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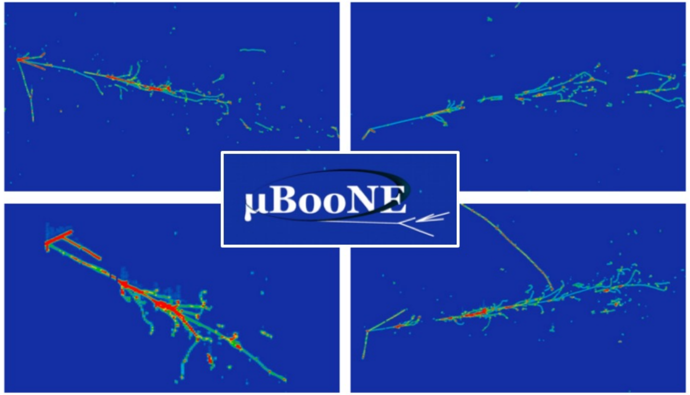
Sterile neutrinos



Justin Evans

Sterile neutrinos

Singlet states with no weak interactions

Dark sector fermion-portal models very naturally produce sterile neutrinos

$$\mathcal{L} \supset y\,(i\sigma^2 H^*)LN$$

Neutrino mass needs right-handed states

- Whether that's through Dirac or Majorana terms

$$\mathcal{L}_{\text{mass}} \supset -M_D^{\alpha\beta}\,\nu^\alpha N^\beta + h.c.$$

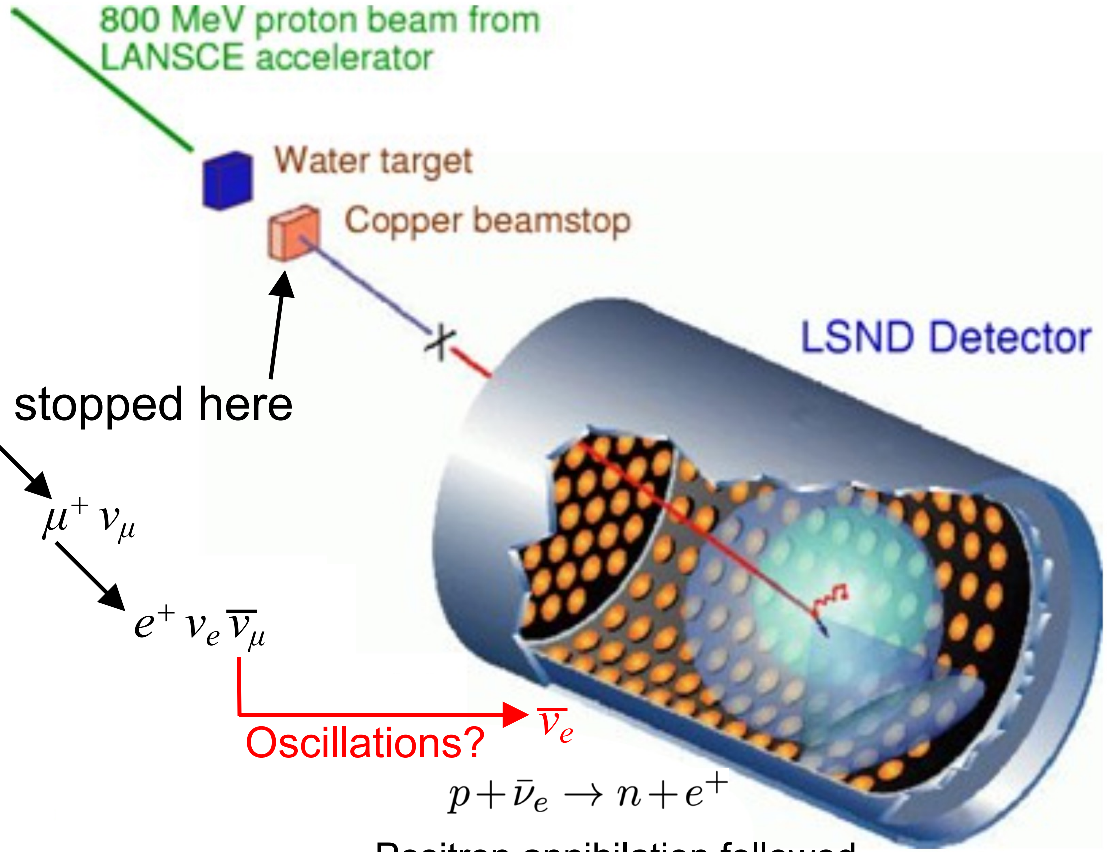
Sterile neutrinos are theoretically very favourable

- 'Just a neutral fermion'
- But tend to be heavy – MeV scale or above

The experimental hints are for light sterile neutrinos

- Around the eV scale

LSND



π^+ stopped here

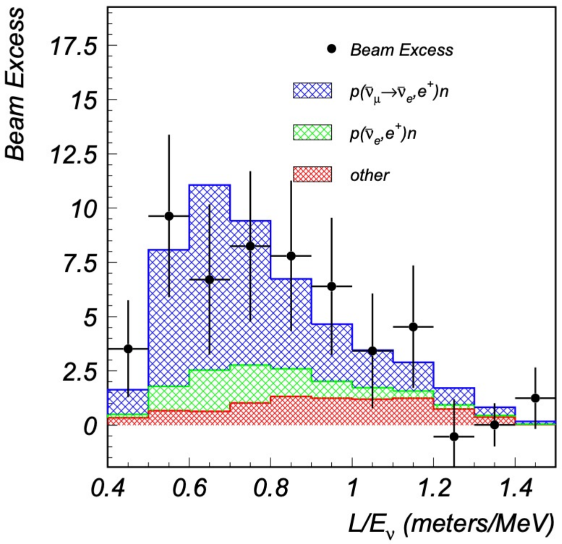
$\mu^+ \nu_\mu$

$e^+ \nu_e \overline{\nu}_\mu$

Oscillations? $\overline{\nu}_e$

$$p + \bar{\nu}_e \rightarrow n + e^+$$

Positron annihilation followed by delayed neutron capture



87.9 ± 22.4 ± 6.0 excess $\overline{\nu}_e$-like events observed

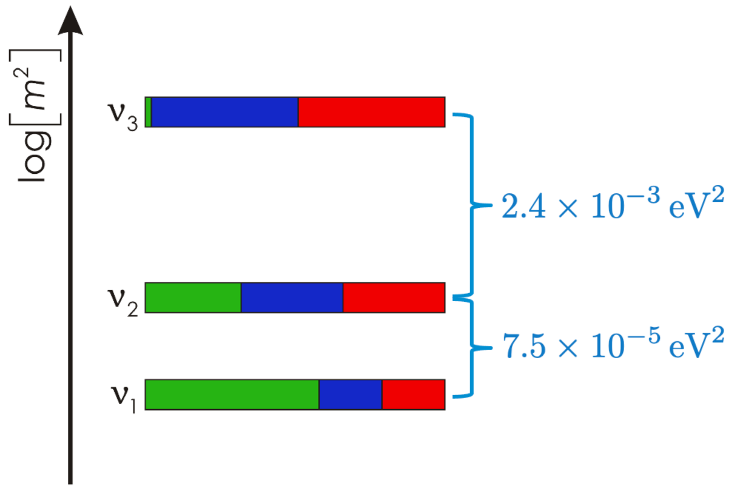
3.8σ significance

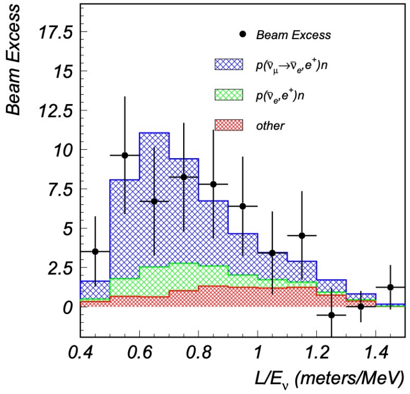
The oscillation interpretation

The neutrinos have not traveled far enough for standard oscillations to occur

Requires a mass splitting O(1 eV^2)

- Fourth neutrino state

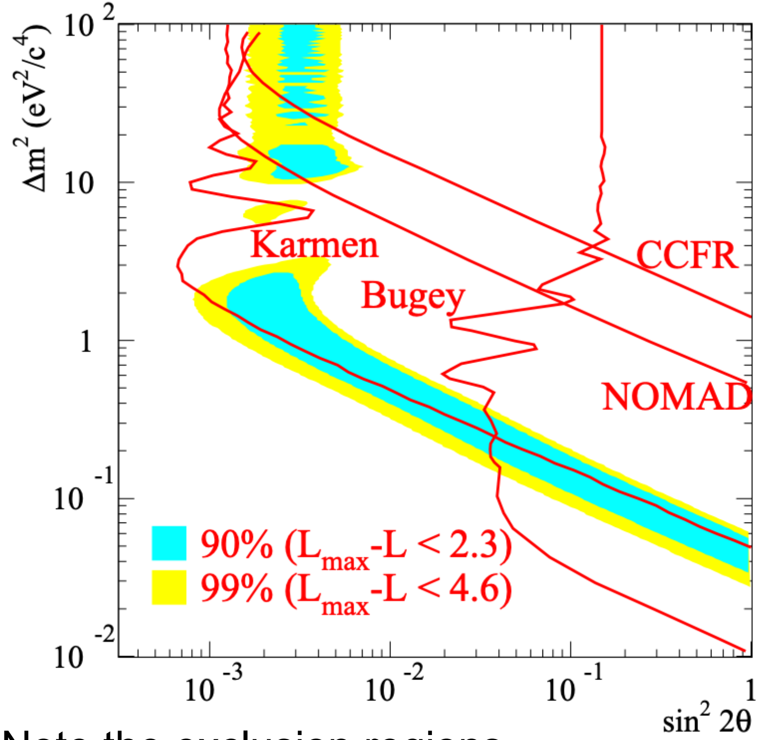




$$P(\overline{\nu}_e \to \overline{\nu}_\mu) = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

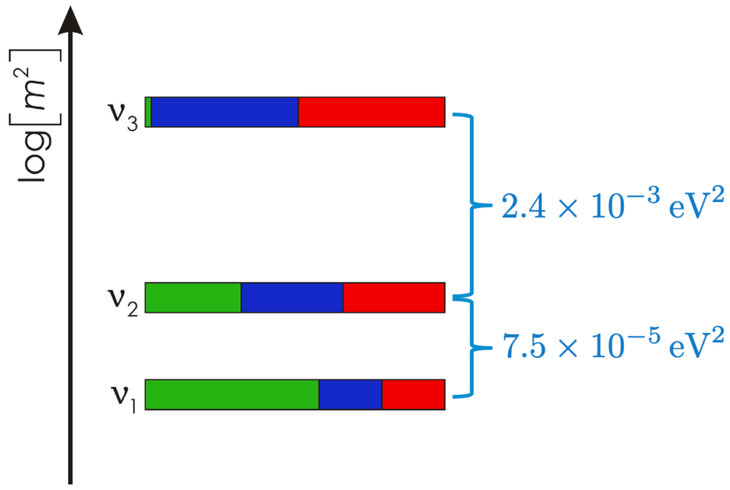
Phys. Rev. D64, 112007 (2001)

The oscillation interpretation

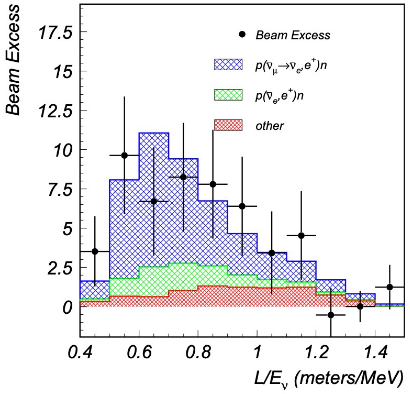


Note the exclusion regions, particularly Karmen

Phys. Rev. D64, 112007 (2001)

