Fermilab E-898

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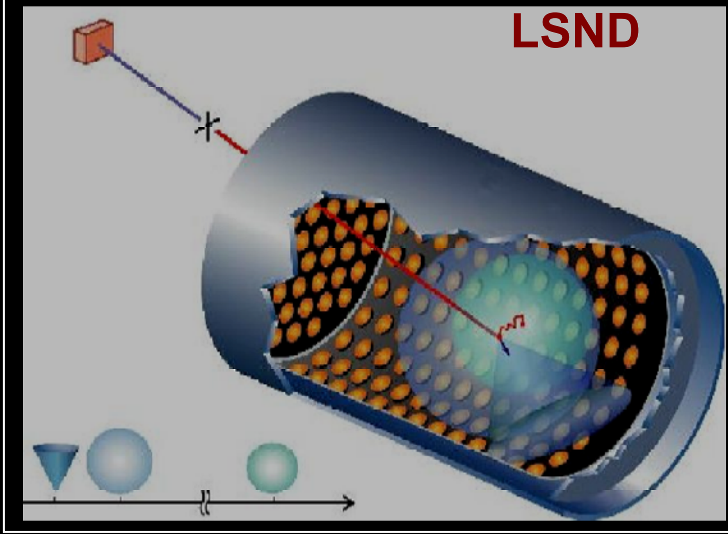
Fermilab

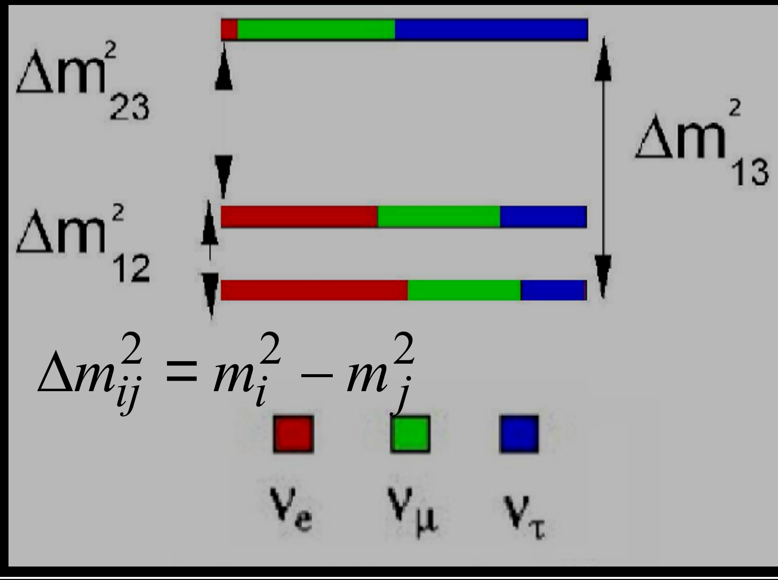
Annual Users Meeting
June 8, 2005

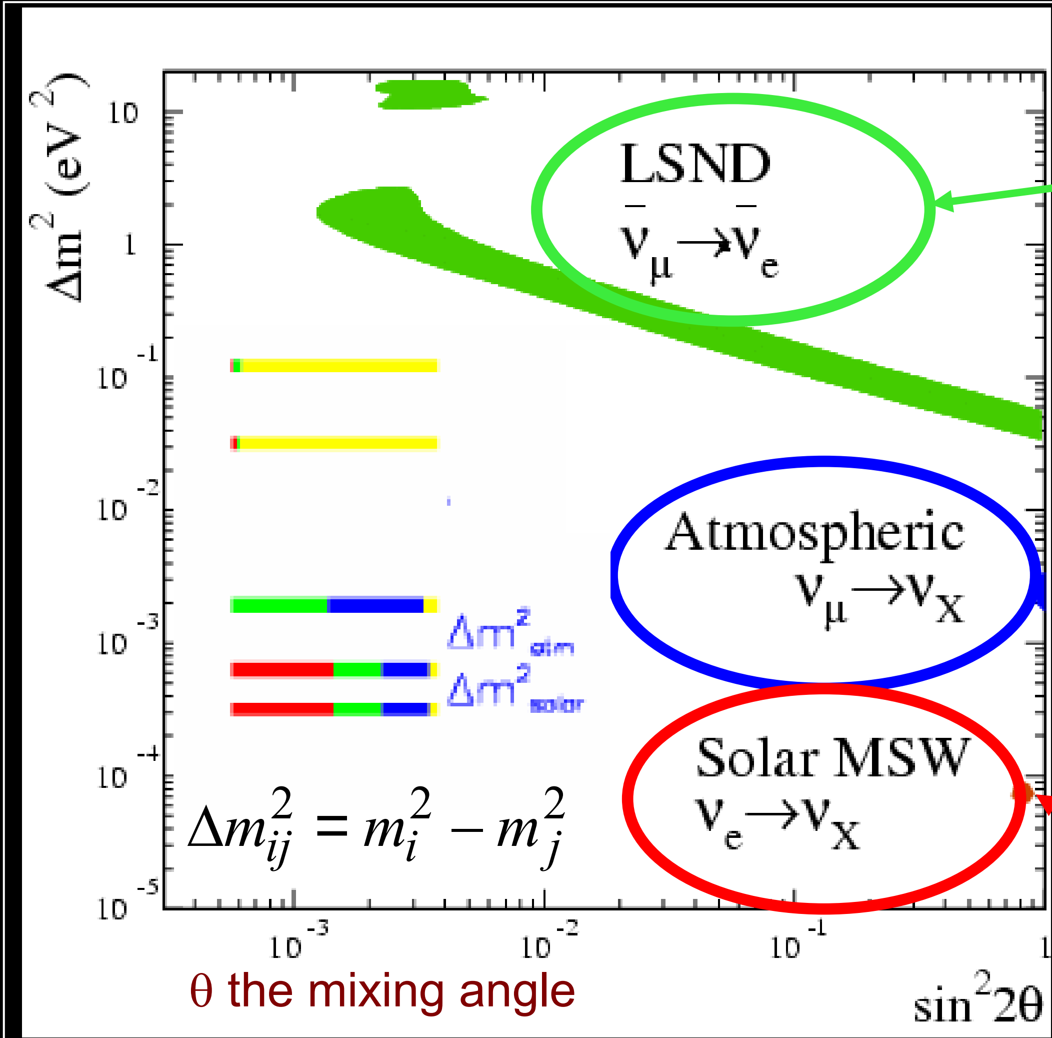
Outline

- νs How many? New flavors? $\nu / \bar{\nu} / \nu_R$ relationship
- Implications of LSND
- Fermilab E-898
  - Accomplishments
  - Progress
- Concluding Remarks

This talk is the complement of most standard neutrino talks. The picture of three neutrino flavors will change in light of LSND, and we will explore the implications.







LSND
$\Delta m^2 \sim 1 eV^2$
$\theta \sim 2°$

Atmospheric oscillations
$\Delta m^2 \sim 10^{-3} eV^2$
$\theta \sim 45°$

Solar oscillations
$\Delta m^2 \sim 10^{-5}$ eV^2
$\theta \sim 32°$

- Problem: That's too many Δm^2 regions!
  - Should find: $\Delta m^2_{12} + \Delta m^2_{23} = \Delta m^2_{13}$

$10^{-5} + 10^{-3} \neq 1$

For a three flavor neutrino world, the mixing matrix is derived by solving a eigenvalue equation in three dimensions. A general solution can be written as three consecutive rotations in a 3-dimensional space:

CP violating phase

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Solar oscillations
$\Delta m^2 \sim 10^{-5}$ eV^2
$\theta \sim 32°$

Reactor Experiments
Long Baseline Exps.

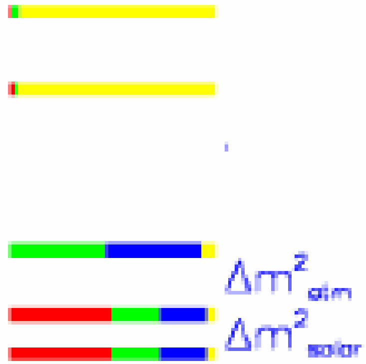
Atmospheric oscillations
$\Delta m^2 \sim 10^{-3}$eV^2
$\theta \sim 45°$

In order to provide a theoretical basis for the LSND effect, one explores the possibility of the existence of additional, non-interacting neutrinos. Models consisting a standard 3 neutrino family along with one or 2 "sterile" neutrinos, and especially the 3+2 hypothesis provides an interesting possibility. As an exercise, let's consider a 3+3 model.

$$\nu_{SM} = U_{SM} \times \nu_M \qquad \nu_S = U_S \times \nu_{M_S}$$

$$\nu_{SM} = \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} \mathrm{U}_{e1} & \mathrm{U}_{e2} & \mathrm{U}_{e3} \\ \mathrm{U}_{\mu 3} & \mathrm{U}_{\mu 3} & \mathrm{U}_{\mu 3} \\ \mathrm{U}_{\tau 3} & \mathrm{U}_{\tau 3} & \mathrm{U}_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \qquad \nu_S = \begin{bmatrix} \nu_{e_S} \\ \nu_{\mu_S} \\ \nu_{\tau_S} \end{bmatrix} = \begin{bmatrix} \mathrm{U}_{e1_S} & \mathrm{U}_{e2_S} & \mathrm{U}_{e3_S} \\ \mathrm{U}_{\mu 3_S} & \mathrm{U}_{\mu 3_S} & \mathrm{U}_{\mu 3_S} \\ \mathrm{U}_{\tau 3_S} & \mathrm{U}_{\tau 3_S} & \mathrm{U}_{\tau 3_S} \end{bmatrix} \begin{bmatrix} \nu_{1_S} \\ \nu_{2_S} \\ \nu_{3_S} \end{bmatrix}$$

Whereas in 3-dimensions we work with an SO(3) symmetry, in Six dimensions we need SO(6); and six dimensional matrices.

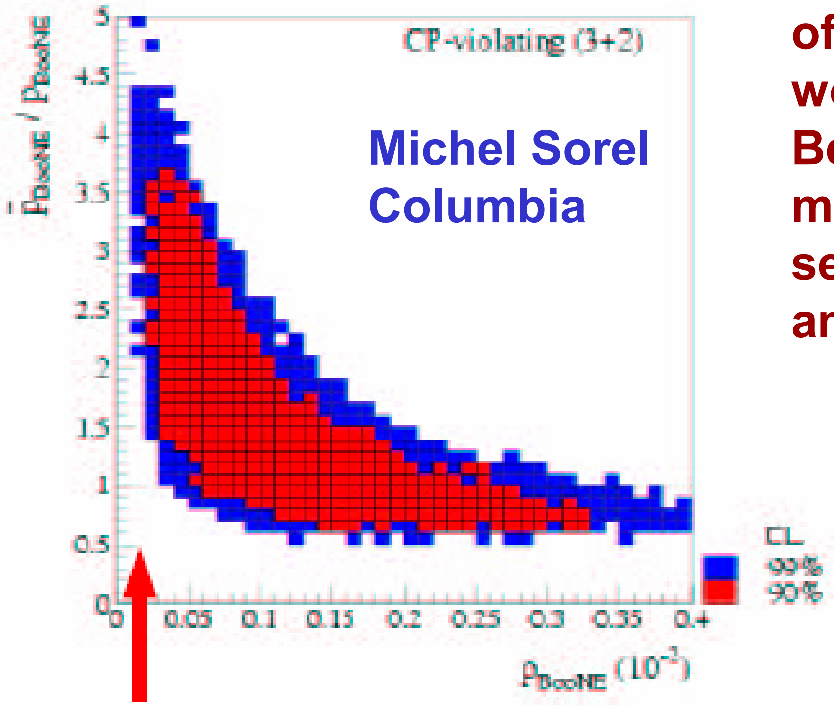


$$\begin{bmatrix} \nu_{SM} \\ \nu_S \end{bmatrix} = \begin{bmatrix} \mathrm{U}_{SM} & \varepsilon \\ \varepsilon & \mathrm{U}_S \end{bmatrix} \begin{bmatrix} \nu_M \\ \nu_{M_S} \end{bmatrix}$$

GUT models and models with extra dimensions favor sterile neutrinos.

