BooNE

The BooNE proposal

BooNE's physics reach and sensitivities

Cost vs. performance trade-offs

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Fermilab PAC
8 December, 2011

Synopsis of the BooNE Proposal:

- Construct an "identical MiniBooNE" second detector at a distance of ~200 meters from the BNB

- Golden discovery opportunity: prove (or disprove) the LSND and MiniBooNE anomalies as oscillations between sterile and active neutrinos

- BooNE will leverage 10 years of MiniBooNE running, analysis development, and operations experience

- Within 1 year it will yield a dramatic improvement in sensitivity from $3\sigma \rightarrow 5\sigma$ in neutrino mode

- By capitalizing on the MiniBooNE civil engineering and development the project could be completed quickly and inexpensively for ~ \$15M*

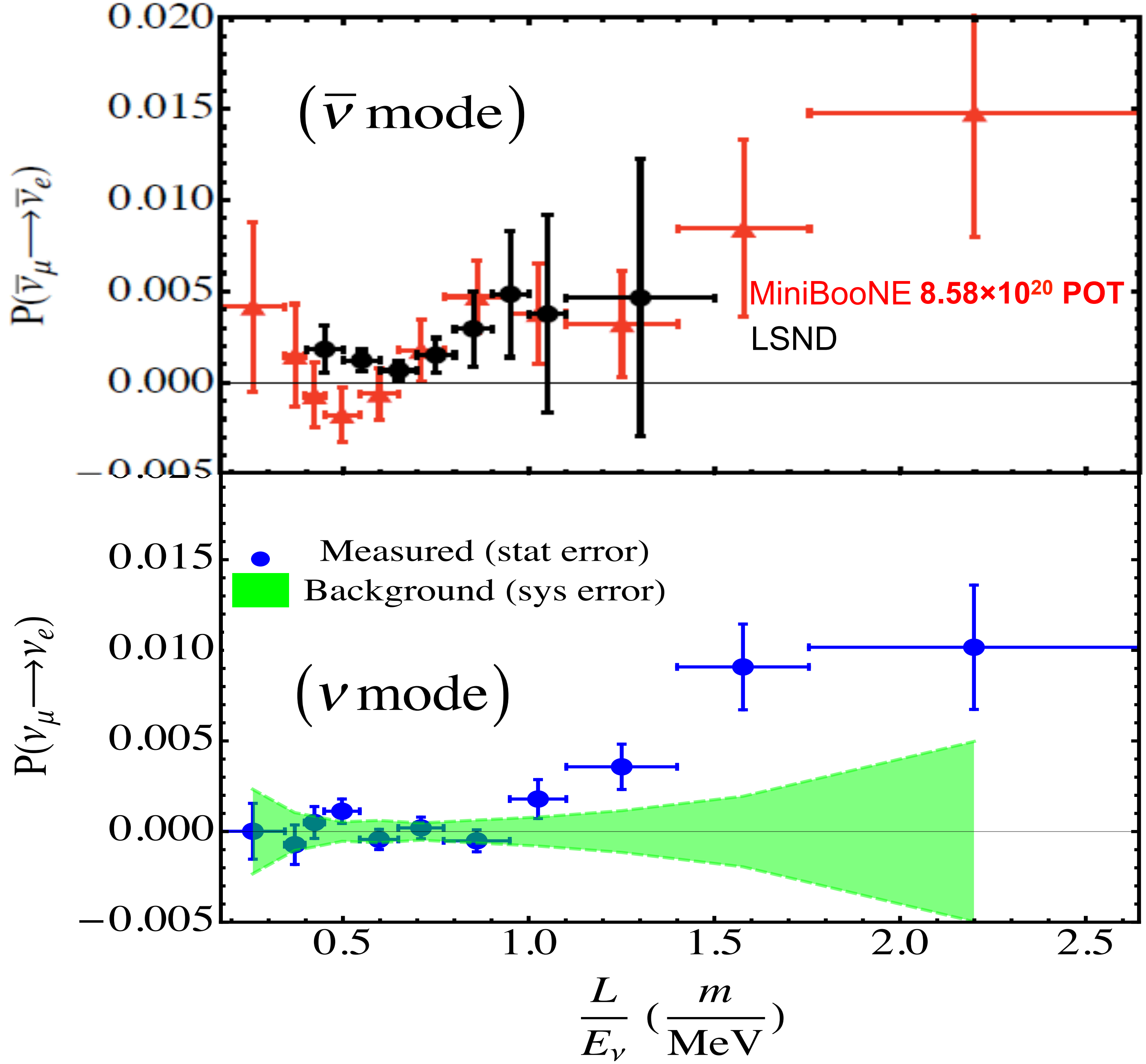
*~\$8M in "low-budget" scenario

Recap of MiniBooNE Results

- Neutrino mode ν_e appearance :
  - 3σ excess in at low energy (6σ statistical error only)
- Antineutrino mode $\bar{\nu}_e$ appearance:
  - ~2.5σ excess (3σ statistical error only)
- Disappearance not very sensitive with one detector
- We now need to *prove* whether or not the excess events are due to an oscillation phenomena with a two-detector experiment

MiniBooNE "Oscillation Probability":

$$\frac{N^{\text{Measured}}_{"\nu_e"} - N^{\text{Predicted}}_{"\nu_e"}}{N^{100\%\ \nu_\mu\rightarrow\nu_e}_{"\nu_e"}}$$



Why a second detector?

Systematic Errors in MiniBooNE

Strategy for Minimizing Systematic Errors (MiniBooNE)

1. Use HARP hadro-production data to constrain the flux

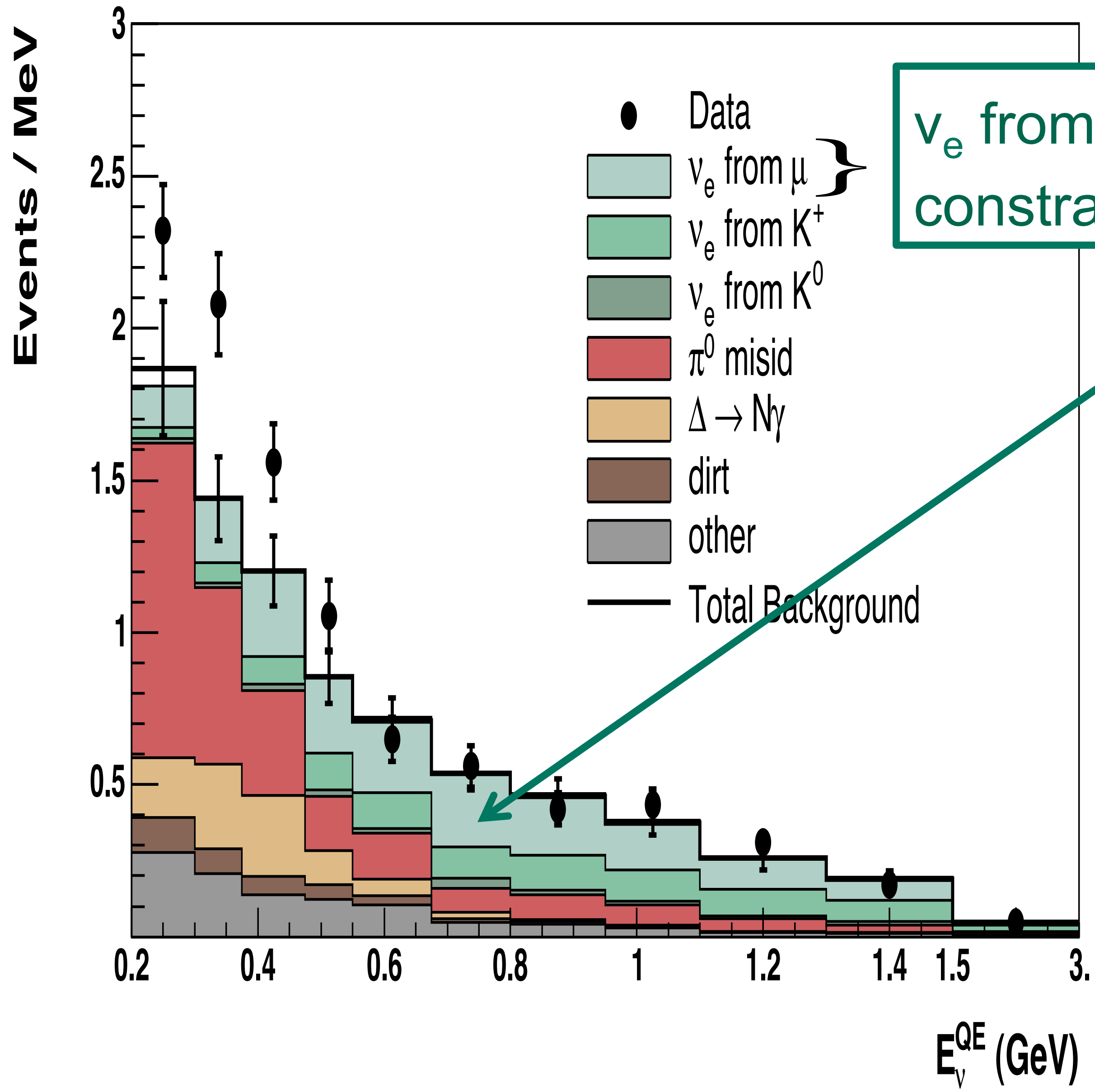
2. Use the observed π^0 event rates to normalize NC photon backgrounds

3. Use the observed ν_μ CCQE event rate to normalize the intrinsic ν_e backgrounds from muon decay-in-flight

4. Simultaneously fit to observed ν_μ and ν_e CCQE events to the predicted rates plus a naïve 2-neutrino model oscillated appearance signal*

*Assuming the ν_μ and ν_e base fluxes don't change (e.g. disappear)

Anatomy of MiniBooNE's ν_e Background



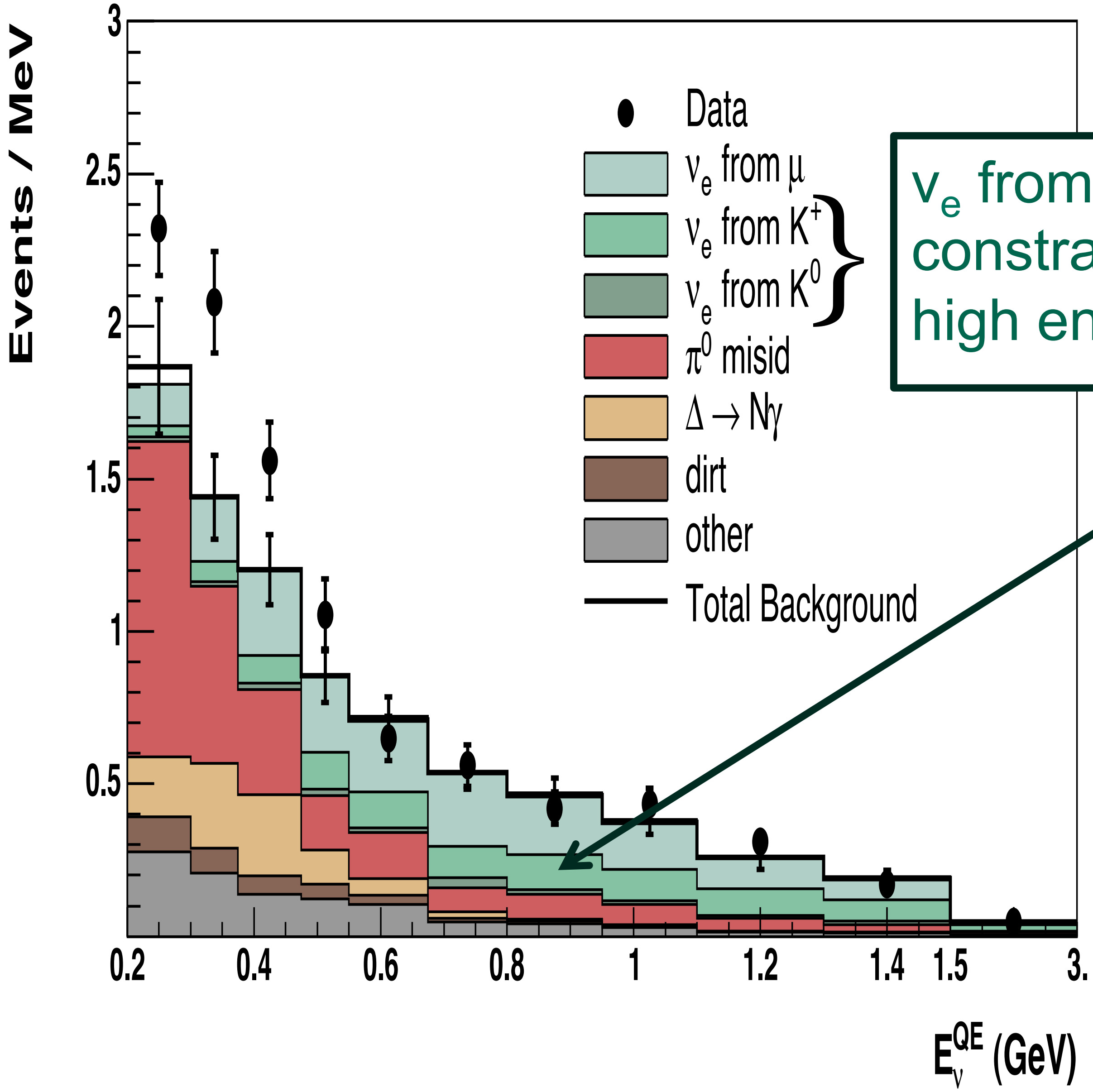
ν_e from muon decay are constrained by measured ν_μ rate

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\downarrow$$

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

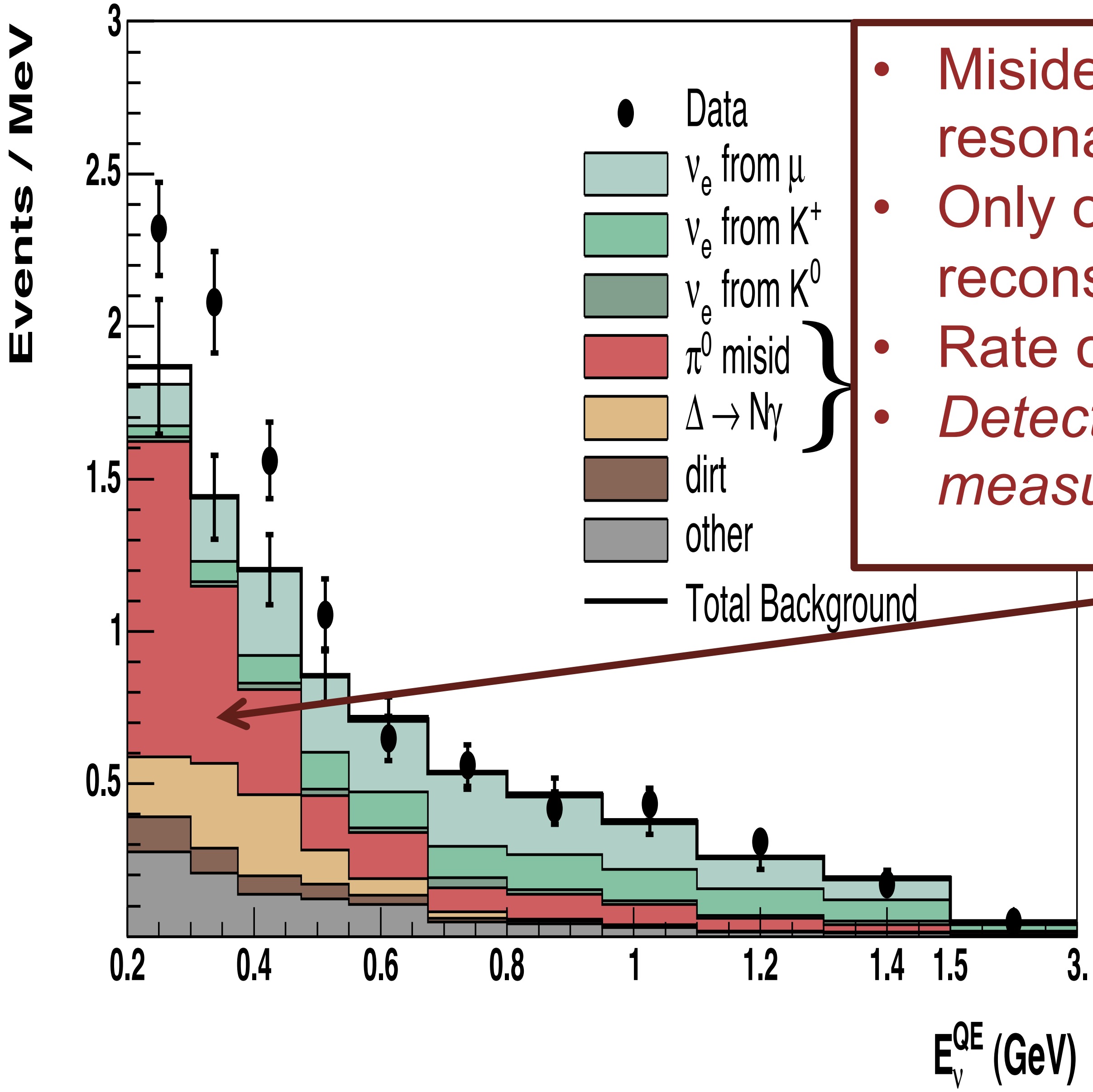
Anatomy of MiniBooNE's ν_e Background



ν_e from kaon decays are constrained by SciBooNE's K^+ high energy ν_μ measurement*

*SciBooNE is not sensitive to ν_e directly and the detector systematics are very different from MiniBooNE's

Anatomy of MiniBooNE's ν_e Background

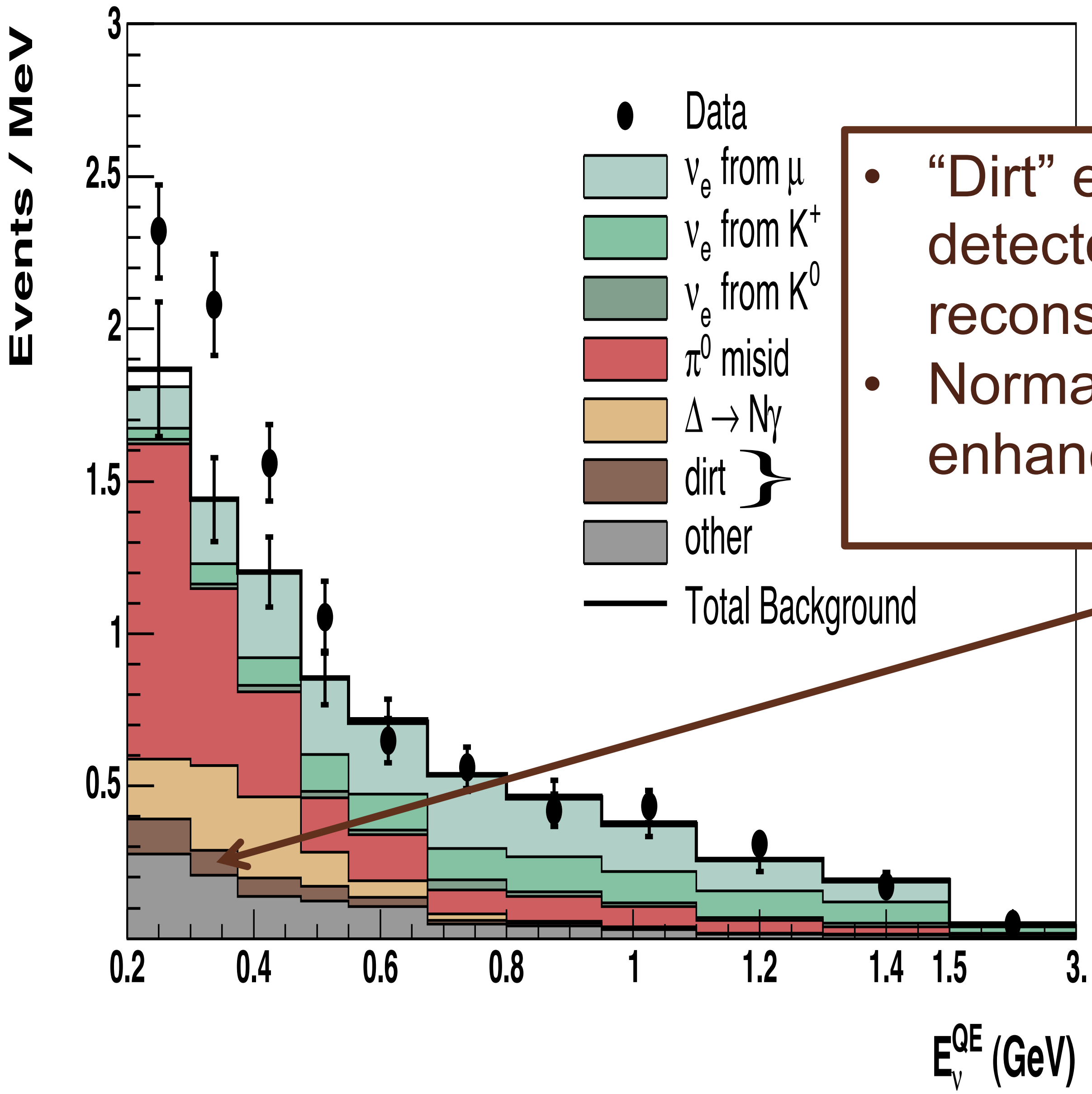


- Misidentified photons from resonance production
- Only one photon ring is reconstructed
- Rate constrained by measured π^0s
- *Detector response error limits measurement at low energy*

