New Observations from the MiniBooNE Experiment

1. Motivation
2. MiniBooNE Appearance Results
3. Comparison of LSND and MiniBooNE
4. Future Possibilities
5. Conclusions

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Neutrino Oscillations

- The oscillation patterns between the 3 known active neutrino species have been demonstrated by a number of experiments over the last two decades:
  - SNO, Kamland
  - Super-K, K2K, MINOS
- Armed with that knowledge, measurements of neutrino behavior outside the standard 3 generations of active neutrinos indicate new physics:
  - LSND indicates that new physics may be operating
- Interpretations of such a non-standard result probe some deep theoretical issues, for example:
  - Light sterile neutrinos, neutrino decays, CP and/or CPT violation, Lorentz invariance, Extra dimensions

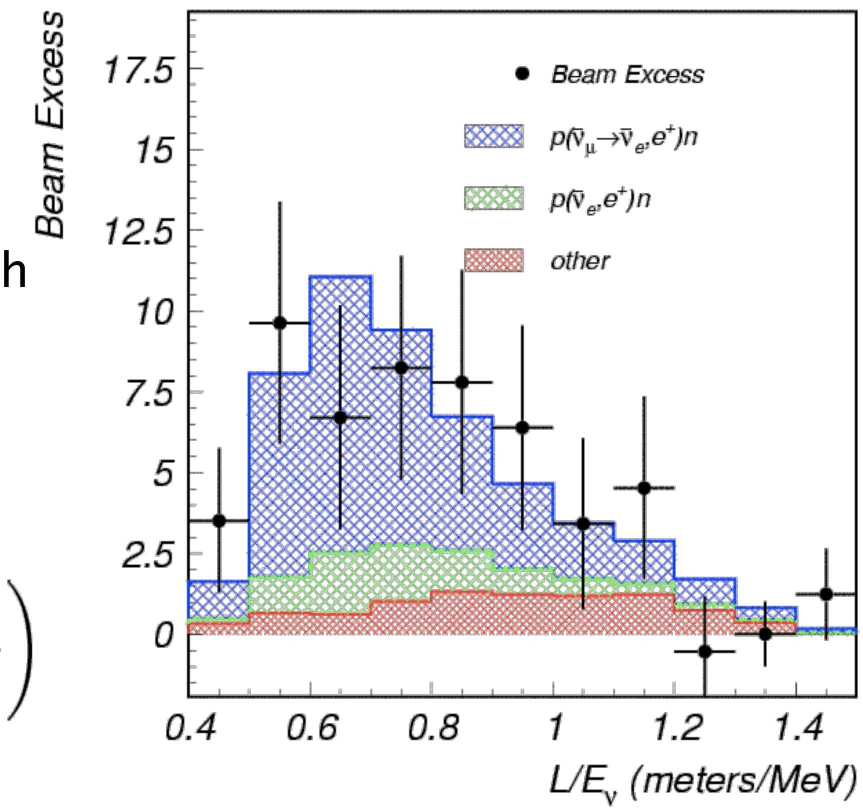
The investigation of neutrino oscillations at the <1% level is unique in its physics reach

Motivation....

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 (3.8σ)
- *The data was analysed under a two neutrino mixing hypothesis**

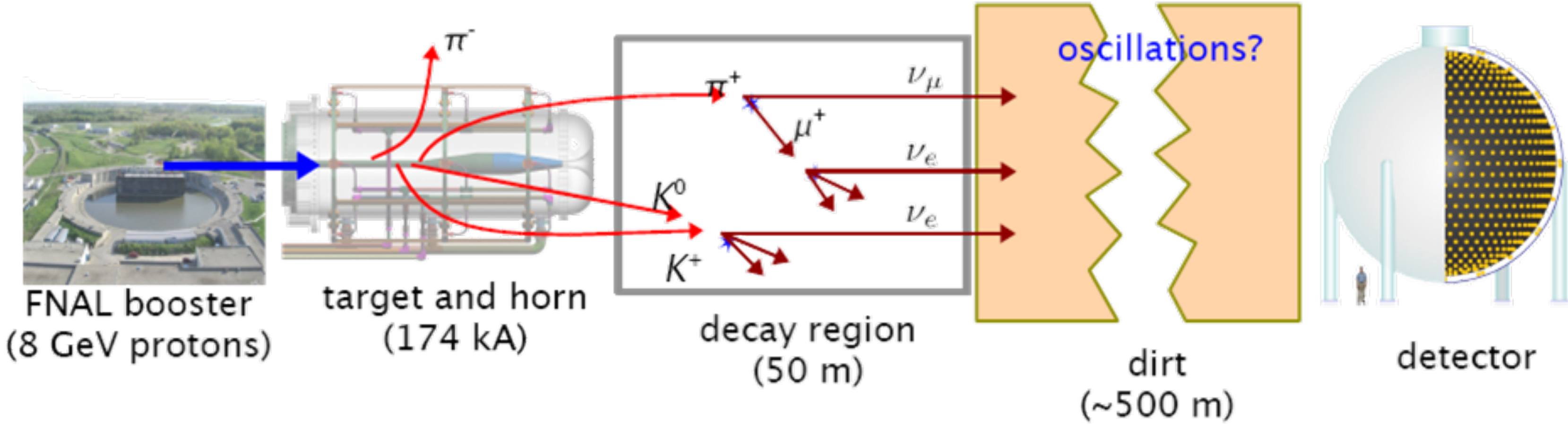
$$P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\, L\, \Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

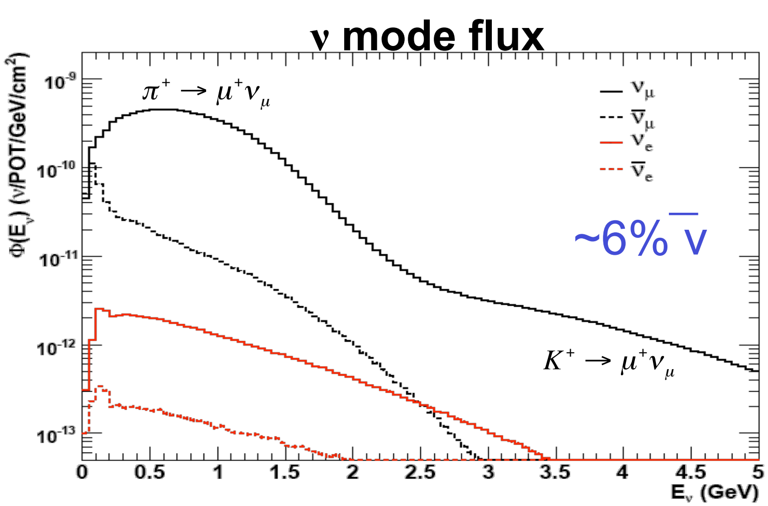


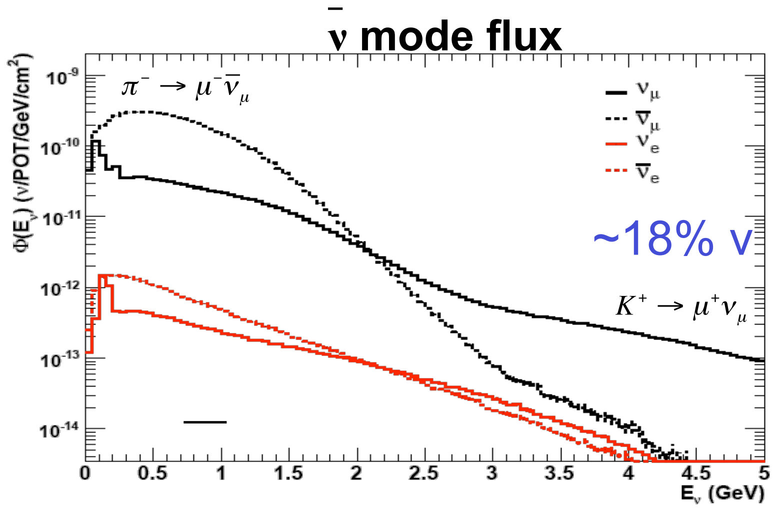
KARMEN at a distance of 17 meters saw no evidence for oscillations →low Δm^2

*3 active + ≥2 sterile vs needed to fit all appearance and disappearance

MiniBooNE looks for an excess of electron neutrino events in a predominantly muon neutrino beam





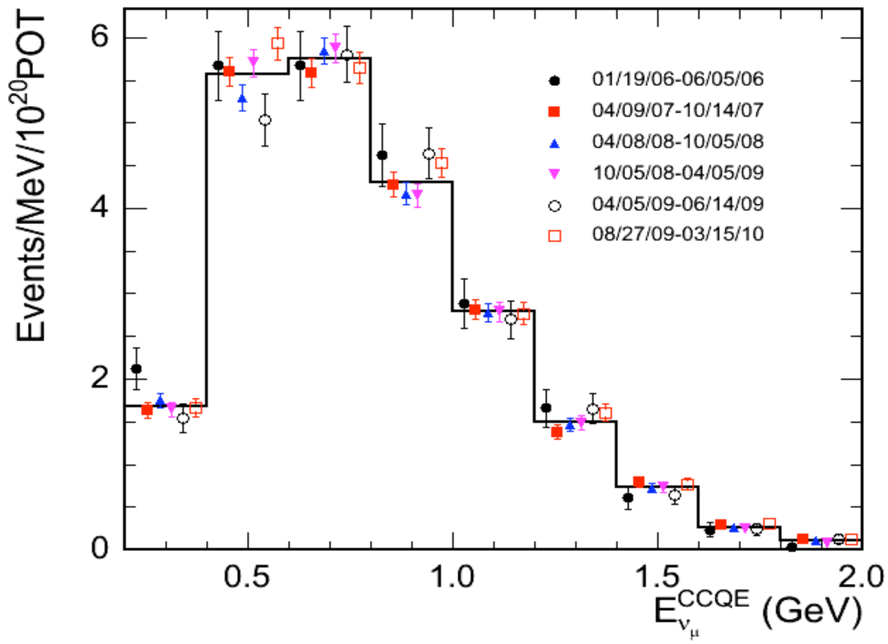


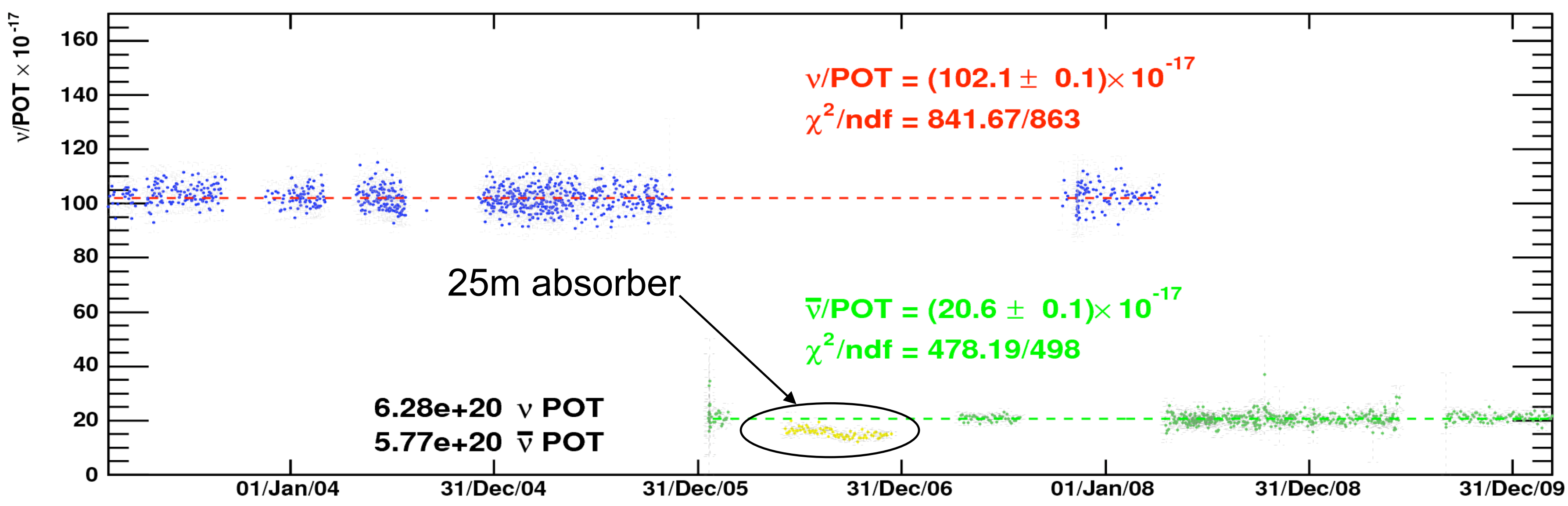
neutrino mode: $\nu_\mu \rightarrow \nu_e$ oscillation search

antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

Data stability

- Very stable throughout the run



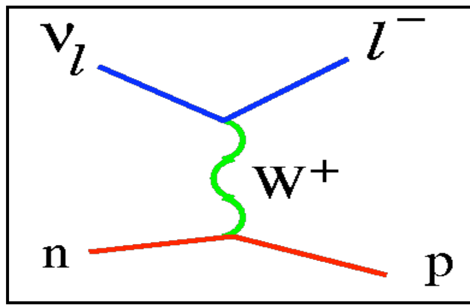


MiniBooNE Detects Cherenkov Light

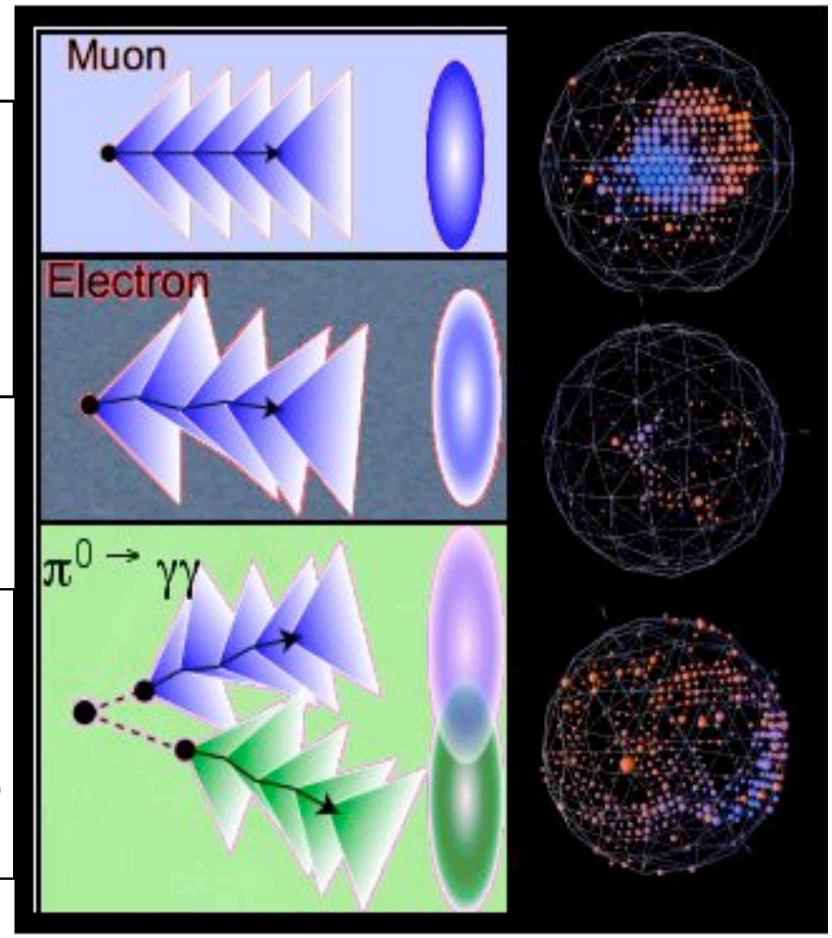
Pattern of Cerenkov Light Gives Event Type

The most important types of neutrino events in the oscillation search:

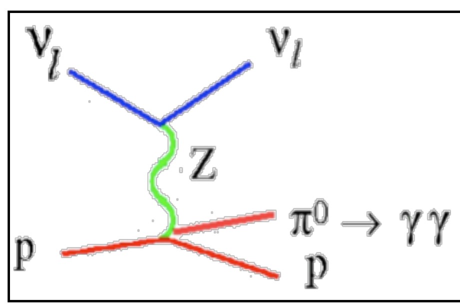
Background Muons (or charged pions):
Produced in most CC events.
Usually 2 or more subevents
or exiting through veto.



