MiniBooNE and Sterile Neutrinos

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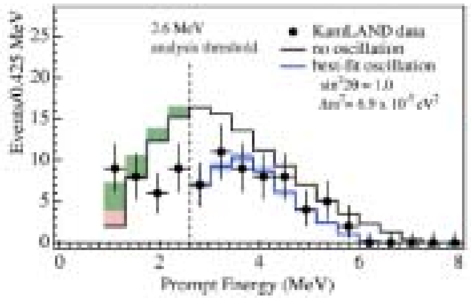
- Extensions to the Neutrino Standard Model: Sterile Neutrinos
- MiniBooNE: Status and Prospects
- Future Directions if MiniBooNE Sees Oscillations

Neutrinos: Open Questions

Issues	Questions	Theorists' Poll*
# of Light Neutrinos	3 active + ? steriles	Three
Majorana vs Dirac	$\nu = \bar{\nu}$, 2 vs 4 states per ν, L viol.	Majorana
Masses	degenerate, normal/inverted	Seesaw
Mixings	$\theta_{13}, \theta_{23} \stackrel{?}{=} \pi/4$, U real vs complex, CP viol., Leptogenesis	???
Exotics	Non-osc., CPT-V, decays, μ-mom, etc.	None

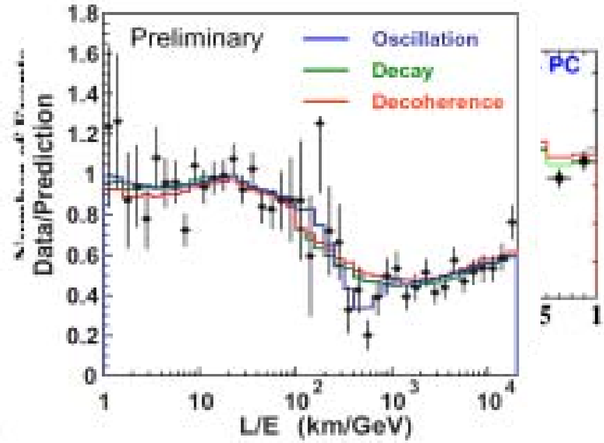
* From S.Parke, FNAL, Nov 2003: "At least one theoretical prejudice is wrong"

Current Situation



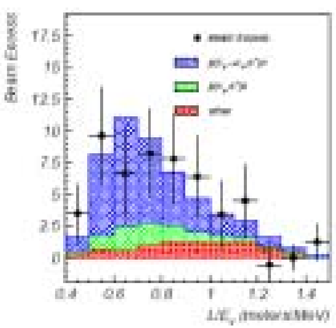
Solar Neutrino Oscillations

- Deficit of ν_e observed from Sun
  Cl (Homestake), H_2O ((Super-)K), Ga (GALLEX, SAGE)
- Confirmation at SNO and KamLAND (reactor $\overline{\nu}_e$)



Atmospheric Neutrino Oscillations

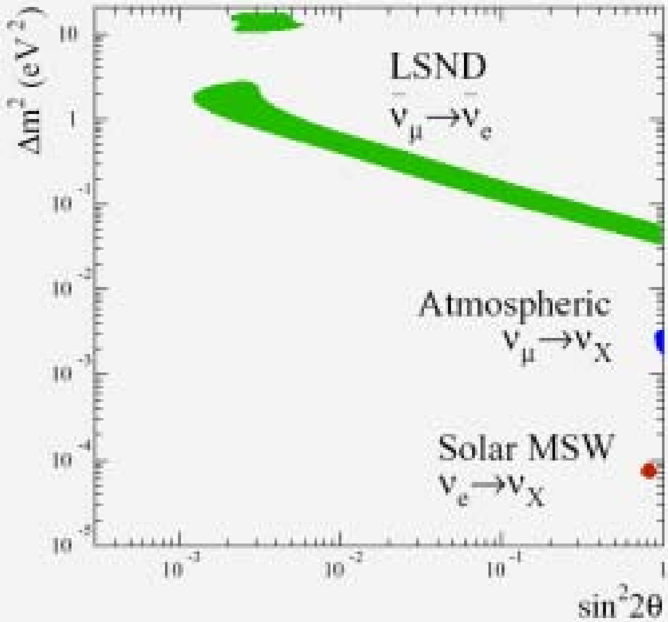
- Zenith angle-dependent deficit of ν_μ:
  Kamioka, Super-Kamiokande, Soudan, MACRO
- Confirmed by accelerator exp K2K; MINOS will be definitive



LSND Neutrino Oscillations

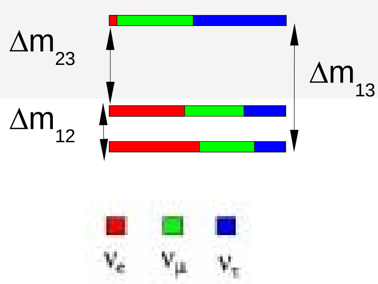
- Excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam produced from μ^+ decay-at-rest
- Unconfirmed by other experiments, but not excluded

Three Signal Regions



- $P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \sin^2[1.27\Delta m^2 (L/E)]$
- LSND:
  $\Delta m^2 \approx 0.1 - 10\,\mathrm{eV}^2$, small mixing
- Atmospheric:
  $\Delta m^2 \approx 2 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2 2\theta \approx 1.0$
- Solar:
  $\Delta m^2 \approx 7 \times 10^{-5}\,\mathrm{eV}^2$, $\sin^2 2\theta \approx 0.8$

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



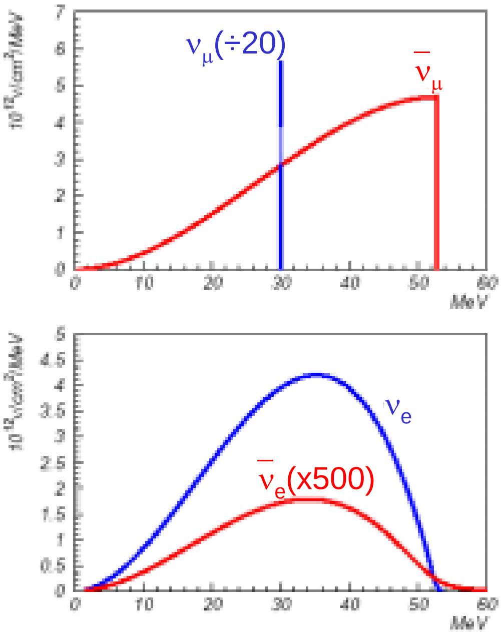
How Can There Be Three Distinct Δm^2 ?

- One of the experimental measurements is wrong
- One of the experimental measurements is not neutrino oscillations
  - Neutrino decay
  - Neutrino production from flavor violating decays
- Additional "sterile" neutrinos involved in oscillations
- CPT violation (or CP viol. and sterile ν's) allows different mixing for ν's and $\bar{\nu}$'s

The LSND Experiment

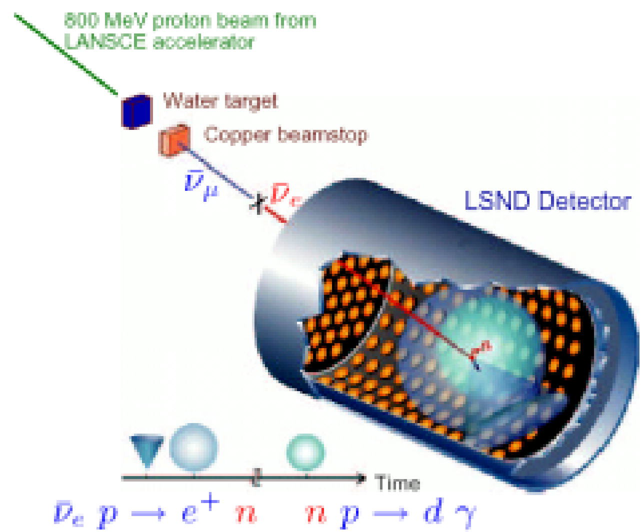
The neutrino source:

- $\bar{\nu}_\mu$ from: $\pi^+ \to \mu^+ \, \nu_\mu$
  $\hookrightarrow e^+ \, \nu_e \, \bar{\nu}_\mu$
- E_ν = 20-53 MeV, L_ν = 25-35 m
- Almost no $\bar{\nu}_e$ at source



The detector:

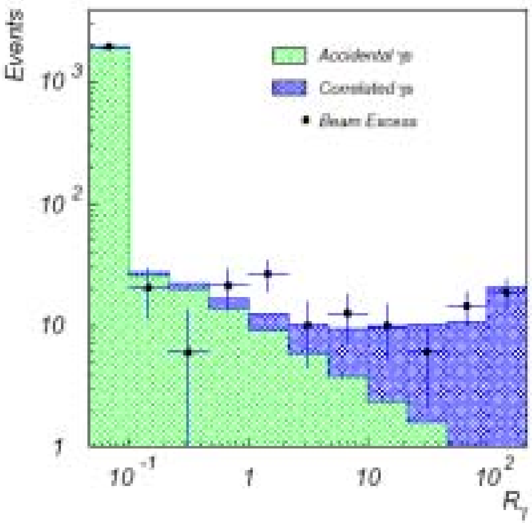
- Liquid scintillator detects both Cherenkov and scintillation light. For $\bar{\nu}_e p \to e^+ n$:
  - Č+scintillation light from e^+
  - Scintillation light from n capture

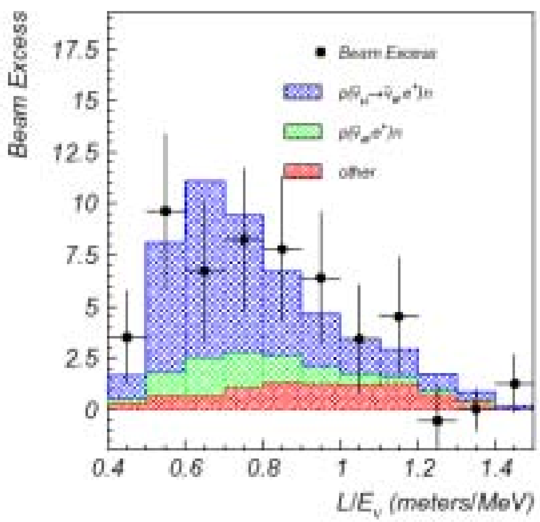


LSND Result

- Excess of candidate $\bar{\nu}_e$ events
- R_γ parameter defines likelihood that γ is correlated to e^+. By fitting R_γ:
- $87.9 \pm 22.4 \pm 6.0$ excess (3.8σ)
- $\langle P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \rangle = (0.264 \pm 0.067 \pm 0.045)\%$