Our ansatz assumes a weak coupling between SM and Sterile particles. Sterile and Standard Model neutrinos behave almost independently. We might ask whether U_S and U_{SM} share similarities? If there are two dominent Mixing angles in U_S, could there be two also in U_{SM}? If LSND is a manifestation Of the real world, is it unique, or might we find oscillations in other allowed Regions of Δm^2 vs. $\sin^2 2\theta$ space?

$$P_{osc}(\nu_\alpha \rightarrow \nu_\beta) \neq P_{osc}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

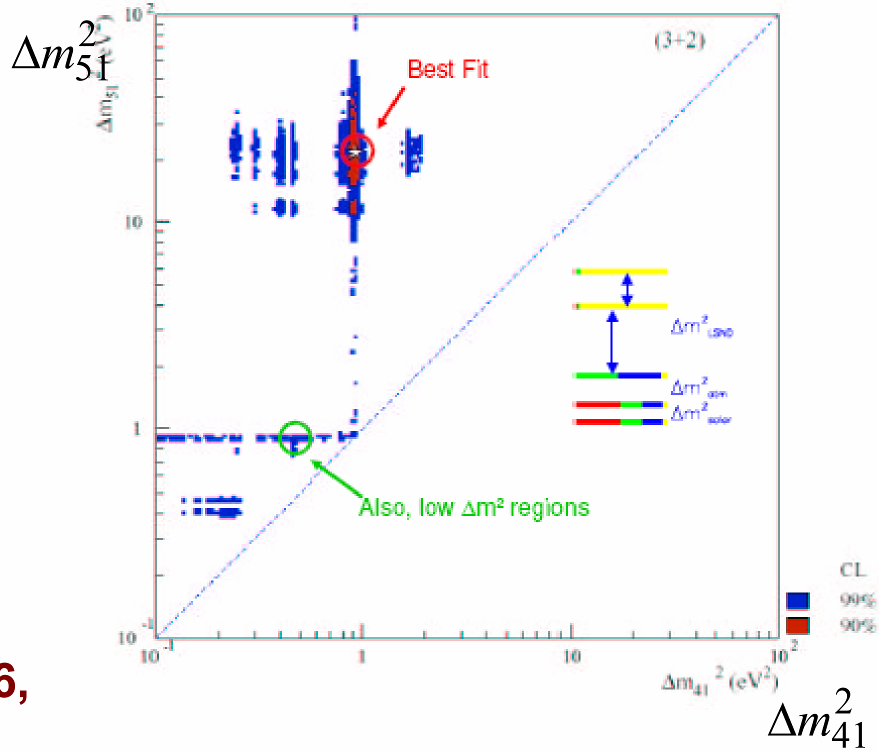


CP violating effects may also be involved in the LSND signal, in which case the effect might not be seen in MiniBooNE. Some form of CP or CPT violation is the neutrino sector would provide a mechanism for leptogenesis. Because the evolution of matter over anti-matter cannot be easily explained in the quark sector, it's important to look for answers among the leptons.

MiniBooNE can have a small Signal in neutrino-mode (which could Fluctuate to a null signal!) and have a 3X larger signal in antineutrino mode.

E-944 is approved to run through 2006, Perhaps with antineutrinos.

(Sorel, Conrad , Shaevitz., hep-ph/0305255)

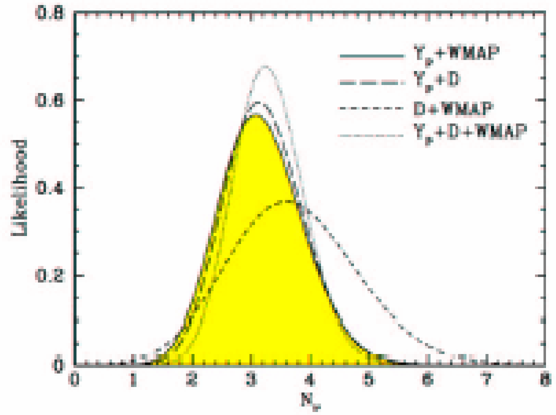


(Each pair of Δm^2 values has a range of allowed mixing angle solutions)

Cosmic Microwave Background/Large Scale Structure

What does the data say?

Big-Bang Nucleosynthesis

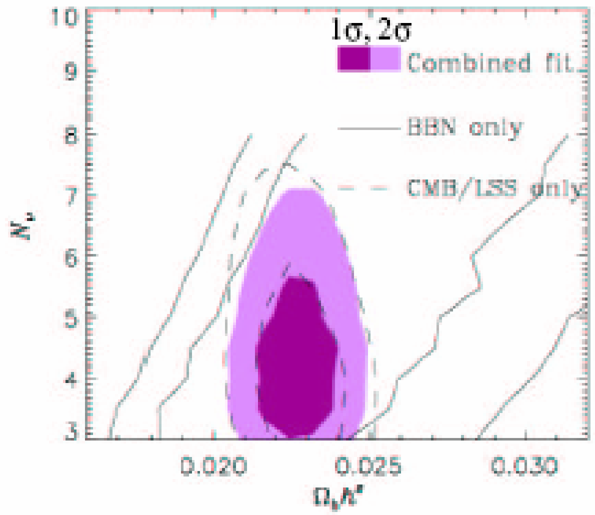


The latest from BBN fits:

Cyburt, Fields, Olive, Skillman, astro-ph/0408033

at 68% CL (1σ) $2.67<N_\nu<3.85$

Including CMB/LSS too:



$$\Omega_\nu h^2 = \frac{m_\nu}{92.5eV}$$

Hannestad astro-ph/0303076

Sterile neutrinos can travel off the brane just like gravitons.

You can wiggle out of the experimental bounds,
but a more likely explanation if LSND is right,
is "standard cosmology" is wrong

TOP 10 Models for a Nearly Neutrinoless Universe...

1) Matter & thermal resonances
2) Large "Lepton Asymmetry" (analogous to "Baryon Asymmetry")
3) Majoran models
4) Baryon-antibaryon inhomogeneties(introduces 4 sterile neutrinos!)
5) Extended quintessence model
6) Low re-heating temperature models
7) Interaction with a [illegible] scalar field
8) Low-scale breaking of global symmetries
9) Mass Varying Neutrinos
10) Something Not Predicted Yet

There are many models where cosmic neutrinos are substantially reduced or are even not out there...

If this is the case, Cosmology cannot address the question!

Theory of Neutrinos R.N. Mohapatra
http://www.physics.umd.edu/ep/mohapatra/apsreportshort.pdf

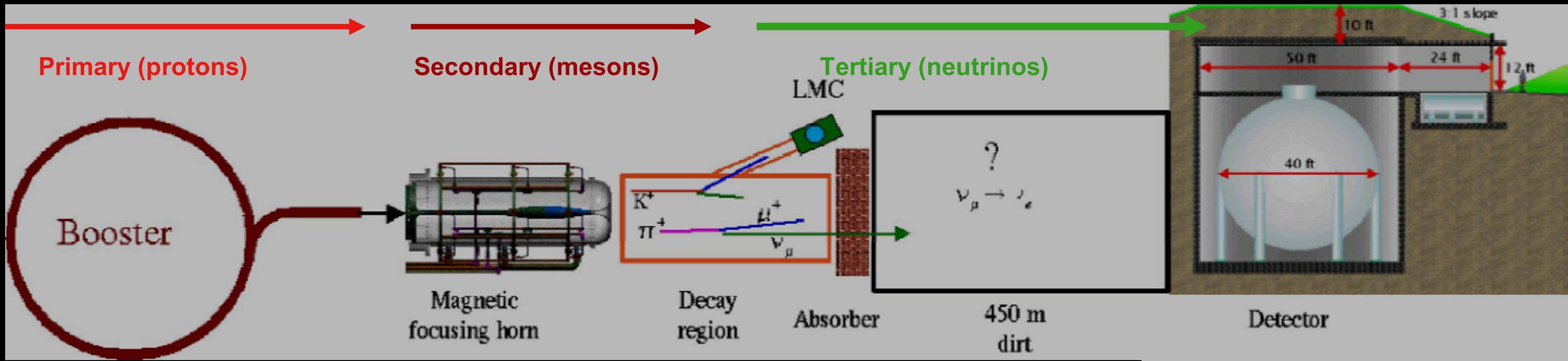
The existing data on neutrinos have already raised very important questions, such as the very different mixing angles, that are blazing new trails in physics beyond that Standard Model. They are also helping to define sharp questions to be addressed by near future experiments:

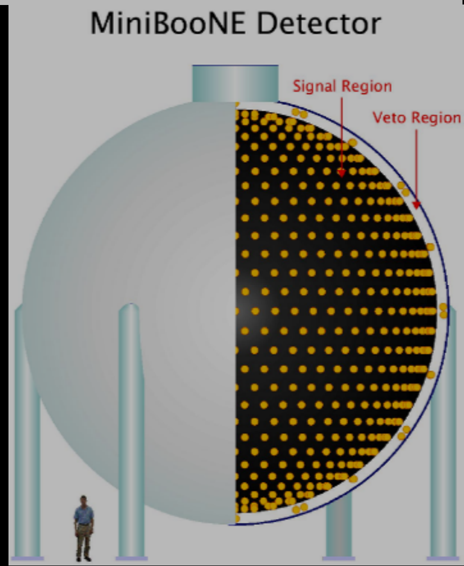
- Are neutrinos Direct or Majorana?
- What is the absolute mass scale of neutrinos?
- How small is θ13?
- How "maximal" is θ23?
- Is there CP Violation in the neutrino sector?
- Is the mass hierarchy inverted or normal?
- Is the LSND evidence for oscillation true? Are there sterile neutrino(s)?

(i) search for ββ0ν decay,
(ii) determination of the sign of the m^2 (13), and
(iii) measurement of the value of θ13.

We believe that all support should be given to MiniBooNE experiment until it provides a complete resolution of the LSND result.

E898: MiniBooNE





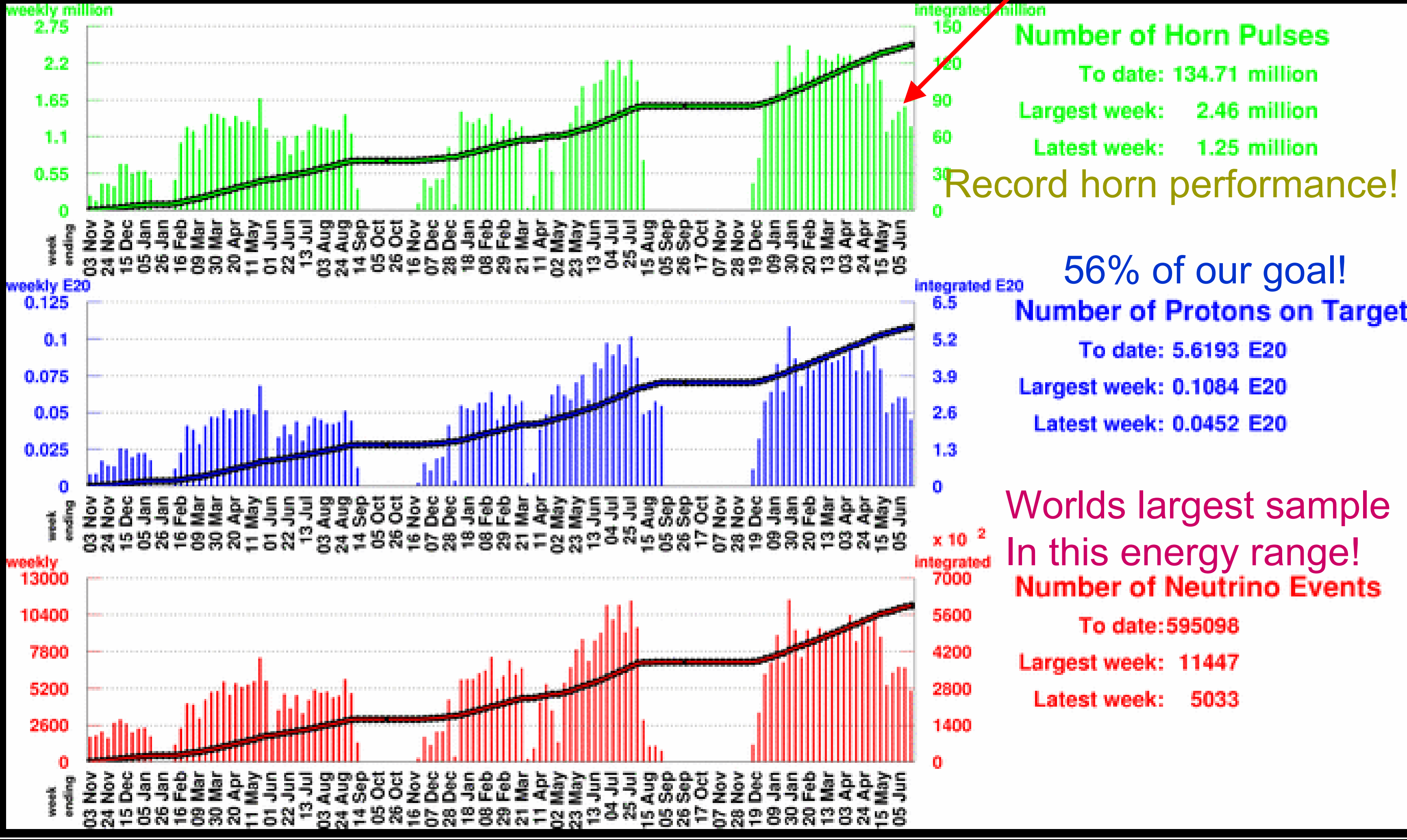
- 8 GeV proton beam
  - 1.6 μs pulse, 5 Hz rate from Booster
  - p + Be → mesons
- Mesons focused by magnetic horn
  - focusing increases ν flux by factor of 6
  - allow ν, anti-ν running
- Mesons → Decay in flight νs
- E ~ 700 MeV, L ~ 541 m (L/E ~ 0.77 m/MeV)

