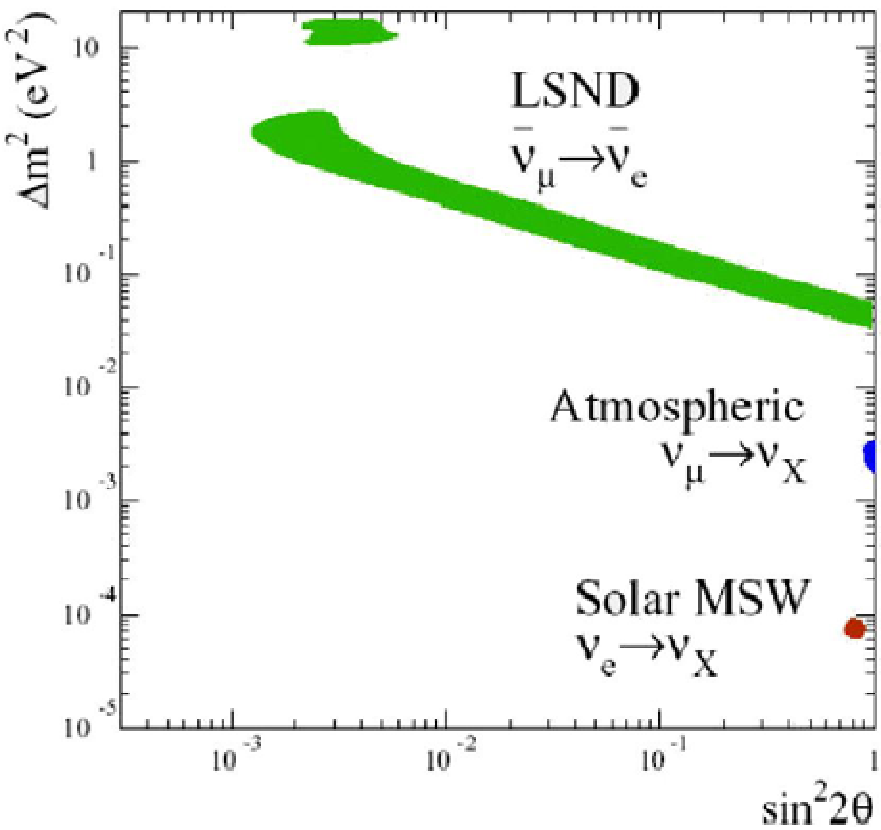
MiniBooNE and Sterile Neutrinos

M. Shaevitz
Columbia University
WIN 05 Workshop

- Extensions to the Neutrino Standard Model: Sterile Neutrinos
- MiniBooNE: Status and Prospects
- Future Directions if MiniBooNE Sees Oscillations

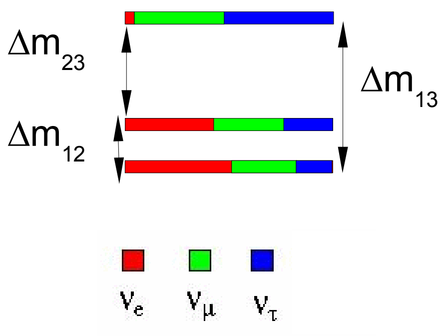
Three Signal Regions



$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L / E)$$

- LSND
  $\Delta m^2 = 0.1 - 10\ \mathrm{eV}^2$, small mixing
- Atmospheric
  $\Delta m^2 = 2.5\times10^{-3}\ \mathrm{eV}^2$, large mixing
- Solar
  $\Delta m^2 = 8.0\times10^{-5}\ \mathrm{eV}^2$, large mixing

- Three distinct neutrino oscillation signals,
  with $\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$
- For three neutrinos,
  expect $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$



How Can There Be Three Distinct Δm^2 ?

- One of the experimental measurements is wrong
  - Many checks but need MiniBooNE to address LSND
- One of the experimental measurements is not neutrino oscillations
  - Neutrino decay $\Rightarrow$ Restriction from global fits
  - Neutrino production from flavor violating decays $\Rightarrow$ Karmen restricts
- Additional "sterile" neutrinos involved in oscillations
  - Still a possibility but probably need (3+2) model
- CPT violation (or CP viol. and sterile ν's) allows different mixing for ν's and $\bar{\nu}$'s
  - Some possibilities still open

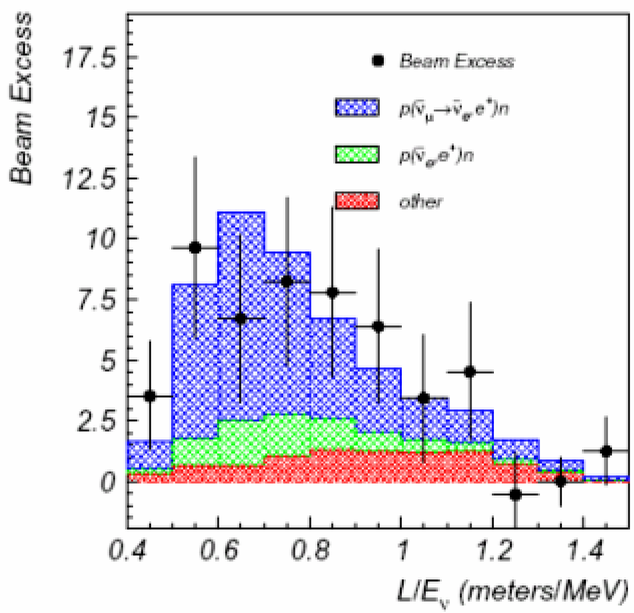
LSND Result

- Excess of candidate $\bar{\nu}_e$ events

  87.9 ± 22.4 ± 6.0 events (3.8σ)

  P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) = 0.264 ± 0.081 %

- Backgrounds in green, red
- Fit to oscillation hypothesis in blue



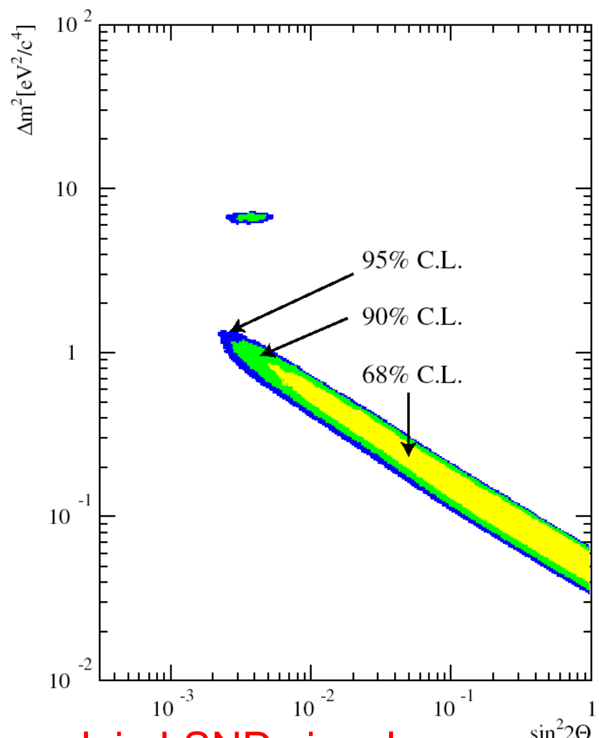
Also Karmen Experiment

- Similar beam and detector to LSND

  Closer distance and less target mass

  ⇒ x10 less sensitive than LSND

- Joint LSND/Karmen analysis gives restricted region (Church et al. hep-ex/0203023)



Also, from Karmen exp.

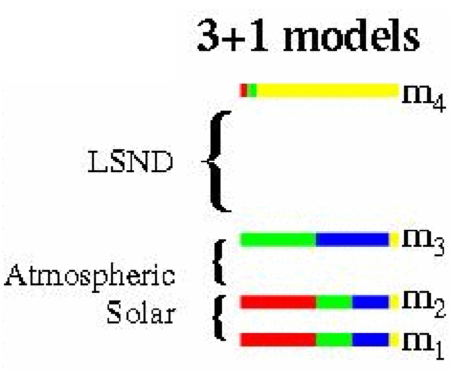
$\mu^+ \rightarrow e^+ \bar{\nu}_e \nu$ unlikely to explain LSND signal

Experimental Situation:
Fits of 3+1 and 3+2 Models to Data

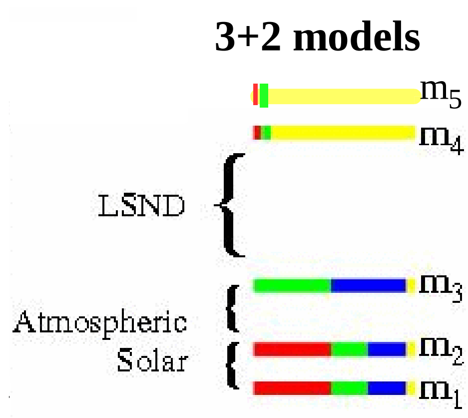
- Global Fits to high Δm^2 oscillations for Short-Baseline exps including LSND positive signal. (M.Sorel, J.Conrad, M.S., hep-ph/0305255)

Is LSND consistent with the upper limits on active to sterile mixing derived from the null short-baseline experiments?

Channel	Experiment	Lowest Δm^2 Reach (90% CL)	$\sin^2 2\theta$ Constraint (90% CL) High Δm^2	Optimal Δm^2
$\nu_\mu \to \nu_e$	LSND	$3 \cdot 10^{-2}$	$> 2.5 \cdot 10^{-3}$	$> 1.2 \cdot 10^{-3}$
	KARMEN	$6 \cdot 10^{-2}$	$< 1.7 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
	NOMAD	$4 \cdot 10^{-1}$	$< 1.4 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
$\nu_e \to \nu_{e'}$	Bugey	$1 \cdot 10^{-2}$	$< 1.4 \cdot 10^{-1}$	$< 1.3 \cdot 10^{-2}$
	CHOOZ	$7 \cdot 10^{-4}$	$< 1.0 \cdot 10^{-1}$	$< 5 \cdot 10^{-2}$
$\nu_\mu \to \nu_{\mu'}$	CCFR84	$6 \cdot 10^{0}$	none	$< 2 \cdot 10^{-1}$
	CDHS	$3 \cdot 10^{-1}$	none	$< 5.3 \cdot 10^{-1}$
$\nu_\mu \to \nu_\tau$	NOMAD	$7 \cdot 10^{-1}$	$< 3.3 \cdot 10^{-4}$	$< 2.5 \cdot 10^{-4}$
	CHORUS	$5 \cdot 10^{-1}$	$< 6.8 \cdot 10^{-4}$	$< 4.5 \cdot 10^{-4}$
$\nu_e \to \nu_\tau$	NOMAD	$6 \cdot 10^{0}$	$< 1.5 \cdot 10^{-2}$	$< 1.1 \cdot 10^{-2}$
	CHORUS	$7 \cdot 10^{0}$	$< 5.1 \cdot 10^{-2}$	$< 4 \cdot 10^{-2}$



Best fit:
Δm^2=0.92 eV^2
U_{e4}=0.136 ,
$U_{\mu 4}$=0.205
with
Compatibility
Level = 3.6%

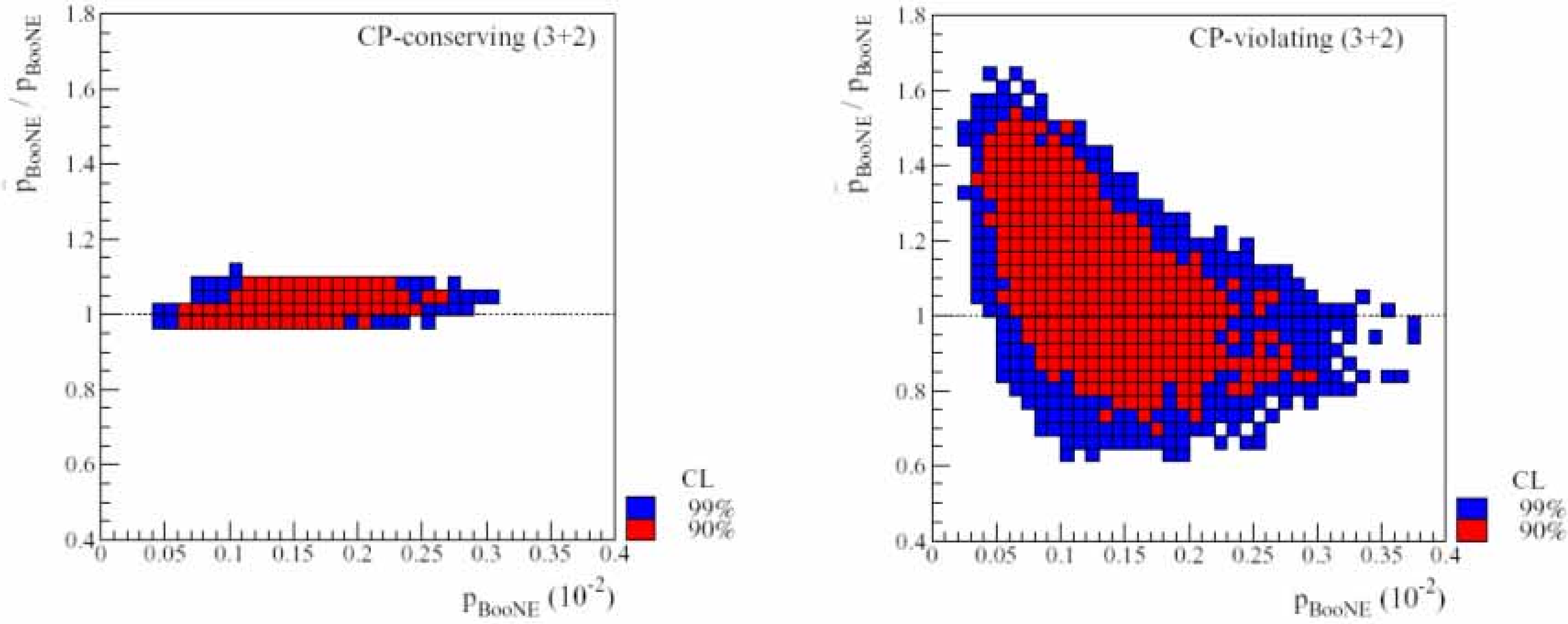


Best Fit:
Δm_{41}^2=0.92 eV^2
U_{e4}=0.121 , $U_{\mu 4}$=0.204
Δm_{51}^2=22 eV^2
U_{e5}=0.036 , $U_{\mu 4}$=0.224
with
Compatibility
Level = 30%

CP Violation Effect for MiniBooNE in 3+2 Models

- CP-violation is possible when more than one Δm^2 participates in the oscillation
- Compare oscillation probabilities in ν and $\bar{\nu}$ running mode:

$$p_{\text{BooNE}} \equiv \langle P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \rangle_{\nu \text{ mode}}, \qquad \bar{p}_{\text{BooNE}} \equiv \langle P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \rangle_{\bar{\nu} \text{ mode}}$$