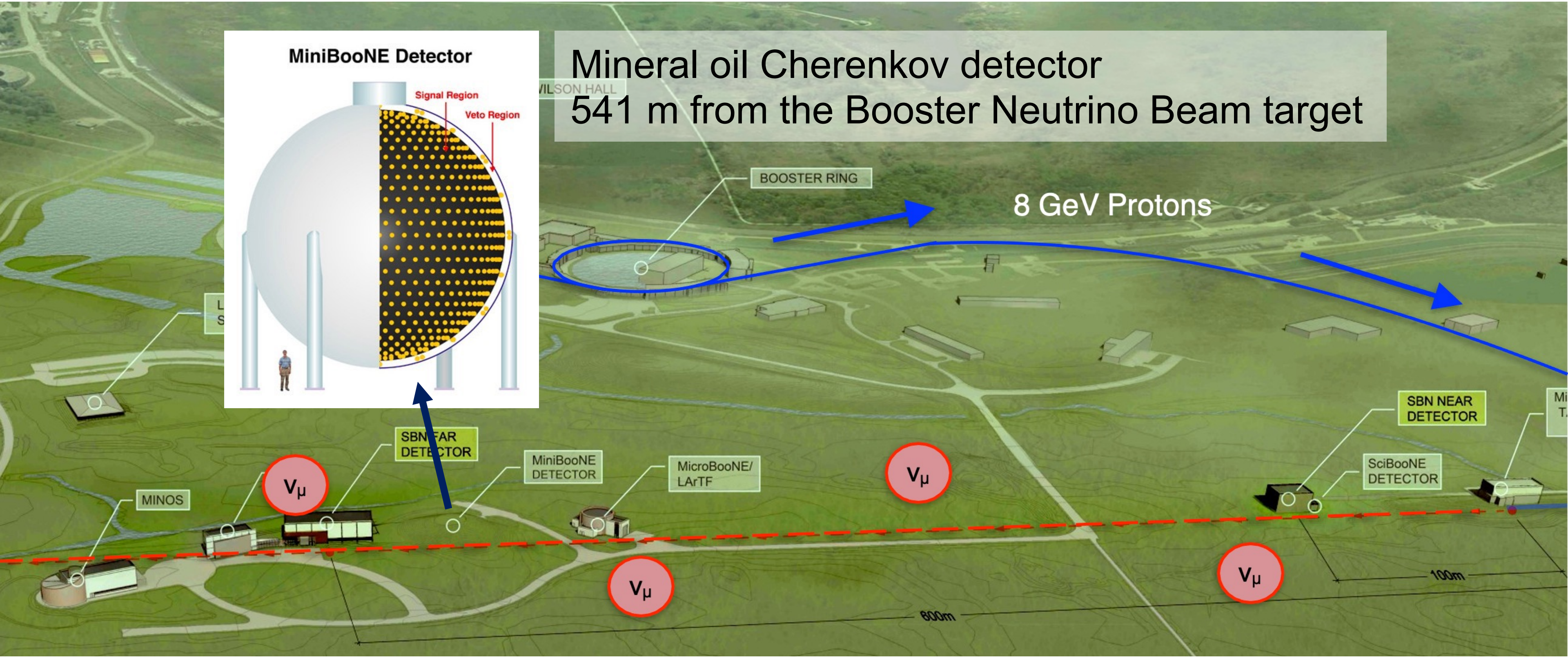


$$P(\overline{\nu}_e \to \overline{\nu}_\mu) = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

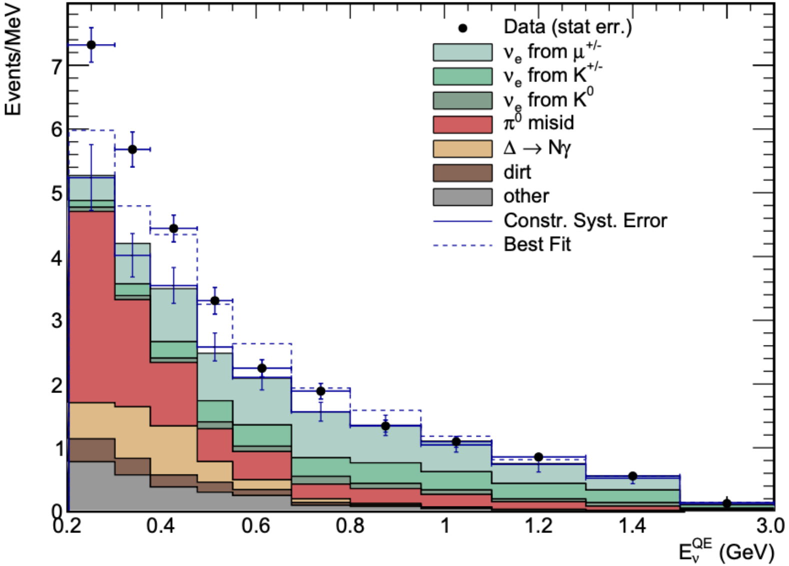


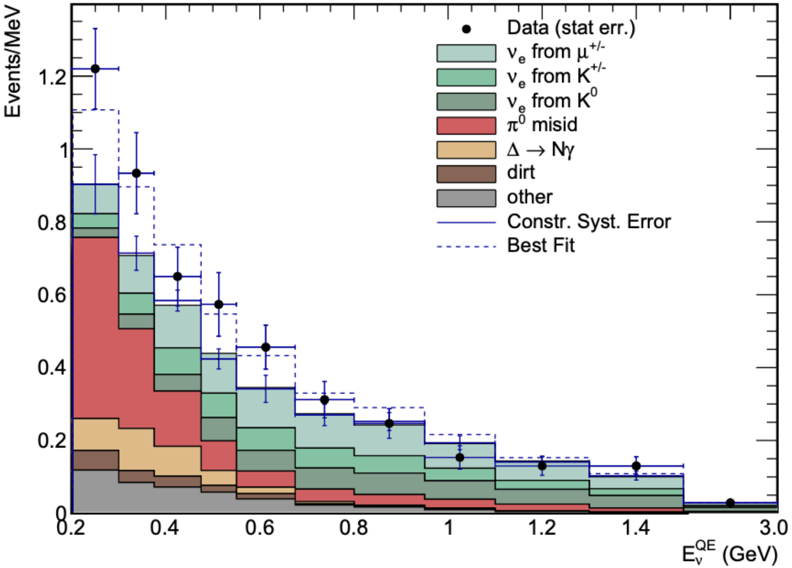
MiniBooNE

Mineral oil Cherenkov detector
541 m from the Booster Neutrino Beam target



MiniBooNE





Excesses of electron-like events observed

- In both neutrino and antineutrino runs

Phys. Rev. Lett. 121, 221801 (2018)

MiniBooNE

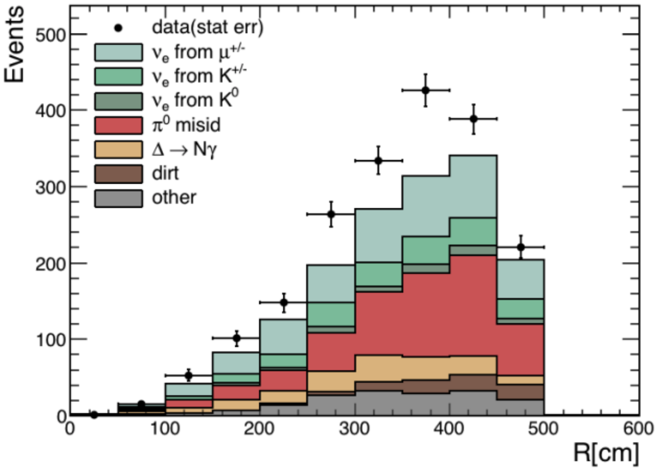
Excess is distributed throughout the detector

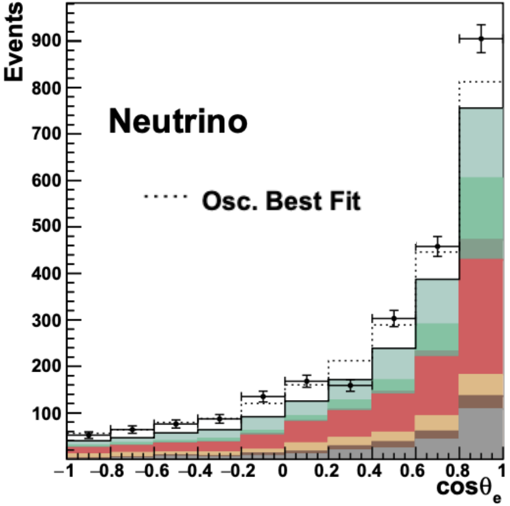
- Not consistent with escaping photons from π^0 decay