A history of amazing progress by the Booster and Accelerator Division!

slow start

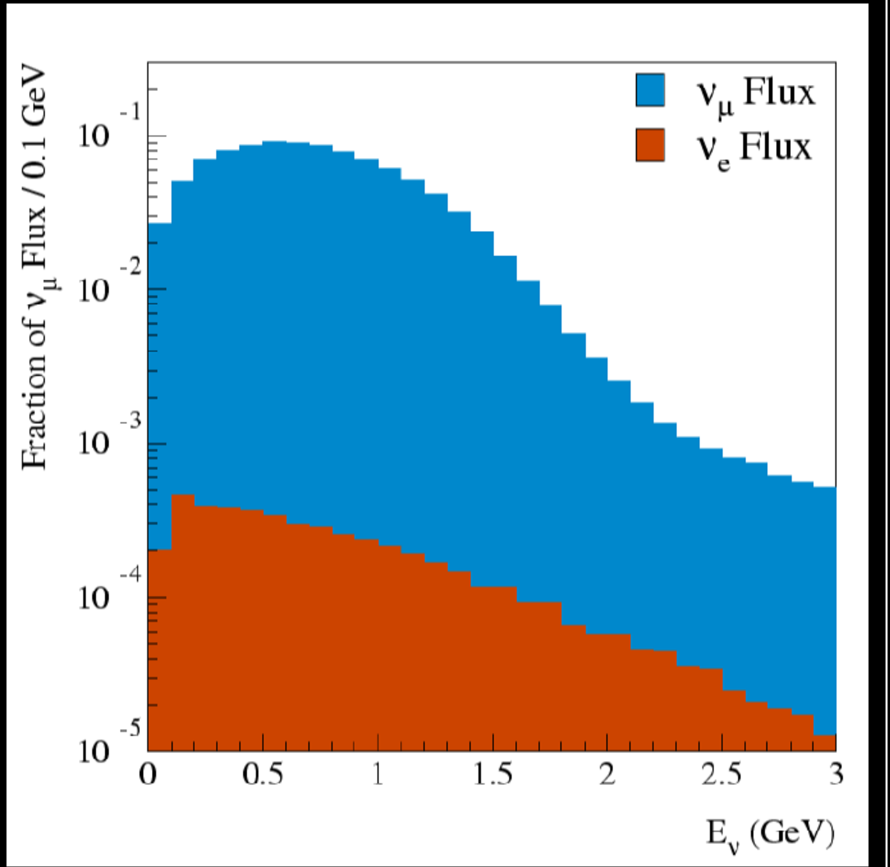
big finish!

we're still alive!



ν_e ν_μ Flux Determination

- ν_μ flux
  - $\pi^+ \to \mu^+ \nu_\mu$
- Intrinsic ν_e flux
  - From μ^+, K^+, K^0_L
  - ~0.4% of ν_μ flux
  - comparable to osc signal!
- E910 (Jon Link; paper in prep.)
  - π, K production @ 6, 12, 18 GeV w/thin Be target
- HARP (CERN; LANL, Columbia)
  - π, K production @ 8 GeV w/ 5, 50, 100% λ thick Be target

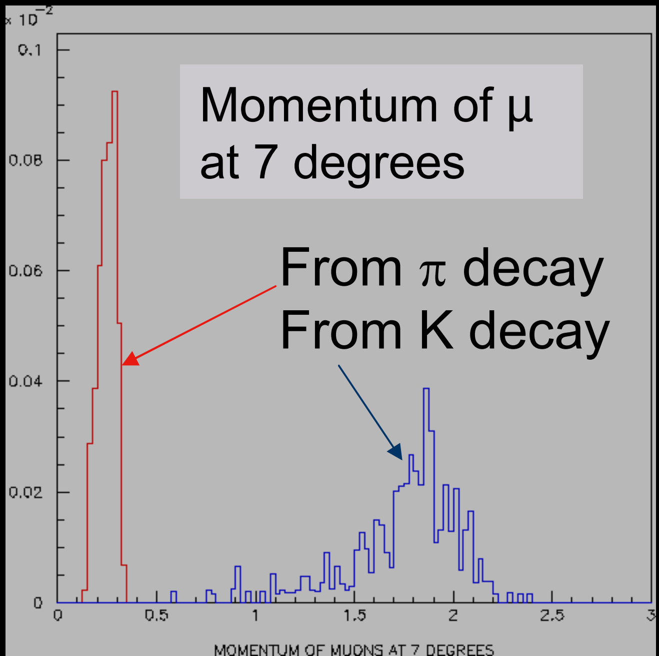


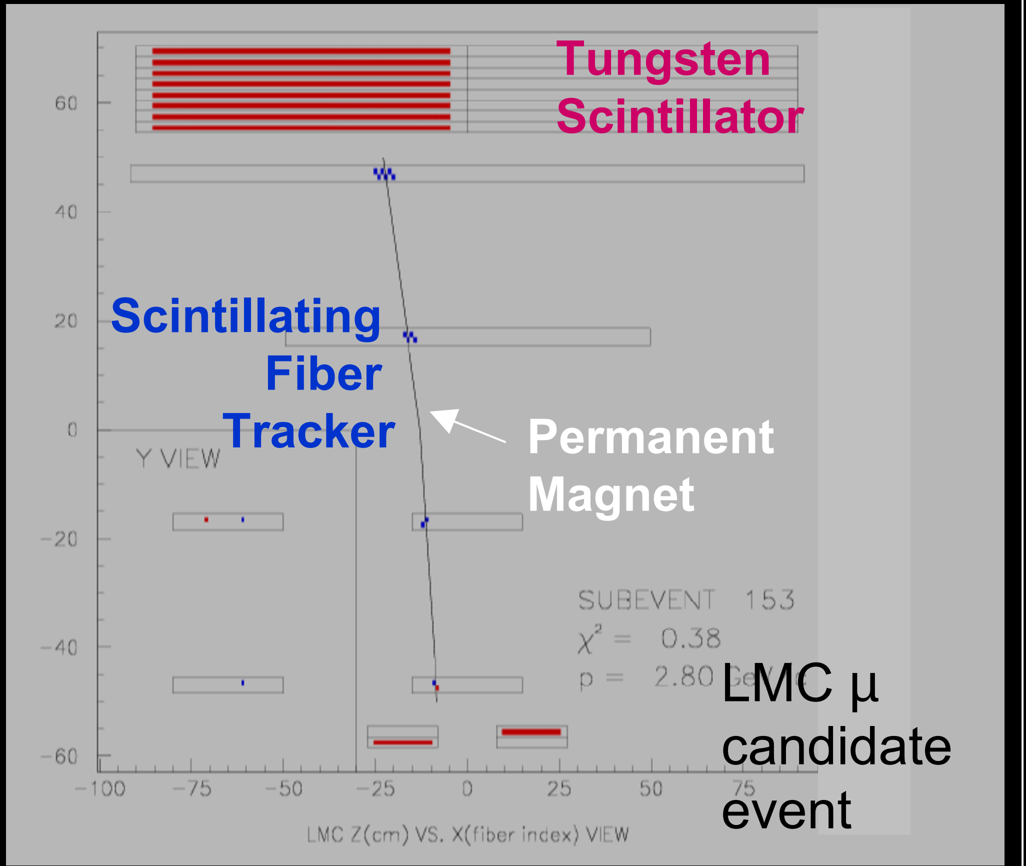
$\pi^+/K^+ \to \mu^+\nu_\mu$
$\pi^-/K^- \to \mu^- \bar{\nu}_\mu$

$K^+/K^0_L \to \pi e \nu_e$
$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
Michel electrons

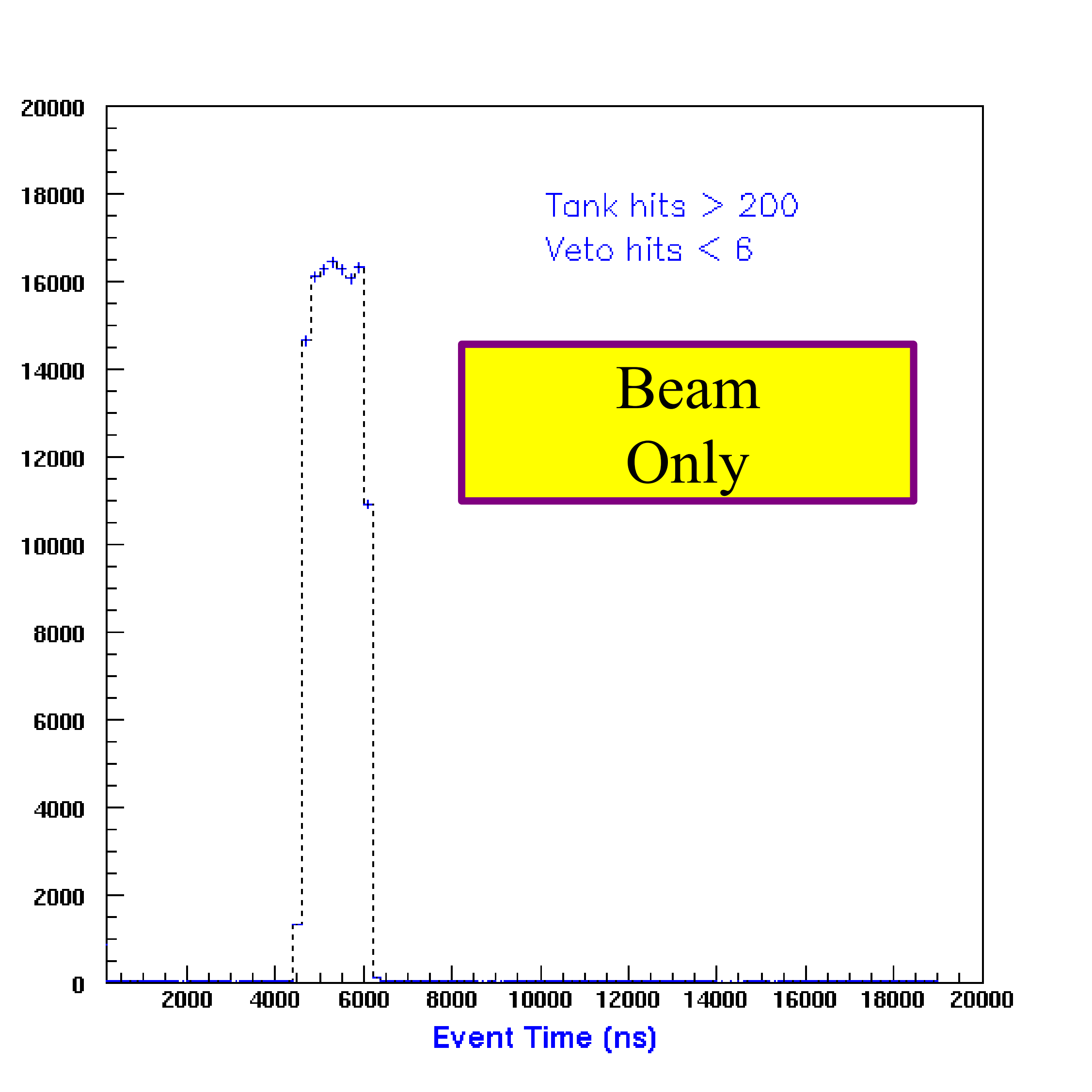
ν_e ν_μ Flux Determination

- LMC spectrometer
  - K decays produce wider angle μ than π decays
  - scintillating fiber tracker





- Times of hit-clusters (sub-events)
- Beam spill (1.6µs) is clearly evident
  - simple cuts eliminate cosmic backgrounds
- Neutrino Candidate Cuts
  - <6 veto PMT hits
    - Gets rid of muons
  - >200 tank PMT hits
    - Gets rid of Michels
  - Only neutrinos are left!