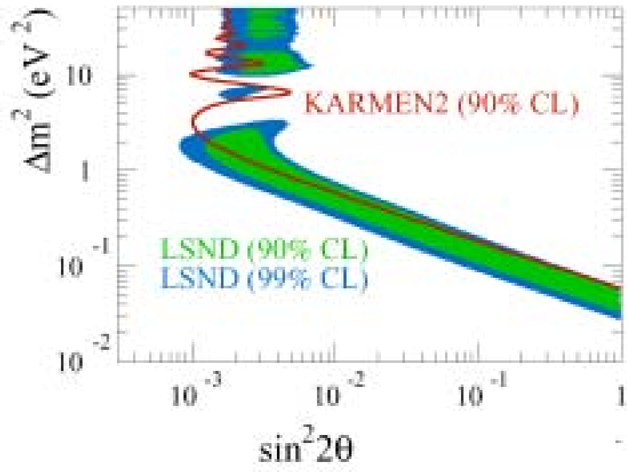
- Clean sample with $R_\gamma > 10$ cut
- L_ν / E_ν distribution of the excess agrees well with oscillation hypothesis
- Backgrounds in green,red
- Fit to oscillation hypothesis in blue

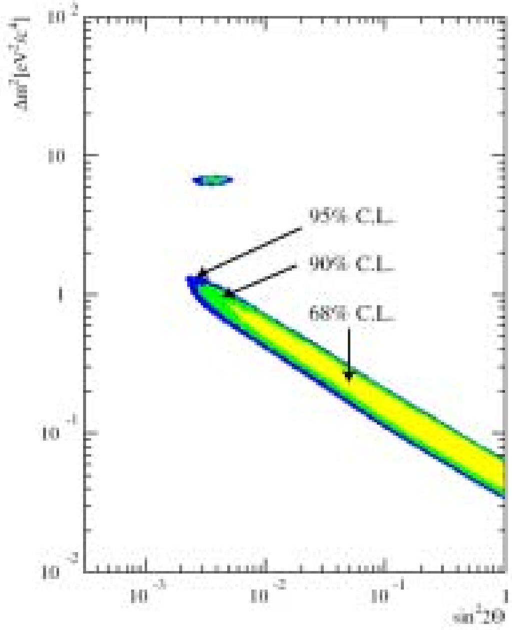




KARMEN Experiment

- Similar beam and detector to LSND
  - Closer distance and less target mass
    $\Rightarrow$ x10 less sensitive than LSND
- Joint analysis with LSND gives restricted region (Church et al. hep-ex/0203023)



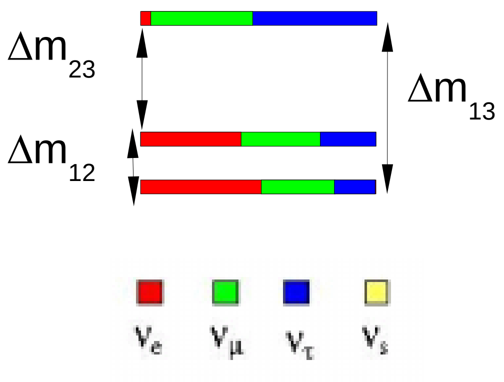


- KARMEN also limits $\mu^+ \to e^+ \bar{\nu}_e \nu$ branching ratio:
  BR < 0.9 x 10^{-3} (90% CL)
- LSND signal would require:
  1.9×10^{-3} < BR < 4.0 x 10^{-3} (90% CL)

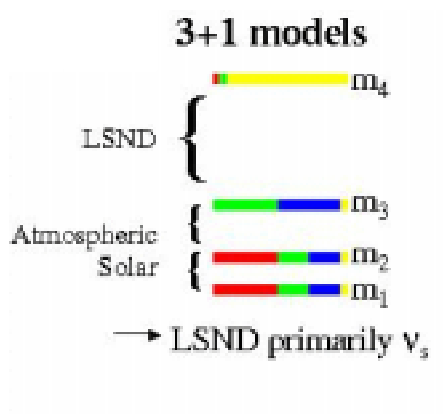
$\Rightarrow$ $\mu^+ \to e^+ \bar{\nu}_e \nu$ unlikely to explain LSND signal

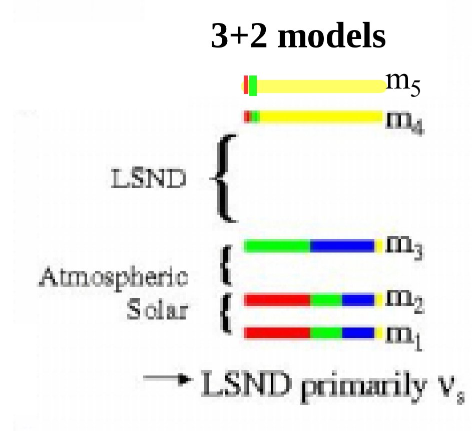
(also will be investigated by TWIST exp. at TRIUMF)

Adding Sterile Neutrinos to the Mix



- Reconcile three separate Δm^2 by adding additional sterile ν's





- Constraints from atmos. and solar data

$\Rightarrow$ **Sterile mainly associated with the LSND Δm^2**

Then these are the main mixing matrix elements

3+1

3+2

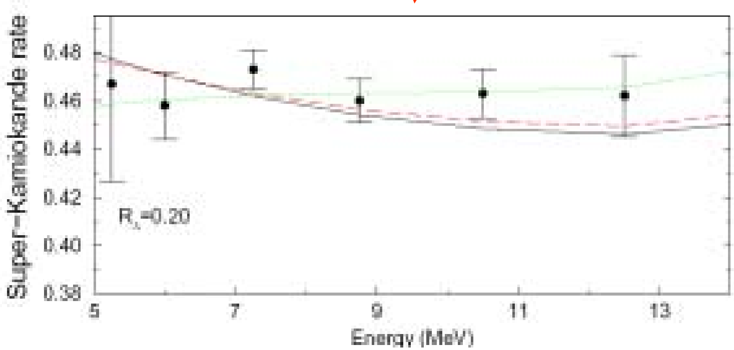
3+3 Models

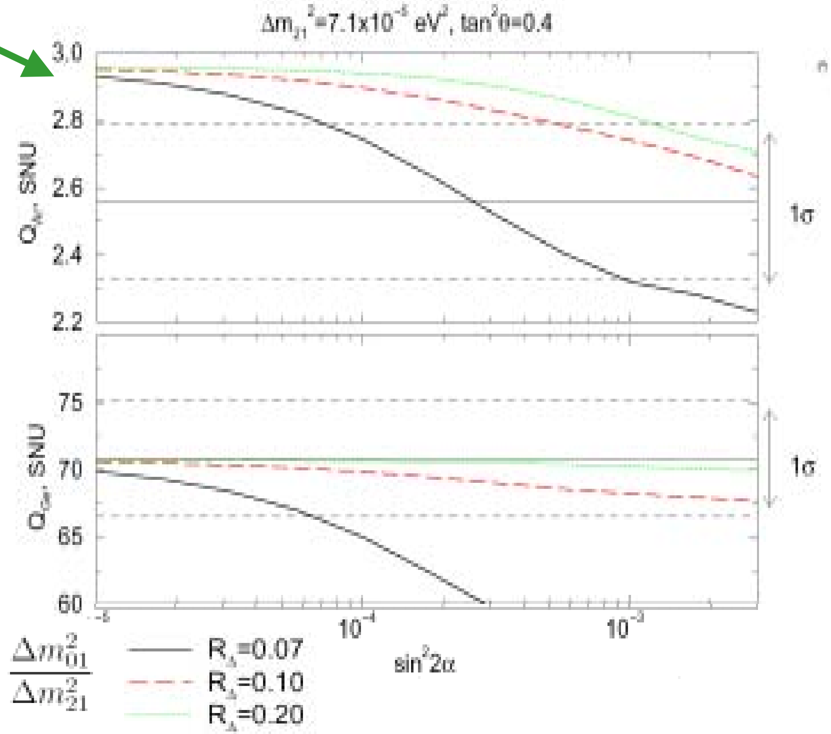
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1}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

Also Proposals for Sterile ν's in Solar Spectrum

- Sterile neutrino component in the solar oscillation phenomenology
  Smirnov et al. hep-ph/0307266
  - Proposed to explain:
    1. Observed Ar rate is 2σ lower than predictions (LMA MSW)
    2. The lack of an upturn at low energies for the SNO and Super-K solar measurements

- Explain with a light sterile
  - $\Delta m^2 \sim (0.2 \text{ to } 2)\times10^{-5}$ eV^2
    $\sin^2 2\alpha \sim (10^{-5} \text{ to } 10^{-3})$





$$R_\Delta \equiv \frac{\Delta m^2_{01}}{\Delta m^2_{21}}$$

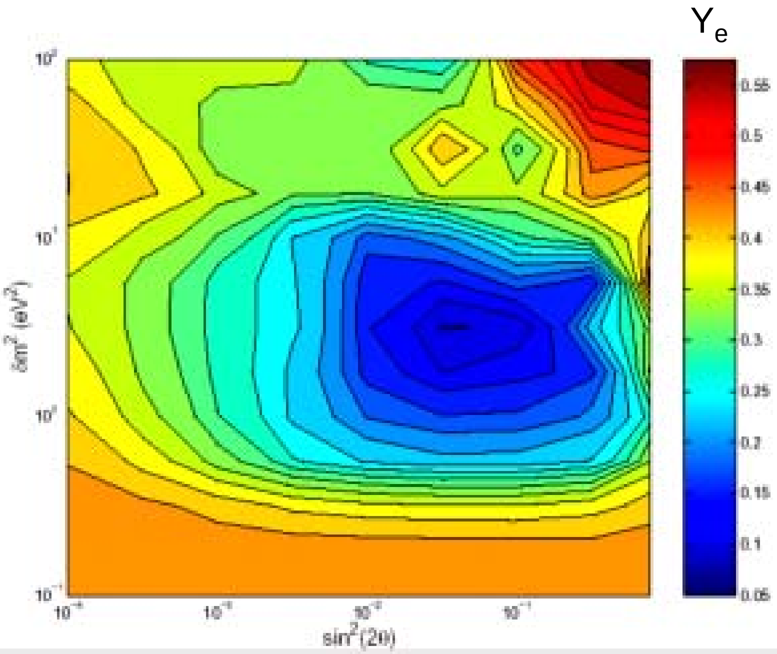
Sterile ν's and the r-process in Supernovae

- Heavy element (A>100) production in supernova (i.e. U) through rapid-neutron-capture (r-process)

  (i.e. Patel & Fuller hep-ph/0003034)

  - Observed abundance of heavy elements
    - Much larger than standard model prediction since available neutron density is too small
  - Required neutron density can be explained if oscillations to sterile neutrinos
    - Then matter effects can suppress the ν_e with respect to ν_e which can then produce a substantial neutron excess

$$\bar{\nu}_e + p \rightleftharpoons e^+ + n,\ \nu_e + n \rightleftharpoons e^- + p$$



