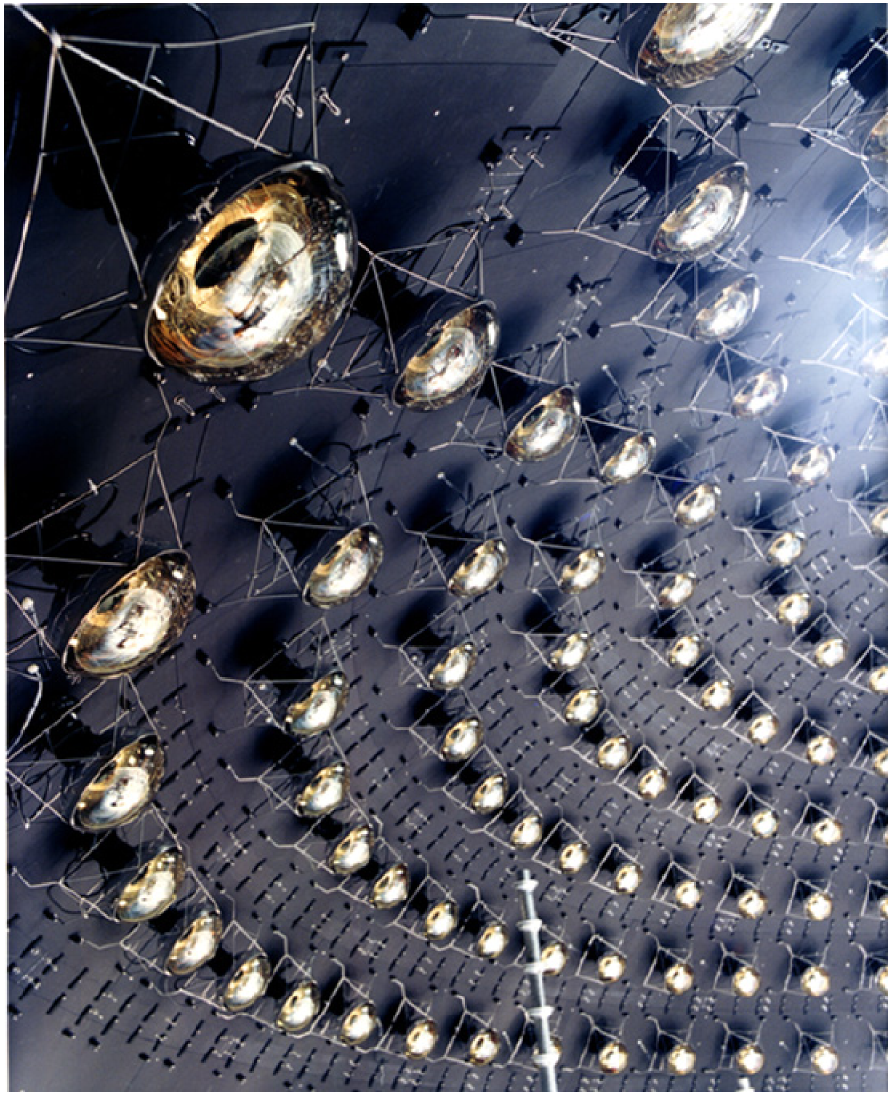


Search for Neutrino Oscillation with MiniBooNE Detector

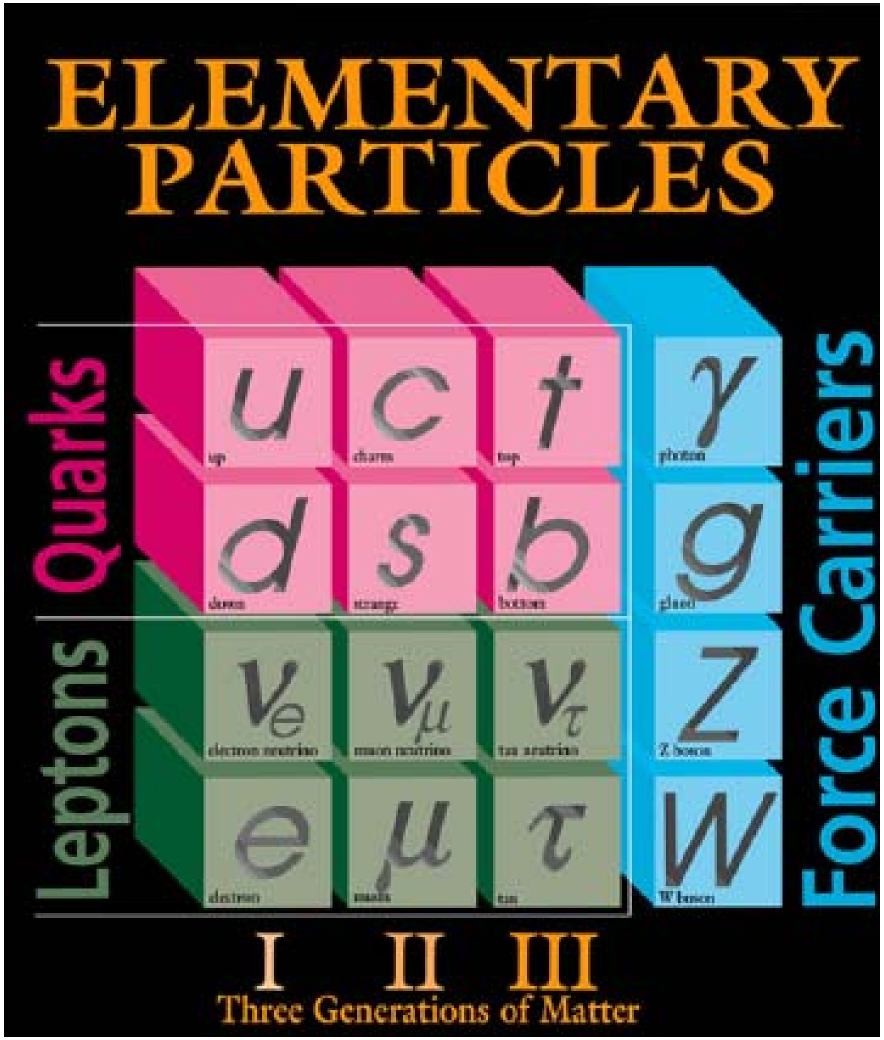
Hai-Jun Yang
University of Michigan

University of Nebraska
Lincoln, Nov. 29, 2007

Outline

- Brief introduction of neutrino
- Physics Motivation of MiniBooNE
- MiniBooNE Neutrino Beam
- Events in the Detector
- Two Independent Analyses
- MiniBooNE Results

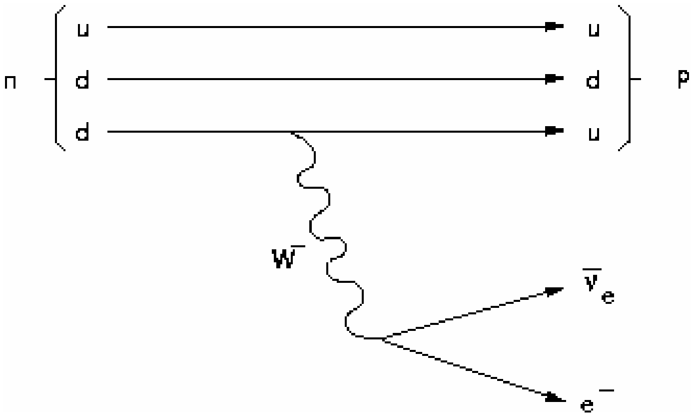
The Standard Model



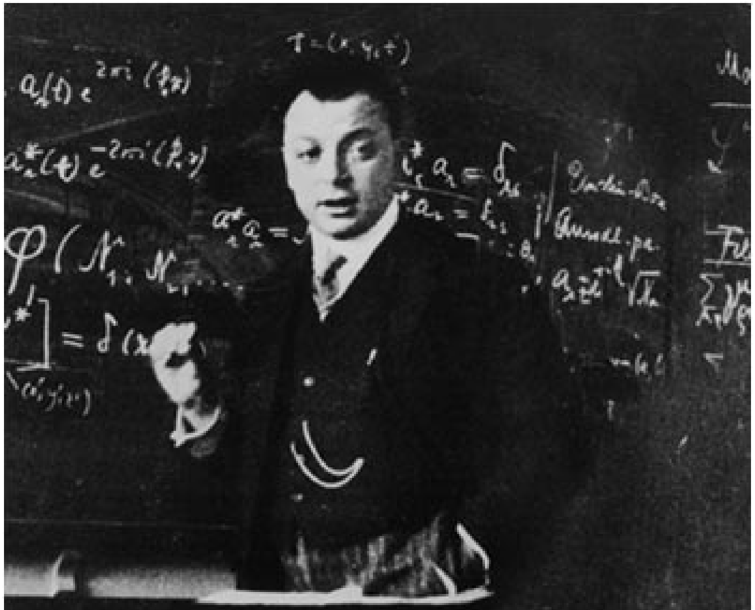
1900s:	e discovered (cathode ray tube)
	γ interpreted as a particle
1930s:	μ discovered (cosmic rays)
1950s:	ν_e observed (nuclear reactor)
	ν_μ discovered (BNL)
1960s:	1st evidence for quarks
	u and d observed (SLAC)
	s observed (BNL)
1970s:	***standard model is born***
	c discovered (SLAC, BNL)
	τ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

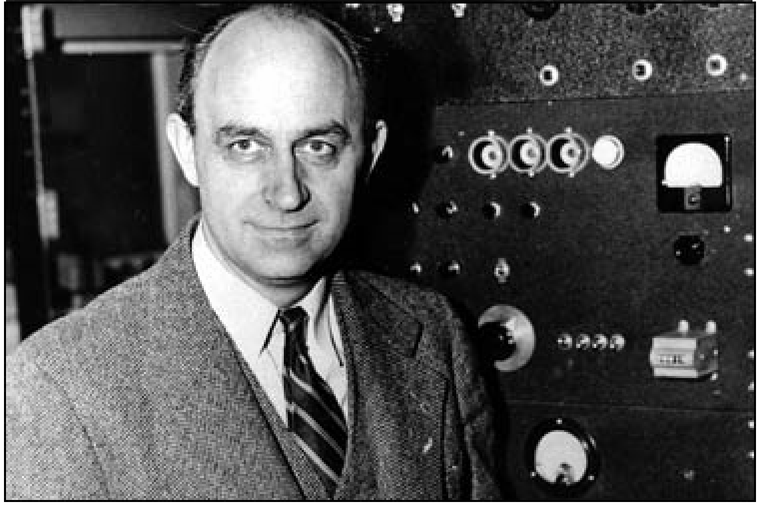
About Neutrino

- Wolfgang Pauli postulated existence of neutrino (“little neutral ones”) in order to explain the missing energy in nuclear β^- decay in 1930.
- Enrico Fermi presented theory of beta decay in 1934.

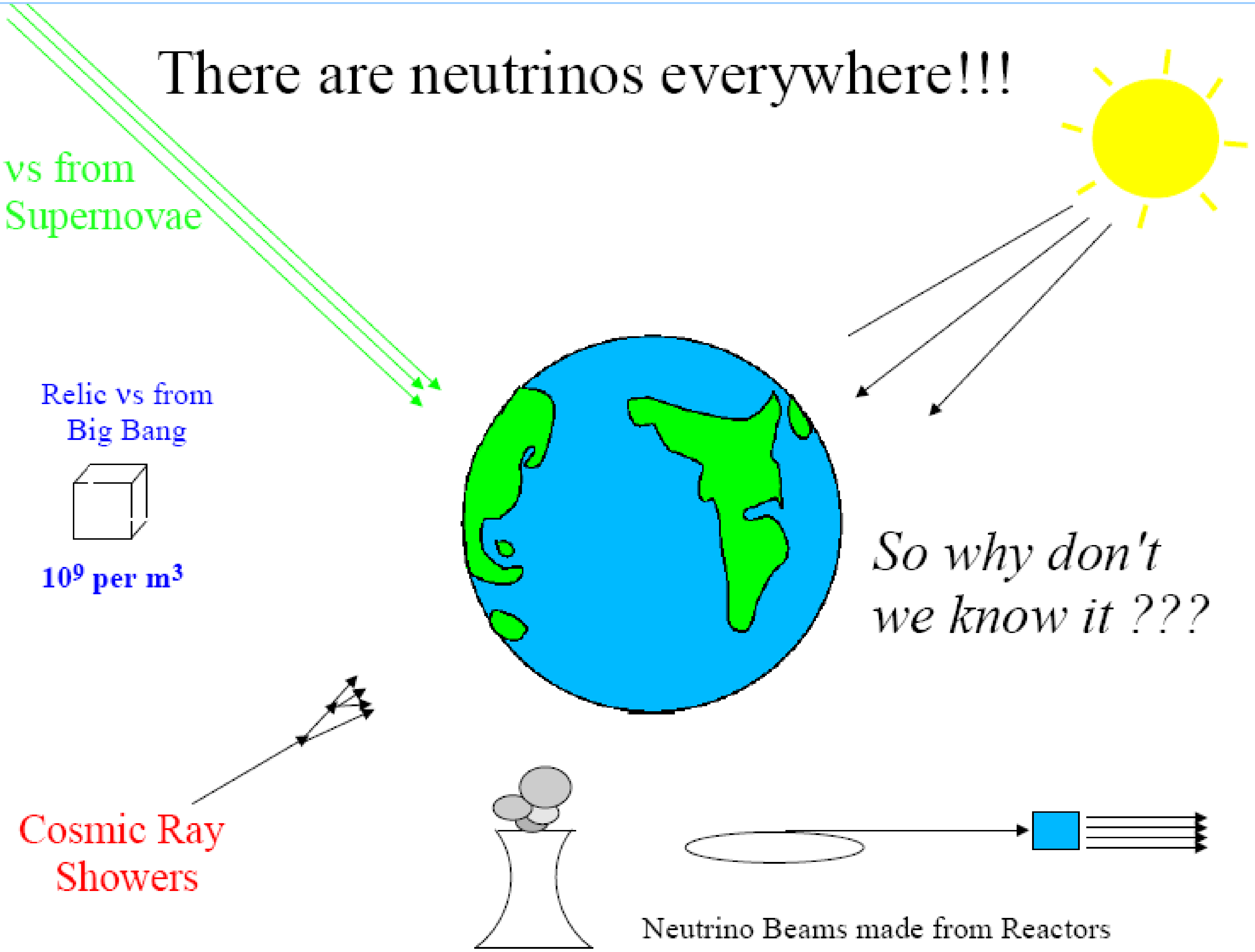


$$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$$





There are neutrinos everywhere!!!



νs from Supernovae

Relic νs from Big Bang

10^9 per m^3

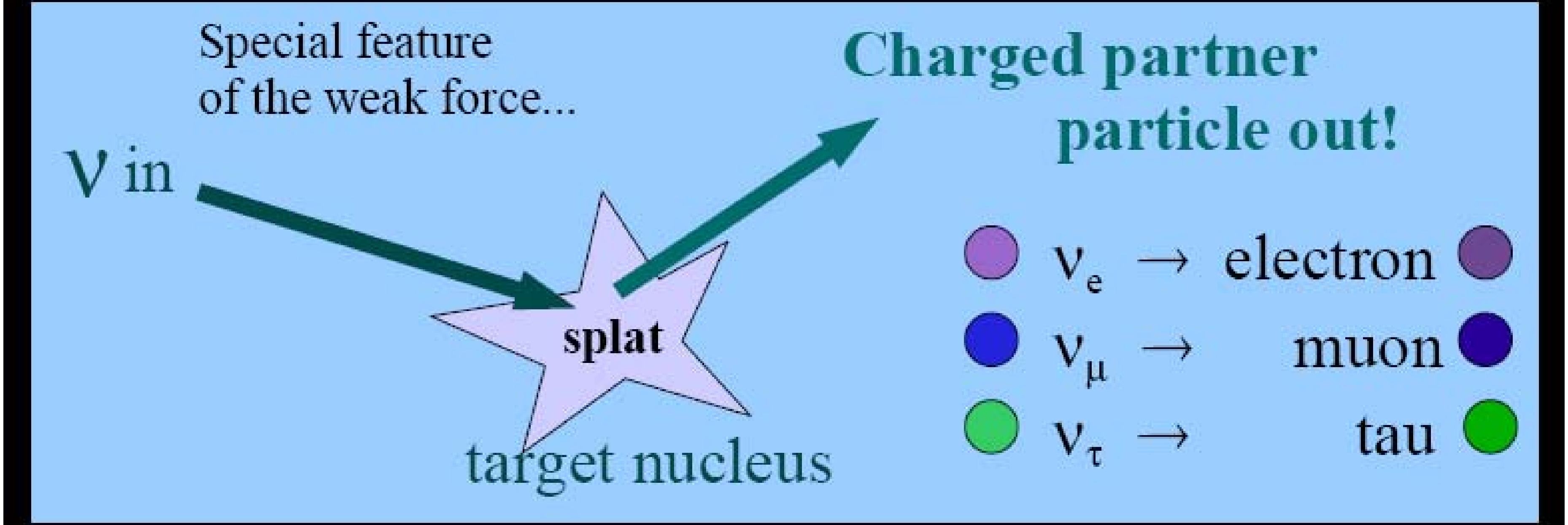
So why don't we know it ???

Cosmic Ray Showers

Neutrino Beams made from Reactors and Particle Accelerators

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



Special feature of the weak force...

ν in

splat

target nucleus

Charged partner particle out!

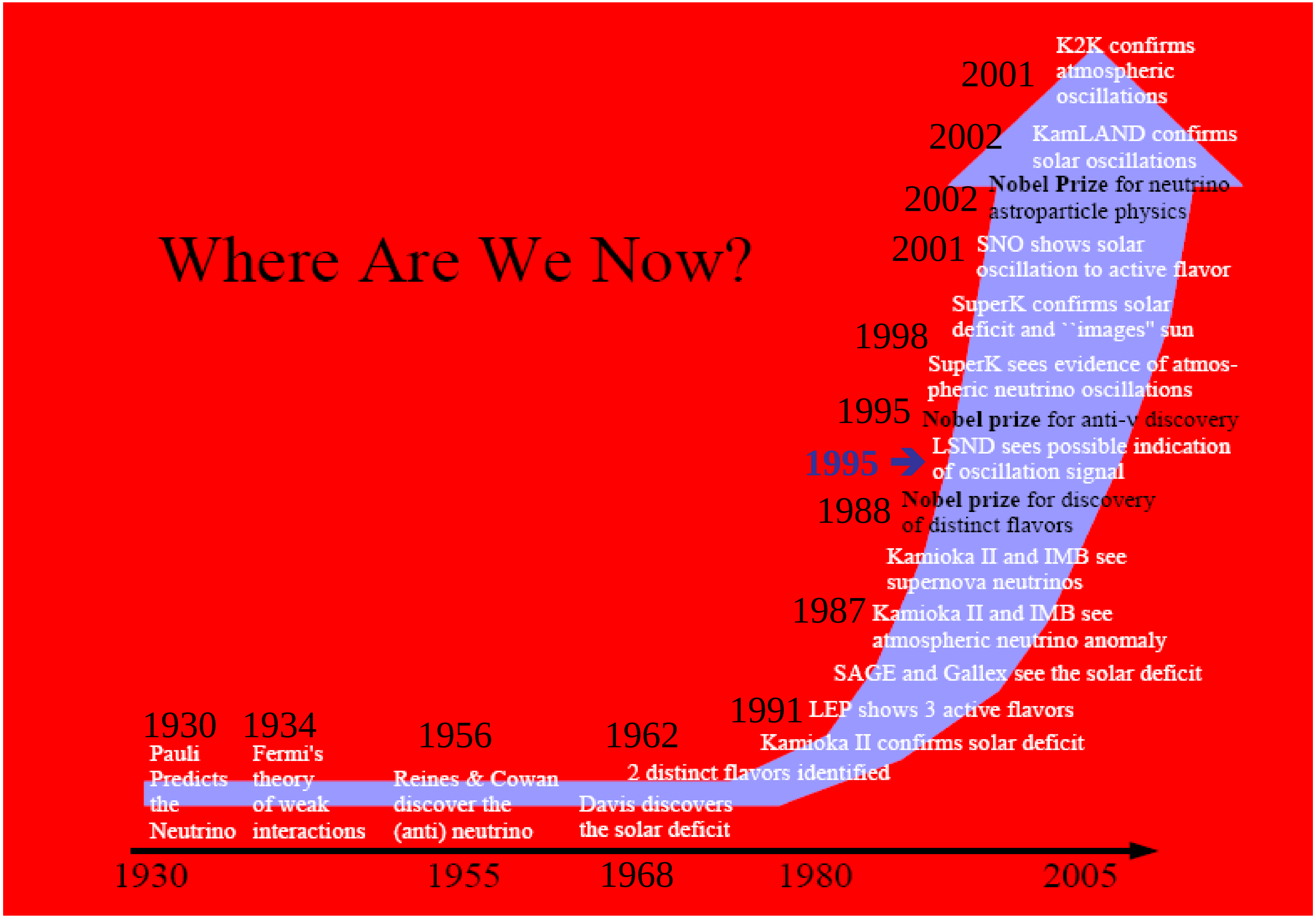
● $\nu_e \rightarrow$ electron ●

● $\nu_\mu \rightarrow$ muon ●

● $\nu_\tau \rightarrow$ tau ●

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

Brief History of Neutrino



Where Are We Now?

2001 K2K confirms atmospheric oscillations

2002 KamLAND confirms solar oscillations

2002 **Nobel Prize** for neutrino astroparticle physics

2001 SNO shows solar oscillation to active flavor

SuperK confirms solar deficit and ``images" sun

1998 SuperK sees evidence of atmospheric neutrino oscillations

1995 **Nobel prize** for anti-ν discovery

1995 → LSND sees possible indication of oscillation signal

1988 **Nobel prize** for discovery of distinct flavors

Kamioka II and IMB see supernova neutrinos

1987 Kamioka II and IMB see atmospheric neutrino anomaly

SAGE and Gallex see the solar deficit

1991 LEP shows 3 active flavors

Kamioka II confirms solar deficit

1930 Pauli Predicts the Neutrino

1934 Fermi's theory of weak interactions

1956 Reines & Cowan discover the (anti) neutrino

1962 2 distinct flavors identified

Davis discovers the solar deficit

Neutrino Oscillations (2 flavors)

(For 3 ν flavors mixing, it needs 3×3 unitary matrix with CP-violating phase.)