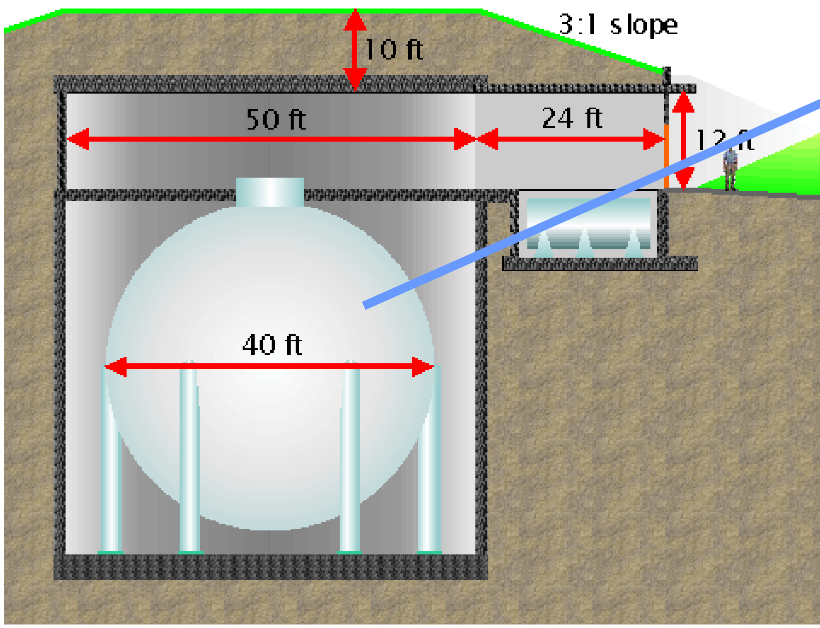


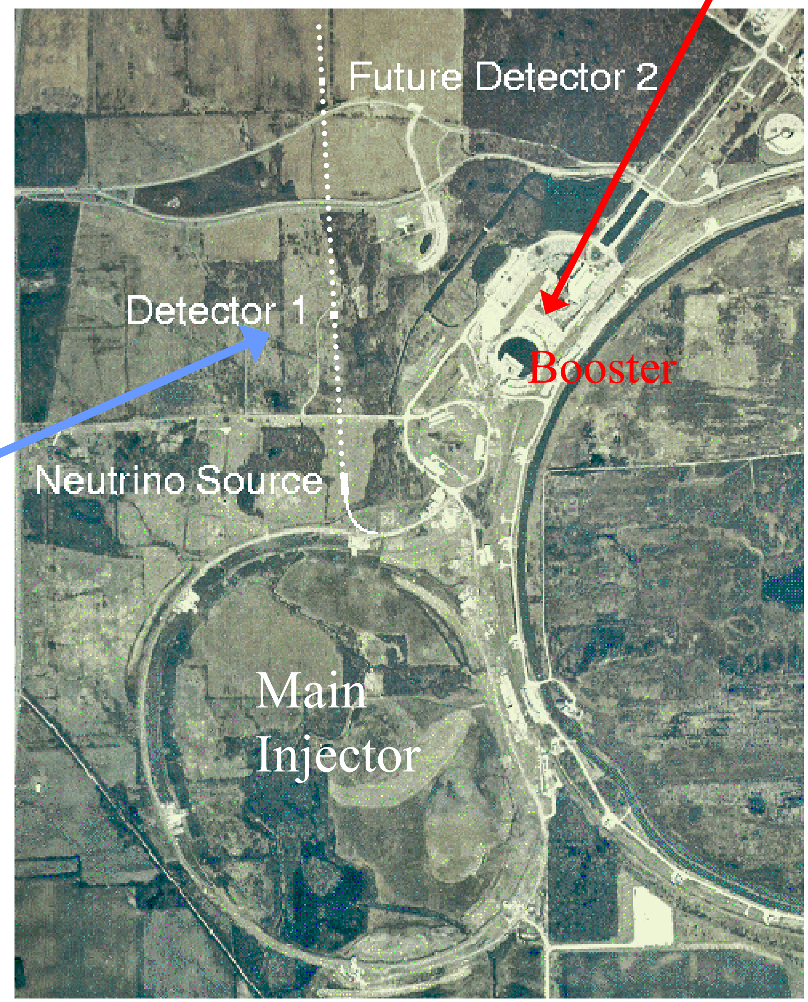
(M. Sorel and K. Whisnant, preliminary)

Next Step Is MiniBooNE

- MiniBooNE will be one of the first experiments to check these sterile neutrino models
  - Investigate LSND Anomaly
  - Investigate oscillations to sterile neutrino using ν_μ disappearance

Use protons from the 8 GeV booster
$\Rightarrow$ Neutrino Beam
$\langle E_\nu \rangle \sim 1$ GeV



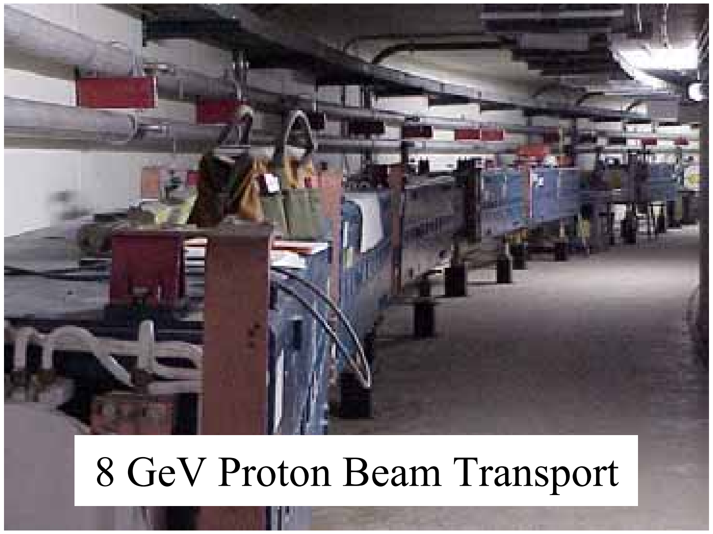


MiniBooNE Collaboration

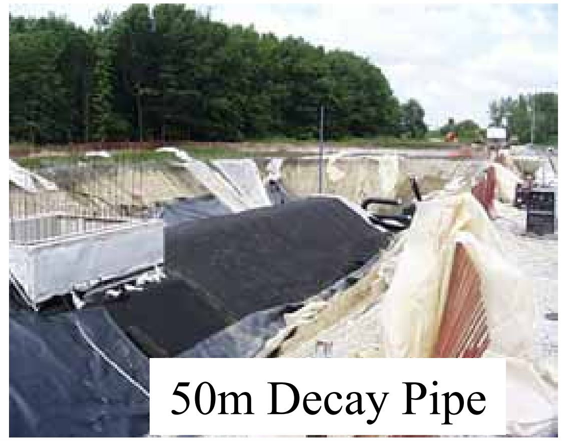
MiniBooNE consists of about 70 scientists from 13 institutions.

Y. Liu, I. Stancu *Alabama*
S. Koutsoliotas *Bucknell*
E. Hawker, R.A. Johnson, J.L. Raaf *Cincinnati*
T. Hart, R.H. Nelson, E.D. Zimmerman *Colorado*
A. Aguilar-Arevalo, L.Bugel, L. Coney, J.M. Conrad, Z. Djurcic, J. Link, J. Monroe, K. McConnel, D. Schmitz, M.H. Shaevitz, M. Sorel, G.P. Zeller *Columbia*
D. Smith *Embry Riddle*
L.Bartoszek, C. Bhat, S J. Brice, B.C. Brown, D.A. Finley, R. Ford, F.G.Garcia, P. Kasper, T. Kobilarcik, I. Kourbanis, A. Malensek, W. Marsh, P. Martin, F. Mills, C. Moore, P. Nienaber, E. Prebys, A.D. Russell, P. Spentzouris, R. Stefanski, T. Williams *Fermilab*
D. C. Cox, A. Green, H.-O. Meyer, R. Tayloe *Indiana*
G.T. Garvey, C. Green, W.C. Louis, G.McGregor, S.McKenney, G.B. Mills, H. Ray, V. Sandberg, B. Sapp, R. Schirato, R. Van de Water, D.H. White *Los Alamos*
R. Imlay, W. Metcalf, M. Sung, M.O. Wascko *Louisiana State*
J. Cao, Y. Liu, B.P. Roe, H. Yang *Michigan*
A.O. Bazarko, P.D. Meyers, R.B. Patterson, F.C. Shoemaker, H.A.Tanaka *Princeton*
B.T. Fleming *Yale*

MiniBooNE Neutrino Beam

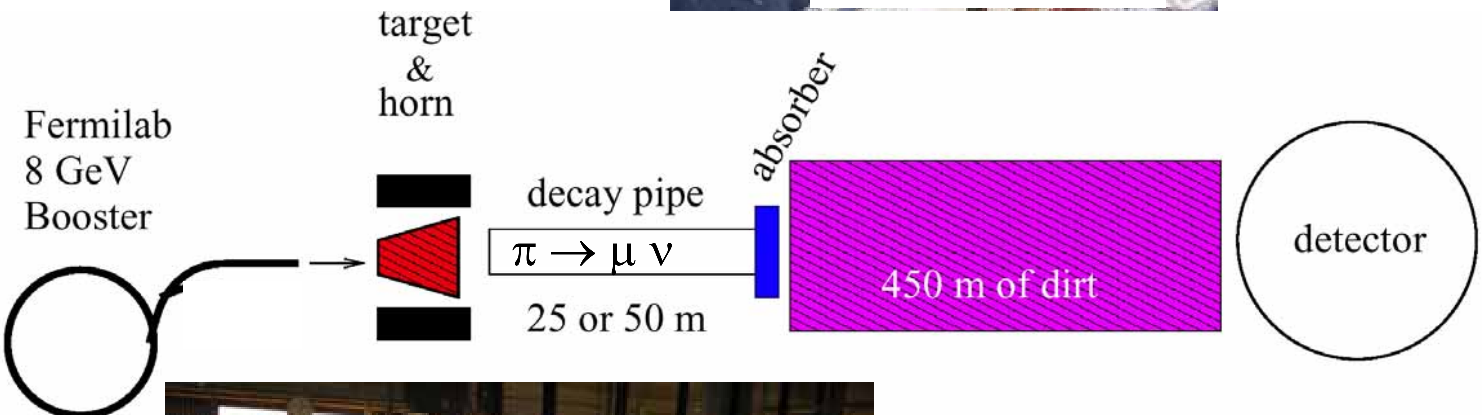


8 GeV Proton Beam Transport



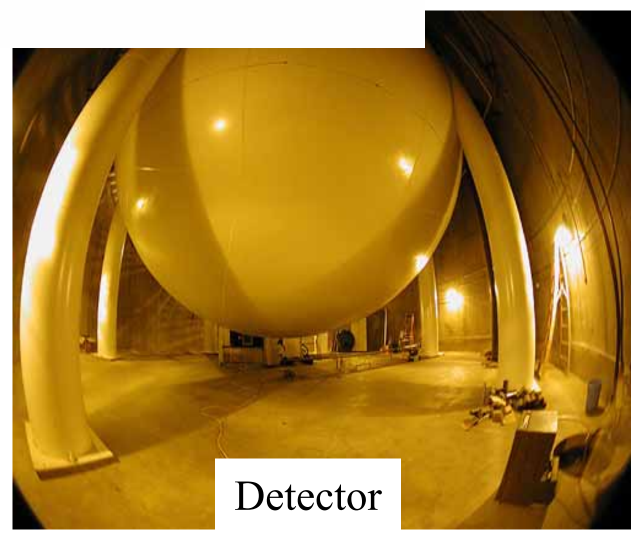
50m Decay Pipe

Variable decay pipe length (2 absorbers @ 50m and 25m)



One magnetic Horn, with Be target

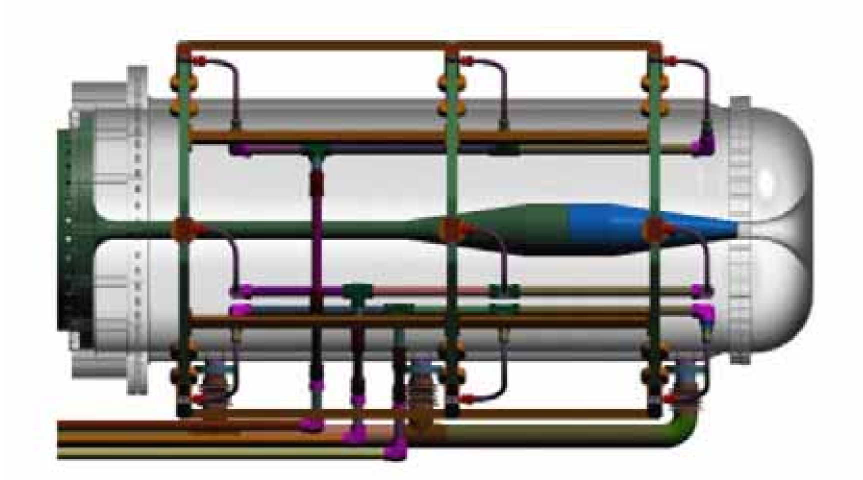
Magnetic Horn



Detector

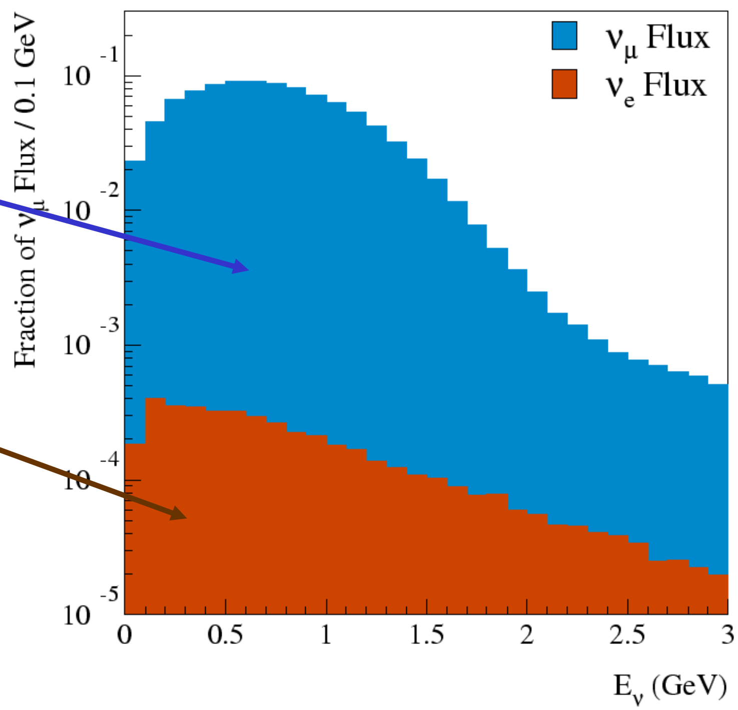
MiniBooNE Horn

- 8 GeV protons impinge on 71cm Be target
- Horn focuses secondaries and increases flux by factor of ~5
- 170 kA pulses, 143 μs long at 5 Hz

