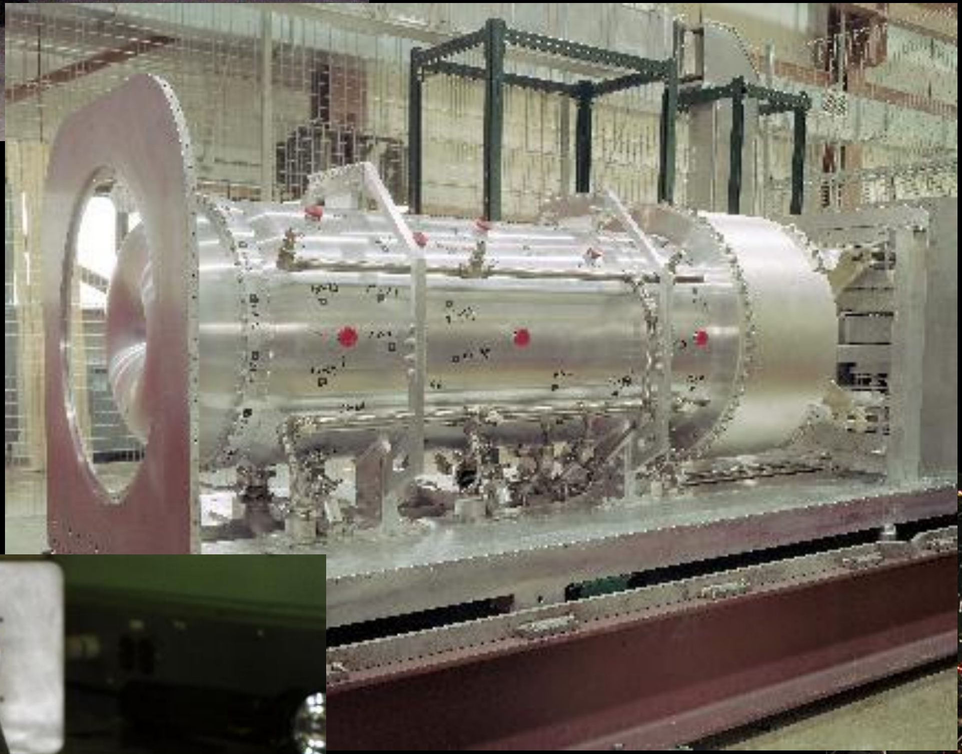
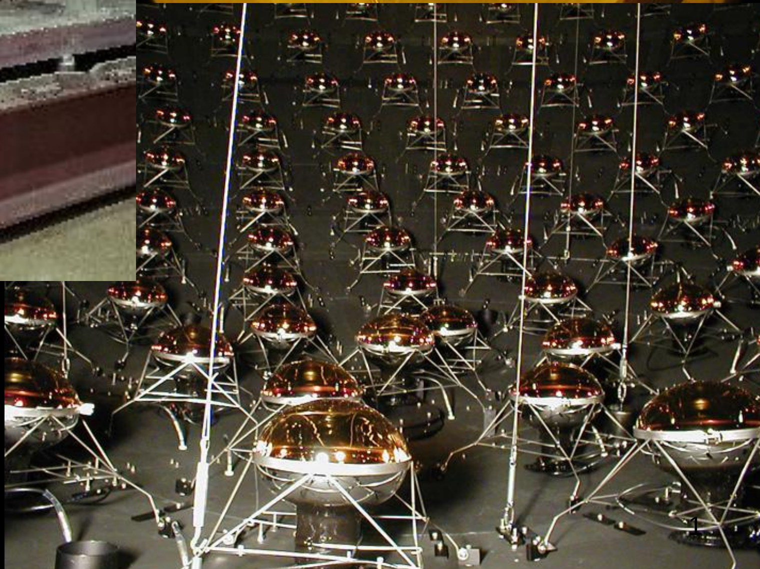
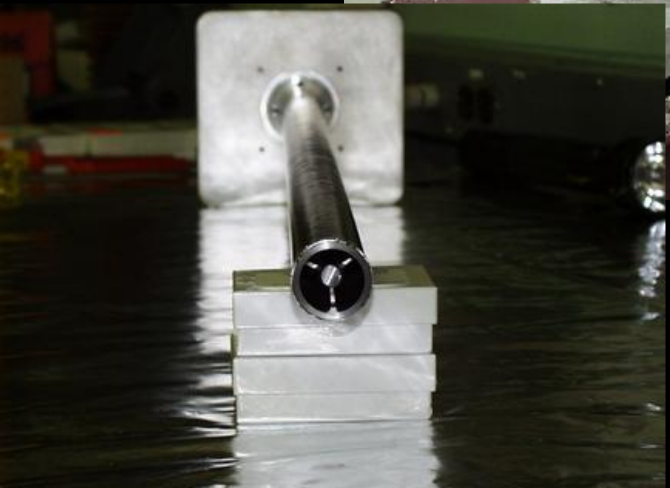
Results and Implications from MiniBooNE: Neutrino Oscillations and Cross Sections

15th Lomonosov Conference, 19 Aug 2011

Warren Huelsnitz, LANL   whuelsn@fnal.gov



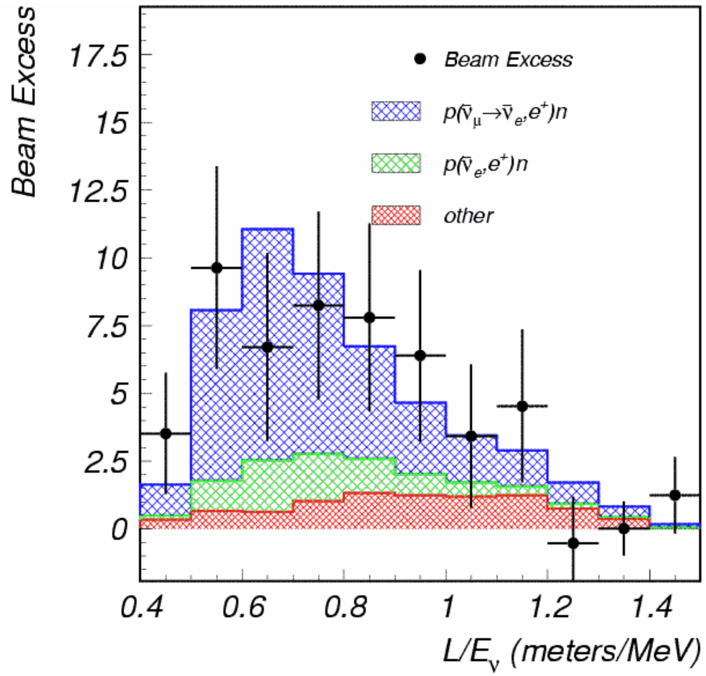


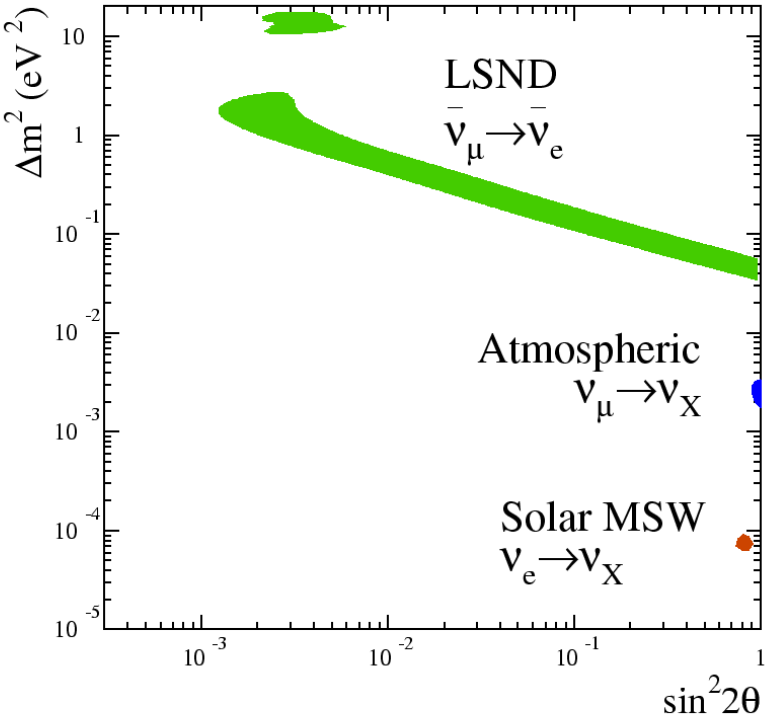


Outline

- Electron Neutrino and Antineutrino Appearance
  - Review of previous results
  - Updated antineutrino appearance results
- Muon Neutrino and Antineutrino Disappearance
  - Review of previous results
  - New MiniBooNE/SciBooNE joint analysis
- Cross Section Measurements from MiniBooNE

Motivation for MiniBooNE: The LSND Evidence for Oscillations



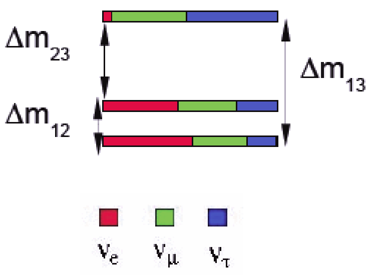


LSND Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

In SM there are only 3 neutrinos



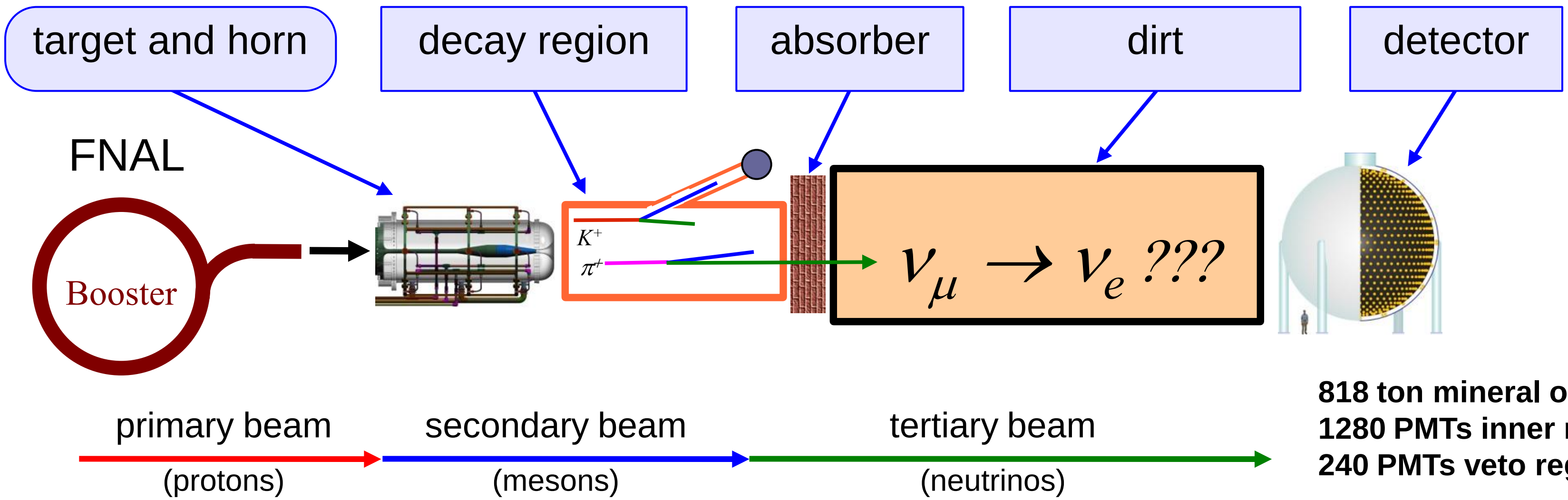
The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics!

MiniBooNE was designed to test the LSND signal

Keep L/E same as LSND
while changing systematics, energy & event signature

$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$ ➔ Two neutrino fits

LSND:	E ~ 30 MeV	L ~ 30 m	L/E ~ 1
MiniBooNE:	E ~ 500 MeV	L ~ 500 m	L/E ~ 1

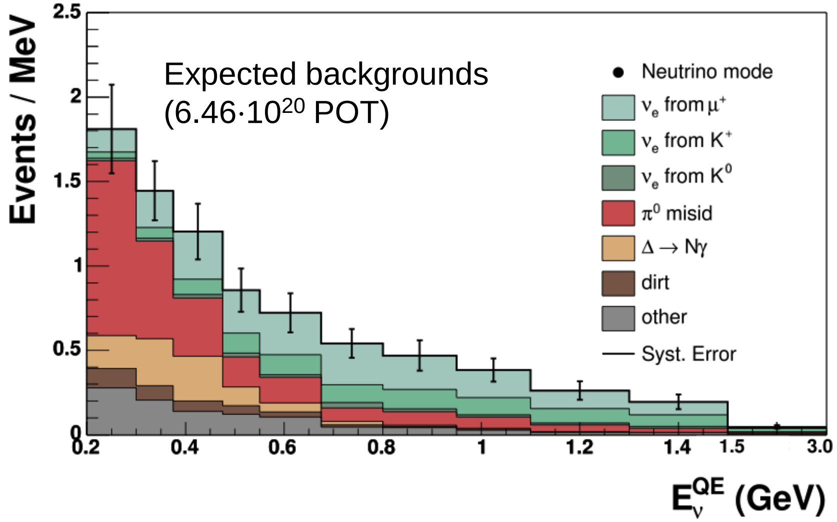


818 ton mineral oil
1280 PMTs inner region
240 PMTs veto region

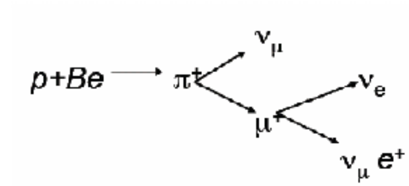
Neutrino mode: search for $\nu_\mu \rightarrow \nu_e$ appearance with 6.5E20 POT ➔ assumes CP/CPT conservation
Antineutrino mode: search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance with 8.58E20 POT ➔ direct test of LSND

FNAL has done a great job delivering beam!

