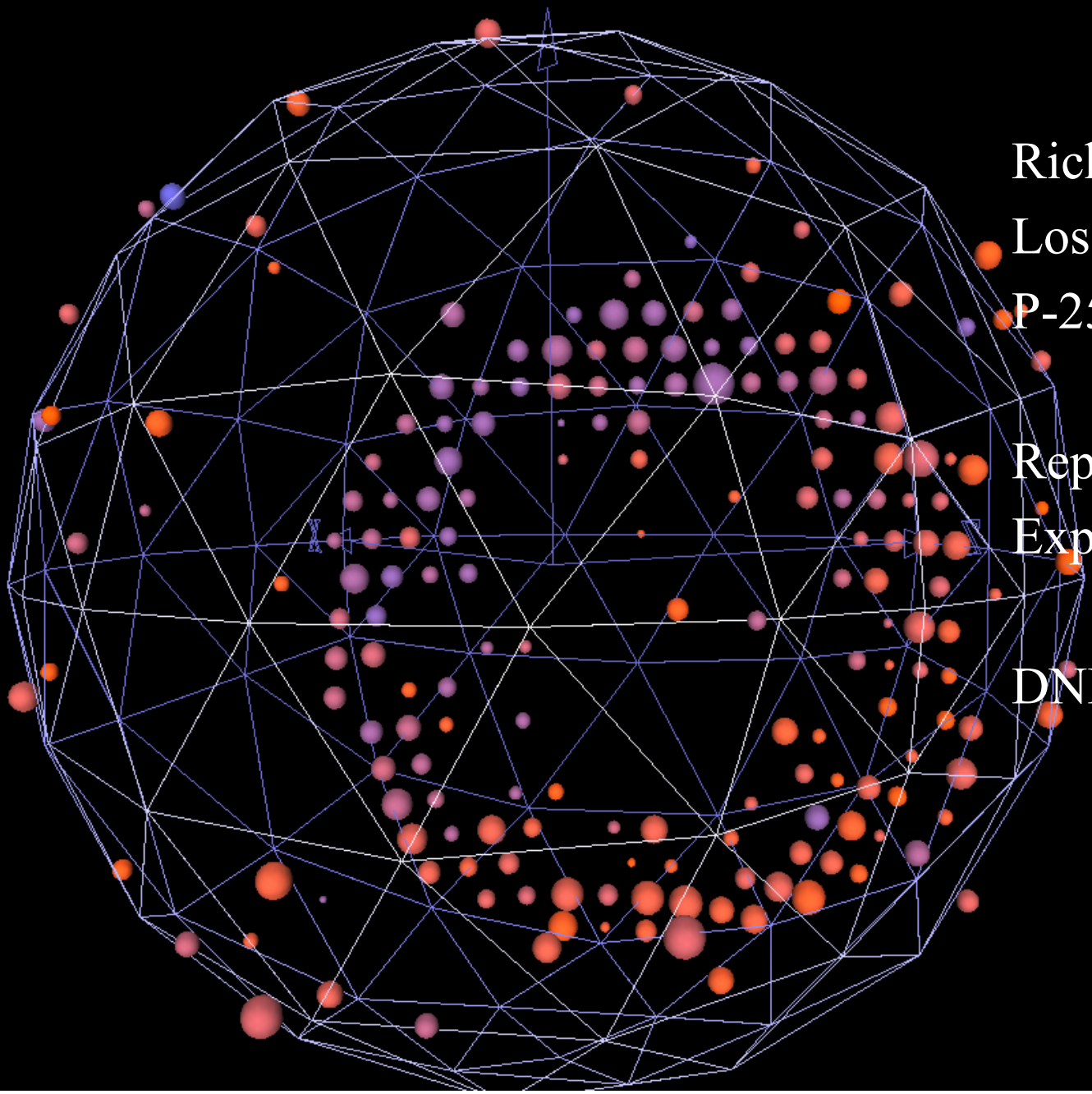
Updated Oscillation Results from MiniBooNE



Richard Van de Water
Los Alamos National Laboratory
P-25 Subatomic Physics Group

Representing the MiniBooNE Experiment

DNP 2008, Oakland, CA

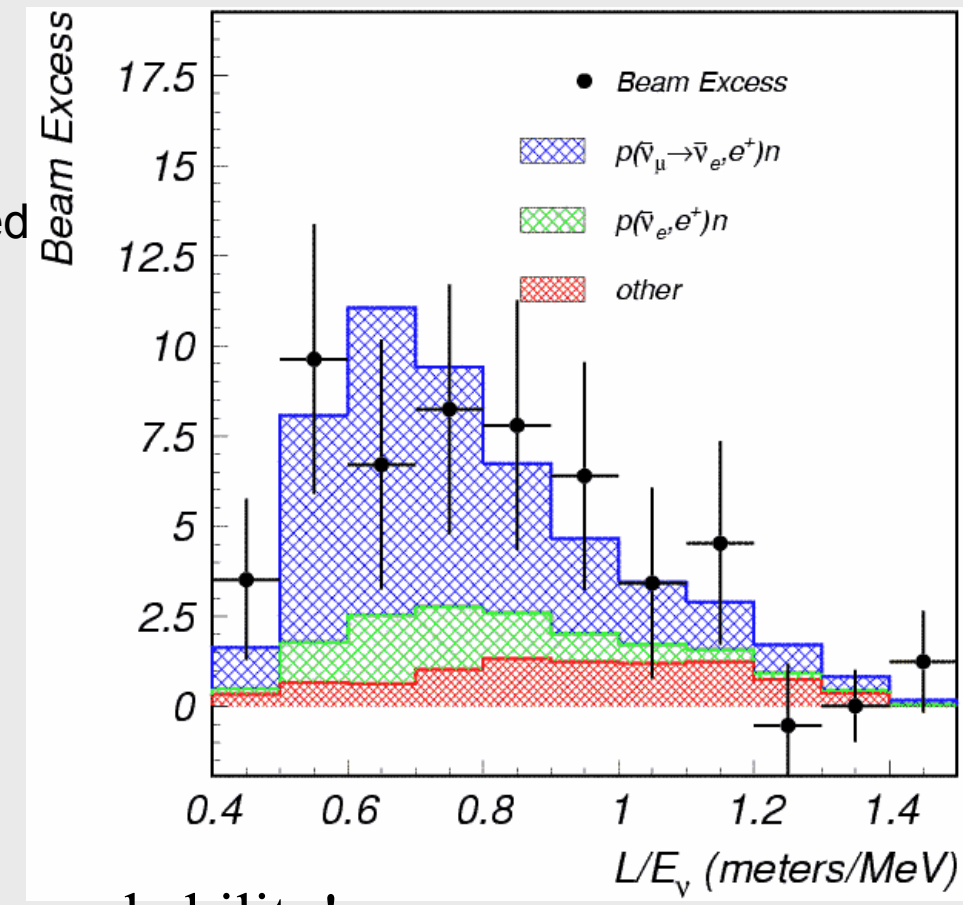
Outline

1. The LSND oscillation signal.
2. The MiniBooNE experiment: Testing LSND.
3. Original oscillation results.
4. New results on low energy anomaly.

Evidence for Oscillations from LSND

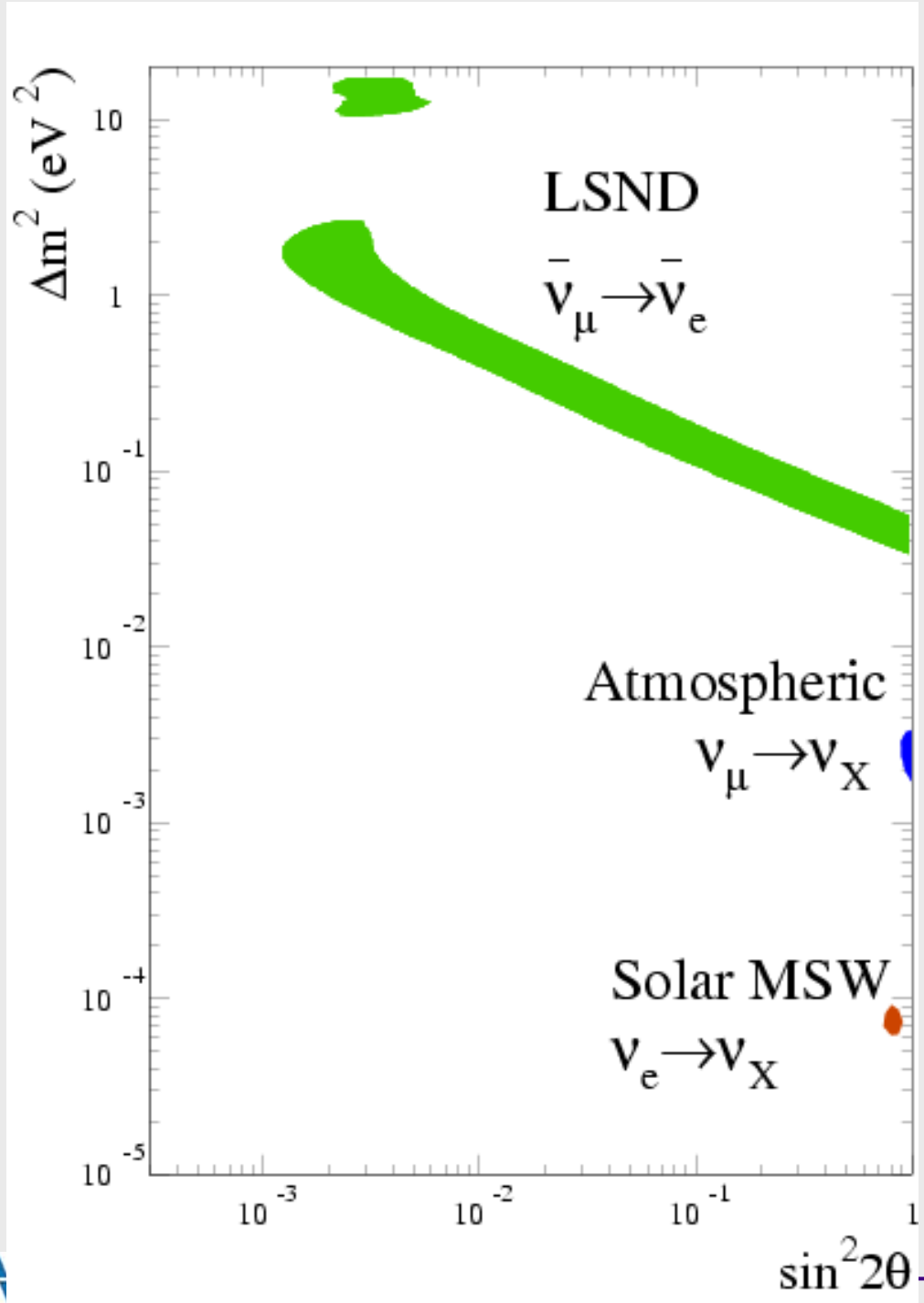
- LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a two neutrino mixing hypothesis:

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$



Extremely small oscillation probability!

Current State of Neutrino Oscillation Evidence



3-ν oscillations require
$\Delta m_{12}^2 + \Delta m_{23}^2 = \Delta m_{13}^2$
and cannot explain the data!

Expt.	Type	Δm^2 (eV^2)	$\sin^2 2\theta$
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	~1	~3×10^{-3}
Atm.	$\nu_\mu \rightarrow \nu_x$	~2×10^{-3}	~1
Solar	$\nu_e \rightarrow \nu_x$	~8×10^{-5}	~0.8

Los Alamos

MiniBooNE: A Test of the LSND Evidence for Oscillations: Search for $\nu_\mu \rightarrow \nu_e$

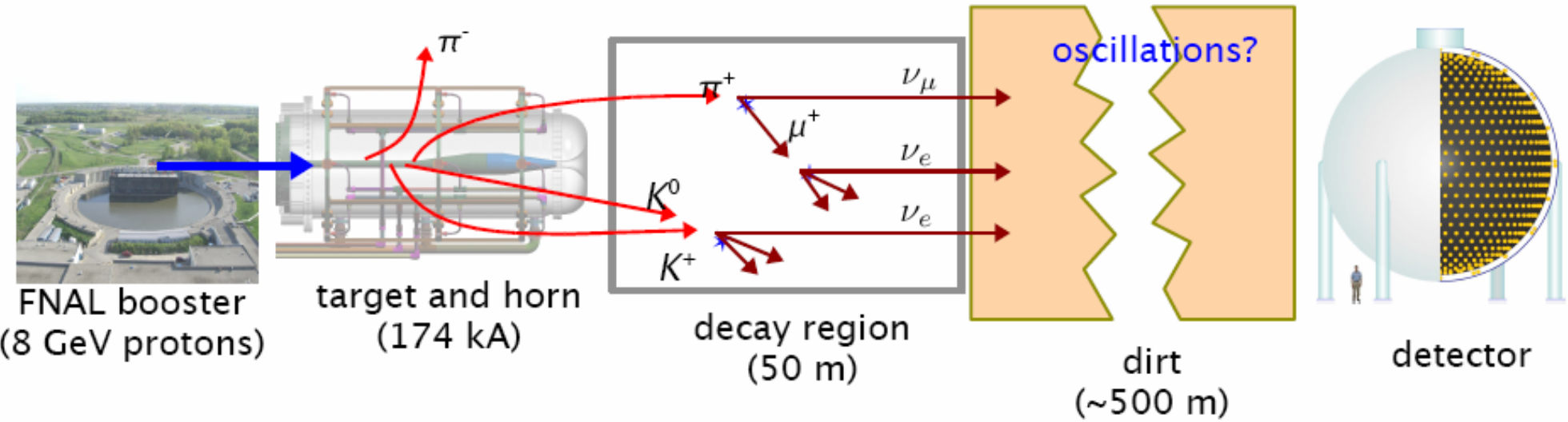
Completely different systematic errors than LSND

Much higher energy than LSND

Blind Analysis

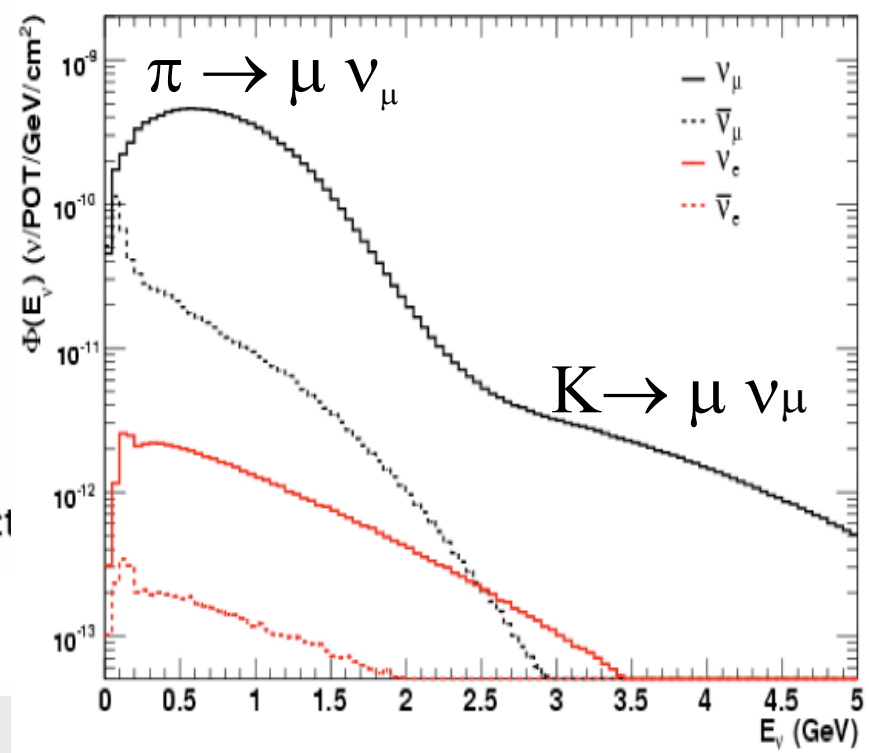
Alabama, Bucknell, Cincinnati, Colorado, Columbia, Embry-Riddle, Fermilab, Florida, Indiana, Los Alamos, LSU, Michigan, Princeton, St. Mary's, Virginia Tech, Yale

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)
- Detect ν interations in 800T pure mineral oil detect

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

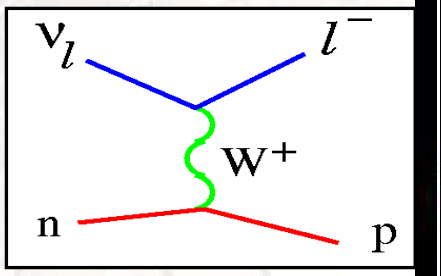


Data collected: 6.5E20 POT in neutrino and 3.4E20 POT in antineutrino mode

MiniBooNE is a Cerenkov Light Detector:

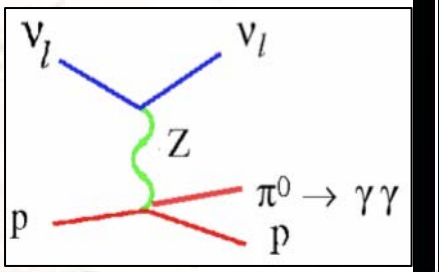
The main types of particles our neutrino events produce:

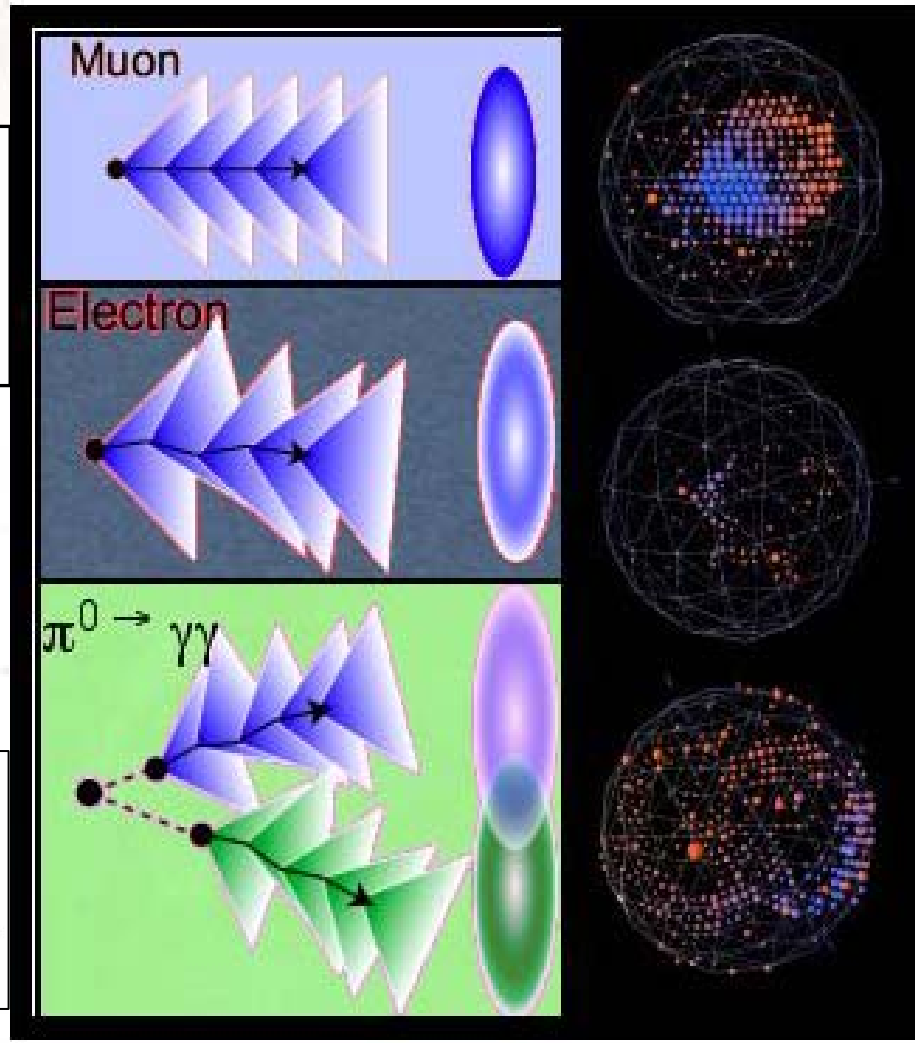
Muons (or charged pions):
Produced in most CC events.
Usually 2 or more subevents or exiting through veto.



Electrons (or single photon):
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

π^0s:
Can form a background if one photon is weak or exits tank.
In NC case, 1 subevent.





ν_e Event Rate Predictions

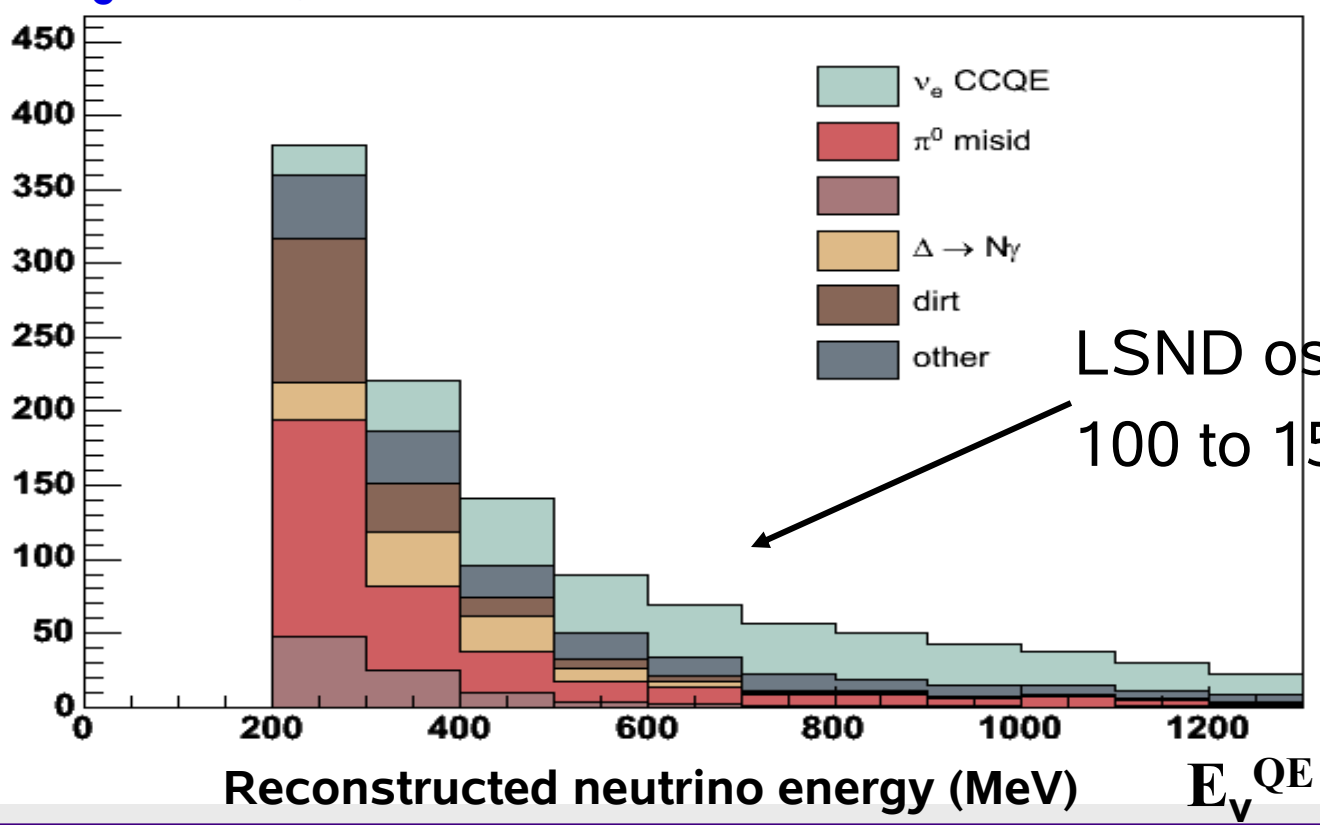
#Events = Flux x Cross-sections x Detector response

External measurements (HARP, etc)
ν_μ rate constrained by neutrino data

External and MiniBooNE measurements
-see talks by Chris Polly, Jaroslaw Nowak, Steven Linden

Detailed detector simulation checked with neutrino data and calibration sources.

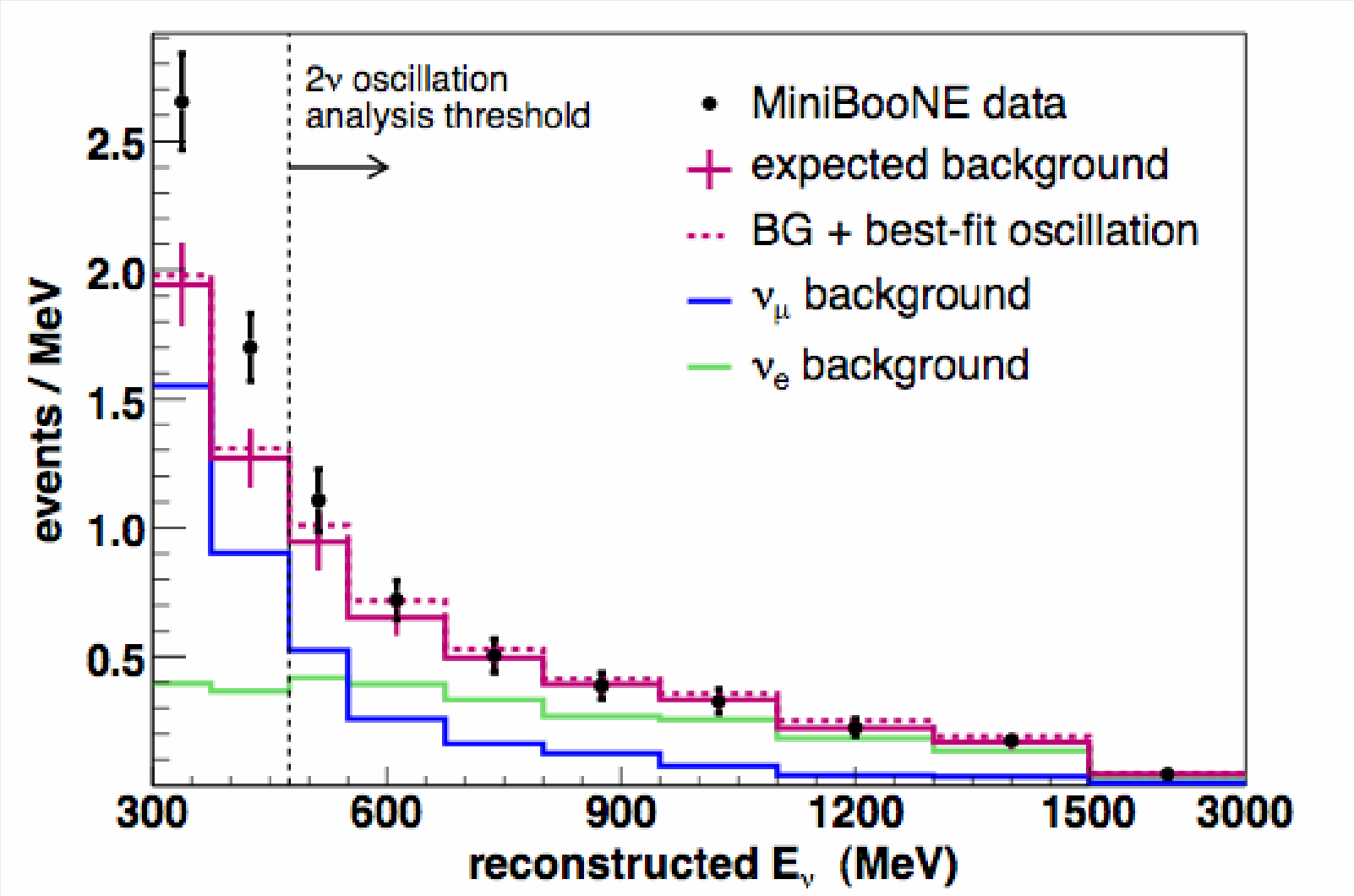
ν_e Backgrounds after PID cuts (Monte Carlo)



LSND oscillations adds 100 to 150 ν_e events

First $\nu_\mu \rightarrow \nu_e$ Oscillation Result from One year ago.

