BSM Explanations of the MiniBooNE Anomaly

SBND Theory Mini Workshop

Sometimes vanilla is not enough!

12/13/2021

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Outline

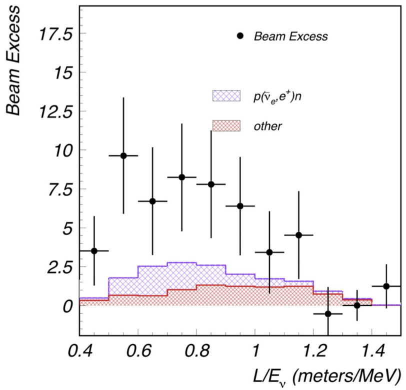
- ★ SBL anomalies and the sterile neutrino hypothesis
- ★ Deep-dive into **alternative LEE models**
  - *Flavor transitions*
  - *New particles in neutrino scattering*
  - *New particles in the beam*
- ★ New physics models ranked!
- ★ Outlook for SBN program
- ★ Final words

Short-baseline Anomalies

Several hints of new physics at the short baselines

Simultaneous explanation possible with a ~1 eV fourth sterile neutrino

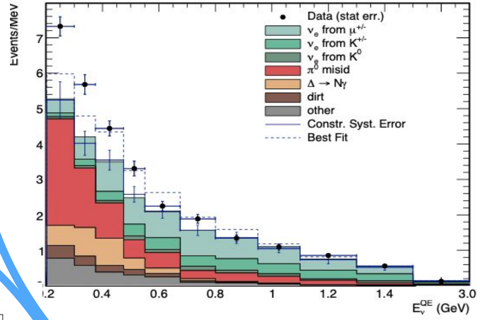
LSND



arXiv:0104049

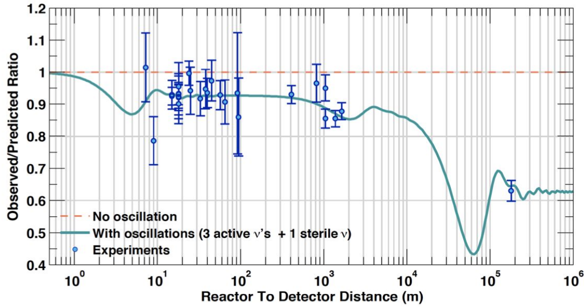
MiniBooNE

arXiv:2006.16883



Reactors

arXiv:1101.2755, arXiv:2106.05913

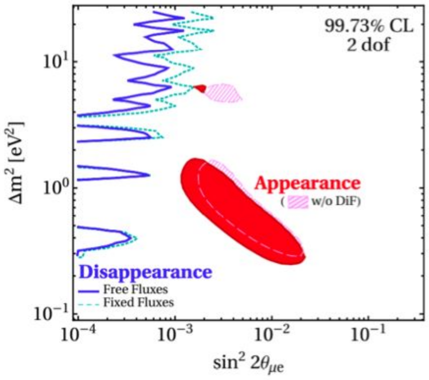


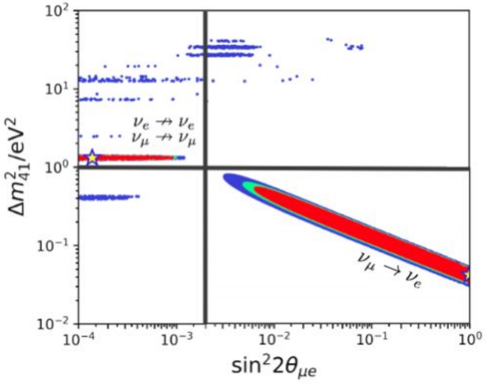
Global Fits and the Vanilla Scenario

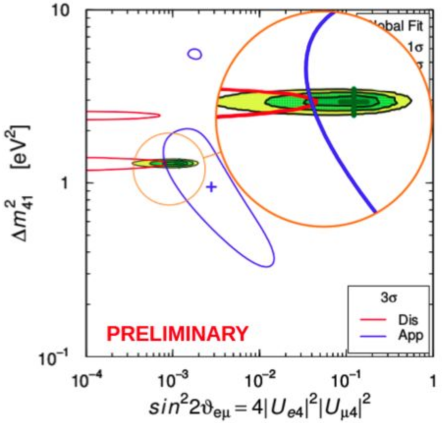
$$P_{\mu e}^{\mathrm{SBL}} = 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\mu\mu}^{\mathrm{SBL}} = 1-4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

➡ Electron neutrino appearance and muon neutrino disappearance are correlated in the SBL limit







3+1 model severely disfavored by tension between appearance and disappearance

All global fit groups agree on this conclusion: Diaz et al arXiv:1906.00045, Gariazzo et al. 1703.00860, and Dentler et al JHEP 1808 (2018)

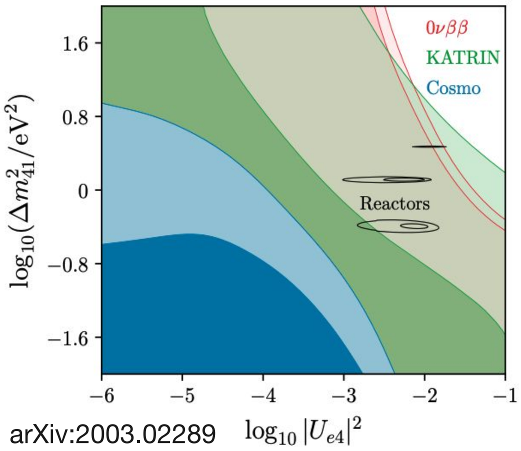
Let's not forget cosmology!

SBL O(eV) steriles severely constrained by cosmological data!

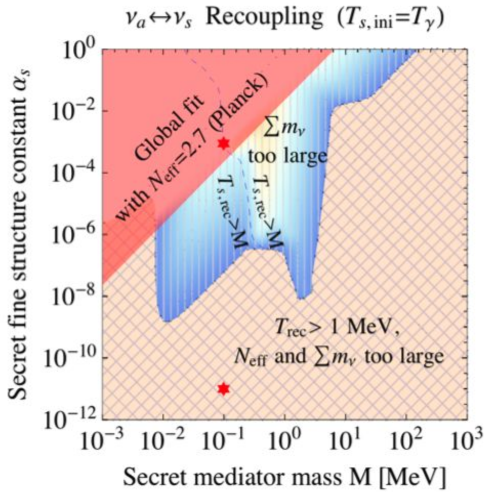
Effective mixing → $\sin^2 2\theta_m = \dfrac{\sin^2 2\theta_0}{\left(\cos^2 2\theta_0 + \frac{2E}{\Delta m^2} V_m\right) + \sin^2 2\theta_0}$ ➡ Keeps $N_{\rm eff}$ at 3

Vacuum mixing ($\sin^2 2\theta_0$); Large ($\frac{2E}{\Delta m^2} V_m$)

arXiv:1806.10629



arXiv:2003.02289



Dasgupta & Kopp 2014; Chu, Dasgupta & Kopp 2015 Saviano et al. 2014; Mirrizi et al. 2015;
Cherry, Friedland & Shoemaker 2016; Chu et al. 2018
See talk by Yvonne Y. Y. Wong at Neutrino 2020 for summary

New physics attempts to avoid constraints have largely failed

From here: The Garden of Forking Paths

- ★ Null results are often not scrutinized as carefully as anomalous ones.
  - ***Are all null results reliable?***
- ★ Experimental setups at MB, LSND, reactors… are markedly different.
  - ***Do the anomalies share a common origin?***
- ★ To what degree do the anomalies themselves constrain the possible explanations?

What ideas have been proposed?

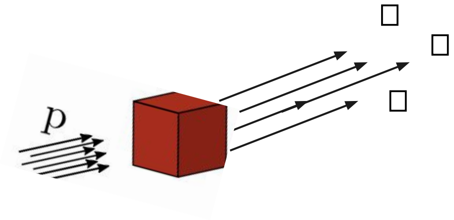
We focus on the MiniBooNE LEE and consider **three broad categories of models**

Flavour transitions

$$\nu_\mu \xrightarrow{?} \nu_e$$

- ★ Oscillations
  - sterile neutrinos
  - sterile neutrino + decays
  - Lorentz violation
  - matter effects
  - LED
- ★ LNV decays

Production of new particles in the beam

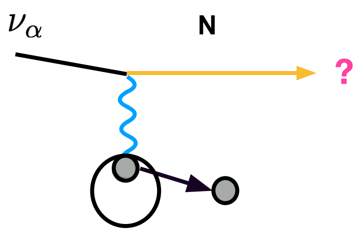


- ★ meson decay-in-flight to:
  - visible states
  - visible + invisible states
  - dark sector states

What ideas have been proposed?

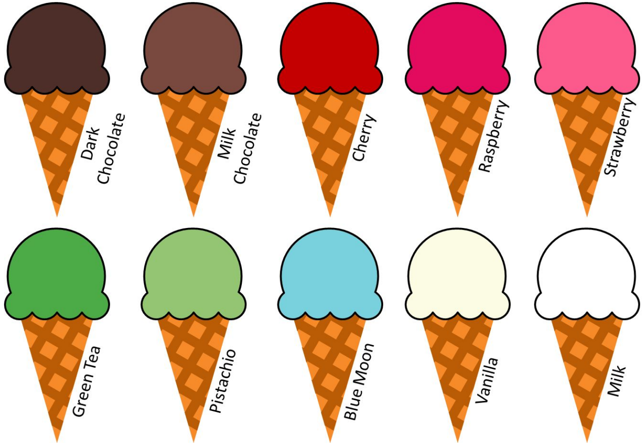
We focus on the MiniBooNE LEE and consider **three broad categories of models**

Production of new particles in neutrino scattering



★ HNL production from neutrino upscattering. Subsequent decays to
  - **electron-positron pairs**
  - **single photons**

Flavor Transitions



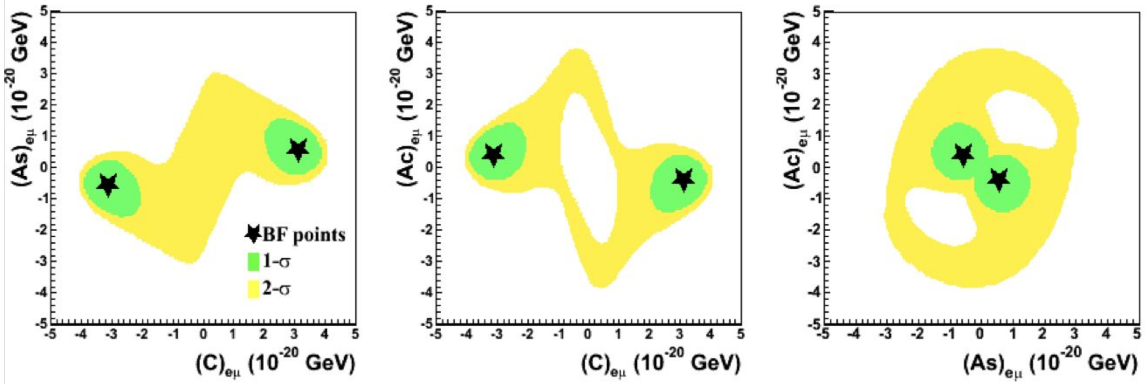
Lorentz-Violation

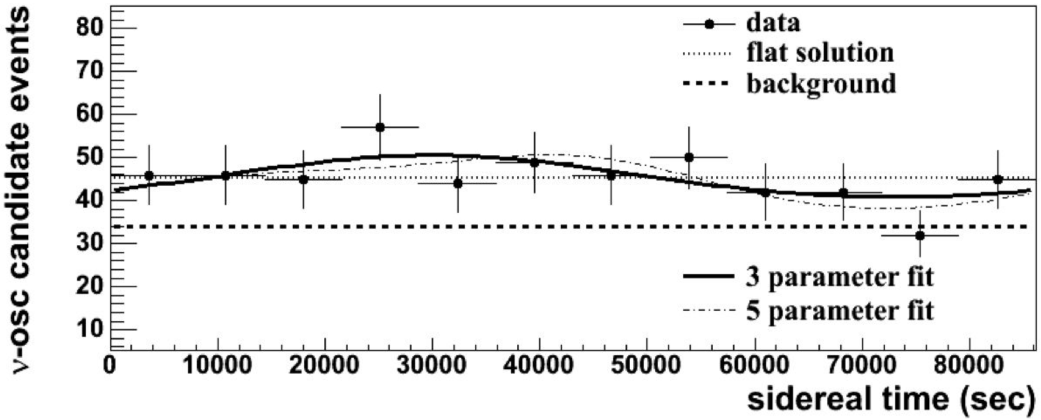
The neutrino mode low-energy excess is consistent with no sidereal variation.