In situ background constraints:



475 MeV – 1250 MeV	
ν_e^K	94
ν_e^μ	132
π^o	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
total	358



- Reconstruct majority of π^0 events; extrapolate into kinematic region where 1 photon is missed due to kinematics or escaping the tank
- Intrinsic ν_e from μ^+ originate from same π^+ as the ν_μ CCQE sample; measuring ν_μ CCQE channel constrains intrinsic ν_e from π^+
- At high energy, ν_μ flux is dominated by kaon production at the target; measuring ν_μ CCQE at high energy constrains kaon production, and thus intrinsic ν_e from K^+

- About 80% of NC π_0 events come from resonant Δ production; constrain $\Delta \rightarrow N\gamma$ by measuring the resonant NC π_0 rate, apply known branching fraction to N, including nuclear corrections
- Dirt events come from neutrinos interacting in surrounding dirt and structure; fit dirt-enhanced sample to extract dirt event rate with 10% uncertainty

Every major source of background can be internally constrained by MiniBooNE

Neutrino Mode MiniBooNE Results (2009)

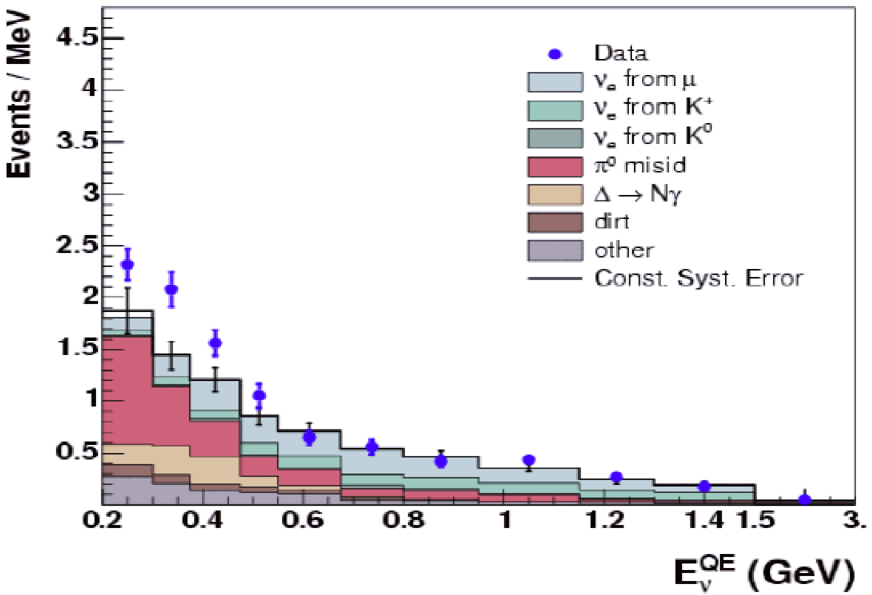
- 6.5E20 POT collected in neutrino mode
- E > 475 MeV data in good agreement with background prediction

  -Energy region has reduced backgrounds and maintains high sensitivity to LSND oscillations.

  -A two neutrino fit rules out LSND at the 90% CL assuming CP conservation.

- E < 475 MeV, statistically large (6σ) excess

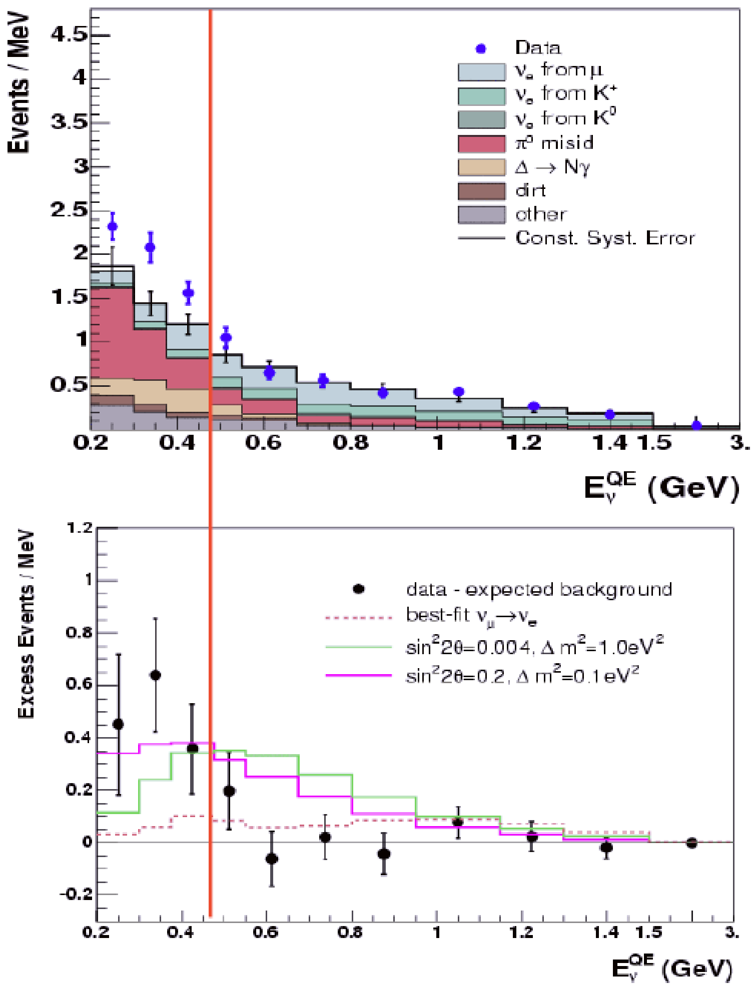
  -Reduced to 3σ after systematics, shape inconsistent with two neutrino oscillation interpretation of LSND. Excess of 129 +/- 43 (stat+sys) events is consistent with magnitude of LSND oscillations.

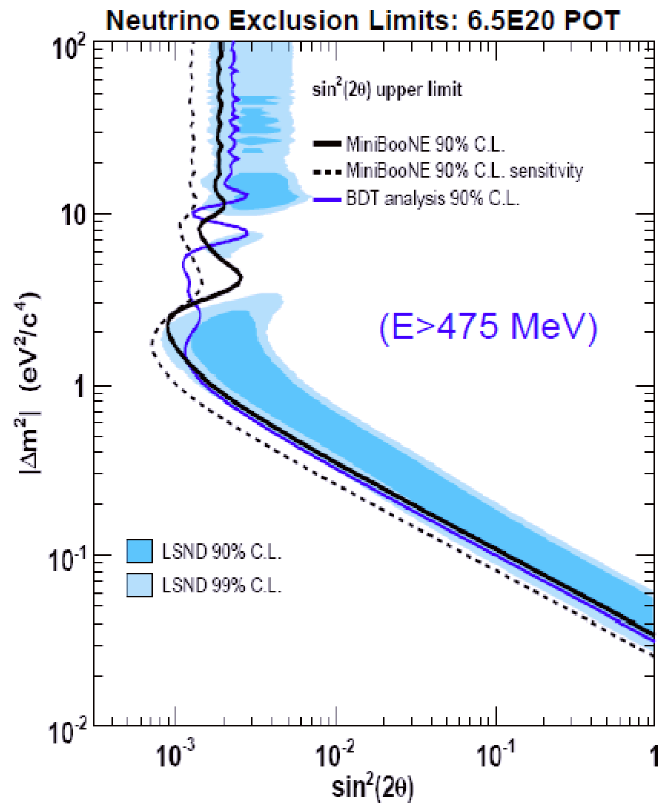


E_ν [MeV]	200-300	300-475	475-1250
total background	186.8±26	228.3±24.5	385.9±35.7
ν_e intrinsic	18.8	61.7	248.9
ν_μ induced	168	166.6	137
NC π^0	103.5	77.8	71.2
NC $\Delta \rightarrow N\gamma$	19.5	47.5	19.4
Dirt	11.5	12.3	11.5
other	33.5	29	34.9
Data	232	312	408
Data-MC	45.2±26	83.7±24.5	22.1±35.7
Significance	1.7σ	3.4σ	0.6σ

Published PRL 102,101802 (2009)

Neutrino Mode MiniBooNE Results (2009): Limit



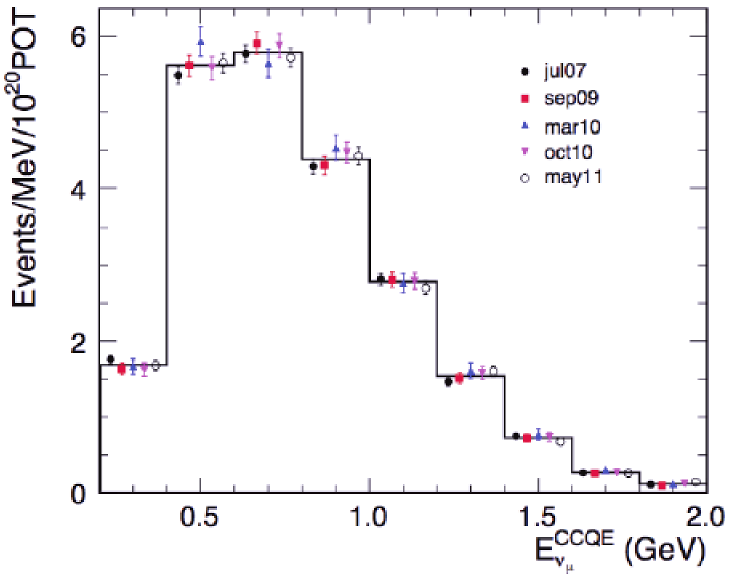


- 3+2 with CP violation
  [Maltoni and Schwetz, hep-ph0705.0107 ; G. K., NuFACT 07 conference]
- Anomaly mediated photon production
  [Harvey, Hill, and Hill, hep-ph0708.1281]
- New light gauge boson
  [Nelson, Walsh, Phys. Rev. D 77, 033001 (2008)]
- Neutrino decay
  [hep-ph/0602083]
- Extra dimensions
  [hep-ph/0504096]
- CPT/Lorentz violation
  [PRD(2006)105009]
- …

New Anti-neutrino mode results: 8.58E20 POT (50% more data)

Data Checks

- $\bar{\nu}_\mu$ rates and energy stable over entire antineutrino run.

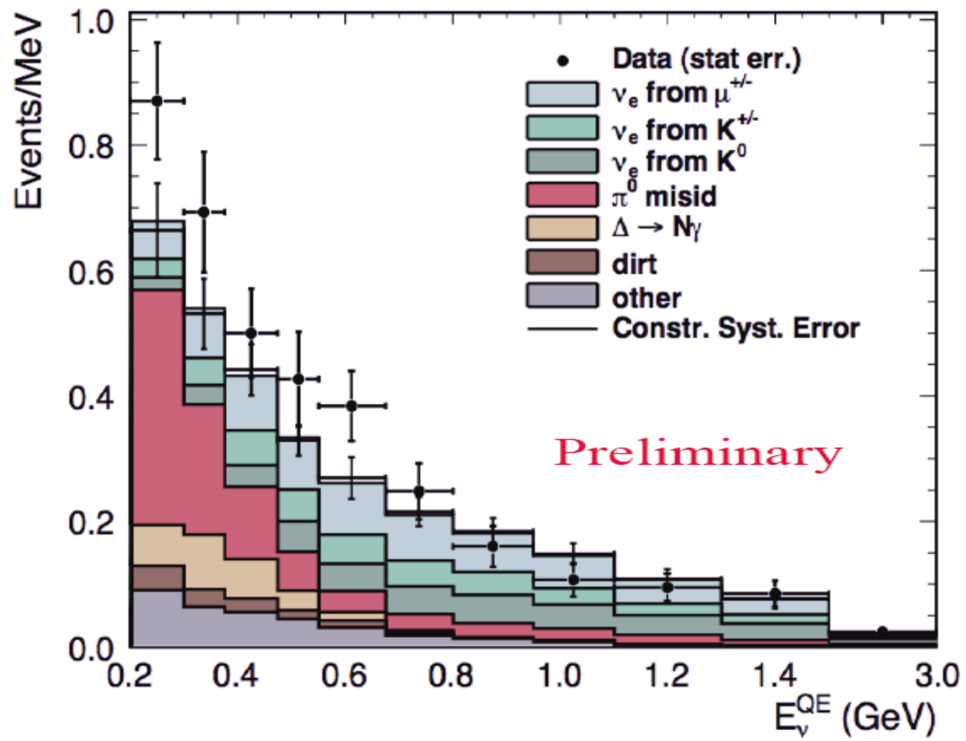


- New SciBooNE constraint on K^+ component of the Booster beam: Reduces this component of background by 3% and reduces uncertainty. (e-print 1105.2871 [hep-ex]). (accepted by Phys. Rev. D)
- Other systematic errors, constrained by MiniBooNE data, reduced due to higher statistics in control samples:
  - π-decay neutrino normalization factors
  - Dirt neutrino background
  - Neutral-current π^0 production.

New Anti-neutrino mode results: 8.58E20 POT

475MeV<E_ν<1250MeV:

- Expected events: 151.7±15.0 (syst) after fit constraints
- Observed events: 168.
- Observed Excess: 16.3±19.4 (total) →0.84σ
- Excess in oscillation search region is reduced somewhat with new data.
- Low-energy excess is more significant and resembles neutrino-mode data.



Oscillation Fit

- Results for 8.58E20 POT
- Maximum likelihood fit.
- For the original osc energy region above 475 MeV, oscillations favored over background only (null) hypothesis at the 91.1% CL.
- Best Fit Point

  $(\Delta m^2, \sin^2 2\theta) = (4.6\ eV^2, 0.0045)$

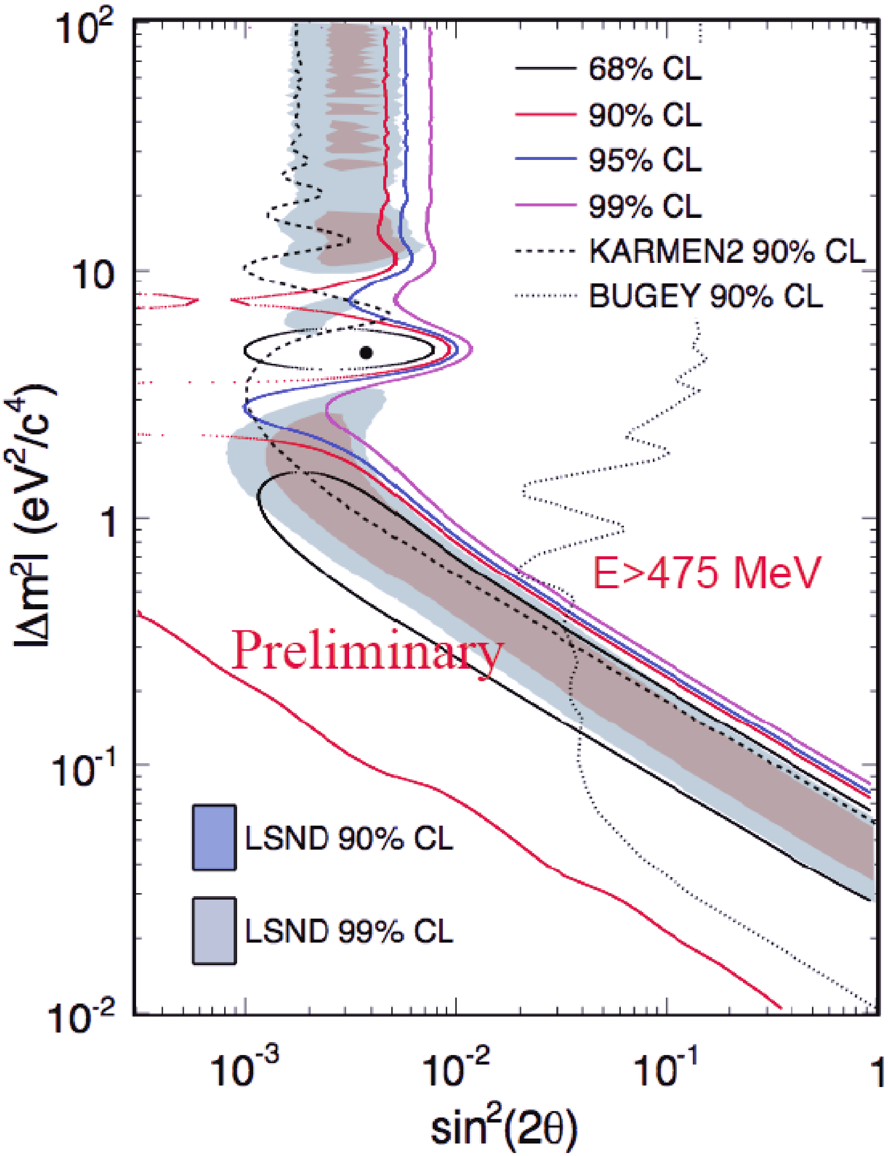
  $\chi^2_{BF}/NDF = 4.3/3.9$ with $P(\chi^2) = 35.5\%$

  $\chi^2_{NULL}/NDF = 9.3/5.9$ with $P(\chi^2) = 14.9\%$
- Consistent with LSND, though evidence for LSND-type oscillations less strong than previous published 5.66E20 result
- Previous result (5.66E20 POT) :

  Oscillation favored over null at 99.4%CL

  $\chi 2_{BF}$ /NDF = 8.0/6 with $P(\chi^2) = 8.7\%$

  $\chi 2_{NULL}$/NDF = 18.5/4 with $P(\chi^2) = 0.5\%$.