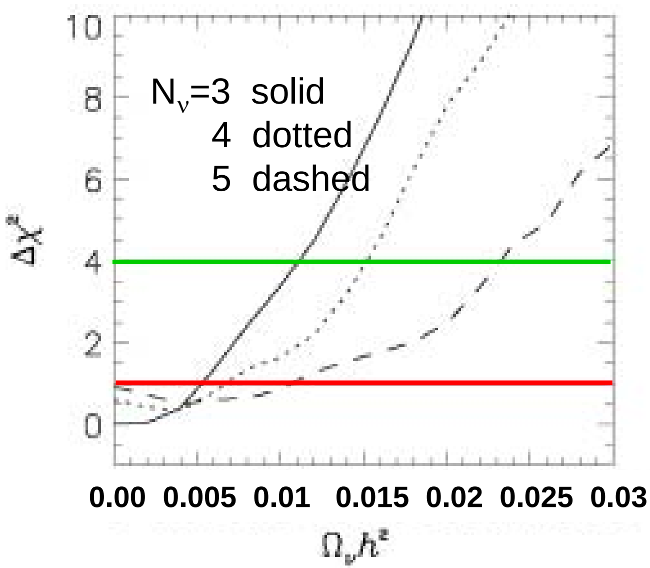
$Y_e = 1/(1+(n/p))$

(Y_e small has neutron excess)

Sterile Neutrinos: Astrophysics Constraints

- Constraints on the number of neutrinos from BBN and CMB
  - Standard model gives N_ν=2.6±0.4 constraint
  - If ^{4}He systematics larger, then N_ν=4.0±2.5
  - If neutrino lepton asymmetry or non-equilibrium, then the BBN limit can be evaded.
    K. Abazajian hep-ph/0307266
    G. Steigman hep-ph/0309347
  - "One result of this is that the LSND result is not yet ruled out by cosmological observations."
    Hannestad astro-ph/0303076

- Bounds on the neutrino masses also depend on the number of neutrinos (active and sterile)
  - Allowed Σm_i is 1.4 (2.5) eV 4 (5) neutrinos

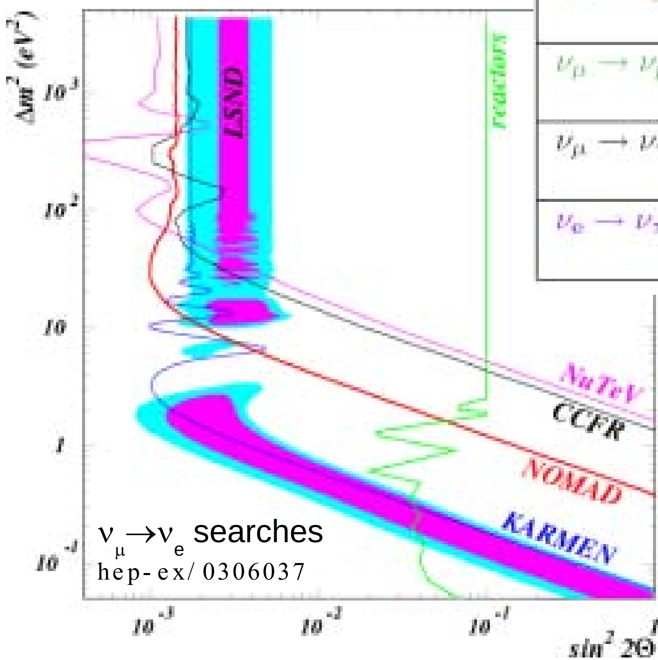


Hannestad astro-ph/0303076

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

- Global Fits to high Δm^2 oscillations for the SBL experiments including LSND positive signal.

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 (Not Included yet)	$4 \cdot 10^{-1}$	$< 1.4 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
$\nu_e \to \nu_{e'}$	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	$7 \cdot 10^{0}$	$< 5.1 \cdot 10^{-2}$	$< 4 \cdot 10^{-2}$



- **Only LSND has a positive signal**
  - CDHS near detector 2σ low also contributes
- **Is LSND consistent with the upper limits on active to sterile mixing derived from the null short-baseline experiments?**
  (M.Sorel, J.Conrad, M.S., hep-ph/0305255)

3 + 1 Model Fits to SBL Data

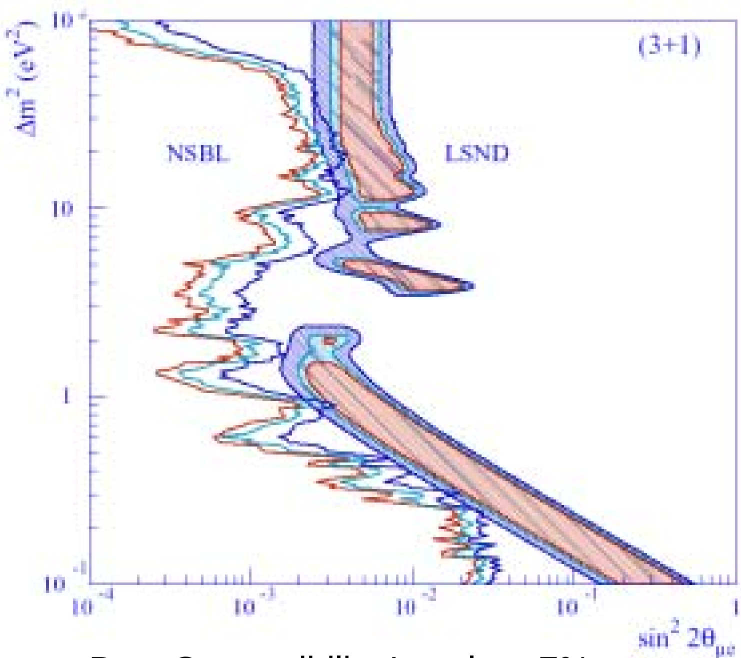
LSND allowed regions

compared to

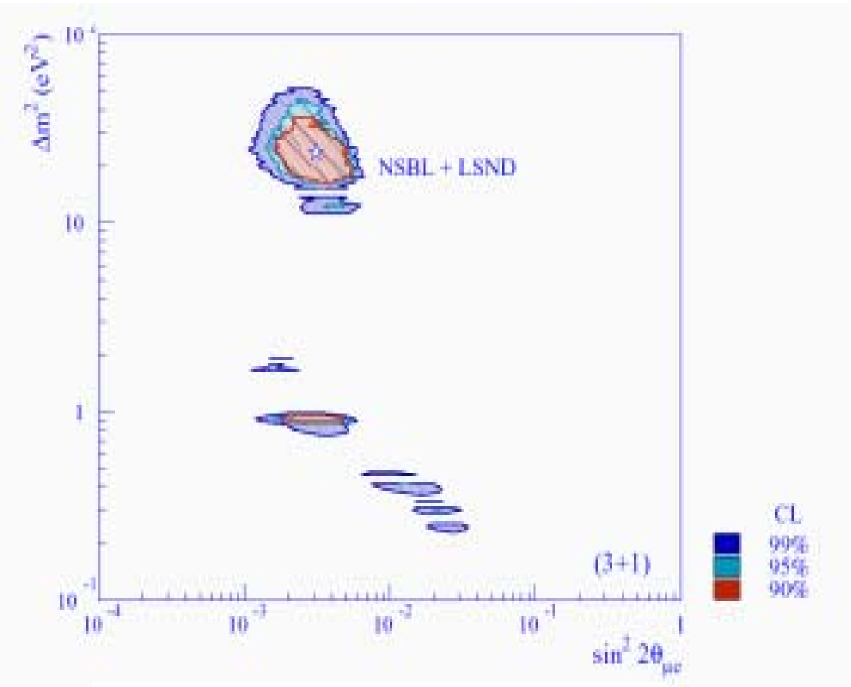
Null short-baseline exclusions

- Doing a combined fit with null SBL and the positive LSND results
  - Yields compatible regions at the 90% CL

Best-fit: $\Delta m^2 = 23.8\ eV^2$, $U_{e4} = 0.13$, $U_{\mu 4} = 0.22$



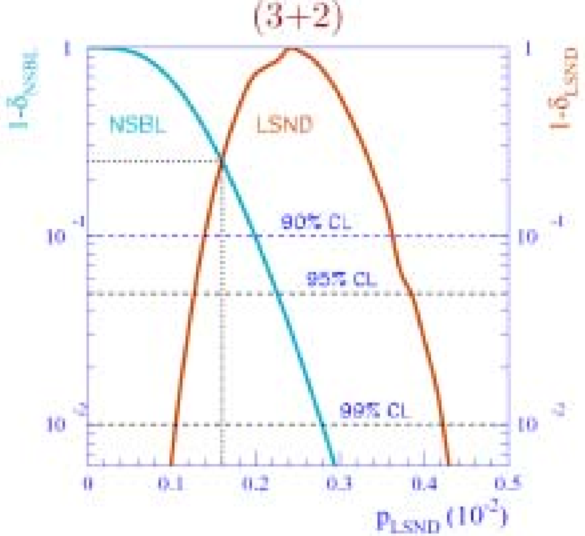
Best Compatibility Level = ~7%

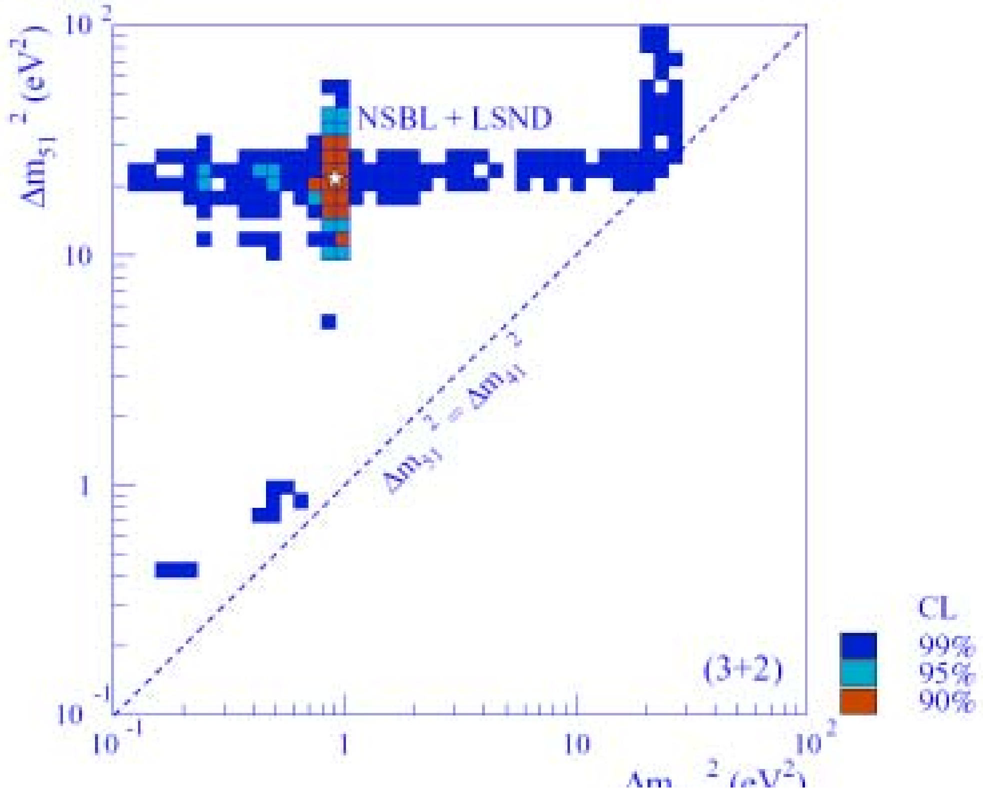


(M.Sorel, J.Conrad, M.S., hep-ph/0305255)

