MicroBooNE results on Short Baseline Neutrino Anomalies

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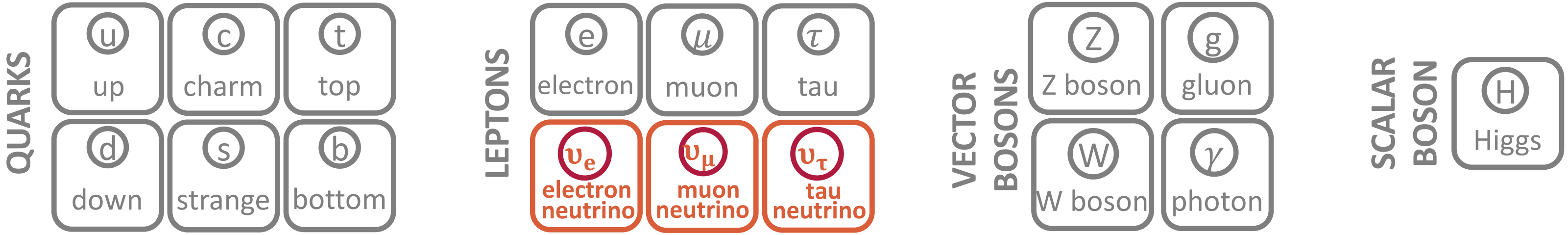
Neutrinos: knowns and unknowns

- Weakly interacting neutral leptons (+ their antiparticles)



- In the **Standard Model**:
  - They are massless, but we have observed **oscillations** (due to mixing)
  - Three flavour active neutrinos, could there be additional **sterile** neutrinos?

Neutrinos: oscillation experiments

Precision measurements

E.g. mass ordering, mass differences and mixing parameters, CP violating phase

→ *Long-baseline experiments*

Investigation of anomalies

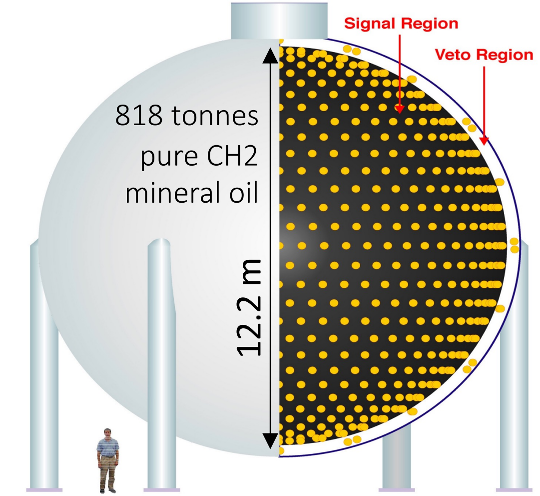
Many observed anomalies could point to eV-mass-scale sterile neutrino

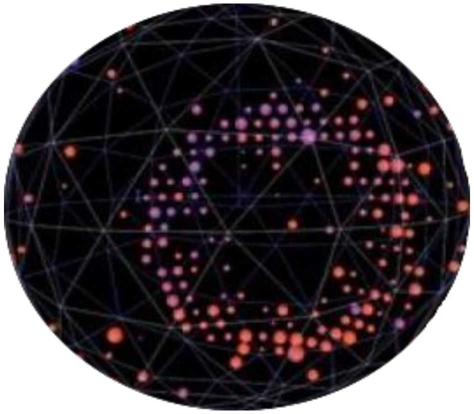
- Radioactive source experiments (GALLEX, BEST, SAGE)
- Neutrino-4
- The LSND/MiniBooNE Low Energy Excess (LEE)

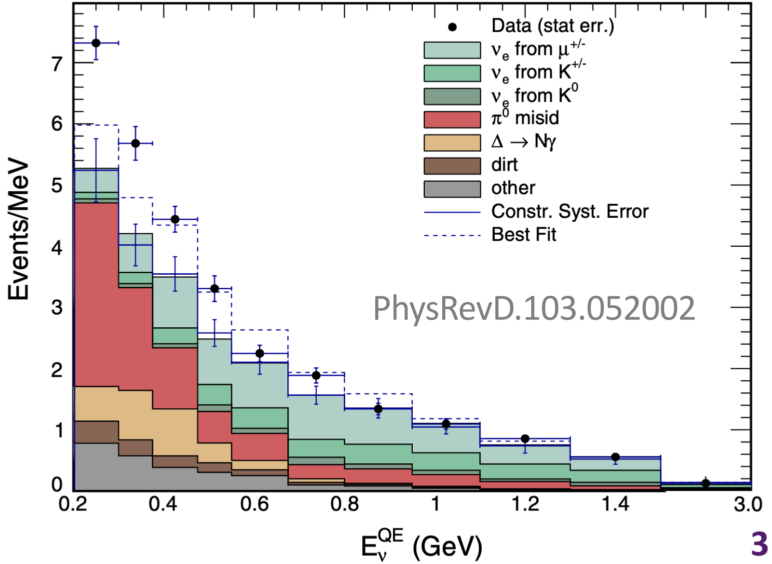
→ *Short-baseline experiments*

MiniBooNE low-energy excess

- Fermilab 8 GeV protons Booster Neutrino Beam (BNB)
- 1520 photomultiplier tubes detect Cherenkov and scintillation light
- Electrons and single (or pairs of collimated) photons, produced in background processes, have the same fuzzy ring signature