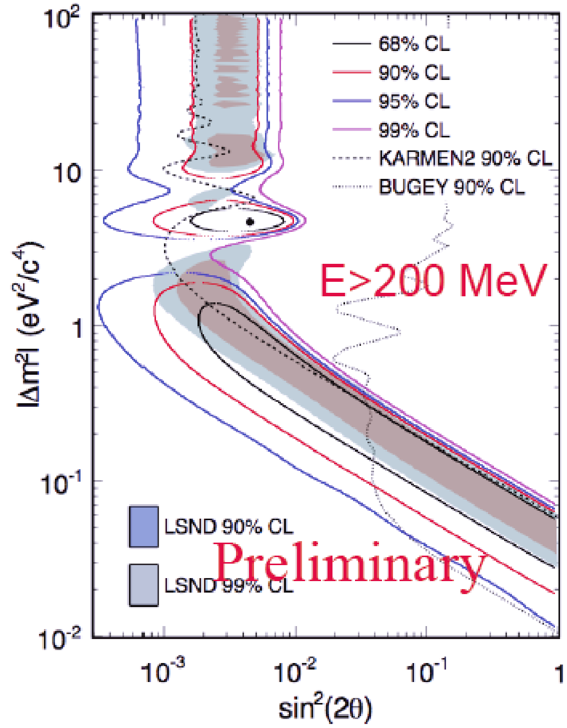


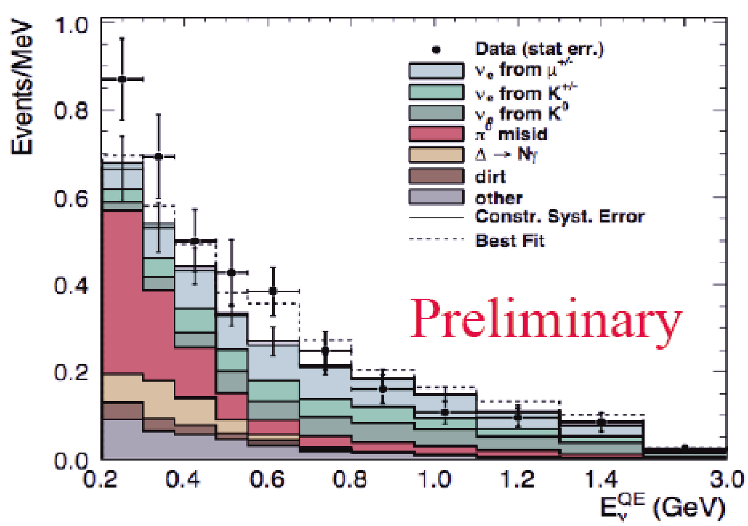
Oscillation Fit with E_ν > 200 MeV

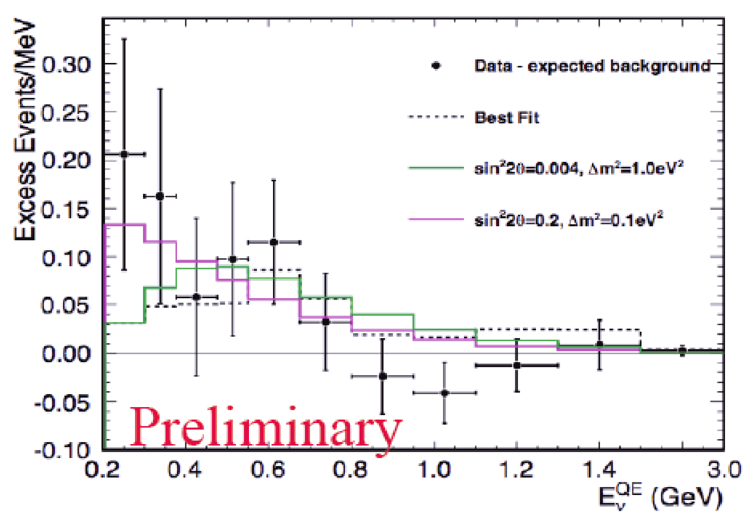
- Results for 8.58e20 POT.
- Use full energy range $200<E_\nu<2000$MeV in the fit.
- Does not include effects (subtraction) of neutrino low energy excess.
- For E< 475 MeV, excess = 38.6 ± 18.5 (For all energies, excess = 57.7 ± 28.5).
- Maximum likelihood fit method.
- Null excluded at 97.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point $(\Delta m^2, \sin^2 2\theta) = (4.6\ eV^2, 0.0038)$

$\chi^2_{BF}/NDF= 6.1/6.9$, $P(\chi^2)= 50.7\%$

$\chi^2_{NULL}/NDF= 14.5/8.9$, $P(\chi^2)= 10.1\%$





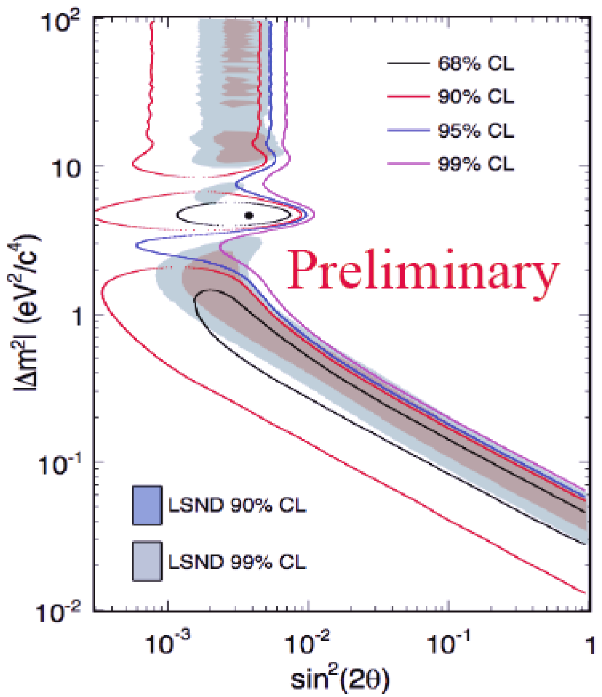


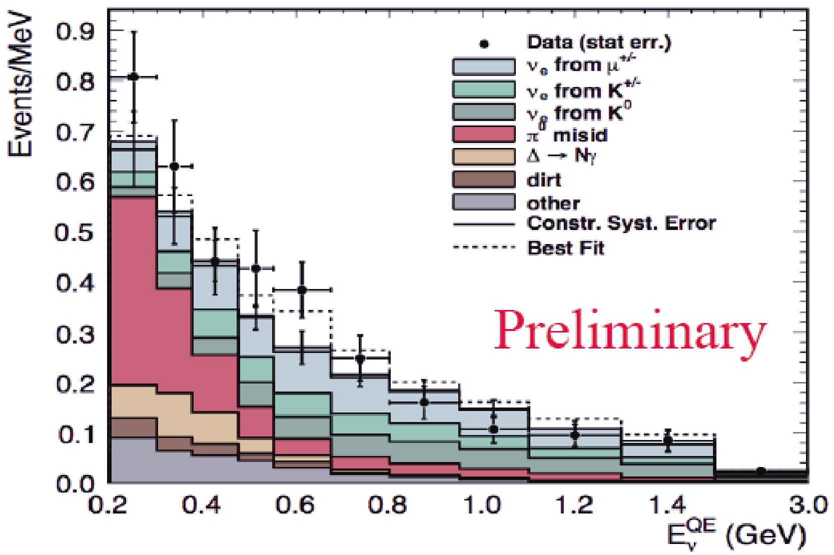
Antineutrino Mode Low Energy Excess: How does it scale

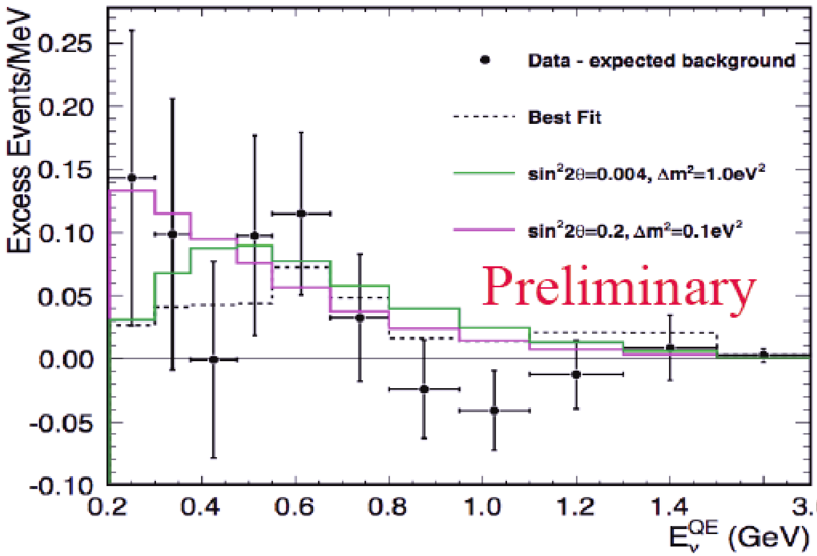
- Excess above background in 200<E<475 MeV is 38.6±18.5 events.
- Scaling from what is observed in neutrino mode we may test various hypotheses.
- Expected number of events in anti-neutrino mode assuming particular background as the source of low-E excess in neutrino mode:
  - -Total background: 50
  - - Neutrino contamination only: 17
  - - $\Delta \rightarrow N\gamma$ decays: 39
  - - Dirt: 46
  - - Protons on target (neutrals in secondary beam): 165
  - - K+ in secondary beam: 67
  - - NC π^0: 48
  - - Inclusive CC: 59

Oscillation Fit with E_ν > 200 MeV
(include low E_ν ν-mode effects)

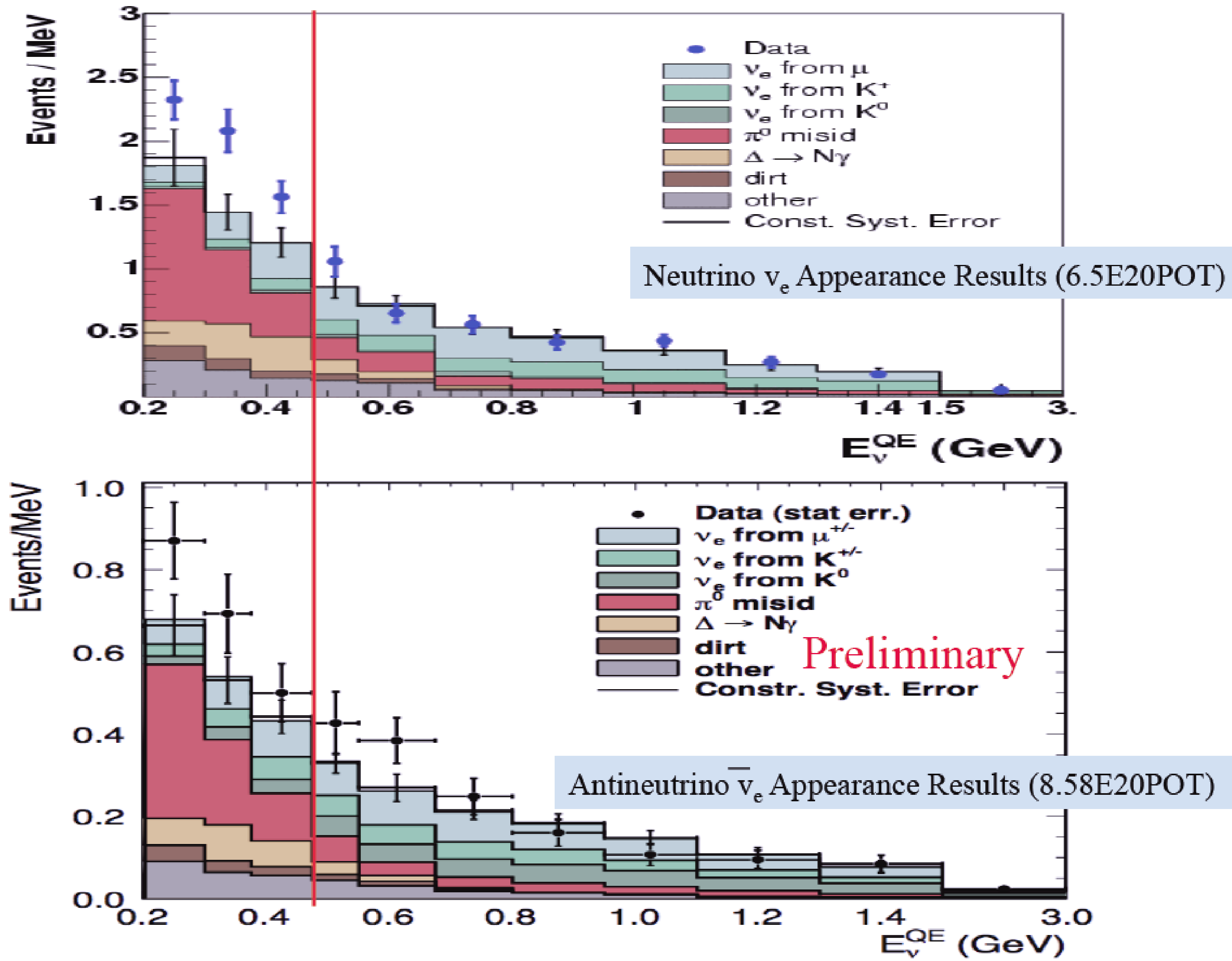
- Results for 8.58e20 POT.
- Assume simple scaling of neutrino low energy excess; subtract 17 events from low energy region (200-475 MeV).
- Maximum likelihood fit method.
- Best Fit Point (Δm^2, $\sin^2 2\theta$) = (4.6 eV^2, 0.0037)
  $P(\chi^2, BF)$= 76.5%
  $P(\chi^2, NULL)$= 28.3%



