Status of the Search for Neutrino Oscillations with MiniBooNE

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Frontiers in Neutrino Physics
APC, Paris, October 6th, 2011

Introduction

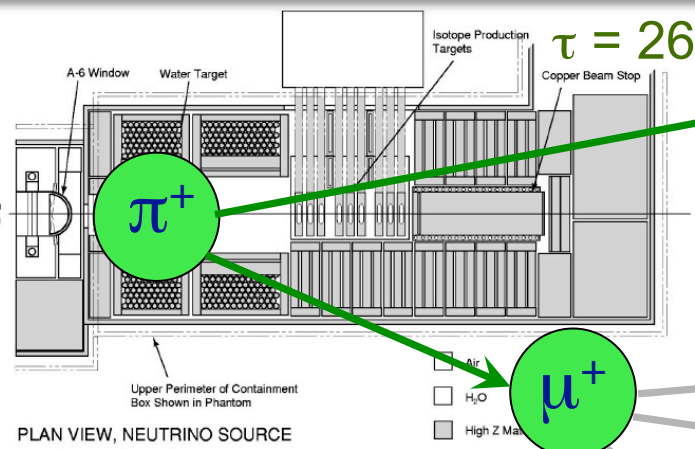
Review of the MiniBooNE oscillation results:

- Motivation for MiniBooNE: testing the LSND signal
- MiniBooNE design strategy and assumptions
- Neutrino oscillation results: PRL 98, 231801 (2007) & PRL 102, 101802 (2009)
- Antineutrino oscillation results: PRL 103, 111801 (2009) & PRL 105, 181801 (2010)
- Updated antineutrino oscillation results:
  ~52% more data
- Summary and future outlook.

LSND @ LANL (1993-1998)

800 MeV

protons



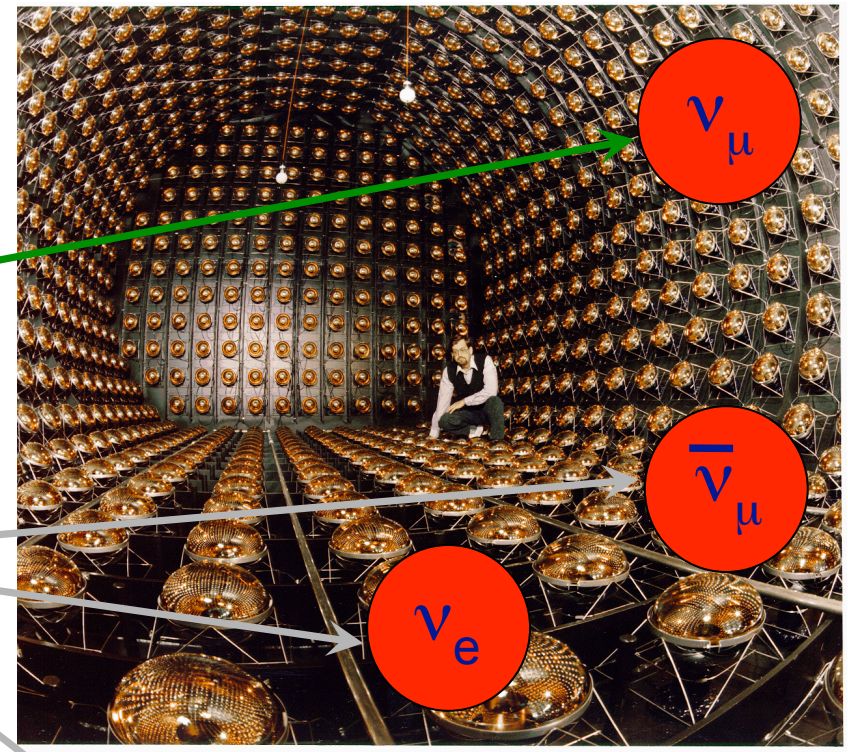
τ = 26 ns

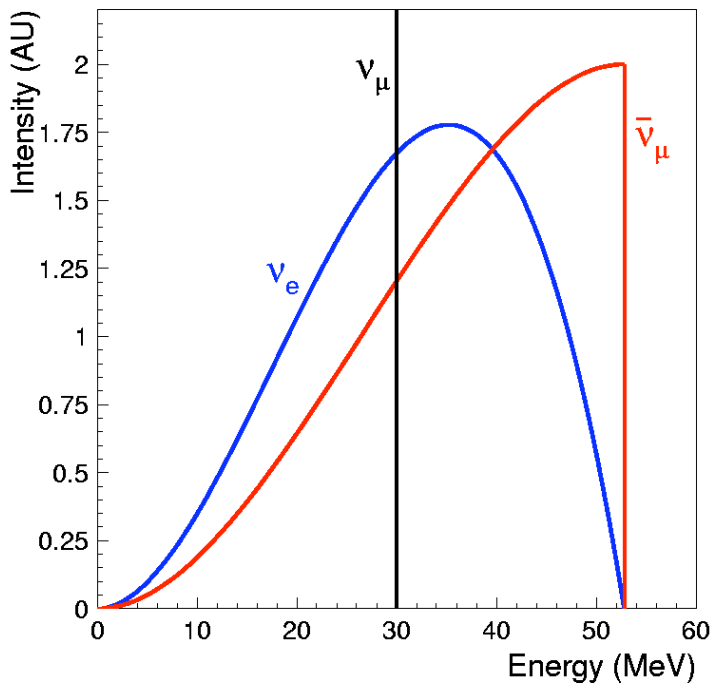
π^+

μ^+

τ = 2.2 μs

e^+





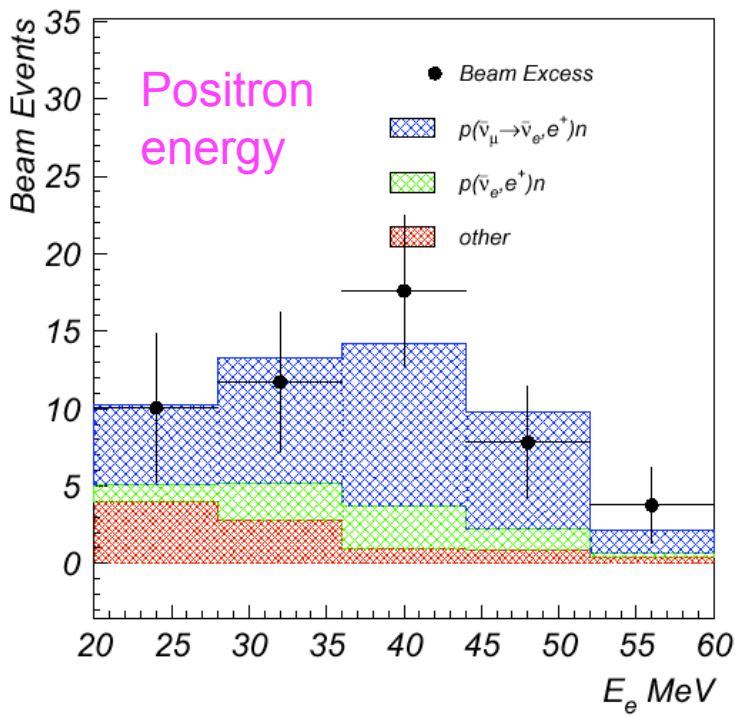
167 tons liquid scintillator (butyl-PBD)

1224 8-inch PMTs (25% coverage)

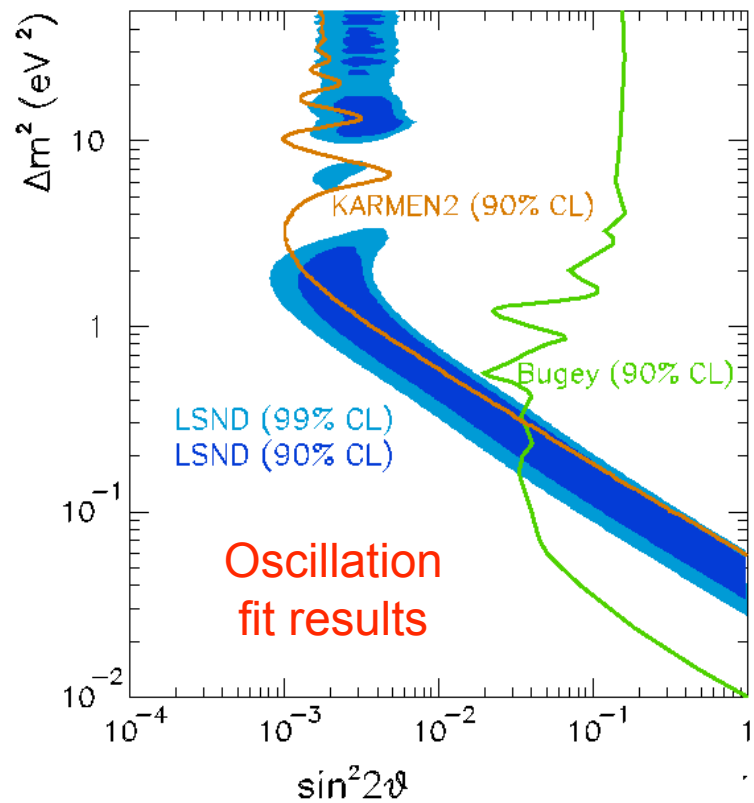
DAR search: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (primary)

DIF search: $\nu_\mu \rightarrow \nu_e$ (secondary)

LSND Results



The KARMEN experiment @ ISIS cannot confirm/dismiss LSND.
Joint analysis: most region allowed!

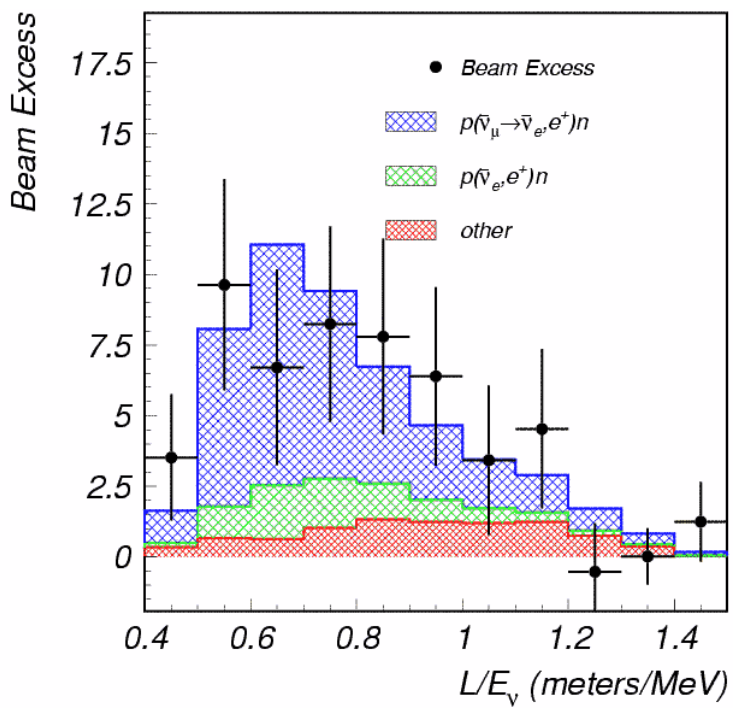


LSND saw an excess of $\bar{\nu}_e$ events:
87.9 ± 22.4 ± 6.0 above background

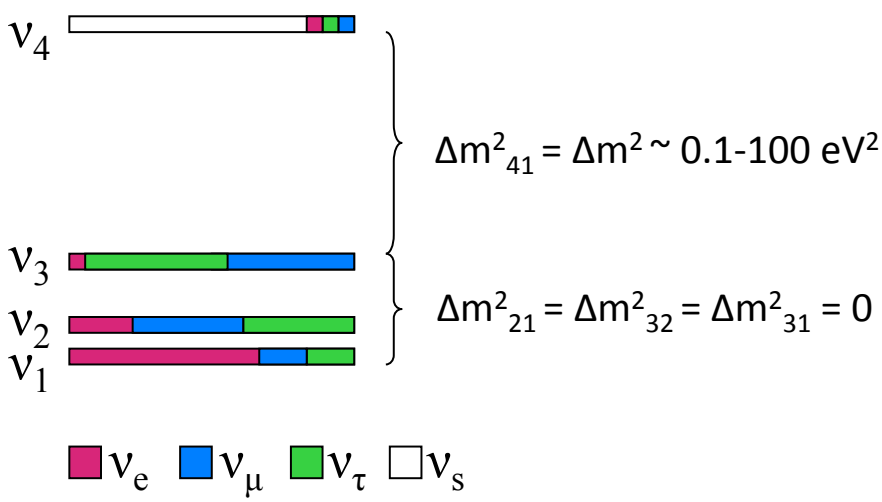
Oscillation probability:
(0.264 ± 0.067 ± 0.045)%

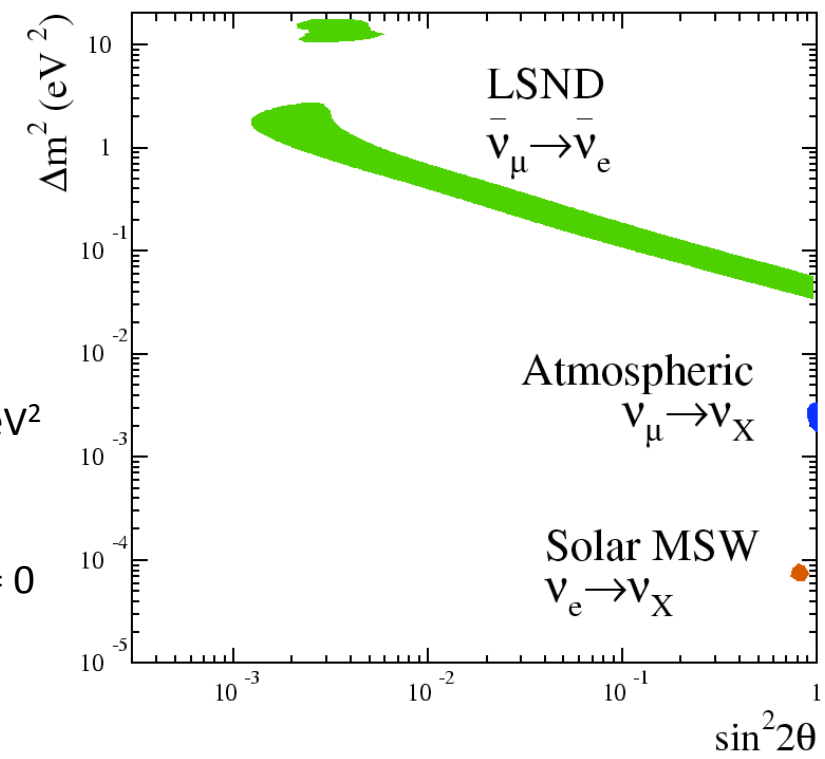
3.8 σ evidence for antineutrino $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

LSND Results

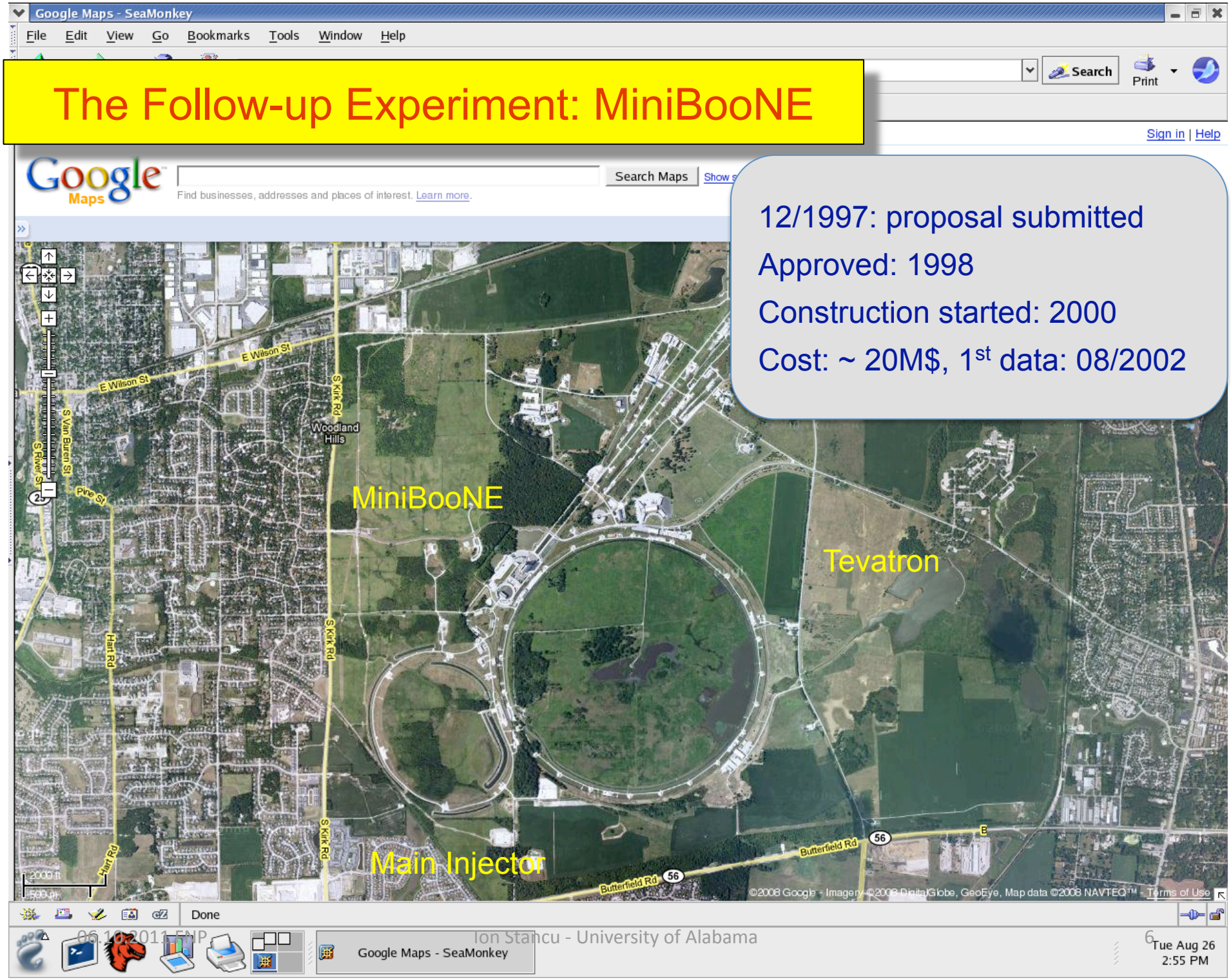


The three oscillation signals cannot be reconciled without introducing Physics beyond the Standard Model!
(e.g., active+sterile: 3+1, 3+2, etc.)