Combined LSND and NSBL Fits to 3+2 Models

- Confidence Levels:
  - 3+1 ⇒ 7% compatibility
  - 3+2 ⇒ 45% compatibility





Best-fit:

$$\Delta m_{41}^2 = 0.91\ eV^2,\ U_{e4} = 0.12,\ U_{\mu 4} = 0.17,\ \Delta m_{51}^2 = 21.5\ eV^2,\ U_{e5} = 0.07,\ U_{\mu 5} = 0.22$$

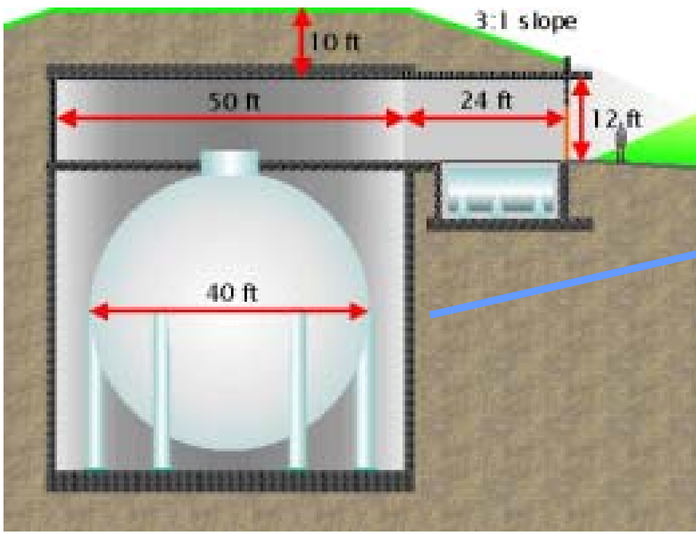
(M.Sorel, J.Conrad, M.S., hep-ph/0305255)

Next Step is MiniBooNE

- MiniBooNE will be one of the first experiments to check these sterile neutrino models
  - Investigate LSND Anomaly
    - Is it oscillations?
    - Measure the oscillation parameters
  - Investigate oscillations to sterile neutrino using ν_μ disappearance

MiniBooNE Experiment

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 12 institutions.

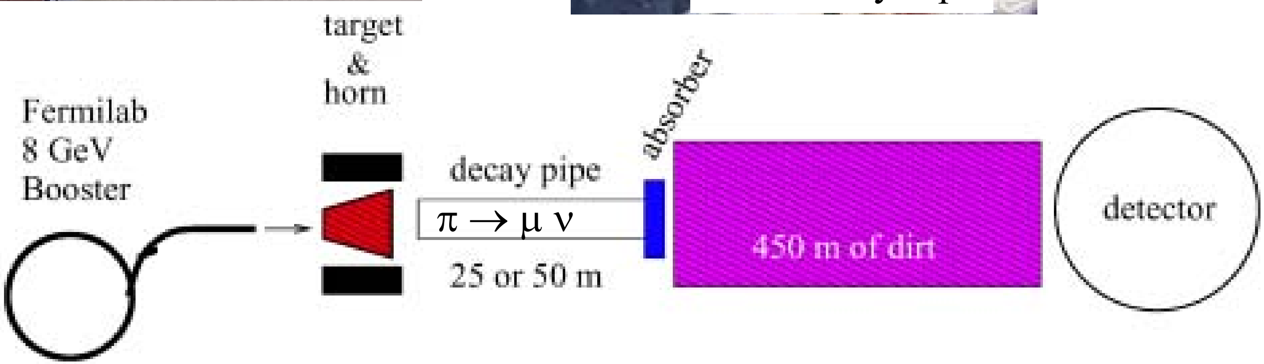
Y. Liu, I. Stancu *Alabama*
S. Koutsoliotas *Bucknell*
E. Hawker, R.A. Johnson, J.L. Raaf *Cincinnati*
T. Hart, R.H. Nelson, E.D. Zimmerman *Colorado*
A. Aguilar-Arevalo, L.Bugel, L. Coney, J.M. Conrad, J. Formaggio, J. Link, J. Monroe, K. McConnel, D. Schmitz, M.H. Shaevitz, M. Sorel, L. Wang, G.P. Zeller *Columbia*
D. Smith *Embry Riddle*
L.Bartoszek, C. Bhat, S J. Brice, B.C. Brown, D.A. Finley, B.T. Fleming, 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, 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*

MiniBooNE Neutrino Beam

8 GeV Proton Beam Transport

50m Decay Pipe

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

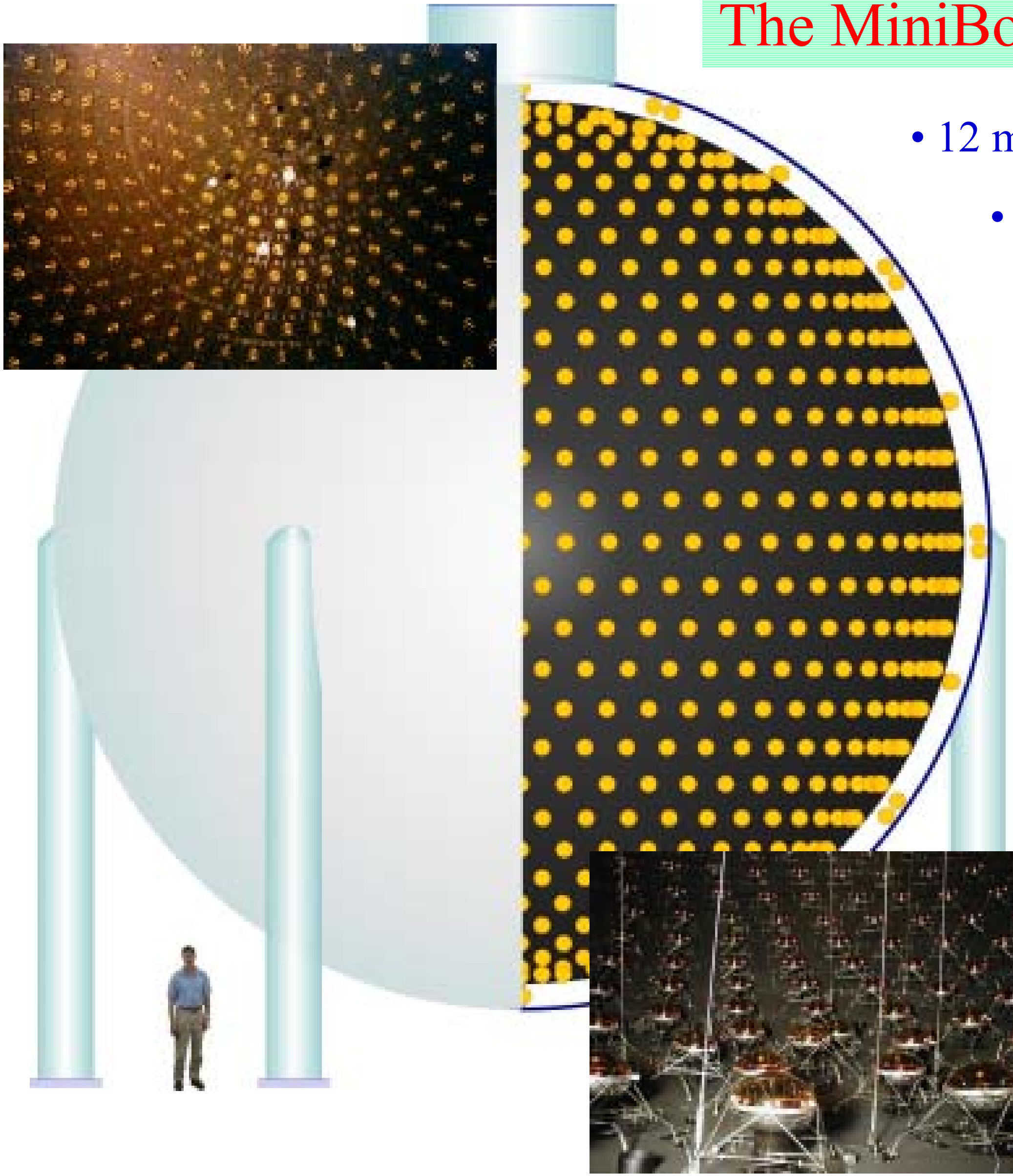


One magnetic Horn, with Be target

Magnetic Horn

Detector

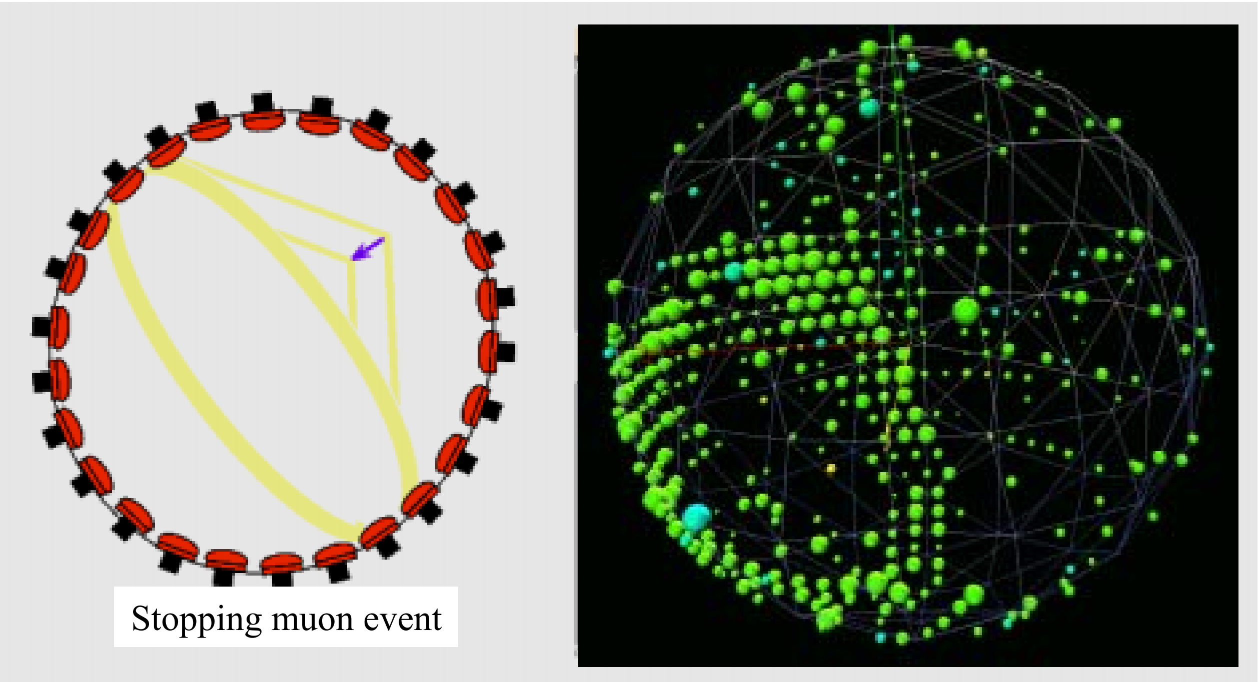
The MiniBooNE Detector

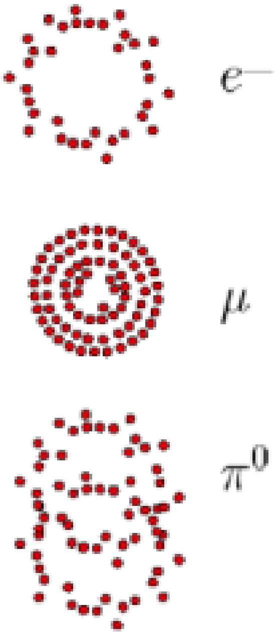


- 12 meter diameter sphere
- Filled with 950,000 liters (900 tons) of very pure mineral oil
- Light tight inner region with 1280 photomultiplier tubes
- Outer veto region with 241 PMTs.
- Oscillation Search Method:
  Look for ν_e events in a pure ν_μ beam