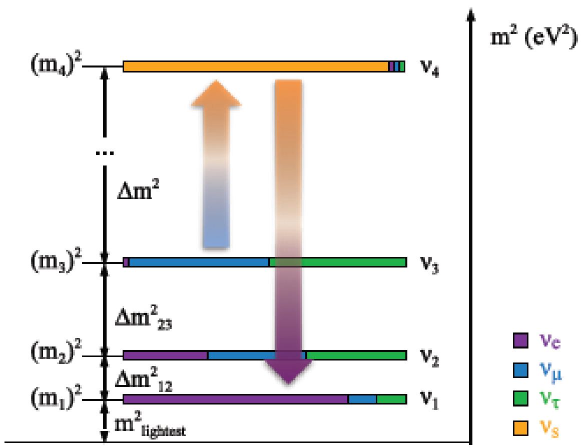




Comparison of ν_e and $\bar{\nu}_e$ Appearance Results



MiniBooNE Muon Neutrino & Antineutrino Disappearance Limits



3+N models require large $\bar{\nu}_\mu$ disappearance

- In general:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \to \bar{\nu}_x) P(\bar{\nu}_e \to \bar{\nu}_x)$$

- From reactor experiments:

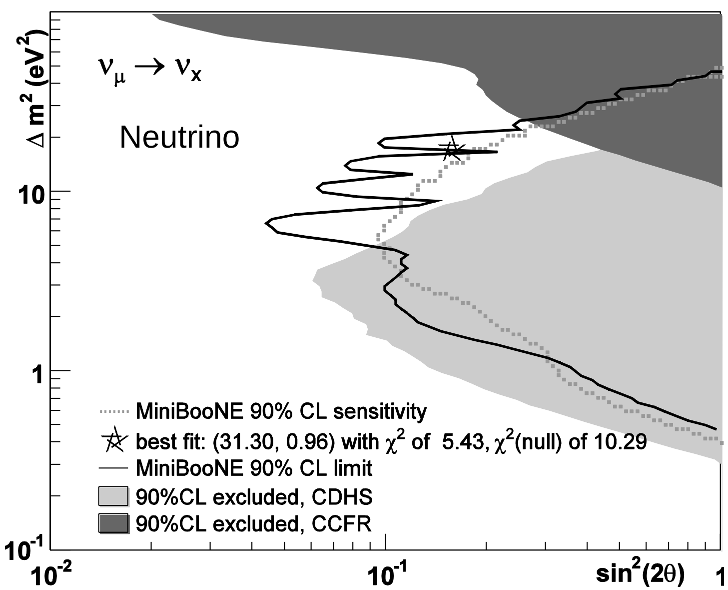
$$P(\bar{\nu}_e \to \bar{\nu}_x) < 8\%$$

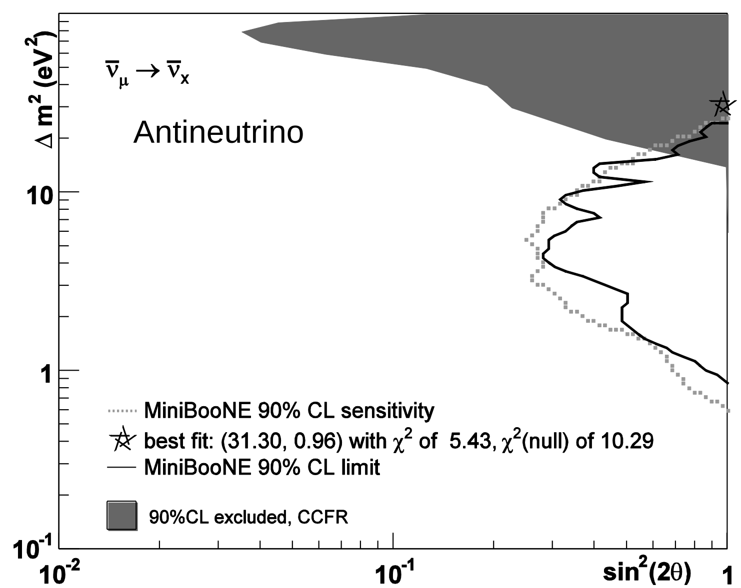
- From LSND/MiniBooNE:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \sim 0.25\%$$

- Therefore:

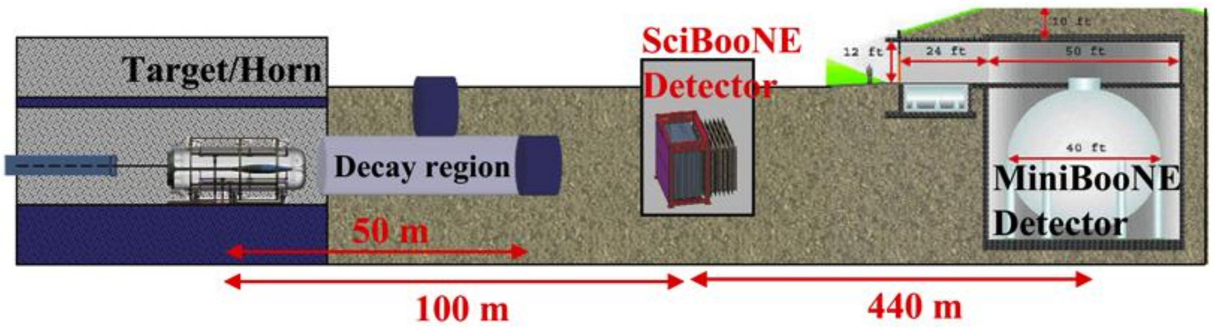
$$P(\bar{\nu}_\mu \to \bar{\nu}_x) > 10\%$$

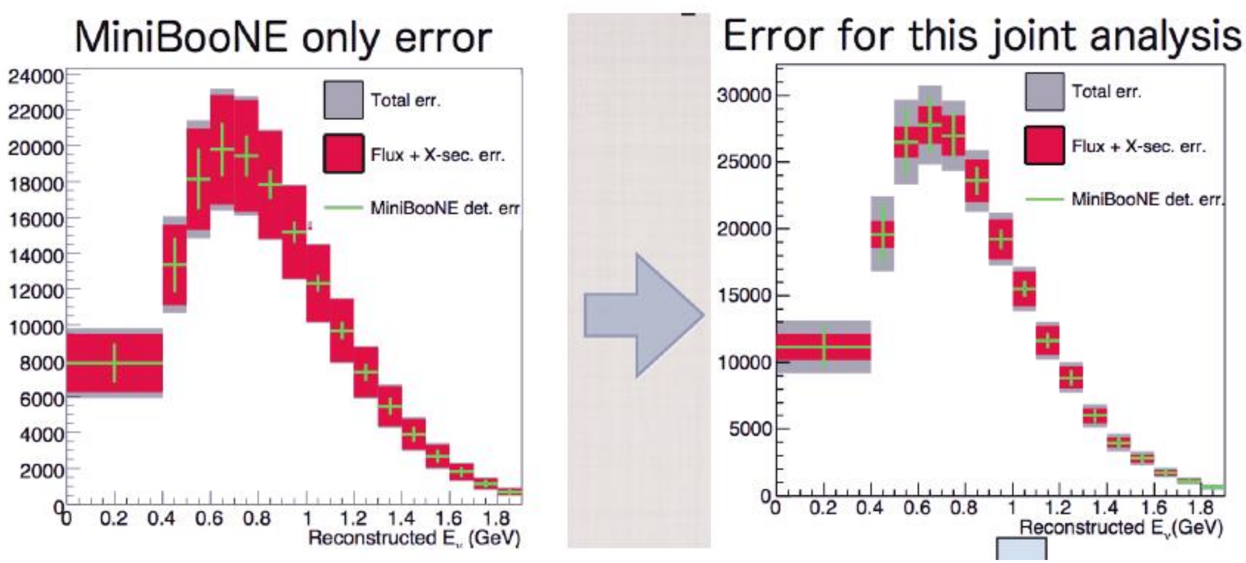




A.A. Aguilar-Arevalo et al., PRL 103, 061802 (2009)

MiniBooNE/SciBooNE Joint ν_μ Disappearance Search

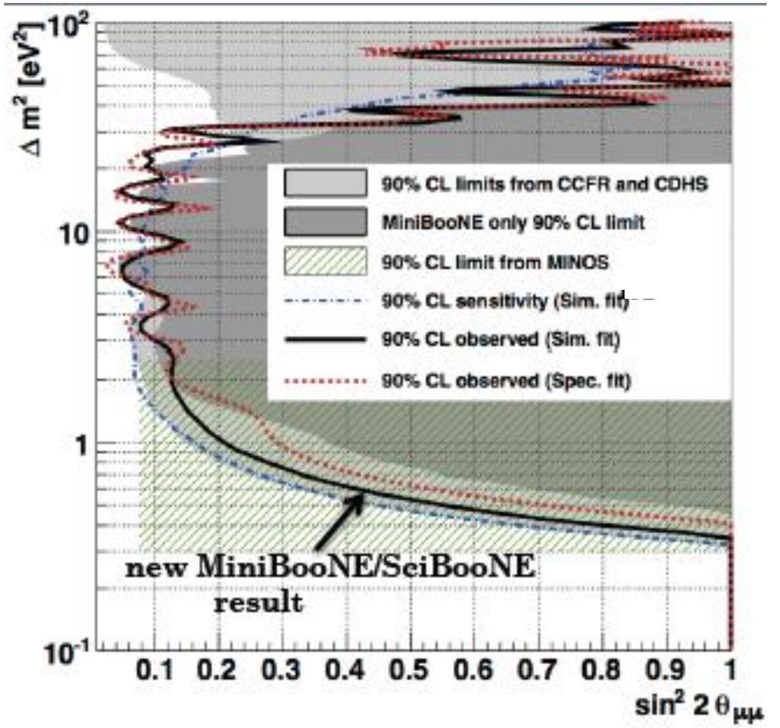




MiniBooNE/SciBooNE Joint ν_μ Disappearance Search

Use the CC rate measured at SciBooNE to constrain the MiniBooNE rate and test for disappearance

Two analysis methods:



Simultaneous fit

1) Fit SciBooNE and MiniBooNE data simultaneously for oscillation
2) Constraint applied within fit, effectively removes systematic uncertainties shared by both detectors

Spectrum fit

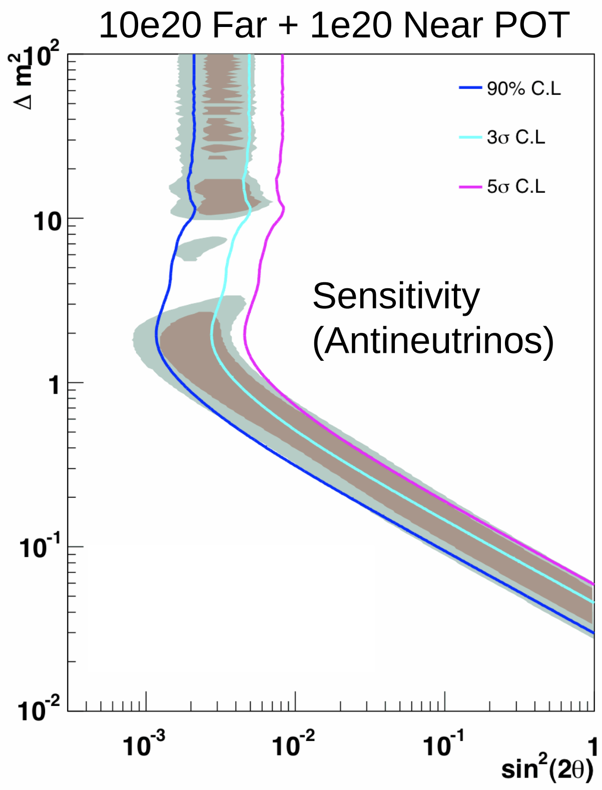
1) Extract neutrino energy spectrum from SciBooNE data Phys.Rev.D83:012005,2011
2) Apply correction to MiniBooNE energy spectrum
3) Fit for oscillation at MiniBooNE
4) Systematics reduced by extraction process

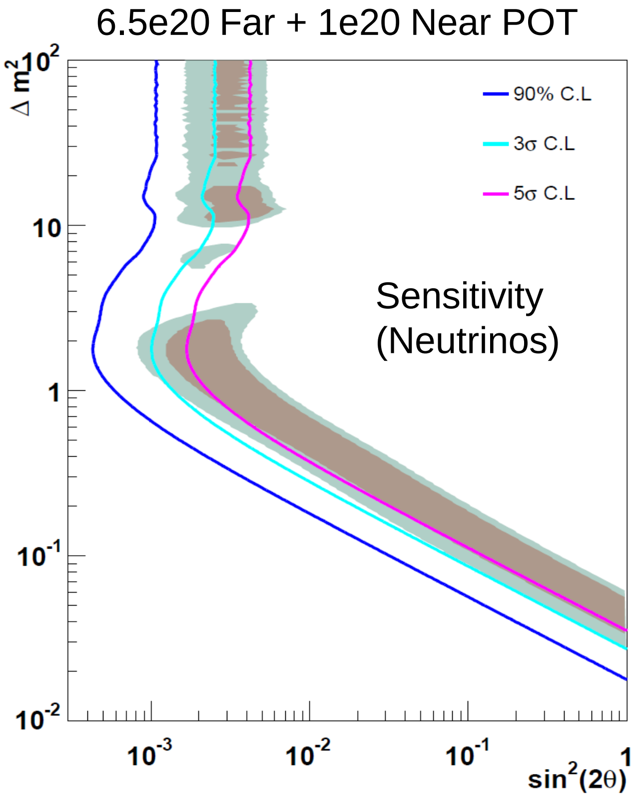
arXiv: 1106.5685 (submitted to PRL)

BooNE: Proposed Near Detector at ~200 m

(LOI arXiv:0910.2698)

- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Gain statistics quickly, already have far detector data
- Measure $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations and CP violation

