Not Just θ_{13}

Other Proton Driver Era Questions in Neutrino Oscillations

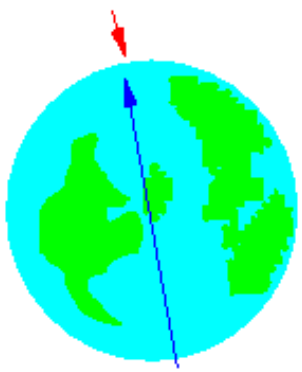
Steve Brice (FNAL)

Neutrino Mixing

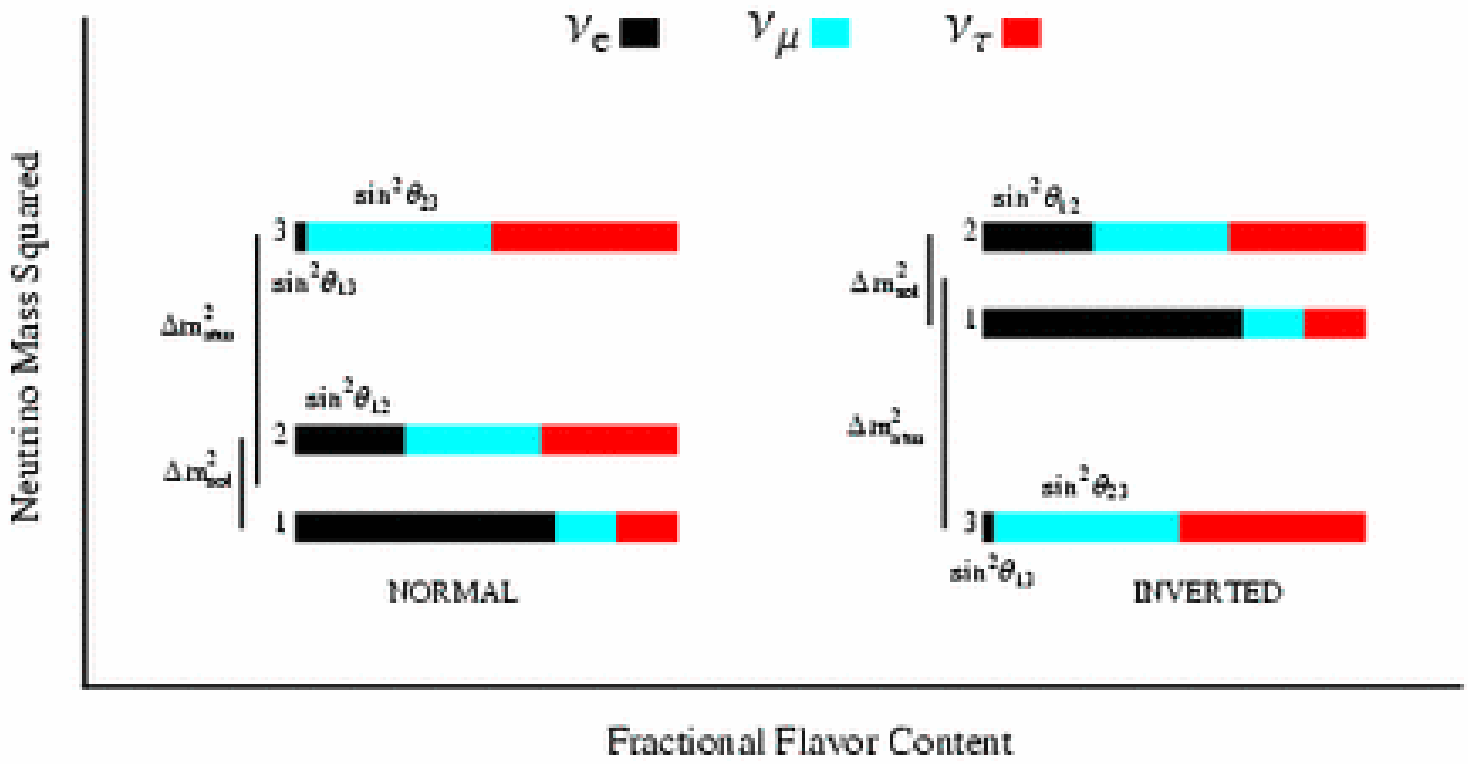
Lesson Learned from CKM: 3 mixing angles and a phase

Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

U=  Reactor and/or Accelerator ν_e

Neutrino Masses



Electron neutrino appearance

Interesting information in $P_{\rm app}$=$P_{\mu e}$ or $P_{\bar{\mu}\bar{e}}$

To second order in $\sin 2\theta_{13}$ and the hierarchy parameter $\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$:

$$
\begin{aligned}
P_{\rm app} \simeq\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
\pm\ & \alpha \sin 2\theta_{13}\, \xi \sin\delta_{\rm CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+\ & \alpha \sin 2\theta_{13}\, \xi \cos\delta_{\rm CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+\ & \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2},
\end{aligned}
$$

- Contains all of the most interesting information: θ_{13}, Mass hierarchy (in matter potential A), CP violation (δ_{CP})
- But: Complicated to extract: Complimentary information needed (antineutrino running, reactor experiments, different L/E, …)
  → The smaller θ_{13}, the more sophisticated!

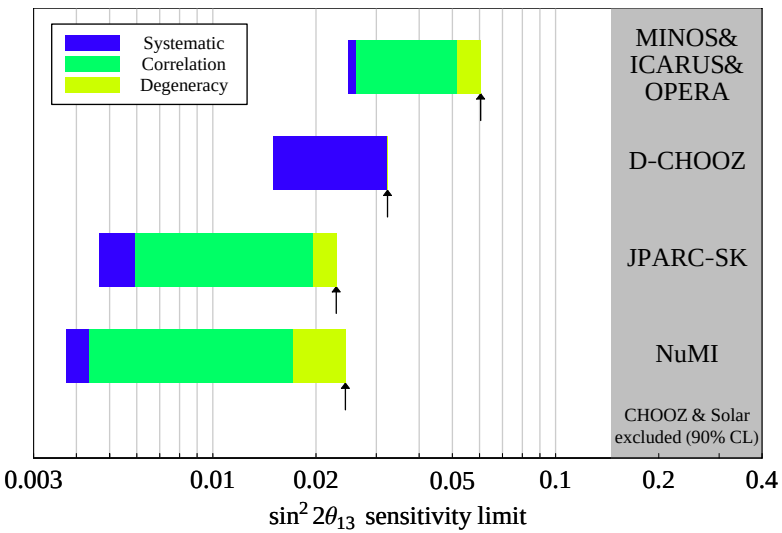
Electron Neutrino Appearance Key Points

- The mixing angle θ_{13} sets the scale for the size of the effect
- CP violation term δ_{CP} flips sign of second term
  - compare ν with anti-ν probability
- Hierarchy changes the sign of matter potential Â
  - Long baseline needed to see effect of Â