Particle Identification

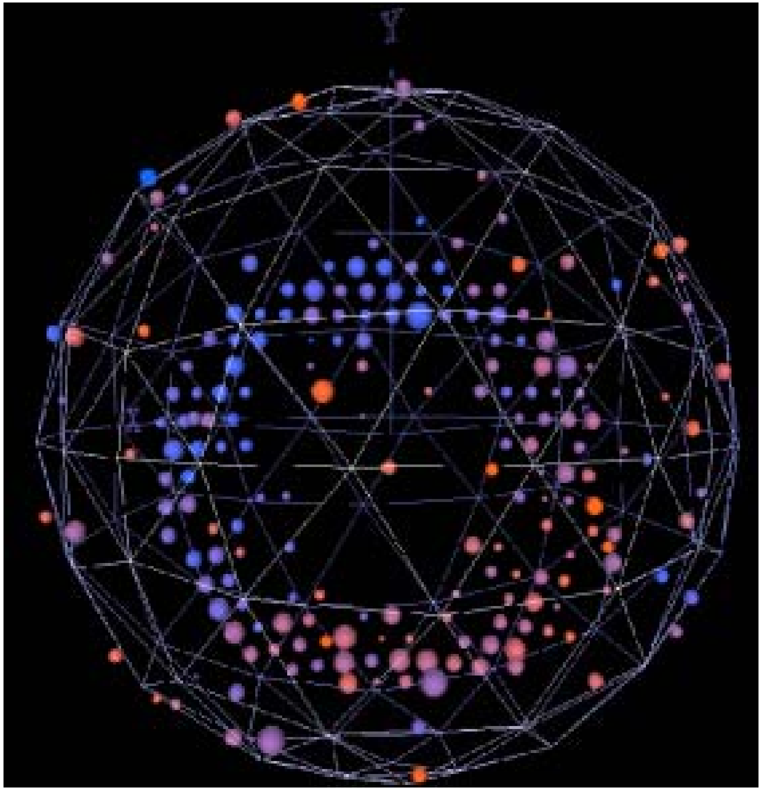
- Separation of ν_μ from ν_e events
  - Exiting ν_μ events fire the veto
  - Stopping ν_μ events have a Michel electron after a few μsec
  - Also, scintillation light with longer time constant $\Rightarrow$ enhanced for slow pions and protons
  - Čerenkov rings from outgoing particles
    - Shows up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


Stopping muon event

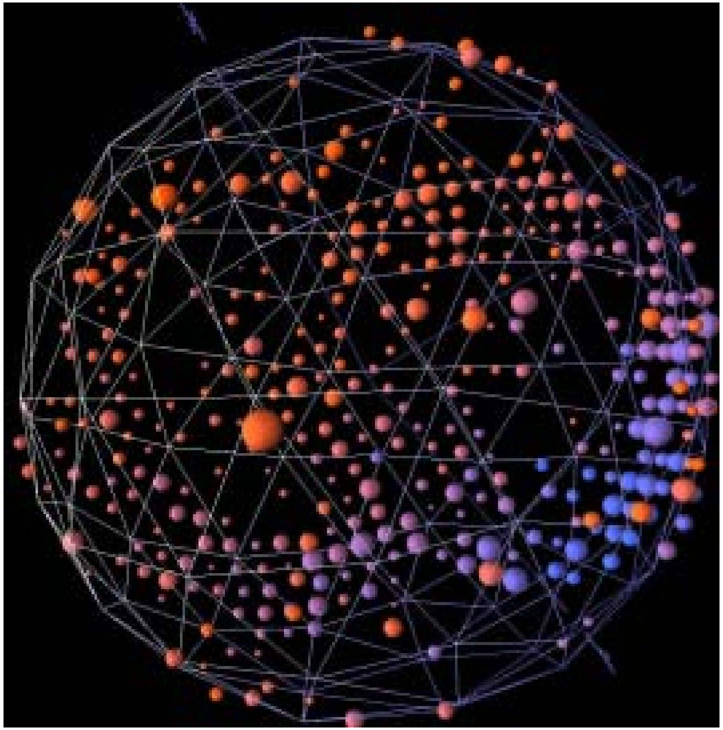


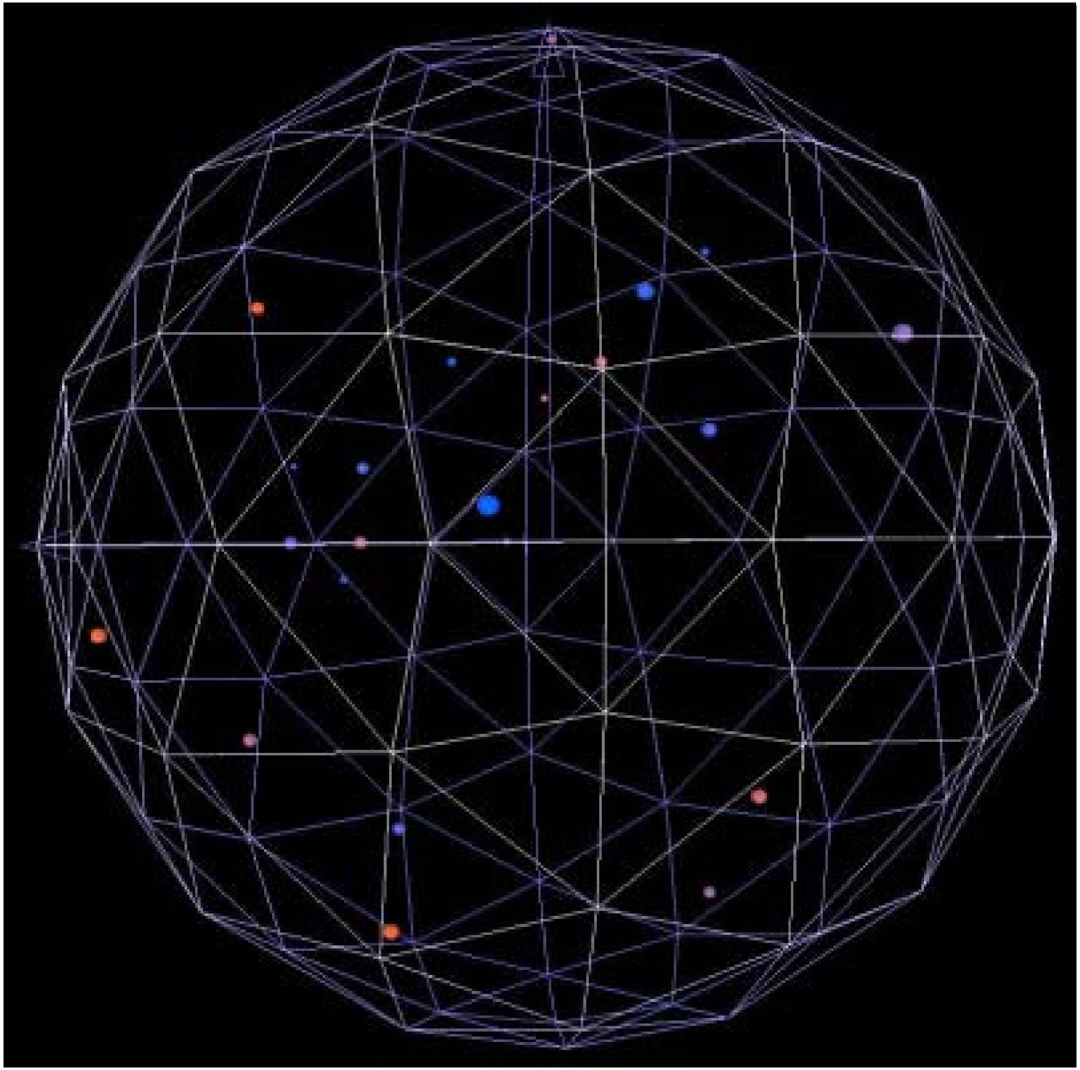
Examples of Real Data Events

Charged Current
$\nu_\mu + n \rightarrow \mu^- + p$
with outgoing muon (1 ring)



Neutral Current
$\nu_\mu + n \rightarrow \nu_\mu + \pi^0 + p$
with outgoing $\pi^0 \rightarrow \gamma\gamma$ **(2 rings)**





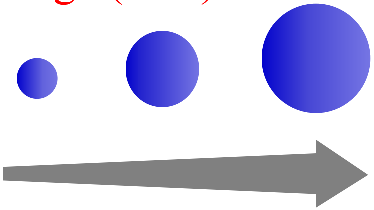
Muon Identification Signature:

$\mu \rightarrow e\ \nu_\mu\ \nu_e$
after ~2μsec

Animation

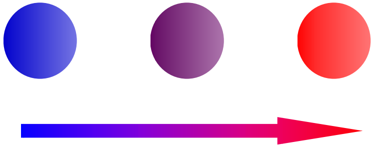
Each frame is 25 ns with 10 ns steps.

