The MiniBooNE Neutrino Oscillations Search

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for the MiniBooNE Collaboration

Outline

1. Motivation
2. Description of the Experiment
3. Oscillation analysis
4. Results and future outlook
5. Summary

The MiniBooNE Collaboration

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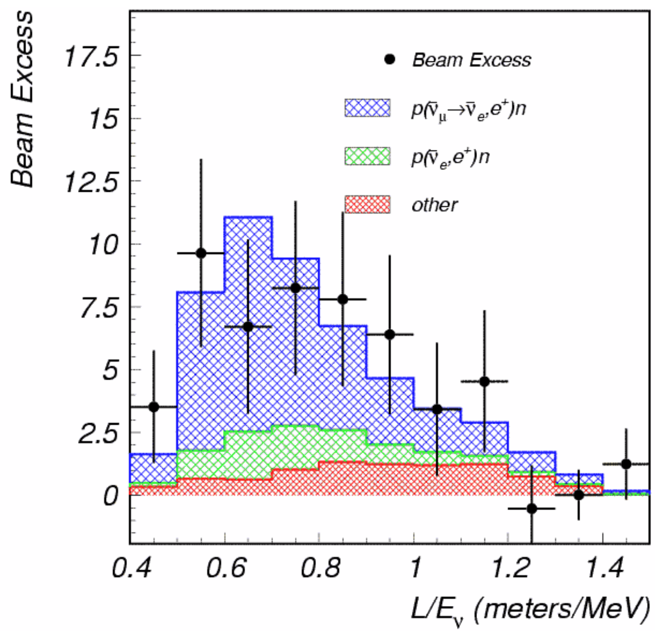
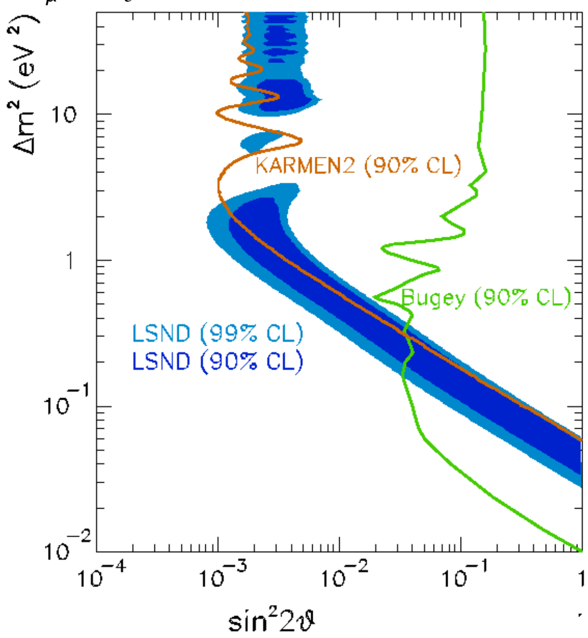
1. Motivation

MiniBooNE was Prompted by the Positive LSND Result

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

Oscillation probability $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$





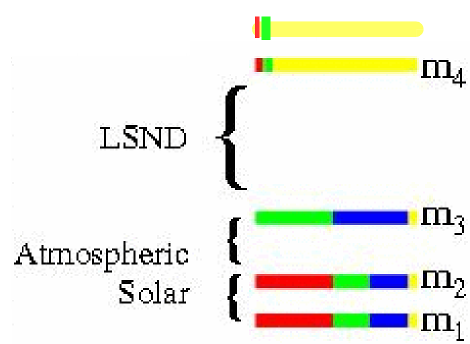
The Karmen Exp. did not confirm the LSND oscillations but had a smaller distance.

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

⇒ Models developed with 2 sterile ν's

or

Maybe one of the experiments is wrong.

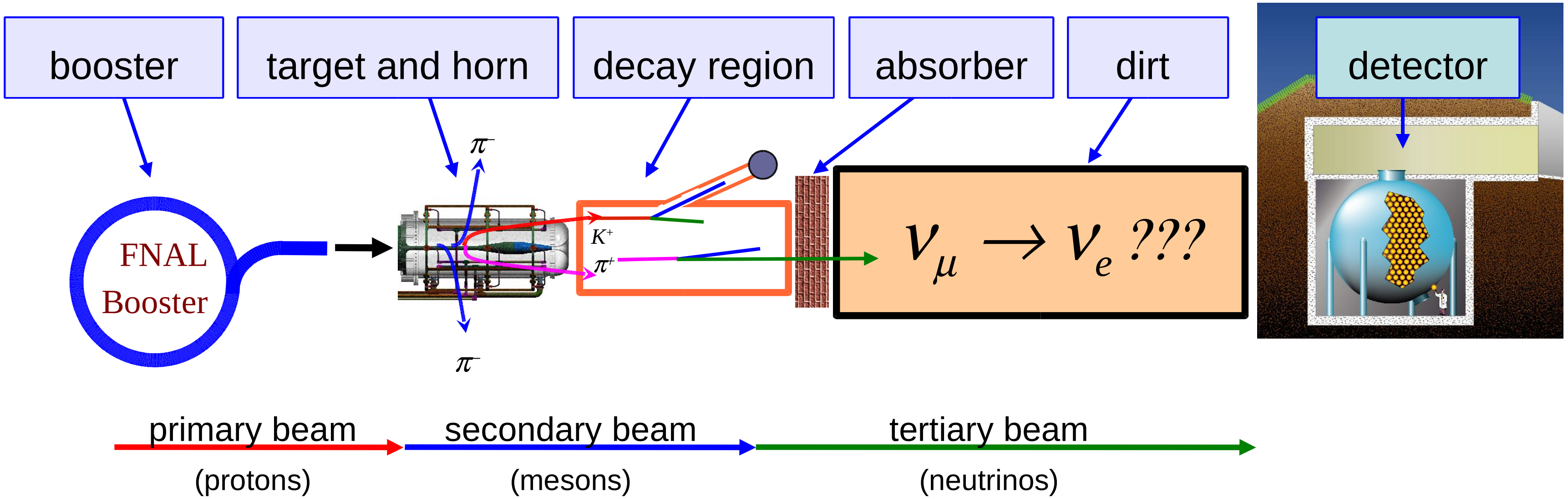


(Sorel, Conrad, and Shaevitz, PRD 70 (2004)073004 (hep-ph/0305255)

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

2. Description of the Experiment

The MiniBooNE Experiment



Strategy: Use similar $L/E \approx 1$

- Longer baseline: L ≈ 541m ≈ x15 LSND
- Higher ν energy: E≈ 0.7 GeV x(10-20) LSND
- Higher statistics: x5 LSND

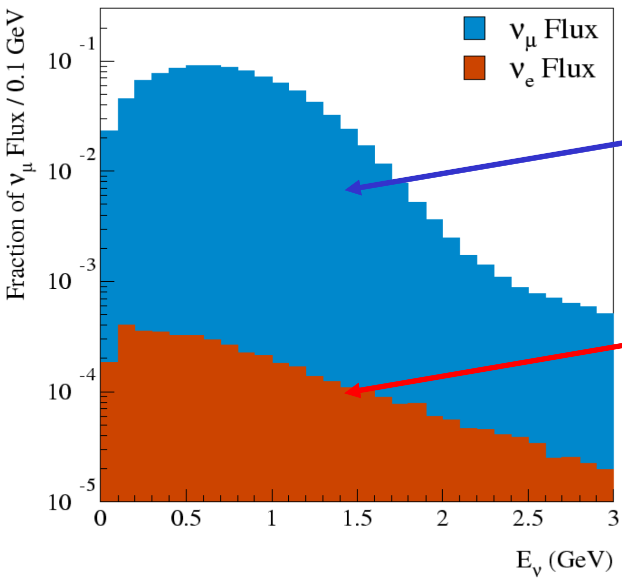
Look for ν oscillations in the same region of parameter space as LSND.
Subject to different systematic errors.

Proposed in 1997, operating since 2002.

Collected 5.58E20 POT in neutrino mode.

Switched Horn polarity to anti-neutrino mode since January 2006.

Beam and Detector

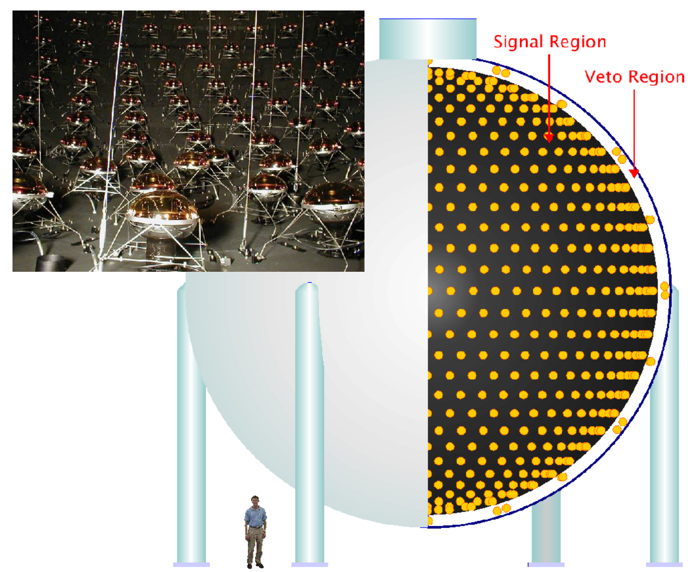


- Main ν_μ flux from $\pi^+ \rightarrow \mu^+ \; \nu_\mu$
- Intrinsic ν_e flux from
  - $\mu^+ \rightarrow \nu_\mu \; e^+ \; \nu_e$
  - $K^+ \rightarrow \pi^0 \; e^+ \; \nu_e$
  - $K^0_L \rightarrow \pi^- \; e^+ \; \nu_e$

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

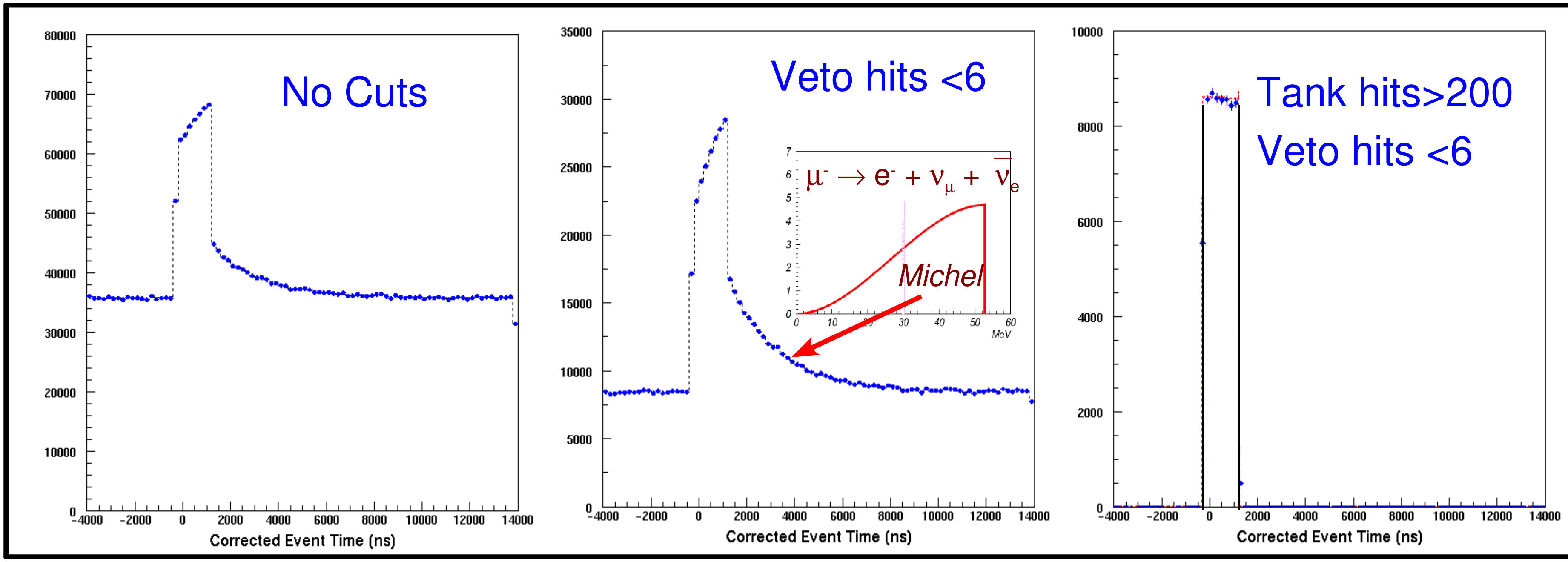
- 12m diameter tank
- Filled with 900 tons of pure mineral oil
- Optically isolated inner region with 1280 PMTs
- Outer veto region with 240 PMTs.

MiniBooNE Detector

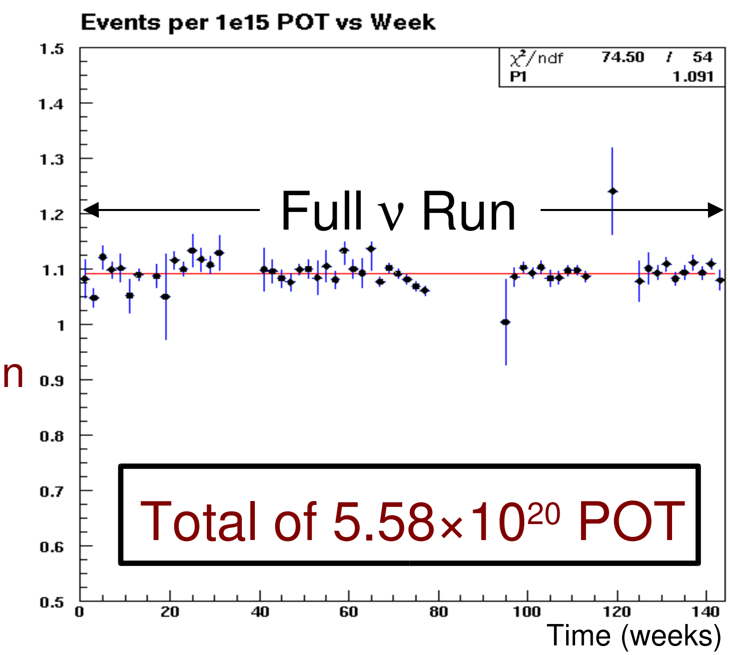


- Detector Requirements:
  - Detect and Measure Events: Vertex, E_ν …
  - Separate ν_μ events from ν_e events

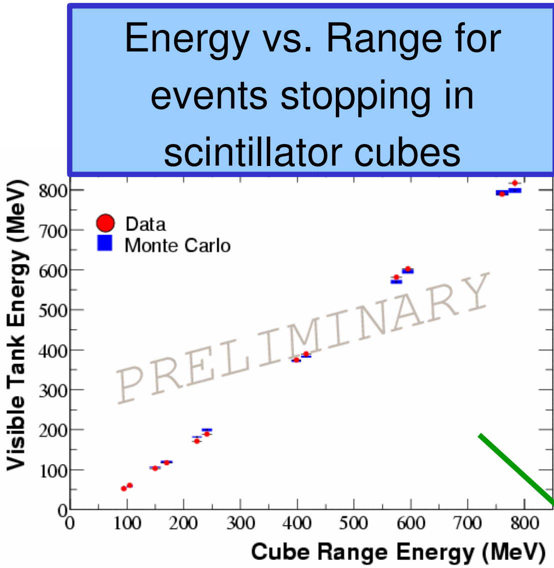
Events in the detector

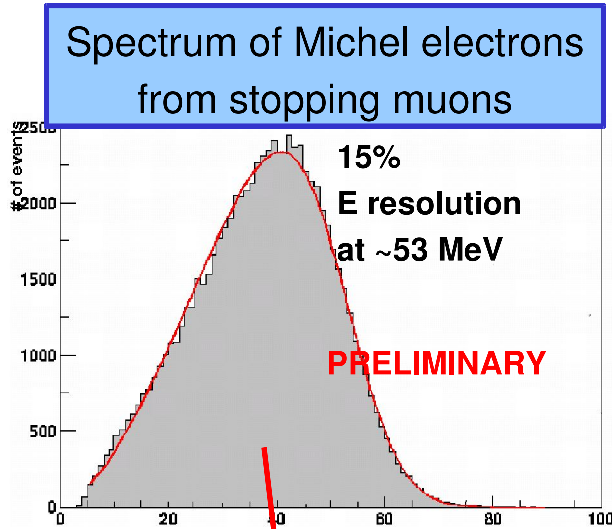


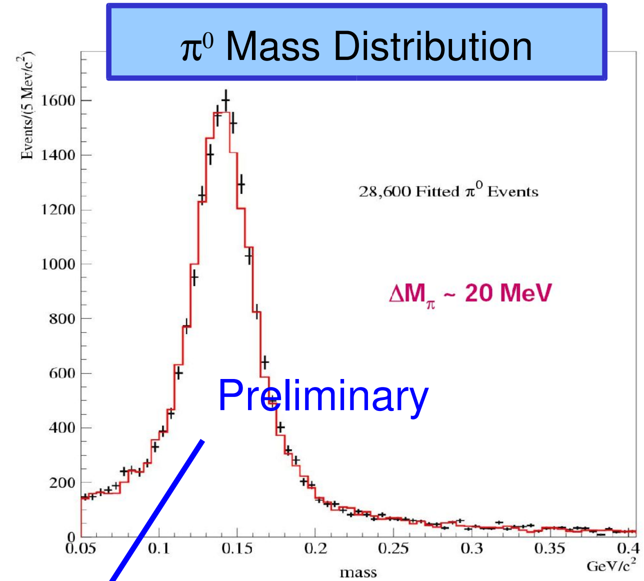
- Neutrino events clearly observed in DAQ time window.
- Beam spill duration is 1600 ns.
- Cosmic muon bkgd rejected with low Veto activity cut.
- Exponential decay component are electrons from muon decay. Rejected with minimum Tank Hits requirement.
- 99% rejection of cosmic ray background.

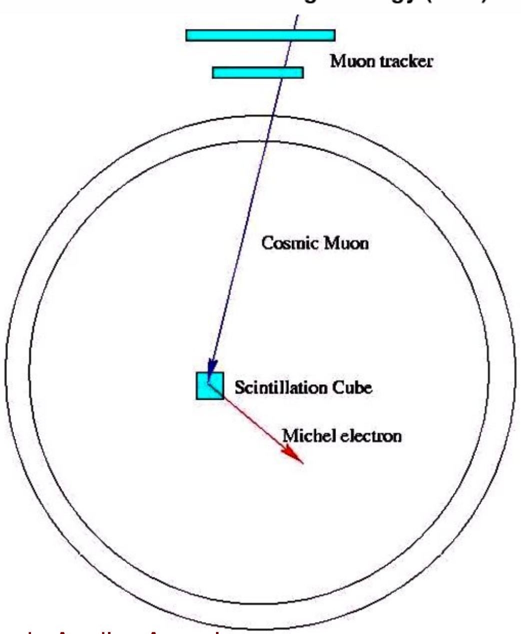


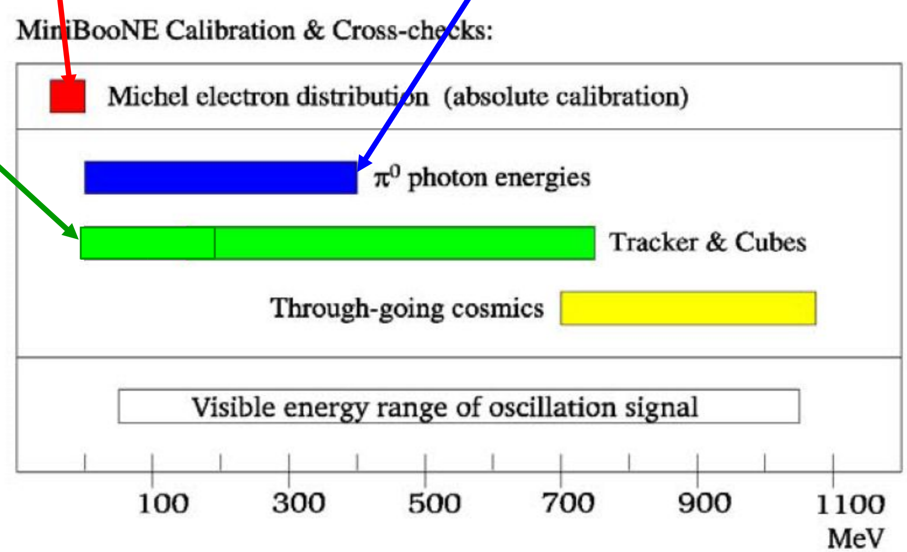
Calibrations











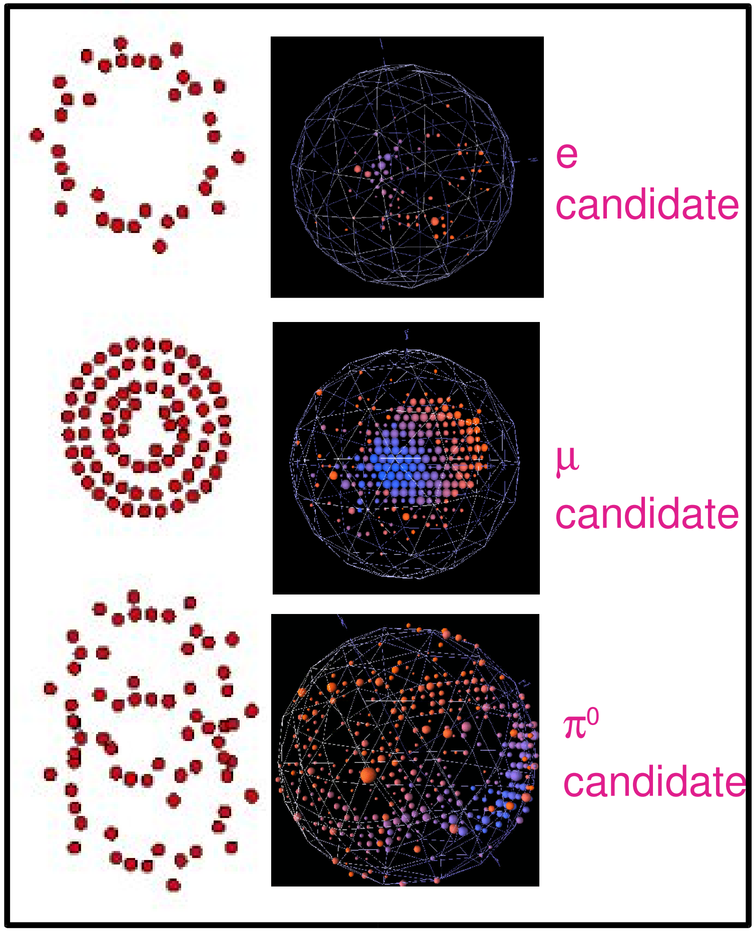
Particle ID Algorithms

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

- Identify events using
  - hit topology

- PID Variables
  - 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 used for Oscillation Analyses:
  1. *A **Likelihood*** based analysis: e/μ and e/π^0
  2. A "***boosted decision tree***" algorithm to separate e, μ, π^0 *(See B. Roe et al. NIM A543 (2005))*



