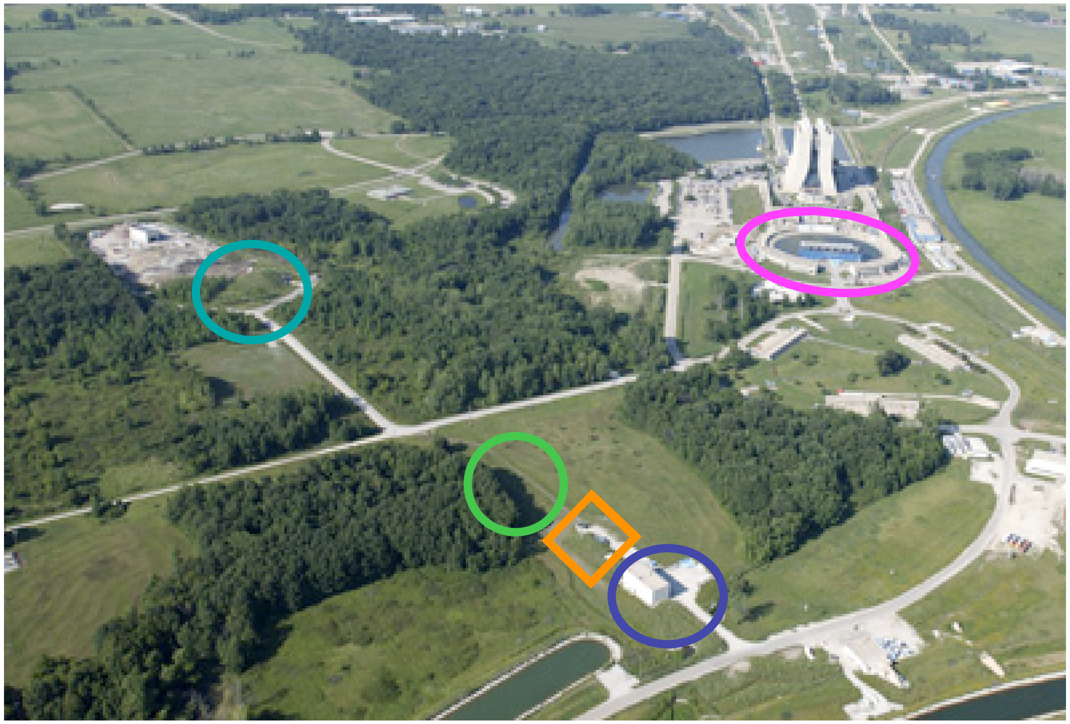
Recent results of and future plans for the Booster Neutrino Beamline

Kendall Mahn, Columbia University
for the MiniBooNE and SciBooNE collaborations

Outline

- One beam...
  - Booster Neutrino Beamline
  - Resulting flux
- Two experiments...
  - SciBooNE detectors
  - MiniBooNE detector
- Physics!
  - Oscillation
  - Cross section measurements
    - Neutrino and Antineutrino
- Summary

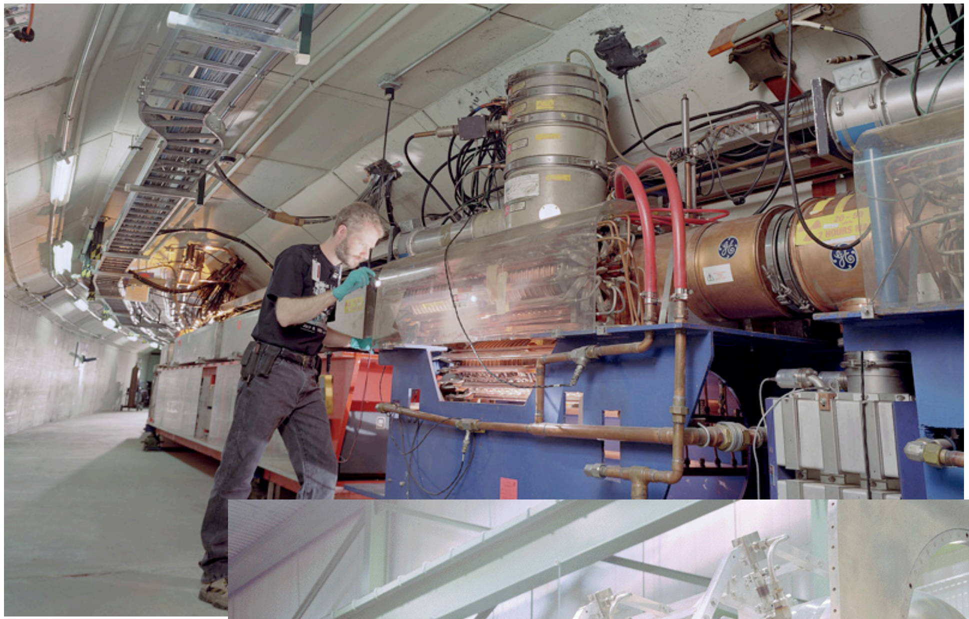
The big picture

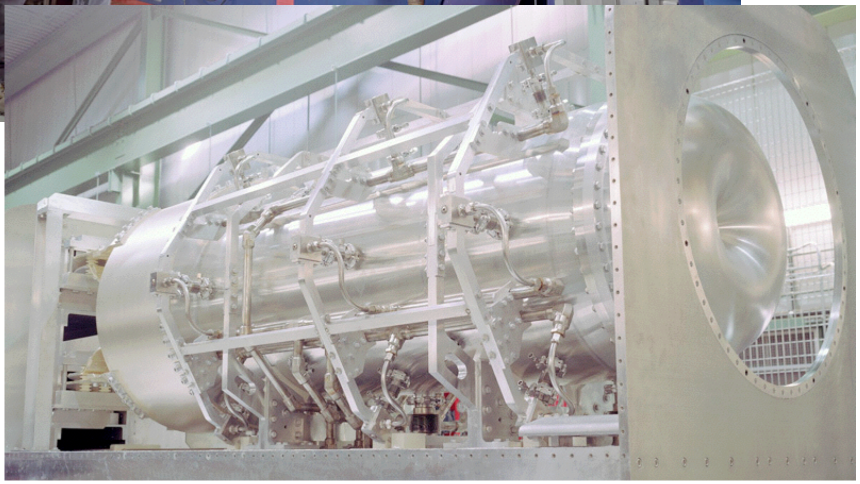


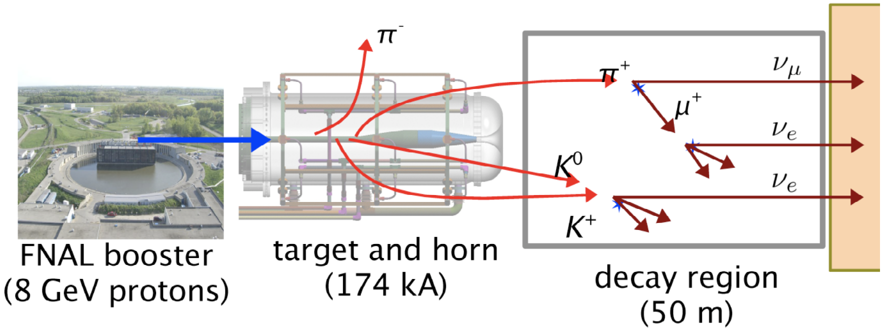
- 8.9 GeV/c protons from Booster accelerator
- protons hit a target within a magnetic focusing horn and produce mesons
- The mesons decay into neutrinos the ~450 m decay region
- Neutrinos are observed in MiniBooNE and SciBooNE

Booster Neutrino Beamline (BNB)

- Booster
  4x10^{12} protons / 1.6 μs pulse delivered at up to 5 Hz
- Target
  1.7 λ Be target
- Magnetic horn
  Pulses at 2.5 kV, 174kA
  Increases flux by ~x6

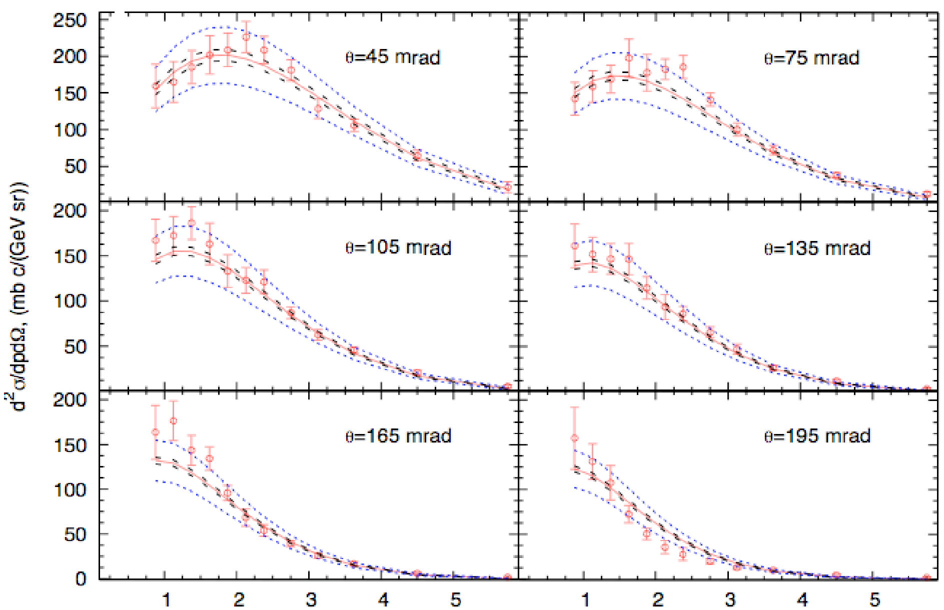




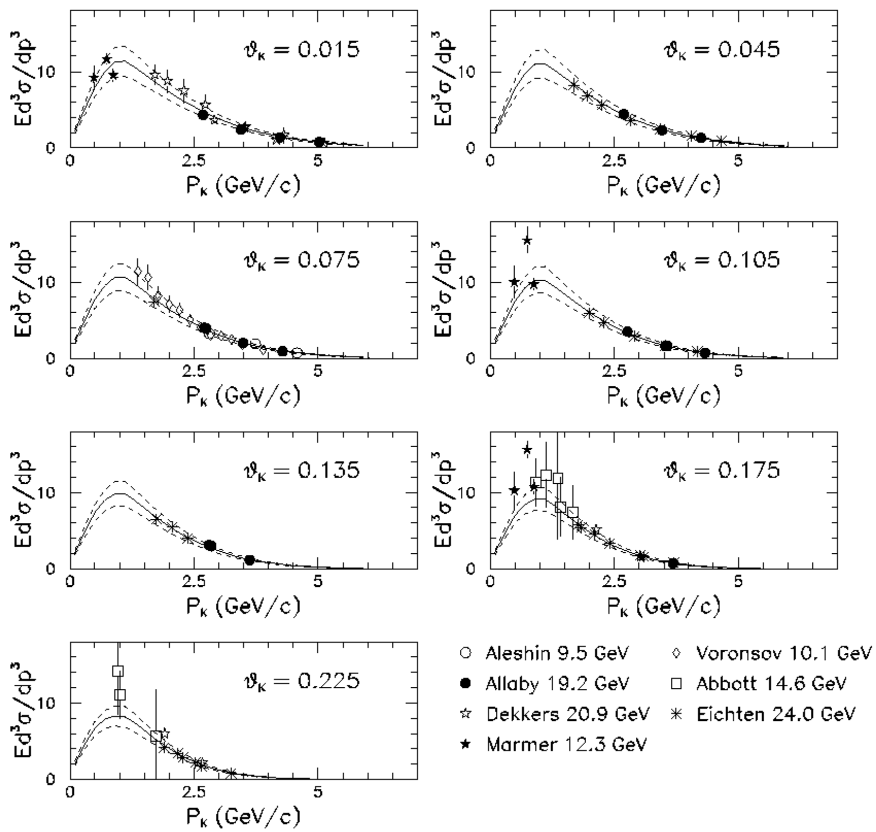


Secondary meson production

HARP 8.9 GeV/c pBe π^+ production



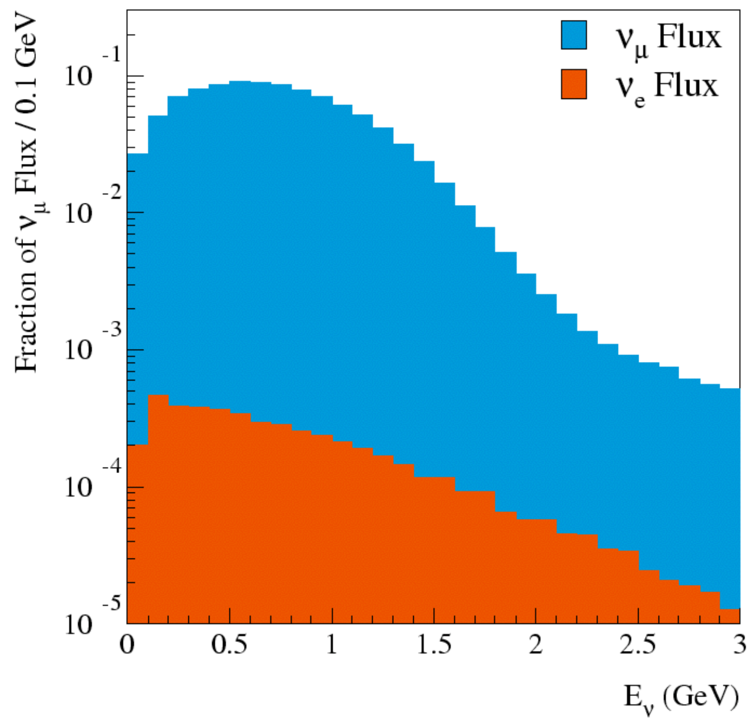
External measurements of pBe K^+ production from 9.5 to 24 GeV, scaled to 8.9 GeV/c



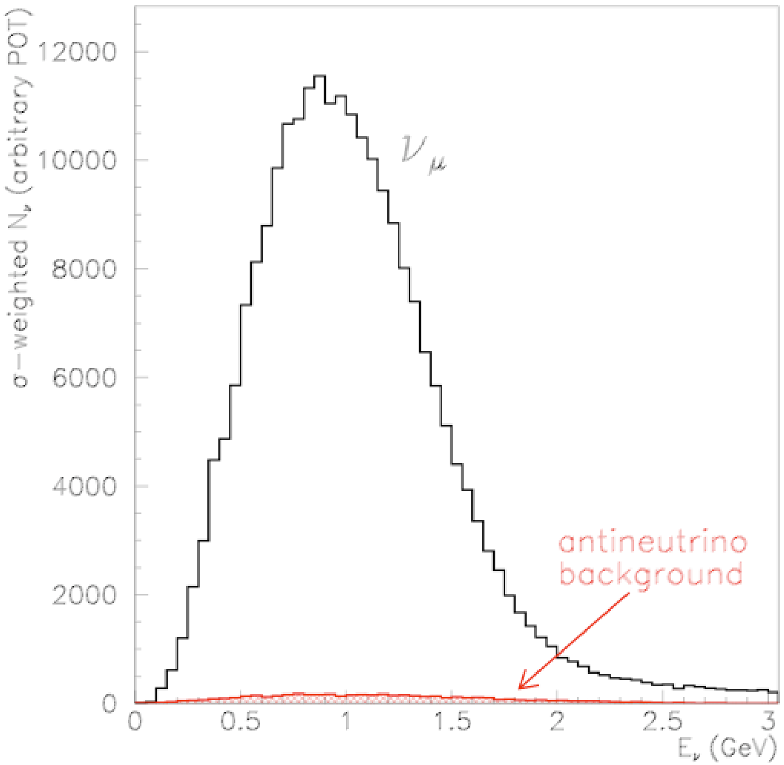
- For π^+, K^+ ,and K^0 production use a parameterization to fit the existing data
- Errors span spread in data as well as fit errors