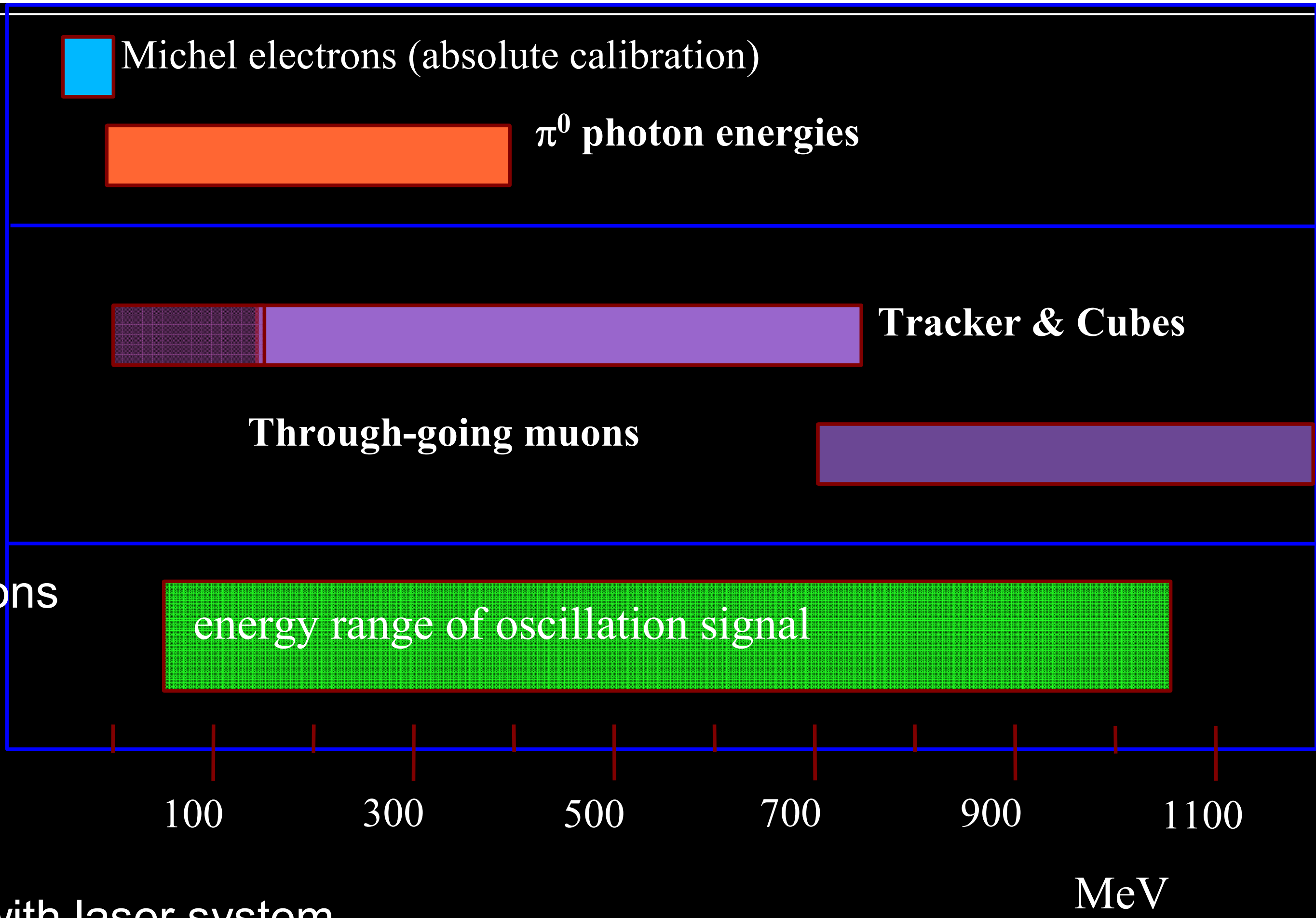
Calibration System:

Calibration data samples span oscillation signal energy range

Electron data samples

Michel electrons

π^0 photons



PMTs calibrated with laser system

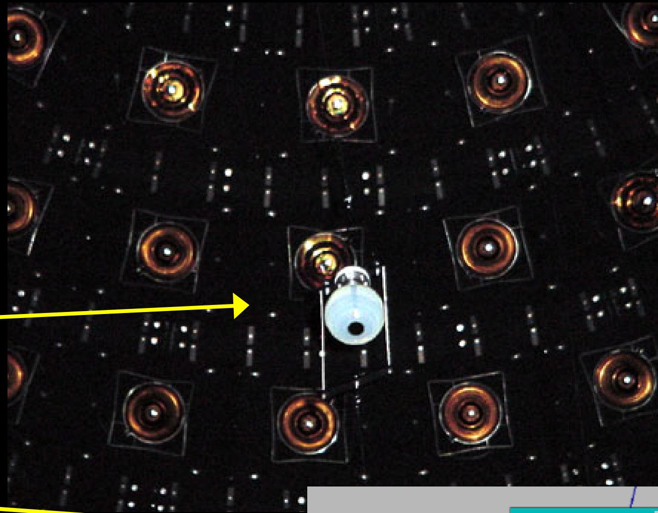
Cosmic Muons

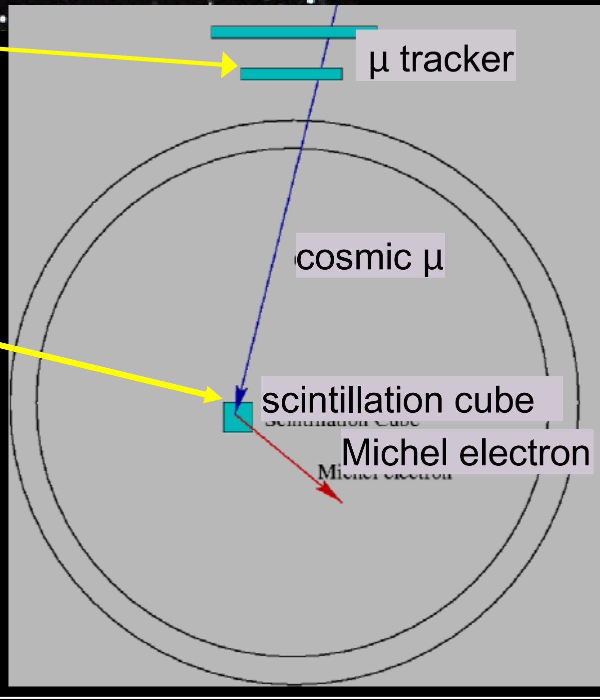
Stopping, through-going

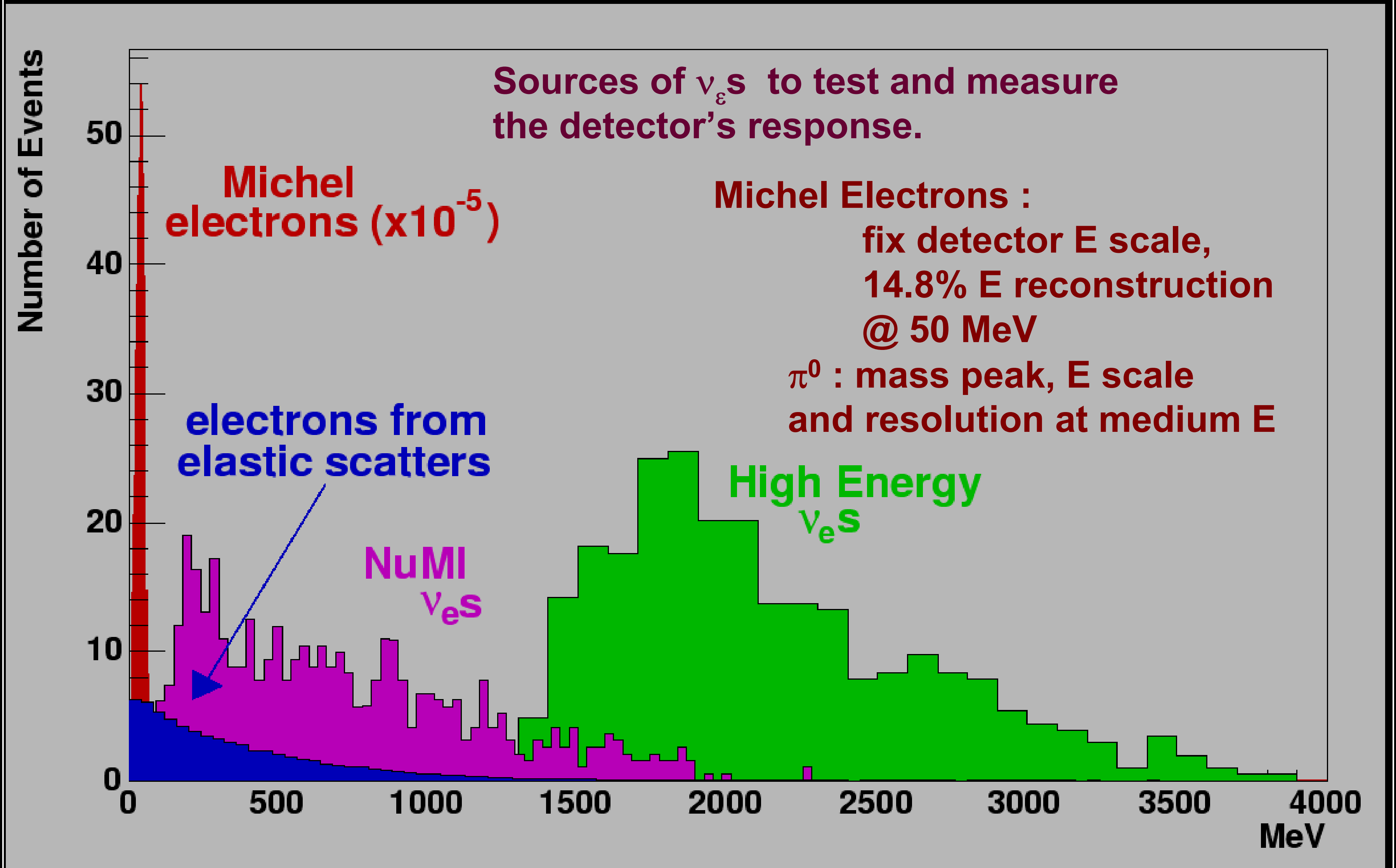
Very important: most neutrino events have muons

Calibration

- Laser Flasks (4)
  - Measure tube Q, timing response
  - Change I = study PMT, oil
- Muon tracker
  - Track dir + entry point = test track reconstruction in tank
- Cube System (7)
  - Optically isolated scint. cubes
  - + tracker = identify cosmic μ, michel ele of known position for E calibration

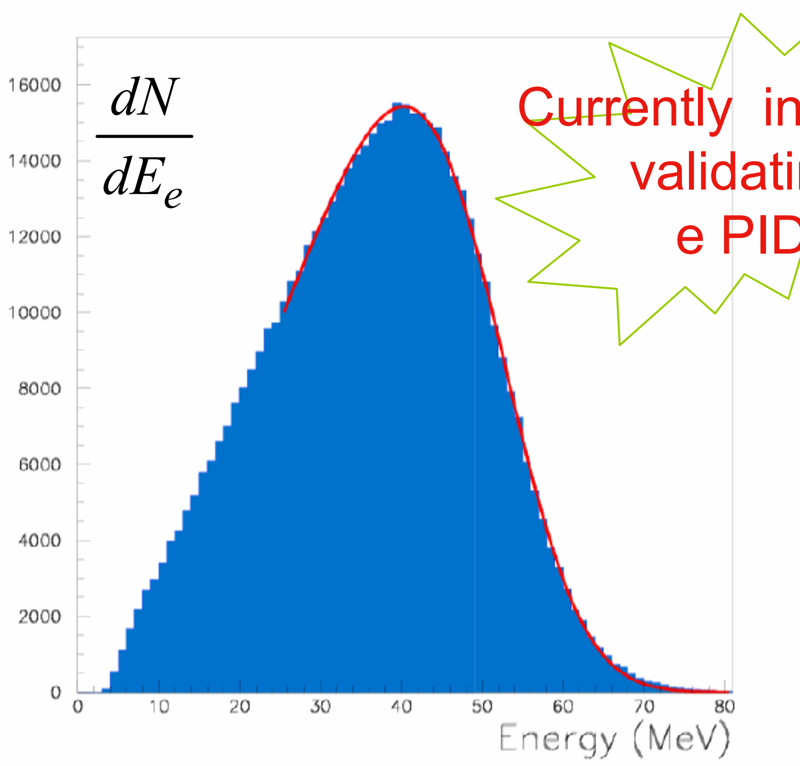





Sources of ν_εs to test and measure the detector's response.
Michel electrons ($x10^{-5}$)
Michel Electrons :
fix detector E scale,
14.8% E reconstruction
@ 50 MeV
π^0 : mass peak, E scale
and resolution at medium E
electrons from elastic scatters
High Energy ν_es
NuMI ν_es
Number of Events
0
10
20
30
40
50
0
500
1000
1500
2000
2500
3000
3500
4000
MeV

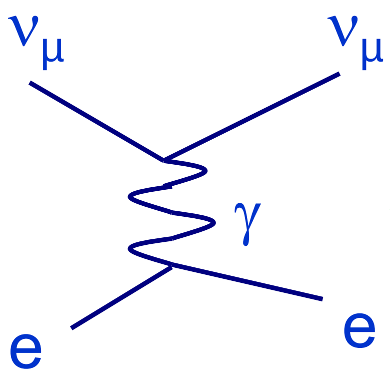
"Low Energy Electron Samples"

1. **Michel Electrons**
   - **E_e < 52MeV**
   - **Unlimited supply (2 KHz stopping μ rate)**
   - **Also fixes energy scale for calibration**



Currently in use for validating e PID!

