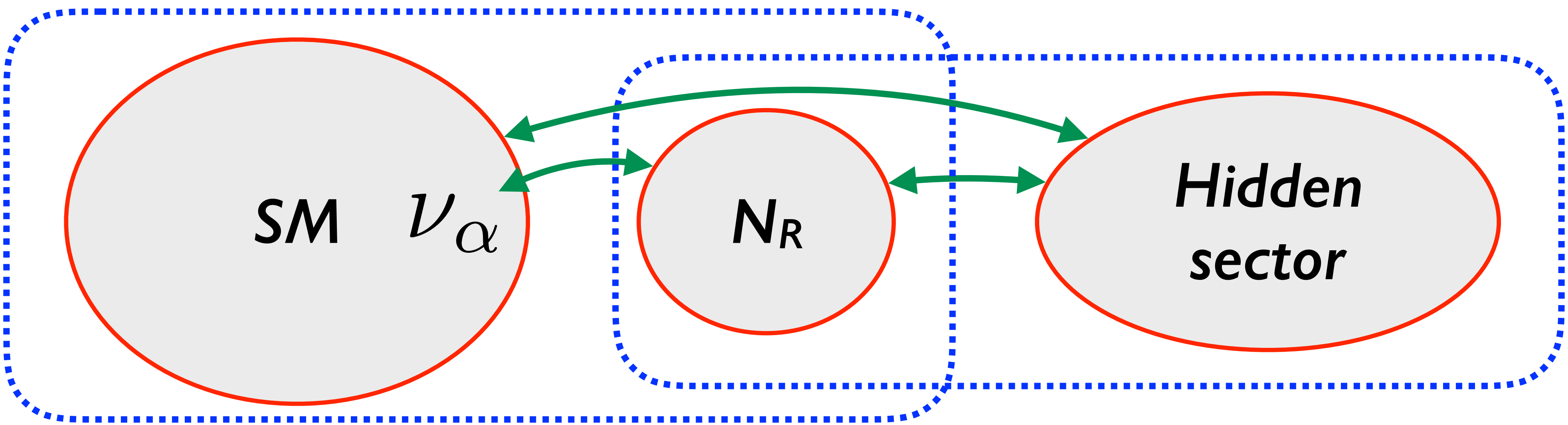
See e.g. Artuso et al., 2210.04765, S. Gori et al, 2209.04671, FIPs 2023 report, 2305.01715

The dark sector can interact with SM via portals:

- the kinetic mixing portal (dark photons);
- the scalar portal (dark scalar);
- the neutrino portal (heavy neutral leptons);
- the axion portal (axion);
- millicharged particles.

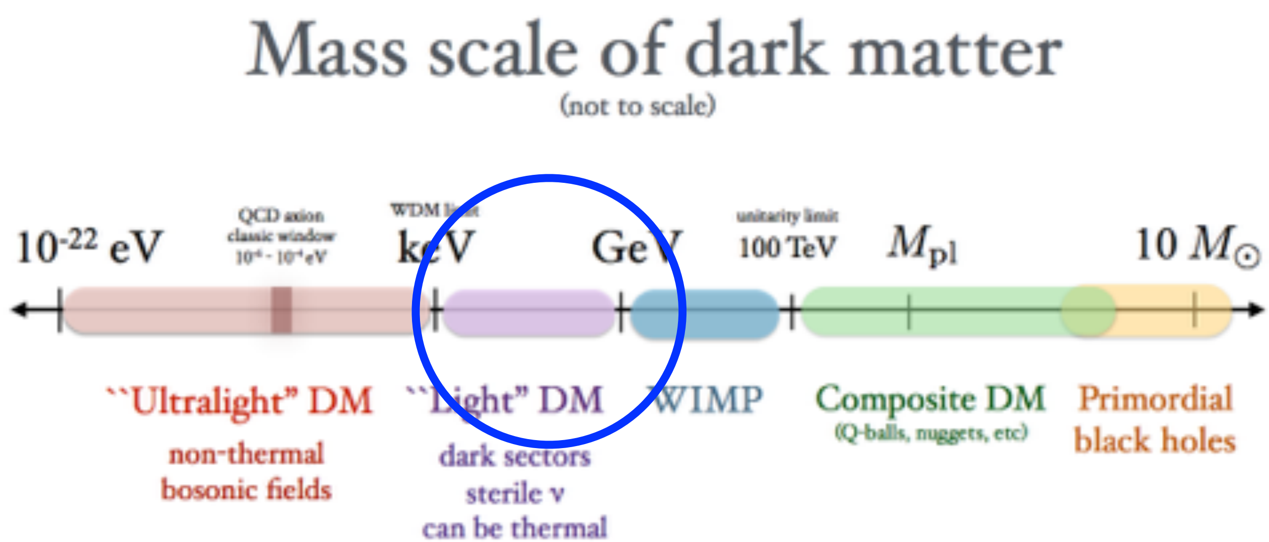
See J. Yoo's talk

Portal	Coupling
Dark Photon, A'	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Axion-like particles, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$
Dark Higgs, S	$(\mu S + \lambda_{\rm HS}S^2)H^\dagger H$
Heavy Neutral Lepton, N	$y_N LHN$
milicharged particle, χ	$\epsilon A^\mu \bar{\chi}\gamma_\mu\chi$



Notable example 1: Vector portal and sub-GeV DM

Light gauge extensions of the SM can involve secluded or (B-)leptonic U(1)'. The associated gauge bosons are called dark photons or Z'.



T. Lin, 1904.07915

The DS can also contain a light DM particle, whose annihilations can be mediated by the dark photon (or other particle.

Notable example 2:
MeV-GeV see-saw

Sterile neutrinos: hypothetical neutral fermionic singlets of the Standard Model. Generically they mix with the light neutrinos and the mass states are HNL.

Flavour state

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

Massive state
Nearly-sterile neutrino, commonly called sterile neutrino

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

HNLs can interact with the SM via mixing and hence be produced and decay into SM particles.

HNLs can be inscribed in see-saw models (type I and extensions, e.g. inverse, linear and extended see saw) and can give raise to neutrino masses.

Symmetry magazine

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

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

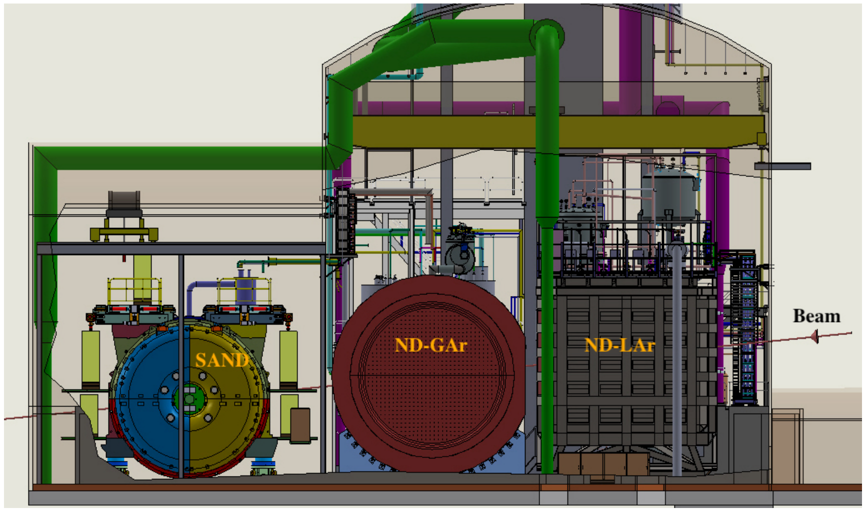
$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

GeV scale See-saw models can also explain the baryon asymmetry via leptogenesis.

Searching for BSM in DUNE ND

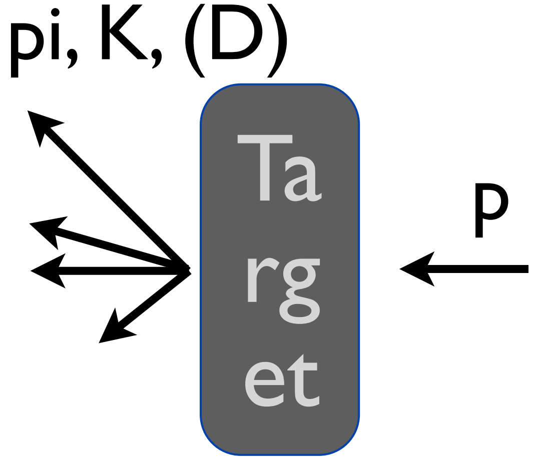
To search directly for BSM in the DUNE ND, one can employ two main exp strategies:

1. a-la beam dump experiments.
2. production (e.g. via NC) and detection in the same detector due to neutrino or other particle (e.g. DM) beam.

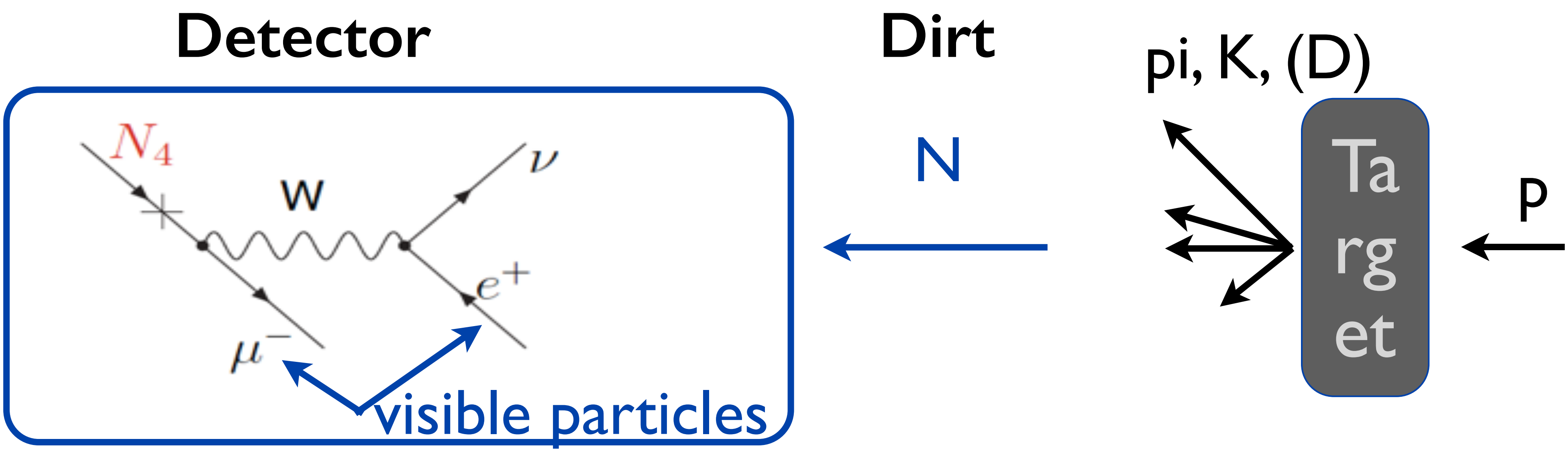


I will refer to the talk presented by M. Bishai yesterday on DUNE ND Phase I and II.

