MINIBOONE

2008!

ν_μ

ν_e

$\bar{\nu}_e$

$\bar{\nu}_\mu$

First Anti-neutrino results!

2010: Latest Results from MiniBooNE

H. Ray

Intrigue in Oscillation Results

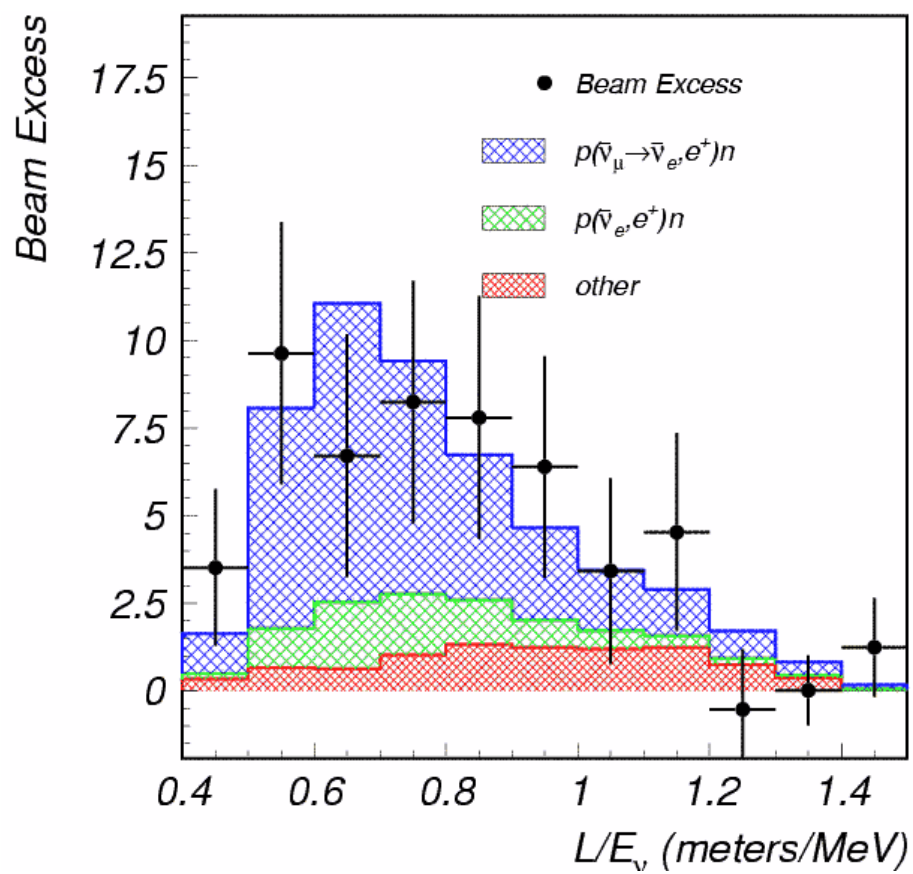
MiniBooNE motivated by an observed excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam (LSND experiment in 1990s)

Used CCQE interaction

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

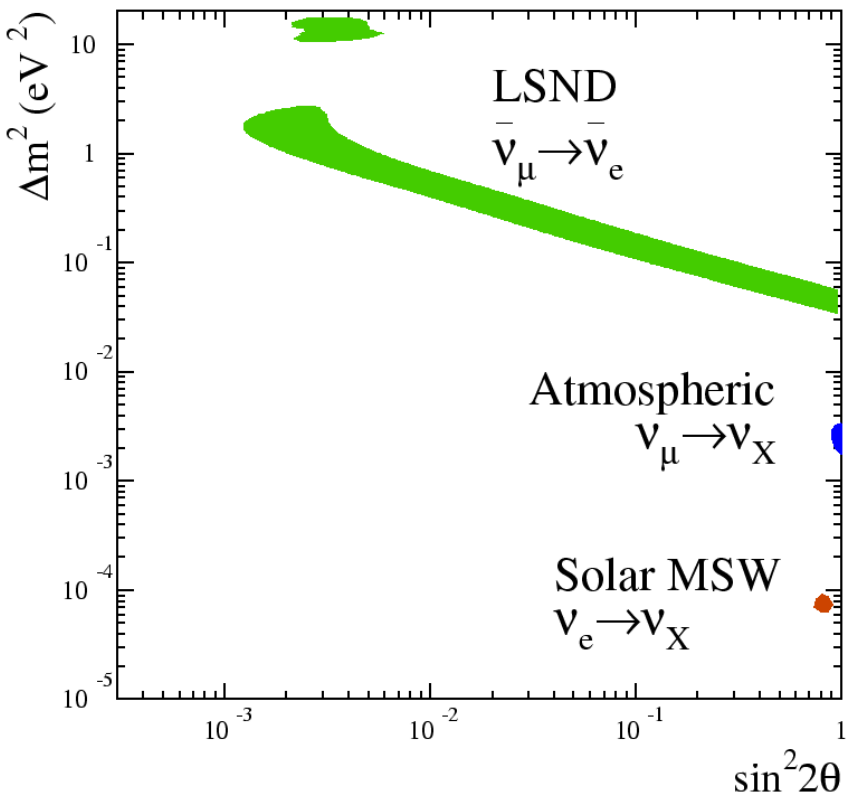
Excess: 87.9 ± 22.4 ± 6.0 (3.8 σ)

Highly controversial result



Phys. Rev. Lett. 77:3082-3085 (1996)
Phys. Rev. C 58:2489-2511 (1998)

LSND = too many masses!



LSND oscillation: $\Delta m^2 \sim 1 eV^2$

Atmospheric oscillation: $\Delta m^2 \sim 10^{-3} eV^2$

Solar oscillation : $\Delta m^2 \sim 10^{-5} eV^2$

$$\Delta m^2_{13} \neq \Delta m^2_{12} + \Delta m^2_{23}$$

$$m^2_1 - m^2_2 + m^2_2 - m^2_3$$

Need to test LSND signal

MiniBooNE designed to have same L/E to test LSND $\Delta m^2 \sim 1 eV^2$

MiniBooNE vs LSND

LSND

(anti) Neutrino beam from accelerator (DAR, average E_ν 70 MeV)

ν_μ too low E to make μ or π

Proton beam too low E to make K

Both analyses performed with a neutrino and anti-neutrino beam

MiniBooNE

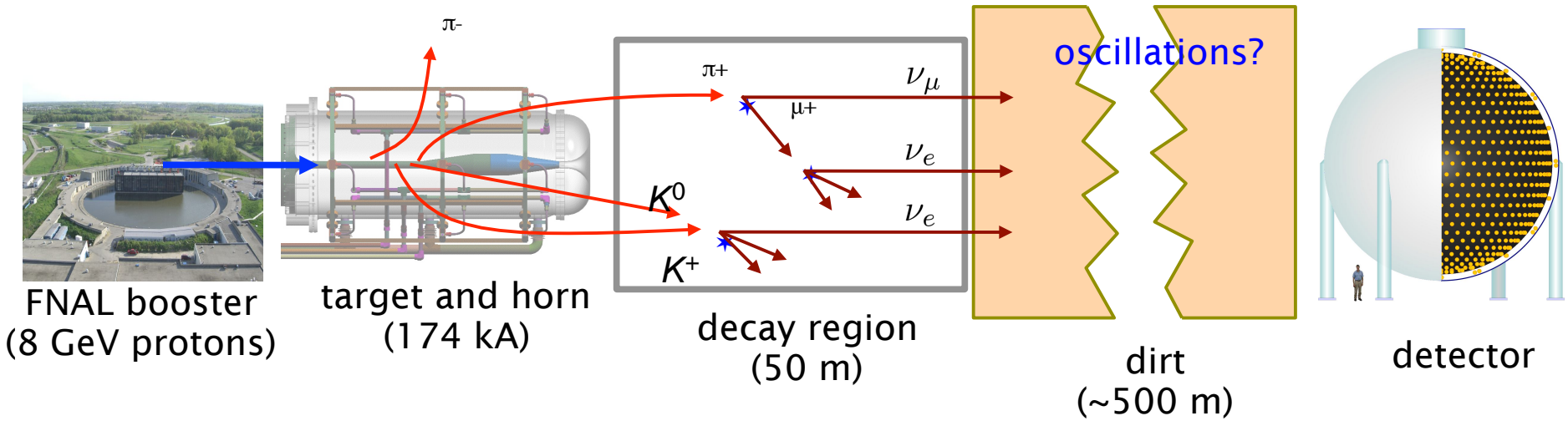
Neutrino beam from accelerator (DIF, average E_ν 800 MeV)

New backgrounds: ν_μ CCQE and NC π^0 mis-id for oscillation search

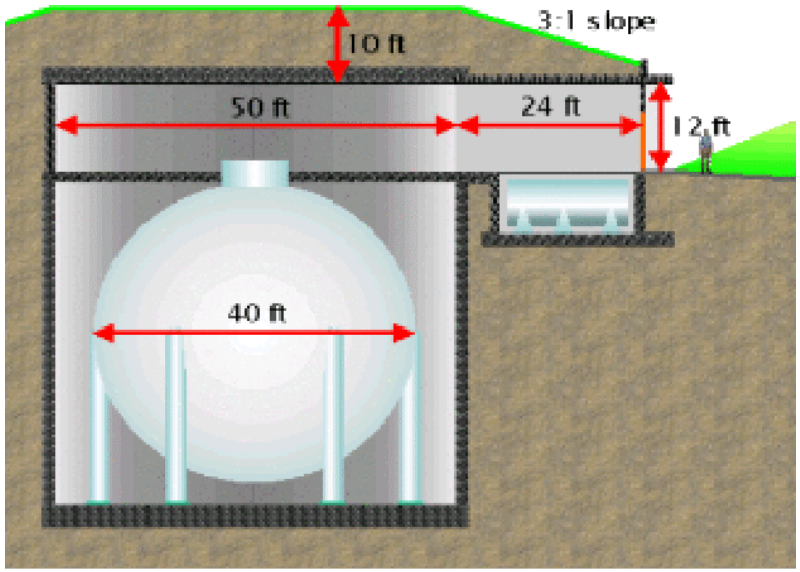
New backgrounds: intrinsic ν_e from K decay (0.5% of p make K)

Detector placed at 500 m from neutrino beam creation point, preserve LSND L/E

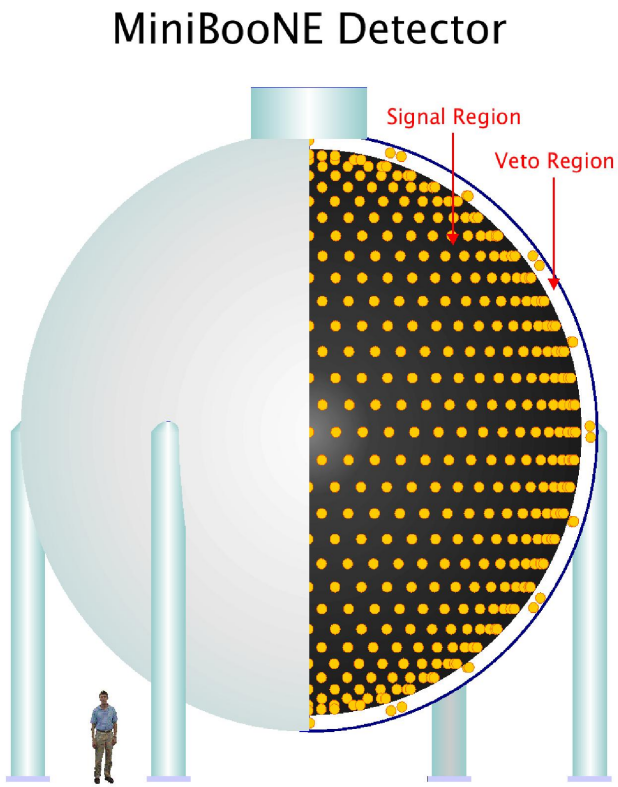
MiniBooNE Neutrino Beam



MiniBooNE Detector



Detector



12.2 meter diameter sphere

Pure mineral oil

2 regions

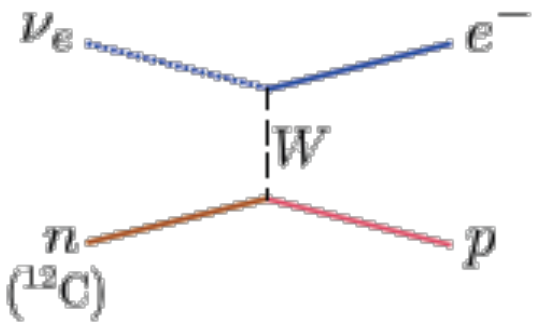
- Inner light-tight region, 1280 PMTs (10% coverage)
- Optically isolated outer veto-region, 240 PMTs

