Results from MiniBooNE

NO-VE IV, International Workshop on: Neutrino Interactions in Venice

April 15-18, 2008

Byron Roe

University of Michigan

for the MiniBooNE collaboration

Outline

1. Review of MiniBooNE experiment
2. Oscillation results
3. Low energy anomaly
4. MiniBooNE-NUMI
5. Neutrino cross sections
6. Anti-neutrino cross sections
7. Publications

Review of the MiniBooNE Experiment

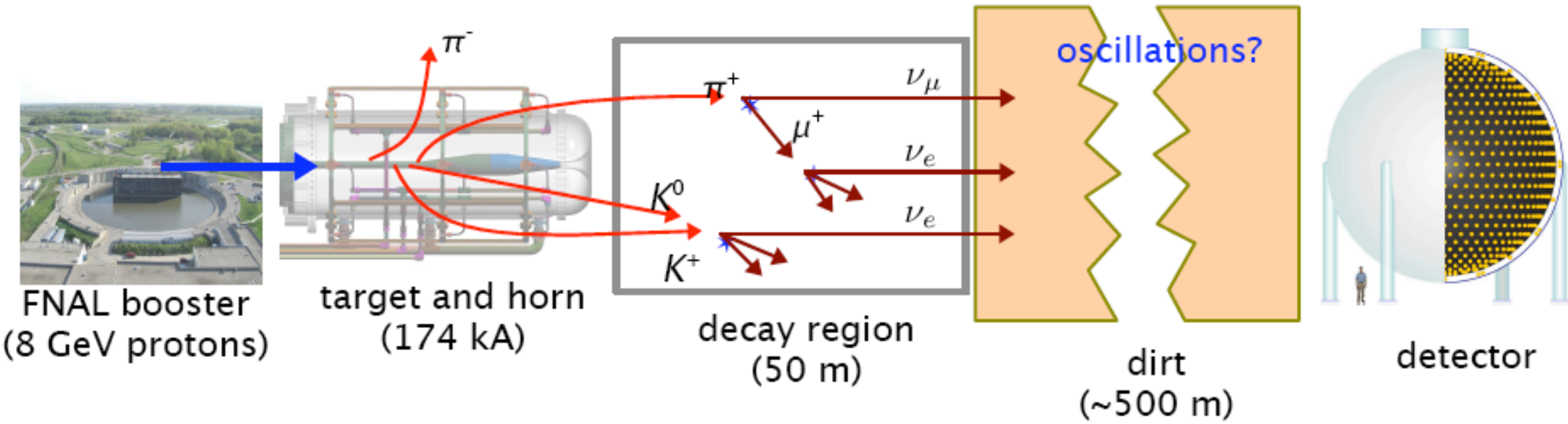
The MiniBooNE Collaboration

A. A. Aguilar-Arevalo, A. O. Bazarko, S. J. Brice, B. C. Brown, L. Bugel, J. Cao, L. Coney, J. M. Conrad, D. C. Cox, A. Curioni, Z. Djurcic, D. A. Finley, B. T. Fleming, R. Ford, F. G. Garcia, G. T. Garvey, J. A. Green, C. Green, T. L. Hart, E. Hawker, R. Imlay, R. A. Johnson, P. Kasper, T. Katori, T. Kobilarcik, I. Kourbanis, S. Koutsoliotas, J. M. Link, Y. Liu, Y. Liu, W. C. Louis, K. B. M. Mahn, W. Marsh, P. S. Martin, G. McGregor, W. Metcalf, P. D. Meyers, F. Mills, G. B. Mills, J. Monroe, C. D. Moore, R. H. Nelson, P. Nienaber, S. Ouedraogo, R. B. Patterson, D. Perevalov, C. C. Polly, E. Prebys, J. L. Raaf, H. Ray, B. P. Roe, A. D. Russell, V. Sandberg, R. Schirato, D. Schmitz, M. H. Shaevitz, F. C. Shoemaker, D. Smith, M. Sorel, P. Spentzouris, I. Stancu, R. J. Stefanski, M. Sung, H. A. Tanaka, R. Tayloe, M. Tzanov, M. O. Wascko, R. Van de Water, D. H. White, M. J. Wilking, H. J. Yang, G. P. Zeller, E. D. Zimmerman

2 National Laboratories, 14 Universities, 77 Researchers

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle University
Fermi National Accelerator Laboratory
Indiana University
Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

The MiniBooNE design strategy...must make ν_μ

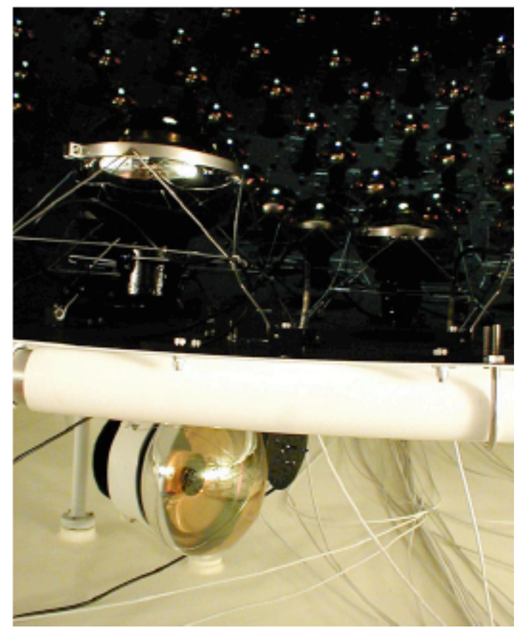


- Start with 8 GeV proton beam from FNAL Booster
- Add a 174 kA pulsed horn to gain a needed x 6
- Requires running ν (not anti-ν) to get flux
- Pions decay to ν with E_ν in the 0.8 GeV range
- Place detector to preserve LSND L/E:

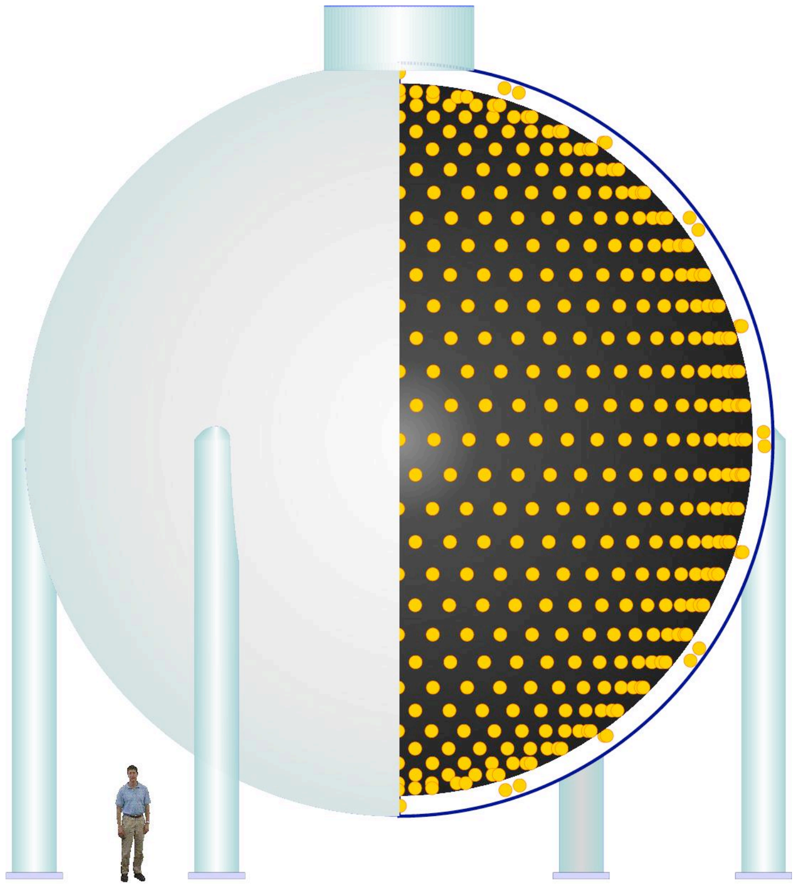
MiniBooNE:	(0.5 km) / (0.8 GeV)
LSND:	(0.03 km) / (0.05 GeV)

- 5.58×10^{20} P.O.T. total; up to 5×10^{12} p/pulse at up to 4 Hz

$$\nu_\mu = 93.5\%,\ \nu_e = 0.5\%,\ \bar{\nu}_\mu = 6\%$$



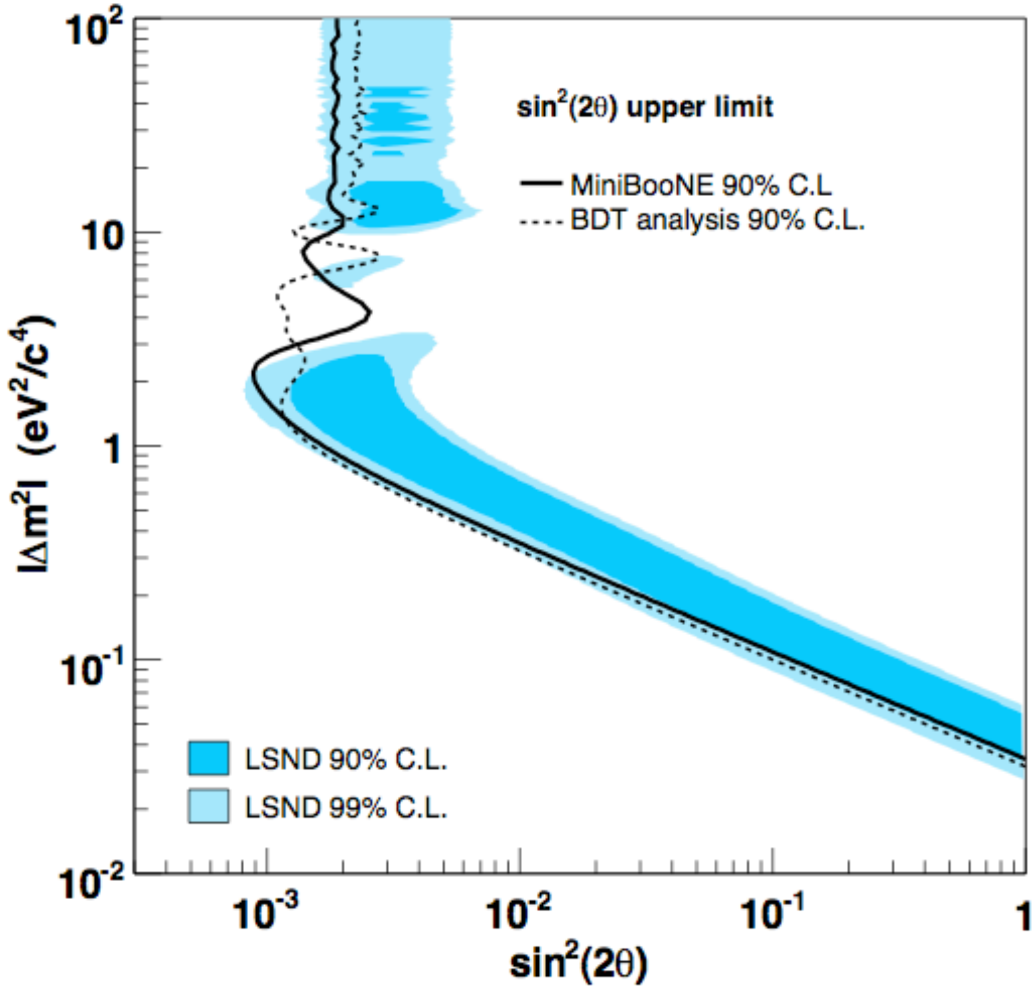
The MiniBooNE Detector



- 541 meters downstream of target
- 3 meter overburden of dirt
- 12 meter diameter sphere
  (10 meter “fiducial” volume)
- Filled with 800 t of pure mineral oil (CH_2--
  density 0.86, n=1.47)
  - (Fiducial volume: 450 t)
  - 1280 inner 8” phototubes-10% coverage,
    240 veto phototubes

(Less than 2% channels failed during run)

MiniBooNE First Results show no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations



Energy-fit analysis:
solid: TB
dashed: BDT

Independent analyses are in good agreement.
(Different reconstructions
And different particle id)

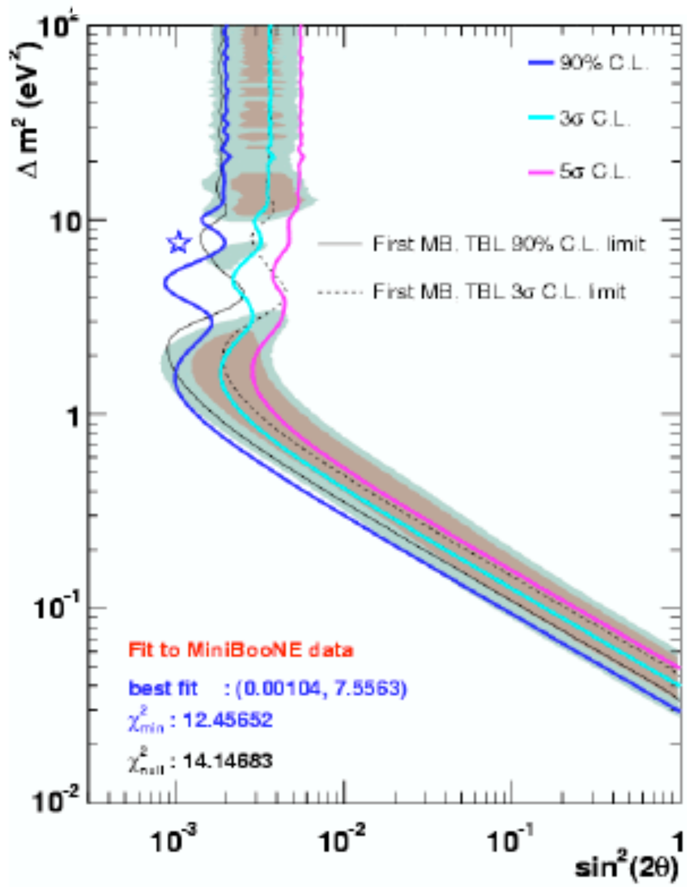
MiniBooNE first results
arXiv:0704.1500
Phys. Rev. Lett. 98, 231801

The ν_eBDT + ν_eTBL + ν_μCCQE results:

The combination of the three samples gives a increase in coverage in the region $\Delta m^2 < 1\ eV^2$.

Differences in the details are due to the specific fluctuations in the three data samples and the interplay with correlations among them.

The combination yields a consistent result.



(A.A. Aguilar-Arevalo)

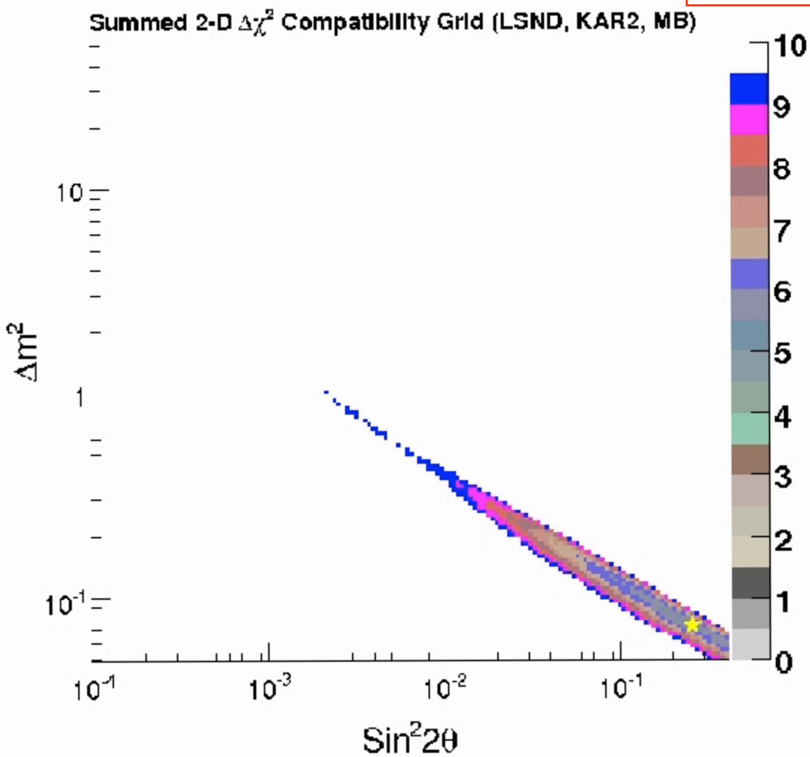
10%-30% improvement in 90% C.L. limit below ~1eV^2.

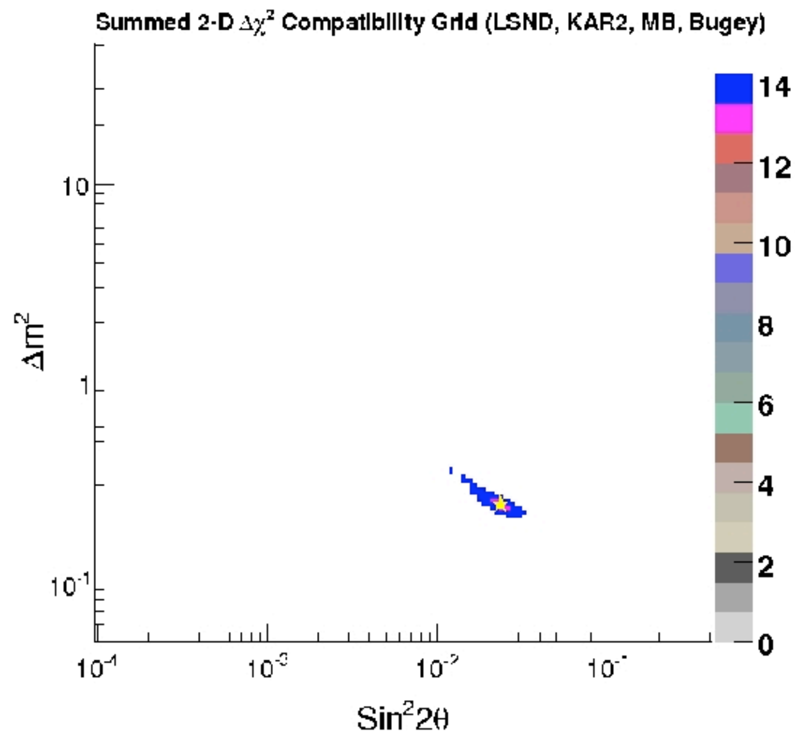
Global Fit Results (H. Ray)

- Combine results from several experiments-- LSND, MiniBooNE, Karmen and Bugey
- Convert each to a chisq. However, only Delta chisq is available.
- Do fits with this. Omits effect of goodness-of-fit of individual experiments
- 2-D fits--both oscillation parameters fitted
- 1-D fits-- only sinsq theta fit. For each delta-msq asks: “ If this is the true deltamsq, what is the compatibility?”

