Seeking New Physics at Neutrino Oscillation Experiments

based on : Babu, VB, de Gouvea, Machado 2108.11961 (PRD 2022)
VB, Kopp 2109.08157 (PRD 2022)
Babu, VB, de Gouvea, Machado 22xx.xxxxx

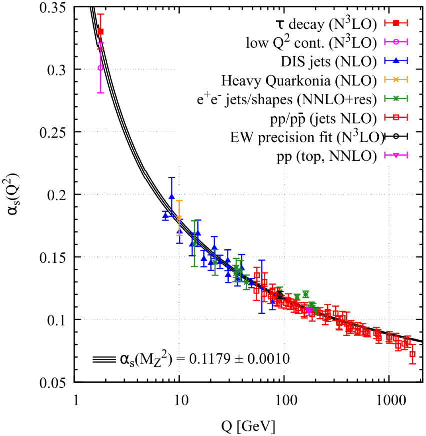
Vedran Brdar

Fermilab

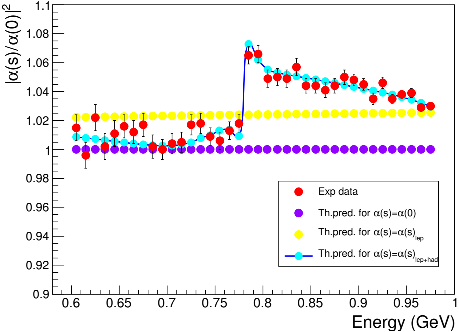
Northwestern University

Running Couplings

PDG



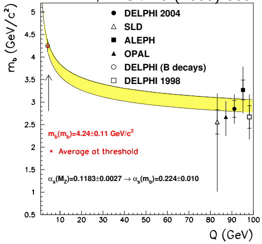
KLOE-2 collaboration, 1609.06631



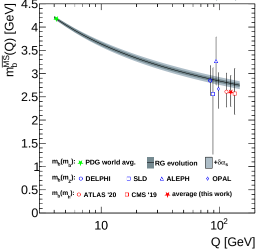
Further Examples for Running in SM

- parameters in the Standard Model and Beyond are energy dependent

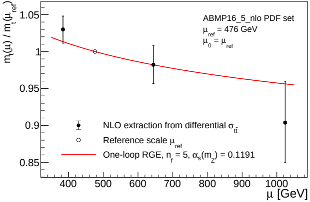
DELPHI, EPJC 46 (2006) 569



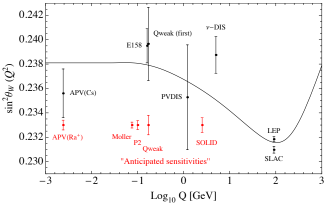
IFIC-UV/CSIC, PSI, U. Tohoku, U. Vienna (2021)



CMS PLB 803(2020)135263 35.9 fb^{-1} (13 TeV)



Davoudiasl et al., arXiv:1507.00352

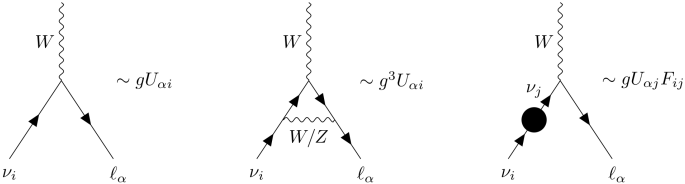


What about the Neutrino Sector?