2. **ν_μ eElastic Scatters**
   - **E_e < 1000MeV**
   - **Expect ~100 events**
   - **Purely leptonic small σ uncertainty**
   - **Event selection based on very forward kinematics**
   - **Used previously to measure $\sin^2\theta_W$ and μ_B**



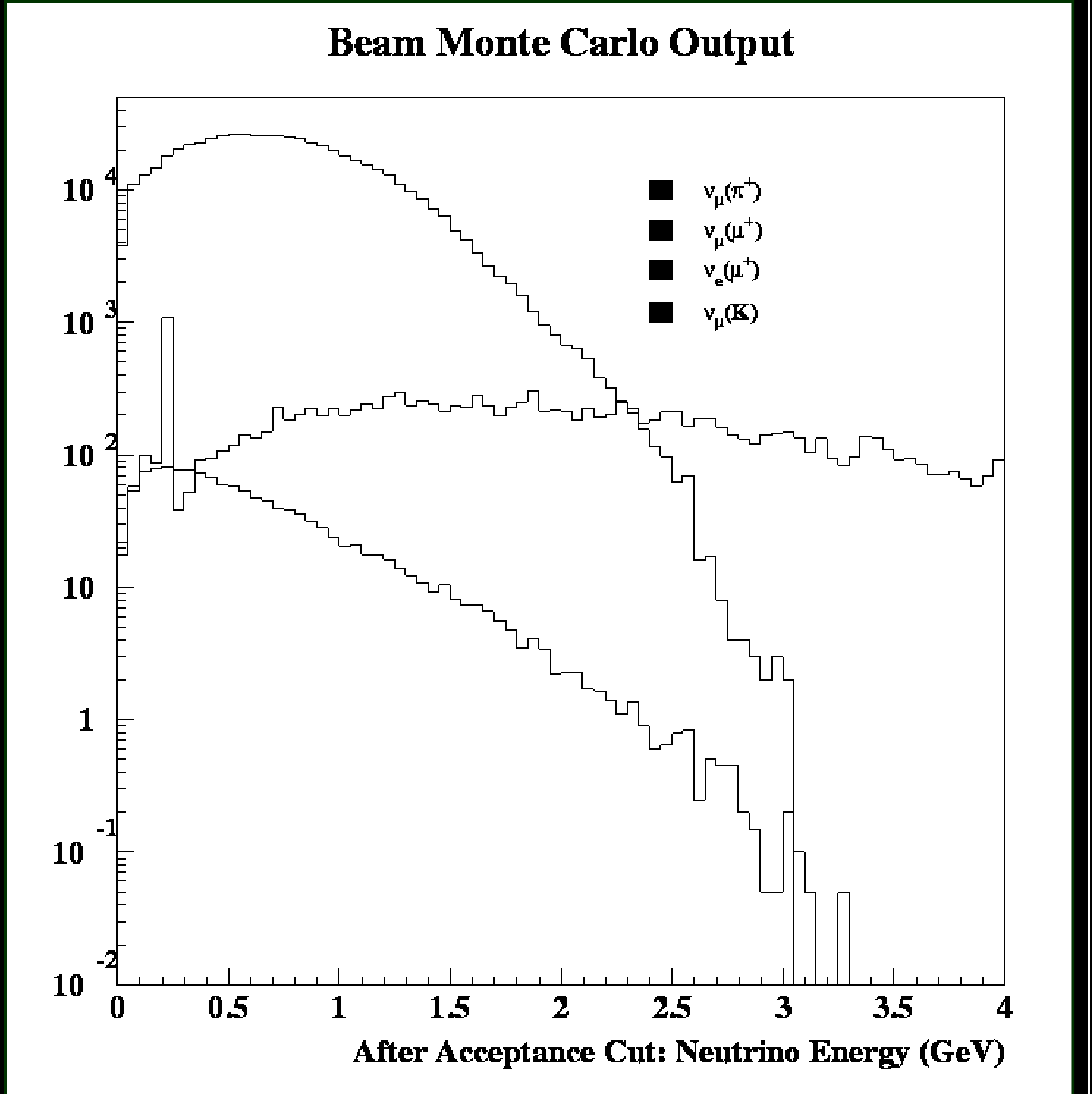
Analysis in Progress!

High Energy Box

E_e >1.5 GeV

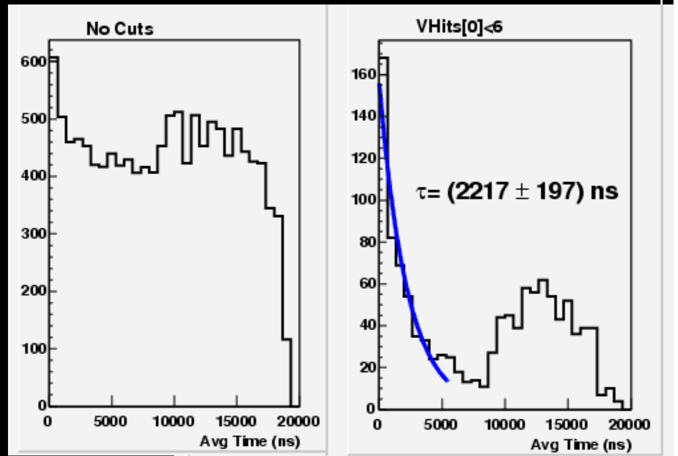
ν_e yield from Kaon decay:

BR($K^+ \rightarrow \nu_e$) = 5%
BR($K^0 \rightarrow \nu_e$) = 30%

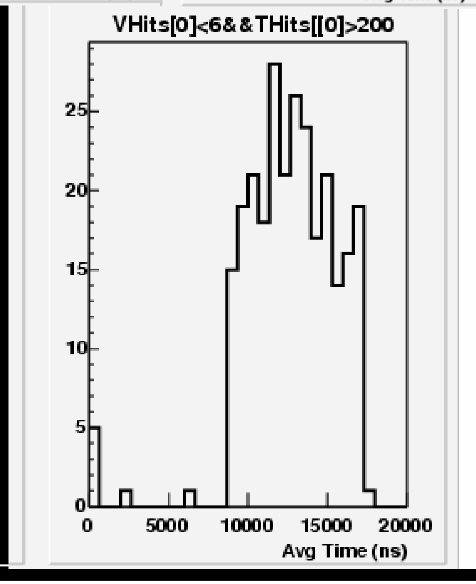


“Electrons from NuMI” (The E-898 ν_e calibration beam)

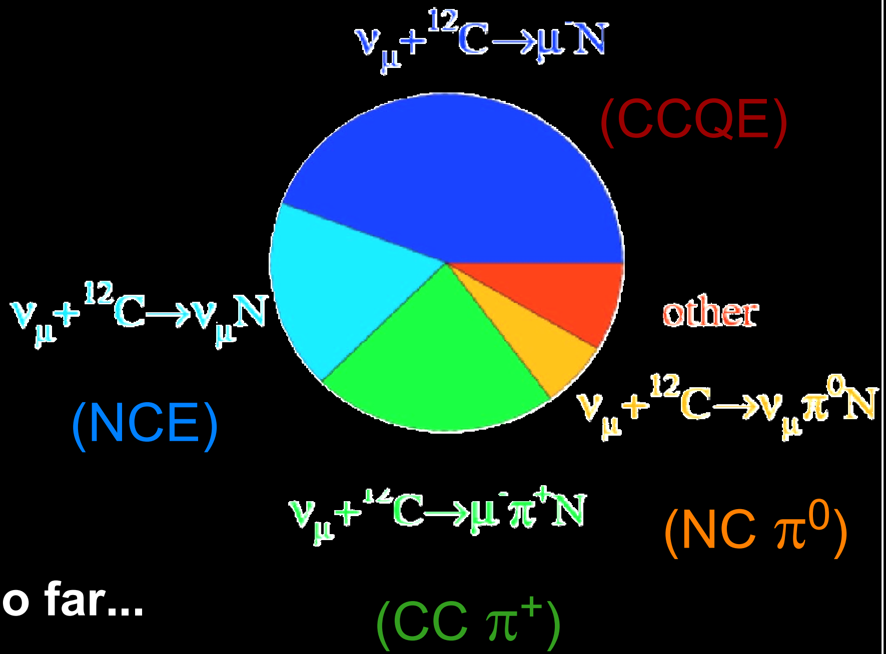
Neutrino interactions have been observed in the E-898 detector, generated by neutrinos from the NuMI beam. MiniBooNE can now claim to be the world’s first off-axis detector.



- E-898 is 111 mrad off the NuMI beam axis, and 750 m away from the NuMI target.
- E-898 triggers off the NuMI extraction kicker in the Main Injector.
- The beam spill contains 5 batches in 8 μs.
- A few 1000 events are expected in the range
- $0<E_{visible}<2$ GeV by the 2005 shutdown.
- The measured   ratio is a few percent ➔ should provide thousands of   events for calibration and particle ID validation!



ν_μ Physics

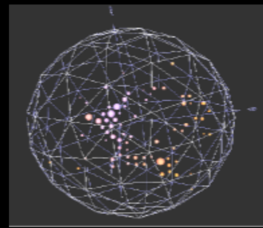


- Data processing chain
- **~595,000 neutrino events recorded so far...**
  - **~5.6×10^{20} POT**
- ~222K CCQE
- ~141K CC π^+
- ~90K NC Elastic
- ~39K NC π^0

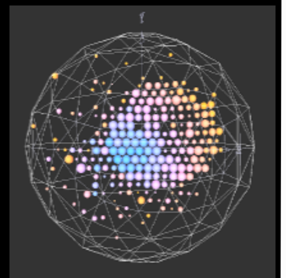
Particle Identification

- Identify events using hit topology
- Use a "boosted tree" algorithm and ANN to separate e, mu, pi, delta
- Particle ID Variables
  - Reconstructed physical observables
    - Track length, particle production angle relative to beam direction
  - Auxiliary quantities
    - Timing, charge related : early/prompt/late hit fractions, charge likelihood
  - Geometric quantities
    - Distance to wall