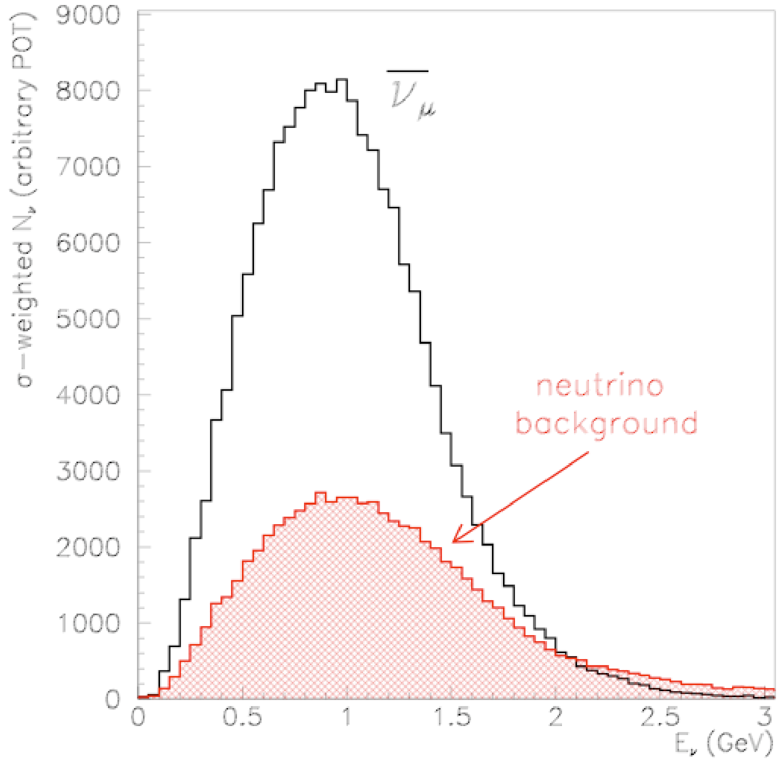
Neutrino flux

- Geant 4 model of beamline
- ν_μ predominantly from π^+ except at high energy (K^+)
- 0.5 % ν_e content
  - 52% $\mu \Rightarrow e^+ \nu_\mu \nu_e$
  - 29% $K^+ \Rightarrow \pi^+ e^+ \nu_e$
  - 14% $K^0 \Rightarrow \pi e \nu_e$
  - 5% other
- 6% antineutrino content



Antineutrino flux



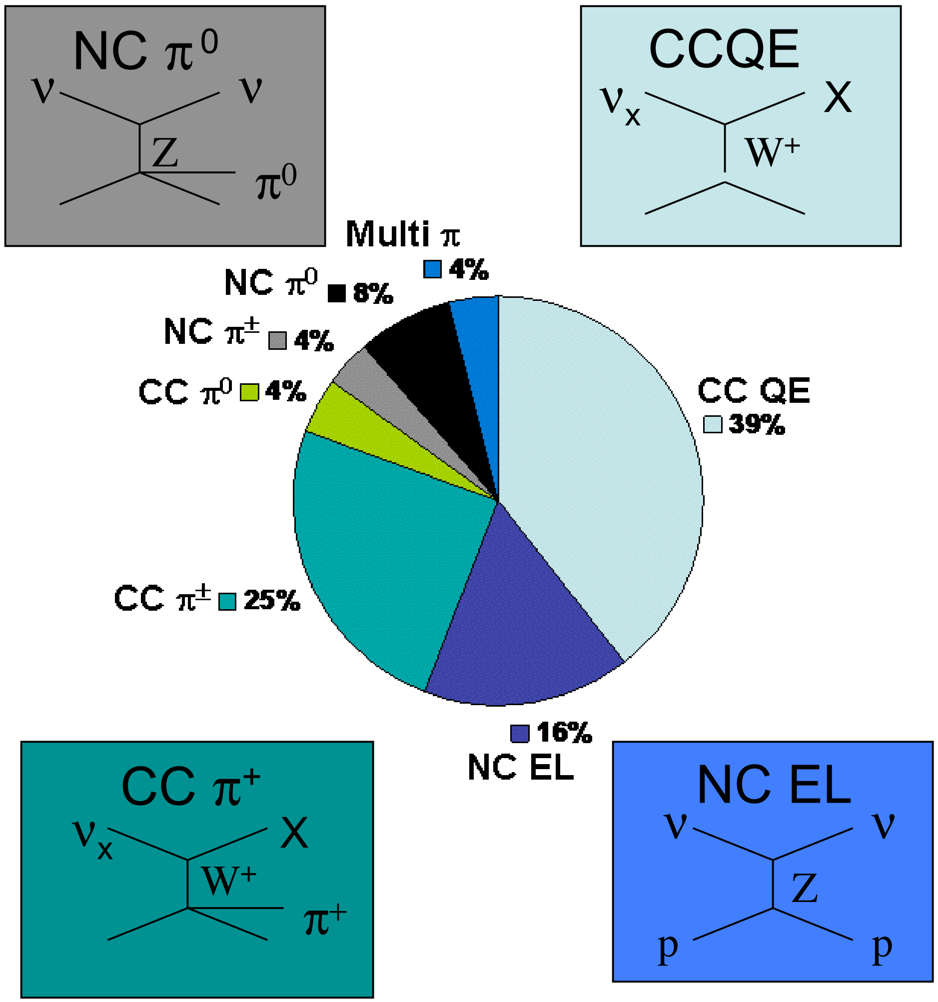


- Reversible horn current; can focus negatively charged mesons for an antineutrino beam

  $\pi^- \Rightarrow \overline{\nu}_\mu$ vs $\pi^+ \Rightarrow \nu_\mu$
- Flux for antineutrino mode has substantial neutrino contamination, lower overall rate

Interactions in the BNB

- Nuance Monte Carlo
  - D. Casper, NPS, 112 (2002) 161
- Largest interaction is charged current quasi elastic (CCQE)
  - Common channel for normalization, oscillation analyses
- Next largest is charged current single pion production (CC π^+)
  - background in CCQE samples
- Also Neutral current pion production (NC π^0) and Neutral current elastic scattering (NC EL)



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  - MiniBooNE detector
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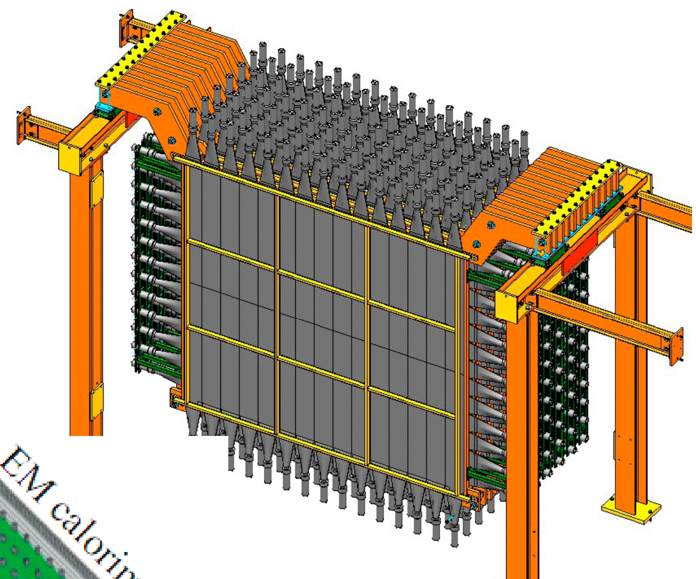
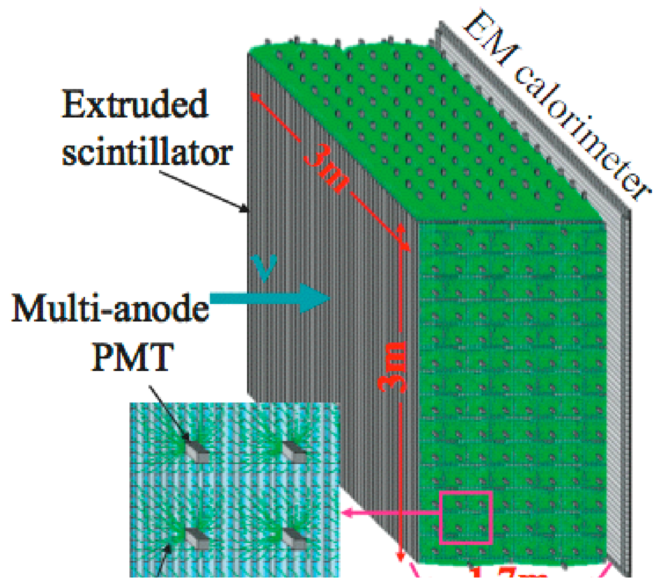
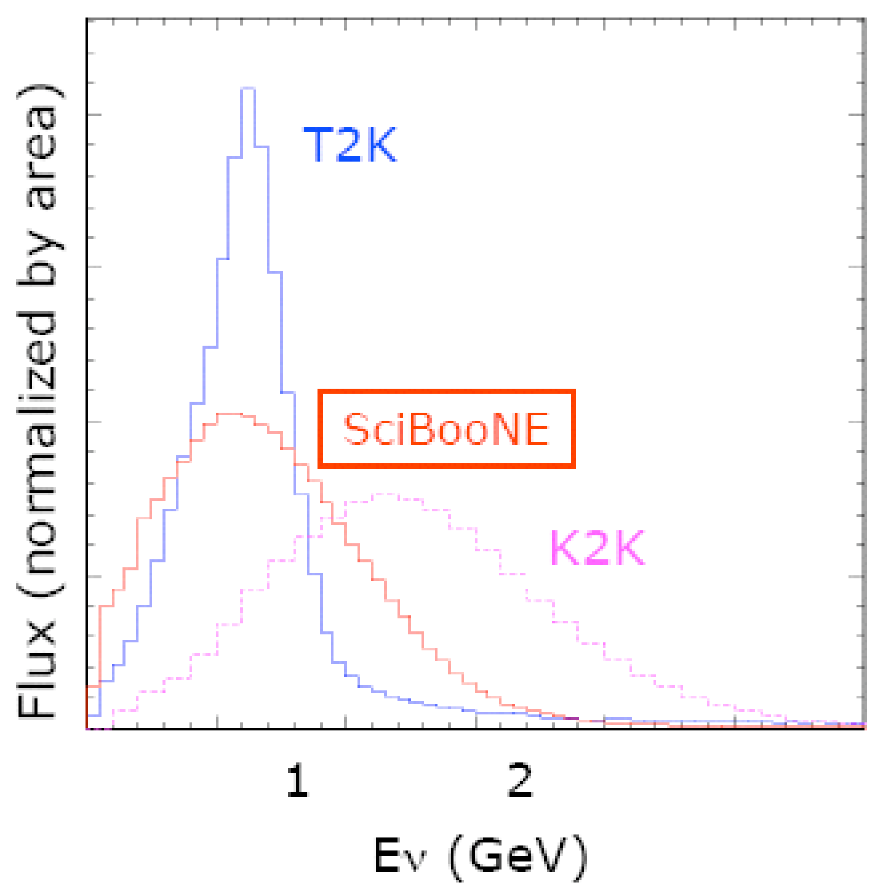




SciBooNE

- Preexisting (free!) fine grained tracking detectors
- Insert into a running, modeled beamline
- Cross section measurements
  - Similar energy as T2K
  - Near detector for MiniBooNE
  - Measurement of rare and antineutrino cross sections
- Intent to run 1e20 pot in neutrino and antineutrino mode



The SciBooNE Collaboration

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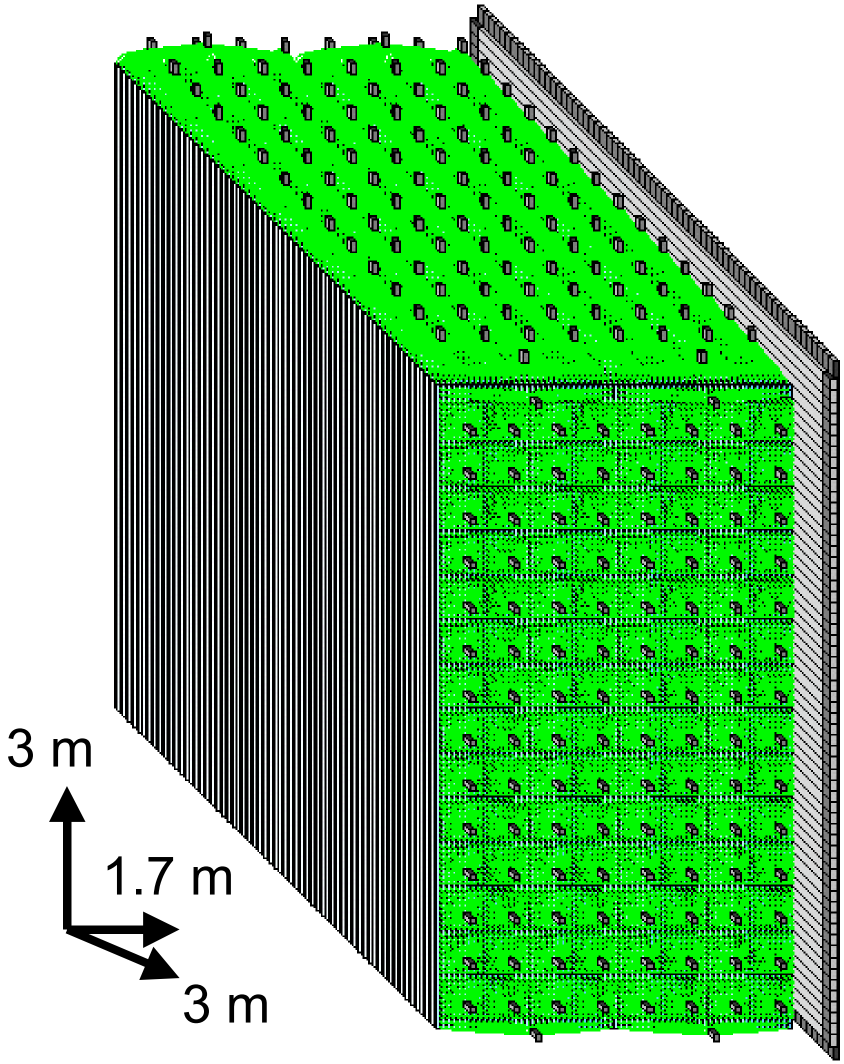
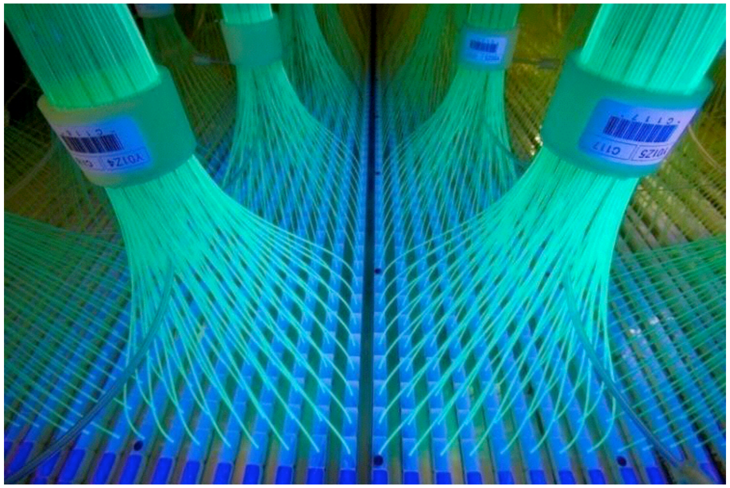
SciBooNE: SciBar



