Title: The Secret Life of Heavy Neutrinos

Speakers: Matheus Hostert

Series: Particle Physics

Date: September 21, 2021 - 1:00 PM

URL: https://pirsa.org/21090019

Abstract: The existence of right-handed neutrinos may shed light on the origin of neutrino masses. It is also conceivable that if these particles exist, they may have a new set of interactions and symmetries of their own. In this talk, I will discuss "lamppost" models where MeV to GeV heavy neutrinos interact with a dark photon, and discuss some novel experimental signatures at neutrino detectors, e+e- colliders, and kaon decays. I will also comment on some connections to MiniBooNE and the (g-2) of the muon.

The Secret Life of Heavy Neutrinos

Perimeter Particle Physics Seminar

Matheus Hostert

Perimeter Institute and University of Minnesota

University of Minnesota

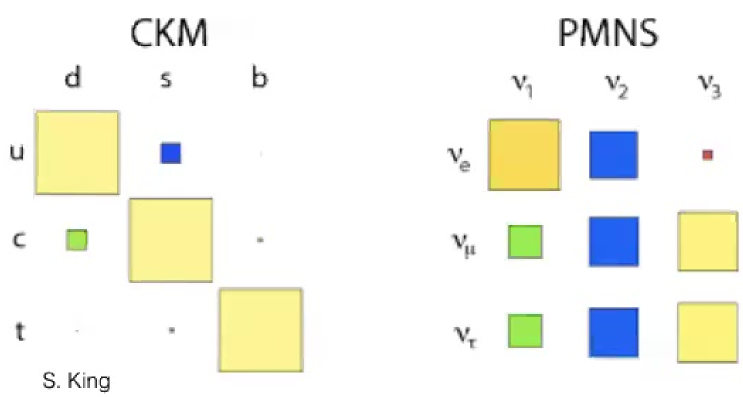
Perimeter Institute

Open questions in the neutrino sector

Neutrino masses

Neutrino oscillations thought us that neutrinos have mass and mix:

$$m_{\nu_{2(3)}} \gtrsim 0.05 \text{ eV}$$



Do neutrinos get a mass from the Higgs, like all other SM fermions?

$$y(LH)\nu_R \text{ ?}$$

If so, is lepton number conserved or not?

$$M\overline{\nu_R^c}\nu_R \text{ ?}$$

Open questions in the neutrino sector

Neutrino oscillation experimental program

- Is there **CP violation** in the lepton sector?
- Which neutrino is the heaviest, 3 or 2 (Normal or Inverted **Ordering**)?
- Can we measure and over-constrain the **PMNS**, like CKM?

Open questions in the neutrino sector

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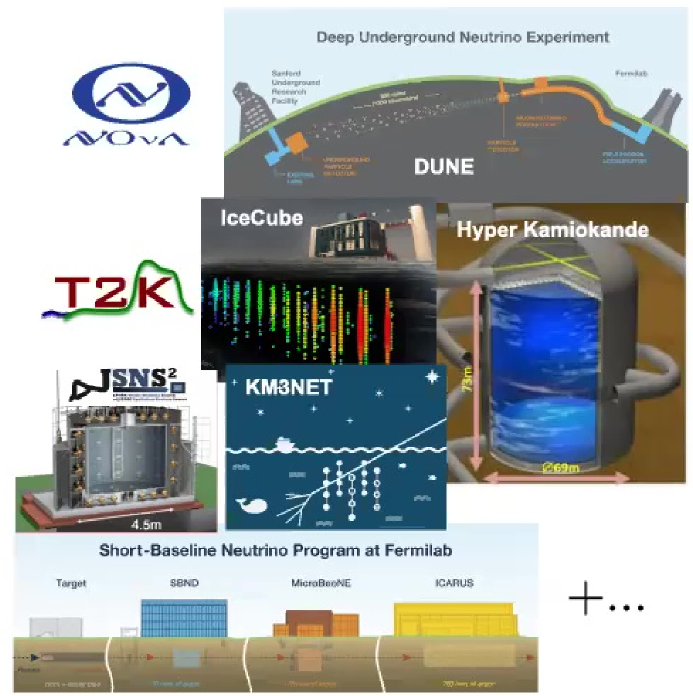

+...

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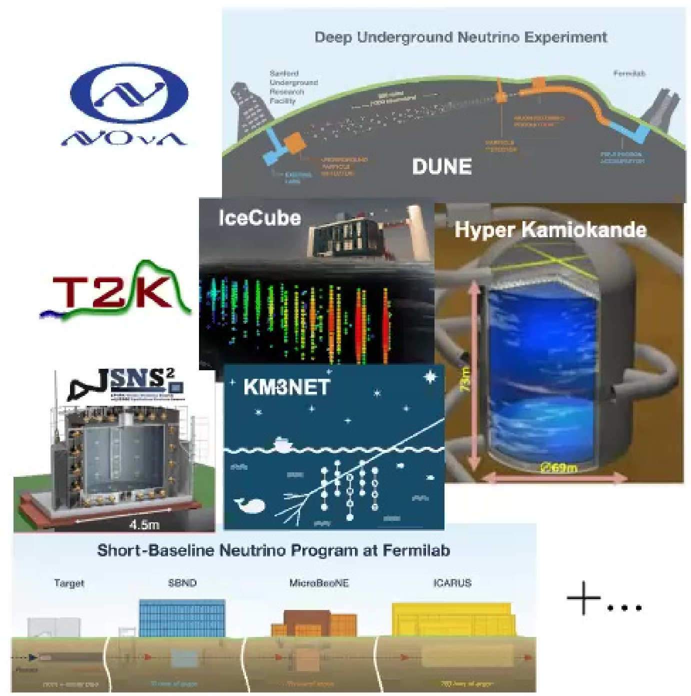


+...

This talk:

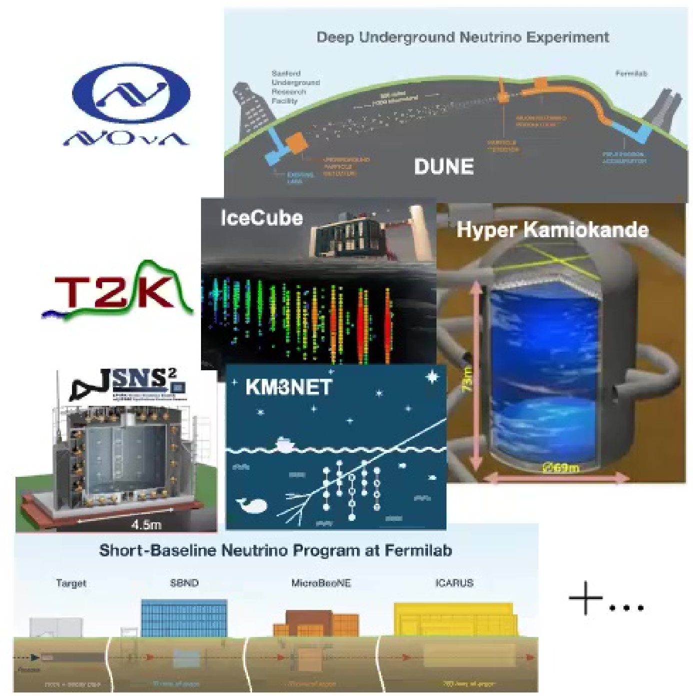
- Can we search for (new*)* new physics in the neutrino sector with this program?

Open questions in the neutrino sector

Neutrino oscillation experimental program

- Is there **CP violation** in the lepton sector?
- Which neutrino is the heaviest, 3 or 2 (Normal or Inverted **Ordering**)?
- Can we measure and over-constrain the **PMNS**, like CKM?

Great bonus if we end up learning something new about these



+...

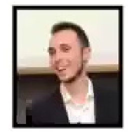
This talk:

- Can we search for (new) new physics in the neutrino sector with this program?

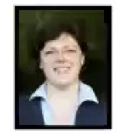
The Outline

- Lamppost seesaw models and secret interactions
- Searches for heavy and "dark" neutrinos
- Phenomenological applications:
    - The MiniBooNE anomaly
    - Dark photons and the $(g-2)_\mu$?

Asli Abdullahi
Durham Uni

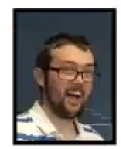


Daniele Massaro
Uni of Bologna



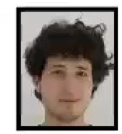
Silvia Pascoli
Uni of Bologna

Georgia Karagiorgi
Columbia Uni



Nicolo Foppiani
Columbia Uni

Carlos Argüelles
Harvard Uni



Nicolo Foppiani
Harvard Uni

P. Ballett, MH,a S. Pascoli arxiv:1903.07589
A. Abdullahi, MH, S. Pascoli arxiv:2007.11813
C. Argüelles, N. Foppiani, MH arxiv:2109.03831

Beyond the naive scaling in the Type-I seesaw

Type-I seesaw Lagrangian:

$$\mathscr{L} \supset -y^{\nu}\left(\overline{L}\tilde{H}\right)N - \frac{M_N}{2}\overline{N^c}N + \text{h.c.}$$

After EWSB, neutrinos get a mass:

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^{\mathsf{T}} & M_N \end{pmatrix}$$ where $M_D = \frac{y^{\nu} v_{\text{EW}}}{\sqrt{2}}$

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Naively, $m_{\nu} \simeq \dfrac{M_D^2}{M_N} \rightarrow \begin{cases} y^{\nu} \sim 10^{-8}\,\dfrac{M_N}{\text{GeV}} \\ \theta \sim 10^{-10}\,\dfrac{\text{GeV}}{M_N} \end{cases}$

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but In reality…

(3x3) (3x?) (?x?) (?x3)

$$M_{\nu} \sim M_D M_N^{-1} M_D^T$$

We know nothing about M_N. It may hide **new symmetries**, **cancellations**, and **new dynamics**.

Low Scale Seesaws

Inverse, Extended and Linear seesaws — Adding complexity to M_N

$$-\mathscr{L}_{\nu-\text{mass}} \supset \frac{1}{2}\left(\overline{\nu_L} \quad \overline{N} \quad \overline{S}\right) \begin{pmatrix} 0 & m & \varepsilon' \\ m & \mu' & \Lambda \\ \varepsilon' & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix} + \text{h.c.}$$

= violating lepton number

(L= -1)

(L= +1)

Neutrino masses protected by **Lepton Number**

Seesaw limit ⟶ $$m_\nu = \frac{\mu m^2 - 2\varepsilon' m \Lambda + \varepsilon'^2 \mu'}{\Lambda^2 - \mu\mu'}.$$

Low Scale Seesaws — two kinds of contributions

P.S.B. Dev et al., 1209.4051
J. Lopez-Pavon et al, 1209.5342

"Inverse Seesaw" (ISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & 0 & \Lambda \\ 0 & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

$$m_\nu \simeq \frac{m_D^2}{\Lambda^2}\mu$$

"Minimal Radiative Inverse Seesaw" (MRISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

$$m_\nu^{\text{tree}} = 0$$

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"Inverse Seesaw" (ISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & 0 & \Lambda \\ 0 & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Integrate out **S** ($\mu \to \infty$)

$$\begin{pmatrix} 0 & m_D \\ m_D & \frac{\Lambda^2}{\mu} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \end{pmatrix}$$

Active-heavy mixing: $|U_{\alpha 4}|^2 \simeq \frac{m_D^2 \mu^2}{\Lambda^4}$

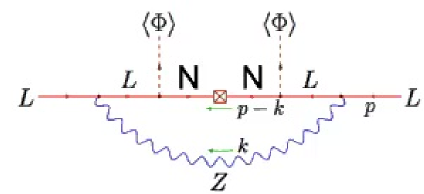
Light state: $m_\nu \simeq \frac{m_D^2}{\Lambda^2} \mu$

"Minimal Radiative Inverse Seesaw" (MRISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Integrate out **N** ($\mu' \to \infty$)

$$\begin{pmatrix} \frac{m_D^2}{\mu'} & \frac{\Lambda m_D}{\mu'} \\ \frac{\Lambda m_D}{\mu'} & \frac{\Lambda^2}{\mu'} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ S^c \end{pmatrix}$$

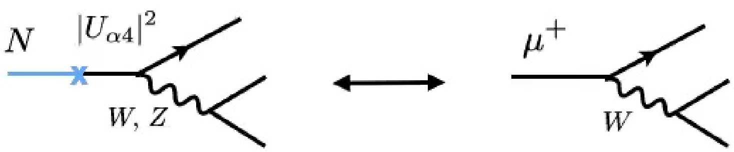


Active-heavy mixing: $|U_{\alpha 4}|^2 \simeq \frac{m_D^2}{\Lambda^2}$

Light state: $m_\nu^{\rm loop} \simeq \frac{\alpha_W}{16\pi} \frac{m_D^2}{\mu'} f(m_Z, m_h, \mu')$

Laboratory searches

Typically, long-lived particles. $\frac{c\tau_\mu}{c\tau_N} \sim |U_{\alpha 4}|^2 \left(\frac{m_N}{m_\mu}\right)^5$



Production and decay proceed via **"weaker-than-weak"** interactions.