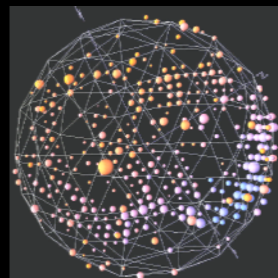
Michel e from μ decay

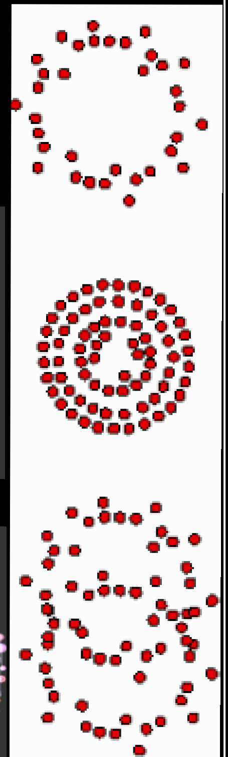


μ candidate



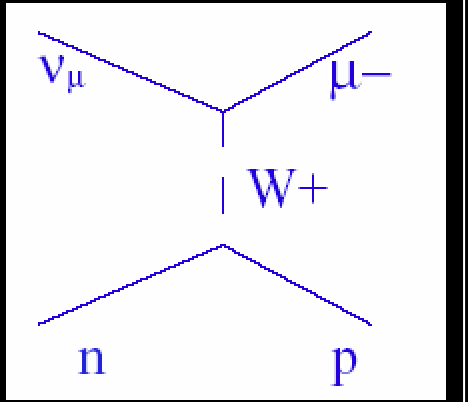
π^0 candidate





Nuc. Inst and Meth A, Vol 543/2-3

ν_μ CCQE



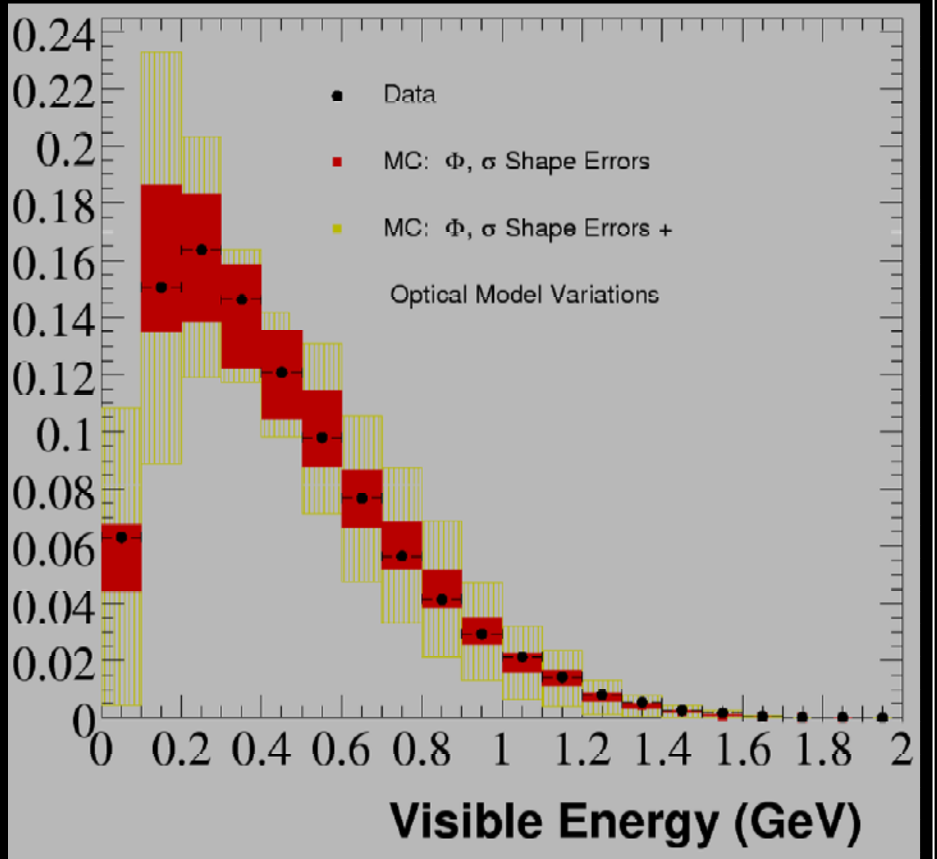
- Largest class of evts; use to validate flux,
- σ predictions
- Intrinsic ν_e bgd due to μ decay can be
- constrained
- Will search for ν_μ disappearance for Δm^2 ~0.1 - 10 eV^2

- Event Selection
  - Use Fisher discriminant to isolate events with μ-like Cerenkov ring in final state
- Preliminary comparisons between measured distributions and MC expectations
  - Ex: Q^2 (sensitive to nuclear effects such as Pauli blocking)

ν_μ **CCQE**

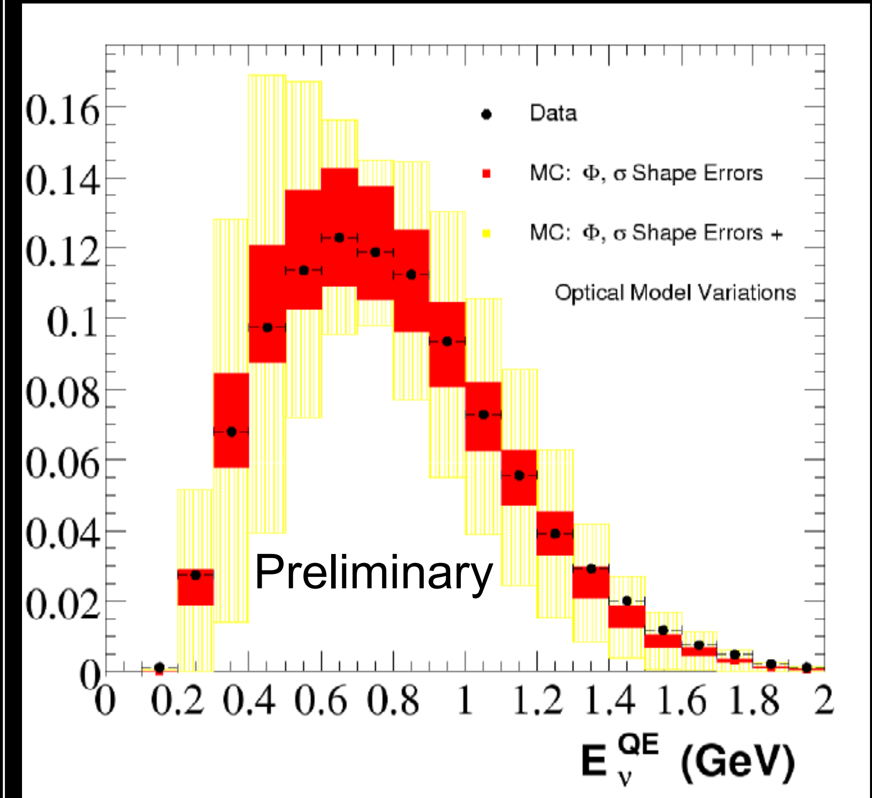
- Flux estimates
  - π^+ production, will be measured to 5% with HARP
- Cross section
  - CCQE from axial mass uncertainty, threshold effects, Pauli blocking
- Optical Model
  - reflects current uncertainty on optical model parameters

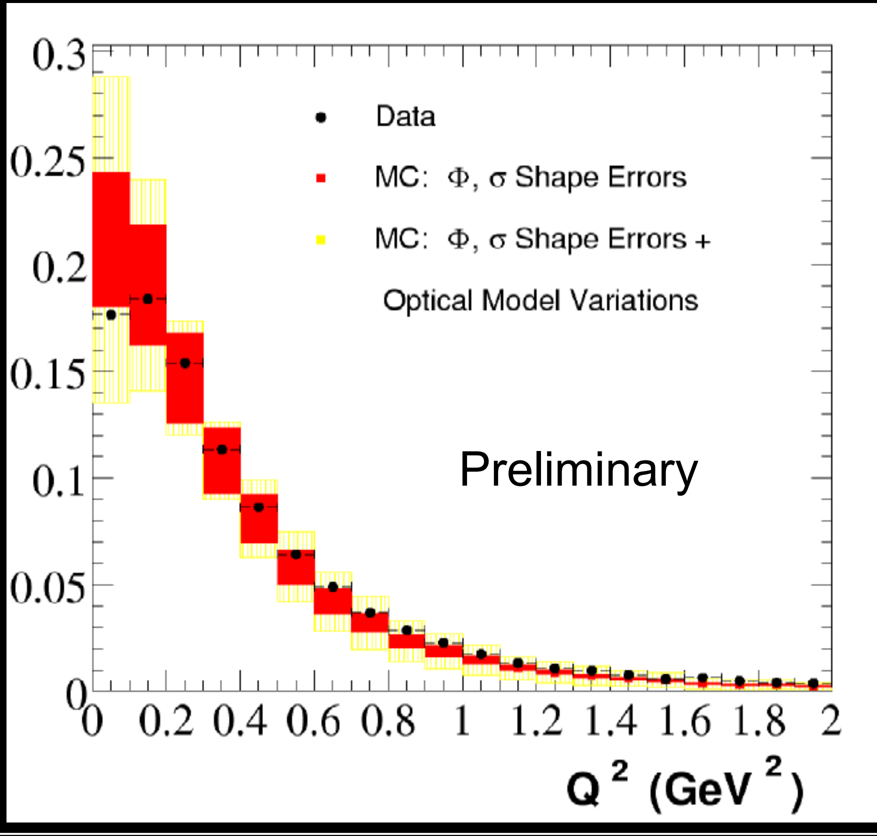
Visible Energy is the muon kinetic energy deposited in the tank



CCQE

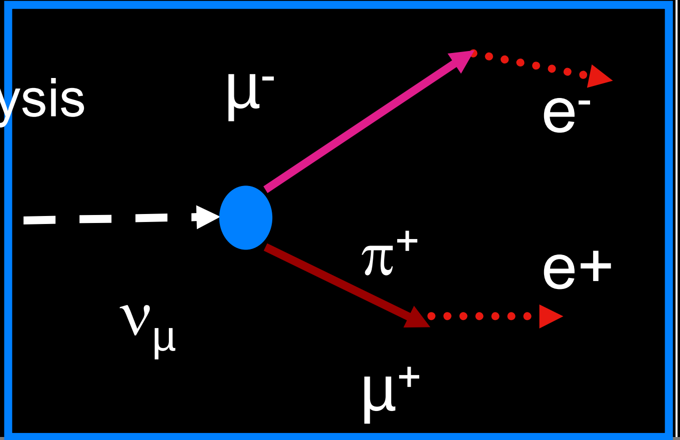
- Simple reconstruction with QE kinematics
  - Measure muon energy and angle
  - Reconstruct neutrino energy an Q^2



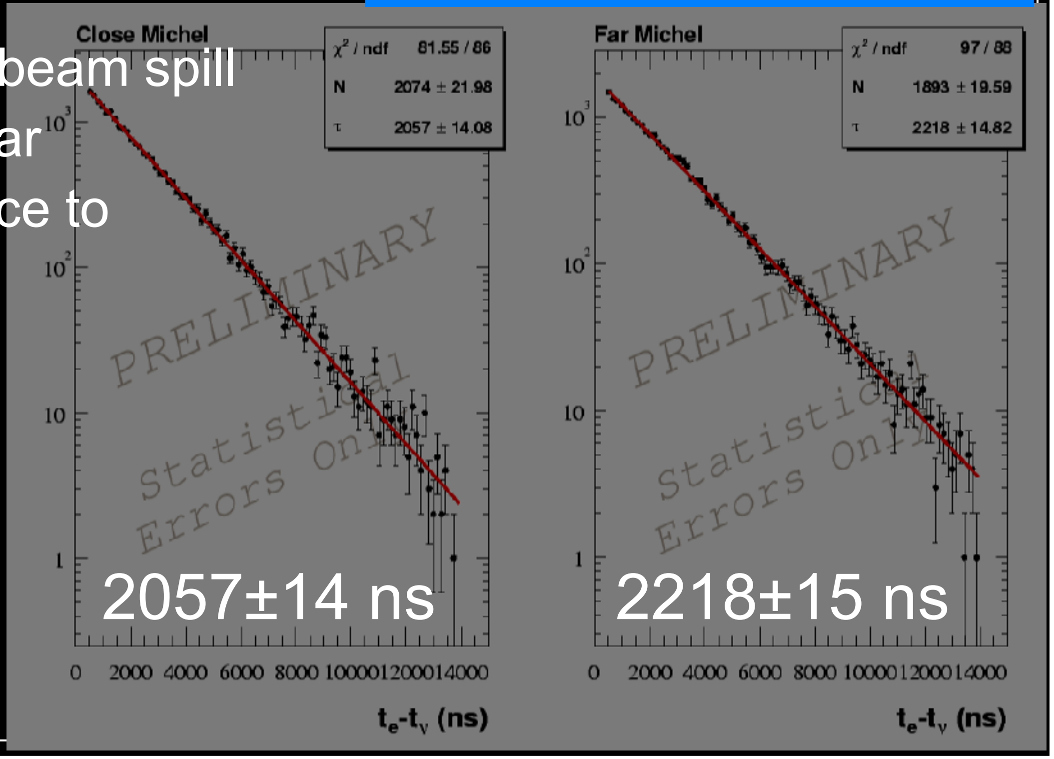


CC π^+

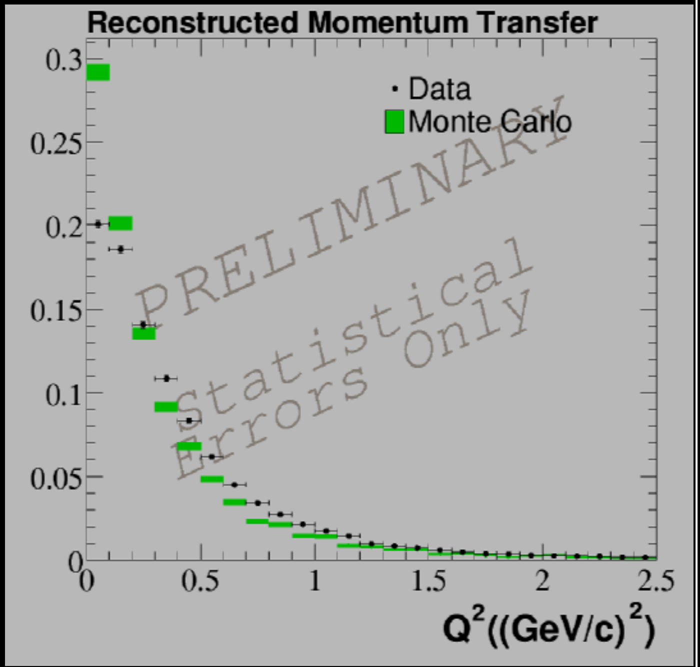
- Primary background to CCQE evts/analysis
- All previous measurements at bubble chambers, 7000 total evts, all on light targets, few measurements at low E