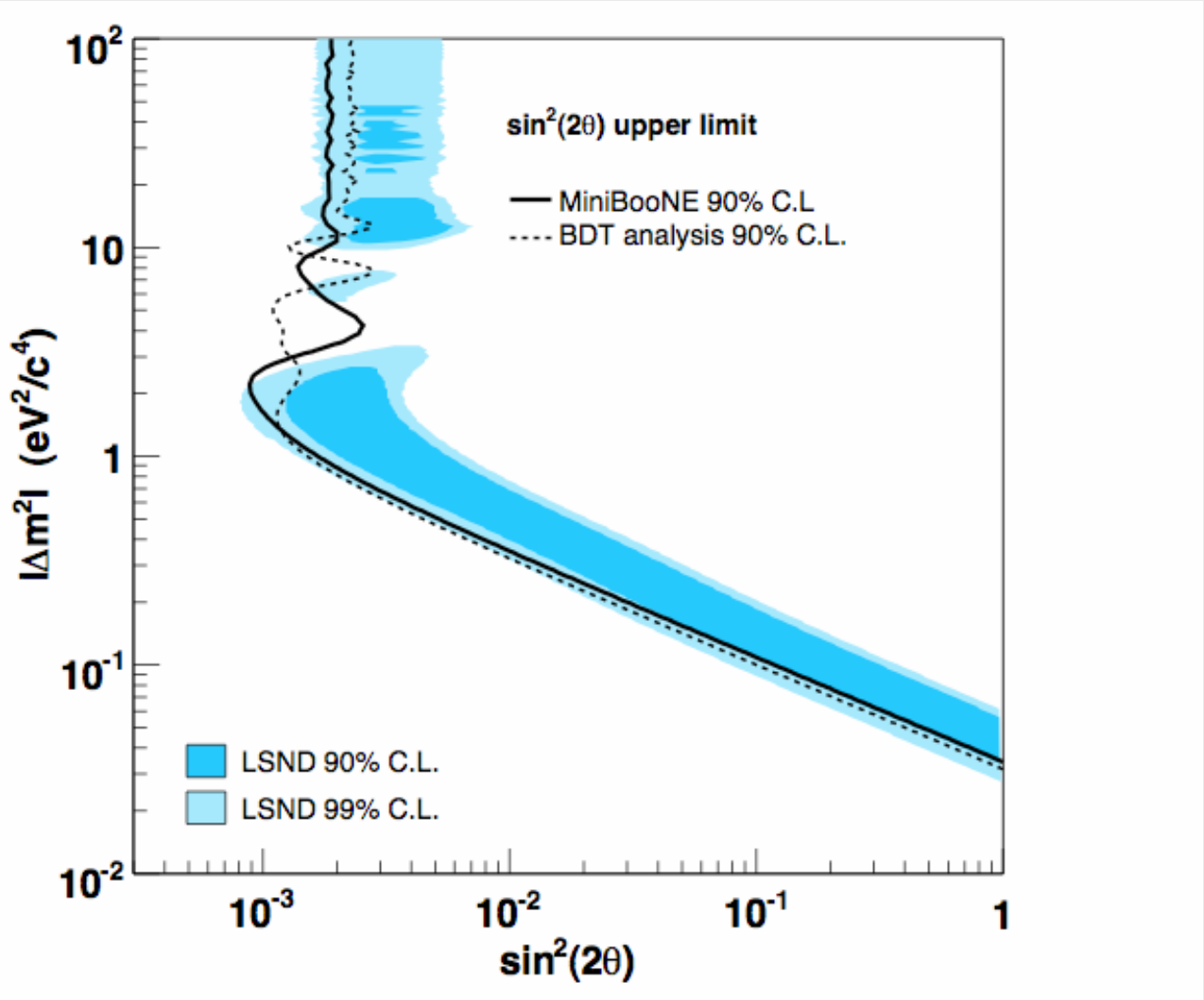
The Track-based $\nu_\mu \rightarrow \nu_e$ Appearance-only Result:



$475 < E_\nu^{QE} < 1250$ MeV : data: 380 events, MC: 358 ±19 ±35 events, 0.55 σ

The result of the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis is a <u>limit</u> on oscillations:

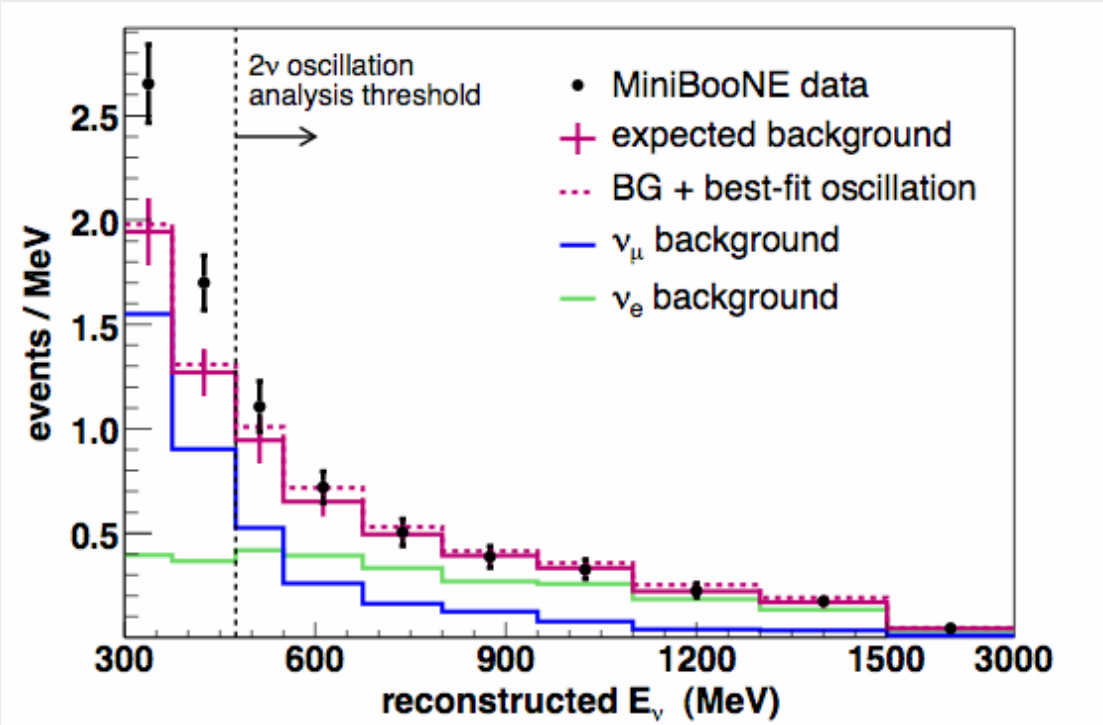
Phys. Rev. Lett. 98, 231801 (2007)



Simple 2-neutrino oscillations excluded at 98% C.L.

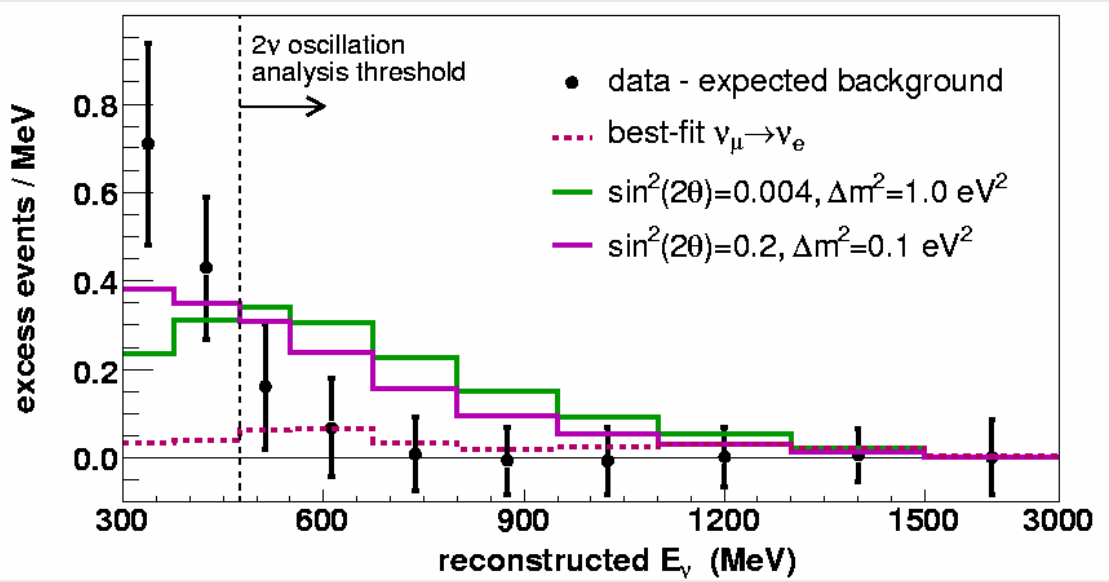
Energy fit: $475 < E_\nu^{QE} < 3000$ MeV

But an Excess of Events Observed Below 475 MeV



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

Deviation: 3.7 σ



Excess Distribution inconsistent with a 2-neutrino oscillation model

Going Beyond the First Result

Investigations of the Low Energy Excess

- Possible detector anomalies or reconstruction problems
- Incorrect estimation of the background
- New sources of background
- New physics including exotic oscillation scenarios, neutrino decay, Lorentz violation, …….

Any of these backgrounds or signals could have an important impact on other future oscillation experiments.

Investigation of the Low Energy Anomaly

Improvements in the Analysis

- Check many low level quantities (PID stability, etc)
- Rechecked various background cross-section and rates (π^0, $\Delta \rightarrow N\gamma$, etc.)
- Improved π^0 (coherent) production incorporated.
- Better handling of the radiative decay of the Δ resonance
- Photo-nuclear interactions included.
- Developed cut to efficiently reject "dirt" events.
- Analysis threshold lowered to 200 MeV, with reliable errors.
- Systematic errors rechecked, and some improvements made (i.e. flux, $\Delta \rightarrow N\gamma$, etc).
- Additional data set included in new results:

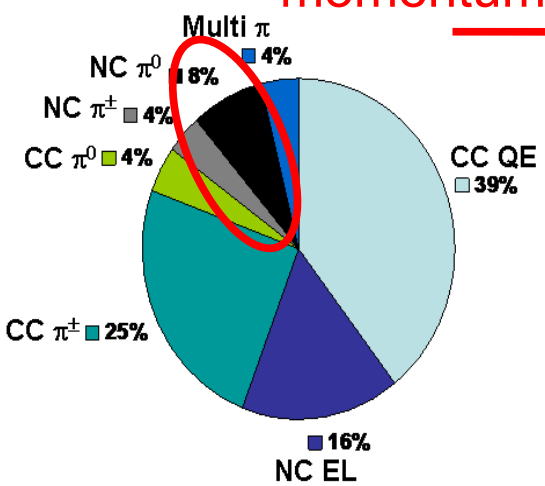
  Old analysis: 5.58×10^{20} protons on target.

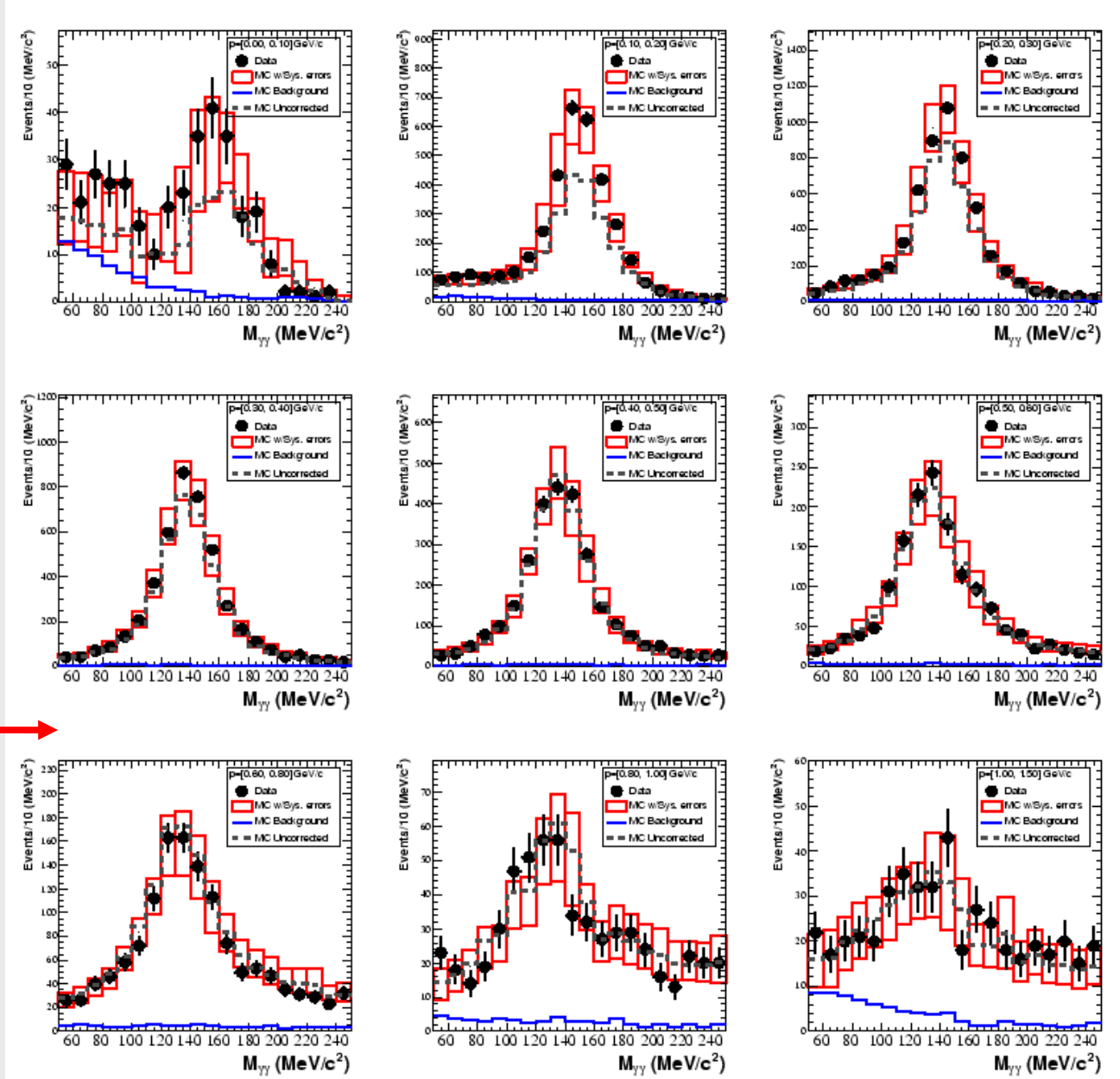
  New analysis: 6.46×10^{20} protons on target.

Tuning the MC on internal NC π^0 data

- NC π^0 important background
- 90%+ pure π^0 sample
- Measure rate as function of momentum
- Default MC underpredicts rate at low momentum
- $\Delta \rightarrow N\gamma$ also constrained

Invariant mass distributions in momentum bins

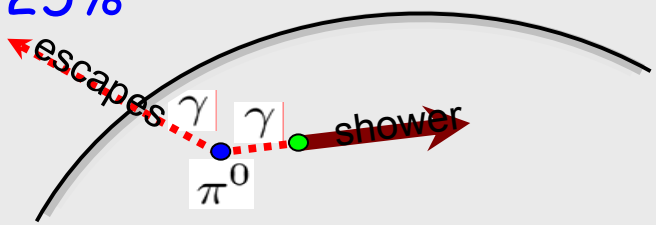




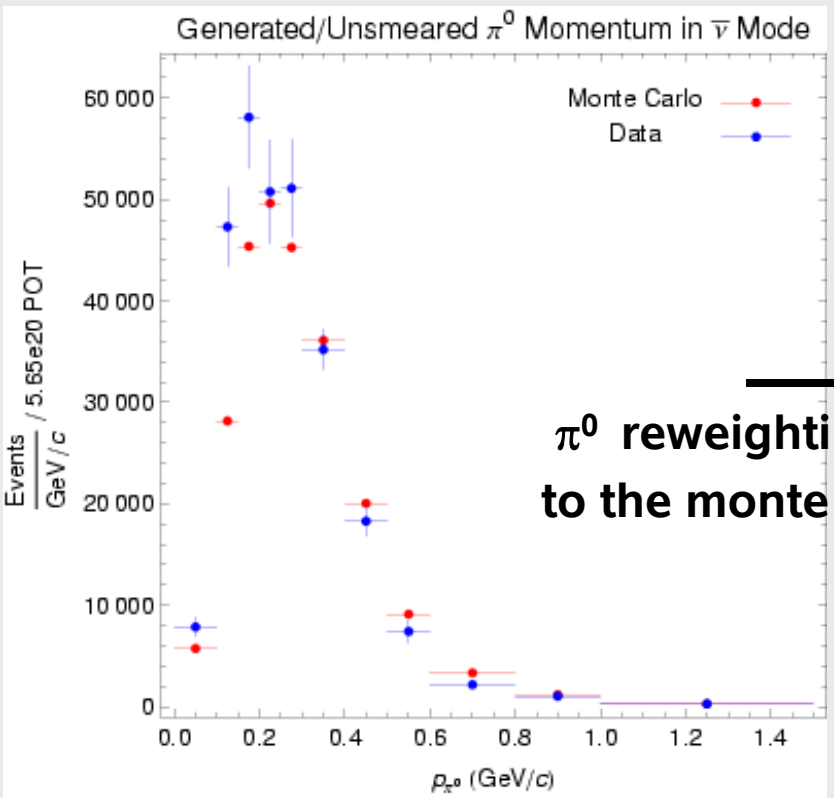
Measuring π^0 and constraining misIDs from π^0

π^0 rate measured to a few percent.
Critical input to oscillation analysis:
without constraint π^0 errors would be ~ 25%

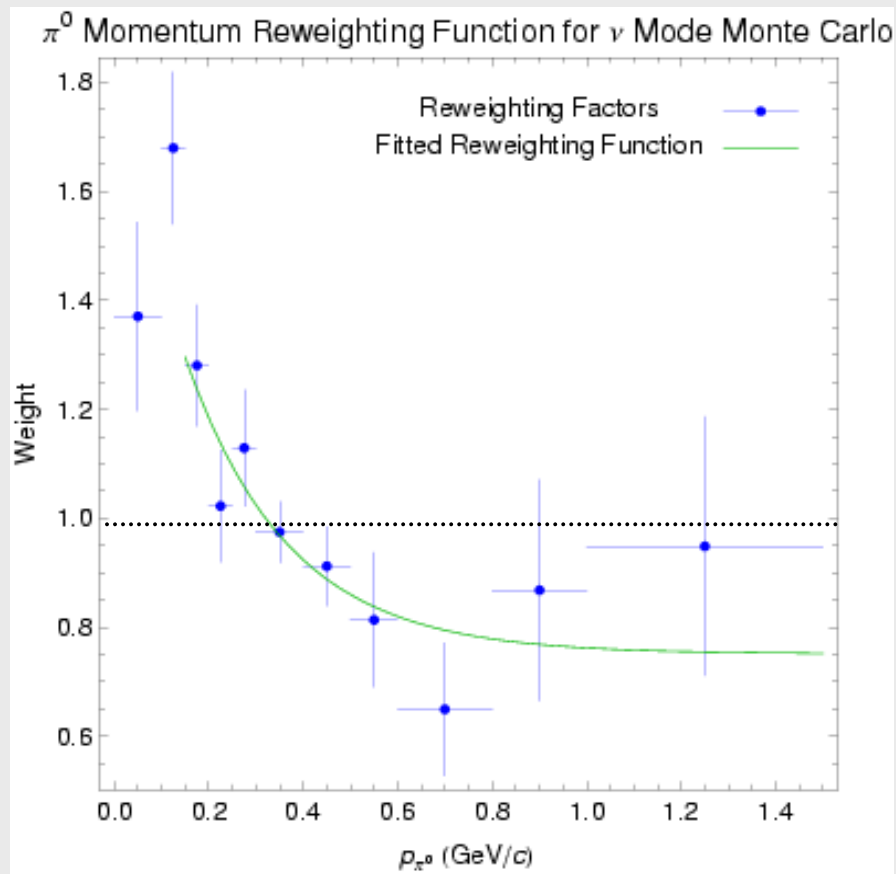
Phys.Lett.B664, 41(2008)



The π^0's constrains the Δ resonance rate, which determines the rate of $\Delta \rightarrow N\gamma$.



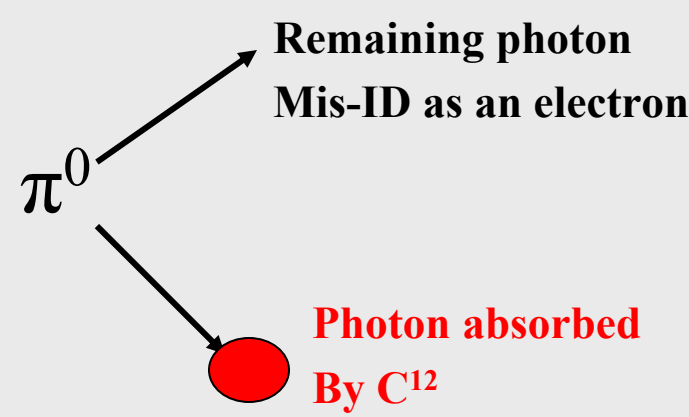
π^0 reweighting applied to the monte carlo



Pion analysis rechecked, only small changes made

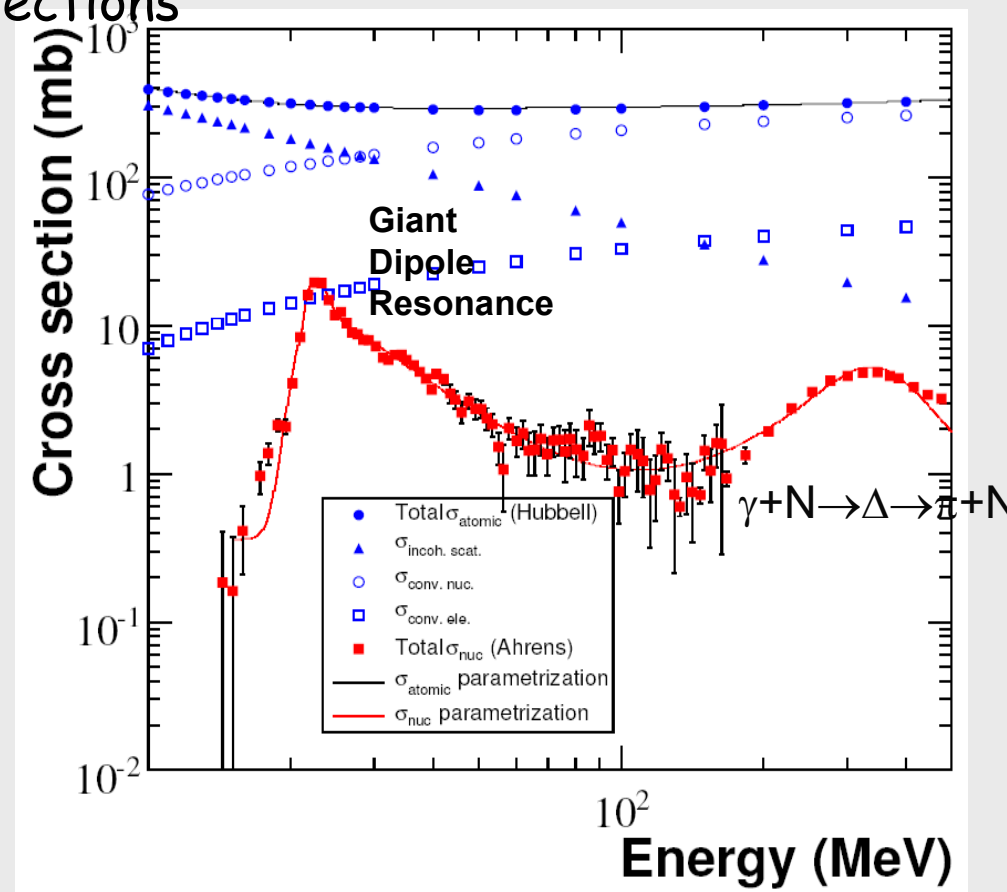
Photonuclear absorption of π^0 photon

Since MiniBooNE cannot tell an electron from a single gamma, any process that leads to a single gamma in the final state will be a background



Photonuclear processes can remove ("absorb") one of the gammas from NC $\pi^0 \rightarrow \gamma\gamma$ event

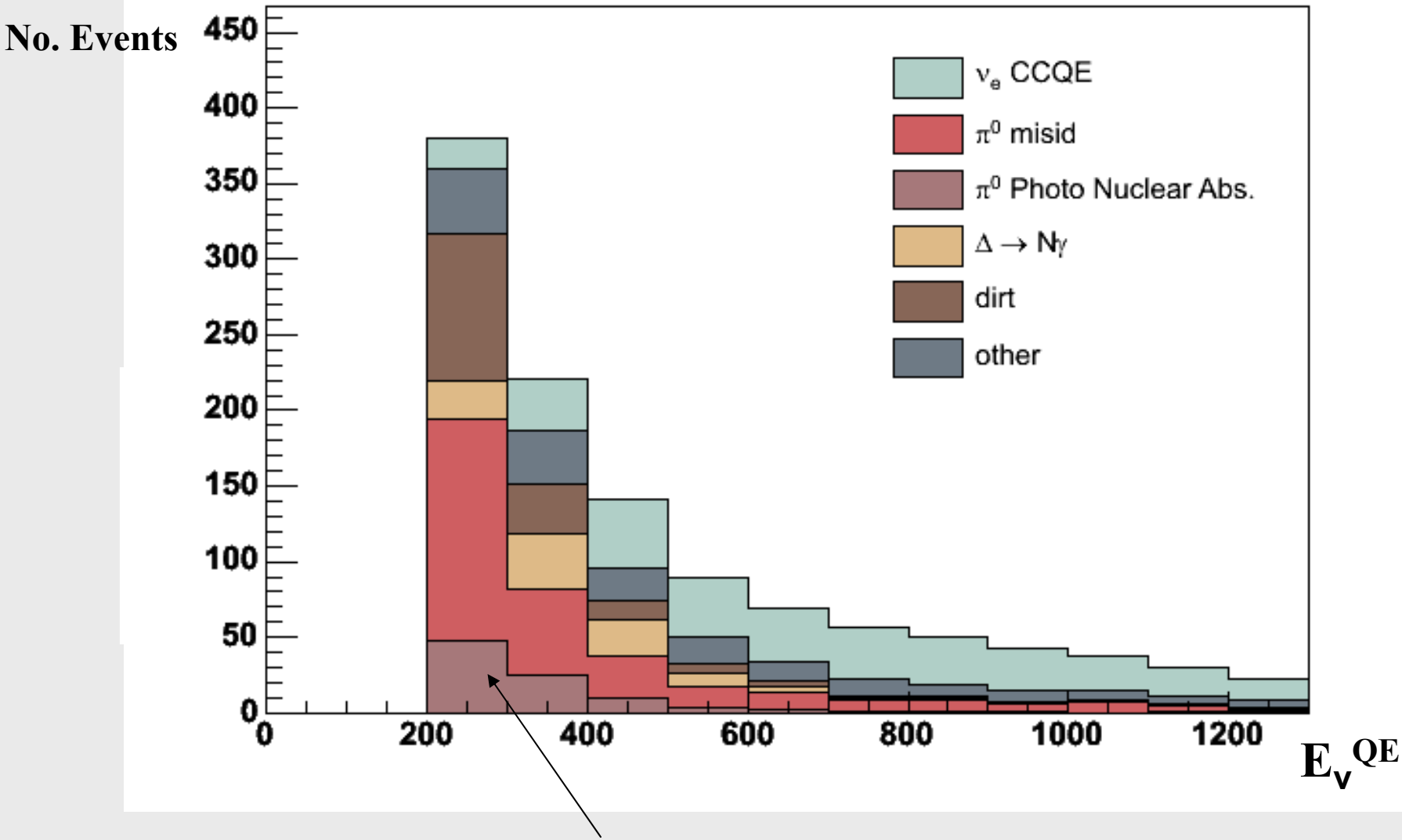
- Total photonuclear absorption cross sections on Carbon well measured.