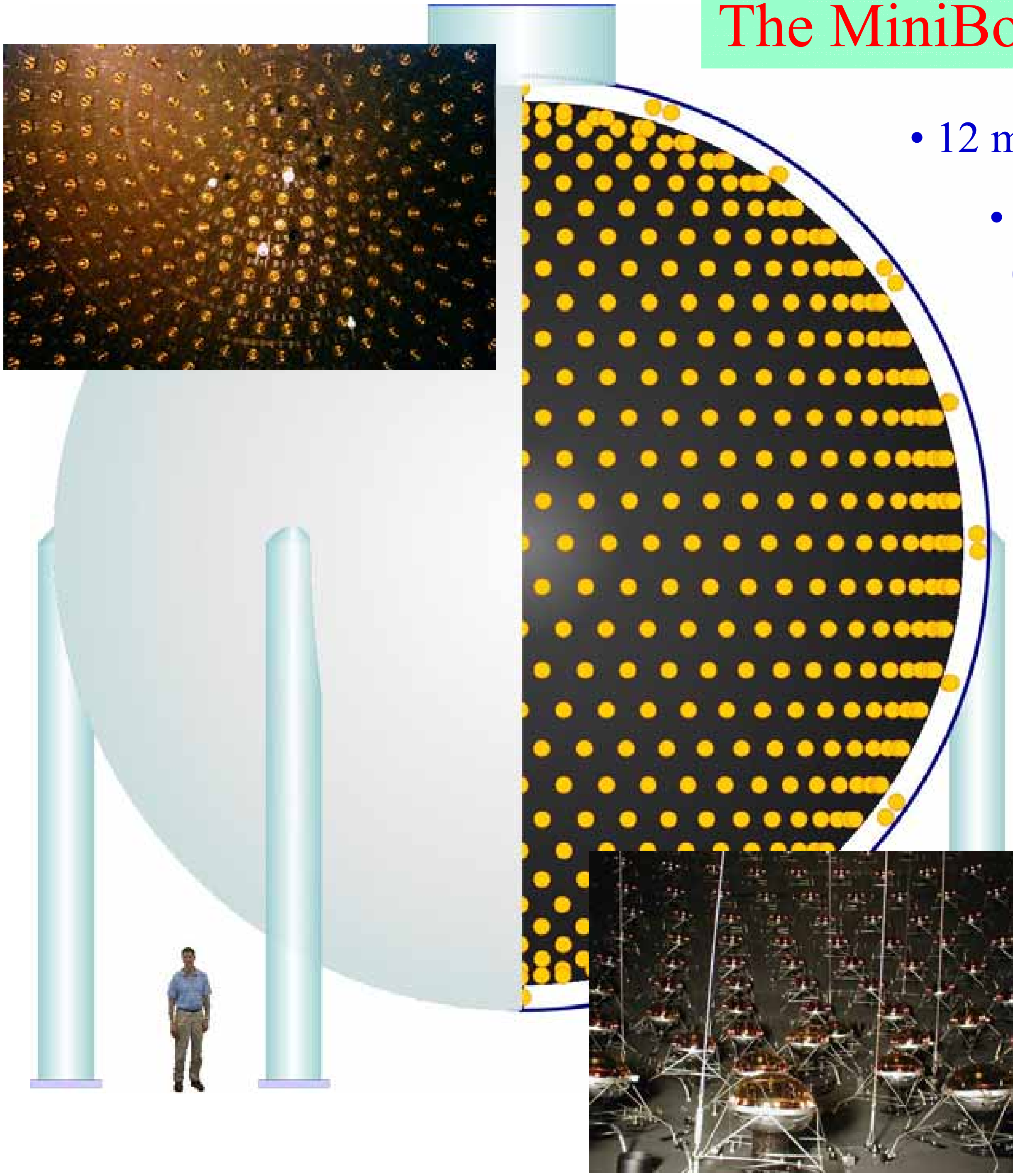


- Main ν_μ flux from $\pi^+ \rightarrow \mu^+ \ \nu_\mu$
- Intrinsic ν_e flux from
  - $\mu^+ \rightarrow \nu_\mu \ e^+ \ \nu_e$
  - $K^+ \rightarrow \pi^0 \ e^+ \ \nu_e$
  - $K^0_L \rightarrow \pi^- \ e^+ \ \nu_e$

$\Rightarrow \nu_e / \nu_\mu \approx 0.5\%$



The MiniBooNE Detector

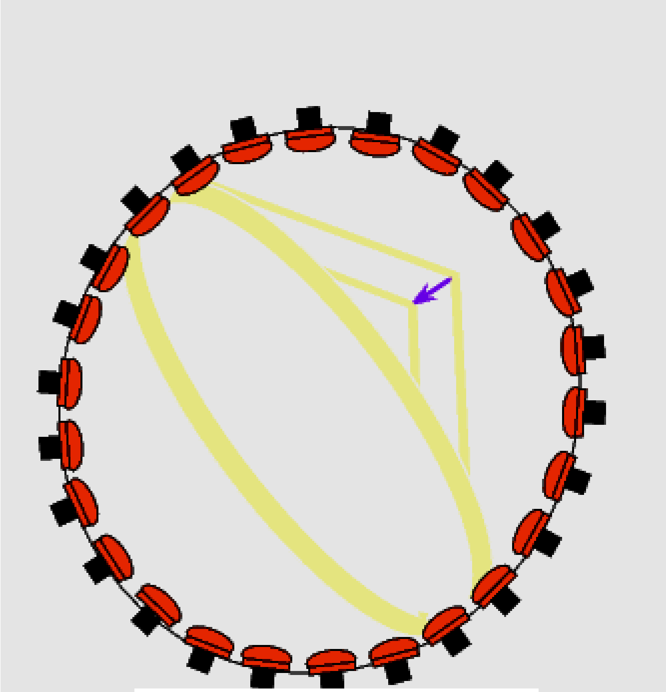


- 12 meter diameter sphere
- Filled with 950,000 liters (900 tons) of very pure mineral oil
- Light tight inner region with 1280 photomultiplier tubes
- Outer veto region with 241 PMTs.
- Oscillation Search Method:

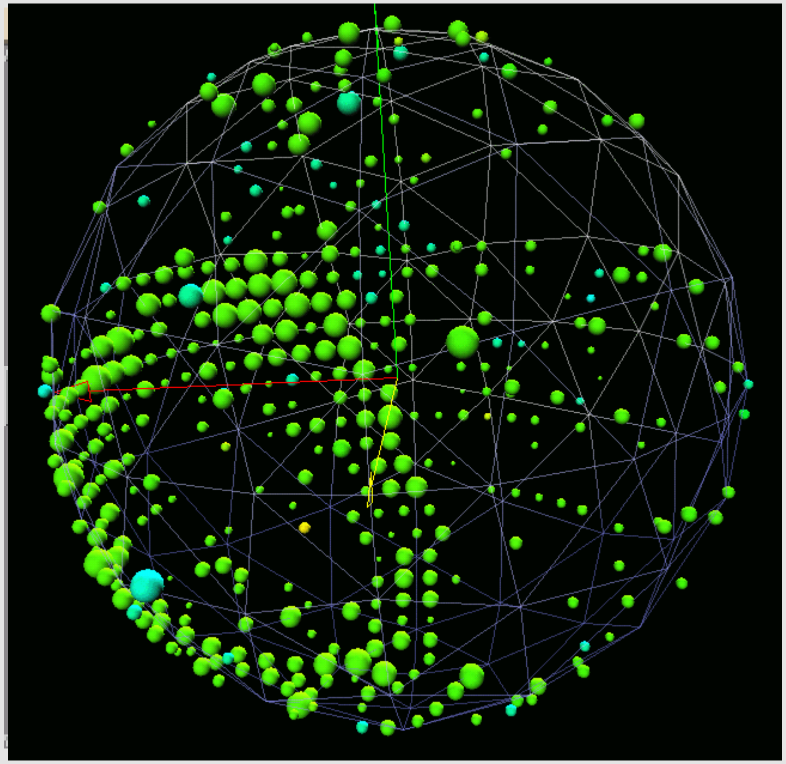
  Look for ν_e events in a pure ν_μ beam

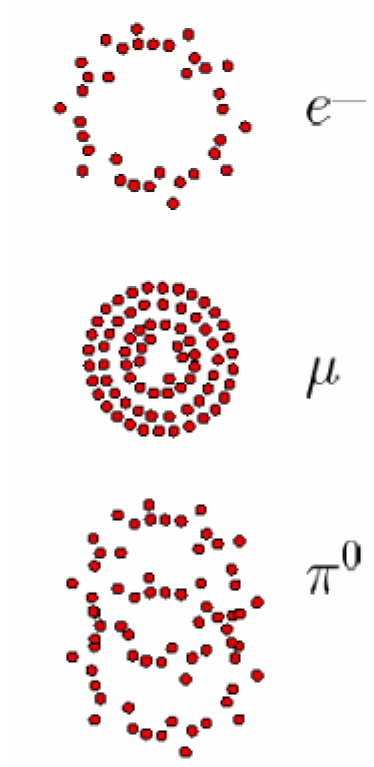
Particle Identification

- Separation of ν_μ from ν_e events
  - Exiting ν_μ events fire the veto
  - Stopping ν_μ events have a Michel electron after a few μsec
  - Also, scintillation light with longer time constant $\Rightarrow$ enhanced for slow pions and protons
  - Čerenkov rings from outgoing particles
    - Shows up as a ring of hits in the phototubes mounted inside the MiniBooNE sphere
    - Pattern of phototube hits tells the particle type



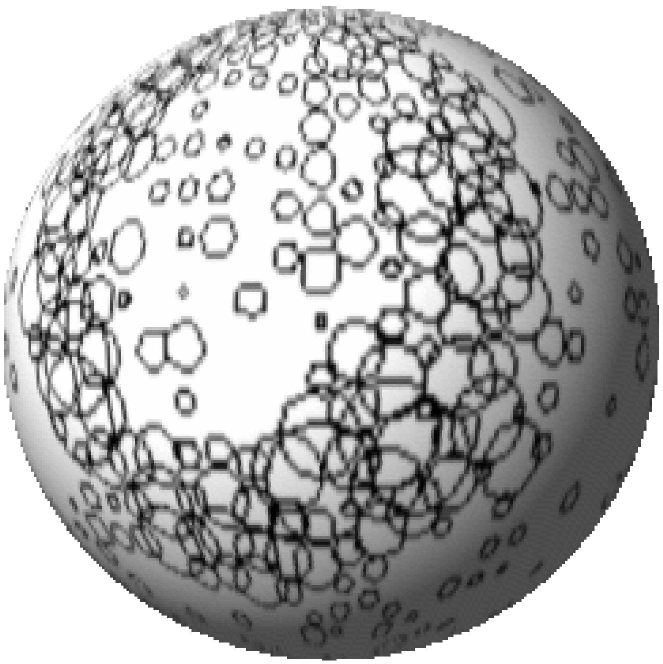
Stopping muon event



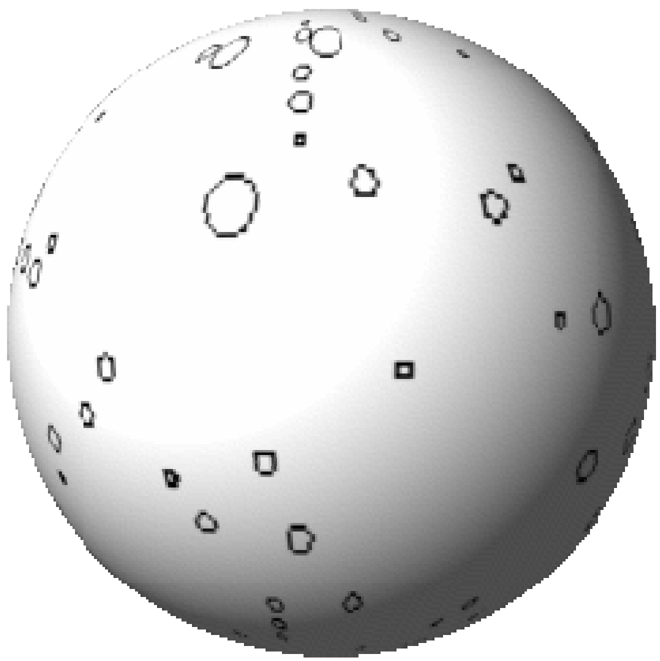


Example Cerenkov Rings

Size of circle is proportional to the light hitting the photomultiplier tube



$$\nu_\mu + n \rightarrow \mu^- + p$$

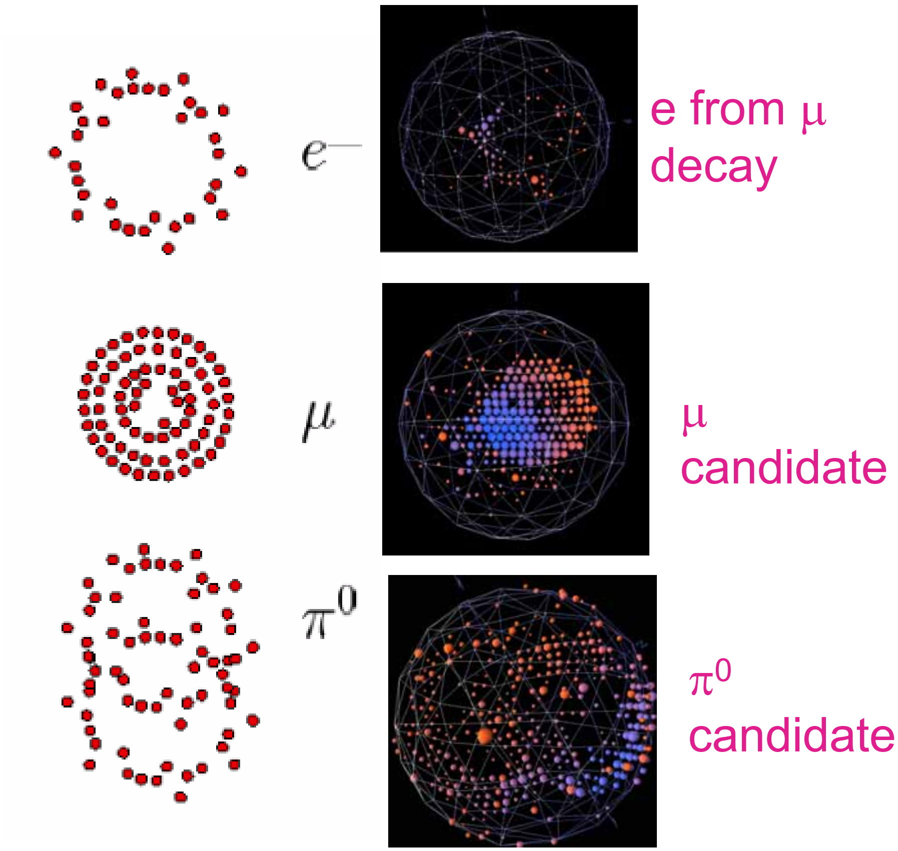


$$\nu_\mu + n \rightarrow \nu_\mu + p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