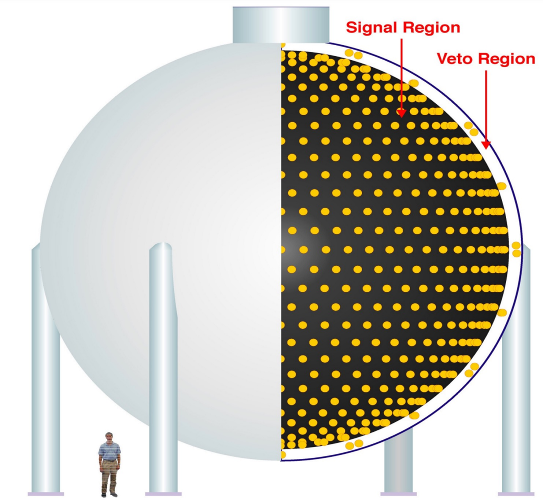


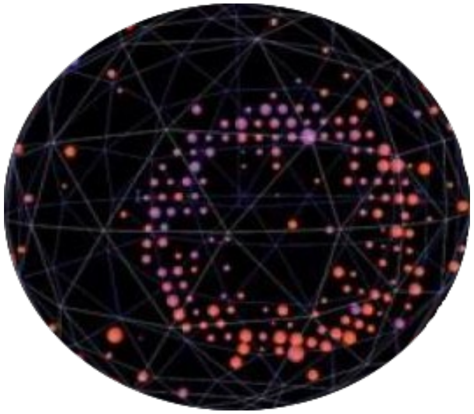
MiniBooNE low-energy excess (2)

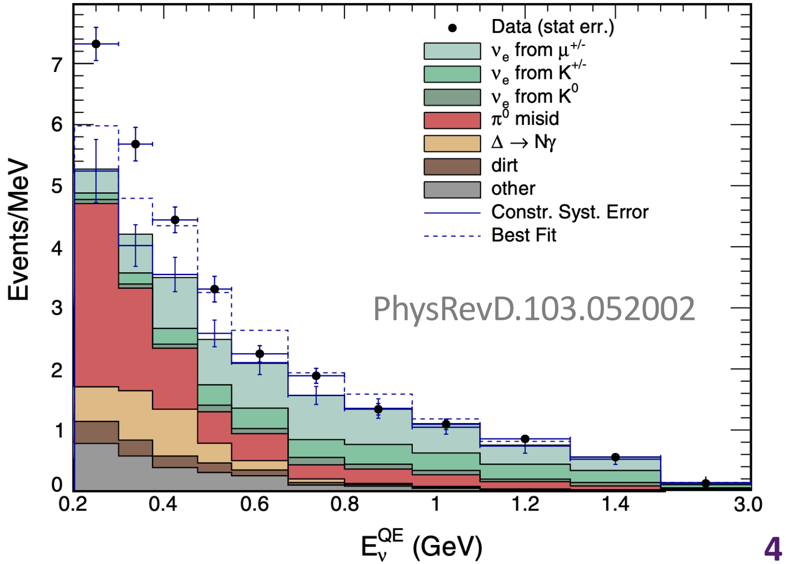
4.8 σ excess in the range $200 < E_{\nu}^{QE} < 1250$ MeV in both ν and $\bar{\nu}$ mode.

Oscillations between active and a light sterile ~1 eV mass scale neutrino?

Excess of electromagnetic background?



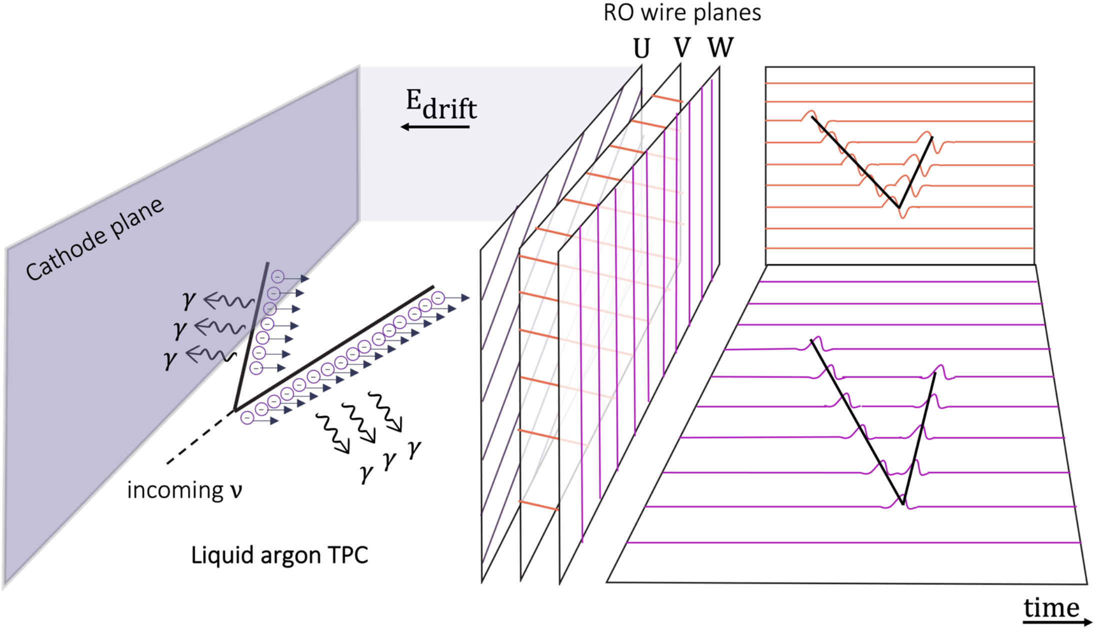




The MicroBooNE detector

Liquid Argon Time Projection Chamber (LArTPC): high-resolution imaging + calorimetry