Photonuclear absorption was missing from our GEANT3 detector Monte Carlo.

- Extra final state particles carefully modelled
- Reduces size of excess
- Systematic errors are small.
- No effect above 475 MeV

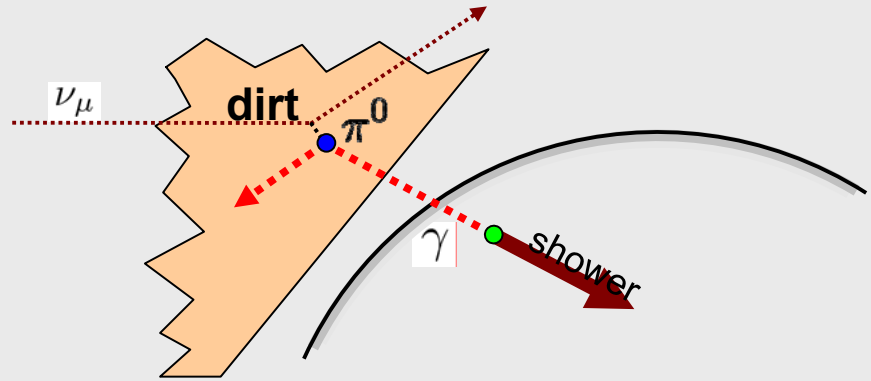
Estimated Effects of Photonuclear Absorption

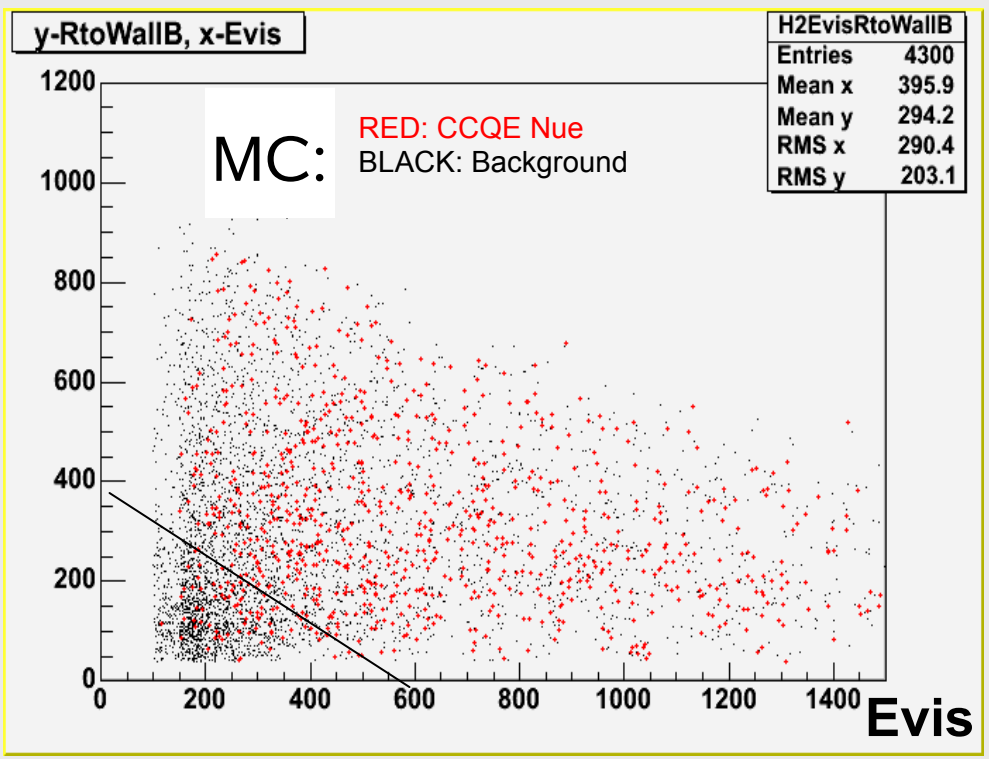


Photonuke adds ~25% to pion background in the 200 <E < 475 MeV region

Reducing Dirt Backgrounds with an Energy Dependent Geometrical Cut

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





Dirt events tend to be at large radius, heading inward

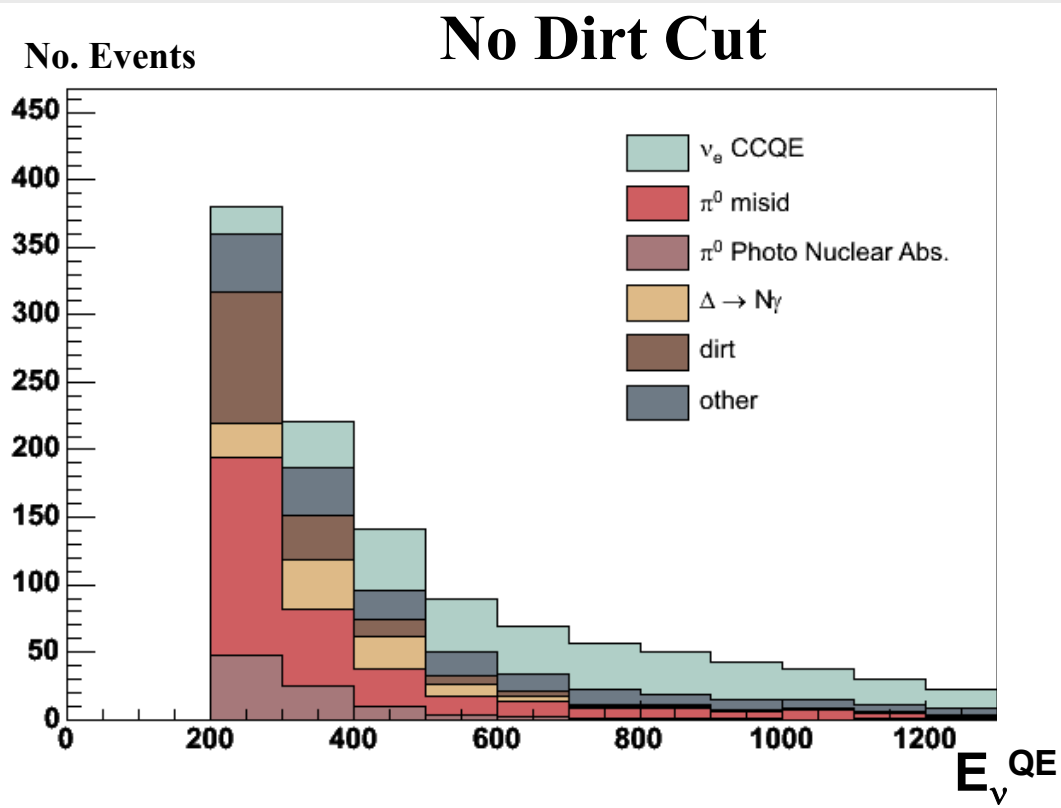
Add a new cut on distance to wall in the track backwards direction, optimized in bins of visible energy.

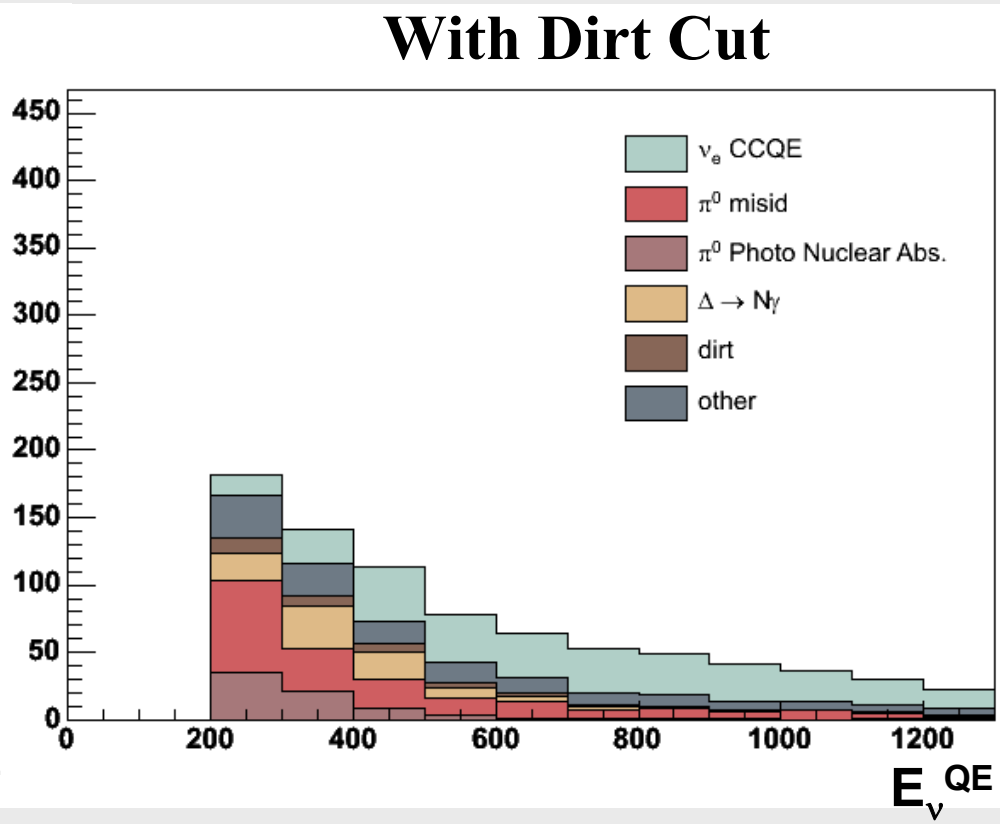
Has significant effect below 475 MeV

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

Has almost no effect above 475 MeV

Effects of the Dirt Cut





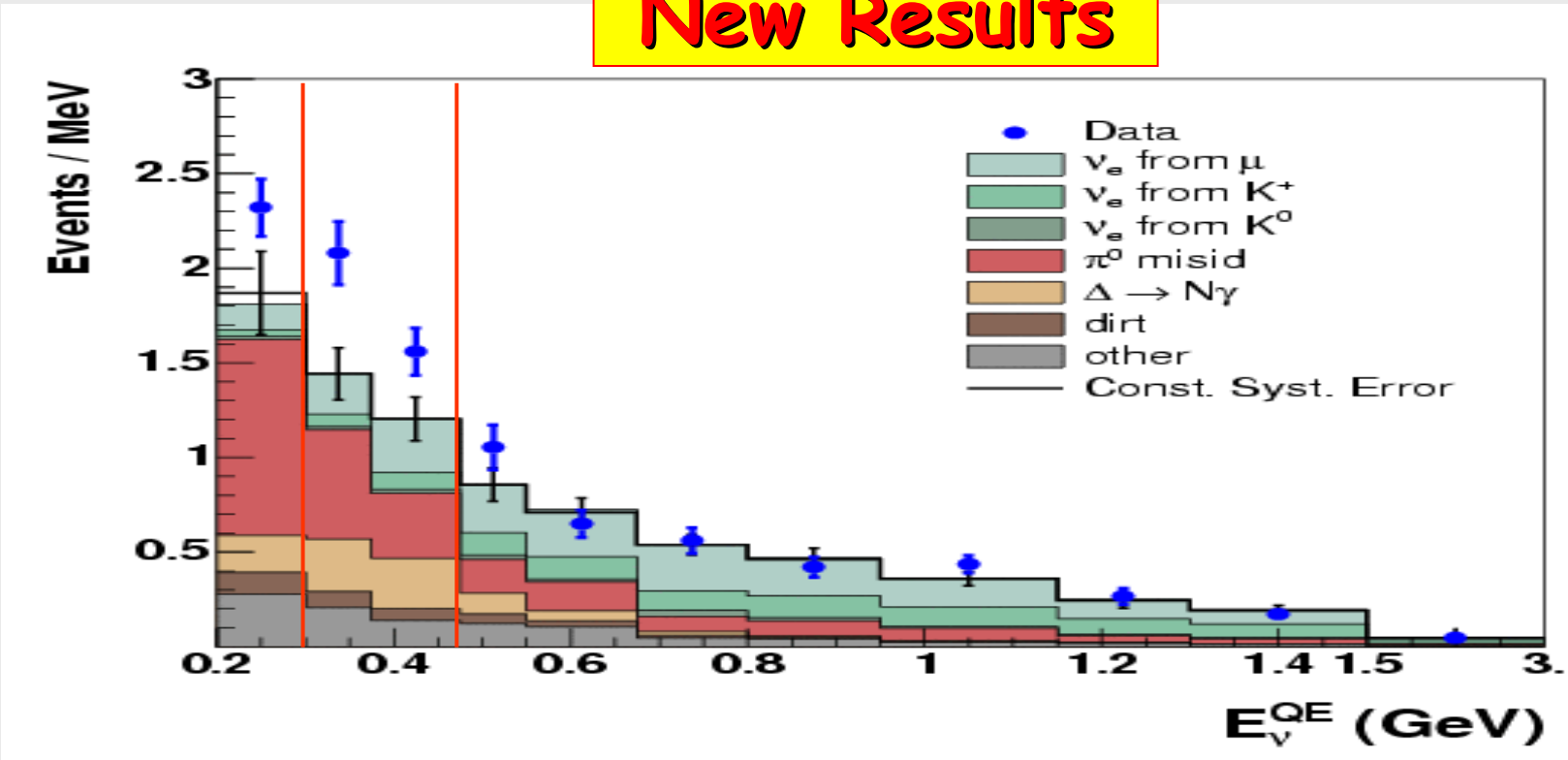
- The dirt cut:
  - significantly reduce dirt background by ~80%,
  - reduce pion background by ~40%
  - reduce electron/gamma-rays by ~20%.

Sources of Systematic Errors

Source of Uncertainty On ν_e background	Track Based error in % 200-475 MeV	475-1250 MeV	Checked or Constrained by MB data
Flux from π^+/μ^+ decay	1.8	2.2 **	√
Flux from K^+ decay	1.4	5.7	√
Flux from K^0 decay	0.5	1.5	√
Target and beam models	1.3	2.5	
ν-cross section	5.9	11.8	√
NC π^0 yield	1.4	1.8	√
External interactions ("Dirt")	0.8	0.4	√
Optical model	9.8	5.7	√
DAQ electronics model	5.0	1.7 **	
Hadronic	0.8	0.3 (new error)	
Total Unconstrained Error	13.0	15.1	

All Errors carefully rechecked; ** = significant decrease

New Results



MC background prediction includes statistical and systematic error

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

"other" mostly muon mid-ID's

The excess at low energy remains significant!

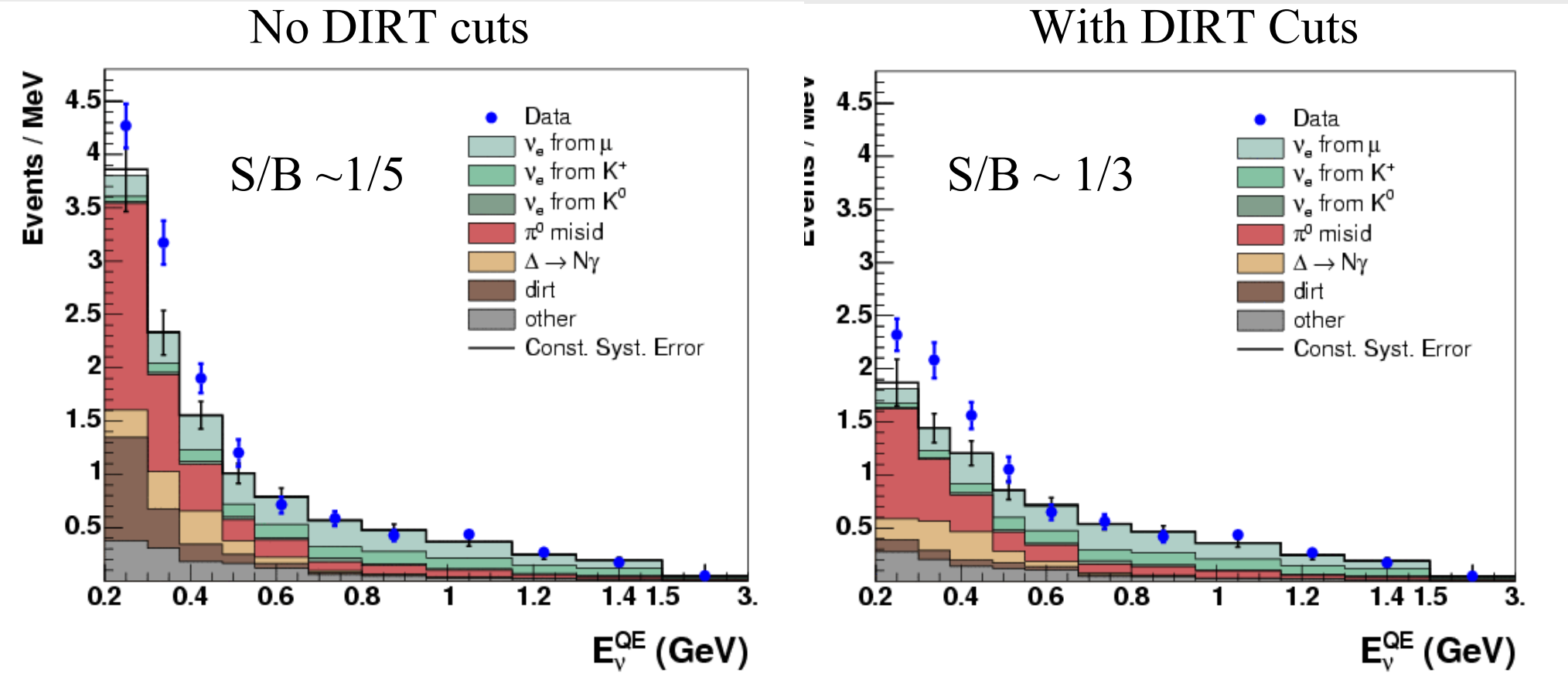
This result to be Published soon.

Excess Significance For Different Analysis

Event Sample	Original analysis 5.58E20 POT (Analysis 1)	Revised analysis 5.58E20 POT (Analysis 2)	Revised Analysis 6.46E20 POT (Analysis 3)	Revised Analysis 6.46E20 POT With DIRT cuts (Analysis 4)
200 – 300 MeV				
Data	375	368	427	232
Background	283 ± 37	332.4 ± 38.9	386.0 ± 44.3	186.8 ± 26.0
Excess	92 ± 37	35.6 ± 38.9	41.0 ± 44.3	45.2 ± 26.0
Significance	2.5σ	0.9σ	0.9σ	1.7σ
300 – 475 MeV				
Data	369	364	428	312
Background	273 ± 26	282.9 ± 28.3	330.0 ± 31.8	228.3 ± 24.5
Excess	96 ± 26	81.1 ± 28.3	98.0 ± 31.8	83.7 ± 24.5
Significance	3.7σ	2.9σ	3.1σ	3.4σ
200 – 475 MeV				
Data	744	732	855	544
Background	556 ± 54	615.3 ± 58.0	716.1 ± 66.2	415.2 ± 43.4
Excess	188 ± 54	116.7 ± 58.0	138.9 ± 66.2	128.8 ± 43.4
Significance	3.5σ	2.0σ	2.1σ	3.0σ
475 – 1250 MeV				
Data	380	369	431	408
Background	358 ± 40	356.0 ± 33.3	412.7 ± 37.6	385.9 ± 35.7
Excess	22 ± 40	13.0 ± 33.3	18.3 ± 37.6	22.1 ± 35.7
Significance	0.6σ	0.4σ	0.5σ	0.6σ

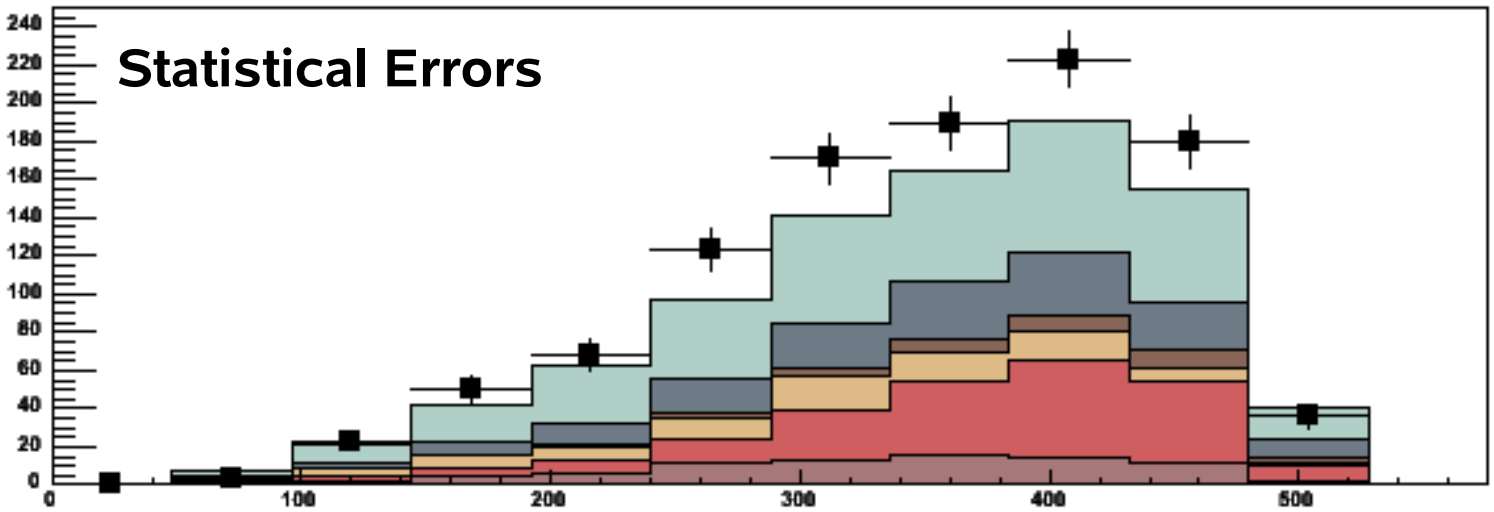
Properties of the Excess
Is it Signal like?

Dirt Cuts Improves Signal/Background

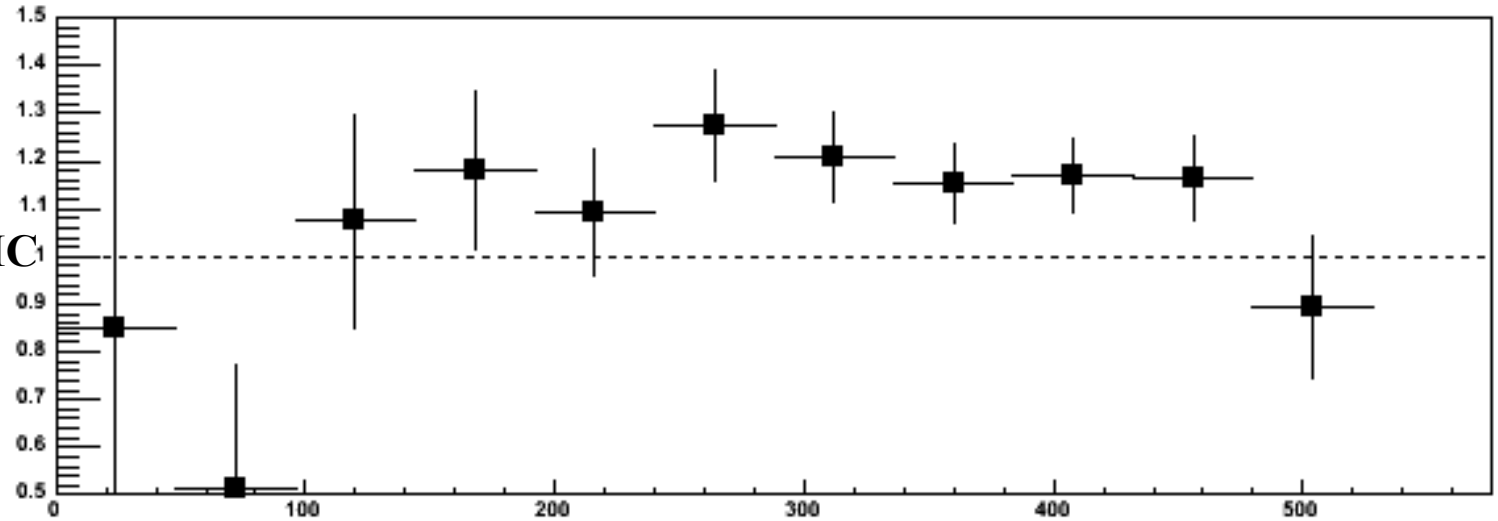


Excess decreases by ~7%, consistent with electron/gamma-ray signal

Reconstructed Radius



Radius (cm)



Ratio Data/MC

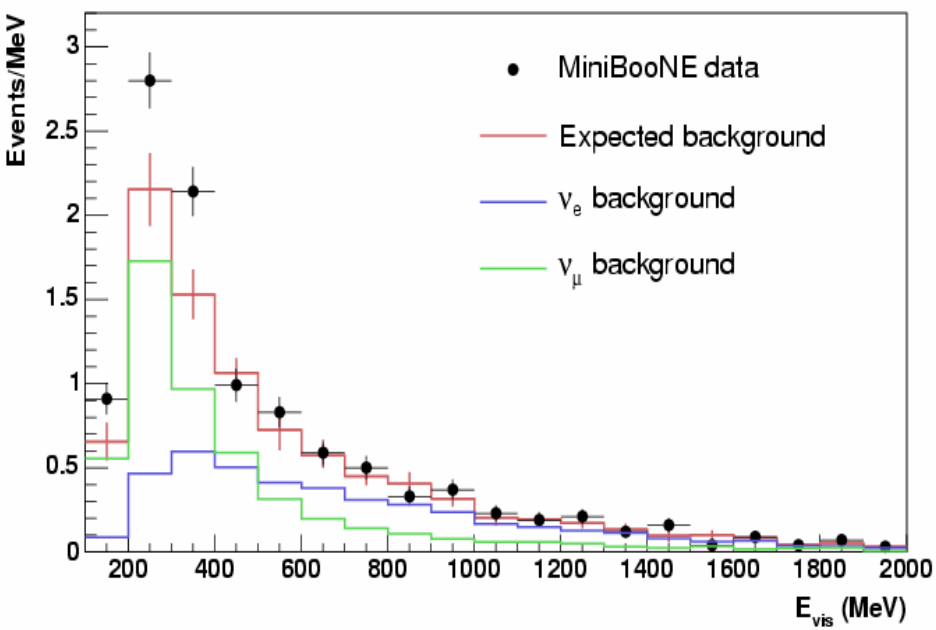
Radius (cm)

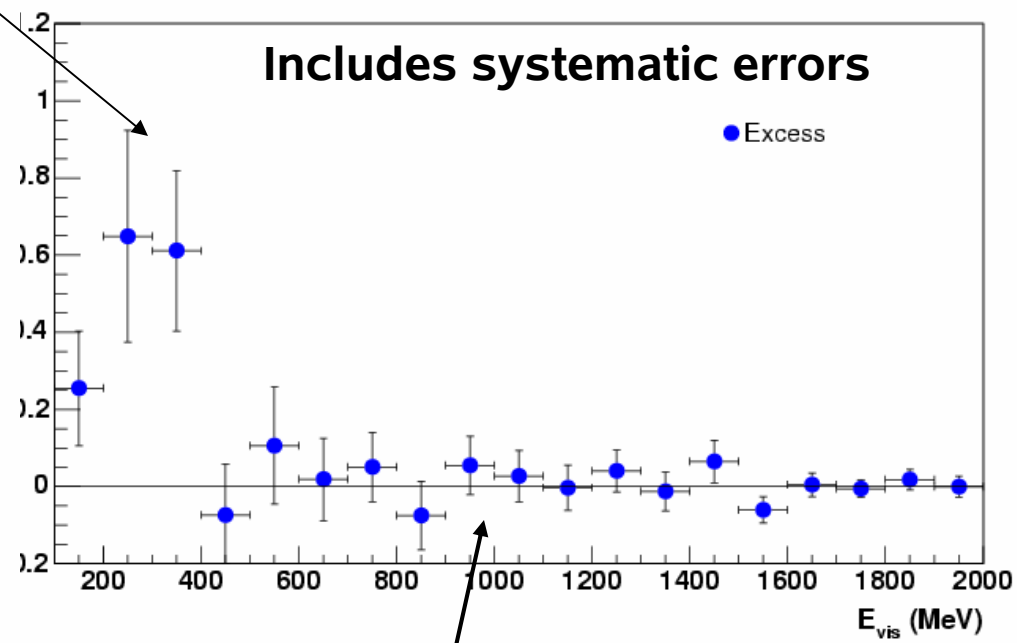
Excess is uniformly distributed throughout tank.

