

New Oscillation Results From MiniBooNE

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Los Alamos, June 28 2010

Outline

- Introduction
- MiniBooNE exp.
- Data analysis
- Results
- Future outlook
- Conclusion



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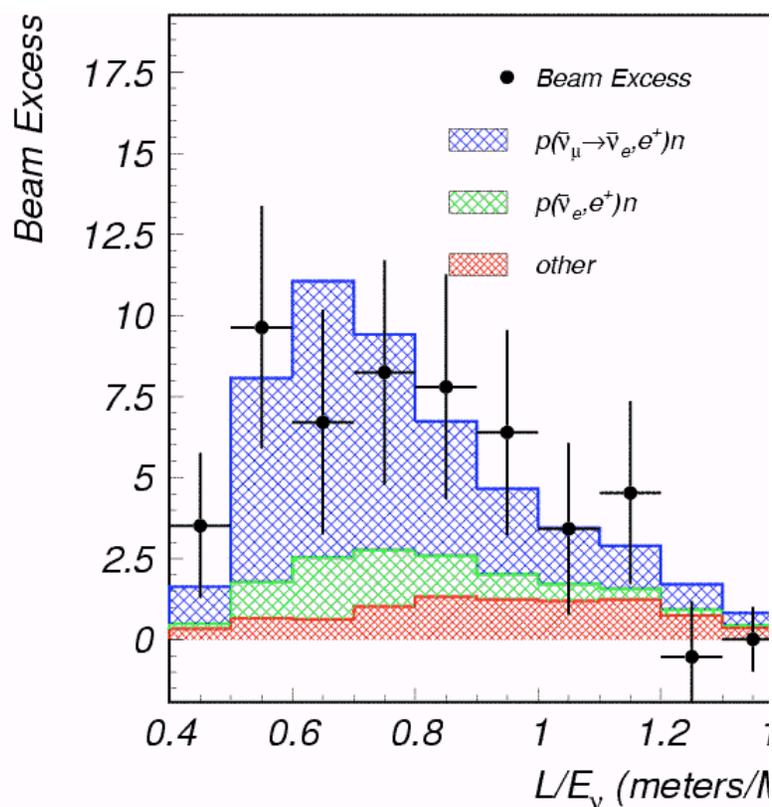
(The MiniBooNE Collaboration)

MiniBooNE motivation

- LSND experiment
- Stopped pion beam

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

$$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$$
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- ν_e signature: Cherenkov light from e^+ with delayed n-capture
- Excess = $87.9 \pm 22.4 \pm 6$ (3.8σ)



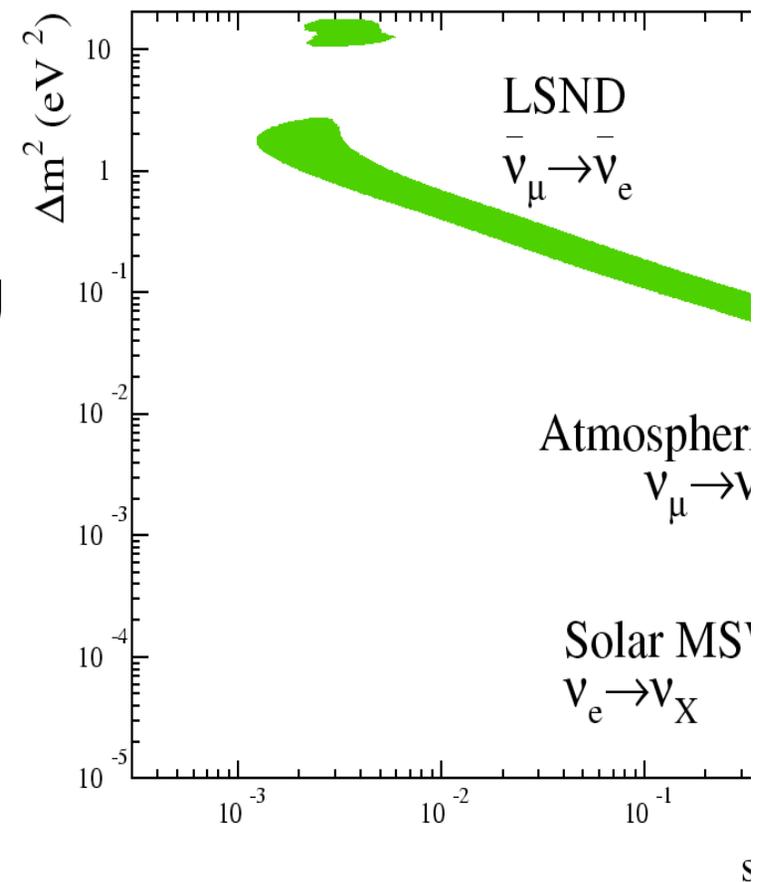
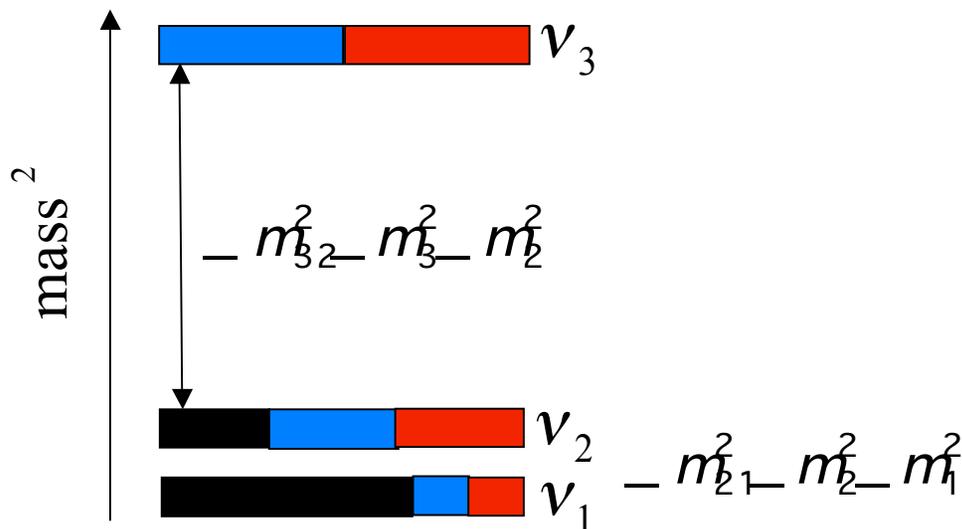
LSND signal

- Assuming two neutrino oscillations

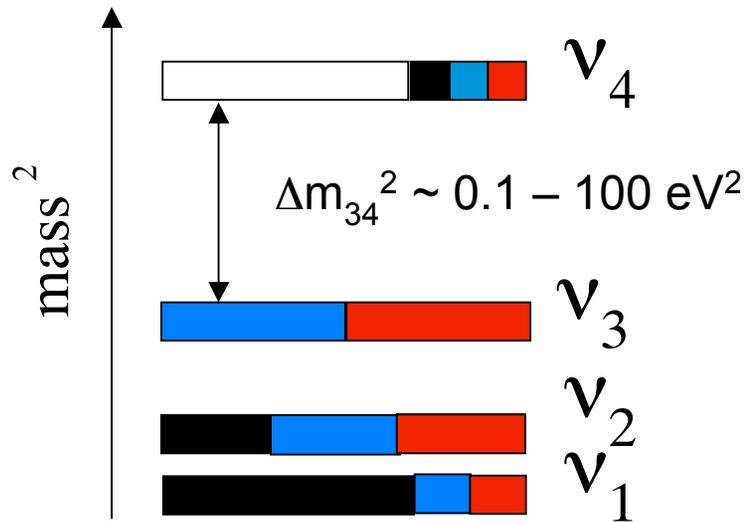
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta) \sin^2\left(\frac{1.27 L \Delta m^2}{E}\right)$$

$$= 0.245 \pm 0.067 \pm 0.045 \%$$

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splittings



Sterile neutrinos



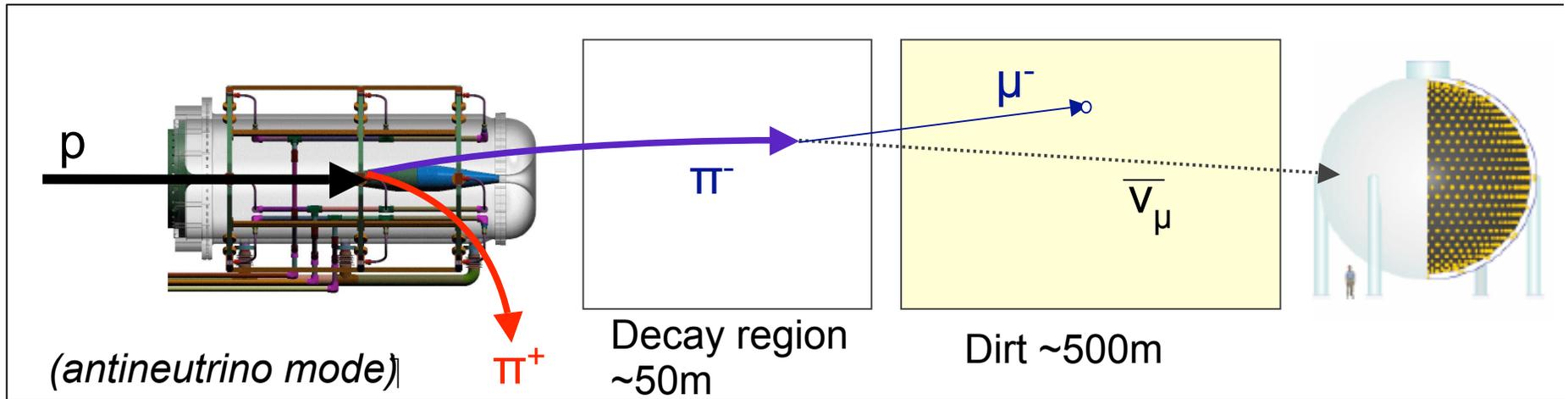
- Can have only 3 light active neutrinos
- 3 active neutrinos + 1 sterile neutrino

$$P_{\nu_e \rightarrow \nu_e} = 4 U_{e4}^2 U_{\mu 4}^2 \sin^2 1.27 \frac{m_{41}^2 L}{E}$$

$$P_{\nu_e \rightarrow \nu_e} = \sin^2 2_{\mu} \sin^2 1.27 \frac{m^2 L}{E}$$

- Model predicts same oscillation probability for neutrinos and anti-neutrinos

MiniBooNE experiment



- Similar L/E as LSND
 - MiniBooNE $\sim 500\text{m}/\sim 500\text{MeV}$
 - LSND $\sim 30\text{m}/\sim 30\text{MeV}$
- Horn focused neutrino beam ($p+\text{Be}$)
 - Horn polarity \rightarrow neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

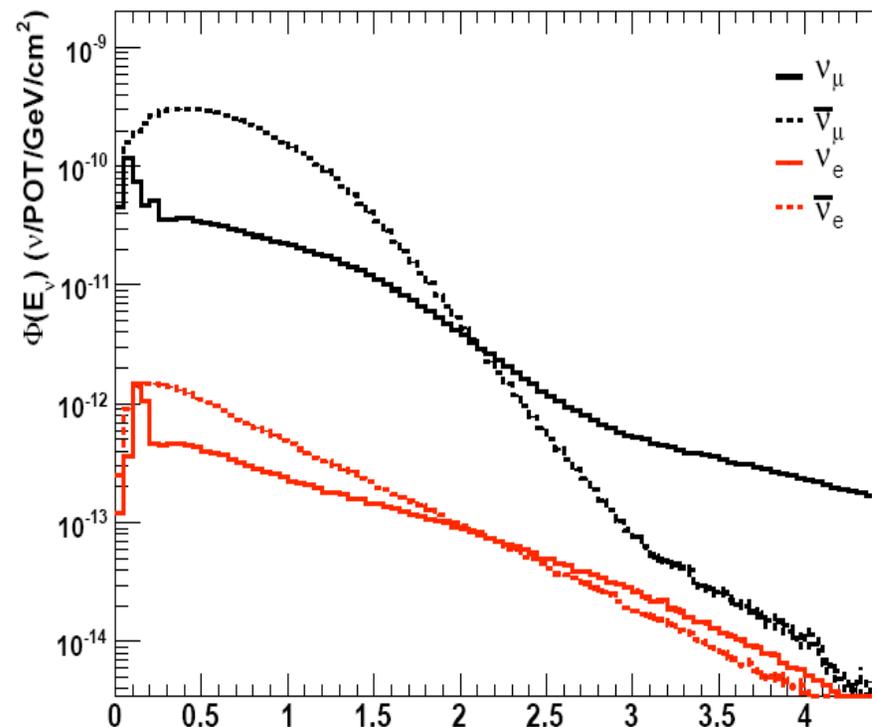
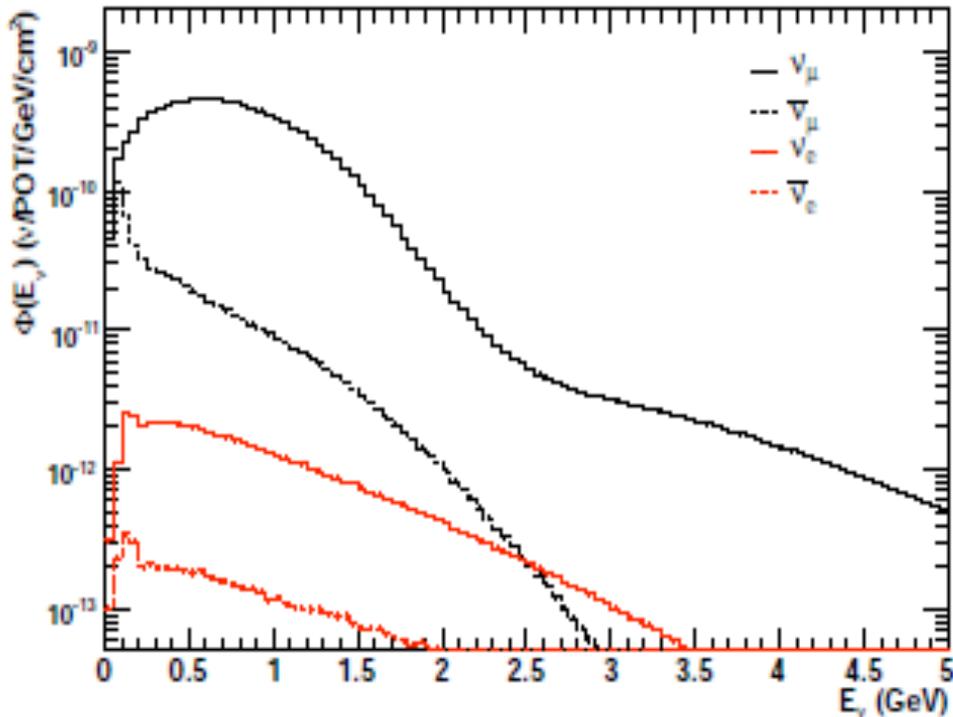
Neutrino flux

- Neutrino mode

ν_μ	93.6%
$\bar{\nu}_\mu$	5.8%
$\nu_e + \bar{\nu}_e$	0.6%

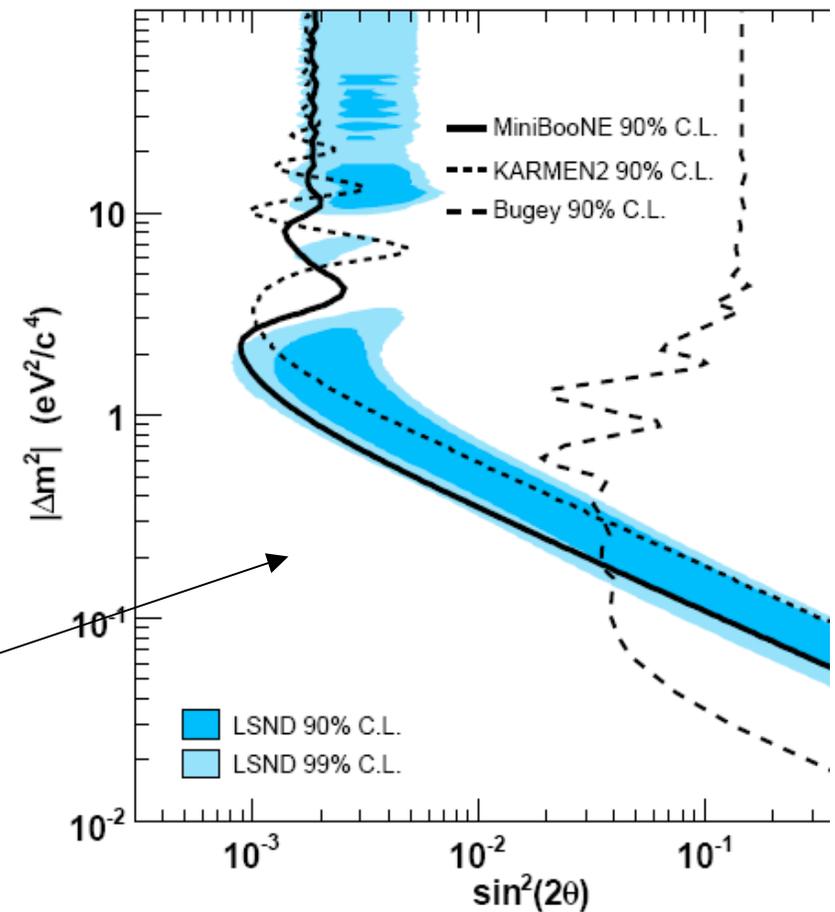
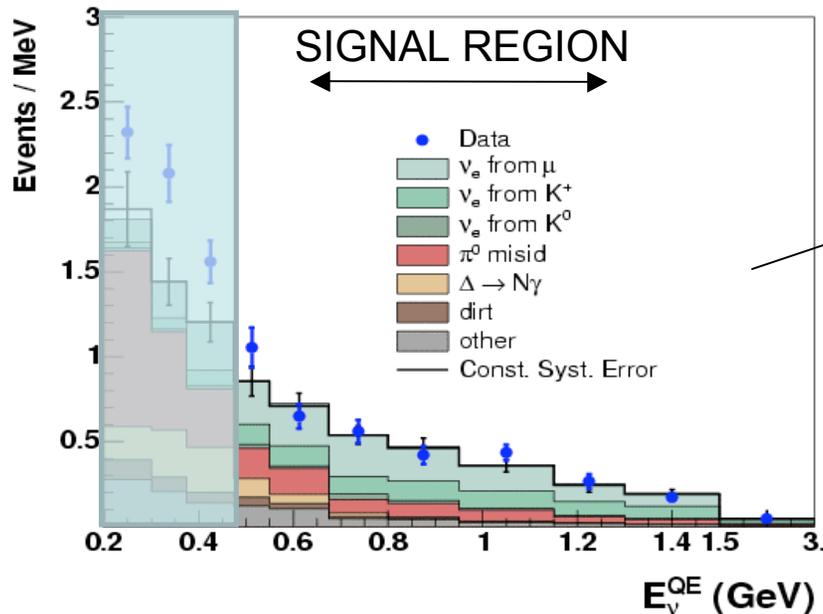
- Anti-neutrino mode

ν_μ	15.7%
$\bar{\nu}_\mu$	83.7%
$\nu_e + \bar{\nu}_e$	0.6%



MiniBooNE neutrino result

- 6.5e20 POT
- No excess of events in signal region ($E > 475$ MeV)
- Ruled out 2 ν oscillation as LSND explanation (assuming no CP or CPT violation)



Phys. Rev. Lett. 98, 231801 (2007)

MiniBooNE neutrino result

Excess of events observed at low energy:

$$128.8 \pm 20.4 \pm 38.3 \text{ (} 3.0\sigma \text{)}$$

Shape not consistent with 2 ν oscillations

Magnitude consistent with LSND

Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density: Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill
arXiv:0708.1281

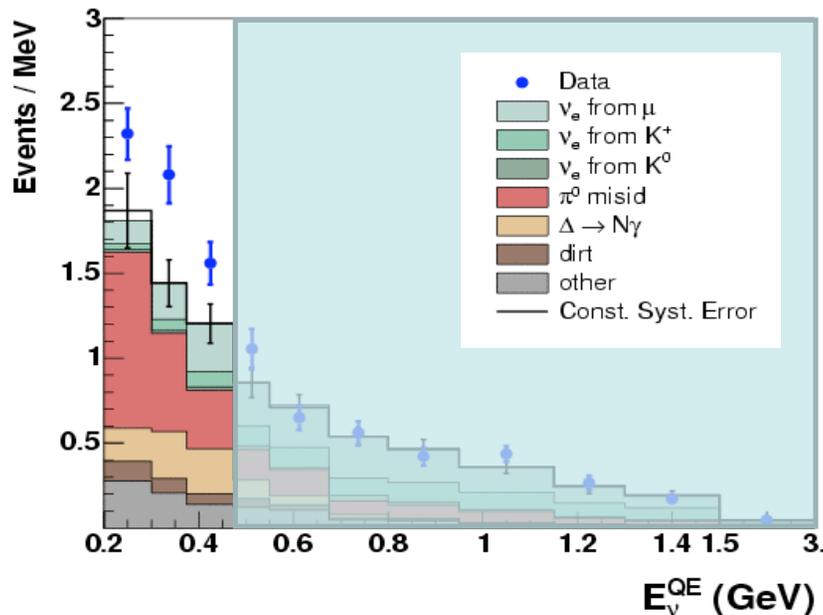
CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.

Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017

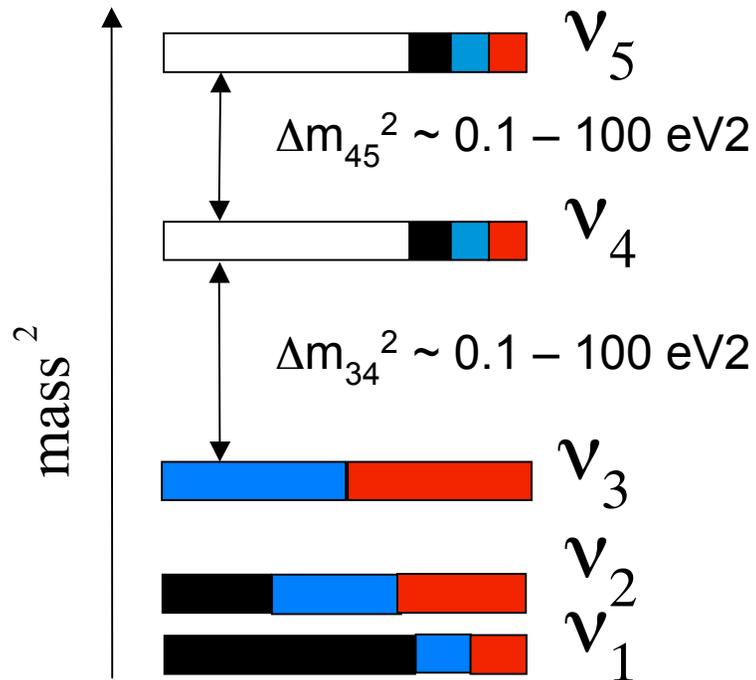
Lorentz Violation: Katori, Kostelecky, & Taylor, Phys. Rev. D74 (2006) 105009

CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

New Gauge Boson with Sterile Neutrinos: An E. Nelson & Jonathan Walsh, arXiv:0711.1363



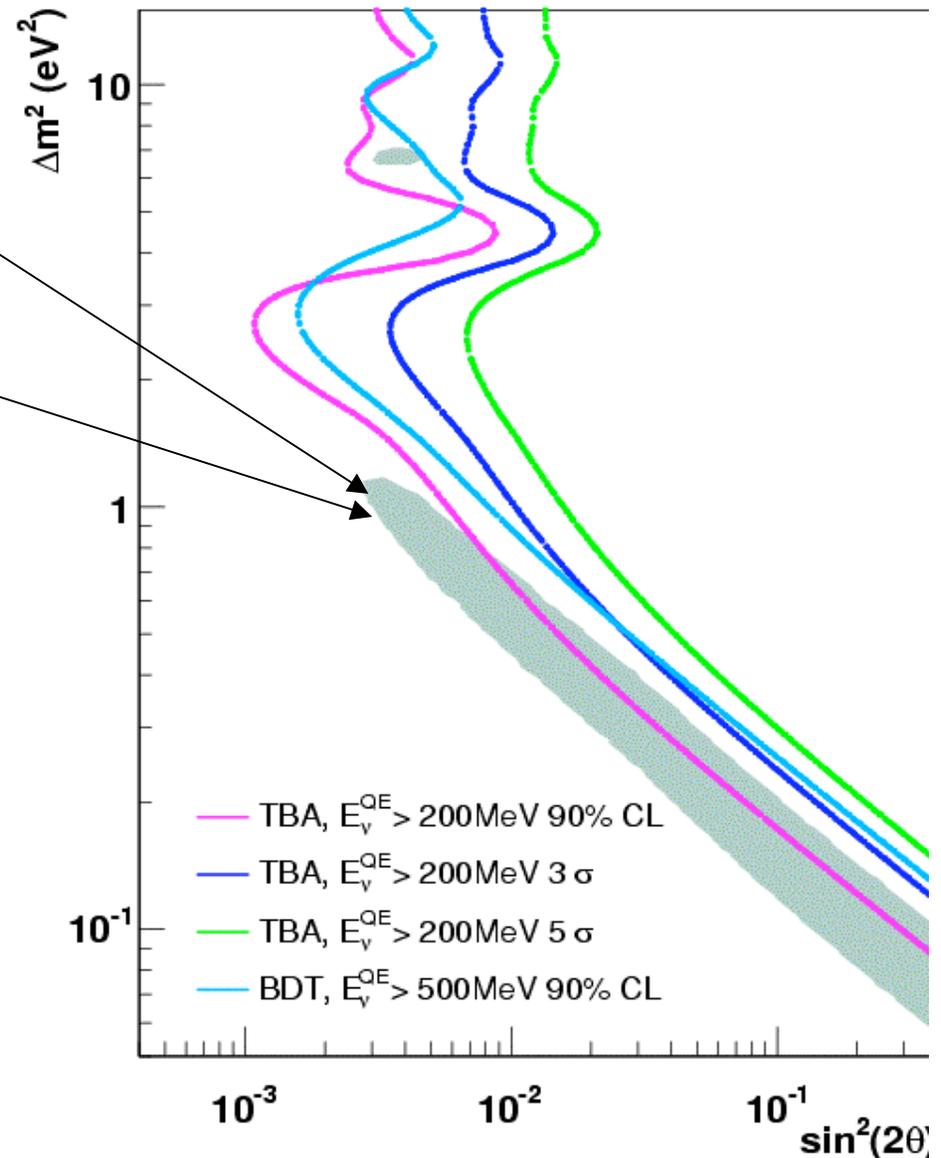
More sterile neutrinos



- Next minimal extension 3+2 models
- Favored by fits to appearance data (hep-ph/0705.0107)
- Model allows CP violation
 - $\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

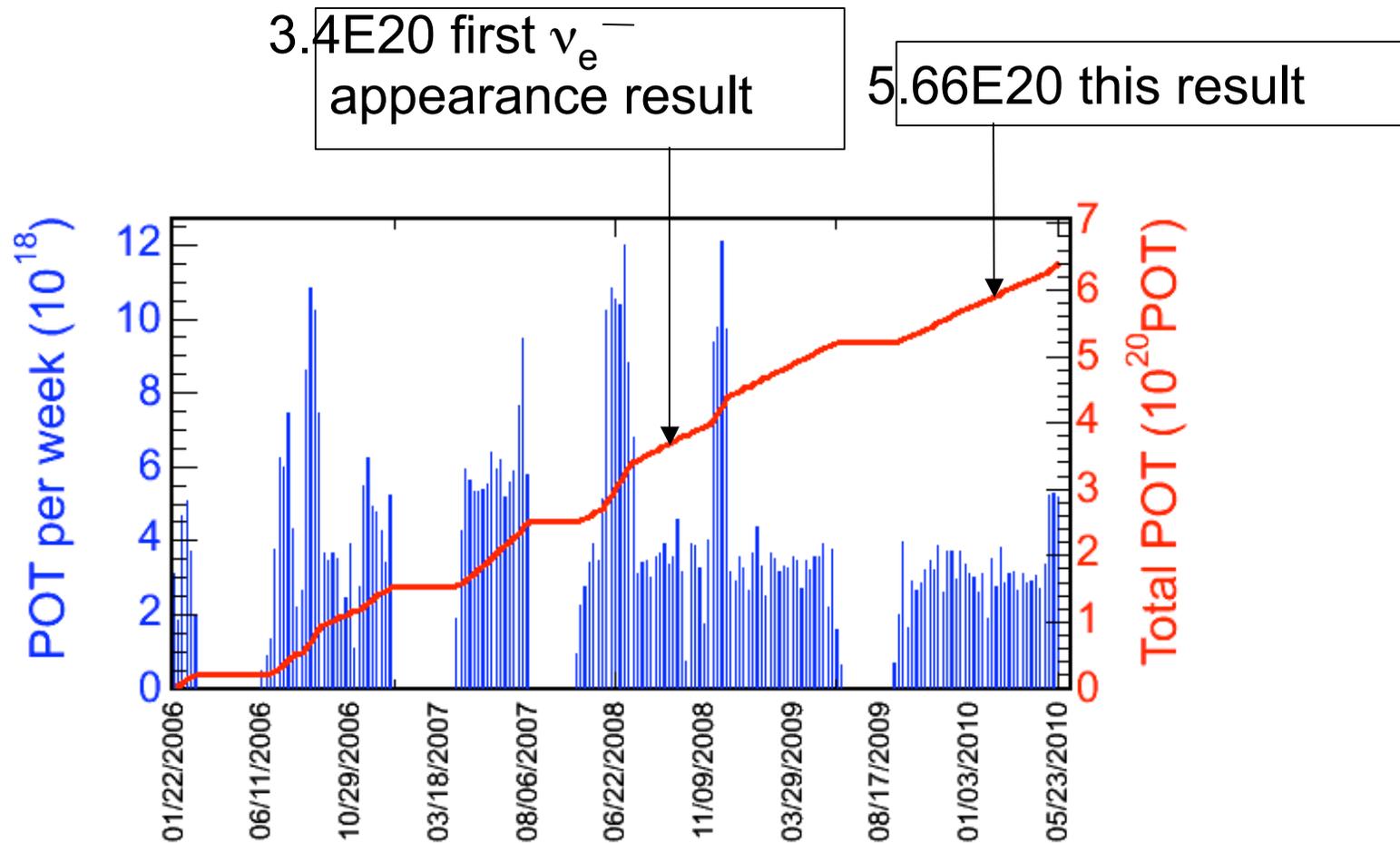
Anti-neutrino results

- LSND - signal
- Karmen – no signal
- MiniBooNE analysis of $3.4e20$ POT
(Phys. Rev. Lett. 103, 111801 (2009))
 - Inconclusive result



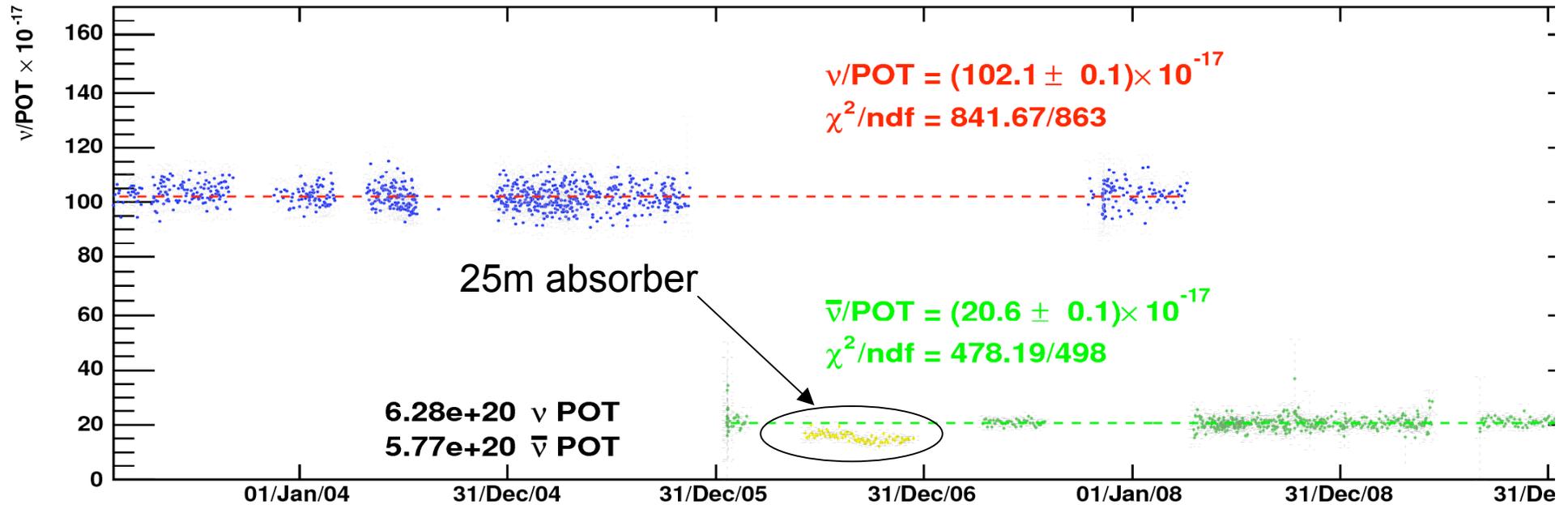
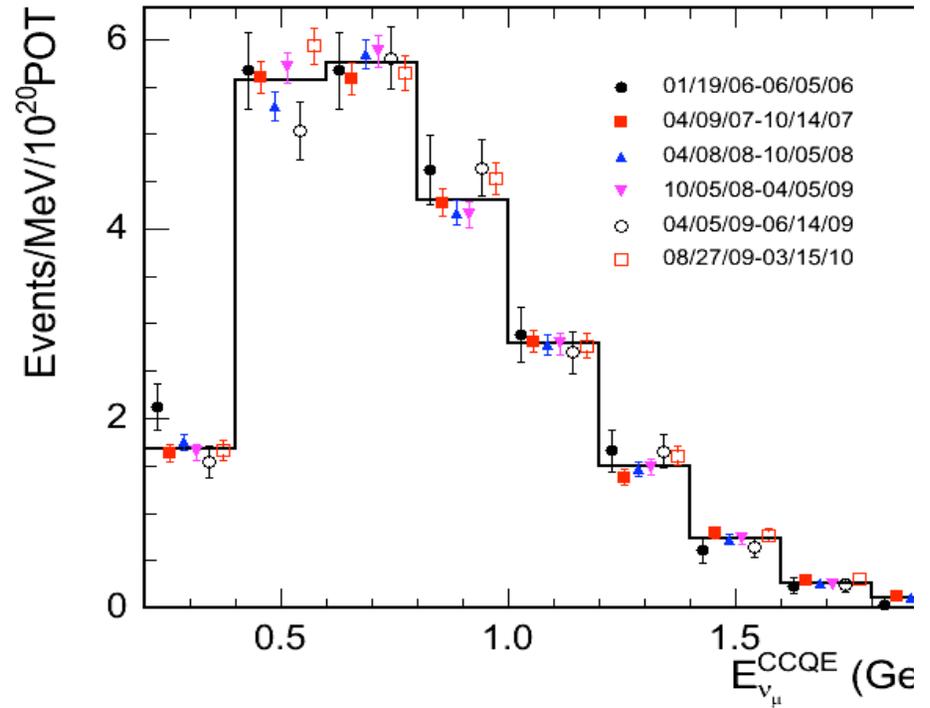
POT collection