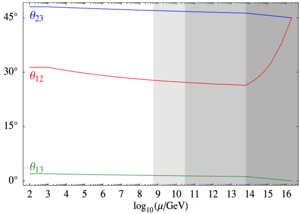
Energy Dependence of the PMNS Matrix

$$\nu_\alpha(Q^2) = U_{\alpha i}(Q^2)\nu_i$$

$\alpha = e, \mu, \tau$
$i, j = 1, 2, 3$



- when higher-order quantum effects are included, do $U_{\alpha i}$ matrix elements change relative to one another?
- higher-order electroweak corrections lead to very minor effects but in neutrino mass models $U_{\alpha i}$ can change in a flavor-dependent way

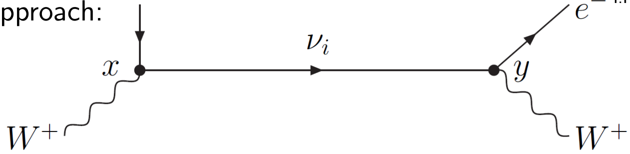


Balaji et al. (PLB 481 (2000))
Casas et al. (NPB 573 (2000))
Antusch et al. (JHEP 03 (2005) 024)
Goswami et al. (PRD 80 (2009))

Connection to Neutrino Experiments

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

QFT approach:



- amplitude: $\sum_i U^*_{\alpha i}\, e^{-i\frac{m_i^2 - p^2}{2|\vec{p}|}L}\, U_{\beta i} \to P_{\alpha\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\, e^{-i\frac{m_j^2 - m_k^2}{2|\vec{p}|}L}$

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 $(Q^2 = p_\nu^2 = m_\nu^2 \approx 0)$
$\Longrightarrow m_i$ in formula is the mass at $\sqrt{Q^2} = m_i$

Neutrino Oscillations in Vacuum

2 flavors:

$$U(Q^2) = \begin{pmatrix} \cos\theta(Q^2) & \sin\theta(Q^2) \\ -\sin\theta(Q^2) & \cos\theta(Q^2) \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\tilde{\beta}(Q^2)} \end{pmatrix}$$

$$\theta(Q_p^2) \equiv \theta_p, \quad \theta(Q_d^2) \equiv \theta_d, \quad \text{and} \quad \tilde{\beta}(Q_d^2) - \tilde{\beta}(Q_p^2) \equiv \beta$$

Grossman, PLB 359 (1995)

$$P_{\mu e} = \sin^2(\theta_p - \theta_d) + \sin 2\theta_p \sin 2\theta_d \sin^2\left(\frac{\Delta m^2 L}{4E} + \frac{\beta}{2}\right)$$

- β appears due to the CP-violating couplings in the new physics sector
- β "shifts" the oscillation phase: $\Delta m^2 L/2E \to \Delta m^2 L/2E + \beta$

3 flavors:

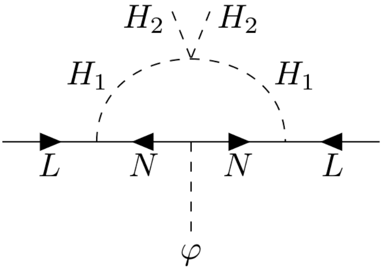
- CP-odd phases β, α, $\delta(Q_p^2)$, $\delta(Q_d^2)$

$$\epsilon_{ij} \equiv \theta_{ij}(Q_d^2) - \theta_{ij}(Q_p^2),\ \epsilon_\delta = \delta(Q_d^2) - \delta(Q_p^2),\ \epsilon_\alpha = \alpha,\ \epsilon_\beta = \beta \qquad \Delta_{ij} \equiv \Delta m_{ij}^2 L/2E$$

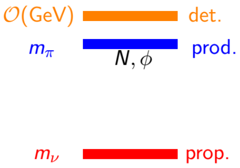
$$P_{\mu e} - P_{\bar{\mu}\bar{e}} \simeq -8\, J\, \Delta_{21} \sin^2\left(\frac{\Delta_{31}}{2}\right) \left[1 + \left(2\frac{\epsilon_{12}}{\sin 2\theta_{12}} + \epsilon_\alpha \frac{c_\delta}{s_\delta}\right) \frac{\cot(\Delta_{31}/2)}{\Delta_{21}}\right]$$

