Introduction to MiniBooNE and ν_μ Charged Current Quasi-Elastic (CCQE) Results

Byron P. Roe

University of Michigan

For the MiniBooNE collaboration

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

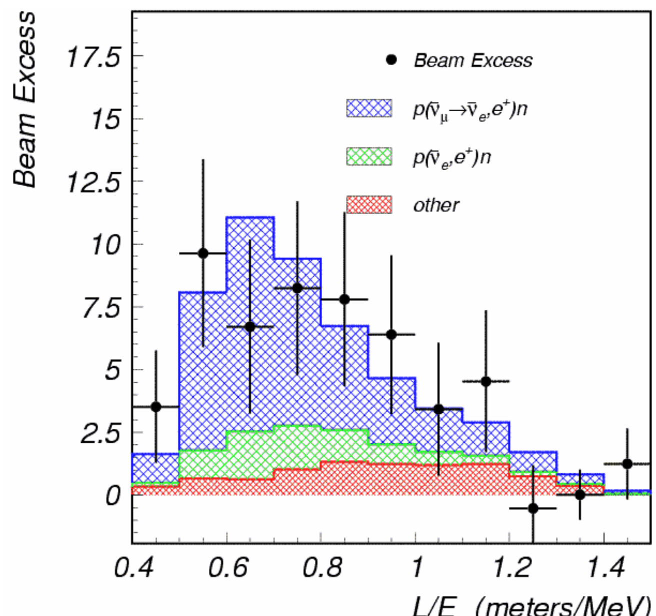
University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle University
Fermi National Accelerator Laboratory
Indiana University
Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's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

74 people, 16 Institutions

MiniBooNE was approved in 1998,
with the goal of addressing the LSND anomaly:

an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam,
87.9 ± 22.4 ± 6.0 (3.8σ)

which can be interpreted as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations:



Points -- LSND data
Signal (blue)
Backgrounds (red, green)

LSND Collab, PRD 64, 112007

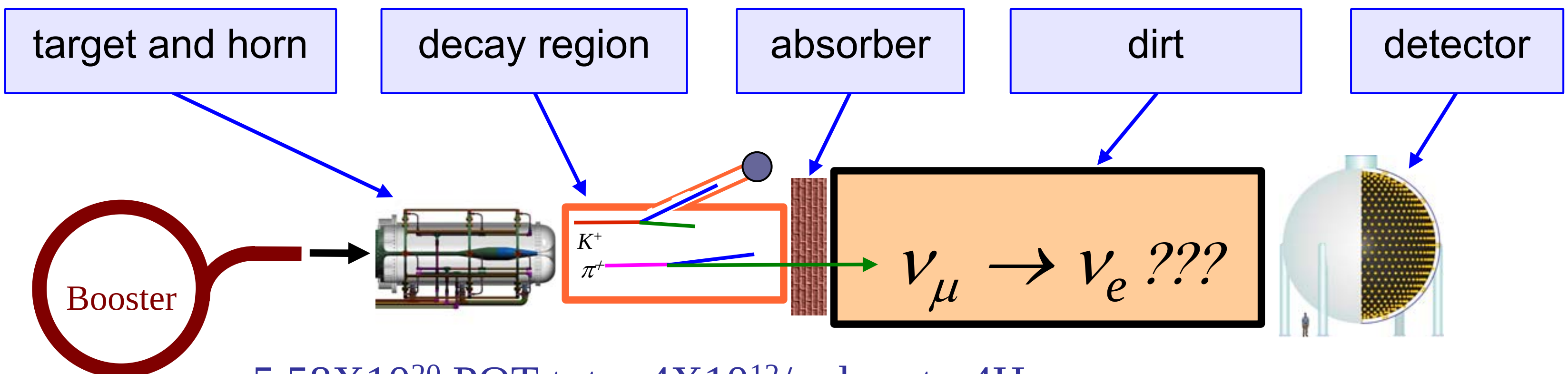
MiniBooNE's Design Strategy...

Keep L/E same

while changing systematics, energy & event signature

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$

71 X 1 cm Be | 50 m, r=91cm | Detector 541 m from target front



5.58×10^{20} POT tot; $\sim 4 \times 10^{12}$/pulse at ~4Hz

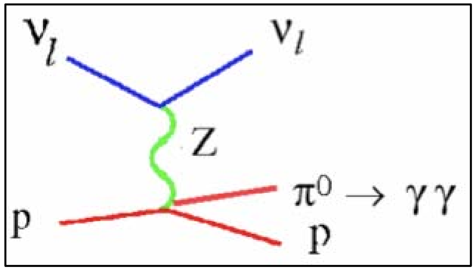
primary beam (protons) → secondary beam (mesons) → tertiary beam (neutrinos)

