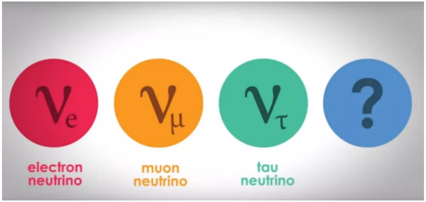
MiniBoone, MicroBoone and New Physics

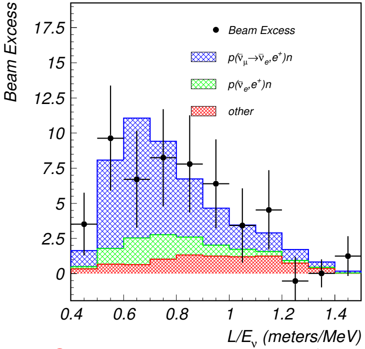


Vedran Brdar

Fermilab

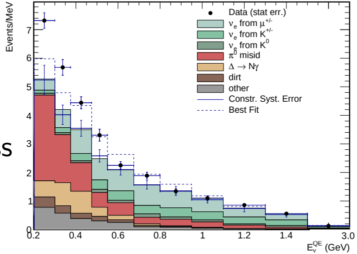
Northwestern University

LSND and MiniBooNE



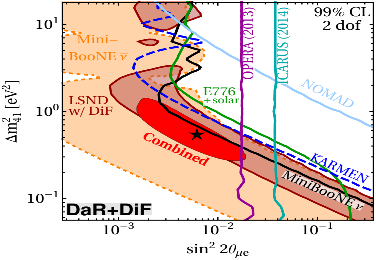
Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	107.6 $\pm$ 28.2	12.9 $\pm$ 4.3
NC π^0	732.3 $\pm$ 95.5	112.3 $\pm$ 11.5
NC $\Delta \to N\gamma$	251.9 $\pm$ 35.2	34.7 $\pm$ 5.4
External Events	109.8 $\pm$ 15.9	15.3 $\pm$ 2.8
Other ν_μ & $\bar{\nu}_\mu$	130.8 $\pm$ 33.4	22.3 $\pm$ 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	621.1 $\pm$ 146.3	91.4 $\pm$ 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	280.7 $\pm$ 61.2	51.2 $\pm$ 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	79.6 $\pm$ 29.9	51.4 $\pm$ 18.0
Other ν_e & $\bar{\nu}_e$	8.8 $\pm$ 4.7	6.7 $\pm$ 6.0
Unconstrained Bkgd.	2322.6 $\pm$ 258.3	398.2 $\pm$ 49.7
Constrained Bkgd.	2309.4 $\pm$ 119.6	400.6 $\pm$ 28.5
Total Data	2870	478
Excess	560.6 $\pm$ 119.6	77.4 $\pm$ 28.5

- LSND: $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$) at $L/E \sim 1\,\text{km}\,\text{GeV}^{-1}$ (arXiv:hep-ex/0104049)
- MiniBooNE: reports electron-like event excess (4.8σ); in combination with LSND at 6.1σ (arXiv:0812.2243, 1805.12028, 2006.16883)

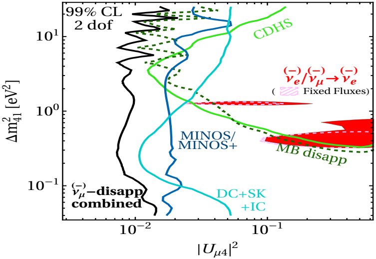


eV-scale ν_s for LSND and MiniBooNE anomalies?

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

Theoretical uncertainties?

arXiv.org > hep-ph > arXiv:2109.08157

Search...

Help | Advanced

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

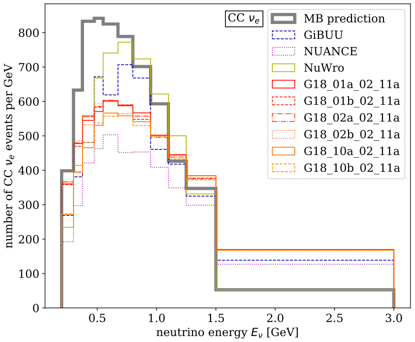
Generator	Tune	Ref.	Comments
NUANCE	–	[40]	the generator used by MiniBooNE
GiBUU	–	[42]	theory-driven generator
NuWro	–	[41]	
GENIE	G18_01a_02_11a	[39, 44]	GENIE baseline tune; see [44] for naming conventions
	G18_01b_02_11a		different FSI implementation compared to G18_01a_02_11a
	G18_02a_02_11a		updated 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