New Results Prior To PD Startup

- Conventional Beam
  - Better measure Δm^2_{23}, some sensitivity to θ_{13}
  - MINOS (Fermilab to Minnesota)
  - ICARUS (CERN to Gran Sasso, Italy)
  - OPERA (CERN to Gran Sasso, Italy)
- SuperBeams
  - Good sensitivity to θ_{13}, precision measurement of θ_{23} , some sensitivity to hierarchy
  - T2K (Tokai to Kamioka, Japan)
  - NOvA (Fermilab to Minnesota)
- Reactor
  - Good sensitivity to θ_{13}
  - Double Chooz (France)
  - "Reactor II" (USA, China, Brazil,…..)
- Short Baseline
  - Investigate LSND result
  - MiniBooNE (Fermilab)

3 Scenarios for $SIN^2 2\theta_{13}$ Knowledge Prior to PD Startup



- 3 Scenarios for $SIN^2 2\theta_{13}$

Scenario 1: $SIN^2 2\theta_{13} > \sim 0.04$

Scenario 2: $\sim 0.01 < SIN^2 2\theta_{13} < \sim 0.04$

Scenario 3: $SIN^2 2\theta_{13} < \sim 0.01$

- Old Detectors, Old Beamlines + Proton Driver

Scenario 1:
$\sin^2 2\Theta_{13} > \sim 0.04$

- New Detectors, "Old" Beamlines
  - T2K measurements: 295km, 0.7GeV beam
  - Other Off-Axis Detectors: 710km, 0.7GeV beam
- New Beamlines, "Old" Detectors
  - Pointed towards NOνA Detector (still under study)
- New Detectors and New Beamlines
  - National (Deep) Underground Science Laboratory
  - One Broad-Band Beam (1290km or 2450km)
  - Two Beamlines, one on axis, one off axis (1290km)

Scenario 2:
$\sim 0.01 < \sin^2 2\Theta_{13} < \sim 0.04$

- New Technology: Un-conventional Beams
  - Neutrino Factory
  - If technology breakthrough: high energy beta-beam
  - Natural synergy with muon physics program

Scenario 3:
$\sin^2 2\Theta_{13} < \sim 0.01$

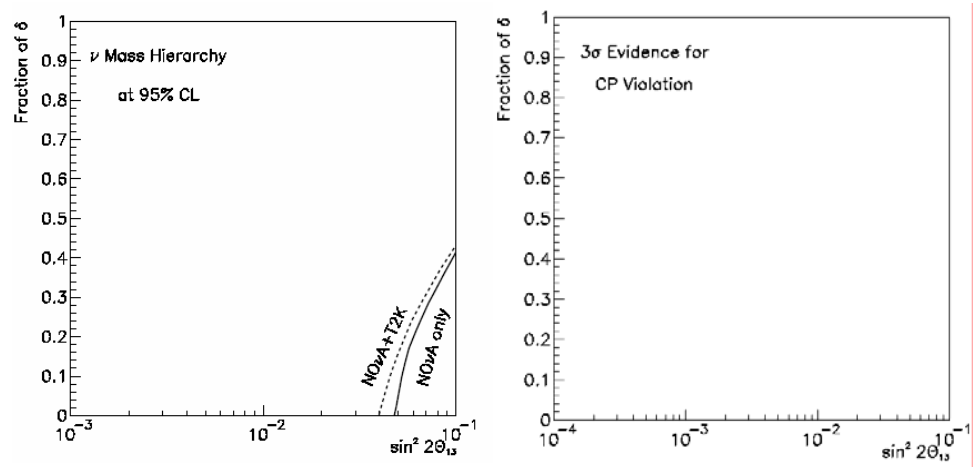
Best Long Term Option depends on what is seen in the next generation, and what happens in the rest of the world!

Summary

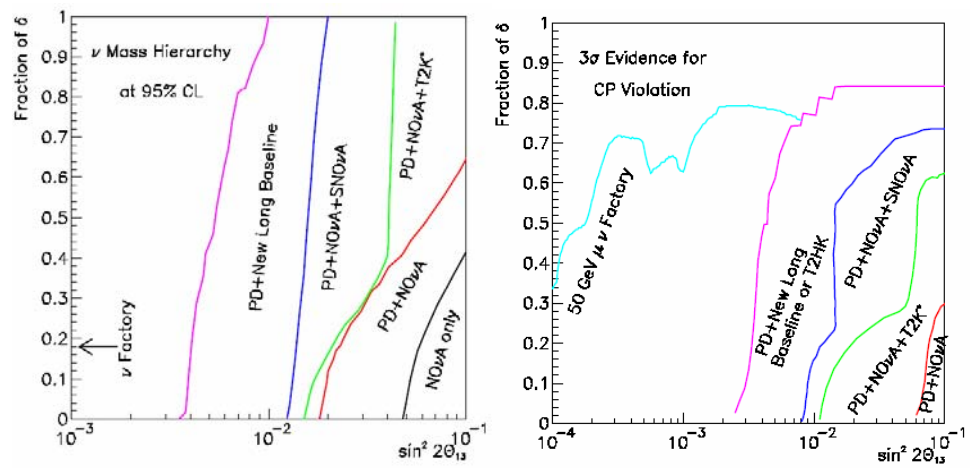
No matter what happens elsewhere, a Fermilab Proton Driver is critical to the global neutrino physics program

There is an extremely strong case to build a Fermilab Proton Driver

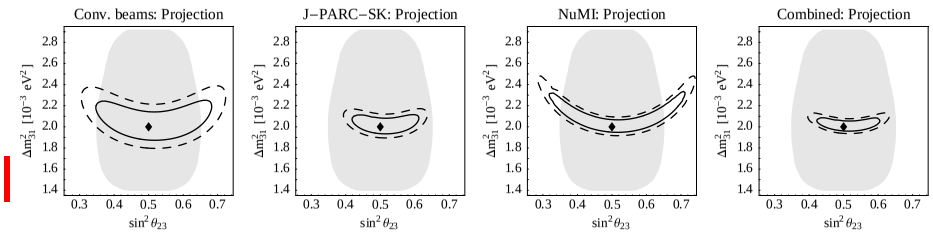
WITHOUT a Proton Driver



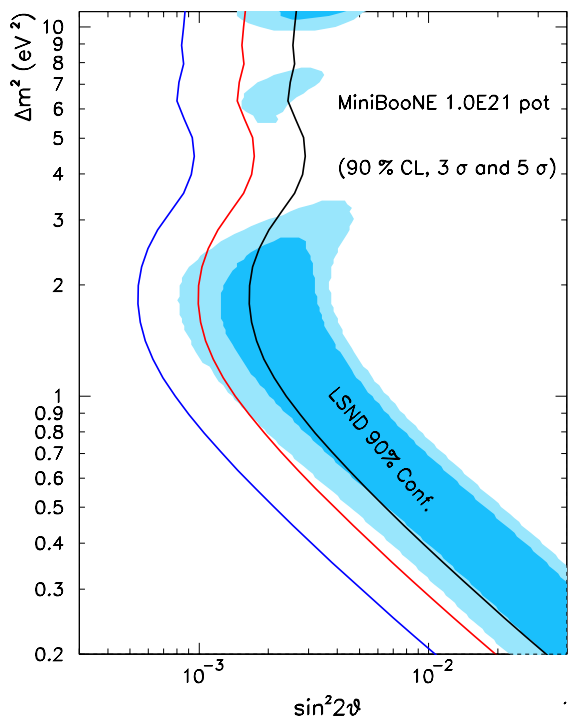
WITH a Proton Driver



3 Special Cases for ν Physics prior to PD Startup



- Special Case 1) θ_{23} is still consistent with maximal



- Special Case 2) MiniBooNE confirms LSND oscillations

- Special Case 3) Something else unexpected is discovered

Muon neutrino disappearance

- To second order in $\sin 2\theta_{13}$ and $\alpha=(\Delta m^2)_{21}/(\Delta m^2)_{31}$:

$$
\begin{aligned}
1 - P_{\mu\mu} &\simeq \sin^2 2\theta_{23}\, \sin^2 \Delta \qquad \leftarrow \text{Beams } \Delta m^2_{31},\, \theta_{23} \\
&- \alpha\, c_{12}^2 \sin^2 2\theta_{23}\, \Delta \sin 2\Delta \\
&+ \mathcal{O}(\alpha^2) + \mathcal{O}\left((\sin^2 2\theta_{13})^2\right) + \mathcal{O}(\alpha \cdot \sin^2 2\theta_{13})
\end{aligned}
$$

Here $\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$ and $\hat{A} \equiv \pm \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}}$.

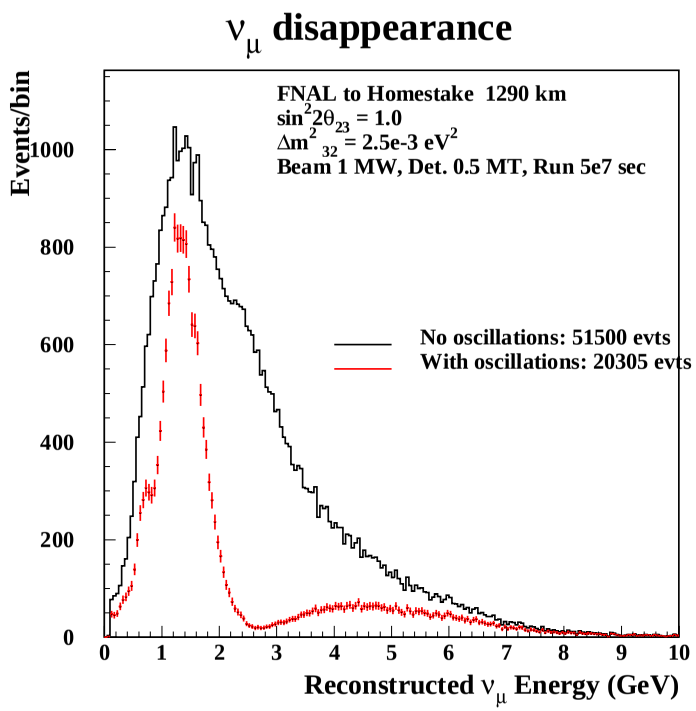
For example: Akhmedov, Johansson, Lindner, Ohlsson, Schwetz, hep-ph/0402175)

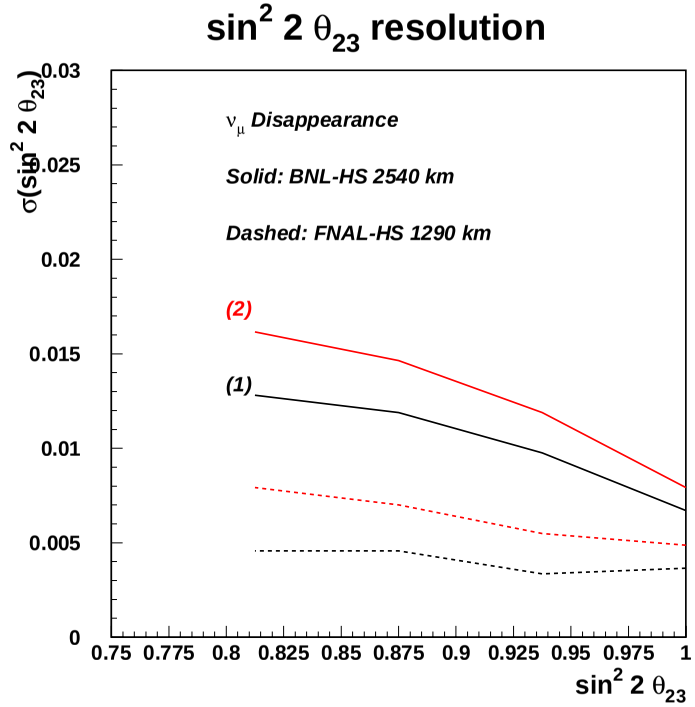
- Contains information on leading atmospheric parameters
- Hardly affected by sub-leading effects, matter effects etc.