- in the $\delta \to 0$ limit, CP violation is present

The Model

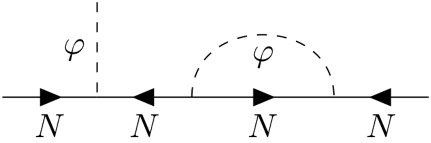


	$U(1)_L$	$\mathbb{Z}_2$
L	0	$+$
H_2	0	$+$
H_1	$+1$	$-$
N_R	$+1$	$-$
ϕ	-2	$+$



Scotogenic-like realization

$$-\mathcal{L}_\nu^{(1)} = \overline{L} Y_\nu \tilde{H}_1 N_R + \varphi \overline{N_R^c} Y_N N_R + \text{h.c.}$$



for $M_N^i = Y_N^i v_\varphi/\sqrt{2} \ll M_{H,A}$,

$$M_\nu \simeq \frac{v_\varphi}{16\sqrt{2}\pi^2} Y_\nu Y_N Y_\nu^T \ln \frac{M_H^2}{M_A^2}$$

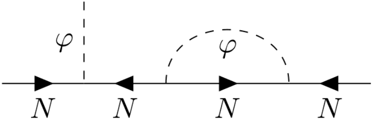
$$16\pi^2\beta(Y_N) \equiv 16\pi^2 \frac{dY_N}{d\ln|Q|} = 4Y_N\left[Y_N^2 + \frac{1}{2}\mathrm{Tr}(Y_N^2)\right]$$

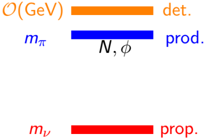
Strategy

$$H = \sum_i \frac{m_i^2}{2E}|\nu_i\rangle\langle\nu_i| + \sqrt{2}G_F N_e|\nu_e(Q^2=0)\rangle\langle\nu_e(Q^2=0)|$$

- at Q_p^2 scale mixing parameters are sampled using NuFIT values
- $Y_N \sim \mathcal{O}(1)$
- Y_ν is obtained using Casas-Ibarra parametrization

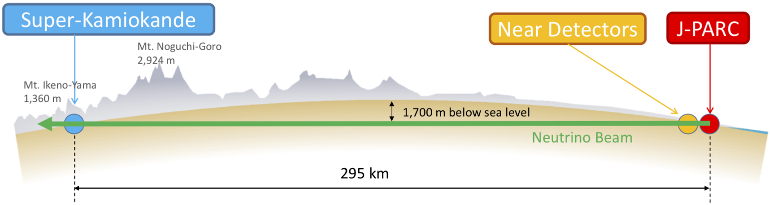
$$16\pi^2\beta(Y_N) \equiv 16\pi^2\frac{dY_N}{d\ln|Q|} = 4Y_N\left[Y_N^2 + \frac{1}{2}\mathrm{Tr}(Y_N^2)\right]$$

