Short-Baseline ν Anomalies

W.C. Louis, December 10, 2016

- Gerry Garvey's contributions to the LANL ν Program
- Short-Baseline ν Anomalies
- The Fermilab Short-Baseline Neutrino Program
- Conclusions

Gerry's Contribution to the LANL Accelerator Neutrino Program Have Been HUGE!

Gerry Provided the Veto Shield to LSND, which reduced cosmic muons by ~10^7!

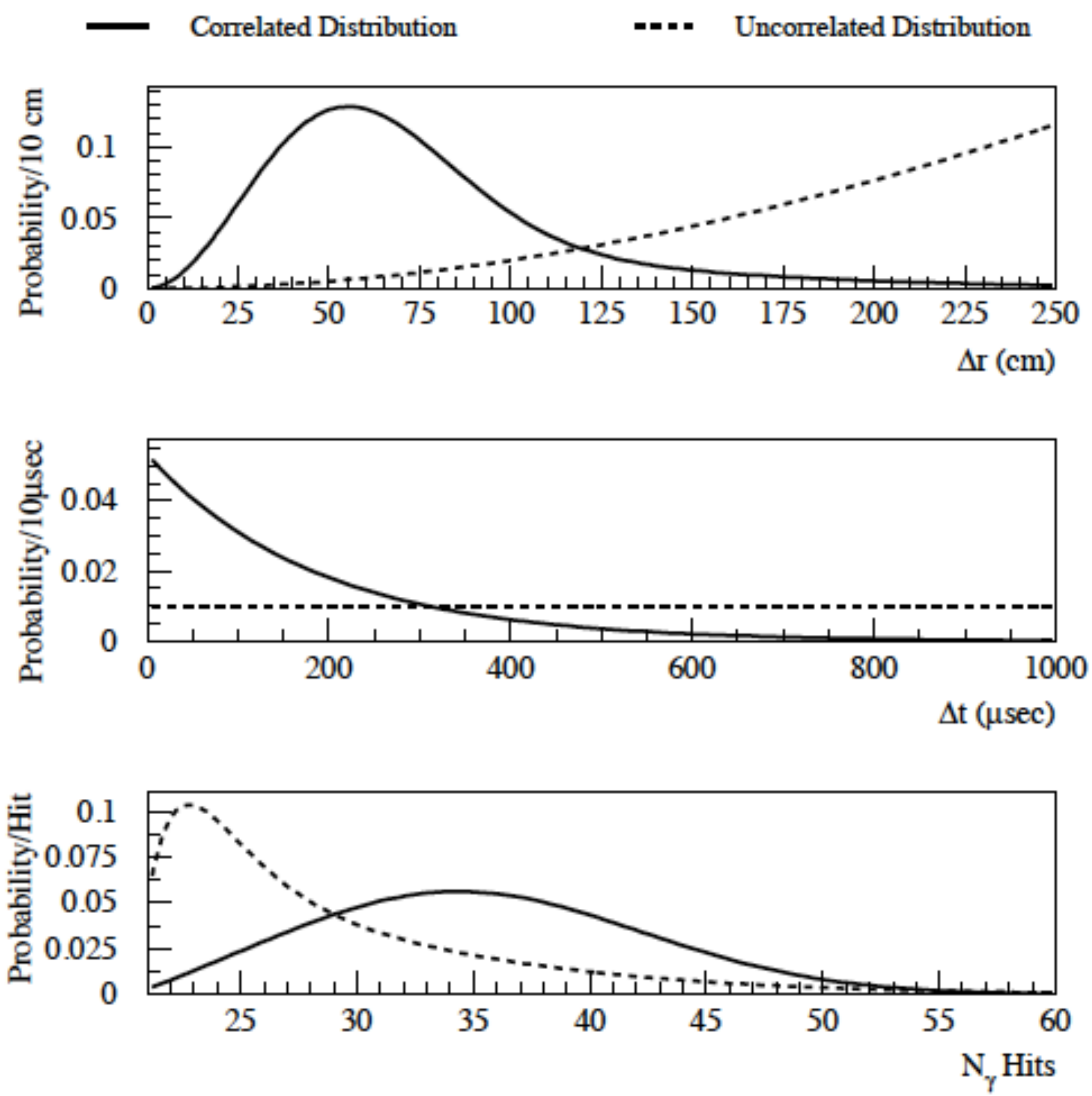
Gerry Also Provided the Muscle on LSND

Who Needs A Forklift!?!

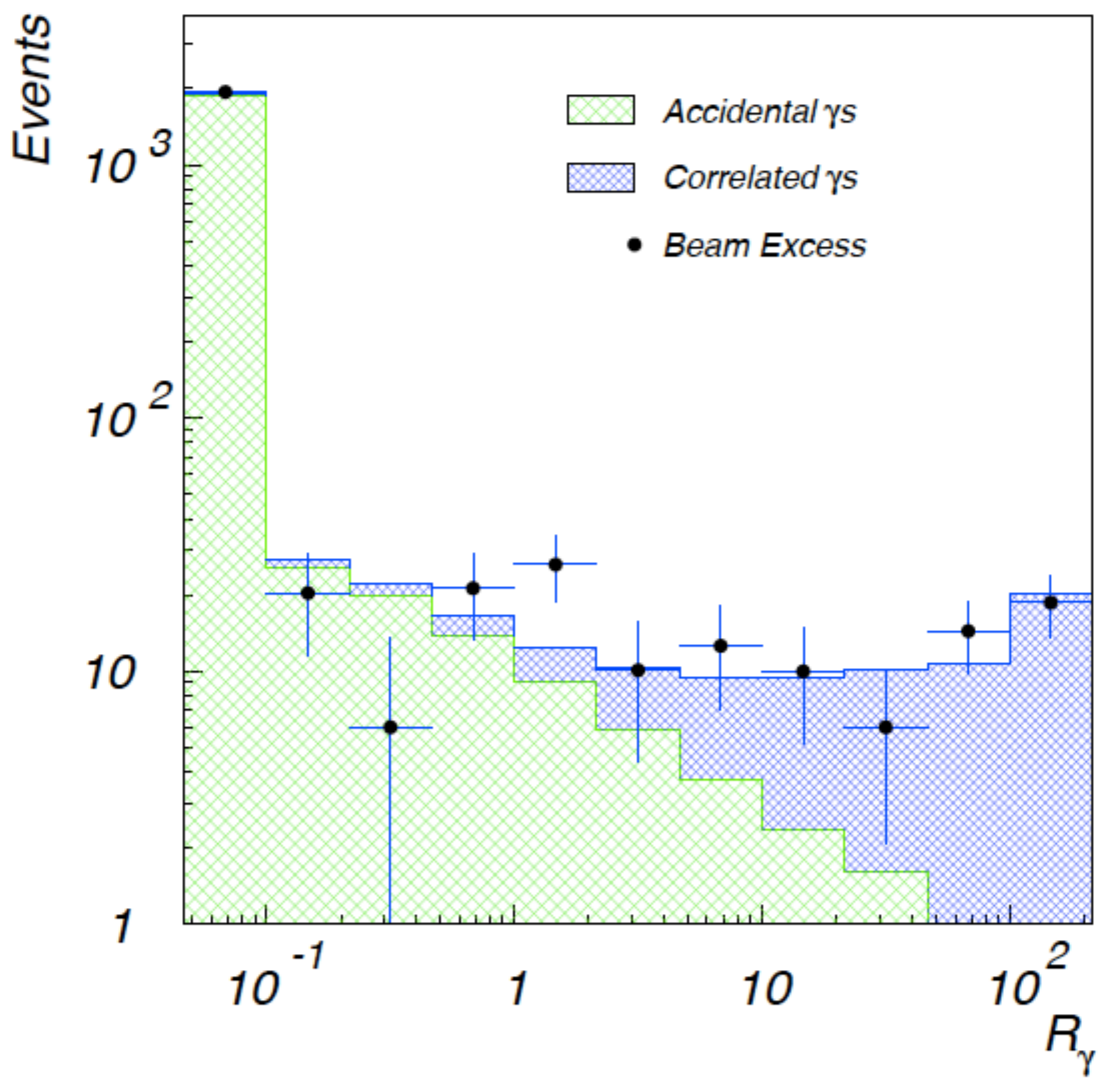
Gerry Estimated the Neutron Capture Time in Mineral Oil (186 μs) for the LSND Likelihood Ratio Fit

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

$n\ p \rightarrow d\ \gamma\ (2.2)$



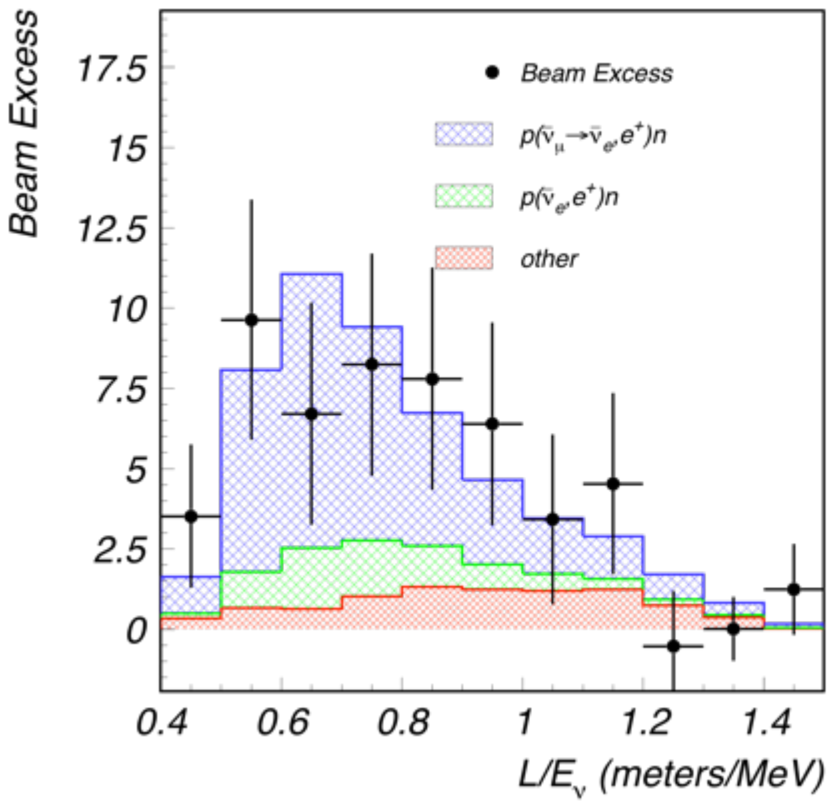
And the Likelihood Ratio Fit is the Key Evidence for $\overline{\nu}_e$ Appearance from LSND

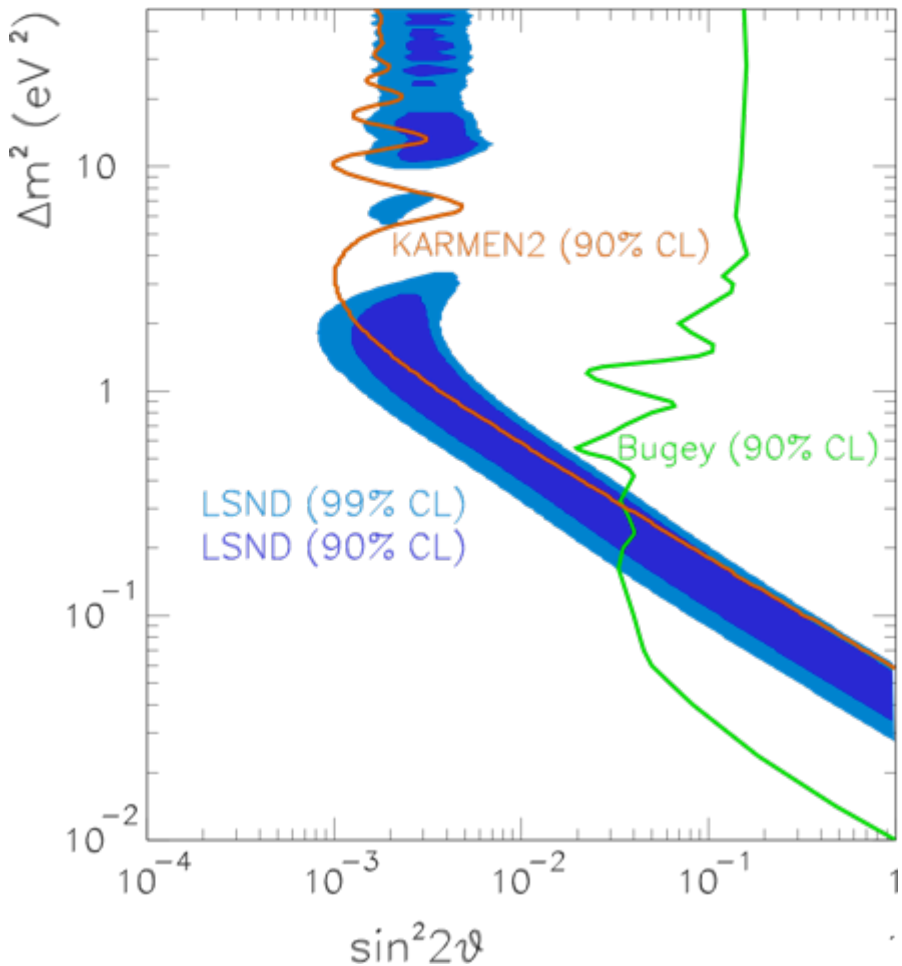


LSND Event Excesses

A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)

$R_{\gamma} > 10$



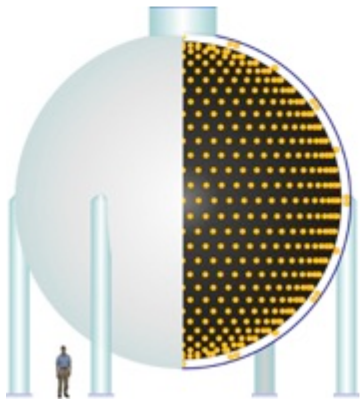


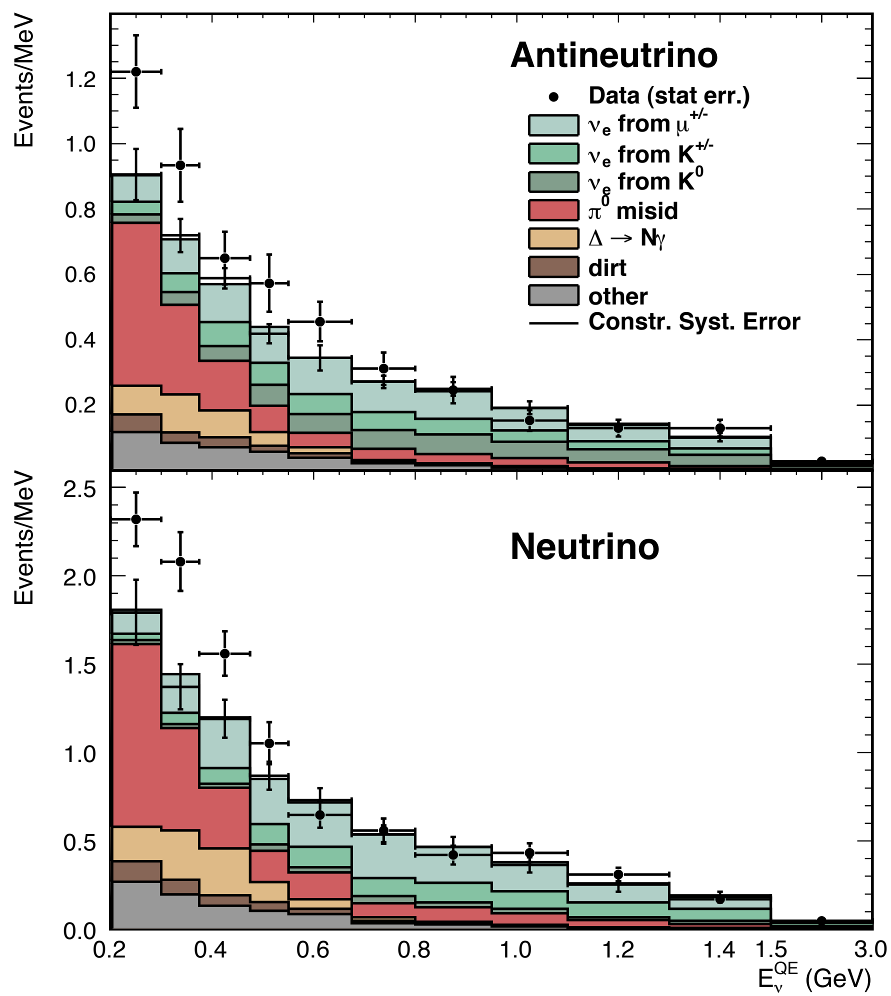
Gerry Wrote Many Technical Notes on MiniBooNE

