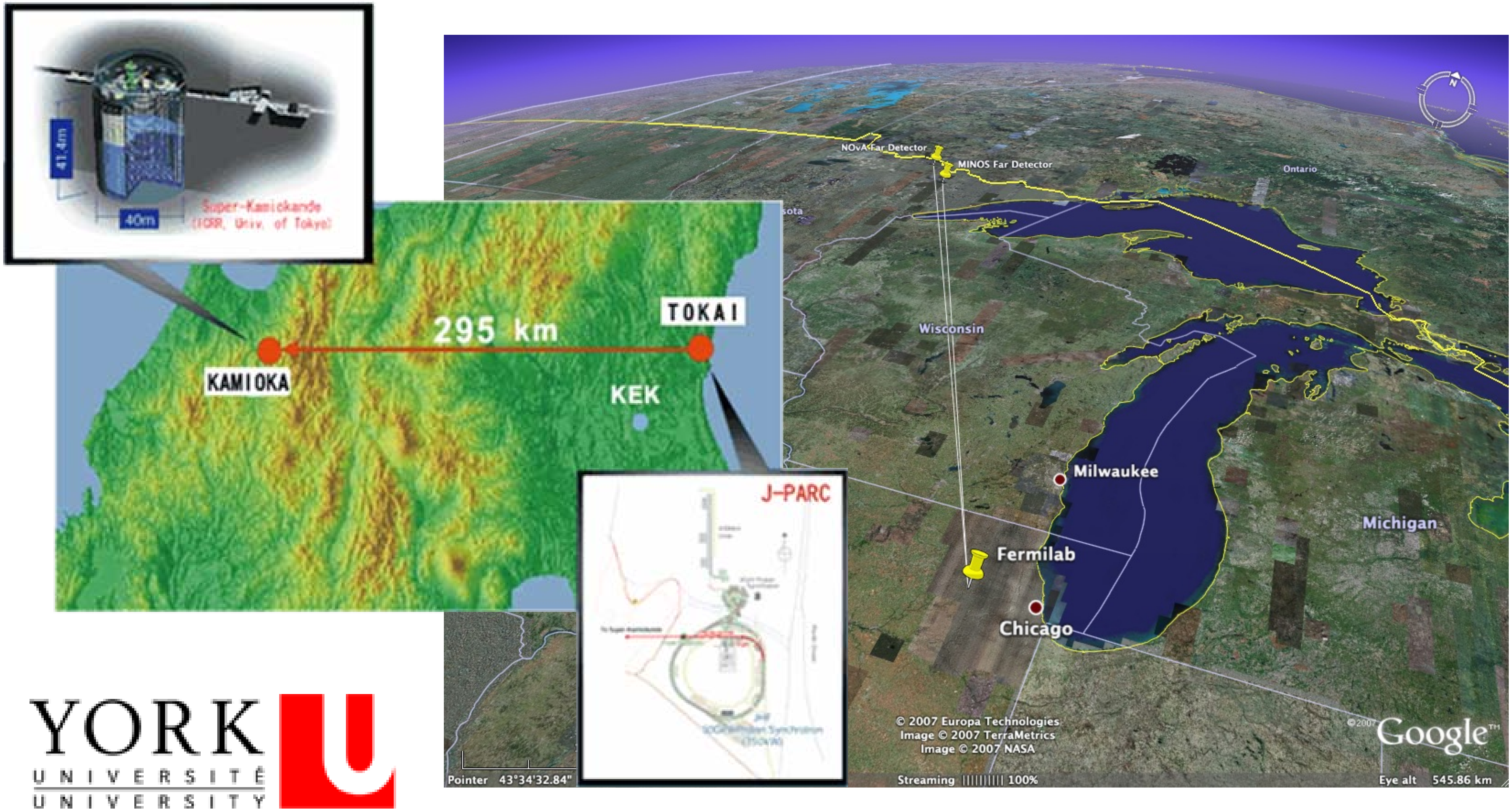
Accelerator Neutrino Experiments



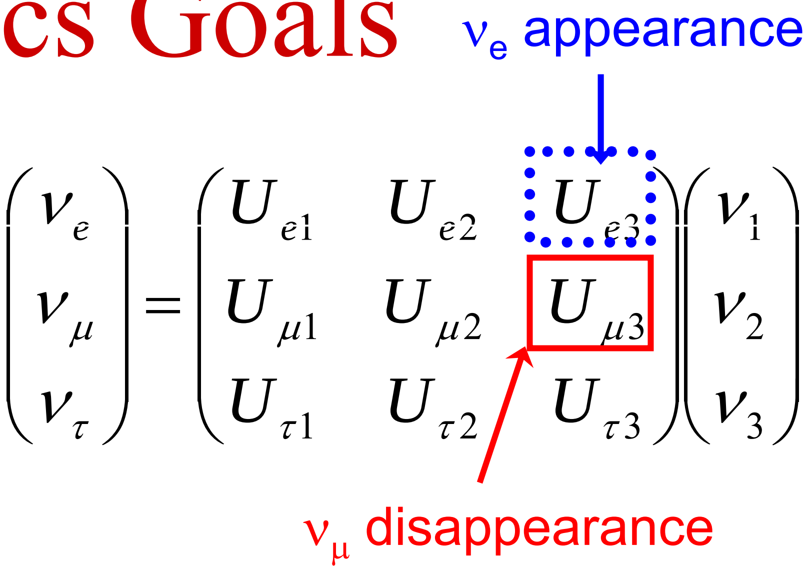
And DEEP CORE

Workshop on “Low Energy”
Neutrino Physics and Astrophysics

Scott Menary –York University

Accelerator Long-Baseline Neutrino Physics Goals

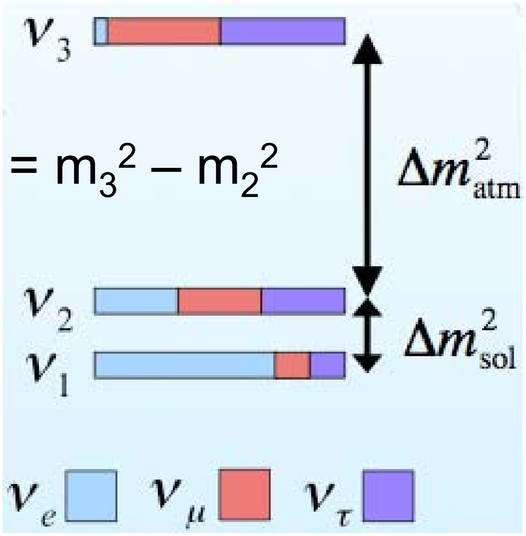
- Test the ν_μ to ν_x oscillation hypothesis
  - Measure precisely $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$
- Search for ν_μ to ν_e oscillations
  - sensitive to θ_{13}
- Determine the mass hierarchy
- Measure δ_{CP}



ν_e appearance

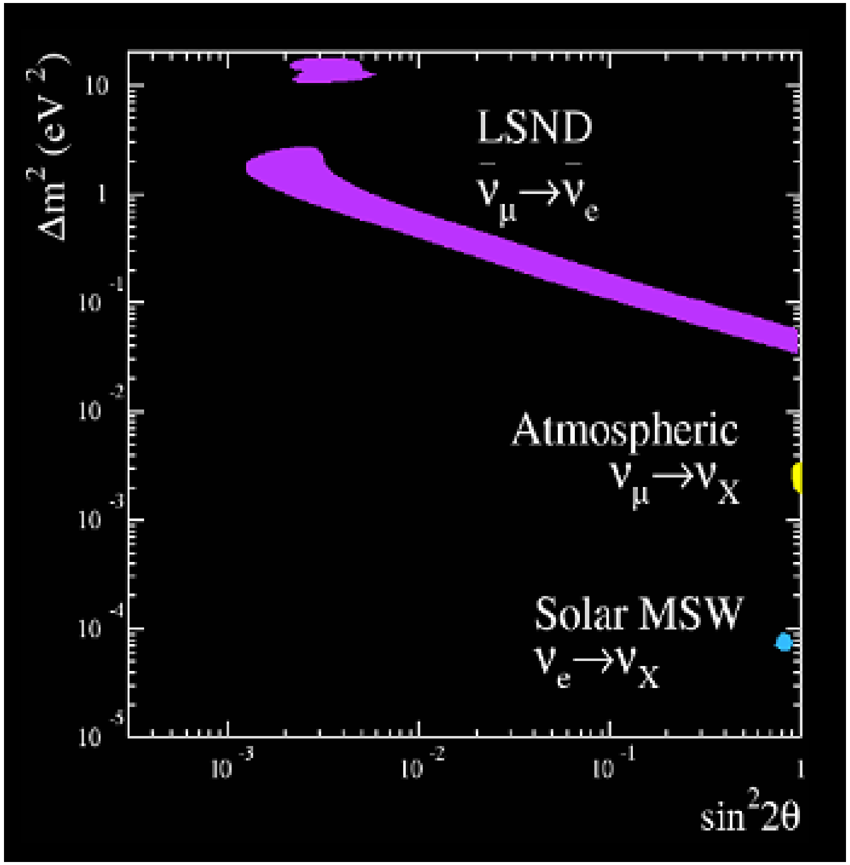
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & \boxed{U_{e3}} \\ U_{\mu 1} & U_{\mu 2} & \boxed{U_{\mu 3}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν_μ disappearance