Global Fit Results-2D Fits

Colors represent $\Delta\chi^2$



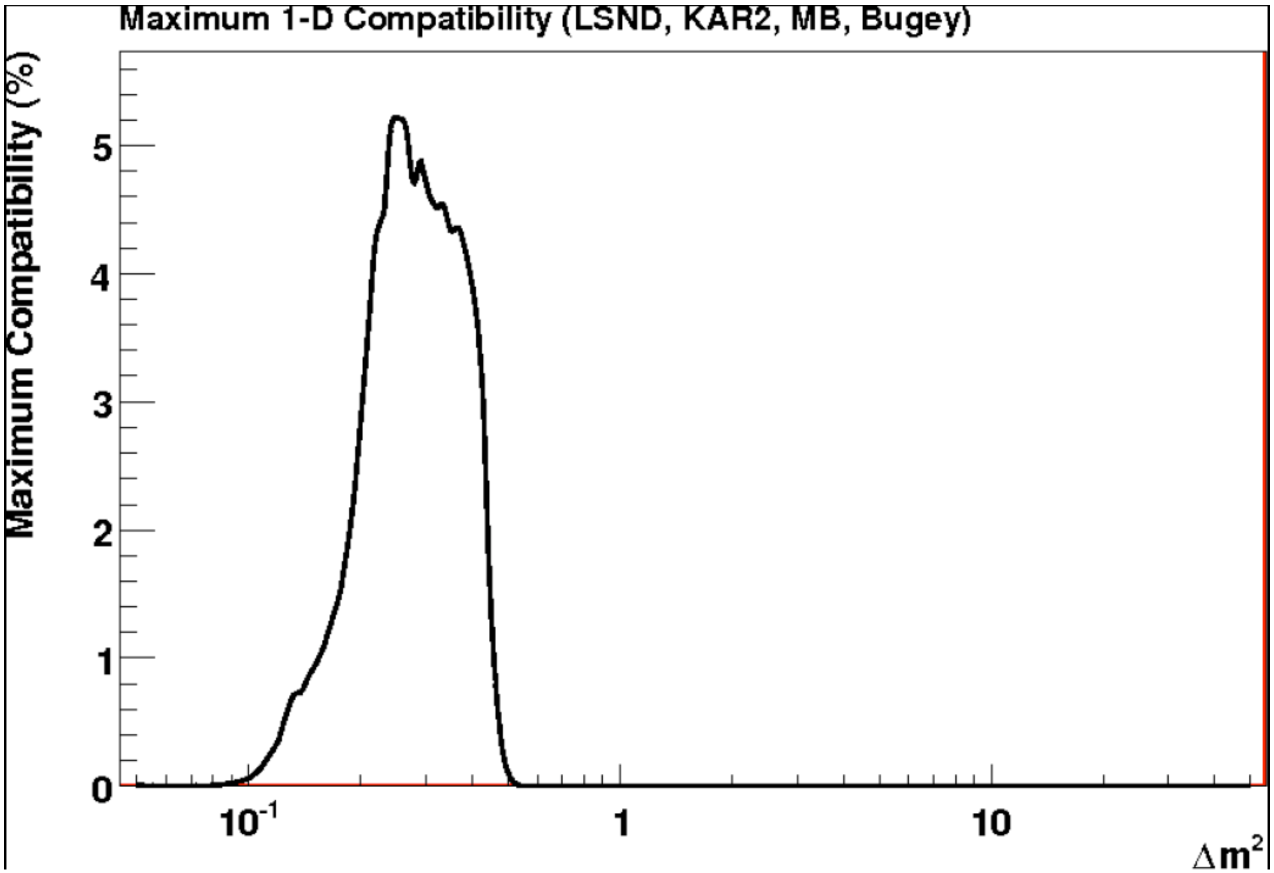


- The star is the point of maximum compatibility
- LSND, KARMEN2, MB + BUGEY

Global Fits to Experiments

LSND	KARMEN 2	MB	Bugey	Max Compat %	Delta M2	Sinsq theta
X	X	X		25.36	0.072	0.256
X	X	X	X	3.94	0.242	0.023
X		X		16.00	0.072	0.256
X		X	X	2.14	0.253	0.023
	X	X		73.44	0.052	0.147
	X	X	X	27.37	0.221	0.012

Global Fits Results--1D



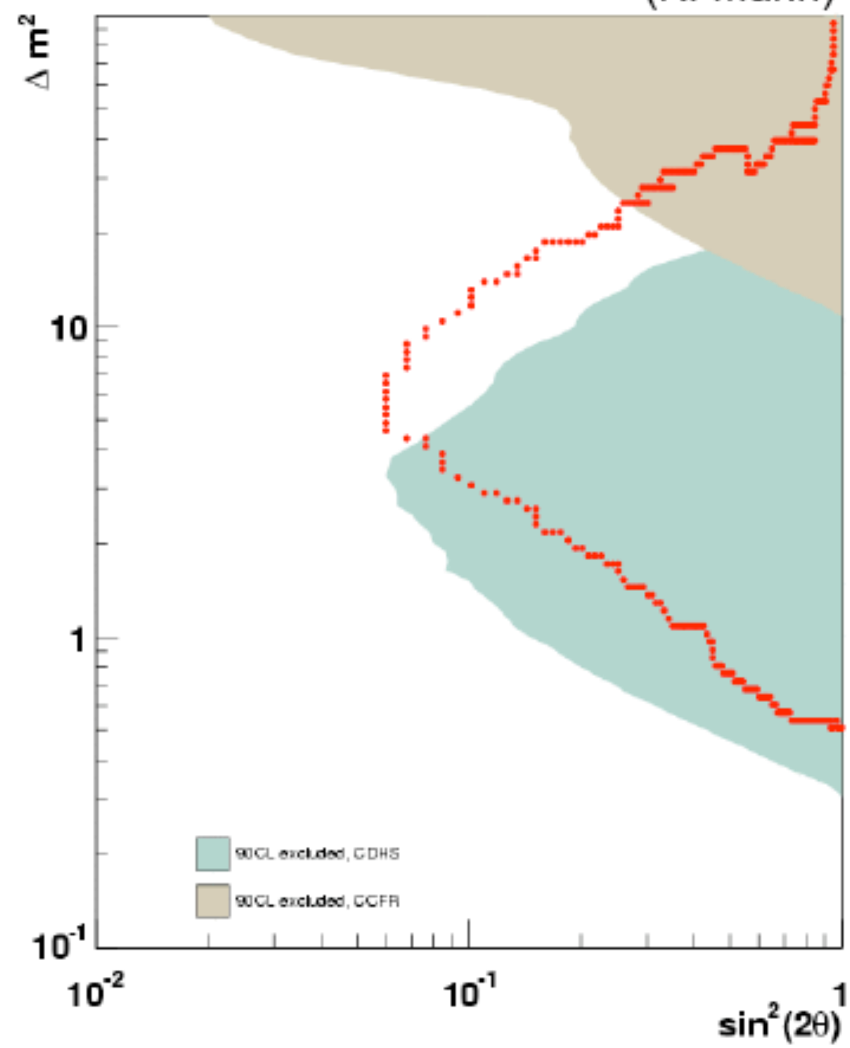
Maximum compatibility as a function of Δm^2 for the 1-D LSND, KARMEN2, MB, BUGEY analysis.

Complete MiniBooNE ν_μ Disappearance Sensitivity

- MiniBooNE only 90% CL sensitivity
- CDHS CCFR 90% CL

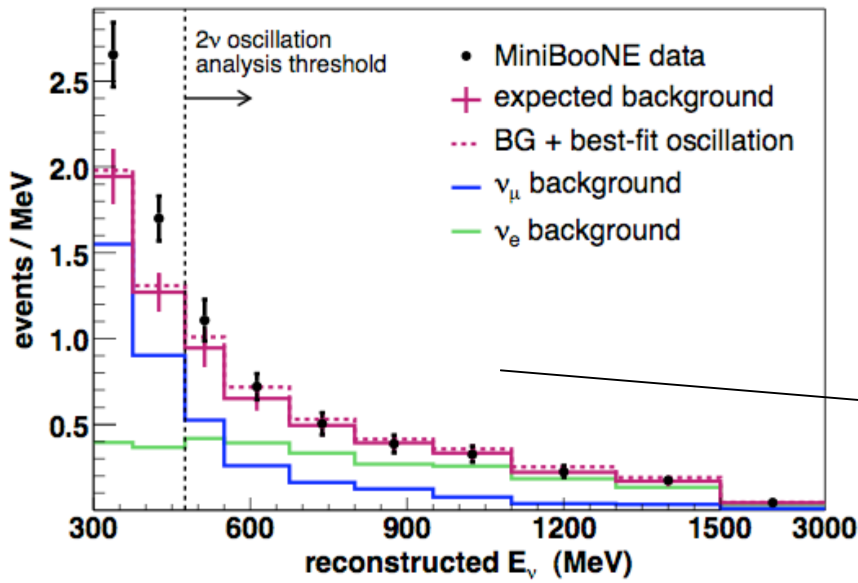
When we use SciBooNE as a near detector, we will be able to improve this sensitivity by reducing flux and cross section uncertainties

(K. Mahn)

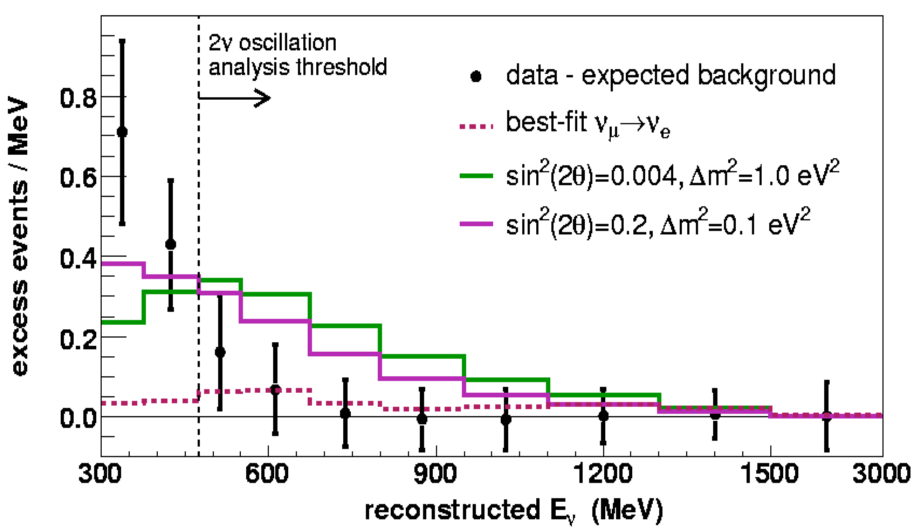


Low Energy Anomaly

oscillation analysis: Results in April 2007



No evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region



track-based analysis:

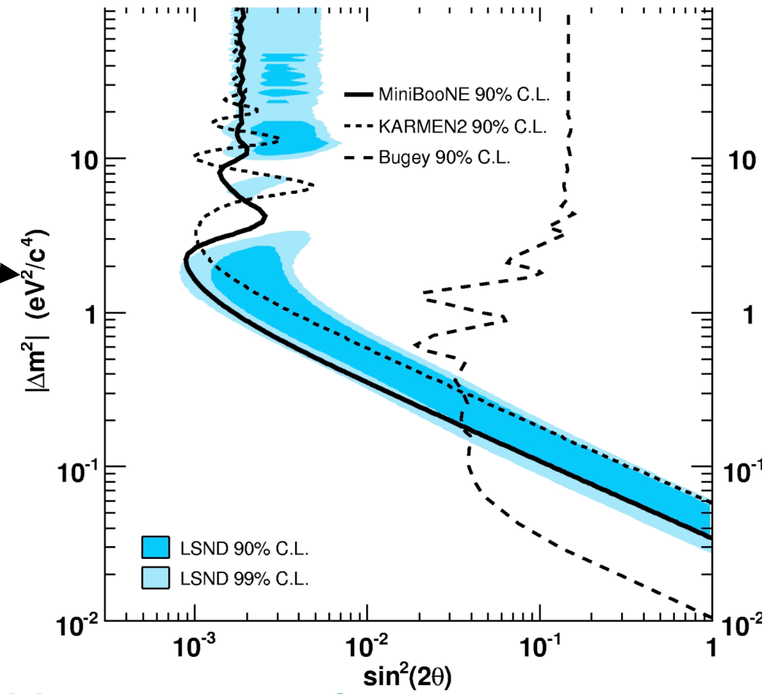
Counting Experiment: $475<E_\nu<1250$ MeV

data: 380 events

expectation: 358 ±19 (stat) ± 35 (sys)

significance: 0.55 σ

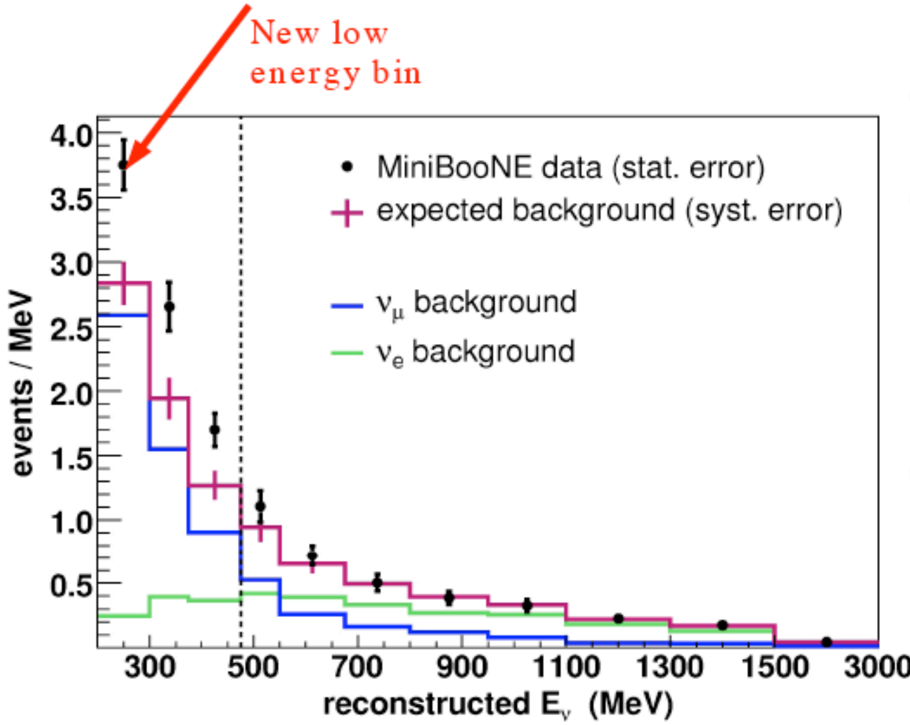
Phys. Rev. Lett. 98, 231801 (2007)



However, at low energy

96 ± 17 ± 20 events above background, for 300< E_ν^{QE} <475MeV

Extending the analysis to lower energies

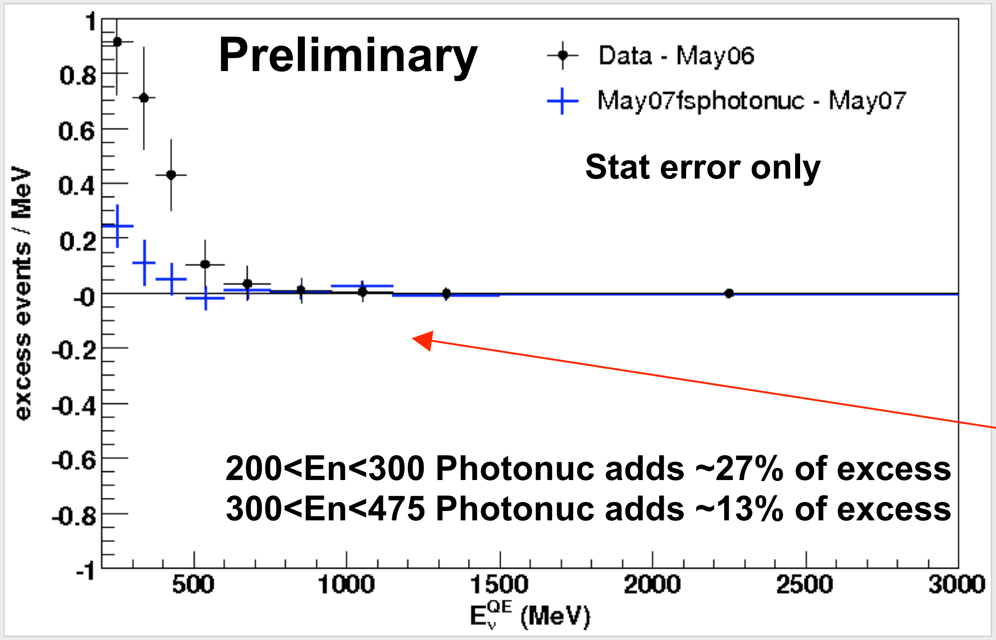


- Excess persists in 200-300 MeV bin
- Significance (stat + syst error)
  - 475-1250 MeV, 22 ± 40
  - 300-475 MeV, 96 ± 26
  - 200-300 MeV, 91 ± 31
- Looking to bring out a full update for the summer conferences

Could anomaly be background?

