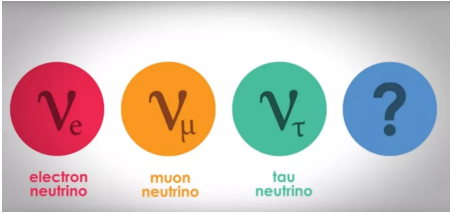
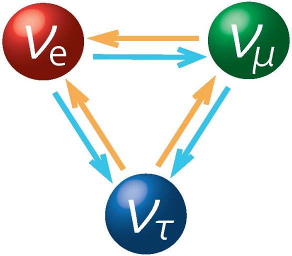
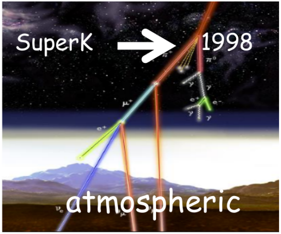
An Altarelli Cocktail for the MiniBooNE Anomaly?

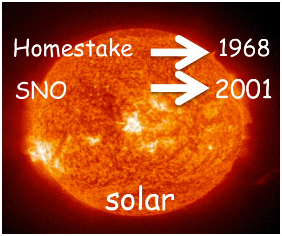


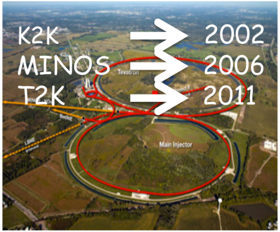


Vedran Brdar (CERN–TH)

Neutrino Oscillations

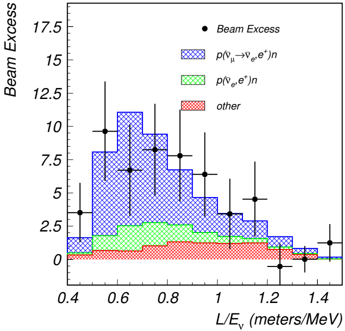


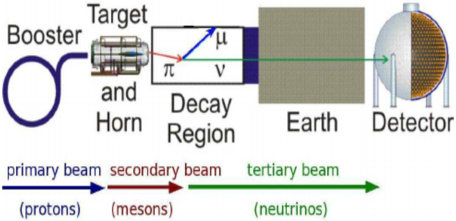




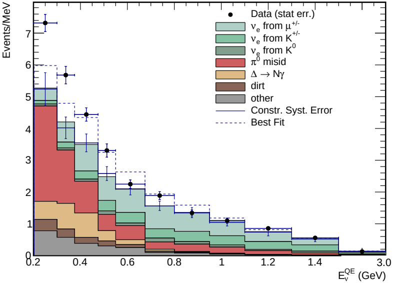
$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Anomalies: LSND and MiniBooNE





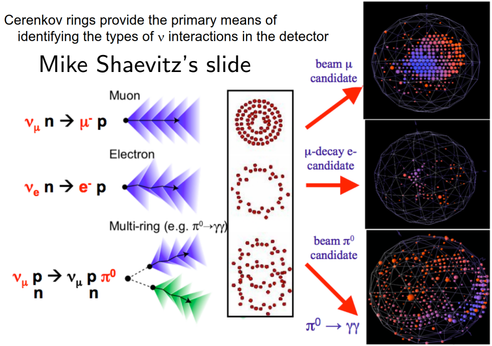
- LSND: $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$) at $L/E \sim 1\text{km GeV}^{-1}$
- MiniBooNE: reports electron-like event excess (4.8σ)
- in combination with LSND 6.1σ

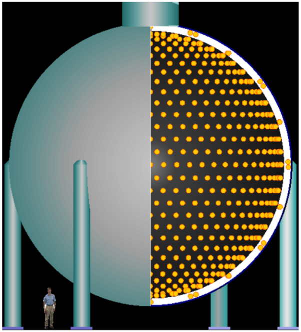


Main Channels for MiniBooNE

- shower events can be produced by e, γ, collimated e^+e^- and $\gamma\gamma$
- in SM, majority of events relevant for MiniBooNE excess arise from

1) CC ν_e events, 2) NC π^0 production, 3) NC γ from e.g. $\Delta(1232)$





arXiv.org > hep-ph > arXiv:2109.08157

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High Energy Physics - Phenomenology

[Submitted on 16 Sep 2021]

An Altarelli Cocktail for the MiniBooNE Anomaly?