“A la beam dump” experiment



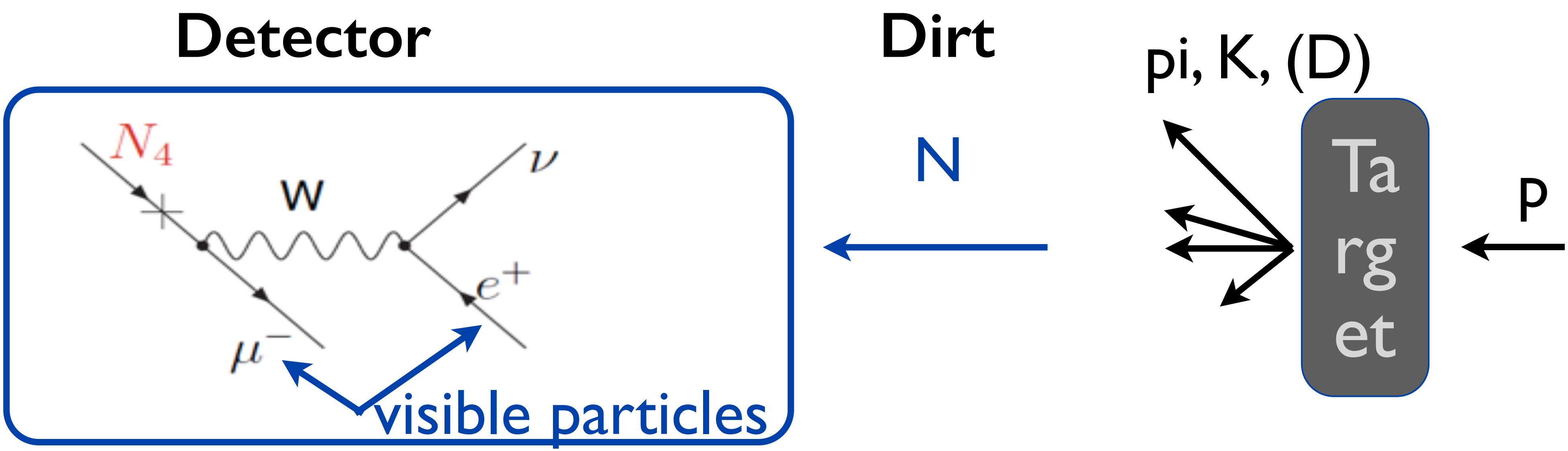
"A la beam dump" experiment

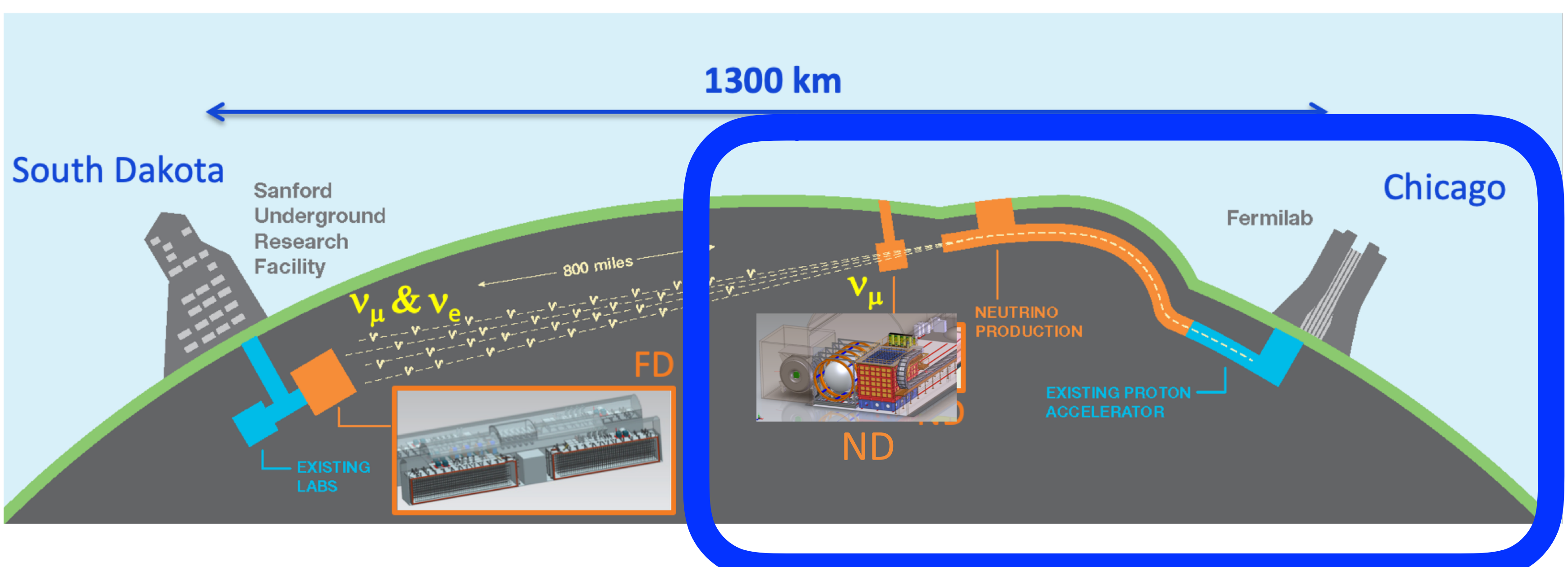


A part from the exp in the 90', in particular PS191, neutrino accelerator experiments (see recent analysis by T2K) and NA62 can search in this mode.

The typical candidate is a heavy neutral lepton or sterile neutrino with ~100 MeV mass.

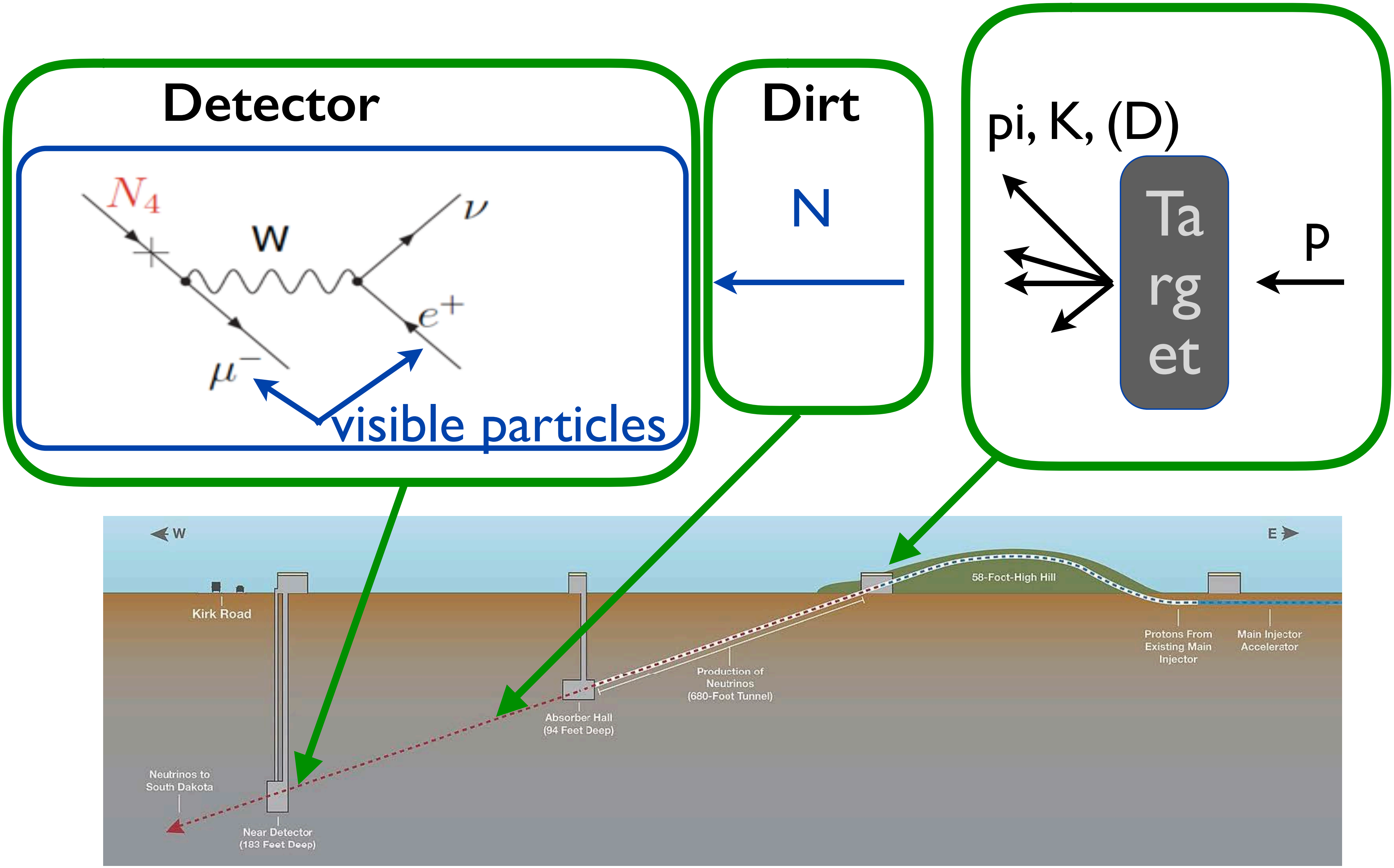
"A la beam dump" experiment





@Silvia Pascoli

"A la beam dump" experiment



The key characteristic:

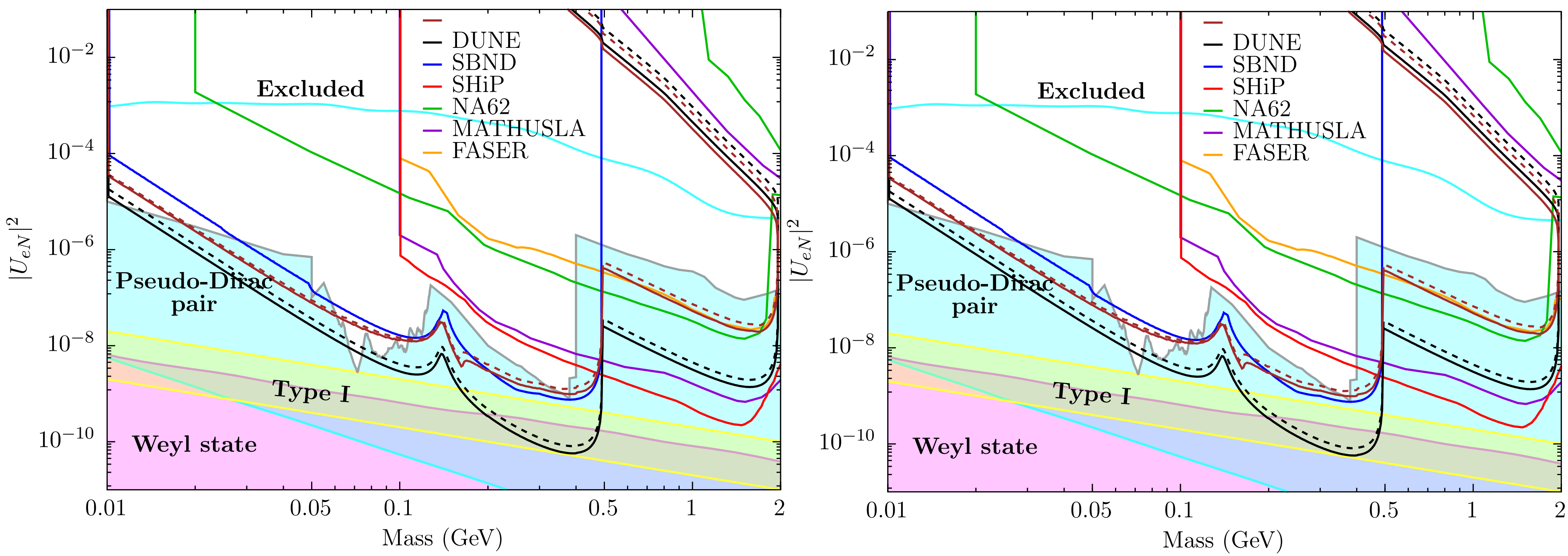
- high proton intensity;
- large volume (not large mass) with excellent reconstruction capabilities (typical backgrounds are gammas, pi0, CCmu+1pi);
- (distance from target).

	PS191	**DUNE ND**	**SBND**	**NA62**	**SHiP**
Baseline	128 m	574 m	110 m	220 m	60 m
Volume	$216\,\mathrm{m}^3$	$150\,\mathrm{m}^3$	$80\,\mathrm{m}^3$	$750\,\mathrm{m}^3$	$590\,\mathrm{m}^3$
Energy	19.2 GeV	80 GeV	8 GeV	400 GeV	400 GeV
POT	0.86×10^{19}	1.32×10^{22}	6.6×10^{20}	3×10^{18}	2×10^{20}
Exposure	1.0	220.9	16.4	8.5	5820

Ballett, Boschi, SP, 1905.00284

DUNE ND has an exposure few 100 x PS191!

Experimental bounds: decays.

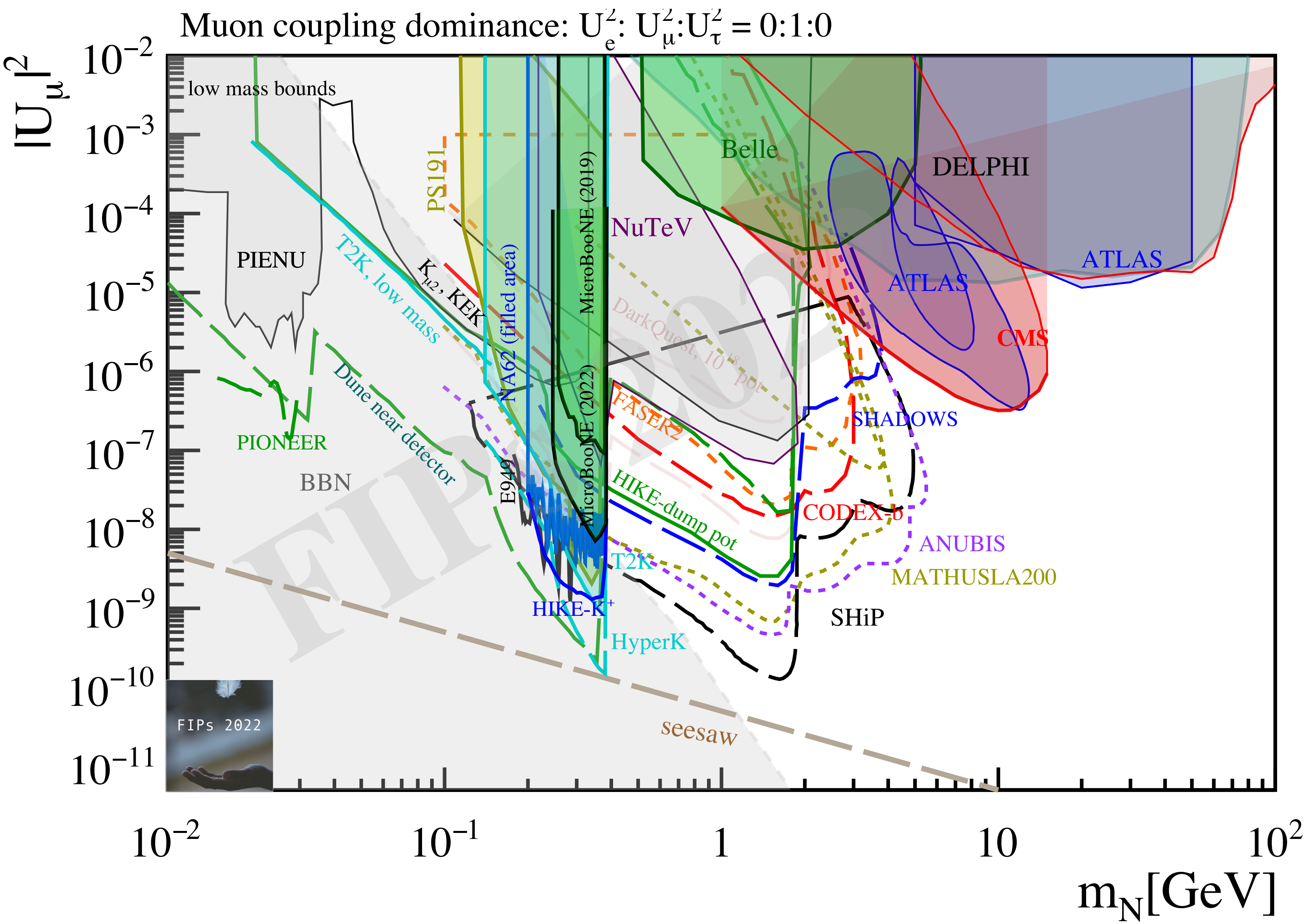


Ballett, Boschi, SP, 1905.00284

DUNE ND is excellently suited for this type of search and has access to GeV masses.

See K. Kelly's and F. Deppisch's talks

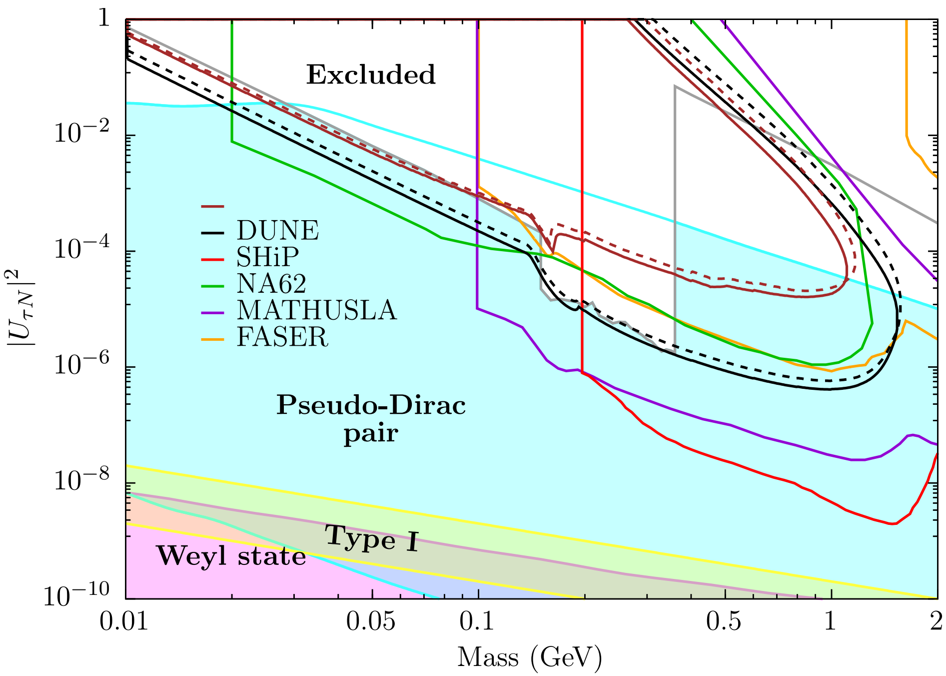
Experimental bounds: decays.