3. Oscillation analysis

Structure of oscillations analysis

1. Use meson production data to determine the ν flux (target simulated in GEANT4)

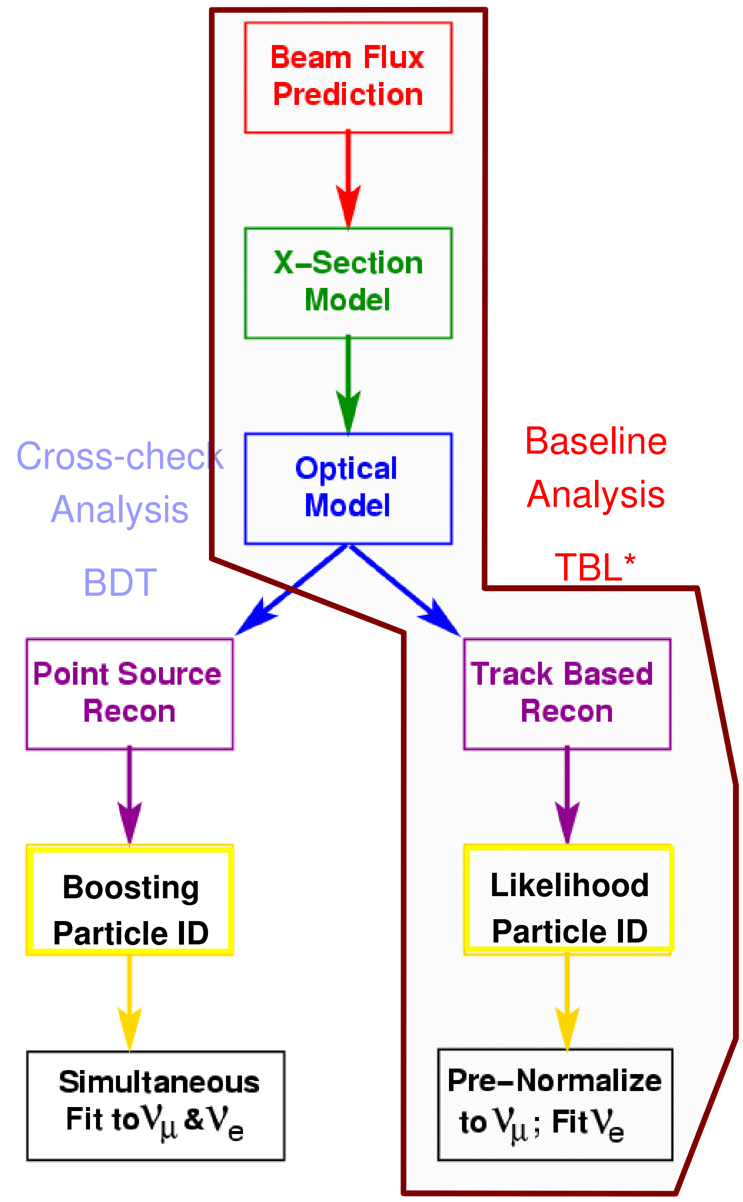
2. Use NUANCE cross-section model to predict ν interaction rates and final states

3. Final state particles are passed to a GEANT3 simulation of the detector to model particle and light propagation in the tank

4. Starting with event reconstruction, two independent analyses follow:
   (1) Track Based Likelihood (TBL*)
   (2) Boosted Decision Tree (BDT)

5. Develop particle-ID cuts to separate signal from background

6. Fit reconstructed E_ν^{QE} distribution in the data for 2ν oscillations



Oscillation Signal

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

Understanding the expected events is the key

- Need to know the neutrino fluxes
  - Electron neutrinos from μ^+, K^+, and K^0 decay
  - ν_μ's can make background or oscillate to give a signal

- Need to know the $\nu_{\mu/e}$ neutrino cross section vs. energy
  - Predicted Events = flux × cross section

- Need to know the ν_e reconstruction efficiency vs energy
  - Observed events = efficiency × Predicted 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)

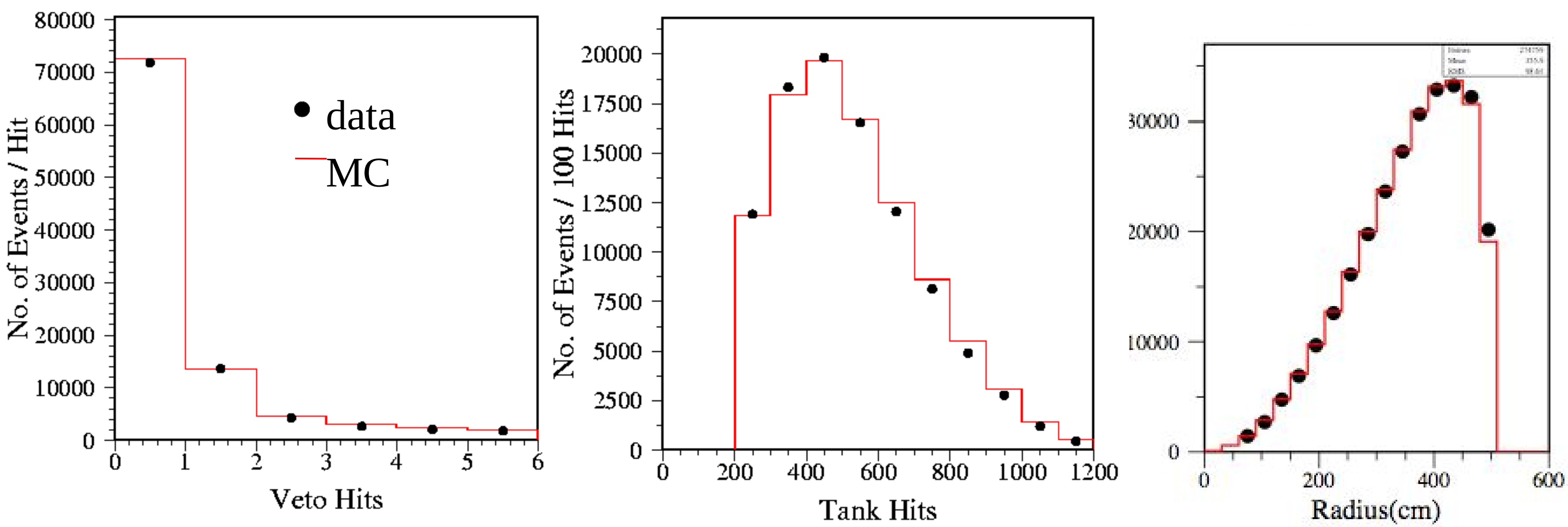
Principle: to understand and calibrate the expected events from the observed non-signal events

Oscillations search basic pre-selection requirements:

- These are shared by the two oscillations analyses: **BDT** and **TBL**
- Fiducial volume cut is algorithm-dependent

We ultimately want to isolate events of the type: $\nu_e + C \rightarrow X + e^-$

Veto hits < 6	Reject cosmic muons, michel decay electrons
Tank Hits > 200	
Only 1 sub-event	Keep electron-like events
Radius < 500 cm	Fiducial volume



TBL Analysis: Cuts Used to Separate ν_μ events from ν_e events

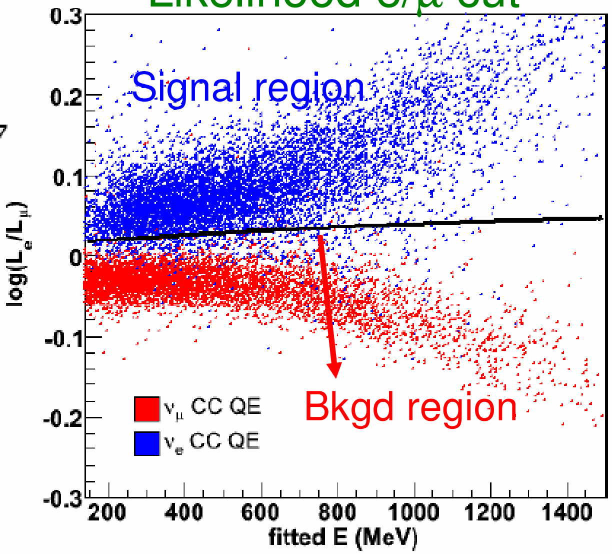
Fit the observed light distributions to three hypotheses:

Use the fit likelihoods as discriminators:

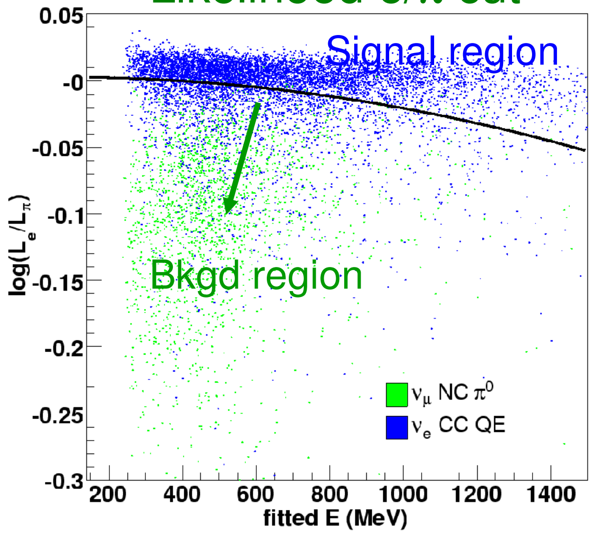
- single electron track L_e
- single muon track L_μ
- two electron-like rings (π^0 event hypothesis) L_π, and M_π

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

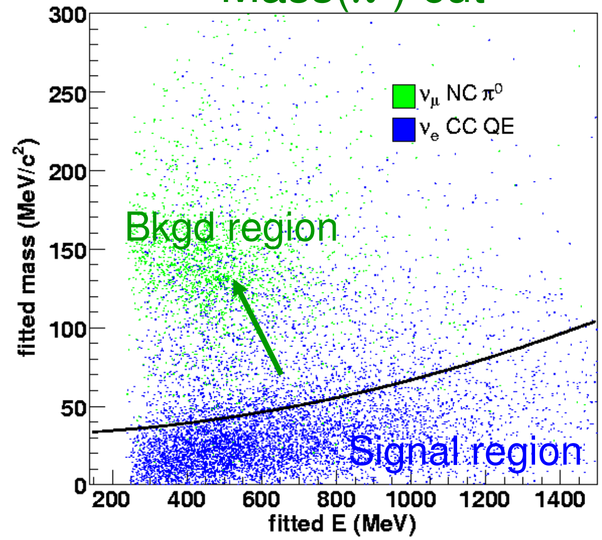
Likelihood e/μ cut



Likelihood e/π cut



Mass(π^0) cut



Blue points are signal ν_e events

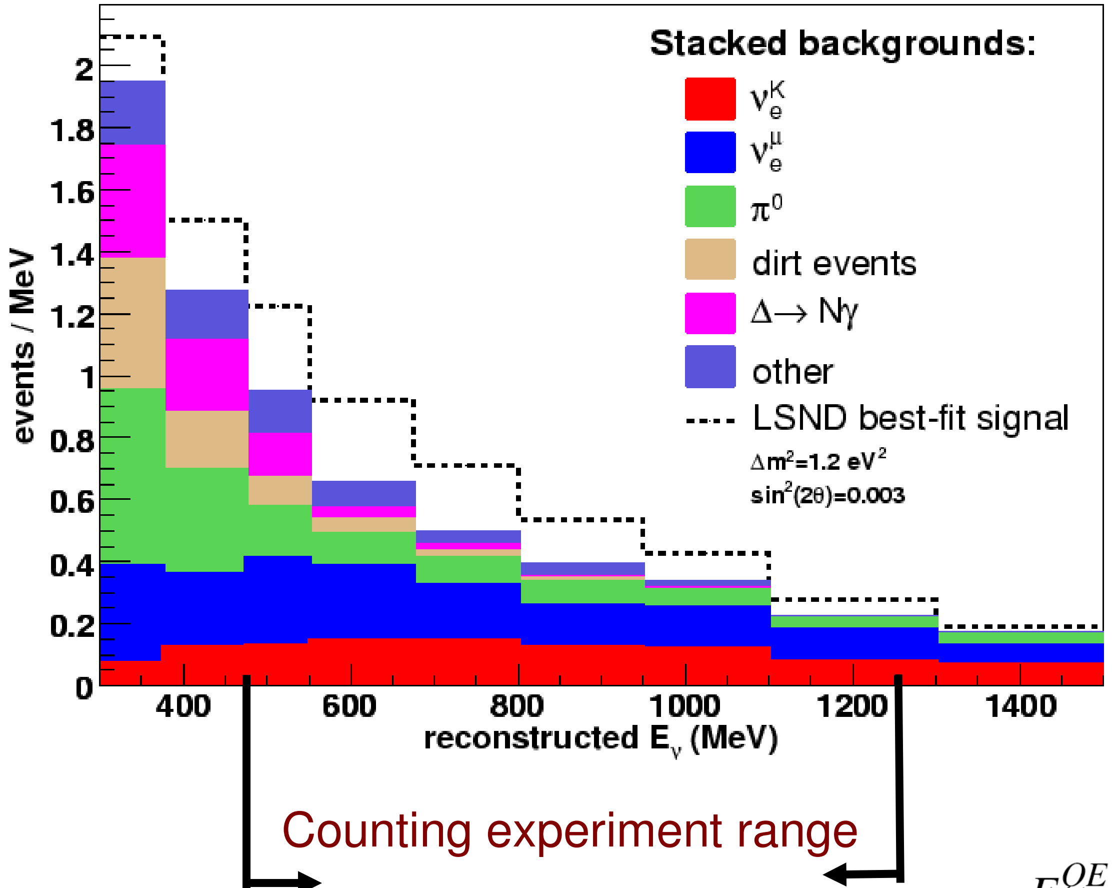
Red points are background ν_μCC QE events

Green points are background ν_μ NC π^0 events

TBL Analysis: expected events

Using the graphical cuts shown in previous slides, select ν_e candidate sample

Composition shown below:



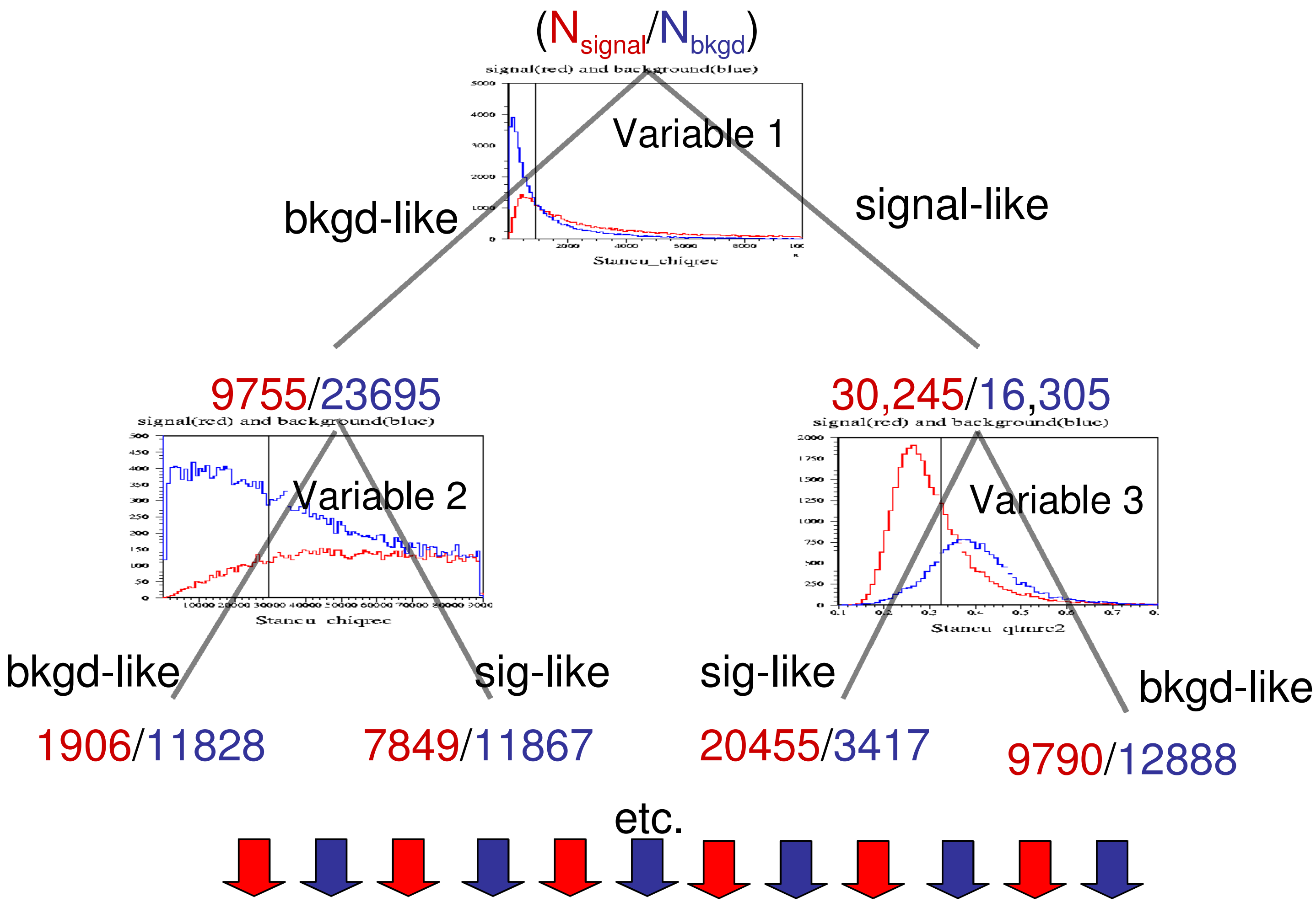
475 MeV – 1250 MeV	
ν_e^K	94 ± 27
ν_e^μ	132 ±10
NC π^0	62 ±10
Dirt	17 ± 3
$\Delta \rightarrow N\gamma$	20 ± 4
Other	33 ± 6
Total	358 ± 35
LSND best fit $\nu_\mu \rightarrow \nu_e$	126 ± 21

Sig/√Bkgd = 6.8

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

BDT Analysis: Boosted Decision Trees

Take a decision Tree: sequential series of cuts based on MC study



This tree is one of many possibilities...

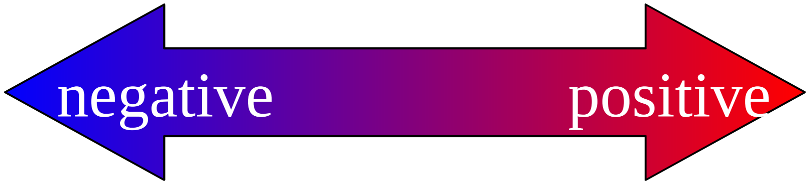
BDT Analysis: Boosted Decision Trees

Now make many decision trees,
each re-weighting the events to enhance identification of backgrounds misidentified by earlier trees **("boosting")**

For each tree, the data event is assigned
+1 if it is identified as signal,
-1 if it is identified as background.