- 15 ton extruded scintillator (carbon target) with wavelength shifting fiber (WLS) readout
- Each cell is 2.5 x 1.3 x 300 cm
- 224 64 channel Multi-Anode PMT (14336 channels)
- Built for K2K



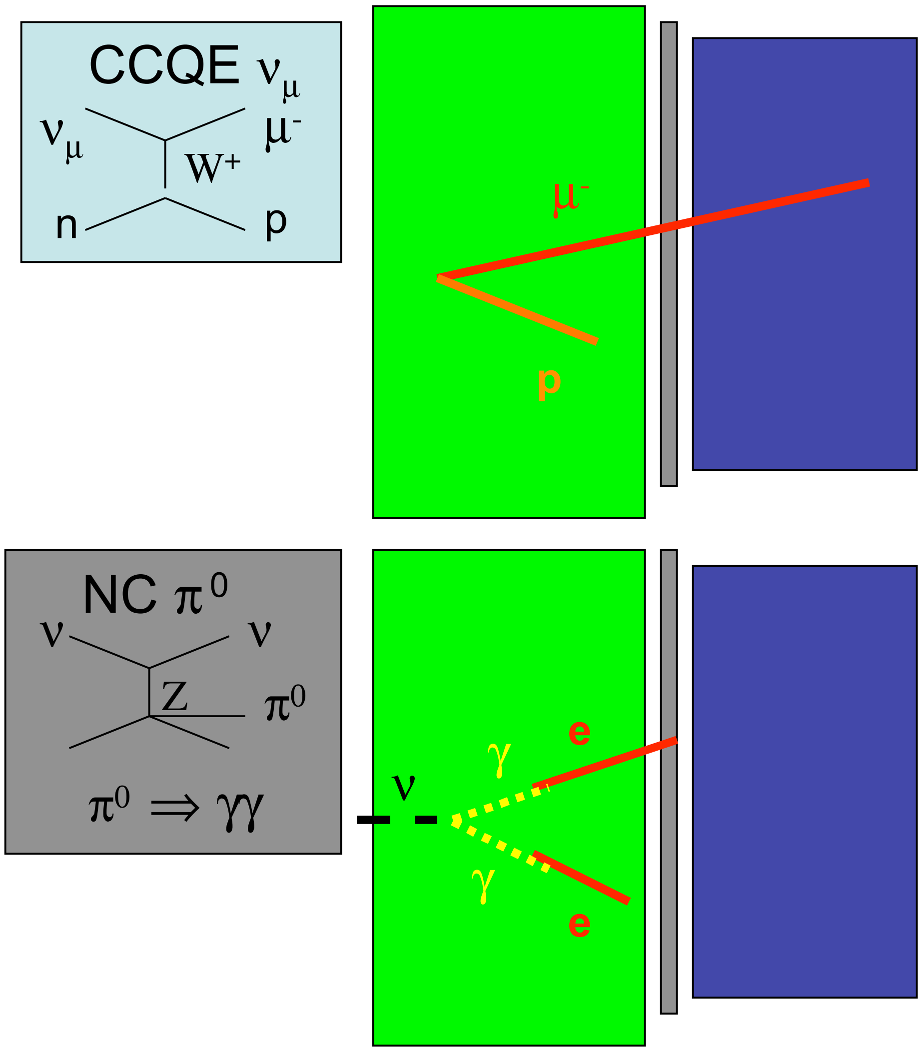
SciBooNE: Electron Catcher (EC)

- "spaghetti" calorimeter
  - 1mm scintillating fibers in grooves between lead foil
  - 256 channels
- 11 X_0 long
- 1 vertical and 1 horizontal plane; PMT readout at both ends
- Built for CHORUS, used for K2K

SciBooNE: Muon Range Detector (MRD)

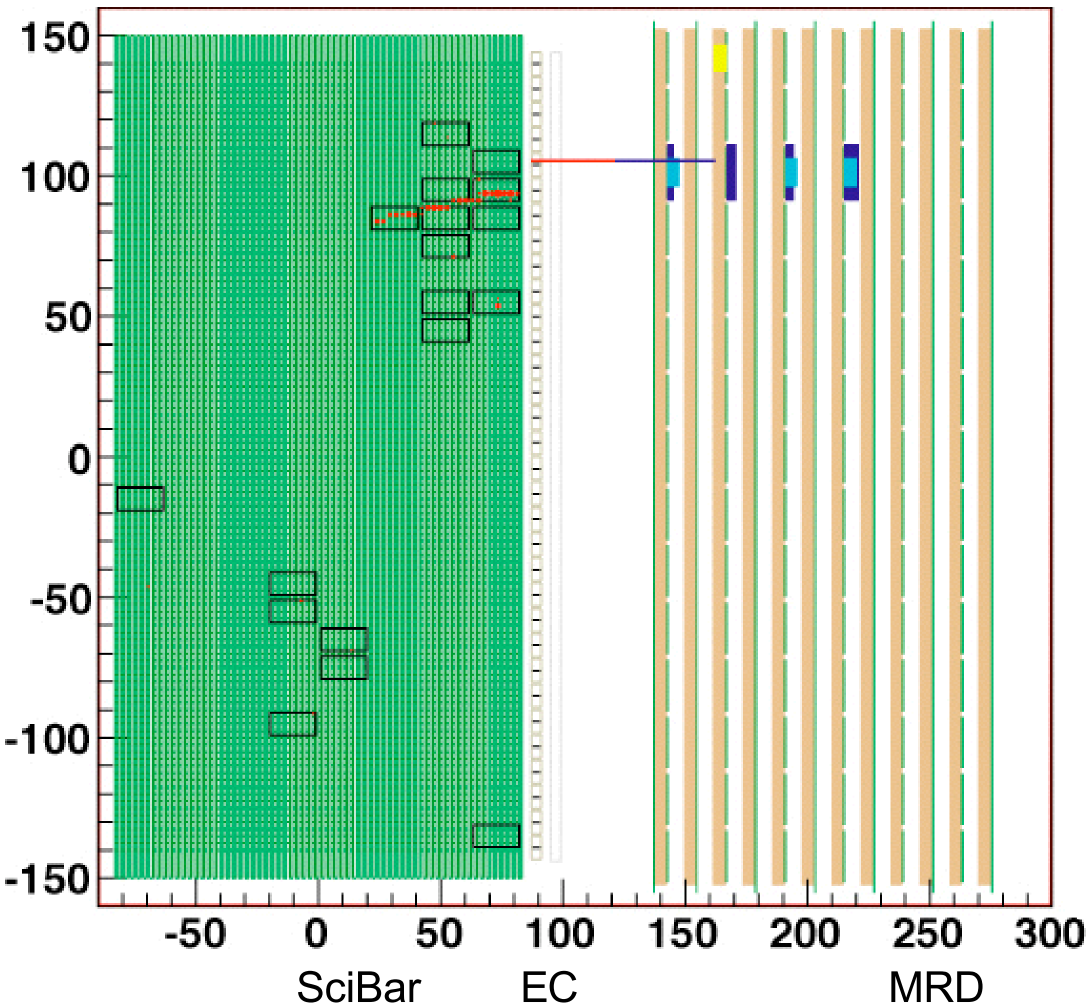
- 12 5cm iron plates interspersed with scintillator counters; ~48 tons of material
- 13 horizontal and 12 vertical planes with 26 or 30 scintillator counters attached, each with a single PMT readout (362 channels)
- Assembled from scratch and spare parts at FNAL

Events in SciBooNE

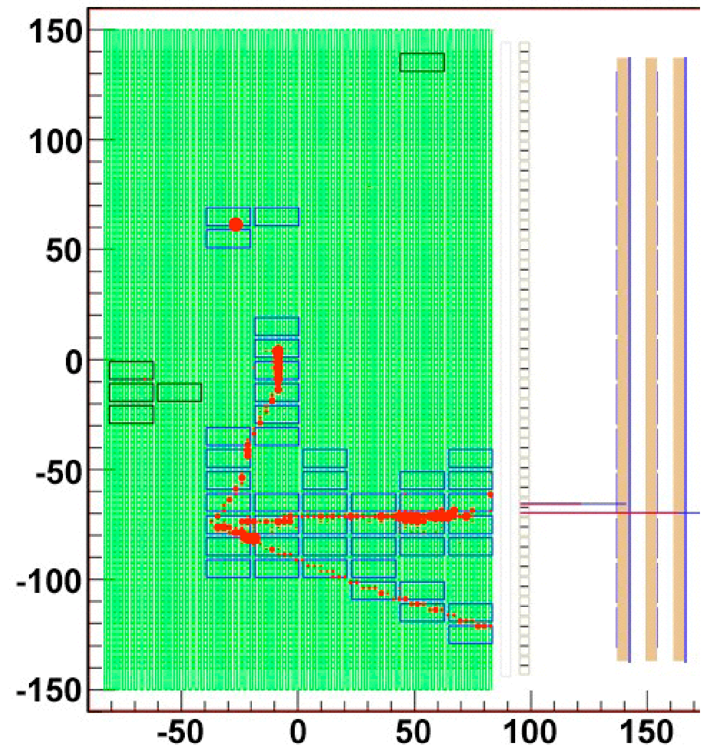


- Tracking detector
  - Can use dE/dX to distinguish
  - pion from proton from muon
  - proton tracks >10 cm are reconstructable
  - electrons stop in EC
  - Muons < 0.9 GeV stop in MRD
- Resolution
  - SciBar: 0.08 GeV muon energy, 1 degree angular resolution
  - EC: 14% $\sqrt{E}$
  - MRD: ~10% $\sqrt{E}$

(Real) Events in SciBooNE

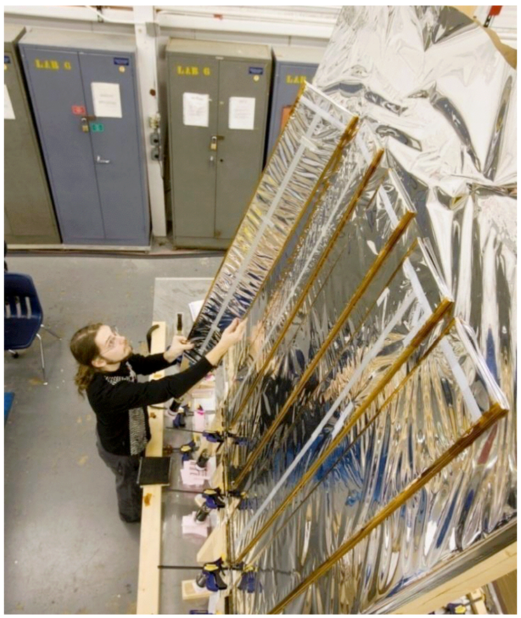


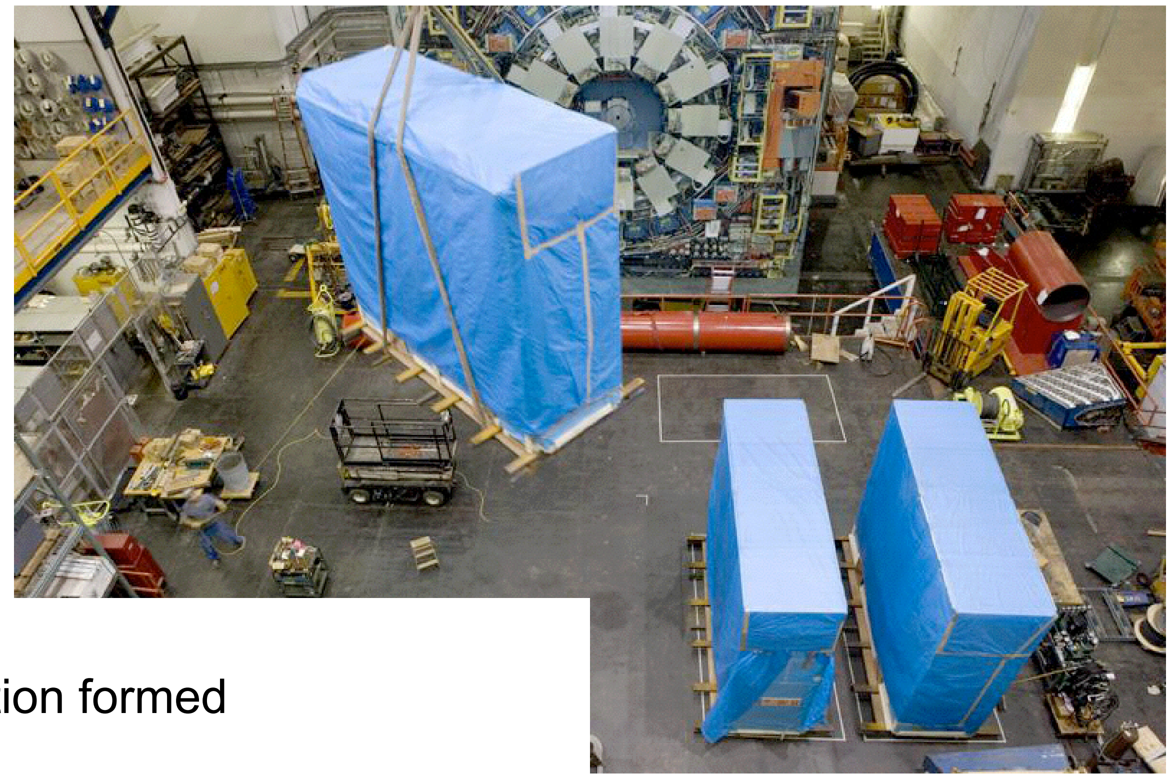
CCQE $\overline{\nu}_\mu$



CC π^+ ν_μ

Timeline

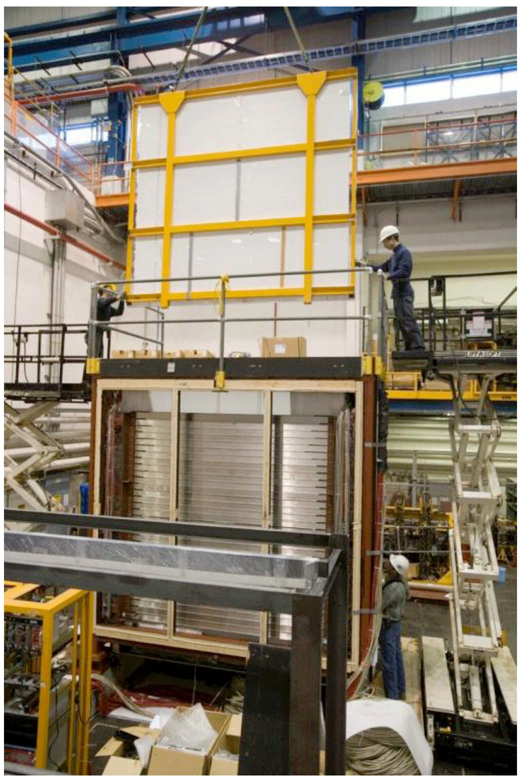




- Mar. 2005: K2K ends
- Summer 2005: collaboration formed
- Nov. 2005: Proposed
- Dec. 2005: Approved, detectors sent from KEK
- July 2006: SciBar and EC arrive, MRD construction begins