Particle ID Algorithms

- Identify events using hit topology
- Use a "boosted tree" algorithm to separate e, mu, pi, delta
  - More stable than neural network in performance and less sensitivity to MC optical model
    (See B. Roe et al. NIM A543 (2005))
- PID Vars
  - 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



Neutrino events

beam comes in spills @ up to 5 Hz
each spill lasts 1.6 μsec

trigger on signal from Booster
read out for 19.2 μsec

no high level analysis needed to see neutrino events

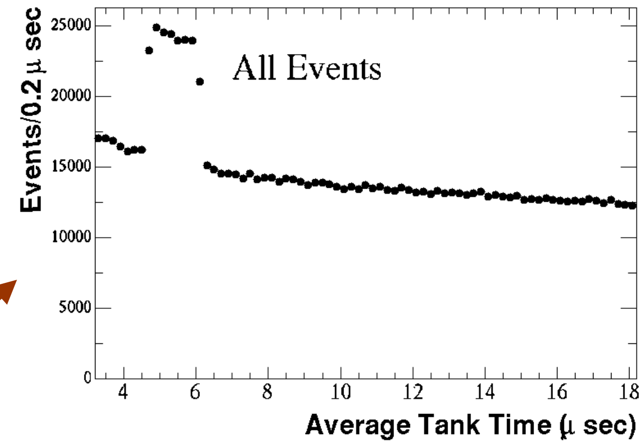
backgrounds: cosmic muons ⇐ N_{Veto}<6 Cut
decay electrons ⇐ N_{Tank}<200 Cut

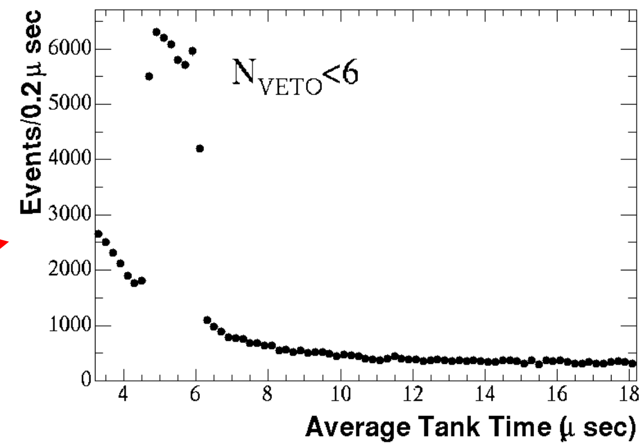
simple cuts reduce non-beam backgrounds to ~10^{-3}

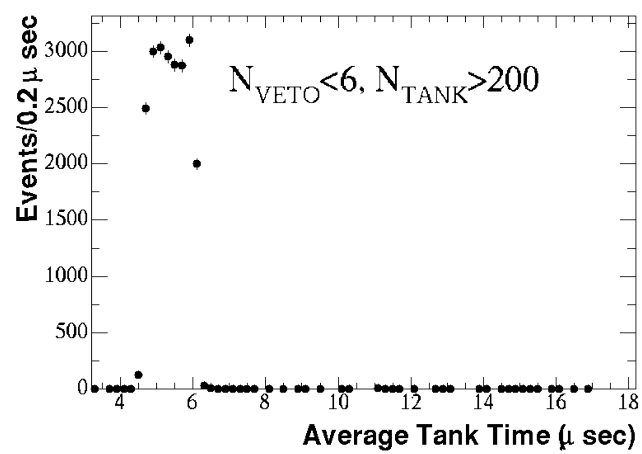
ν event every 1.5 minutes

Current Collected data:

~600k neutrino candidates
for 5.6 × 10^{20} protons on target

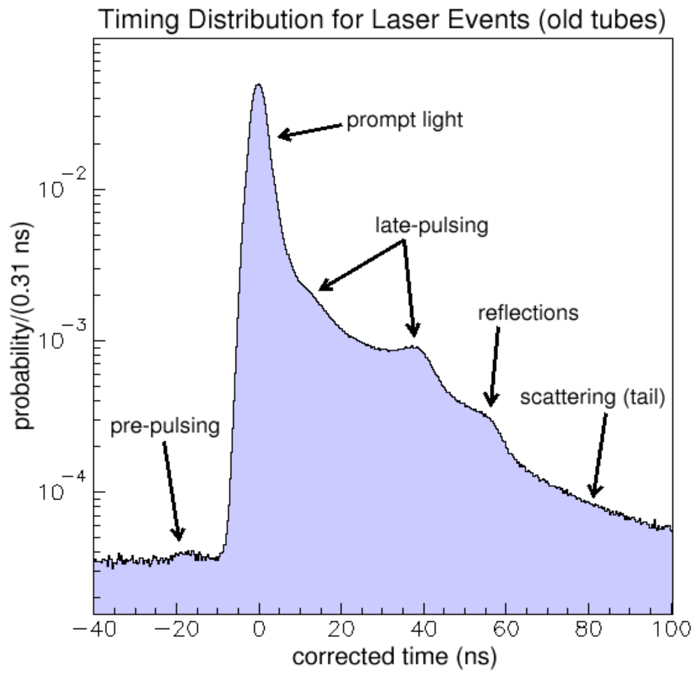






Optical Model

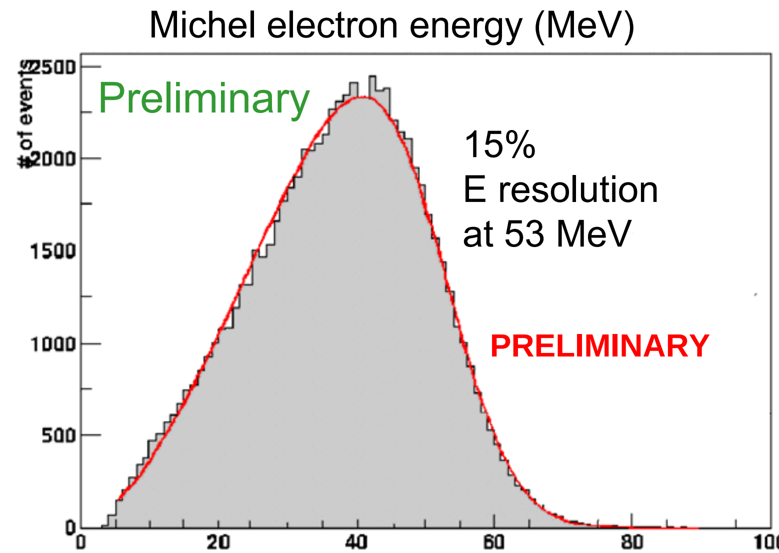
- Light Creation
  - Cerenkov – well known
  - Scintillation
    - yield
    - spectrum
    - decay times
- Light Propagation
  - Fluoresence
    - rate
    - spectrum
    - decay times
  - Scattering
    - Rayleigh
    - Particulate (Mie)
  - Absorption



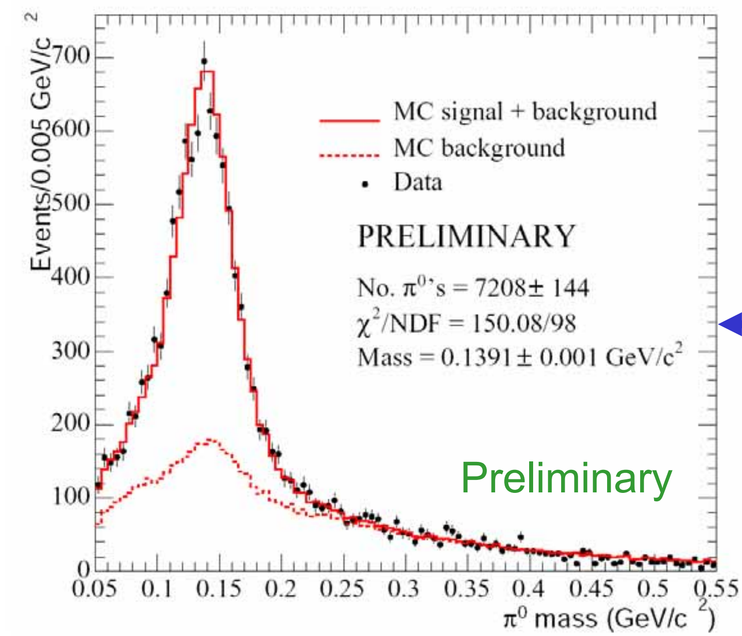
- In Situ
  - Cosmics muons, Michel electrons, Laser
- Ex Situ
  - Scintillation from p beam (IUCF)
  - Scintillation from cosmic μ (Cincinnati)
  - Fluorescence Spectroscopy (FNAL)
  - Time resolved spectroscopy (JHU)
  - Attenuation (Cincinnati)

Energy Calibration Signals

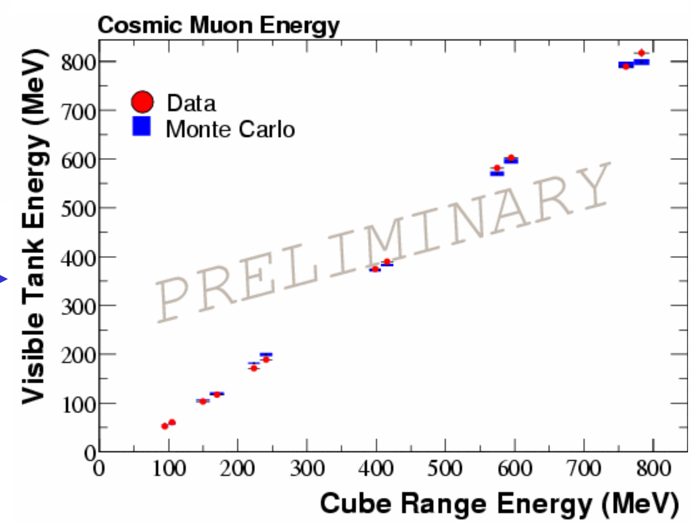
Spectrum of Michel electrons from stopping muons

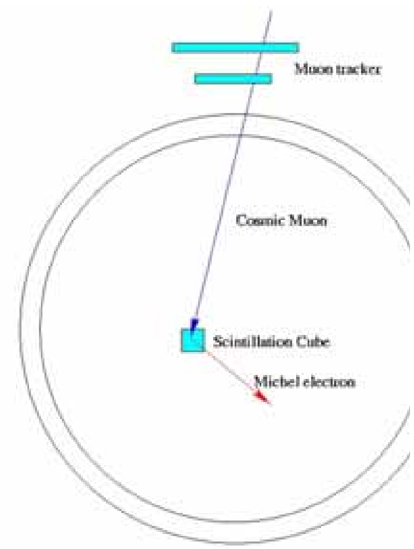


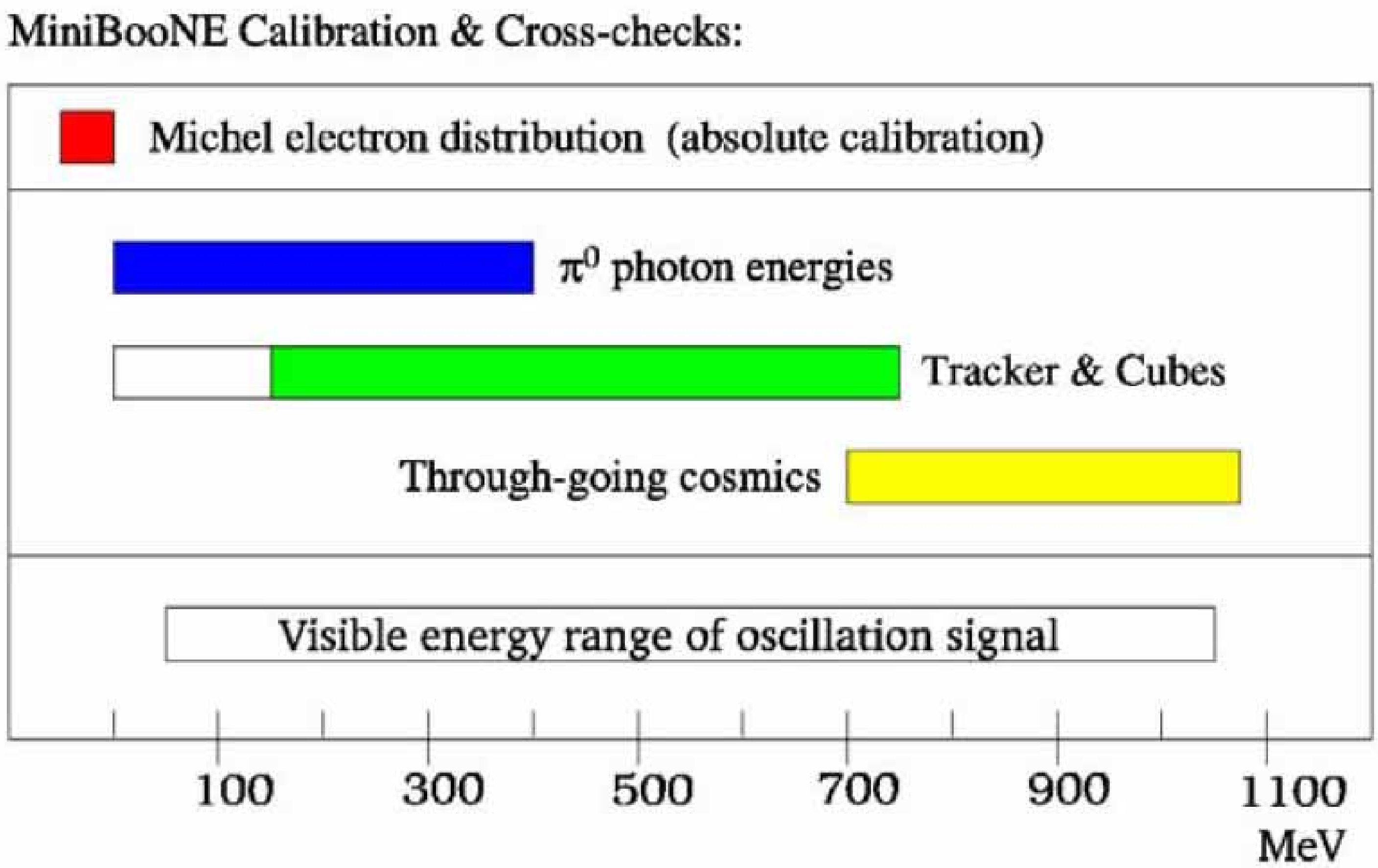
Mass distribution for isolated π^0 events