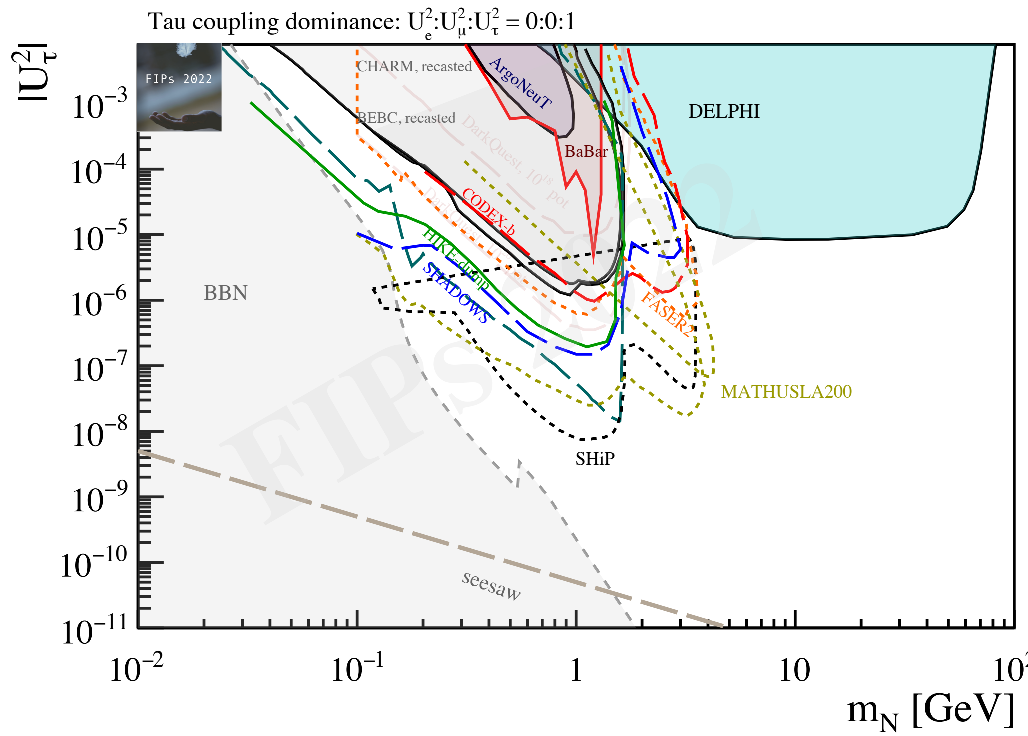
FIPs 2022 report, 2305.01715

Note: these studies focus on one flavour mixing at a time, but this is not compatible with see-saw type I.

Experimental bounds: tau mixing.



Ballett, Boschi, SP, 1905.00284

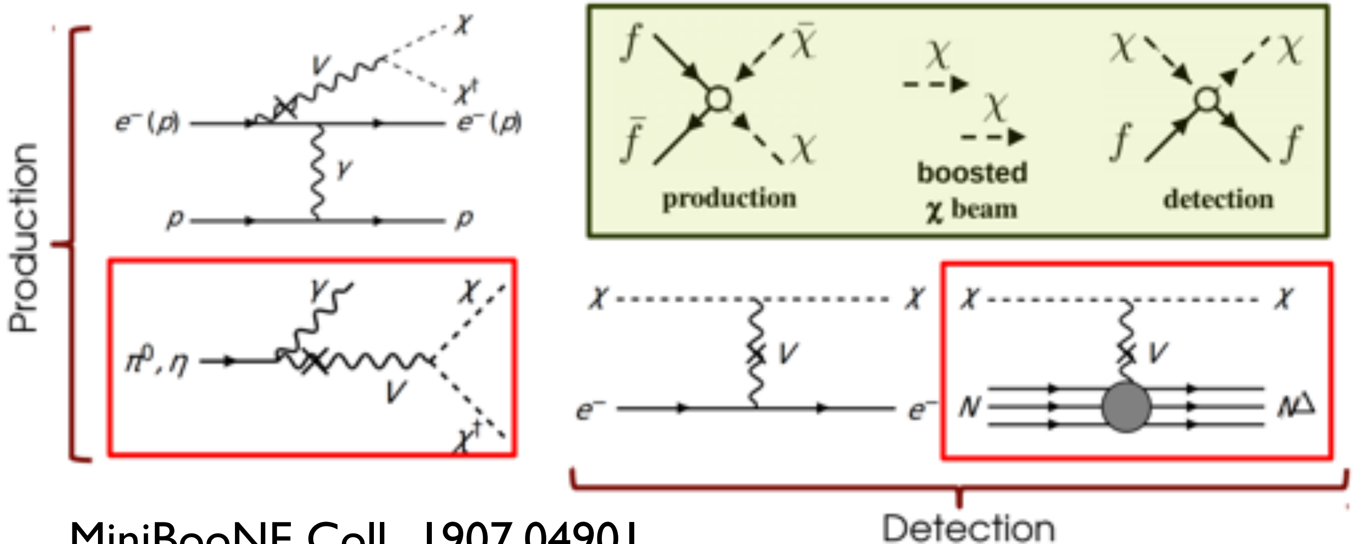


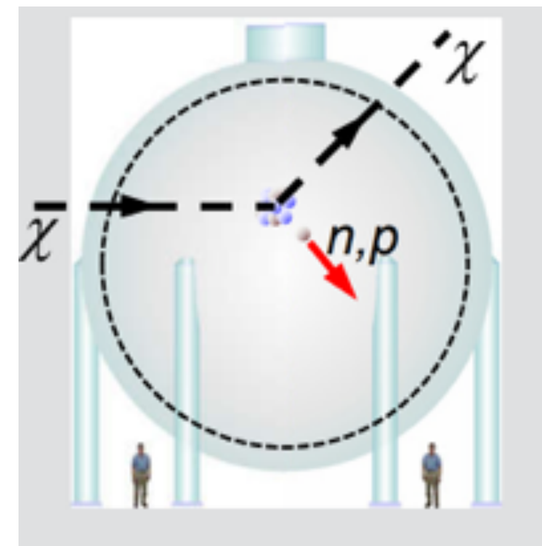
FIPs 2022 report, 2305.01715

Thanks to the Ds production, DUNE ND will have also sensitivity to the mixing with tau neutrinos.

Neutrino or dark sector scattering

If dark sector particles (e.g. LDM) interacts with the SM, it can be produced in beam dump experiments (directly or via subsequent DS particle decays).

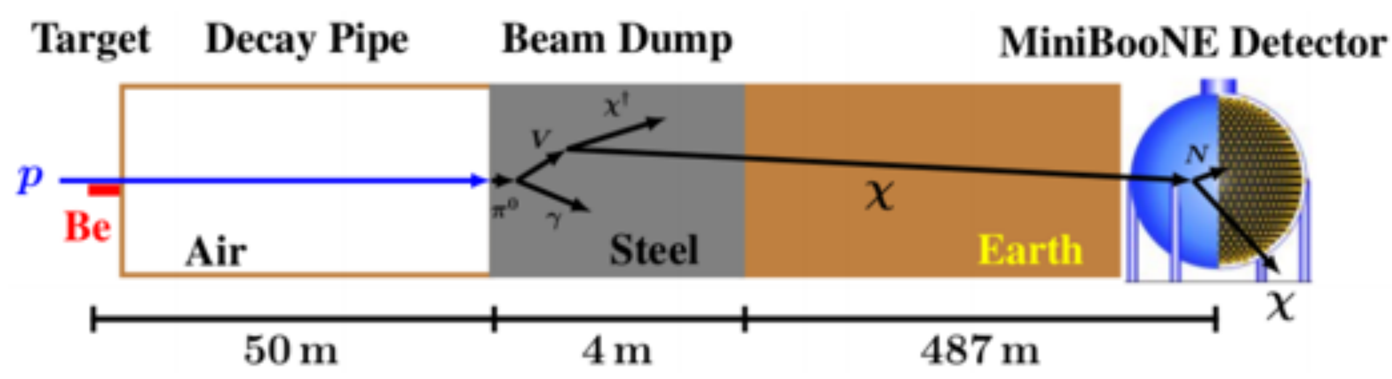




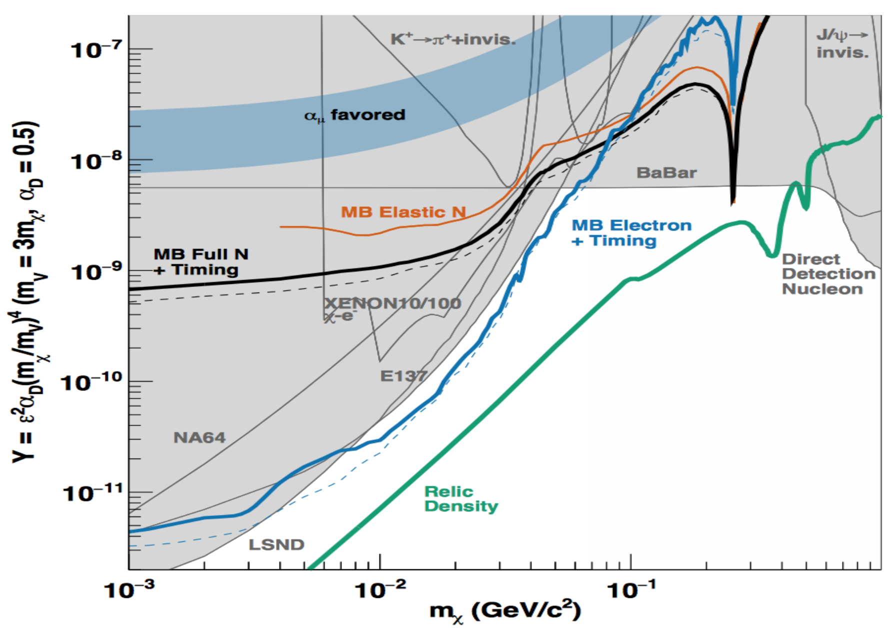
MiniBooNE Coll., 1907.04901

Detection proceeds via long lived Dark Sector particle scattering in the detector, e.g. nucleon elastic scattering with recoil energy ~100 MeV (similar to neutrino-nucleon NC elastic scattering).

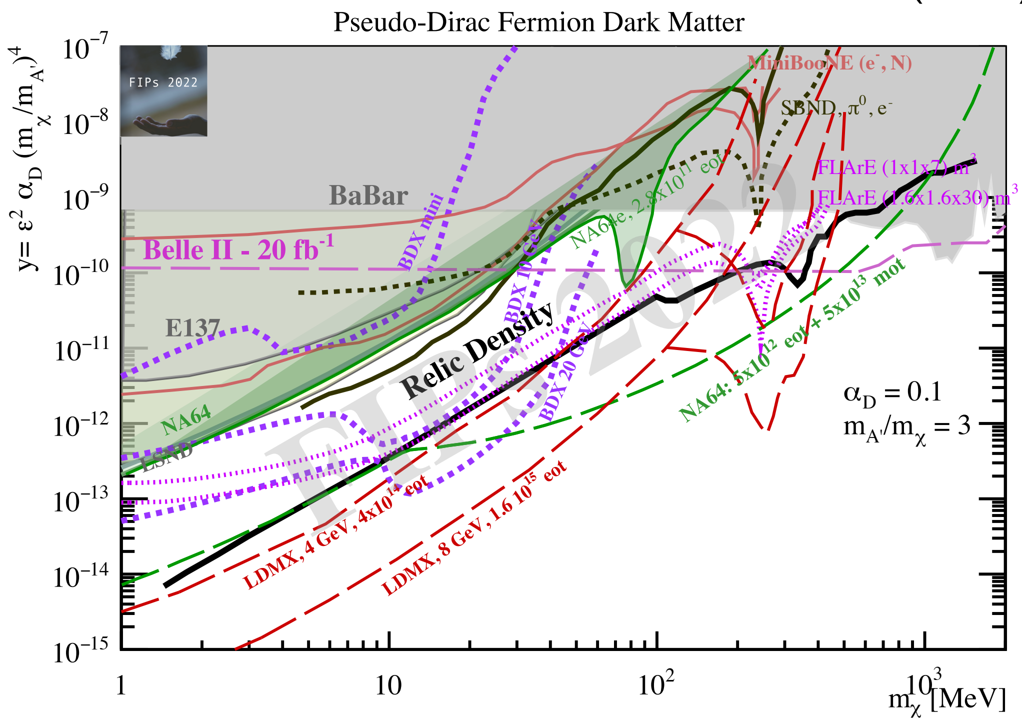
MiniBooNE has done a search both with nucleon and electron recoils.



