Bounds on the Non-Oscillatory Explanations of MiniBooNE Excess

based on arXiv:2007.14411 in collaboration with
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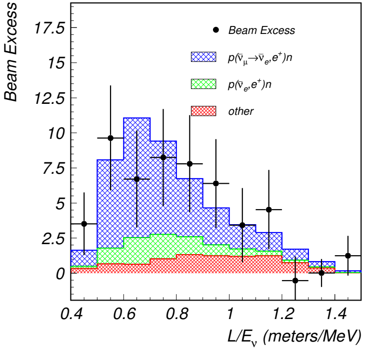
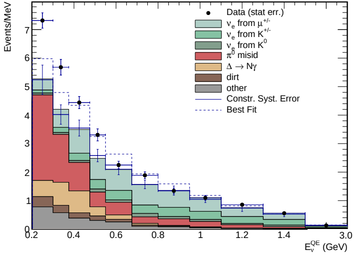
LSND and MiniBooNE



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

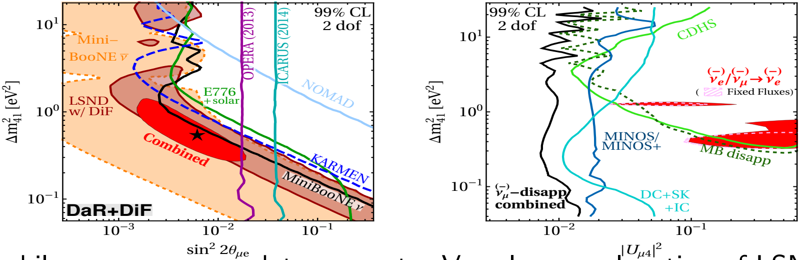
- **LSND**: $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$) at $L/E \sim 1\text{km GeV}^{-1}$ (arXiv:hep-ex/0104049)
- **MiniBooNE**: reports electron-like event excess (4.8σ); in combination with LSND at 6.1σ (arXiv:0812.2243, 1805.12028, 2006.16883)



eV-scale ν_s for LSND and MiniBooNE anomalies?

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

From interactions of protons on target to 1 shower events

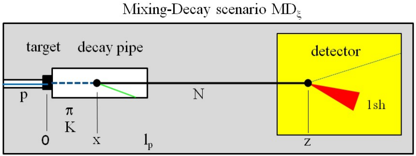
- The source of events are 8 GeV protons from Booster that hit the Beryllium target producing secondary particles. The 818 ton liquid scintillation detector observes the single shower events

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

- 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)
  - $N \to \nu + B, \quad B \to e^+ + e^- \text{ or } B \to \gamma + \gamma$
  - $N \to ...\nu_e...$ followed by ν_e scattering in the detector
  - N can also scatter $\to$ additional smallness

Scenarios involving right-handed neutrino N

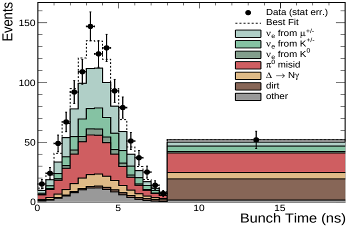
1) $M_N D_\xi$, Mixing - Decay scenario: the heavy neutrino N produced in the K and $\pi-$decay via mixing in ν_μ and decays as $N \to N' + \xi$



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

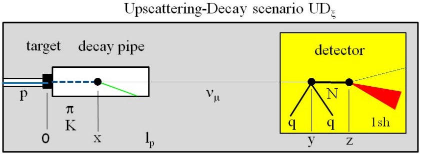
$$P_{dec} \approx \frac{d}{\lambda_N}\, e^{-l/\lambda_N}$$

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



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

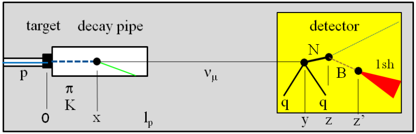
$$N^{in}_{\xi-s} = \epsilon V_d n_d \int dE_N f_{\xi-s}(E_N) \frac{d\phi_N^\sigma(E_\nu)}{dE_N} \left[1 - \frac{\lambda_N}{d}(1 - e^{-d/\lambda_N})\right]$$