Signal and Background
Electrons (or single photon):
Tag for :$\nu_\mu \to \nu_e$ CCQE signal.
1 subevent

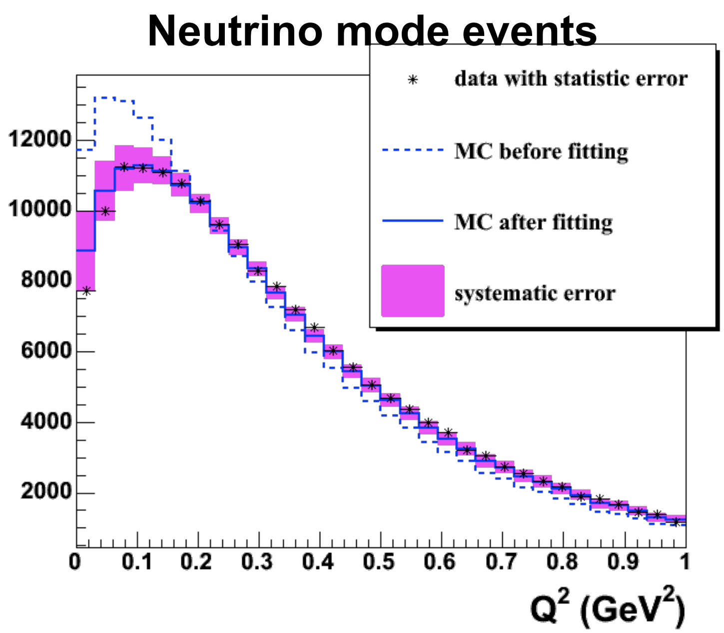


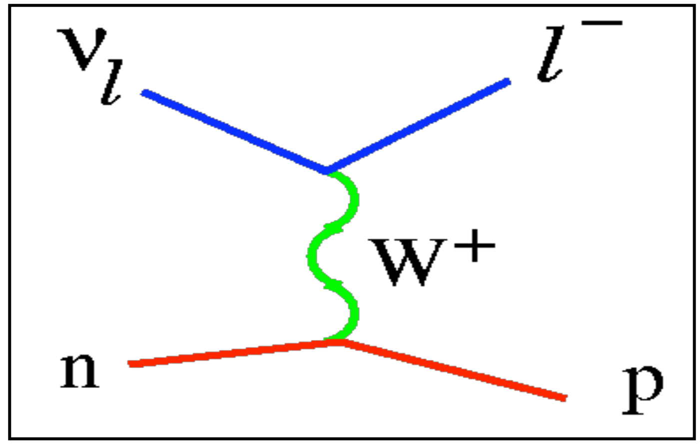
Background π^0s:
Can form a background if one
photon is weak or exits tank.
In NC case, 1 subevent.



Benchmark Reaction: Charged Current Quasi Elastic (CCQE)

Normalizes our (flux ***x*** cross section)





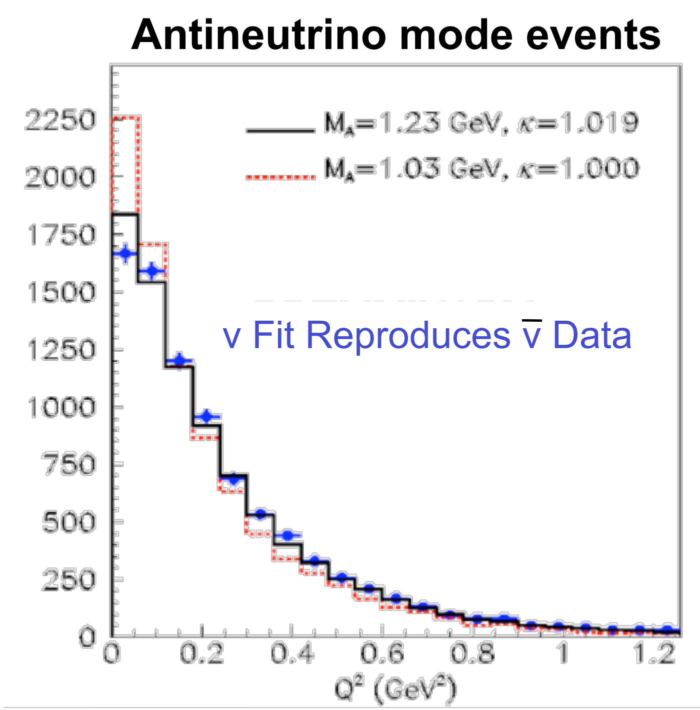
We adjust the parameters of a Fermi Gas model to match our observed Q^2 Distribution.

Fermi Gas Model describes CCQE ν_μ data well

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

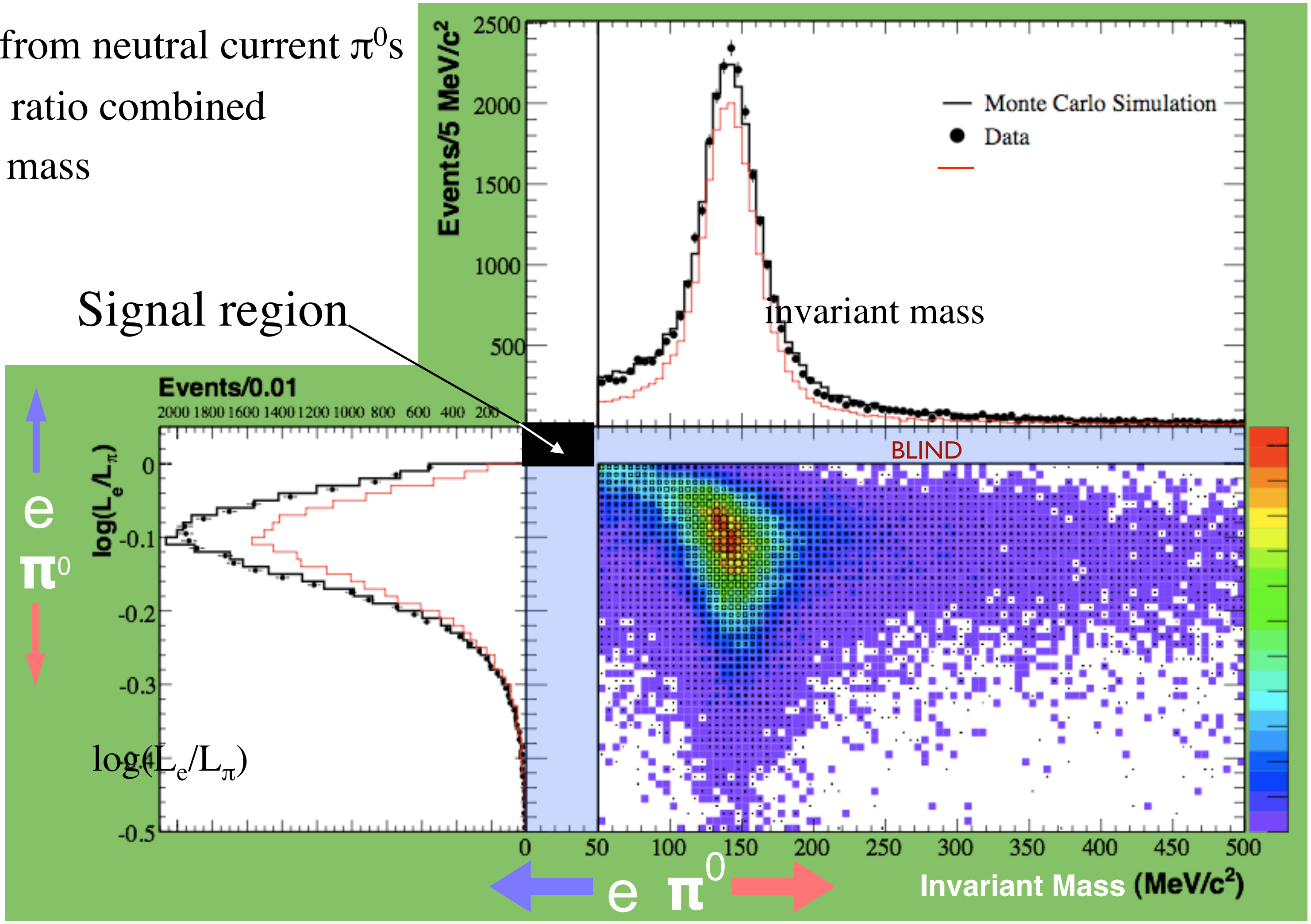
$\varkappa$ = 1.019+-0.011

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



Reconstruction of NC π^0 events

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



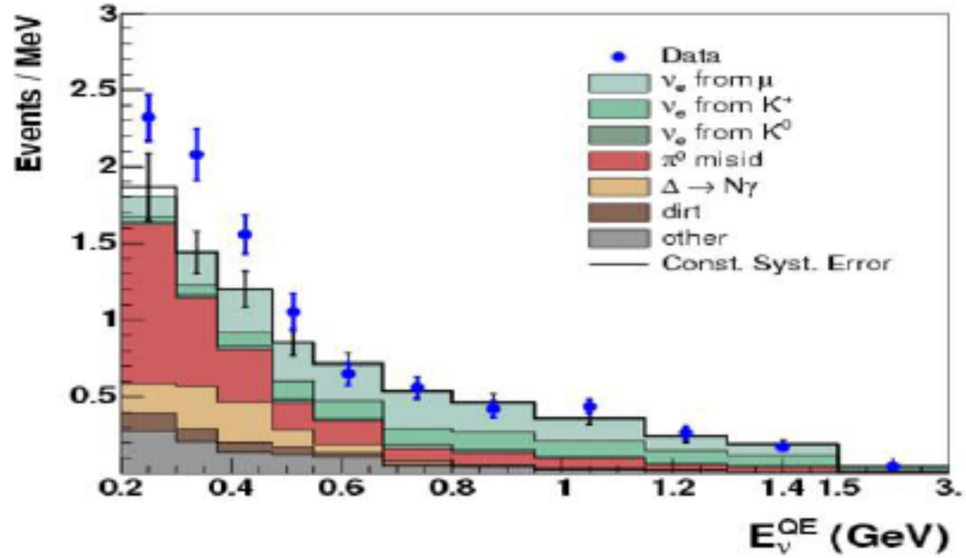
MiniBooNE Oscillation Searches

- Neutrino mode ν_e appearance: $$\nu_\mu \rightarrow \nu_e$$
  - Seach for excess ν_e events above expected background
  - Pure sample of neutrinos

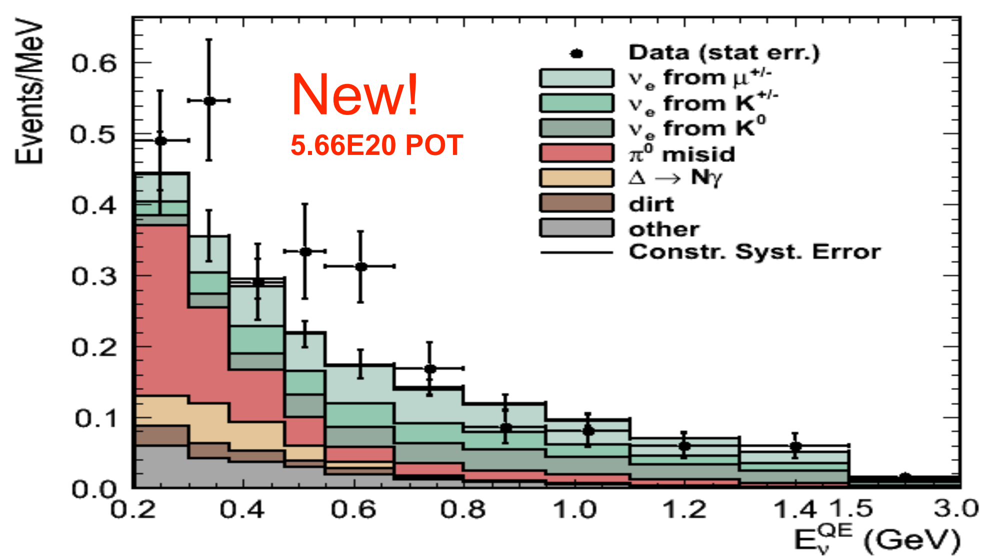
- Antineutrino mode $\bar{\nu}_e$ appearance: $$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$
  - Search for excess $\bar{\nu}_e$ events above expected background
  - *Contamination from large amount of in* ν_e *antineutrino mode which creates ambiguities in the analysis, e.g. how does one treat the observed low energy excess seen in neutrino mode?*

MiniBooNE ν_e and $\bar{\nu}_e$ Data

ν Mode



$\bar{\nu}$ Mode



$\bar{\nu}_e$ 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
- Propagate input uncertainties from either MiniBooNE measurement or external data

(ν_μ constrained error ~10%)

Model Independent Views of Oscillations
Why L/E?

- *Neutrino oscillations usually appear as simple trigonometric functions of L/E, e.g.:*

$$P\left(\nu_\alpha \to \nu_\beta\right) = \delta_{\alpha\beta} - 4\sum_{i>j}^{N} \Re\left(U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*}\right)\sin^2(\Delta m_{ij}^2 \frac{L}{E}) + 2\sum_{i>j}^{N} \Im\left(U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*}\right)\sin(2\Delta m_{ij}^2 \frac{L}{E})$$

$$(\text{antineutrinos}: U \to U^{*})$$

$$\left(\Delta m^2 \frac{L}{E_\nu}\right) \text{ is just the phase difference of the two states}$$

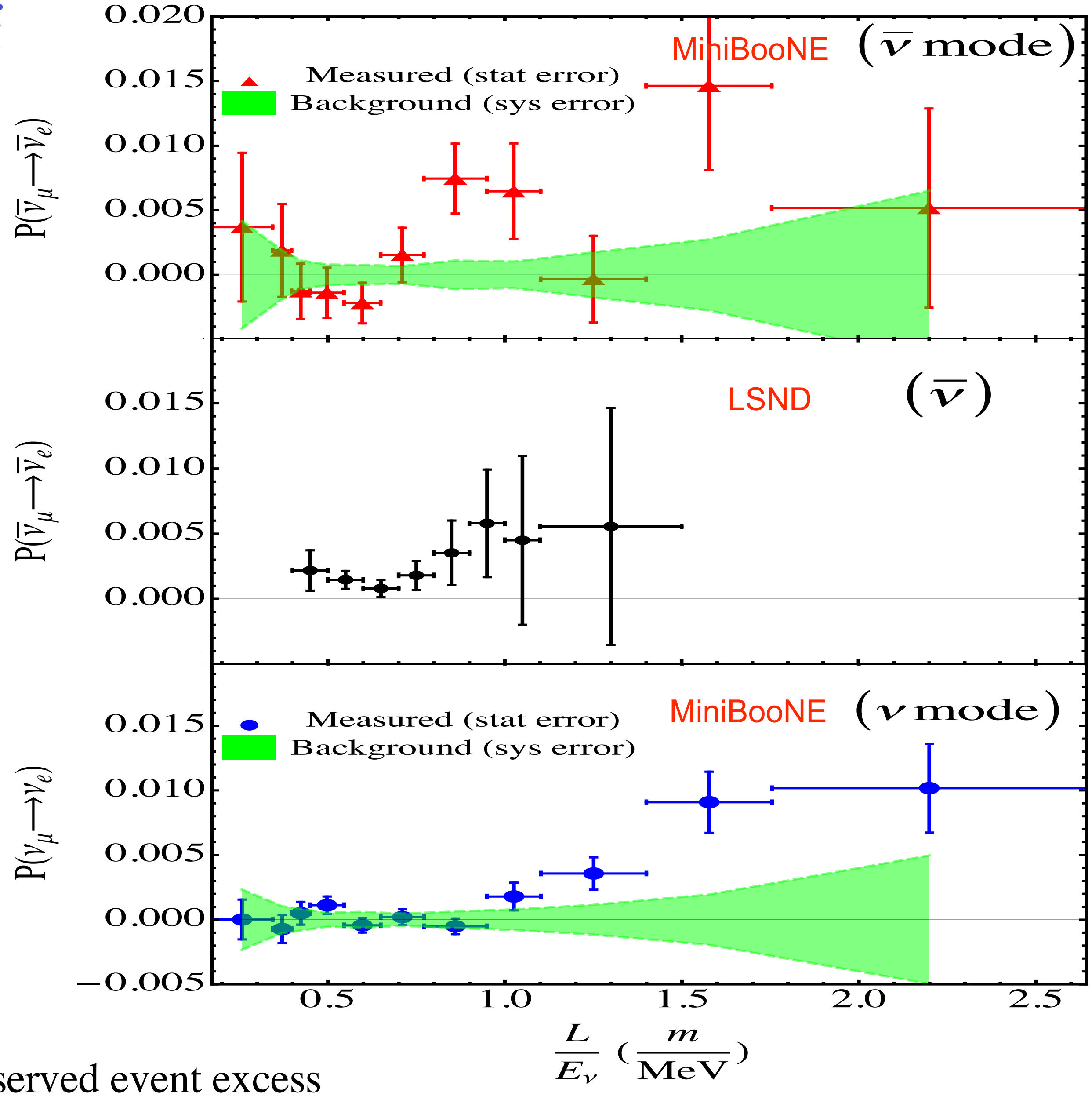
- *Experiments can be compared directly to each other in L/E to look for the interference of mass states and oscillation effects*