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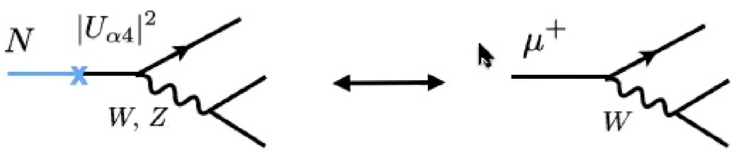

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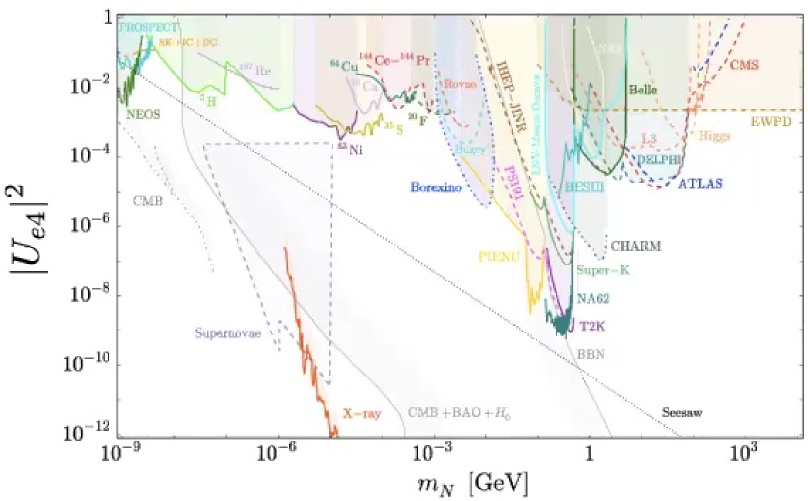

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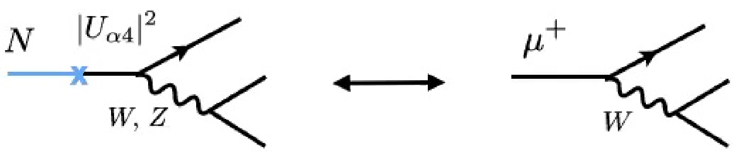

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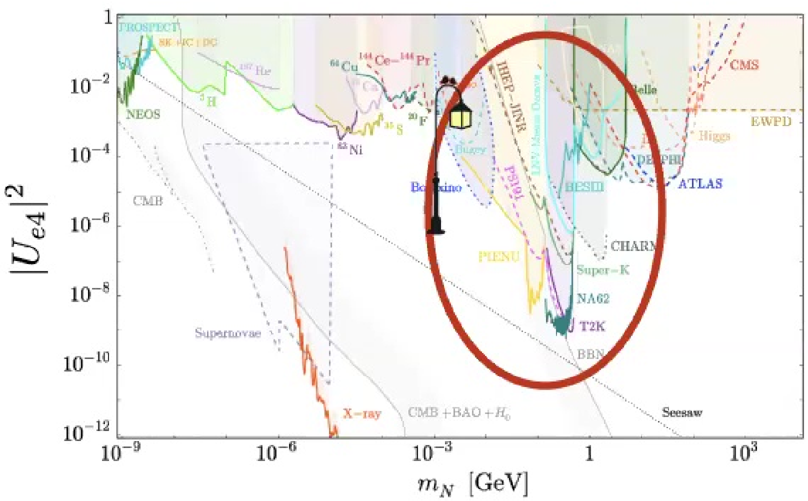


Under the MeV-GeV lamppost:

1) Missing mass in pion or kaon decays

$$\pi/K \to \ell N \longrightarrow (p_{\pi,K} - p_\ell)^2 \stackrel{?}{=} M_N^2$$

2) Decay-in-flight beam dumps / neutrino exps

$\pi/K \to \ell N \longrightarrow$ N propagates $\longrightarrow$ N decays visibly

Most progress made with **invisible** or **long-lived HNLs**.

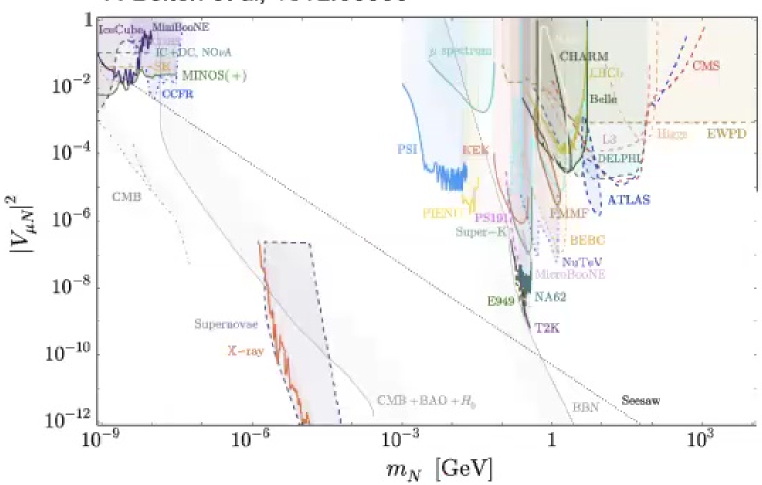
Lifetime is bounded from above due to BBN constraints (t_N < 0.1 s).

In all generality, there is no lower bound.