Vedran Brdar (Fermilab and Northwestern U), Joachim Kopp (CERN and JGU Mainz)

We critically examine a number of theoretical uncertainties affecting the MiniBooNE short-baseline neutrino oscillation experiment in an attempt to better understand the observed excess of electron-like events. We re-examine the impact of fake charged current quasi-elastic (CCQE) events, the background due to neutral current π^0 production, and the single-photon background. For all processes, we compare the predictions of different event generators (GENIE, GiBUU, NUANCE, and NuWro) and, for GENIE, of different tunes. Where MiniBooNE uses data-driven background predictions, we discuss the uncertainties affecting the relation between the signal sample and the control sample. In the case of the single-photon background, we emphasize the large uncertainties in the radiative branching ratios of heavy hadronic resonances. We find that not even a combination of uncertainties in different channels adding up unfavorably (an "Altarelli cocktail") appears to be sufficient to resolve the MiniBooNE anomaly. Varying the radiative branching ratios of the $\Delta(1232)$ and $N(1440)$ resonances by $\pm 2\sigma$, however, reduces its significance from 4σ to less than 3σ. We finally investigate how modified background predictions affect the fit of a 3+1 sterile neutrino scenario. We carefully account for full four-flavor oscillations not only in the signal, but also in the background and control samples. We emphasize that because of the strong correlation between MiniBooNE's ν_e and ν_μ samples, a sterile neutrino mixing only with ν_μ is sufficient to explain the anomaly, even though the well-known tension with external constraints on ν_μ disappearance persists.

Comments:	25 pages, 10 figures, 2 tables, analysis codes available at this https URL
Subjects:	**High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)
Report number:	CERN-TH-2021-131, FERMILAB-PUB-21-450-T, MITP-21-042, NUHEP-TH/21-14
Cite as:	arXiv:2109.08157 **[hep-ph]**
	(or arXiv:2109.08157v1 **[hep-ph]** for this version)

Employed MC Generators

Generator	Tune	Ref.	Comments
NUANCE	–	[40]	the generator used by MiniBooNE
GiBUU	–	[42]	theory-driven generator
NuWro	–	[41]	
GENIE	G18_01a_02_11a	[39, 44]	GENIE baseline tune; see [44] for naming conventions
	G18_01b_02_11a		different FSI implementation compared to G18_01a_02_11a
	G18_02a_02_11a		updated res./coh. scattering models compared to G18_01a_02_11a
	G18_02b_02_11a		updated res./coh. scattering models and different FSI
	G18_10a_02_11a		theory-driven configuration; similar to G18_02a
	G18_10b_02_11a		theory-driven configuration; similar to G18_02b

Strategy

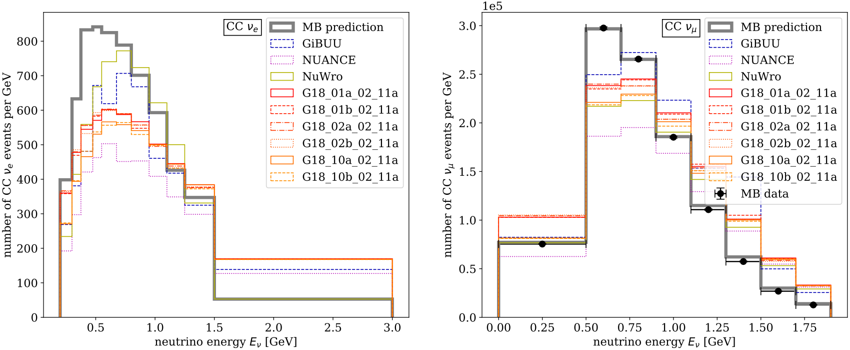
1. From a Monte Carlo simulation using the NUANCE generator, we predict the event sample under consideration.

2. The predicted event spectrum from (1) is then compared with the corresponding prediction obtained by the MiniBooNE collaboration; the differences are compensated by bin-by-bin tuning.