The Follow-up Experiment: MiniBooNE



12/1997: proposal submitted

Approved: 1998

Construction started: 2000

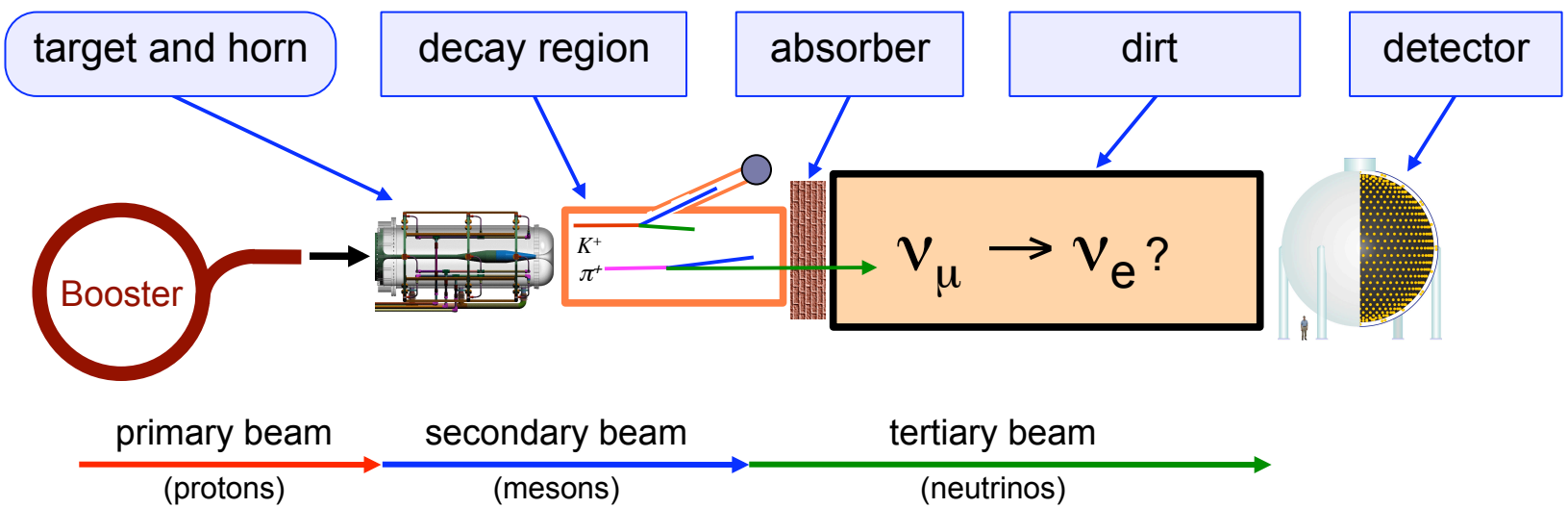
Cost: ~ 20M$, 1st data: 08/2002

The MiniBooNE Strategy

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

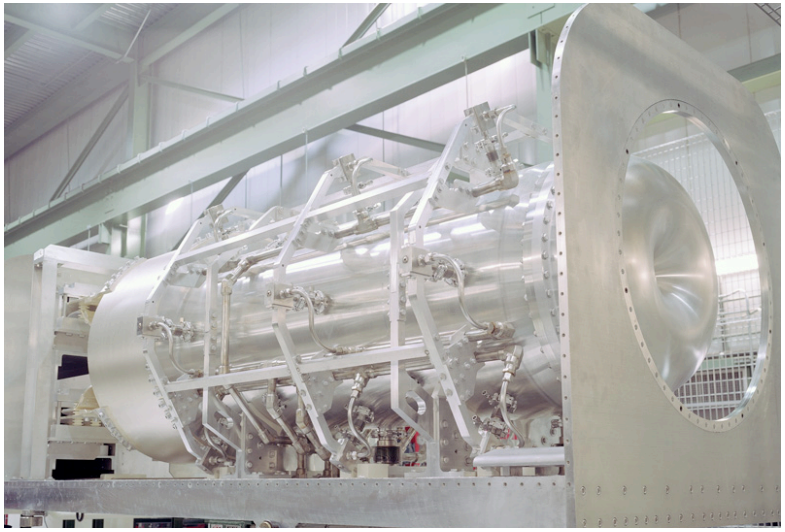
$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27\, \Delta m^2\ L/E)$

LSND: E ~ 45 MeV, L ~ 30 m, L/E ~ 0.66
MiniBooNE: E ~ 800 MeV, L ~ 500 m, L/E ~ 0.63

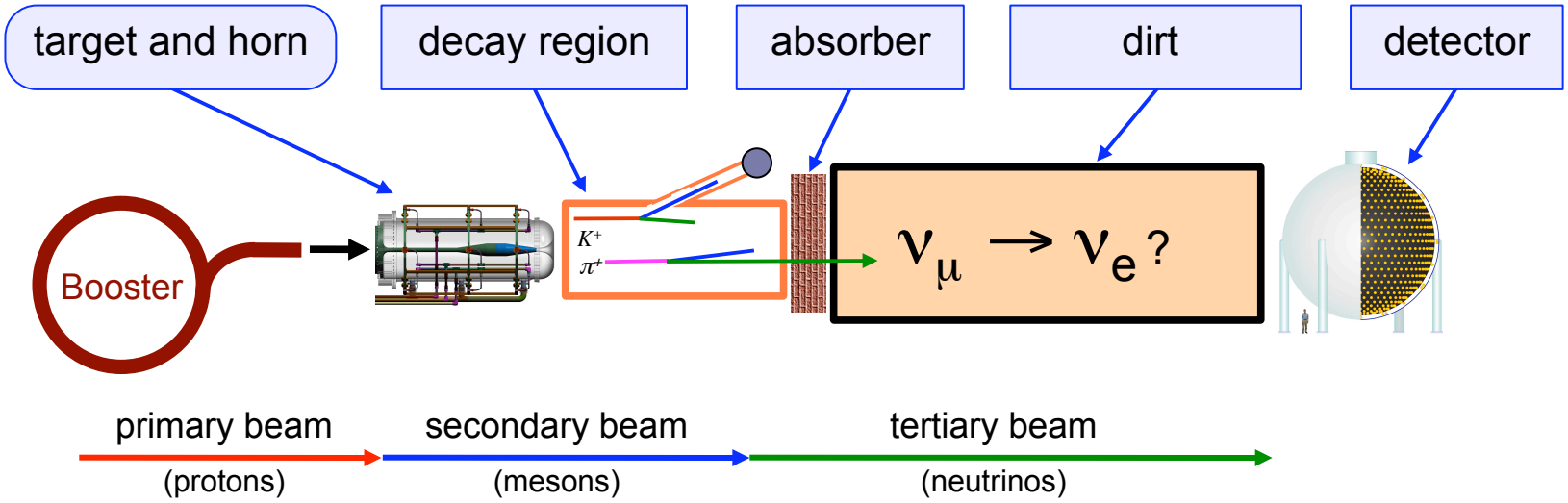


The MiniBooNE Beam

Magnetic focusing horn, I = 174 kA @ 5 Hz

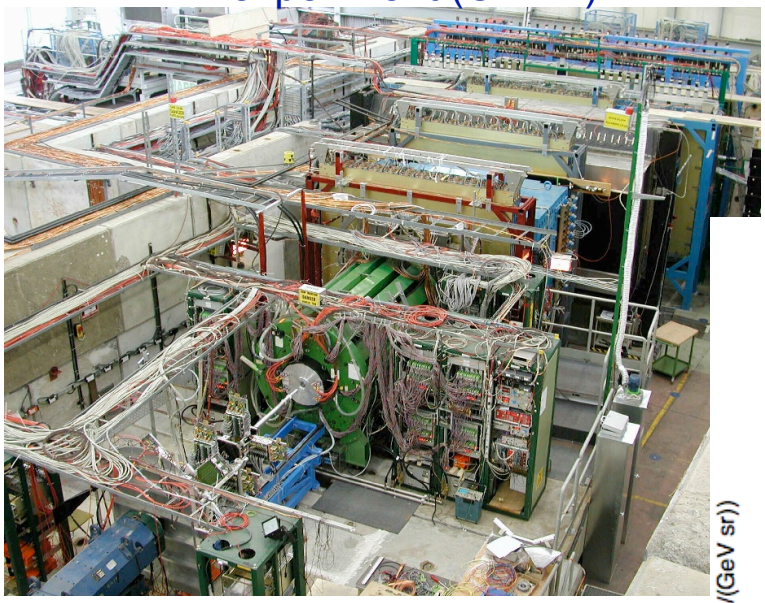


Neutrino flux increase @ detector: ~ 6



The MiniBooNE Beam

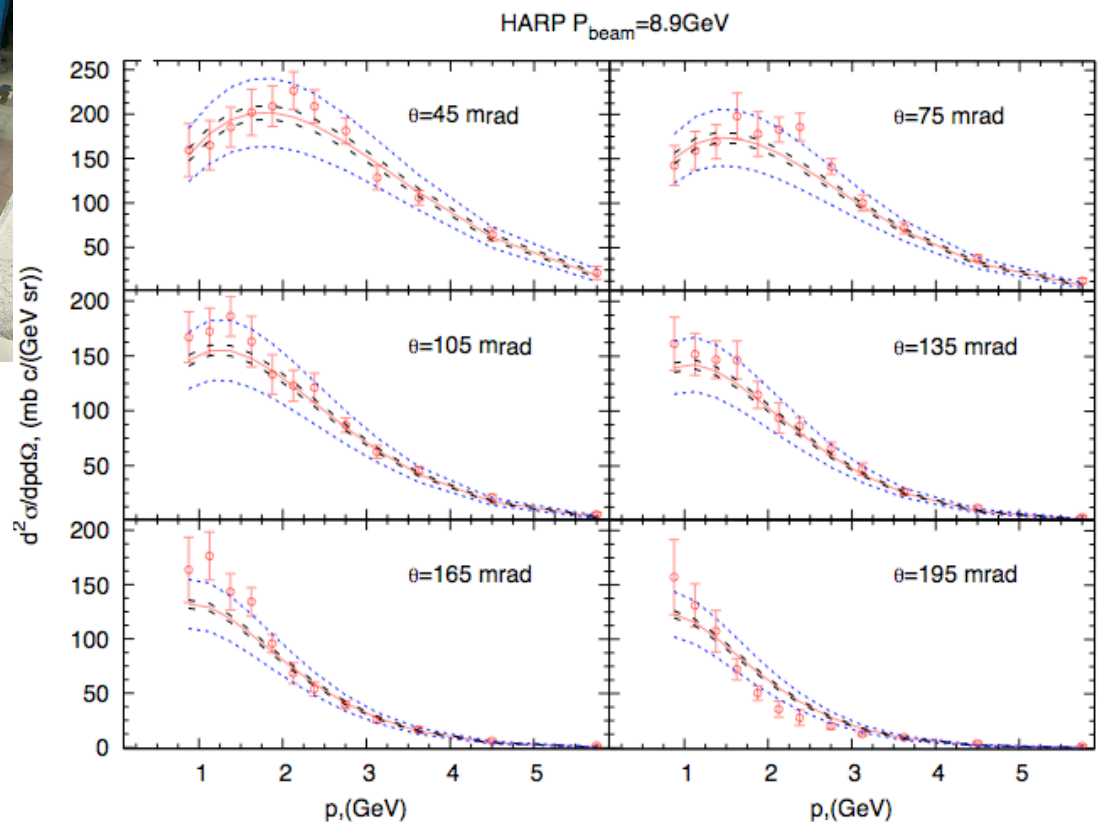
HARP experiment (CERN)



MB modeling of meson production based on the HARP measurement:

- identical, but 5% λ Beryllium target
- 8.9 GeV/c proton beam momentum

Sanford-Wang parameterization.



Majority of pions that create MB neutrinos are directly measured by HARP (>80%).

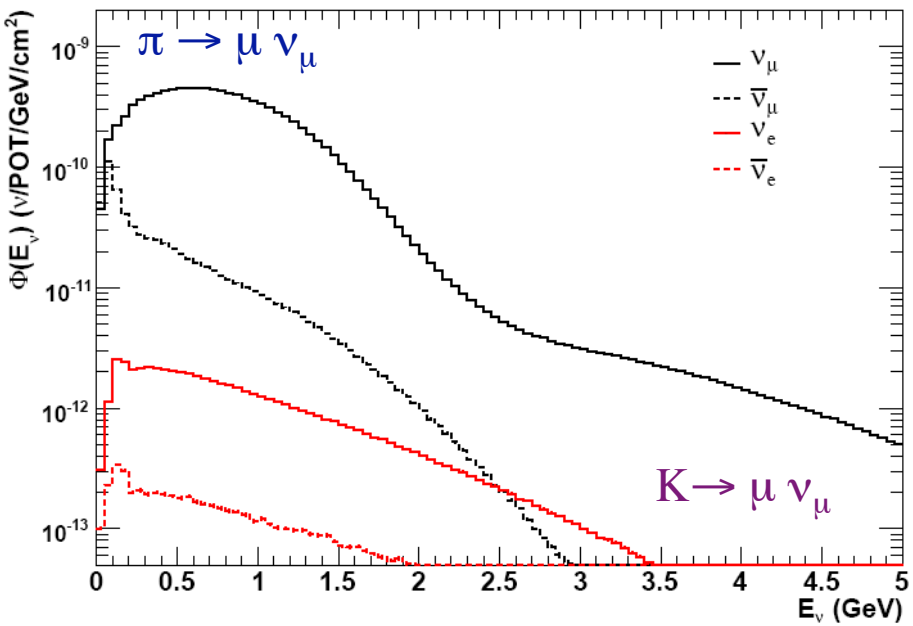
Eur. Phys. J. C52 (2007) 2.

The Neutrino Flux

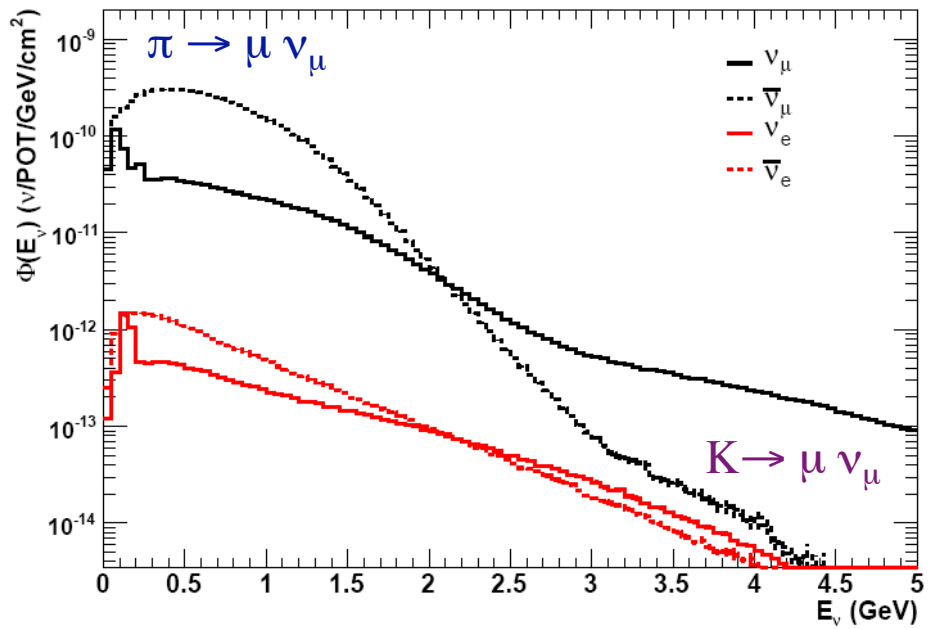
Phys. Rev. D79 (2009) 072002.

MiniBooNE is an appearance experiment: it looks for an excess of electron (anti)neutrino events in a predominantly muon (anti)neutrino beam.

Neutrino mode: E_{avg} ~ 0.8 GeV



Antineutrino mode: E_{avg} ~ 0.6 GeV



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

GEANT- 4 simulations

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

The MiniBooNE Detector

541 m downstream of target, 3 m overburden

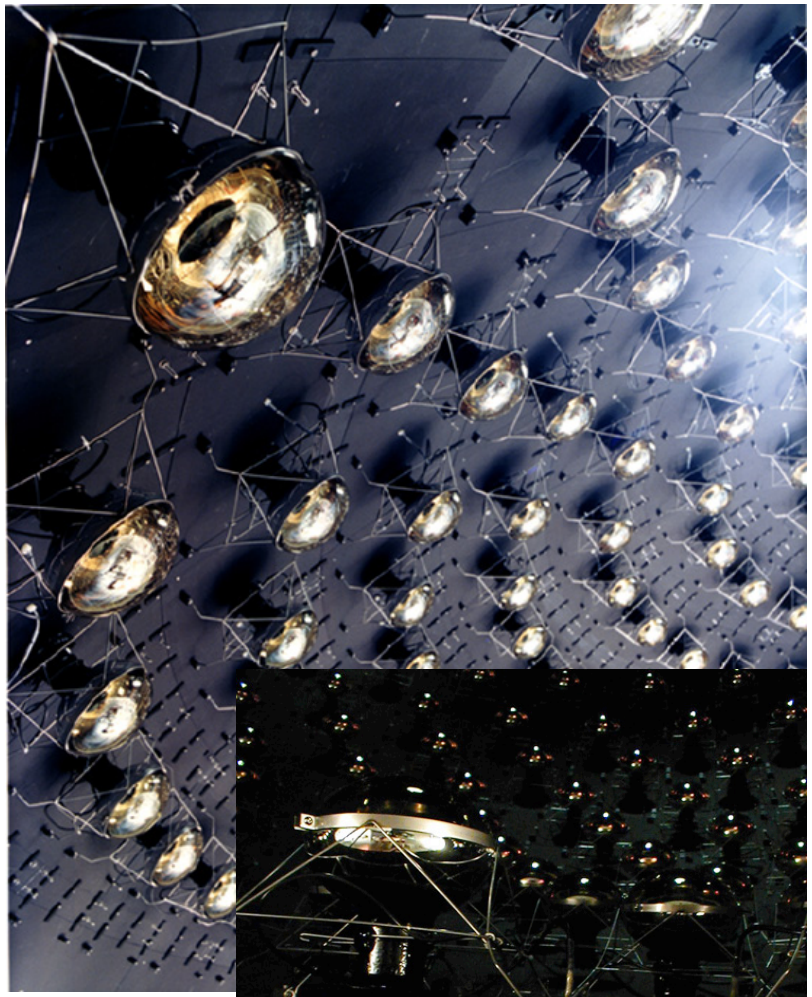
12.2-m diameter sphere (10 m fiducial volume)

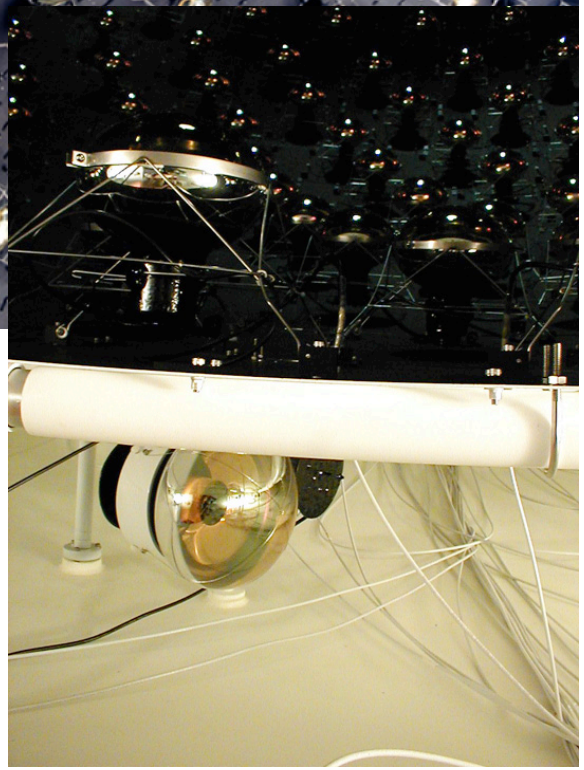
800 tons pure mineral oil (CH_2), fiducial = 450 tons

1280 inner phototubes, 10% area (320 new, 960 old)

240 veto phototubes (old LSND)