- *The next graphs show P(osc) vs L/E:*

$$P\left(\alpha \to \beta\right) \equiv \frac{\text{observed event excess}}{\text{number expected for full transmutation of } \nu_\mu \text{ or } \bar{\nu}_\mu}$$

Data plotted vs L/E

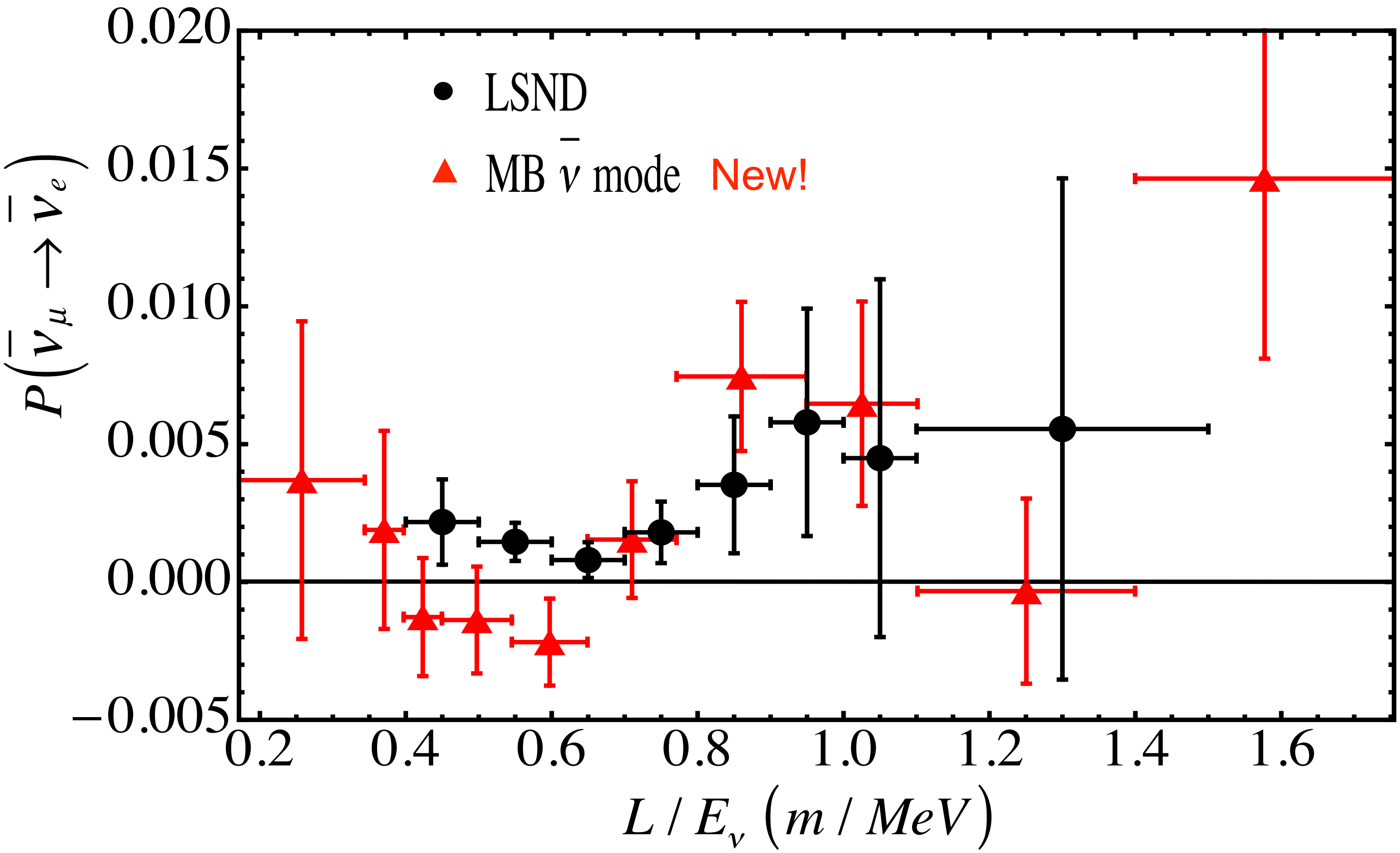
New!
5.66E20 POT



- MiniBooNE L/E bins match the standard MB energy bins, just recast in L/E

$$P(\alpha \to \beta) \equiv \frac{\text{observed event excess}}{\text{number expected for full transmutation of } \nu_\mu \text{ or } \bar{\nu}_\mu}$$

Direct MiniBooNE-LSND Comparison of $\bar{\nu}$ Data



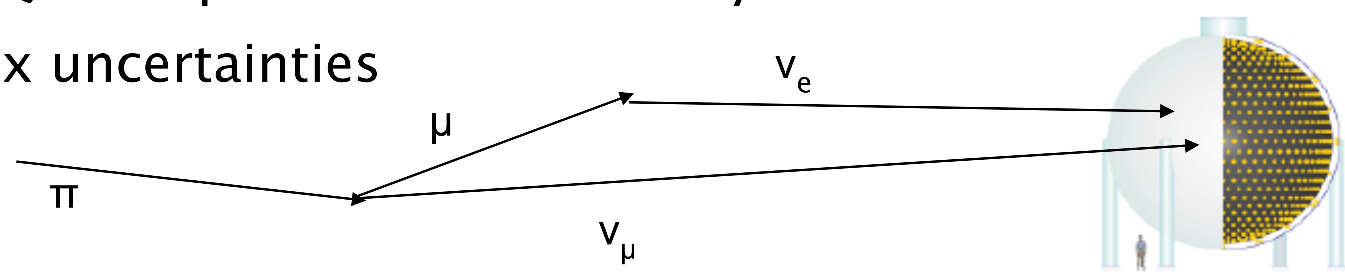
Oscillation Fit Method

- Maximum likelihood fit:

$$-2\ln(L) = (x_1 - \mu_1, ...x_n - \mu_n)M^{-1}(x_1 - \mu_1, ...x_n - \mu_n)^T + \ln(|M|)$$

- Simultaneously fit
  - ν_e CCQE sample
  - High statistics ν_μ CCQE sample

- ν_μ CCQE sample constrains many of the uncertainties:
  - Flux uncertainties



  - Cross section uncertainties

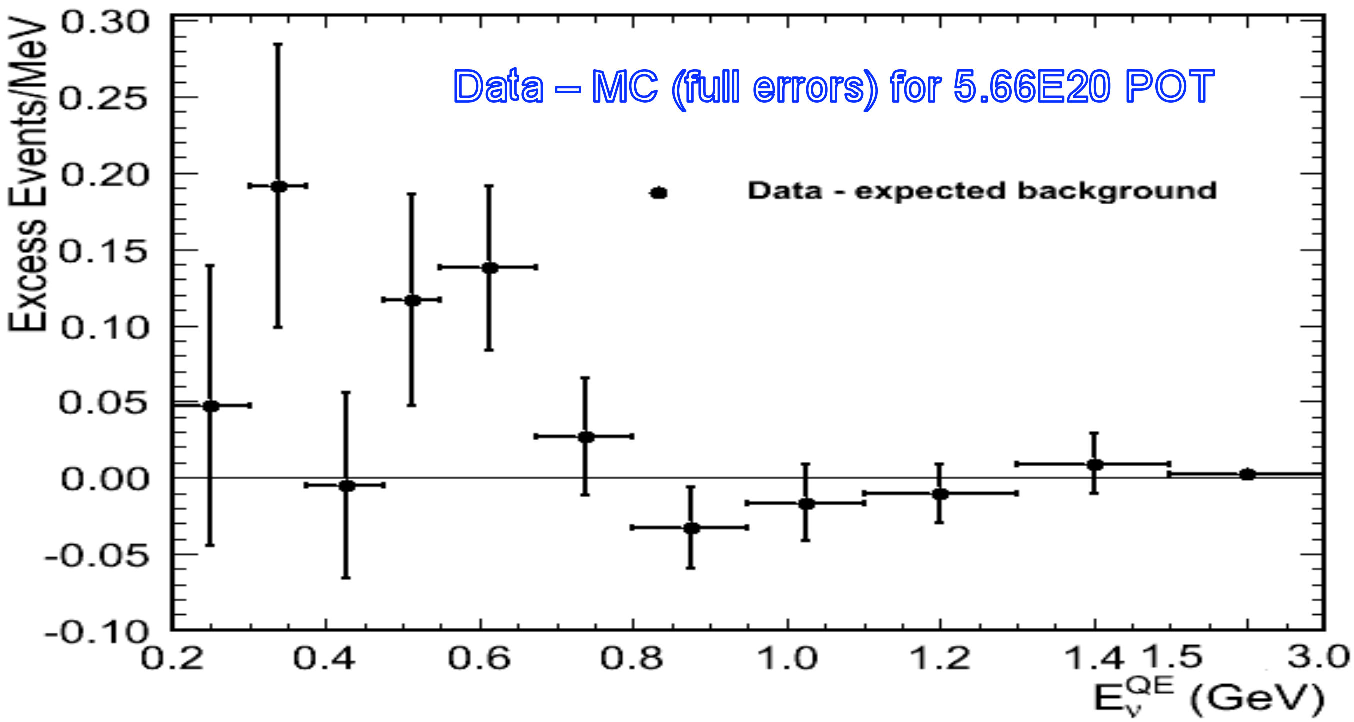
Testing the Null Hypothesis in $\bar{\nu}$-mode

- Model independent, uses only the background estimate and constrains ν_e backgrounds to ν_μ event rate.
- Generate the χ^2 distribution of fake experiments thrown from background-only error matrix (null)

$$P_{null}(\text{MB excess}) \sim 1.6\% \quad \text{(full energy range)}$$

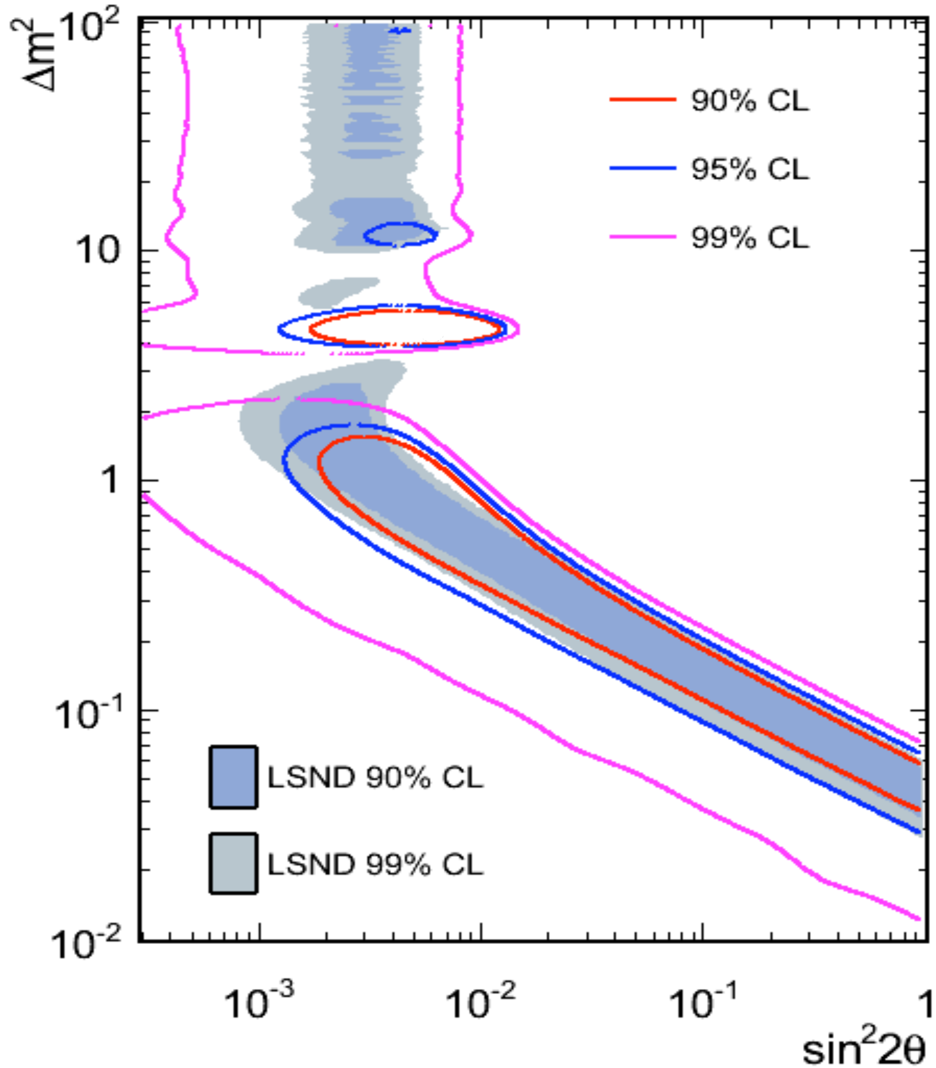
$$P_{null}(\text{MB excess}) \sim 3.0\% \quad \text{(E>475)}$$

$$P_{null}(\text{MB excess}) \sim 0.5\% \quad \text{(signal } \nu_e \text{ bins only)}$$