- TN31 – Oil Attenuation Measurements with the Bama Oil Tester
- TN47 – Effects of Flow Rates and Diffusion on Air Emissions
- TN61 – Residual Radiation Levels at the Back of the Horn Box
- **TN192 – Photon Decay of the Delta**
- TN208 – Coherent Photon Background
- TN218 – Findings on the "Elo" RFG Parameter
- TN227 – Neutron Emission of Energetic Gamma Rays as a Potential Source of the "Electron Excess" Above 300 MeV
- TN230 – A Mostly Model Independent Method for Comparing MiniBooNE Neutrino and Antineutrino Cross Sections
- **TN242 – Nuclear Effects on the Radiative Decay of Deltas**
- **TN245 – Check of MiniBooNE's Predicted Δ Radiative/NC π^0 Ratio**
- **TN262 – Some Notes on The Axial Anomaly and MiniBooNE**

MiniBooNE Neutrino Oscillation Results

Phys. Rev. Lett. 110, 161801 (2013)





11.27×10^{20} POT

6.46×10^{20} POT

MiniBooNE observes an excess of events consistent with $\nu_\mu \rightarrow \nu_e$ & $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillations

TN192 – Photon Decay of the Delta

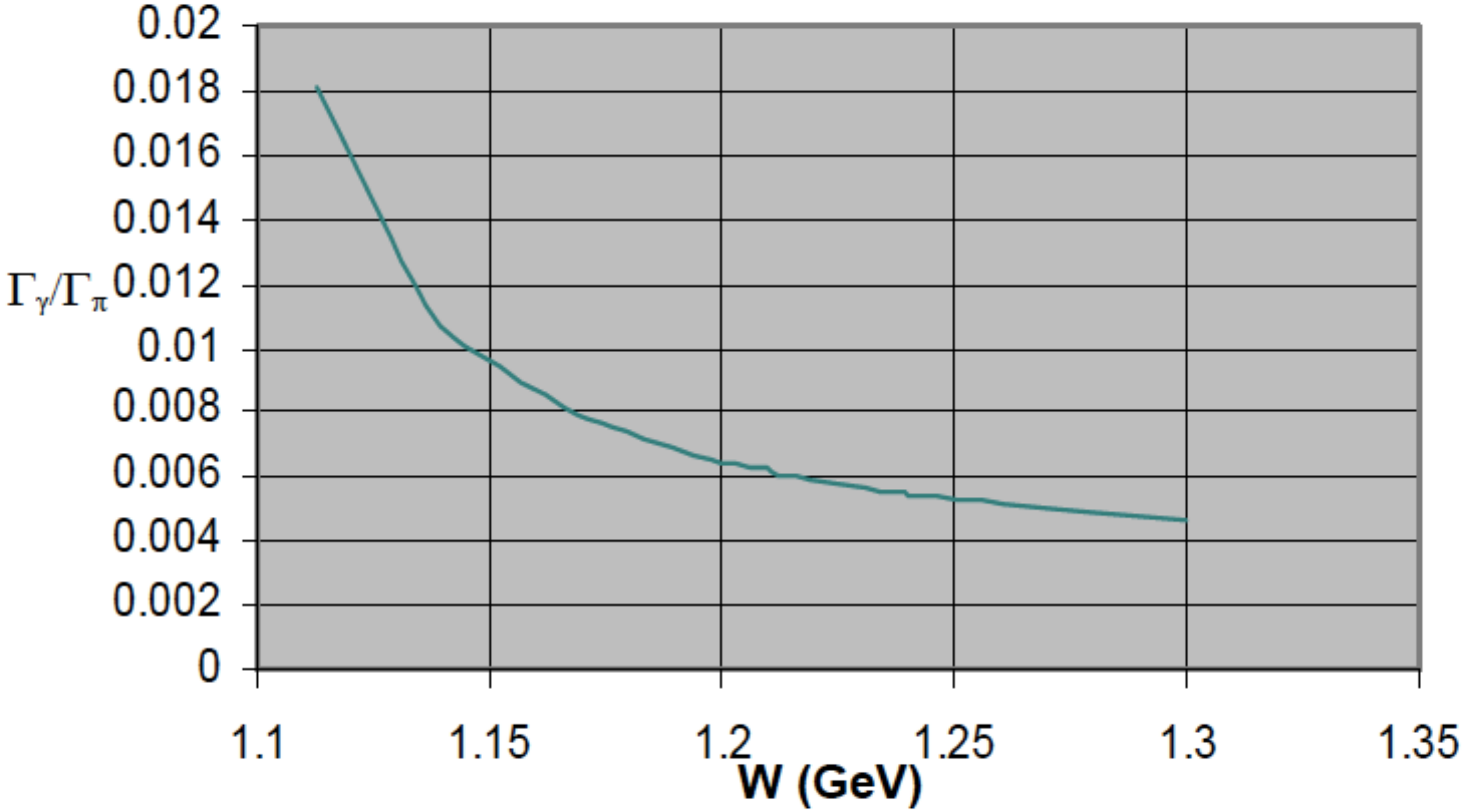
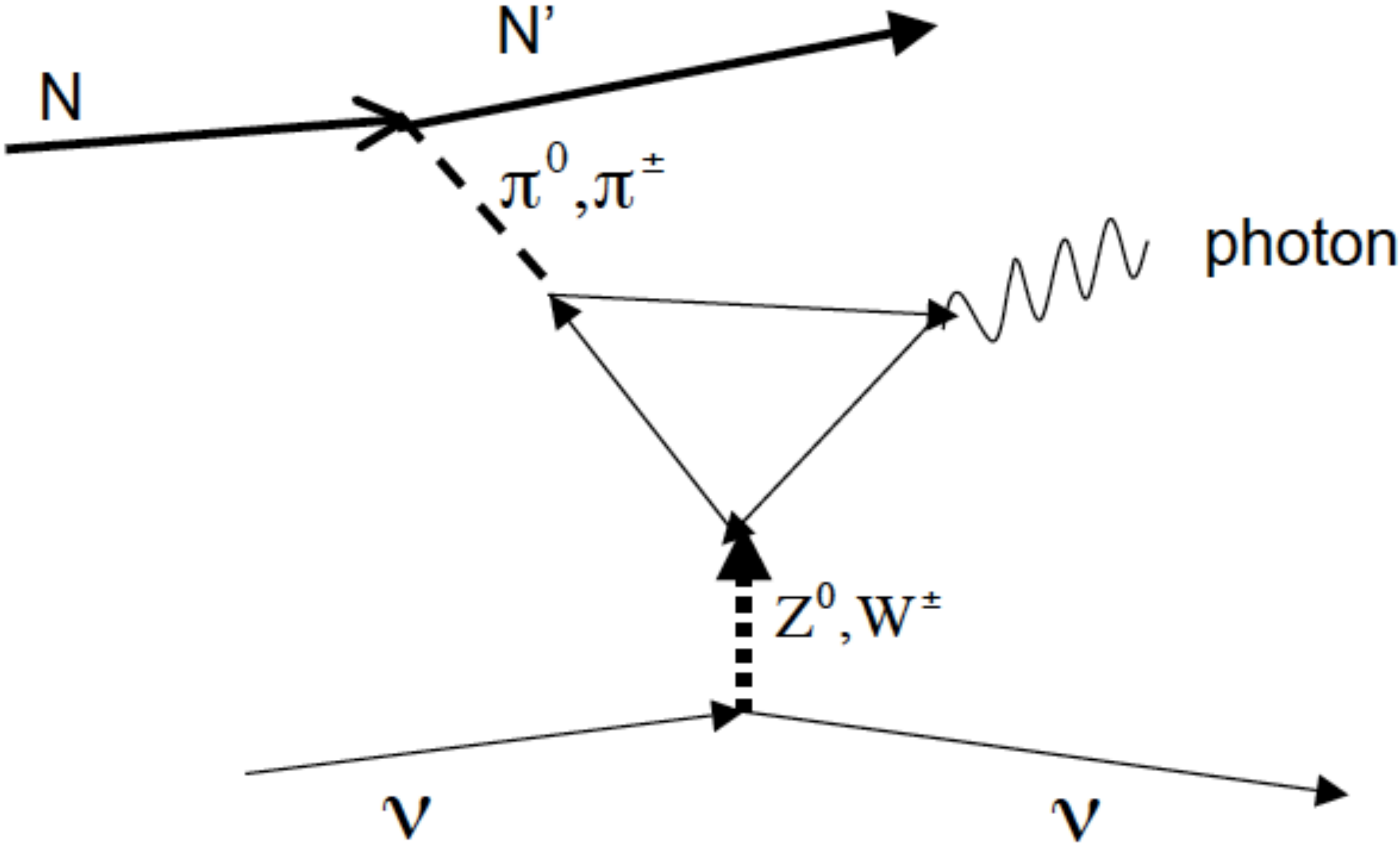


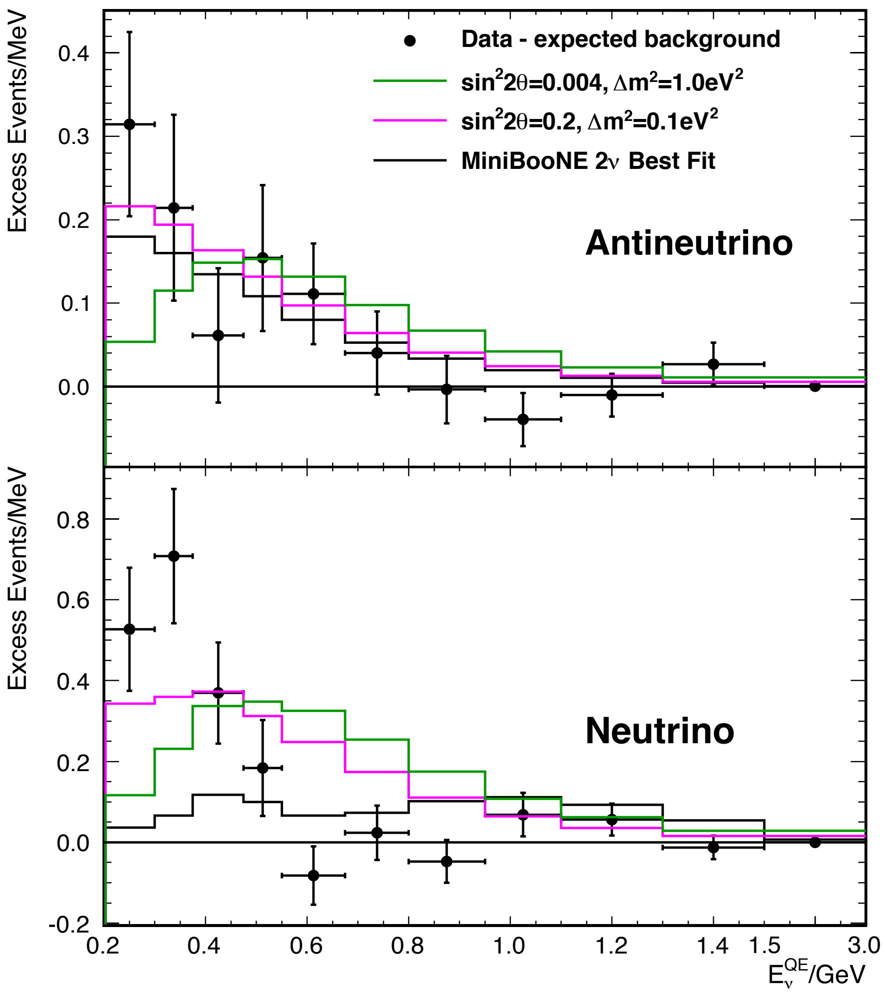
Fig.4. The ratio of photon decay to pion decay from eqs.7 and 9.

Axial Anomaly Photon Contribution



MiniBooNE Neutrino Oscillation Results

Phys. Rev. Lett. 110, 161801 (2013)



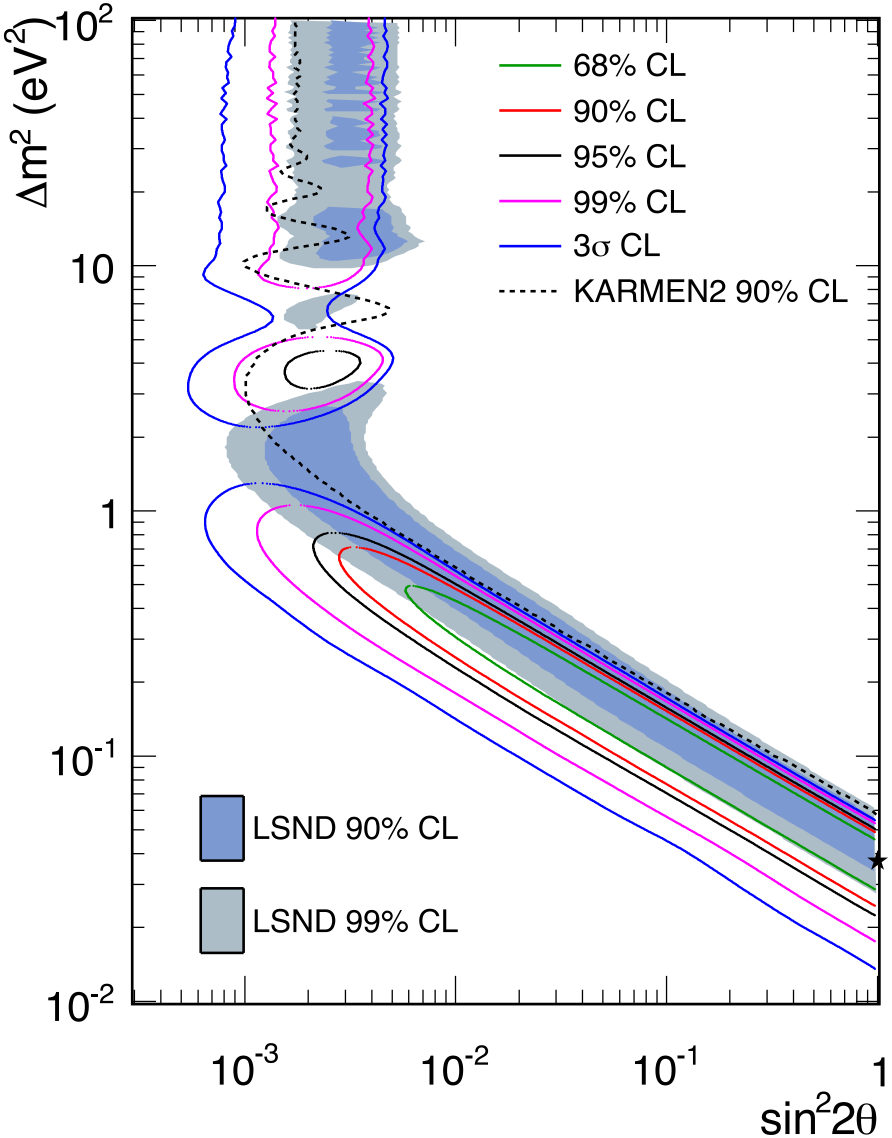
Antineutrino Event Excess from 200-1250 MeV = 78.4+-20.0+-20.3 (2.8σ)

Neutrino Event Excess from 200-1250 MeV = 162.0+-28.1+-38.7 (3.4σ)

Combined Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)

Caveats Associated with MiniBooNE Combined Neutrino + Antineutrino 2ν Fit

arXiv:1207.4809



P_{bf} = 6.7%, P_{null} = 0.1%
P_{null} relative to P_{bf} = 0.03%

Caveats:
ν energy distortions can affect the oscillation fits:
- 2-body N-N interactions
- ν_e & ν_μ disappearance
- 3+N models with C̸P

Gerry Helped Resolve the Anomalous ν_μ CCQE Section Measured By MiniBooNE

2-body N-N interactions, which are not yet included in most neutrino generators, can greatly affect neutrino cross sections and neutrino energy reconstruction!