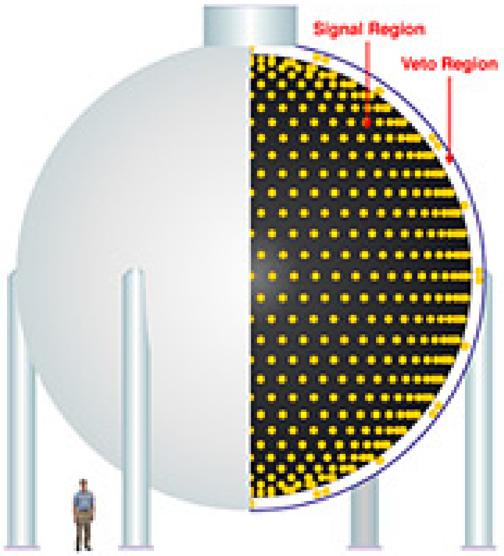


$\Delta m^2_{32} = m_3^2 - m_2^2$

MiniBooNE - A search for ν_e appearance at $\Delta m^2 \sim 1$ eV^2

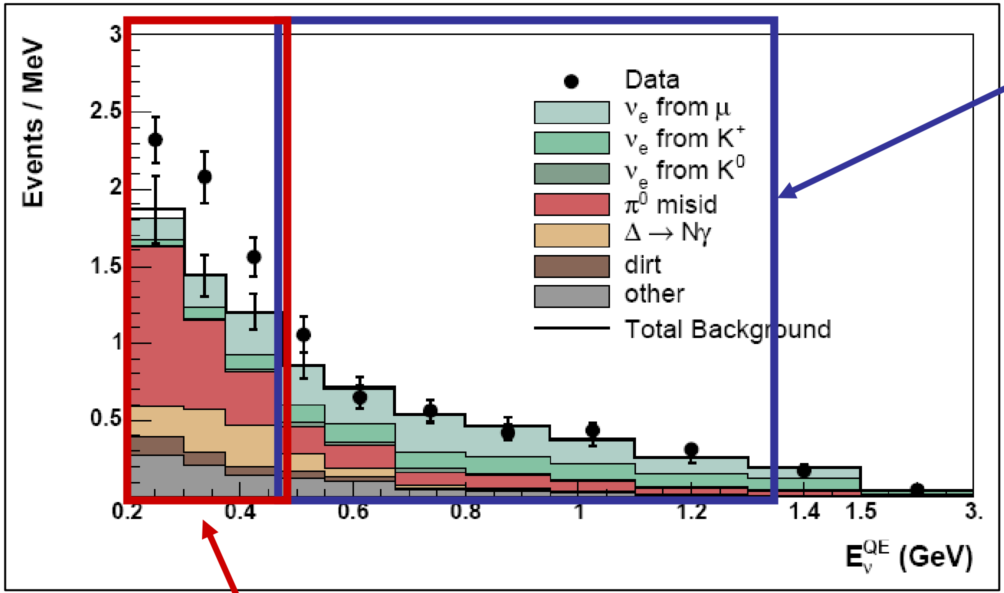


MiniBooNE Detector



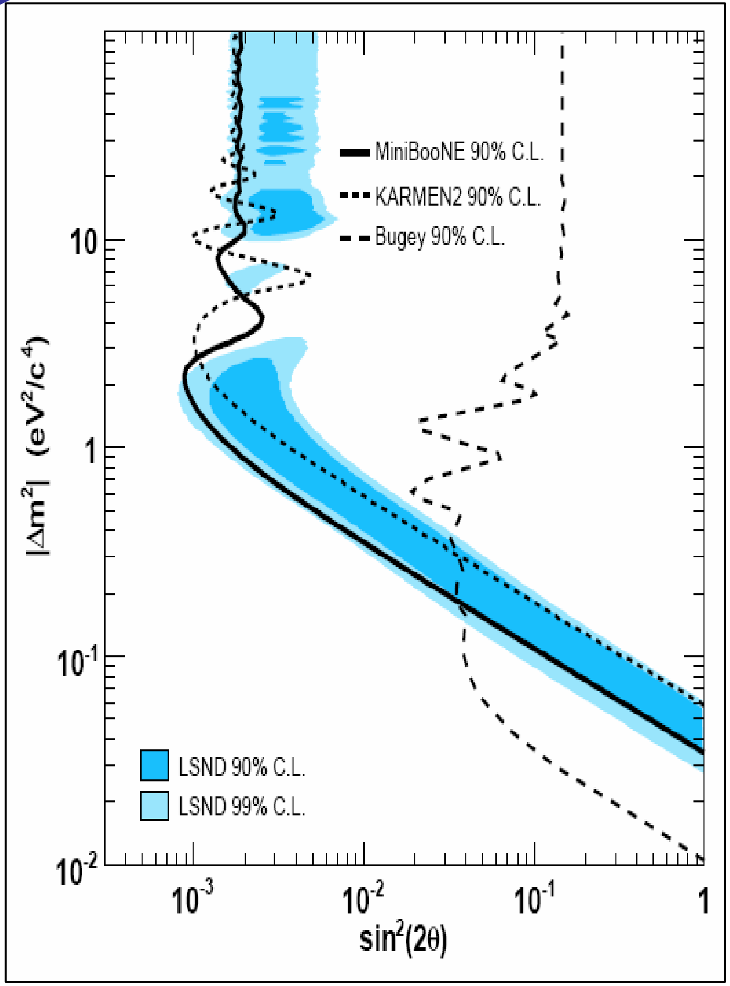
LSND Best fit: $\sin^2(2\theta) = 0.003$, $\Delta m^2 = 1.2$ eV^2

Observed no excess consistent with the LSND two-neutrino oscillation



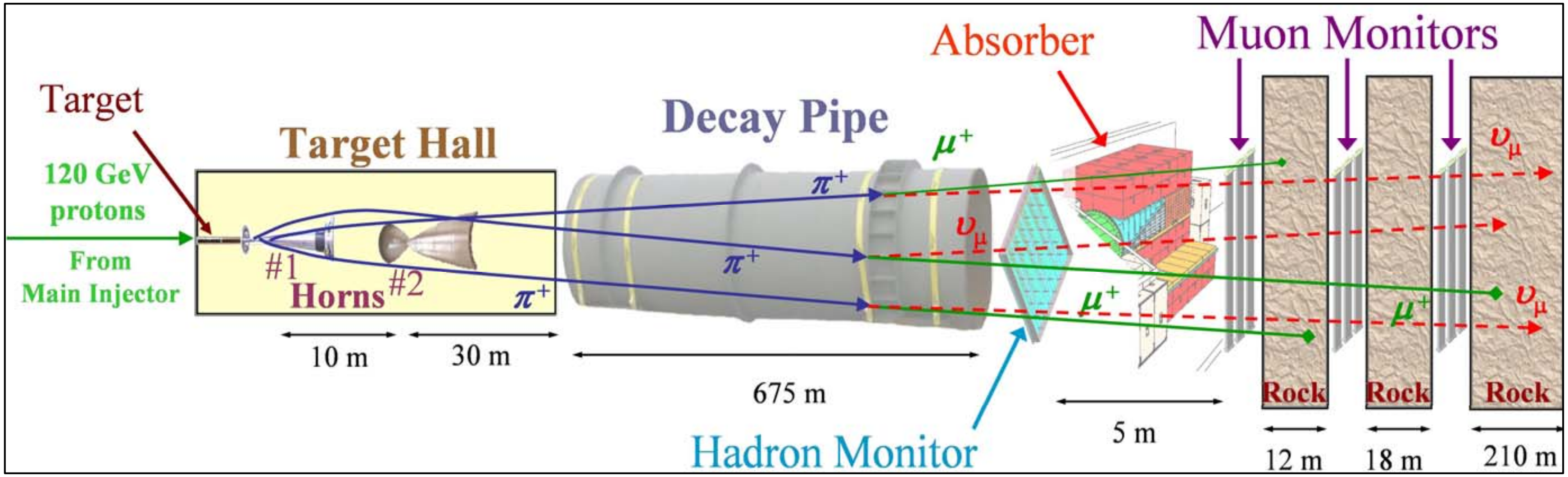
$\nu_\mu \rightarrow \nu_e$ signal region

low energy excess region
128.8 ± 43.4 excess events (3.0σ)

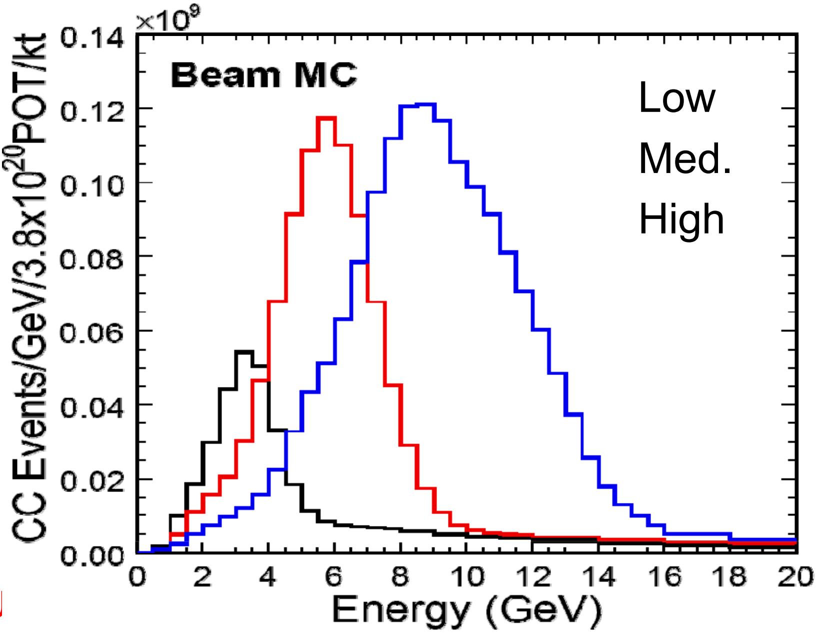


No sign of excess in recent $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ data

Neutrino Beam (NuMI)



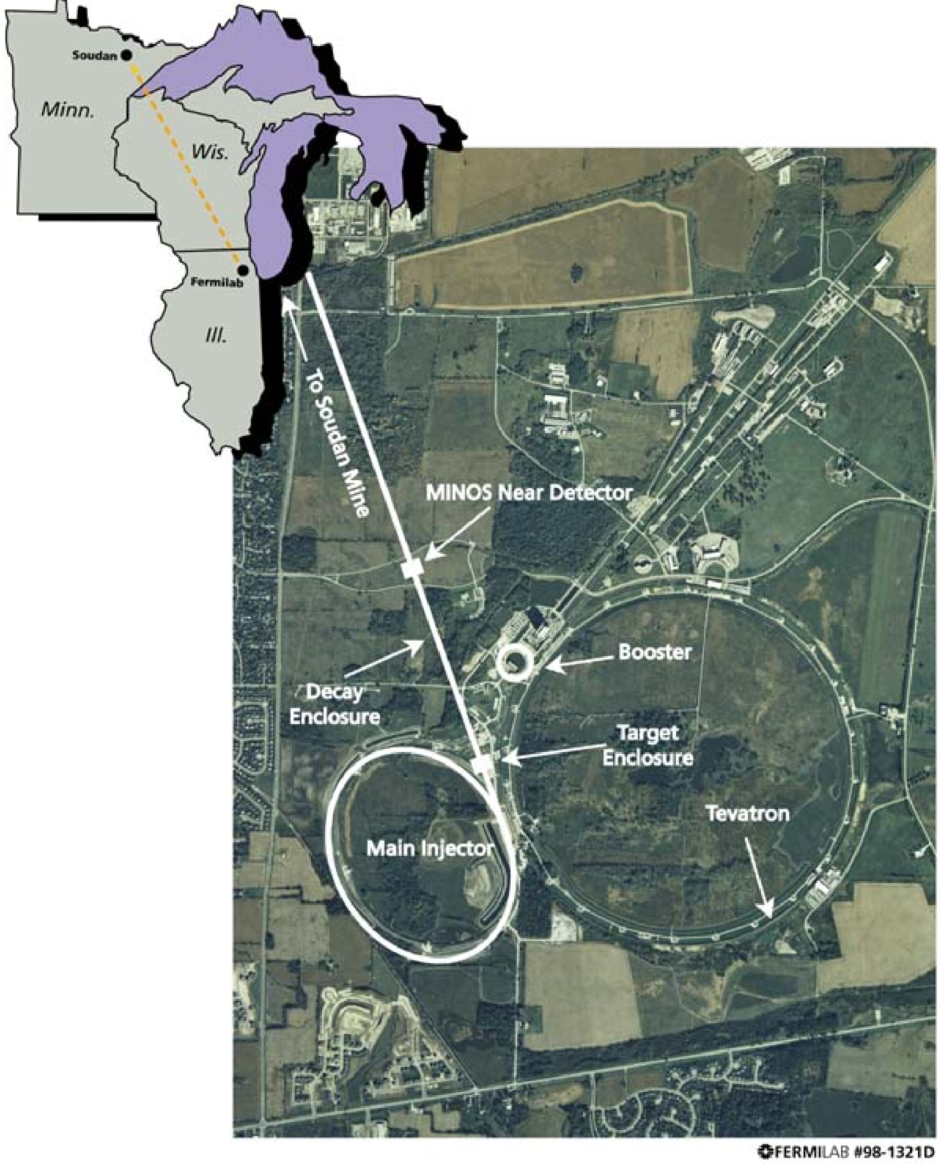
- 120 GeV protons strike target
- 10 μs long pulse of $3\text{x}10^{13}$ protons every 2.2 seconds (275 kW)
- Two magnetic horns focus secondary π/K
  - decay of π/K produce neutrinos
- Variable neutrino beam energy

