# MiniBooNE and Sterile Neutrinos

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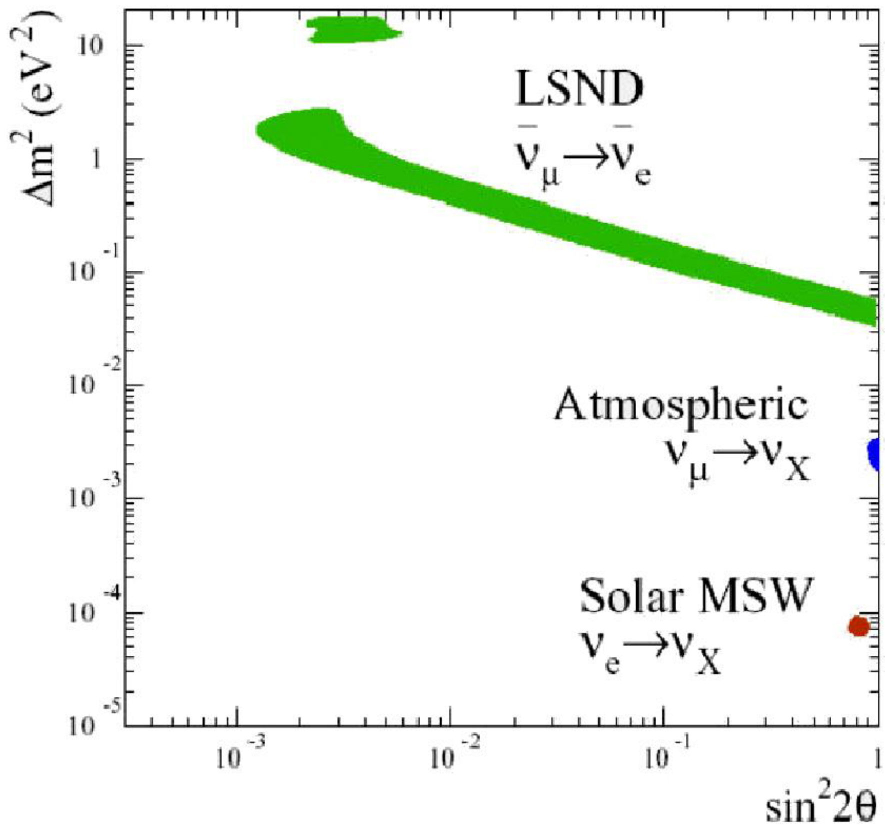
NOW2004 Workshop

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

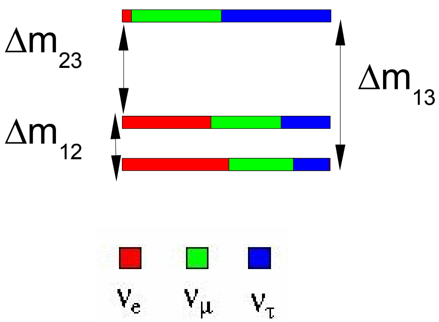
# Three Signal Regions




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

- LSND
  $\Delta m^2 = 0.1 - 10\ eV^2$ , small mixing
- Atmospheric
  $\Delta m^2 = 2.5\times10^{-3}\ eV^2$ , large mixing
- Solar
  $\Delta m^2 = 8.2\times10^{-5}\ eV^2$ , 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 $\Delta m^2$ ?

- 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 $\nu$'s) allows different mixing for $\nu$'s and $\bar{\nu}$'s
  - Some possibilities still open

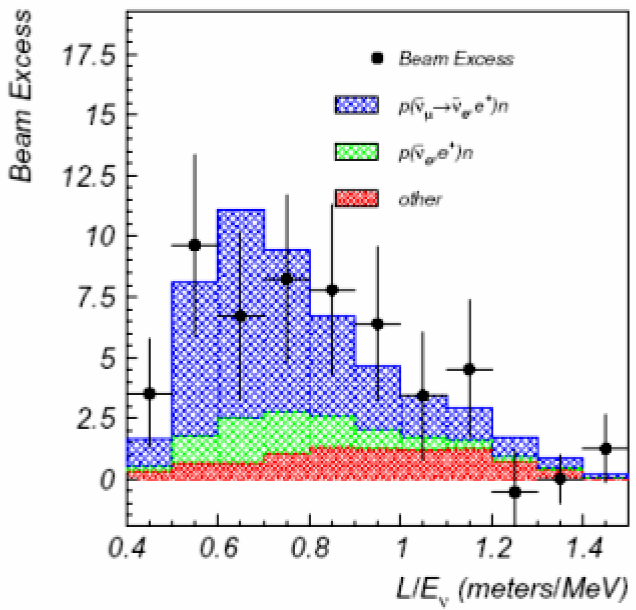
# LSND Result

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

  87.9 ± 22.4 ± 6.0 events (3.8σ)

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

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



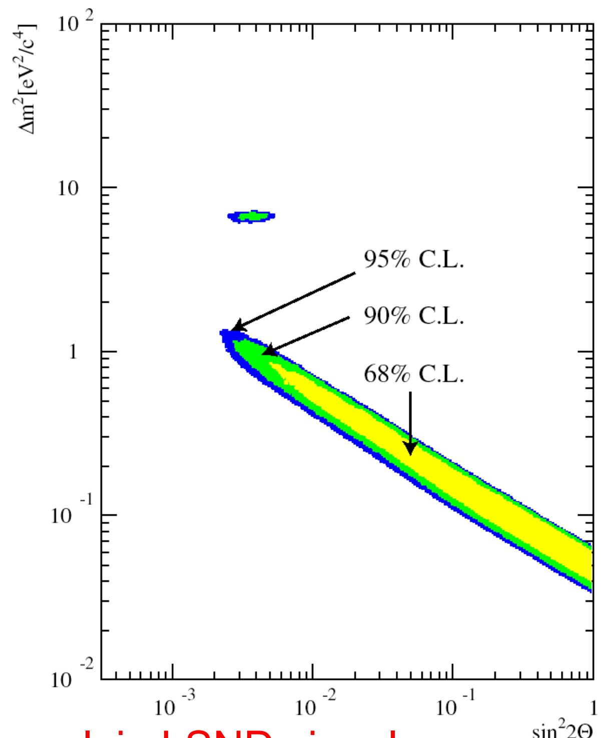

Also Karmen Experiment

- 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.

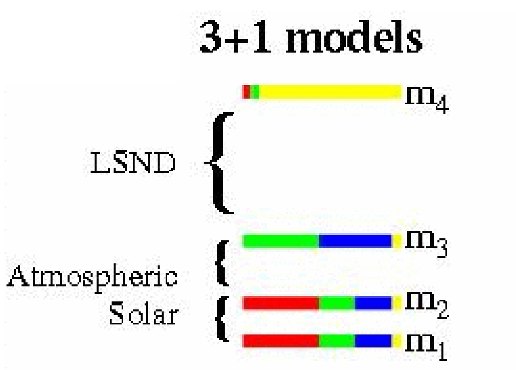
$\mu^+ \rightarrow e^+ \bar{\nu}_e \nu$ unlikely to explain LSND signal

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

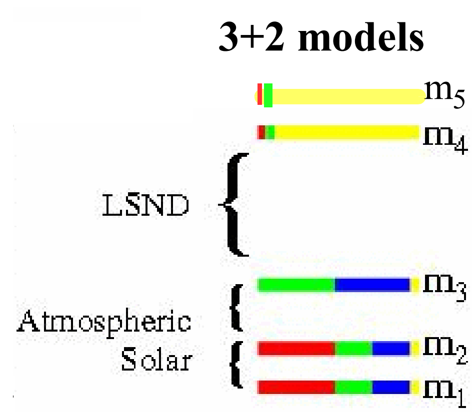
- Global Fits to high $\Delta m^2$ oscillations for Short-Baseline exps including LSND positive signal. (M.Sorel, J.Conrad, M.S., hep-ph/0305255)

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

| Channel | Experiment | Lowest $\Delta m^2$ Reach (90% CL) | $\sin^2 2\theta$ Constraint (90% CL) High $\Delta m^2$ | Optimal $\Delta m^2$ |
|---|---|---|---|---|
| $\nu_\mu \rightarrow \nu_e$ | 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 | $4 \cdot 10^{-1}$ | $< 1.4 \cdot 10^{-3}$ | $< 1.0 \cdot 10^{-3}$ |
| $\nu_e \rightarrow \nu_{\not e}$ | Bugey | $1 \cdot 10^{-2}$ | $< 1.4 \cdot 10^{-1}$ | $< 1.3 \cdot 10^{-2}$ |
| | CHOOZ | $7 \cdot 10^{-4}$ | $< 1.0 \cdot 10^{-1}$ | $< 5 \cdot 10^{-2}$ |
| $\nu_\mu \rightarrow \nu_{\not\mu}$ | CCFR84 | $6 \cdot 10^{0}$ | none | $< 2 \cdot 10^{-1}$ |
| | CDHS | $3 \cdot 10^{-1}$ | none | $< 5.3 \cdot 10^{-1}$ |
| $\nu_\mu \rightarrow \nu_\tau$ | NOMAD | $7 \cdot 10^{-1}$ | $< 3.3 \cdot 10^{-4}$ | $< 2.5 \cdot 10^{-4}$ |
| | CHORUS | $5 \cdot 10^{-1}$ | $< 6.8 \cdot 10^{-4}$ | $< 4.5 \cdot 10^{-4}$ |
| $\nu_e \rightarrow \nu_\tau$ | 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:
$\Delta m^2$=0.92 eV$^2$
$U_{e4}$=0.136 ,
$U_{\mu 4}$=0.205
with
Compatibility
Level = 3.6%