π^0 rate is measured in data

Excess enhanced in forward lepton angles

- Less consistent with oscillations

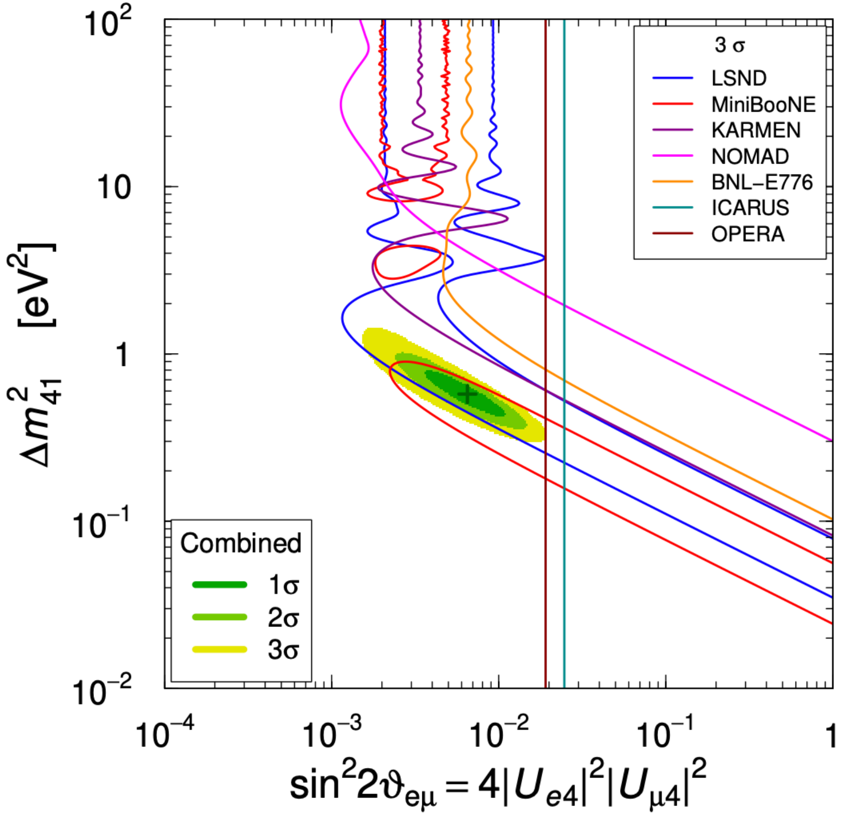




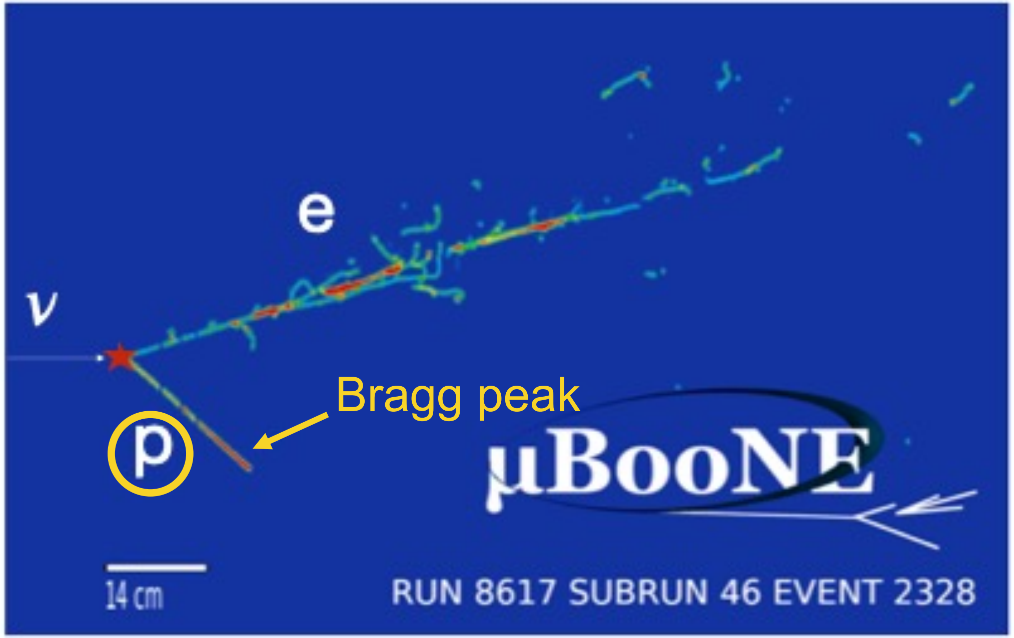
MiniBooNE & LSND

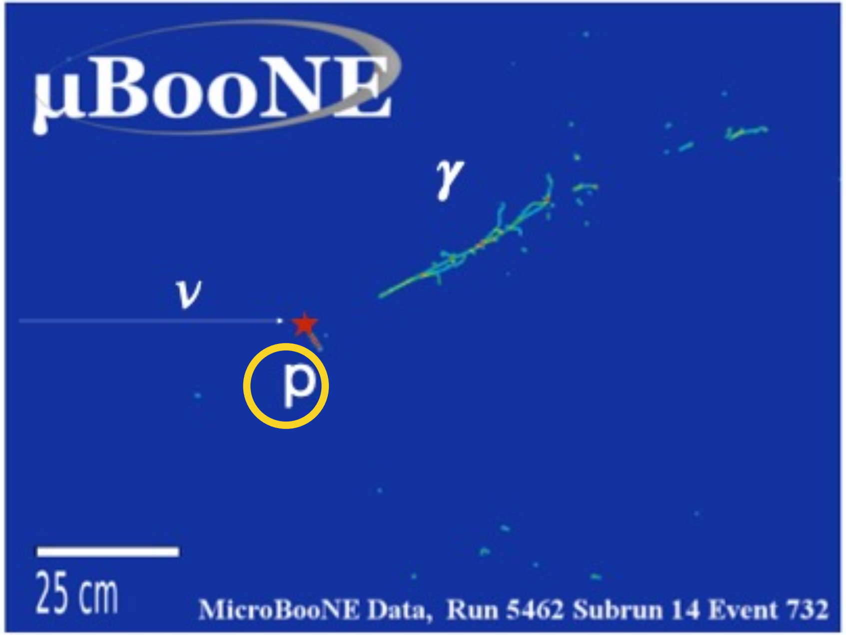
When combined together, along with exclusion regions, a mass splitting a little below 1 eV² can fit the data reasonably well

- e.g. Giunti & Lasserre, Ann. Rev. Nucl. Part. Sci. **69**, 163 (2019)



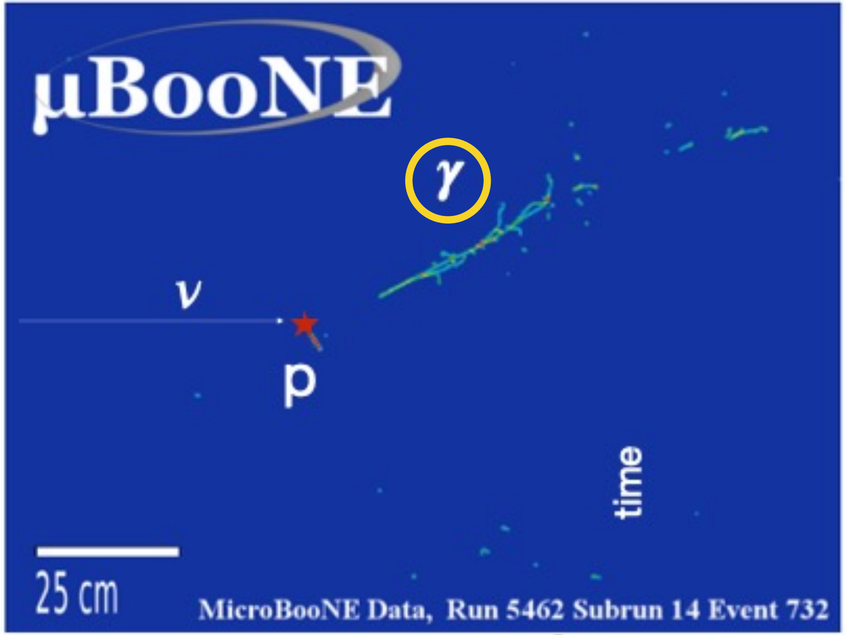
Liquid argon: MicroBooNE

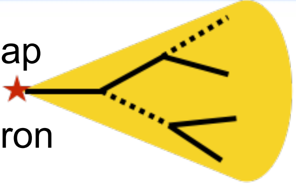




We can see the hadronic final state

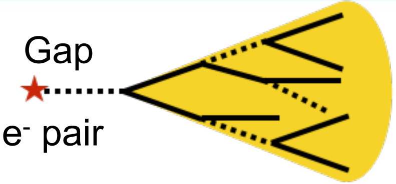
Liquid argon: MicroBooNE





No gap

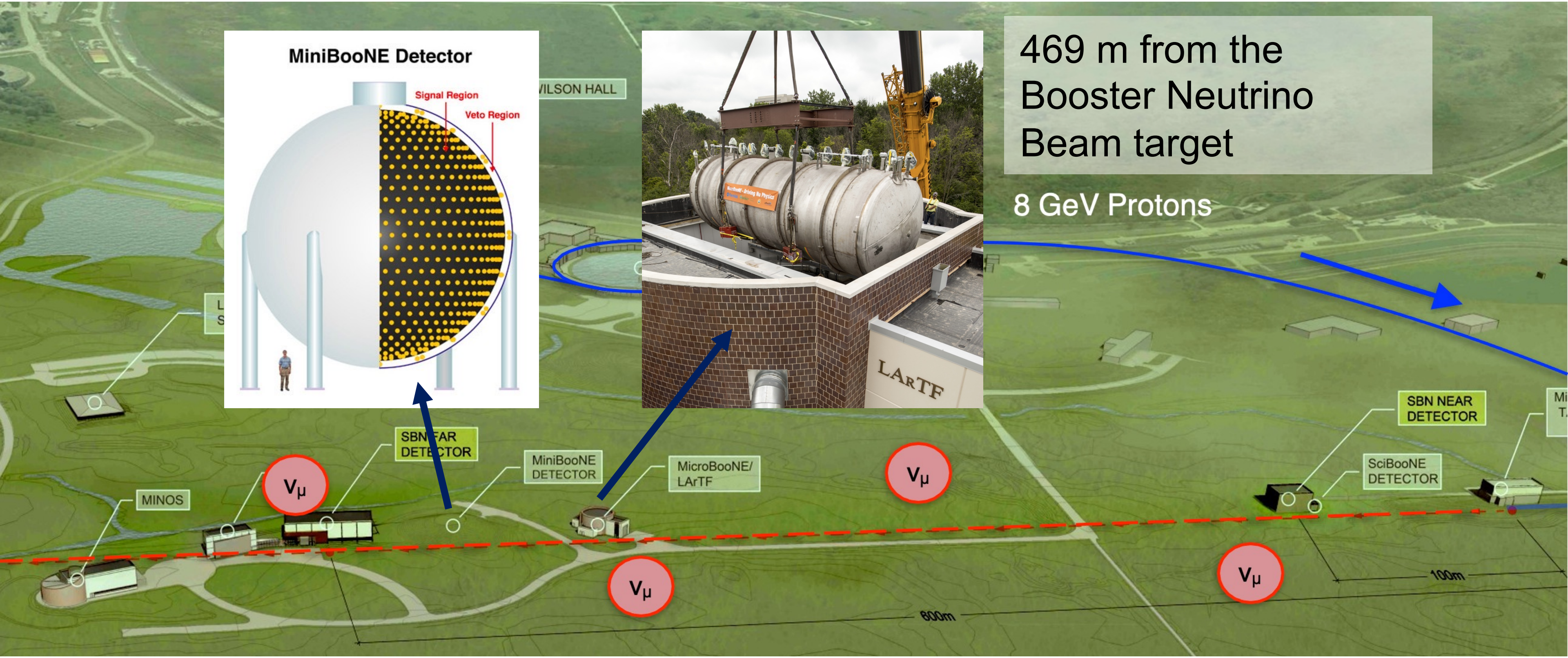
dE/dx of one electron



Gap

dE/dx of e^+e^- pair

Liquid argon: MicroBooNE

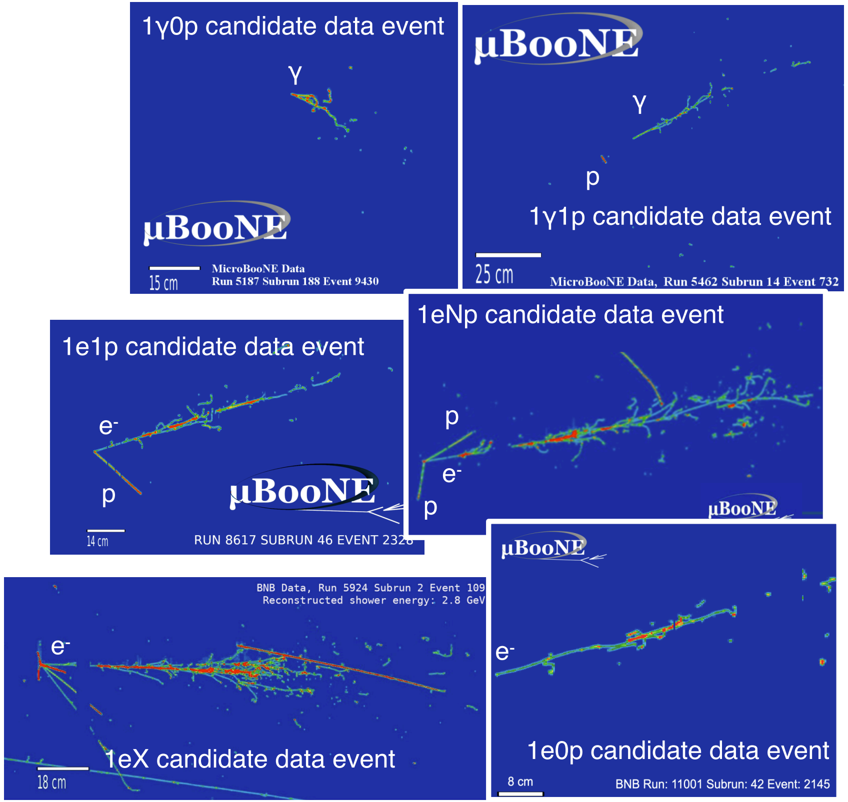


469 m from the Booster Neutrino Beam target

8 GeV Protons

First low-energy excess search

- Four independent analyses
  - Targeting six different final states
- Single-photon analysis
  - NC Δ → Nγ hypothesis
  - 1γ0p, 1γ1p
- Searches for a ν_e excess
  - Quasi-elastic kinematics (1e1p)
  - MiniBooNE-like final states (1eNp, 1e0p)
  - All ν_e final states (1eX)