-consistent with neutrino induced interactions

Reconstructed Visible Energy (E_{vis})

Pronounced excess/peak
From 140 - 400 MeV





Excellent agreement
for Evis > 400 MeV

Also looking at other kinematic distributions, e.g. Q^2, $\cos\theta_{beam}$

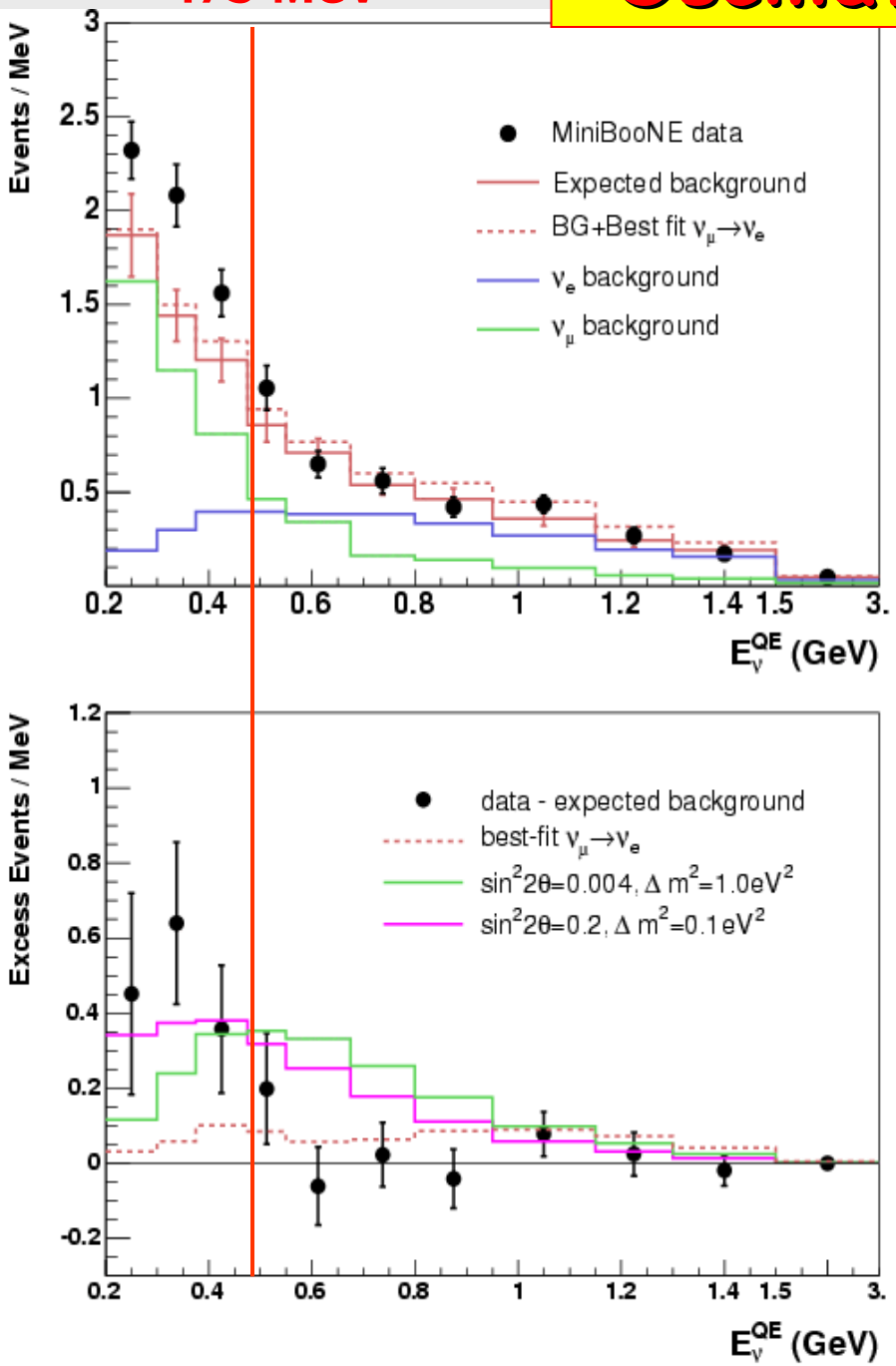
.

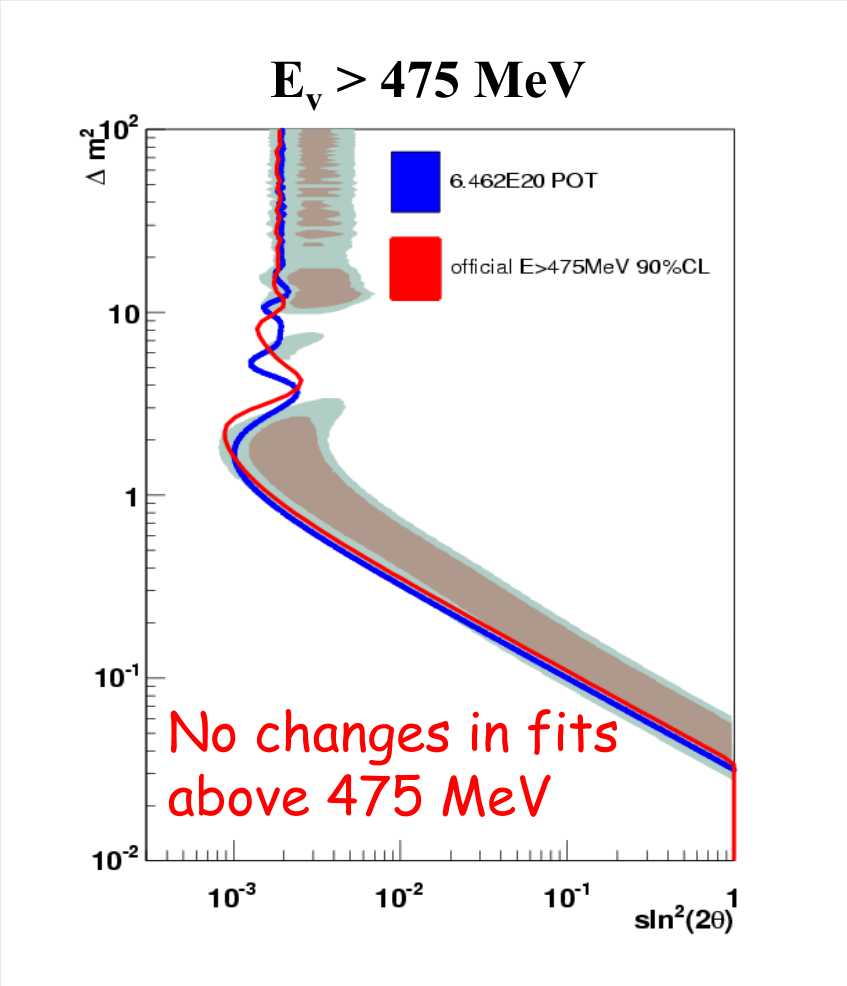
What is the Source of the Excess?

-consistent with neutrino induced electrons or gamma-rays.

Oscillation Fit Check

475 MeV





	E_ν>475 MeV	E_ν>200 MeV
Null fit χ^2 (prob.):	9.1(91%)	22(28%)
Best fit χ^2 (prob.):	7.2(93%)	18.3(37%)

Inclusion of low energy excess does not improve oscillation fits

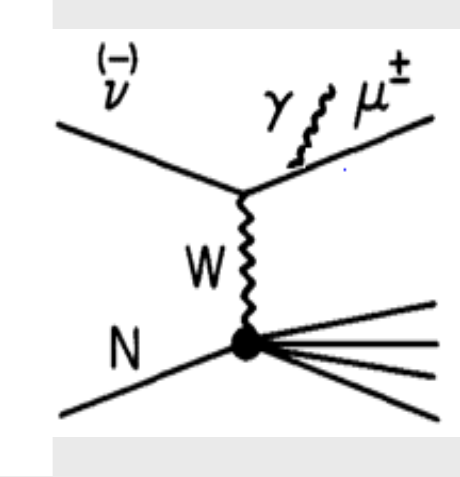
Is MiniBooNE Low Energy Excess consistent with LSND??

- LSND assumed excess was two neutrino oscillations,
  - Prob($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) = $\sin^2(2\theta)\ \sin^2(1.27\ \ \Delta m^2\ \ L/E)$
- L/E: Both LSND and MiniBooNE are at the same L/E and look for an excess of (anti)electron neutrinos in a (anti)muon neutrino beam
  - Yes, consistent! Though looking at different charge species.
- Rates: LSND measures Prob($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)= (0.25 +/- 0.08) %, MiniBooNE measures Prob($\nu_\mu \rightarrow \nu_e$)= (0.17 +/- 0.07)%
  - Yes, appearance rates consistent!
- Spectrum: MiniBooNE excess fails two neutrino oscillation fits to reconstructed neutrino energy.
  - No, energy fit not consistent!!

The low E excess has fueled much speculation...

Commonplace

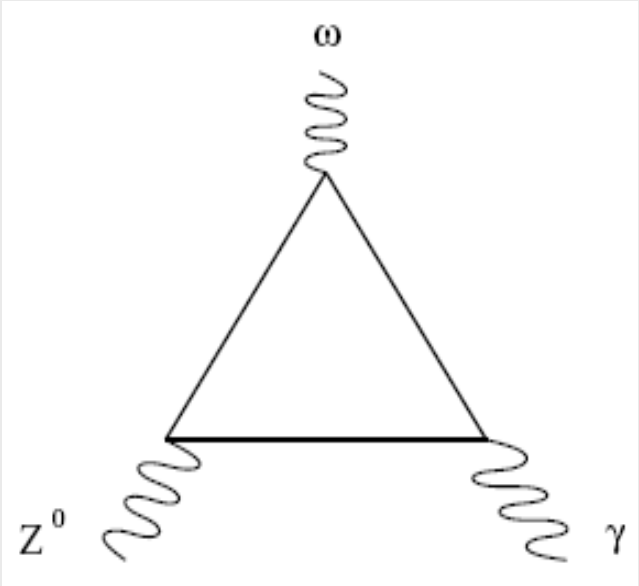
- Muon bremstrahlung (Bodek, 0709.4004)



- Easy to study in MB with much larger stats from events with a Michel tag
- Proved negligible in 0710.3897

SM, but odd

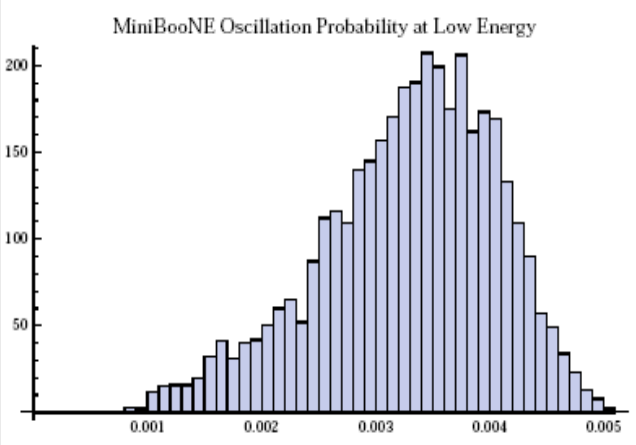
- Anomaly-mediated γ (Harvey, Hill, Hill, 0708.1281)



- Still under study, large rate uncertainties
- NC process; anti-neutrino data could determine if it is source of the excess

Beyond the SM

- New gauge boson (Nelson, Walsh,0711.1363)



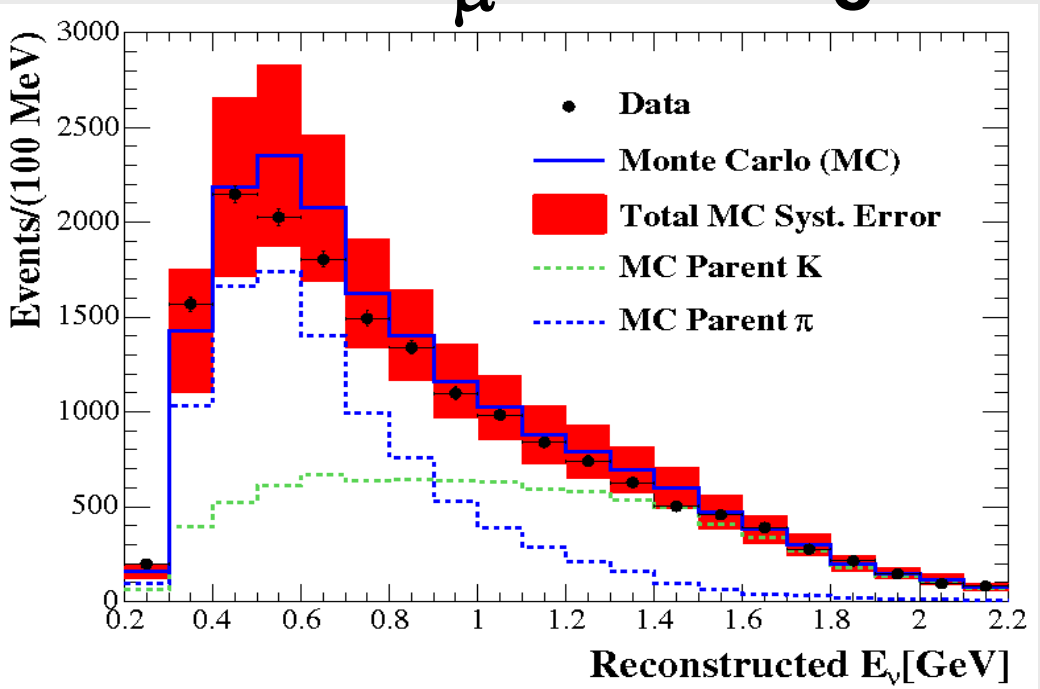
- Firm prediction for anti-neutrinos
- Many other beyond the Standard Model ideas.

Other Data Sources

- Limitations of MiniBooNE:
  - We do not have two detectors or complete set of source and background calibration sources.
- We do have different detectors and sources of neutrinos that provide more information on background estimates, signal cross sections, PID, etc
  - SciBooNE detector at 100m -- measure neutrino flux and cross sections.
  - Off axis neutrinos (NuMI) -- ν_e rich source, test cross sections and PID.
  - Anti-neutrino running – test backgrounds which are similar to neutrino mode, can also test Axial Anomaly.

NuMI ν_μ and ν_e Data

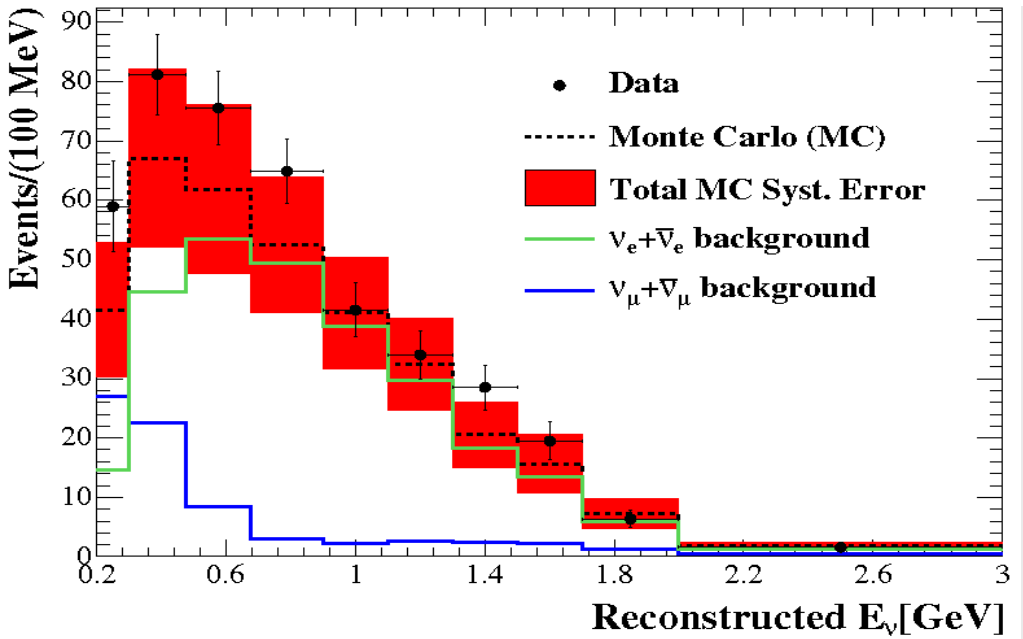
ν_μ CCQE sample



arXiv:0809.2447v1
See talk by Zelimir Djurcic

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

ν_e CCQE sample



Very different backgrounds compared to MB (Kaons vs Pions)

Ongoing effort to reduce ν_e CCQE sample systematics

NuMI ν_e data provide limits on cross sections and PID

MiniBooNE Anti-neutrino Run

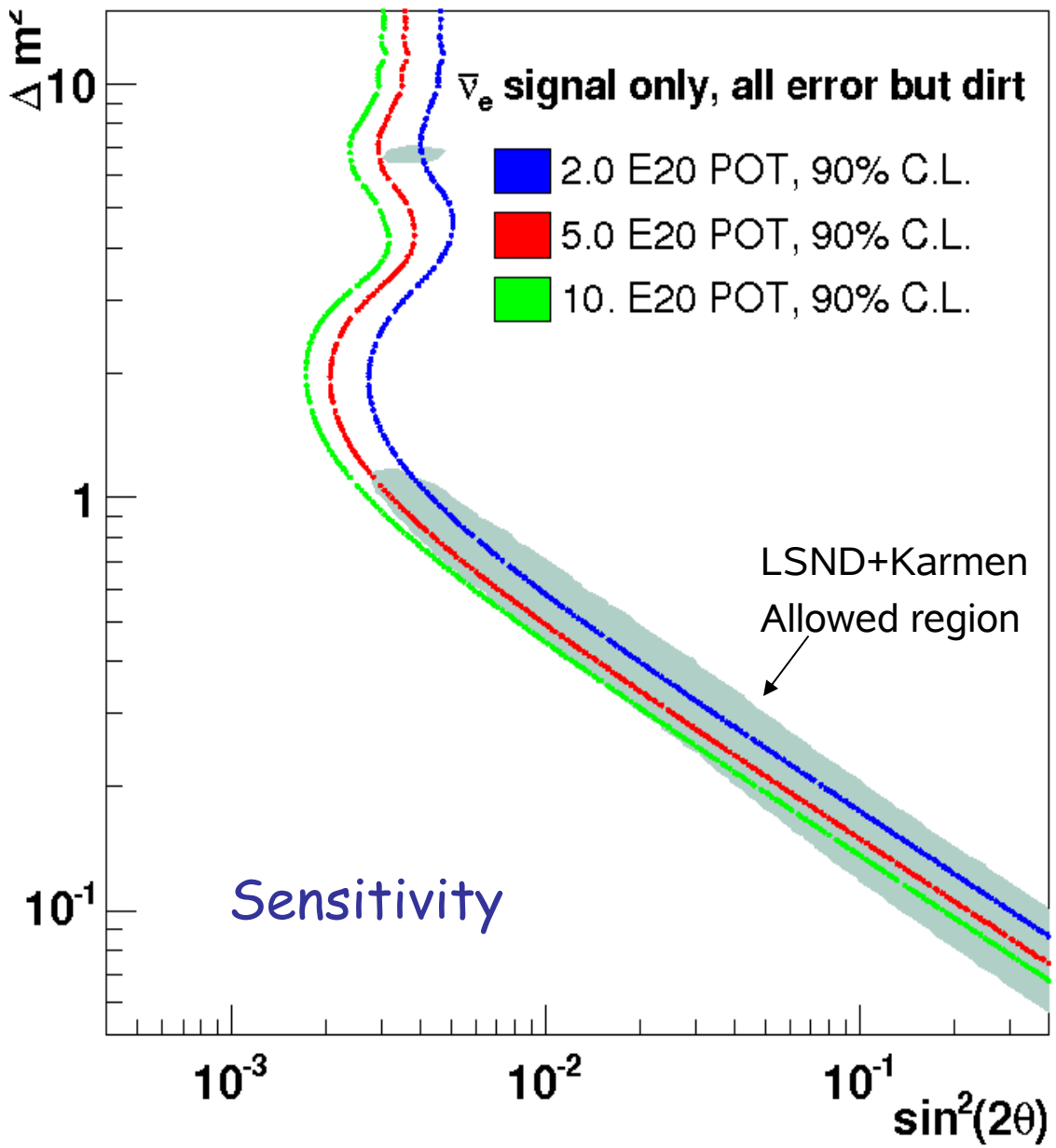
See talk by Zarko Pavlovic

In November 07 Physics Advisory Committee (Fermilab) recommended MiniBooNE run to get to a total of 5×10^{20} POT in anti neutrino mode.

Provides direct check of LSND result.

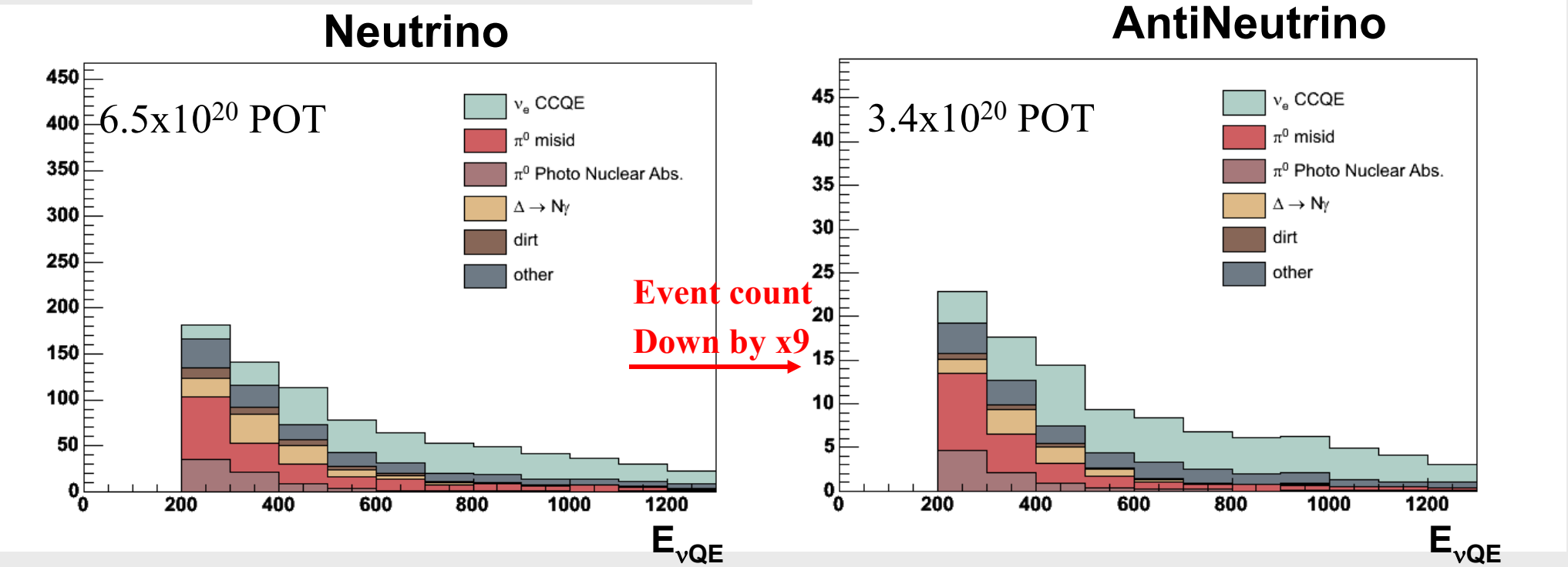
Provides additional data set for low energy excess study.

Collected ~3.4×10^{20} POT so far. Oscillation data set "blinded". Box opened Oct 22, 2008, results to be made public early December.



Comparing Neutrino/Antineutrino Low Energy ν_e Candidates

Background breakdown is very similar between neutrino and antineutrino mode running



- Various background/signal hypotheses for the excess can have measurably different effects in the two modes:
  - Backgrounds at low energy, expect an excess a few 10's of events.
  - Two neutrino oscillations produce ~13 events at higher energy.
- Can compare the two modes to test some of the hypotheses.

Conclusions

- MiniBooNE rules out a simple two neutrino $\nu_\mu \rightarrow \nu_e$ appearance-only model as an explanation of the LSND excess at 98% CL. (Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500v2 [hep-ex])
- However, a 128.8 +/- 43.4 event (3.0σ stat+sys, 6.4σ stat)) excess of electron or gamma-ray events are observed in the low energy range from $200 < E_\nu < 475$MeV (will be published soon).
  - This could be important to next generation long baseline neutrino experiments (T2K, Nova).
- This unexplained deviation is under intense investigation.
  - Event kinematics, NuMI analysis, muon neutrino disappearance (Oct 31), and antineutrino analysis (Dec 11) will provide more information, stay tuned!
- New Experiments might be required to fully understand the low energy excess. See talk by Bill Louis

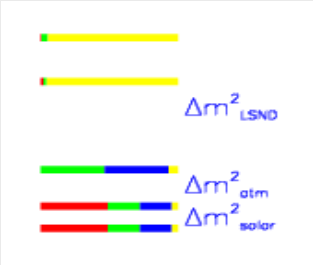
Current MiniBooNE Publication List

- P. Adamson et al., "First Measurement of νμ and νe Events in an Off-Axis Horn-Focused Neutrino Beam", arXiv:0809.2446 [hep-ex], submitted to Phys. Rev. Lett.
- A.A. Aguilar-Arevalo et al., "The MiniBooNE Detector", arXiv:0806.4201 [hep-ex], submitted to Nucl. Instr. Meth. A
- A.A. Aguilar-Arevalo et al., "The Neutrino Flux Prediction at MiniBooNE", arXiv:0806.1449 [hep-ex], submitted to Phys. Rev. D.
- A.A. Aguilar-Arevalo et al., "Compatibility of high Δm2 νe and νebar Neutrino Oscillation Searches", arXiv:0805.1764 [hep-ex], Phys. Rev. D. 78, 012007 (2008)
- A.A. Aguilar-Arevalo et al., "First Observation of Coherent π0 Production in Neutrino Nucleus Interactions with Eν<2 GeV", arXiv:0803.3423 [hep-ex], Phys. Lett. B. 664, 41 (2008)
- A.A. Aguilar-Arevalo et al., "Constraining Muon Internal Bremsstrahlung As A Contribution to the MiniBooNE Low Energy Excess", arXiv:0706.3897 [hep-ex]
- A.A. Aguilar-Arevalo et al., "Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon", arXiv:0706.0926 [hep-ex], Phys. Rev. Lett. 100, 032301 (2008)
- A.A. Aguilar-Arevalo et al., "A Search for Electron Neutrino Appearance at the Δm2 ~1 eV2 Scale", arXiv:0704.1500 [hep-ex], Phys. Rev. Lett. 98, 231801 (2007)

BACKUP SLIDES

If LSND Excess Confirmed: Physics Beyond the Standard Model!