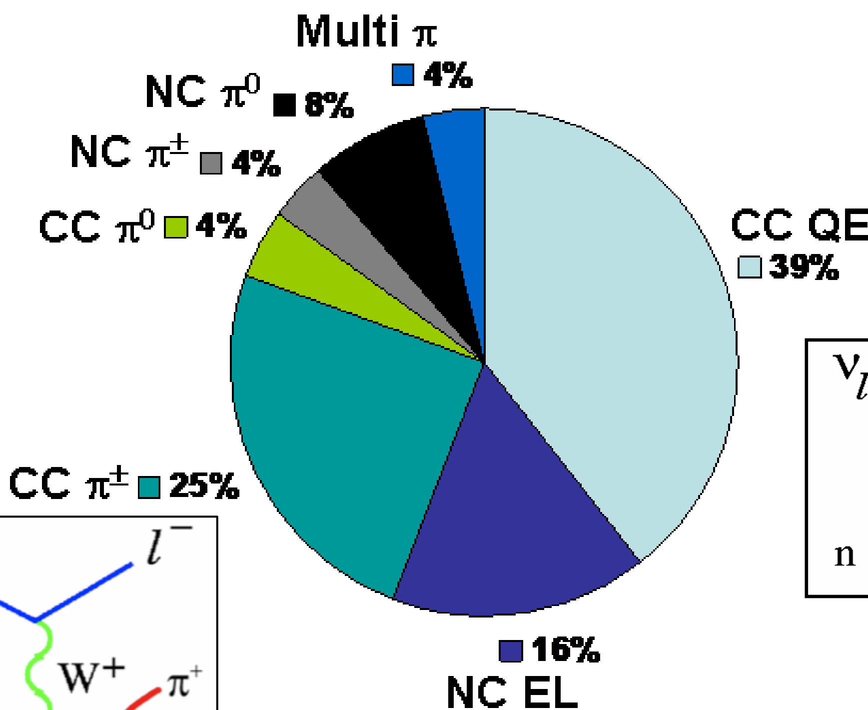
Order of magnitude higher energy (~500 MeV) than LSND (~30 MeV)

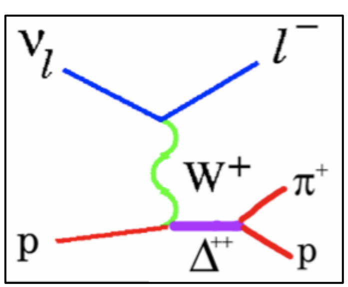
Order of magnitude longer baseline (~500 m) than LSND (~30 m)

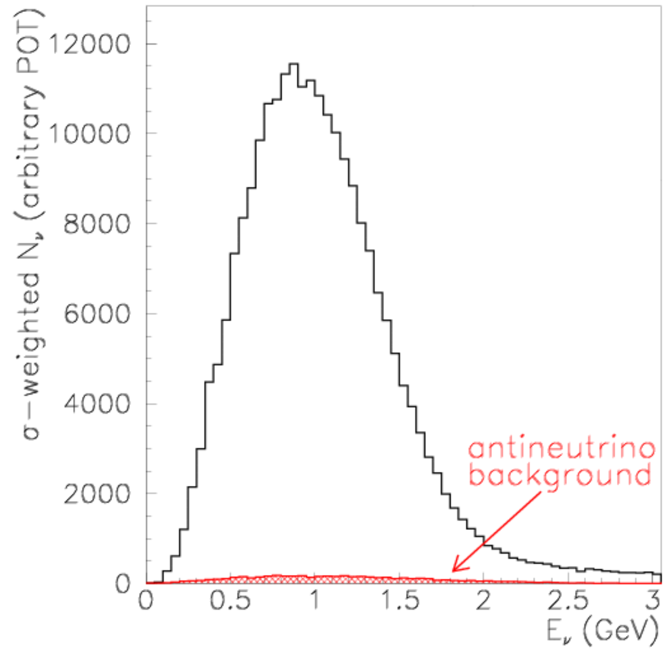
Predicted event rates before cuts (NUANCE Monte Carlo)