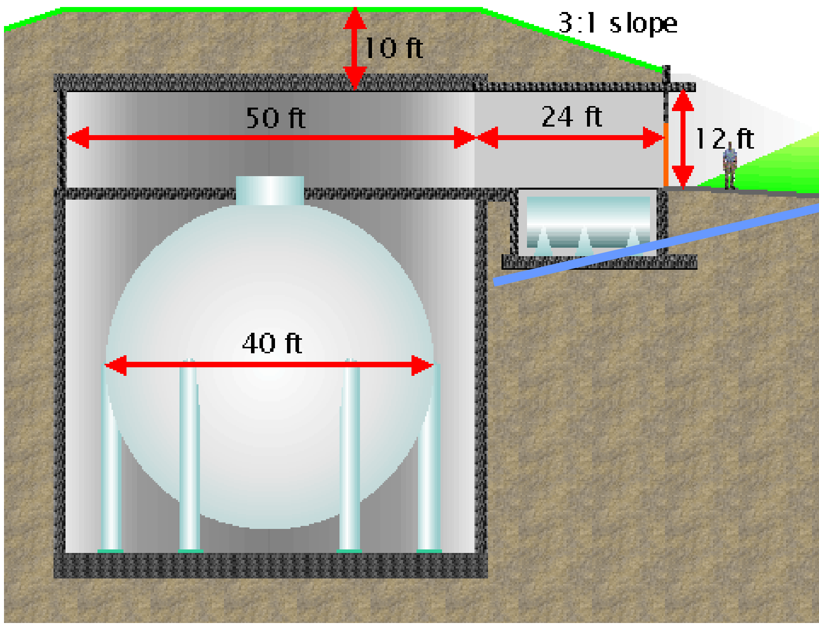


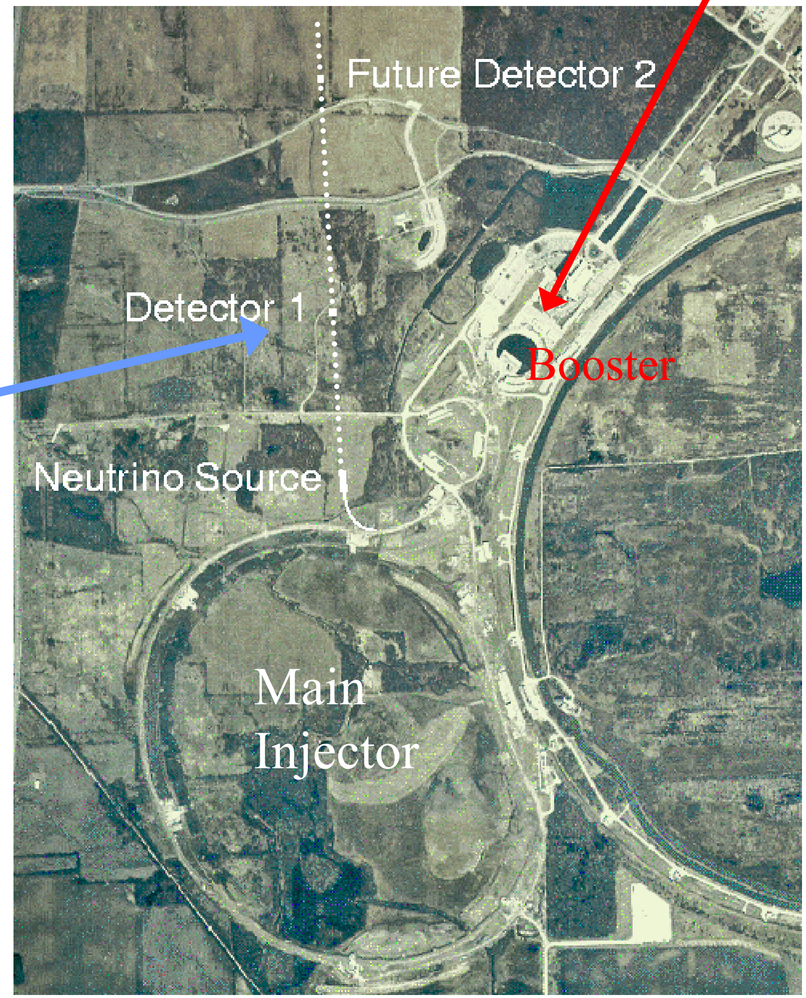

Best Fit:
$\Delta m_{41}^2$=0.92 eV$^2$
$U_{e4}$=0.121 , $U_{\mu 4}$=0.204
$\Delta m_{51}^2$=22 eV$^2$
$U_{e5}$=0.036 , $U_{\mu 4}$=0.224
with
Compatibility
Level = 30%

# 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 $\nu_\mu$ disappearance

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



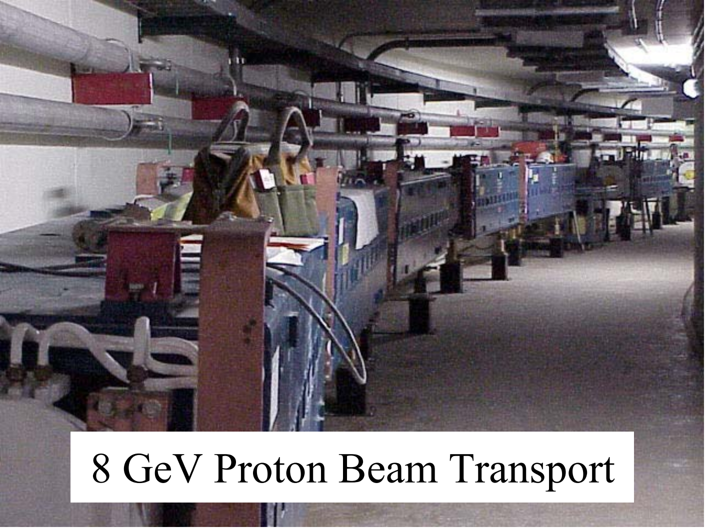

12m sphere filled with mineral oil and PMTs located 500m from source

# MiniBooNE Collaboration

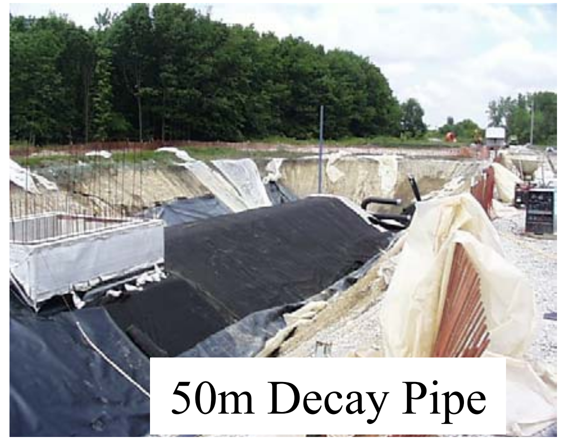
**MiniBooNE consists of about 70 scientists from 13 institutions.**

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, J. Formaggio, J. Link, J. Monroe, K. McConnel, D. Schmitz, M.H. Shaevitz, M. Sorel, L. Wang, 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, N.L.Walbridge, D.H. White *Los Alamos*
R. Imlay, W. Metcalf, S.Ouedraogo, 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

