DUNE's Sensitivity to BSM Physics

NOW 2024
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University of Toronto &
Institute of Particle Physics

INSTITUTE OF PARTICLE PHYSICS
INSTITUT DE PHYSIQUE DES PARTICULES

Outline

- Effective Field Theory & Parameterizations for BSM
  - caveat: from an experimentalist
- PMNS non-unitarity
- Sterile Neutrinos
- Non-standard Neutrino Interactions (NSI)
- Dark Matter portals
- and many more…

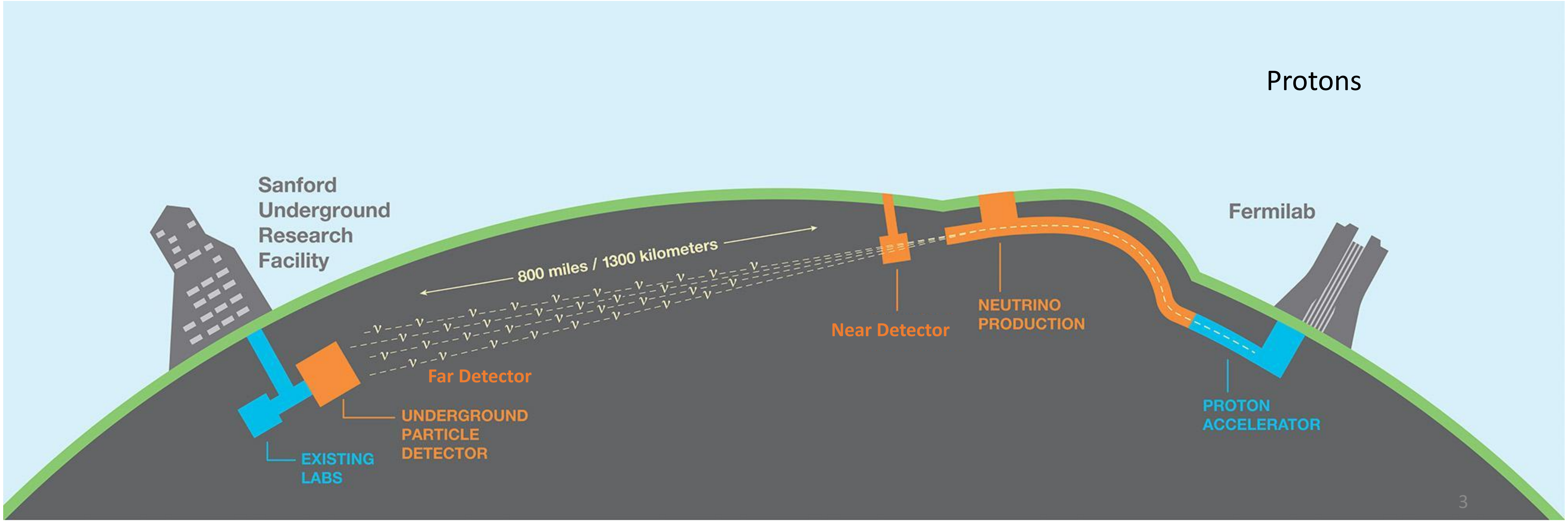
note: plots without references are taken from DUNE Technical Design Report Volume II arXiv:2002.03005v2

LBNF DUNE Facility

1-6 GeV muon neutrinos/antineutrinos obtained from high-power proton beam (1.2 MW – upgradable to 2.4 MW)

Near detector will characterize the beam (100s of millions of neutrino interactions)

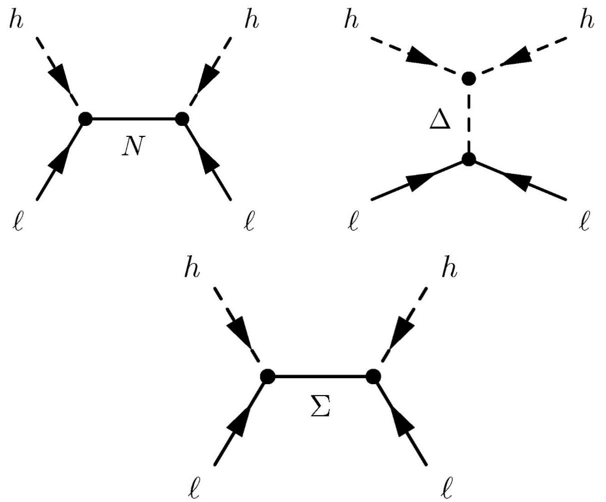
Far Detector is >40 kton fiducial mass Liquid Argon Time Projection Chambers (LAr TPC) – fine granularity



Effective Field Theory for BSM Physics: $\mathcal{L} = \mathcal{L}_{SM} + \ldots$

$+ \delta\mathcal{L}^{d=5}$

- Majorana mass, big mass hierarchy gives light SM neutrino, but no observable phenomena (Seesaw I/II/III)
- Lepton Number Violation
- possible to address lepton/baryon asymmetry
- d=5 can also induce small Dirac mass



10^{-3}eV .1 eV eV KeV MeV GeV 10^2GeV TeV 10 TeV 10^2 TeV 10^3 TeV 10^{12} TeV

Extra neutrinos can participate in oscillations

accessible at osc. Exp

Accessible at ND/ B-factories

Accessible at LHC

Effective Field Theory for BSM Physics: $\mathcal{L} = \mathcal{L}_{SM} + \ldots$

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- after EW symmetry breaking detectable PMNS non-unitarity induced by mixing with heavy neutrinos
- breaks lepton universality, predicts lepton flavor violation (LFV)
- model-independent approach gives strong limits from LFV - Minimal Unitarity violation
- Eg: NSI, inverse/linear seesaw
- Tau couplings least contrainted.

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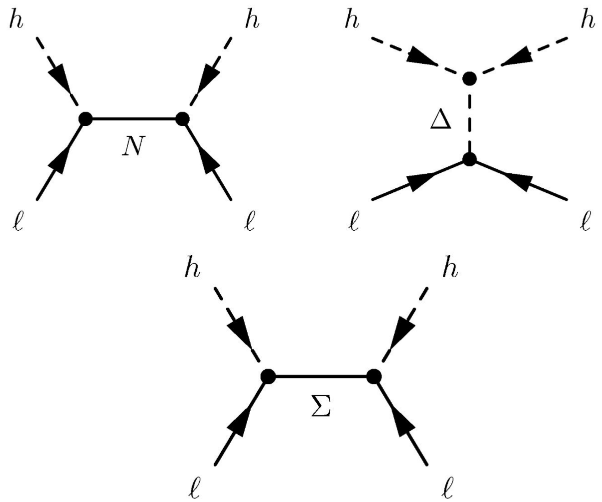

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Effective Field Theory for BSM Physics: $\mathcal{L} = \mathcal{L}_{SM} + \ldots$

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- strong NSI matter effects
- can evade strong LFV constraints since two Higgs fields after EW breaking lead to interaction only in neutrino sector. -Sensitivity only at neutrino facilities

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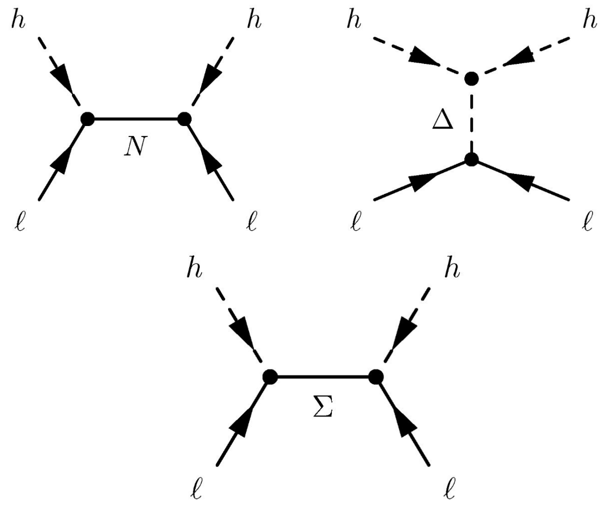

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$+\phi$

- add new Scalar - Radiative models. (some type 1 radiative models have NSI, all type II radiative models don't have NSI)
- Eg with NSI: Zee model, MRIS, LQ, Zee-Babusinglet/doublet/ triplet

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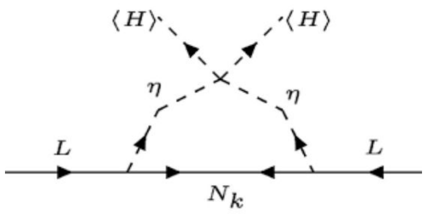

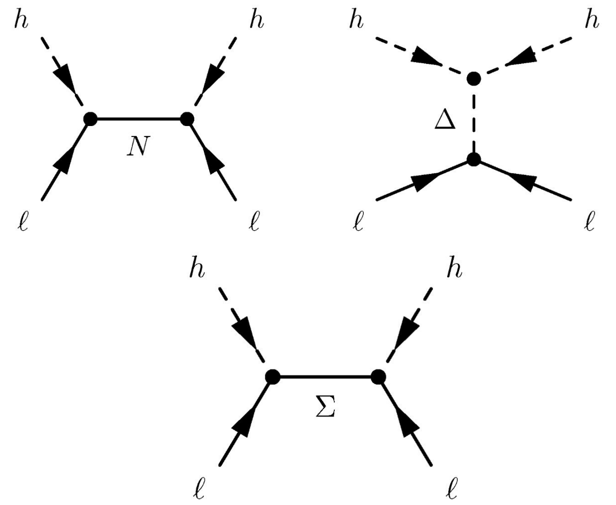

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Parameterizations for Extra Neutrinos Searches

3x3 active ν — Active-heavy mix

$$\mathcal{U} = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Active-sterile mix — Sterile-heavy mix

New states kinematically accessible (sterile neutrinos), produced in beam and participating in oscillations
R allowed at % level

3+1, 3+N scenarios : $\theta_{14}, \theta_{24}, \delta_{14}$

$$\mathcal{U} = \begin{pmatrix} c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \cdots & \cdots & c_{13}c_{24}s_{23} - s_{13}s_{14}s_{24}e^{i(\delta_{14}-\delta_{13})} & c_{14}s_{24} \\ \cdots & \cdots & \cdots & c_{14}c_{24}s_{34}e^{-i\delta_{34}} \end{pmatrix}$$

arXiv:1901.08330v1

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New states at EW scale - searches at LHC

New heavy states above EW scale (right-handed N/ heavy neutral leptons), PMNS non-unitary

Triangular

$$N = (I - \alpha)U$$

$$\begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

Unitary PMNS

Hermitian

$$N = (I - \eta)U'$$

$$\begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta^*_{e\mu} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta^*_{e\tau} & \eta^*_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix}$$

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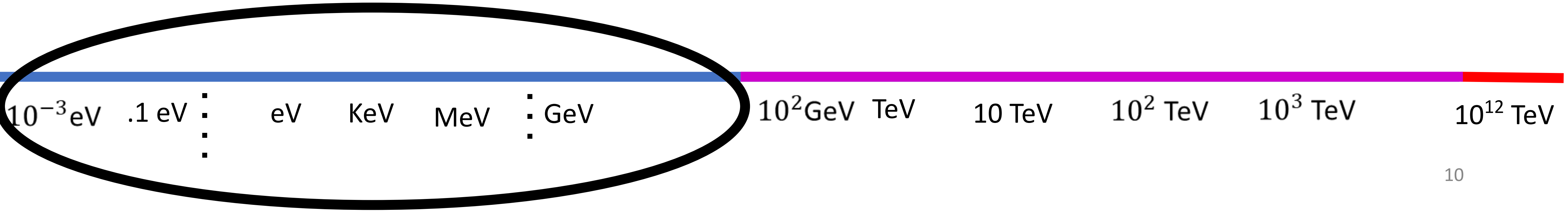
Triangular, Hermitian, NSI mapping:: arXiv:1609.08637v3

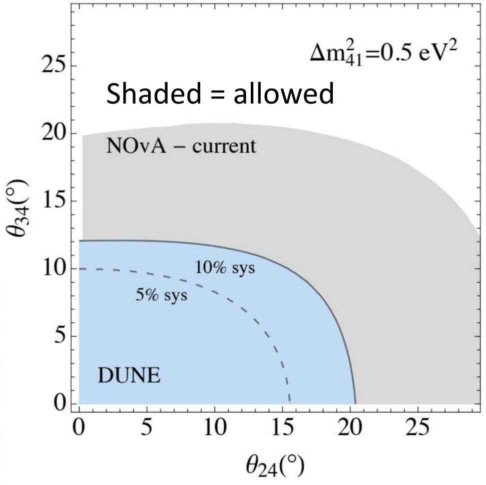
Sterile Neutrino Searches



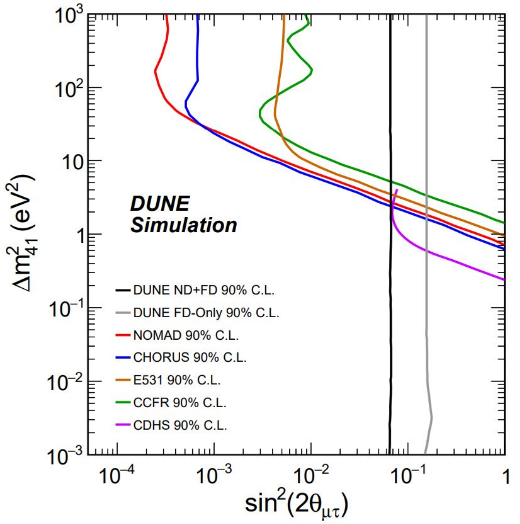
Sterile Neutrino Searches

Case 1 ($\Delta m^2_{14} \sim 0.1 - 1\ eV^2$): slow light-sterile neutrino oscillations, underdeveloped in ND, visible at FD

Coloma, Forero, Parke arXiv:1707.05348v1



3+1



eV KeV GeV

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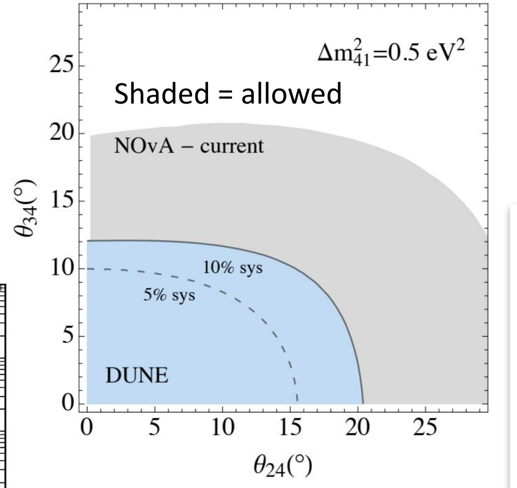

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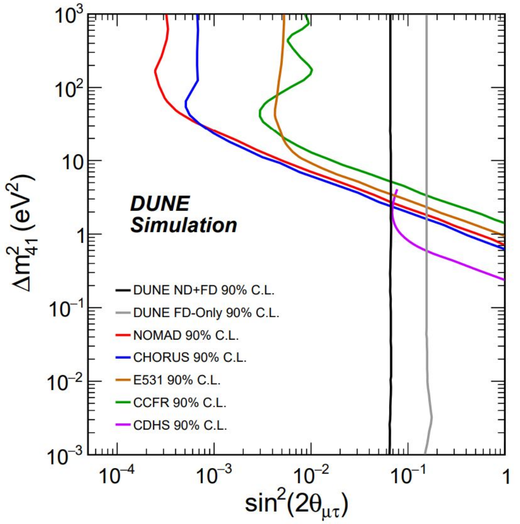
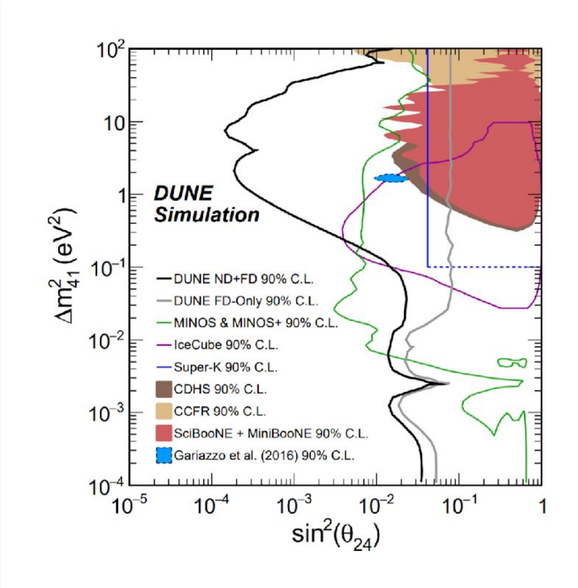