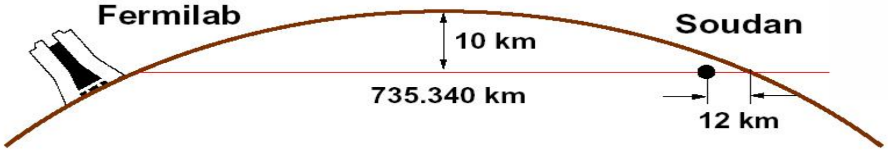


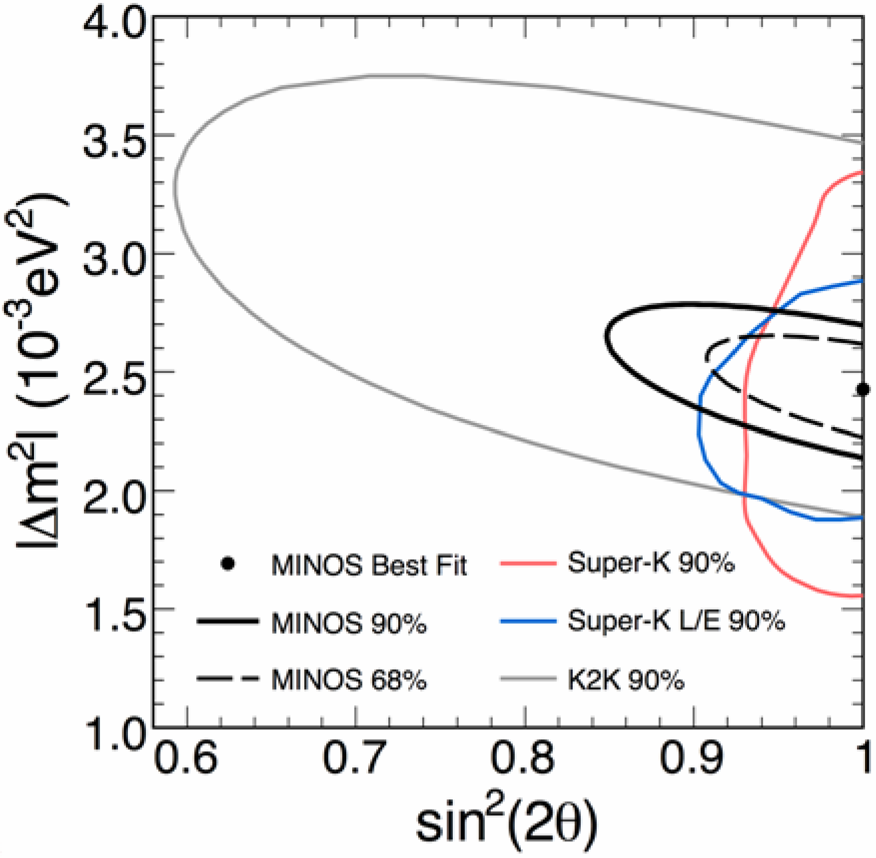
MINOS

$|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}\ \mathrm{eV}^2$

(68% C.L.)







rsity

Far Detector Energy Spectrum

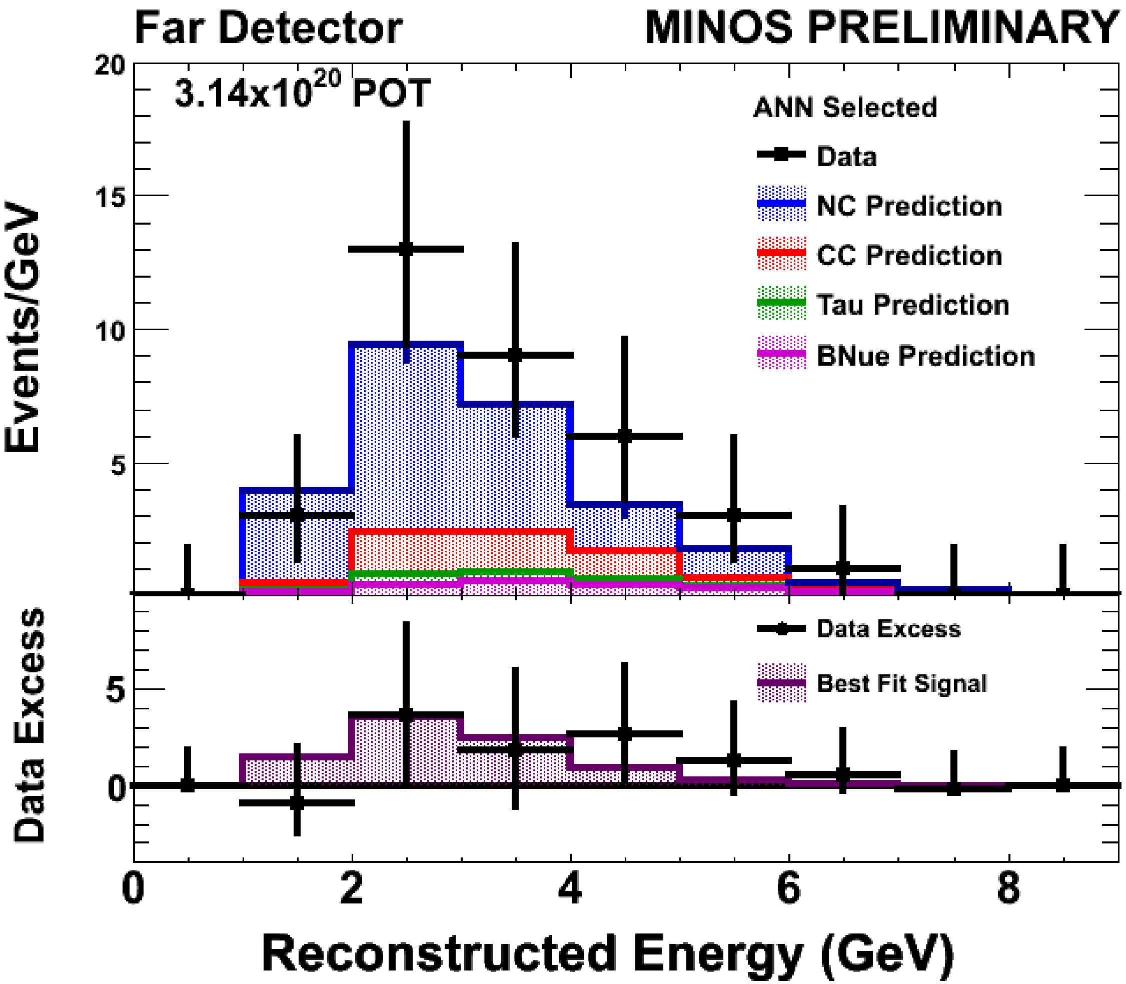
- A blind analysis was performed:
  - all procedures for calculating background and signal were finalised before the Far detector data were looked at
- Expected background:

27 ± 5(stat) ± 2(sys)

- Observed events:

35

- A 1.5σ excess over background prediction



Fit the data to the oscillation hypothesis, obtain the signal prediction for the best fit point

Allowed Region

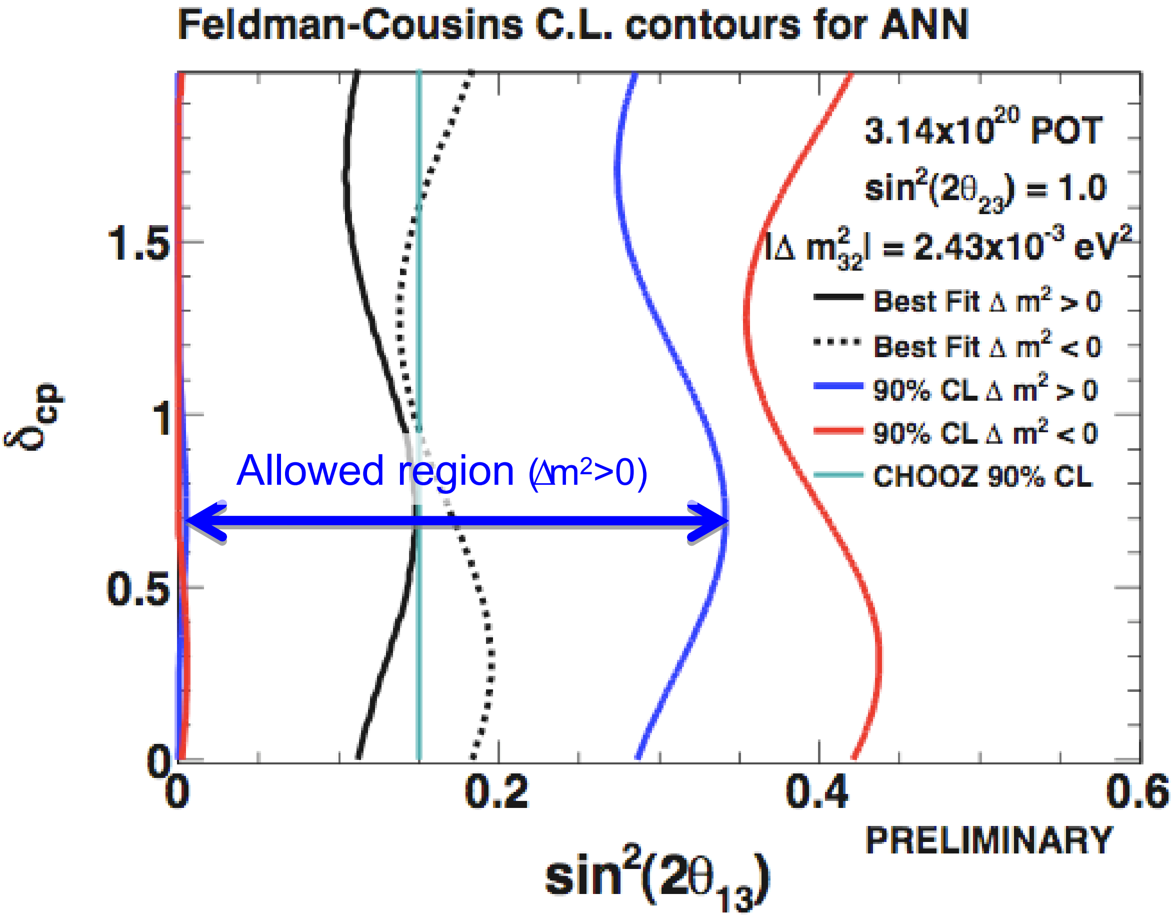
- A Feldman-Cousins method was used
- Fit simply to the number of events from 1-8 GeV
- Best fit and 90% C.L. limits are shown:
  - for both mass hierarchies
  - at MINOS best fit value for Δm^2_{32} & $\sin^2(2\theta_{23})$
- Results:

Normal hierarchy (δ_{CP}=0):

$\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)

Inverted hierarchy (δ_{CP}=0):

$\sin^2(2\theta_{13}) < 0.42$ (90% C.L.)



Jeff Hartnell, La Thuile 2009

CERN Neutrinos to Gran Sasso

long base-line appearance experiment:

- Produce muon neutrino beam at CERN
- Measure tau neutrinos in Gran Sasso

Experiments:
OPERA (1200 ton), ICARUS (600 ton)

$4.5 \cdot 10^{19}$ pot/year (200 days, nominal intensity)

→ $2.2 \cdot 10^{17}$ pot/day ~10^{17} ν_μ /day~10^{11} ν_μ /day in detector

→ 3600 ν_μ interactions/year in OPERA (charged current interactions)

→ 2-3 ν_τ interactions detected/year in OPERA

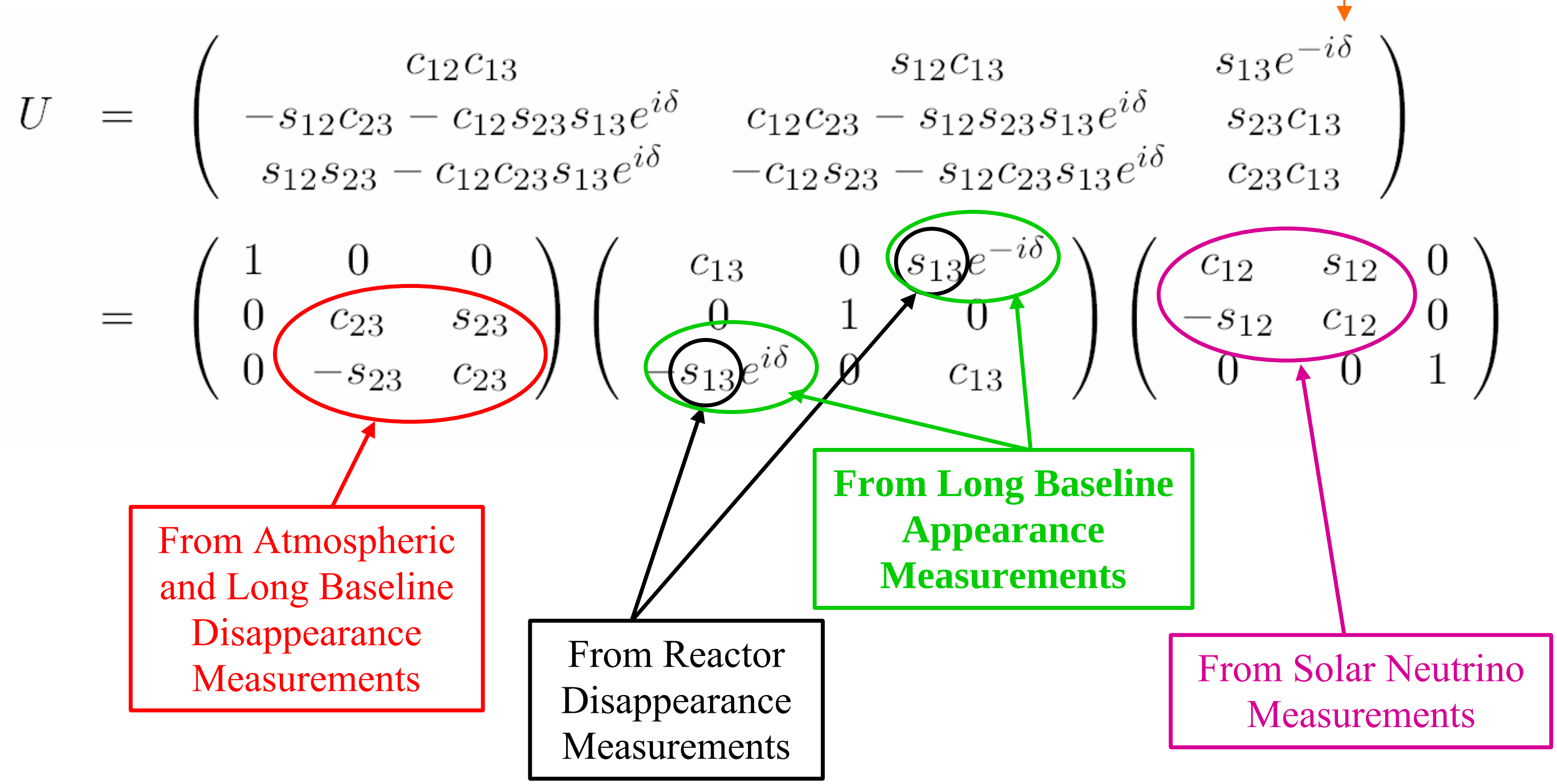
~1ν_τ observed interaction with $2 \cdot 10^{19}$ pot

CNGS Run 2008: $1.78 \cdot 10^{19}$ pot

The Known and Unknown in Neutrino Physics

The CP Violation Parameter

Three Neutrino PMNS Mixing Matrix:



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

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

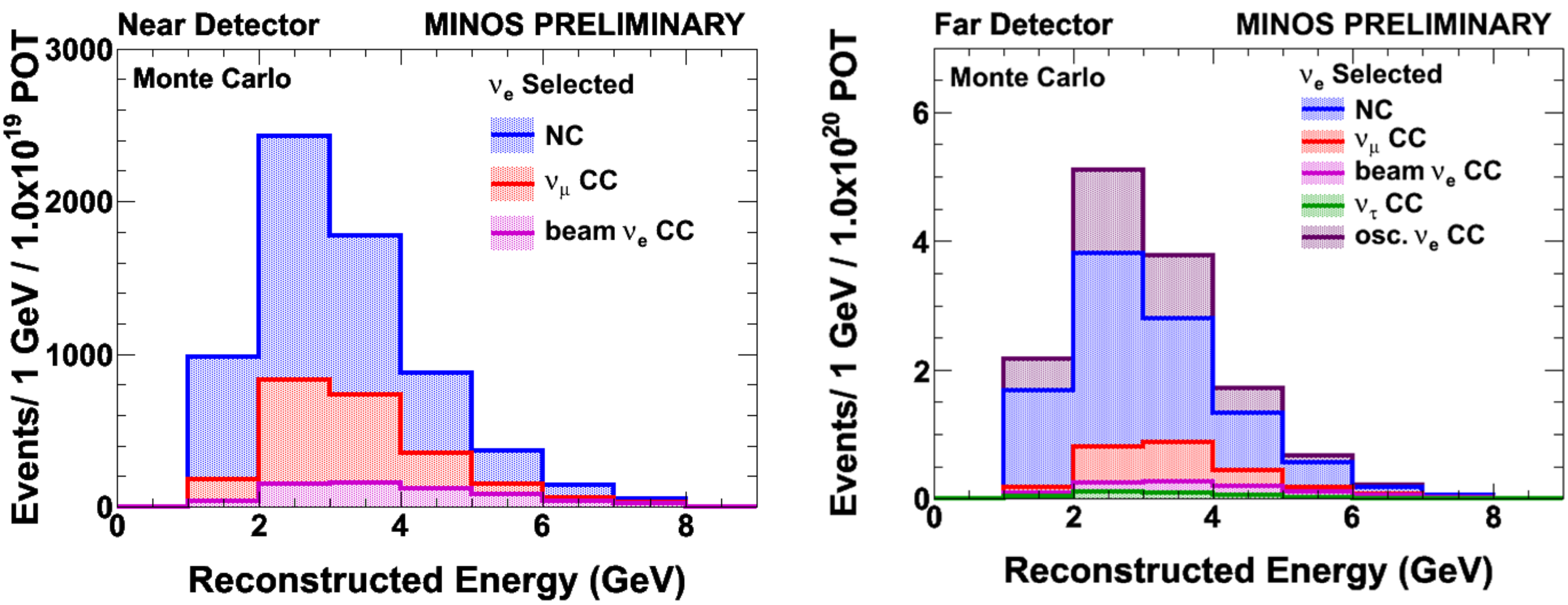
From Solar Neutrino Measurements

In Vacuum the Oscillation Probability is:

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$
  - $P_3 = \quad J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

  where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})$ x $\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

MINOS MC Event Composition in 2 Detectors



- Primary background from NC events, also
  - high-y ν_μ CC, beam ν_e, oscillated ν_τ at Far detector
- Right plot: purple shows an appearance signal at the Chooz limit ($\sin^2 2\theta_{13}=0.15$)

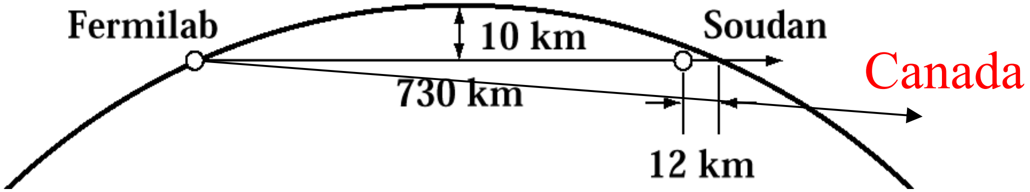
- In matter, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.
  - Different baselines "pick out" different terms which helps to break some of the degeneracies.