  → Almost no correlations

Special Case 1) θ_{23} is still consistent with maximal

- Broadband measurement – FNAL to Homestake

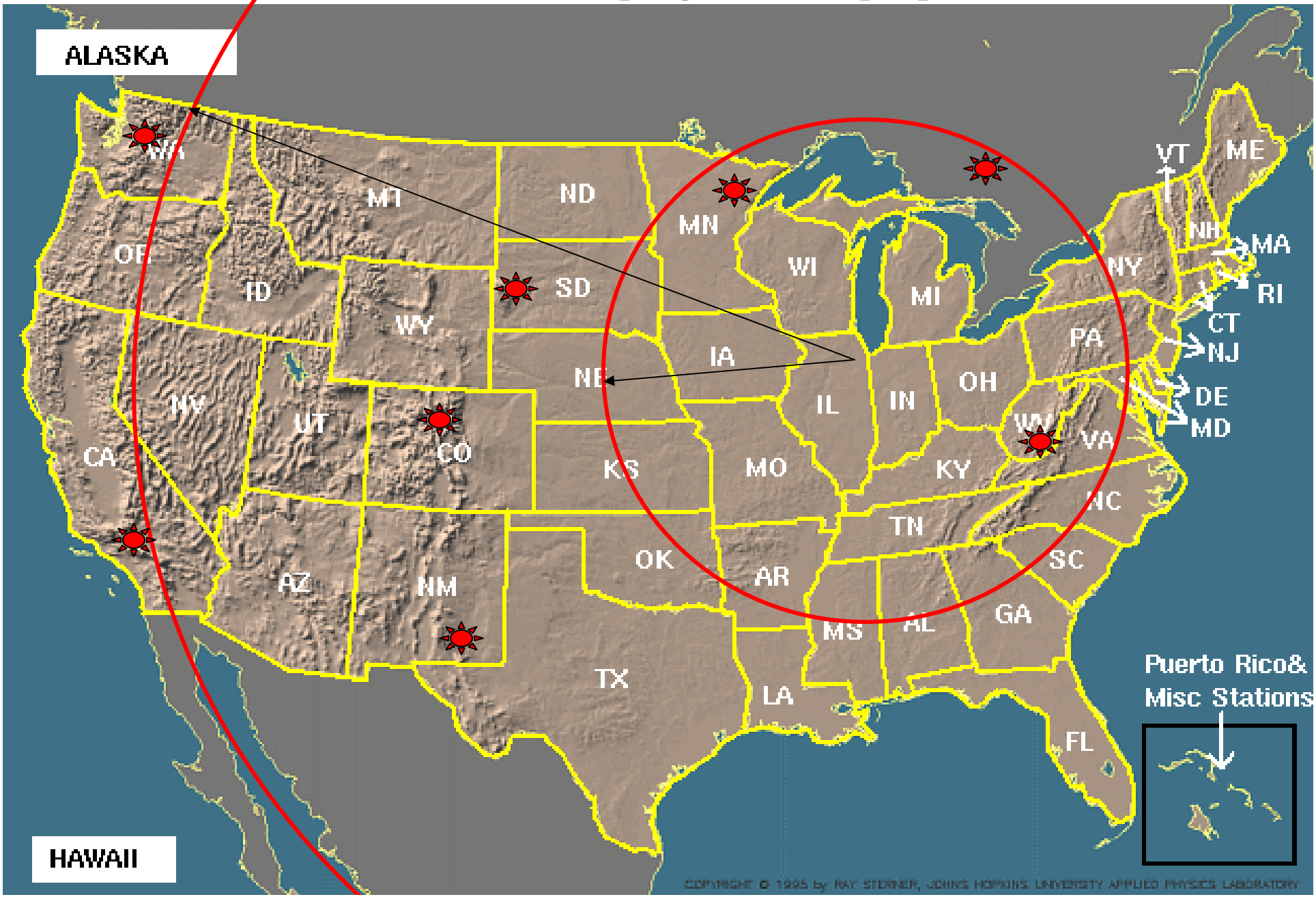




Plots from Milind Diwan

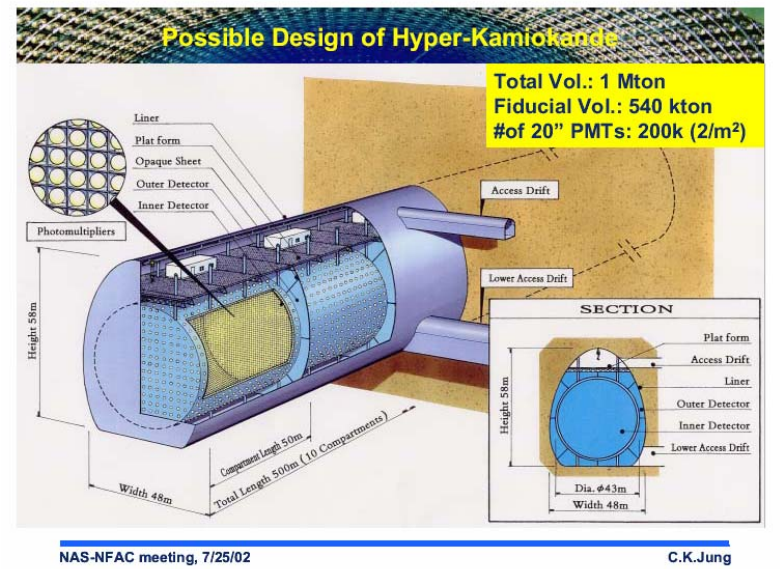
Slide from Gina Ramieka

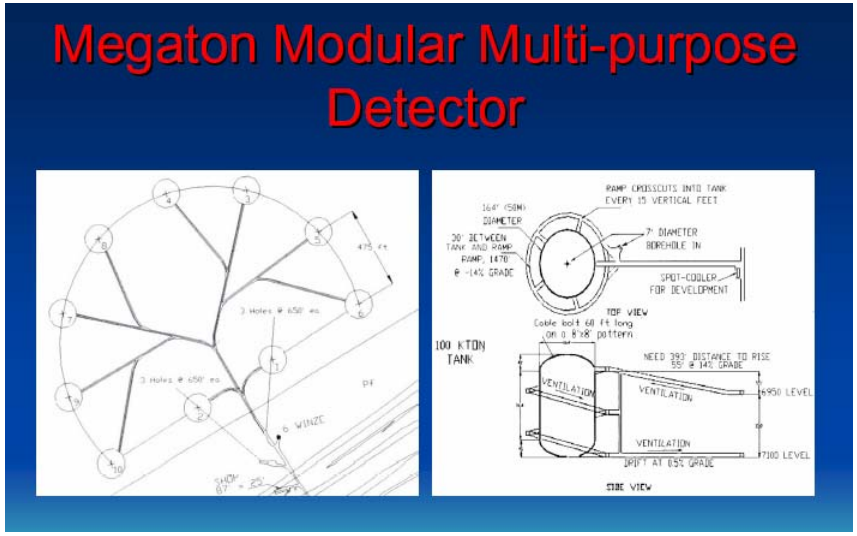
Sites developing DUSEL proposals

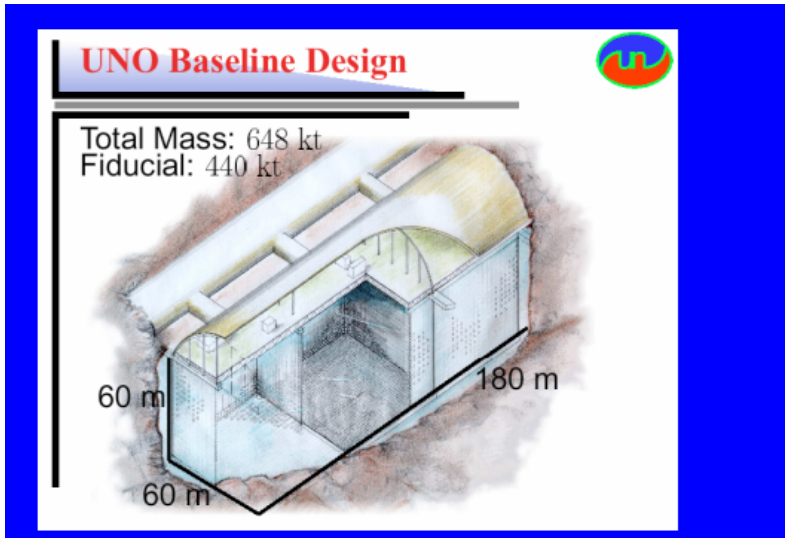


Slide from Gina Ramieka

Detector vs Cavern Size



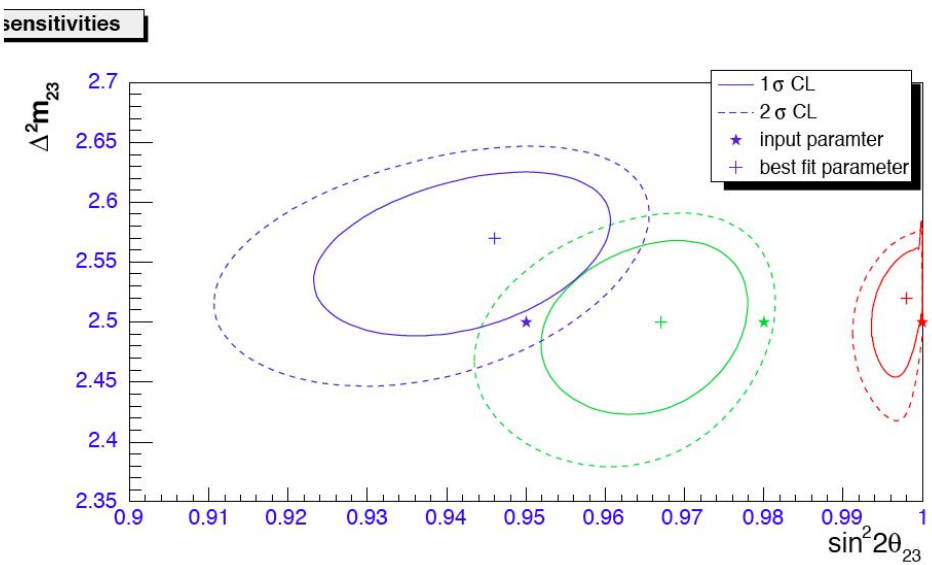




Rock mechanics experts have real reservations about spans of ~100m dimension and >~5000 ft depths;
i.e. Hard to guarantee long lifetime