- Use scintillation and ionization to find 3D position of particles and interactions
- Drift charge recorded by several readout (RO) wire planes, with different orientations, forming images
- Light collected by photon detection system



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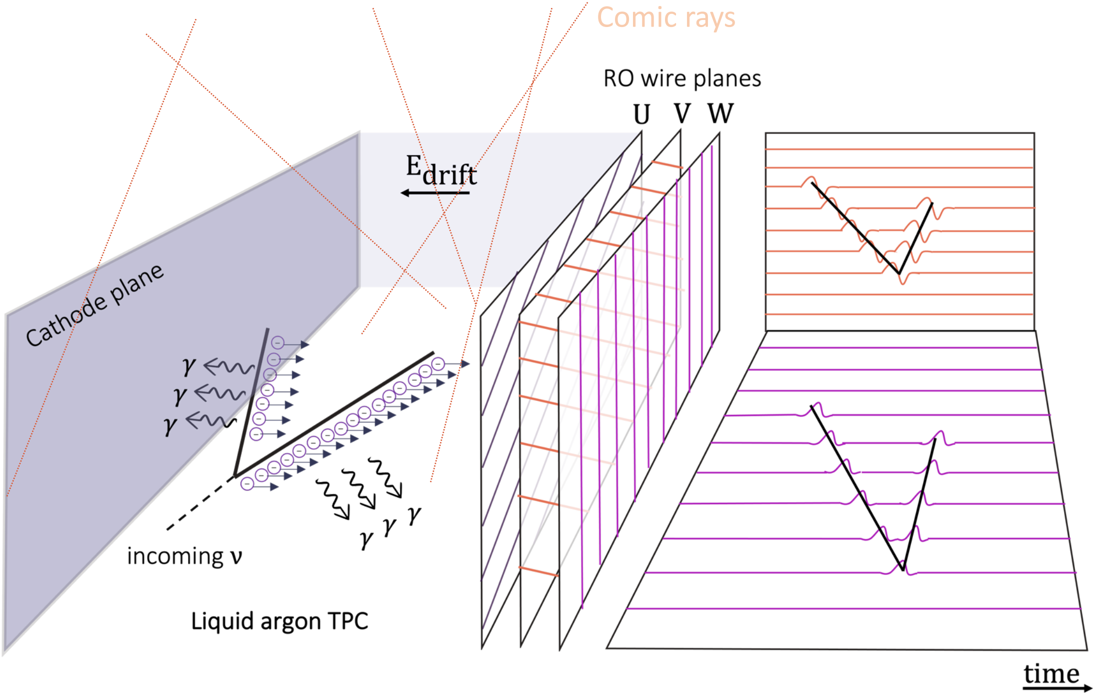
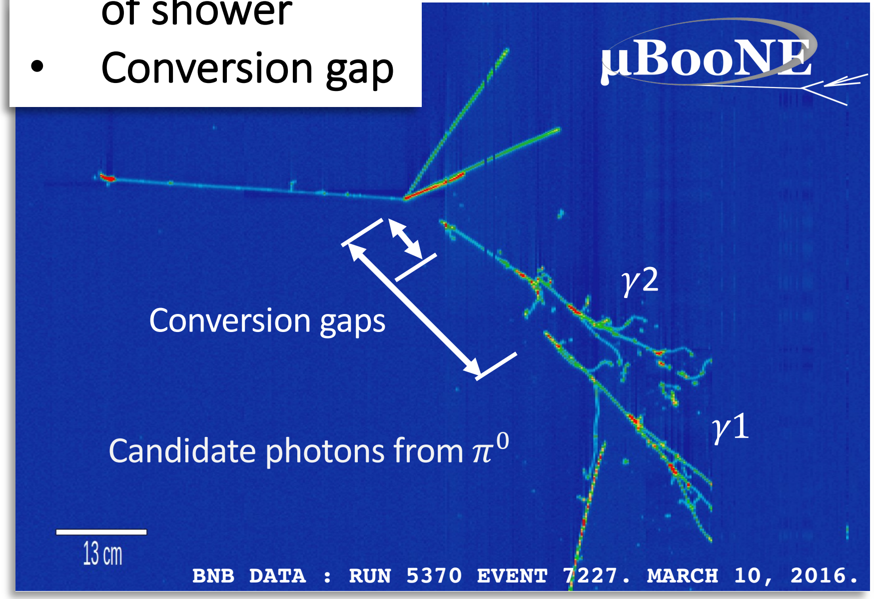


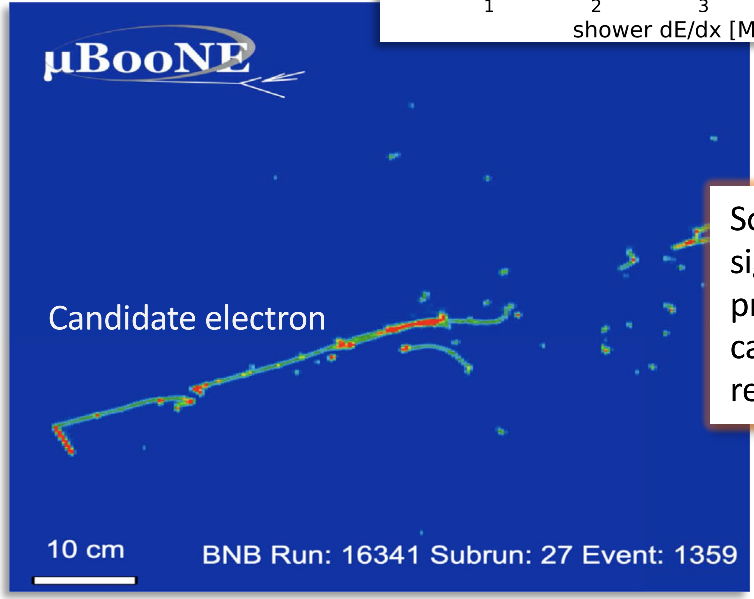
The MicroBooNE detector (2)

