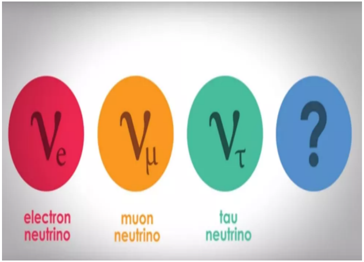
MiniBoone, MicroBoone and New Physics



Vedran Brdar

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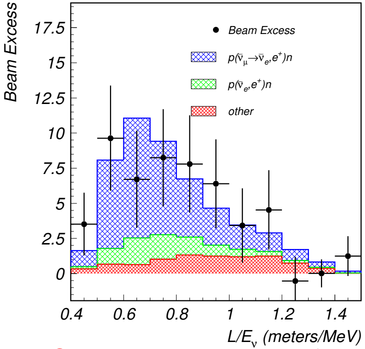
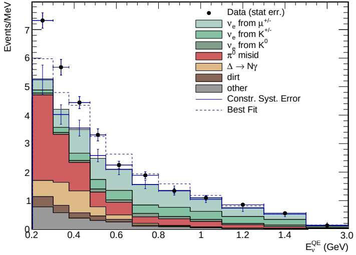
Northwestern University

LSND and MiniBooNE



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

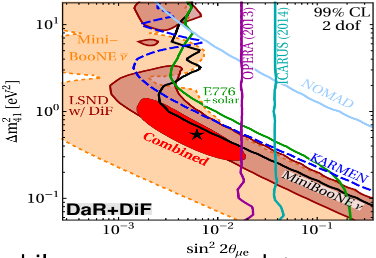
- LSND: $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$) at $L/E \sim 1\text{km GeV}^{-1}$ (arXiv:hep-ex/0104049)
- MiniBooNE: reports electron-like event excess (4.8σ); in combination with LSND at 6.1σ (arXiv:0812.2243, 1805.12028, 2006.16883)

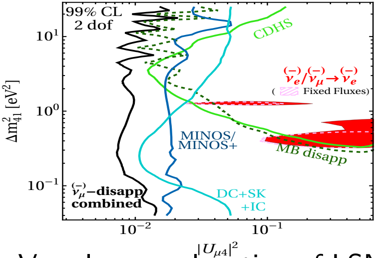


eV-scale ν_s for LSND and MiniBooNE anomalies?

- Oscillation maxima for standard oscillations expected at
  - $L/E \sim 500$ km/GeV (from $\Delta m^2_{31} \sim 2.4 \times 10^{-3}\text{eV}^2$)
  - $L/E \sim 15000$ 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 and practically excludes this possibility $\Rightarrow$ necessity for alternative models

Altarelli Cocktail?

An Altarelli Cocktail for the MiniBooNE Anomaly?

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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.

Employed MC Generators

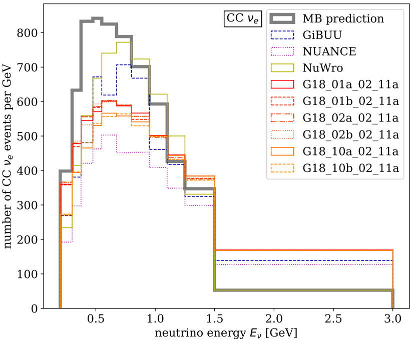
Generator	Tune	Ref.	Comments
NUANCE	–	[40]	the generator used by MiniBooNE
GiBUU	–	[42]	theory-driven generator
NuWro	–	[41]	
GENIE	G18_01a_02_11a	[39, 44]	GENIE baseline tune; see [44] for naming conventions
	G18_01b_02_11a		different FSI implementation compared to G18_01a_02_11a
	G18_02a_02_11a		updated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