Case 2 ($\Delta m^2_{14} > 1\ eV^2$): light-sterile oscillation frequency matches ND distance (LSND & MiniBoone)



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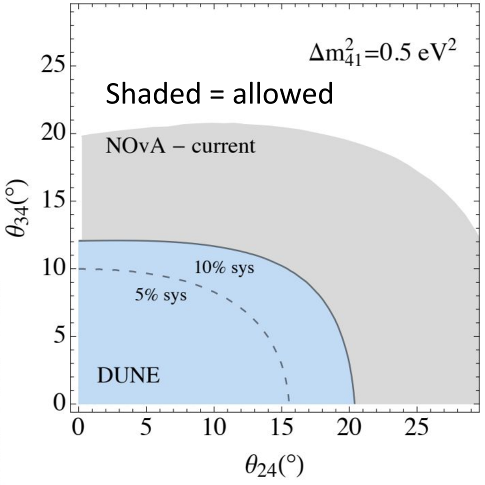

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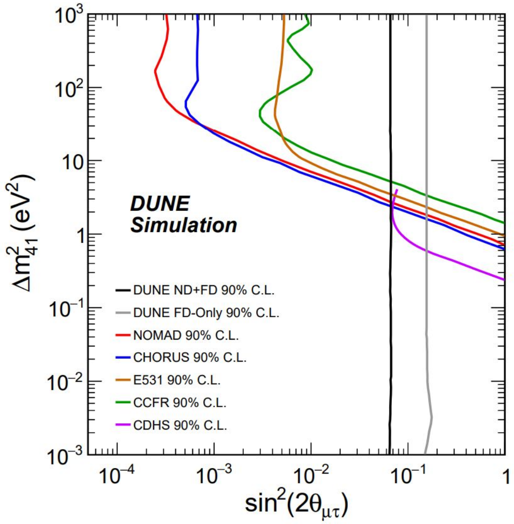

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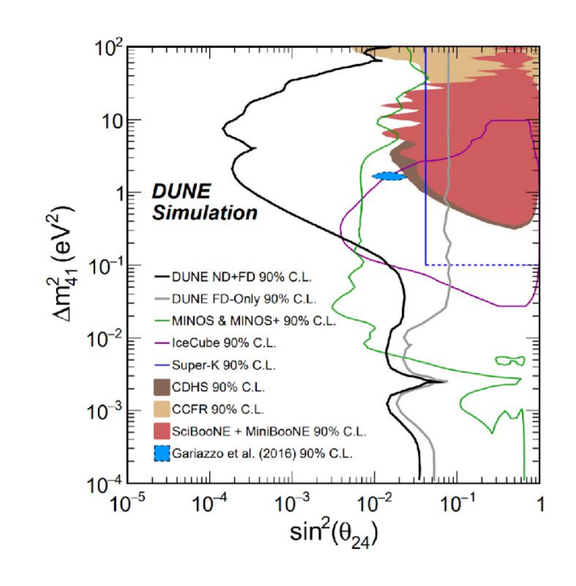
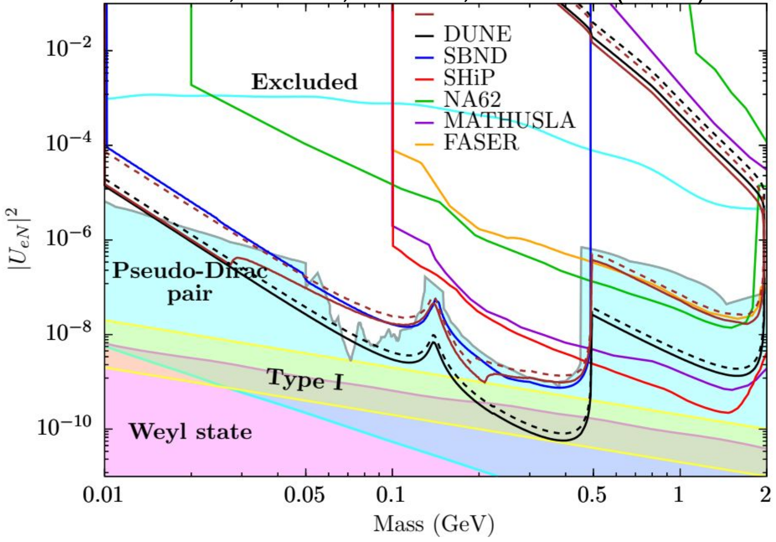


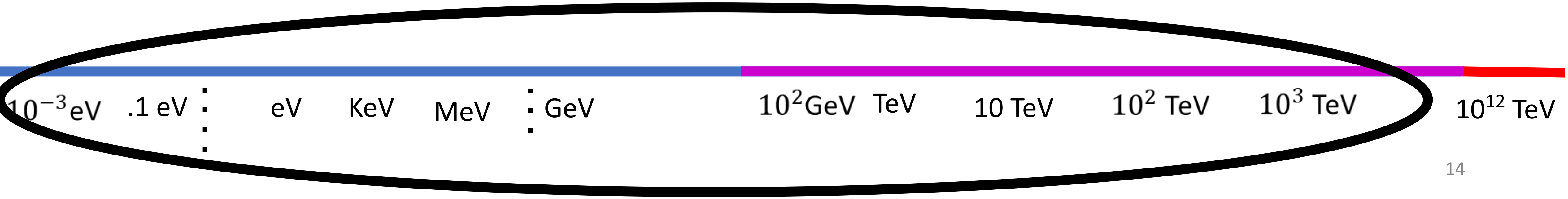
Case 3 ($\Delta m_{14}^2 > 100\ eV^2$): fast sterile neutrino oscillations, averaged out in ND and FD (same as PMNS non-unitarity from heavy neutrinos)

Ballet, Boschi, Pascoli, JHEP 03 (2020) 111



eV KeV GeV

NSI Searches



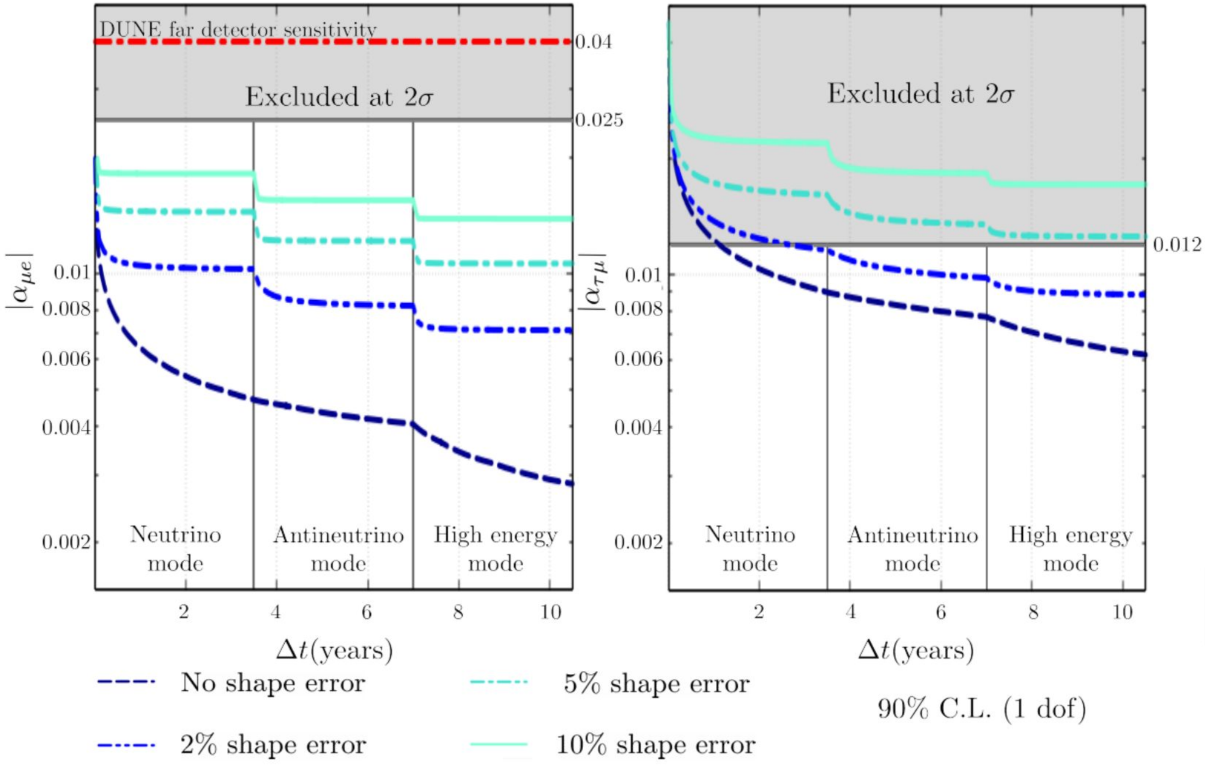
NSI Searches

Coloma, Lopez-Pavon, Rosauro-Alcaraz, Urrea 2105.11466

EFT Wilson coefficients

$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta)(\bar{f}\gamma_\mu P f')$$

source/detector



$$2|\alpha_{\beta\gamma}|^2 = |\epsilon^d_{\beta\gamma}|^2 + |\epsilon^s_{\beta\gamma}|^2 + 2|\epsilon^d_{\beta\gamma}||\epsilon^s_{\beta\gamma}|\cos(\Phi^s_{\beta\gamma} - \Phi^d_{\beta\gamma}) \,.$$

$\epsilon_{\alpha\beta}$ measure of NSI normalized to weak interaction strength – diagonal ϵ break LFU (Z invisible constraints), off-diagonal $\epsilon_{\alpha\beta}$ are flavour-changing ($l \longrightarrow \gamma l$ constraints)

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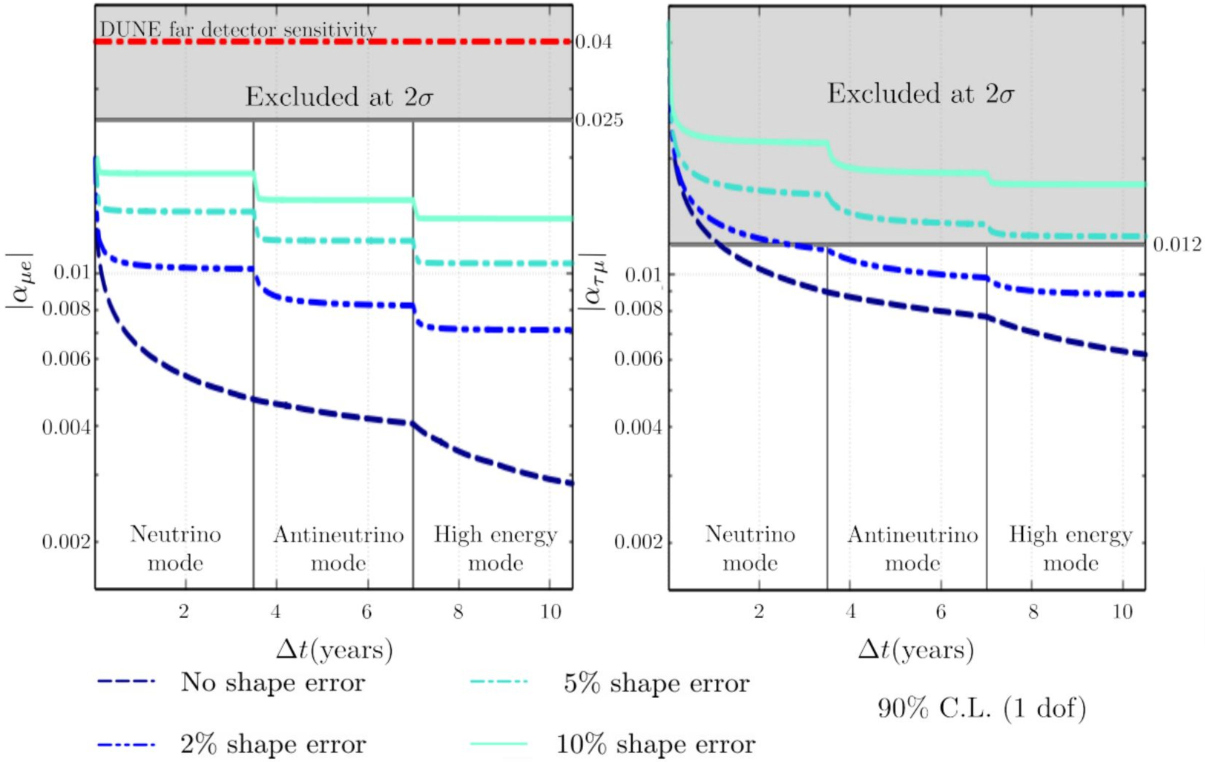
$$\mathcal{L}_{\rm NC} = -2\sqrt{2} G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

through matter



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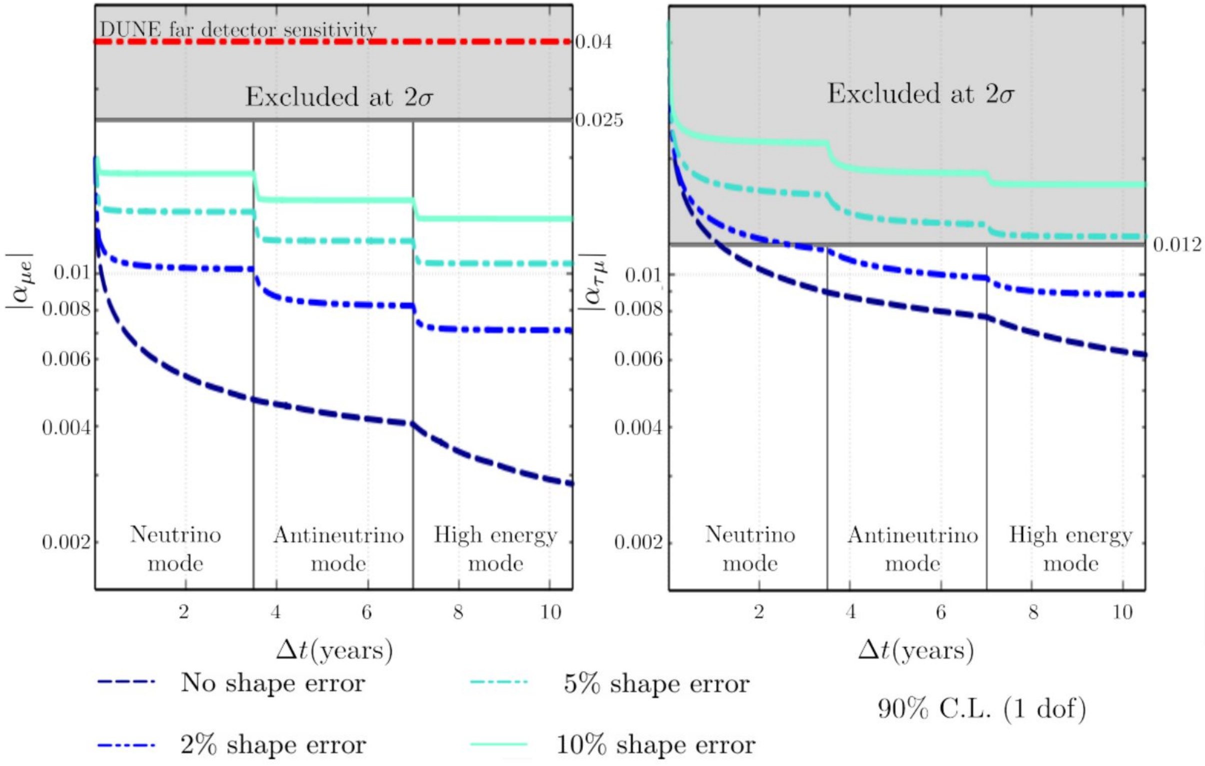