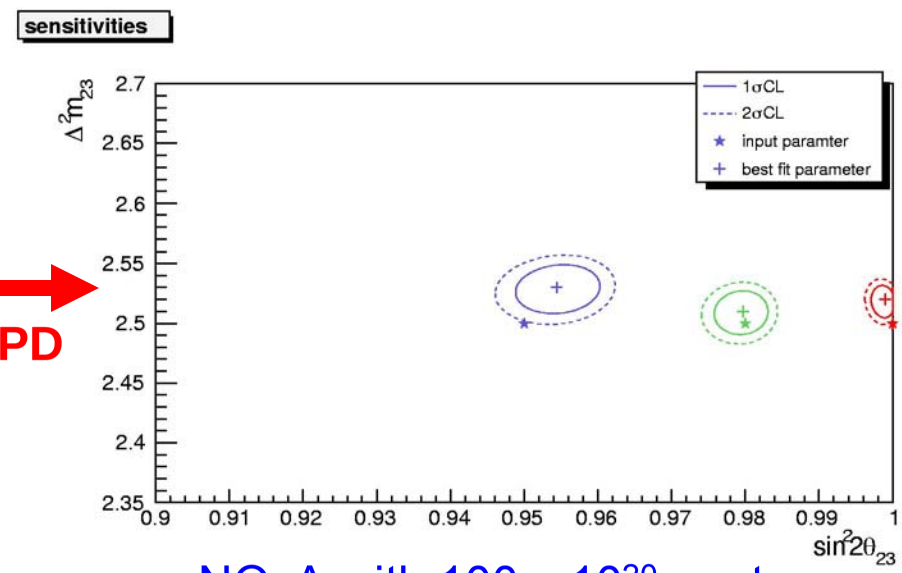
Special Case 1) θ_{23} is still consistent with maximal

- See how close to maximal θ_{23} really is.
- Systematics will be important (see next talk from Jorge)
- Good measurements with muon neutrino disappearance in PD + NOνA, or Scenario 2-style experiments



NOvA with 20 x 10^{20} p.o.t.

+PD



NOvA with 100 x 10^{20} p.o.t.

Plots from Gary Feldman

Special Case 2) MiniBooNE Confirms LSND Oscillations

- Very exciting and rich neutrino physics
  - More than 3x3 mixing
  - Sterile neutrinos
- A wide suite of measurements needed to understand the new landscape
- Short baseline (~1km) measurement become as important of Long Baseline (~800km)
- Both short AND long baseline experiments needed (and others!!)

LSND anomaly/new physics?

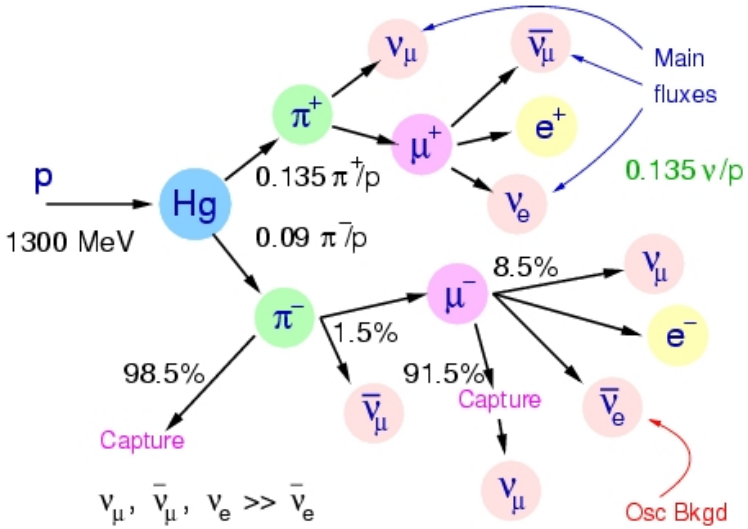
- LSND: $\bar{\nu}_e$ appearance at L≈30m, E ≈30MeV
  - Therefore Δm^2_{LSND} = O(1eV²)

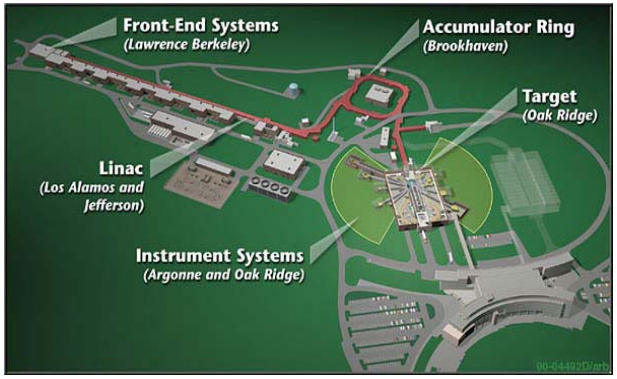
- 3 active, light neutrinos (Z width from LEP)
- But $\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$
- If all 3 measurements are oscillations something fundamental has to give

- Sterile neutrino(s) are one possibility
  - add extra neutrino flavours, but don't allow them to interact weakly

Stopped Pion/Muon Neutrino Source

- Neutrino Production from a Stopped Pion/Muon Source: nucl-ex/0309014 hep-ex/0408135





	FNAL (8 GeV)	FNAL (5 GeV)	SNS
P/yr	4.9×10^{22}	4.9×10^{22}	2.2×10^{23}
DAR $\nu(\nu/P)$	1.5	0.9	0.13
DAR $\nu(\nu/yr)$	7.3×10^{22}	4.4×10^{22}	2.9×10^{22}