Timeline

- Sept. 2006: Groundbreaking for new detector hall
- Nov. 2006 - Feb 2007: Assembly and construction of all 3 detectors



Timeline

- March 2007: Testing of detectors with cosmic rays
- April 2007: Detectors lowered into new detector hall

Timeline

Fermilab

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July 20, 2007

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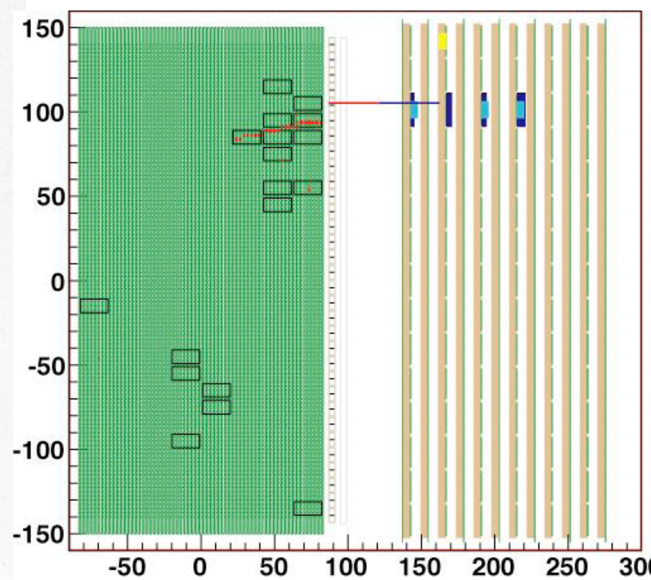
Dear Tsuyoshi and Morgan,

Given your progress on the SciBooNE experiment, including a formal Memorandum of Understanding between SciBooNE and the Laboratory, I am pleased to grant formal Stage II approval to the experiment.

I wish you successful continuation of the data taking.

Sincerely,

Piermaria Oddone



- May 31st, 2007: First data events in all 3 detectors!
- July 20th, 2007: Received Stage II approval

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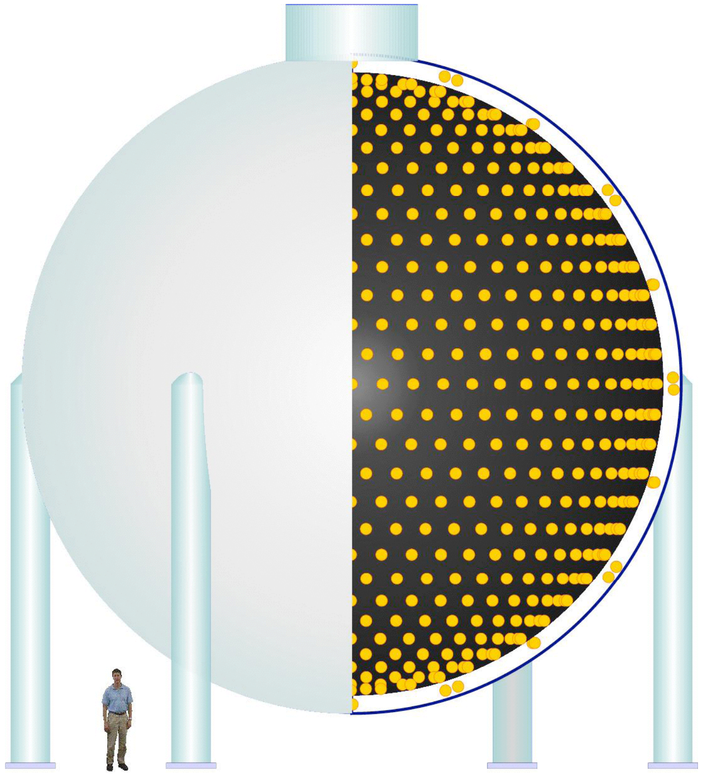

The MiniBooNE Collaboration

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E.Hawker ***Western Illinois University***
A.Curioni, B.T.Fleming ***Yale University***

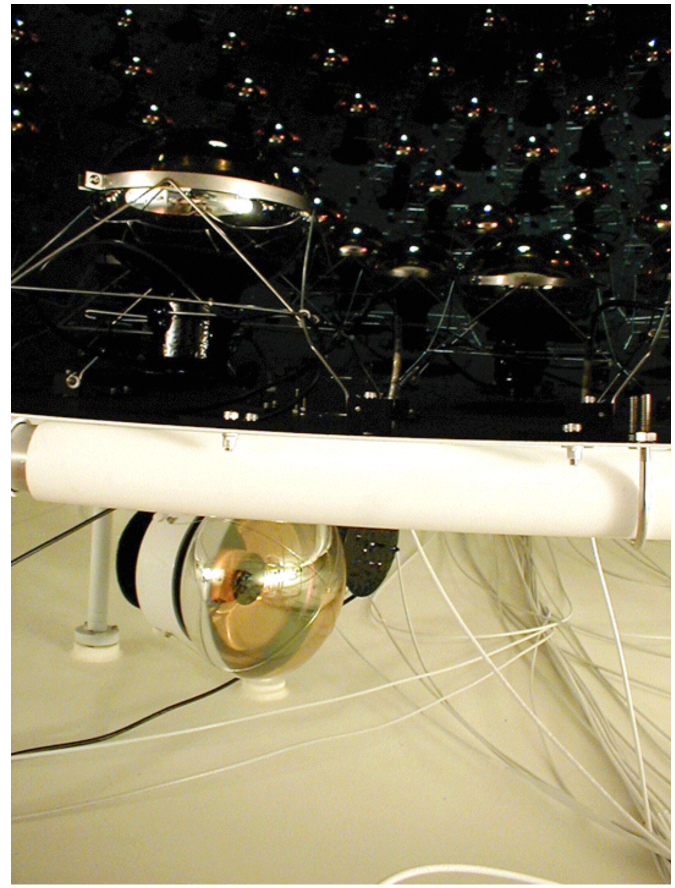
MiniBooNE: Detector

800 ton mineral oil (carbon target) Cherenkov detector

- 12 m diameter sphere
- 1280 inner region 8” PMTs, 10% photocathode coverage
- 240 outer ‘veto’ region PMTs

Resolution:

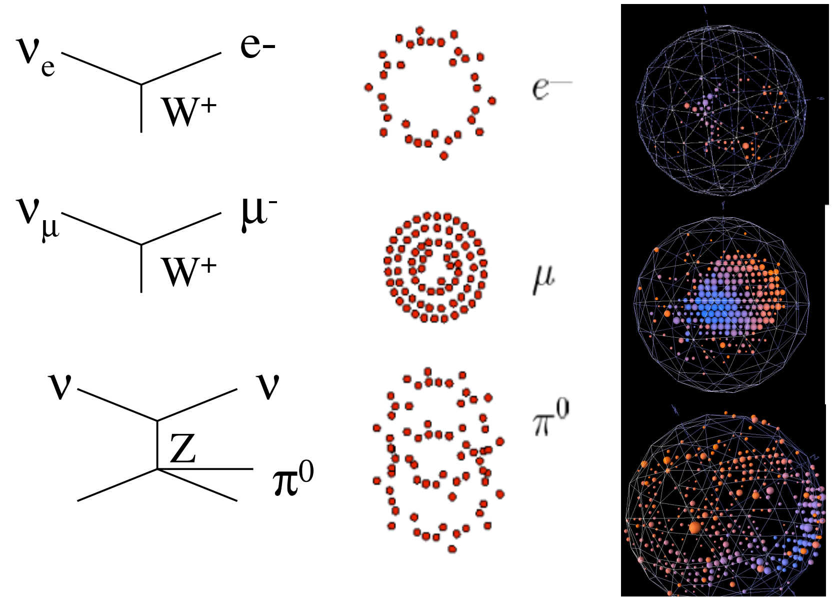
- Charge: 1.4 PE
- Time: 1.7 ns



Events in MiniBooNE

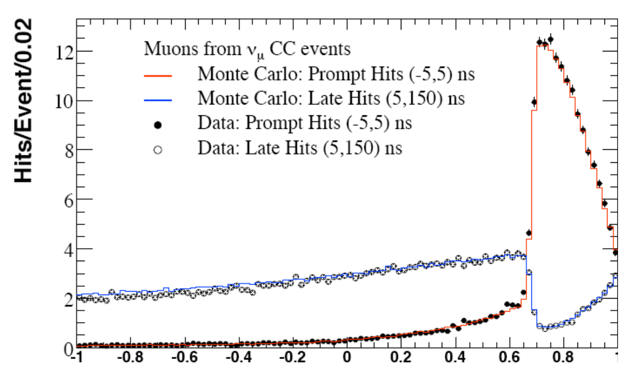
Use hit topology, timing to determine event type

- Outgoing lepton implies flavor of neutrino for charged current events
- Reconstructed quantities: track length, angle relative to beam direction
- Fundamental: timing, charge of hits, early/late hit fractions
- Geometry: position from wall of tank

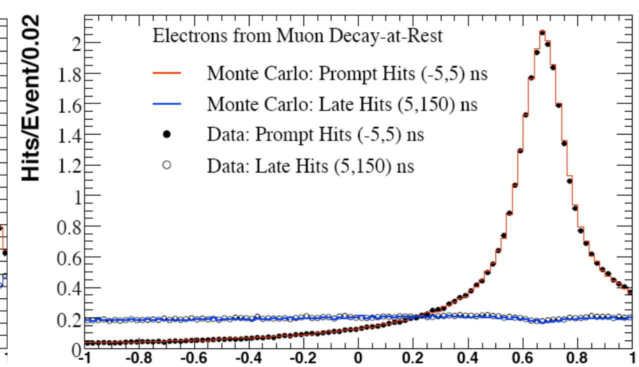


Additional information in scintillation light

- ~25% of the light in the tank due to mineral oil
- Unlike prompt Cherenkov light, scintillation light is delayed
- Amount depends on particle type

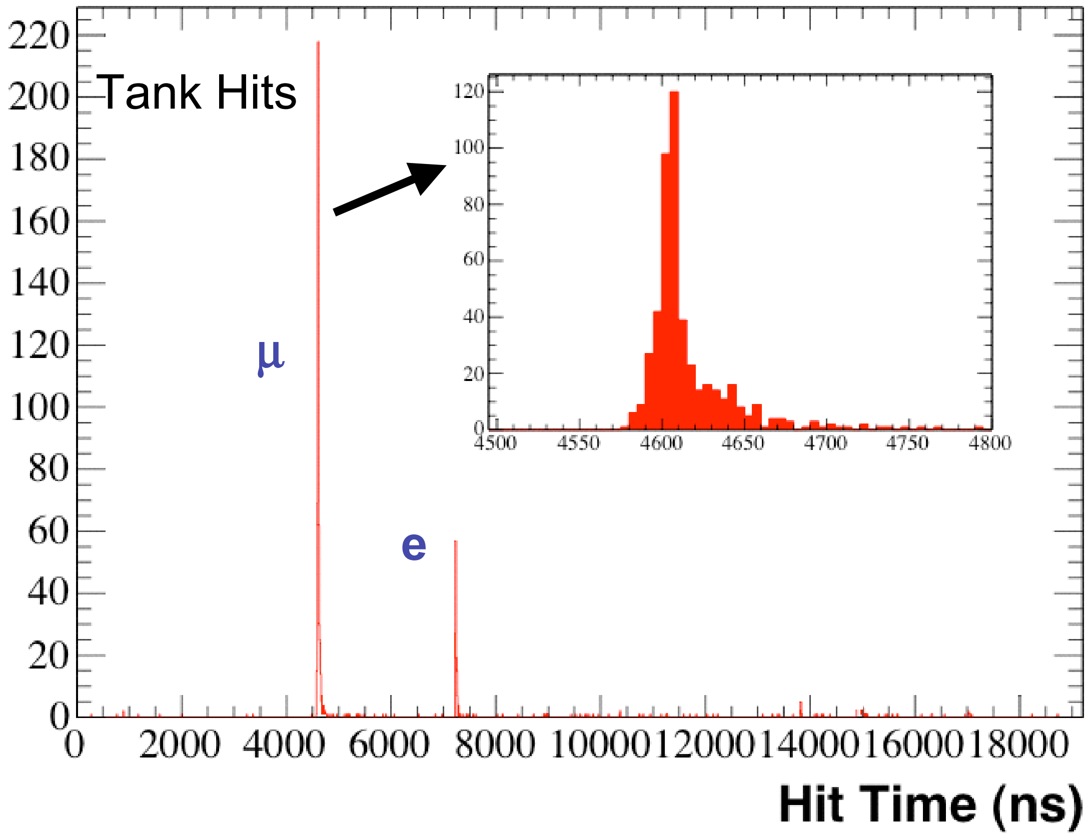


Muon



Electron

Subevents in MiniBooNE

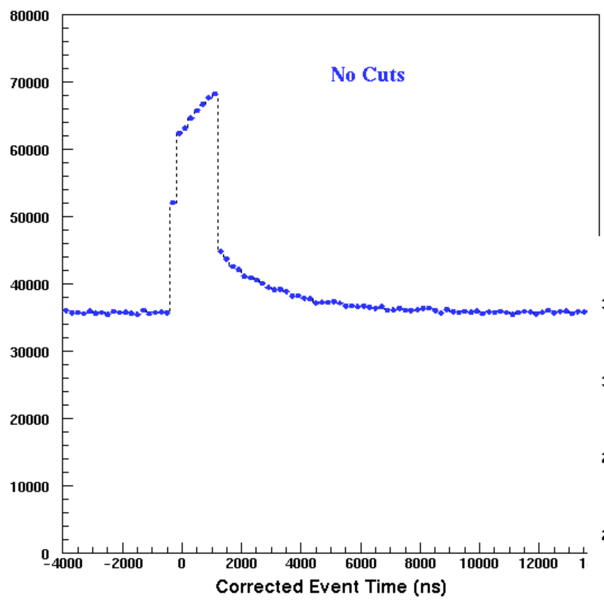


19.2 μsec trigger window around 1.6μsec beam

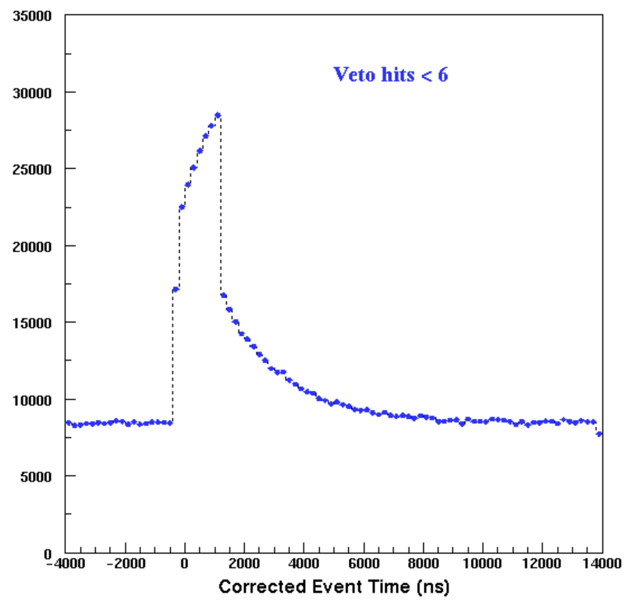
Trigger on neutrino event ($\nu_\mu + n \Rightarrow \mu + p$) initially, subsequent electron from muon decay ($\mu \Rightarrow e^+ \nu_\mu \nu_e$)