Only C-parameter is nonzero, but this is sidereal independent parameter.

$$P \simeq \frac{L^2}{(\hbar c)^2} \left| (\mathcal{C})_{e\mu} + (\mathcal{A}_s)_{e\mu} \sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{e\mu} \cos\omega_\oplus T_\oplus + (\mathcal{B}_s)_{e\mu} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{e\mu} \cos 2\omega_\oplus T_\oplus \right|^2.$$

MiniBooNE [1109.3480](1109.3480)



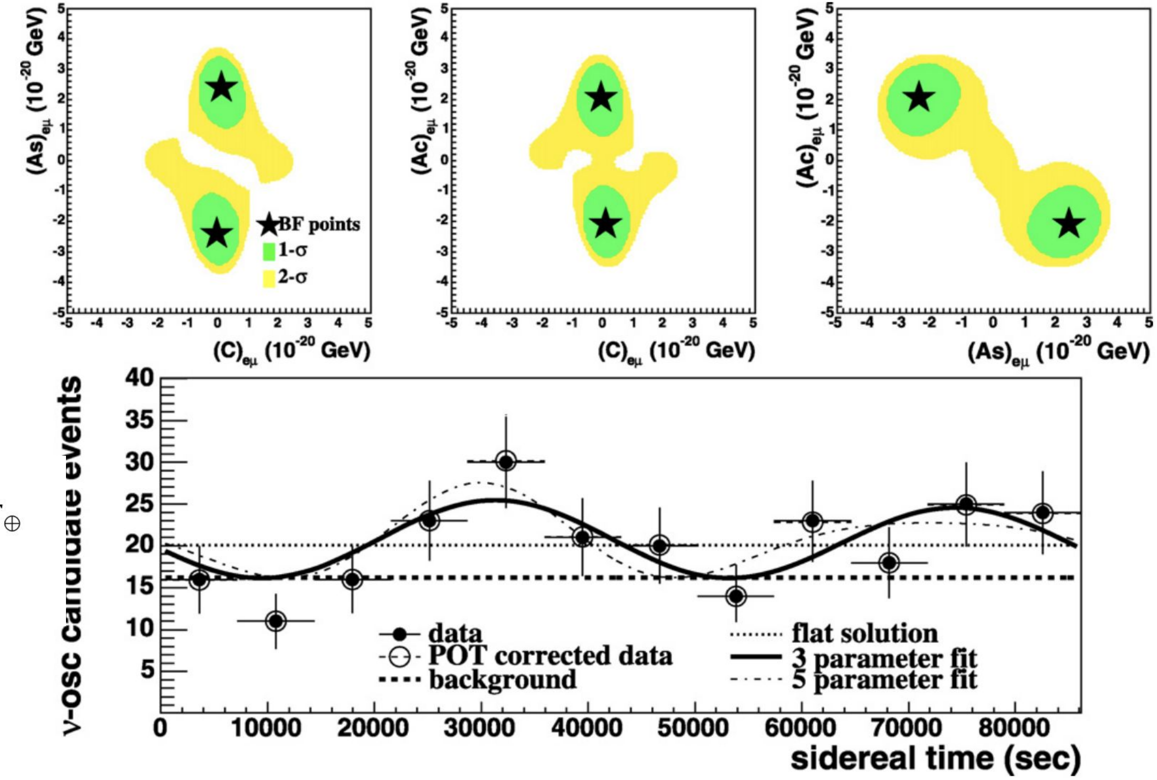


Lorentz-Violation

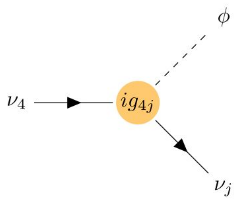
Antineutrino mode showed some hint of siderial dependence.

Analysis has not been updated since 2013.

$$P \simeq \frac{L^2}{(\hbar c)^2} \Big| (\mathcal{C})_{e\mu} + (\mathcal{A}_s)_{e\mu} \sin \omega_\oplus T_\oplus + (\mathcal{A}_c)_{e\mu} \cos \omega_\oplus T_\oplus + (\mathcal{B}_s)_{e\mu} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{e\mu} \cos 2\omega_\oplus T_\oplus \Big|^2 .$$

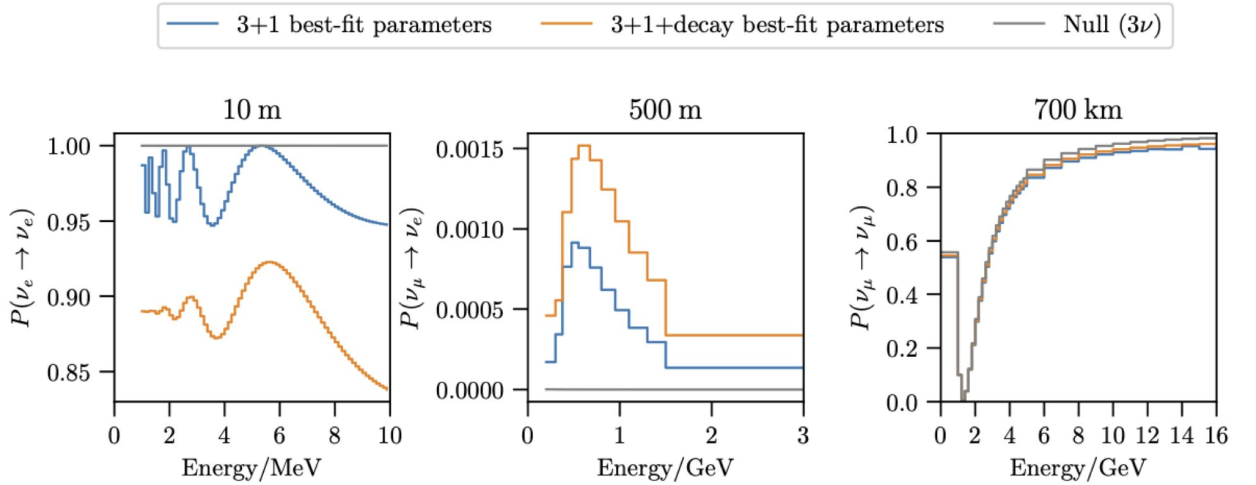


MiniBooNE 1109.3480



Sterile Neutrino Decay (3+1 with Invisible Decay)

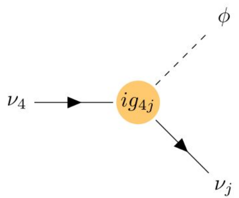
Moulai et al https://arxiv.org/abs/1910.13456



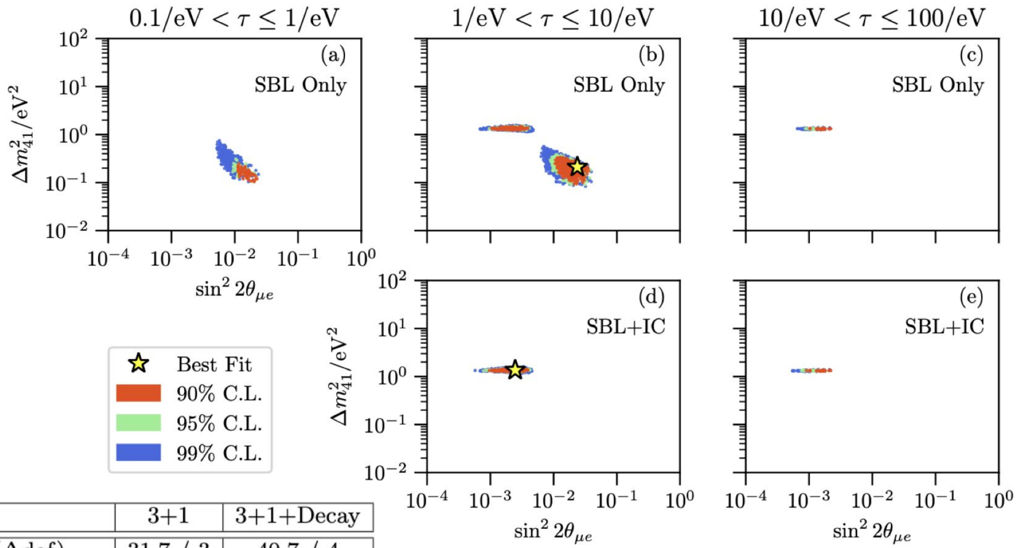
Reactors MiniBooNE Long-baseline

Moss Moss *et al* https://arxiv.org/abs/1711.05921
Moulai *et al* https://arxiv.org/abs/1910.13456

Sterile Neutrino Decay
(3+1 with Invisible Decay)



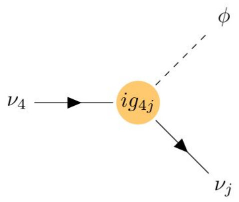
$$\tau = \frac{16\pi}{g^2 m_4}$$

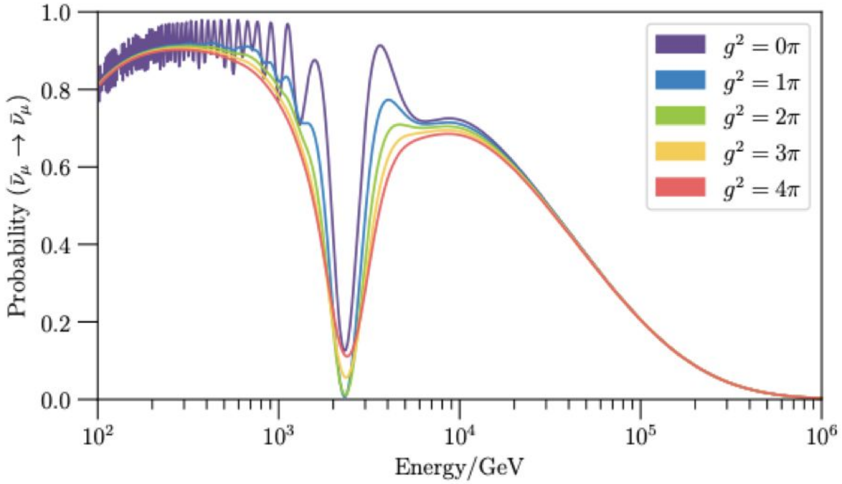


	3+1	3+1+Decay
$(\Delta\chi^2/\Delta\text{dof})_{\text{Null}}$	31.7 / 3	40.7 / 4
$(\Delta\chi^2/\Delta\text{dof})_{3+1}$	–	9.1 / 1

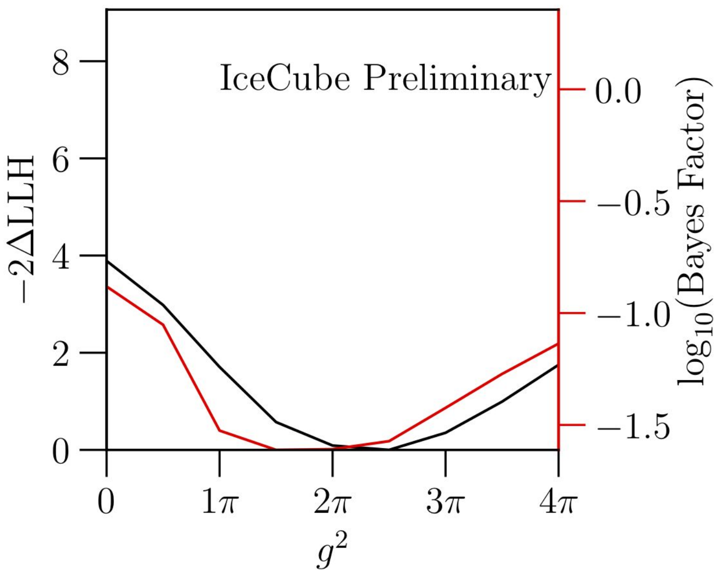
Moss Moss *et al* https://arxiv.org/abs/1711.05921
Moulai *et al* https://arxiv.org/abs/1910.13456

Sterile Neutrino Decay (3+1 with Invisible Decay)

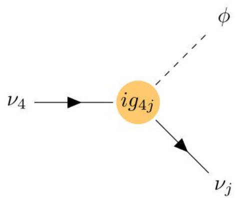




NEW!!!