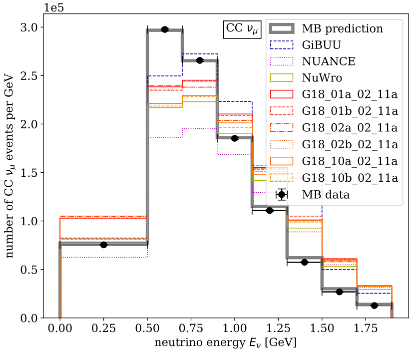
Strategy

1. From a Monte Carlo simulation using the NUANCE generator, predict the event sample under consideration.
2. The predicted event spectrum is then compared with the corresponding prediction obtained by the MiniBooNE collaboration; the differences are compensated by bin-by-bin tuning.
3. 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. Apply the tuning factors determined in previous step.

Charged Current Events

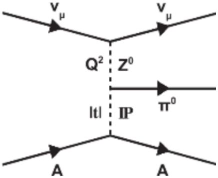
$$\nu_{e,\mu} + n \to e^- / \mu^- + p \qquad E_\nu = \frac{2m'_n E_\ell - (m'^2_n + m^2_\ell - m^2_p)}{2[m'_n - E_\ell + \sqrt{E^2_\ell - m^2_\ell}\cos\theta_\ell\,]}$$

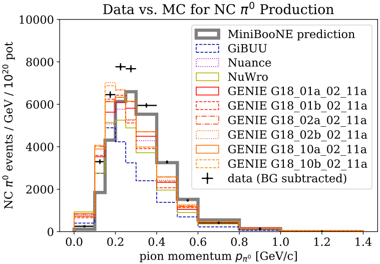


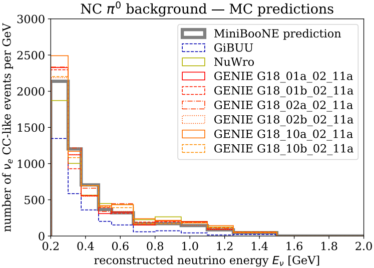


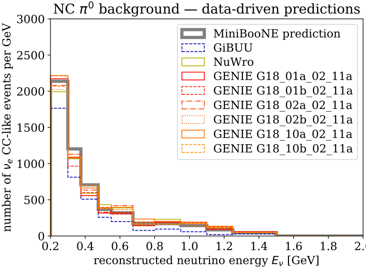
Neutral Current π^0 Production

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



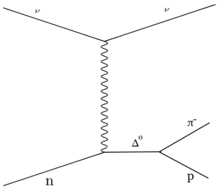


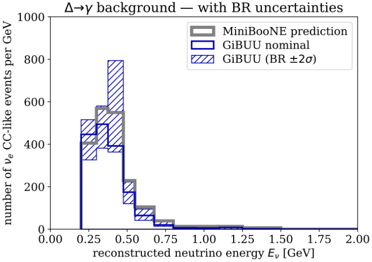


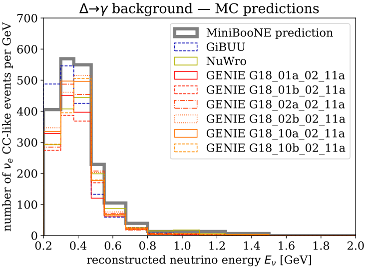


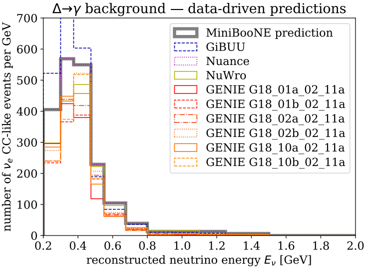
Neutral Current Single γ Production

$\Delta \to N\gamma$









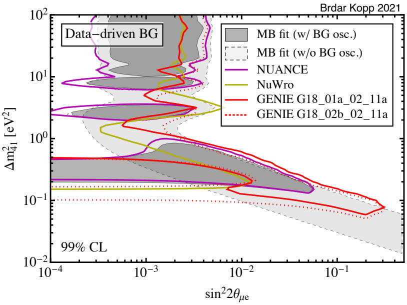
3+1 model with eV-scale sterile neutrino