Nucl. Instr. Meth. A599 (2009) 28-46

$\overline{\nu}_e$ Event Selection

Looking for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations

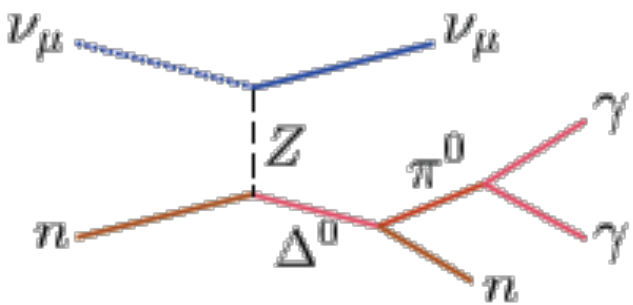
Use charged current interaction to identify $\overline{\nu}_e$ events

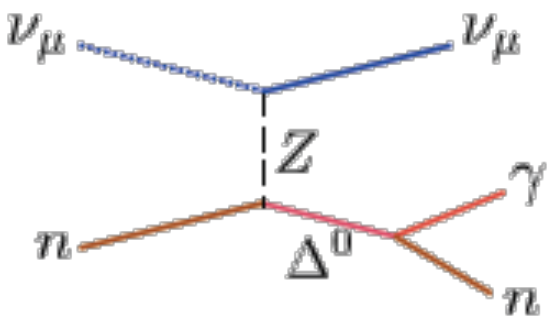


True $\overline{\nu}_e$ inherent in beam

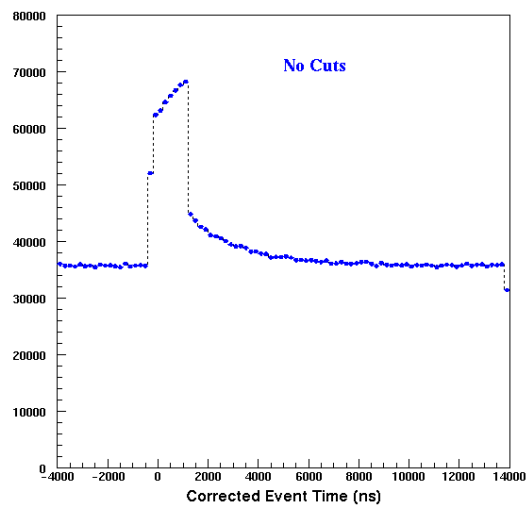
Mis-identified "electron-like" events

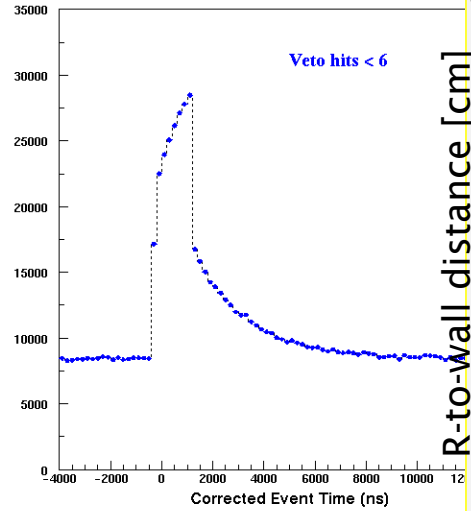
NC π^0, Radiative Delta decays, etc.

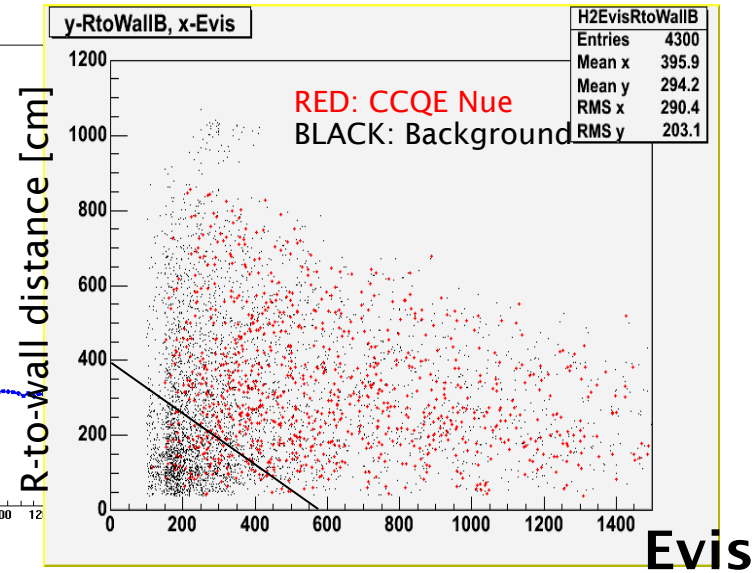




$\overline{\nu}_e$ Event Selection





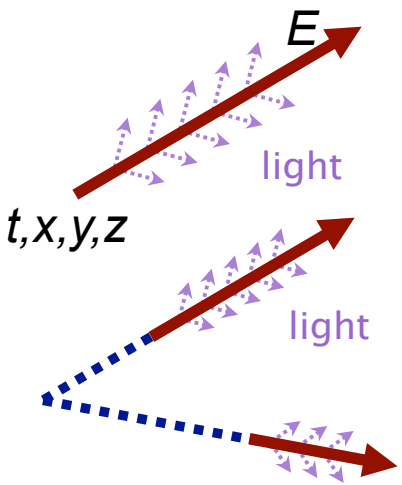


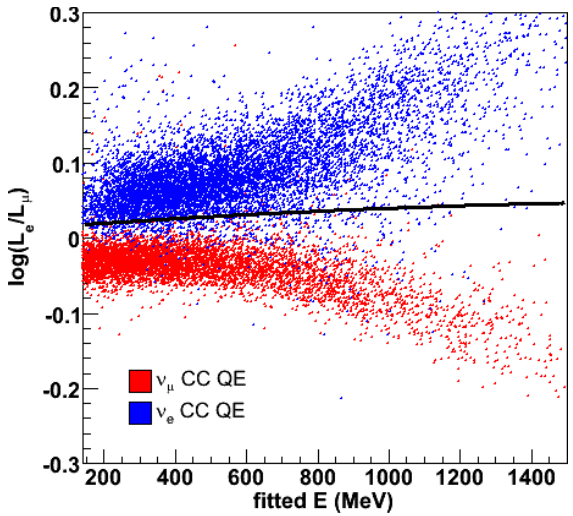
- 1 contained cluster of PMT activity in beam time window
- # Veto Hits < 6, # Tank Hits > 200

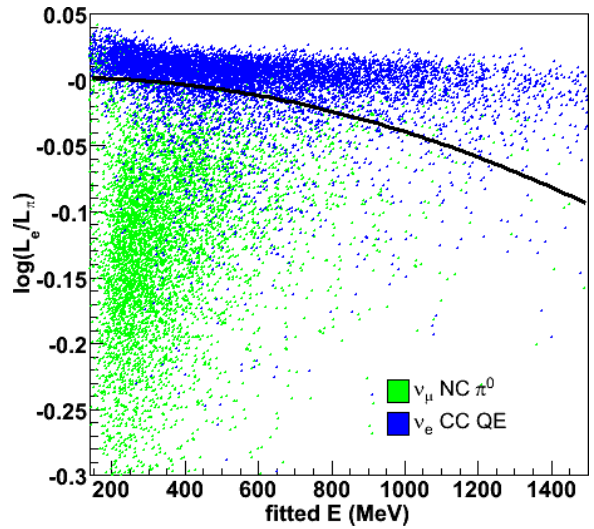
  Removes cosmic rays, removes low E electrons from muon decays
- Reconstructed interaction vertex within fiducial volume of detector
- R-to-wall backward cut

  Removes ϒ from dirt events

Apply Track-Based Likelihood Cuts





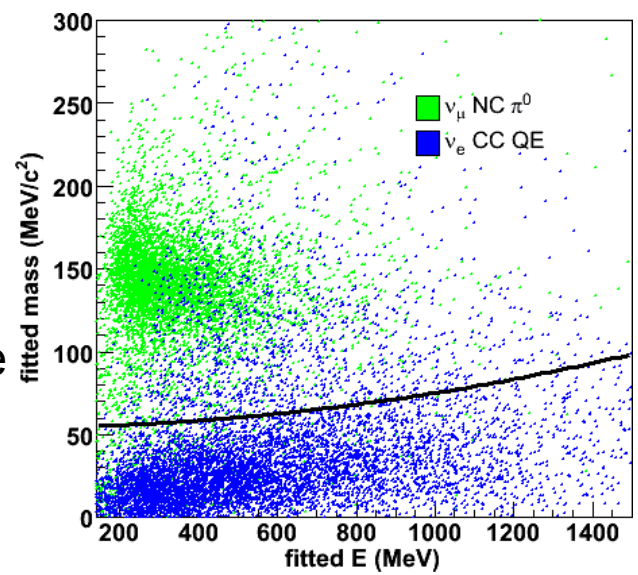


Form Q and T pdfs, fit for track parameters under 3 hypotheses

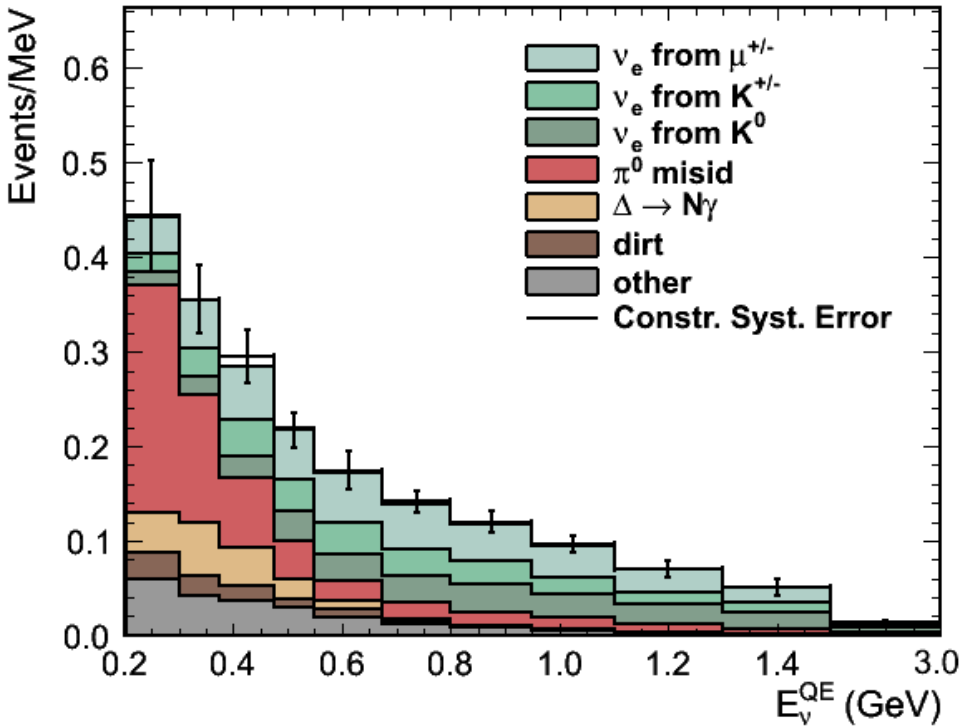
- The track is due to an electron
- The track is coming from a muon
- The "track" is a two-track(ring) π^0 event

Apply energy-dependent cuts on L(e/μ), L(e/π), and the π^0 mass

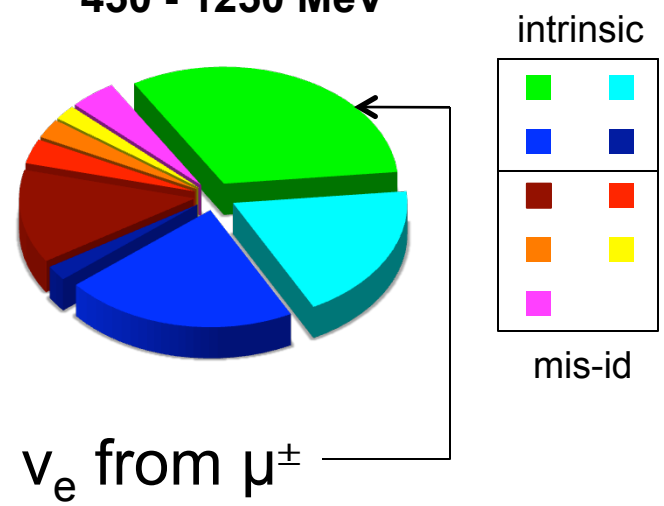
Plot remaining events versus E_ν(QE) and fit