$$\pi^0 \rightarrow \gamma\gamma$$

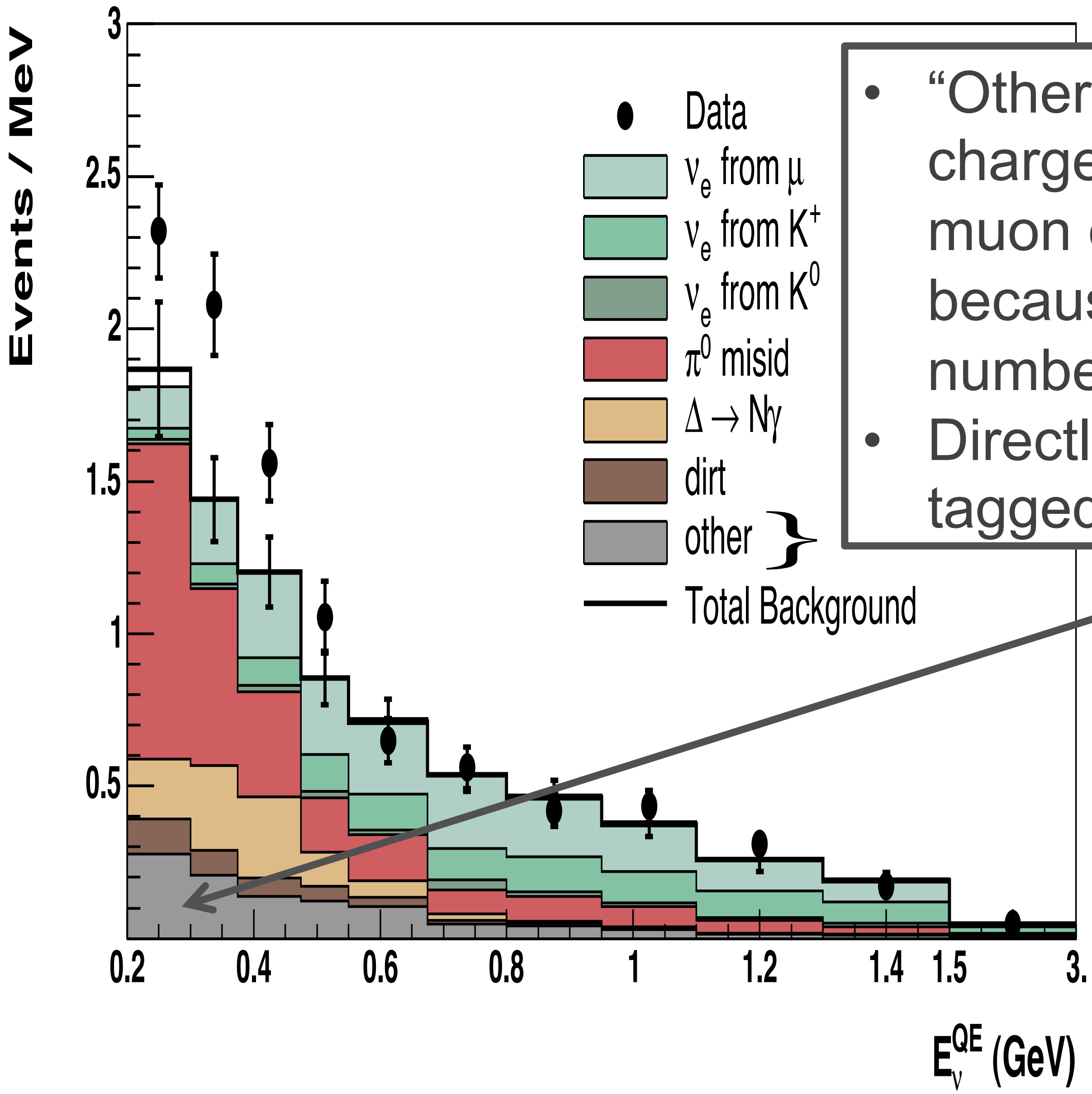
$$\Delta \rightarrow N\gamma$$

Anatomy of MiniBooNE's ν_e Background



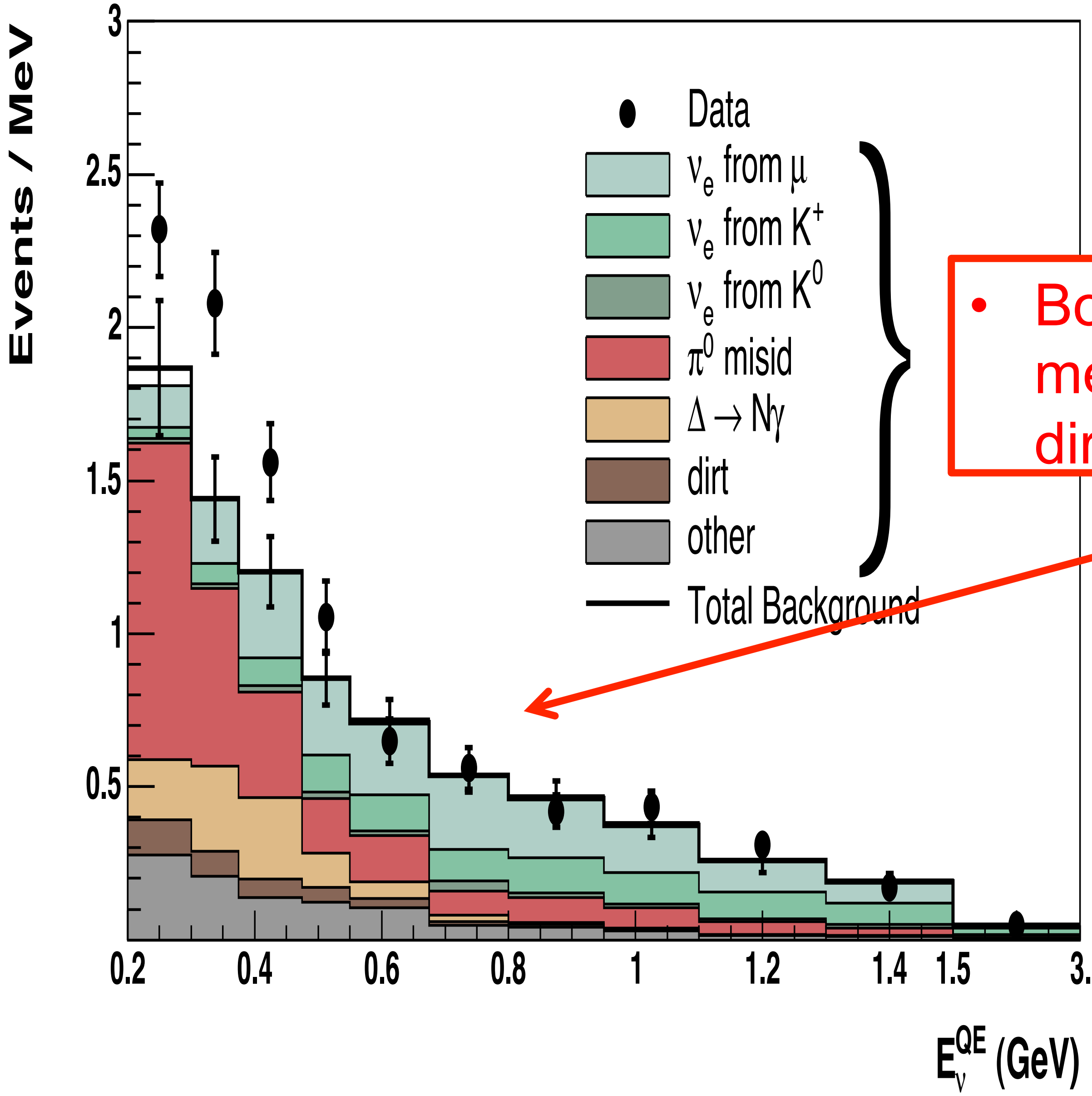
- "Dirt" events originate outside the detector but produce an event reconstructed in the detector
- Normalized to measured "dirt enhanced" sample

Anatomy of MiniBooNE's ν_e Background



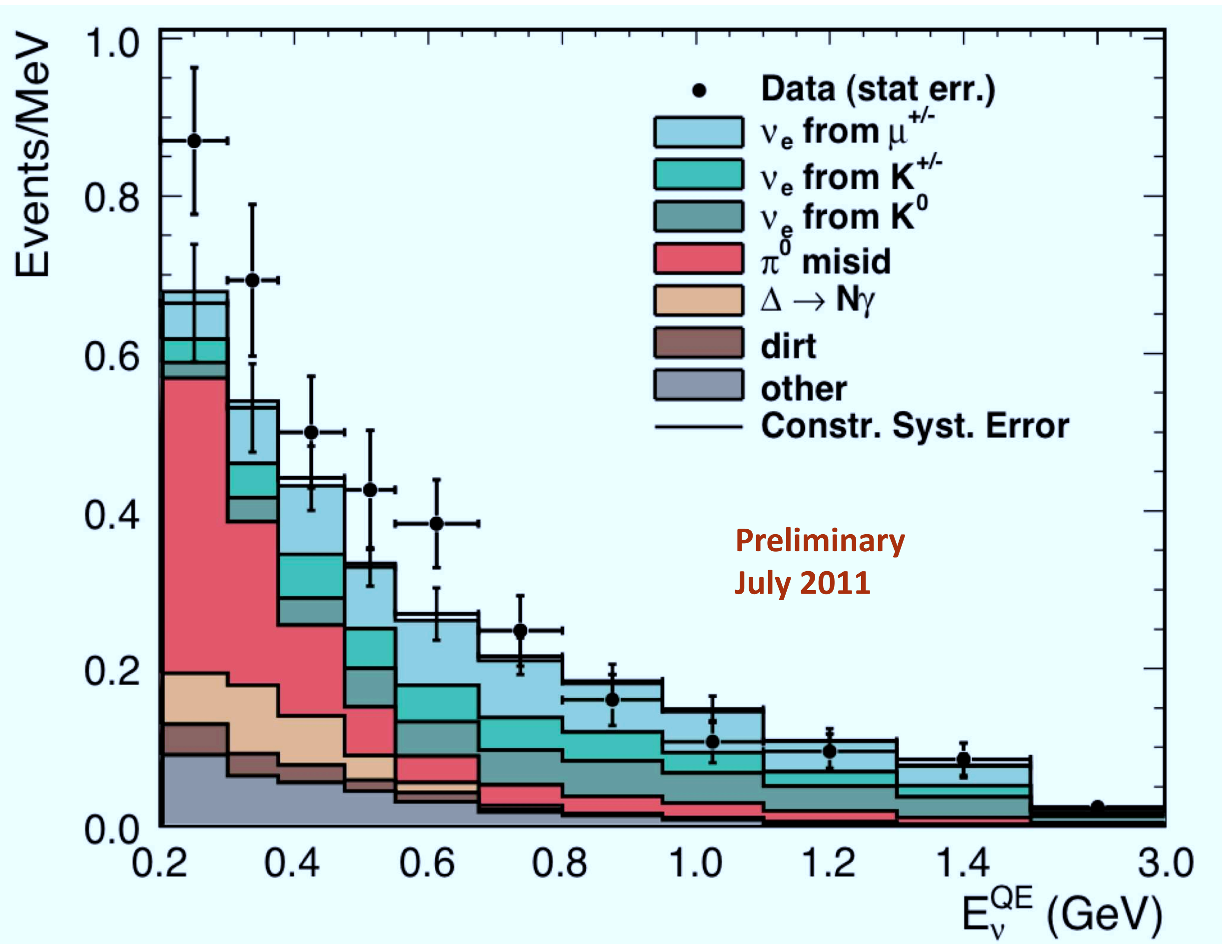
- "Other" are predominantly ν_μ charged current events where muon decay was missed because of capture or low number of hits
- Directly measured in events tagged by following muon decay

BooNE ν_e Background



- BooNE near detector will measure *all* backgrounds directly

Background prediction $\bar{\nu}$ mode



8.58e20 Protons on Target			
	200-475	475-1250	
$\mu^{\pm}$	20.39	47.58	Intrinsic ν_e
$K^{\pm}$	12.35	28.21	
K^0	7.78	32.14	
Other ν_e	1.91	3.11	
NC π^0	63.03	19.05	Mis-ID
$\Delta \rightarrow N\gamma$	18.78	5.11	
dirt	9.34	3.99	
ν_μ CCQE	6.52	3.09	
Other ν_μ	10.66	6.40	
Total	150.76	148.68	

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$\bar{\nu}_e$ Background Uncertainties

Uncertainty (%)	200-475MeV	475-1100MeV
π^+	0.4	0.9
π^-	3	2.3
K^+	2.2	4.7
K^-	0.5	1.2
K^0	1.7	5.4
Target and beam models	1.7	3
Cross sections	6.5	13
NC π^0 yield	1.5	1.3
Hadronic interactions	0.4	0.2
Dirt	1.6	0.7
Electronics & DAQ model	7	2
Optical Model	8	3.7
Total	13.4%	16.0%

- Unconstrained $\bar{\nu}_e$ background uncertainties
- Biggest contributors:
  - Detector response
  - Cross sections

($\bar{\nu}_\mu$ constrained error ~10%)

The solution: BooNE

- A MiniBooNE near detector at ~200 meters
  - Accumulate a sufficient data sample for both neutrino and antineutrino modes in < 1 year (x7 rate!)
  - Will dramatically reduce errors in neutrino mode and anti-neutrino mode, the 3σ low energy excess has a ~ 6σ significance with statistical errors only and BooNE would achieve 5σ
  - Many short runs for checking systematic effects would be possible, as was done for MINOS (e.g. 25 meter absorber down and different horn currents) .

A Proposal to Build a MiniBooNE Near Detector:BooNE

October 12, 2011

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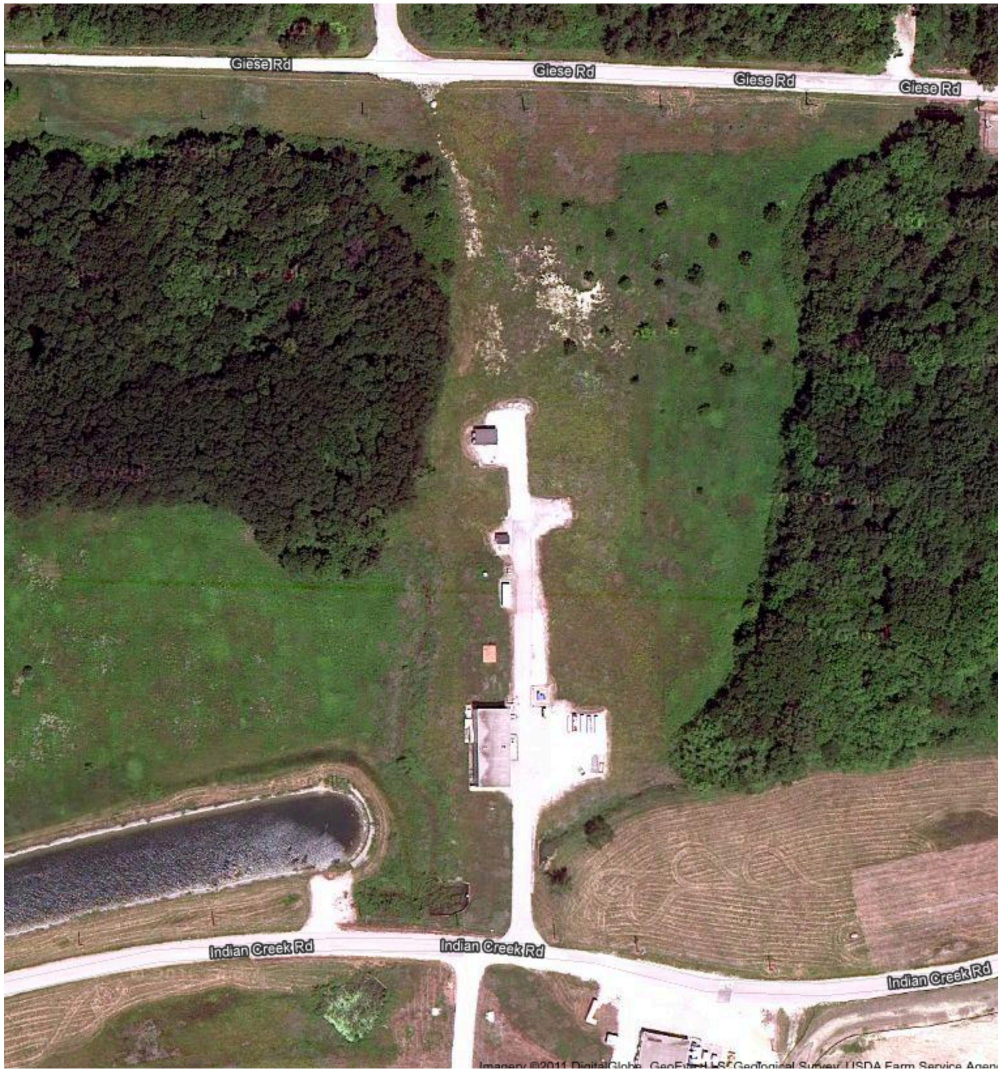
Pine St
United States Government
Lederman Science Center
Kirk Rd
Kautz Rd
Niu Institute Neutron Therapy
Fermi National Lab Library
Rd A-1
Rd A-2
Rd D
Outer Ring Rd
Central Utility Building
Booster Ring Rd
Final
Giese Rd
SB 10
SB 30
SB 50
Indian Creek Rd
Holter Rd
Garden Ct
Cherry Dr


Giese Rd
Giese Rd
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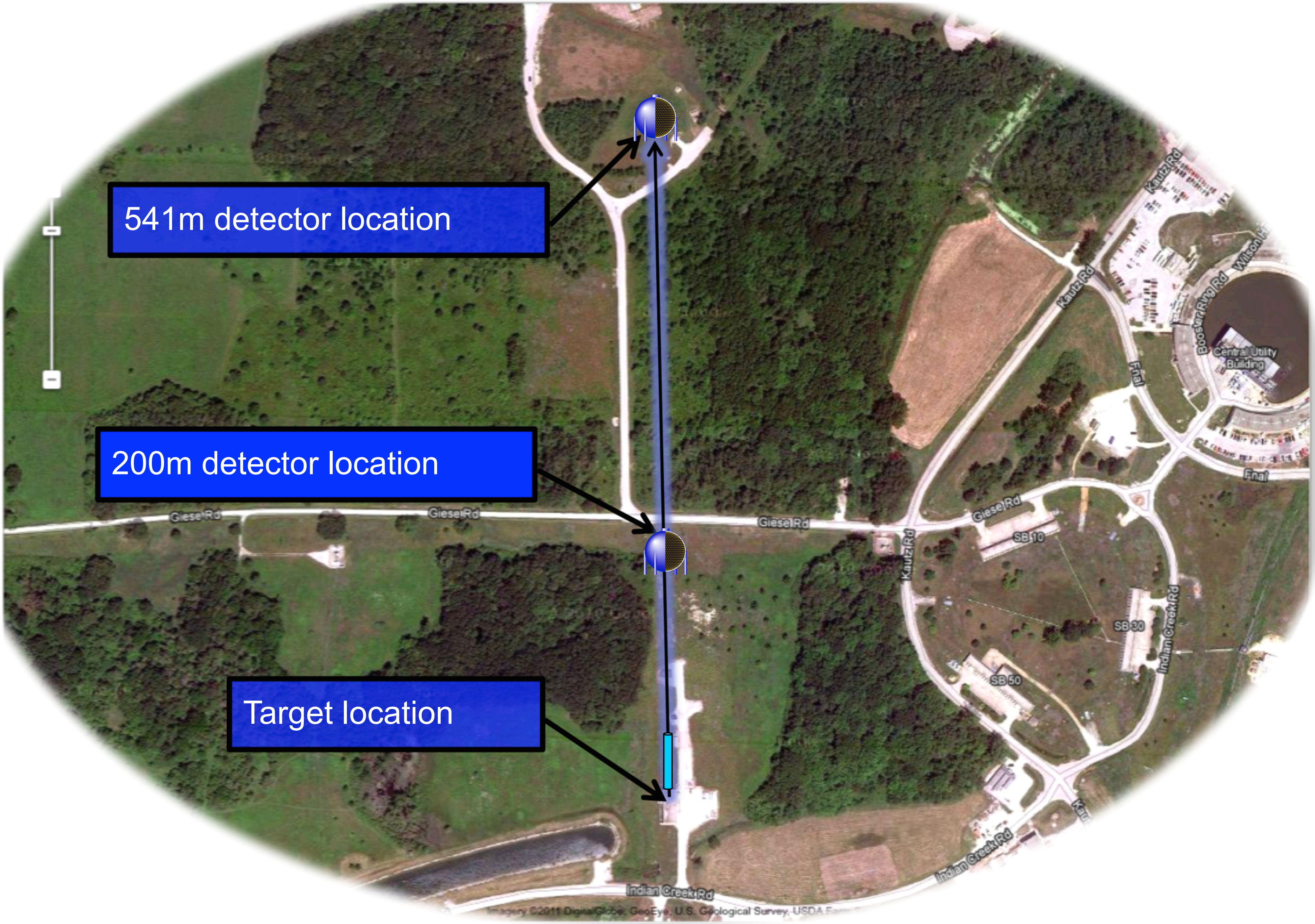
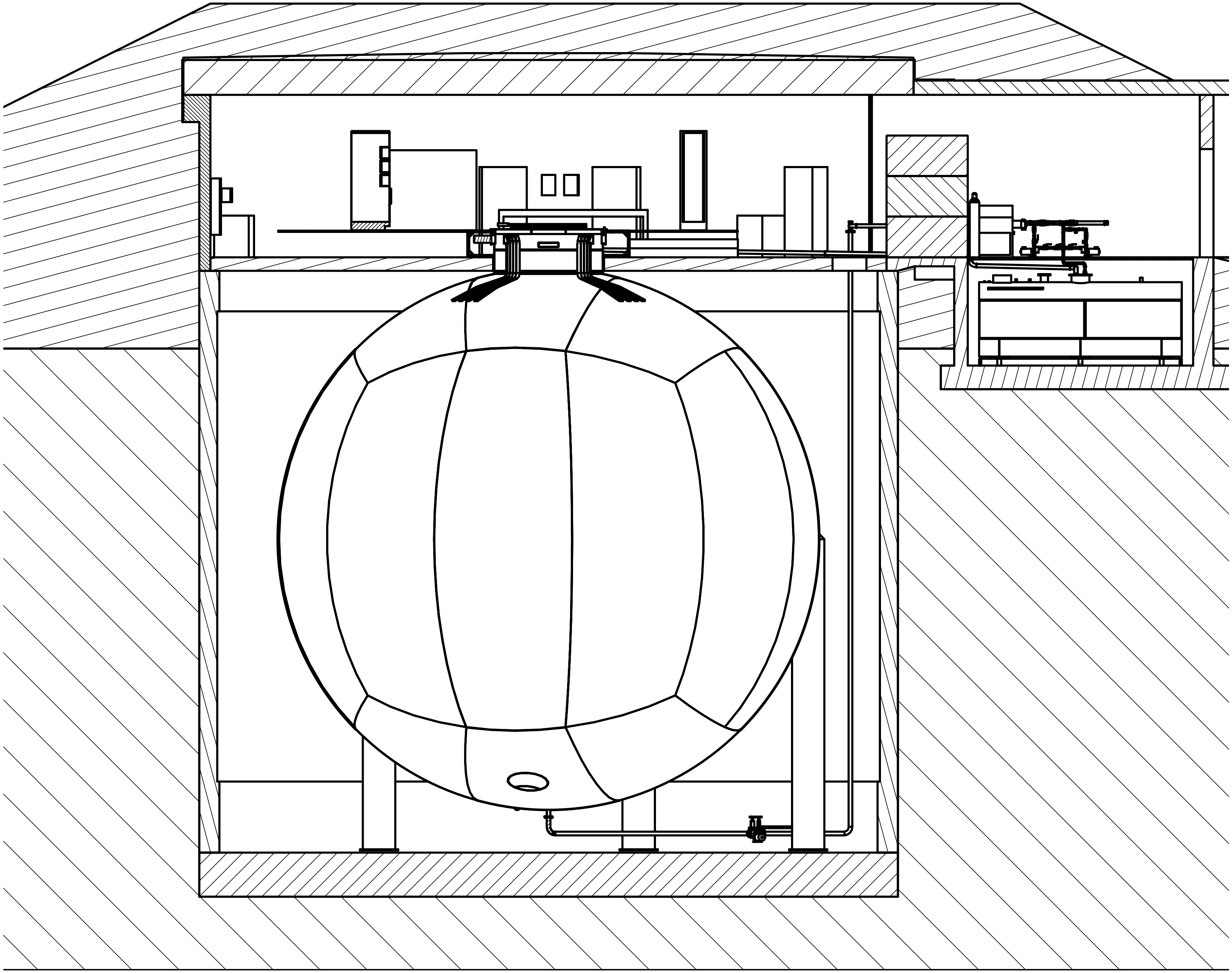
Indian Creek Rd
Indian Creek Rd