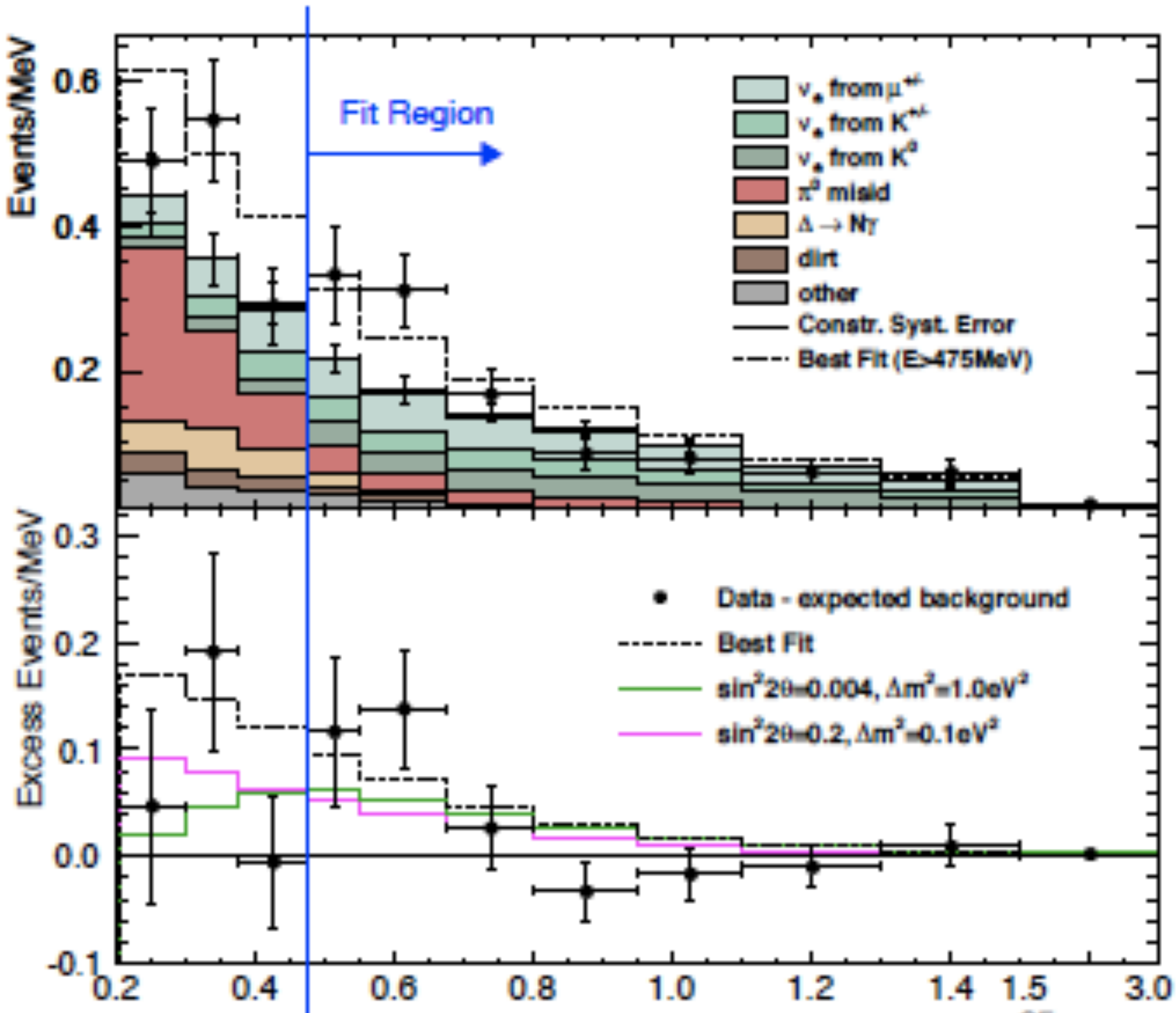
Antineutrino mode MB results Full Energy Range

- Results for **5.66E20 POT**
- Maximum likelihood fit in *simple 2 neutrino model*
- Null excluded at 99.5% with respect to the two neutrino oscillation fit
- P_{χ^2}(best fit)= 17.1%



2 neutrino fit excluding low energy region

(E>475 avoids question of low energy excess in nu-mode)



Antineutrino mode MB results for E>475 MeV

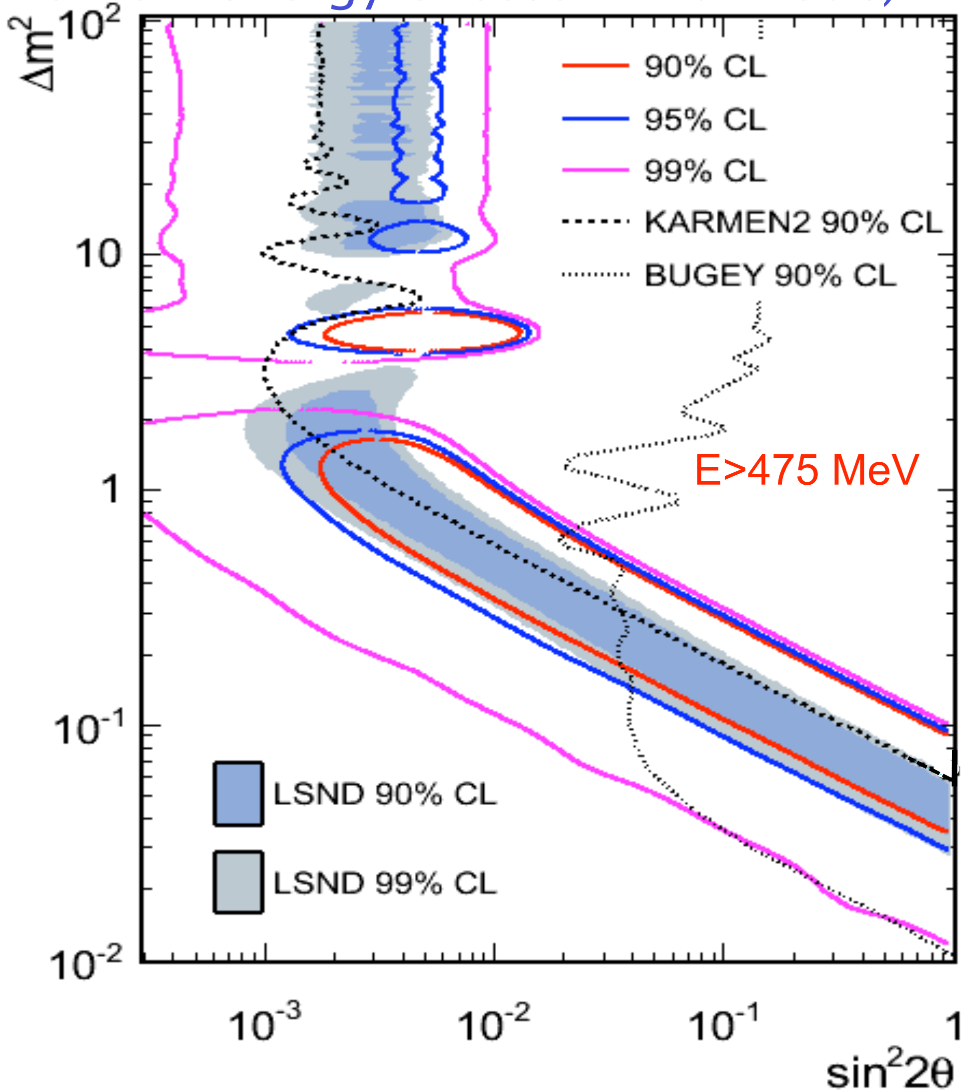
(E>475 avoids question of low energy excess in nu-mode)

- Results for **5.66E20 POT**
- Maximum likelihood fit for *simple two neutrino model*
- Null excluded at 99.4% with respect to the two neutrino oscillation fit.
- $P_{\chi 2}$(best fit)= 20.5%

- Signal ν_e bins only:
  - $P_{\chi 2}$(null)= 0.5%
  - $P_{\chi 2}$(best fit)= ~10%

Submitted to PRL

arXiv: 1007.5510



Conclusions

- Significant ν_e (~3 σ) and $\bar{\nu}_e$ (~2.5 σ) excesses above background are emerging in both neutrino mode and antineutrino mode in MiniBooNE

- The two modes do not appear to be consistent with a simple two flavor neutrino model

- Neutrino mode systematic errors dominate (near detector?)

- Antineutrino mode statistical errors dominate (more data?)

- MiniBooNE plans to accumulate more data until the goal of 10^{21} protons on target is reached

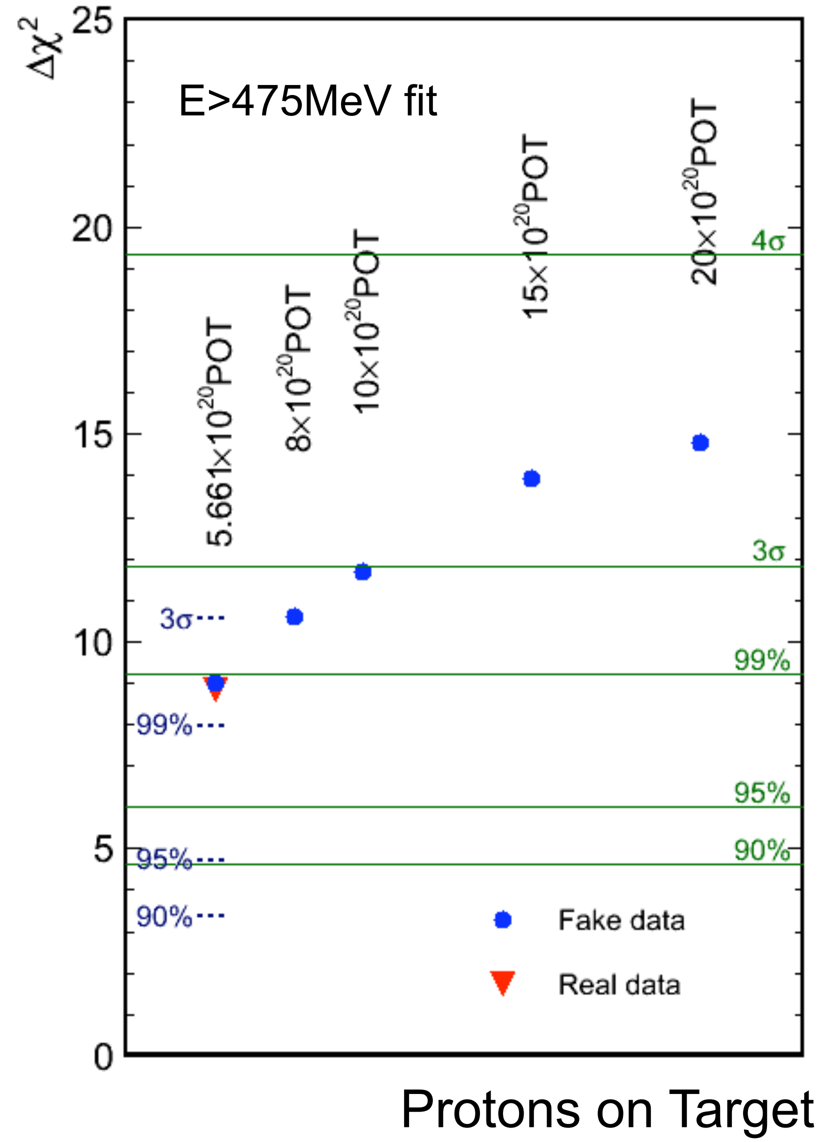
Long-Baseline News, May 2010:

" *** LSND effect rises from the dead… "

BACKUP

Future sensitivity in $\bar{\nu}$ Data

- MiniBooNE approved for a total of 1×10^{21} POT
- Potential 3σ exclusion of null point assuming best fit signal
- Combined analysis of ν_e and $\bar{\nu}_e$

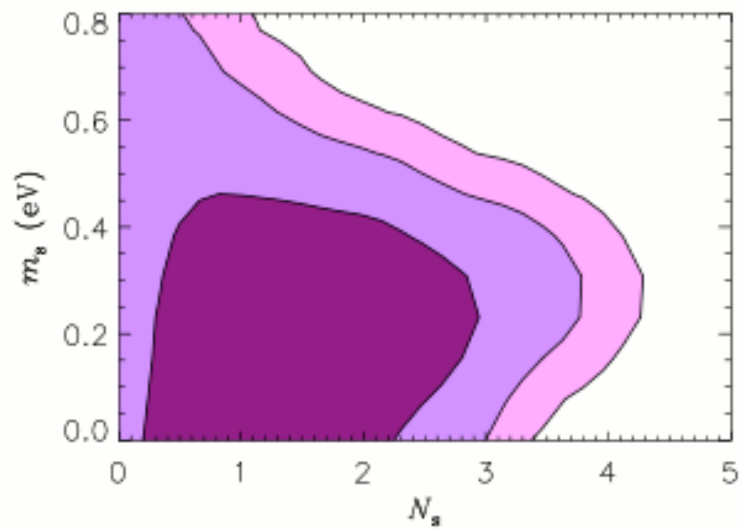


Outlook

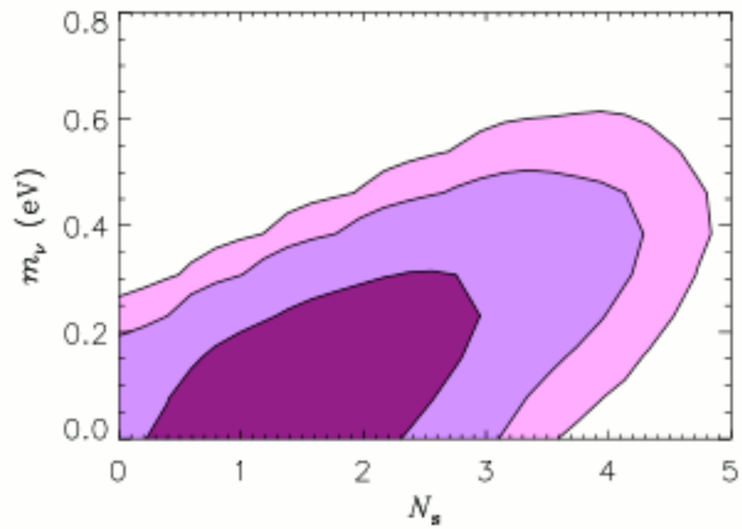
- Additional experiments under consideration or design:
  - Moving MiniBooNE to a near position following the $\bar{\nu}$ run
    - High statistics in a 1 year run
  - MicroBooNE
    - 70 ton Liquid Argon TPC
    - Good electron-gamma separation
  - ICARUS @PS
    - 600 ton Liquid Argon TPC running at Grand Sasso
    - Move to CERN PS beam and augment with small near detector (~<100 tons)
    - Good electron-photon separation
  - Repeat LSND:
    - SNS (OscSNS) is running now at 1 MW
      (neutrinos are going to waste as we speak!!)

Cosmology Fits for the Number of Sterile Neutrinos

(J. Hamann, et. al. arXiv:1006.5276)



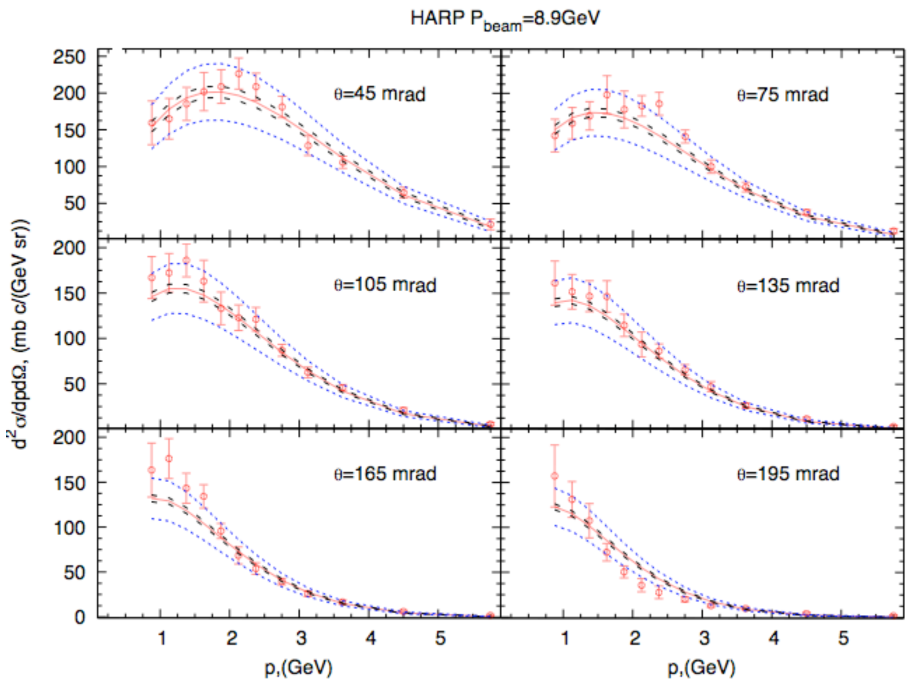
3 + N_s
$m_\nu = 0$



3 + N_s
$m_s = 0$

Meson production at the Proton Target

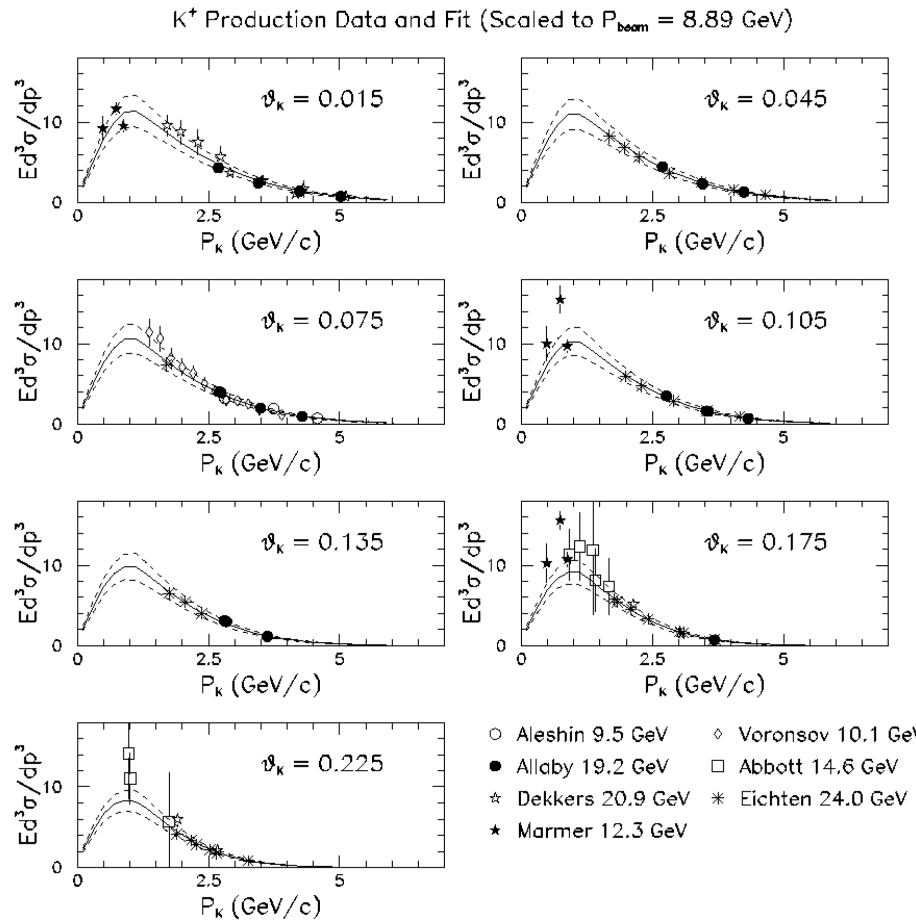
Pions(+/-):