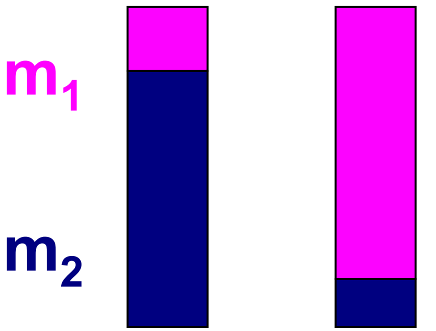
Flavor eigenstates **Mass eigenstates**

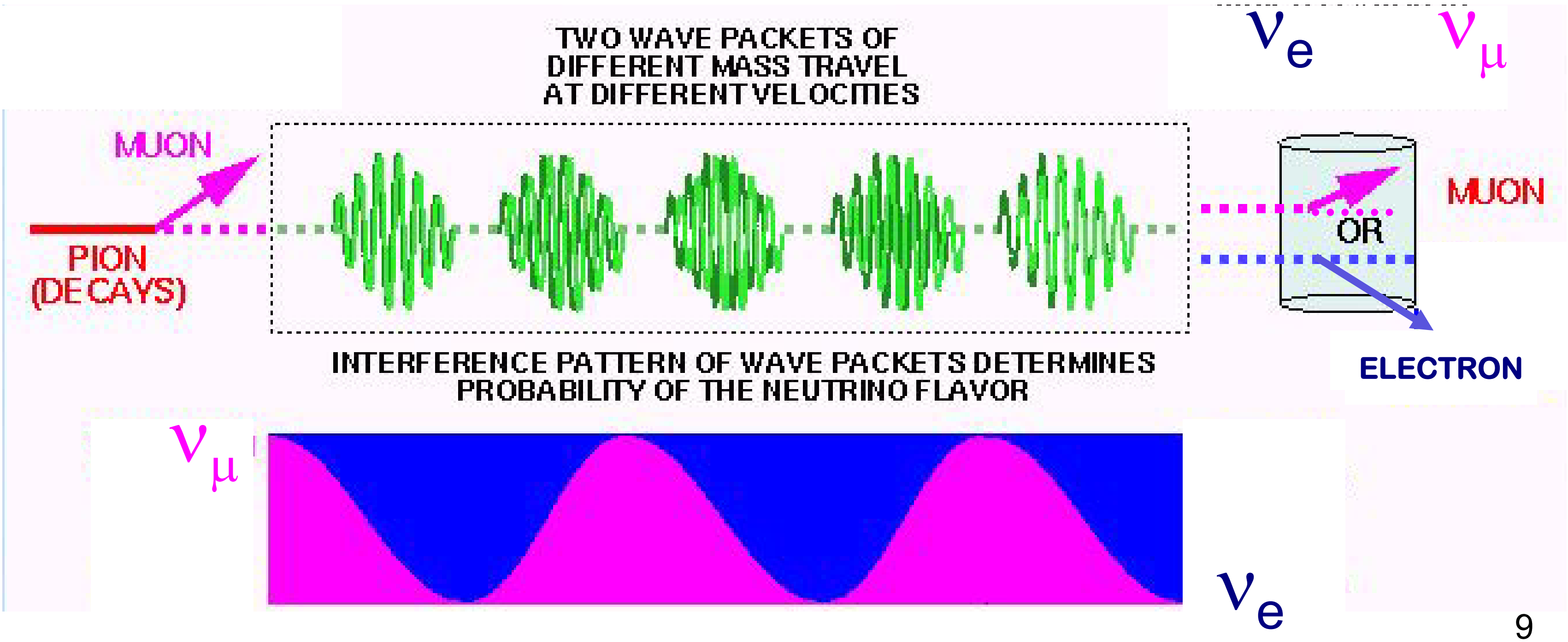
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_\mu(t)> = -\sin\theta\ |\underset{\substack{\uparrow \\ e^{-iE1t}}}{\nu_1}> + \cos\theta\ |\underset{\substack{\uparrow \\ e^{-iE2t}}}{\nu_2}>$$

Neutrino Oscillations (2 flavors)

Neutrino flavor states are comprised of mass states





Neutrino Oscillations (2 flavors)

Δm^2 is the difference of the squared masses of the two neutrino states (eV^2)

Distance from neutrino beam creation point to detection point (m)

$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\, \Delta m^2\, L}{E}\right)$$

θ is the mixing angle

E is the energy of the neutrino (MeV)

Neutrino Oscillation Parameters

➔Solar Neutrino Oscillation (Homestake, GALLEX, SAGE, Kamiokande-II, Super-K, SNO etc.), confirmed by KamLAND (reactor beam)

$$\Delta m^2_{21} = \Delta m^2_{\mathrm{sol}} = 8.0^{+0.6}_{-0.4} \cdot 10^{-5}\mathrm{eV}^2$$

$$\tan^2(\theta_{12}) = 0.45^{+0.09}_{-0.07} \qquad \theta_{12} = \theta_{\mathrm{sol}} = 33.9^\circ{}^{+2.4^\circ}_{-2.2^\circ}$$

➔Atmospheric Neutrino Oscillation (IMB,MARCO,Soudan, Kamiokande-II, Super-K etc.), confirmed by K2K, MINOS (accelerator beam)

$$\Delta m^2_{31} \approx \Delta m^2_{32} = \Delta m^2_{\mathrm{atm}} = 2.4^{+0.6}_{-0.5} \cdot 10^{-3}\mathrm{eV}^2$$

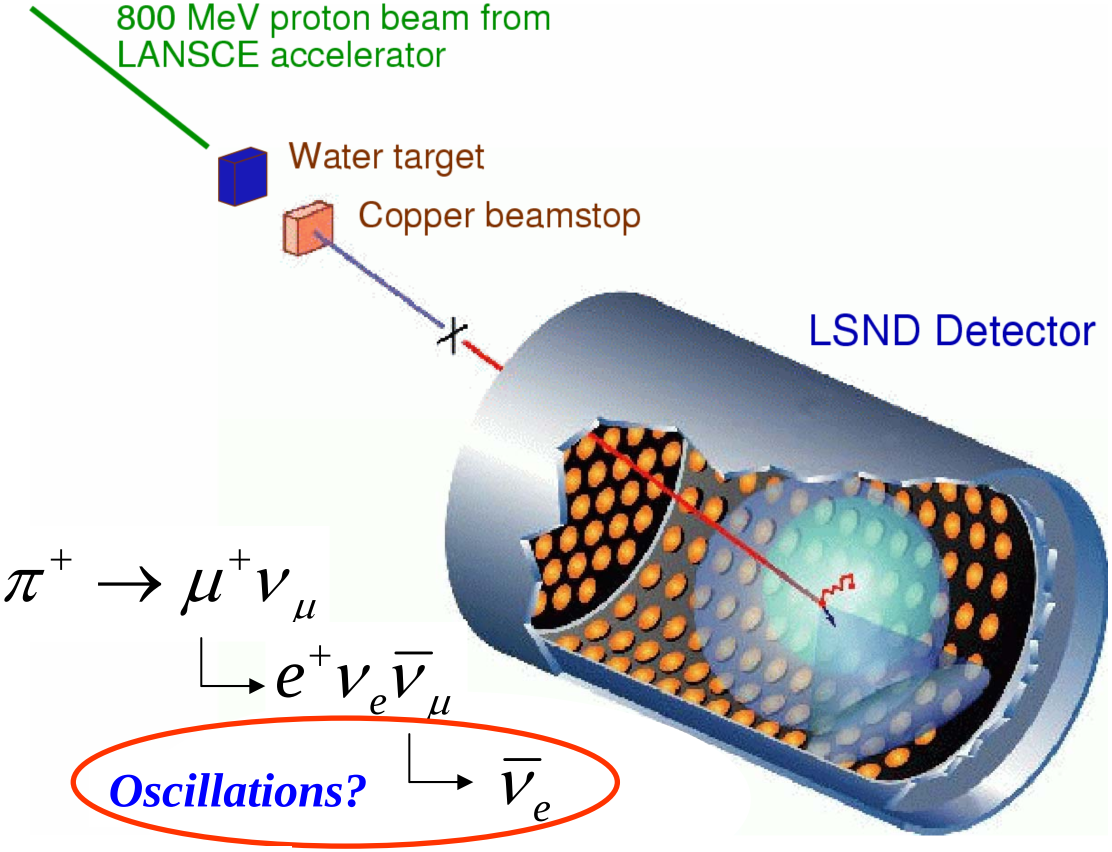
$$\sin^2(2\theta_{23}) = 1^{+0}_{-0.1} \qquad \theta_{23} = \theta_{\mathrm{atm}} = 45 \pm 7^\circ$$

➔Chooz (reactor beam)

future exp., Double Chooz, Daya Bay(reactor), NOvA, T2K(accelerator)

$\sin^2(2\theta_{13}) < 0.12$ (10°)

The LSND Experiment



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

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

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

Signal: $\bar{\nu}_e\, p \rightarrow e^+ n$

$n\, p \rightarrow d\, \gamma(2.2\text{MeV})$

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

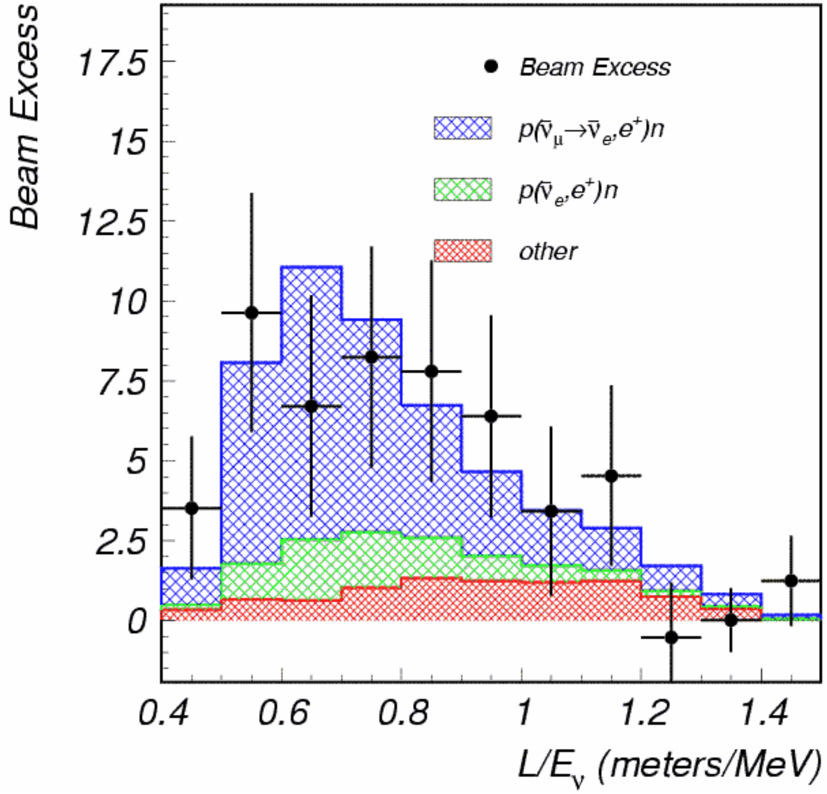
Observe an excess of $\bar{\nu}_e$:
- -- 87.9 ± 22.4 ± 6.0 events.

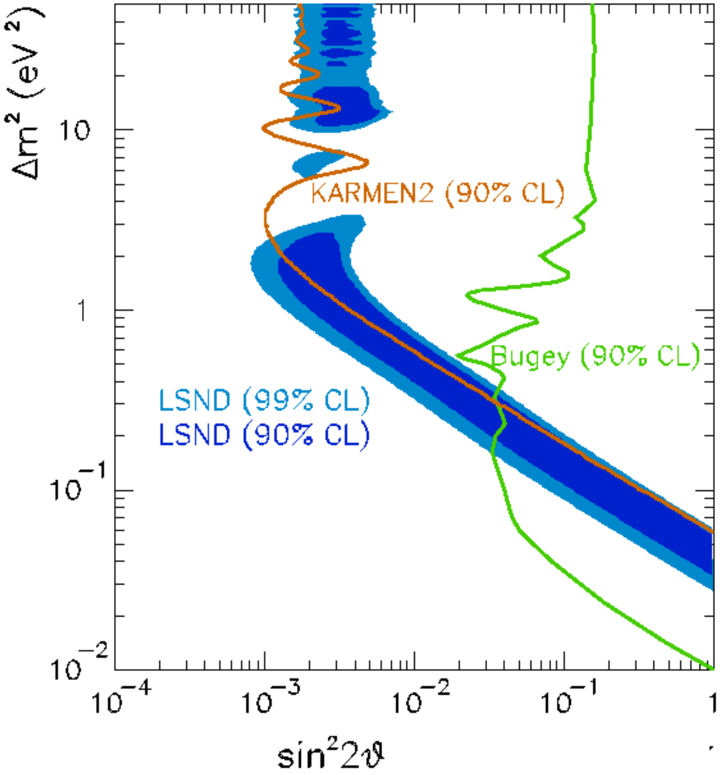
LSND Collab, PRD 64, 112007

The LSND Experiment

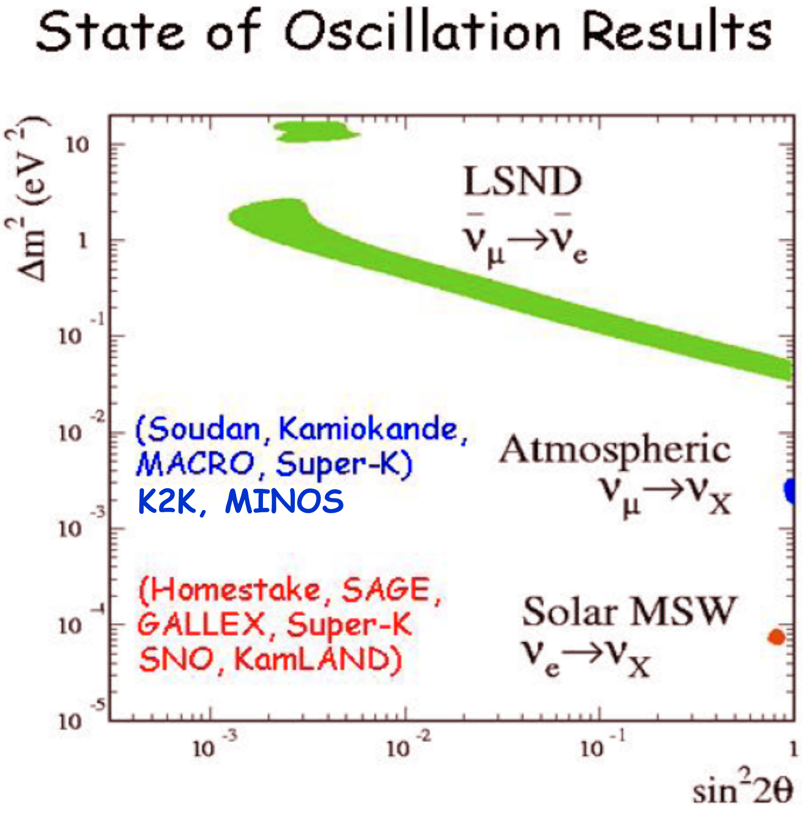
➔ LSND observed a positive signal(~3.8σ), but not confirmed.

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





Physics Motivation



➔ Simplest model has three Neutrino mass eigenstates,

$\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$

➔ Data indicates 3 mass differences

$\Delta m^2_{atm} \sim 2.4 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{sol} \sim 8 \times 10^{-5}\ \mathrm{eV}^2$

$\Delta m^2_{lsnd} \sim 0.1 \sim 2\ \mathrm{eV}^2$

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

➔ If the LSND signal does exist, it may imply new physics beyond SM.

LSND Signal: Yes or NO ?

The MiniBooNE Experiment

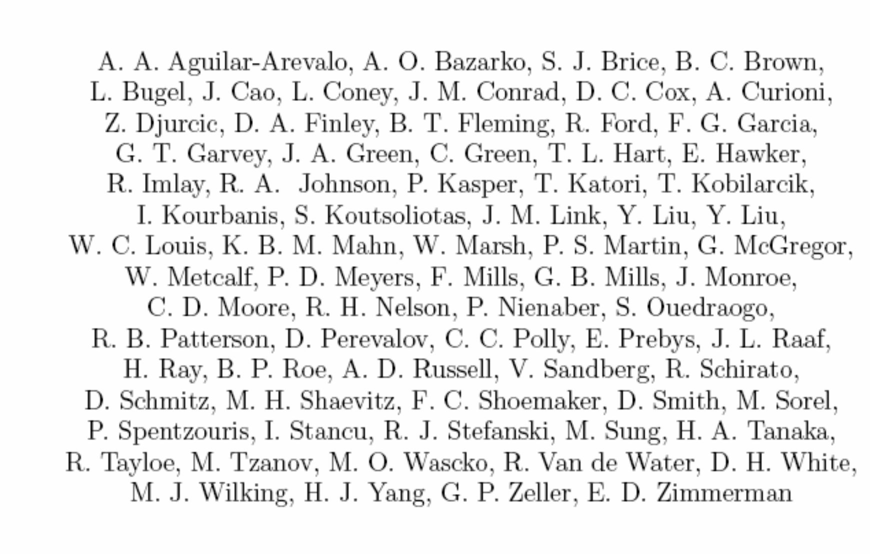
- Proposed in 1998， operating since 2002
- The goal of the MiniBooNE Experiment:
  to confirm or exclude the LSND result and
  extend the explored oscillation parameter space

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

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

MiniBooNE and LSND have similar L/E, but have different signal, background and systematics.

The MiniBooNE Collaboration



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

2 National Laboratories, 14 Universities, 77 Researchers

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle University
Fermi National Accelerator Laboratory
Indiana University

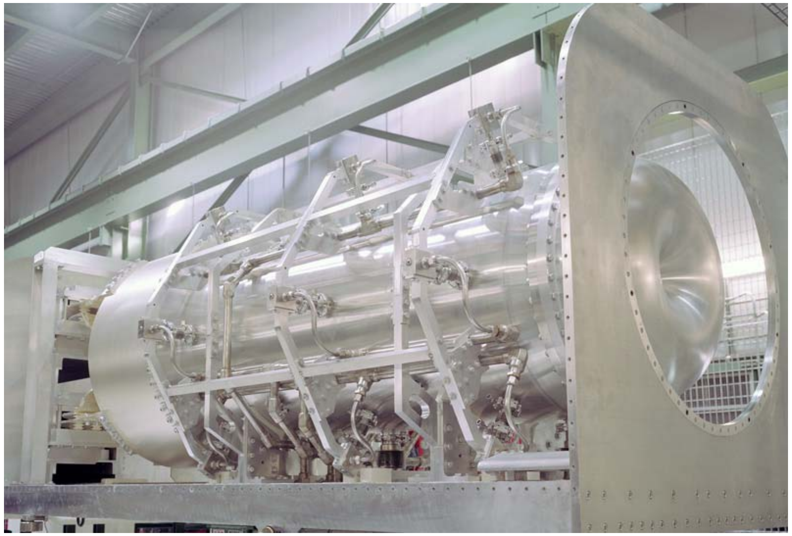
Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

MiniBooNE Neutrino Beam

Fermilab Proton Booster

MiniBooNE extracts beam from the 8 GeV Proton Booster

Delivered to a 1.7 λ Be target

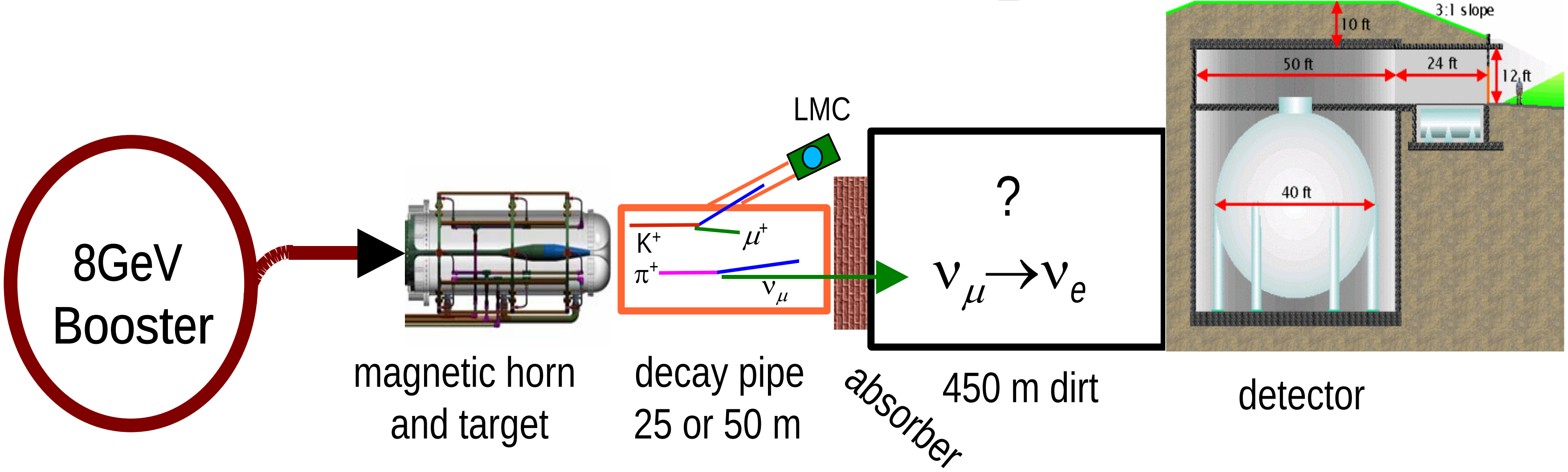


within a magnetic horn (2.5 kV, 174 kA) that (increases the flux by ×6)

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

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

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:

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

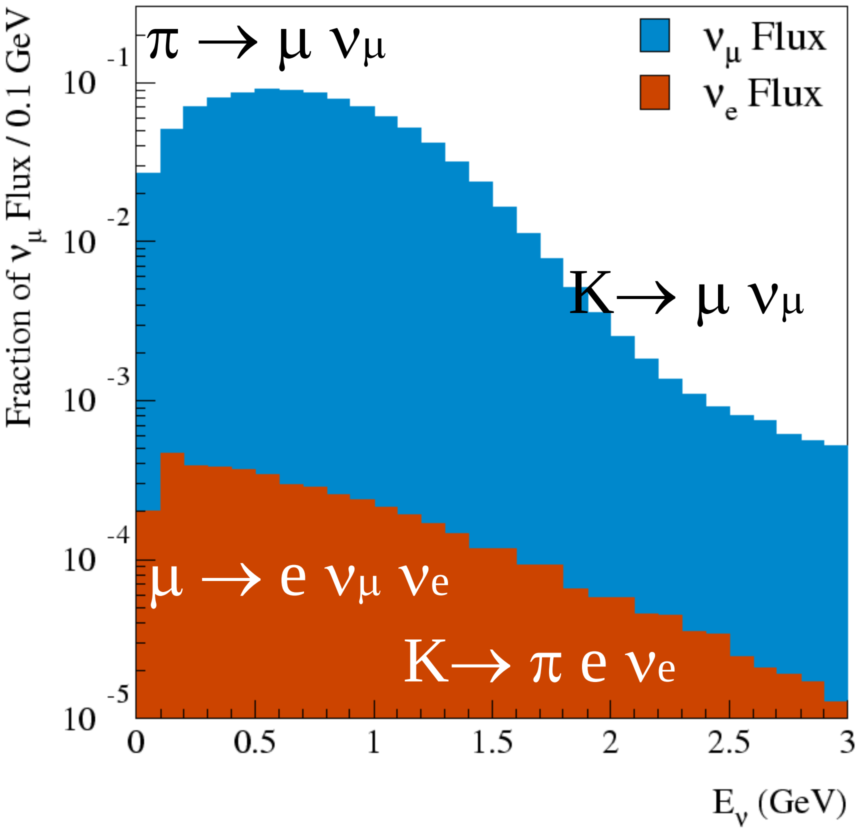
ν_μ beam from:

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

"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 $\nu_\mu \rightarrow \nu_e$ search.