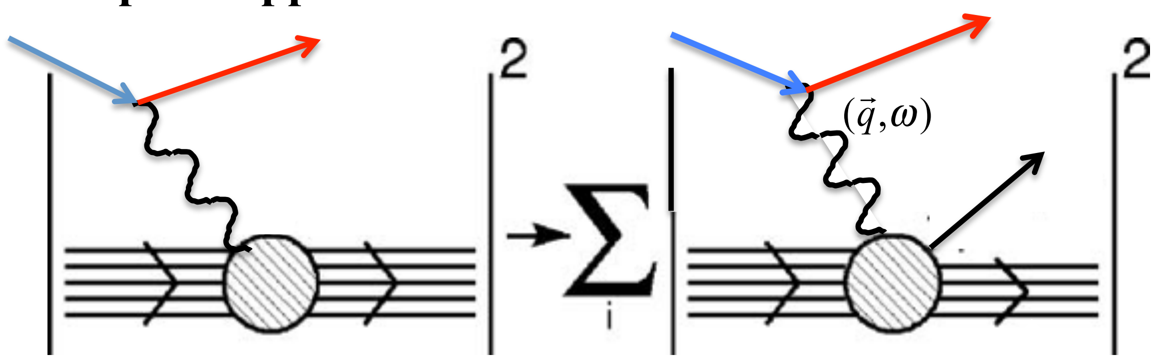
Good neutrino energy reconstruction is needed for determining Δm^2 from neutrino oscillations, and correct cross sections are needed for determining $\sin^2 2\theta$.

Circa 2009 AD

Inclusive Quasi Elastic Scattering

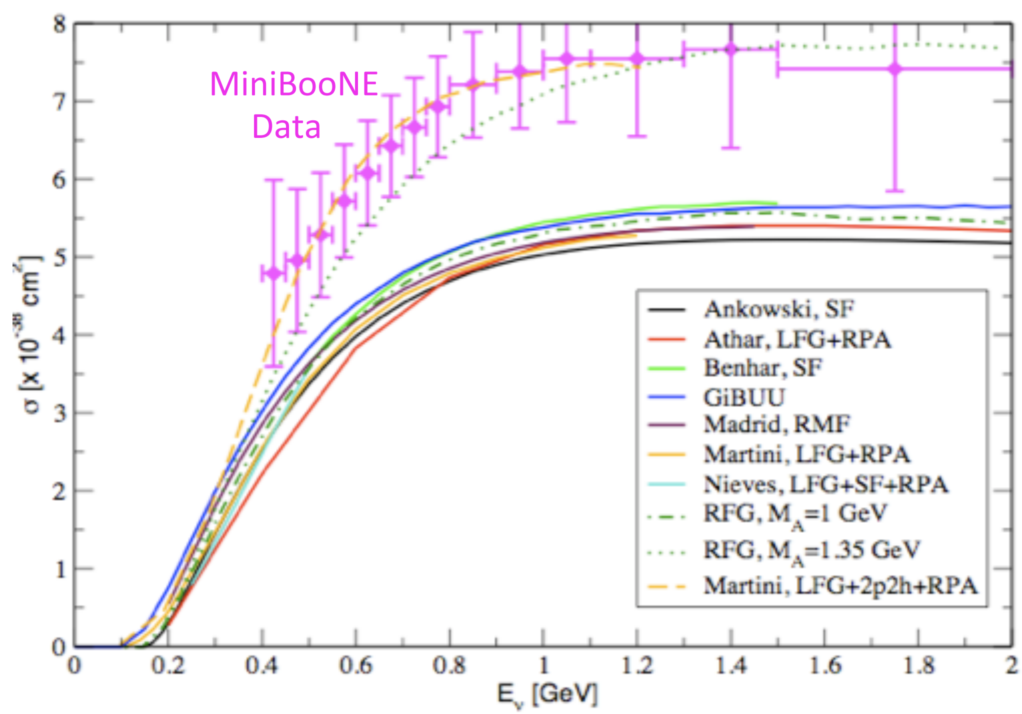
Impulse approximation –Fermi Gas

Model



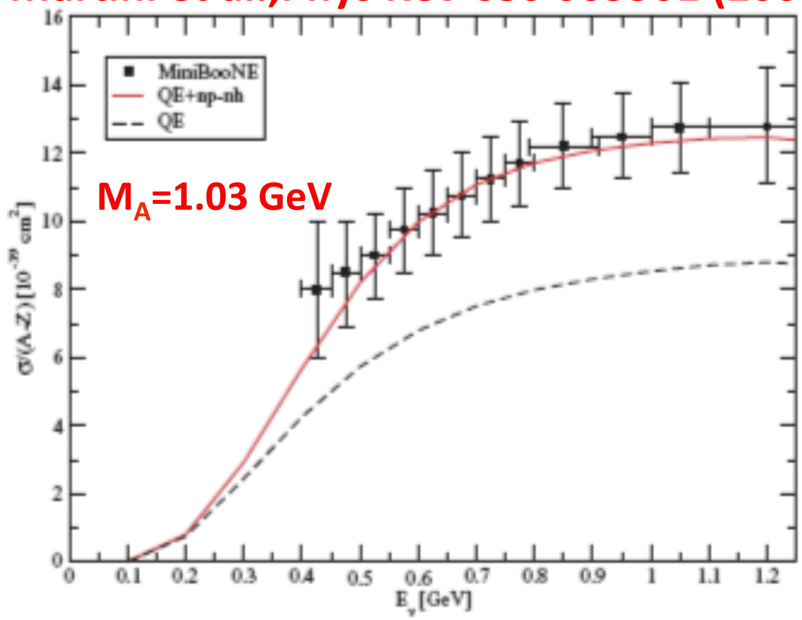
Produced

$\sigma(\nu_\mu + {}^{12}C \rightarrow \mu^- + X(\not{\pi})$

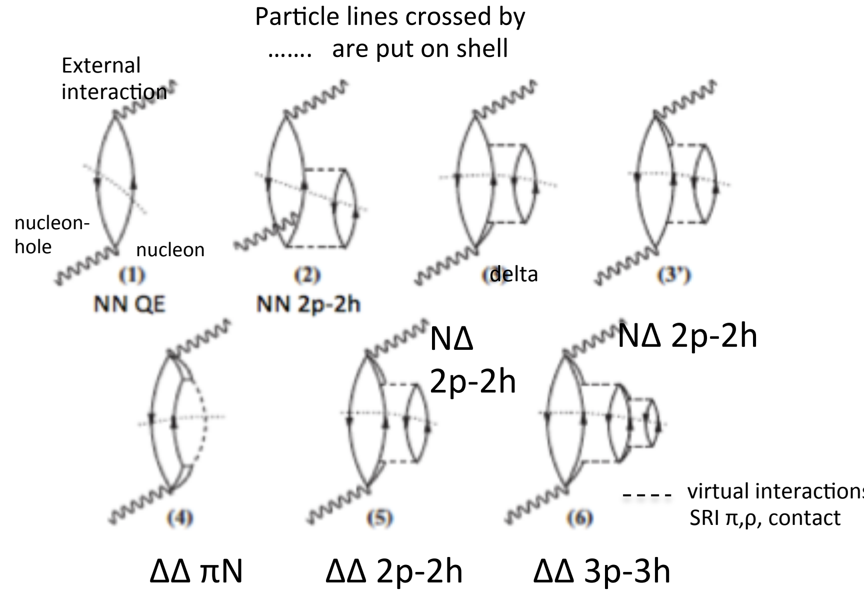


Including N-N interactions via RPA produced

M. Martini et al.,Phys Rev C80 065501 (2009)



The starting point is a Fermi gas with interactions treated diagrammatically



But introduces uncertainty into $E_\nu = E_\mu + \omega$

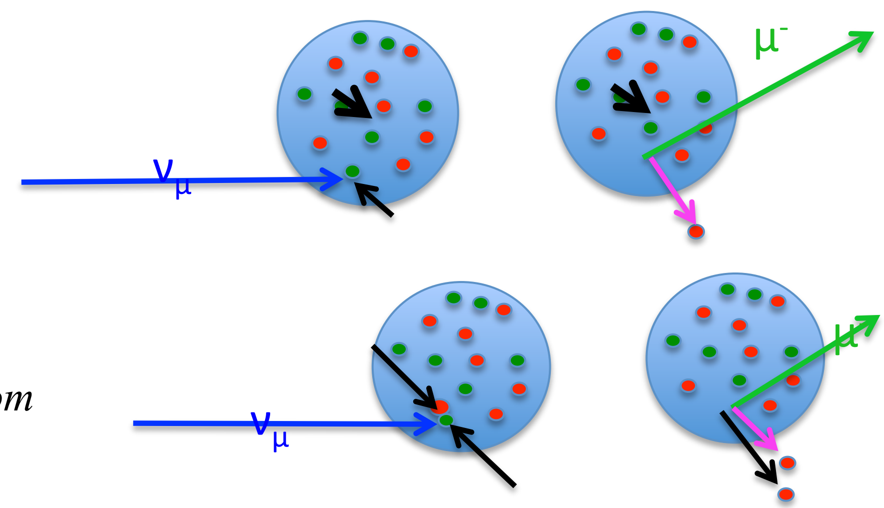
In Mean Field:

$$\omega_1 = \left(\sqrt{(\vec{q}+\vec{p})^2 + m^2} - m\right) + \frac{p^2}{2(A-1)m} + S_1$$

In 2 body Correlation assuming p_{CM}=0:

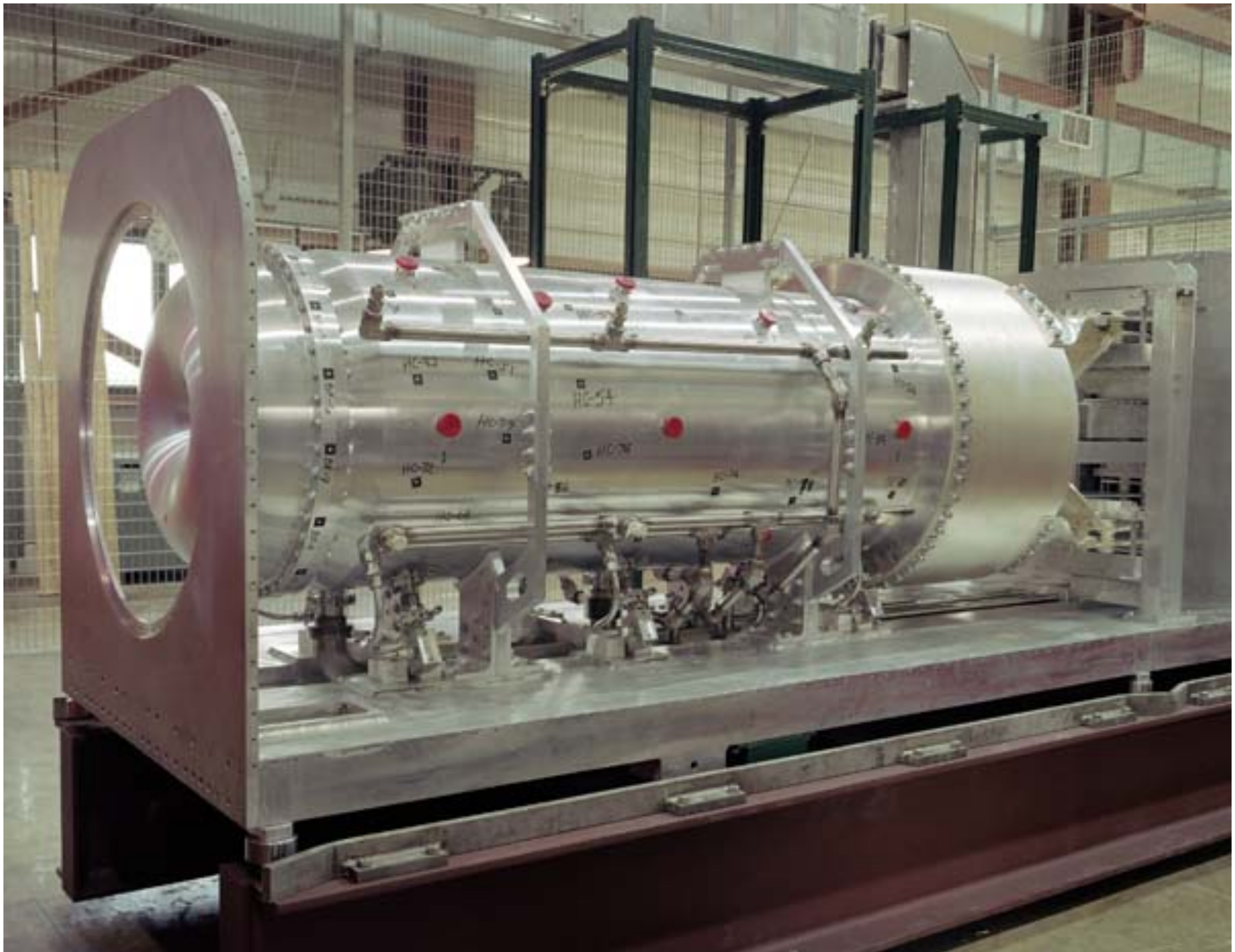
$$\omega_2 = \left(\sqrt{(\vec{q}+\vec{p})^2 + m^2} + \sqrt{p^2 + m^2} - 2m\right) + S_2$$

Correlated partner



ω *can be much larger than inferred from mean field assumption !!*

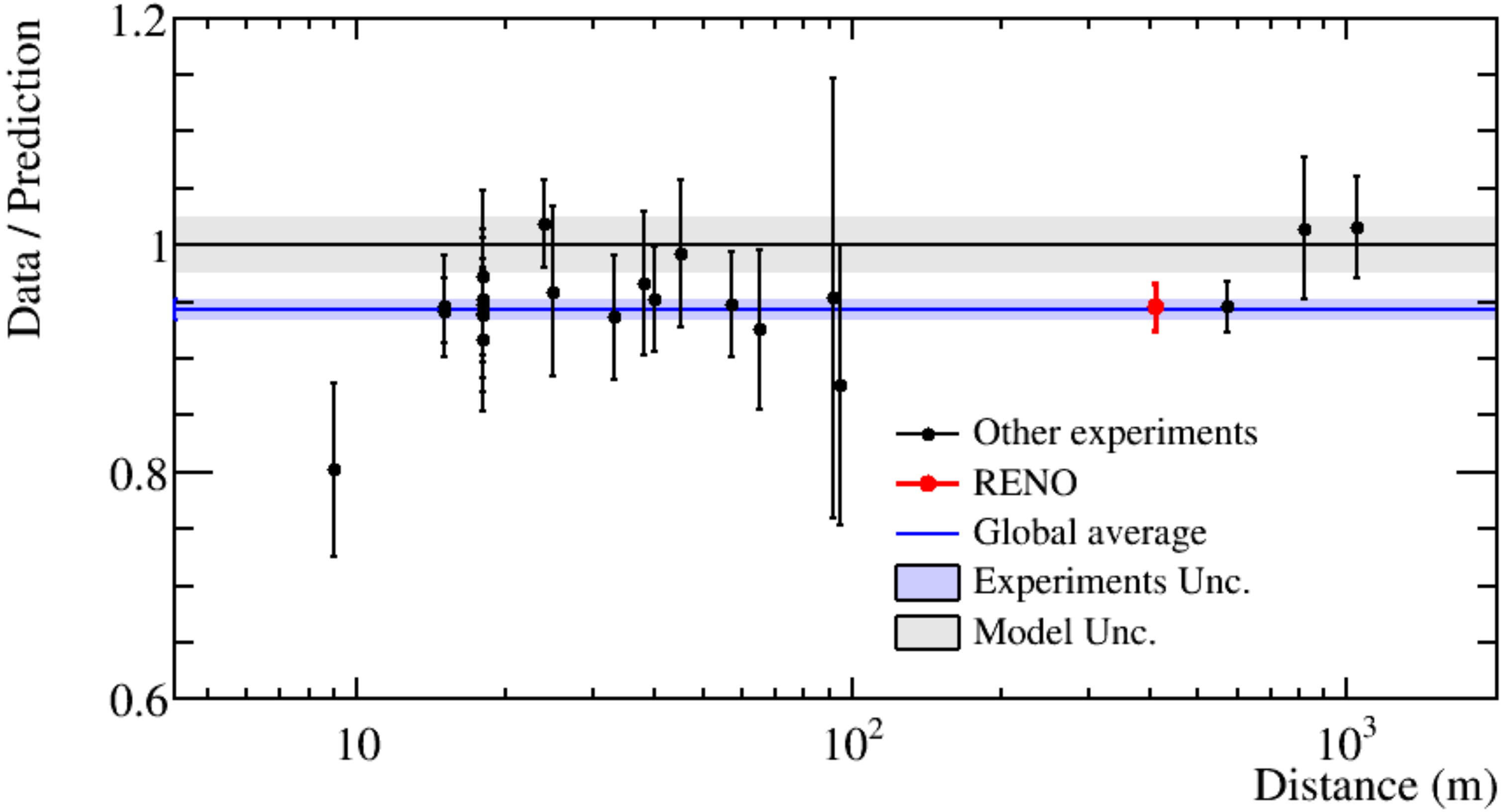
Gerry Determined the Cause of the Short in the MiniBooNE Horn