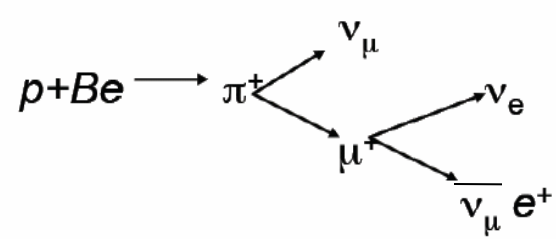
Background Predictions



Predicted Backgrounds
450 - 1250 MeV

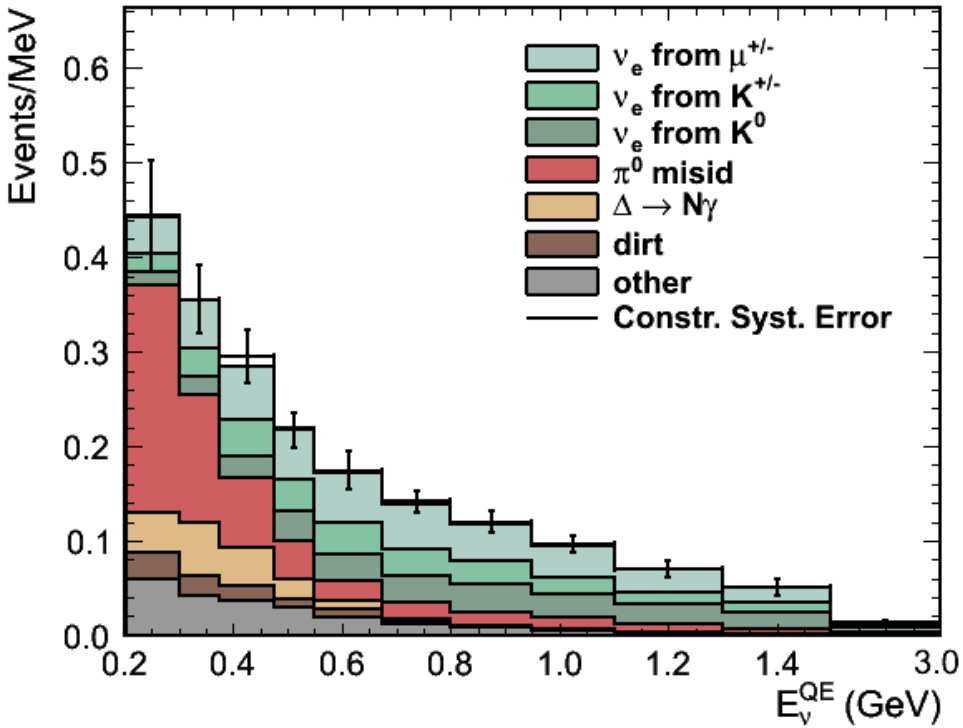


Intrinsic ν_e from μ^- originate from same π^- as the ν_μ CCQE sample

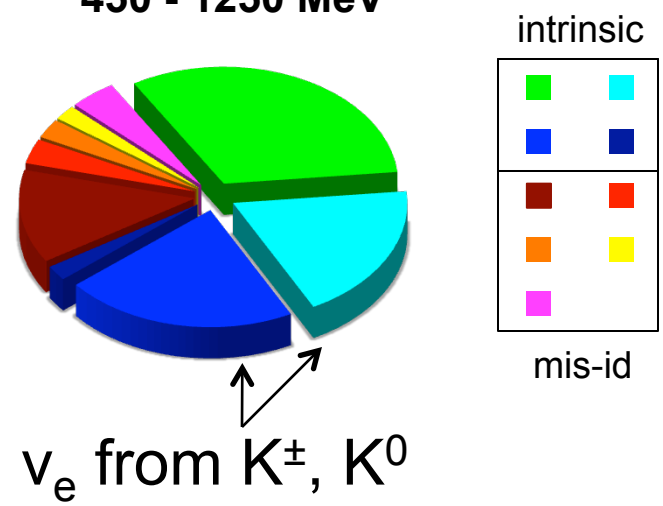


Measuring ν_μ CCQE channel constrains intrinsic ν_e from π^-

Background Predictions



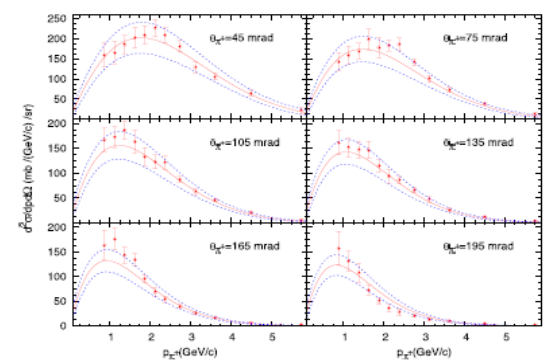
Predicted Backgrounds
450 - 1250 MeV



At high energy, ν_μ flux is dominated by kaon production at the target

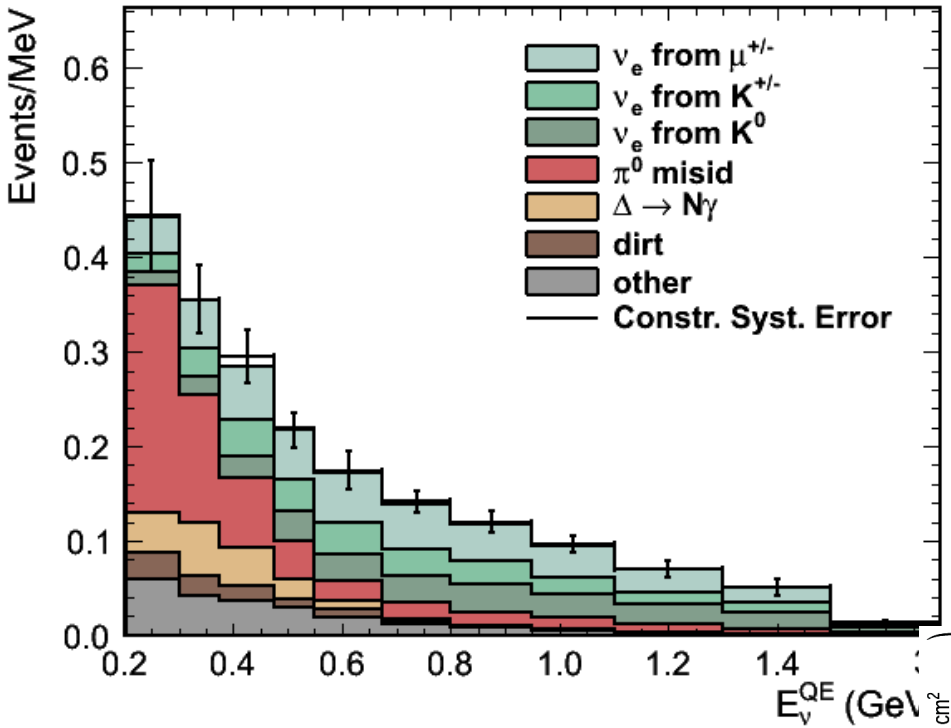
Measuring ν_μ CCQE at high energy constrains kaon production, and thus intrinsic ν_e from K

Also use external measurements from HARP



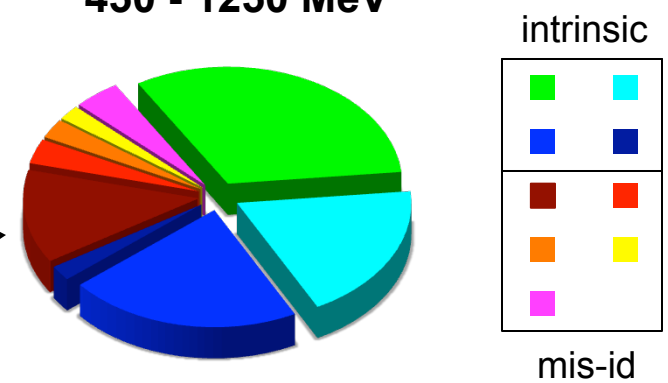
Sanford-Wang fits to world K^+/K^0 data
Phys. Rev. D79, 072002 (2009)

Background Predictions

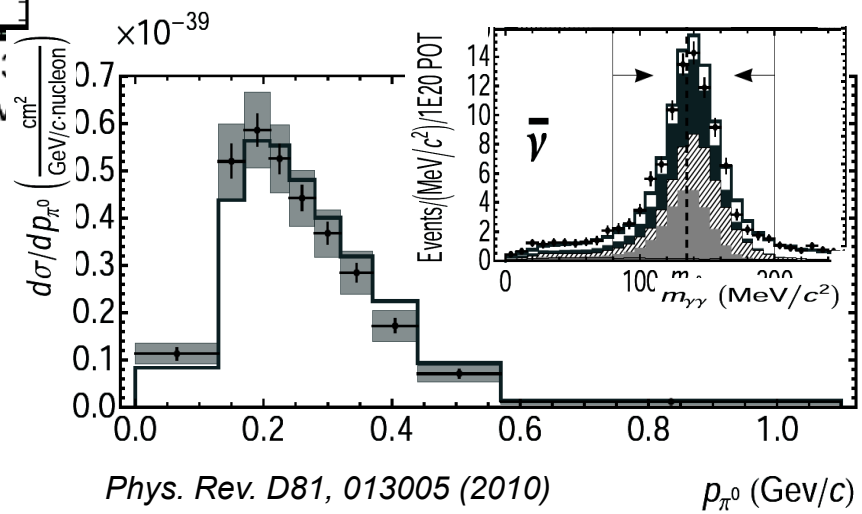


Measured in MiniBooNE

Predicted Backgrounds
450 - 1250 MeV

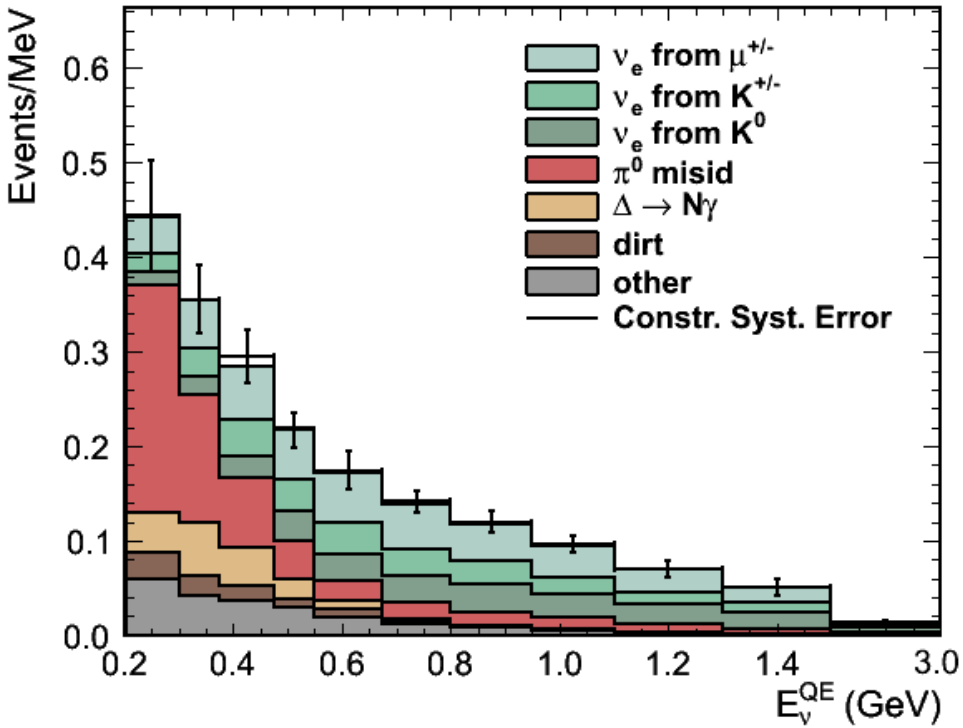


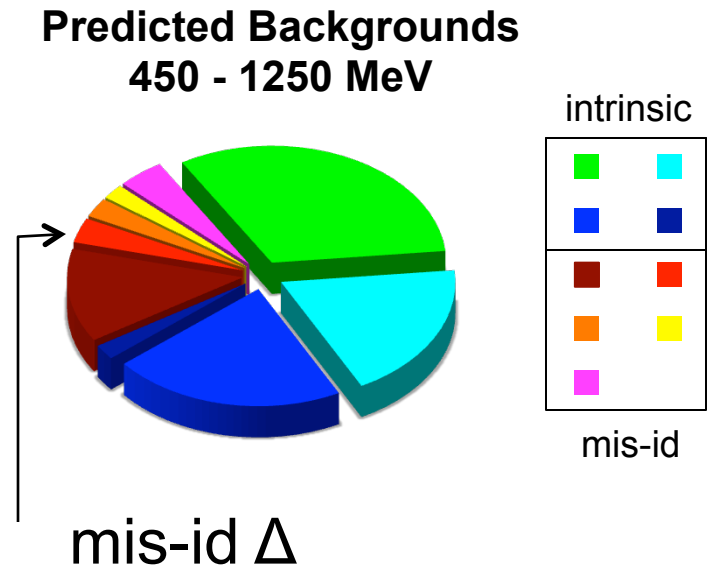
mis-id π^0



Phys. Rev. D81, 013005 (2010)