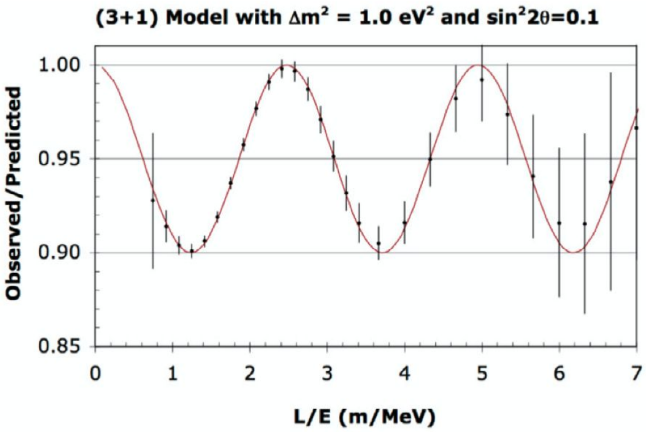


Moss Moss *et al* https://arxiv.org/abs/1711.05921
Moulai *et al* https://arxiv.org/abs/1910.13456

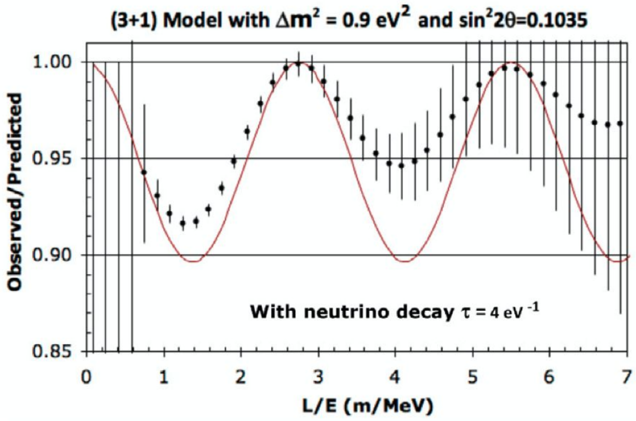


Sterile Neutrino Decay
(3+1 with Invisible Decay)

No decay



With decay



IsoDAR@Yemilab

J. Alonso et al 2111.09480

Moss Moss *et al* https://arxiv.org/abs/1711.05921
Moulai *et al* https://arxiv.org/abs/1910.13456

Non-Standard Matter Effects (3+1+NSI)

Muon-neutrino disappearance can be reconciliated with **MiniBooNE**

- **NSI-CC** relax the **MINOS+** bounds on the mixing

$$\mathcal{L}_{\text{CC-NSI}} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{ff'C}[\overline{\nu_\beta}\gamma^\rho P_L \ell_\alpha]\,[\bar{f}'\gamma_\rho P_C f]$$

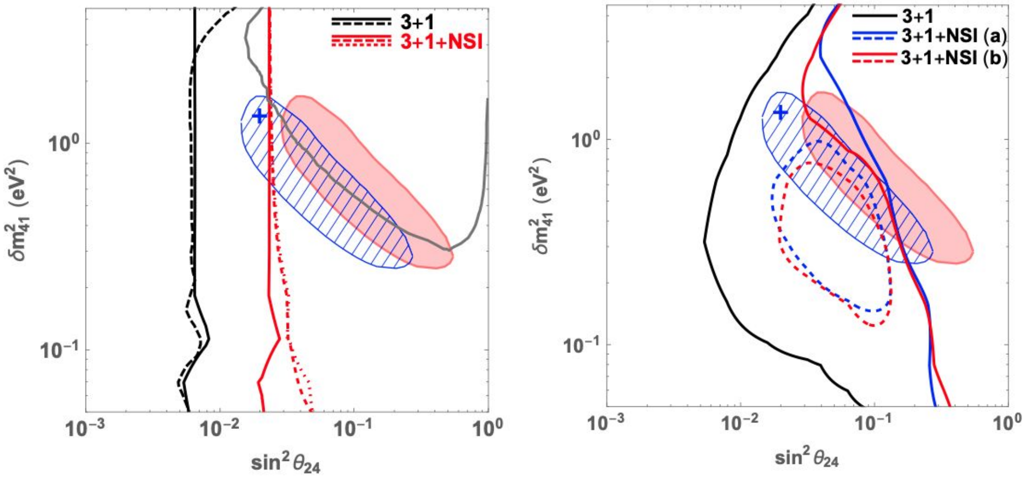
- **NSI-NC** relax the sensitivity of **IceCube** to 3+1 at high energy

$$\mathcal{L}_{\text{NC}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P}(\bar{\nu}_\alpha\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

J. Liao et al https://arxiv.org/abs/1810.01000

MINOS+ modified by NSI

IceCube modified by NSI



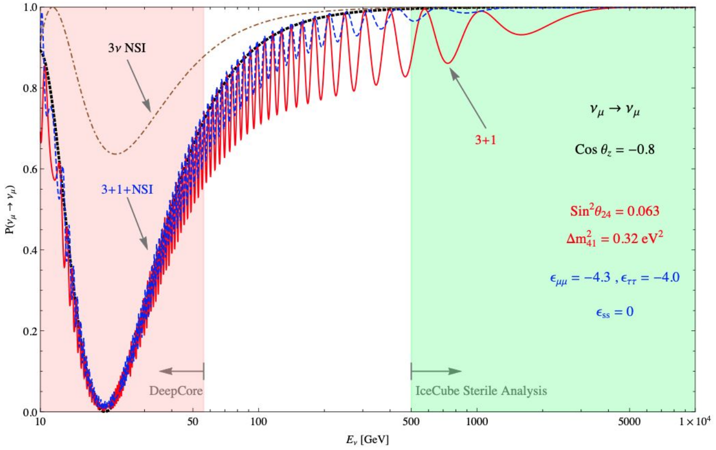
See also E. Akhmedov et al https://arxiv.org/pdf/1007.4171.pdf
Denton et al https://arxiv.org/pdf/1811.01310.pdf
Bhupal Dev et al https://arxiv.org/pdf/1907.00991.pdf

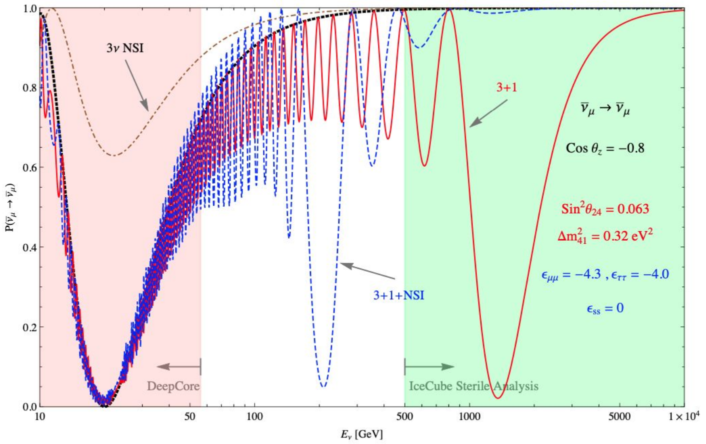
Non-Standard Matter Effects (3+1+NSI)

- The 3+1+NSI can be tested in IceCube

- NSI-NC will shift to lower energies the MSW resonance

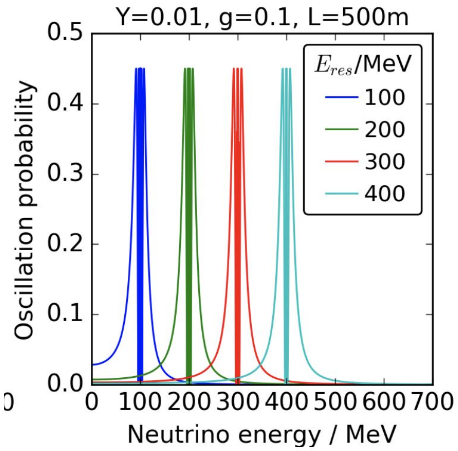
$$E_\nu^{\rm res} \simeq 4\ \cos 2\theta_{24} \left(\frac{\Delta m_{41}^2}{1\ {\rm eV}^2}\right)\left[\frac{1}{1-2\varepsilon_{\mu\mu}+2\varepsilon_{ss}}\right]\ {\rm TeV}$$

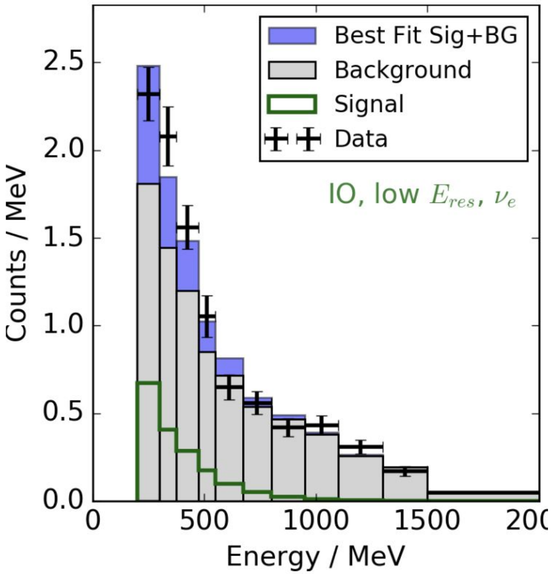


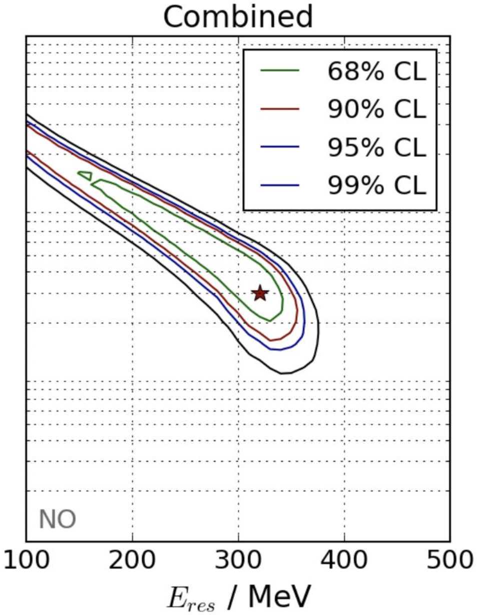


A. Esmaili et al https://arxiv.org/abs/1810.11940

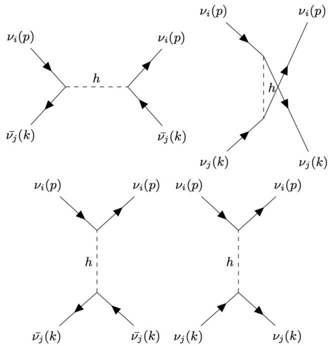
"Matter" may matter







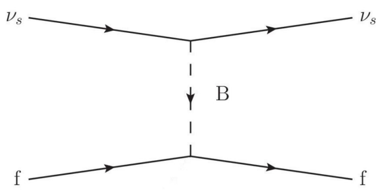
J. Assadi et al [1712.08019,](https://arxiv.org/abs/1712.08019)



$$P_{\alpha\beta} = \sin^2_{\alpha\beta} 2\theta \sin^2 \left[\frac{Y}{2} \left(\frac{E - E_{res}}{(E - E_{res})^2 + \left(\frac{1}{2} E_{res} g_i^2\right)^2} + \frac{-E - E_{res}}{(E + E_{res})^2 + \left(\frac{1}{2} E_{res} g_i^2\right)^2} \right) L \right]$$

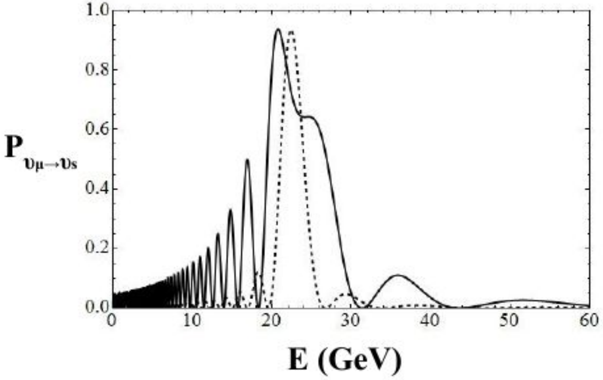
Anomalous Matter Effects

U(1) vector coupling between sterile neutrinos and fermions

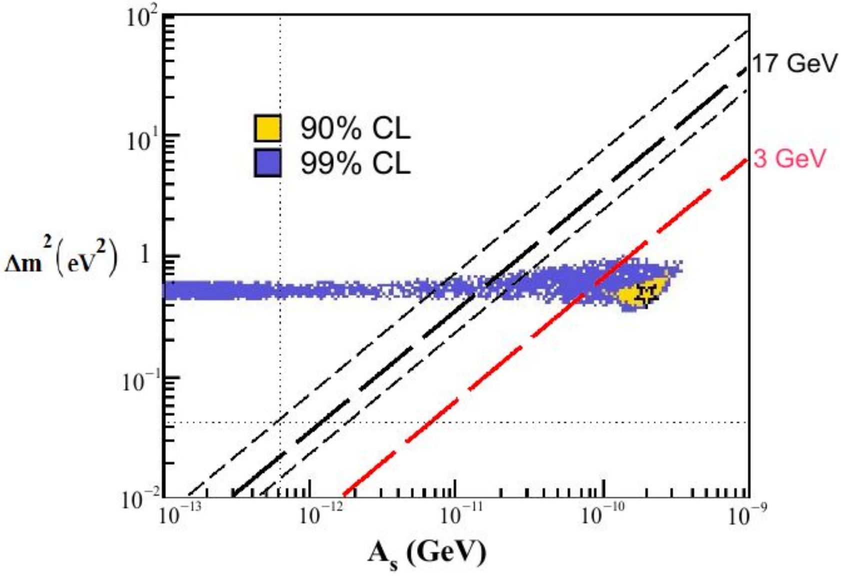


$$\mathcal{H}_{eff}^{(B)} = -\frac{g_s g_f}{8 m_B^2}[\bar{\nu}_s \gamma^\mu \nu_s][\bar{f}_{R,L}\gamma_\mu f_{R,L}]$$