Bartoszek Engineering

Reactor Neutrino Anomaly

K.K. Joo, Talk given at Neutrino2016 Conference

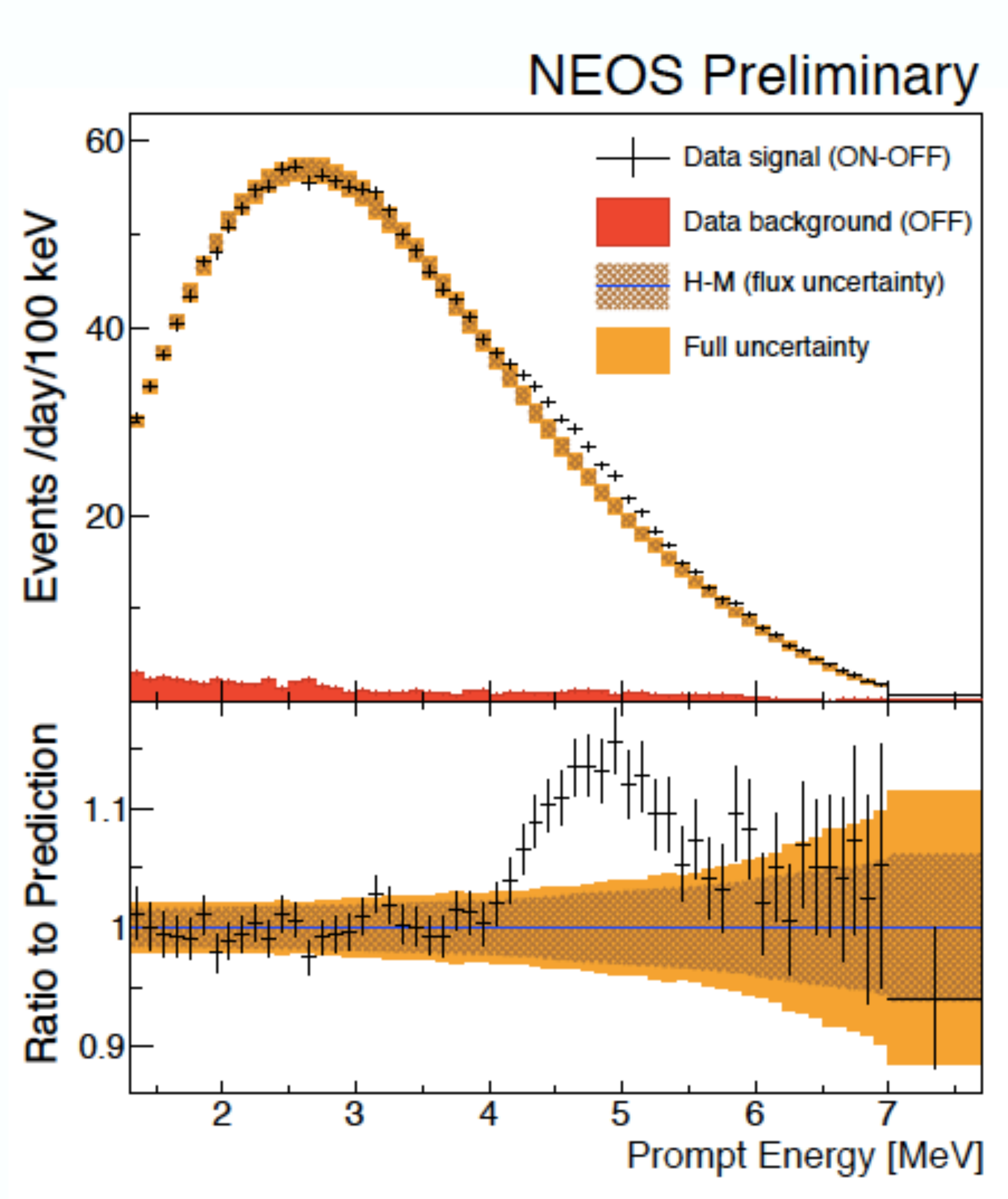


Reactor Neutrino experiments observe fewer events than expected, consistent with $\overline{\nu}_e$ disappearance to sterile neutrinos. However, what is systematic uncertainty in neutrino flux?

RENO Experiment

Daya Bay Experiment

Shoulder in the Reactor Neutrino Spectra



Gerry Has Contributed to the Understanding of the Reactor Neutrino Anomaly

Systematic Uncertainties in the Analysis of the Reactor Neutrino Anomaly

A.C. Hayes[1], J.L. Friar[1], G.T. Garvey[1], Gerard Jungman[1], G. Jonkmans[2]
[1]*Los Alamos National Laboratory, Los Alamos, NM, USA 87545*
[2]*AECL, Chalk River Laboratories, Chalk River, Ontario, Canada, K0J 1J0*

We examine uncertainties in the analysis of the reactor neutrino anomaly, wherein it is suggested that only about 94% of the emitted antineutrino flux was detected in short baseline experiments. We find that the form of the corrections that lead to the anomaly are very uncertain for the 30% of the flux that arises from forbidden decays. This uncertainty was estimated in four ways, is larger than the size of the anomaly, and is unlikely to be reduced without accurate direct measurements of the antineutrino flux. Given the present lack of detailed knowledge of the structure of the forbidden transitions, it is not possible to convert the measured aggregate fission beta spectra to antineutrino spectra to the accuracy needed to infer an anomaly. Neutrino physics conclusions based on the original anomaly need to be revisited, as do oscillation analyses that assumed that the antineutrino flux is known to better than approximately 4%.

arXiv:1309.4146

As Well As To the Shoulder in the Reactor Neutrino Spectra

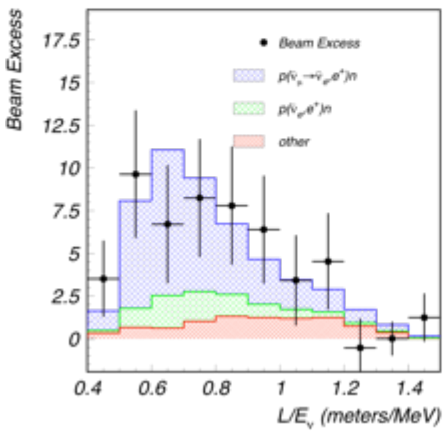
Possible Origins and Implications of the Shoulder in Reactor Neutrino Spectra

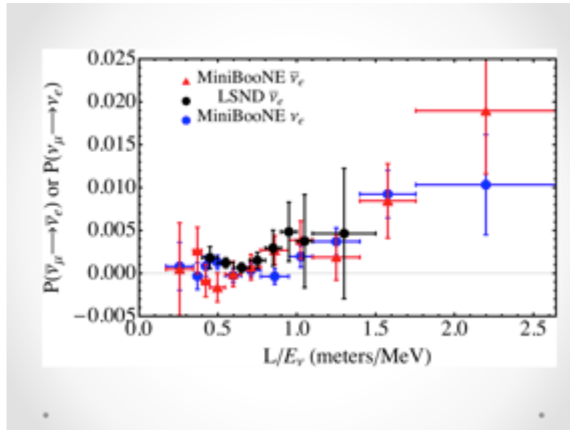
A. C. Hayes[1], J. L. Friar[1], G. T. Garvey[1], Duligur Ibeling[1,2], Gerard Jungman[1], T. Kawano[1], Robert W. Mills[3]
[1]*Los Alamos National Laboratory, Los Alamos, NM, USA 87545*
[2]*Harvard College, Cambridge, MA, USA 02138 and*
[3]*National Nuclear Laboratory, Sellafield, CA20 1PG UK*

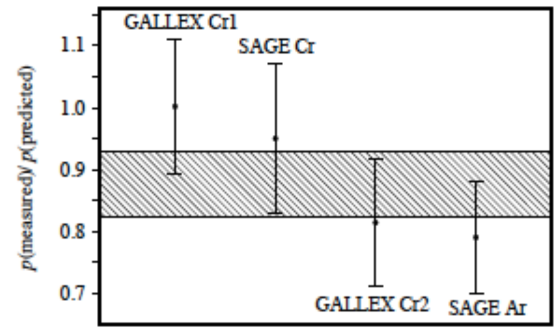
We analyze within a nuclear database framework the shoulder observed in the antineutrino spectra in current reactor experiments. We find that the ENDF/B-VII.1 database predicts that the antineutrino shoulder arises from an analogous shoulder in the aggregate fission beta spectra. In contrast, the JEFF-3.1.1 database does not predict a shoulder for two out of three of the modern reactor neutrino experiments, and the shoulder that is predicted by JEFF-3.1.1 arises from ^{238}U. We consider several possible origins of the shoulder, and find possible explanations. For example, there could be a problem with the measured aggregate beta spectra, or the harder neutron spectrum at a light-water power reactor could affect the distribution of beta-decaying isotopes. In addition to the fissile actinides, we find that ^{238}U could also play a significant role in distorting the total antineutrino spectrum. Distinguishing these and quantifying whether there is an anomaly associated with measured reactor neutrino signals will require new short-baseline experiments, both at thermal reactors and at reactors with a sizable epithermal neutron component.