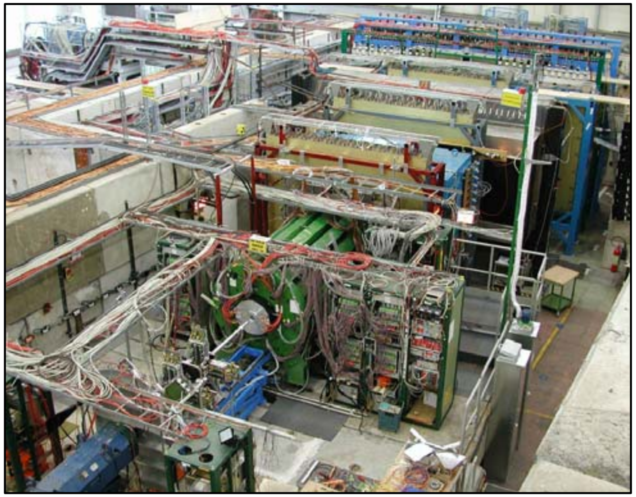
$\nu_e/\nu_\mu = 0.5\%$

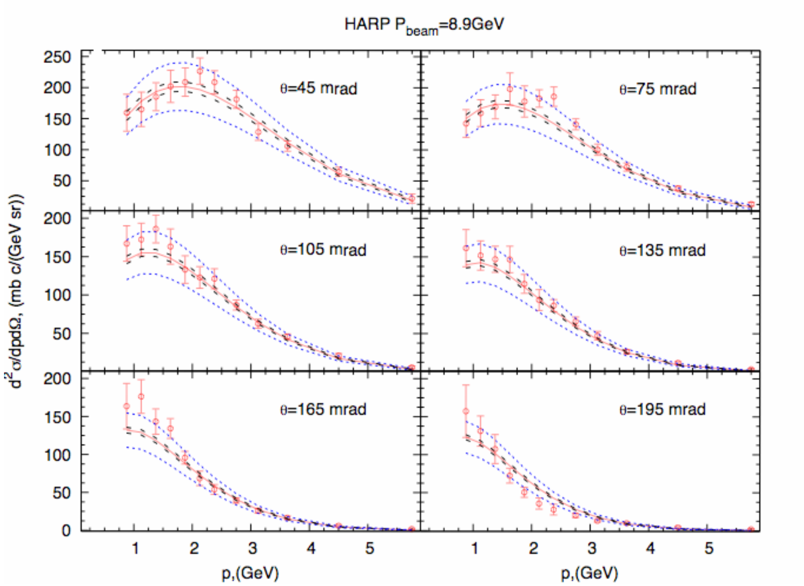
Antineutrino content: 6%

Modeling Production of Secondary Pions

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

HARP collab., hep-ex/0702024





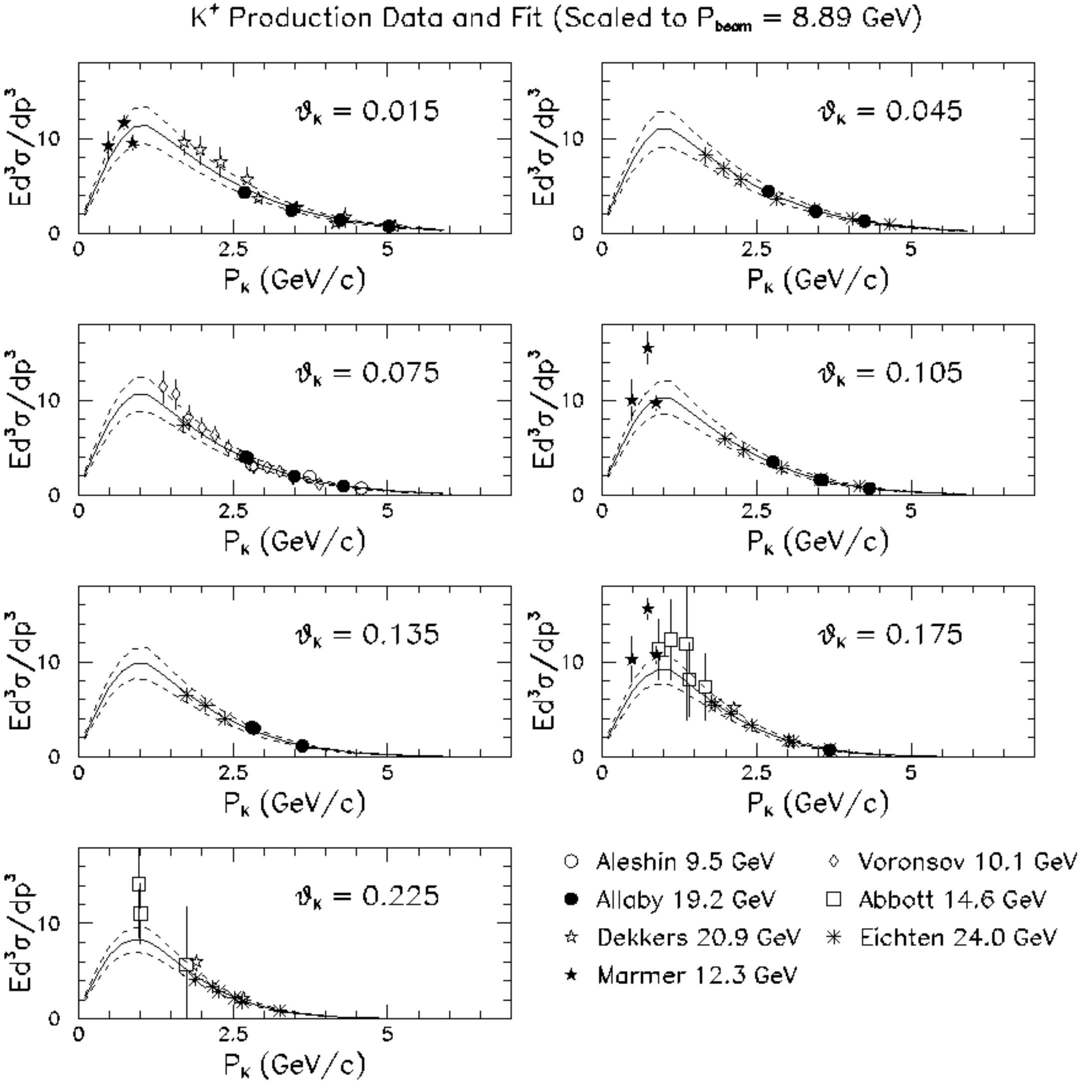
Modeling Production of Secondary Kaons

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

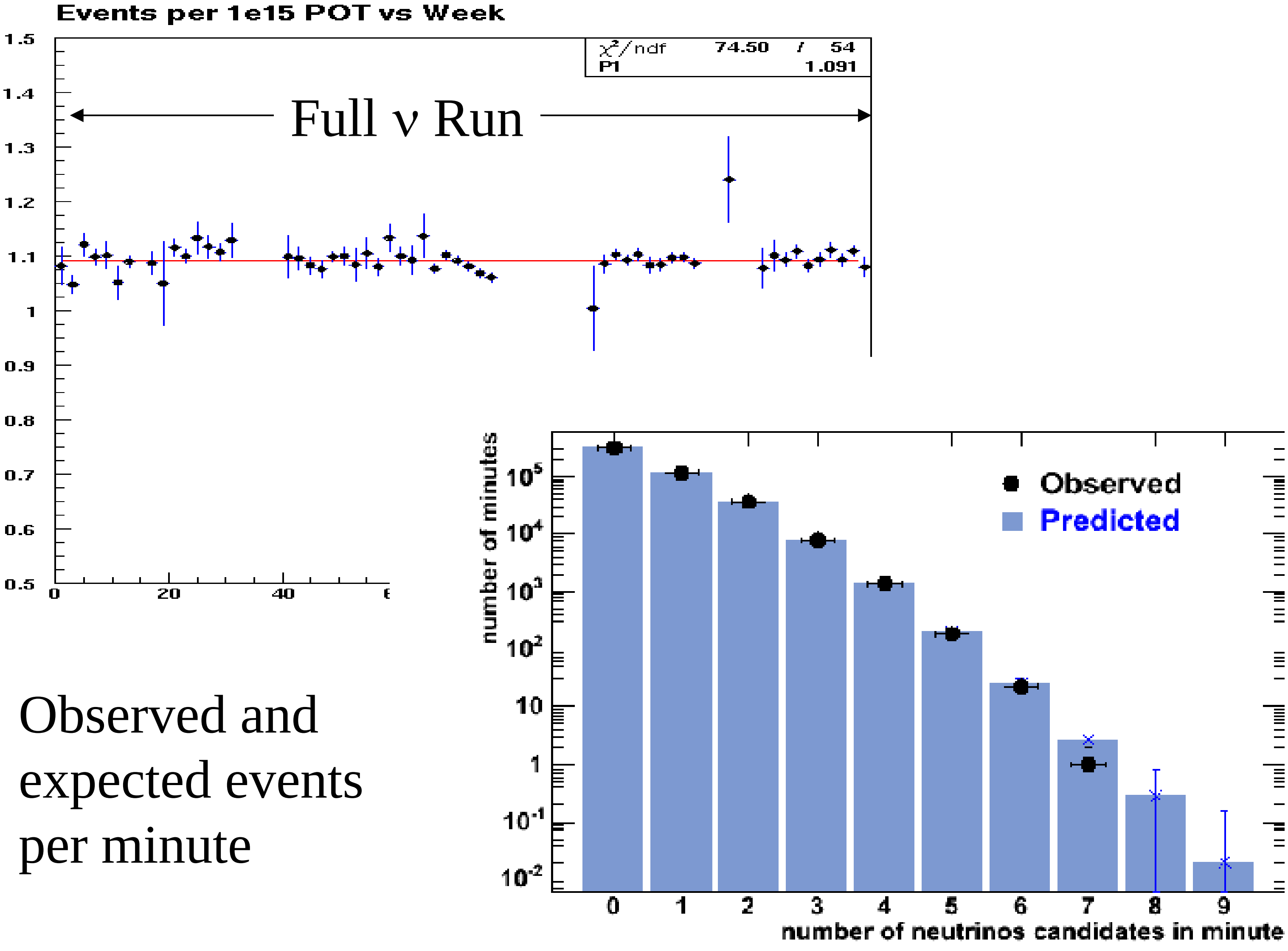
data -- points
dash --total error
(fit ⊕ parameterization)

K^0 data are also parameterized.

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



Stability of Running

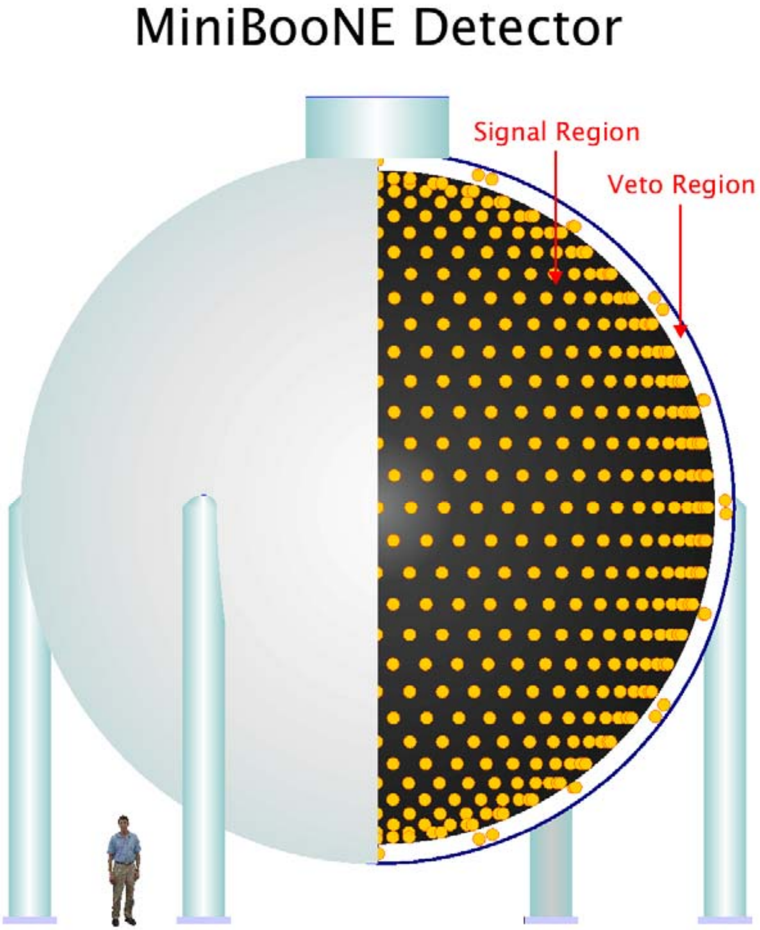


Full ν Run

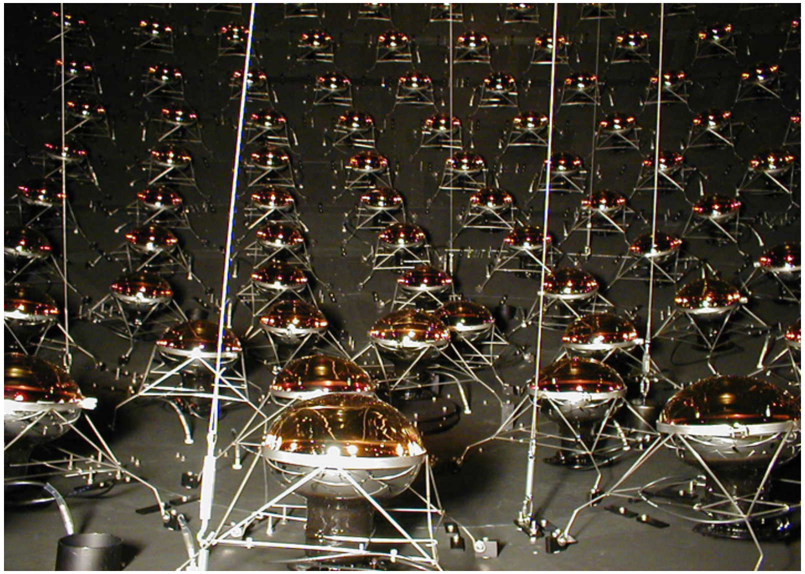
Observed and expected events per minute

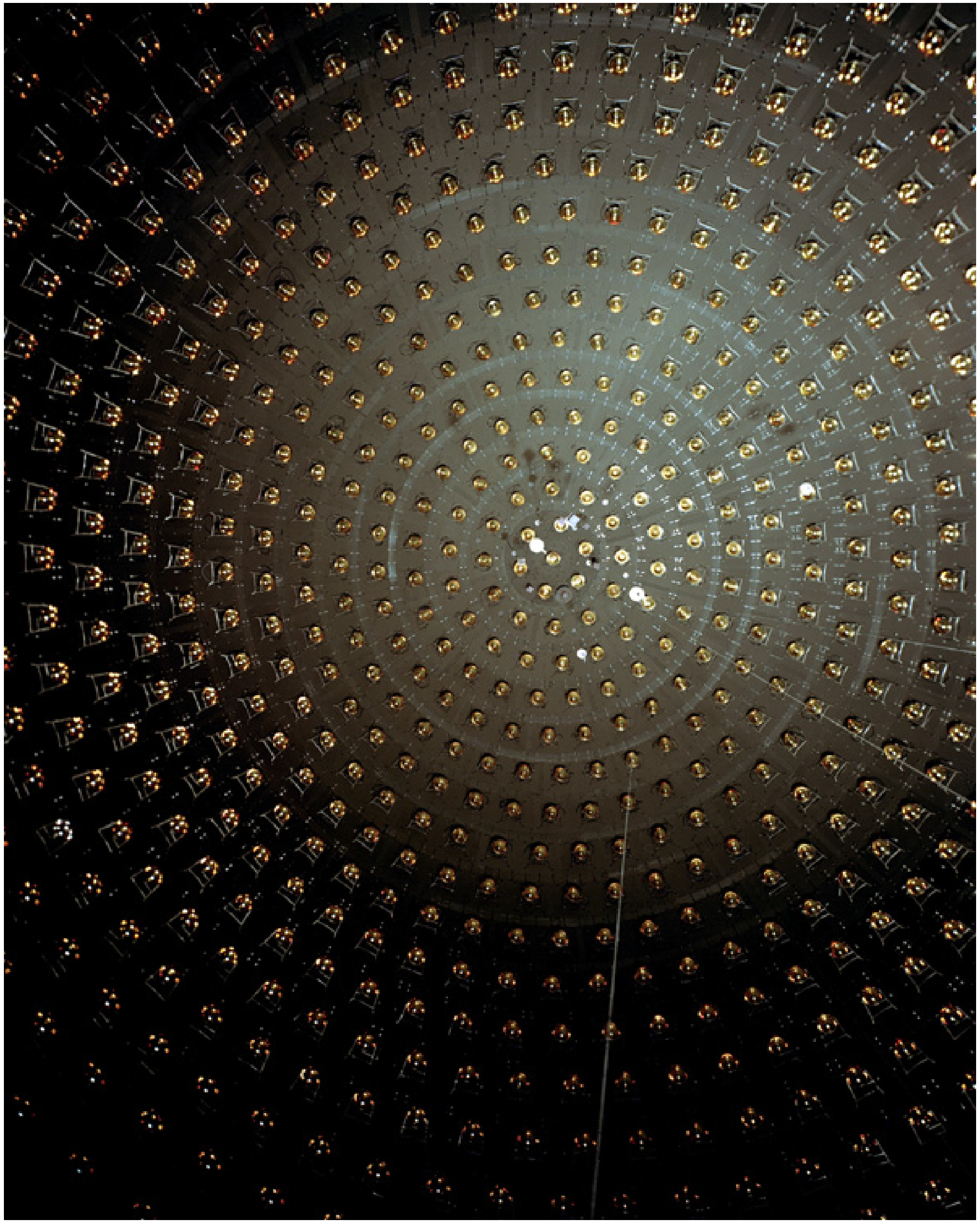
Events in the Detector

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% PMT coverage

Two types of Hamamatsu PMT Tubes:

- R1408(79%, from LSND)
- R5912(21%, new)

Charge Resolution:
1.4 PE, 0.5 PE
Time Resolution
1.7 ns, 1.1ns

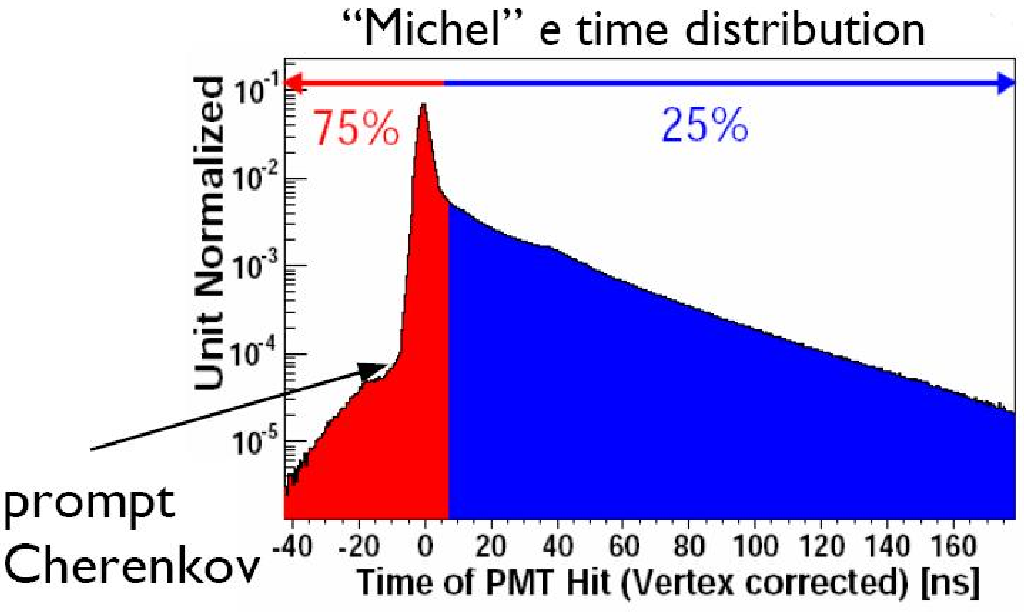
Optical Model

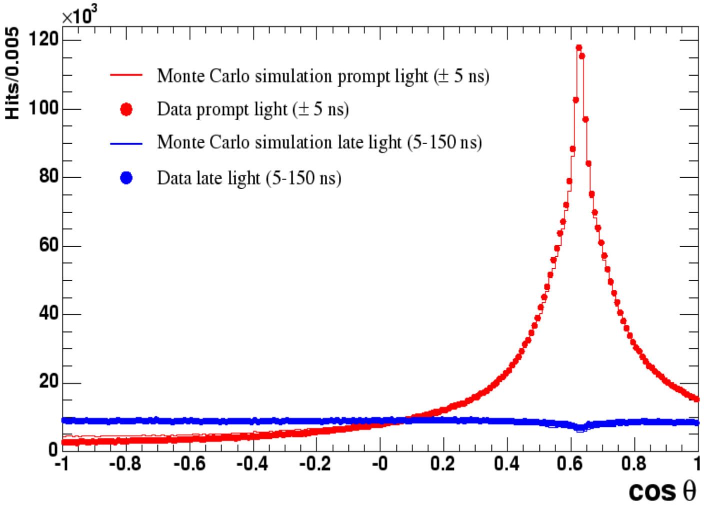
Attenuation length: >20 m @ 400 nm

Detected photons from

- Cherenkov (prompt, directional)
- Scintillation (delayed, isotropic)
- Ratio of prompt/late light ~ 3:1

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





Beam Window

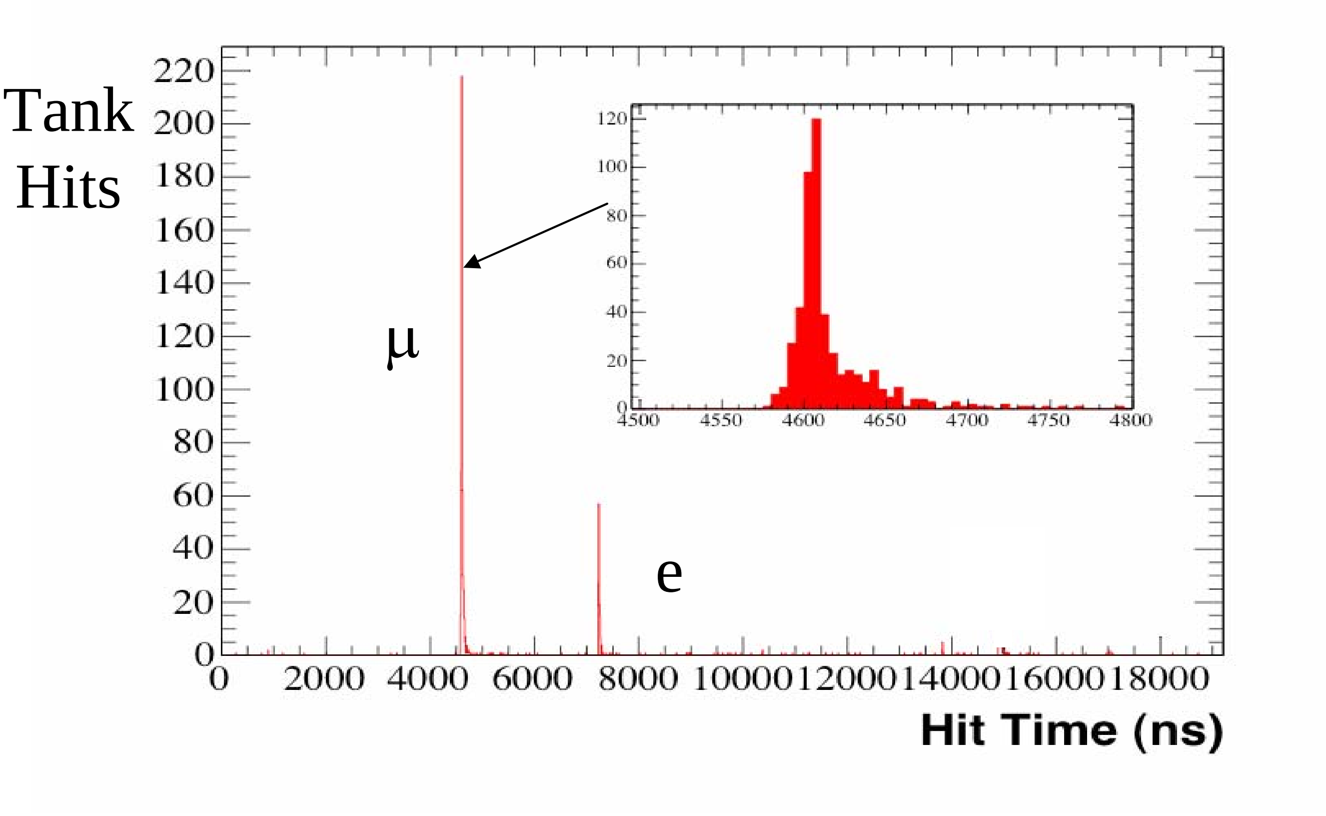
A 19.2 μs beam trigger window encompasses the 1.6 μs spill.