The sum from all trees is combined into a "score"

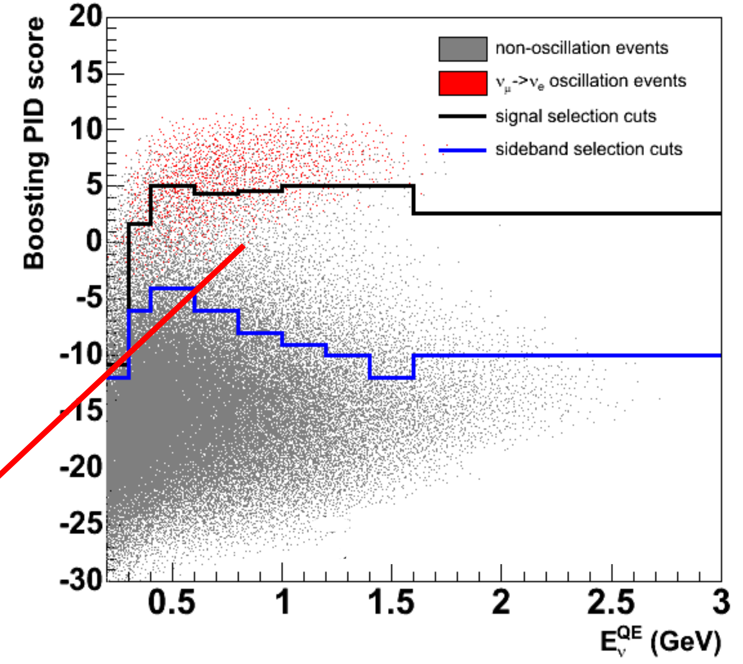
Background -like

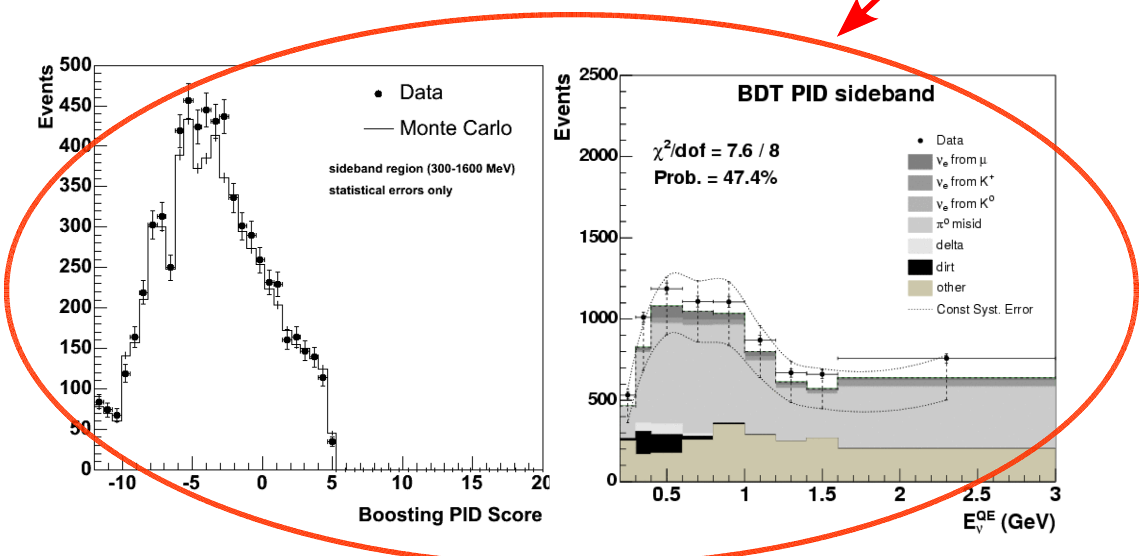


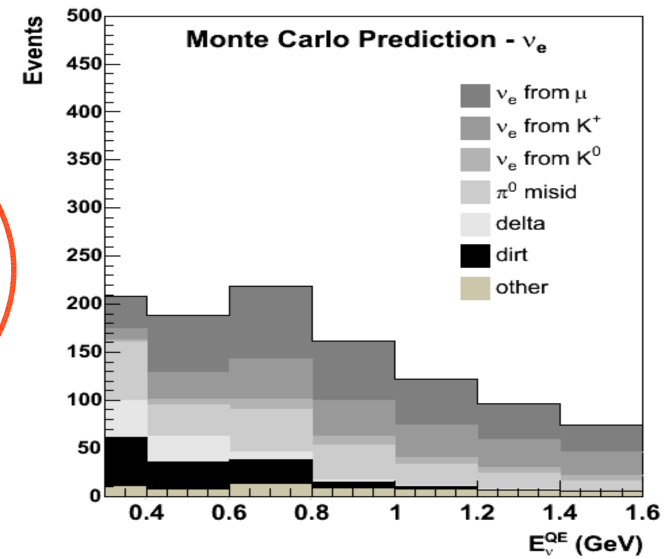
signal-like

BDT Analysis: signal/background separation

- **Boosting PID score** cut is chosen as a function of energy to maximize sensitivity to oscillations.
- Signal region (red points) separated from all backgrounds
- Comparison to data in “sideband” region adjacent to signal region shows good agreement







Backgrounds Constraints from MiniBooNE Data

All of the major backgrounds for the oscillation search can be constrained directly from measurements using MiniBooNE data

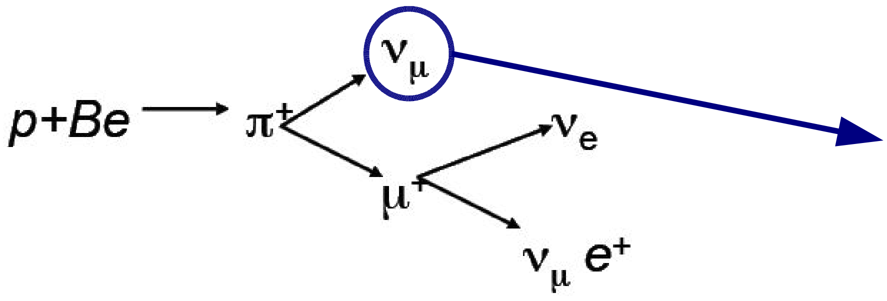
- NC π^0 production:
  Largest Mis-ID background, where one of the decay photons is missed.
  Constrained from the large fraction of NC π^0 events that are observed and measured in MiniBooNE

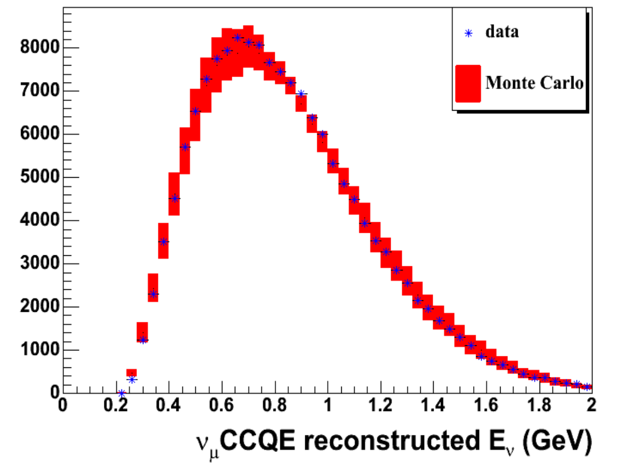
- External events (Dirt):
  Backgrounds from interactions with material outside of the MiniBooNE detector. Constrained by the isolation and measurement of such events.

- Intrinsic kaon decay ν_e's:
  Constrained by observed ν_e events at high energy where there are no oscillation events

- Intrinsic muon decay ν_e's:
  Largest intrinsic ν_e background. Highly constrained by the observed ν_μ events. The constraint can applied by using the combined ν_e/ ν_μ oscillation fit.

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 $E_\nu \approx 0.43\ E_\pi$
  - 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 background from μ-decay.

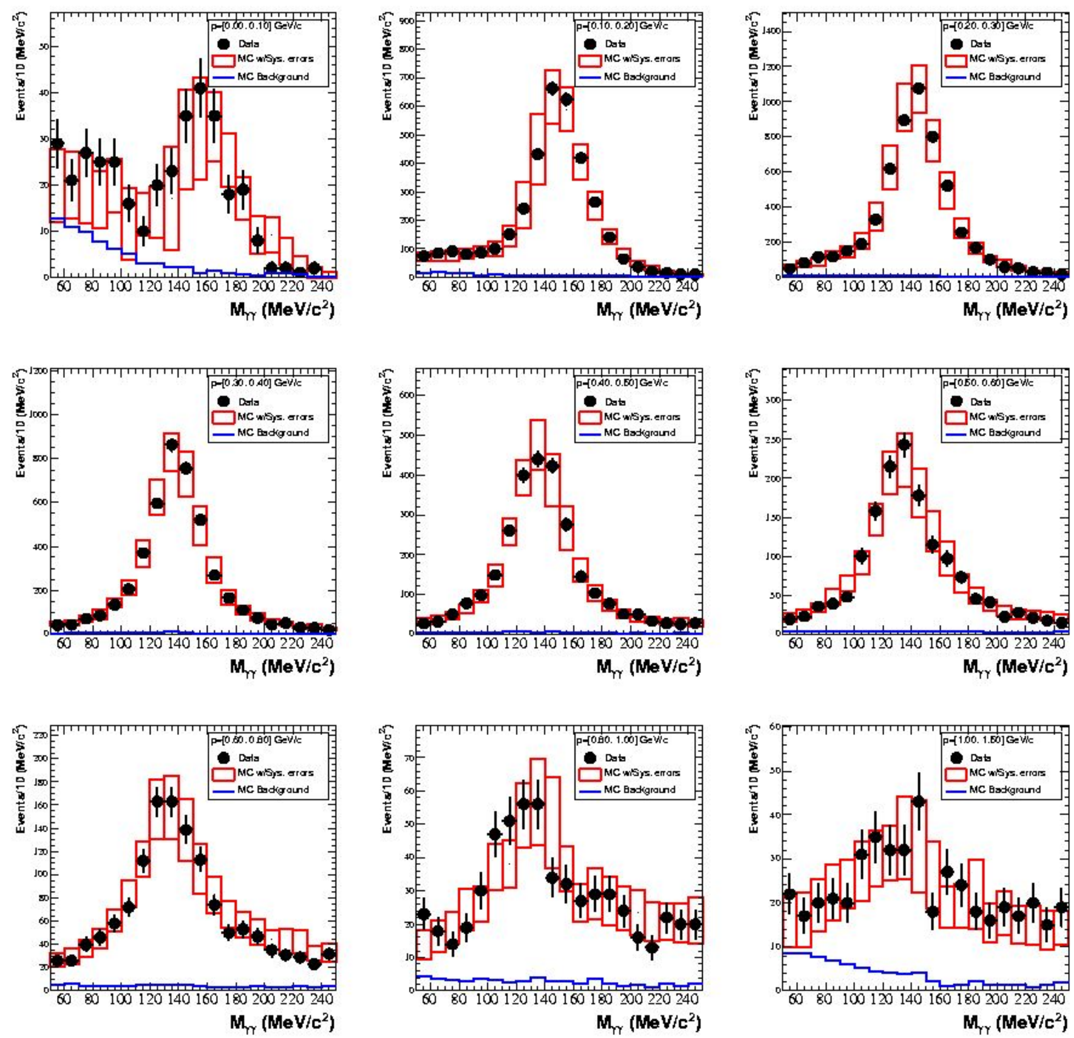
- ***The combined ν_μ/ ν_e oscillation fit:***
  - ***Automatically takes this correlation into account***
  - ***Effectively constrains the ν_e background with an error that depends primarily on the ν_μ event statistics.***

Constraining NC π^0 and Radiative $\Delta \rightarrow N\gamma$ Backgrounds

- Using PID variables isolate a very pure sample of NC 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

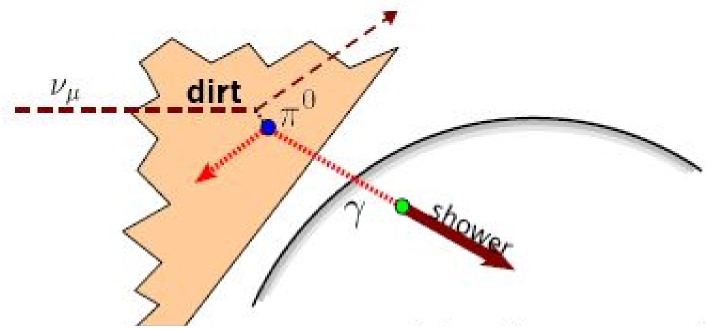
  (Also can be used to correct the $\Delta \rightarrow N + \gamma$ radiative background)

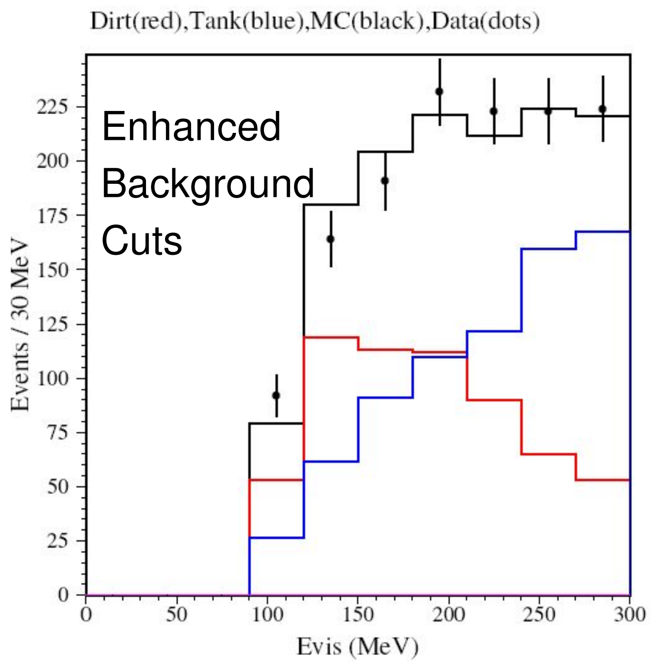
$M_{\gamma\gamma}$ Mass Distribution for Various $p_{\pi 0}$ Momentum Bins



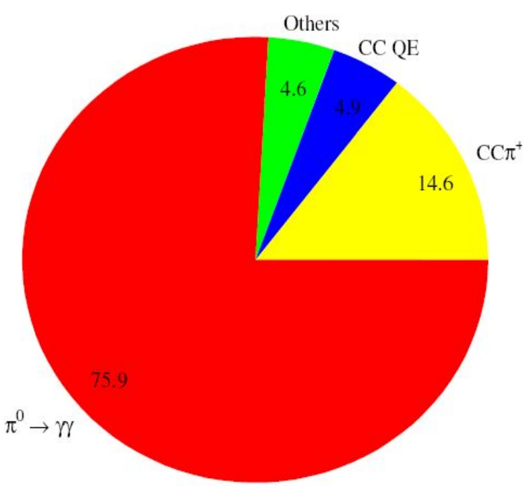
External Sources of Background: “Dirt” events

ν interactions outside of the detector $N_{data}/N_{MC} = 0.99 \pm 0.15$





Event Type of Dirt after PID cuts



Sources of systematic uncertainty

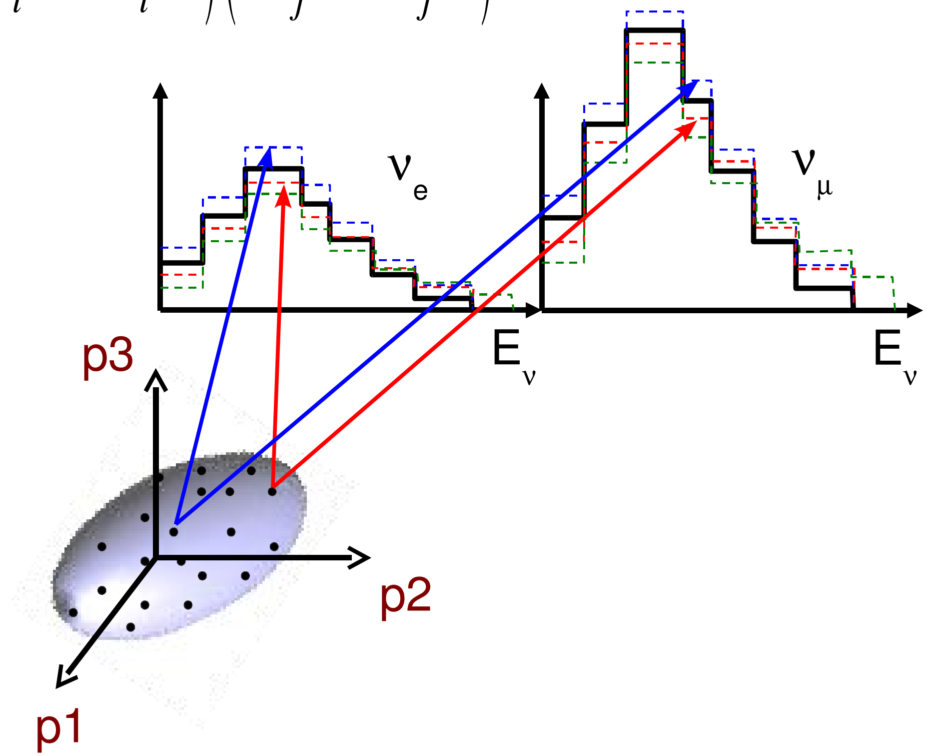
Source of uncertainty on ν_e background	TBL/BDT error in %	Constrained by MB data	Reduced by tying ν_e to ν_μ
Flux from π^+/μ^+ decay	6.2 / 4.3	√	√
Flux from K^+ decay	3.3 / 1.0	√	√
Flux from K^0_L decay	1.5 / 0.4	√	√
Target and beam models	2.8 / 1.3	√	
ν-cross sections	12.3 / 10.5	√	√
NC π^0 yield	1.8 / 1.5	√	
External interactions ("Dirt")	0.8 / 3.4	√	
Optical model	6.1 / 10.5	√	√
DAQ electronics model	7.5 / 10.8	√	

- All errors had some in-situ constraint
- Correlations between ν_μ and ν_e samples allow to further reduce some errors
- BDT has larger signal to bkgd ratio, but is more sensitive to systematic errors

Constructing the error Matrix: *Multisims*

$$E_{ij} \approx \frac{1}{M-1}\sum_{\alpha=1}^{M}\left(N_i^{\alpha}-N_i^{MC}\right)\left(N_j^{\alpha}-N_j^{MC}\right)$$

- N_i is number of events passing cuts
- *MC* is standard monte carlo
- α represents a given multisim
- *M* is the total number of multisims
- *i,j* are E_ν^{QE} bins



Total error matrix is the sum of all sources.

$$E_{ii} = E_{ii}^{\pi^+} + E_{ii}^{K^+} + E_{ii}^{K^0} + E_{ii}^{X\,\mathrm{sec}} + E_{ii}^{\pi^0\,\mathrm{rate}} + E_{ii}^{\mathrm{beam}} + E_{ii}^{\mathrm{dirt}} + E_{ii}^{\mathrm{Optical\ Model}}$$

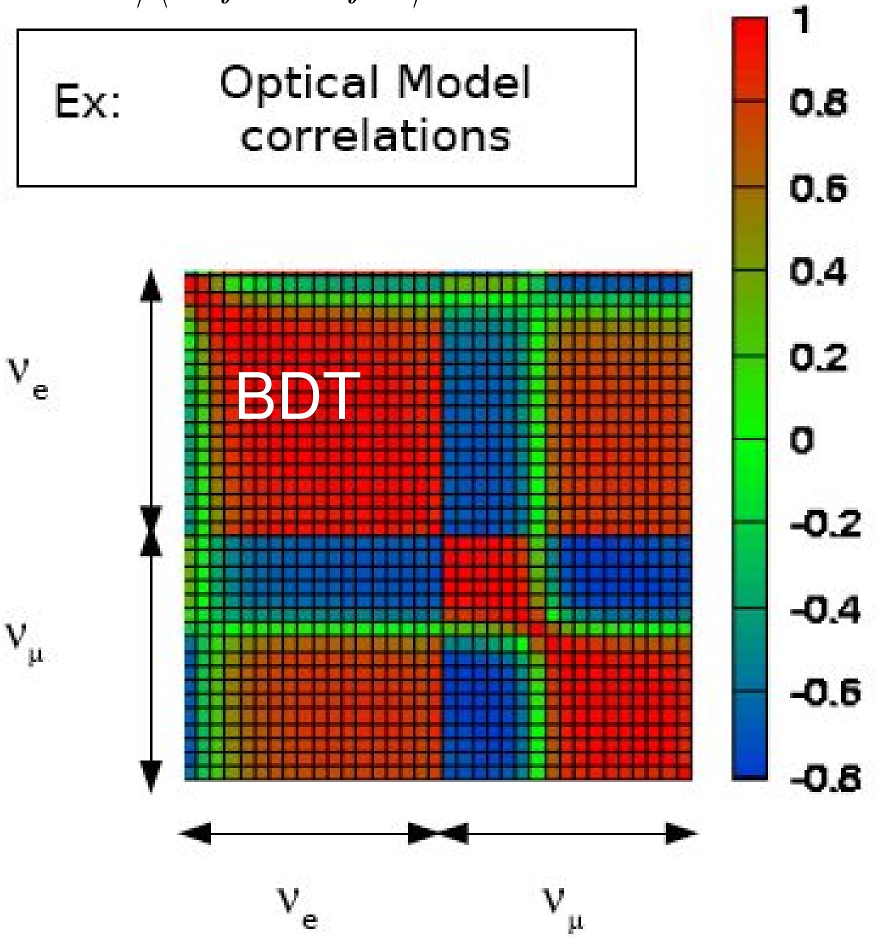
Multisim: Simulation with randomly varied parameters

Constructing the error Matrix:

$$E_{ij} \approx \frac{1}{M-1}\sum_{\alpha=1}^{M}\left(N_i^{\alpha}-N_i^{MC}\right)\left(N_j^{\alpha}-N_j^{MC}\right)$$

- N_i is number of events passing cuts
- *MC* is standard monte carlo
- α represents a given multisim
- *M* is the total number of multisims
- *i,j* are E_{ν}^{QE} bins

Total error matrix is the sum of all sources.