Single photons: Δ→Nγ

Several photon sources in MiniBooNE

NC π^0 misidentification

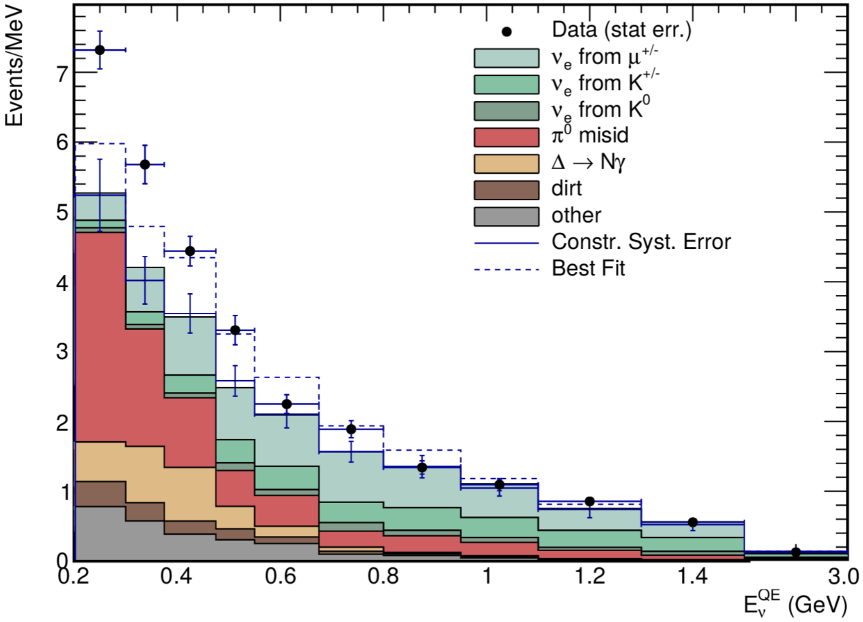
- Measured in MiniBooNE with sidebands

Interactions outside the detector

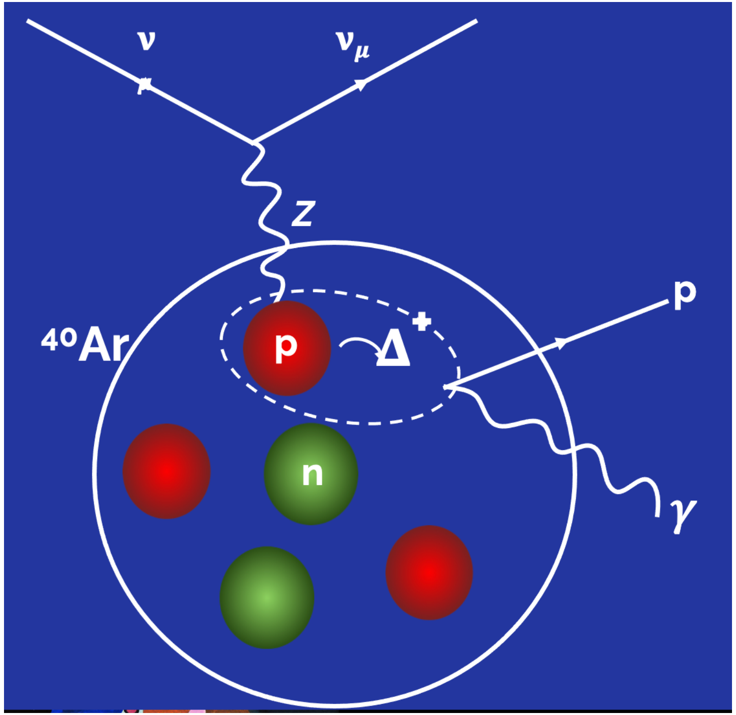
- Eliminated using beam timing and radial cuts

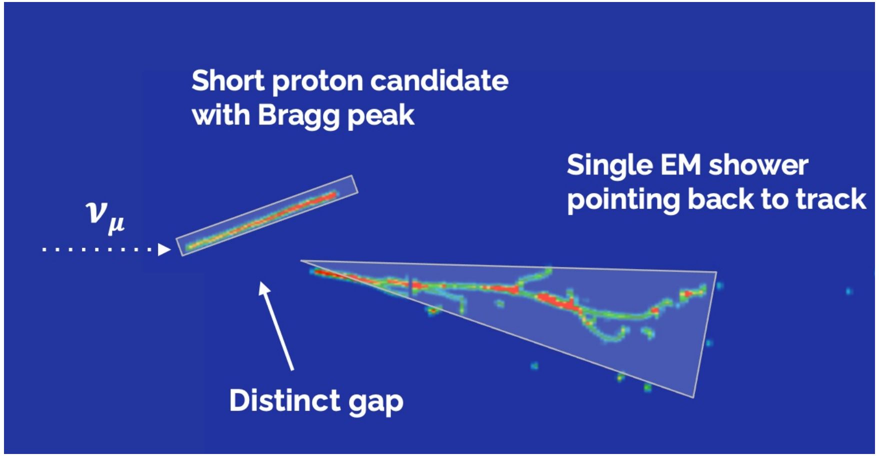
NC Δ → Nγ

- **NC delta radiative decay**
- Not constrained directly by MiniBooNE
- Used π^0 measurements and a theoretical branching ratio for the delta radiative decay



$\Delta \rightarrow N\gamma$: 1γ1p topology



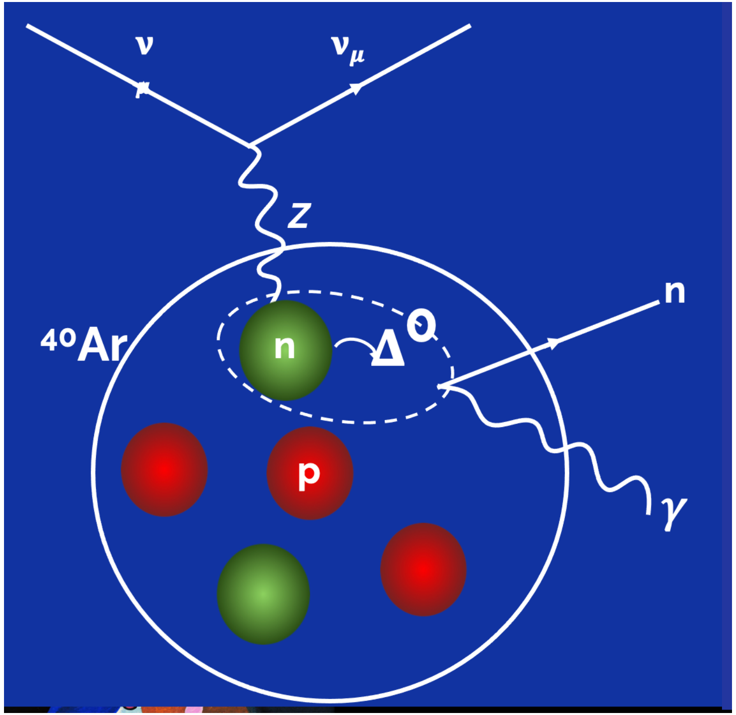


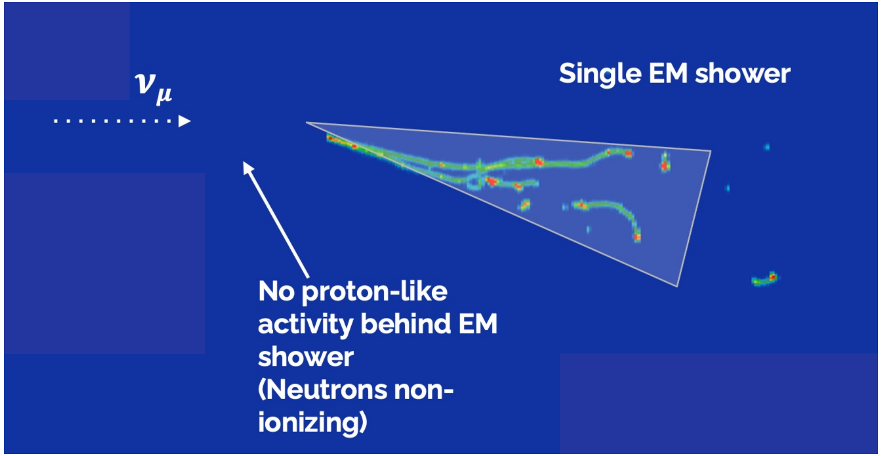
Short proton candidate with Bragg peak

Single EM shower pointing back to track

Distinct gap

Δ→Nγ: 1γ0p topology





Single EM shower

No proton-like activity behind EM shower (Neutrons non-ionizing)

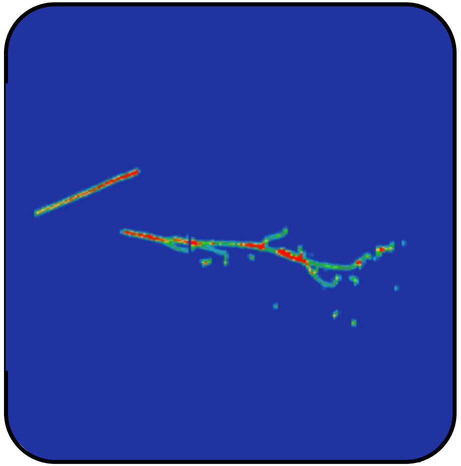
Single photon analysis

Simultaneous fit of four topologically distinct samples

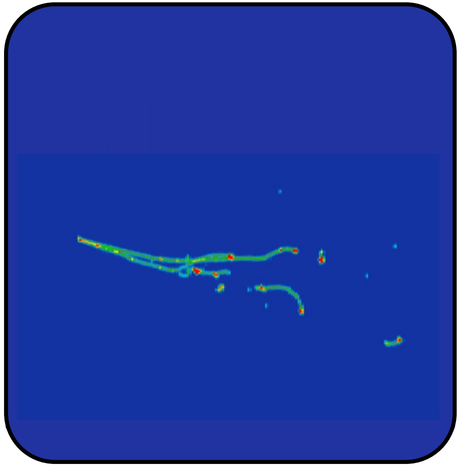
Two **NC $\Delta \rightarrow N\gamma$** rich **single-photon** selections

Two high-statistics **NC π^0 rich two-photon** selections to constrain backgrounds

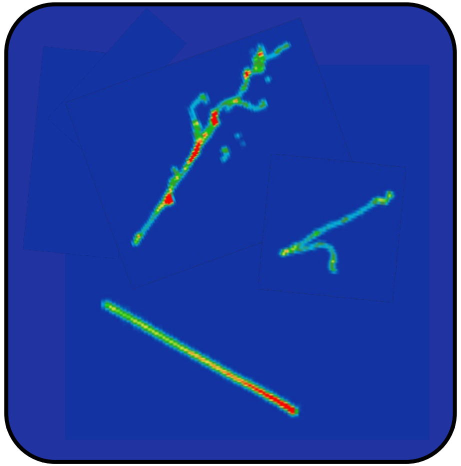
$1\gamma1p$



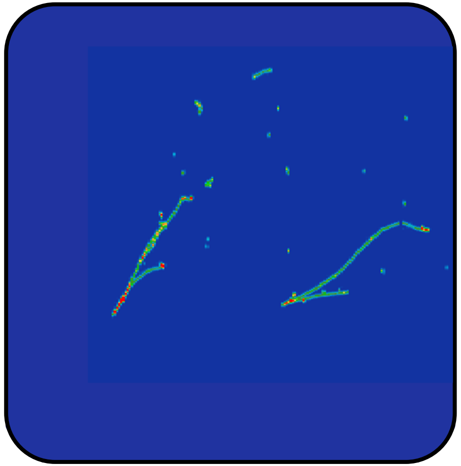
$1\gamma0p$



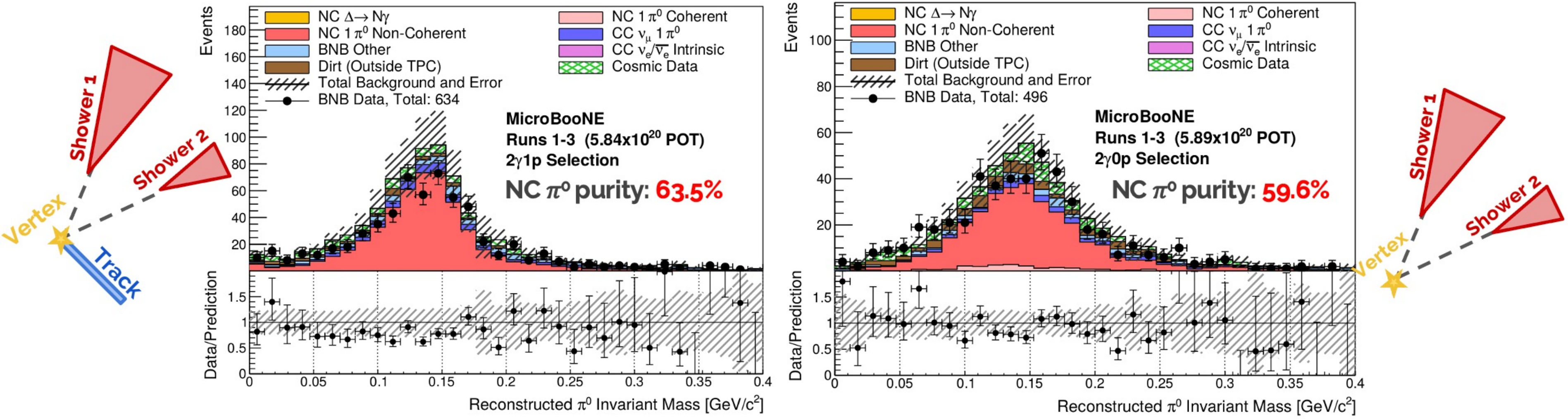
$2\gamma1p$



$2\gamma0p$



1p2γ and 0p2γ samples



High statistics: 1130 candidate π^0 interactions

Used to constrain the π^0 backgrounds in the Δ→Nγ signal samples

- And validate shower reconstruction and energy measurement

Single-photon results

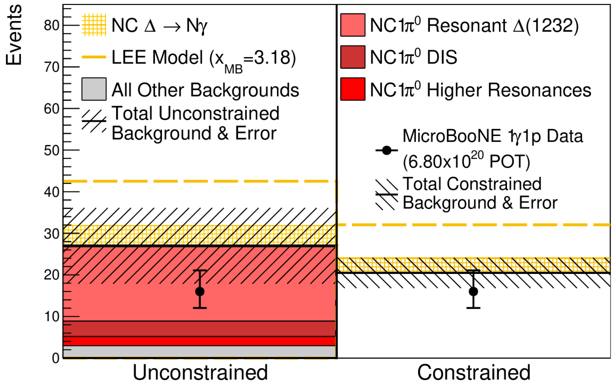
No evidence for an enhanced rate of single photons from NC Δ→Nγ decay above nominal GENIE expectations