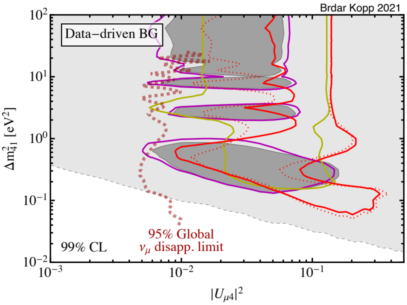
$$U^{4\text{flavor}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$P_{\mu\mu} = 1 - 4|U_{\mu4}|^2(1 - |U_{\mu4}|^2) \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$

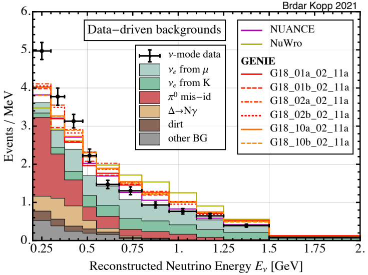
$$P_{\mu e} = 4|U_{\mu4}U_{e4}|^2 \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$

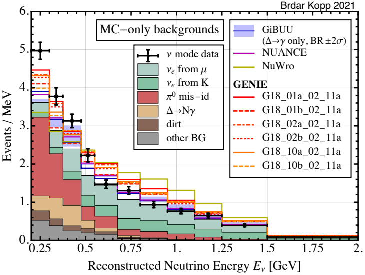
$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu4}|^2$$





3+1 model with eV-scale sterile neutrino





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

Monte Carlo-only background predictions

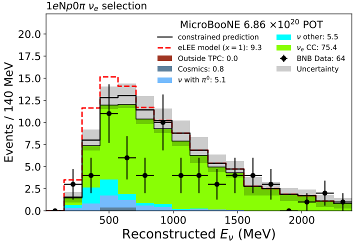
Generator	Tune	Δm^2_{41} [eV^2]	$\sin^2 2\theta_{\mu e}$	$\lvert U_{\mu 4}\rvert^2$	χ^2/dof	$\Delta\chi^2_{\text{no osc.}}$	Significance
MB official		0.25	0.01	0.062	12.0	19.1	4.0σ
GiBUU	default	0.25	0.01	0.076	12.0	24.6	4.6σ
	BR$(\Delta \to \gamma) - 2\sigma$	0.32	0.0063	0.076	12.2	28.5	5.0σ
	BR$(\Delta \to \gamma) + 2\sigma$	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

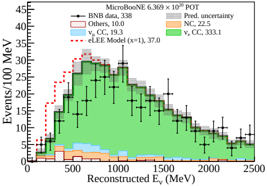
MicroBooNE

two-body ν_e CCQE scattering (1e1p)

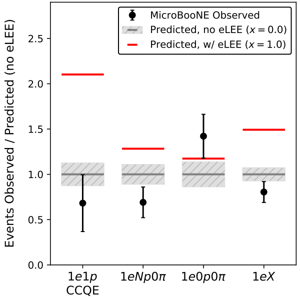
pionless ν_e scattering ($1eNp0\pi$, $1e0p0\pi$)

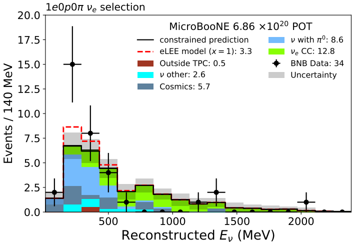
inclusive ν_e scattering ($1eX$)





2110.14054





MicroBooNE

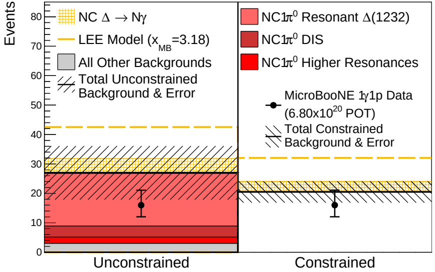
$1\gamma1p$

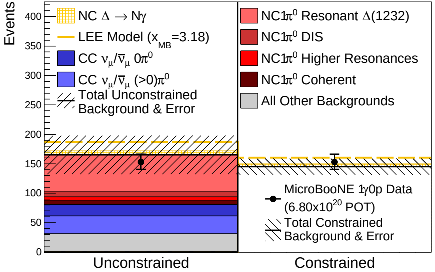
$1\gamma0p$

	$1\gamma1p$	$1\gamma0p$
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 ($x_{\rm MB} = 3.18$)	15.5	20.1
Data	16	153

Process	$1\gamma1p$	$1\gamma0p$
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

2110.00409





Coming back to MiniBooNE...