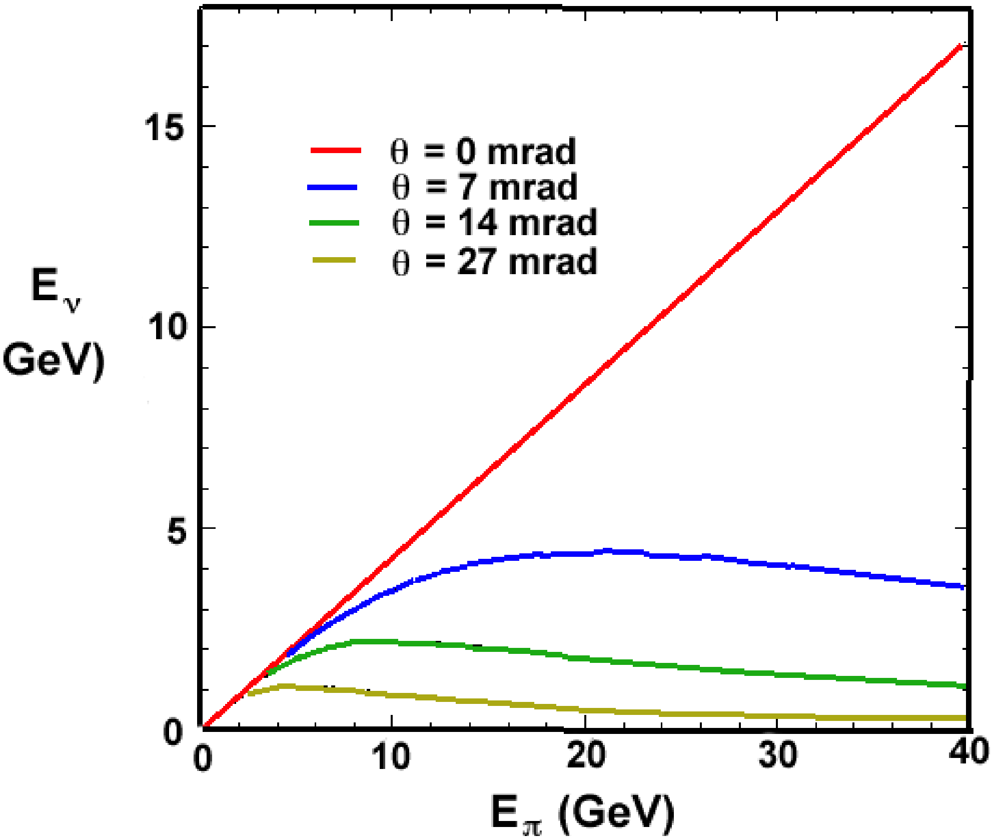
$$\boldsymbol{P} = \boldsymbol{f}(\sin^2 2\theta_{13}, \delta, \mathrm{sgn}(\Delta \boldsymbol{m}_{13}^2), \Delta \boldsymbol{m}_{12}^2, \Delta \boldsymbol{m}_{13}^2, \sin^2 2\theta_{12}, \sin^2 2\theta_{23}, \boldsymbol{L}, \boldsymbol{E})$$

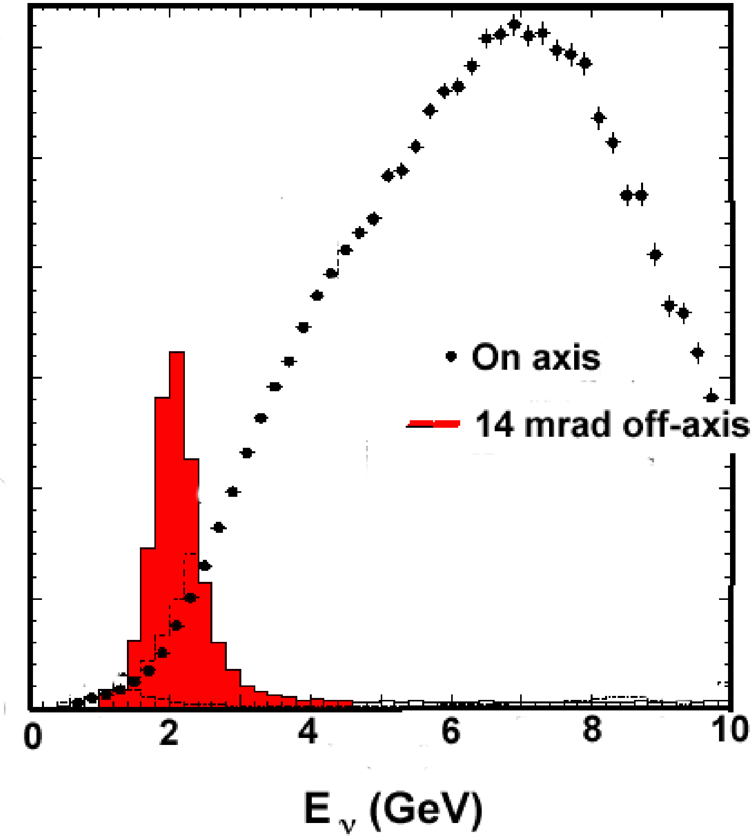
3 unknowns, 3 parameters under control L,E + ν_μ /anti ν_μ

To fight neutral-current background could use a narrow-band beam and a detector technology which does a good job of e VS π^0 identification

The “Off-axis” Beam



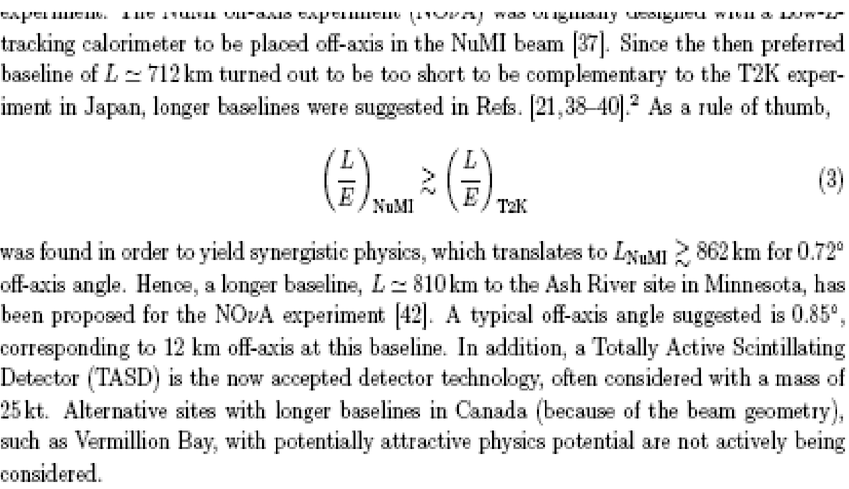




P_{max} for L/E ~ 500 so for E ~ 2 GeV you want detector at L~1000 km - Canada

Where to Put NOνA?

“The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NOνA’s sensitivity to the mass ordering.”
M. Goodman, NOW 2008 (Sept)

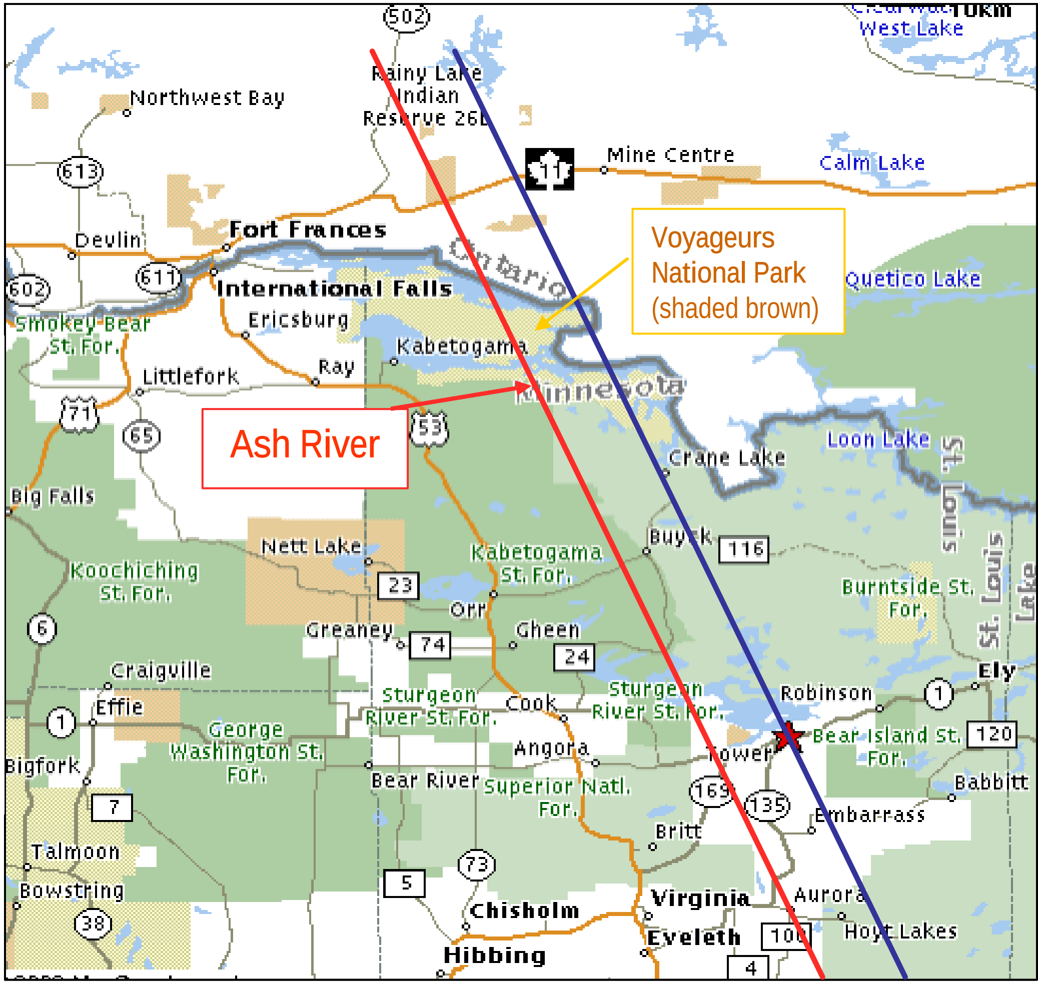


experiment. The NuMI off-axis experiment (NOνA) was originally designed with a Low-Z-tracking calorimeter to be placed off-axis in the NuMI beam [37]. Since the then preferred baseline of $L \simeq 712\,\mathrm{km}$ turned out to be too short to be complementary to the T2K experiment in Japan, longer baselines were suggested in Refs. [21,38–40].[2] As a rule of thumb,

$$\left(\frac{L}{E}\right)_{\mathrm{NuMI}} \gtrsim \left(\frac{L}{E}\right)_{\mathrm{T2K}} \tag{3}$$

was found in order to yield synergistic physics, which translates to $L_{\mathrm{NuMI}} \gtrsim 862\,\mathrm{km}$ for 0.72° off-axis angle. Hence, a longer baseline, $L \simeq 810\,\mathrm{km}$ to the Ash River site in Minnesota, has been proposed for the NOνA experiment [42]. A typical off-axis angle suggested is 0.85°, corresponding to 12 km off-axis at this baseline. In addition, a Totally Active Scintillating Detector (TASD) is the now accepted detector technology, often considered with a mass of 25 kt. Alternative sites with longer baselines in Canada (because of the beam geometry), such as Vermillion Bay, with potentially attractive physics potential are not actively being considered.