Background Predictions

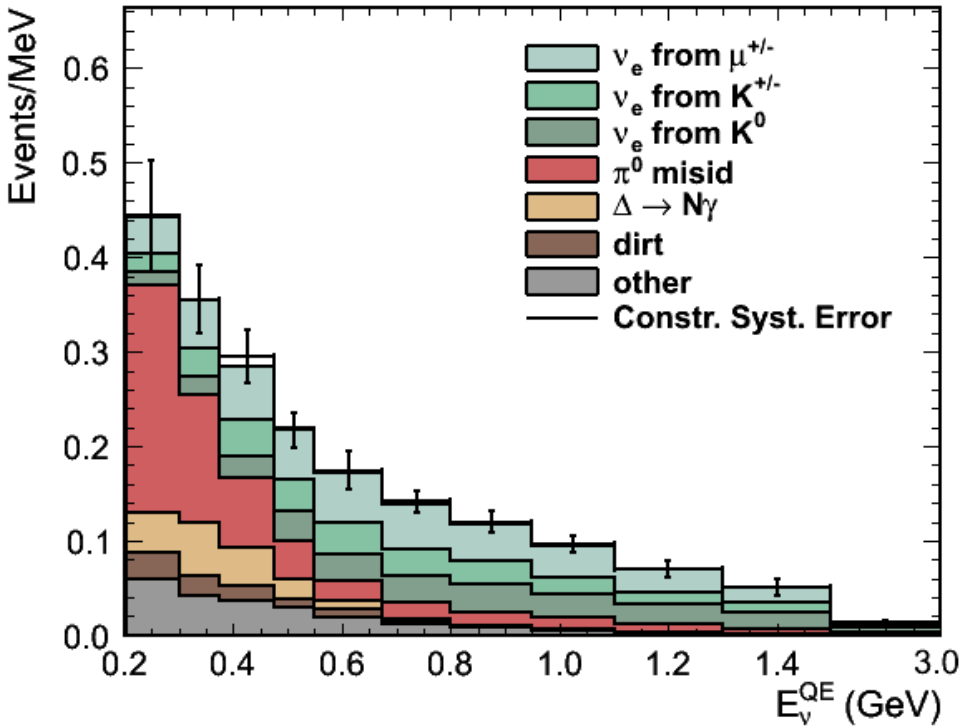




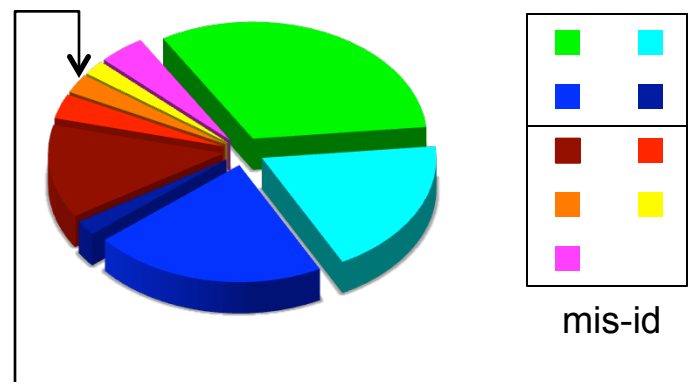
About 80% of our NC π^0 events come from resonant Δ production

Constrain $\Delta \rightarrow N\gamma$ by measuring the resonant NC π^0 rate, apply known branching fraction to N, including nuclear corrections

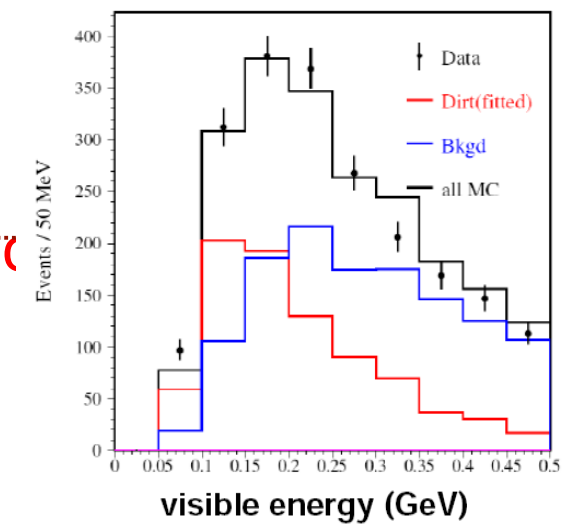
Background Predictions



Predicted Backgrounds
450 - 1250 MeV



dirt events



Come from ν events in surrounding dirt

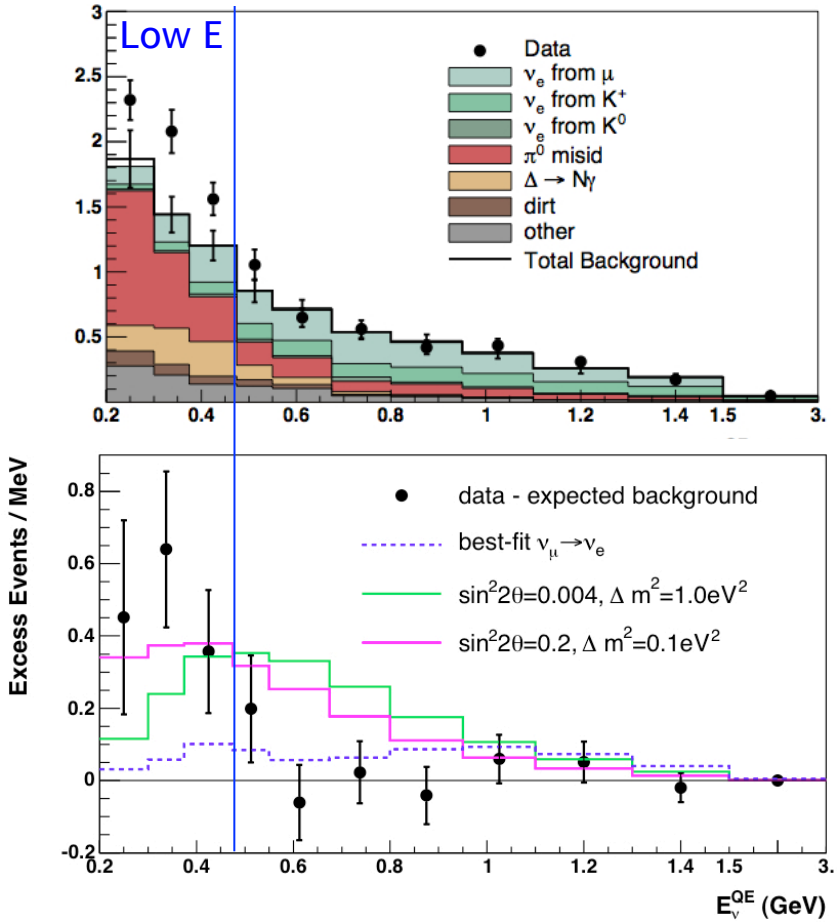
Pileup at high radius and low E

Fit dirt-enhanced sample to extract dirt event rate with 10% uncertainty

☆ Every major source of background c
constrained by MB.

MiniBooNE Neutrino Beam Results

6.5e20 POT collected in neutrino mode



Above 475 MeV

Excellent agreement with background predictions

Observe 408 events, expect 386 ± 20(stat) ± 30(syst)

Region of highest sensitivity to an LSND-like 2ν mixing hypothesis, use it to exclude that model assuming CP conservation

Below 475 MeV

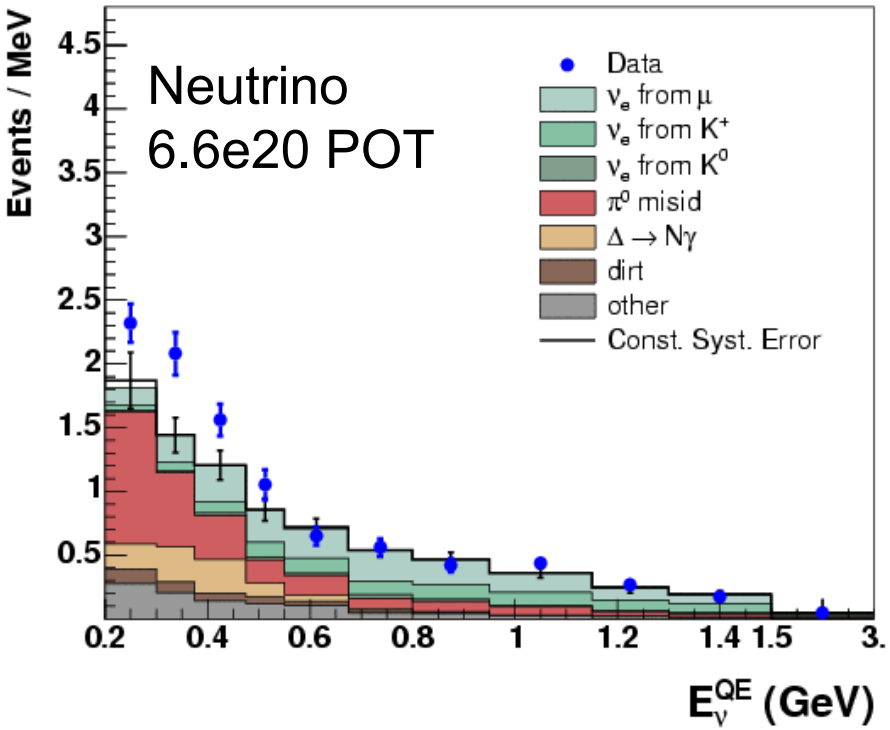
Find 544 events, expect 415 ± 20(stat) ±39 (syst)

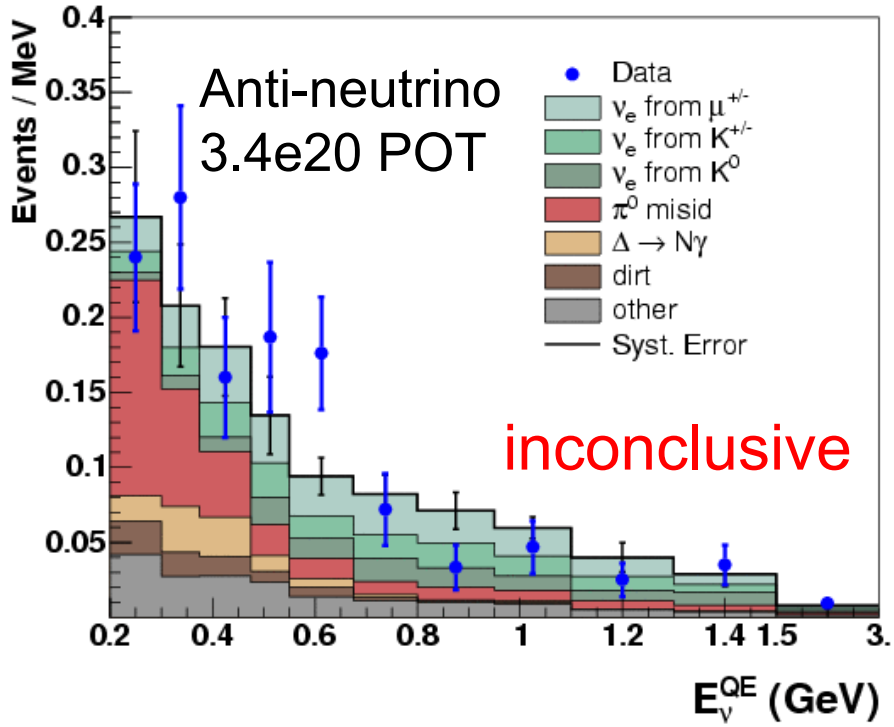
Excess is 128 ± 20(stat) ± 39(syst) events (3σ excess)

Shape inconsistent with 2ν oscillation interpretation of LSND

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

First Anti-Neutrino Beam Results





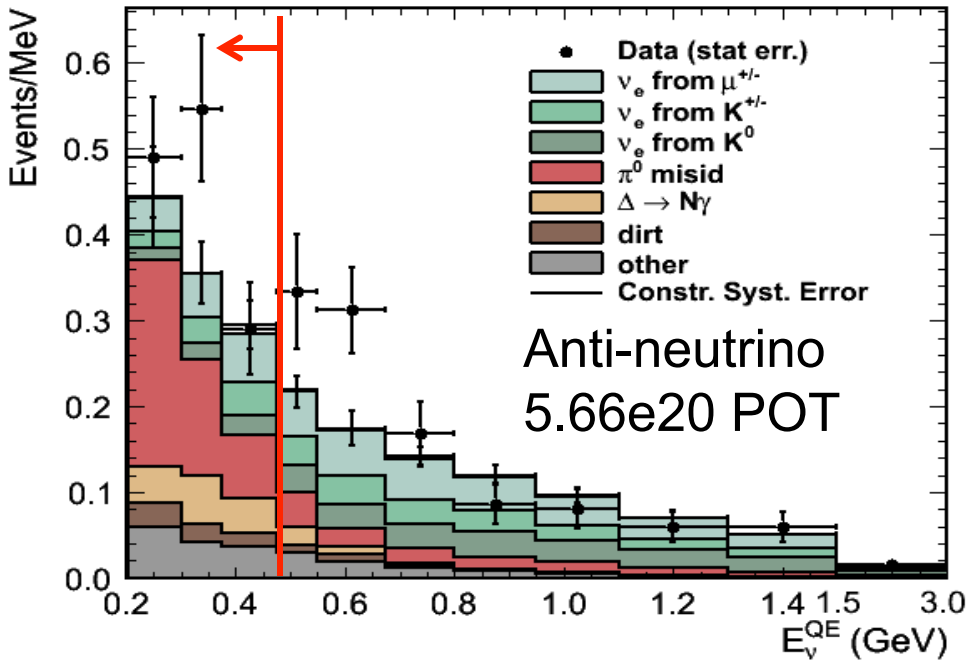
Anti-neutrino beam contains 30% WS background, fits above 475 MeV assume only anti-nus are allowed to oscillate