- Protons on target in anti-neutrino mode

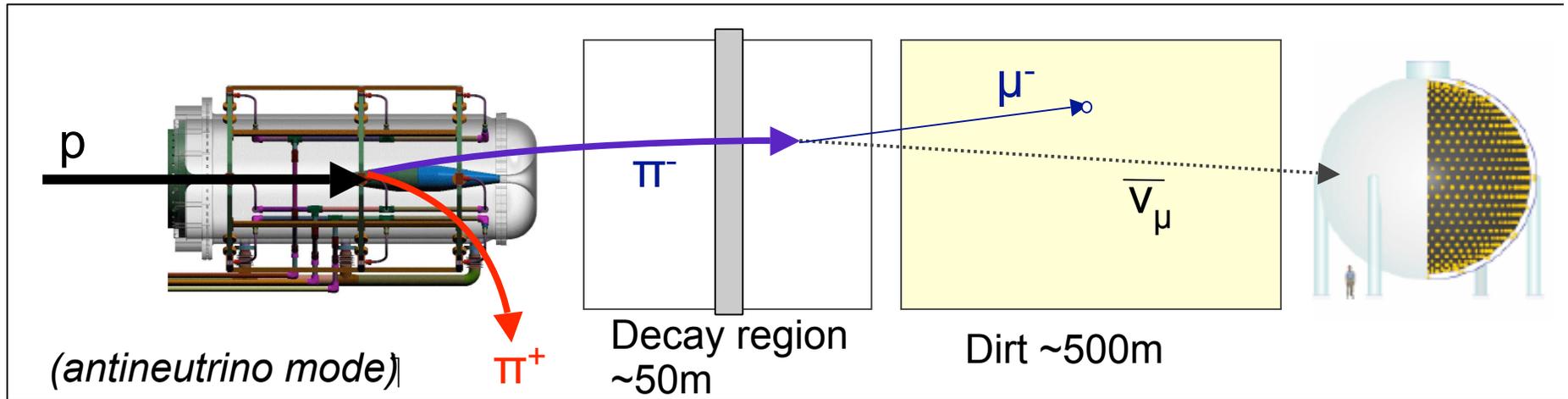


Data stability

- Very stable throughout the run



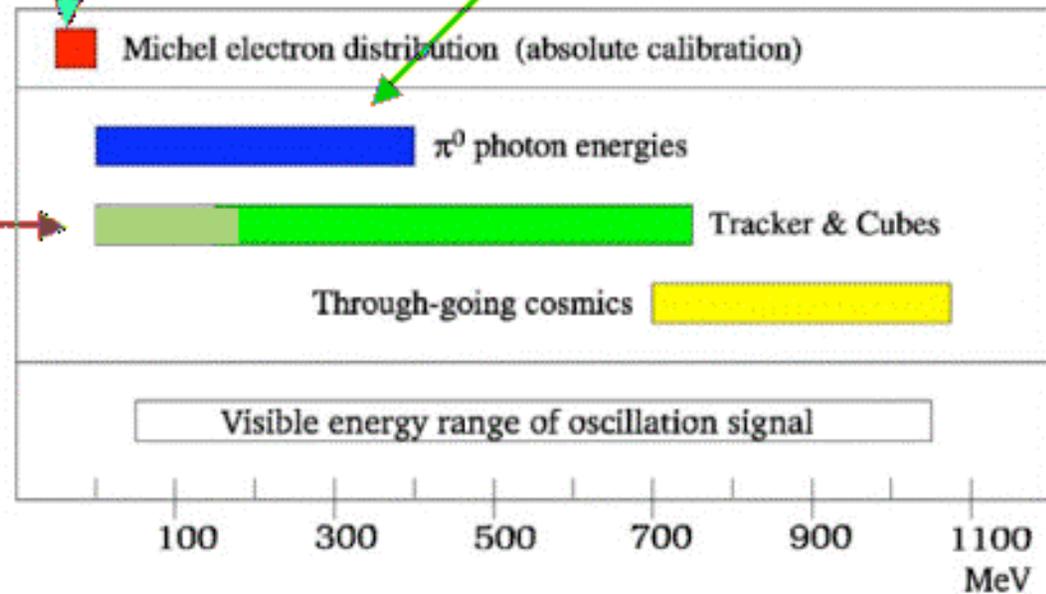
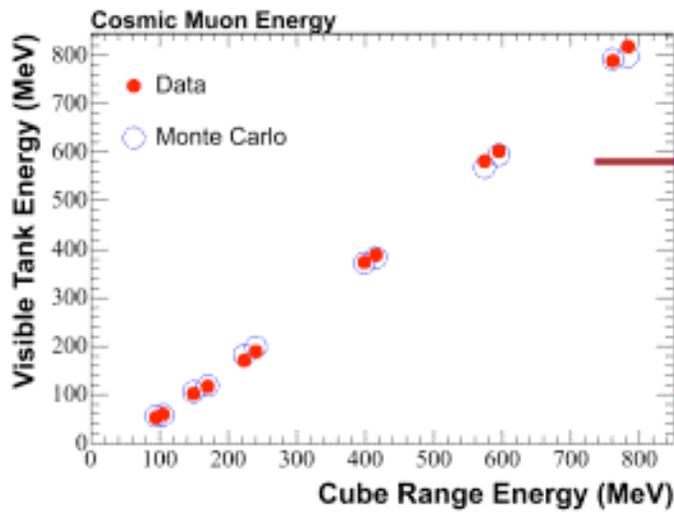
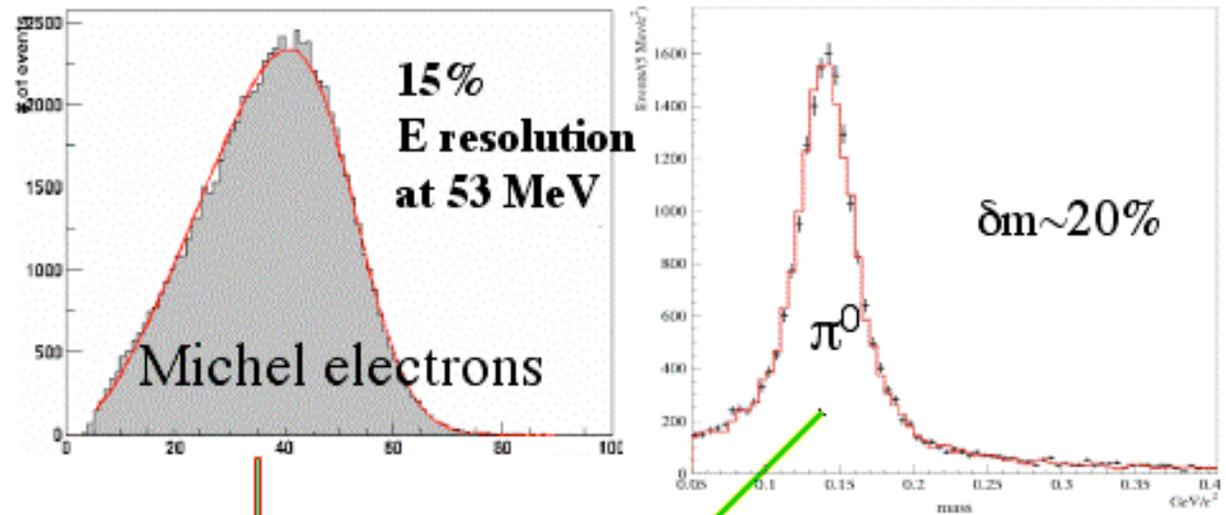
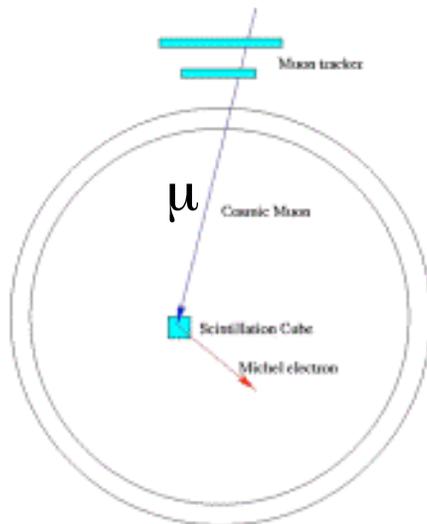
25m Absorber



- Two periods of running with 1 & 2 absorber plates
 - 1 absorber plate - 0.569E20 POT
 - 2 absorber plates - 0.612E20 POT
- Good data/MC agreement in high statistics samples ($\bar{\nu}_\mu$ CCQE, NC π^0 , ...)
- Data included in this analysis

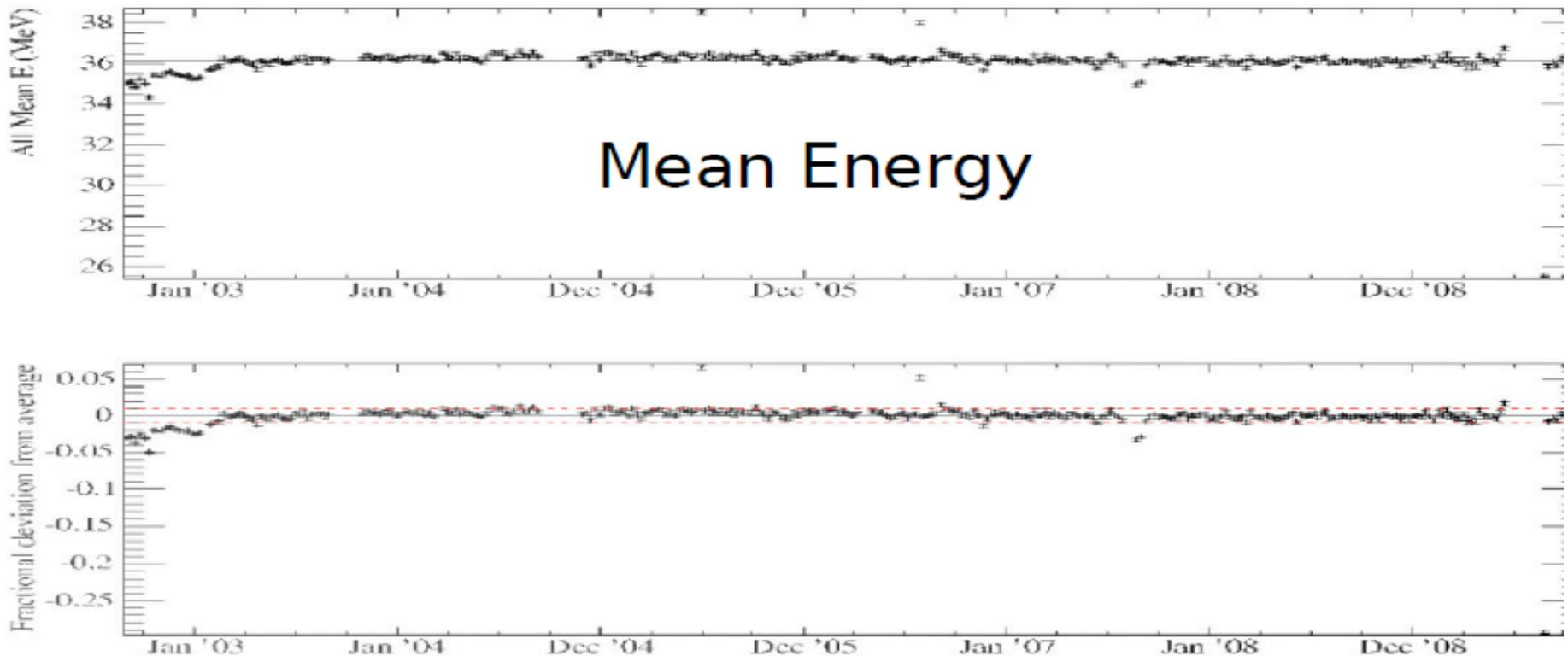
Calibration Sources

Tracker system



Detector calibration

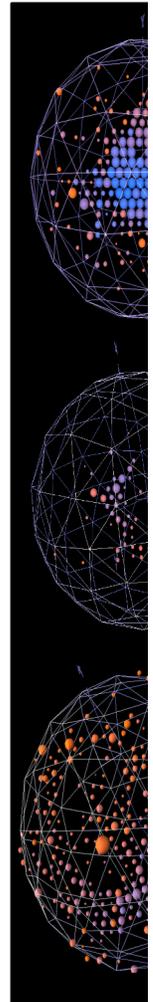
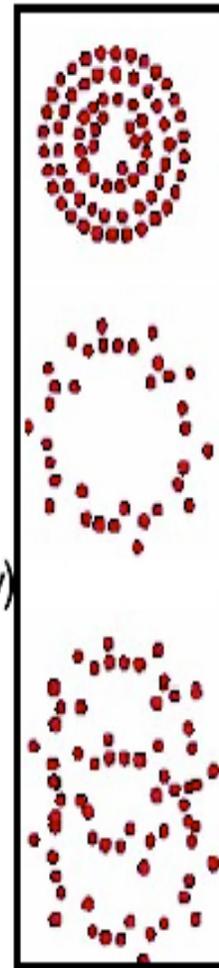
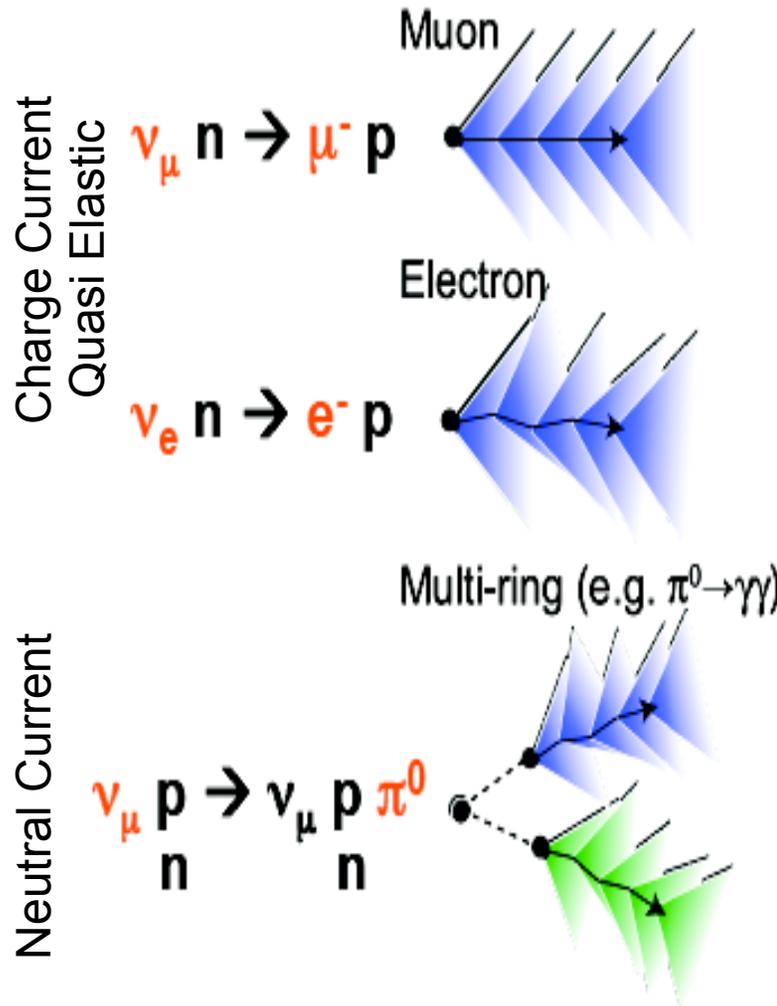
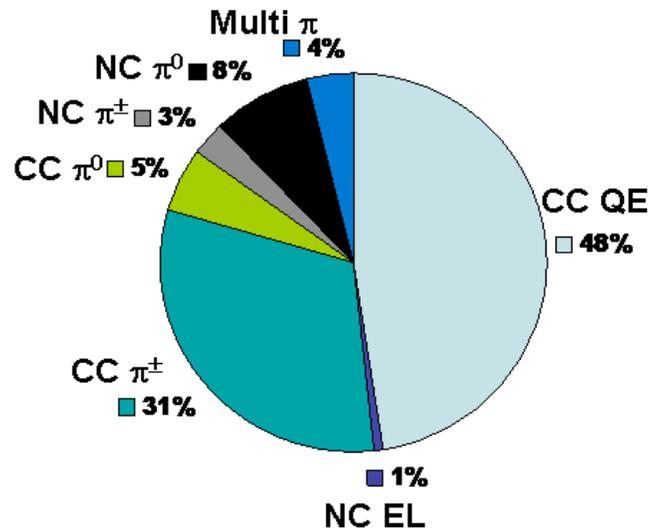
- Very stable
- For example: Michel electron mean energy within 1% since beginning of run (2002)



Events in MB

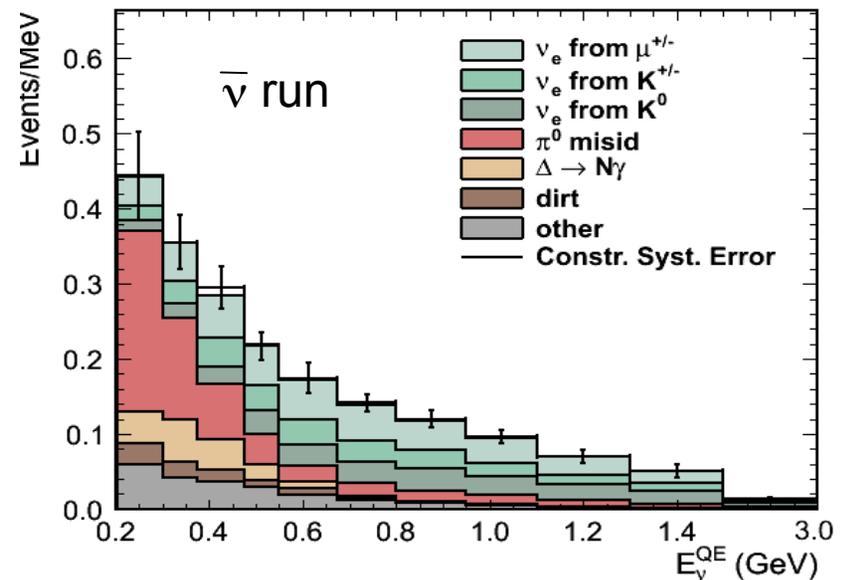
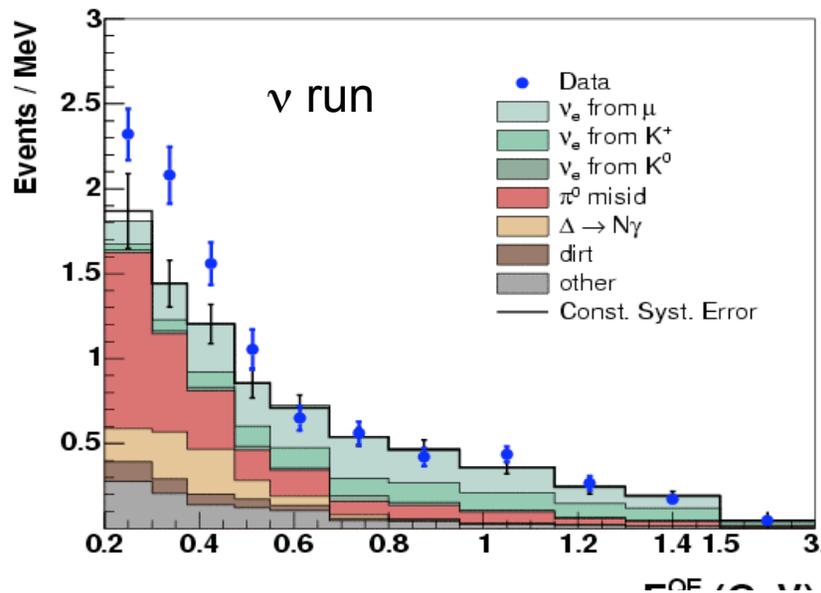
- Identify events using timing and hit topology
- Use primarily Cherenkov light

Interactions in MiniBooNE (neutrino mode):

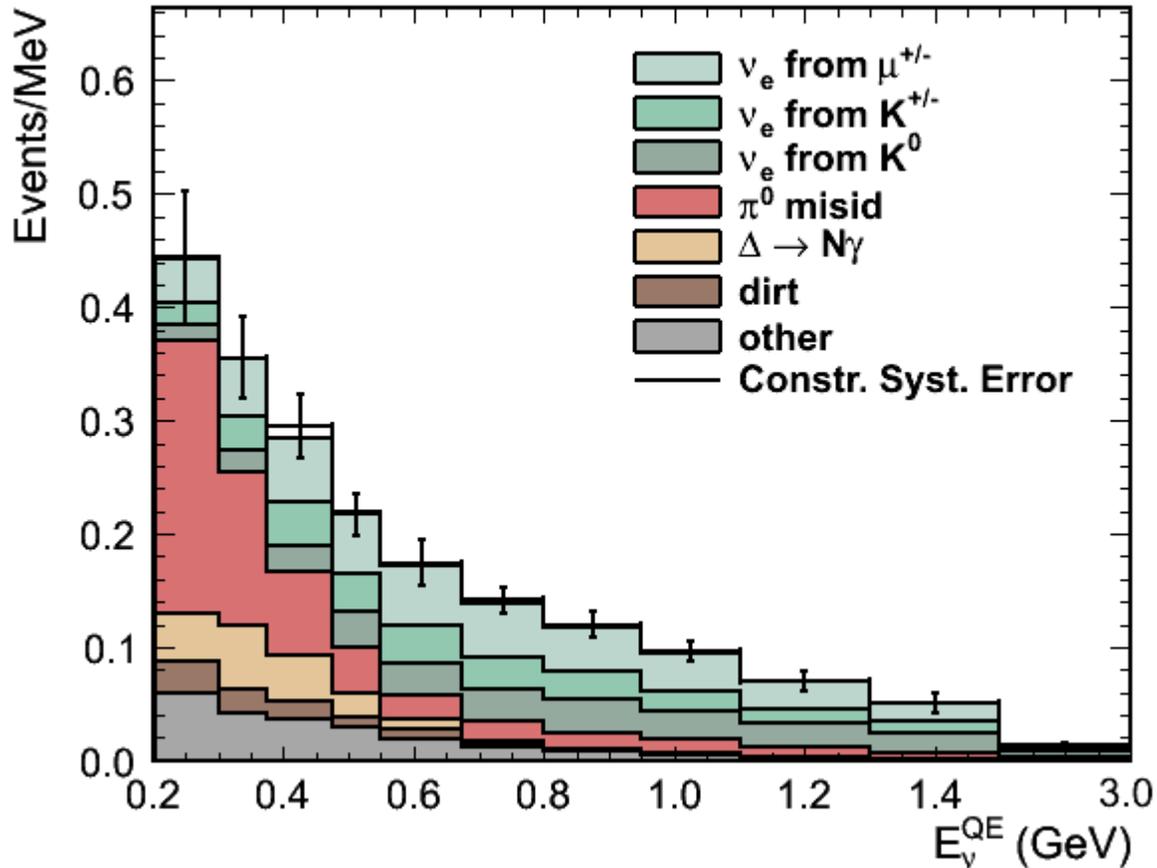


Particle ID

- Same as the one used for ν_e appearance results and also for the first $\bar{\nu}_e$ appearance result
- ID based on ratio of fit likelihoods under different particle hypothesis
- Similar backgrounds in neutrino and anti-neutrino run