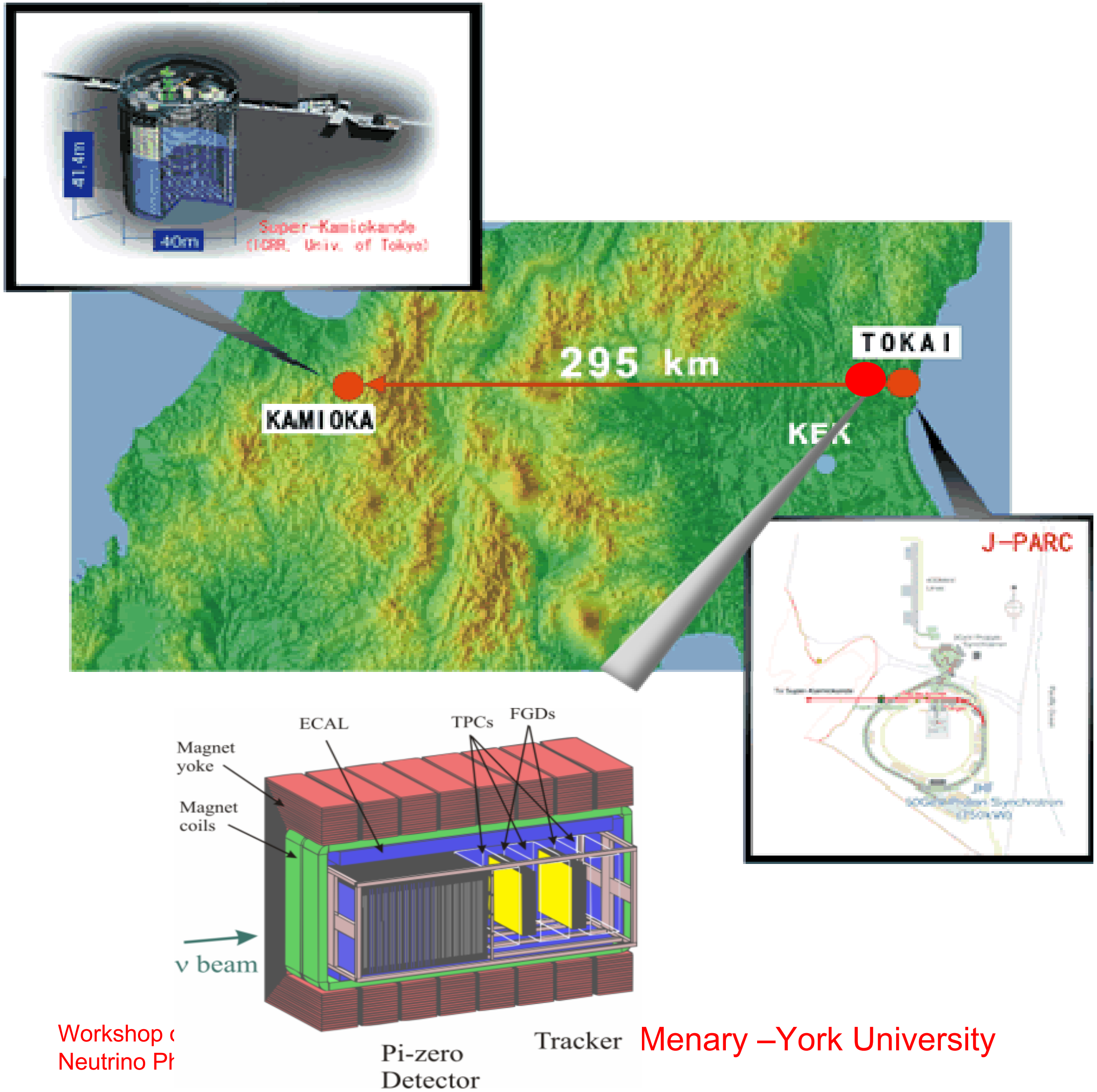
V. Barger, P. Huber, D. Marfatia,
W. Winter
arXiv:hep-ph/0703029



Voyageurs National Park (shaded brown)

Ash River

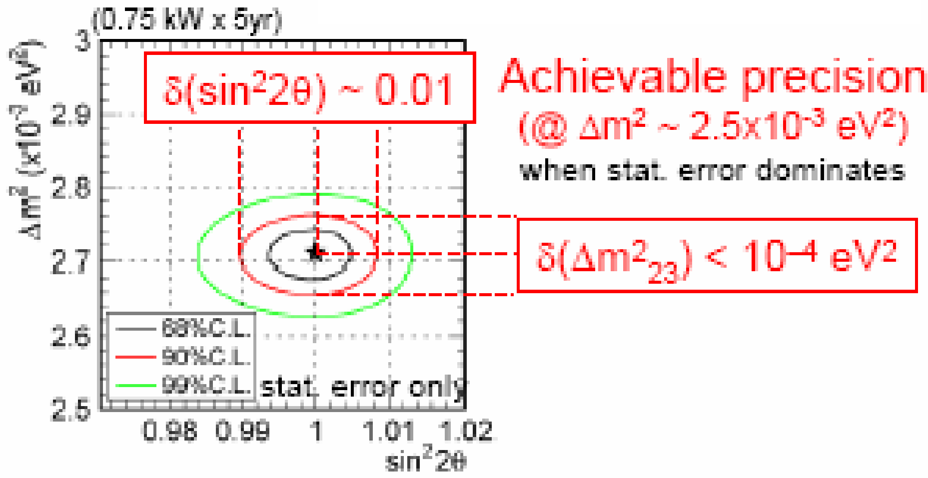
T2K – J-PARC to SuperK



- 30 GeV Protons first transported to **J-PARC Hadron Experimental Hall** in January of this year.
- Were on track for first neutrinos this year.
- Opposite situation to NOνA – here they have a detector but not a beam.
- Much smaller matter effect than NOνA

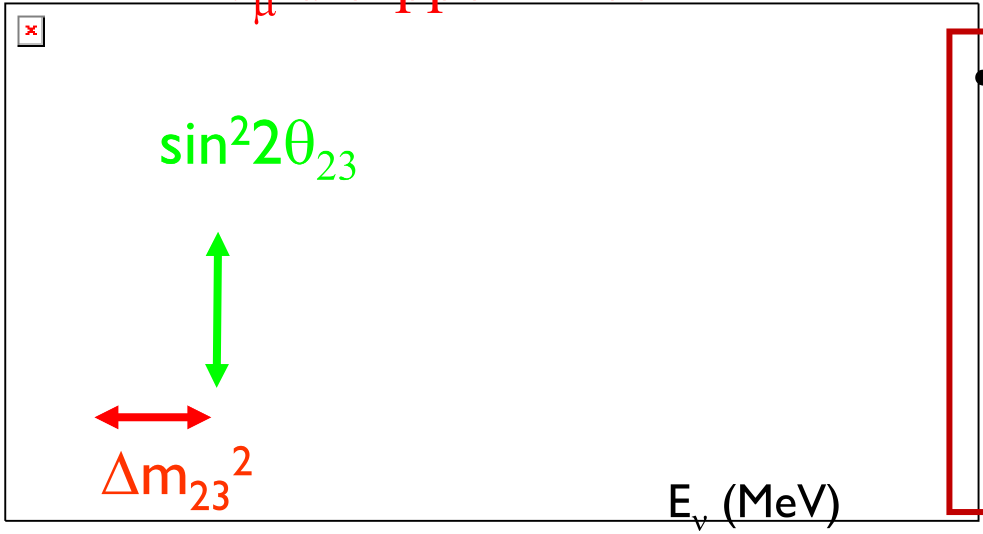
Main T2K Measurements: $\sin^2 2\theta_{23}$, Δm^2_{23}

- Phase 1:
  - 5 years X 0.75 MW beam
  - $5\mathrm{x}10^{21}$ pot
  - Measurement of mixing angles



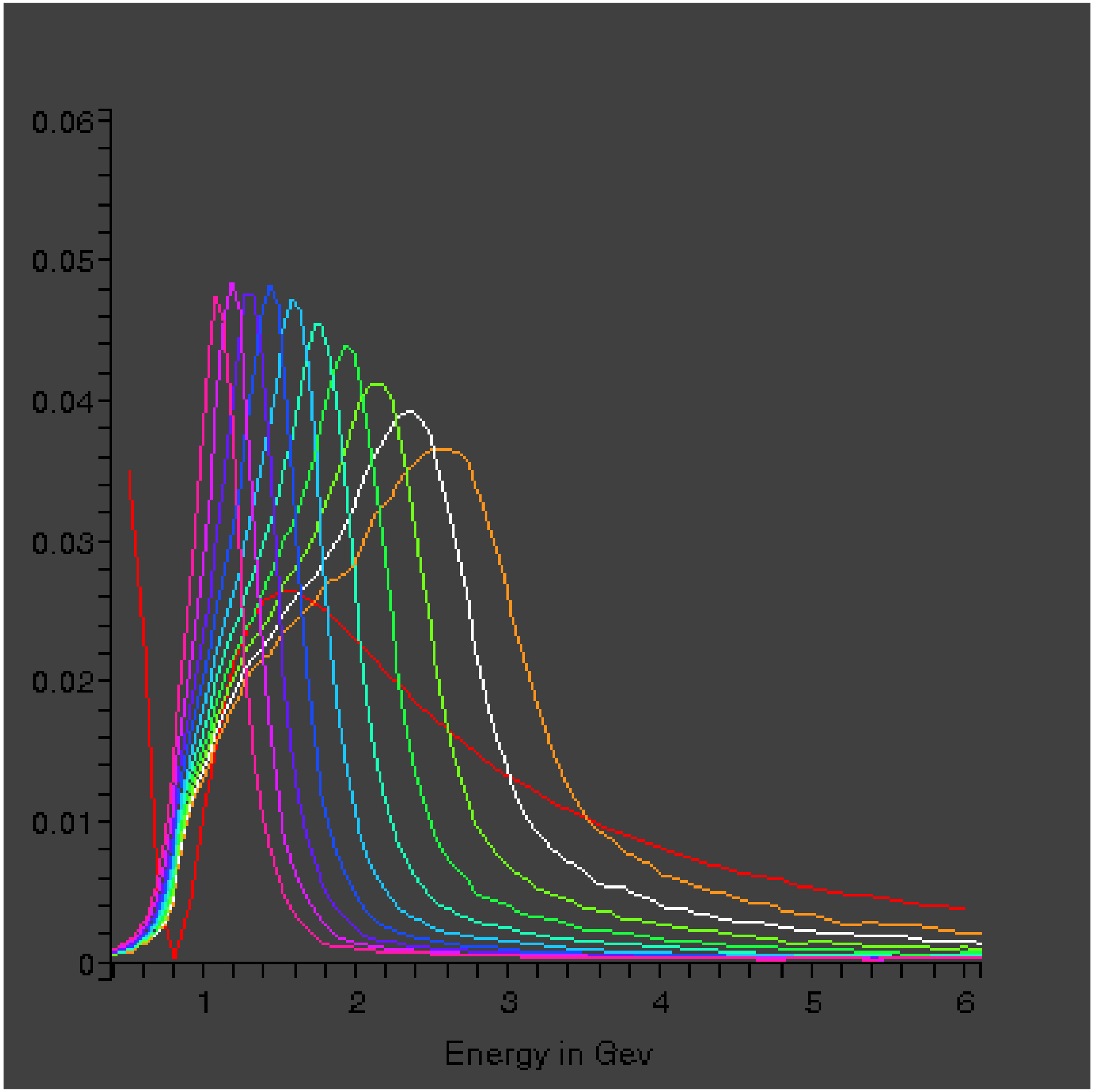
Achievable precision
(@ $\Delta m^2 \sim 2.5\mathrm{x}10^{-3}$ eV^2)
when stat. error dominates