3+2 Sterile Neutrinos — Sorel, Conrad, & Shaevitz (PRD70(2004)073004)



Explain Pulsar Kicks?
Explain R-Process in Supernovae?
Explain Dark Matter?

Sterile Neutrino — Kaplan, Nelson, & Weiner (PRL93(2004)091801)

Explain Dark Energy?

New Scalar Bosons — Nelson, Walsh (arXiv:0711-1363)

CPT Violation — Barger, Marfatia, & Whisnant (PLB576(2003)303)

Explain Baryon Asymmetry in the Universe?

Quantum Decoherence — Barenboim & Mavromatos (PRD70(2004)093015)

Lorentz Violation — Kostelecky & Mewes (PRD70(2004)076002)
Katori, Kostelecky, Tayloe (hep-ph/0606154)

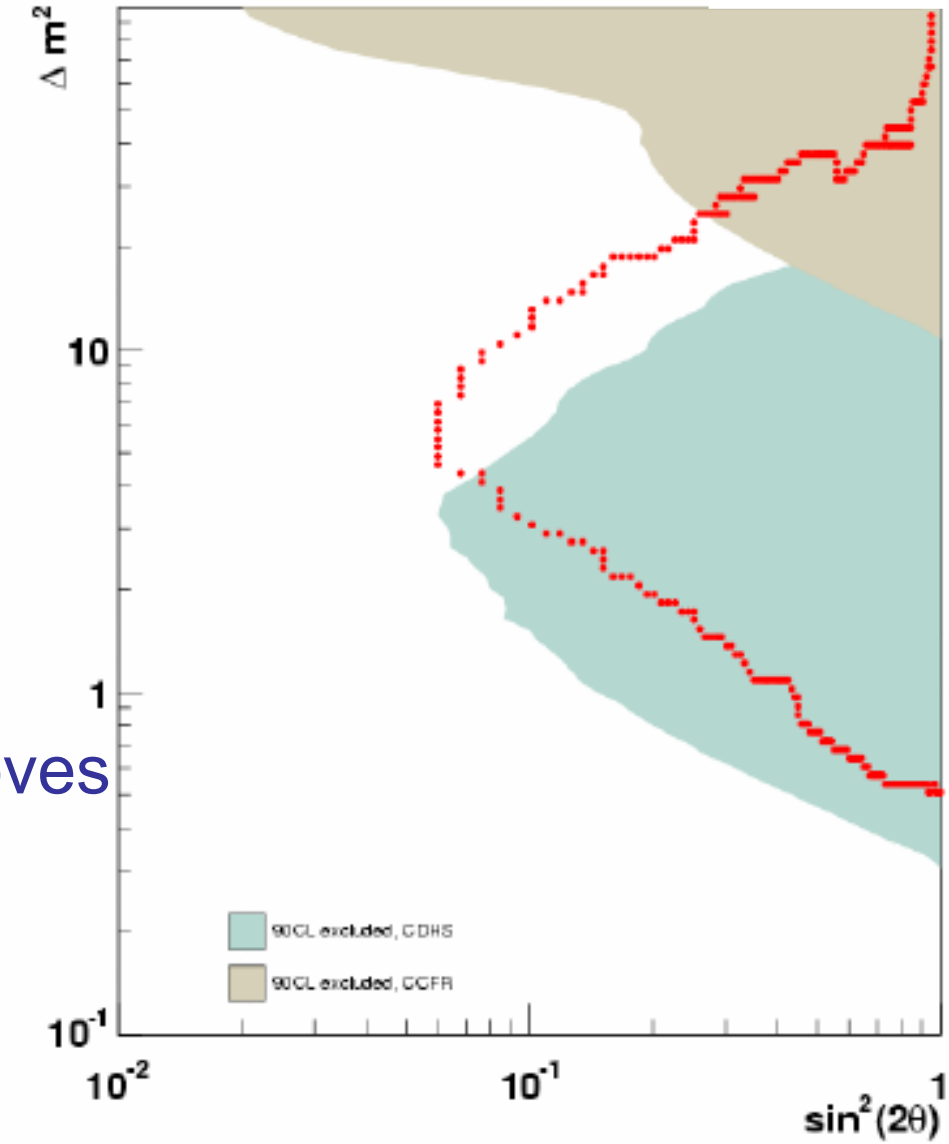
Extra Dimensions — Pas, Pakvasa, & Weiler (PRD72(2005)095017)

Sterile Neutrino Decay — Palomares-Ruiz, Pascoli, & Schwetz (JHEP509(2005)48)

Complete MiniBooNE ν_μ Disappearance Sensitivity

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

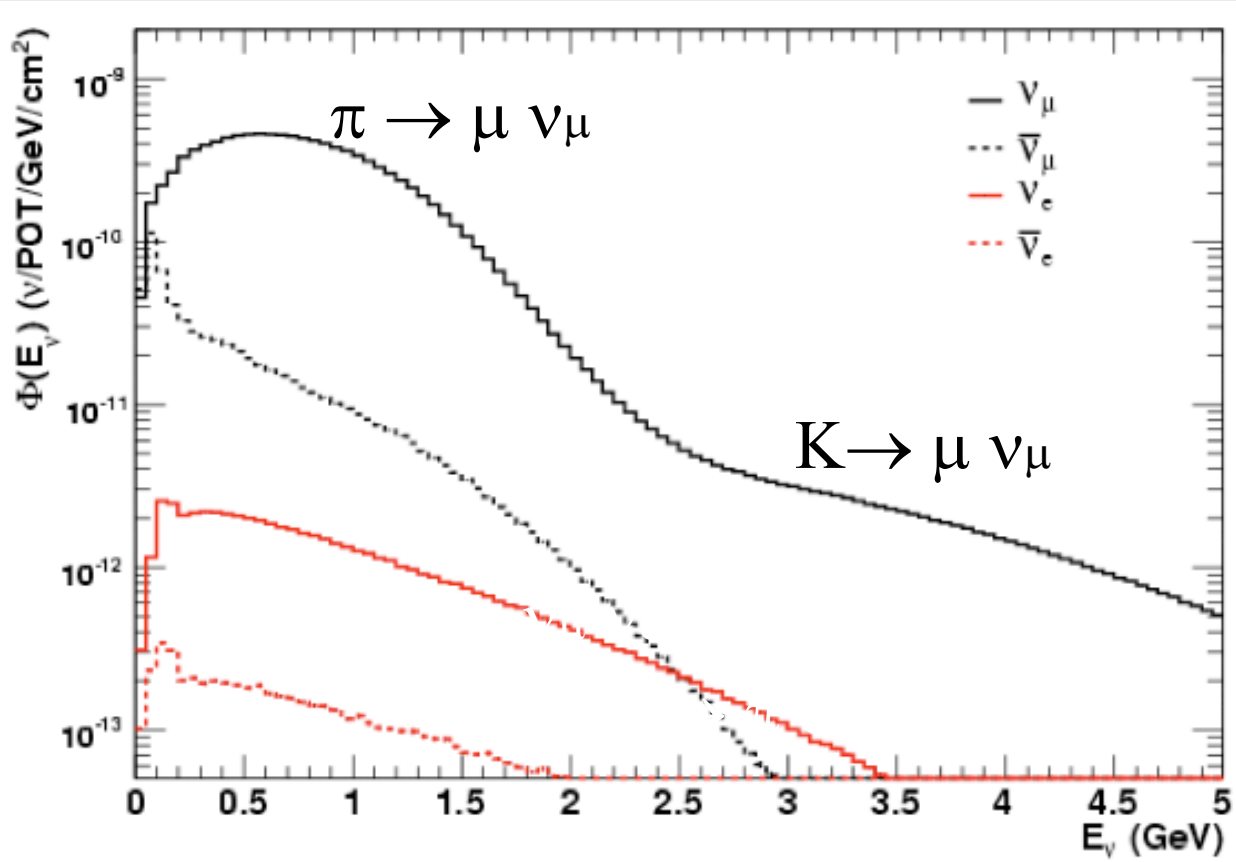
Inclusion of SciBooNE as a near detector, dramatically improves the sensitivity by reducing flux and cross section uncertainties



Many oscillations models predict large muon disappearance.

Neutrino Flux from GEANT4 Simulation

See Flux paper for details
arXiv: 0806.1449



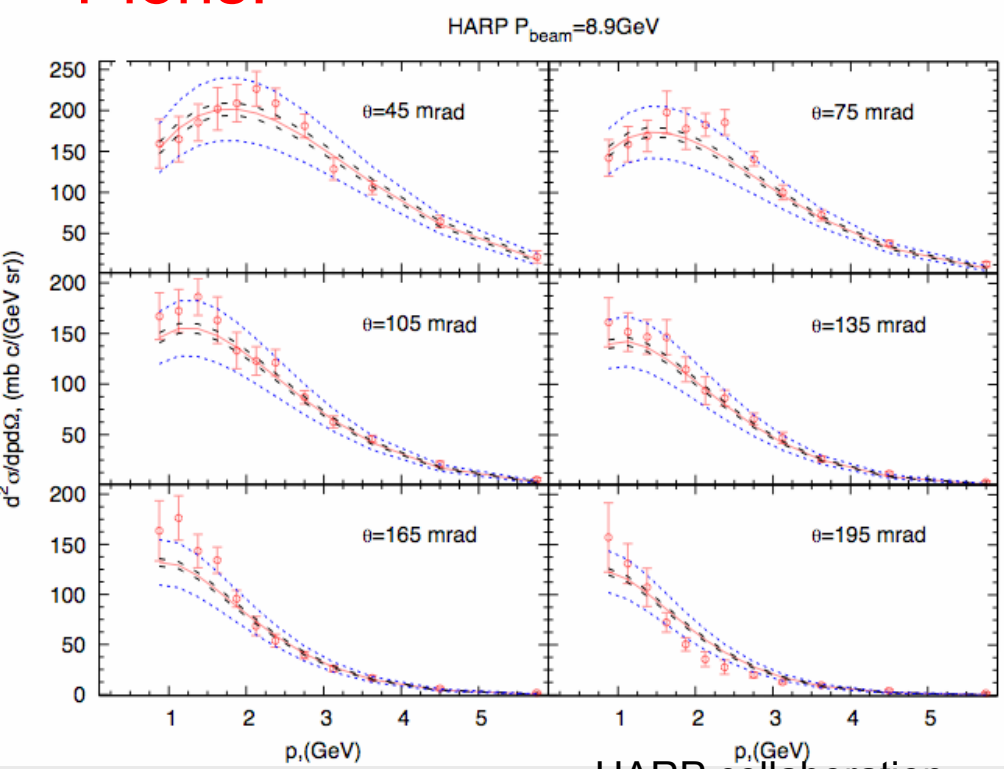
"Intrinsic" $\nu_e + \bar{\nu}_e$ sources:

$\mu^+ \rightarrow e^+\ \bar{\nu}_\mu\ \nu_e$ (52%)
$K^+ \rightarrow \pi^0\ e^+\ \nu_e$ (29%)
$K^0 \rightarrow \pi\ e\ \nu_e$ (14%)
Other (5%)

$\nu_e/\nu_\mu = 0.5\%$
Antineutrino content: 6%

Meson production at the target

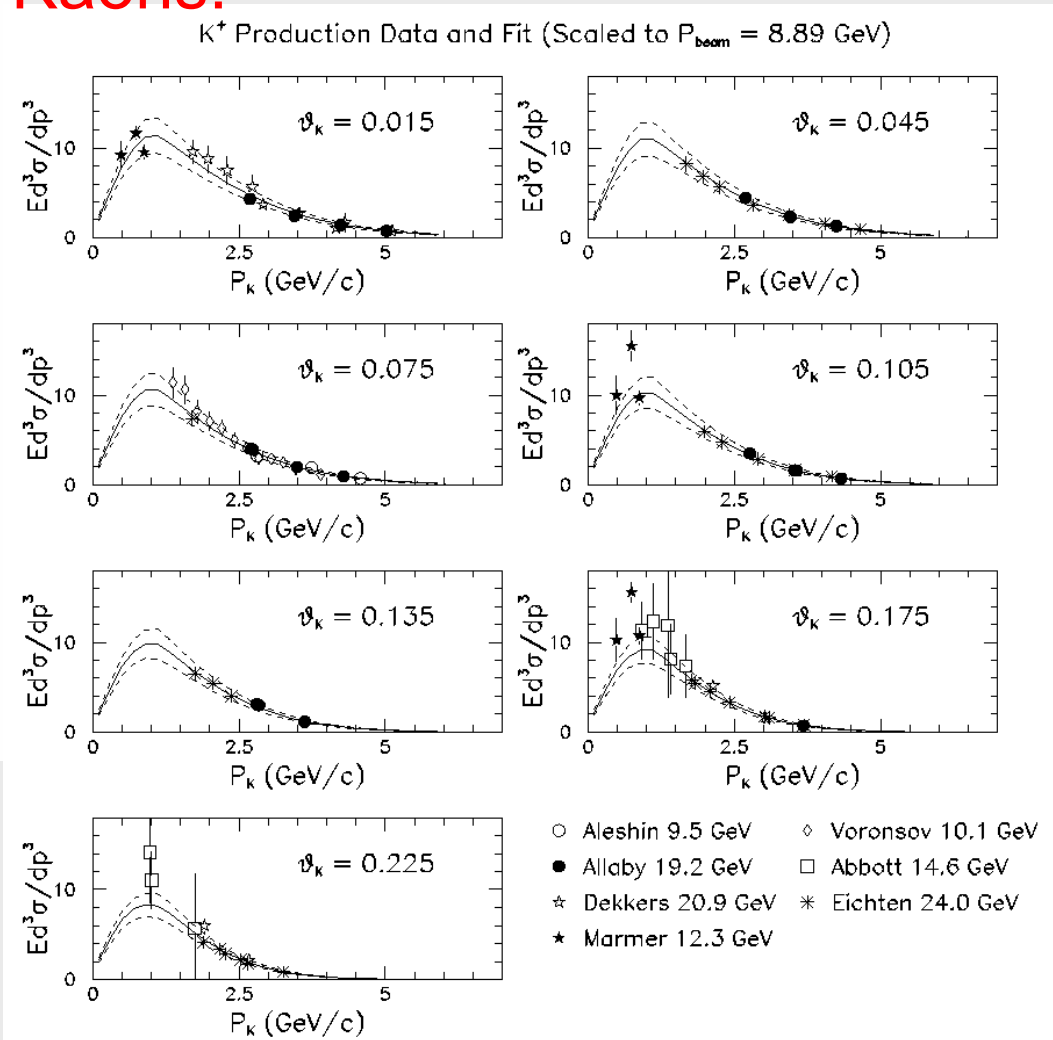
Pions:



HARP collaboration, hep-ex/0702024

- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% ● Beryllium target
- Spline fits were used to parameterize the data.

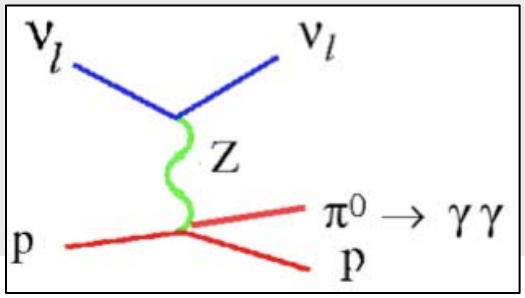
Kaons:

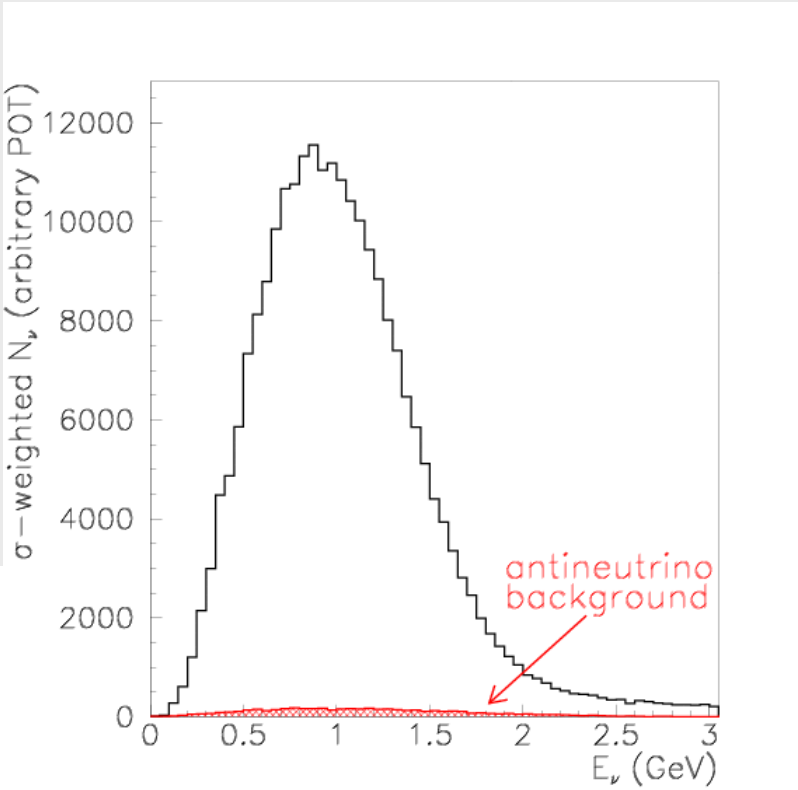


- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed

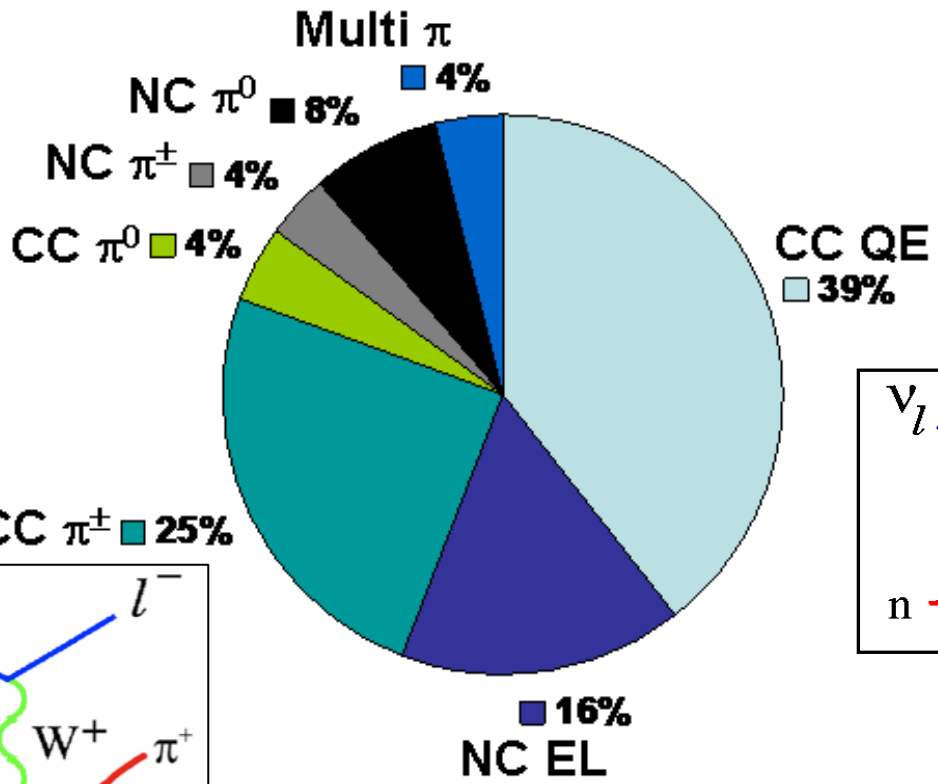
Predicted event rates before cuts (NUANCE Monte Carlo)

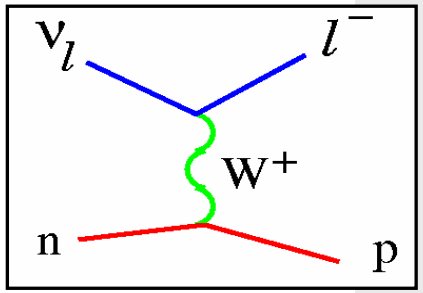
D. Casper, NPS, 112 (2002) 161

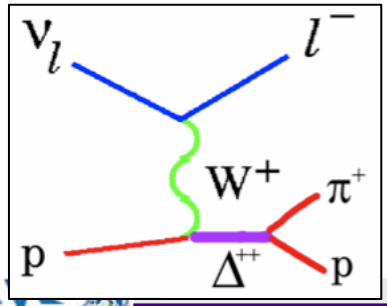




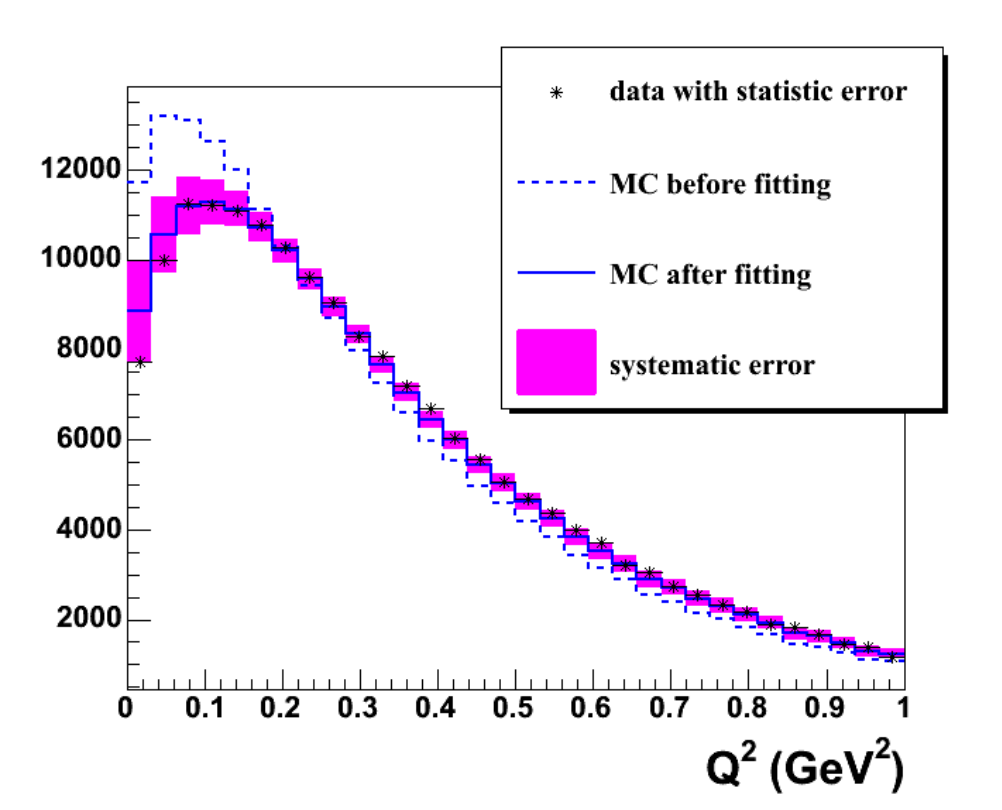
Event neutrino energy (GeV)







CCQE Scattering (Phys. Rev. Lett 100, 032301 (2008))



From Q^2 fits to MB ν_μ CCQE data:

- M_A^{eff} -- effective axial mass
- κ -- Pauli Blocking parameter

From electron scattering data:

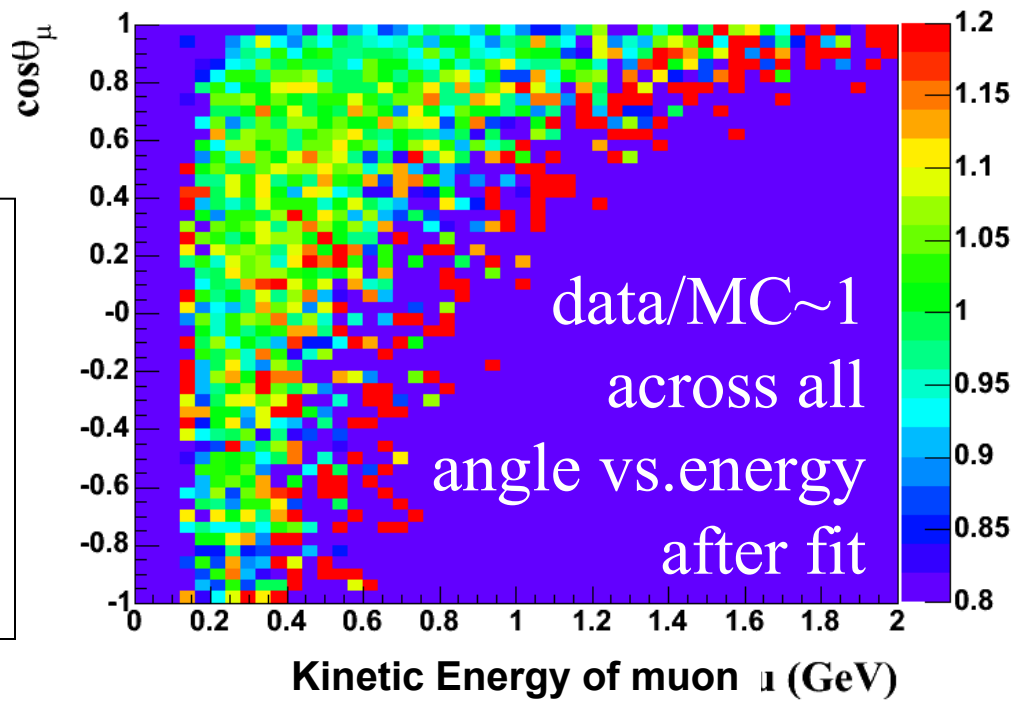
- E_b -- binding energy
- p_f -- Fermi momentum