8 GeV protons from Booster hit the Beryllium target producing secondary particles. The 818 ton detector observes single shower events

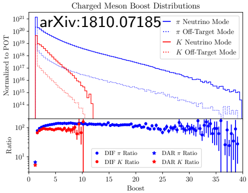
$$p + A\ [target] \to [X] \to 1sh\ events\ [detector]$$

X_s can be produced

- ~~on target in pA collisions~~
- from charged particles produced in the pA−collisions
- from ν_μ in the detector

X_d

- $N \to \nu + \gamma$, $N \to \nu + e^+ + e^-$
- $N \to \nu + B$, $B \to e^+ + e^-$ or $B \to \gamma + \gamma$
- $N \to ...\nu_e...$ where ν_e scatters in detector
- ~~N can also scatter $\to$ additional smallness~~

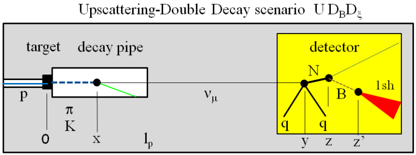


VB, Fischer, Smirnov, 2007.14411

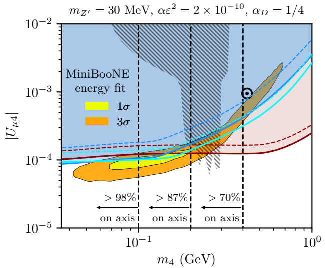
Model	Scenario	LSND
[6]	$M_N D_\gamma$	✗
[5]	$U_N D_\gamma$	✗
[7–9]	$U_N D_{ee}$	✗
[10–12]	$U_N D_B D_{ee}$	✗
[13]	$U_N D_B D_{ee}$	✓
[14–17]	$M_N D_\nu U_e$	✓
[18]	$U_B D_{ee}$	✗
–	$M_N D_B D_\xi$	
–	$U_N D_\nu U_e$	

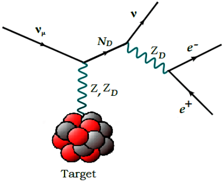
Scenarios, Models

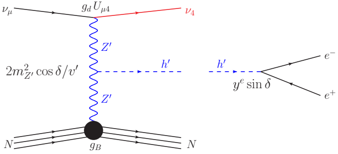
$U_N D_B D_\xi$, Upscattering - double decay scenario



Bertuzzo et al. (1807.09877)
Arguelles et al. (1812.08768)
Datta et al. (2005.08920)
Dutta et al. (2006.01319)
Abdallah et al. (2006.01948)



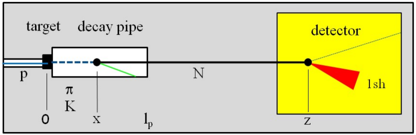




Scenarios, Models

$M_N D_\xi$, Mixing - Decay scenario

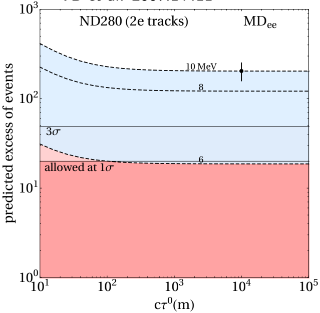
Mixing-Decay scenario MD_ξ



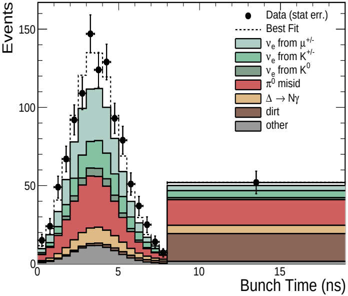
Fischer et al. (arXiv:1909.09561)

$$P_{dec} \approx \frac{d}{\lambda_N}\ e^{-l/\lambda_N}$$

VB et al. 2007.14411

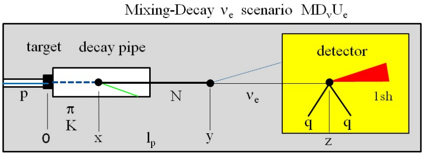


arXiv:2006.16883

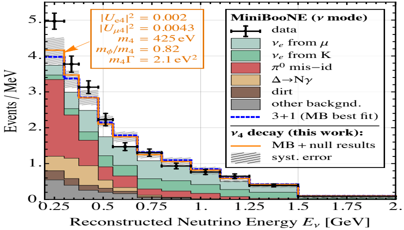


Scenarios, Models

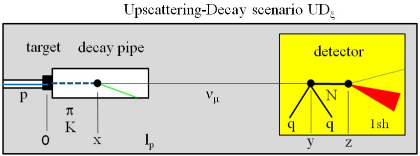
$M_N D_\nu U_e$, Mixing - Decay into ν_e scenario



