MinibooNE Oscillation Results and Implications

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for the MiniBooNE Collaboration

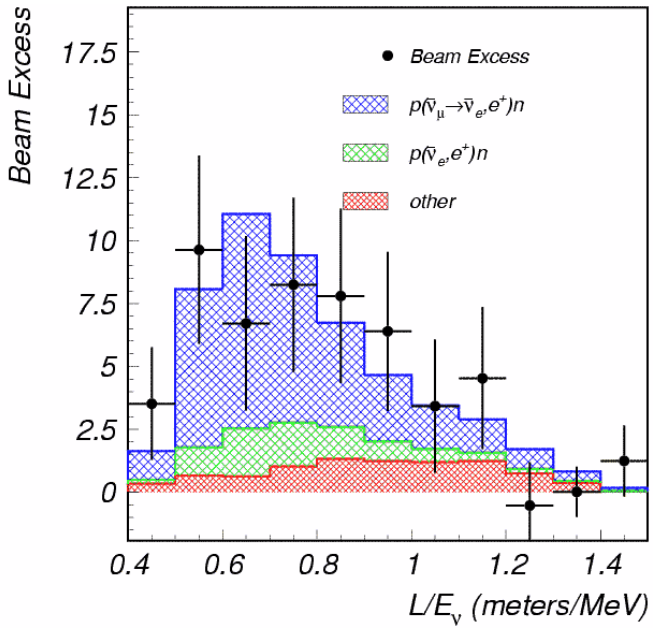
Outline

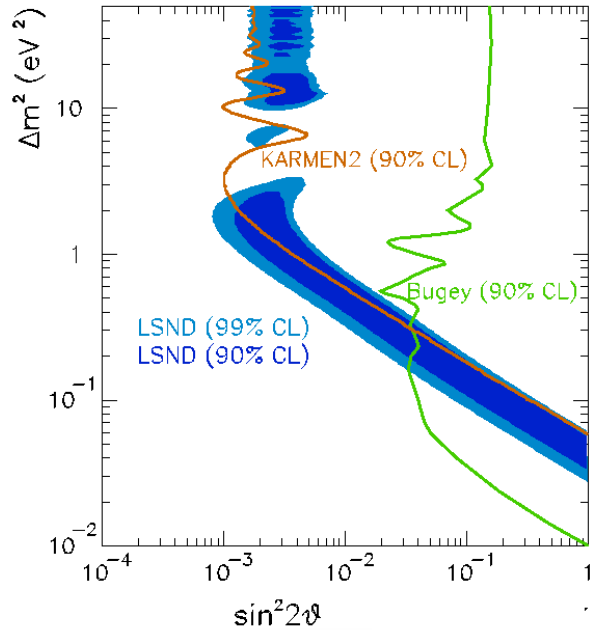
- MiniBooNE Experiment and Analysis Techniques
- MiniBooNE First Oscillation Result
- Going Beyond the First Result
- Future Plans and Prospects

MiniBooNE was Prompted by the Positive LSND Result

LSND observed a (~3.8σ) excess of $\bar{\nu}_e$ events in a pure $\bar{\nu}_\mu$ beam: 87.9 ± 22.4 ± 6.0 events

Oscillation Probability: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$





The Karmen Exp. did not confirm the LSND oscillations but had a smaller distance

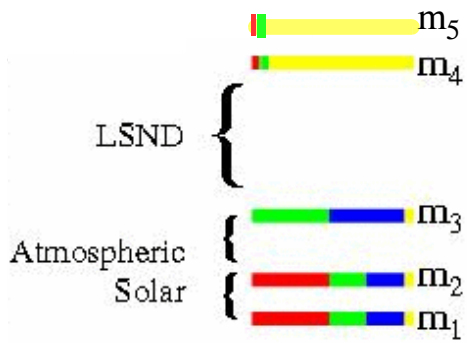
LSND in conjunction with the atmospheric and solar oscillation results needed more than 3 ν's

⇒ Models developed with 2 sterile ν's

or

⇒ Other new physics models

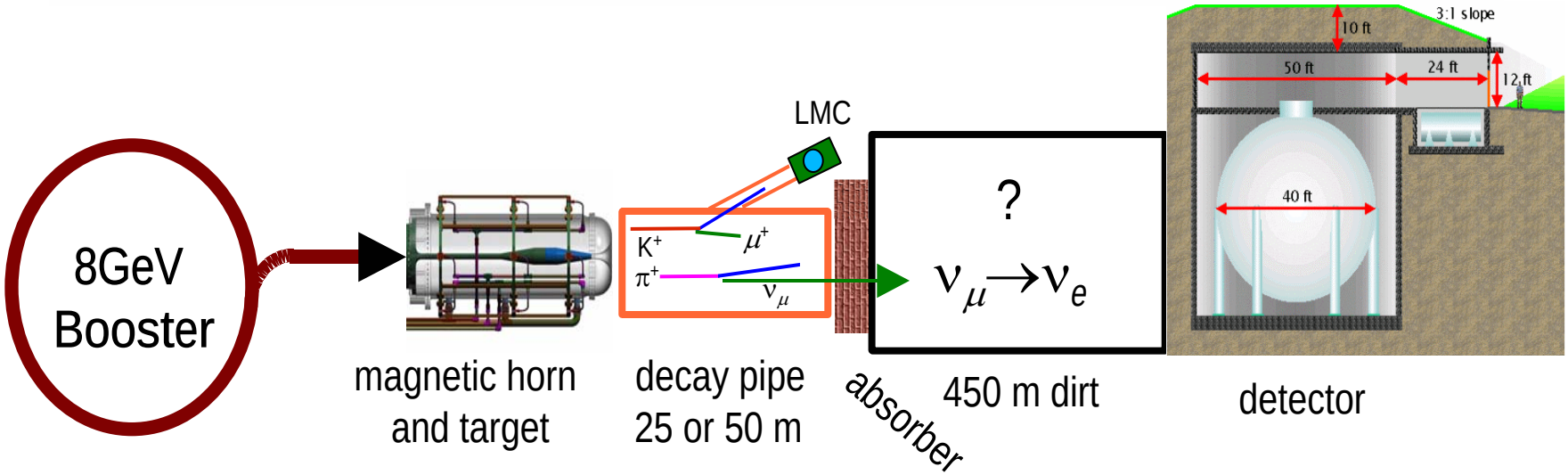
3+2 models



(Sorel, Conrad, and Shaevitz, PRD 70(2004)073004 (hep-ph/0305255)

Karagiorgi et al., PRD75(2007)013011 (hep-ph/0609177)

The MiniBooNE Experiment at Fermilab



- Proposed in summer 1997, operating since 2002
- Goal to confirm or exclude the LSND result
- Similar L/E as LSND
  - Baseline: L = 451 meters, ~ x15 LSND
  - Neutrino Beam Energy: E ~ x(10-20) LSND
- Different systematics: event signatures and backgrounds different from LSND
- High statistics: ~ x5 LSND
- 5.579E20 POT for neutrino mode since 2002.
- Switch horn polarity to run anti-neutrino mode since January 2006.

The MiniBooNE Collaboration

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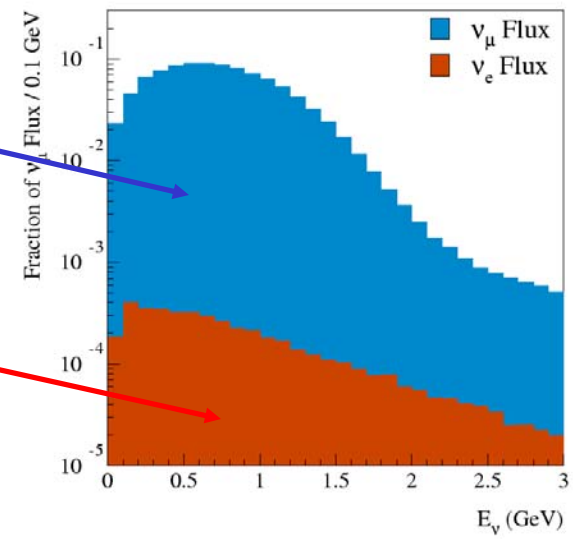
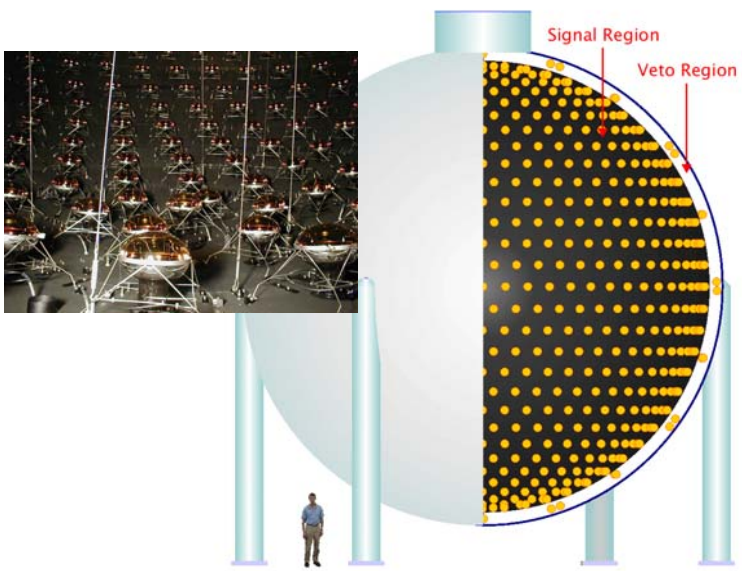
MiniBooNE $\nu_\mu \rightarrow \nu_e$ Oscillation Search

- Beam
  - Main ν_μ flux from $\pi^+ \rightarrow \mu^+ \ \nu_\mu$
  - Intrinsic ν_e flux from
    - $\mu^+ \rightarrow \nu_\mu \ e^+ \ \nu_e$
    - $K^+ \rightarrow \pi^0 \ e^+ \ \nu_e$
    - $K^0_L \rightarrow \pi^- \ e^+ \ \nu_e$

  $\Rightarrow \nu_e / \nu_\mu \approx 0.5\%$



- Detector



- 12m diameter tank
- Filled with 900 tons of pure mineral oil
- Optically isolated inner region with 1280 PMTs
- Outer veto region with 240 PMTs.

- Detector Requirements:
  - Detect and Measure Events: Vertex, E_ν …
  - Separate ν_μ events from ν_e events

Oscillation Signal
$\Rightarrow$ An Excess of "ν_e" Events over Expectation

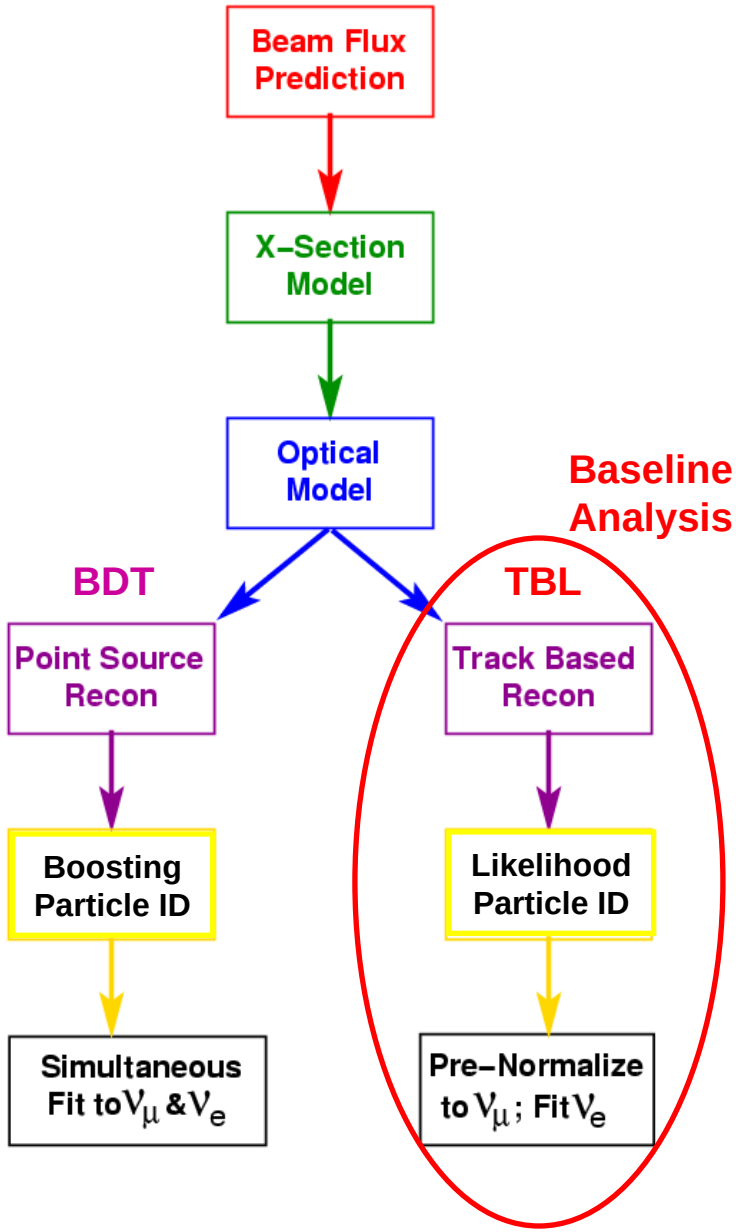
Understanding the expected events is therefore the key

- Need to know the neutrino fluxes
  - Electron neutrinos from μ, K^+, and K^0 decay
  - Muon neutrinos can make background or oscillate to give a signal
- Need to know the $\nu_{\mu/e}$ neutrino cross section vs. energy
  - Events = flux × cross section
- Need to know the ν_e reconstruction efficiency vs energy
  - Observed events = efficiency × events
- Need to know the probability for ν_μ events to be mis-identified as ν_e events $\Rightarrow$ Events with single EM showers look like ν_e events in MiniBooNE
  - Neutral current (NC) π^0 events are the main mis-id background
  - NC Δ production followed by radiative decay, $\Delta \rightarrow N\gamma$
  - Photons entering from outside detector ("Dirt" background)

MiniBooNE's Principle is to understand and calibrate the expected events from the observed non-signal events