Multiple hits within a ~100 ns window form “subevents”

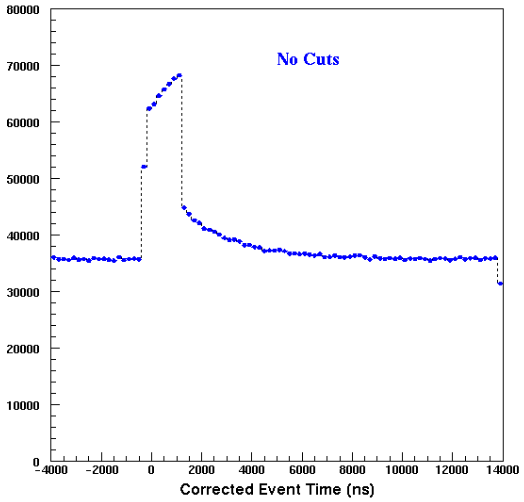
Most events are from ν_μ CC interactions (ν_μ+n → μ+p) with characteristic two “subevent” structure from stopped $\mu \rightarrow \nu_\mu \nu_e e$

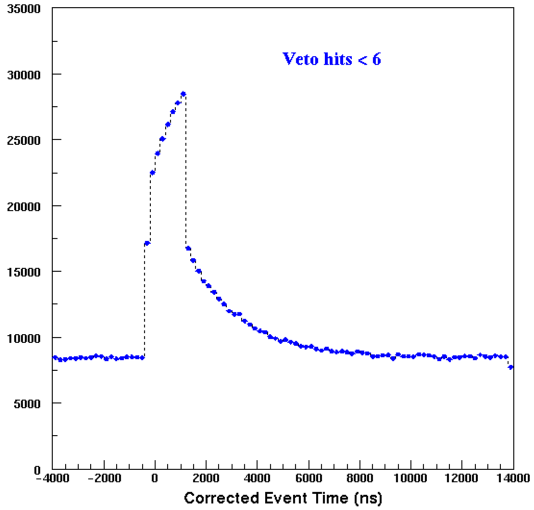
Tank Hits

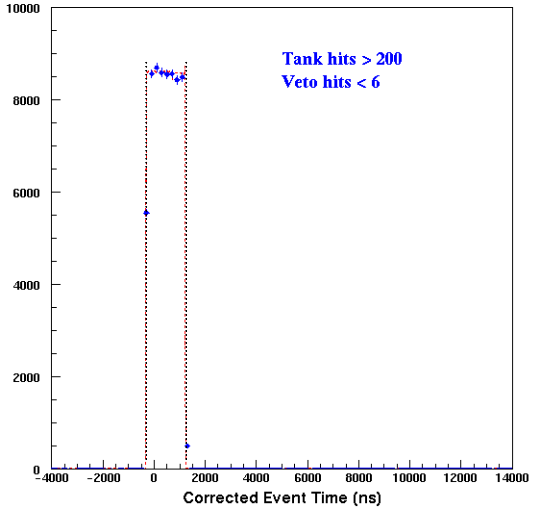
Example Event



Cuts to Select Neutrino Events







Raw data

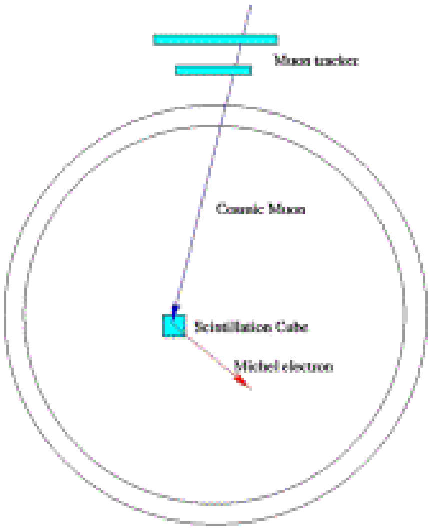
Veto Hits < 6 removes through-going cosmics

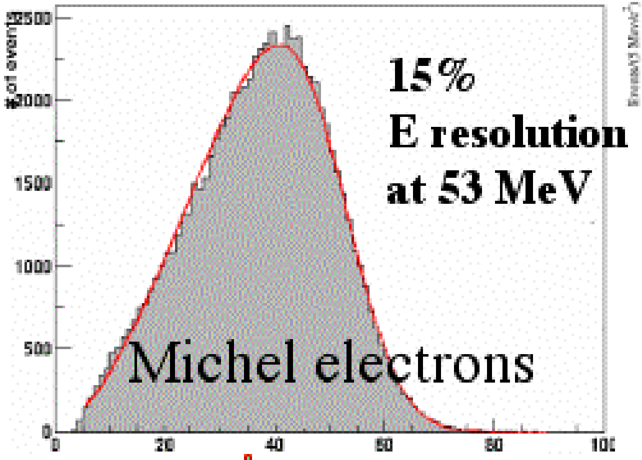
This leaves
" Michel electrons"
($\mu \rightarrow \nu_\mu \nu_e e$) from cosmics

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

Calibration Sources

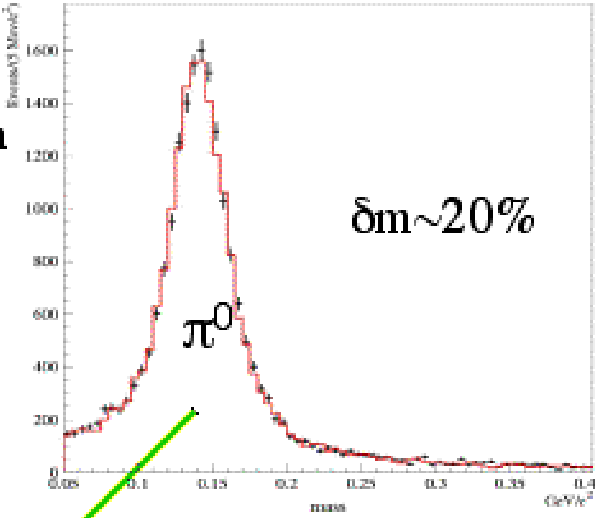
Tracker system





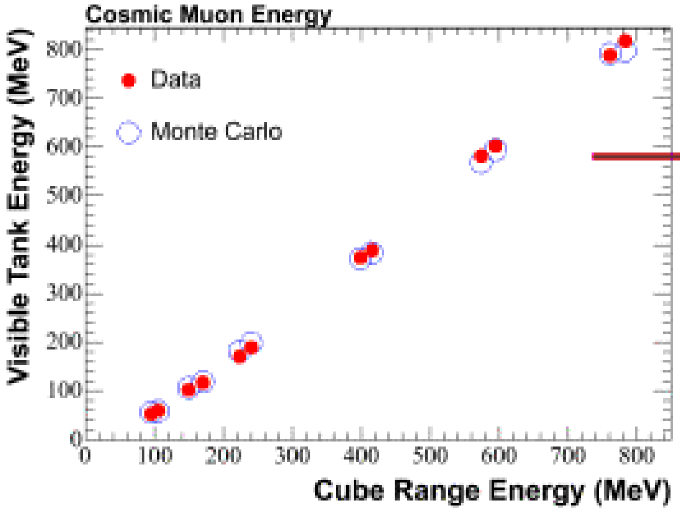
15%
E resolution
at 53 MeV

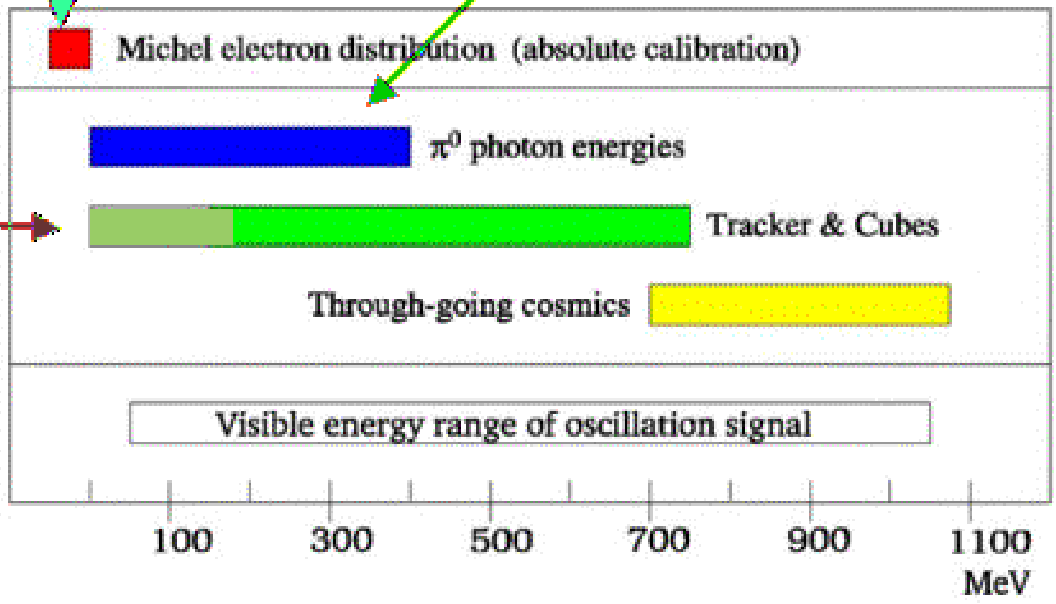
Michel electrons



δm~20%

π^0





🟥 Michel electron distribution (absolute calibration)

π^0 photon energies

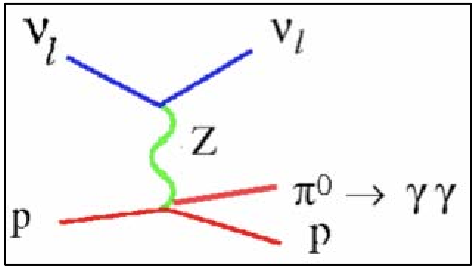
Tracker & Cubes

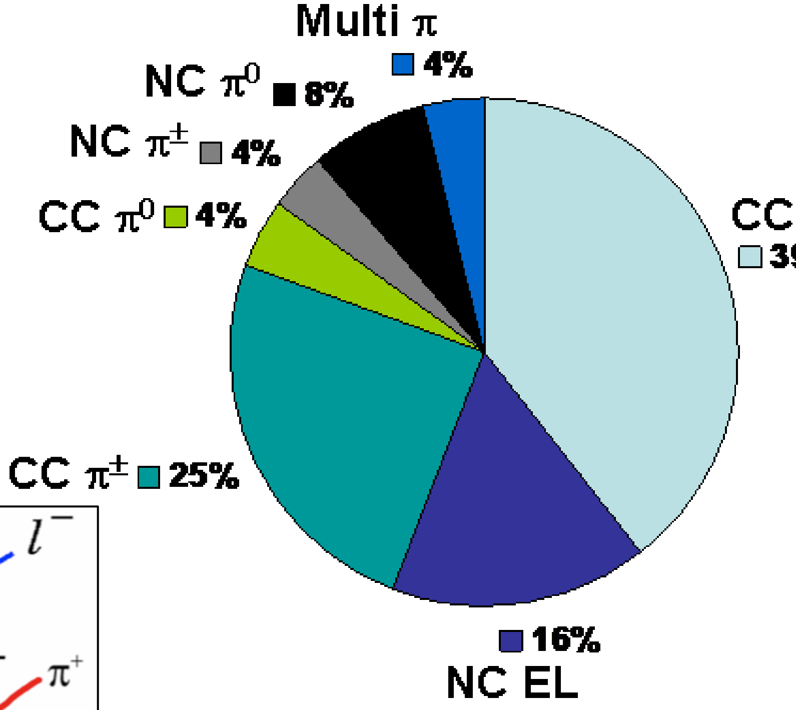
Through-going cosmics

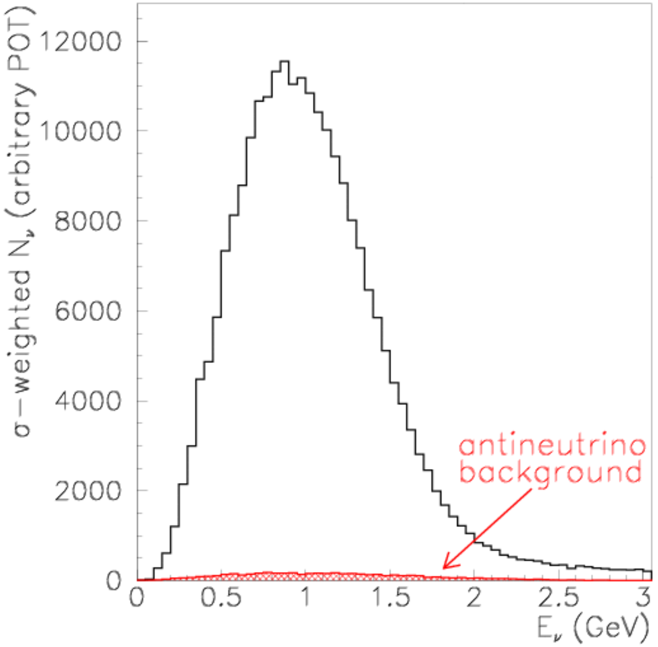
Visible energy range of oscillation signal

Nuance MC Event Rates

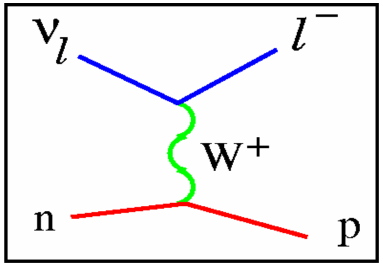
D. Casper, NPS, 112 (2002) 161

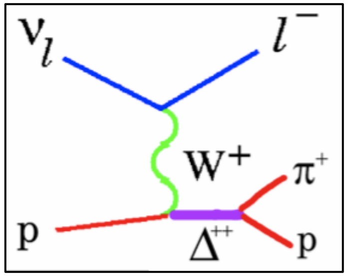


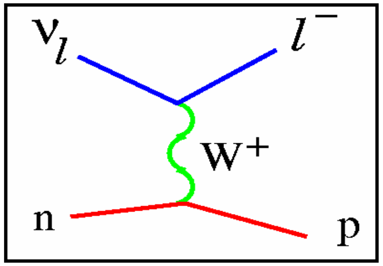




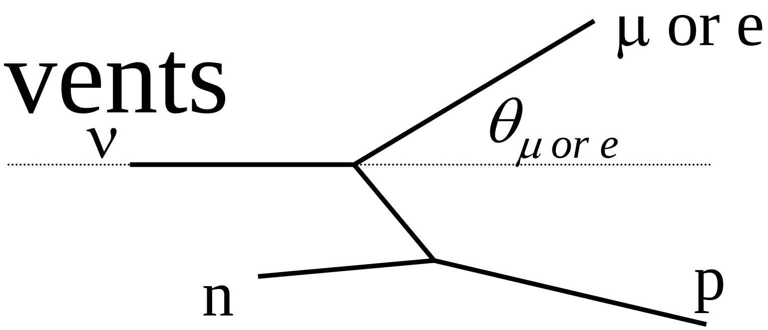
Event neutrino energy (GeV)







CCQE Events

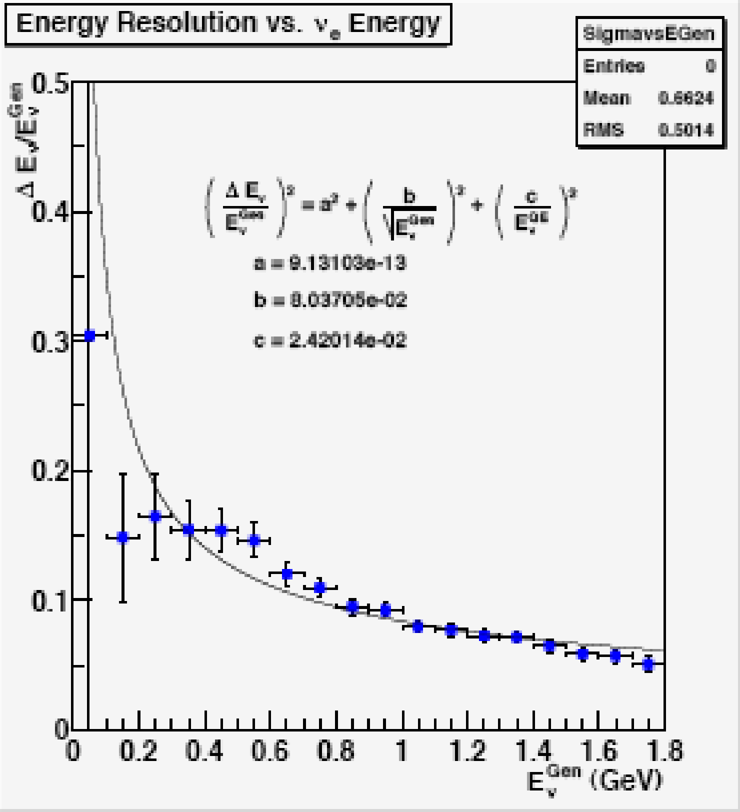


CCQE (Charged Current Quasi-Elastic)

39% of total

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

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

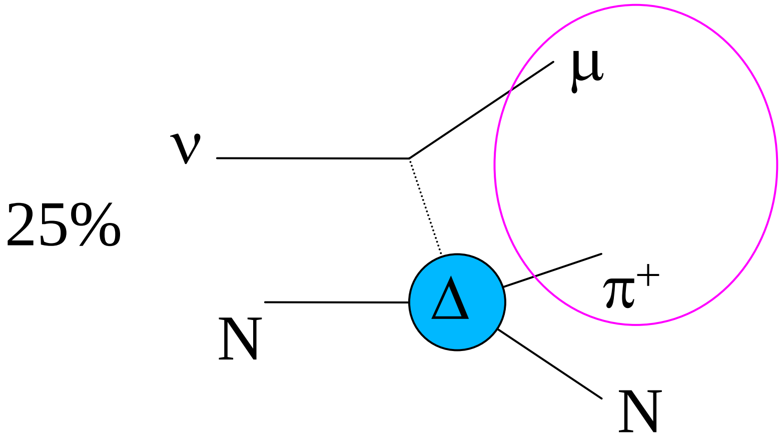


Reconstructed from:

Scattering angle

Visible energy ($E_{visible}$)

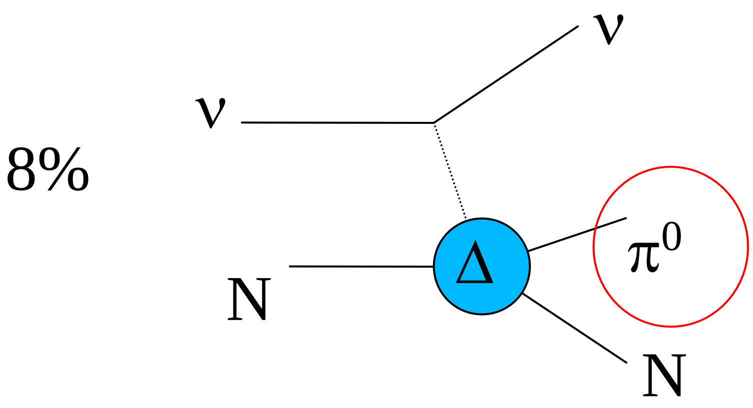
Events Producing Pions



$CC\pi^+$

Easy to tag due to 3 subevents.

Not a substantial background to the oscillation analysis.



$NC\pi^0$

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)

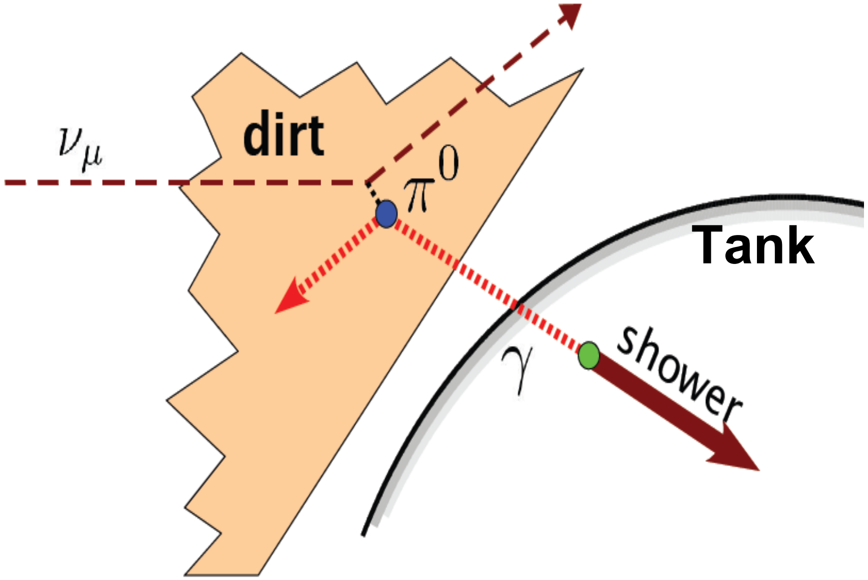
<1% of π^0 contribute to background.

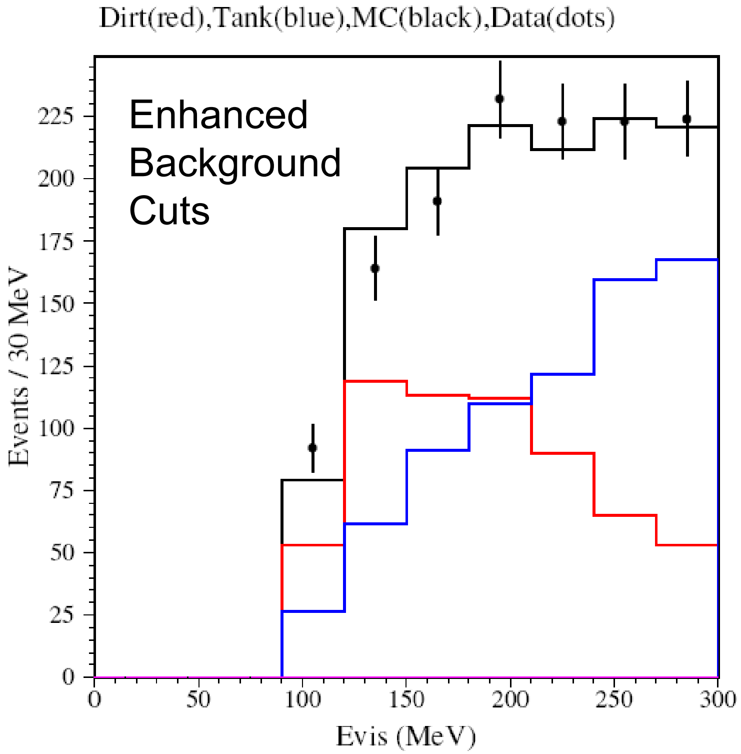
External Sources of Background

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

“Dirt” Events:

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



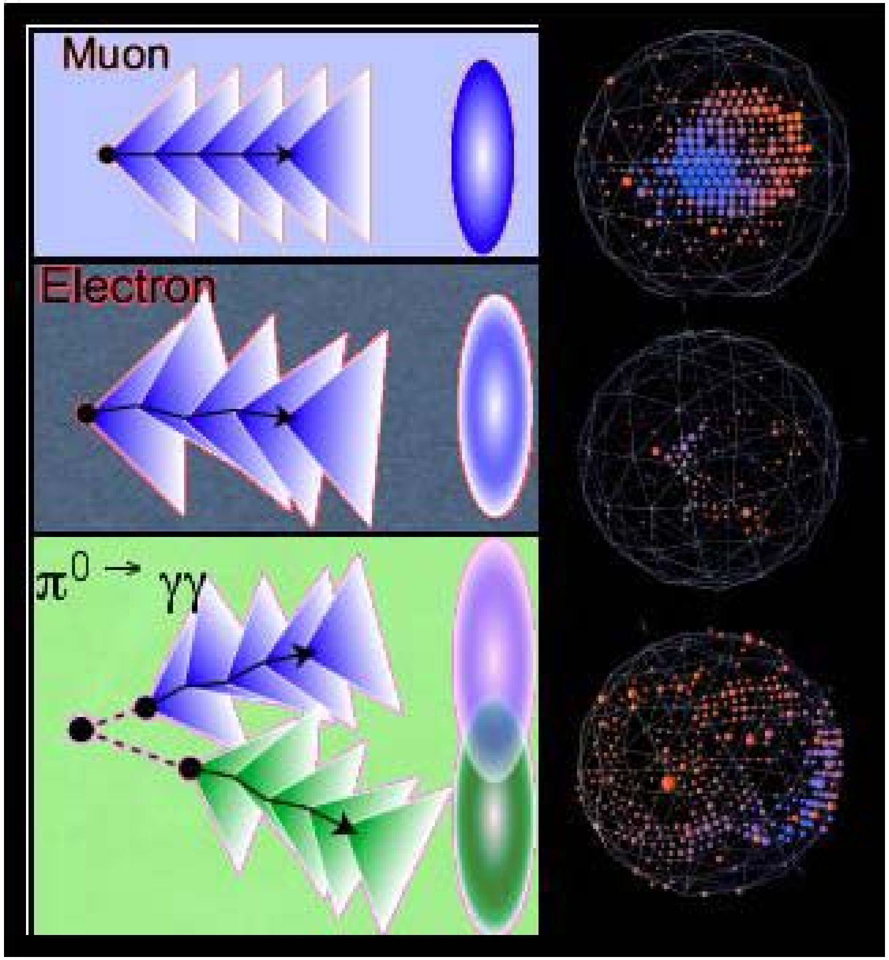


MiniBooNE Event Types

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

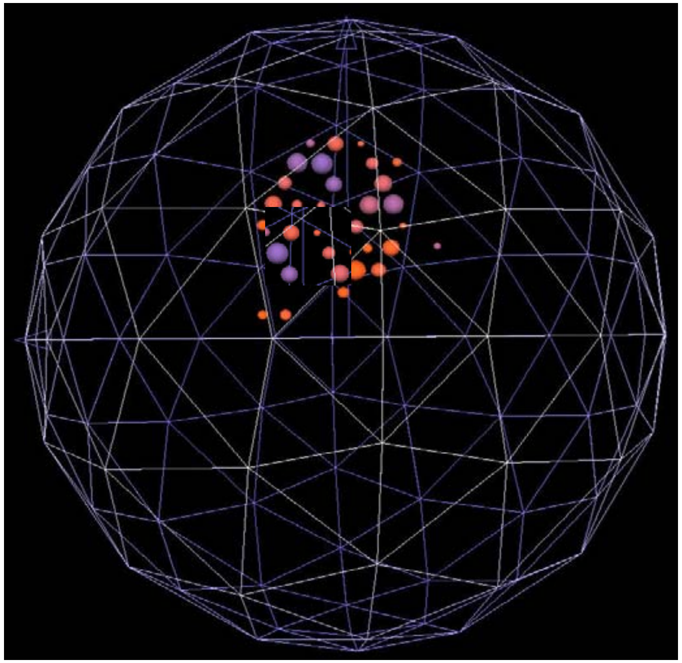
Electrons:
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent, fuzzy ring.

