MiniBooNE and
MiniBooNE Followup oscillation measurements

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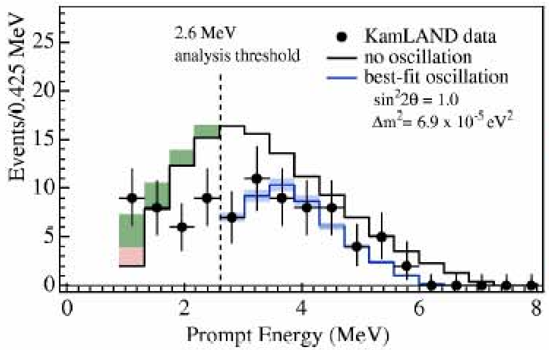
Superbeam working group meeting, APS neutrino study
5 March 2004 BNL

MiniBooNE (Phase 1) status, prospects

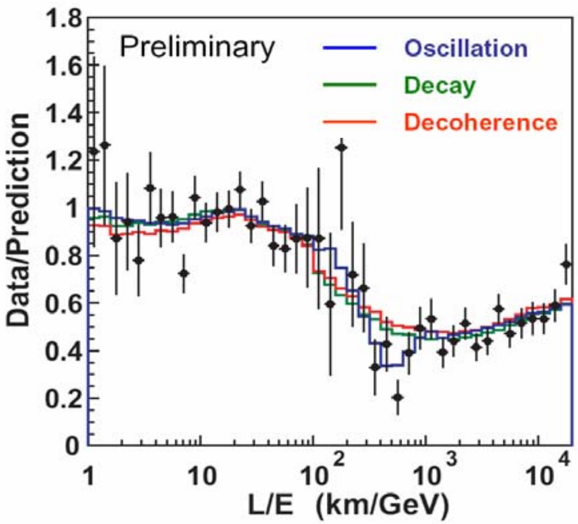
Follow up experiments after MiniBooNE
What if MiniBooNE confirms LSND → impact/opportunities?

Current situation



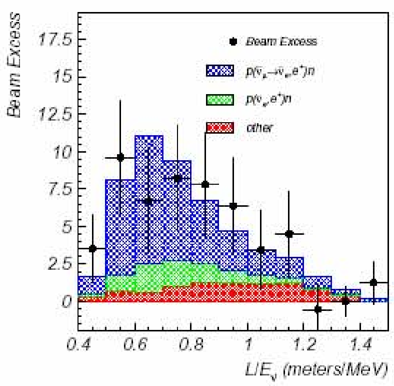
Solar Neutrino Oscillations

- 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

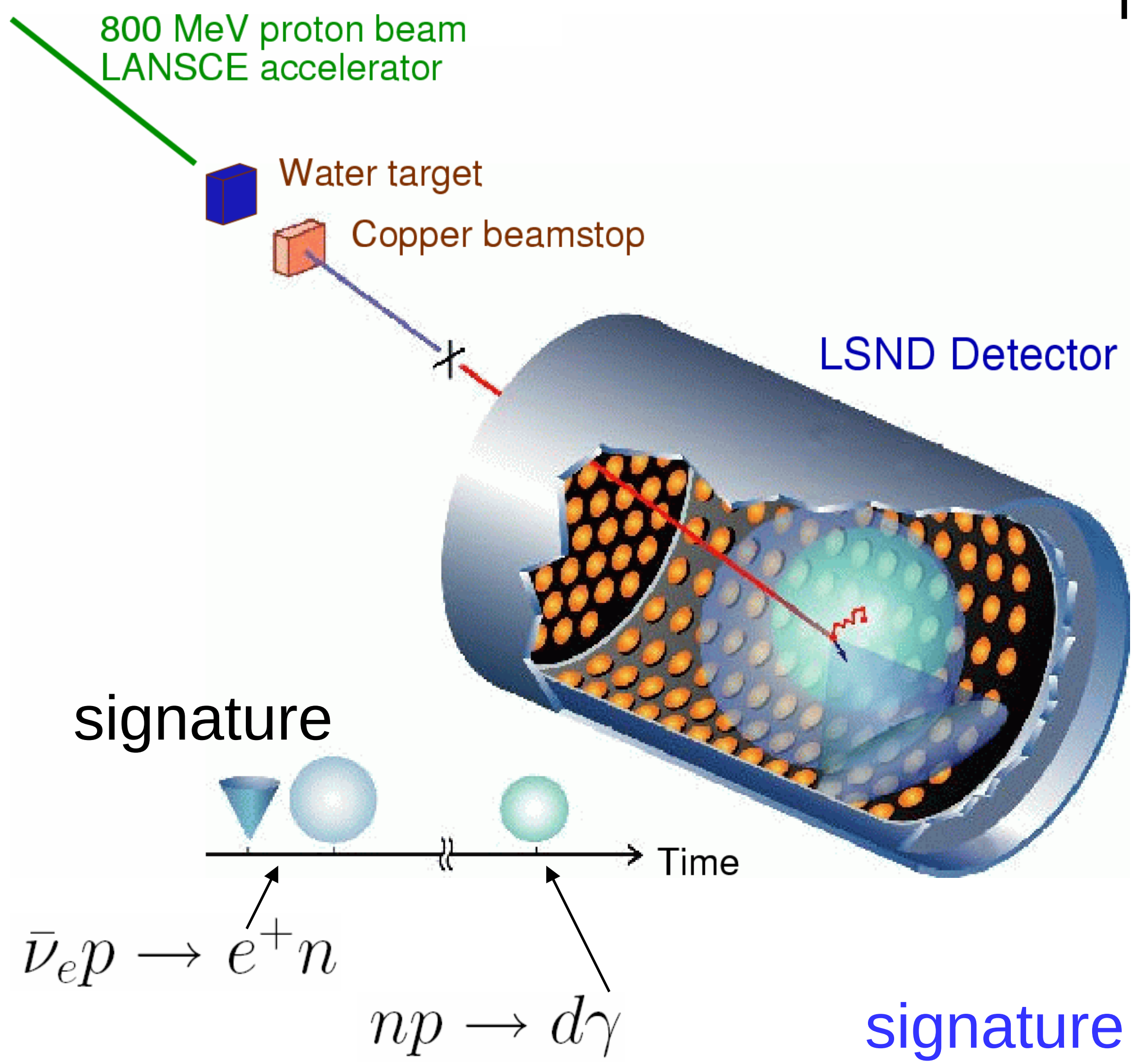


LSND Neutrino Oscillations

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

LSND (1993-1998)