Oscillation resonance due to the sterile neutrino matter potential



J. Bramante, https://arxiv.org/pdf/1110.4871.pdf



Region favored by LSND and MiniBooNE

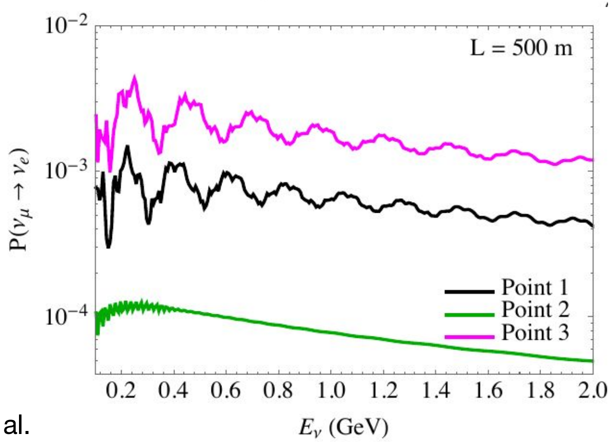
See also G. Karagiorgi et al. https://arxiv.org/pdf/1202.1024

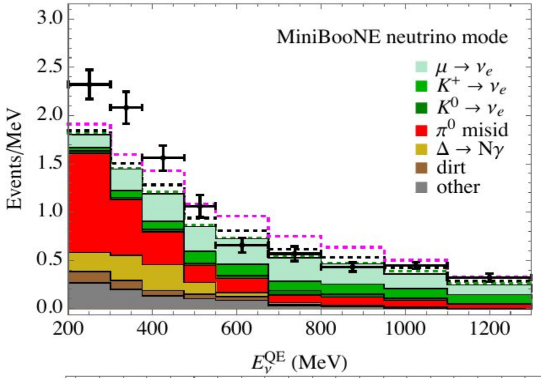
Large Extra Dimensions

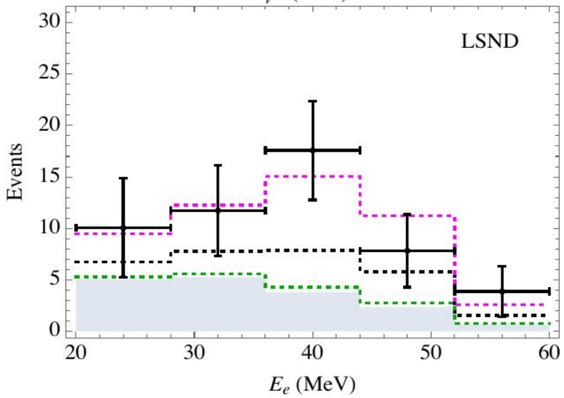
M. Carena et al. https://arxiv.org/pdf/1708.09548.pdf

- Right handed neutrinos propagate in the bulk and SM fermions are restricted to 4D
- Masses in the bulk for the sterile neutrinos lead a seizable appearance

$$\mathcal{A}(\nu_{\alpha,0} \to \nu_{\beta,0}; L) = \sum_{i,n} \mathcal{U}^{0n}_{\alpha i} (\mathcal{U}^{0n}_{\beta i})^* \exp\left(i \frac{m^2_{i,n} L}{2E} \right)$$



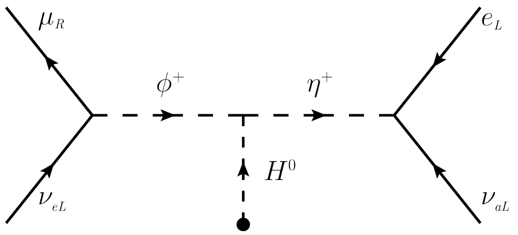




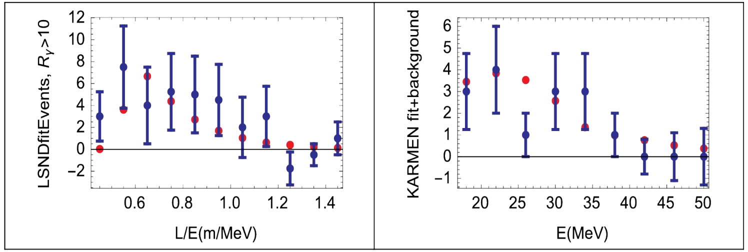
See also G. Barenboim et al. https://arxiv.org/pdf/1808.07460

Lepton-Number-Violating Decays + Sterile

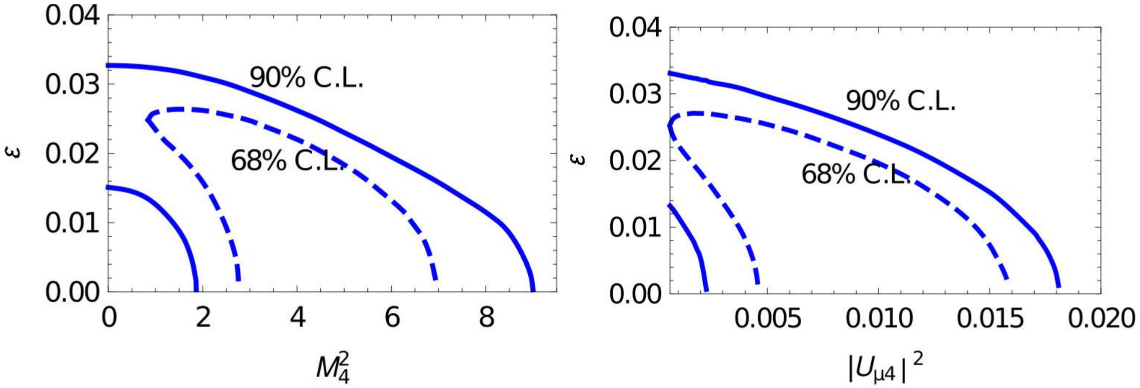
K.S. Babu et al, https://arxiv.org/pdf/1605.03625.pdf



$$\mathcal{L}_{eff} = -4\frac{G_F}{\sqrt{2}}\left[(\bar{e}_L\gamma_\lambda\nu_{eL})(\bar{\nu}_{\mu L}\gamma^\lambda\mu_L) + 2\epsilon(\bar{\mu}_R\nu_{eL})(\nu_{\mu L}^T C e_L)\right]$$



- The new interaction enable smaller values for the mass and the mixing
- Sterile + LNV get a better agreement between LSND, KARMEN and MiniBooNE

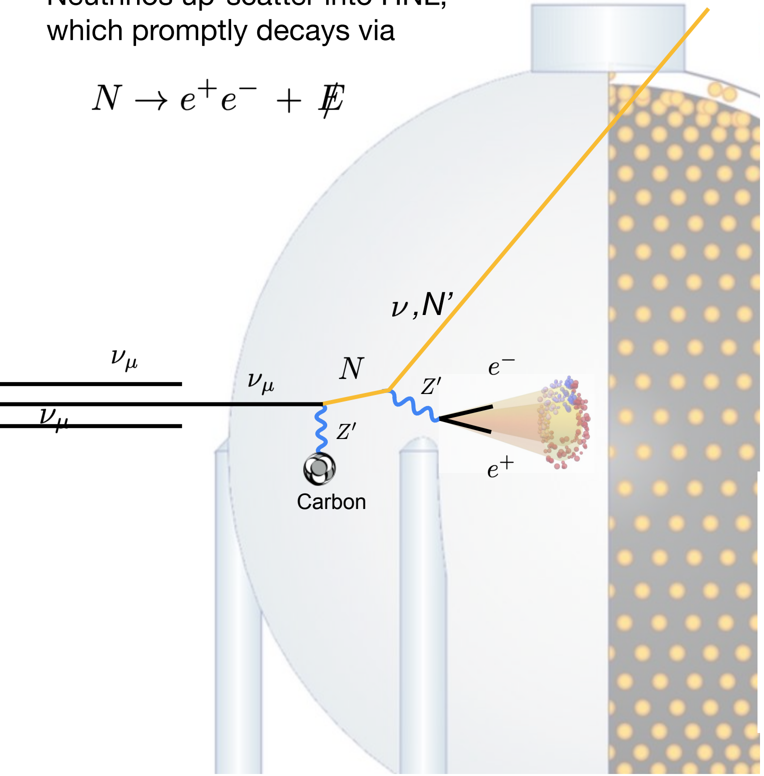


New particles produced by neutrino scattering

Neutrino Upscattering with N→ ν e⁺e⁻

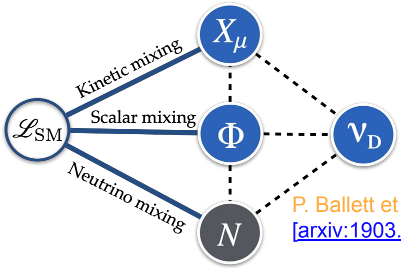
Neutrinos up-scatter into HNL, which promptly decays via

$$N \to e^+e^- + \not{E}$$

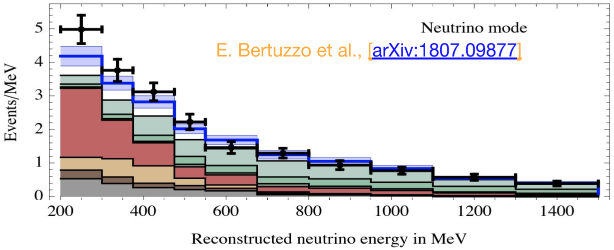


Dark sector coupled via neutrino portal + vector portal

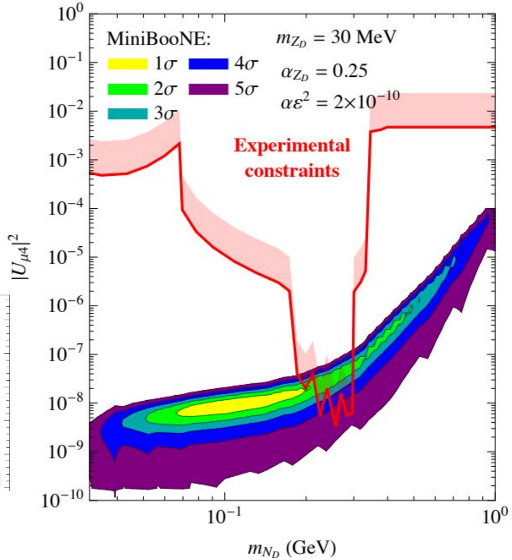
$$\mathcal{L} \supset -\frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} + y\,LHN + y'(\nu_D N)\Phi + g_D X_\mu(\nu_D\gamma^\mu\nu_D)$$



P. Ballett et al, [arxiv:1903.07589]



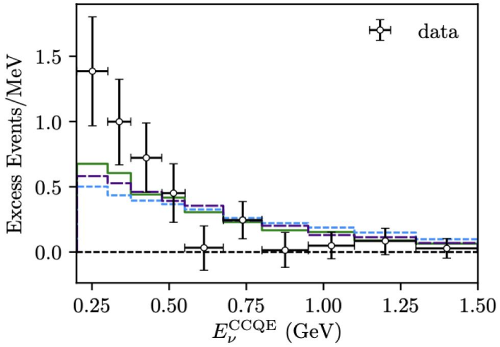
E. Bertuzzo et al., [arXiv:1807.09877]