New Location at 200 meters

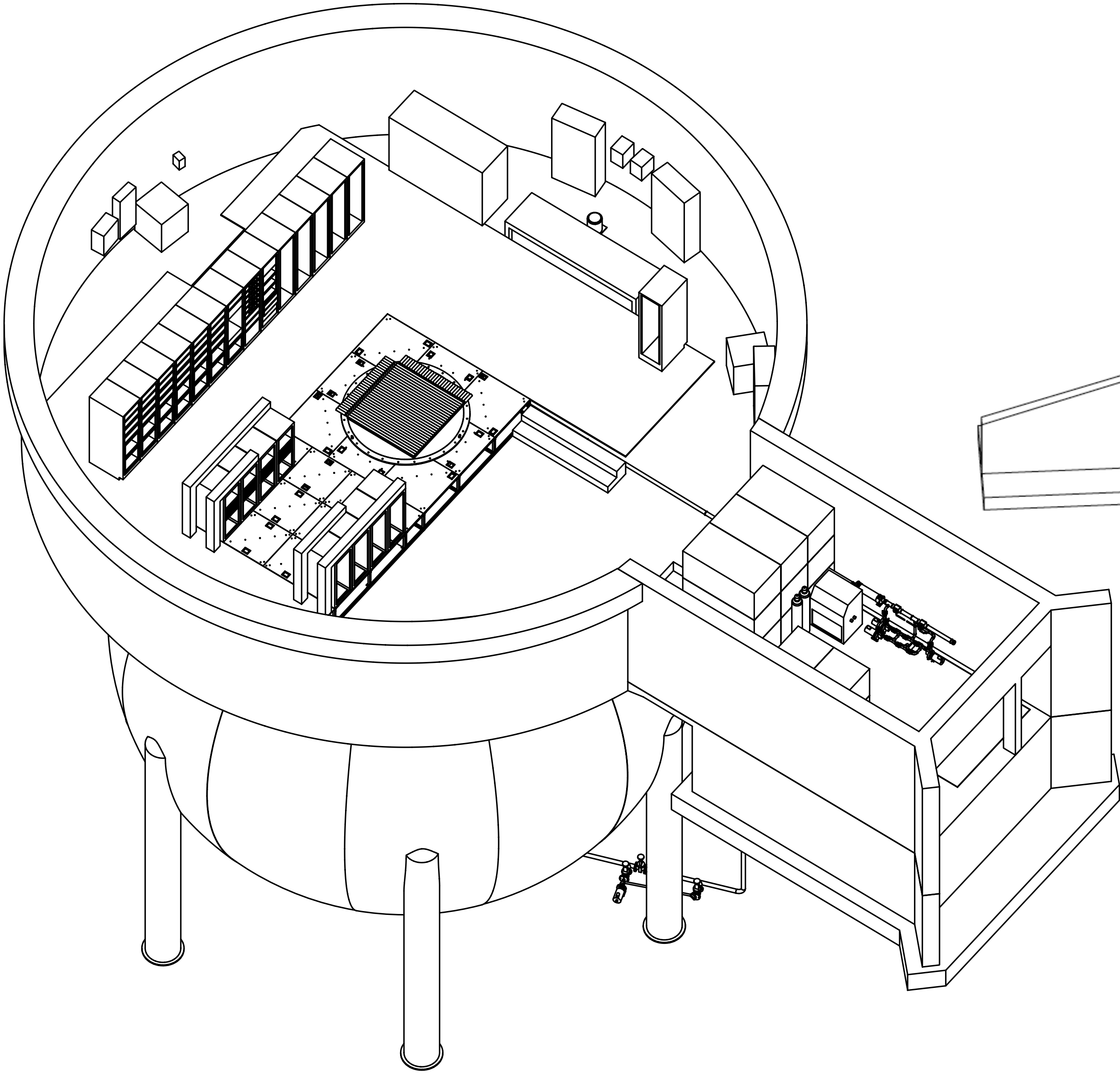


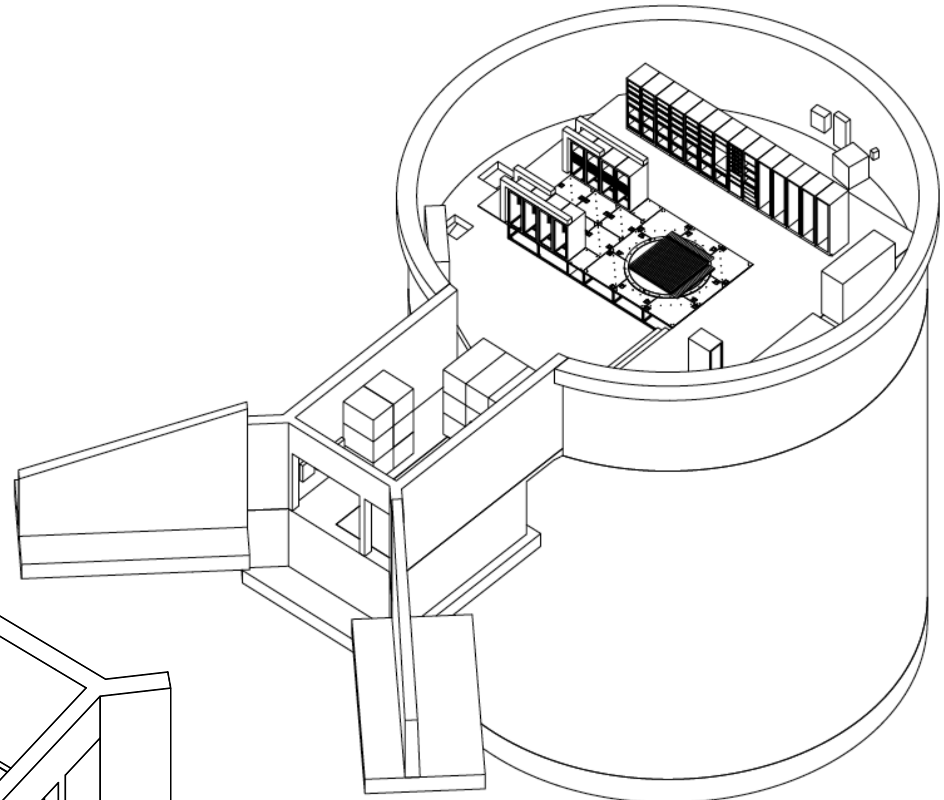

MiniBooNE Site

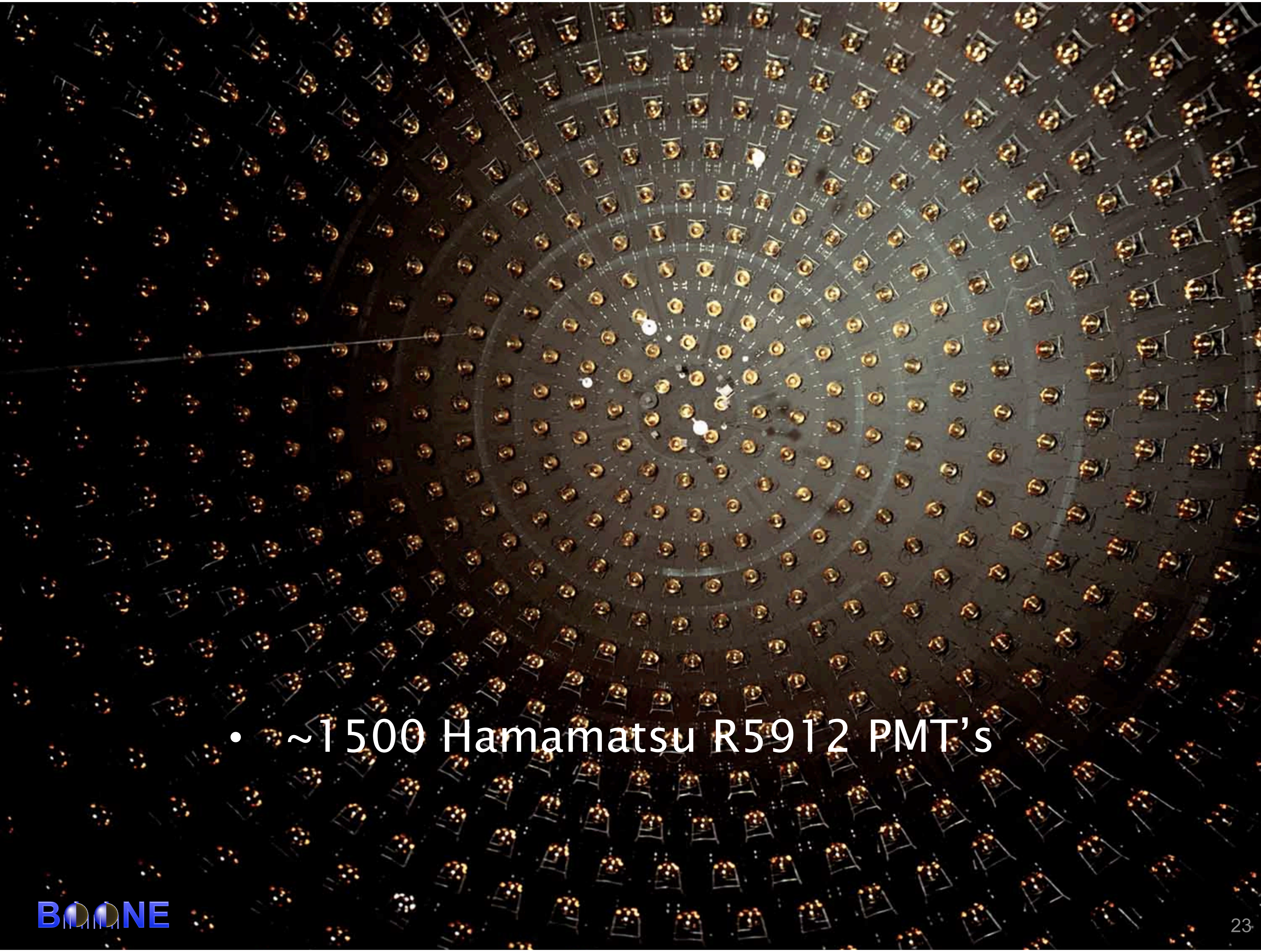
MiniBooNE Detector Hall Elevation View



MiniBooNE Detector Hall 3D Model

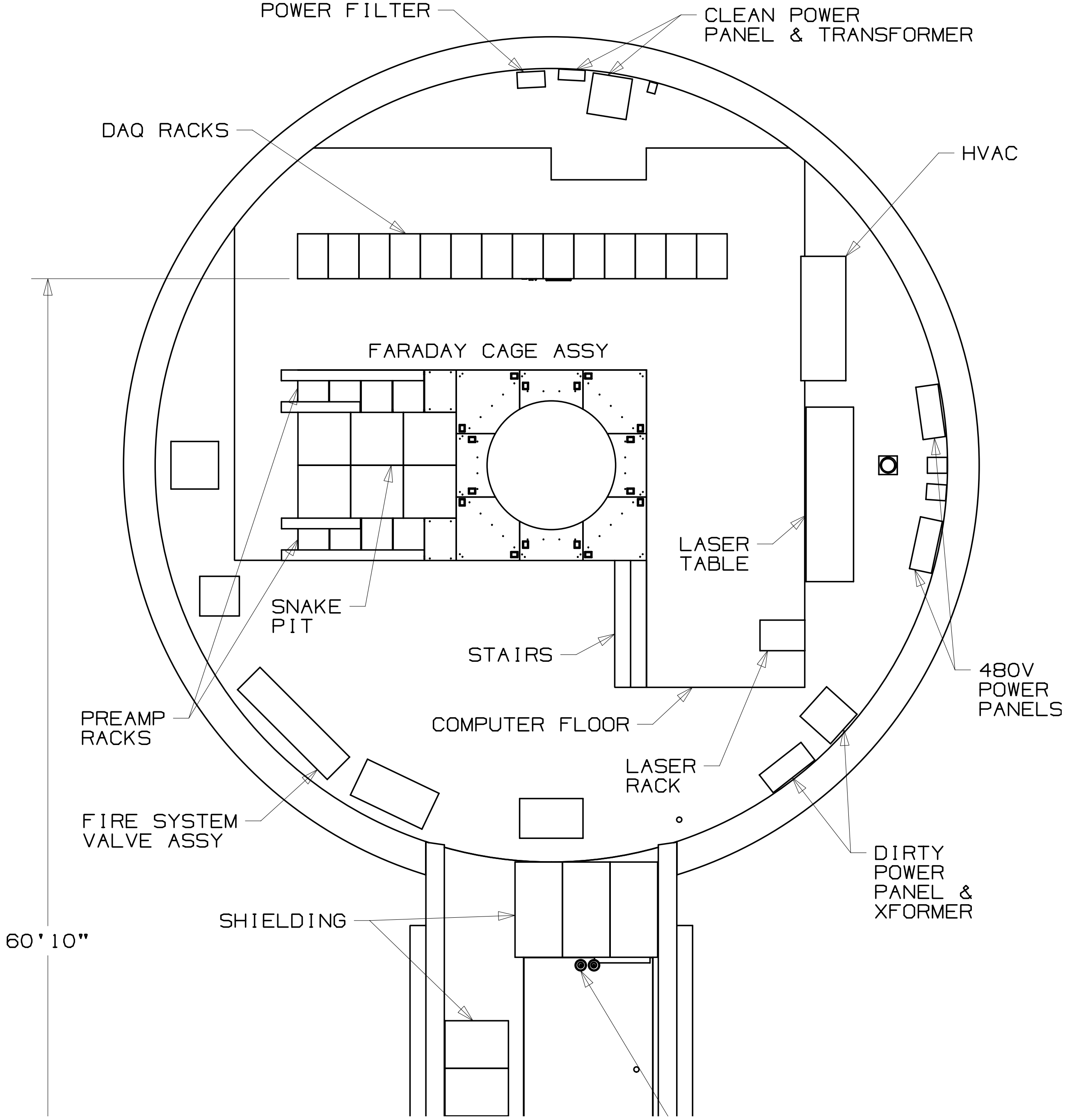




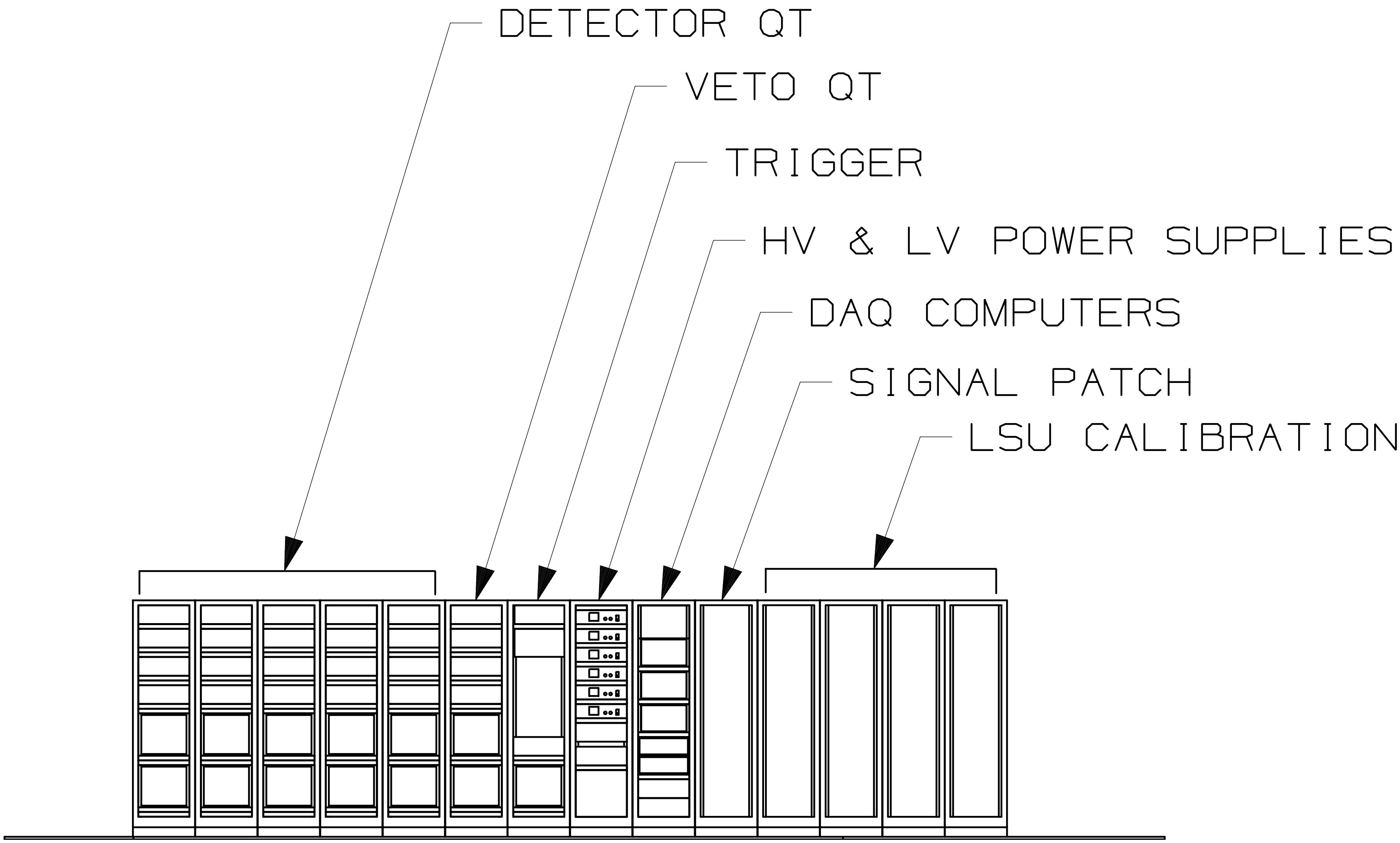


- ~1500 Hamamatsu R5912 PMT's

MiniBooNE Electronics and Services Plan View



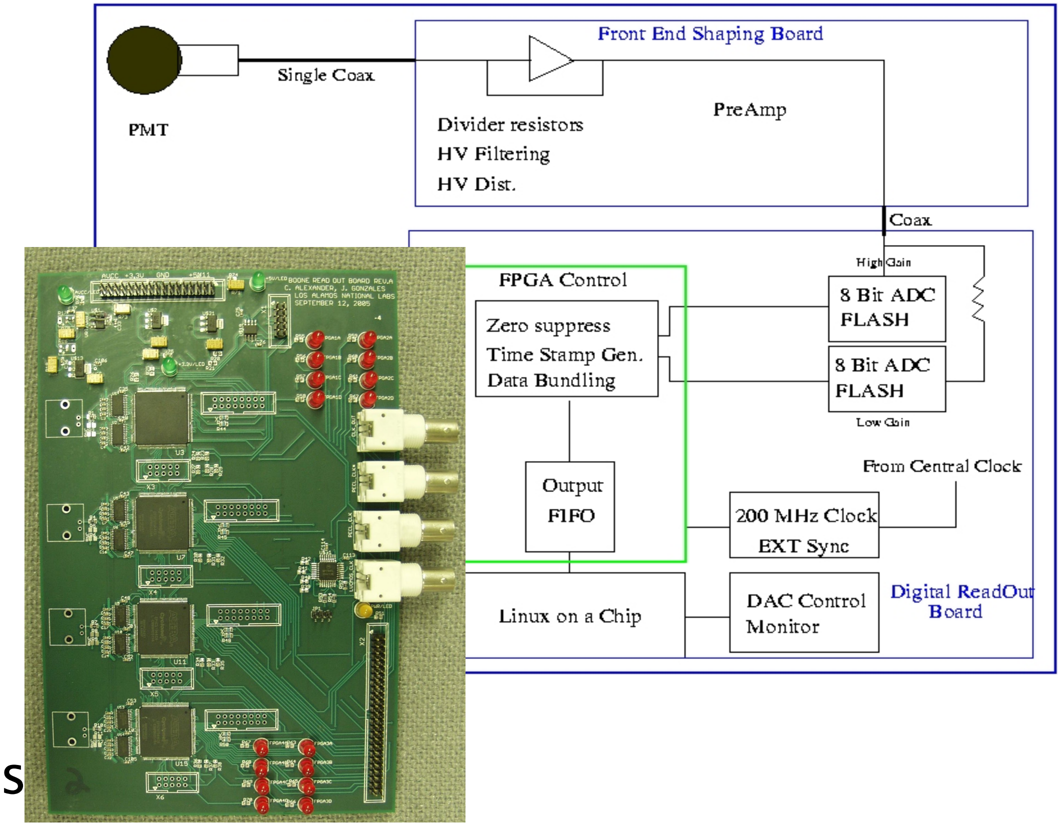
MiniBooNE Electronics Racks

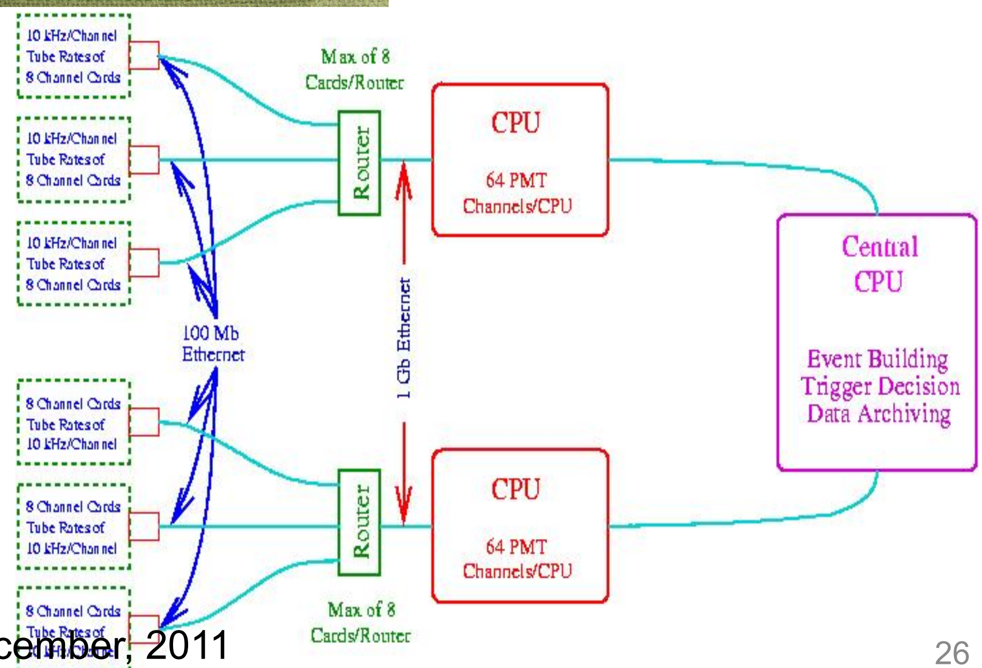


New Electronics:

- Have designed new prototype electronics for large PMT arrays with improved performance.

- Goals:
  - 400 MHz FADC's, pulse to pulse timing ~1 nsec.
  - Records individual photoelectrons
  - Large charge dynamic range (0-1000 pe).
  - Xilinx FPGA signal processing
  - Enables software triggering





BooNE Cost Estimate

- Based on as-built MiniBooNE costs
  - 28% contingency added
  - 3%/year escalation assuming 2013 start

Item	Cost ($K)
Tank	265.3
Support Structure	28.1
PMTs	2768.9
Preamps	30.6
Electronics	355.5
DAQ	67.2
Conventional Construction	4212.0
Plumbing	25.9
Oil	1283.6
Total	9037.2

BooNE Schedule

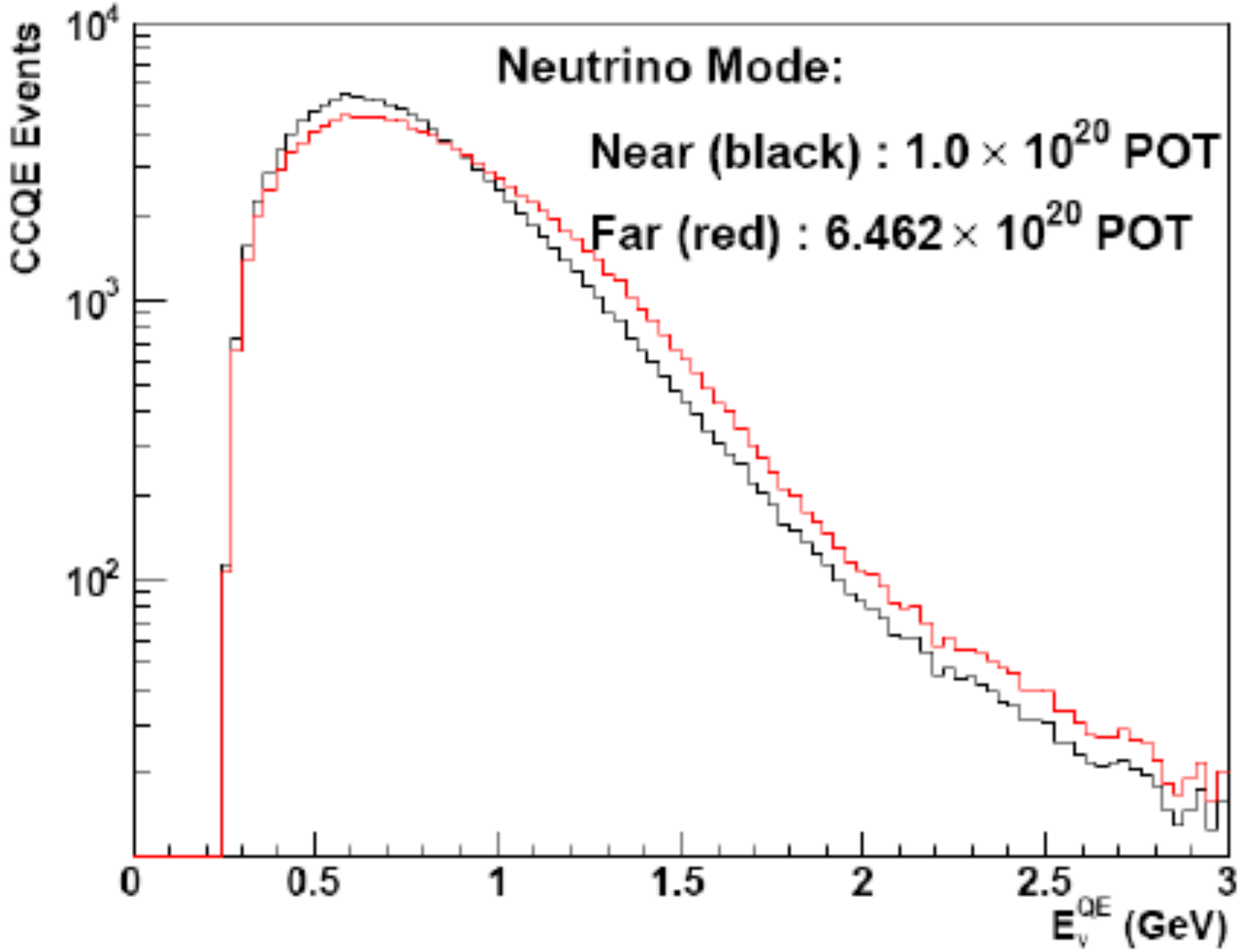
- Project is ideal for fast-tracking
  - Much of the original design could be used
  - Well known performance characteristics
  - Have complete simulation/analysis software in-hand

Milestone	Date
CD-0	3/26/12
CD-1	7/17/12
CD-2	9/26/12
CD-3 Construction Start	5/24/13
Tank Complete	8/1/13
Conventional Construction Complete	12/3/13
Electronics Complete	10/19/13
DAQ Start	5/24/13
PMTs Installed	4/24/14
CD-4	5/26/14

BooNE Performance Estimate

- *Uses full MiniBooNE sensitivity machinery*
  - Full MiniBooNE oscillation analysis package applied: full simulation and reconstruction and fitting package
  - Use identical detector response (fully correlated errors)
  - 1×10^{20} POT per mode (2×0.5 years at current rates)
  - Reweight MC events for fluxes at 200 meters
  - Incorporates 10 years of accumulated knowledge from MiniBooNE experience