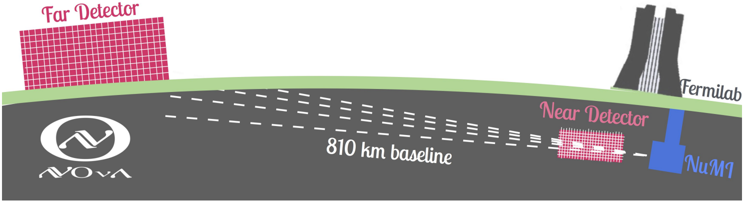




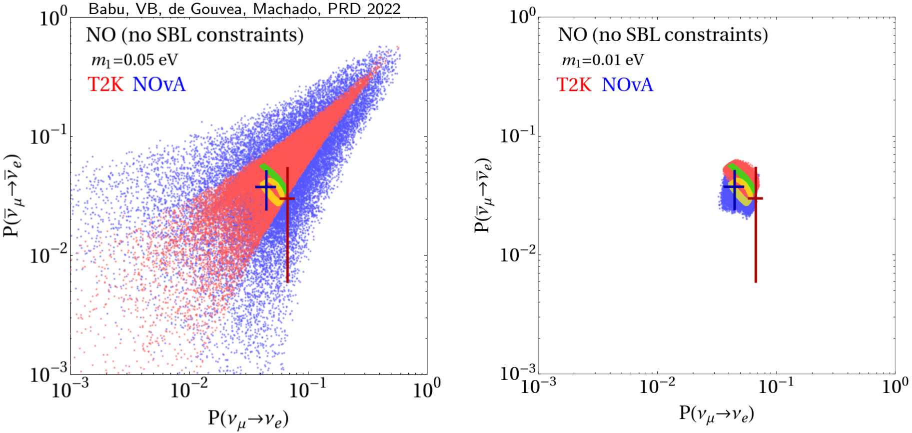
- at Q_d^2 scale, Y_N and hence $M_\nu(Q_d^2)$ is found
- diagonalize M_ν to get PMNS matrix at higher scale

Long-Baseline Experiments





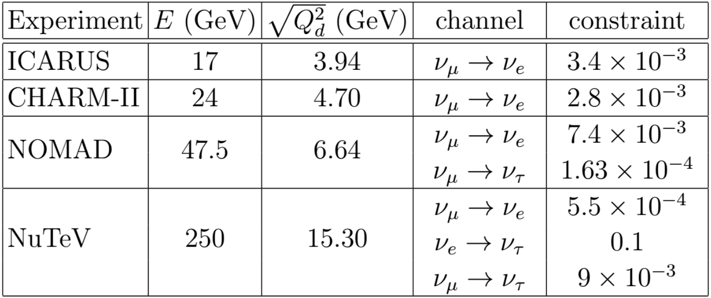
RGE Effect


Babu, VB, de Gouvea, Machado, PRD 2022
NO (no SBL constraints)
m_1=0.05 eV
T2K NOvA
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$P(\nu_\mu \to \nu_e)$
10^{0}
10^{-1}
10^{-2}
10^{-3}
NO (no SBL constraints)
m_1=0.01 eV
T2K NOvA

Constraints from Short Baseline Experiments

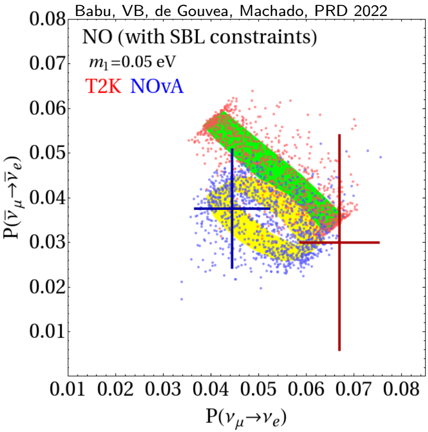
$$P_{\mu e} = \sin^2(\theta_p - \theta_d) + \sin 2\theta_p \sin 2\theta_d \sin^2\left(\frac{\Delta m^2 L}{4E} + \frac{\beta}{2}\right)$$

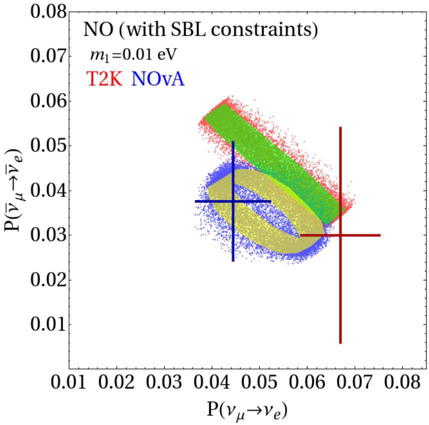
- experiments with high average neutrino energy are especially sensitive due to the larger difference between $Q_p^2 = m_\pi^2$ and Q_d^2
- while we found successful explanations or LSND and MiniBooNE, constraints from short baseline experiments rule out such possibilities