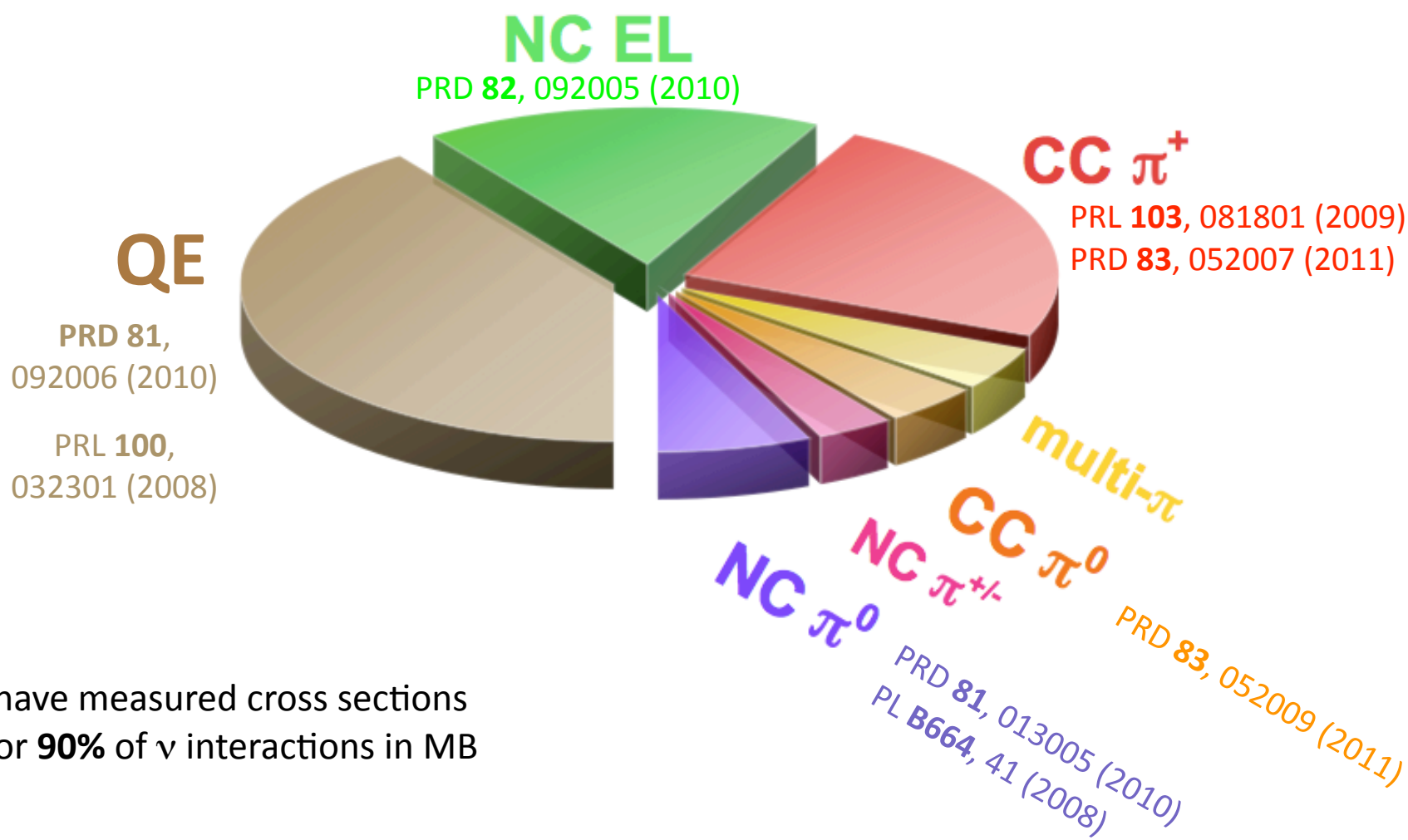
Simulated with a GEANT-3 Monte Carlo





The MB Neutrino Event Rates

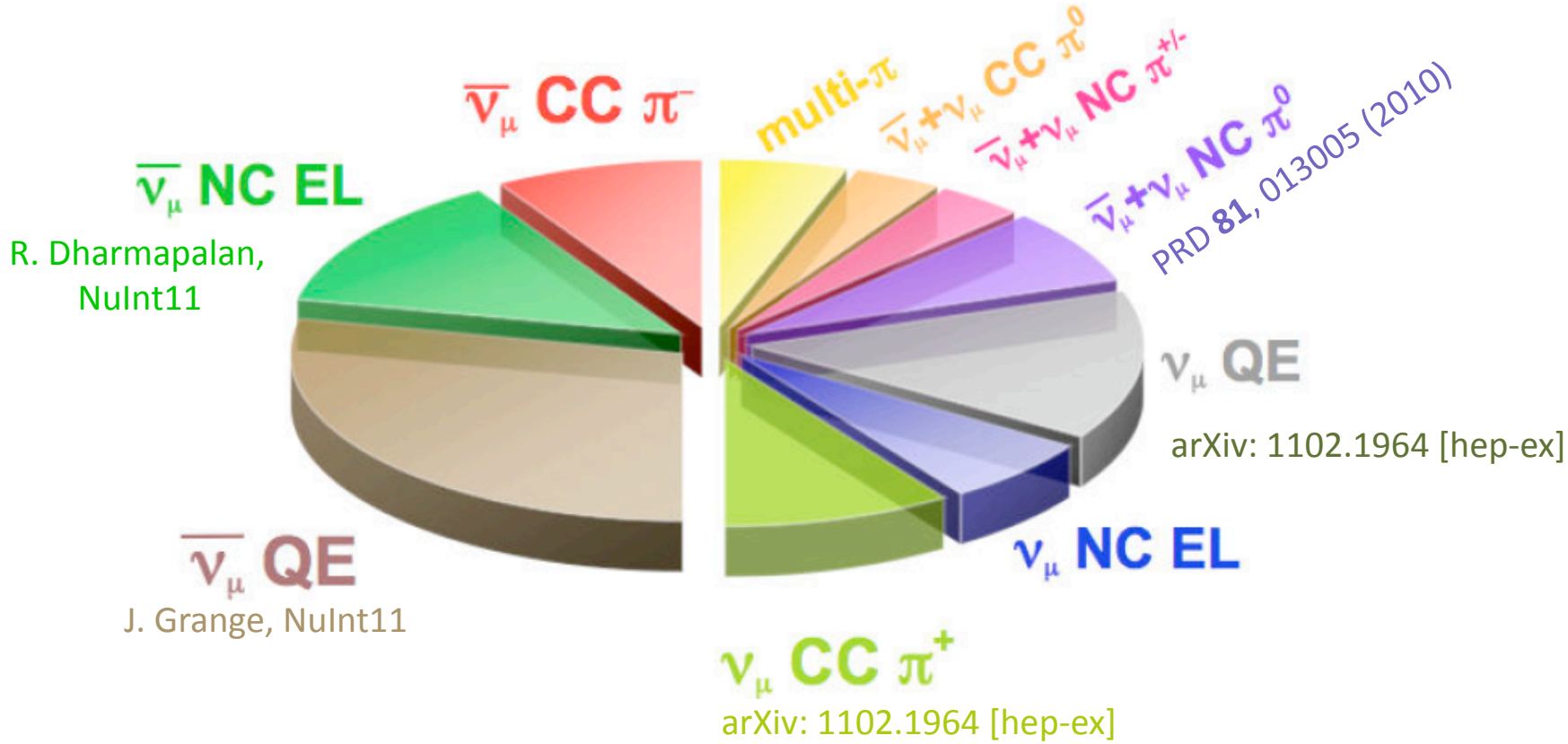
- 8 neutrino cross section publications (NUANCE)



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

The MB Antineutrino Event Rates

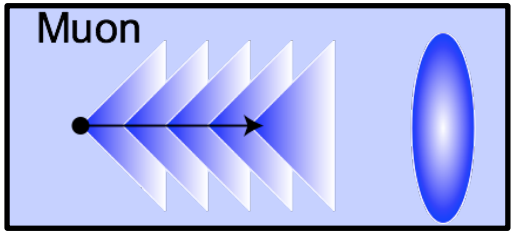
- 2 antineutrino cross section papers (NUANCE)



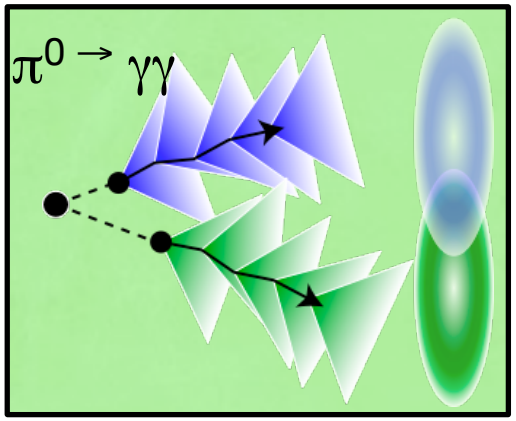
- additional antineutrino analyses currently underway

The MiniBooNE Events

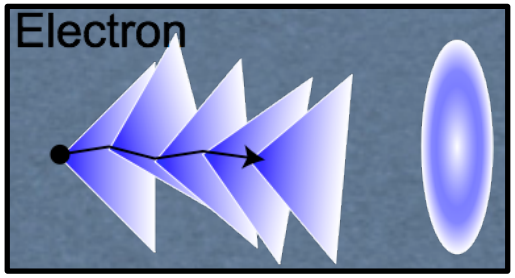
Muons:
Produced in most CC events.
Usually 2 subevents, or exiting.
Potentially dangerous if electron is missing (low E, same subevt).

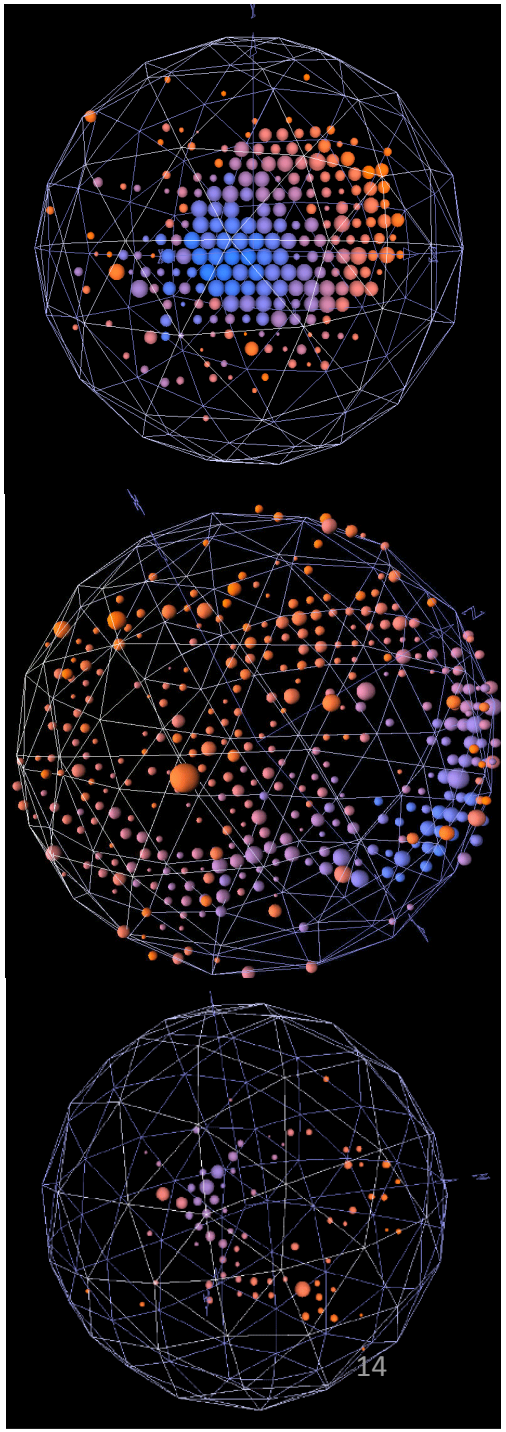


Neutral Pions:
Can form a background if one photon is weak or exits tank.
Potentially dangerous if high E.
In NC case, 1 subevent.



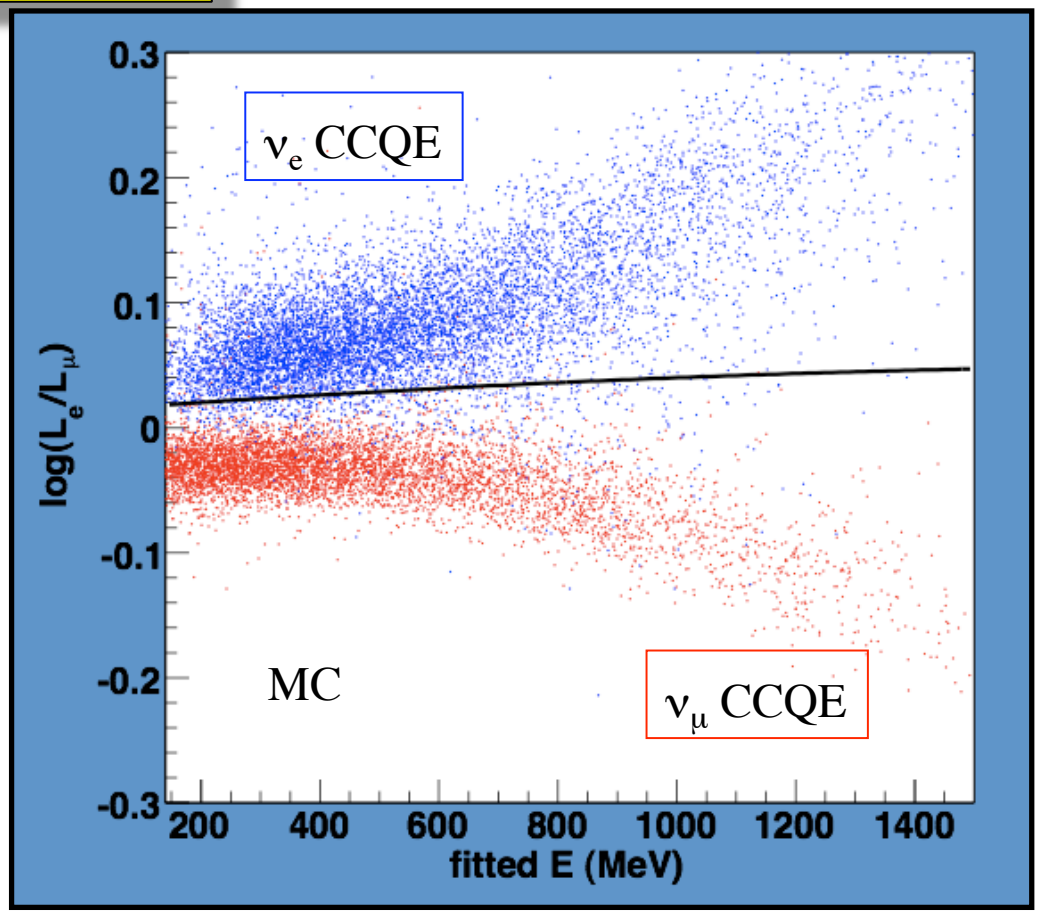
Electrons:
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent only.
Anti-nu: no 2.2 MeV γ tag!





MiniBooNE Tracking & PID

- Each event is reconstructed under 5 hypotheses:
  - 1-track electron
  - 1-track muon
  - 2-track fixed mass (m_π)
  - 2-track unconstrained
  - point-like proton



- Particle identification:
  - $\log(L_e/L_\mu)$, $\log(L_e/L_\pi)$, $M_{\gamma\gamma}$

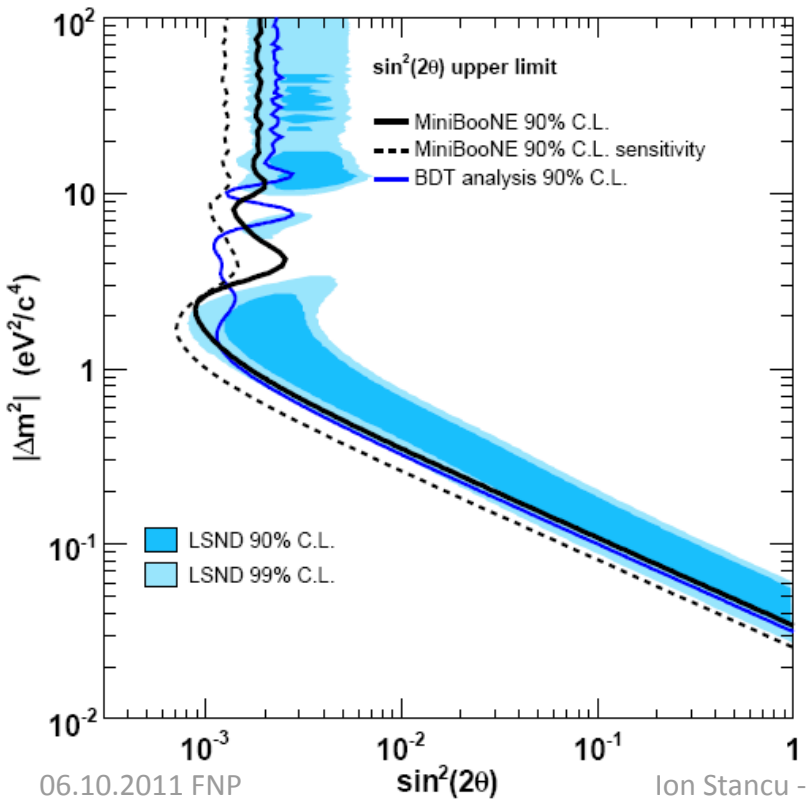
- Alternative particle identification:
  - Boosted Decision Trees (BDT) – developed @ UA
  - - better efficiency and background rejection
  - - more sensitive to optical model variations

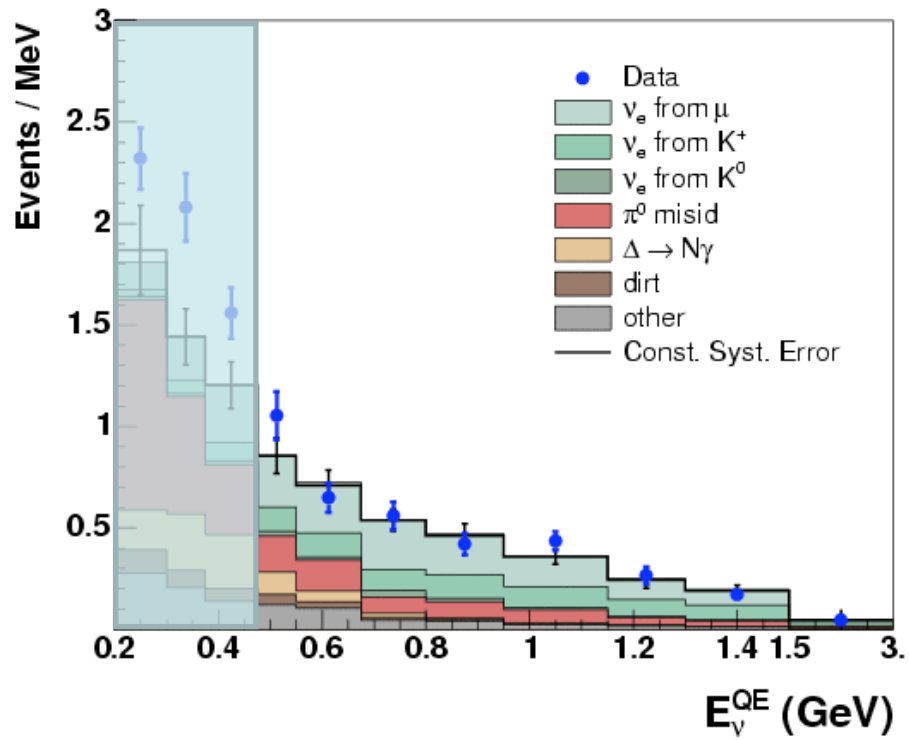
- Additional cuts: Nsub = 1, VHits < 6, THits > 200, R < 5 m, beam timing (& R_{btw}).

The Neutrino Data

PRL 98 (2007) 231801, POT = 5.58e20
PRL 102 (2009) 101802, POT = 6.46e20

- Results: $475 < E_\nu < 1250$ MeV
  Data = 408 events
  Bkgd = 385.9 ± 35.7 (syst+stat)
  XCS = 22.1 ± 35.7 (0.6 σ)



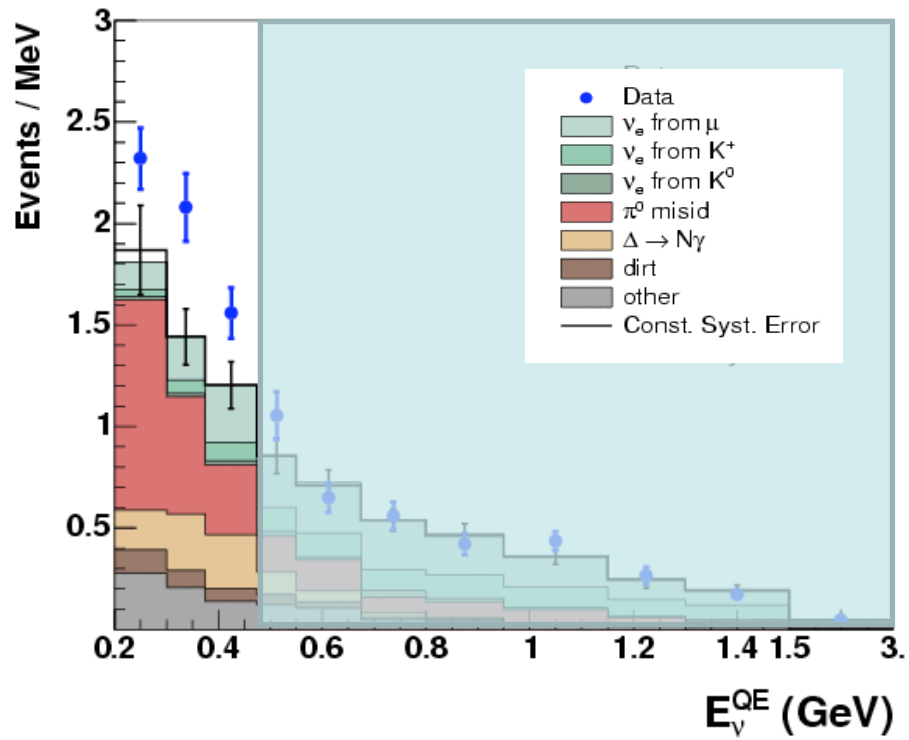


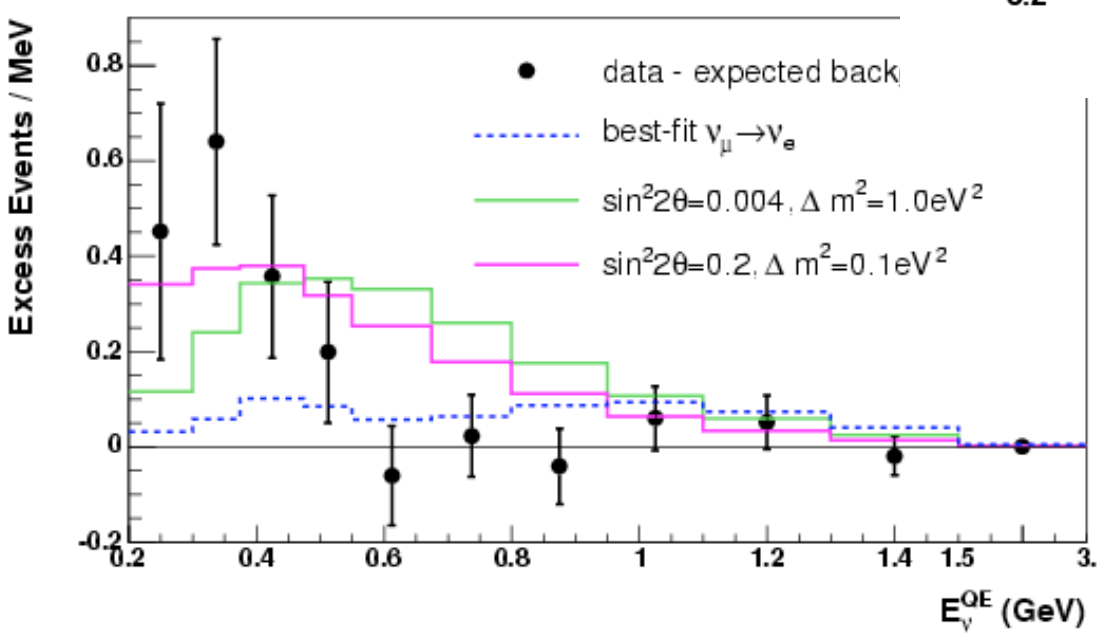
- No significant excess above 475 MeV!
- Good agreement with BKGD prediction.
- Simple 2-neutrino fit excludes LSND @ the 90% CL assuming CP conservation.
- Both analyses yield similar limits.
- But …

The Neutrino Data

- Large excess for $E_\nu < 475$ MeV
  Data = 544 events
  Bkgd = 415.2 ± 43.4 (syst+stat)
  XCS = 128.8 ± 20.4 ± 38.3 (3.0 σ)
  (statistics only: 6.3 σ effect)

- Shape not consistent w. 2ν oscillations
- Magnitude consistent with LSND!