FNAL ~2.5 x SNS

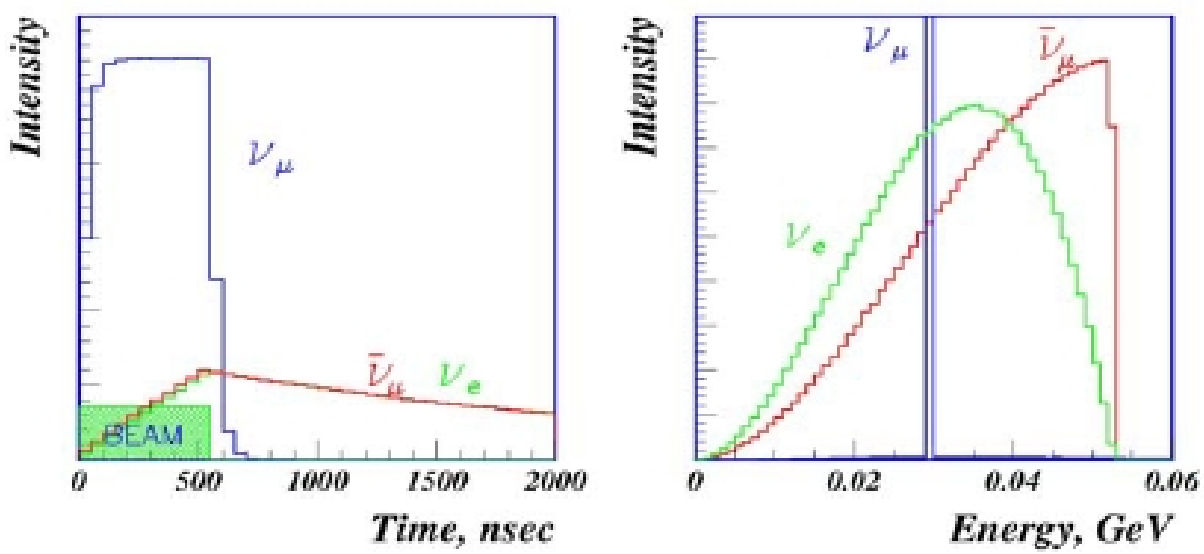
Stopped Pion/Muon Neutrino Source

- Neutrino Flux from a Stopped Pion/Muon Source:

$\pi^+ \rightarrow \mu^+ \nu_\mu, \quad \tau = 26 nsec$

$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e, \quad \tau = 2.2 \mu sec.$

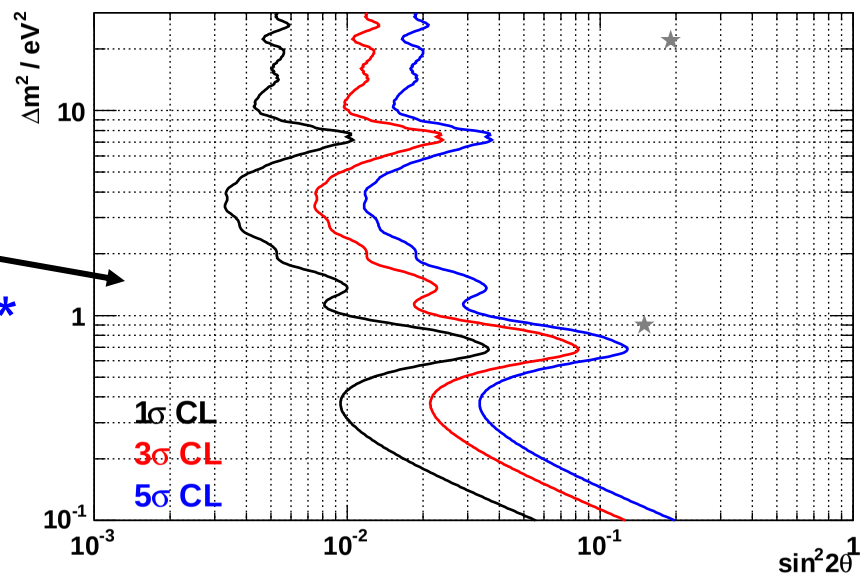
event types	$0 \rightarrow 0.695\mu$sec	$0.695 \rightarrow 5\mu$sec	$> 5\mu$sec
π^+ DAR and $\pi^\pm$ DIF events	96.3%	3.7%	0
μ^+ DAR and oscillation candidates	14.3%	73.6%	12.1%



Special Case 2) MiniBooNE Confirms LSND Oscillations

- Precision measurements with μ and π decay at rest.
- SNS will get there before PD but..
  - Higher stats and better target control with PD
- Shape measurement of $\bar{\nu}_e$ from μ decay spectrum
  - Precision measurement of LSND oscillation parameters

- Two detector, explicit, neutral current searches for sterile neutrinos
- Uses $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$ (15.11MeV)

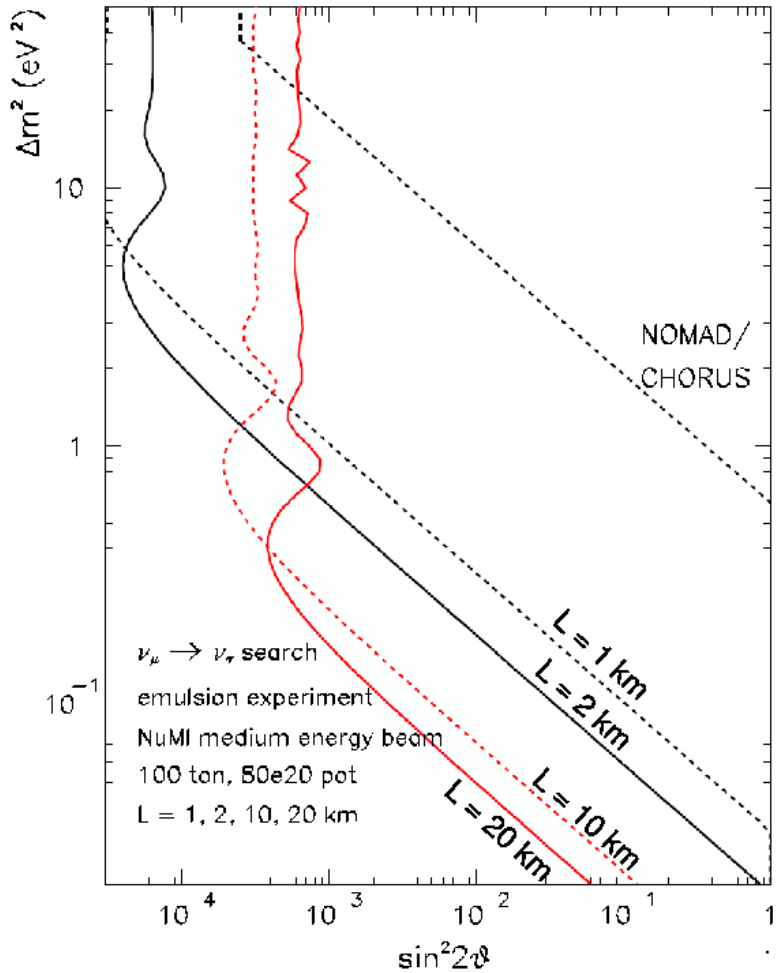


Plot from Gordon McGregor

Special Case 2) MiniBooNE Confirms LSND Oscillations

- Search for short(ish) baseline tau neutrino appearance

- Use NuMI beam and OPERA style emulsion detector
- Medium Energy Beam
- 1-20km baselines appropriate for LSND L/E and τ threshold