- we also considered upscattering in the dirt as well as various detector subcomponents
- the models by Gninenko and Ballett et al. belong to this class of scenarios

Scenarios involving right-handed neutrino N

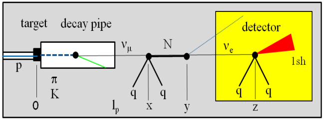
3) $U_N D_B D_\xi$, Upscattering - double decay scenario: N produced by ν_μ upscattering undergoes double decay: $N \to B \to \xi$. If B decays promptly, calculations match previous scenario

Upscattering-Double Decay scenario $U\,D_BD_\xi$



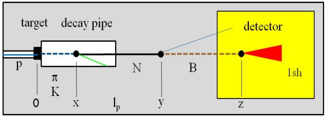
4) $U_N D_\nu U_e$, Upscattering-decay into ν_e scenario: N produced by the ν_μ upscattering decays with emission of ν_e, which then scatters in the detector via CCQE producing e shower

Upscattering-Decay into ν_e scenario, $U_ND_\nu U_e$



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

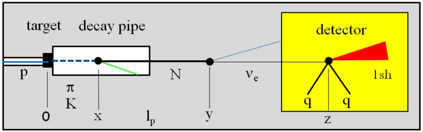
Mixing-Double Decay scenario, $M_ND_BD_\xi$



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 $e^\pm$

Mixing-Decay ν_e scenario $MD_\nu U_e$

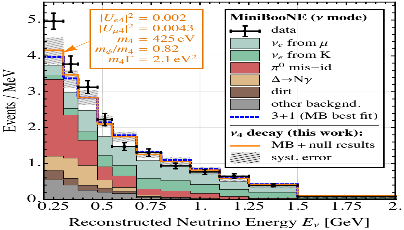


- for small N decay length $c\tau^0 \to 0$

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

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

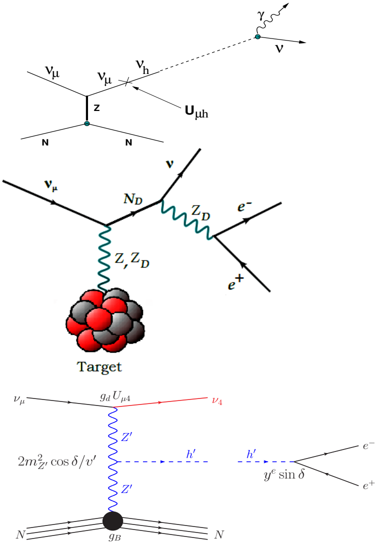
Dentler et al. 2019



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)



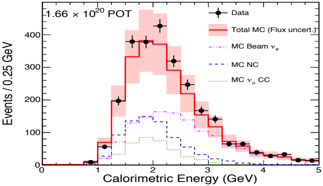
Strategy

- we employ several neutrino experiments to test aforementioned scenarios
- we normalize the numbers of events in a given detector, *i*, to the MiniBooNE excess

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

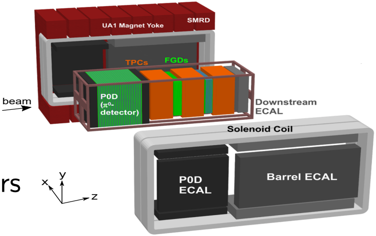
where $N^{MB}_{1sh,exp} = 638$ and the remainder of the expression is the ratio of theoretical numbers of events in a given experiment and MiniBooNE

- in this way we ensure that a given scenario explains the MB excess; furthermore, various factors cancel in the ratio of predictions (mixing parameter, coupling constants...)
- for a given search, we use measured number of events as well as SM theory expectation and compute upper limit on the allowed number of new physics events at given confidence level