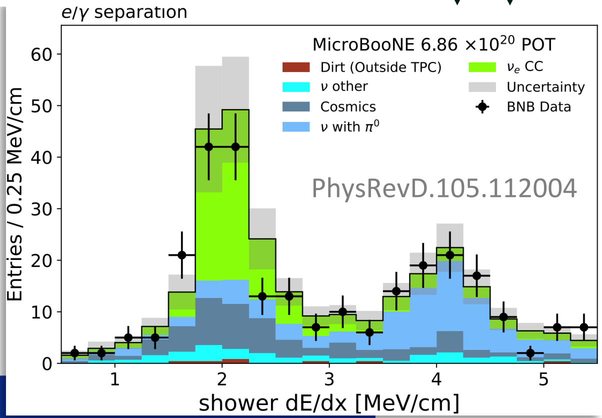
3D reconstruction and ID of different particle types

e/γ separation:

- dE/dx at start of shower
- Conversion gap



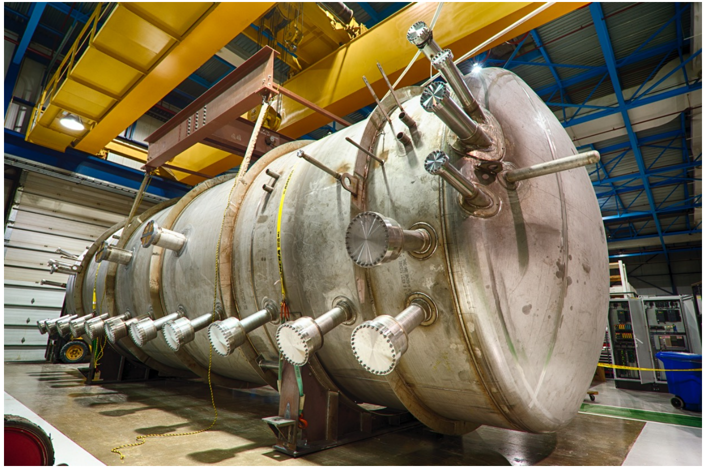


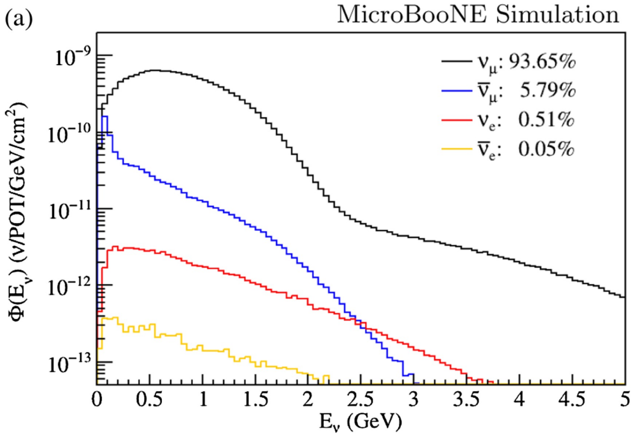


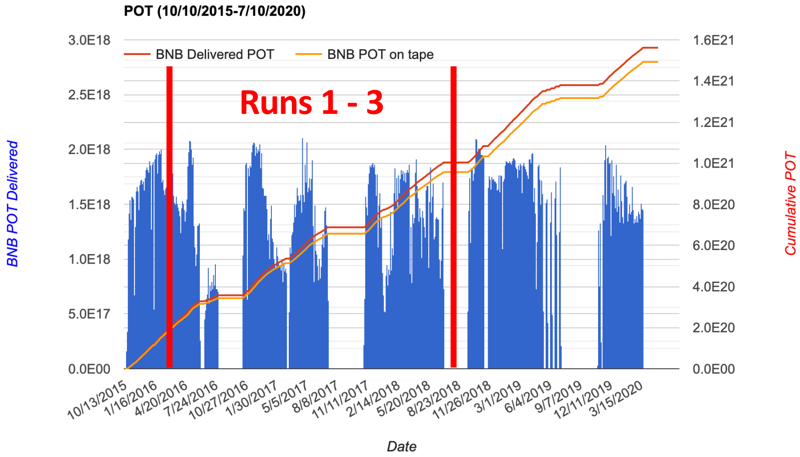
Sophisticated signal processing, calibration and reconstruction

The MicroBooNE detector (3)

- 2.56 m x 2.32 m x 10.36 m
- 85 tonnes of liquid argon, 273 V/cm E field
- Wire spacing 3 mm, wire angles 0, ± 60 deg
- 32 PMTs, O(ns) time resolution







Largest sample of ν_e interactions on argon in the world

MicroBooNE test of the MiniBooNE LEE

1. Construct model from MiniBooNE dataset (via unfolding or simple scaling)
   (MicroBooNE and MiniBooNE both at BNB; similar L/E)