D. Casper, NPS, 112 (2002) 161

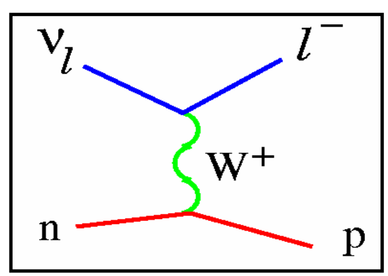








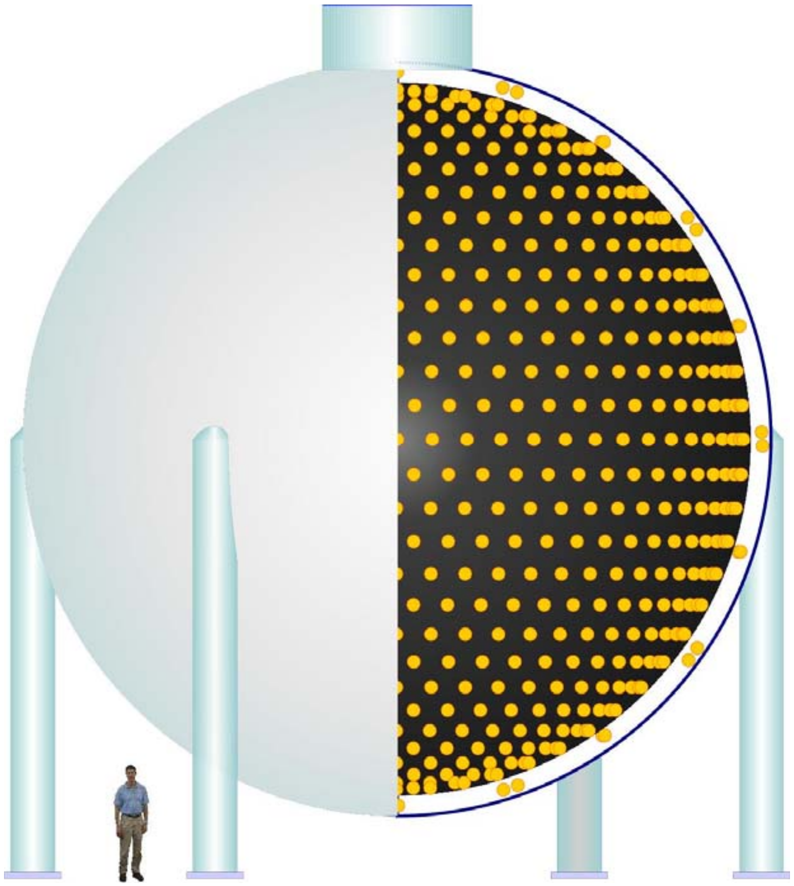
Event neutrino energy peaks at ~0.7 GeV



ν_e/ν_μ=0.5%; anti-ν=6%

Most ν_e from μ, K decays

The MiniBooNE Detector

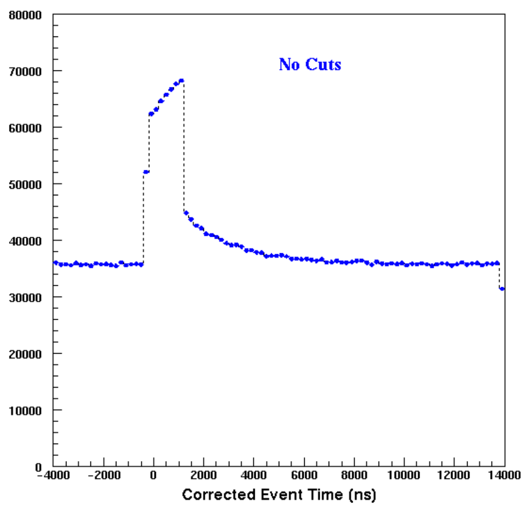


- 541 meters downstream of target
- 3 meter overburden of dirt
- 12 meter diameter sphere
  (10 meter "fiducial" volume)
- Filled with 800 t of pure mineral oil (CH_2--
  density 0.86, n=1.47)
  - (Fiducial volume: 450 t)
  - 1280 inner 8" phototubes-10% coverage,
    240 veto phototubes

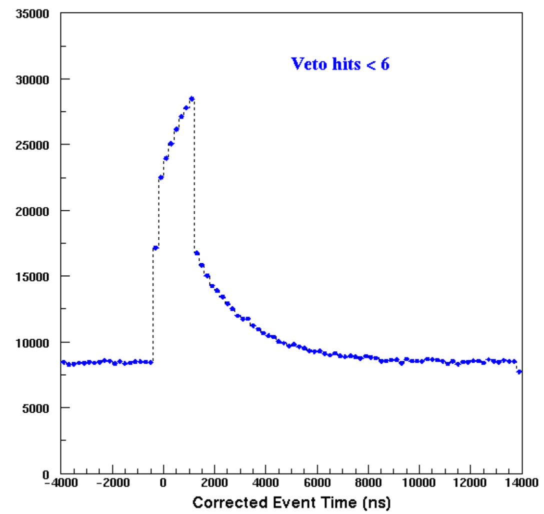
(Less than 2% channels failed during run)

Progressively introducing cuts (19.2 μs time window starting 4 μs before beam)

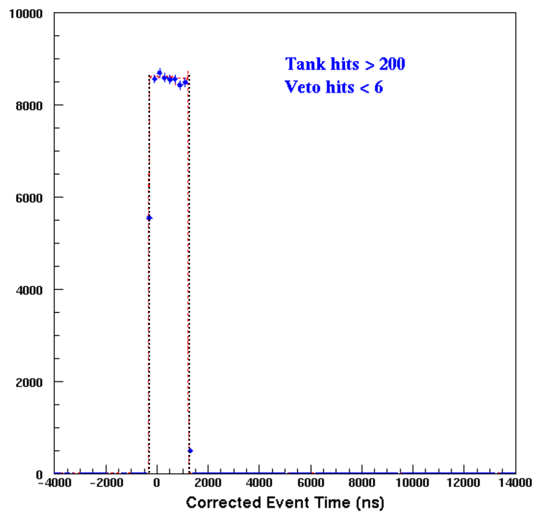
Phototubes have 1.7 ns (~75%) and 1.2 ns time resolutions



Raw data



Veto<6 removes through-going cosmics (~2 CR in entire oscillation set)
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 MeV endpoint