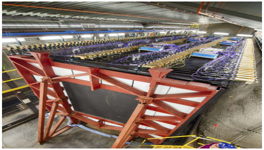


Experiments

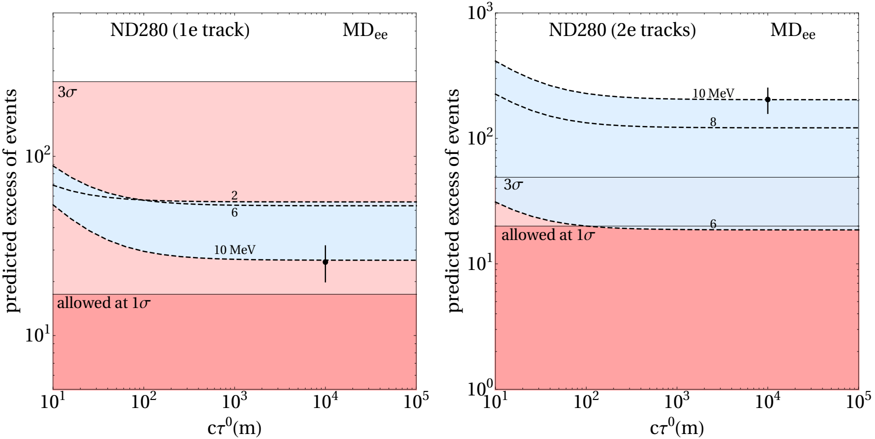
- T2K ND280: sourced by 30 GeV protons that interact with a graphite target
- sub-detectors: the π^0 detector P0D, the tracking detector containing the three Time Projection Chambers (TPC) filled by Ar gas, and two Fine Grained Detectors (FGD) filled by scintillatiors



- MINERνA: consists of scintillator strips; Good particle ID allows to identify $1e-$ from 1γ and e^+e^- showers using the energy loss dE/dx
- PS191: was sourced by the PS proton beam with an energy of 19.2 GeV interacting with a beryllium target; measured excess of the $e-$like events in the calorimeter of 23 ± 8 events
- NOνA: uses NuMI neutrino beam (120 GeV protons); composed of fine-grained cells of liquid scintillator

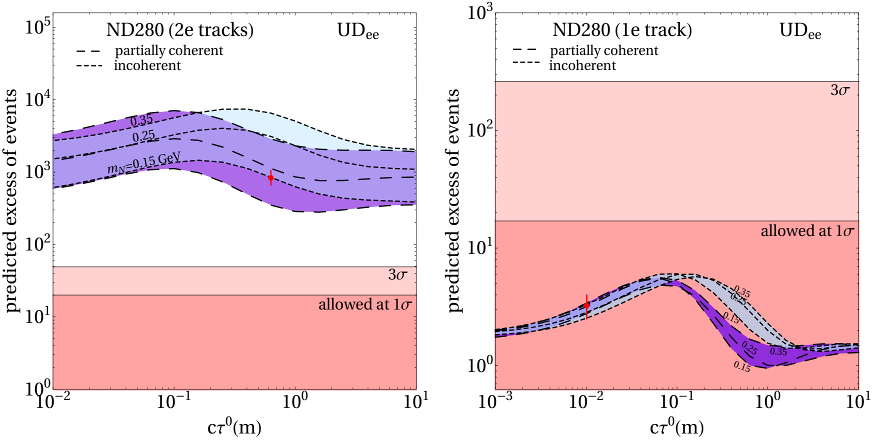


MD_{ee}



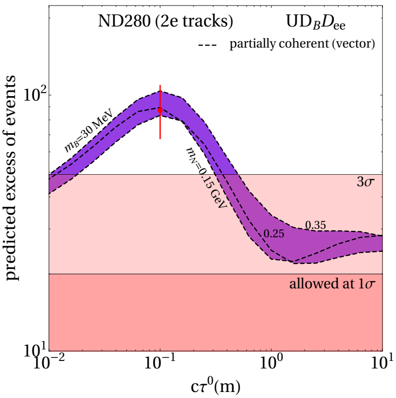
- timing limits impose consideration of $\mathcal{O}$(MeV) masses
- invariant mass of e^+e^- pair used as a criterion for distinguishing between 1 and 2 showers