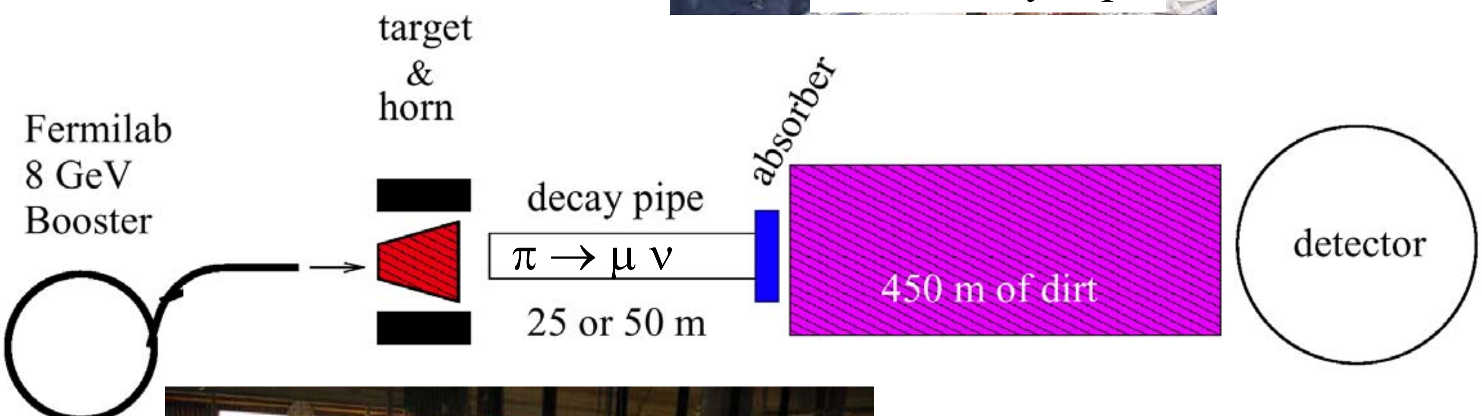


8 GeV Proton Beam Transport



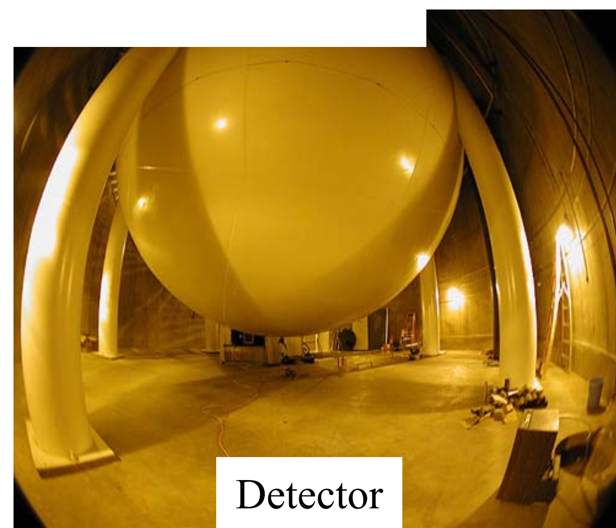
50m Decay Pipe

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



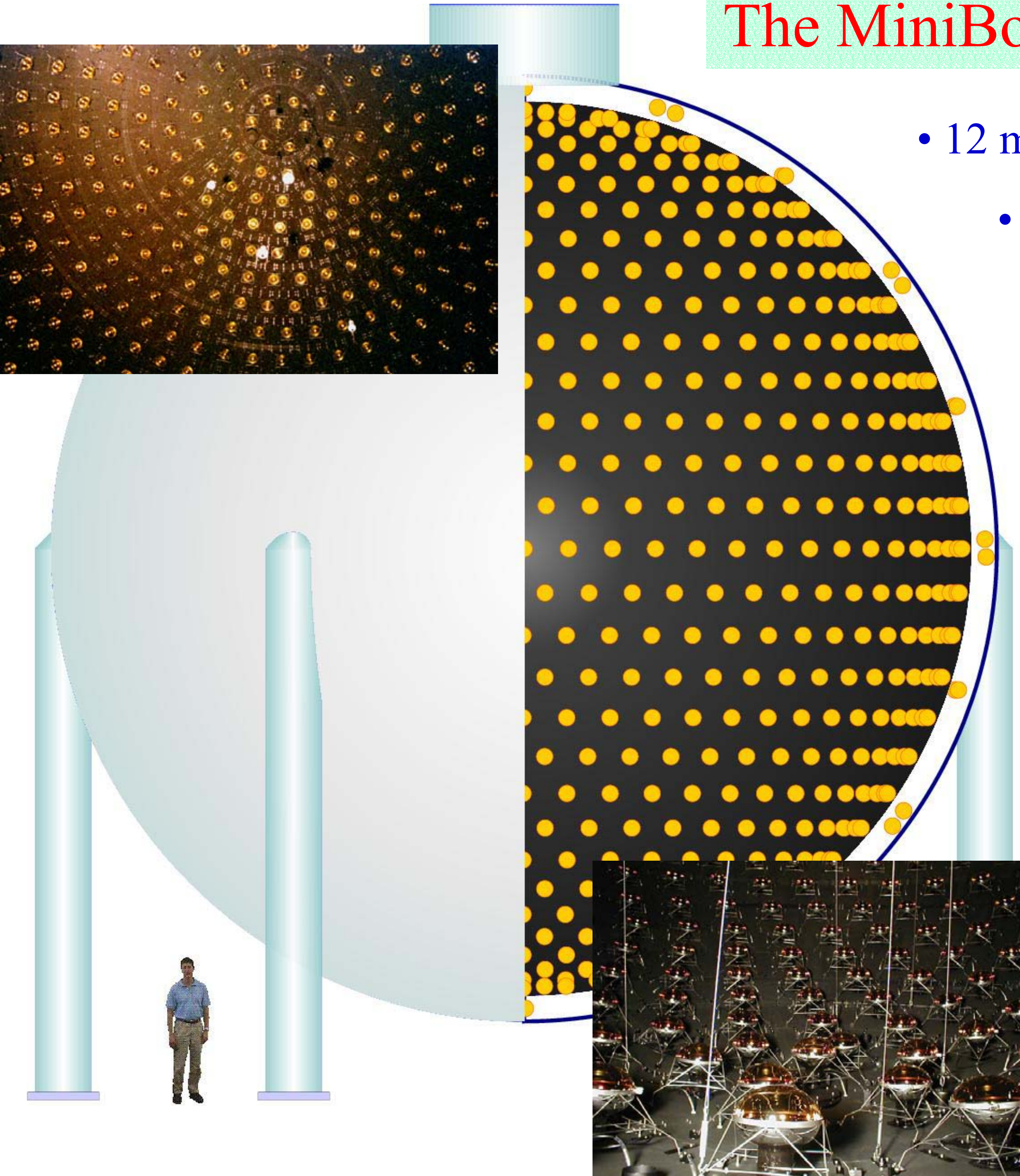

One magnetic Horn, with Be target

Magnetic Horn



Detector

# The MiniBooNE Detector

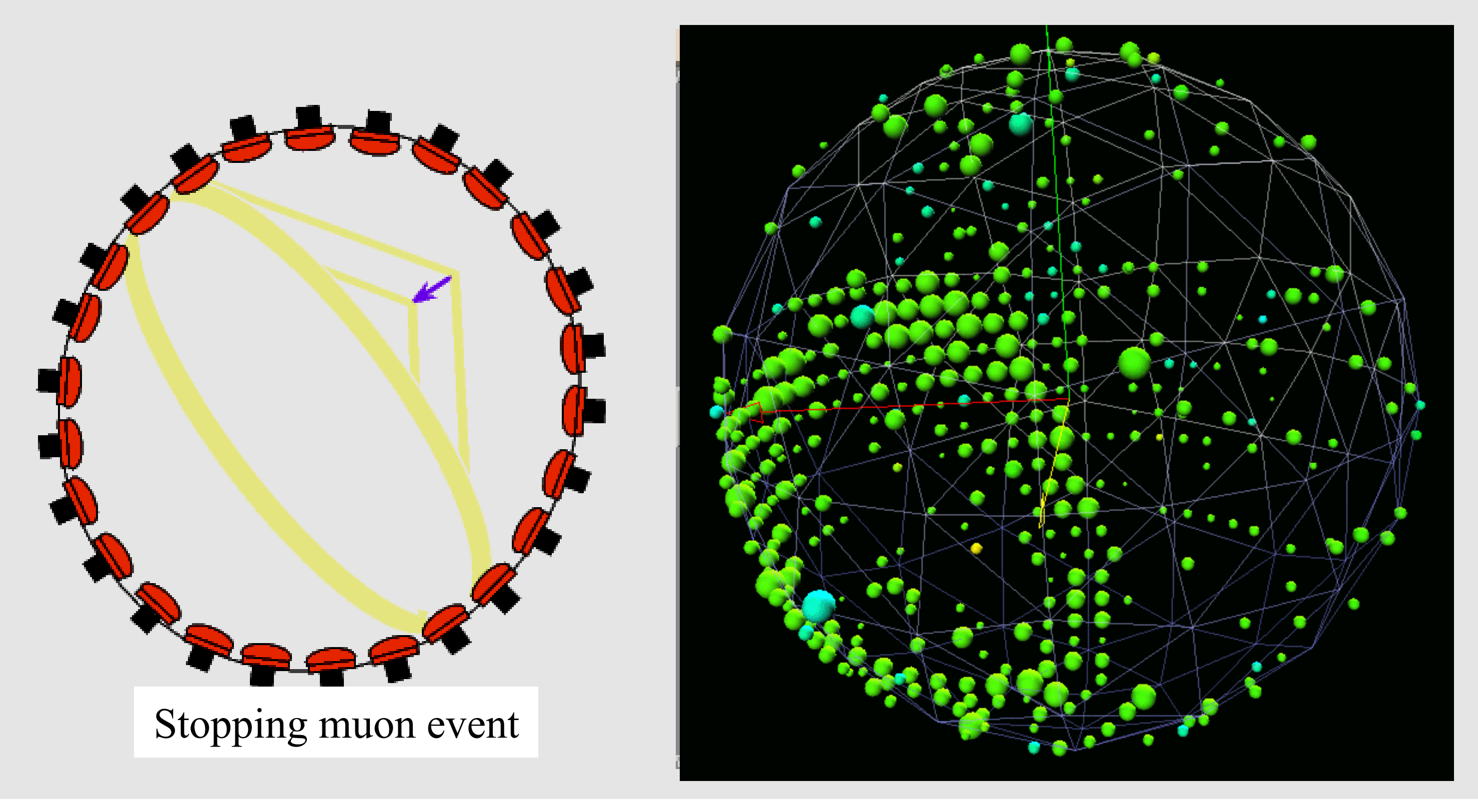


- 12 meter diameter sphere
  - Filled with 950,000 liters (900 tons) of very pure mineral oil
    - Light tight inner region with 1280 photomultiplier tubes
    - Outer veto region with 241 PMTs.
    - Oscillation Search Method:

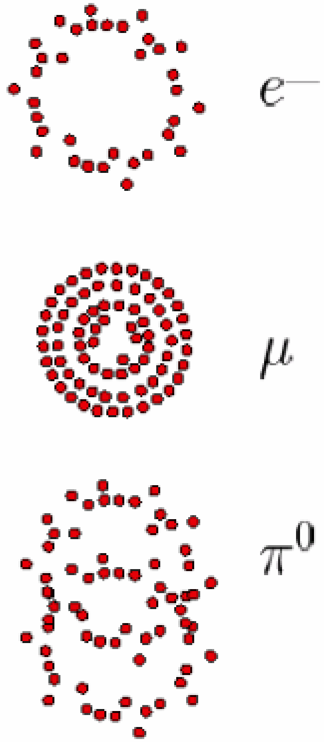
      Look for $\nu_e$ events in a pure $\nu_\mu$ beam

# Particle Identification

- Separation of $\nu_\mu$ from $\nu_e$ events
  - Exiting $\nu_\mu$ events fire the veto
  - Stopping $\nu_\mu$ events have a Michel electron after a few $\mu$sec
  - 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

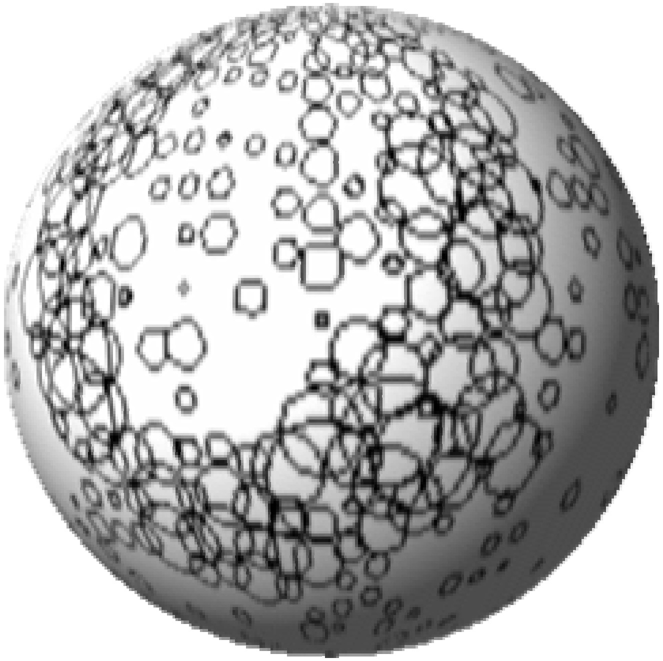


Stopping muon event

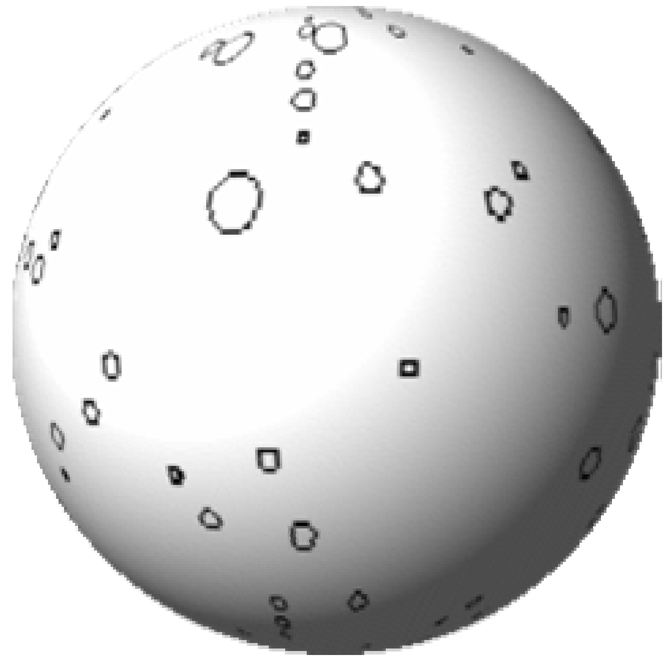


# Example Cerenkov Rings

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



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



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

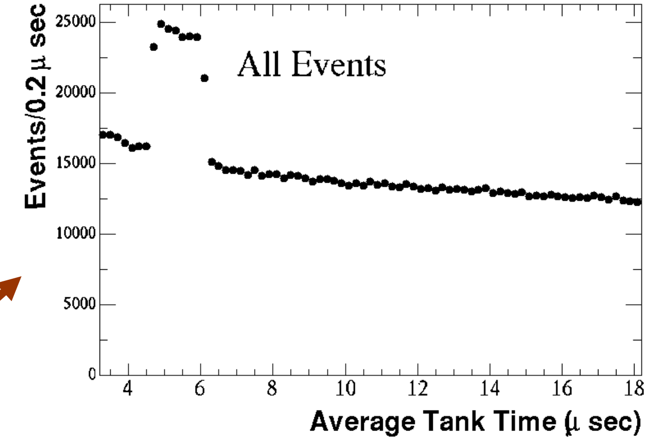
$$\pi^0 \rightarrow \gamma + \gamma$$

# Neutrino events

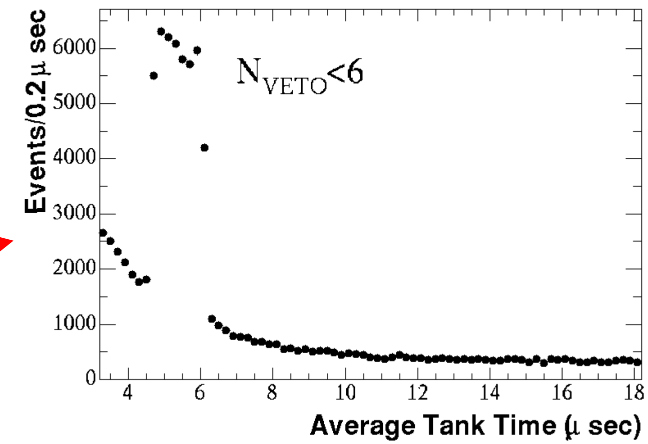
beam comes in spills @ up to 5 Hz
each spill lasts 1.6 μsec

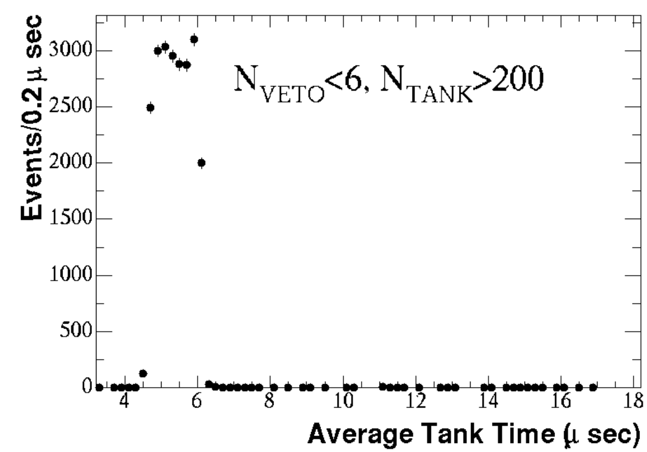
trigger on signal from Booster
read out for 19.2 μsec