Fermi Gas Model describes CCQE ν_μ data well

M_A = 1.23+-0.20 GeV

κ = 1.019+-0.011

Also used to model ν_e interactions

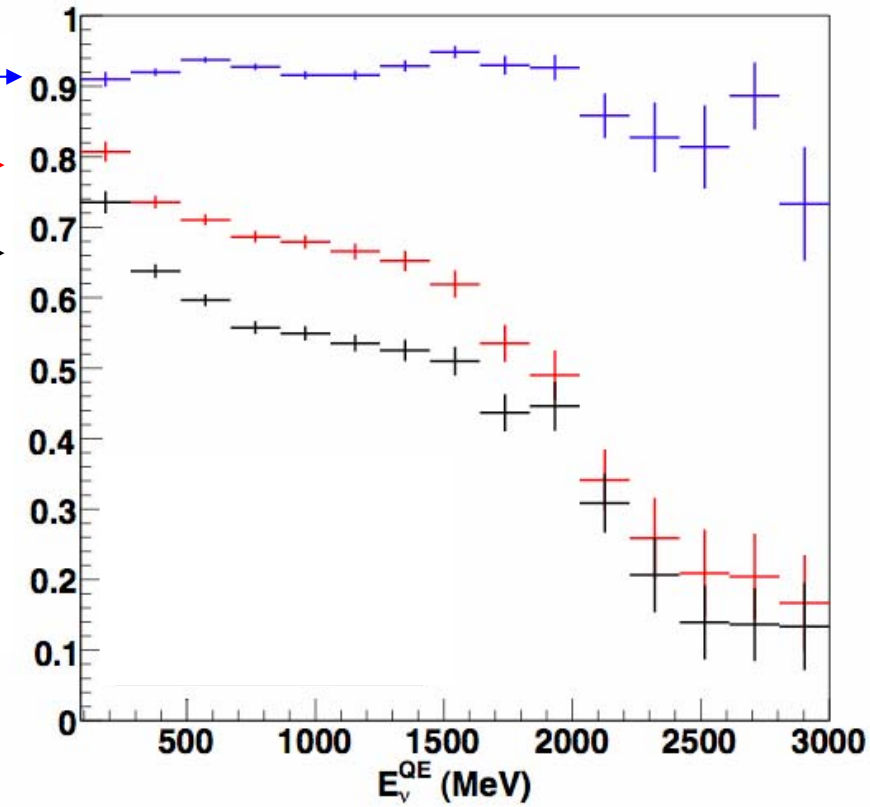


Summary of Track Based ν_e cuts

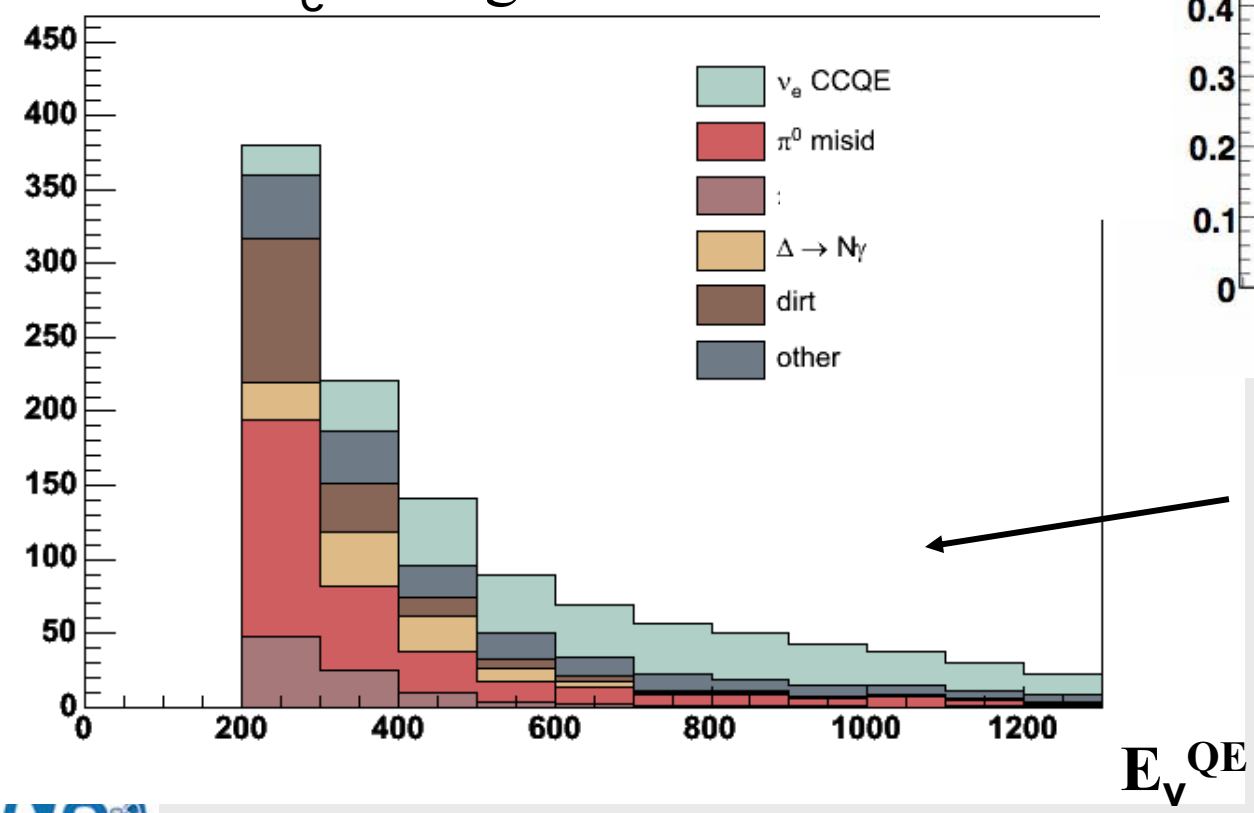
"Precuts" +

$\mathrm{Log}(L_e/L_\mu)$
+ $\mathrm{Log}(L_e/L_\pi)$
+ invariant mass

Efficiency:



ν_e Backgrounds after cuts

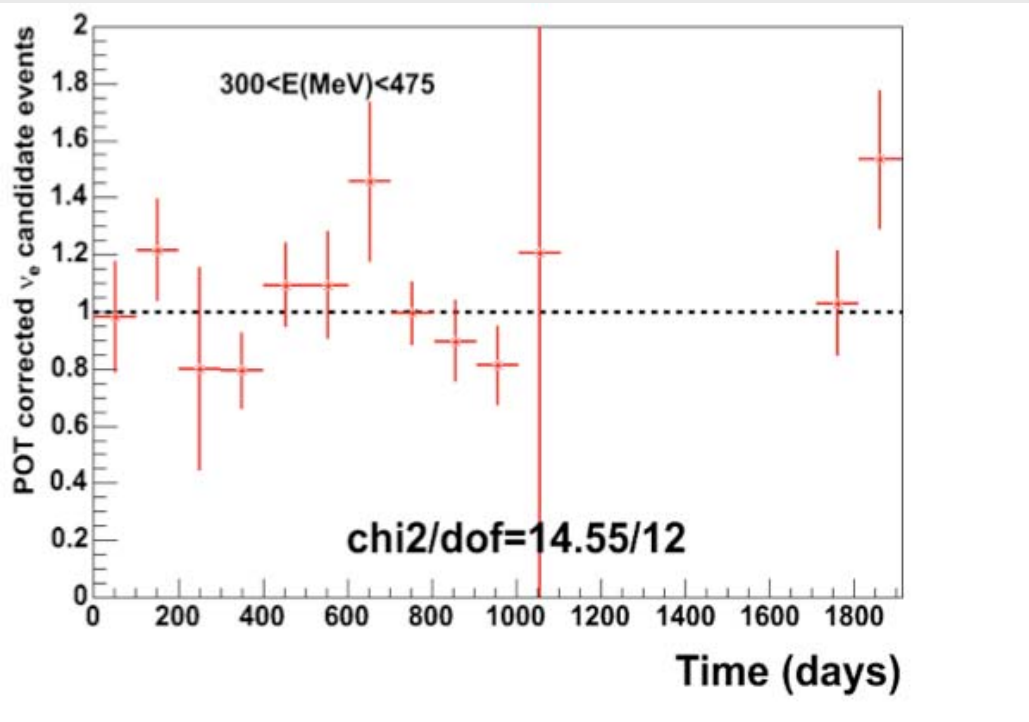


LSND oscillations adds 100 to 150 ν_e events

Detector Anomalies or Reconstruction Problems

No Detector anomalies found

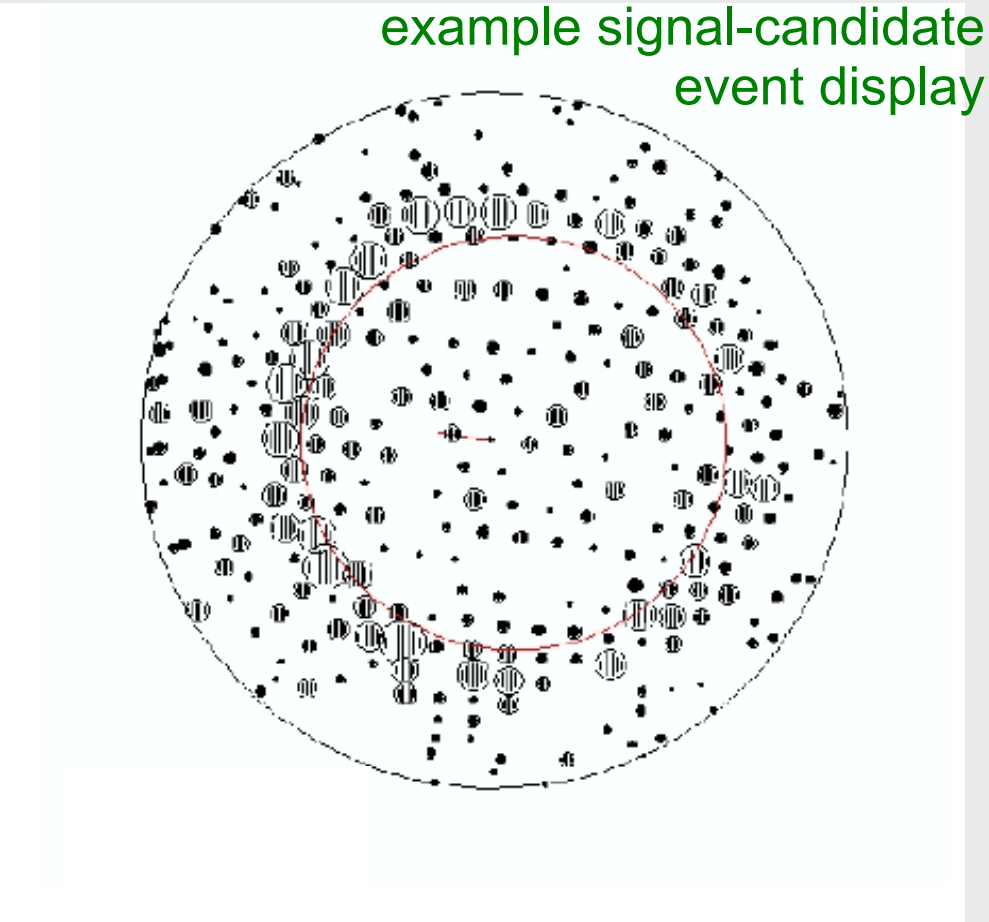
- Example: rate of electron candidate events is constant (within errors) over course of run



No Reconstruction problems found

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

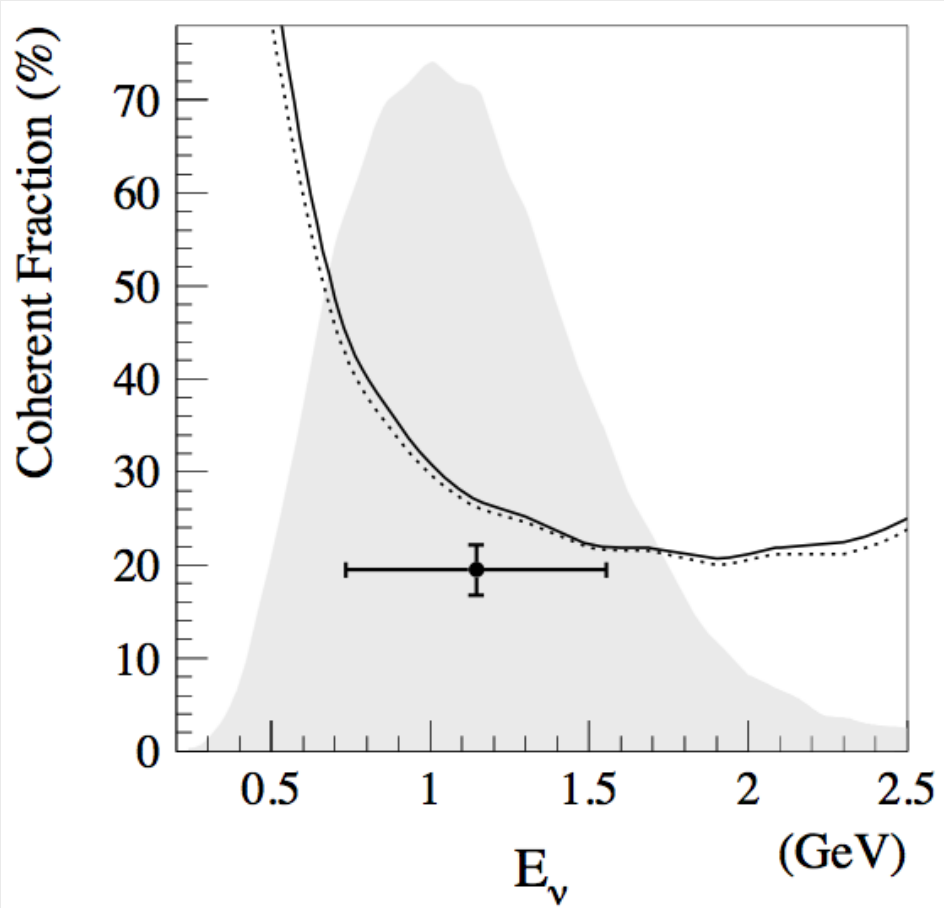
example signal-candidate event display

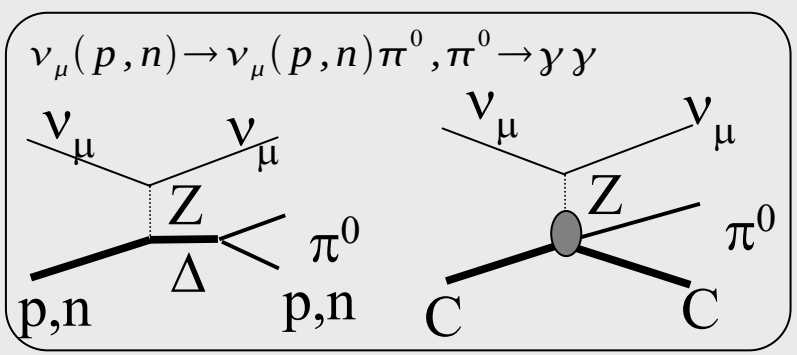


Signal candidate events are consistent with single-ring neutrino interactions

$\Rightarrow$ But could be either electrons or photons

Improved π^0 and radiative Δ analysis



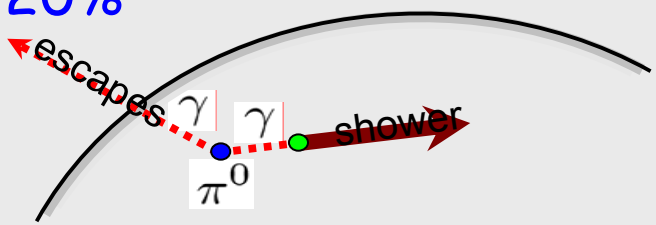


- Applied *in situ* measurement of the coherent/resonant production rate
  - Coherent event kinematics more forward
  - Resonant production increased by 5%
- Improvements to $\Delta \rightarrow N\gamma$ bkg prediction
  - Resonant π^0 fraction measured more accurately
  - Old analysis, π created in struck nucleus not allowed to reinteract to make new Δ
  - $\Delta \rightarrow N\gamma$ rate increased by 2%
  - Error on $\Delta \rightarrow N\gamma$ increased from 9 to 12%
- bottom line: Overall, produces a small change in ν_e appearance bkgs

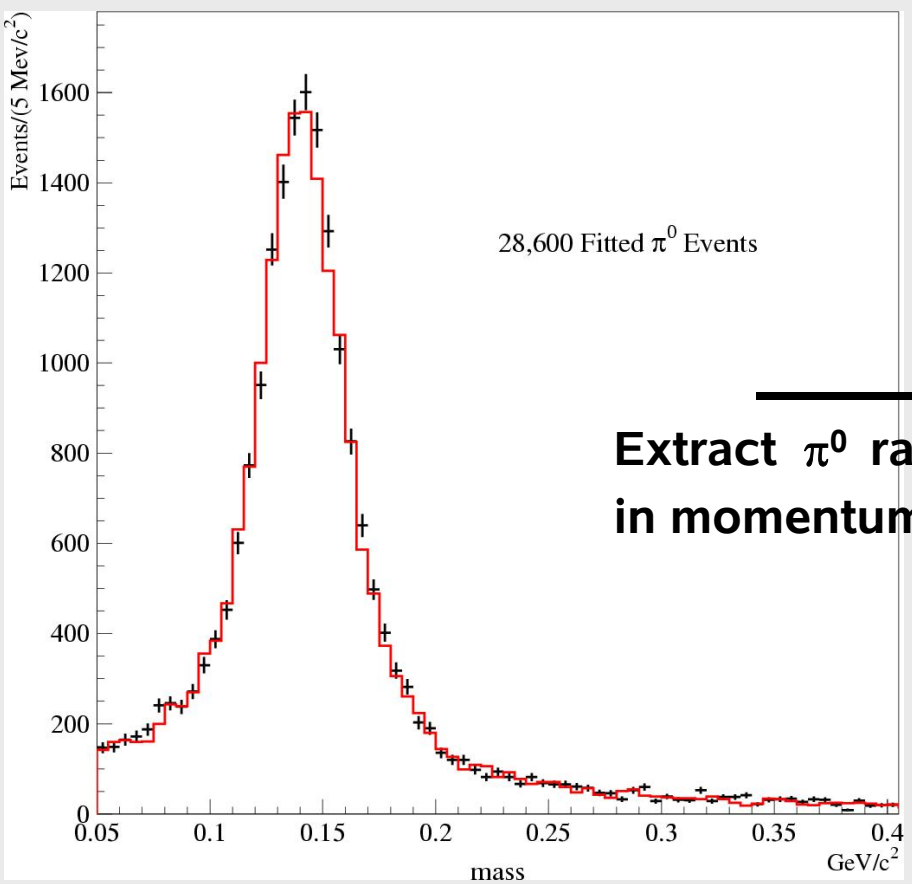
Measuring π^0 and constraining misIDs from π^0

π^0 rate measured to a few percent.
Critical input to oscillation analysis:
without constraint π^0 errors would be ~ 20%

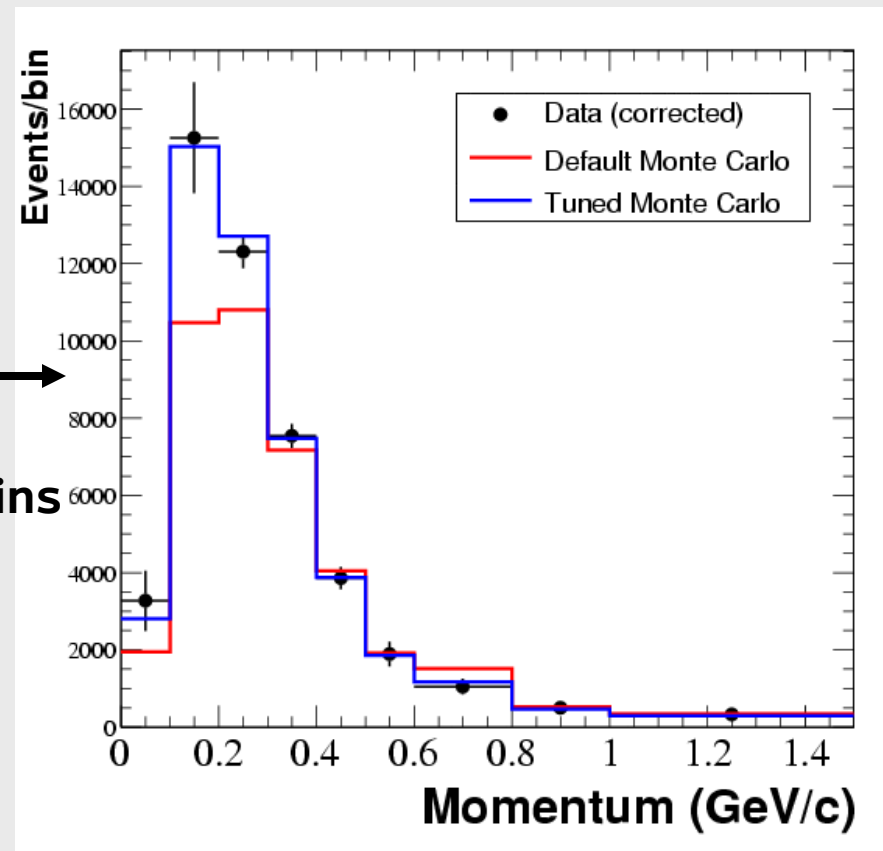
Phys.Lett.B664, 41(2008)



The π^0's constrains the Δ resonance rate, which determines the rate of Δ→Nγ. Rechecked Δ re-interaction rate. Increased errors 9 -> 12%

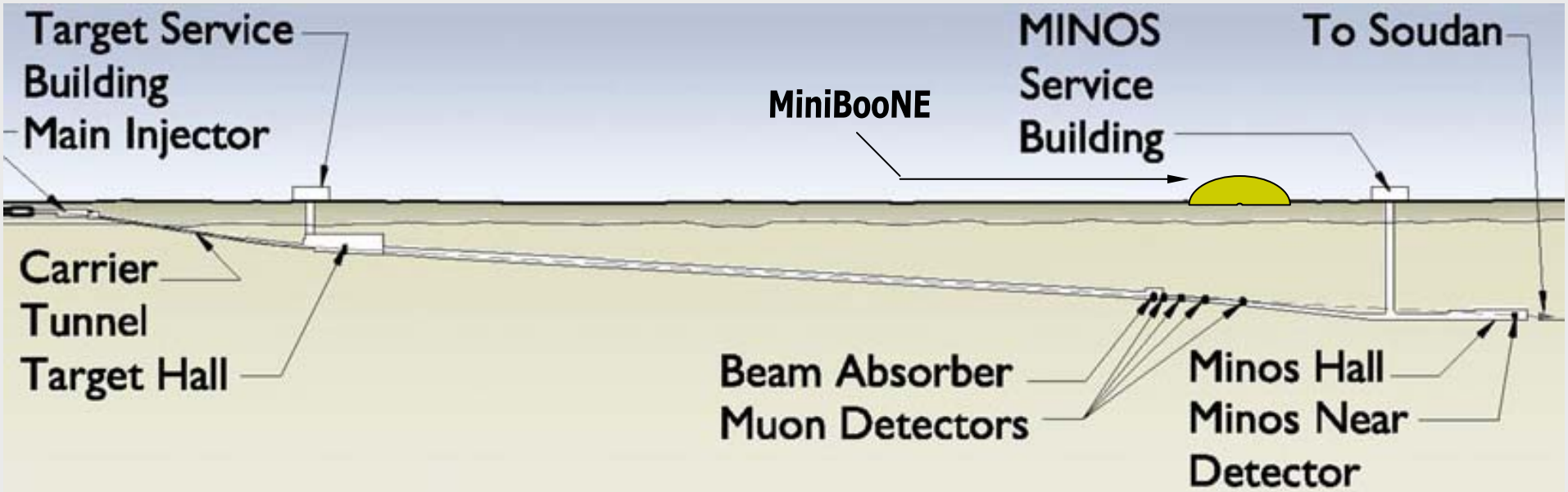


Extract π^0 rate in momentum bins

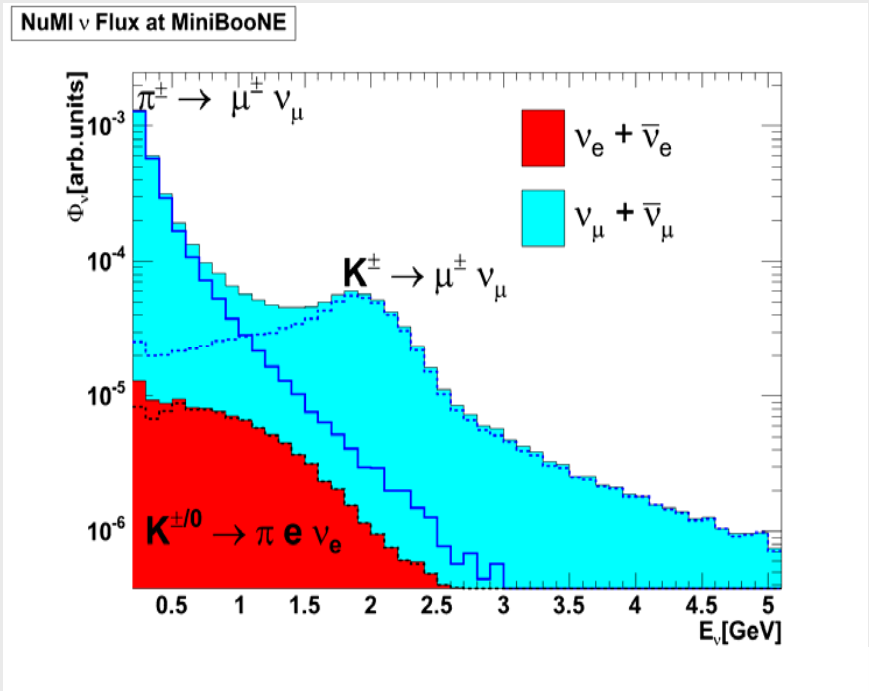


Pion analysis rechecked, only small changes made

NuMI Events in MiniBooNE



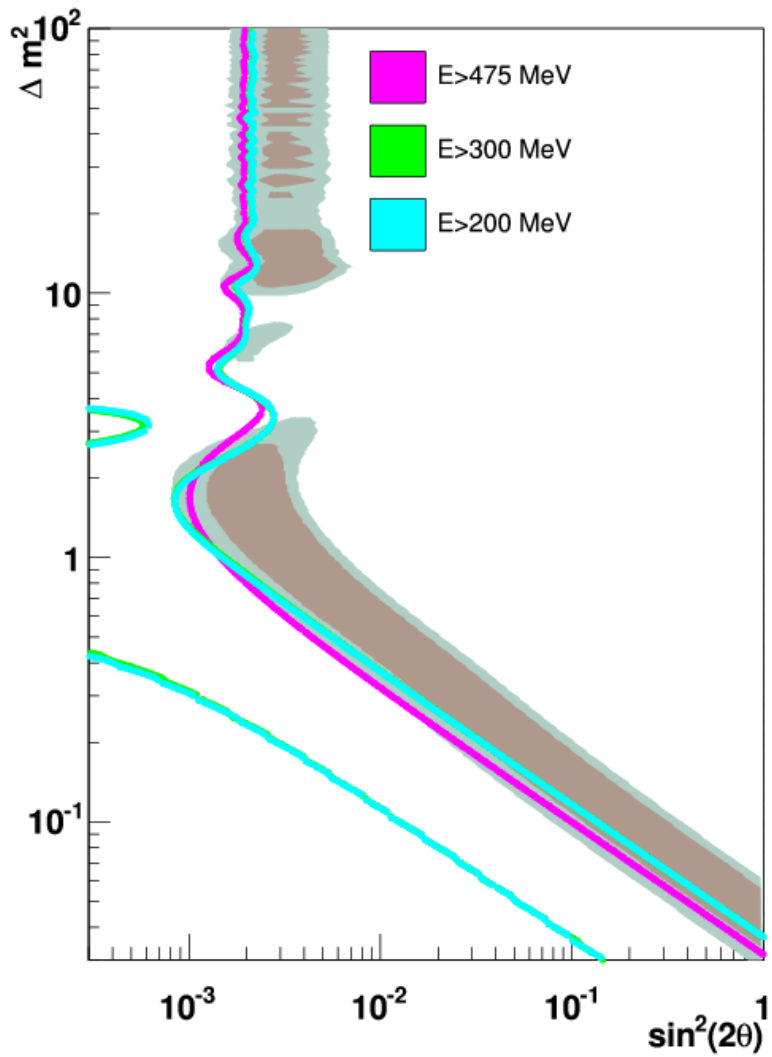
The beam at MiniBooNE from NuMI is significantly enhanced in ν_e from K decay because of the 110 mrad off-axis position. MiniBooNE is 745m from NuMI target



NuMI event rates:

ν_μ: 81% ν_e: 5% $\bar{\nu}_\mu$: 13% $\bar{\nu}_e$: 1%

numu->nue Oscillation Fits



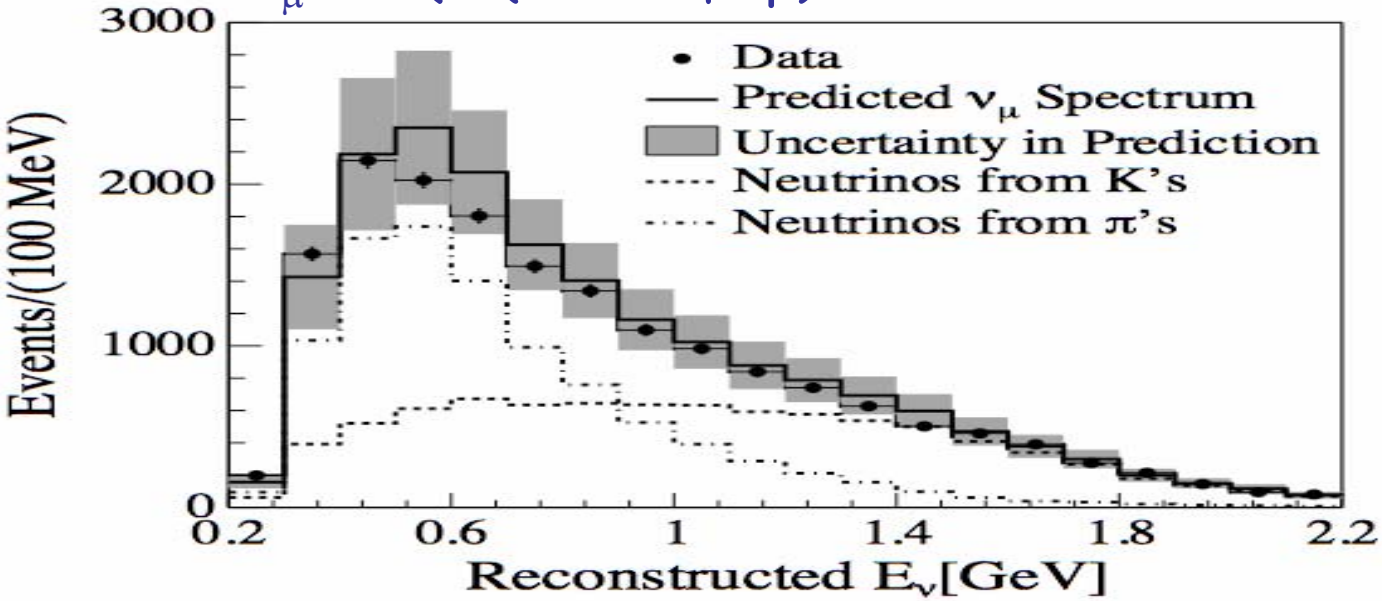
Energy	χ2_null(prob)	χ2_bf(prob)	(dm2, sin2theta)
>200	22.0(28%)	18.3(37%)	(3.1, 0.0017)
>300	21.8(24%)	18.3(31%)	(3.1, 0.0017)
>475	9.1(91%)	7.2(93%)	(3.5, 0.0012)

-Low energy best fits only marginally better than null!