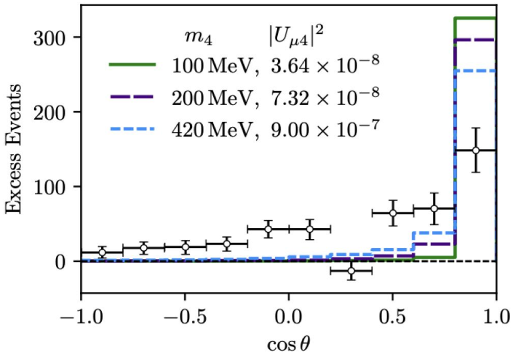


Neutrino Upscattering with N→ ν e^+e^-

Light mediators (10 - 100s of MeV Z')

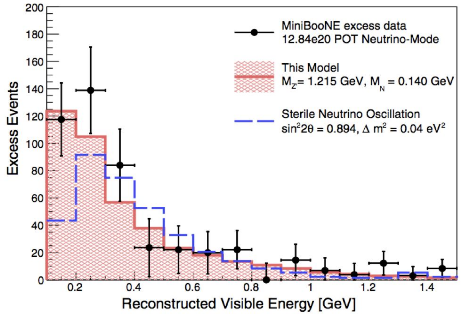
E. Bertuzzo et al., [arXiv:1807.09877]
C. Argüelles et al, [arXiv:1812.08768]

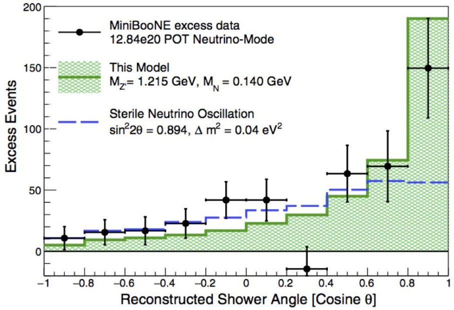




Heavy mediators (~ GeV scale Z')

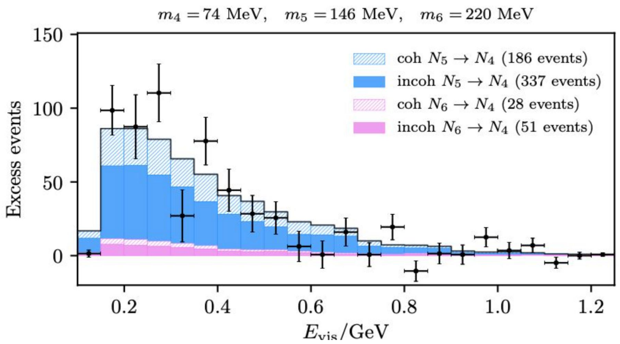
P. Ballett et al, [arxiv:1808.02915]

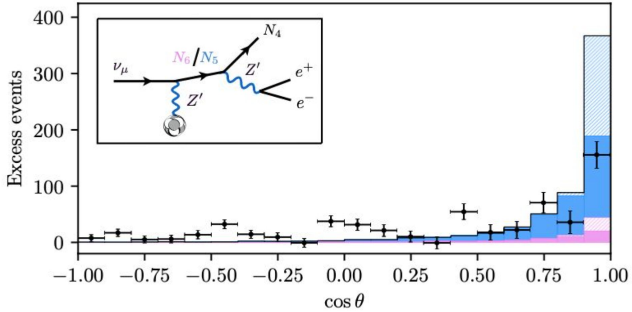




Inter-generational decays (~GeV scale Z')

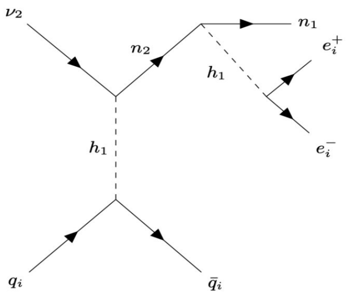
P. Ballett, MH, S. Pascoli [arxiv:1903.07589]
A. Abdullahi, MH, S. Pascoli, [arXiv:2007.11813]



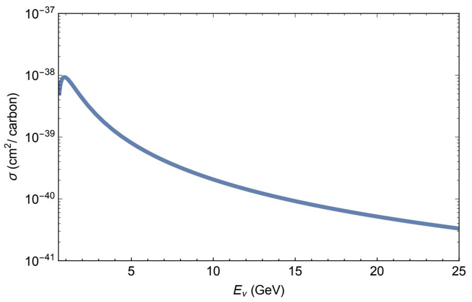


Neutrino Upscattering with N$\rightarrow$ ν e$^+$e$^-$

Scattering and decay may also be mediated by a scalar particle:



B. Dutta et al. [arxiv:2006.01319]



Cross section goes **down** in energy, so MINERvA and CHARM-II may have a harder time testing this.

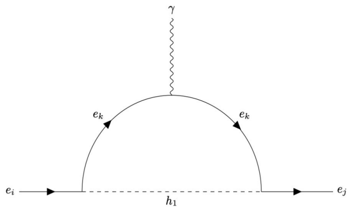
SBN would be in the sweet-spot for producing HNLs via this scalar

$$\Delta\mathcal{L}_S = -\frac{1}{4}\kappa S F_{\mu\nu}F^{\mu\nu}$$

A. Datta et al. [arXiv:2005.08920]

Scalars are interesting also because they Can decay to two photons.

Would mimic a π^0 signature – overlapping photons would contribute to the signal.



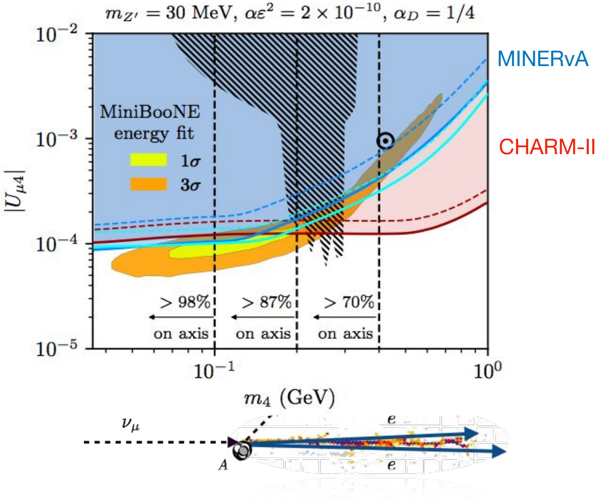
Same scalars can also appear in a contribution to the muon (g-2)$_\mu$

A. Datta et al. [arXiv:2005.08920]
B. Dutta et al. [arxiv:2006.01319]

Neutrino Upscattering with N⟶ ν e⁺e⁻

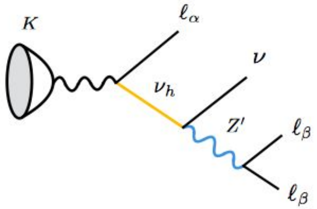
Mimicking photon final states
neutrino-electron scattering
(MINERvA, CHARM-II)

C. Argüelles et al, [arXiv:1812.08768]



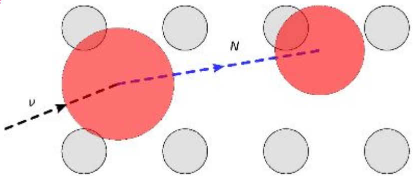
Measurements can also be done at
MINERvA, NOvA, and at the SBN program.

Rare kaon decays at NA62
P. Ballett et al [arxiv:1903.07589]

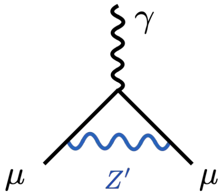


Double cascades in IceCube

P. Coloma et al, [arxiv:1707.08573]
P. Coloma et al, [arxiv:2105.09357]

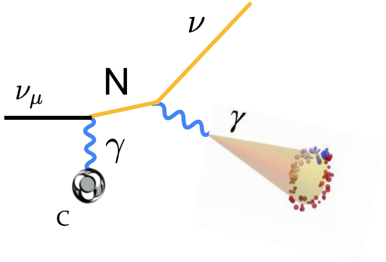


Dark sector may also be related to other anomalies:
KOTO, muon (g-2), dark matter



B. Dutta et al, [arxiv:2006.01319]
W. Abdallah et al, [arXiv:2006.01948]
A. Datta et al, [arXiv:2005.08920]
A. Abdullahi et al, [arXiv:2007.11813]

Neutrino Upscattering with N→ νγ



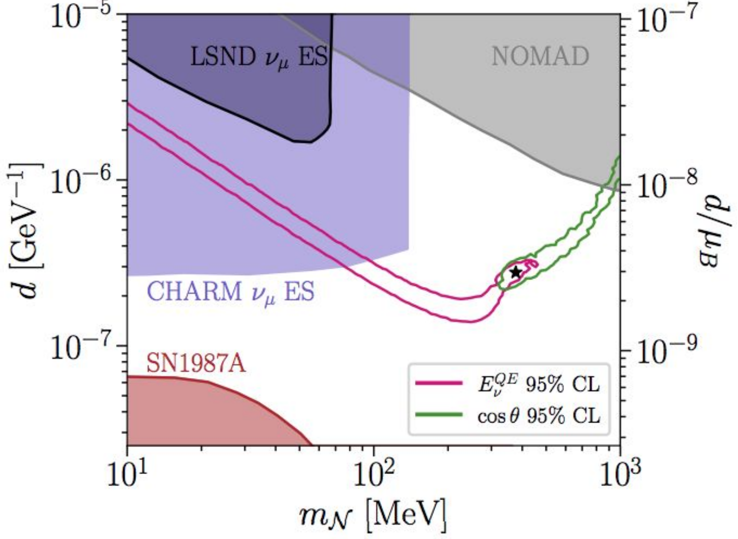
Transition magnetic moment (“dipole portal”)

$$\mathcal{L}_\mu = \frac{\mu_\nu^\alpha}{2} F_{\mu\nu} \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R \,.$$

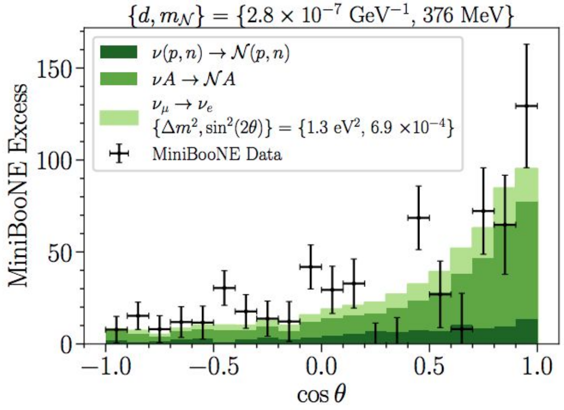
Dim-5 operator – needs further UV completion – may be challenging?

Simple model – 2 parameter model (d, mHNL)

Vergani et al, [arXiv:2105.06470]



Angular distribution benefits from Dirac nature and helicity-flipping interactions.

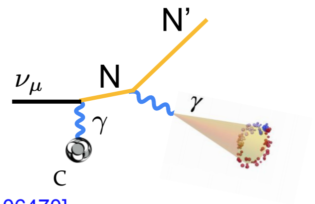


S. Gninenko, [arXiv:0902.3802], S. Gninenko, [arXiv:1201.5194], M.Masip et al, [arXiv:1210.1519], G. Magill et al, [arXiv:1803.03262], Vergani et al, [arXiv:2105.06470], Luis Alvarez-Ruso et al [arXiv:2111.02504]

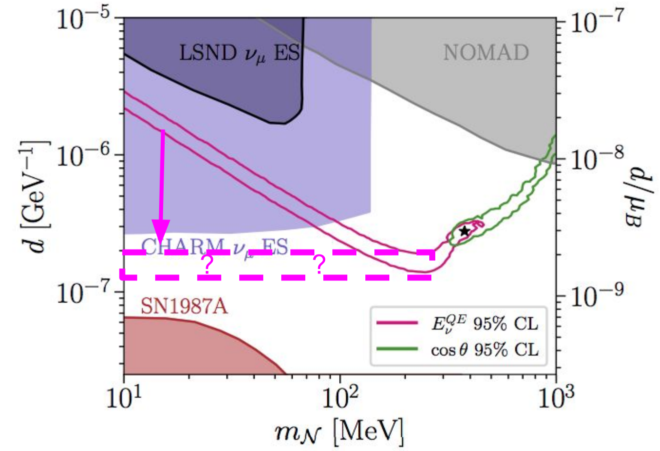
Neutrino Upscattering with N→ νγ
related ideas

Multiple HNLs – faster N decay for lower-masses:

$$\mathcal{L} \supset \frac{\mu_{NN'}}{2} F_{\mu\nu} \overline{N'}_L \sigma^{\mu\nu} N_R$$

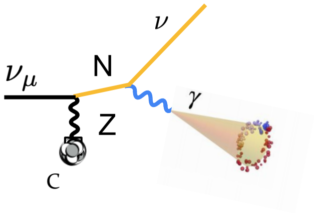


Vergani et al, [arXiv:2105.06470]

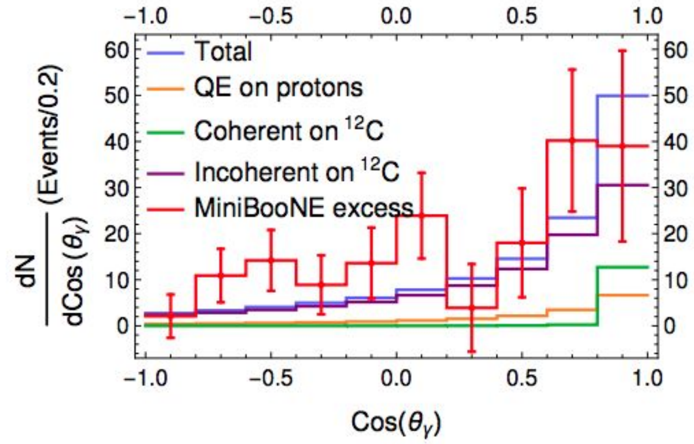


Weak scattering for better angular distribution.