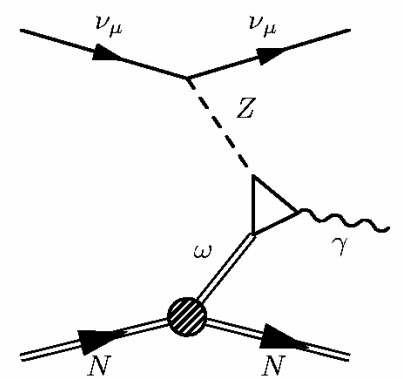


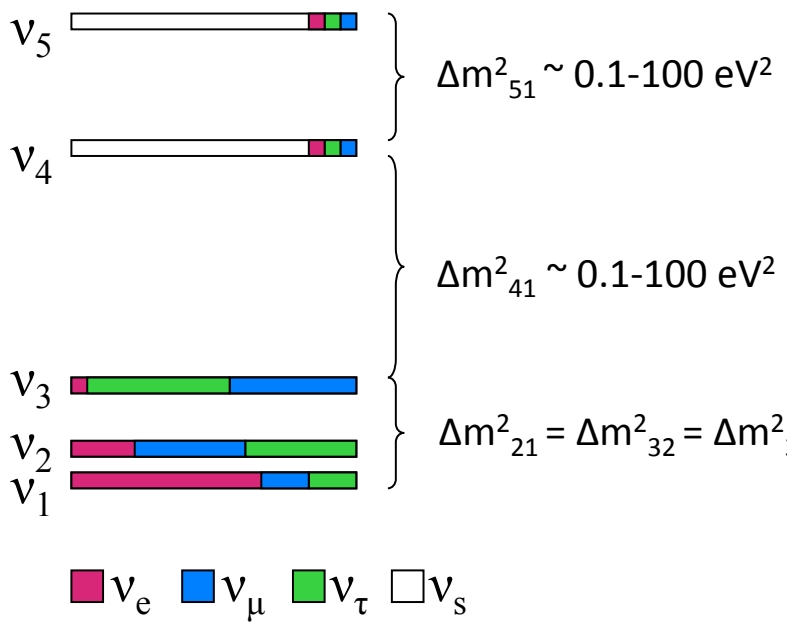


- Best-fit point for $E_\nu > 200$ MeV
  $\Delta m^2 = 3.14$, $\sin^2 2\theta = 0.0017$
  $\chi^2/DF = 18.3/17$

- Null hypothesis:
  $\chi^2/DF = 22.0/19$

Possible Theories





Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density:
Harvey, Hill & Hill, arXiv:0708.1281.

CP-Violation 3+2 Model:
Maltoni & Schwetz, PRD 76 (2007) 093005;
Goldman, Stephenson & McKellar, PRD 75 (2007) 091301.

Extra Dimensions 3+1 Model:
Pas, Pakvasa, & Weiler, PRD 72 (2005) 095017.

Lorentz Violation:
Katori, Kostelecky, & Tayloe, PRD 74 (2006) 105009.

CPT Violation 3+1 Model:
Barger, Marfatia, & Whisnant, PLB 576 (2003) 303.

New Gauge Boson with Sterile Neutrinos:
Nelson & Walsh, PRD 77 (2008) 033001.

The Antineutrino Run

- January 2006: switch to antineutrino mode
- Fall 2007 – Spring 2008: neutrinos 4 SciBooNE

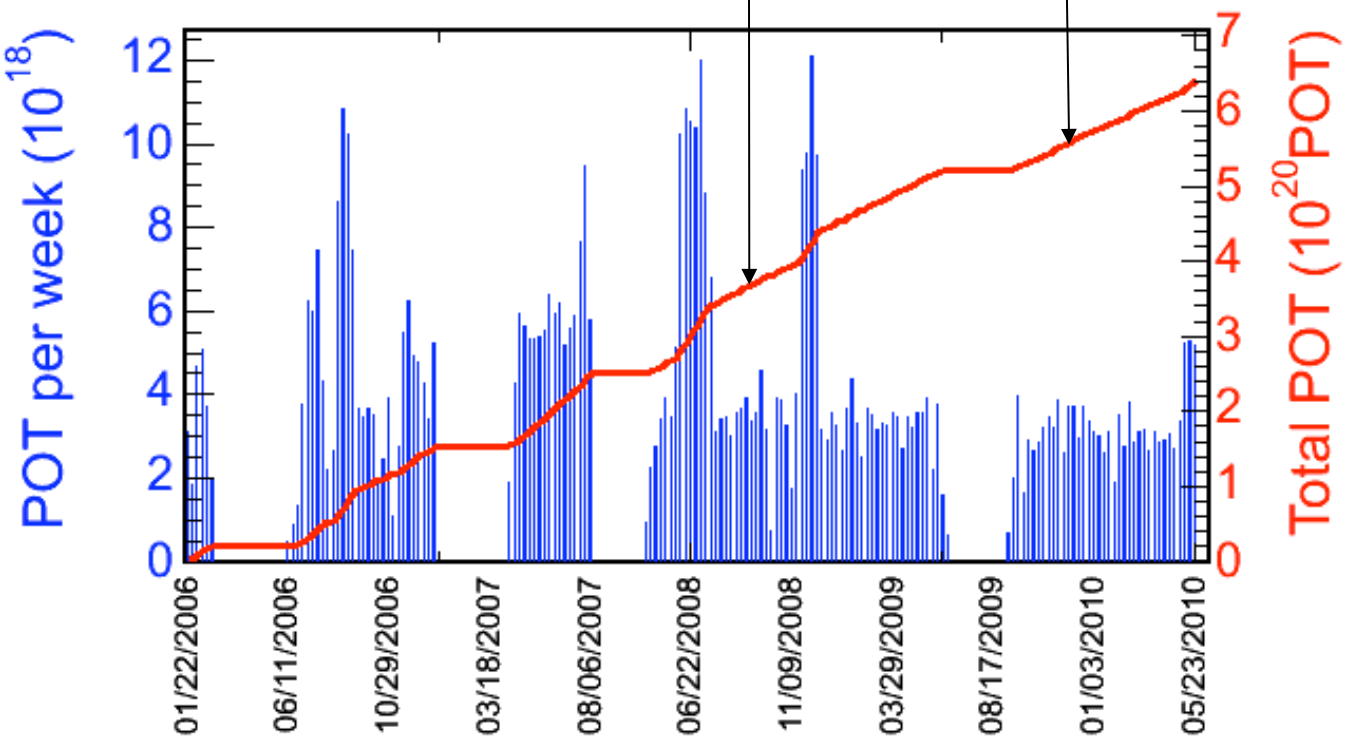
PRL 103 (2009) 111801

3.39e20 POT
first $\bar{\nu}_e$ appearance result

PRL 105 (2010) 181801

5.66e20 POT
2nd result

8.58e20 POT
this result (05/11)

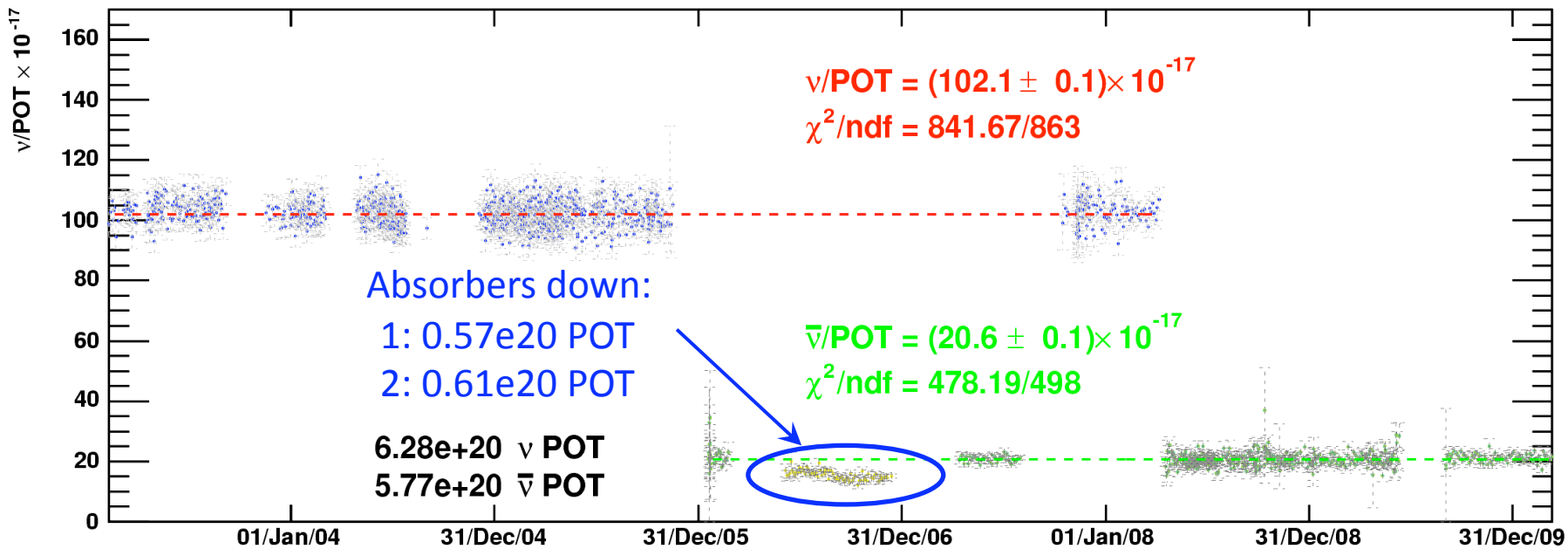


Antineutrino Event Rates

- Collected about 1/5 the number of interactions as in neutrino mode when same number of POT is considered:
  - flux per POT is lower (~ 1.5) in anti-nu mode
  - cross section is lower (~ 3) in anti-nu mode

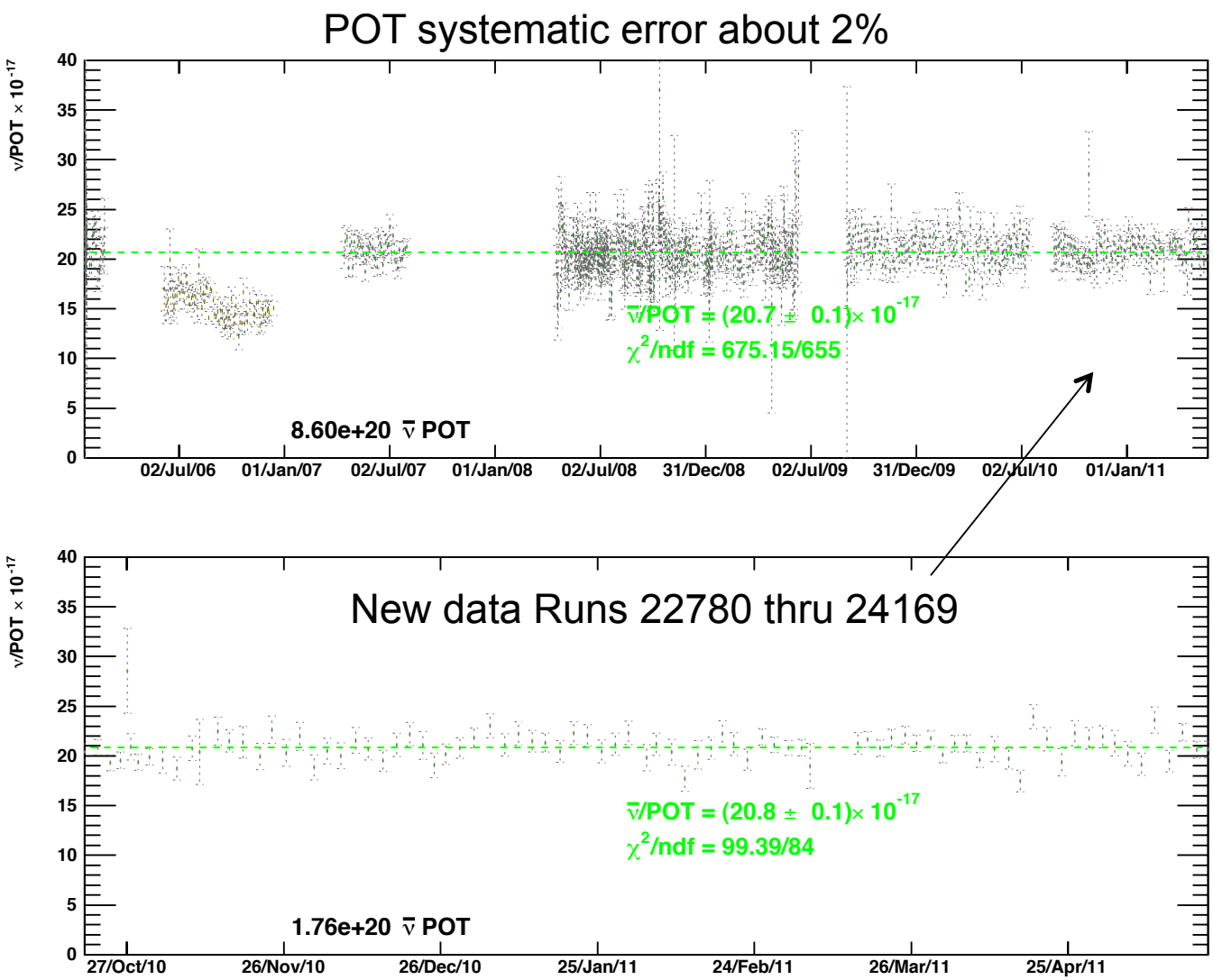
- Background types and relative rates are similar for neutrino and antineutrino mode (except for the higher wrong-sign contamination – about 16%)

- Fit analysis and errors are similar
- Absorber down periods included (good data/MC agreement: CCQE, NCπ^0)

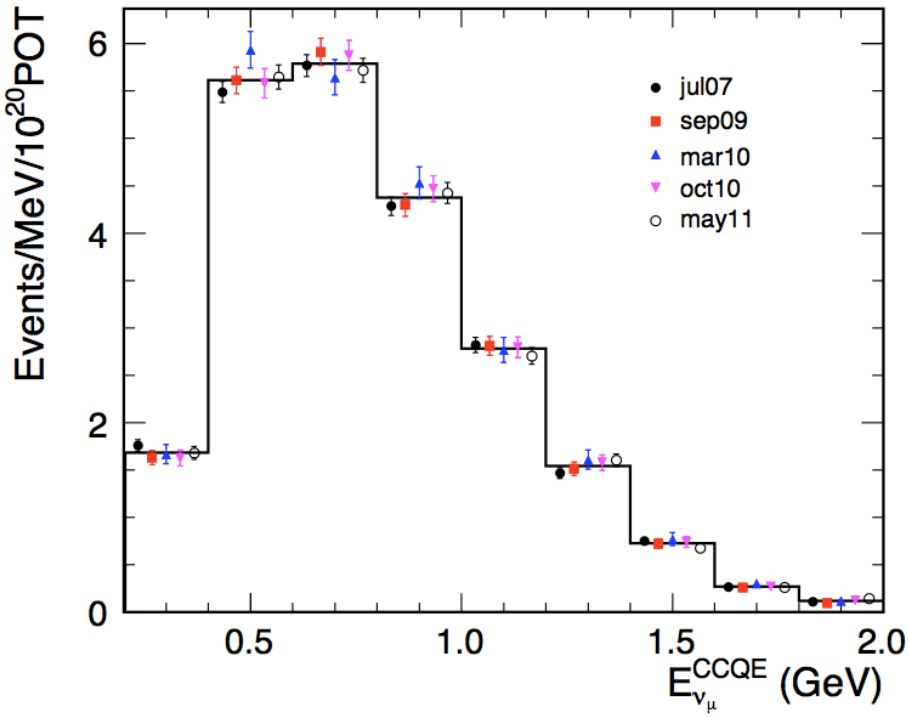


Data Checks

- Beam stable to 2%
- Detector energy response stable to 1%



Data Checks



- Antineutrino rates and energy spectrum stable over entire antineutrino run

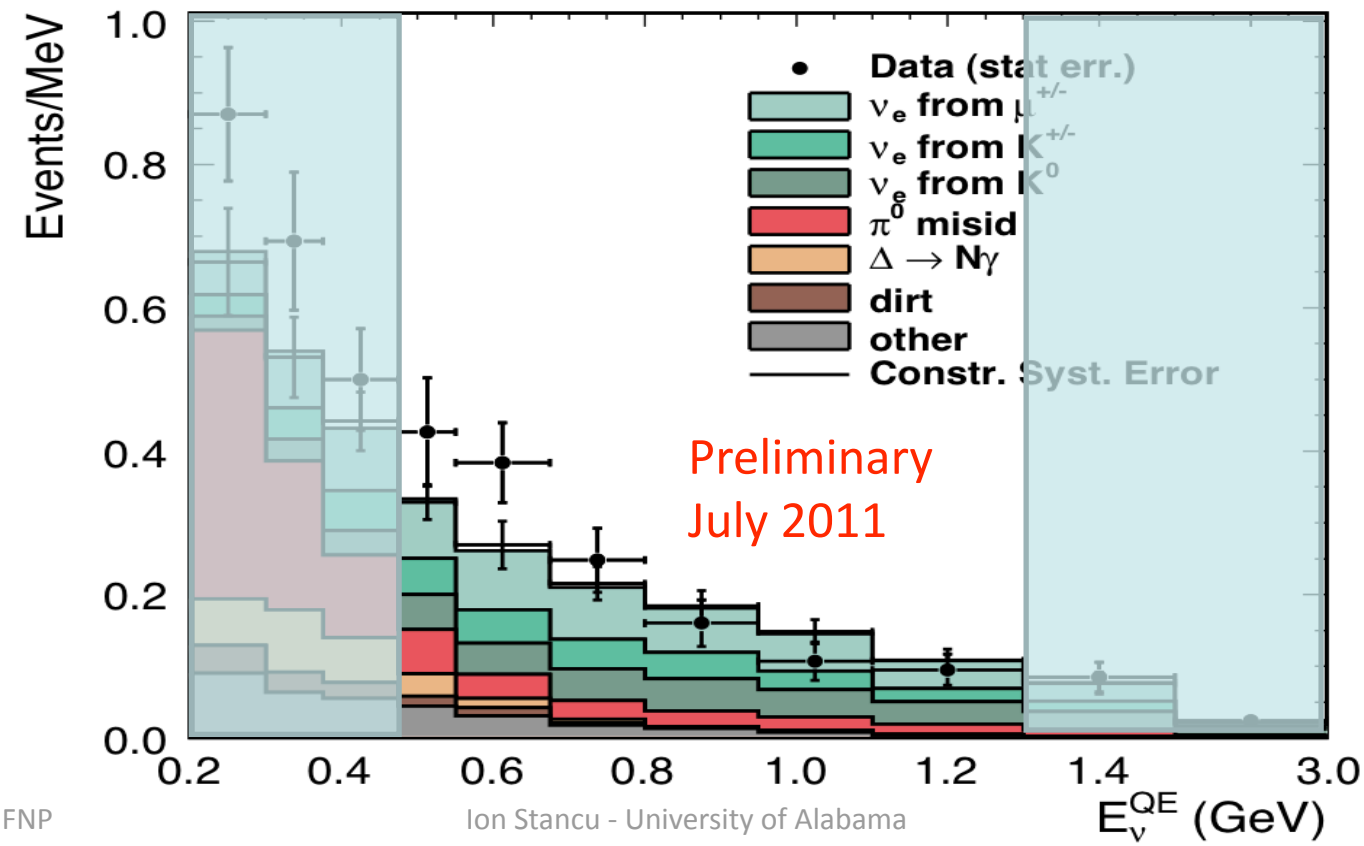
- New SciBooNE constraint on K^+ component of the Booster beam: 1105.2871 [hep-ex] (PRD in print)
  Reduces this component of background by 3% and error by factor of 3.