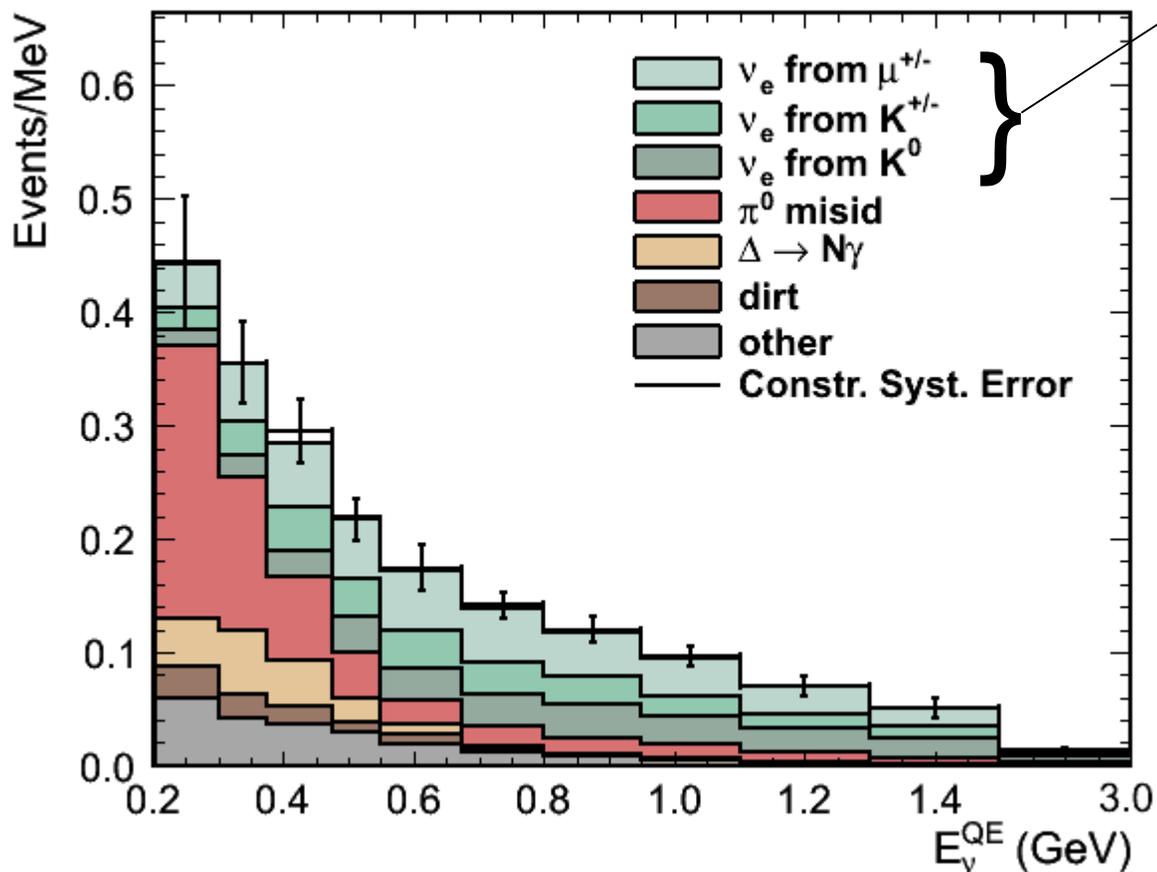


Background prediction



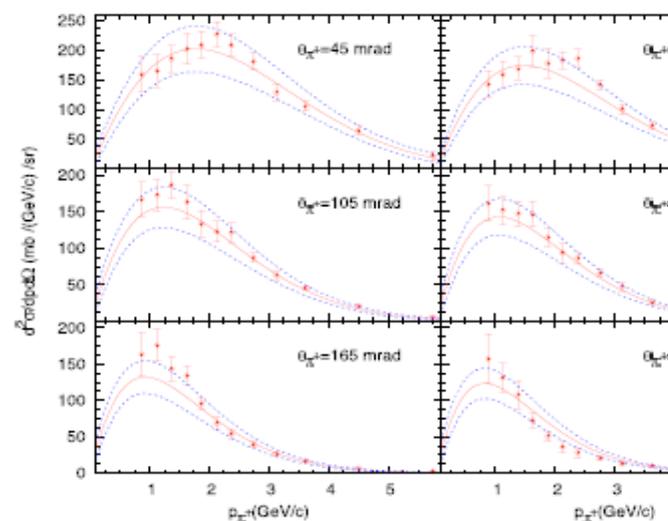
	5.66e20 Protons on Target	
	200-475	475-1250
μ^\pm	13.45	31.39
K^\pm	8.15	18.61
K^0	5.13	21.2
Other ν_e	1.26	2.05
NC π^0	41.58	12.57
$\Delta \rightarrow N\gamma$	12.39	3.37
dirt	6.16	2.63
ν_μ CCQE	4.3	2.04
Other ν_μ	7.03	4.22
Total	99.45	98.08

Background prediction



- Intrinsic nue

- External measurement
- HARP p+Be for π^\pm

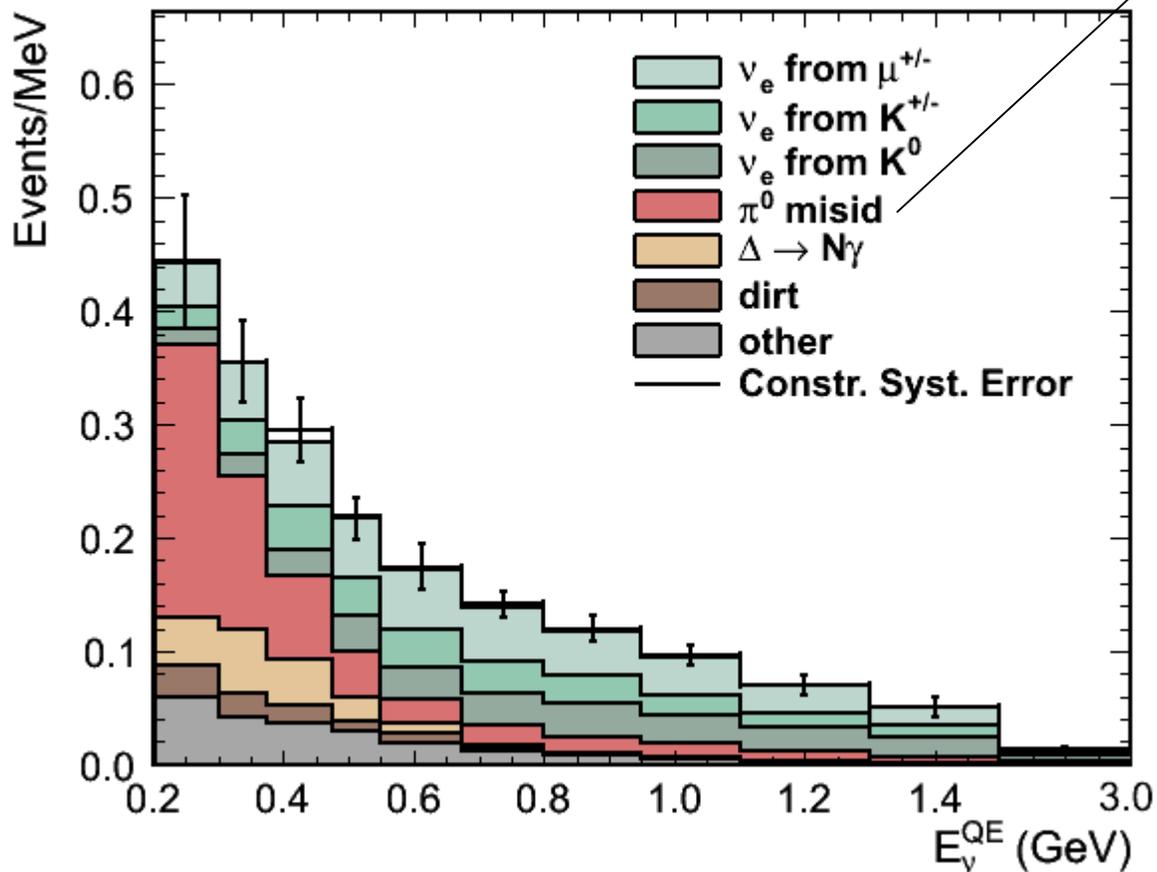


- Sanford-Wang fits world K^+/K^0 data

Phys. Rev. D79, 072002 (2009)

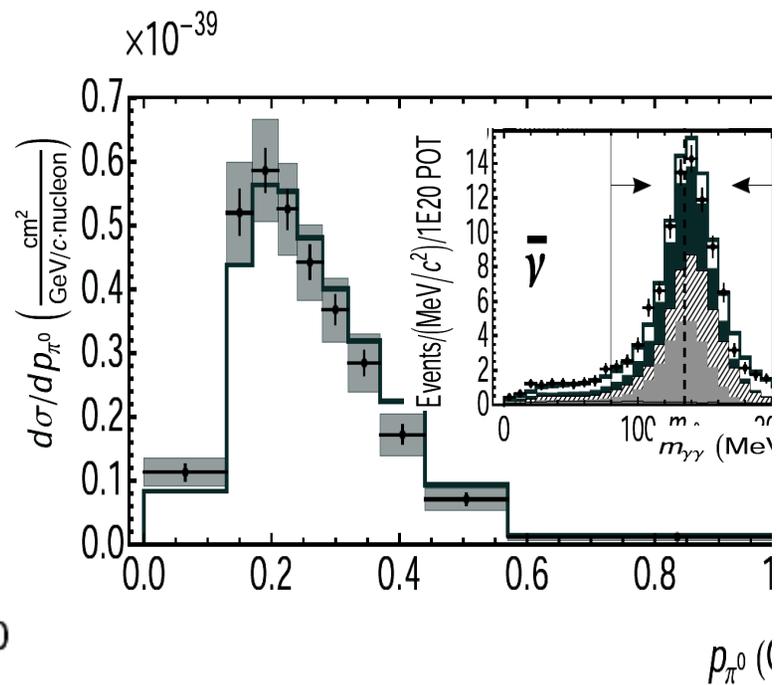
- MiniBooNE data constrained

Background prediction



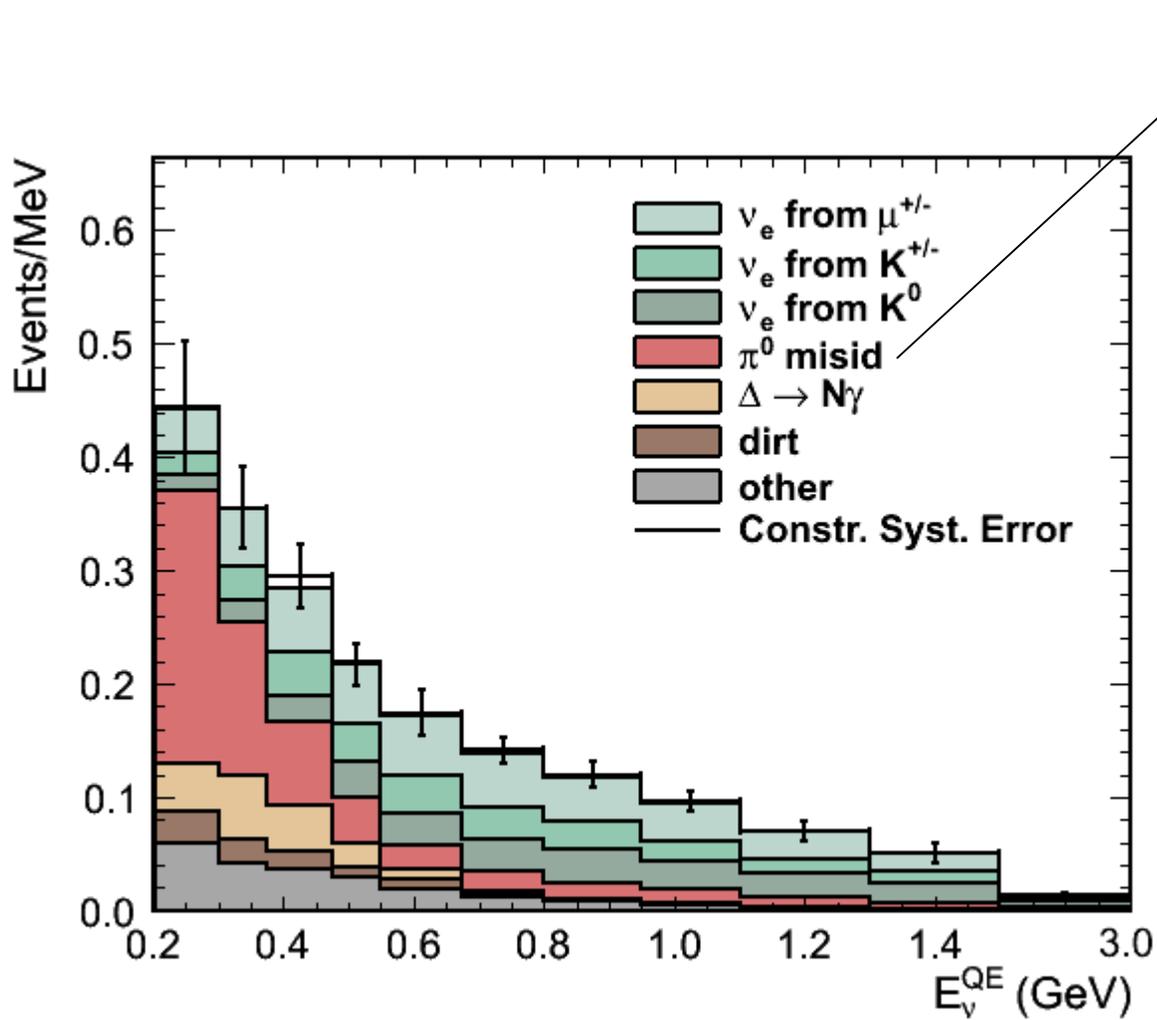
• NC π^0

• MiniBooNE measurement

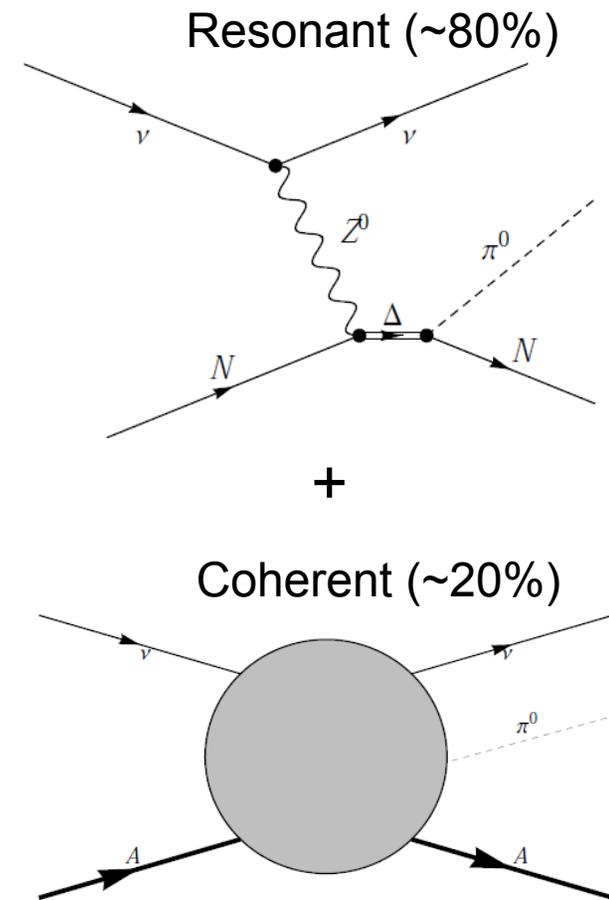


Phys. Rev. D81, 013005 (2010)

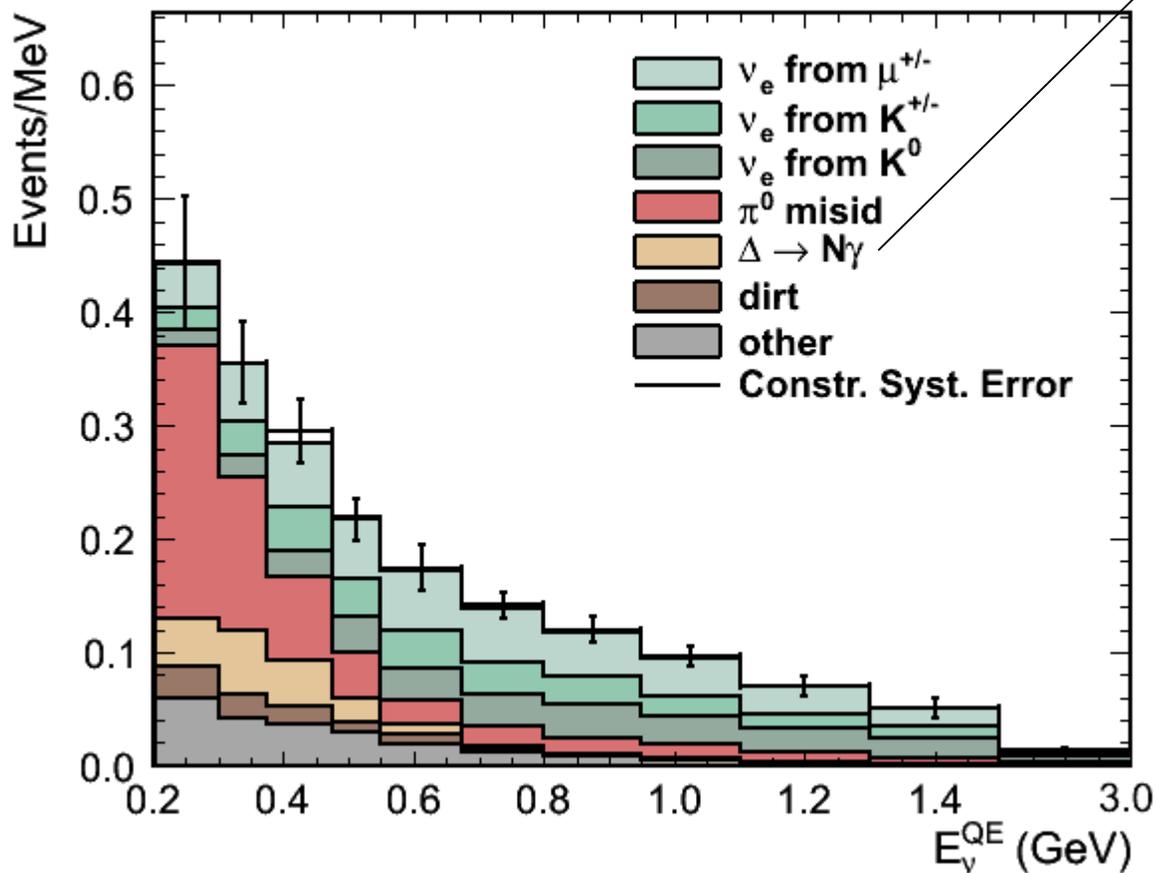
Background prediction



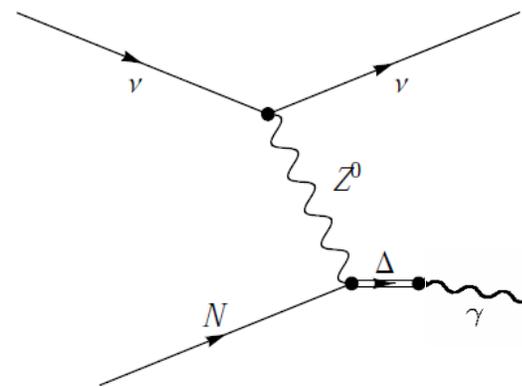
• NC π^0



Background prediction

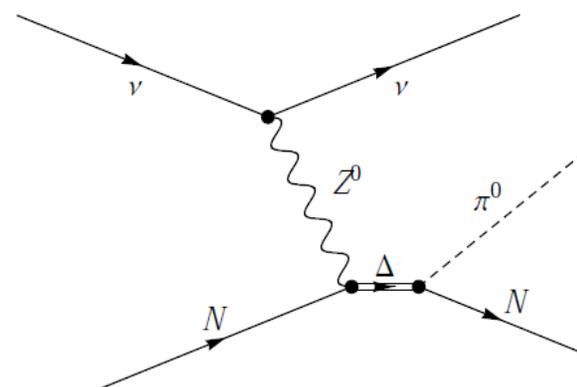


- Radiative delta

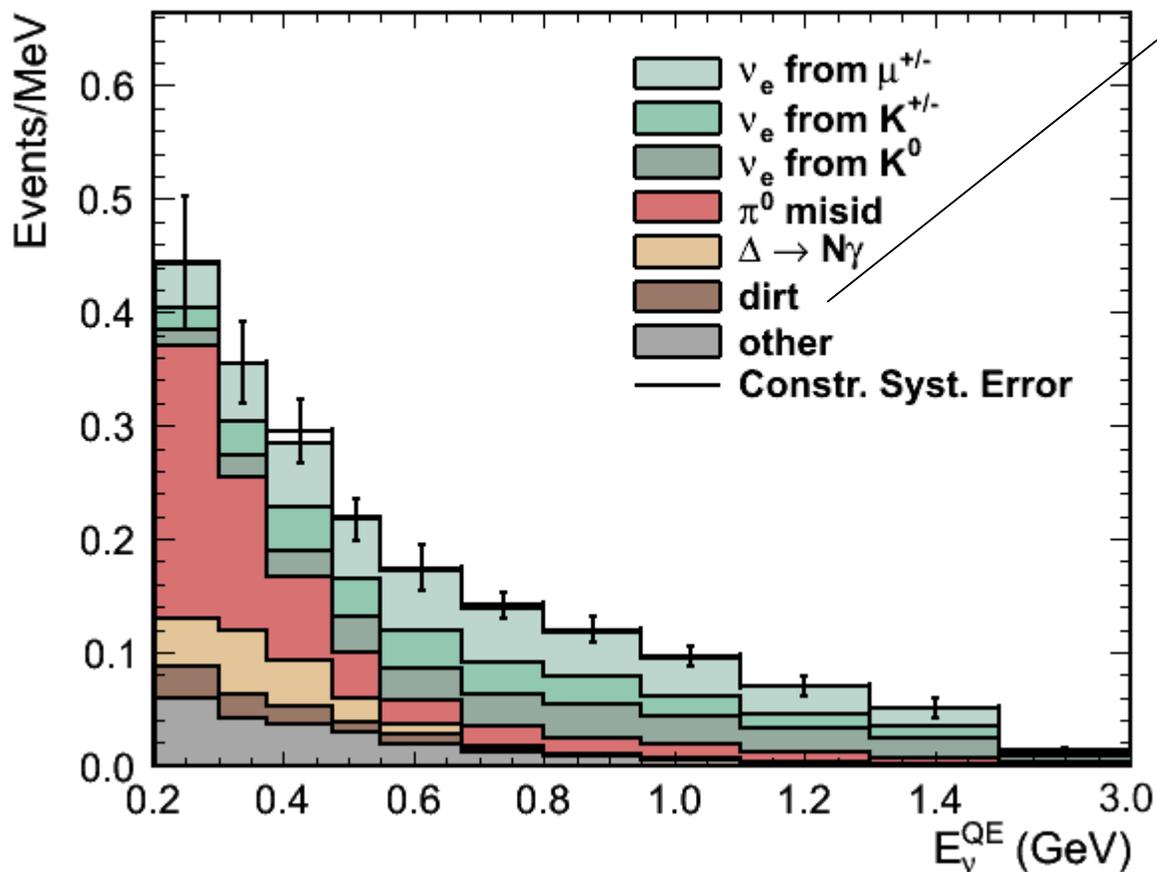


- Use NC π^0 measurer to constrain

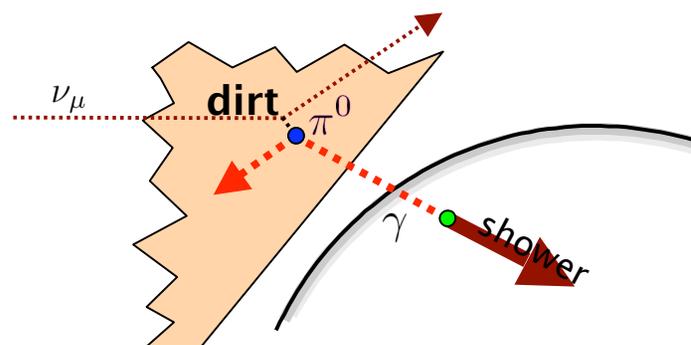
Resonant π^0



Background prediction



- **Dirt:**



- Events at high F pointing toward center of detector
- MiniBooNE measurement

ν_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 pi0 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 ν_e background uncertainties
- Propagate input uncertainties from either MiniBooNE measurement or external data