MiniBooNE Coll., PRL118 (2017)



MiniBooNE DM Collaboration, 1807.06137



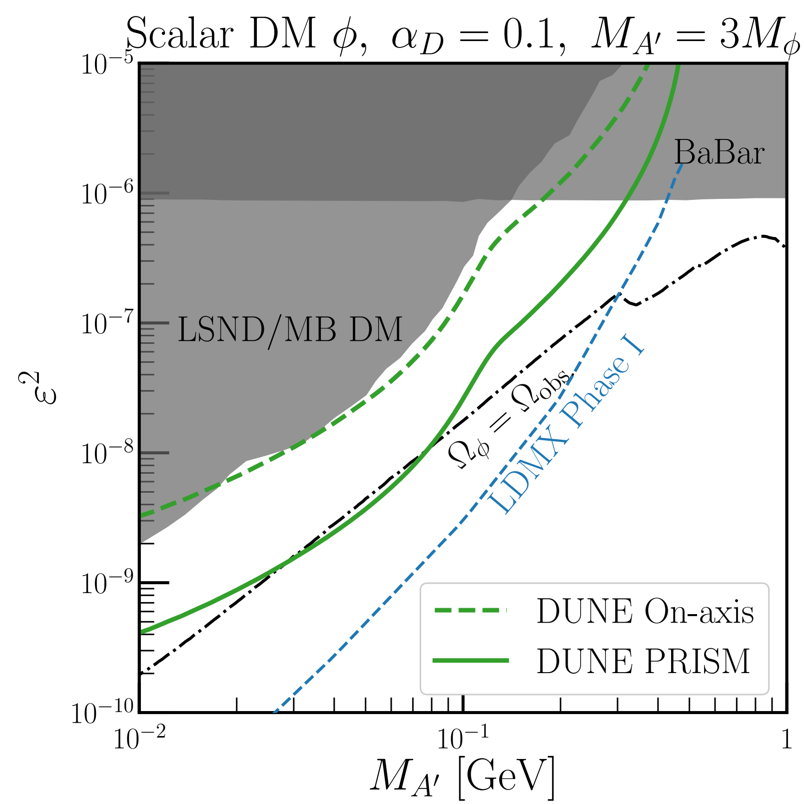
FIPs 2022 report, 2305.01715

@Silvia Pascoli

Key characteristics:

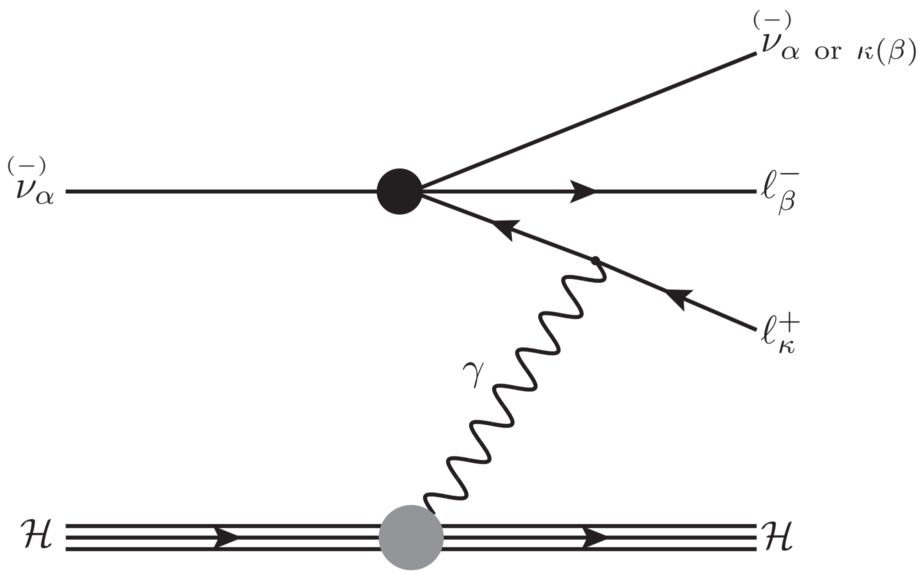
- **beam intensity**
- **detector mass (needed for scattering)**
- **position on/off-axis for bkgd reduction (DUNE Prism) due to different DM flux.**

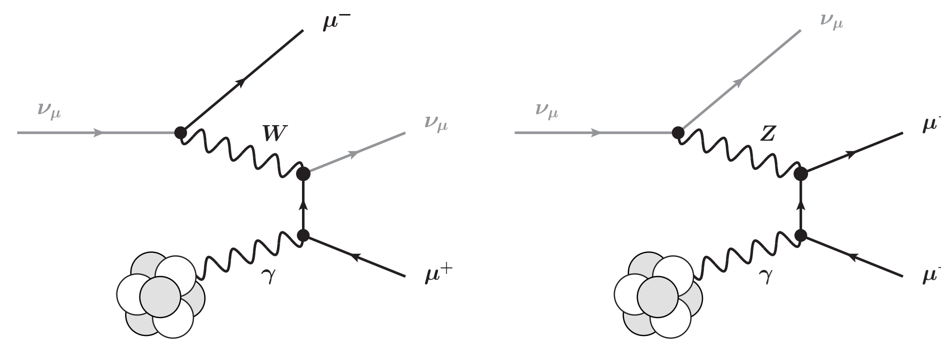
Dominant background is typically due to neutrino interactions (e.g. QE NC events, nu scattering off electrons and QE CC electron scattering events).



De Romeri, Kelly, Machado, 1903.10505. See also, Breitbach et al., 2102.03383, Brdar et al., 2206.06380

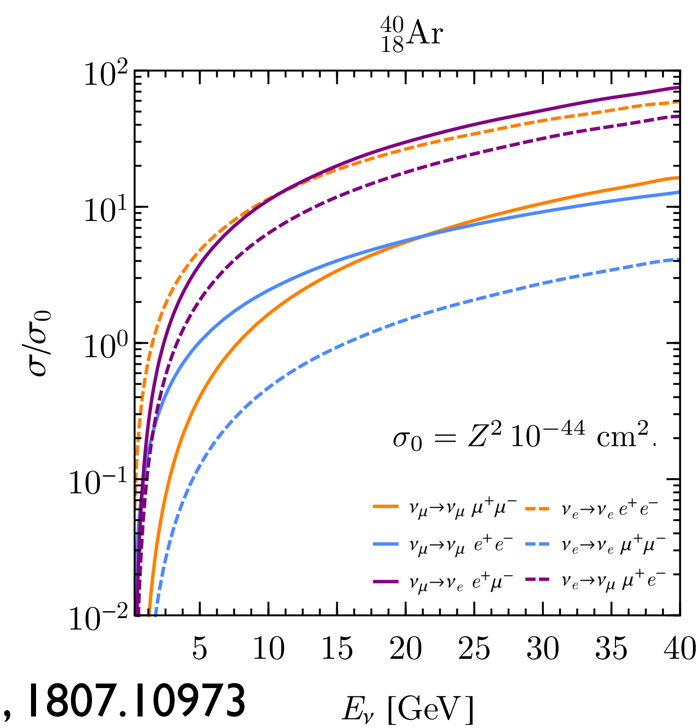
Trident





Altmannshofer et al., 1902.06765

Trident processes are expected in the SM but are very suppressed.



$$\frac{\sigma(\nu_\mu \to \nu_\mu \mu^+\mu^-)_{\rm exp}}{\sigma(\nu_\mu \to \nu_\mu \mu^+\mu^-)_{\rm SM}} = \begin{cases} 1.58 \pm 0.64 & \text{(CHARM-II)} \\ 0.82 \pm 0.28 & \text{(CCFR)} \\ 0.72^{+1.73}_{-0.72} & \text{(NuTeV)} \end{cases}$$

Ballett et al., 1807.10973

Neutrino accelerator experiments offer new opportunities to discover them.

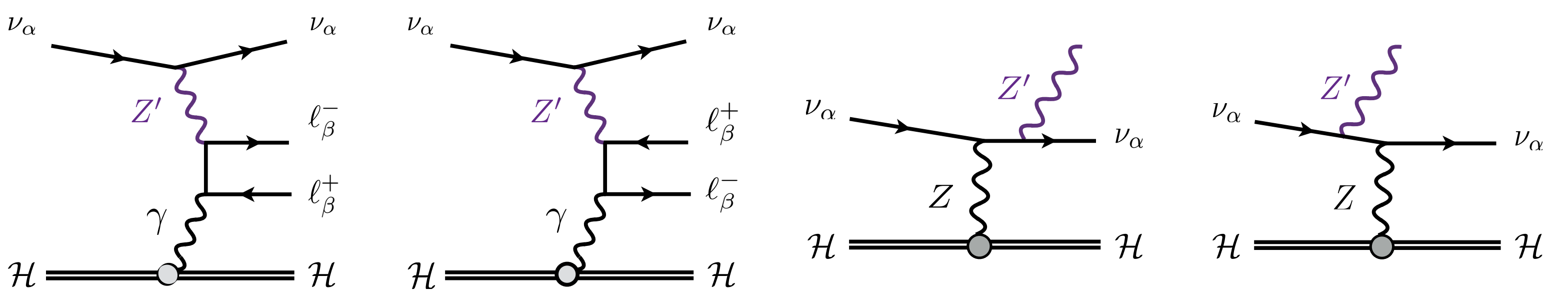
Experiment	Baseline (m)	Total Exposure (POT)	Fiducial Mass (t)	E_ν (GeV)
SBND	110	6.6×10^{20}	112	$0-3$
μBooNE	470	1.32×10^{21}	89	$0-3$
ICARUS	600	6.6×10^{20}	476	$0-3$
DUNE	574	$12.81\ (12.81) \times 10^{21}$	50	$0-40$
νSTORM	50	10^{21}	100	$0-6$