-Above 475, fit consistent with original results, i.e. inconsistent with two neutrino oscillations.

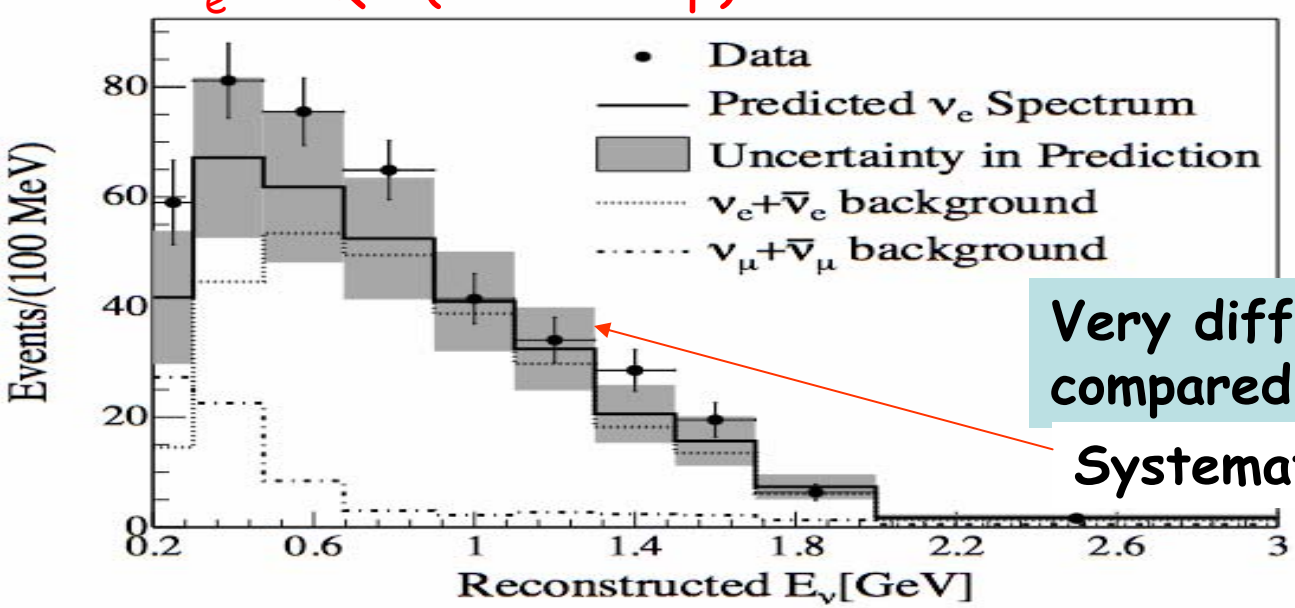
ν_μ CCQE and ν_e CCQE samples from NuMI

ν_μ CCQE (ν+n $\rightarrow$ μ+p)



Because of the good data/MC agreement in ν_μ flux and because the ν_μ and ν_e share same parents the beam MC can now be used to predict:
ν_e rate and mis-id backgrounds for a ν_e analysis.

ν_e CCQE (ν+n $\rightarrow$ e+p)



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

Systematics not yet constrained!

NuMI ν_e data provide limits on cross sections and PID

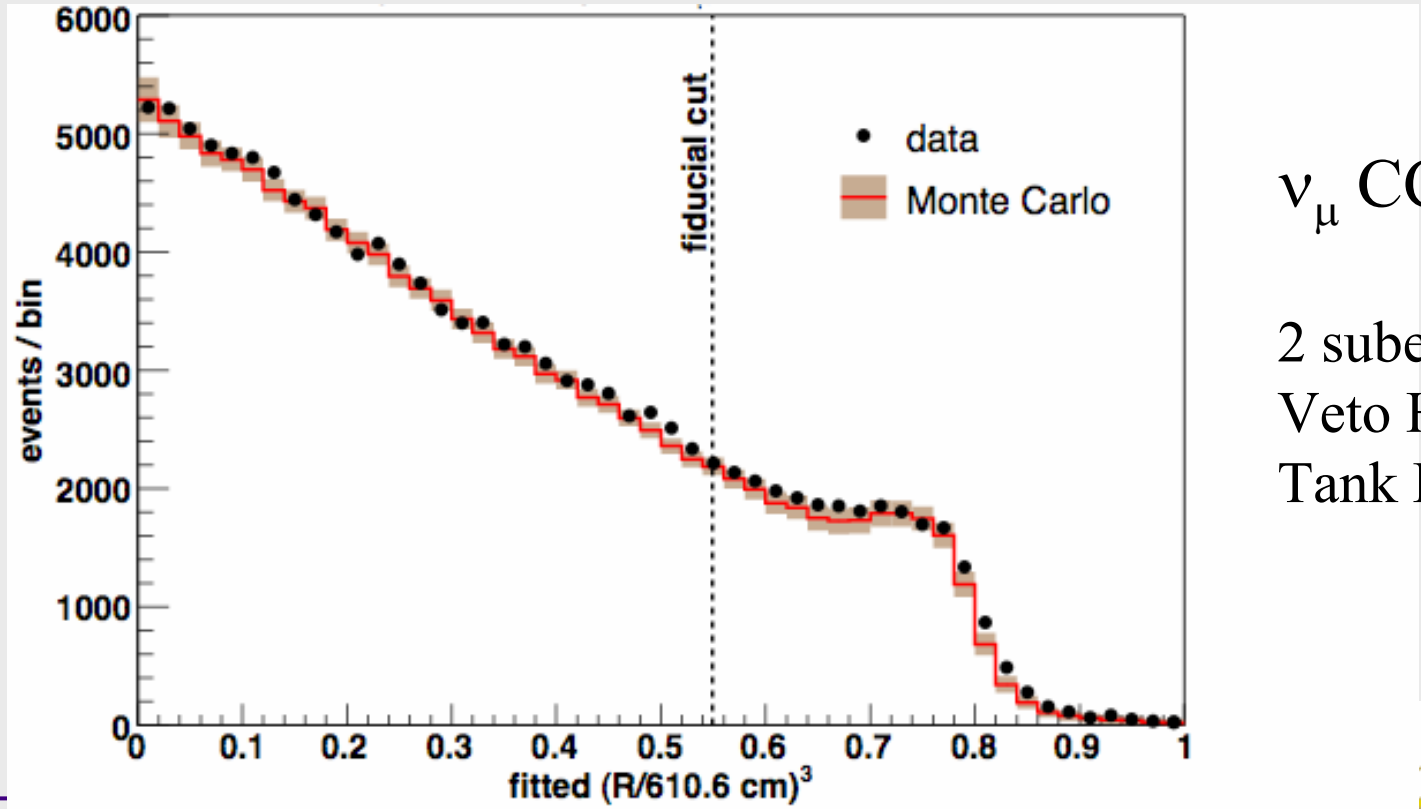
Each event is characterized by 7 reconstructed variables:

vertex (x,y,z), time, energy, and direction $(\theta,\phi) \Leftrightarrow (U_x, U_y, U_z)$.

Resolutions: vertex: 22 cm

direction: 2.8°

energy: 11%

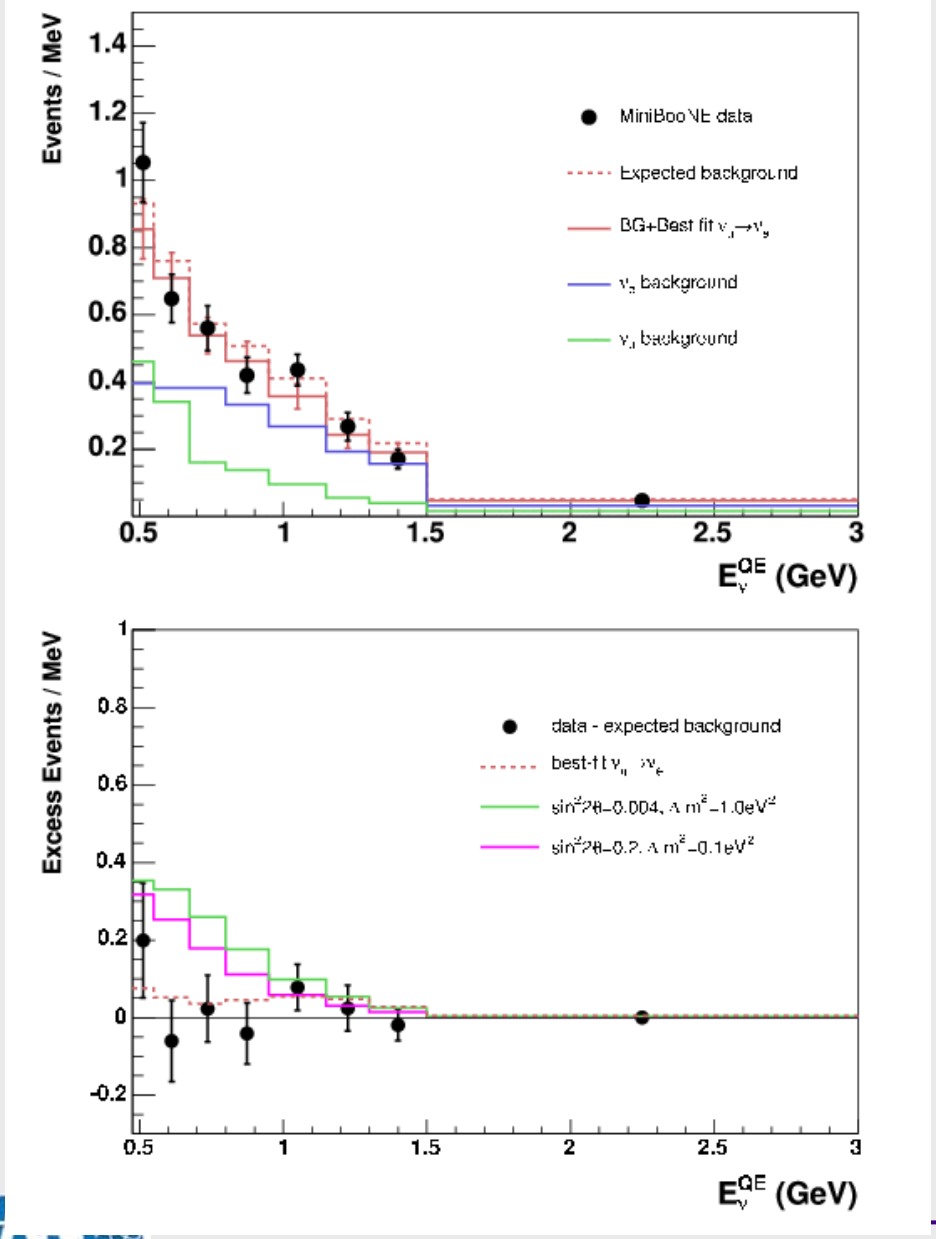


ν_μ CCQE events

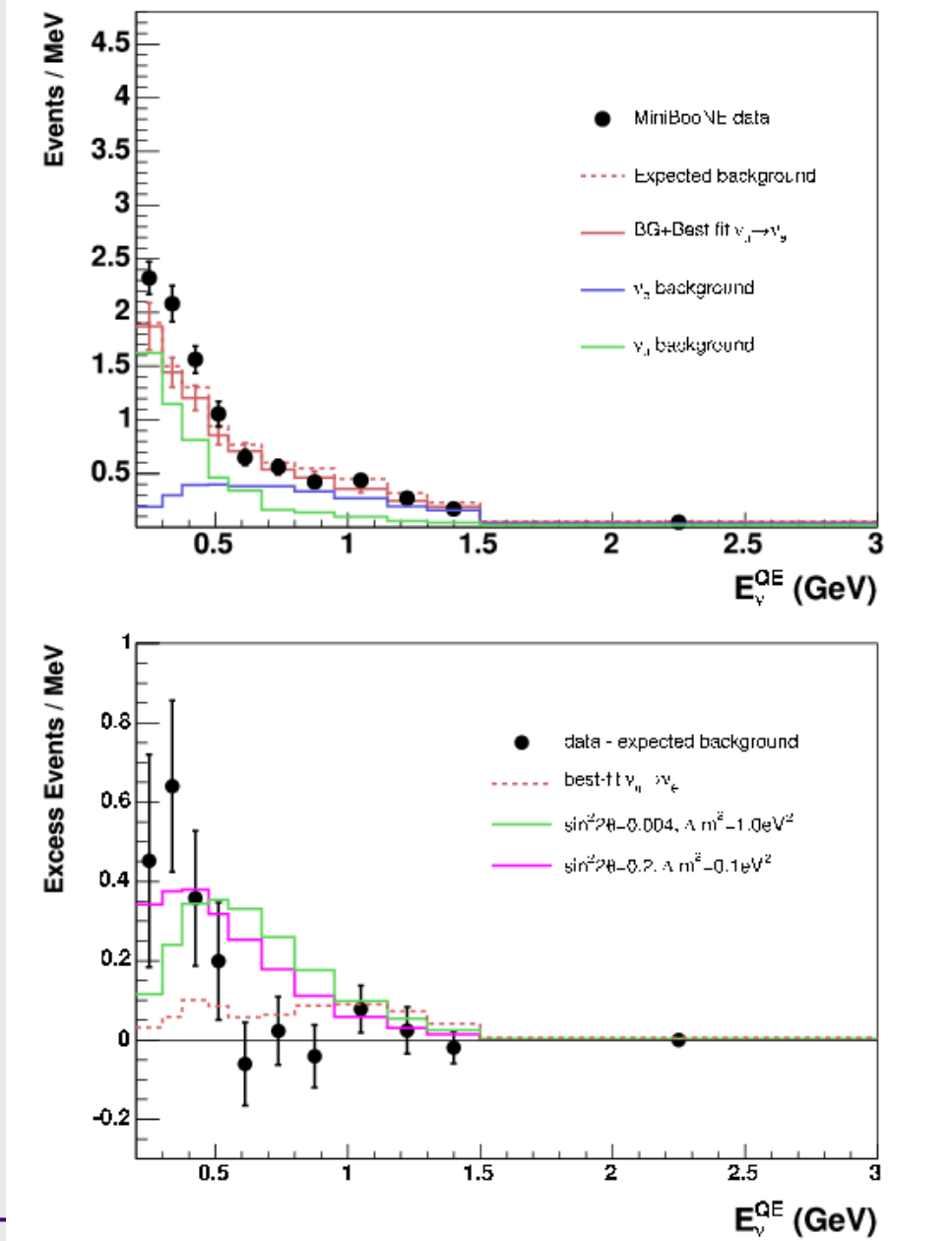
2 subevents
Veto Hits<6
Tank Hits>200

Oscillations Fits

Fit above 475 MeV



Fit above 200 MeV

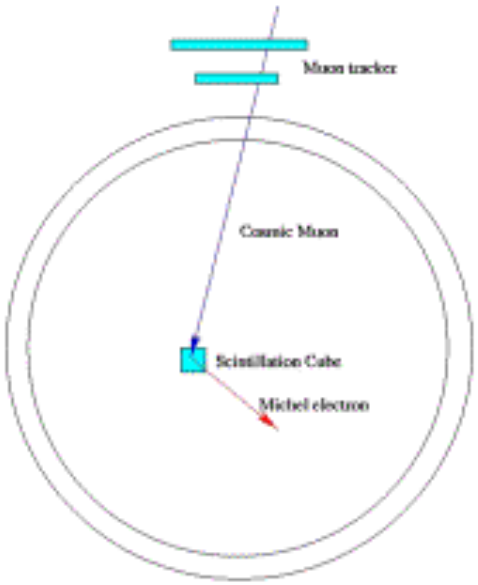


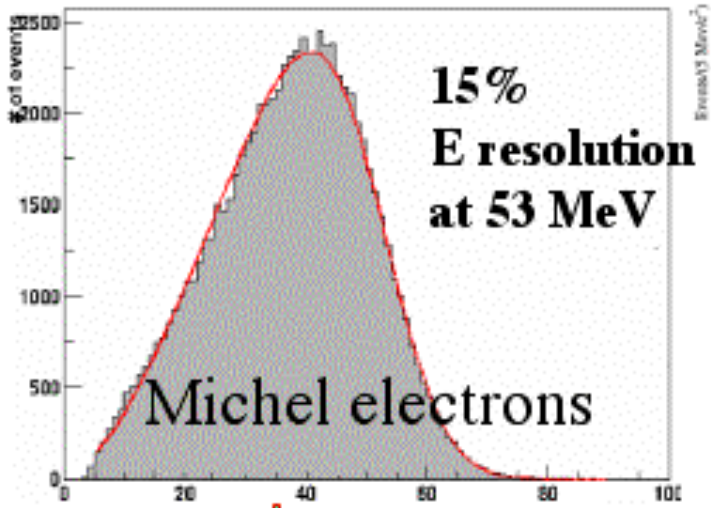
Background Rates (with DIRT cuts)

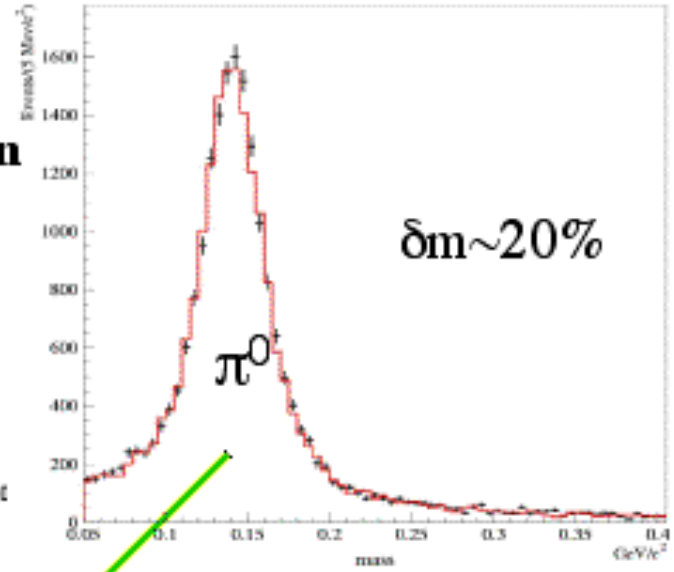
Process	$200-300$	$300-475$	$475-1250$
ν_μ CCQE	9.0	17.4	11.7
$\nu_\mu e \rightarrow \nu_\mu e$	6.1	4.3	6.4
NC π^0	103.5	77.8	71.2
NC $\Delta \rightarrow N\gamma$	19.5	47.5	19.4
Dirt Events	11.5	12.3	11.5
Other Events	18.4	7.3	16.8
ν_e from μ Decay	13.6	44.5	153.5
ν_e from K^+ Decay	3.6	13.8	81.9
ν_e from K_L^0 Decay	1.6	3.4	13.5
Total Background	186.8 ± 26.0	228.3 ± 24.5	385.9 ± 35.7

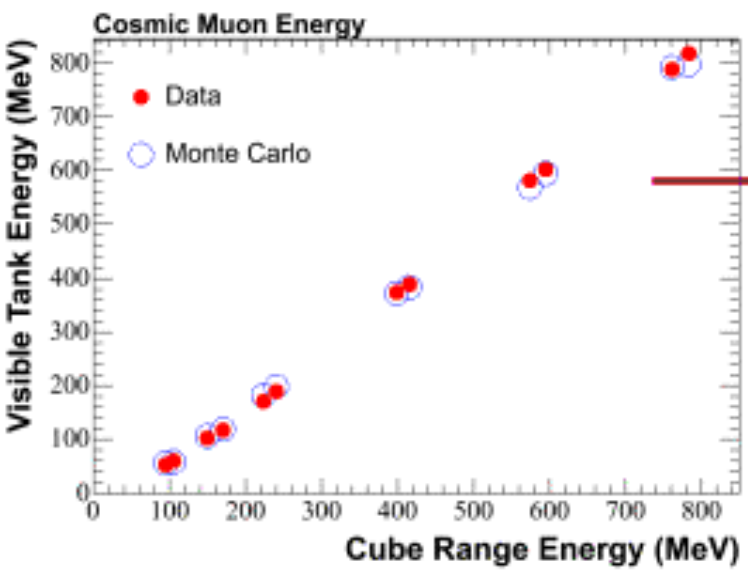
Calibration Sources

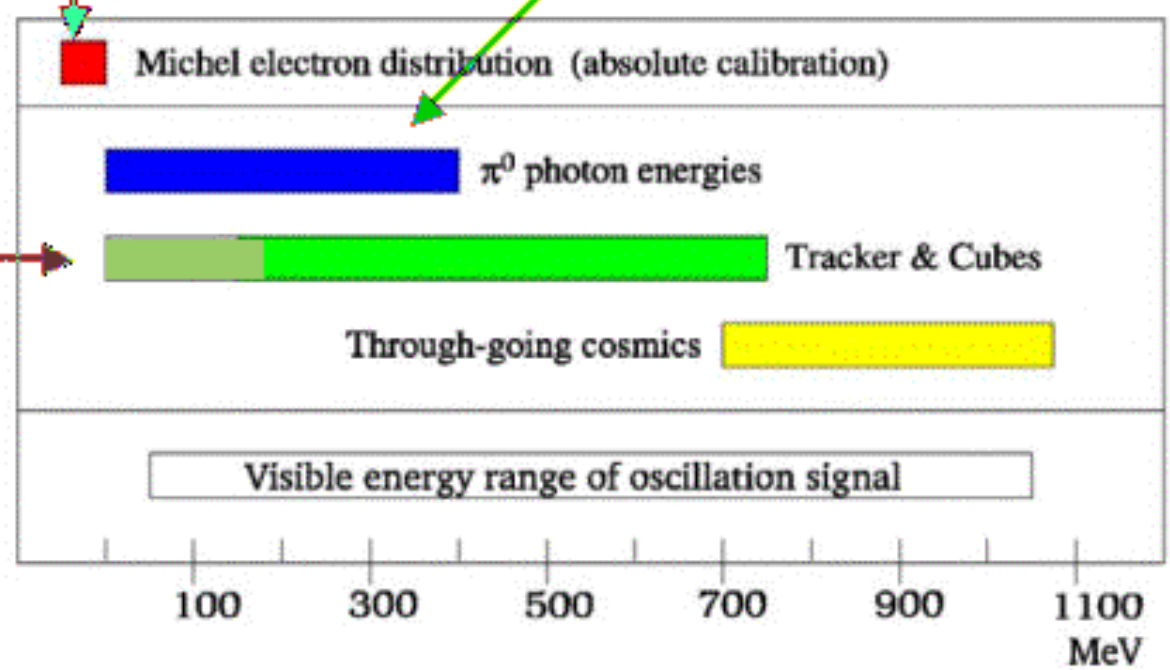
Tracker system











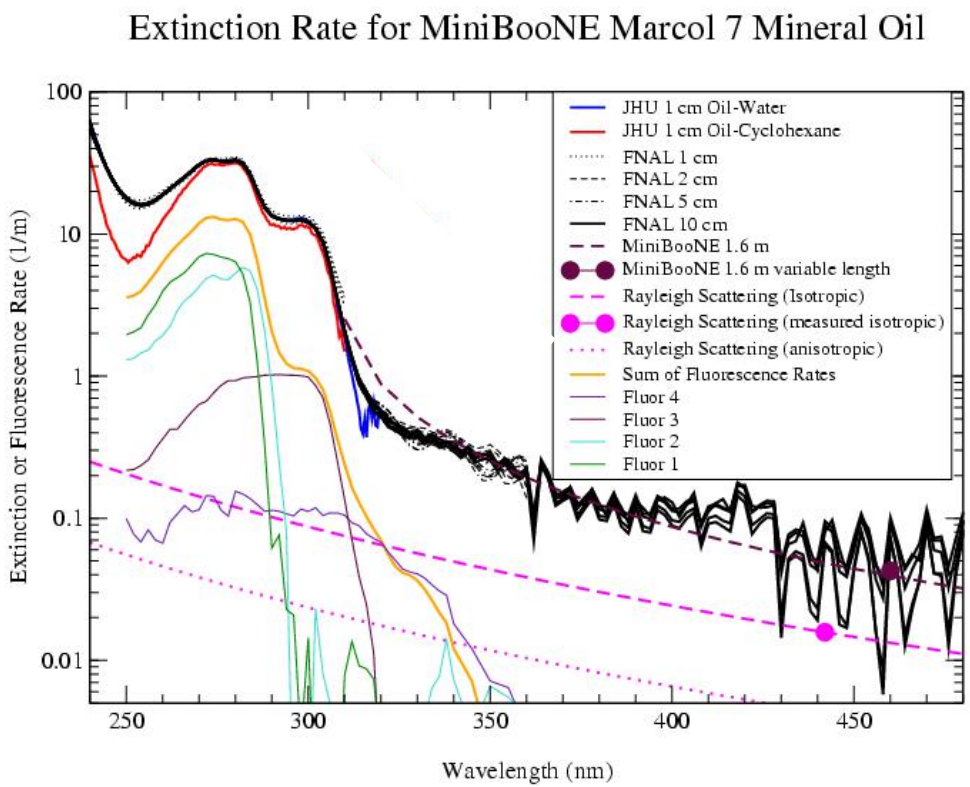
Optical Model

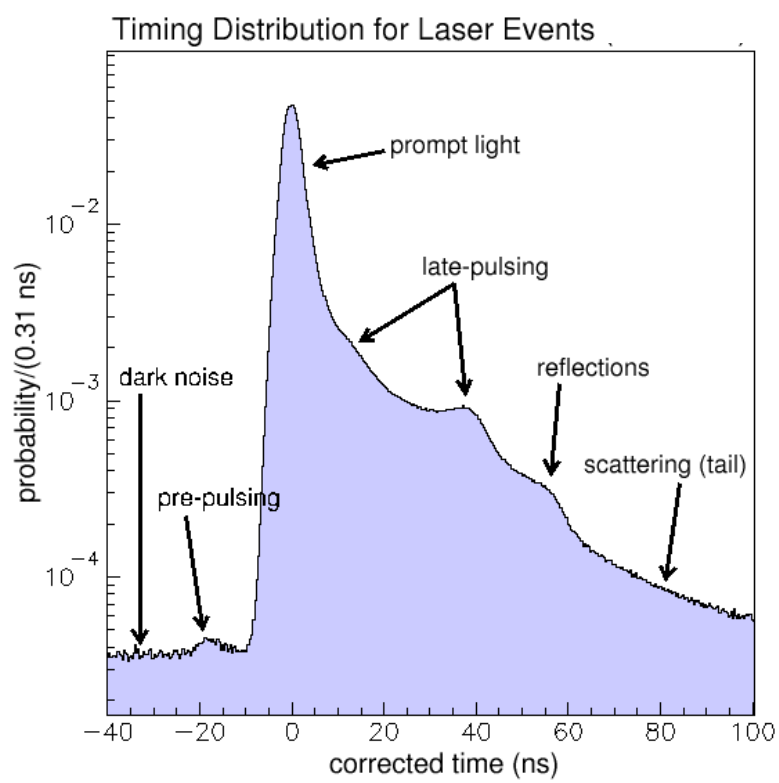
Attenuation length: >20 m @ 400 nm

Detected photons from

- Prompt light (Cherenkov)
- Late light (scintillation, fluorescence) in a 3:1 ratio for β~1