$\bar{\nu}_\mu$ from
muon decay at rest



167 tons of mineral oil
doped with scintillator

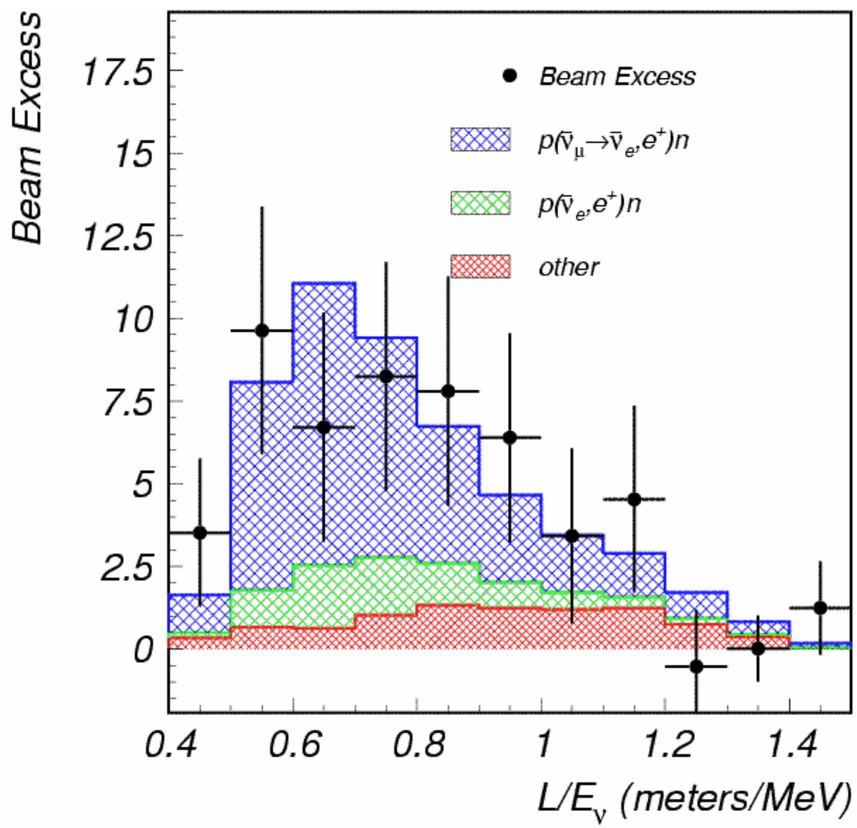
Baseline 30 m

Energy range
20-53 MeV

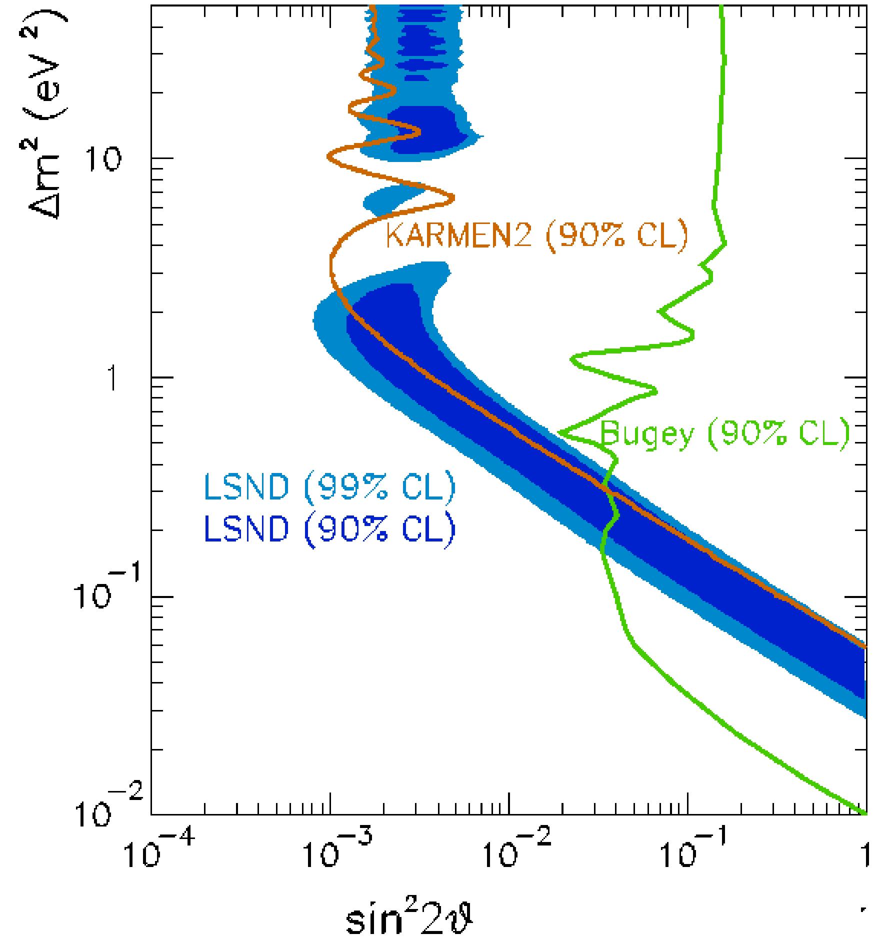
L/E ~ 1 m/MeV

signature is *e* and γ sequence

LSND: Evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$



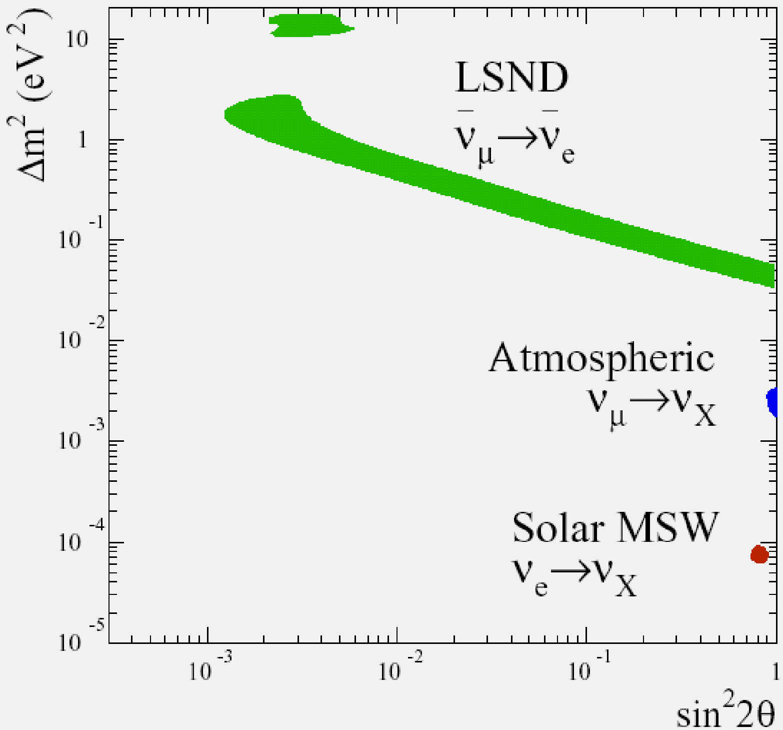
87.9±22.4±6.0 events



$\Delta m^2 \sim 0.2$ - 2 eV^2

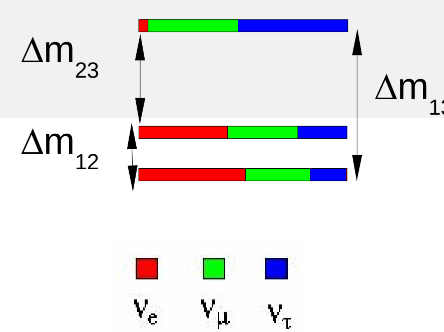
(Bugey is $\overline{\nu}_e$ disappearance)

Three signal regions

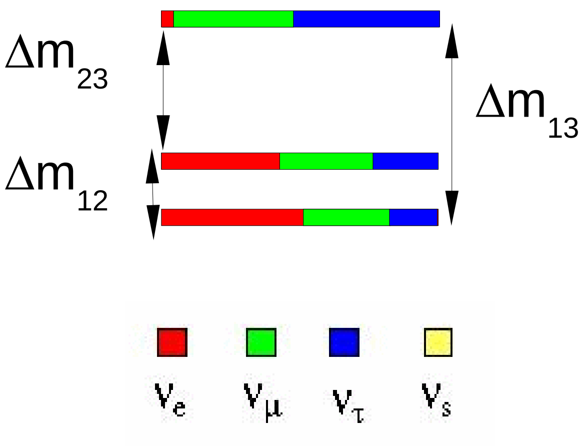


- $\mathbf{P}(\nu_\alpha \to \nu_\alpha) = \mathbf{1} - \sin^2 \mathbf{2}\theta \sin^2[\mathbf{1.27}\boldsymbol{\Delta}\mathbf{m}^2(\mathbf{L}/\mathbf{E})]$
- LSND:
  $\Delta m^2 \approx 0.1 - 10\,\mathrm{eV}^2$, small mixing
- Atmospheric:
  $\Delta m^2 \approx 2 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2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

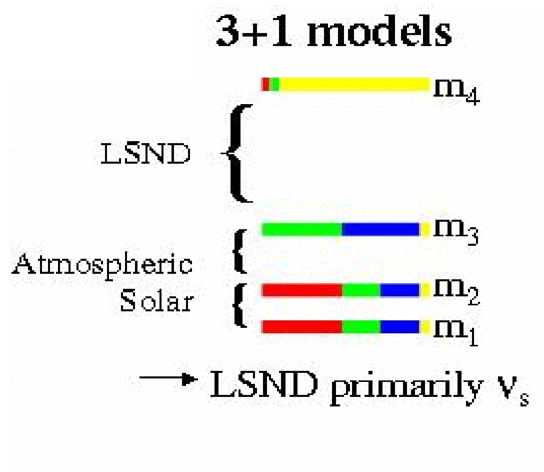
- Three distinct neutrino oscillation signals, with: $\Delta m^2_{sol} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$
- For three neutrinos, expect: $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$!

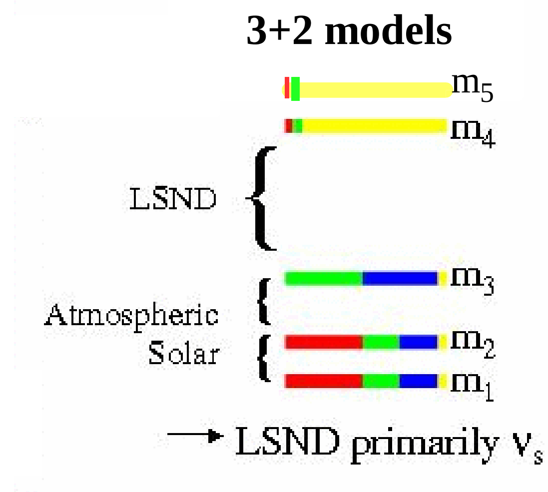


Adding sterile neutrinos



- 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

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

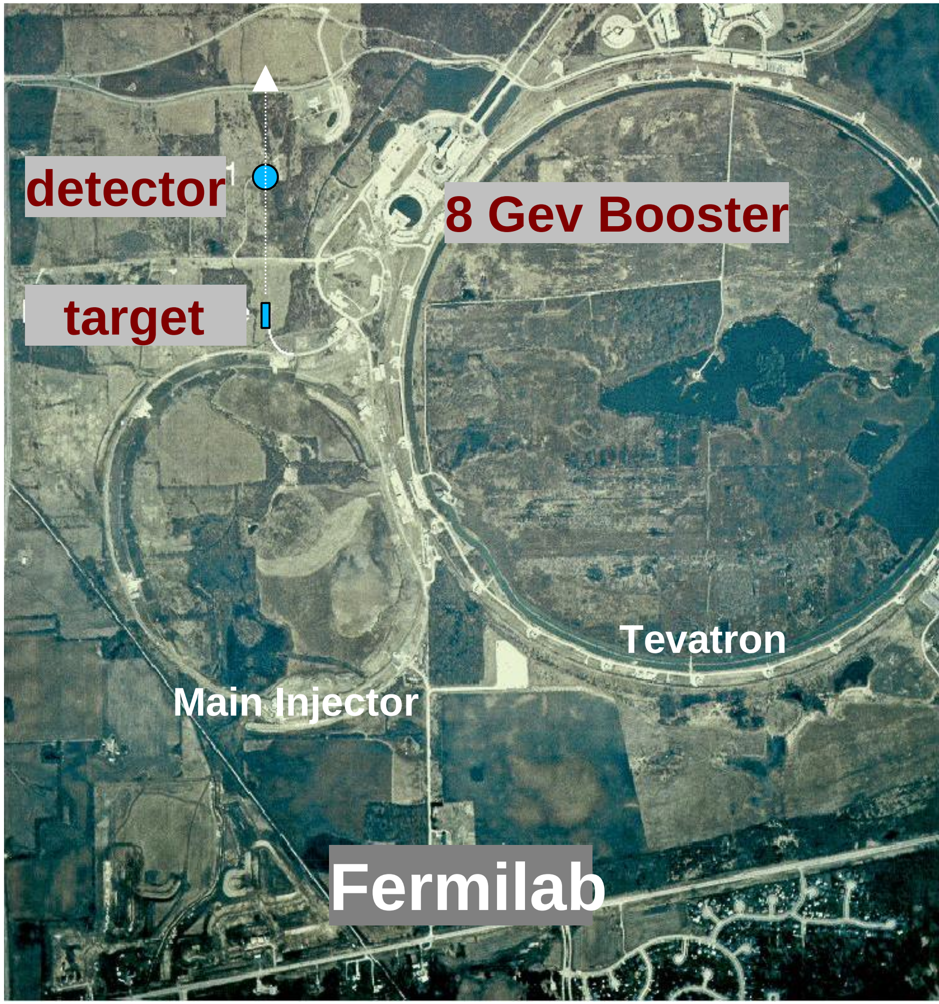
MiniBooNE
is the next step

single detector experiment
to investigate LSND

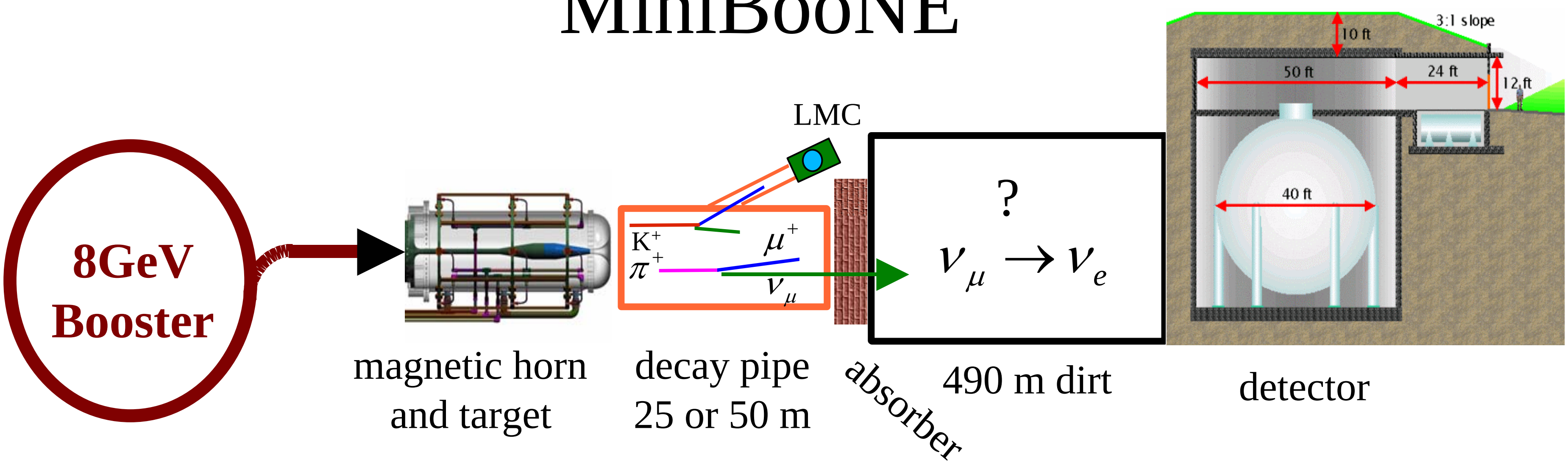
$\nu_\mu \rightarrow \nu_e$ appearance

ν_μ disappearance

L/E ~ 500 m/500 MeV

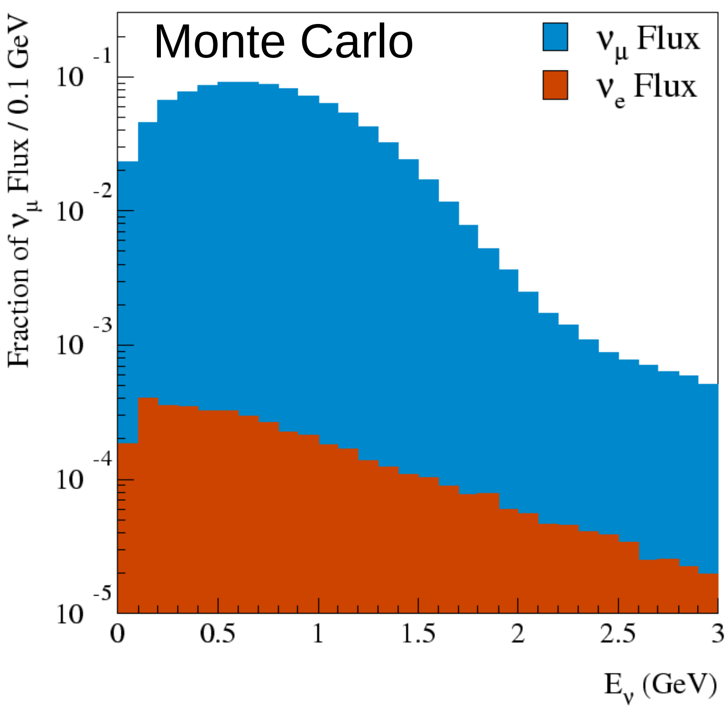


MiniBooNE



ν_μ from π^+ decay
(possible to change horn polarity
in the future)

search for electron appearance
using 800 ton pure mineral oil detector



The Booster

8 GeV proton accelerator supplies beam to all Fermilab experiments

It must now run at record intensity

MiniBooNE runs simultaneously with the collider program; goals:

Booster → MiniBooNE: 5×10^{20} p.o.t per year (1×10^{21} total)

Booster → Main Injector →
- antiproton source
- TeVatron
- NuMI
- 120 GeV fixed target

MiniBooNE: negligible impact on collider; improvements to Booster good for NuMI

Booster performance

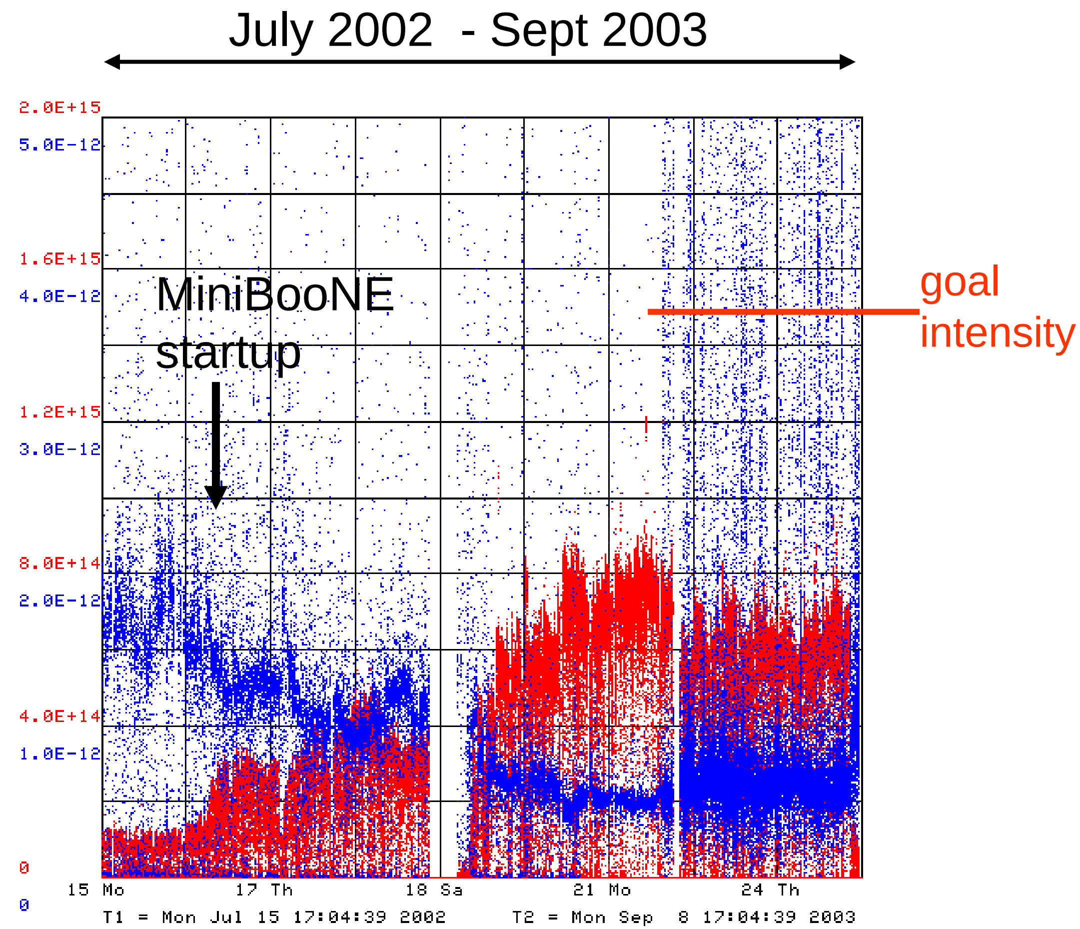
We are pushing the Booster hard

Must limit radiation damage and activation of Booster components:
  increase protons
  but decrease beam loss

~steady improvements
  careful tuning
  understanding optics

need factor of 2-3 to reach goal 10^{21} p.o.t. by early 2005

further improvements:
  new Booster collimators
  large-aperture RF cavities



red: Booster output (protons/minute)

blue: energy loss per proton (W-min/proton)

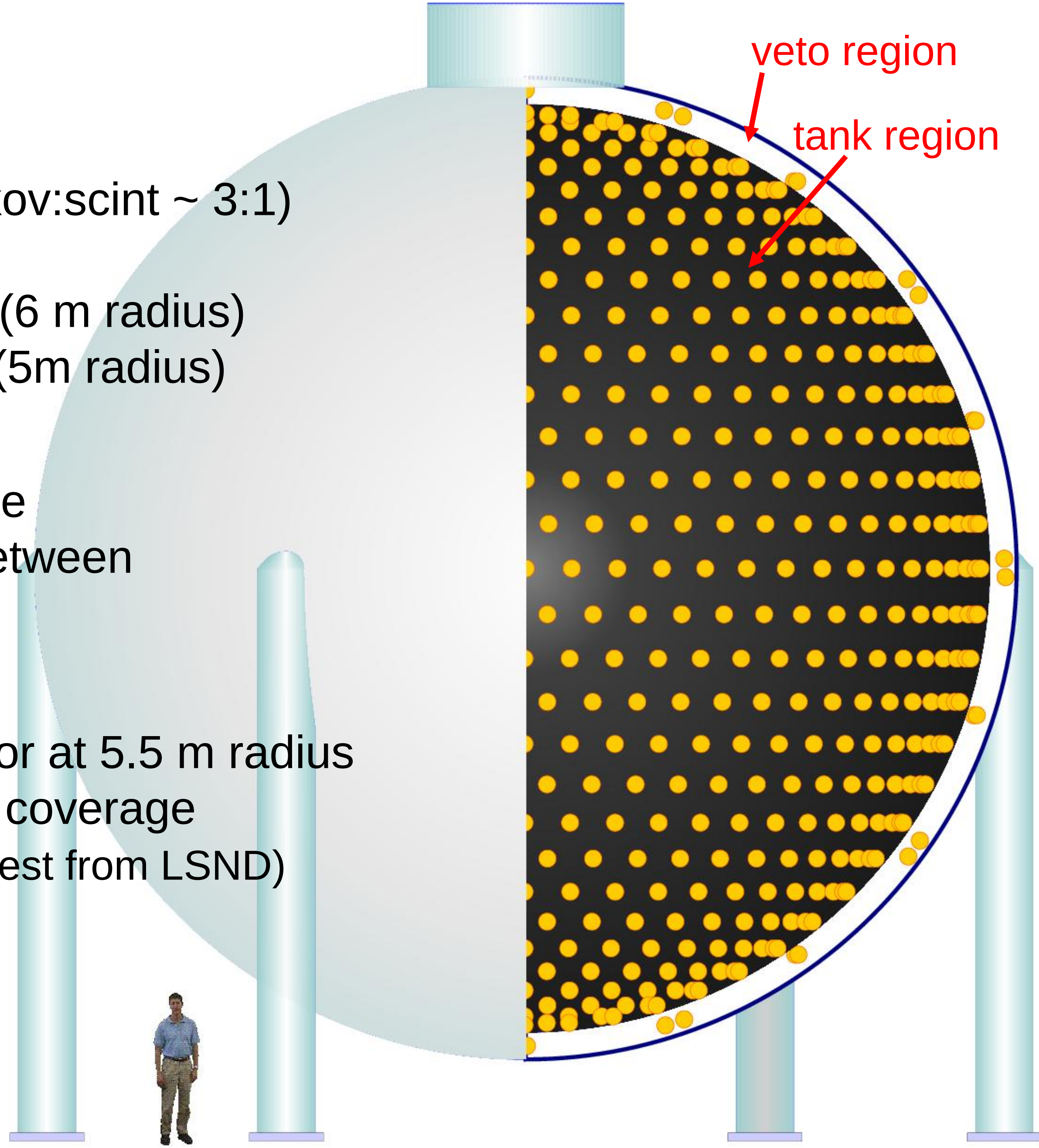
MiniBooNE detector

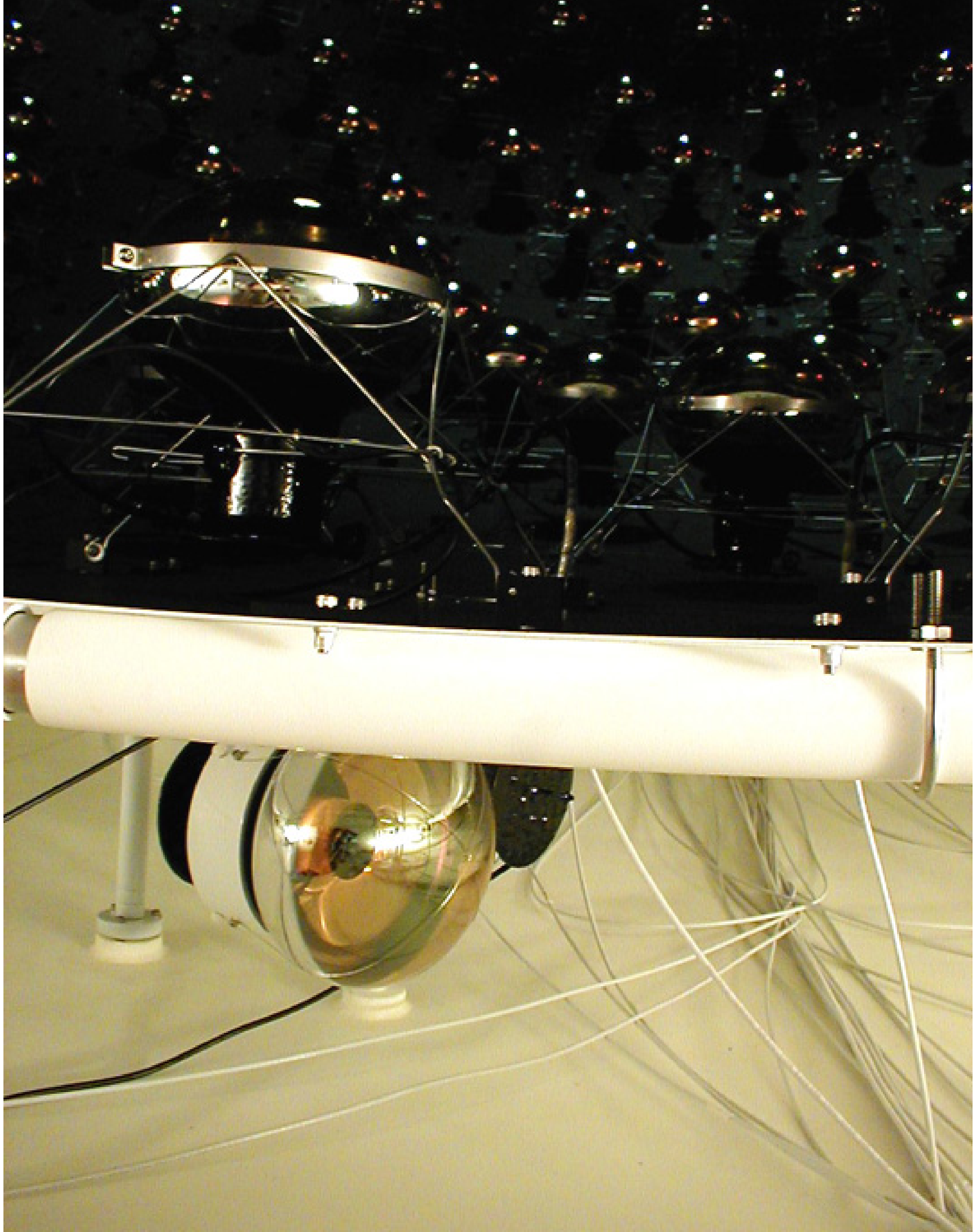
pure mineral oil (Cherenkov:scint ~ 3:1)

total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5m radius)