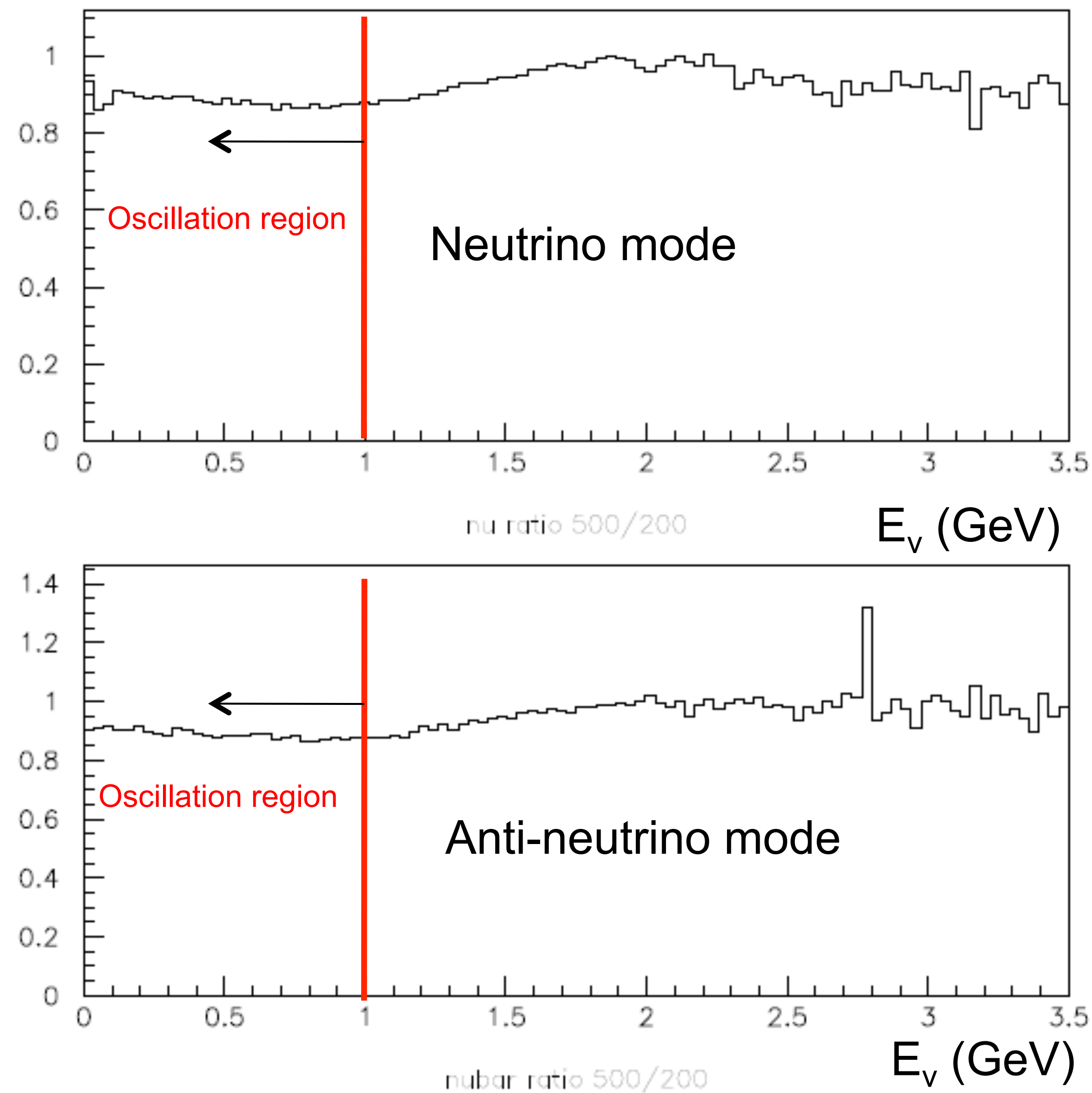
ν_μ Charged Current Event Rates Near and Far



Quasi elastic event rates

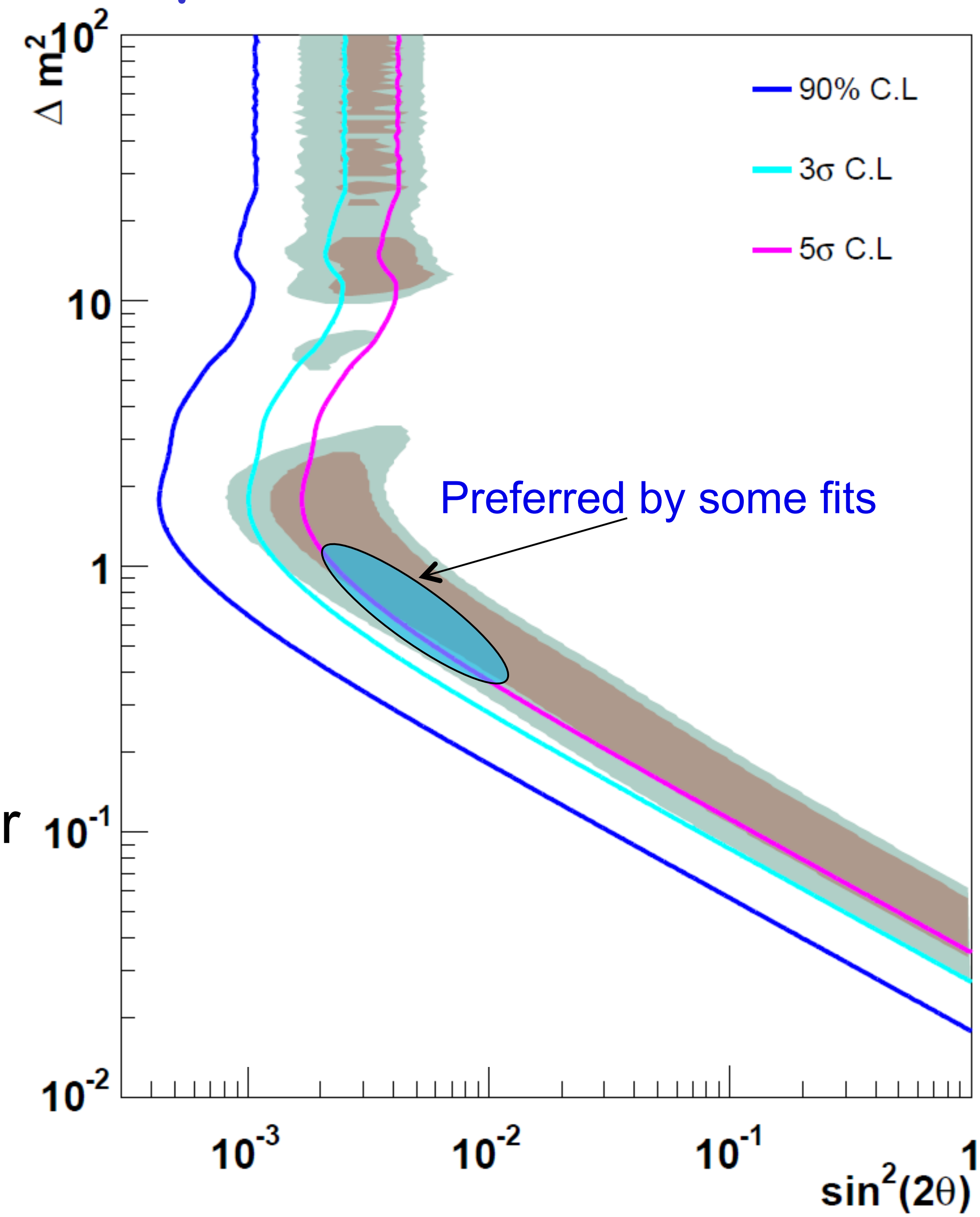
Far to Near ν_e Flux Ratios at 200 m

MiniBooNE Far/Near fluxes Scaled by $1/r^2$



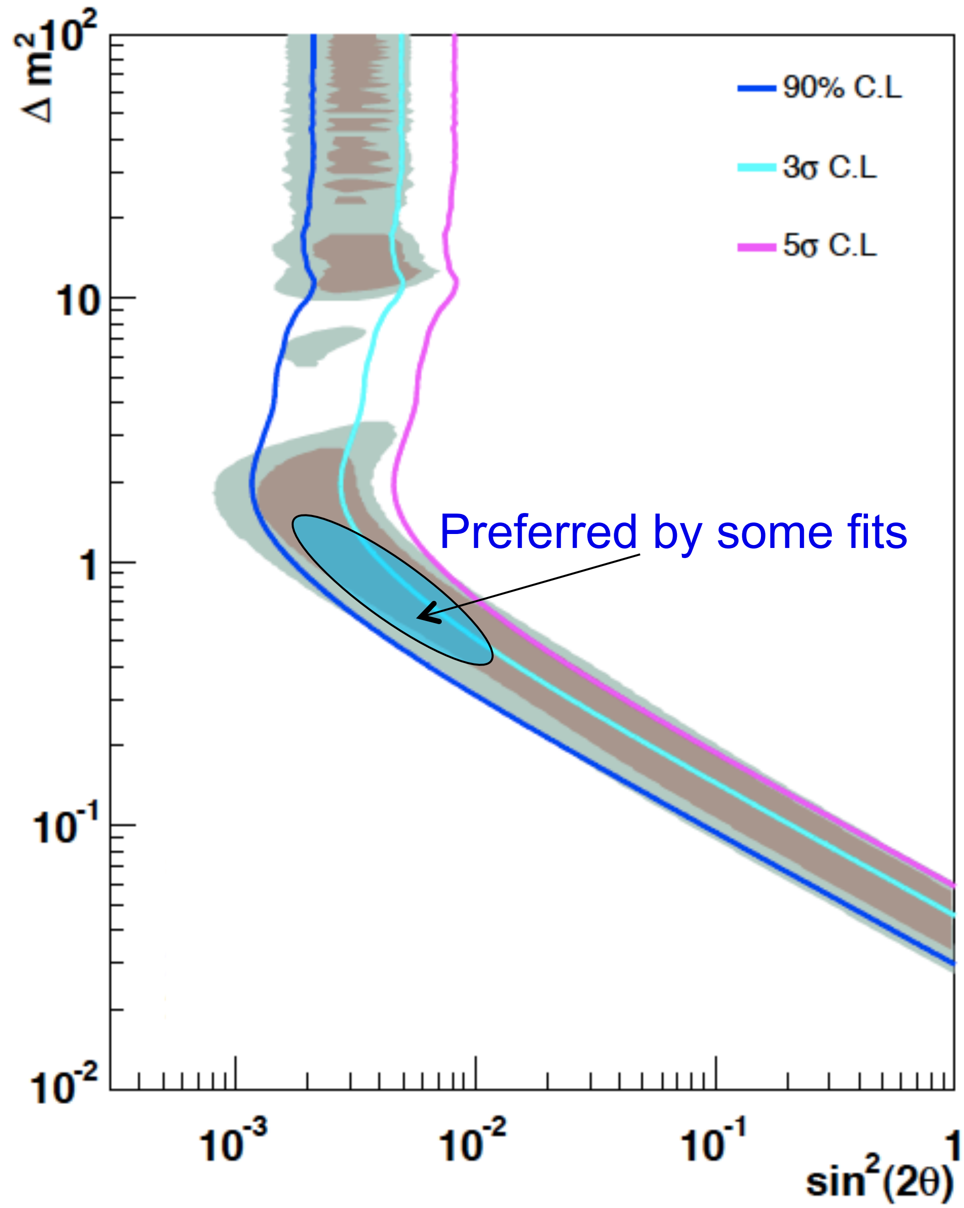
Sensitivity with Near/Far Comparison

- Near/Far comparison sensitivity
  - ➢Near location at 200 meter
    - ✓ 1×10^{20} pot ~1 yr of running
  - ➢ Full systematic error analysis
    - ✓Flux, cross section, detector response

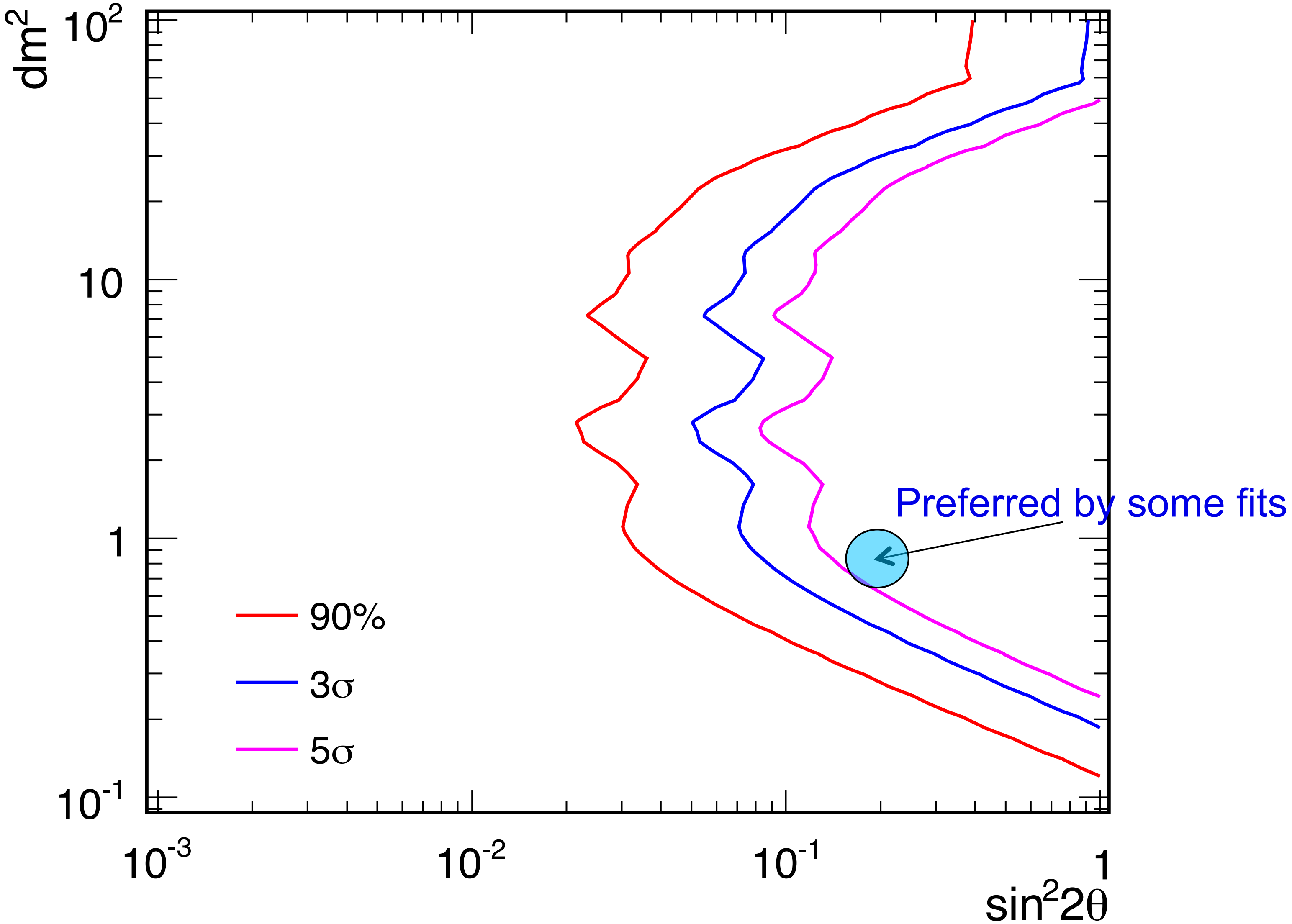


Sensitivity with Near/Far Comparison Anti-nu Mode

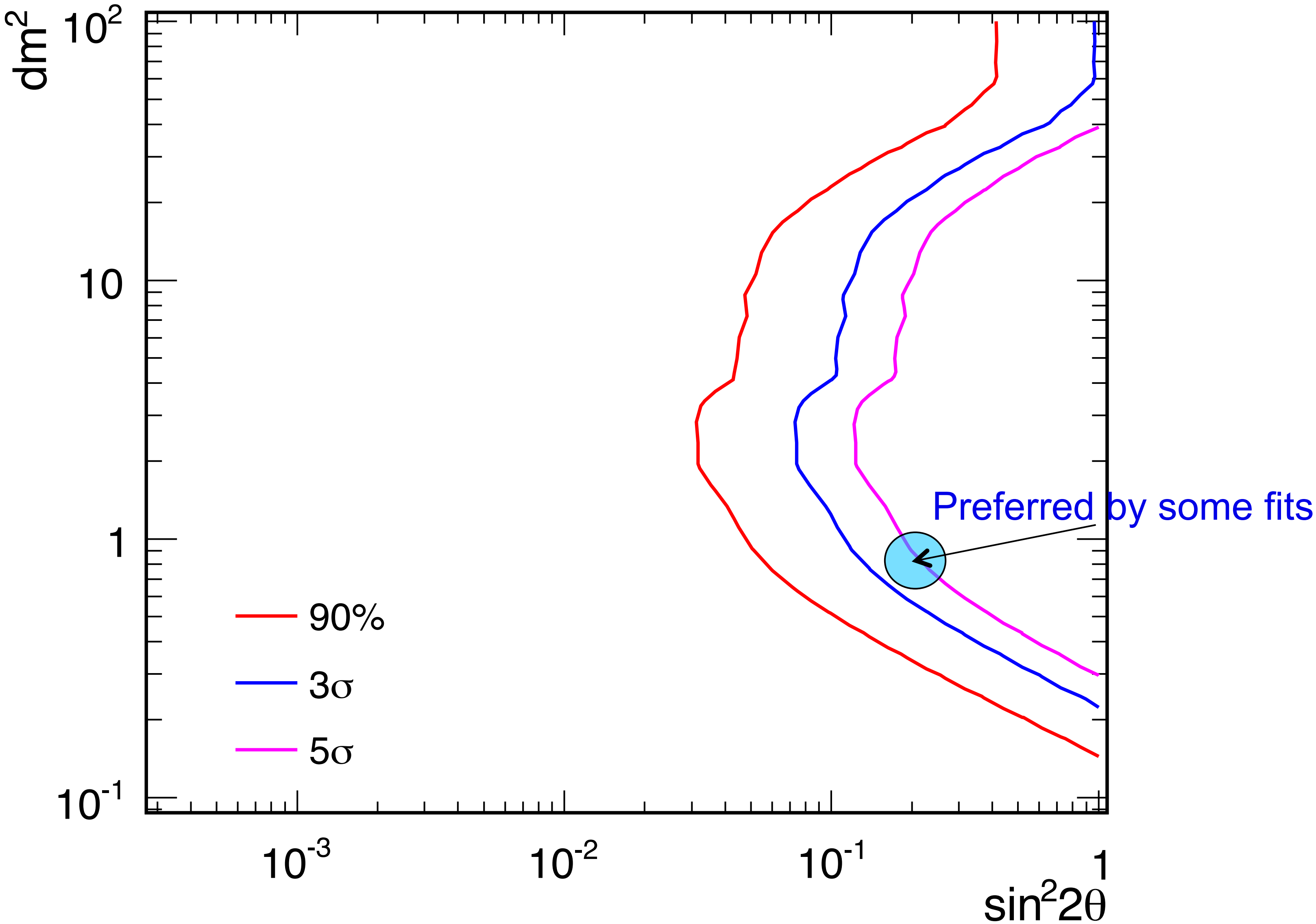
- Near/Far comparison sensitivity
  - ➢Near location at 200 meter
    - ✓ 1×10^{20} pot ~1 yr of running
  - ➢ Full systematic error analysis
    - ✓Flux, cross section, detector response



Neutrino Disappearance Sensitivity with Detector at 200 Meters

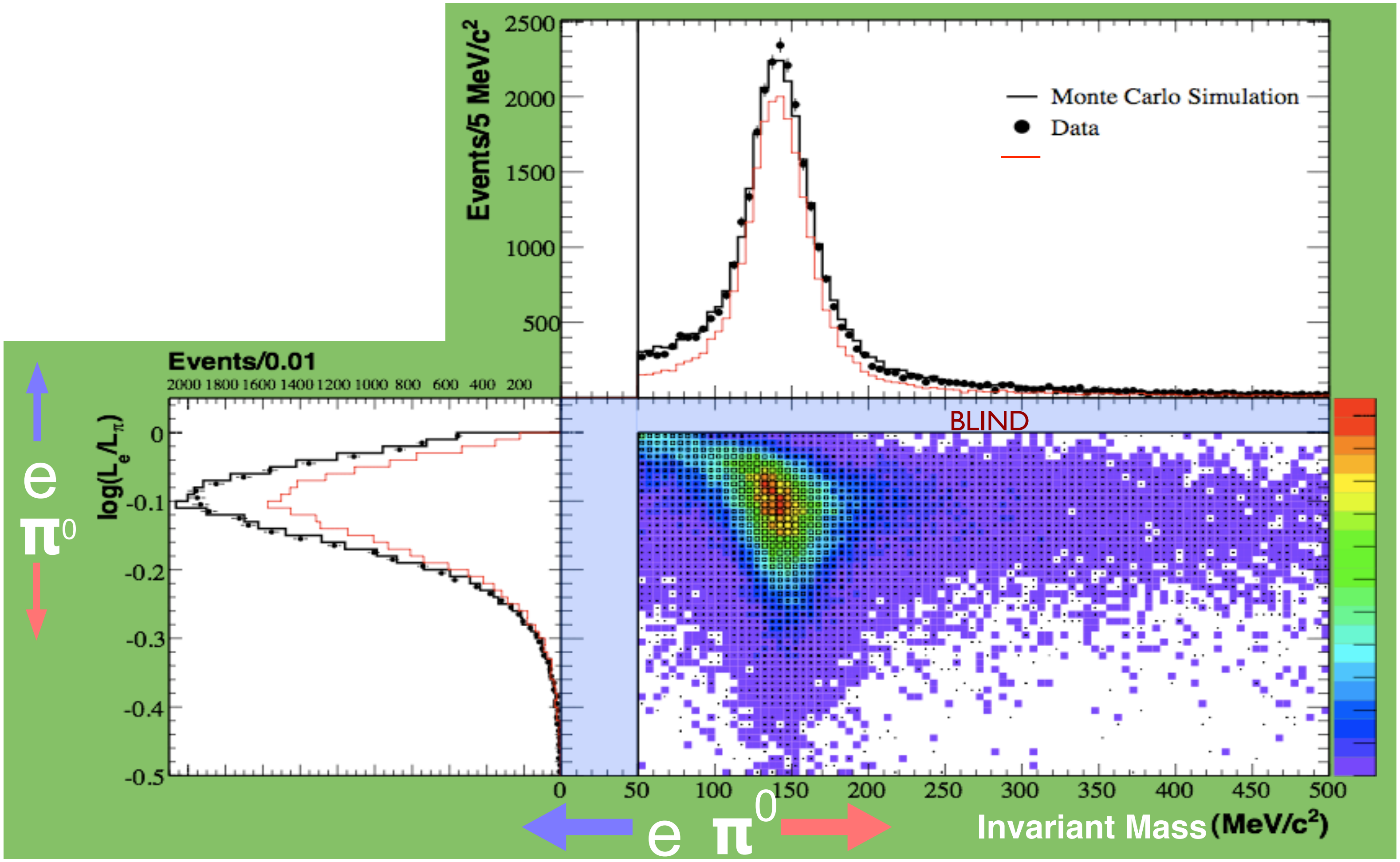


Antineutrino Disappearance Sensitivity with Detector at 200 Meters



Sterile Neutrinos Detection with NC Elastic and NC π^0s

- Change in rate of NC π^0s and NC Elastic could verify sterile neutrino hypothesis
  - Clean selection, ~90,000 NC elastic events in far detector
  - Clean selection, ~20,000 NC π^0s events in far detector
  - Potential measurement at ~ 2-3 percent with near-far comparison

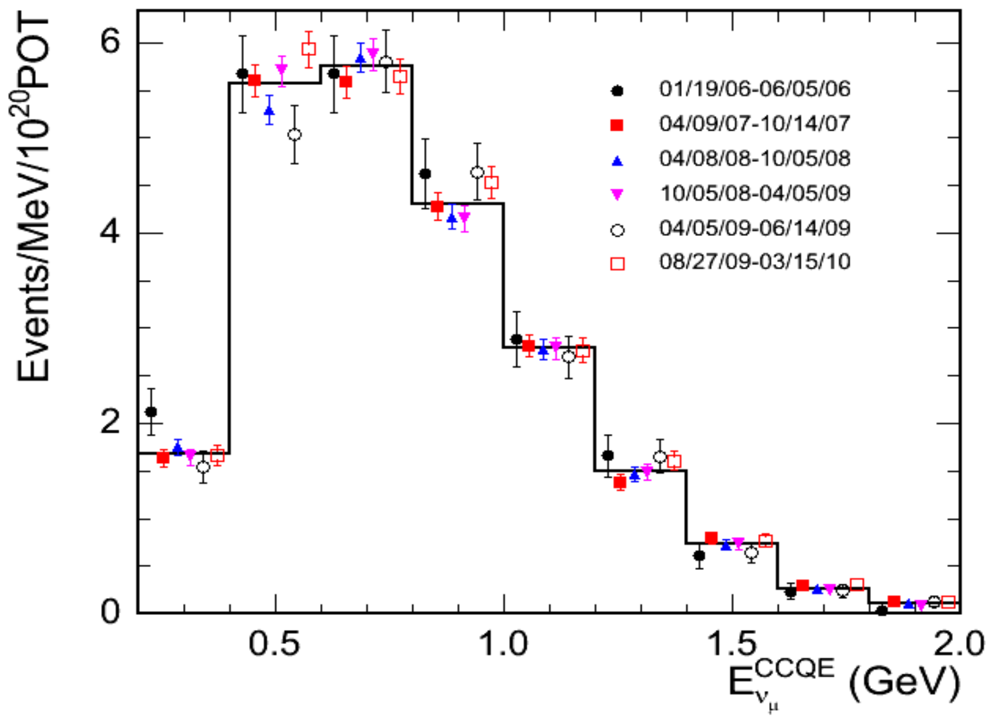


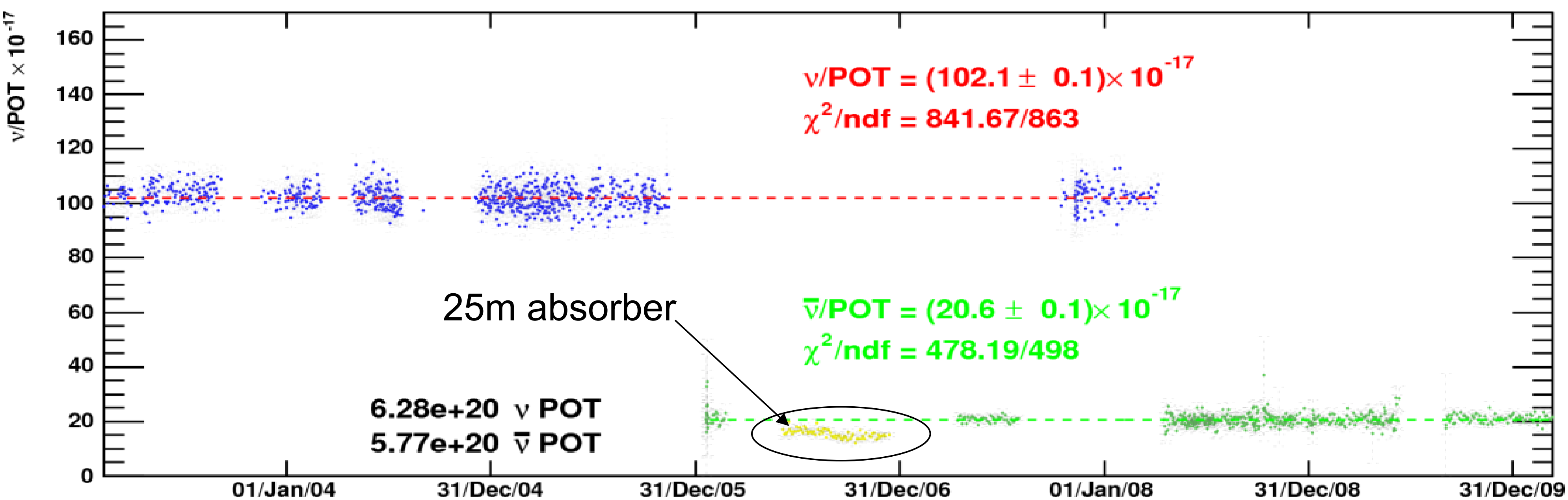
Why a *new* second detector?