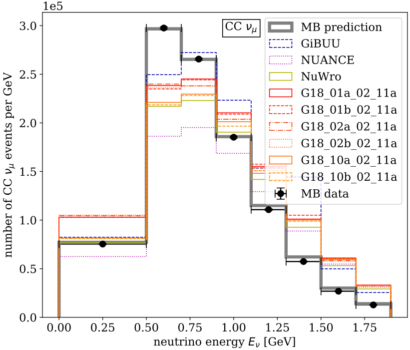
Strategy

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

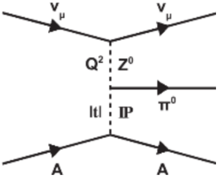
$$\nu_{e,\mu} + n \to e^- / \mu^- + p \qquad E_\nu = \frac{2m'_n E_\ell - (m'^2_n + m^2_\ell - m^2_p)}{2[m'_n - E_\ell + \sqrt{E^2_\ell - m^2_\ell}\cos\theta_\ell\,]}$$

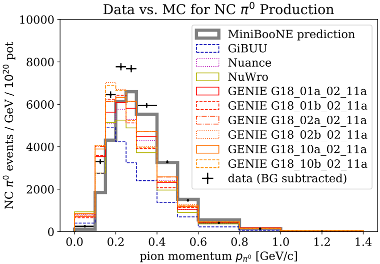


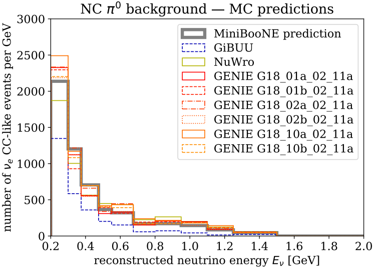


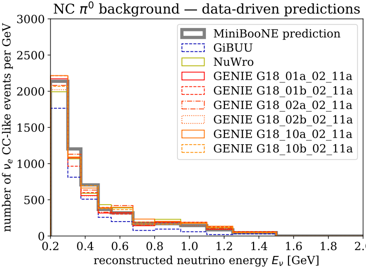
Neutral Current π^0 Production

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



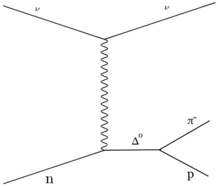


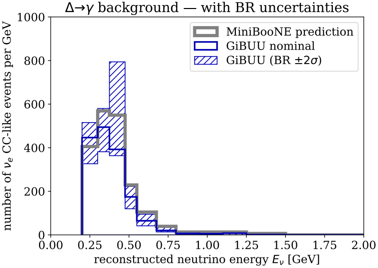


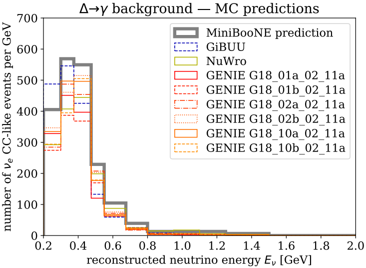


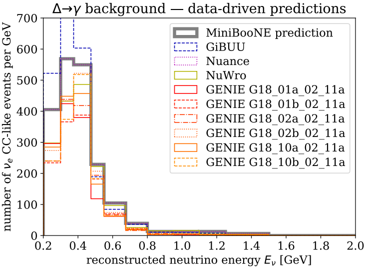
Neutral Current Single γ Production

$\Delta \to N\gamma$

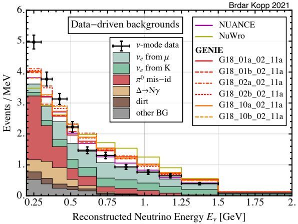


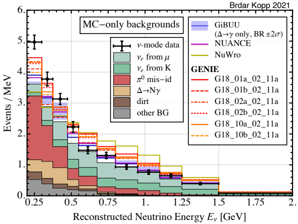




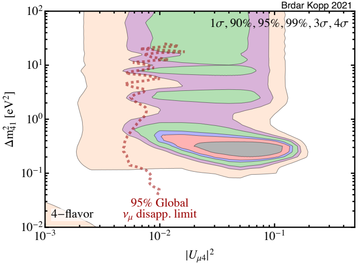


3+1 model with eV-scale sterile neutrino





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



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

data-driven backgrounds

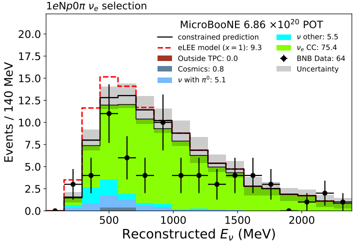
Generator	Tune	Δm^2_{41}	$\sin^2 2\theta_{\mu e}$	$\lvert U_{\mu 4}\rvert^2$	χ^2/dof	$\Delta\chi^2_{\text{no osc.}}$	Significance
MB official		0.25	0.01	0.062	12.0	19.1	4.0σ
NUANCE	–	0.32	0.0079	0.051	12.3	19.3	4.0σ
NuWro	–	3.2	0.0016	0.040	13.3	12.7	3.1σ
GENIE	G18_01a_02_11a	0.79	0.00020	0.14	12.2	23.3	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