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 $\sim 10^{-3}$

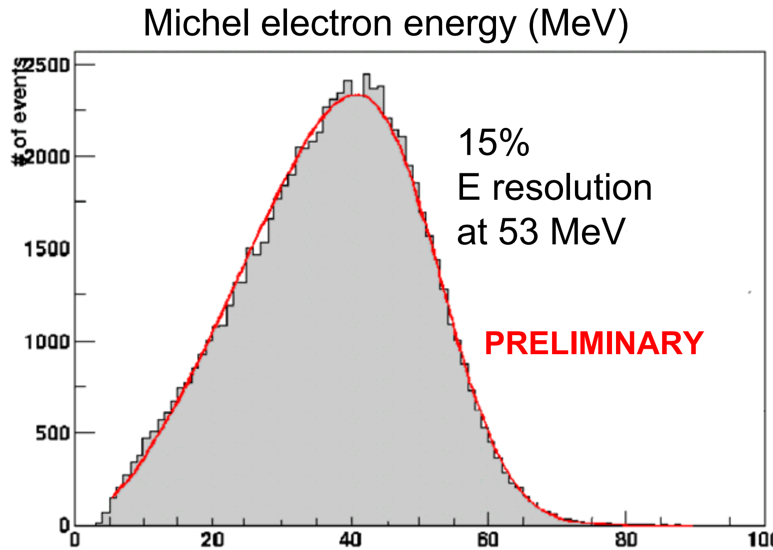
ν event every 1.5 minutes

## Current Collected data:

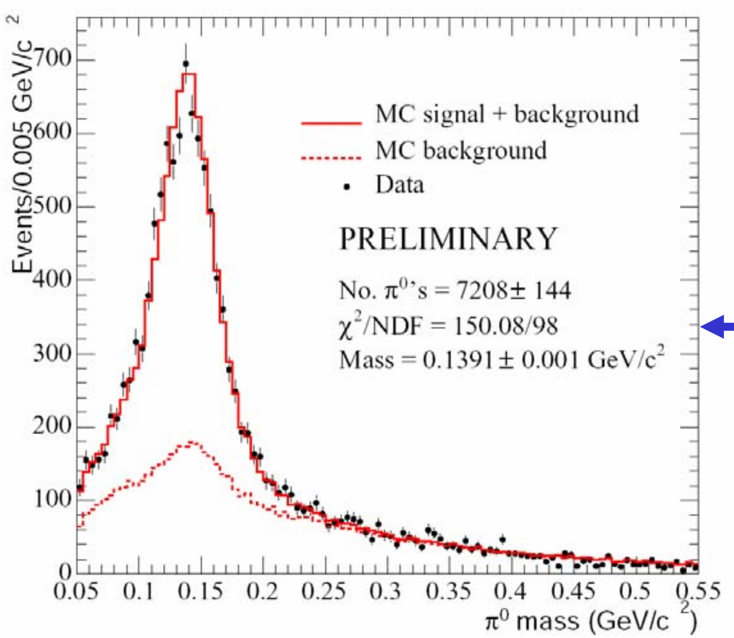
400k neutrino candidates
for $3.7 \times 10^{20}$ protons on target

# Energy Calibration Checks

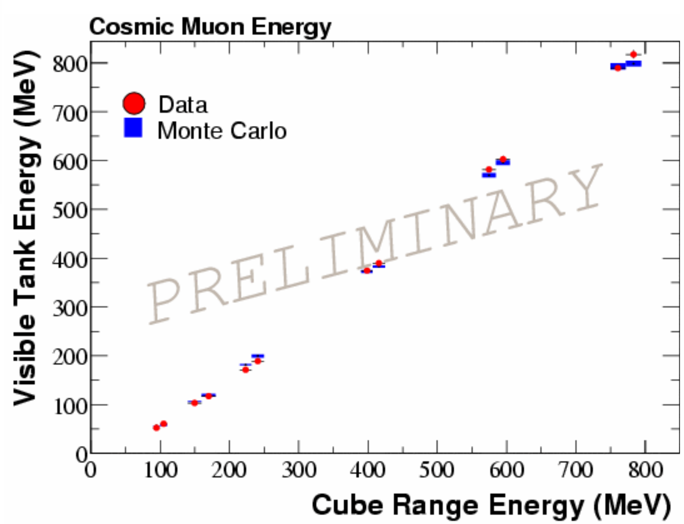
Spectrum of Michel electrons from stopping muons

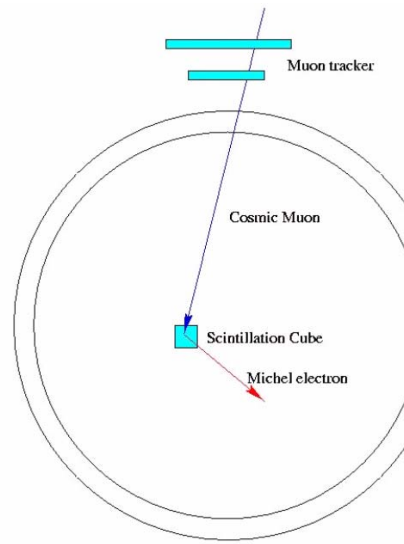



Mass distribution for isolated $\pi^0$ events




Energy vs. Range for events stopping in scintillator cubes



# Oscillation Analysis: Status and Plans

- Blind (or "Closed Box") $\nu_e$ appearance analysis

  you can see all of the info on some events

  or

  some of the info on all events

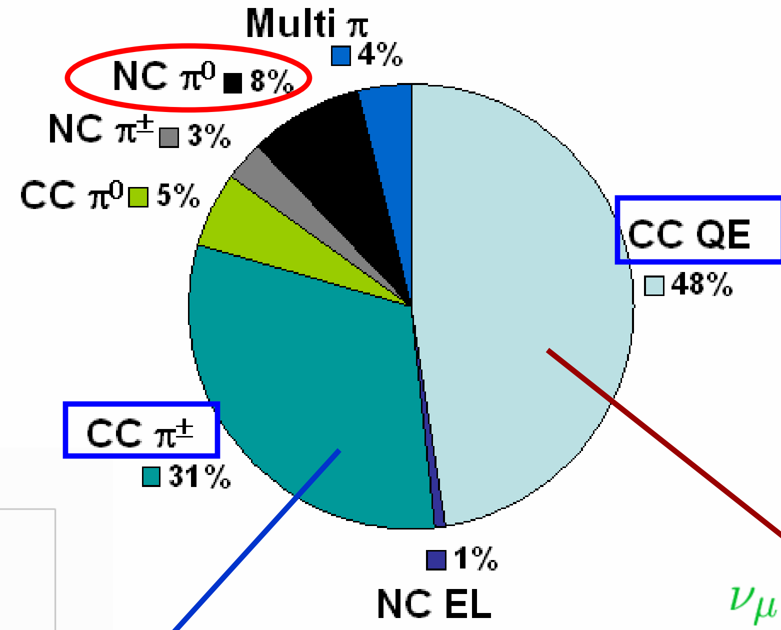
  but

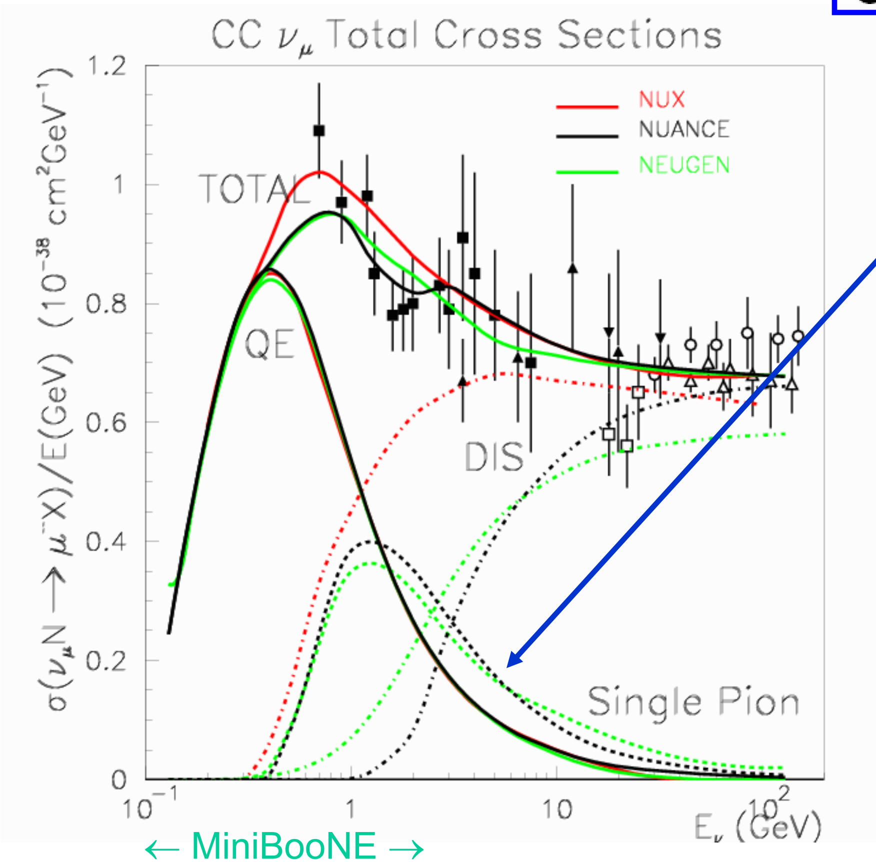
  **you cannot see all of the info on all of the events**