Each cluster of hits in time is a ‘subevent’

Precuts in MiniBooNE

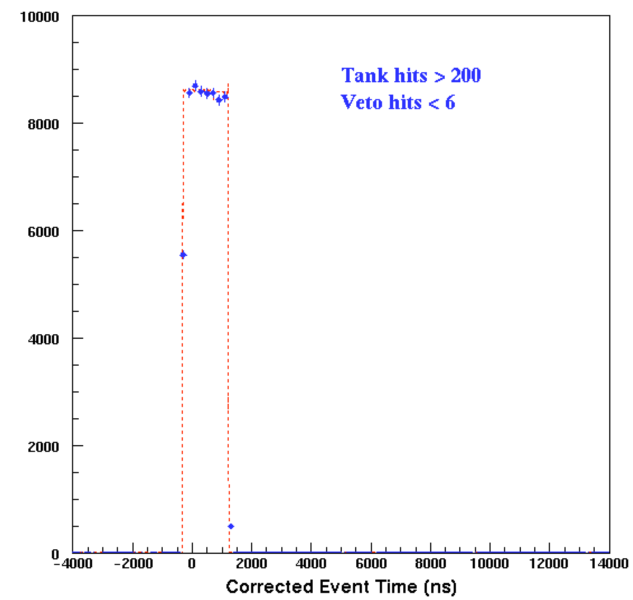


Apply precuts to eliminate 10 kHz cosmic ray background



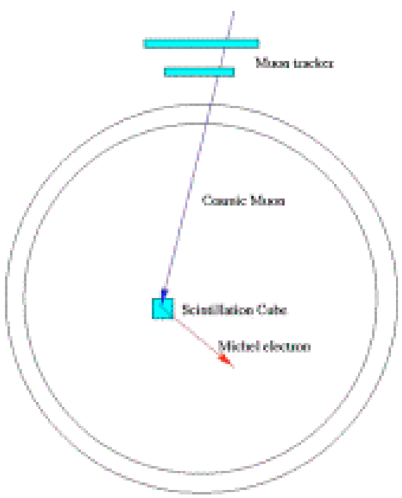
Minimal veto activity (veto hits < 6)

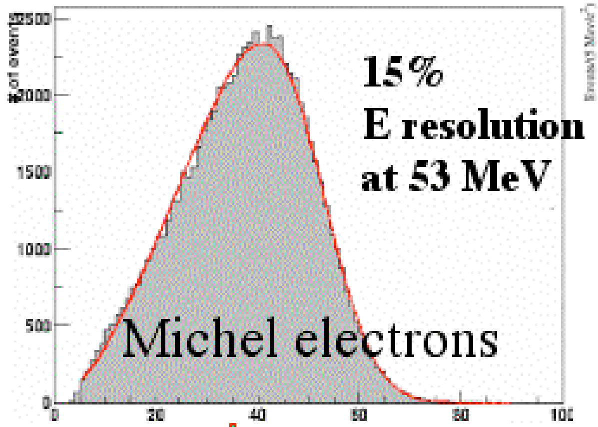
First subevent with tank hits above decay electron endpoint (tank hits > 200)

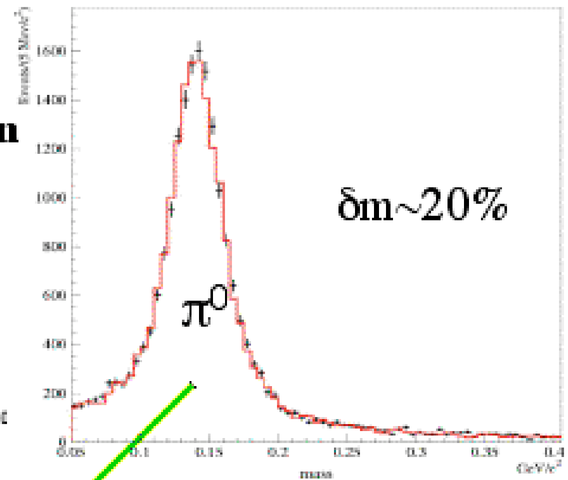


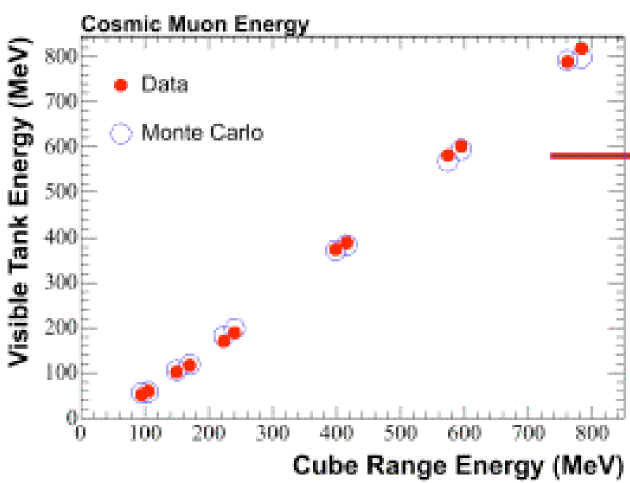
Calibrating MiniBooNE

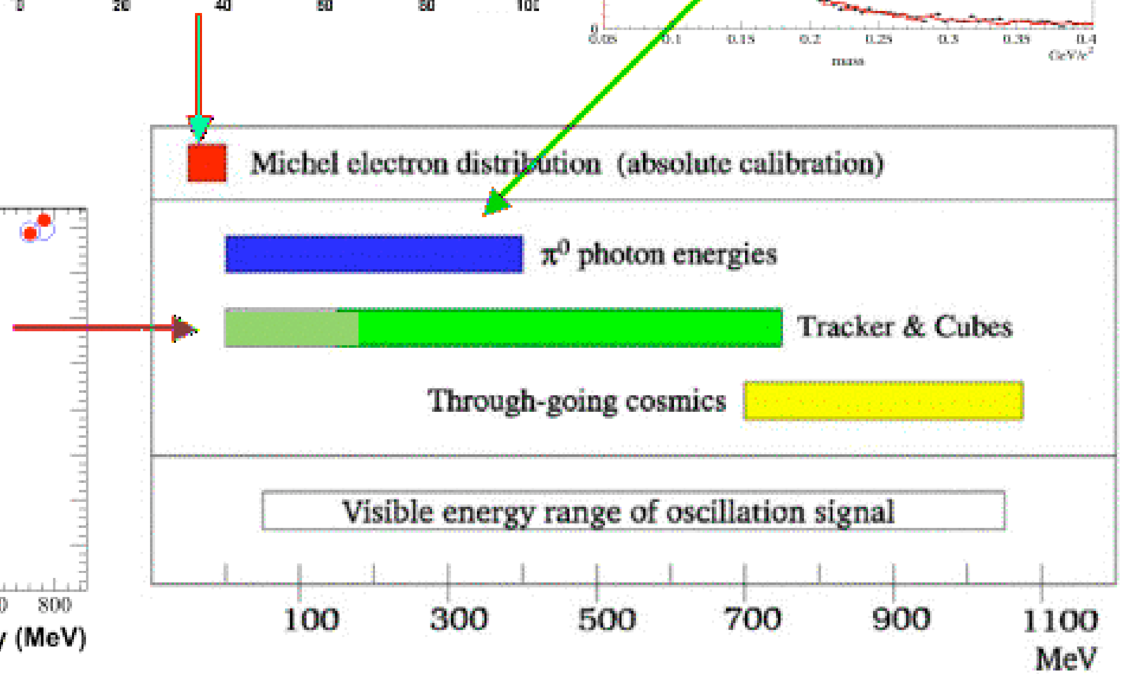
Tracker system











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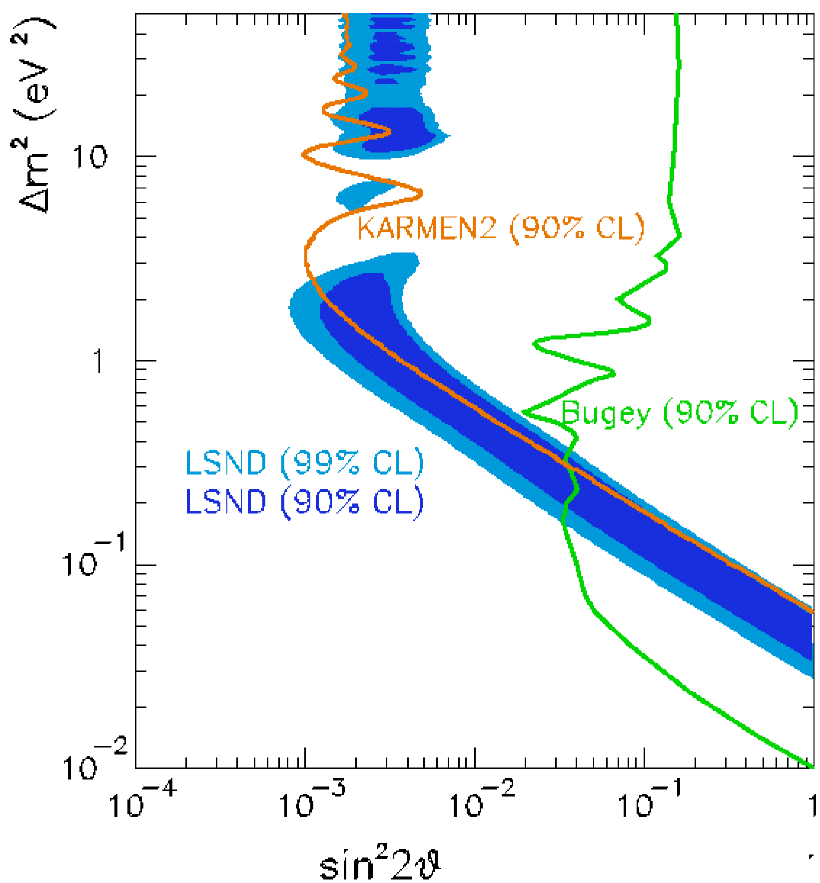
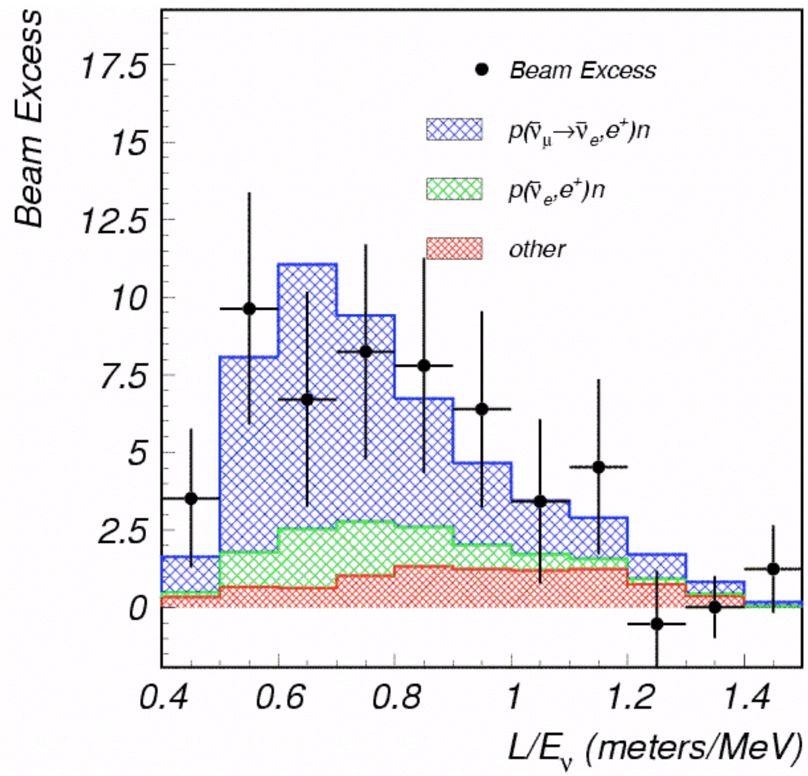


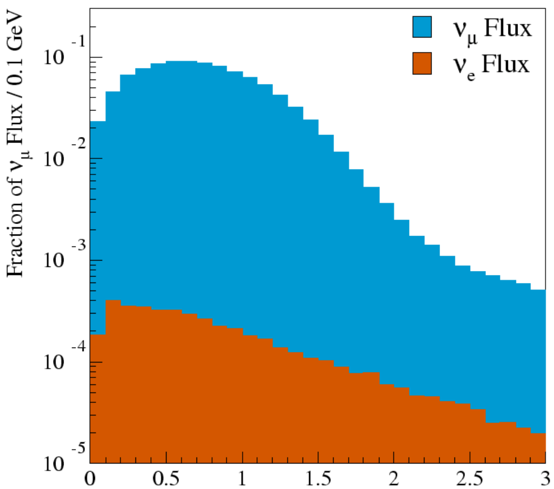
MiniBooNE

- Purpose: confirm or refute LSND
  - LSND observed an excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam; assuming 2 parameter mixing gives a 0.25% oscillation probability
  - Run with same L/E, different L, E, signal signature
- Started in 1998, oscillation results this year
  - 5.57e20 protons on target in neutrino mode
  - 2.2e20 protons on target and counting in antineutrino mode



LSND Beam Excess

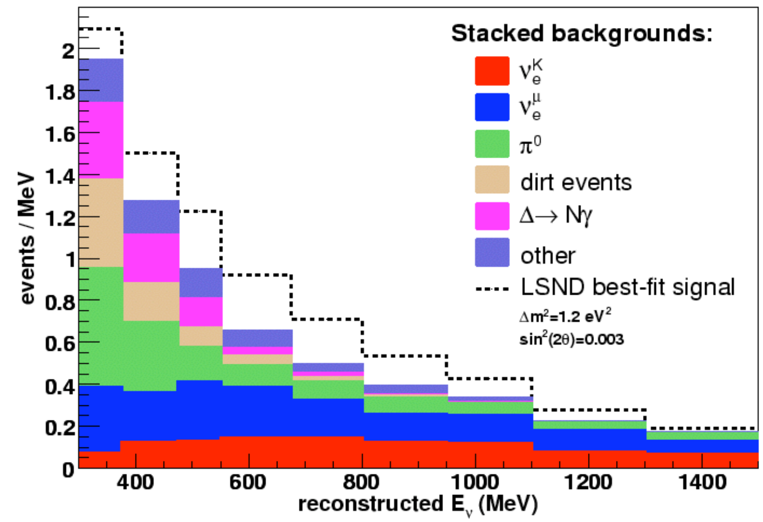
Oscillation Analysis



ν_μ E_ν(QE)

0.5% intrinsic ν_e

ν_e selection cuts



Signal E_ν(QE)

(Δm^2=1.2 eV^2, $\sin^2 2\theta$=0.003)

Background

- misidentified ν_μ (mainly π^0s)
- ν_e from μ^+ decay
- ν_e from K^+, K^0 decay
- $\Delta \Rightarrow N\gamma$
- Out of tank events ('dirt')

<u>Do the ν_μ oscillate into ν_e ?</u>

- Produce ν_μ
- Select ν_e
- Observe an excess or not?