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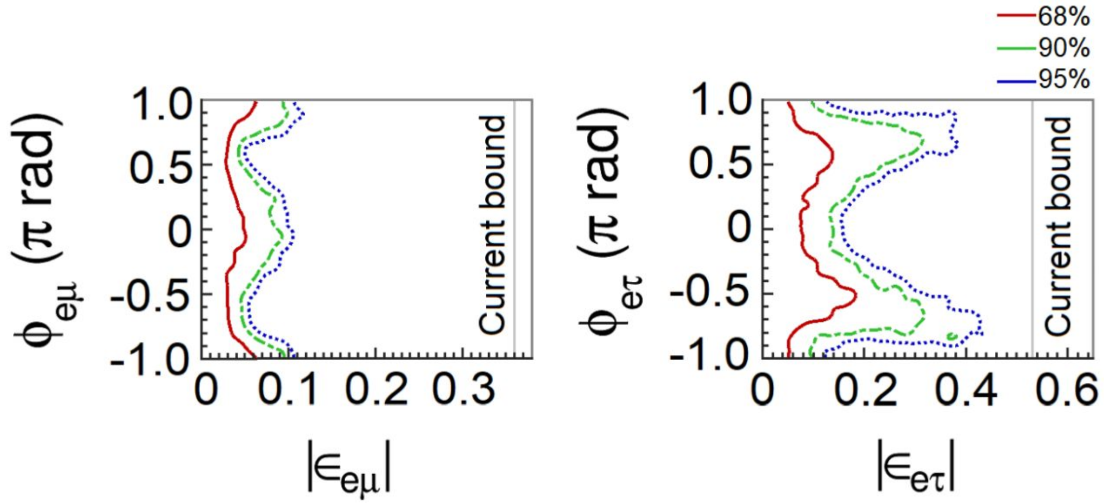
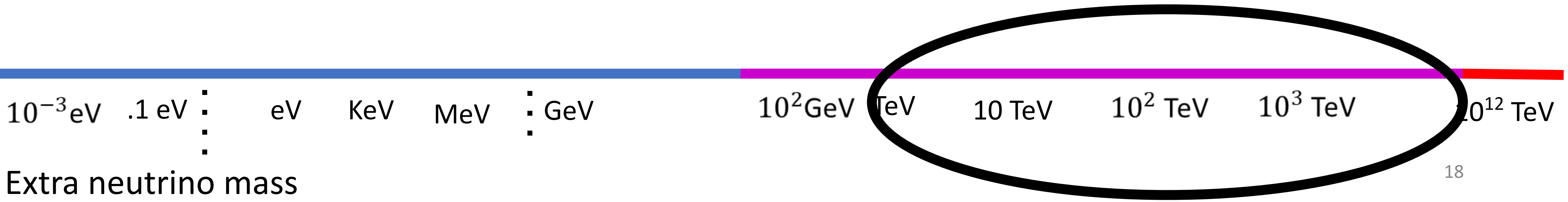
NC NSI can can be parameterized as new contributions to MSW effect (QM and EFT approach map: arXiv:1910.02971v3):

$$H = \frac{1}{2E}\left[U_{\rm PMNS}\begin{pmatrix}0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger_{\rm PMNS} + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$



PMNS Unitarity at DUNE



Extra neutrino mass

PMNS Unitarity at DUNE

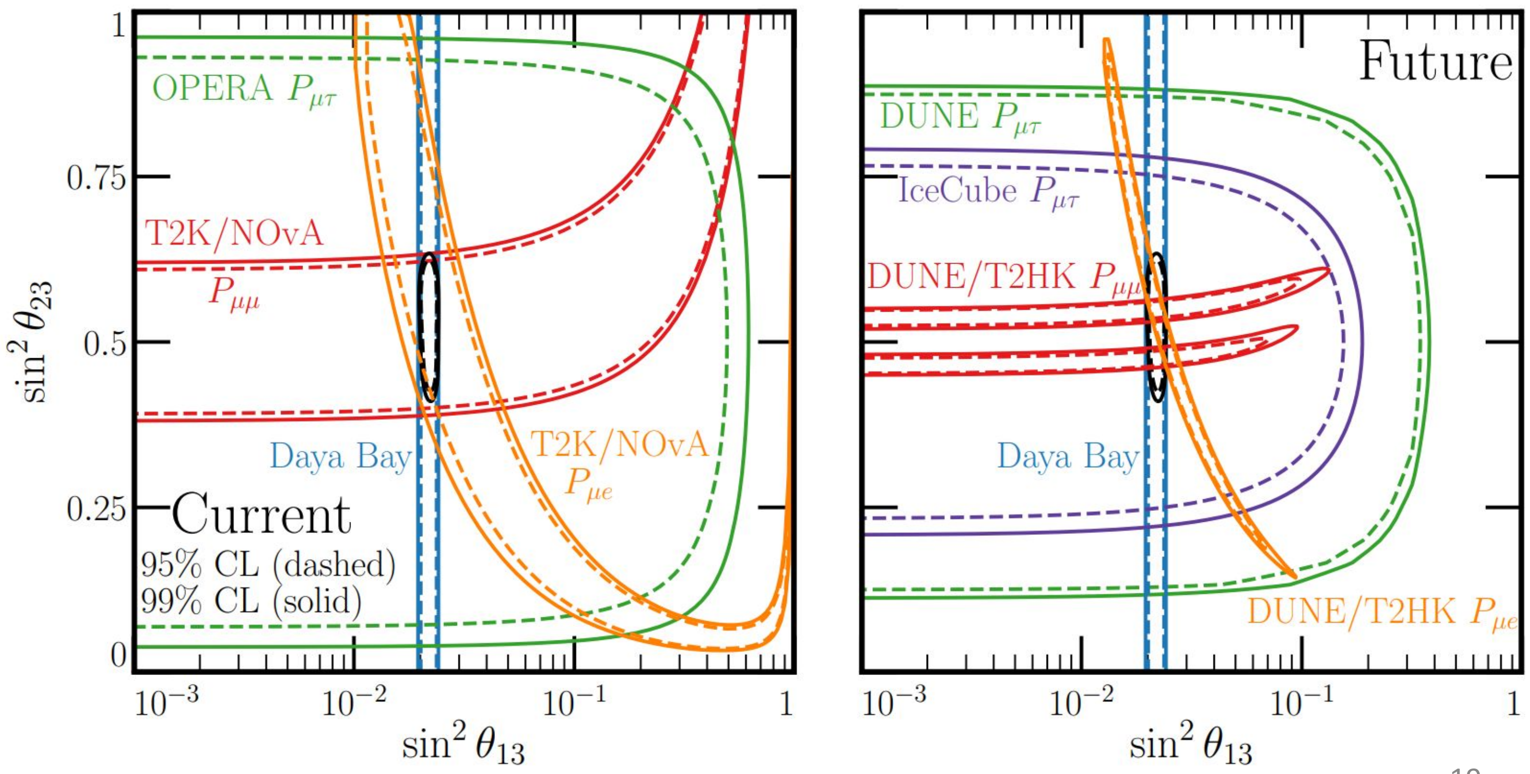
PMNS non-unitarity bound at per mil level from Lepton Universality, Lepton Flavor Violation & EW observables

- α constrained at 10^{-3} - 10^{-5} level
- 2-3 σ hints of LVF: arXiv:1502.07400, arXiv:1508.03372, arXiv:1605.08774v2 (2016), arXiv:1310.2057v2 (2014), arXiv:1407.6607v2 (2014), Phys. Rept. 427 257 (2006), Phys Rev. B 784 (2018) 248-254

Limits do have some model dependence, so direct tests with neutrinos are important

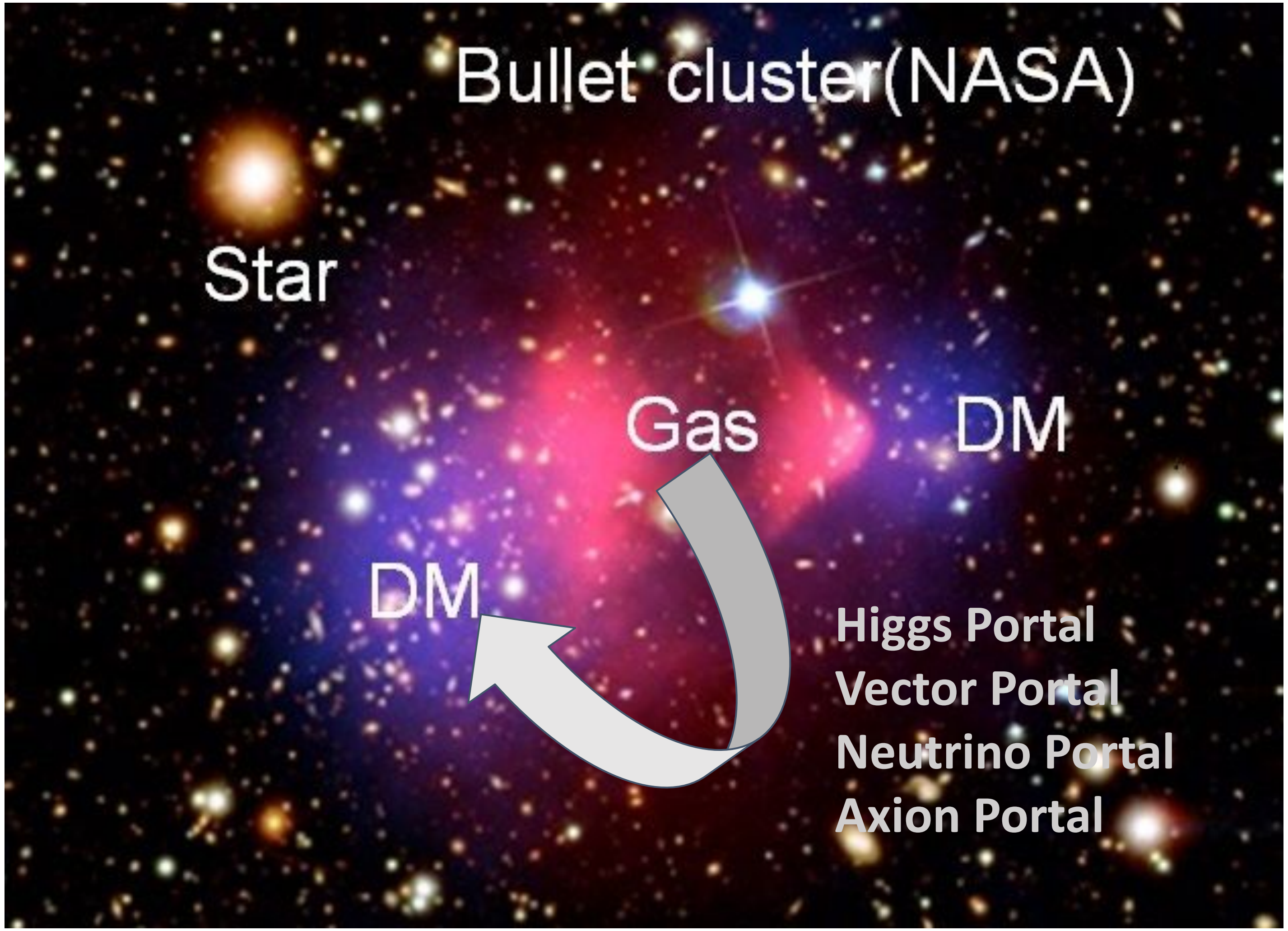
Ellis, Kelly, Li JHEP12 (2020) 068

Parameter	Constraint
α_{ee}	0.3
$\alpha_{\mu\mu}$	0.2
$\alpha_{\tau\tau}$	0.8
$\alpha_{\mu e}$	0.04
$\alpha_{\tau e}$	0.7
$\alpha_{\tau\mu}$	0.2



Explaining Dark Matter through Dark Sectors

Portals with simplest UV-complete dark sectors models can explain Dirac and Majorana neutrino mass, a variety of models for low mass non-thermal dark matter, and the minimal mechanism of leptogenesis



Explaining Dark Matter through Dark Sectors : $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \ldots$

$$+\delta\mathcal{L}^{d=3,4}_{\text{Higgs portal}}$$

$$= -(\mu S + \lambda S^2) H^\dagger H$$

$$\rightarrow -\frac{\mu v}{m_h^2 - m_S^2} S J_h + \ldots$$

S: dark singlet scalar

H: SM Higgs Doublet

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$$= -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'_{\mu\nu}$$

$$\to \epsilon e A'_\mu J^\mu_{EM} + \ldots$$

A_{0}: dark photon
J^μ_{EM} : SM EM current

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$$= \sum y_\nu^{\alpha I} (\bar{L}_\alpha H) N_I$$

$$\to -\frac{1}{\sqrt{2}} \sum v y_\nu^{\alpha I} \bar{\nu}_\alpha N_I + \ldots$$

N_I: right handed neutrino/dark neutral lepton

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Higgs portal

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Vector portal

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Neutrino portal

$$= \sum y_\nu^{\alpha I} (\bar{L}_\alpha H) N_I$$

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N_I: right handed neutrino/dark neutral lepton

Axion portal

$$= -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

a: axion like particle
$F_{\mu\nu}$ photon field tensor

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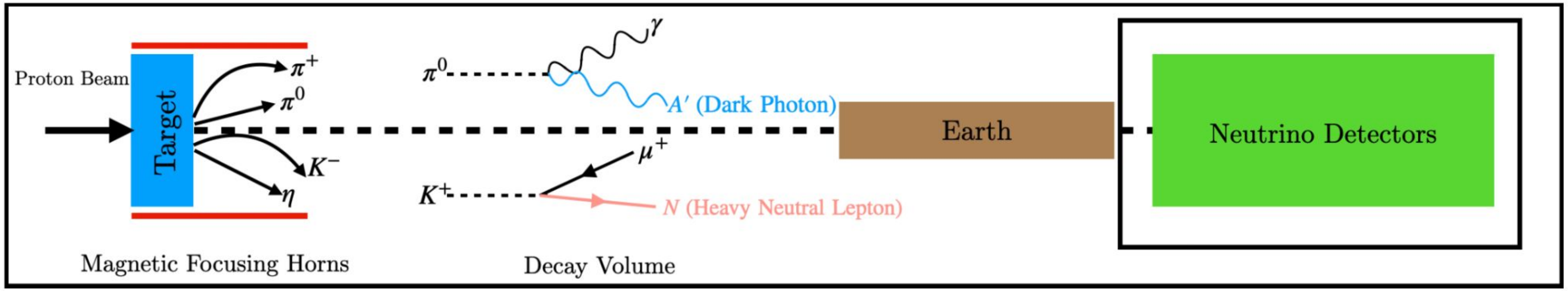

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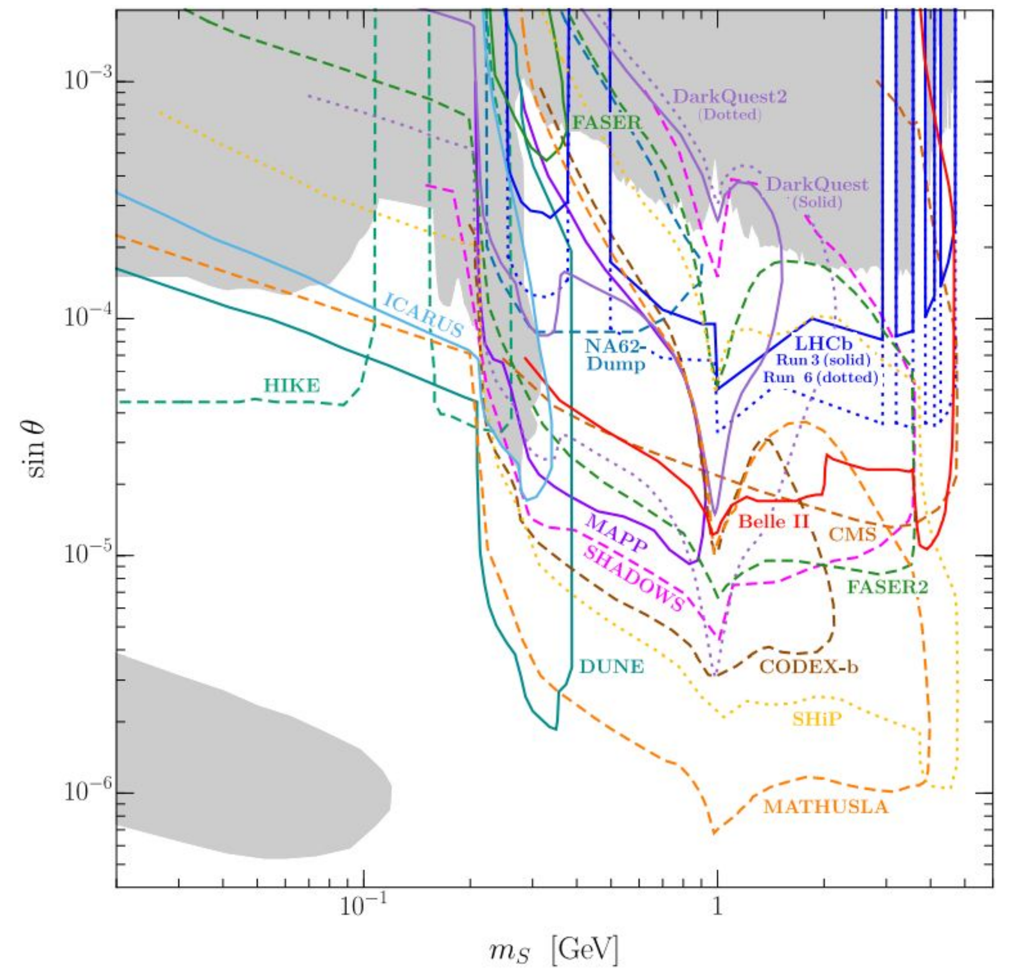