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- Uncertainty determined by varying underlying cross section model parameters (M_A , Pauli blocking, ...)
- Many of these parameters measured in MiniBooNE

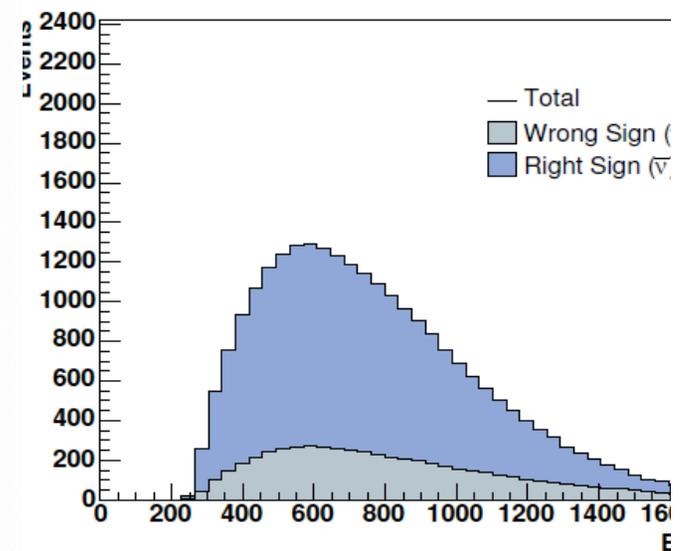
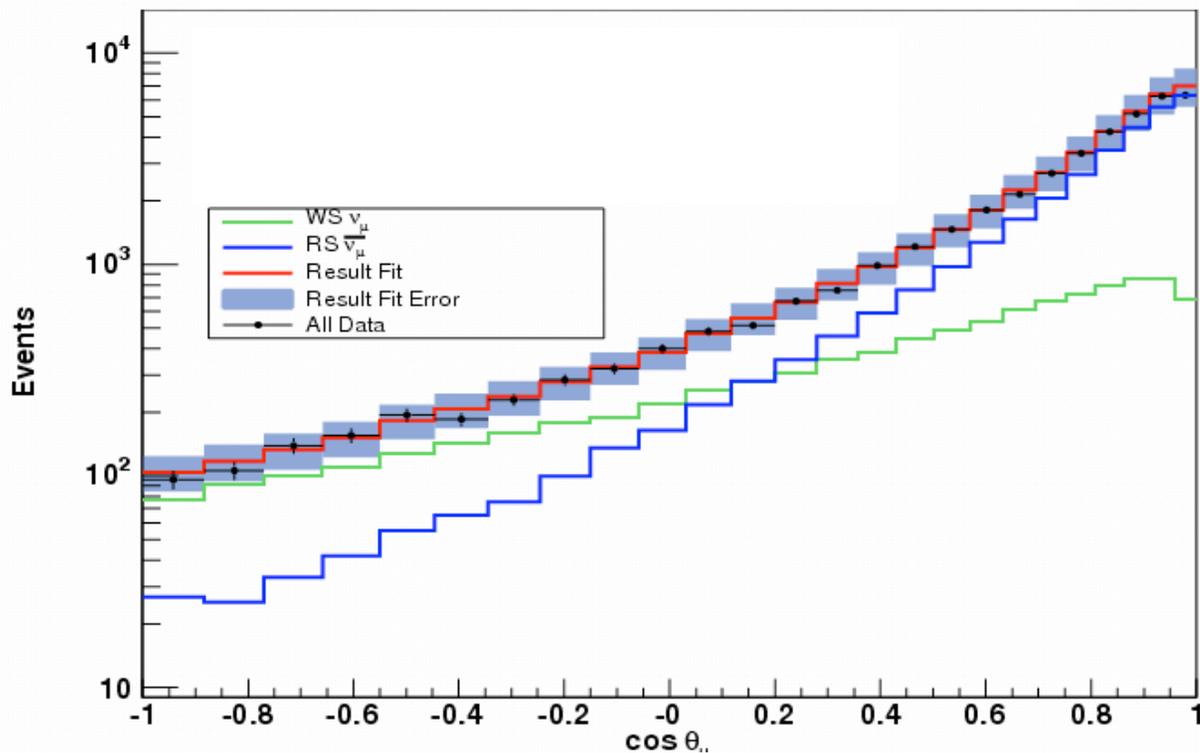
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Electronics & DAQ model	7	2
Optical Model	8	3.7
Total	13.4%	16.0%

- Uncertainty in li creation, propagation and detection in the detector

Signal prediction

- Assuming only right sign oscillates ($\bar{\nu}_\mu$)
- Need to know wrong sign vs right sign
- ν_μ CCQE gives more forward peaked muon



Paper in progress

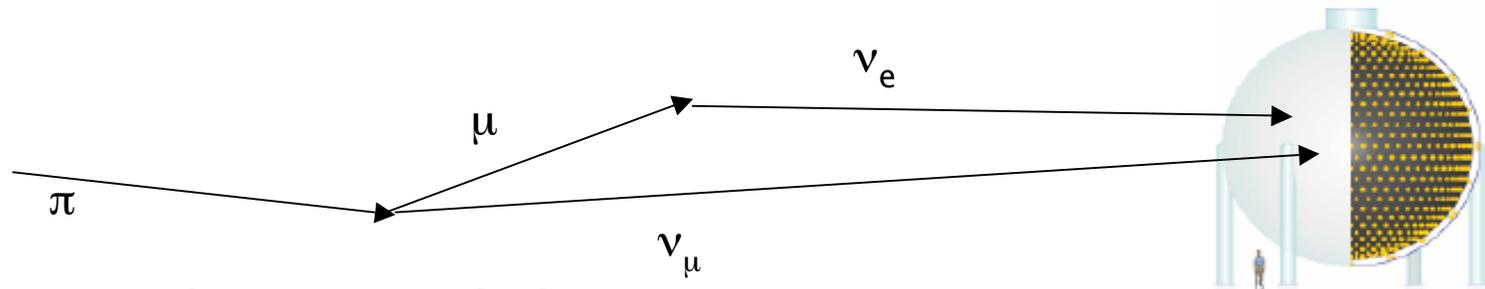
Oscillation Fit Method

- Maximum likelihood fit:

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

- Simultaneously fit

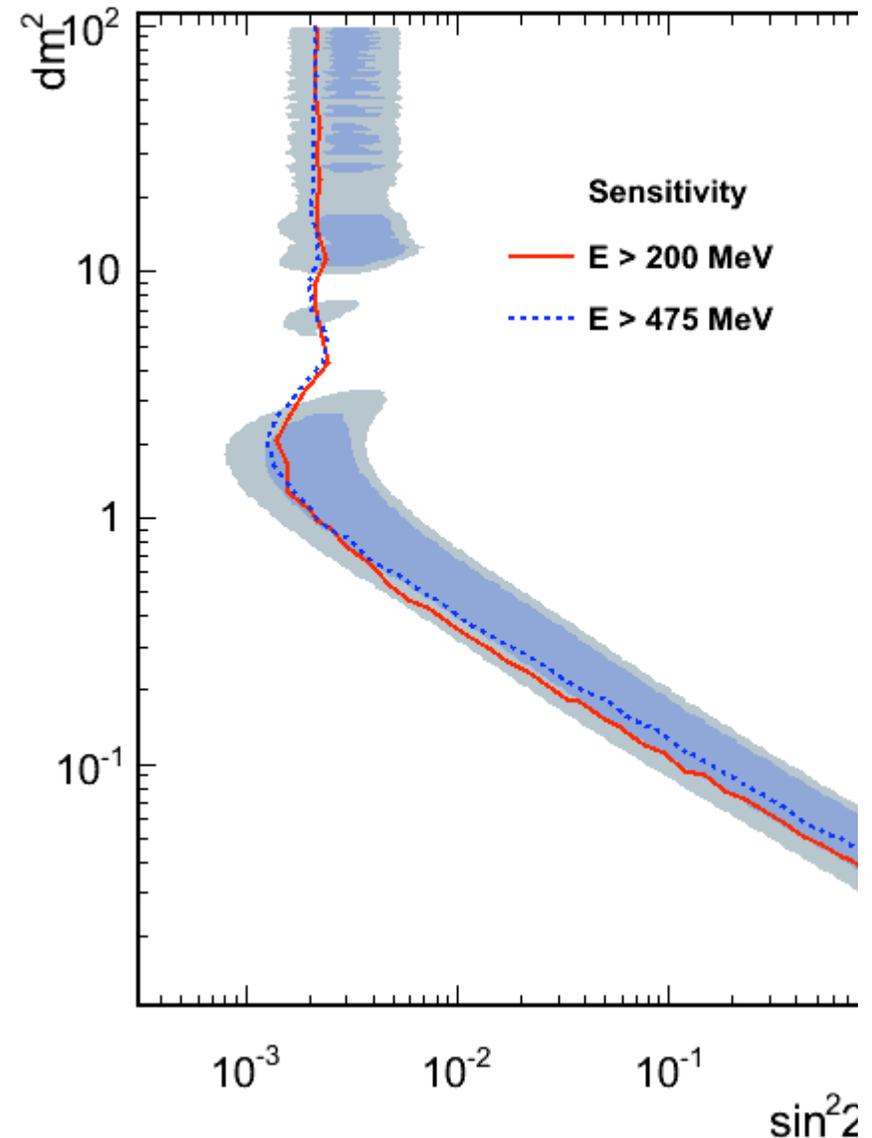
- ν_e CCQE sample
- High statistics ν_μ CCQE sample
- ν_μ CCQE sample constrains many of the uncertainties:
 - Flux uncertainties



- Cross section uncertainties

Sensitivity

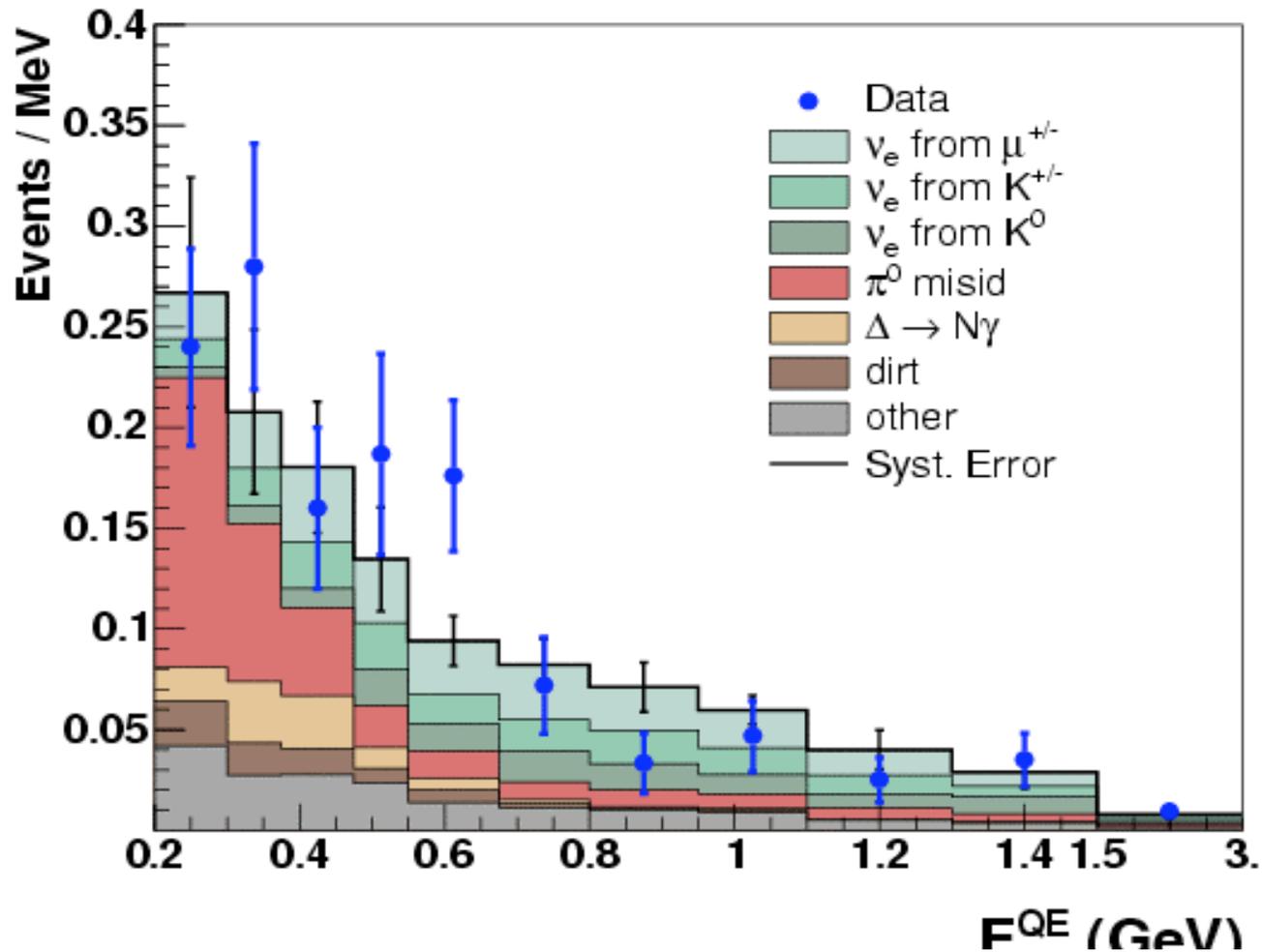
- MiniBooNE uses $E > 475 \text{ MeV}$ for oscillation fits
- Energy region where expect LSND type signal
- $E < 475$:
 - Large backgrounds
 - Big systematics
 - Not sensitive to LSND oscillation signal