Energy vs. Range for events stopping in scintillator cubes

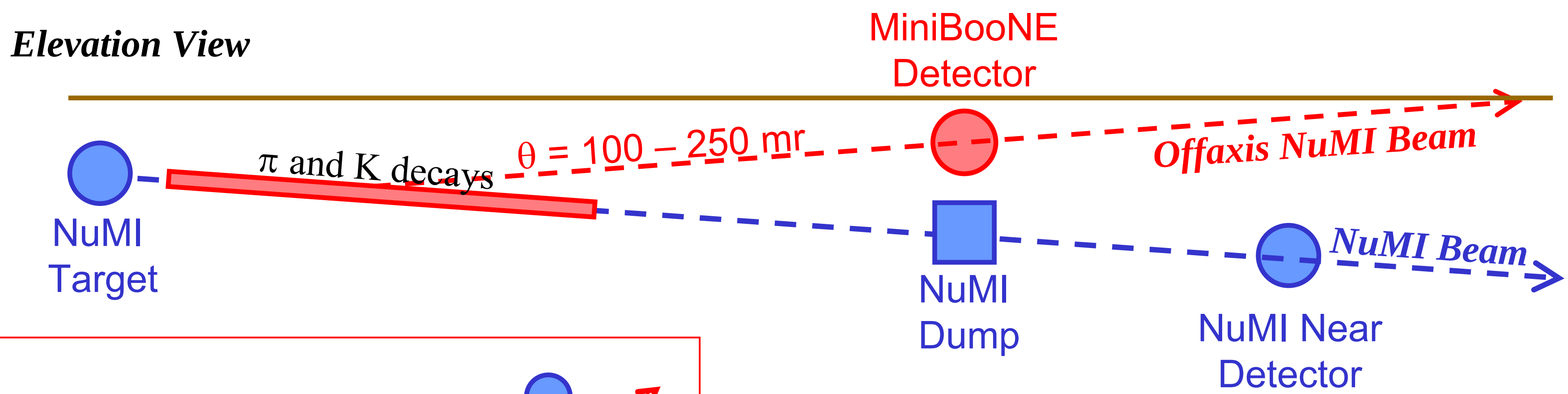


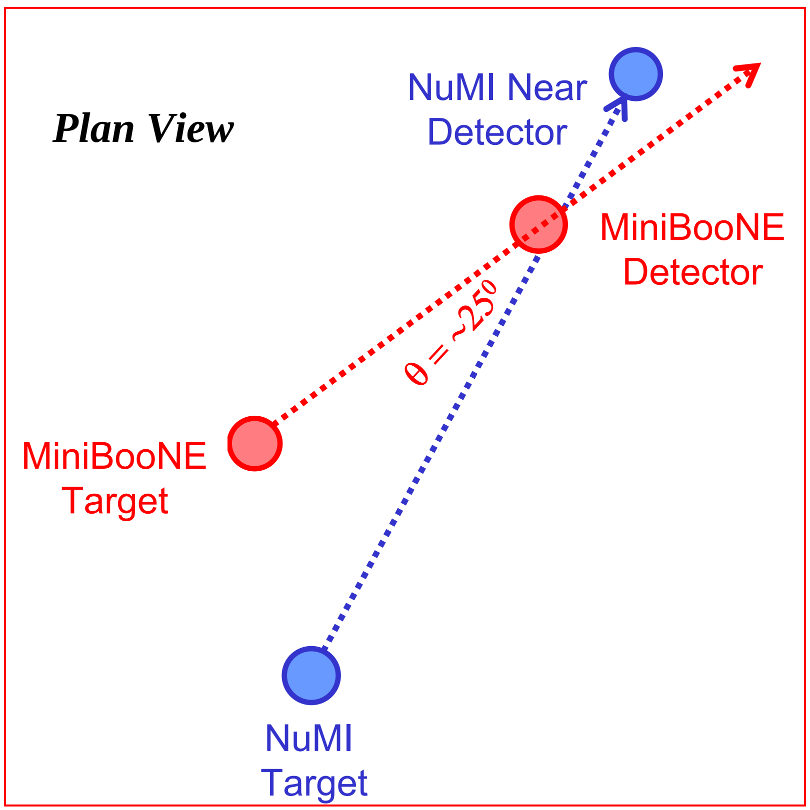



MiniBooNE Calibration & Cross-checks:
Michel electron distribution (absolute calibration)
π0 photon energies
Tracker & Cubes
Through-going cosmics
Visible energy range of oscillation signal
100
300
500
700
900
1100
MeV

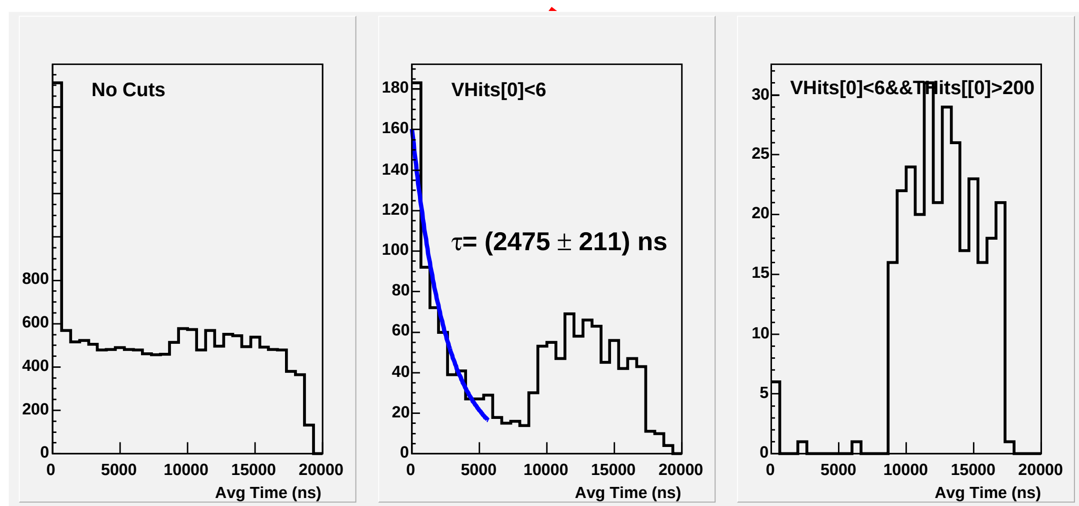
NuMI Beam Events in MiniBooNE

(World's 1st Offaxis Neutrino Beam !!)



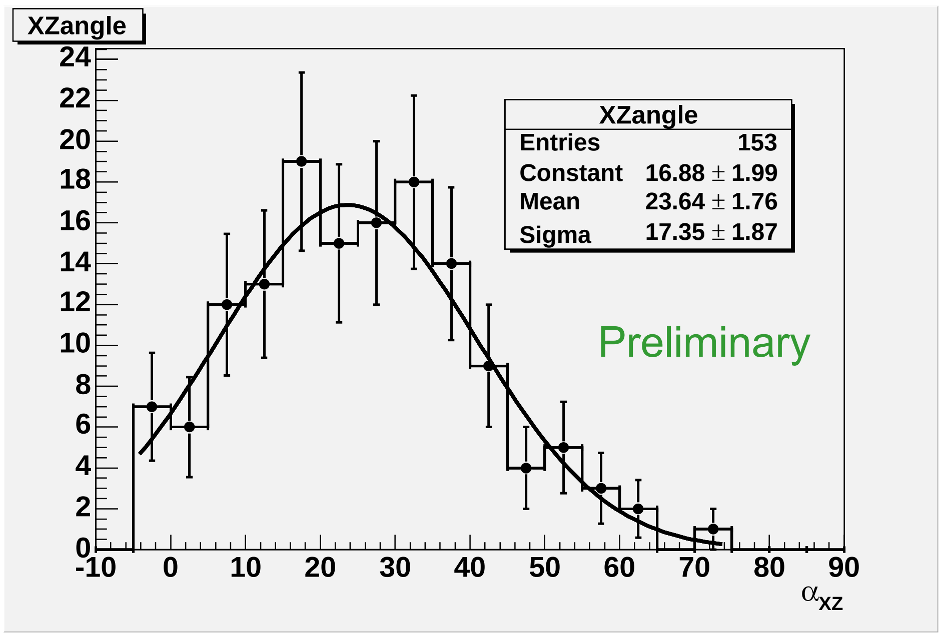


- MiniBooNE sees ν events in the 8 μs NuMI beam window

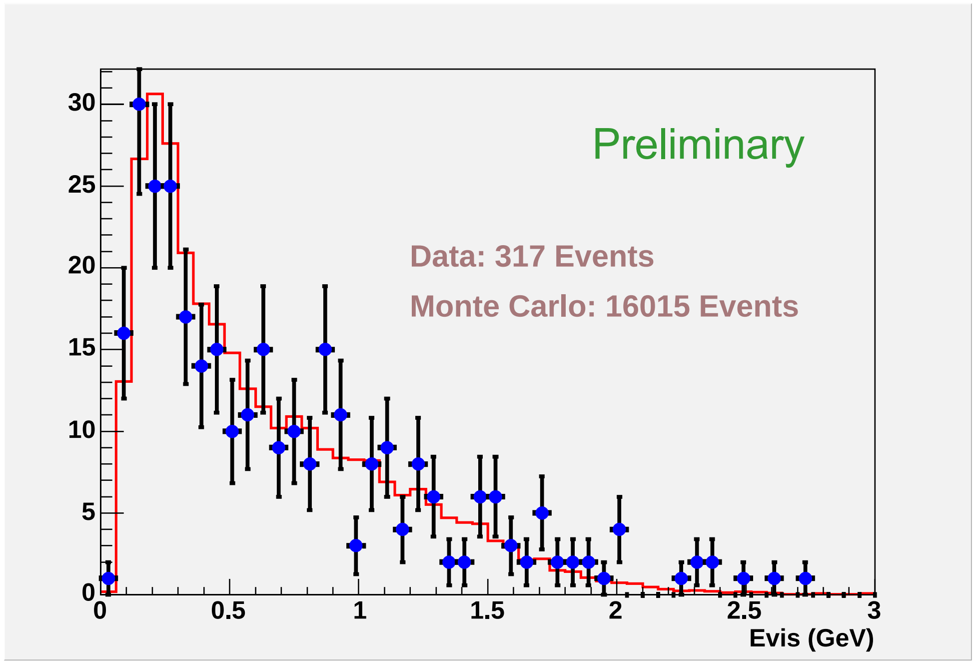


NuMI Offaxis Events Agree with Monte Carlo Prediction

- Observed reconstructed angle point back to the NuMI beam direction (at ~25^0)



- Data to Monte Carlo comparison of reconstructed $E_{visible}$ for contained events



⇒ NuMI Offaxis beam will be a calibration beam for MiniBooNE
(and we can look at electron neutrino interactions)

Oscillation Analysis: Status and Plans

- Blind (or "Closed Box") ν_e appearance analysis

  you can see all of the info on some events

  or

  some of the info on all events

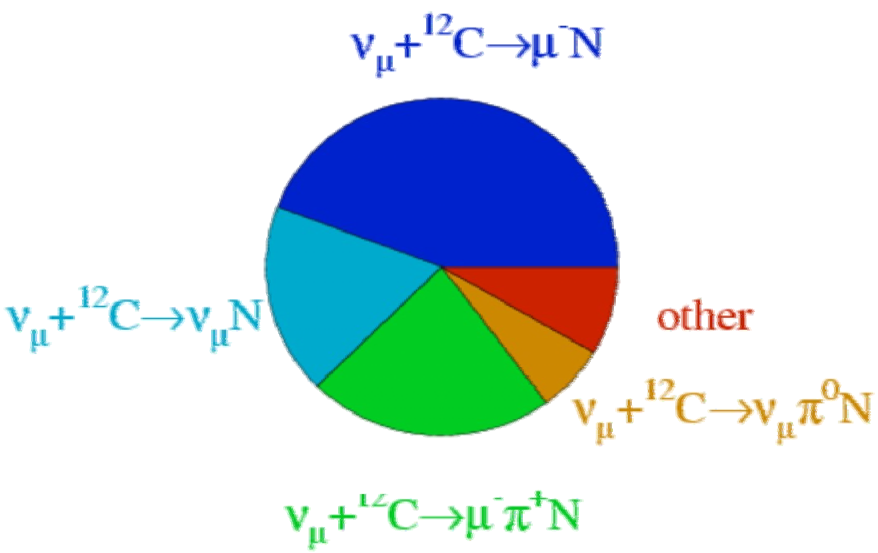
  but

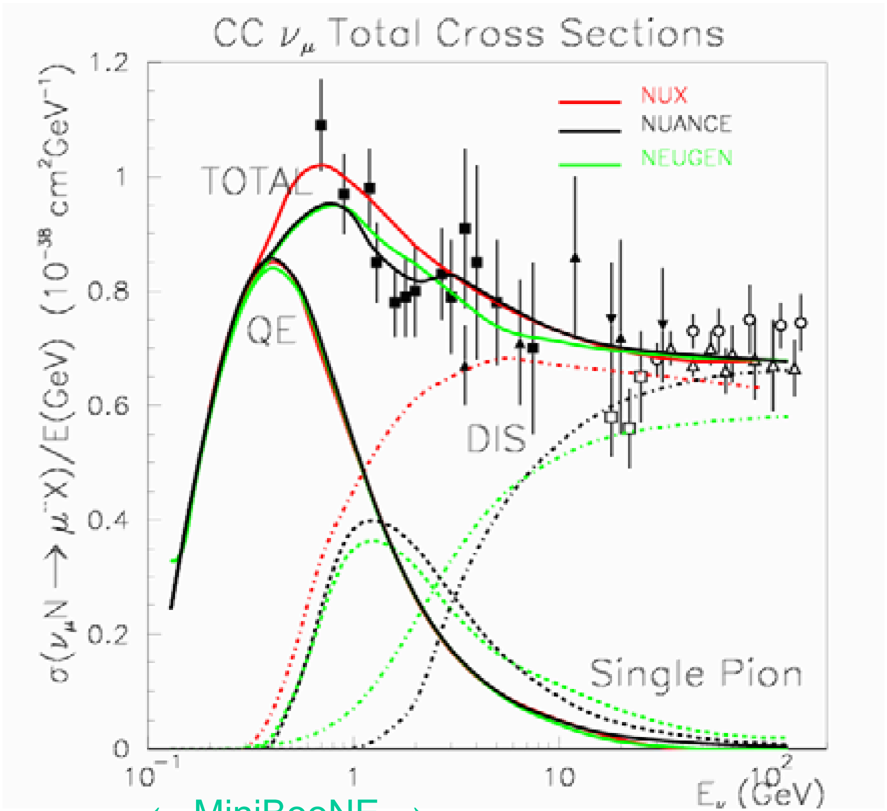
  you cannot see all of the info on all of the events

- Other analysis topics give early interesting physics results and serve as a cross check and calibration before "opening the ν_e box"
  - Cross section measurements for low-energy ν processes
  - ν_μ disappearance oscillation search
  - Studies of ν_μ NC π^0 production
    $\Rightarrow$ coherent (nucleus) vs nucleon
  - Studies of ν_μ NC elastic scattering
    $\Rightarrow$ Measurements of Δs (strange quark spin contribution)