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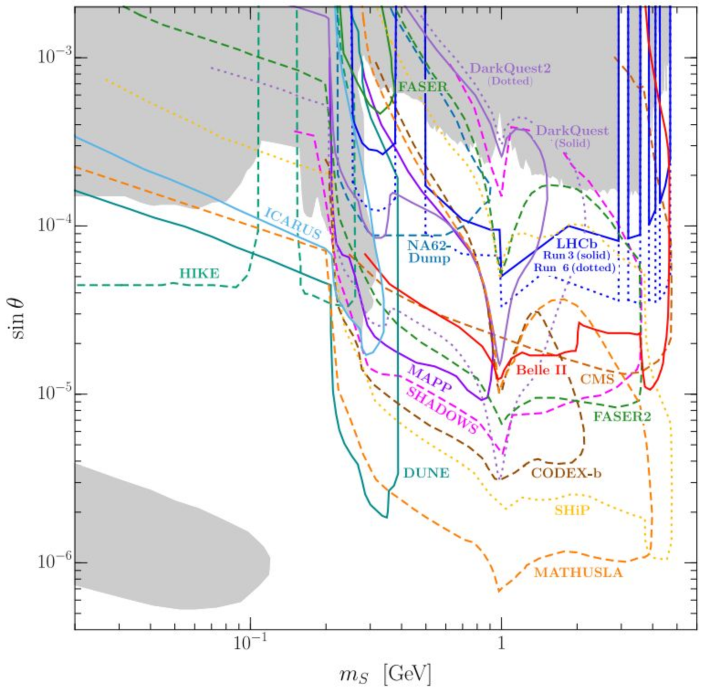
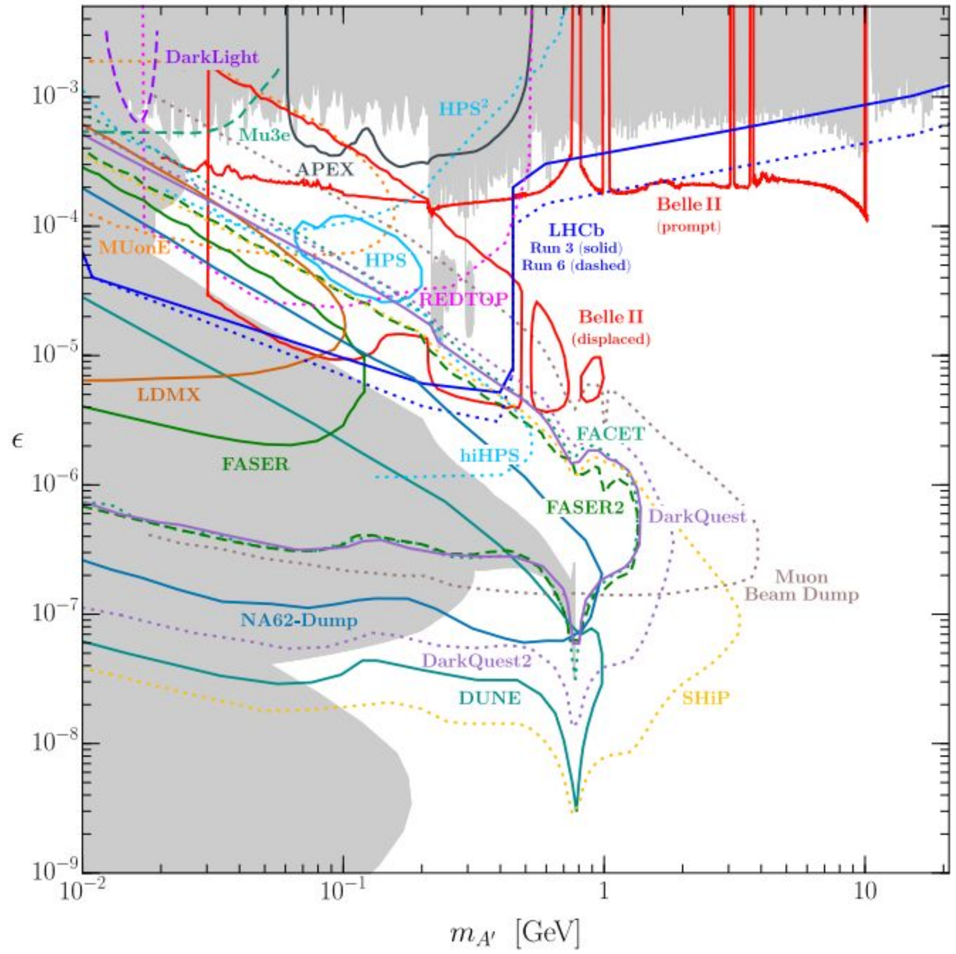
$+\delta\mathcal{L}^{d=3,4}_{\text{Higgs portal}}$ $+\delta\mathcal{L}^{d=4}_{\text{vector portal}}$

Snowmass NF03 arXiv:2207.06898v2



S: dark singlet scalar

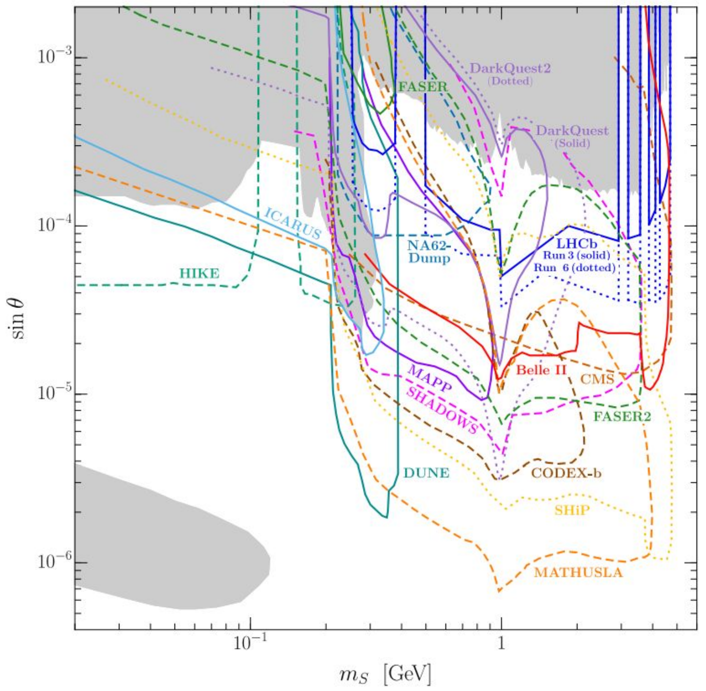


$A_{0:}$: dark photon, g-2 connection?

Explaining Dark Matter through Dark Sectors : $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \ldots$

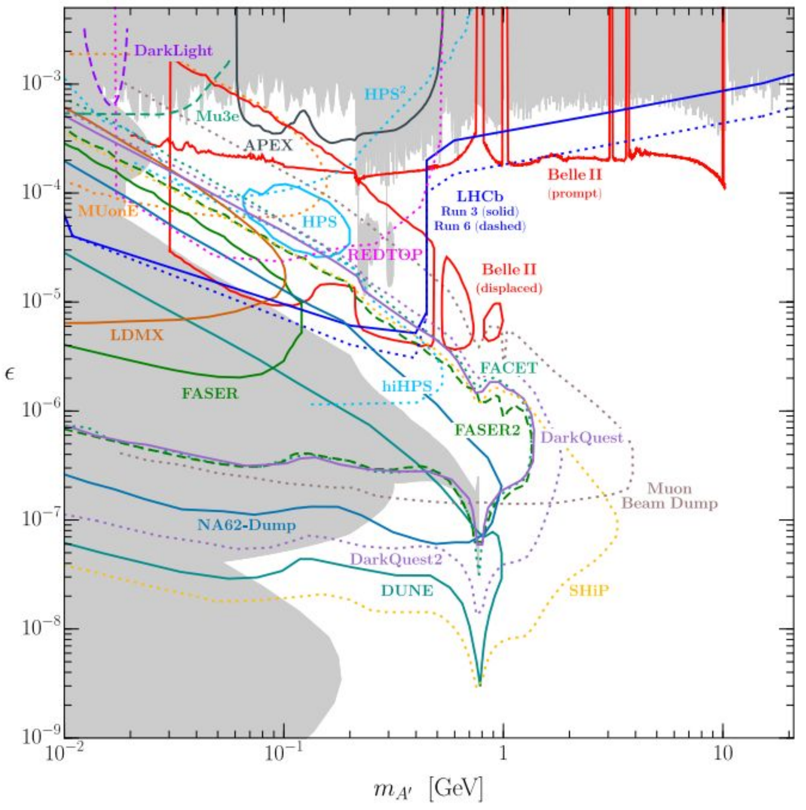
$+\delta\mathcal{L}^{d=3,4}_{\text{Higgs portal}}$ $+\delta\mathcal{L}^{d=4}_{\text{vector portal}}$ $+\delta\mathcal{L}^{d=5}_{\text{axion portal}}$

Snowmass NF03 arXiv:2207.06898v2

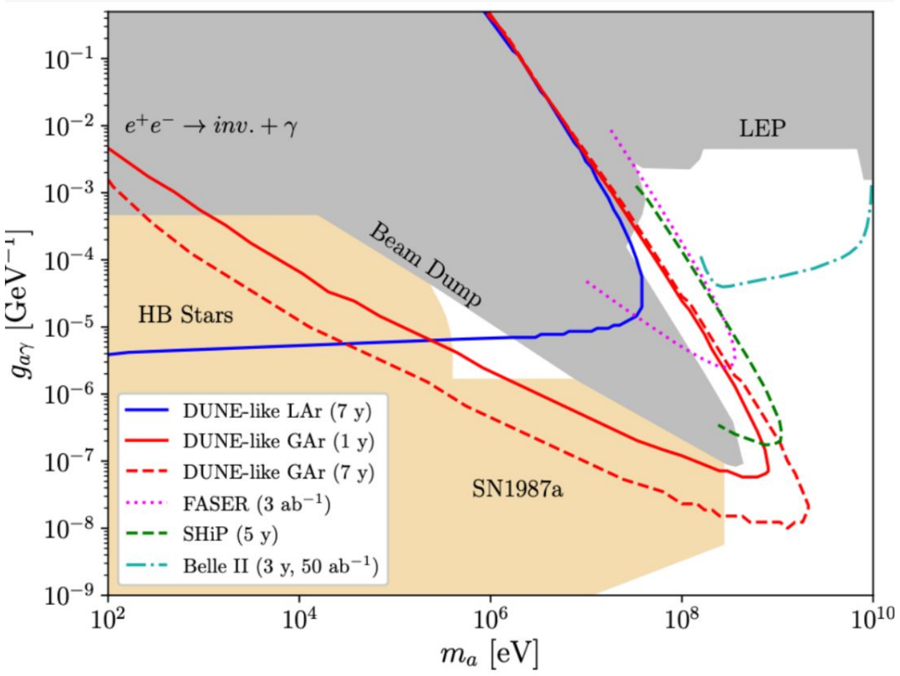


S: dark singlet scalar

Snowmass NF03 arXiv:2207.06898v2



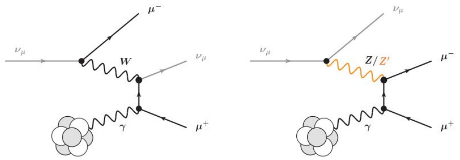
A_0: dark photon

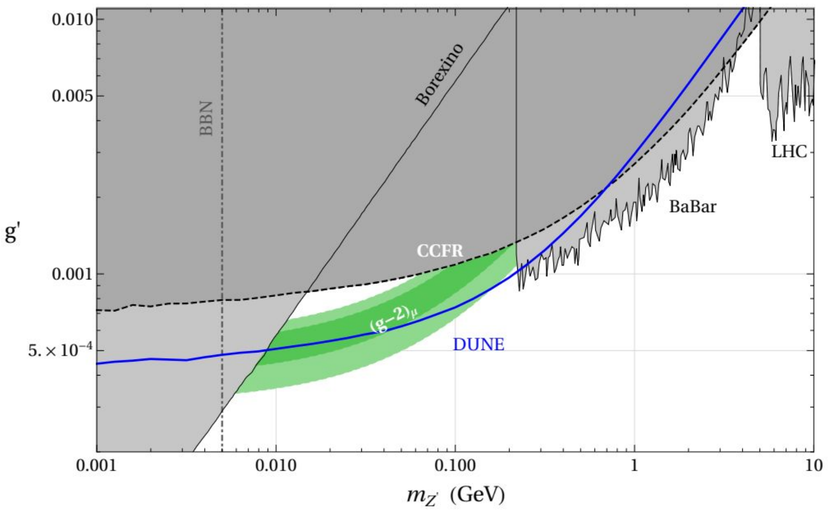


a: axion like particle

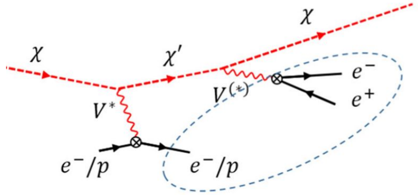
and many more…

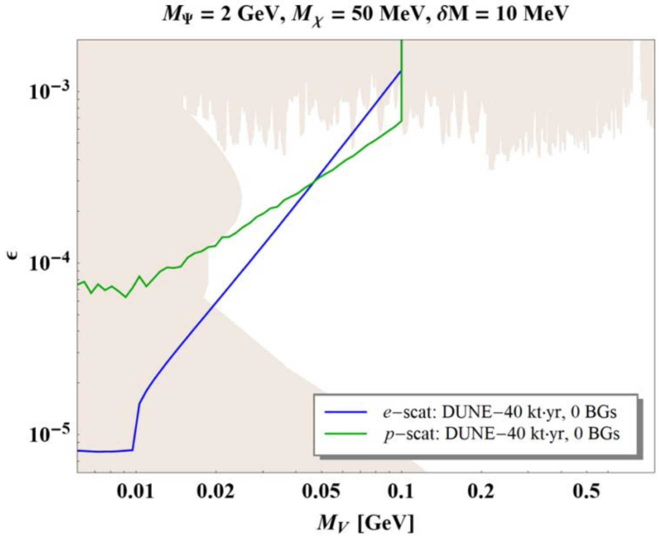
neutrino tridents



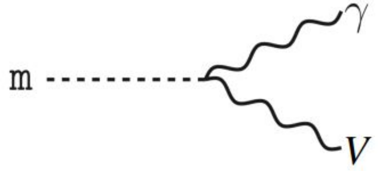


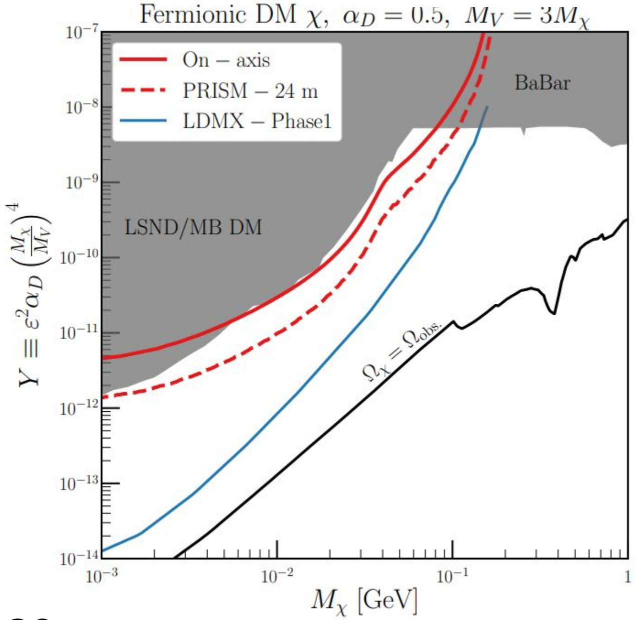
boosted dark matter



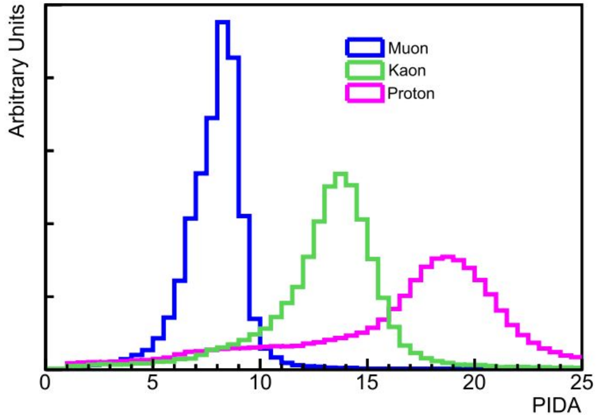


low-mass dark matter

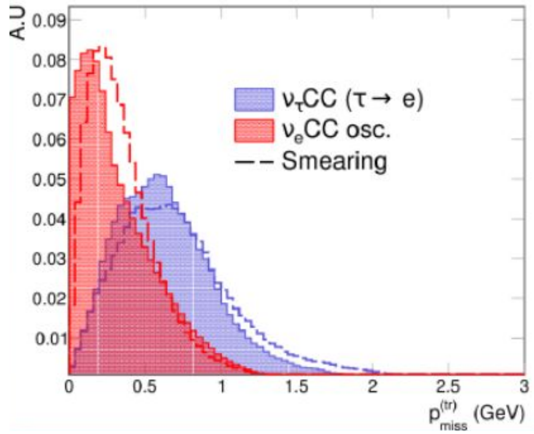




proton decay



tau neutrinos



Conclusion

DUNE will be sensitive to a wide range of BSM physics, it will

- provide competitive sterile neutrino limits
- improve limits on some source/detector NSI by factor of 2-5
- provide a direct probe of PMNS non-unitarity
- be uniquely sensitive to Dark Matter portals in uncovered mass ranges