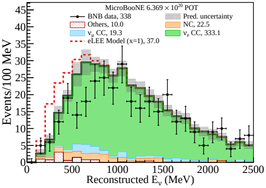
MicroBooNE (2110.14054)

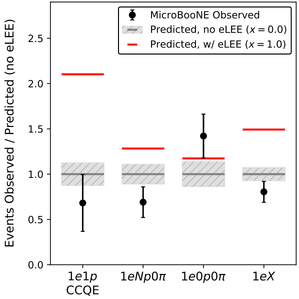
two-body ν_e CCQE scattering (1e1p)

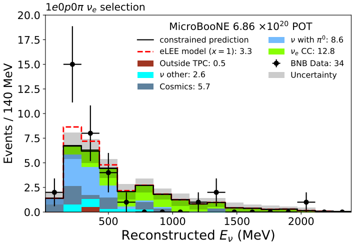
pionless ν_e scattering ($1eNp0\pi$, $1e0p0\pi$)

inclusive ν_e scattering ($1eX$)









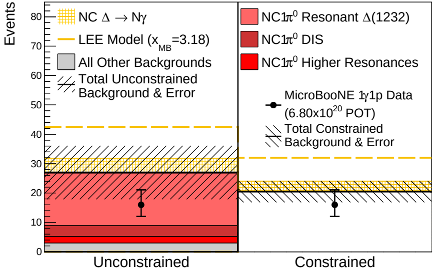
MicroBooNE (2110.00409)

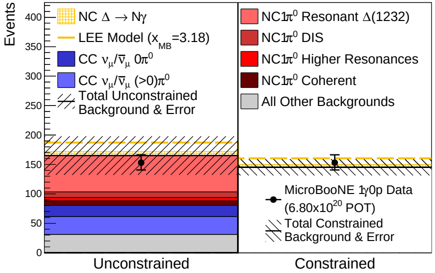
$1\gamma 1p$

$1\gamma 0p$

	$1\gamma 1p$	$1\gamma 0p$
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





New Physics?

From interactions of protons on target to 1 shower events

- The source of events are 8 GeV protons from Booster that hit the Beryllium target producing secondary particles. The 818 ton liquid scintillation detector observes the single shower events

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

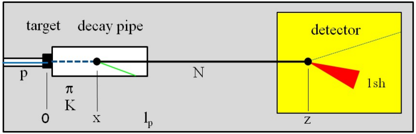
- The "black box" , X, is assumed to be represented by a particle (or a system of particles) that are produced in the source (X_s) and evolve to detector where they interact or decay (X_d) producing 1 shower events
- X_s can be produced
  - ~~on target in pA collisions immediately~~
  - in decays (interactions) of known particles produced in the $pA-$collisions, such as π, K, heavy mesons. But those particles need to be charged!
  - from neutrinos ν_μ in detector or/and surrounding matter along the baseline
- X_d
  - $N \to \nu + \gamma,\ N \to \nu + e^+ + e^-$ (decay into particle(s) ξ that give shower)
  - $N \to \nu + B,\ \ B \to e^+ + e^-$ or $B \to \gamma + \gamma$
  - $N \to ...\nu_e...$ followed by ν_e scattering in the detector
  - N can also scatter $\to$ additional smallness

Scenarios involving right-handed neutrino N

VB, Fischer, Smirnov, 2007.14411:

1) $M_N D_\xi$, Mixing - Decay scenario: the heavy neutrino N produced in the K and $\pi-$decay via mixing in ν_μ and decays as $N \to N' + \xi$