2. Apply to MicroBooNE simulation to construct LEE hypothesis

3. Hypothesis test: are observations compatible with MiniBooNE LEE model?

Semi-inclusive CC $1eXp0\pi$
Fully inclusive CC $1e$X
Exclusive CCQE-like $1e1p$

Single electron

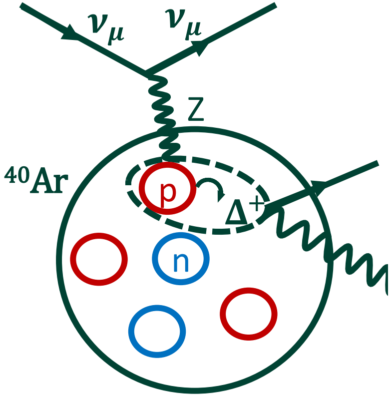
Single photon

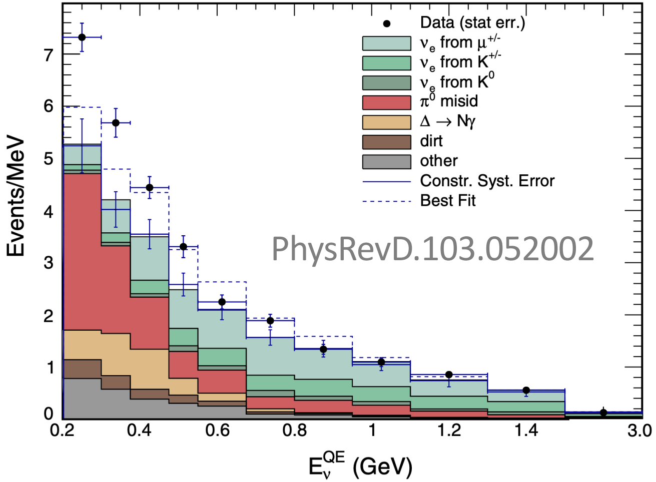
NC $\Delta \rightarrow N\gamma$

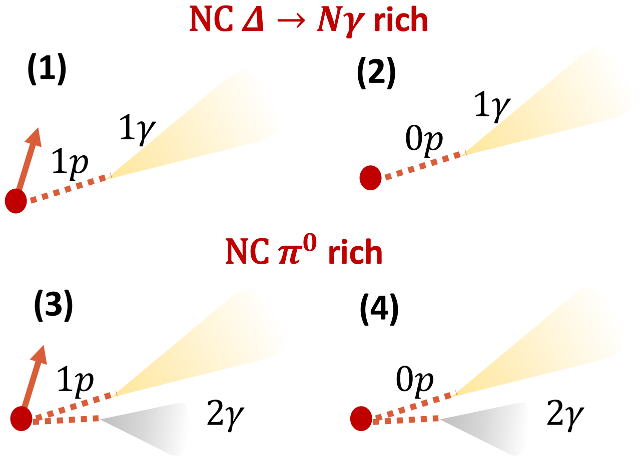
Blind analyses

NC Δ→ Nγ single photon search

- Previously never been directly observed in neutrino scattering
- Dominant background at low energy as found by MiniBooNE
- Shape of excess consistent with scaling this background × 3.18
- Four topologically distinct samples



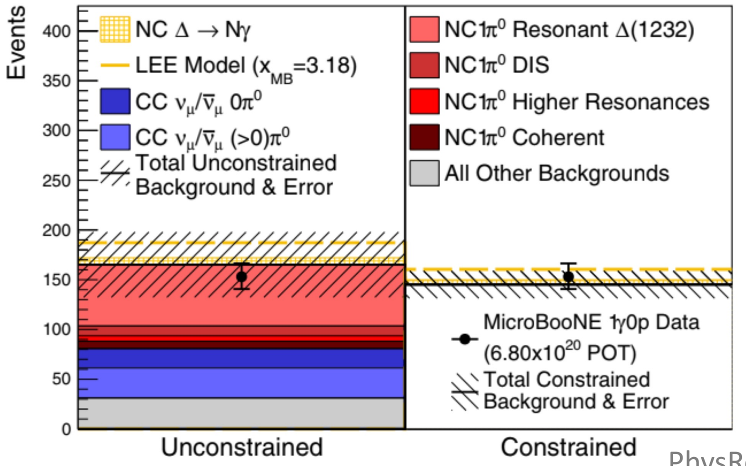




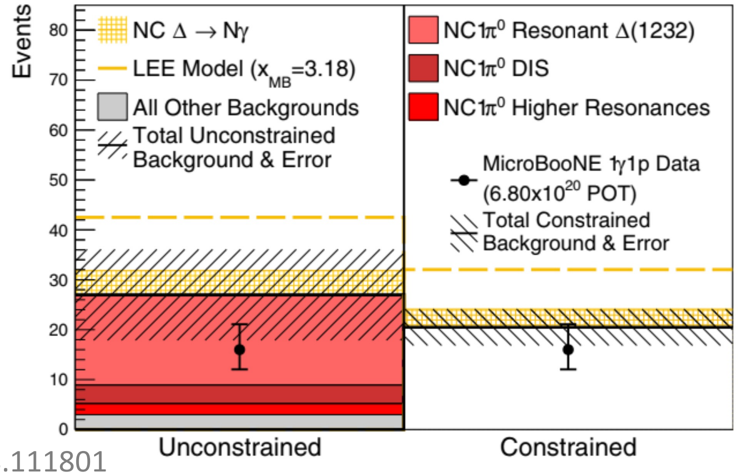
NC $\Delta\rightarrow N\gamma$ single photon search (2)