S. Gninenko, [arXiv:0902.3802]:
NC scattering for **LSND** to produce free neutron.

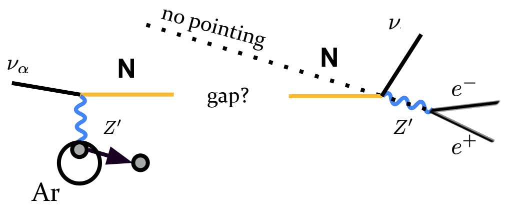


Luis Alvarez-Ruso et al [arXiv:2111.02504]

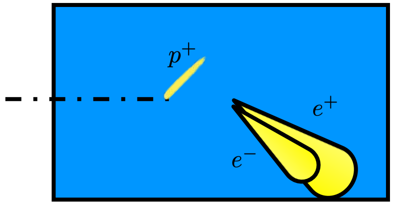


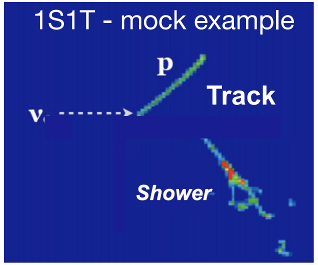
Neutrino Upscattering with N→ ν (e^+e^-) or γ

Liquid Argon TPCs can search for (e+e-) events as either single showers or separated e+ and e- showers.



Signatures in LAr.



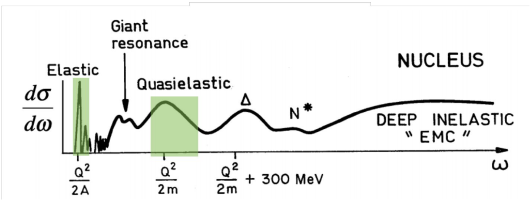


μBooNE

1S0T | 2S0T
1S1T | 2S1T

Light Z' or Dipole: no proton so smaller efficiencies, but enhanced in LAr (A^2coherent.)

Heavy Z': shower displaced from proton. *Mostly photon-like showers.*



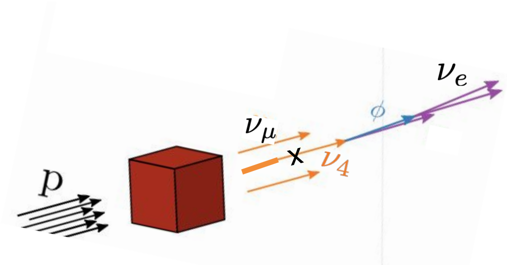
Nuclear modelling so far has been rather simple.

New particles in the beam

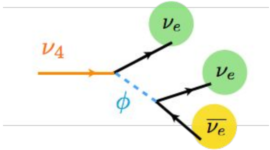
Sterile Neutrino Decay
(3+1) Visible Neutrino Decay

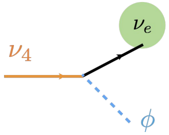
Light “steriles” coupled to a new scalar

$$\mathcal{L} \supset -g\,\bar{\nu}_s \nu_s \phi - \sum_{a=e,\mu,\tau,s} m_{\alpha\beta}\,\bar{\nu}_\alpha \nu_\beta$$

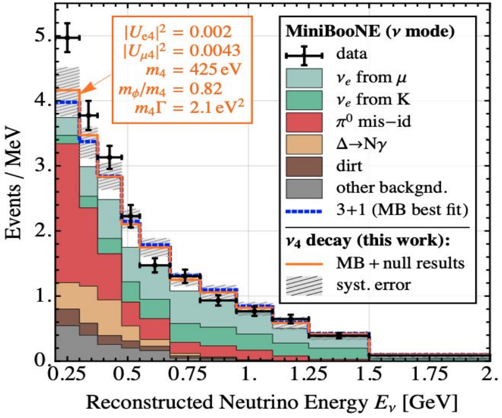


I.Esteban,10.5281/zenodo.3509890.

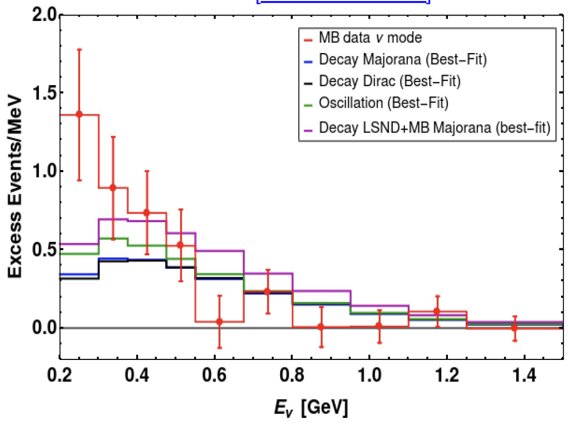




M. Dentler et al [arXiv:1911.01427]

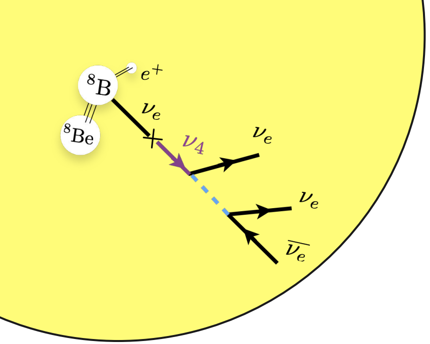


A. de Gouvea et al [arXiv:1911.01447]

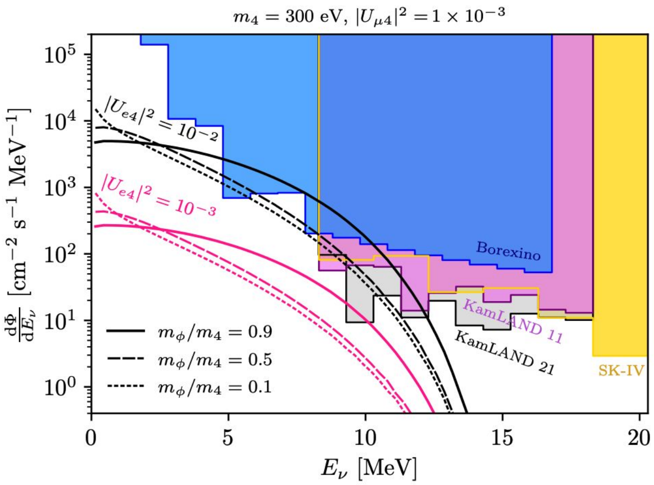


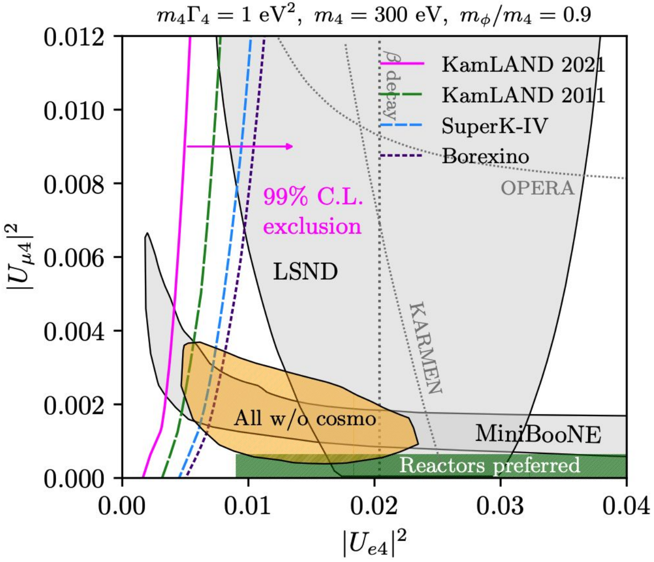
S. Palomares-Ruiz et al [arXiv:0505216]
Y. Bai et al [arXiv:1512.05357]
A. de Gouvea et al [arXiv:1911.01447]
M. Dentler et al [arXiv:1911.01427]

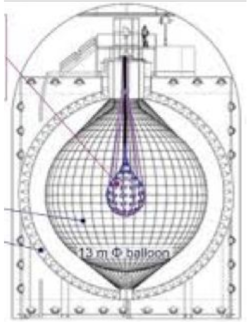
- **m_ϕ > 0** “favored compared to the $m_\phi = 0$ case at more than 99% C.L.”
- At LSND, **anti-ν_e** can be produced from both μ or π decays.



Sterile Neutrino Decay
(3+1) Visible Neutrino Decay







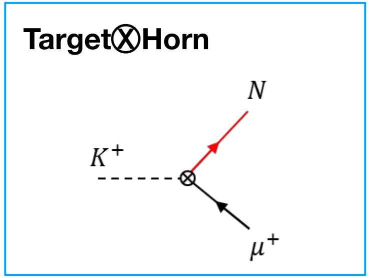
Strong but model-dependent bound:

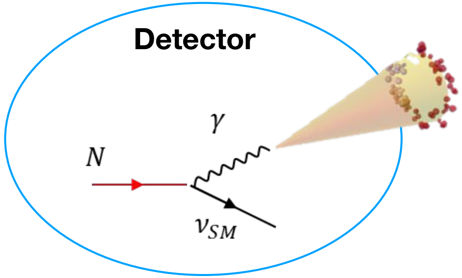
Requires sterile neutrino to be of Dirac nature with stable mediator.

M. Hostert & M. Pospelov [arXiv:2008.11851]

Visible Decays in the Detector Fiducial Volume

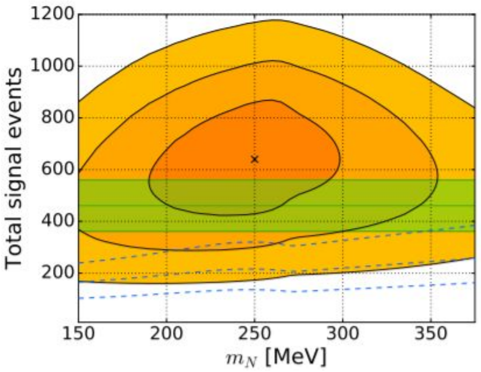
$$U_{\ell 4} V_{q_u q_d} G_F \, [\bar{q}_u \gamma^\mu (1-\gamma_5) q_d] \, [\bar{\ell} \gamma_\mu (1-\gamma_5) N] + \text{h.c.}$$

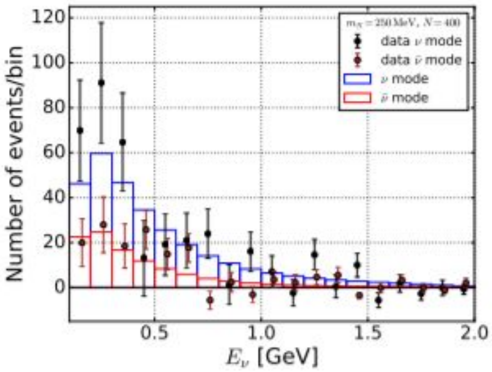


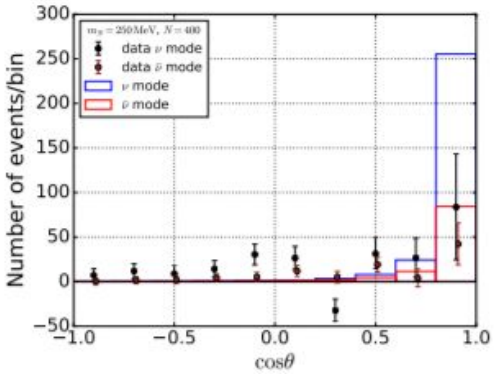


$$\frac{1}{\Lambda} \bar{N} \sigma^{\alpha\beta} \nu F_{\alpha\beta}$$

- Decays of a heavy sterile neutrino (~250 MeV) allows the photon to be emitted in the off-beam direction.
- Such heavy sterile neutrinos may travel in a less relativistic way and leave the delayed decay signal. (cf. Timing measurement by MiniBooNE disfavors the delayed signal MiniBooNE Collaboration, arXiv:2006.16883)