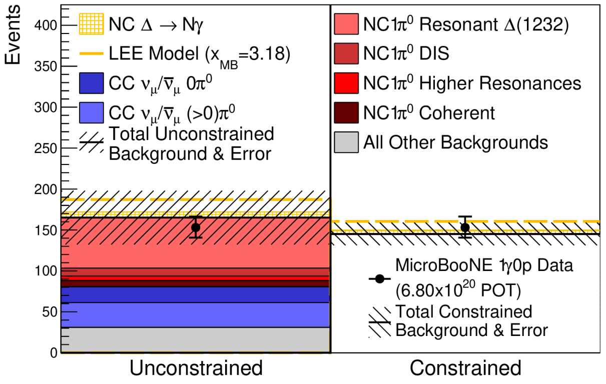
- x3.18 scaling disfavoured at 94.8% C.L.

One-sided bound on the normalisation of NC Δ→Nγ events of $\mathbf{x_\Delta < 2.3}$ (90% C.L.)

$$\mathcal{B}_{\text{eff}}(\Delta \to N\gamma) < 1.38\% \quad \text{(90\% C.L.)}$$

More than 50 times better than the world's previous limit



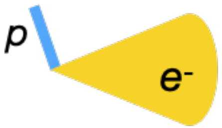


Phys. Rev. Lett. **128**, 111801 (2022) 111801

Electron search

Three independent searches across multiple final states

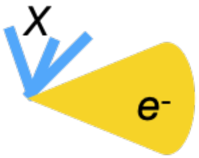
Two-body CC quasi-elastic: 1e1p



CC νe interactions without final-state pions: 1eNp0π & 1e0p0π

- Matches the topology of MiniBooNE events

Fully inclusive charged-current ν_e: 1eX



Start with muon neutrinos

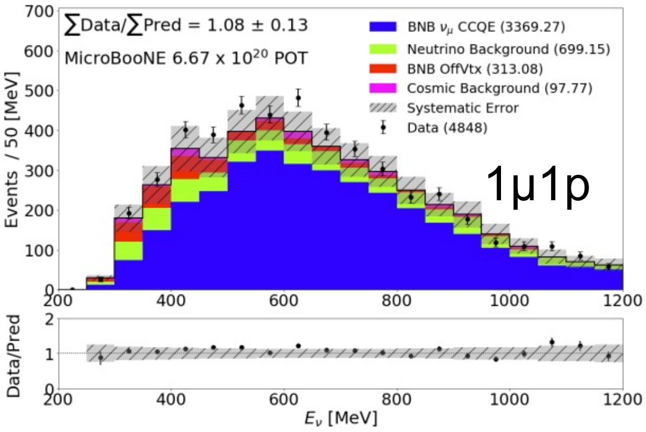
High-statistics CC ν_μ samples

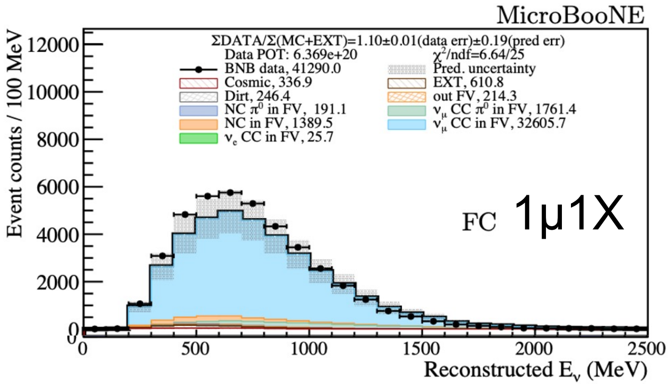
Leverage ν_μ and ν_e correlations

- Common flux parentage
- Lepton universality

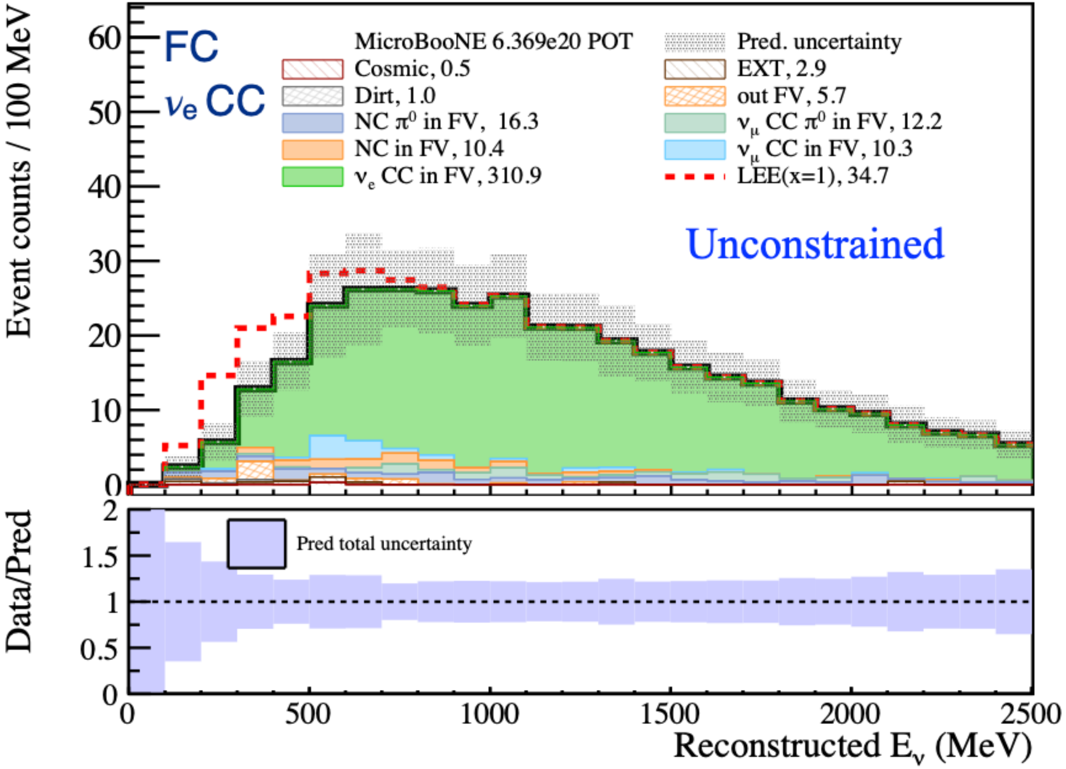
Use our ν_μ sample to create a data-driven ν_e prediction

- Systematic uncertainties incorporated through a covariance matrix
- This process reduces the uncertainty on the ν_e prediction