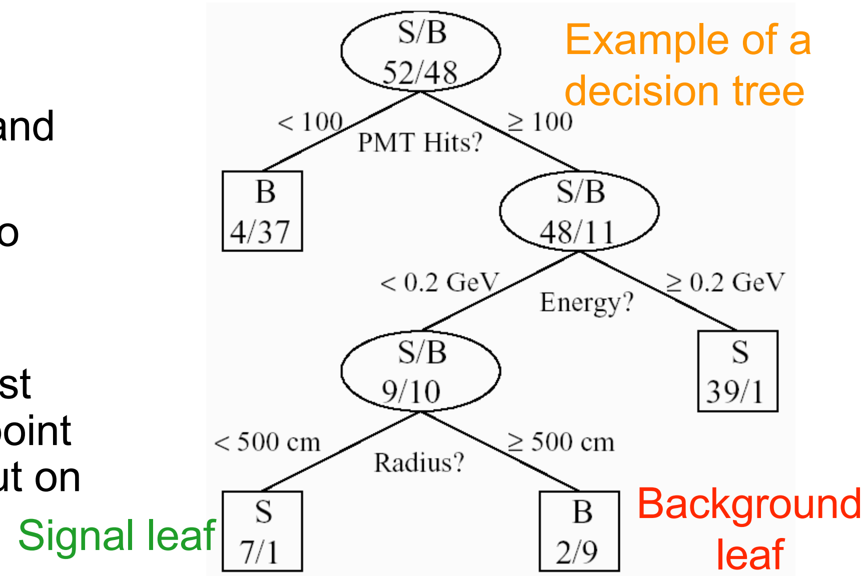
ν_e selection cuts: particle identification (PID)

Two PID algorithms used

- Likelihood based analysis (TBL): e/μ, e/π^0 and $m_{\pi 0}$ cuts
- A "boosted decision tree" (BDT) algorithm to separate e, μ, π^0

A decision tree is similar to a neural net

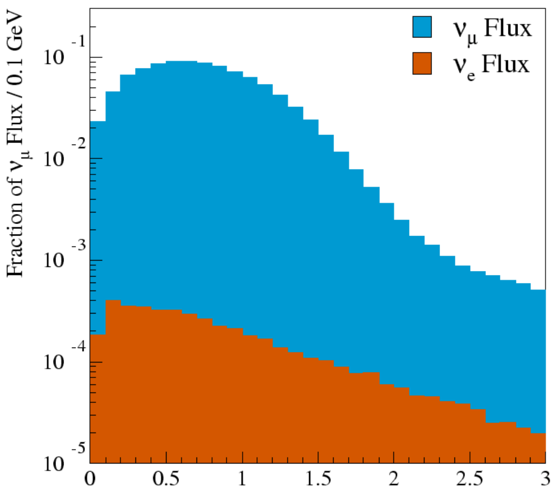
- Cut first on the variable which gives the most separation of signal to background, at the point where it gives the most separation. Then cut on next best variable...



"Boosting" is a method to additionally separate signal from background, by weighting events

- Increase weight of misclassified events in current tree, and remake tree. Repeat ~100-1000x. Sum all the trees, by counting events on signal leaves as +1, and -1 otherwise. This forms the PID variable.

Oscillation Analysis

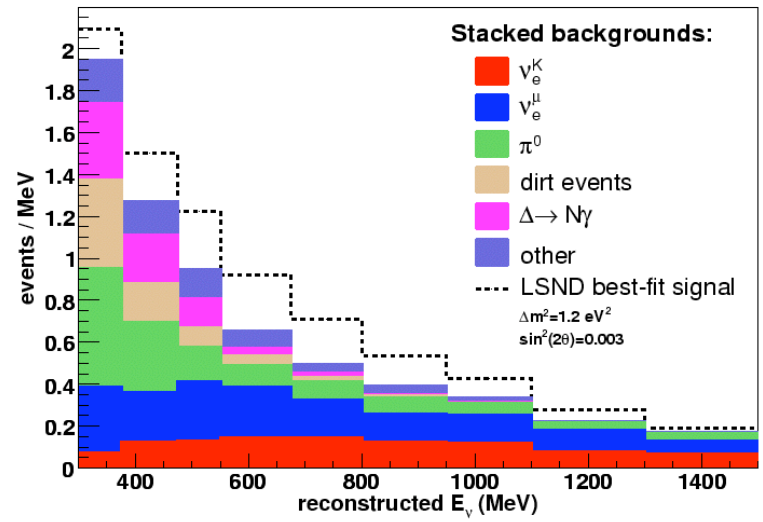


E_ν(QE)

ν_μ

0.5% intrinsic ν_e

ν_e selection cuts



E_ν(QE)

Signal

(Δm^2=1.2 eV^2, $\sin^2 2\theta$=0.003)

Background

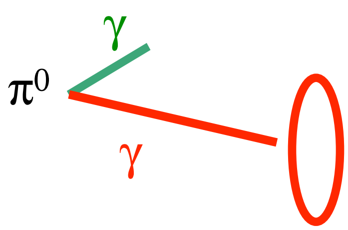
- misidentified ν_μ (mainly π^0s)
- ν_e from μ^+ decay
- ν_e from K^+, K^0 decay
- $\Delta \Rightarrow N\gamma$
- Out of tank events ('dirt')

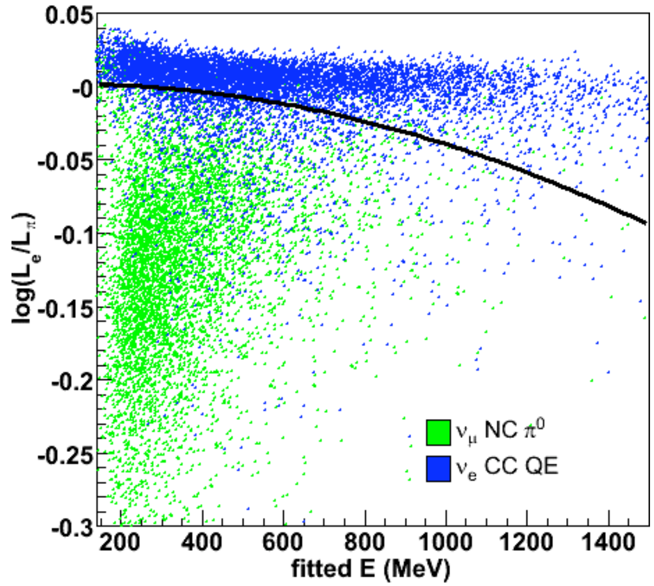
Do the ν_μ oscillate into ν_e ?

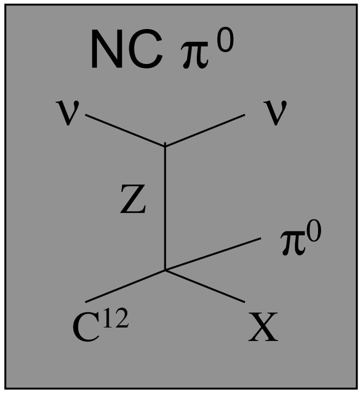
- Produce ν_μ
- Select ν_e
- Observe an excess or not?

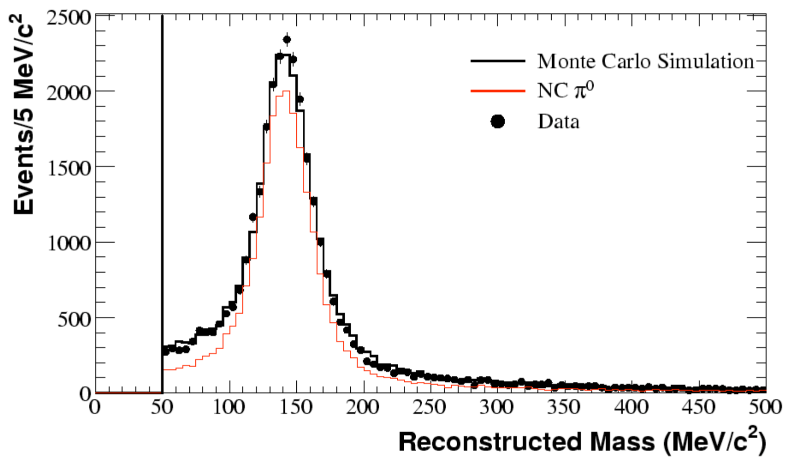
NC π^0 tagging

- Asymmetric decays where only one photon is observed look just like a single electron, or a CCQE ν_e event
- Select 1 subevent, minimal veto activity, above decay endpoint, and within fiducial volume
- Create two likelihood variables-- 1 ring vs 2 ring hypothesis, and 1 ring electron or muon like
- Select events which fit well to 2 ring, electron like, and which fall within the reconstructed π^0 mass peak
- very pure (~90%) sample





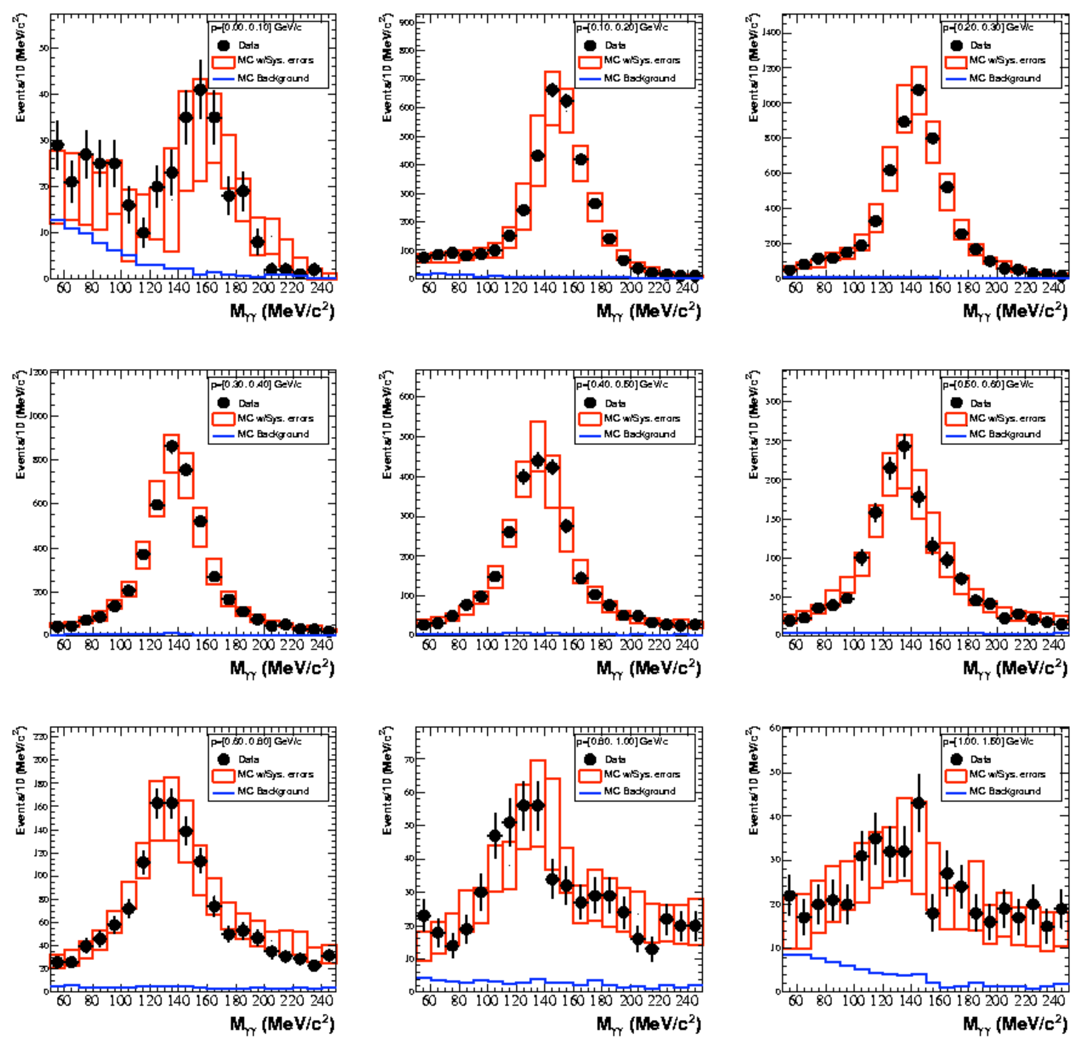




NC π^0 rate measurement

- Compare the observed π^0 rate to the MC as a function of π^0 momentum, and make a correction factor
- Reweight the misidentified π^0s based on their momentum by this correction factor
- This is also the correction applied to the $\Delta \Rightarrow N\gamma$ events for the oscillation analysis

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



Error 'budget'

source of uncertainty on nue background	TBL/BDT % error	constrained by MB data?	Reduced by relating ν_μ to ν_e
Flux from π^+/μ^+ decay	6.2 / 4.3	Y	Y
Flux from K^+ decay	3.3 /1.0	Y	Y
Flux from K^0 decay	1.5 / 0.4	Y	Y
Target/Beam model	2.8 / 1.3	Y	Y
ν cross section	12.3 / 10.5	Y	Y
NC π^0 yield	1.8 / 1.5	Y	
Out of tank events	0.8 / 3.4	Y	
Optical Model	6.1 / 10.5	Y	Y
DAQ electronics model	7.5 / 10.8	Y	