- Instrumental background? NO
- Track and Boosting analyses consistent? YES
- Is excess electron/gamma ray like? YES
- Dirt or Delta(1232) radiative decays? NO
- Pion or muon mis-id (including brem.)? NO
- Photonuclear process. Excess down(~~20%)
- More comprehensive hadr. errors and better handling of pi+/- interactions. Excess down
- Modification of pi0 background calculation. Excess down
- Improved meas. of nu induced pi0's. Excess up
- Better handling of beam pi+ production uncertainties. ?
- **None of these are expected to have any appreciable effect above 475 MeV**

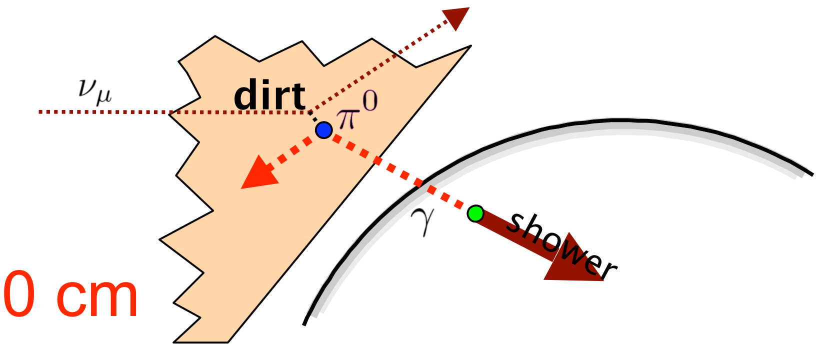
Possible Sources of Additional Single Gamma Backgrounds



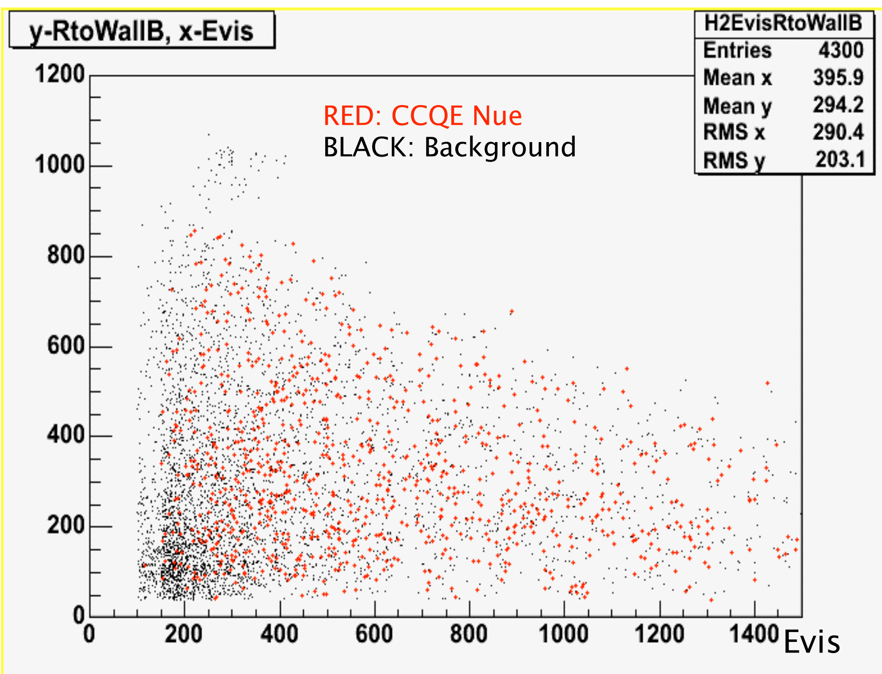
- Processes that remove/absorb one of the gammas from a ν_μ-induced NC $\pi^0 \rightarrow \gamma\gamma$
  - Photonuclear absorption was missing from our GEANT3 detector Monte Carlo
    - But tends to give extra final state particles.
    - Reduces size of excess
    - Systematics being calculated
    - No effect above 475 MeV

Distance to Wall Backward Cut

In low energy region there is a significant background from neutrino interactions in the dirt



Gamma conversion length = 70 cm



Dirt events tend to be at large radius, heading inward

Add a new cut on "DistancetoWall backward" to reduce these.

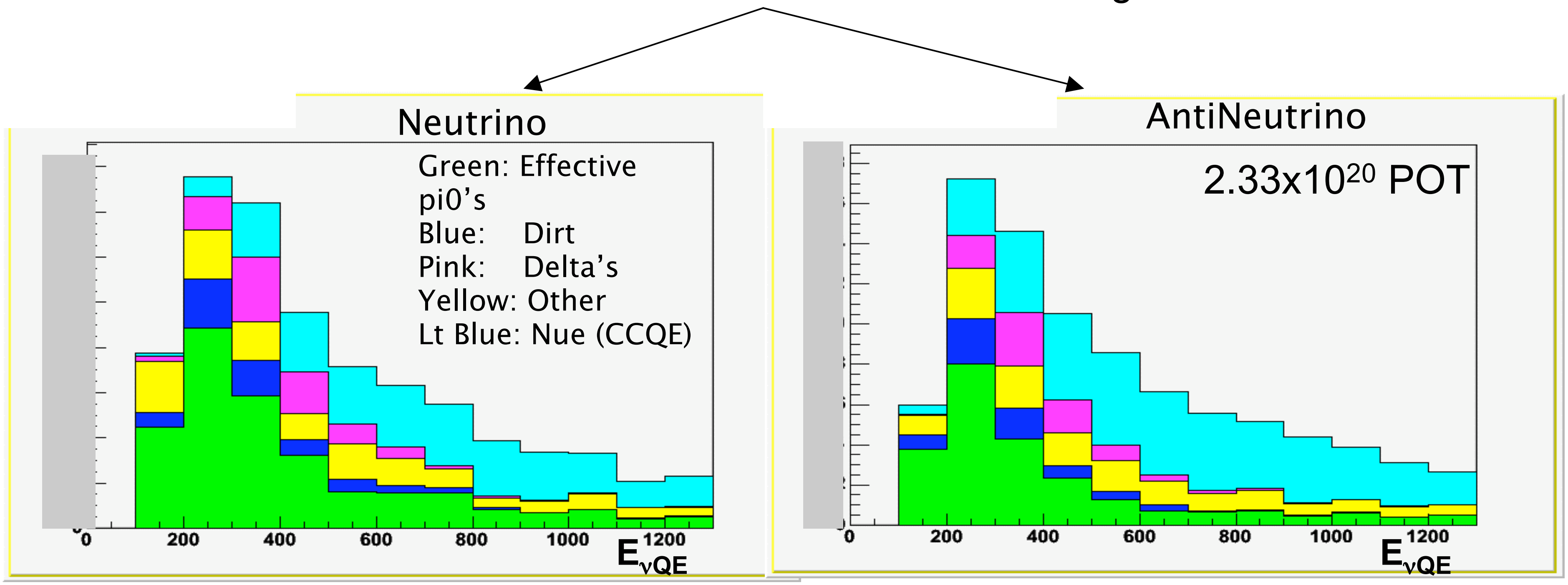
Has significant effect below 475 MeV

- Big reduction in dirt
- Some reduction of π^0s
- Small effect on ν_es

Has almost no effect above 475 MeV

Comparing Neutrino/Antineutrino Low Energy ν_e Candidates

The ν_e background breakdown is very similar between neutrino and antineutrino mode running

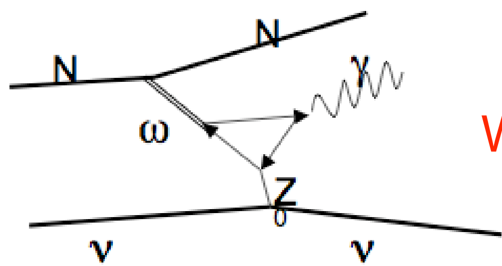


But different hypotheses for the excess can have measurably different effects in the two modes

Can compare the two modes to test some of the hypotheses

Axial Anomaly- an explanation within the standard model

- Recent paper by Harvey &Hill[2], hep-ph 0708.1281 ,0712.1230 has put forth an explanation of the MiniBooNE low energy electron excess by employing the axial anomaly.
- The anomaly is employed to create a (ν_μ,γ) process that mimics (ν_e,e)



Wine and cheese FL Feb 29,08

The low energy limit cross section with no proton recoil is

$$\sigma = \frac{\alpha g_\omega^4 G_F^2}{480\pi^6 m_\omega^4} E_\nu^6 = 2.2(10)^{-41}\left(\frac{E_\nu}{\mathrm{GeV}}\right)^6\left(\frac{g_\omega}{10}\right)^4$$

g_ω can vary from 10 - 30.

$\sim 140(g_\omega/10)^4$ events

Use photon energy and angle to examine this

Gauge Boson in Nelson and Walsh

- arXiv:0711.1363, “Short Baseline Neutrino Oscillations and a New Light Gauge Boson”, Ann Nelson & Jonathan Walsh.
- An MSW-like potential in matter which affects low E neutrino oscillations makes LSND and MB compatible, while obtaining a low energy anomaly about 40% of that seen by MB.

Gauge Boson in Nelson and Walsh 2

- The new light gauge vector boson ("paraphoton") has a mass of ~10 keV (short range to avoid 5th force measurements) and a coupling strength of g2/e2~ 10-9 coupling to B-L charge
- Because of low coupling strength, authors thought boson undetectable.
- BR(P –> νν) ~ 100%, BR(P->γγγ) ~ 10-7. Lifetime ~2.5 ns.

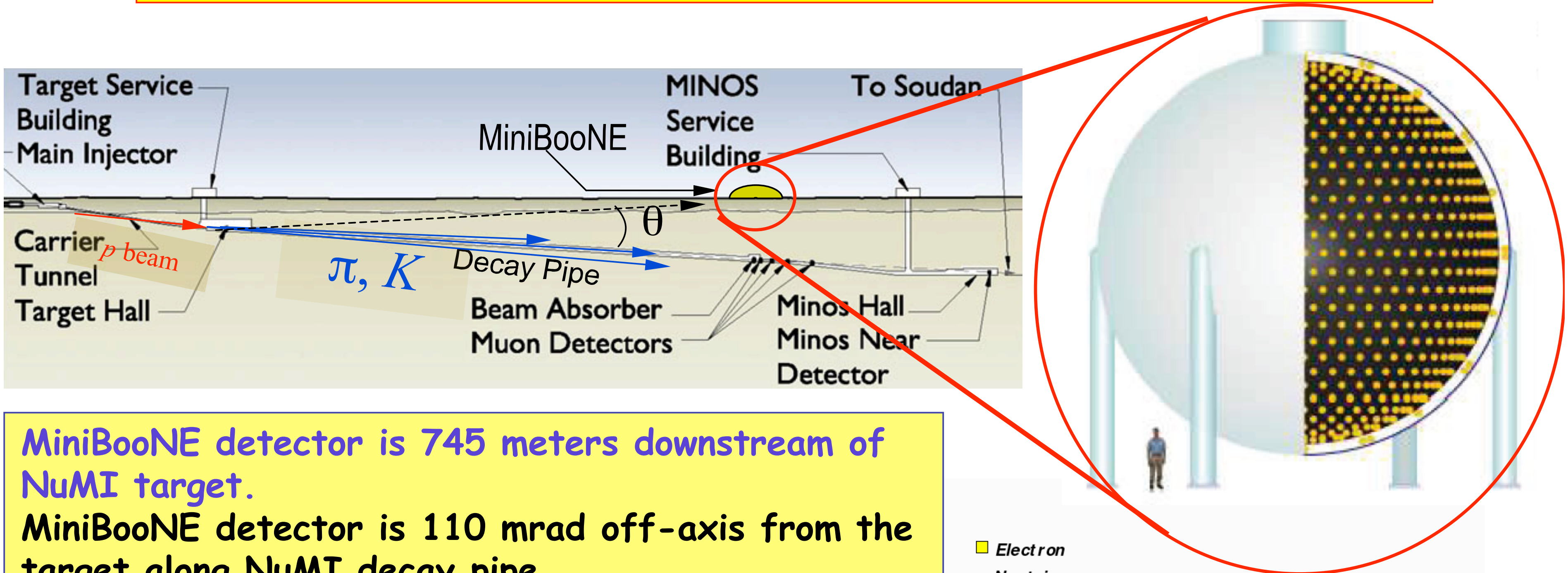
But--MB has LOTS of POT

- The paraphotons can be produced by hadronic bremsstrahlung of the incident proton beam(~1%) [X10-9] in the forward direction (~5-10mr) in inclusive reactions
- Assume PID & Fiducial Volume efficiency ~ 30%, and look for em shower
- Assume 50 cm radiation length ·Number of radiation lengths in MB ~ 5m/50cm = 10 [X10-9]
- See of the order of 10-20 events in the forward direction.

Examination of our present forward events is underway, but will need more events for definitive answer.

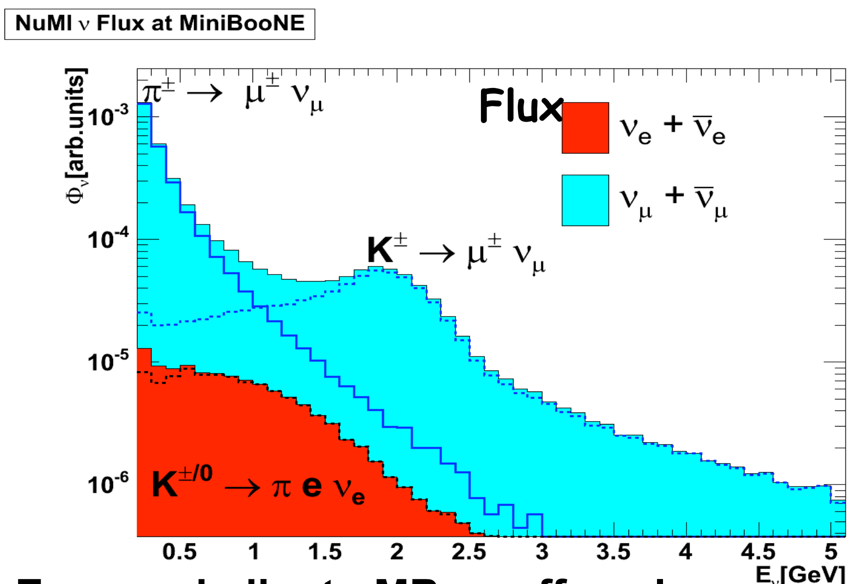
- Main point is that MiniBooNE can do very sensitive searches for a variety of rare processes

Events from NuMI detected at MiniBooNE

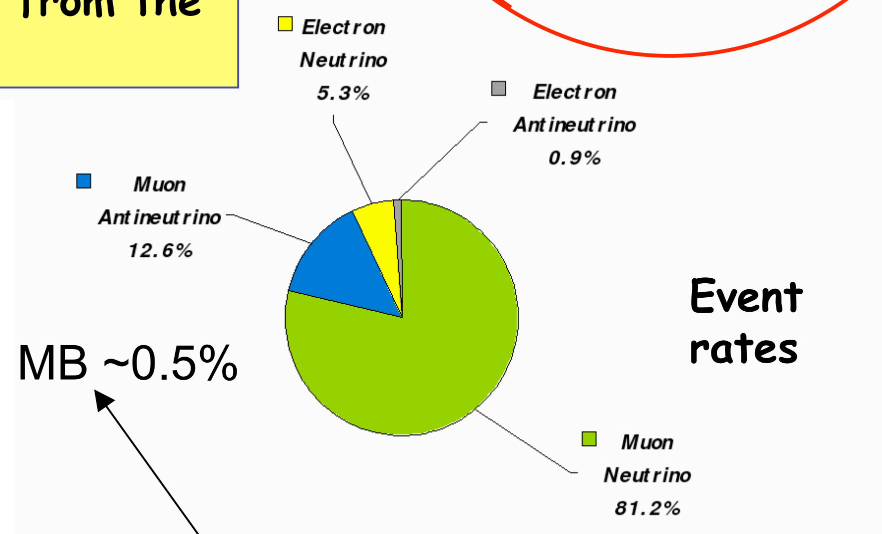


MiniBooNE detector is 745 meters downstream of NuMI target.

MiniBooNE detector is 110 mrad off-axis from the target along NuMI decay pipe.



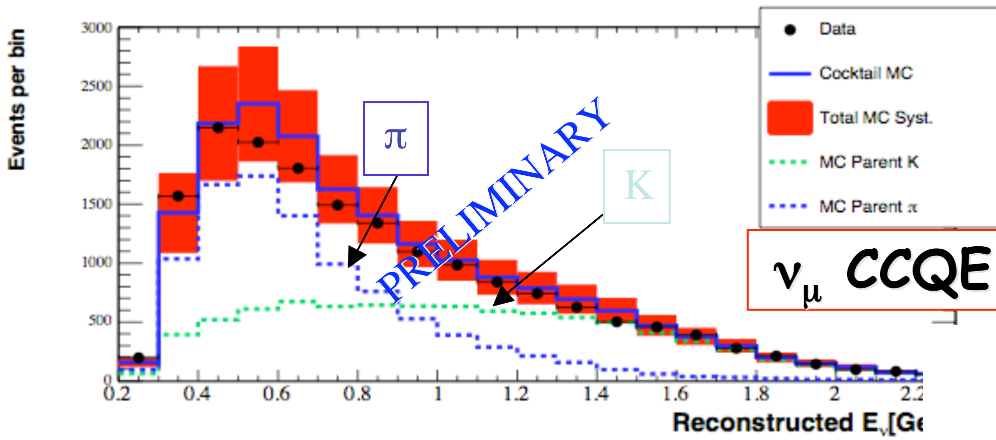
Energy similar to MB as off angle



NuMI event composition at MB
ν_μ-81%, ν_e-5%, $\bar{\nu}_\mu$-13%, $\bar{\nu}_e$-1%

Data Analyses

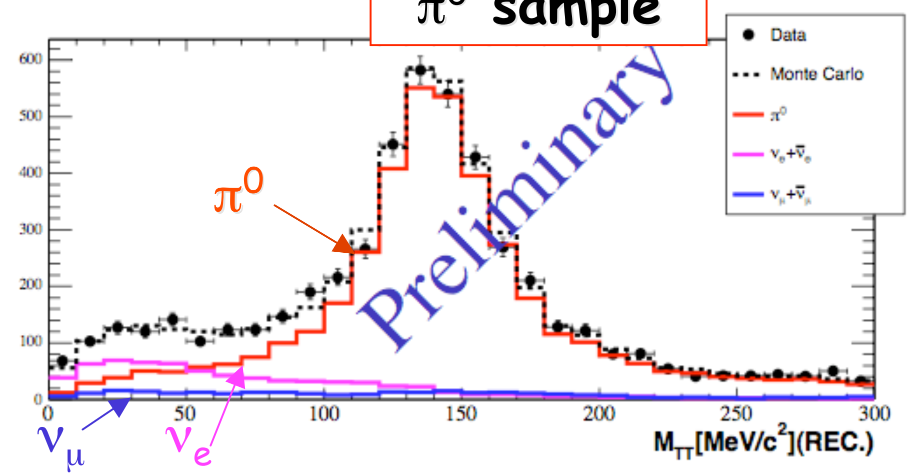
MC is normalized to data POT number !