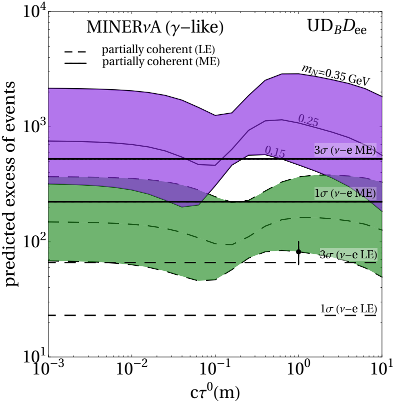
UD_{ee}



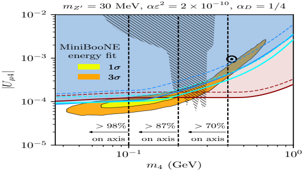
- partially coherent cross section adopted from Bertuzzo et al. while incoherent one matches the benchmark point of Ballett et al.

$UD_B D_{ee}$

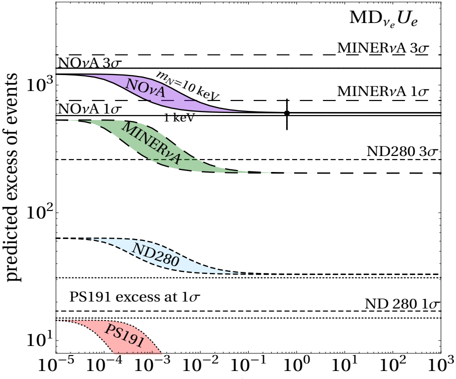


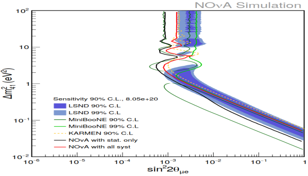


- Bertuzzo et al. model was tested by Arguelles et al. (arXiv:1812.08768) using MINERνA and CHARM-II data



$MD_{\nu_e}U_e$





- NOνA can test this scenario at 2σ and disfavor MiniBooNE best fit point at $\sim 3\sigma$

Summary

- a model independent study of the non-oscillatory explanations of the MiniBooNE excess was performed

- we carried out a systematic search of the simplest scenarios which can be classified by the number of new interaction points

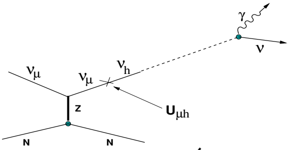
- new physics scenarios allow to directly connect the observed MiniBooNE excess of events to expected excesses in other experiments (T2K ND280, MINERνA, PS-191, NOνA)

- each of the studied scenarios can be tested (portions of parameter space being already disfavored) using present neutrino data

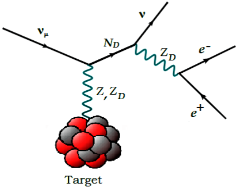
BACKUP SLIDES

Non-oscillatory Explanations of MiniBooNE Anomaly

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



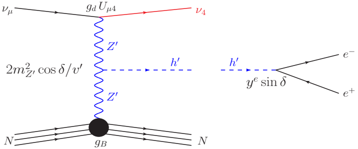
- Gninenko (arXiv:0902.3802): upscattering of ν_μ into $\mathcal{O}(100)$ MeV right-handed neutrino which decays through magnetic moment operator into γ $\implies |U_{\mu 4}|^2 \sim 10^{-3}$, $\mu \sim 10^{-9}\mu_B$



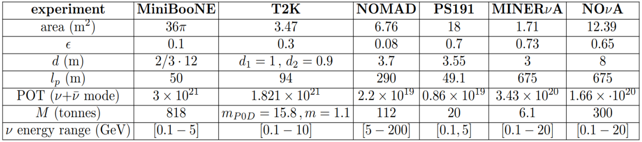
- Bertuzzo et al. (arXiv:1807.09877): upscattering of ν_μ into $\mathcal{O}(100)$ MeV right-handed neutrino which decays to on-shell Z' and ν; Z' then decays into collimated e^+e^- pair
- Ballett et al. (arXiv:1808.02915): identical particle content, however qualitatively different mechanism: right-handed neutrino N undergoes 3-body decay through the exchange of off-shell Z'; final state e^+e^- pair can mimic MiniBooNE 1 shower signature (this realization typically yields longer N lifetimes in comparison to previous scenario with on-shell Z')