Thank you!

https://arxiv.org/pdf/2210.00109

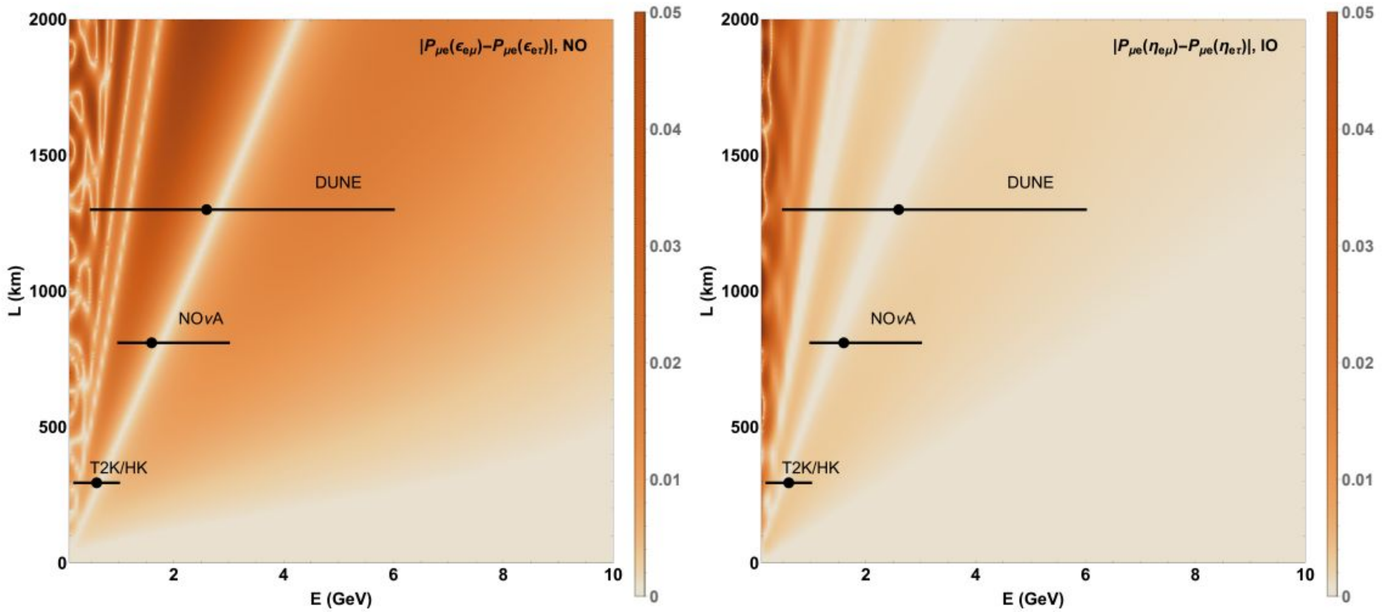


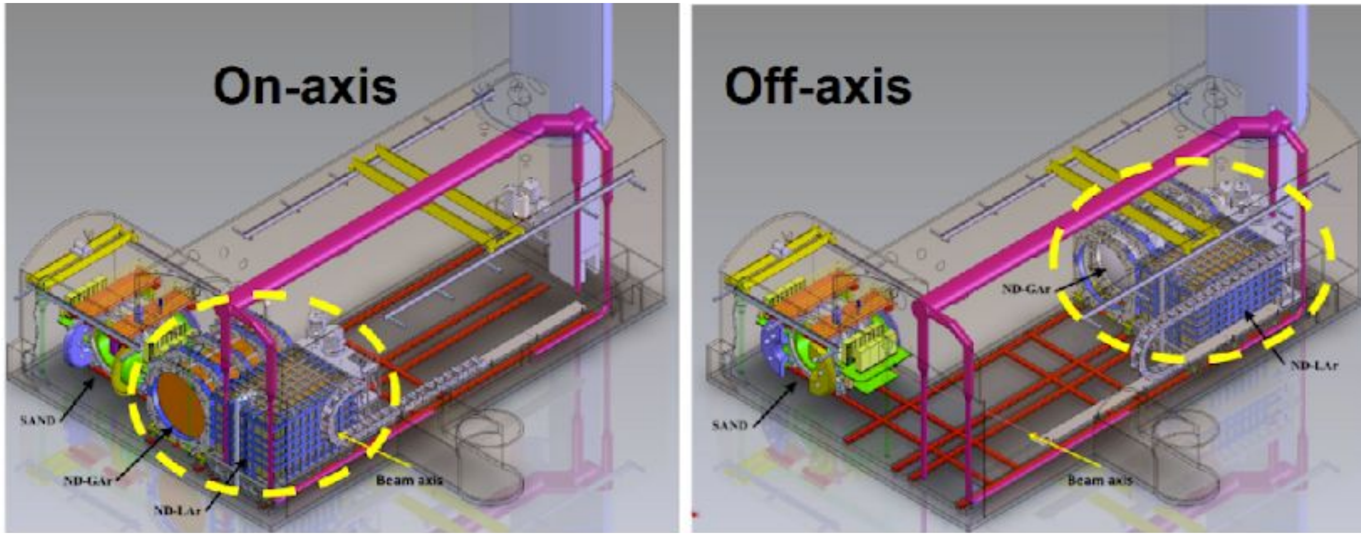
Figure 1. The difference in neutrino appearance probabilities for two benchmark cases (see table 6) as a function of baseline and neutrino energy. On the left the difference is between the probabilities with vector NSI and $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ in normal ordering and the right is between probabilities with scalar NSI and $\eta_{e\mu}$ and $\eta_{e\tau}$ in inverted ordering. The regions probed by the different long-baseline experiments are indicated. The density is taken to be that for DUNE, 2.848 g/cm^3, throughout.

MO	Δm^2_{41} [eV^2]	θ_{14} [°]	θ_{24} [°]	δ_{13}/π	δ_{12}/π
NO	1	8	8	1.9	0.7
IO	1	8	8	0	0.5

Table 1. Benchmark sterile neutrino parameters from NOvA and T2K data from Ref. [7]. Sterile parameters not shown are zero and standard oscillation parameters not shown are taken to the standard values shown in table 2.

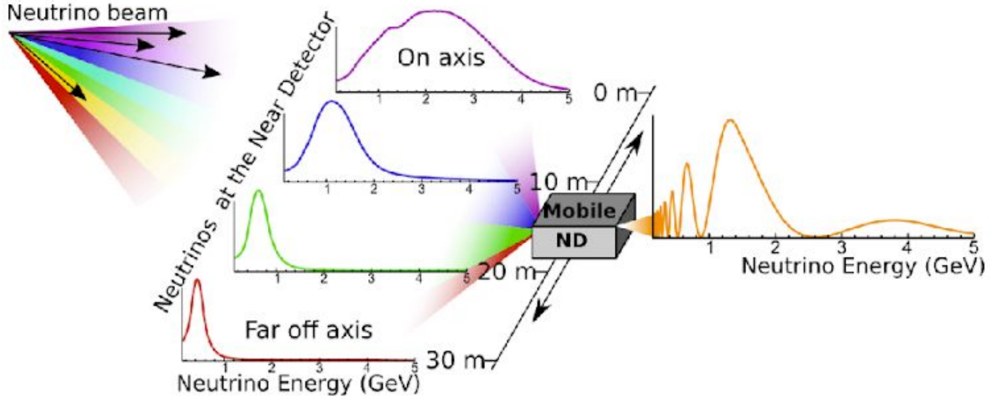
DUNE Near Detector

- **ND-LAR:** liquid argon TPC with muon spectrometer (TMS) 50t fiducial mass, modular detector with pixel readout to reduce pileup
  - Similar to FD to characterize beam flux and neutrino interactions



- **ND-GAr**: Gaseous argon detector
  - surrounded by ECAL and muon system in magnetic field
  - good tracking resolution, can study low- Ar interactions

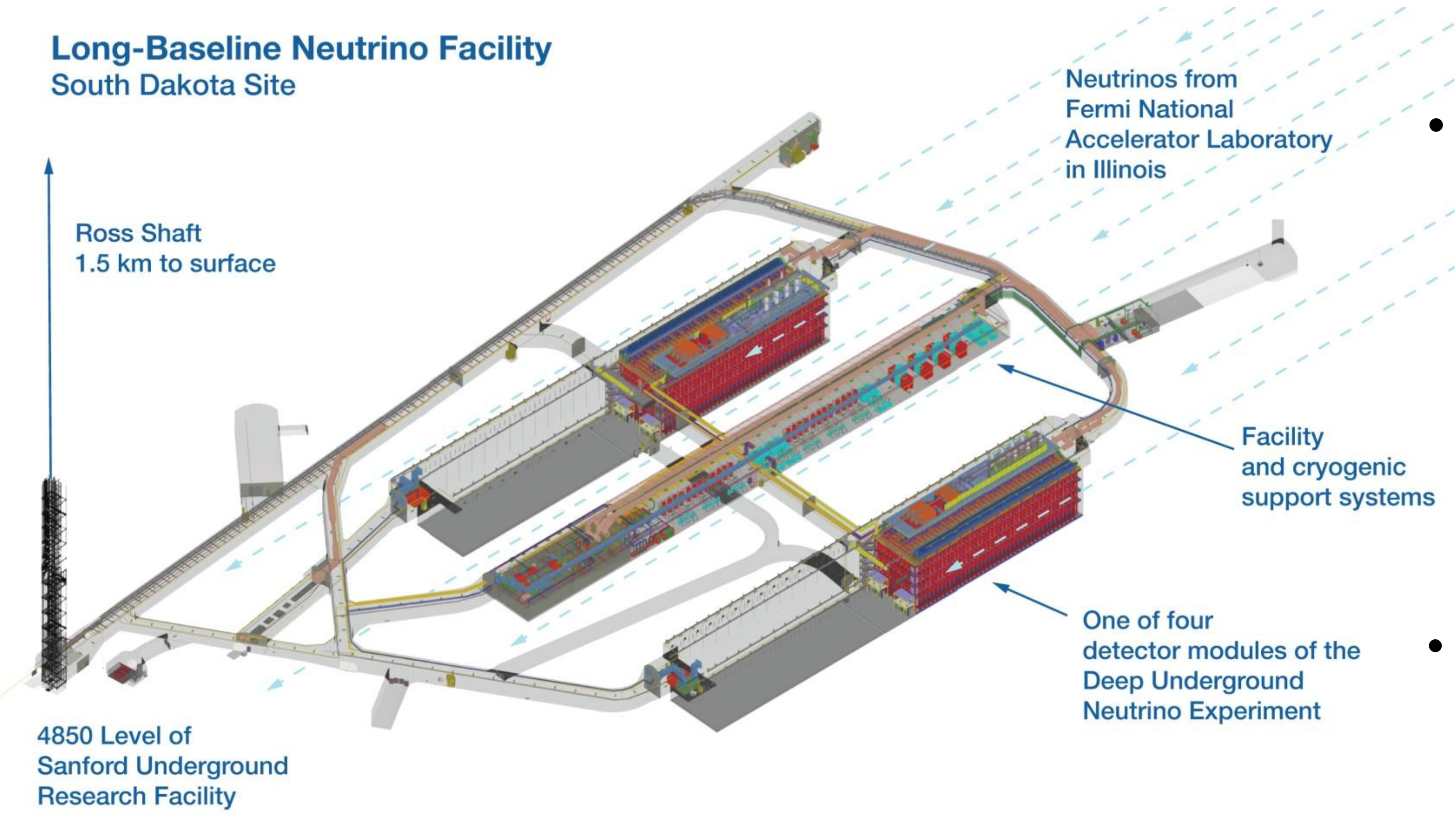
DUNE PRISM



- **SAND**: System for on-Axis Neutrino Detection
  - Inner tracker & ECAL in magnetic field serve as beam monitor

- **PRISM** for ND-LAr/GAr: Precision Reaction-Independent Spectrum
  - Can measure flux at different off-axis angles,

DUNE Far Detector



- 4 Far Detector modules in cryostats (15.1m wide x 14 m high by 62 m long) containing 17 kt of LAr mass
- Two factors affect the performance
  - High LAr purity needed to minimize charge and light attenuation
  - Low electronics noise such that the signal from the drifting electrons can be differentiated over the baseline
- 1st module - Single Phase (SP), horizontal drift, LAr Time Projection Chamber (LArTPC) Installed mid 2020s
- 2nd module - SP vertical drift LAr TPC
- 3rd / 4th module - to be defined

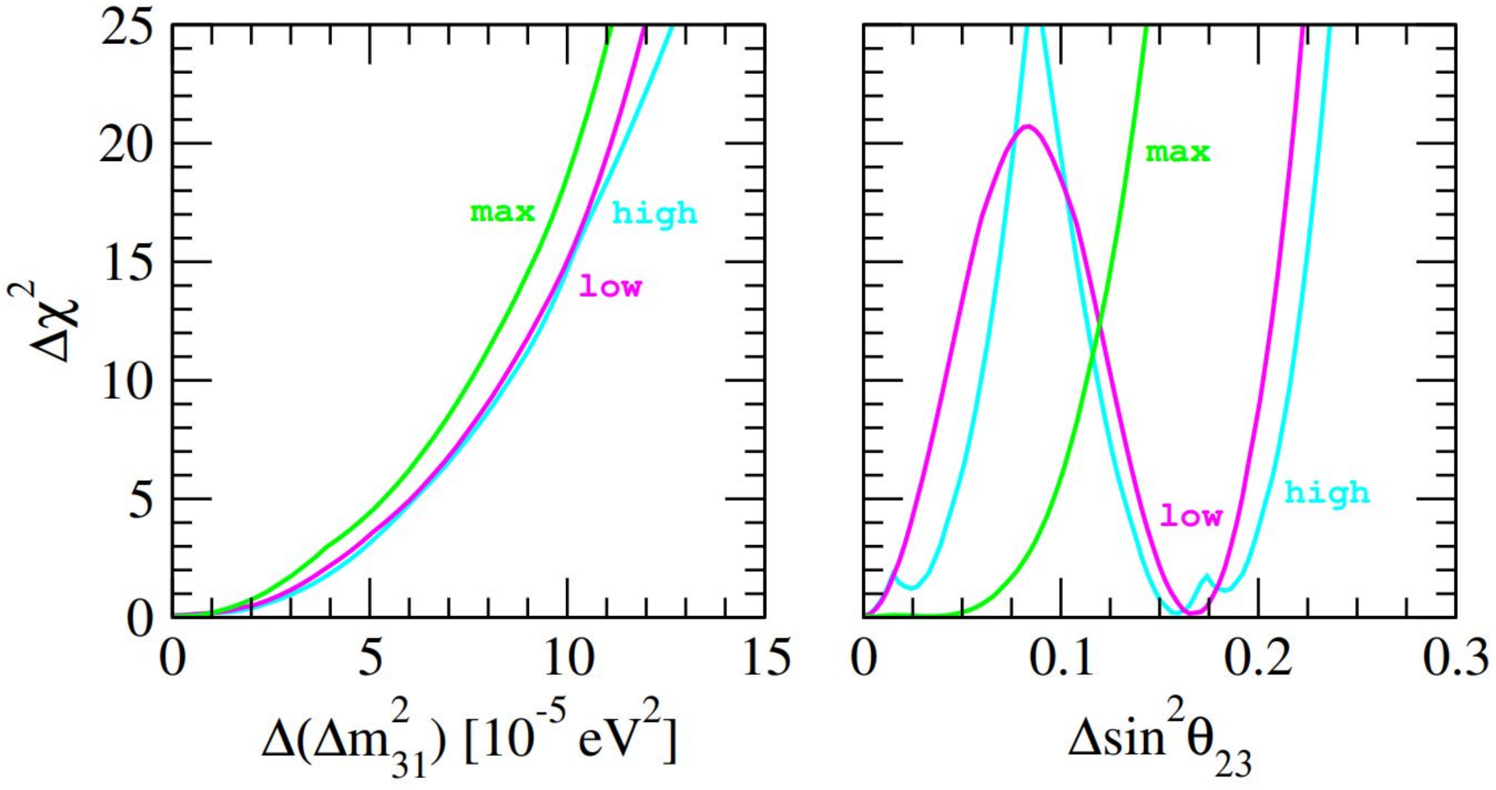
Excavation started!