To move or not to move…

Data stability

- Very stable throughout the run





New Detector BooNE versus Recycling MiniBooNE

- Advantages:
  - Far detector can monitor stability of the beam from pre-shutdown to post-shutdown era
    - Potential for horn failure/replacement
  - Can operate two detectors during MicroBooNE run and double neutrino mode data
  - Will increase anti-neutrino mode running in far detector (which is stats-limited) before MicroBooNE run
- Disadvantages:
  - Cost (parts) ~ $9M versus $5M for moving

BooNE Cost Estimate in Tight Budget Scenario

- Recycle MiniBooNE oil, PMT's, electronics, etc.
  - Could be done for ~< $10M total

Item	Cost ($K)
Tank	265.3
Support Structure	28.1
PMTs	~~2768.9~~
Preamps	~~30.6~~
Electronics	~~355.5~~
DAQ	~~67.2~~
Conventional Construction	4212.0
Plumbing	25.9
Oil	~~1283.6~~
Total	~~9037.2~~
Total	4531.0

Summary

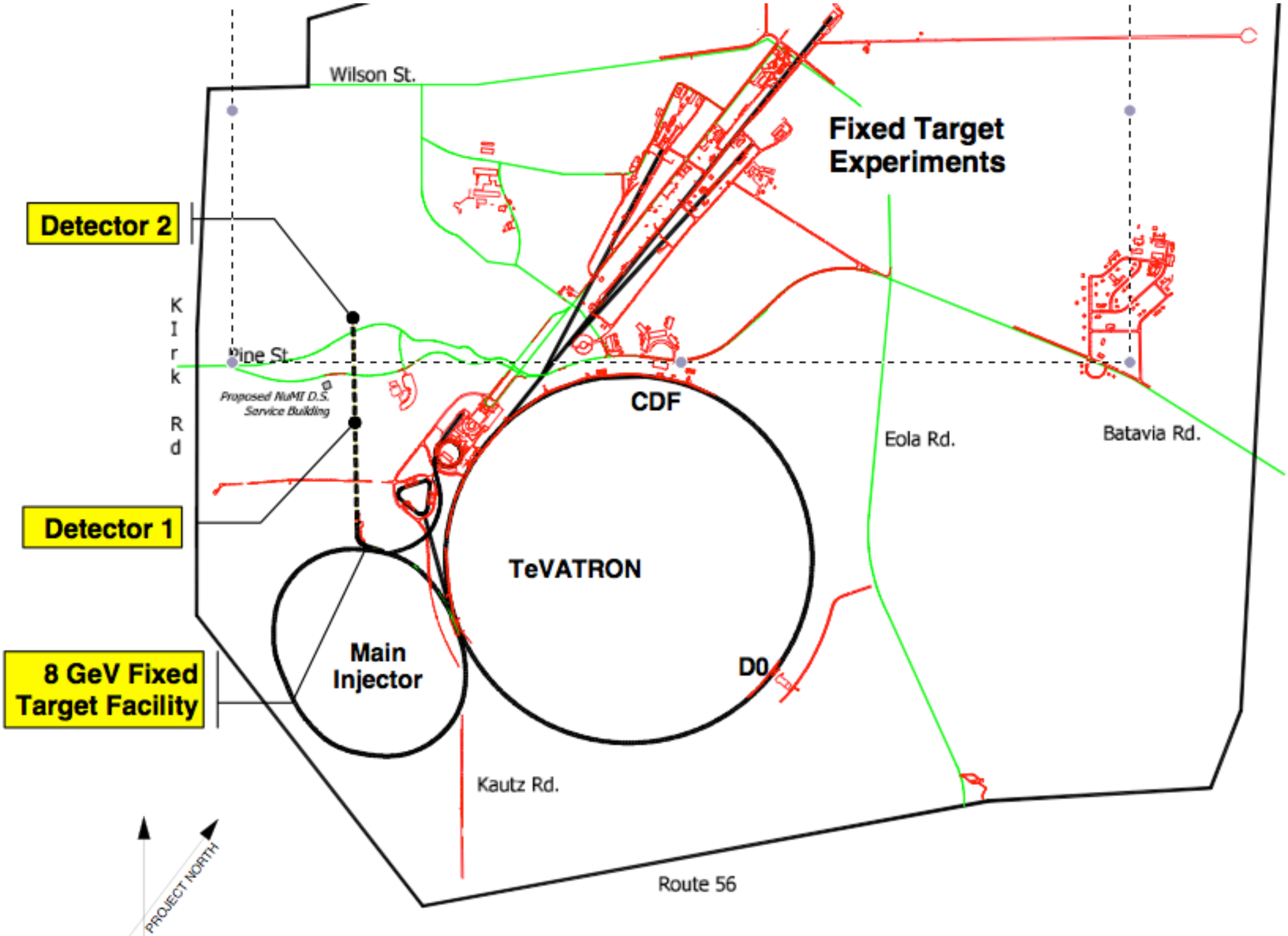
- BooNE proposal:
  - *Potential for discovery of light-sterile neutrinos*
  - Precision measurements of both *disappearance and appearance* in neutrino and in antineutrino mode
  - Data can be accumulated in < 1 yr at present proton delivery rates
  - Capitalize on extensive MiniBooNE ~ 10 year run
  - Low cost ~ $15M for new detector, <$10M reusing the existing MiniBooNE detector.

- Powerful addition to MicroBooNE/MiniBooNE running
  - Photon/electron rates
  - Nu/nubar disappearance and appearance (~5σ for both in some cases)
  - Very little systematic error

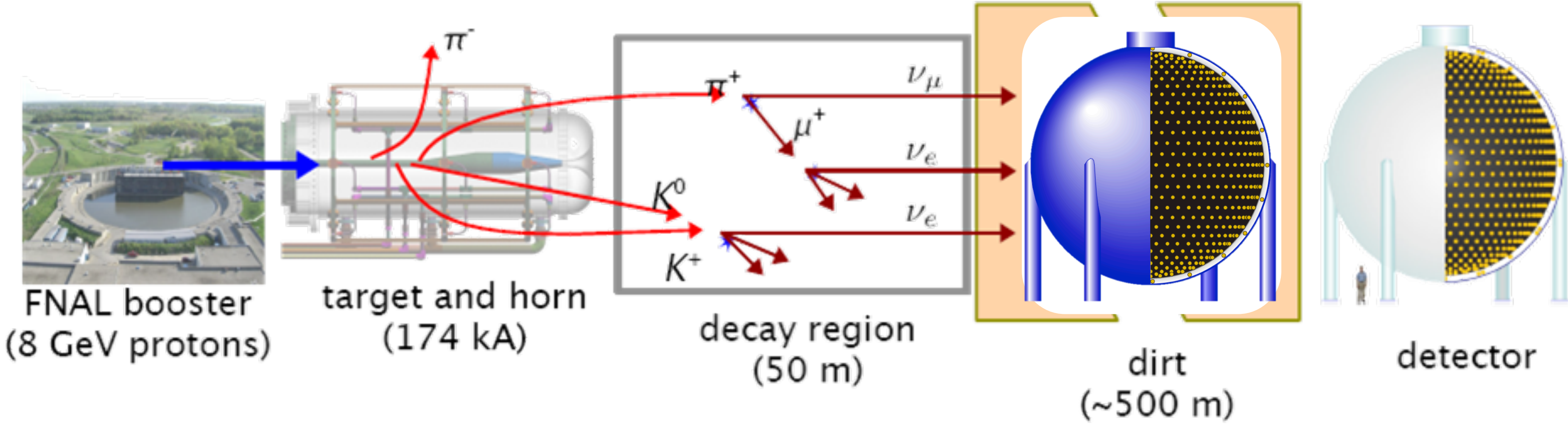
BACKUP

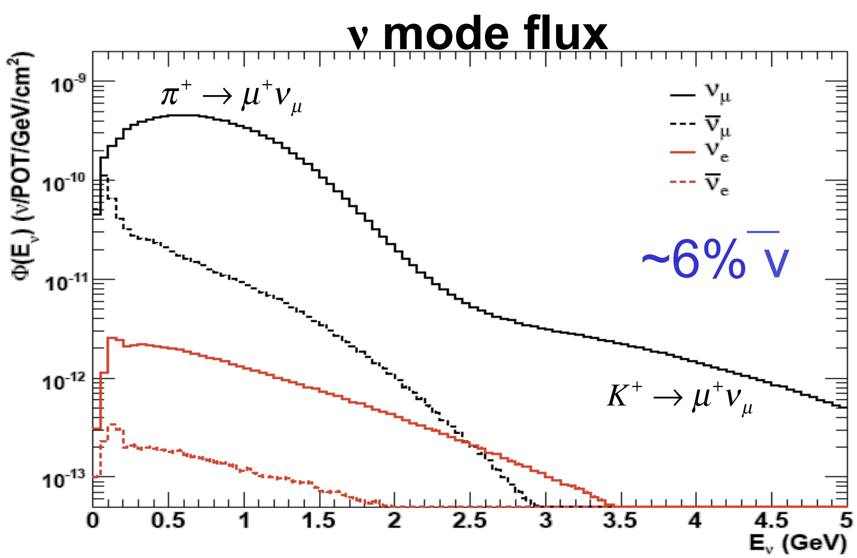
BACKUP

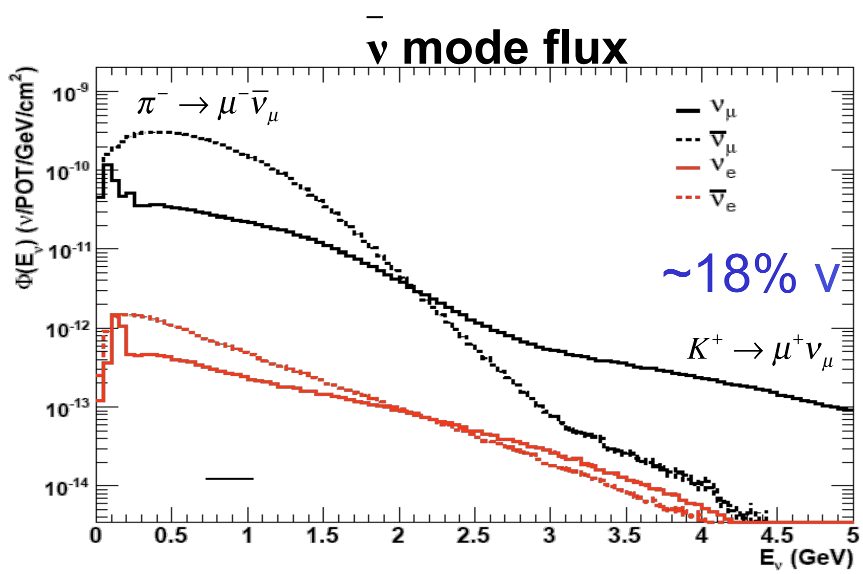
Fermilab Overview



BooNE will look for an excess of electron neutrino events in a predominantly muon neutrino beam with two detectors







neutrino mode:	$\nu_\mu \to \nu_e$ oscillation search
antineutrino mode:	$\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation search

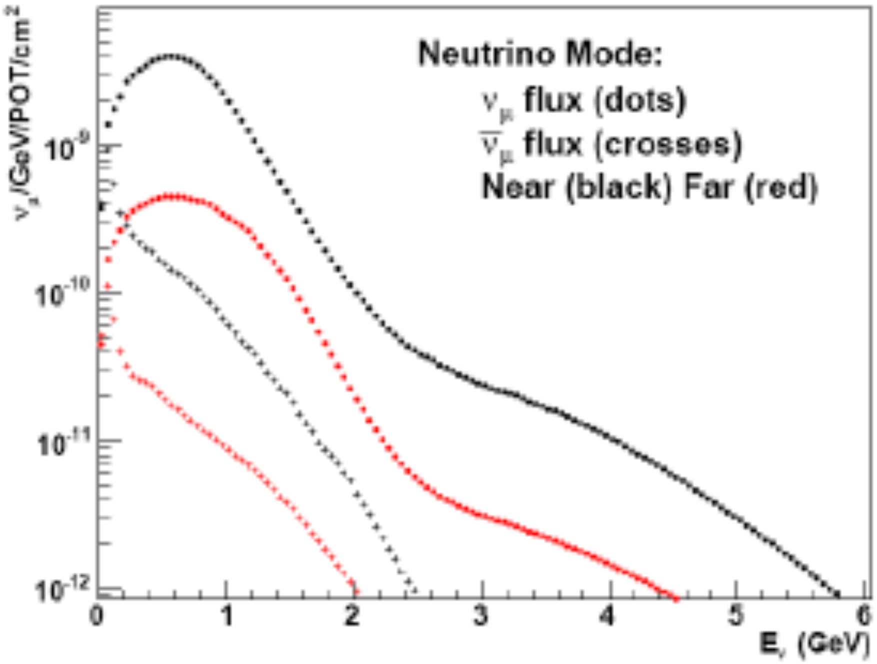
$5M AIP: MiniBooNE 8 GeV Civil Construction

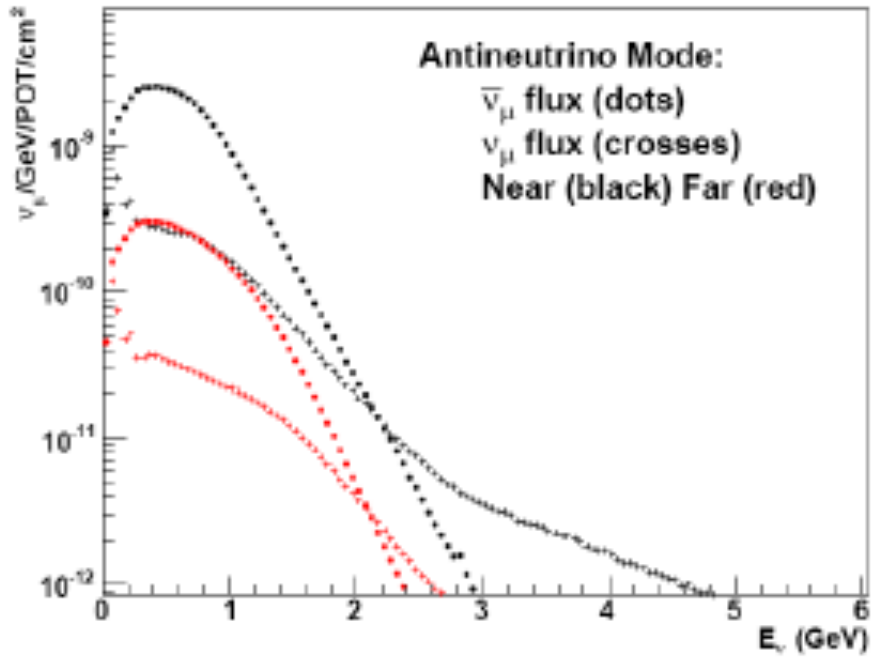
$5M AIP for 8 GeV Civil Construction

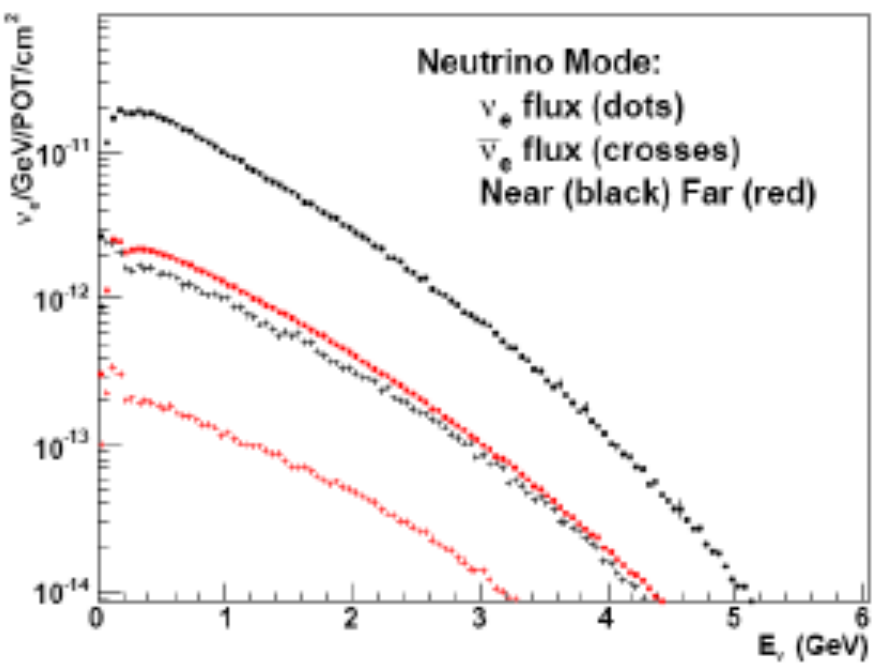
Beam Line

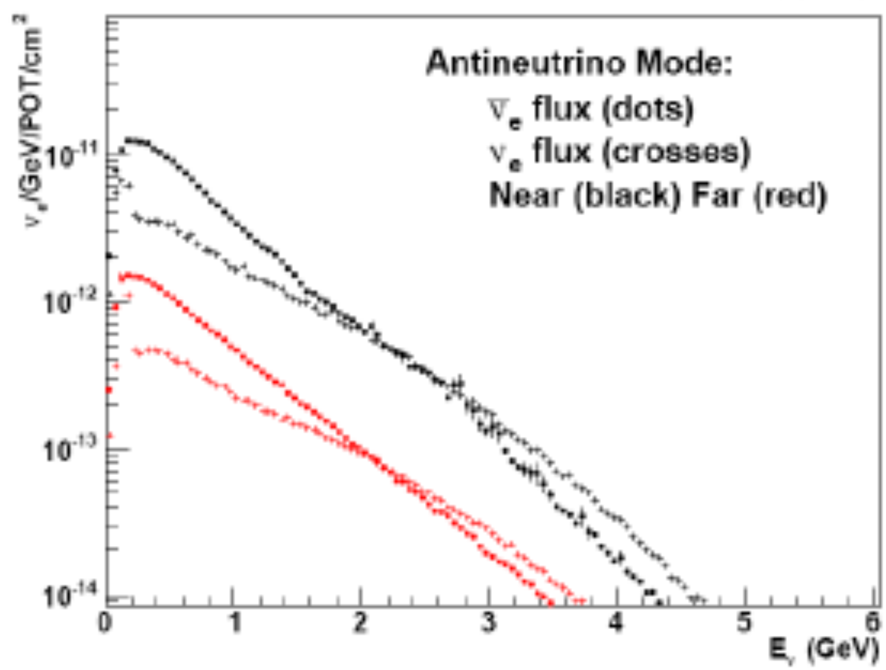
WBS	Name	Baseline Cost	Current Cost	% Complete	BCWS	BCWP ACWP	ACWP Cost	Cost to Complete
1.2.	8 GeV Beamline Civil	$2,798,972	$3,204,207	43%	$2,527,908	$1,276,497	$1,388,717	$1,815,490
1.2.1	EDIA	$3[illegible],335	$302,000	53%	$290,639	$203,635	$198,130	$103,870
1.2.2	Procurement	$1,8[illegible]	$2,549,207	55%	$1,[illegible]18,441	$1,030,655	$1,162,587	$1,386,620
1.2.3	Remaining Contingency	$529,646	$253,000	0%	$481,726	$0	$0	$253,000
1.2.4	Indirects	$150,741	$100,000	28%	$137,102	$42,207	$28,000	$72,000
2.3.	MiniBooNE Civil	$4,969,531	$4,997,669	66%	$4,671,737	$3,124,817	$3,308,559	$1,689,110
2.3.1	Target Hall & Decay Pipe	$3,167,212	$3,350,452	55%	$2,869,418	$1,520,891	$1,661,342	$1,689,110
2.3.1.1	EDIA	$314,335	$344,000	69%	$314,335	$238,855	$268,180	$75,820
2.3.1.2	Procurement	$2,146,250	$2,509,452	46%	$1,906,209	$1,197,888	$1,288,112	$1,221,340
2.3.1.3	Remaining Contingency	$553,632	$306,000	0%	$508,383	$0	$0	$306,000
2.3.1.4	Indirects	$152,995	$191,000	55%	$140,491	$84,147	$105,050	$85,950
2.3.2	Detector Enclosure	$1,802,319	$1,647,216	100%	$1,802,319	$1,603,926	$1,647,216	$0
2.3.2.1	EDIA	$315,679	$342,507	100%	$315,679	$315,679	$342,507	$0
2.3.2.2	Procurement	$1,135,000	$1,191,036	100%	$1,135,000	$1,135,000	$1,191,036	$0
2.3.2.3	Remaining Contingency	$198,393	$0	100%	$198,393	$0	$0	$0
2.3.2.4	Indirects	$153,248	$113,673	100%	$153,248	$153,248	$113,673	$0

Neutrino Fluxes at Near and Far Locations







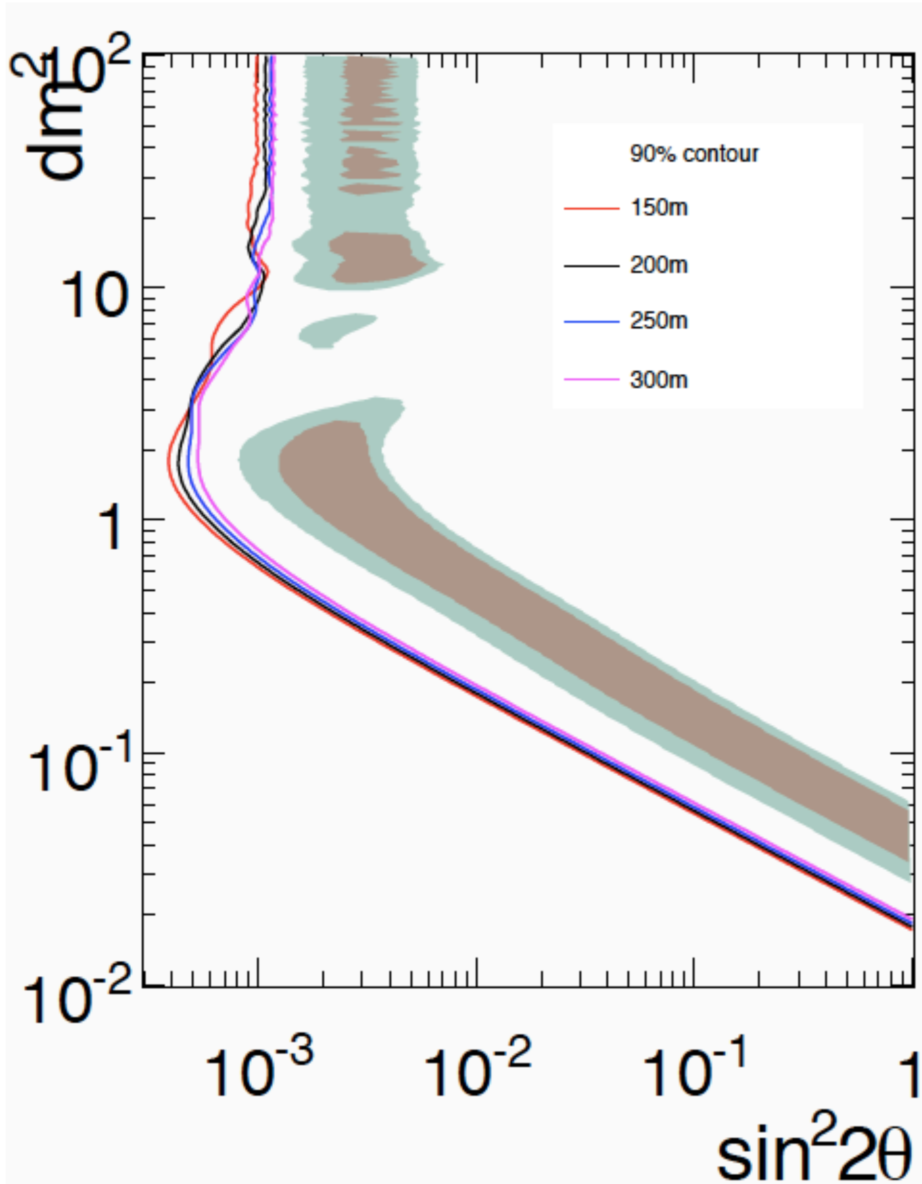


Near/Far Sensitivity for Several Distances

- 150 m : 0.6×10^{20} POT
- 200 m : 1.0×10^{20} POT
- 250 m : 1.5×10^{20} POT
- 300 m : 2.0×10^{20} POT