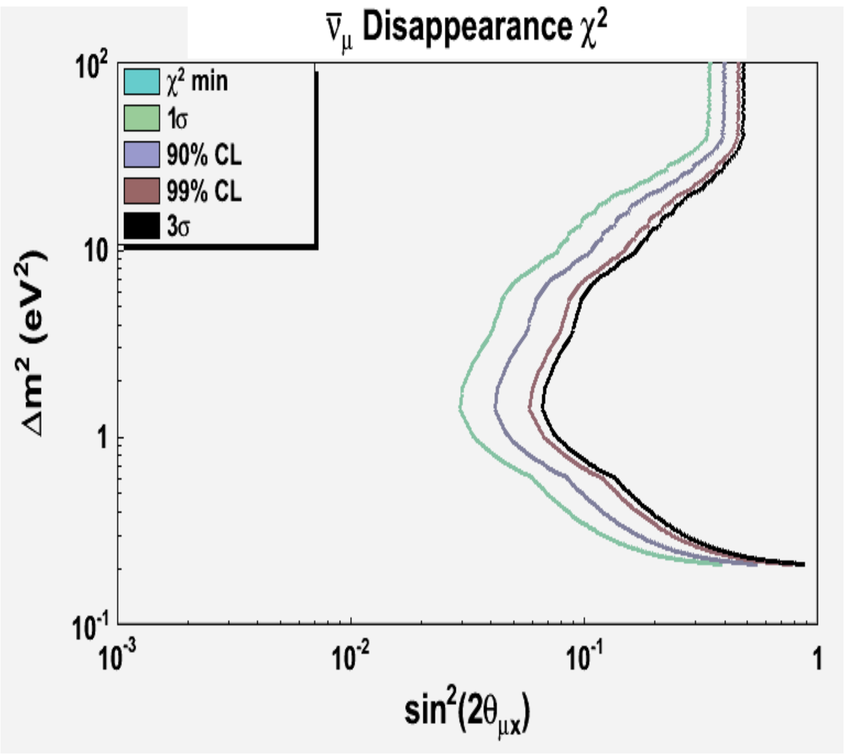




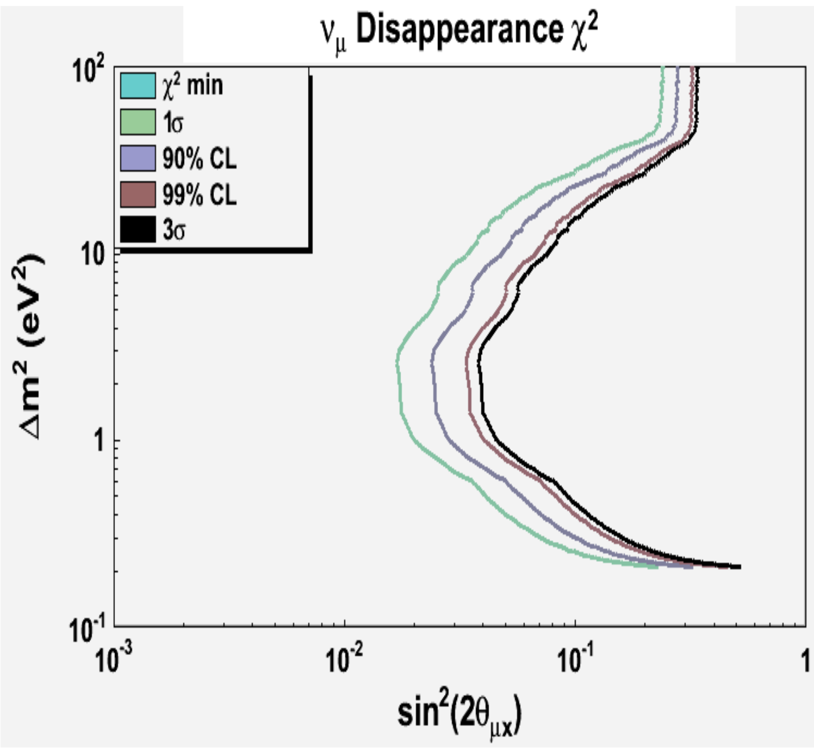
BooNE: Proposed Near Detector at ~200 m

- Much better sensitivity for ν_μ & $\bar{\nu}_\mu$ disappearance
- Look for CPT violation

10e20 Far/1e20 Near POT

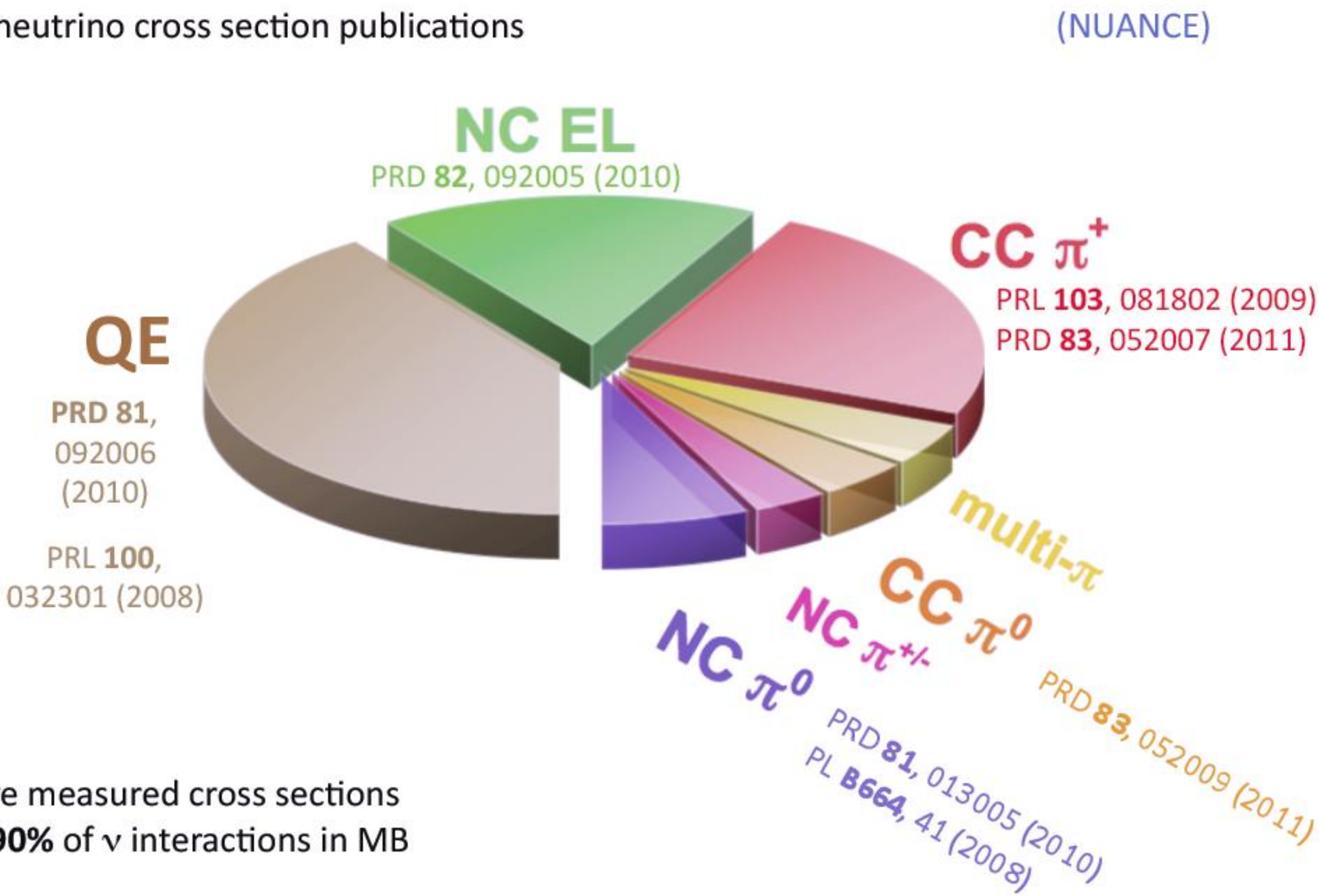


6.5e20 Far/1e20 Near POT



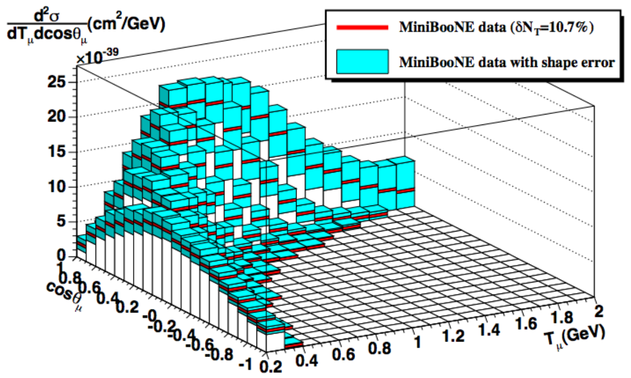
Neutrino Cross Sections

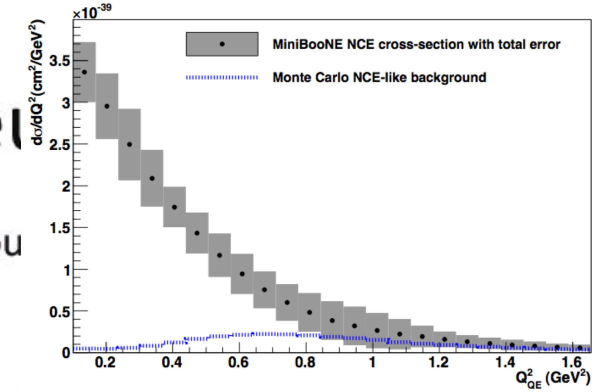
- 8 neutrino cross section publications

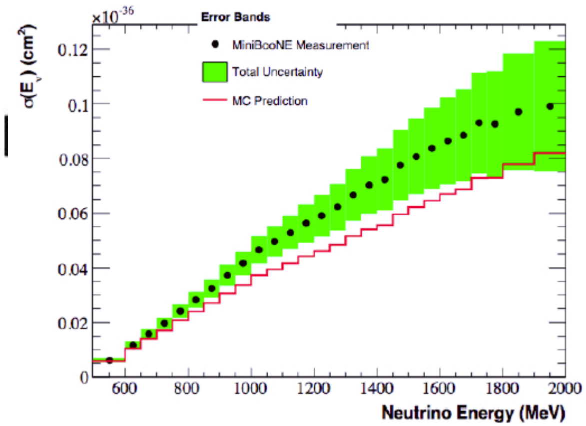


- have measured cross sections for **90%** of ν interactions in MB

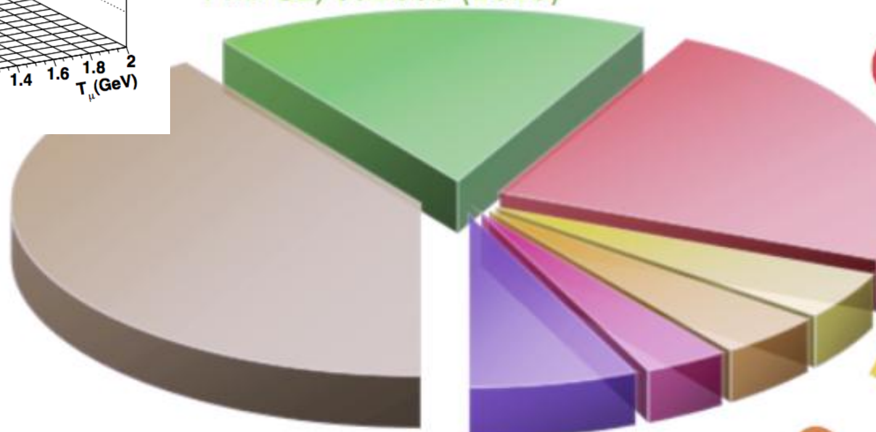
Neu… …io…

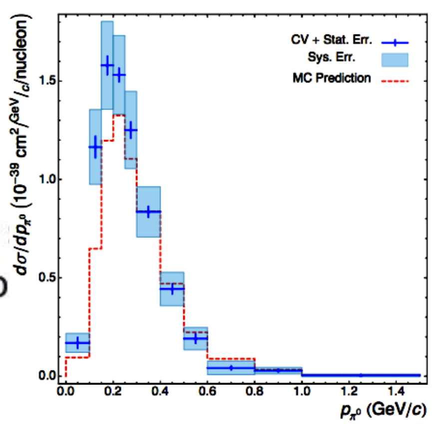


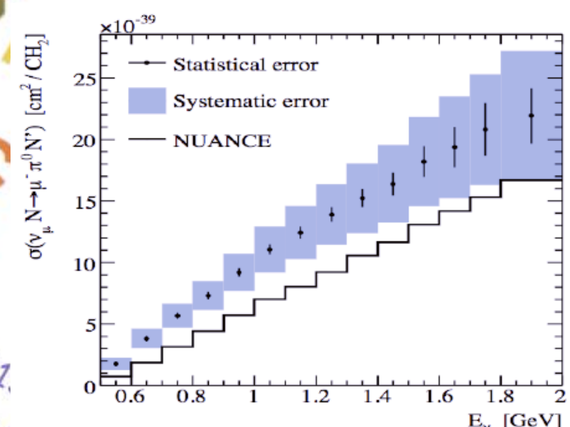




pu…



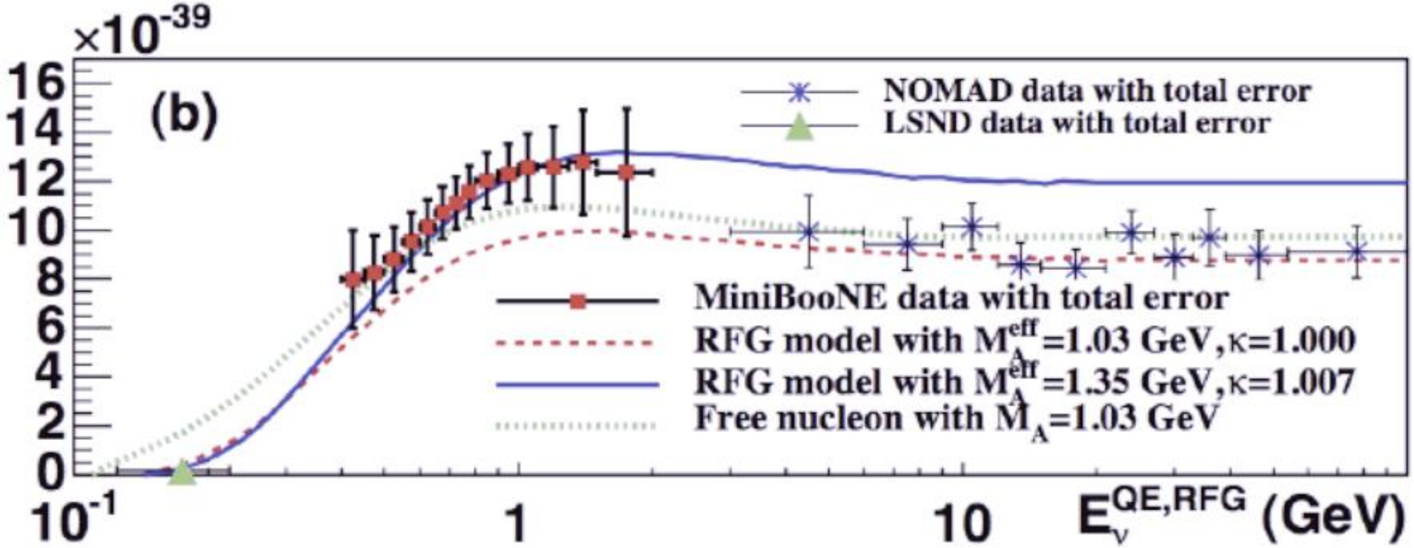




- have measured cross… for **90%** of ν interactio…

ν_μ CCQE Scattering

A.A. Aguilar-Arevalo, Phys. Rev. D81, 092005 (2010).