Subevents; Kinds of Light

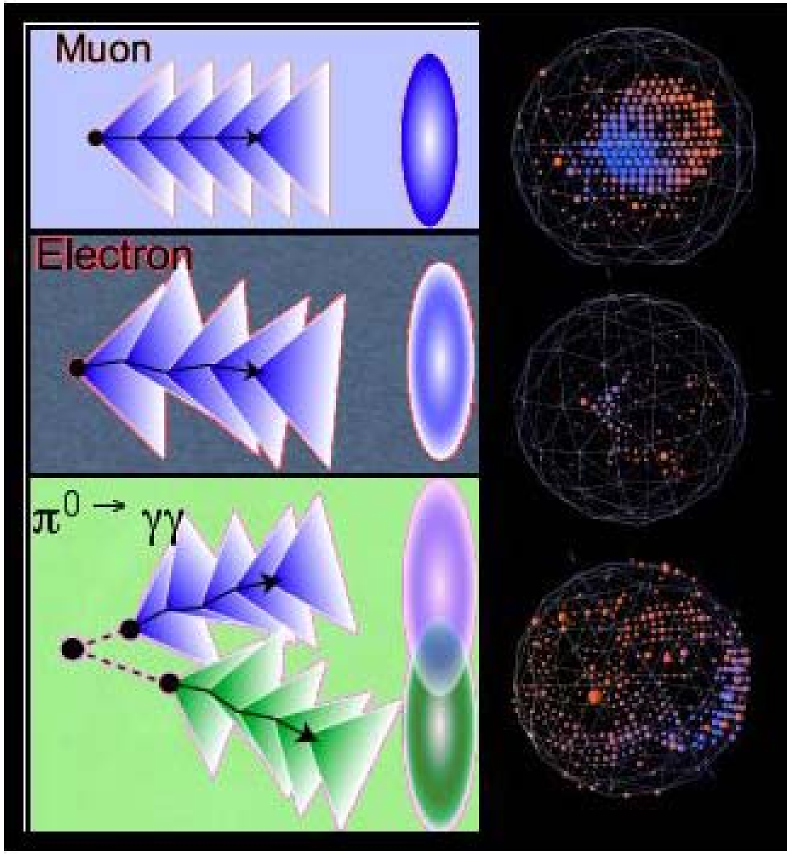
- 100 ns bins for subevents (separate mu-decays)
- Cherenkov/scintillation light about 8/1. Cherenkov comes at fixed angle to track direction and is prompt. Scintillation light and light scattered by flourescence is delayed.
- Flourescence and attenuation important and functions of frequency; prompt/delayed light at phototubes is about 10/1 on the average.

The types of particles these events produce:

Muons:
Produced in most CC events.
Usually 2 subevents (only 8% μ^- capture) 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.



Reconstruction

- Initial guess. Position mainly from timing of hits; angle from a grid of possibilities using prompt (Cherenkov) light
- Final fit. Minuit fits to hypotheses

  a. One outgoing muon track

  b. One outgoing electron track

  c. Two tracks (aimed at π^o events)

Two Analysis Chains

For most of analysis had two equal reconstructions, sfitter, rfitter

- Toward end of analysis, a new more powerful reconstruction based on sfitter—the pfitter became available. Better especially on 2 track fits (22 cm position error, 2.8^o 1 track angle error, ~20 MeV π^0 mass resolution)—BUT takes about 10 times more computer time.
- rfitter dropped, sfitter and pfitter retained.

Simulations

- Use measured proton cross sections (Harp, BNL910, earlier experiments)
- Geant4 for following produced particles through magnetic horn, decay region…
- V3 Nuance for neutrino cross sections (mod. by MiniBooNE measurements and other improvements.)
- Detailed optical model for detector using GEANT3. (39 model parameters--obtained from measurements)