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



Two Independent Analyses

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: <1σ 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”:

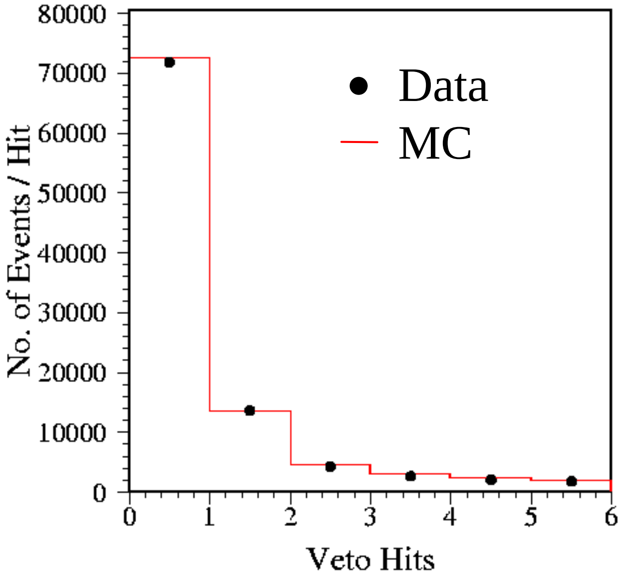
Only 1 subevent

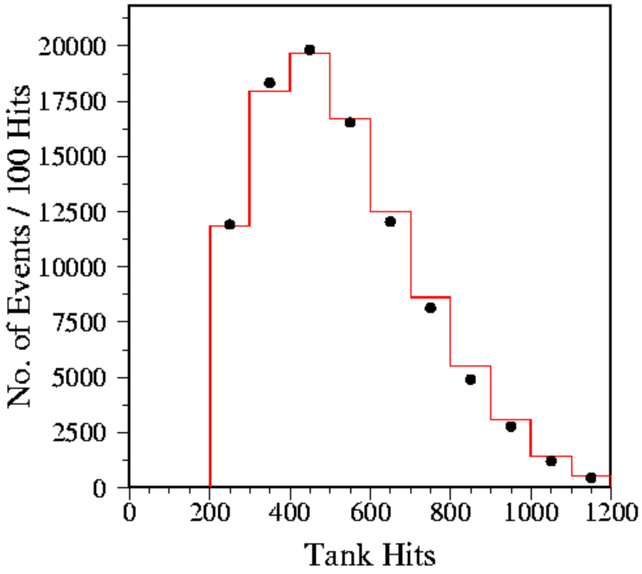
Number of Veto hits < 6

Number of Tank hits > 200

And a track radius precut:

R < 500 cm





Track-Based (TB) Analysis

Philosophy:

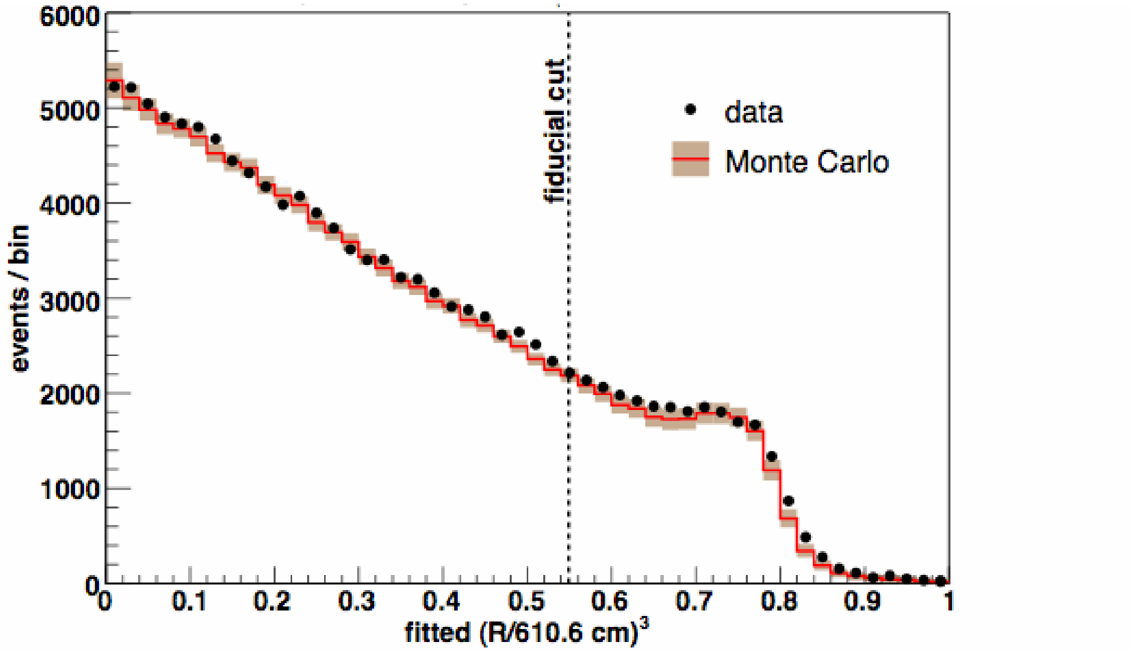
➔Uses detailed, direct reconstruction of particle tracks, and ratio of fit likelihoods to identify particles.

Each event is characterized by 7 reconstructed variables:

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

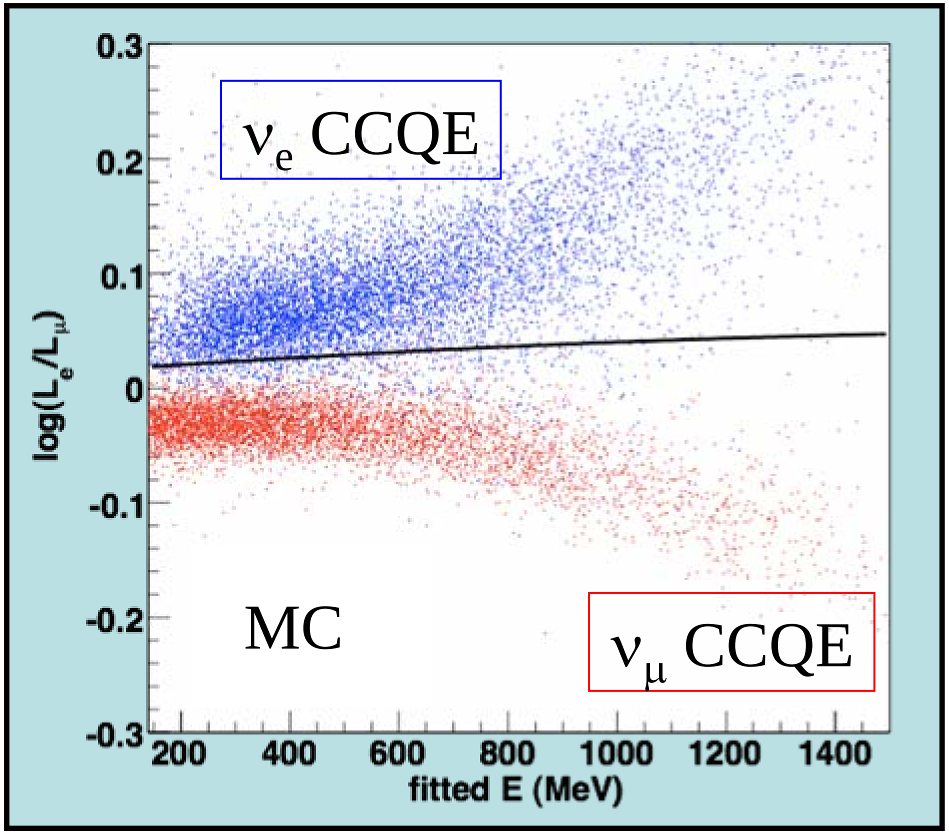
Resolutions:

- vertex: 22 cm
- direction: 2.8°
- energy: 11%



e / μ Separation

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

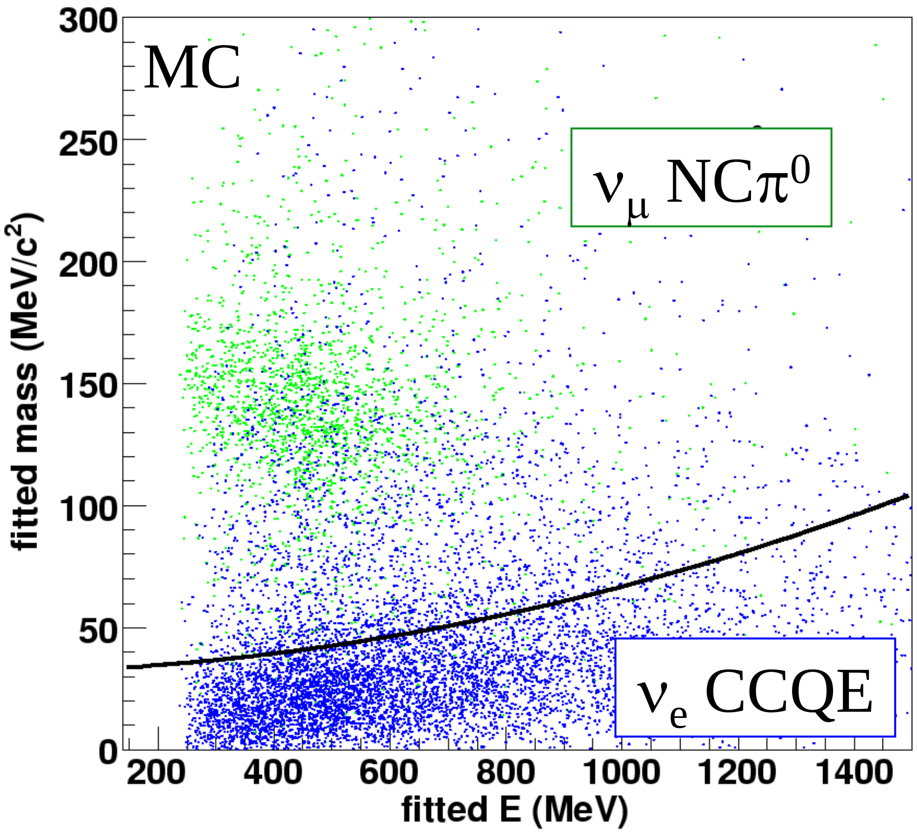


Separation is clean at high energies where muon-like events have long tracks.

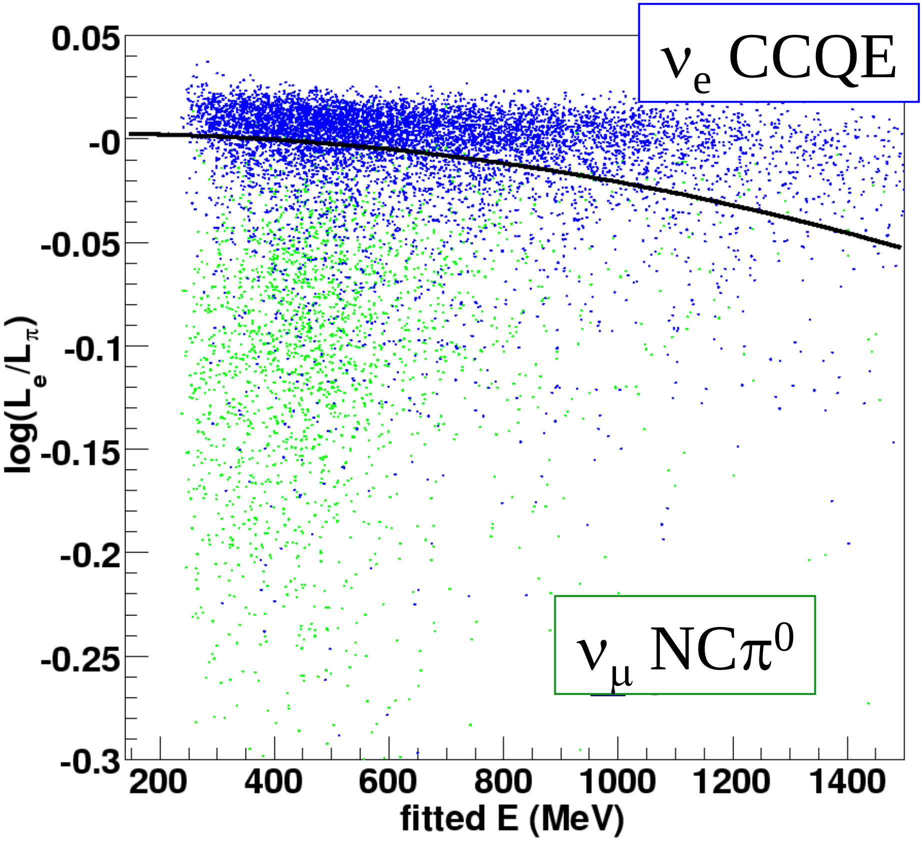
Analysis cut was chosen to maximize the $\nu_\mu \to \nu_e$ sensitivity

e / π^0 Separation

Using a mass cut



Using $\log(L_e/L_\pi)$



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

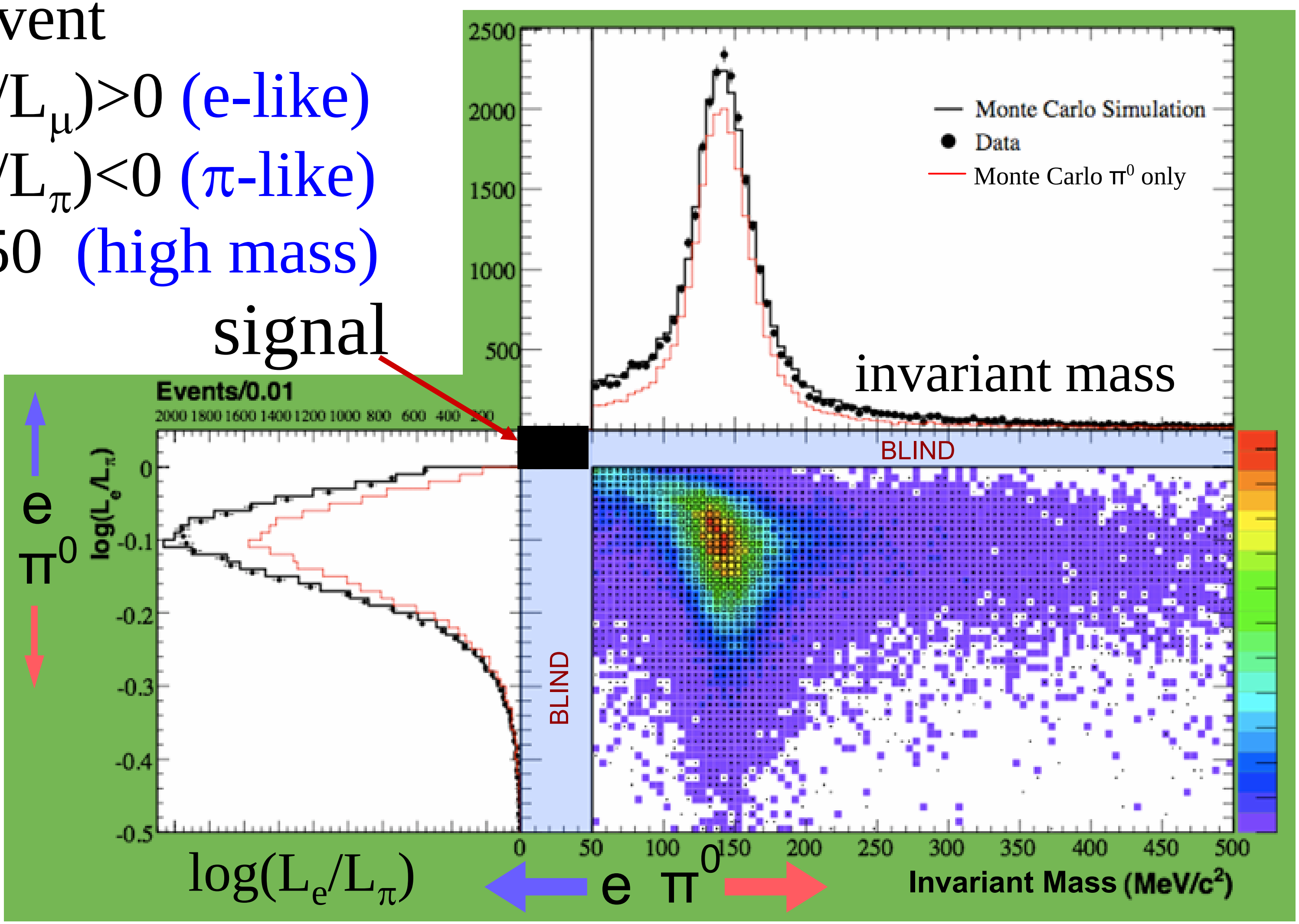
Testing e / π^0 Separation using data

1 subevent

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

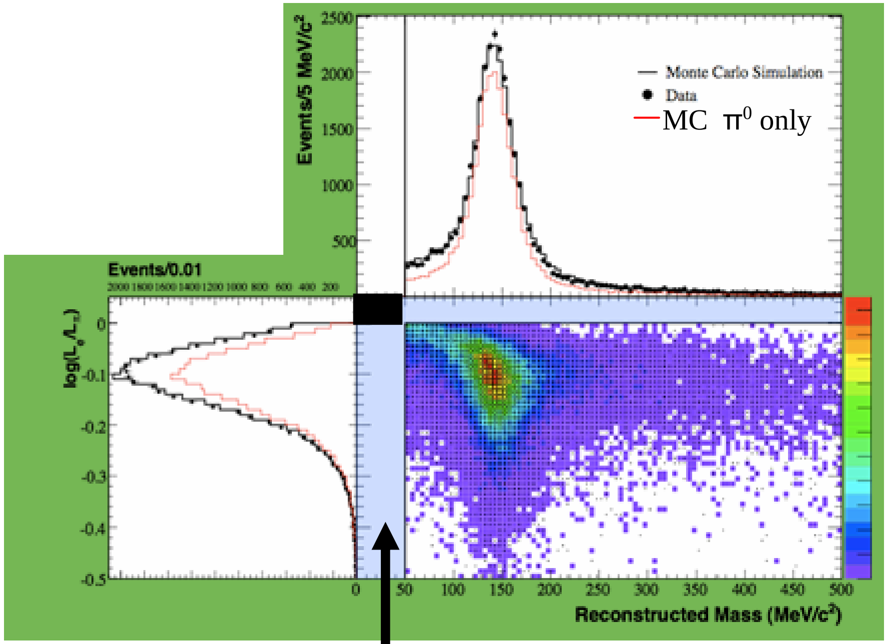
$\log(L_e/L_\pi)<0$ (π-like)

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



signal

invariant mass



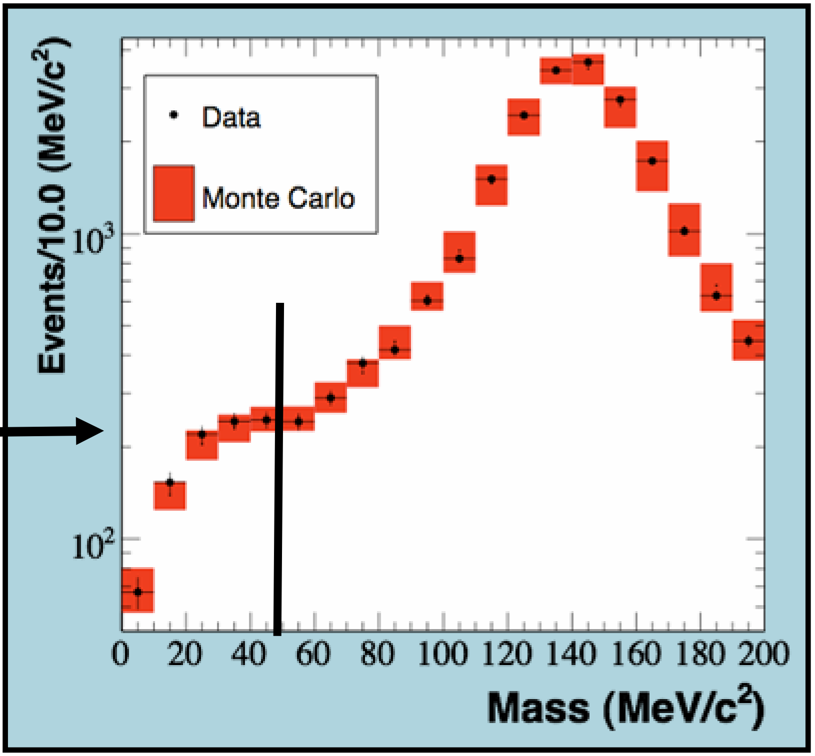
1 subevent

$\log(L_e/L_\mu)>0$ (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

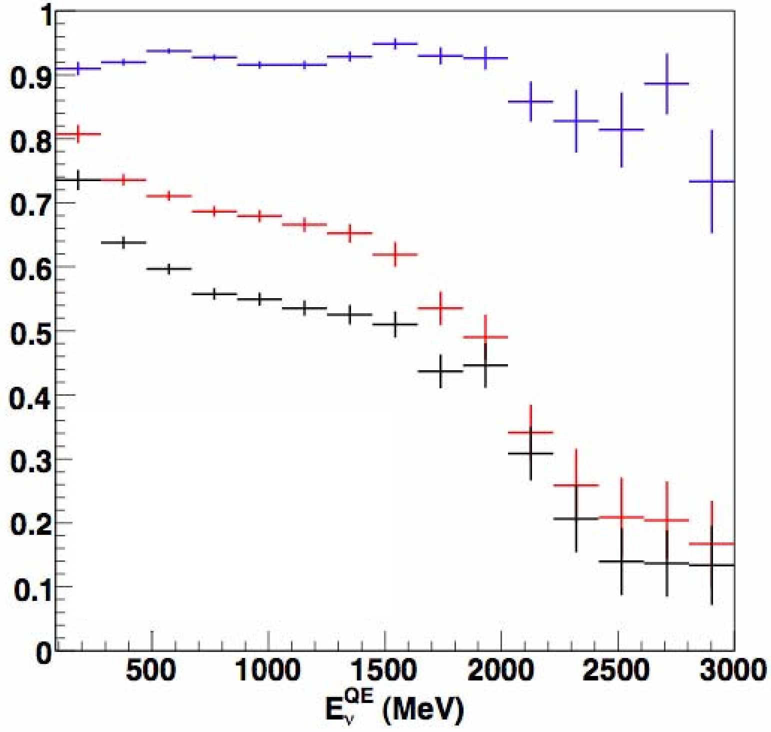
“Precuts” +

Efficiency:

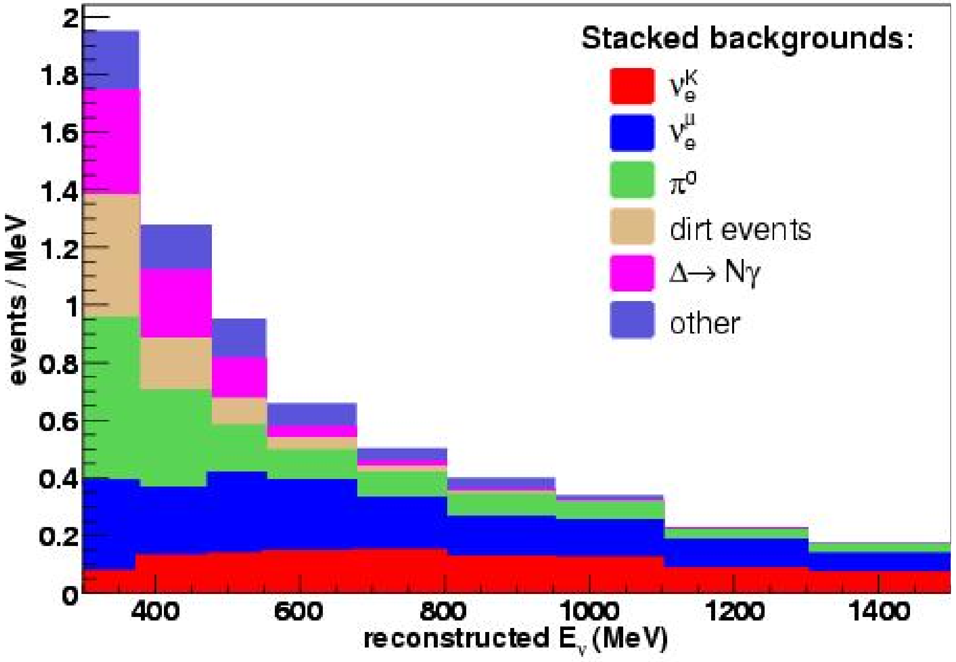
$\text{Log}(L_e/L_\mu)$

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

invariant mass



Backgrounds after cuts



Boosted Decision Trees (BDT) Analysis

Philosophy:

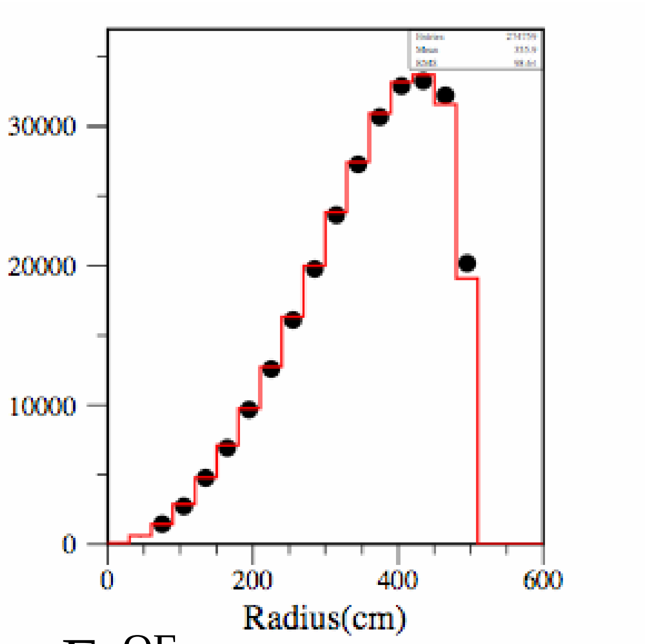
- ➔Construct a set of low-level analysis variables which are used to make a series of cuts to classify the events – decision tree.

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

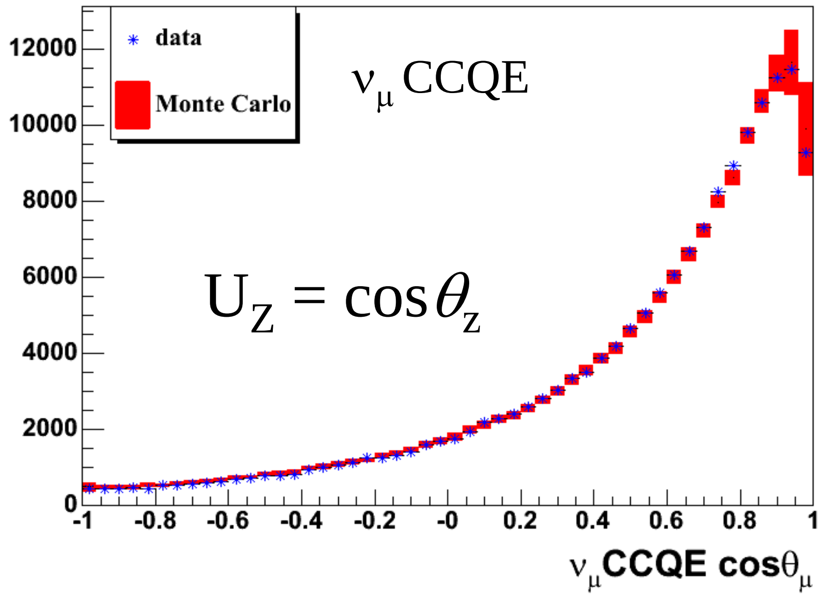
Examples of “Analysis Variables”

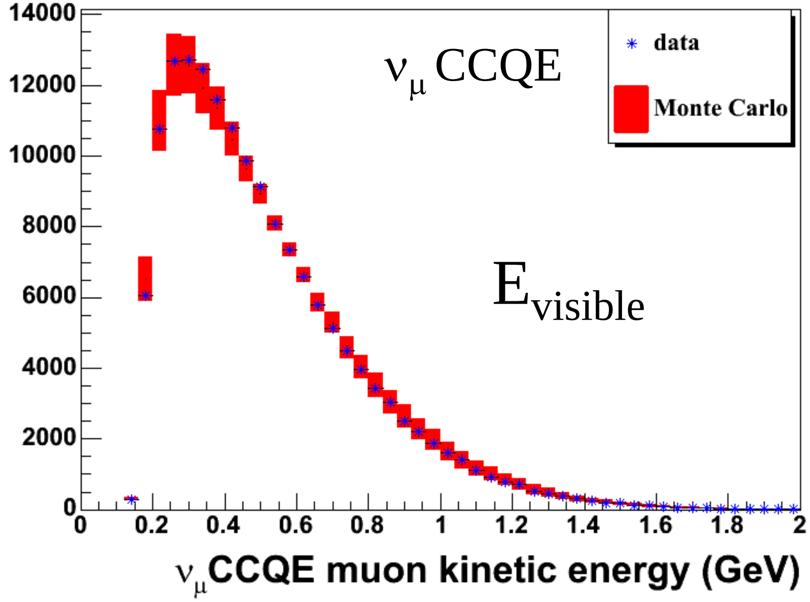
Resolutions:

- 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"

hit level
(charge, time, position)

→

analysis variables

→

One single PID "score"

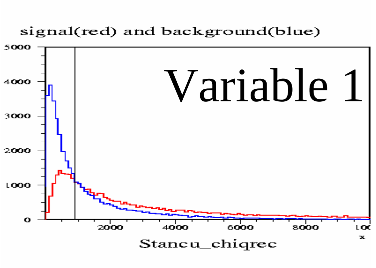
Byron P. Roe, Hai-Jun Yang, Ji Zhu *et al.*, NIM A543 (2005) 577, physics/0408124
Hai-Jun Yang, Byron P. Roe, Ji Zhu, NIM A555 (2005) 370, physics/0508045

A Decision Tree

(sequential series of cuts
based on MC study)

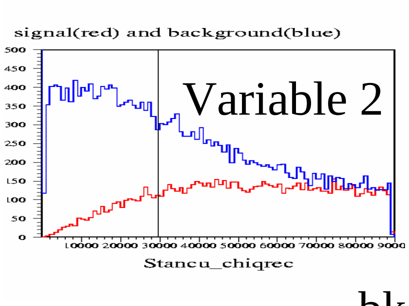
(N_{signal}/N_{bkgd})

40000/40000



bkgd-like

signal-like



9755/23695

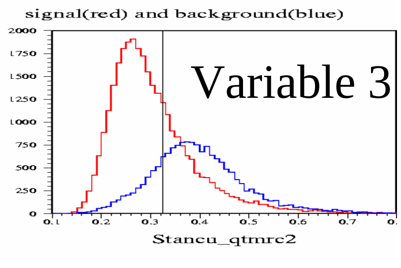
bkgd-like

1906/11828

bkgd-like

7849/11867

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,

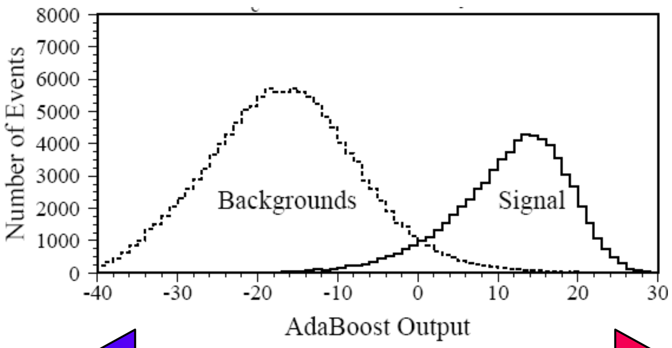
each re-weighting the events to enhance identification of backgrounds misidentified by earlier trees   ("boosting")

For each tree, the data event is assigned

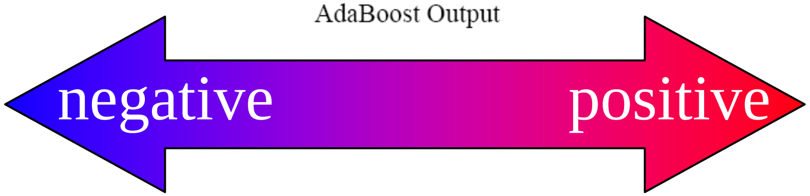
+1 if it is identified as signal,

-1 if it is identified as background.

The total for all trees is combined into a "score"



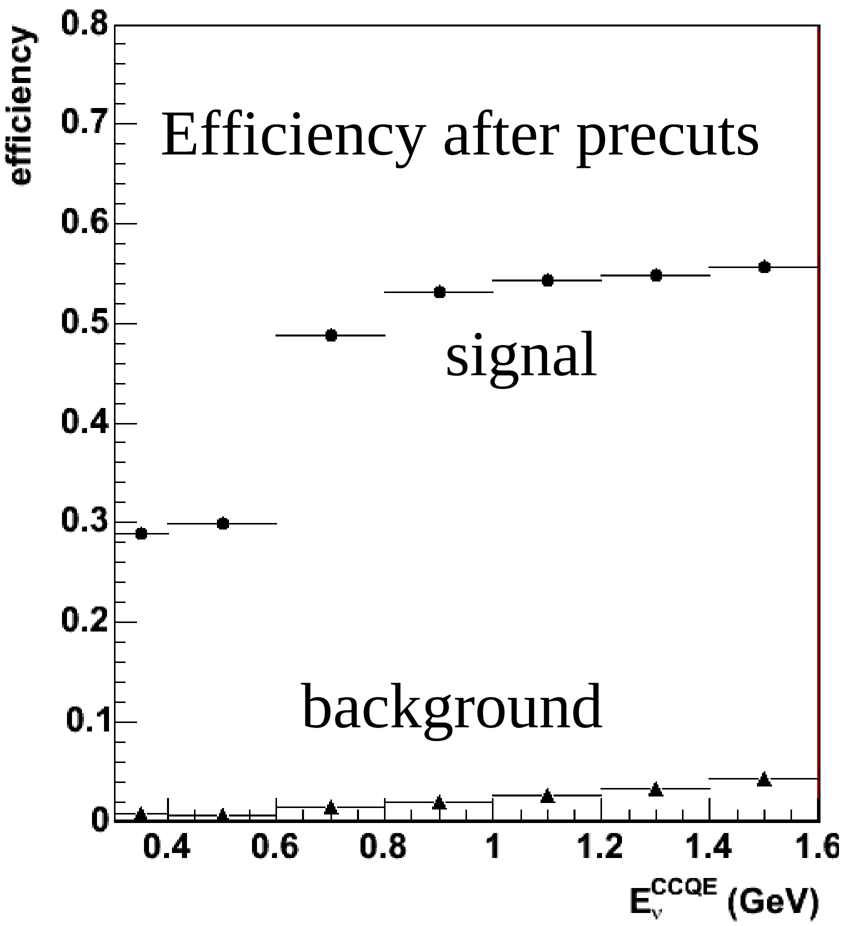
Background-like



signal-like

BDT Efficiency and backgrounds after cuts:

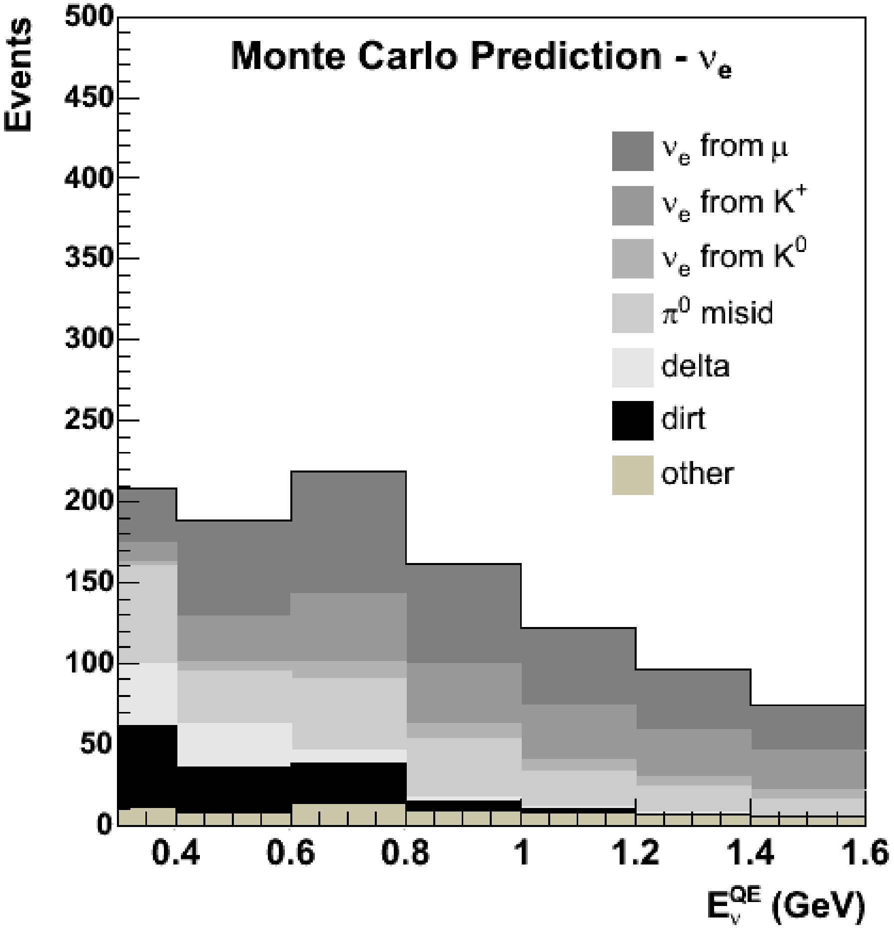
Analysis cuts on PID score as a function of Energy



Efficiency after precuts

signal

background



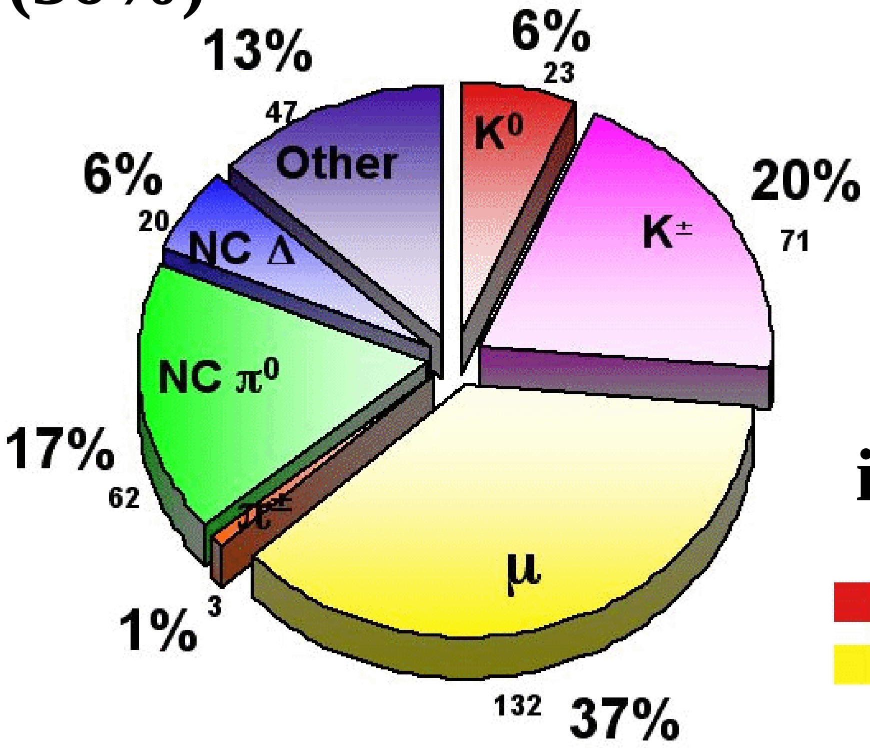
Sources of Uncertainty

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	√	

Main Backgrounds

ν_μ mis-id (36%)

🟪
🟦
🟩

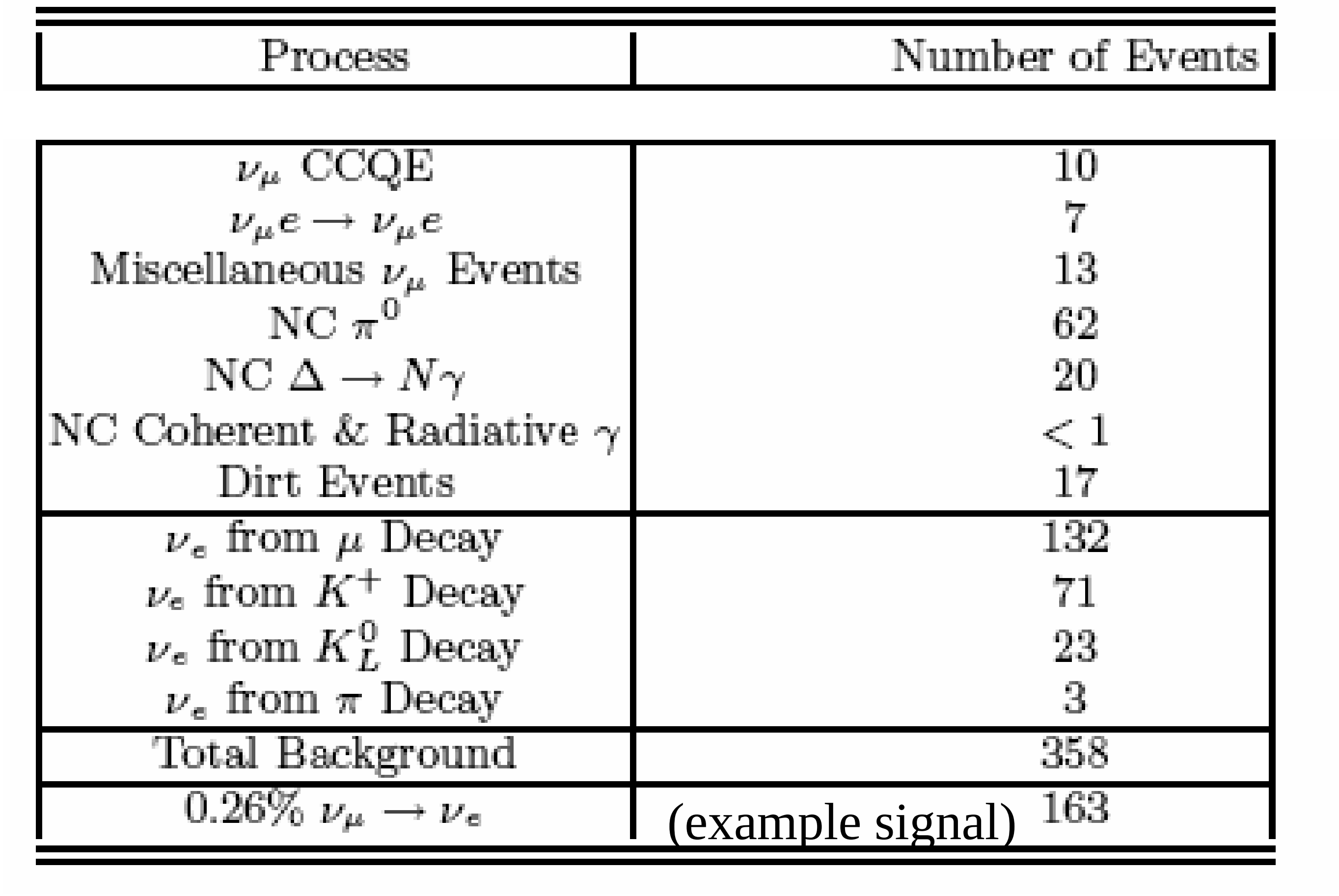


intrinsic ν_e (64%)

🟥 🟪
🟨 🟧

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

Summary of predicted backgrounds for the final MiniBooNE result



Process	Number of Events
ν_μ CCQE	10
$\nu_\mu e \rightarrow \nu_\mu e$	7
Miscellaneous ν_μ Events	13
NC π^0	62
NC $\Delta \rightarrow N\gamma$	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% $\nu_\mu \rightarrow \nu_e$	(example signal) 163

The Neutrino Oscillation Results

Track-based Analysis Results

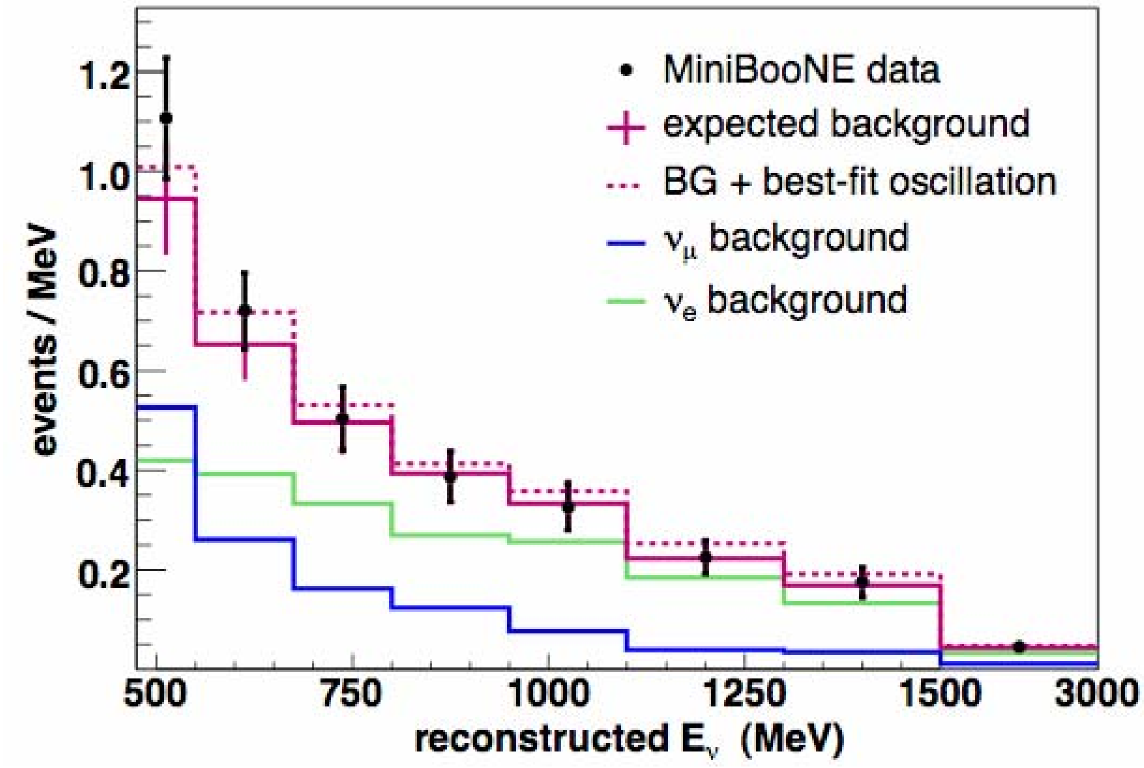
Counting Experiment: $475 < E_\nu^{QE} < 1250$ MeV

data: 380 events

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

significance:
$0.55\ \sigma$

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



Error bars are diagonals of error matrix.