Results

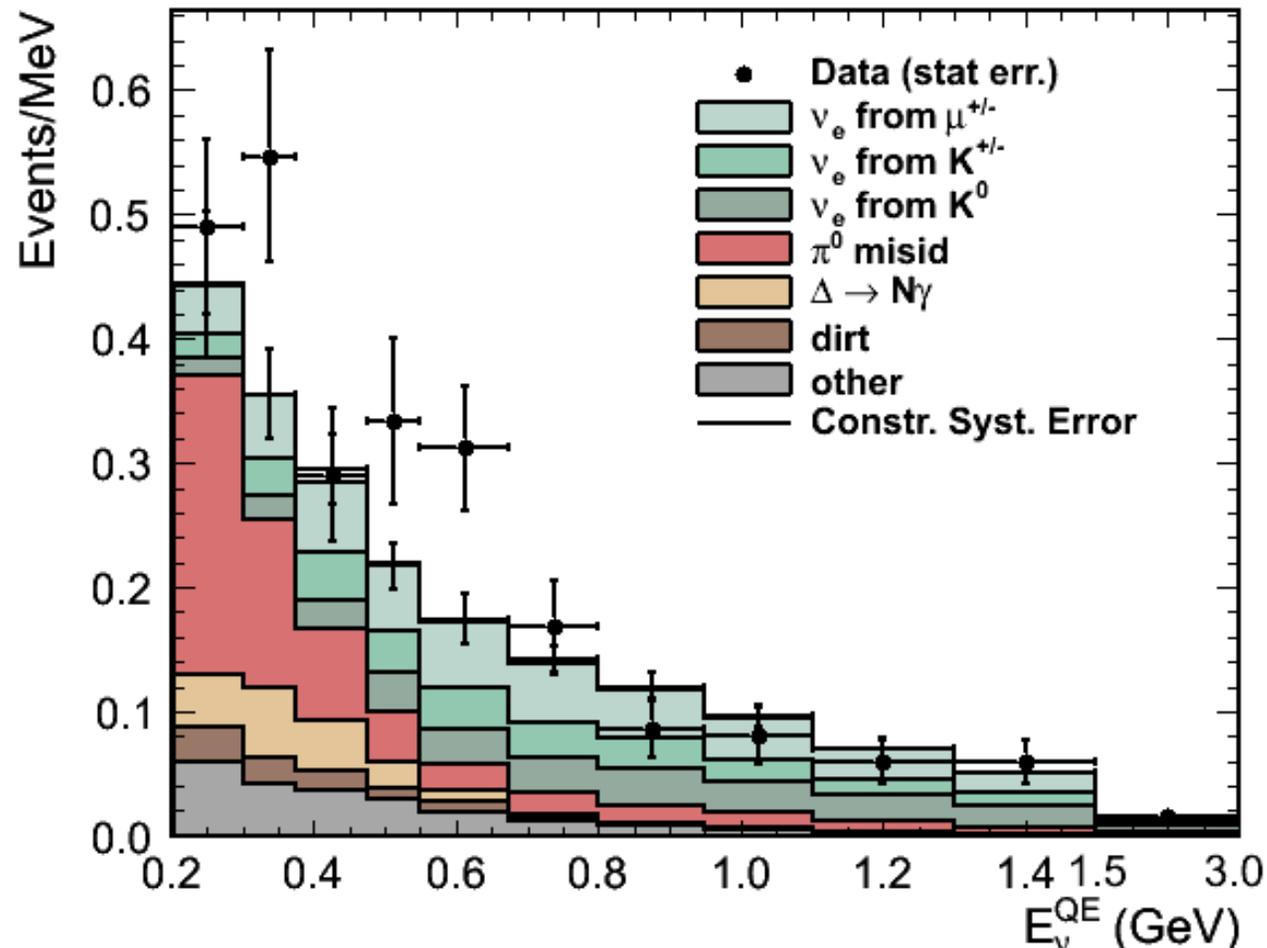
First $\bar{\nu}_e$ appearance result

- W&C December 2008
- Using 3.4e20 POT

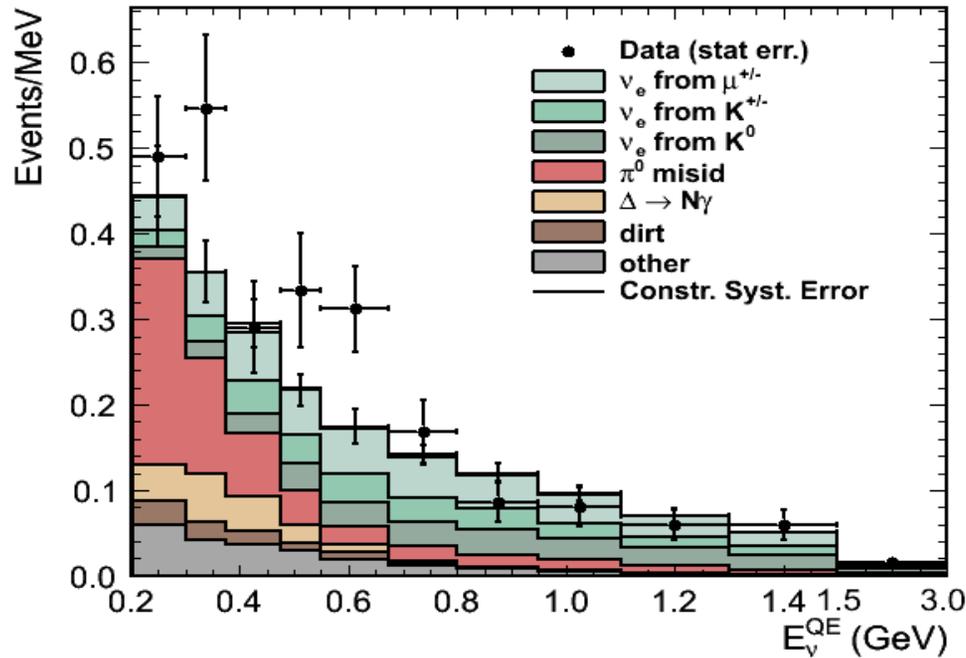


New Anti-neutrino data

- 5.66e20 POT
- ~70% more data



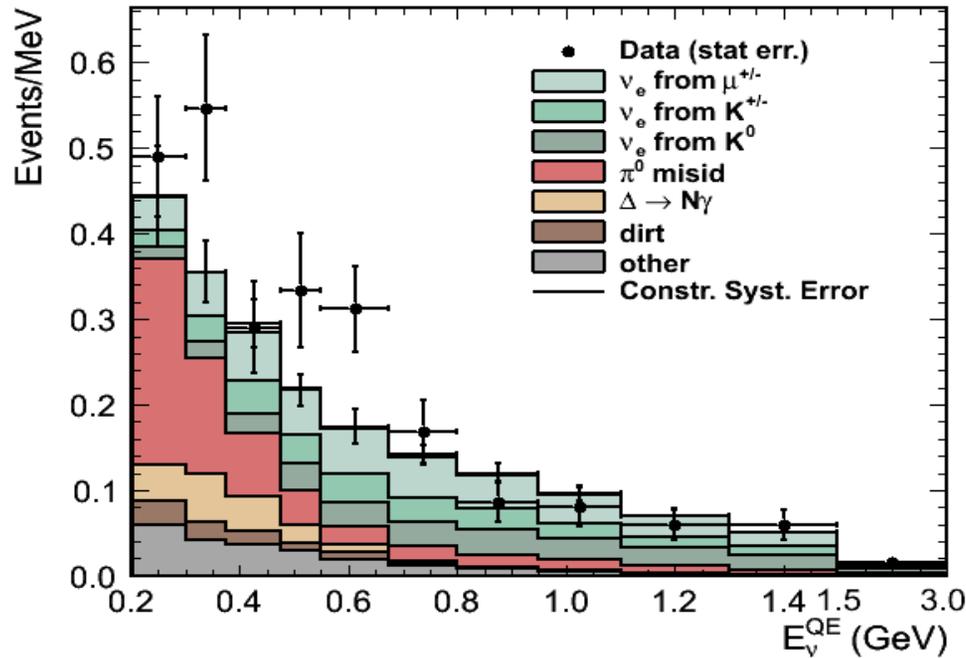
New Anti neutrino data



- Excess of events in the 200-475MeV and 475-1250MeV region
- Assuming only neutrinos produce low energy excess expected 11.6 events in 200-475MeV region

	200-475MeV	475-1250MeV
Data	119	120
MC	100.5±14.3	99.1±14.0
Excess	18.5±14.3	20.9±14.0
LSND Best Fit	7.6	22
Expectation from	11.6	0
LSND+Low E	19.2	22

New Anti neutrino data



- Excess of events in both 200-475MeV and 475-1250MeV region

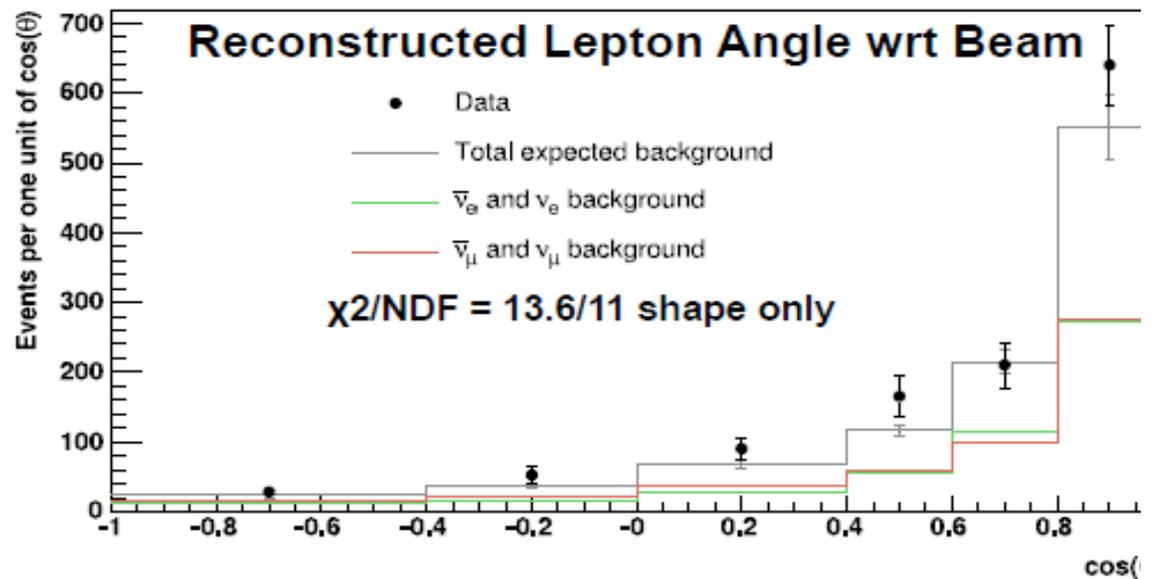
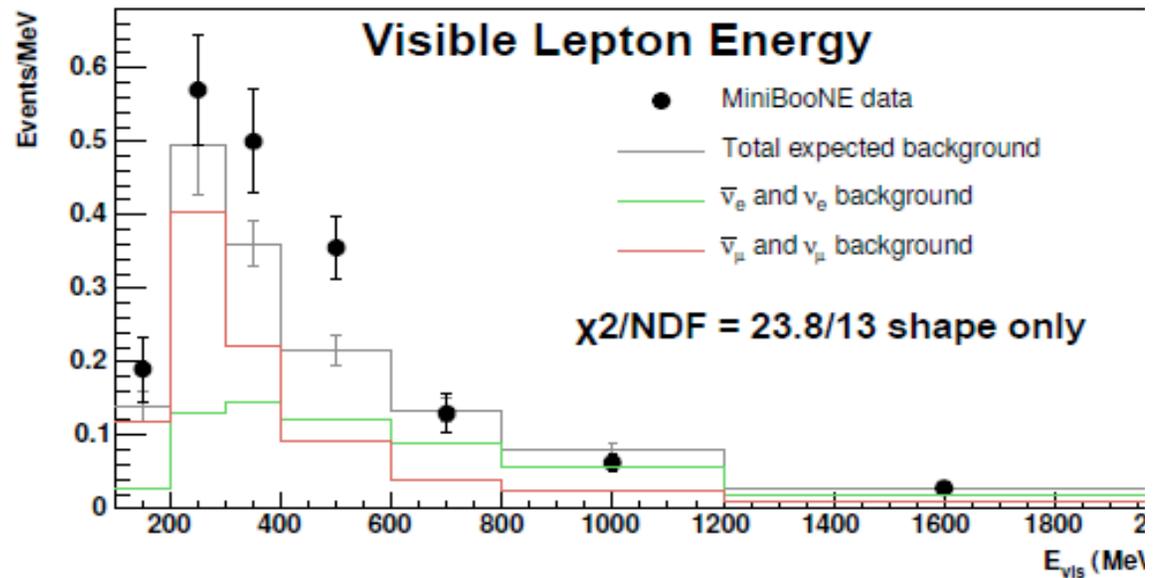
- If low E excess is due to Standard Model NC gamma-ray mechanism eg Axial Anomaly, expect ~67 excess events in 200-475MeV

	200-475MeV	475-1250MeV
Data	119	120
MC	100.5±14.3	99.1±14.0
Excess	18.5±14.3	20.9±14.0
LSND Best Fit	7.6	22
Expectation from	11.6	0
LSND+Low E	19.2	22

(scaling excess by the ratio of total flux in $\bar{\nu}_e$ ν_e mode)

Other kinematic distributions

- $5.66e20$ POT
- $\bar{\nu}_e$ sample

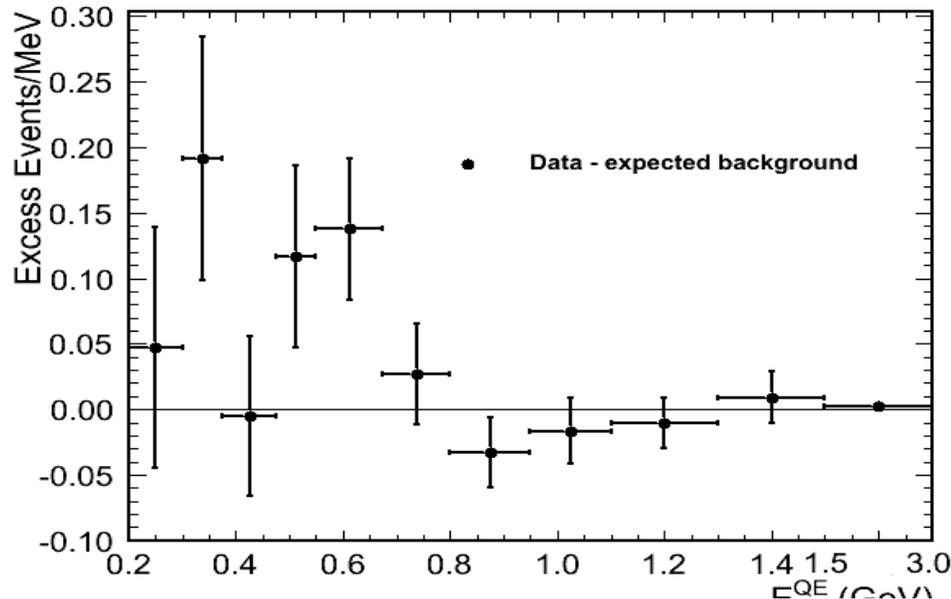


Null probability

- Absolute χ^2 probability of null point (background only) - model independent
- Frequentist approach

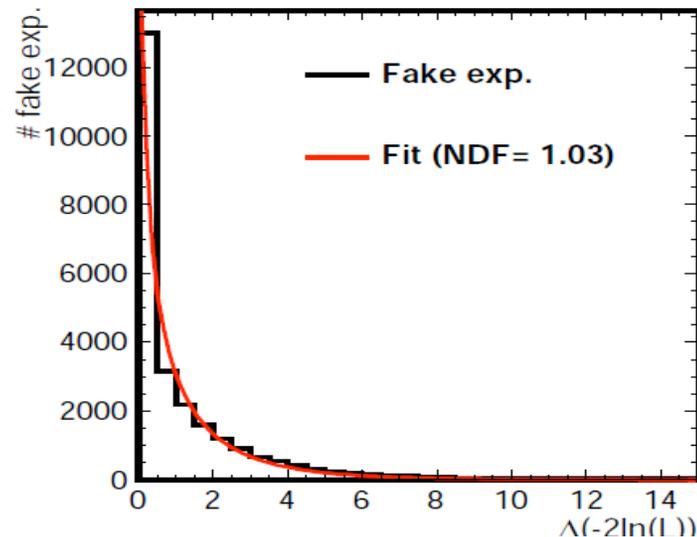
	chi2/NDF	probability
E>475MeV	26.8/14.9	3.0%
* E>200MeV	33.2/18.0	1.6%

* No assumption about low E excess made



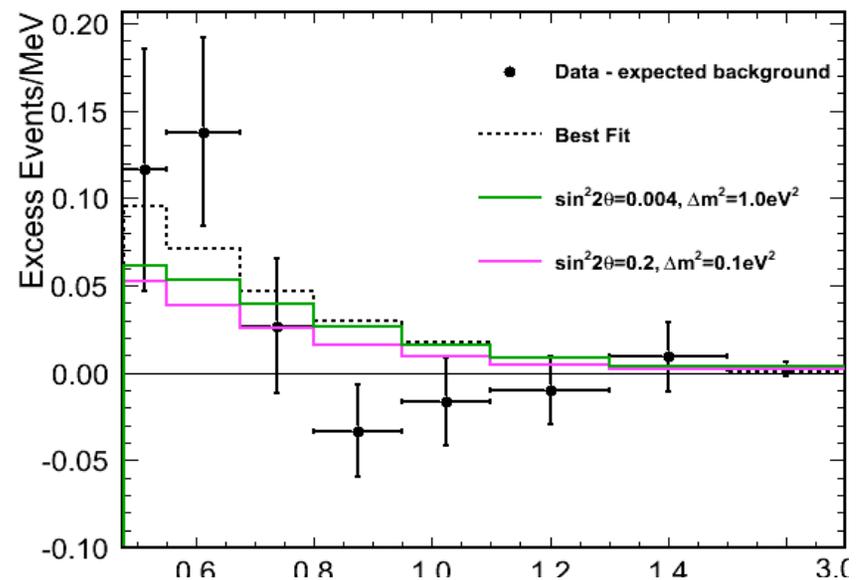
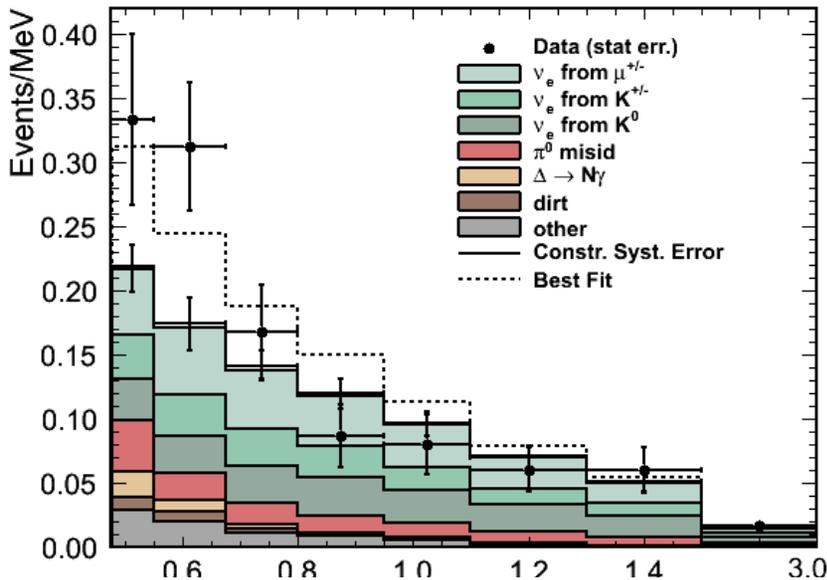
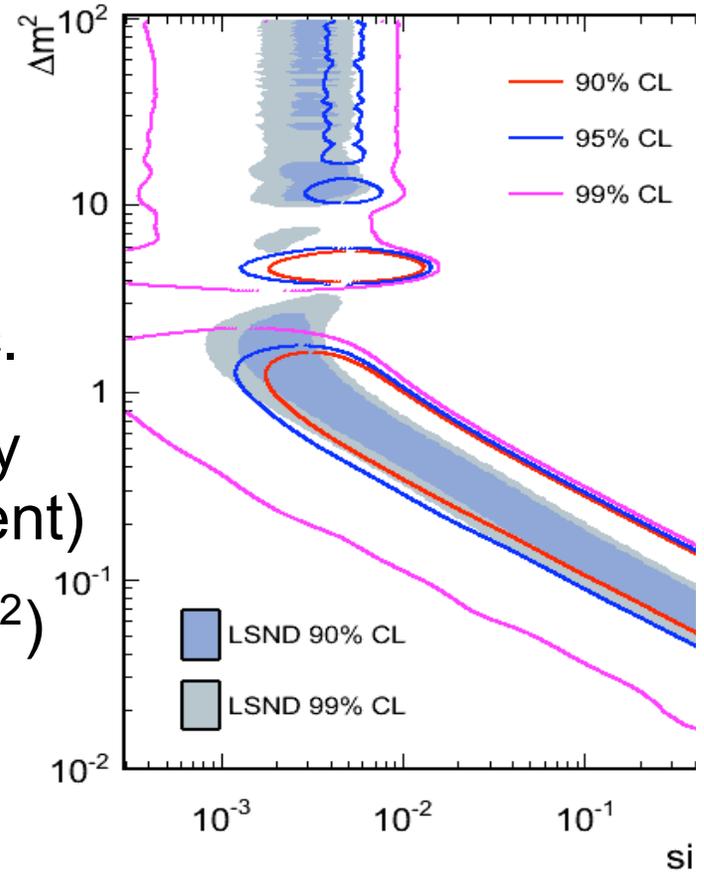
Drawing contours

- Frequentist approach
- Fake data experiments on grid of $(\sin^2 2\theta, \Delta m^2)$ points
- At each point find the cut on likelihood ratio for $X\%$ confidence level such that $X\%$ of experiments below cut
- Fitting two parameters, so naively expect χ^2 distribution with 2 degrees of freedom, in reality at null it looks more like 1 degree freedom