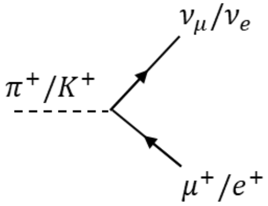




[O. Fischer et al, arXiv:1909.09561]

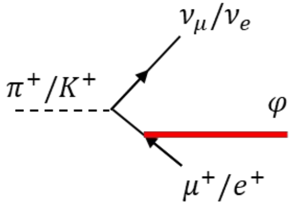
Dark-Sector Interpretation with Charged Meson Decays

- Dark-sector interpretation B. Dutta et al, arXiv:2110.11944

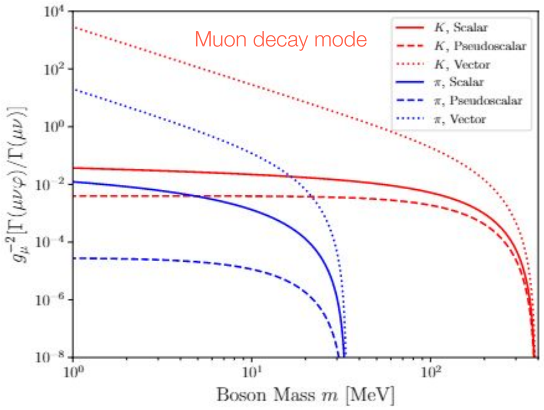


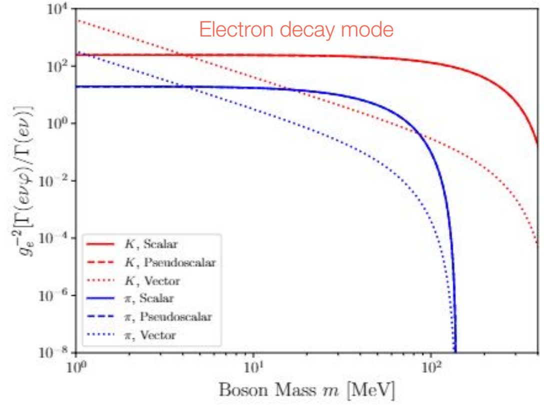
Suppressed by a "wrong" helicity assignment

VS



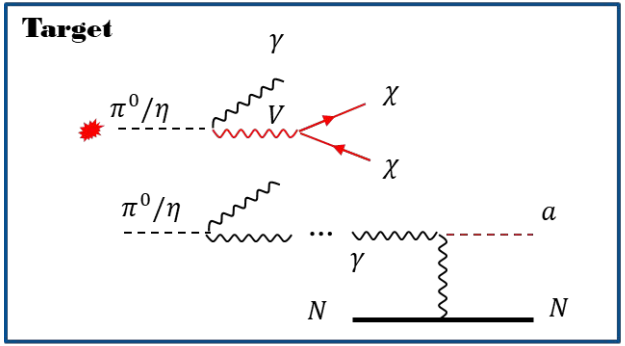
scalar, pseudoscalar, vector etc

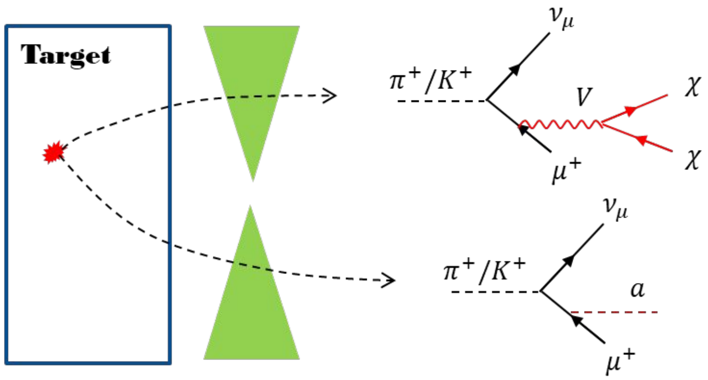




By adding the third particle ϕ, the helicity suppression can be evaded, i.e., 3-body decays can be hugely enhanced. The decay to a massive vector is even more enhanced due to the longitudinal polarization. e.g., C.E. Carlson et al, arXiv:1206.3587

Neutral Meson vs. Charged Meson

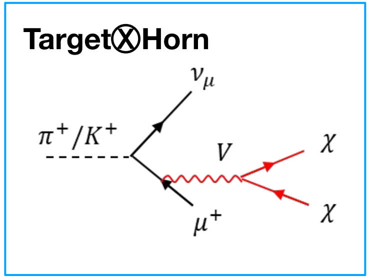


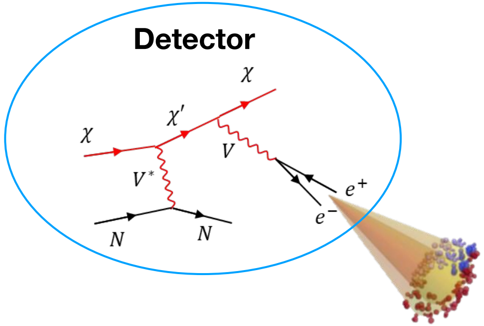


- Comparable production rate: $\pi^0:\pi^+:\pi^-:\eta:K^+:K^- \approx 1:1:1:0.1:0.1:0.1$
- Unfocused π^0, η vs. Focused $\pi^\pm, K^\pm$
- Wider spreading π^0, η-induced signal flux vs. Forward-directed $\pi^\pm, K^\pm$-induced signal flux
- No BR enhancement vs. Large BR enhancement

Dark-Matter Upscattering Scenario

$$-\mathcal{L}_{V,\text{int}} \supset e(\epsilon_1 V_{1,\mu} + \epsilon_2 V_{2,\mu})J^{\mu}_{\text{EM}} + (g_1 V_{1,\mu} + g_2 V_{2,\mu})J^{\mu}_{D} + (g'_1 V_{1,\mu} + g'_2 V_{2,\mu})J'^{\mu}_{D}$$



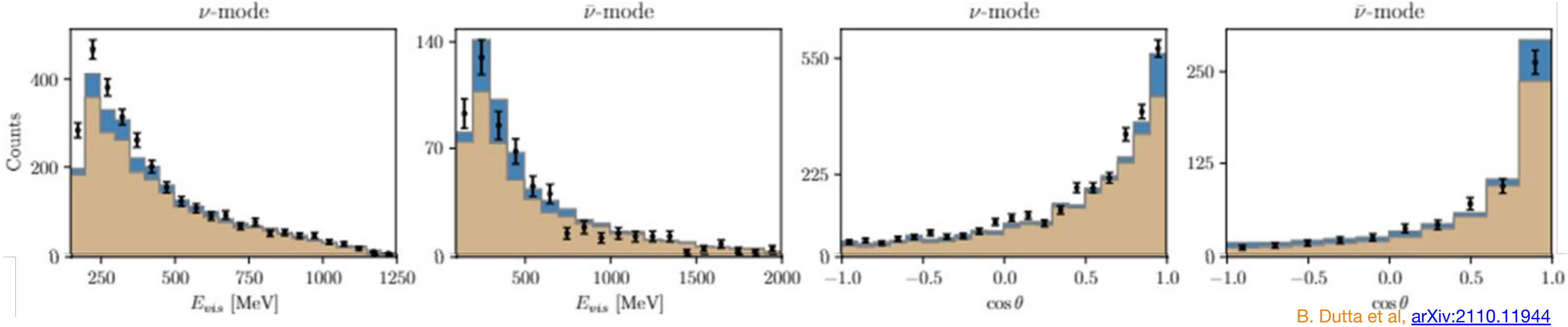


- Electron-positron pair collimated
- Scattering may happen through an exchange of a different mediator. [The different mediator could be massless, e.g., dipole operator, $\bar{\chi}'\sigma^{\mu\nu}\chi F_{\mu\nu}$]

$\text{BR}(V \to 2\chi):\text{BR}(V \to 2e) = 50\%:50\%$
for illustration

Example fit in the double-mediator scenario

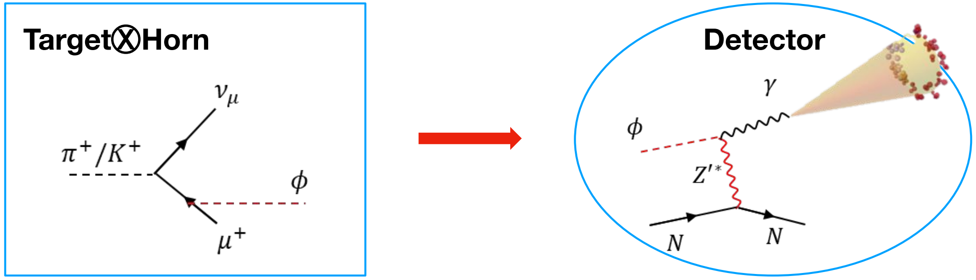
Scenario	$(m_{V_1}, m_{V_2}, m_\chi, m_{\chi'})$	$\epsilon_1\epsilon_2 g_2'^2/(4\pi)$
Double	(17, 200, 8, 50)	1.3×10^{-7}



B. Dutta et al, arXiv:2110.11944

Inverse Primakoff Scattering of (Pseudo)Scalar

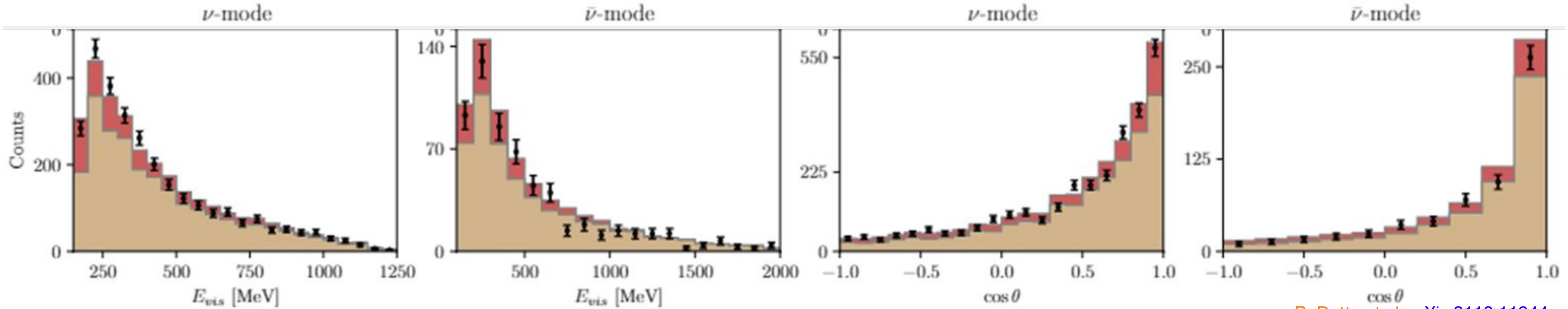
$$\mathcal{L}_S \supset g_\mu \phi \bar{\mu}\mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4}\phi F'_{\mu\nu}F^{\mu\nu} + \text{h.c.},$$



- Photon signal mimicking electron
- Scattering through a massive Z' lets a sizable number of events populate in the off-forward region.