Background compositions are fairly similar

Anti-nu rates reduced by ~5 due to lower flux and cross-section

Phys. Rev. Lett. 103, 111801 (2009)

2010 Low Energy Anti-Neutrino Results



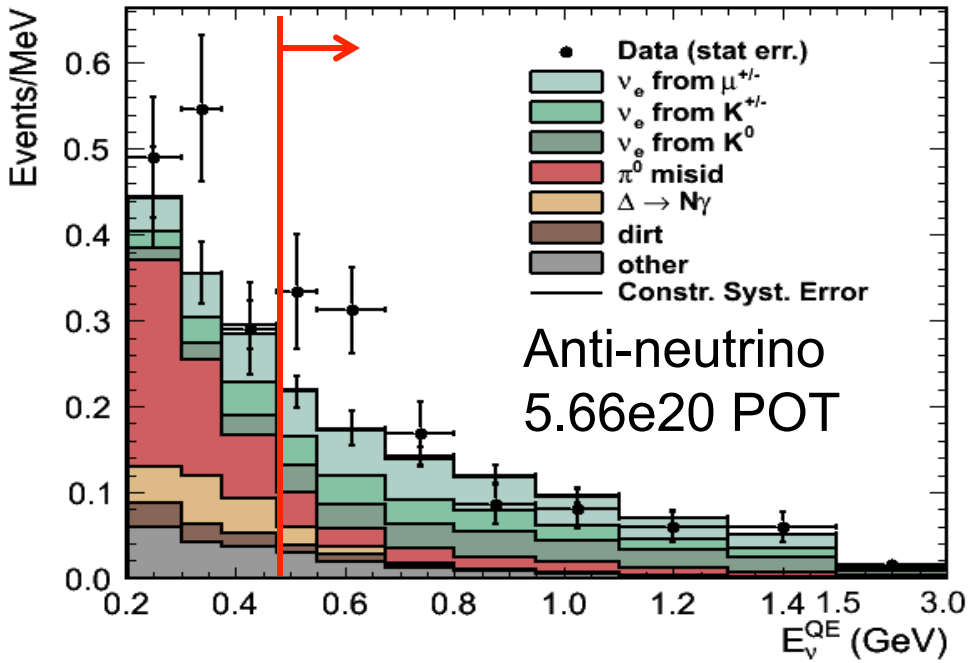
	200-475MeV	475-1250MeV
Data	119	120
MC	100.5±14.3	99.1±14.0
Excess	18.5±14.3	20.9±14.0
LSND Best Fit	7.6	22
Expectation from ν low E excess	11.6	0
LSND+Low E	19.2	22

Below 475 MeV find 119 events, expect 100 ± 10(stat) ± 10(syst)
Excess is 18.5 ± 10(stat) ± 10(syst) events

Starting to become inconsistent with many hypotheses explaining the neutrino mode low E excess
If low E excess due to SM NC gamma-ray mechanism (aka axial anomaly), expected ~67 event excess in 200 – 475 MeV range

Phys. Rev. Lett.105, 181801 (2010)

2010 Oscillation Region Results



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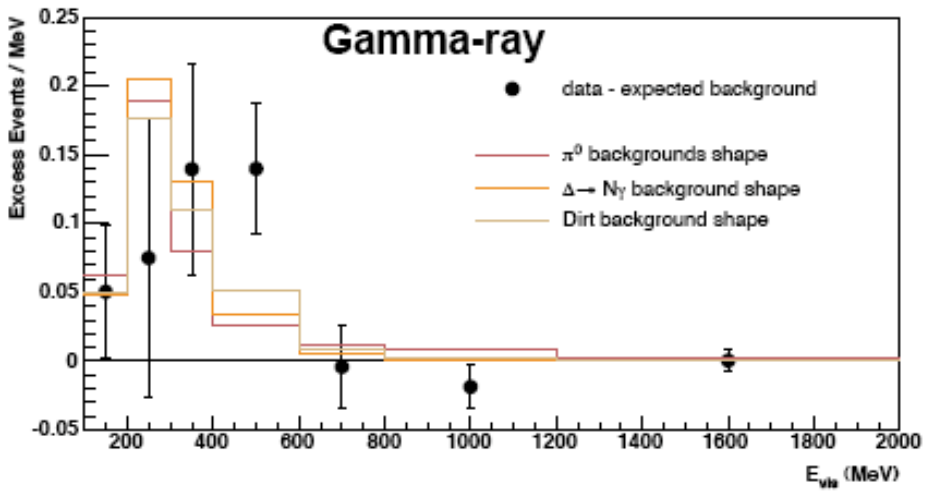
Phys. Rev. Lett.105, 181801 (2010)

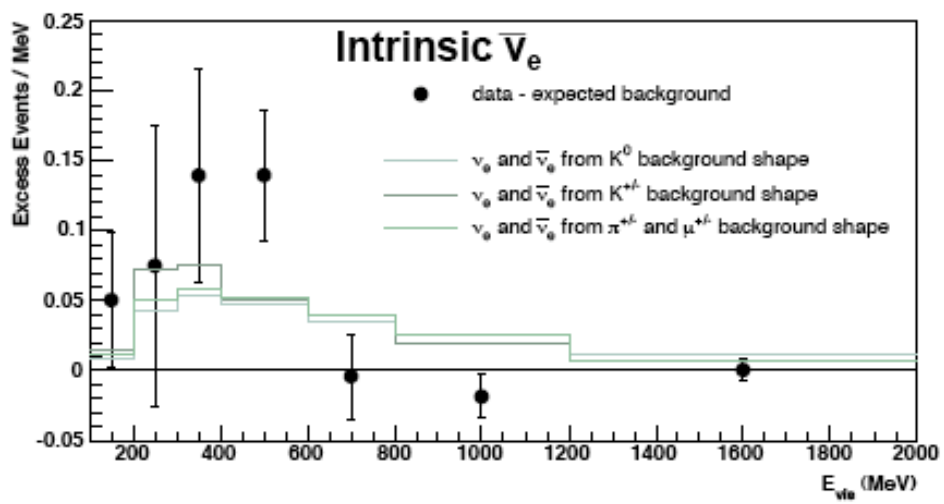
Checking the Excess



How well do the background shapes agree with the observed excess?

π^0 ➔ scale by 1.79
Δ ➔ scale by 3.95
Dirt ➔ scale by 6.22

Require a background modification at >5σ



$K^{\pm}$ ➔ scale by 2.45 >3σ
K^0 ➔ scale by 2.84 >4σ
$\mu^{\pm}$ ➔ scale by 1.88 >3σ

Performing the Oscillation Fit

Maximum likelihood fit:

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

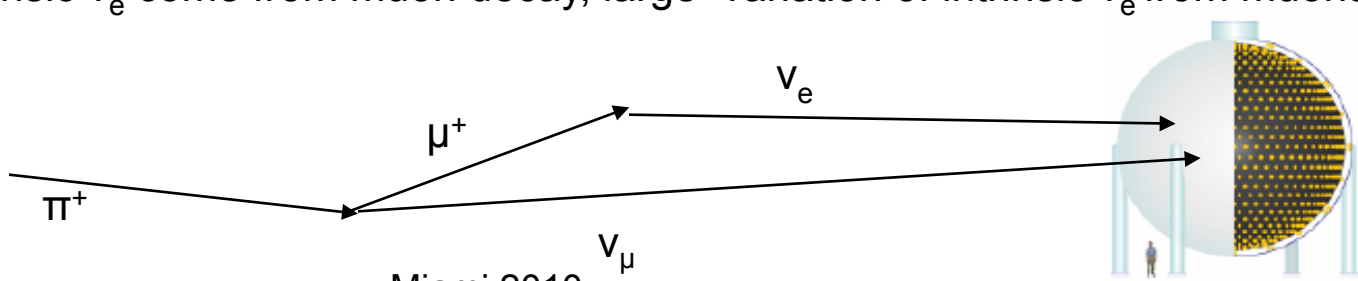
$$M = M_{om} + M_{xsec} + M_{flux} + M_{\pi^0} + M_{dirt} + M_{K^0} + ...$$

1000's of MC universes go into forming M

Simultaneously fit ν_e CCQE signal + high statistics ν_μ CCQE sample

- Oscillation candidate events cannot be interpreted as an incorrect ν_μ flux prediction
- If oscillation candidate events were due to incorrect ν_μ flux, we wouldn't get a good fit for ν_μ CCQE

- Constrains number of intrinsic ν_e events
  - ~50% of intrinsic ν_e come from muon decay, large variation of intrinsic ν_e from muons not allowed



Wrong Sign Background

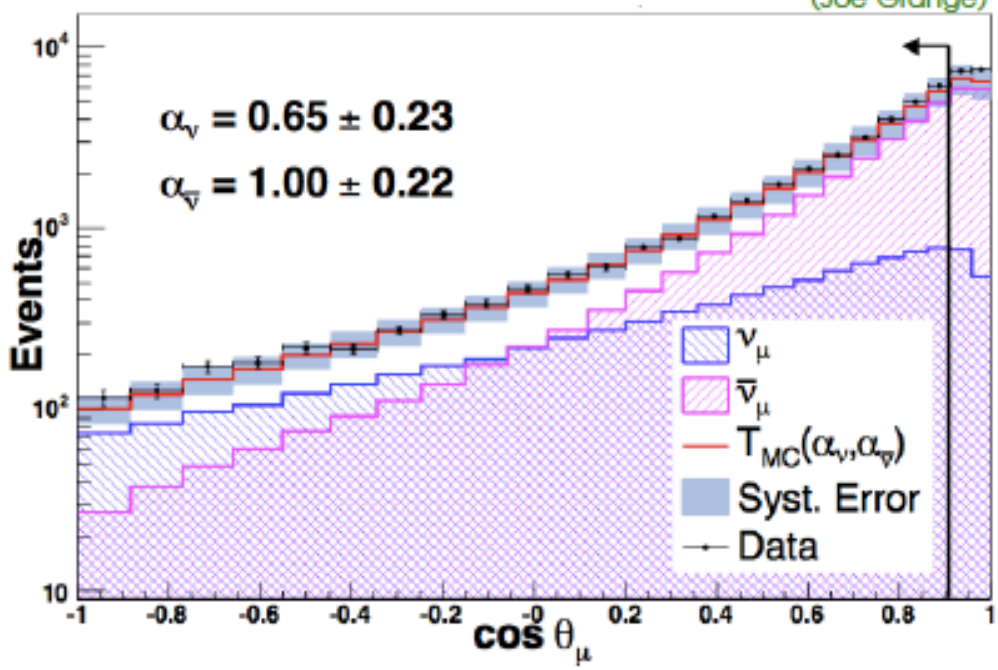
- We assume only *right-sign* oscillates ($\bar{\nu}_\mu$)
- Need to know fraction of *wrong-sign* events.
- Two constraint methods:

  a) measuring angular distribution of CCQE muons

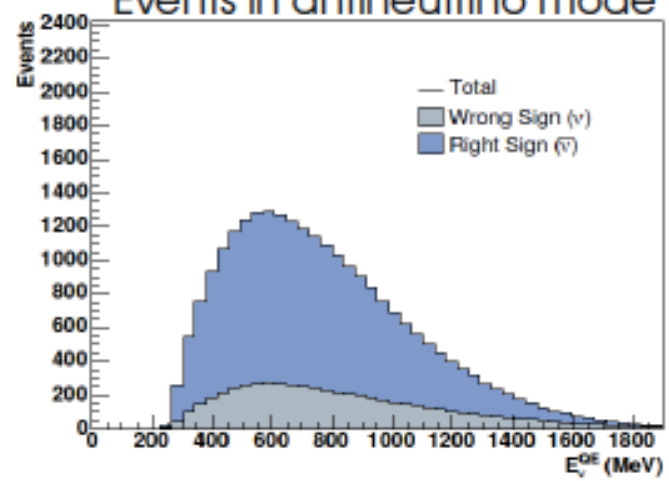
  b) measuring the CCπ^+ rate (indep. of nuclear effects modeling)

- **Result: WS BG prediction reduced by ~30%**

(Joe Grange)



Events in antineutrino mode



Paper in preparation

Fit E > 475 MeV

In 475-1250 MeV, excess 20.9 ± 14 events (1.4σ)
In 475-675 MeV, excess is 25.7 ± 7.2 events (3.6σ)