TBL: Uses ν_e-only total error matrix

BDT: Uses ν_μ-ν_e total error matrix

Combined ν_μ,ν_e Oscillations Fit Method

- Do a combined oscillation fit to the observed ν_μ and ν_e energy distribution for data vs prediction

$$\chi^2 = \begin{pmatrix} \Delta_i^{\nu_e} & \Delta_i^{\nu_\mu} \end{pmatrix} \begin{pmatrix} M_{ij}^{e,e} & M_{ij}^{e,\mu} \\ M_{ij}^{\mu,e} & M_{ij}^{\mu,\mu} \end{pmatrix}^{-1} \begin{pmatrix} \Delta_j^{\nu_e} \\ \Delta_j^{\nu_\mu} \end{pmatrix}$$

$$\text{where } \Delta_i^{\nu_e} = \text{Data}_i^{\nu_e} - \text{Pred}_i^{\nu_e}(\Delta m^2, \sin^2 2\theta) \text{ and } \Delta_i^{\nu_\mu} = \text{Data}_i^{\nu_\mu} - \text{Pred}_i^{\nu_\mu}$$

- Systematic (and statistical) uncertainties in $(M_{ij})^{-1}$ matrix
  - Uncertainties come from analyses of external and internal data
  - Covariance matrix includes correlations between ν_e and ν_μ events

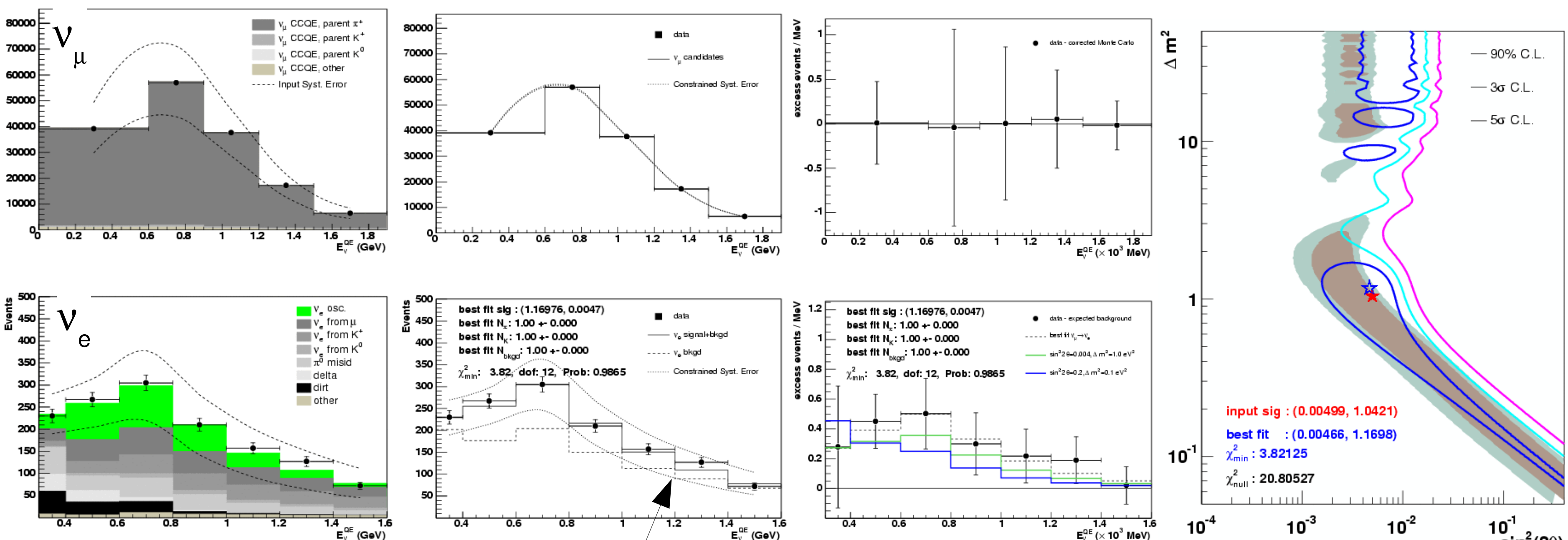
- Predictions for the various backgrounds are directly constrained by actual MiniBooNE measurements
  - Constraints significantly reduce systematic uncertainties
  - Combined fit also reduces ν_e uncertainties using high stat ν_μ events

Fake study: Strong signal in the BDT analysis

Fit to fake data with strong signal:

1) Fake data is a statistical fluctuation of Monte Carlo Prediction. Unconstrained errors from "*multisims*" are large.
2) Fit constrains errors and re-shapes the distributions due to high stats. of ν_μ sample.
3) Excess distributions, ν_e sample compared to 2 other LSND signals.
4) Result of fit in oscillation parameter space.

(1) (2) (3) (4)



Before Fit

After Fit

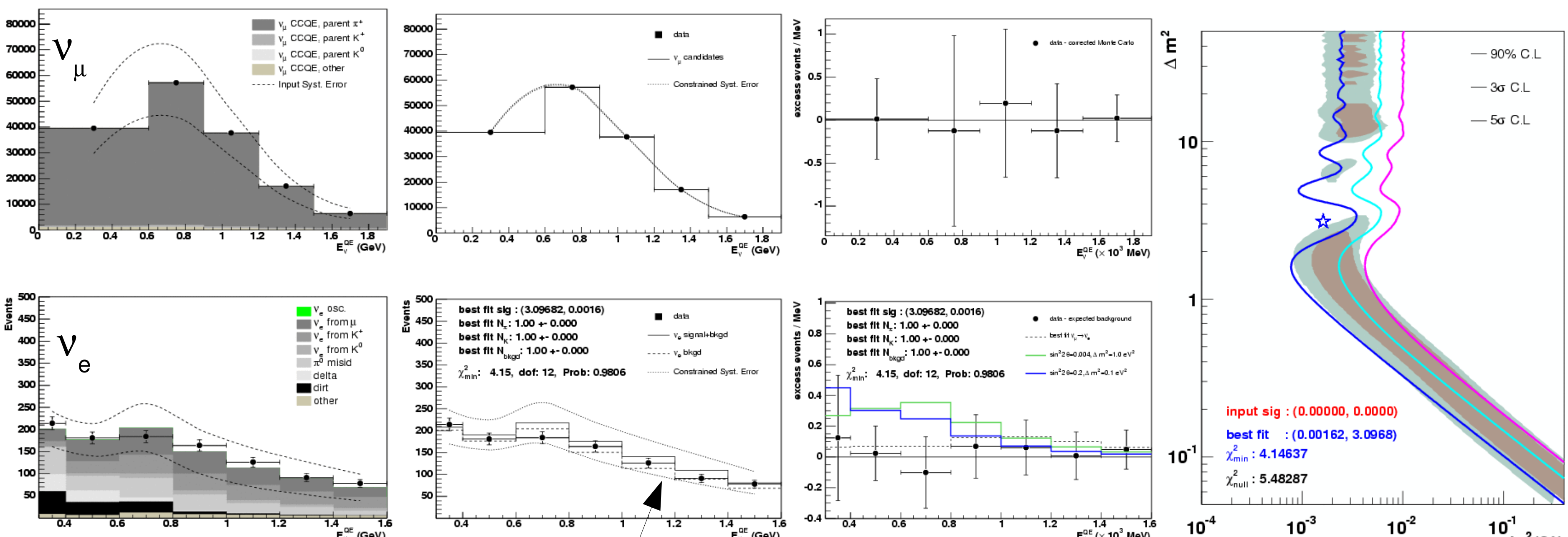
Constrained ν_e errors

Fake study: No signal in the BDT analysis

Fit to fake data with no signal: (setting a limit)

1) Fake data is a statistical fluctuation of Monte Carlo Prediction. Unconstrained errors from “*multisims*” are large.
2) Fit constrains errors and re-shapes the distributions due to high stats. of ν_μ sample.
3) Excess distributions, ν_e sample compared to 2 other LSND signals.
4) Result of fit in oscillation parameter space.

(1) (2) (3) (4)

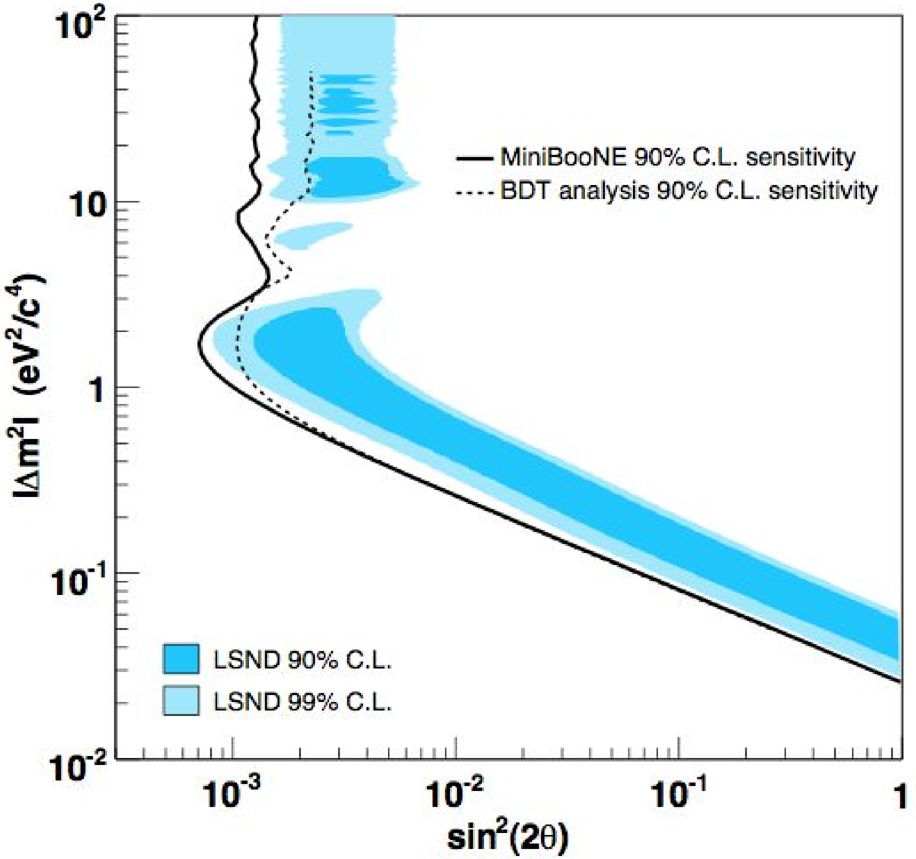


Before Fit After Fit

Constrained ν_e errors

Comparing the sensitivities: BDT vs TBL

Determined from simulation only



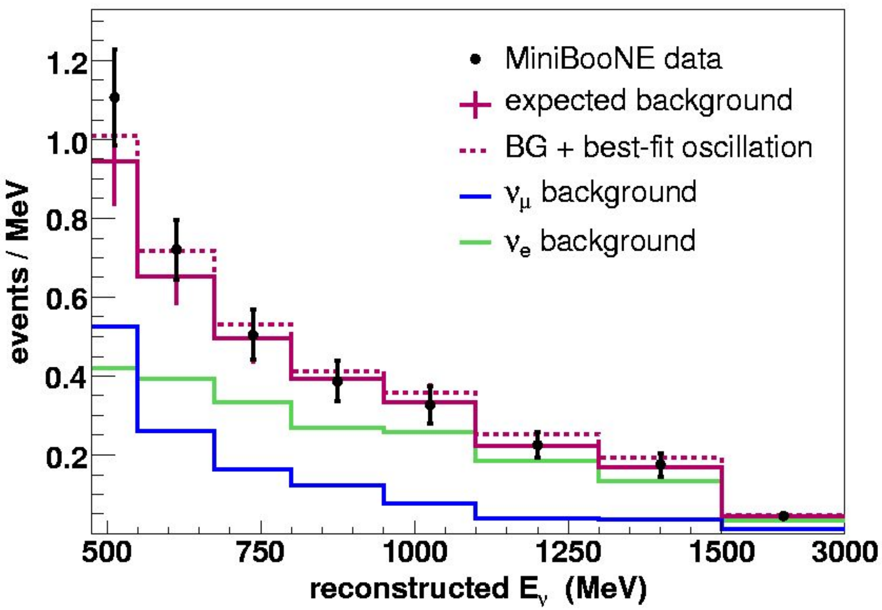
- TBL analysis (solid) has higher sensitivity. **Chosen as the primary analysis on this basis**
- Decision made previous to un-blinding
- 90% C.L. determined with $\Delta\chi^2 = 1.64$

4. Results and future outlook

BDT and TBA analyses data vs prediction

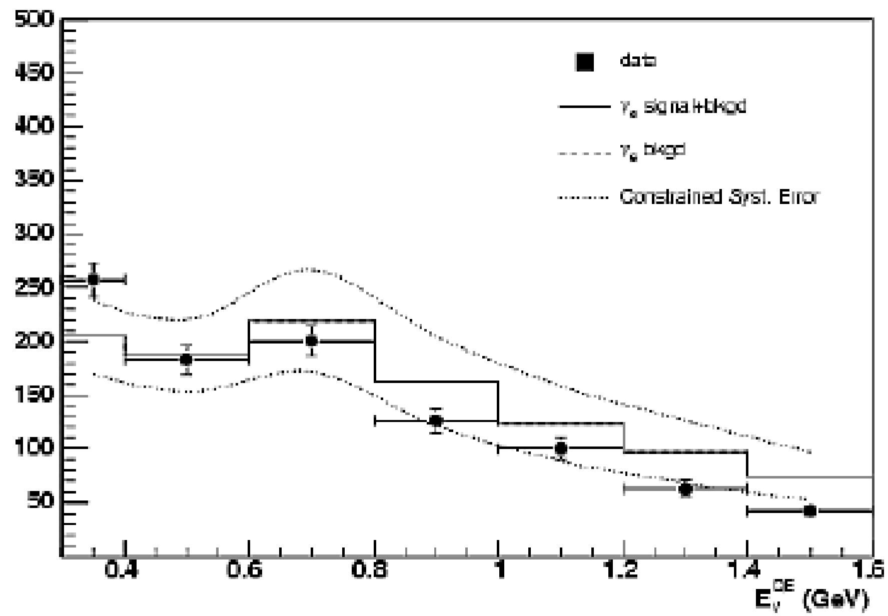
TBL analysis

No sign of an excess in the analysis region (E_ν>475 MeV), where the LSND signal is expected for 2ν oscillations.

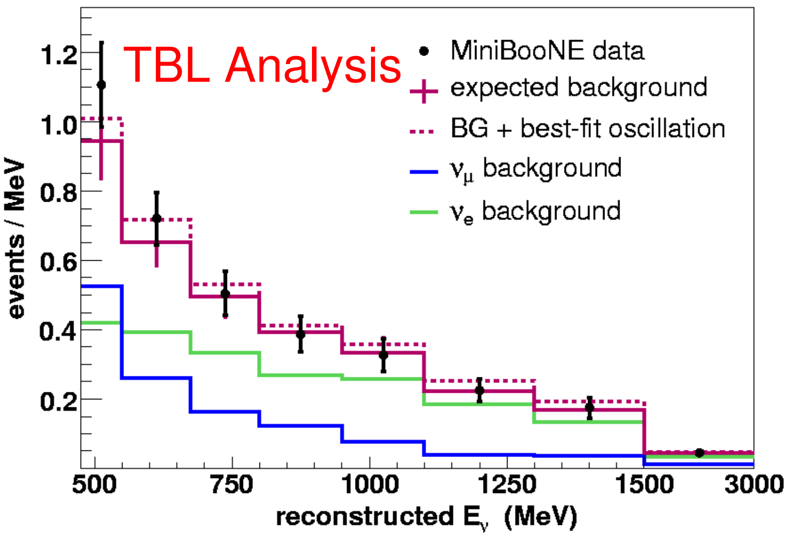


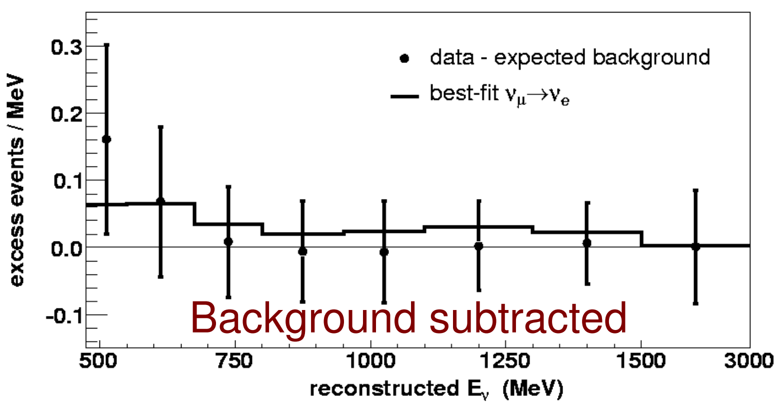
BDT analysis

Also no sign of an excess, in fact the data is low relative to the prediction.



MiniBooNE First Results (April, 2007)



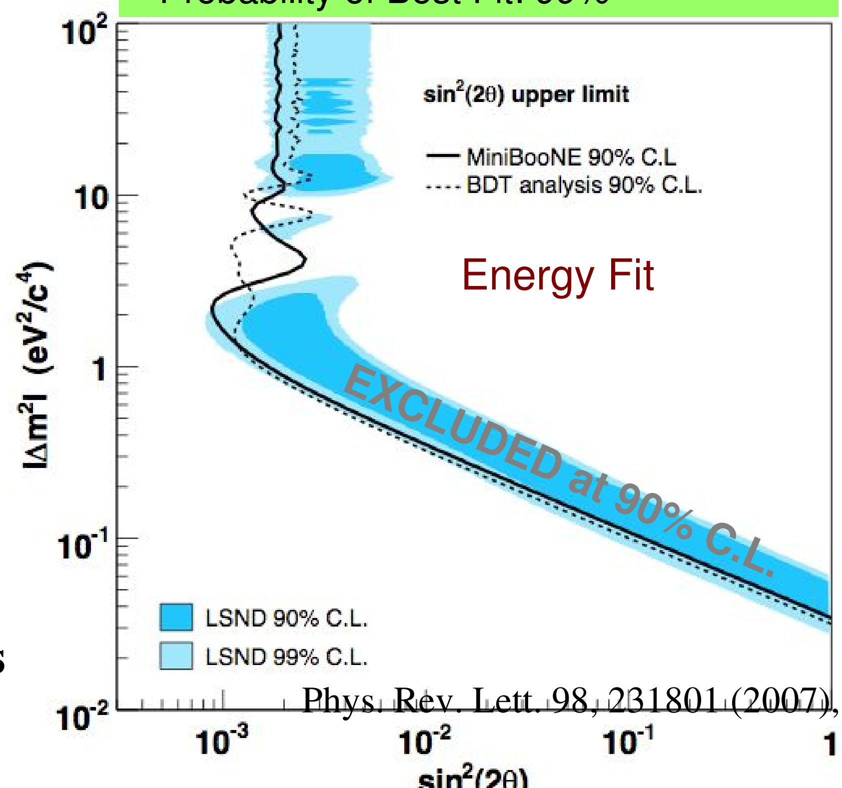


Oscillation Search Region
$475 < E_\nu < 1250$ MeV

data: 380 ± 19 (stat) events
expectation: 358 ± 35 (sys) events
significance: $0.55\ \sigma$

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

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



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

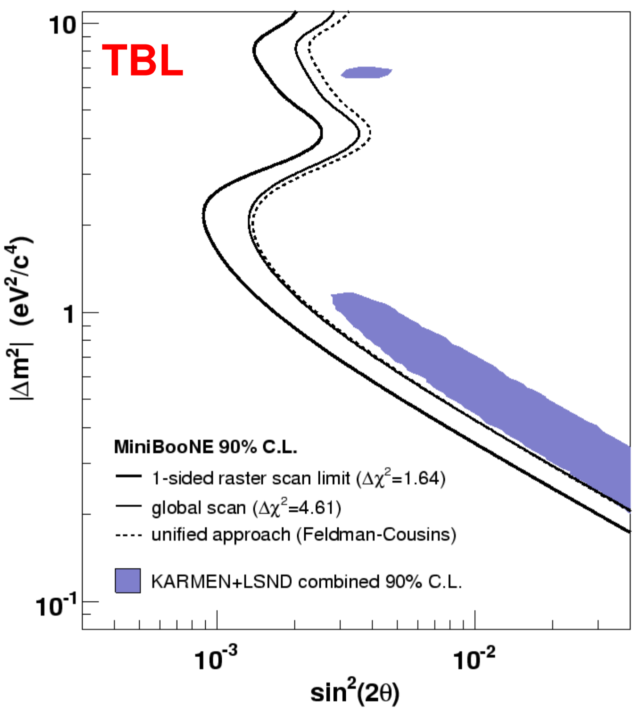
Data consistent with expected background

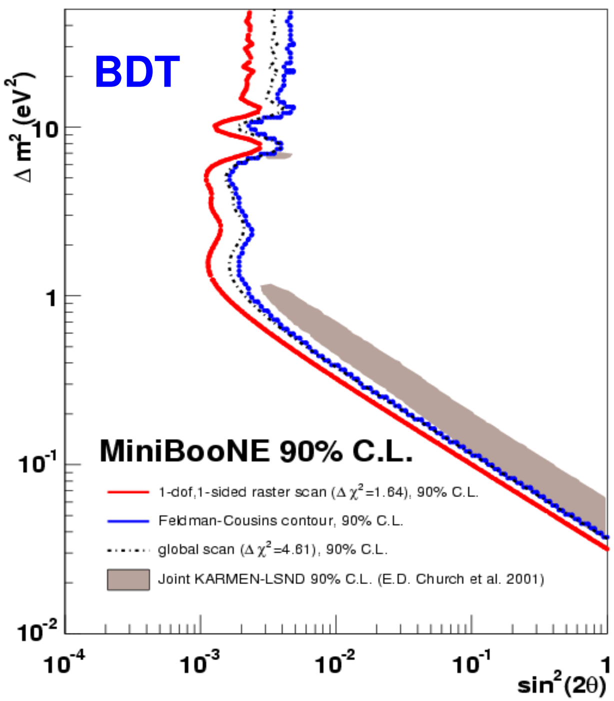
⇒ Inconsistent with a $\nu_\mu \rightarrow \nu_e$ oscillations

Exclude region in parameter space.

Interpreting the limits

- Single sided raster scan , $\Delta\chi^2$ = 1.64 , fit to $\sin^2 2\theta$ for each Δm^2 (historically used)
- Global scan ($\Delta\chi^2$ = 4.61, 2-dim fit)
- Unified approach (frequentist method)

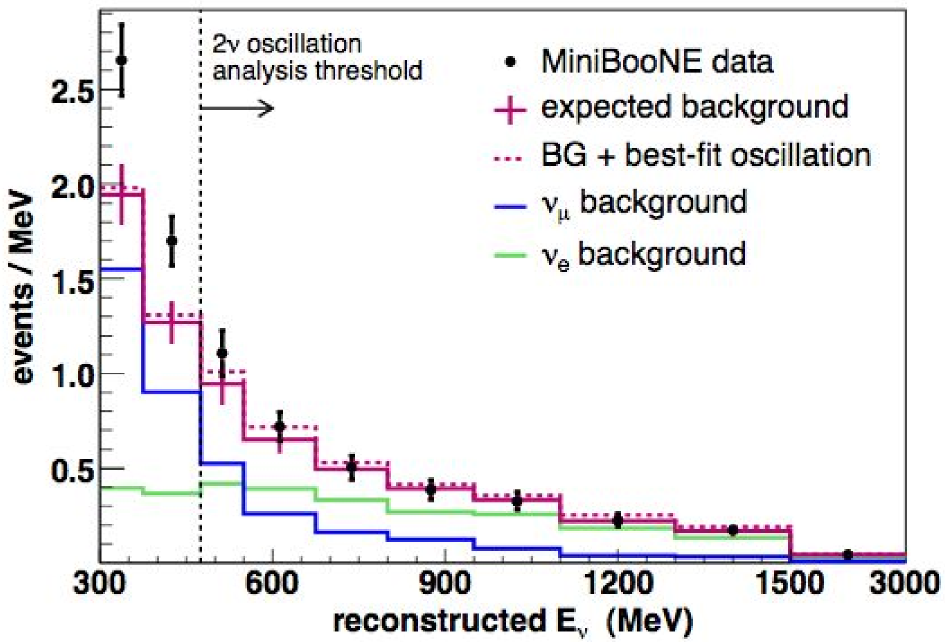


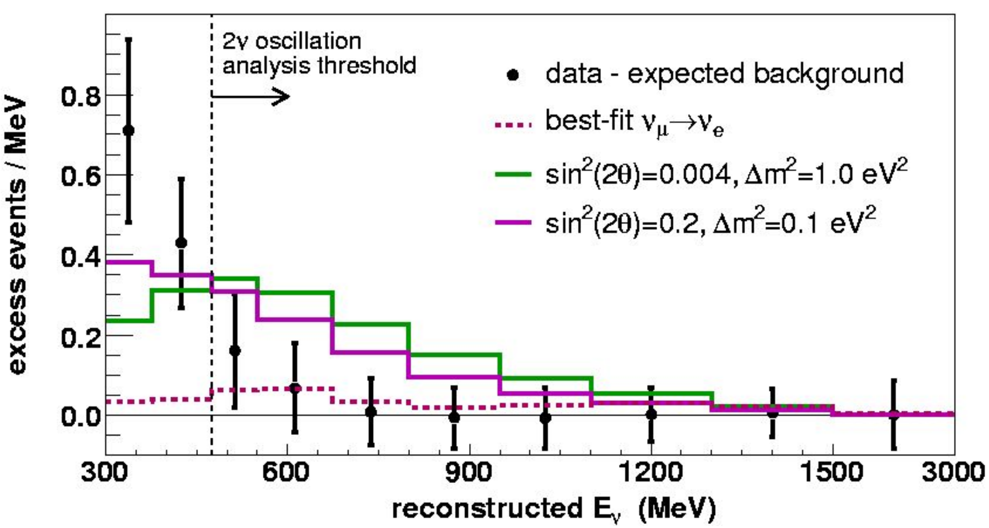


Here the various prescriptions are compared to the joint KARMEN-LSND allowed region [Church*, et al.,* PRD 66, 013001].

The Collaboration is preparing to present a combined analysis of the data of the three experiments: LSND-KARMEN-MiniBooNE

But an Excess of Events Observed Below 475 MeV





96 ± 17 ± 20 events above background, for $300 < E_\nu^{QE} < 475$MeV

Deviation: 3.7 σ

Excess Distribution is inconsistent with a simple two-neutrino oscillation model

Investigating the low E excess (300 MeV < E_ν < 475 MeV)

No Detector anomalies found

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

No Reconstruction problems found

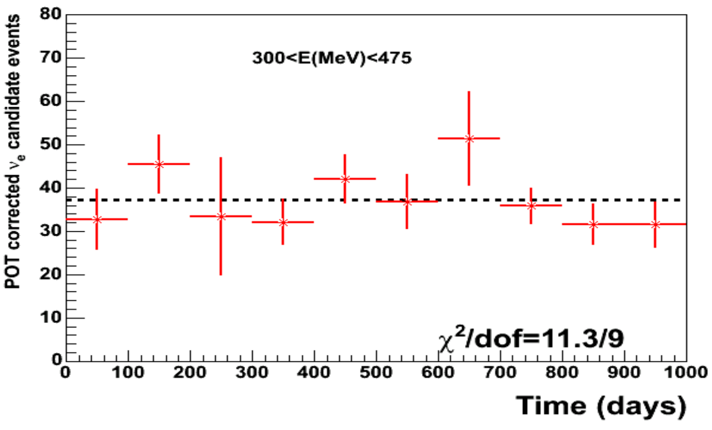
All low-E electron candidate events have been examined via event displays, consistent with 1-ring events.

Could be electrons or photons.

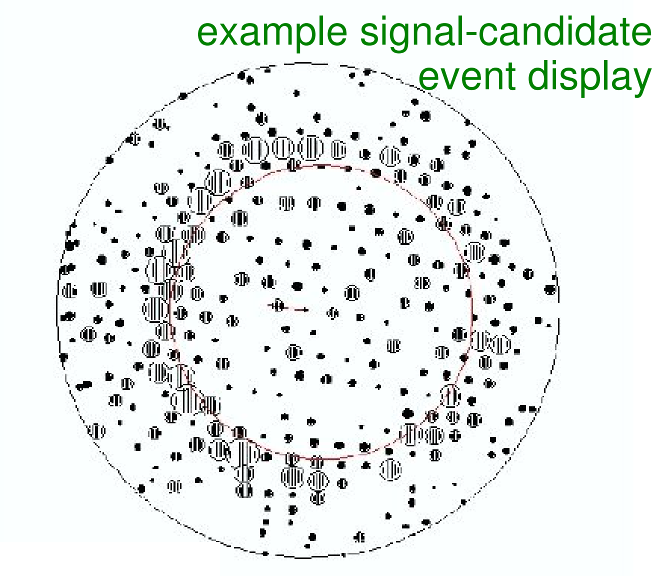
MiniBooNE cannot distinguish electron from single gammas. Processes leading to a single gamma in the final state will be a background.

New type of γ background not properly simulated in GEANT?

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

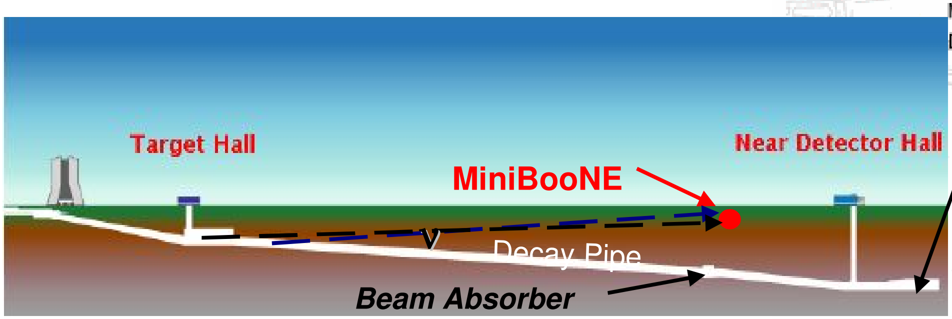


example signal-candidate event display



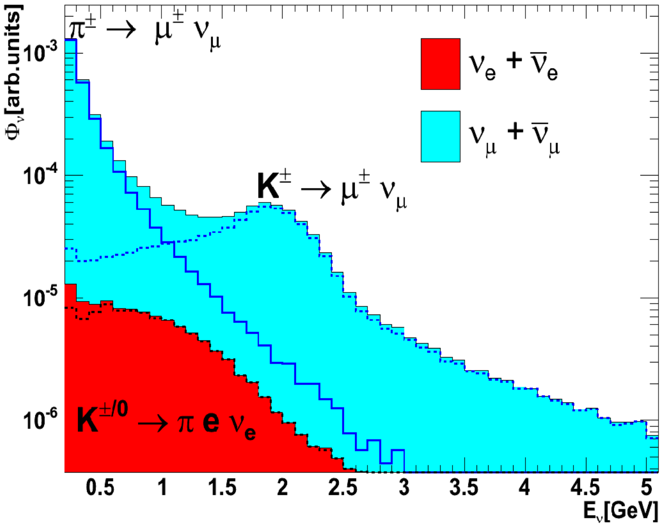
Can test some hypotheses using neutrinos from a different source ....

Neighboring neutrino source: NuMI → MINOS

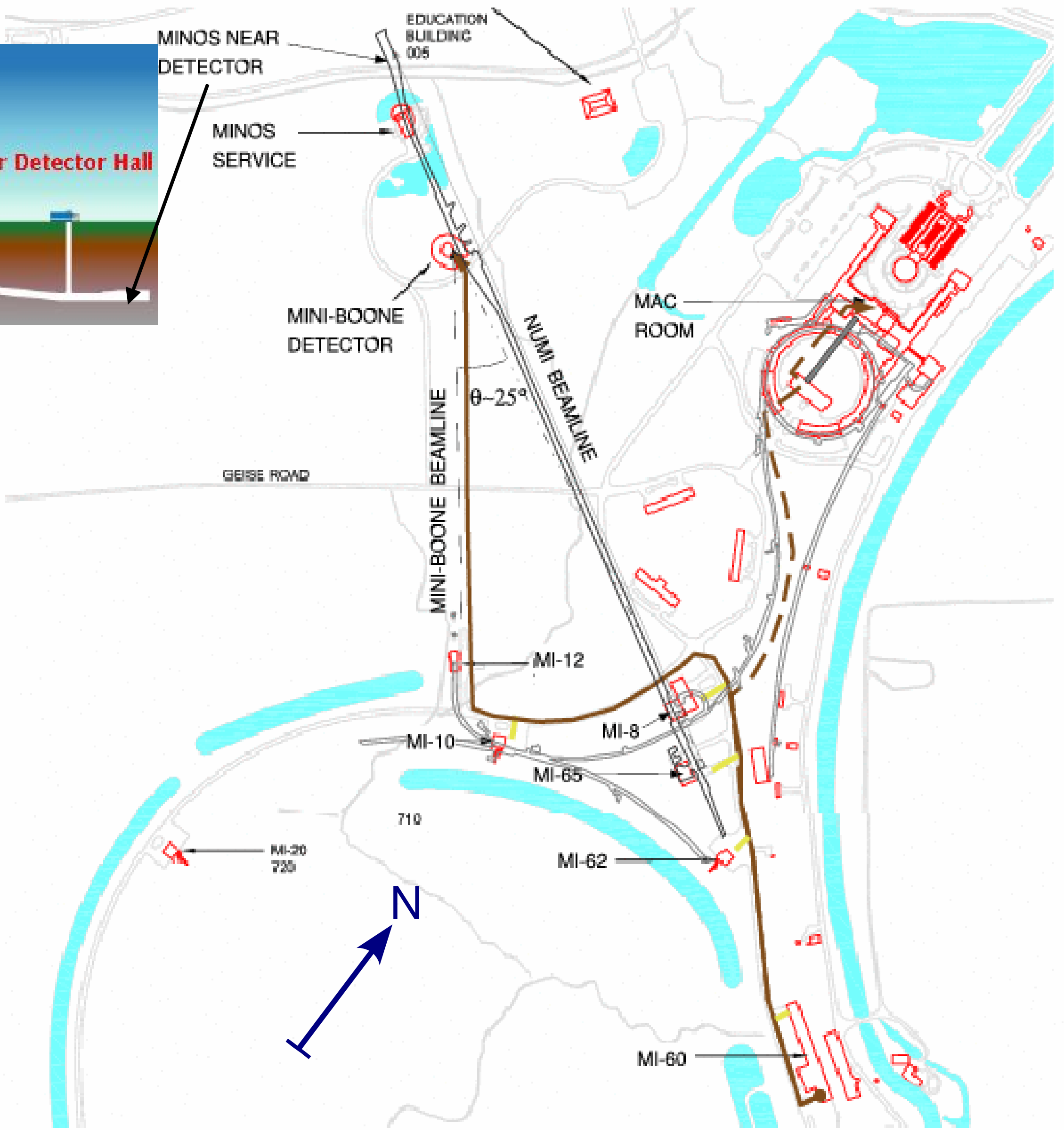


NuMI flux composition:

ν_μ(66%), ν_e(2%), $\bar{\nu}_\mu$(31%), $\bar{\nu}_e$(1%)



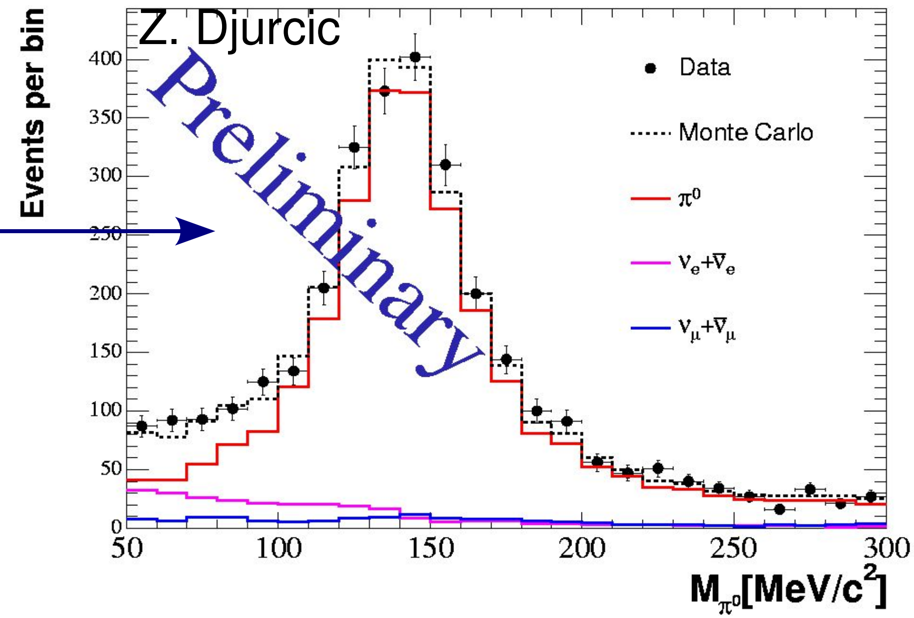
Enhanced in ν_e from K decay because of the off-axis position (~111 mrad off axis).



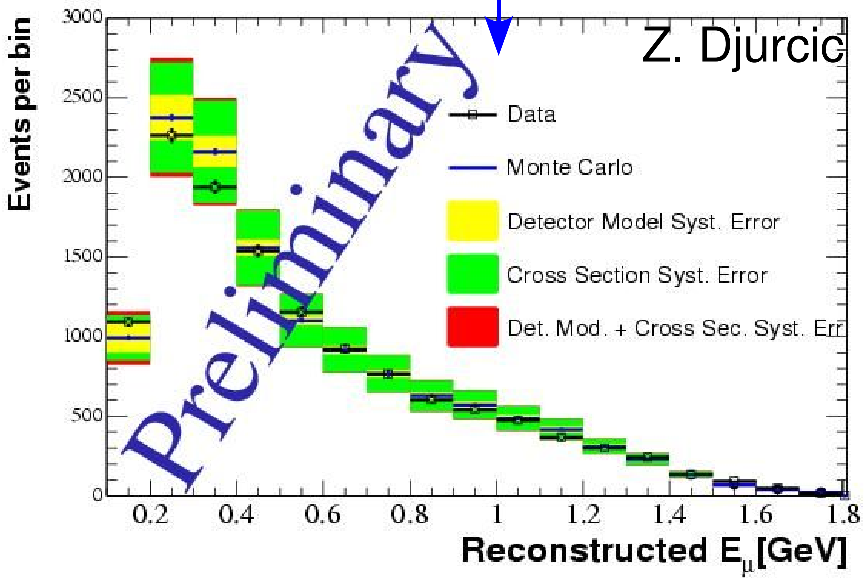
NuMI Events in MiniBooNE

Good Data to MC agreement for π^0 enhanced sample.

$\Rightarrow$ Good Understanding of the backgrounds for ν_e oscillation search.



Good Data vs MC Agreement for NuMI ν_μ events in MiniBooNE.



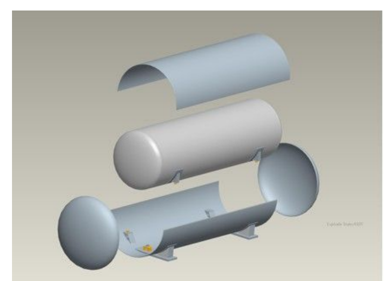
Next Step is the analysis of ν_e events: do we see a similar excess?
Search for low energy excess at MiniBooNE with NuMI beam:
Goal to have results in Nov. 2007

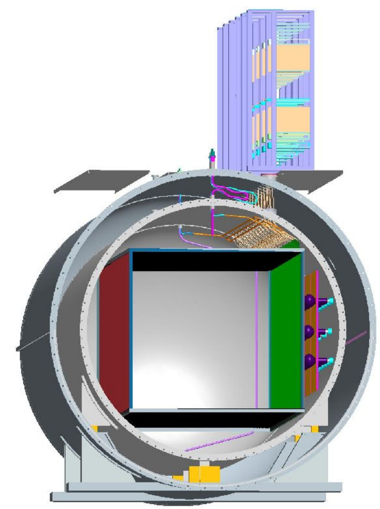
Future plans

- Run MiniBooNE in anti-neutrinos for several more years to make oscillations search in anti-neutrino mode.
  - Statistics are less but background are smaller and somewhat different.
  - Provides another low E data set and directly checks LSND

- MiniBooNE sees off-axis 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
  - ⇒ First MiniBooNE(NuMI) 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





Summary

Finding no significant excess of ν_e events above background expectations, MiniBooNE rules out (98%C.L.) the LSND result interpreted as $\nu_\mu \to \nu_e$ 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:

- $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations (w/"standard" assumptions of CPT ,CP , E-dependence)
- $\bar{\nu}_\mu \to \bar{\nu}_e$ via a single sterile neutrino ("DITTO")

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

... Or perhaps, new physics

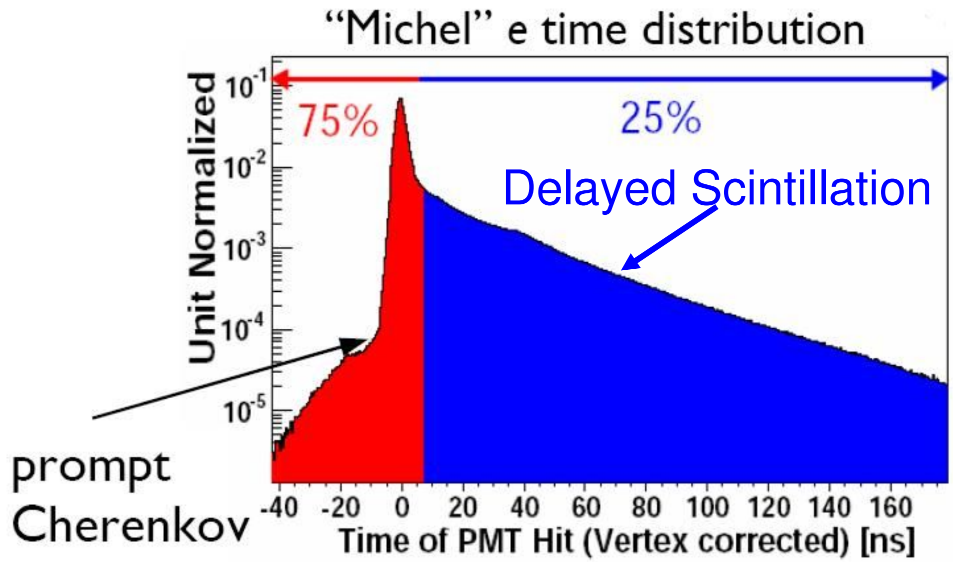
... Currently working on this with high priority

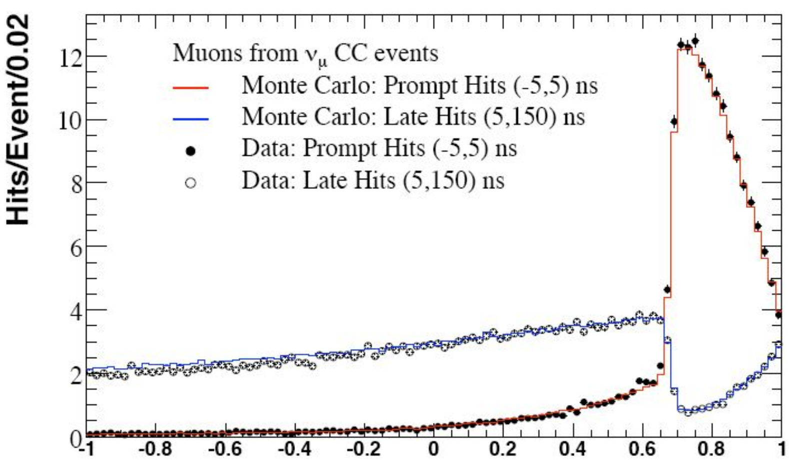
Backup Slides

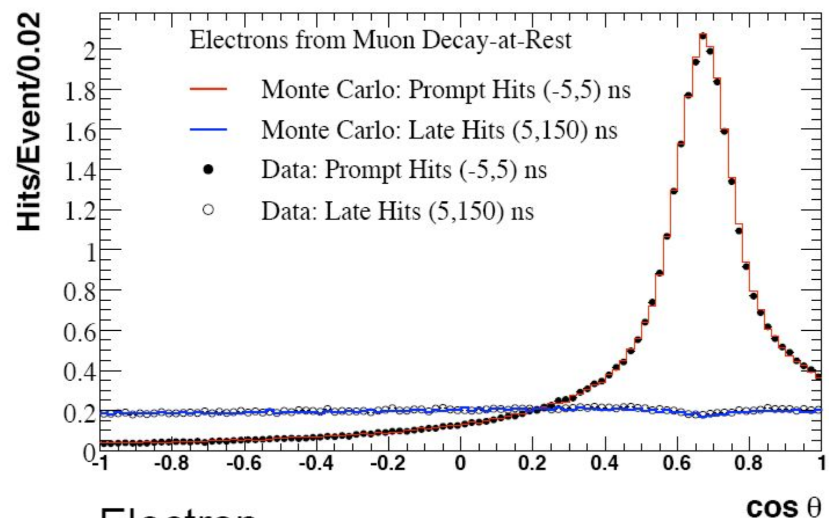
Event Reconstruction

Use energy deposition and timing of hits in the phototubes:

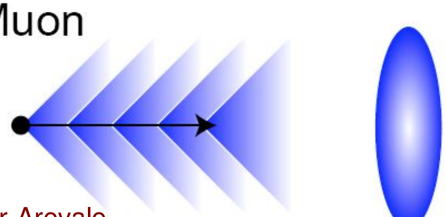
- Prompt Cherenkov light
    - Highly directional with respect to particle direction
    - Used to give particle track direction and length
- Delayed scintillation light
    - Amount depends on particle type







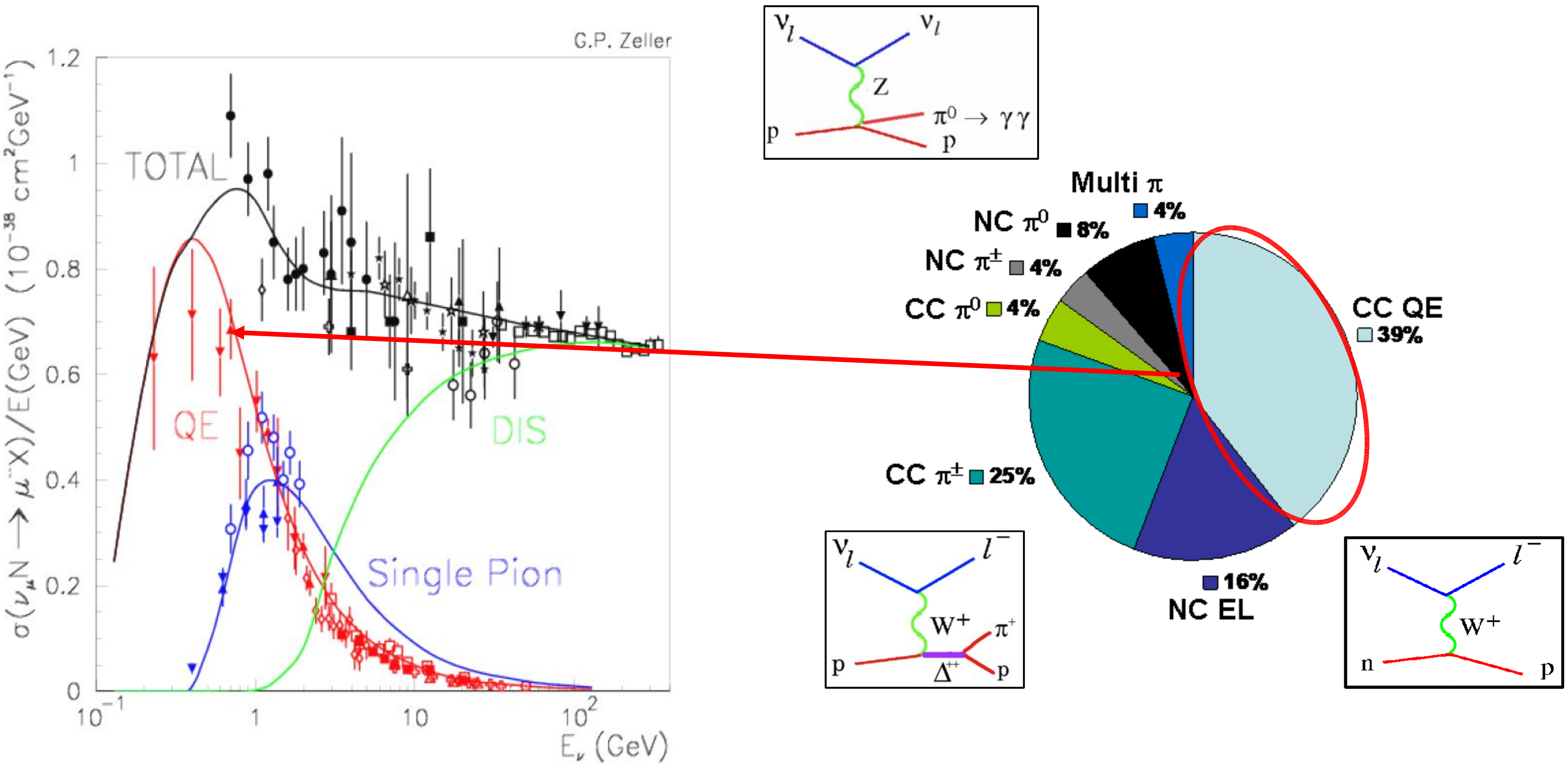
Muon



Electron

Cross Section Model: NUANCE Monte Carlo

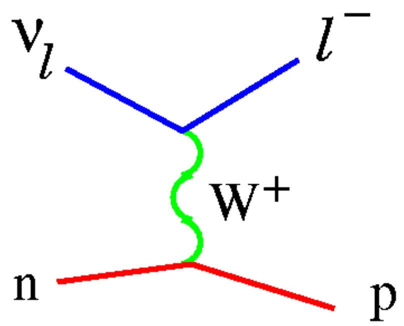
Casper, Nucl.Phys.Proc.Suppl. 112 (2002) 161

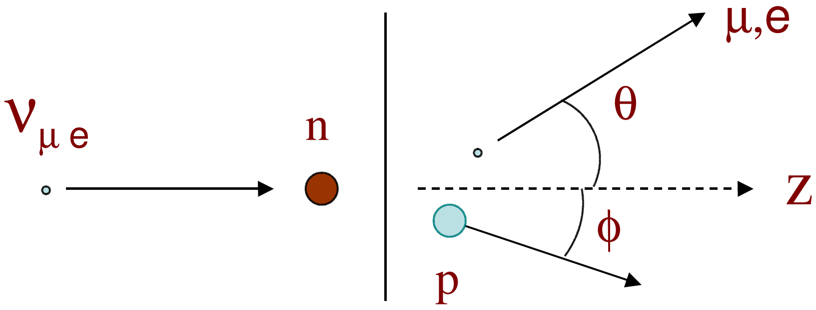


CCQE interactions (39% of total before any selection)

Most oscillations signal events will interact via this channel.

Reconstructing the neutrino energy for CCQE events E_ν^{QE}





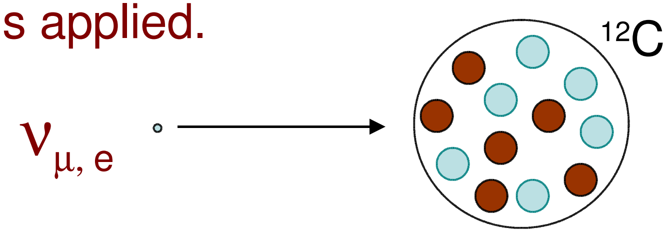
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$

Reconstruct the energy of the neutrino in a CCQE interaction.

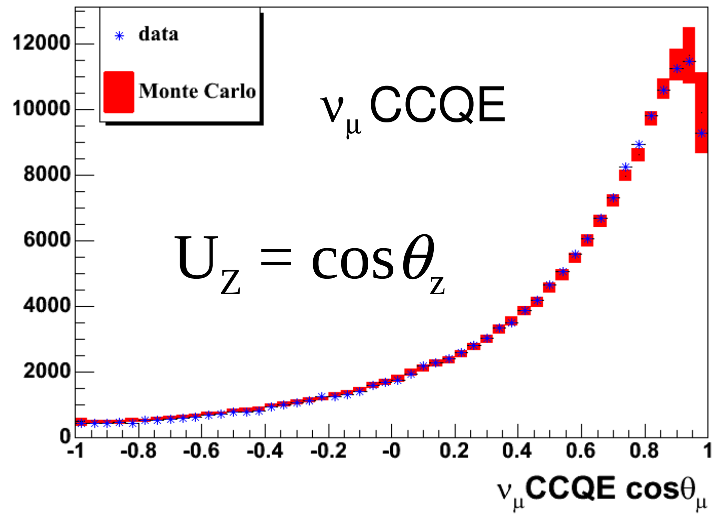
Only need to know angle and energy of scattered lepton.

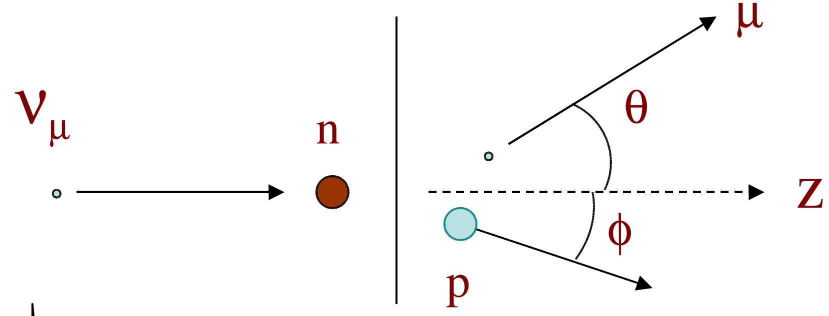
Incoming ν direction is known

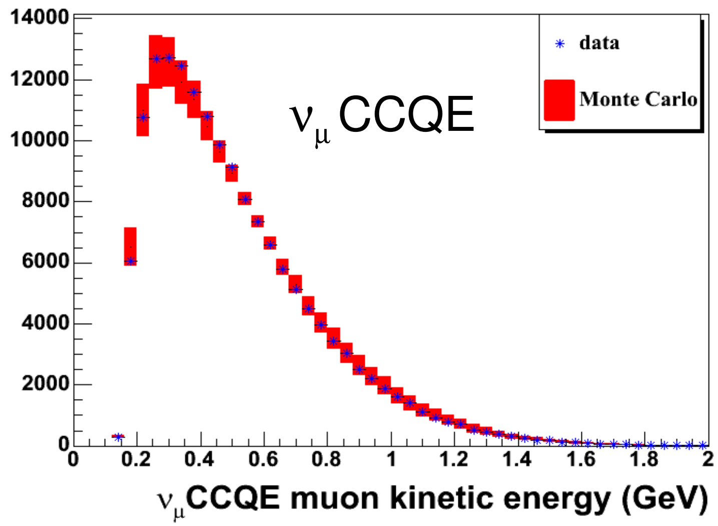
A correction due to Fermi Motion of nucleons in the target nucleus is applied.

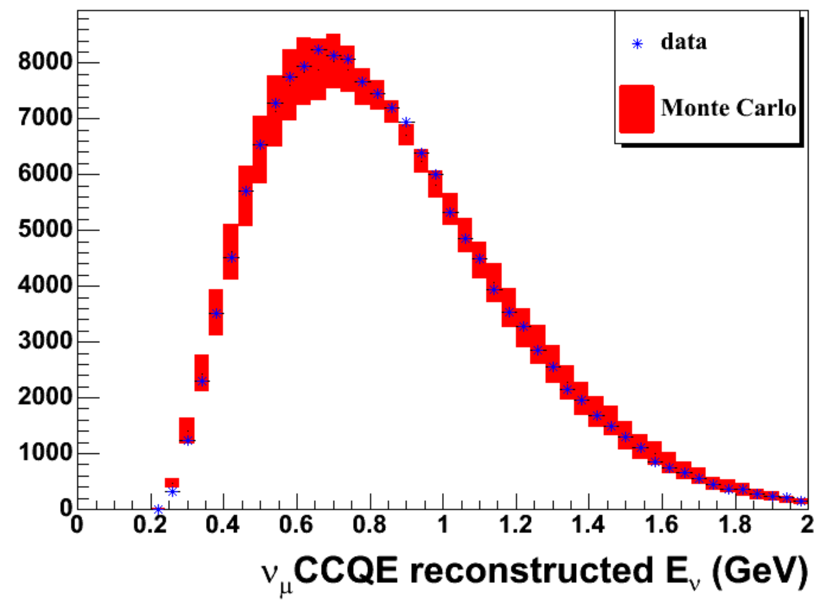


Comparing CCQE events in data and Monte Carlo



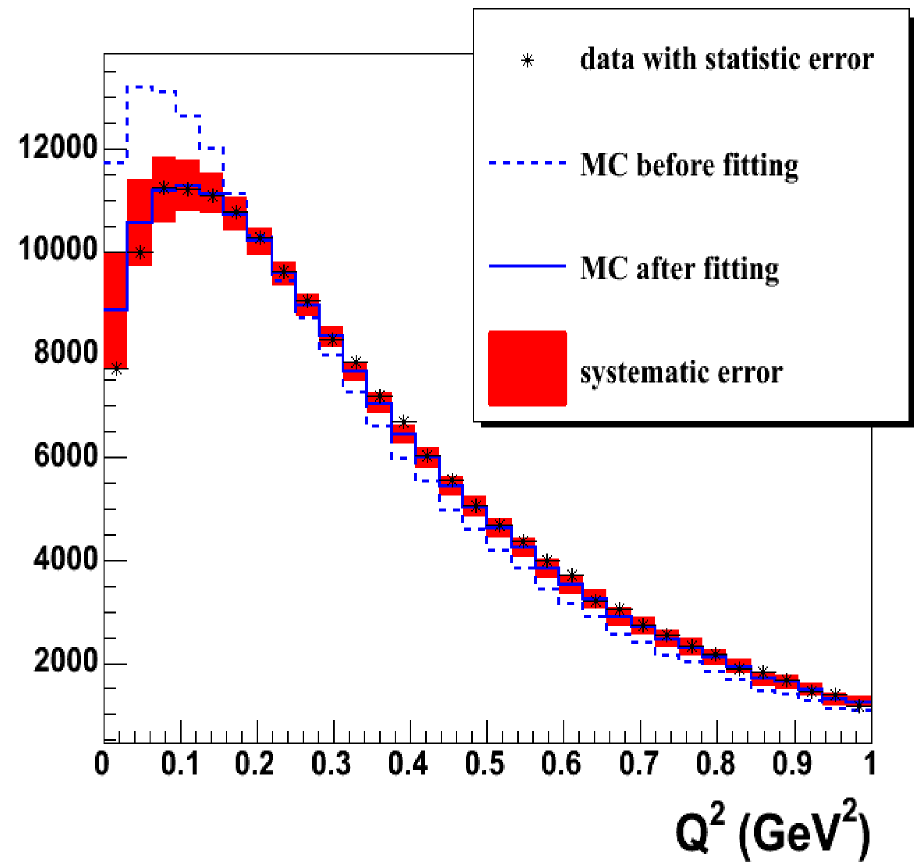






ν Cross Section Uncertainties

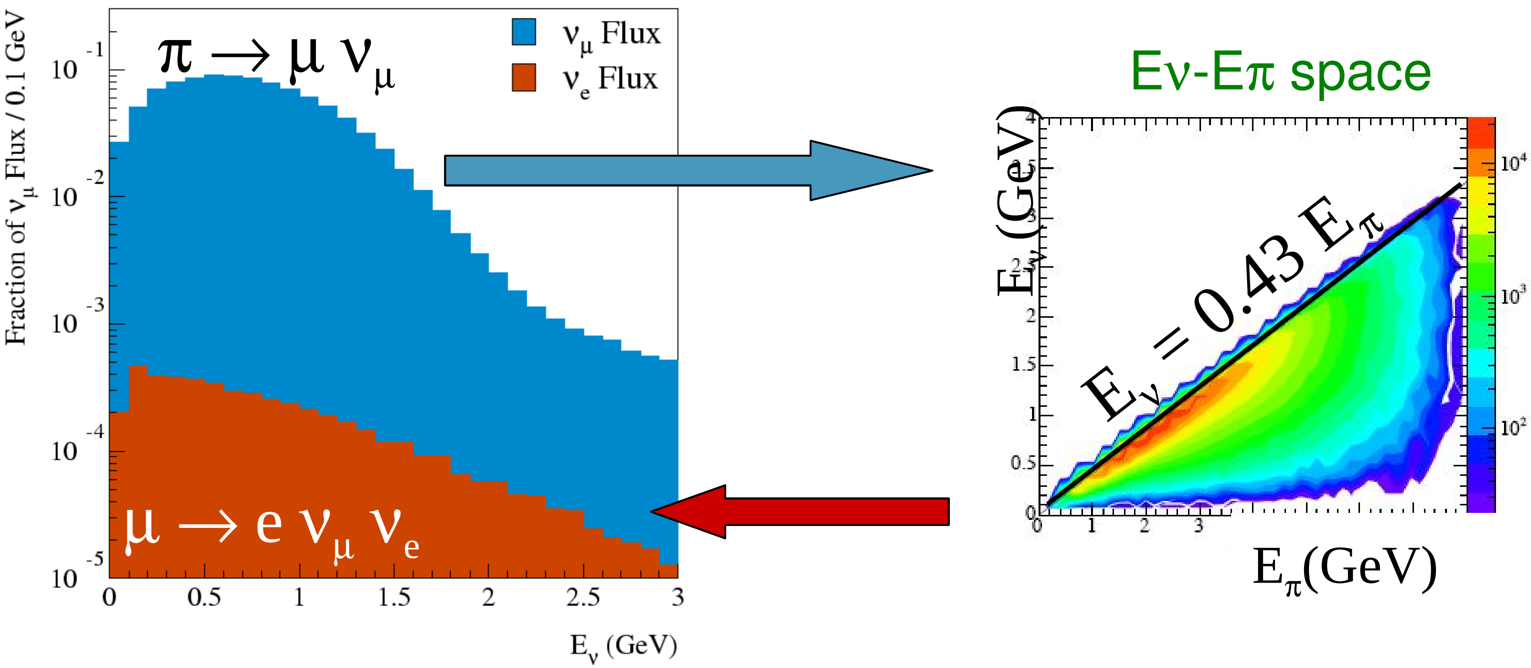
- Differential cross section for quasi-elastic scattering determined from MiniBooNE data
- Shape fits are performed to observed data Q^2 distribution using a relativistic-Fermi-gas model
- Two parameters (and their uncertainties) are determined:
  - Axial mass parameter $M_A = 1.23 \pm 0.20$ GeV
  - 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



ν_μ-CCQE events as a constraint on predictions

Measuring the ν_μ energy spectrum provides a constraint on the number of muons producing part of the intrinsic ν_e background

This is possible because of decays need to be very forward to reach the detector



Handling uncertainties in the analyses:

What we begin with...

... what we need

For a given source
of uncertainty,

Errors on a wide range
of parameters
in the underlying model

For a given source
of uncertainty,

Errors in bins of
E_ν^{QE}
and information on
the correlations
between bins

"multisim"
nonlinear error propagation

Input error matrix
keep the all correlation
of systematics

Output error matrix
keep the all correlation
of E_ν^{QE} bins

Example: Cross Section Uncertainties

M_A^{QE}, e_{lo}^{sf}	6%, 2% (stat+bkg only)	from MiniBooNE ν_μ **CCQE** data
QE σ norm	10%	
QE σ shape	function of E_ν	
ν_e/ν_μ QE σ	function of E_ν	

NC π^0 rate	function of π0 mom	from MiniBooNE ν_μ **NC** π^0 data
M_A^{coh}, coh. σ	±25%	
$\Delta \rightarrow N\gamma$ rate	function of γ mom + 7% BF	

E_B, p_F	9 MeV, 30 MeV	from other experiments
Δs	10%	
$M_A^{1\pi}$	25%	
$M_A^{N\pi}$	40%	
DIS σ	25%	

Most of these uncertainties are common to ν_μ and ν_e and cancel when the Correlations between the ν_μ and ν_e samples is taken into account in the analysis

A MiniBooNE-LSND Compatibility Test

$$\chi_0^2 = \frac{(z_{MB} - z_0)^2}{\sigma_{MB}^2} + \frac{(z_{LSND} - z_0)^2}{\sigma_{LSND}^2}$$

- For each Δm^2, determine the MB and LSND measurement:

$$z_{MB} \pm \delta z_{MB},$$
$$z_{LSND} \pm \delta z_{LSND} \quad ,$$

where $z = \sin^2(2\theta)$, and δz is the 1σ error.