Low Energy Neutrino Cross sections

MiniBooNE Events Fractions





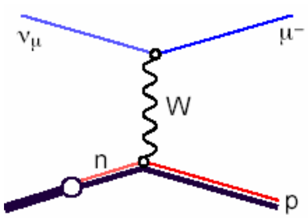
← MiniBooNE →

- MiniBooNE will measure the cross sections for all of these processes

On the Road to a ν_μ Disappearance Result

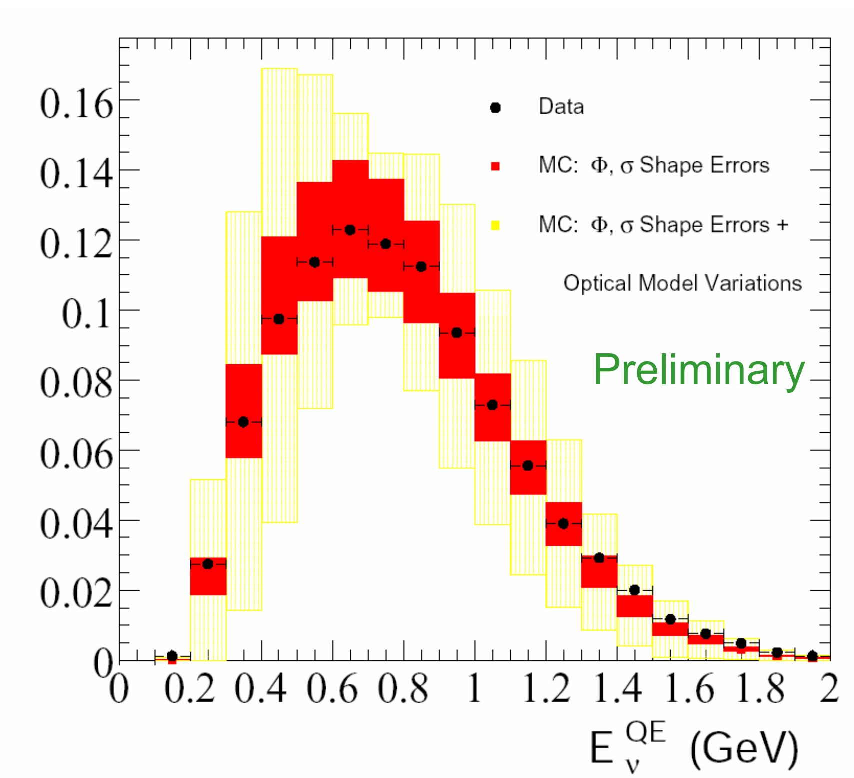
- Use ν_μ quasi-elastic events

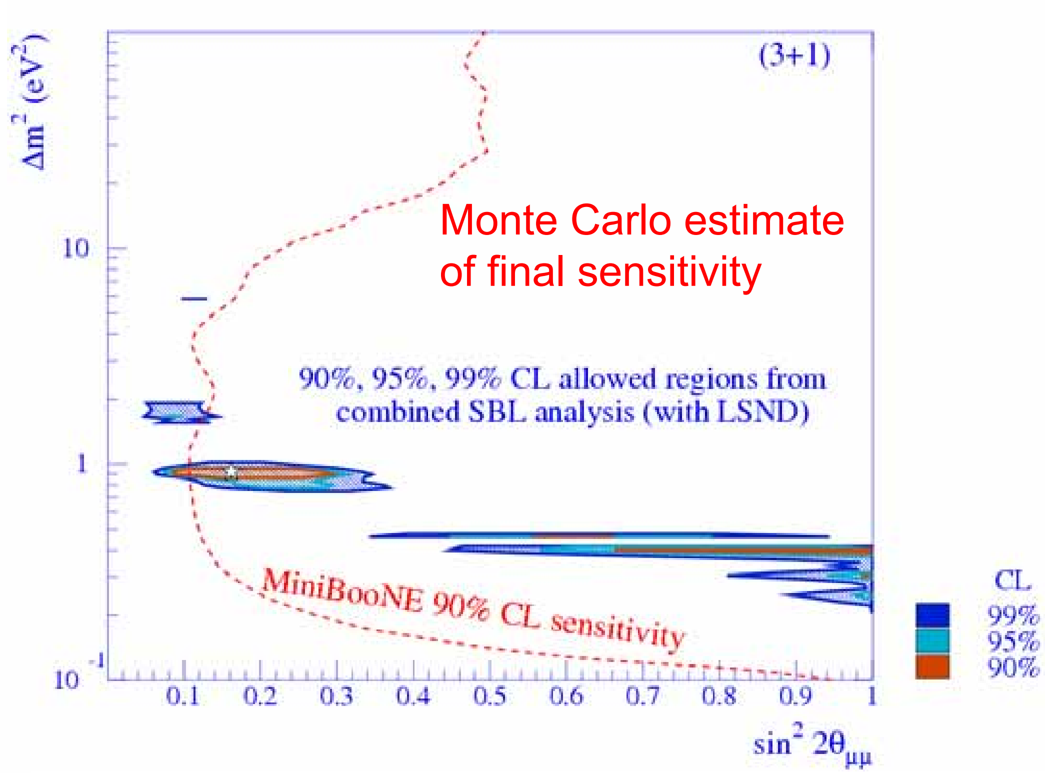
  $\nu_\mu + n \rightarrow \mu^- + p$



  - Events can be isolated using single ring topology and hit timing
  - Excellent energy resolution
  - High statistics: ~30,000 events now (Full sample: ~500,000)

- E_ν distribution well understood from pion production by 8 GeV protons
  - Sensitivity to $\nu_\mu \rightarrow \nu_\mu$ disappearance oscillations through shape of E_ν distribution





Will be able to cover a large portion of 3+1 models

Neutrino Single Pion Production Cross Sections

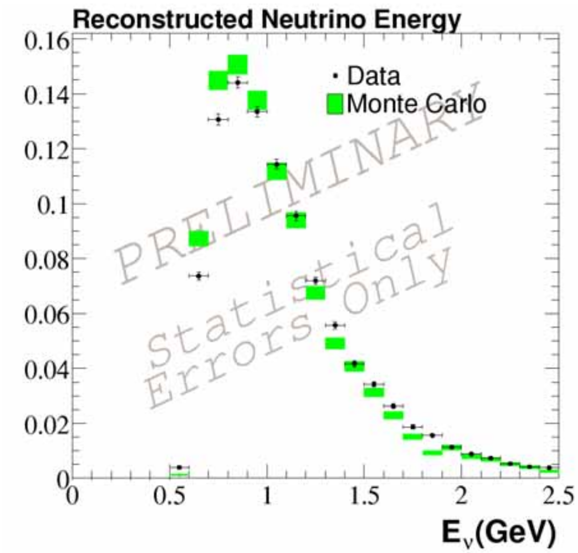
- Charged current π^+ events

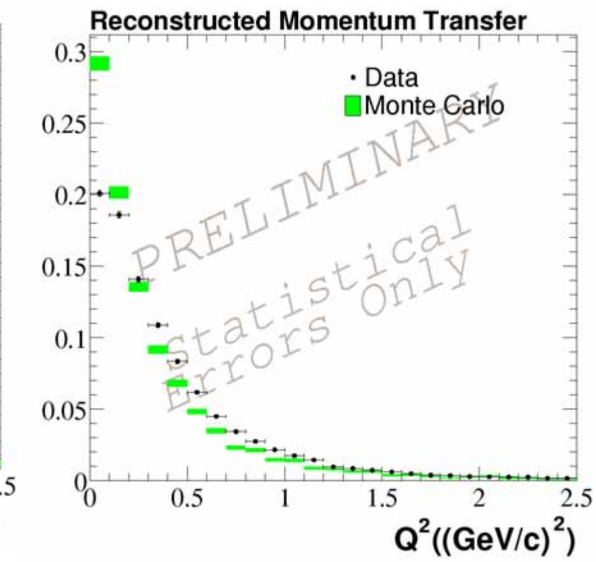
  Resonant

  $\nu_\mu + \mathbf{p} \rightarrow \mu^- + \Delta^{++}$, $\Delta^{++} \rightarrow \mathbf{p} + \pi^+$

  Coherent

  $\nu_\mu + \mathbf{N} \rightarrow \mu^- + \mathbf{N} + \pi^+$





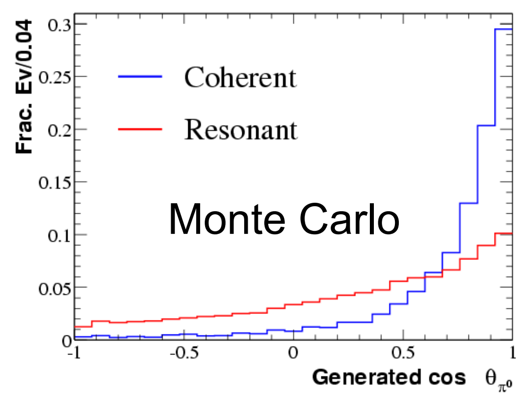
- Neutral current π^0 events

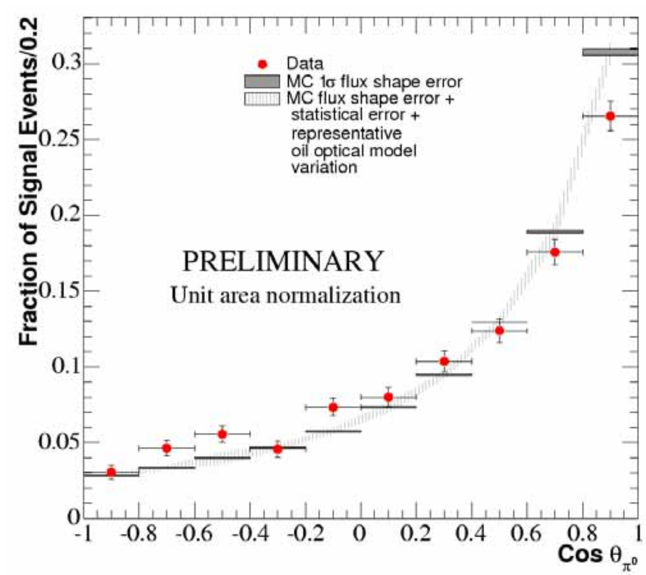
  Resonant

  $\nu_\mu + \mathbf{n} \rightarrow \nu_\mu + \Delta^0$, $\Delta^0 \rightarrow \mathbf{n} + \pi^0$

  Coherent

  $\nu_\mu + \mathbf{N} \rightarrow \nu_\mu + \mathbf{N} + \pi 0$

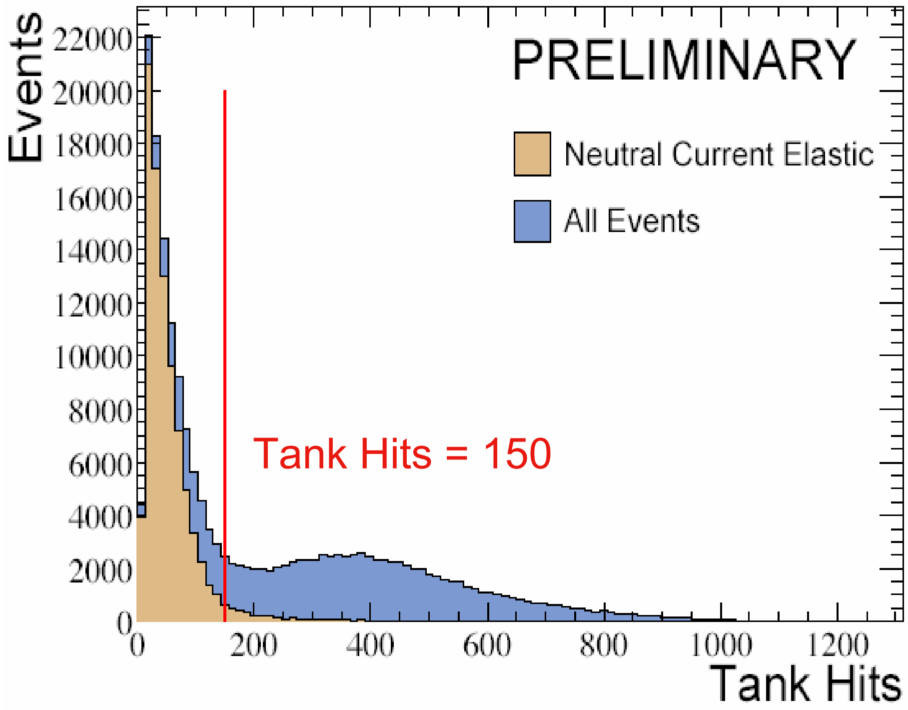




Investigations of ν_μ NC elastic scattering

$$\nu_\mu + p \rightarrow \nu_\mu + p$$

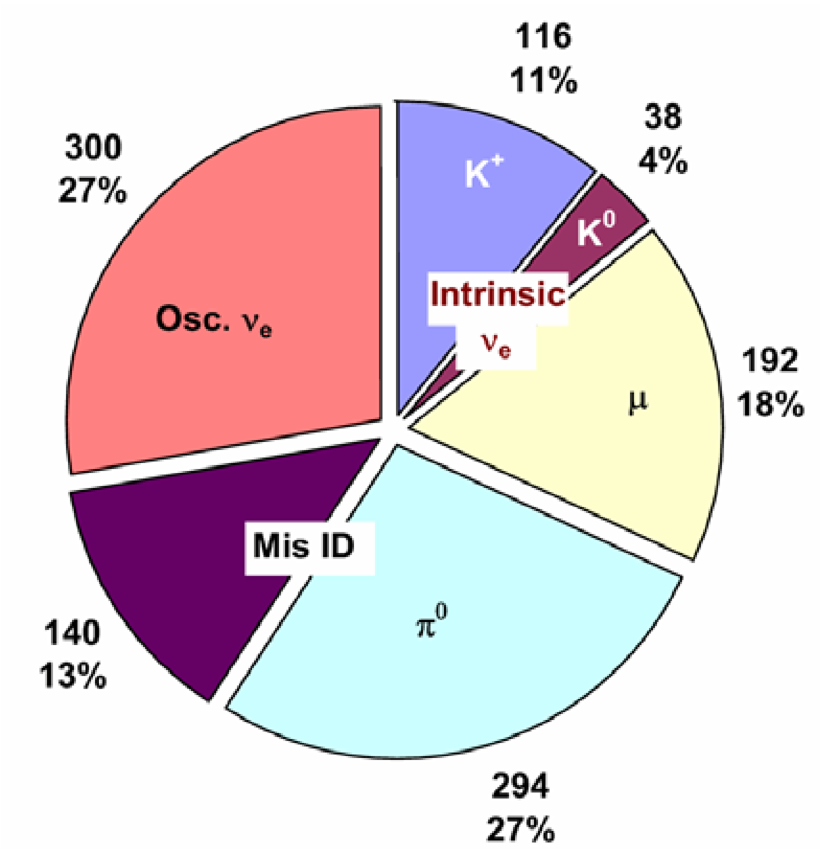
- Study scint. properties of oil, low E response of detector
  - Reconstruct p energy from scint. light
- Measure σ ($\nu_\mu + p \rightarrow \nu_\mu + p$)
  - Help understand scint. light for ν_e osc analysis
- σ(NCE) / σ (CCQE)
  - Measure Δs (component of proton spin carried by strange quarks)