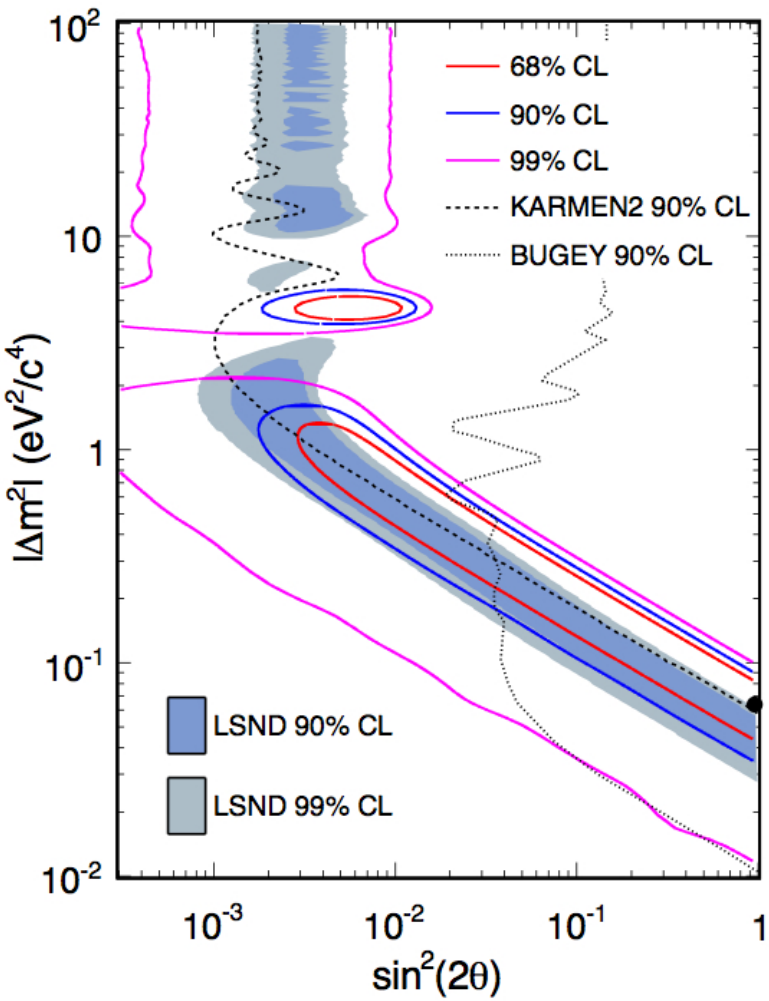
True significance comes from fit over entire > 475 MeV energy region + ν_μ constraint

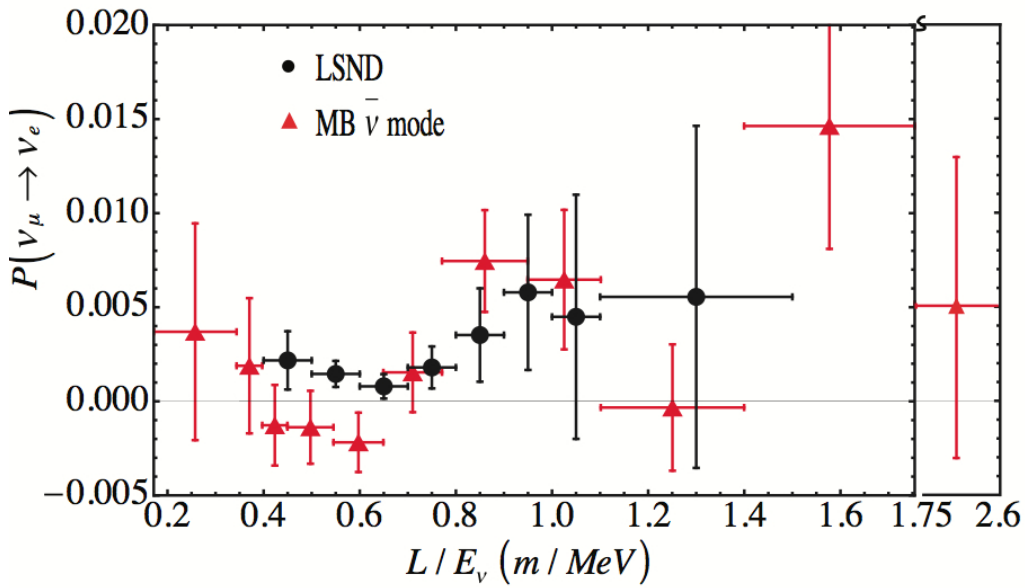
Best fit preferred over null at 99.4% CL (2.7σ)

Probability of null hypothesis (no model dep.) is 0.5% in 475-1250 MeV region

MiniBooNE vs LSND

Fit to 2ν mixing model





Model-independent plot of inferred oscillation probability

$$P = \frac{(\text{\# measured} - \text{predicted e-like evts})}{\text{\# evts predicted for full transmutation}}$$

Phys. Rev. Lett.105, 181801 (2010)

MiniBooNE's Oscillation Summary

Neutrino mode analysis

- no excess is observed in the region where excess is expected from LSND
- significant excess is observed in low energy region, doesn't fit well to a neutrino oscillation hypothesis

Antineutrino mode analysis

- small excess is observed in low energy region
- LSND consistent excess is observed in the oscillation energy region

Is MiniBooNE wrong???

A Word of Caution!

Neutrinos are massless

Wrong

Solar neutrino oscillation solution is SMA

Wrong

Natural scale of neutrino mass is ~10-100 eV

Wrong

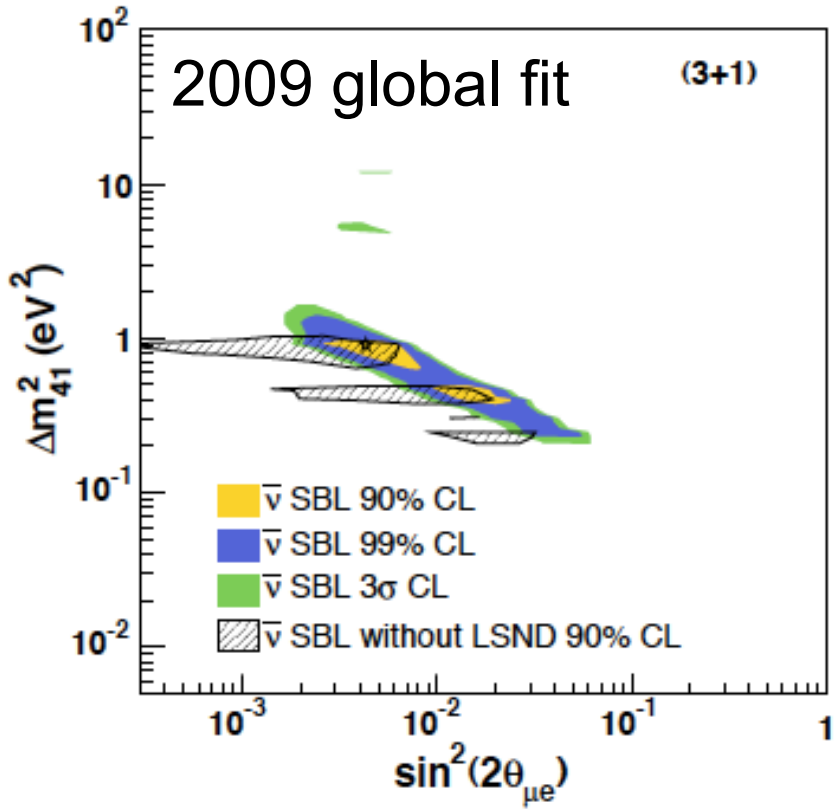
Atmospheric mixing should be small, analogous to the CKM matrix element V_{cb} (~0.04)

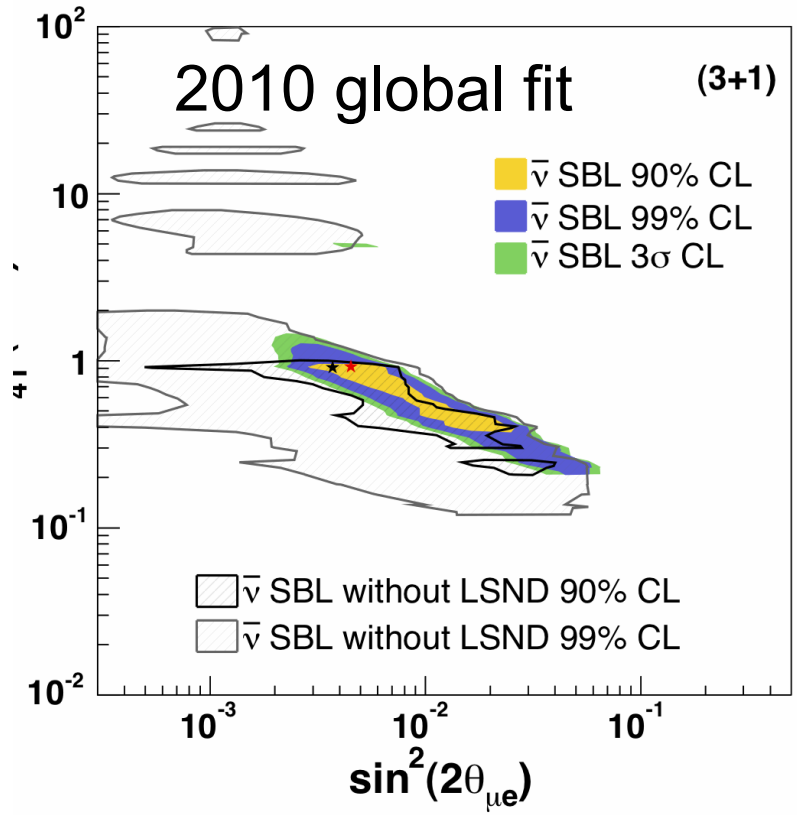
Wrong

LSND is incorrect because it requires physics beyond the Standard Model to reconcile with solar and atmospheric results (aka sterile neutrinos)

???

3+1 Global Fit to World Anti-ν Data



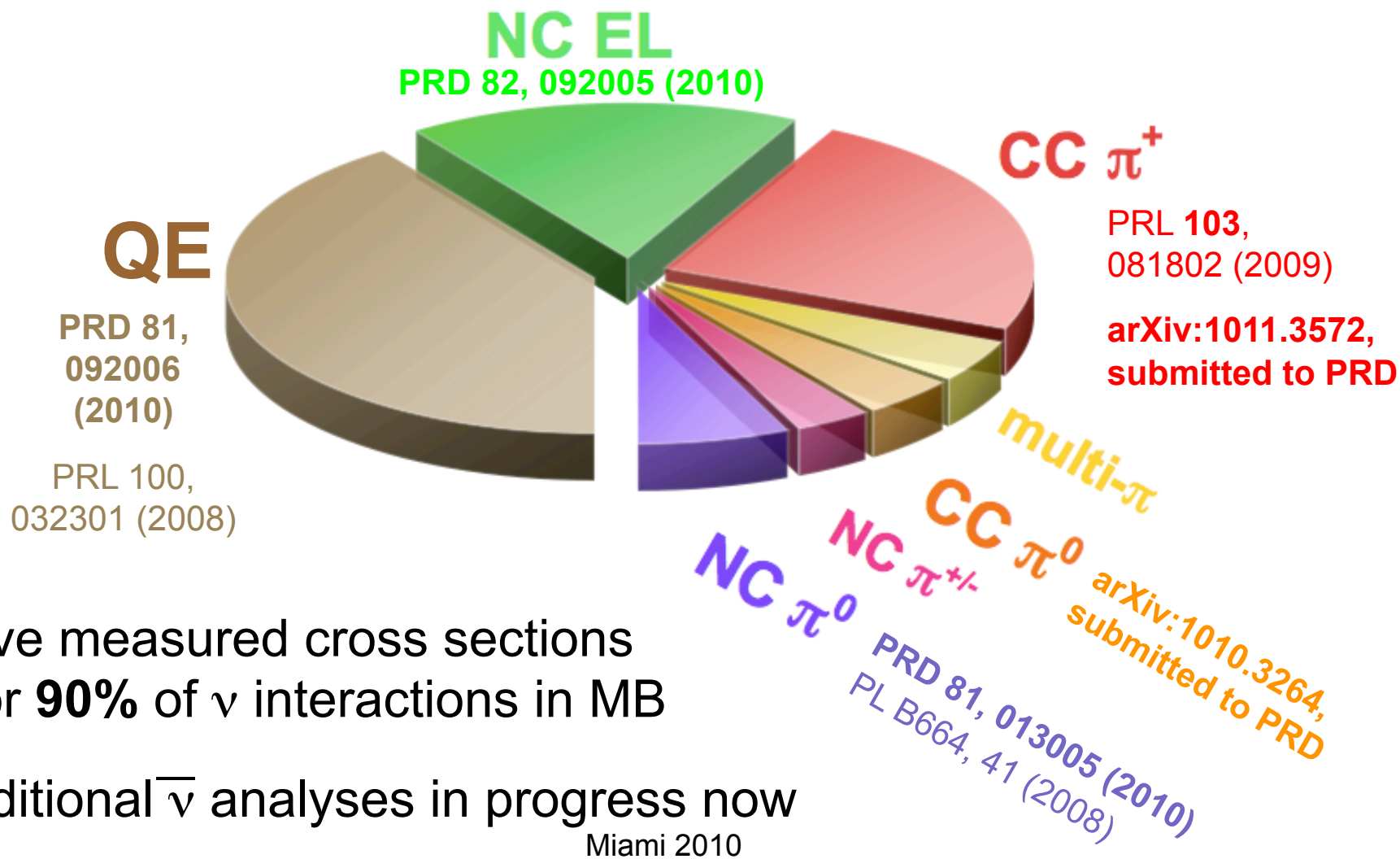


G. Karagiorgi et al.
Phys. Rev. D. 80, 073001 (2009)

G. Karagiorgi, updated 2010 results
Giunti and Laveder, arXiv:1012.0267

Neutrino Cross Sections at MiniBooNE

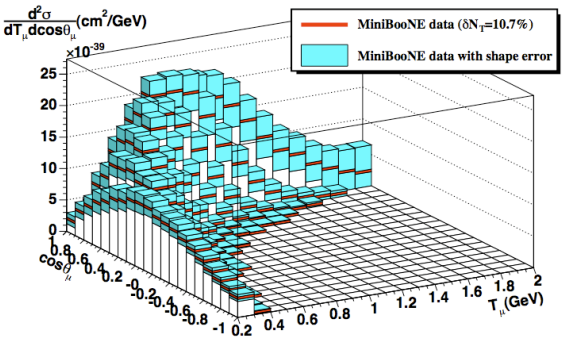
8 ν cross section publications in the period from 2008-2010