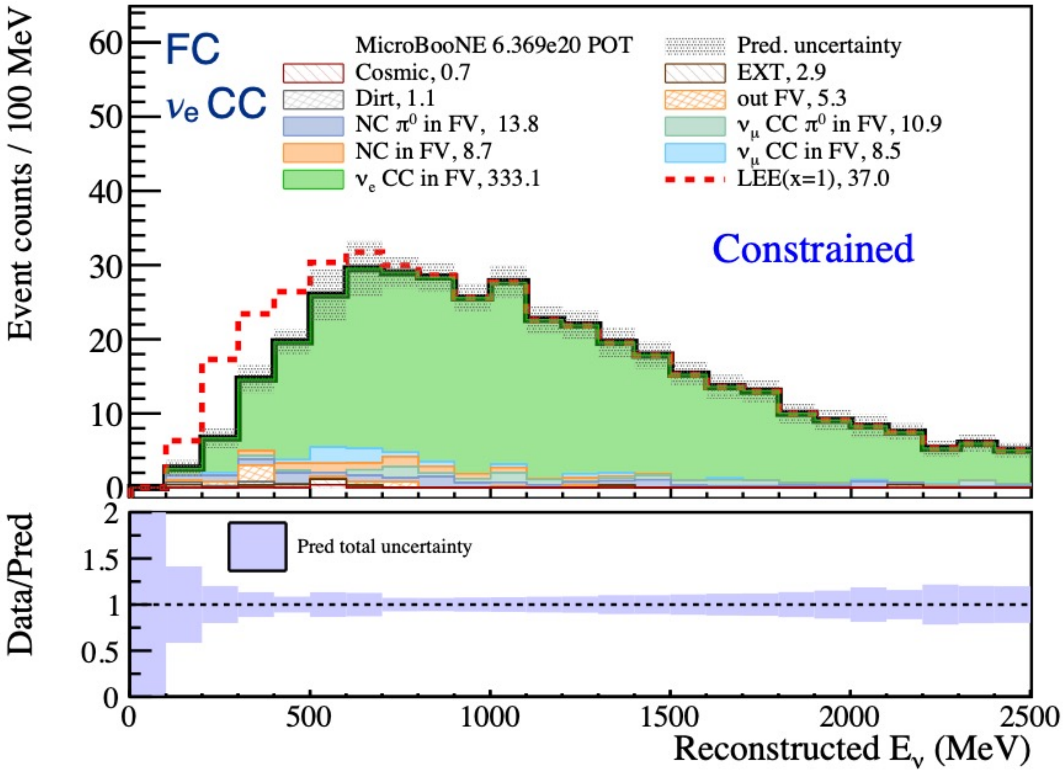




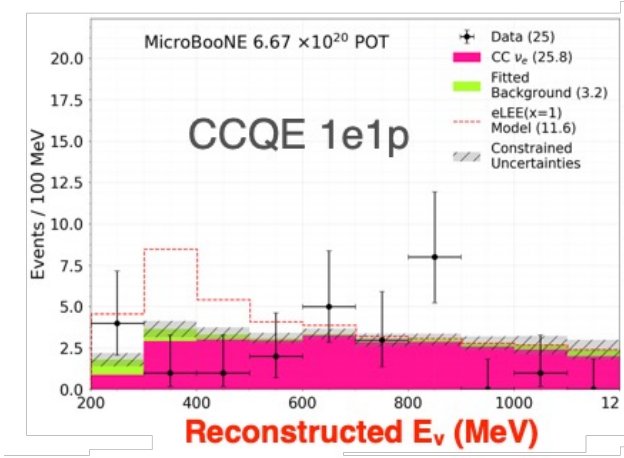
1eX prediction before constraint

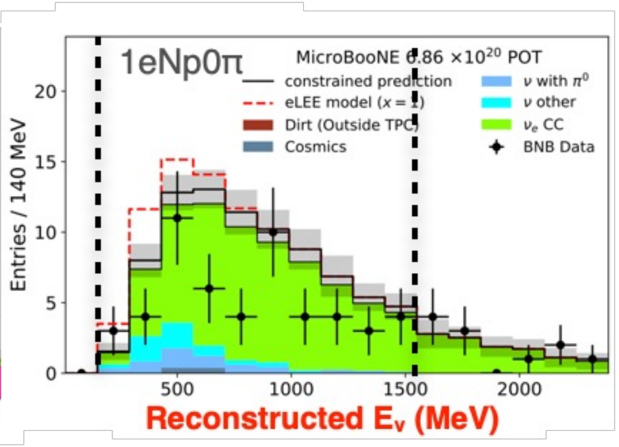


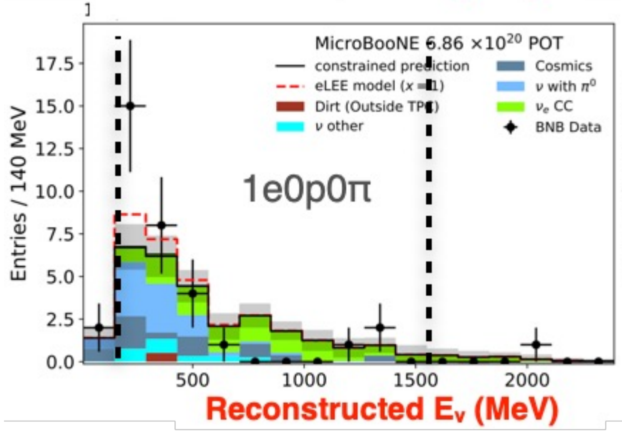
1eX prediction after constraint

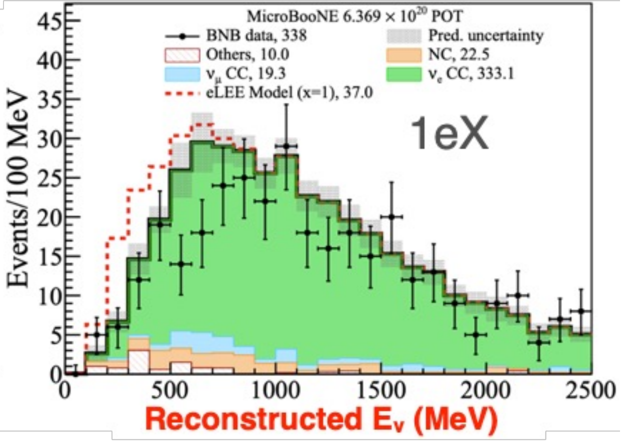


Electron results





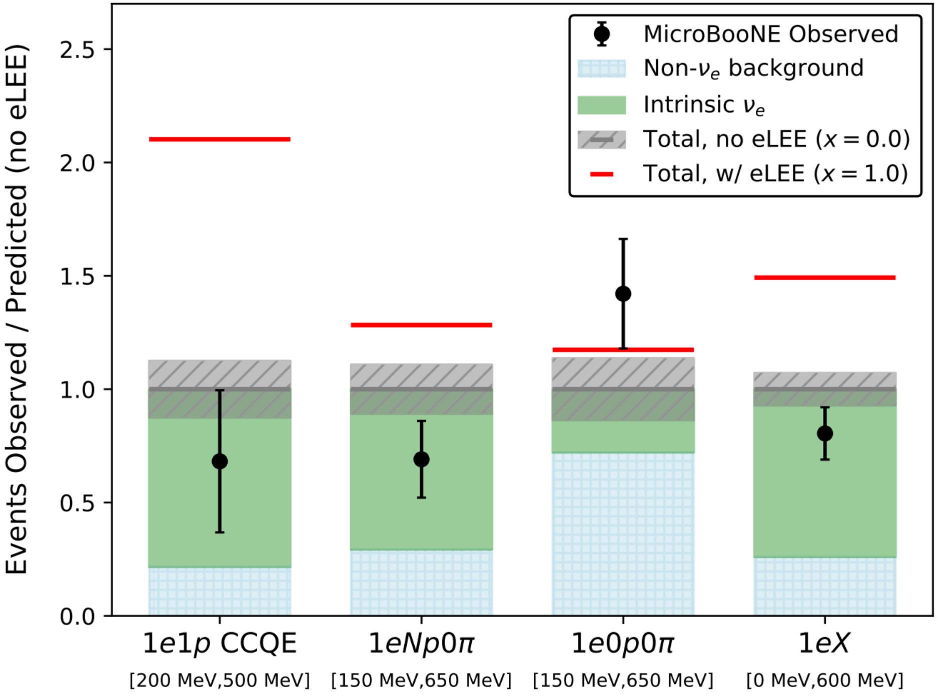




Phys. Rev. D **105**, 112003 (2022); Phys. Rev. D **105**, 112004 (2022); Phys. Rev. D **105**, 112005 (2022)

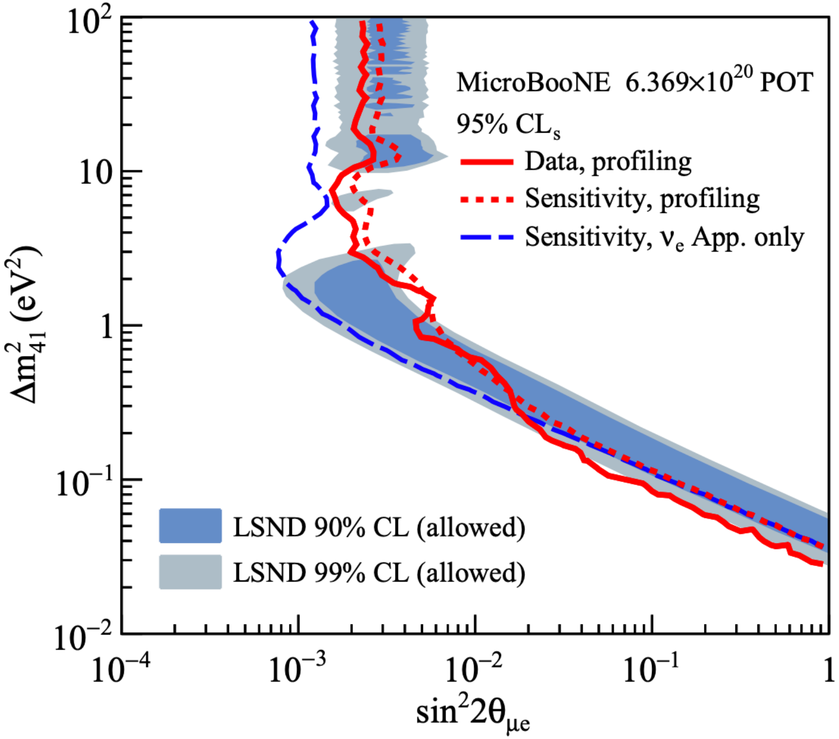
Electron results

- Observe ν_e candidate event rates in agreement with, or below, the predicted rates
- Reject the hypothesis that ν_e CC interactions are fully responsible for the MiniBooNE excess at >97% C.L. in all analyses
- Inclusive analysis rejects our median MiniBooNE electron-excess model at 3.75σ



Phys. Rev. Lett. **128**, 241801 (2022)

MicroBooNE oscillation limits

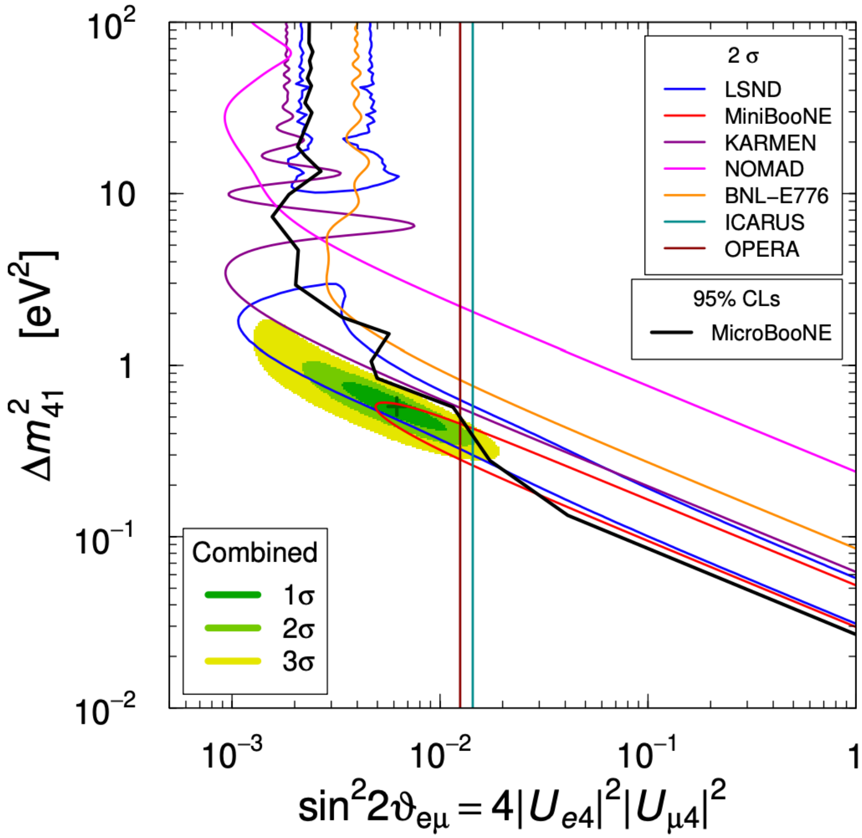


With the first half of our data, we are excluding part of the LSND allowed region

- Note that a degeneracy between ν_e disappearance and appearance reduces our sensitivity
- But we will use the NuMI beam – a second baseline – to overcome this in a future analysis

arXiv:2210.10216, under review by Phys. Rev. Lett.

MicroBooNE and the global fits



Giunti, NOW 2022

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$\nu_\mu \rightarrow \nu_e$ is not the only observable

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

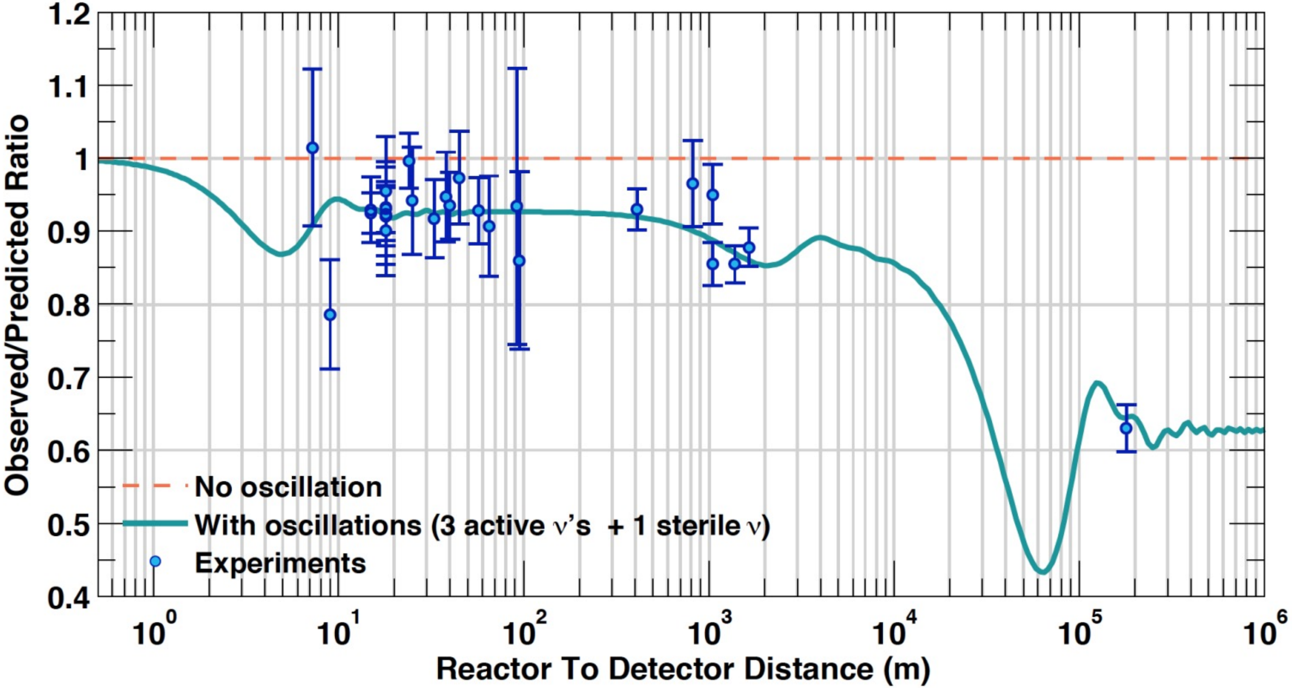
θ_{14}: ν_e disappearance
θ_{24}: ν_μ disappearance
θ_{34}: ν_τ disappearance