Experiment	E (GeV)	$\sqrt{Q_d^2}$ (GeV)	channel	constraint
ICARUS	17	3.94	$\nu_\mu \to \nu_e$	3.4×10^{-3}
CHARM-II	24	4.70	$\nu_\mu \to \nu_e$	2.8×10^{-3}
NOMAD	47.5	6.64	$\nu_\mu \to \nu_e$	7.4×10^{-3}
			$\nu_\mu \to \nu_\tau$	1.63×10^{-4}
NuTeV	250	15.30	$\nu_\mu \to \nu_e$	5.5×10^{-4}
			$\nu_e \to \nu_\tau$	0.1
			$\nu_\mu \to \nu_\tau$	9×10^{-3}

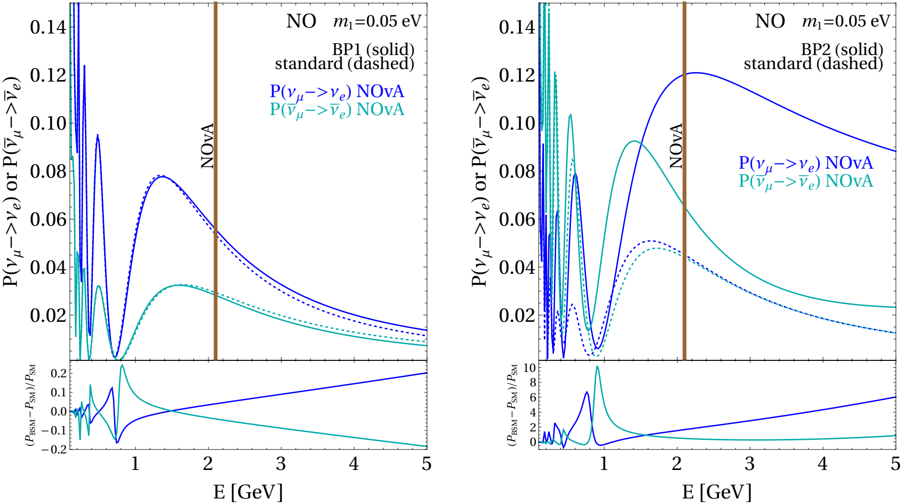
Constraints from Short Baseline Experiments





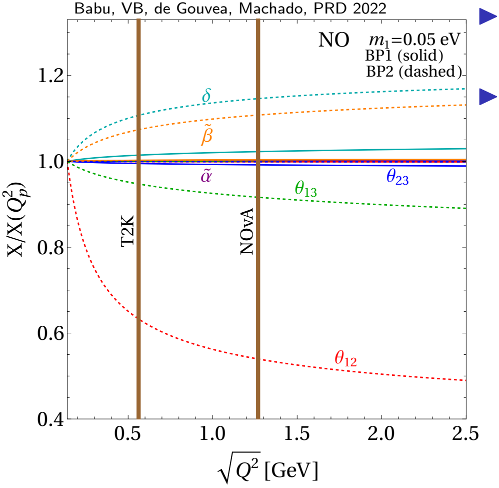
- short baseline constraints remove parameter points with strongest running

Oscillation Probabilities – NOvA

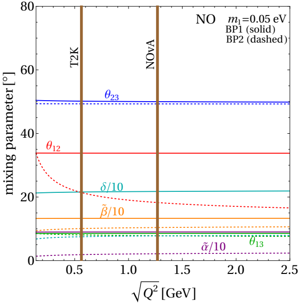


- BP1 best fits T2K and NOvA data and BP2 is strongly disfavoured by both short and long baseline experiments