CPT Violation

Predictions of CPT invariance is that particles and antiparticles have the same masses and, if unstable, the same lifetimes

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow \text{CP violation}$$

$$P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \Rightarrow \text{CPT violation}$$



Exposure of 300 kton MW yr and three values of Θ_{23} maximal mixing (green), lower octant (purple), upper octant (blue)

current bounds

$$\Delta(\Delta m_{31}^2) \equiv \left| \Delta m_{31}^2 - \Delta \bar{m}_{31}^2 \right| < 3.7 \times 10^{-4}\ \text{eV}^2$$

$$\Delta(\sin^2\theta_{23}) \equiv \left| \sin^2\theta_{23} - \sin^2\bar{\theta}_{23} \right| < 0.32$$

Limits on Extra Neutrinos

For neutrinos with masses below the electroweak scale, best limits from oscillation data. BUT most future experiments (DUNE) won't add too much here (see arXiv:1609.08637v3)

- Preference for non zero η_{ee} and $\eta_{\tau\tau}$: arXiv:1407.6607v2 (2014)
- Z_{inv} LEP measurement is 2σ from SM : Phys.Rept. 427, 257 (2006)
- Sensitivity to the ϵ in NSI have reached levels to explain 3.1 σ B-anamolies : Phys Rev. B 784 (2018) 248-254

arXiv:1609.08637v3

	"Light steriles" $\Delta m^2 \gtrsim 100$ eV^2	$\Delta m^2 \sim 0.1 - 1$ eV^2
α_{ee}	$2.4 \cdot 10^{-2}$ [48]	$1.0 \cdot 10^{-2}$ [48]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-2}$ [49]	$1.4 \cdot 10^{-2}$ [50]
$\alpha_{\tau\tau}$	$1.0 \cdot 10^{-1}$ [49]	$1.0 \cdot 10^{-1}$ [49]
$\|\alpha_{\mu e}\|$	$2.5 \cdot 10^{-2}$ [51]	$1.7 \cdot 10^{-2}$
$\|\alpha_{\tau e}\|$	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\|\alpha_{\tau\mu}\|$	$1.2 \cdot 10^{-2}$ [52]	$5.3 \cdot 10^{-2}$

48: Buggy

49: SuperK atmospheric

50: Minos

51/52: Nomad

Parameter	Constraint
α_{ee}	0.3
$\alpha_{\mu\mu}$	0.2
$\alpha_{\tau\tau}$	0.8
$\alpha_{\mu e}$	0.04
$\alpha_{\tau e}$	0.7
$\alpha_{\tau\mu}$	0.2

	"Non-Unitarity" ($m >$ EW)
α_{ee}	$1.3 \cdot 10^{-3}$ [46]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$ [46]
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$ [46]
$\|\alpha_{\mu e}\|$	$6.8 \cdot 10^{-4}$ ($2.4 \cdot 10^{-5}$) [46]
$\|\alpha_{\tau e}\|$	$2.7 \cdot 10^{-3}$ [46]
$\|\alpha_{\tau\mu}\|$	$1.2 \cdot 10^{-3}$ [46]

.1 eV | eV | KeV | MeV | GeV | GeV | TeV | 10 TeV | TeV | TeV | 10^{12} TeV

Extra neutrinos can participate in oscillations

accessible at osc. Exp

Accessible at B-factories

Accessible at LHC

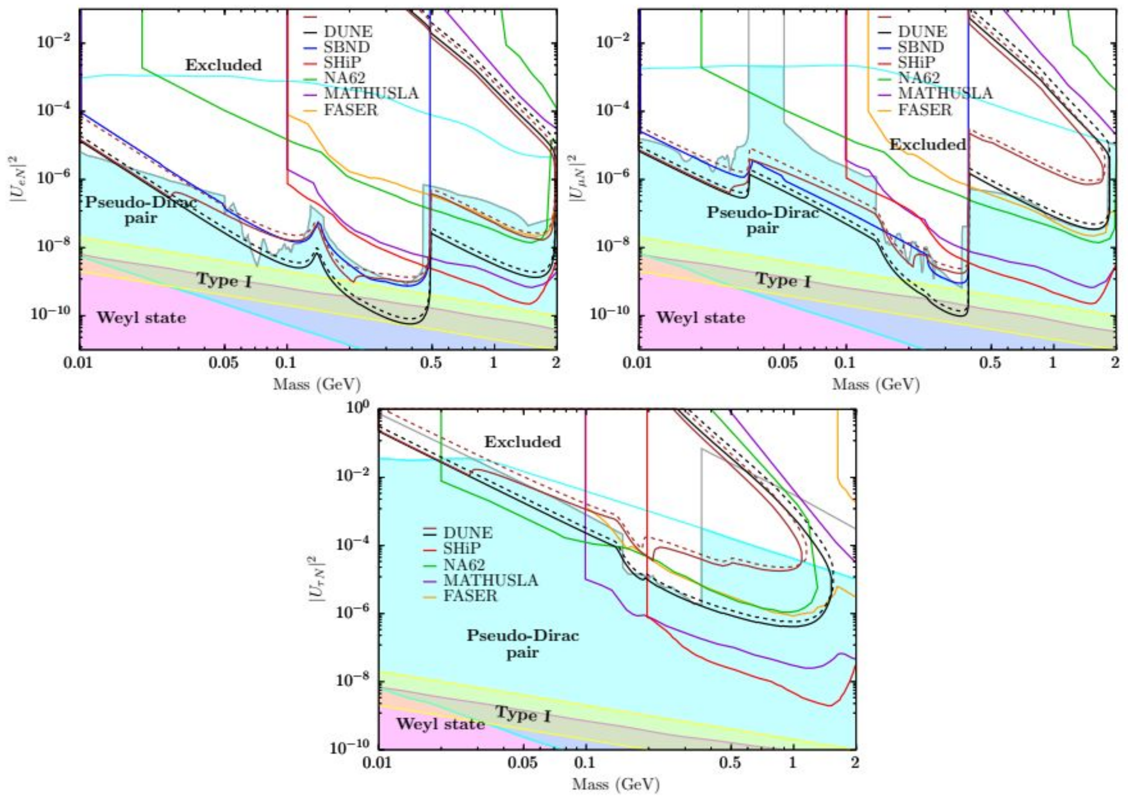


Figure 8. The 90 % C.L. sensitivity regions for dominant mixings $|U_{eN}|^2$ (top left), $|U_{\mu N}|^2$ (top right), and $|U_{\tau N}|^2$ (bottom) are presented combining results for channels with good discovery prospects (see text). The study is performed for Majorana neutrinos (solid) and Dirac neutrinos (dashed), in the case of no background (black) and after the background analysis (brown). The region excluded by experimental constraints (grey) is obtained by combining the results from PS191 [60, 61], peak searches [55–59], CHARM [63], NuTeV [65], DELPHI [64], and T2K [77], with the lines reinterpreted for Majorana neutrinos (see [154]). The sensitivity for DUNE ND (black) is compared to the predictions of future experiments, SBN [78] (blue), SHiP [129] (red), NA62 [119] (green), MATHUSLA [122] (purple), and FASER [124] with 1 m radius (orange). The shaded areas corresponds to possible neutrino mass models considered in this article: the simulations of the ISS (2,2) and ISS (2,3) models where the lightest pseudo-Dirac pair is the neutrino decaying in the ND (cyan); the ISS (2,3) scenario when the single Majorana state is responsible for a signal (magenta); the type I seesaw scenario with a neutrino mass starting from 20 meV to 0.2 eV (yellow).

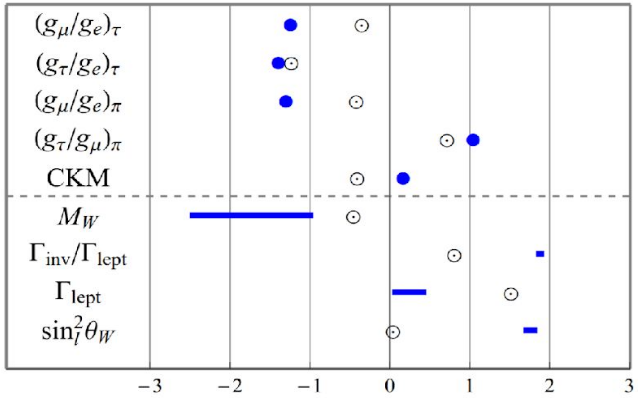
Hints of Extra Neutrinos?

LSND, MiniBoone, Gallium Anomalies

- some preference for 3ν + NSI with current data in NSI + matter: arXiv:1907.00991v1

lepton universality violation at $O(10^{-3})$ or 3σ . Presumably due to PMNS non-unitarity

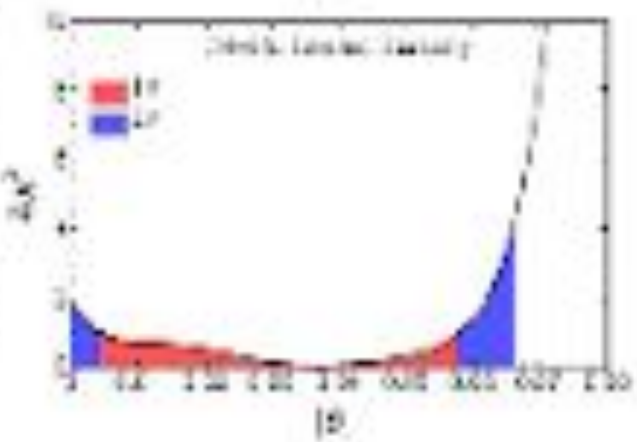
arXiv:1310.2057v2 (2014)



$$\frac{\Gamma(W \to \tau\bar{\nu}_\tau)}{\Gamma(W \to \mu\bar{\nu}_e)}$$ $2\,\sigma$ deviation in LEP

Lepton Flavor Violation: $1 - 2\sigma$ preference for non-zero heavy neutrino mixing in e & τ

arXiv:1605.08774v2 (2016)



- Preference for non zero η_{ee} and $\eta_{\tau\tau}$: arXiv:1407.6607v2 (2014)
- Z_{inv} LEP measurement is 2σ from SM : Phys.Rept. 427, 257 (2006)
- Sensitivity to the ϵ in NSI have reached levels to explain 3.1 σ B-anamolies : Phys Rev. B 784 (2018) 248-254

10^{-3}eV .1 eV eV KeV MeV GeV 10^2GeV TeV 10 TeV 10^2 TeV 10^3 TeV 10^{12} TeV

Extra neutrinos can participate in oscillations

accessible at osc. Exp

Accessible at B-factories

Accessible at LHC

PMNS non - unitarity through Charged lepton flavour violation

Lepton Flavor Violation & non Unitarity of PMNS

arXiv:1407.6607v2 [hep-ph] 6 Aug 2014

$$\Gamma_{W,\alpha} = \sum_i \Gamma(W \to \ell_\alpha \nu_i) = \frac{G_\mu M_W^3}{6\sqrt{2}\pi} \frac{(NN^\dagger)_{\alpha\alpha} F_W(m_{\ell_\alpha})}{\sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}}$$

$$F_W(m_{\ell_\alpha}) = \left(1 - \frac{m_{\ell_\alpha}^2}{m_W^2}\right)^2 \left(1 + \frac{m_{\ell_\alpha}^2}{m_W^2}\right).$$

$$R_{\alpha\beta}^W = \sqrt{\frac{\Gamma_{W,\alpha} F(m_{\ell_\beta})}{\Gamma_{W,\beta} F(m_{\ell_\alpha})}} = \sqrt{\frac{(NN^\dagger)_{\alpha\alpha}}{(NN^\dagger)_{\beta\beta}}}$$

arXiv:1605.08774v2, 21 Dec 2016

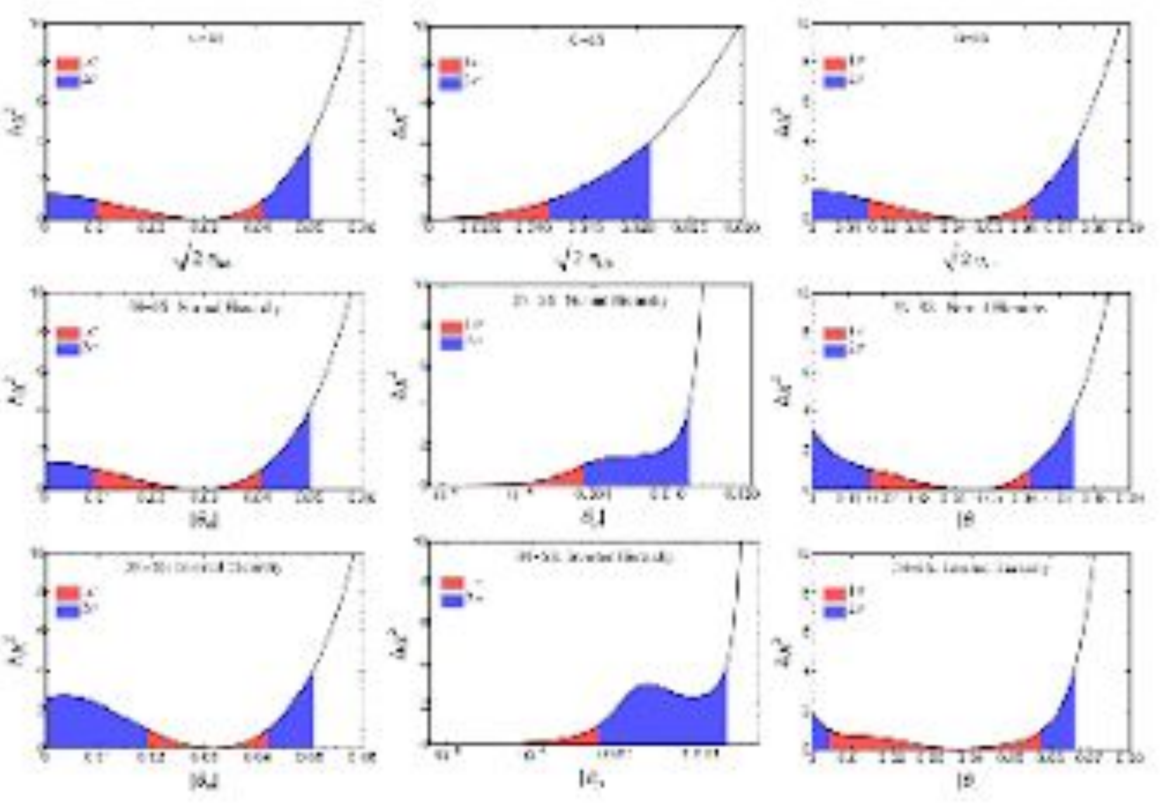


FIG. 3: $\Delta\chi^2$ profile minimized over all fit variables except for one θ_α (or $\sqrt{2}\eta_{\alpha\alpha}$ in the case of the G-SS) at a time. The upper panels are for the G-SS, and the middle and lower panels for the 3N-SS for a normal and inverted hierarchy respectively.