Agnostic about the HNL decay properties

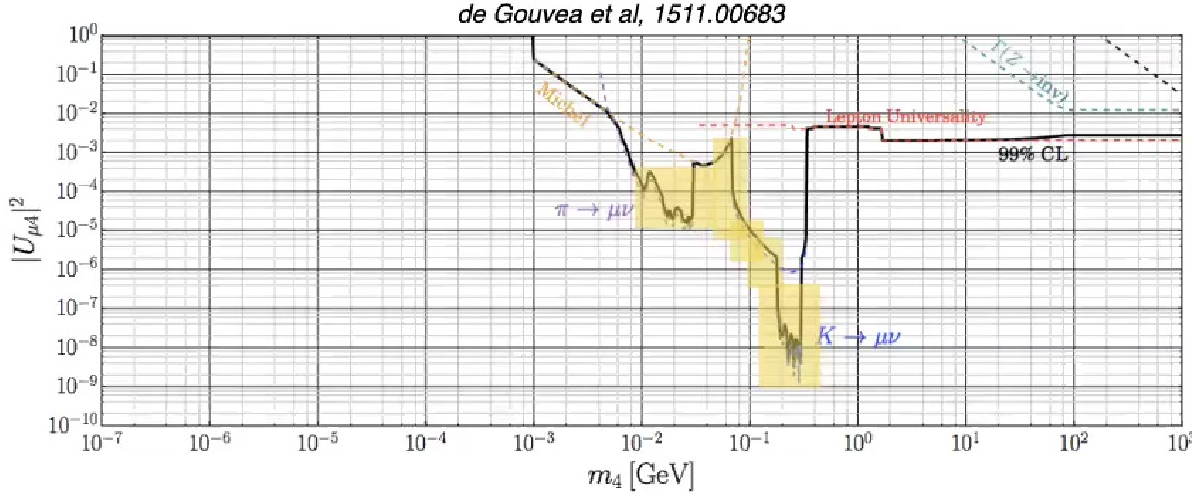
Minimal single flavor model

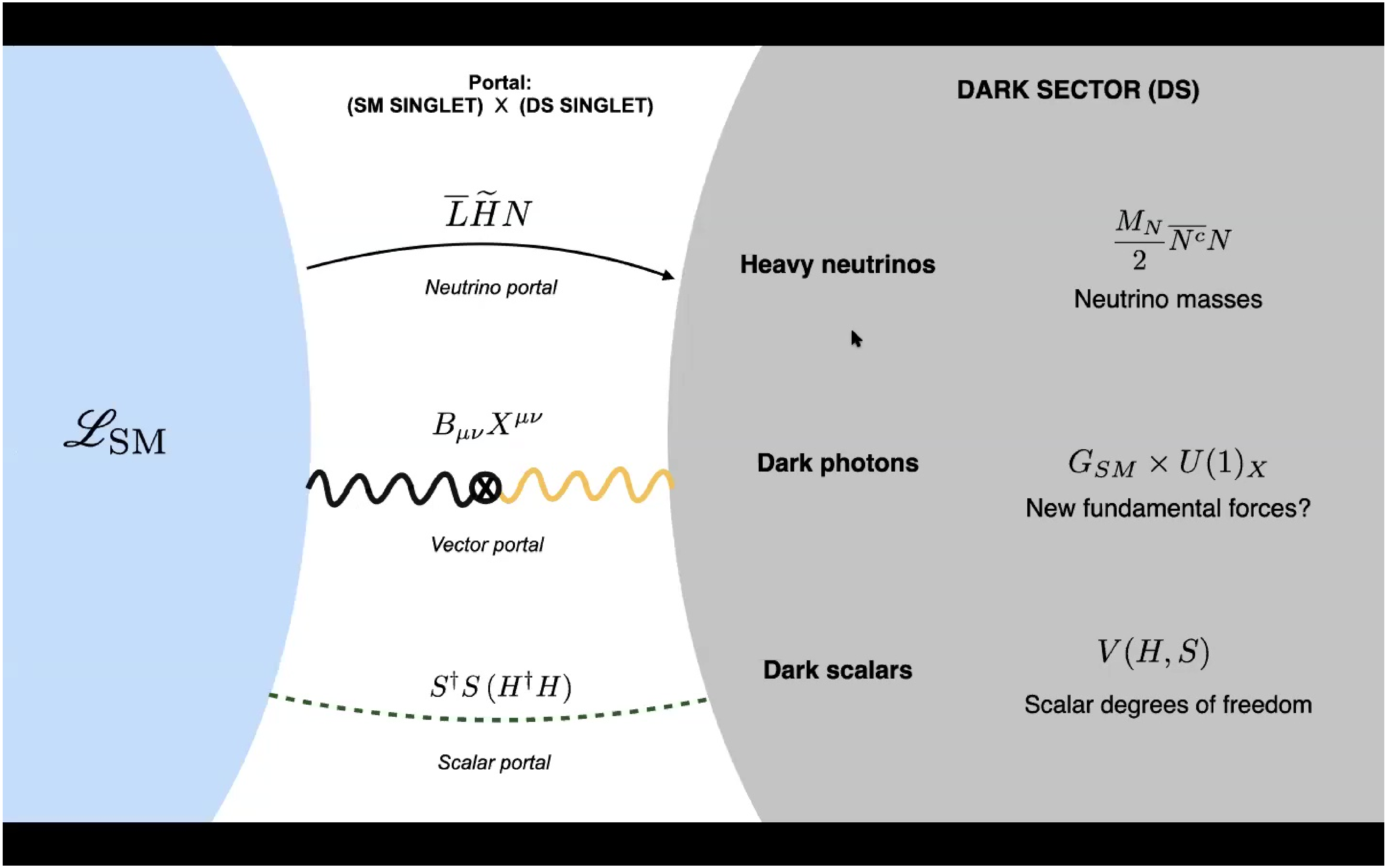
P. Bolton et al, 1912.03058

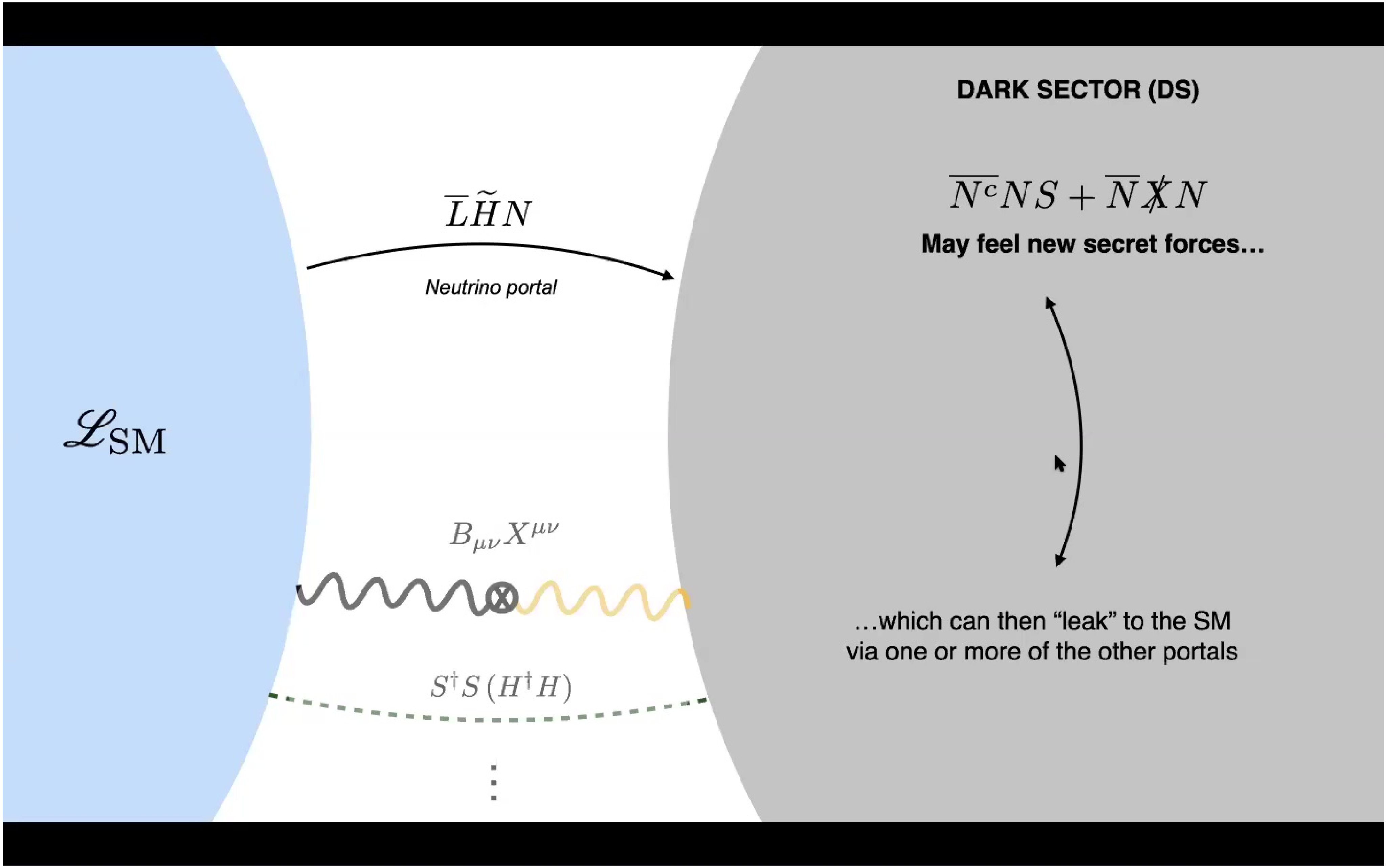


Remaining agnostic about HNL decay properties:

de Gouvea et al, 1511.00683



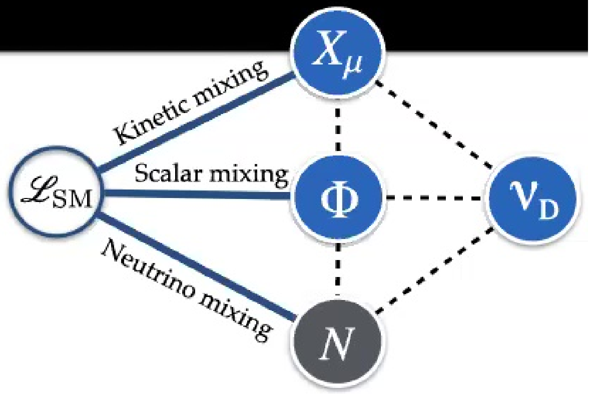

Portal:
(SM SINGLET) X (DS SINGLET)
DARK SECTOR (DS)
$\mathscr{L}_{\rm SM}$
$\overline{L}\widetilde{H}N$
Neutrino portal
Heavy neutrinos
$\frac{M_N}{2}\overline{N^c}N$
Neutrino masses
$B_{\mu\nu}X^{\mu\nu}$
Vector portal
Dark photons
$G_{SM} \times U(1)_X$
New fundamental forces?
$S^\dagger S\,(H^\dagger H)$
Scalar portal
Dark scalars
$V(H,S)$
Scalar degrees of freedom



DARK SECTOR (DS)
$\overline{N^c} N S + \overline{N} \not{X} N$
May feel new secret forces…
…which can then "leak" to the SM via one or more of the other portals
$\overline{L}\widetilde{H}N$
Neutrino portal
$\mathscr{L}_{\rm SM}$
$B_{\mu\nu}X^{\mu\nu}$
$S^\dagger S\,(H^\dagger H)$

A simple model for a "dark" neutrino sector

A. Abdullahi, MH, S. Pascoli
arXiv:2007.11813



1) A minimal renormalizable model:

	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
ν_N	**1**	0	0
ν_{D_L}	**1**	0	Q
ν_{D_R}	**1**	0	Q
Φ	**1**	0	Q

Heavy neutrinos charged under a dark U(1)' symmetry, broken at the GeV

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sin\chi}{2}X_{\mu\nu}B^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi) - \lambda_{\Phi H}|H|^2|\Phi|^2$$

$$+\overline{\widehat{\nu}_N}i\partial\!\!\!/\widehat{\nu}_N + \overline{\widehat{\nu}_D}i D\!\!\!\!/_X\widehat{\nu}_D - \left[(\overline{L}\widetilde{H})Y\widehat{\nu}_N^c + \frac{1}{2}\overline{\widehat{\nu}_N}M_N\widehat{\nu}_N^c + \overline{\widehat{\nu}_N}\left(Y_L\widehat{\nu}_{D_L}^c\Phi + Y_R\widehat{\nu}_{D_R}\Phi^*\right) + \overline{\widehat{\nu}_D}M_X\widehat{\nu}_D + \text{h.c.}\right],$$

See also B. Batell et al, JHEP 1608 (2016) 052, Bertuzzo et al, PLB 791 (2019) 210-214 + others

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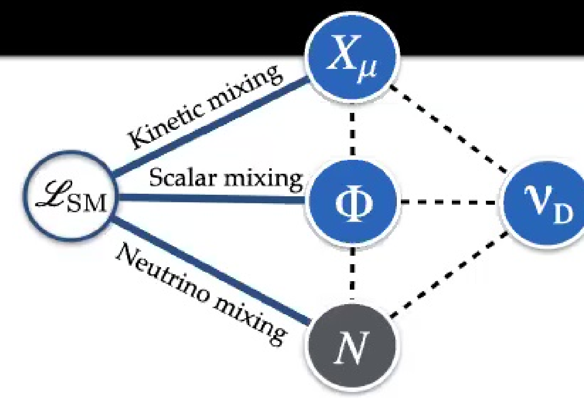

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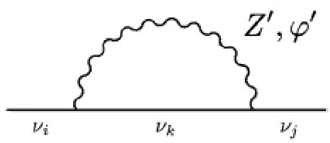
Heavy neutrinos charged under a dark U(1)' symmetry, broken at the GeV

2) Neutrinos masses:



$$\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & M_N & \Lambda \\ 0 & \Lambda^T & \mathcal{M}_X \end{pmatrix} \begin{pmatrix} \nu_\alpha^c \\ \nu_N^c \\ \nu_D^c \end{pmatrix} \Rightarrow \quad m_\nu \simeq M_D^T (\Lambda^T)^{-1} \mathcal{M}_X \Lambda^{-1} M_D + \delta M_{1-\text{loop}}(M_N, M_Z, M_{Z'})$$

Tree-level (ISS)

Loop-level (MRISS)

A simple model for a "dark" neutrino sector

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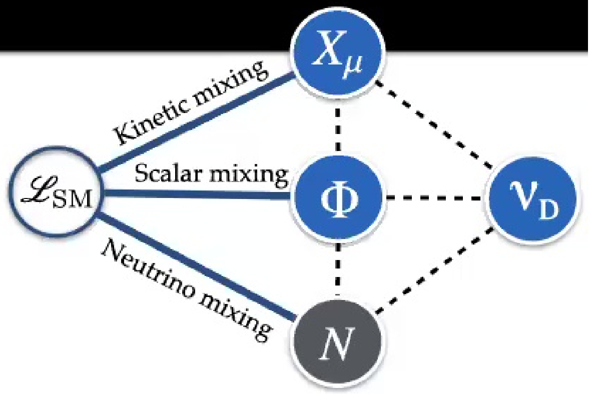