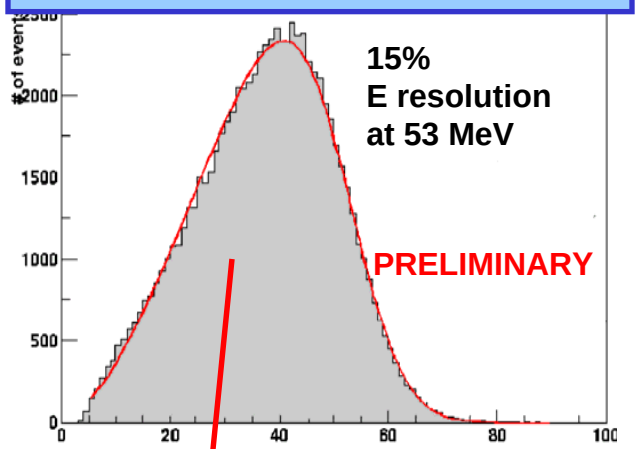
MiniBooNE analysis structure

- Start with a Geant 4 flux prediction for the ν spectrum from π and K produced at the target
- Predict ν interactions using the Nuance cross section parameterization
- Pass final state particles to Geant 3 to model particle and light propagation in the tank
- Starting with event reconstruction, independent analyses:
  - Boosted Decision Tree (BDT)
  - Track Based Likelihood (TBL) $\Leftarrow$ baseline
- Develop particle ID/cuts to separate signal from background
- Fit reconstructed E_ν spectrum for oscillations

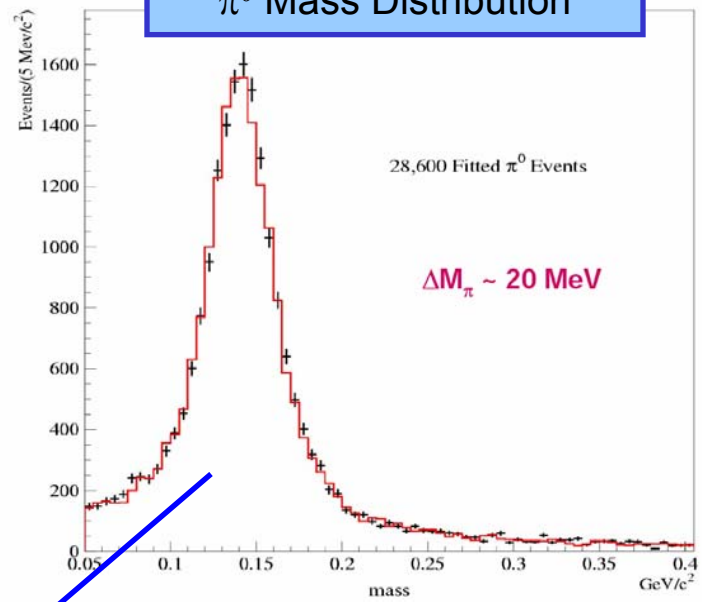


Calibrations

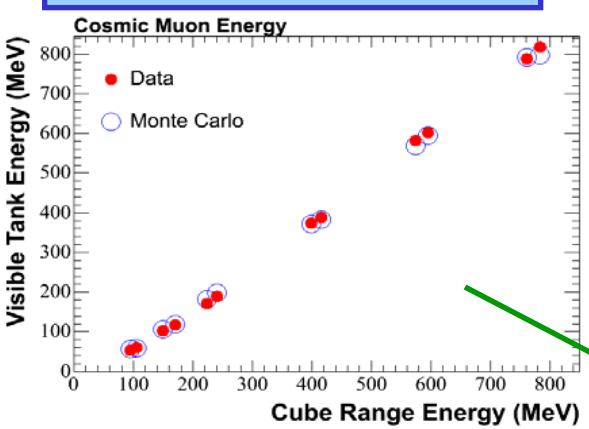
Spectrum of Michel electrons from stopping muons

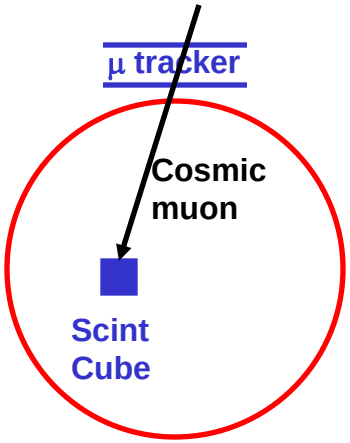


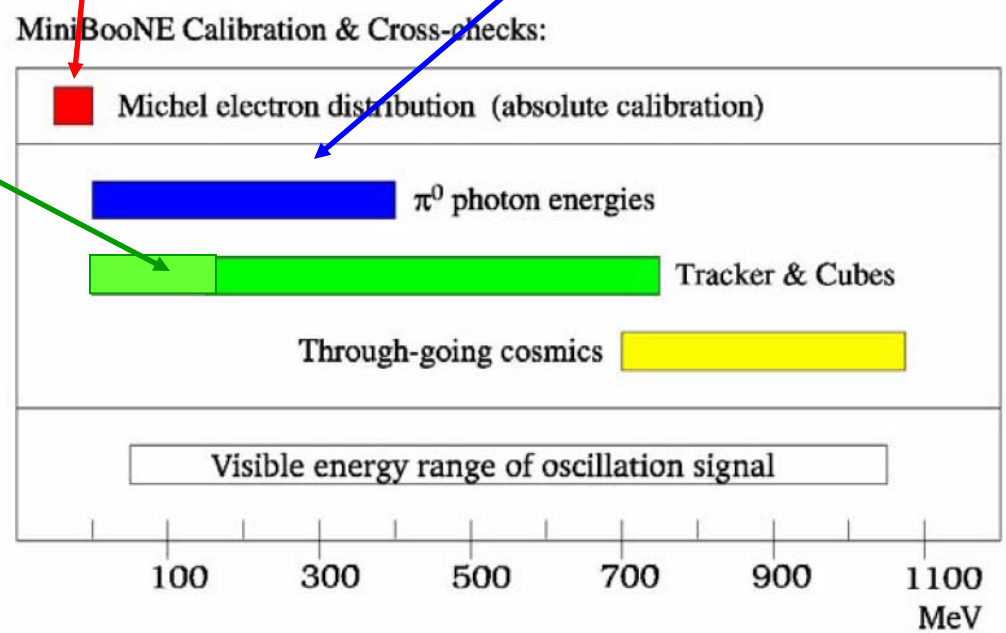
π^0 Mass Distribution



Energy vs. Range for events stopping in scintillator cubes







Particle ID Algorithms

- ν_μ id from delayed μ-decay electron signature (92% non-capture probability)

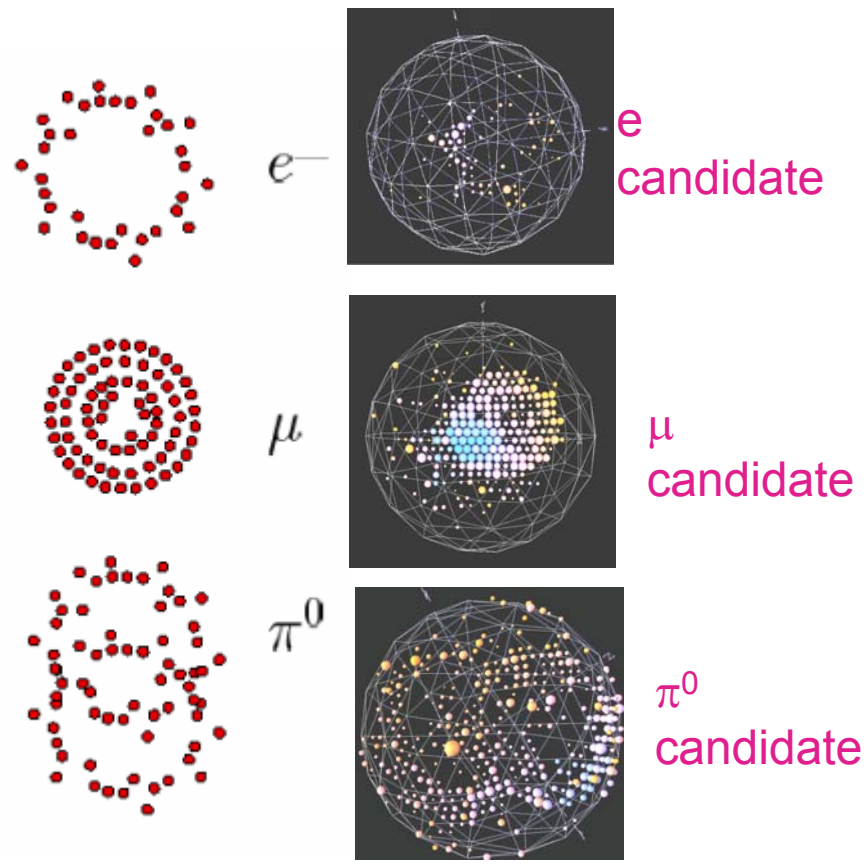
- Identify events using
  - hit topology

- PID Vars
  - Reconstructed physical observables
    - Track length, particle production angle relative to beam direction
  - Auxiliary quantities
    - Timing, charge related : early/prompt/late hit fractions, charge likelihood
  - Geometric quantities
    - Distance to wall

- Two PID algorithms

  1. **TBL**: Likelihood based analysis: e/μ and e/π^0 (Baseline)

  2. **BDT:** A "boosted decision tree" algorithm to separate e, μ, π^0
     (See B. Roe et al. NIM A543 (2005))



Cuts Used to Separate ν_μ events from ν_e events

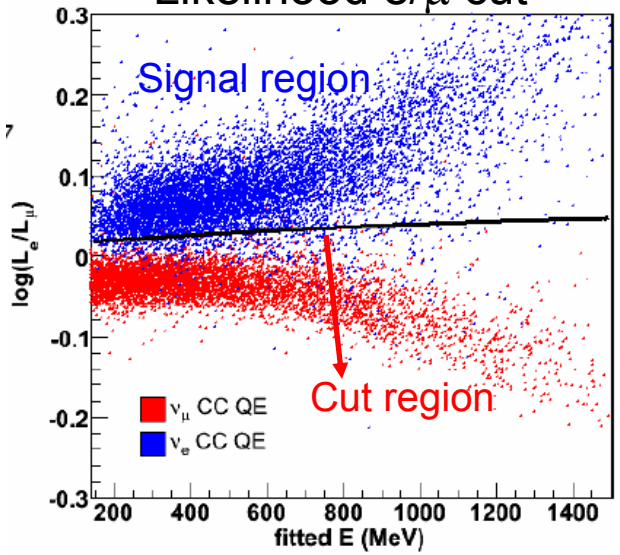
Compare observed light distributions to fit prediction:

Apply these likelihood fits to three hypotheses: **TBL Analysis**

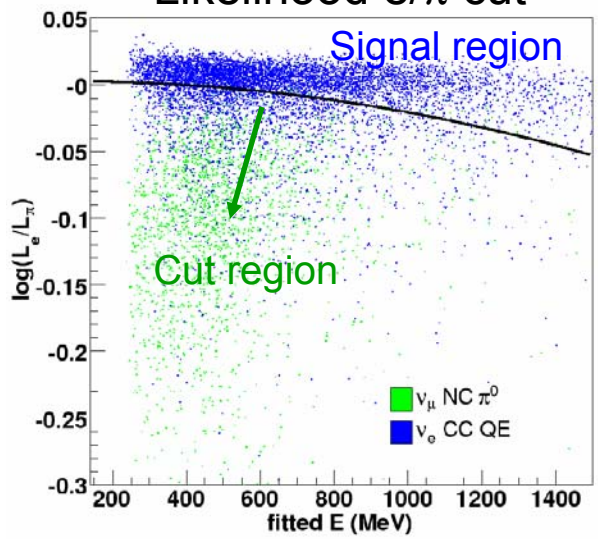
- **single electron track L_e**
- **single muon track L_μ**
- **two electron-like rings (π^0 event hypothesis) L_π**

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

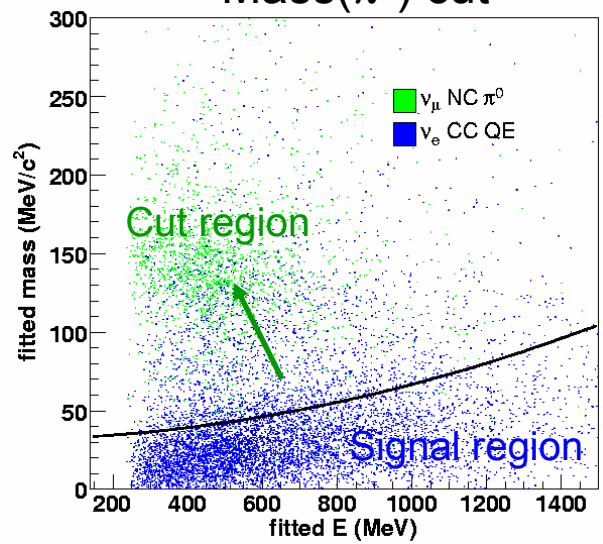
Likelihood e/μ cut



Likelihood e/π cut



Mass(π^0) cut



Blue points are signal ν_e events

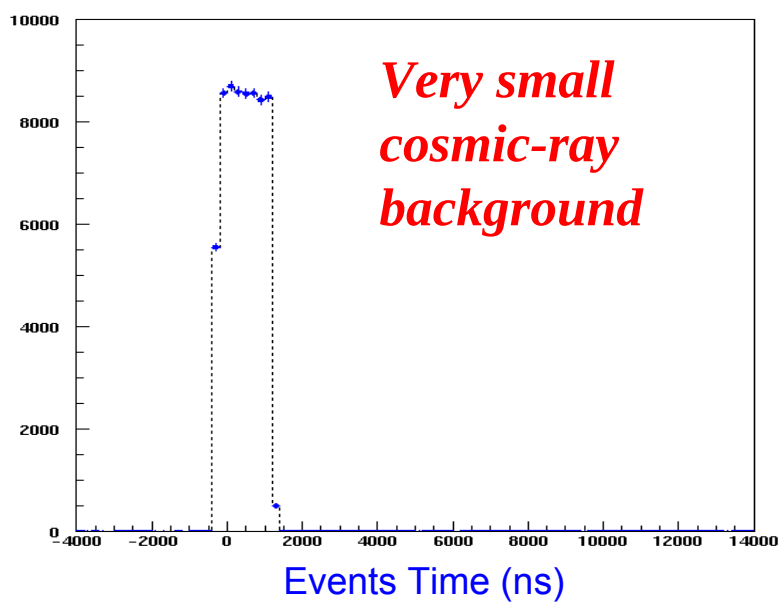
Red points are background ν_μCC QE events