Non-oscillatory Explanations of MiniBooNE Anomaly II

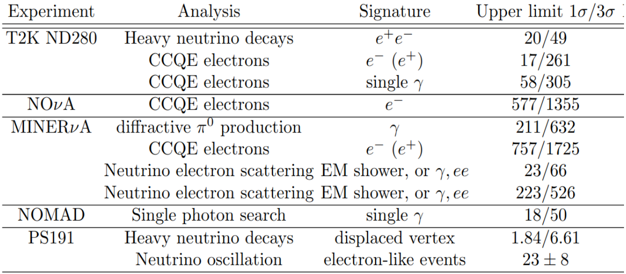
- Fischer et al. (arXiv:1909.09561): production of N via mixing in ν_μ in the decay pipe and further radiative decay along the beamline and mainly in the detector
- Dentler et al. (1911.01427) and de Gouvea et al. (1911.01447): N production via mixing in the decay pipe and then decay $N \to \nu_e \phi$ along the baseline with emission of ν_e which then produces electron via CCQE scattering in the detector (ϕ decay into $\nu_e \bar{\nu}_e$ also contributes to the signal)
- Datta et al. (2005.08920) and Dutta et al. (2006.01319): analogous realization to Bertuzzo et al.; the crucial difference is usage of scalar ϕ instead of Z' for the purpose of relaxing MINERνA limit
- Abdallah et al. (2006.01948): production of the light scalar B in upscattering of ν_μ, which then decays as $B \to e^+e^-$



Experiments and Searches

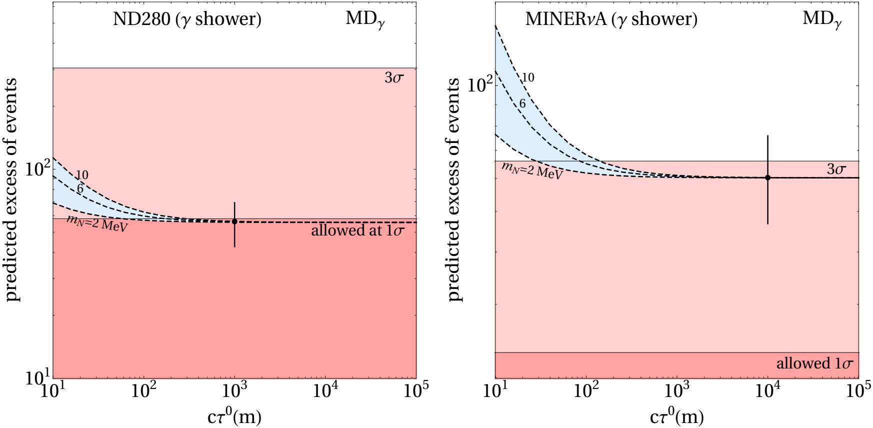


experiment	**MiniBooNE**	**T2K**	**NOMAD**	**PS191**	**MINERνA**	**NOνA**
area (m^2)	36π	3.47	6.76	18	1.71	12.39
ϵ	0.1	0.3	0.08	0.7	0.73	0.65
d (m)	$2/3 \cdot 12$	$d_1 = 1\,,\, d_2 = 0.9$	3.7	3.55	3	8
l_p (m)	50	94	290	49.1	675	675
POT (ν+$\bar{\nu}$ mode)	3×10^{21}	1.821×10^{21}	2.2×10^{19}	0.86×10^{19}	3.43×10^{20}	$1.66 \times \cdot 10^{20}$
M (tonnes)	818	$m_{P0D} = 15.8\,, m = 1.1$	112	20	6.1	300
ν energy range (GeV)	$[0.1 - 5]$	$[0.1 - 10]$	$[5 - 200]$	$[0.1, 5]$	$[0.1 - 20]$	$[0.1 - 20]$