$\sin^2(2\theta_{14})\sin^2\theta_{24}$: $\nu_\mu \rightarrow \nu_e$

The simplest sterile neutrino oscillation model has a single sterile flavour+mass state

- Introduces three new mixing angles

Reactor neutrinos

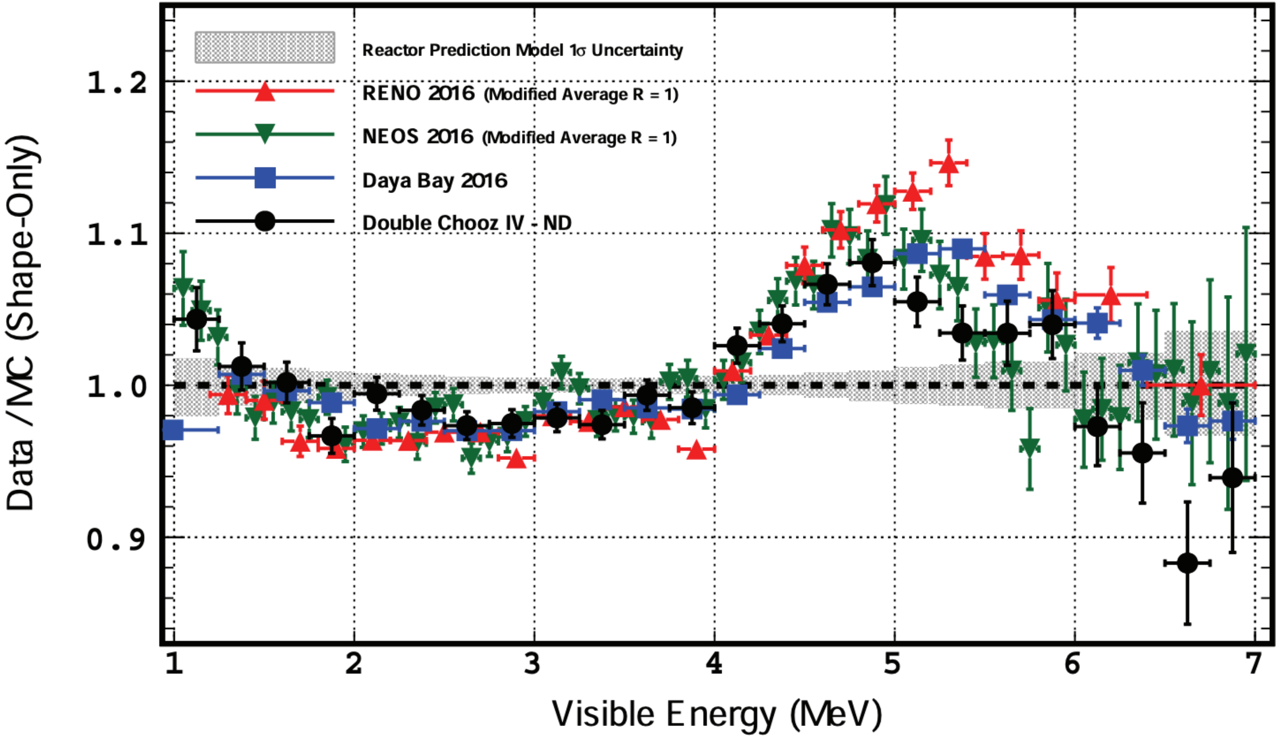


In 2011 recalculations of reactor neutrino fluxes left historic experiments now seeing few-percent deficits at ~3σ significance

- Non-zero θ_{14}?

Mueller et al., Phys. Rev. C **83**, 054615 (2011); Huber, Phys. Rev. C **84**, 024617 (2011)

Reactor neutrinos



- But can we trust reactor flux predictions at the few-percent level?

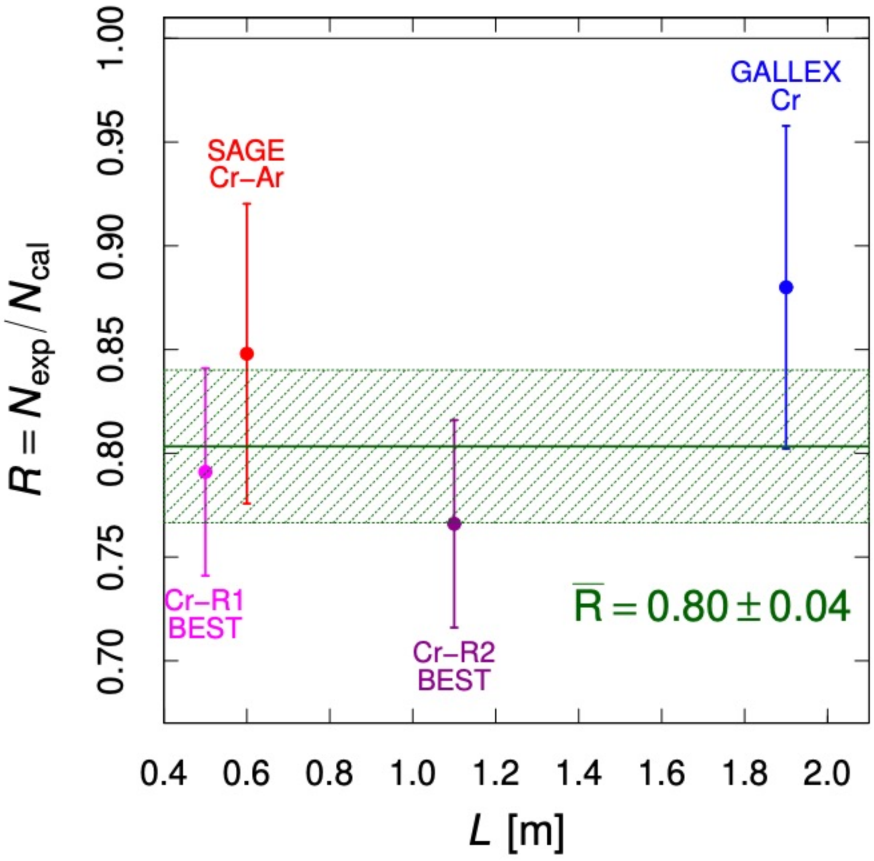
Gallium detectors

Calibration runs with ^{51}Cr and ^{37}Ar sources at the SAGE and GALLEX solar-neutrino experiments

- Recently confirmed by the BEST experiment

Deficits of ν_e interactions seen with respect to the expectation

- Requires dead-reckoning of cross-sections, but all cross-section models confirm the deficit
- No clear oscillatory pattern seen as a function of distance



Barinov *et al.*, Phys. Rev. Lett. **128**, 232501 (2022)
Giunti *et al.*, JHEP **2022**, 164 (2022)

Electron-neutrino disappearance

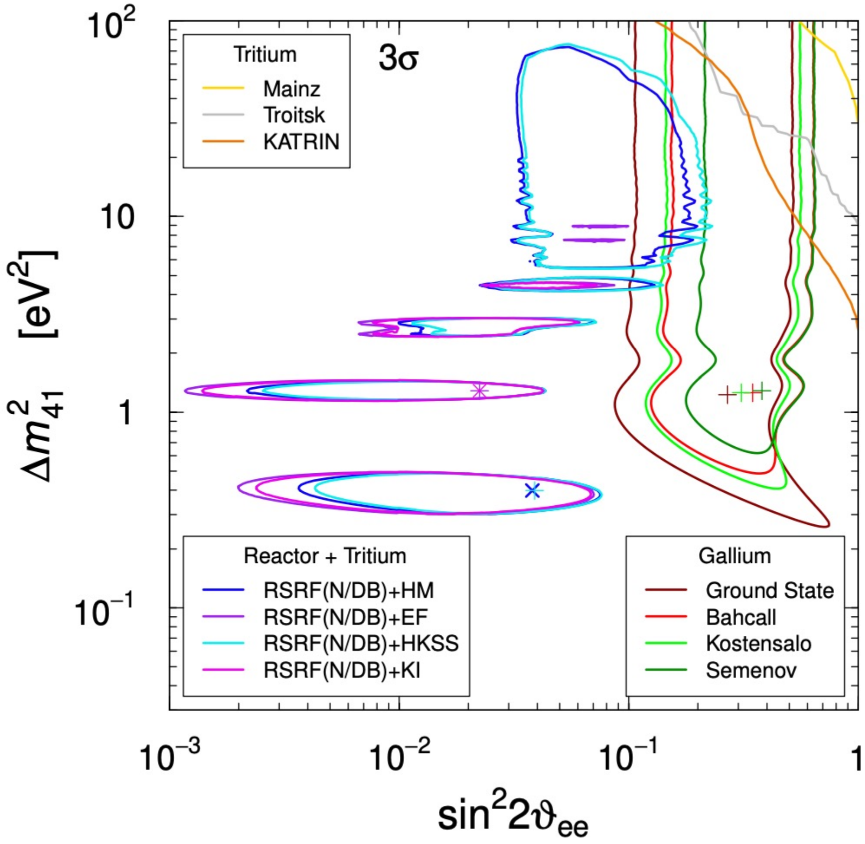
Tritium experiments (such as KATRIN) also place limits at high Δm²

$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 .$$

No flux or cross-section model choices can get the reactor and gallium anomalies to agree on a sterile-neutrino cause

- And the gallium anomaly is in tension with bounds from solar neutrinos

N.B. the Neutrino-4 anomaly has received some criticism, and is largely ruled out by more recent measurements



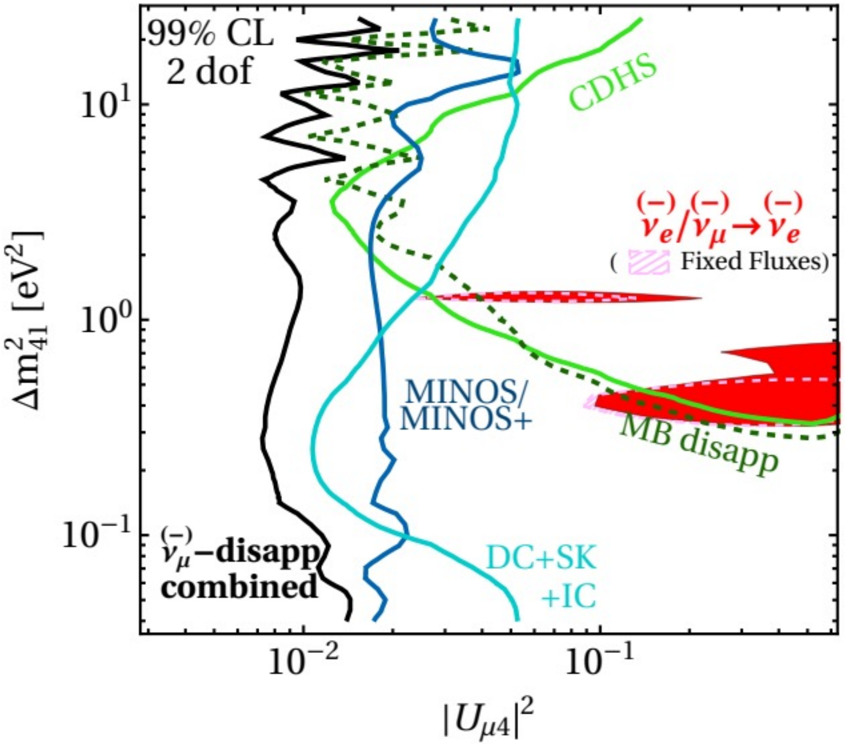
Giunti *et al.*, JHEP **2022**, 164 (2022)

Muon neutrino disappearance

If $\nu_\mu \rightarrow \nu_e$ happens, then muon neutrinos must disappear

Here, the red area shows the level of ν_μ disappearance required to explain the $\nu_\mu \rightarrow \nu_e$ appearance in LSND, given the ν_e-disappearance allowed regions