Charge (Size)



Low High

Time (Color)



Early Late

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; beam at [4.6, 6.2] μsec

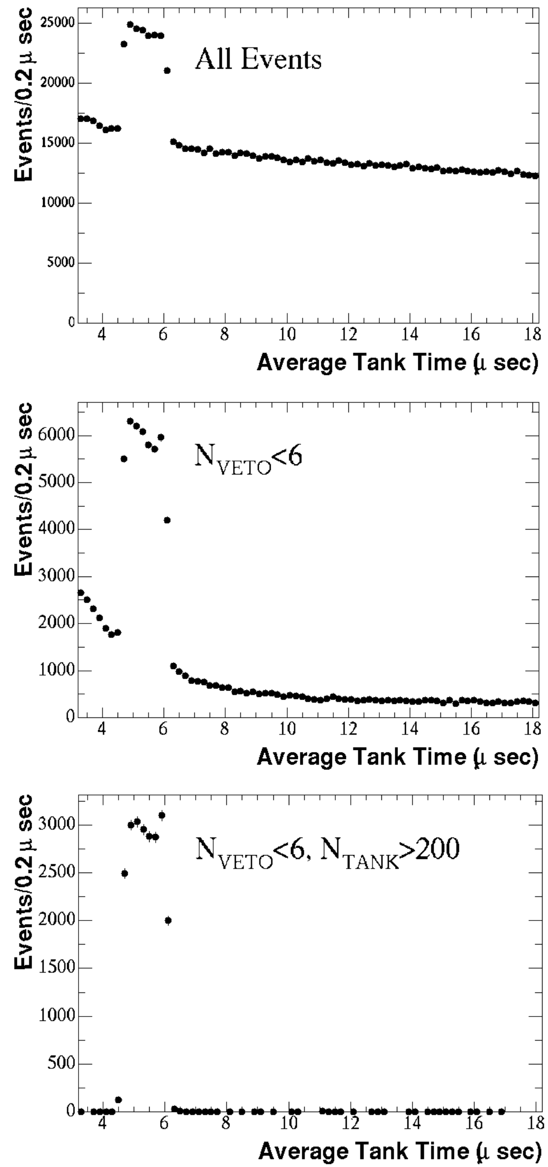
no high level analysis needed to see neutrino events

backgrounds: cosmic muons
decay electrons

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

Current Collected data:

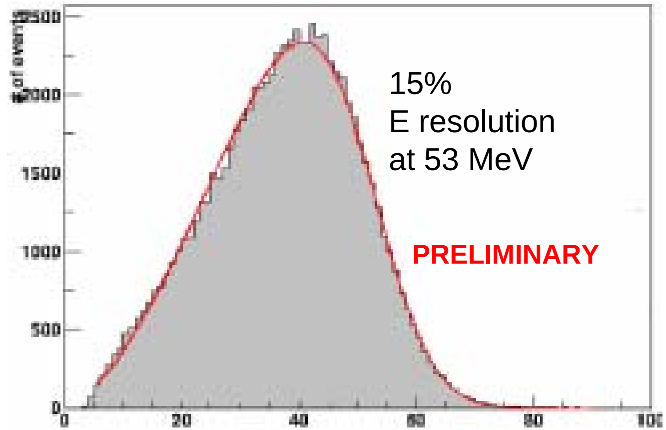
220k neutrino candidates
for 2 x 10^{20} protons on target

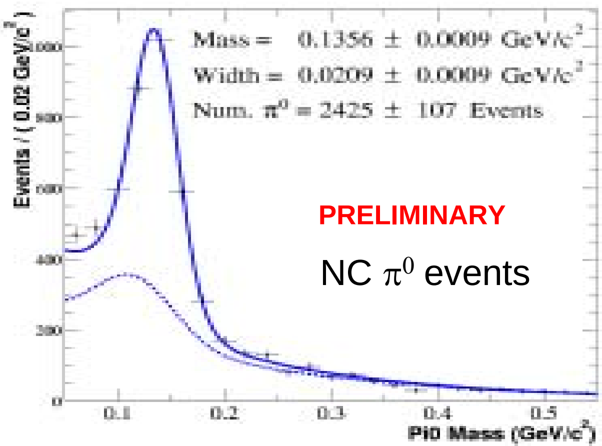


Energy Calibration Checks

- Spectrum of Michel electrons from stopping muons

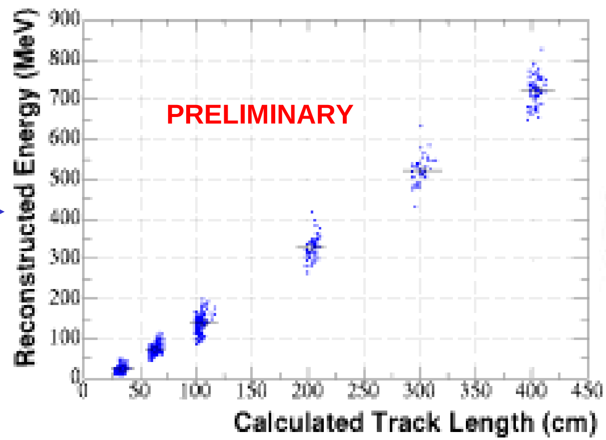
Michel electron energy (MeV)

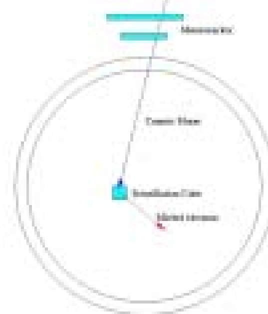




Mass distribution for isolated π^0 events

- Energy vs. Range for events stopping in scintillator cubes



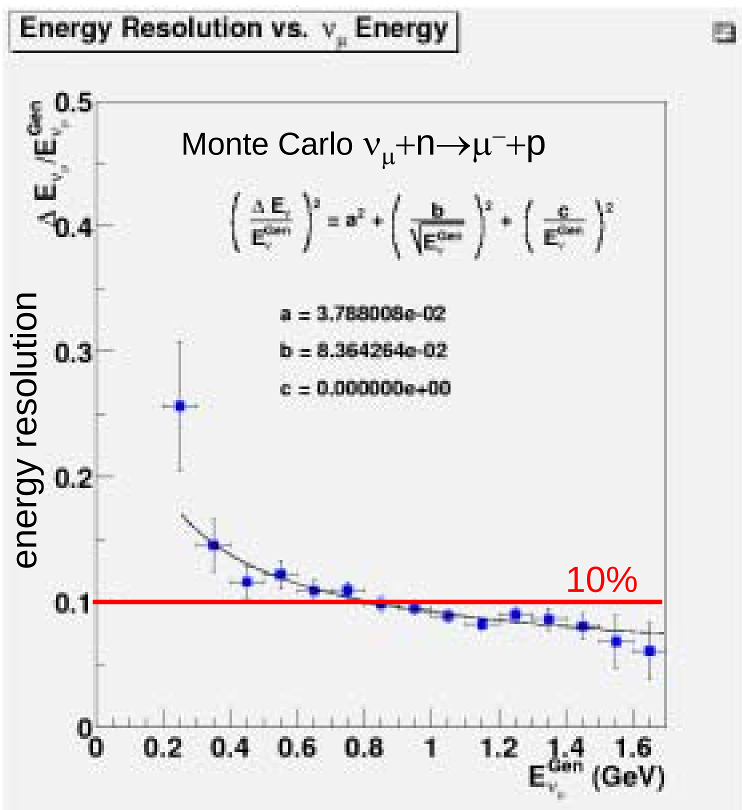


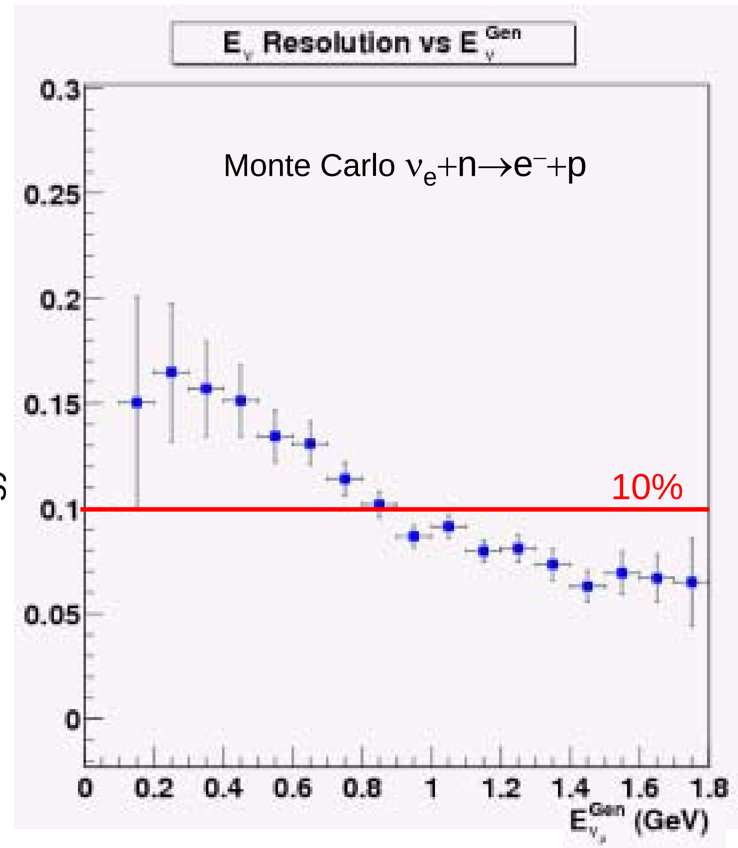
Neutrino Energy Reconstruction

For quasi-elastic events (ν_μ+n→μ^-+p and ν_e+n→e^-+p)

⇒ **Can use kinematics to find E_ν from $E_{\mu(e)}$ and $\theta_{\mu(e)}$**

$$E_\nu^{QE} = \frac{1}{2}\frac{2ME_l - m_l^2}{M - E_l + P_l \cos\theta_e}$$





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

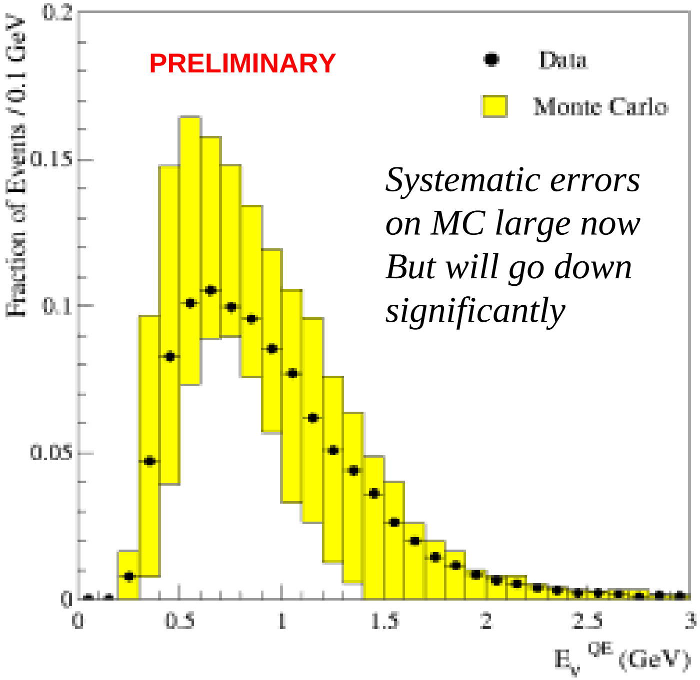
  you cannot see all of the info on all of the events

- Other analysis topics give early interesting physics results and serve as a cross check and calibration before "opening the ν_e box"
  - ν_μ disappearance oscillation search
  - Cross section measurements for low-energy ν processes
  - 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)