HARP collaboration,
hep-ex/0702024

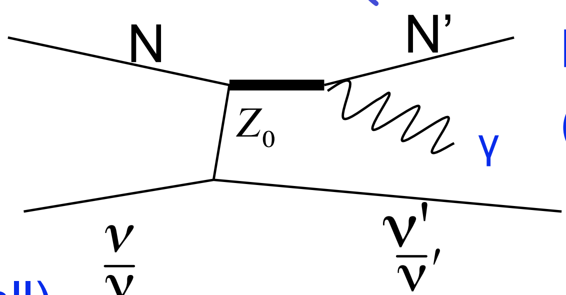
- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% Beryllium target
- Spline fits were used to parameterize the data.

Kaons:



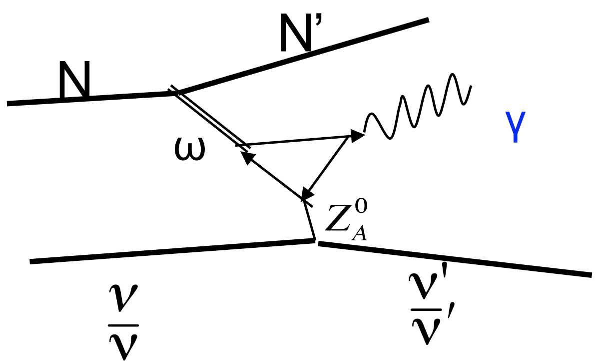
- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed

Backgrounds: Order(α_{QED} x NC) , single photon FS

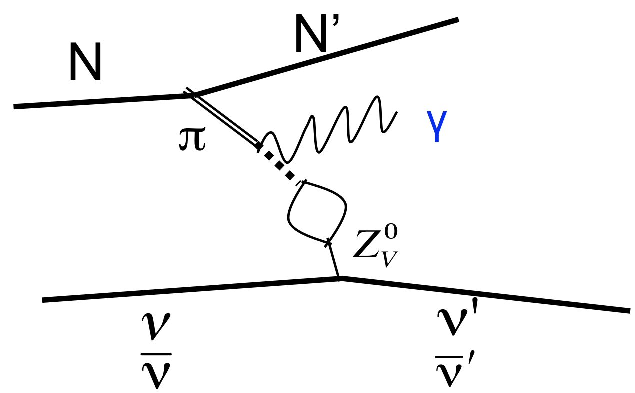


Radiative Delta Decay
(constrained by NCπ^0)

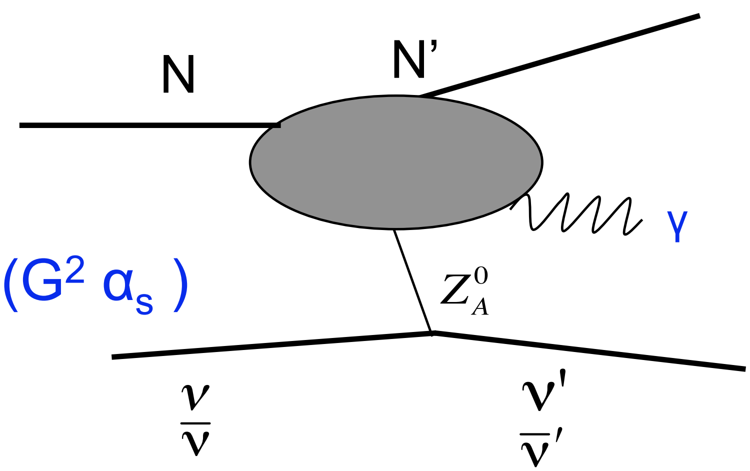
Axial Anomaly (small)



Other PCAC (small)



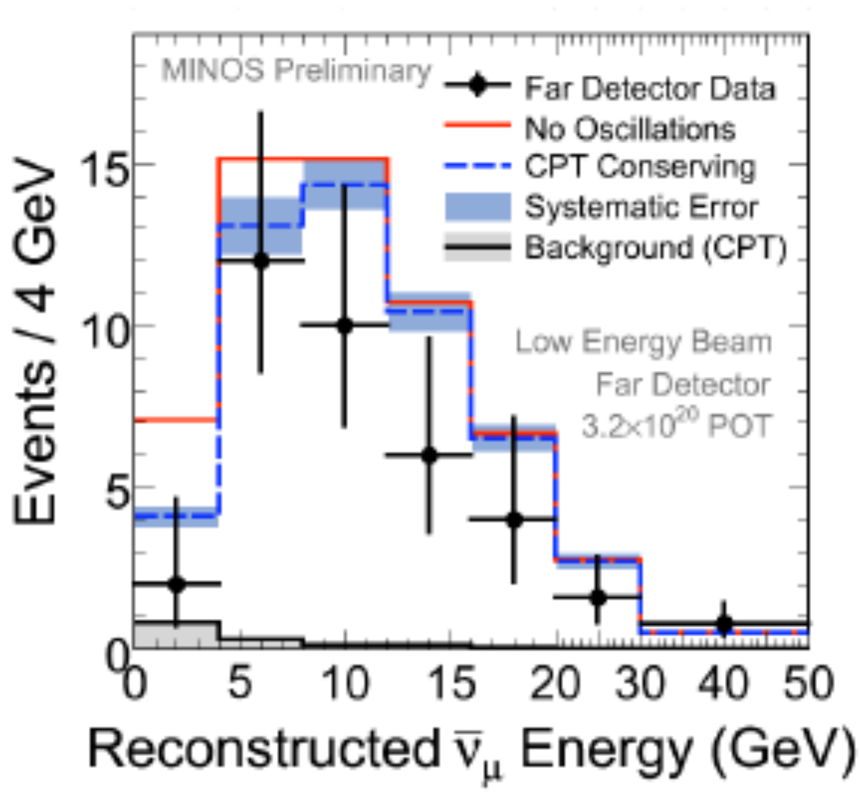
All order (G^2 α_s)

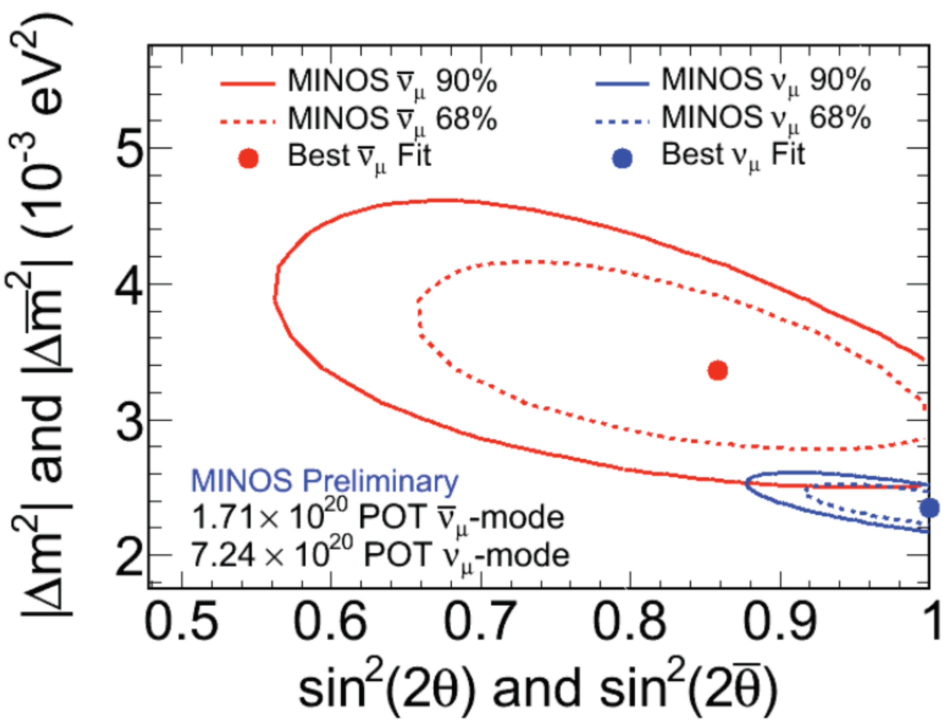


$\nu - \overline{\nu}$ comparison disfavors neutral current hypothesis since radiative Δ is constrained by NCπ^0