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

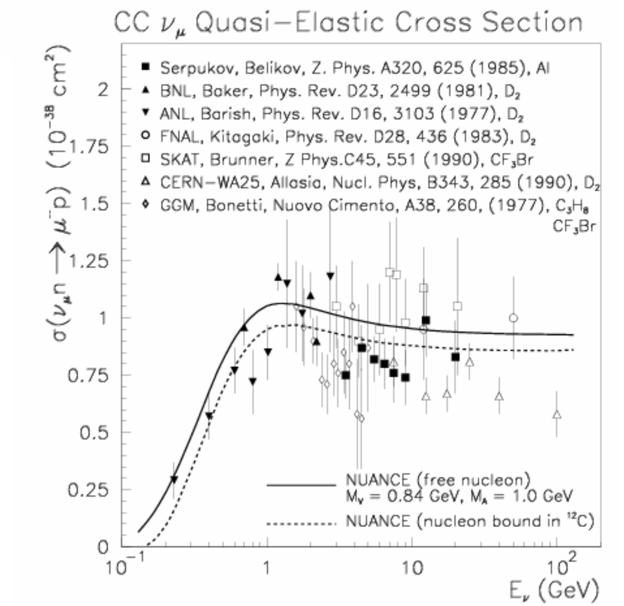
# Low Energy Neutrino Cross sections

Events in MiniBooNE with $E_{vis}$>100 MeV



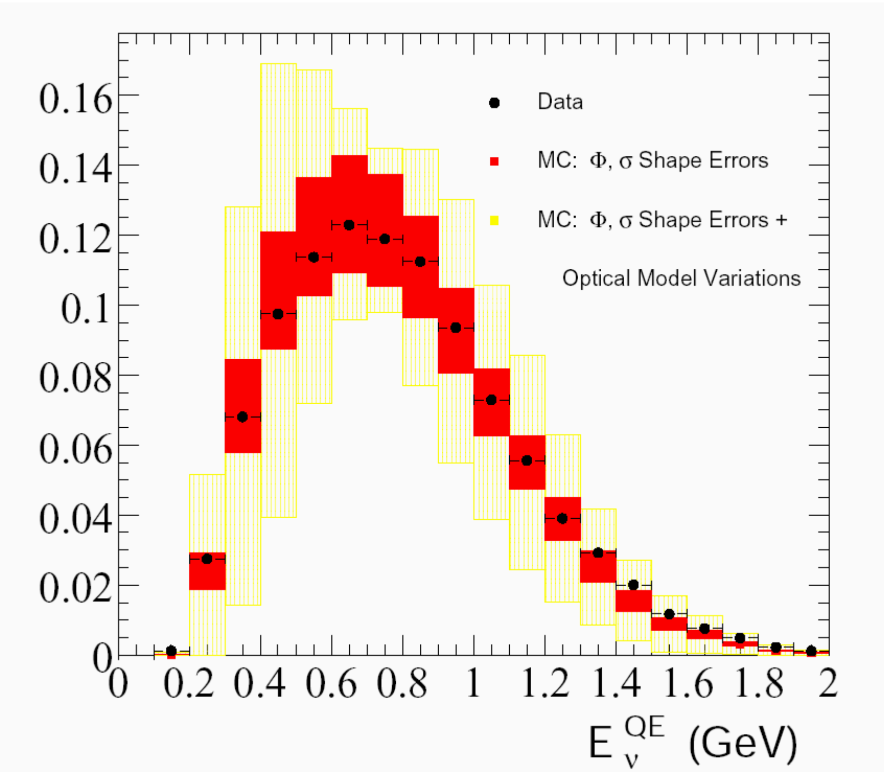

$\nu_\mu n \to \mu^- p$



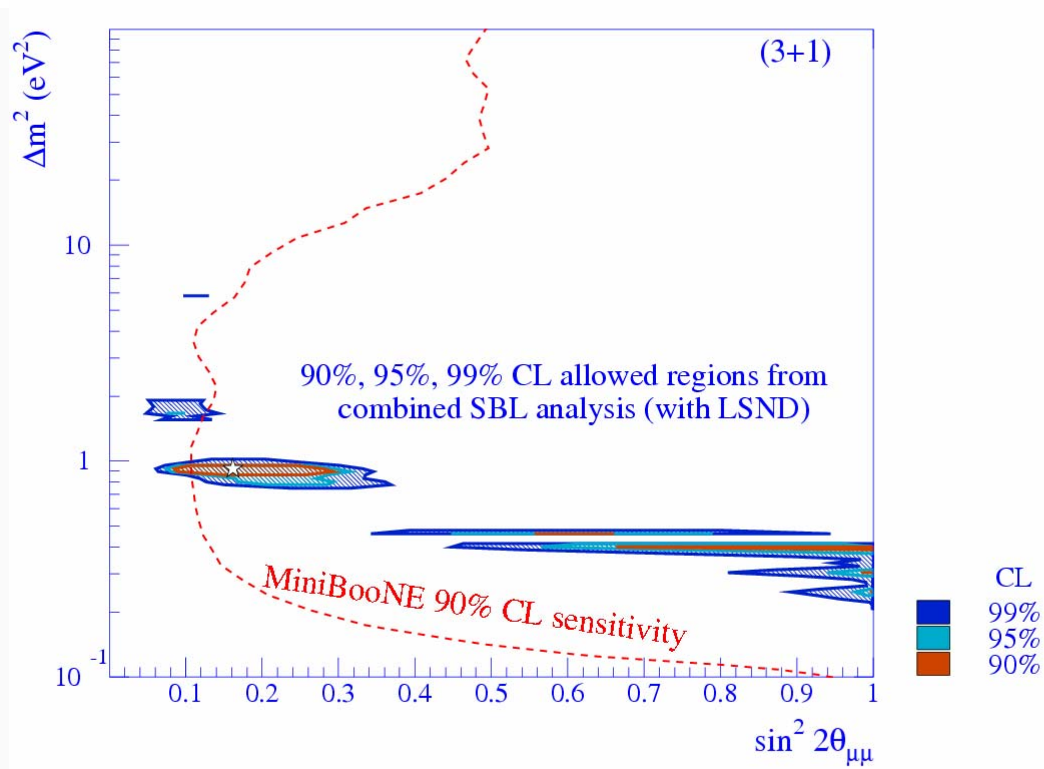
# On the Road to a $\nu_\mu$ Disappearance Result

- Use $\nu_\mu$ 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 in plot (Full sample: ~500,000)