- Other systematic errors, constrained by MiniBooNE data, reduced due to higher statistics in control samples:
  - pion decay neutrino normalization factors
  - ”dirt” neutrino background
  - neutral current π^0 production

Latest Antineutrino Data

- Results: $475 < E_\nu < 1250$ MeV (oscillations-sensitive region)

- Data = 168 events
  Bkgd = 151.7 ± 15.0 (syst) after fit constraints
  XCS = 16.3 ± 19.4 (syst+stat), i.e., 0.84 σ effect.
- Excess in oscillation search region is reduced somewhat with new data
- Low-energy excess is more significant and resembles neutrino-mode data



The Antineutrino Fit

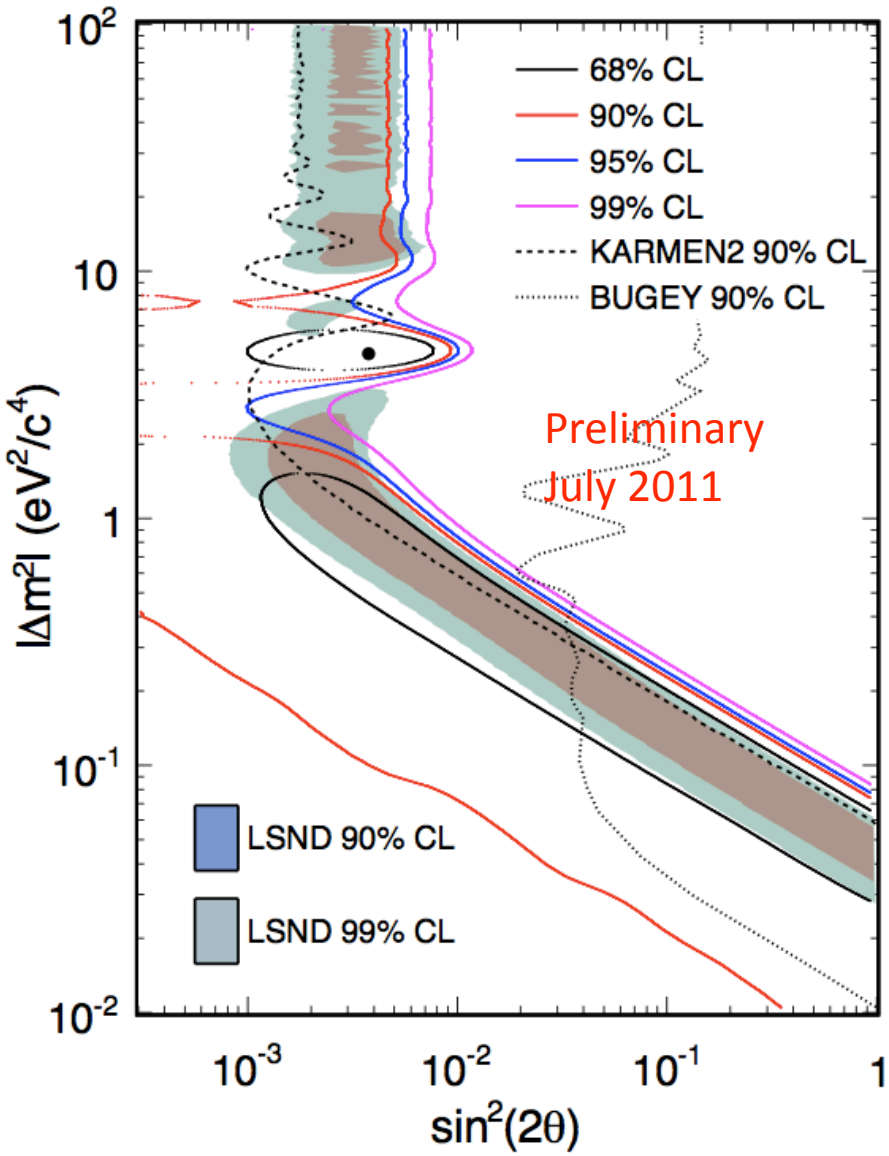
- Results for 8.58e20 POT & E > 475 MeV
- Maximum likelihood fit (simple 2-nu model)

- Oscillations favoured over background only (null) hypothesis at 91.1% CL

- Best Fit Point:
  $(\Delta m^2, \sin^2 2\theta) = (4.6\ eV^2, 0.0045)$
  χ^2_{BF} /NDF = 4.3/3.9 with $P(\chi^2)$= 35.5%
  χ^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:

  - oscillations favored over null at 99.4% CL
  - χ^2_{BF} /NDF = 8.0/4 with $P(\chi^2)$= 8.7%
  - χ^2_{NULL}/NDF = 18.5/6 with $P(\chi^2)$= 0.5%



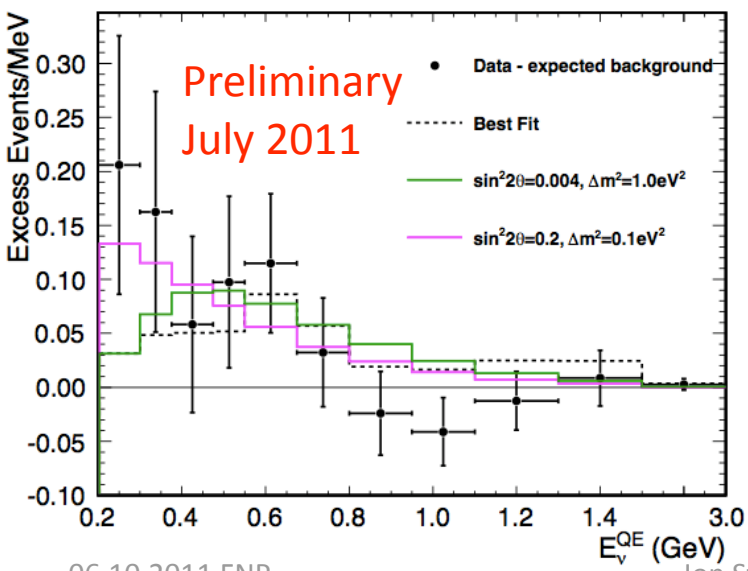
Fitting the Full Energy Range

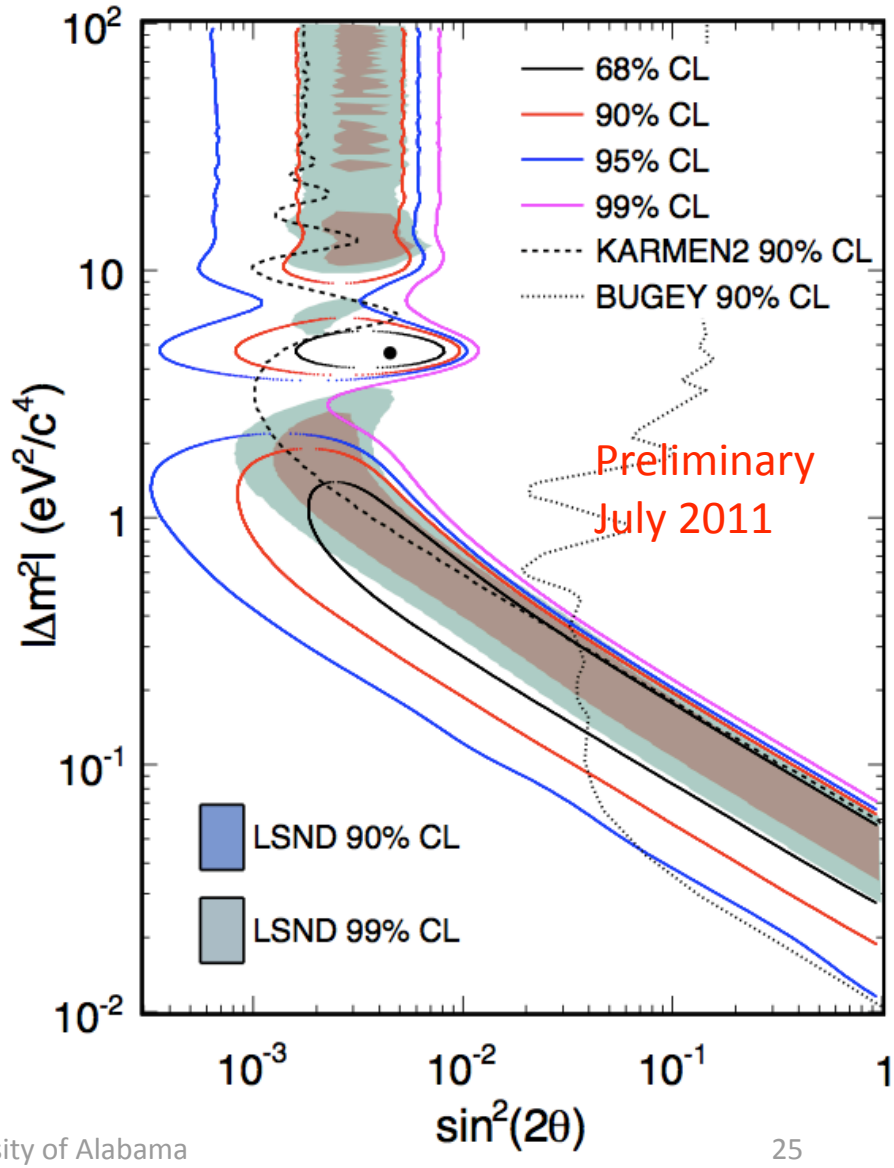
XCS = 57.7 ± 28.4 (tot)
XCS = 38.6 ± 18.5 (tot) below 475 MeV

- Use full energy range: 200 < E < 2000 MeV
- Does NOT include low-E neutrino XCS!

- Oscillations favoured over background only (null) hypothesis at 97.6% CL

- Best Fit Point:
  $(\Delta m^2, \sin^2 2\theta) = (4.6\ eV^2, 0.0038)$
  χ^2_{BF} /NDF = 6.1/6.9 with $P(\chi^2)$= 50.7%
  χ^2_{NULL}/NDF = 14.5/8.9 with $P(\chi^2)$= 10.1%





Scaling the Low-E Neutrino XCS

- 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 backgrounds as the source of low-E excess in neutrino mode:

  - Total background: 50
  - Neutrino contamination only: 17
  - Δ to Nγ decays: 39
  - Dirt: 46
  - Protons on target (neutrals in secondary beam): 165
  - K^+ in secondary beam: 67
  - NC π^0: 48
  - Inclusive CC: 59

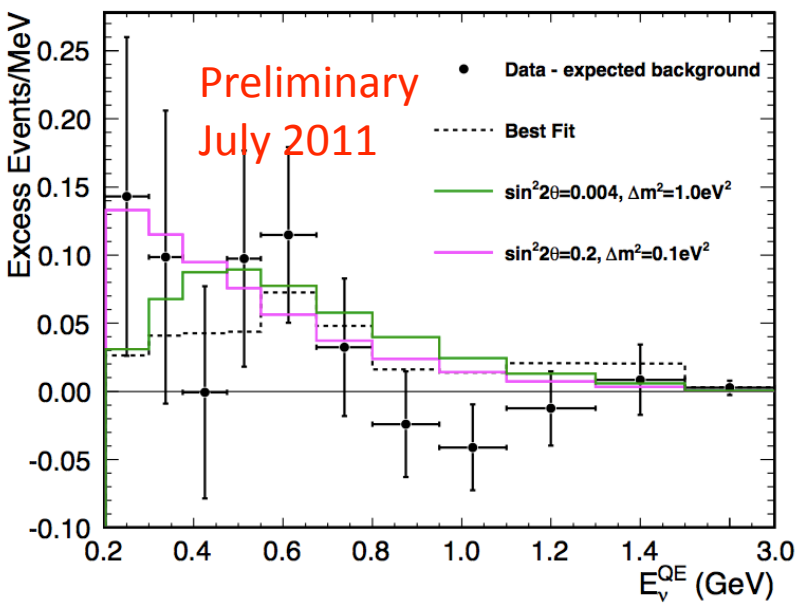
- These backgrounds must fluctuate up at least 5s to account for the low-E XCS!

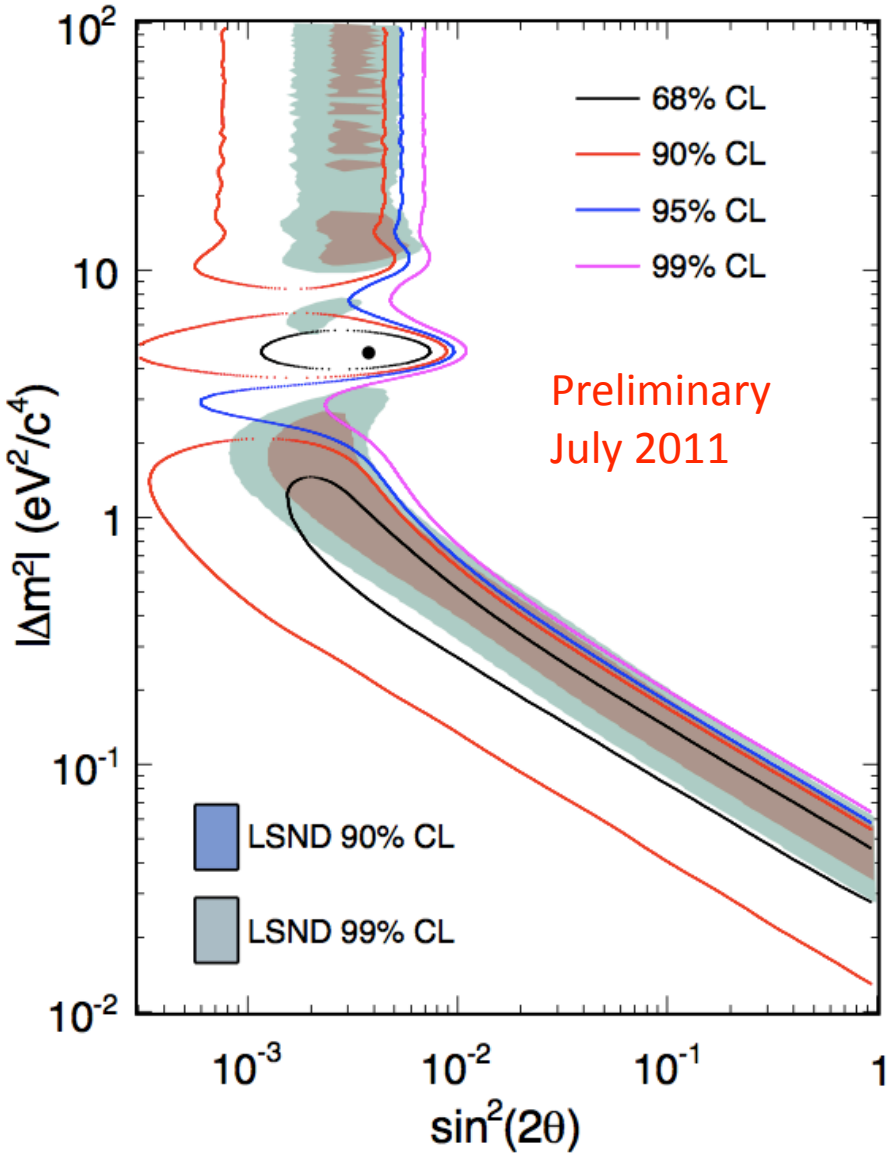
Fitting the Full Energy Range

- Assume simple scaling for low-E nu XCS: subtract 17 events from the low-E region
- Oscillations favoured over background only (null) hypothesis at 94.2% CL
- Best Fit Point:

  $(\Delta m^2, \sin^2 2\theta) = (4.6\ eV^2, 0.0037)$

  $P(\chi^2,BF) = 76.5\%$ & $P(\chi^2,NULL) = 28.3\%$

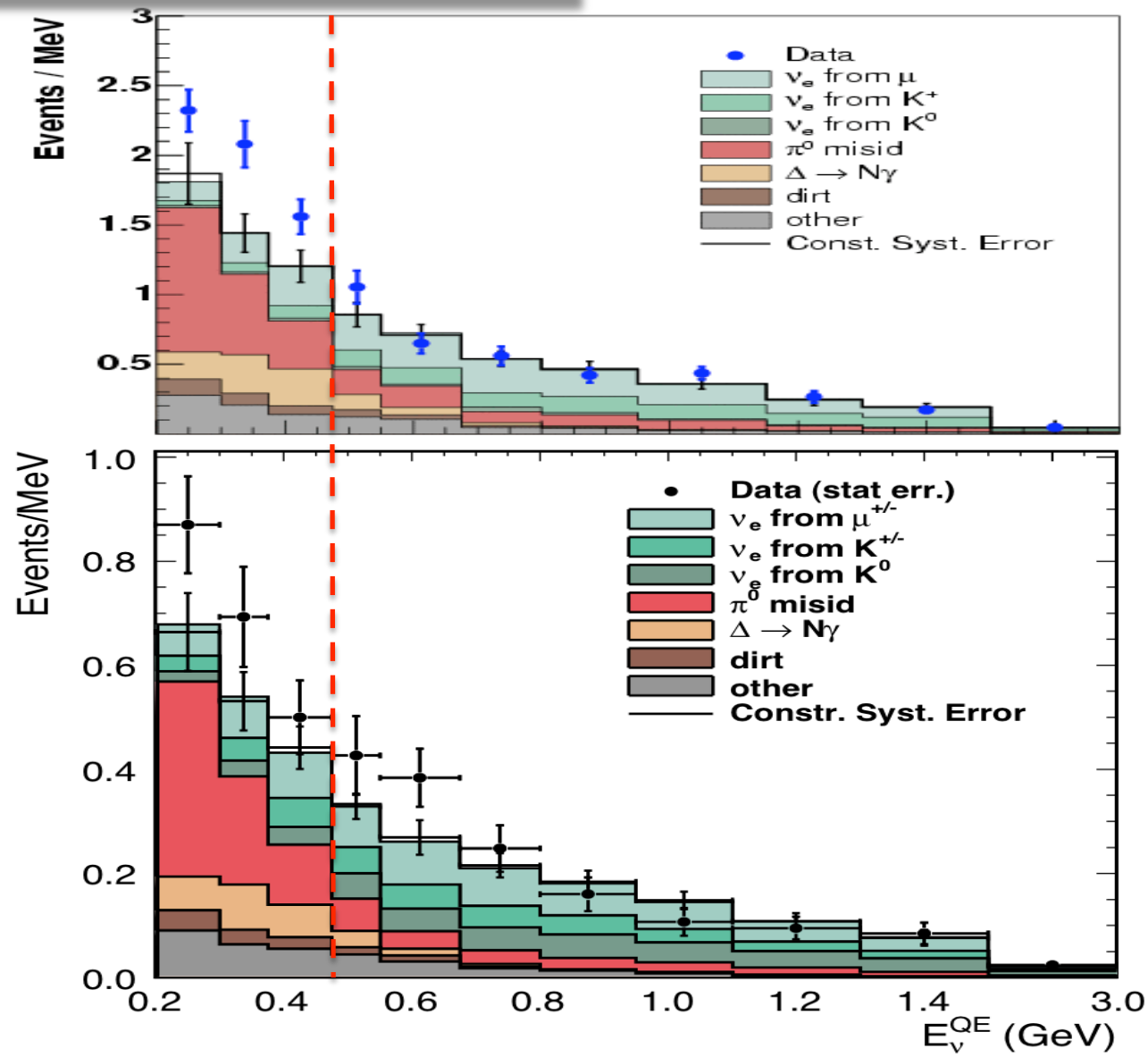




Comparing the MiniBooNE Results

Neutrinos:
6.5e20 POT

Antineutrinos:
8.6e20 POT



Summary of MiniBooNE Results

- The MiniBooNE ν_e and $\bar{\nu}_e$ appearance picture starting to emerge is the following:

1) Neutrino Mode

a) E < 475 MeV: An unexplained 3 σ electron-like excess.

b) E > 475 MeV: A two neutrino fit rules out LSND at the 98% CL.

2) Antineutrino mode

a) E < 475 MeV: An electron-like excess of 38.6 ± 18.5 events.