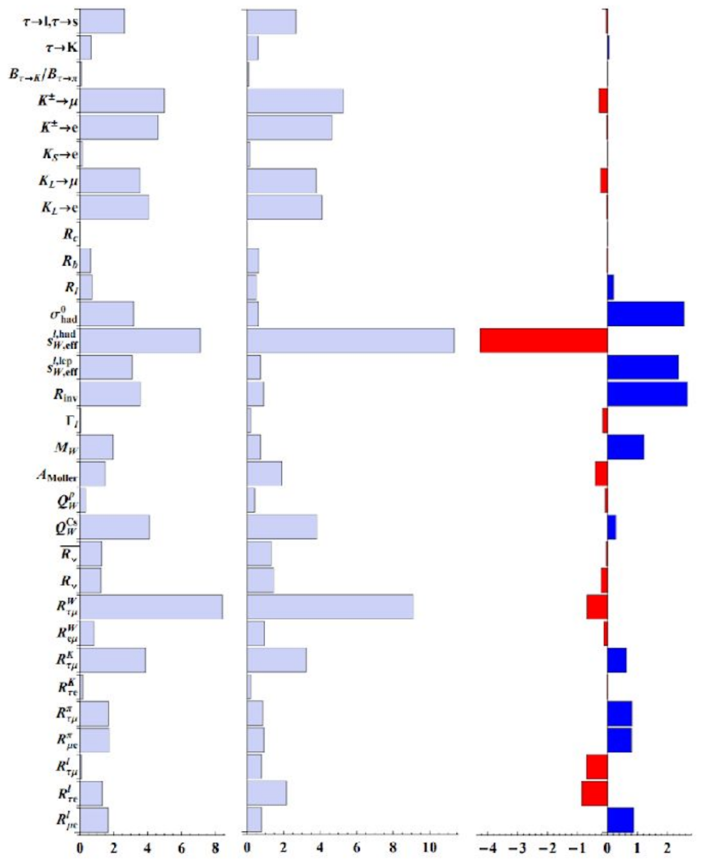
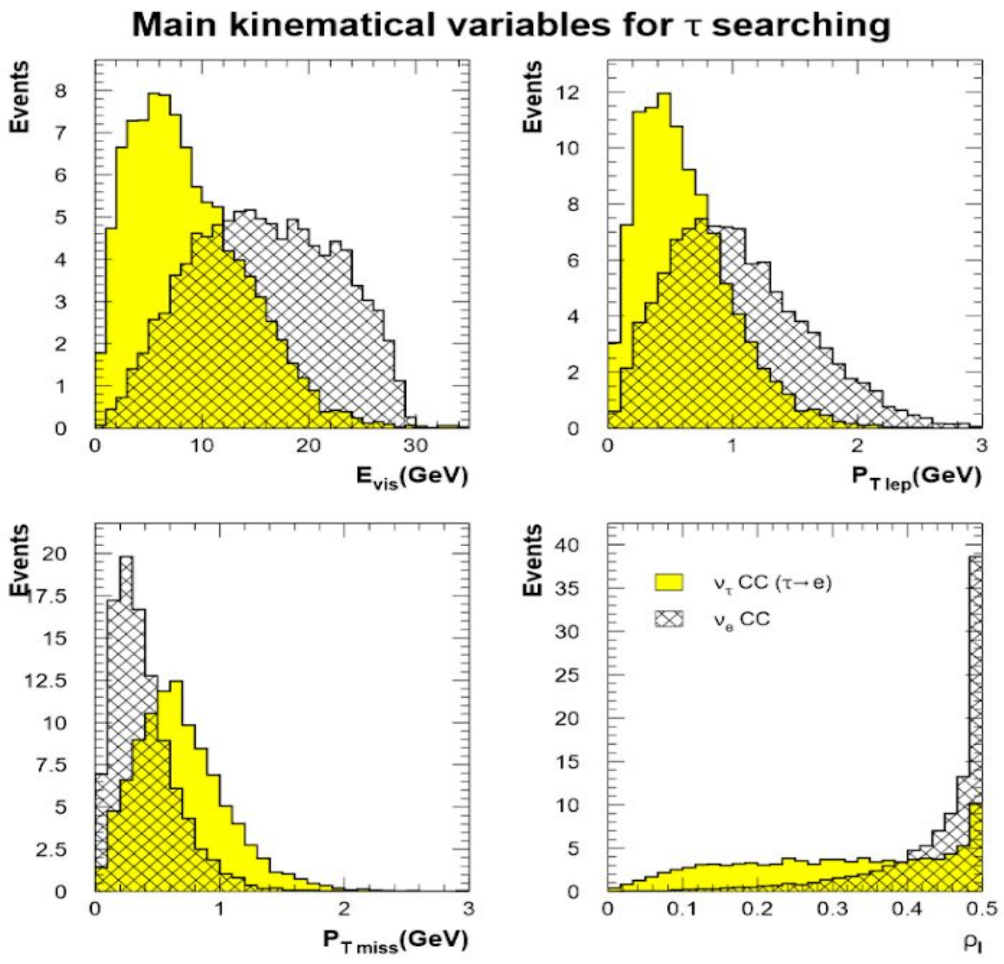


Figure 1: Individual contributions to the total χ^2 from the considered observables. The left column shows the SM and the middle column the MUV scheme with best-fit parameters. The right column shows $\chi_i^2(SM) - \chi_i^2(MUV)$ for the observable i. The positive blue (negative red) bars indicate an improvement (worsening) of the MUV scheme best fit compared to the SM.

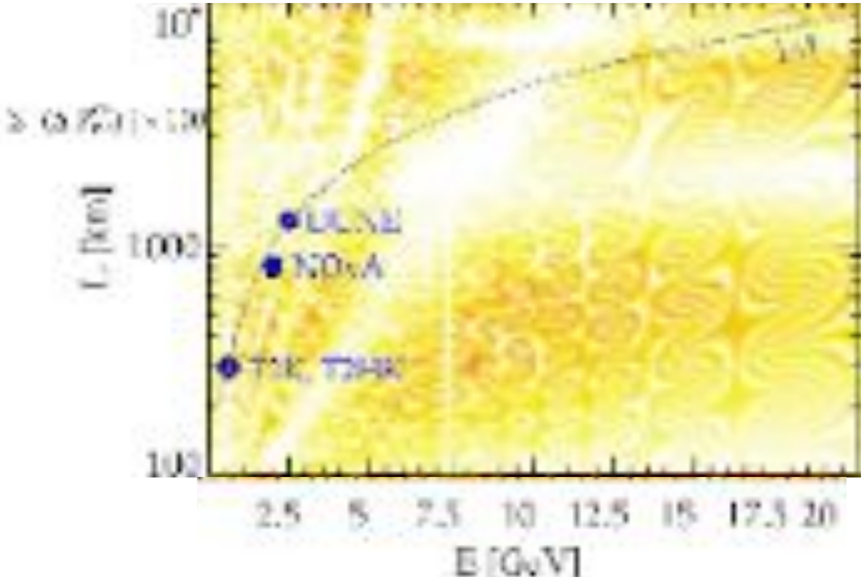
Tau Neutrinos in DUNE

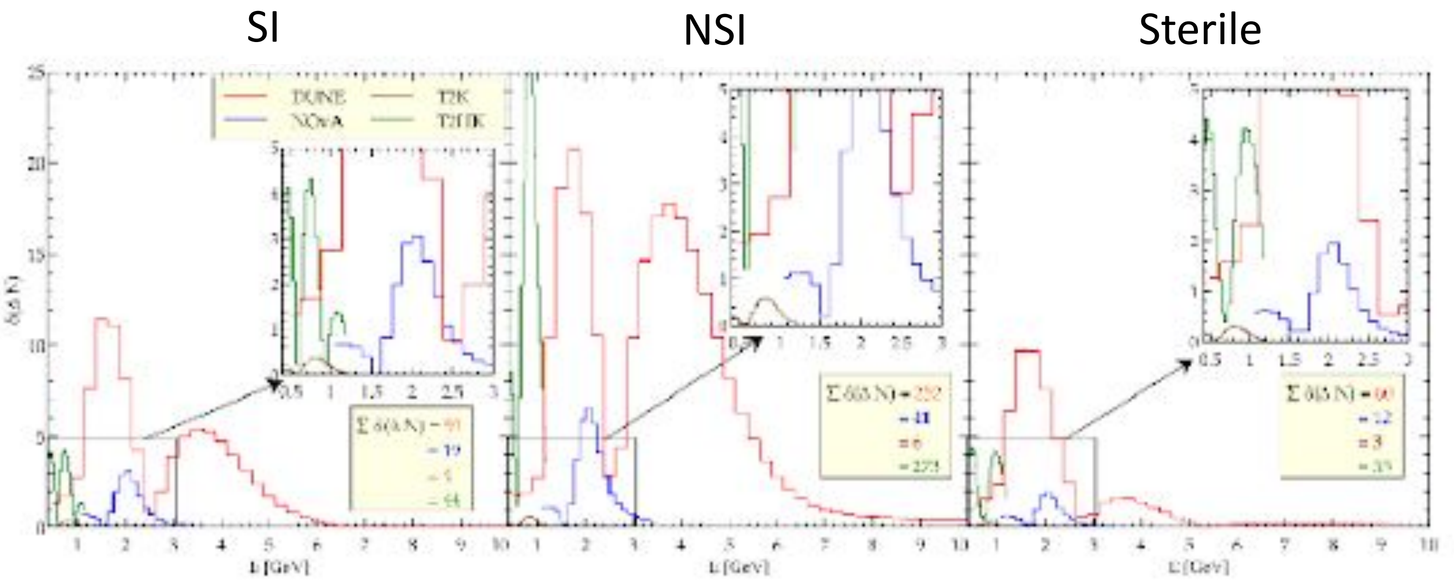


The discriminating power of , between induced interactions, represented by the filled yellow distributions, and the background events represented by the hashed distribution.

Sensitivity to Extra Neutrinos and NSI

Darker regions = larger amount of non-unitarity in sterile
Can't probe non-unitarity at better than 6%





$$\delta[\Delta N^{CP}_{\alpha\beta}] = [\Delta N^{CP}_{\alpha\beta}](\delta_{13} = \pi/2) - [\Delta N^{CP}_{\alpha\beta}](\delta_{13} = 0)$$

- NSI with matter gives rise to NSI at source and/or detector (arXiv:0807.1003v3). Bounds on source & detector NSI an order of magnitude more strict than matter NSI. DUNE can probe matter (dim 8), Hyper – K source & detector NSI (dim 6)
- NSI can be probed with supernova neutrinos in Hyper-K : arXiv:1907.01059v2

eV KeV MeV GeV 100 GeV

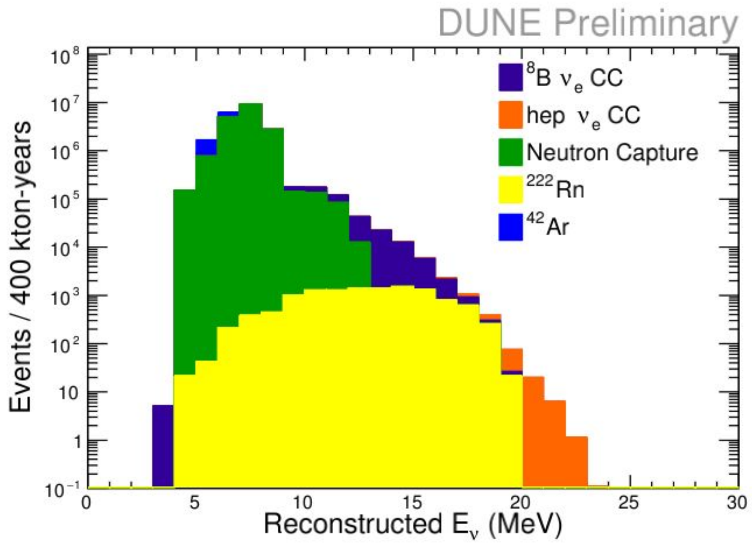
Extra neutrinos can participate in oscillations

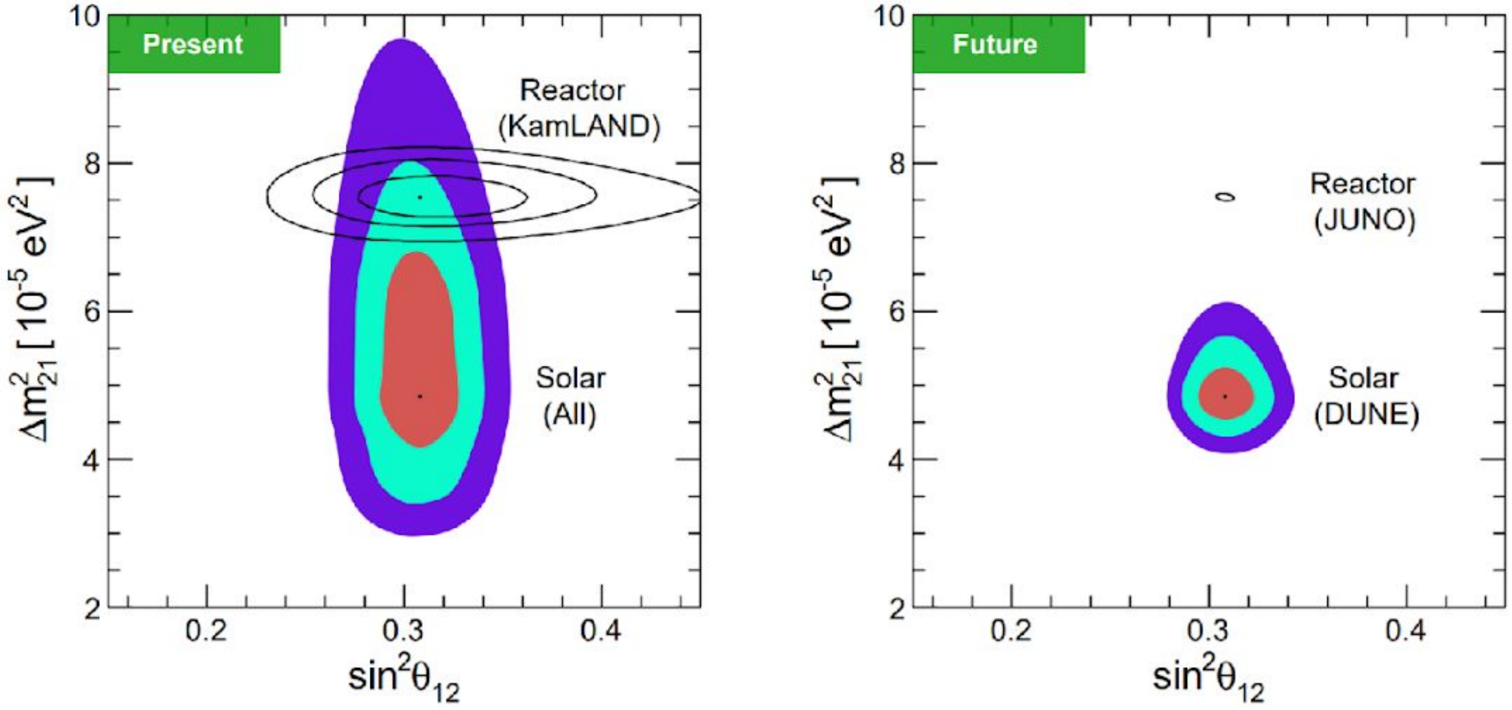
accessible at osc. Exp

Accessible at B-factories

DUNE as the Next-Generation Solar Neutrino Experiment

- https://arxiv.org/pdf/1808.08232.pdf





Non Standard Interactions

DUNE will improve current constraints on τe and μe, the magnitude of the NSI relative to standard weak interactions, by a factor of 2 to 5.

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\rm MSW}$$

$$\tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

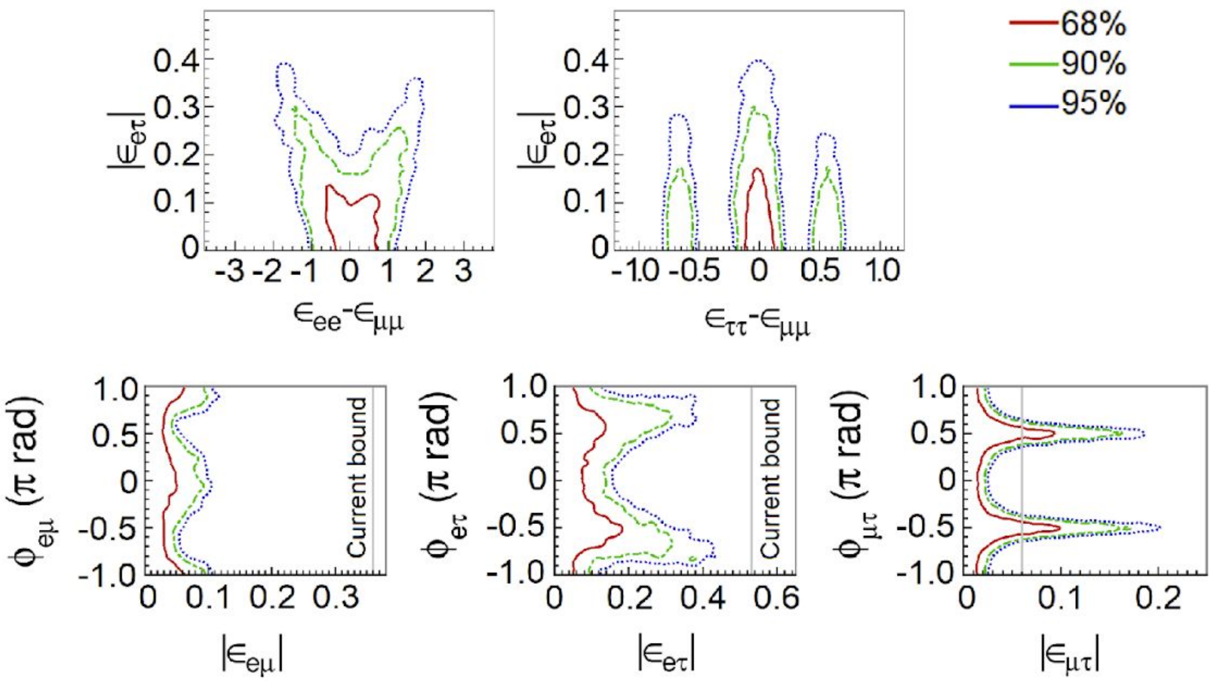


Figure 8.7: Allowed regions of the non-standard oscillation parameters in which we see important degeneracies (top) and the complex non-diagonal ones (bottom). We conduct the analysis considering all the NSI parameters as non-negligible. The sensitivity regions are for 68% CL [red line (left)], 90% CL [green dashed line (middle)], and 95% CL [blue dotted line (right)]. Current bounds are taken from [397].