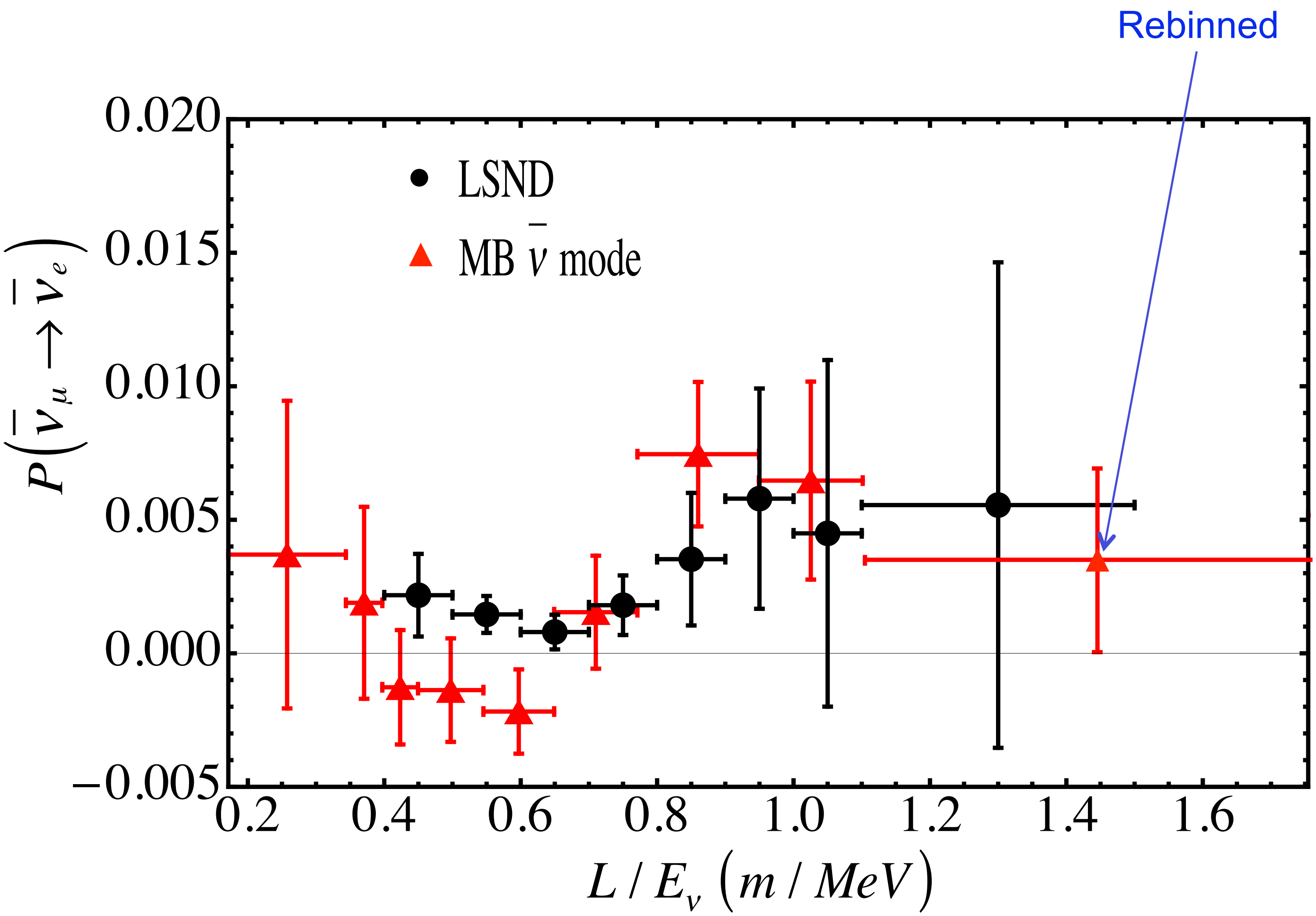
MINOS Antineutrino Disappearance

Low statistics but results hint at possible new effect in $\bar{\nu}_\mu$

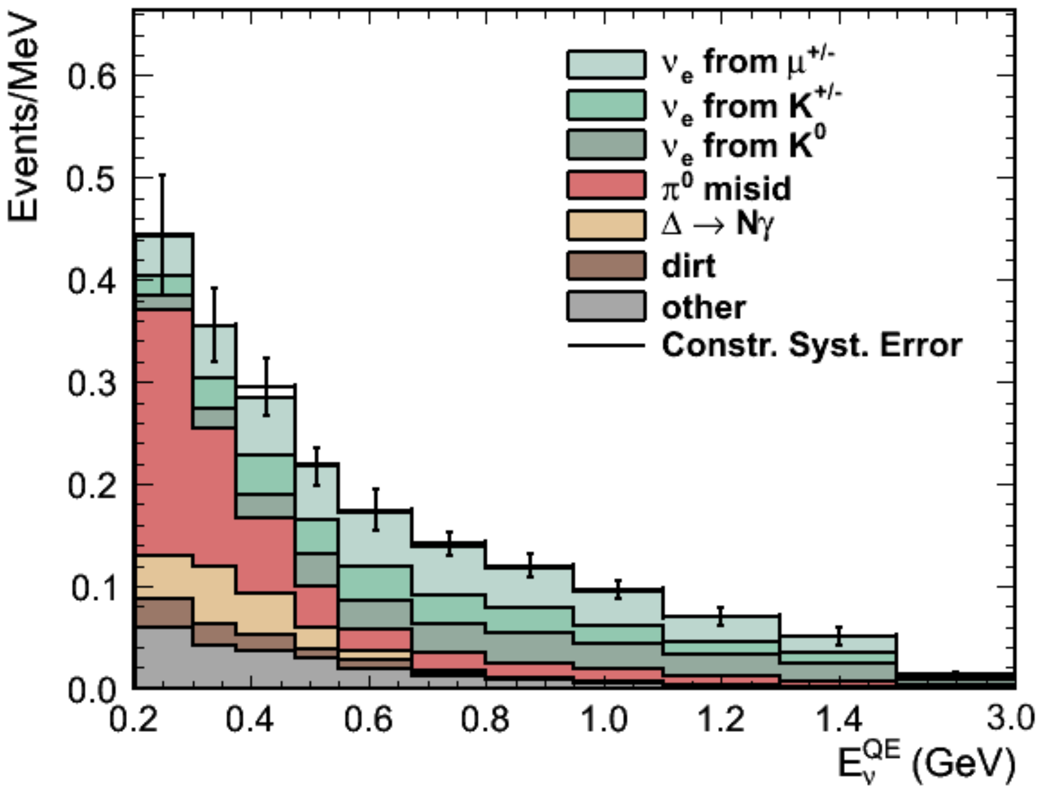




Direct MiniBooNE-LSND Comparison of $\bar{\nu}$ Data

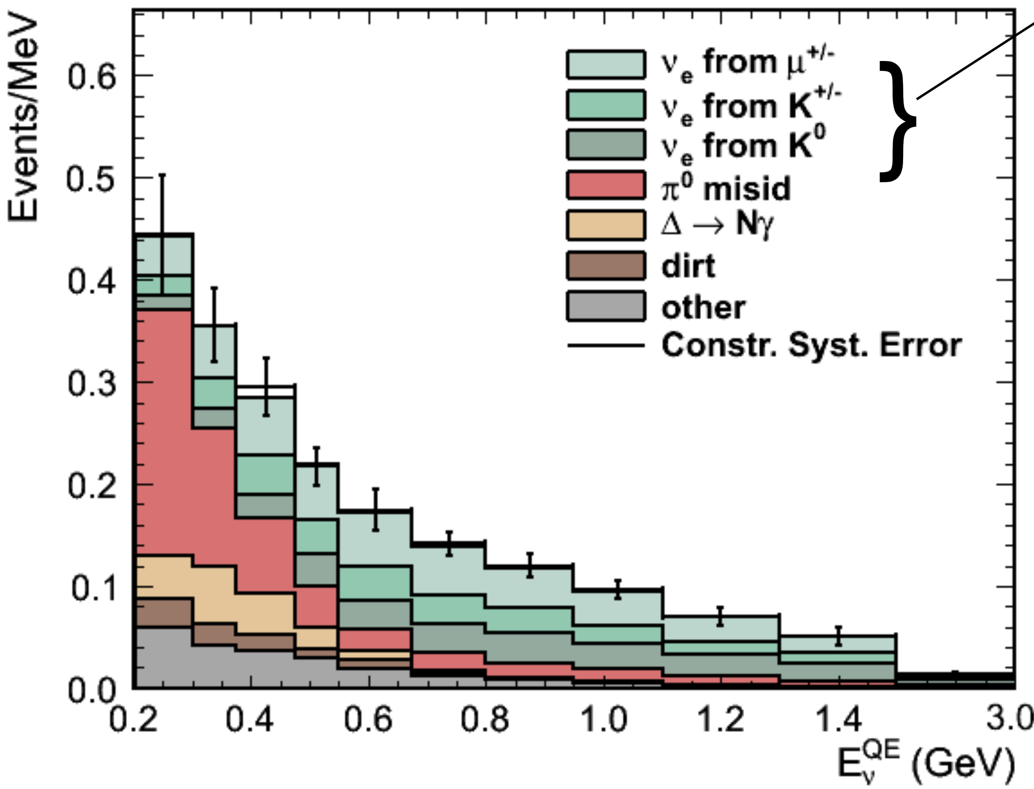


Background prediction



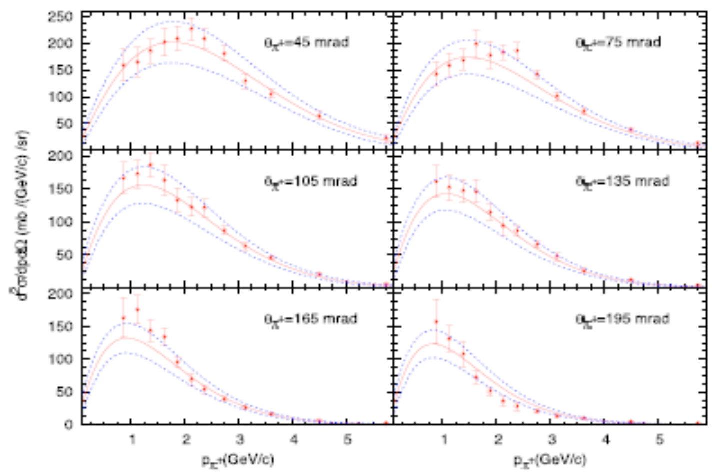
5.66e20 Protons on Target			
	200-475	475-1250	
$m^{\pm}$	13.45	31.39	Intrinsic v_e
$K^{\pm}$	8.15	18.61	
K^0	5.13	21.2	
Other v_e	1.26	2.05	
NC π^0	41.58	12.57	
$\Delta \rightarrow N\gamma$	12.39	3.37	Mis-ID
dirt	6.16	2.63	
v_m CCQE	4.3	2.04	
Other v_m	7.03	4.22	
Total	99.45	98.08	

Background prediction



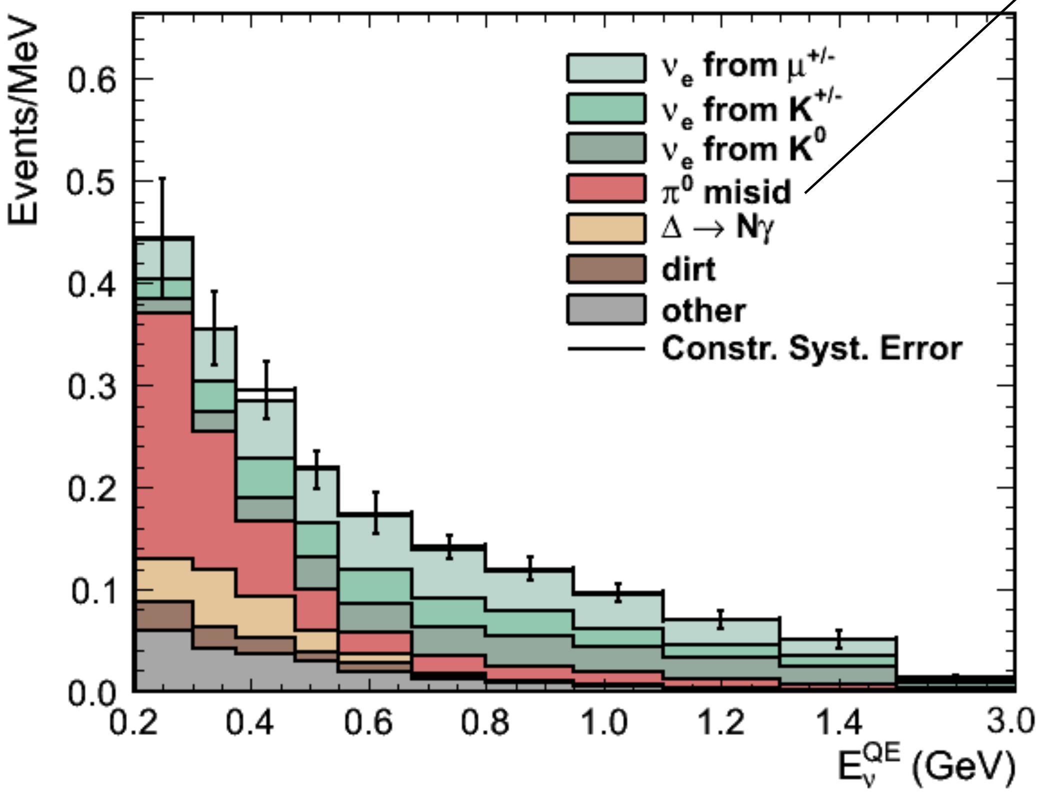
Phys. Rev. D79, 072002 (2009)

- Intrinsic $\bar{\nu}_e$ & ν_e
  - External measurements - HARP p+Be for $\pi^{\pm}$

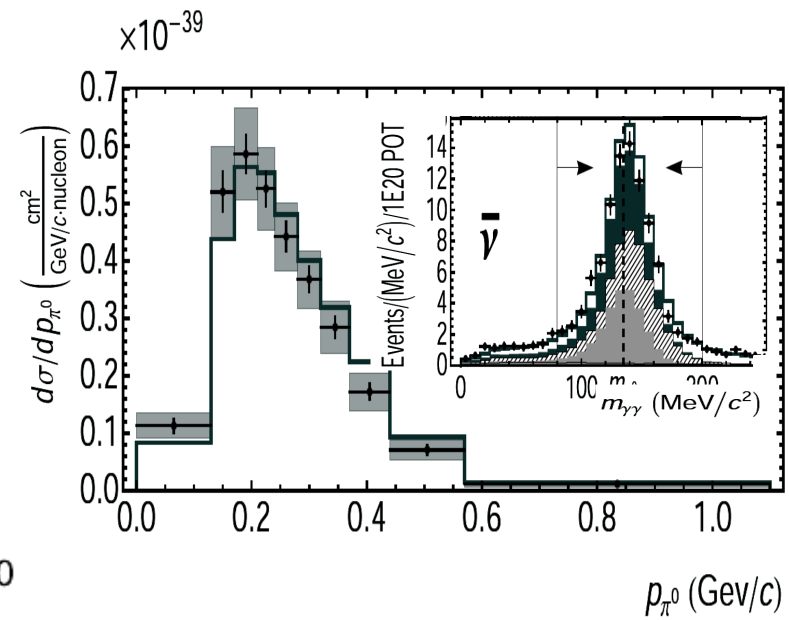


  - - Sanford-Wang fits to world K^+/K^0 data
  - MiniBooNE data constrained

Background prediction



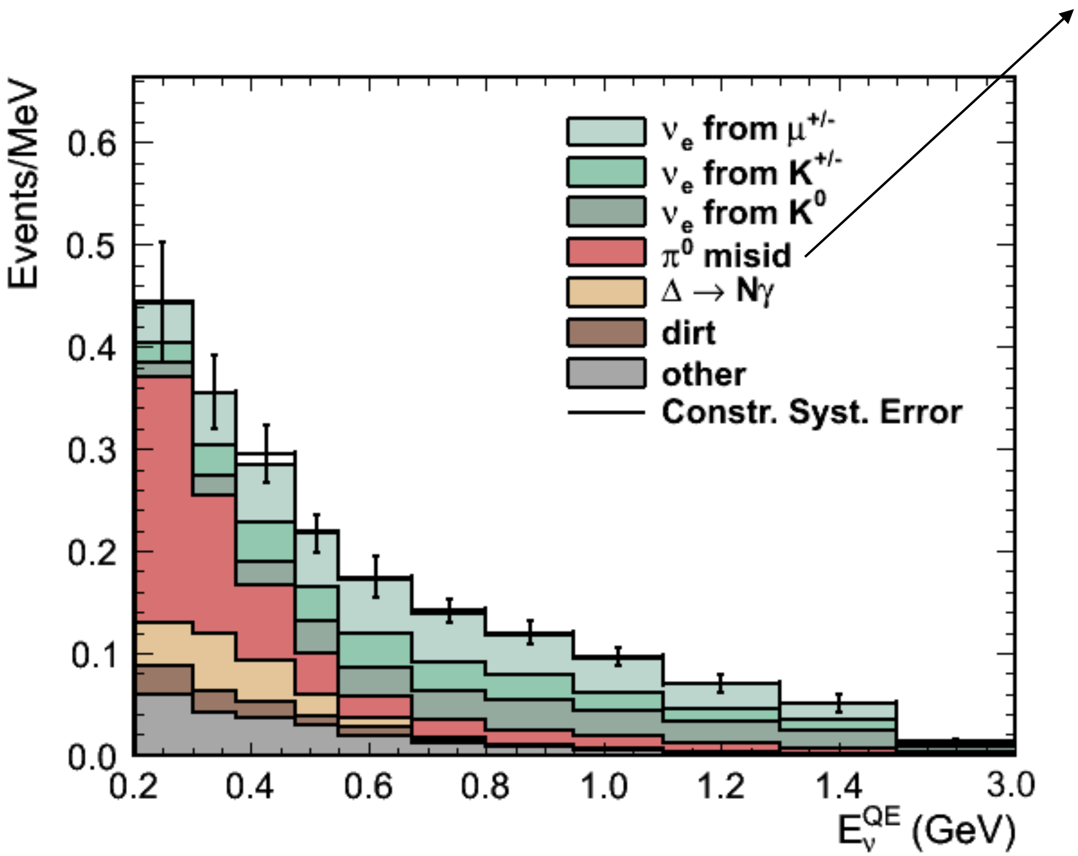
- NC π^0
  - MiniBooNE measurement



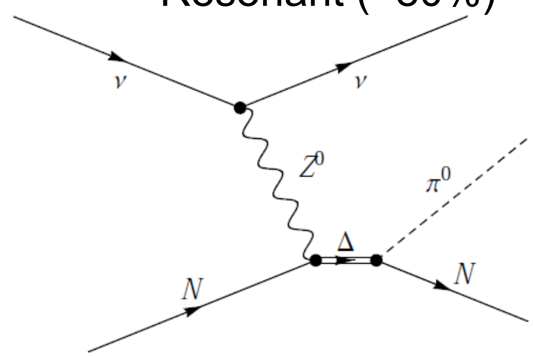
Phys. Rev. D81, 013005 (2010)

Background prediction

- NC π^0

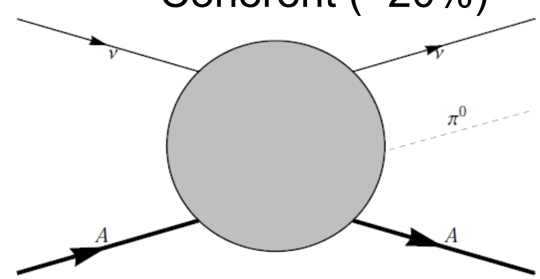


Resonant (~80%)

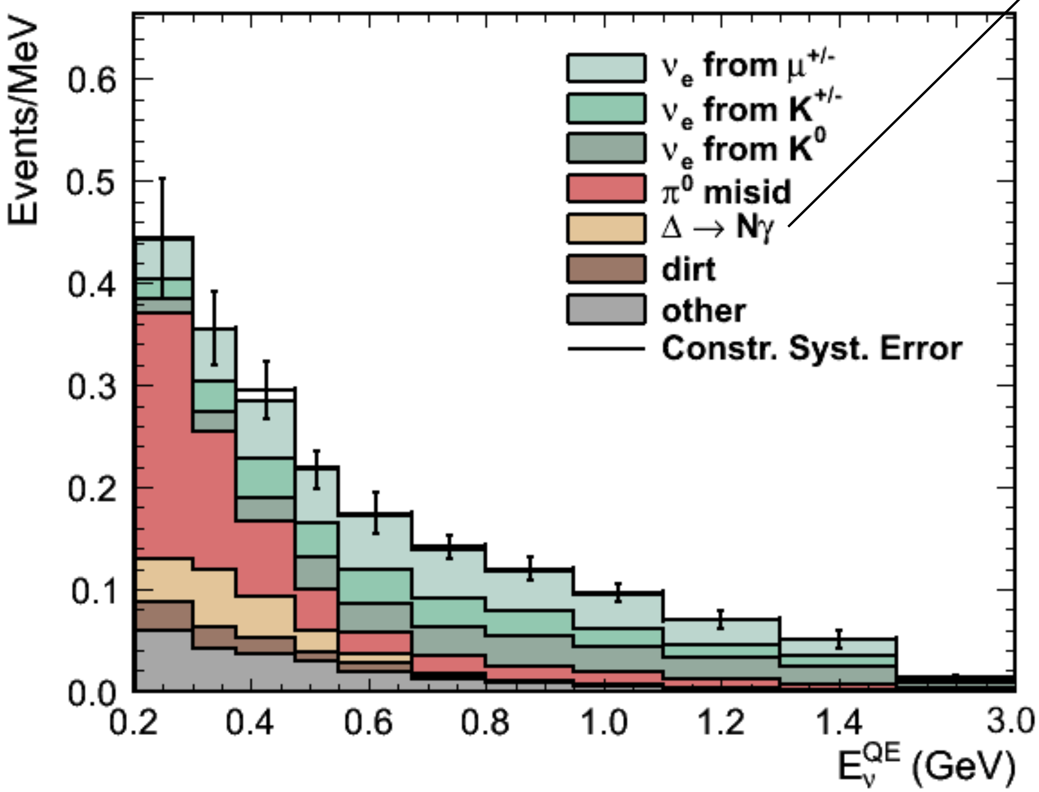


+

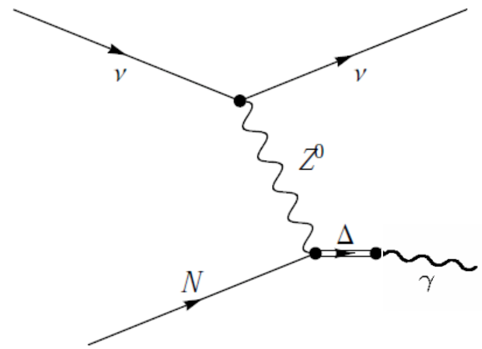
Coherent (~20%)