ν_μ disappearance



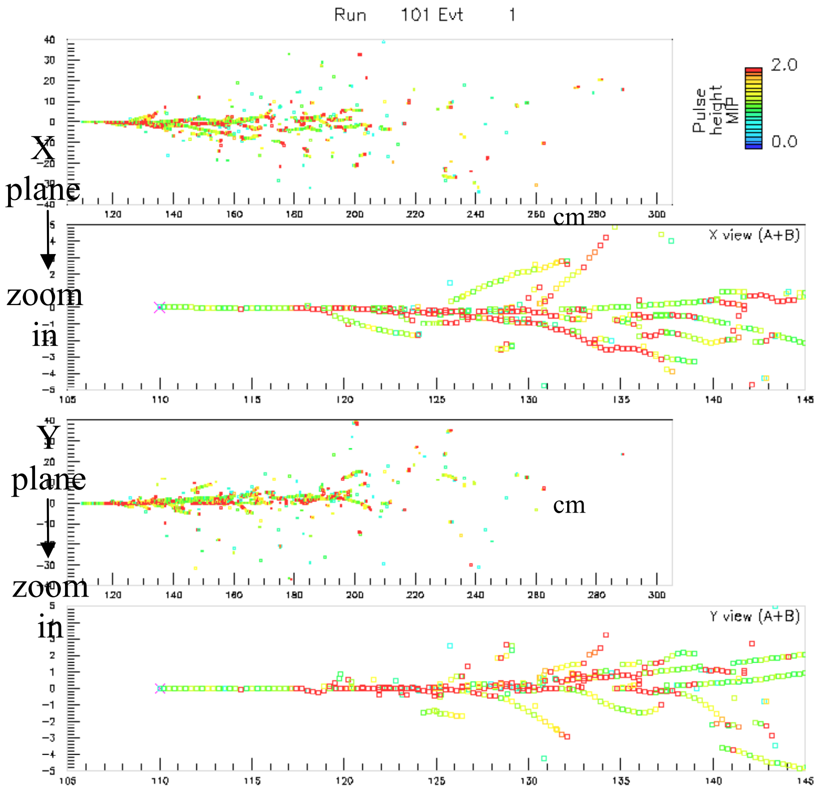
- Use CC Quasi Elastic Events
  - Can reconstruct Neutrino Energy.
  - Background from non-CCQE interactions.

The narrow-band beam at first seemed ideal but the energy at which the oscillation maximum occurs can be quite dependent on the value of δ_{cp}. The **Report of the US long baseline neutrino experiment study arXiv:0705.4396** recognized that there is a great deal of power in using a wide-band beam (the first two oscillation maxima in the same experiment) but you must have excellent e versus π^0 recognition - you need a Liquid Argon TPC (LArTPC)



Electrons versus π^0's at 1.5 GeV in a Liquid Argon TPC

Dot indicates hit- colour indicates collected charge
green=1 mip, red=2 mips



X
plane
↓
zoom
in

Y
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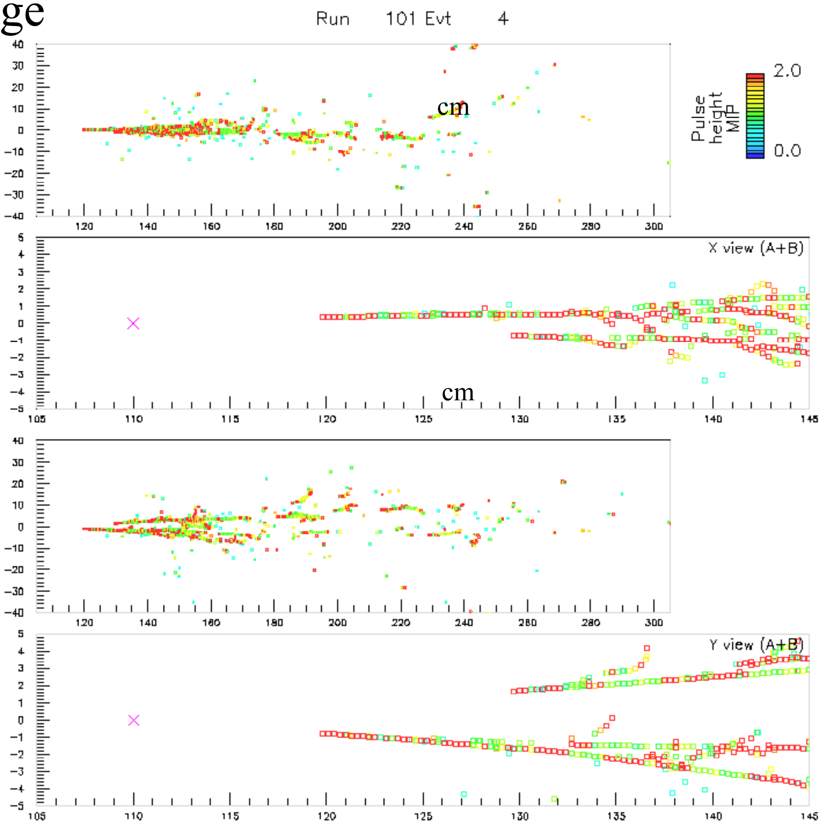
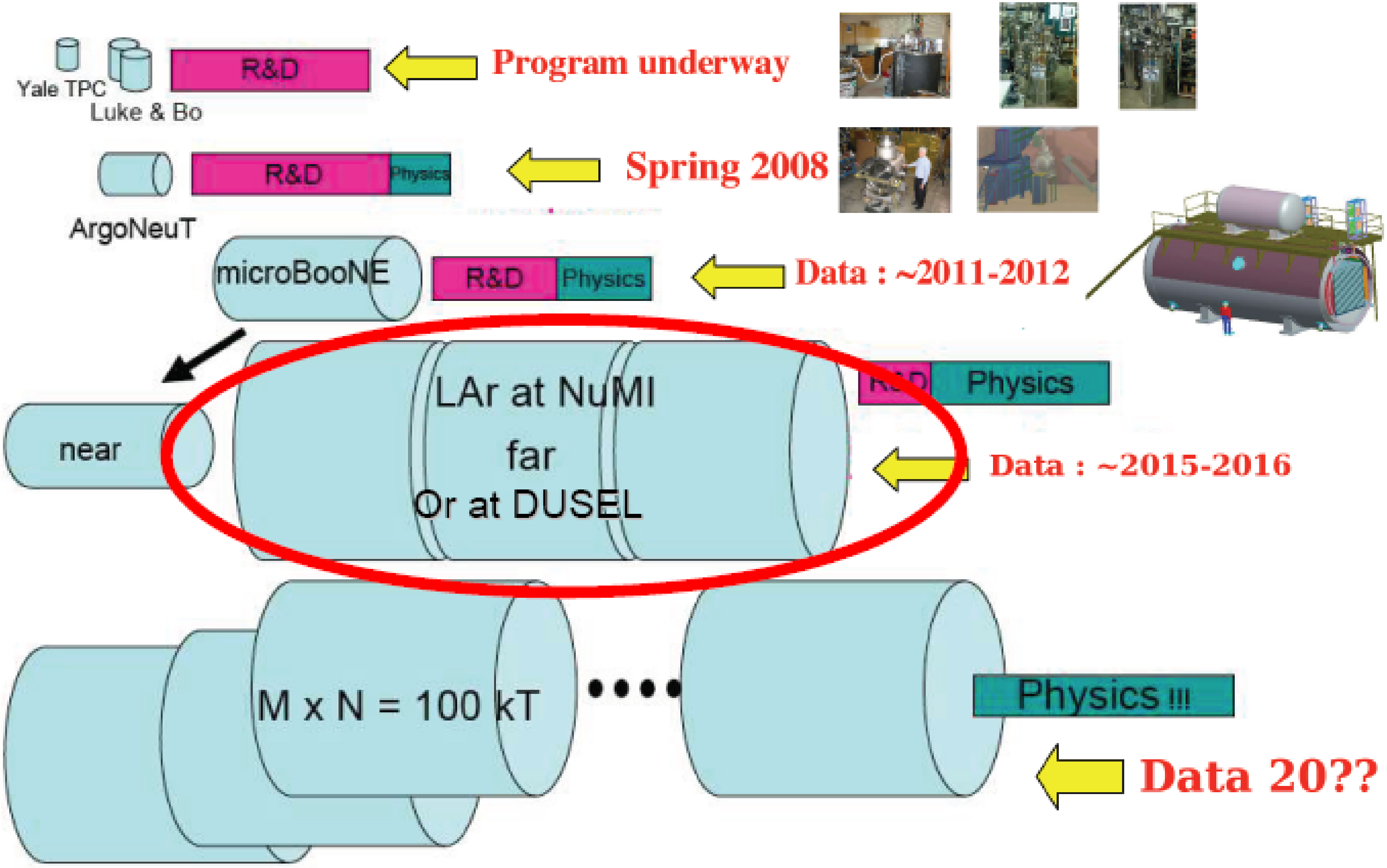