- Near/Far comparison relatively insensitive to detector distance for roughly the same number of events

  - 200 meters gives similar flux shapes



Near Term Steps Towards BooNE

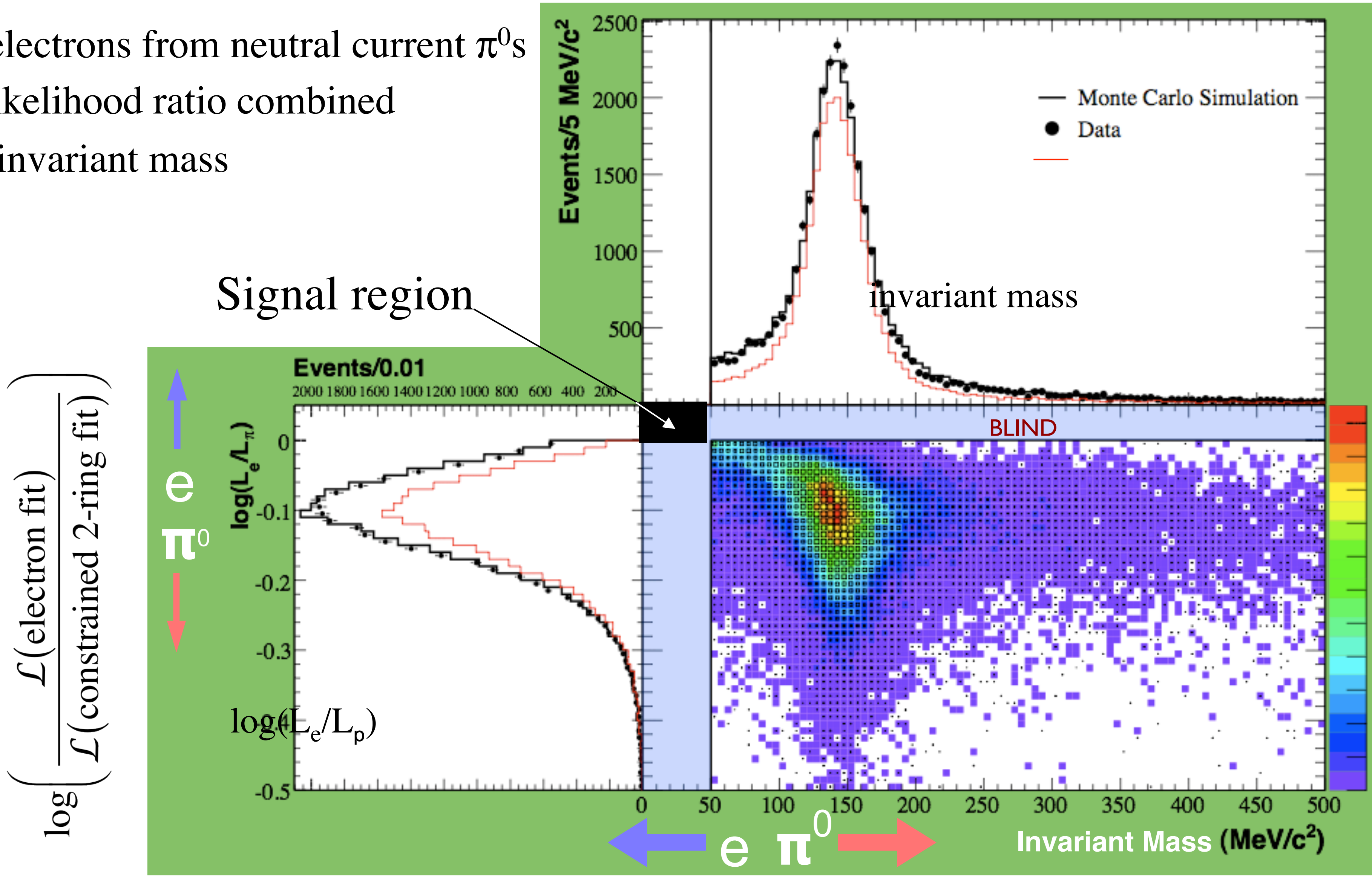
- Dust off MiniBooNE engineering designs
  - Would like to reproduce MiniBooNE as much as possible
  - May transfer old oil an/or electronics to new location in order to reduce any systematic changes
- Optimistic schedule would put turn-on (CD-4) in early FY2014

MINIBOONE BACKUP

Rejection of NC π^0 events

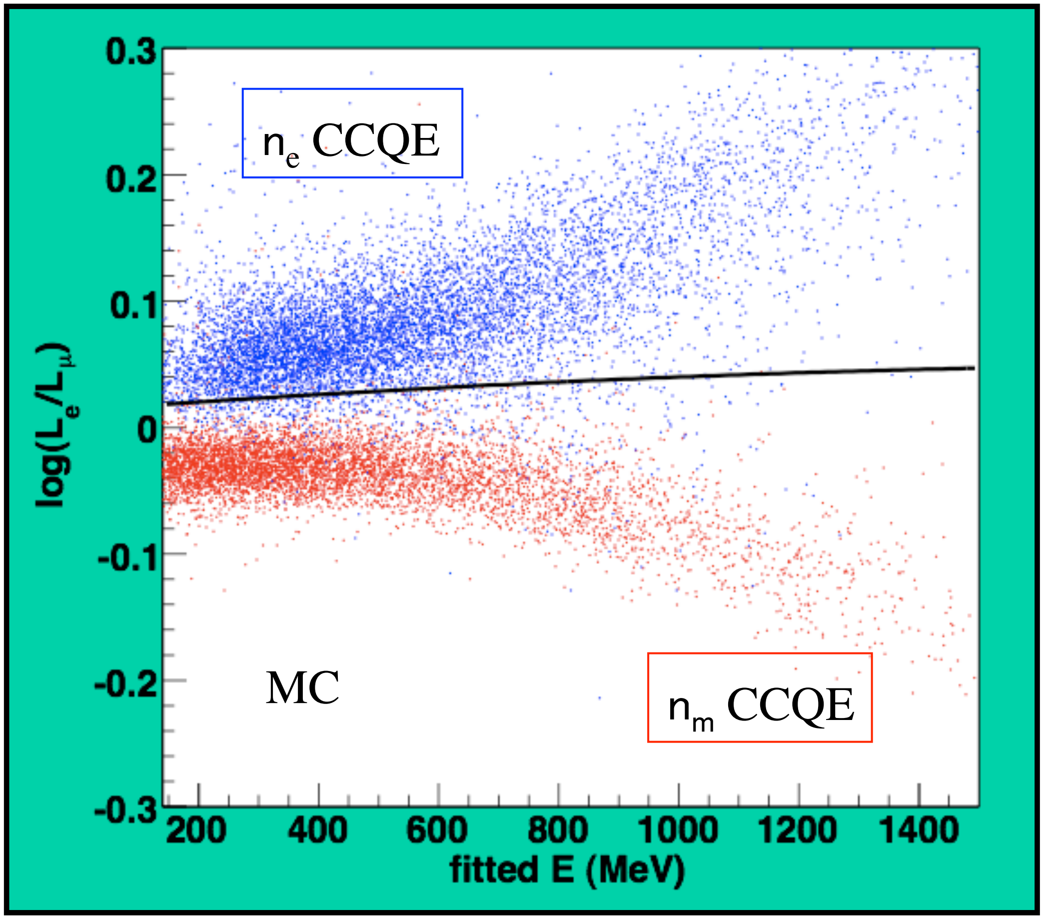
2-ring fit invariant mass

Separating electrons from neutral current π^0s by using a likelihood ratio combined with the $\gamma\gamma$ invariant mass



Separating muon-like and electron-like events by using a likelihood ratio technique

$\log(L_e/L_m) > 0$ favors electron-like hypothesis



Note: photon conversions are electron-like.

This does not separate e/π^0.

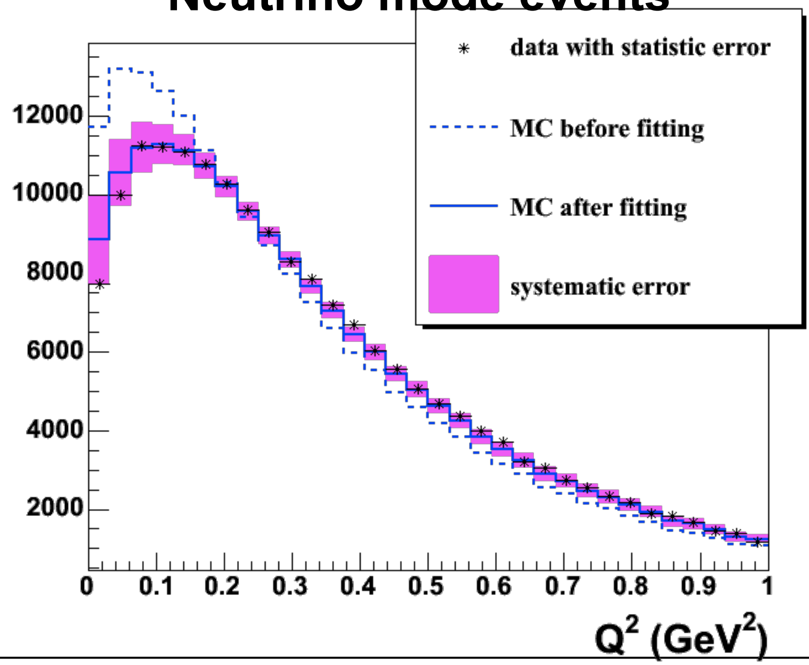
Separation is clean at high energies where muon-like events are long.

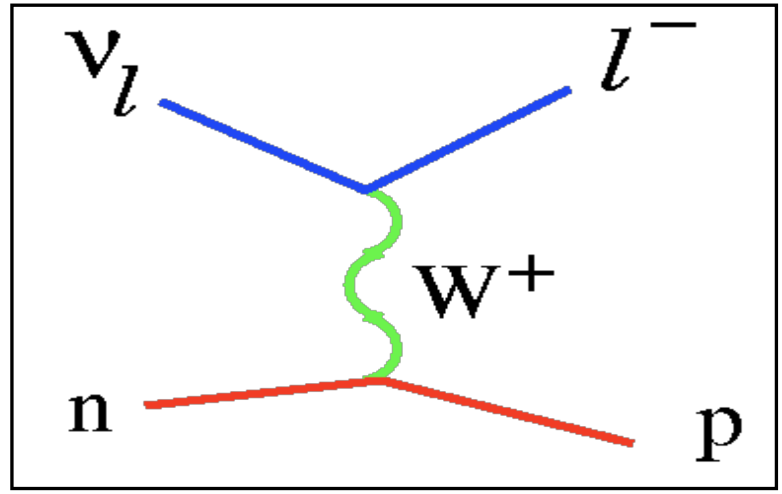
Analysis cut was chosen to maximize the $\nu_\mu \rightarrow \nu_e$ sensitivity

Benchmark Reaction: Charged Current Quasi Elastic (CCQE)

Normalizes our (flux × cross section)

Neutrino mode events





We adjust the parameters of a Fermi Gas model to match our observed Q^2 Distribution shape.

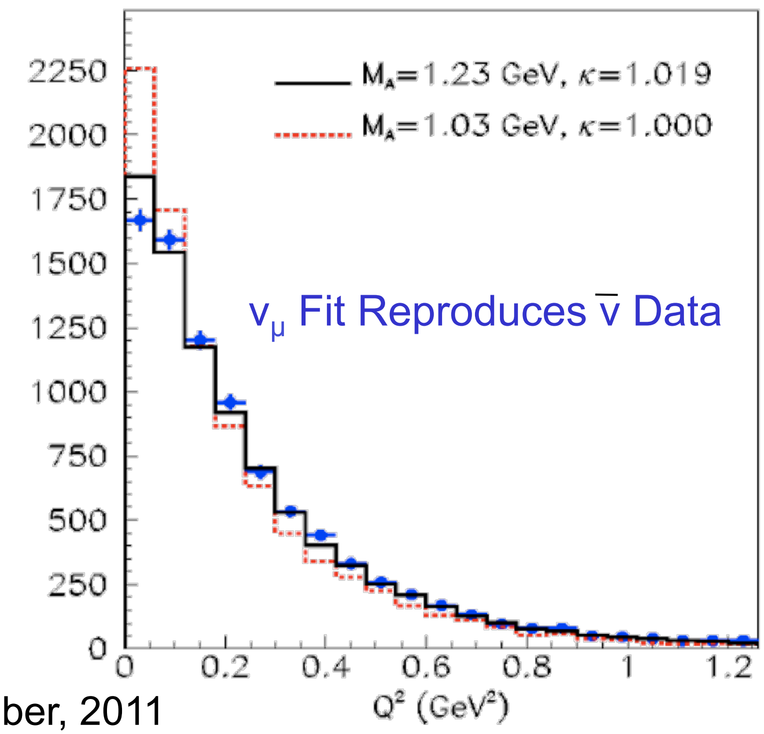
Fermi Gas Model describes CCQE ν_μ data well

$M_{A,eff}$ = 1.23+-0.20 GeV

$\varkappa$ = 1.019+-0.011

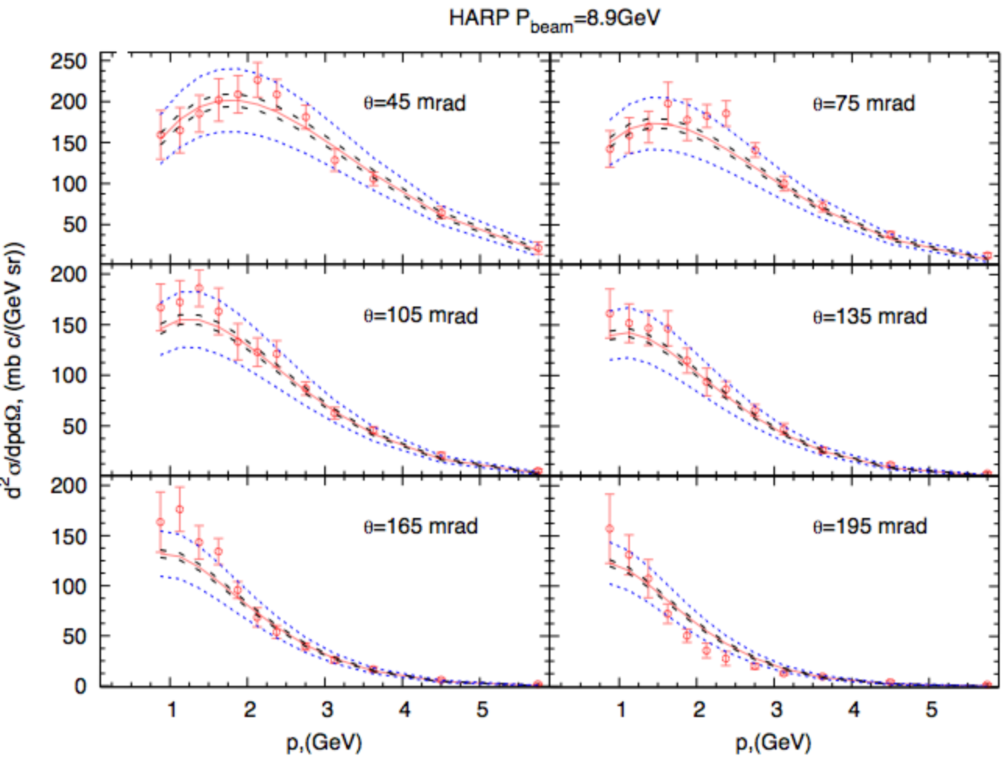
Also used to model ν_e and $\bar{\nu}_e$ interactions

Antineutrino mode events



Meson production at the Proton Target

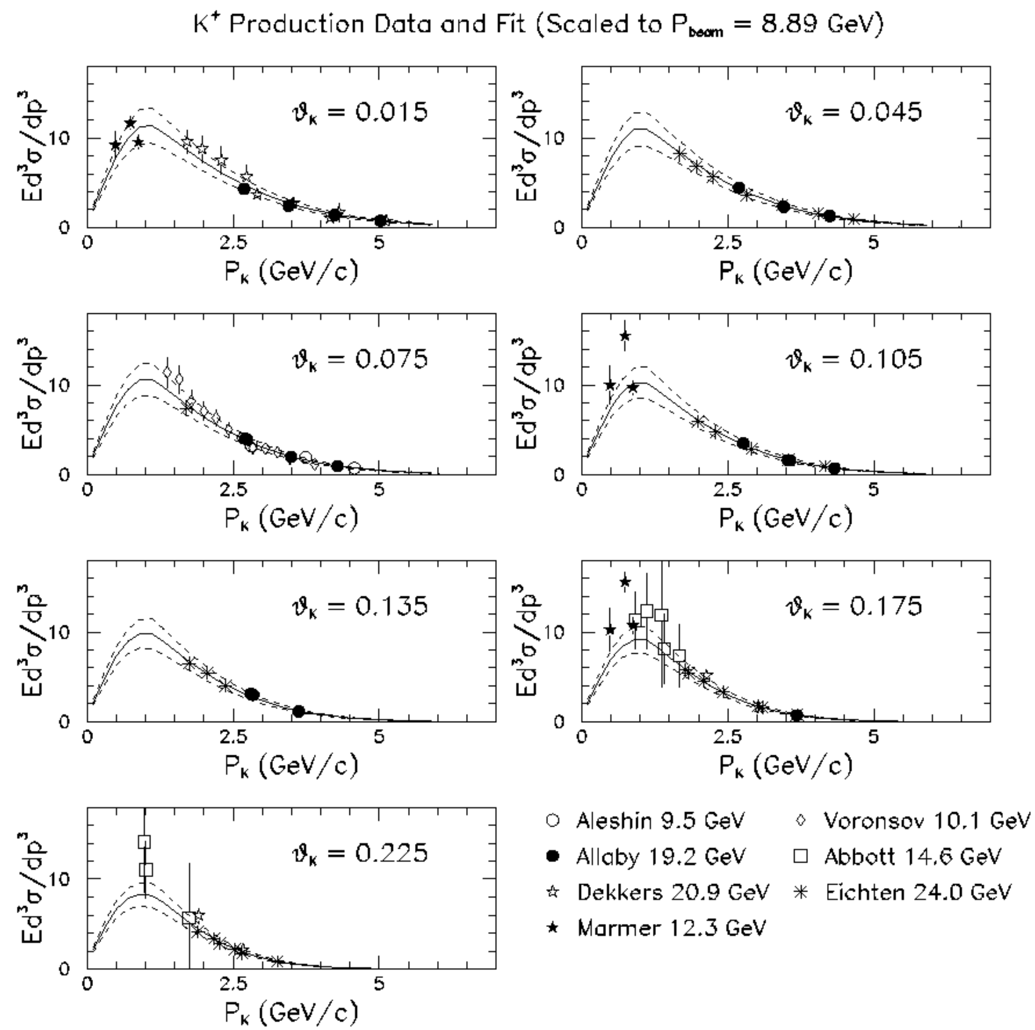
Pions(+/-):



HARP collaboration,
hep-ex/0702024

- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% Beryllium target
- Spline fits were used to parameterize the data.

Kaons:

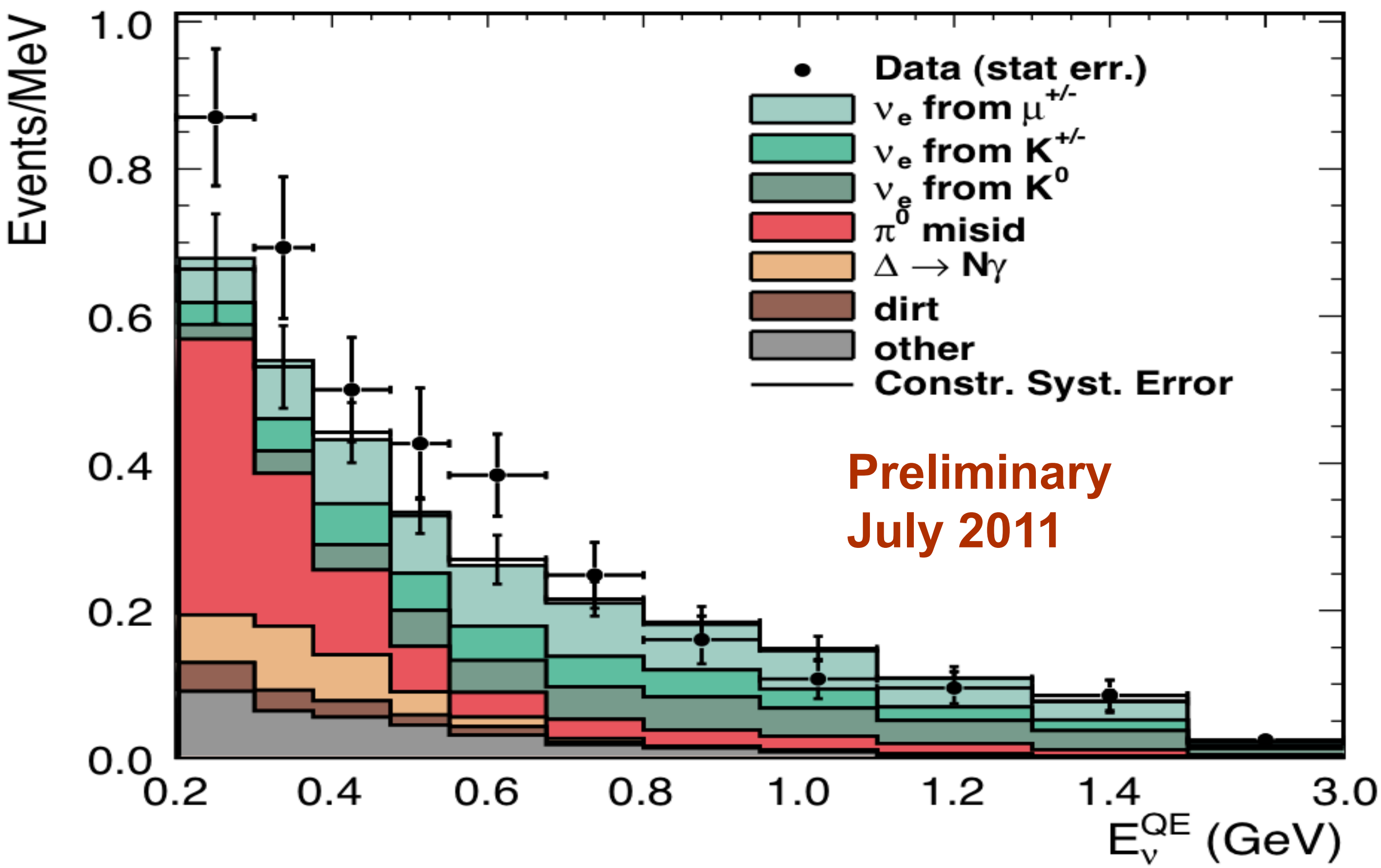


- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed

MiniBooNE Antineutrino Oscillation Results

update of A. A. Aguilar-Arevalo, Phys. Rev. Lett. 105, 181801 (2010)

- 8.58E20 POT (~50% more data than published and new K+ constraint from SciBooNE)
- Excess = 57.7+-18.8+/-22.4 (200-3000 MeV)



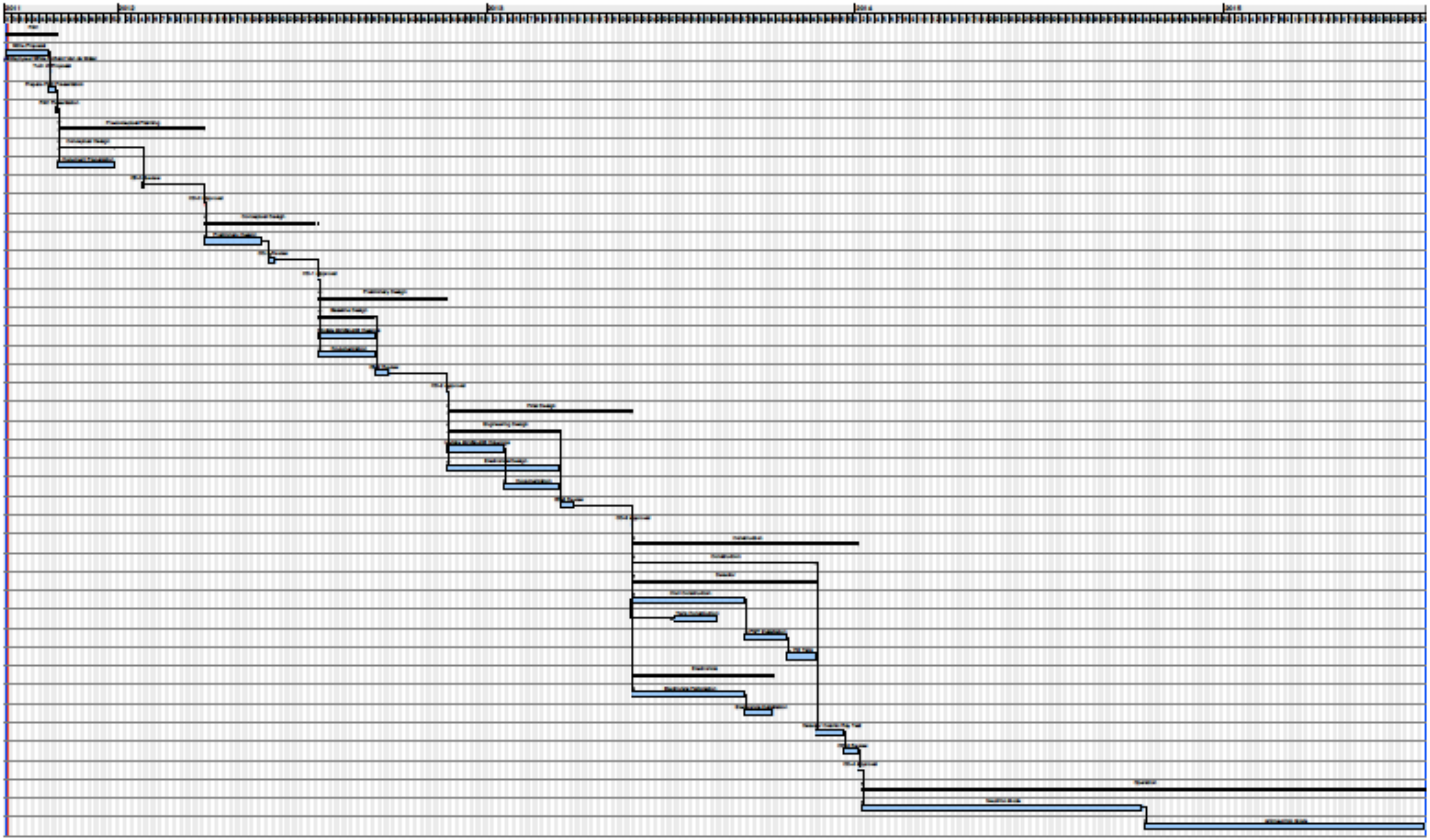
BOONE

BooNE Proposal

Sep 14, 2011

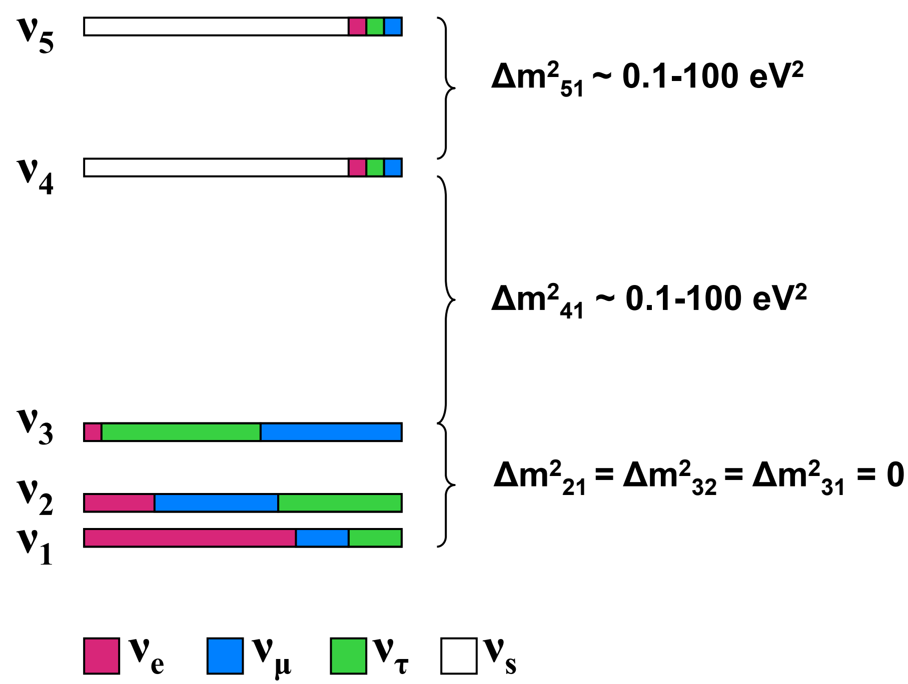
Gantt Chart

5



Can the anomalies be due to a more complicated oscillation picture?