Background prediction

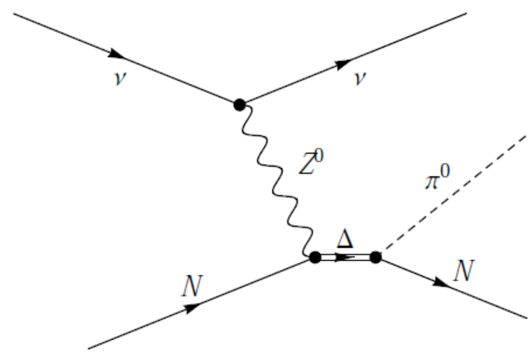


- Radiative delta

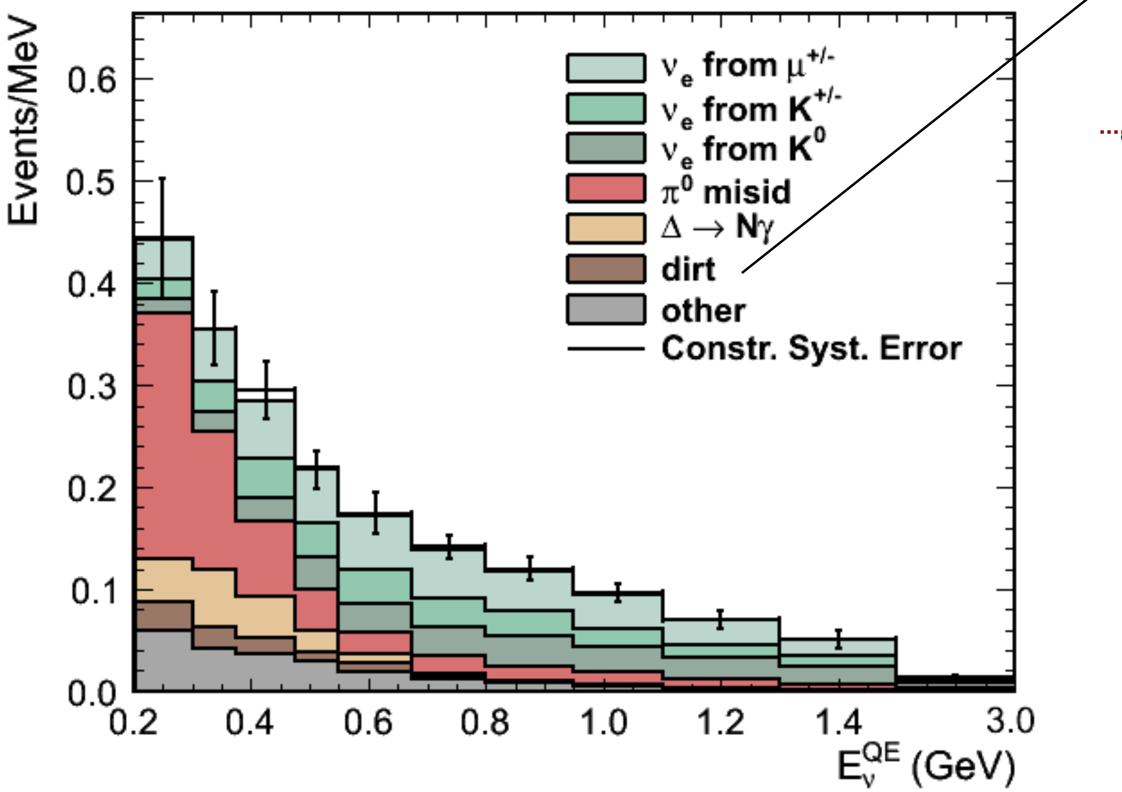


- Use NC π^0 measurement to constrain

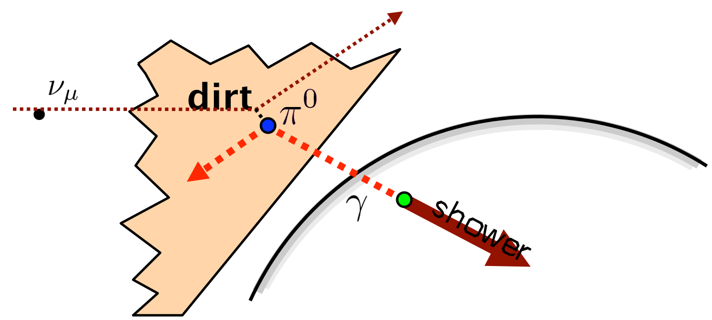
Resonant π^0



Background prediction

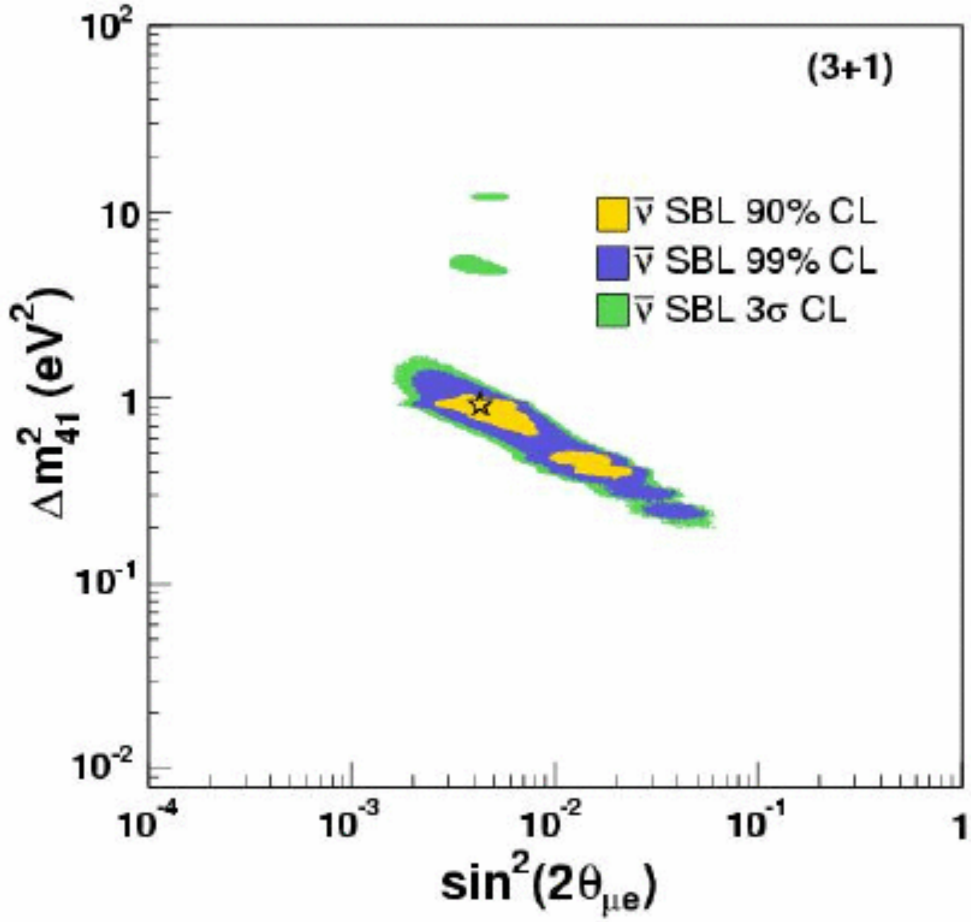


- Dirt:



- Events at high R pointing toward center of detector
- MiniBooNE measurement normalizes MC prediction

3+1 Global Fit to World Antineutrino Data

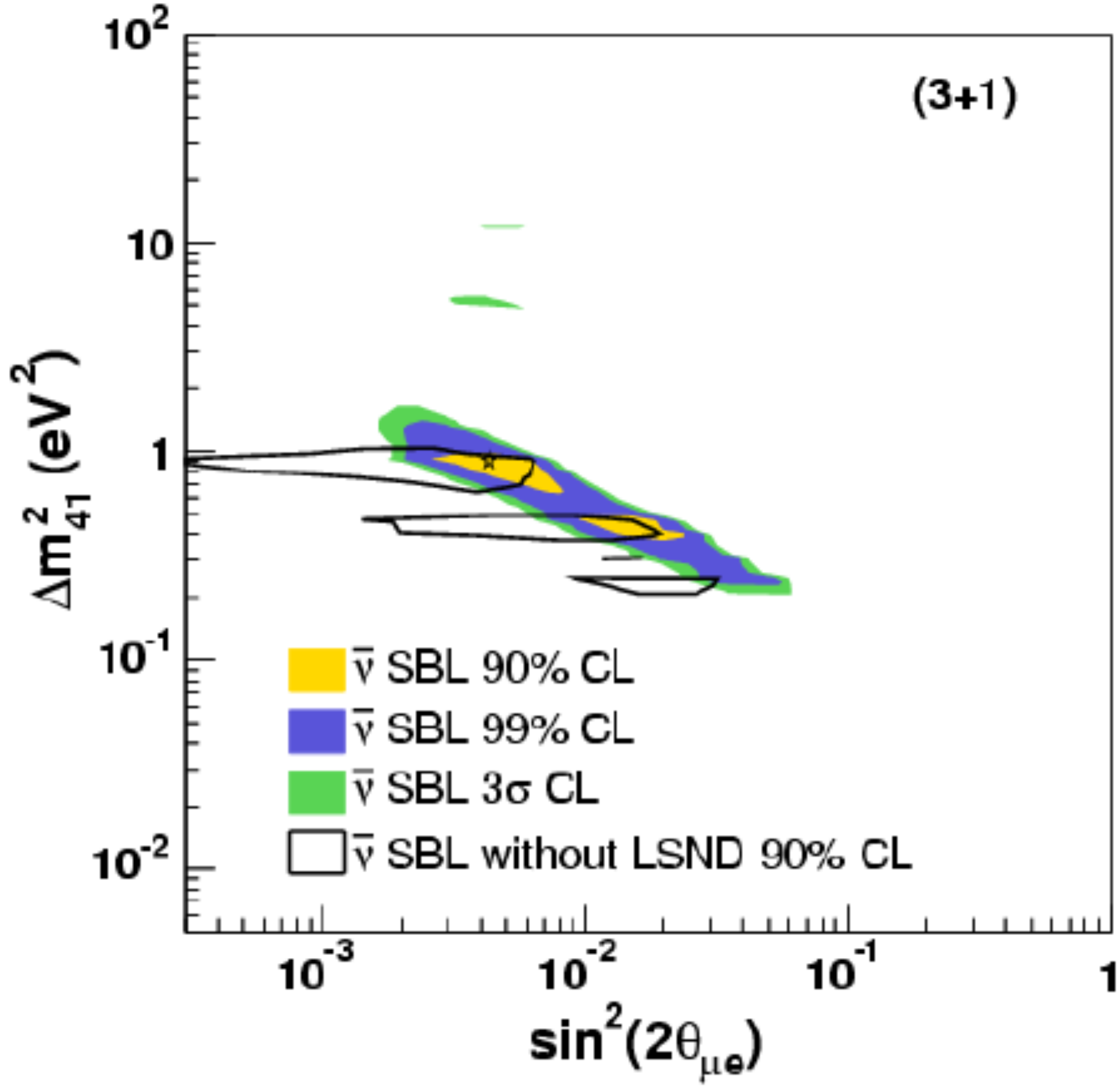


G. Karagiorgi et al., arXiv:0906.1997

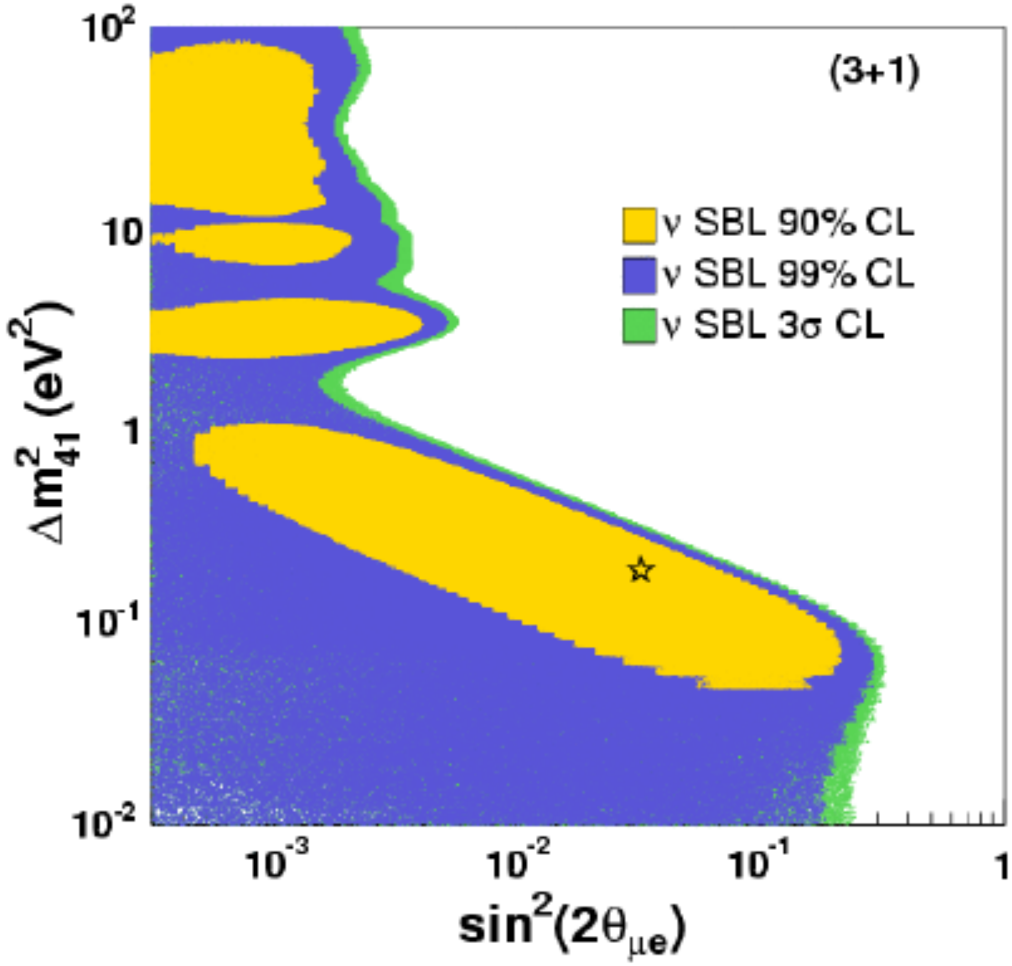
Best 3+1 Fit:
$\Delta m_{41}{}^2 = 0.915$ eV^2
$\sin^2 2\theta_{\mu e} = 0.0043$
$\chi^2 = 87.9/103$ DOF
Prob. = 86%

Predicts $\overline{\nu_\mu}$ & $\overline{\nu_e}$ disappearance of $\sin^2 2\theta_{\mu\mu} \sim 35\%$ and $\sin^2 2\theta_{ee} \sim 4.3\%$

3+1 Global Fit to World Antineutrino Data w/o LSND



3+1 Global Fit to World Neutrino Data



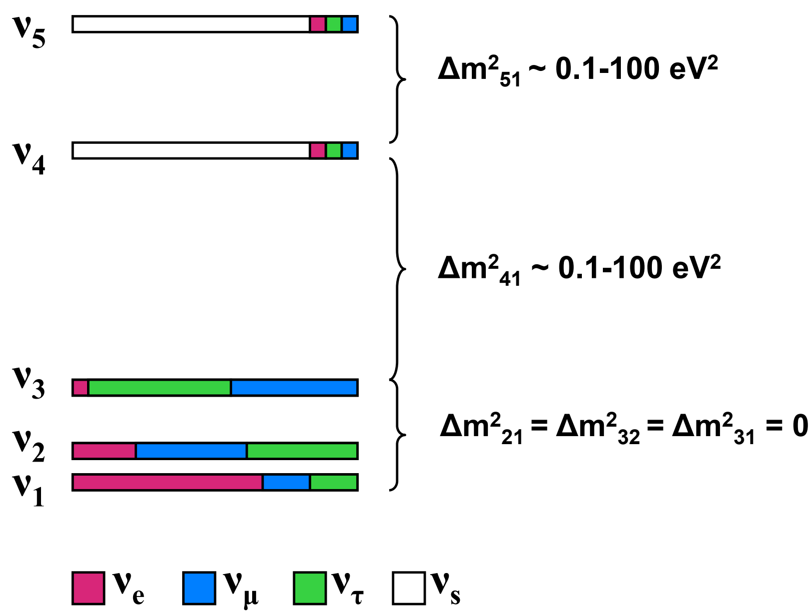
G. Karagiorgi et al., arXiv:0906.1997

Best 3+1 Fit:
$\Delta m_{41}{}^2 = 0.19\ eV^2$
$\sin^2 2\theta_{\mu e} = 0.031$
$\chi^2 = 90.5/90$ DOF
Prob. = 46%

Predicts ν_μ & ν_e disappearance of $\sin^2 2\theta_{\mu\mu} \sim 3.1\%$ and $\sin^2 2\theta_{ee} \sim 3.4\%$

LSND interpretation: More complicated Oscillations (e.g. 3+2)

- 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

Oscillation probability:

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

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

Are LSND and MiniBooNE Consistent with Oscillations?