Plot from Andrew Bazarko

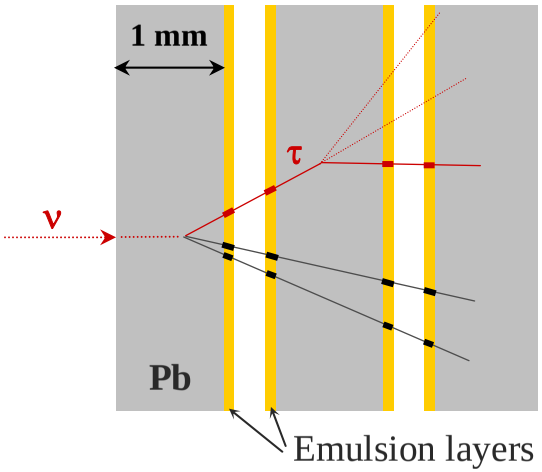
Tau detection with a large detector

OPERA: kiloton emulsion detector

Target:
Emulsion bricks
Scintillator strip trackers

Magnetic spectrometer:
RPCs and drift tubes

Slide from Andrew Bazarko



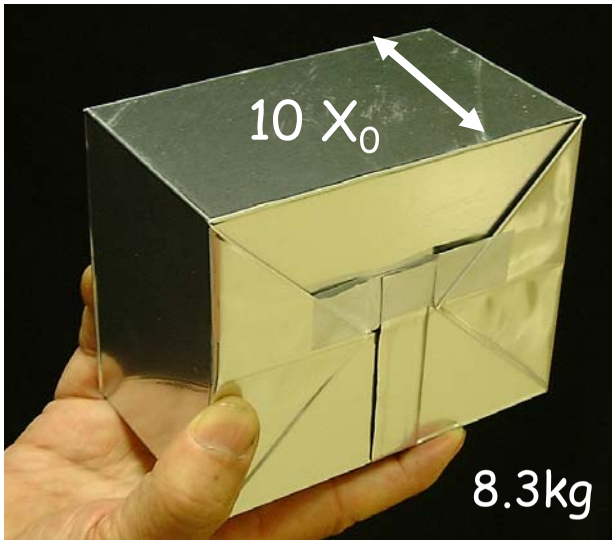
The basic unit is the emulsion-Pb brick

56 Pb sheets (1 mm) and
emulsion sheets (Fuji, industrial production)

ECC – emulsion cloud chamber

each brick is a stand-alone detector:

neutrino vertex and kink topology
dE/dx p/m separation at low energy
electron identification
hadron momentum via multiple scattering



10.2 x 12.7 x 7.5 cm

In total: ~206k bricks
and 1.76 ktons

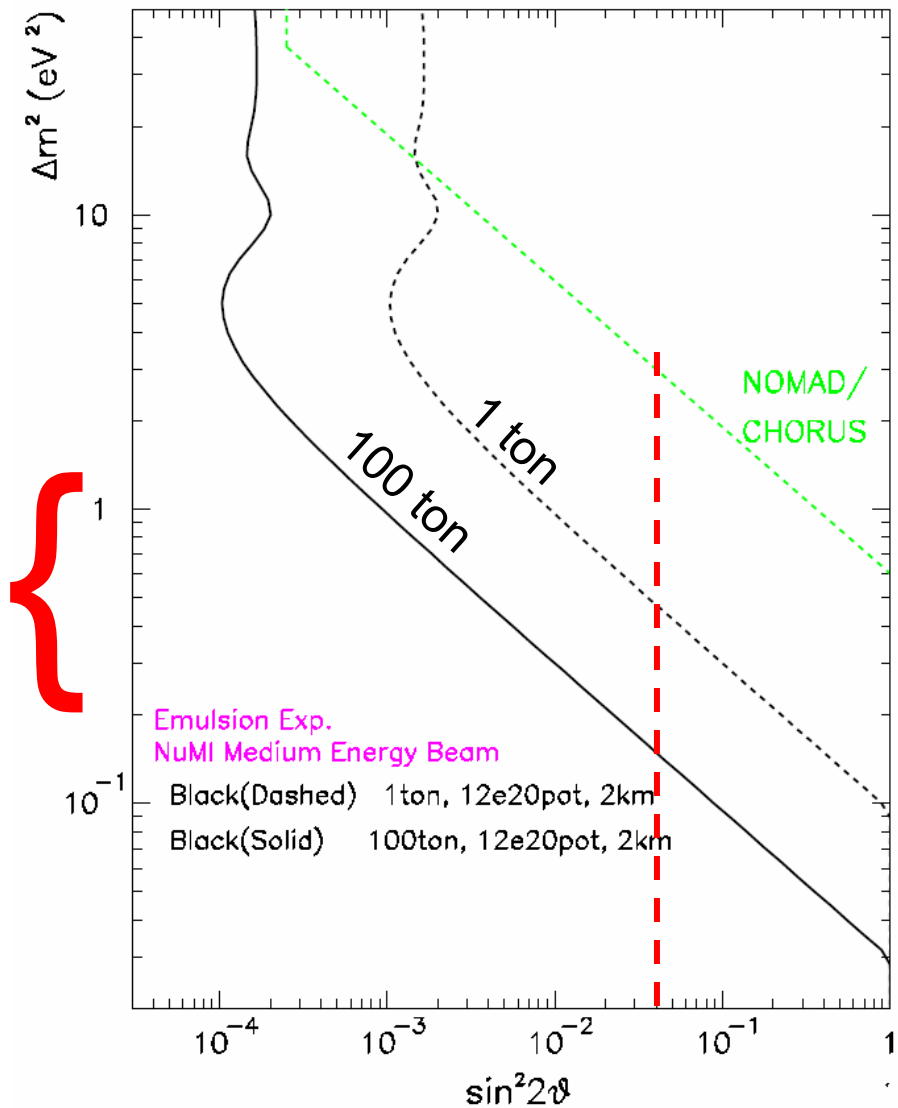
Plot from Andrew Bazarko

NuMI med energy
12e20 p.o.t.