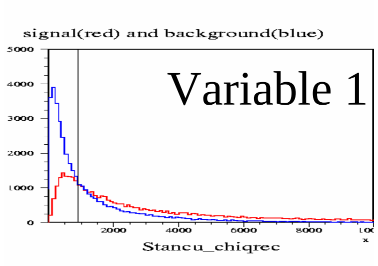
Plan

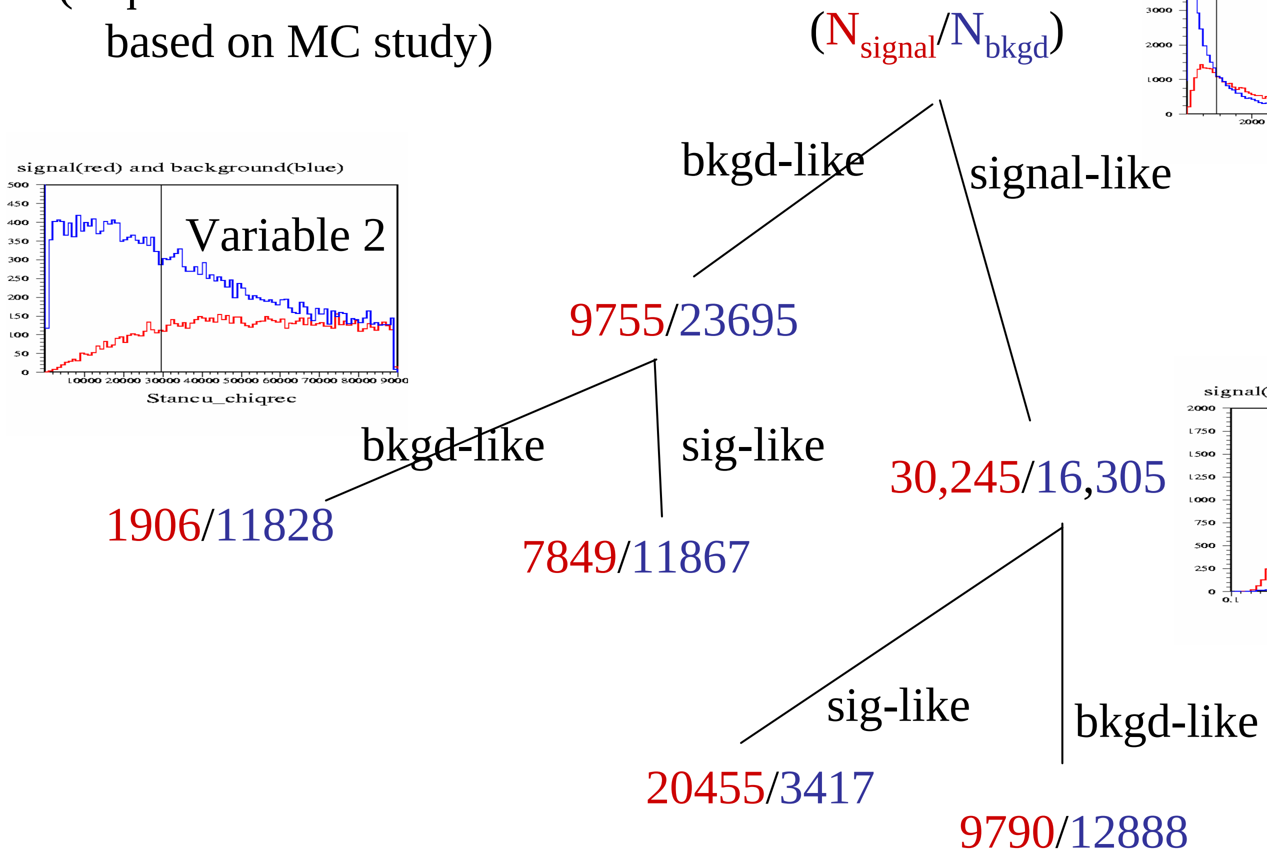
- First discuss ν_e CCQE selection for the oscillation analysis
- Then present ν_μ CCQE cross section results.

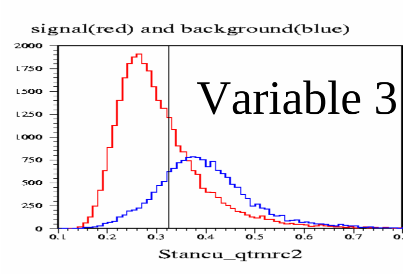
Event Classification Schemes for Oscillation Measurement

- Signal events were defined as ν_e CCQE events
- Pfitter used simple cuts (TB--"Track based analysis") to separate these events based on:
  a. Likelihood of 1 track e-fit vs 1 track μ-fit
  b. Likelihood of 1 track e-fit vs 2 track fit
  c. Mass of π^0 in 2 track fit
- Sfitter used a method new to physics— boosted decision trees (BDT) with many variables (172)

A Decision Tree
(sequential series of cuts based on MC study)