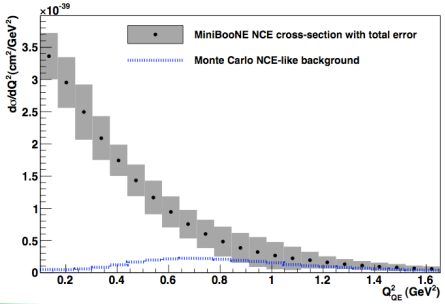


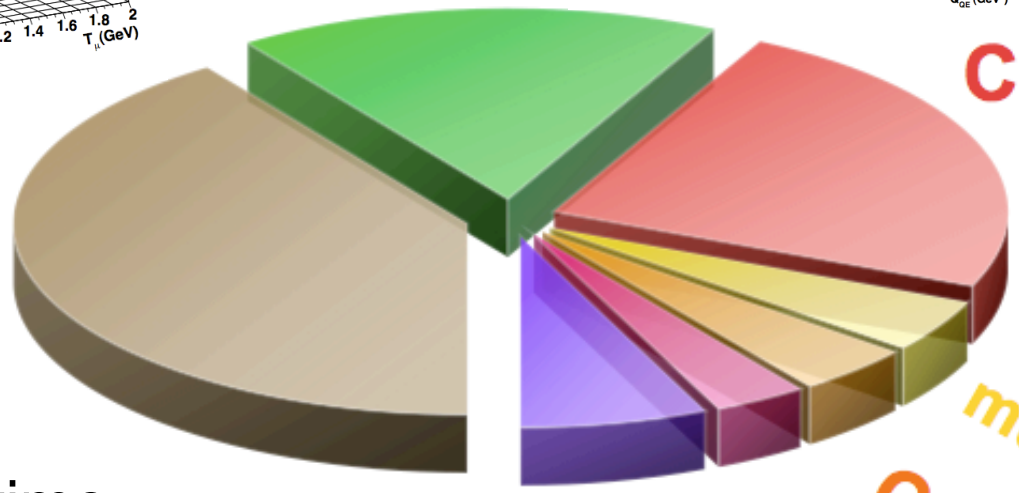
have measured cross sections for **90%** of ν interactions in MB

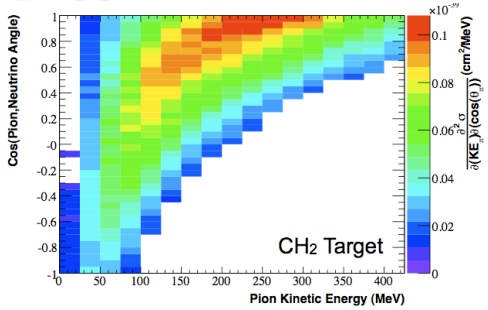
additional $\bar{\nu}$ analyses in progress now

Neutrino Cross Sections at MiniBooNE

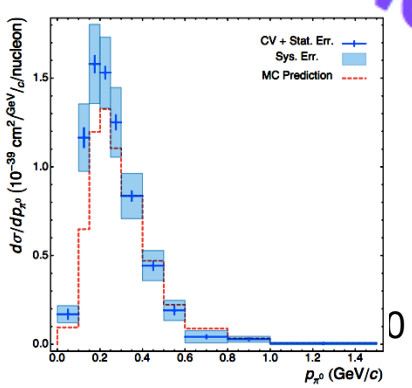


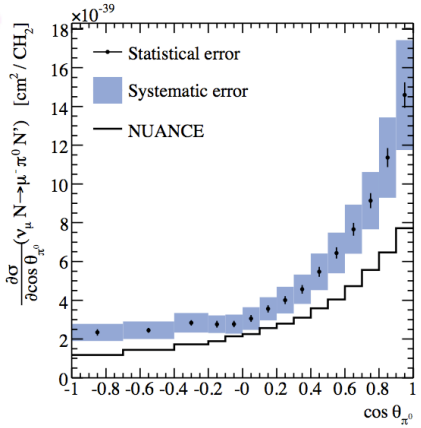




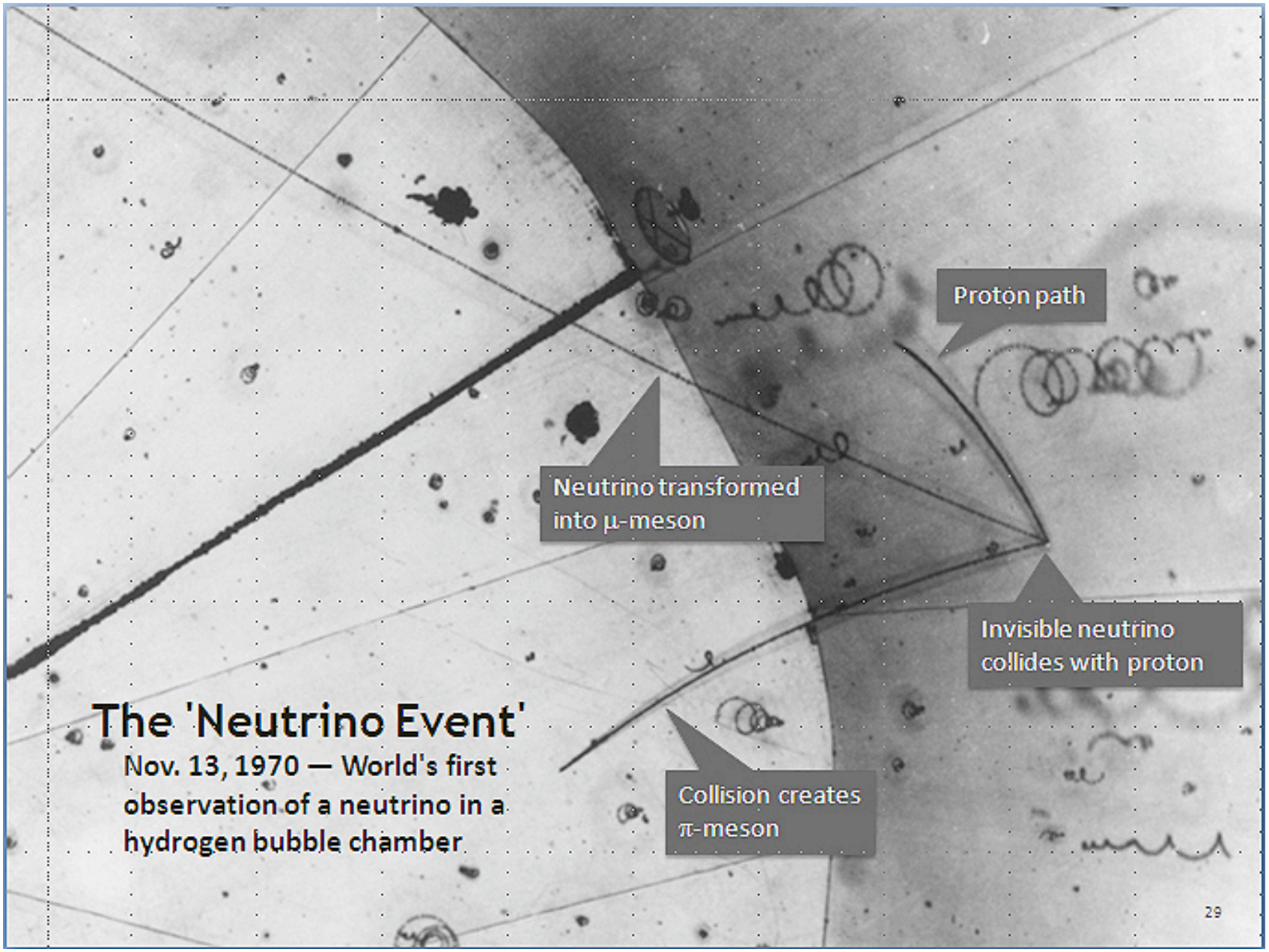


also the 1st time full kinematics have been reported for many of these reaction channels





In Conclusion


Proton path
Neutrino transformed into μ-meson
Invisible neutrino collides with proton
Collision creates π-meson
The 'Neutrino Event'
Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber
29

Backup

"I forgot to make a back-up copy of my brain, so everything I learned last semester was lost."

Need To Add

Several slides on GK's 3+1 analysis, see Bill's latest talk

Prediction for additional stat collection

One slide per xsection?

Expected Backgrounds

5.66e20 POT			
Source	200-475	475-1250	
$\mu^{\pm}$	13.4	31.4	Intrinsic ν_e
$K^{\pm}$	8.2	18.6	
K^0	5.1	21.2	
other ν_e	1.3	2.0	
NCπ^0	41.6	12.6	Mis-ID ν_μ
$\Delta \rightarrow \gamma$	12.4	3.4	
dirt	6.2	2.6	
ν_μ CCQE	4.3	2.0	
other ν_μ	7.0	4.2	
TOTAL	**99.5**	**98.0**	

Background Uncertainties

Source	Neutrino (MeV) 200-475	Neutrino (MeV) 475-1100	Antineutino (MeV) 200-475	Antineutino (MeV) 475-1100
Flux from π^+/μ^+ decay	0.4	0.9	1.8	2.2
Flux from π^-/μ^- decay	3.0	2.3	0.1	0.2
Flux from K^+ decay	2.2	4.7	1.4	5.7
Flux from K^- decay	0.5	1.2	-	-
Flux from K^0 decay	1.7	5.4	0.5	1.5
Target and beam models	1.7	3.0	1.3	2.5
ν cross section	6.5	13.0	5.9	11.9
NC π^0 yield	1.5	1.3	1.4	1.9
Hadronic interactions	0.4	0.2	0.8	0.3
External interactions (dirt)	1.6	0.7	0.8	0.4
Optical model	8.0	3.7	8.9	2.3
Electronics & DAQ model	7.0	2.0	5.0	1.7
TOTAL (unconstrained)	**13.5**	**16.0**	**12.3**	**14.2**

(numbers are %)