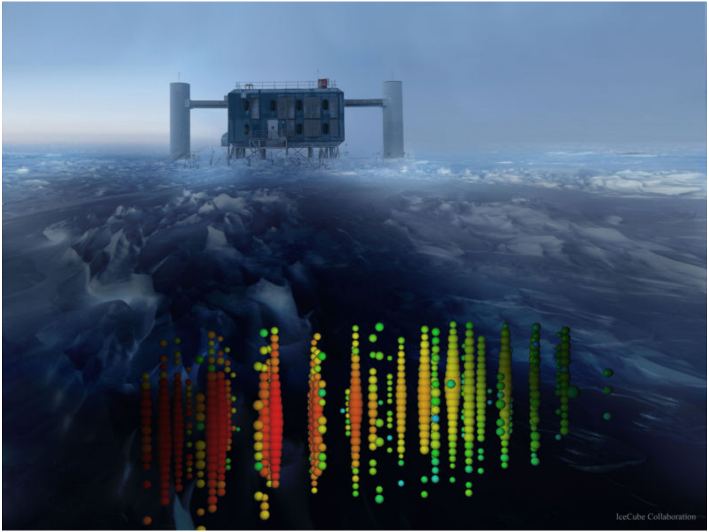
RG Evolution of the Mixing Parameters



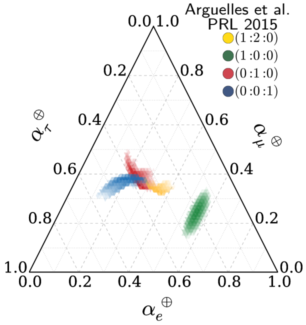
- the strongest effects are in running of θ_{12}
- variation of θ_{12} relative to the other mixing angles θ_{13} and θ_{23} is enhanced by $|\Delta\theta_{12}/\Delta\theta_{13}|$, $|\Delta\theta_{12}/\Delta\theta_{23}| \propto |\Delta m^2_{31}/\Delta m^2_{21}|$

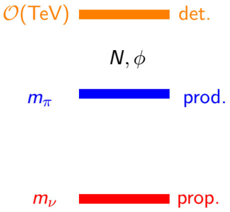


Ultra-High Energy Neutrinos



Ultra-High Energy Neutrinos - Flavor Ratios





$\mathcal{O}$(TeV) det.

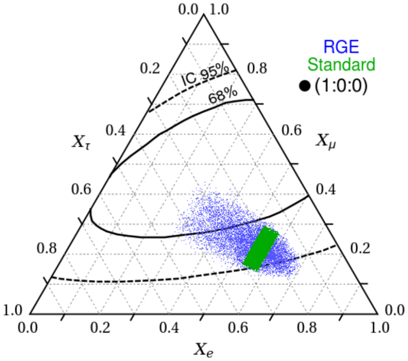
N, ϕ

m_π prod.

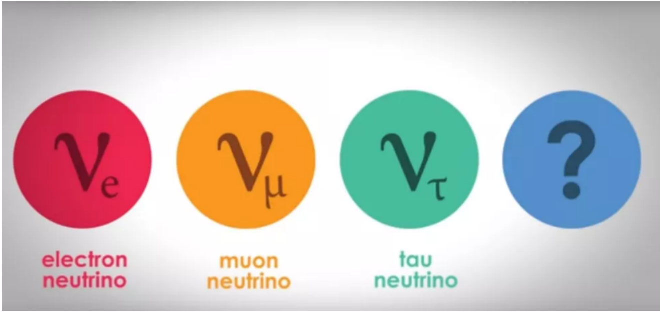
m_ν prop.

- detected neutrinos are incoherent superposition of mass eigenstates

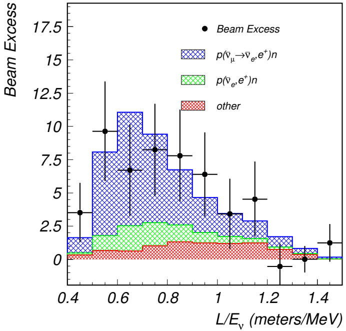
$$P_{\alpha\beta} = \sum_{j=1}^{3} \left|U_{\alpha j}(Q_p^2)\right|^2 \left|U_{\beta j}(Q_d^2)\right|^2$$