- The ν_μ disappearance results strongly exclude this red region
- Adding more neutrinos (beyond 3+1) does not help



Dentler *et al.*, JHEP **08**, 010 (2018)

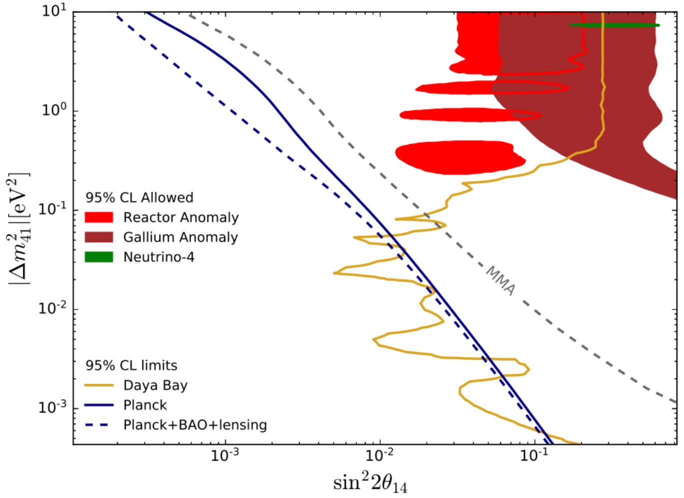
Cosmological constraints

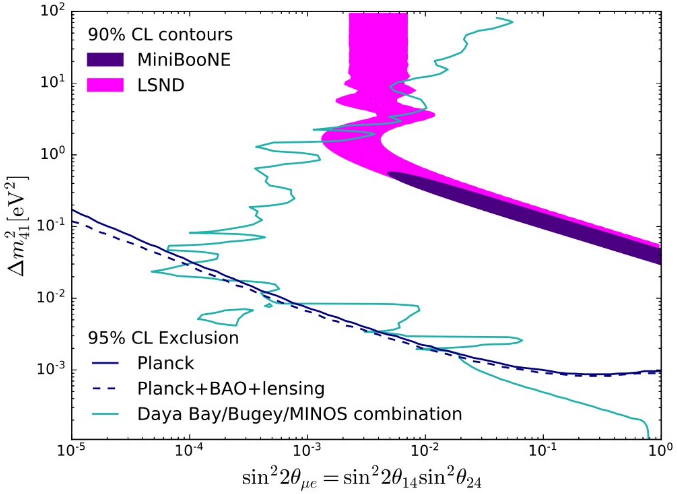
Planck data sets strong limits on the effective neutrino mass

- This mass would increase if active flavour states mixed into heavier mass states

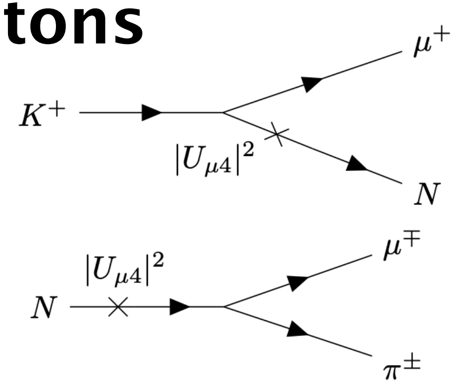
These strong limits also exclude the parameter space needed to explain the $\nu_\mu \rightarrow \nu_e$ and ν_e-disappearance anomalies with sterile neutrinos

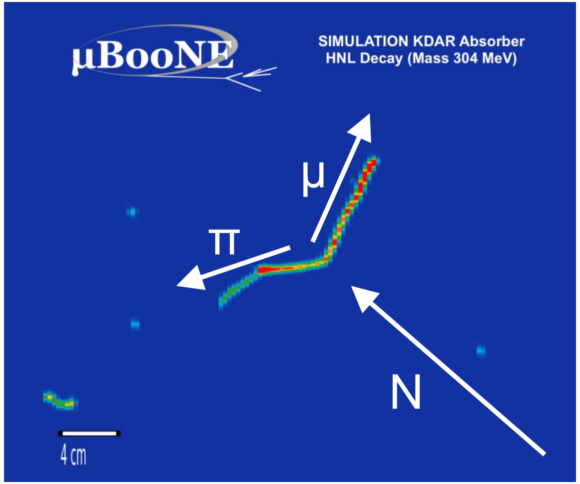
Eur. Phys. J. C **80**, 8 (2020)





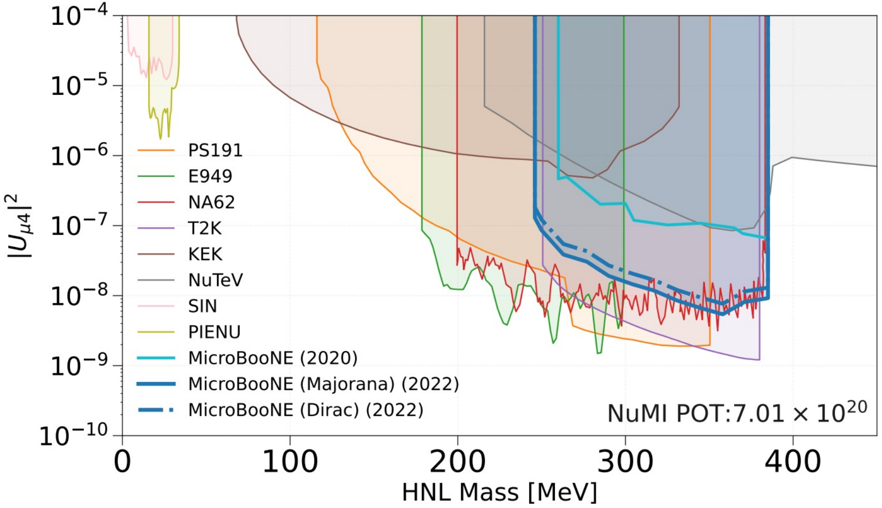
Heavy neutral leptons





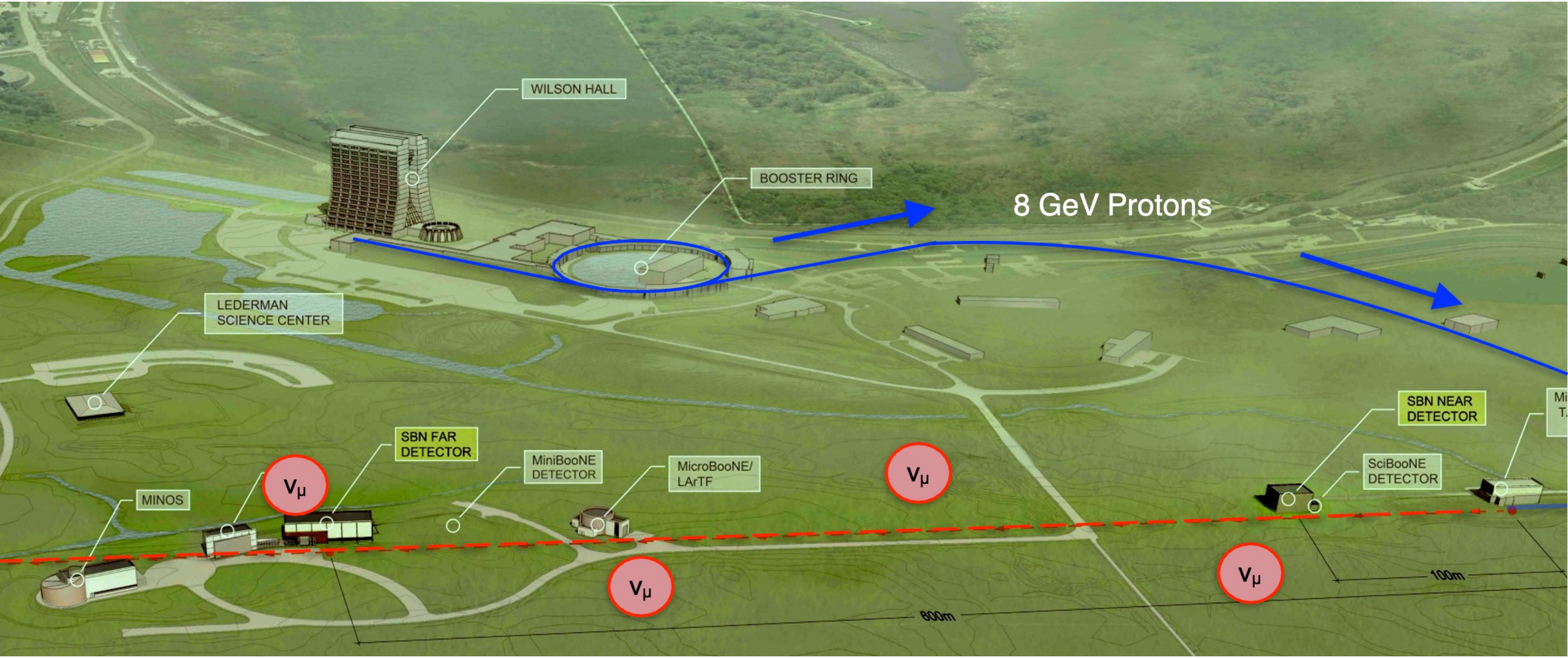
Many theoretically-favoured sterile neutrinos are MeV-scale or higher in mass

- ➢ We can look for these in short-baseline experiments as they would be produced in the beam and decay in the detector



arXiv:2207.03840, accepted by Phys. Rev. D

Onwards to the SBN programme



The SBN programme

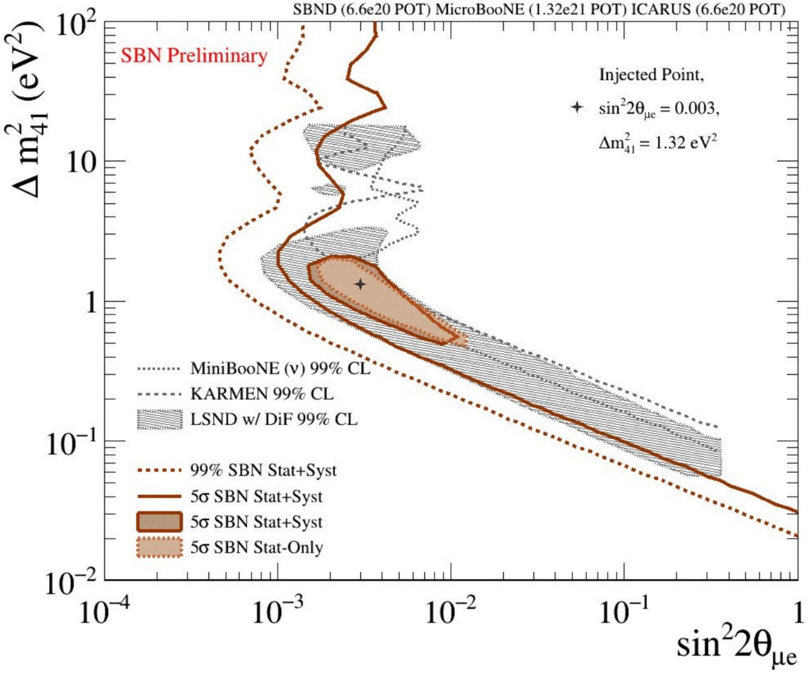
MicroBooNE alone still has half its data to analyse

- And by including data from the NuMI can resolve degeneracies between ν_e appearance and disappearance
- Expect new results, with significantly improved sensitivity, next year

The SBN programme will take a three-detector approach to the sterile-neutrino problem

- With multiple baselines, the need to dead-reckon cross-sections and fluxes cancels out

ν_e appearance SBN sensitivity



Summary

Neutrino physics is hard!

- Dead-reckoning fluxes and cross sections is fraught with challenges
- Extensive neutrino cross-section programmes (e.g. MicroBooNE, SBN) are essential
- Multiple baselines (i.e. near detectors) are essential to cancel model uncertainties

There are numerous appearance and disappearance anomalies that can individually be explained by a light sterile neutrinos

- But looked at together, no sterile neutrino can fit all the pieces of the puzzle

Heavy sterile neutrinos are theoretically favourable

- An active experimental programme is ongoing here

We cannot yet explain away many of the anomalies

- But future programmes, such as the SBN programme, will continue to shed light on the short-baseline behaviour of neutrinos