Phototube support structure
provides opaque barrier between
veto and main volumes

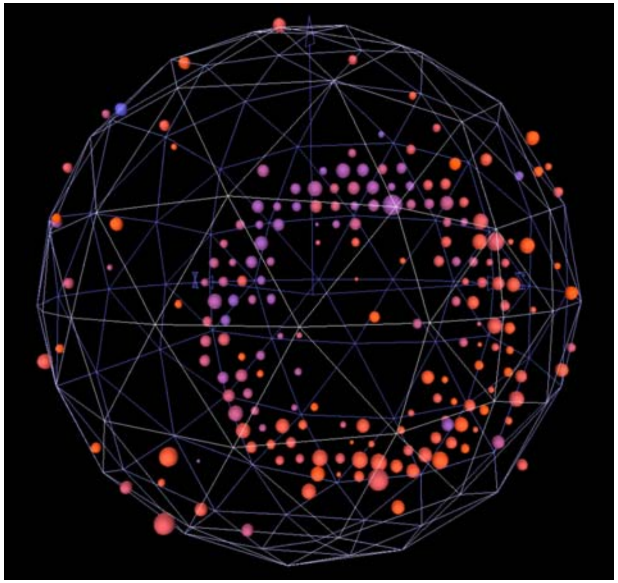
1280 20-cm PMTs in detector at 5.5 m radius
→ 10% photocathode coverage
(330 new tubes, the rest from LSND)
240 PMTs in veto



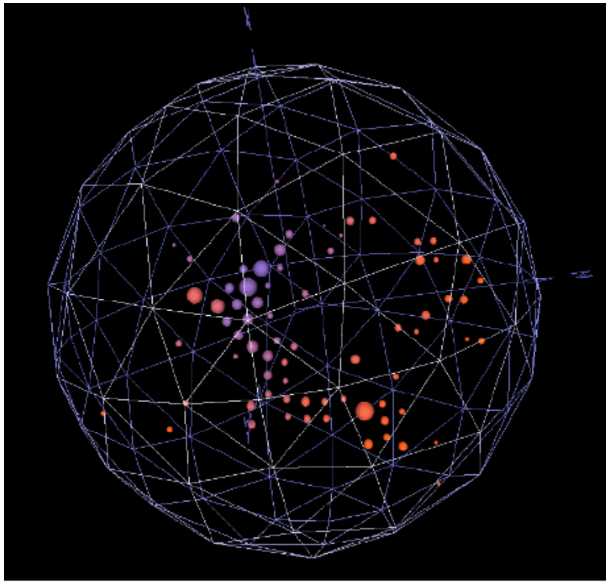


Pattern of hit tubes (with charge and time information) allows reconstruction of track location and direction and separation of different event types.

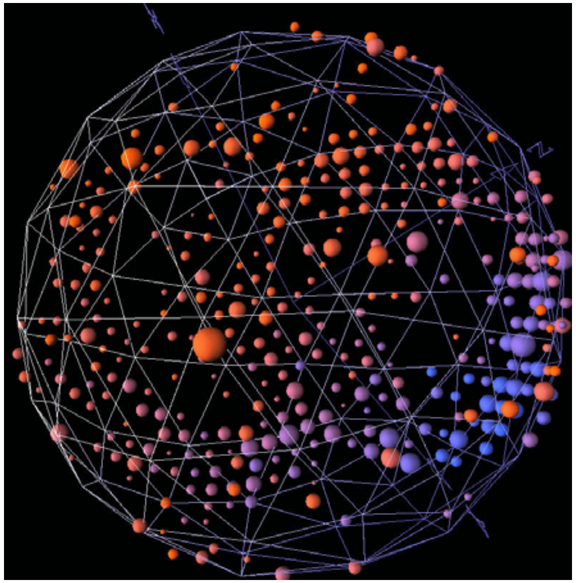
e.g. candidate events: size = charge, color = time



muon
from ν_μ interaction



Michel electron
from stopped μ decay
after ν_μ interaction



$\pi^0 \rightarrow$ two photons
from ν_μ interaction

Neutrino events

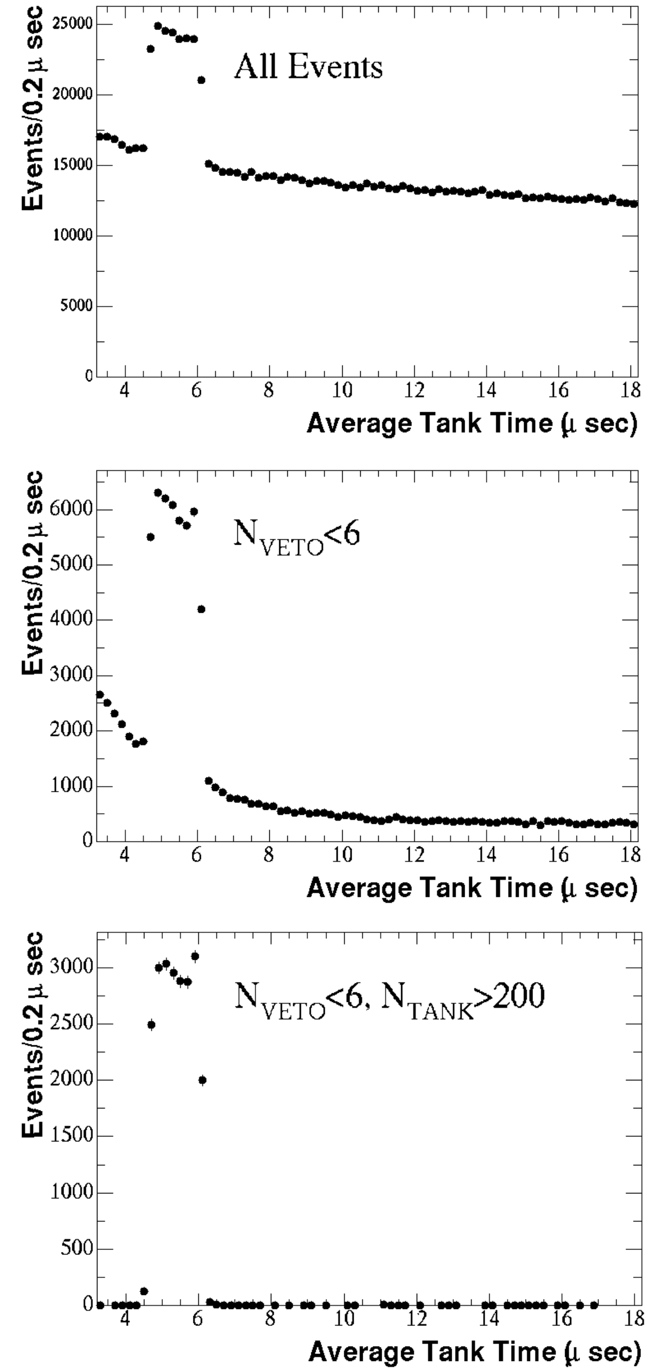
beam comes in spills @ up to 5 Hz
each spill lasts 1.6 μsec

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

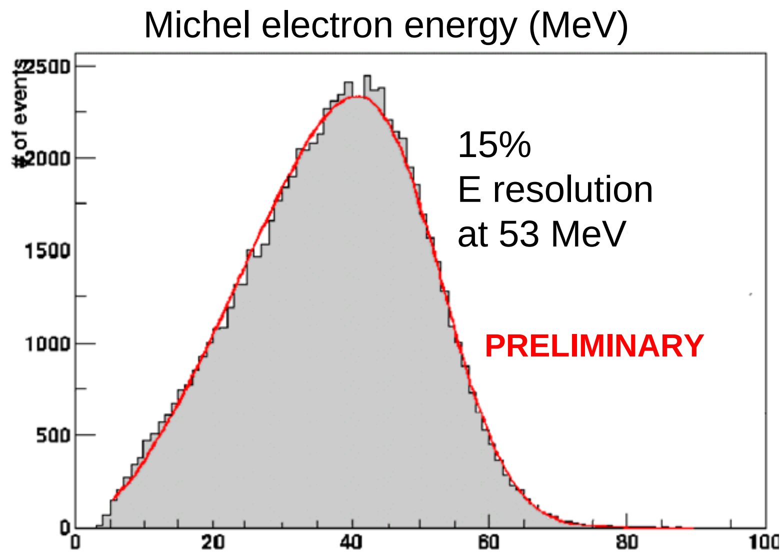
simple cuts reduce non-beam backgrounds to ~10^{-3}



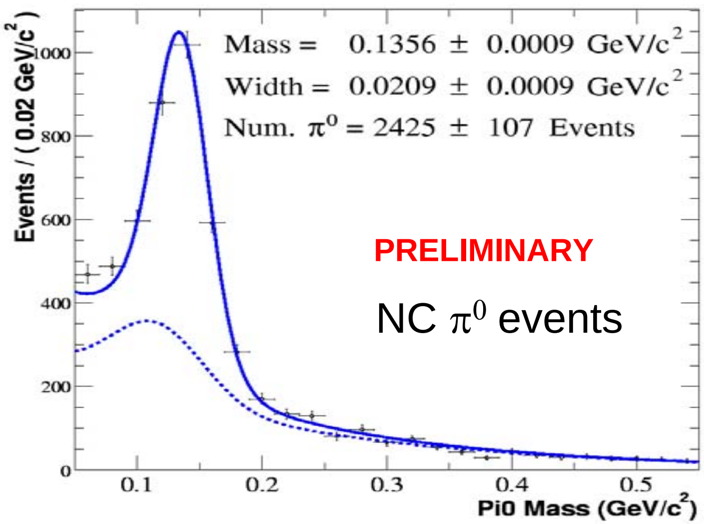
220k neutrino candidates in 2.0 x 10^{20} protons on target

Energy Calibration Checks

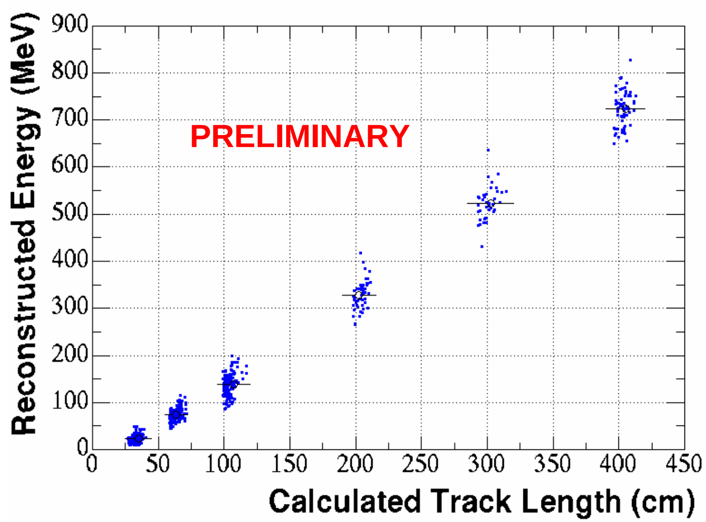
- Spectrum of Michel electrons from stopping muons