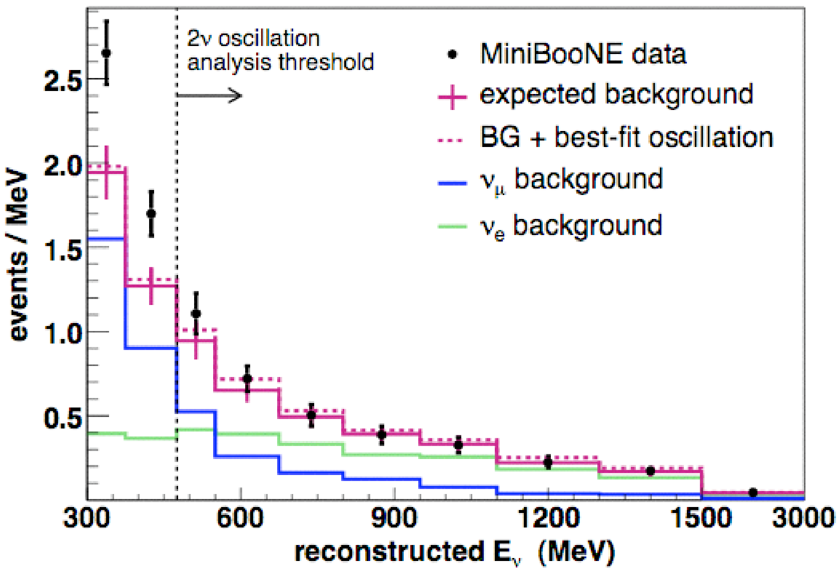
All of our errors are highly correlated, but here are the diagonal errors

Constrain all samples with MiniBooNE data

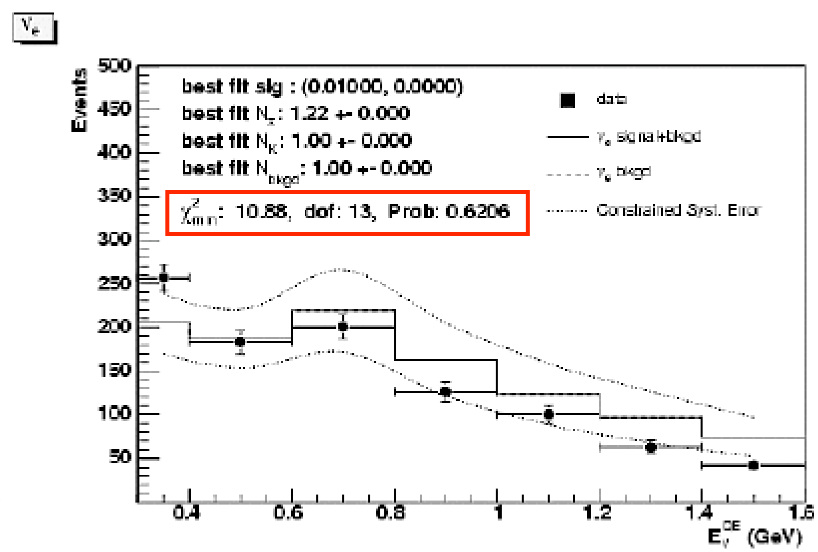
Link between ν_e and ν_μ samples further reduces errors, like a 'near to far ratio'

* shows errors before ν_e / ν_μ constraint is applied

Result

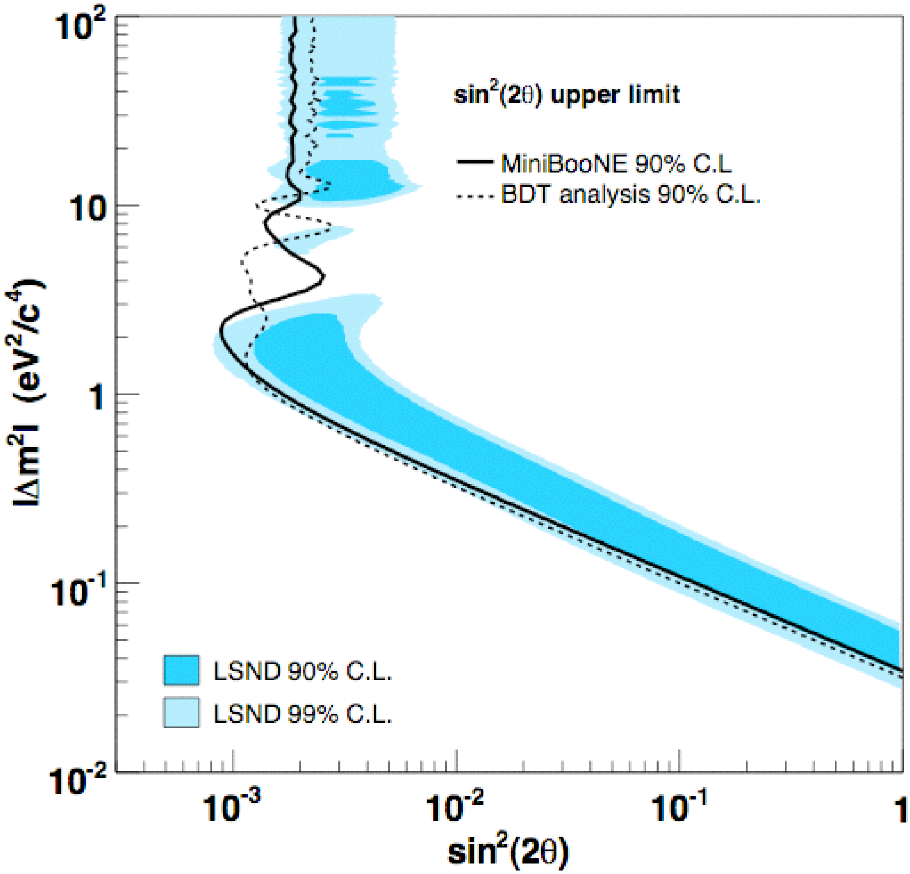


- TBL analysis shows no excess in analysis region, but excess at low energy
- Excess cannot be described based on LSND and a simple 2 ν mixing hypothesis; still under investigation



- BDT also has no sign of excess in analysis region
- Also shows an excess at low energy, but errors are larger and data low relative to prediction elsewhere complicates the issue

Sensitivity



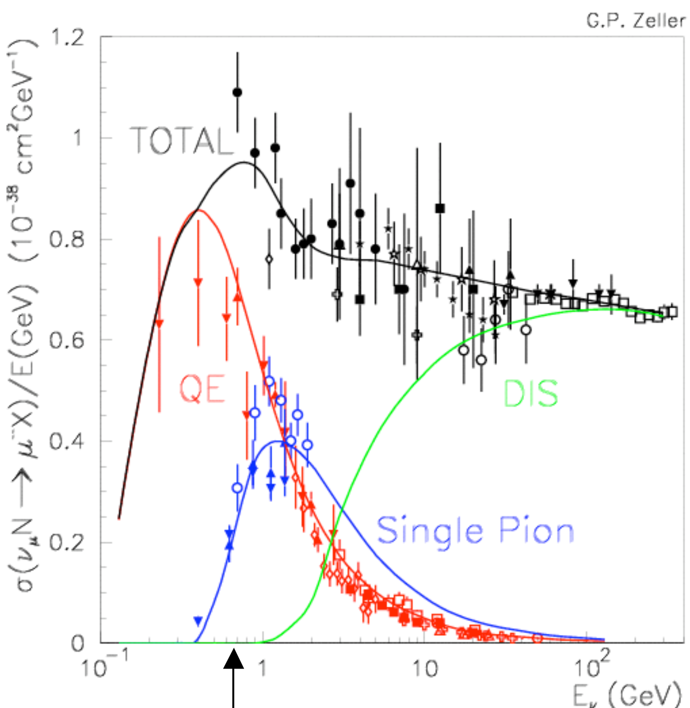
- TBL limit (solid), BDT (dash)
- Agreement between independent analyses
- Incompatible with LSND at 98% CL at all Δm^2 for 2 neutrino mixing hypothesis

Outline

- One beam...
  - Booster Neutrino Beamline
  - Resulting flux
- Two experiments...
  - MiniBooNE detector
  - SciBooNE detectors
- Physics!
  - Oscillation
  - Cross section measurements
    - Neutrino and Antineutrino
- Summary

Cross sections around 1 GeV

World's data on neutrino cross sections vs Eν

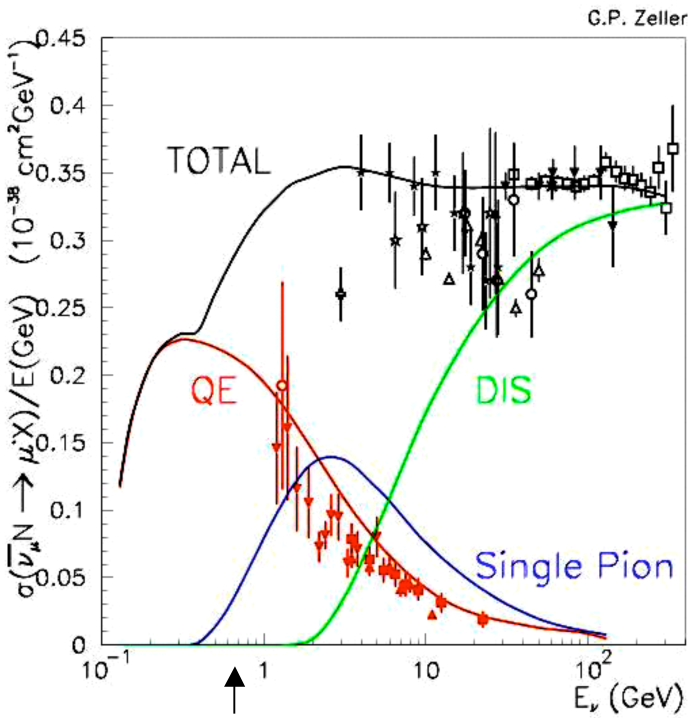


BNB
mean Eν (GeV)

- Nothing measured to better than 15-20%
- Many measurements not on nuclear targets
- Can take ratios of processes to CCQE to avoid some flux uncertainties
- Or measure same process in two detectors

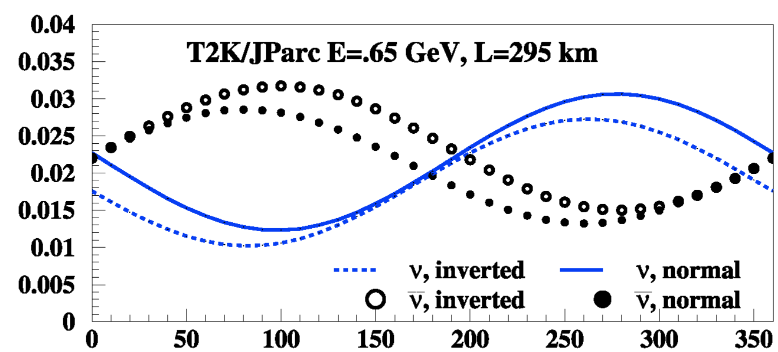
Cross sections around 1 GeV

World's data on antineutrino cross sections vs Eν



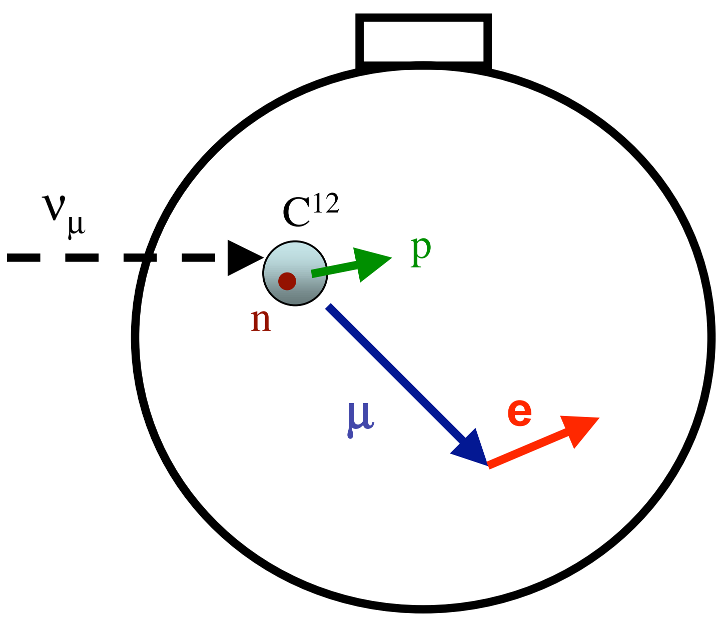
BNB, T2K
mean Eν (GeV)

- Need antineutrino cross sections for future experiments
  - Compare oscillation in neutrino and antineutrino modes to map out CP violation and mass hierarchy in neutrino mixing



P(osc) vs δCP, for normal and inverted hierarchies

Charged Current Quasi-Elastic (CCQE) interaction



- Tag single muon events and their decay electron
  - 2 subevents, minimal veto activity in both
  - muon-like track, 2nd event below decay electron energy endpoint
  - both events within fiducial volume
  - 74% purity, 197k event sample
- Neutrino energy is related to energy of muon, angle between muon and neutrino, and binding energy
- Simple relationship between neutrino, and lepton measurables makes this a ‘golden’ mode for oscillation measurements

CCQE cross section formalism

C. H. Llewellyn Smith, Phys. Rep. 3C, 261 (1972)

$$< N'|J_\mu|N > \;=\; \overline{u}(N')\left[\gamma_\mu \underline{F_V^1(q^2)} + \frac{i\sigma_{\mu\nu}q^\nu \xi \underline{F_V^2(q^2)}}{2M} + \gamma_5\gamma_\mu \underline{F_A(q^2)}\right] u(N)$$

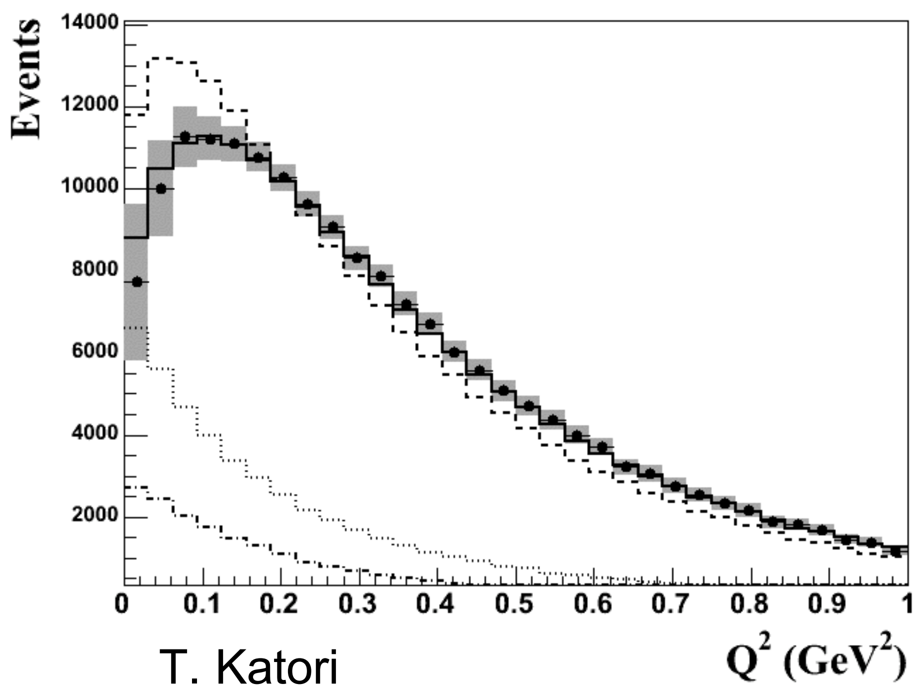
- QE cross section can be written in as a function of Q^2, in terms of vector (F_V) and axial vector (F_A) form factors
- F_V are constrained by electron scattering experiments; F_A by neutrino scattering only
- Assuming a dipole form:

$$F_A(Q^2) = \frac{g_A}{(1+Q^2/M_A{}^2)^2}$$

where M_A is the 'axial mass'