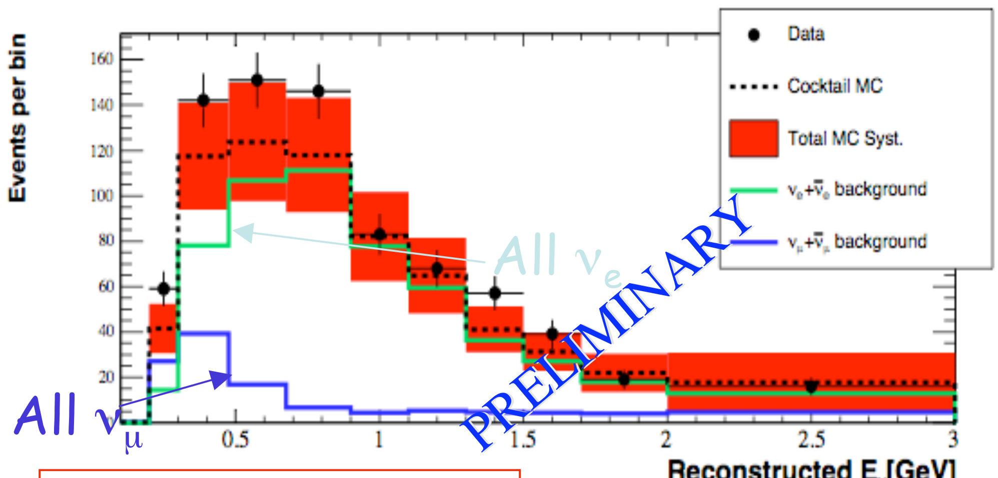
ν_μ CCQE sample

Good agreement between data and Monte Carlo:the MC tuned well.

π^0 sample



π^0 (and Δ) events well understood.

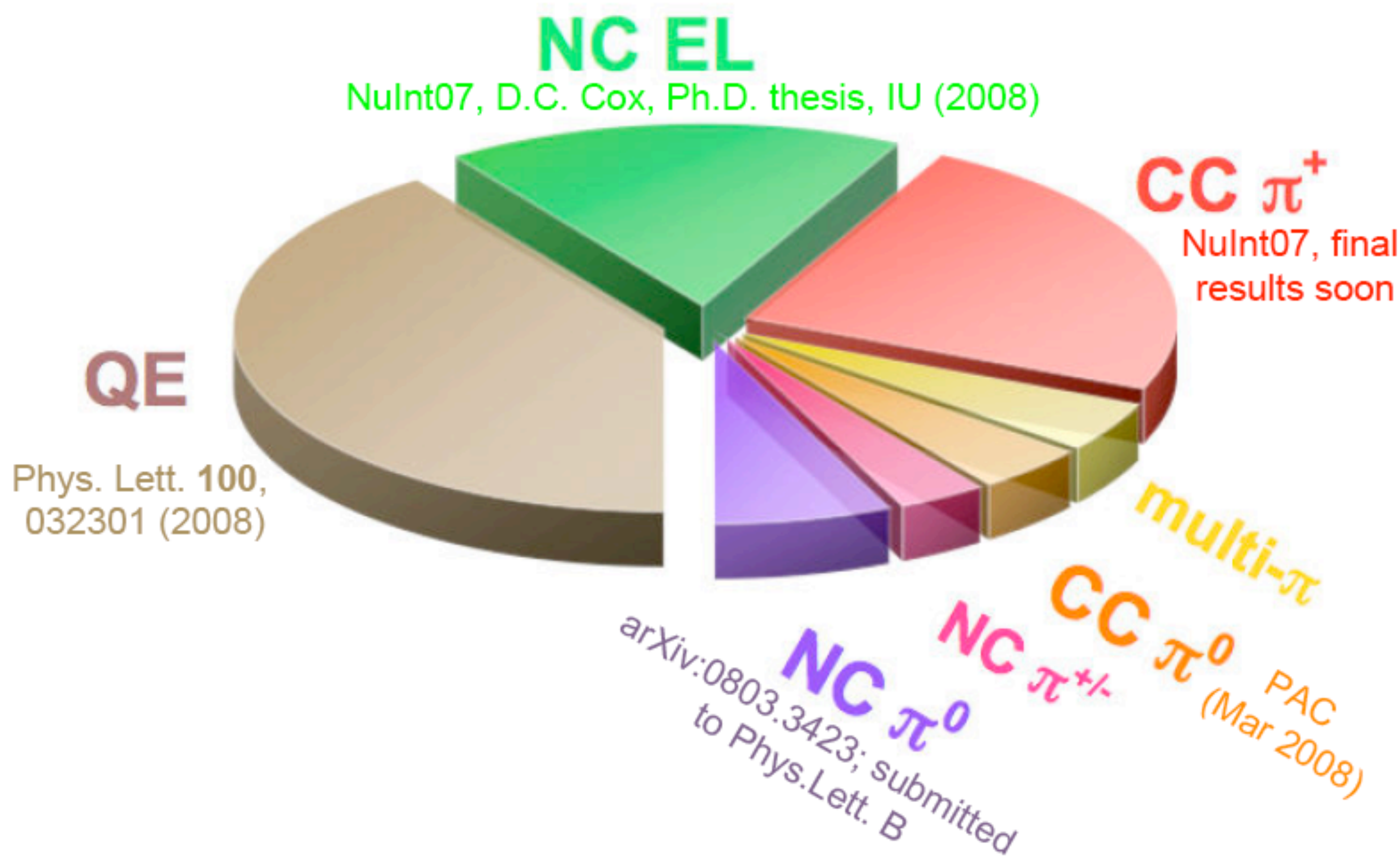


ν_e CCQE sample

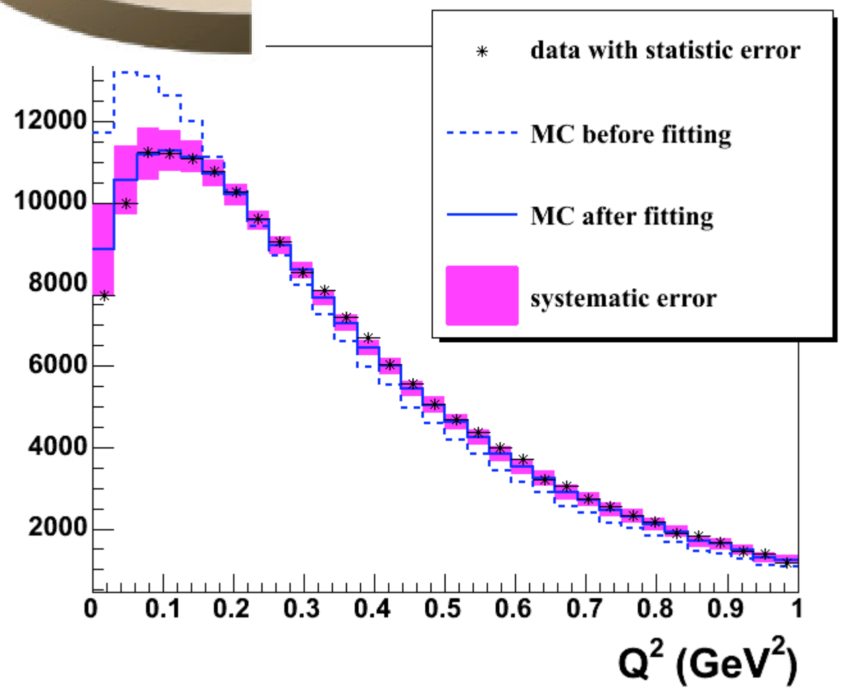
Very different backgrounds compared to MB (Kaons vs Pions)!

Ongoing effort is to reduce ν_e CCQE sample systematics constraining it with ν_μ CCQE sample.

Neutrino Cross Sections



Nuance Parameters (ν_μ CCQE)



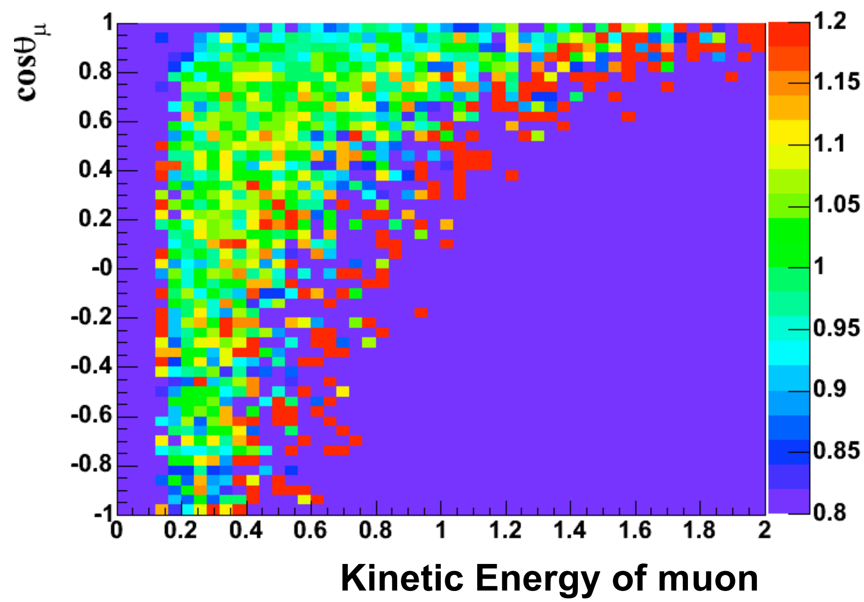
From Q^2 fits to MB ν_μ CCQE data:

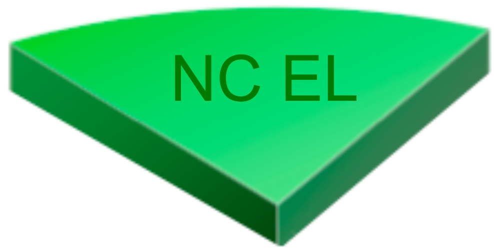
- M_A^{eff} -- effective axial mass
  1.23+/-.20 GeV
- E_{lo}^{SF} -- Pauli Blocking parameter
  kappa = 1.019+/-.011

From electron scattering data:

- E_b -- binding energy
- p_f -- Fermi momentum

Model describes CCQE ν_μ data well (arXiv:0706.0926)





ν_μ NC Elastic

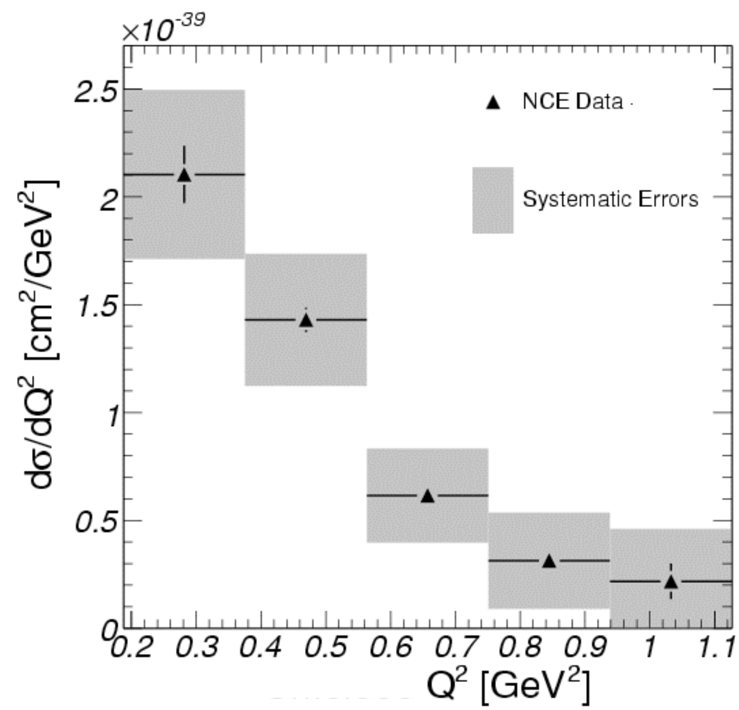
Results (from 10% nu sample):

- NC elastic diff. cross section
  (per nucleon, n+p averaged, flux averaged)

- Flux Integrated Cross-Section
  = 8.8 ±0.6(stat) ±2.0(syst) $\times 10^{-40}$ cm^2

- Measured axial mass (NC)
  = 1.34 +0.38–0.25 GeV

(D.C. Cox)



- work of Chris Cox, Indiana U., Ph.D. 2008
- further analysis on full nu data set and with goal of reducing systematic errors in progress (D. Perevalov, Alabama)
- eventual analysis goal:
  NC/CCQE ratio measurement and antinu data

NC Pi0 reconstruction unsmearing

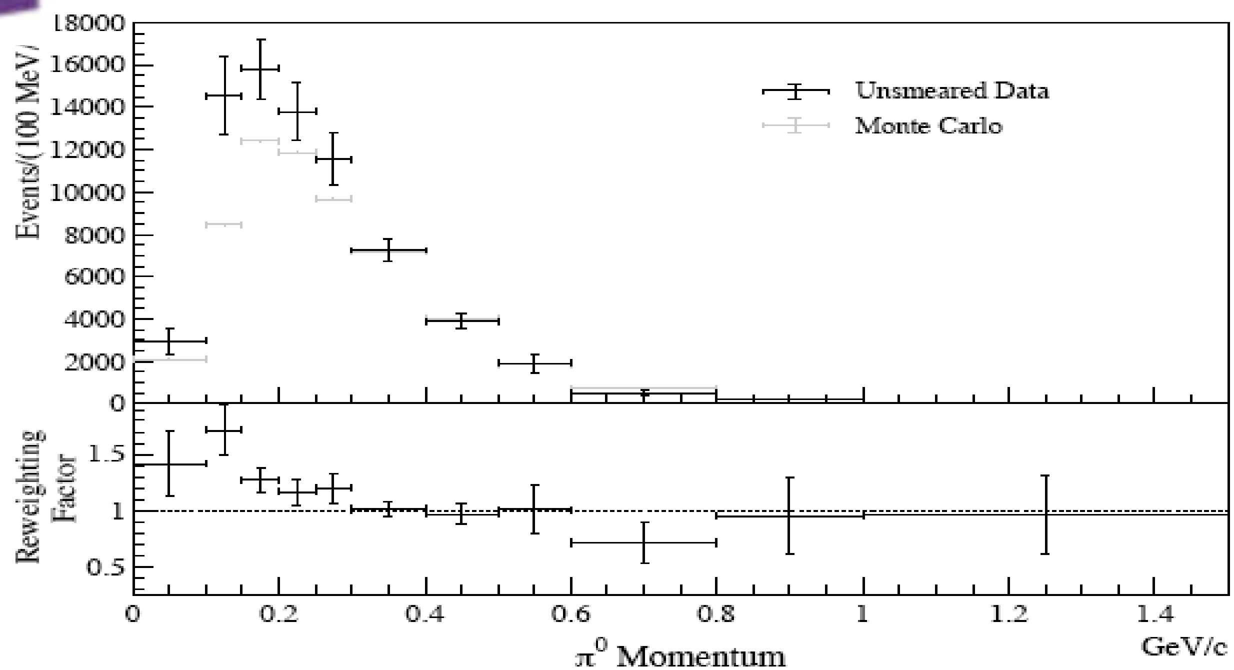
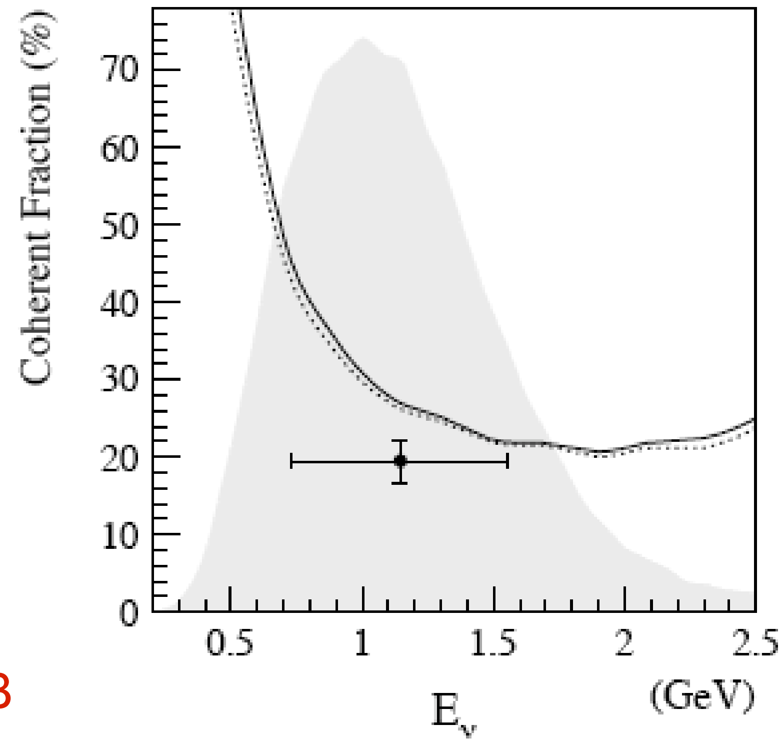


Fig. 1. Top: Results of the π^0 unsmearing in bins of momentum. The dark points show the unsmeared data π^0 momentum distribution and the light points show the uncorrected MC π^0 momentum distribution. The unsmeared data error bars contain all sources of error propagated through the unsmearing, while the MC error bars are from finite MC statistics. Bottom: The reweighing function, formed by taking ratio of the two points above (data/MC).