3. We then predict the same event sample using GiBUU, NuWro, as well as six different GENIE tunes, using the same cuts and efficiency factors as for NUANCE. We then apply the tuning factors determined in (2) as the ratio between our NUANCE prediction and MiniBooNE's.

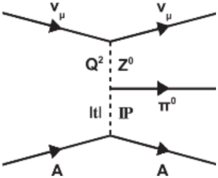
Charged Current Events

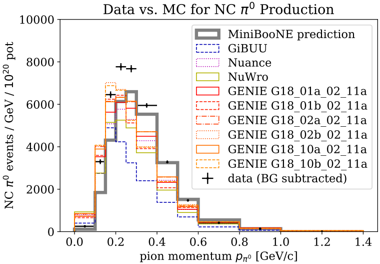
$$\nu_{e,\mu} + n \to e^- / \mu^- + p \qquad E_\nu = \frac{2m'_n E_\ell - (m'^2_n + m^2_\ell - m^2_p)}{2[m'_n - E_\ell + \sqrt{E^2_\ell - m^2_\ell}\cos\theta_\ell\,]}$$

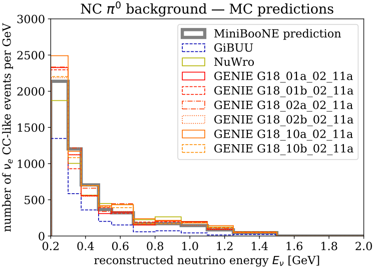


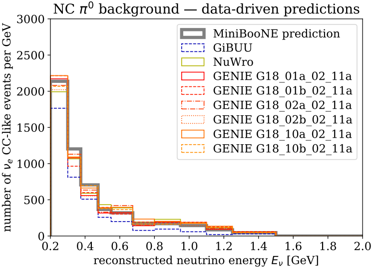
Neutral Current π^0 Production

$$\nu + N \to \nu + N + \pi^0(\gamma\gamma)$$



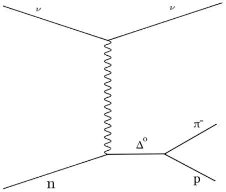


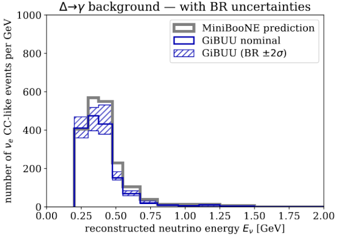


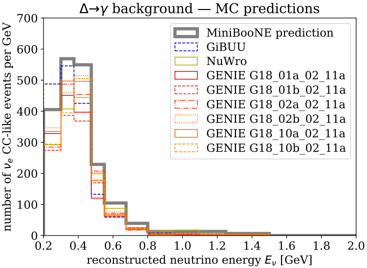


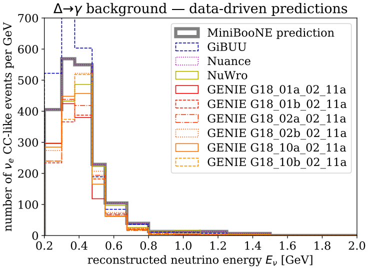
Neutral Current Single γ Production

$\Delta \to N\gamma$





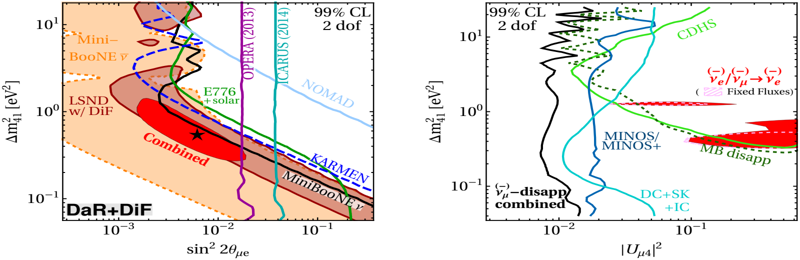




eV-scale ν_s for LSND and MiniBooNE Anomalies?