- This picture is complicated by the presence of nuclear effects, strong at low Q^2

CCQE measurement



T. Katori

Simultaneous shape fit for M_A and nuclear effect parameter (κ) in Q^2 with a relativistic Fermi Gas model

M_A= 1.23 +/- 0.20 GeV,
κ = 1.019 +/- 0.011

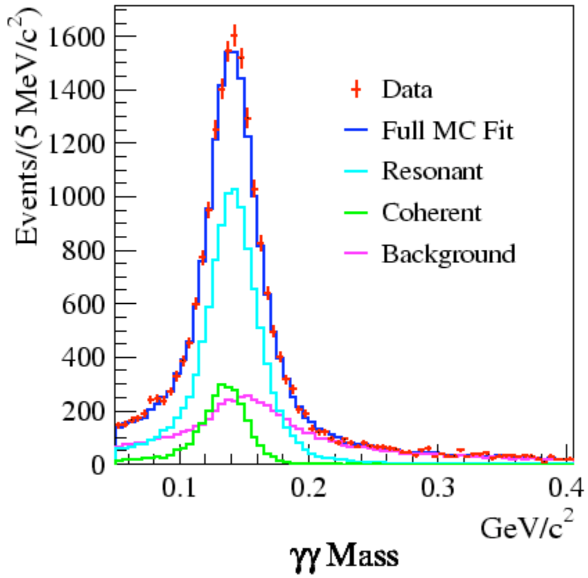
Recent K2K SciBar result:

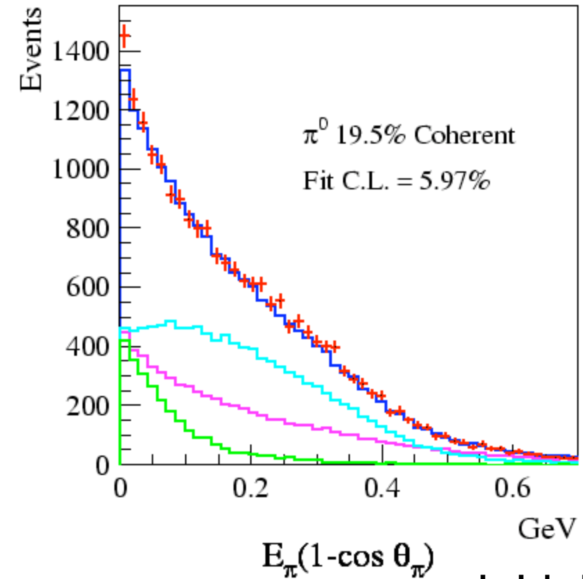
M_A= 1.14 +/- 0.11 GeV

World Average: M_A= 1.03 +/- 0.02 GeV

NC π^0:Coherent fraction

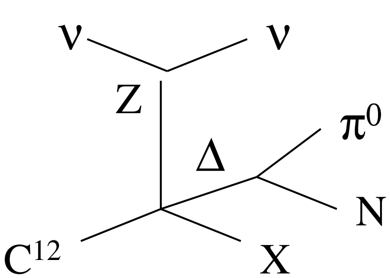
- π^0 can be produced either from the excitation of a delta (resonant), or from the excitation of the whole nucleus (coherent)
- Coherent production is forward peaked, and a larger component of antineutrino running



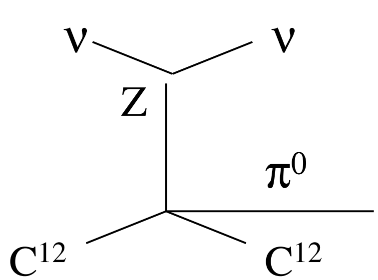


J. Link

resonant



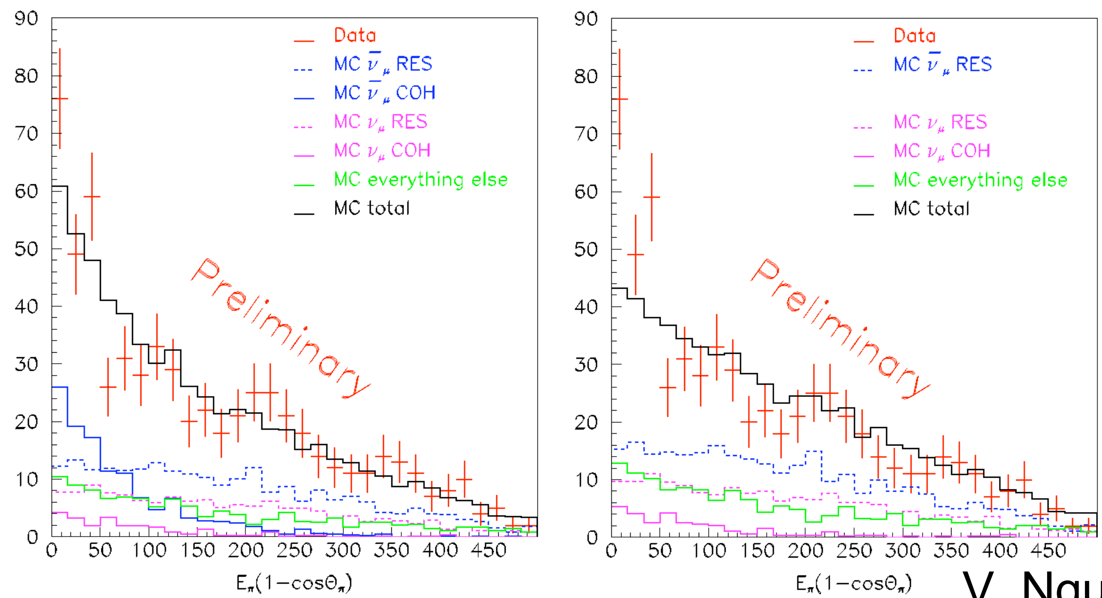
coherent



Will convert rate measurement into a cross section
Make a measurement of the coherent fraction:
Coh/Res = (19.5 +/-1.1 (stat) +/- 2.5 (sys))%

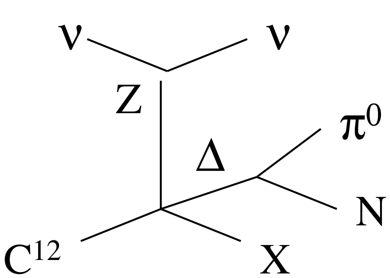
Antineutrinos: Coherent fraction

- π^0 can be produced either from the excitation of a delta (resonant), or from the excitation of the whole nucleus (coherent)
- Coherent production is forward peaked, and a larger component of antineutrino running

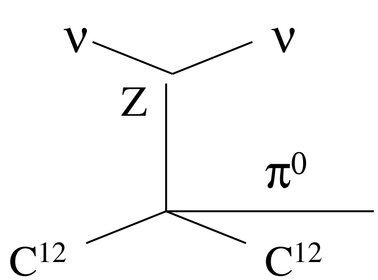


V. Nguyen

resonant

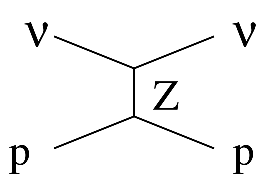


coherent



- Preliminary antineutrino sample fits better to a nonzero coherent fraction, as does the neutrino sample

NC Elastic

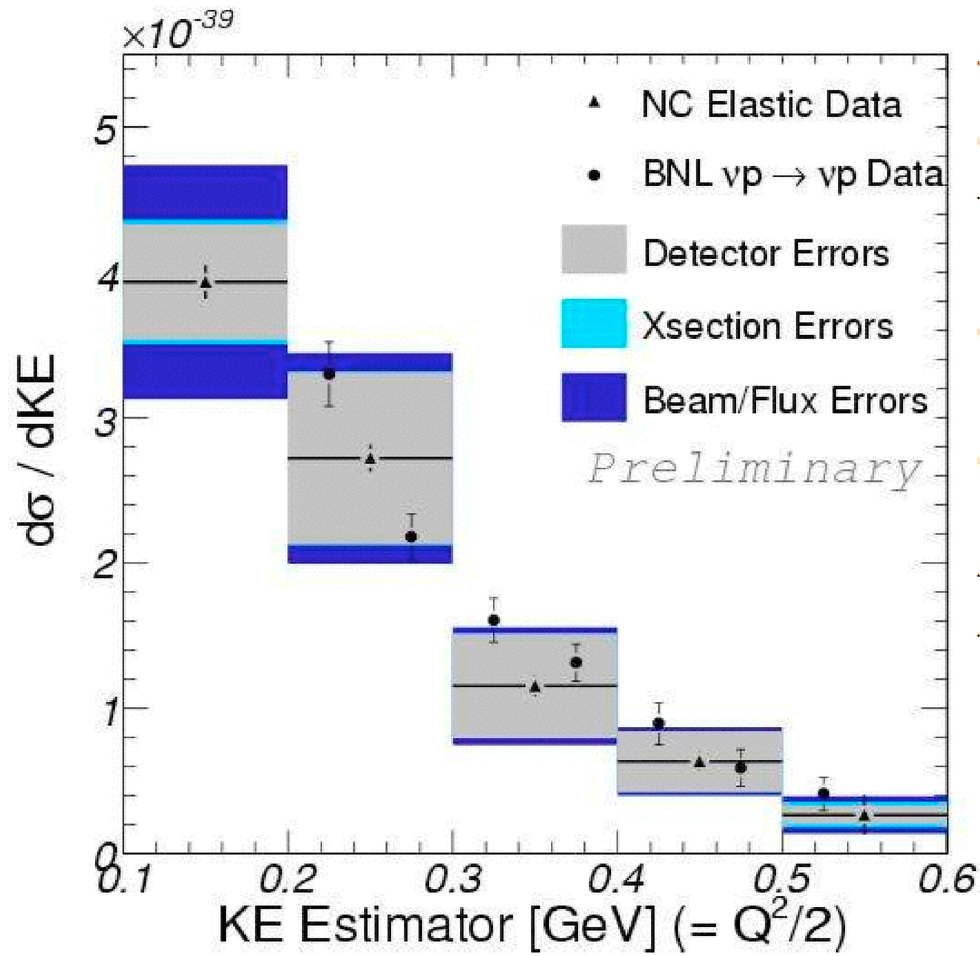


Signature is scintillation light of proton below Cherenkov threshold

- 1 subevent, minimal veto activity
- Cutting on late light fraction eliminates the Cherenkov light from low energy electron events
- Radial cut to reduce events from surrounding dirt which don't fire veto
- ~84% purity

Only 1 other measurement made so far (overlaid here)

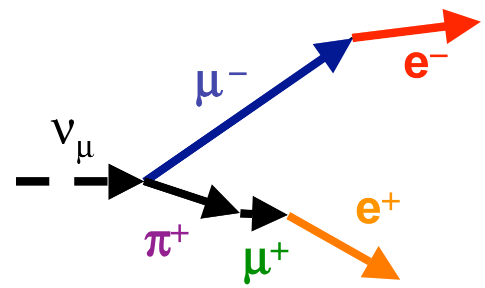
Sensitive to the same M_A as CCQE

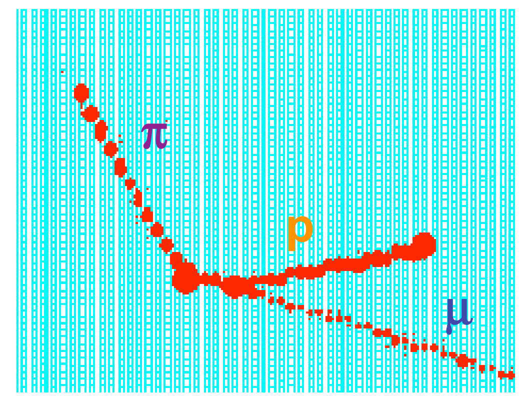


D. Cox

Prospects: SciBooNE and MiniBooNE

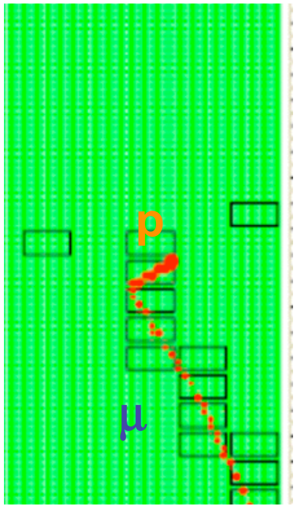
- SciBooNE has superior efficiency and reconstruction capabilities, however, MiniBooNE dominates with statistics
- Leverage each other
  - ν_μ disappearance: measure initial rate of events in SciBooNE, compare directly to MiniBooNE
- MiniBooNE: tags CC π^+ with 3 subevents (1 muon/pion, and two decay electrons)
- SciBooNE: reconstruct entire final state!
  - If pion is absorbed, will affect kinematics



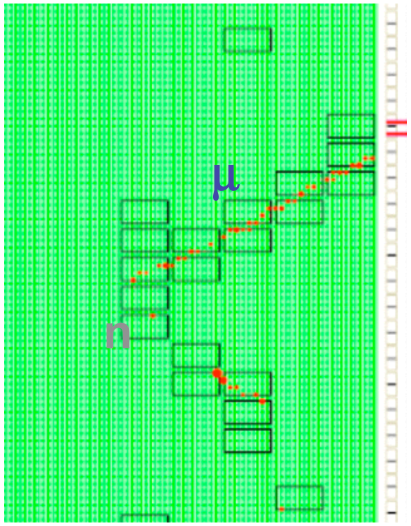


Prospects: SciBooNE and MiniBooNE

- SciBooNE has superior efficiency and reconstruction capabilities, however, MiniBooNE dominates with statistics
- Antineutrino running:
  - MiniBooNE can select CC π^+ (neutrino only process) in antineutrino beam to measure neutrino contamination
  - SciBooNE can tag on an event by event basis



CCQE ν_μ



CCQE $\overline{\nu_\mu}$

Summary

Lots of physics done with the Booster Neutrino Beam

- Recent MiniBooNE oscillation result
- Cross section results from MiniBooNE (CCQE)

And more to come!

- Soon NC π^0 and NC elastic, and CC π^+
- ν_μ disappearance

SciBooNE proposed, installed, and running

- Will complement MiniBooNE's capabilities
- Map out cross sections around 1 GeV in both neutrino, and antineutrino interactions