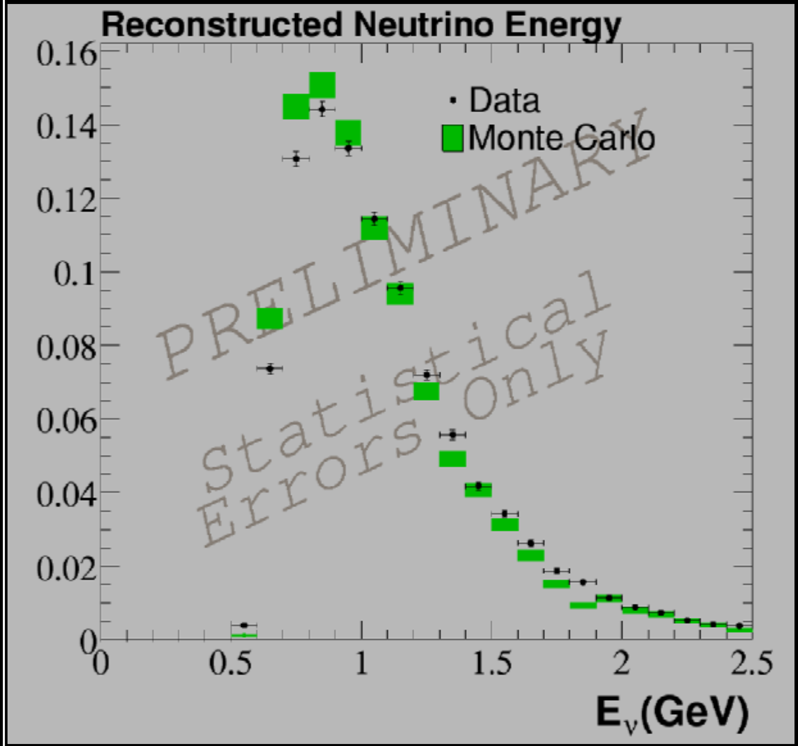


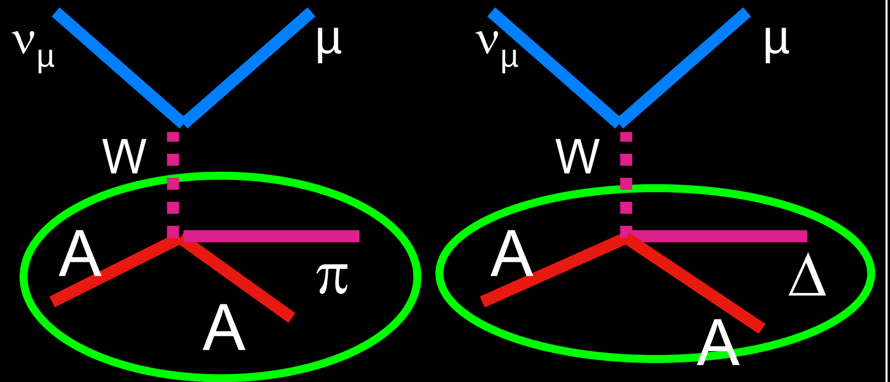
- Event Selection
  - At least 2 Michels,
  - parent neutrino event in beam spill
  - Separate into near and far Michels based on distance to muon track
  - Close Michels from μ^-
    - μ^- capture on C
    - τ = 2026±1.5 ns
  - Far michels from μ^+
    - τ = 2197±0.04 ns



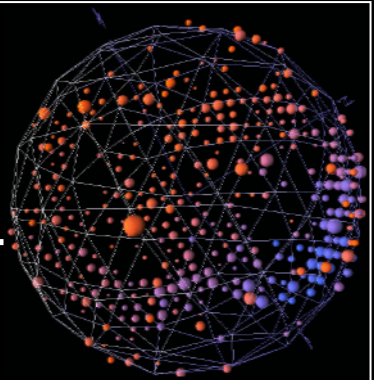
- Simple reconstruction (for now)
  - Assume events are QE with Delta, instead of having recoil nucleon
  - Don't use pion information in reconstruction







NC π^0 Jen Raaf, Cincinatti

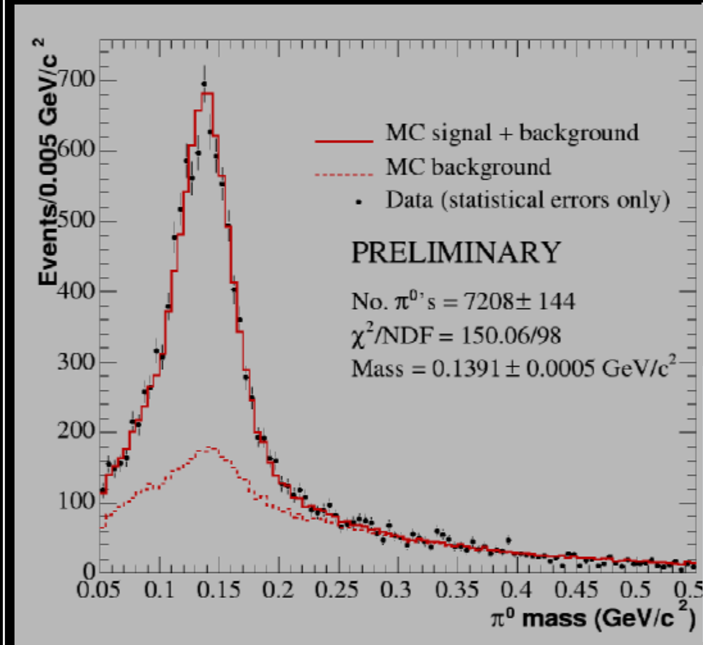


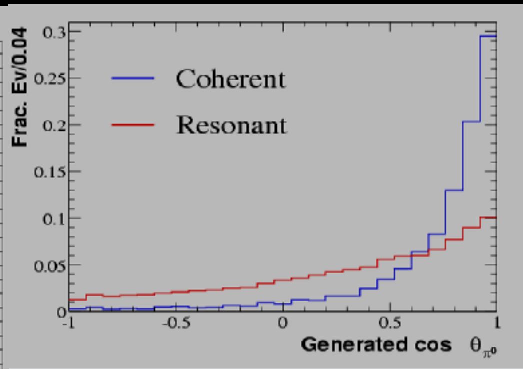
Background to ν_e appearance (dominant mis-ID)

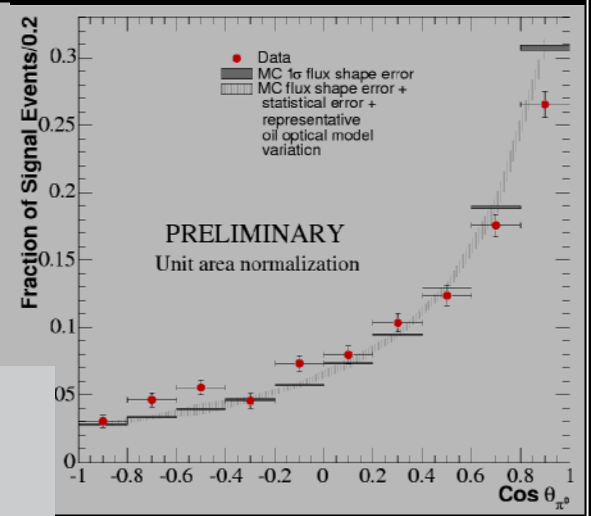
- σ : crucial for distinguishing ν_μ->ν_τ, ν_μ->ν_s in atm.
  - + angular distribution constrain mechanisms for NC π^0 production

- Event Selection
  - No decay electron, 2 Cerenkov rings > 40 MeV each
  - signal yield extracted from fit with bgd MC : fit assuming 2 rings
- Examine mass spectrum, kinematics
  - Bin data in kin. quantities : π^0 momentum, E asymmetry, angle of π^0 relative to beam, extract binned yields
  - Compare distributions to MC expectations