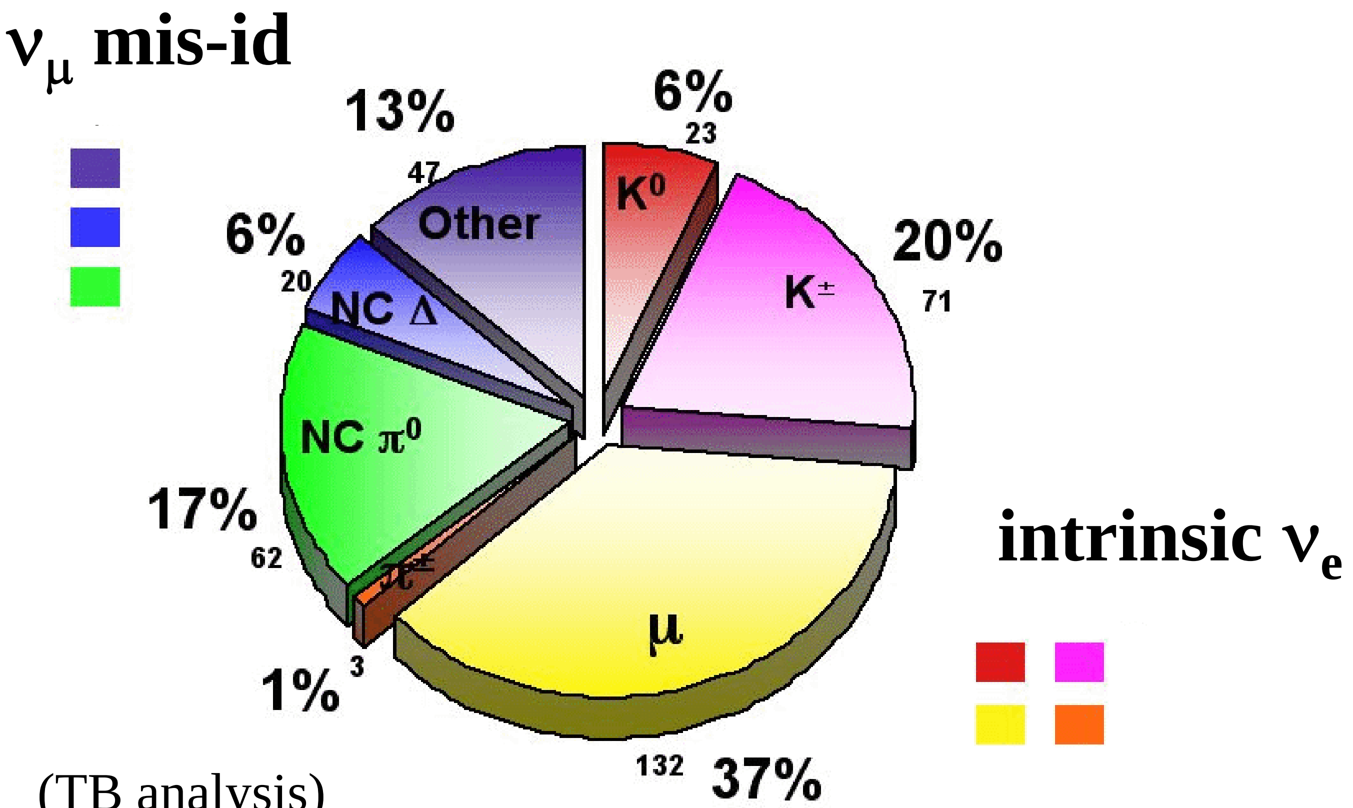




etc.

Weight events misclassified higher and make new “boosted tree”. Continue 100’s of times; sum results of each tree: 1 if signal leaf, -1 if background leaf

We have two categories of backgrounds:



(TB analysis)

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 Tree 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*	√	

* Errors quoted are before constraints from measured ν_μ flux which strongly reduces them

Charged Current ν_μ Quasi Elastic Events

- Close to 2 o.m. more events than any previous experiment
- 39% of all neutrino interactions before cuts
- 193,709 events asking for 2 subevents and that the second subevent be consistent with μ decay in position and have <200 hits. 60% eff.
- KE resolution 7% at 0.3 GeV, angular res. ~5^o
- 74% pure—mostly π backgrounds
- Mainly $0<Q^2<1$ GeV^2

Standard Parameters Don't Work

- Relativistic Fermi Gas nuclear model
- P_F=220 MeV/c; E_B=34 MeV; F_V from electron experiments.
- Axial Vector FF = $g_A/(1+ Q^2/M_A{}^2)^2$ with g_A =1.2671 and M_A= 1.03 GeV from previous low statistics ν expts mostly on lighter targets.

Discrepancy tends to follow lines of constant Q^2 rather than lines of constant energy

Correction to Pauli Blocking Term

Smith & Moniz model

- Carbon is described by the collection of incoherent Fermi gas particles.
- all complications come from hadronic tensor;

$(W_{\mu\nu})_{lab} = \int_{Elo}^{Ehi} f(\vec{k}, \vec{q}, \omega) T_{\mu\nu}$: hadronic tensor

$f(\vec{k}, \vec{q}, \omega)$: density function (energy conservation, state distirubtion)

$T_{\mu\nu} = T_{\mu\nu}(F_1, F_2, F_A, F_P)$: nucleon tensor

Ehi : the highest energy state of nucleon $= \sqrt{(PF^2 + M^2)}$

Elo : the lowest energy state of nucleon (for QE interaction $= \sqrt{(PF^2 + M^2)} - \omega_{eff}$)