Green points are background ν_μ NC π^0 events

Expected Event Numbers

Events with ν_μ Selection Requirements

Events = 193,730 (mainly ν_μ CCQE)
(Final data sample for 5.58 × 10^{20} pot)

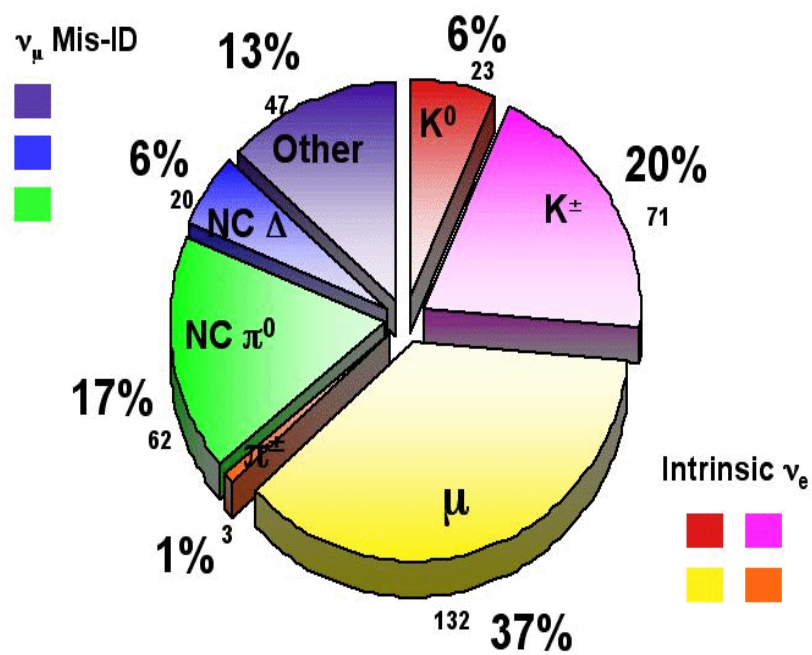


Events with ν_e Selection Requirements $475<E_\nu<1250$ MeV

TBL analysis predicted backgrounds

Total Expected Background = 358 events

Example LSND Osc Signal = 163 events
(Δm^2 = 0.4 eV^2 , $\sin^2 2\theta$ = 0.017)

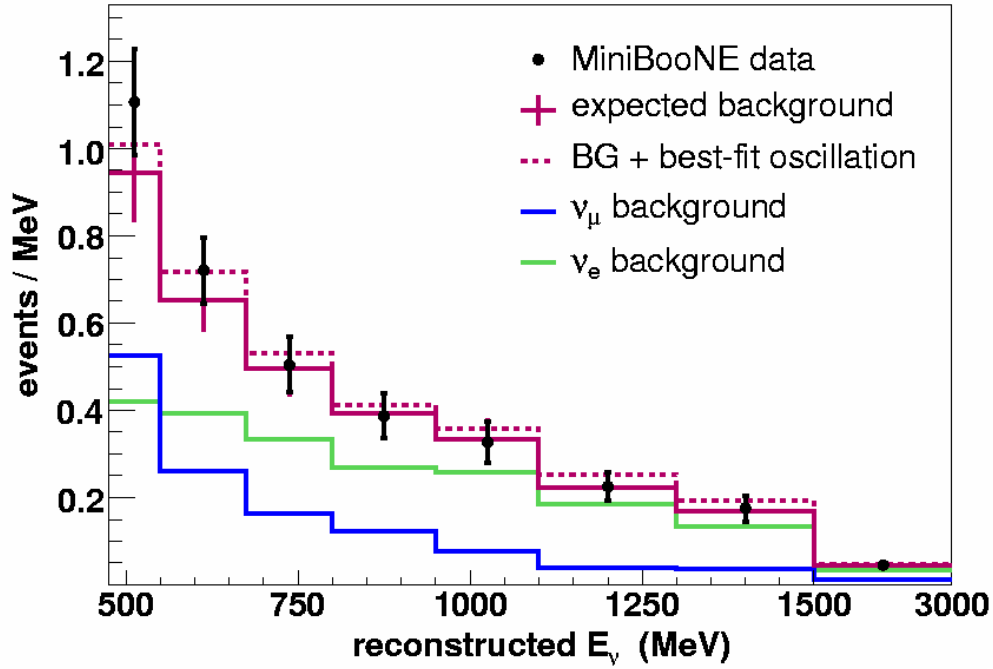


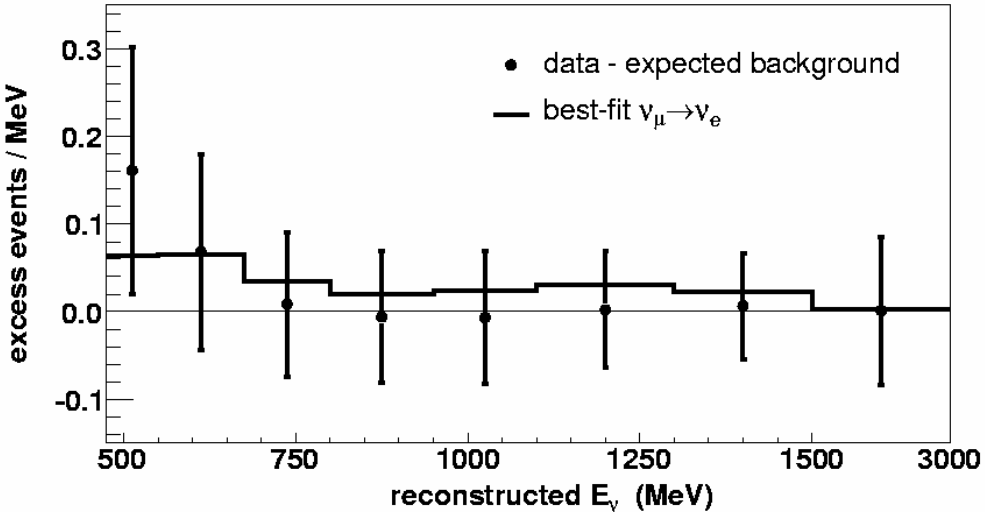
Systematic Uncertainties

source of uncertainty on ν_e background	TBL syst. error (%)	constrained by MB data?	Reduced by relating ν_e to ν_μ
Flux from π^+/μ^+ decay	6.2	Y	Y
Flux from K^+ decay	3.3	Y	
Flux from K^0 decay	1.5	Y	
Target/Beam model	2.8	Y	Y
ν cross section	12.3	Y	Y
NC π^0 yield	1.8	Y	
Out of tank events	0.8	Y	
Optical Model	6.1	Y	Y
DAQ electronics model	7.5	Y	

For the oscillation analysis, these systematic uncertainties are applied through a fully correlated systematic error matrix

MiniBooNE First Results (April, 2007)





Data consistent with expected background
$\Rightarrow$ No indications of oscillations

Oscillation Search Region
$475 < E_\nu < 1250$ MeV

data: 380 ± 19 (stat) events
expectation: 358 ± 35 (sys) events
significance: 0.55 σ

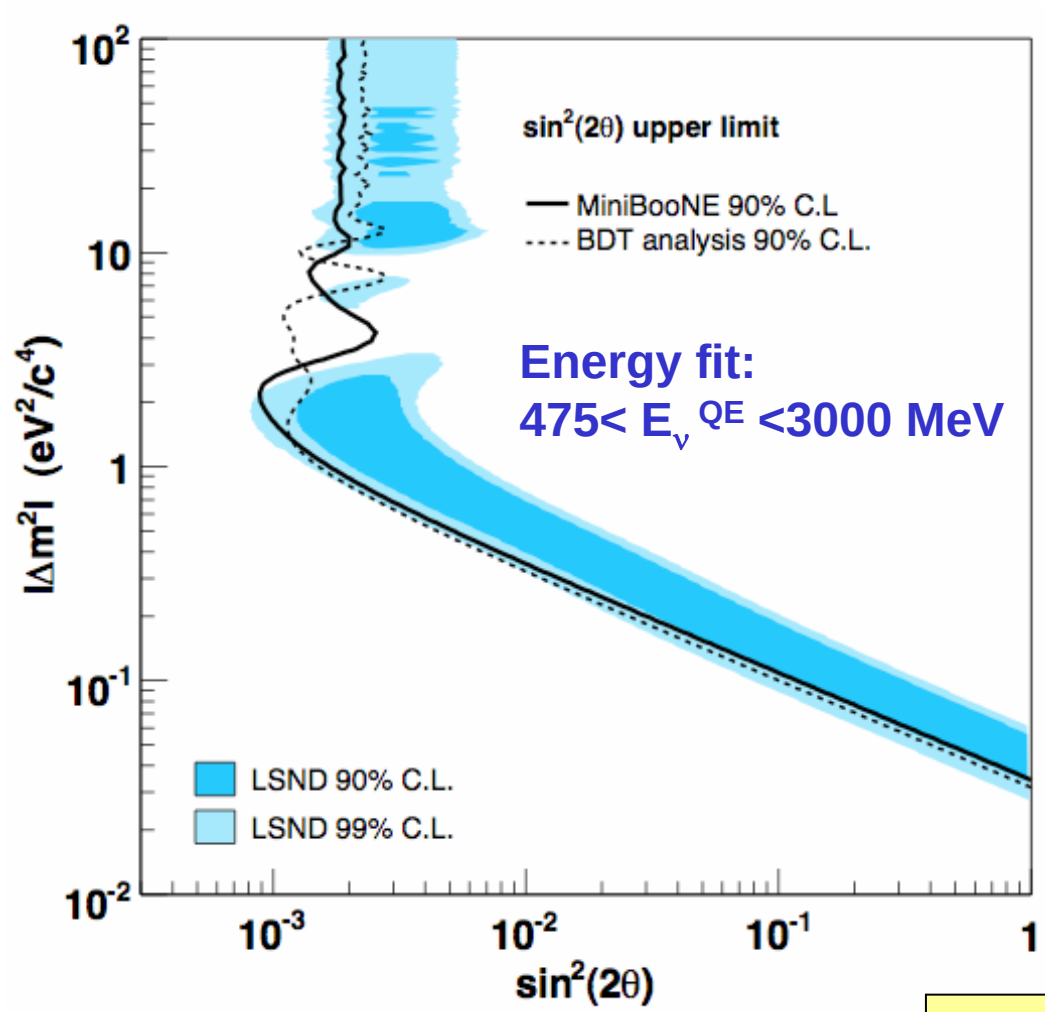
Best Fit (dashed):
$(\sin^2 2\theta, \Delta m^2) = (0.001, 4\ \text{eV}^2)$

Probability of Null Fit: 93%
Probability of Best Fit: 99%

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_p E_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}\cos\theta_\ell}$$

Data consistent with expected background

$\Rightarrow$ Inconsistent with a $\nu_\mu \rightarrow \nu_e$ 2-neutrino oscillation model so we set a limit.

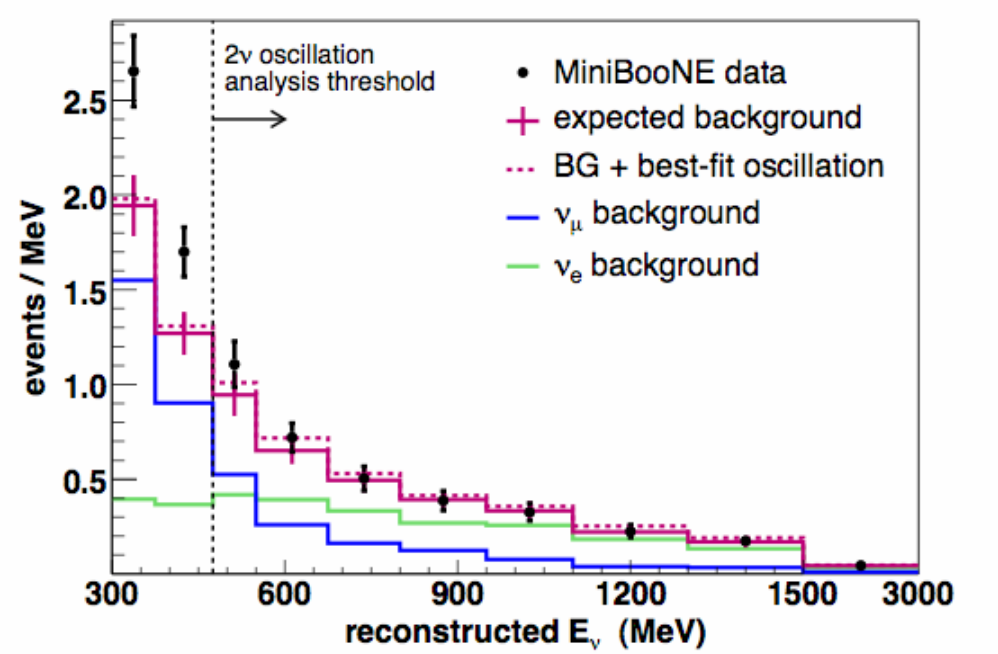


Energy-fit analysis:
Solid: TBL (baseline)
Dashed: BDT

Details:

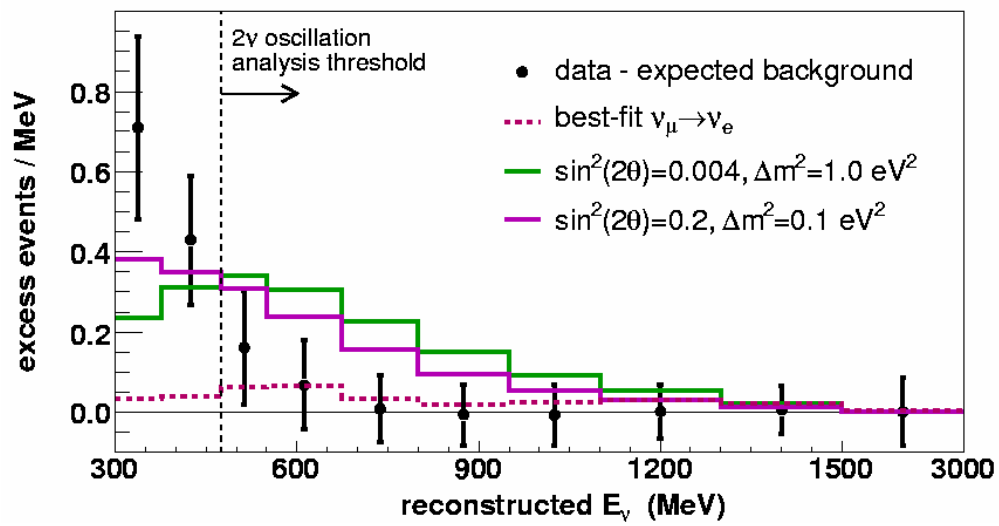
Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500 [hep-ex]

But an Excess of Events Observed Below 475 MeV



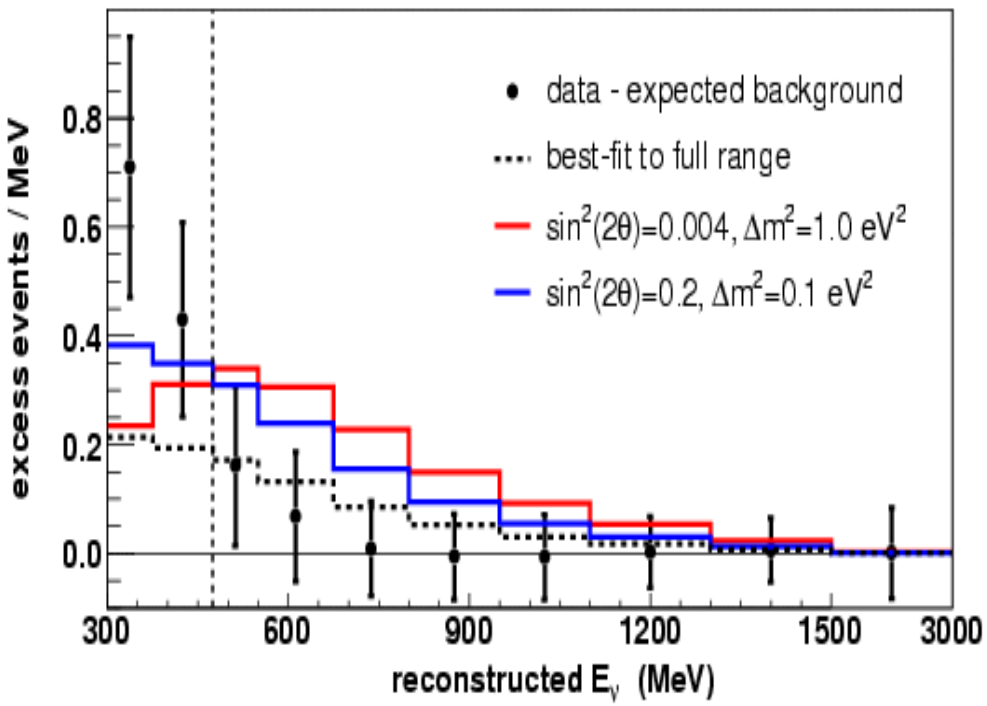
96 ± 17 ± 20 events above background, for 300< E_ν^{QE} <475MeV

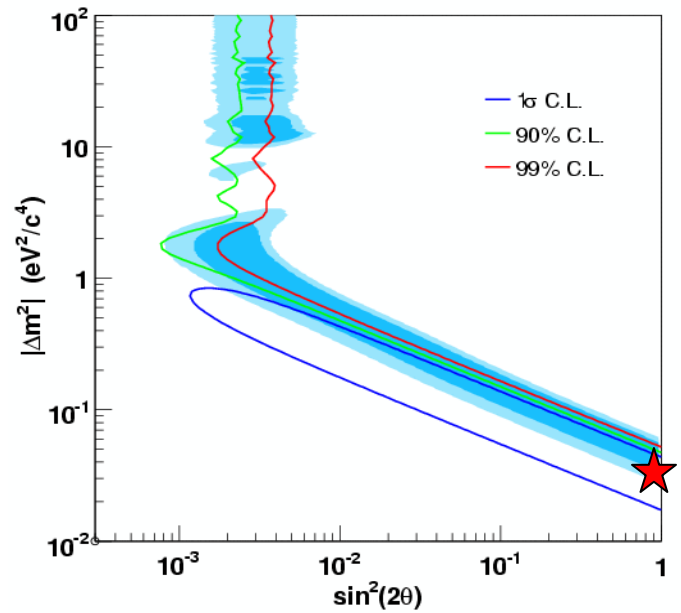
Deviation: 3.7 σ

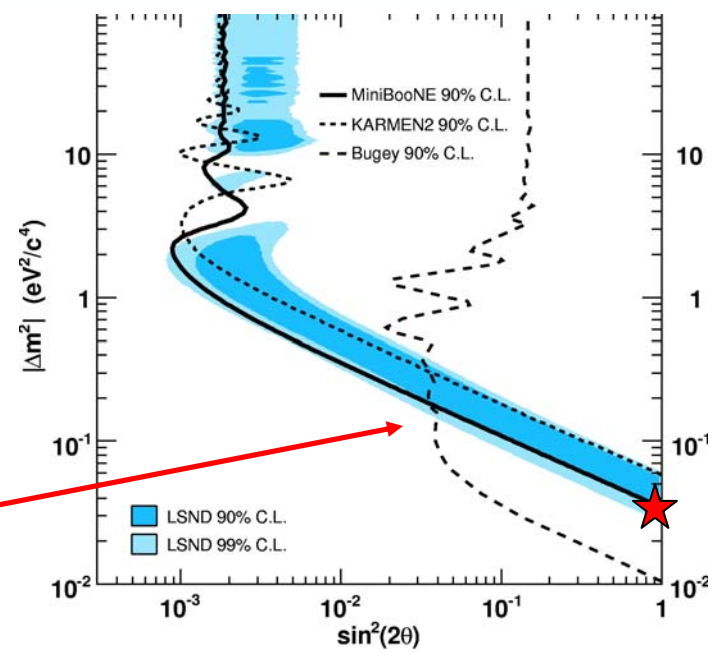


Excess Distribution inconsistent with a 2-neutrino oscillation model for LSND

2-neutrino Oscillation Fits for 300 – 3000 MeV







Best Fit (dashed):
($\sin^2 2\theta$, Δm^2) = (1.0, 0.03 eV^2)
χ^2 Probability: 18%

This best fit is not probable but also ruled out by the Bugey and Chooz reactor experiment.

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, …….

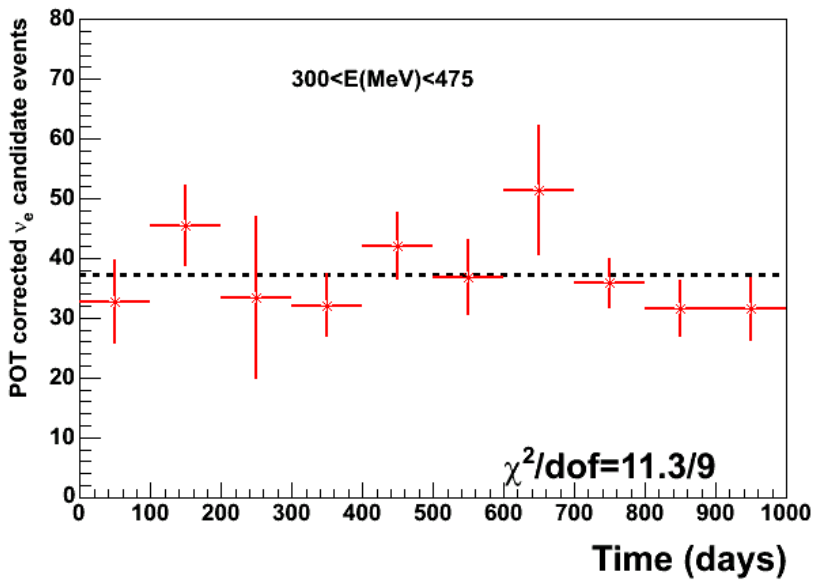
Any of these backgrounds or signals could have an important impact on other future oscillation experiments.

Detector Anomalies or Reconstruction Problems

No Detector anomalies found

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

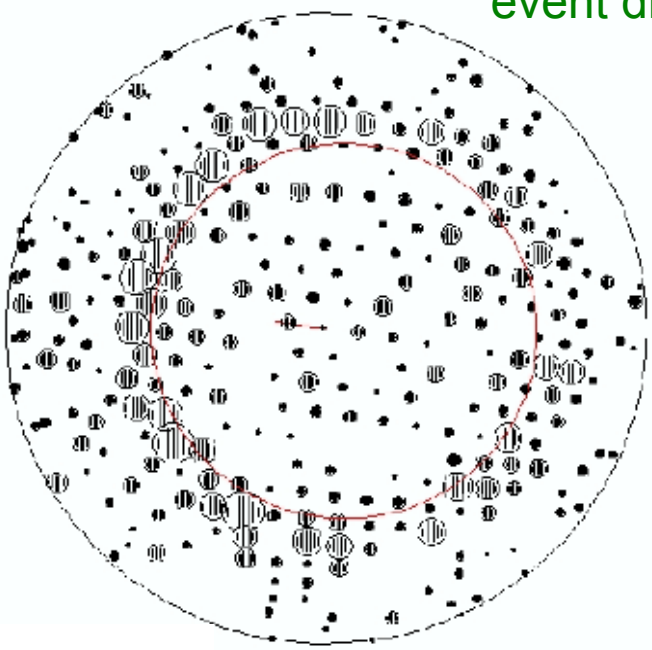
event/POT vs day, 300<Enu<475 MeV



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



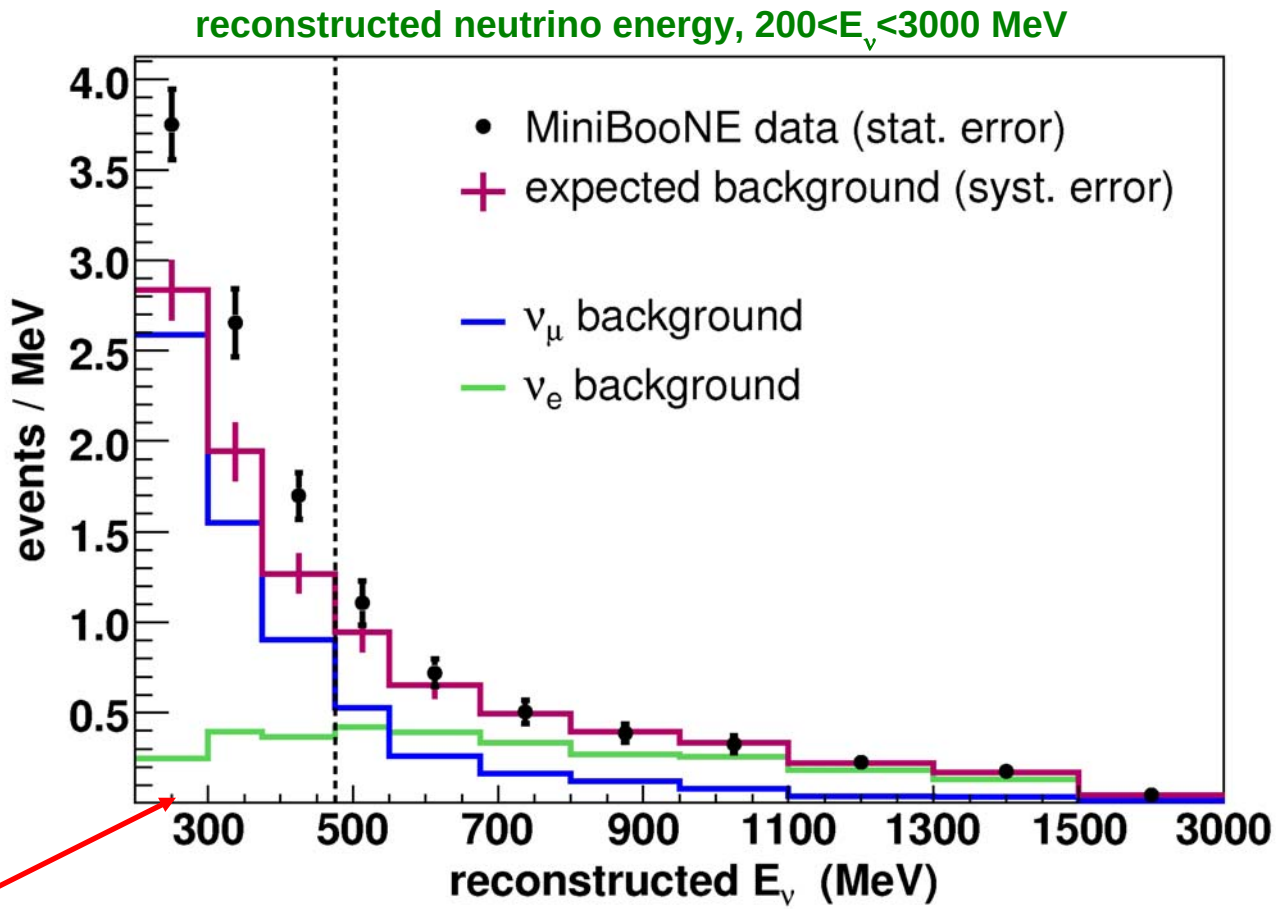
Signal candidate events are consistent with single-ring neutrino interactions

$\Rightarrow$ But could be either electrons or photons

New Result for 200 – 300 MeV Bin

Excess persists below 300 MeV

⇒ as one goes to lower energy background increasing but excess is not



New low energy bin

Background Estimates

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	95±28	22±40	(stat+syst)

"Dirt Background"
ν interactions outside of the detector that mainly give a single gamma from π^0 decay