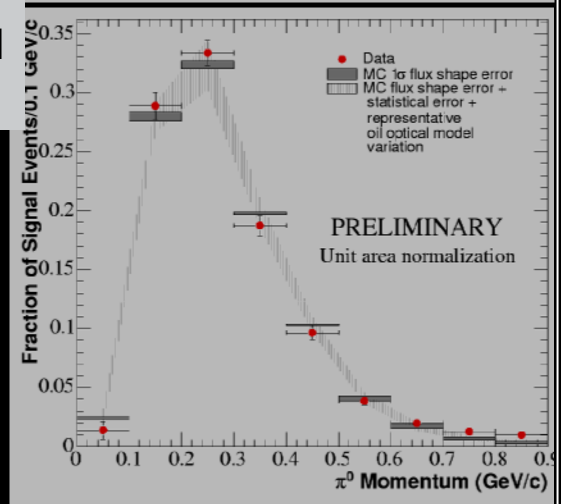
NC π^0



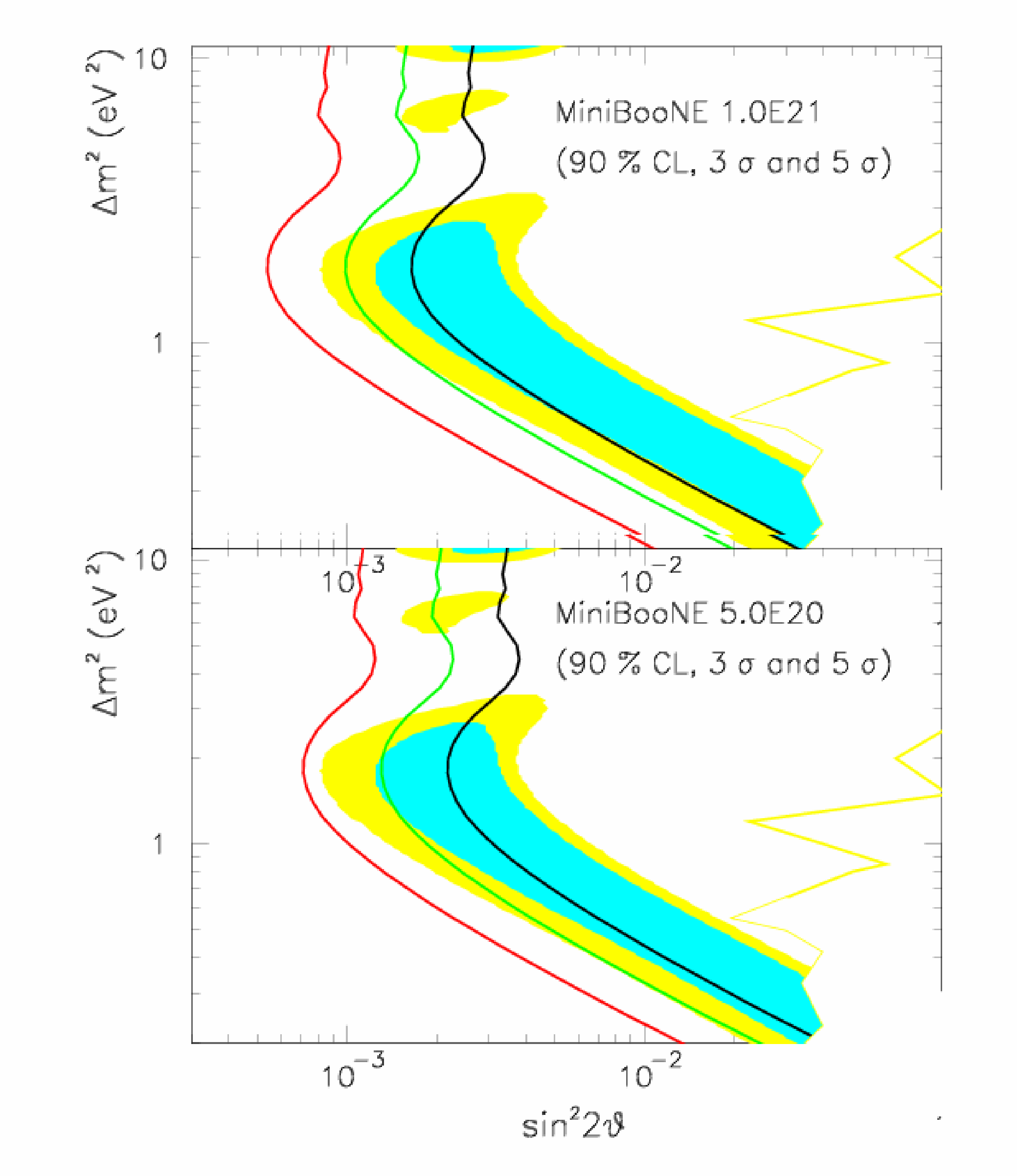




Errors are shape errors
Dark grey : flux errors
Light grey : optical model



- π^0 momentum = good data/mc agreement. Fall-off at high p = due to flux falloff
- Cos $\theta_{\pi 0}$ sensitive to production mechanism (coherent = forward, resonant = not so forward)



MiniBooNE oscillation sensitivity for 10^{21} p.o.t. (top) and 5 X 10^{20} (bottom) using the energy fit method. Blue (yellow) is LSND's 90% (99%) CL allowed region

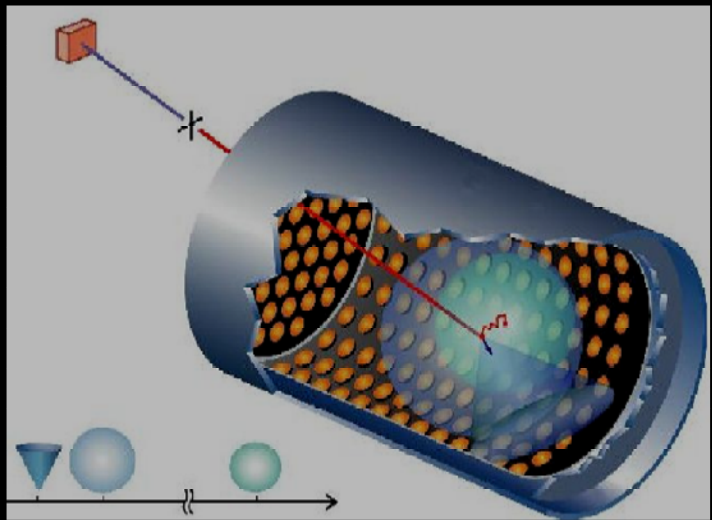
Conclusion

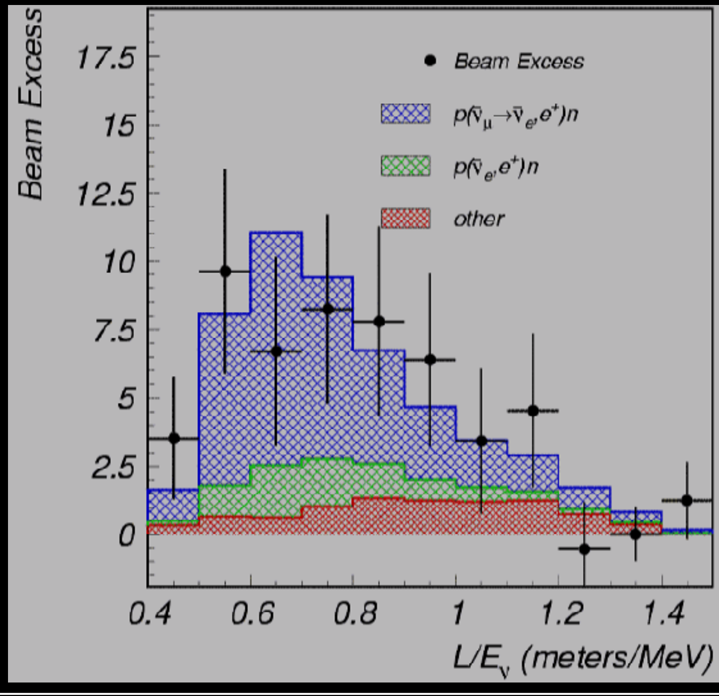
- The LSND effect provides a hint of what might be a complex and wonderful world of extra neutrios.
- MiniBooNE has accumulated ~**56%** of 10^{21} pot needed for 4-5 σ coverage of LSND
- Already have worlds largest ν dataset in 1 GeV range
- Reconstruction and analysis algorithms are working well :
  - CCQE : compare with flux predictions, disappearance analysis
  - CC π^+ : measure cross section, oscillation search
  - NC π^0 : measure cross section, analyze coherent contribution
- ν_e appearance analysis well under way; plan on opening box in late later this year.
- E-944 is approved to run through 2006, perhaps with anti-neutrinos.

Backup Slides

LSND

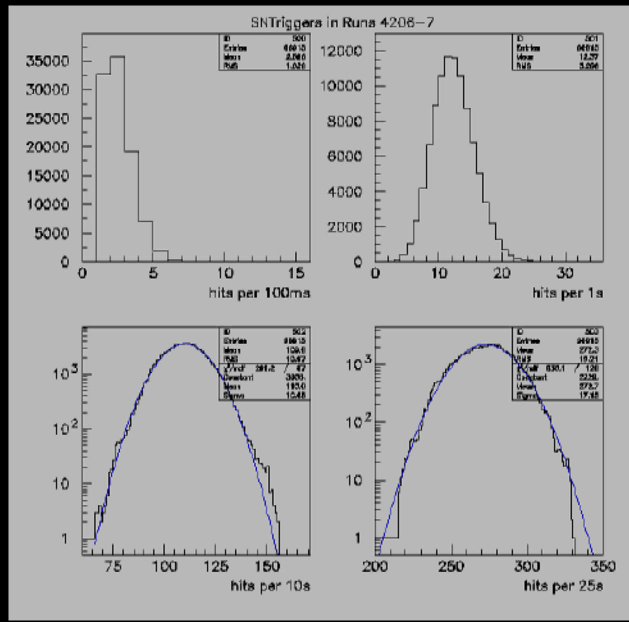
- 800 MeV proton beam -> water target
- 167 ton, liquid scintillator, 25% PMT coverage
- E ~ 20-53 MeV, L ~ 25 - 35 m (L/E ~ 1m/MeV)
- Measure $\nu_{\mu} \rightarrow \nu_e$ osc. from DAR
  - P = 2.64±0.67±0.45 x 10^{-3}, see 4 sigma excess

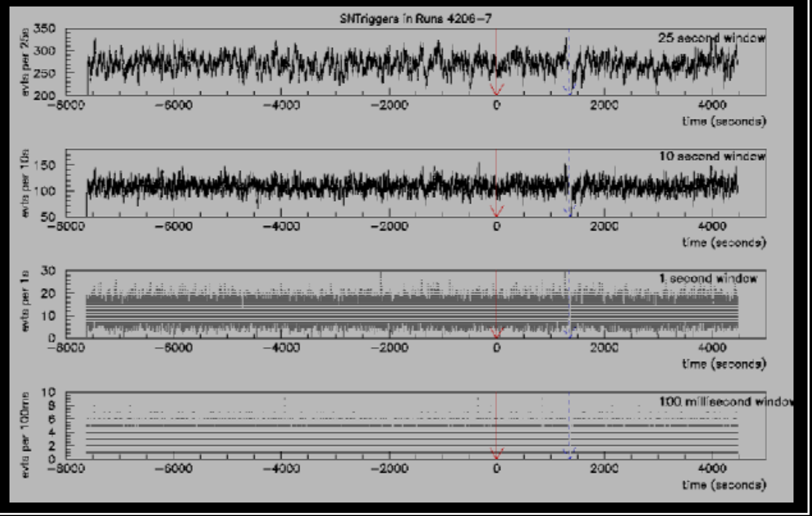




Exotic Searches

- Muon magnetic moment search
  - Massive $\nu \rightarrow \nu_R$, expect non-zero muon mag moment
  - Need full dataset
- Rare particle searches
  - Take advantage of beam structure
  - Proton dribble monitor
    (if p between buckets,
    no search!)
- Astrophysics
  - Supernova searches
    - Gamma Ray bursts (GRB 030329)
  - Solar flare emission searches
  - Gamma Ray bursts





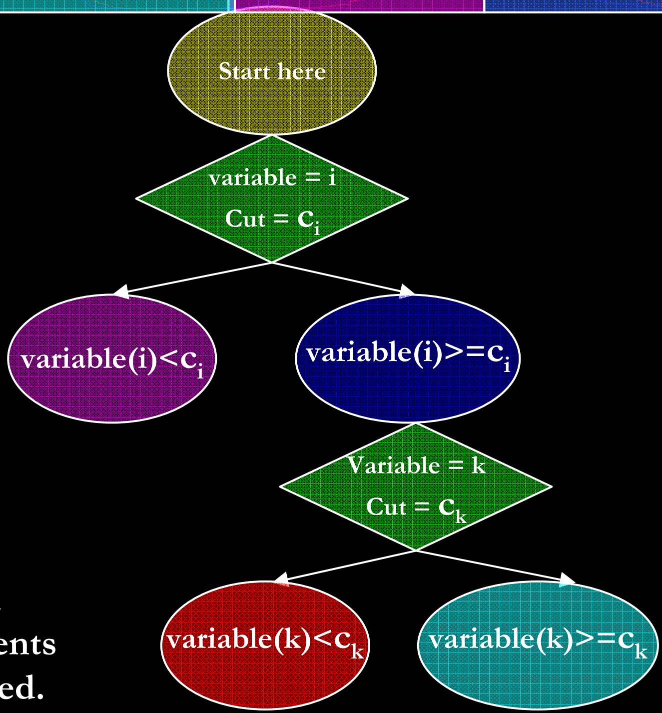
Particle ID Software Optimization

1. Boosting: how to split node ? – choose variable and cut

Define Gini Index = P (1 - P) and P = $\sum \omega^{S} / \sum \omega^{(S+B)}$ here, ω is event weight

For a given node, determine which variable and cut value maximizes:

$$\mathcal{G} = \text{GiniIndex}^{\text{Father}} - (\text{GiniIndex}^{\text{LeftSon}} + \text{GiniIndex}^{\text{RightSon}})$$



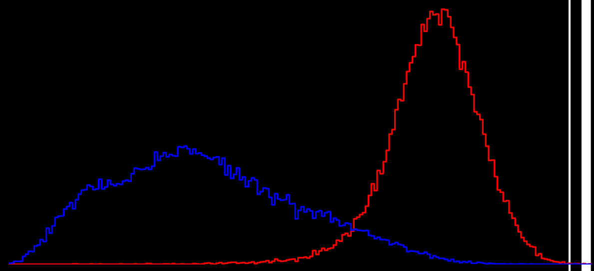
2. Boosting: how to generate tree? – choose node to split

Among the existing leaves, find the one which gives the biggest $\mathcal{G}$ and split it. Repeat this process to generate a tree of the chosen size.

3. Boosting: how to boost tree ? – choose algorithm to change event weight

Take ALL the events in a leaf as signal events if there are more signal events than background events in that leaf. Otherwise, take all the events as background events. Mark down those events which are misidentified. Reduce the weight of those correctly identified events while increase the weight of those misidentified evens. Then, generate the next tree.

4. Boosting: output value – sum over (polarity x tree weight) in all trees



See B. Roe et al. NIM A543 (2005) 577 and references therein