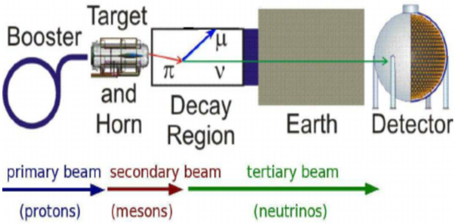


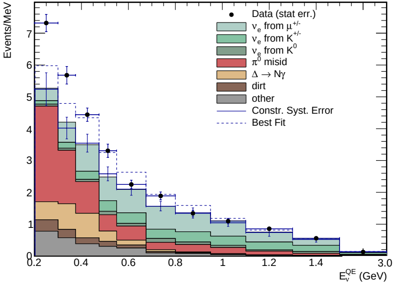
eV-Scale Sterile Neutrinos



LSND and MiniBooNE







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

Nuclear Physics Uncertainties?

- large nuclear and hadronic physics uncertainties in ν-nucleus scattering
- MiniBooNE used not-so-recent MC event generator for background studies

Genie

UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

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

NuWro

Wrocław Neutrino Event Generator

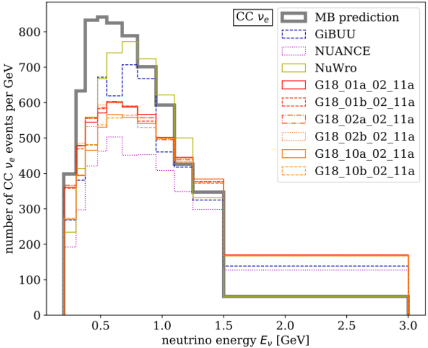
Relevant Channels

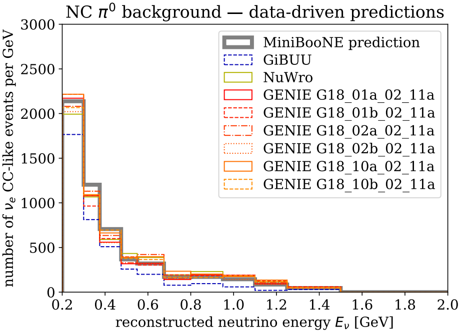
$$\nu_e + N \to e^- + N'$$

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

$$\nu + N \to \nu + \Delta \to \nu + N\gamma$$

VB, Kopp 2109.08157





3+1 model with eV-scale sterile neutrino

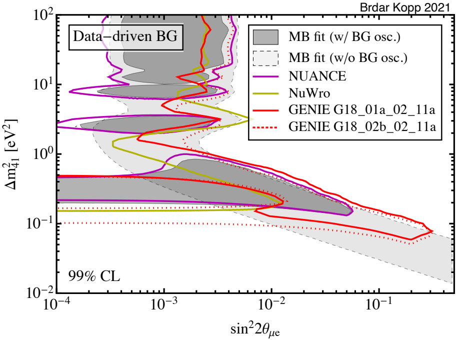
- $P_{\alpha\beta} \propto \sin^2(\Delta m^2_{41} L/E)$ → the minimal solution for LSND and MiniBooNE requires an additional mass squared difference of $\Delta m^2_{41} \sim 1\,\mathrm{eV}^2$

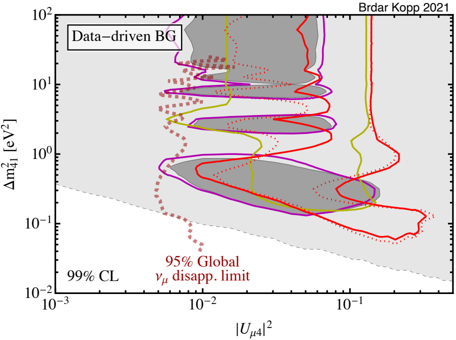
$$U^{\text{4flavor}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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

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

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

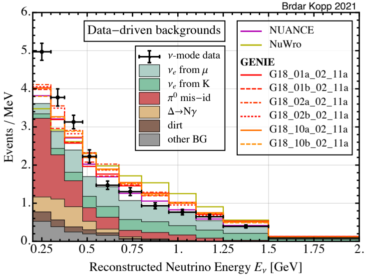




New Physics?