Coherent Fraction 19.5%

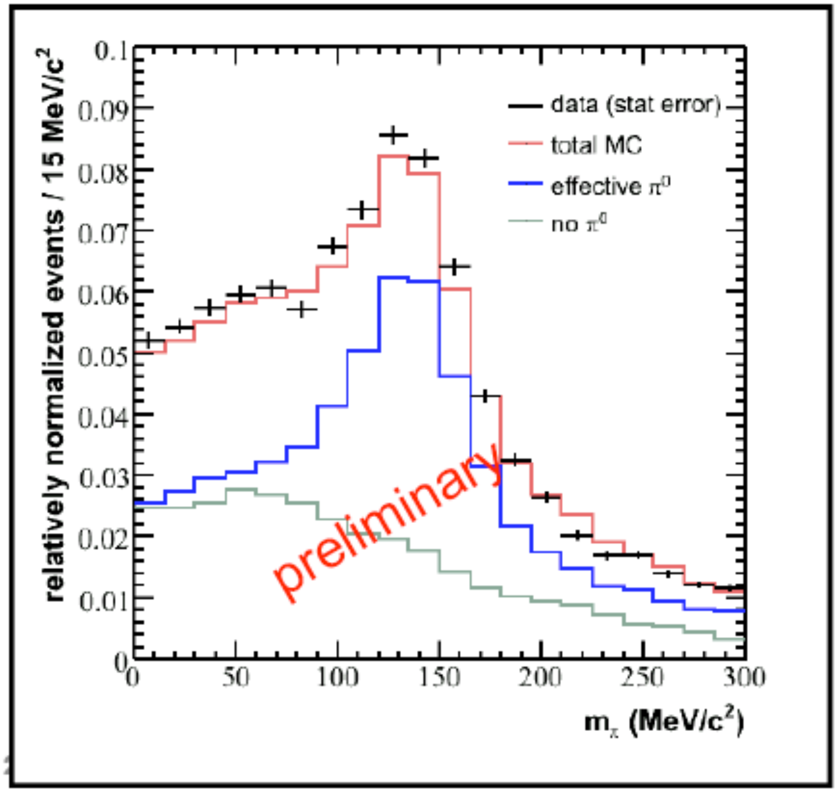


Submitted to PL B
ArxiV:0803.3423

Fig. 4. The coherent fraction in the Rein and Seghal based MC vs. neutrino energy compared to this measurement. The solid line only includes carbon interactions, while the dotted line includes scattering off hydrogen with diffractive events counted as part of the coherent. The measured value is shown with error bars which indicate the total error on the measurement (vertical) and the spread in the participating neutrino energy distribution. The shaded distribution is MC energy for neutrinos which produce exclusive NC π^0 events in MiniBooNE with arbitrary normalization.

ν_μ CC π^0

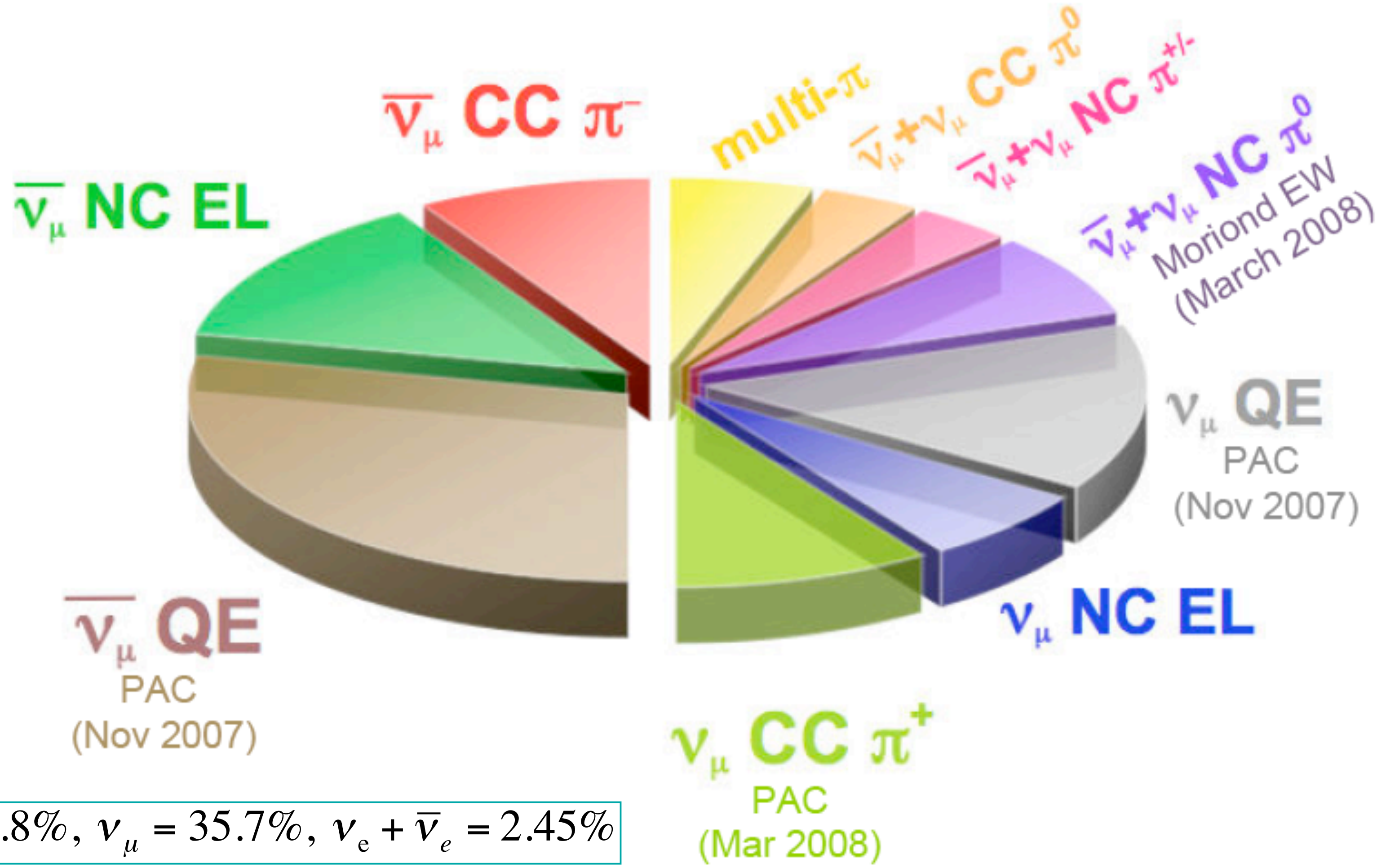
- developed a new 3-ring fitter ($\mu + \gamma\gamma$) for this new σ_ν analysis



- provides a means to test a pure resonant single-π sample (w/ no coherent π contribution)
- 31,755 events

(R. Nelson)

Antineutrino Cross Sections

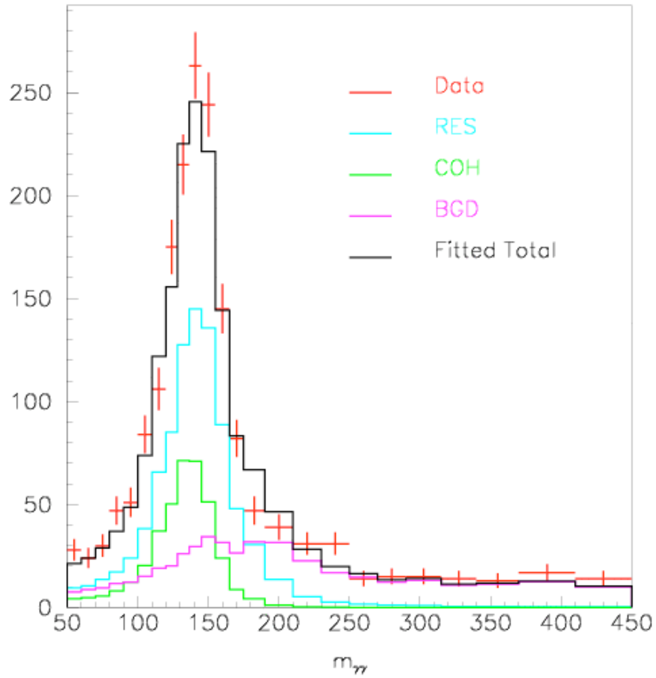


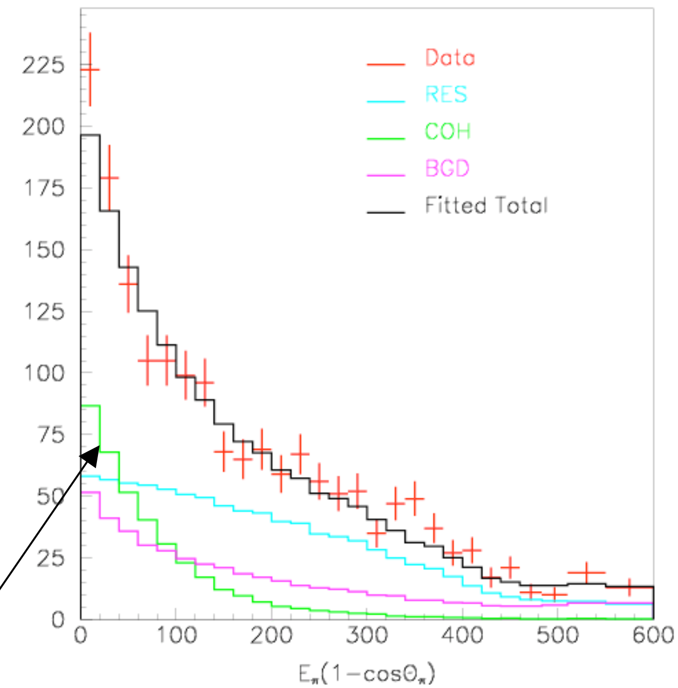
$$\bar{\nu}_\mu = 61.8\%,\ \nu_\mu = 35.7\%,\ \nu_e + \bar{\nu}_e = 2.45\%$$

$\overline{\nu_\mu}$ NC π^0

- shown at Moriond in March.
- 1,744 events (plus, will be taking more data in $\overline{\nu}$ mode soon)

(V. Nguyen)



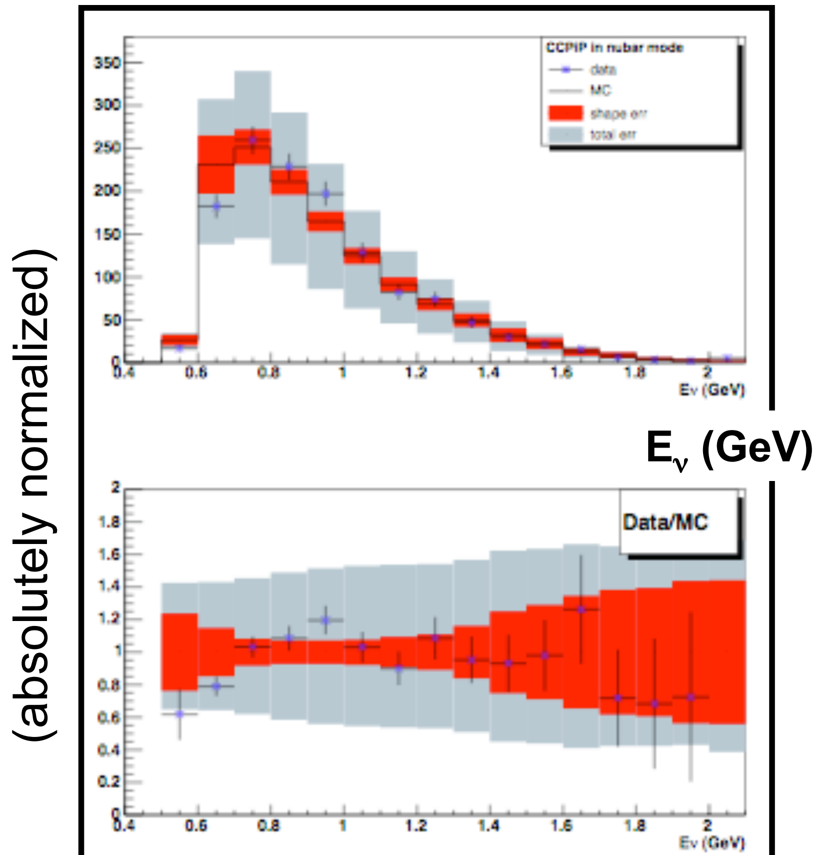


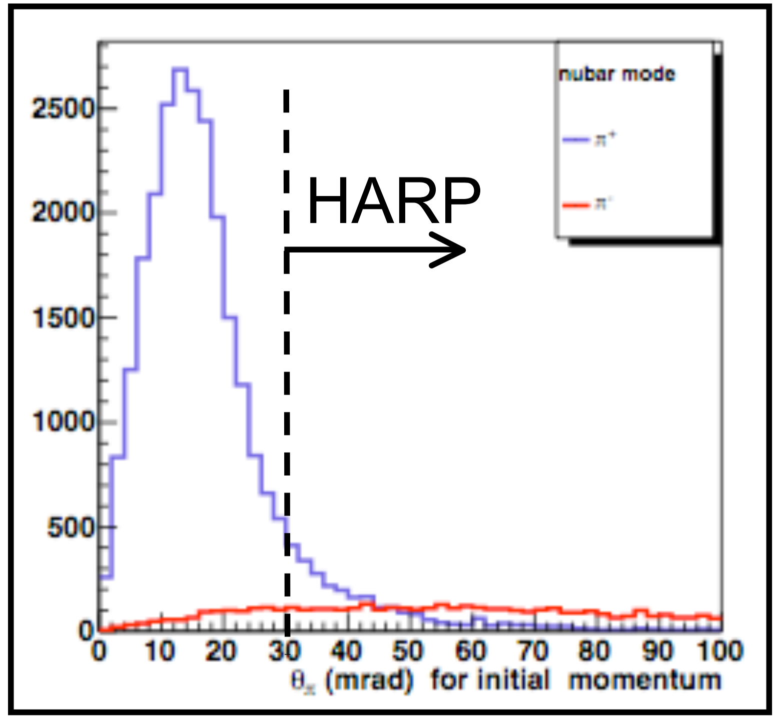
Coherent fraction (from fit) disagrees with Rein-Sehgal

ν_μ CC π^+ in $\overline{\nu}$ Mode

- direct way to check predicted rate and energy dependence of ν backgrounds in $\overline{\nu}$ mode

(J. Nowak)





- as well as most forward π^+ production (outside HARP data)

Antineutrinos in MiniBooNE

- Data acquired to date:

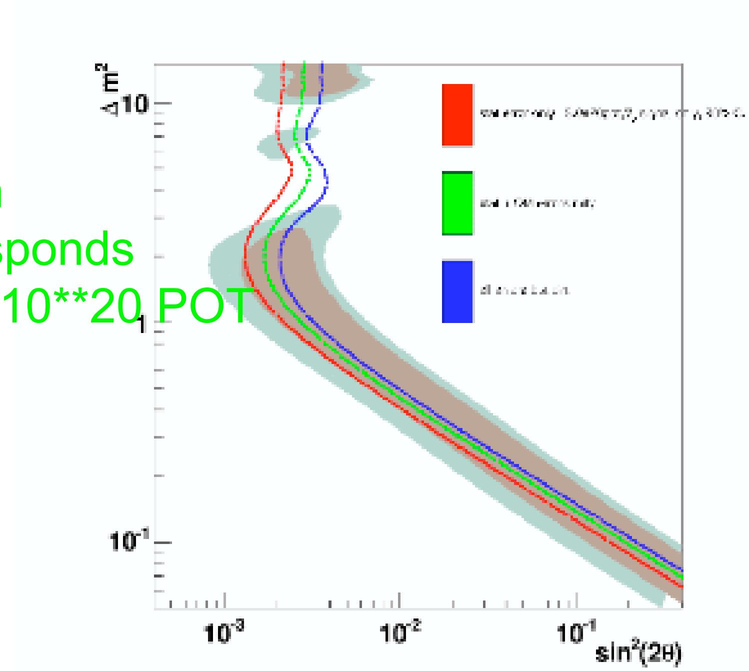
ν channel	events
all channels	810k
CC quasielastic	340k
NC elastic	150k
CC π^+	180k
CC π^0	30k
NC π^0	48k
NC $\pi^{+/-}$	27k
CC/NC DIS, multi-π	35k

6x10[20] POT
ν mode

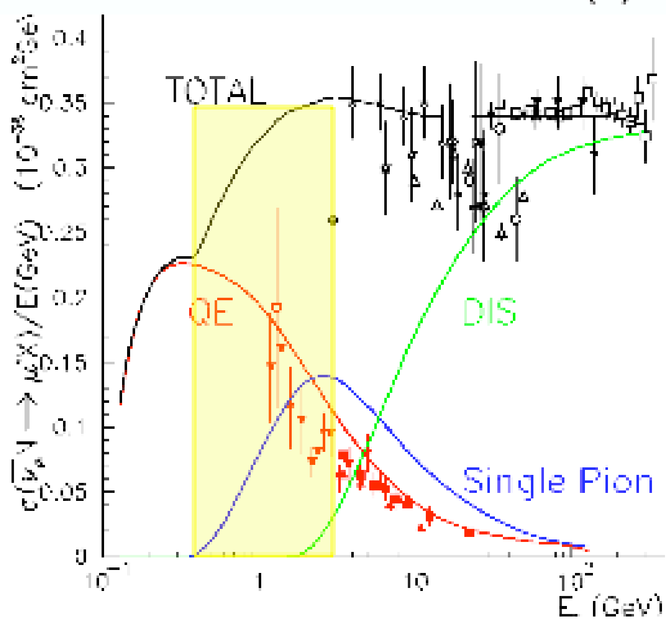
$\bar{\nu}$ channel	events
all channels	54k
CC quasielastic	24k
NC elastic	10k
CC π^-	8.9k
CC π^0	1.7k
NC π^0	4.9k
NC $\pi^{+/-}$	1.8k
CC/NC DIS, multi-π	1.9k

2×10^{20} POT
$\bar{\nu}$ mode

Green corresponds To 5X10**20 POT



- In November PAC recommended MB run to get to a total of about $5\times10^{20}\ \bar{\nu}$ POT
  - Understanding low E excess
  - Cross-sections measurements



Publications:

A.A. Aguilar-Arevalo et. Al.:

0707.0926, PRL 98, 231801 (2007) Oscillation search

0706.0926, PRL 100, 032301 (2008) numu CCQE

0706.3897, showing mu internal bremsstrahlung small

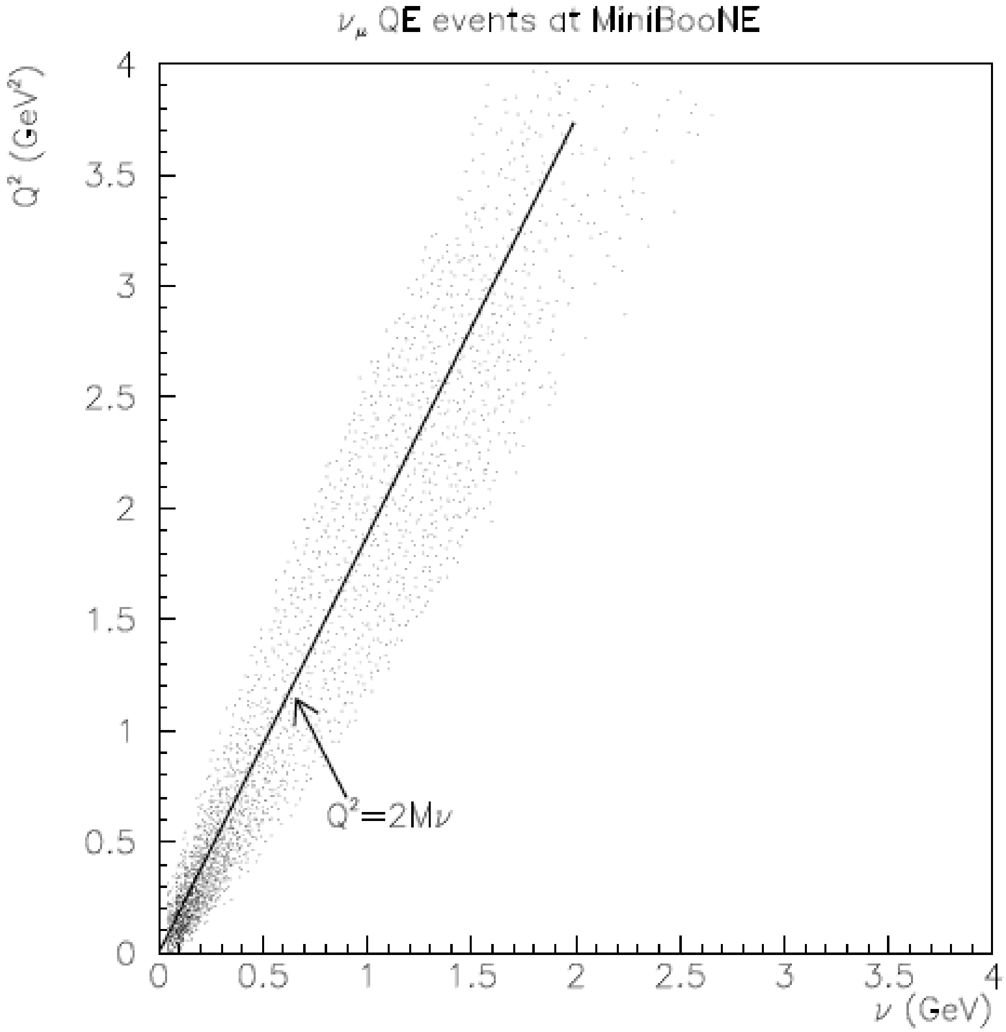
0803.3423, submitted to PL, neutral current pi0 prod.