- Oscillation maxima for standard oscillations expected at
  - $L/E \sim 500$ km/GeV (from $\Delta m^2_{31} \sim 2.4 \times 10^{-3}\text{eV}^2$)
  - $L/E \sim 15000$ km/GeV (from $\Delta m^2_{21} \sim 7.5 \times 10^{-5}\text{eV}^2$)
- the minimal solution for LSND and MiniBooNE requires an additional mass squared difference $\Delta m^2_{41} \sim 1\,\text{eV}^2$; this calls for an introduction of eV-scale sterile neutrino (3+1 scheme)

Kopp et al., arXiv:1803.10661



- while ν_e appearance data supports eV-scale ν_s explanation of LSND and MiniBooNE, ν_μ disappearance data puts such solution in strong tension

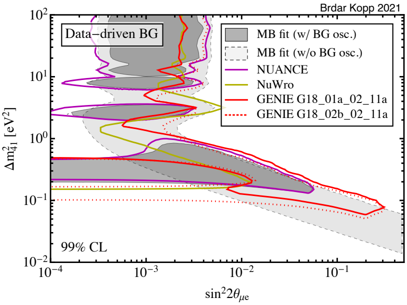
3+1 Model with eV-scale Sterile Neutrino

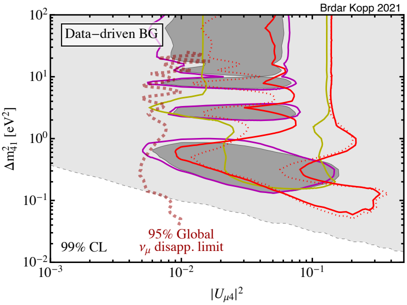
$$U^{4\text{flavor}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$P_{\mu\mu} = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$

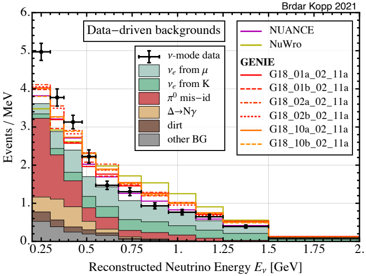
$$P_{\mu e} = 4|U_{\mu 4} U_{e4}|^2 \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 |U_{\mu 4}|^2$$





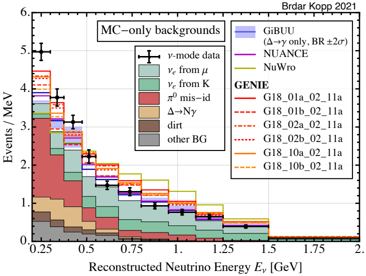
Results



data-driven backgrounds

Generator	Tune	Δm^2_{41}	$\sin^2 2\theta_{\mu e}$	$\lvert U_{\mu 4}\rvert^2$	χ^2/dof	$\Delta\chi^2_{\text{no osc.}}$	Significance
MB official		0.25	0.01	0.062	12.0	19.1	4.0σ
NUANCE	–	0.32	0.0079	0.051	12.3	19.3	4.0σ
NuWro	–	3.2	0.0016	0.040	13.3	12.7	3.1σ
GENIE	G18_01a_02_11a	0.79	0.00020	0.14	12.2	23.3	4.4σ
	G18_01b_02_11a	0.79	0.0001	0.12	12.2	15.5	3.5σ
	G18_02a_02_11a	0.13	0.063	0.18	12.2	19.2	4.0σ
	G18_02b_02_11a	0.13	0.050	0.20	12.3	16.9	3.7σ
	G18_10a_02_11a	0.25	0.016	0.062	12.3	15.1	3.5σ
	G18_10b_02_11a	0.40	0.013	0.016	12.1	19.5	4.0σ