Example fit in the scalar scenario

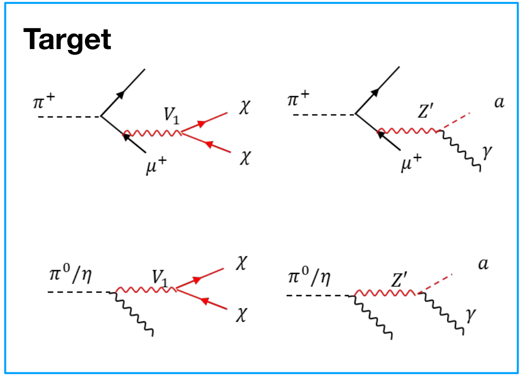
Scenario	$(m_{Z'}, m_{\phi/a})$	$(g_\mu g_n \lambda)$ [MeV^{-1}]
Scalar	(49, 1)	2.2×10^{-8}

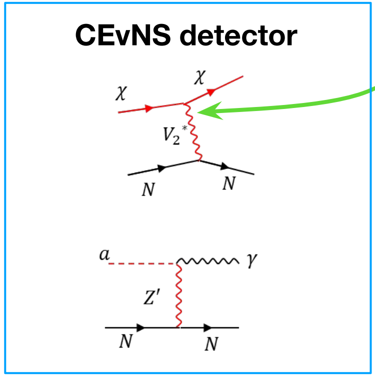


B. Dutta et al, arXiv:2110.11944

Predictions in Other Neutrino Experiments

Stopped-pion neutrino experiments (CCM, COHERENT, JSNS2)



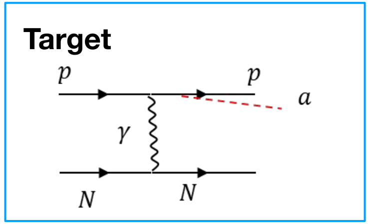


This dark-sector coupling in the double-mediator scenario can be large enough for CEvNS experiments to observe MB signal events.

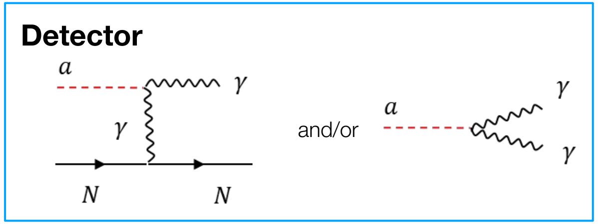
CCM is testing the dark-sector scenarios.

- Charged meson production channels become subdominant because of no focusing.
- Dark-sector coupling associated with V_1 is as small as $\sim\epsilon_1$ to have 50%:50% BRs.

Neutrino experiments with detectors located in the forward region



Very forward-moving (pseudo)scalar



Photon signal populated in the very forward region creating "hot-spot" excess in the beam direction

Features of Dark-Sector Solutions

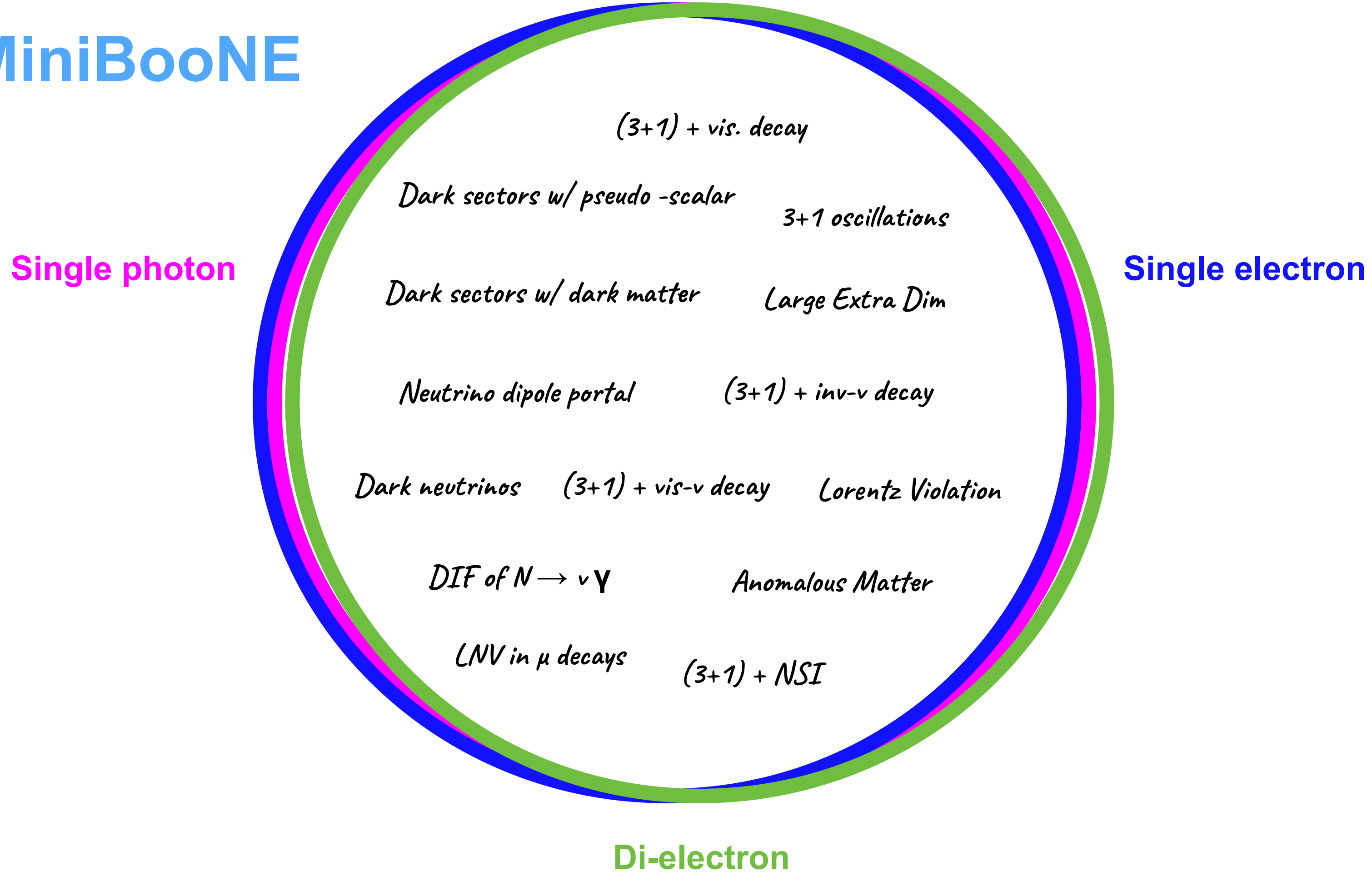
- Charged pion/kaon decays → They allow to explain the difference between the neutrino and antineutrino mode excesses.
- Consistent with negligible events in the MiniBooNE dump mode: signals from neutral mesons are subdominant or negligible.
- Solutions can emerge from upscattering of dark matter (collimated e+e- pair) or forward scattering of (pseudo)scalar via inverse Primakoff (photon)
- Allowed by the MicroBooNE results
- Predictions for stopped-pion neutrino experiments (vis neutral pion), on-axis measurement at SBND (smaller distance), off-axis NuMI measurements at MiniBooNE, SBN (ICARUS, MicroBooNE, SBND) etc

Summary of Models

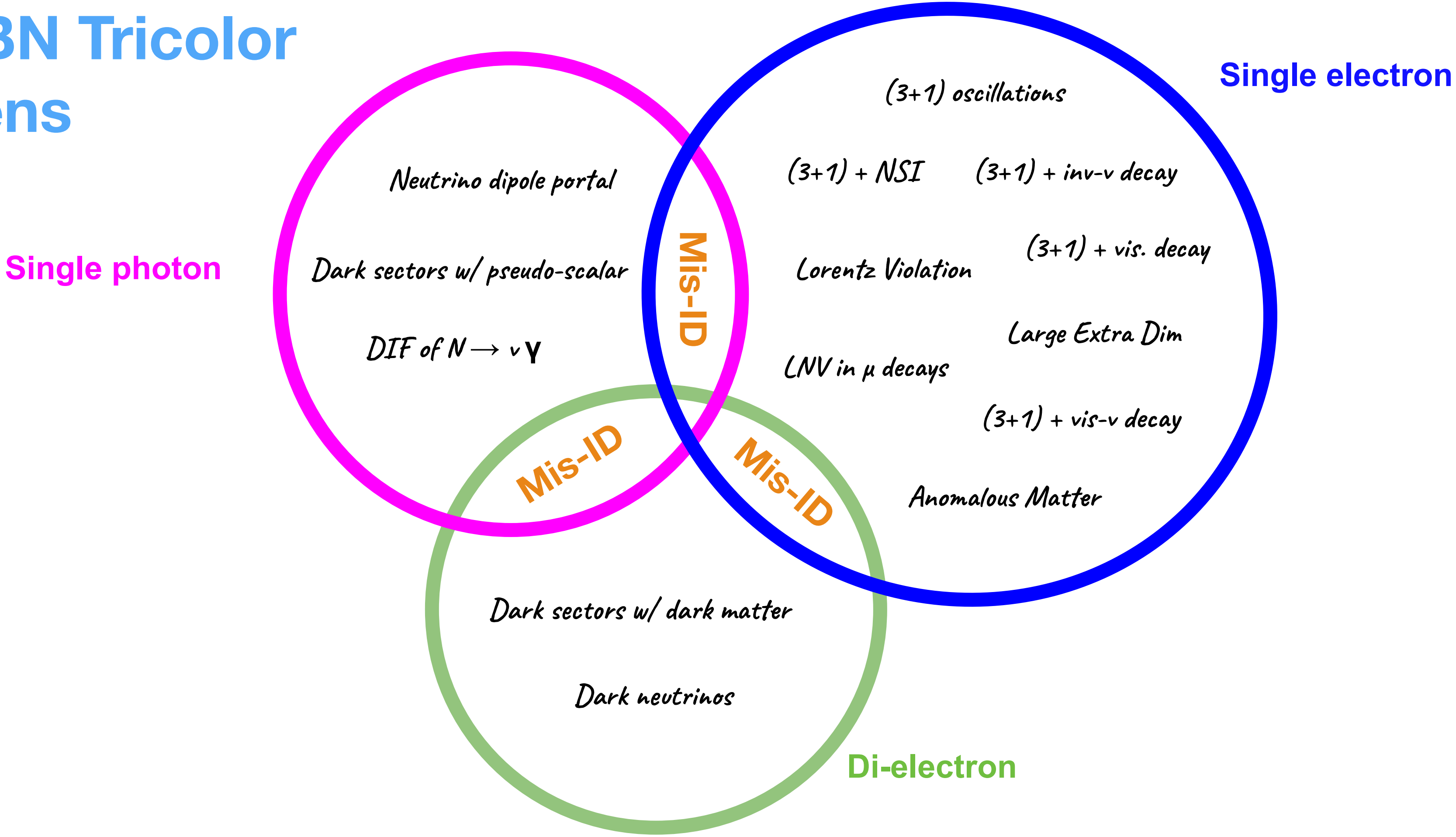
(and other considerations)

Model	U. Signature	LSND	MB	Reactors	Cosmology	Issues	Score
3+1	Oscillations					Appearance-disappearance tension.	**6**
(3+1) + inv-ν decay	Damped oscillations					Large couplings. UV model?	**4**
(3+1) + NSI	Modified matter effects					Large NSI couplings. DeepCore tension.	**11**
Anomalous matter	Resonant appearance				unknown	Tension with T2K if resonance in E.	**9**
Large extra dim	Osc with related freqs.				unknown	Same issues as 3+1 or worse.	**12**
LNV in μ decays	$\mu^+ \to$ anti-ν_e					Michel params in tension w/ TRIUMF.	**8**
Lorentz violation	Sidereal time variation				unknown	HE IceCube tension.	**10**
Dark neutrinos	Upscattering to $N \to \nu\, e^+e^-$					MINERvA/CHARM-II/ND280 tension?	**2**
Dipole portal	Upscattering to $N \to \nu\, \gamma$					MINERvA/CHARM-II/ND280 tension?	**3**
(3+1) + vis-ν decay	DIF of $\nu_s \to \nu_e$					Tension with solar antineutrinos.	**5**
(3+1) + vis decay	DIF of $N \to \nu\, \gamma$					TIming at MB.	**7**
Dark sectors: dark matter	Upscattering to $\chi' \to \chi\, e^+e^-$					MINERvA/CHARM-II/ND280 tension?	**5**
Dark sectors: (pseudo)-scalar	Forward scattering to γ					MINERvA/CHARM-II/ND280 tension?	**1**

The MiniBooNE Lens



SBN Tricolor Lens



Take home message

- **Vanilla eV sterile neutrino is extremely disfavored as a solution, but is still an important benchmark model.**

- **Large number of proposals put forward:**
    - important to use benchmark models
    - improved PID at the SBN program can discriminate between them,
    - as a result, there is a need for more tailored analyses.

- **<u>Non-oscillatory</u> models have more predictions at other facilities – multi-prong approach**
    - if a signal is seen, other experiments can provide additional discrimination,
    - e+e- colliders, kaons, beam dumps, large volume neutrino detectors.

Gracias!