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

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

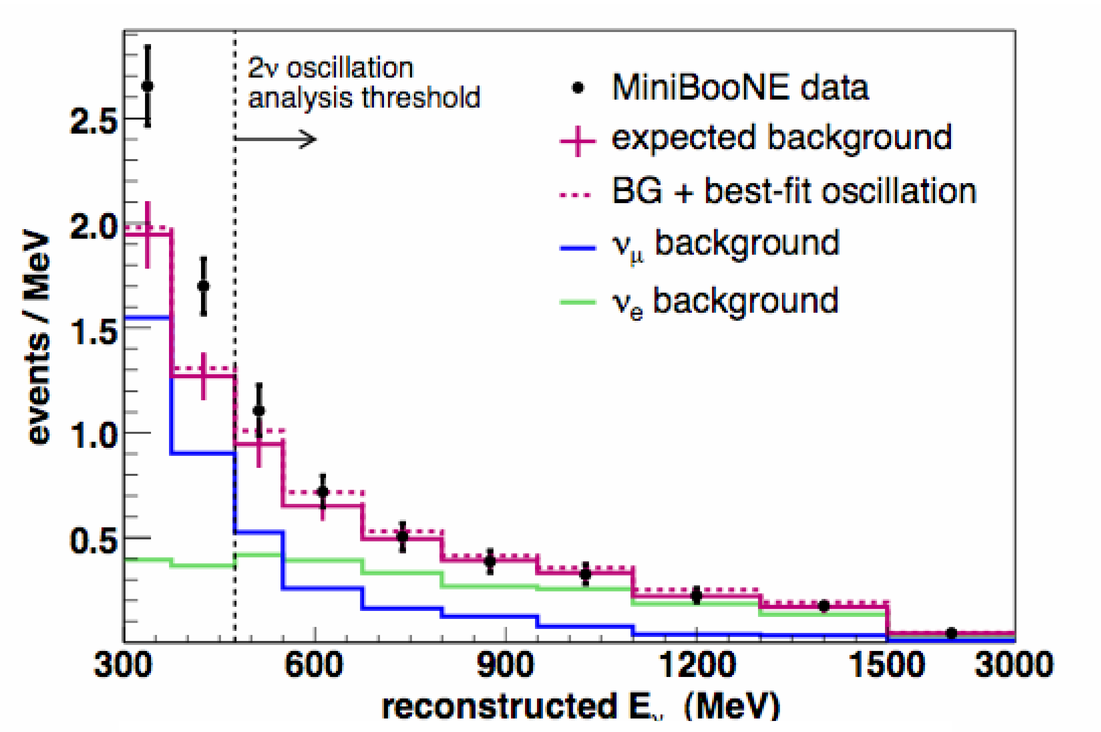
Low E Excess

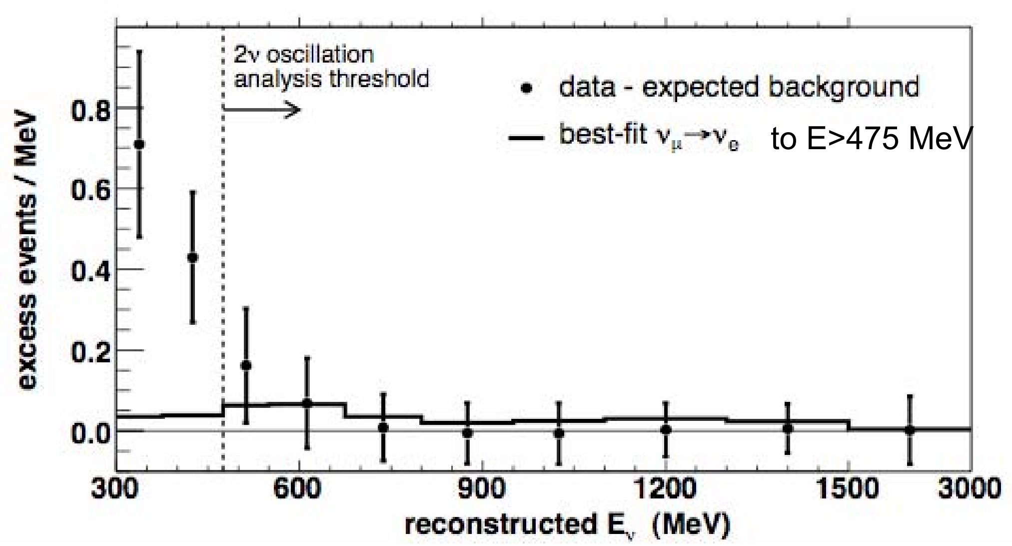
Report the full range:
$300<E_\nu^{QE}<3000$ MeV

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

Deviation: 3.7σ

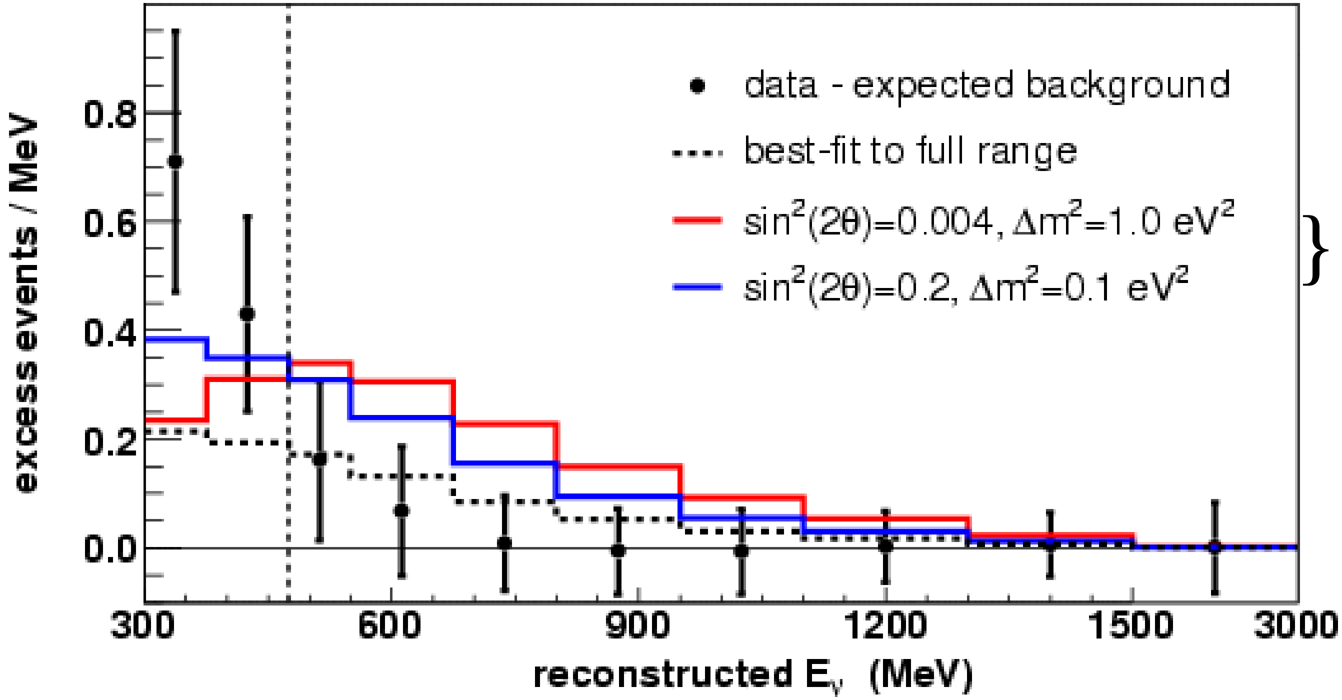
Background-subtracted:





Fit to the > 300 MeV range

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



} **Ex. in LSND allowed range**

➔ Low E excess cannot be explained with $\nu_\mu \rightarrow \nu_e$ oscillation.

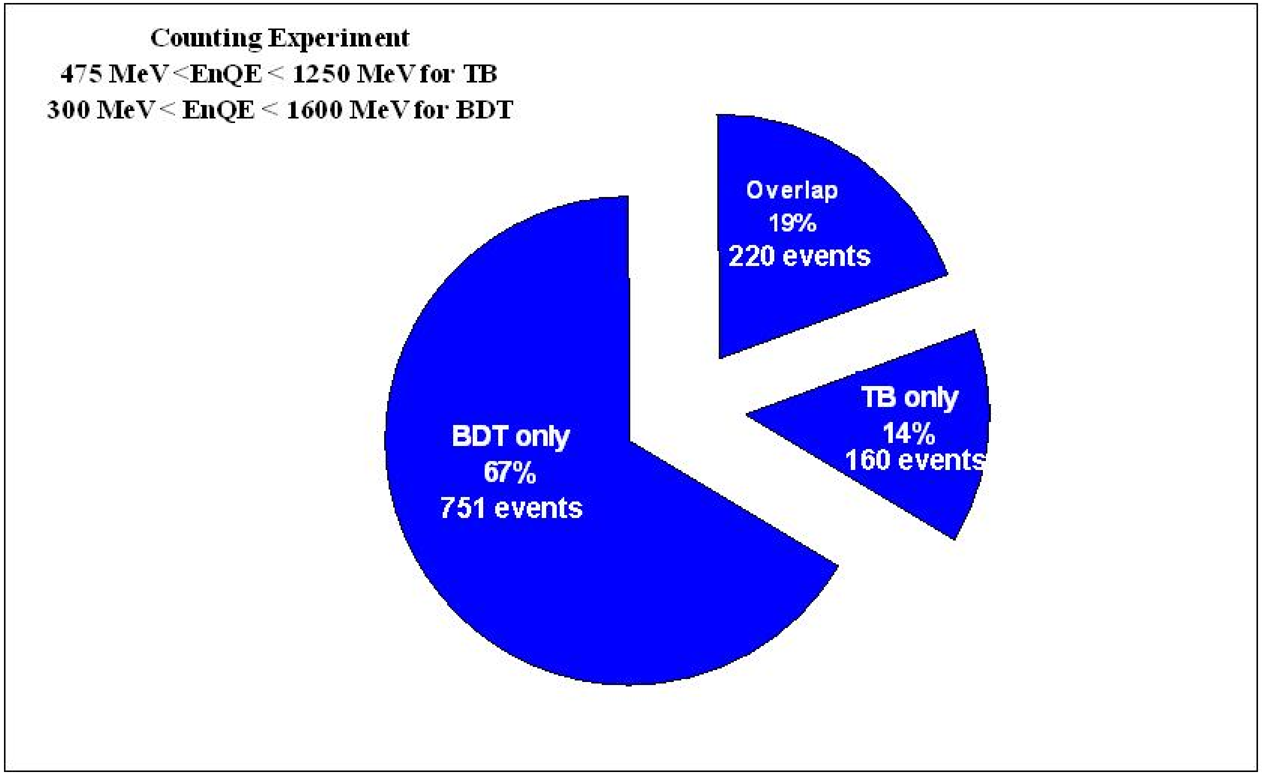
Boosted Decision Trees Analysis

Counting Experiment: 300<E_ν^{QE}<1600 MeV

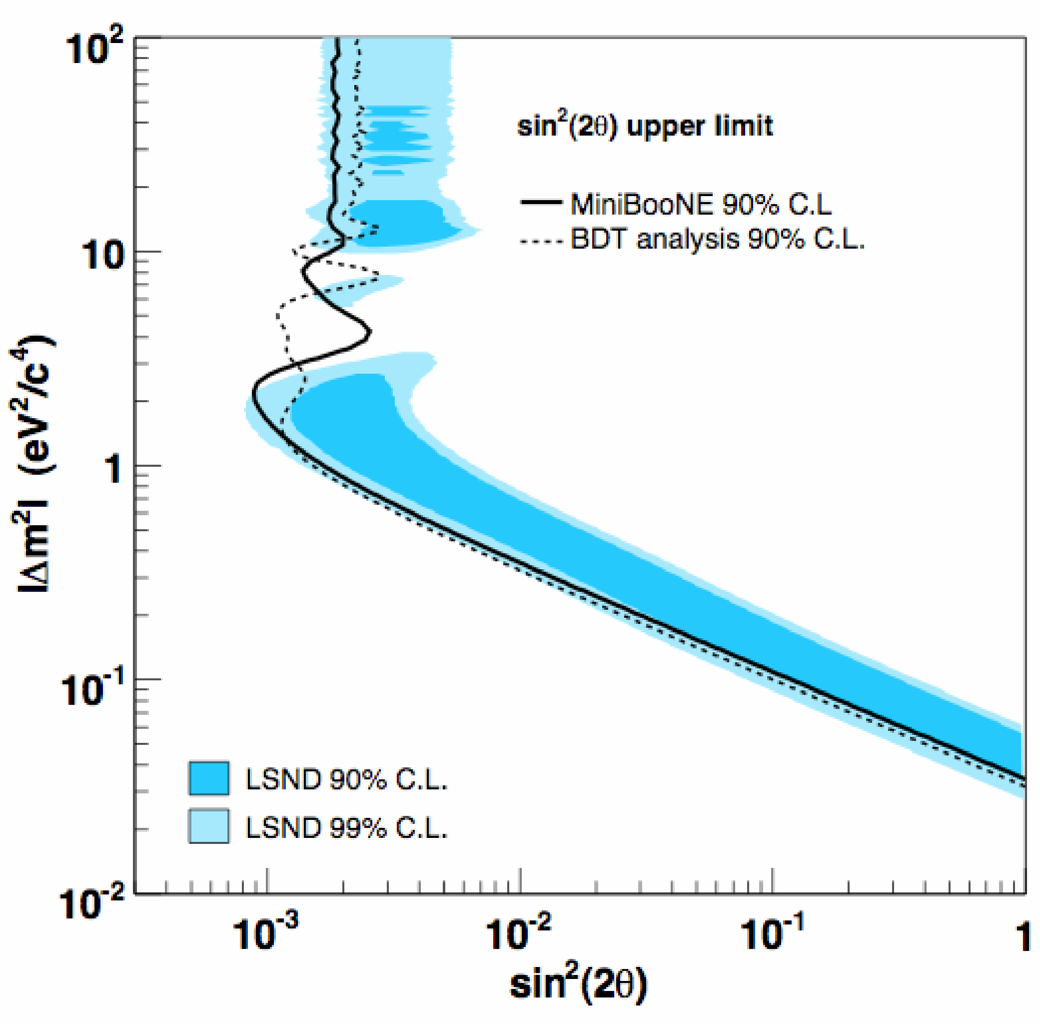
data: 971 events

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

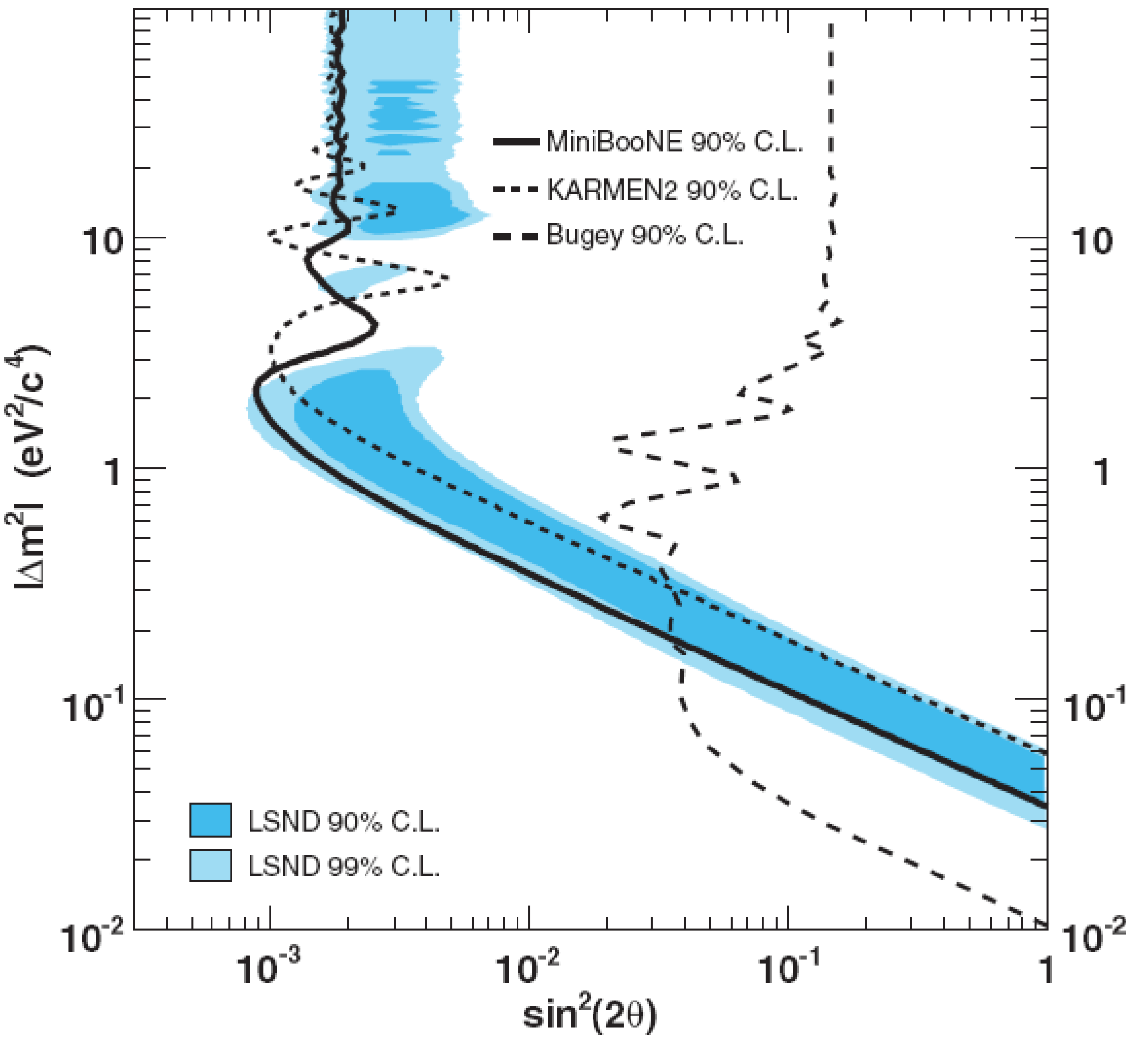


Energy-fit analysis:
solid: TB
dashed: BDT

Independent analyses are in good agreement.

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

Exclusion Limits (90% CL)



LSND signal: Yes or NO ? → **NO**

"As in many particle physics experiments, we have a result that answers some questions and raises others," said MiniBooNE co-spokesperson William Louis.

"It clears one mystery but it leaves us with a puzzle that is important to understand," said Fermilab Director Pier Oddone.

MiniBooNE low E excess: Yes or NO ?

Backup Slides

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.

Low E Excess (current status)

- ? Instrumental background: NO
- ? Study the excess with both Track and Boosting analysis
  - Are they consistent in energy and numbers: YES
  - Are there any reco issues (sidebands, etc): TB NO
  - Excess down to 200 MeV with systematic errors.
  - Is the excess electron/gamma-ray like: YES
- ? Is it a source of background
  - Dirt/Delta rays: NO
  - Pion or muon mis-id (including brem): NO
  - Evis and UZ (low stats) shapes favor numu background(?)
  - Photonuclear: ~20% of excess. Needs systematic errors.
  - Other source of backgrounds? Still Investigating
- ? Do other data sets have low E excess
  - NuMI -- different source, energy, baseline, backgrounds:
  - appears consistent in energy and scales with nue rate.

Low E Excess

- Future Work
- ? Continue checking reconstruction/PID.
- ? Study PN contribution to excess, confirm in data.
- ? Study new sources of backgrounds.
- ? Understand systematics below ~200 MeV
-   Apply to other distributions.
- ? Continue investigating forward excess.
- ? NuMI analysis matured, study correlations with
-   MB excess, i.e. excess/numu, excess/nue,
-   excess/pi0, etc. Does it scale with anything?
- ? Check excess with CCPi+ sample
- ? Check excess in Horn-off and anti-neutrino data.
-   Look for POT or (flux*xsec) scaling.

One, Two or Three Sterile Neutrinos ?

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

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

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

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

A MB-LSND-KARMEN-Bugey 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:

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

  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

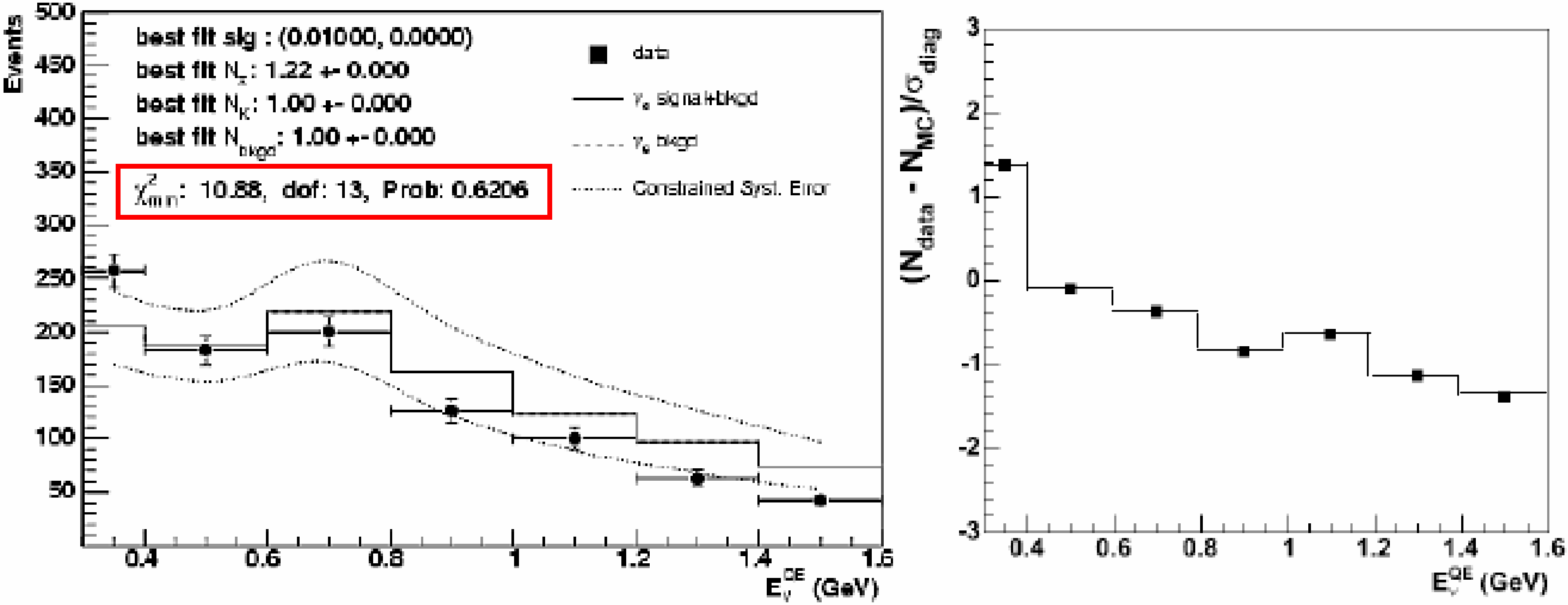
  (weighted average of two measurements) and this gives χ^2_{min}

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

  this is the joint compatibility probability for this Δm^2

➔ The combined compatible is at 8.6% C.L.