Interpreting MiniBooNE's Result

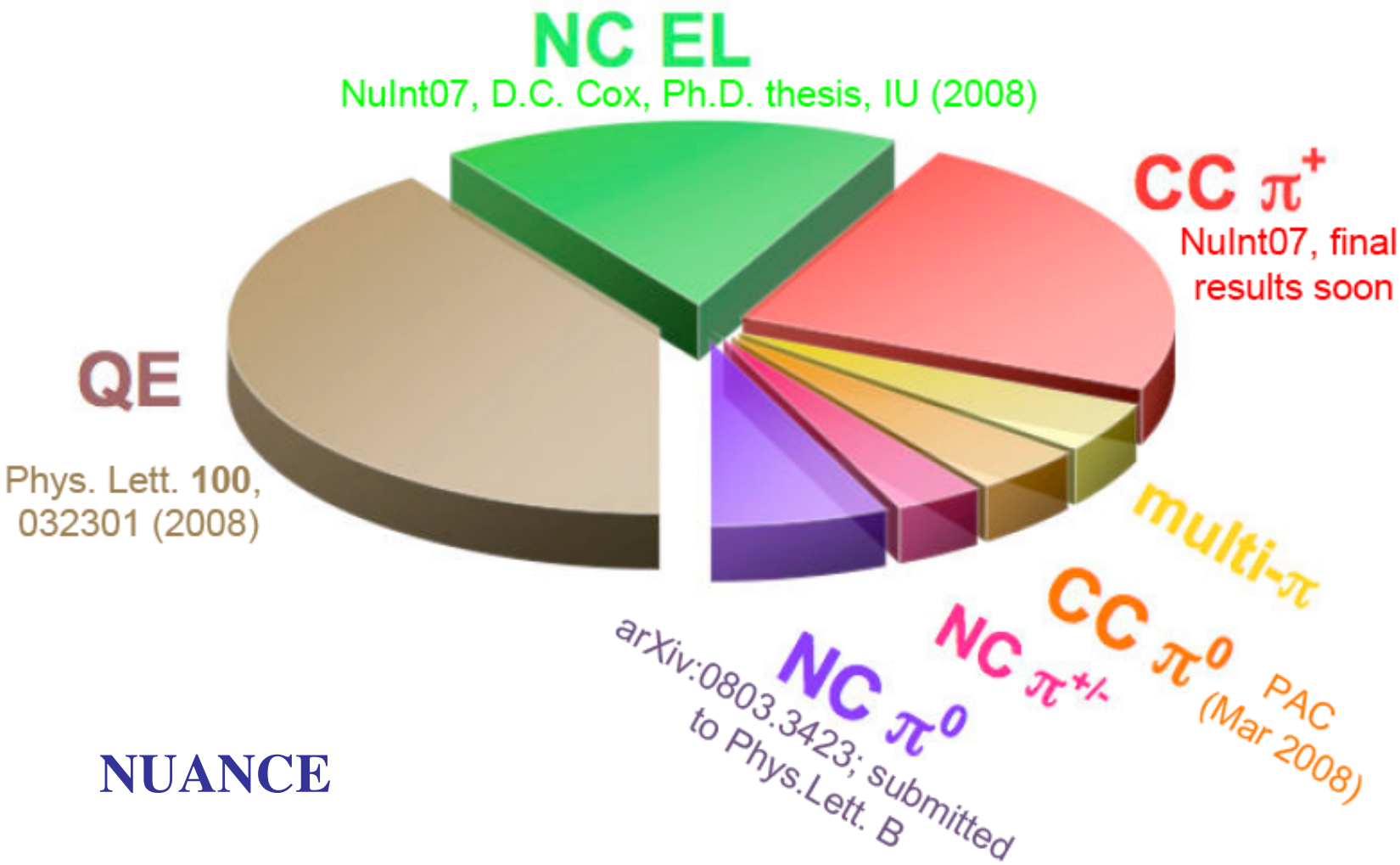
In a ν_μ beam above 475 MeV, we see no evidence for an excess of ν_e-like events.

In a ν_μ beam below 475 MeV, we see a 3σ excess (128 ± 43) of ν_e signal candidates that don't fit well to a 2ν mixing hypothesis.

In a anti-ν_μ beam below 475 MeV, we see a small excess (18 ± 14). It rules out some explanations of the ν_μ beam low-E excess.

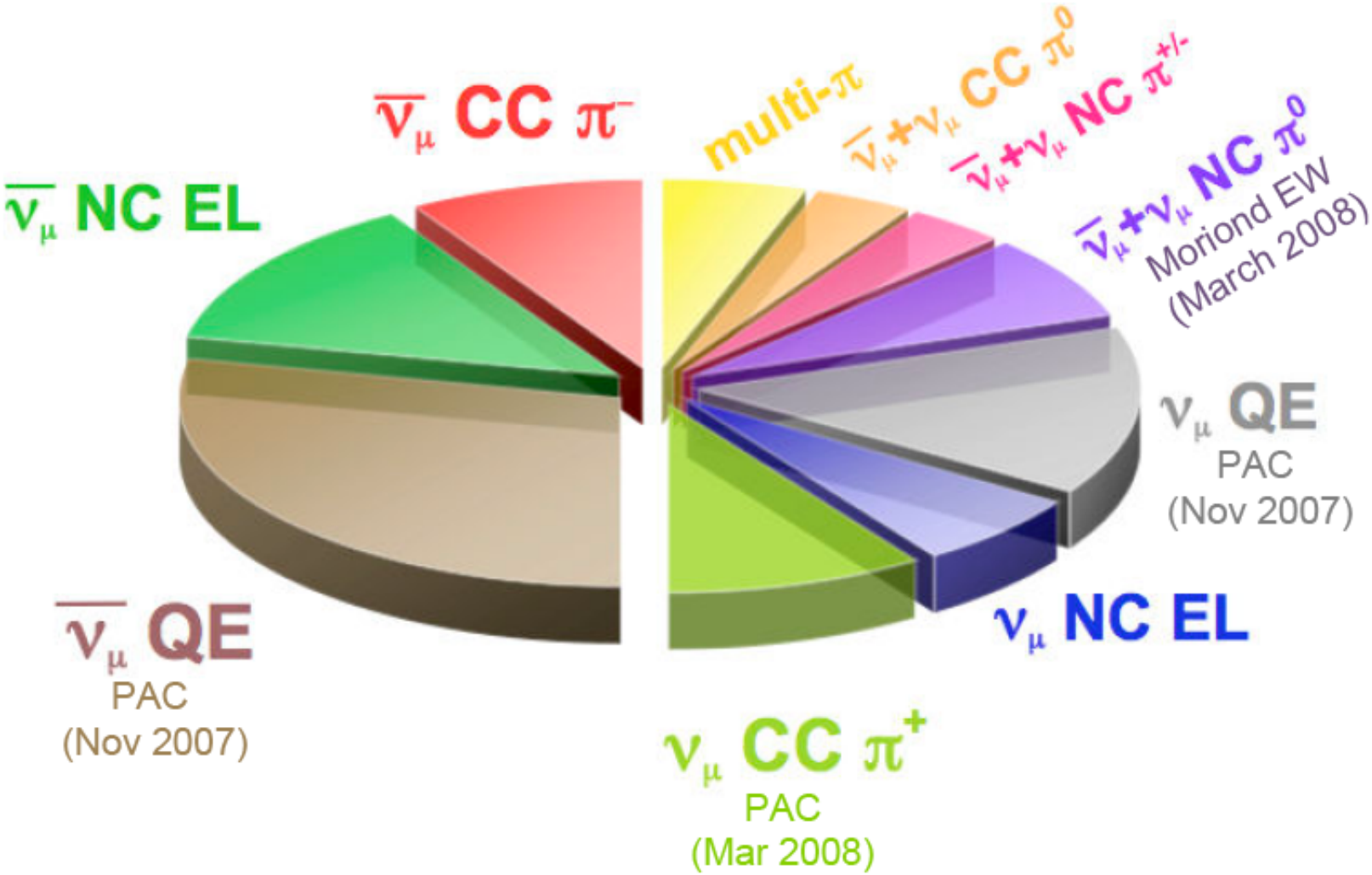
In a anti-ν_μ beam above 475 MeV, we see an excess of events. The null hypothesis in the 475-1250 MeV region is only 0.5% probable. A 2ν fit prefers an LSND-like signal at 99.4% CL.

Neutrino Cross Sections



NUANCE

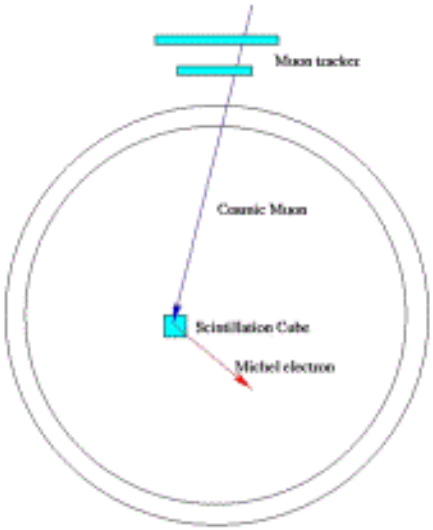
Antineutrino Cross Sections

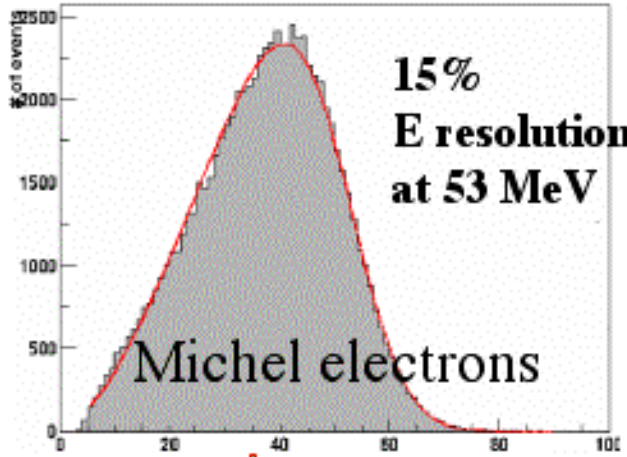


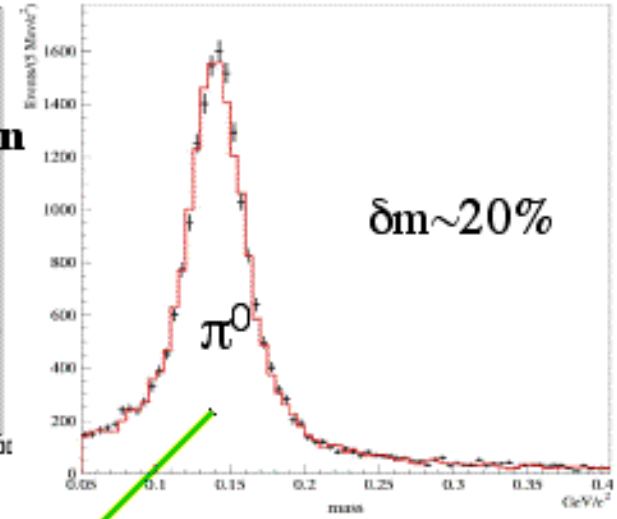
NUANCE

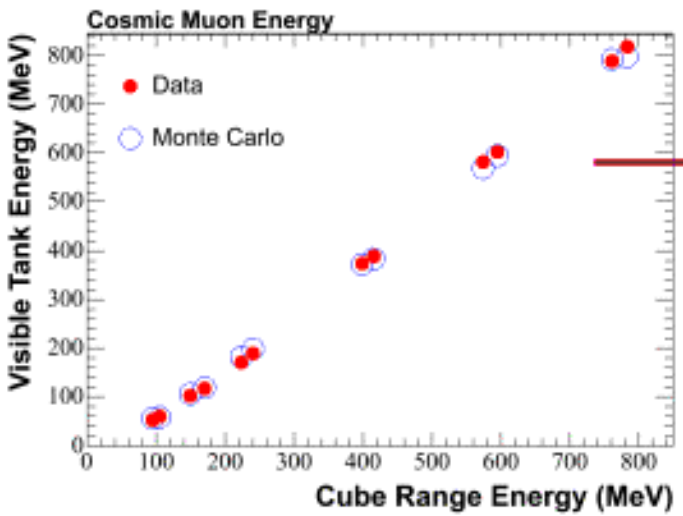
Calibration Sources

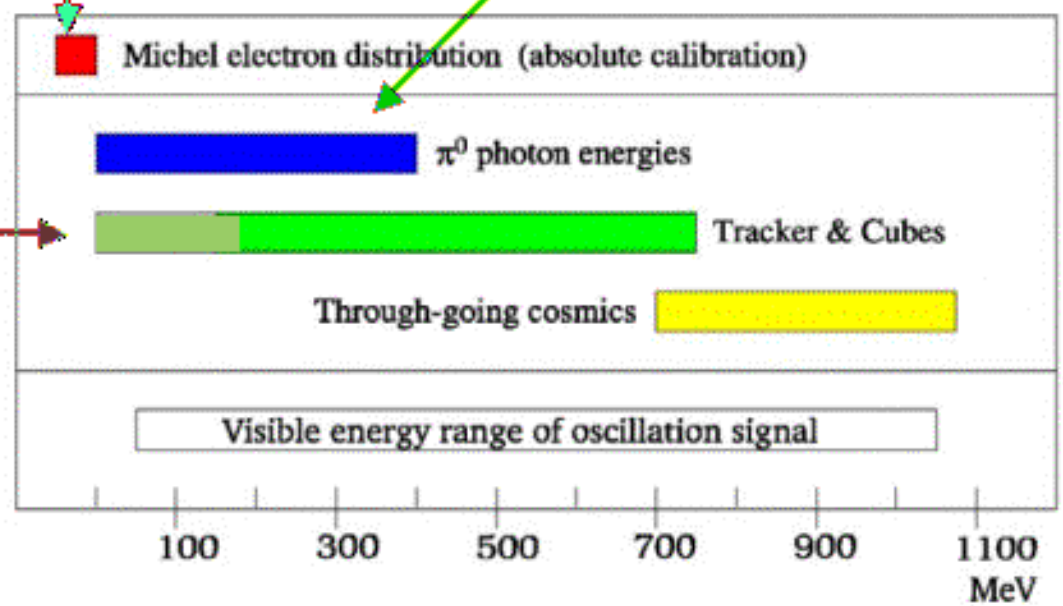
Tracker system











H. Ray, University of Florida