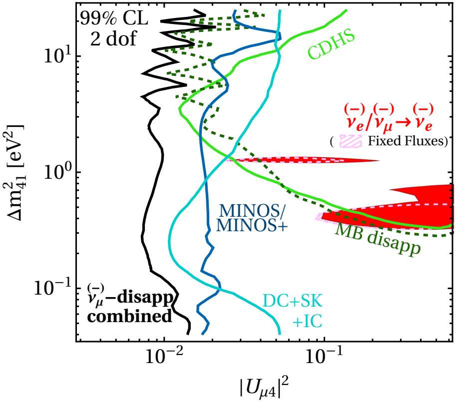
data-driven backgrounds

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

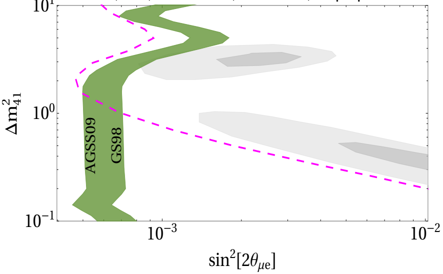


the tension when all the data is included is still present...

3+1 Tension

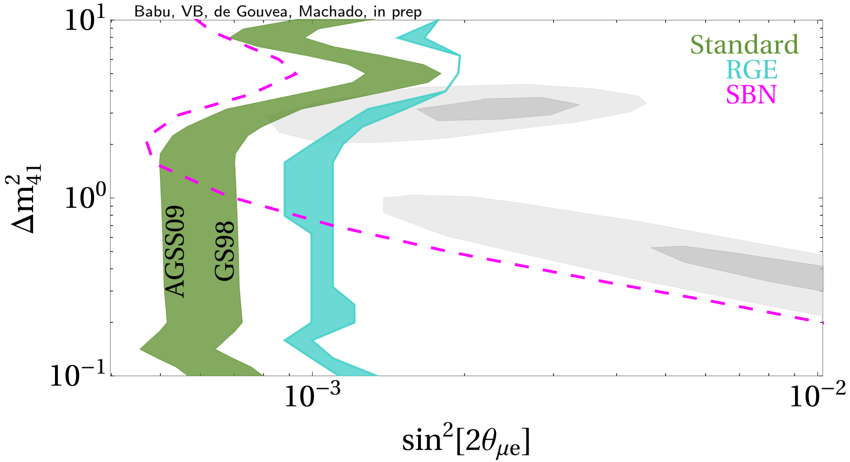

Dentler et al, arXiv:1803.10661

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu4}|^2$$


Babu, VB, de Gouvea, Machado, in prep

BSM^2: eV-scale Sterile+Running

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



Beyond 3+1, Non-Oscillatory Explanations

Evolving Theory Landscape

taken from MicroBooNE talks

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - [13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)
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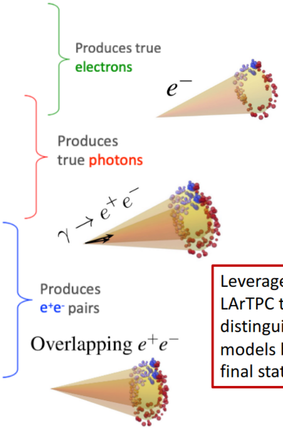

Leverage the power of LArTPC technology to distinguish between models based on exclusive final state topologies!

Summary

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- shown in this talk:
  (*i*) potentially observable effects at T2K and NOvA
  (*ii*) flavor composition of ultra-high energy neutrinos
  (*iii*) improvement in the 3+1 picture