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



Error Matrix Elements:

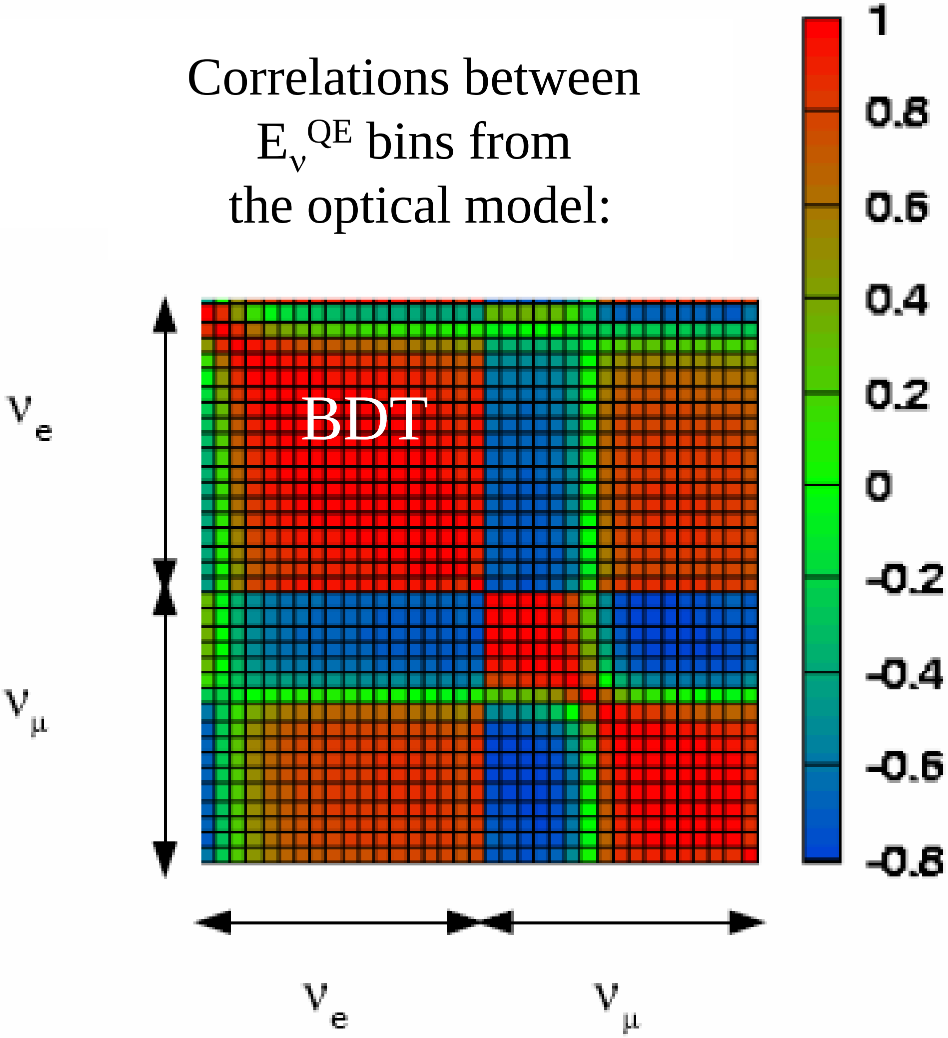
$$E_{ij} \approx \frac{1}{M} \sum_{\alpha=1}^{M} \left(N_i^\alpha - N_i^{MC}\right)\left(N_j^\alpha - N_j^{MC}\right)$$

- 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:



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)
QE σ norm	10%
QE σ shape	function of E_ν
ν_e/ν_μ QE σ	function of E_ν

determined from MiniBooNE ν_μ QE data

NC π^0 rate	function of π^0 mom
M_A^{coh}, coh σ	±25%
$\Delta \rightarrow N\gamma$ rate	function of γ mom + 7% BF

determined from MiniBooNE ν_μ NC π^0 data

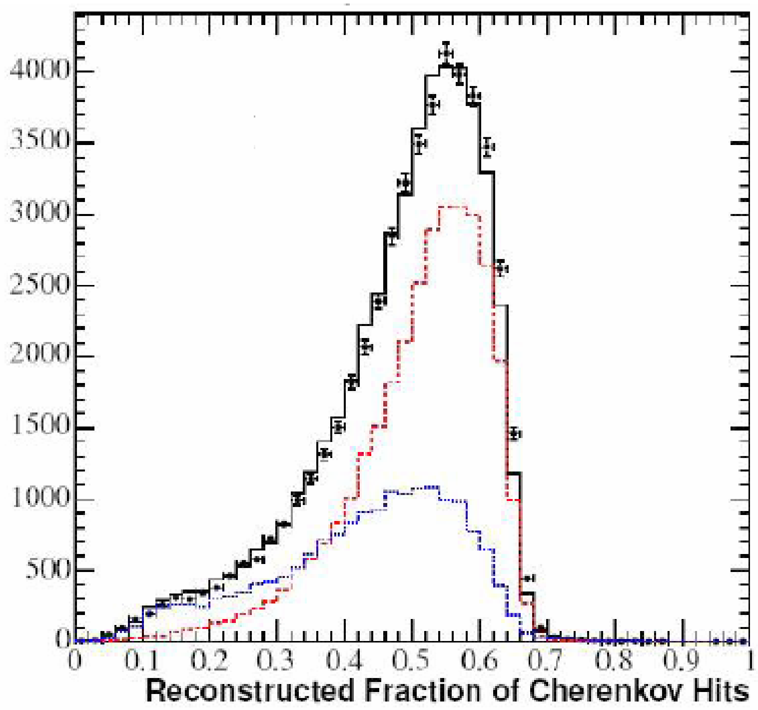
E_B, p_F	9 MeV, 30 MeV
Δs	10%
$M_A^{1\pi}$	25%
$M_A^{N\pi}$	40%
DIS σ	25%

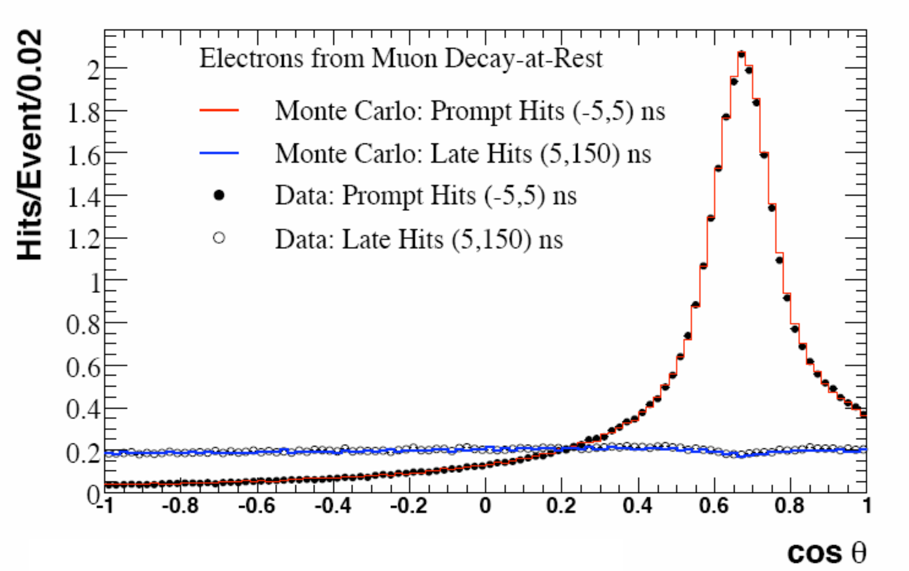
determined from other experiments

Example:
Optical Model Uncertainties

39 parameters must be varied

Allowed variations are set by the Michel calibration sample

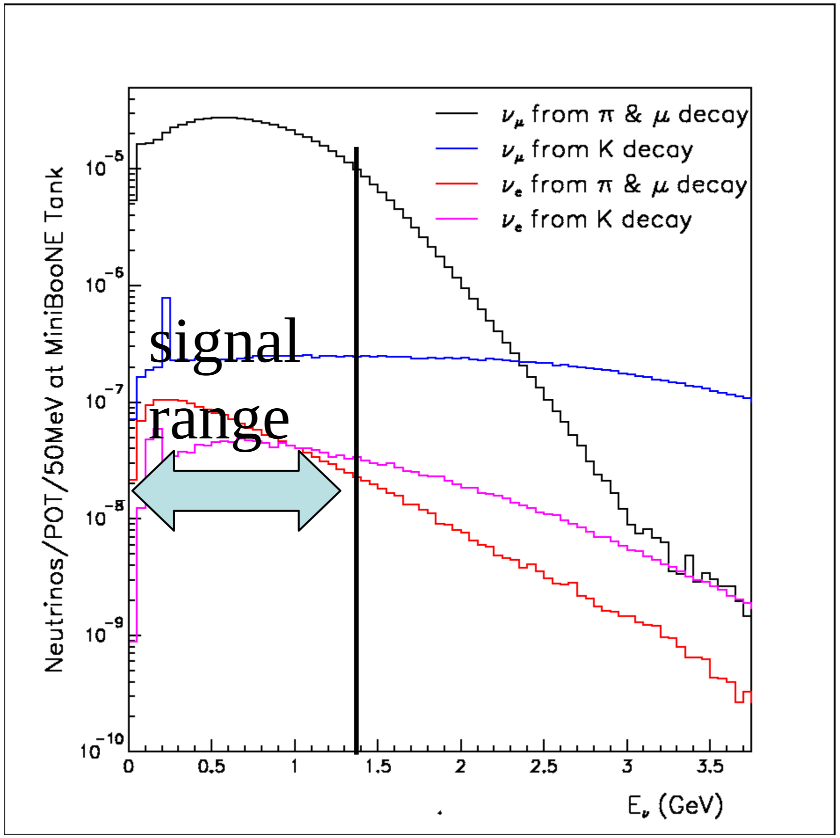




To understand allowed variations, we ran 70 hit-level simulations, with differing parameters.

$\Rightarrow$“Multisims”

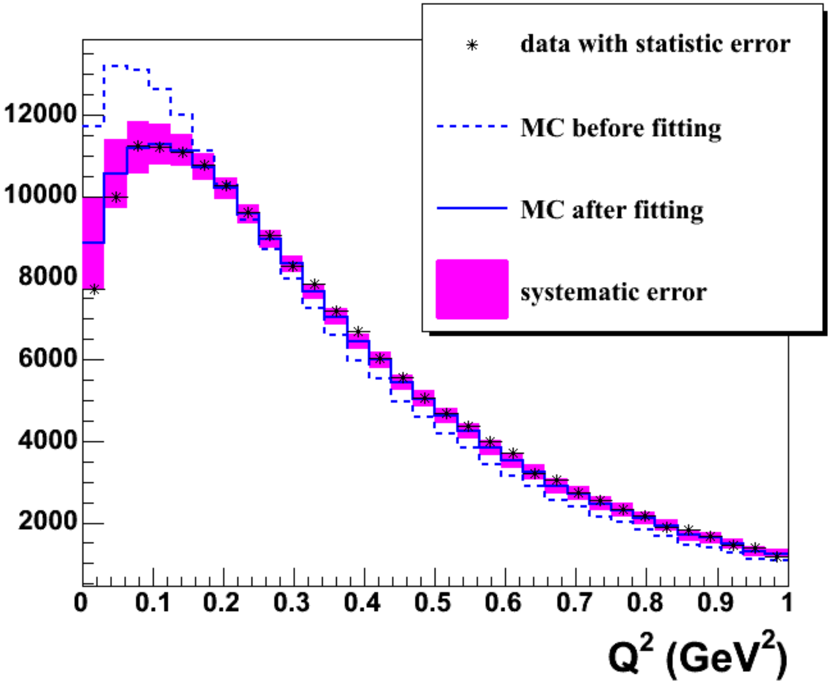
K^+ and K^0 Decay Backgrounds



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.

Nuance Parameters (ν_μ CCQE)



From Q^2 fits to MB ν_μ CCQE data:

M_A^{eff} -- effective axial mass

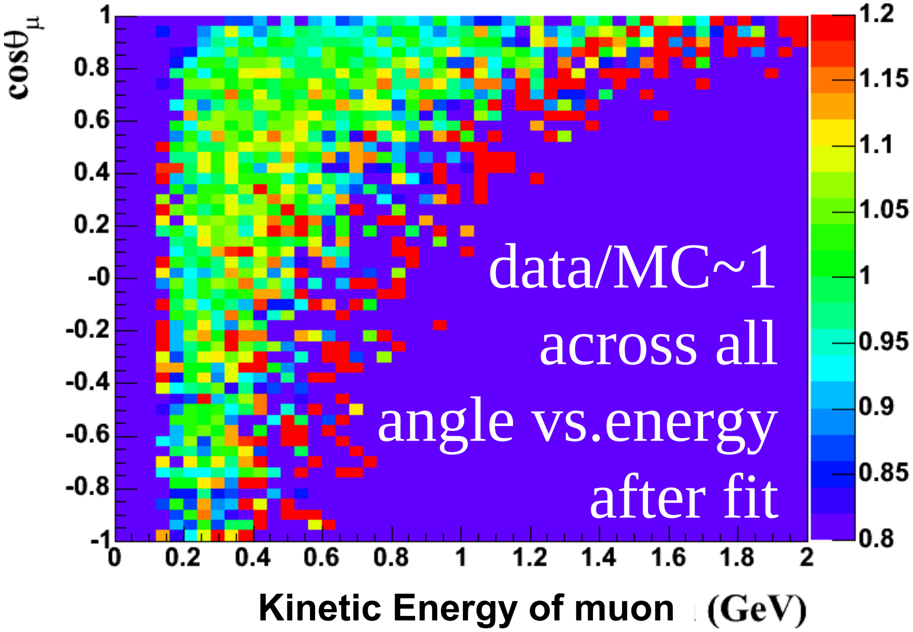
E_{lo}^{SF} -- Pauli Blocking parameter

From electron scattering data:

E_b -- binding energy

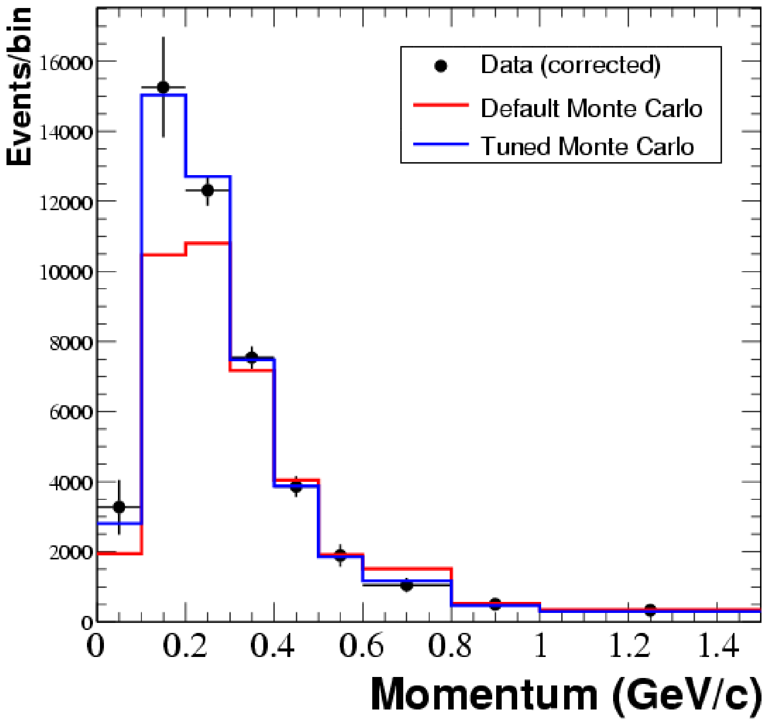
p_f -- Fermi momentum

Model describes CCQE ν_μ data well (arXiv:0706.0926)

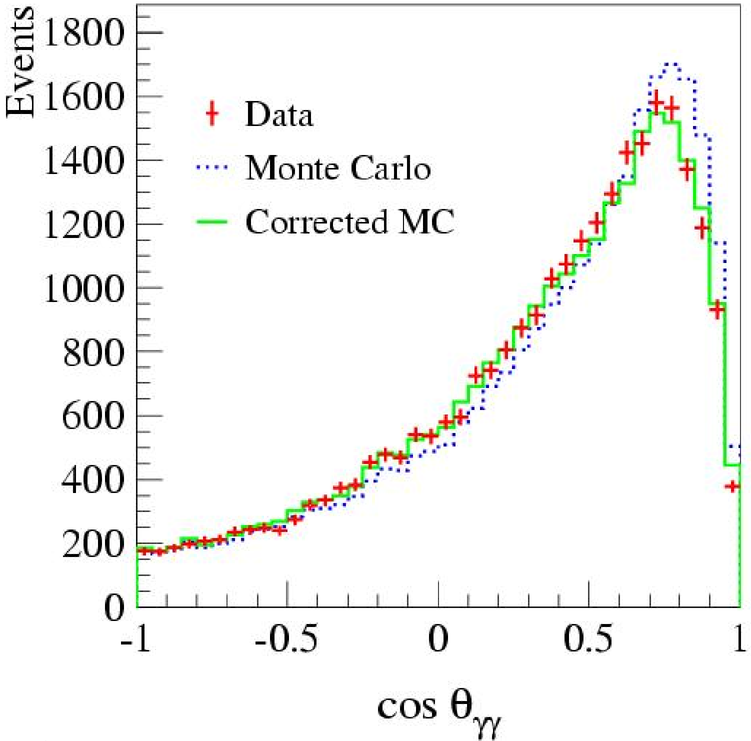


data/MC~1 across all angle vs.energy after fit

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.⇒

Because this constrains the Δ resonance rate, it also constrains the rate of Δ→Nγ

Other Single Photon Sources

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

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

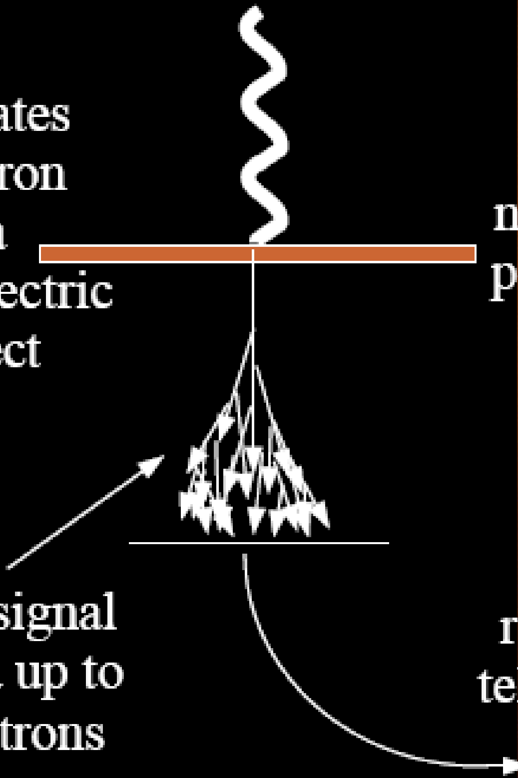
Charged Current < 6 events @ 95% CL

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

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.

Photo-Multiplier Tubes



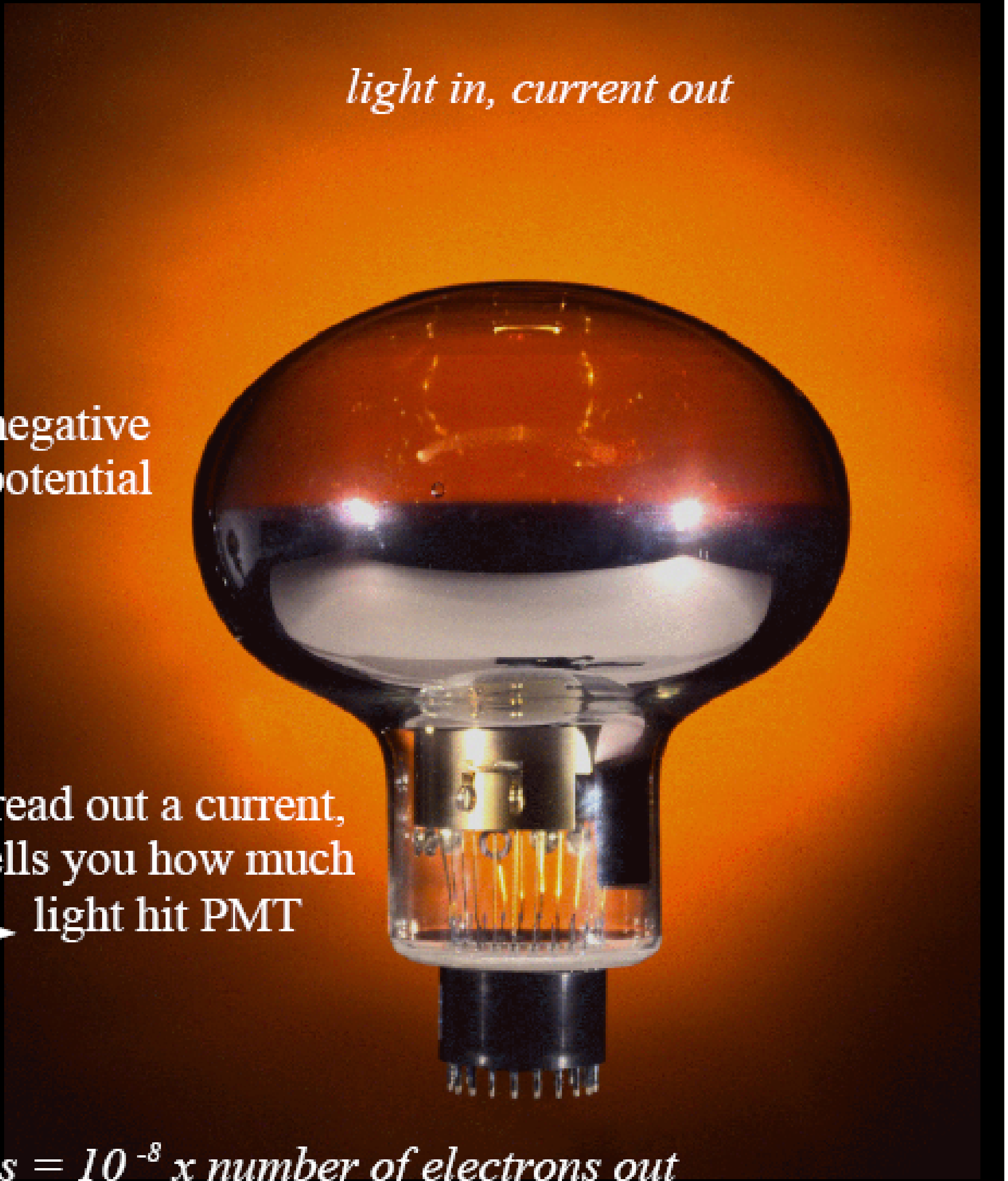
Photon

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



light in, current out

number of photons = 10^{-8} x number of electrons out

Neutrino Oscillations

Maki-Nakagawa-Sakata matrix (MNS matrix – neutrino mixing matrix)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

$|\nu_\alpha\rangle$ is a neutrino with definite flavor. α = e, μ, τ.

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i}\,|\nu_\alpha\rangle$$

$|\nu_i\rangle$ is a neutrino with definite mass. i = 1, 2, 3.

phase factor δ is non-zero if neutrino oscillation violates CP symmetry

phase factors α_1 and α_2 are non-zero if neutrinos are Majorana particles

$s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

$$\begin{aligned}
U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \\
&= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}
\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}
\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}
\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
&= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}
\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix},
\end{aligned}$$