- Single bin counting experiments: no evidence for an enhanced rate of single-photons from NC $\boldsymbol{\Delta}\rightarrow N\gamma$ decay, above nominal generator expectations
- Data rejects the LEE model hypothesis, agrees with nominal prediction at 94.8% CL
- Most stringent limit on eff. branching fraction: $\mathrm{B}(\mathrm{NC}\,\Delta\rightarrow N\gamma) < 1.38\%$ (90%CL)

$1\gamma0p$



$1\gamma1p$



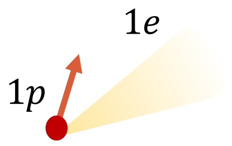
PhysRevLett.128.111801

Single electron searches

1. Exclusive

CCQE-like $1e\ 1p$

Dominant process at low energy



Deep Learning reconstruction

PhysRevD.105.112003

2. Semi-inclusive

CC $1e\ \mathrm{X}p\ 0\pi$

X=0, ≥1 combined match MiniBooNE electron-like event signature

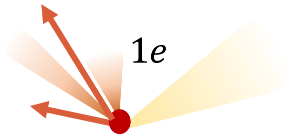
Pandora reconstruction

PhysRevD.105.112004

3. Fully inclusive

CC $1e$ X

Highest statistic ν_e analysis



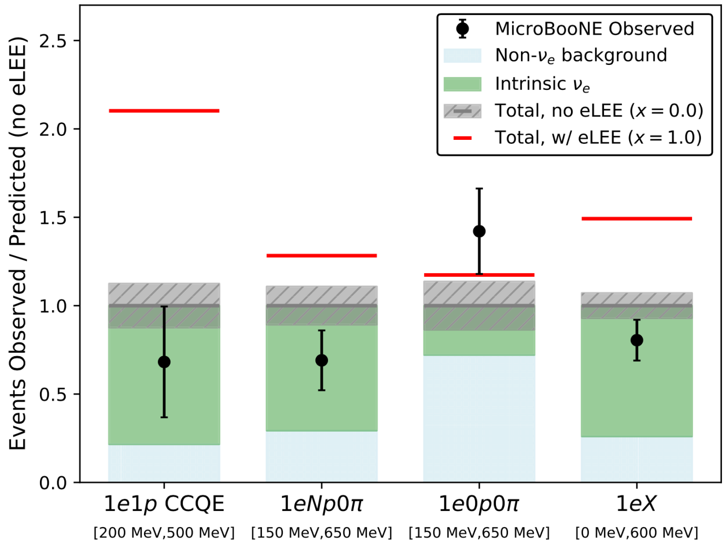
Wirecell reconstruction

PhysRevD.105.112005

- Common beam and detector simulation
- Common framework for flux, cross sections and detector systematics
- Systematics constrained with high stats samples (ν_μCCQE, ν_μCC, ν_μCC/NC π^0)

Single electron searches (2)

- Except for 1e0p0π (seeing excess at low energy due to low sensitivity), deficit is observed
- Interpretation of MiniBooNE's observed LEE signature as CC ν_e disfavoured



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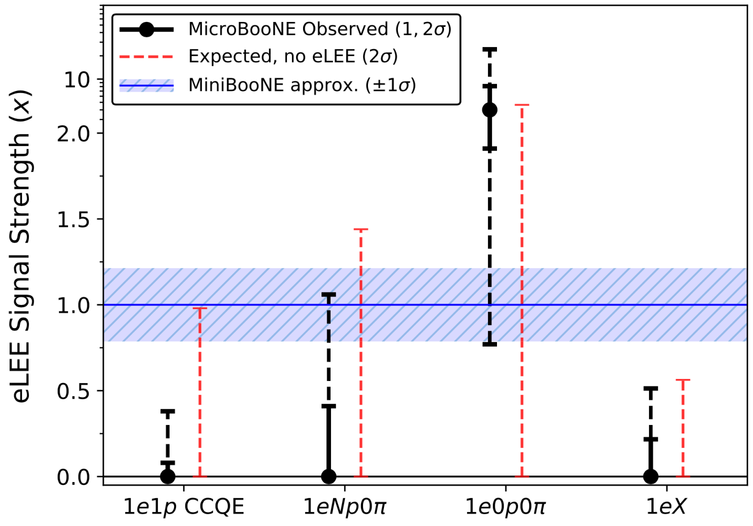
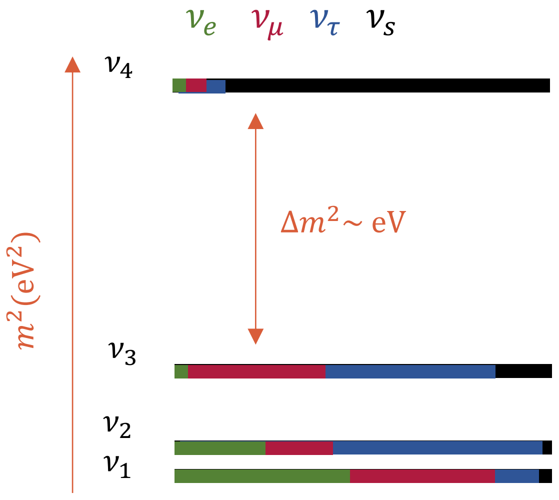


Combining 1e Np 0π and 1e 0p 0π gives 0.36 best fit signal strength

3+1 Oscillation Analysis

- MicroBooNE results disfavor hypothesis that MiniBooNE LEE originates solely from an excess of ν_e interactions
- Additional mechanisms required! **Mixing of 3 active + 1 sterile neutrino?**