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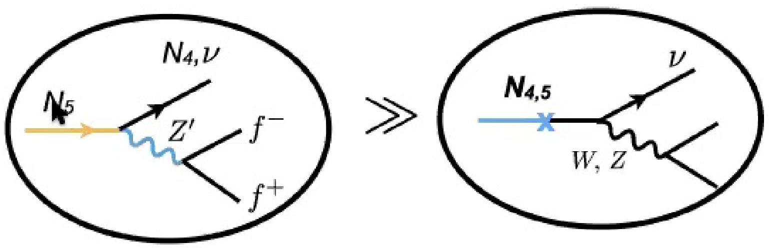
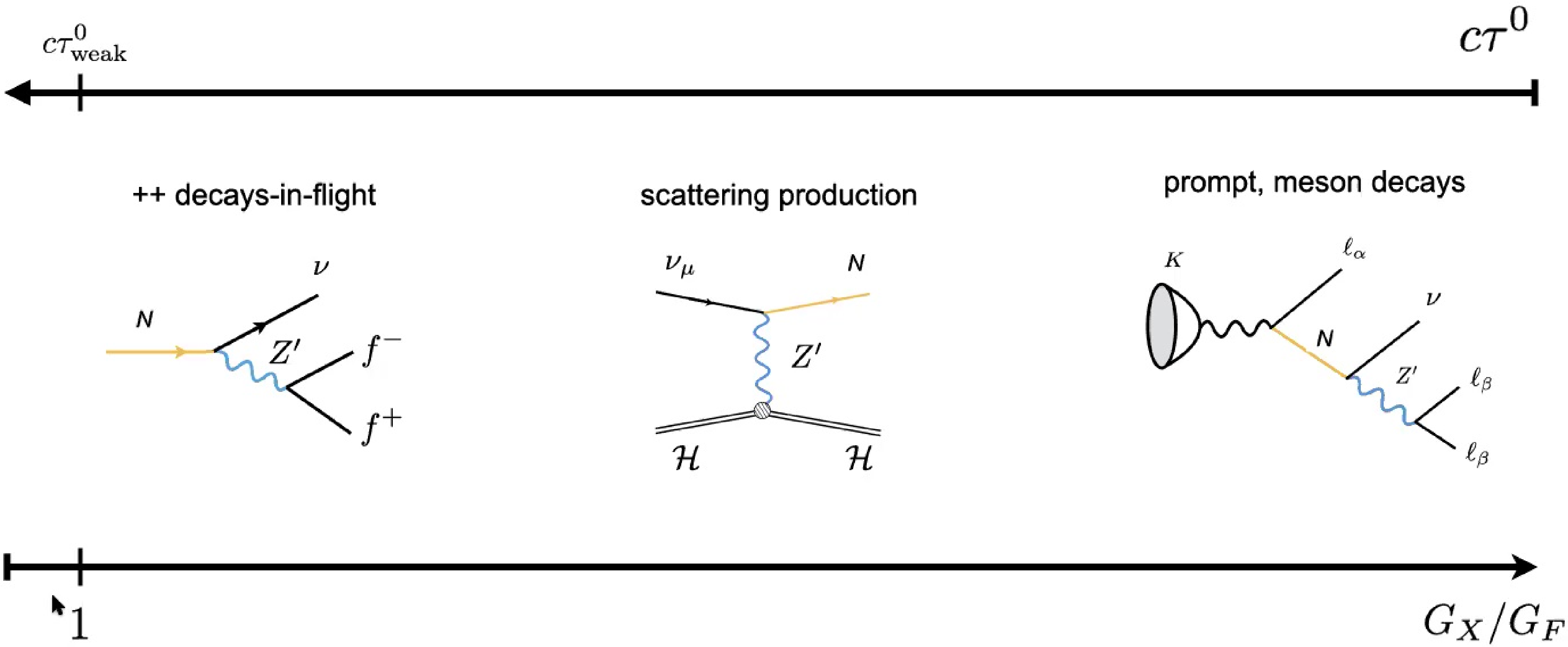
3) Modified decays:



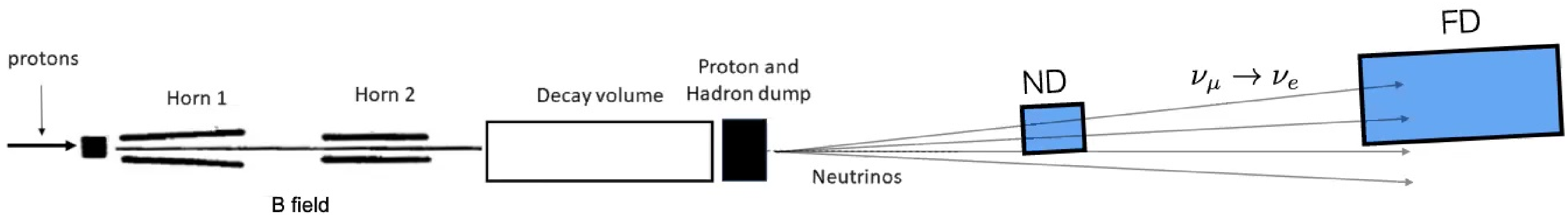
- Faster decays
- CC decays buried under the new physics
  - No visible lepton number violation, e.g. in $K \to \mu^+ \mu^+ \pi^-$
- N is always accompanied by missing energy

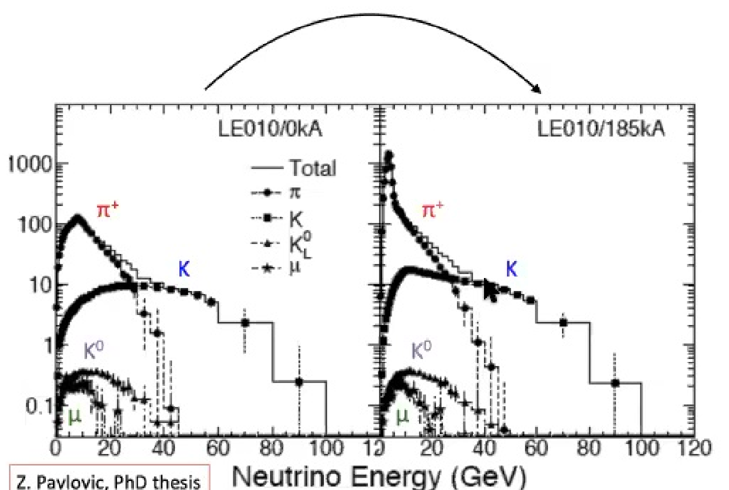
The Impact of Secret Interactions



Decay-in-flight searches
T2K near detector (ND280)

C. Argüelles, N. Foppiani, MH arxiv:2109.03831





Z. Pavlovic, PhD thesis

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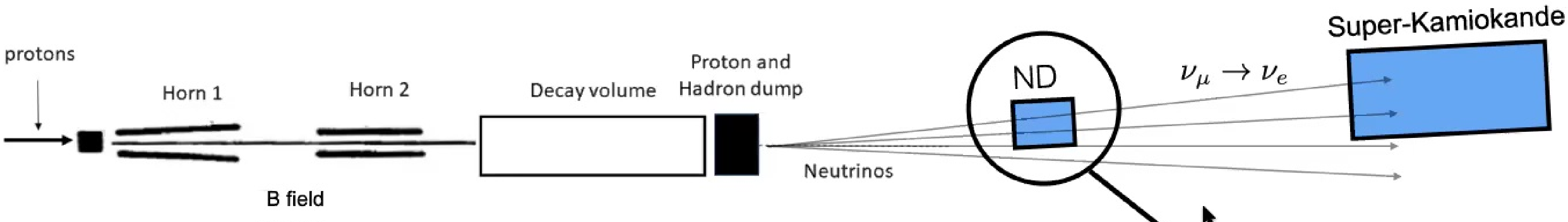
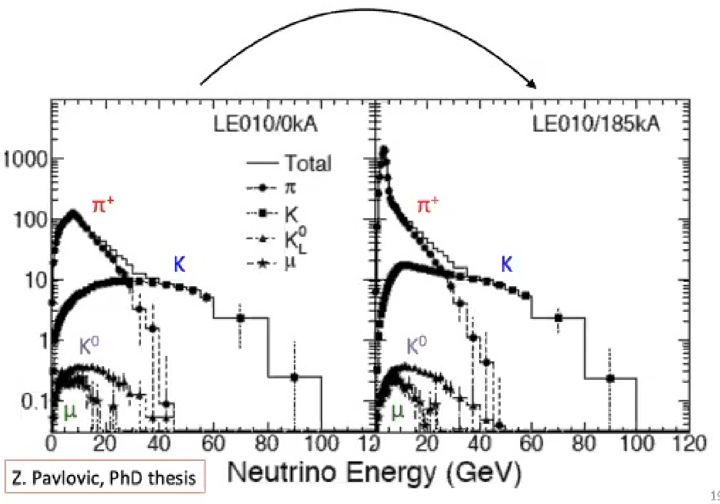
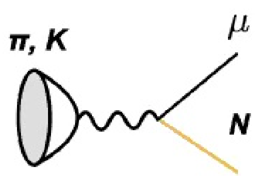
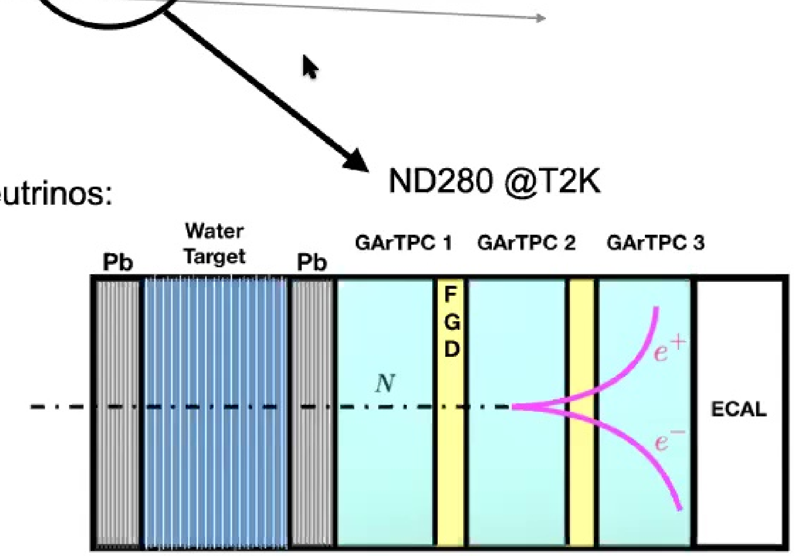




Also a source of heavy neutrinos:





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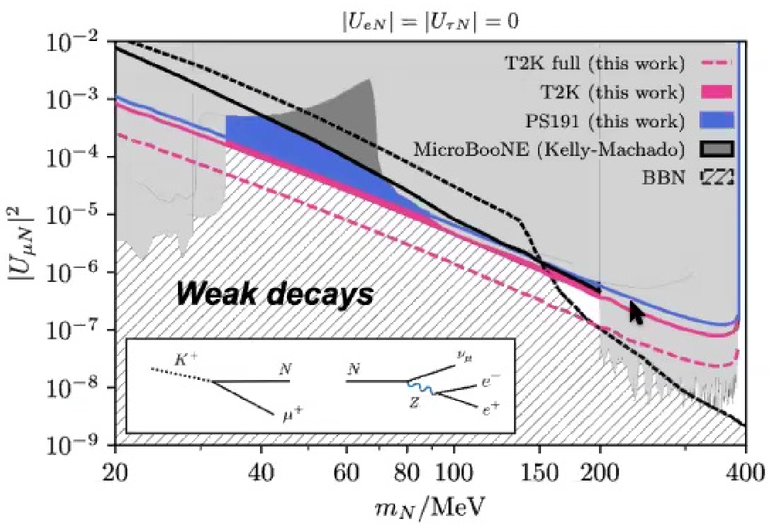
C. Argüelles, N. Foppiani, MH arxiv:2109.03831

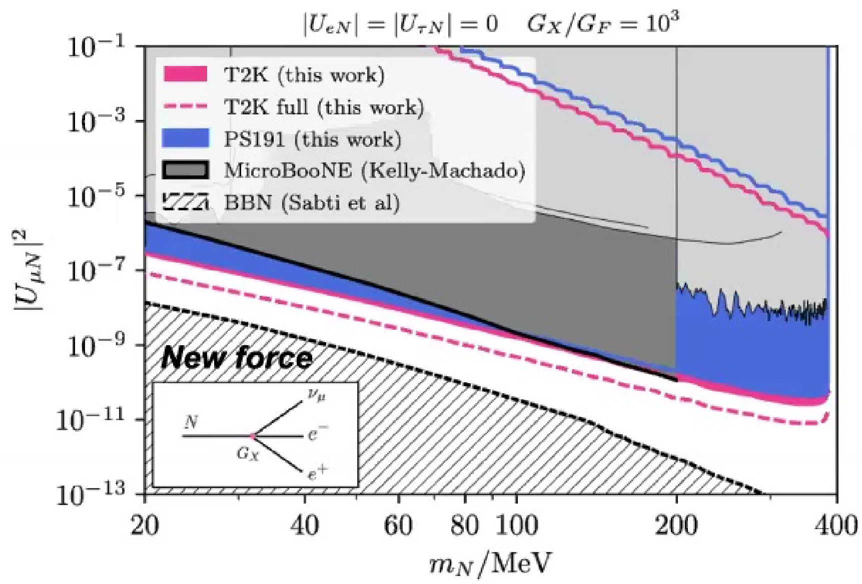
We revisited DIF and cleared some confusion regarding a PS191, Previously thought to give the strongest constraints…

T2K provides the best limits on HNLs below the kaon mass.