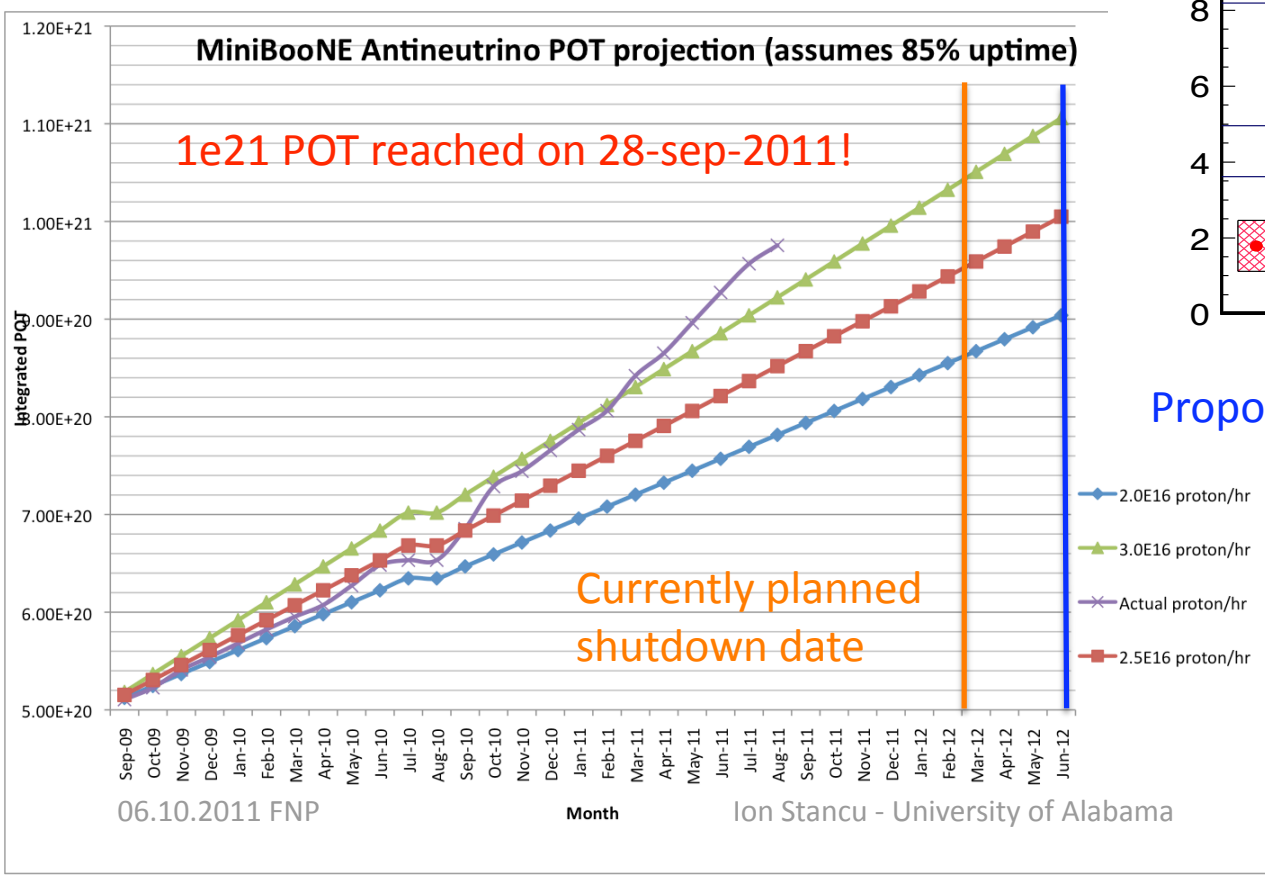
b) E > 475 MeV: An excess that is 14.9% consistent with null.

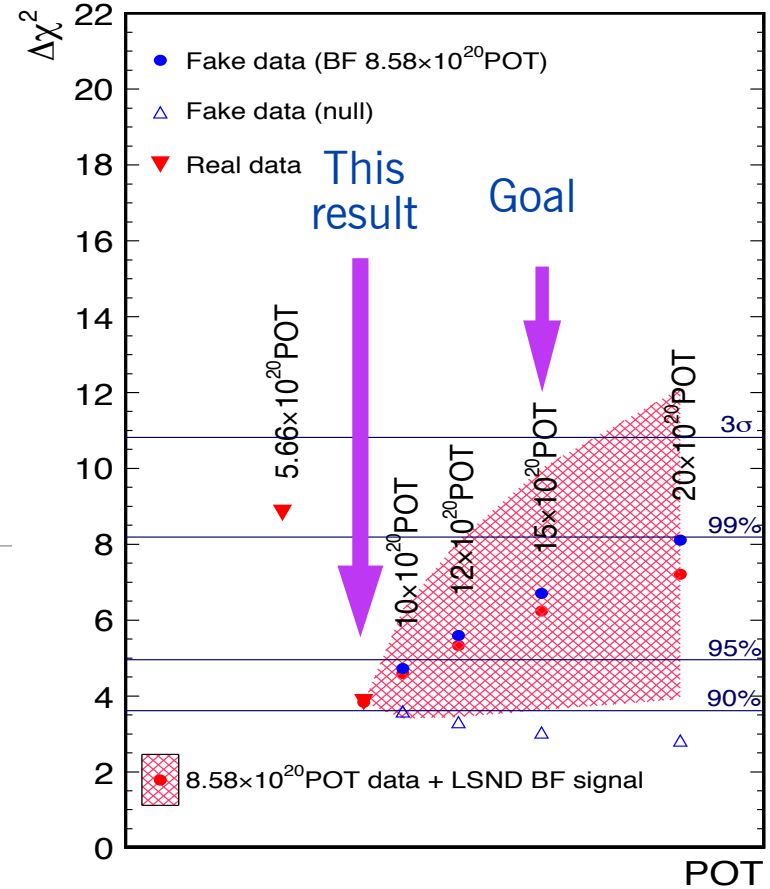
Two neutrino oscillation fits consistent with LSND at 35.5% CL relative to null.

- Low-E excess now more prominent for anti-neutrino running than previous result.
- Perform a combined analysis of the combined ν_e and $\bar{\nu}_e$ data.

The Future of MiniBooNE

- MiniBooNE continue running …
- Request to PAC for 15e20 POT
- Longer term:
  MiniBooNE-like near detector (200m), μBooNE

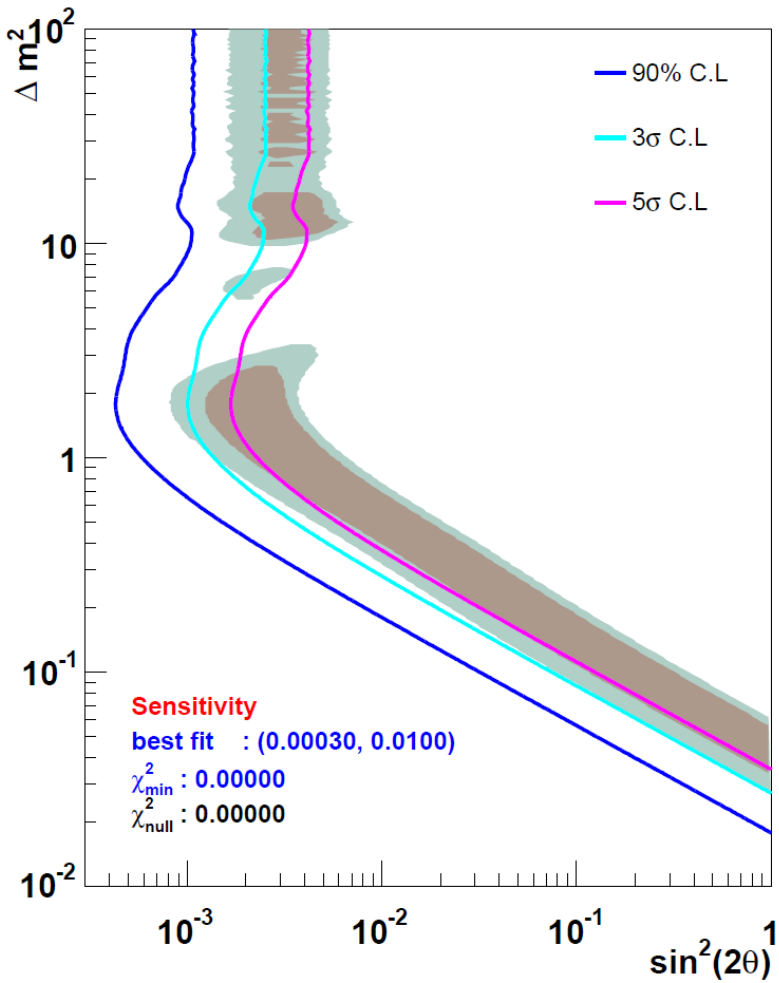


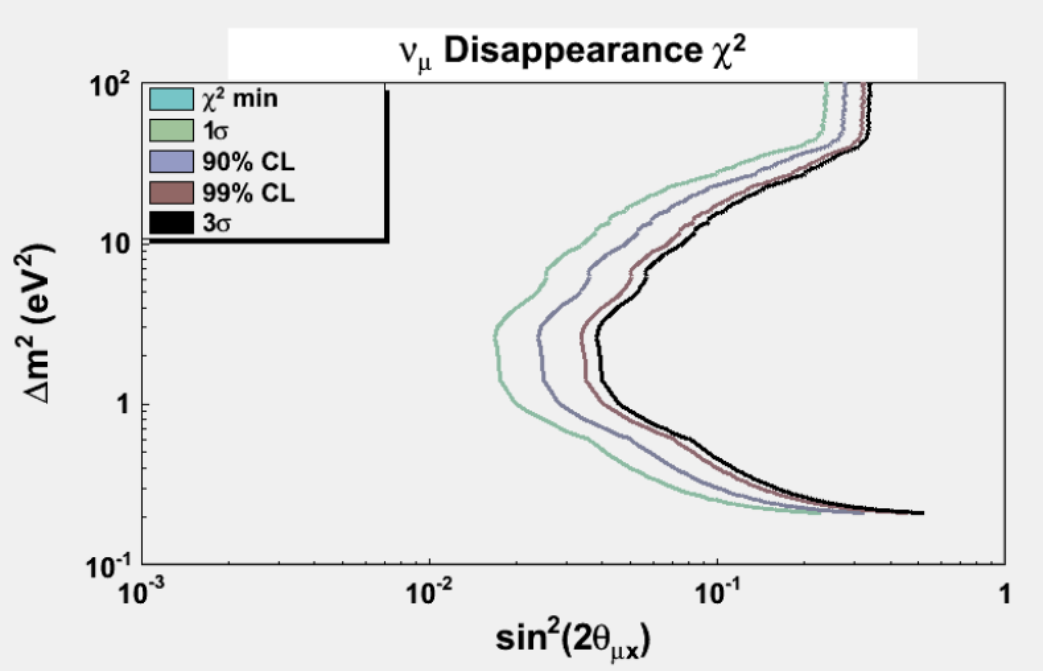


Proposed shutdown date

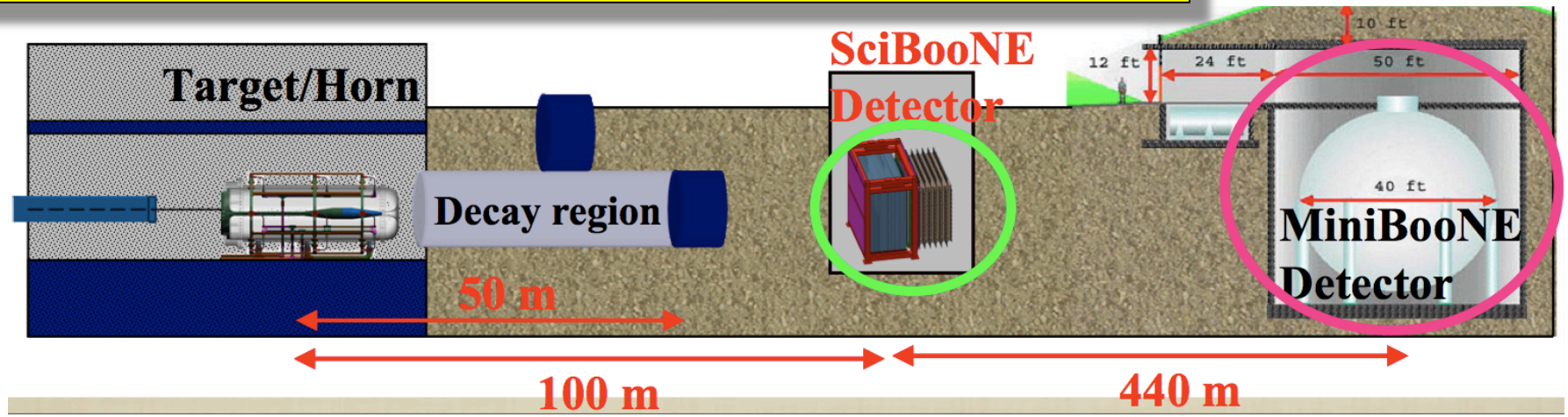
BooNE

- Clone (10M$) or cannibalize (5M$) MB
- Data: < 1 yr @ present proton rates



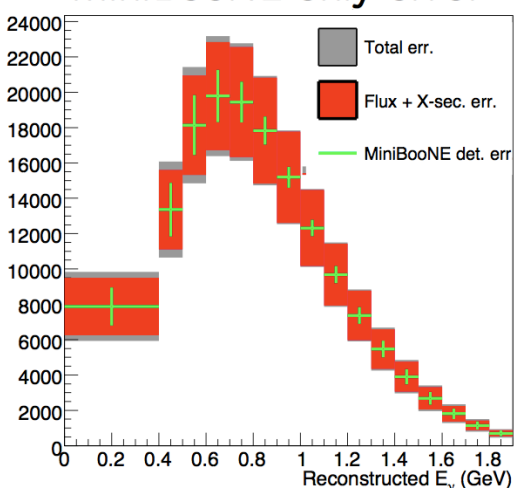


MiniBooNE + SciBooNE ν_μ Disappearance

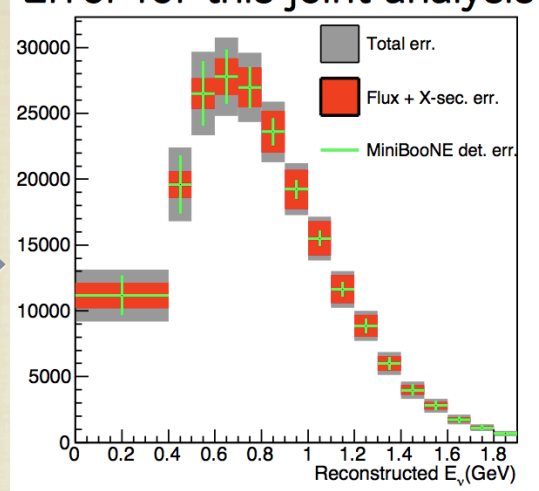


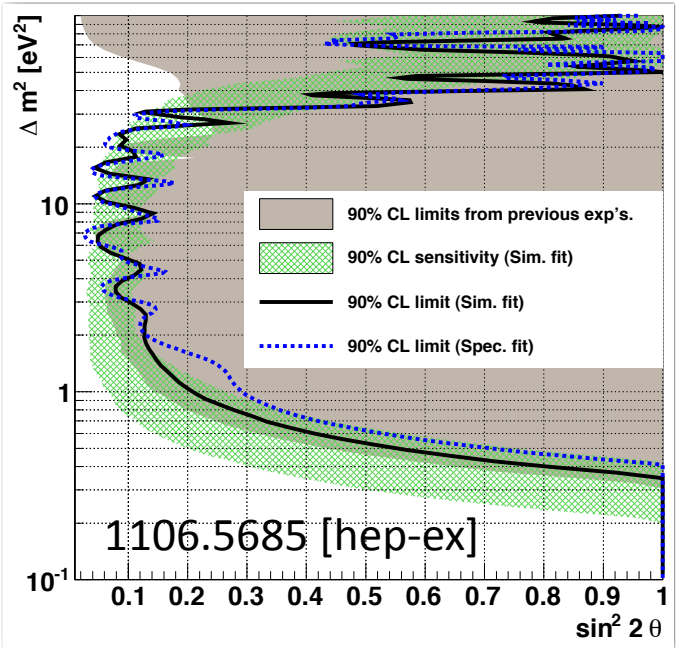
- No evidence for oscillations! Better than other expts in 10-30 eV^2 region.
- Flux errors 1-2%; XS errors still significant (kinematics acceptance).
- On-going: joint antineutrino disappearance search!

MiniBooNE only error



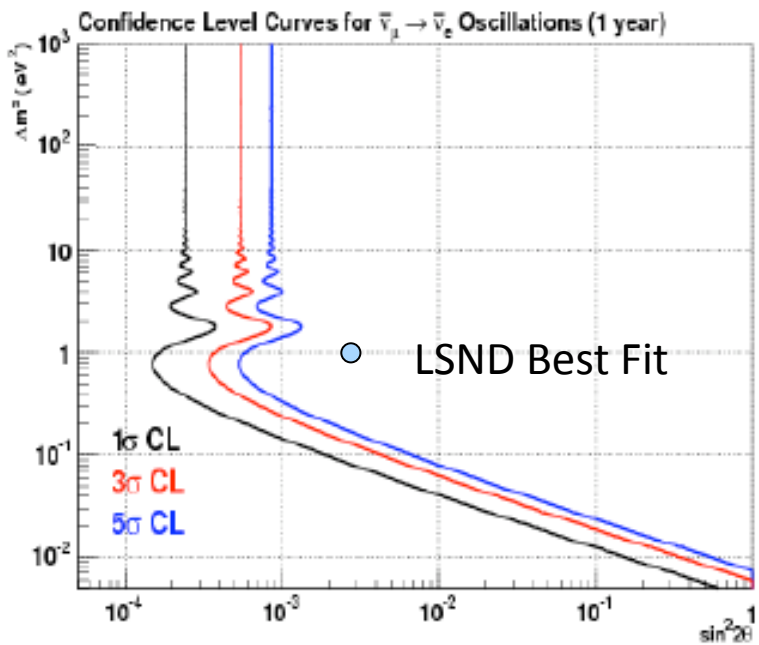
Error for this joint analysis

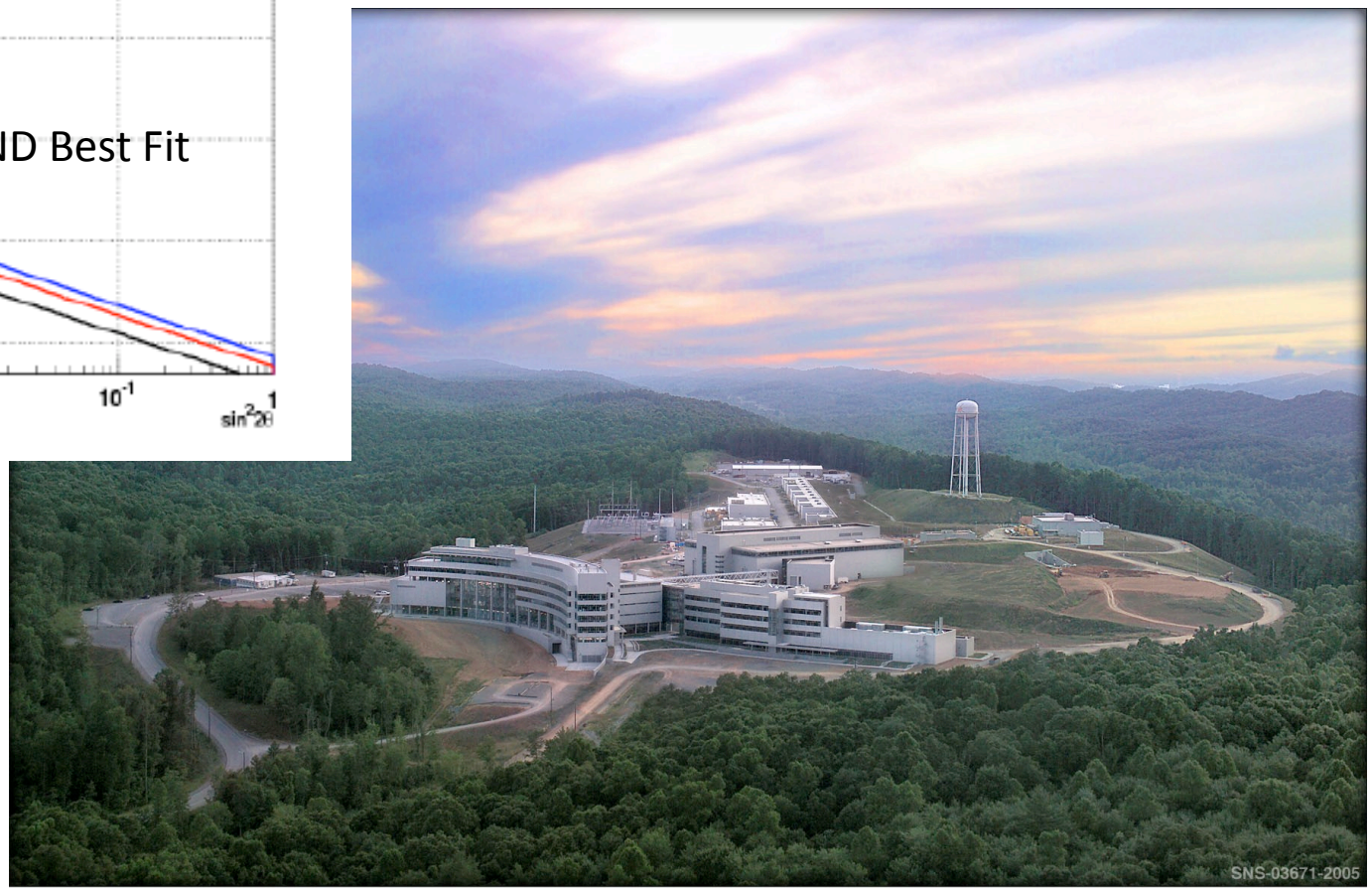




OscSNS

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





Conclusions

MiniBooNE was supposed to confirm or dismiss LSND…
9 years later we still don't know for sure!