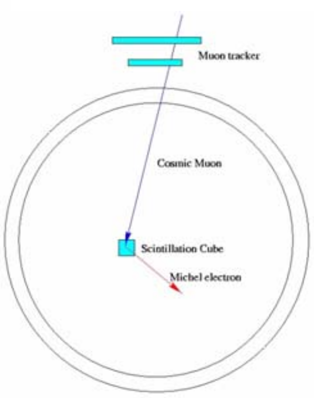


Mass distribution for isolated π^0 events



- Energy vs. Range for events stopping in scintillator cubes



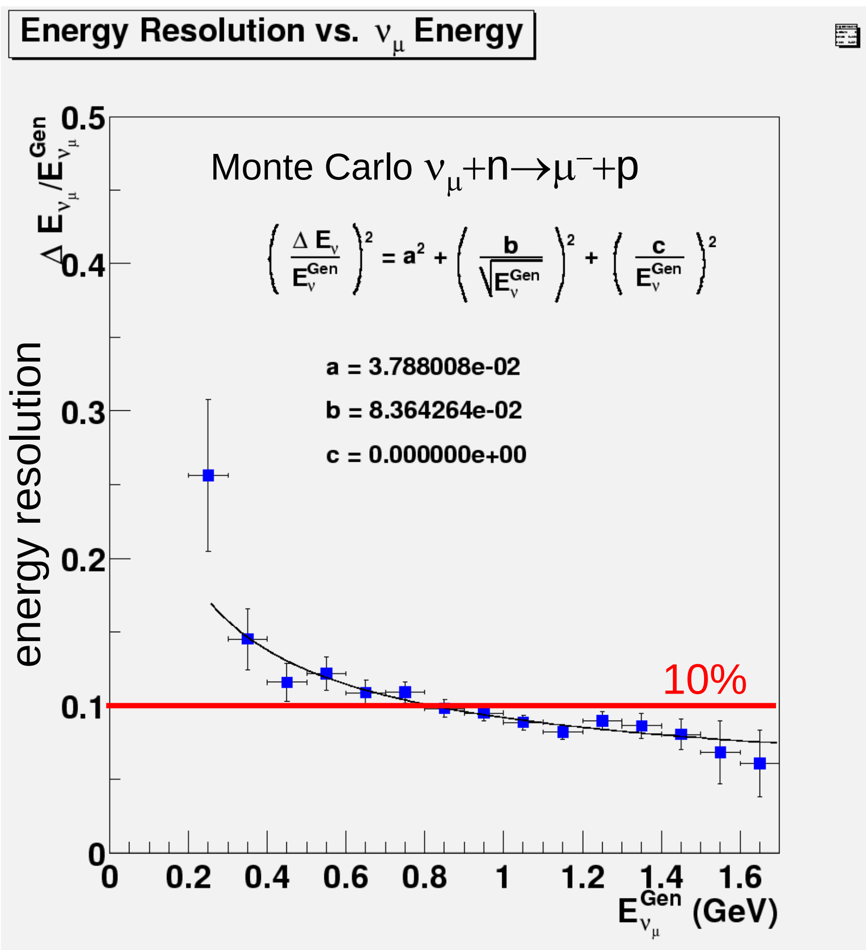


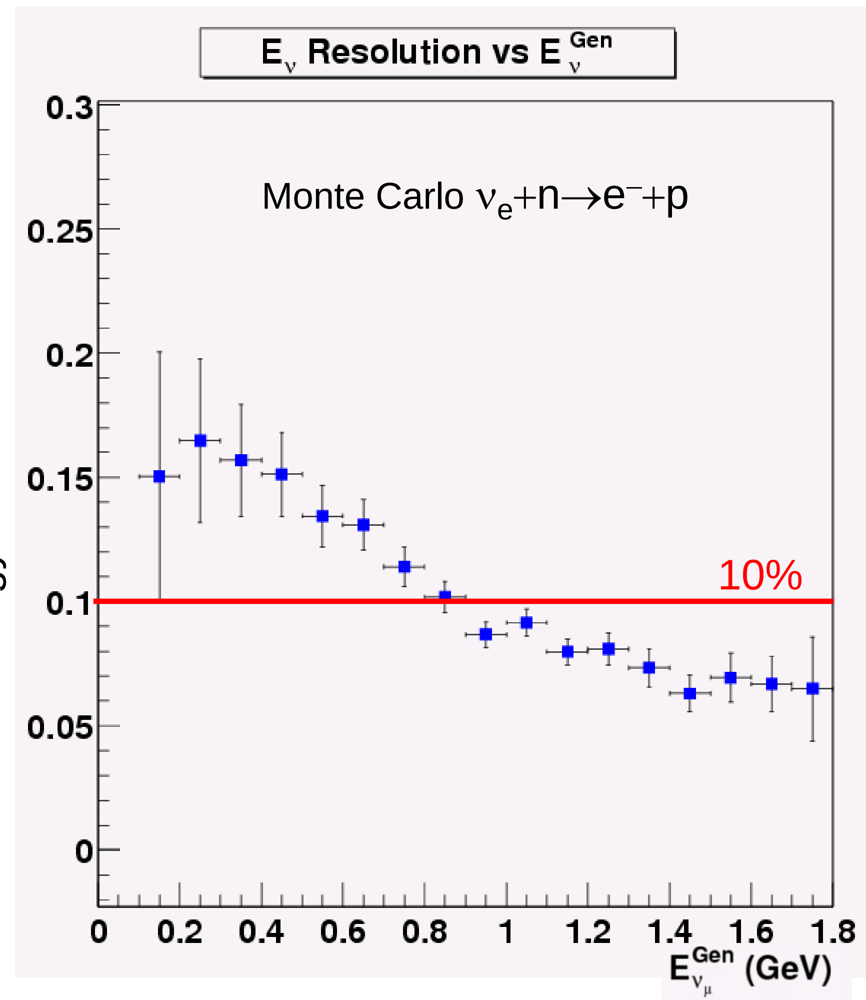
Neutrino energy reconstruction

For quasi-elastic events ($\nu_\mu + n \rightarrow \mu^- + p$ and $\nu_e + n \rightarrow e^- + p$)

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

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





The road to $\nu_\mu \rightarrow \nu_e$ appearance analysis

Blind 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

Early physics: other analyses before $\nu_\mu \rightarrow \nu_e$ appearance

vets data-MC agreement (optical properties, etc.)
and reliability of reconstruction algorithms

progress in understanding backgrounds

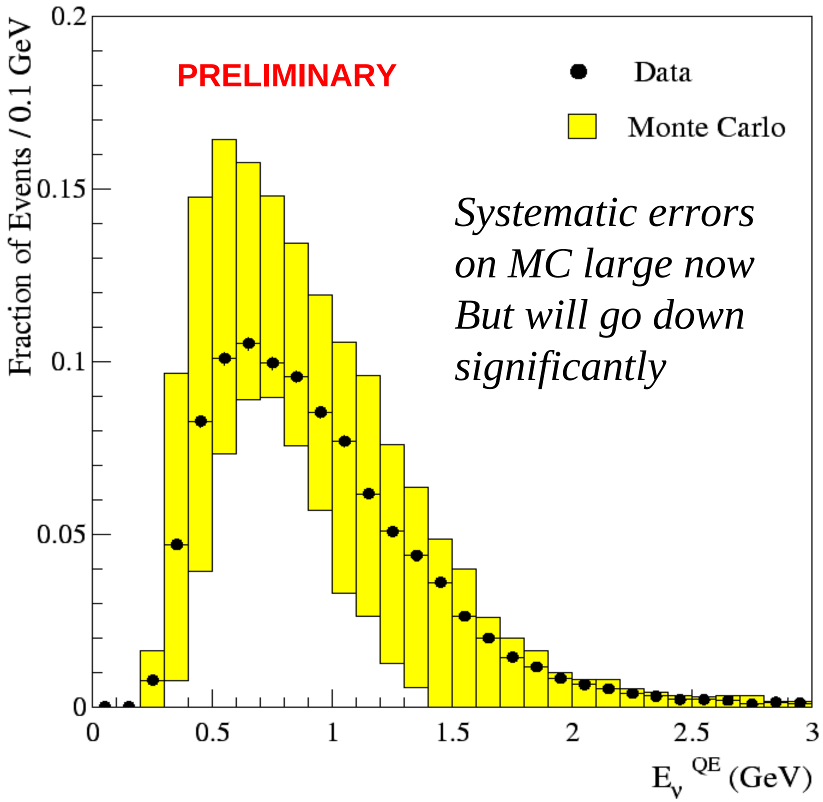
CC ν_μ quasi-elastic scattering
NC ν_μ π^0 production
NC ν_μ elastic scattering

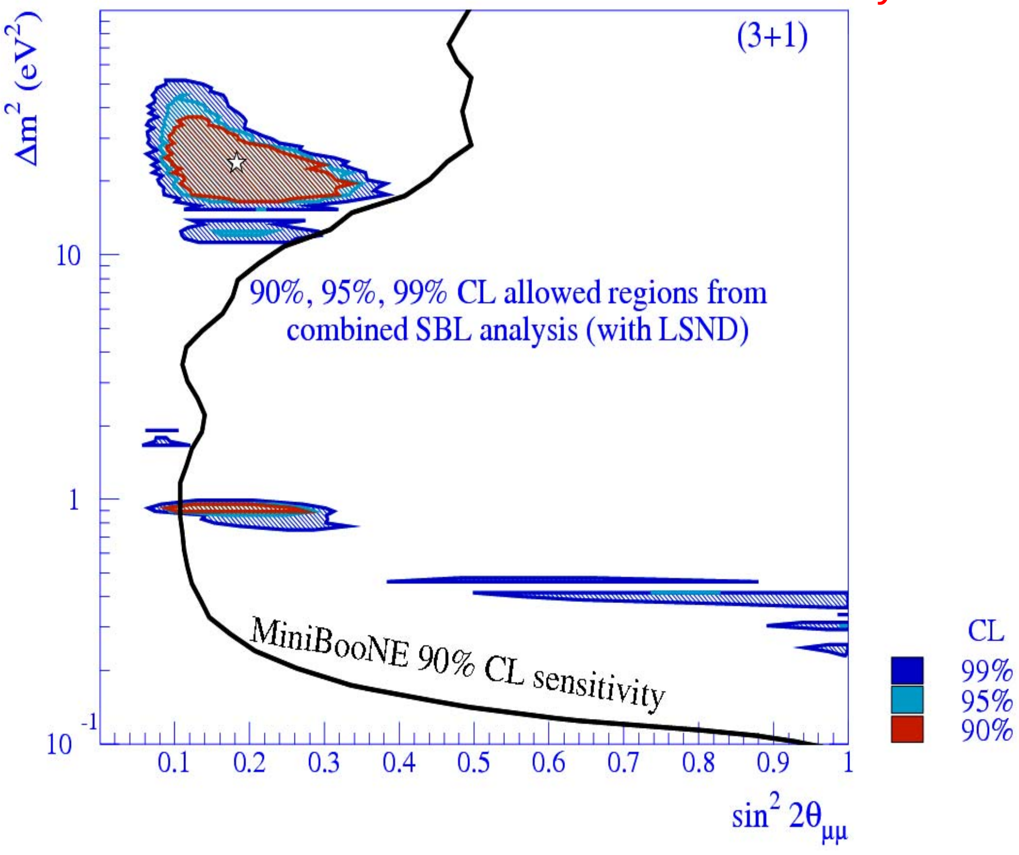
And the road to a ν_μ Disappearance Analysis

- Use CC 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





$\nu_\mu \rightarrow \nu_e$ search

signal: ν_e CC quasi-elastic

$$\nu_e + n \rightarrow e^- + p$$

backgrounds:

muon mis-id: $\nu_\mu + n \rightarrow \mu^- + p$

π^0 mis-id:

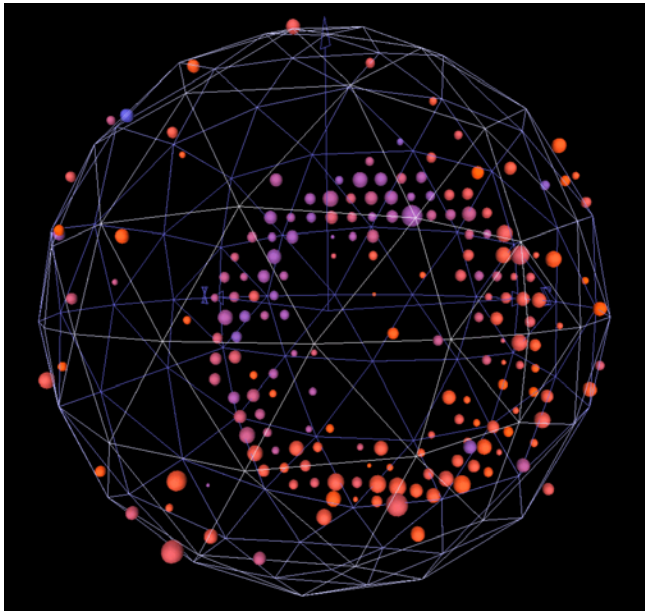
$$\nu_\mu + (n/p) \rightarrow \nu_\mu + \pi^0 + (n/p)$$