Previous experiments performed appearance or disappearance only searches

MicroBooNE: **Search for eV-scale sterile neutrino oscillations in a framework with both appearance and disappearance**

4×4 unitary PMNS matrix
Additional parameters in 3+1 mixing scenario:

- $\theta_{14}, \theta_{14}, \theta_{34}$ (mixing angles)
- δ_{14}, δ_{34} (Dirac CP-violating phases)

3+1 Oscillation Analysis (2)

- Use samples from ν_μ and ν_e inclusive LEE search; free fit parameters:

Δm^2_{41} $\sin^2\theta_{14}$ $\sin^2\theta_{24}$

- Cancellation of ν_e appearance and ν_e disappearance effects leads to degeneracy

Number of intrinsic ν_e in the flux

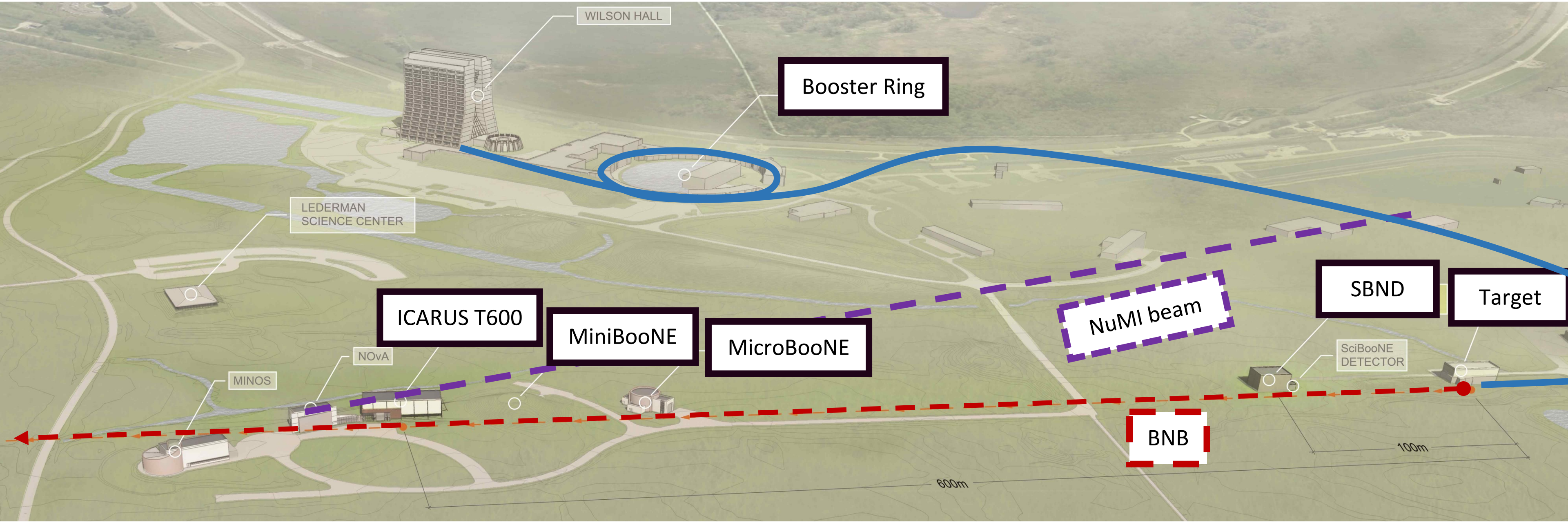
$\Delta m^2_{41} L / 4E$

$$N_{\nu_e}(E_\nu) = T_{\nu_e}(E_\nu)[1 + (R(E_\nu) \times \sin^2\theta_{24} - 1) \times \sin^2 2\theta_{14} \sin^2\Delta_{41}(E_\nu)]$$

True neutrino energy

Ratio between the number of intrinsic ν_μ and ν_e

3+1 Oscillation Analysis (3)