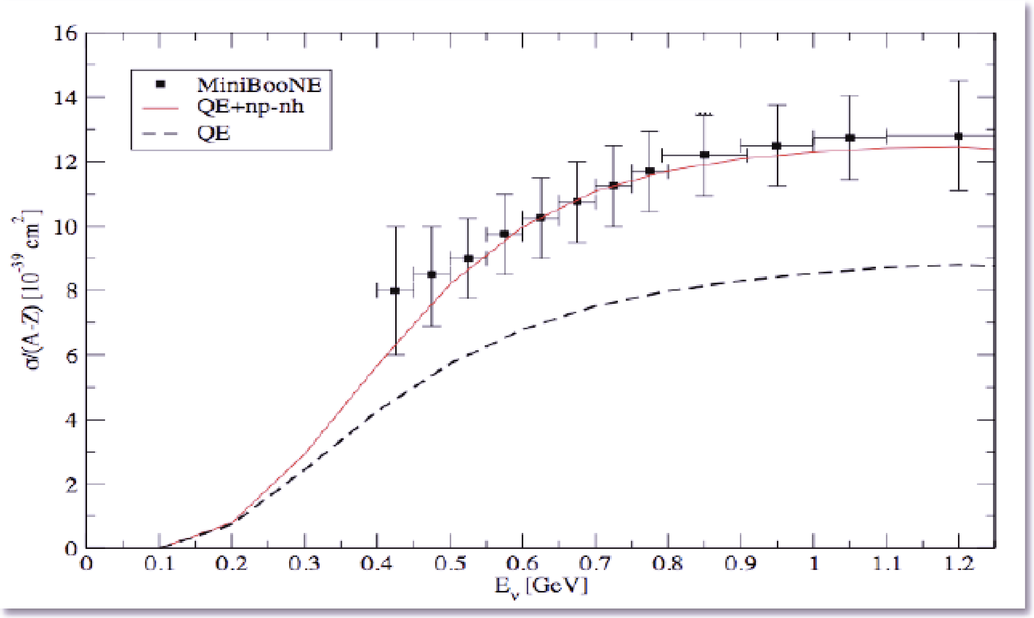
Extremely surprising result - CCQE $\sigma_{\nu\mu}(^{12}C)>6\ \sigma_{\nu\mu}(n)$

How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

A possible explanation involves short-range correlations & 2-body pion-exchange currents: Joe Carlson et al., Phys.Rev.**C65,** 024002 (2002); Martini et al., PRC80, 065001 (2009).

Nuclear Effects to the Rescue?

- *possible explanation*: extra contributions from multi-nucleon correlations in the nucleus (all prior calcs assume indep particles)



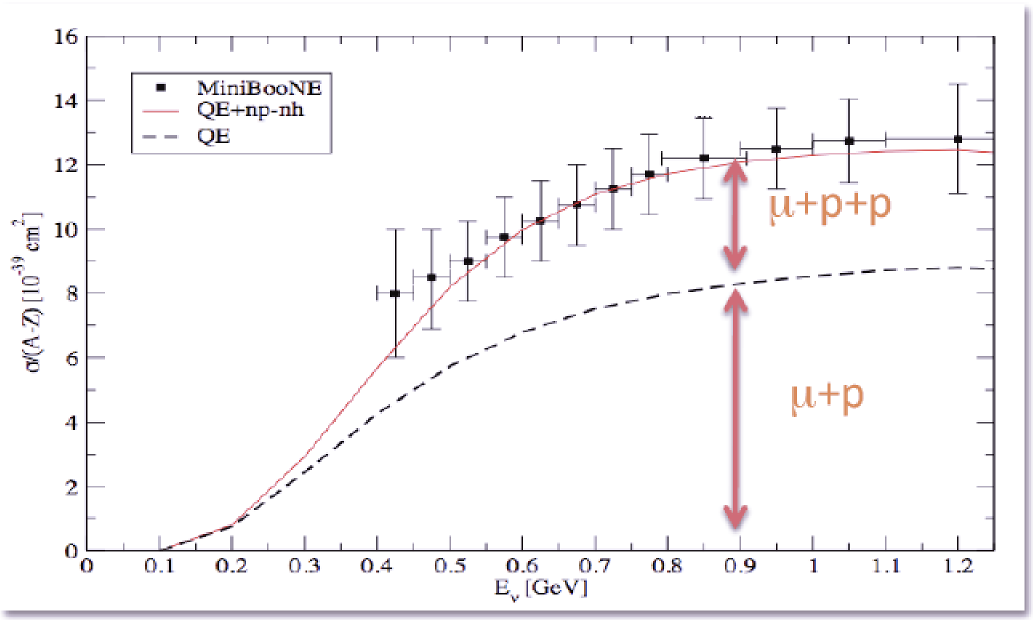
Martini *et al.*, PRC **80**, 065001 (2009)

- large enhancement from short range correlations (SRC) and 2-body currents
- can predict MiniBooNE data without having to increase M_A (here, M_A=1.0 GeV)

From Sam Zeller

Nuclear Effects to the Rescue?

- *possible explanation*: extra contributions from multi-nucleon correlations in the nucleus (all prior calcs assume indep particles)



Martini *et al.*, PRC **80**, 065001 (2009)

- could this explain the difference between MiniBooNE & NOMAD?

NOMAD: μ & μ + p

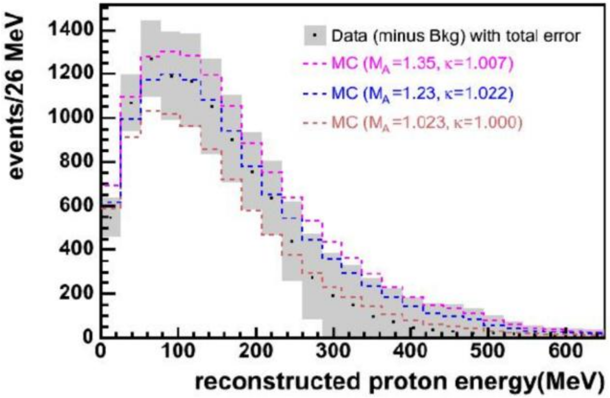
MiniBooNE: μ + no π's + any # p's

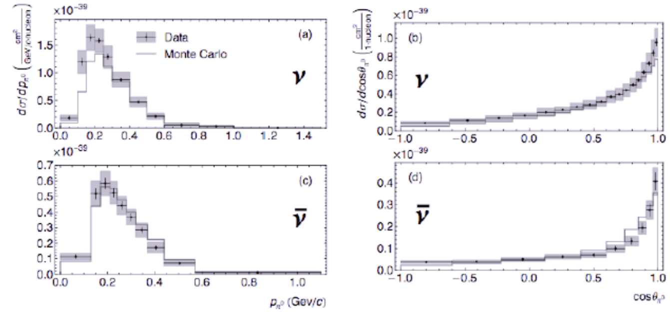
jury is still out on this

need to be clear what we mean by "QE"

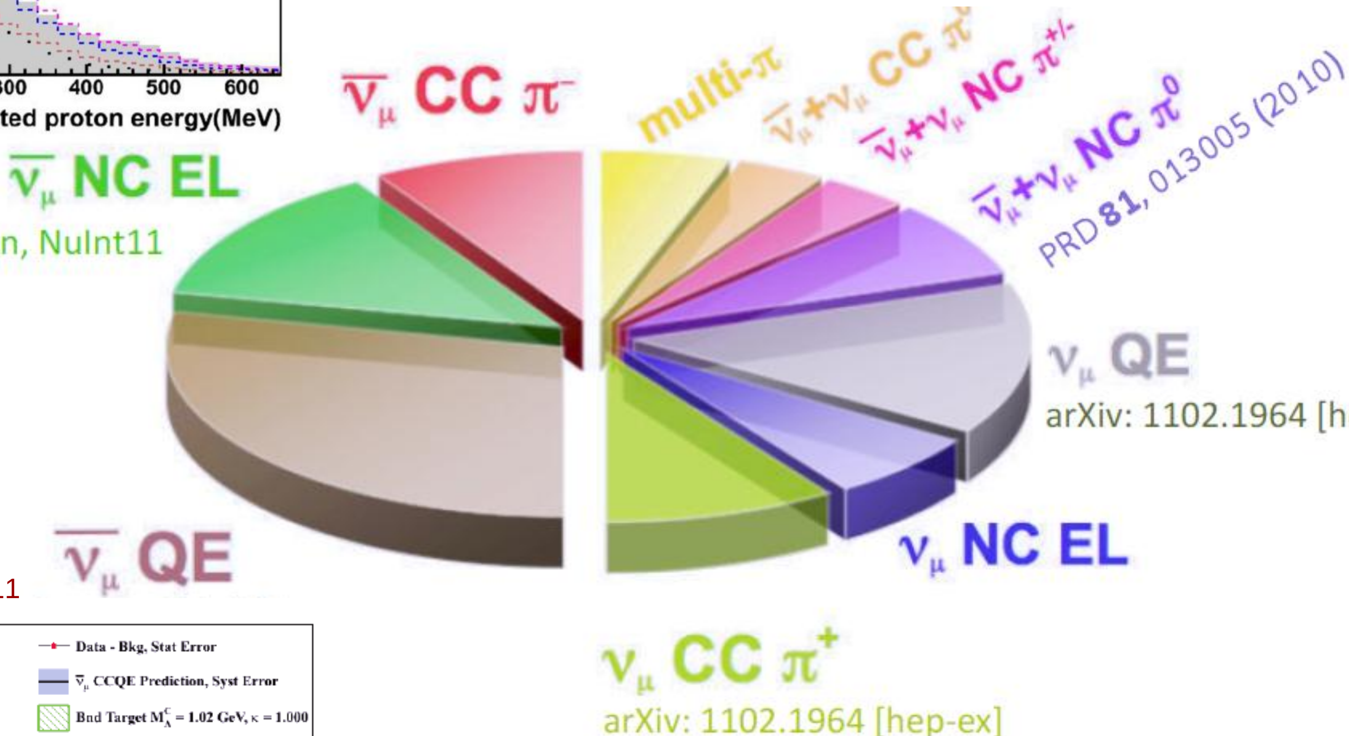
From Sam Zeller

Antineutrino Cross Sections



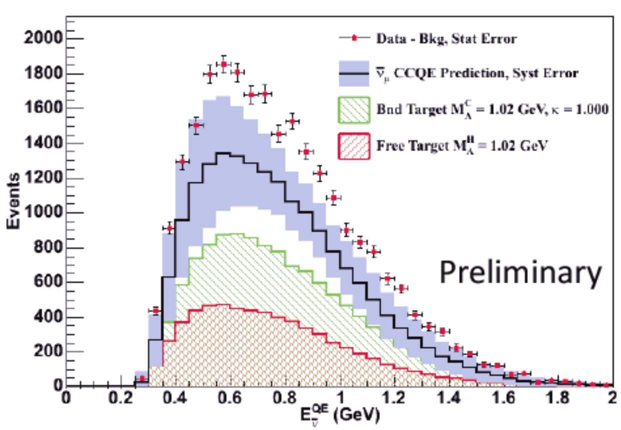


Ph.D. thesis, C. Anderson, Yale University
Phys. Rev. D. **81**, 013005 (2010)

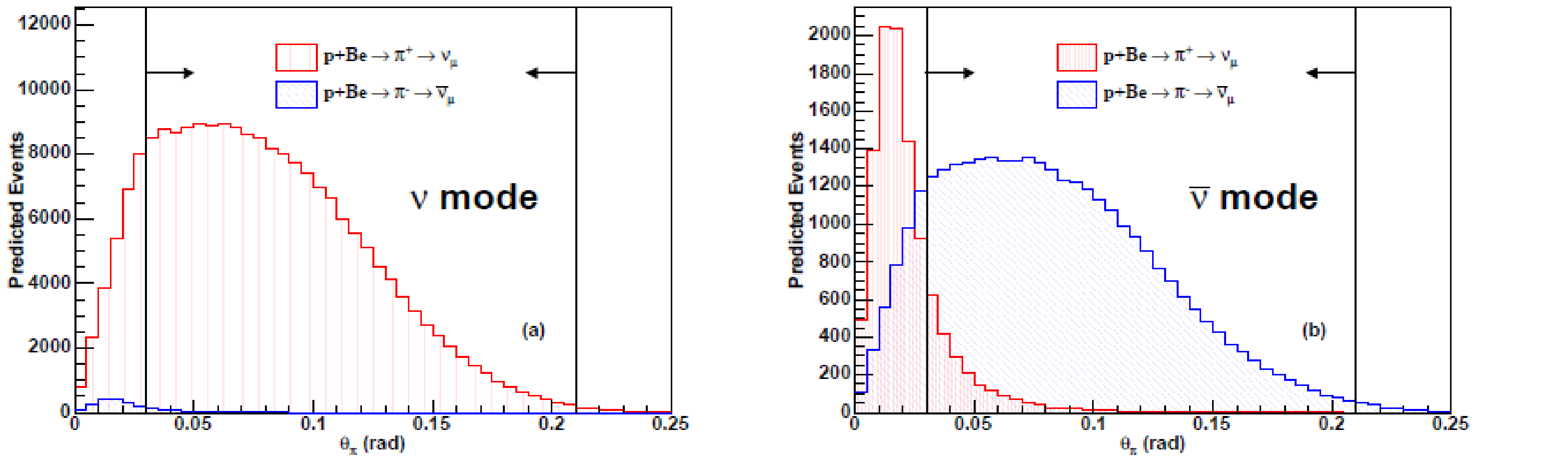


R. Dharmapalan, NuInt11

J. Grange, NuInt11

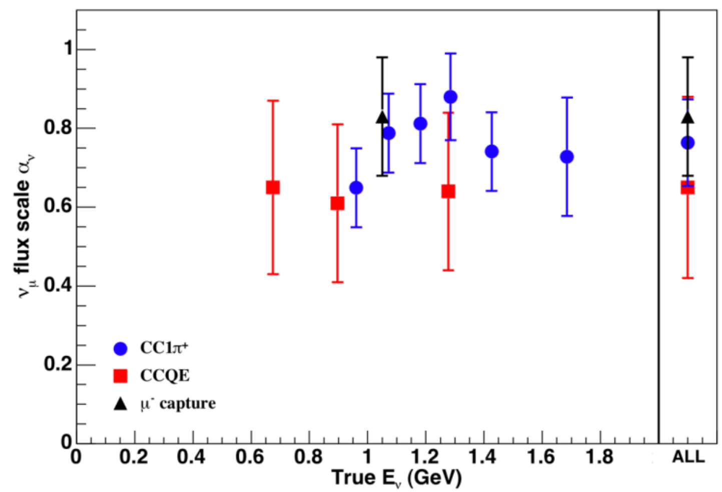


Neutrino Flux Revisited



- First measurement of neutrino contribution to anti-neutrino beam with non-magnetized detector: arxiv: 1102.1964 [hep-ex], submitted to Phys. Rev. D

- **3 independent, complementary** measurements (arXiv: 1107.5327)
  - μ^+/μ^- angular distribution
  - μ^- capture
  - π^- absorption (CC1π^+ sample)