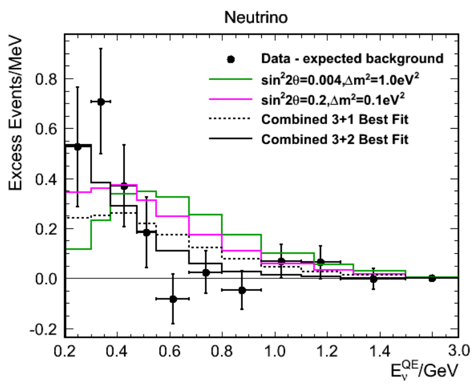
arXiv:1506.00583

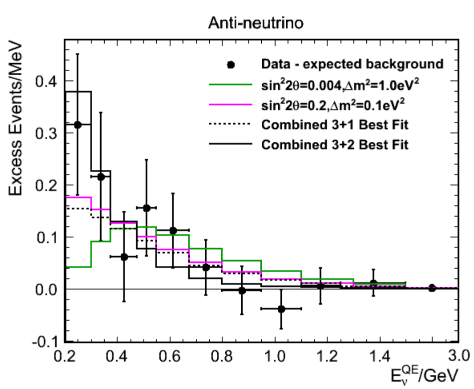
Short-Baseline Neutrino Anomalies

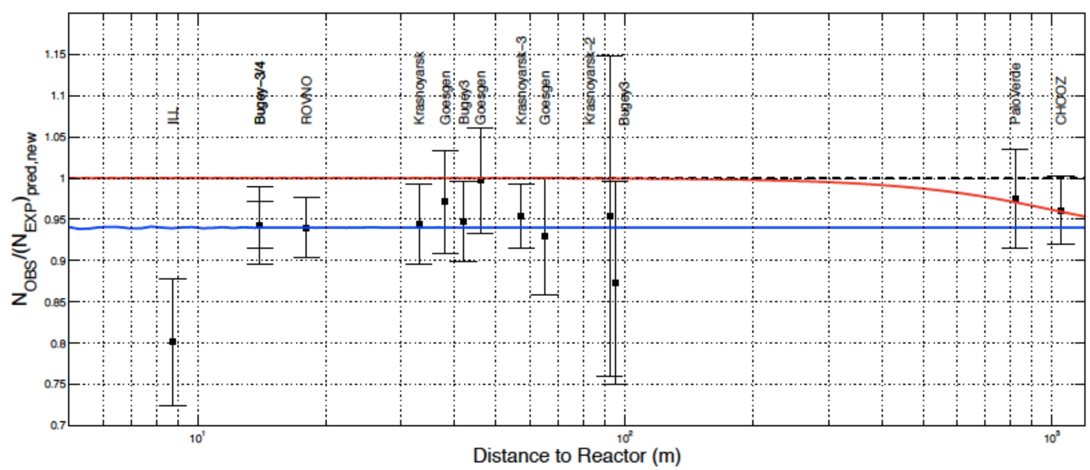




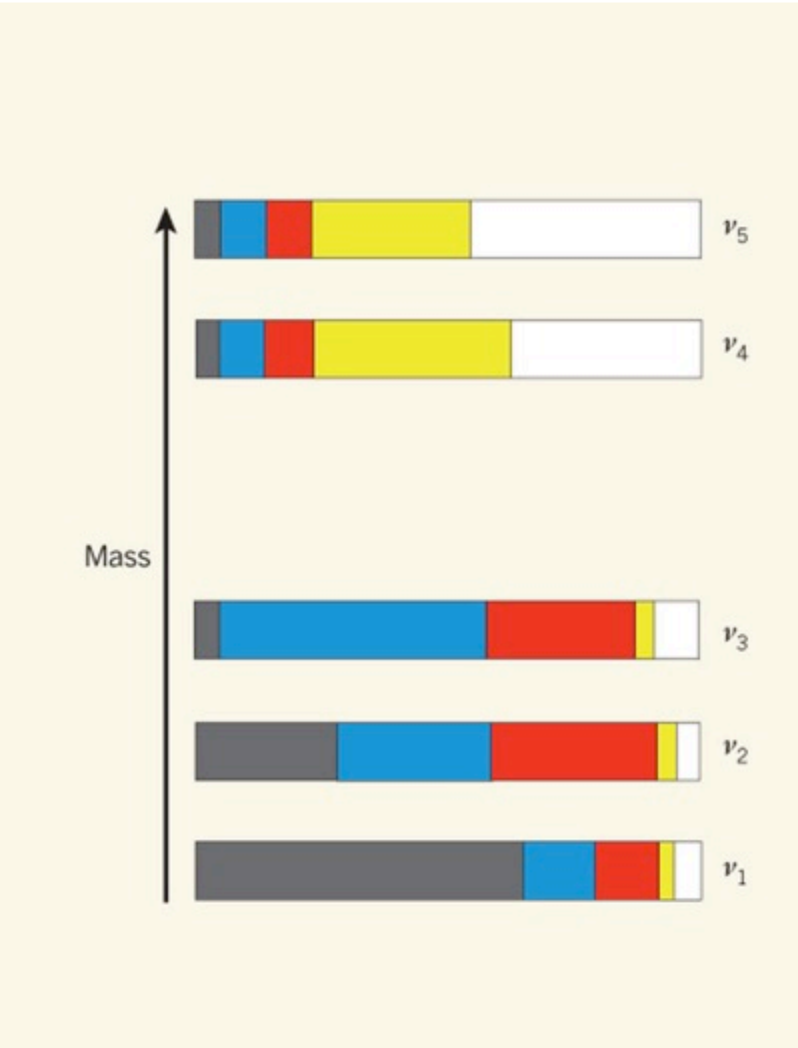








3+N Sterile Neutrino Models

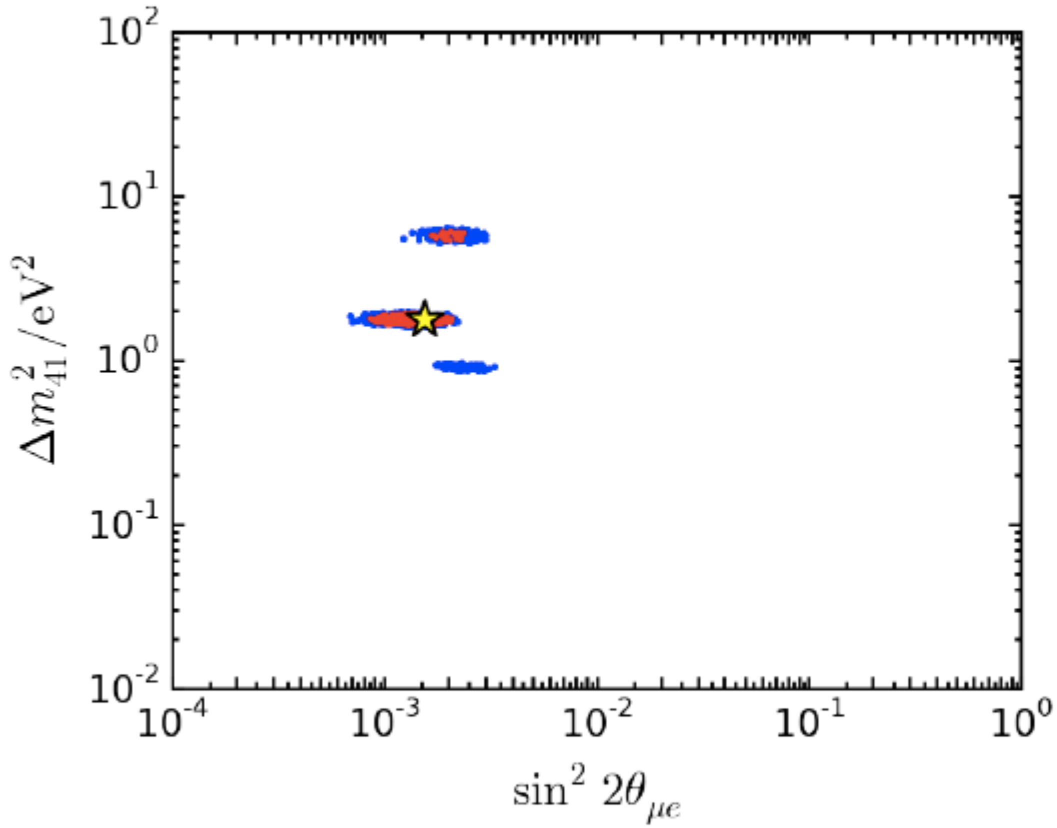


- 3+N models
- N>1 allows CP violation for short baseline experiments
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e \neq \nu_\mu \rightarrow \nu_e$

Note: There are also other, more exotic possibilities

Global 3+1 Fit to World Data

G.H. Collin, C.A. Arguelles, J.M. Conrad, & M.H. Shaevitz, PRL 117, 221801 (2016)



3+1 (P=51%)

3+1	Δm_{41}^2	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\tau 4}\rvert$	N_{bins}	$\chi^2_{\min}$	χ^2_{null}	$\Delta\chi^2$ (dof)
SBL	1.75	0.163	0.117	-	315	306.81	359.15	52.34 (3)
SBL+IC	1.75	0.164	0.119	0.00	524	518.23	568.84	50.61 (4)
IC	5.62	-	0.314	-	209	207.11	209.69	2.58 (2)

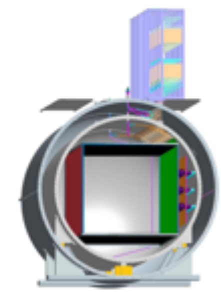
More Exotic SBL Possibilities

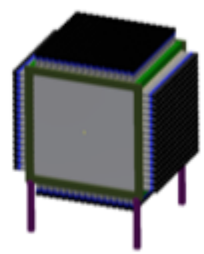
- Sterile Neutrino Decay
- Sterile Neutrino Interactions & New Gauge Bosons
- Light WIMP Production (Light WIMPs can behave like neutrinos)
- Lorentz Violation & CPT Violation
- Extra Dimensions (active neutrinos are stuck on the brane, while sterile neutrinos can propagate in the bulk)
- Mass-Varying Neutrinos
- Neutrino Decoherence
- etc.

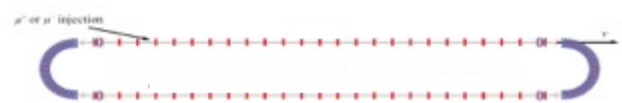
Future Short-Baseline ν Experiments

• There is a diverse set of experiments, spanning vastly different energy Scales (from ~1 MeV to ~10 TeV), that have been proposed to test the 3+N models & resolve the present anomalies:

• Accelerator ν Experiments: MicroBooNE+SBND+ICARUS, MINOS+, NOvA, DUNE, OscSNS at ORNL, J-PARC E56, IsoDAR, nuPRISM



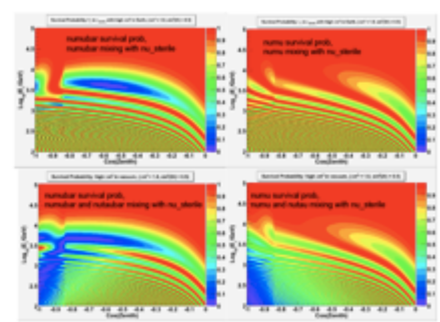


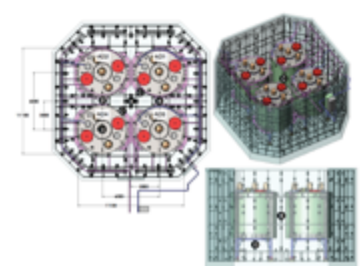


• Reactor ν Experiments:
SOLID, PROSPECT, NEOS, DANSS

• Radioactive Source ν Experiments: BOREXINO-SOX, KamLAND, Daya Bay

• Atmospheric ν Experiments: IceCube

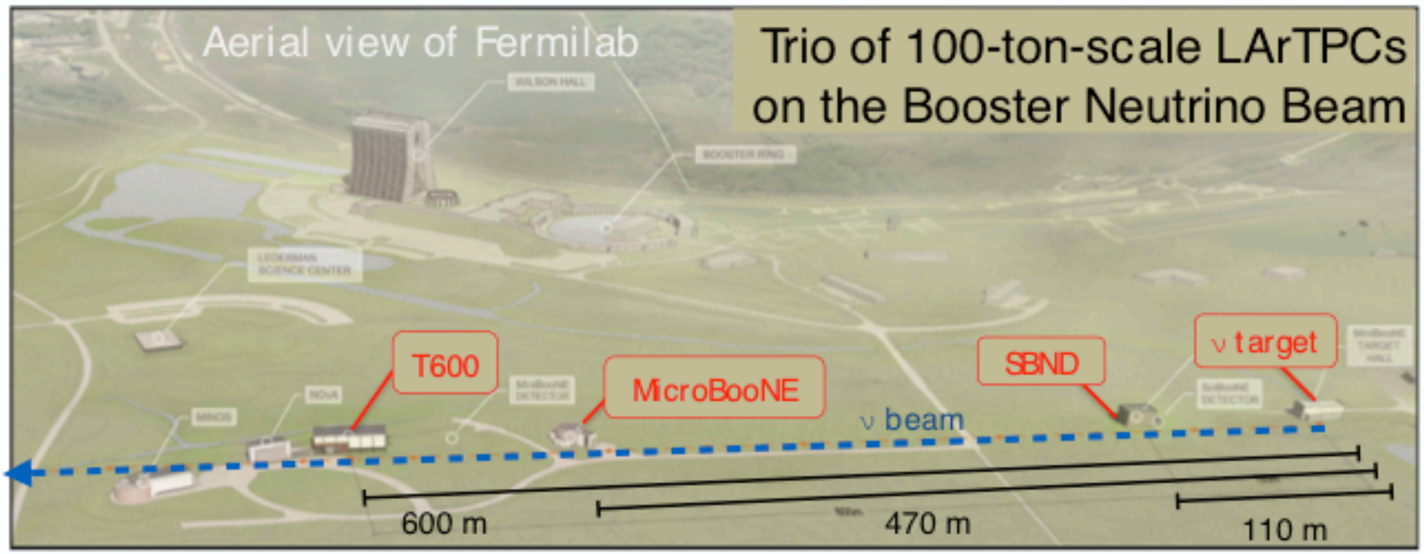


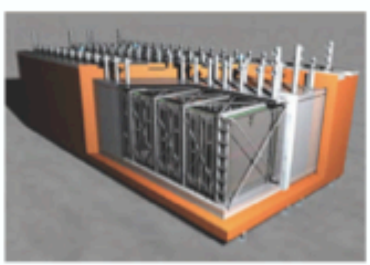


• Beta Decay & Double Beta Decay

Short Baseline Neutrino (SBN) Program

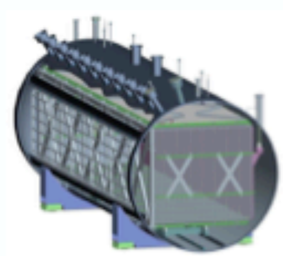
See talk by D. Schmitz





ICARUS-T600

476t



MicroBooNE

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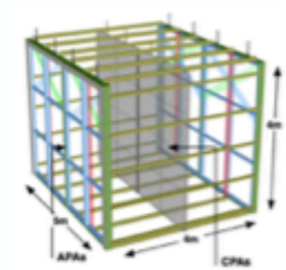
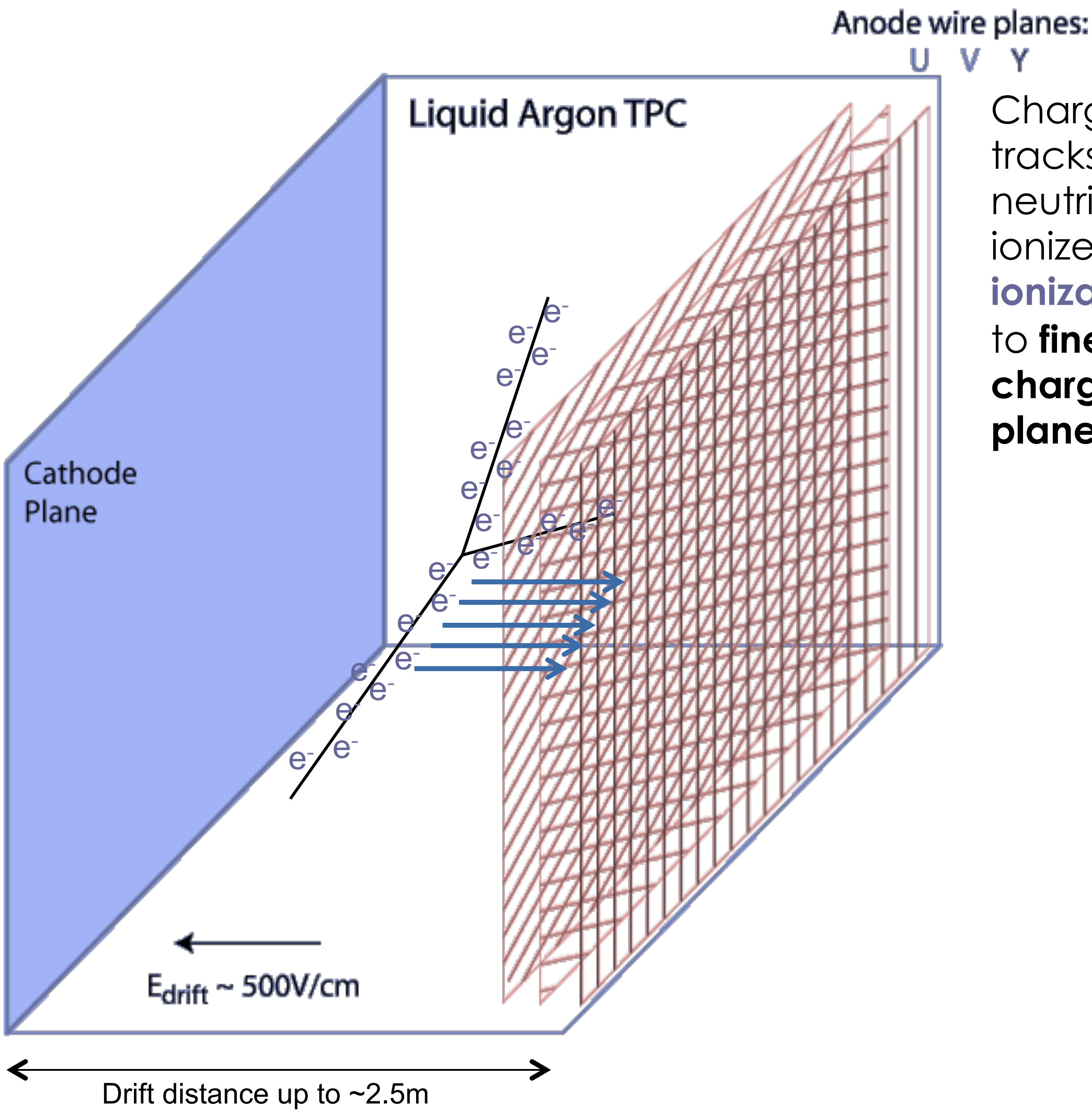


Short Baseline Near Detector (SBND)

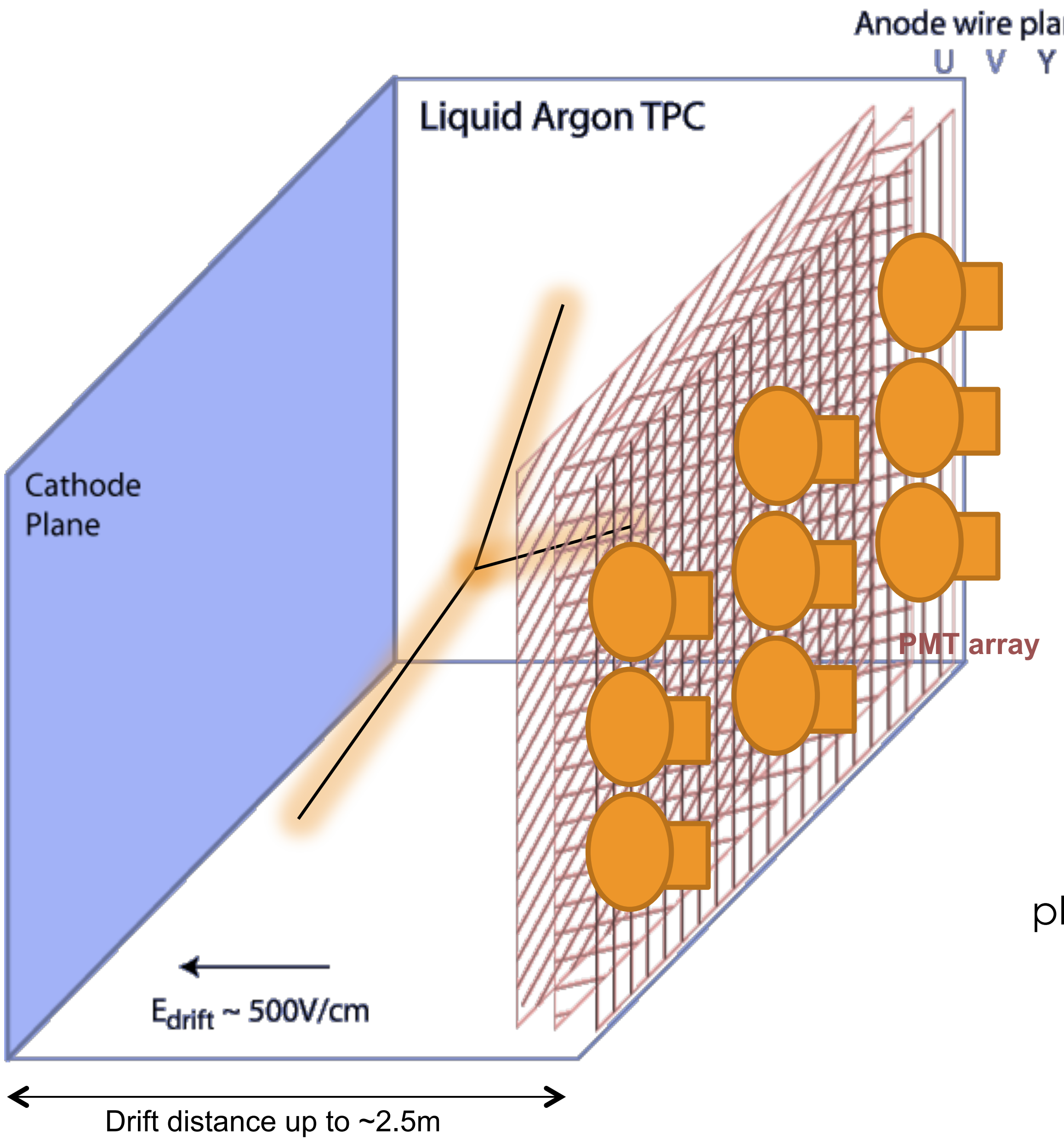
112t

LArTPC working principle



Charged particle tracks produced in neutrino interactions ionize argon atoms; **ionization charge** drifts to **finely segmented charge collection planes** over ~1-few ms.