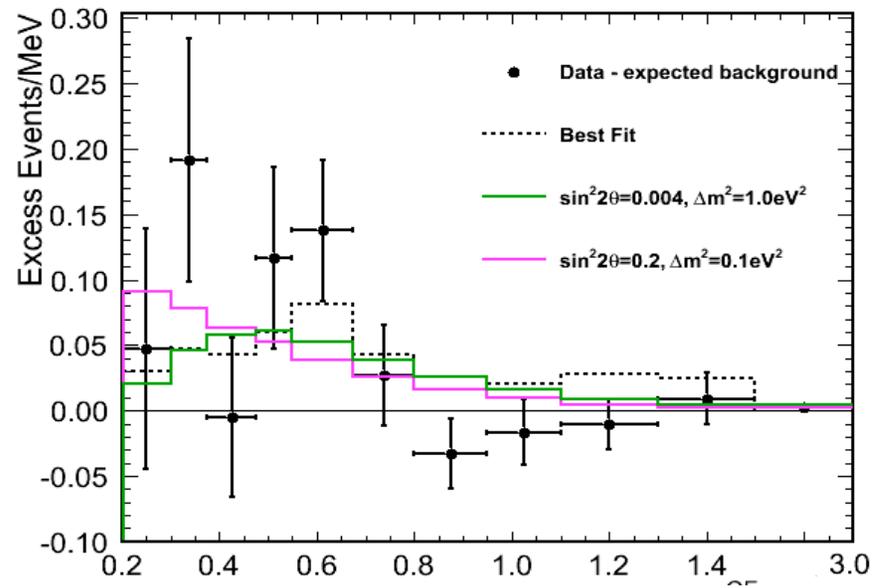
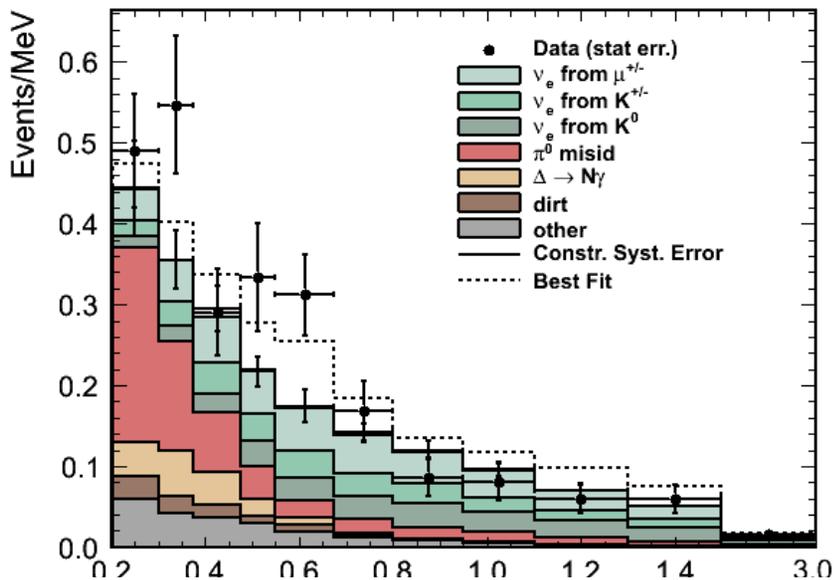
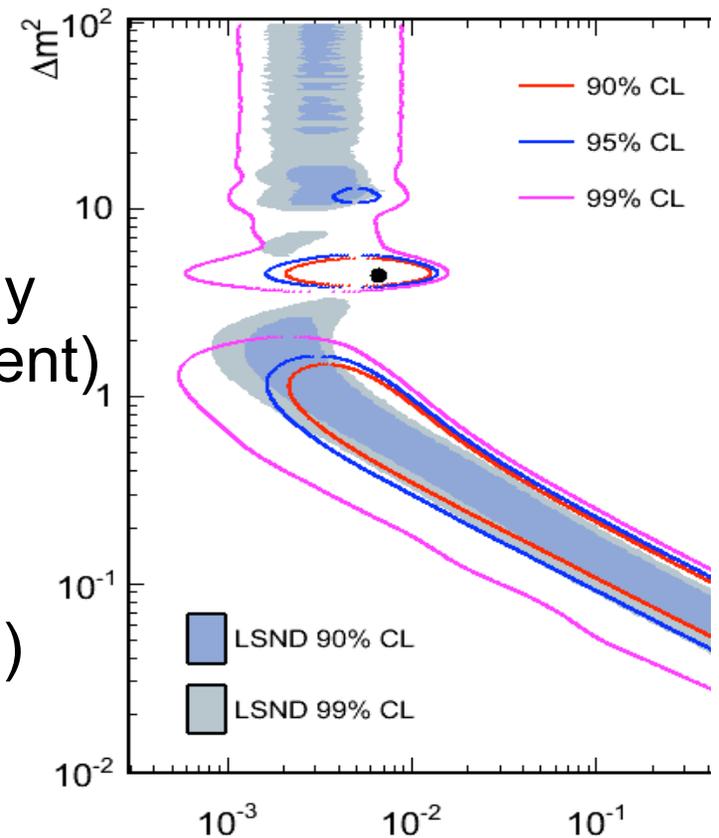
Fit E>475

- 5.66E20 POT
- E>475 is signal region for LSND type osc.
- Oscillations favored over background only hypotheses at 99.4% CL (model dependent)
- Best fit $(\sin^2 2\theta, \Delta m^2) = (0.9584, 0.064 \text{ eV}^2)$
 $\chi^2/\text{NDF} = 16.4/12.6$
 $p=20.5\%$



E > 200 MeV

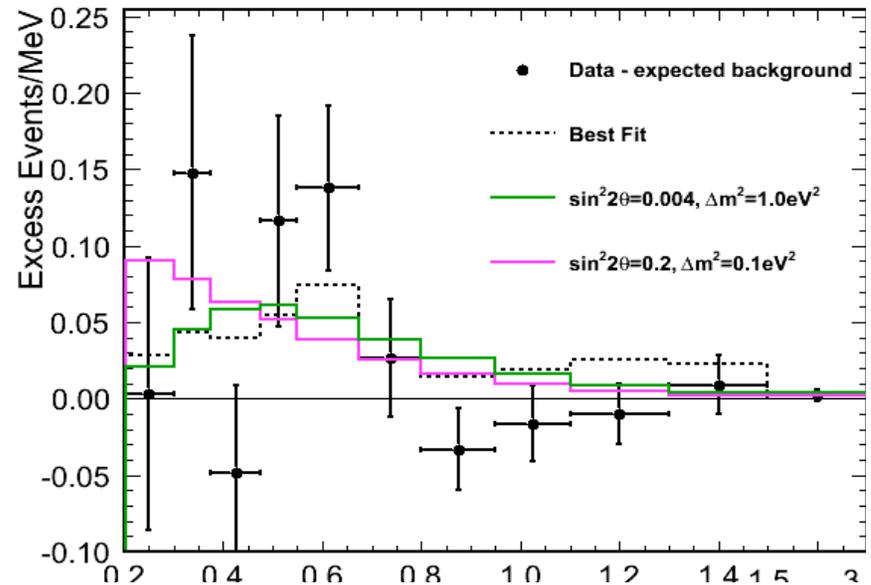
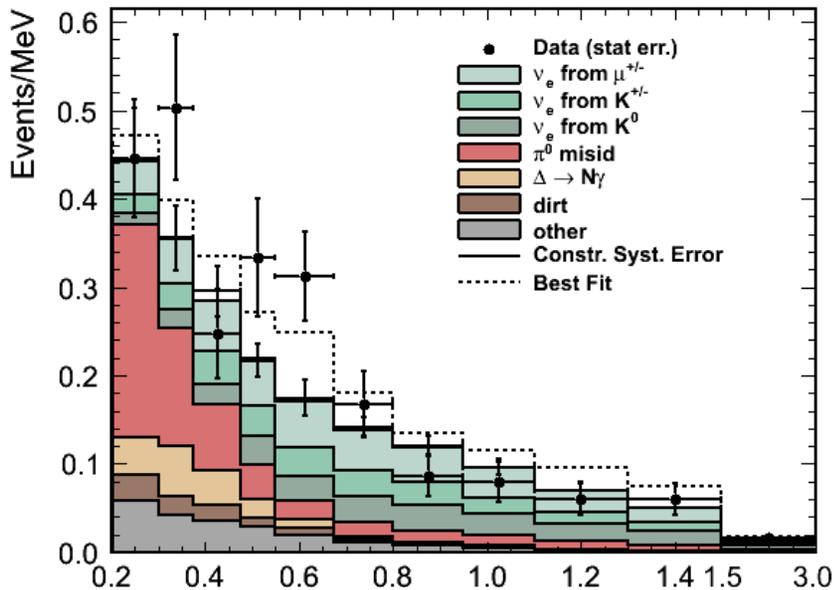
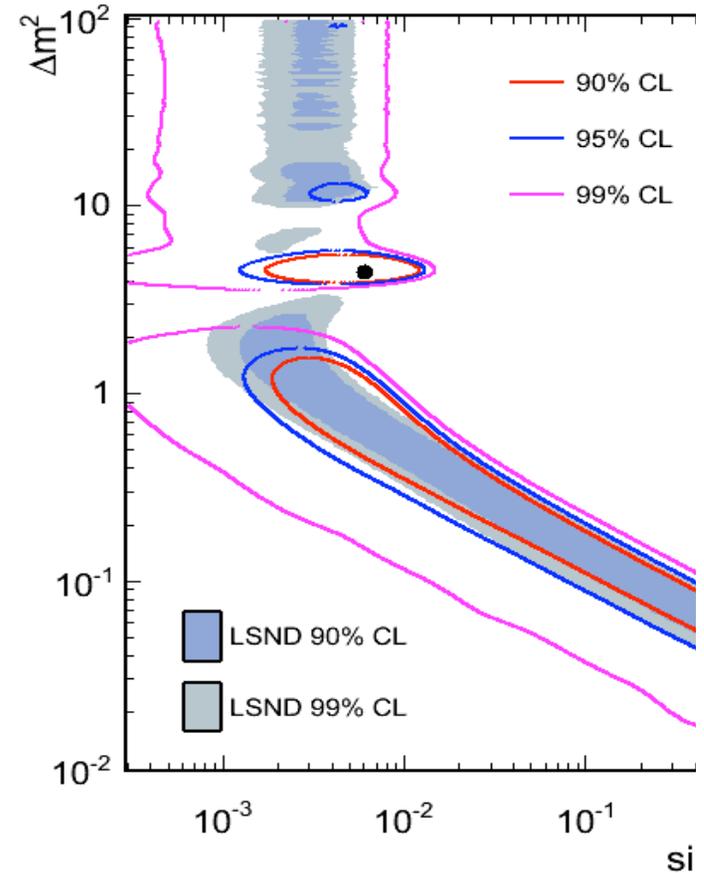
- 5.66E20 POT
- Oscillations favored over background only hypotheses at 99.6% CL (model dependent)₁
- No assumption made about low energy excess
- Best fit ($\sin^2 2\theta$, Δm^2) = (0.0066, 4.42 eV²)
 χ^2/NDF = 20.4/15.3
p=17.1%



$E > 200 \text{ MeV}$

- Subtract excess produced by neutrinos in $\bar{\nu}$ mode (11.6 events)
- $E < 475 \text{ MeV}$:
 - Large background
 - Not relevant for LSND type osc.
 - Big systematics
- Null $\chi^2 = 32.8$; $p = 1.7\%$

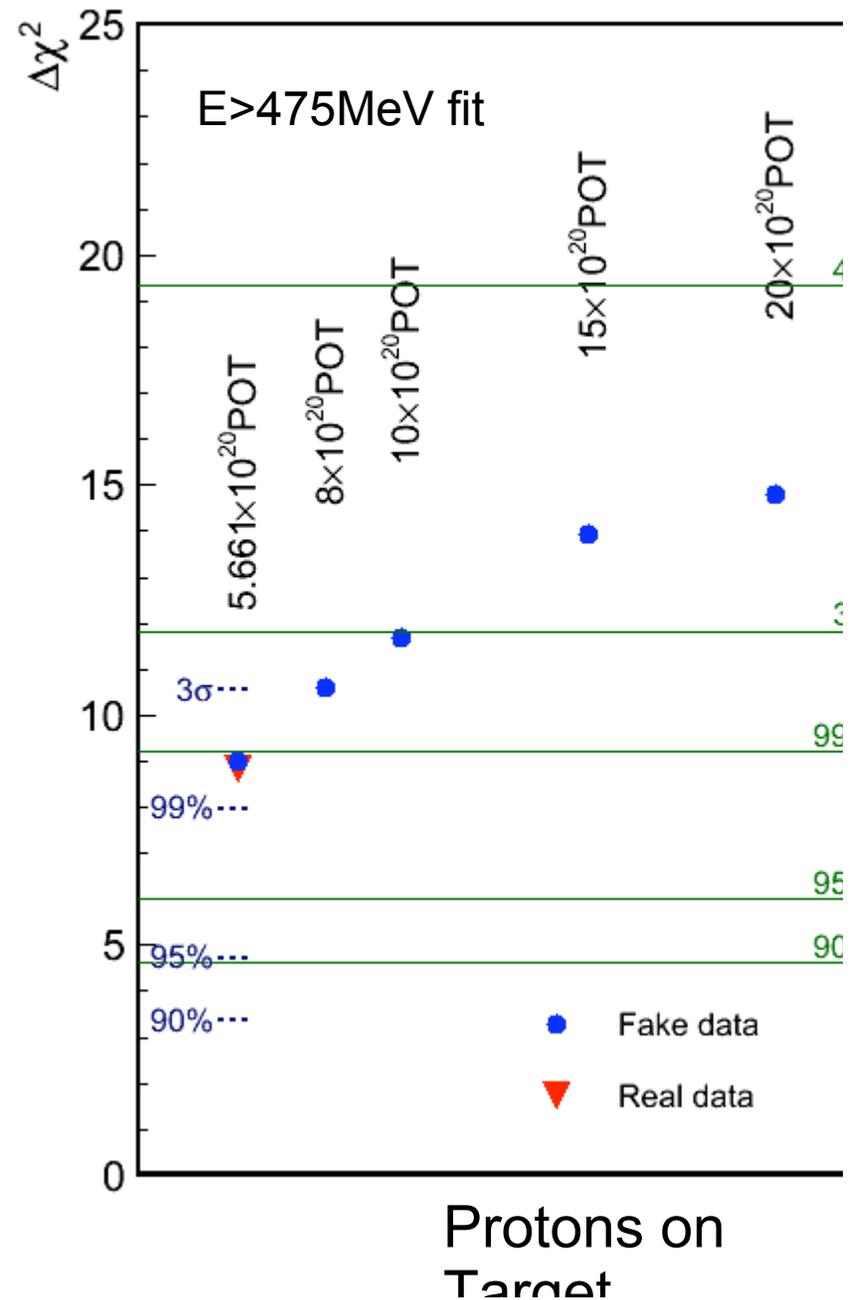
Best fit $(\sin^2 2\theta, \Delta m^2) = (0.0061, 4.42 \text{ eV}^2)$
 $\chi^2/\text{NDF} = 21.6/15.3$; $p = 13.7\%$



Future outlook

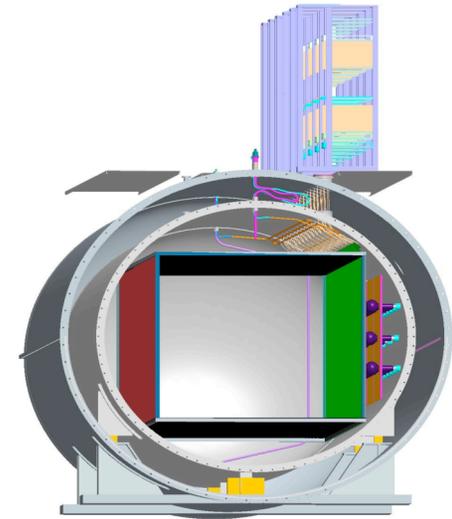
Future sensitivity

- MiniBooNE approved for a total of $1e21$ POT
- Potential exclusion of null point assuming best fit signal
- Combined analysis of ν_e and $\bar{\nu}_e$



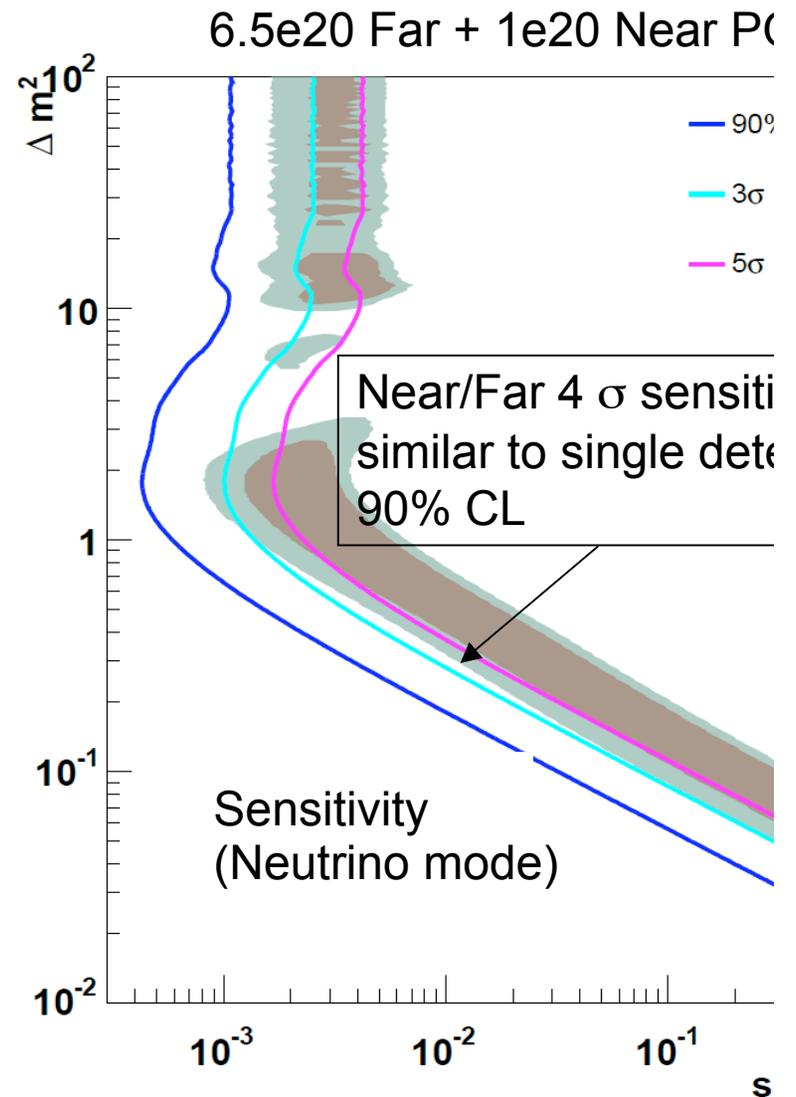
Future experiments

- Microboone
 - CD1 approved
 - Address low energy excess
- Few ideas under consideration:
 - Move or build a MiniBooNE like detector at 200m (LOI arXiv:0910.2698)
 - Redoing a stopped pion source at ORNL (OscSNS - <http://physics.calumet.purdue.edu/~oscsns/>) or Project X
 - A new search for anomalous neutrino oscillations at the CERN-PS (arxiv:0909.0355v3)



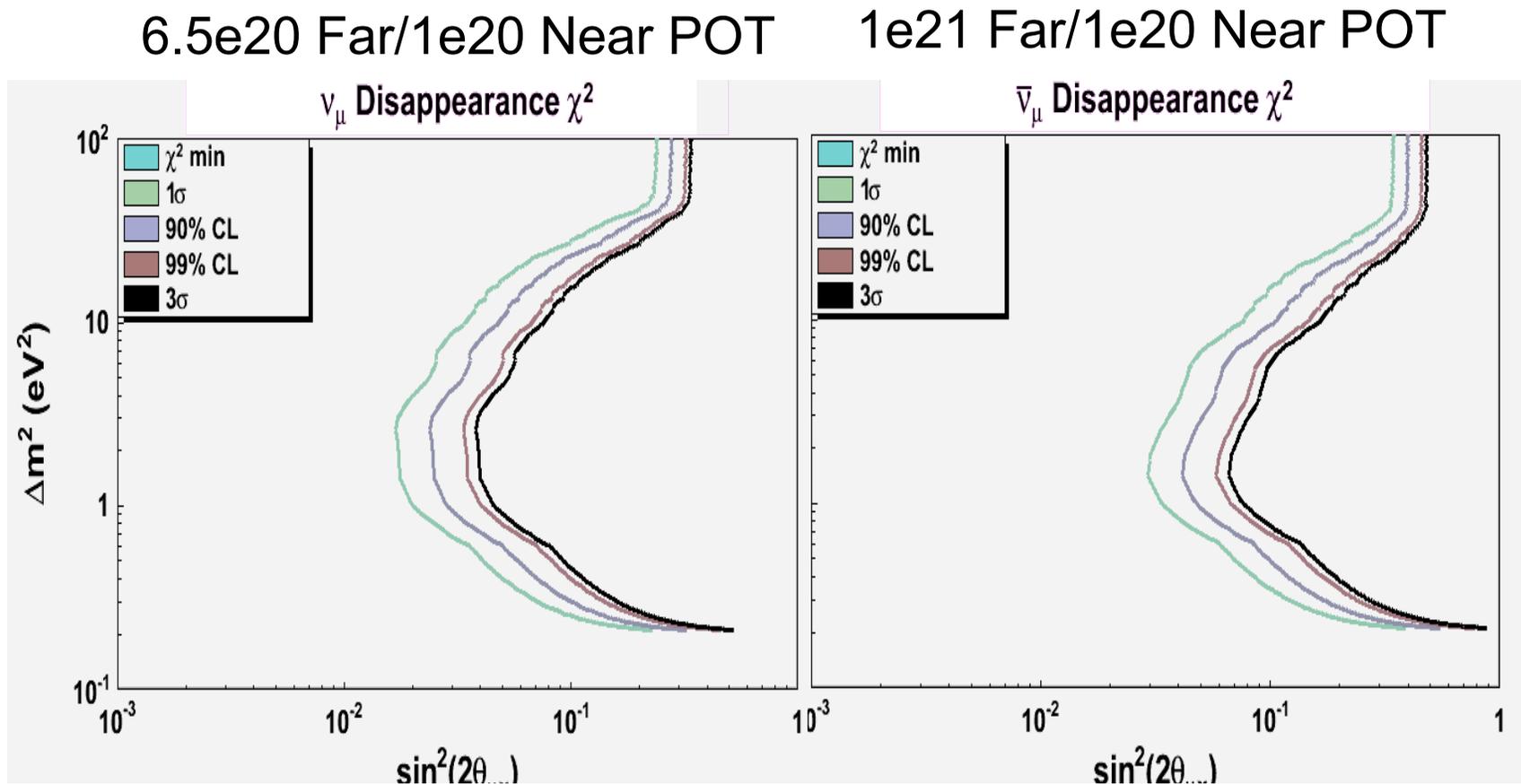
BooNE

- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Present neutrino low energy excess is 6 sigma statistical; 3 sigma when include systematics
- Study L/E dependence
- Gain statistics quickly, already have far detector data