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



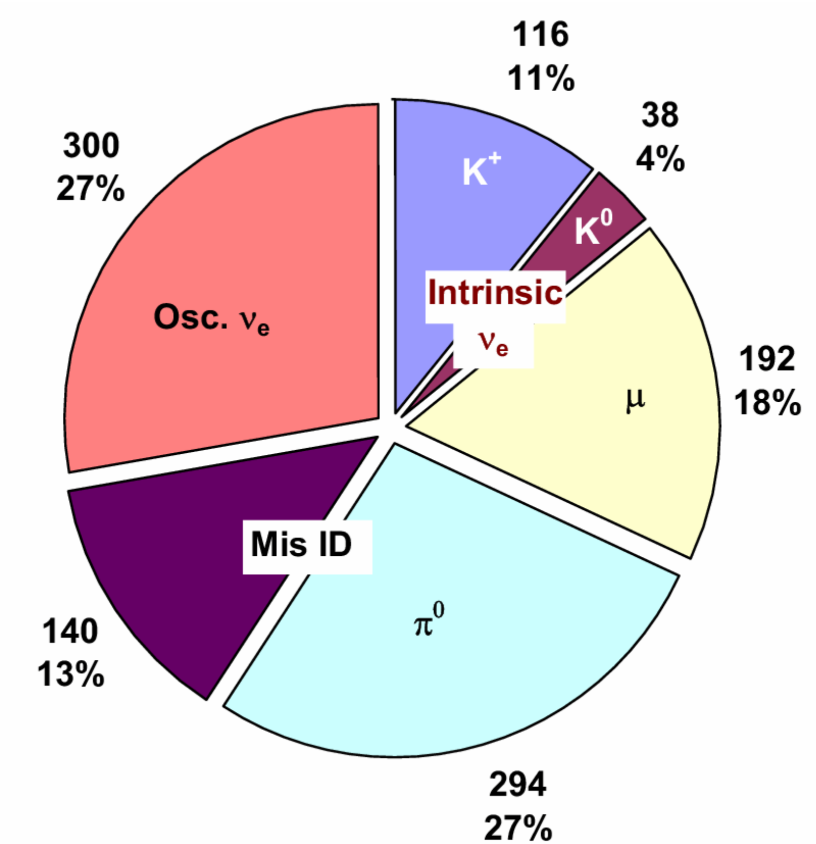

Monte Carlo estimate of final sensitivity



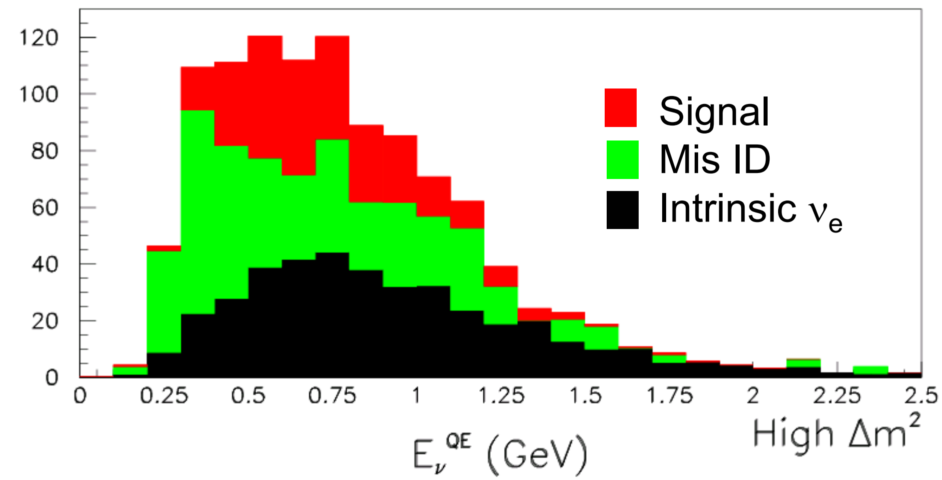

Will be able to cover a large portion of 3+1 models

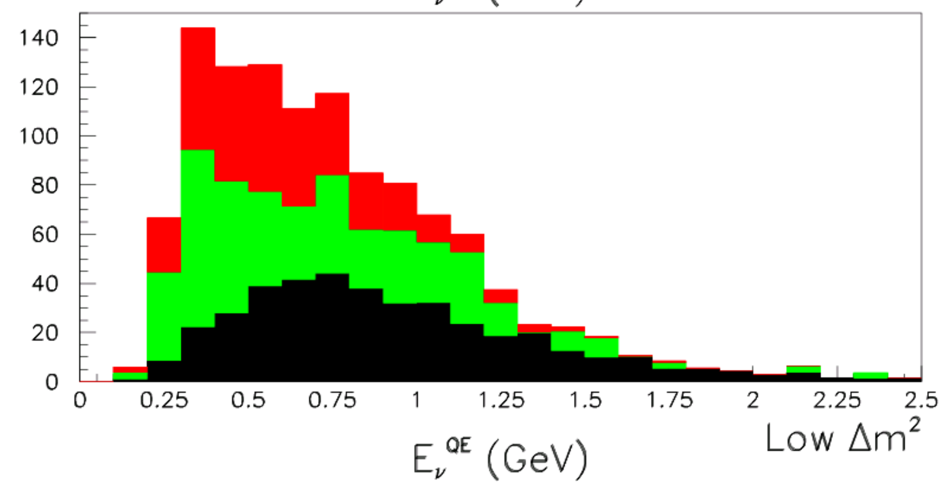
# Estimates for the $\nu_\mu \rightarrow \nu_e$ Appearance Search

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




- Fit to $E_\nu$ distribution used to separate background from signal.



# Intrinsic $\nu_e$ in the beam

Small intrinsic $\nu_e$ rate $\Rightarrow$ Event Ratio $\nu_e/\nu_\mu$=6x10$^{-3}$

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

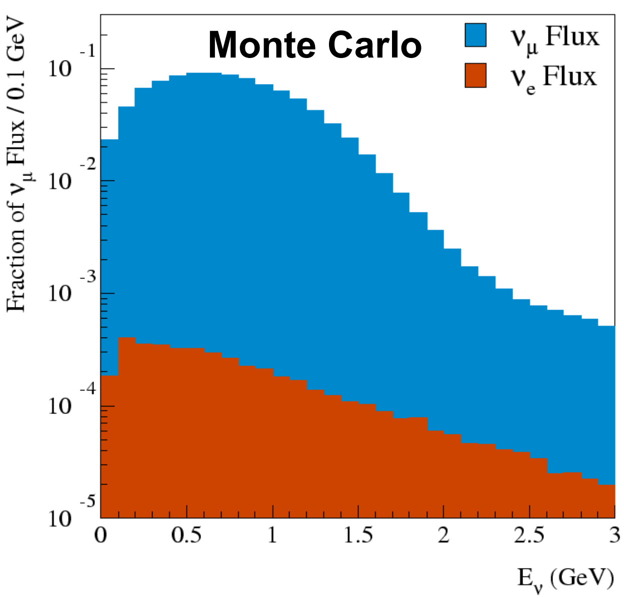
$\nu_e$ from $\mu$–decay
- Directly tied to the observed half-million $\nu_\mu$ interactions

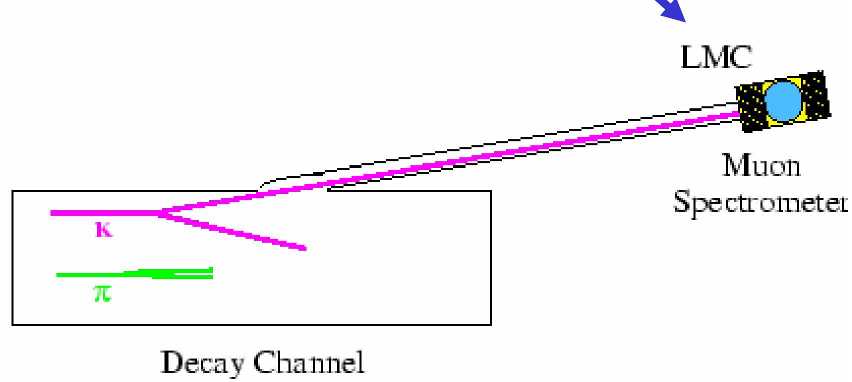
$K^+ \rightarrow \pi^0 e^+ \nu_e$

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

Kaon rates measured in low energy proton production experiments
- HARP experiment (CERN)
- E910 (Brookhaven)

- "Little Muon Counter" measures rate of kaons *in situ*



# Mis-identification Backgrounds

- Background mainly from NC $\pi^0$ production

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

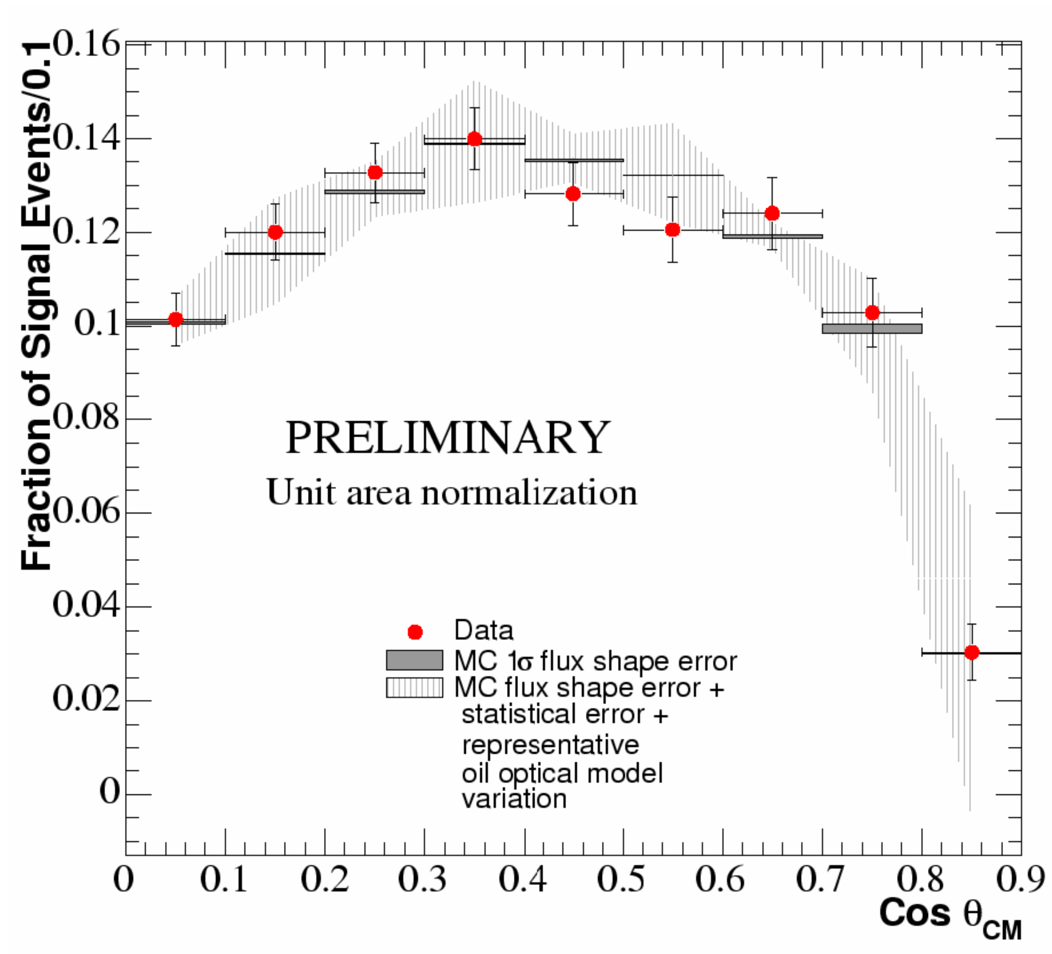
  followed by

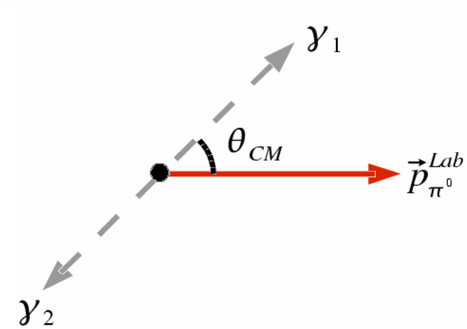
  $\pi^0 \rightarrow \gamma\,\gamma$

  where one $\gamma$ is lost because it has too low energy

- Over 99.5% of these events are identified and the $\pi^0$ kinematics are measured