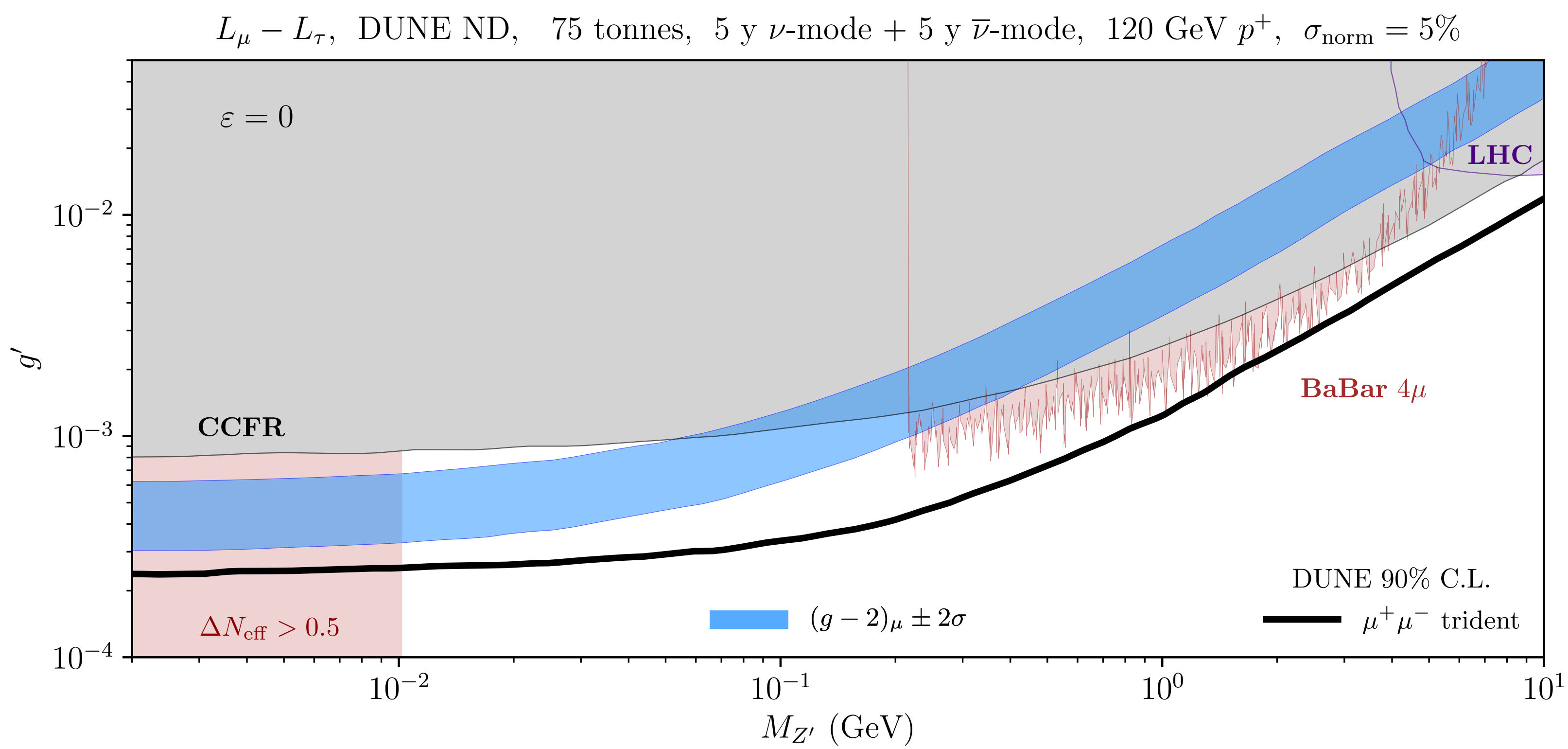
It is a very rare process with a cross section which increases with energy. DUNE is well suited for this search.

$\nu_\mu \to \nu_\mu e^+ e^-$	6	0.4	0.7	913 (58)	73
	0.7	0.04	0.07	128 (9)	9
$\overline{\nu}_\mu \to \overline{\nu}_\mu e^- e^+$	0.2	0.01	0.02	34 (695)	9
	0.03	0.001	0.002	5 (95)	1
$\nu_e \to \nu_e e^- e^+$	0.2	0.01	0.02	50 (13)	32
	0.02	0.001	0.002	8 (2)	4
$\overline{\nu}_e \to \overline{\nu}_e e^+ e^-$	0.02	0.001	0.002	10 (34)	–
	0.003	0.0001	0.0002	2 (5)	–
Total e^+e^-	6	0.4	0.7	1007 (800)	114
	0.7	0.0	0.1	143 (111)	14
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	0.4	0.03	0.04	271 (32)	9
	0.4	0.03	0.04	186 (19)	8
$\overline{\nu}_\mu \to \overline{\nu}_\mu \mu^- \mu^+$	0.01	0.001	0.001	14 (177)	2
	0.01	0.0009	0.001	9 (127)	1
$\nu_e \to \nu_e \mu^+ \mu^-$	0.002	0.0001	0.0001	1 (0.5)	0.4
	0.001	0.0001	0.0001	0.7 (0.2)	0.3
$\overline{\nu}_e \to \overline{\nu}_e \mu^+ \mu^-$	0.0002	0.0000	0.0000	0.3 (0.9)	–
	0.0001	0.0000	0.0000	0.2 (0.5)	–
Total $\mu^+\mu^-$	0.4	0.0	0.0	286 (210)	11
	0.4	0.0	0.0	196 (147)	9

Ballett et al., 1807.10973

Trident events can be used to search for light vector boson mediators (Z').





Ballett et al., 1902.08579, see also Altmannshofer et al., 1902.06765

From minimality to richness

eV keV MeV GeV TeV Intermediate scale GUT scale

MINIMAL

nuMSM

See-saw type I

See-saw type I: 2 RHN

See-saw type I: 3 RHN

Extended see-saw:
e.g. inverse see-saw

Gauge extensions
(U(1)_B-L, L-R)