BooNE

- Better sensitivity to ν_μ ($\bar{\nu}_\mu$) disappearance
- Look for CPT violation ($\nu_\mu \rightarrow \nu_\mu \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)



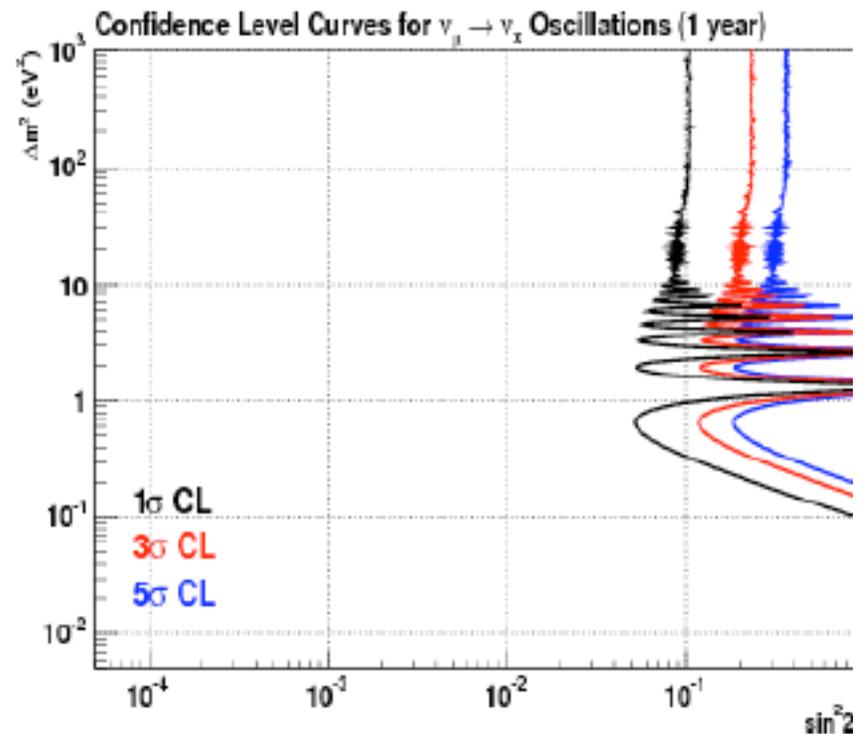
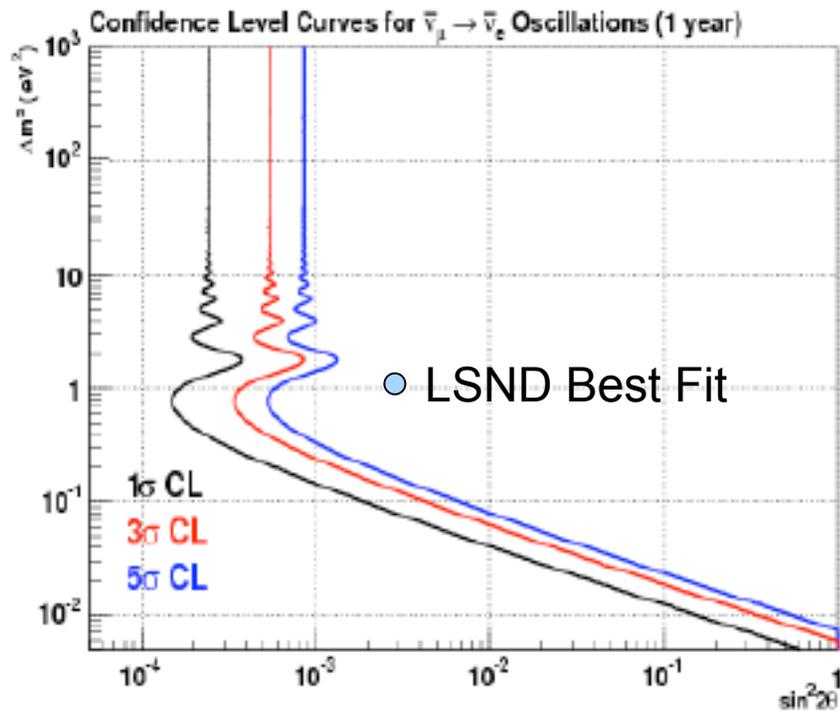
OscSNS

- Spallation neutron source at ORNL
- 1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos



OscSNS

- $\bar{\nu}_e$ appearance (left) and ν_μ disappearance sensitivity (right) for 1 year of running

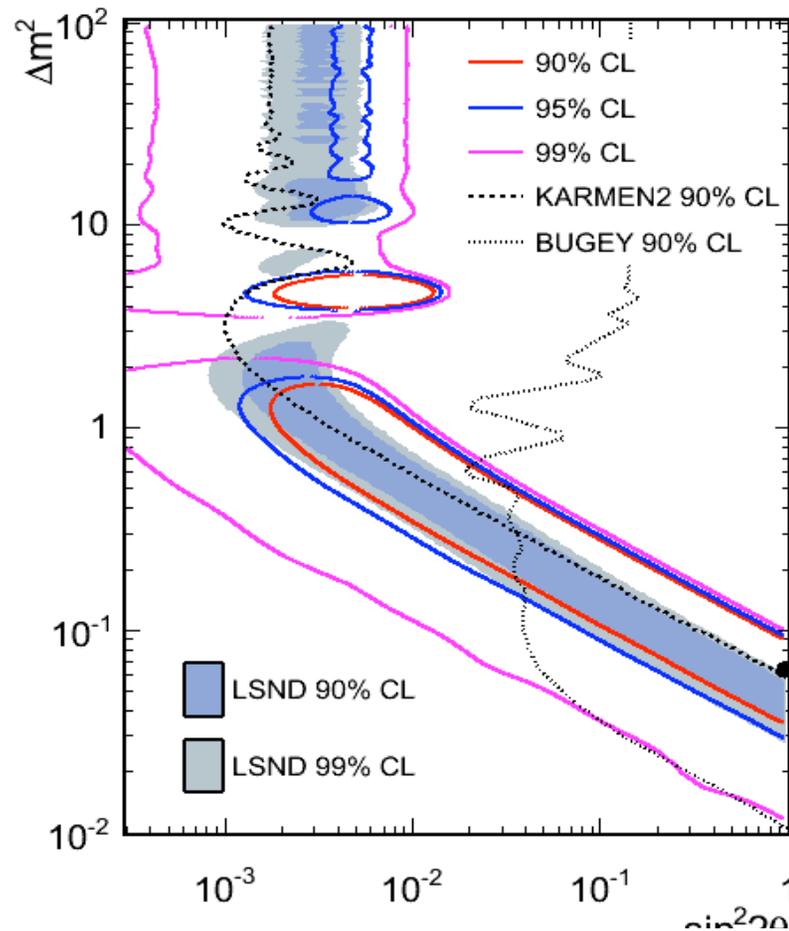


Summary

- MiniBooNE analyzed anti-neutrino data corresponding to $5.66e20$ POT
- See 1.3σ excess of events at low (200-475MeV) energy
- See excess of events at high (475-1250MeV) energy with absolute χ^2 probability $p=3.0\%$ for null signal (model independent)

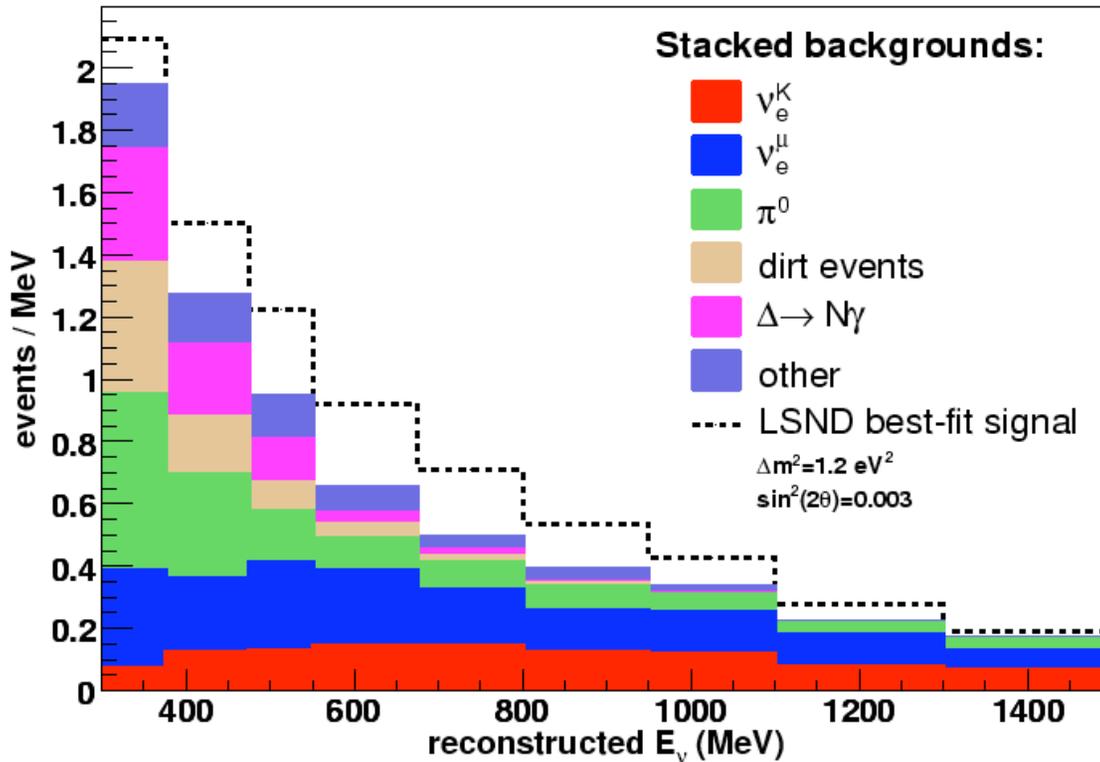
Summary

- Oscillations favored over background only hypotheses at 99.4% CL ($E > 475 \text{ MeV}$)



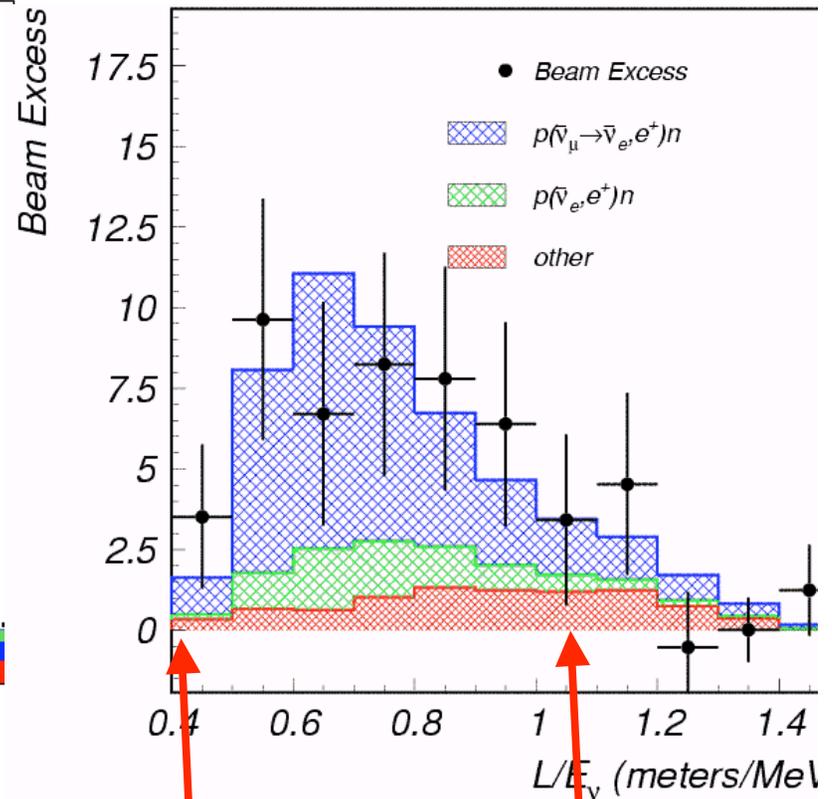
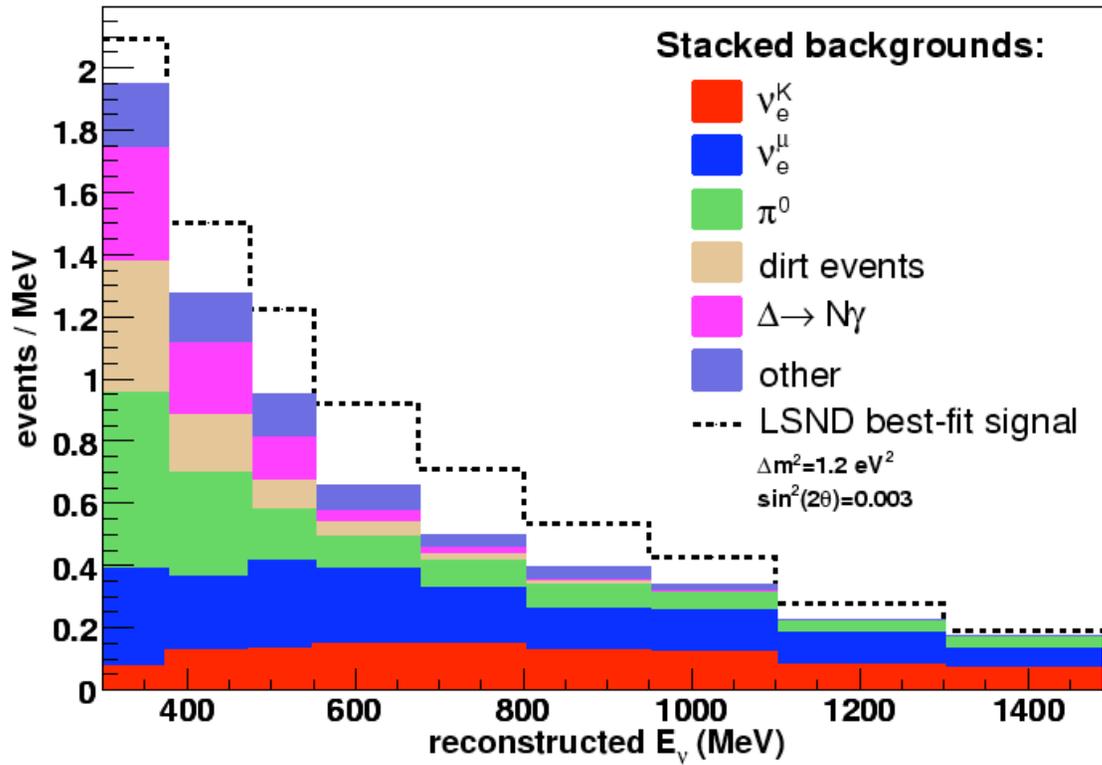
Backup

Reminders of some analysis choices



- Data bins chosen to be variable to minimize N bins without sacrificing shape information
 - Technical limitation on N bins using building syst error covariance matrix with limited statistics MC
- First step in unblinding revealed poor χ^2 for oscillation fits extended below 475 MeV
 - Region below 475 MeV not improved LSND-like signal -> chose to cut and proceed

Reminders of some pre-unblinding choices



- Why is the 300-475 MeV region unimportant?
 - Large backgrounds from mis-ids reduce S/B
 - Many systematics grow at lower energies
 - Most importantly, small S/B so not a good L/E region to look for LSND type oscillations

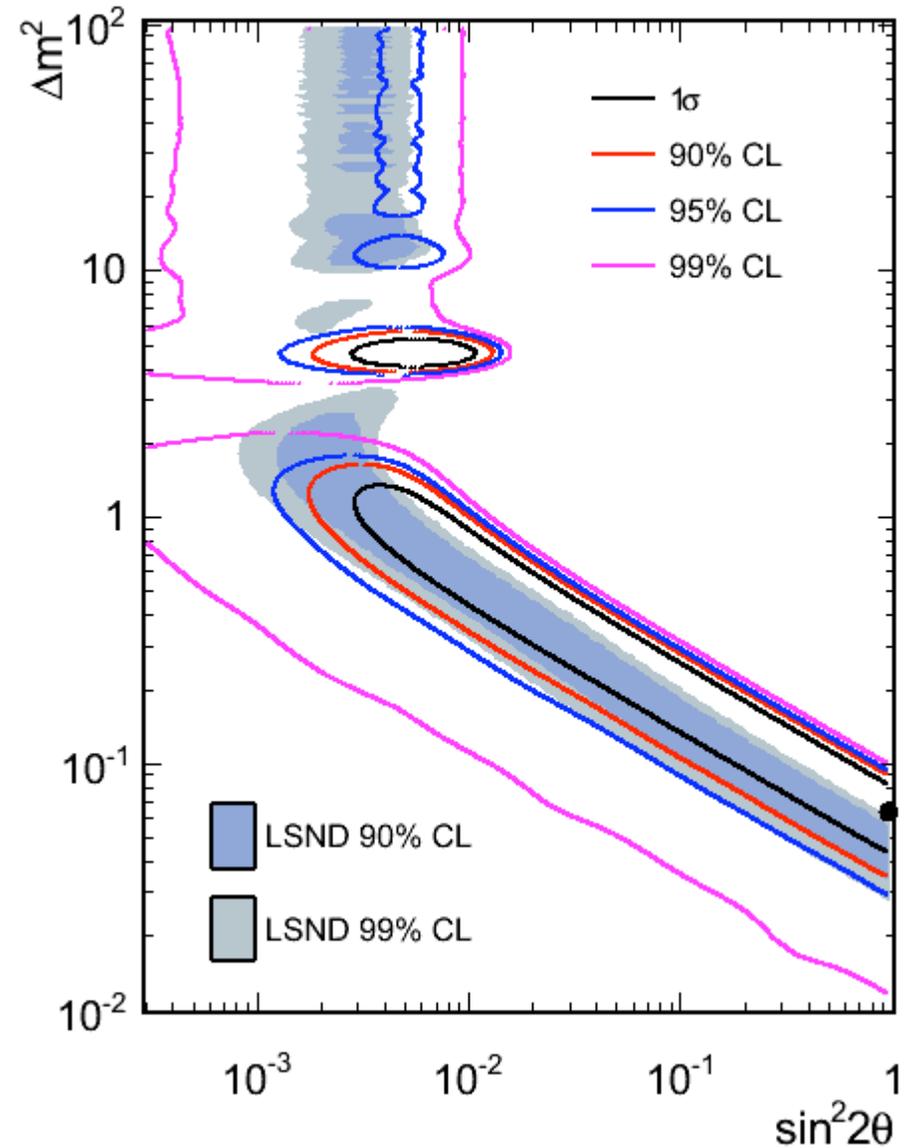
1250

475

Energy in MB [MeV]

$E > 475$ MeV

- 1 sigma contour includes $0.003 < \sin^2 2\theta < 1$



Subevent structure

- ν_μ CCQE have 2 sub-events separated in time
- Multiple hits in ~ 100 ns window form a subevent