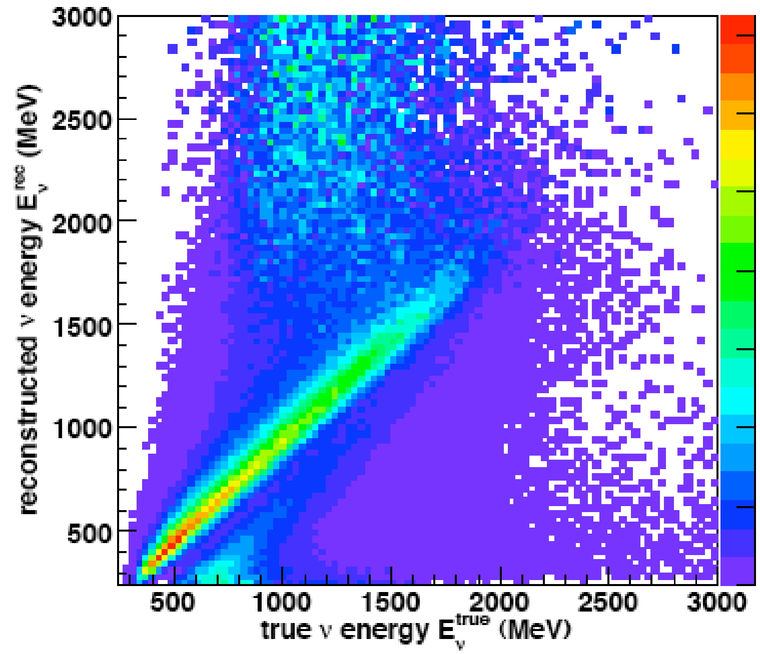
In draft form within the collaboration:
3 NIM papers--Flux, Detector, and Reconstruction
3 others--combined limits, NUMI/MB, improved osc fit

9 further physics papers in various stages of progress
At least 8 more contemplated

BACKUP

Smearing induced by moving nucleon target





Two Analysis Chains

For most of analysis had two equal reconstructions, sfitter, rfitter

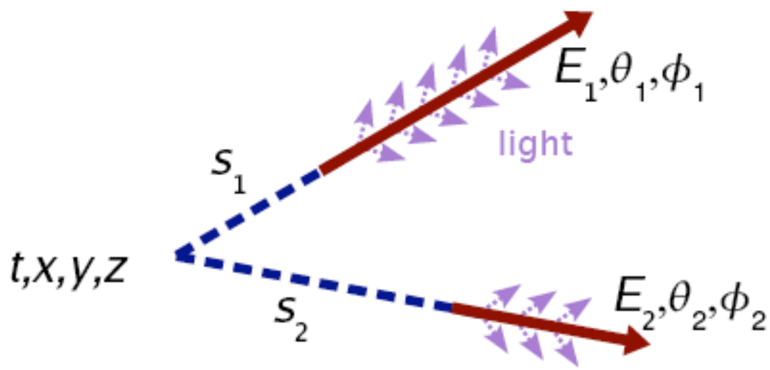
- Toward end of analysis, a new more powerful reconstruction based on sfitter—the pfitter (TB) became available. Better especially on 2 track fits (22 cm position error, 2.8^o 1 track angle error, ~20 MeV π^0 mass resolution)—BUT takes about 10 times more computer time.
- sfitter and pfitter retained.

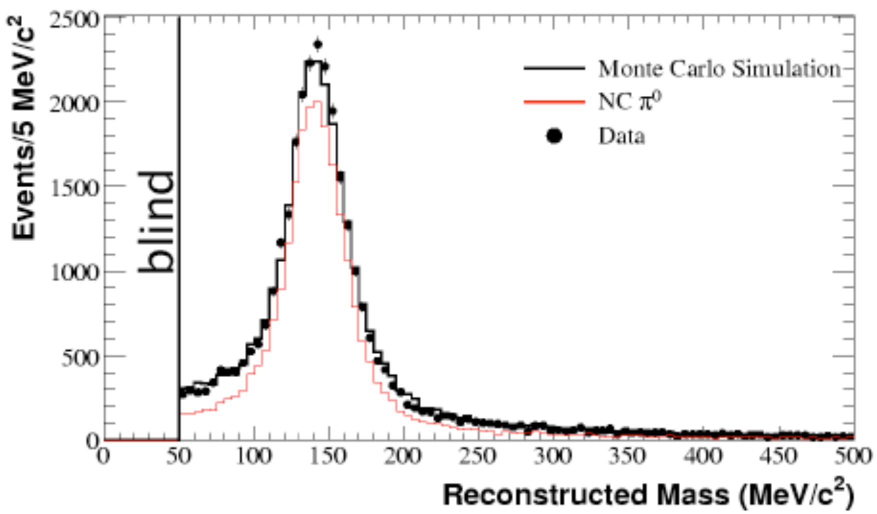
Event Classification Schemes for Oscillation Measurement

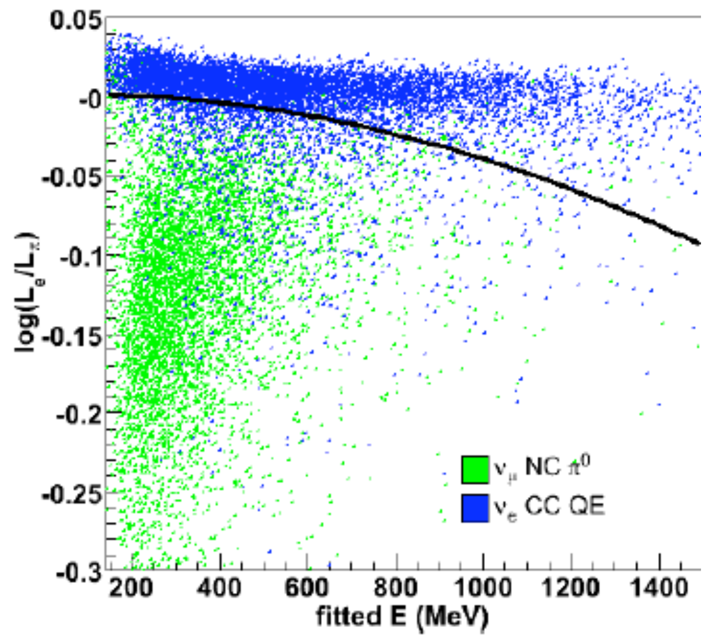
- Signal events were defined as ν_e CCQE events. From Evis and angle -->Enu
- Pfitter used simple cuts (TB--"Track based analysis") to separate these events based on:
  a. Likelihood of 1 track e-fit vs 1 track μ-fit
  b. Likelihood of 1 track e-fit vs 2 track fit
  c. Mass of gamma-gamma in 2 track fit (pi0)

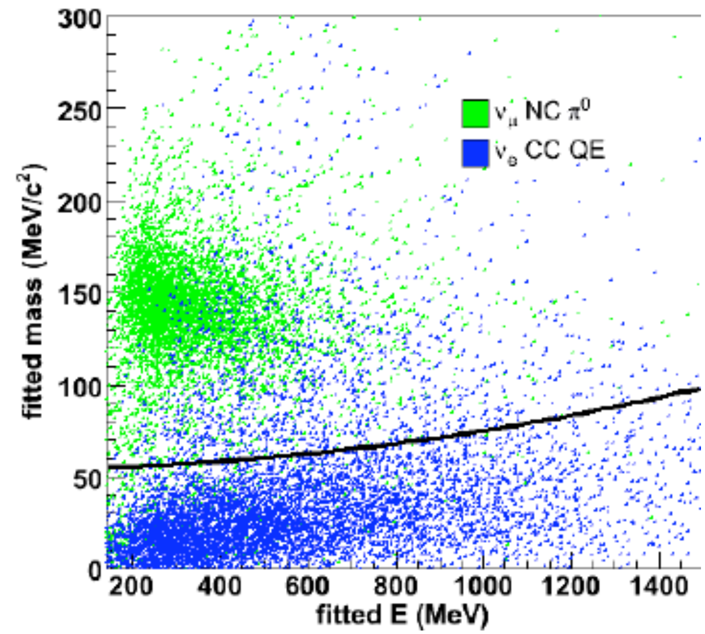
Separating e from π^0

- Extend fit to include two e-like tracks
- Very tenacious fit…8 minutes per event
- Nearly 1M CPU hours used (thanks OSG!)



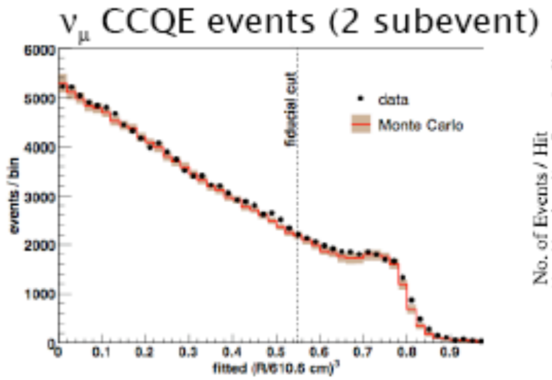


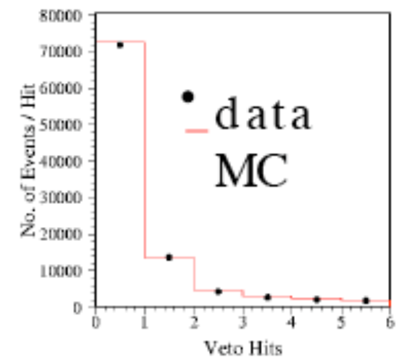


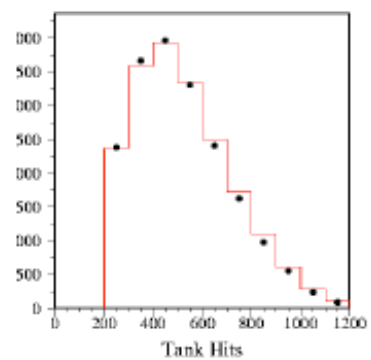


TBL Analysis: Separating e from μ

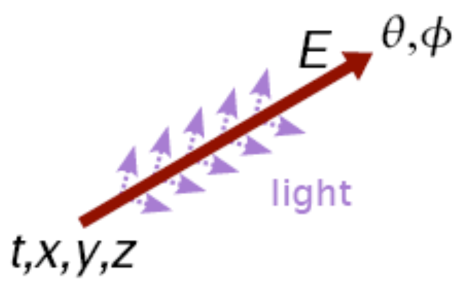
- Analysis pre-cuts
  - Only 1 subevent
  - Veto hits < 6
  - Tank hits > 200
  - Radius < 500 cm

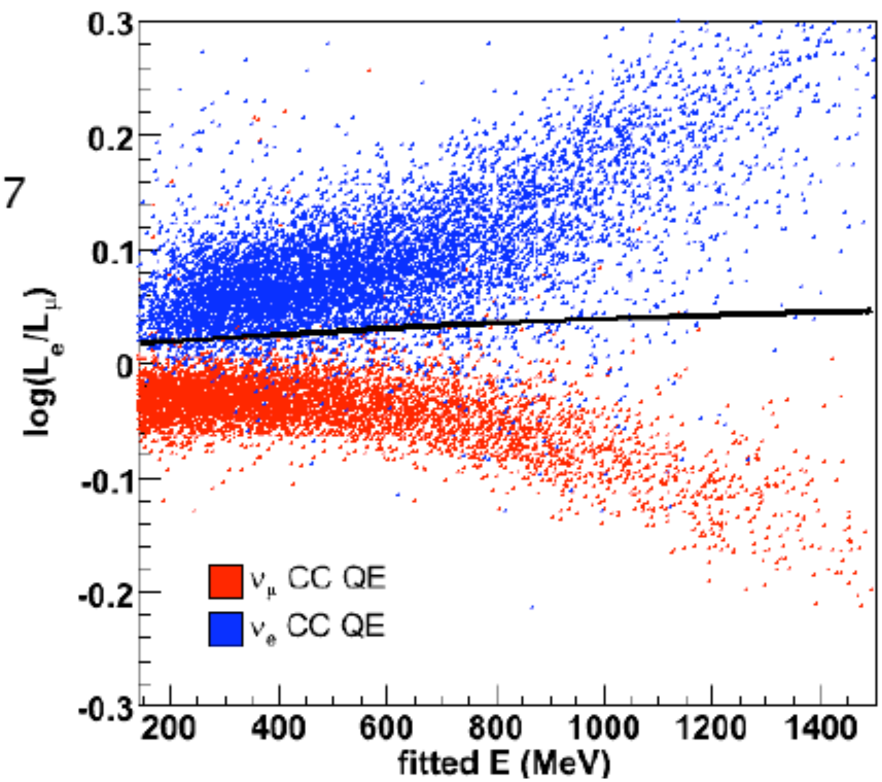






- Event is a collection of PMT-level info (q,t,x)
- Form sophisticated Q and T pdfs, and fit for 7 track parameters under 2 hypotheses
  - The track is due to an electron
  - The track is coming from a muon

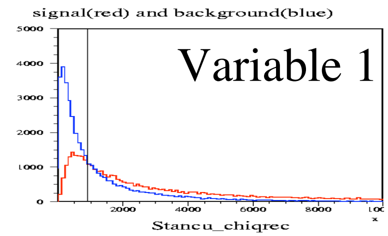




Other analysis-- Sfitter and Boosted Decision Tree

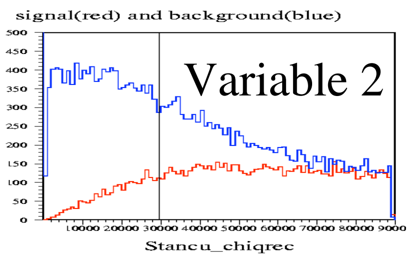
(sequential series of cuts based on MC study)

(N_{signal}/N_{bkgd})



bkgd-like

signal-like



9755/23695

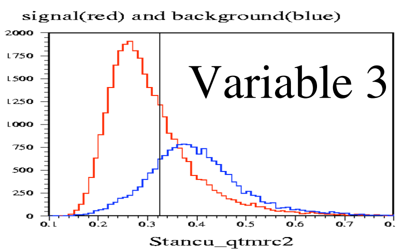
bkgd-like

sig-like

1906/11828

7849/11867

30,245/16,305



sig-like

bkgd-like

20455/3417

9790/12888

etc.