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9 years later we still don't know for sure!

MiniBooNE has delivered some very interesting physics
(and hopefully will continue to do so …)

I hope that the LSND/MB puzzle will be solved soon!
(and that it's been worth waiting for …)

Thank you.

Backup slides

The MiniBooNE Collaboration

A. A. Aguilar-Arevalo[12], C. E. Anderson[15], S. J. Brice[6], B. C. Brown[6], L. Bugel[11], J. M. Conrad[11], Z. Djurcic[2], B. T. Fleming[15], R. Ford[6], F. G. Garcia[6], G. T. Garvey[9], J. Mirabal[9], J. Grange[7], J. A. Green[8,9], R. Imlay[10], R. A. Johnson[3], G. Karagiorgi[11], T. Katori[8,11], T. Kobilarcik[6], S. K. Linden[15], W. C. Louis[9], K. B. M. Mahn[5], W. Marsh[6], C. Mauger[9], W. Metcalf[10], G. B. Mills[9], C. D. Moore[6], J. Mousseau[7], R. H. Nelson[4], V. Nguyen[11], P. Nienaber[14], J. A. Nowak[10], B. Osmanov[7], Z. Pavlovic[9], D. Perevalov[1], C. C. Polly[6], H. Ray[7], B. P. Roe[13], A. D. Russell[6], M. H. Shaevitz[5], M. Sorel[5*], J. Spitz[15], I. Stancu[1], R. J. Stefanski[6], R. Tayloe[8], M. Tzanov[4], R. G. Van de Water[9], M. O. Wascko[10†], D. H. White[9], M. J. Wilking[4], G. P. Zeller[6], E. D. Zimmerman[4]

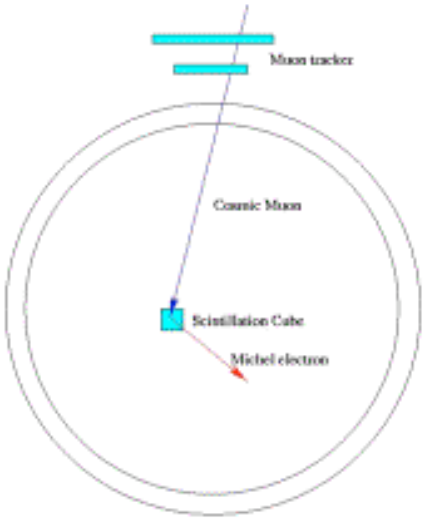
(The MiniBooNE Collaboration)

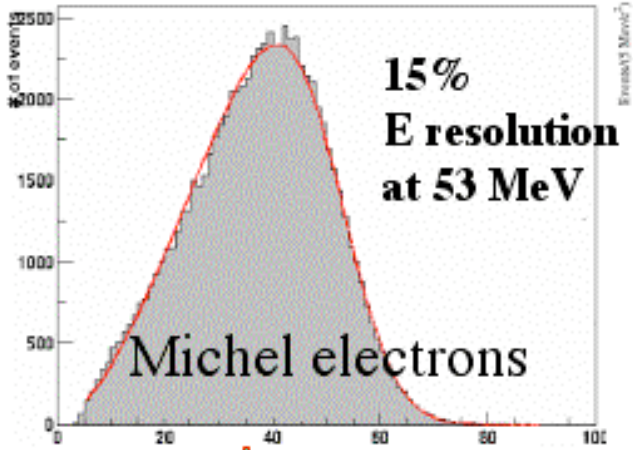
52 physicists, 13 universities, 2 national laboratories (FNAL & LANL)

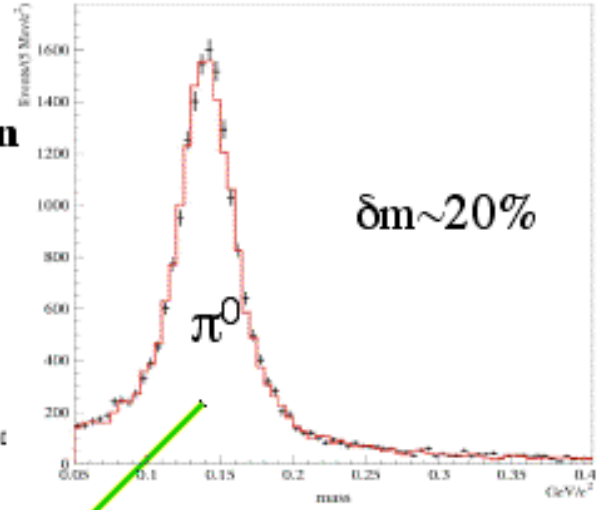
MiniBooNE Calibration

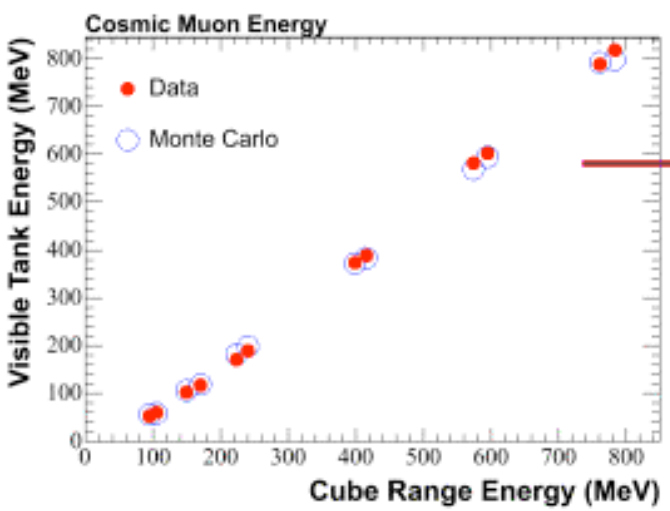
on Sources

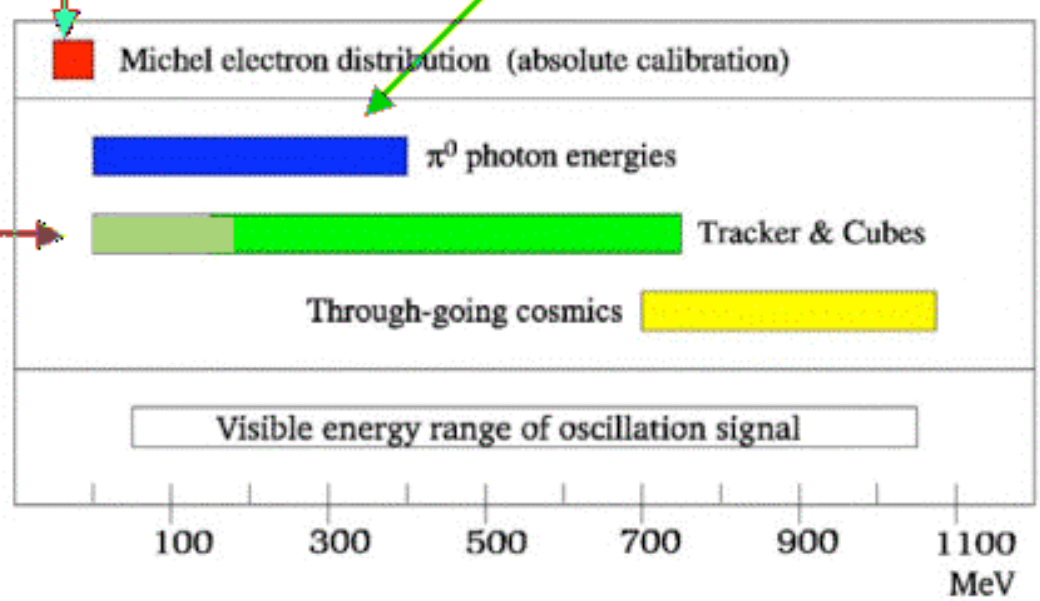
Tracker system











Systematic Uncertainties

Statistics limited!

Many errors are similar between neutrino and antineutrino mode.

Errors propagated from MiniBooNE measurements or external data.

Vary underlying XS parameters: M_A, Pauli blocking, etc.

Uncertainty in light creation, propagation & detection in apparatus.

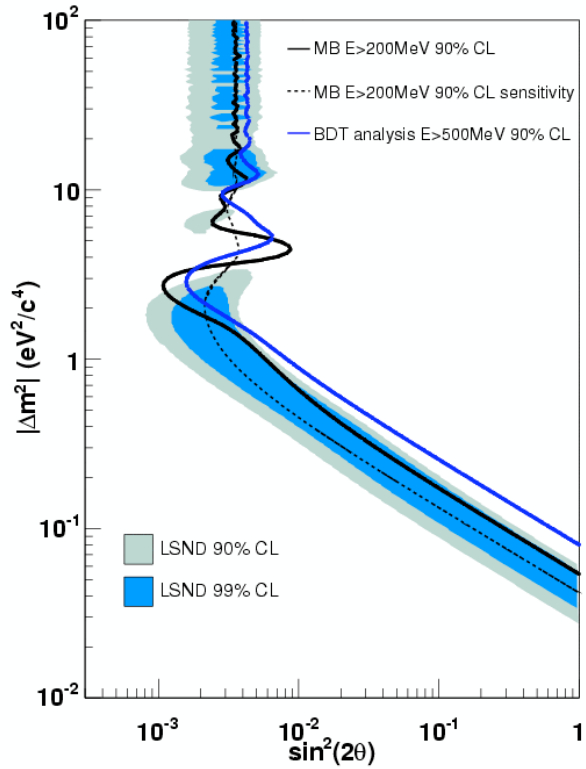
Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
E_ν^{QE} range (MeV)	*200-475*	*475-1100*	*200-475*	*475-1100*
Flux from π^+/μ^+ decay	0.4	0.9	1.8	2.2
Flux from π^-/μ^- decay	3.0	2.3	0.1	0.2
Flux from K^+ decay	2.2	4.7	1.4	5.7
Flux from K^- decay	0.5	1.2	-	-
Flux from K^0 decay	1.7	5.4	0.5	1.5
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*

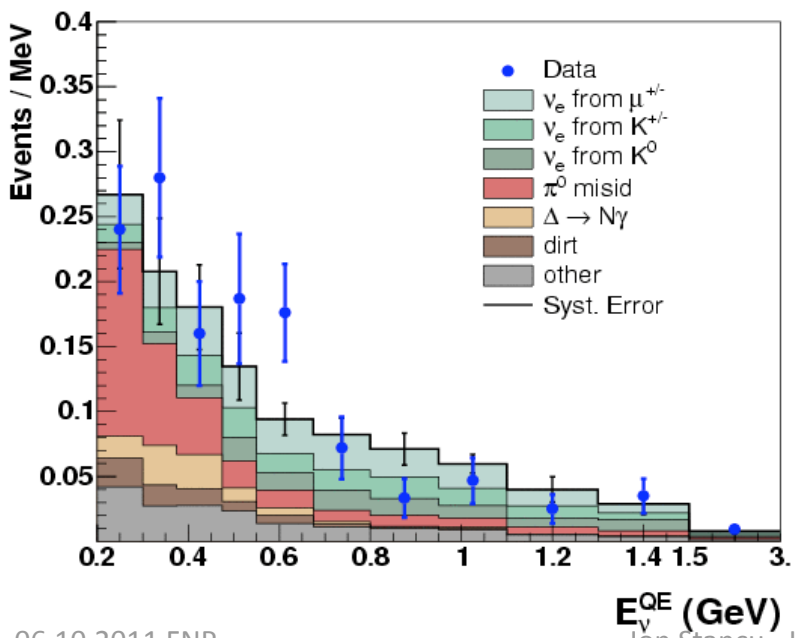
The First Antineutrino Data

PRL 103 (2009) 111801, POT = 3.39e20

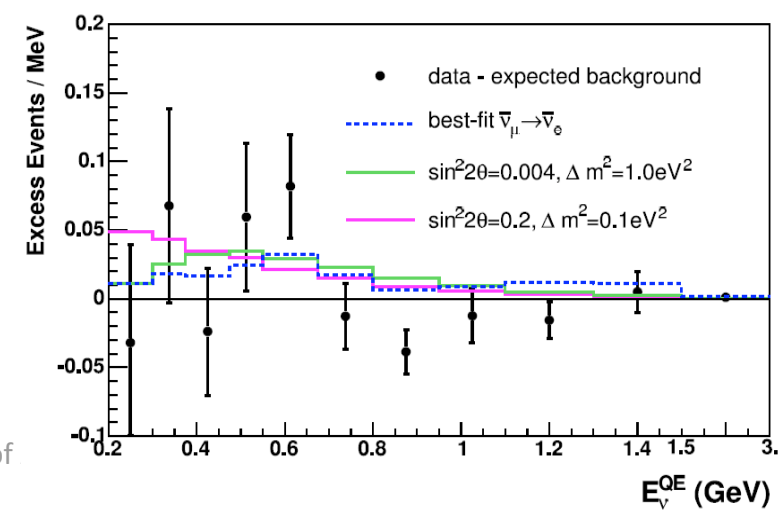
$200 < E_\nu < 3000$ MeV:
data = 144 & bkgd = 139.2 ± 17.6 (stat+syst), XCS = 4.8

- Only antineutrinos allowed to oscillate in fit
- Limit from two neutrino fit excludes less area than sensitivity due to fit adding a LSND-like signal to account for wiggle (2.8 σ between 475-675 MeV)
- Stat error too large to distinguish LSND-like from null





BF=(4.42,0.004), χ^2/DF=18.2/16, P(χ^2)=31%
Null: χ^2/DF=24.5/18, P(χ^2)=14%



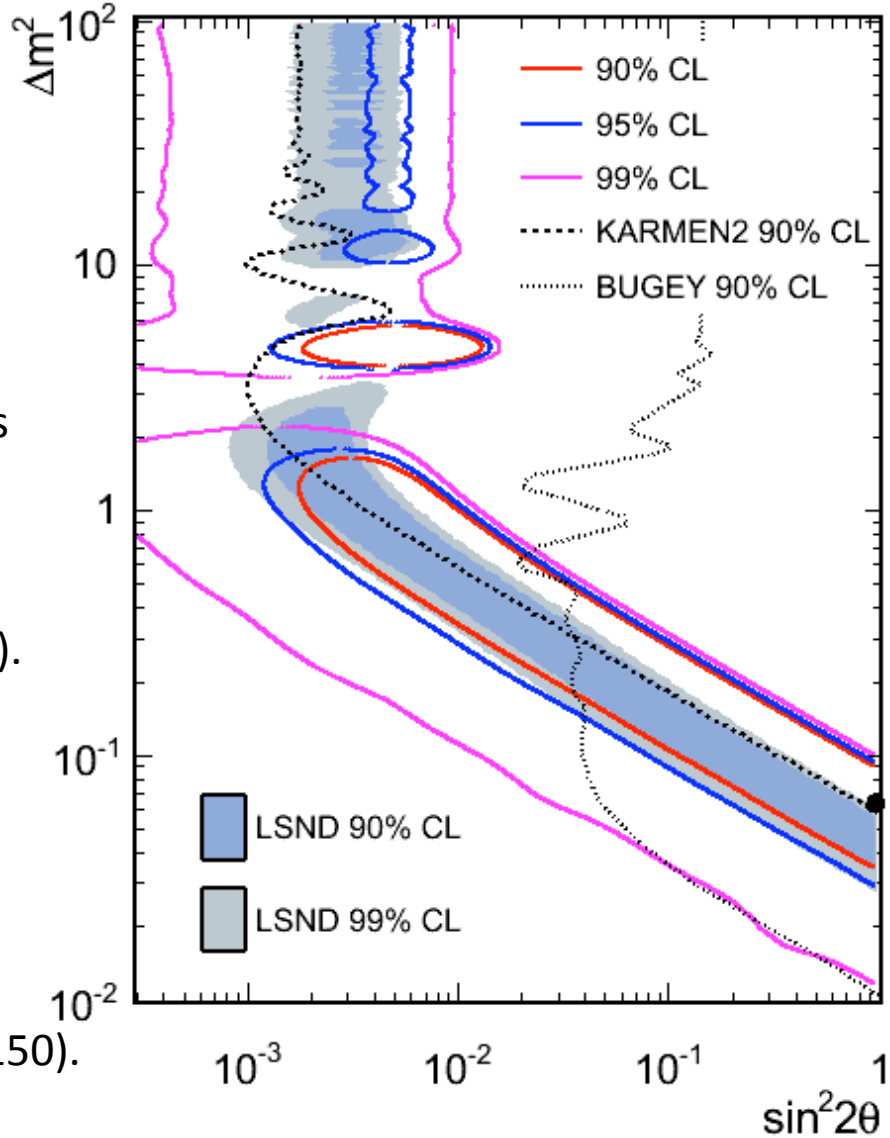
The Antineutrino Fit

- Results for 5.66E20 POT.
- Maximum likelihood fit.
- Only antineutrinos allowed to oscillate.
- E > 475 MeV region is free of effects of low energy neutrino excess.
  This is the same official oscillation region as in the neutrino mode.

- Oscillations favoured over background only hypotheses at 99.4% CL (model dependent).

- Best Fit Point:
  $(\Delta m^2, \sin^2 2\theta) = (0.064\ eV^2, 0.96)$
  $\chi^2/NDF = 16.4/12.6$
  $P(\chi^2) = 20.5\%$

- Results published in PRL 105 (arXiv:1007.1150).



The Likelihood Fit

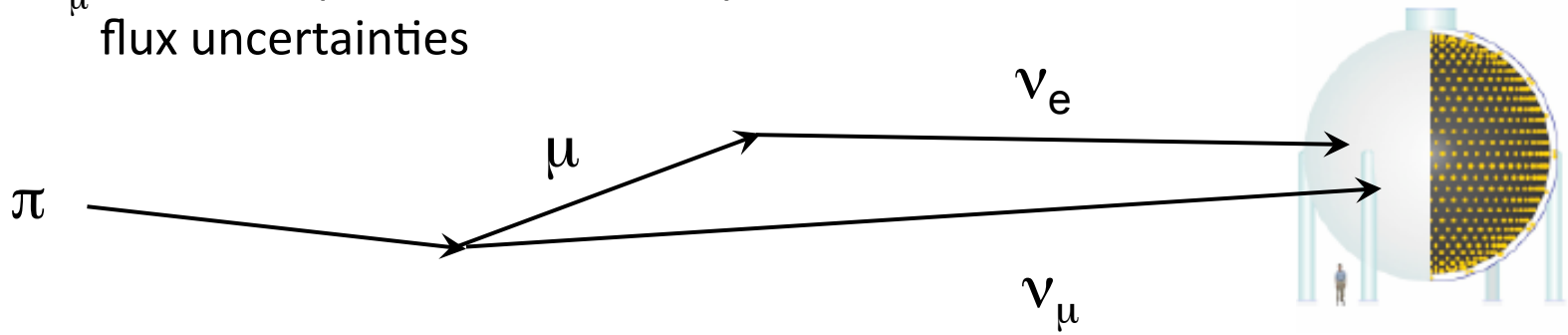
Maximum likelihood fit:

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

Simultaneously fit:

ν_e CCQE sample
high statistics ν_μ CCQE sample

The ν_μ CCQE sample constrains many of the uncertainties:
flux uncertainties

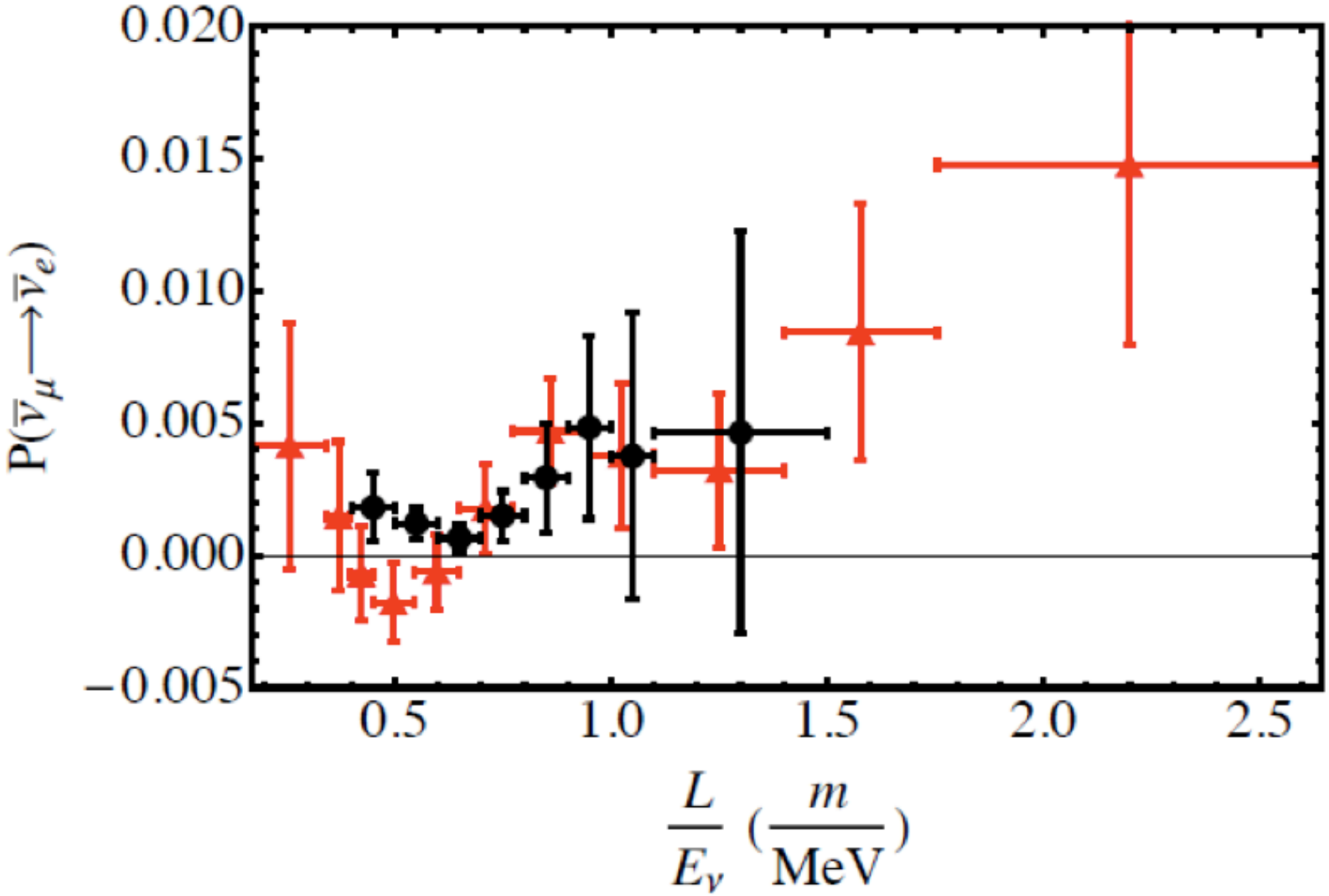


cross section uncertainties.