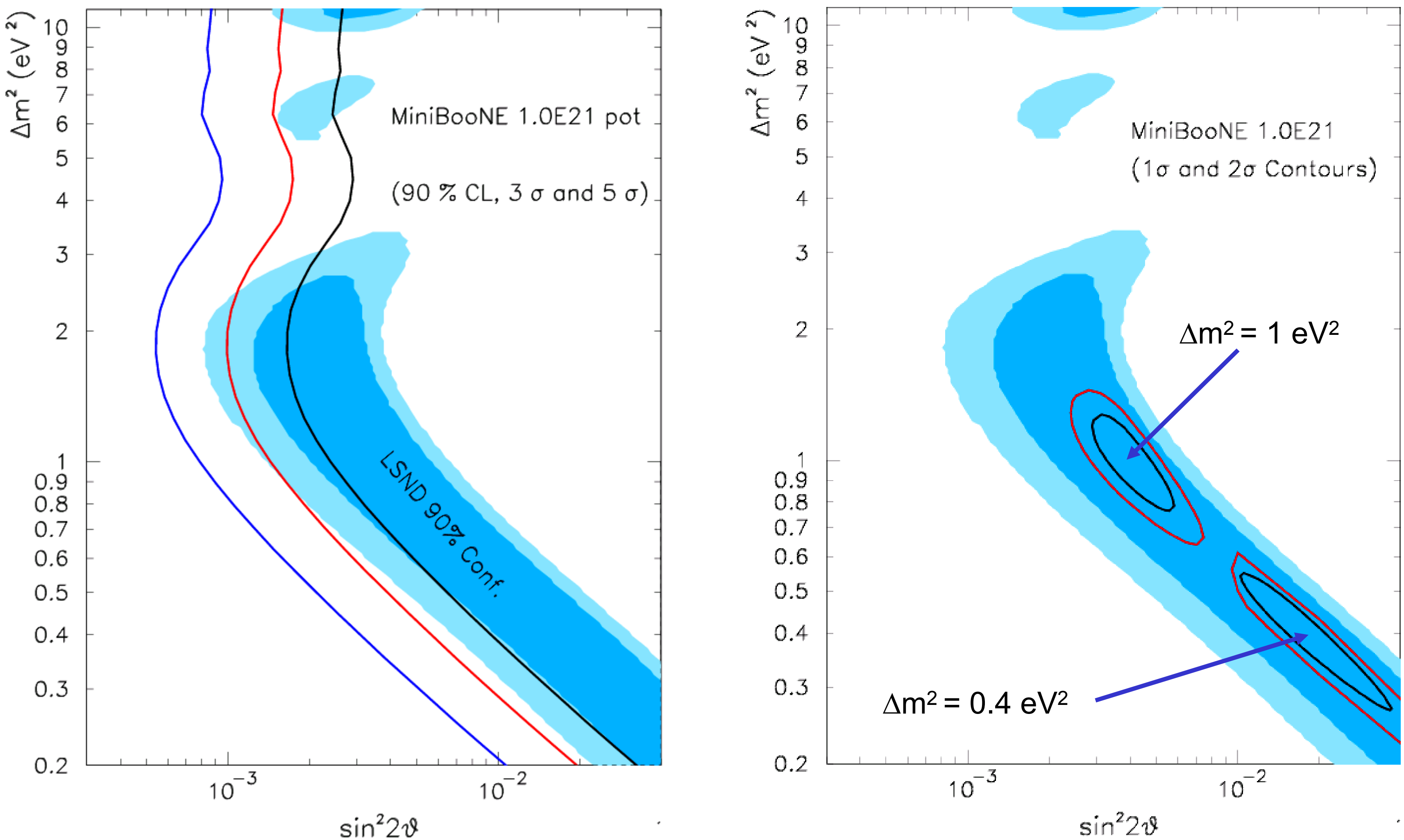
  $\Rightarrow$ Can constrain this background directly from the observed data



# MiniBooNE Oscillation Sensitivity

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



# Run Plan

- At the current time have collected $3.7\times10^{20}$ p.o.t.
  - Data collection rate is steadily improving as the Booster accelerator losses are reduced
  - Many improvements in the Booster and Linac (these not only help MiniBooNE but also the Tevatron and NuMI in the future)

- Plan is to "open the $\nu_e$ appearance box" when the analysis has been substantiated and when sufficient data has been collected for a definitive result

  ⇒ ***Current estimate is sometime in 2005***

- Which then leads to the question of the next step

  - If MiniBooNE sees no indications of oscillations with $\nu_\mu$

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

  - If MiniBooNE sees an oscillation signal

    ⇒ **Then …………**

# Experimental Program with Sterile Neutrinos

*If sterile neutrinos then many mixing angles, CP phases, and $\Delta m^2$ to include*

- Measure number of extra masses $\Delta m_{14}{}^2$, $\Delta m_{15}{}^2$ …
- 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 $\nu_\mu \rightarrow \nu_\tau$**

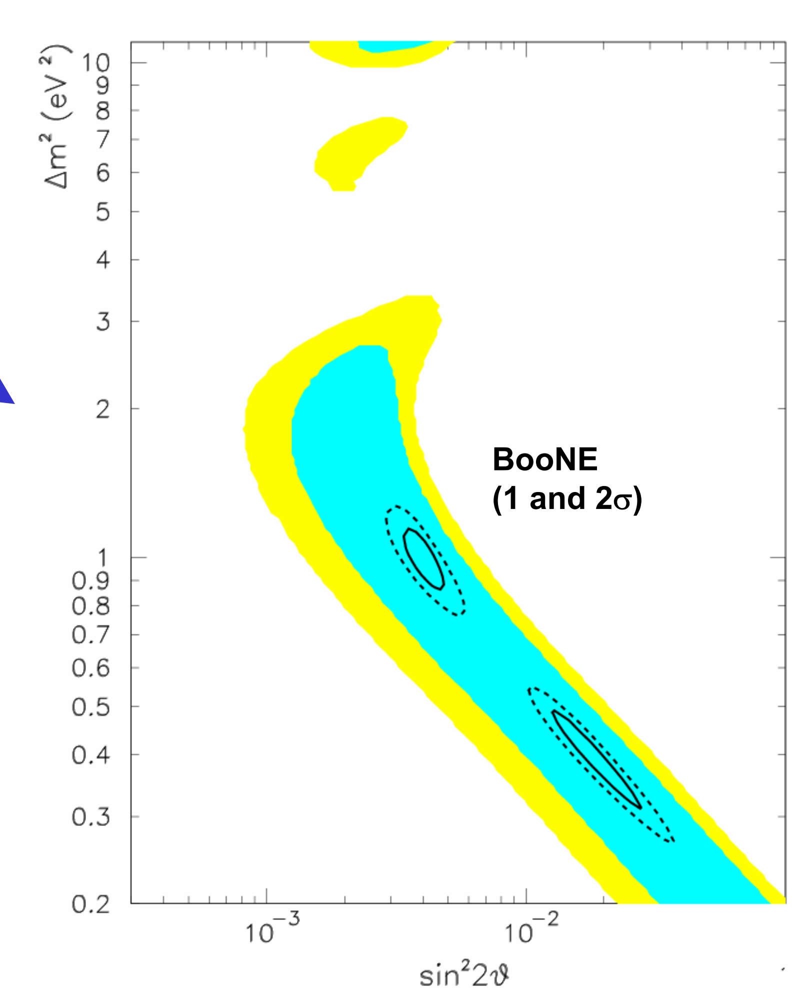
- Oscillations to sterile neutrinos could effect
  long-baseline measurements and strategy

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

# Next Step: BooNE: Two (or Three) Detector Exp.

➢ Add Far detector at 2 km for low $\Delta m^2$ or 0.25 km for high $\Delta m^2$ $\Leftarrow$ **BooNE**

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




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

# 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 $\nu$ area to explore