Event rate proportional to new physics decay rate

$$P_{N\to X} \simeq \frac{\ell_{\rm det}}{\gamma\beta}\,\Gamma_{N\to X}$$



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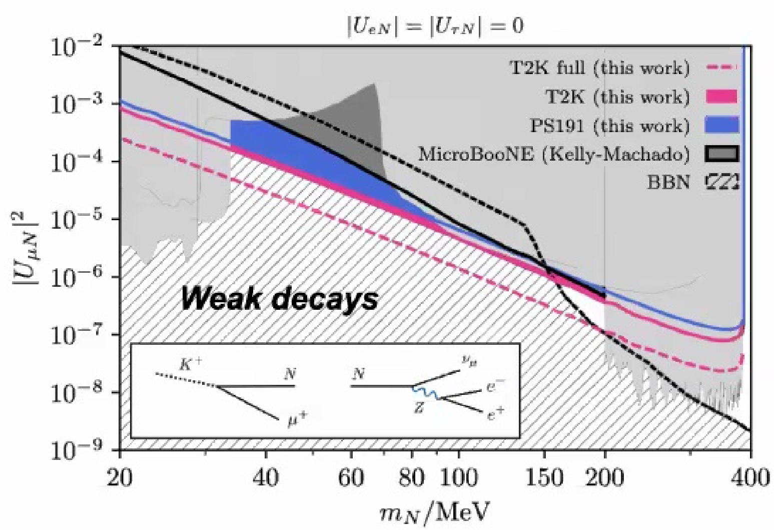
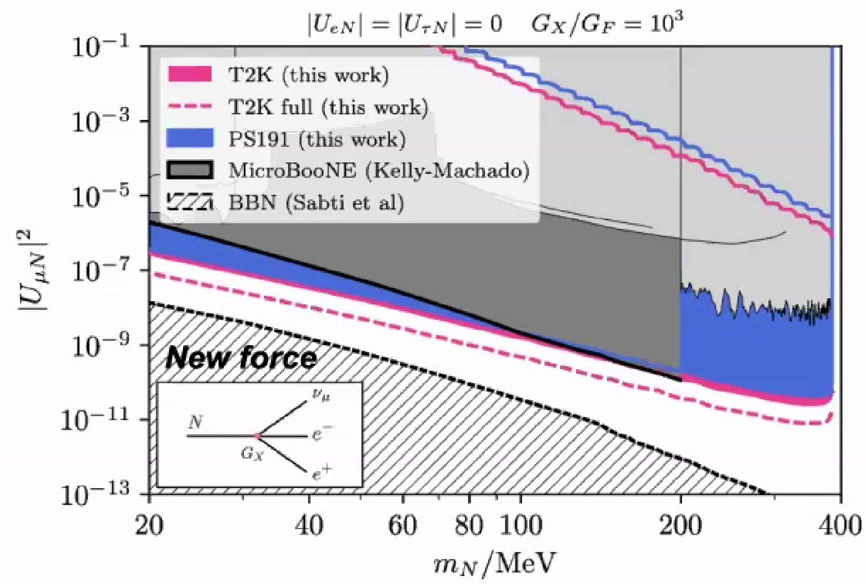


Event rate proportional to new physics decay rate

$$P_{N\to X} \simeq \frac{\ell_{\rm det}}{\gamma\beta}\,\Gamma_{N\to X}$$

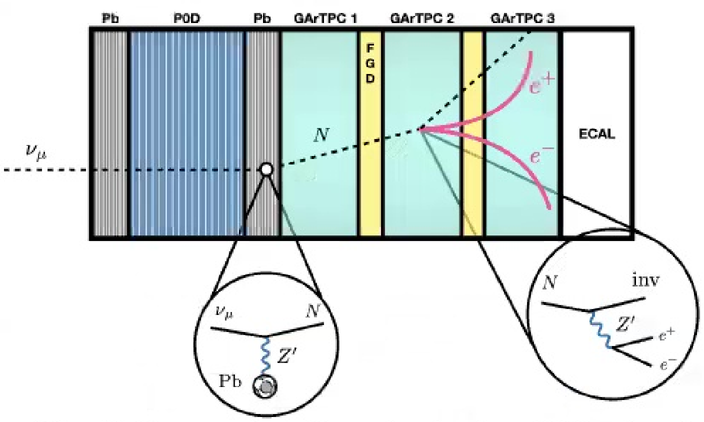


Upscattering in dense neutrino detectors
T2K near detector (ND280)

C. Arguelles, MH, N. Foppiani, in preparation.

T2K Collaboration, Phys. Rev. D 100, 052006 (2019)
See also, Vedran Brdar et al, arXiv:2007.14411

Heavy **lead** plates
+ Gaseous Argon modules
+ Magnetic field to separate e+e-



Constrains events with no hadronic activity at vertex and HNLs w/ finite lifetimes.

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T2K near detector (ND280)

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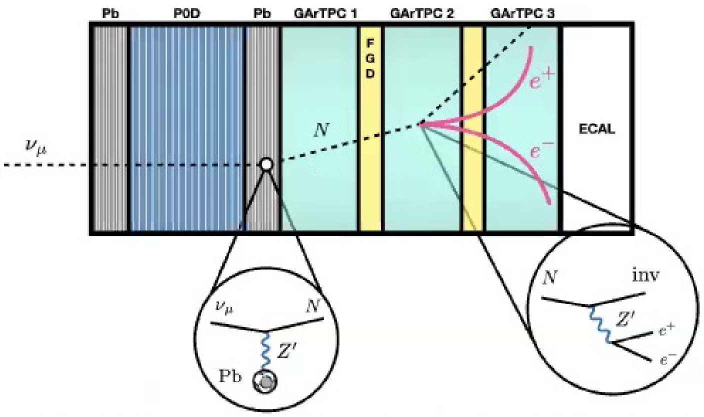
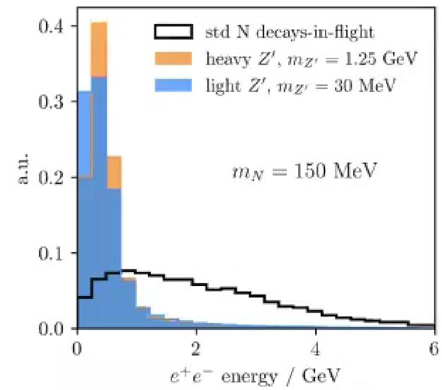


Constrains events with no hadronic activity at vertex and HNLs w/ finite lifetimes.

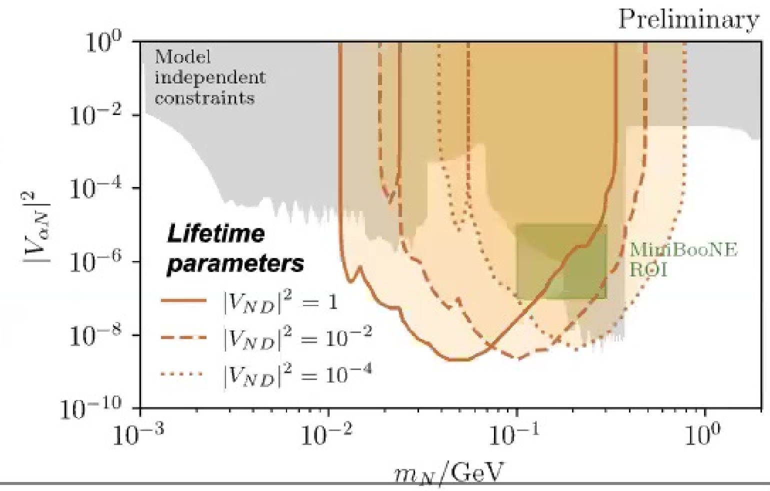


Precludes any signature of upscattering at other neutrino experiments if

ctau > O(5) cm

Scattering signal is softer than DIF one, but efficiencies remain large.

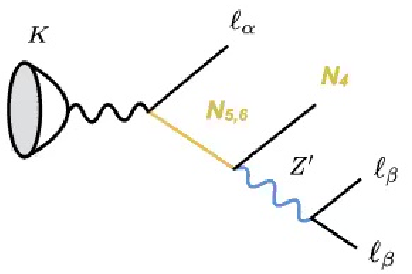
Backgrounds close to the Lead layers are large, so restricted to gaseous volume.



Prompt decays at Kaon factories
Three charged lepton signatures

Rare leptonic kaon decays

Peak search + (displaced) e+e- vertex



At **NA62**, would expect ~3000 events in existing data for our *benchmark*.

$$|p_K - p_\ell| = m_{5,6}$$
$$m_{\rm miss} = |p_K - p_\ell - p_{ee}| = m_4$$
$$m_{ee} < m_{5,6} - m_4$$

Existing measurements:

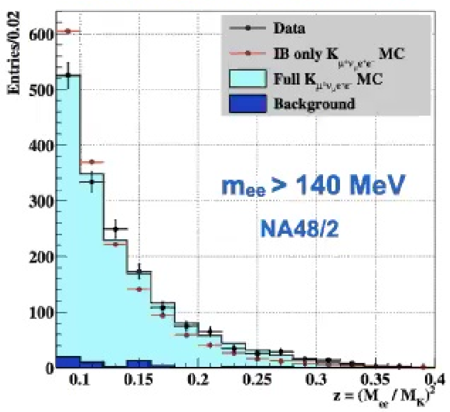
$$\mathrm{BR}(K^+ \to \mu^+ \nu e^+ e^-) = (7.81 \pm 0.21\,\mathrm{stat.}) \times 10^{-8}$$ @ NA48/2

$$\mathrm{BR}(K^+ \to \mu^+ \nu \mu^+ \mu^-) < 4.7 \times 10^{-7}$$ @ E787

Both SM process will be measured by NA62.