L = 2 km

small Δm^2 →
(detector mass)$^{1/4}$

high Δm^2 →
(detector mass)$^{1/2}$

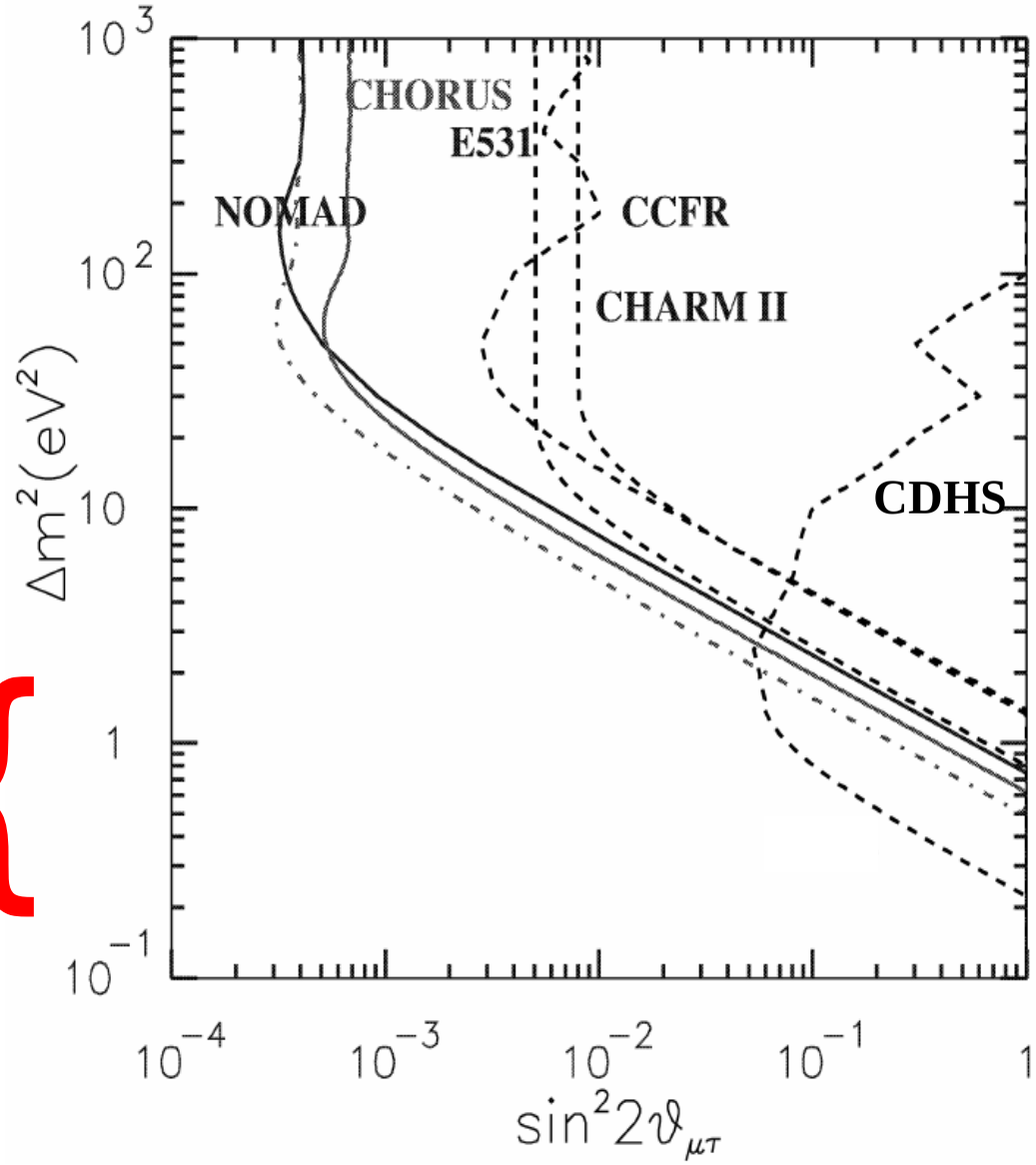


12e20 p.o.t. 1 ton @ 2km N_τ = 9857 N_μ=795k N_{bkgd}=23.8

Current $\nu_\mu \rightarrow \nu_\tau$ limits

direct limits

region of interest



Special Case 3) Something Else Unexpected is Discovered

- We should ‘EXPECT’ this!
- The Neutrino – UNEXPECTED
- Solar Neutrino Oscillations – UNEXPECTED
- Atmospheric Neutrino Oscillations – UNEXPECTED
- Large Mixing Angles – UNEXPECTED

- Bottom Line: Anything unexpected in upcoming accelerator neutrino experiments will be a rare process and further investigation will require the large statistics only deliverable by a Proton Driver

Summary

- Possible Landscapes for Neutrino Physics at Proton Driver Startup
  - Scenario 1: $SIN^2 2\theta_{13} > \sim 0.04$
    - With existing beamline and detectors Proton Driver has great chance to get mass hierarchy and some CP violation reach
  - Scenario 2: $\sim 0.01 < SIN^2 2\theta_{13} < \sim 0.04$
    - With new beamlines and/or new detectors Proton Driver has great chance to get mass hierarchy and some CP violation reach
  - Scenario 3: $SIN^2 2\theta_{13} < \sim 0.01$
    - With new beamlines and/or new detectors Proton Driver would significantly improve knowledge of θ_{13} and form the basis of a Neutrino Factory.

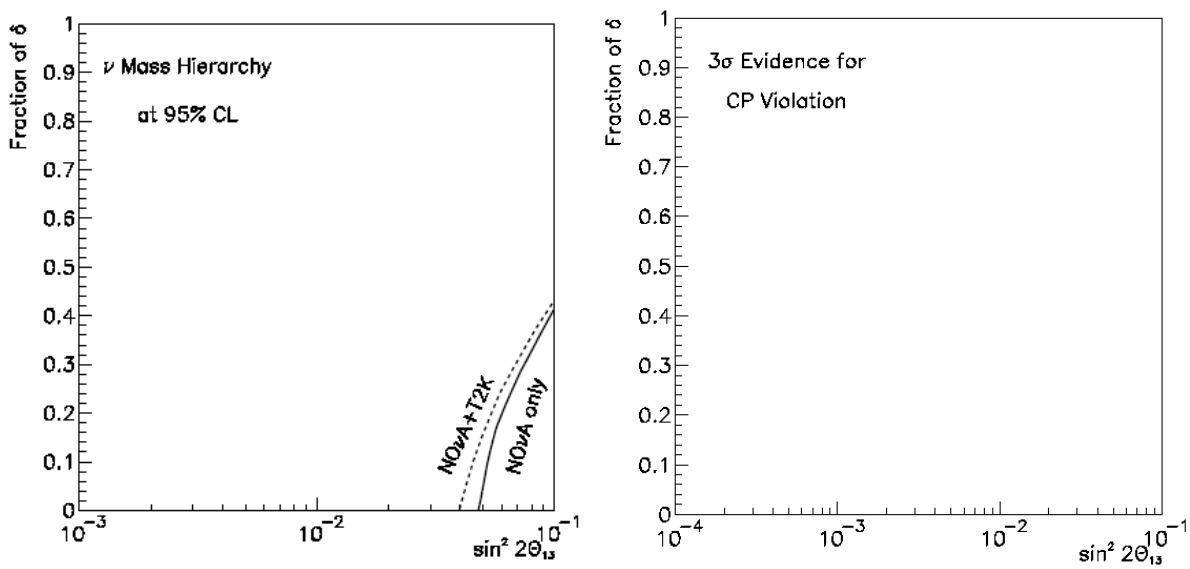
Summary

- Possible Landscapes for Neutrino Physics at Proton Driver Startup
  - Special Case 1: θ_{23} is still consistent with maximal
    - Proton Driver and existing beamline and detector will powerfully probe the possibility of a new symmetry
  - Special Case 2: MiniBooNE confirms LSND oscillations
    - Proton Driver will feed an array of new experiments exploring a rich, new landscape
  - Special Case 3: Something else unexpected is discovered
    - Further understanding will need the statistics that only a Proton Driver can deliver

Discovery Potential

- Answer depends MOSTLY on size of θ_{13}, but…
  - The farther away δ is from 0 or π, the easier it will be to measure as being non-zero
  - If mass hierarchy and CP are in "same direction" that also helps…
- No matter what,
- we need more
- protons…

"Map" to define the parameter space:

As function of $\sin^2 2\Theta_{13}$, over how much of δ can each physics goal be met?

Reach without a new Proton Driver at FNAL: