MiniBooNE First Results (1998-2007)

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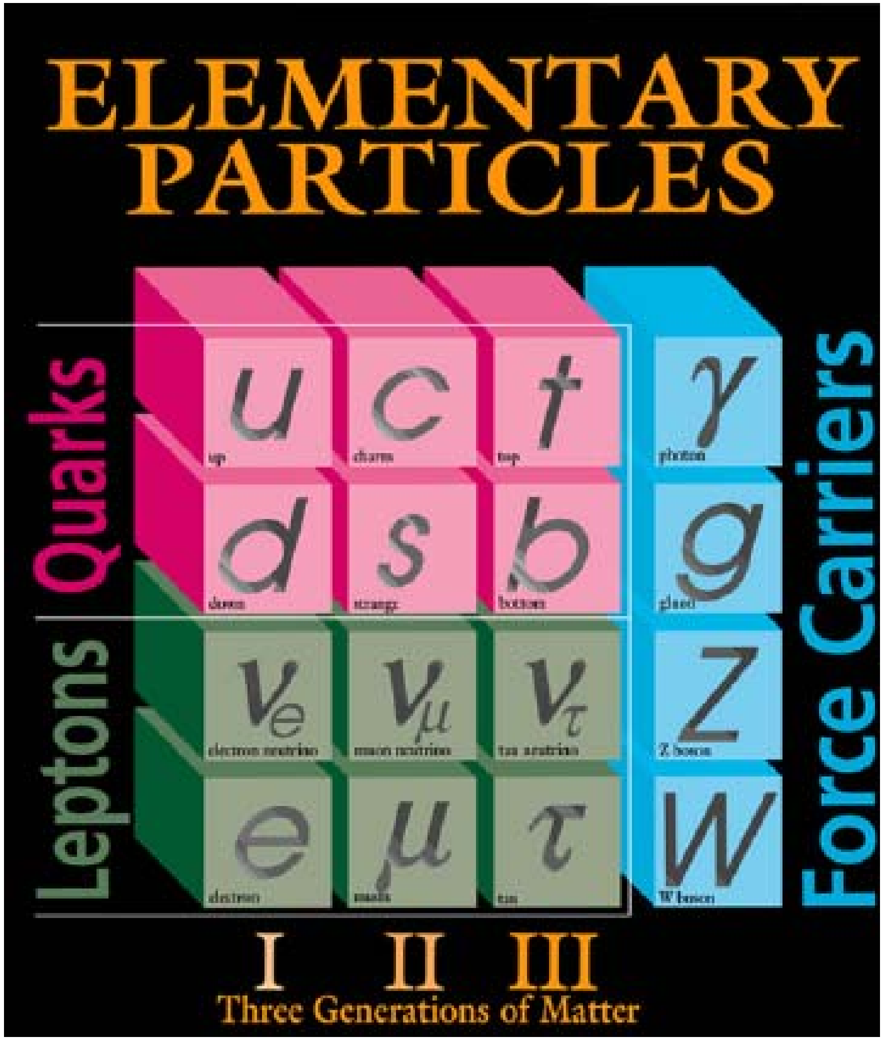
Outline

- Brief introduction of neutrino
- Physics Motivation of MiniBooNE
- MiniBooNE Neutrino Beam
- Events in the Detector
- Event Reconstruction and Particle ID
- Two Independent Analyses
- Errors, Constraints
- MiniBooNE Initial Results

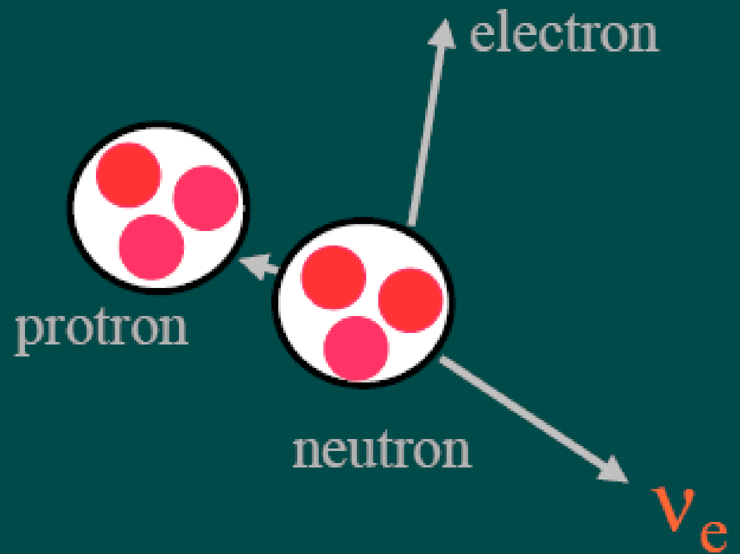
The Standard Model



1900s:	e discovered (cathode ray tube)
	γ interpreted as a particle
1930s:	μ discovered (cosmic rays)
1950s:	ν_e observed (nuclear reactor)
	ν_μ discovered (BNL)
1960s:	1^{st} evidence for quarks
	u and d observed (SLAC)
	s observed (BNL)
1970s:	***standard model is born***
	c discovered (SLAC, BNL)
	τ observed (SLAC)
	b observed (FNAL)
1980s:	W and Z observed (CERN)
1990s:	t quark observed (FNAL)
2000s:	ν_τ observed (FNAL)

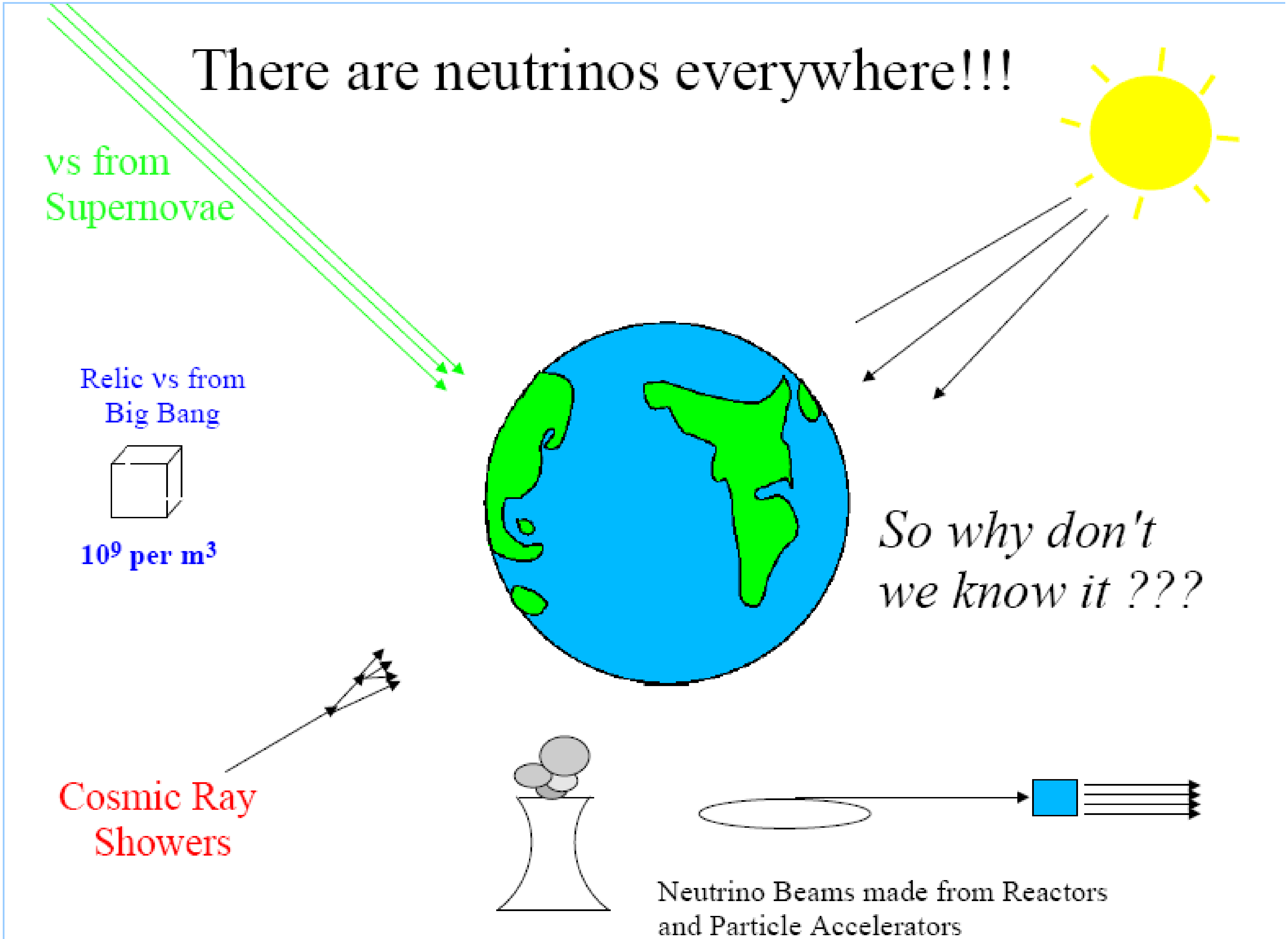
About Neutrinos
or "*little neutral ones*"

postulated to exist by Wolfgang Pauli in 1930 in order to explain the missing energy in nuclear beta decay



The "desperate way out"

electrically neutral
weakly interacting
extremely light or perhaps massless


There are neutrinos everywhere!!!
νs from Supernovae
Relic νs from Big Bang
10^9 per m^3
So why don't we know it ???
Cosmic Ray Showers
Neutrino Beams made from Reactors and Particle Accelerators

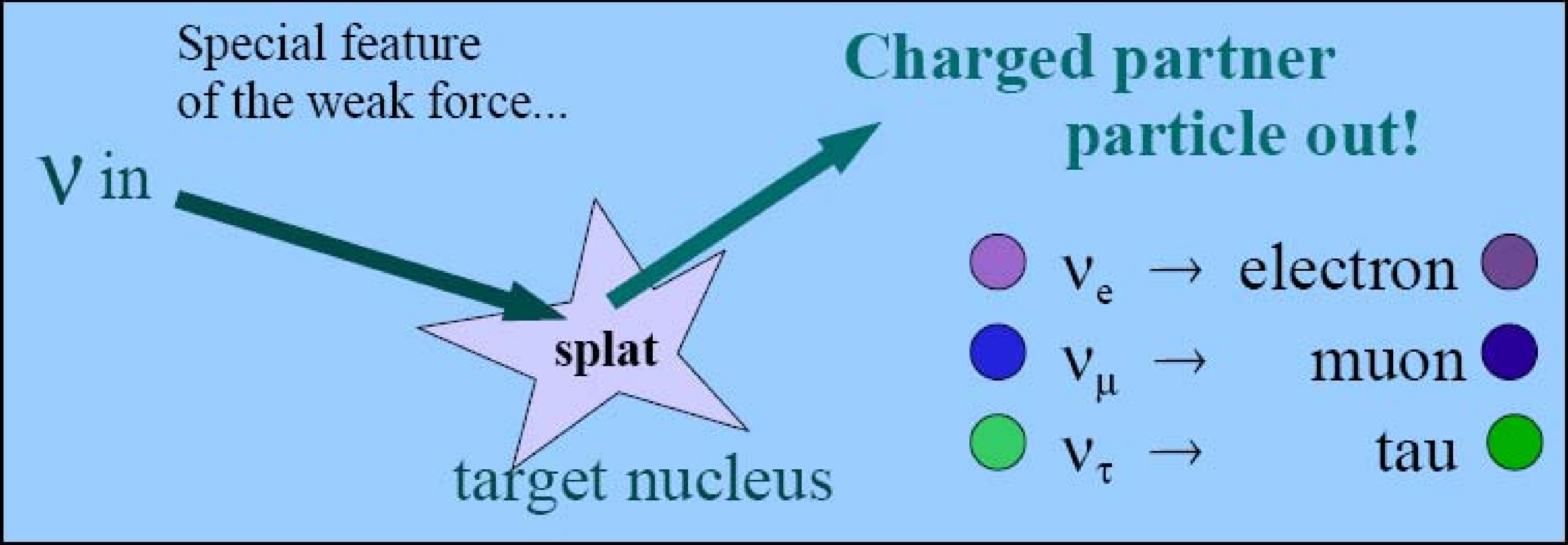
They call it the weak force for a reason!

neutrinos interact
100,000,000,000
times less often than quarks

A neutrino has a good chance of traveling through
200 earths before interacting at all!

Detecting Neutrinos

Seeing *neutral* particles is really hard, but when νs interact via the ``Charged Current Interaction," a ν goes in, and its *charged* partner particle comes out

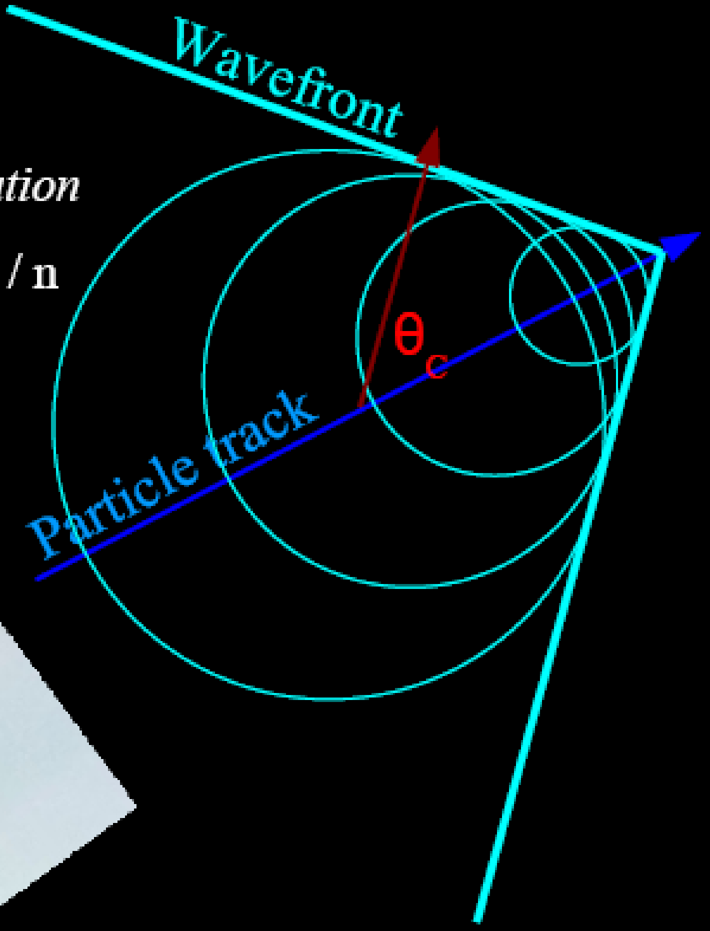


*...by observing the charged particle partner, one can **infer** the neutrino flavor*

Detecting Charged Particle Partners

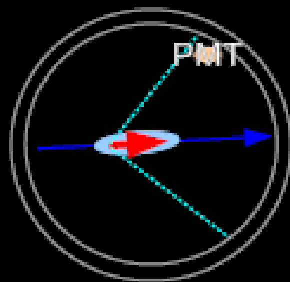
Charged particles passing through material can produce visible light via Cherenkov radiation

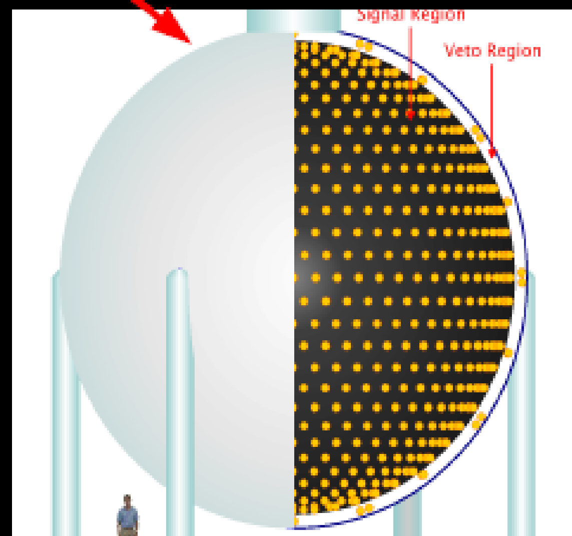
- Light emitted by material if particle v > c / n
- Similar to a sonic boom

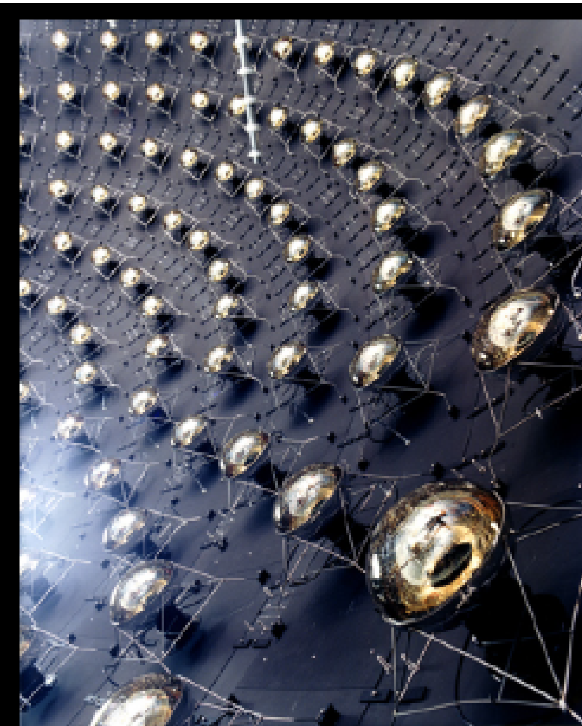


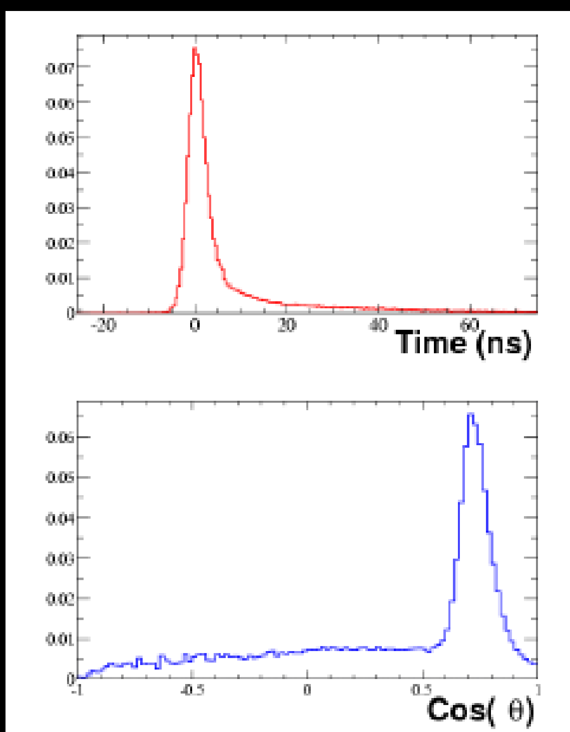
Example: the MiniBooNE Detector

4-story tall spherical tank, filled with oil, lined with photo-multiplier tubes (PMTs)









PMTs detect photons from ν-interaction induced light emission in oil, record time of arrival and number of photons

Reconstruct particle tracks from time and angular distributions

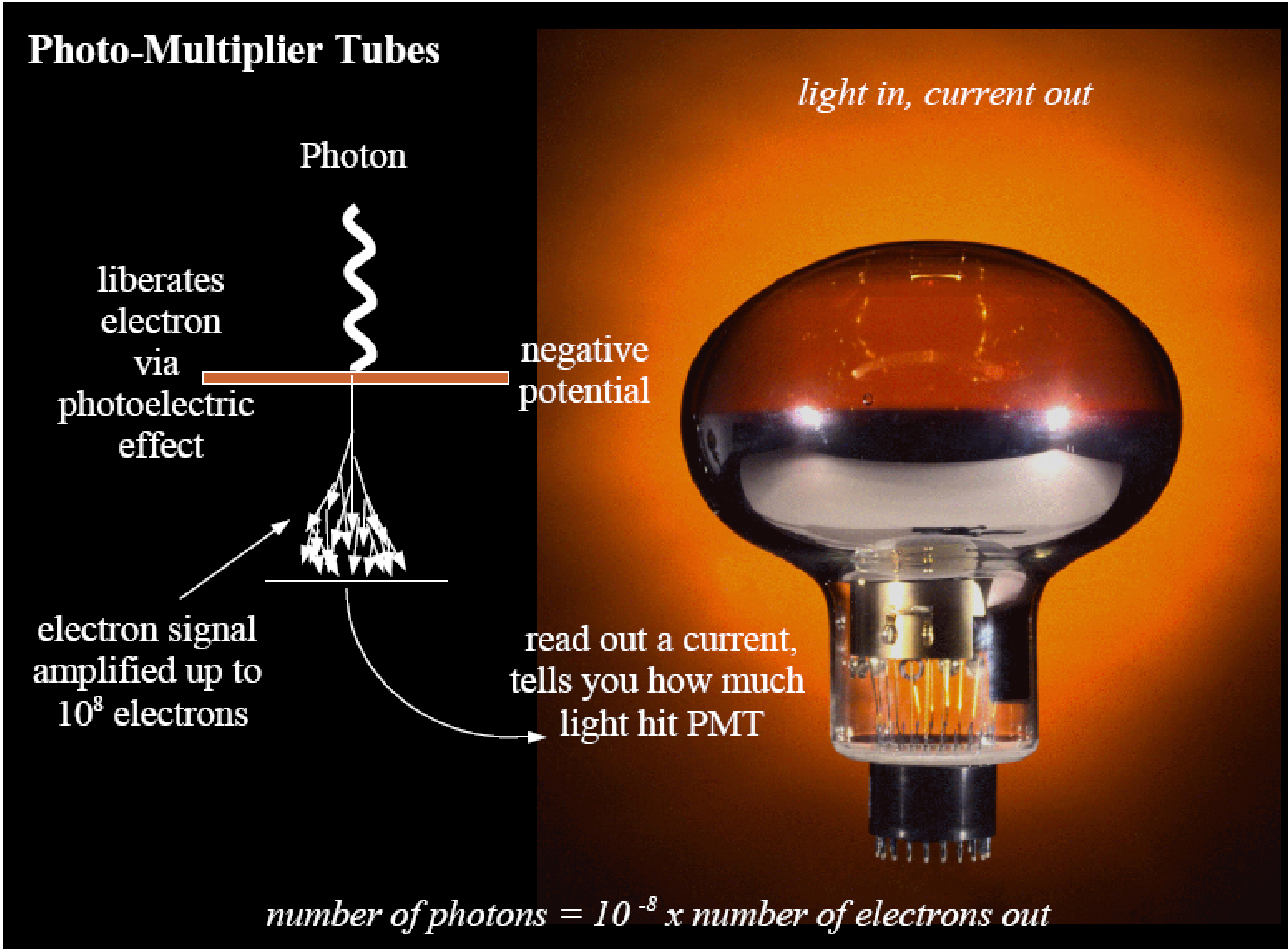
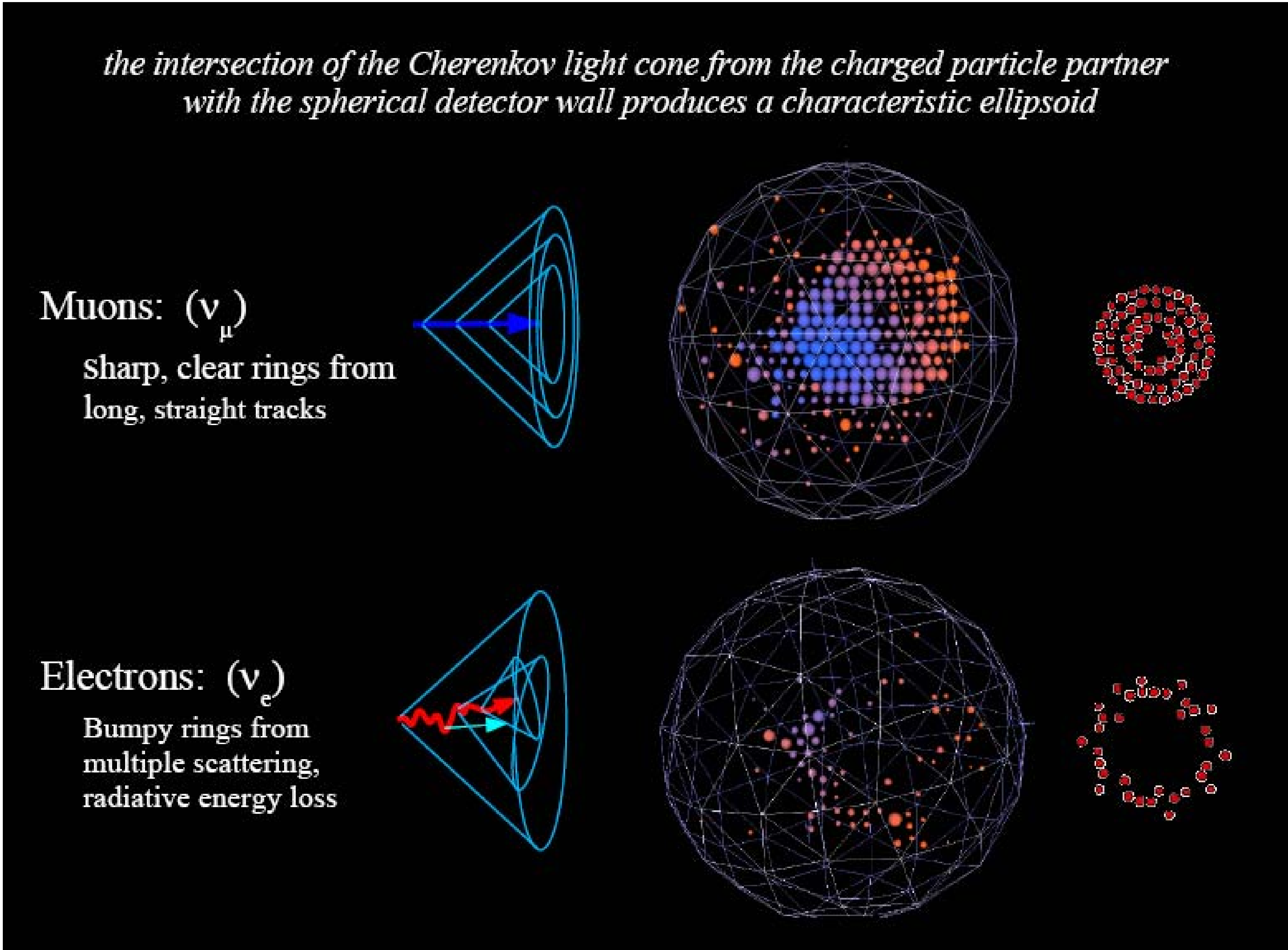
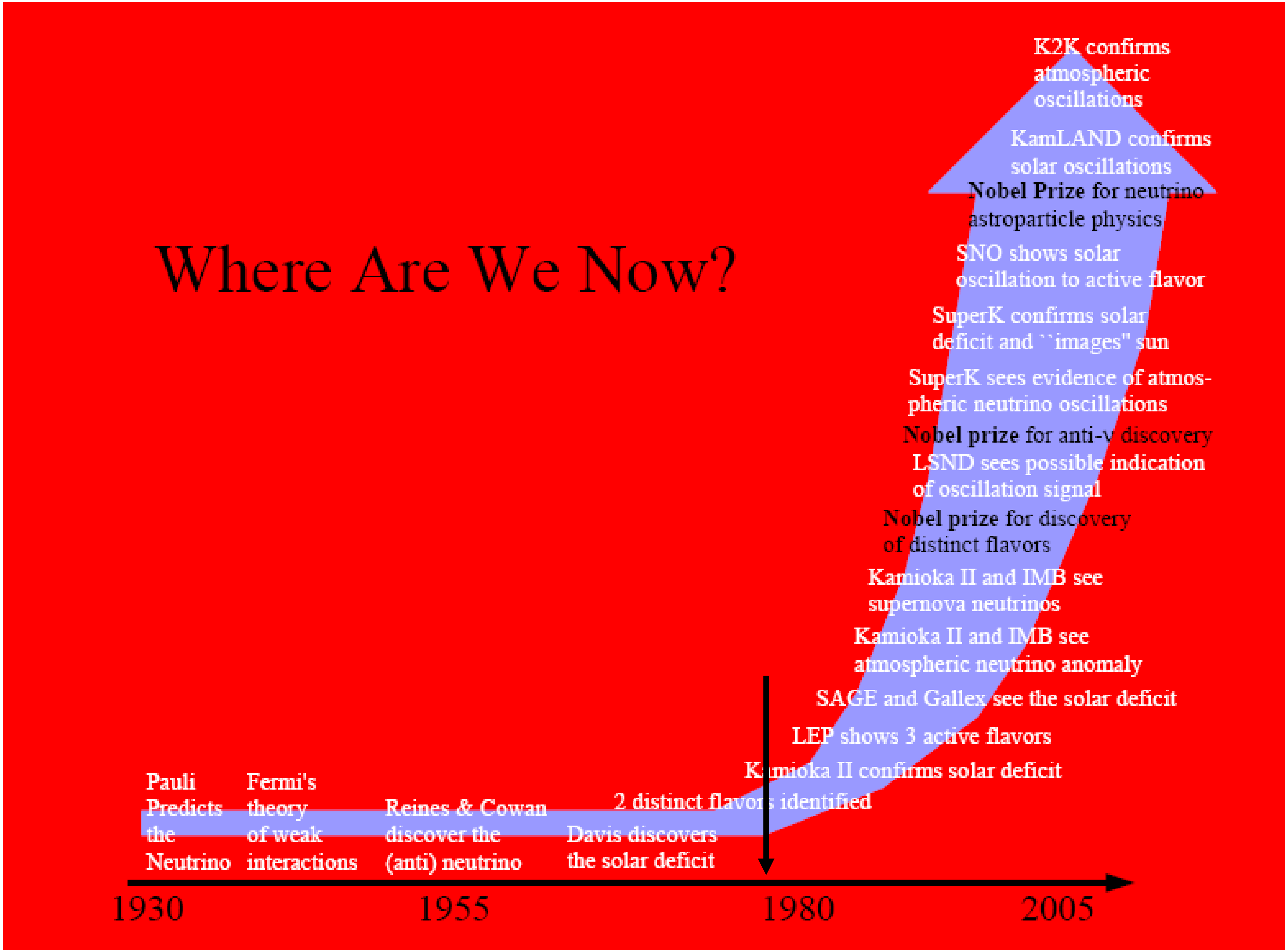
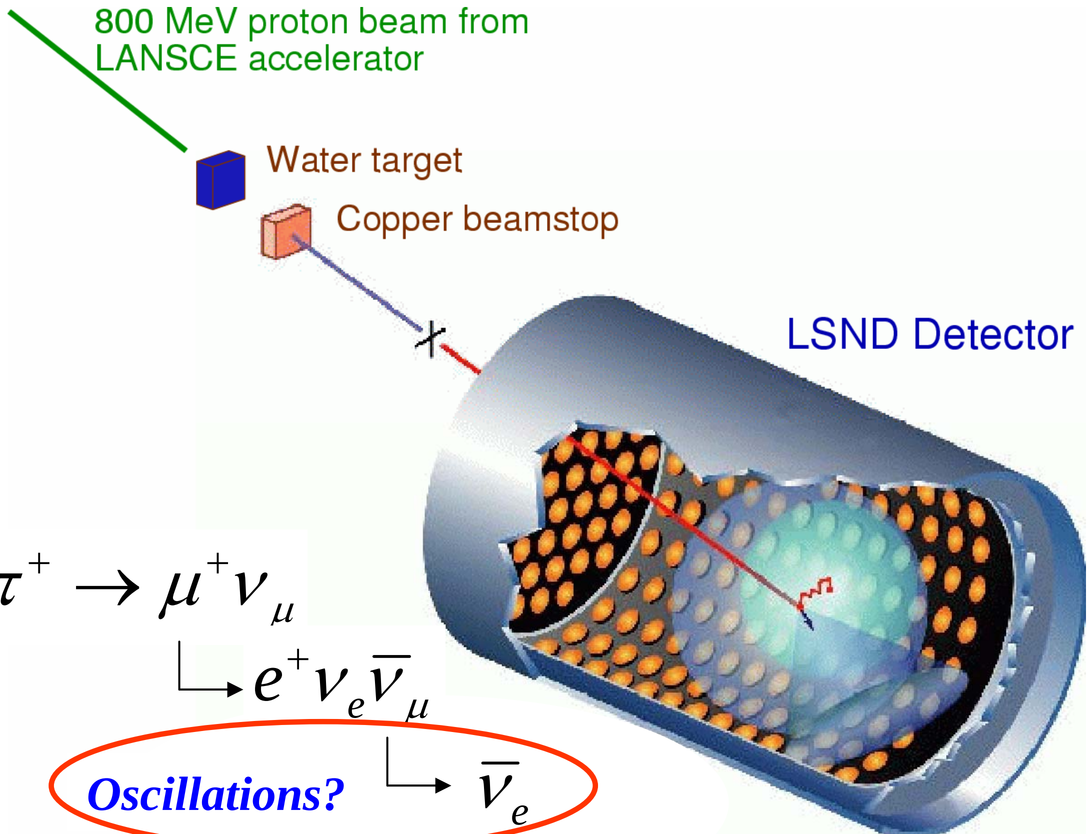


Photo-Multiplier Tubes
light in, current out
Photon
liberates electron via photoelectric effect
negative potential
electron signal amplified up to 10^8 electrons
read out a current, tells you how much light hit PMT
number of photons = 10^{-8} x number of electrons out


the intersection of the Cherenkov light cone from the charged particle partner
with the spherical detector wall produces a characteristic ellipsoid
Muons: (ν_μ)
Sharp, clear rings from
long, straight tracks
Electrons: (ν_e)
Bumpy rings from
multiple scattering,
radiative energy loss


Where Are We Now?
K2K confirms atmospheric oscillations
KamLAND confirms solar oscillations
Nobel Prize for neutrino astroparticle physics
SNO shows solar oscillation to active flavor
SuperK confirms solar deficit and ``images" sun
SuperK sees evidence of atmos-pheric neutrino oscillations
Nobel prize for anti-ν discovery
LSND sees possible indication of oscillation signal
Nobel prize for discovery of distinct flavors
Kamioka II and IMB see supernova neutrinos
Kamioka II and IMB see atmospheric neutrino anomaly
SAGE and Gallex see the solar deficit
LEP shows 3 active flavors
Kamioka II confirms solar deficit
2 distinct flavors identified
Pauli Predicts the Neutrino
Fermi's theory of weak interactions
Reines & Cowan discover the (anti) neutrino
Davis discovers the solar deficit
1930
1955
1980
2005

The LSND Experiment



$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

Oscillations? $\hookrightarrow \bar{\nu}_e$

Signal: $\bar{\nu}_e$ p → e^+ n

n p → d γ(2.2MeV)

LSND took data from 1993-98

Nearly 49000 Coulombs of protons on target

Baseline: 30 meters

Neutrino Energy: 20-55 MeV

LSND Detector:
- -- 1280 phototubes
- -- 167 tons Liquid Scintillator

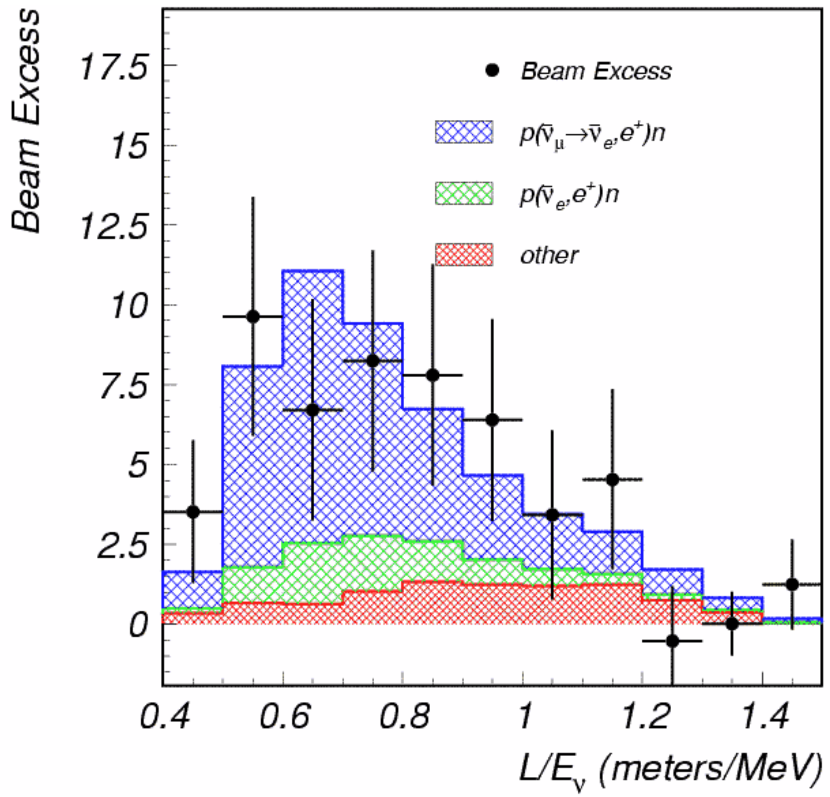
Observe an excess of $\bar{\nu}_e$:
- -- 87.9 ± 22.4 ± 6.0 events.

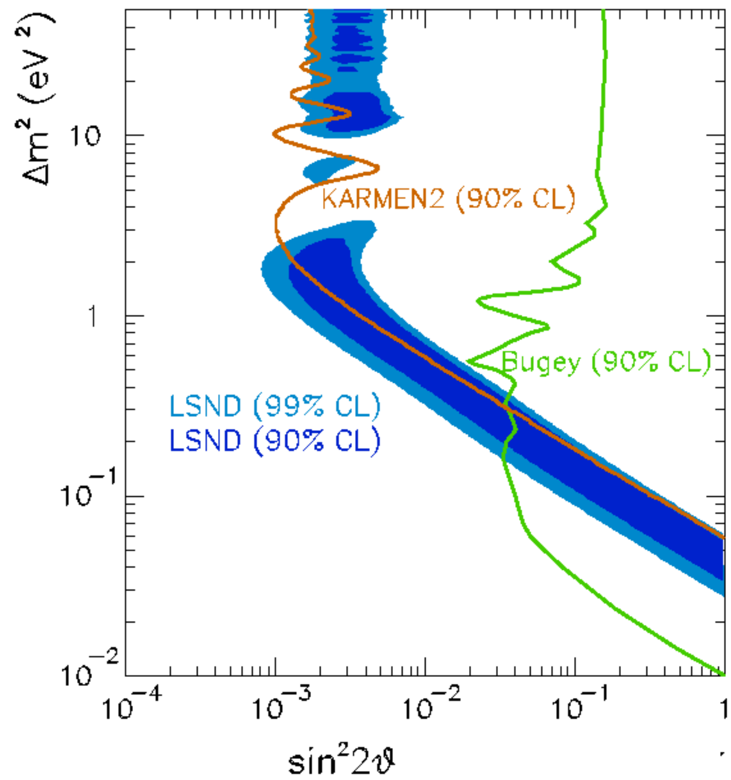
LSND Collab, PRD 64, 112007

The LSND Experiment

➔ LSND observed a positive signal(~3.8σ), but not confirmed.

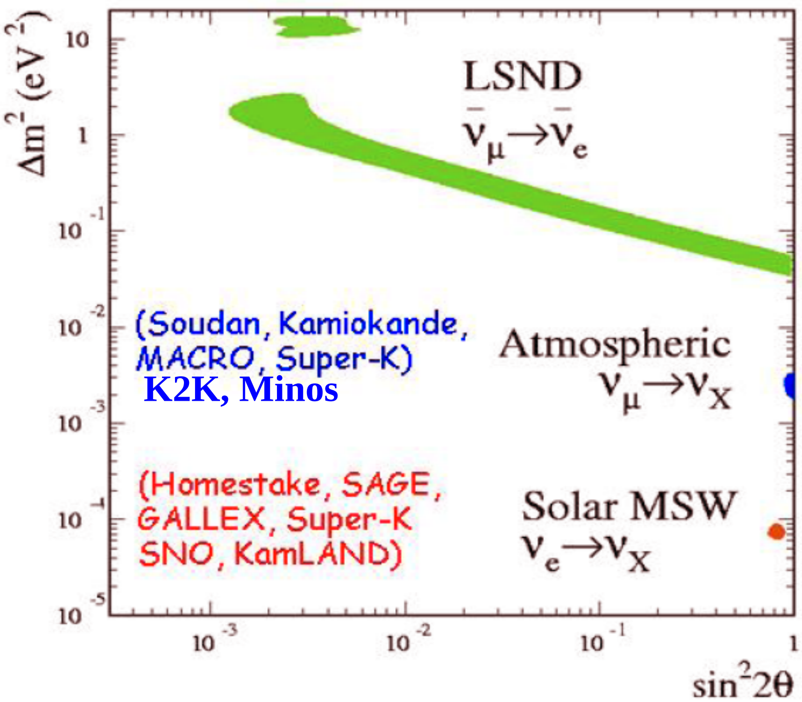
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta)\sin^2(\frac{1.27\,L\Delta m^2}{E}) = (0.264 \pm 0.067 \pm 0.045)\%$$





Physics Motivation

State of Oscillation Results



- Simplest model has three neutrino mass eigenstates, but…
- Data indicates 3 mass differences
  - $\Delta m^2_{atm} \sim 2\text{-}3 \times 10^{-3}$ eV^2
  - $\Delta m^2_{sol} \sim 7 \times 10^{-5}$ eV^2
  - $\Delta m^2_{LSND} \sim .1\text{-}10$ eV^2

$$\Delta m^2_{atm} + \Delta m^2_{sol} \neq \Delta m^2_{lsnd}$$

➔ If the LSND signal does exist, it will imply new physics beyond SM.
➔ The MiniBooNE is designed to confirm or refute LSND oscillation result at $\Delta m^2 \sim 1.0$ eV^2 .

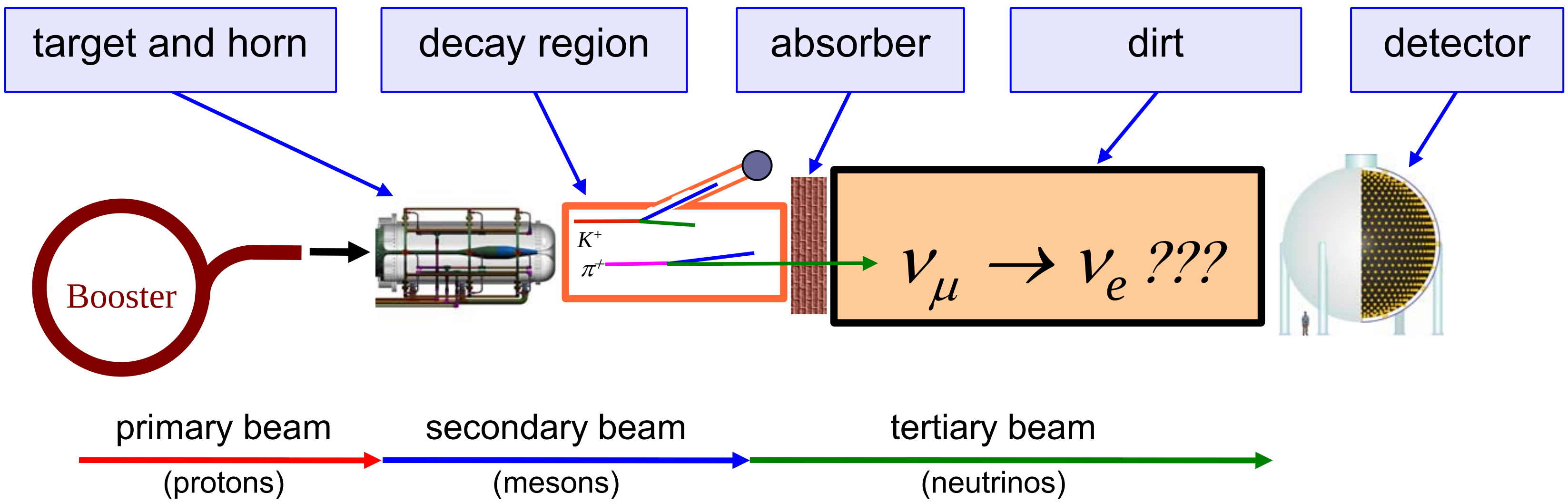
How can there be 3 distinct Δm^2 ?

- **Mass Difference Equation:**
  $(m_1^2 - m_2^2) + (m_2^2 - m_3^2) = (m_1^2 - m_3^2)$

1. One of the experimental measurements is wrong
2. One of the experimental measurements is not neutrino oscillations:
   → Neutrino decay
   → Neutrino production from flavor violating decays
3. Additional “sterile” neutrinos involved in oscillation
4. CPT violation or CP violation + sterile ν’s allows different mixing for ν’s and ν bars.

The MiniBooNE Experiment

- Proposed in 1998，operating since 2002
- **The goal of the MiniBooNE Experiment: to confirm or exclude the LSND result and extend the explored oscillation parameter space**



Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

Order of magnitude
longer baseline (~500 m)
than LSND (~30 m)

The MiniBooNE Collaboration

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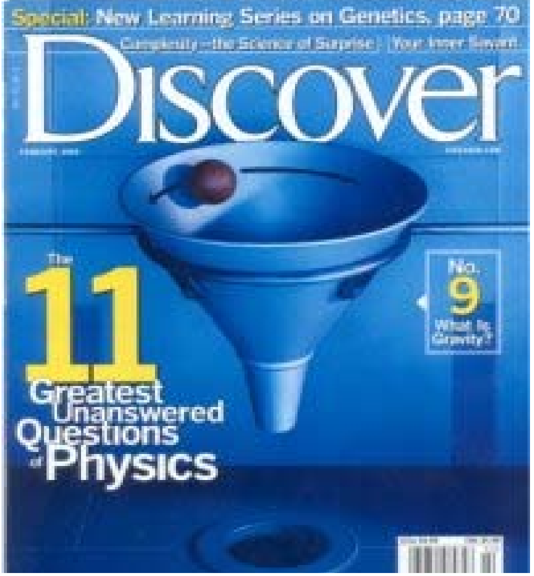
M. J. Wilking, H. J. Yang, G. P. Zeller, E. D. Zimmerman

2 National Laboratories, 14 Universities, 77 Researchers

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



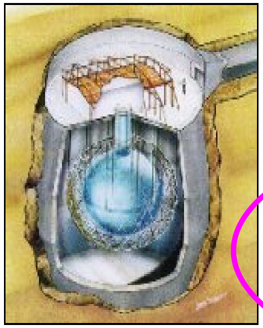
MiniBooNE aims to address 2 of 11 Greatest Unanswered Questions in Physics in 21st Century(Discover, 2002)

What is dark matter? Do Neutrinos have mass?

1. What is dark matter?

Astronomers have shown that the objects in the universe from galaxies a million times smaller than ours to the largest clusters of galaxies are held together by a form of matter that is not what we are made of and that gives off no light. This matter probably consists of one or more as-yet-undiscovered elementary particles, and aggregations of it produce the gravitational pull leading to the formation of galaxies and large-scale structures in the universe. At the same time these particles may be streaming through our Earth-bound laboratories.

Recent results from accelerator experiments at the Liquid Scintillator Neutrino Detector (LSND) at DOE's Los Alamos National Laboratory and underground detectors, Sudbury Neutrino Observatory (SNO) in Canada and Super-Kamiokande in Japan, give strong evidence that neutrinos "oscillate" among various types and must therefore have mass. Although it is a very small mass, the vast numbers of neutrinos in the universe could add up to a substantial total mass and contribute to dark matter in part. New accelerator experiments, MiniBooNE and MINOS at DOE's Fermi National Laboratory, will study neutrino oscillations and mass.



The Sudbury Neutrino Observatory (SNO) in its underground cavern.

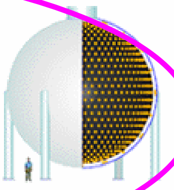
4. Do neutrinos have mass?

Cosmology tells us that neutrinos must be abundantly present in the universe today. Physicists have recently found increasing evidence that they have a small mass. There may even be additional types of neutrinos beyond the three of the current standard models.

First results released from the Sudbury Neutrino Observatory (SNO) in Canada, combined with results of the Super-Kamiokande experiment in Japan, explain the missing solar neutrinos and add to the growing evidence that neutrinos have mass. Both experiments are international efforts with substantial support from DOE.

A long baseline neutrino detection experiment called MINOS is currently being assembled at Fermilab and in Minnesota, and a dedicated beam of neutrinos called NuMI is being built for it. With this new facility, Fermilab will have the opportunity to confirm early indications that the neutrino has a small mass and, if it does, to make precise mass measurements.

The Liquid Scintillator Neutrino Detector (LSND) at Los Alamos found evidence in 1995 that muon neutrinos change into electron neutrinos. A new detector at Fermilab called MiniBooNE will investigate this phenomenon, collecting much more data than LSND due to a stronger neutrino beam. The MiniBooNE neutrino beam will consist of high-intensity pulses about 10,000 times shorter than the LSND beam. This greatly improves the experiment's capability of separating beam-induced neutrino events from naturally occurring cosmic-ray nteractions, which take place at random times.



MiniBooNE detector

MiniBooNE Neutrino Beam

Fermilab Proton Booster

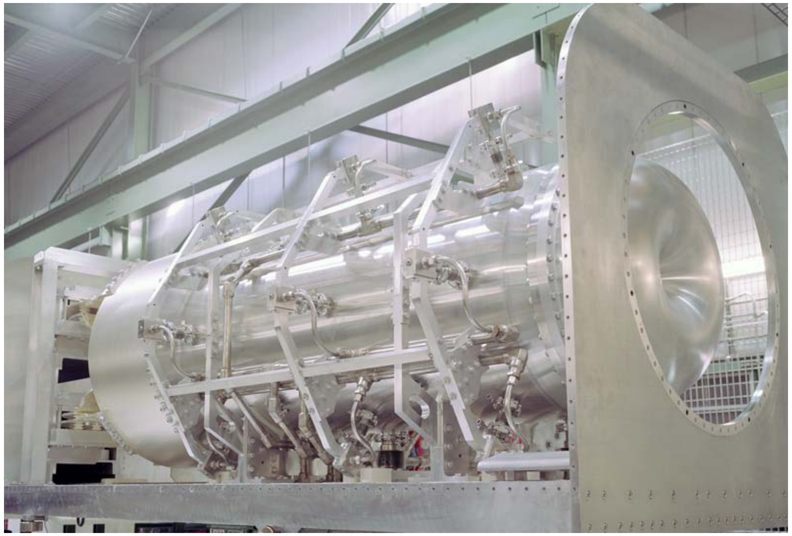
4×10^{12} protons per 1.6 μs pulse delivered at up to 5 Hz.

6.3×10^{20} POT delivered.

Results correspond to $(5.58 \pm 0.12) \times 10^{20}$ POT

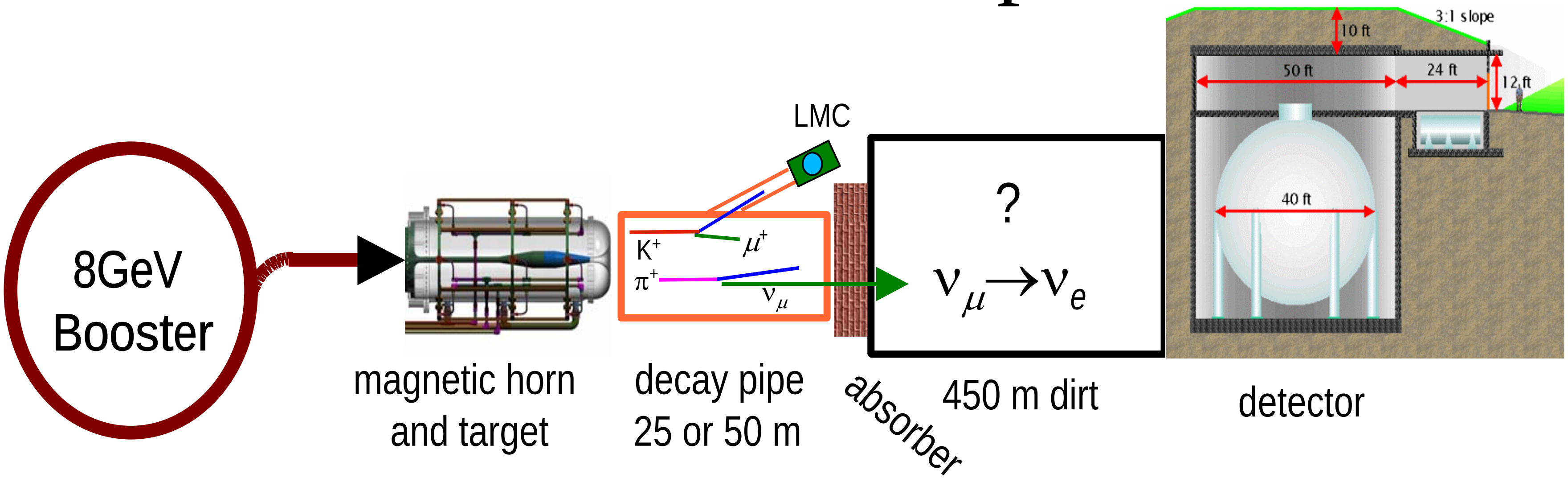
MiniBooNE extracts beam from the 8 GeV Booster

Delivered to a 1.7 λ Be target



within a magnetic horn (2.5 kV, 174 kA) that (increases the flux by ×6)

The MiniBooNE Experiment



- The FNAL Booster delivers 8 GeV protons to the MiniBooNE beamline.
- The protons hit a 71cm beryllium target producing pions and kaons.
- The magnetic horn focuses the secondary particles towards the detector.
- The mesons decay into neutrinos, and the neutrinos fly to the detector, all other secondary particles are absorbed by absorber and 450 m dirt.
- 5.6E20 POT for neutrino mode since 2002.
- Switch horn polarity to run anti-neutrino mode since January 2006.

MiniBooNE Flux (Geant 4 Simulation)

8 GeV protons on Be target gives:

$p + Be \rightarrow \pi^+ , K^+ , K^0_L$

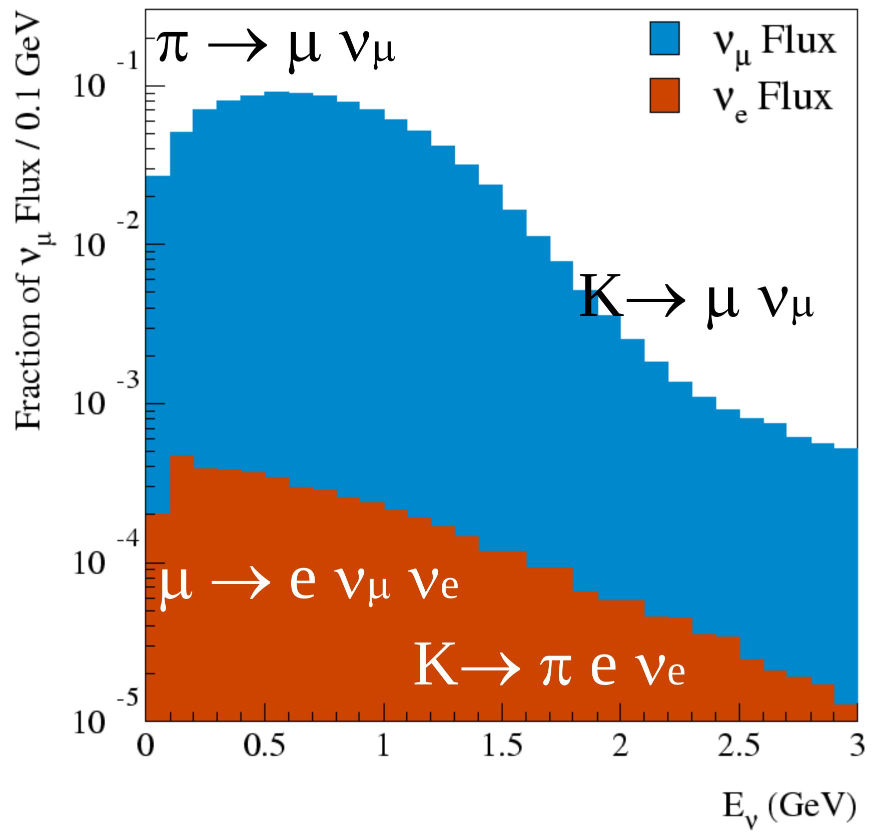
ν_μ from:

$\pi^+ \rightarrow \mu^+ \nu_\mu$ $K^+ \rightarrow \mu^+ \nu_\mu$ $K^0_L \rightarrow \pi^- \mu^+ \nu_\mu$

"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%)

The intrinsic ν_e is ~0.5% of the neutrino Flux, it's one of major backgrounds for $\nu_\mu \rightarrow \nu_\varepsilon$ search.



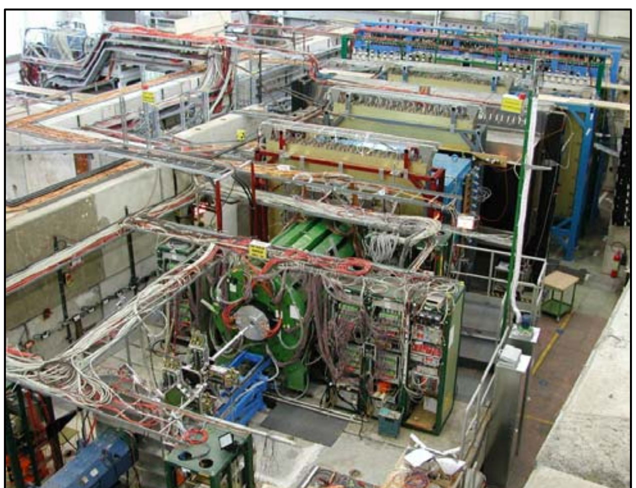
$\nu_e/\nu_\mu = 0.5\%$

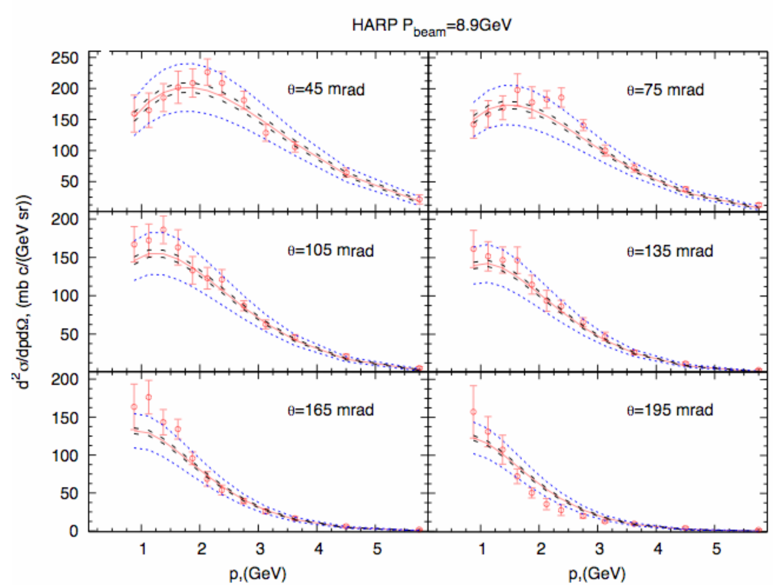
Antineutrino content: 6%

Modeling Production of Secondary Pions

- E910 @ BNL + previous world data fits
  - Basis of current MB π production model
- HARP @ CERN, 8.9 GeV Proton Beam
  - Measure π production
  - 5% λ Beryllium target

HARP collaboration, hep-ex/0702024





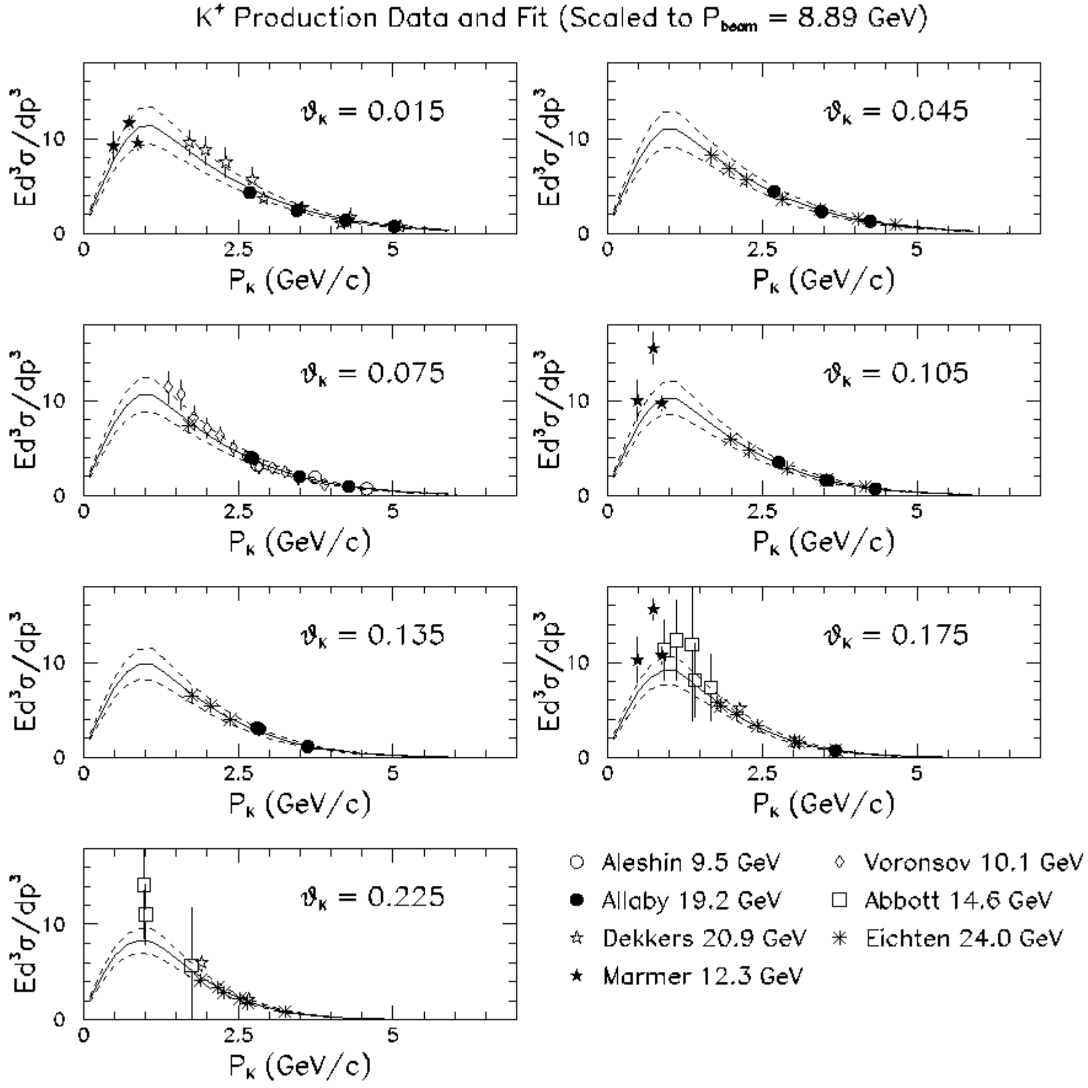
Modeling Production of Secondary Kaons

K^+ Data from 10 - 24 GeV.
Uses a Feynman Scaling Parameterization.

data -- points
dash --total error
(fit ⊕ parameterization)

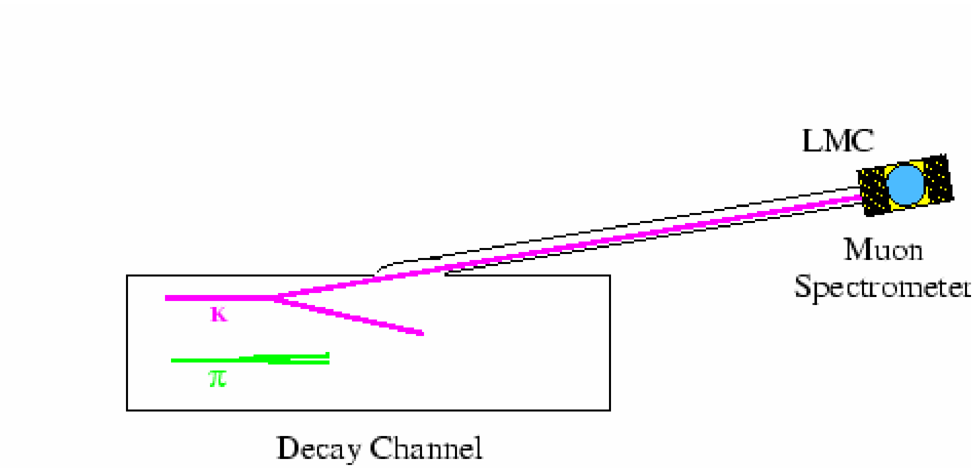
K^0 data are also parameterized.

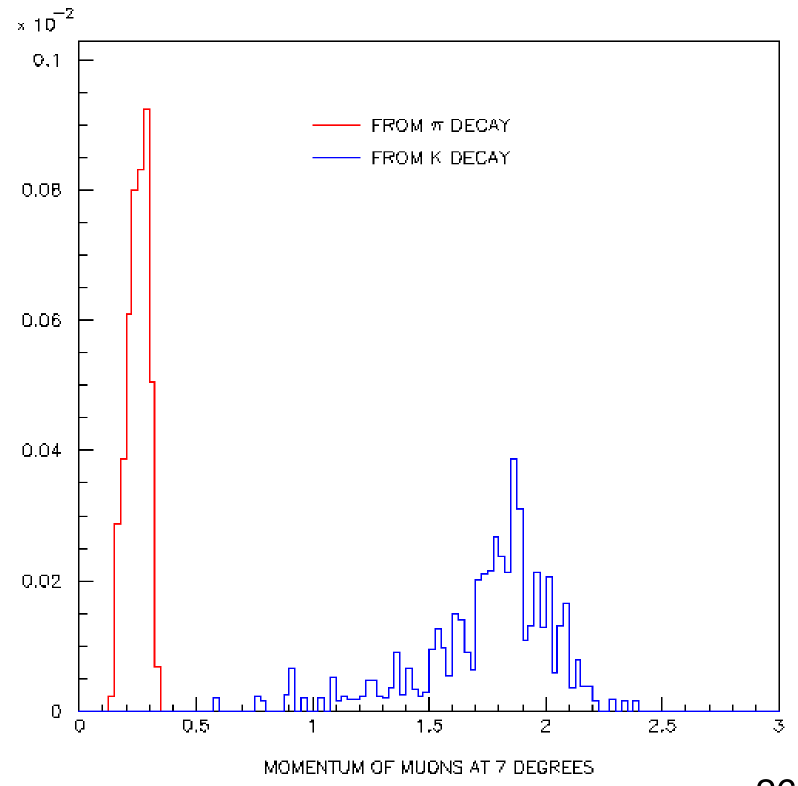
In situ measurement of K^+ from LMC agrees within errors with parameterization



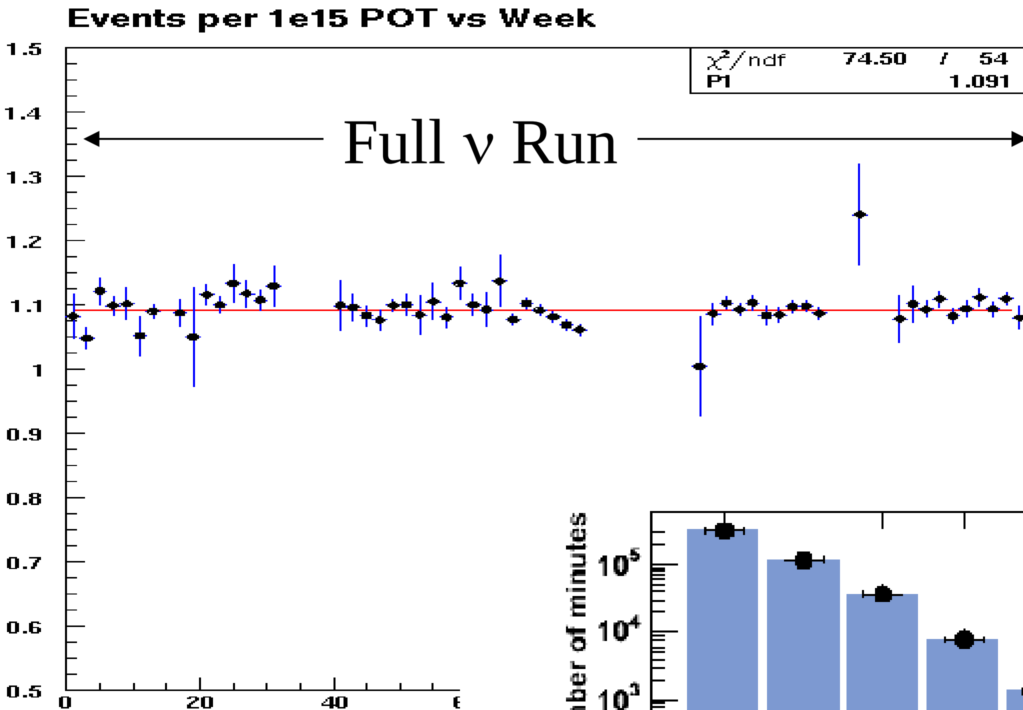
Measurement of K^+ from LMC

- Little Muon Counter (LMC)
  - K decays produce wider angle μ than π decays
  - Scintillating fibre tracker 7 degrees off axis

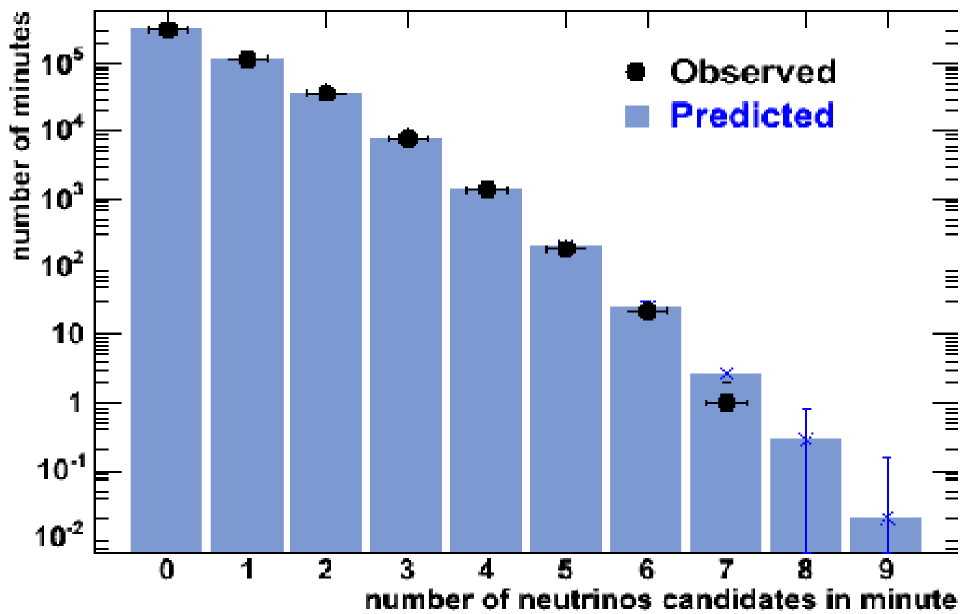




Stability of Running

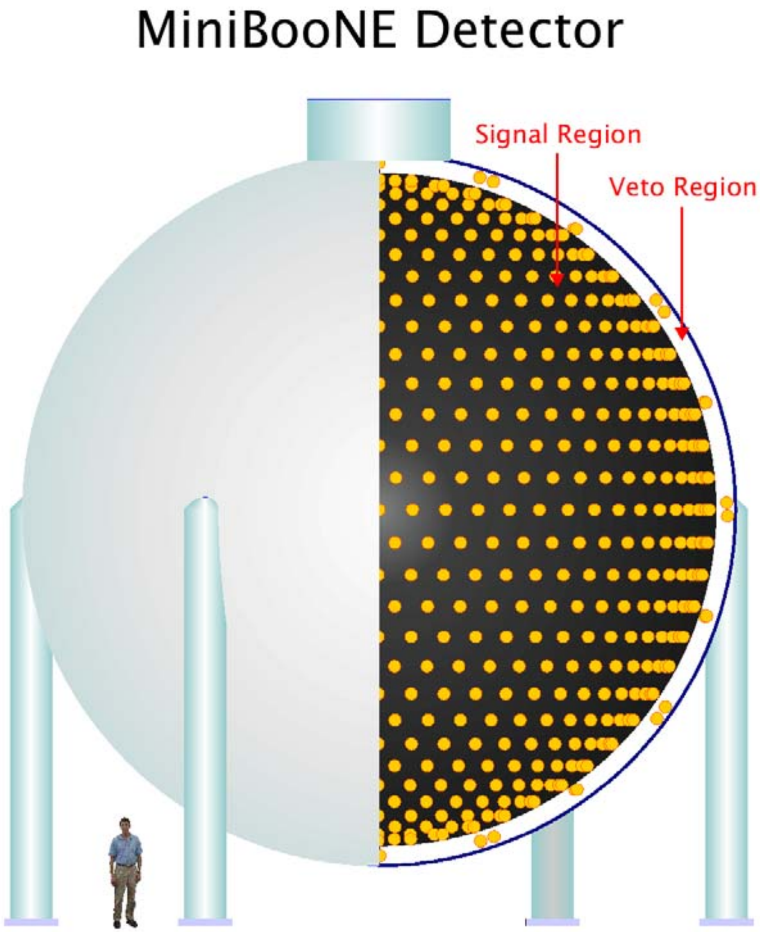


Observed and expected events per minute

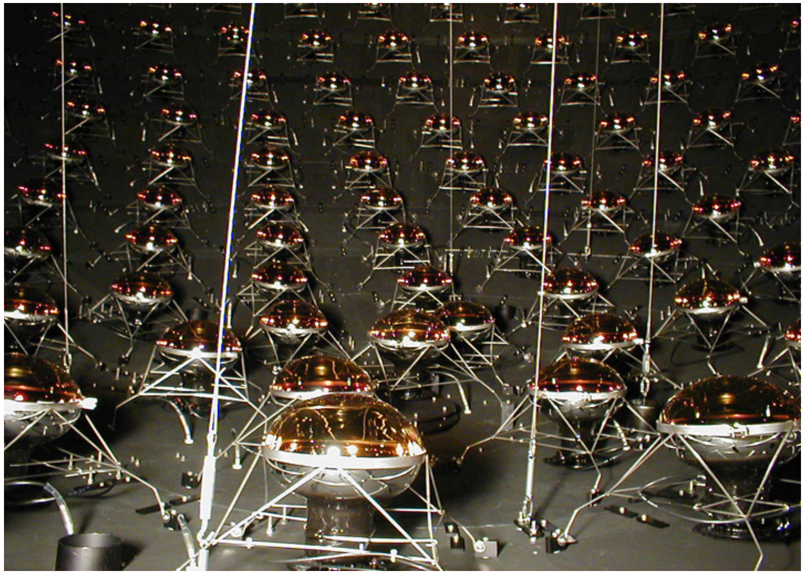


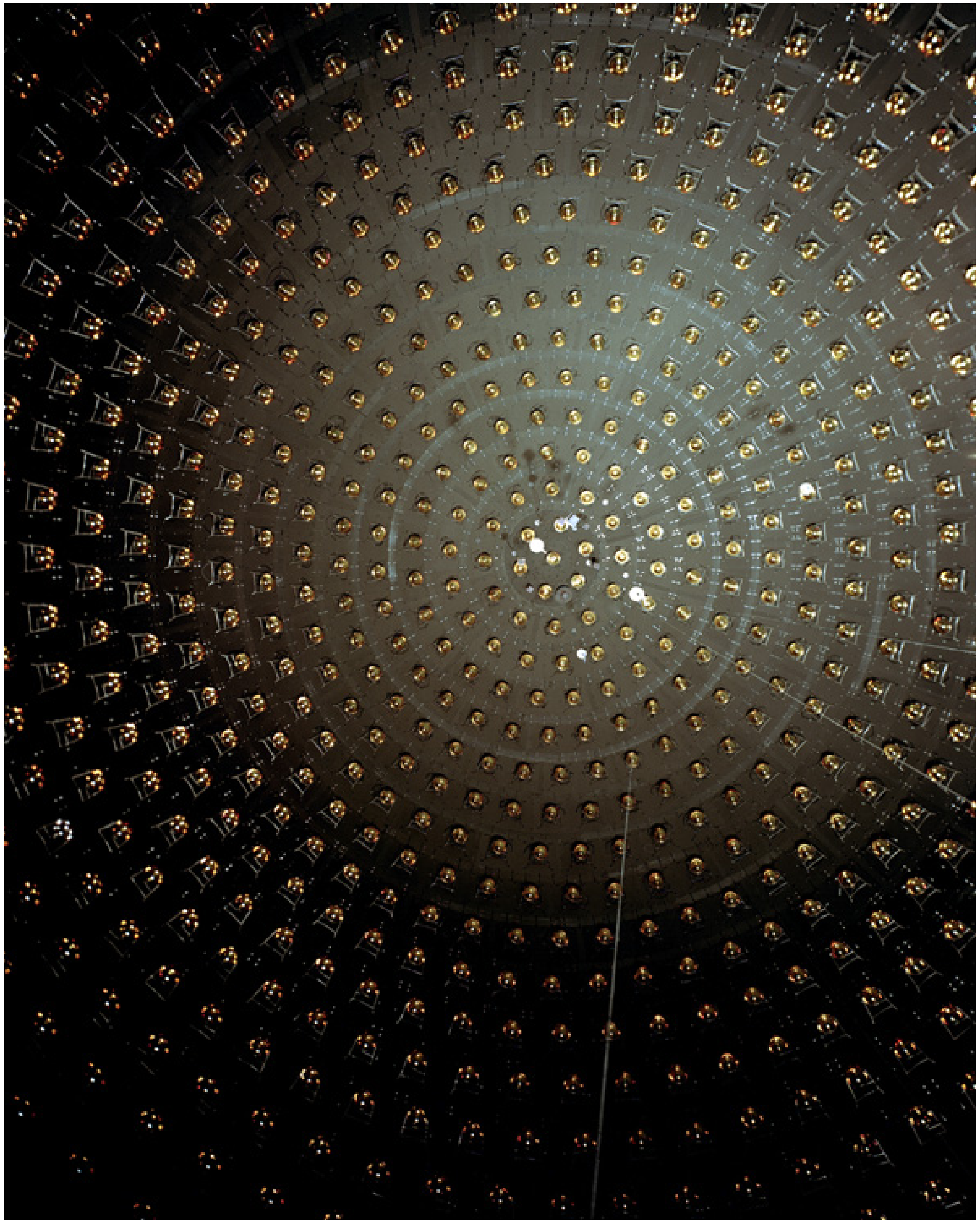
Events in the Detector

The MiniBooNE Detector



- 12m diameter tank
- Filled with 800 tons of ultra pure mineral oil
- Optically isolated inner region with 1280 PMTs
- Outer veto region with 240 PMTs.





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

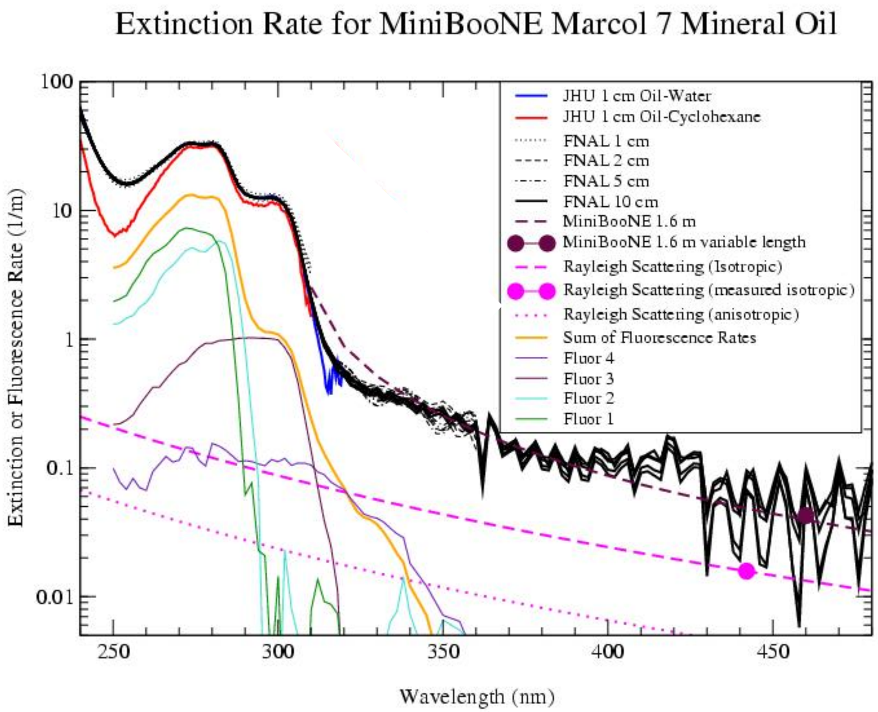
Optical Model

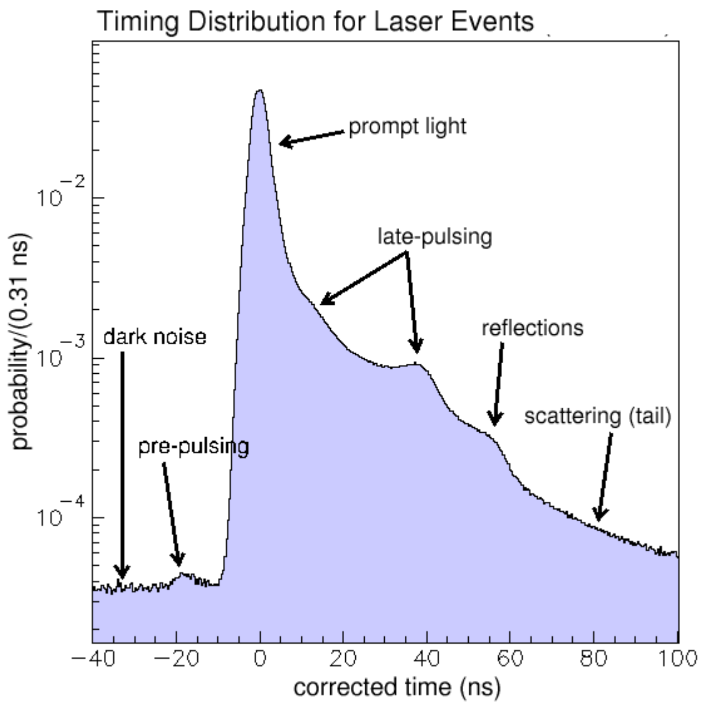
Attenuation length: >20 m @ 400 nm

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

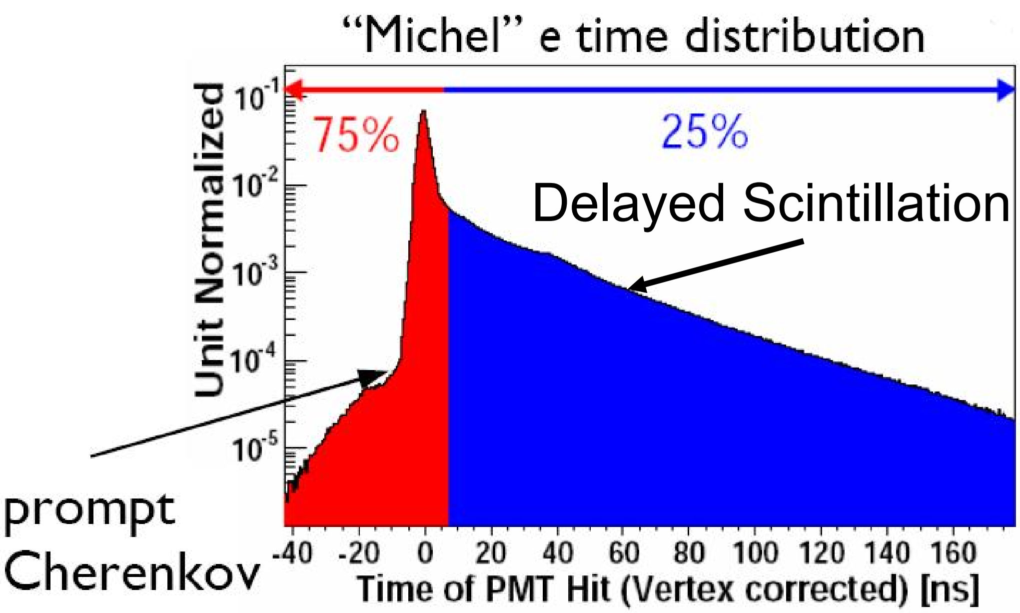


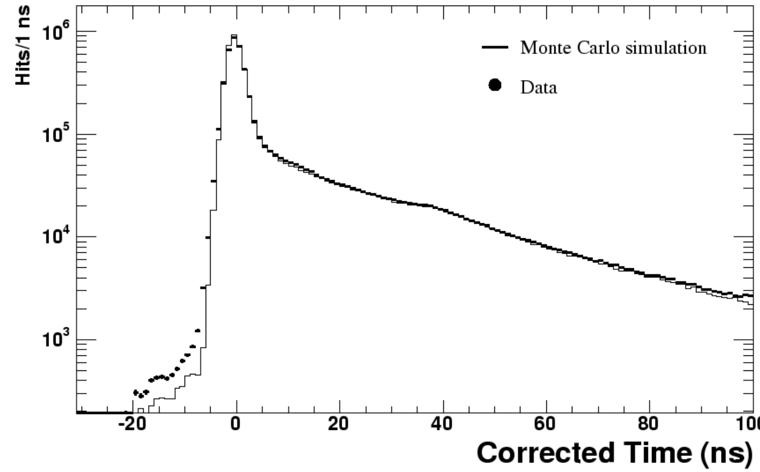


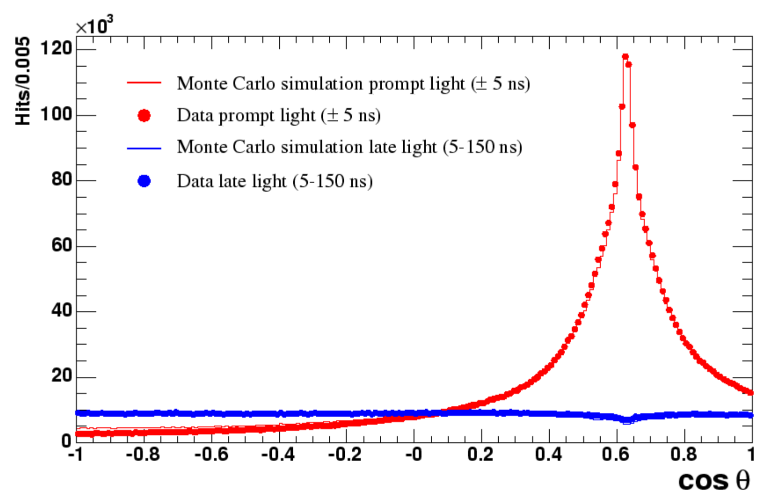
Cerenkov and Scintillation Light

Cerenkov light: Prompt, Directional

Scintillation light: Delayed, Isotropic





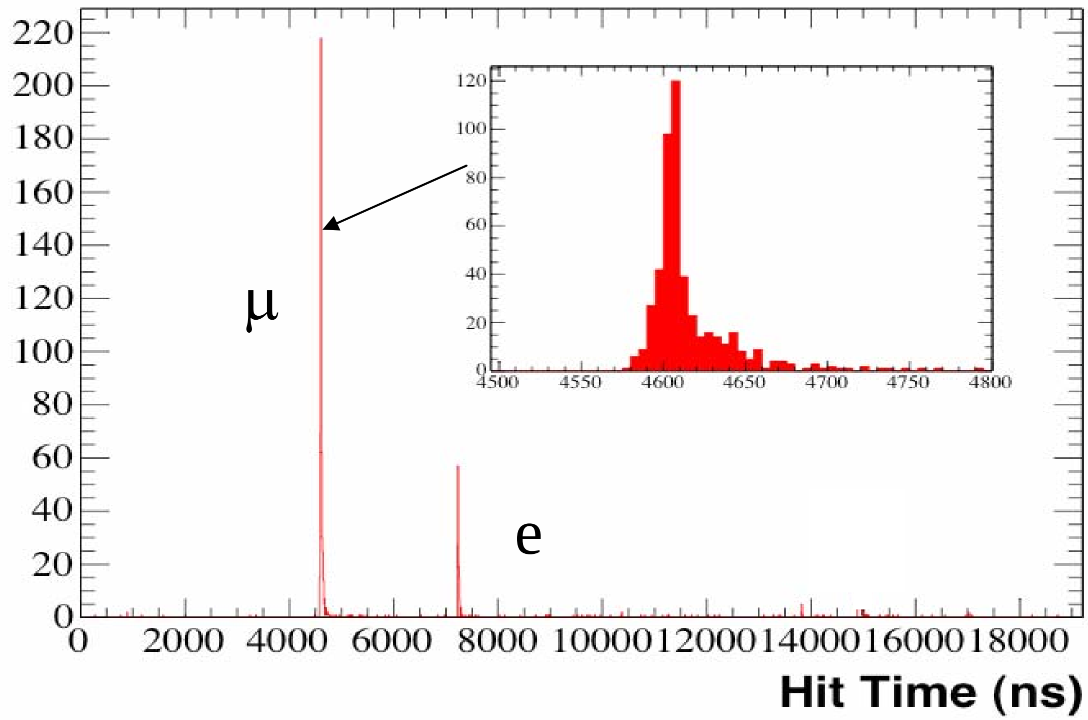


Beam Window

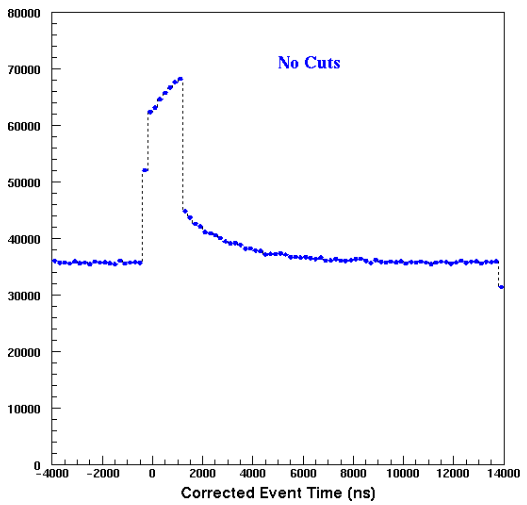
A 19.2 μs beam trigger window encompasses the 1.6 μs spill
Multiple hits within a ~100 ns window form "subevents"
Most events are from ν_μ CC interactions (ν+n $\rightarrow$ μ+p) with characteristic two "subevent" structure from stopped $\mu \rightarrow \nu_\mu \nu_e e$

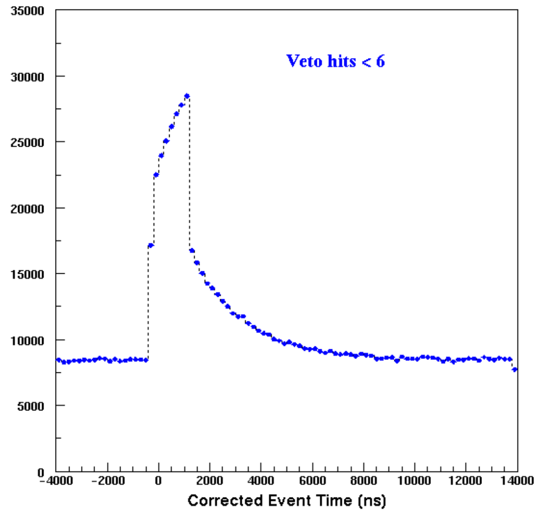
Tank Hits

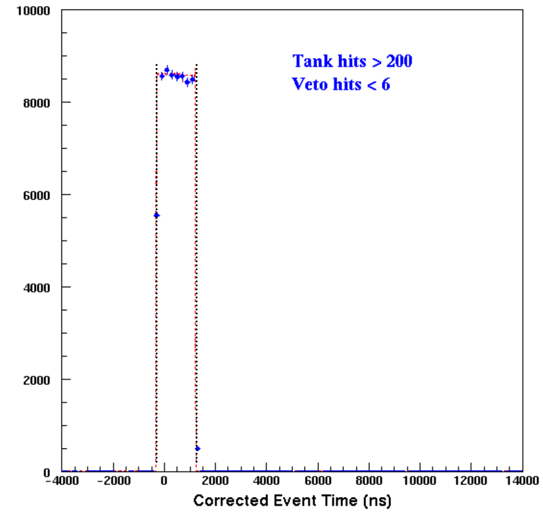
Example Event



Cuts to Select Neutrino Events







Raw data

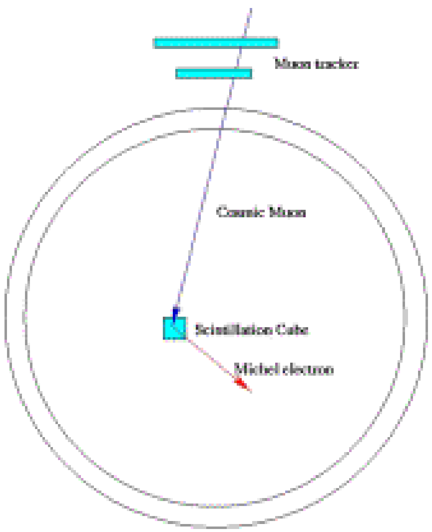
Veto<6 removes through-going cosmics

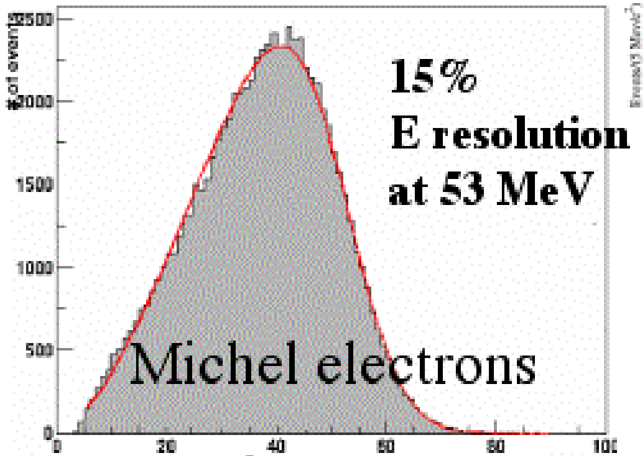
This leaves "Michel electrons" ($\mu \rightarrow \nu_\mu \nu_e e$) from cosmics

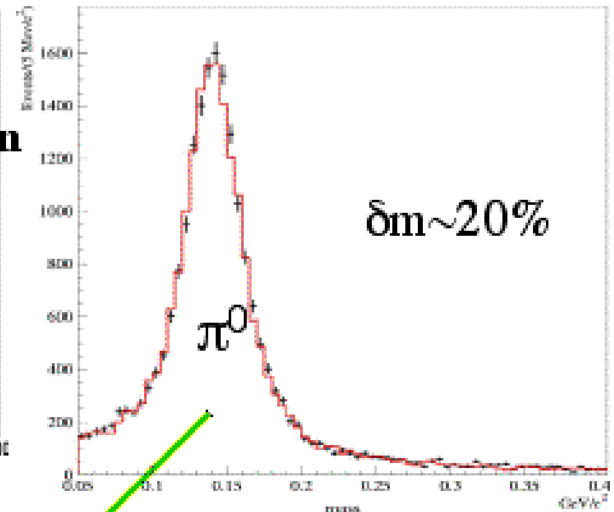
Tank Hits > 200 (equivalent to energy) removes Michel electrons, which have 52.8 MeV endpoint

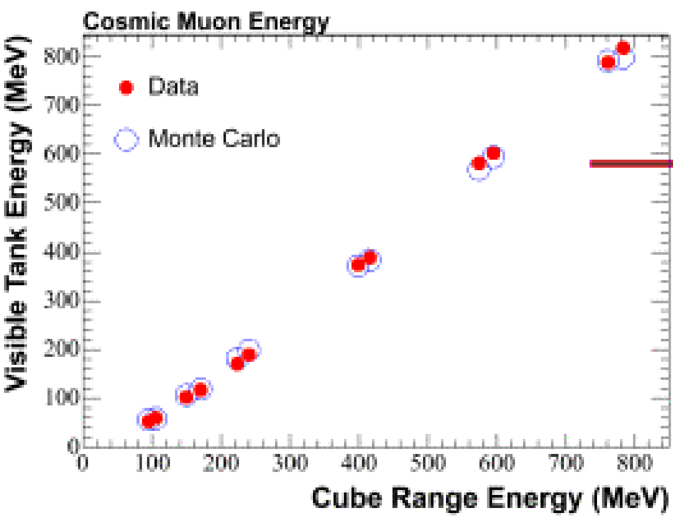
Calibration Sources

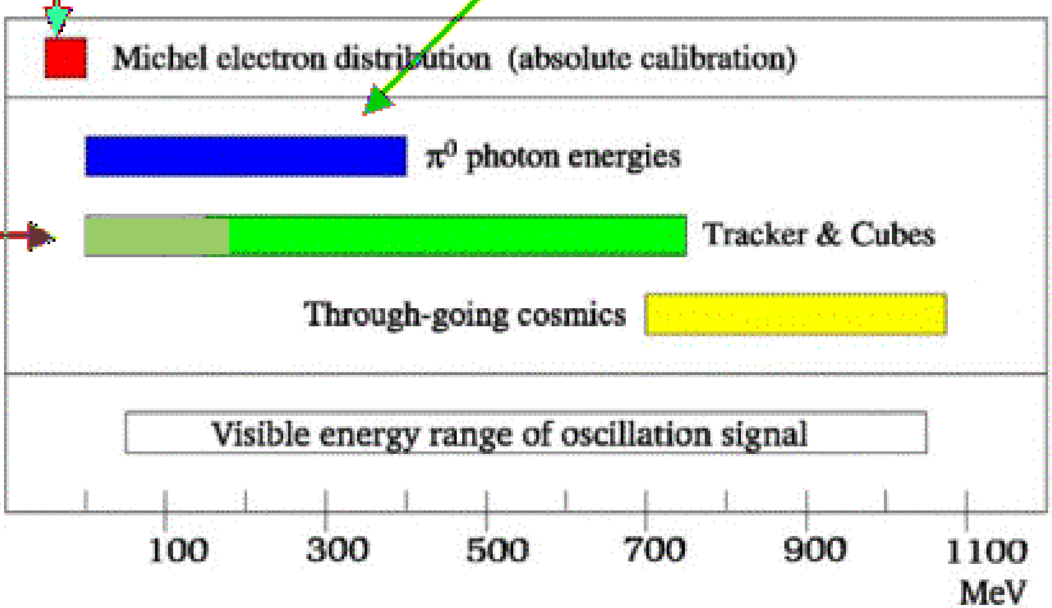
Tracker system





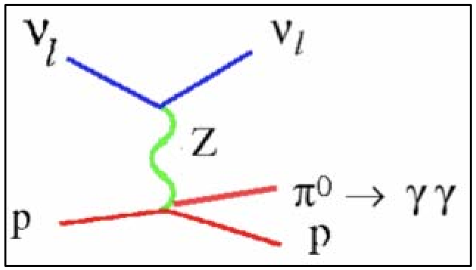


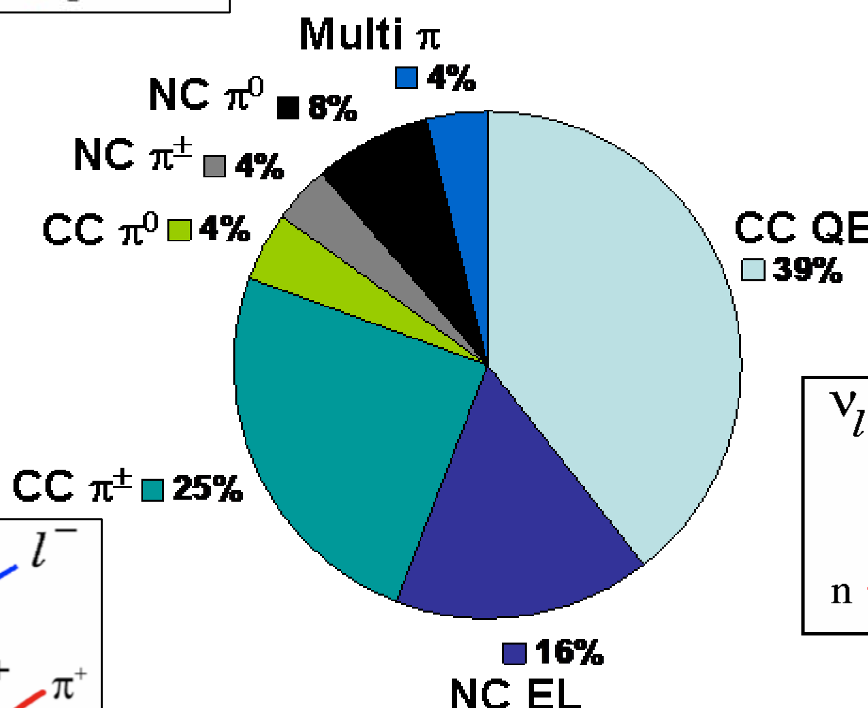


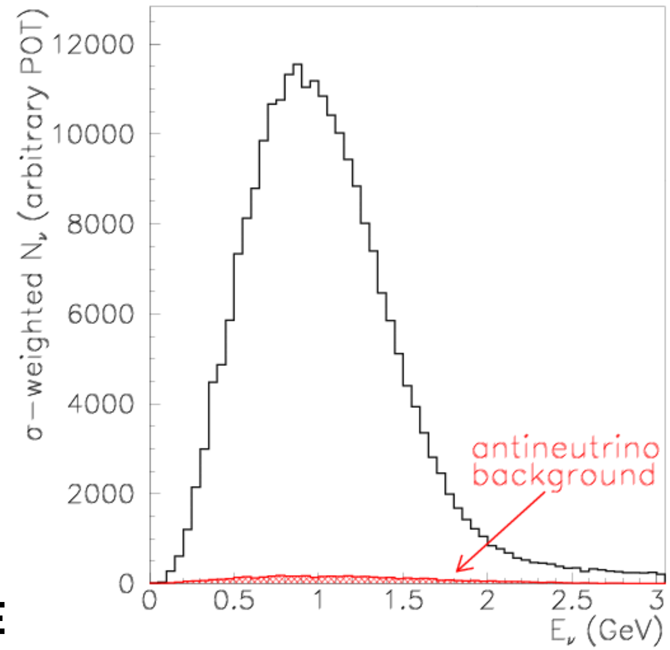


Nuance MC Event Rates

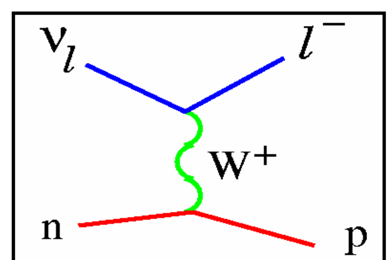
D. Casper, NPS, 112 (2002) 161

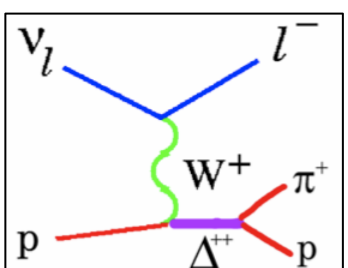


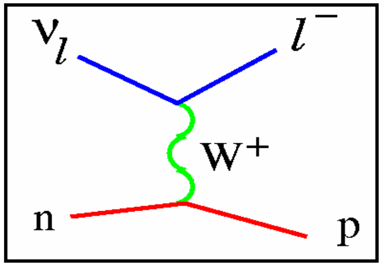




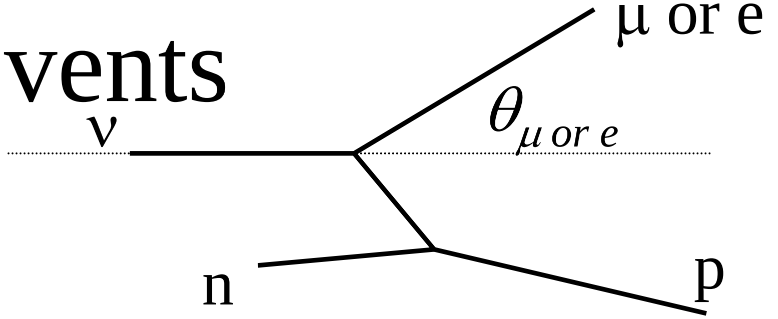
Event neutrino energy (GeV)







CCQE Events

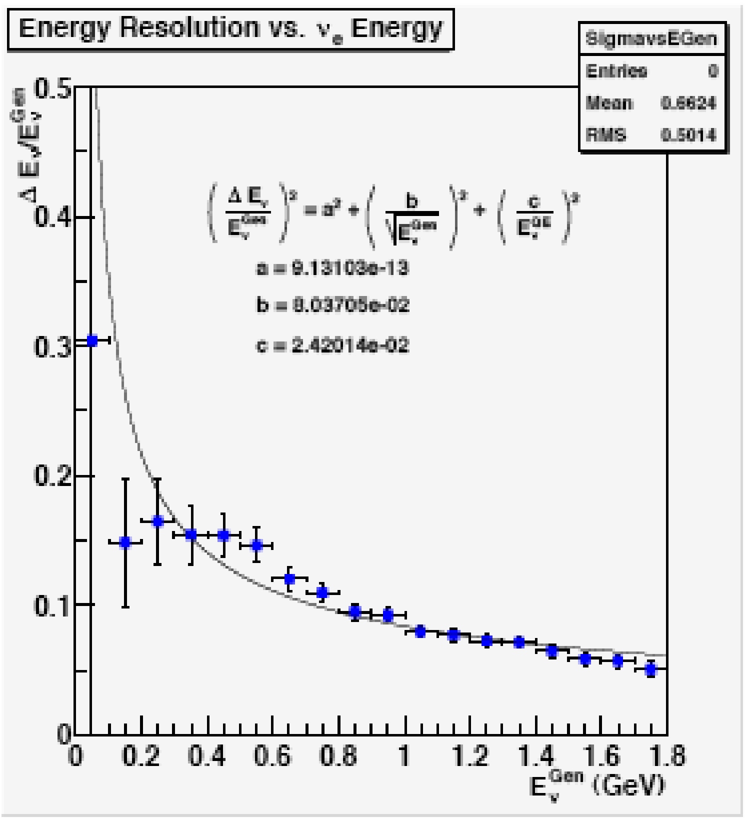


CCQE (Charged Current Quasi-Elastic)

39% of total

- Events are "clean" (few particles)
- Energy of the neutrino can be reconstructed

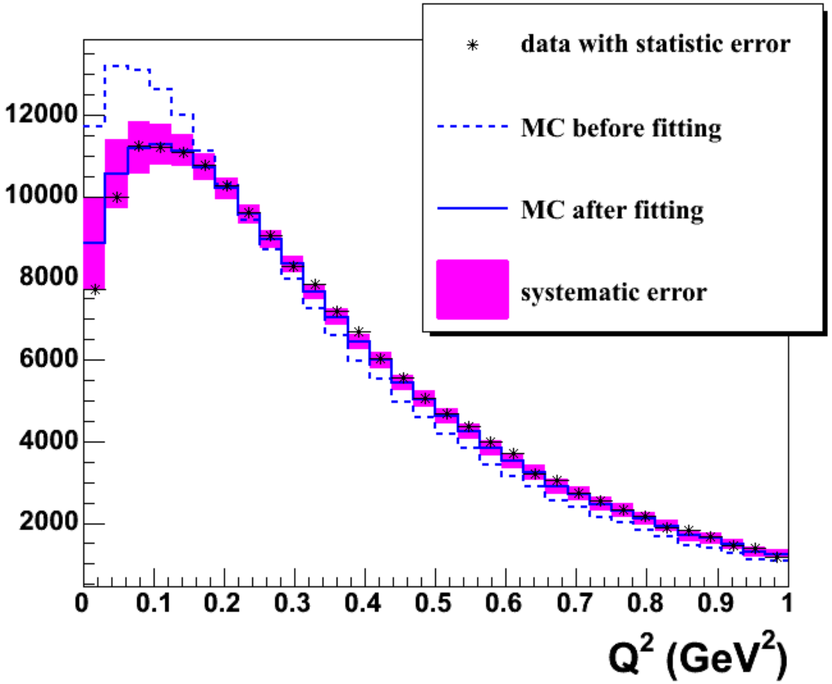
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$



Reconstructed from:
Scattering angle
Visible energy ($E_{visible}$)

An oscillation signal is an excess of ν_e events as a function of E_ν^{QE}

Nuance Parameters



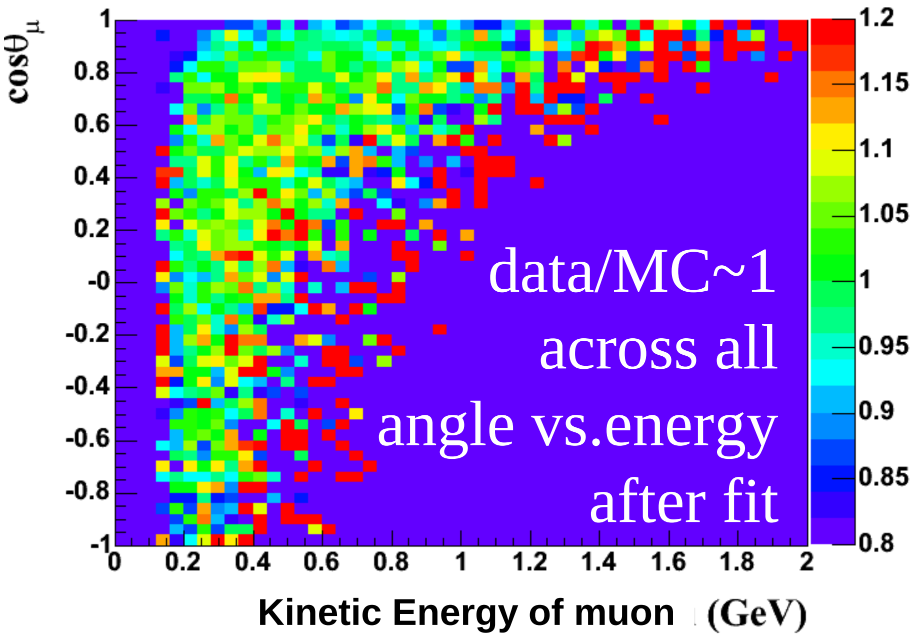
From Q^2 fits to MB ν_μ CCQE data:

- M_A^{eff} -- effective axial mass
- E_{lo}^{SF} -- Pauli Blocking parameter

From electron scattering data:

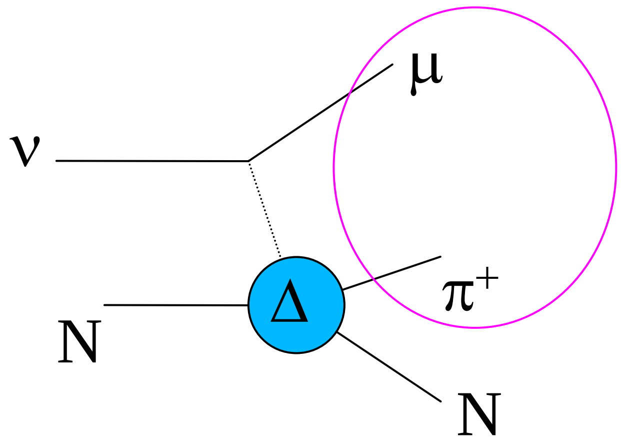
- E_b -- binding energy
- p_f -- Fermi momentum

Model describes CCQE ν_μ data well



Events Producing Pions

25%

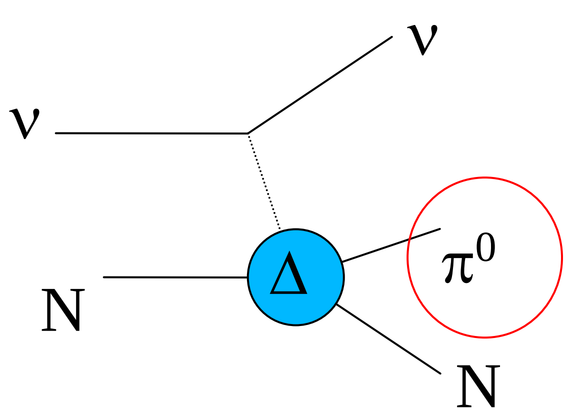


$CC\pi^+$

Easy to tag due to 3 subevents.

Not a substantial background to the oscillation analysis.

8%



$NC\pi^0$

The π^0 decays to 2 photons, which can look “electron-like” mimicking the signal...

(also decays to a single photon with 0.56% probability)

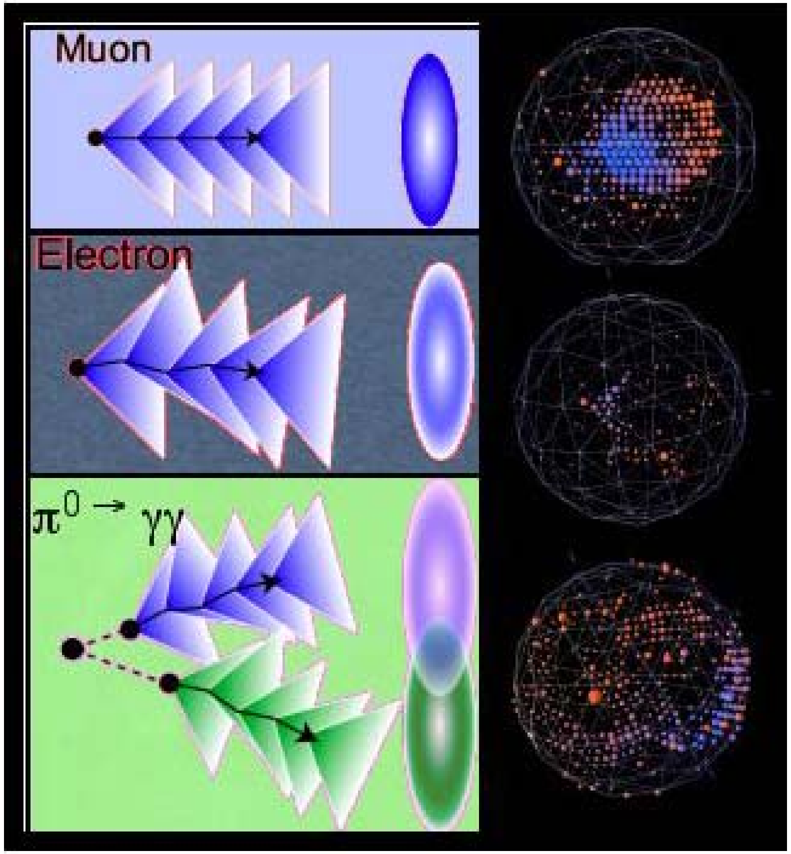
<1% of π^0 contribute to background.

MiniBooNE Event Types

Muons:
Produced in most CC events.
Usually 2 subevent or exiting.

Electrons:
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.



Two Independent Analyses

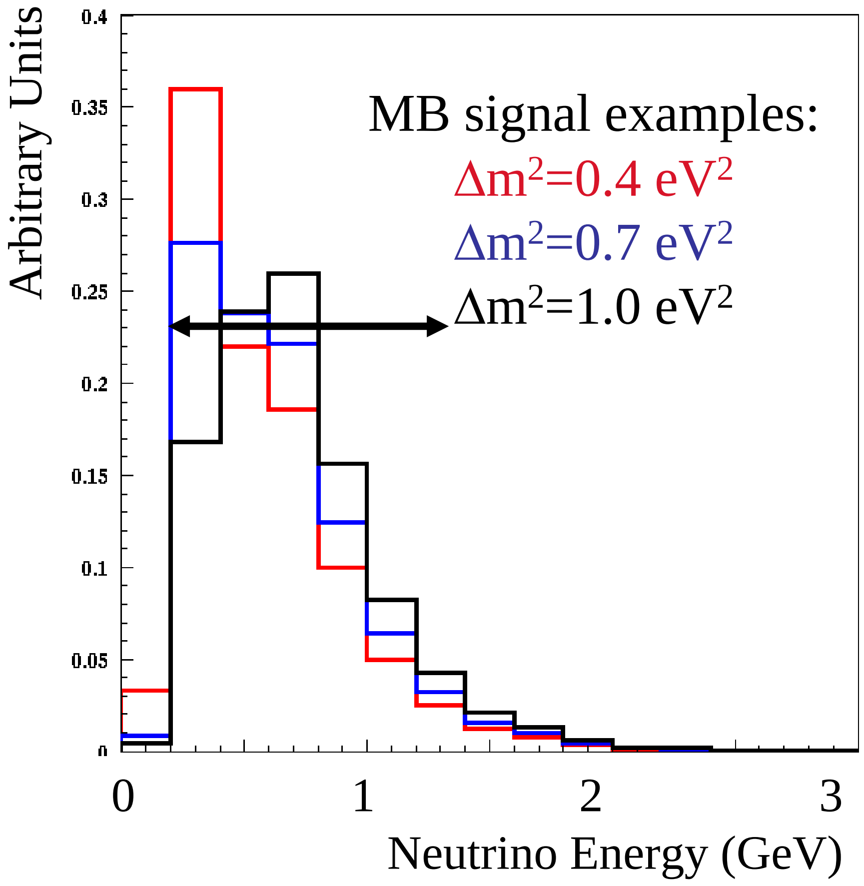
Analysis Goal

Minimize background &
Maximize signal efficiency.

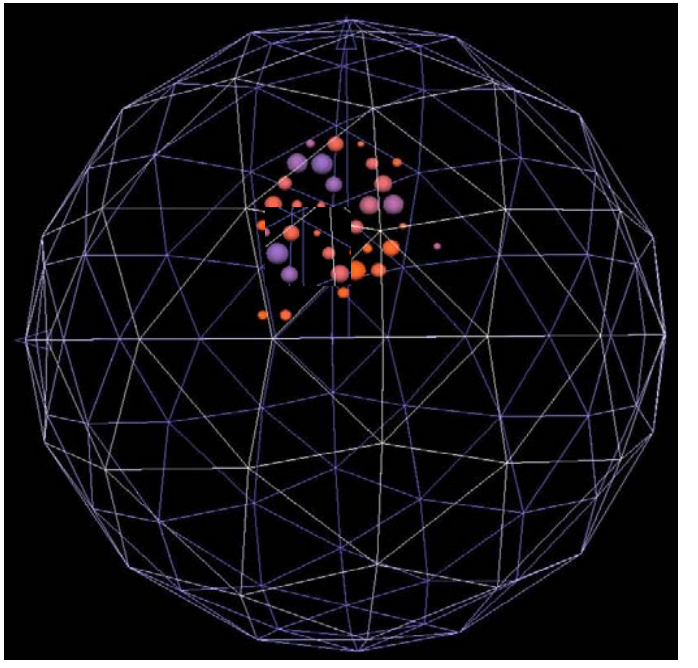
"Signal range" is about
300 MeV < E_ν^{QE} < 1500 MeV

One can then either:

- look for a total excess
  ("counting experiment")
- fit for both an excess and
  energy dependence
  ("energy fit")



Blindness Analysis



MiniBooNE is searching for a small but distinctive event signature (electron)

In order to maintain blindness,
Electron-like events were sequestered,
Leaving ~99% of the in-beam events available for study.

Rule for cuts to sequester events: $<1\sigma$ signal outside of the box

Low level information which did not allow particle-id was available for all events.

Pre-selection Cuts

Both Algorithms and all analyses presented here share "hit-level pre-cuts":

Only 1 subevent

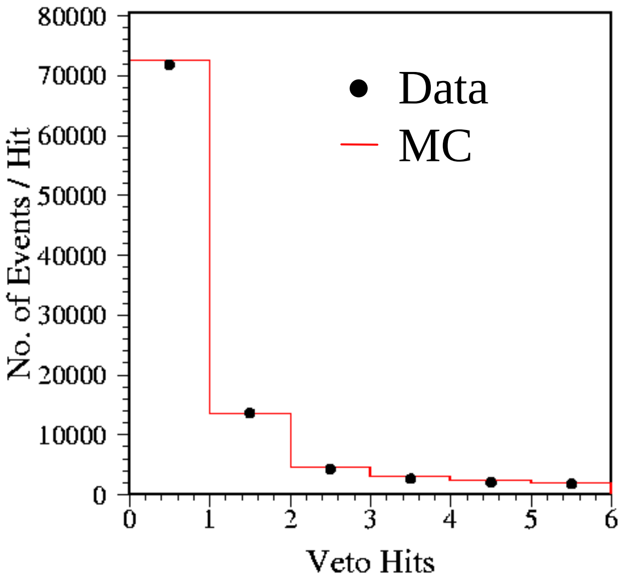
Number of Veto hits < 6

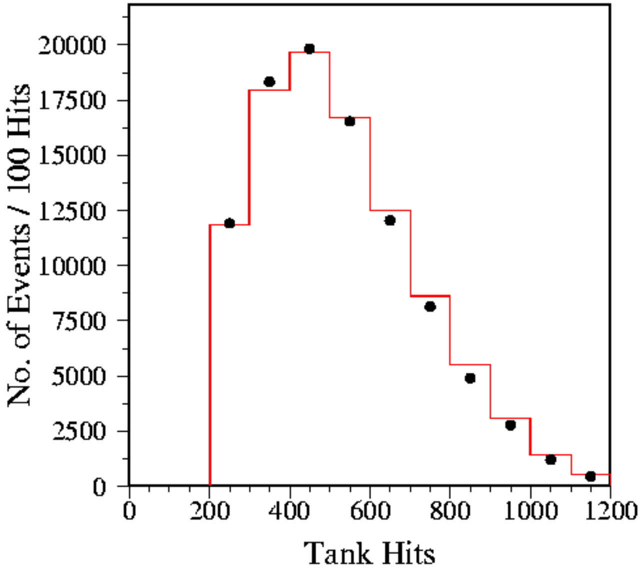
Number of Tank hits > 200

And a radius precut:

R<500 cm

(where reconstructed R is algorithm-dependent)





Track-Based (TB) Analysis

Philosophy:

➔Uses detailed, direct reconstruction of particle tracks, and ratio of fit likelihoods to identify particles.

Each event is characterized by 7 reconstructed variables:

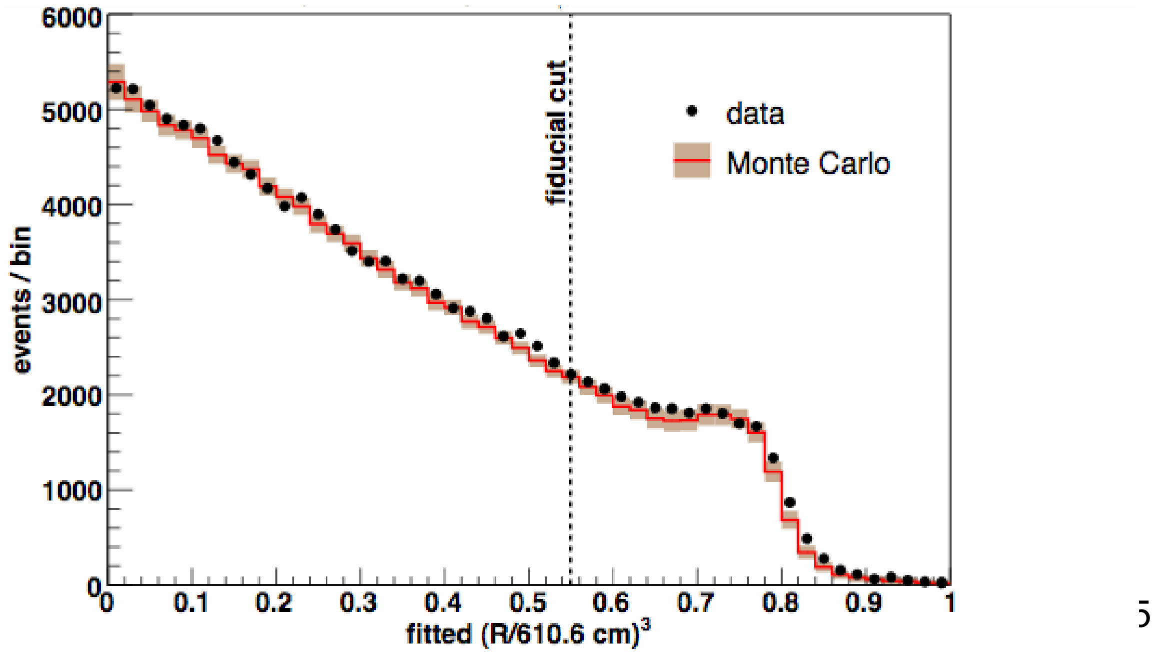
vertex (x,y,z), time, energy, and direction $(\theta,\phi)\Leftrightarrow(U_x, U_y, U_z)$.

Resolutions:

vertex: 22 cm

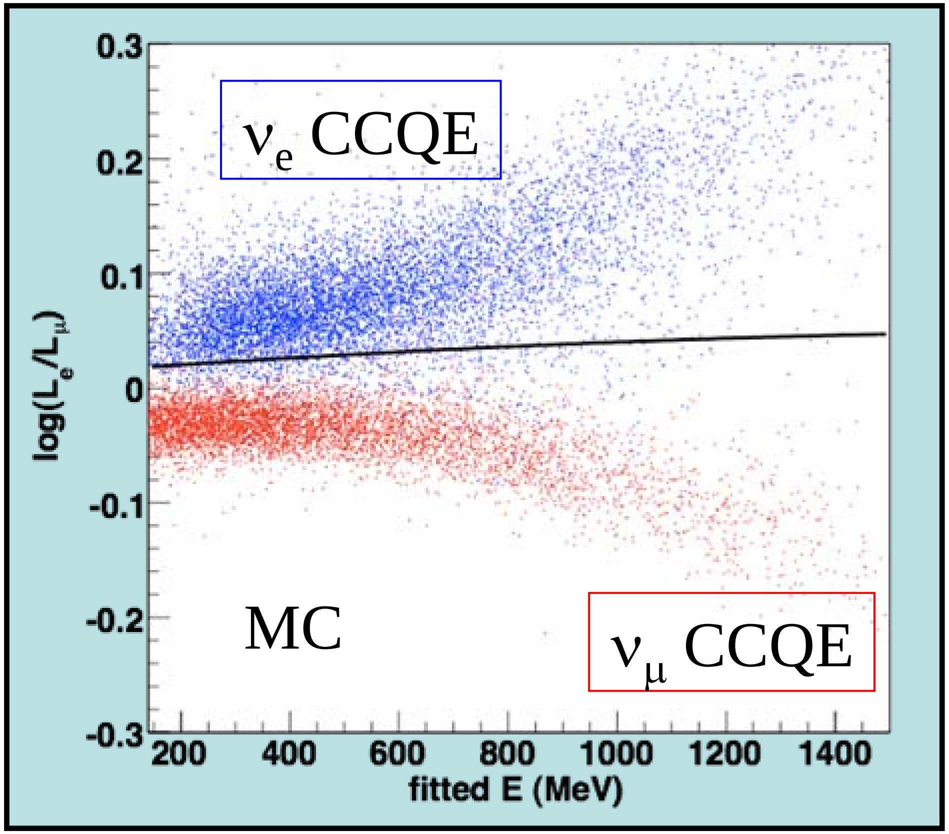
direction: 2.8°

energy: 11%



e / μ Separation

$\log(L_e/L_\mu)>0$ favors electron-like hypothesis



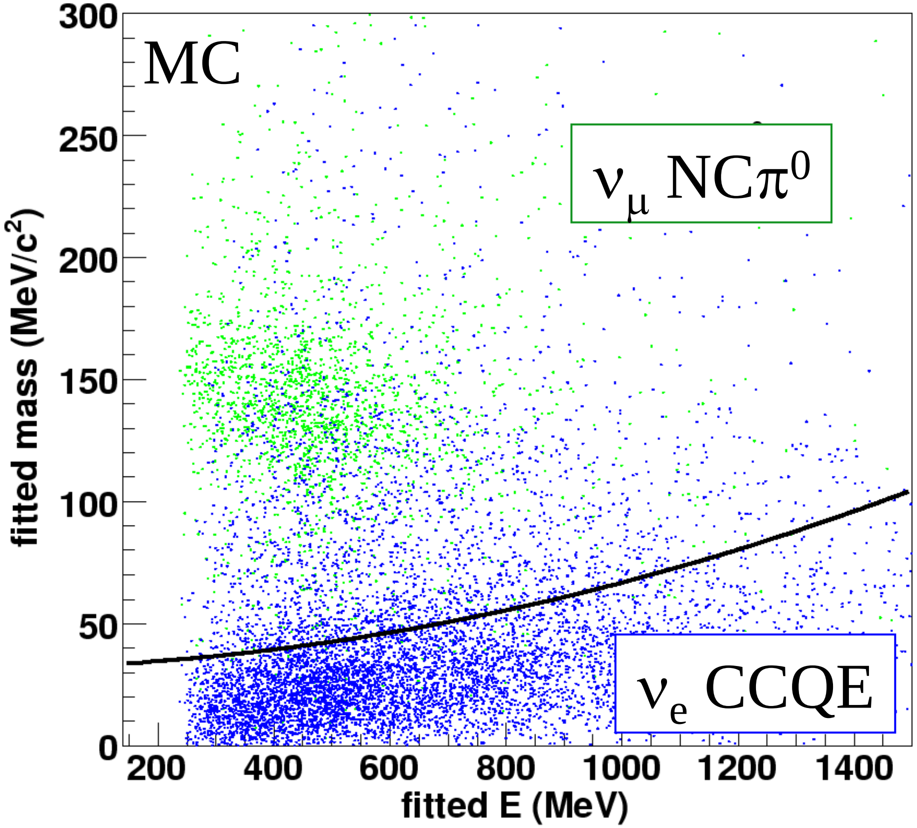
Note: photon conversions are electron-like.
This does not separate e/π^0.

Separation is clean at high energies where muon-like events are long.

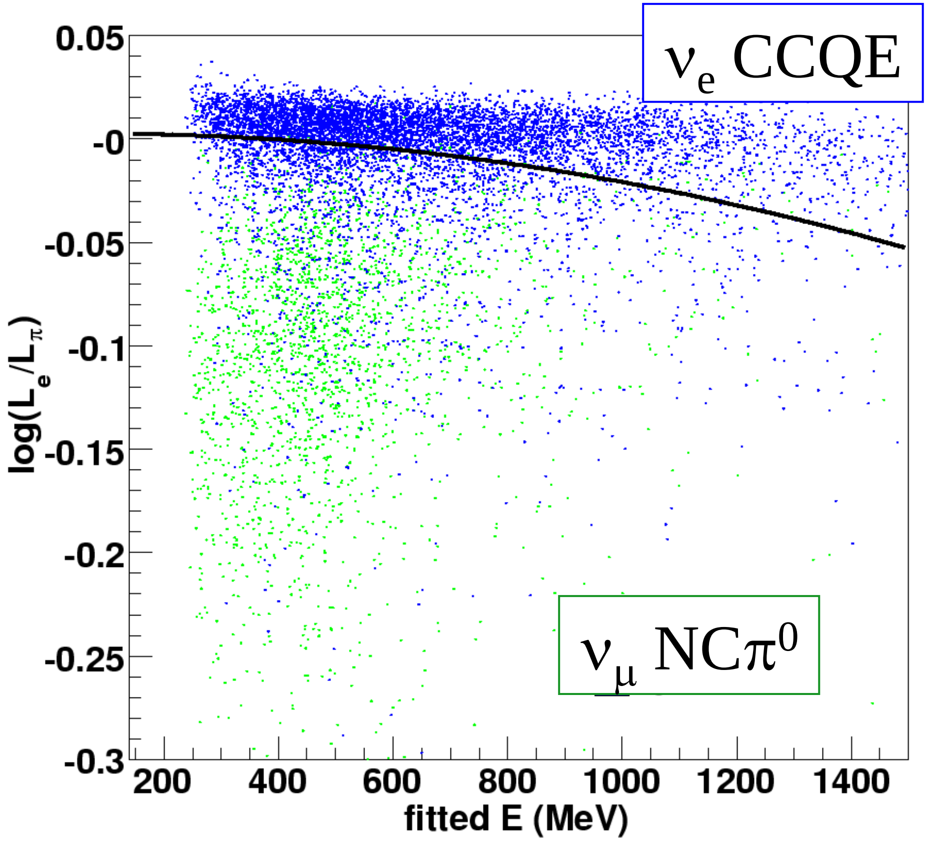
Analysis cut was chosen to maximize the $\nu_\mu \rightarrow \nu_e$ sensitivity

e / π^0 Separation

Using a mass cut



Using log(L_e/L_π)



Cuts were chosen to maximize $\nu_\mu \rightarrow \nu_e$ sensitivity

Testing e / π^0 Separation using data

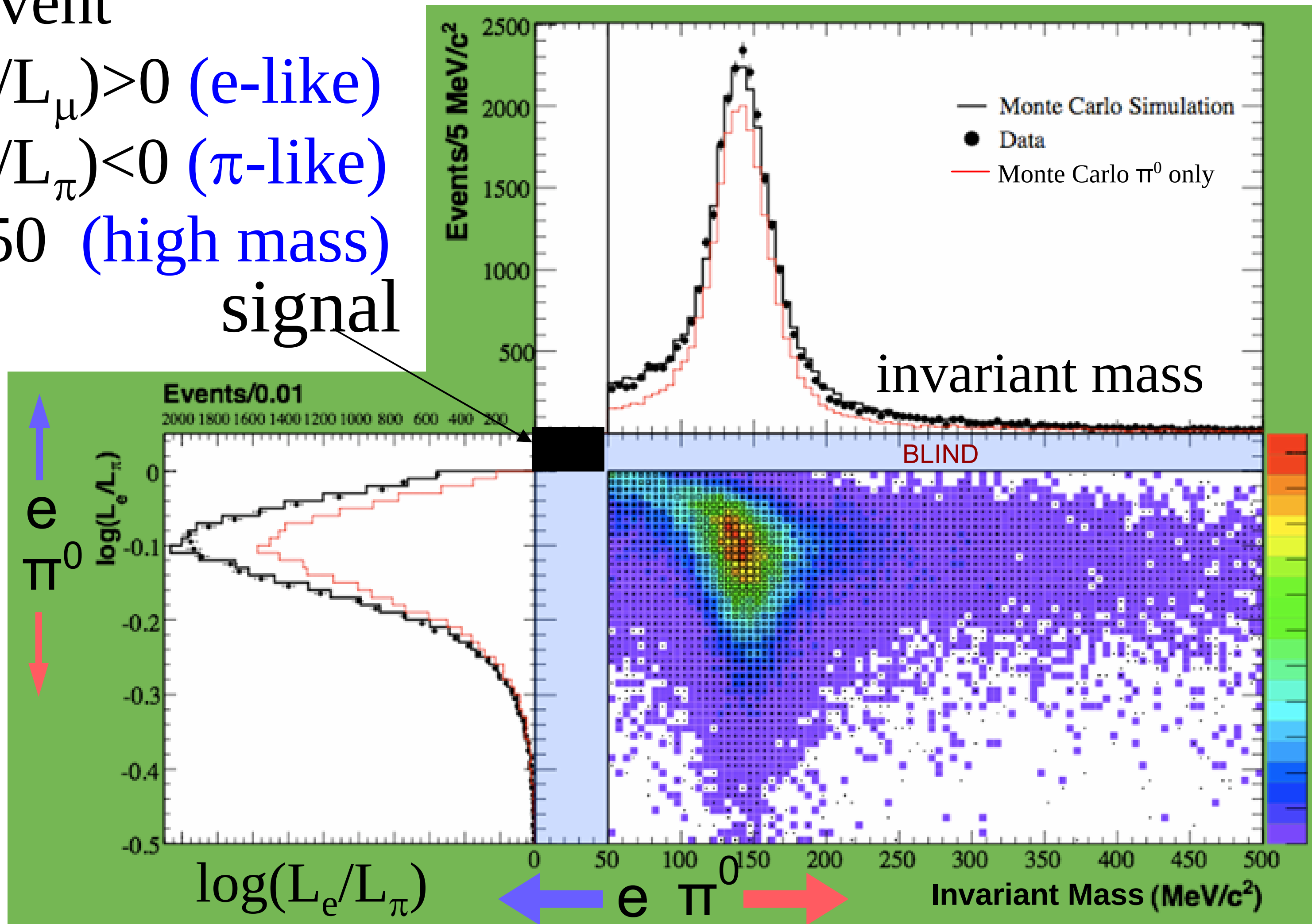
1 subevent

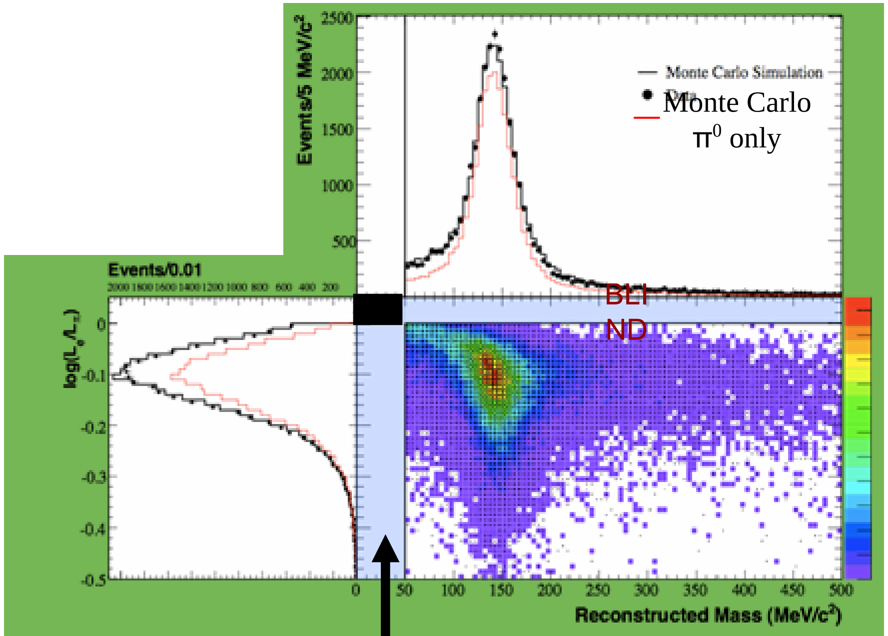
$\log(L_e/L_\mu)>0$ (e-like)

$\log(L_e/L_\pi)<0$ (π-like)

$M_{\pi 0} > 50$ (high mass)

signal





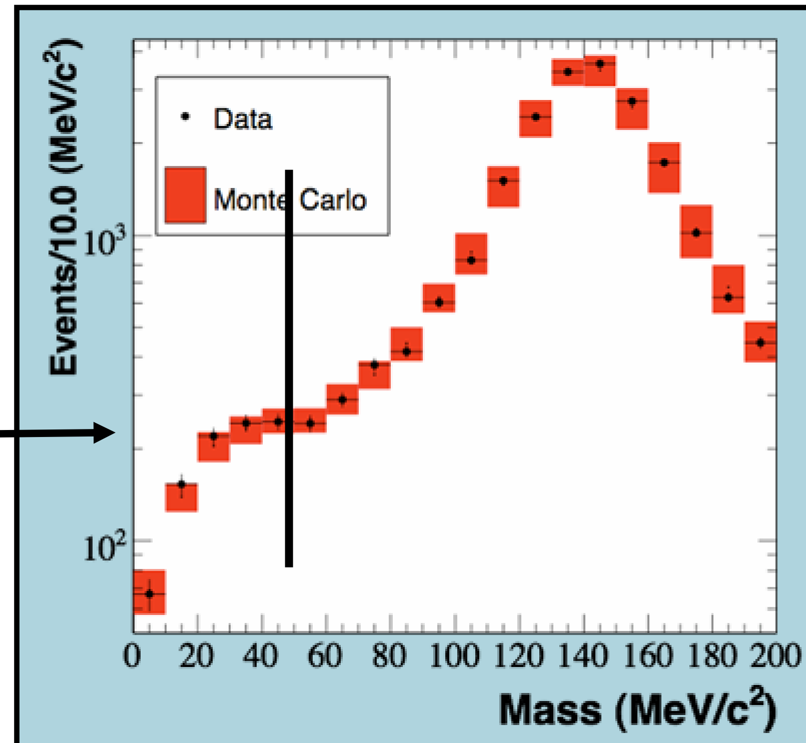
1 subevent

$\log(L_e/L_\mu)>0$ (e-like)

$\log(L_e/L_\pi)<0$ (π-like)

mass<200 (low mass)

Next: look here....



χ^2 Prob for mass<50 MeV ("most signal-like"): 69%

Summary of Track-Based Cuts

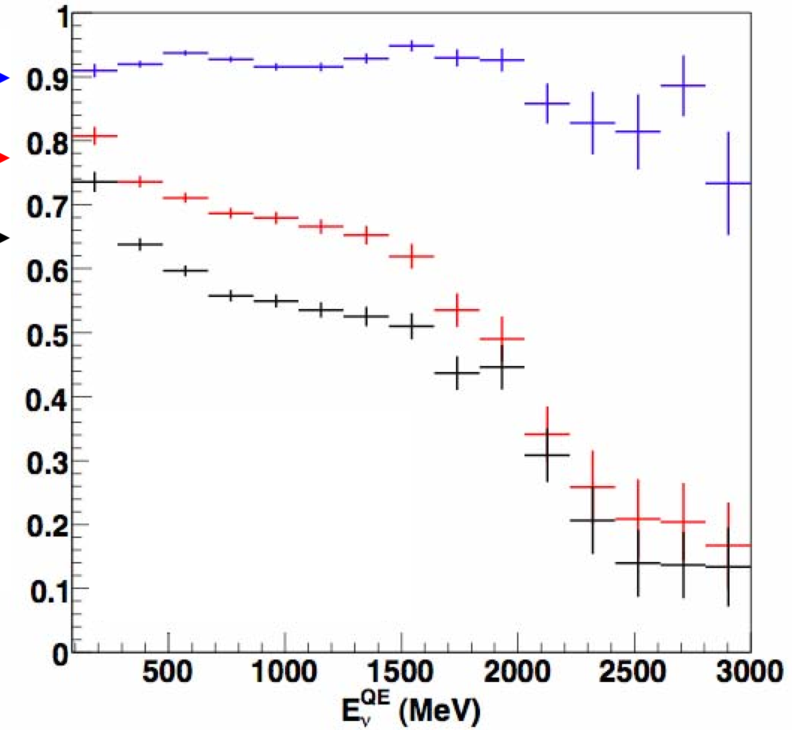
"Precuts" +

Efficiency:

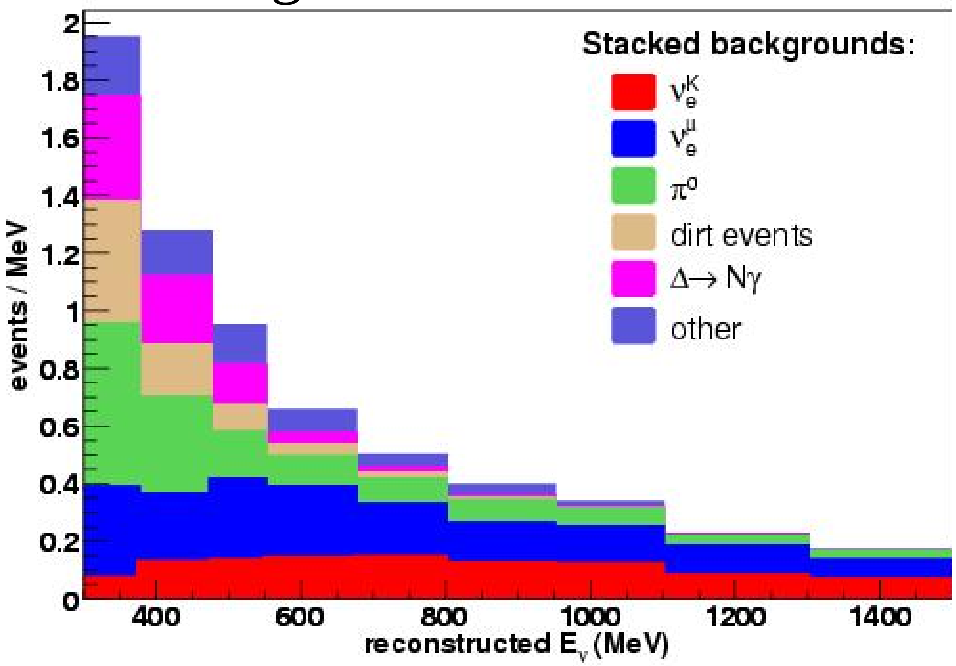
$\text{Log}(L_e/L_\mu)$

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

invariant mass



Backgrounds after cuts



Overall PID efficiency ~ 37%

Boosted Decision Trees (BDT) Analysis

Philosophy:

➔Construct a set of low-level analysis variables which are used to make a series of cuts to classify the events – decision tree.

➔Boosted Decision Trees combine many trees (weak classifiers) to build a powerful committee to improve signal efficiency.

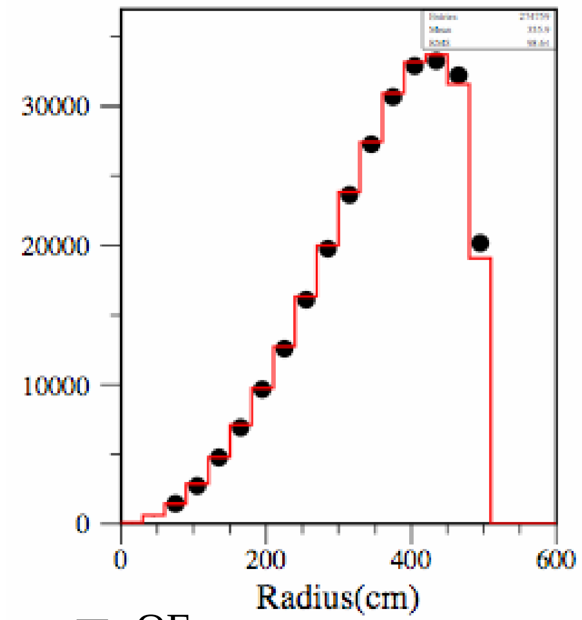
Examples of "Analysis Variables"

Resolutions:

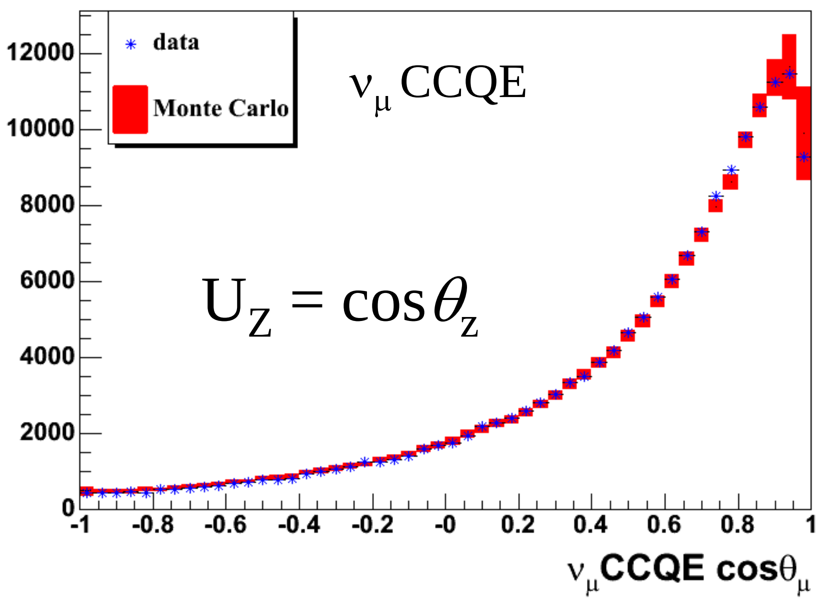
vertex: 24 cm

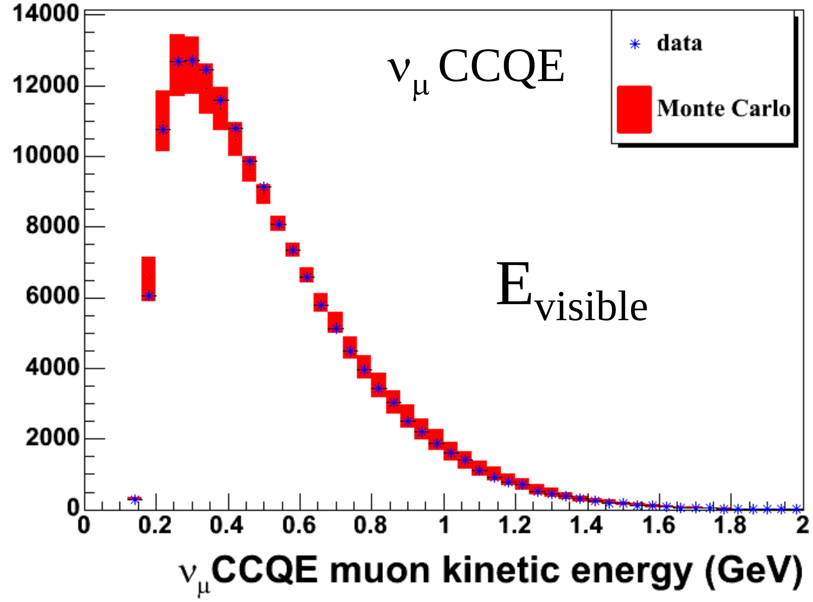
direction: 3.8°

energy 14%



Reconstructed quantities which are inputs to E_{ν}^{QE}

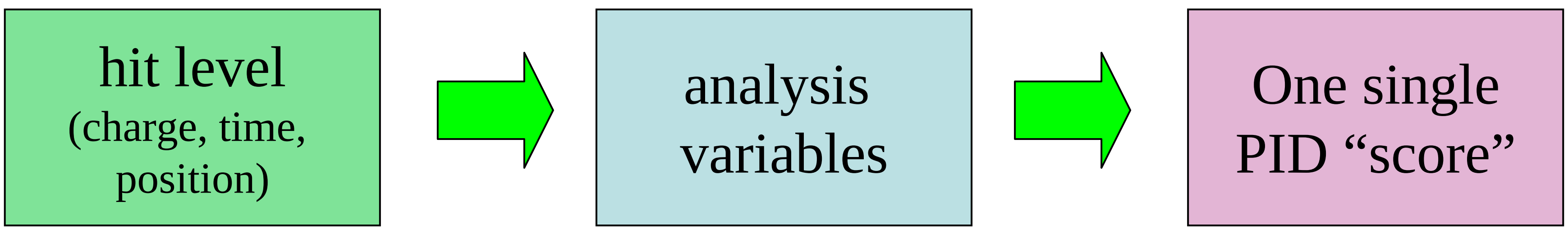




Many Variables ➔ A Single PID Variable

Boosted Decision Trees

"A procedure that combines many weak classifiers to form a powerful committee"



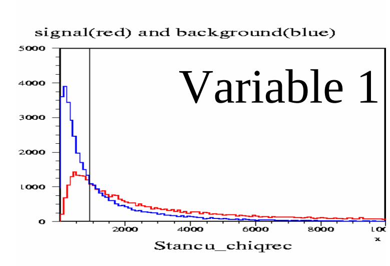
Byron P. Roe, Hai-Jun Yang, Ji Zhu *et al.*, NIM A543 (2005) 577, physics/0408124
Hai-Jun Yang, Byron P. Roe, Ji Zhu, NIM A555 (2005) 370, physics/0508045
Hai-Jun Yang, Byron P. Roe, Ji Zhu, NIM A574 (2007) 342, physics/0610276

A Decision Tree

(sequential series of cuts based on MC study)

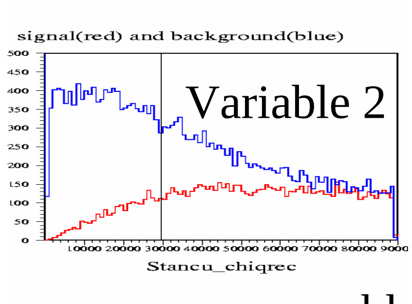
(N_{signal}/N_{bkgd})

40000/40000



bkgd-like

9755/23695



bkgd-like

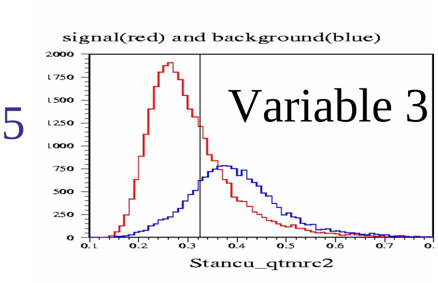
1906/11828

bkgd-like

7849/11867

signal-like

30,245/16,305



signal-like

20455/3417

bkgd-like

9790/12888

etc.

This tree is one of many possibilities...

A set of decision trees can be developed,

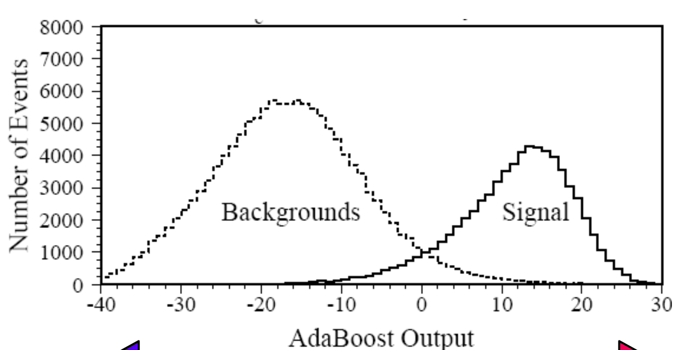
each re-weighting the events to enhance identification of backgrounds misidentified by earlier trees   (“boosting”)

For each tree, the data event is assigned

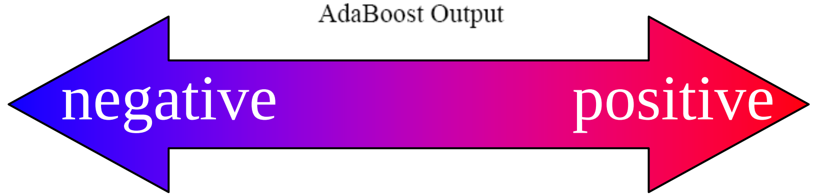
+1 if it is identified as signal,

-1 if it is identified as background.

The total for all trees is combined into a “score”



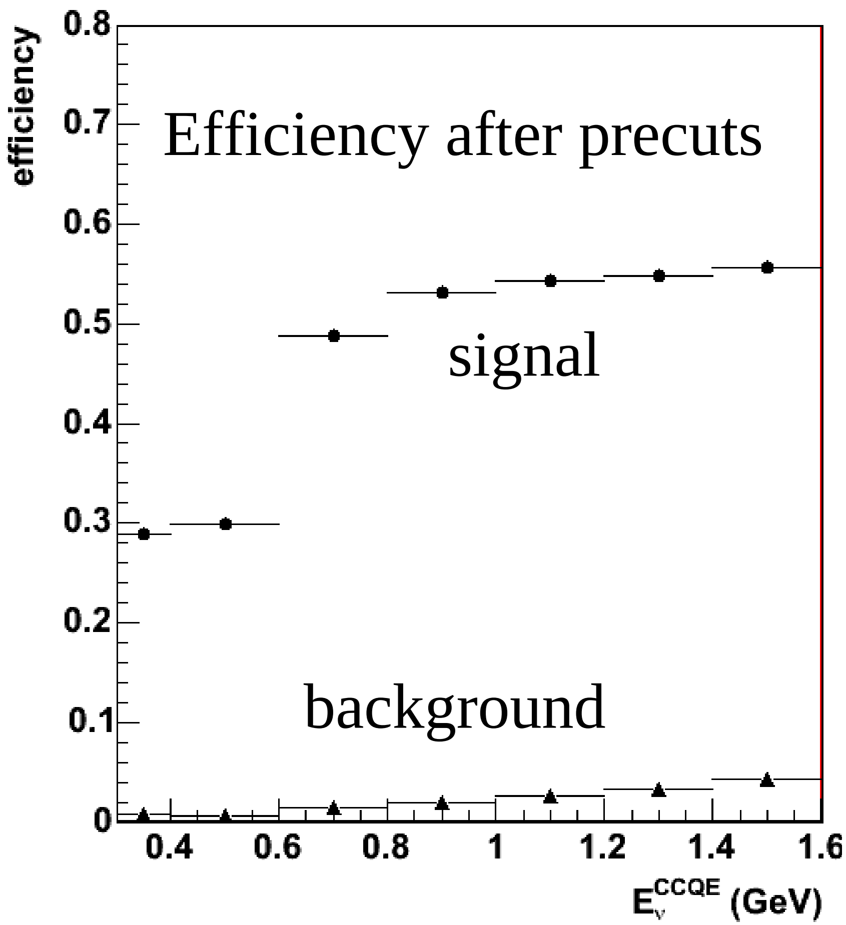
Background-like

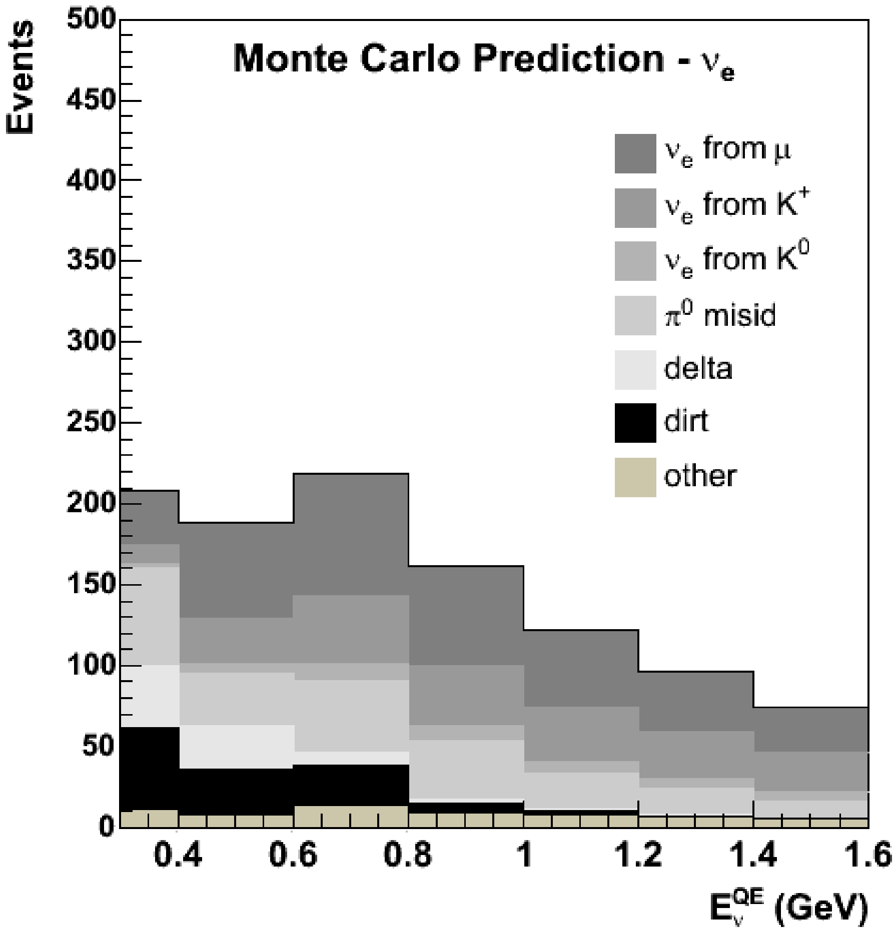


signal-like

BDT Efficiency and backgrounds after cuts:

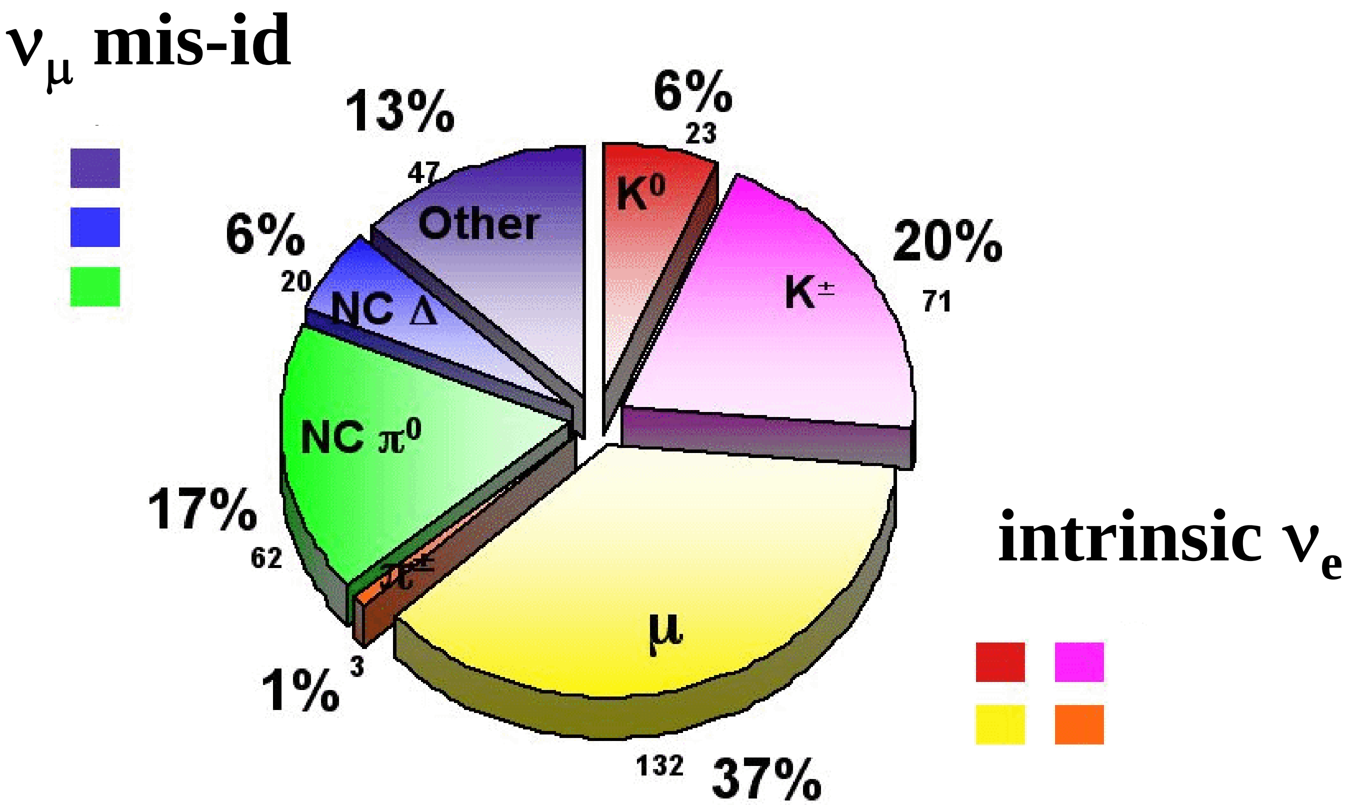
Analysis cuts on PID score as a function of Energy





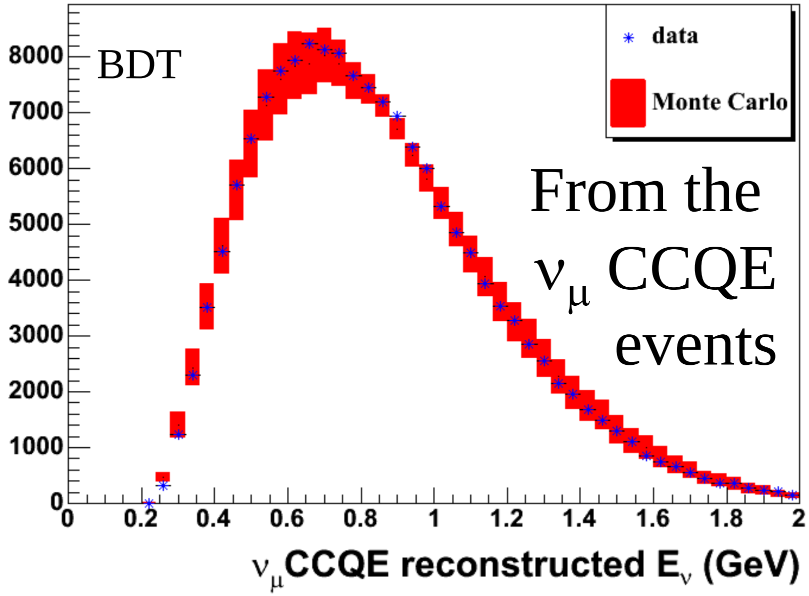
Errors and Constraints

We have two categories of backgrounds:



Predictions of the backgrounds are among the nine sources of significant error in the analysis

Source of Uncertainty On ν_e background	Track Based /Boosted Decision Trees error in %	Checked or Constrained by MB data	Further 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 decay	1.5 / 0.4	√	√
Target and beam models	2.8 / 1.3	√	
ν-cross section	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	√	



Predict →

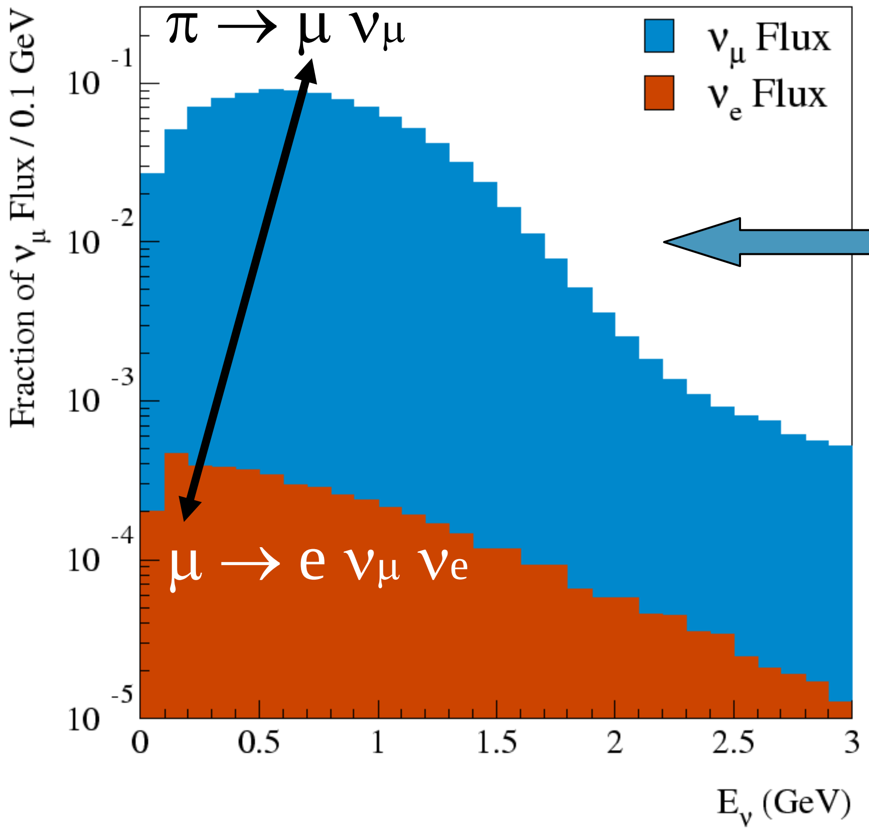
Normalization
& energy dependence
of both background
and signal

Data/MC Boosted Decision Tree: 1.22 ± 0.29

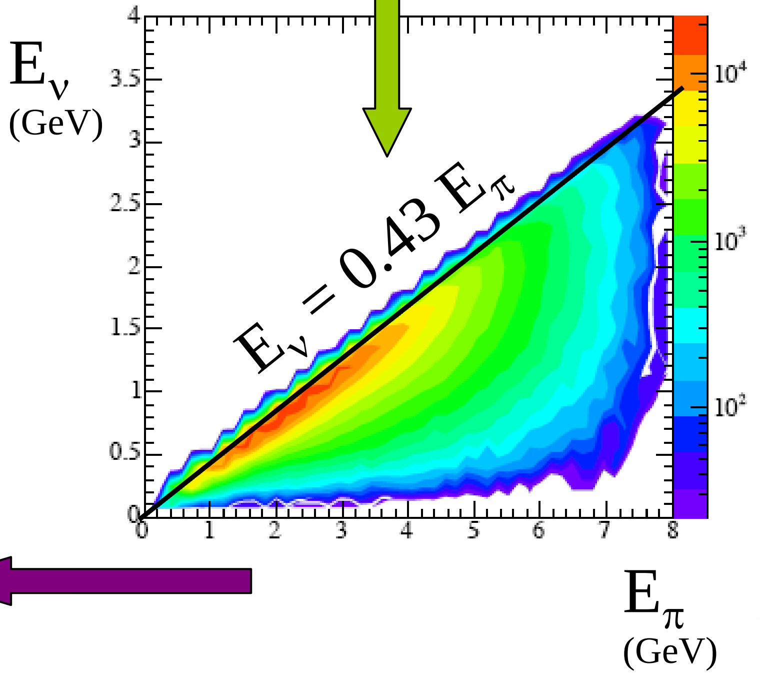
Track Based: 1.32 ± 0.26

Tying the ν_e background and signal prediction to the ν_μ flux constrains this analysis to a strict $\nu_\mu \rightarrow \nu_e$ appearance-only search

ν_μ constraint on intrinsic ν_e from π^+ decay chains

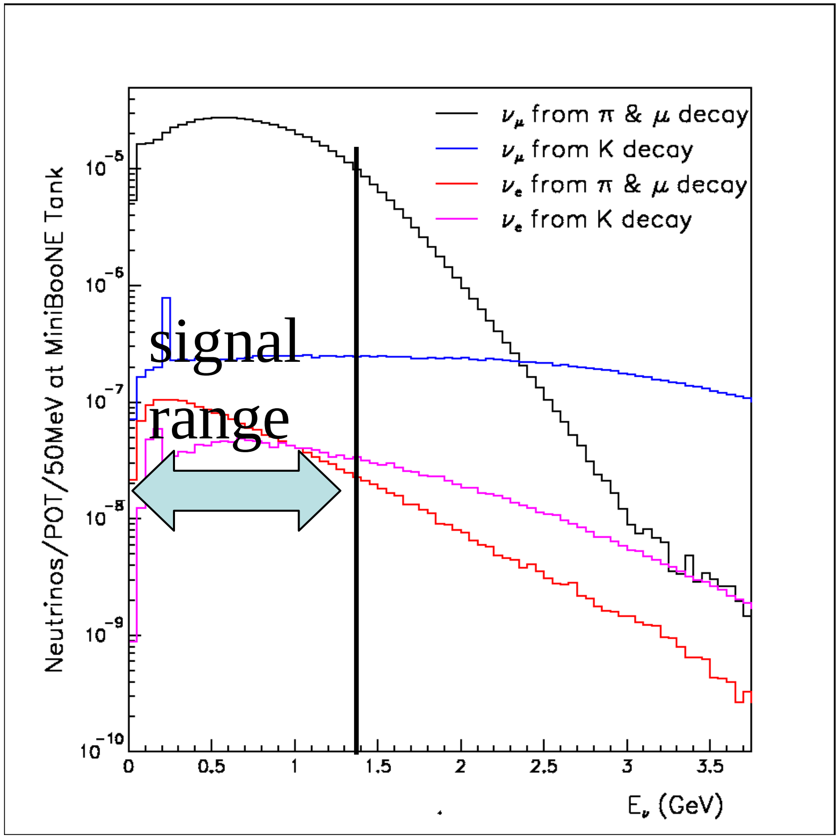


- Measure the ν_μ flux
- Kinematics allows connection to the π flux



- Once the π flux is known, the μ flux is determined

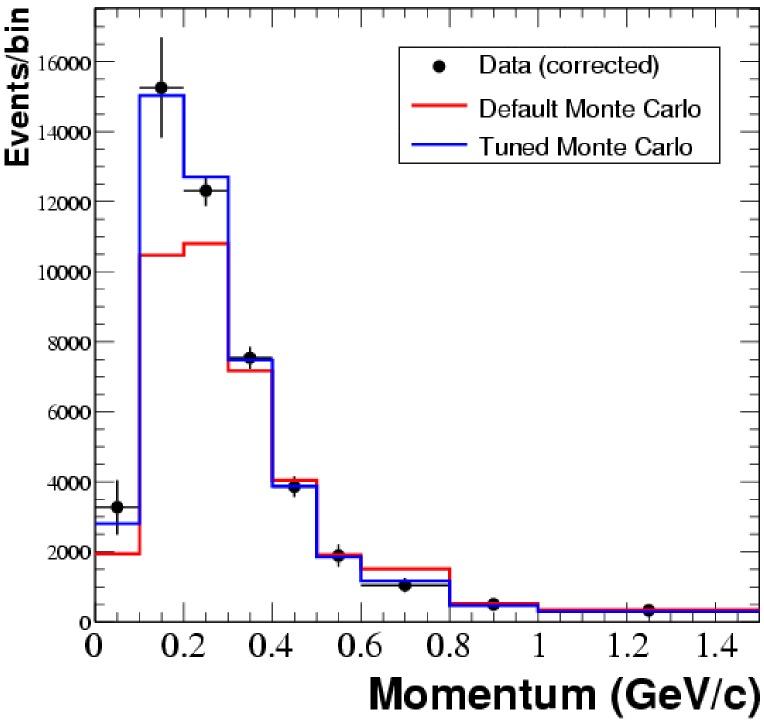
K^+ and K^0 Decay Backgrounds



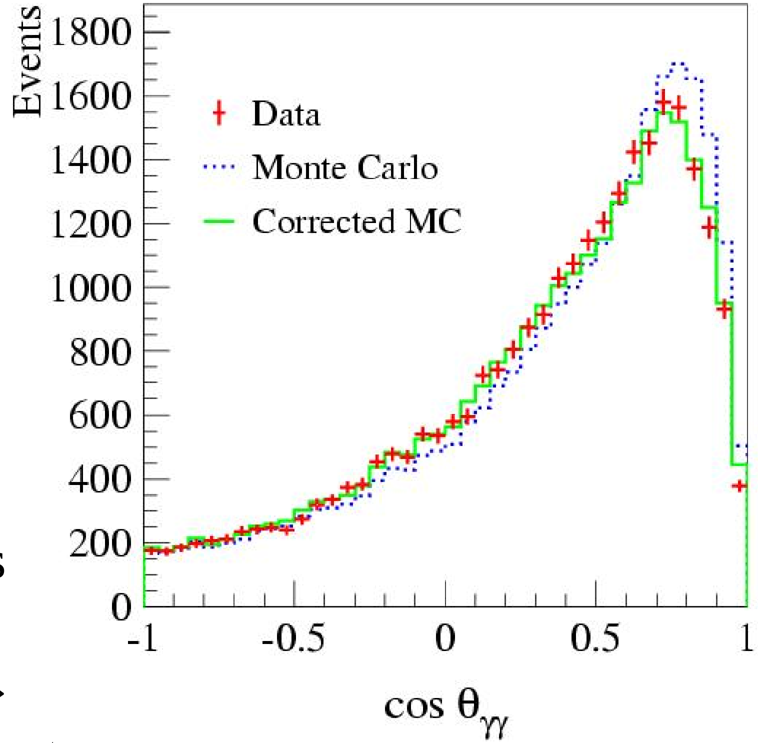
At high energies > 1.5 GeV, above "signal range" ν_μ and "ν_e -like" events are largely due to kaon decay

By measuring high energy box events (>1.5 GeV) to estimate K^+ & K^0 production rate.

We constrain π^0 production using data from our detector



This reduces the error on predicted mis-identified π^0s



Reweighting improves agreement in other variables, e.g.$\Rightarrow$

Because this constrains the Δ resonance rate, it also constrains the rate of $\Delta \rightarrow N\gamma$

Other Single Photon Sources

Neutral Current: $\nu + N \rightarrow \nu + N + \gamma$ negligible

From Efrosinin, hep-ph/0609169,
calculation checked by Goldman, LANL

Charged Current < 6 events @ 95% CL

$$\nu + N \rightarrow \mu + N' + \gamma$$

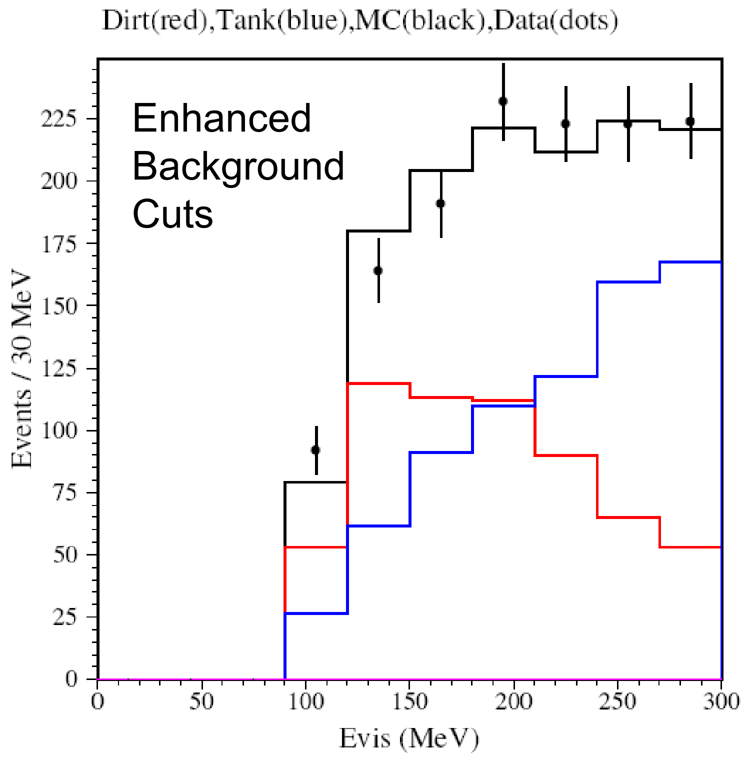
where the presence of the γ leads to mis-identification

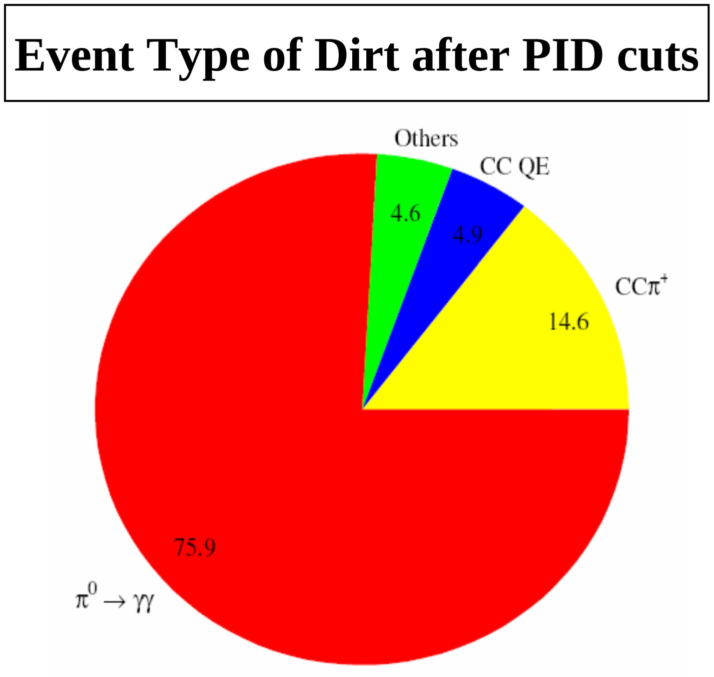
Use events where the μ is tagged by the michel e^-,
study misidentification using BDT algorithm.

External Sources of Background

"Dirt" Events

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





Cosmic Rays: Measured from out-of-beam data: 2.1 ± 0.5 events

Summary of predicted backgrounds for the final MiniBooNE result

Process	Number of Events
ν_μ CCQE	10
$\nu_\mu e \to \nu_\mu e$	7
Miscellaneous ν_μ Events	13
NC π^0	62
NC $\Delta \to N\gamma$	20
NC Coherent & Radiative γ	< 1
Dirt Events	17
ν_e from μ Decay	132
ν_e from K^+ Decay	71
ν_e from K^0_L Decay	23
ν_e from π Decay	3
Total Background	358
0.26% $\nu_\mu \to \nu_e$	(example signal) 163

Example: Cross Section Uncertainties

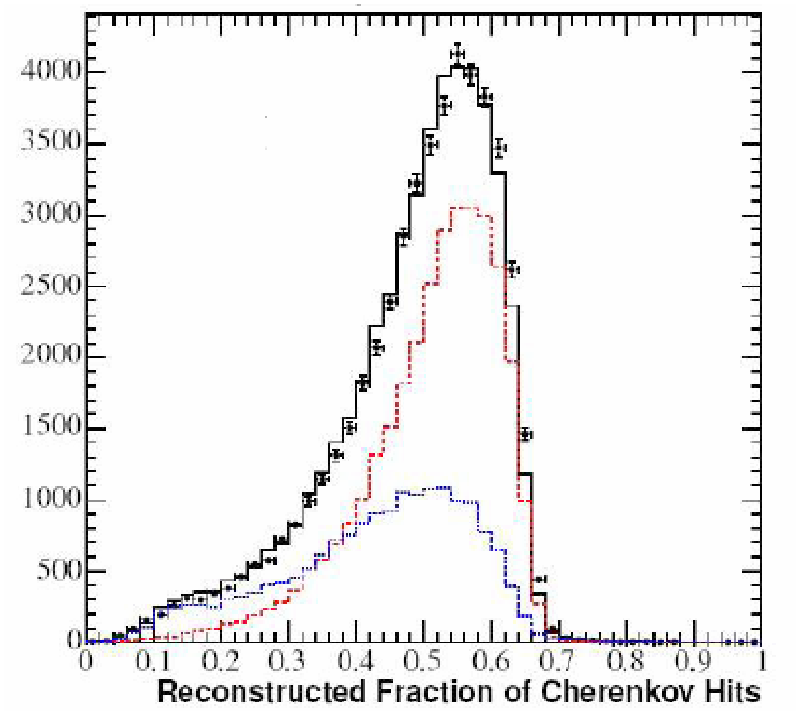
(Many are common to ν_μ and ν_e and cancel in the fit)

M_A^{QE}, e_{lo}^{sf}	6%, 2% (stat + bkg only)	determined from MiniBooNE ν_μ QE 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 π^0 mom	determined from MiniBooNE ν_μ NC π^0 data
M_A^{coh}, coh σ	$\pm$25%	
$\Delta \rightarrow N\gamma$ rate	function of γ mom + 7% BF	

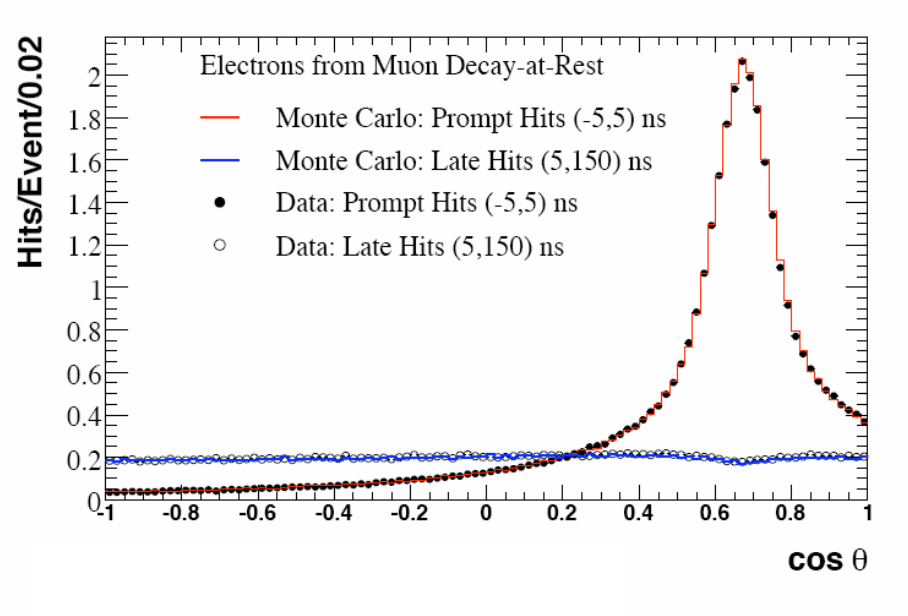
E_B, p_F	9 MeV, 30 MeV	determined from other experiments
Δs	10%	
$M_A^{1\pi}$	25%	
$M_A^{N\pi}$	40%	
DIS σ	25%	

Example:
Optical Model Uncertainties



39 parameters must be varied

Allowed variations are set by the Michel calibration sample



To understand allowed variations, we ran 70 hit-level simulations, with differing parameters.

⇒“Multisims”

Error Matrix Elements:

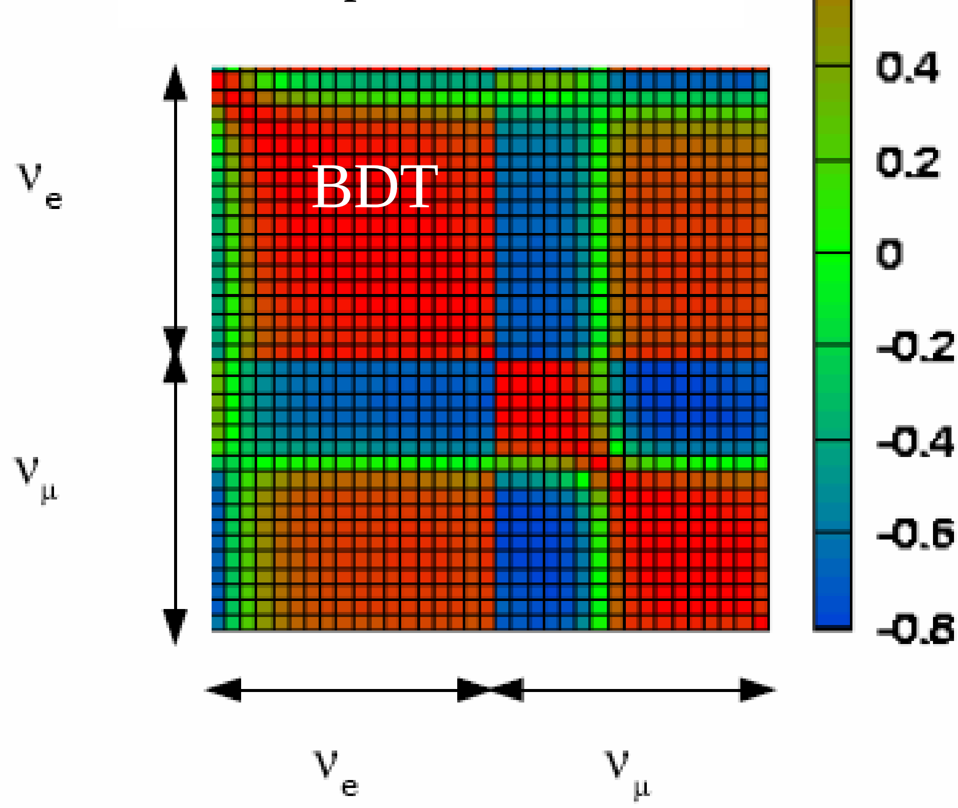
$$E_{ij} \approx \frac{1}{M}\sum_{\alpha=1}^{M}\left(N_i^{\alpha} - N_i^{MC}\right)\left(N_j^{\alpha} - N_j^{MC}\right)$$

- N 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 sum from each source.

TB: ν_e-only total error matrix
BDT: ν_μ-ν_e total error matrix

Correlations between E_ν^{QE} bins from the optical model:



The Initial Results

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

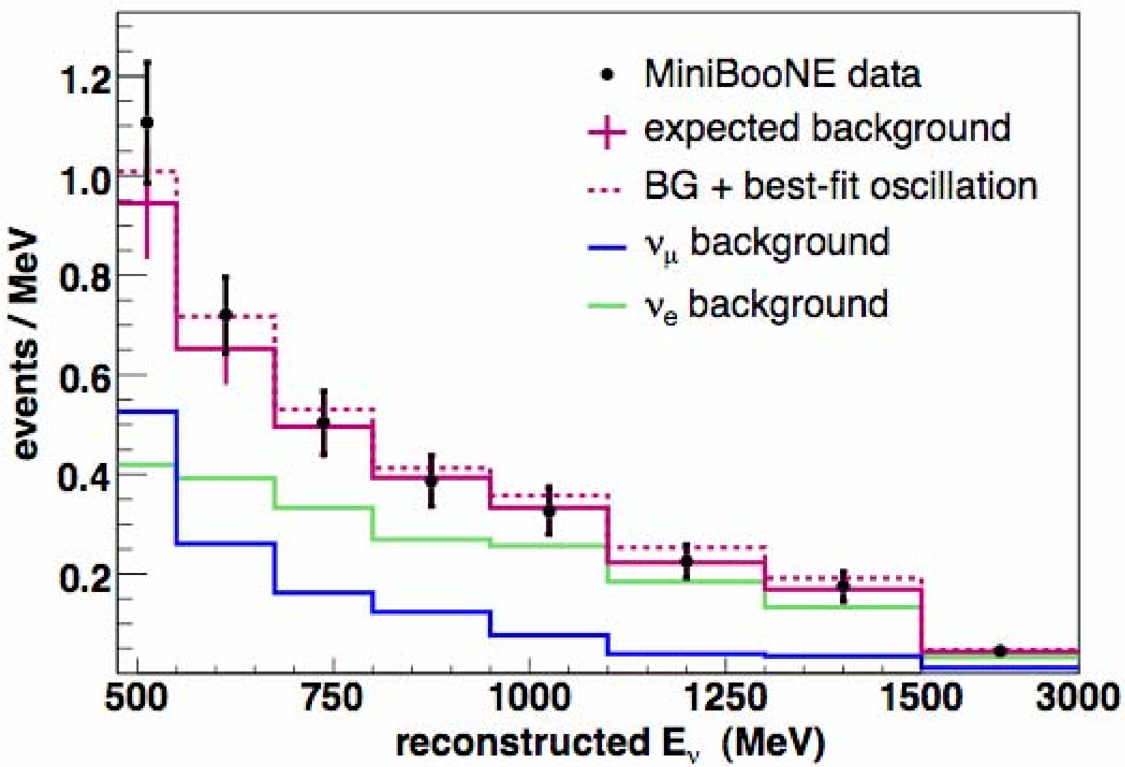
Counting Experiment: $475 < E_\nu^{QE} < 1250$ MeV

data: 380 events

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

significance:
0.55 σ

Track Based energy dependent fit results:
Data are in good agreement with background prediction.



Error bars are diagnonals of error matrix.

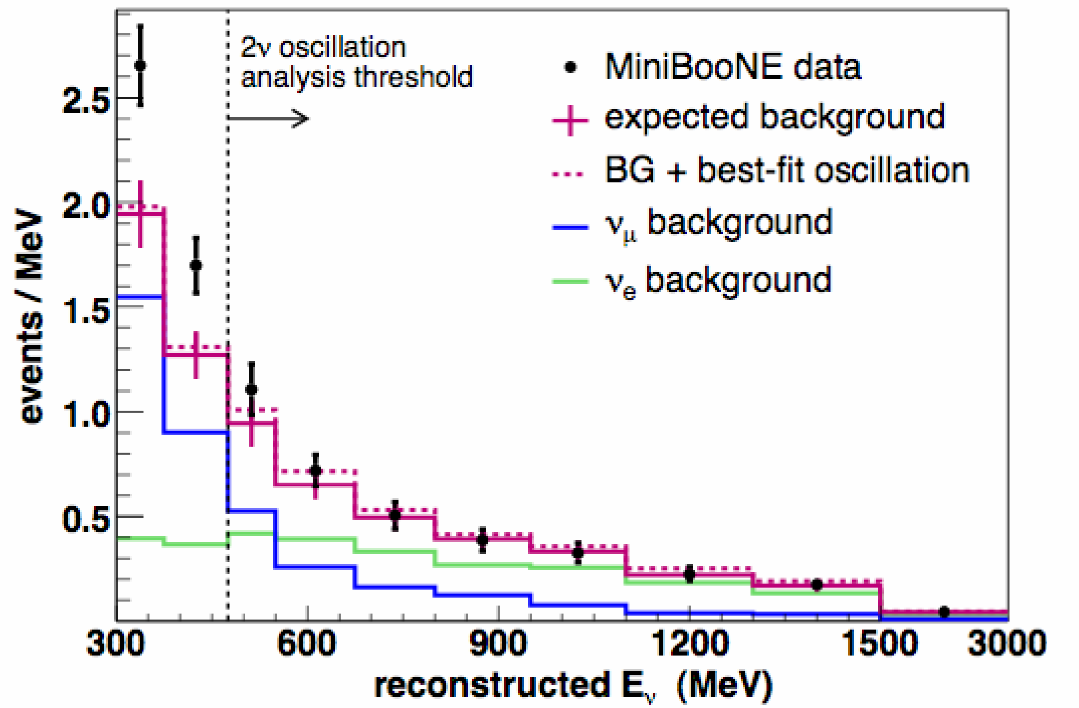
Fit errors for >475 MeV:
Normalization 9.6%
Energy scale: 2.3%

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

As planned before opening the box....

Report the full range:

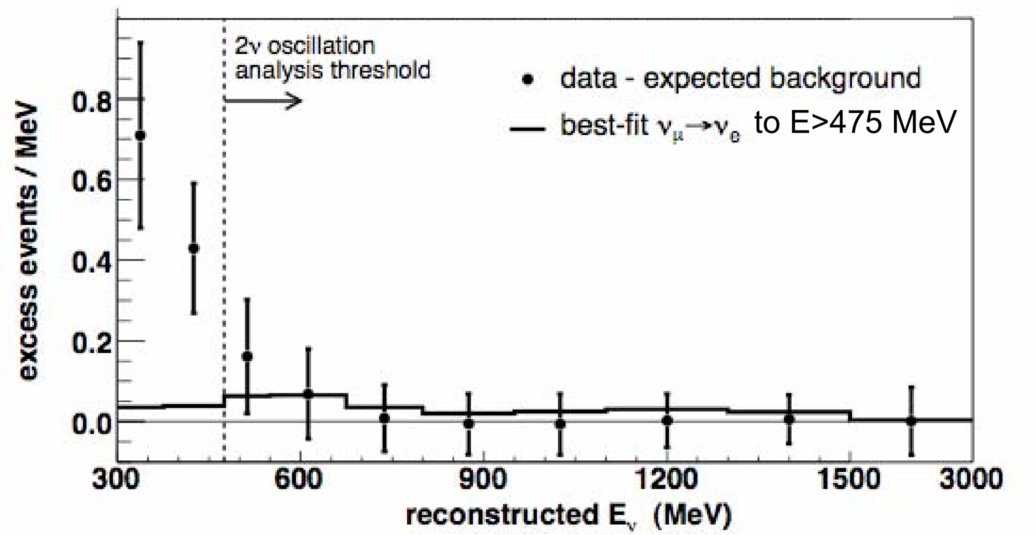
$300 < E_\nu^{QE} < 3000$ MeV



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

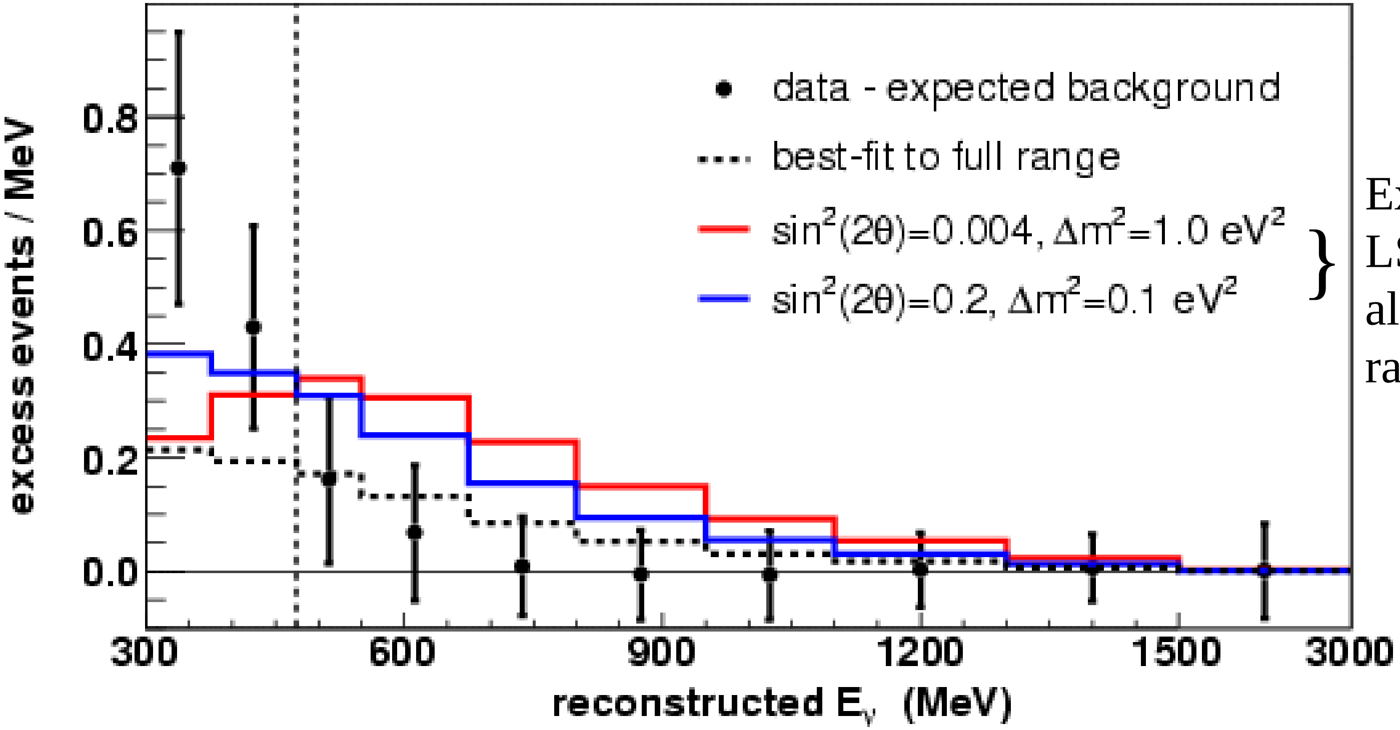
Deviation: 3.7σ

Background-subtracted:



Fit to the > 300 MeV range:

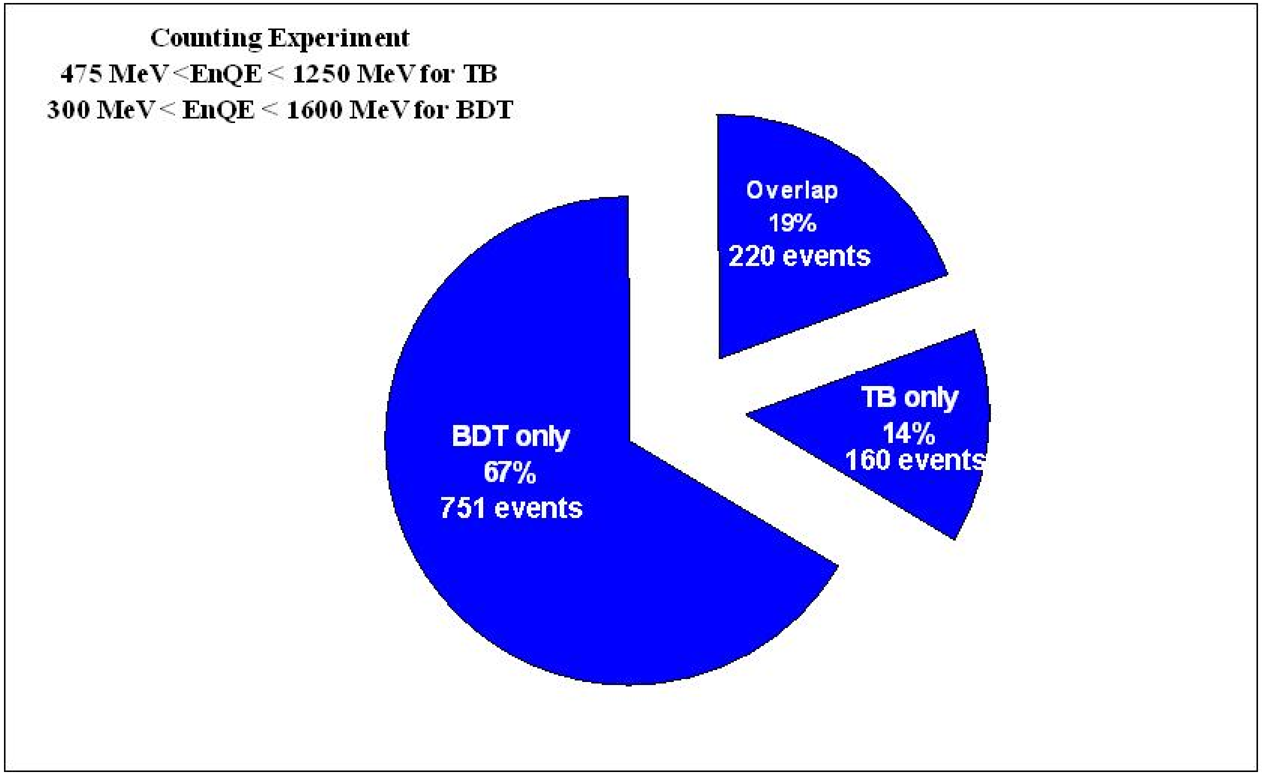
Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (1.0, 0.03\ eV^2)$
χ^2 Probability: 18%



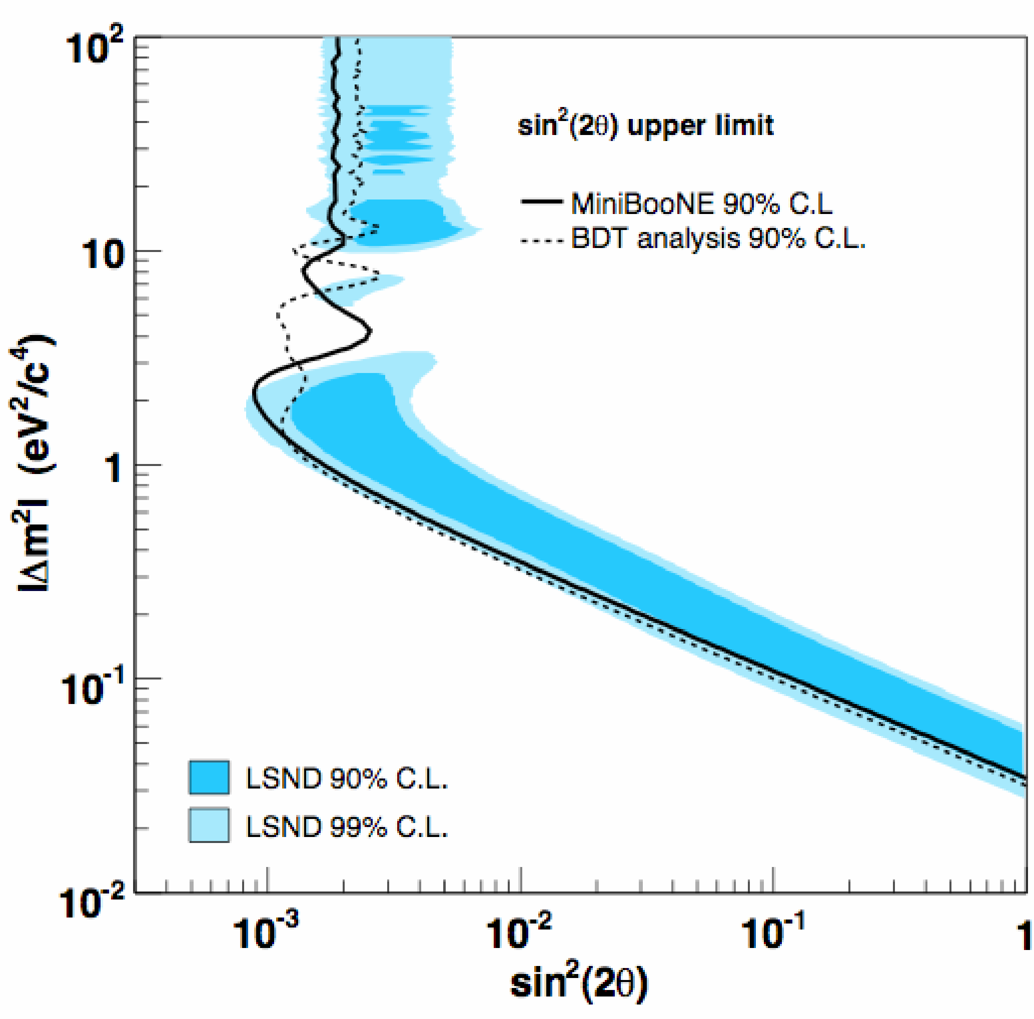
} Examples in LSND allowed range

Boosted Decision Tree Analysis

Counting Experiment: 300<E_ν^{QE}<1600 MeV
data: 971 events
expectation: 1070 ±33 (stat) ± 225 (sys) events
significance: –0.38 σ



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



Energy-fit analysis:
solid: TB
dashed: BDT

Independent analyses are in good agreement.

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

Future Plans:

Many more papers supporting this analysis will follow,
in the very near future:

ν_μ CCQE production (arXiv:0706.0926)
π^0 production
MiniBooNE-LSND-Karmen joint analysis

We are pursuing further analyses of the neutrino data, including...

an analysis which combines TB and BDT,
more exotic models for the LSND effect.

We are working hard to understand the low E excess.

MiniBooNE is presently taking data in antineutrino mode.

MiniBooNE First Results Announced at Fermilab on April 11, 2007 (1998-2007)

PRL 98, 231801 (2007) PHYSICAL REVIEW LETTERS week ending 8 JUNE 2007

Search for Electron Neutrino Appearance at the $\Delta m^2 \sim 1$ eV^2 Scale

A. A. Aguilar-Arevalo,[5] A. O. Bazarko,[12] S. J. Brice,[7] B. C. Brown,[7] L. Bugel,[5] J. Cao,[11] L. Coney,[5] J. M. Conrad,[5] D. C. Cox,[8] A. Curioni,[16] Z. Djurcic,[5] D. A. Finley,[7] B. T. Fleming,[16] R. Ford,[7] F. G. Garcia,[7] G. T. Garvey,[9] C. Green,[7,9] J. A. Green,[8,9] T. L. Hart,[4] E. Hawker,[15] R. Imlay,[10] R. A. Johnson,[3] P. Kasper,[7] T. Katori,[8] T. Kobilarcik,[7] I. Kourbanis,[7] S. Koutsoliotas,[2] E. M. Laird,[12] J. M. Link,[14] Y. Liu,[11] Y. Liu,[1] W. C. Louis,[9] K. B. M. Mahn,[5] W. Marsh,[7] P. S. Martin,[7] G. McGregor,[9] W. Metcalf,[10] P. D. Meyers,[12] F. Mills,[7] G. B. Mills,[9] J. Monroe,[5] C. D. Moore,[7] R. H. Nelson,[4] P. Nienaber,[13] S. Ouedraogo,[10] R. B. Patterson,[12] D. Perevalov,[1] C. C. Polly,[8] E. Prebys,[7] J. L. Raaf,[3] H. Ray,[9] B. P. Roe,[11] A. D. Russell,[7] V. Sandberg,[9] R. Schirato,[9] D. Schmitz,[5] M. H. Shaevitz,[5] F. C. Shoemaker,[12] D. Smith,[6] M. Sorel,[5] P. Spentzouris,[7] I. Stancu,[1] R. J. Stefanski,[7] M. Sung,[10] H. A. Tanaka,[12] R. Tayloe,[8] M. Tzanov,[4] R. Van de Water,[9] M. O. Wascko,[10] D. H. White,[9] M. J. Wilking,[4] H. J. Yang,[11] G. P. Zeller,[5] and E. D. Zimmerman[4]

(MiniBooNE Collaboration)

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(Received 20 April 2007; published 8 June 2007)

The MiniBooNE Collaboration reports first results of a search for ν_e appearance in a ν_μ beam. With two largely independent analyses, we observe no significant excess of events above the background for reconstructed neutrino energies above 475 MeV. The data are consistent with no oscillations within a two-neutrino appearance-only oscillation model.

DOI: 10.1103/PhysRevLett.98.231801 PACS numbers: 14.60.St, 14.60.Lm, 14.60.Pq

This Letter reports the initial results from a search for $\nu_\mu \to \nu_e$ oscillations by the MiniBooNE Collaboration. MiniBooNE was motivated by the result from the liquid scintillator neutrino detector (LSND) experiment [1], which has presented evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations at the $\Delta m^2 \sim 1$ eV^2 scale. Although the Karlsruhe Rutherford medium energy neutrino (KARMEN) experiment observed no evidence for neutrino oscillations [2], a joint analysis [3] showed compatibility at 64% C.L. Evidence for neutrino oscillations also comes from solar-neutrino [4–8] and reactor-antineutrino experiments [9], which have observed ν_e disappearance at $\Delta m^2 \sim 8 \times 10^{-5}$ eV^2, and atmospheric-neutrino [10–13] and long-baseline accelerator-neutrino experiments [14,15], which have observed ν_μ disappearance at $\Delta m^2 \sim 3 \times 10^{-3}$ eV^2.

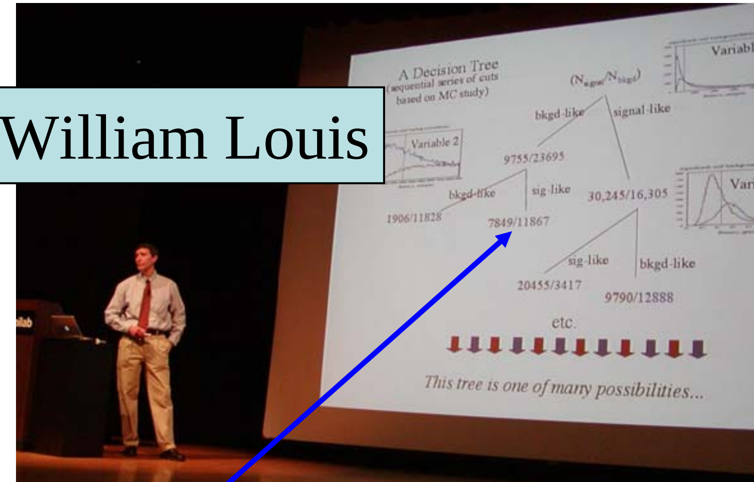
If all three phenomena are caused by neutrino oscillations, these three Δm^2 scales cannot be accommodated in an extension of the standard model that allows only three neutrino mass eigenstates. An explanation of all three mass scales with neutrino oscillations requires the addition of one or more sterile neutrinos [16] or further extensions of the standard model (e.g., [17]).

The analysis of the MiniBooNE neutrino data presented here is performed within a two-neutrino appearance-only $\nu_\mu \to \nu_e$ oscillation model which uses ν_μ events to constrain the predicted ν_e rate. Other than oscillations between these two species, we assume no effects beyond the standard model.

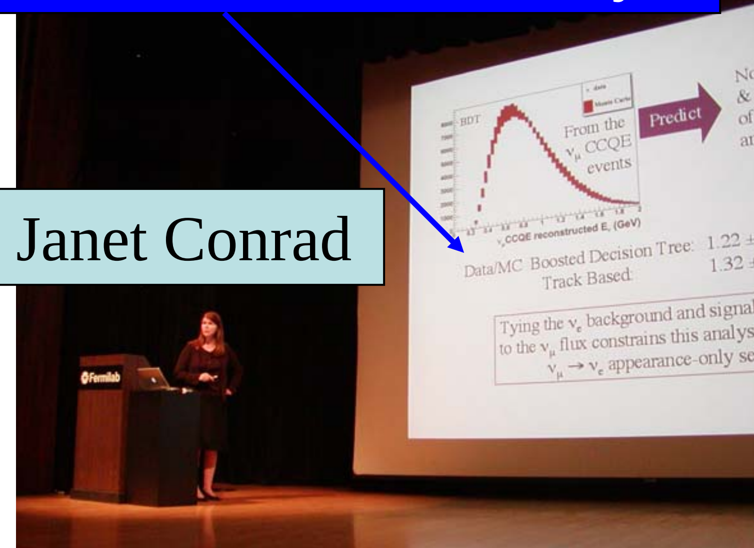
The experiment uses the Fermilab Booster neutrino beam, which is produced from 8 GeV protons incident on a 71-cm-long by 1-cm-diameter beryllium target. The proton beam typically has 4×10^{12} protons per $\sim$1.6 μs beam spill at a rate of 4 Hz. The number of protons on target per spill is measured by two toroids in the beam line.

0031-9007/07/98(23)/231801(7) 231801-1 © 2007 The American Physical Society

William Louis



Boosted Decision Trees Analysis



Janet Conrad

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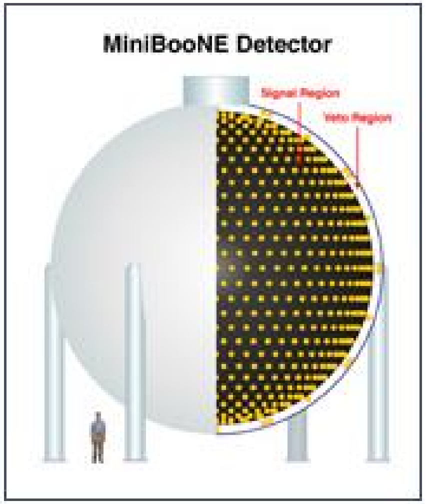
Apr. 12, 2007

MiniBooNE opens the box with U-M physicists help

Results from Fermilab experiment resolve long-standing neutrino question



MiniBooNE tank

ANN ARBOR, Mich.—Scientists of the MiniBooNE experiment at the Department of Energy's Fermilab in Batavia, Ill., announced their first findings.

A spokesman for MiniBooNE, William Louis, obtained his doctorate at the University of Michigan in 1978. His former thesis adviser, physics professor Byron Roe, is also a member of the collaboration as is assistant research scientist Hai-jun Yang. The Michigan group has made a major contribution to this experiment.

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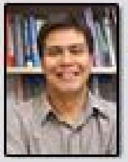

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News in Science Magazine

we would leave other people to worry about it."

Everitt and other scientists on the Gravity Probe B team point out that the experiment has value beyond just measuring relativistic effects. It has produced technical advances already used on other space missions and has provided helpful lessons for planning future precision space probes, such as the proposed LISA mission to measure gravitational radiation from space.

And Will said that the very fact that the mission flew, and worked as well as it did after decades of waiting, should be considered a triumph.

"Everything worked almost perfectly," he said. "A few things didn't work as well. And there are these strange effects that nobody could have imagined beforehand. But that's physics."

Neutrino Study Finds Four's a Crowd

The family of self-effacing subatomic particles known as neutrinos should give up hope for the existence of an eccentric cousin, new results from the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, suggest.

Physicists know of three types, or "flavors," of neutrino, designated electron, muon, and tau for their associations with other particles with those names. Neutrinos are notoriously difficult to detect and are very nearly massless. They must, however, possess at least a small mass, as they have shown the ability to switch identity in flight, a trick impossible for massless particles.

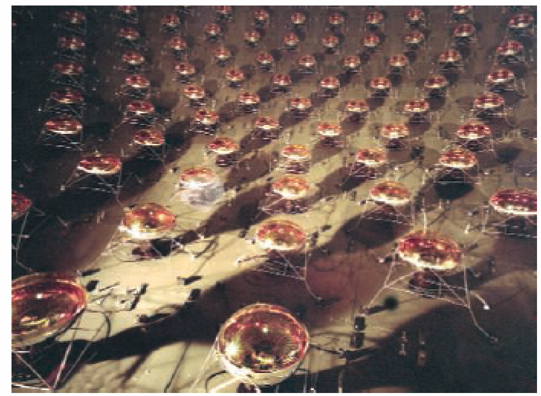
These identify shifts, or "flavor oscillations," have been well-established for years. Measurements of the oscillation rate provide clues to the differences in mass among the three known flavors. Such experiments at New Mexico's Los Alamos National Laboratory in the 1990s implied an unusually large mass difference, hinting that a fourth neutrino flavor ought to exist, in a "sterile" form that does not interact with other particles as ordinary neutrinos do.

Over the past decade, an international team of researchers using a neutrino beam at a Fermilab particle accelerator has sought evidence to confirm or refute the Los Alamos results. If correct, the Los Alamos findings imply that many of the muon neutrinos in the Fermilab beam should oscillate into electron neutrinos before reaching a detector 500 meters away. But the Fermilab experiment, known as MiniBooNE (for "Mini Booster Neutrino Experiment"), found no evidence for the brand of flavor shifting reported at Los Alamos.

"We do not see any evidence for muon neutrinos oscillating into electron neutrinos," Los Alamos physicist Heather Ray, a member of the MiniBooNE team, said at the meeting.

Although apparently ruling out the Los Alamos evidence for a sterile neutrino, the MiniBooNE experiment turned up a possible new mystery: a higher number of low-energy electron neutrinos than expected from "background" sources.

"They may be a misestimation of the background, but they may be interesting," said team member Eric Zimmerman of the University of Colorado, Boulder.



No trace. MiniBooNE's sensor array failed to confirm earlier hints of noninteracting "sterile" neutrinos.

Further analysis of the data and tests of new data now being gathered will be needed to clarify the reason for the low-energy anomalies, said Janet Conrad of Columbia University, one of the leaders of the MiniBooNE team. "There's still some possibility that there are some bizarre effects going on," she said.

–TOM SIEGFRIED

Tom Siegfried is a writer in Los Angeles, California.

CREDITS (TOP TO BOTTOM): THE COBE PROJECT, DIRBE, NASA; FERMILAB

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PARTICLE PHYSICS

Wobbly oscillations

David Wark

Neutrinos seem to oscillate: they change back and forth between one type and another and, by extension, have a tiny mass. But one experiment that predicted a particularly large mass looks to have been mistaken.