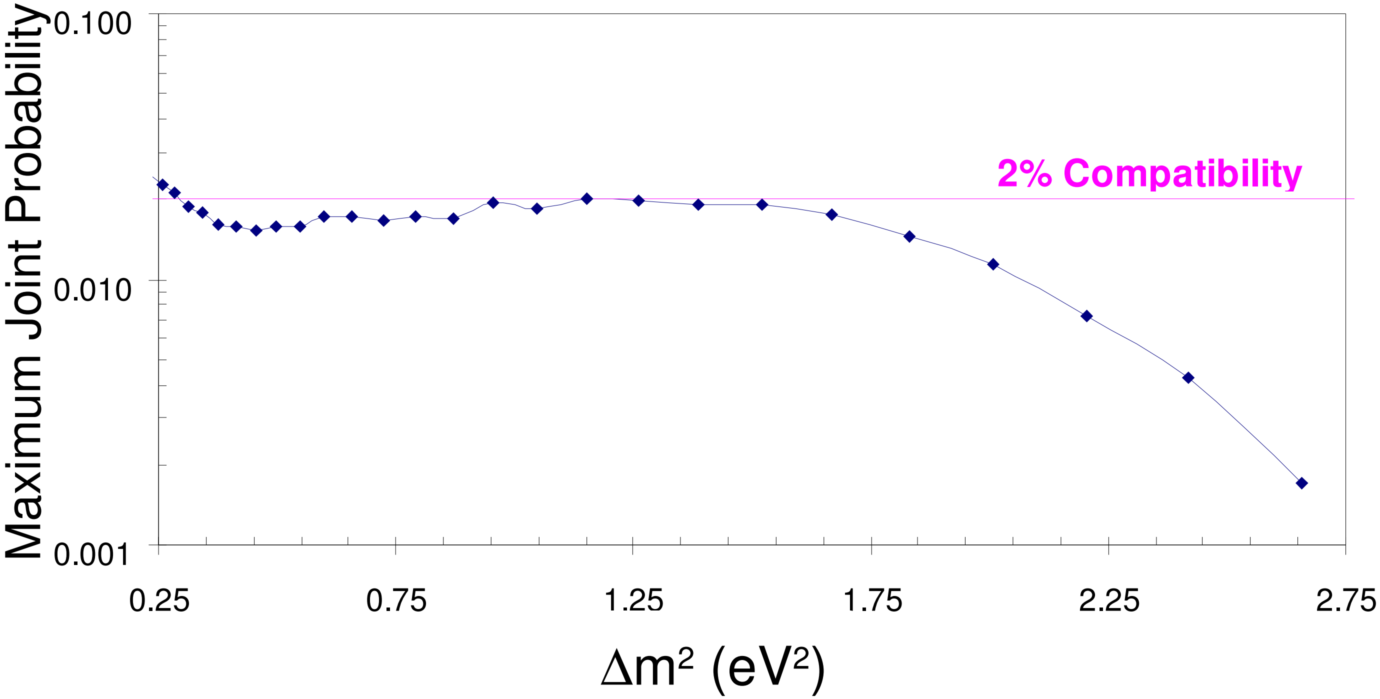
- For each Δm^2, form χ^2 between MB and LSND measurement

- Find z_0 that minimizes χ^2 (weighted average of two measurements) and this gives χ^2_{min}

- Find probability of χ^2_{min} for 1 dof;

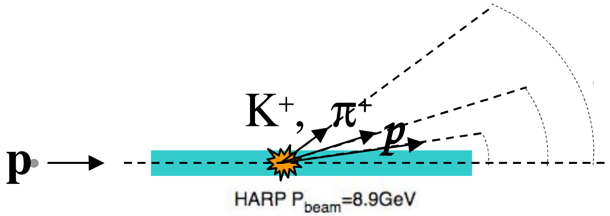
  This is the joint compatibility probability for this Δm^2

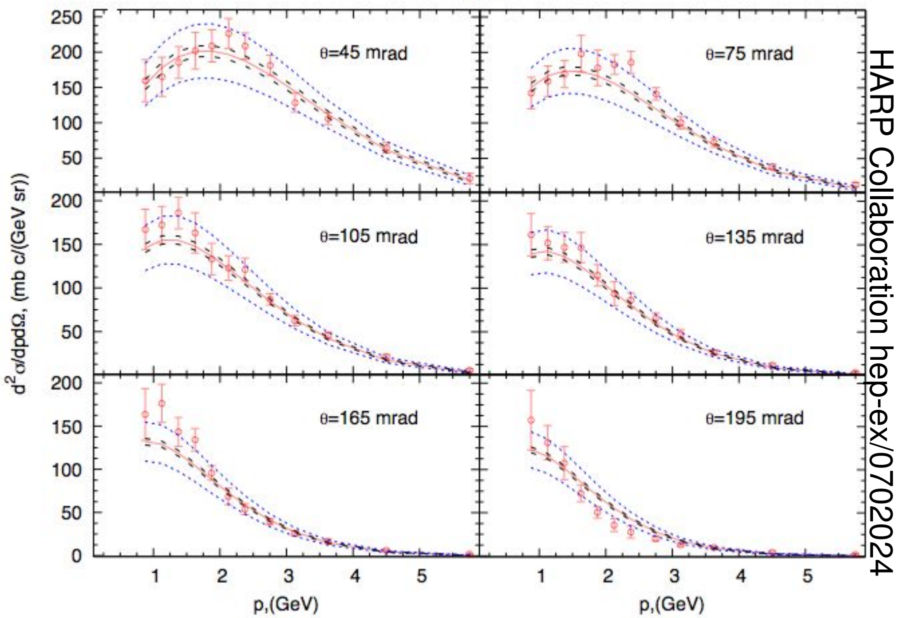
A MiniBooNE-LSND Compatibility Test

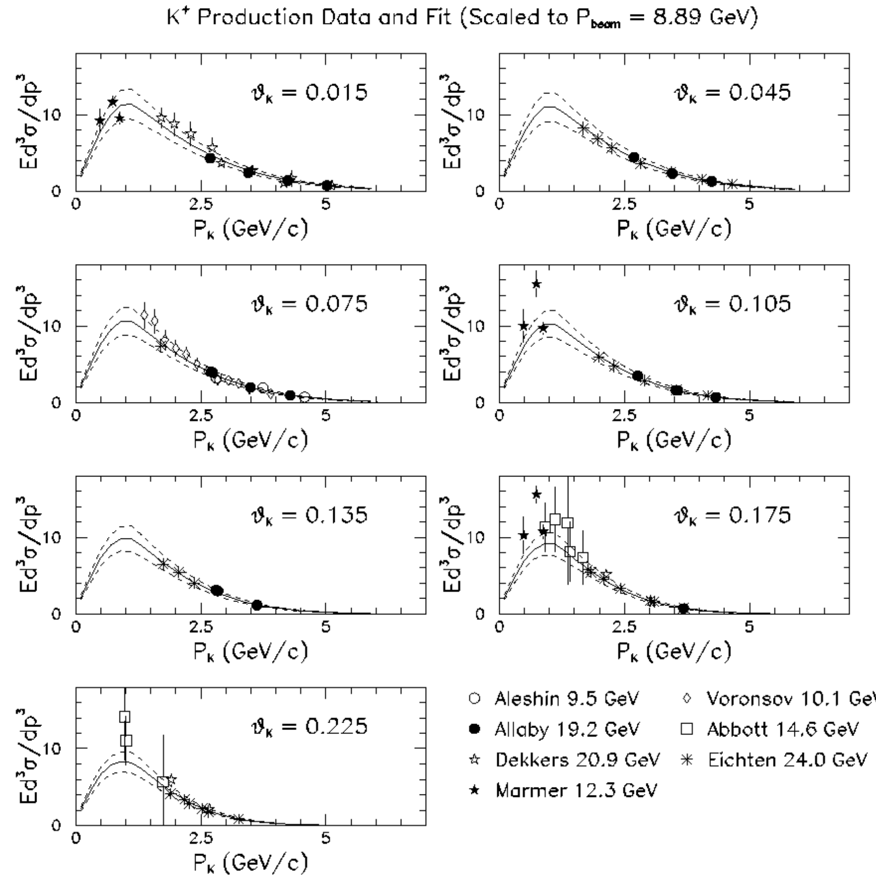


This leads to a 98% incompatibility with the $\nu_\mu \rightarrow \nu_e$ appearance only interpretation of LSND and MiniBooNE.

Production of π^+ and K^+ at the target







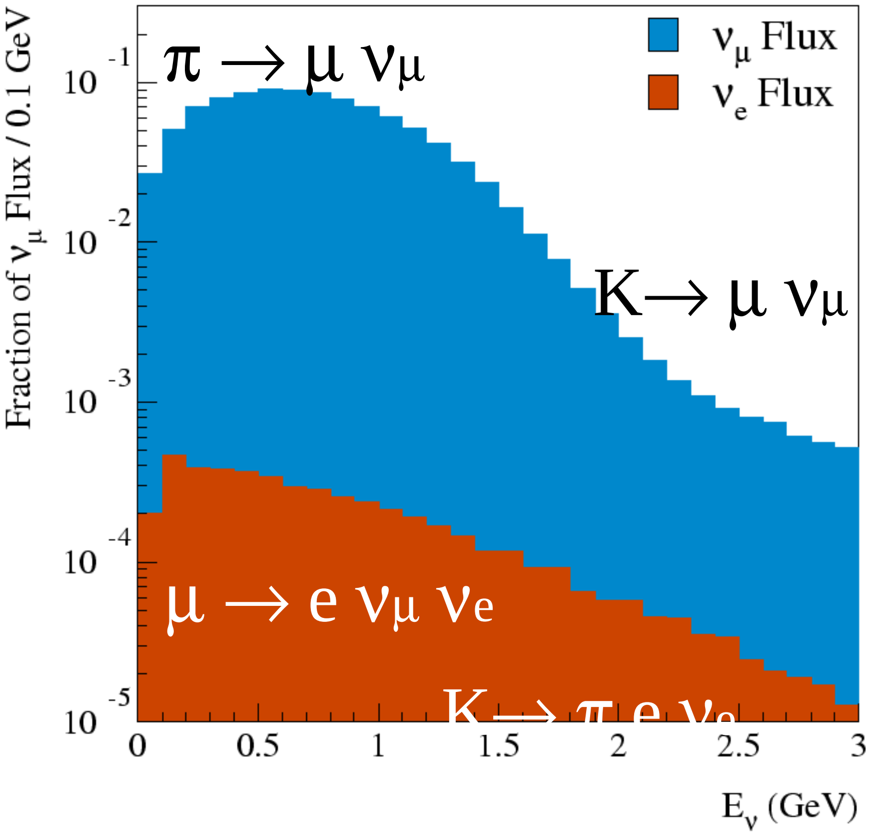
Pions

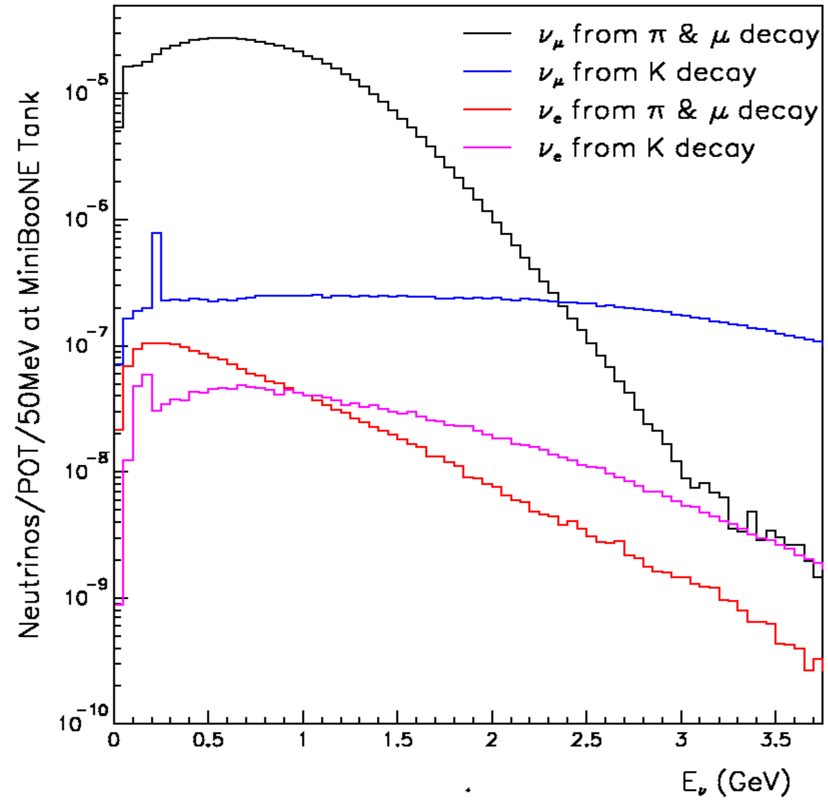
- MiniBooNE members joined HARP Collab. Took π^+ production data with target replica at CERN.
  - 5% λ Beryllium target
  - 8.9 GeV proton beam momentum
- Data are fit to a Sanford-Wang parameterization

Kaons

- K^+ production data taken on multiple targets in 10-24 GeV range.
- Fit to a Feynman-scaling param. (30% uncertainty)

Neutrino Flux from GEANT4 Simulation





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

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

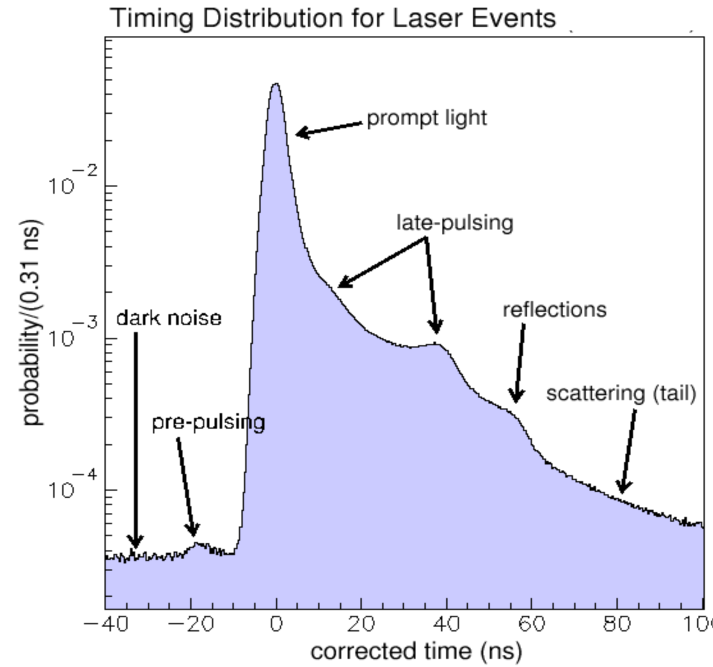
Other (5%) $K^0 \to \pi\ e\ \nu_e$ (14%)

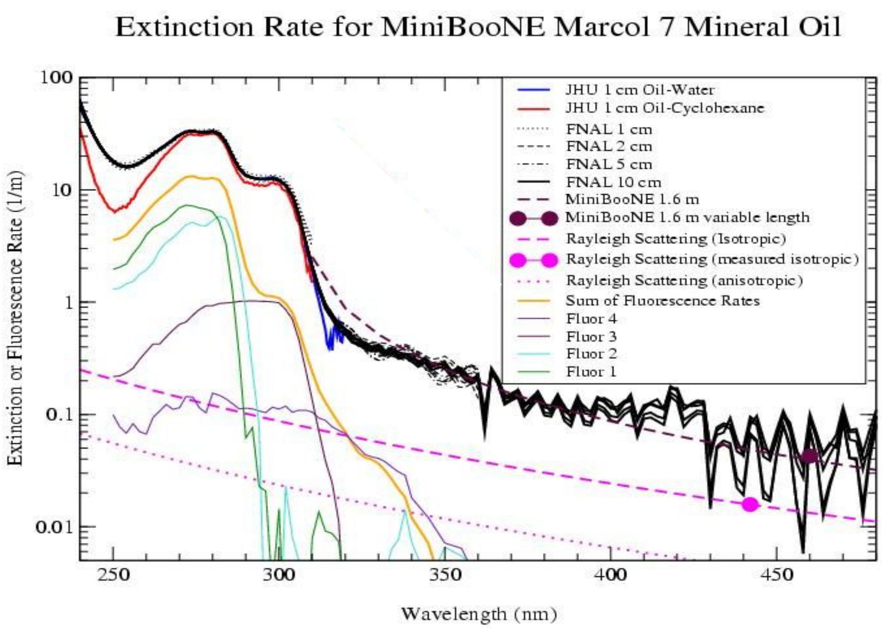
ν_e/ν_μ = 0.5%

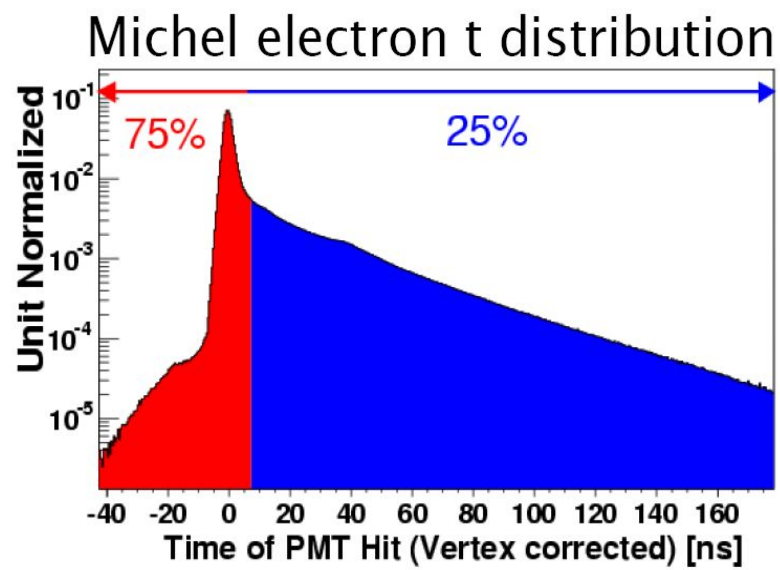
Antineutrino content: 6%

Detector Optical Model

- Light: Cerenkov, Scintillation, Fluorescence
- Charge/Time response of PMT's taken into account
- Scattering, reflections, PMT prepulsing
- Overall, ~40 parameters need to be set
- Laser and Michel e^- data used to tune.







Summary of Track Based cuts

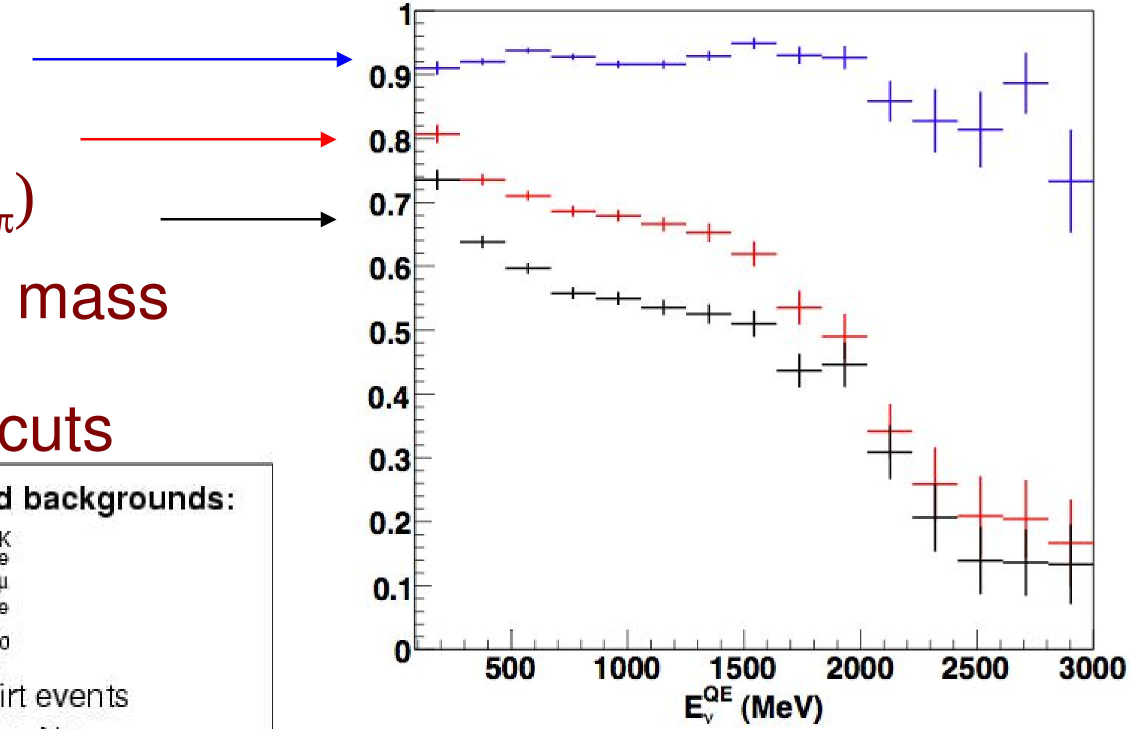
"Precuts" +

$\text{Log}(L_e/L_\mu)$

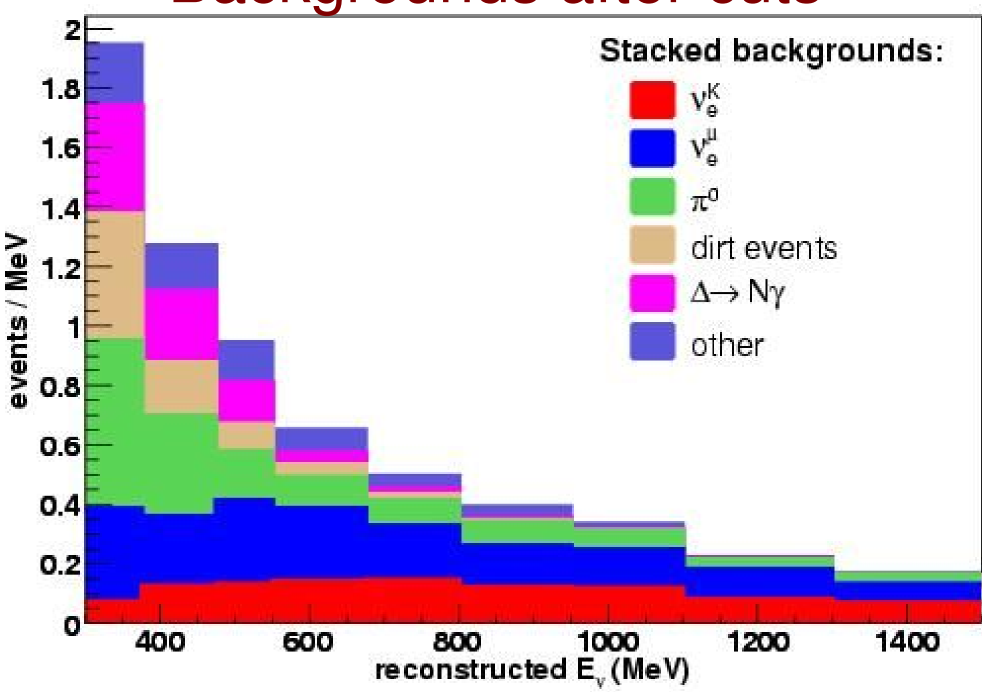
$+ \text{Log}(L_e/L_\pi)$

+ invariant mass

Efficiency:

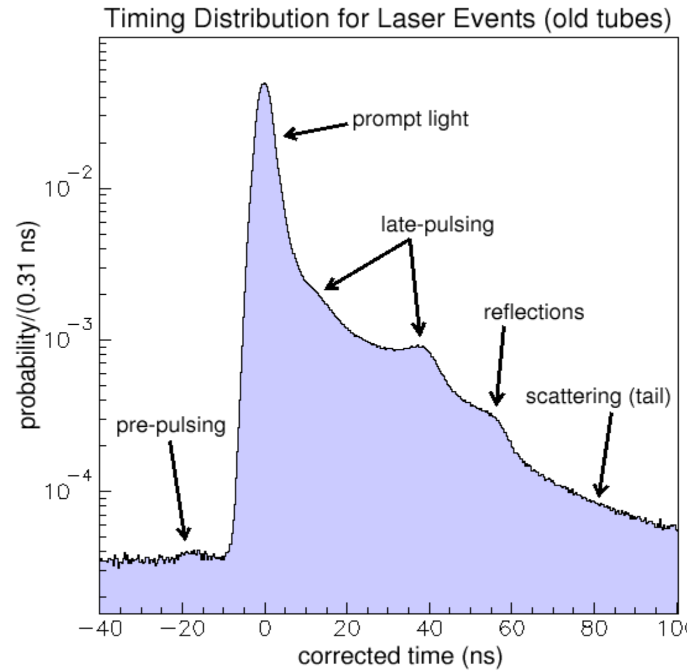


Backgrounds after cuts



Optical Model Uncertainties

Uncertainties on the parameters associated with optical model are used to determine the uncertainties for the oscillation search