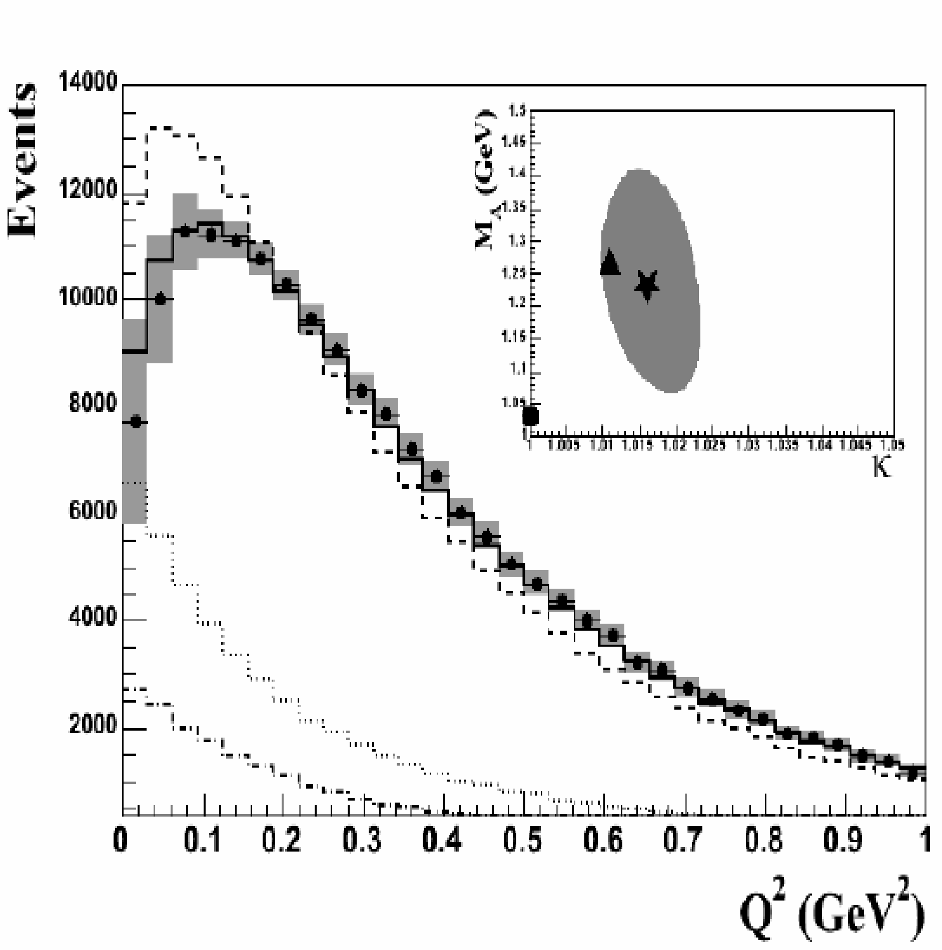
ω = energy transfer

New term: Scale Elo—multiply by κ. (Default 1) Effectively changing energy level distribution.

Best fit is M_A=1.23 +/- 0.20; κ=1.019+/-0.011

arXiv:0706.0926 (hep-ex), submitted to PRL.

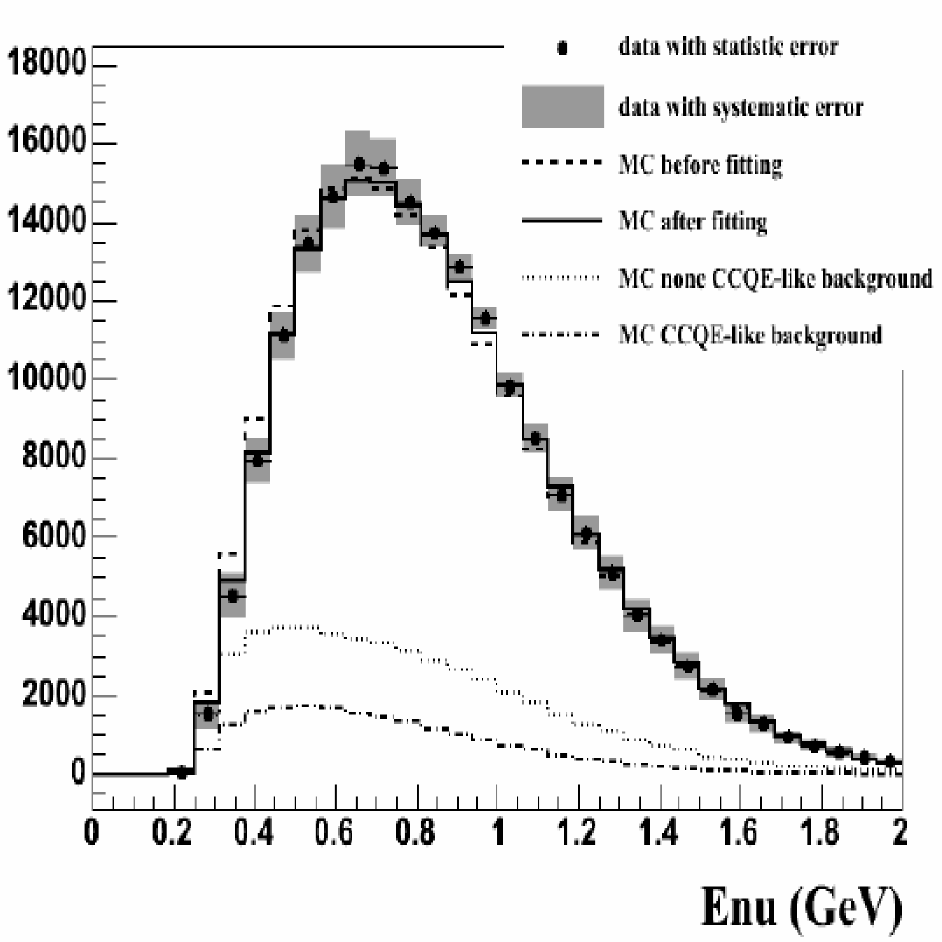
Results



- Dashed—before fit
- Solid—after fit
- Dotted—background
- Dash dotted CCQE-like background (only μ in final state)
- Dots—data with error
- Star—best fit point
- Circle—Original values
- Triangle—Best varying CCPIP background

- χ^2/dof 58.1 before 32.8 after fit for 30 d.f.