When is a discovery not a discovery? When it can't be reproduced, of course. That scientific ground-rule has plagued the members of the LSND (Liquid Scintillator Neutrino Detector) collaboration since they first saw evidence[1] for so-called neutrino oscillations. Had the LSND results been confirmed, they would have rewritten much of what we think we know about the ever-elusive neutrinos (Box 1, overleaf). But results just announced[2] from the MiniBooNE detector at Fermilab, near Chicago, could prove those earlier results' nemesis.

The story begins in 1996, with observations made by LSND of the decay products of a pion particle beam at the Los Alamos Meson Physics Facility (LAMPF) accelerator in New Mexico. The neutrinos came mainly from the decay of positively charged pions into positive muons and muon neutrinos, and the subsequent decay of these positive muons to positrons (positively charged electrons), muon antineutrinos and electron neutrinos (Fig. 1a, overleaf). What

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Box 1 | Neutrinos and their oscillations: a short history

Neutrinos belong to the class of elementary particles known as leptons. The electron is the most familiar lepton, but is merely a member of the lightest of — according to the standard model of particle physics — three families. Equivalent to the electron in every way except its mass (which is more than 200 times greater than the electron's 0.511 megaelectronvolts) is the muon; nearly 3,500 times as massive is the monstrous tau. Each of these three has its antimatter equivalent, which has an opposite electric charge of +1. The six charged leptons each have an uncharged, almost massless counterpart — the three neutrinos, and three antineutrinos.

Whether neutrinos do have mass and, if so, how much of it, is of considerable interest both to particle physicists, for the development of 'grand unified theories', and to cosmologists. Neutrinos are one component of the invisible 'dark matter' that makes up roughly a third of the Universe's mass, and their mass has a significant effect on how the matter in the Universe is distributed.

If neutrinos do have mass, then it is possible that neutrino states will oscillate. An electron neutrino, for instance, might spontaneously change into a muon neutrino, and back again, in a regular rhythm. The larger the difference in neutrino masses, the shorter the distance over which this will happen. The idea was originally invented to explain why, in pioneering measurements made by Ray Davis in the 1960s, far fewer neutrinos were seen coming from the Sun than models of the nuclear-fusion processes taking place there demanded.

In 1998, results from the Super Kamiokande detector in Japan[4] showed that the flux of neutrinos resulting from collisions of cosmic rays with Earth's atmosphere varies with direction. This convinced most physicists that neutrino oscillations had clearly been seen. In 2001, the Sudbury Neutrino Observatory in Ontario, Canada, showed[5] that the Sun emits neutrinos other than electron neutrinos, which is very difficult to explain except through oscillations.

These results were further strengthened by the KamLAND experiment, which observed[6] the apparent disappearance of electron antineutrinos from power reactors in Japan as they oscillated into muon and tau antineutrinos, which the detector could not see. The K2K (ref. 7) and MINOS (ref. 8) experiments saw a similar apparent disappearance of muon neutrinos from beams that had propagated for hundreds of kilometres through the ground. Collectively, these experiments have built a case for the oscillation of atmospheric and solar neutrinos that looks almost bullet-proof. These oscillations determine the two independent mass differences that exist between the three neutrino types; both are found to be much less than 1 electronvolt.

The results from five years of data-taking at the LSND experiment[1] were distinguished by finding a much larger mass difference of around 1 electronvolt. If confirmed, this would wreck the simple explanation of the other experiments in terms of neutrino oscillations, and require much more complicated physics. But is it right? The MiniBooNE experiment aimed to find out. **D.W.**

the LSND collaboration found on examining the reaction products was an excess of electron antineutrinos[1] — which are produced nowhere in the positive-pion decay chain. The conclusion was that muon antineutrinos were changing into electron antineutrinos while propagating. This is the process known as neutrino oscillation, and is itself by now relatively uncontroversial[3]. But the oscillations that LSND saw seemed to indicate much larger neutrino mass differences than other experiments had predicted. That was indeed controversial.

Perhaps the LSND results pointed to some new physics even more surprising than neutrino oscillations. Many possibilities have been suggested, including the existence of other, 'sterile' neutrino families beyond the three that participate in the interactions of particle physics' standard model. But the first attempt to test the results — KARMEN, a comparable, but slightly less sensitive experiment at the Rutherford Appleton Laboratory in Didcot, England — failed to see any signal, although it could not rule out the LSND claim. A new experiment with much higher rates, and therefore higher sensitivity, was needed to test the LSND claim conclusively.

Thus was born Fermilab's MiniBooNE, so called because it was a scaled-down version of the proposed Booster Neutrino Experiment. In MiniBooNE, a beam of either positive or negative pions decays to form beams of positive or negative muons, and muon neutrinos or antineutrinos, whose oscillations are looked for (Fig. 1b). But the muons also decay, producing, among other things, electron neutrinos and antineutrinos — a potential source of confusion for the oscillation measurement. This is minimized at MiniBooNE by stopping the muons before significant numbers of them decay, and also — unlike the LSND and KARMEN experiments — using a higher-energy pion beam, which produces a clean differentiation in energy between the different sources of neutrinos.

The muon neutrino beam propagates for around 500 metres before hitting a detector consisting of 1,520 light-sensitive photomultiplier tubes embedded in a 12-m-diameter tank of mineral oil. The charged particles resulting from neutrino interactions travel faster than the speed of light in the oil, resulting in the emission of a characteristic cone of 'Čerenkov' light, rather like the sonic boom produced by a jet breaking the sound barrier. The detection of this light allows the particle's energy and position to be measured, and one type of neutrino to be distinguished from another through its characteristic interactions (Fig. 2).

The analysis of the data[2] is complicated, partly owing to physics and partly to psychology. The physics complication lies in the number of background signals that mimic the real one. Added together, these outnumber the postulated 'real' events by two to one. To add to the fun, neutrino cross-sections — the probability that a neutrino will interact in a particular way — are poorly known in the MiniBooNE energy range.

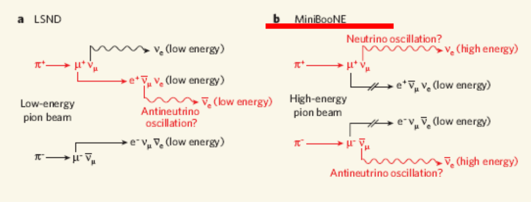

Figure 1 | Cleaning up the oscillation signal. **a**, The controversial LSND evidence for antineutrino oscillation used a low-energy beam of mainly positively charged pions (π^+). These decay into positive muons (μ^+) and muon neutrinos (ν_μ); the positive muons decay further into positrons (e^+), muon antineutrinos ($\bar{\nu}_\mu$) and electron neutrinos (ν_e). The presence of these last electron neutrinos made it difficult to obtain a clean measurement of the oscillation of ν_μ directly produced in the initial pion decay; instead, the oscillation of $\bar{\nu}_\mu$ from the secondary decay into electron antineutrinos ($\bar{\nu}_e$) was investigated. A further potential source of confusion is the presence of a small negative-pion (π^-) component in the initial pion beam. These pions decay just as do positive pions, but conjugately — positive particles are swapped for negative, and antineutrinos for neutrinos, and so on — thus also producing a small number of $\bar{\nu}_e$. **b**, The MiniBooNE experiment uses a high-energy pion beam, and the muons produced in the pion decays are mostly stopped before they can decay further. Oscillation of neutrinos directly produced in the π^+ decay can thus be measured cleanly, as these neutrinos are distinguished by their higher energy. Equally, oscillations of antineutrinos from π^- decay can be seen, albeit at a slower rate — this decay channel remains to be investigated.

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News

MiniBooNE solves neutrino mystery

The MiniBooNE Collaboration at Fermilab has revealed its first findings. The results announced on 11 April resolve questions that were raised in the 1990s by observations of the LSND experiment at Los Alamos, which appeared to contradict findings of other neutrino experiments. MiniBooNE now shows conclusively that the LSND results could not be due to simple neutrino oscillation.

The observations made by LSND suggested the presence of neutrino oscillation, but in a region of neutrino mass vastly different from other experiments. Reconciling the LSND observations with the other oscillation results would have required the presence of a fourth, or "sterile" type of neutrino, with properties different from the three standard neutrinos. The existence of sterile neutrinos would indicate physics beyond the Standard Model, so it became crucial to have some independent verification of the LSND results.

The MiniBooNE experiment took data for this analysis from 2002 until the end of 2005 using muon neutrinos produced by the Booster accelerator at Fermilab. The detector consists of a 250,000 gallon tank filled with ultrapure mineral oil, located about 500 m from the point at which the muon neutrinos were produced (*CERN Courier* July/August 2002 p5). A layer of 1280 light-sensitive photomultiplier tubes, mounted

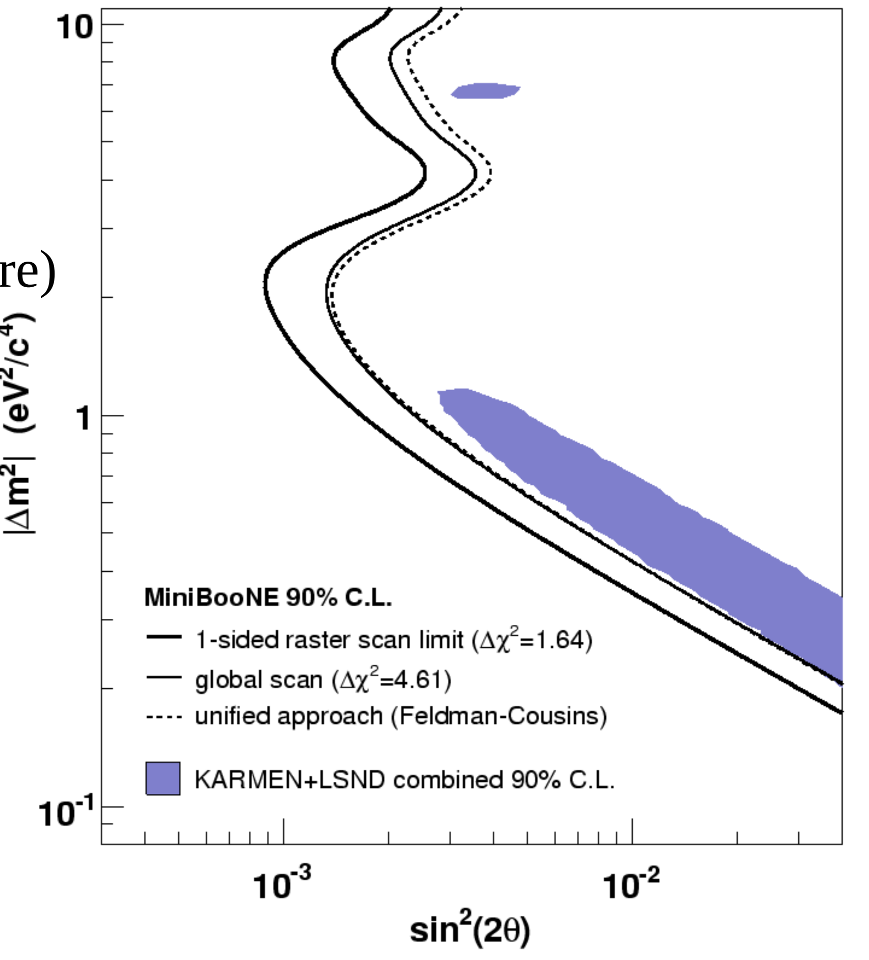
MiniBooNE

Backup Slides

Two points on interpreting our limit

1) There are various ways to present limits:

- Single sided raster scan (historically used, presented here)
- Global scan
- Unified approach (most recent method)



2) This result must be folded into an LSND-Karmen joint analysis.

Church, et al., PRD 66, 013001

We will present a full joint analysis soon.

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:

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

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

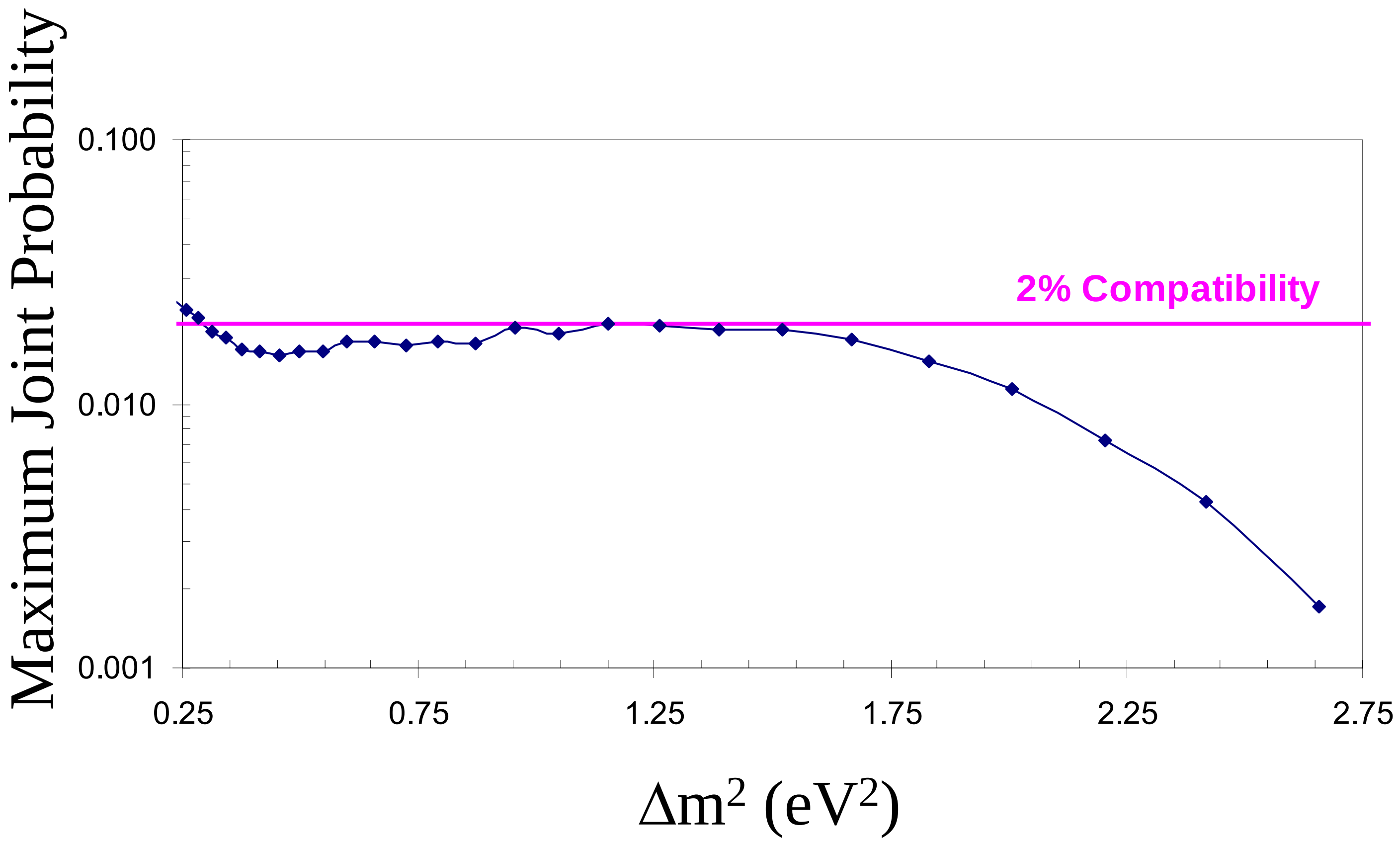
- For each Δm^2, form χ^2 between MB and LSND measurement

- Find z_0 that minimizes χ^2

  (weighted average of two measurements) and this gives χ^2_{min}

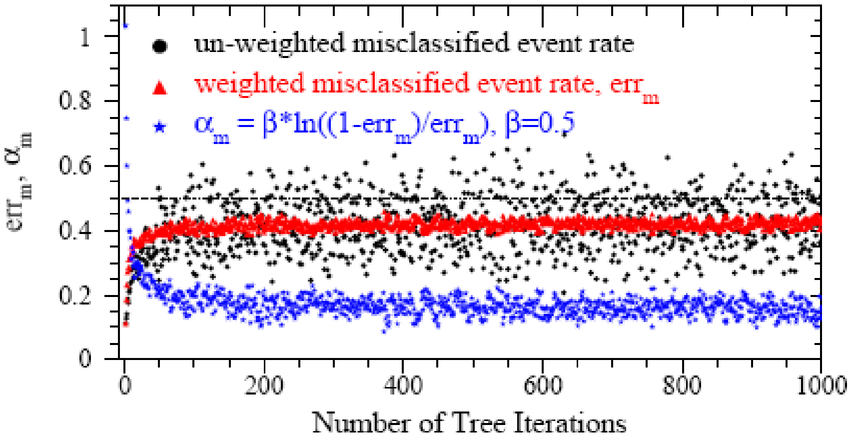
- Find probability of χ^2_{min} for 1 dof;

  this is the joint compatibility probability for this Δm^2



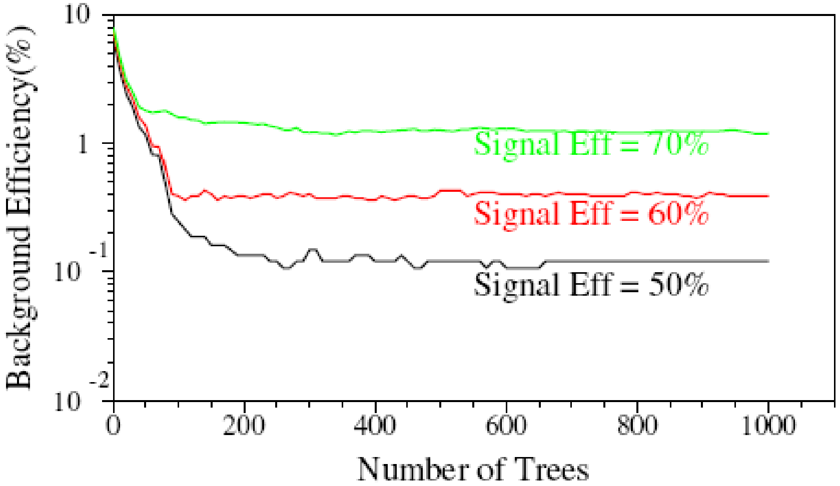
MiniBooNE is incompatible with a
$\nu_\mu \rightarrow \nu_e$ appearance only interpretation of LSND
at 98% CL

“Weak” → Powerful Classifier



→ Boosted decision trees focus on the misclassified events which usually have high weights after hundreds of tree iterations. An individual tree has a very weak discriminating power; the weighted misclassified event rate err_m is about 0.4-0.45.

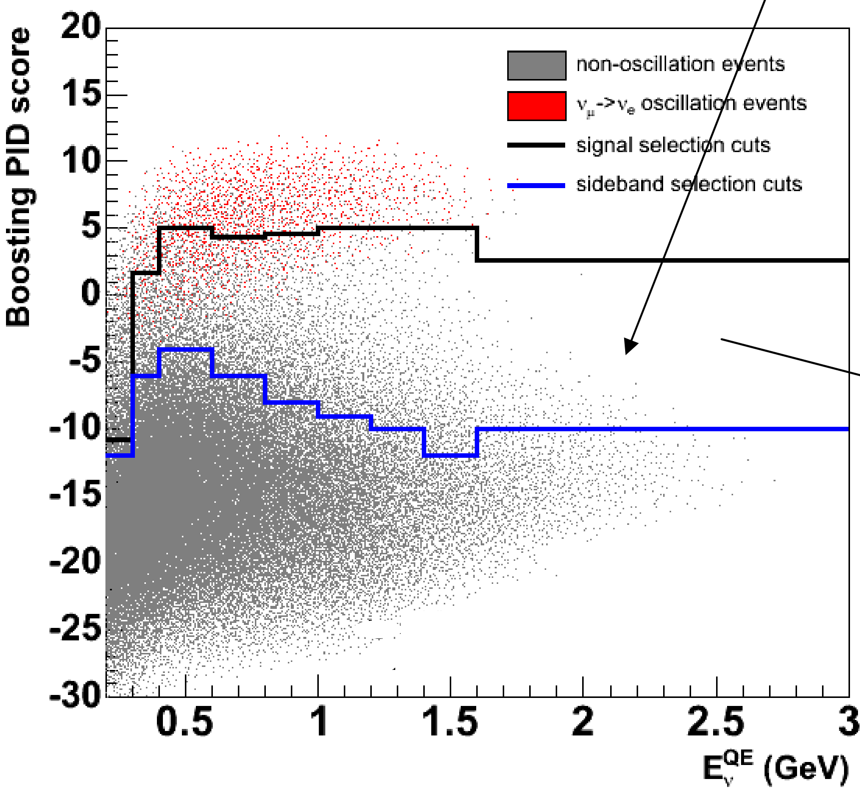
→The advantage of using boosted decision trees is that it combines many decision trees, “weak” classifiers, to make a powerful classifier. The performance of boosted decision trees is stable after a few hundred tree iterations.

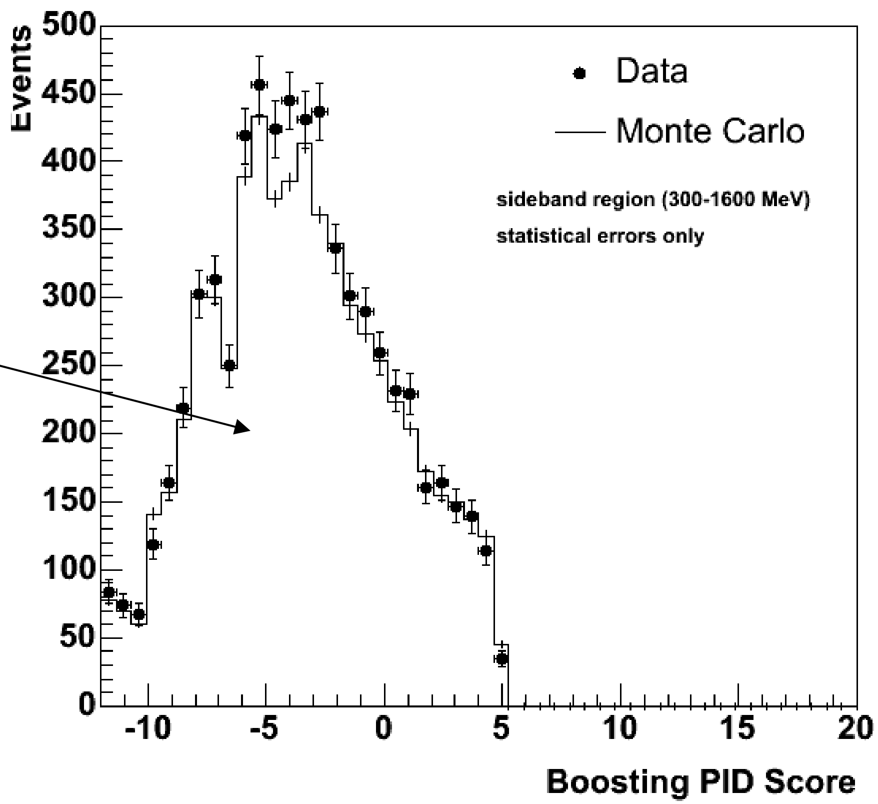


Ref1: H.J.Yang, B.P. Roe, J. Zhu, “*Studies of Boosted Decision Trees for MiniBooNE Particle Identification*”, physics/0508045, Nucl. Instum. & Meth. A 555(2005) 370-385.

Ref2: H.J. Yang, B. P. Roe, J. Zhu, "*Studies of Stability and Robustness for Artificial Neural Networks and Boosted Decision Trees* ", physics/0610276, Nucl. Instrum. & Meth. A574 (2007) 342-349.

BDT cuts on PID score as a function of energy.
We can define a “sideband” just outside of the signal region





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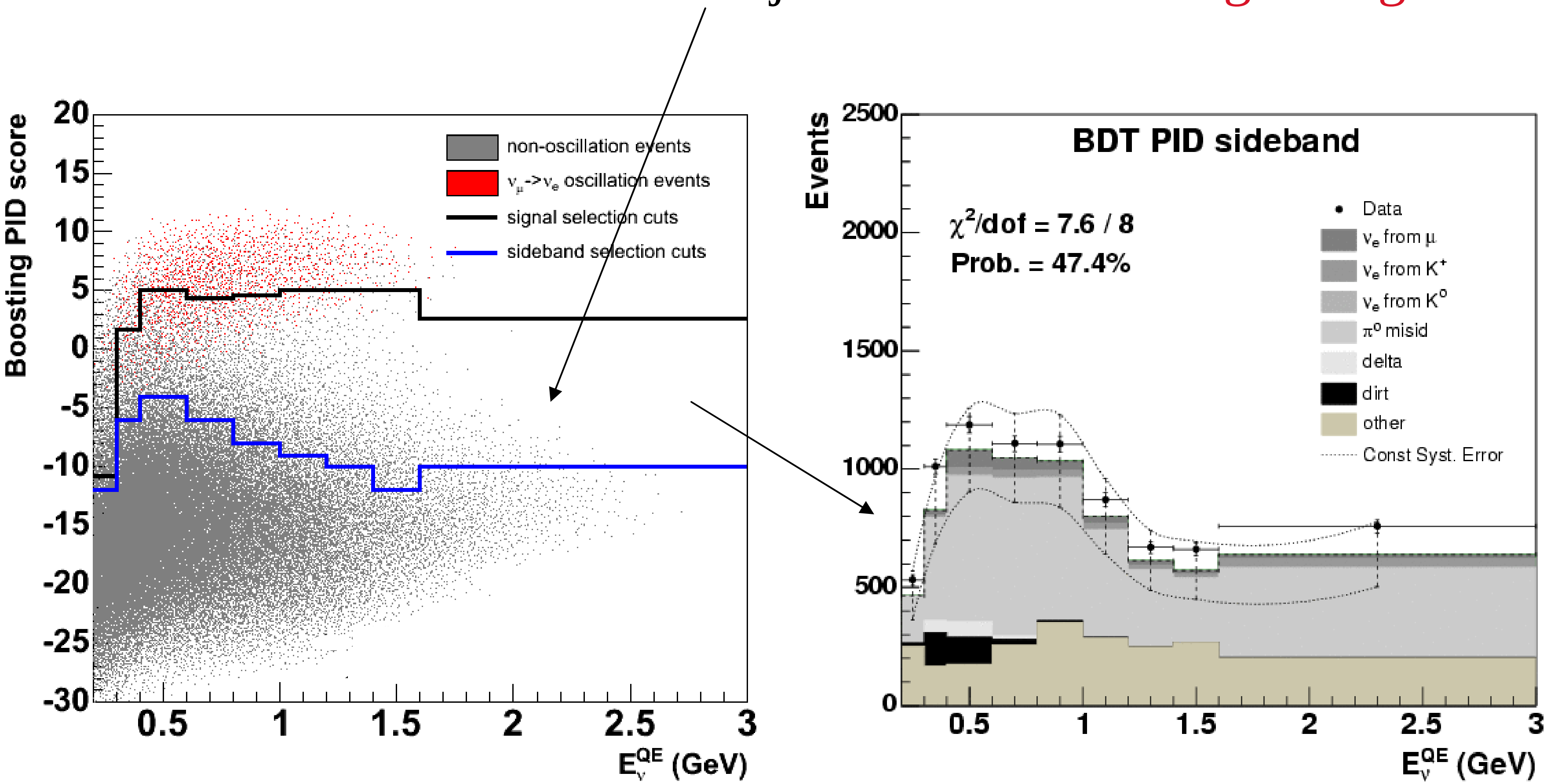
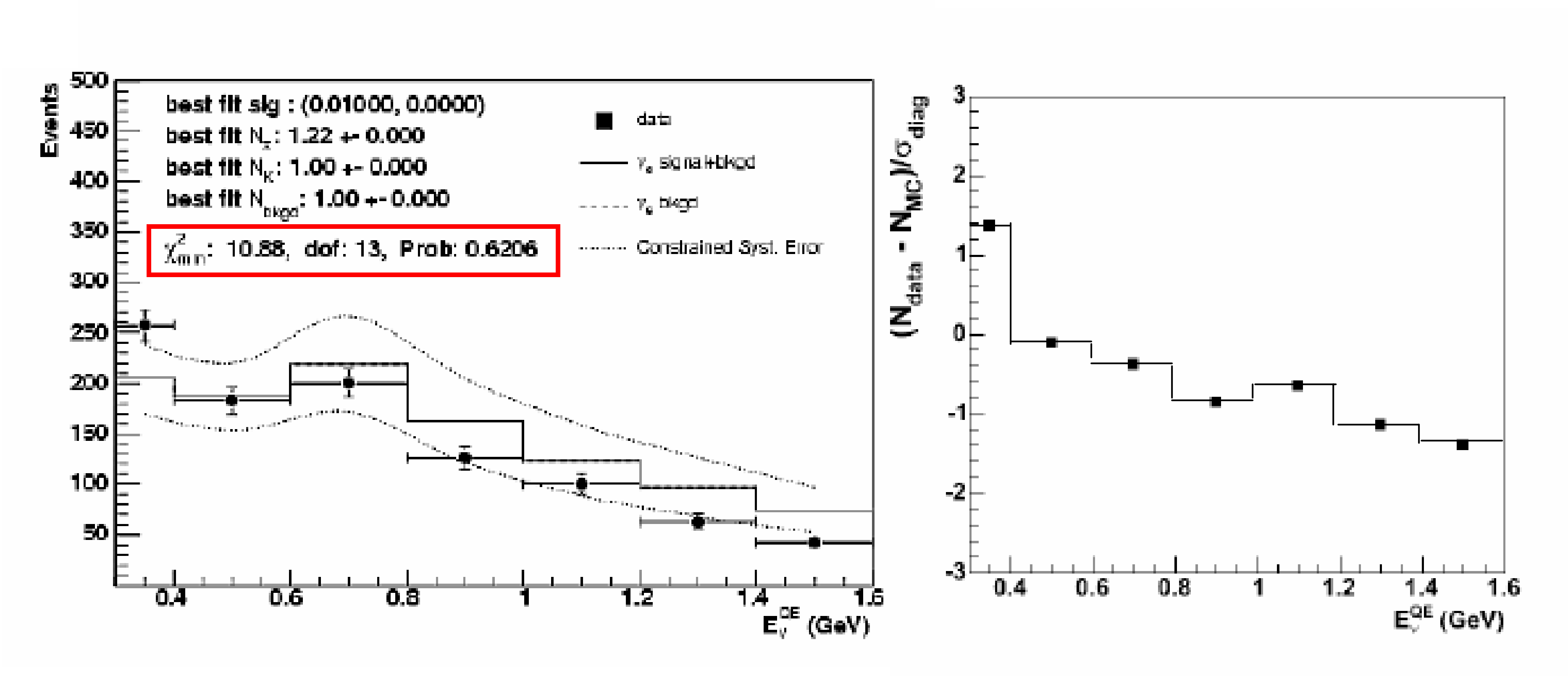


Boosted Decision Tree E_ν^{QE} data/MC comparison:



Step 1:
Convert the “Fundamental information” into “Analysis Variables”

Analysis variables \ *Fundamental information from PMTs*	Hit Position	Charge	Hit Timing
Energy	√	√	
Time sequence		√	√
Event shape	√	√	√
Physics	√	√	√

“Physics” = π^0 mass, E_ν^{QE}, etc.