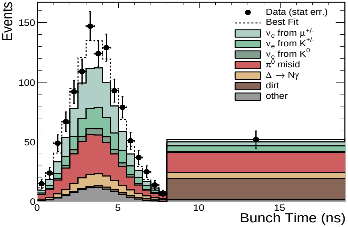
Mixing-Decay scenario MD_ξ



$$N_{\xi-s} = \epsilon A |U_{\mu 4}|^2 \int dE_N \frac{d\phi_N^0(E_N)}{dE_N} f_{\xi-s}(E_N) P_{dec}$$

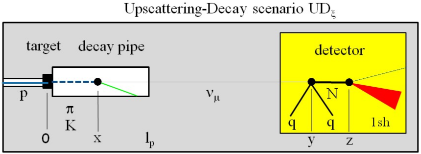
$$P_{dec} \approx \frac{d}{\lambda_N}\, e^{-l/\lambda_N}$$

- event excess peaks in the 8 ns window associated with beam bunch time, as expected from neutrino events in the detector $\Longrightarrow$ $m_N < 10\,\mathrm{MeV}$ for $M_N D_\xi$ scenario



Scenarios involving right-handed neutrino N

2) $U_N D_\xi$, Upscattering - decay scenario: N is produced in the ν_μ interactions with particles of medium between the source and the detector and in the detector. Then N decays in the detector, producing ξ state



$$\frac{d\phi_N^\sigma(E_N)}{dE_N} \equiv \int dE_\nu \frac{d\phi_\nu(E_\nu)}{dE_\nu} \frac{d\sigma(E_\nu, E_N)}{dE_N}$$

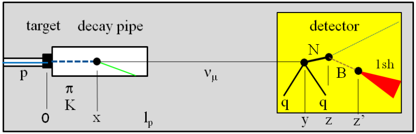
$$N^{in}_{\xi-s} = \epsilon V_d n_d \int dE_N f_{\xi-s}(E_N) \frac{d\phi_N^\sigma(E_\nu)}{dE_N} \left[1 - \frac{\lambda_N}{d}(1 - e^{-d/\lambda_N})\right]$$

- we also considered upscattering in the dirt as well as various detector subcomponents

Scenarios involving right-handed neutrino N

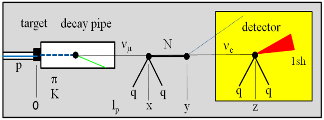
3) $U_N D_B D_\xi$, Upscattering - double decay scenario: N produced by ν_μ upscattering undergoes double decay: $N \to B \to \xi$. If B decays promptly, calculations match previous scenario

Upscattering-Double Decay scenario $U D_B D_\xi$



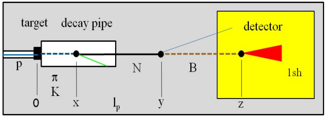
4) $U_N D_\nu U_e$, Upscattering-decay into ν_e scenario: N produced by the ν_μ upscattering decays with emission of ν_e, which then scatters in the detector via CCQE producing e shower

Upscattering-Decay into ν_e scenario, $U_N D_\nu U_e$



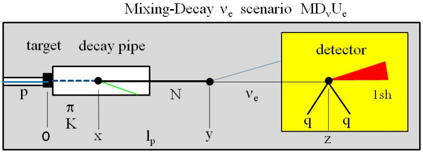
5) $M_N D_B D_\xi$, Mixing-double decay scenario: N produced via mixing decays invisibly into another new particle B, which in turn decays into (or with emission of) ξ

Mixing-Double Decay scenario, $M_N D_B D_\xi$



Scenarios involving right-handed neutrino N

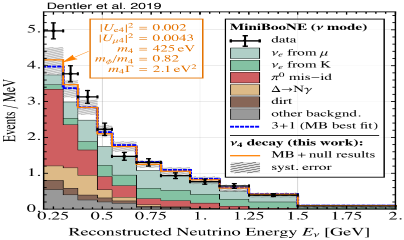
6) $M_N D_\nu U_e$, Mixing - Decay into ν_e scenario: N is produced via mixing and decays with emission of ν_e: $N \to \nu_e + B$. Then ν_e upscatters in the detector, producing $e^\pm$