LArTPC working principle

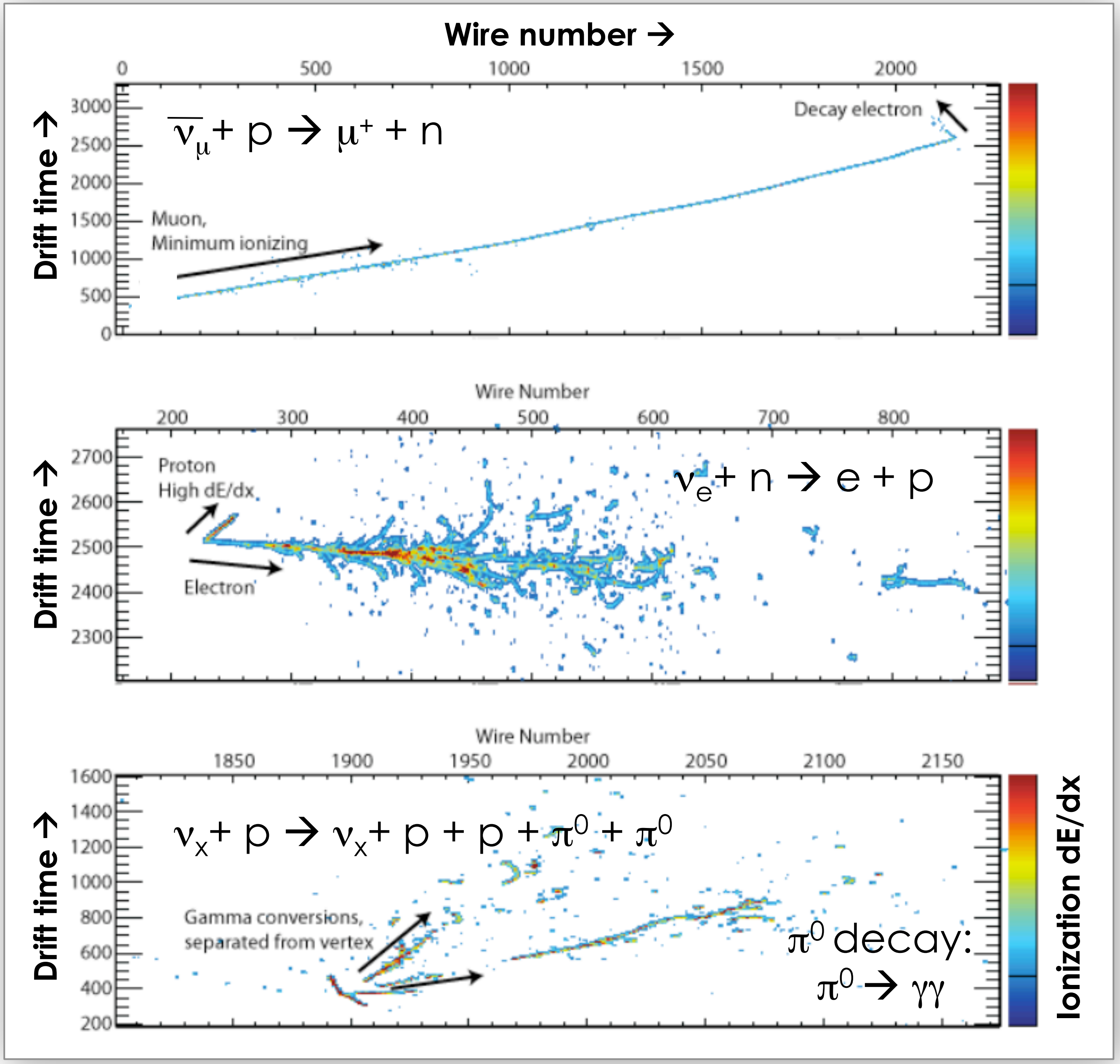


Prompt **scintillation light** (~few ns) is detected by photo-sensitive detectors for event t_0, drift coordinate determination, and triggering

LArTPC exquisite event topology

Bubble chamber-quality data, with calorimetric information (ionization dE/dx)

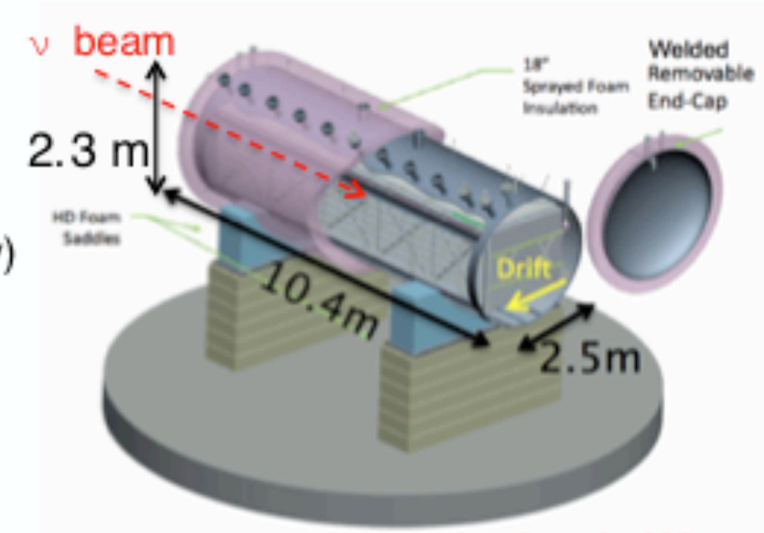
High event selection efficiency and excellent background rejection!

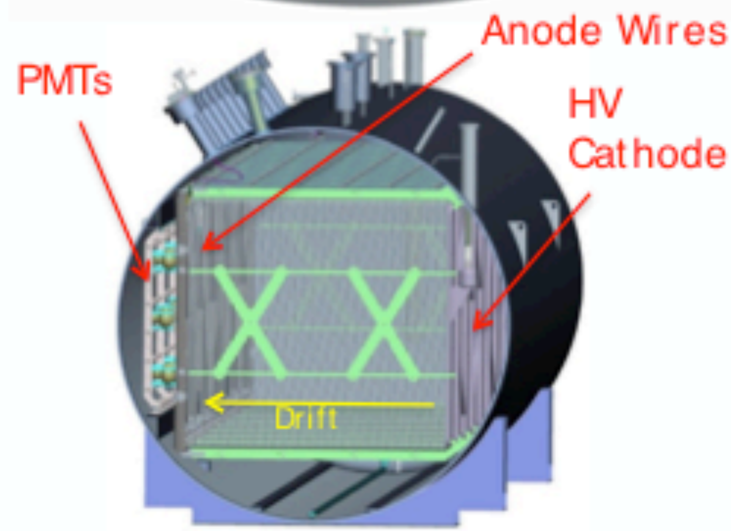


Example simulated neutrino events (E_ν ~ 0.5-1 GeV)

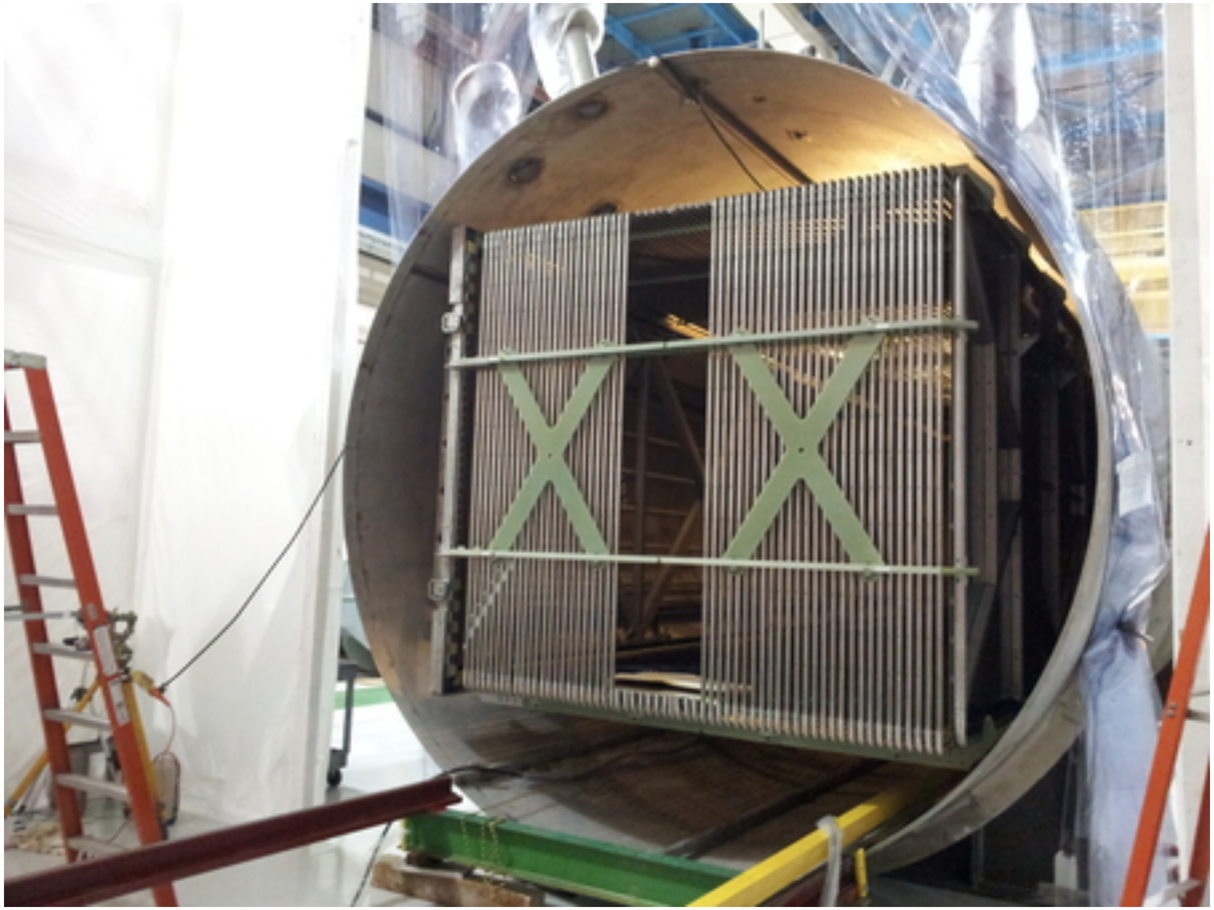
The MicroBooNE Detector

- 170 ton LArTPC (total mass)
- 8192 wires (3 mm pitch)
  - 3456 collection channels (oriented vertically)
  - 4736 induction channels (oriented at ±60°)
- 32 8" Cryogenic PMTs + 4 light guide "paddles"
- UV laser calibration system
  - 2 ports: upstream, downstream (maneuverable heads)
- Purity monitors
- External muon tagger system