Loop-mass models

R-parity violating SUSY

RICH

Multiportal dark
sector models

GUTs: SO(10)…

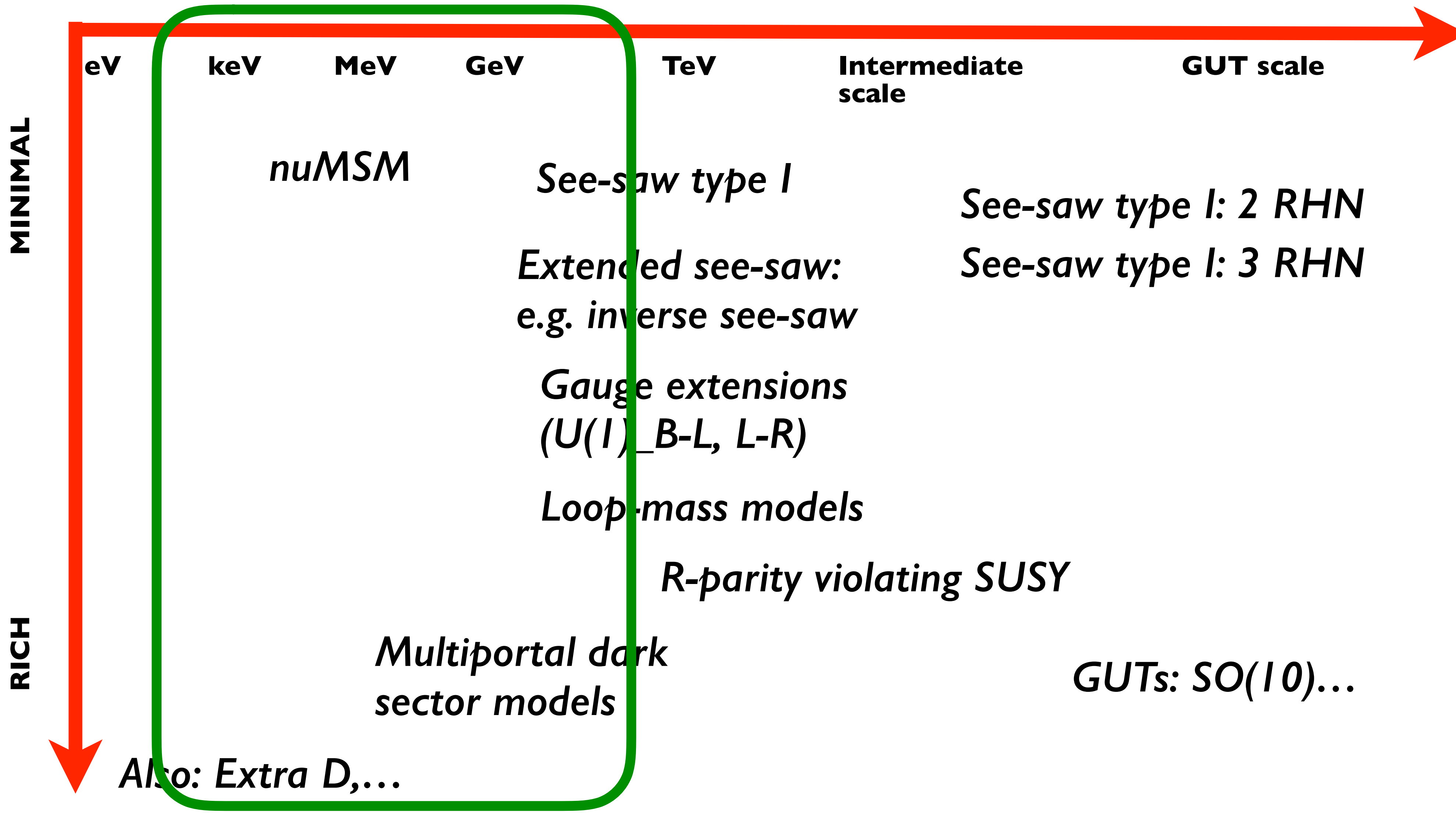
Also: Extra D,…

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

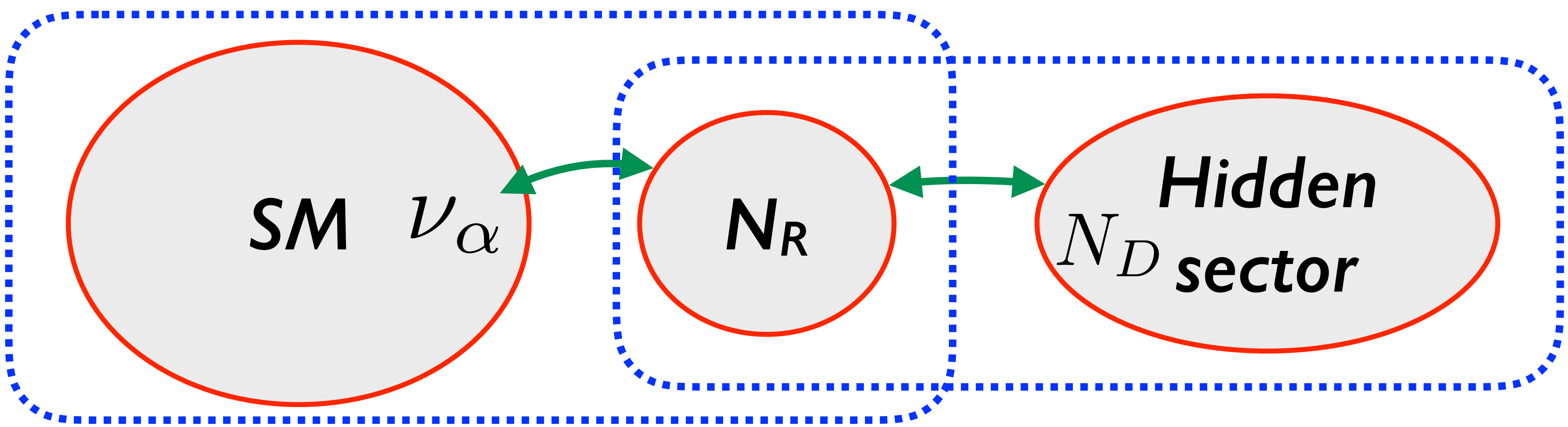
Richness (theory-motivated): connections, new signatures

HNLs and other DS particles could be part of a new low energy sector that contains several new states (neutral fermions, gauge bosons, scalars, DM.)… This is the case for the Standard Model!

Example: Three portal model

neutrino portal

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

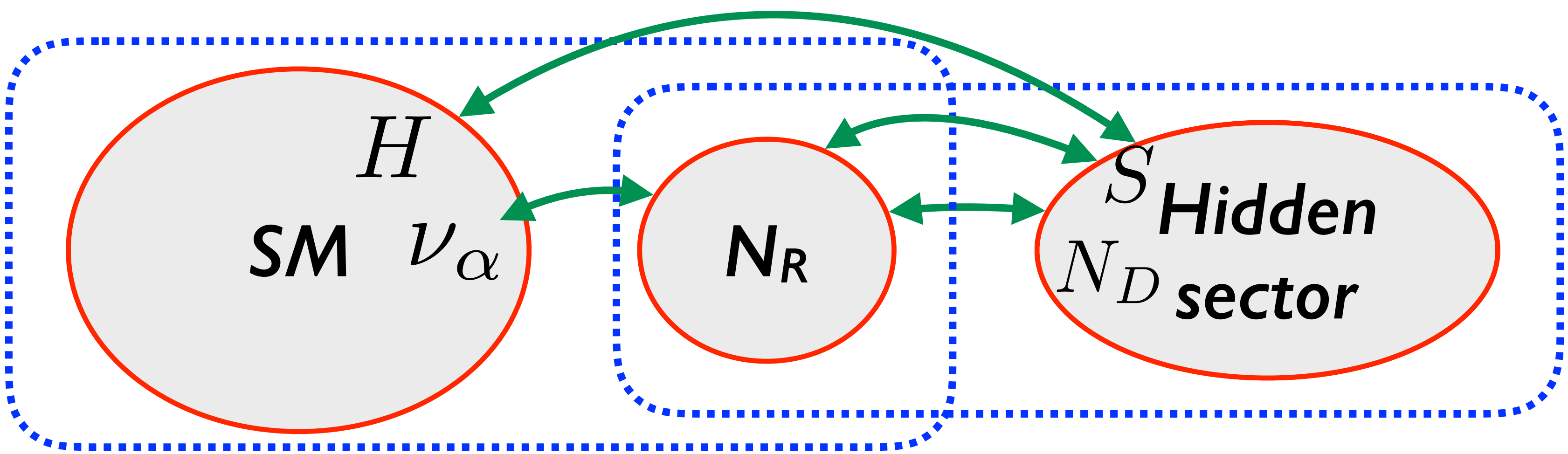


HNLs and other DS particles could be part of a new low energy sectors which contain several new states (neutral fermions, gauge bosons, scalars, DM.)… This is the case for the Standard Model!

Example: Three portal model

neutrino portal, ***Higgs portal***

$\bar{L} \cdot H N_R \quad (+ ... \overline{N_R} N_S)$ $\lambda_{\phi H} \phi^\dagger \phi H^\dagger H$

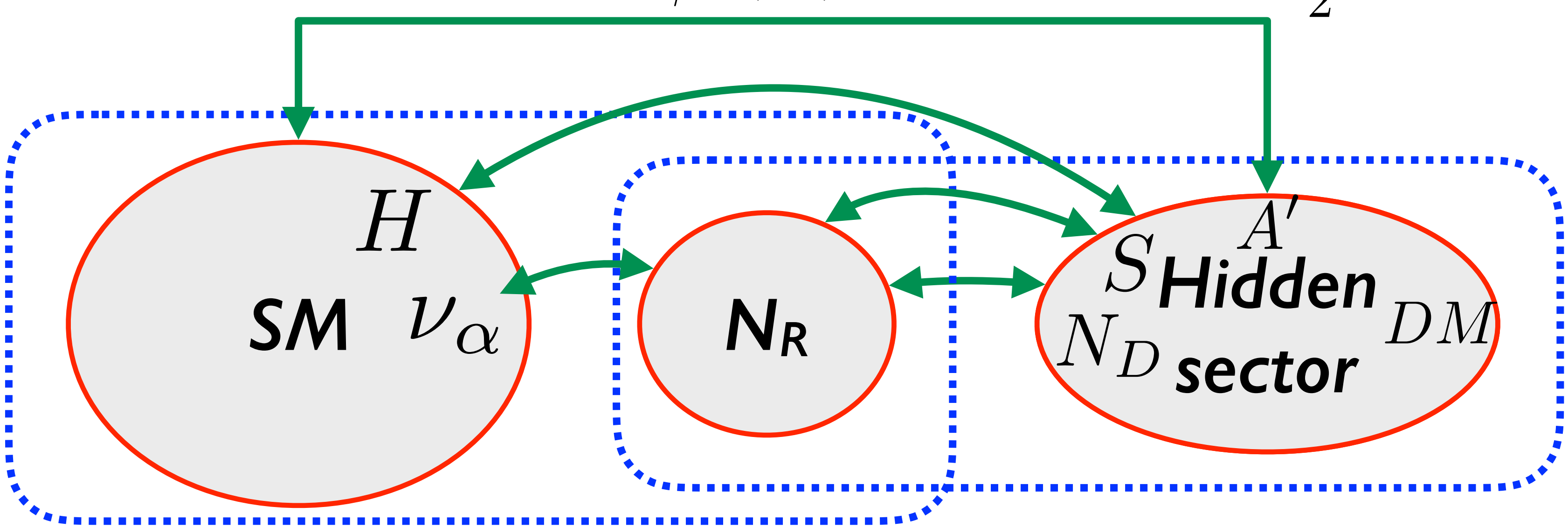


HNLs and other DS particles could be part of a new low energy sectors which contain several new states (neutral fermions, gauge bosons, scalars, DM.)… This is the case for the Standard Model!

Example: Three portal model

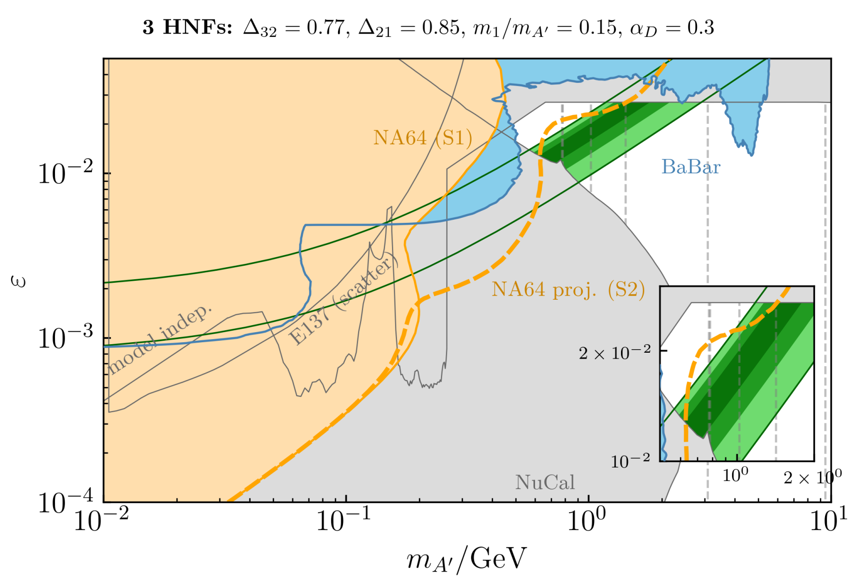
neutrino portal, ***Higgs portal,*** ***vector portal***

$\bar{L} \cdot H N_R \quad (+ ... \overline{N_R} N_S)$ $\quad \lambda_{\phi H} \phi^\dagger \phi \, H^\dagger H$ $\quad \frac{\sin \chi}{2} X_{\mu\nu} B^{\mu\nu}$

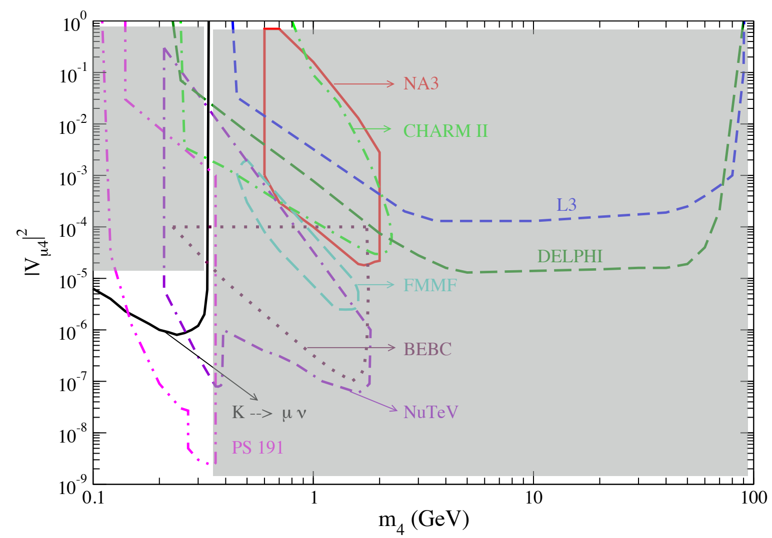


This type of models have a distinct phenomenology, very different from minimal models.