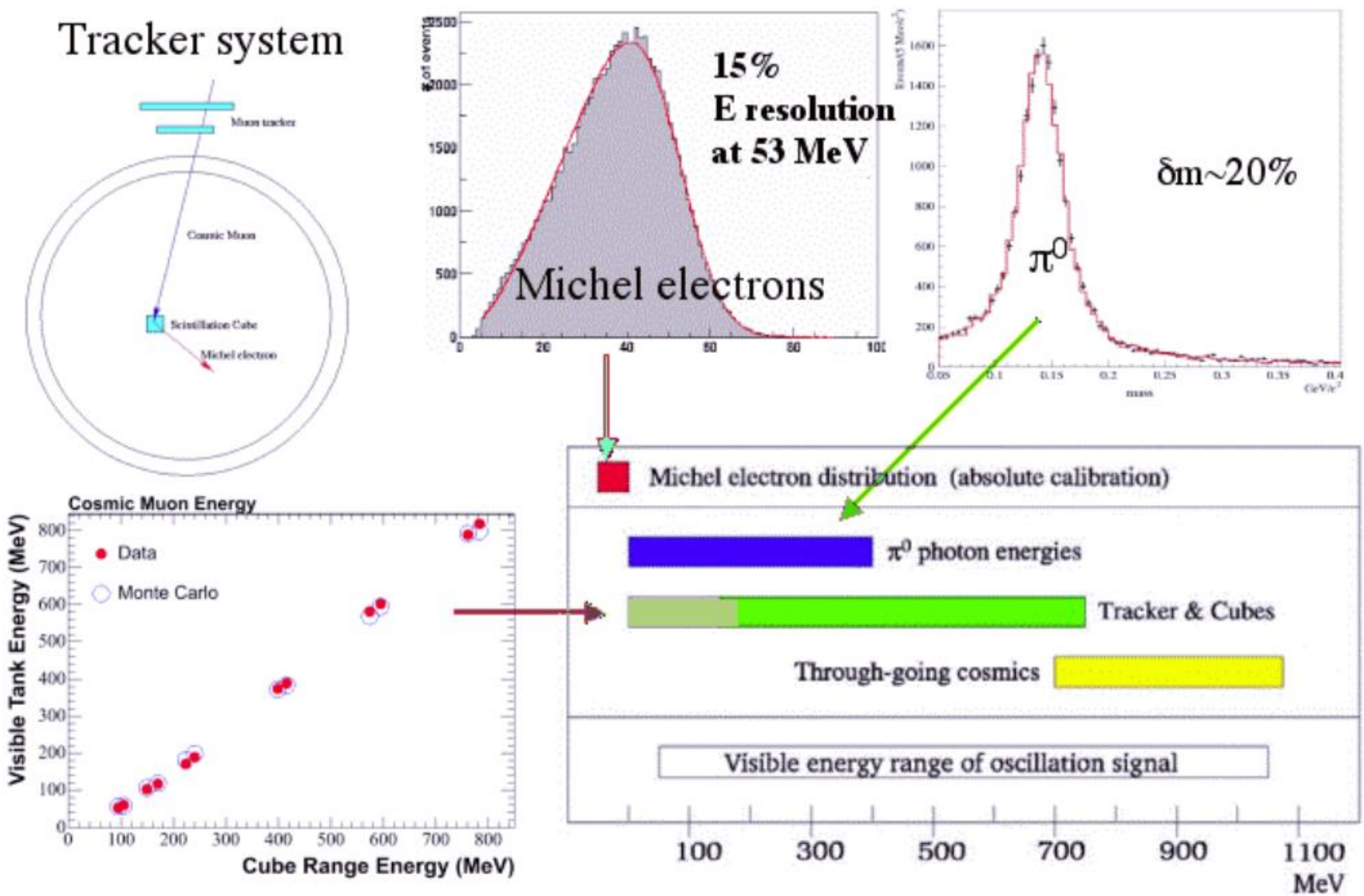


Conclusions

- Electron Neutrino and Antineutrino Appearance
  - Significant neutrino (antineutrino) excesses above background in both neutrino and antineutrino mode at low energy; with new data update, excess in antineutrino mode looking more like excess in neutrino mode
  - Antineutrino data are consistent with LSND result; significance of oscillation signal relative to null is reduced
  - See also Georgia Karagiorgi's talk from DPF 2011 for fits to 3+1 and 3+2 models
- Muon Neutrino and Antineutrino Disappearance
  - SciBooNE data used in joint neutrino-mode analysis
  - Joint analysis underway for anti-neutrino mode, also taking advantage of improved reconstructions in MiniBooNE
  - Ultimately, would like to have two identical detectors at different distances for SBL disappearance to cover region of interest
- Cross Section Measurements
  - MiniBooNE neutrino cross sections are more interesting than expected; must carefully specify what is meant by QE and what is assumed
  - Fermi Gas Model is inadequate; realistic models have to include initial and final state correlations and 2-body currents
  - Differences between neutrino and antineutrino cross sections and energy reconstruction will have to be understood when searching for CP violation

Backup slides

Calibration Sources

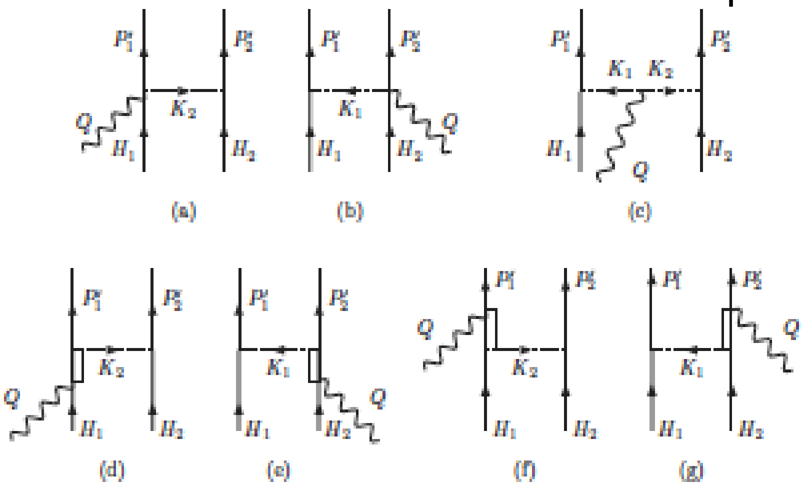


Is the Neutrino Energy Estimated Correctly in CCQE?

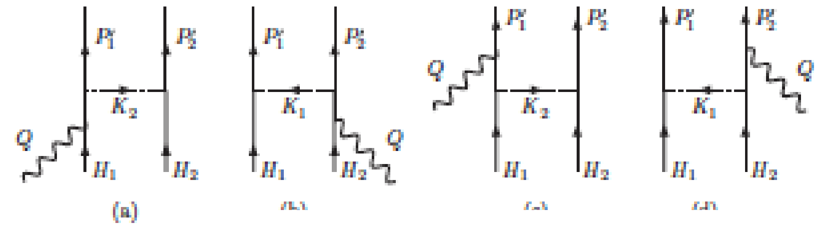
Amaro, et al, PHYSICAL REVIEW C **82, 044601 (2010)**

Meson Exchange Diags.

2p-2h fin. sts.

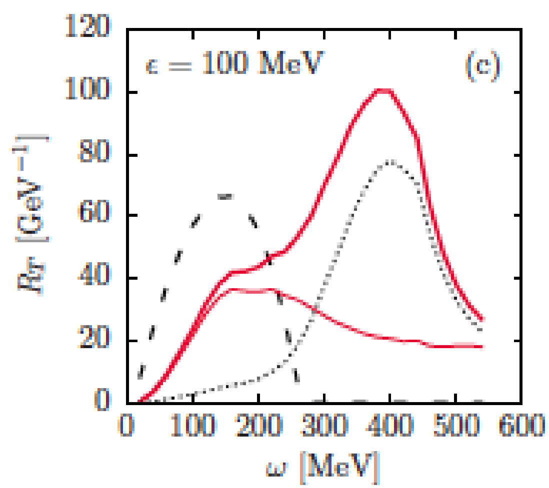


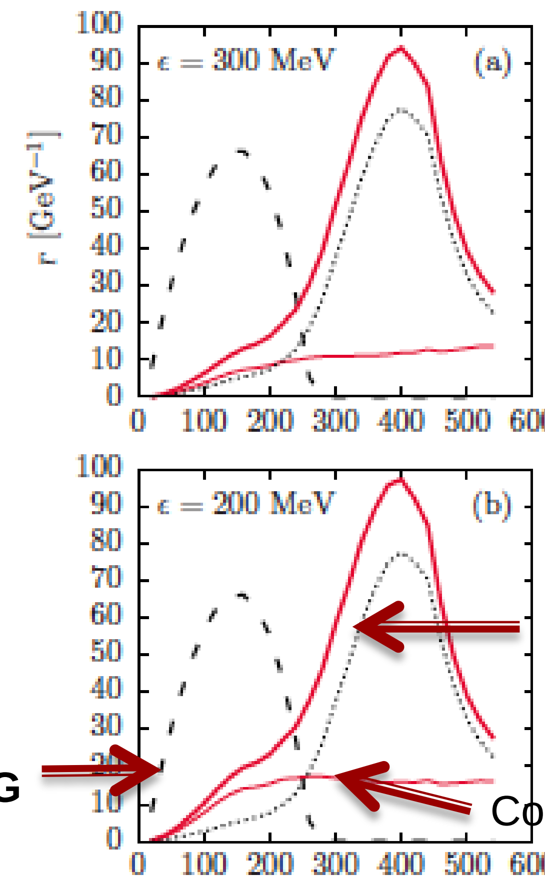
Correlation Diags.



<u>Electron Scattering</u>

^{56}Fe, q=0.55GeV/c





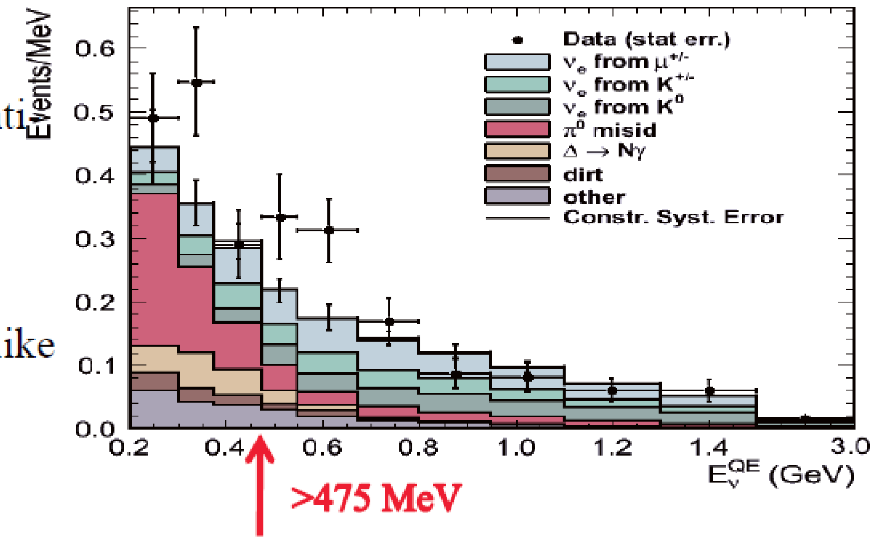
Meson exchange

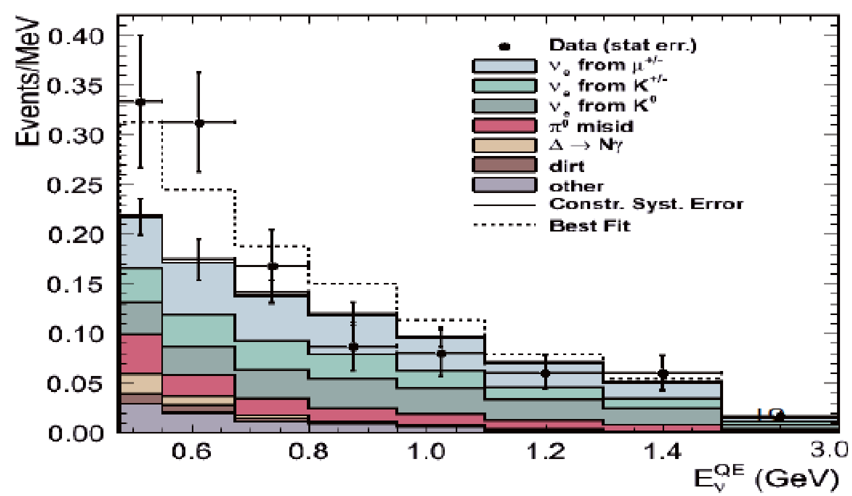
One body RFG

Correlation

Previous Anti-neutrino Mode Results (2010): 5.66E20 POT

- Results for 5.66E20 POT collected in anti-neutrino mode
- Only antineutrino's allowed to oscillate in fit
- In E < 475 MeV: A small 1.3σ electron-like excess.
- E > 475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.





Published
Phys.Rev.Lett.105:181801,2010.
e-Print: **arXiv:1007.1150** [hep-ex])

Previous Anti-neutrino Mode Results (2010): 5.66E20 POT

Null excluded at 99.4% with respect to the two neutrino oscillation fit.