Results



Monte Carlo-only background predictions

Generator	Tune	Δm^2_{41} [eV^2]	$\sin^2 2\theta_{\mu e}$	$\lvert U_{\mu 4}\rvert^2$	χ^2/dof	$\Delta\chi^2_{\text{no osc.}}$	Significance
MB official		0.25	0.01	0.062	12.0	19.1	4.0σ
GiBUU	default	0.25	0.01	0.076	12.0	24.6	4.6σ
	$\text{BR}(\Delta \to \gamma) - 2\sigma$	0.32	0.0063	0.076	12.2	28.5	5.0σ
	$\text{BR}(\Delta \to \gamma) + 2\sigma$	0.25	0.01	0.062	11.9	18.4	3.9σ
NUANCE	–	0.32	0.0079	0.051	12.3	19.3	4.0σ
NuWro	–	3.2	0.0020	0.040	13.7	15.6	3.5σ
GENIE	G18_01a_02_11a	0.13	0.079	0.16	12.2	21.6	4.3σ
	G18_01b_02_11a	0.79	0.0001	0.12	12.2	16.1	3.6σ
	G18_02a_02_11a	0.13	0.050	0.16	12.0	15.1	3.5σ
	G18_02b_02_11a	0.13	0.050	0.18	12.1	15.0	3.5σ
	G18_10a_02_11a	0.25	0.016	0.051	12.1	11.2	2.9σ
	G18_10b_02_11a	0.40	0.013	0.016	12.1	17.9	3.8σ

More SM ingredients for the cocktail?

More Ingredients for an Altarelli Cocktail at MiniBooNE

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(Dated: September 8, 2022)

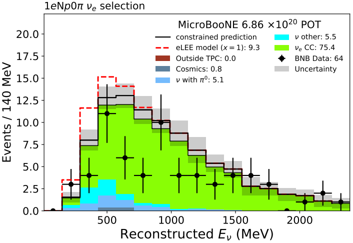
The MiniBooNE Low-Energy electron-neutrino-like Excess persists as one of the most significant puzzles in particle physics today, and remains the subject of intense experimental and theoretical focus. A key feature of this excess in MiniBooNE is the lack of ability to discriminate between electron-like signals and backgrounds from single-photons or pairs of overlapping and/or highly-asymmetric photons. In this work, we study these two background classes in depth, first considering a novel single-photon background arising from multi-nucleon scattering effects. This effect can explain $\sim$40 of the $\sim$560 neutrino-mode excess events observed by MiniBooNE. Second, we consider the backgrounds in MiniBooNE from neutral-current single-pion scattering, where the two photons from $\pi^0 \to \gamma\gamma$ decay are mis-identified as an electron-like shower. We find two significant effects when comparing our results to those of MiniBooNE, stemming from limited Monte Carlo statistics and in comparing different neutrino-scattering Monte Carlo generators. In tandem, we demonstrate that, when combining all effects, the significance of the MiniBooNE neutrino-mode low-energy excess is reduced from 4.7σ to between 2.6 and 3.5σ.

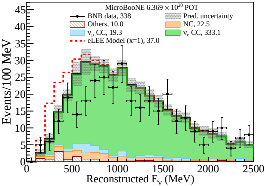
First Results from MicroBooNE

two-body ν_e CCQE scattering (1e1p)

pionless ν_e scattering ($1eNp0\pi$, $1e0p0\pi$)

inclusive ν_e scattering ($1eX$)





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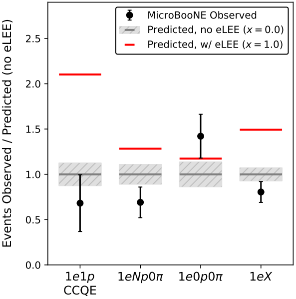
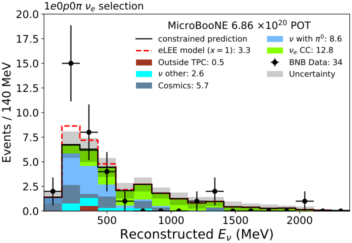




First Results from MicroBooNE

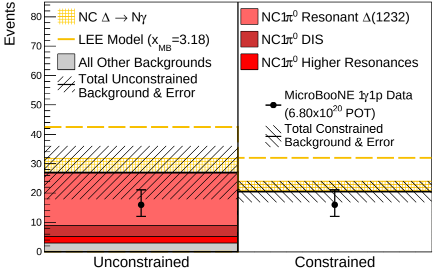
arXiv:2110.00409

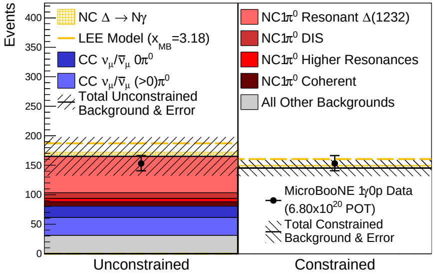
$1\gamma 1p$

$1\gamma 0p$

	$1\gamma 1p$	$1\gamma 0p$
Unconstr. bkgd.	27.0 ± 8.1	165.4 ± 31.7
Constr. bkgd.	20.5 ± 3.6	145.1 ± 13.8
NC $\Delta \to N\gamma$	4.88	6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	15.5	20.1
Data	16	153