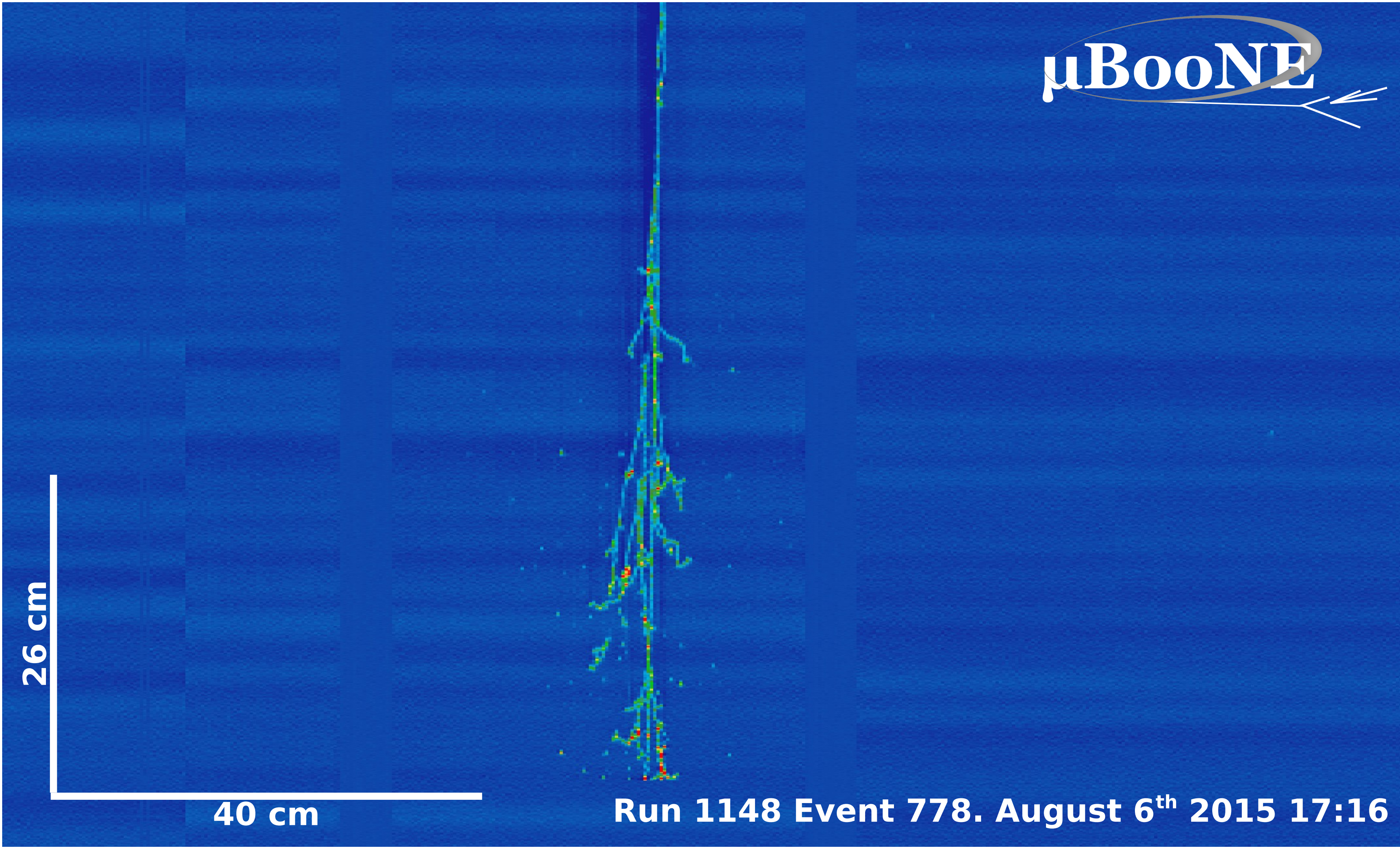
MicroBooNE TPC in Cryostat



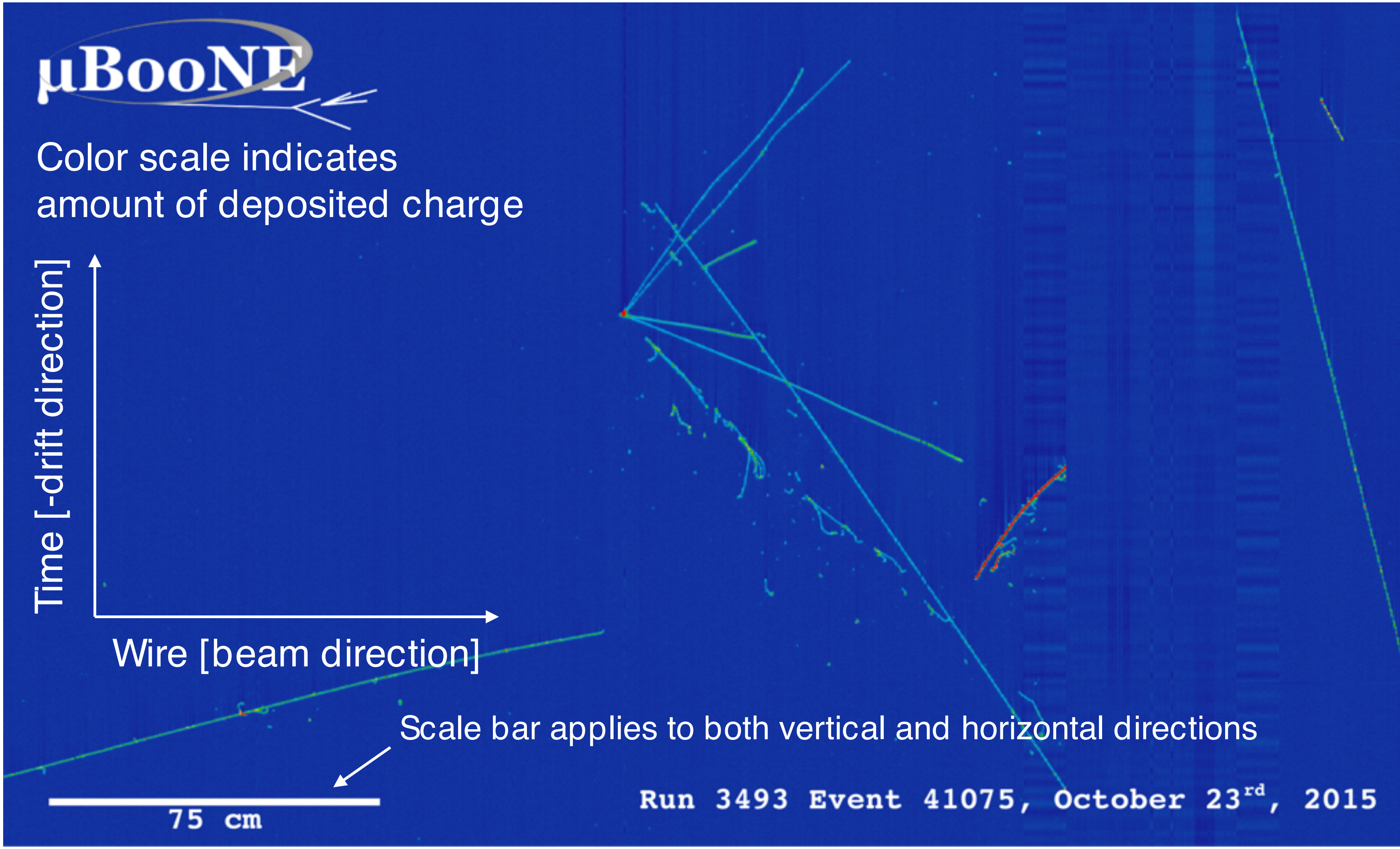
MicroBooNE Liquid Argon TPC


Driving Nu Physics

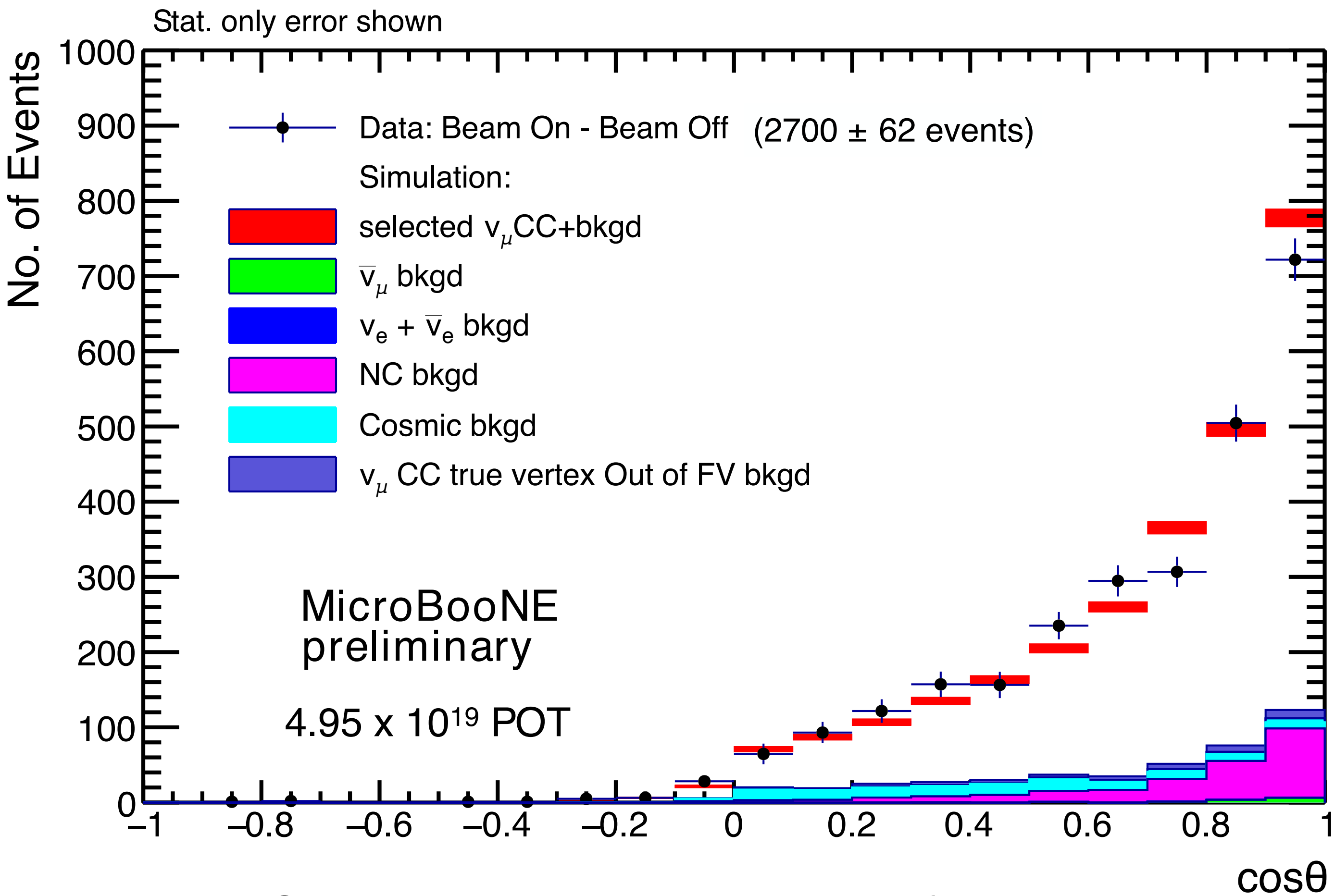
MicroBooNE Clearly Observes Cosmic Ray Events



MicroBooNE Clearly Observes Neutrino Events

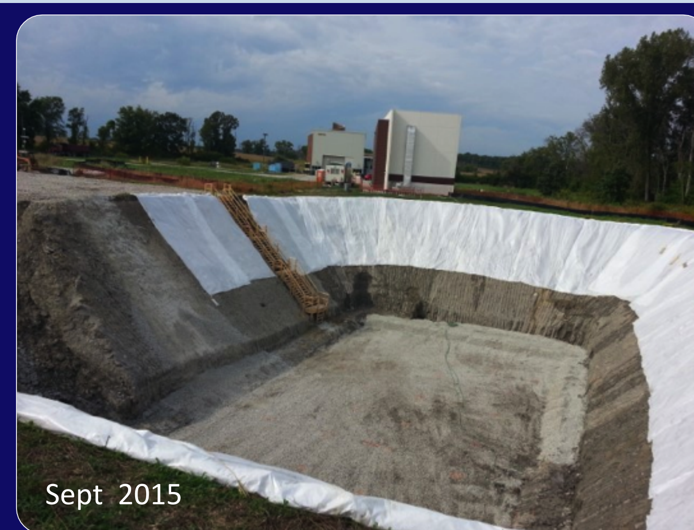


First ν_μ CC Distributions From MicroBooNE Data



Simulation scaled to same number of events as data

Far Detector Building Construction

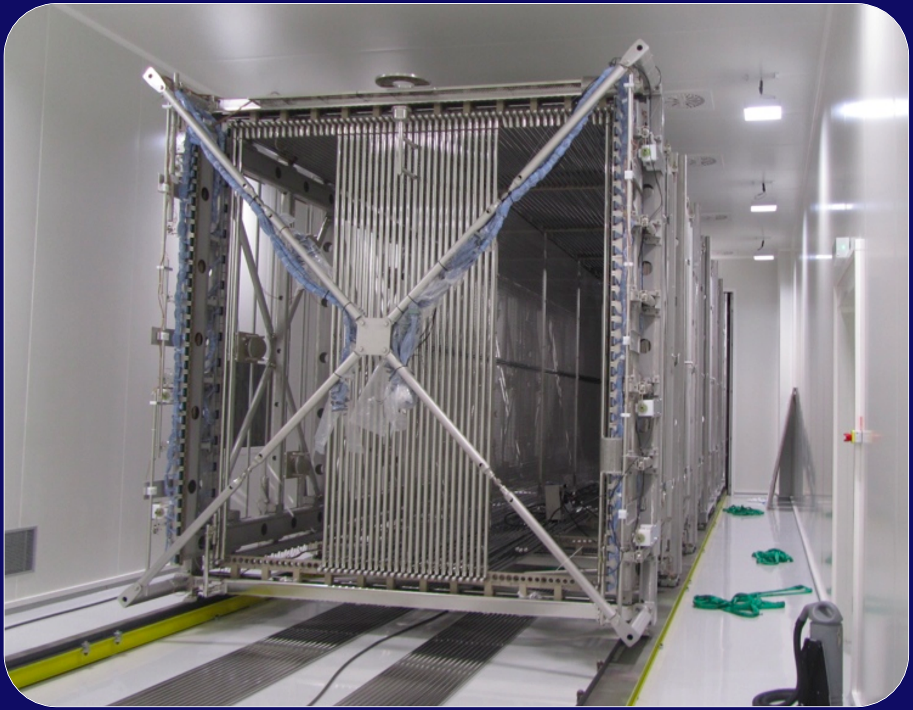


Broke ground on the Far Detector building in July 2015

Ready for installation end of 2016

The SBN Far Detector – The ICARUS-T600

- ICARUS is the largest existing LArTPC in the world
  - Completed a successful three-year physics run in CNGS neutrino beam at Gran Sasso Laboratory 2010-2012
  - Currently at CERN being overhauled and prepared for transport to Fermilab



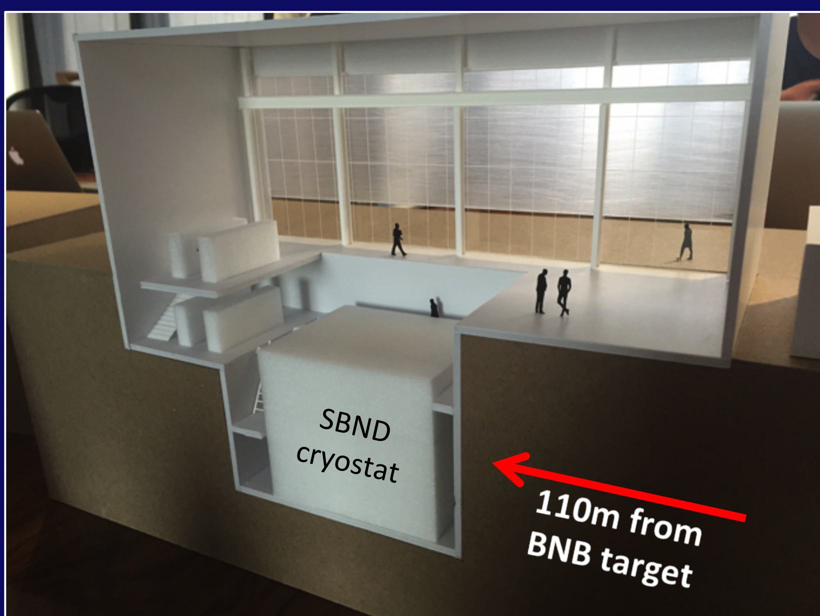
Near Detector Building Construction

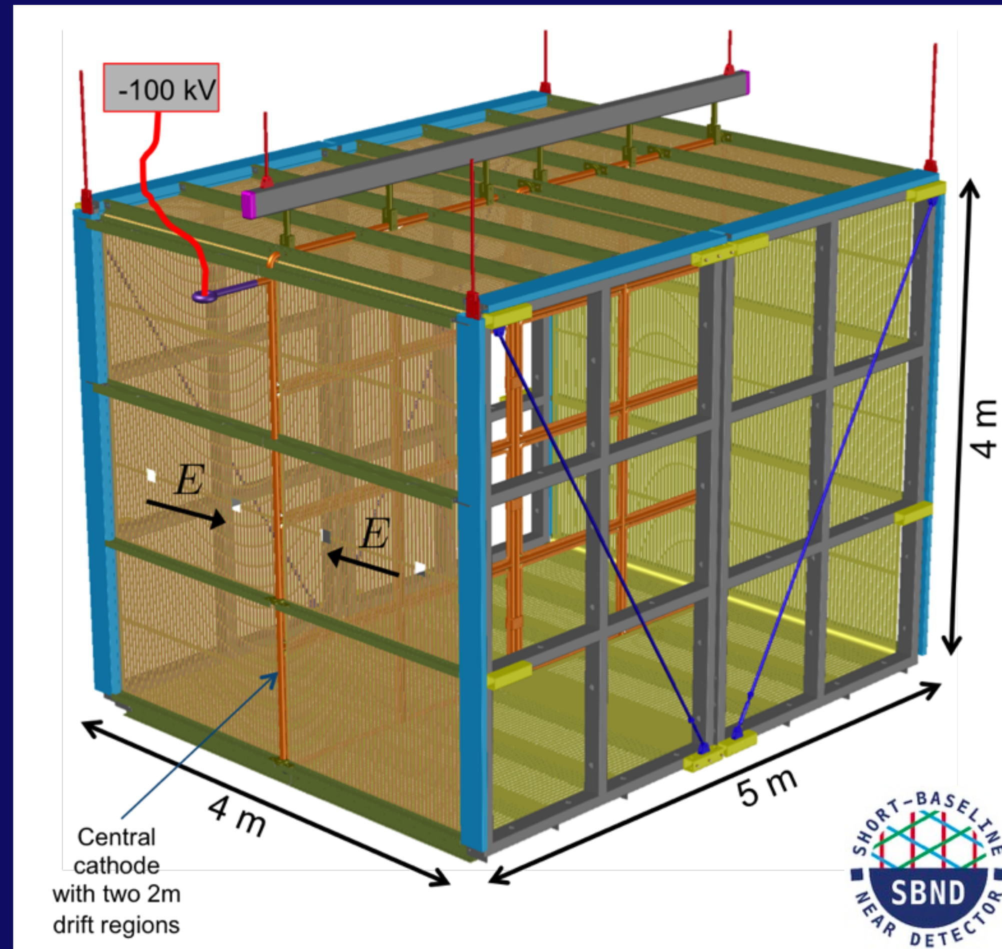
Broke ground on the Near Detector building in early 2016