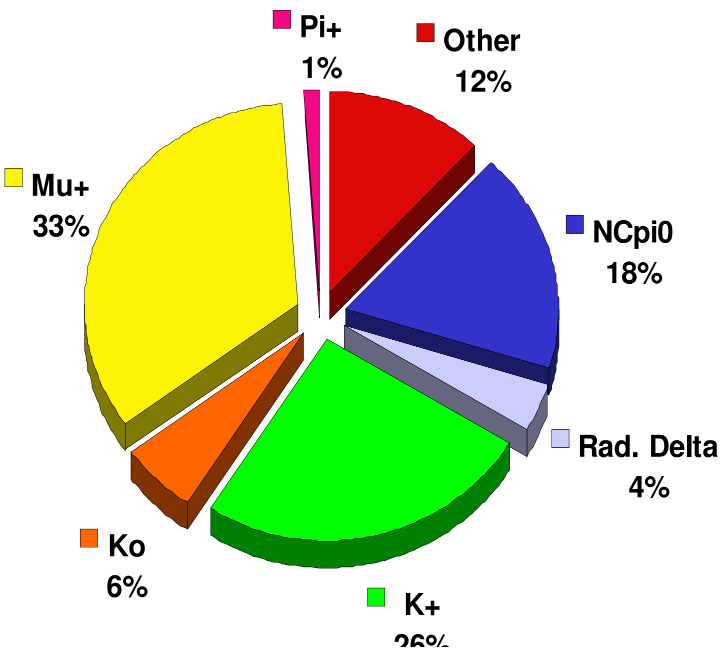
- Light Creation
  - Cerenkov – well known
  - Scintillation
    - yield
    - spectrum
    - decay times
- Light Propagation
  - Fluoresence
    - rate
    - spectrum
    - decay times
  - Scattering
    - Rayleigh
    - Particulate (Mie)
  - Absorption

- In Situ
  - Cosmics muons, Michel electrons, Laser
- External
  - Scintillation from p beam (IUCF)
  - Scintillation from cosmic μ (Cincinnati)
  - Fluorescence Spectroscopy (FNAL)
  - Time resolved spectroscopy (Princeton, JHU)
  - Attenuation (Cincinnati)

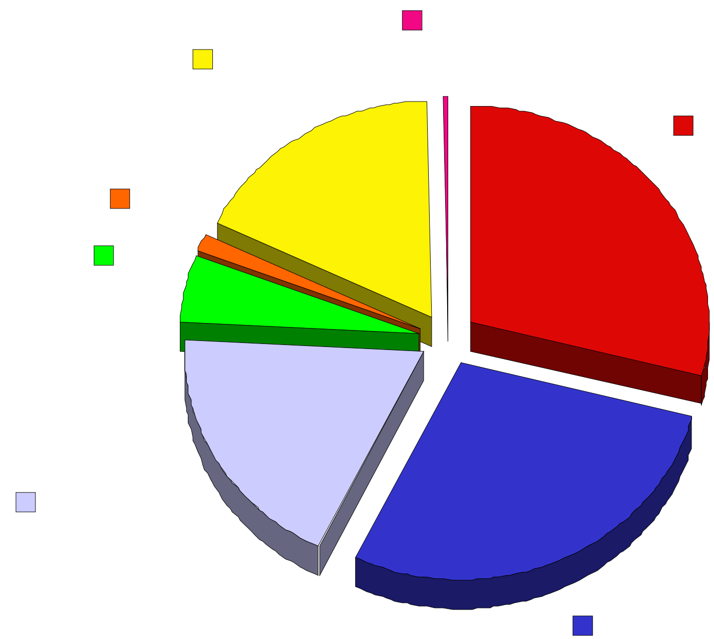
Composition of Likelihood analysis electron candidate sample

intrinsic ν_e

ν_μ mis-id



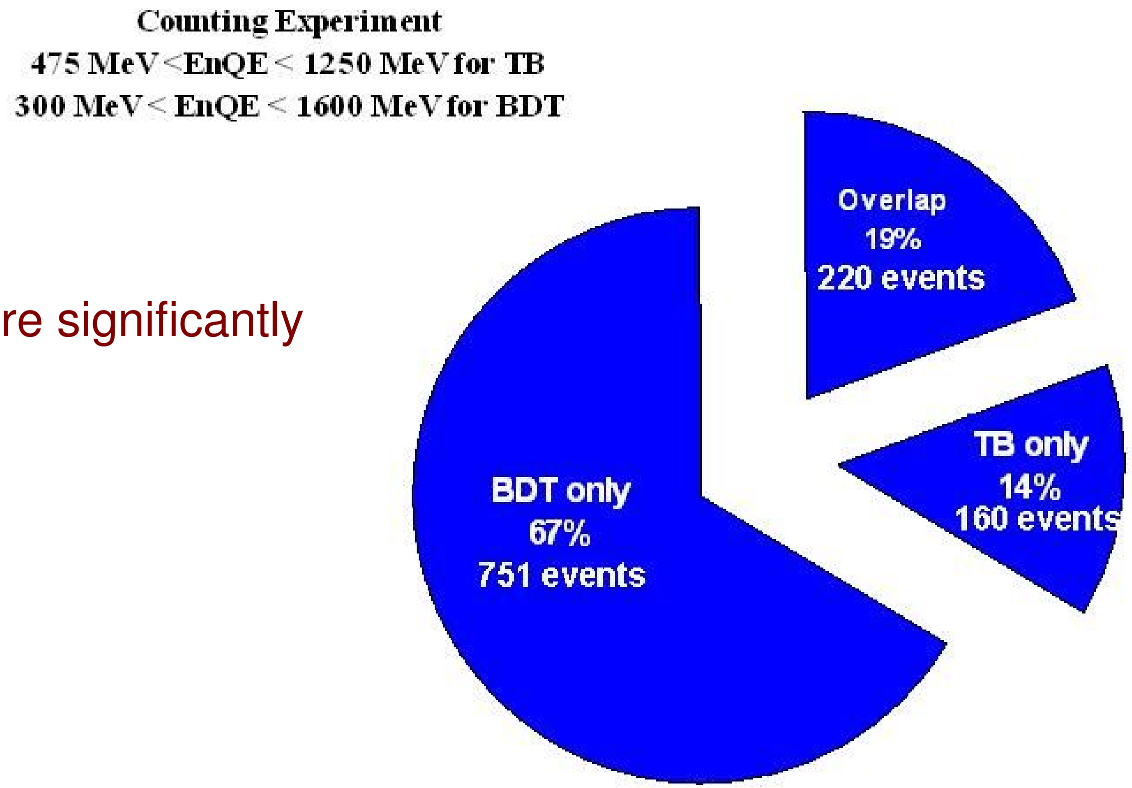
- Likelihood Analysis
- 475 MeV to 3 GeV



- Likelihood Analysis
- 300 MeV to 475 MeV

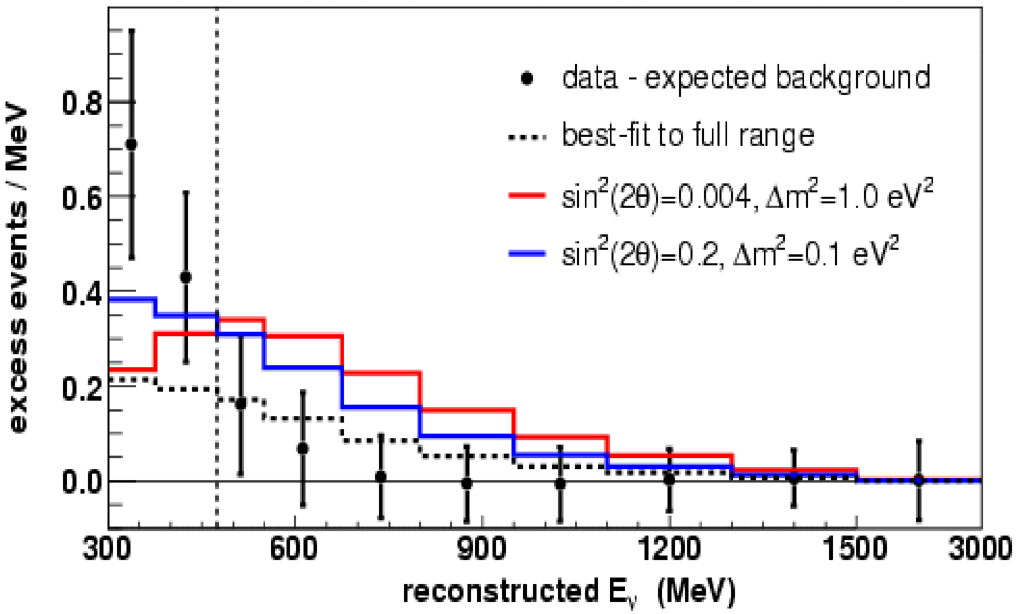
Counting experiment results at box opening:

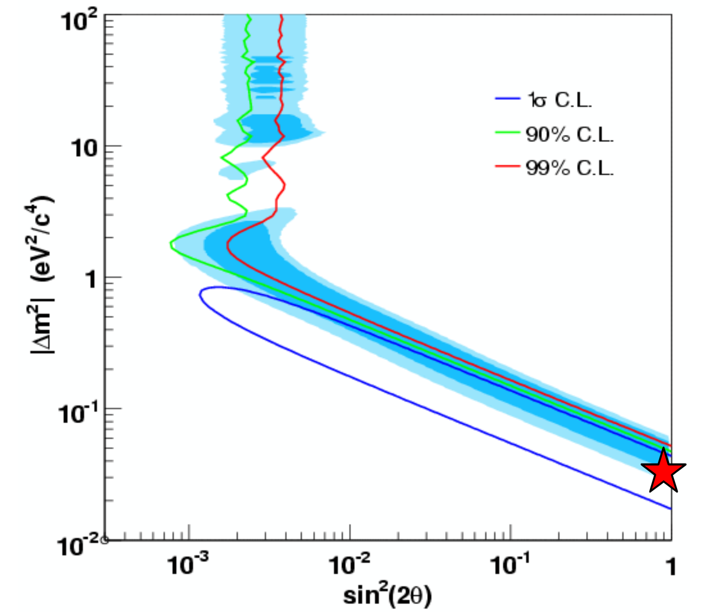
	TBL	BDT
Range	$475 < E_\nu^{QE} < 1250$ MeV	$300 < E_\nu^{QE} < 1600$ MeV
Data	380 events	971 events
expectation	358 ±19 (stat) ± 35 (sys)	1070 ±33 (stat) ± 225 (sys)
significance	0.55 σ	-0.38 σ



BDT and TBL analyses are significantly different.

2-neutrino Oscillation Fits for 300 – 3000 MeV



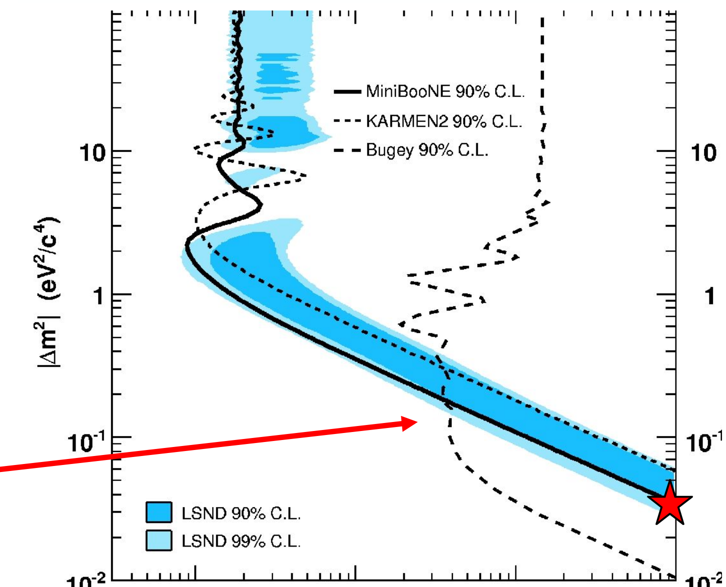


Best Fit (dashed):

$(\sin^2 2\theta, \Delta m^2) = (1.0, 0.03\ eV^2)$

χ^2 Probability: 18%

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



Sterile Neutrinos That Take Shortcuts in Extra Dimensions

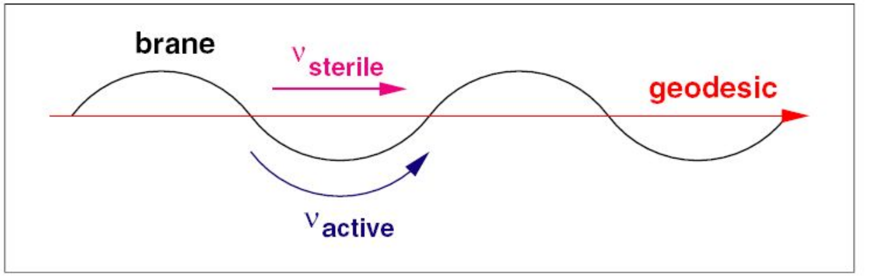
- Prior to MiniBooNE's first result, it was put forward that sterile neutrinos can take shortcuts in extra dimensions.

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

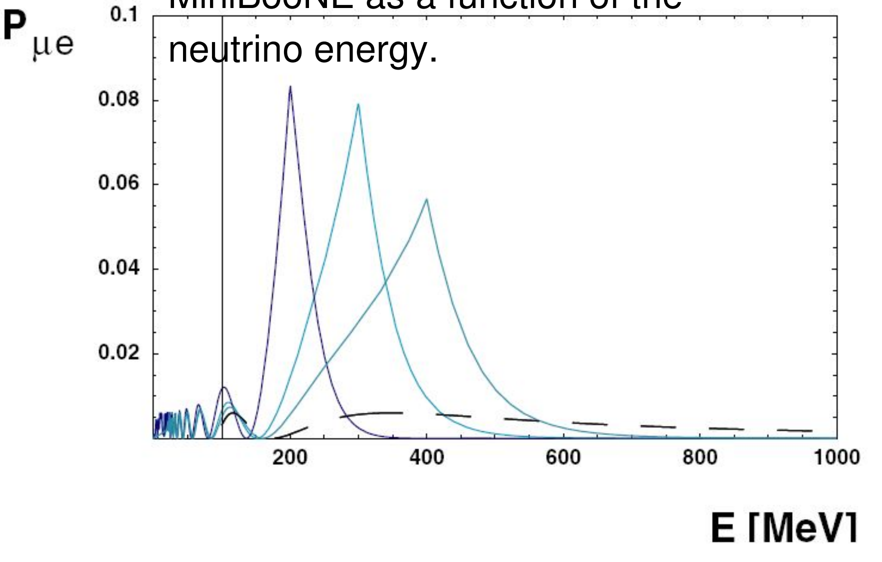
  – A resonance in active-sterile neutrino oscillations arises from an increase in the path-length of active neutrinos relative to sterile neutrinos in the bulk.
    - Below the resonance, the standard oscillation formulas apply.
    - Above the resonance, active-sterile oscillations are suppressed.
    - 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.



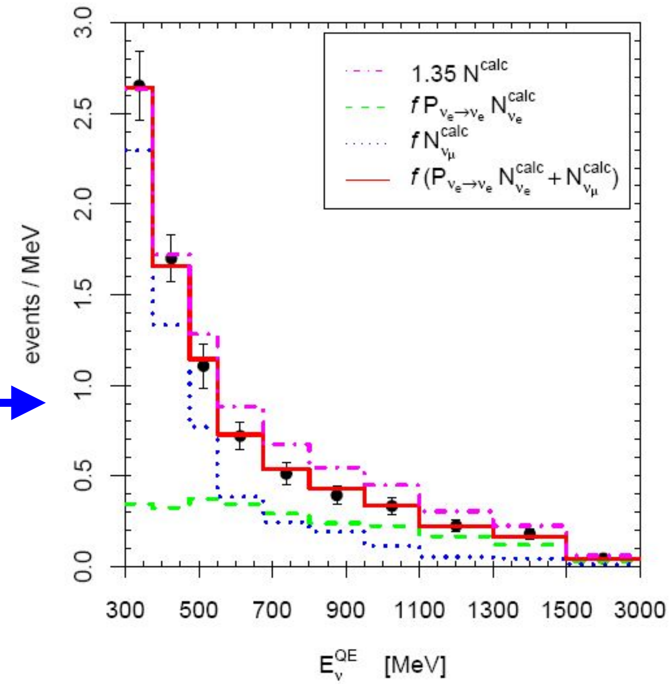
Oscillation probabilities for MiniBooNE as a function of the neutrino energy.



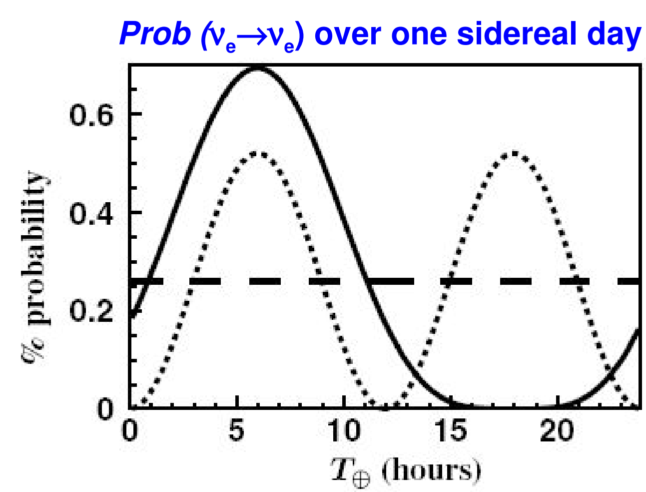
Other New Physics Models

- Electron neutrino disappearance
  (Giunti and Laveder, hep-ph 0707.4593)
  – Prompted by the deficit seen in the Ga exps 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



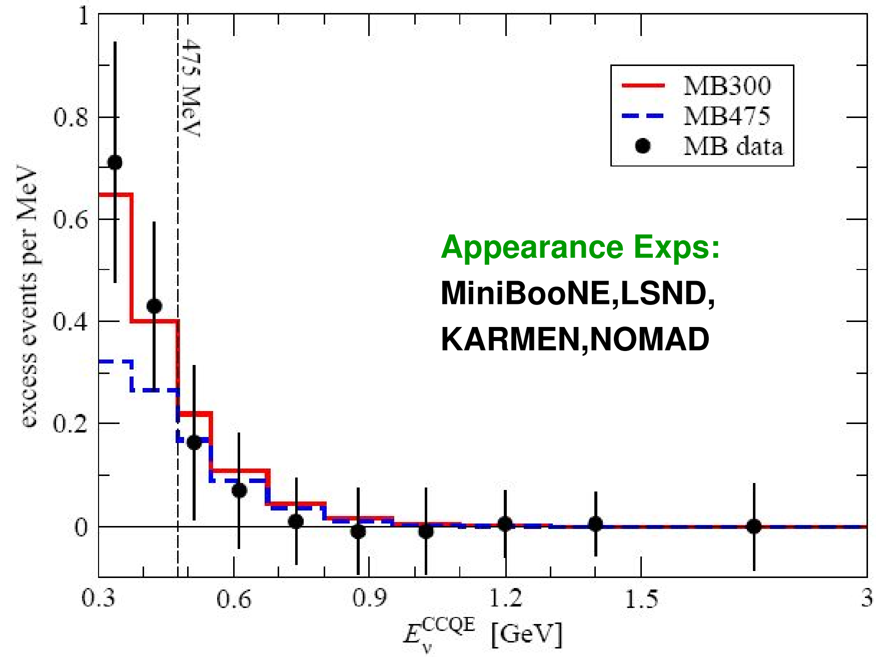
- Lorentz Invariance Violation
  (Katori, Kostelecký, Tayloe, PRD 74,1050009)
  – Adding Lorentz invariance violating terms in the Hamiltonian that depend on neutrino flavor can produce interference terms for the neutrino propagation
  – New oscillation phenomenology
    - Osc length dependence on E*L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



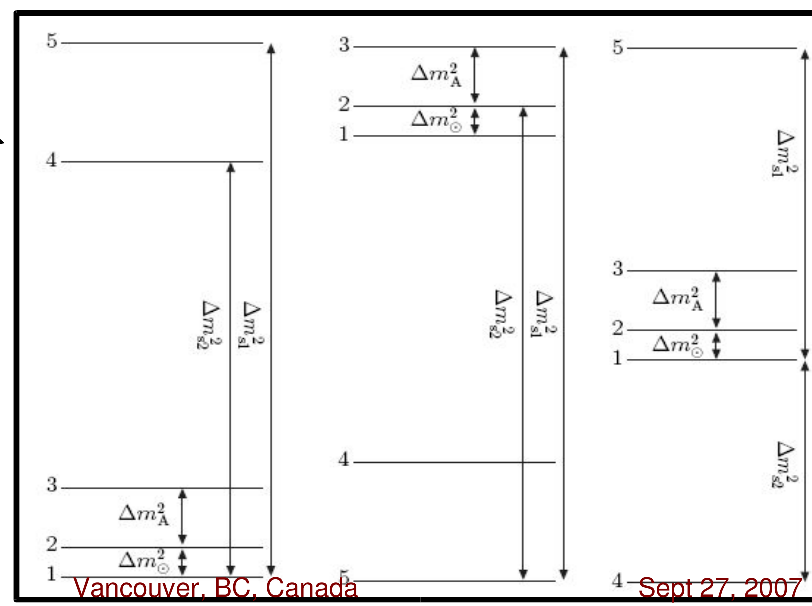
New Physics: Models with Sterile Neutrinos

- 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 there is discrepant with the disappearance results: Bugey,Chooz,PaloVerde,CDHS. (Appearance and disappearance incompatible at the 4σ level) (Maltoni and Schwetz, hep-ph0705.0107)



- Best fit masses in the 3+2 model are in the range of 0.6 to 6.5 eV^2 for the two added sterile neutrinos. This could start to run into cosmological bounds. Other hierarchies might be able avoid these bounds. (Goswami and Rodejohann, hep-ph0706.1462)



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