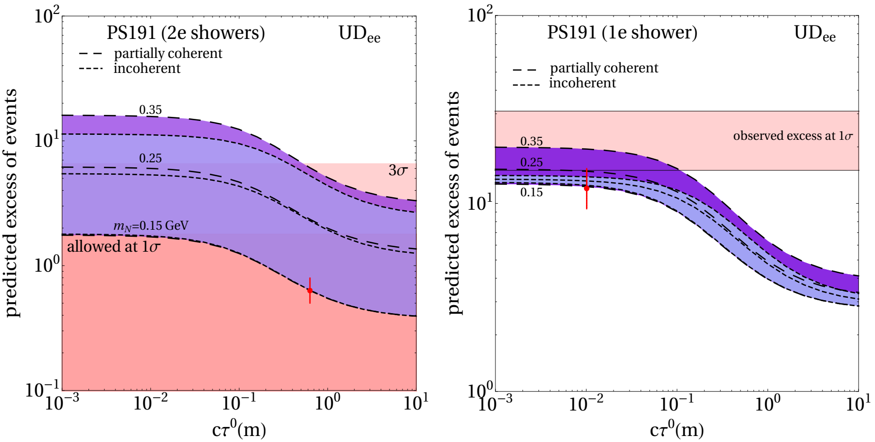


Experiment	Analysis	Signature	Upper limit $1\sigma/3\sigma$
T2K ND280	Heavy neutrino decays	e^+e^-	20/49
	CCQE electrons	e^- (e^+)	17/261
	CCQE electrons	single γ	58/305
NOνA	CCQE electrons	e^-	577/1355
MINERνA	diffractive π^0 production	γ	211/632
	CCQE electrons	e^- (e^+)	757/1725
	Neutrino electron scattering	EM shower, or γ, ee	23/66
	Neutrino electron scattering	EM shower, or γ, ee	223/526
NOMAD	Single photon search	single γ	18/50
PS191	Heavy neutrino decays	displaced vertex	1.84/6.61
	Neutrino oscillation	electron-like events	23 ± 8

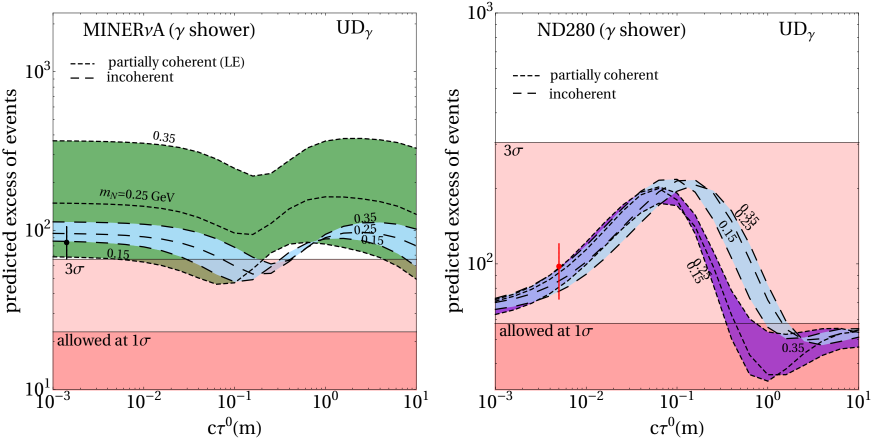
MD_γ


ND280 (γ shower)
MDγ
3σ
10
6
mN=2 MeV
allowed at 1σ
predicted excess of events
10^1
10^2
10^1
10^2
10^3
10^4
10^5
cτ^0(m)
MINERνA (γ shower)
MDγ
10
6
mN=2 MeV
3σ
allowed 1σ
predicted excess of events
10^2
10^1
10^2
10^3
10^4
10^5
cτ^0(m)

UD_{ee}


PS191 (2e showers)
UD_{ee}
partially coherent
incoherent
0.35
0.25
m_N=0.15 GeV
3σ
allowed at 1σ
predicted excess of events
10^{-1}
10^{0}
10^{1}
10^{2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
$c\tau^0$(m)
PS191 (1e shower)
UD_{ee}
partially coherent
incoherent
observed excess at 1σ
0.35
0.25
0.15
predicted excess of events
10^{0}
10^{1}
10^{2}
$c\tau^0$(m)

UD_γ



- for MINERVA, limits from $\nu - e$ scattering search are used
- important cut on $E\theta^2$