- Sterile neutrino models
  - 3+2 → next minimal extension to 3+1 models



- 2 independent Δm^2
- 4 mixing parameters
- 1 Dirac CP phase which allows difference between neutrinos and antineutrinos

$$\Delta m^2_{\bar\nu} \stackrel{?}{=} \Delta m^2_{\nu}$$

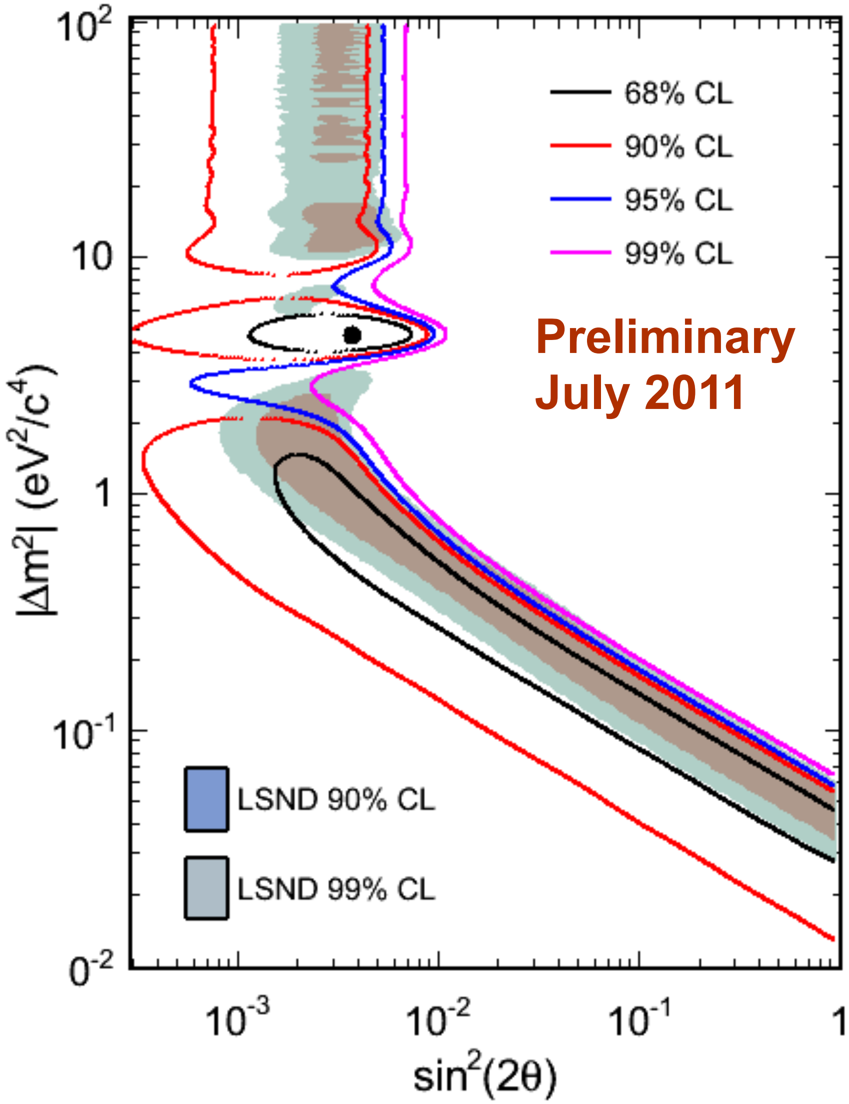
Oscillation probability:

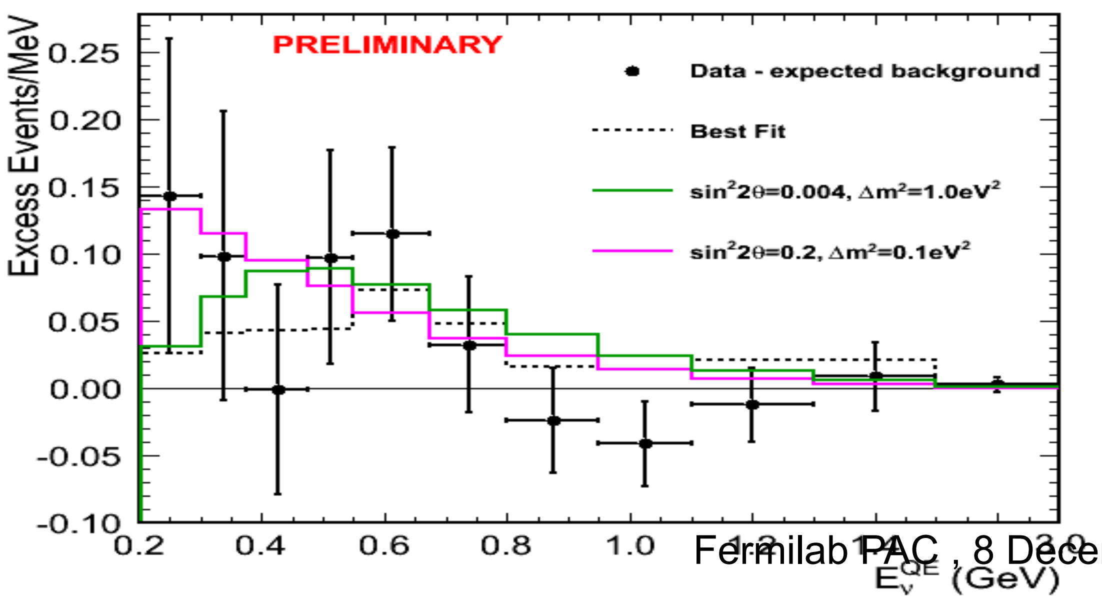
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2 x_{41} + 4|U_{\mu 5}|^2|U_{e5}|^2 \sin^2 x_{51} +$$

$$+\ 8\,|U_{\mu 5}||U_{e5}||U_{\mu 4}||U_{e4}| \sin x_{41} \sin x_{51} \cos(x_{54} \pm \varphi_{45})$$

E>200MeV

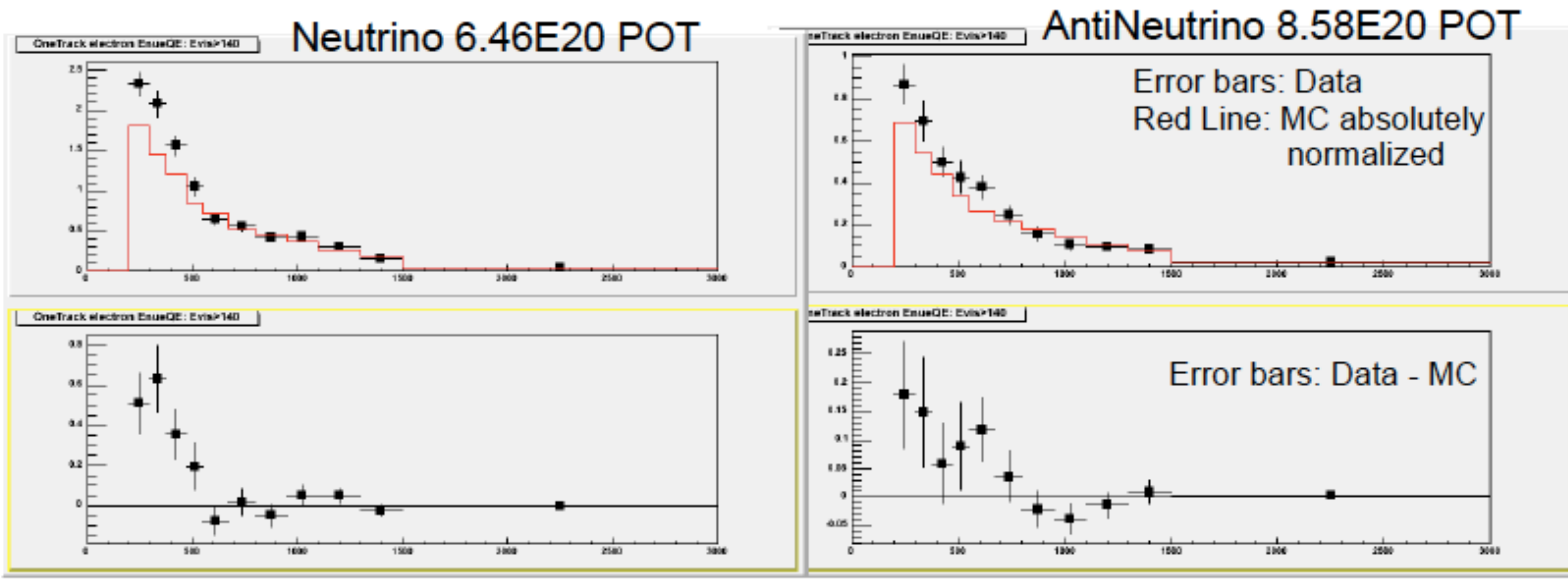
- 8.58E20 POT antineutrino mode
- Oscillations favored over background only hypotheses at 94.2% CL (model dependent)
- Subtract low energy excess assuming neutrinos in antinu mode contribute to excess (17 events)
- P(null) = 28.3%
- P(best fit) = 76.5%





and...

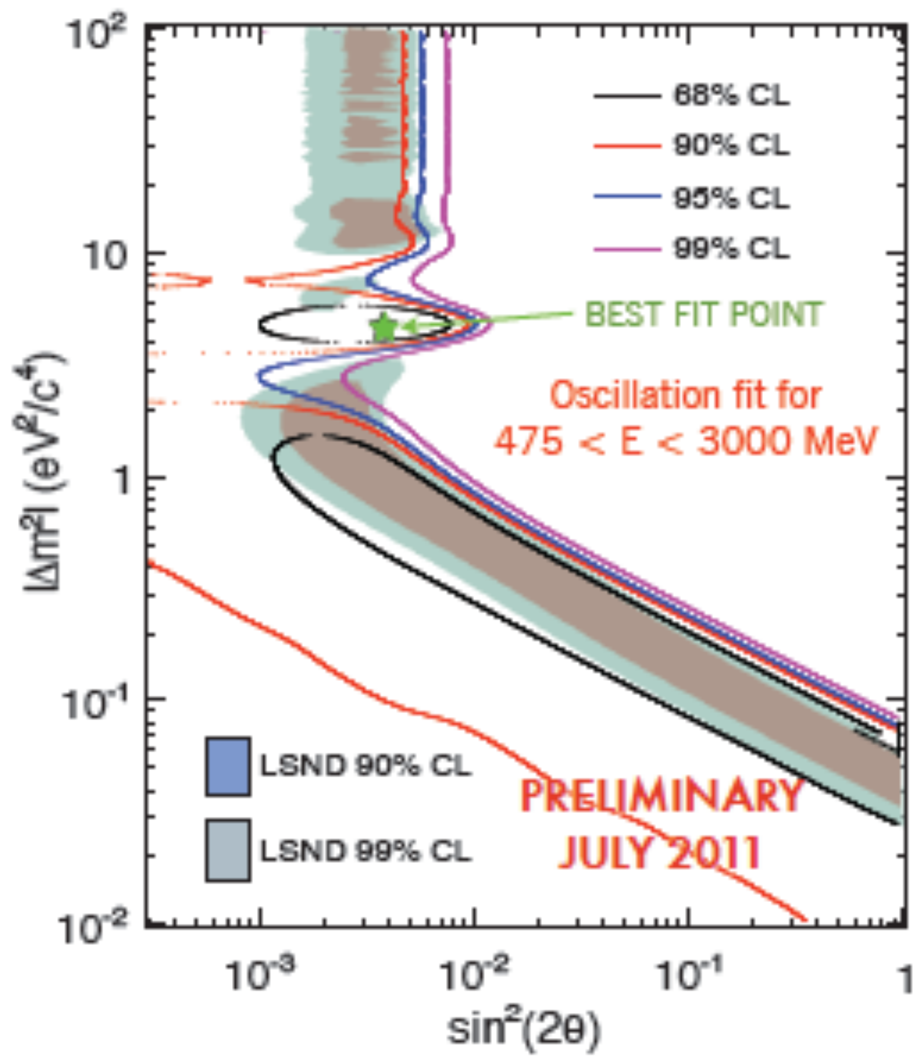
The EnueQE Oscillation Signal

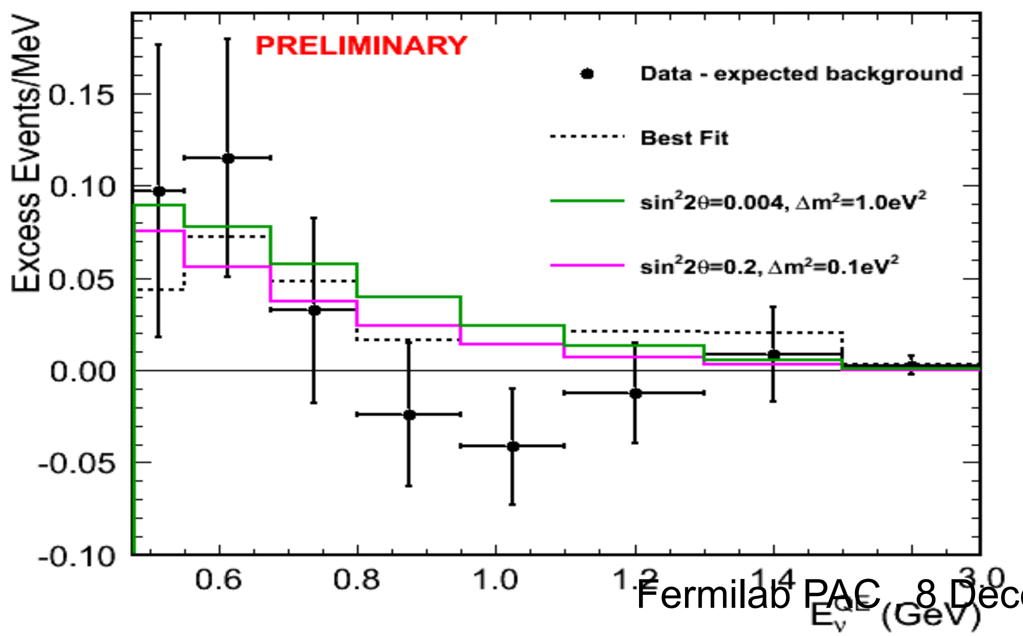


Underscores need for near detector!

MiniBooNE Oscillation Fit E>475

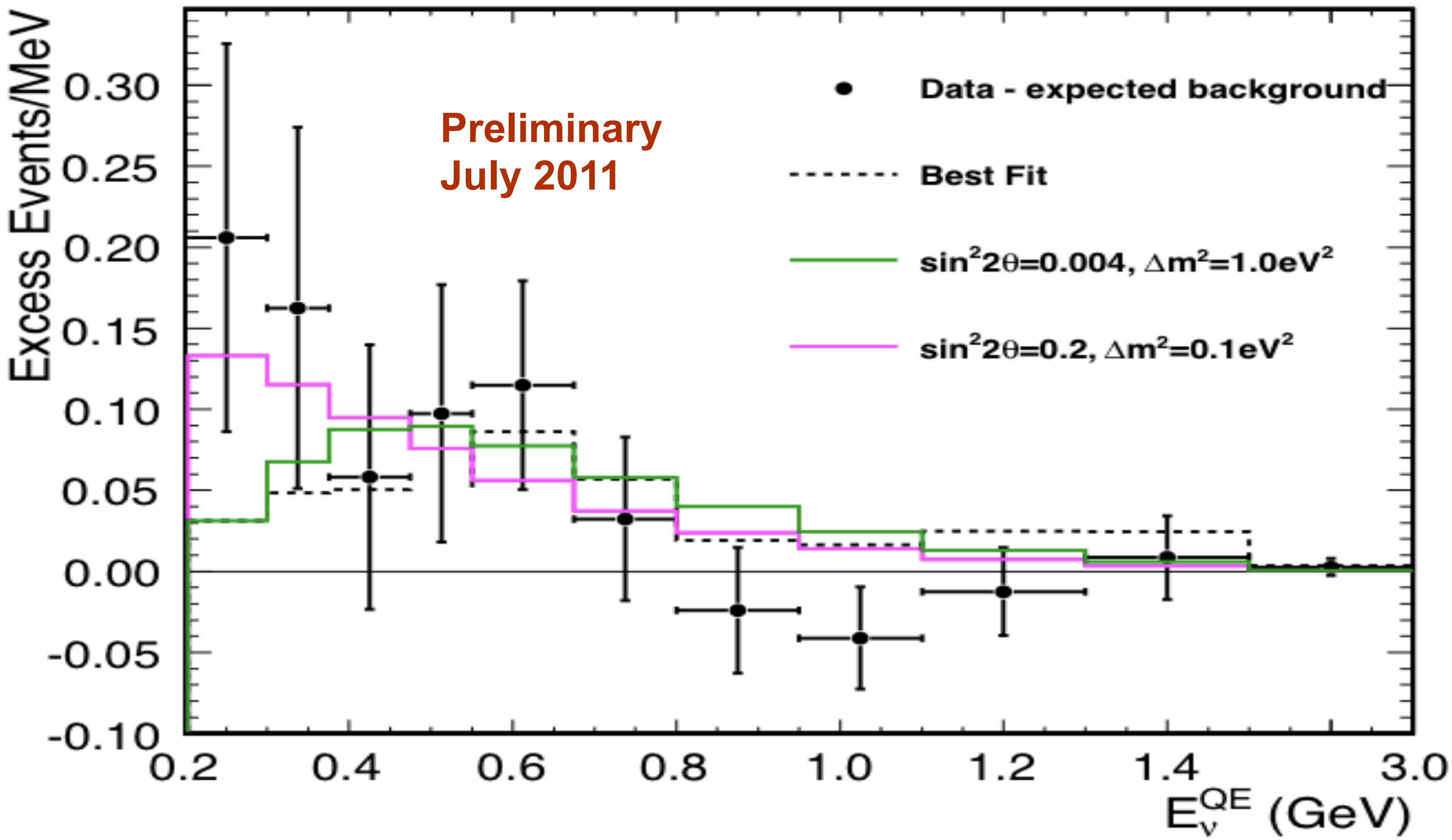
- 8.58E20 POT antineutrino mode
- E>475 is official osc. region
- Oscillations favored over background only hypotheses at 91.4% CL (model dependent)
- P(null) = 14.9%
- P(best fit) = 35.5%





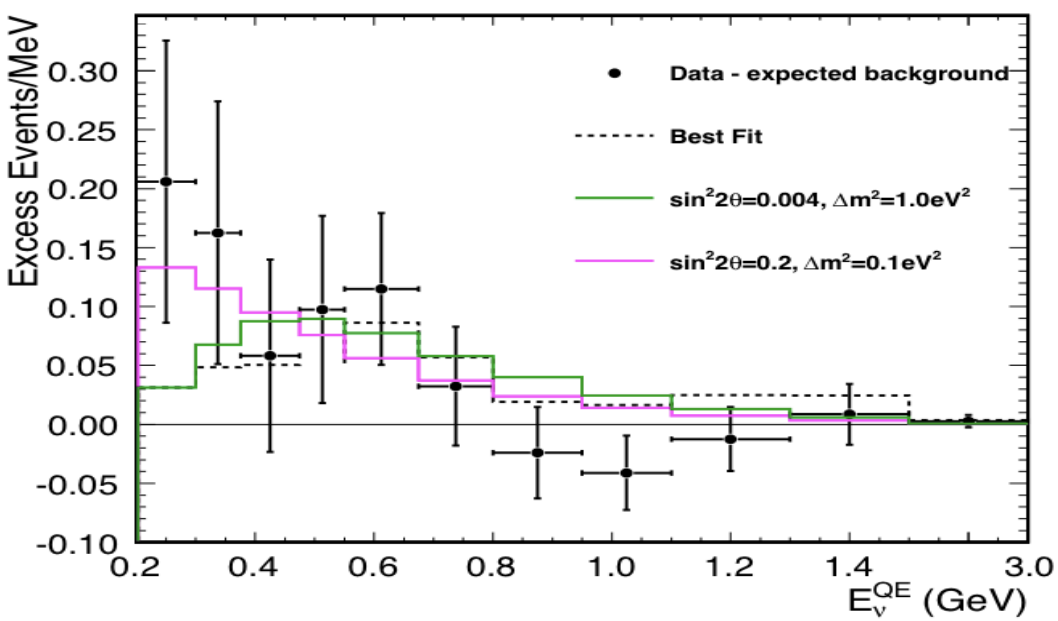
MiniBooNE Antineutrino Oscillation Results