- NC π^0 largest
- Dirt background significant
- NC $\Delta \rightarrow N\gamma$ and Intrinsic ν_e falling off

- All have similar rates:
  - NC π^0
  - Dirt bkgnd
  - NC $\Delta \rightarrow N\gamma$
  - Intrinsic ν_e

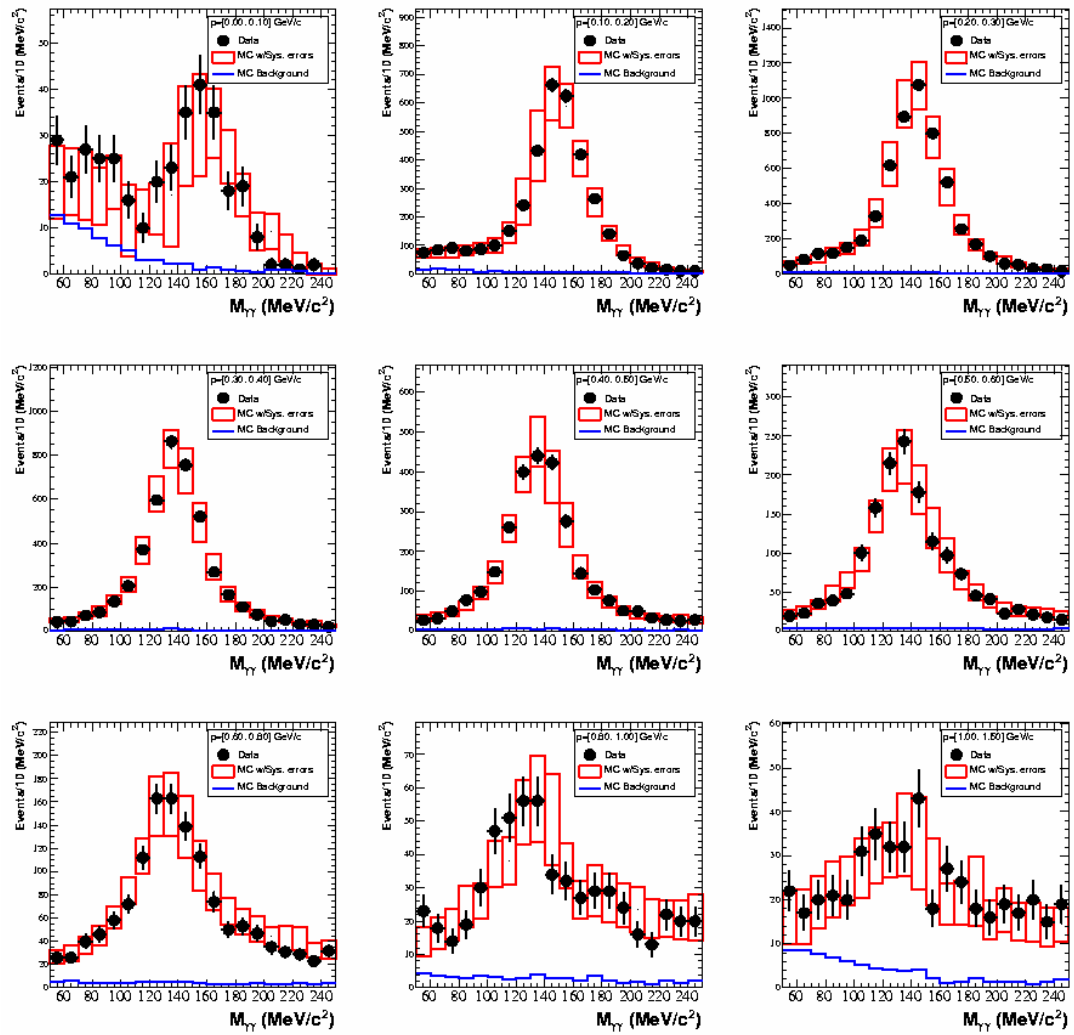
- Intrinsic ν_e largest
- NC π^0 significant
- Others small

NC π^0 and Radiative $\Delta \rightarrow N\gamma$ Backgrounds are Constrained by Identified NC π^0 Events

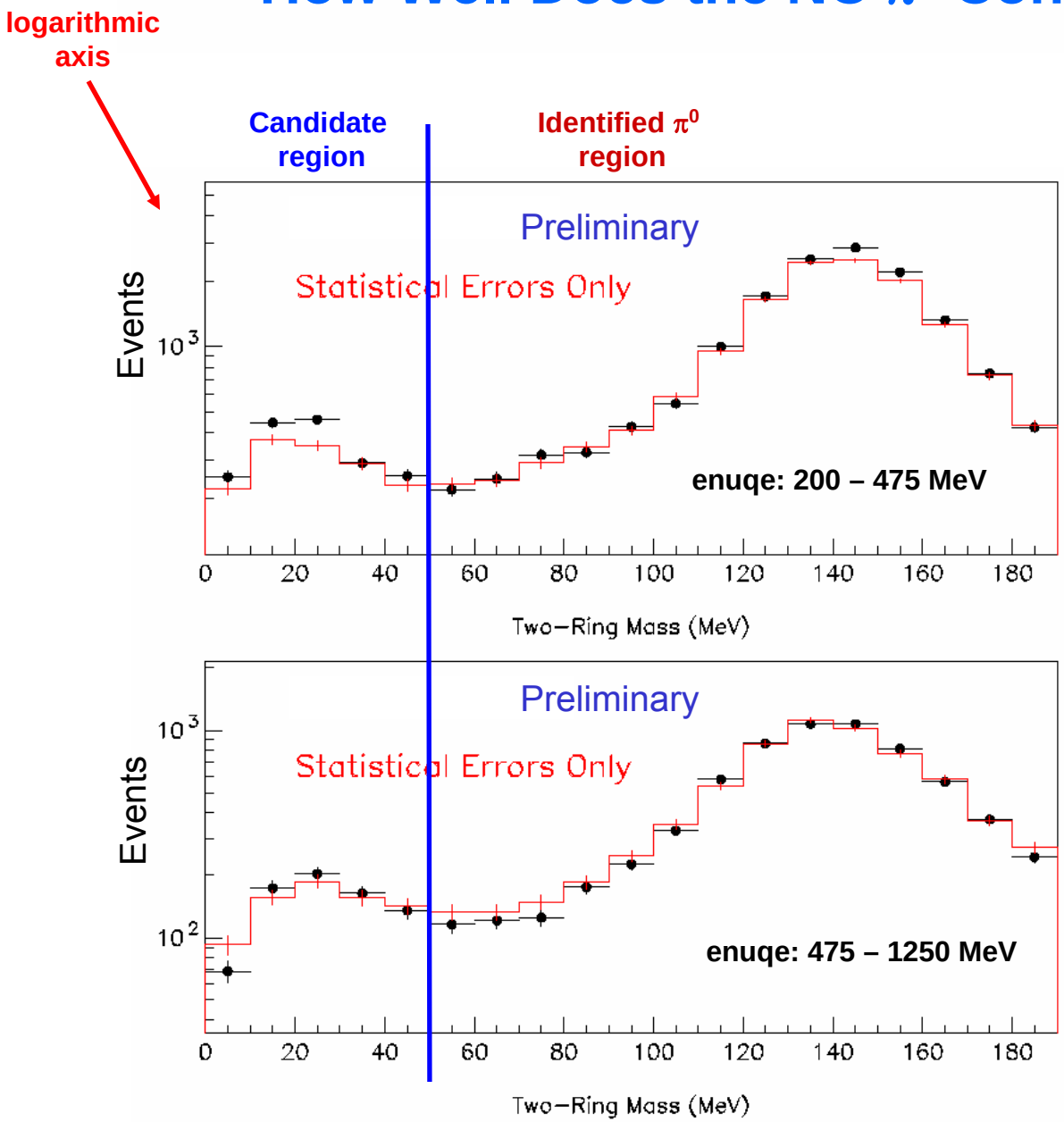
- Using PID variables isolate a very pure sample π^0 events from $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$ (mainly from $\Delta \rightarrow N + \pi^0$)
- Purity ~90% or greater
- Measure π^0 production rate as a function of π^0 momentum and compare to MC prediction to calculate a correction factor.
- Correct NC π^0 mis-ID rate using this measured correction factor

  (Also can be used to correct the $\Delta \rightarrow N + \gamma$ radiative background)

$M_{\gamma\gamma}$ Mass Distribution for Various $p_{\pi 0}$ Momentum Bins



How Well Does the NC π^0 Constraint Work?

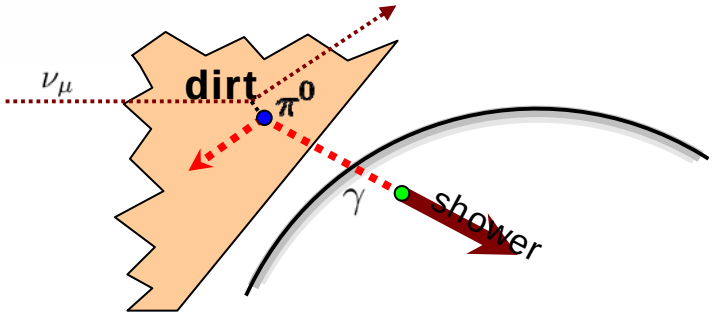


Results after removing the mass and $L_{e\pi}$ cut

- Good agreement in "Identified π^0 region"
- Excess for low energy sample clearly observed below 50 MeV
- Excess cannot be explained by simply scaling up the π^0 and Rad-Δ background

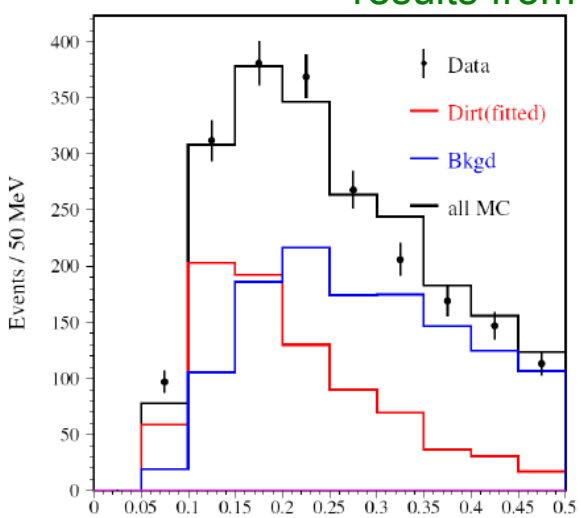
Black points: Data
Red histogram: Prediction

"Dirt" background

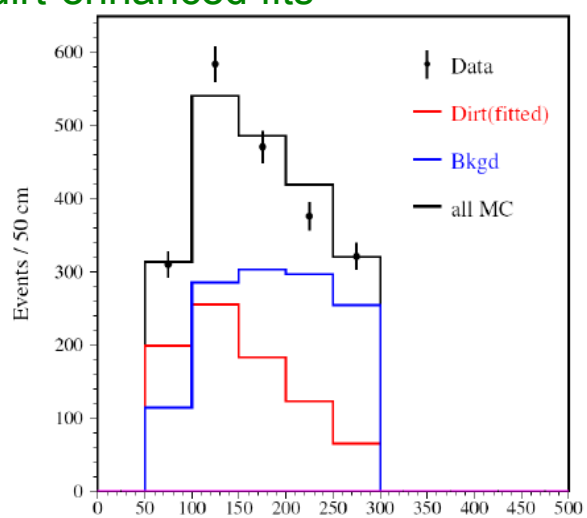


- dirt background is due to ν interactions outside detector creating neutrals that enter tank
- **measured** in "dirt-enhanced" samples:
  - before box-opening, fit predicted: 1.00±0.15
  - in different (open) sample, a fit says that meas/pred is 1.08±0.12.
- shape of visible E and distance-to-wall distributions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

results from dirt-enhanced fits

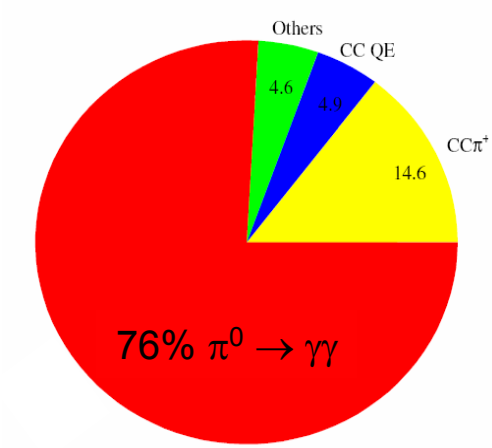


visible energy (GeV)



dist to tank wall along track (cm)