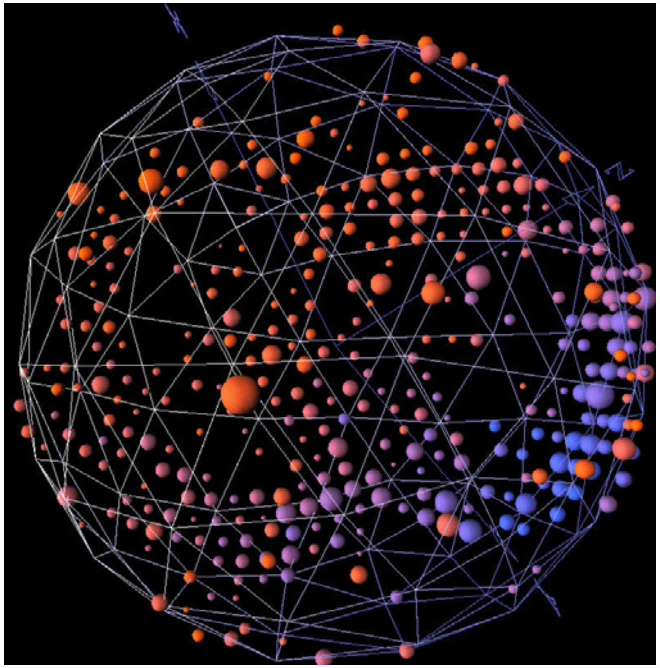
radiative Δ decay:

$$\nu_\mu + (n/p) \rightarrow \nu_\mu + \Delta$$

$$\Delta \rightarrow (n/p)\gamma$$

intrinsic ν_e in the beam





MiniBooNE's goal is to acquire 10^{21} protons on target by mid-2005

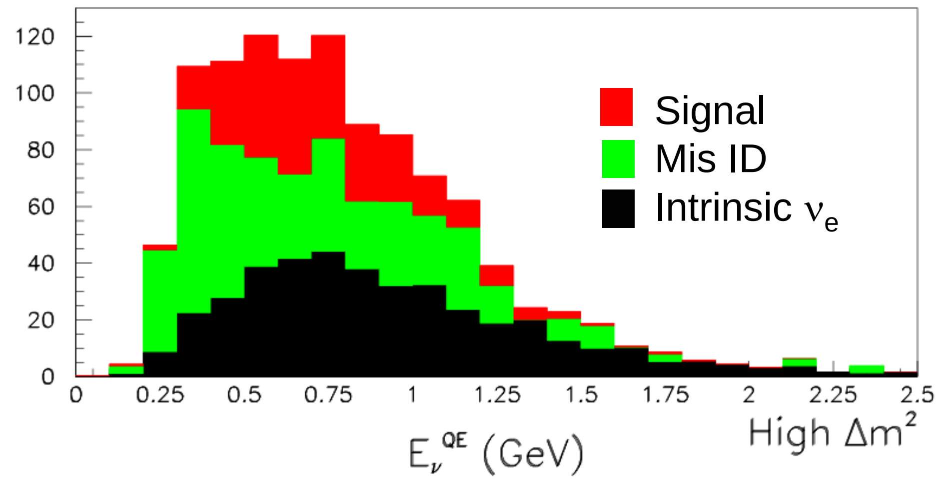
Sensitivity at MiniBooNE: background and signal (if LSND)

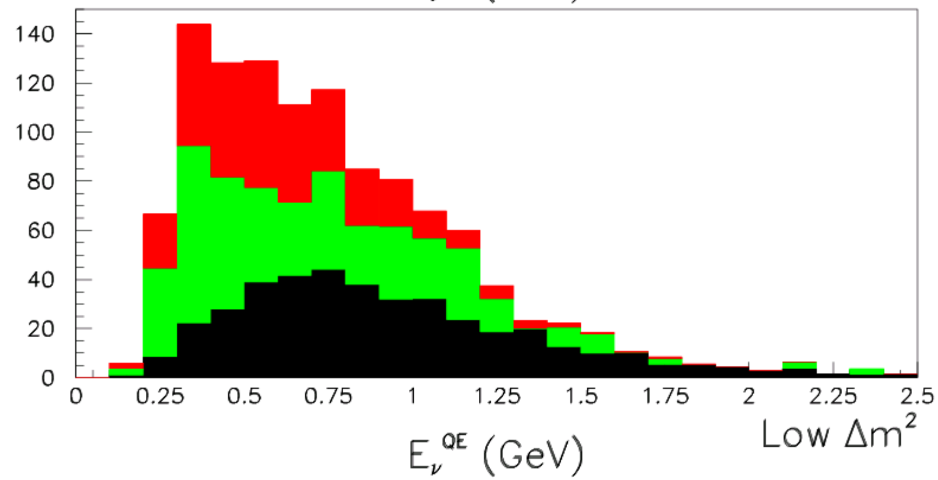
summary of expected event statistics for 10^{21} protons on target

ν_μ CC QE	10
π^0 mis-id	290
$\Delta \rightarrow N\gamma$	80
ν_e from K^+ decay	120
ν_e from K^0 decay	40
ν_e from μ decay	190
total background	730

signal (Δm^2=1.0 eV^2, $\sin^2 2\theta$ =0.004) 260

signal (Δm^2=0.4 eV^2, $\sin^2 2\theta$ =0.017) 320

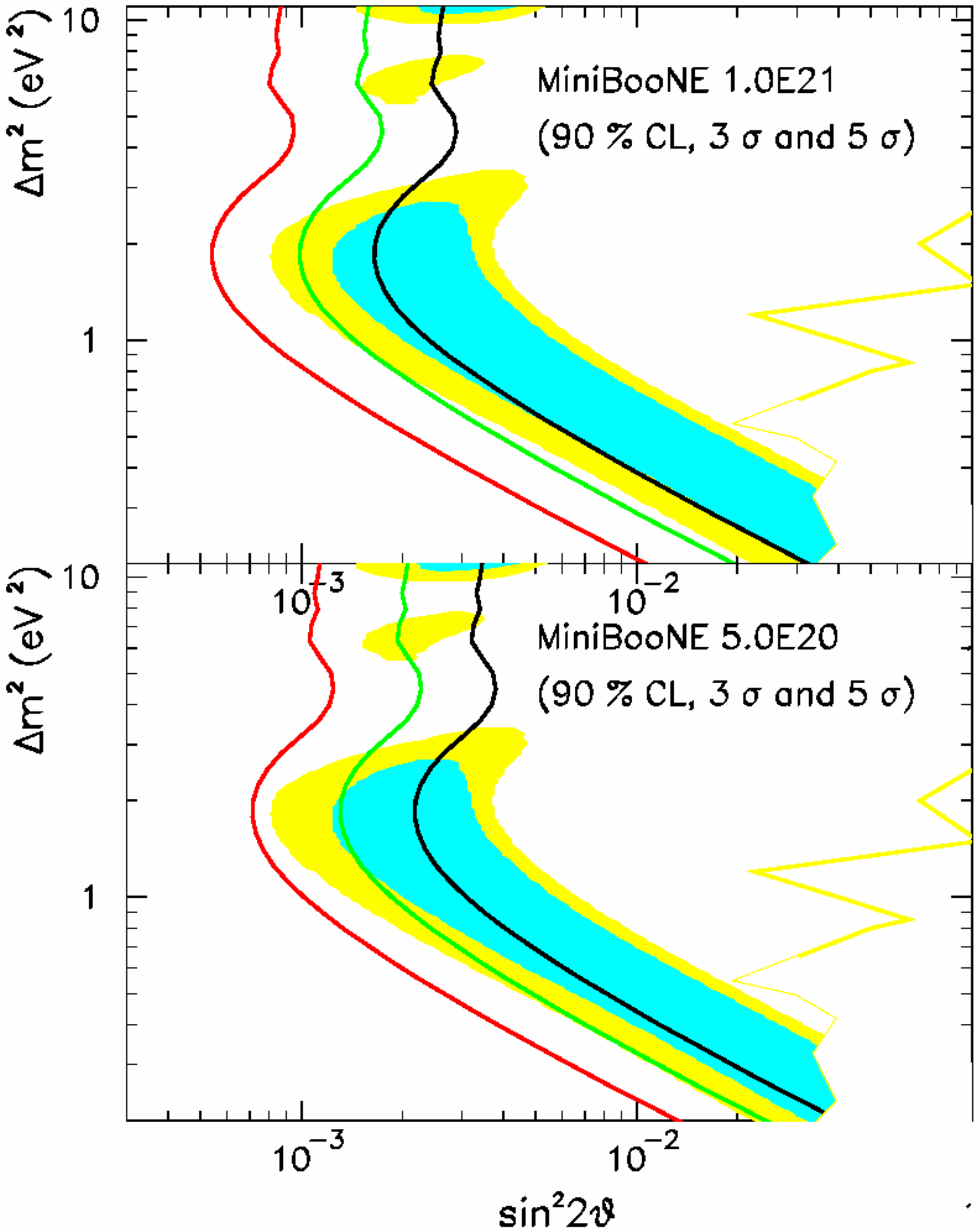




Sensitivity

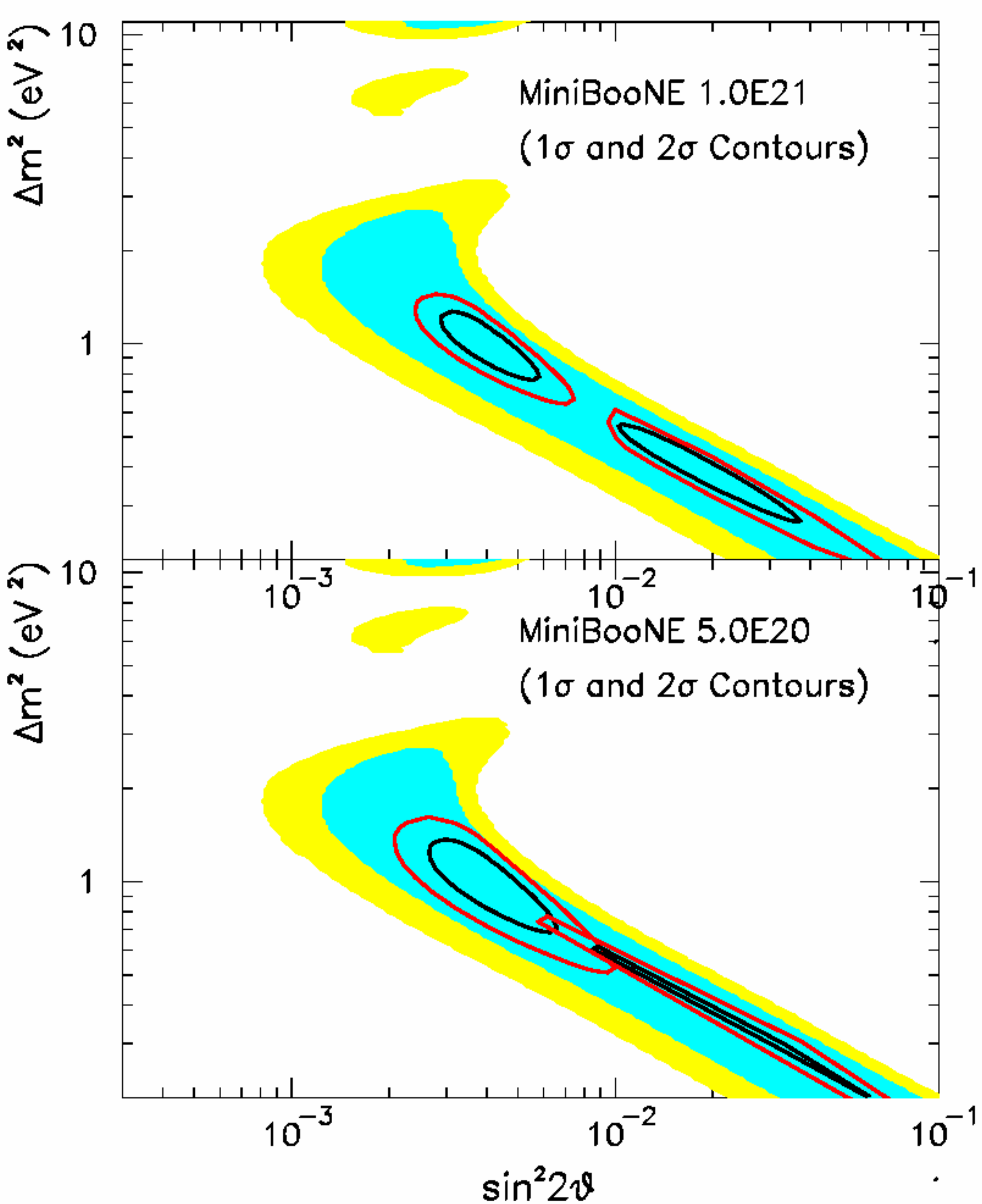
Expected for 1 x 10^{21} p.o.t

and for 5 x 10^{20} p.o.t.