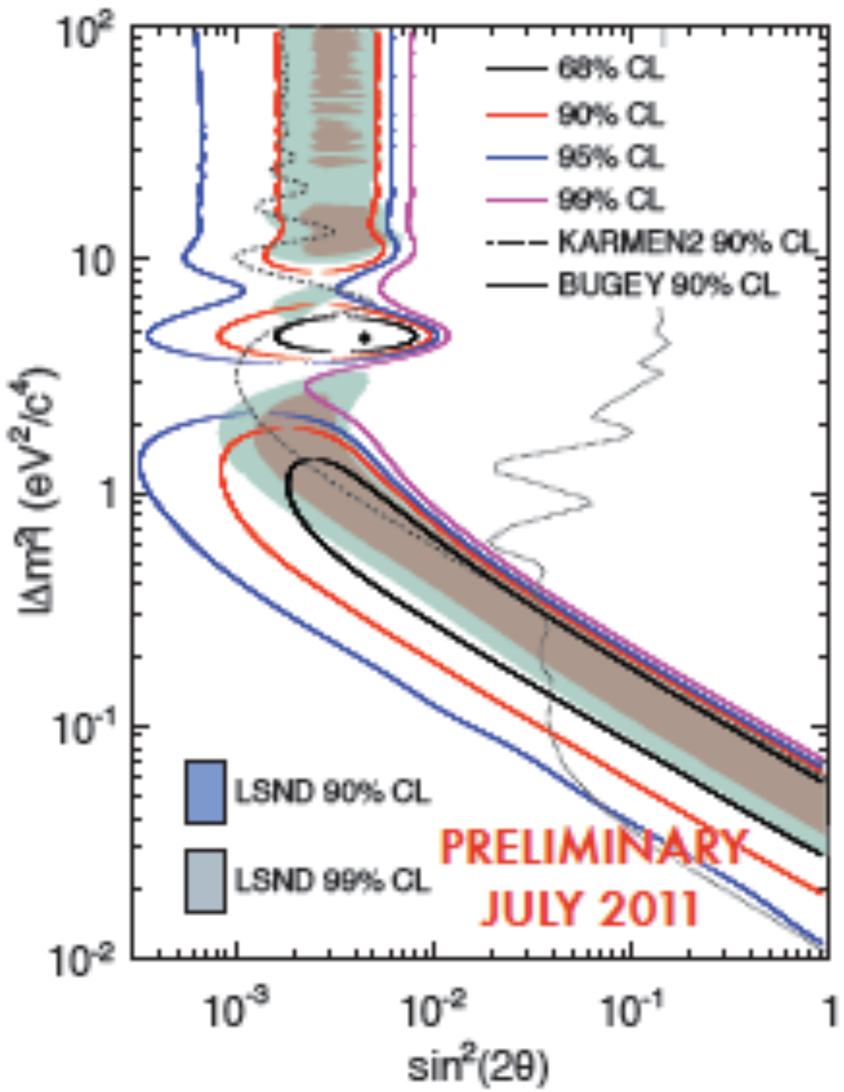
update of A. A. Aguilar-Arevalo, Phys. Rev. Lett. 105, 181801 (2010)



Fit to a 2-(anti)Neutrino Model

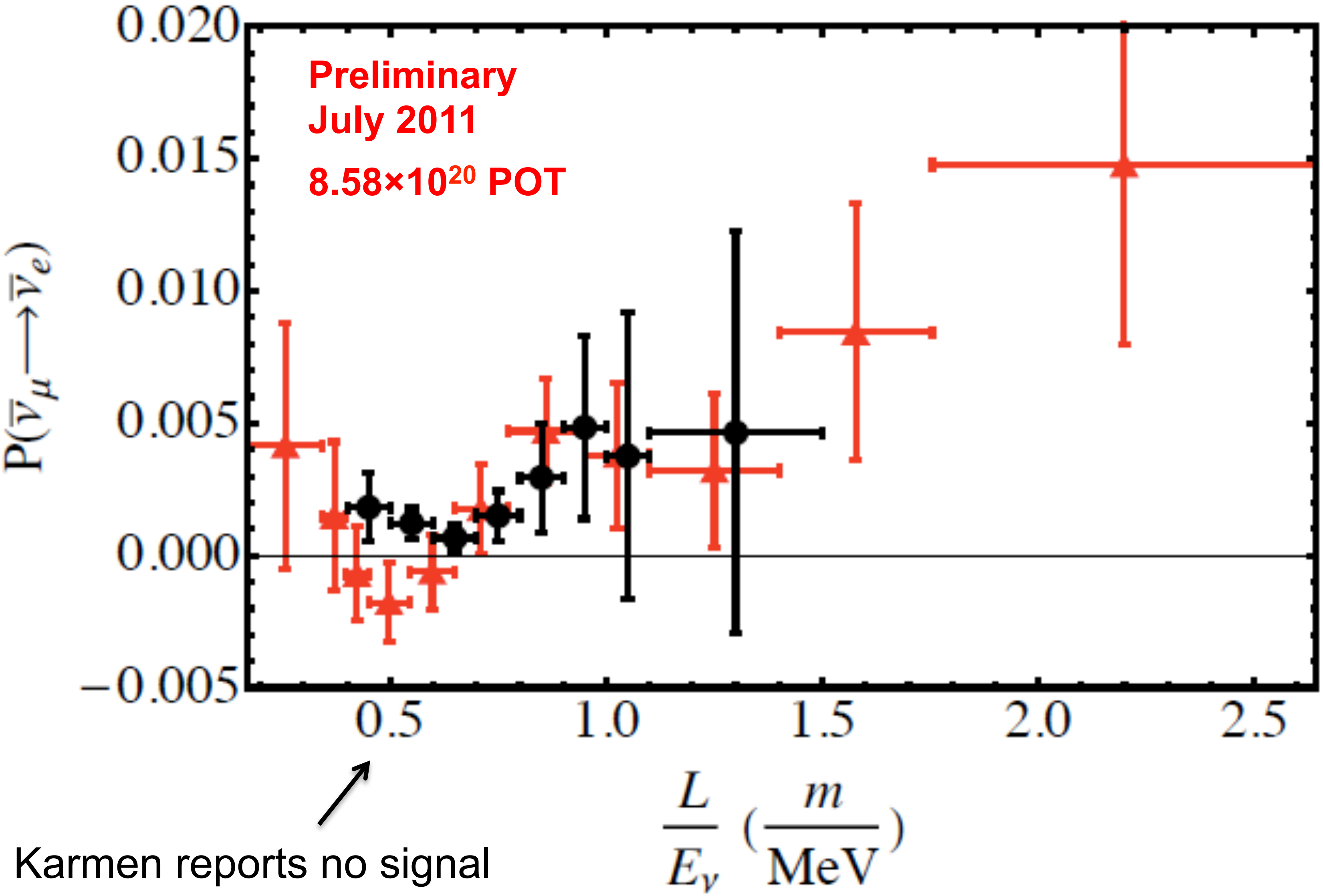
- Oscillations favored over background only hypotheses at 97.6% CL (model dependent)
- No assumption made about low energy excess
  - P(null) = 10.1%
  - P(best fit) = 50.7%
- *Clearly a 2-neutrino model doesn't describe the data very well*
  - *No ν disappearance included in fit*





8.58E20 POT

Model Independent Comparison of LSND & MiniBooNE Antineutrino mode



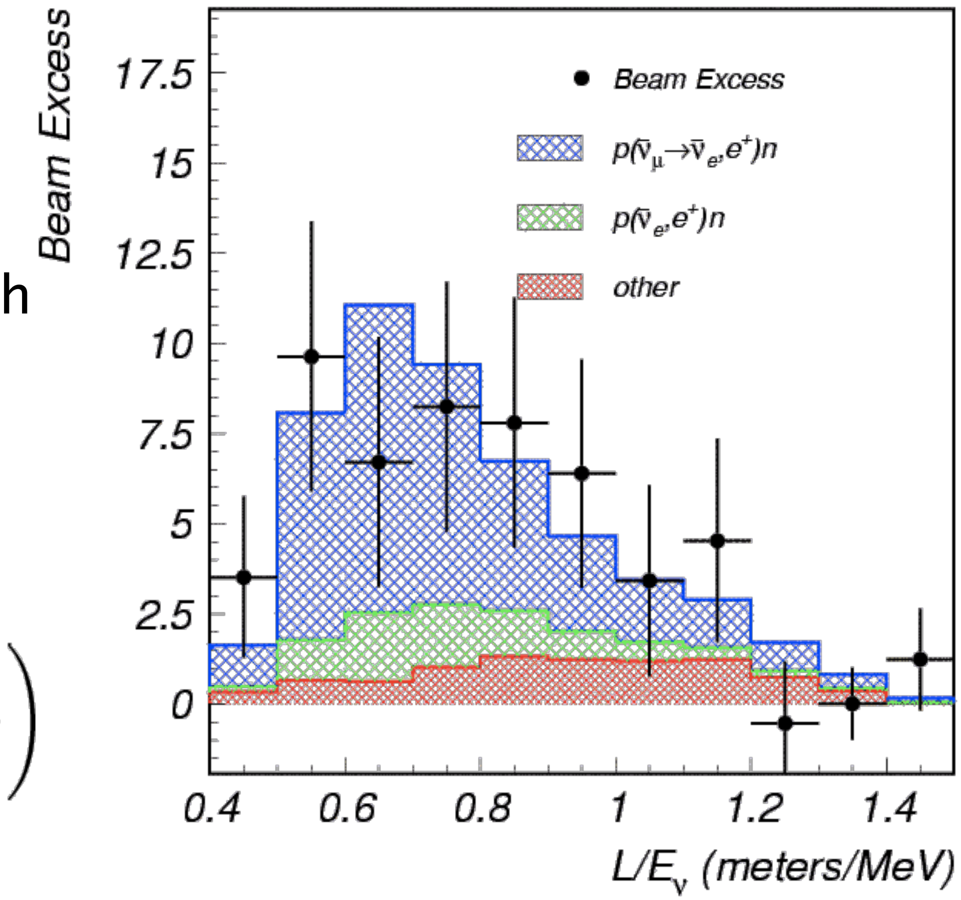
Karmen reports no signal around L/E ~ 0.5

Anomalies in Neutrino Data

Excess Events from LSND still remain:

- LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8s)
- *The data was analysed under a two neutrino mixing hypothesis**

$$P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\, L\, \Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$



KARMEN at a distance of 17 meters saw no evidence for oscillations →low Δm^2

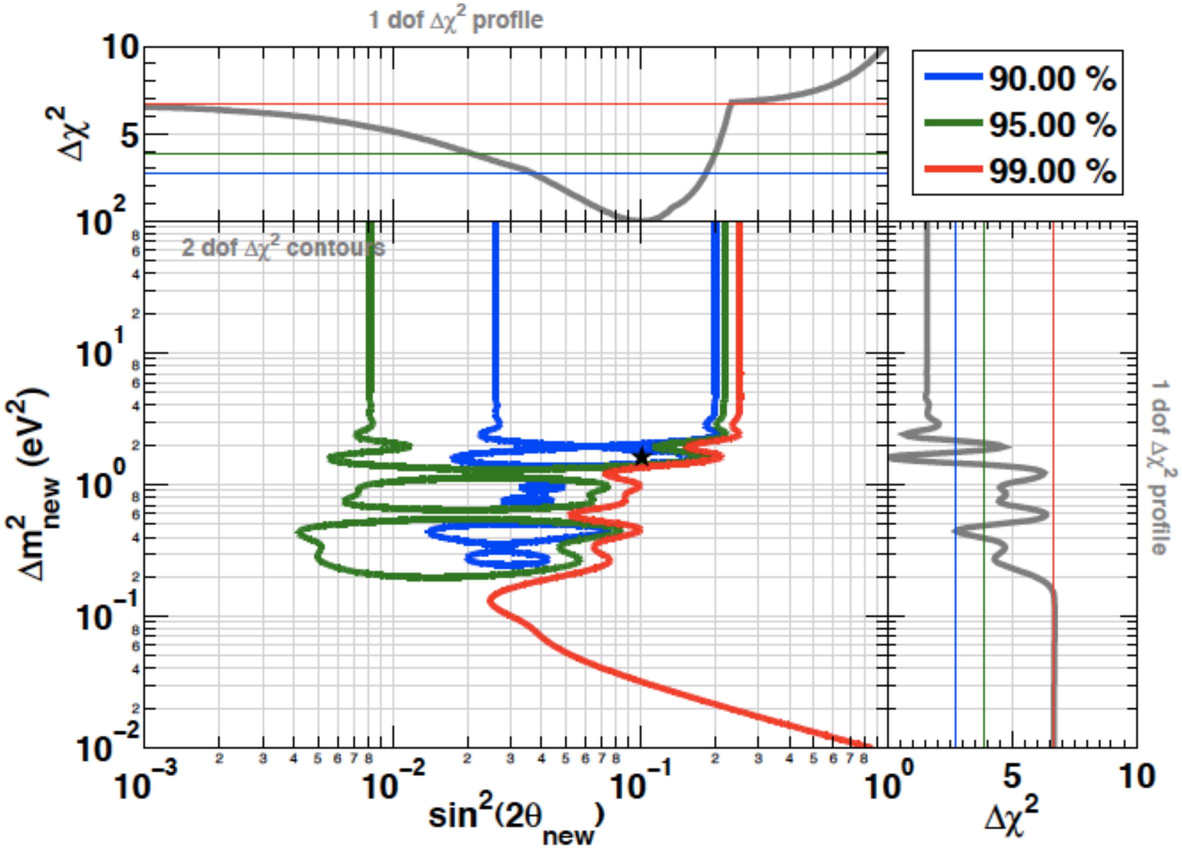
Motivation….

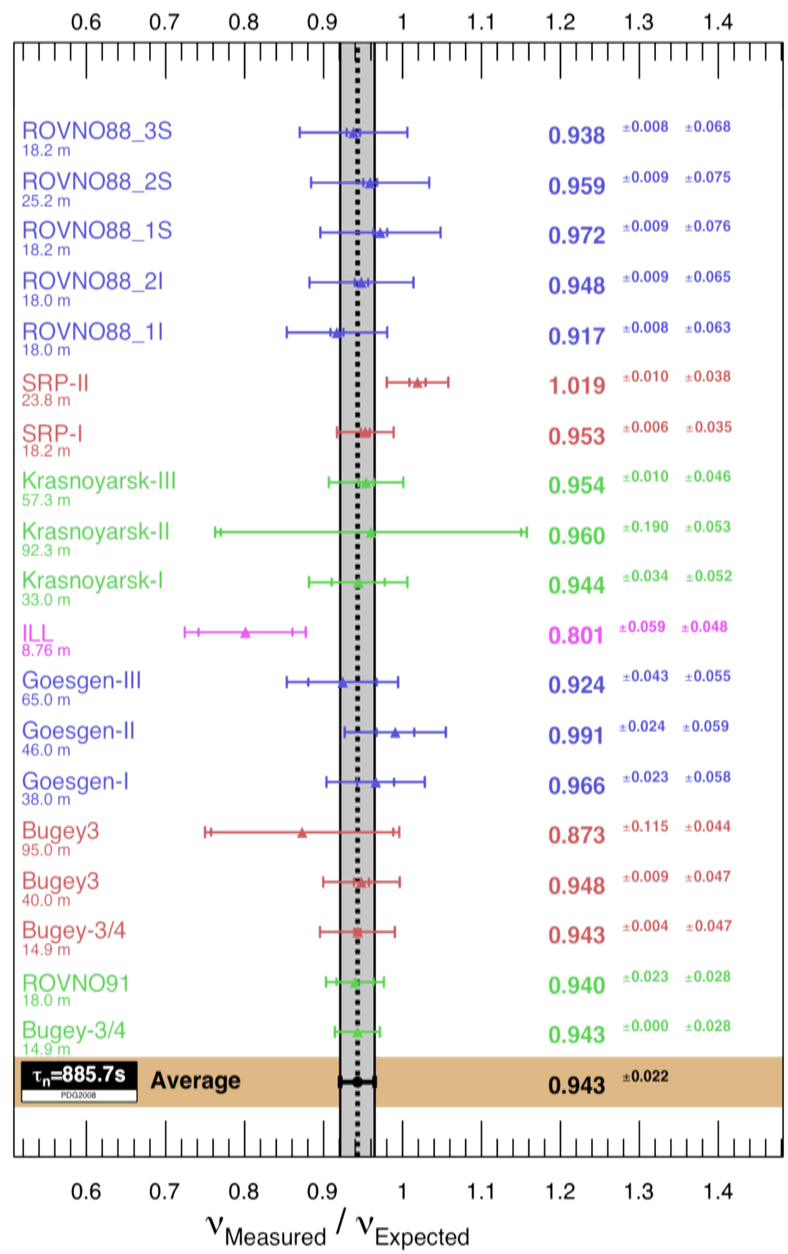
Reactor Anomaly in $\bar{\nu}_e$ Data

- Inclusion of new beta decay estimates in reactor flux calculations
- Increases expected flux

Best fit: 0.943 ± 0.023

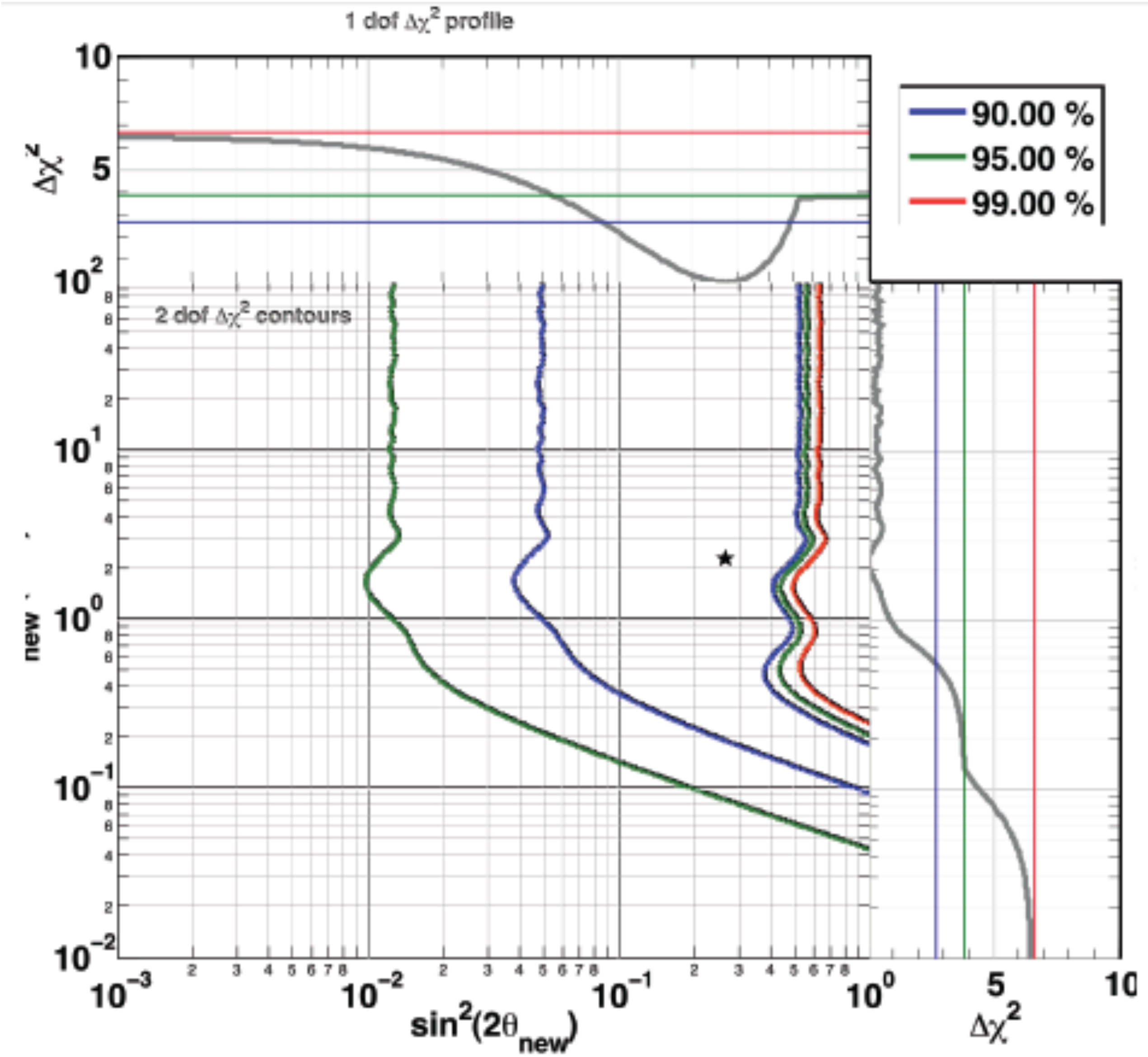
P_{osc}~10%, Δm^2~1 eV^2



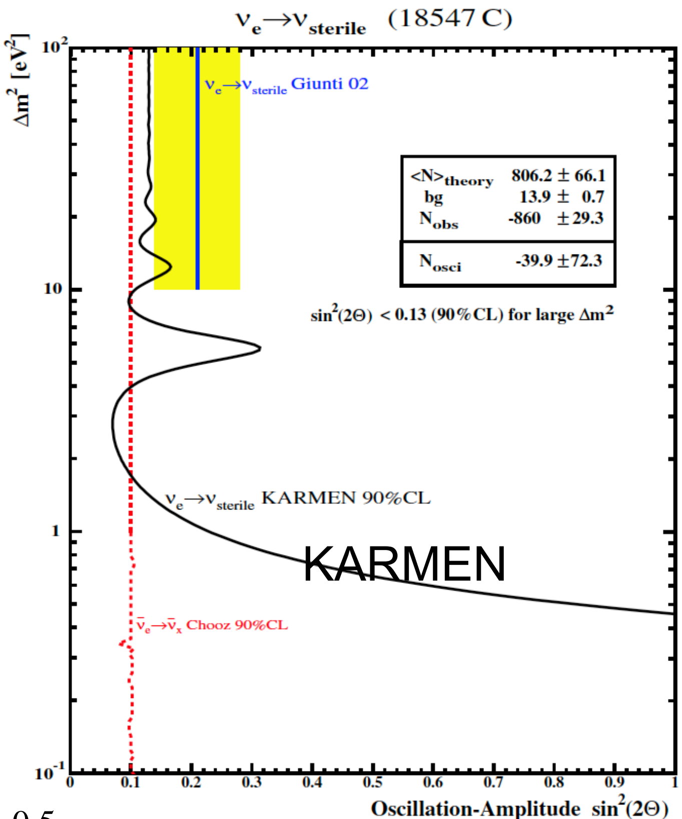


Gallium Source Anomaly in ν_e Data

- Observed too few ν_e interactions observed from an electron capture source



Other data: KARMEN & LSND ν_e Disappearance Limit



$^{12}C(\nu_e,e^-)\,^{12}N_{GS}$

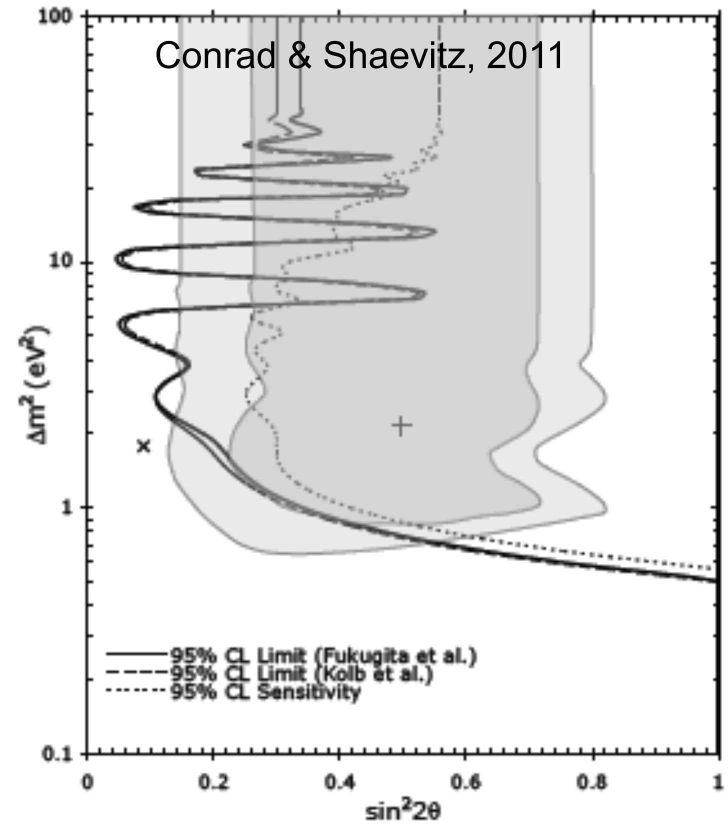
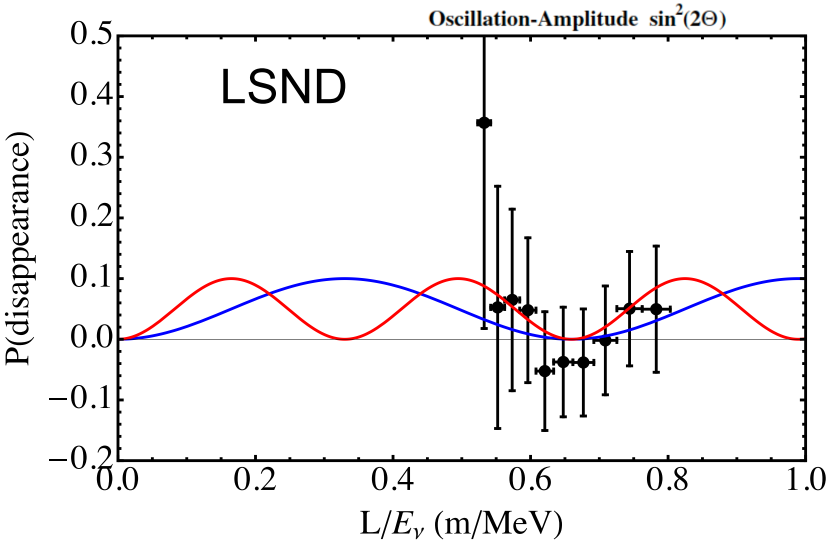


FIG. 4: The 95% ν_e disappearance limit from the Fukugita (EPT) fit (solid, black line) compared to the predicted sensitivity (dotted line). Also shown is the 68% (darker, shaded region) and 90% (lighter, shaded region) contours from the Gallium experiments. The dashed line is the Kolbe (CRPA) fit. The Gallium best fit point and the Reactor Anomaly best fit point are shown as the plus and cross symbols respectively. The Gallium best fit point is excluded at 3.6σ.



Not usually included in global fits

Cosmology Fits for the Number of Sterile Neutrinos

•CMB + LSS + ΛCDM

$N_s = 1.6 \pm 0.9$

Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301

• BBN:

$N_s = 0.64 \pm 0.4$

Izotov, Thuan, ApJL 710 (2010) L67