New physics challenges:

M. S. Atiya *et al.*, PRL.63, 2177 (1989)



Main challenge comes from pion Dalitz decays at m_{ee} < 140 MeV

$$K^+ \to \mu^+ \nu_\mu (\pi^0 \to \gamma e^+ e^-)$$

Additional cuts can reduce pi+ decay backgrounds:

$$K^+ \to (\pi^+ \to \mu^+ \nu) e^+ e^- \qquad m_{\mu\nu} > 150\,\mathrm{MeV}$$

Ultimately, depends on exp resolution, but BKGs can also be reduced with displaced vertices. At NA62, this is feasible for

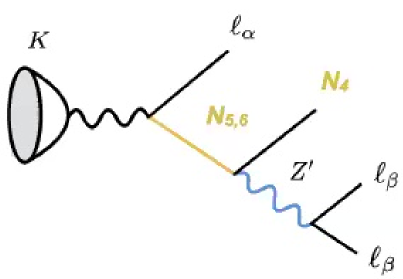
$c\tau$ > 10 ps

Prompt decays at Kaon factories

Three charged lepton signatures

Rare leptonic kaon decays

Peak search + (displaced) e+e- vertex



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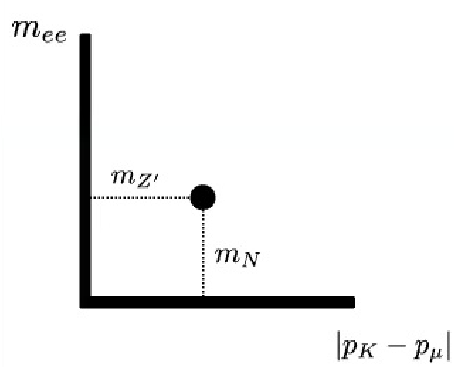
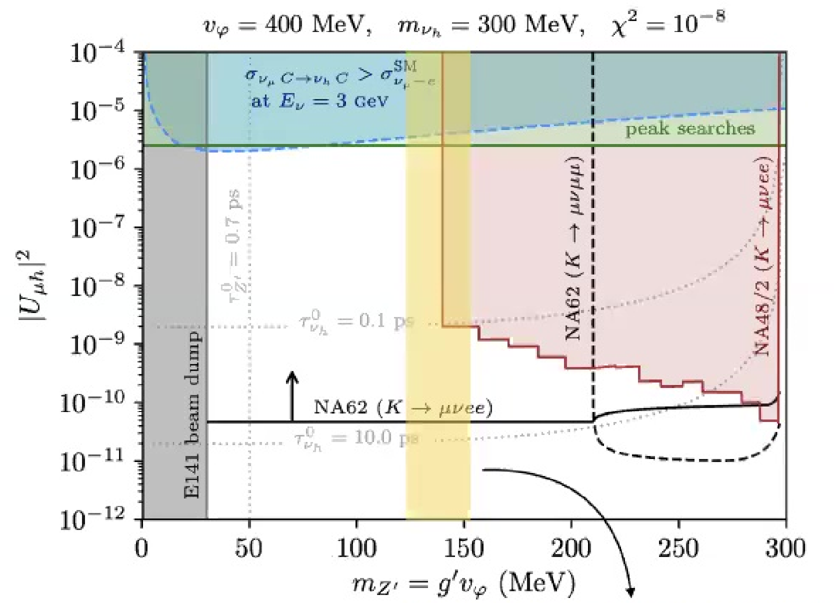
$$m_{ee} < m_{5,6} - m_4$$

Light dark photon case

Smoking gun peak at light dark photon and HNL mass





Competing with pion Dalitz decays.

Bump hunt and displaced vertex search currently being carried out at NA62.

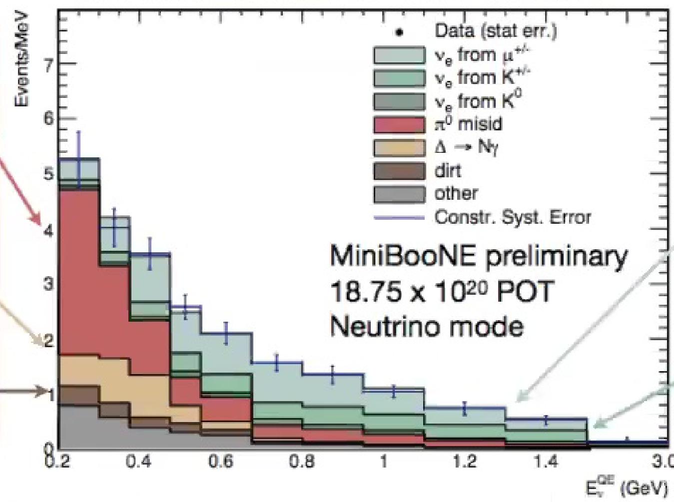
Data-Driven Background Estimates

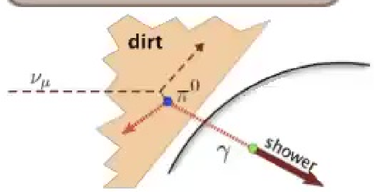
Hourlier, Adrien, MiniBooNE Coll. Neutrino2020

π^0 MisID
constrained from *in situ* measurement of NC π^0 rate

Δ-> Nγ resonance
constrained from *in situ* measured NC π^0 rate and theoretical prediction

Dirt
constrained from *in situ* dirt data sample





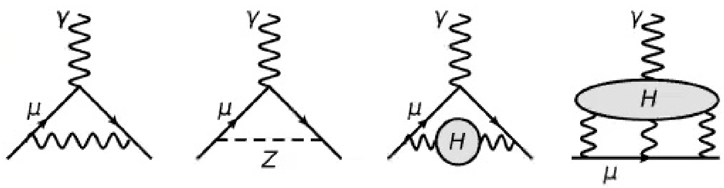
ν_e from μ decay
is constrained by *in situ* ν_μ CCQE measurement

ν_e from K decay
constrained from *in situ* high energy events + SciBooNE high energy ν_μ event rate

Dark forces contributing to $(g\text{-}2)_\mu$

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HVP,\,LO} + a_\mu^{\rm HVP,\,NLO} + a_\mu^{\rm HVP,\,NNLO} + a_\mu^{\rm HLbL} + a_\mu^{\rm HLbL,\,NLO}$$
$$= 116\,591\,810(43) \times 10^{-11}\,.$$

Phys. Rept. 887 (2020) 1-166

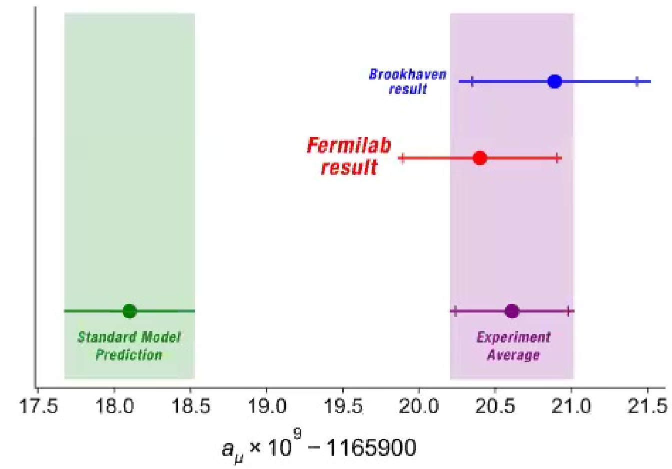


$$a_\mu^{\rm EXP} = 116592061(41) \times 10^{-11}$$

Muon (g-2) BNL., PRD73:072003,2006
Muon (g-2) FNAL 10.1103/PhysRevLett.126.141801

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = 251 \times 10^{-11}$$

Combination of BNL and FNAL results stands at a 4.2 σ discrepancy with theory white-paper calculations.



If theory predictions are indeed under control, then new physics must not be too far out of reach:

$$\Delta a_\mu^{\rm NP} \sim \frac{g^2}{16\pi^2}\frac{m_\mu^2}{\Lambda^2}$$

$$\frac{\Lambda}{g} \sim \text{ few 100s of GeV}$$

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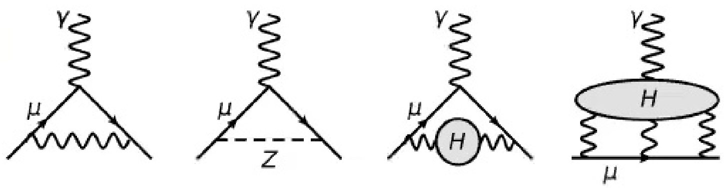
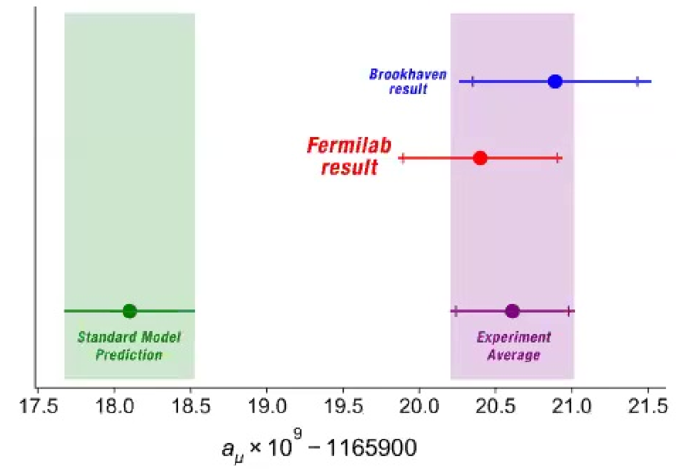
Phys. Rept. 887 (2020) 1-166





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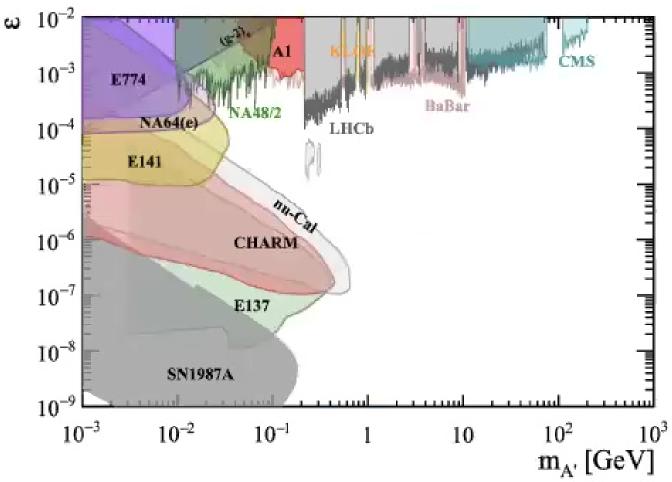
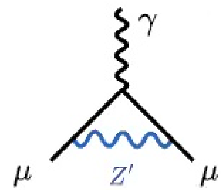
Minimal Dark Photon models

Hypothetical vector bosons contribute positively:

M. Fabbrichesi et al,
SpringerBriefs in Physics 2020, 2005.01515





Dark photon:

$$\mathscr{L} \supset \frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

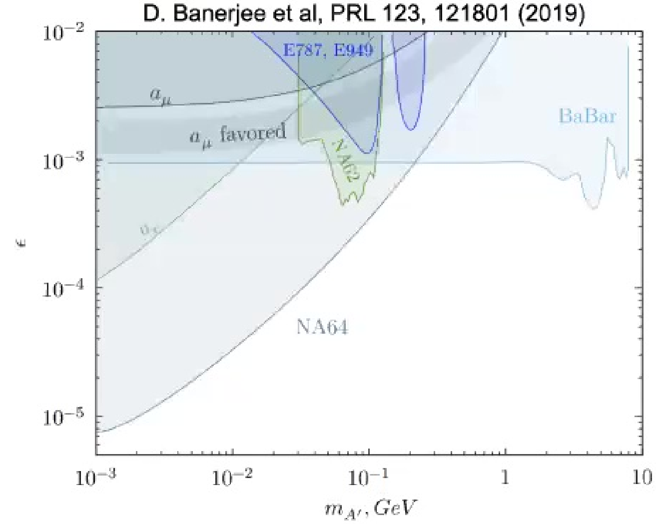
$$a_\mu^{Z'} \simeq \frac{\epsilon^2 \alpha}{\pi} \frac{m_\mu^2}{3 m_{Z'}^2}$$

for

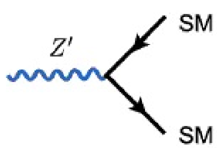
$$m_\mu \ll m_{Z'}$$

Pospelov, PRD80:095002,2009

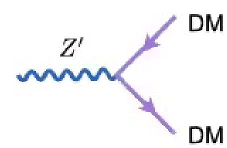
D. Banerjee et al, PRL 123, 121801 (2019)



Visible:



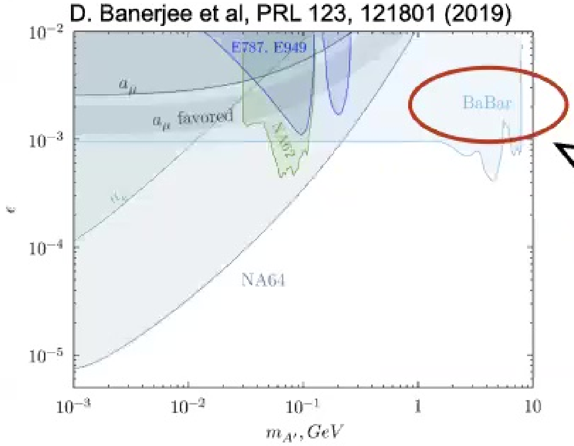
Invisible:



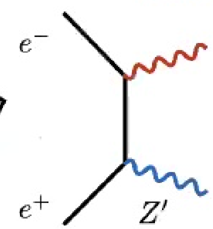
Monophoton searches for dark photon at B factories

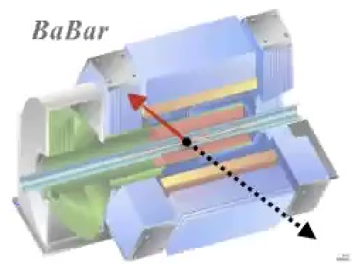
Most stringent constraint for invisible case in the GeV mass range

D. Banerjee et al, PRL 123, 121801 (2019)



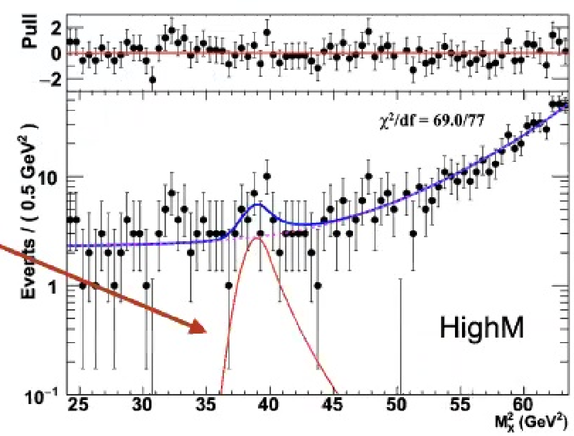
ISR monophoton





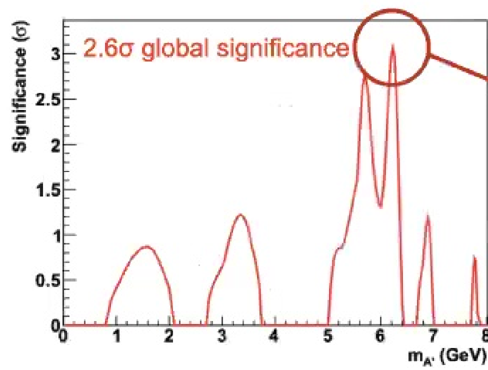
Invisible Z'

BaBar collab., PRL 119, 131804 (2017)



Dark photon mass reconstructed as:

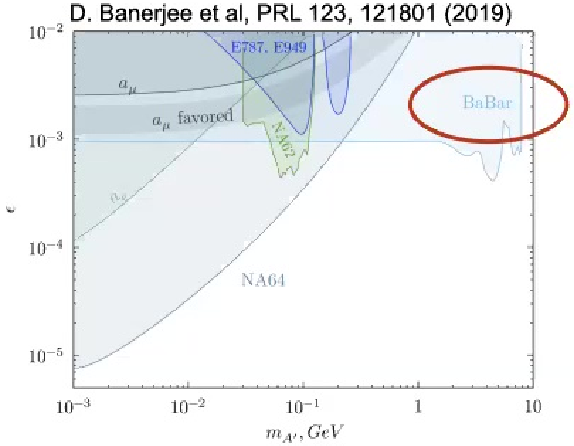
$$M_X^2 = s - 2E_\gamma^{\mathrm{CM}}\sqrt{s}$$

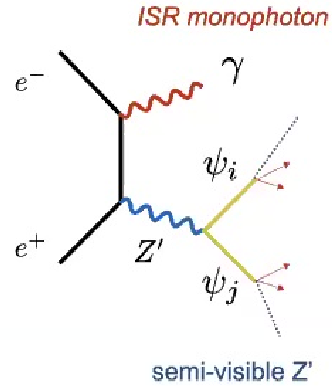


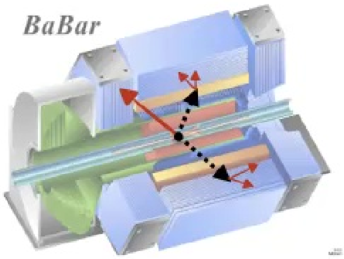
Revisiting the muon (g-2) with semi-visible dark photons

Weakening the BaBar constraints with additional semi-visible decays

D. Banerjee et al, PRL 123, 121801 (2019)







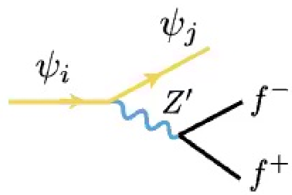
If dark photon decays semi-visibly, then additional tracks are vetoed in the mono photon selection.

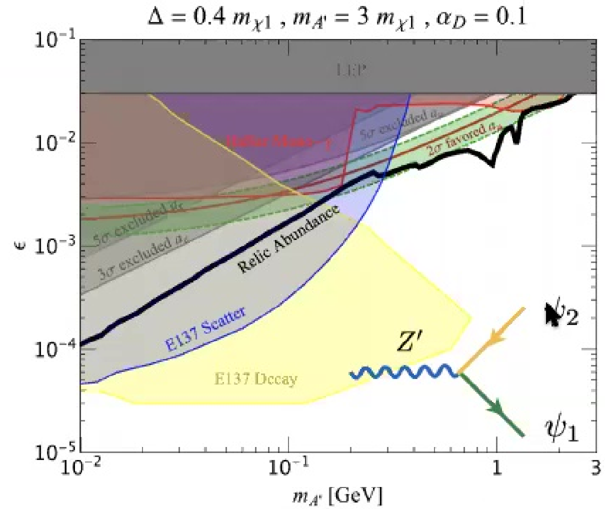
New parameter space opens for (g-2)$_\mu$

For example, taking
$$\varepsilon^2 = 4.6 \times 10^{-4}$$
$$m_{Z'} = 1.25 \text{ GeV}$$

we need:

$$P_{\text{missing } Z'} < 2.2 \times 10^{-3}$$



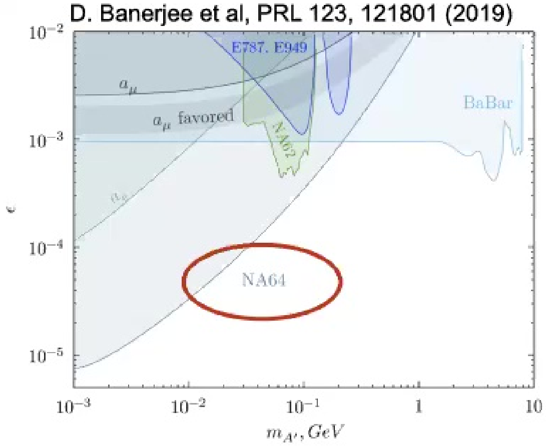


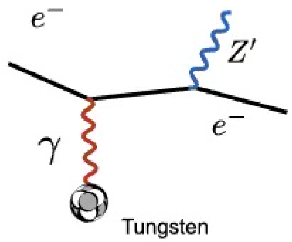
G. Mohlabeng, Phys. Rev. D 99, 115001 (2019)

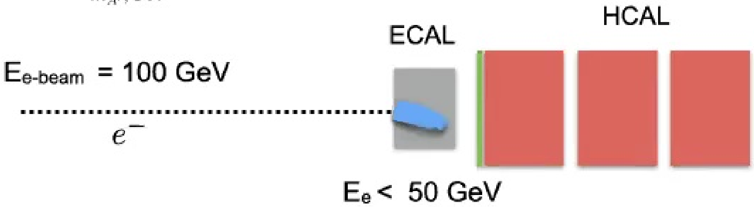
Searches for invisible dark photons at NA64

Electrons on target

D. Banerjee et al, PRL 123, 121801 (2019)





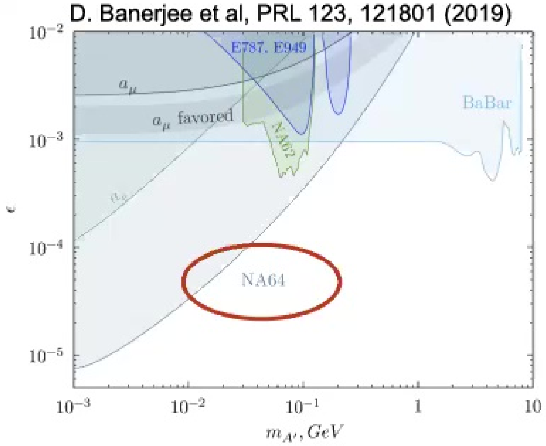


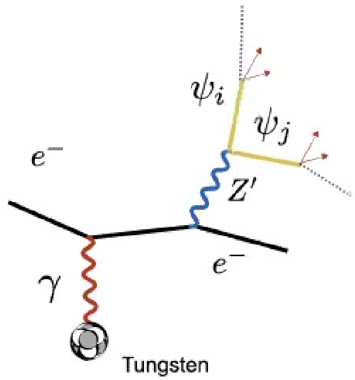
Search for missing energy due to Z' radiation.

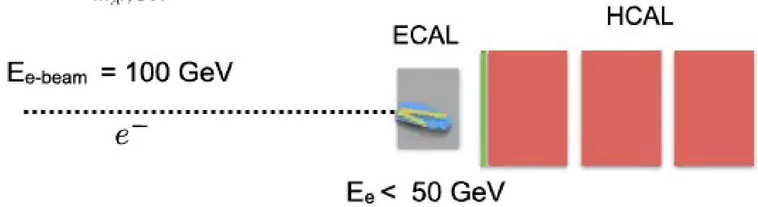
Semi-invisible dark photons at NA64

Electrons on target — additional energy deposition

D. Banerjee et al, PRL 123, 121801 (2019)







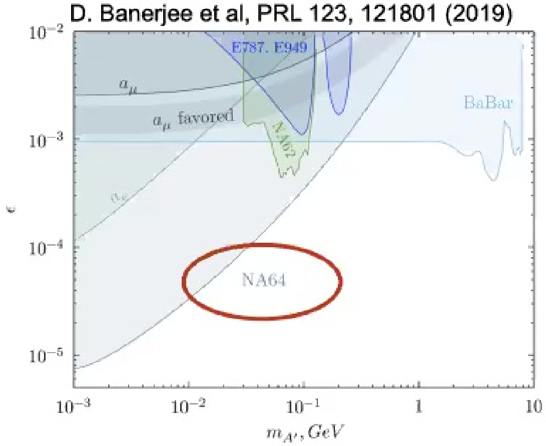
If ψ_i decays promptly it will often **not be vetoed** from the analysis.

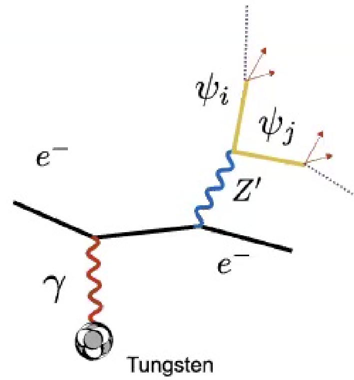
NA64 is still sensitive to semi-visible decays as long as additional decay products are contained in the primary electron shower.