CCQE Energy Distribution



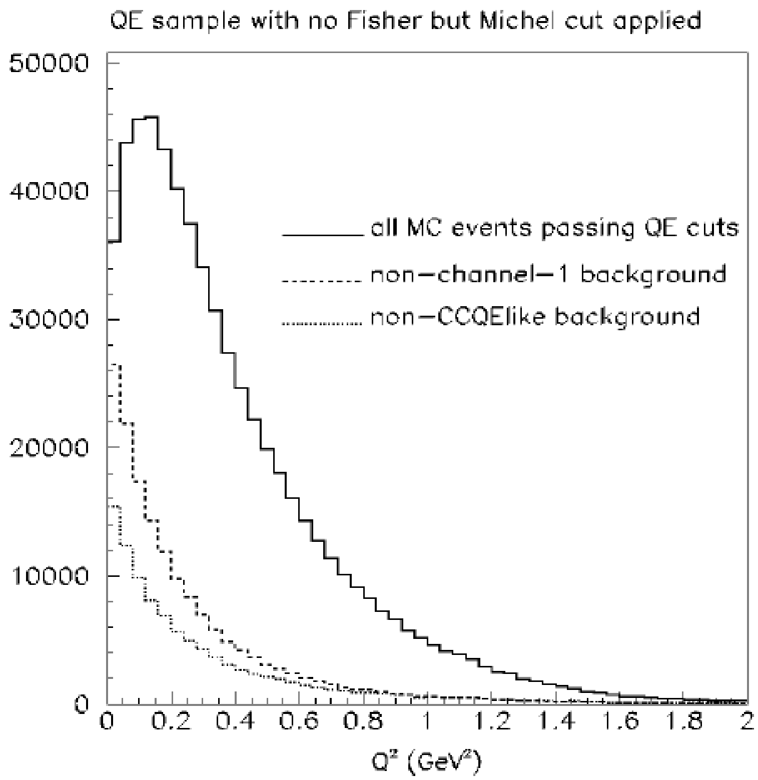
- The new variable, κ, is empirical. It corresponds to a change in the nuclear energy levels.
- This data should provide a guide leading to a better nuclear model.
- The fitted distribution was critical for normalization for the oscillation analysis: 5.6% increase in pred. ν_μ CCQE events

BACKUP

Modifications to V3 NUANCE

- MiniBooNE measured CCQE results
- MiniBooNE measured p dependence of π^0 production
- MiniBooNE measured cohent pion production
- Tuned final state interaction model
- Explicit nuclear de-excitation photon emission model
- Angular correlation for Delta (1232) to agree with Rein-Sehgal model

Charged Current Quasi-Elastic Events



Close to 2 o.m. larger sample than any previously

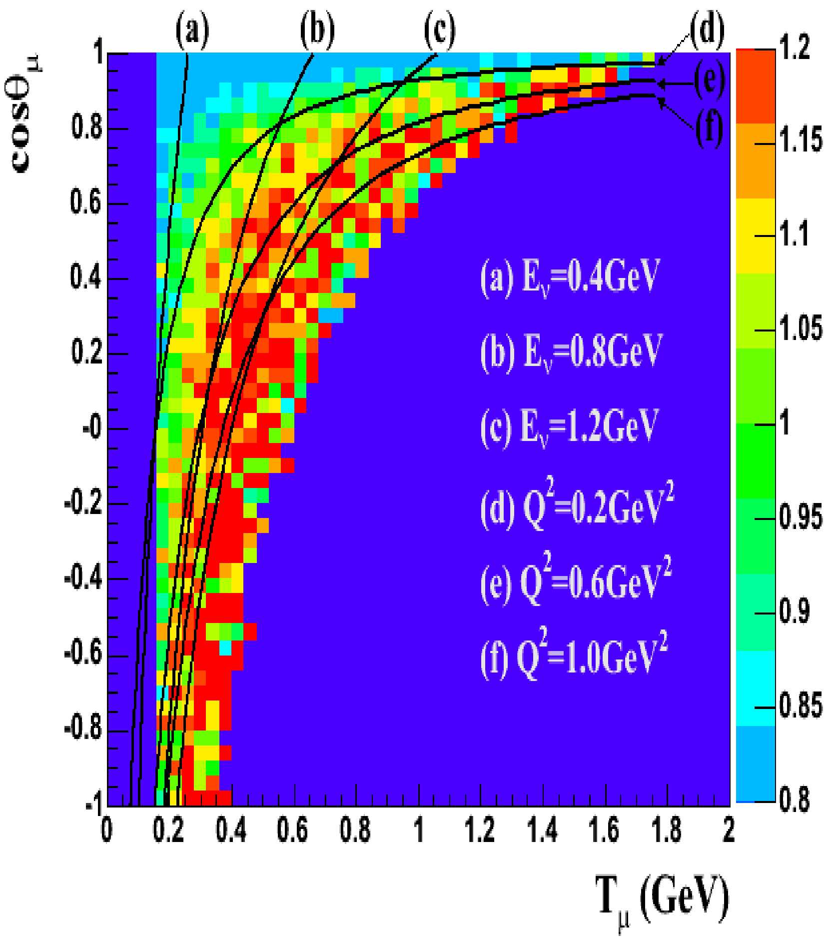
193,709 CCQE events asking 2 subevents and 2nd vertex consistent with decay <200 hits (60% eff.)

KE res 7% at 0.3 GeV; angular res. ~5°

74% pure—mostly π backrounds

- $0<Q^2< 1$ GeV^2

Standard Parameters Don't Work



- Relativistic Fermi Gas
- p_F=220, E_B=34 MeV, F_V (from electron expts)
- AV FF M_A=1.03GeV; g_A=1.2671 (from previous ν expts) $F_A=g_A/(1+Q^2/M_A{}^2)^2$
- Discrepancy follows lines of constant Q more than constant E