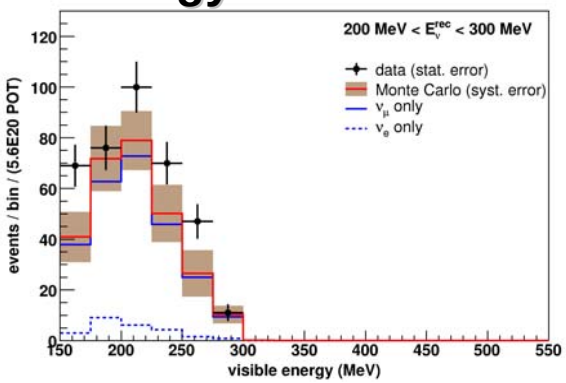
Event Type of Dirt Events

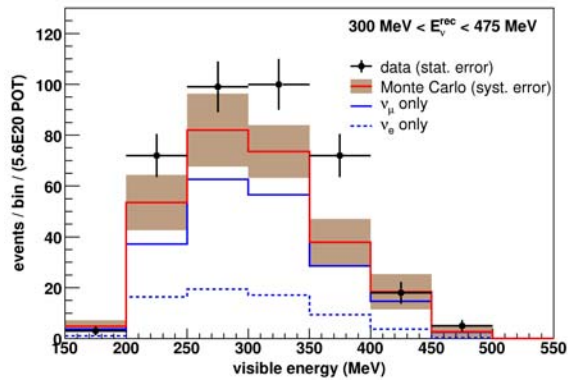


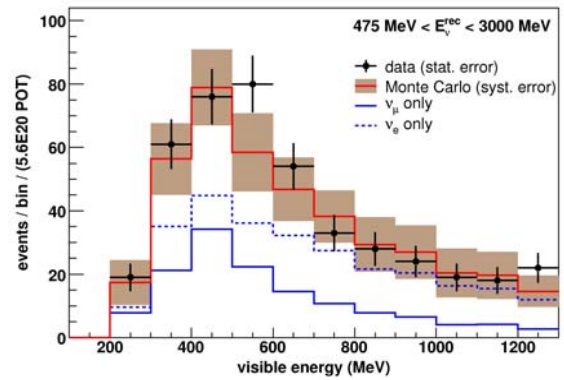
Visible Energy and cosθ of Events

200<E_ν<300 MeV **300<E_ν<475 MeV** **475<E_ν<3000 MeV**

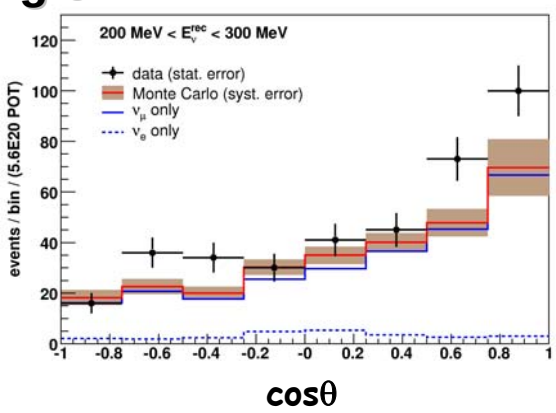
Visible energy

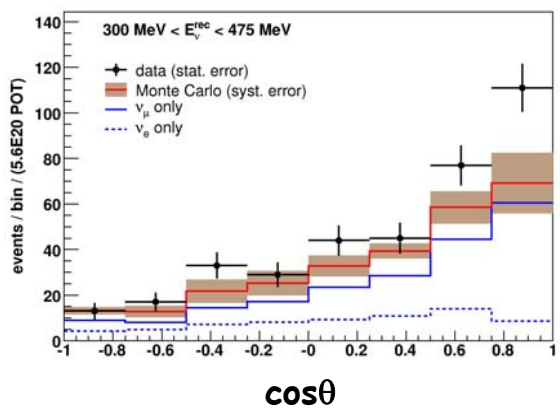


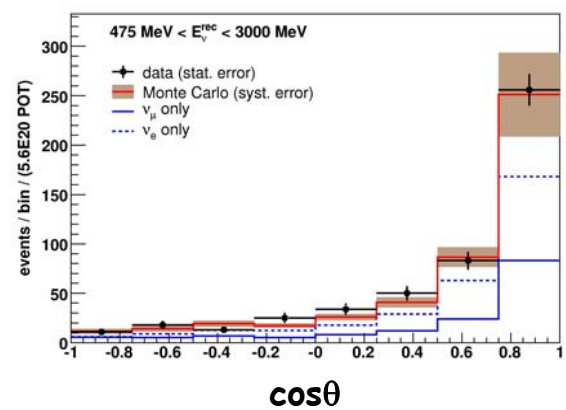




Angle







-Low Energy: Excess distributed among visible E, cos Θ bins.

-High Energy:Predicted background agrees with data.

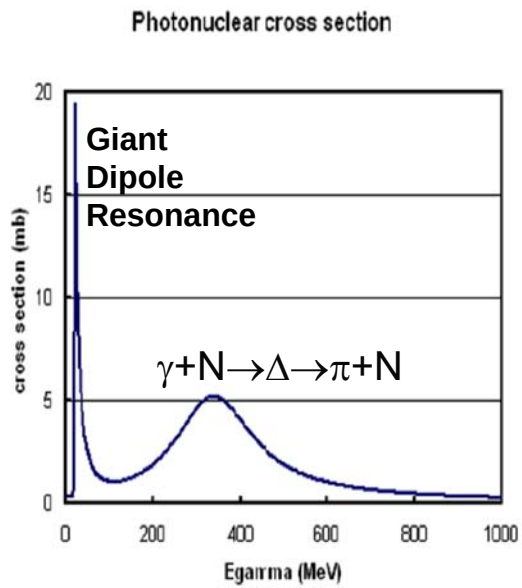
Possible Sources of Single Gamma Backgrounds

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

- Processes that remove/absorb one of the gammas from a ν_μ-induced NC $\pi^0 \rightarrow \gamma\gamma$
  - These processes should be in the GEANT detector Monte Carlo but there might be exceptions or inaccurate rates
    - Example: photonuclear absorption

      But tends to give extra final state particles.

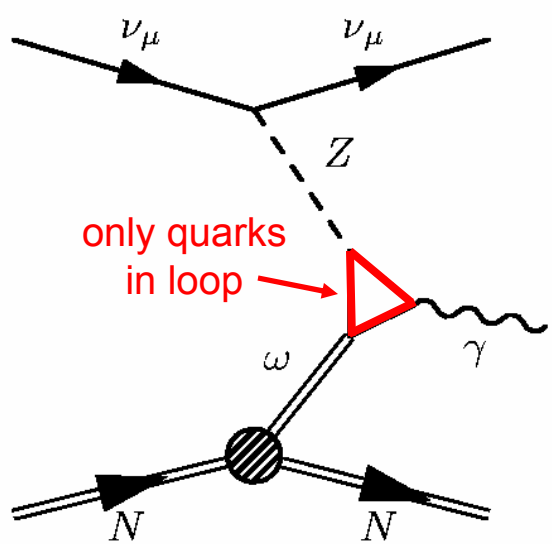
      $\Rightarrow$ Under active investigation



- ν processes that produce a final state single gamma
  - Example: "Anomaly mediated neutrino-photon interactions at finite baryon density."
    - No quark vs. lepton cancellation in loop since only quarks can contribute

      $\Rightarrow$ Under active investigation

(Harvey, Hill, and Hill, hep-ph0708.1281)

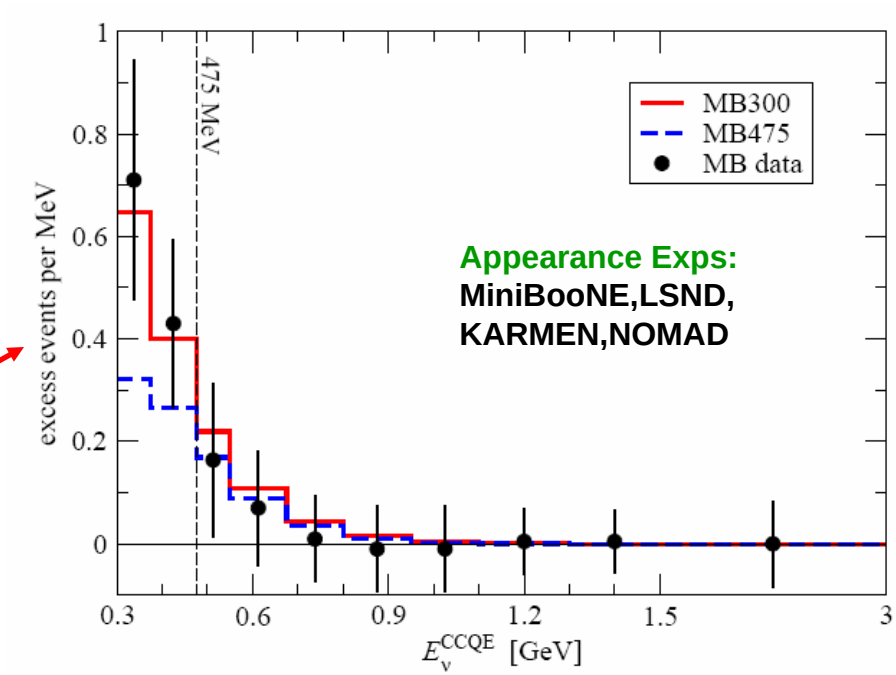


New Physics: Models with Sterile Neutrinos

- Models with 3 active and 1 sterile neutrino (3+1) are excluded by various ν_μ and ν_e disappearance measurements

- 3+2 models can give a good fit to appearance data but fit is discrepant with the disappearance results: Bugey,Chooz,PaloVerde,CDHS. (Appearance and disappearance incompatible at the 4σ level) (Maltoni and Schwetz, hep-ph0705.0107 G. Karagiorgi, NuFACT 07 conference)

- 3+2 models may also produce measurable effects in the Double Chooz experiment especially for the near detector (Bandyopadhyay and Choubey, hep-ph0707.2481)



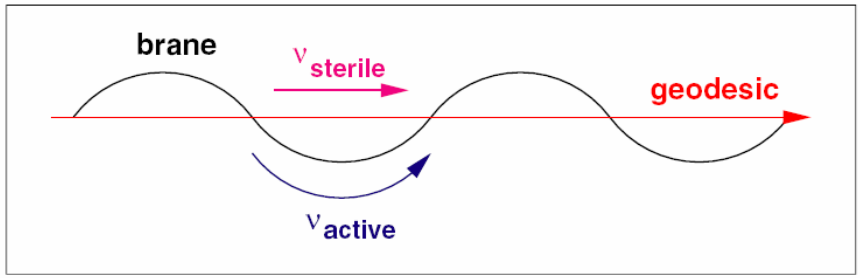
Sterile Neutrinos That Take Shortcuts in Extra Dimensions

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

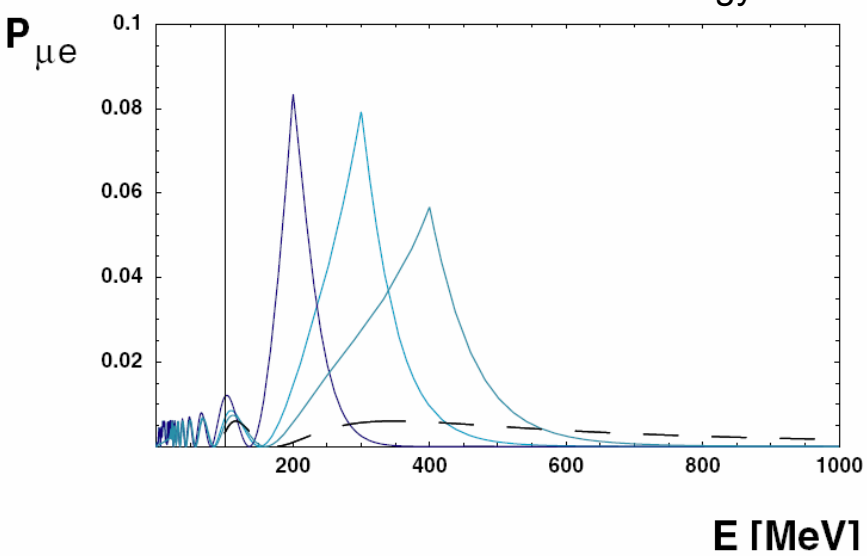
(Päs, Pakvasa, Weiler, Phys.Rev. D72 095017, 2005)

  - 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.

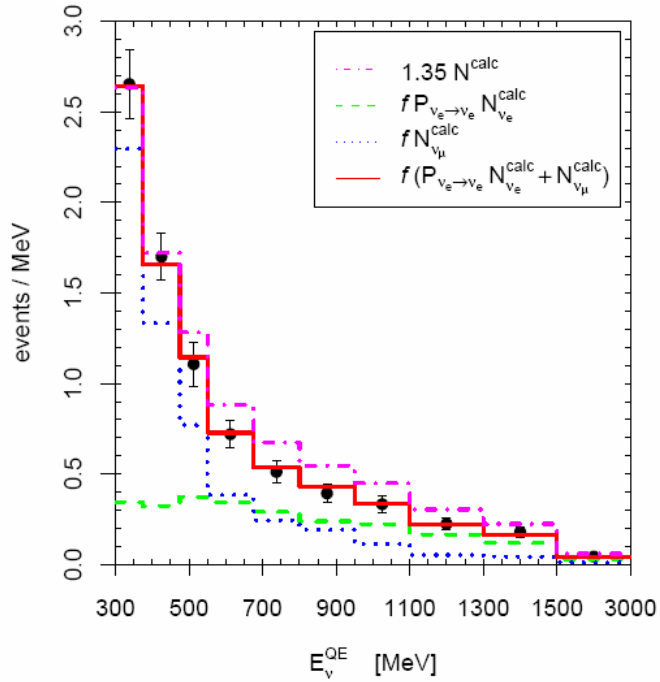


Oscillation probabilities for MiniBooNE as a function of the neutrino energy.