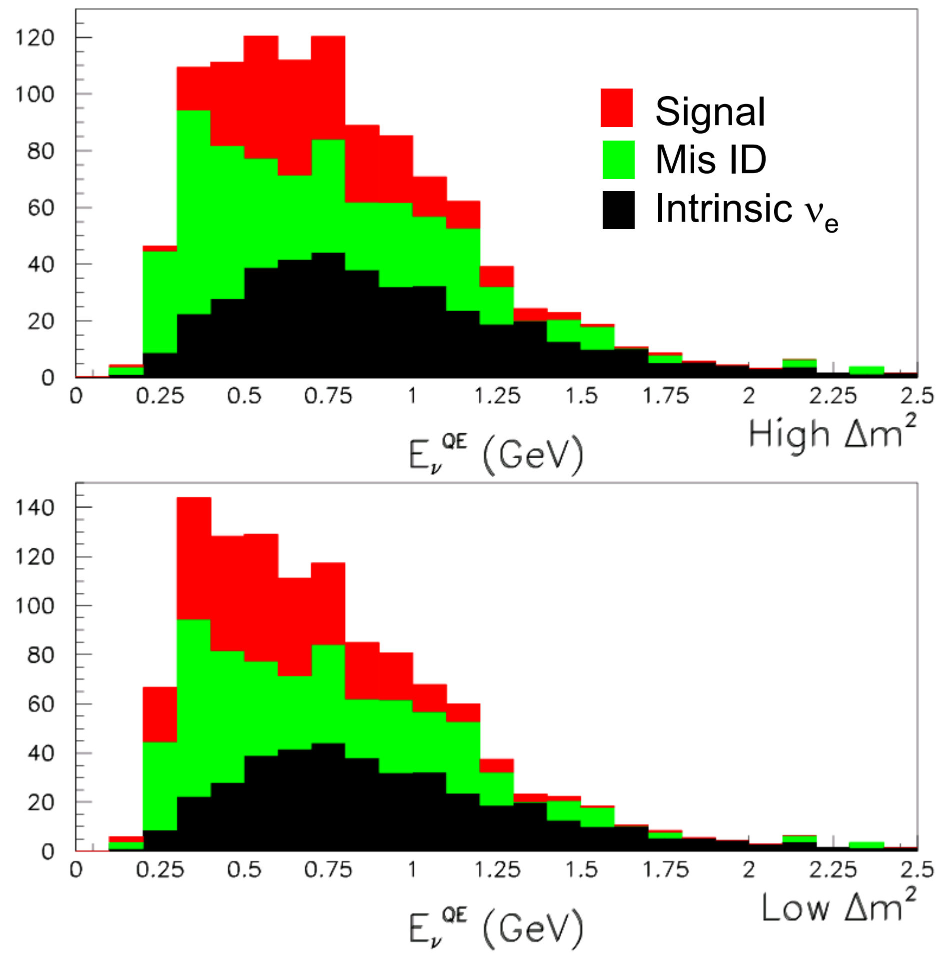
Tank hits < 150, veto < 6, 1 sub-event : ε = 70%, purity = 80%

Estimates for the $\nu_\mu \rightarrow \nu_e$ Appearance Search

- Look for appearance of ν_e events above background expectation
  - Use data measurements both internal and external to constrain background rates



- Fit to E_ν distribution used to separate background from signal.



Intrinsic ν_e in the beam

Small intrinsic ν_e rate $\Rightarrow$ Event Ratio ν_e/ν_μ=6x10^{-3}

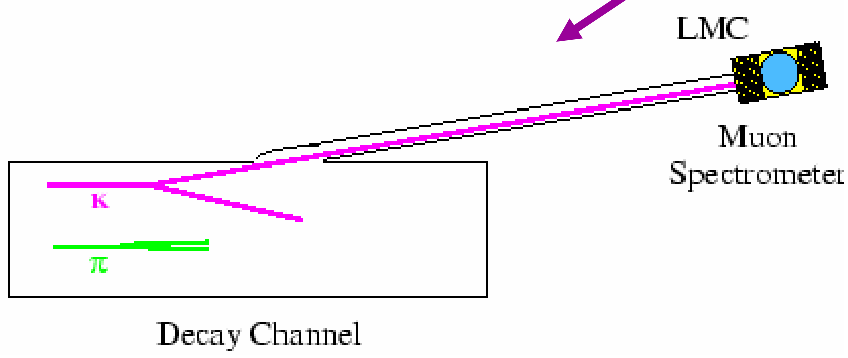
$\pi^+ \to \mu^+ \nu_\mu$
$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

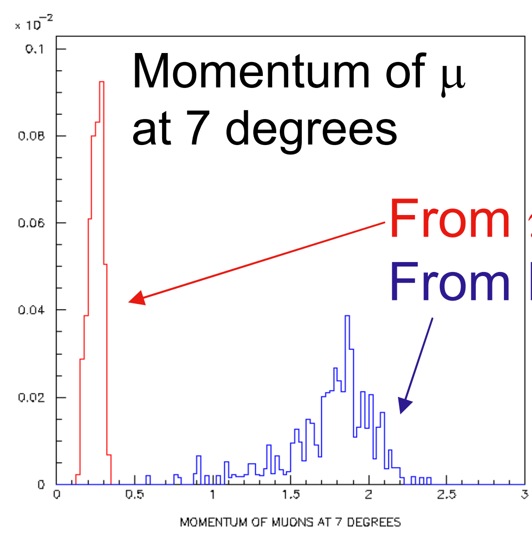
ν_e from μ–decay
- Directly tied to the observed half-million ν_μ interactions

$K^+ \to \pi^0 e^+ \nu_e$

$K_L \to \pi^- e^+ \nu_e$

- Kaon rates measured in low energy proton production experiments
  - New HARP experiment (CERN)
- Observed high E_ν events from K-decay
- "Little Muon Counter" measures rate of kaons *in situ*





Mis-identification Backgrounds

- Background mainly from NC π^0 production

  $\nu_\mu + \mathbf{p} \rightarrow \nu_\mu + \mathbf{p} + \pi^0$

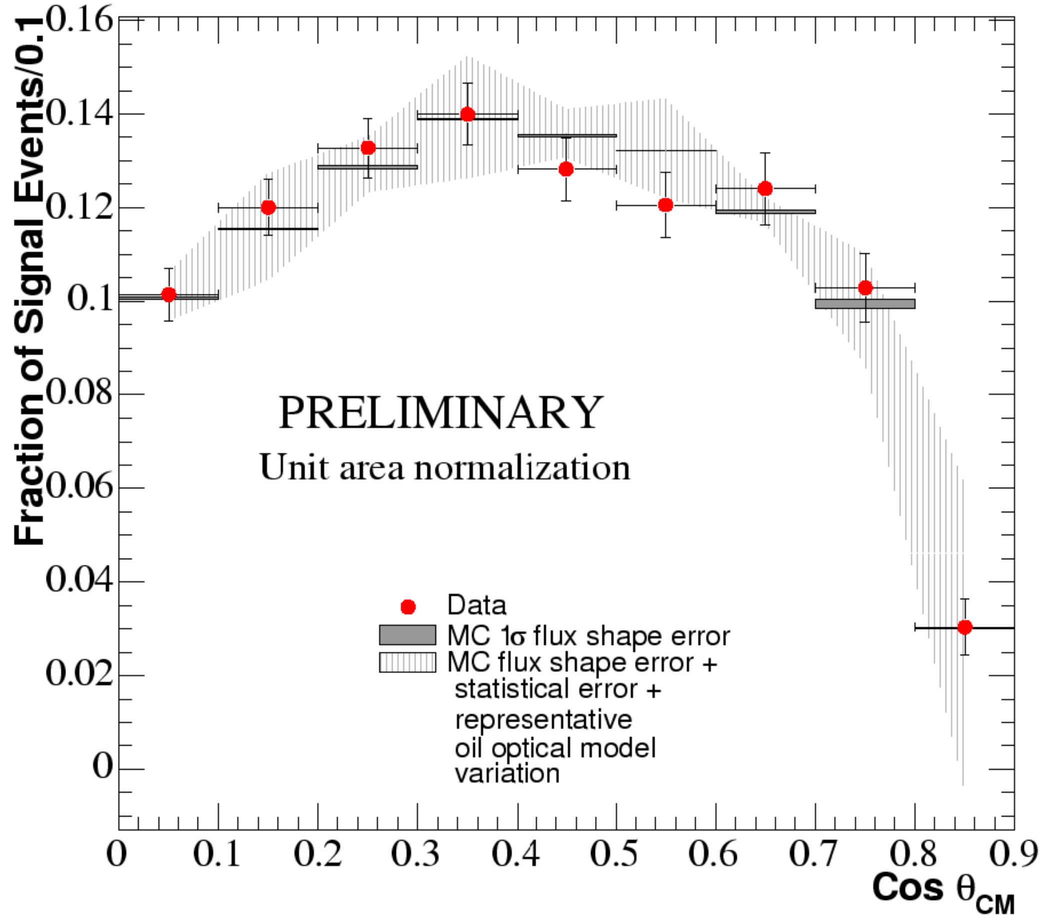
  followed by

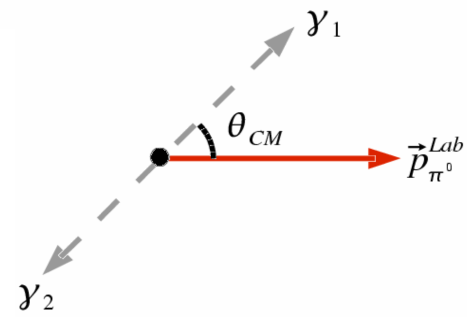
  $\pi^0 \rightarrow \gamma\,\gamma$

  where one γ is lost because it has too low energy or have overlapping rings

- Over 99.5% of these events are identified and the π^0 kinematics are measured

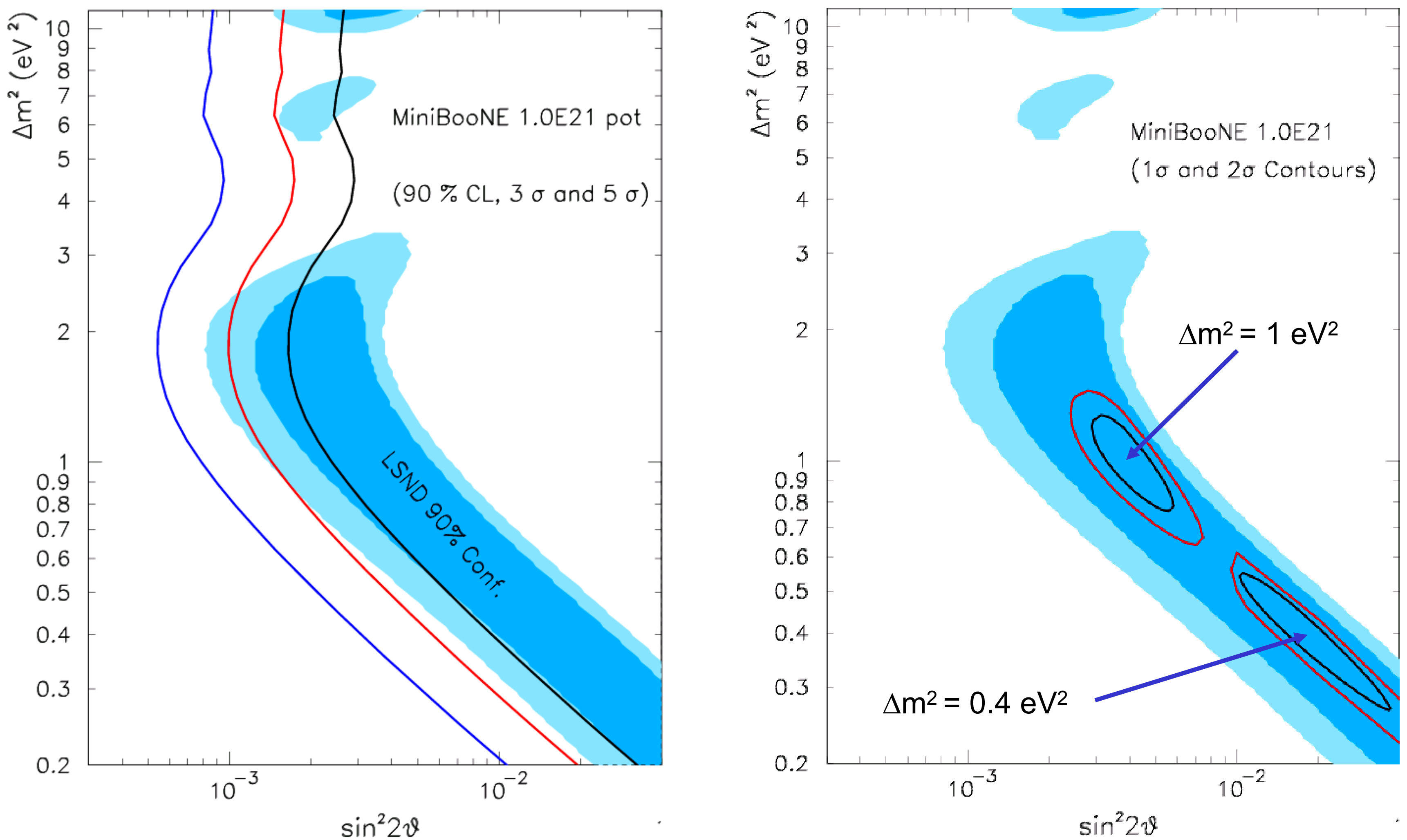
  $\Rightarrow$ Can constrain this background directly from the observed data





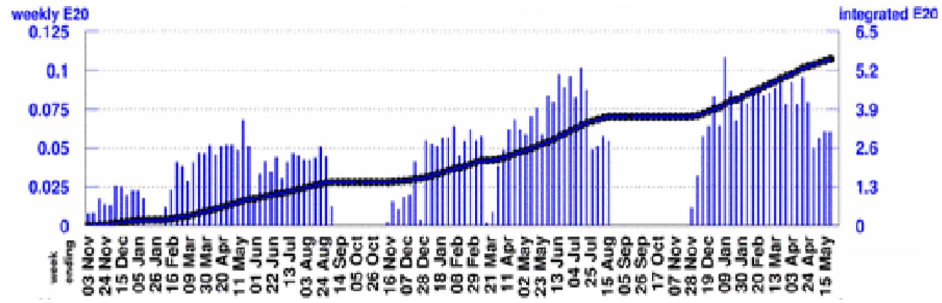
MiniBooNE Oscillation Sensitivity

- Oscillation sensitivity and measurement capability
  - Data sample corresponding to $1x10^{21}$ pot
  - Systematic errors on the backgrounds average ~5%