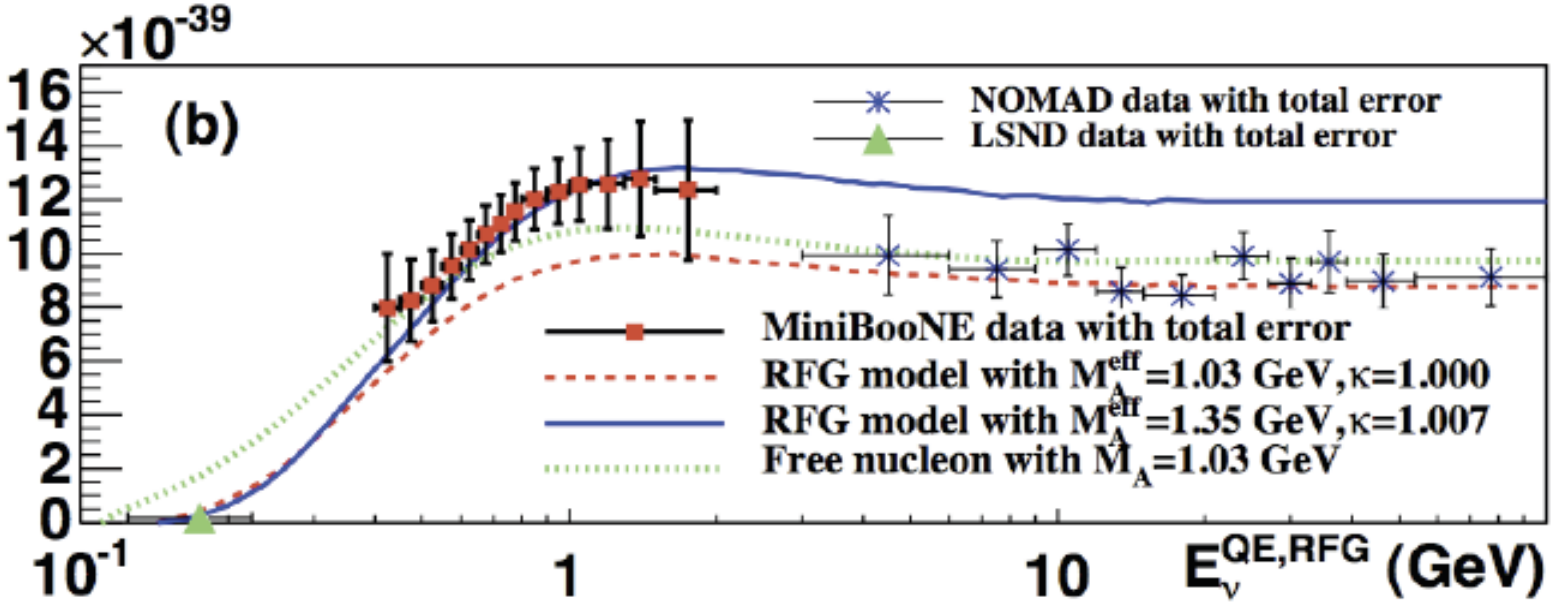
Previous fit: $\chi^2 = \sum_{i,j}^{N} \left(D_i - \left(B_i + S_i(\sin^2 2\vartheta, \Delta m^2)\right)\right) M_{ij}^{-1} \left(D_j - \left(B_j + S_j(\sin^2 2\vartheta, \Delta m^2)\right)\right)$

The L/E Distributions

LSND: 20 < E < 60 MeV
MiniBooNE: 200 < E < 3000 MeV



The CCQE XS



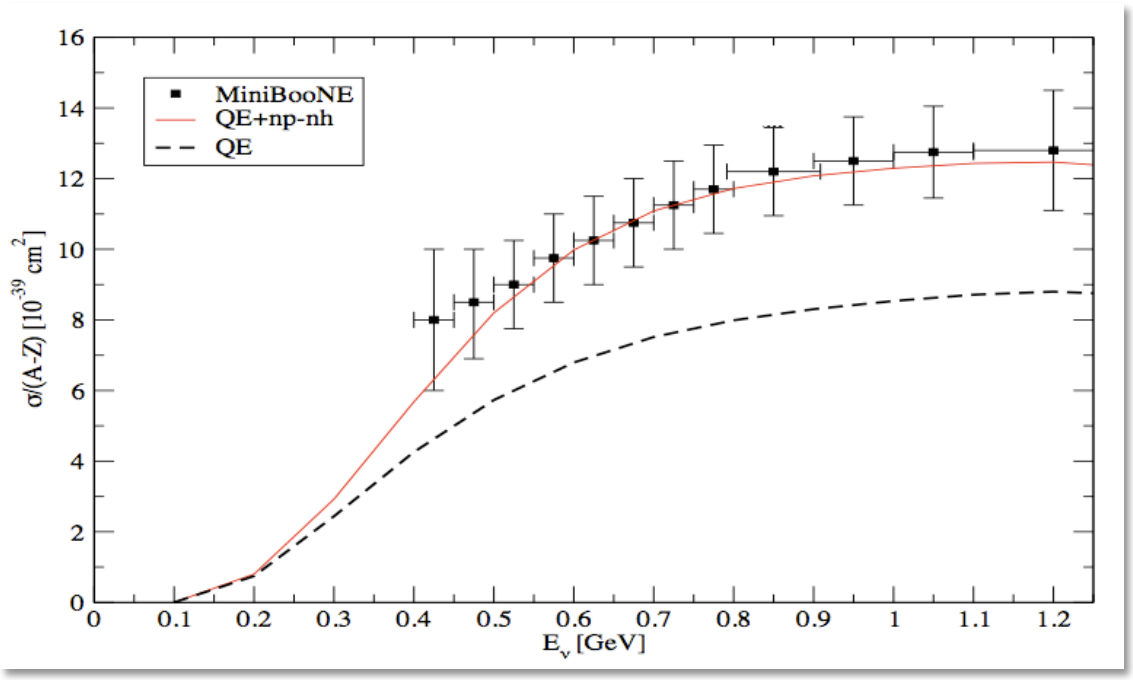
Extremely surprising result: CCQE $\sigma_{\nu\mu}(^{12}C) > 6\ \sigma_{\nu\mu}(n)$

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).

The CCQE XS

- *Possible explanation*: extra contributions from two-nucleon correlations in the nucleus (all prior calculations assume independent particles)



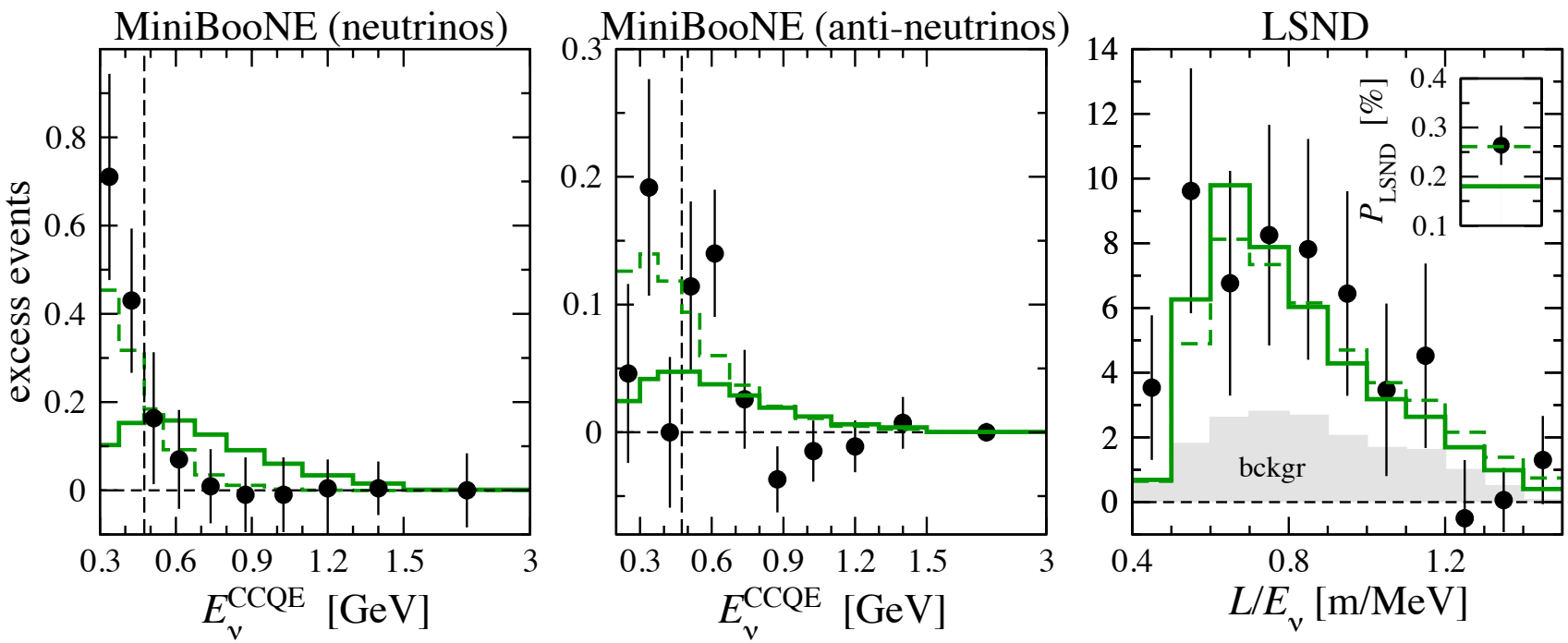
- large enhancement from short range correlations (SRC)
- can predict MiniBooNE data without having to increase M_A (here, M_A=1.0 GeV)

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

The 3+2 Model

Dashed: appearance only fit
Solid: global data fit

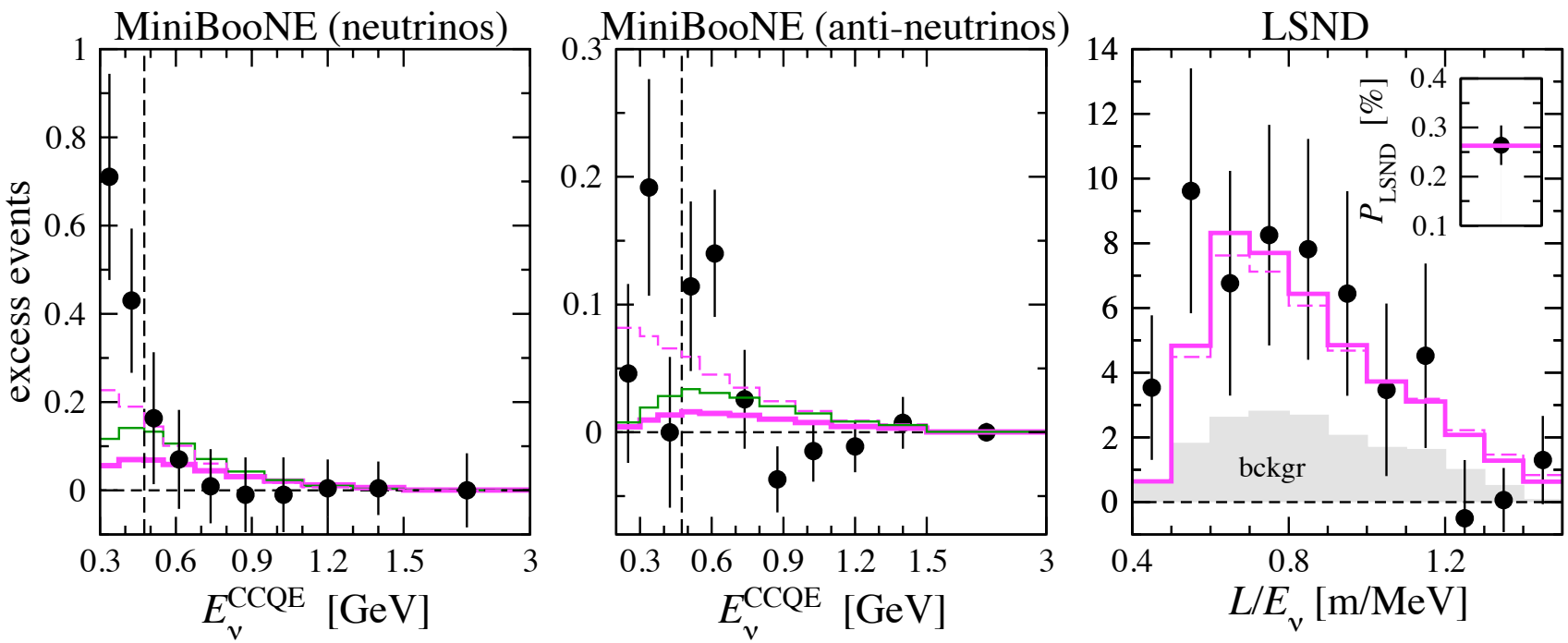
$\chi^2_{min}(3+1) - \chi^2_{min}(3+2) = 5.0$ (4 DOF)



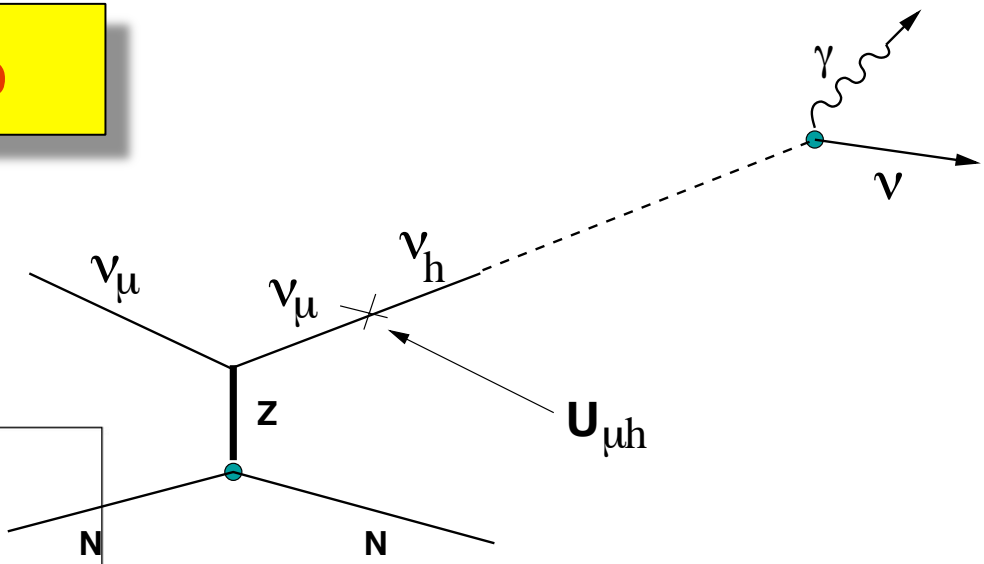
The 3+1 NSI-g Model

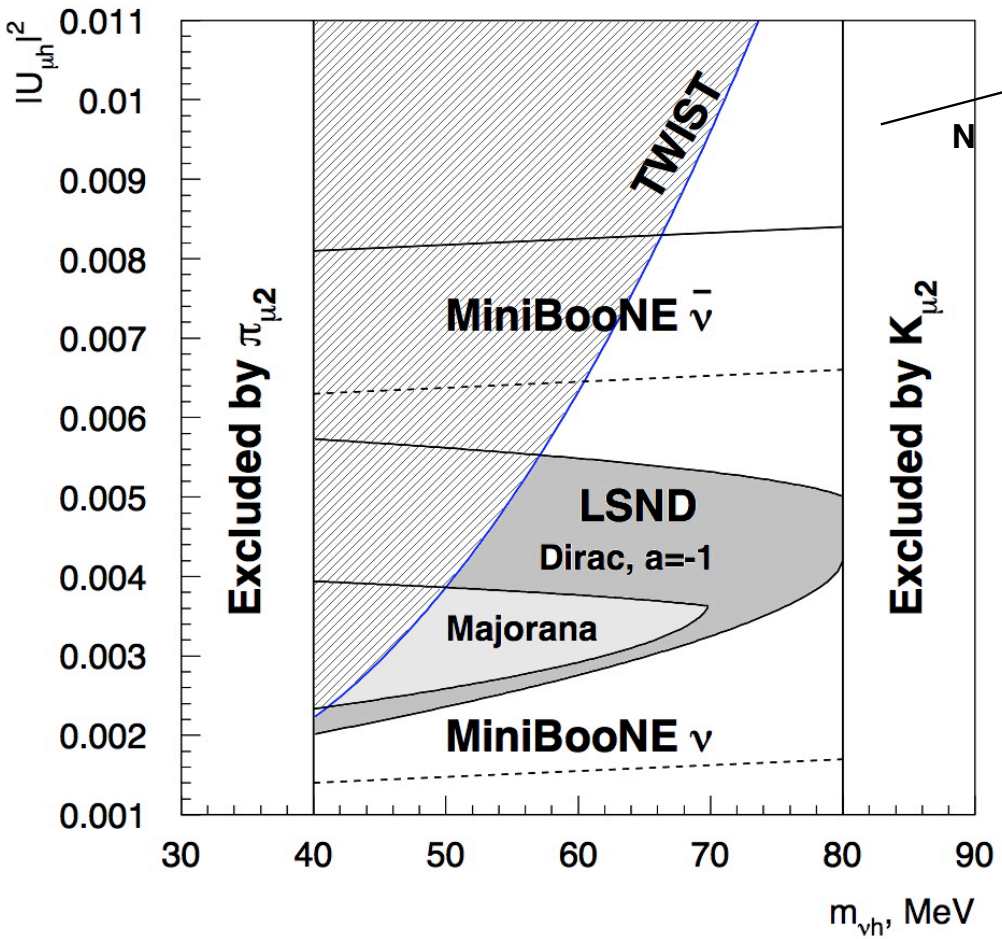
Dashed: appearance only fit
Solid: global data fit

$\chi^2_{min}(3+1) - \chi^2_{min}(3+1+NSI\text{-}g) = 18.5$ (5 DOF)



The Heavy Sterile Neutrino





$\nu_\mu\ {}^{12}C \rightarrow \nu_h\ n\ X \rightarrow \gamma\ \nu\ n\ X$

LSND: all due to DIF flux

KARMEN: all DIF flux below 50 MeV (at 90^0 wrt the beam)
Threshold = 58.6 MeV for $m(\nu_h)$ = 40 MeV!