Parameter measurement capability

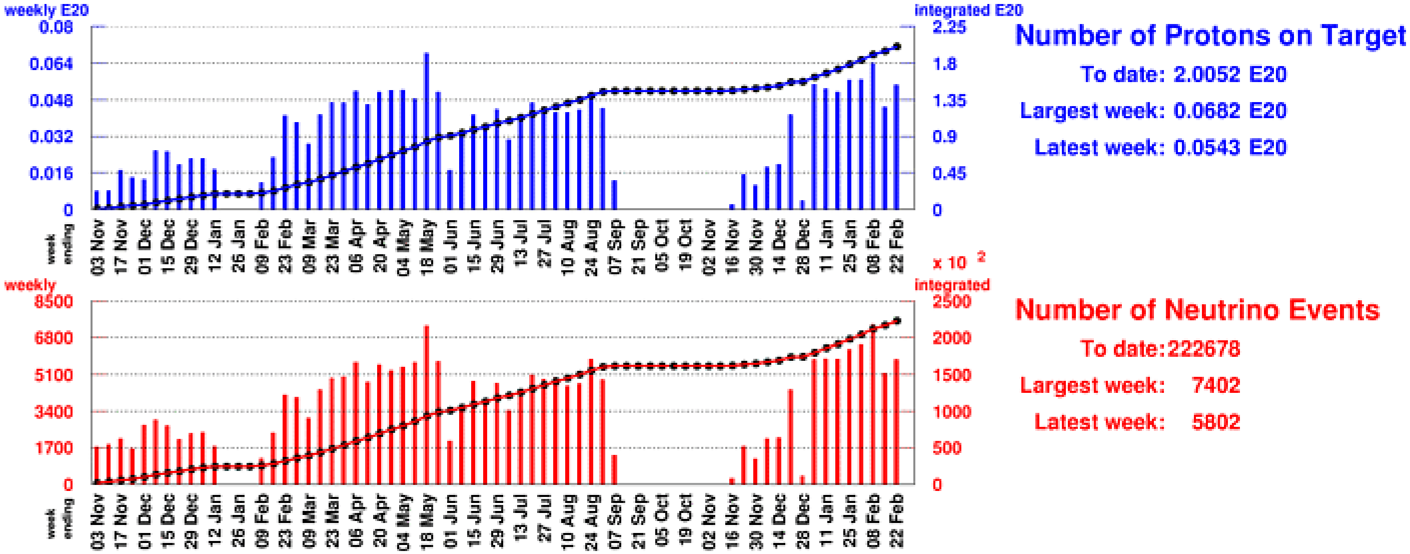
expected contours for signals at $\Delta m^2 = 1.0$ and $0.4\ eV^2$ at the center of LSND's allowed region



MiniBooNE run progress

Currently running at about 60% of goal intensity

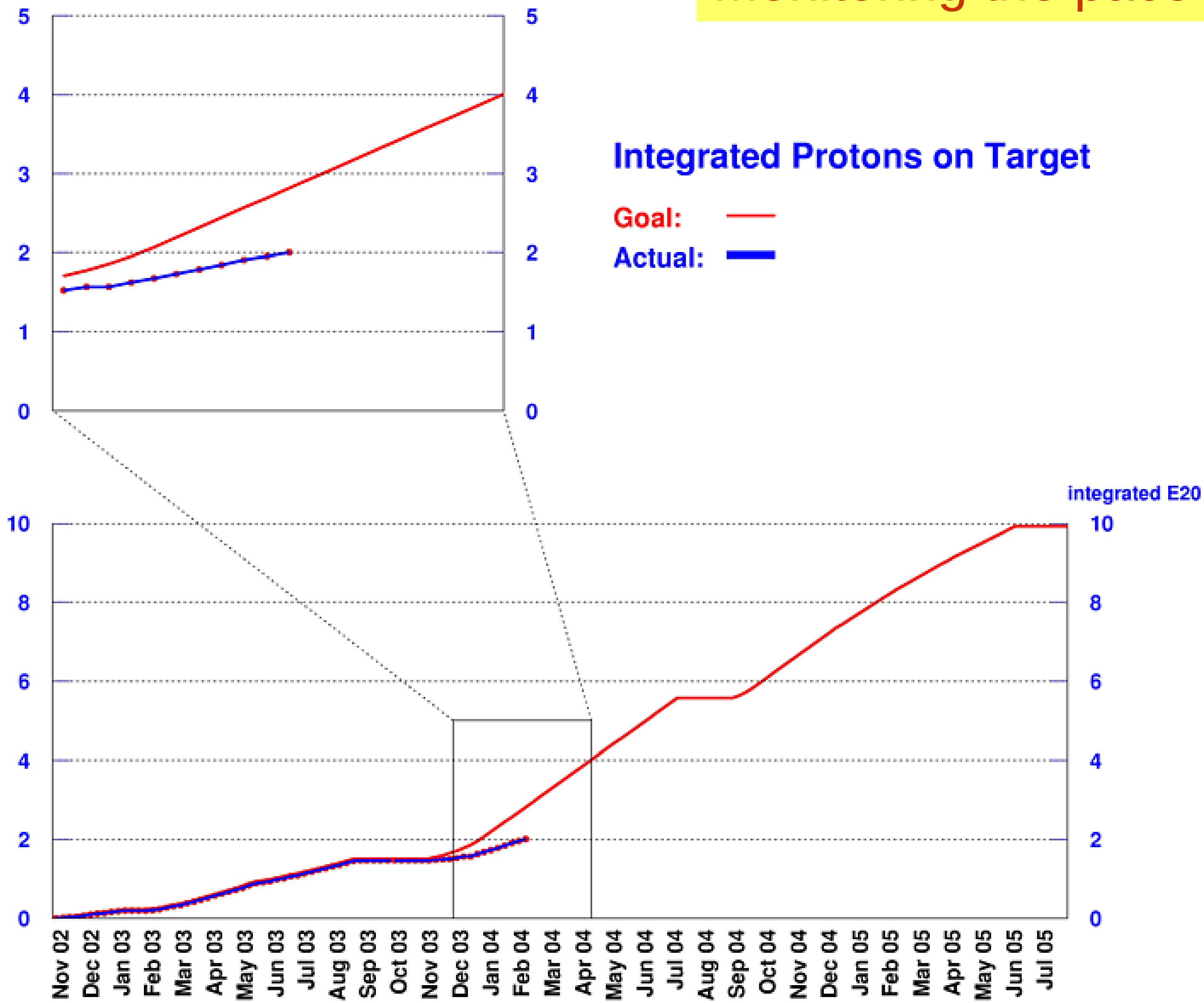
Hope to reach goal with new Booster collimator system



Nov 2002

Feb 2004

Monitoring the pace



What to do after MiniBooNE depends on what MiniBooNE finds

MiniBooNE phase 1 will conclude in mid-2005

Plan is to "open the box" when analysis is ready and experiment has collected 10^{21} p.o.t

Is there an LSND-type signal?

→ No Run MiniBooNE phase 2, which includes: switching the horn polarity, $\bar{\nu}_\mu$ beam

LSND signal is with $\bar{\nu}_\mu$ beam.
Also, discriminate free proton vs. nuclear scattering
charged kaon background validation

And other systematics studies, including running with 25 m decay length

Is there an LSND-type signal?

→ Yes Neutrino physics becomes even more interesting!

MiniBooNE phase 2 becomes very compelling
important vetting of the phase 1 result

BooNE collaboration would propose building a second detector

Impact on the entire neutrino oscillation industry

Sterile neutrinos → at least three Δm^2 scales are present

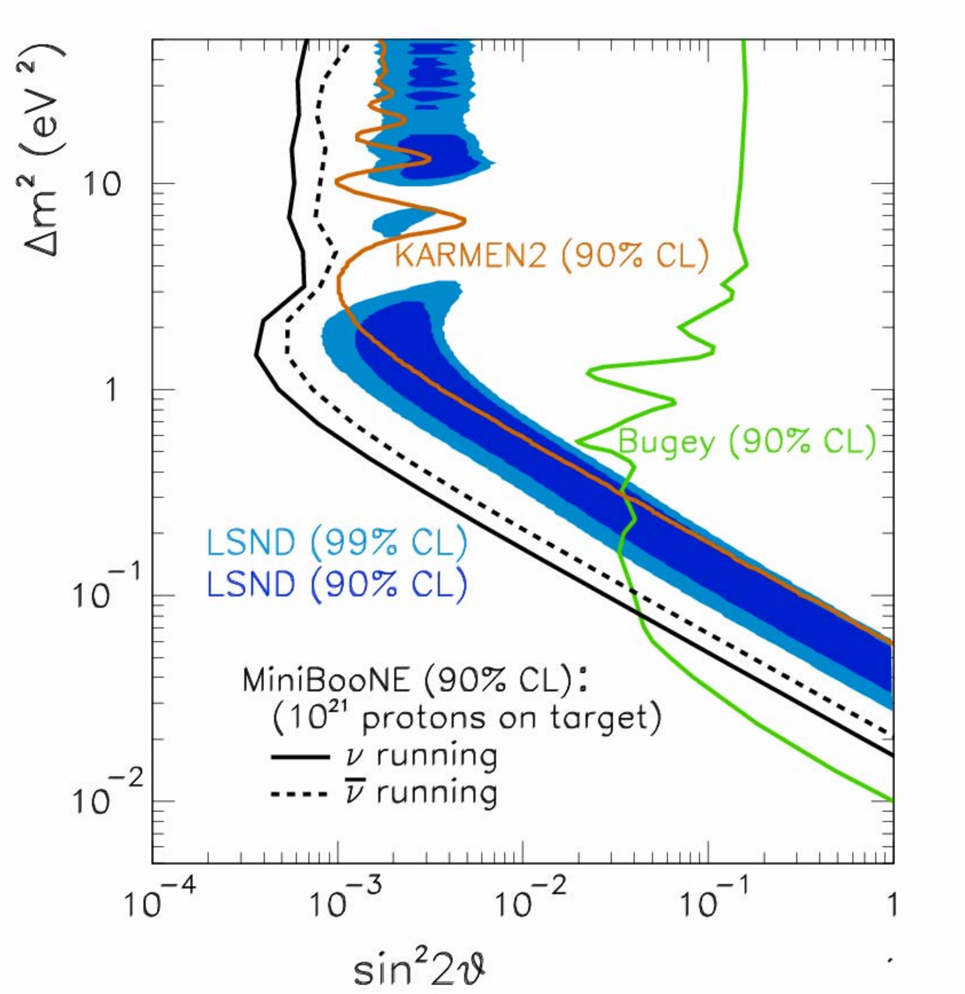
more mixing angles, CP phases
how many sterile neutrinos, Δm^2's?