- They can evade standard bounds as the DS particles can decay fast and semivisibly.
- Typical signatures: semivisible decays into multileptons and missing energy with decay chains.



A. Abdullahi et al., 2302.05410

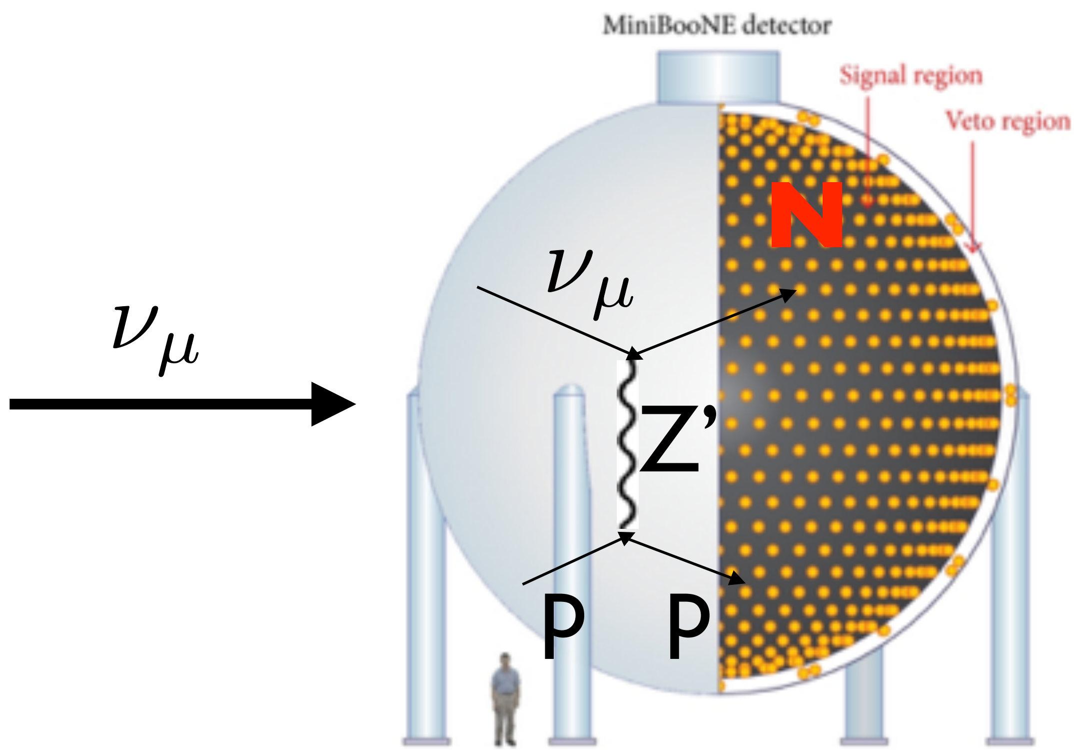


Collider bounds can be weakened.

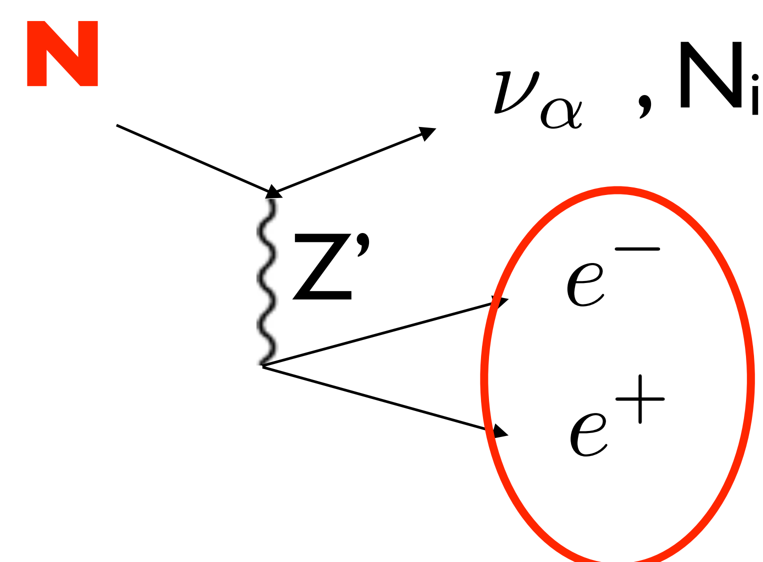
HNL decay bounds need to be recomputed.

A MiniBooNE low-E excess explanation

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.



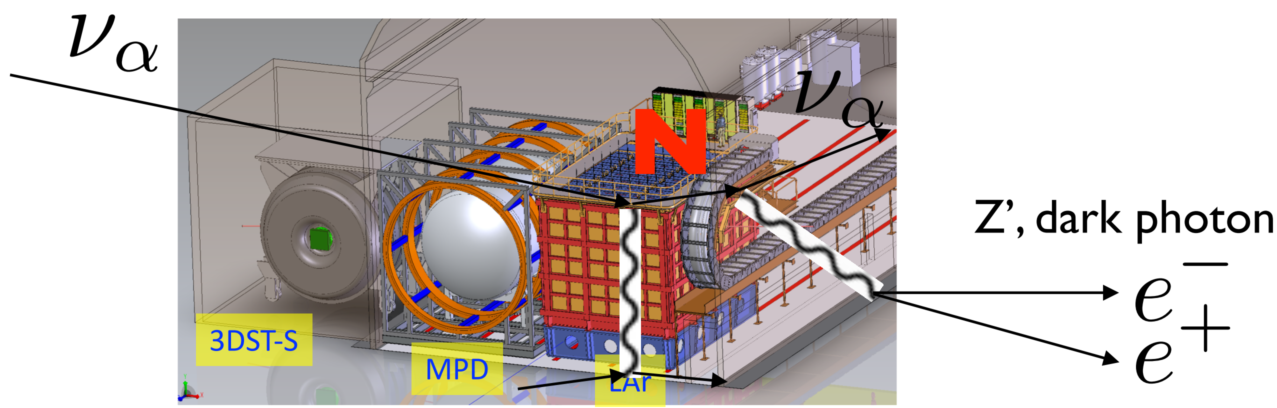
It builds on a decay explanation of MiniBooNE by S. Gnineko, PRL 103 (2009). A similar analysis appeared at the same time but with light Z' by E. Bertuzzo et al., PRL 121 (2018).



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

Unique signatures and future tests

These models 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.

Weak Mixing Angle

$$\sin^2\theta_W = \frac{g'^2}{g^2+g'^2}$$

The weak mixing angle is a key parameter in the SM. It can be measured in electron scattering.

Agarwalla, Huber, 1005.1254

Sterile neutrinos

Sterile neutrinos with eV masses could be searched for at the DUNE ND with a different L/E dependence w.r.t. SBN.

See J. Penedo's talk

Non-unitarity and 0-distance NSIs

Non-unitarity effects or NSIs could lead to specific appearance and disappearance signatures.

See M. Bishai's comments in talk

Conclusions

BSM models with light sectors (eg. heavy neutral fermions, dark photons, light DM…) are very interesting extension of the SM. They can explain neutrino masses and can be connected to the other compelling observational evidences of BSM (DM and the baryon asymmetry).

DUNE-ND has unique opportunities to search for them thanks to high flux, very capable detector complex (and DUNE-PRISM):

- a-la beam dump experiment;
- scattering searches;
- other searches (sterile neutrinos, NSI…).

Models with enhanced mixing

The mixing-mass relation can be avoided if neutrino masses are suppressed. A typical example are the inverse see-saw and extended see-saw models, in which two sterile neutrinos are introduced.

$$\mathcal{L} = Y\bar{L} \cdot HN_1 + Y_2 \bar{L} \cdot HN_2^c + \Lambda \bar{N}_1 N_2 + \mu' N_1^T C N_1 + \mu N_2^T C N_2$$

The neutrino mass matrix is

$$\begin{pmatrix} 0 & Yv & Y_2 v \\ Yv & \mu' & \Lambda \\ Y_2 v & \Lambda & \mu \end{pmatrix}$$

Neutrino masses are suppressed by the (small) lepton number parameters:

$$m_{tree} \simeq -m_D^T M^{-1} m_D \simeq \frac{v^2}{2(\Lambda^2 - \mu'\mu)} \left(\mu Y_1^T Y_1 + \epsilon^2 \mu' Y_2^T Y_2 - \Lambda\epsilon (Y_2^T Y_1 + Y_1^T Y_2) \right)$$

Two limits:

- Inverse see-saw: $\Lambda \gg \mu, Y_2 v, \mu'$

Gavela et al., 0906.1461; Ibarra, Molinaro, Petcov, 1103.6217

Two quasi-Dirac neutrinos with large mixing:

$$m_4 \approx -m_5 \approx \tilde{M}_1 \approx -\tilde{M}_2 \approx \Lambda, \qquad U_{e4} \approx U_{e5} \approx Y_{1e} v / 2\Lambda,$$
$$\Delta\tilde{M} \equiv |\tilde{M}_2| - |\tilde{M}_1| \approx \mu',$$

- Extended see-saw: $\mu' \gg \Lambda, \mu$

Kang, Kim, 2007; Majee et al., 2008; Mitra, Senjanovic, Vissani, 1108.0004

One light and one heavy sterile neutrino:

$$m_4 \approx \tilde{M}_1 \approx -\Lambda^2/\mu', \qquad U_{e4} \approx Y_{1e} v/\sqrt{2}\Lambda$$
$$m_5 \approx \tilde{M}_2 \approx \mu', \qquad U_{e5} \approx Y_{1e} v/\sqrt{2}\mu'$$

Other models with enhanced sterile neutrino production require new interactions (e.g. Z’, see-saw type III...)