Also completed end 2016/early 2017

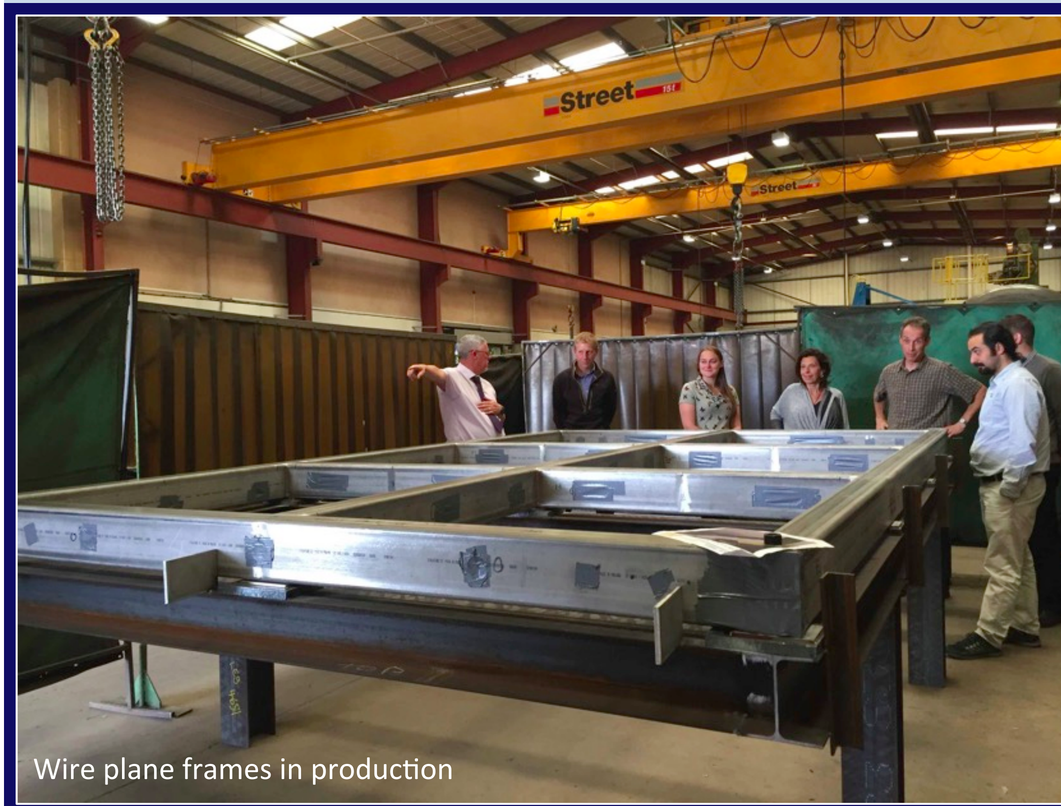
The Short-Baseline Near Detector (SBND)

- SBND will be a new LArTPC
  - Build upon experience and apply lessons learned from MicroBooNE and other detectors at FNAL and elsewhere
  - Common design elements to ICARUS and the DUNE single phase far detector and protoDUNE-SP

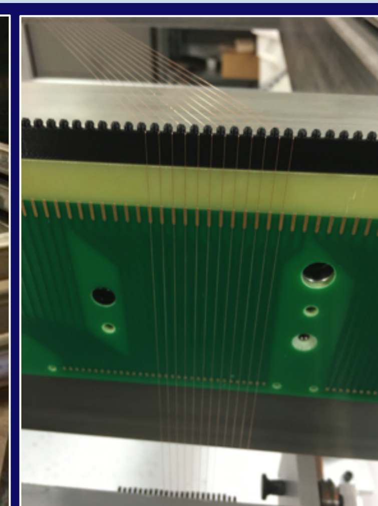


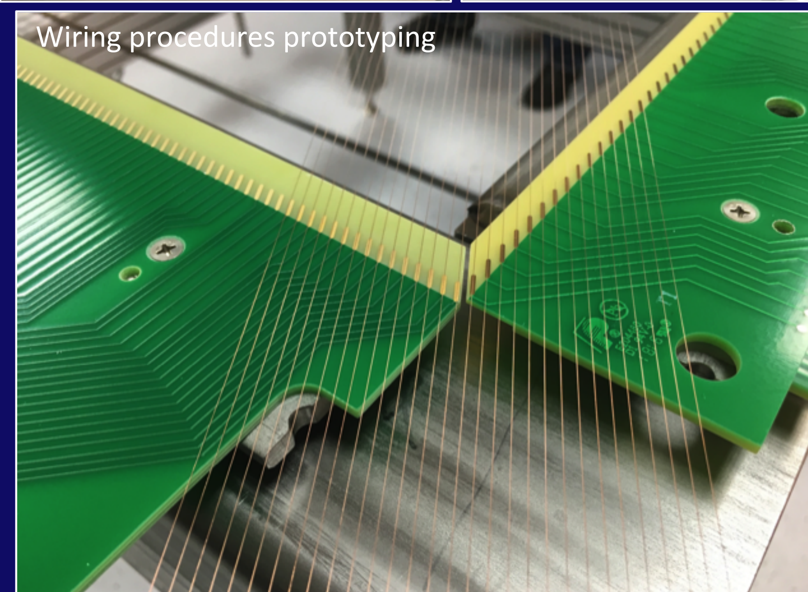


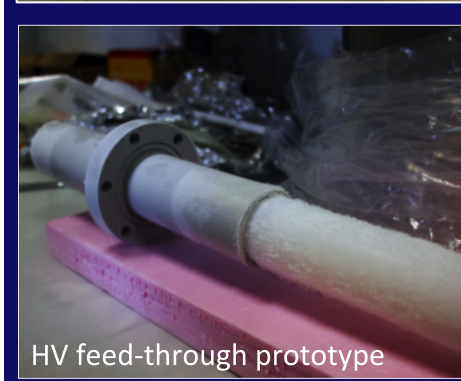
SBND: TPC Construction Has Begun



Wire plane frames in production



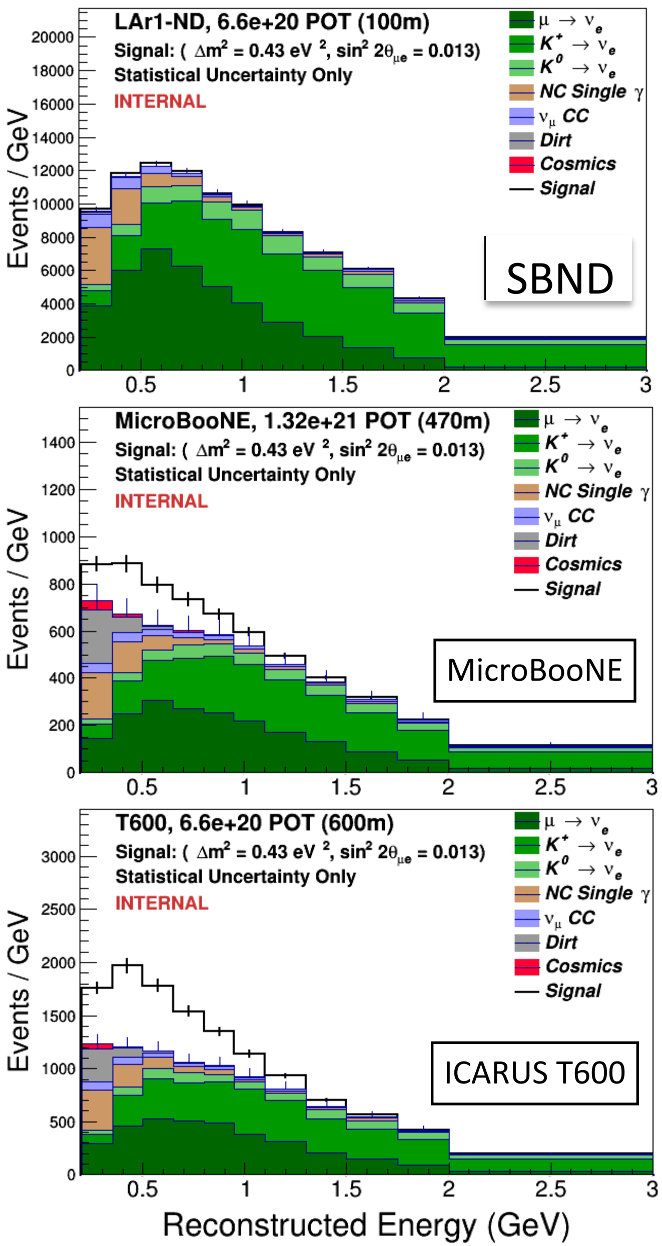

Wiring procedures prototyping

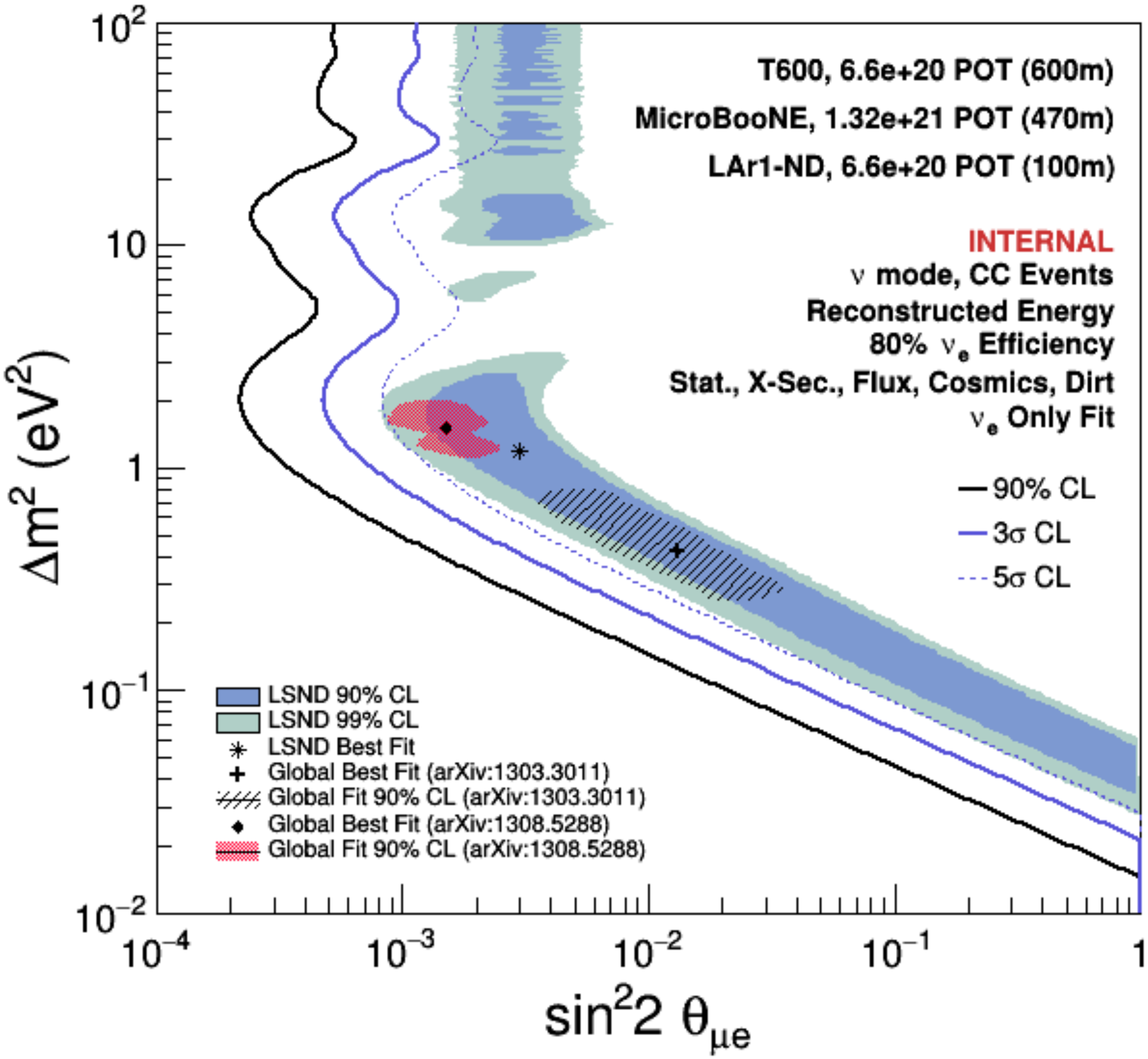

HV feed-through prototype


Cathode plane mesh prototype

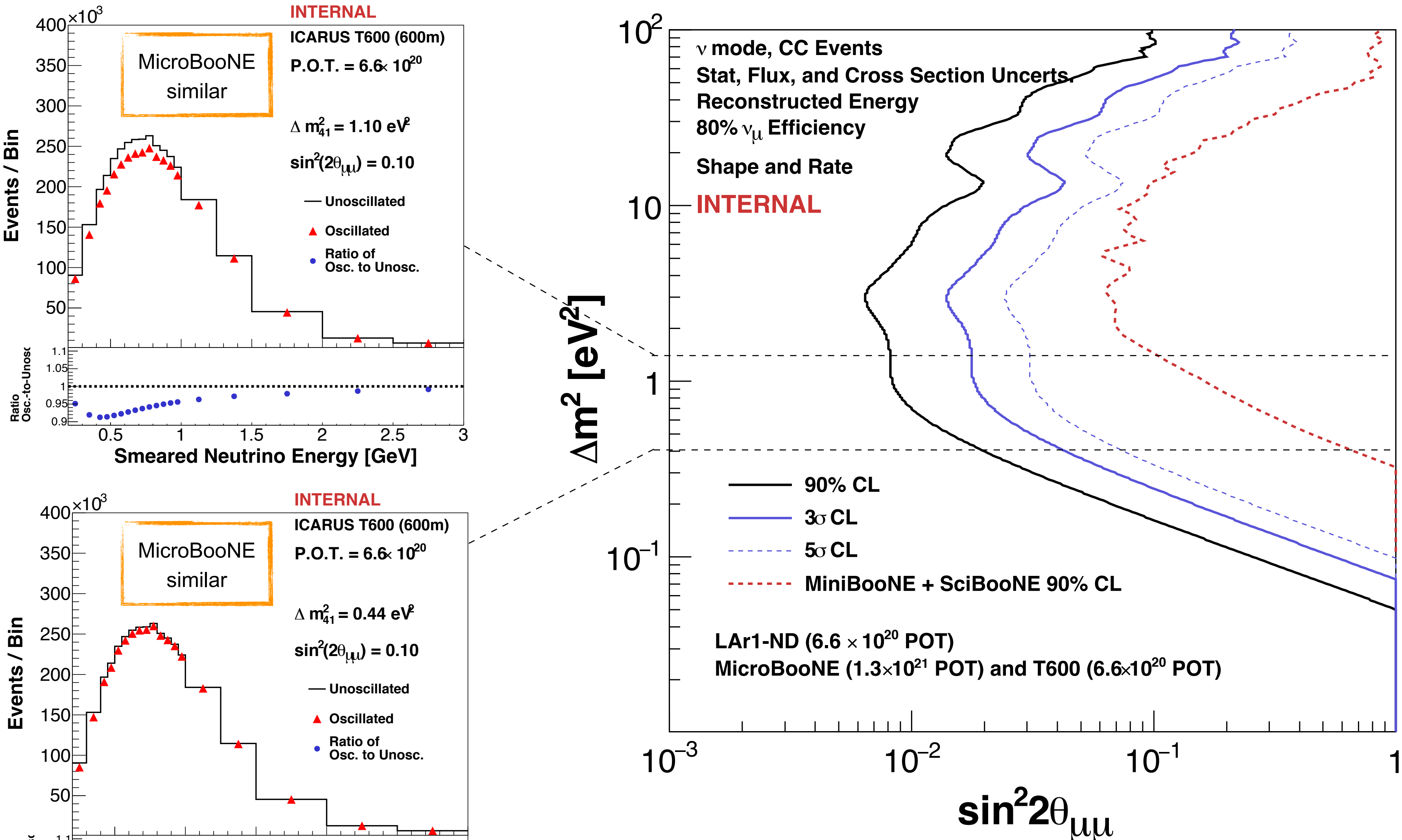
Neutrino 2016 Poster: *"SBND: Status of the Fermilab Short-Baseline Near Detector"* by Nicola McConkey

ν_e Appearance Sensitivity





ν_μ Disappearance Sensitivity



Sensitivity includes full flux and cross section systematics, but not detector systematics at this time.

Short-Baseline Conclusions

• The results from LSND & MiniBooNE and the other anomalies in short baseline ν experiments cannot be explained by the 3 ν paradigm and suggest the existence of sterile ν.

• Sterile ν would contribute to the dark matter of the universe and would have a big impact on particle physics, nuclear physics, astrophysics and cosmology.

• The world neutrino & antineutrino data can be fit fairly well to a 3+N oscillation model, although there is tension at present between appearance and disappearance experiments.

• Future experiments (e.g. SBN at Fermilab) have the golden opportunity of proving whether short-baseline oscillations and light, sterile neutrinos exist!

Thanks Gerry for your 32 Years of Leadership & Scientific Excellence at LANL!

Backup

Searches for Sterile Neutrinos with the IceCube Detector