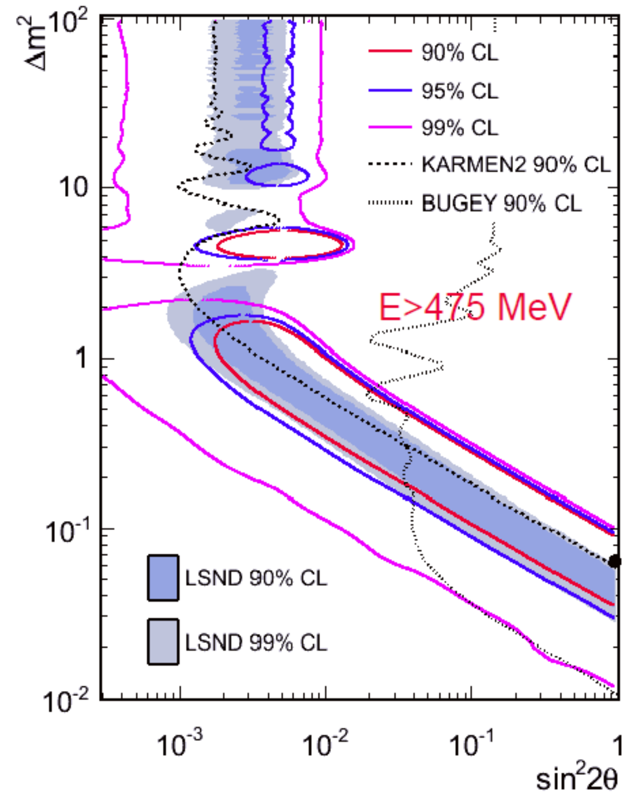
Best Fit Point

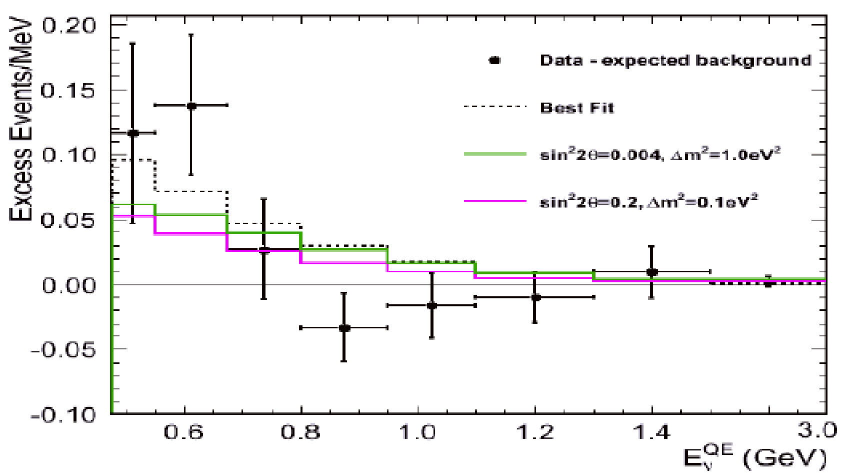
$(\Delta m^2, \sin^2 2\theta) =$

$(0.064\ eV^2, 0.96)$

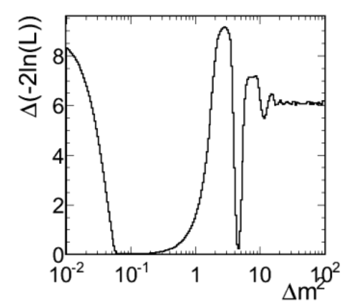
$\chi^2/NDF = 16.4/12.6$

$P(\chi^2) = 20.5\%$

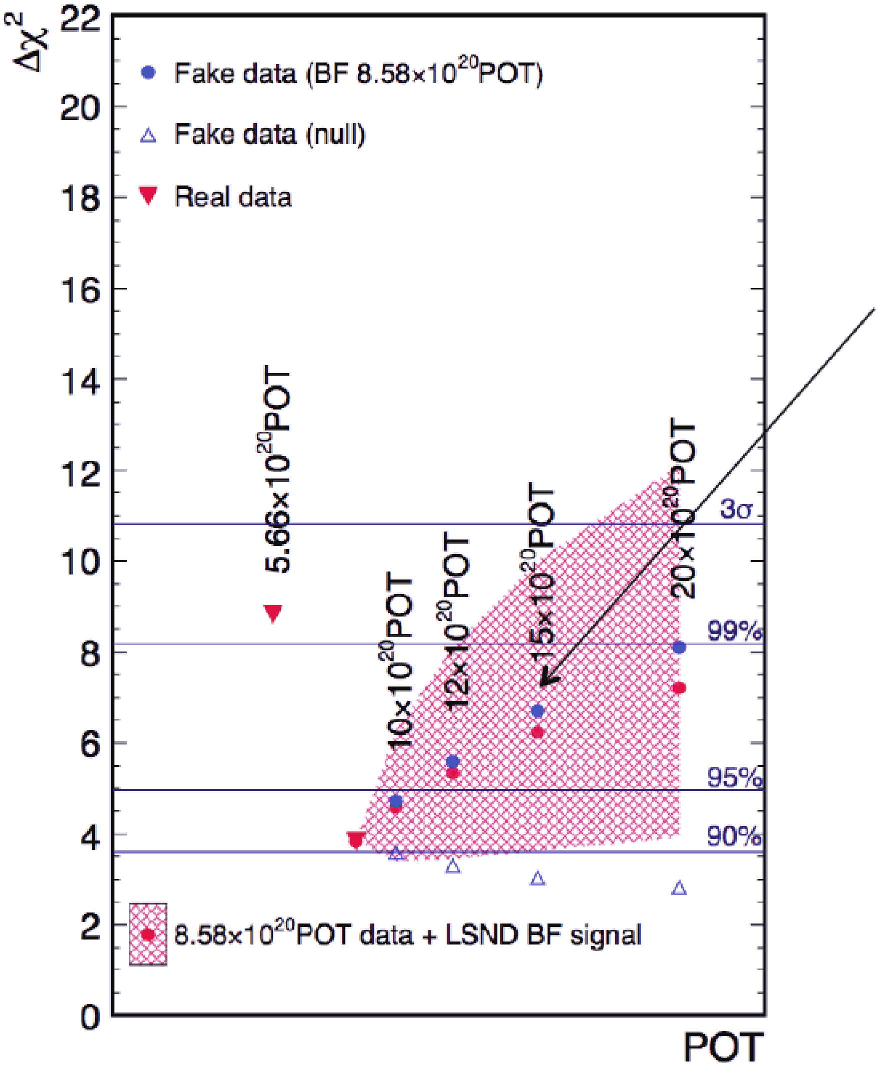




$\Delta\chi^2$ vs Δm^2



Future MiniBooNE Running

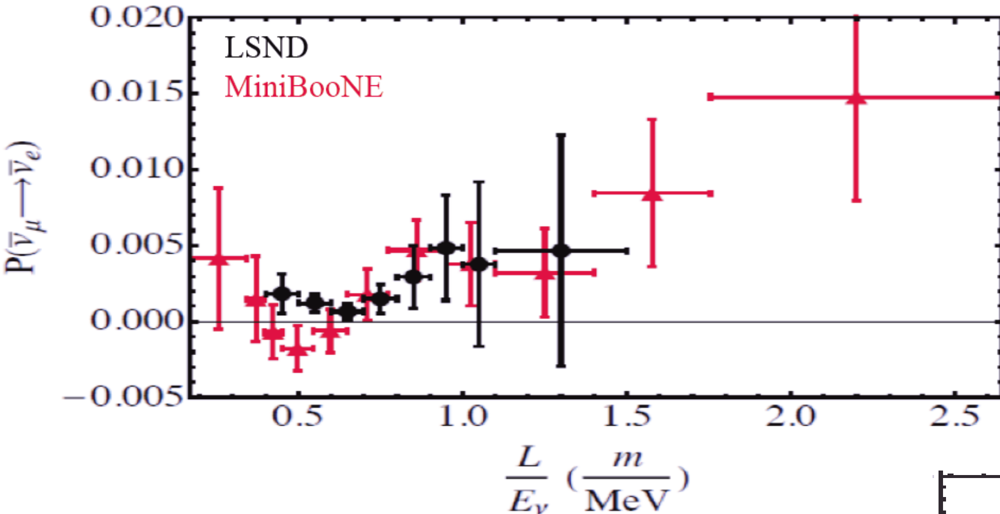


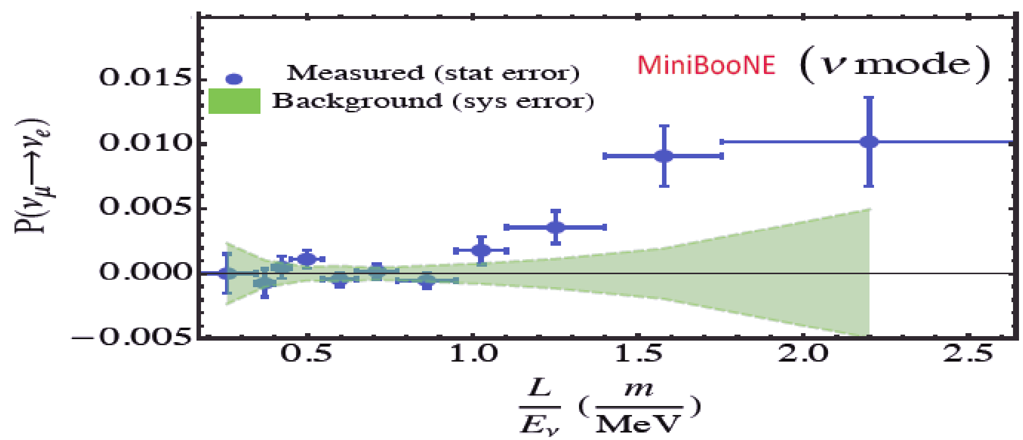
MiniBooNE Collaboration requested $15x10^{20}$ POT to complete the run in current configuration.

The data set will probe LSND signal at 2-3 σ level.

L/E Plot

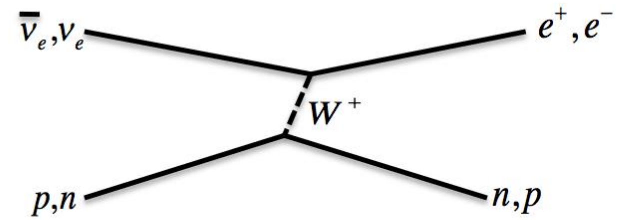
- Data used for LSND and MiniBooNE correspond to $20<E_\nu<60$ MeV and $200<E_\nu<3000$ MeV, respectively.
- Oscillation probability is event excess divided by the number of events expected for 100% $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transformation.
-L is reconstructed distance travelled by the antineutrino from the mean neutrino production point to the interaction vertex; E_ν is the reconstructed antineutrino energy.



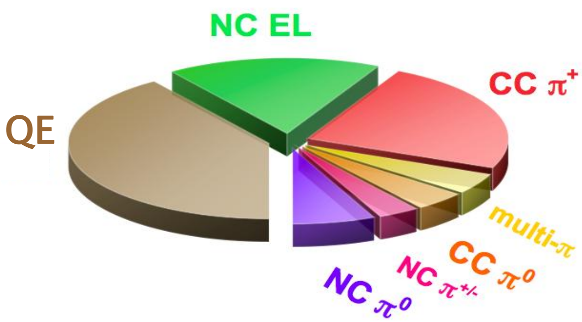


Particle Identification

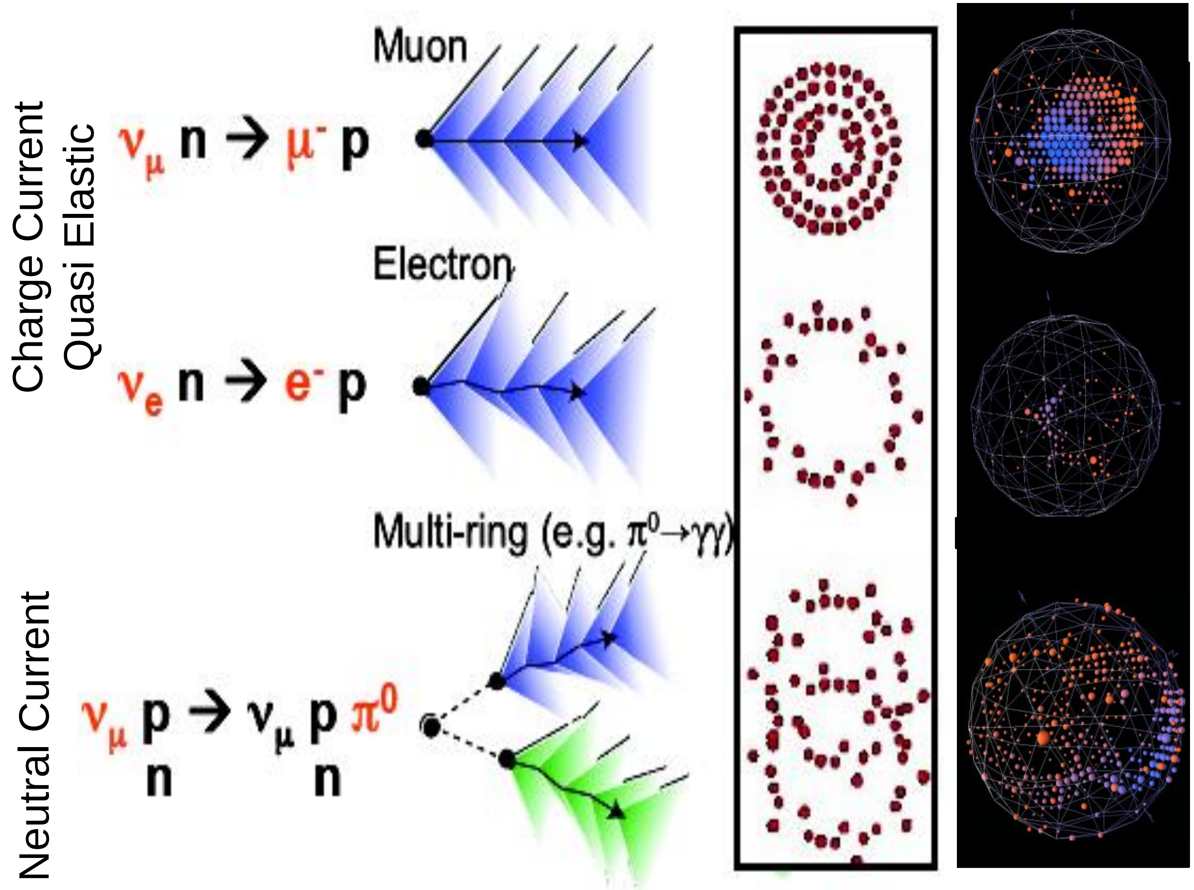
- Identify events using timing and hit topology
- Use primarily Cherenkov light
- Can't distinguish electron from photon



Interactions in MiniBooNE (neutrino mode):



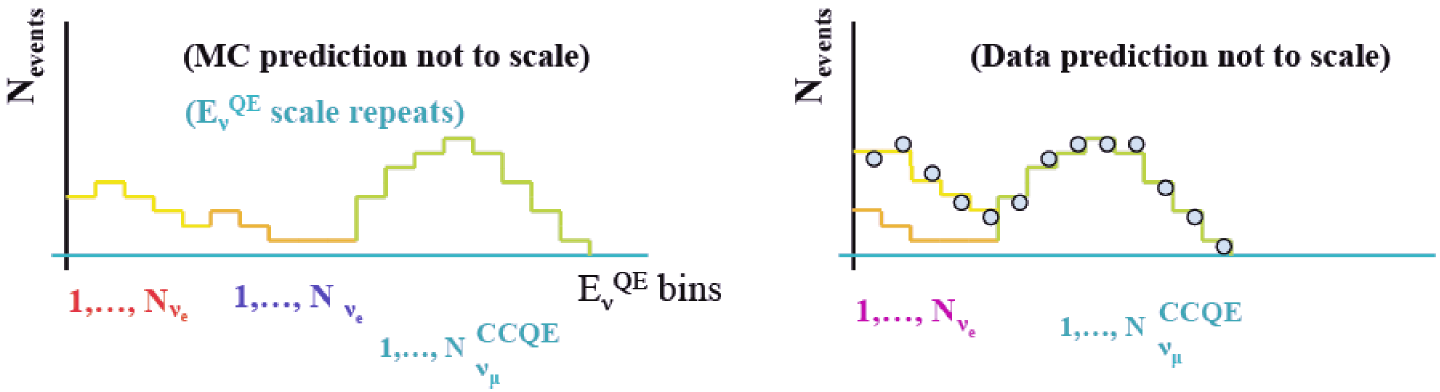
(similar mix for antineutrino mode, except rate down by factor of 5)



Constrained Fit

The following three distinct samples are used in the oscillation fits:

1. Background to ν_e oscillations
2. ν_e Signal prediction (dependent on Δm^2, $\sin^2 2\theta$)
3. ν_μ CCQE sample, used to constrain ν_e prediction (signal+background)



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

M_{ij} = full syst+stat covariance matrix at best fit prediction

logL calculated using both datasets (ν_e and ν_μ CCQE), and corresponding covariance matrix