Give higher weight to misclassified events and make new "boosted tree". Continue 100's of times; sum results of each tree: 1 if signal leaf, -1 if background leaf

Neutral Current Single Pi0 Production coherent fraction=19.5%

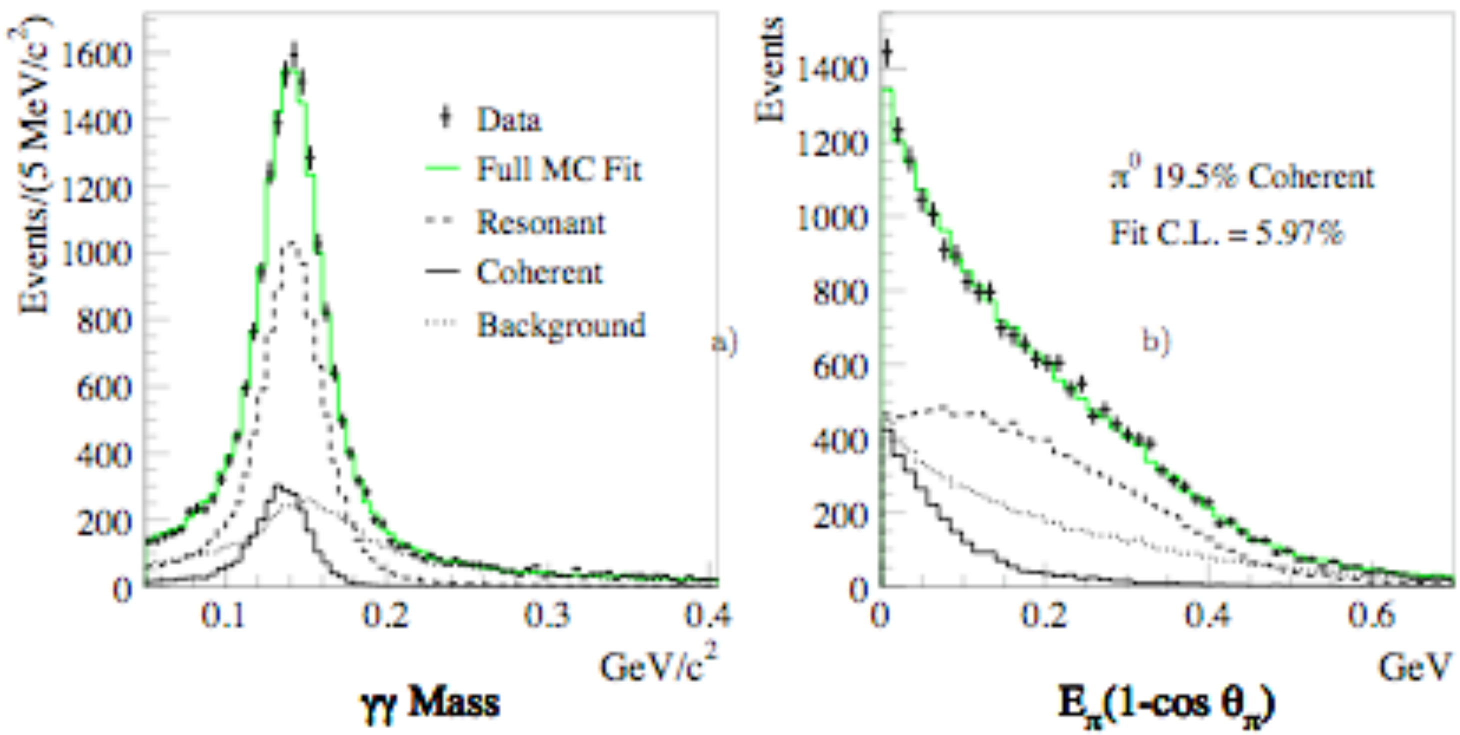


FIG. 3: Monte Carlo overlay of the template fitted π^0 data in a) $m_{\gamma\gamma}$ invariant mass, and b) $E_\pi(1-\cos\theta_\pi)$.

Is MiniBooNE and LSND consistent if there are One, Two or Three Sterile Neutrinos ?

- Michael Maltoni, arXiv:0711.2018
- Parameter goodness of fit (PG) test to appearance and disappearance datasets from MiniBooNE, LSND, KARMEN and NOMAD experiments.

  PG = 4.0×10^{-6} for (3+1 sterile ν) model

  PG = 4.8×10^{-5} for (3+2 sterile ν) model

➔ Severe tension between different datasets. With present experimental results, (3+1), (3+2) and (3+3) neutrino oscillation schemes is NOT possible to explain the LSND signal in terms of sterile neutrinos.

MiniBooNE preparing own examination including systematic errors and bin-to-bin correlations

Sterile Neutrinos That Take Shortcuts in Extra Dimensions

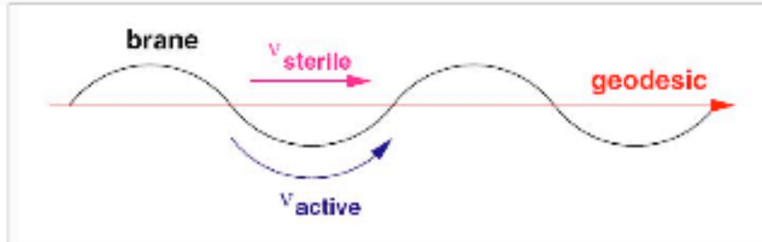
- Prior to MiniBooNE's first result, it was put forward that sterile neutrinos can take shortcuts in extra dimensions.

(Päs, Pakvasa, Weiler, Phys.Rev. D72 095017, 2005)

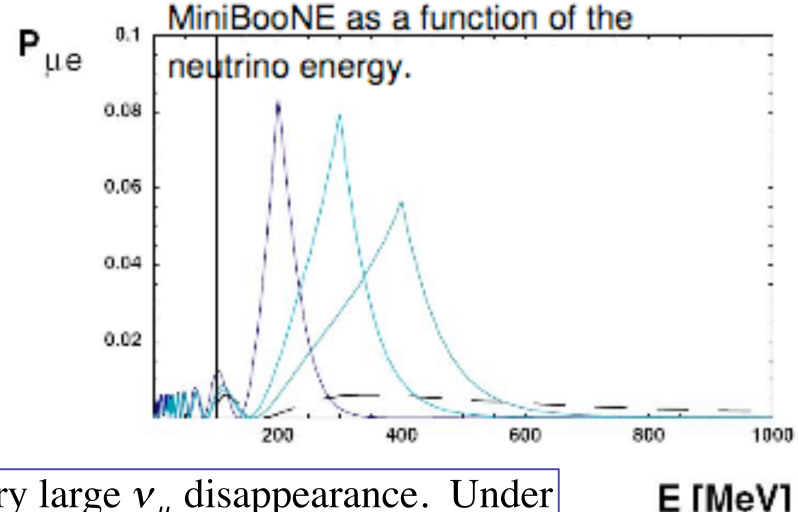
  – A resonance in active-sterile neutrino oscillations arises from an increase in the path-length of active neutrinos relative to sterile neutrinos in the bulk.
    - Below the resonance, the standard oscillation formulas apply.
    - Above the resonance, active-sterile oscillations are suppressed.
    - A resonance energy in the range of 30– 400 MeV allows an explanation of all neutrino oscillation data, including LSND data in a 3+1 model
    - And this model can evade the problems with the Bugey and CDHS limits.

  – This paper predicted that a significant oscillation signal would only be seen in MiniBooNE at low energy.

Schematic representation of a periodically curved brane in Minkowski spacetime.



Oscillation probabilities for MiniBooNE as a function of the neutrino energy.

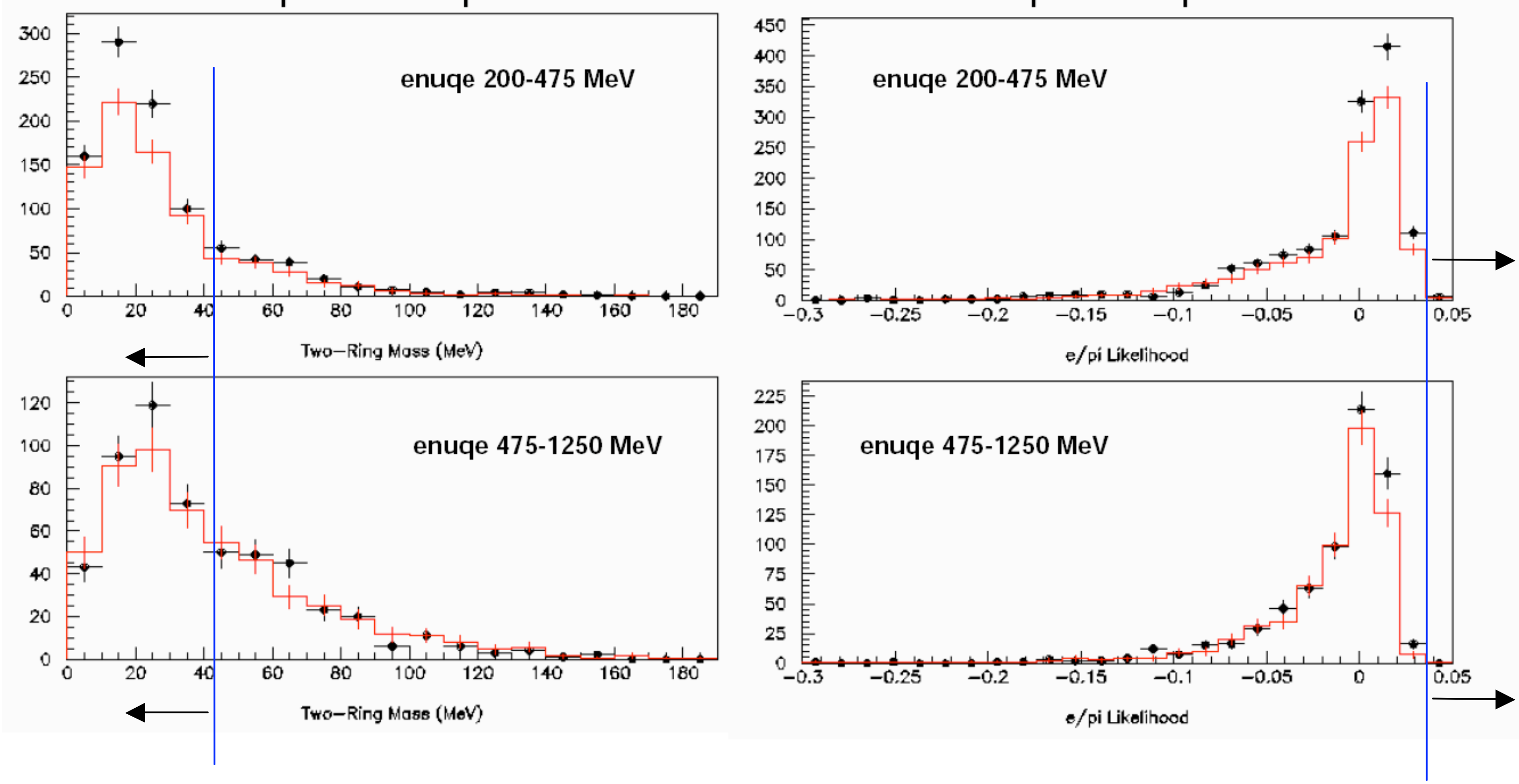


Predicts very large ν_μ disappearance. Under examination.

Particle Identification

mpi0 with Lepi cuts

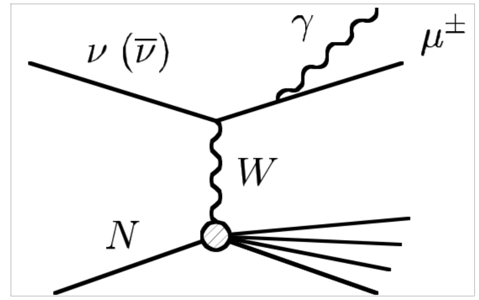
Lepi with mpi0 cuts

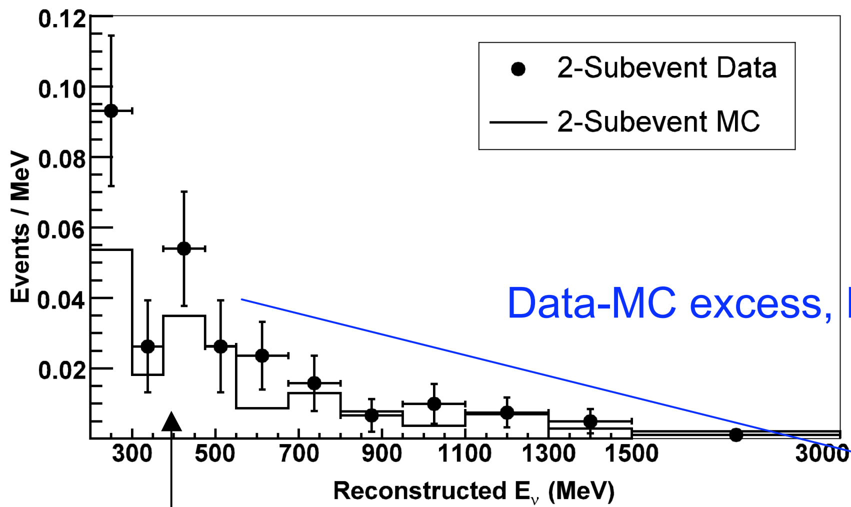


old pi0 reweighting

No major discrepancy in Particle Identification

Muon Misidentification (including muon internal bremsstrahlung)





Apply reconstruction and particle identification to clean sample muon CCQE events (muon decay visible).

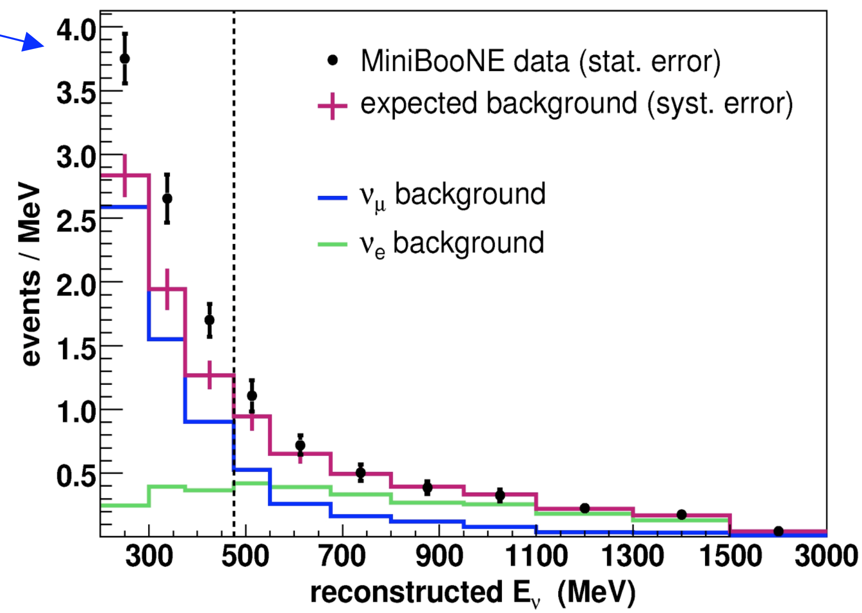
Then scale normalization to account for how often the second subevent is missing

What results is a direct measurement and MC prediction for almost all the rate at which events with a final state muon enter the ν_e background

-Misidentified Muons not a problem.

Paper on this work:
arXiv:0710.3897 [hep-ex]

Data-MC excess, but note the scale!



Update on the low E excess...

E_ν^{QE} [MeV]	200-300	300-475	475-1250	
total background	284±25	274±21	358±35	(syst. error)
ν_e intrinsic	26	67	229	
ν_μ induced	258	207	129	
NC π^0	115	76	62	
NC $\Delta \rightarrow N\gamma$	20	51	20	
Dirt	99	50	17	
other	24	30	30	
Data	375±19	369±19	380±19	(stat. error)
Data – MC	91 ± 31	96 ± 26	22 ± 40	data + syst

200-300 MeV:
- NC π^0 largest
- Dirt background significant
- NC $\Delta \rightarrow N\gamma$ falling off
- Intrinsic ν_e negligible

300-475 MeV:
- Three main:
  - NC π^0
  - Dirt bkgnd
  - NC $\Delta \rightarrow N\gamma$
- Intrinsic ν_e small

475-1250 MeV:
- Intrinsic ν_e largest
- NC π^0 significant
- Others small

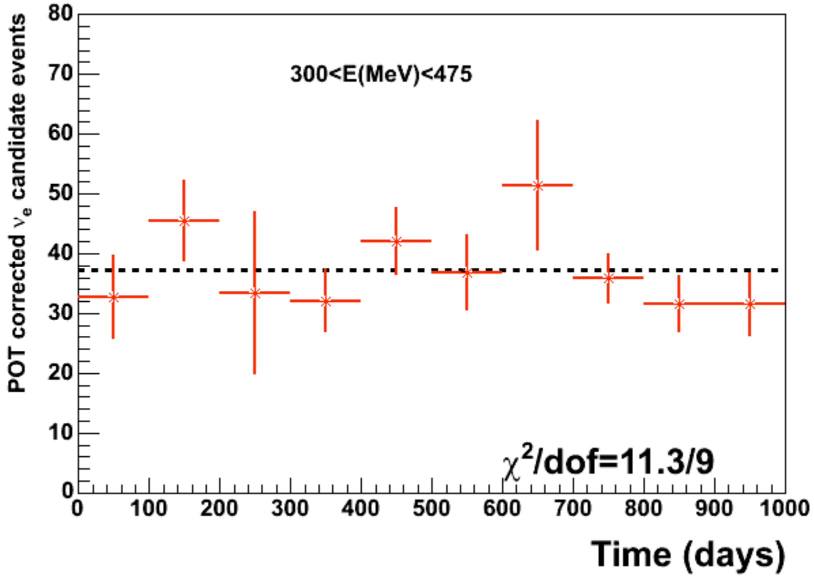
★ Systematics / backgrounds at low E still under study...