Electrons- Single track (mip scale) starting from a single vertex

Multiple secondary tracks can be traced back to the same primary vertex

Use both topology and dE/dx to identify interactions

Liquid Argon TPC R&D Path in the US



Yale TPC
Luke & Bo
R&D
Program underway

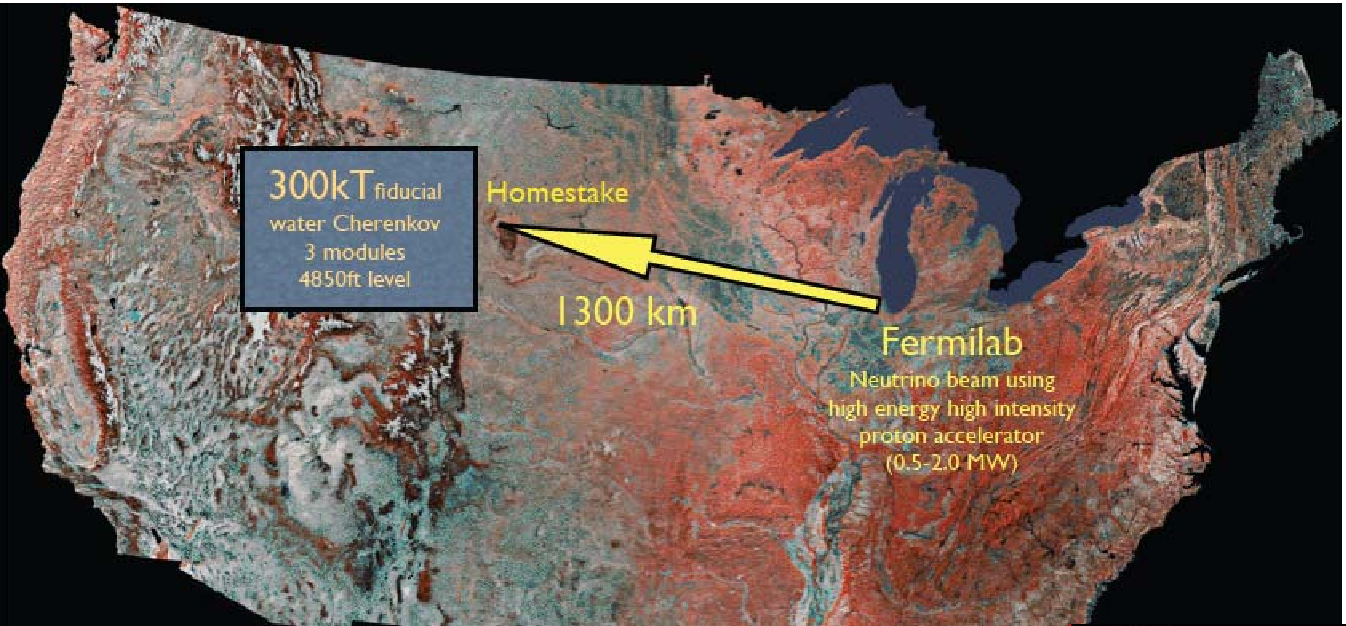
ArgoNeuT
R&D
Physics
Spring 2008

microBooNE
R&D
Physics
Data : ~2011-2012

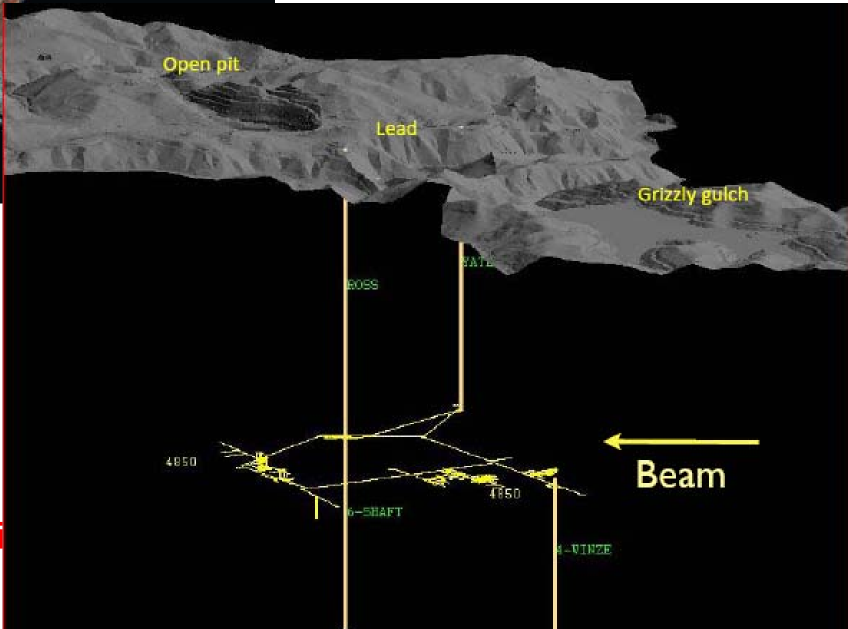
near
LAr at NuMI
far
Or at DUSEL
R&D
Physics
Data : ~2015-2016

M x N = 100 kT
••••
Physics !!!
Data 20??

The Future

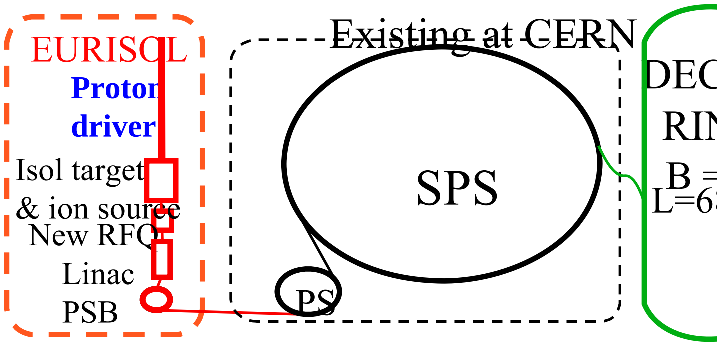


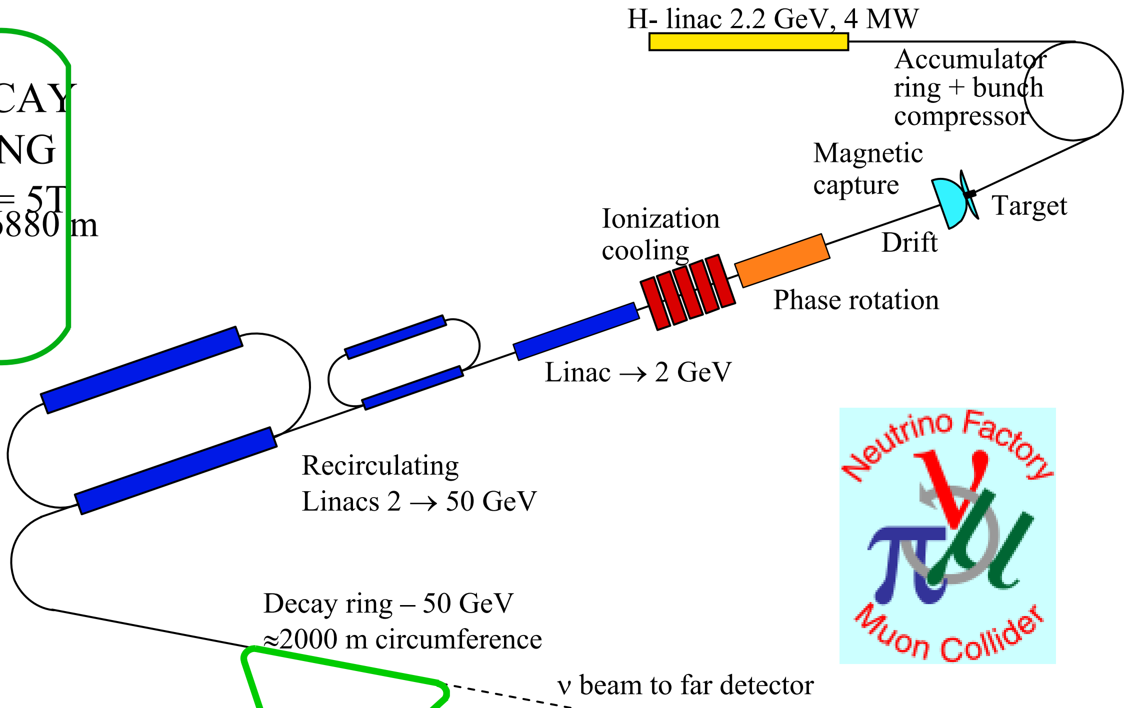
In the US, a wideband ν_μ beam from Fermilab to DUSEL (Homestake)



Far (ever?) Future

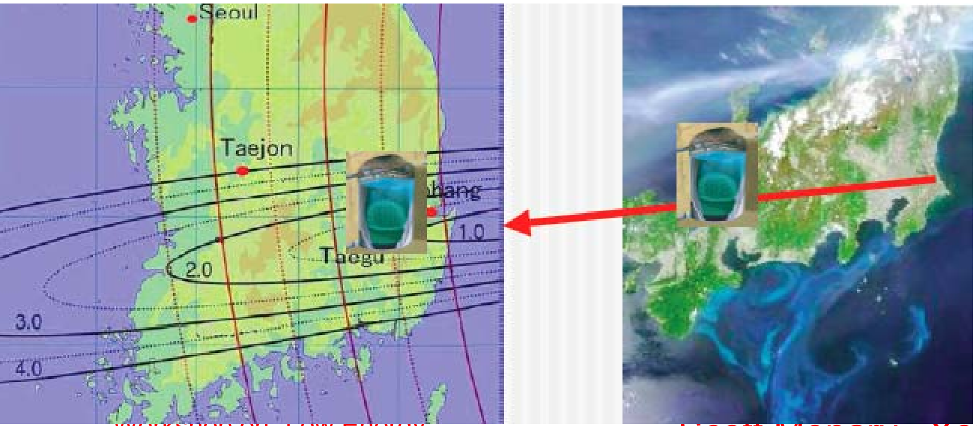
Beta-Beam





Neutrino Factory
Muon Collider

T2KK



Conclusions

- Long-baseline neutrino accelerator experiments will always have the advantage of control of the neutrino source
- There are a number of upcoming experiments designed to measure/improve the limit on θ_{13} but, of course, one is constrained by a complete lack of knowledge of this angle. If it has a high value (near the Chooz limit) then "traditional" long-baseline experiments have a chance but if it is "small" then really only a Neutrino Factory has a chance of making useful measurements.