The Current Excitement in Neutrino Physics

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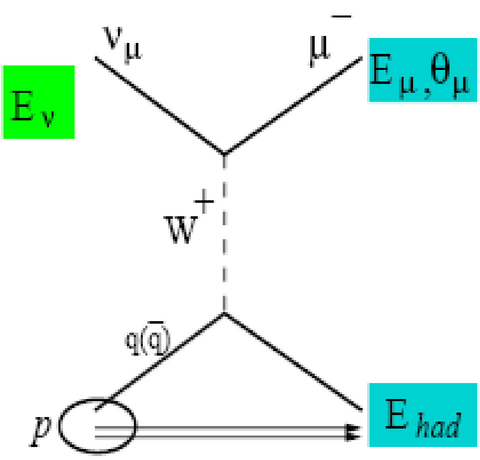
Lectures Presented to CTEQ 2007
Part 2

Deep Inelastic Scattering in Neutrino Physics

Classic, mature field
Still a lot to do!

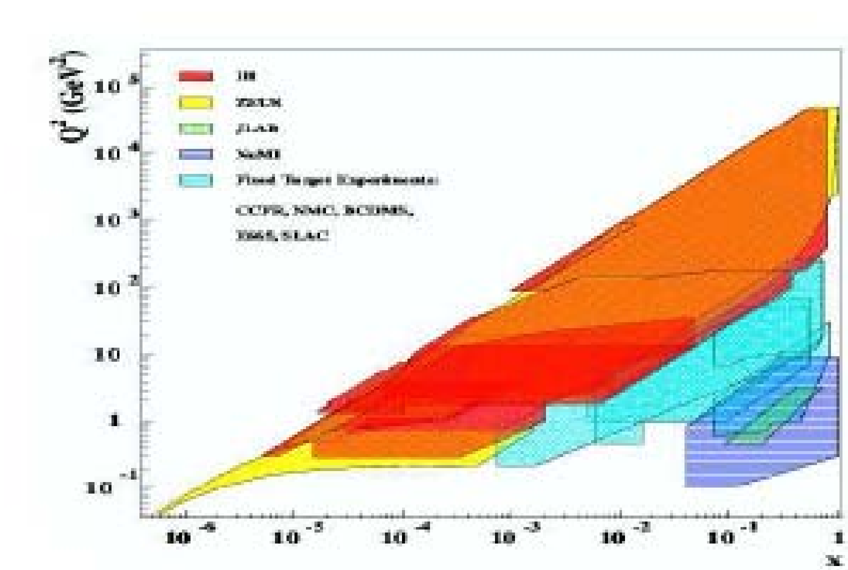


Reconstruct $E_\nu = E_{HAD} + E_\mu$

Shower energy resolution: $55\%/\sqrt{E}$

Muon Momentum resolution: 6% range,13% curvature

$Q^2 = 4E_\nu E_\mu \sin^2 \frac{\theta}{2}$,	Squared four momentum transfer
$x = \frac{Q^2}{2ME_{HAD}}$,	Fractional quark momentum
$y = \frac{E_{HAD}}{E_\nu}$,	Inelasticity
$W^2 = M^2 + 2ME_{HAD} - Q^2$,	Squared final state invariant mass



Coverage of x, Q^2 range for input to CTEQ!

Courtesy D. Naples, DPF 2006

More on Neutrino DIS

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2}{\pi(1+Q^2/M_W^2)^2}\{Z(M,x,y,E,Q^2)F_2^{\nu(\bar{\nu})} \pm y(1-\frac{y}{2})xF_3^{\nu(\bar{\nu})}\}$$

Derived from basic structure of Lepton-hadron interactions.

F_2, F_3 are related via Quark-Parton model to PDF's

F_3 measures difference in quark-antiquark content of nucleon.