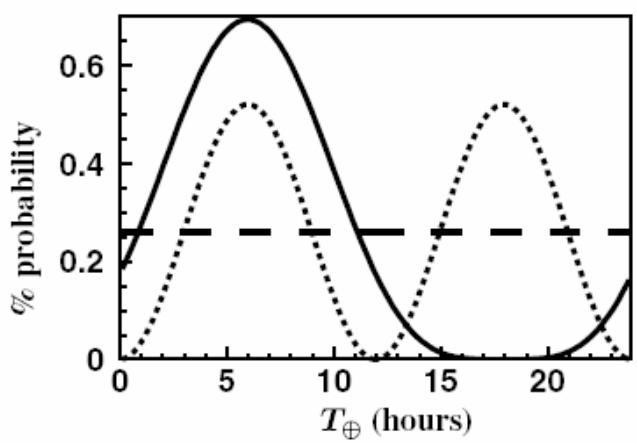
Other New Physics Models

- Electron neutrino disappearance
  (Giunti and Laveder, hep-ph 0707.4593)
  - Prompted by the deficit seen in the Ga exp's source calibrations
  - To fit the MiniBooNE data, postulate that the neutrino flux is off by x1.48 and that electron neutrino disappearance probability is 0.59
  - ⇒ This model disagrees with the MiniBooNE constraints on the measured π^0 background



- Lorentz Invariance Violation
  (Katori, Kostelecký, Tayloe, PRD 74,1050009)
  - Adding Lorentz invariance violating terms in the Hamiltonian that depend on neutrino flavor can produce interference terms for the neutrino propagation
  - New oscillation phenomenology
    - Osc length dependence on E*L
    - Variation with sidereal position

Prob **($\nu_e \rightarrow \nu_e$) over one sidereal day**



Future Plans and Expectations

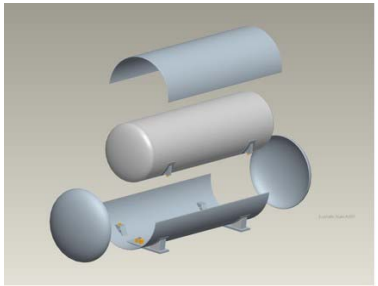
- MiniBooNE has been running with an antineutrino beam and is proposing to run antineutrinos for several more years.
  - Statistics are less but backgrounds are smaller and somewhat different.
  - Provides another low E data set and directly checks LSND

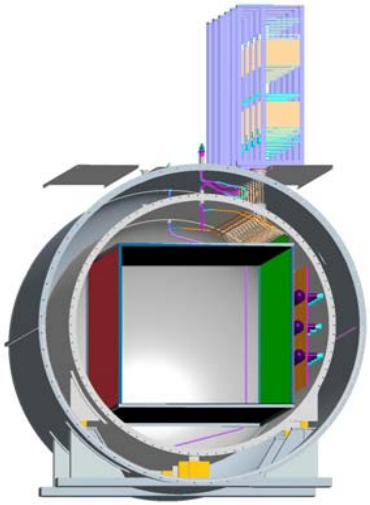
- SciBooNE is a near detector experiment now running that should be able to make a cross check of the intrinsic ν_e's from kaon decay.
  - SciBooNE will not have the statistics to address the low E excess

- MiniBooNE sees offaxis neutrinos from the NuMI (Minos) beam
  - Distance and energy is not very much different from MiniBooNE
  - Backgrounds are much different with enhanced intrinsic ν_e's

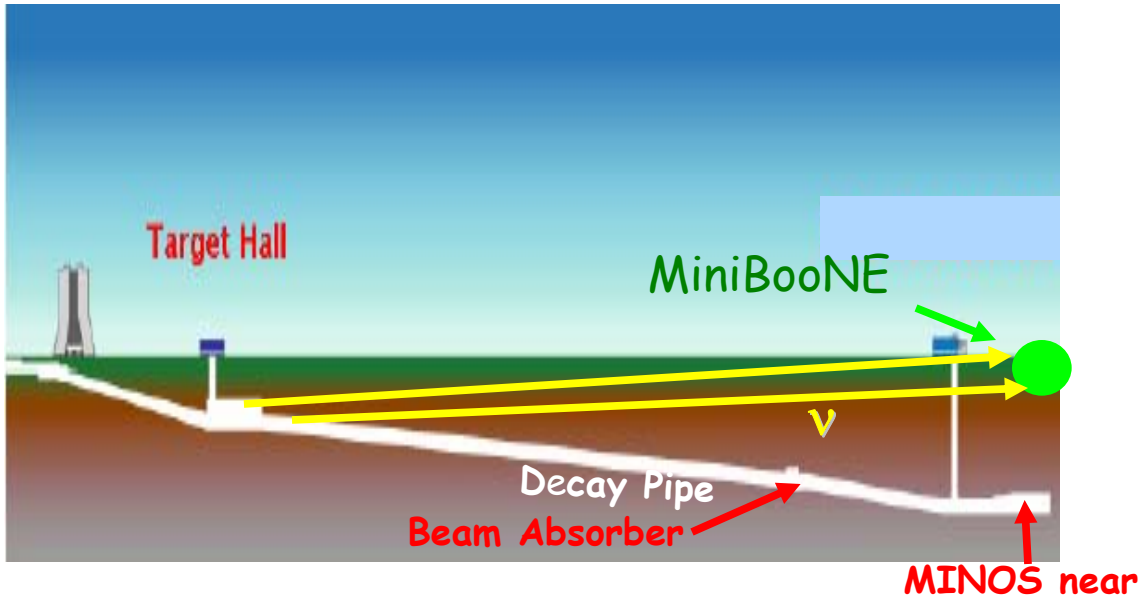
  $\Rightarrow$ MiniBooNE(NuMI) oscillation results expected in Nov. 2007

- MicroBooNE
  - New proposed experiment to put a 70 ton Liquid Argon detector near MiniBooNE
    - High ν_e efficiency down to low energies
    - Can tell electron from gamma events
    - Nearly free of background from misidentified particles





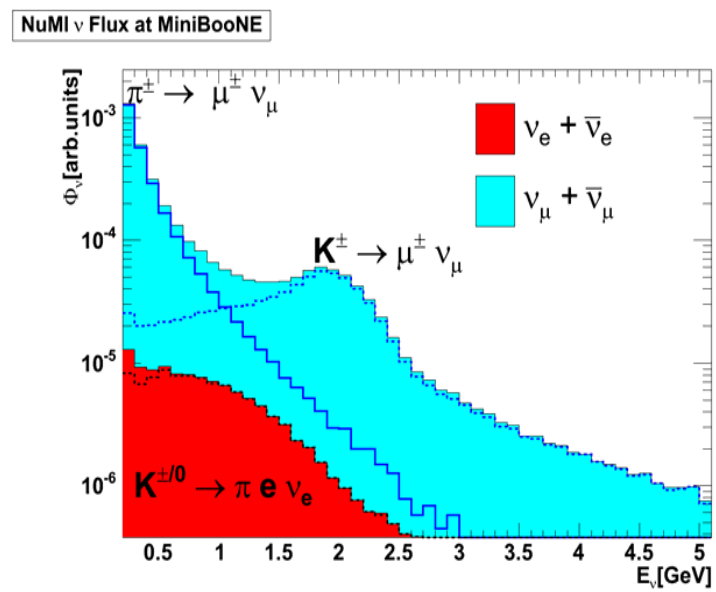
NuMI Events in MiniBooNE



- NuMI beam events in MiniBooNE
  - Have similar L/E as MiniBooNE
    - distance (L) 750 m
    - energy (E) about 1.25 GeV
  - NuMI events significantly enhanced with ν_e from K decay

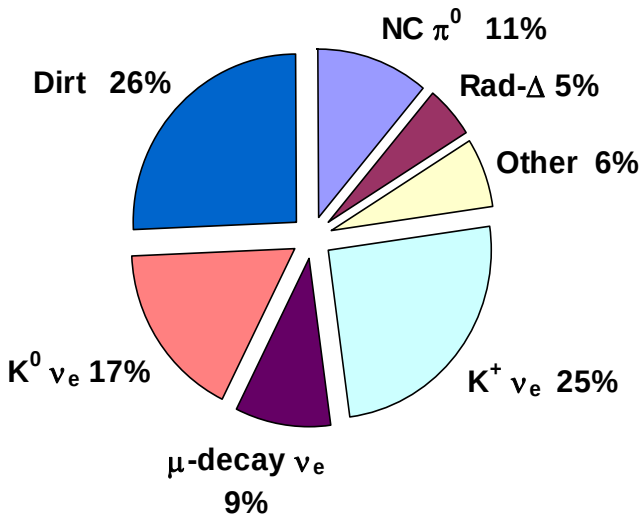
NuMI event composition:
ν_μ 81% ν_e 5% $\bar{\nu}_\mu$ 13% $\bar{\nu}_e$ 1%

- NuMI events can be used to check the low energy excess
  - If a background enhancement, then will show different relative rate due to different event composition
  - If from ν_μ induced production (i.e. osc. or γ), then will show similar relative rate.

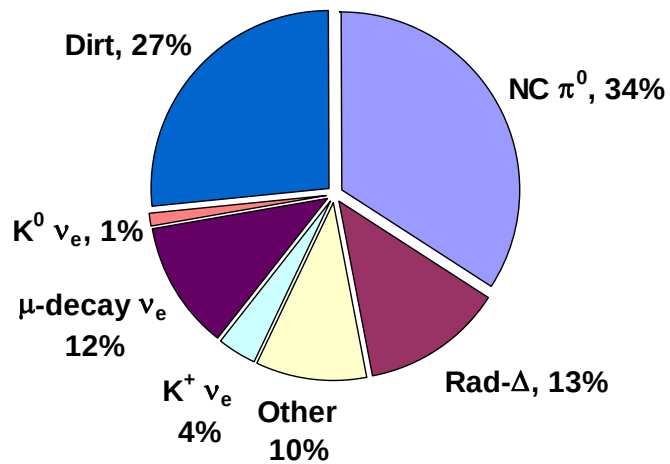


ν_e Backgrounds – NuMI vs MiniBooNE events

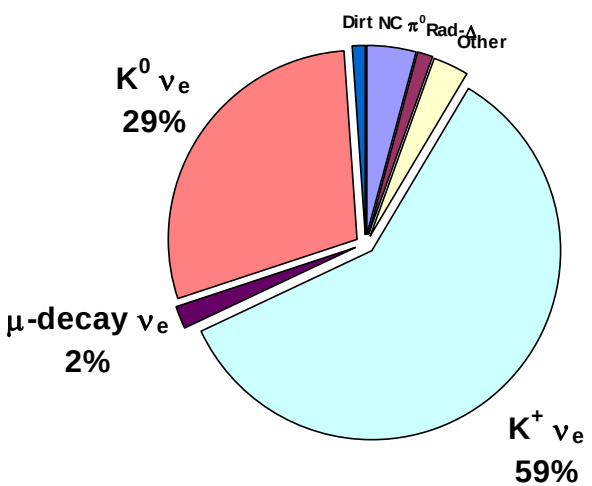
NuMI Background Events (200 - 475 MeV)



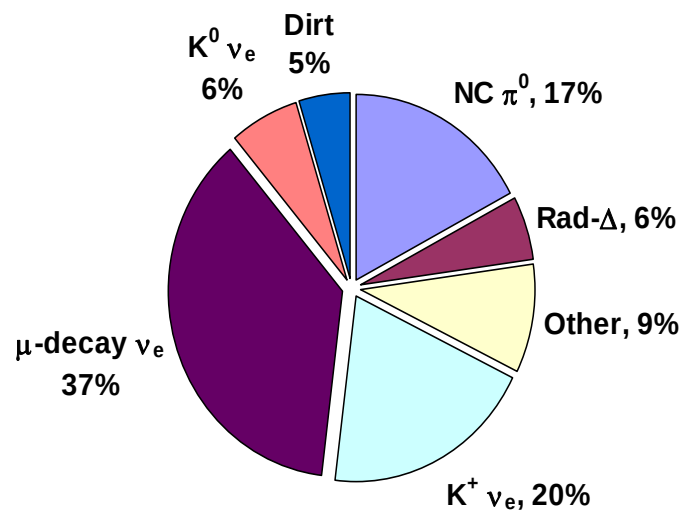
MiniBooNE Background Events (200 - 475 MeV)



NuMI Background Events (> 475 MeV)



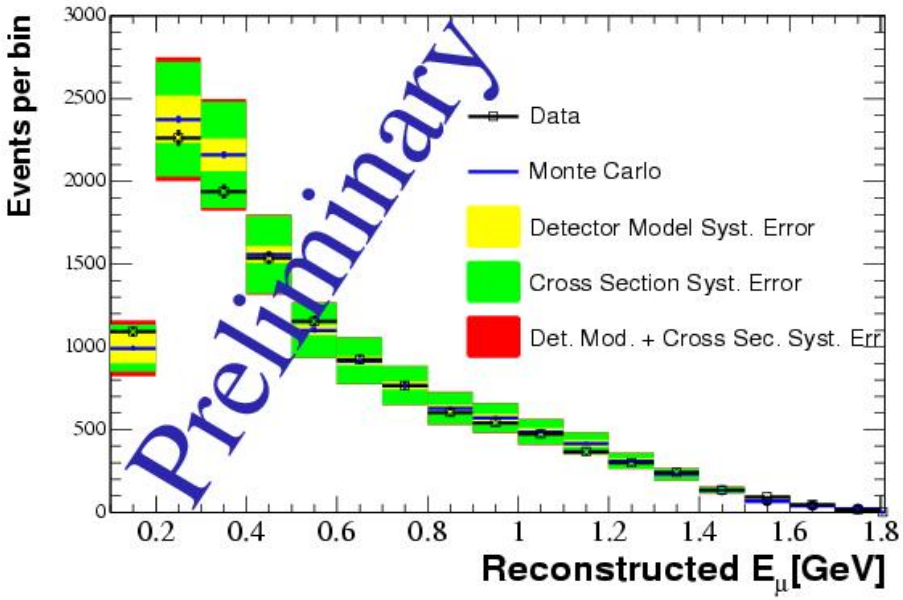
MiniBooNE Background Events (>475 MeV)



First steps: analysis of the ν_μ and π^0 events from NuMI beam

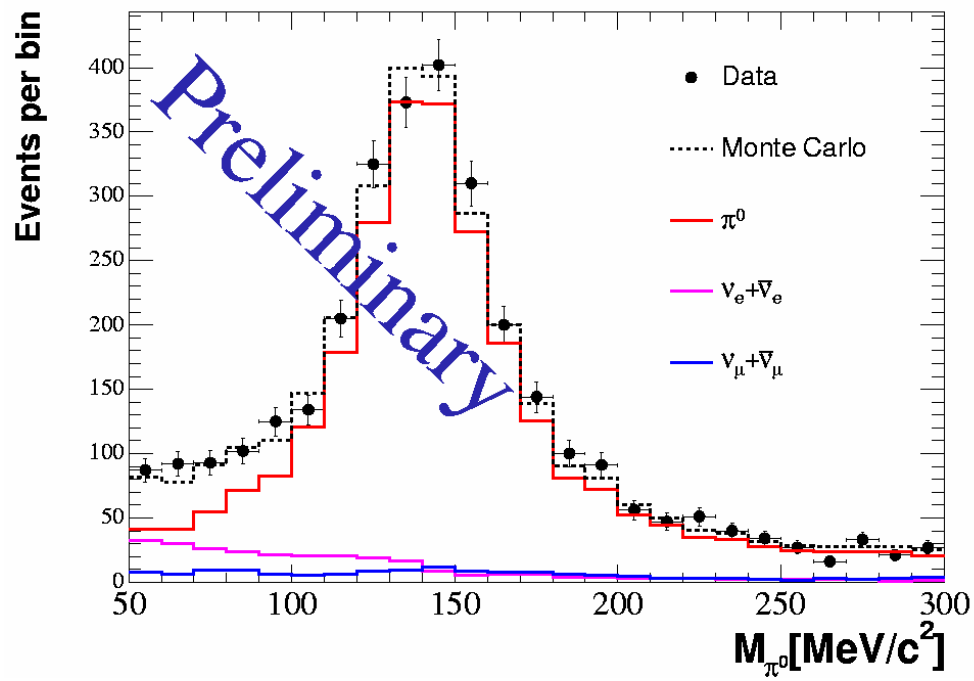
Data to MC comparison for ν_μ events

Good agreement ⇒ Good Understanding of the neutrino flux.