My own attempts to reconcile Data:

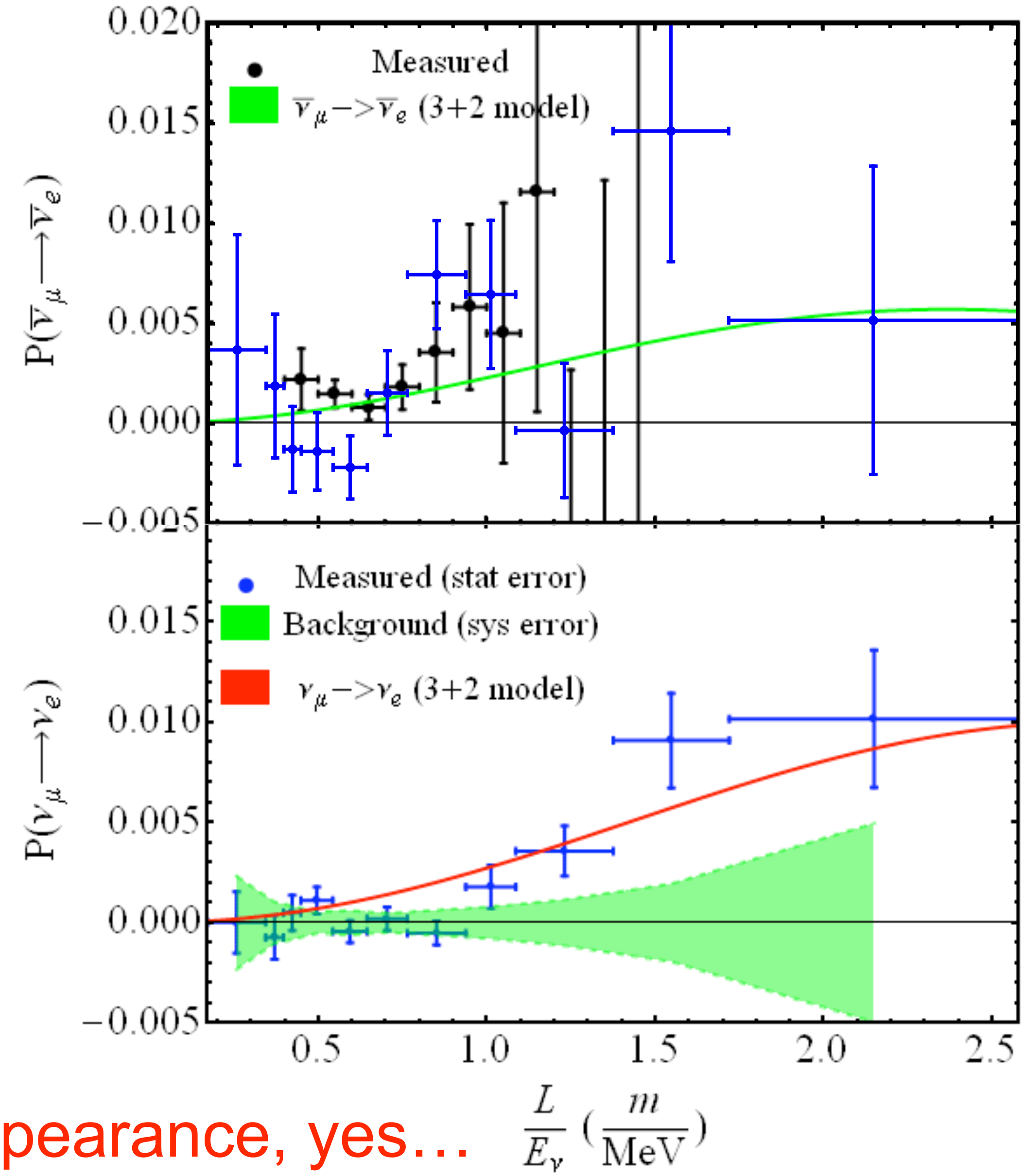
"low-low" solution

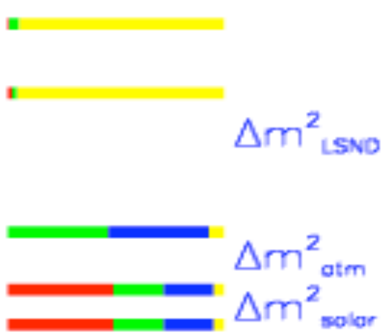
3+2 model (suggestive)

∞m^2_{aa} 0.5 eV,0.04

∞m^2_{bb} 0.25 eV,0.025

$A_{CP} = \text{rad}\frac{M}{2}$



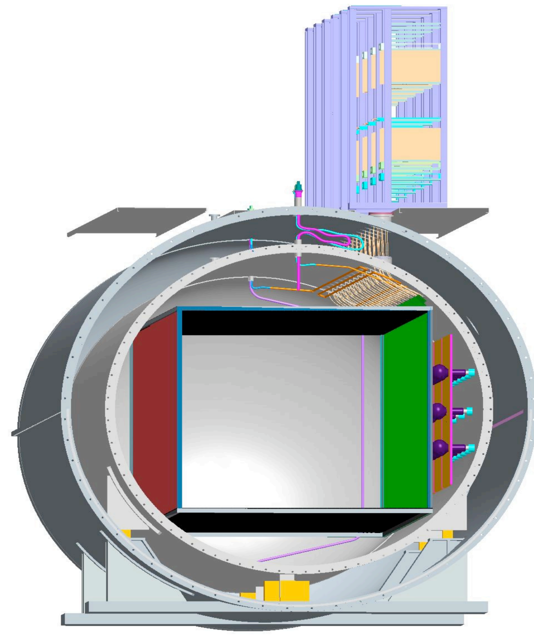


In appearance, yes…

Resolving the MiniBooNE Low Energy Excess

- Moving the MiniBooNE detector to 200m (~ 40 tons without oil)
  - Letter of Intent: arXiv:0910.2698
  - Accumulate a sufficient data sample in < 1 year
  - will dramatically reduce systematic errors (low energy excess is ~ 6 sigma significance with statistical errors only.
  - Can study L dependence of excess: backgrounds scale as 1/L**2, oscillation signal as $\sin^2(L/E)$, and decay as L/E.
- MicroBooNE:
  - is a 70 ton liquid argon time projection chamber in the Fermilab BNB
  - can differentiate single gamma-rays from electrons
  - Likely to be too small for anti-neutrino running….
- CERN: ICARUS @PS
  - Discussed in arXiv:0909.0355v3
  - 600T Far detector exists @ Grand Sasso, ~ 100 T near detector needed
  - Use old PS neutrino beam line and CDHS Hall

MicroBooNE



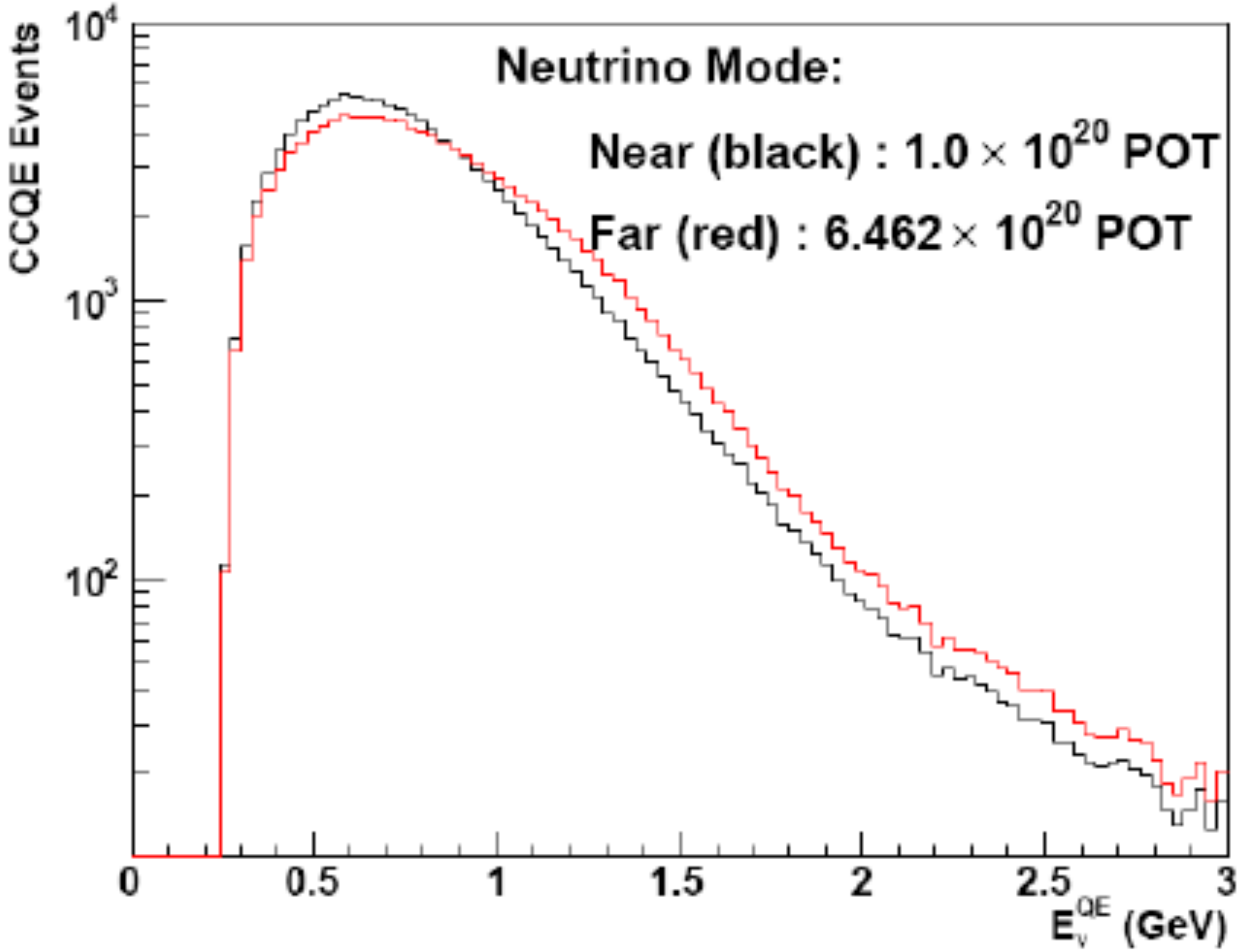
- 70 tons Liquid Argon TPC
- Good photon-electron separation
- Replaces MiniBooNE (850 ton)
- Similar sensitivity to MiniBooNE
- Would require ~ >6 years of running

Options for Near BooNE Detector

- Transport existing MiniBooNE detector (~80 tons) to new location 150-200 meters from BNB target (~4M$)
- Dismantle existing MiniBooNE detector and construct a new detector at 150-200 meters. (~4M$)
- Construct brand new detector at 150-200 meters (~8M $)

New Location at 200 meters from BNB Target

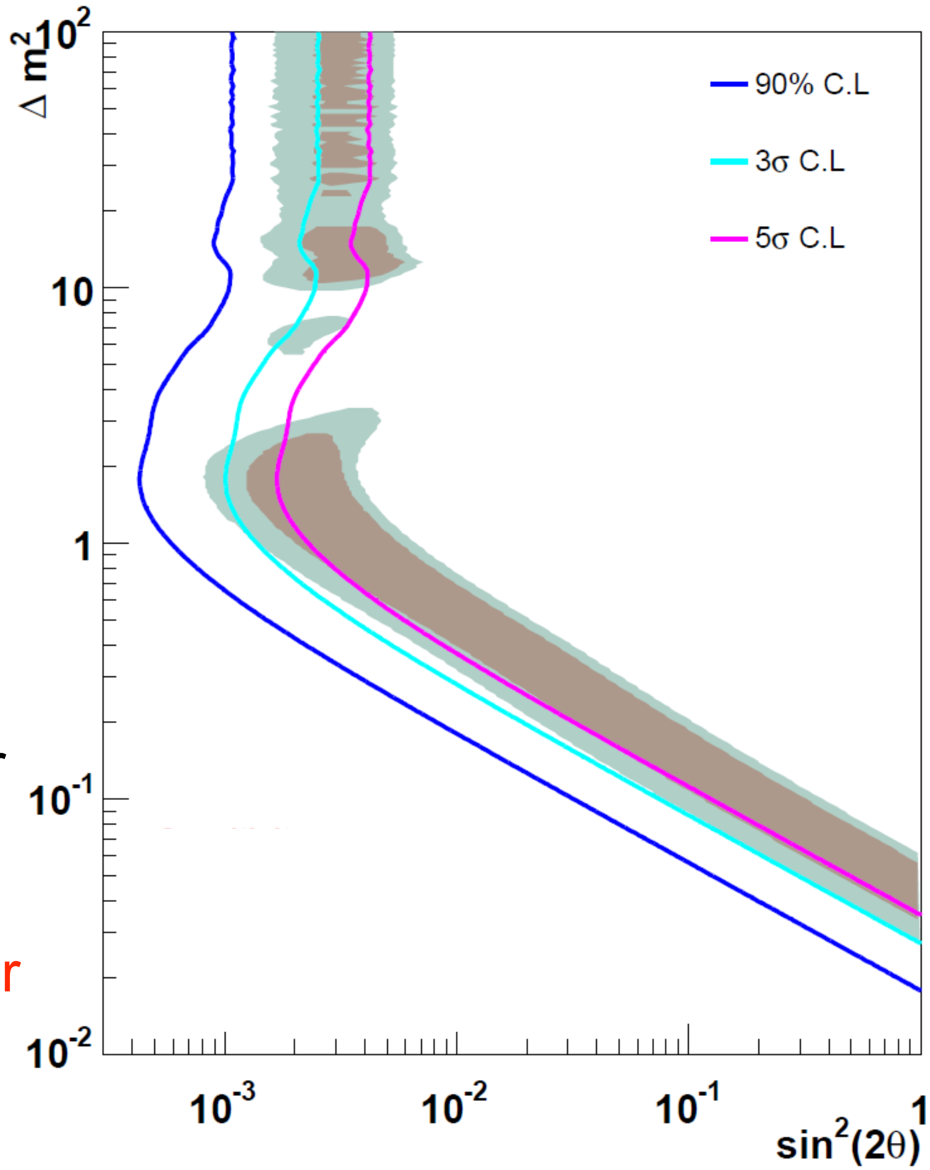
ν_μ Charged Current Event Rates Near and Far



Quasi elastic event rates

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
  - ➢ 90%CL becomes ~ 4 σ contour



Antineutrino Disappearance Seinsitivity with Detector at 200 Meters