We have developed 39-parameter "Optical Model" based on internal calibration and external measurement





Cuts Used to Separate ν_μ events from ν_e events

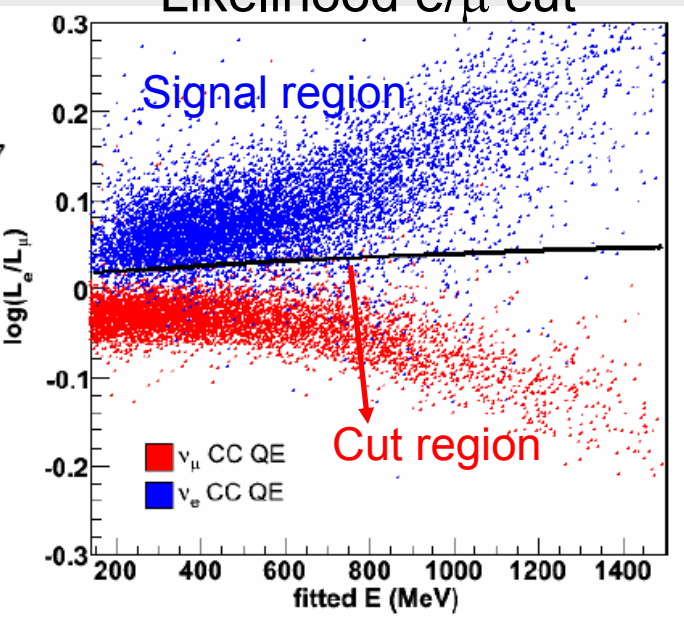
Compare observed light distributions to fit prediction:

Apply these likelihood fits to three hypotheses:
- **single electron track L_e**
- **single muon track L_μ**
- **two electron-like rings (π^0 event hypothesis) L_π**

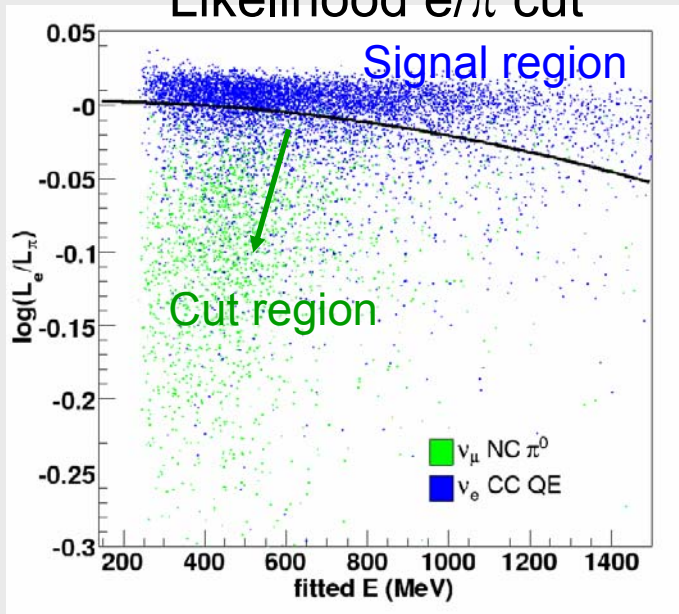
TBL Analysis

Combine three cuts to accomplish the separation: $L_{e\mu}$, $L_{e\pi}$, and 2-track mass

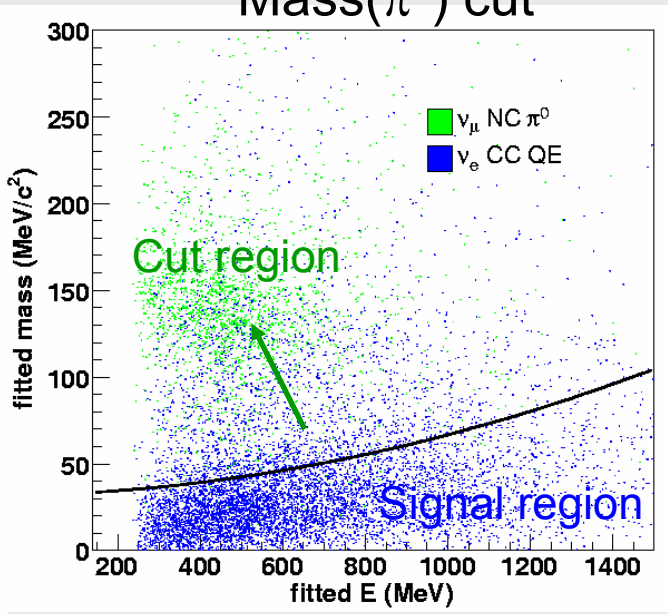
Likelihood e/μ cut



Likelihood e/π cut



Mass(π^0) cut



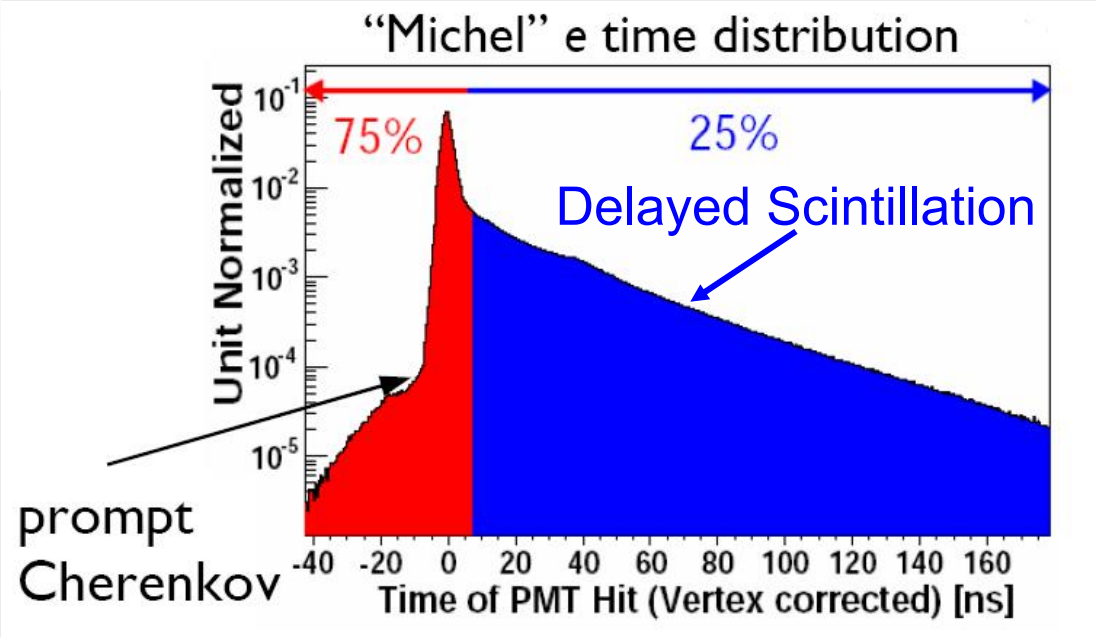
Blue points are signal ν_e events

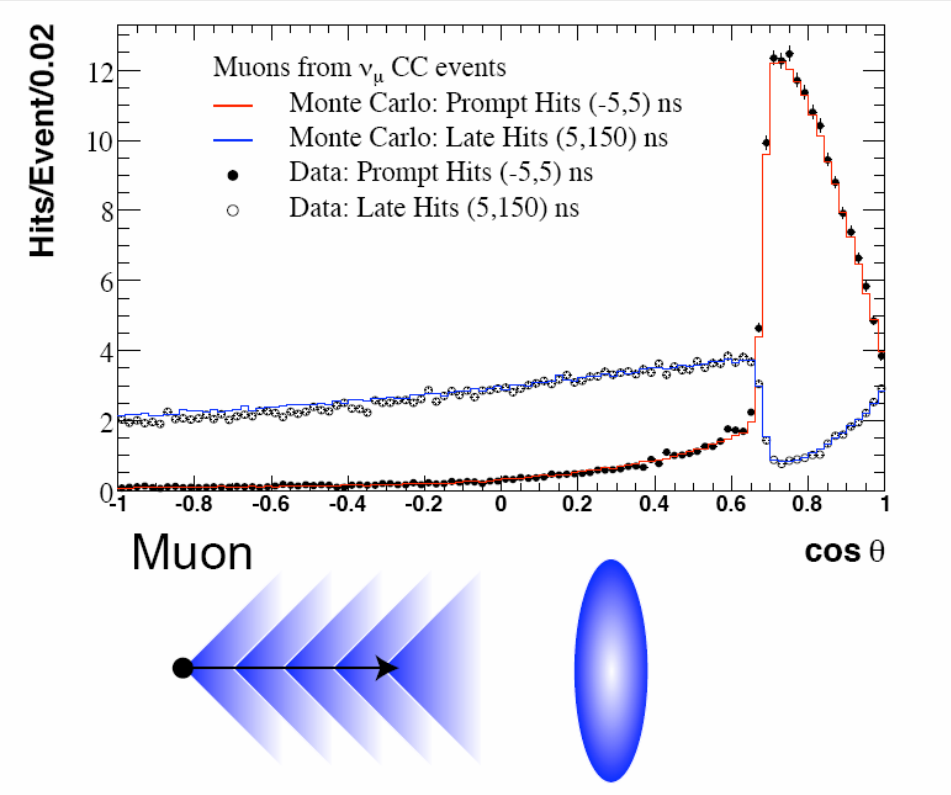
Red points are background ν_μCC QE events

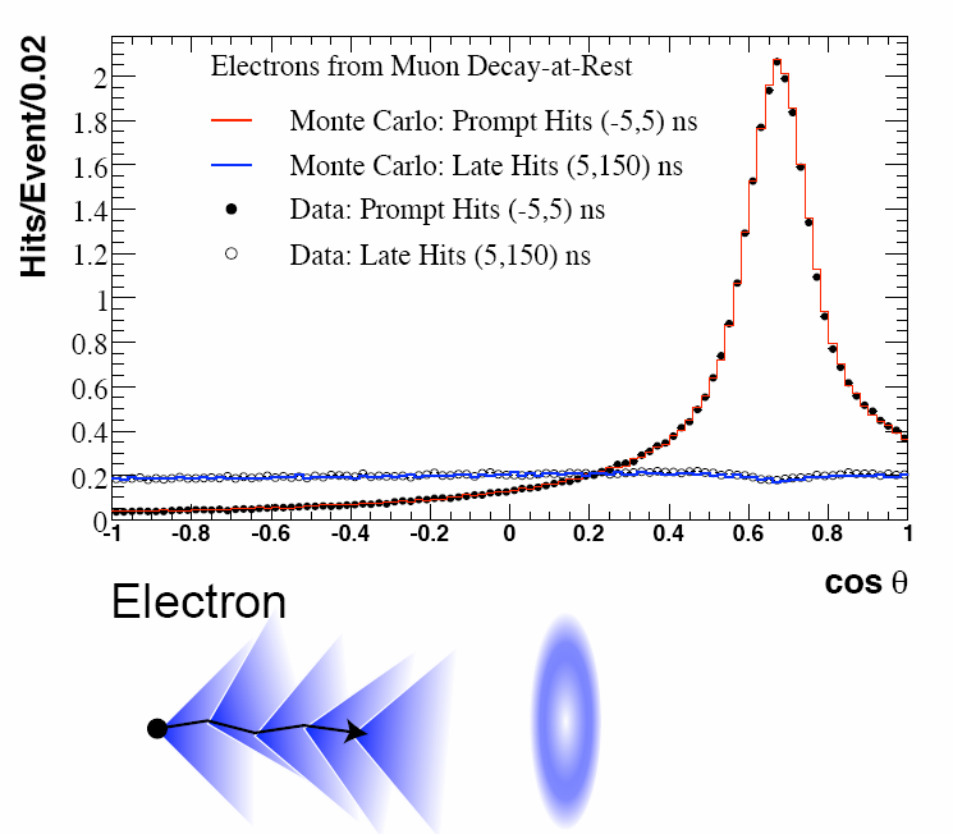
Green points are background ν_μ NC π^0 events

Event Reconstruction

- Use energy deposition and timing of hits in the phototubes
  - Prompt Cherenkov light
    - Highly directional with respect to particle direction
    - Used to give particle track direction and length
  - Delayed scintillation light
    - Amount depends on particle type





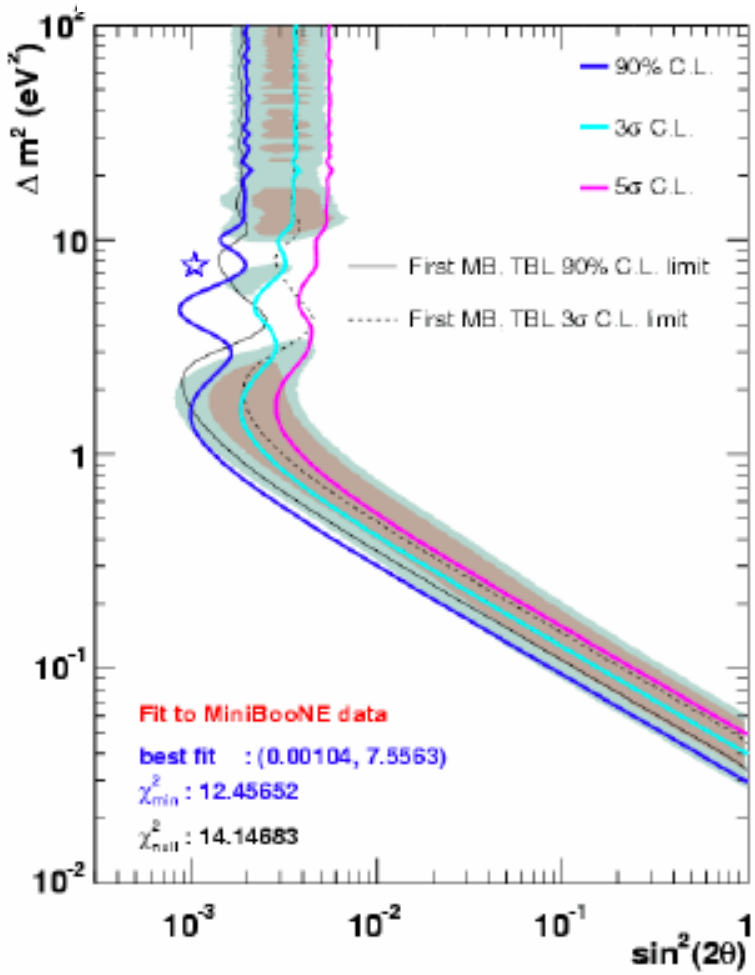


The ν_eBDT + ν_eTBL + ν_μCCQE results:

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

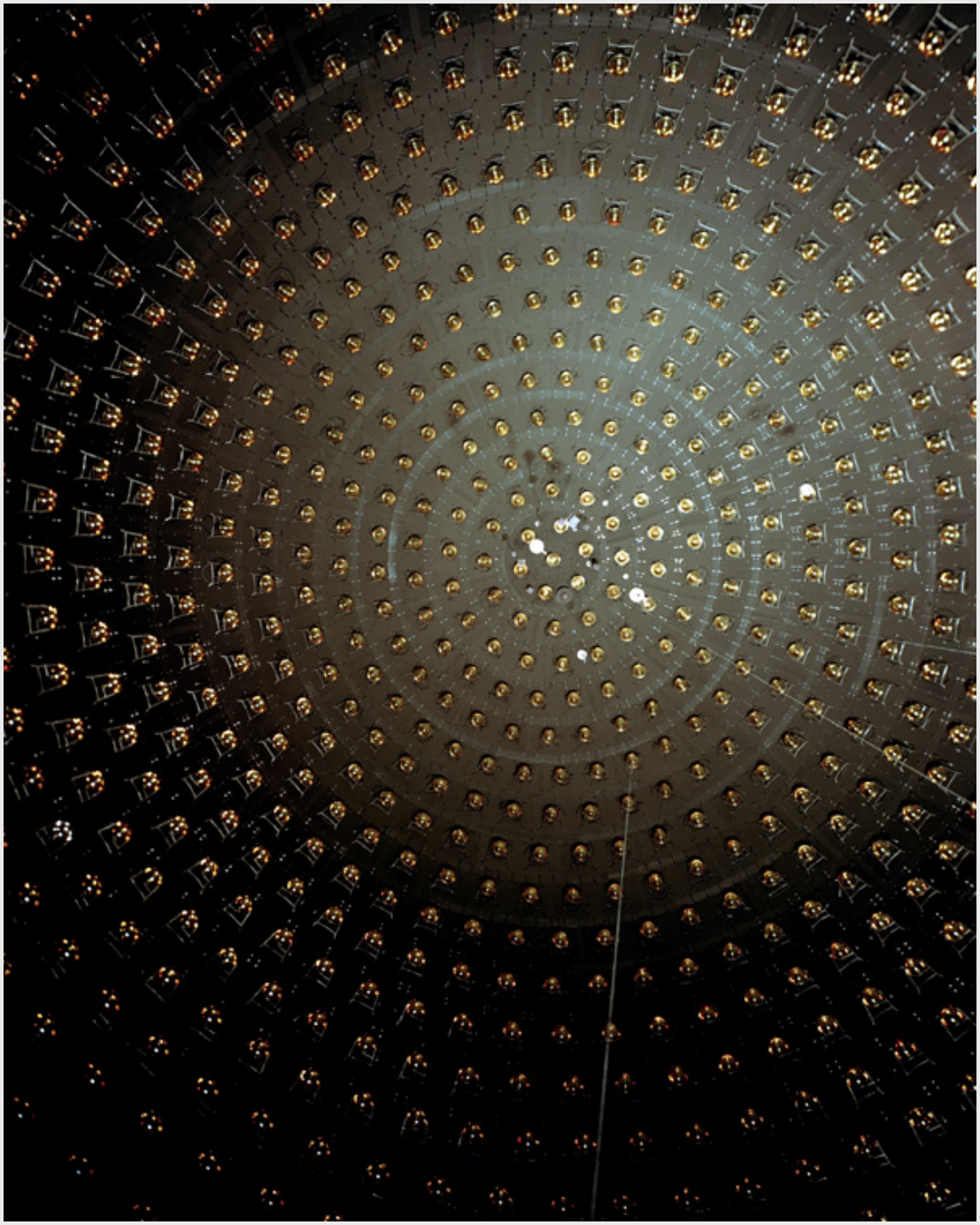
Differences in the details are due to the specific fluctuations in the three data samples and the interplay with correlations among them.

The combination yields a consistent result.



(A.A. Aguilar-Arevalo)

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



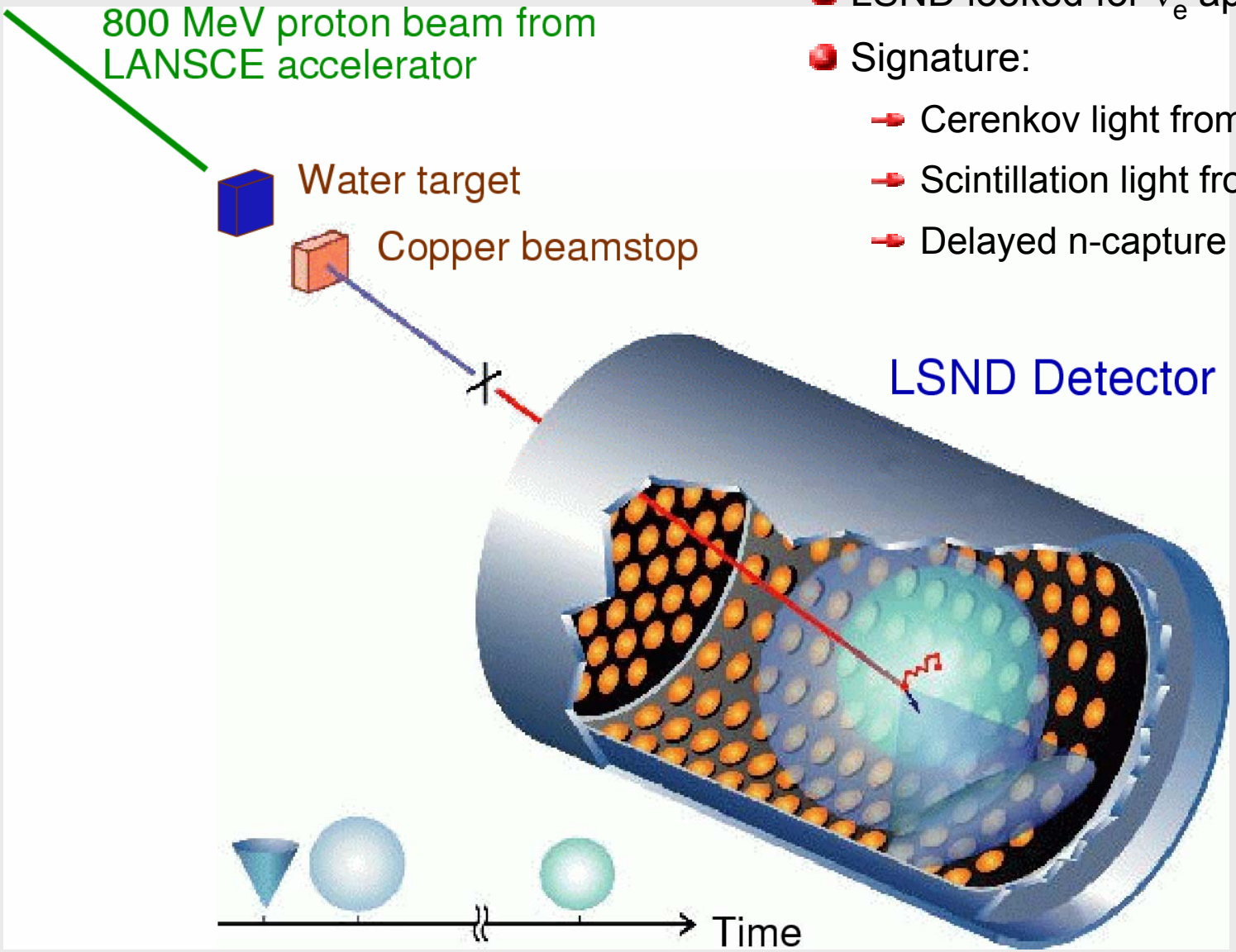
10% Photocathode coverage

Two types of Hamamatsu Tubes: R1408, R5912

Charge Resolution: 1.4 PE, 0.5 PE

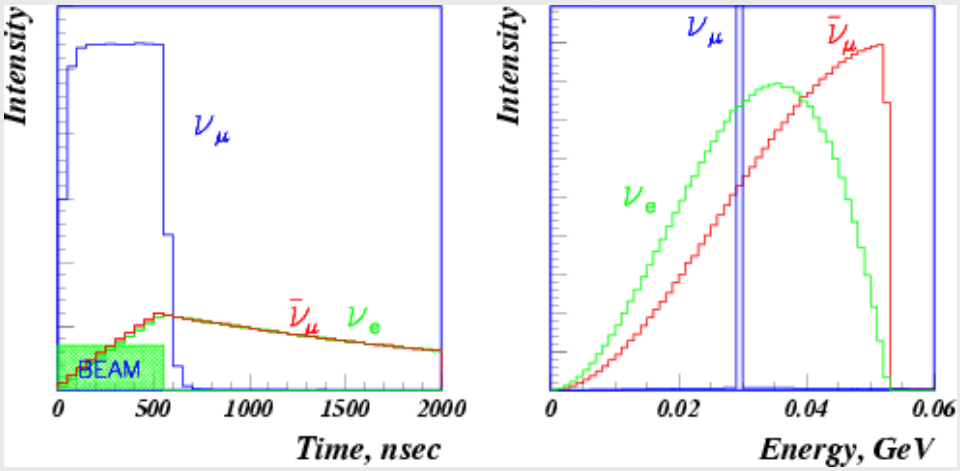
Time Resolution 1.7 ns, 1.1ns

The Liquid Scintillator Neutrino Detector at LANL



- LSND looked for $\overline{\nu}_e$ appearing in a $\overline{\nu}_\mu$ beam
- Signature:
  - Cerenkov light from e^+ (CC)
  - Scintillation light from nuclear recoil
  - Delayed n-capture (2.2 MeV)

OscSNS at ORNL: A Smoking Gun Measurement of Active-Sterile Neutrino Oscillations



SNS: ~1 GeV, ~1.4 MW

ν_μ -> ν_e ; ν_e p -> e^+ n => re-measure LSND an order of magnitude better.

ν_μ -> ν_s ; **Monoenergetic ν_μ** ; ν_μ C -> ν_μ C*(15.11) => search for sterile ν

OscSNS would be capable of making precision measurements of ν_e appearance & ν_μ disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)). Flux shapes are known perfectly and cross sections are known very well.