- for small N decay length $c\tau^0 \to 0$

$$N^i_{1e} \approx \sigma^i_{CC}\, V_i\, n_i\, B_N\, \phi^0_\pi\, (1 - \mathrm{Exp}[-l_T/\lambda_\pi]) \approx \sigma^i_{CC}\, V_i\, n_i\, B_N\, \phi_{\nu_\mu}$$

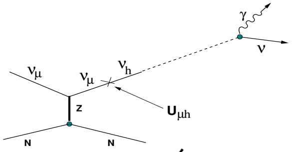
- the spectrum for this scenario looks similar to the one in the 3+1 scenario
- viable N masses $\mathcal{O}(\mathrm{keV})$

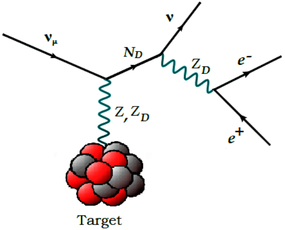


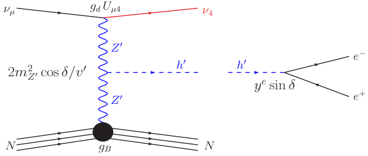
Non-oscillatory Explanations of MiniBooNE Anomaly

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

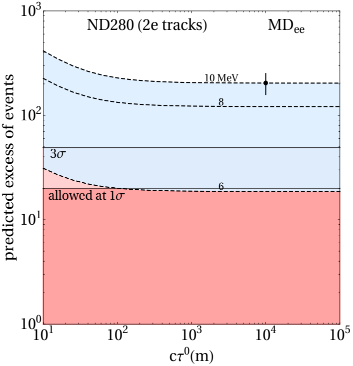
- $M_N D_\xi$:
  Fischer et al. (arXiv:1909.09561)
- $U_N D_\xi$:
  Gninenko (arXiv:0902.3802)
  Ballett et al. (arXiv:1808.02915)
- $U_N D_B D_\xi$:
  Bertuzzo et al. (arXiv:1807.09877)
  Datta et al. (2005.08920)
  Dutta et al. (2006.01319)
  Abdallah et al. (2006.01948)
- $M_N D_\nu U_e$:
  Dentler et al. (1911.01427)
  de Gouvea et al. (1911.01447)

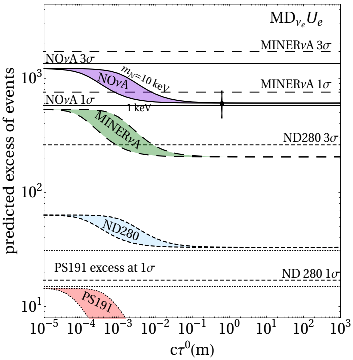






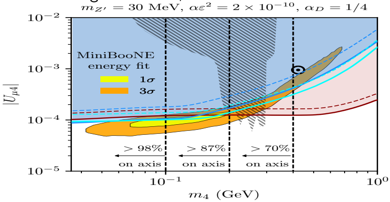
VB, Fischer, Smirnov, 2007.14411





$$N^i_{\xi,exp} = N^{MB}_{1sh,exp} \; \frac{N^i_{\xi-s^i}}{N^{MB}_{1sh}}$$

Arguelles et al., 1812.08768



Mini SBN-Theory workshop

13 Dec 2021, 14:55 → 15 Dec 2021, 18:00 UTC

online

Description Given the recent exciting developments in Fermilab's SBN Program, we are organizing the special SBN-Theory mini-workshop "**Physics opportunities at the Short Baseline Neutrino Program**" on **December 13-15, 2021**.

The goal of the workshop is to foster collaborations among theorists and experimentalists to discuss future searches in the SBN Program, particularly in the context of the MiniBooNE anomaly, though not limited to it.

As in other SBN-Theory events, this mini-workshop will be informal, focused on the physics, and in the intersection between theory and experiment.

We aim to get work done and to distribute tasks among participants by the end of the event.

Registration Participants — Register

Summary

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- Recent background re-evaluations as well as MicroBooNE data did not unravel it
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- Alternative models with heavier sub-GeV new physics?
- Short-Baseline Neutrino Program at Fermilab may be the key