Data to MC comparison for π^0 enhanced events

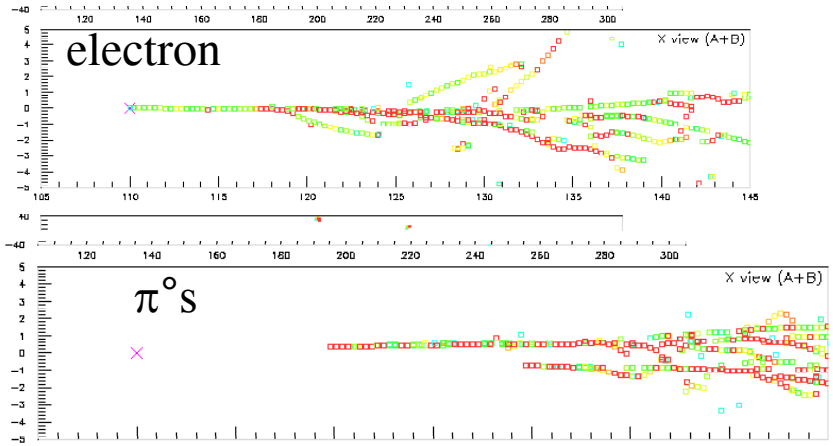
Good agreement ⇒ Good Understanding of the backgrounds for ν_e oscillation search.



Next Step is the analysis of ν_e events: do we see a similar excess?
Search for low energy excess at MiniBooNE with NuMI beam:
Goal to have results in Nov. 2007

MicroBooNE

- Liquid Argon TPC near MiniBooNE
- Proposal to be submitted Oct.07
  - Brookhaven, Columbia, Fermilab, Michigan State, St, Mary's, Yale + Others



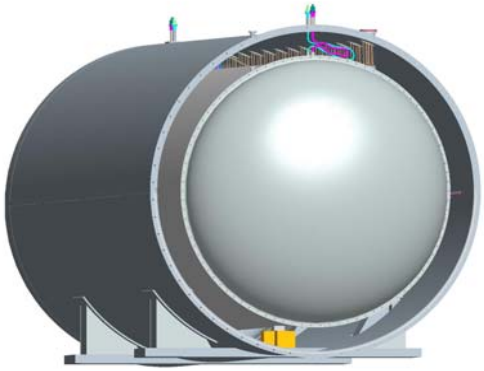
Ideal detector to understand miniBooNE low energy excess:

Liquid Argon TPC

- sensitive at low energies
- e/gamma separation
- high efficiency for "signal"
- low background

- 70 ton fiducial volume TPC
- 170 ton total volume
- 3 years at 2E20 pot/year

$\Rightarrow$ resolve miniBooNE excess



Summary

- MiniBooNE rules out (to 98%CL) the LSND result interpreted as $\nu_\mu \rightarrow \nu_e$ oscillations described with standard L/E dependence

  (Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500v2 [hep-ex])

  This eliminates the following interpretations of LSND:
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with (w/"standard" assumptions of CP, E-dependence)
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ via a single sterile neutrino (" ")

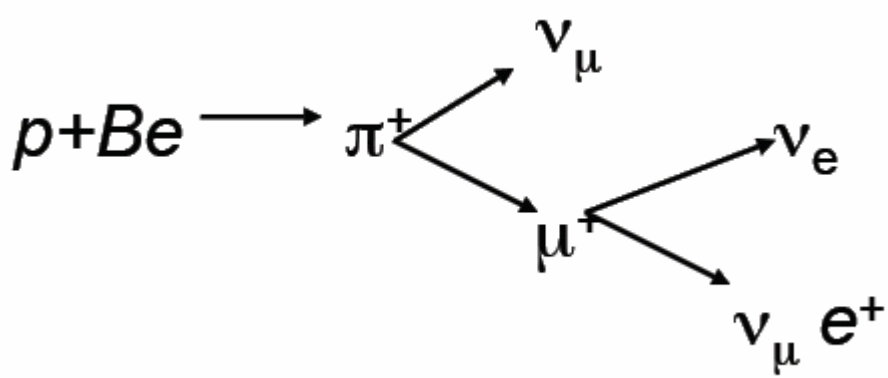
- The as-yet-unexplained deviation of MiniBooNE data from prediction at low-energy could be a background

  ... Currently working on this with high priority

  ... Or perhaps, new physics

Backup Slides

Constraining the Intrinsic ν_e Background from Muon Decay

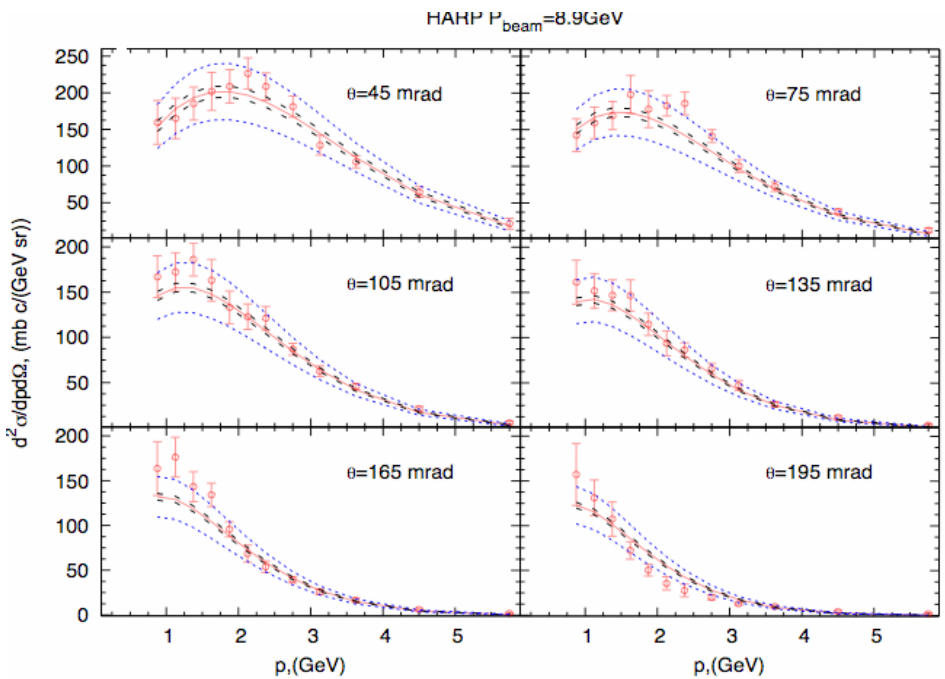


- Muon decay is the largest source of ν_e background but is highly constrained by the observed ν_μ events.
  - MiniBooNE subtends a very small forward solid angle for neutrinos from pion decay $\Rightarrow$ observed $E_\nu \approx 0.6\ E_\pi$
  - So, the measured ν_μ energy spectrum gives both the number and energy spectrum of the decaying pions
  - These decaying pions are the source of the ν_e mu-decay background

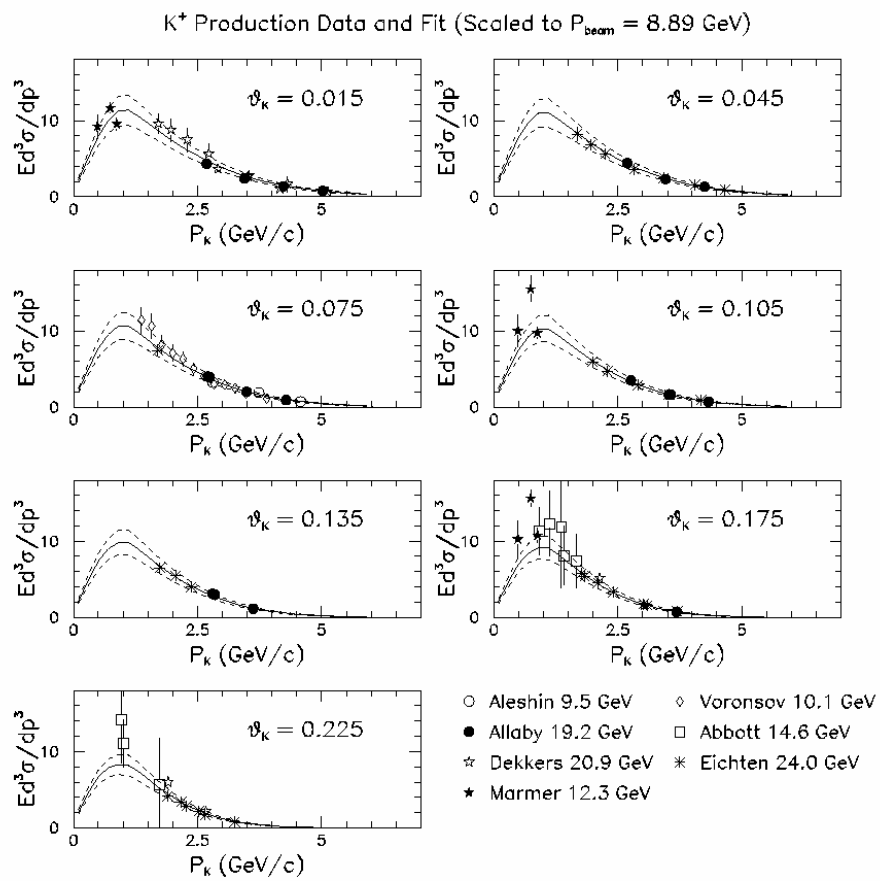
- ***The combined ν_μ/ ν_e oscillation fit:***
  - ***Automatically takes this correlation into account***
  - ***Effectively constrains the ν_e background with an error that depends primarily on the ν_μ event statistics.***

Pion and Kaon Production

- pBe Pion production
  - pBe production σ measured by the HARP collaboration at p_{proton} = 8.9 GeV
  - MiniBooNE uses a parameterization with uncertainties set to cover measurements.



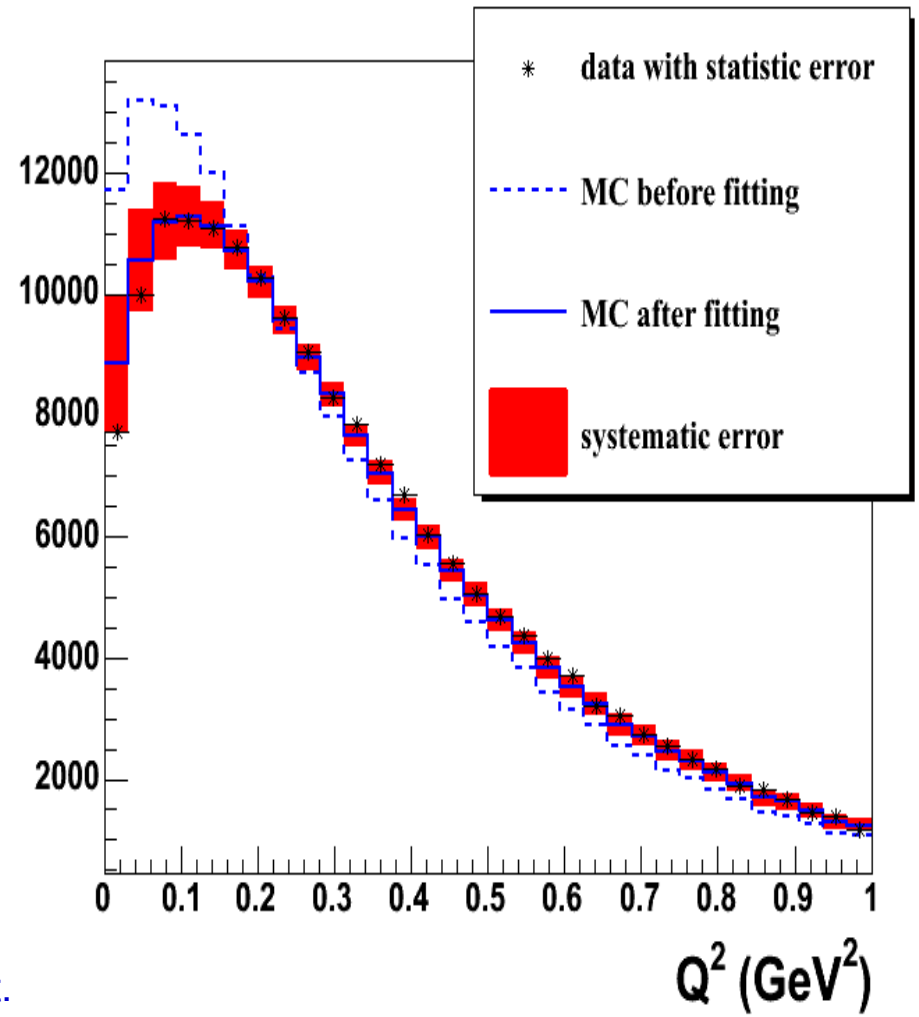
- pBe K^+ and K^0 production
  - Use external pBe cross section measurements for beam momenta from 9.5 – 24 GeV
  - MiniBooNE uses a parameterization with uncertainties set to cover measurements.



ν Cross Section Uncertainties

- Differential cross section for quasi-elastic scattering determined from MiniBooNE data
- Shape fits are performed to observed data Q^2 distribution using a relativistic-Fermi-gas model
- Two parameters (and their uncertainties) are determined:
  - Axial mass parameter
    $M_A = 1.23 \pm 0.20$ GeV
  - A Pauli blocking parameter
    $\kappa = 1.019 \pm 0.011$
- Fit also agrees well with neutrino energy distributions
- Other cross sections (i.e. CC1π) are determined from MiniBooNE data combined with previous external measurements

Quasi-Elastic Scattering: $\nu_\mu + n \rightarrow \mu^- + p$



Submitted to Phys.Rev.Lett.
e-Print: **arXiv:0706.0926** [hep-ex]