Tau Neutrino

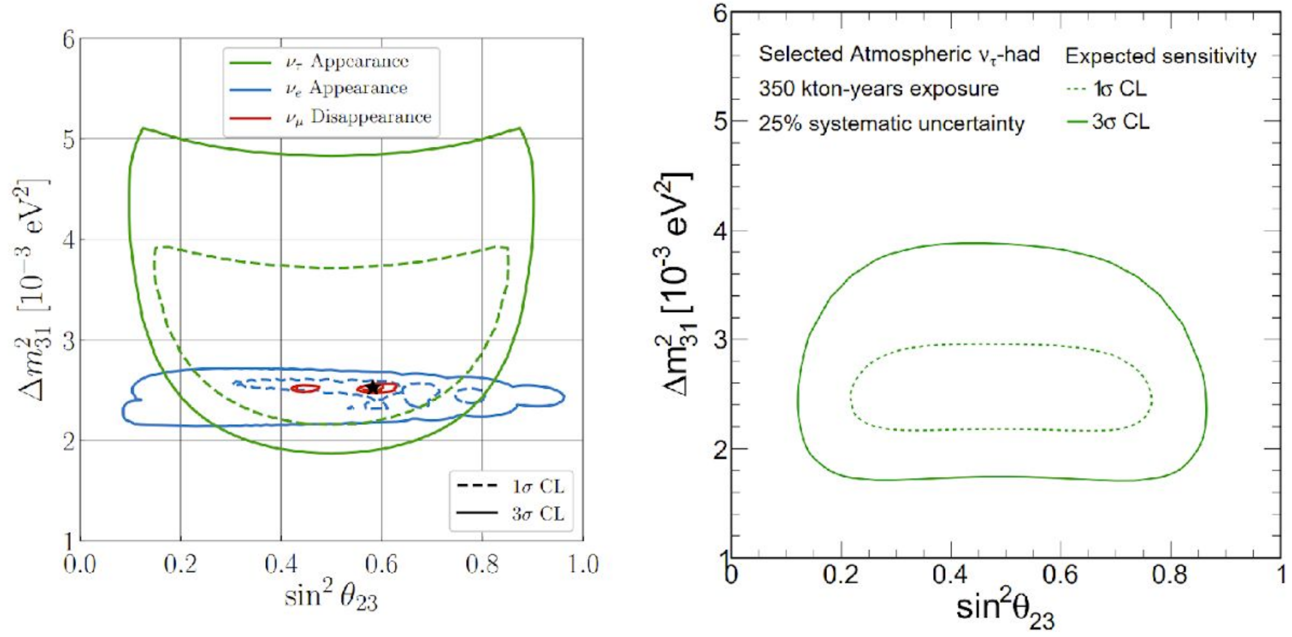


Figure 8.26: The 1σ (dashed) and 3σ (solid) expected sensitivity for measuring Δm^2_{31} and $\sin^2\theta_{23}$ using a variety of samples. Left: The expected sensitivity for seven years of beam data collection, assuming 3.5 years each in neutrino and antineutrino modes, measured independently using ν_e appearance (blue), ν_μ disappearance (red), and ν_τ appearance (green). Adapted from Ref. [498]. Right: The expected sensitivity for the ν_τ appearance channel using 350 kton-years of atmospheric exposure.

Proton Decay

- The 90% CL limit of a bound neutron lifetime is 6.45×10^{32} years for a 400 kt · year exposure. The corresponding limit for the oscillation time of free neutrons is calculated to be 5.53×10^{8} s. This is approximately an improvement by a factor of two from the current best limit, which comes from Super–Kamiokande

- With a 30% signal efficiency and an expected background of one event per Mt · year , a 90% CL lower limit on the proton lifetime in the $p \rightarrow K^{+}\nu$ channel of 1.3×10^{34} years can be set, assuming no signal is observed over ten years of running with a total of 40 kt of fiducial mass. This calculation assumes constant signal efficiency and background rejection over time and for each of the FD modules.

(from TDR)

Dark Matter

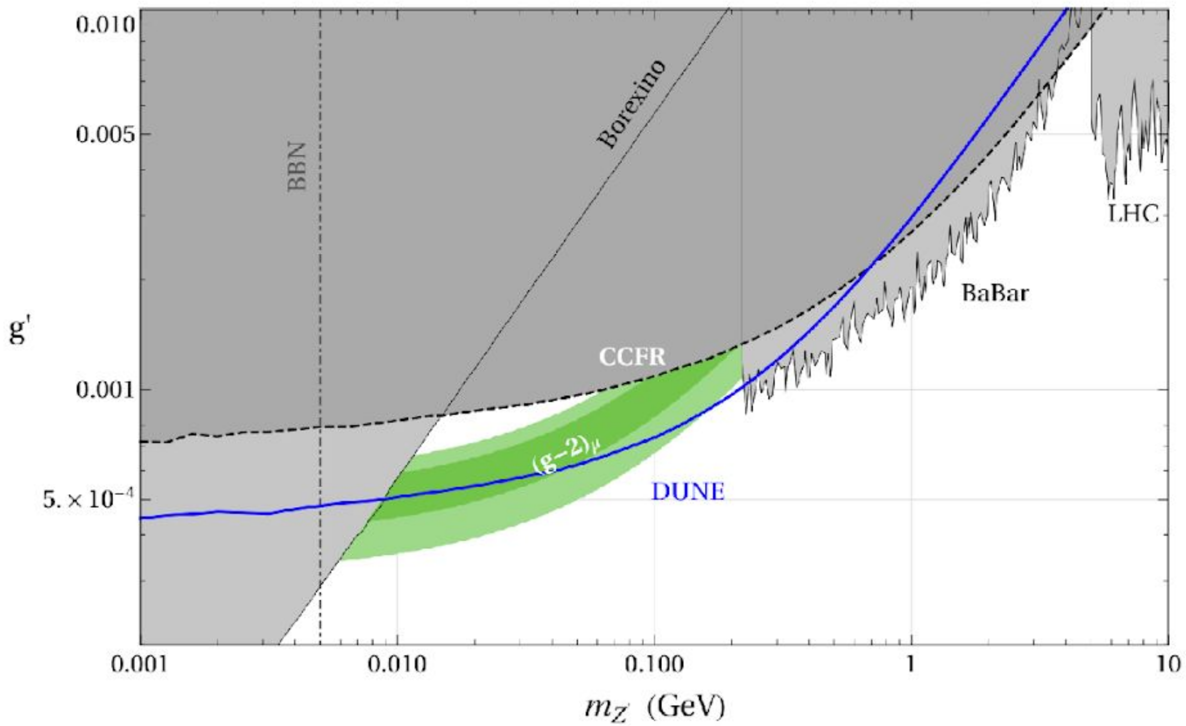


Figure 8.15: Existing constraints and projected DUNE sensitivity in the $L_\mu - L_\tau$ parameter space. Shown in green is the region where the $(g-2)_\mu$ anomaly can be explained at the 2σ level. The parameter regions already excluded by existing constraints are shaded in gray and correspond to a CMS search for $pp \to \mu^+\mu^- Z' \to \mu^+\mu^-\mu^+\mu^-$ [444] ("LHC"), a BaBar search for $e^+e^- \to \mu^+\mu^- Z' \to \mu^+\mu^-\mu^+\mu^-$ [445] ("BaBar"), precision measurements of $Z \to \ell^+\ell^-$ and $Z \to \nu\bar{\nu}$ couplings [446, 441] ("LEP"), a previous measurement of the trident cross section [434, 436] ("CCFR"), a measurement of the scattering rate of solar neutrinos on electrons [447, 448, 449] ("Borexino"), and bounds from big bang nucleosynthesis [450, 451] ("BBN"). The DUNE sensitivity shown by the solid blue line assumes a measurement of the trident cross section with 40% precision.

BSM Simulation Assumptions

•

Energy (GeV)	Beam Power (MW)	Uptime Fraction	POT/year
120	1.2	0.56	1.1×10^{21}

Table 8.2: ND properties used in the BSM physics analyses.

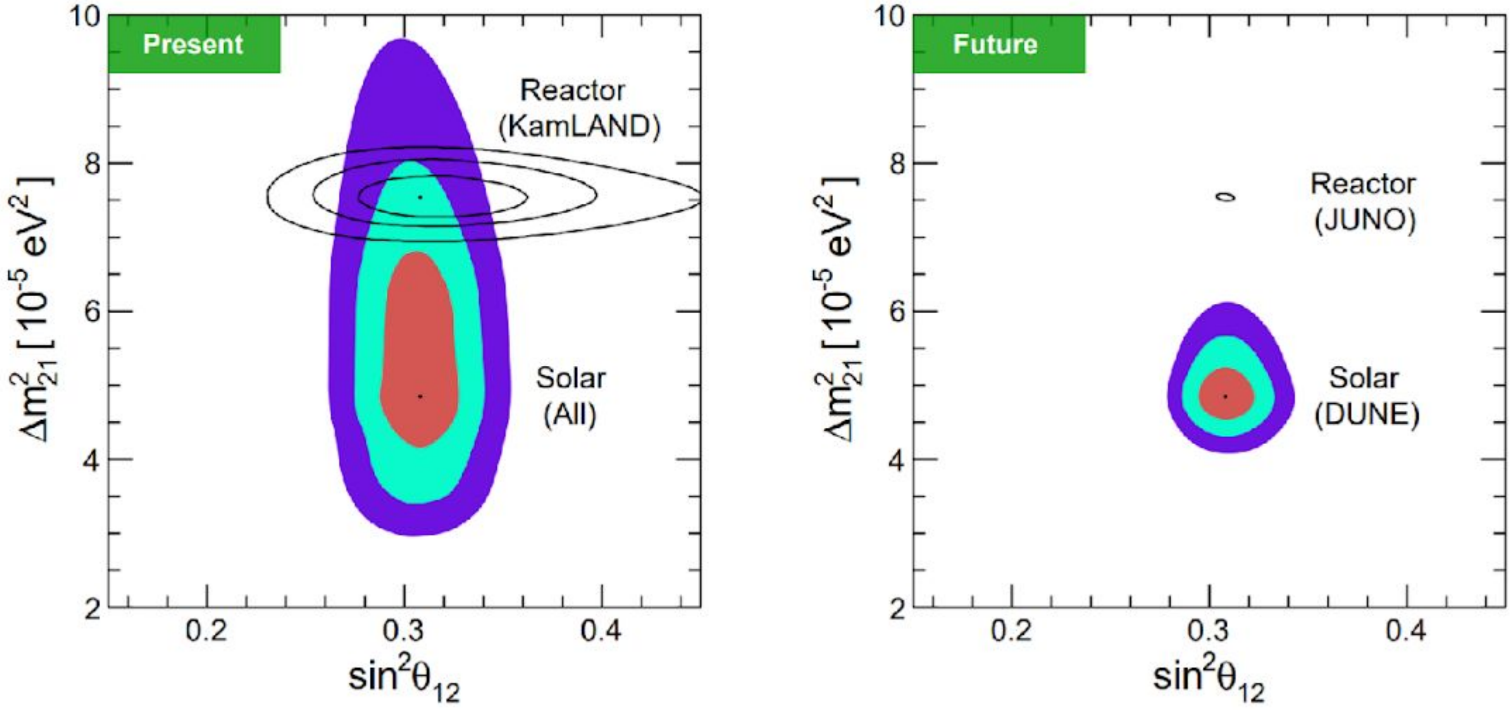
ND Properties	Values
Dimensions	7 m wide, 3 m high, and 5 m long
Dimensions of fiducial volume	6 m wide, 2 m high, and 4 m long
Total mass	147 ton
Fiducial mass	67.2 ton
Distance from target	574 m

Table 8.3: FD properties used in the BSM physics analyses.

Particle Type	Threshold	Energy Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained track: track length	1^o
$e^{\pm}$	30 MeV	2%	1^o
$\pi^{\pm}$	100 MeV	30%	5^o

DUNE as the Next-Generation Solar Neutrino Experiment

- https://arxiv.org/pdf/1808.08232.pdf



From DUNE Physics TDR

Parameter	Central Value	Relative Uncertainty
θ_{12}	0.5903	2.3%
θ_{23} (NO)	0.866	4.1%
θ_{23} (IO)	0.869	4.0%
θ_{13} (NO)	0.150	1.5%
θ_{13} (IO)	0.151	1.5%
Δm^2_{21}	7.39×10^{-5} eV^2	2.8%
Δm^2_{32} (NO)	2.451×10^{-3} eV^2	1.3%
Δm^2_{32} (IO)	-2.512×10^{-3} eV^2	1.3%

Table 5.1: Central value and relative uncertainty of neutrino oscillation parameters from a global fit [2, 3] to neutrino oscillation data. Because the probability distributions are somewhat non-Gaussian (particularly for θ_{23}), the relative uncertainty is computed using 1/6 of the 3σ allowed range from the fit, rather than the 1σ range. For θ_{23}, θ_{13}, and Δm^2_{31}, the best-fit values and uncertainties depend on whether normal mass ordering (NO) or inverted mass ordering (IO) is assumed.

x_P	Description of P	P_{cv}	$\delta P/P$
	Quasielastic		
$x^{CCQE}_{M_A}$	Axial mass for CCQE		$^{+0.25}_{-0.15}$ GeV
x^{CCQE}_{VecFF}	Choice of CCQE vector form factors (BBA05 $\leftrightarrow$ Dipole)		N/A
x^{CCQE}_{kF}	Fermi surface momentum for Pauli blocking		$\pm$30%
	Low W		
$x^{CCRES}_{M_A}$	Axial mass for CC resonance	0.94	$\pm$0.05 GeV
$x^{CCRES}_{M_V}$	Vector mass for CC resonance		$\pm$10%
$x^{\Delta Decay}_{\eta\ BR}$	Branching ratio for $\Delta \to \eta$ decay		$\pm$50%
$x^{\Delta Decay}_{\gamma\ BR}$	Branching ratio for $\Delta \to \gamma$ decay		$\pm$50%
$x_{\theta_\pi^{\Delta Decay}}$	θ_π distribution in decaying Δ rest frame (isotropic $\to$ RS)		N/A
	High W		
$x^{DIS}_{A^{BY}_{HT}}$	A_{HT} higher-twist param in BY model scaling variable ξ_w		$\pm$25%
$x^{DIS}_{B^{BY}_{HT}}$	B_{HT} higher-twist param in BY model scaling variable ξ_w		$\pm$25%
$x^{DIS}_{C^{BY}_{V1u}}$	C_{V1u} valence GRV98 PDF correction param in BY model		$\pm$30%
$x^{DIS}_{C^{BY}_{V2u}}$	C_{V2u} valence GRV98 PDF correction param in BY model		$\pm$40%
	Other neutral current		
$x^{NCEL}_{M_A}$	Axial mass for NC elastic		$\pm$25%
x^{NCEL}_{η}	Strange axial form factor η for NC elastic		$\pm$30%
$x^{NCRES}_{M_A}$	Axial mass for NC resonance		$\pm$10%
$x^{NCRES}_{M_V}$	Vector mass for NC resonance		$\pm$5%
	Misc.		
x_{FZ}	Vary effective formation zone length		$\pm$50%

Table 5.4: Neutrino interaction cross-section systematic parameters considered in GENIE. GENIE default central values and uncertainties are used for all parameters except $x^{CCRES}_{M_A}$. Missing GENIE parameters were omitted where uncertainties developed for this analysis significantly overlap with the supplied GENIE freedom, the response calculation was too slow, or the variations were deemed unphysical.

level NSI. The distinction is that at the Hamiltonian level the strength of the NSI is given relative to the electron number density which controls the standard matter effect. These two are related via,

$$\varepsilon_{\alpha\beta} = \sum_{f\in\{e,u,d\}} \left\langle \frac{N_f(x)}{N_e(x)} \right\rangle \varepsilon_{\alpha\beta}^{f,V} \,, \tag{1.5}$$

where $N_f(x)$ is the number density of fermion f at position x, and the Lorentz structure is typically taken to mean vector in the context of oscillation experiments unless otherwise