Detector Anomalies or Reconstruction Problems

No Detector anomalies found

- Example: rate of electron candidate events is constant (within errors) over course of run

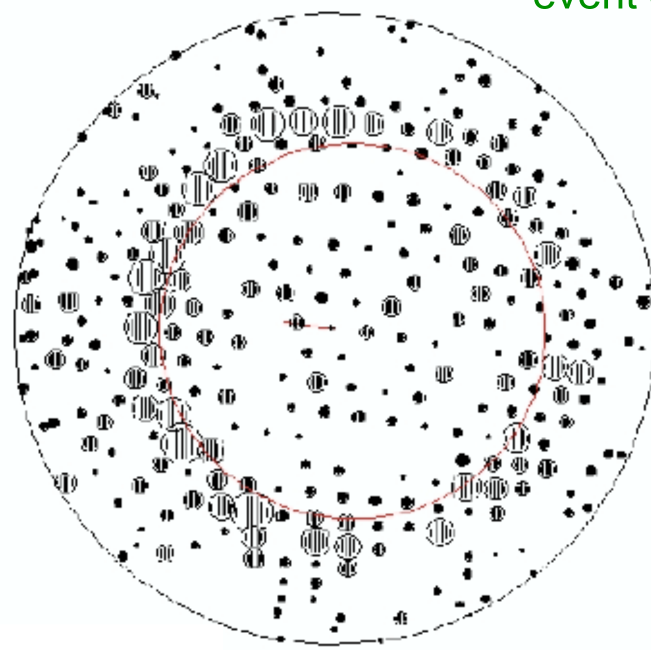
event/POT vs day, 300<Enu<475 MeV



No Reconstruction problems found

- All low-E electron candidate events have been examined via event displays, consistent with 1-ring events

example signal-candidate event display



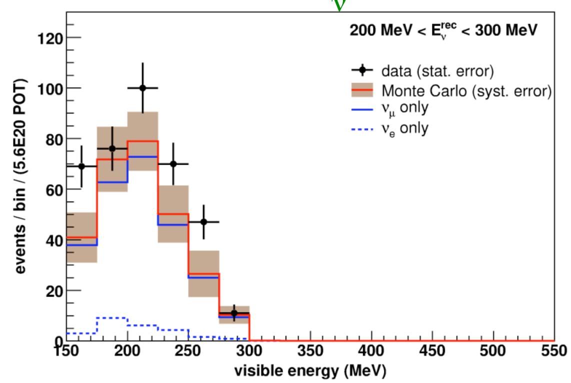
Signal candidate events are consistent with single-ring neutrino interactions

$\Rightarrow$ But could be either electrons or photons

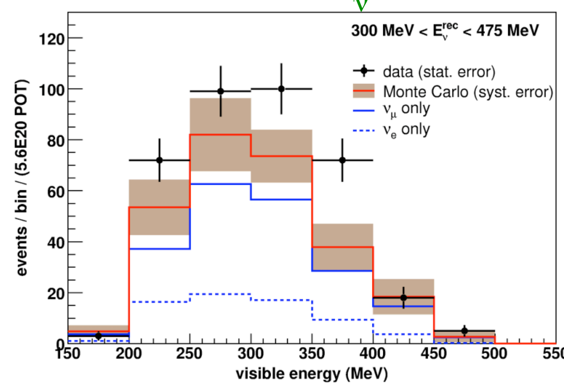
energy/angle distributions in E_ν bins

visible energy distributions:

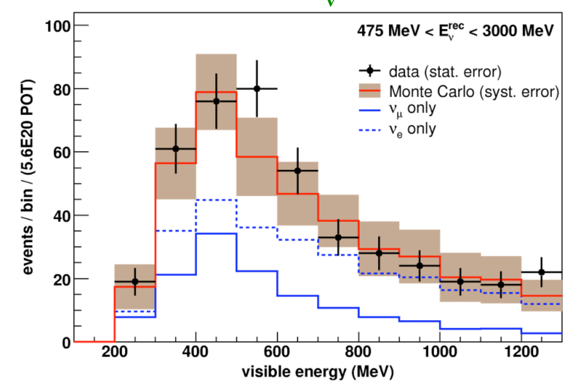
200< E_ν<300 MeV



300 <E_ν<475 MeV

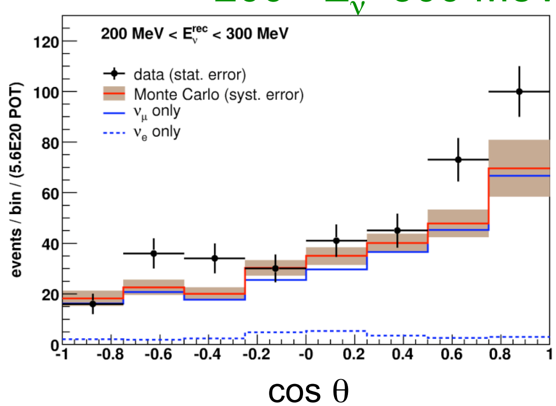


475 <E_ν<3000 MeV

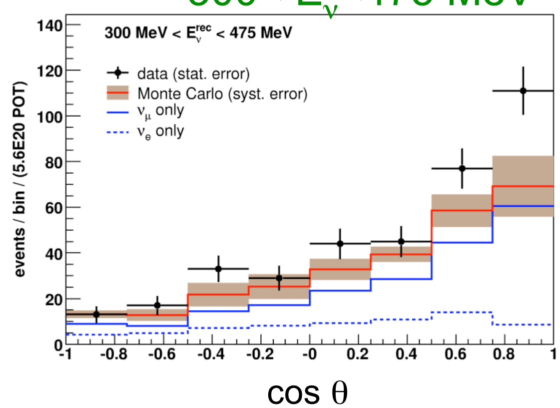


cos θ distributions:

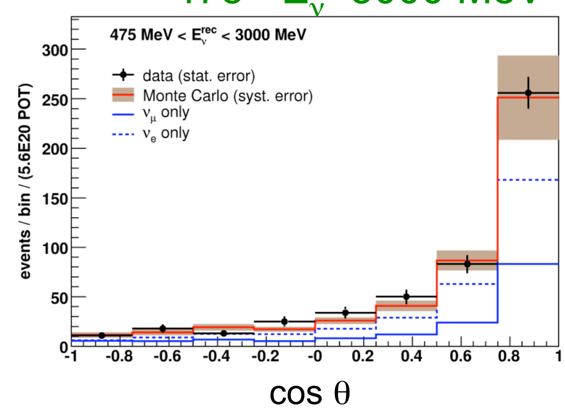
200< E_ν<300 MeV



300< E_ν<475 MeV



475< E_ν<3000 MeV



Excess distributed among visible E, cos θ bins

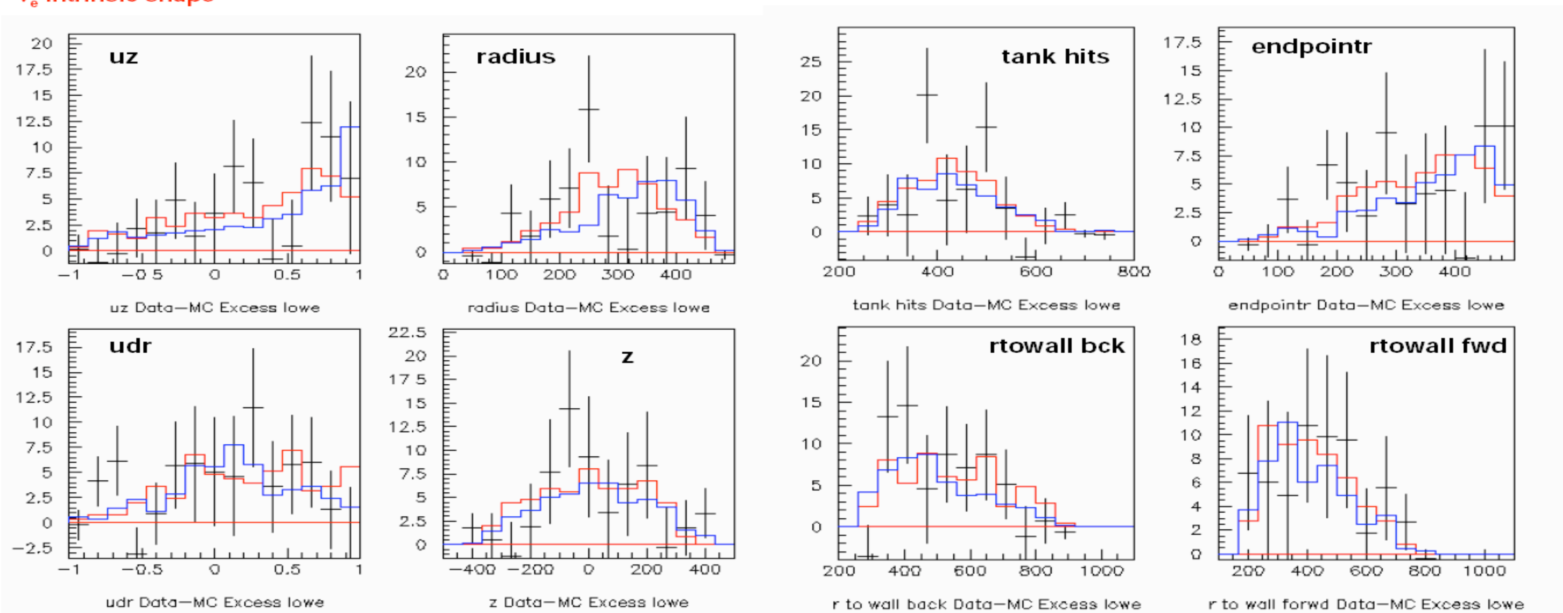
At higher energy, data are well-described by predicted background

Other Distributions
UZ, Radius, RtoWall, etc.

Kinematic Distributions of Data-MC Excess
with All TB Signal Region Cuts
(300 < Enuqe < 475 MeV)

ν_μ bkgnd shape
ν_e intrinsic shape

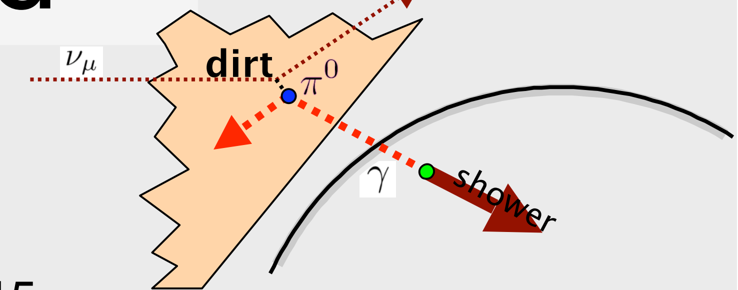
With Lepi
and $m_{\pi 0}$ cuts



With rtw(1)>300..and.rtw(2)>100.

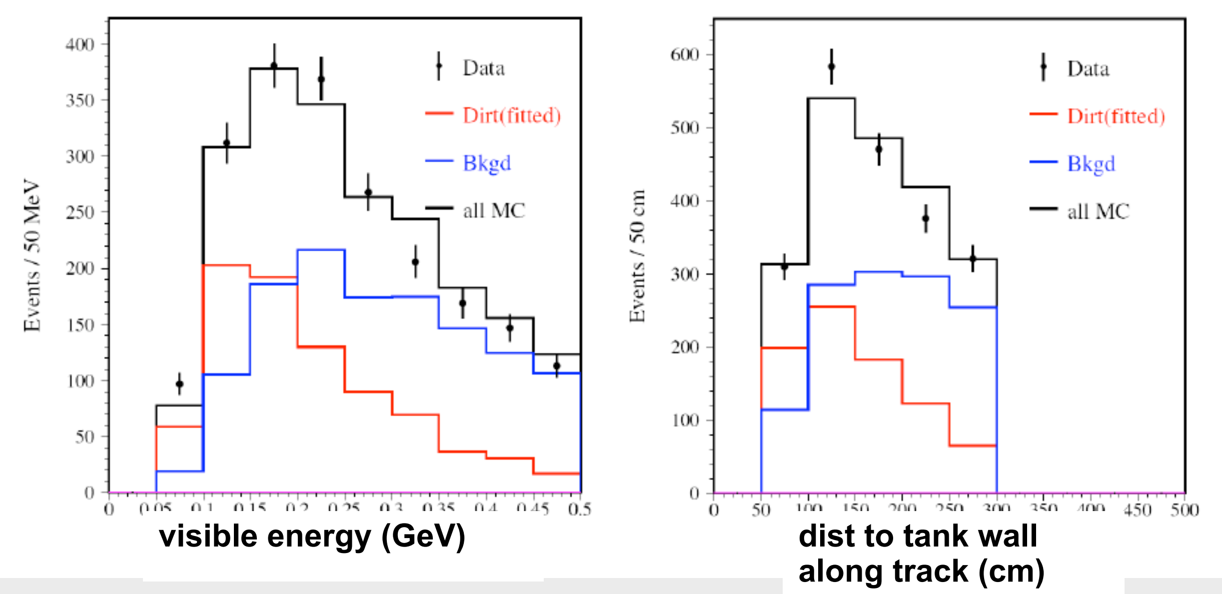
=> Events distributed throughout tank, no indication of edge effects.

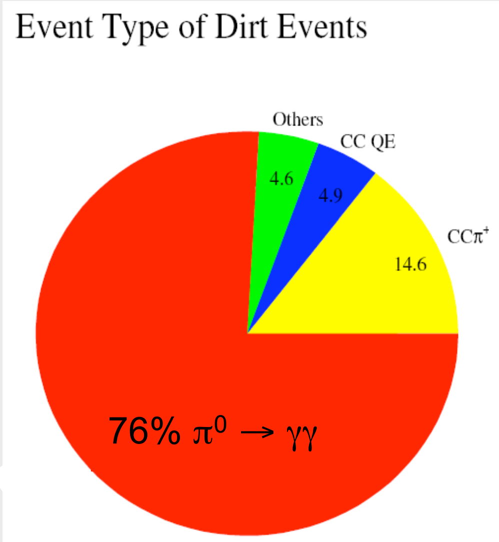
“Dirt” background



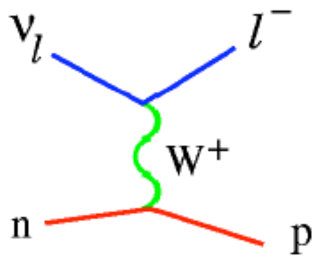
- Dirt background is due to ν interactions outside detector creating neutrals that enter tank
- **Measured** in “dirt-enhanced” samples:
  - before box-opening, fit predicted: 1.00±0.15
  - in different (open) sample, a fit says that meas/pred is 1.08±0.12.
- Shape of visible E and distance-to-wall distributions are well-described by MC

results from dirt-enhanced fits

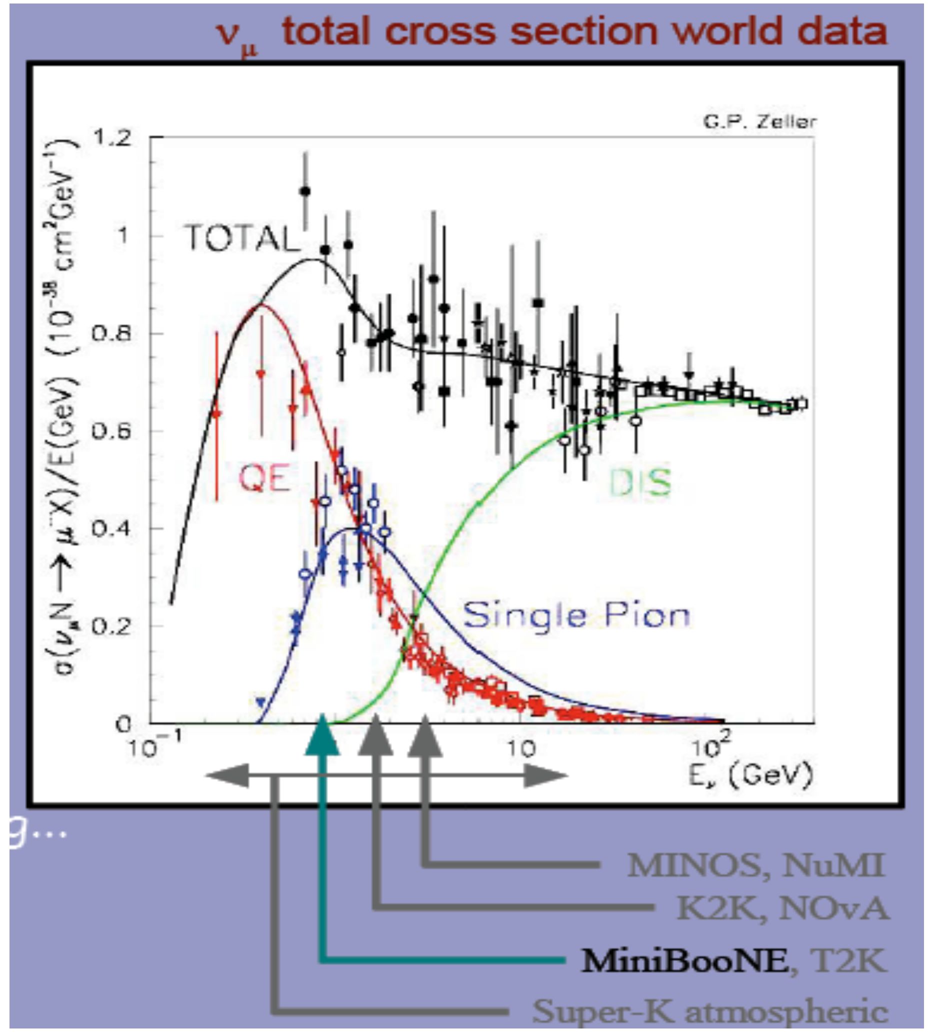




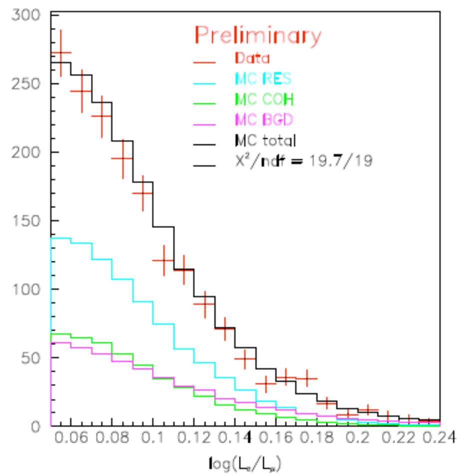
CCQE Cross Section

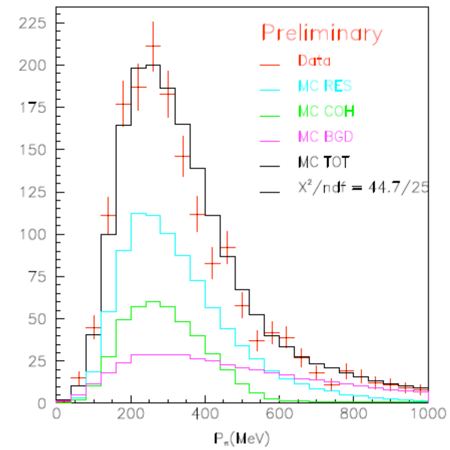


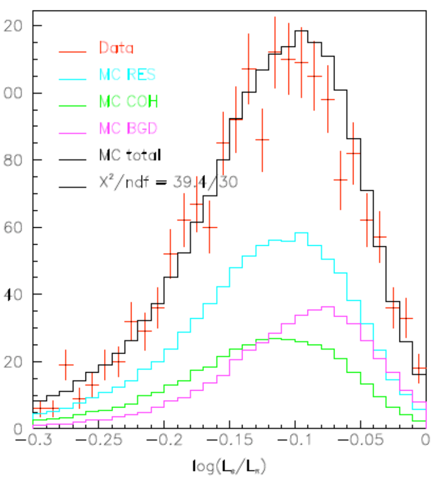
- CCQE reaction is used to search for oscillations
- Cross section industry is booming
  - Data is pouring in from expts
  - Monte Carlo Generators
    - NUANCE, NEUGEN, NEUT, NUX ...
  - Low energy σ_ν soon to be included in Durham database



Anti-neutrinos







Upper left : $\log(L_e/L_\mu)$

Lower left : $\log(L_e/L_\pi)$

Upper right : π^0 momentum

$\overline{\nu_\mu} = 61.8\%,\ \nu_\mu = 35.7\%,\ \overline{\nu_e} + \nu_e = 2.45\%$