Dentler et al. 2019 see also de Gouvea et al. 1911.01447

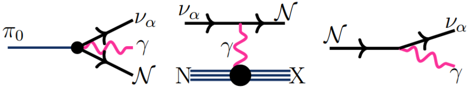


$U_N D_\xi$, Upscattering - decay scenario



Vergani et al. 2105.06470

see also Gninenko 0902.3802, Ballett et al. 1808.02915

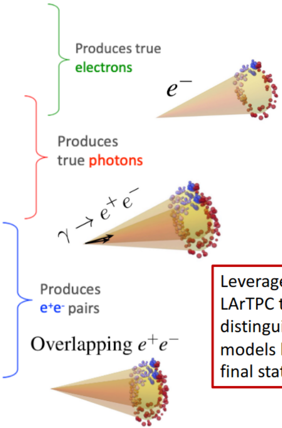


Scenarios, Models

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)
  - [14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141
- New resonance matter effects
  - [5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - [7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470
- Decay of heavy sterile neutrinos produced in beam
  - [4] Gninenko, Phys.Rev.D83:015015,2011
  - [12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)
  - [15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)
  - [11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - [1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)
  - [2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531
  - [3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)
  - [10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)
  - [6] Abdallah, Gandhi, Roy, Phys. Rev. D 104, 055028 (2021)
- Decay of axion-like particles
  - [8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)
- A model-independent approach to any new particle
  - [9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)

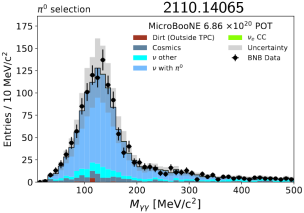


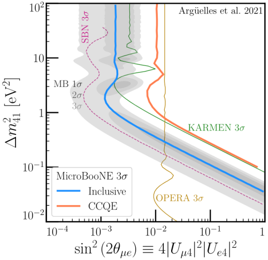
Leverage the power of LArTPC technology to distinguish between models based on exclusive final state topologies!

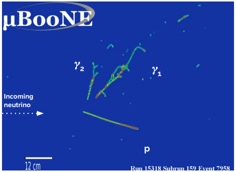
88

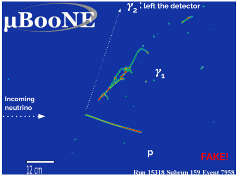
Where do we go from here?

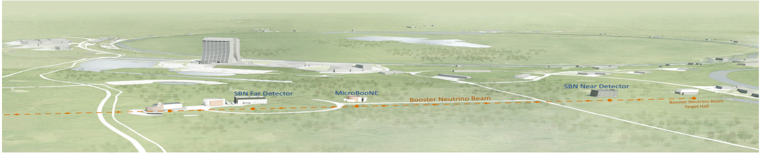
- MicroBooNE is finished with data taking. ν_e and $\Delta \to \gamma$ analyses used data collected by July 2018
- π^0 and e^+e^- analyses under way
- eV-scale steriles











Summary

Summary

- **MiniBooNE anomaly has been a mystery for over a decade**

Summary

- **MiniBooNE anomaly has been a mystery for over a decade**

- **Recent background re-evaluations as well as MicroBooNE data did not unravel it**

Summary

- **MiniBooNE anomaly has been a mystery for over a decade**
- **Recent background re-evaluations as well as MicroBooNE data did not unravel it**
- **Light eV-scale sterile neutrino hypothesis is disfavored**

Summary

- **MiniBooNE anomaly has been a mystery for over a decade**
- **Recent background re-evaluations as well as MicroBooNE data did not unravel it**
- **Light eV-scale sterile neutrino hypothesis is disfavored**
- **Alternative models with heavier sub-GeV new physics?**

Summary

- **MiniBooNE anomaly has been a mystery for over a decade**
- **Recent background re-evaluations as well as MicroBooNE data did not unravel it**
- **Light eV-scale sterile neutrino hypothesis is disfavored**
- **Alternative models with heavier sub-GeV new physics?**
- **Short-Baseline Neutrino Program at Fermilab**