Run Plan

- In its 30 year history, the Fermilab Booster has never worked this hard and this well



  - Before NuMI turn-on were averaging ...
    ~ 7×10^{16} protons/hour
  - Co-running with NuMI now averages …
    ~ 3.5×10^{16} protons/hour

Have now reached 5.6×10^{20} protons on target in total

- Already have world's largest ν dataset in the 1 GeV region
- Physics results show that reconstruction and analysis algorithms are working well
- Plan is to "open the ν_e appearance box" when the analysis has been substantiated and when sufficient data has been collected for a definitive result

$\Rightarrow$ **Estimate is before the end of 2005**

- Which then leads to the question of the next step
  - If MiniBooNE sees no indications of oscillations with ν_μ

    $\Rightarrow$ **Need to run with $\bar{\nu}_\mu$ since LSND signal was $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$**

  - If MiniBooNE sees an oscillation signal
    $\Rightarrow$ **Then …………**

Experimental Program with Sterile Neutrinos

If sterile neutrinos then many mixing angles, CP phases, and Δm^2 to include

- Measure number of extra masses Δm_{14}^2, Δm_{15}^2 …

- Measure mixings
  Could be many small angles

Map out mixings associated with $\nu_\mu \rightarrow \nu_e$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ & & \cdots & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}$$

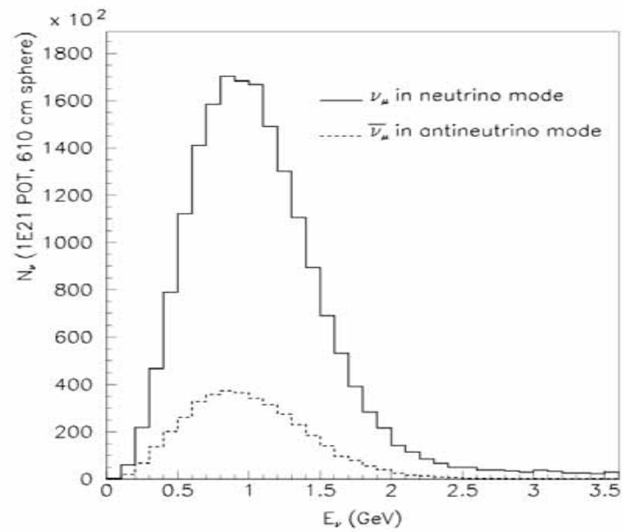
Map out mixings associated with $\nu_\mu \rightarrow \nu_\tau$

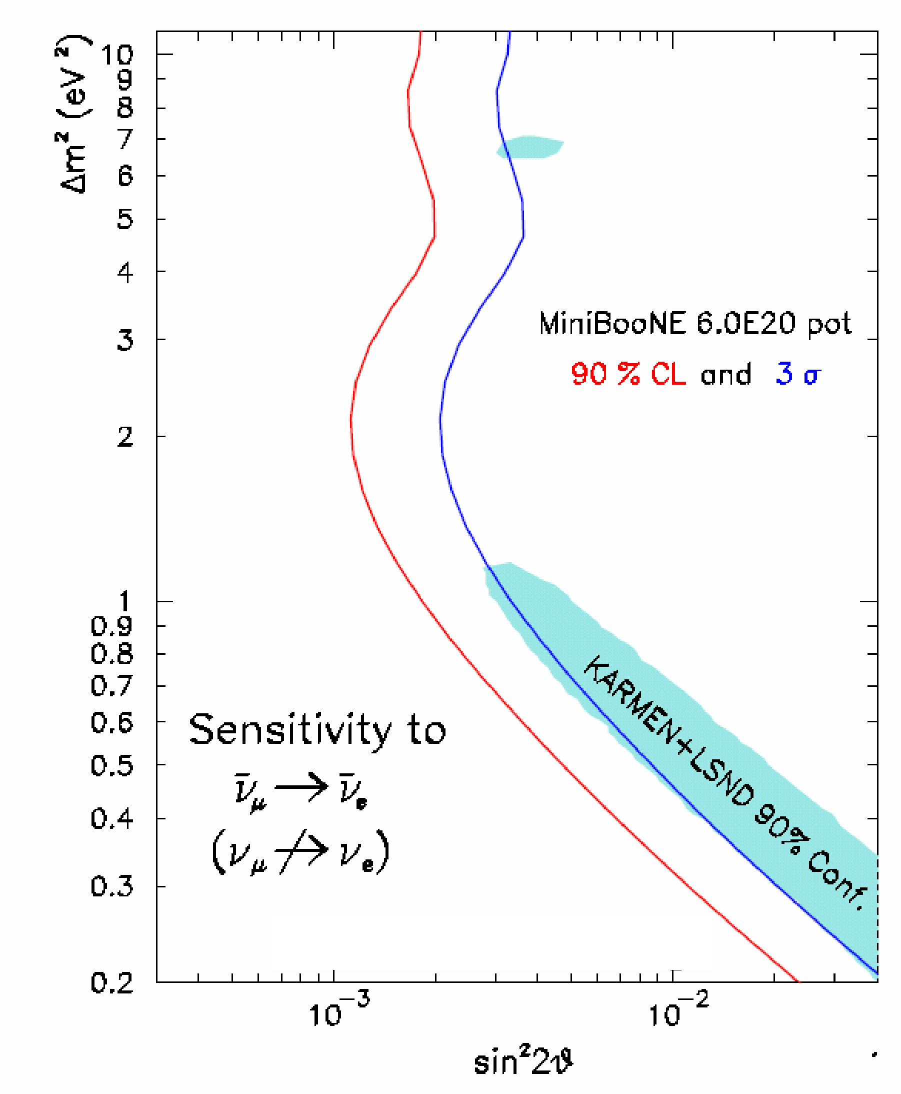
- Oscillations to sterile neutrinos could effect
  long-baseline measurements and strategy

- Compare ν_μ and $\bar{\nu}_\mu$ oscillations $\Rightarrow$ CP and CPT violations

If MiniBooNE sees $\nu_\mu \rightarrow \nu_e$ (or not) then: Run BooNE with anti-neutrinos for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Direct comparison with LSND
- Are ν_μ and $\bar{\nu}_\mu$ the same?
  - Mixing angles, Δm^2 values
- Explore CP (or CPT) violation by comparing ν_μ and $\bar{\nu}_\mu$ results
- Running with antineutrinos takes about x2 longer to obtain similar sensitivity

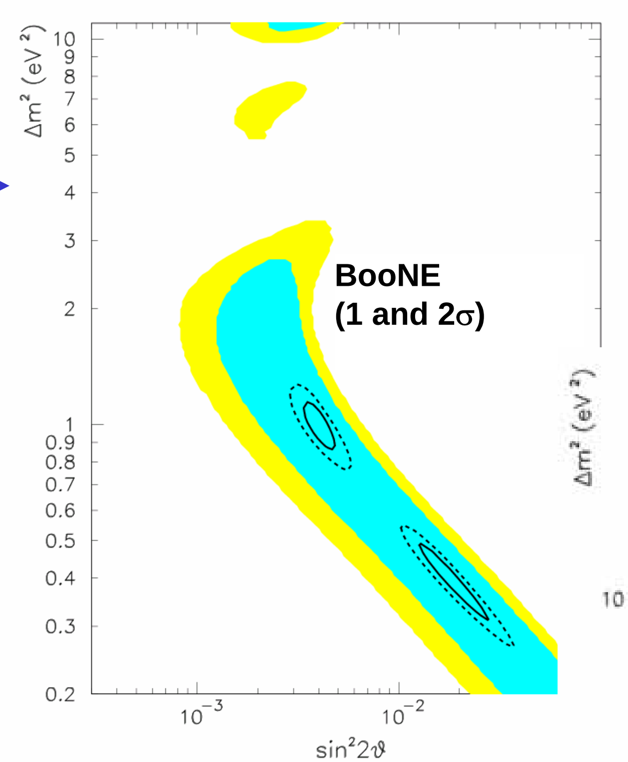


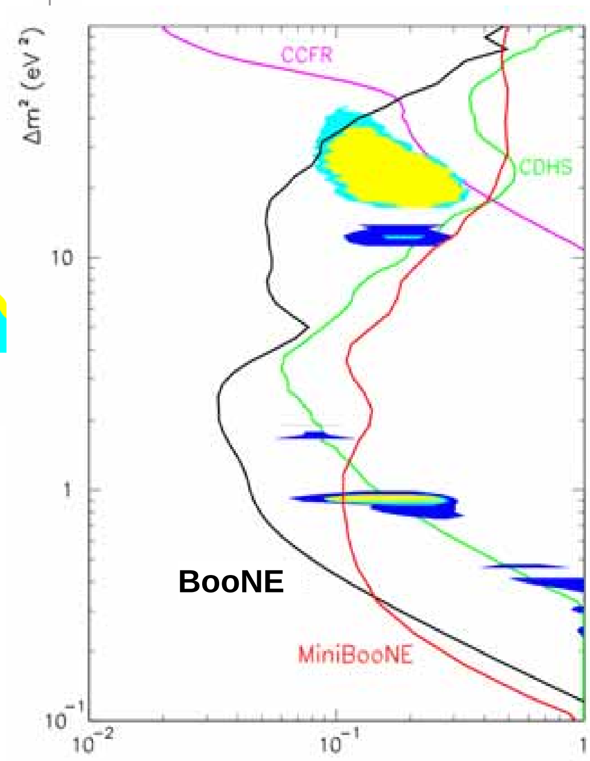


Next Step: BooNE: Two Detector Exp.

➢ Add a second detector at 1 - 2 km distance ⇐ **BooNE**

- Precision measurement of oscillation parameters
  - $\sin^2 2\theta$ and Δm^2
  - Map out the nxn mixing matrix
- Determine how many high mass Δm^2's
  - 3+1, 3+2, 3+3 …………..
- Show the L/E oscillation dependence
  - Oscillations or ν decay or ???
- Explore disappearance measurement in high Δm^2 region
  - Probe oscillations to sterile neutrinos



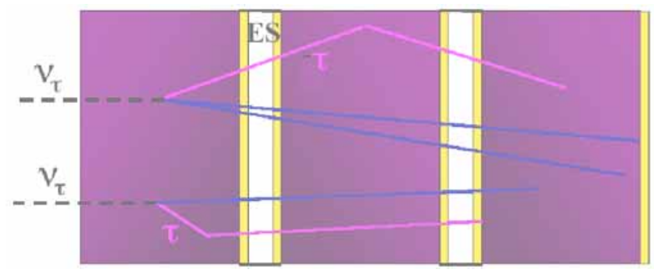


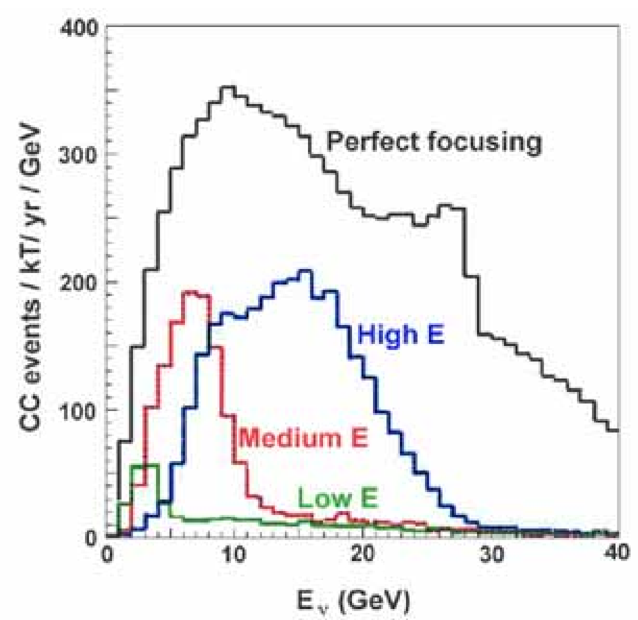
(These exp's could be done at FNAL, BNL, CERN, JPARC)

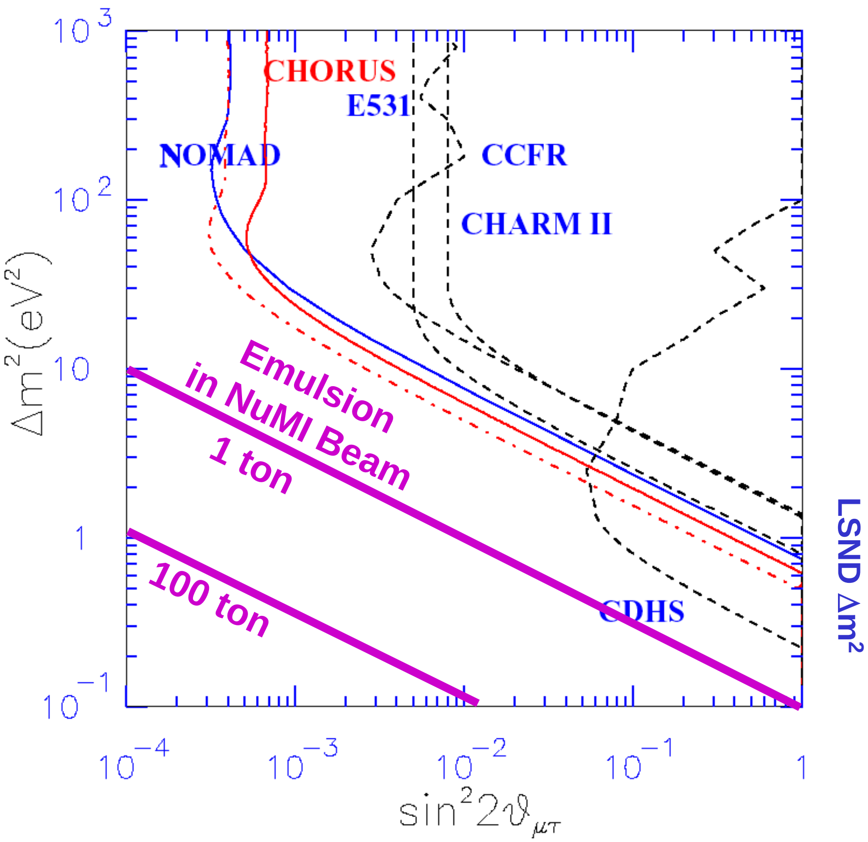
Another Next Step:
Do $\nu_\mu \rightarrow \nu_\tau$ Appearance Experiment at High Δm^2

- Appearance of ν_τ would help sort out the mixings through the sterile components
- Need moderately high neutrino energy to get above the 3.5 GeV τ threshold (~6-10 GeV)
- Example: NuMI Med energy beam 8 GeV with detector at L=2km (116m deep)

Emulsion Detector or Liquid Argon







Conclusions

- Neutrinos have been surprising us for some time
  and will most likely continue to do so

- Although the "neutrino standard model" can be used as a guide,
  the future direction for the field is going to be determined by what we discover from experiments.

- Sterile neutrinos may open up a whole ν area to explore