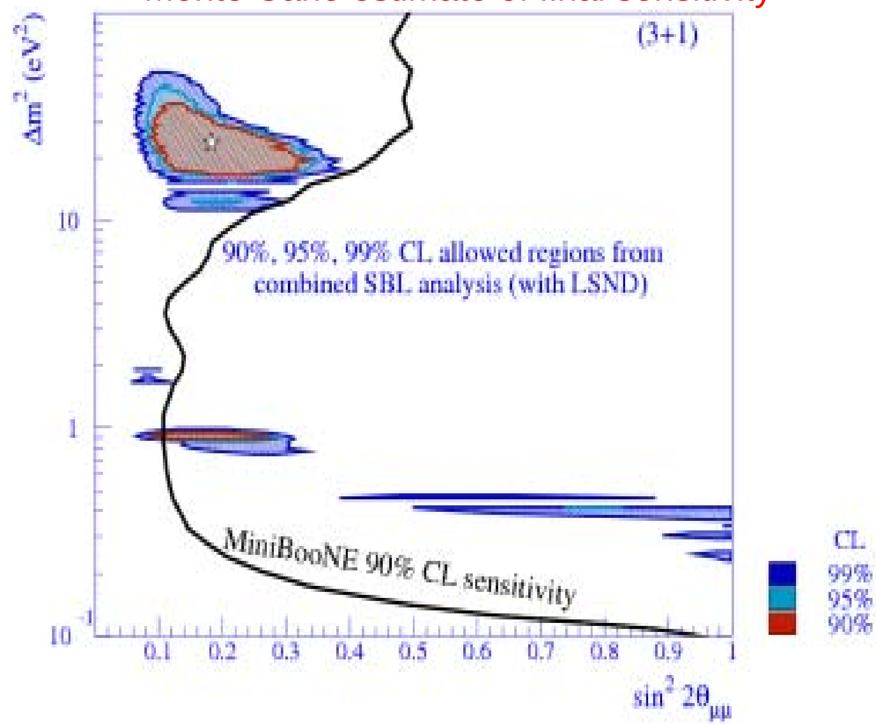
On the Road to a ν_μ Disappearance Result

- 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

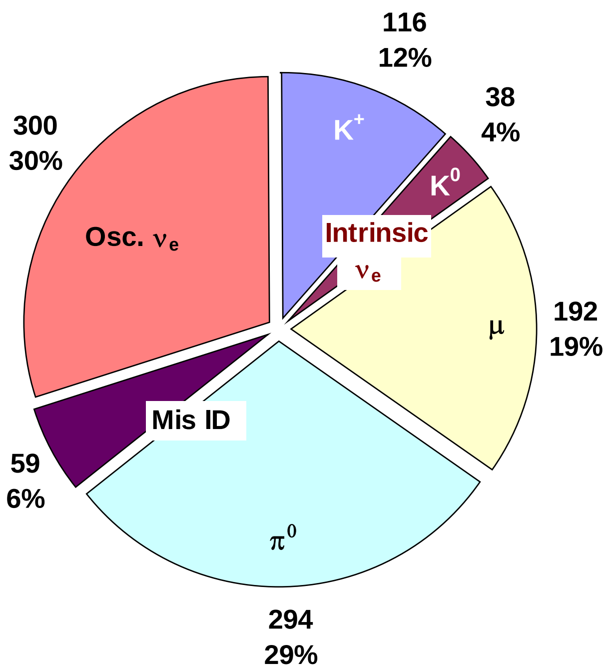


Monte Carlo estimate of final sensitivity

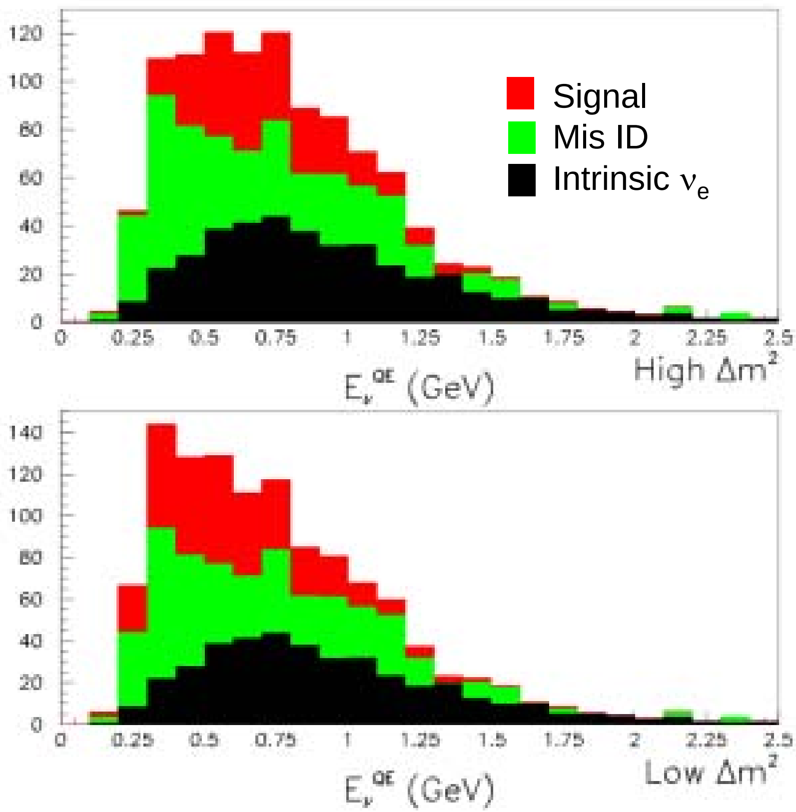


Estimates for the $\nu_\mu \to \nu_e$ Appearance Search

- 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 $\nu_e/\nu_\mu = 6\text{x}10^{-3}$

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

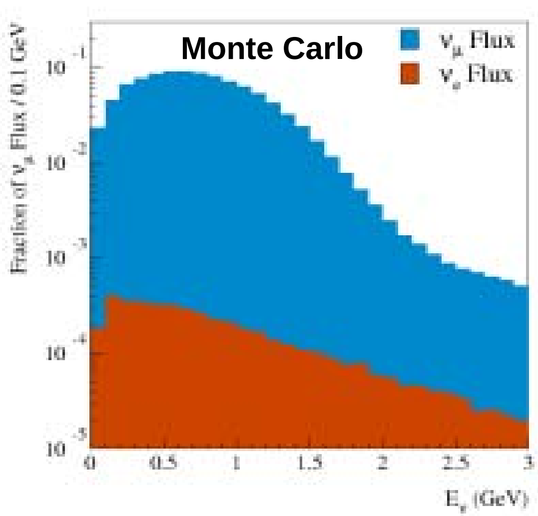
ν_e from μ–decay
- Directly tied to the observed half-million ν_μ interactions

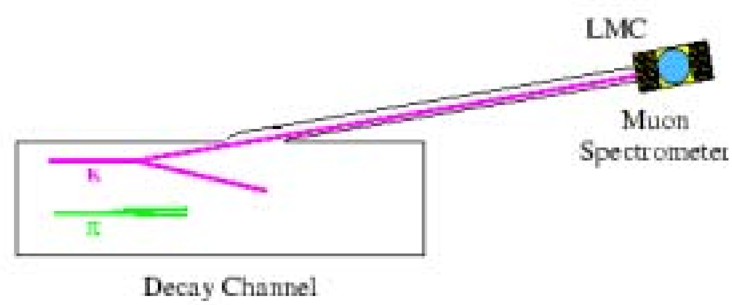
$K^+ \rightarrow \pi^0 e^+ \nu_e$

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

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

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





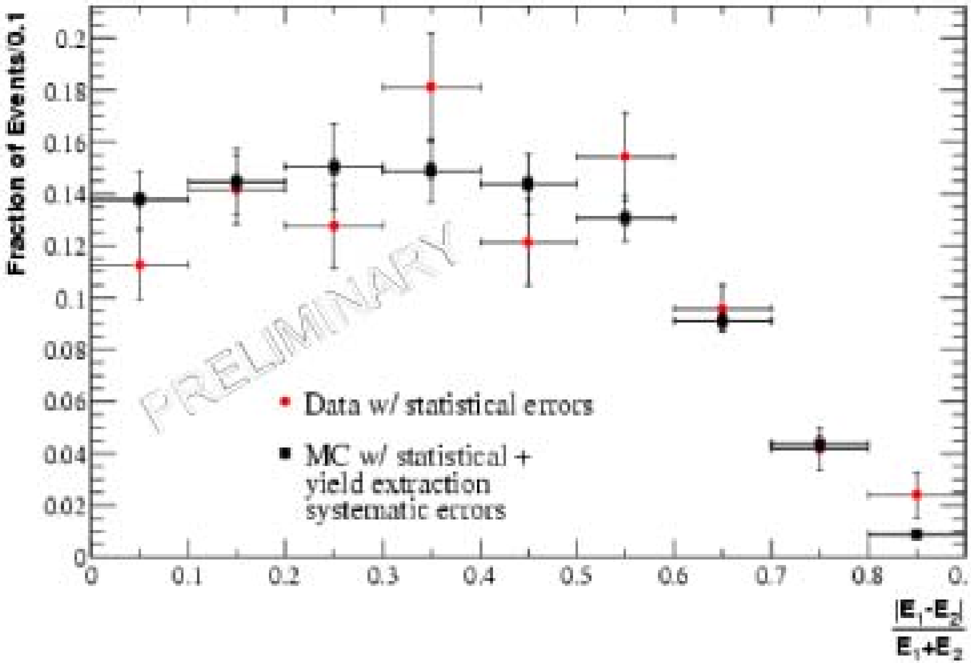
Mis-identification Backgrounds

- Background mainly from NC 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 is too low energy