MiniBooNE with antineutrinos

direct comparison with LSND

Are ν_μ and $\bar{\nu}_\mu$ the same?
explore
CP (or CPT) violation

Running with antineutrinos takes about x2 longer to obtain similar sensitivity



If signal at high Δm^2

exploit all channels: ν_μ disappearance
$\nu_\mu \rightarrow \nu_e$
$\nu_\mu \rightarrow \nu_\tau$

at short baseline

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

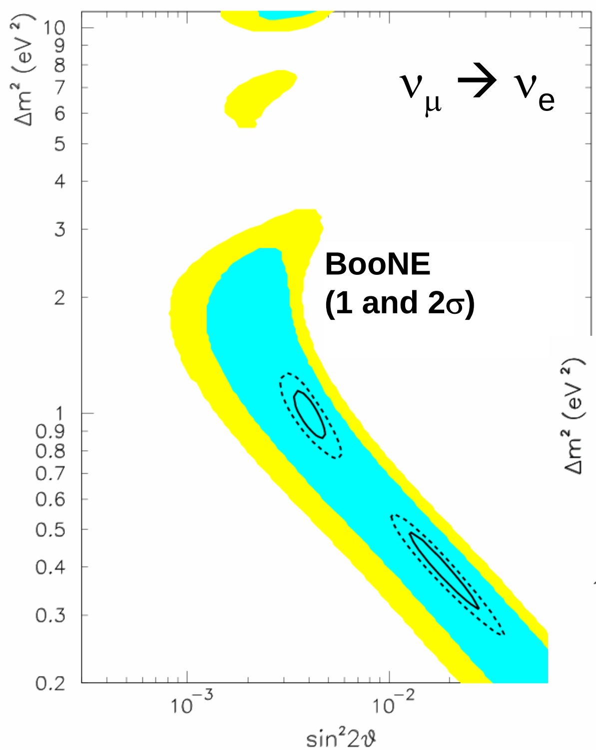
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1}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

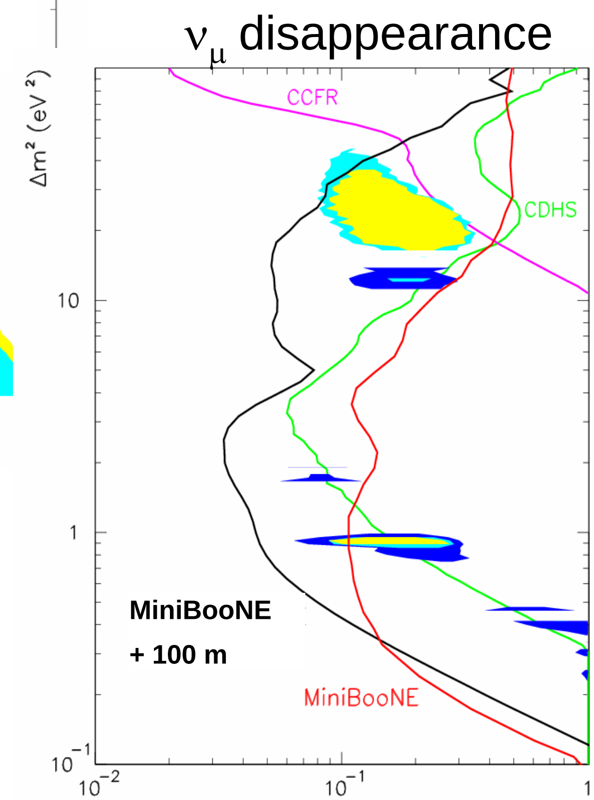
Map out mixings associated with $\nu_\mu \rightarrow \nu_\tau$

BooNE: Two (or three) detector experiment

- ➢ 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



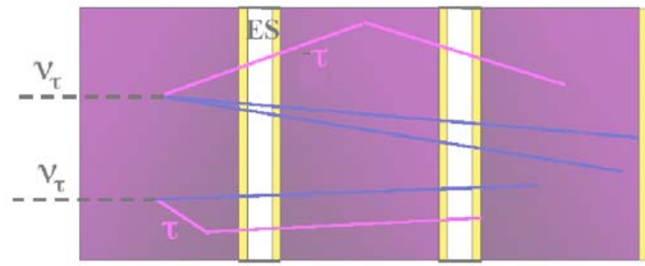


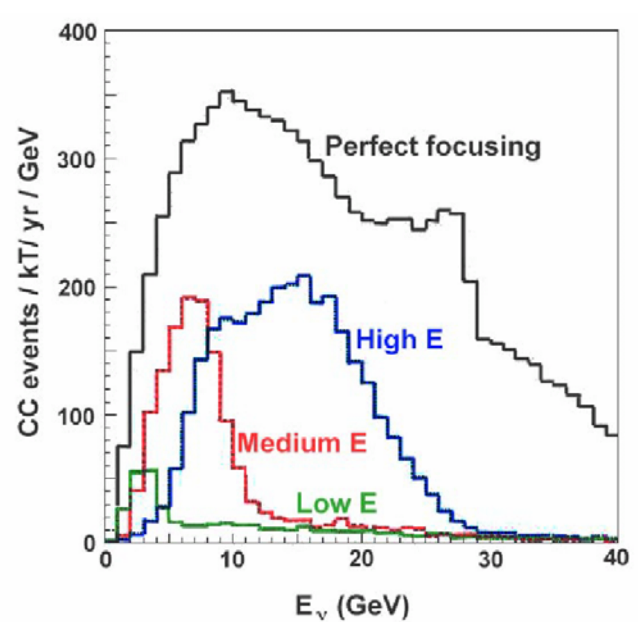
$\nu_\mu \rightarrow \nu_\tau$ at short baseline

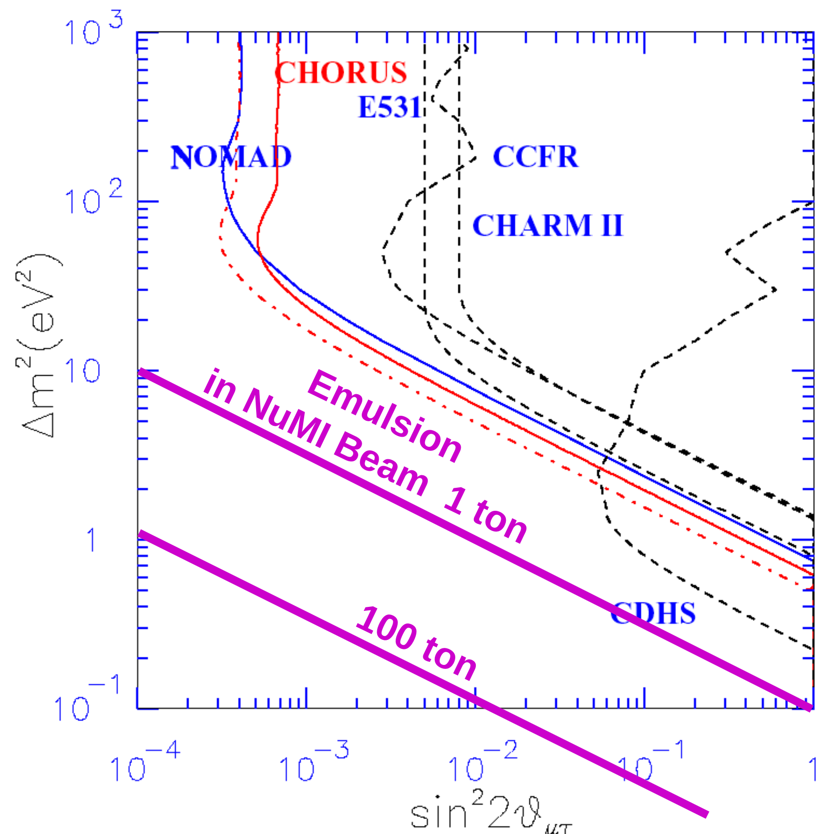
Need moderately high neutrino energy to get above the 3.5 GeV τ threshold (~6-10 GeV)

Example: NuMI Med energy beam 8 GeV with detector at L=2km (116m deep) (Mike Shaevitz)

Emulsion Detector or Liquid Argon







SNS

1.3 GeV, 1.4 MW proton source
60 x 700ns proton pulses / s
10^{15} ν_μ /s from μ^+ DAR

Space available inside the building for a ~20 t detector
at a distance of ~21 m from the neutrino source:
e.g. for cross section measurements of interest to supernova astrophysics

Unlimited space available outside the building.
Choose an oscillation detector location at ~100 m.
Build a duplicate MiniBooNE detector but with more PMTs and b-PBD scintillator

(Bill Louis [Gordon VanDalen])

Son of LSND at SNS

signal: $\nu_e\, p \rightarrow e^+ n$, $n\, p \rightarrow d\, \gamma$ (2.2 MeV)

For LSND parameters, expect ~350 oscillation events per year
(x2 more neutrinos, x5 more mass)

(Bill Louis)

backgrounds

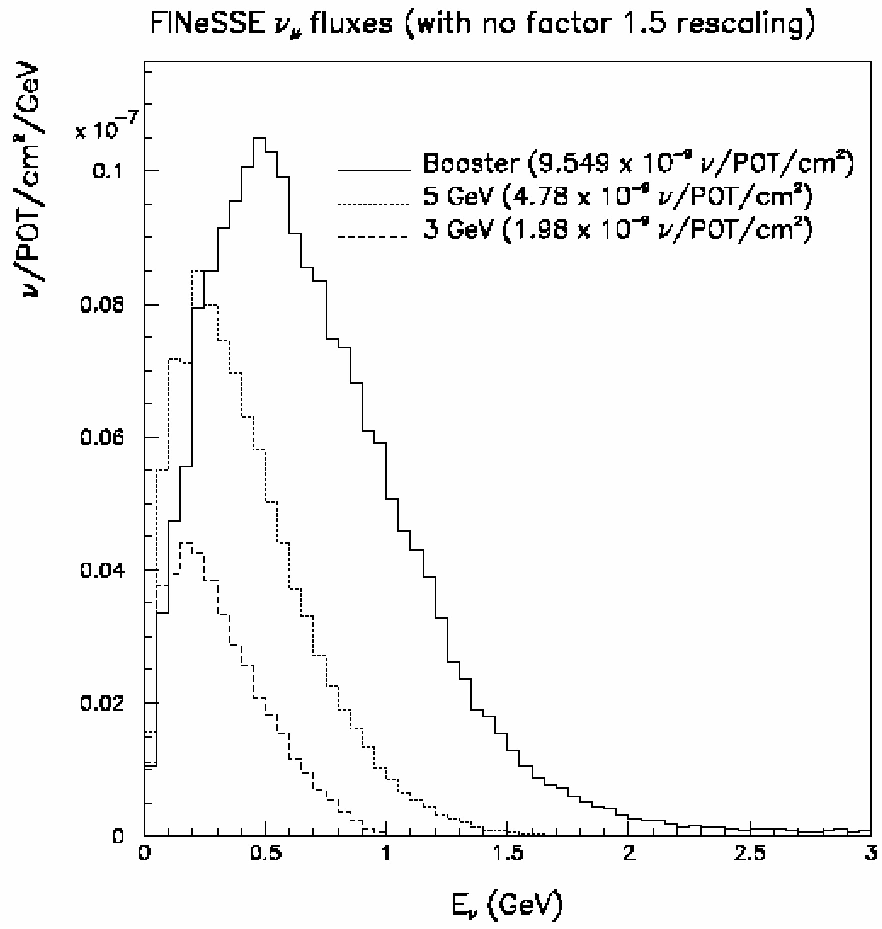
expect ~10 intrinsic ν_e background events per year
(background reduced by $r^{-2} = 1/10$)

expect ~20 beam-off background events per year
(duty factor lower by 100)

S/B > 10 for $\Delta m^2 \sim 0.3\ eV^2$

Other labs, new/existing facilities:

Compare 3, 5, 8 GeV proton source



Some questions being studied:

neutrino vs. antineutrino and CP violation at SBL:
Can CP violation help distinguish 3+1, 3+2, 3+3?

$\nu_\mu \rightarrow \nu_\tau$ at high Δm^2: current indirect limits in 3+1, etc. models.

Impact on LBL?

→ observations that differ from 3-neutrino mixing predictions
→ possibility of large CP violation effects

Conclusions

What if MiniBooNE confirms LSND is an exciting question.

We hope to convey the excitement and anticipate the opportunities.