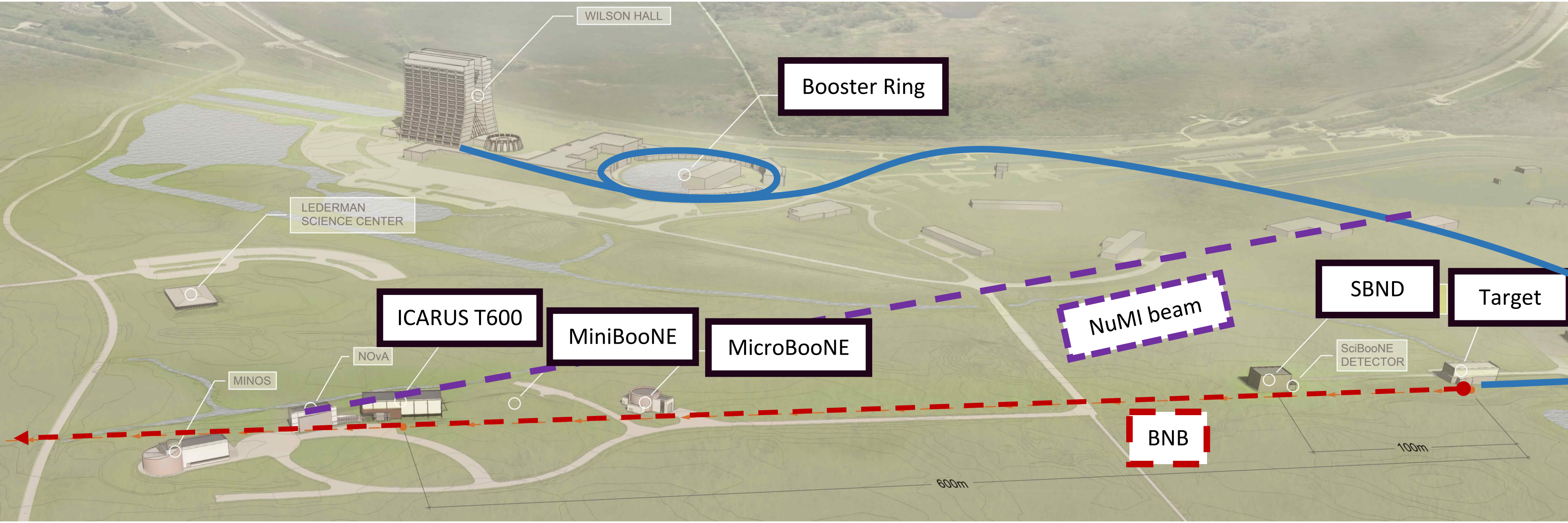


MicroBooNE can break this degeneracy by using NuMI beam in addition to BNB

Different ν_e/ν_μ fluxes → different appearance/disappearance cancellation

The Short Baseline Neutrino (SBN) programme to improve this – multi-detector, different L/E

3+1 Oscillation Analysis (4)



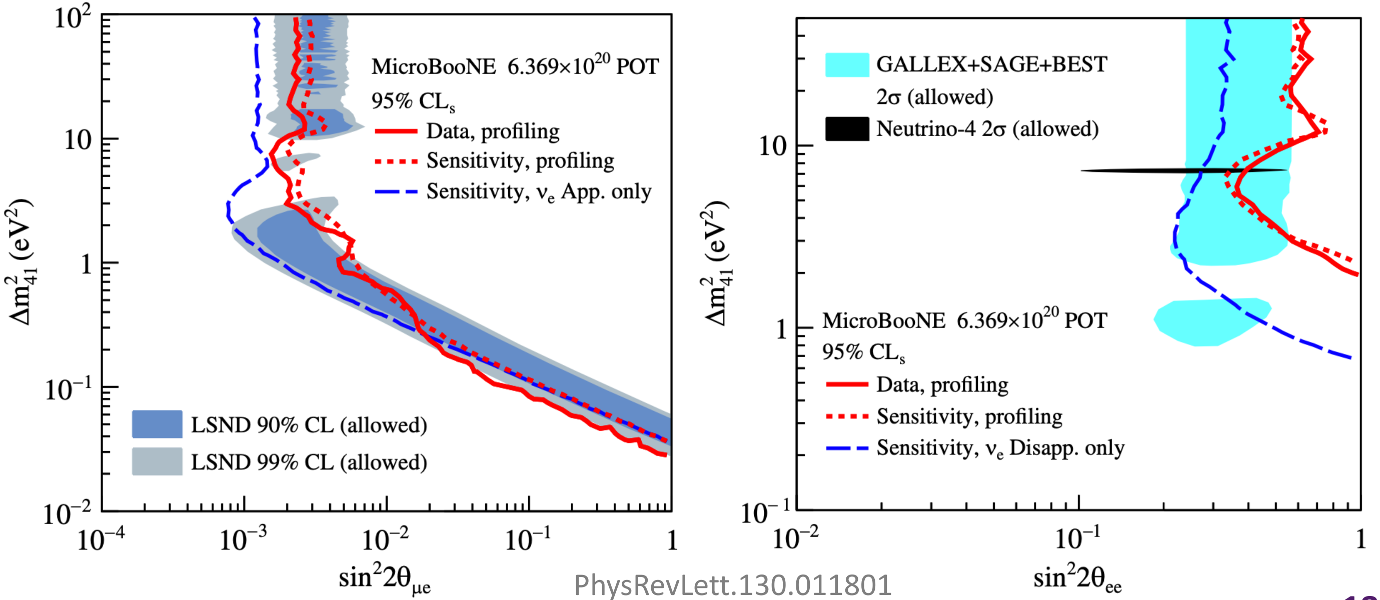
- SBND, ICARUS T600 Near and Far Detectors for SBN
- Investigate anomalies, perform sterile neutrino searches, broad short baseline oscillation and cross section measurement programme

3+1 Oscillation Analysis (4)

- Test part of sterile neutrino parameter space suggested by other experimental anomalies
- Exclusion contours in 2D parameter space obtained by profiling third dimension

Data agrees with 3ν hypothesis within 1 σ

Competitive constraints on eV-scale sterile neutrino parameter space in a LArTPC from accelerator neutrinos



PhysRevLett.130.011801

Lots more possibilities…

Single photon LEE search

Inclusive single single photon search

Search for pair of overlapping $e^+ e^-$

Search for pair of overlapping photons

BSM physics beyond sterile neutrinos

Dark neutrinos

Heavy neutral leptons

Dark Matter

New scalars

Conclusions

- Numerous anomalies, compatible with oscillations to a sterile eV mass-scale neutrino, observed in the past decades
- The MicroBooNE experiment at Fermilab BNB/NuMI exploits the unprecedented imaging capabilities of LArTPCs to investigate the anomalies and test the 3+1 oscillation paradigm
- First results disfavour MiniBooNE LEE model in favour of nominal predictions, and search for 3+1 eV-scale sterile neutrino oscillation agrees with 3 ν model
- SBN programme will further probe the sterile neutrino parameter space

...A lot more to MicroBooNE than LEE/oscillation searches, e.g. check out Chris Thorpe's talk on cross section measurements

And stay tuned for new results!

Thank you!