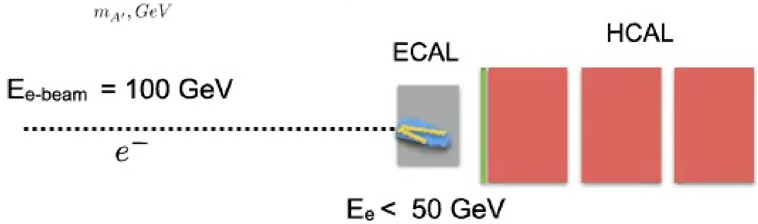
Semi-invisible dark photons at NA64

Electrons on target — additional energy deposition

D. Banerjee et al, PRL 123, 121801 (2019)







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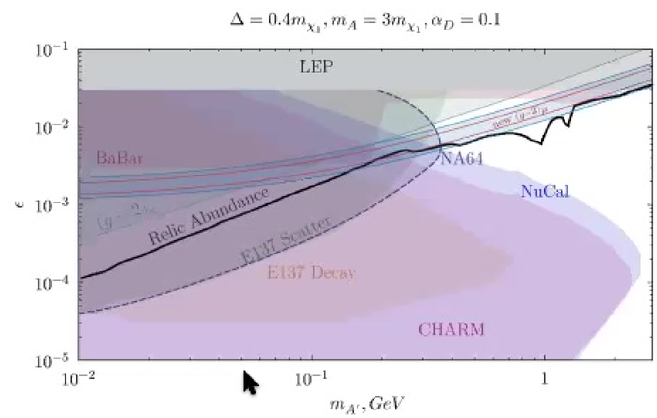
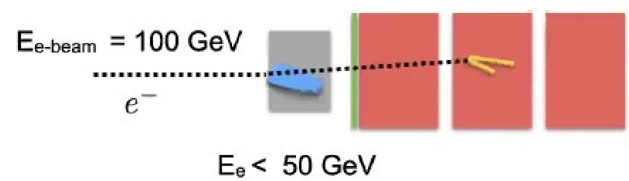
Recently, NA64 also searched for displaced vertices of the fermions in the HCAL.





Cazzaniga et al, arXiv:2107.02021

Inelastic Dark Matter model

Results from our re-analysis

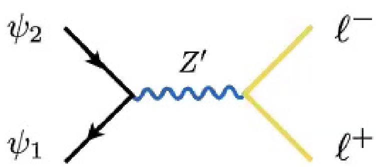
A. Abdullahi, D. Massaro, MH, S. Pascoli, in preparation

A pair of oppositely charged Majorana fermions:

$$\mathscr{L}_{\text{mass}} = \frac{1}{2}\begin{pmatrix}\overline{\psi_L} & \overline{\psi_R^c}\end{pmatrix}\begin{pmatrix}\mu_L & m_D \\ m_D & \mu_R\end{pmatrix}\begin{pmatrix}\psi_L^c \\ \psi_R\end{pmatrix} + \text{h.c.}$$

For small Majorana masses, we have pseudo-Dirac fermions.

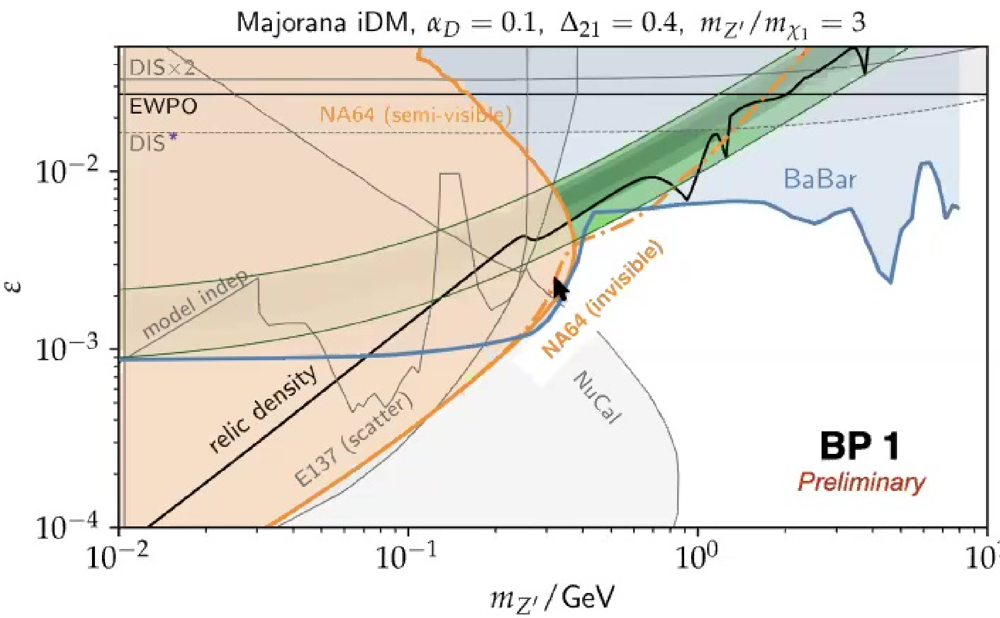
$$\mathcal{J}^\mu_{\text{DM}} \simeq \overline{\psi_2}\gamma^\mu\psi_1 \quad \text{with} \quad \frac{\mathcal{B}(Z'\to\psi_1\psi_1)}{\mathcal{B}(Z'\to\psi_1\psi_2)} \simeq \left(\frac{\mu_L - \mu_R}{4m_D}\right)^2$$



Annihilation

$$Z' \to \psi_1\psi_2$$

Z' decay channels



Minimal model excluded by BaBar and NA64.

Only a single "semi-visible" decay from the dark photon is can be easily missed at BaBar when soft*.

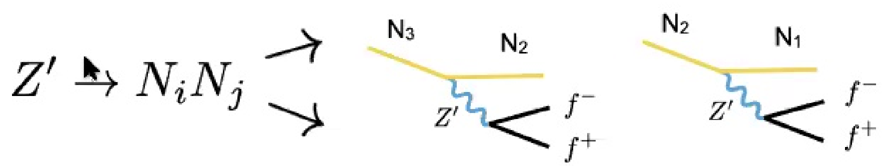
Constraint from PRL 126, 011801 (2021), compare it with PRD99 (2019) 9, 092006

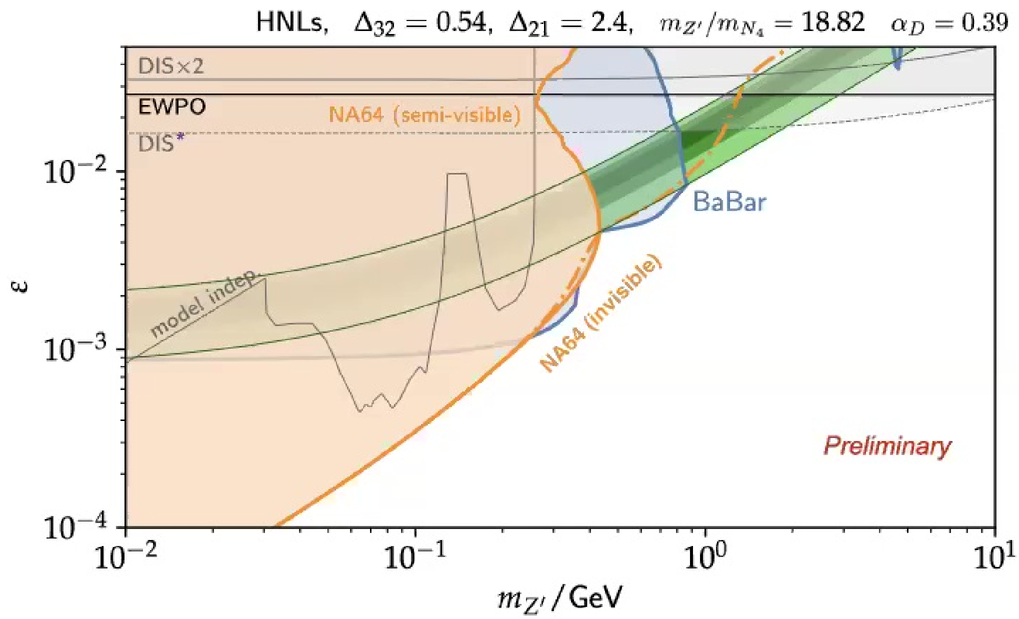
Heavy neutral lepton models

Several generations of particles

A. Abdullahi, D. Massaro, MH, S. Pascoli, in preparation

Dark photon cascades of decays down the HNL generations.





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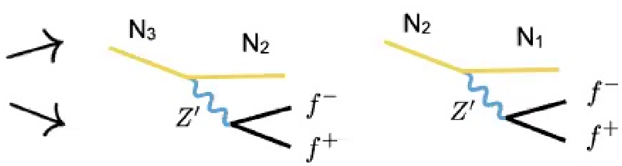
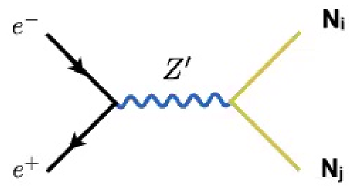
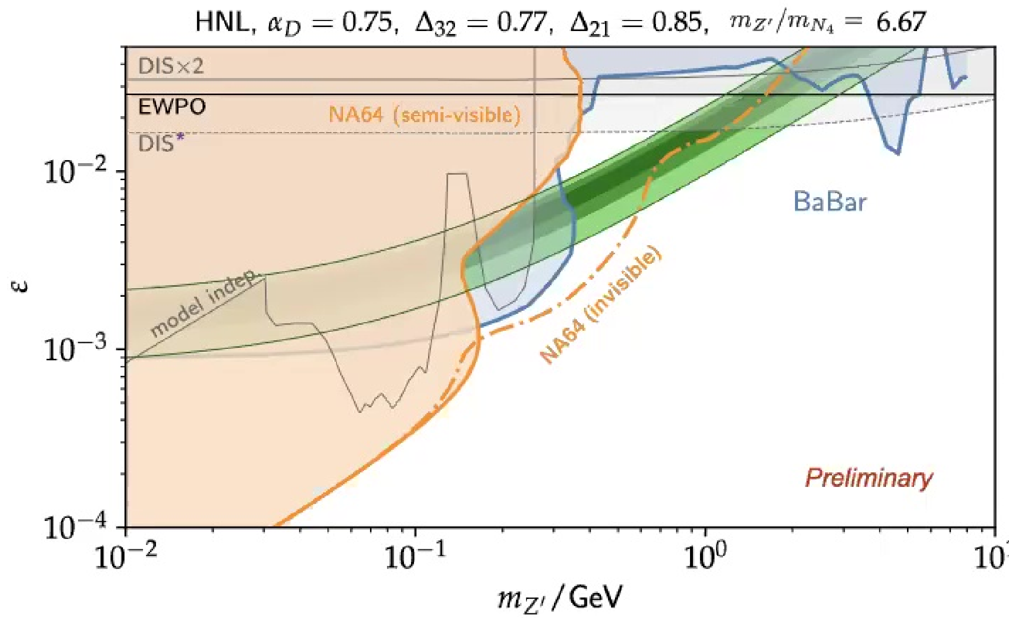
$Z' \to N_i N_j$





$\sim \frac{\alpha_D}{\alpha}$ of ISR rate

$\mathcal{O}(10^4)$ s-channel events, with displaced vertices and multi-lepton final state.



Explanation is **possible**, but only for large dark couplings:

i) Landau pole not too far from GeV scale…

ii) S-channel production can dominate

Constraint from PRL 126, 011801 (2021), compare it with PRD99 (2019) 9, 092006

Conclusions

Still a lot of space for new physics in the neutrino sector at the MeV-GeV scale from low-scale seesaw models.

Extending the reach to short-lived heavy neutrinos — fast decays via new force:

Decay in flight —> upscattering —> meson decays

New ideas for explaining MiniBooNE with dilepton pairs, currently being tested at μBooNE.

Revisited semi-visible dark photon explanation to (g-2). If this is to work, the dark photon must:

1. Decay to dark particles close in mass, $m_\psi/m_{Z'} \gtrsim 0.1$, which in turn have large mass splittings, $\Delta_{ij} \gtrsim 0.3$
2. Decay to Short-lived particles.
3. Have large dark couplings (pushing pertubativity and large s-channel production)

Thank you!