Process	$1\gamma 1p$	$1\gamma 0p$
NC $1\pi^0$ Non-Coherent	24.0	68.1
NC $1\pi^0$ Coherent	0.0	7.6
CC ν_μ $1\pi^0$	0.5	14.0
CC ν_e and $\bar{\nu}_e$	0.4	11.1
BNB Other	2.1	18.1
Dirt (outside TPC)	0.0	36.4
Cosmic Ray Data	0.0	10.0
Total Background (Unconstr.)	27.0	165.4
NC $\Delta \to N\gamma$	4.88	6.55



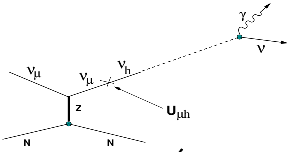


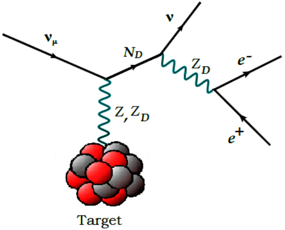
BSM ingredients for the cocktail?

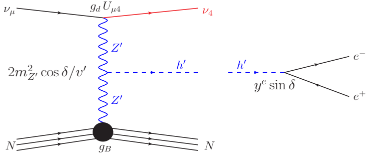
Non-oscillatory Explanations of MiniBooNE Anomaly

- 1 shower events can be produced by e, γ, collimated e^+e^- and $\gamma\gamma$

Model	U. Signature	LSND	MB
3+1	Oscillations		
(3+1) + inv-ν decay	Damped oscillations		
(3+1) + NSI	Modified matter effects		
Anomalous matter	Resonant appearance		
Large extra dim	Osc with related freqs.		
LNV in μ decays	$\mu^+ \to$ anti-ν_e		
Lorentz violation	Sidereal time variation		
Dark neutrinos	Upscattering to $N \to \nu\, e^+e^-$		
Dipole portal	Upscattering to $N \to \nu\, \gamma$		
(3+1) + vis-ν decay	DIF of $\nu_s \to \nu_e$		
(3+1) + vis decay	DIF of $N \to \nu\, \gamma$		
Dark sectors: dark matter	Upscattering to $\chi' \to \chi\, e^+e^-$		
Dark sectors: (pseudo)-scalar	Forward scattering to γ		



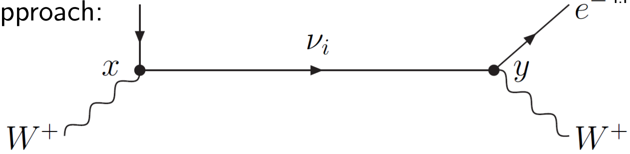




“Saving” eV-scale ν_s: Energy Dependent U_{PMNS}

M. Beuthe, arXiv:hep-ph/0109119
I.P. Volobuev, arXiv:1703.08070

QFT approach:



$$P_{\alpha\beta} = \sum_{j,k} U^*_{\alpha j}(Q^2) U_{\beta j}(Q^2) U_{\alpha k}(Q^2) U^*_{\beta k}(Q^2)\, e^{-i\frac{m_j^2(Q^2)-m_k^2(Q^2)}{2E}L}$$

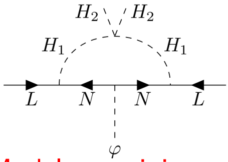
PRODUCTION: contribution to the amplitude should be Lorentz invariant; in the rest frame of decaying pion $E = m_\pi \to U_{\alpha i} = U_{\alpha i}(Q_p^2 = m_\pi^2)$

DETECTION: $U_{\beta i}(Q_d^2)$ where Q_d^2 has no dependence on m_π^2

PROPAGATION: neutrino is on shell $(Q^2 = p_\nu^2 = m_\nu^2 \approx 0)$
$\implies m_i$ in formula is the mass at $\sqrt{Q^2} = m_i$

Energy Dependent U_{PMNS}

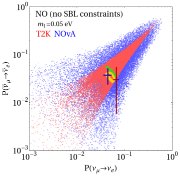
Babu, VB, de Gouvêa, Machado, PRD 2022



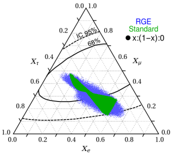
Model containing light new particles

$$\Longrightarrow \quad U(Q_p^2) \neq U(Q_d^2) \quad \Longrightarrow$$

Mismatch between PMNS matrix at Q_p^2 and Q_d^2



T2K
NOvA



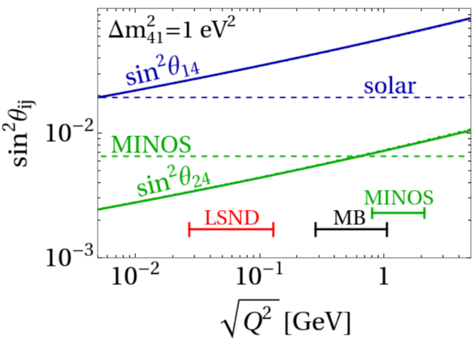
IceCube

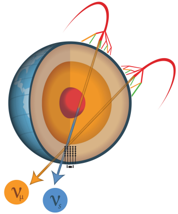
Energy Dependent $U_{\text{PMNS}}+\nu_s$ for Addressing Anomalies

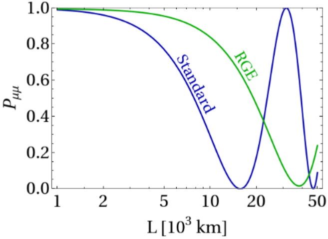
Babu, VB, de Gouvêa, Machado, arXiv:2209.00031

$\sin\theta_{14} = U_{14}$
$\sin\theta_{24}\cos\theta_{14} = U_{24}$

- $\tan\theta_{14} \simeq \frac{\mu_e}{M}$, $\tan\theta_{24} \simeq \frac{\mu_\mu}{M}$
- M decreases with energy if ν_s interacts with Z', like e^- mass in QED
- θ_{14} and θ_{24} increase with energy







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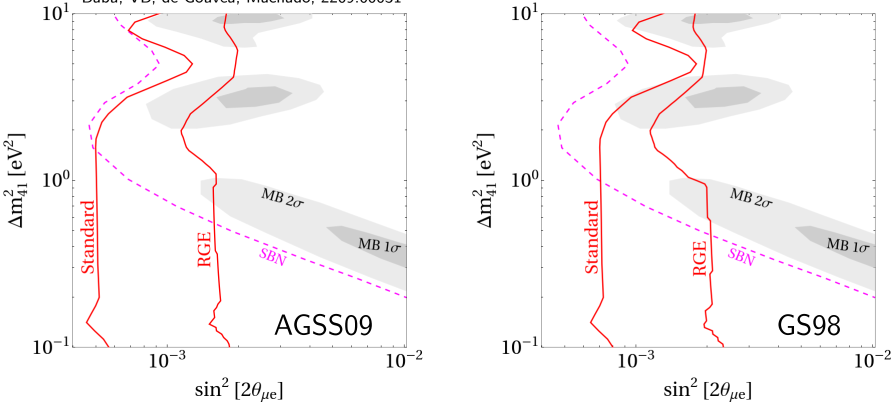

Summary

- MiniBooNE anomaly has been a mystery for over a decade
- Recent background reevaluations alleviated its significance but did not fully explain it
- Vanilla eV-scale sterile neutrino hypothesis is disfavored. Alternative models with heavier sub-GeV new physics? eV-scale sterile neutrino in energy dependent mixing angle picture?
- Bright Future: MiniBooNE $\rightarrow$ MicroBooNE, ICARUS, SBND