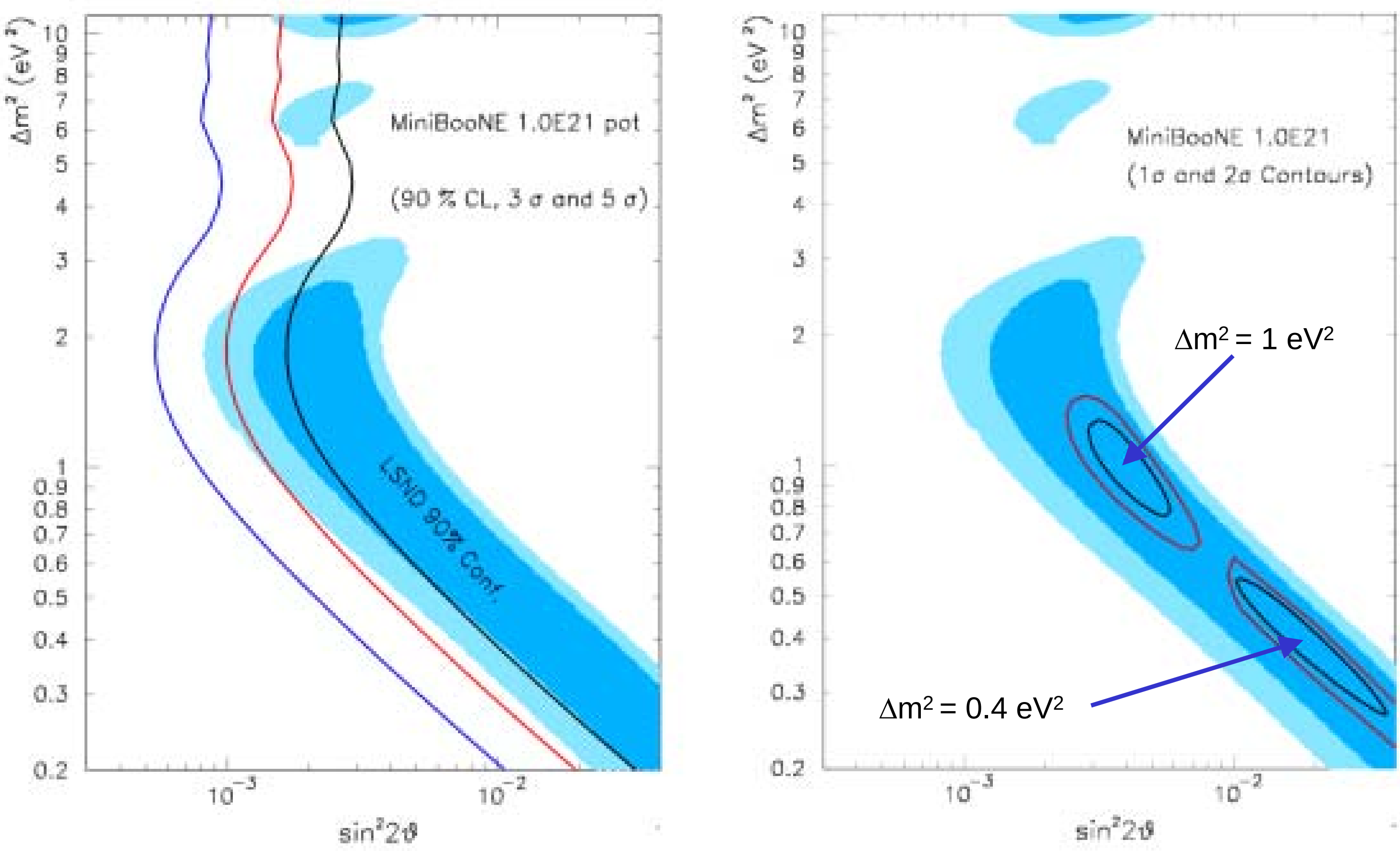
- Over 99.5% of these events are identified and the π^0 kinematics are measured

  $\Rightarrow$ 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

- At the current time have collected $2x10^{20}$ p.o.t.
  - Data collection rate is steadily improving as the Booster accelerator losses are reduced
  - Many improvement being implemented into the Booster and Linac (these not only help MiniBooNE but also the Tevatron and NuMI in the future)

- Plan is to “open the box” when analysis has been substantiated and experiment has collected $1x10^{21}$ p.o.t.

  $\Rightarrow$ **Current estimate is sometime in 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 $\nu_\mu \rightarrow \nu_\tau$

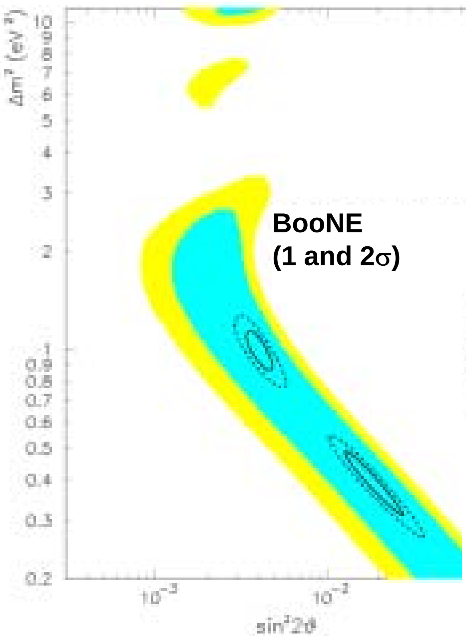
- Oscillations to sterile neutrinos could effect
  long-baseline measurements and strategy

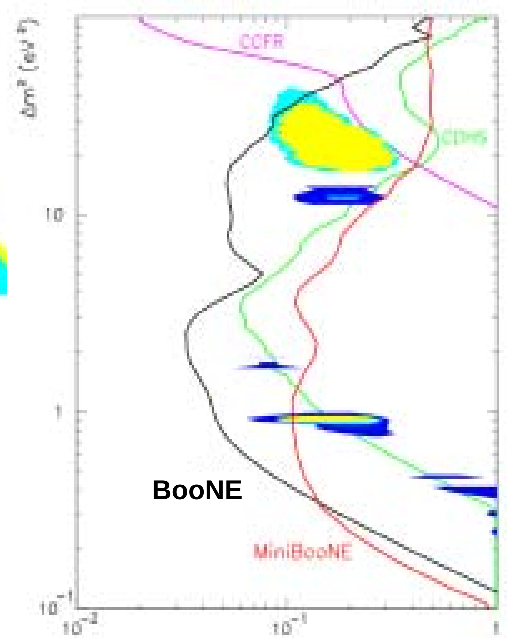
- Compare ν_μ and $\bar{\nu}_\mu$ oscillations $\Rightarrow$ CP and CPT violations

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

- Far detector at 2 km for low Δm^2 or 0.25 km for high Δm^2 $\Leftarrow$ **BooNE**
- Near detector at ~100m (Finesse Proposal) for disappearance and precision background determination

- 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

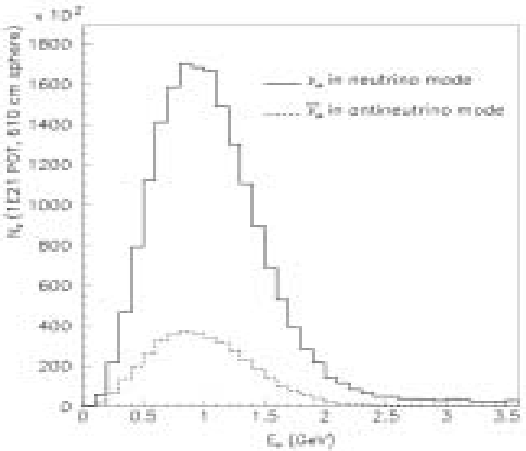


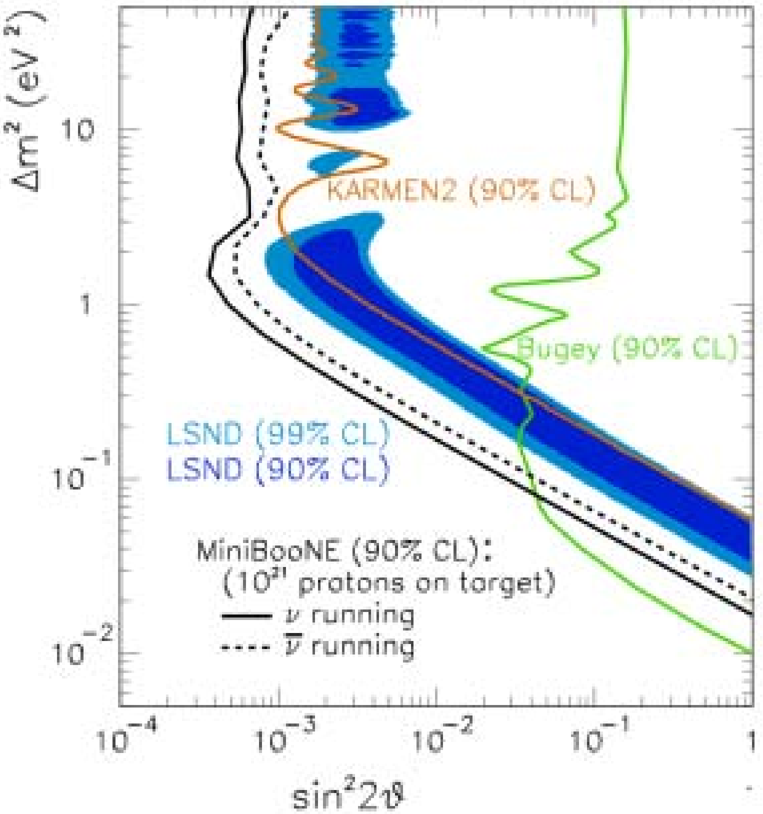


(These studies could be done at FNAL, BNL, JPARC)

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

- 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

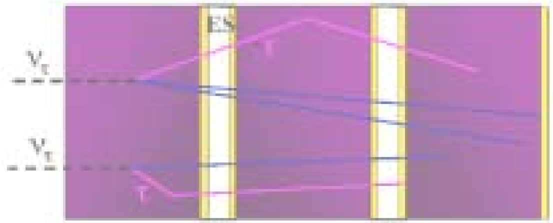


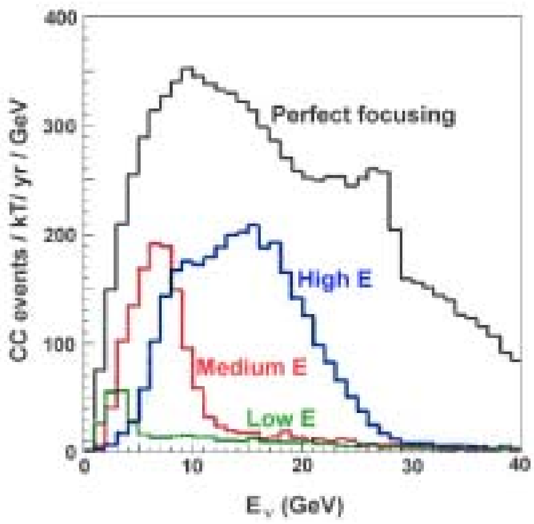


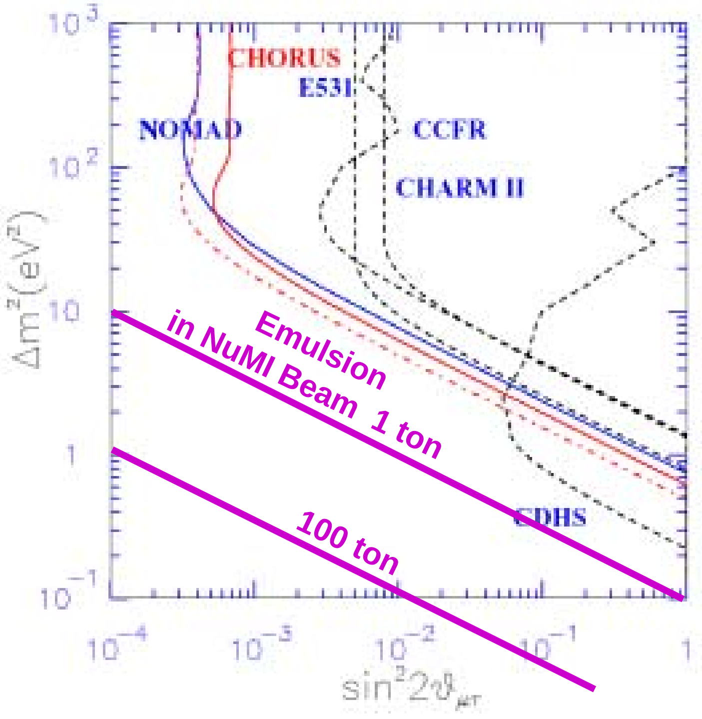
Another Next Step:
Do $\nu_\mu \rightarrow \nu_\tau$ Appearance Experiment at High Δm^2

- 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