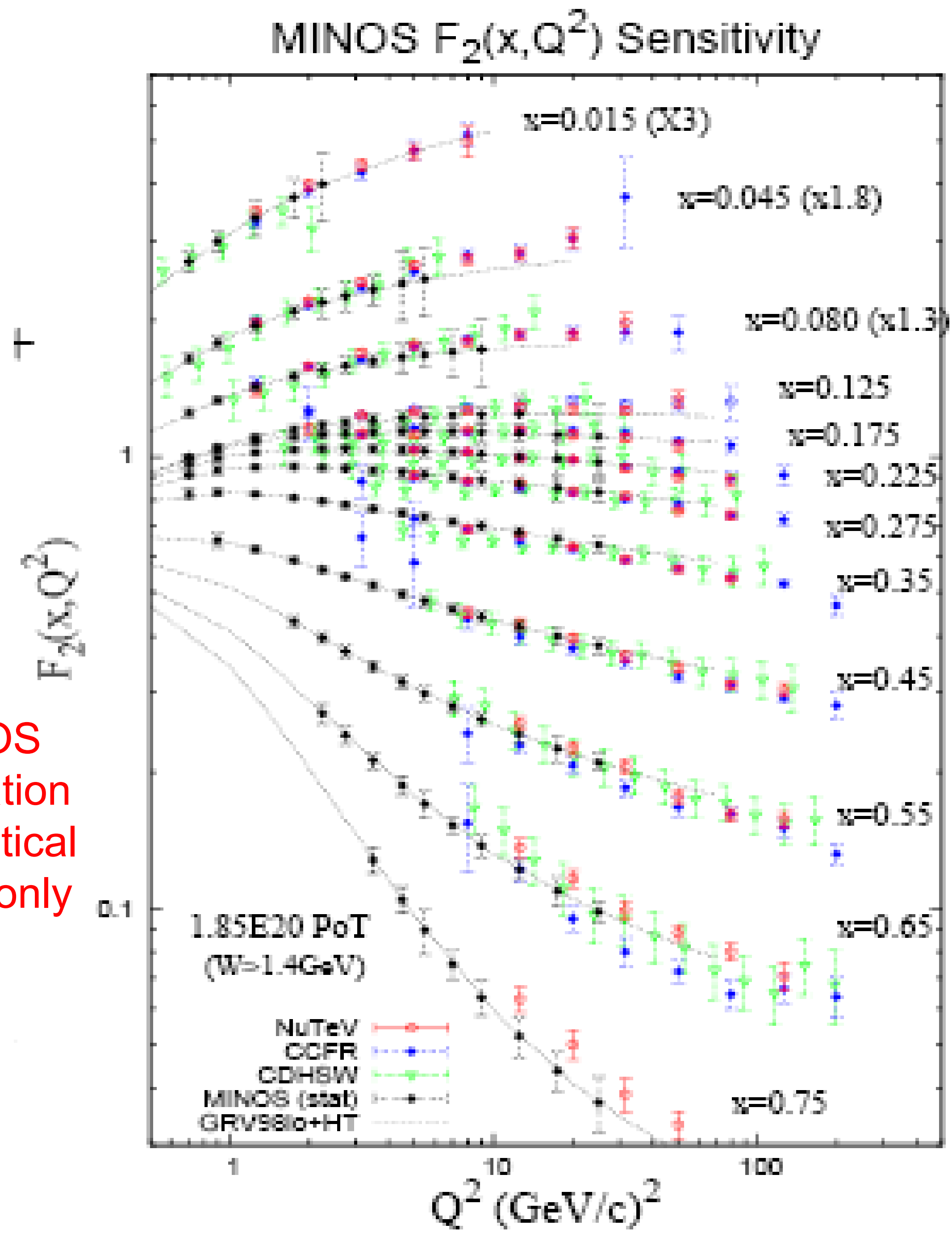
F_1 shows parton spin, not controversial to absorb into the others.

Extract F_2 from sum of neutrino, antineutrino cross-sections.

Only (anti)neutrinos can be used to get at F_3

Many world experts at this gathering!

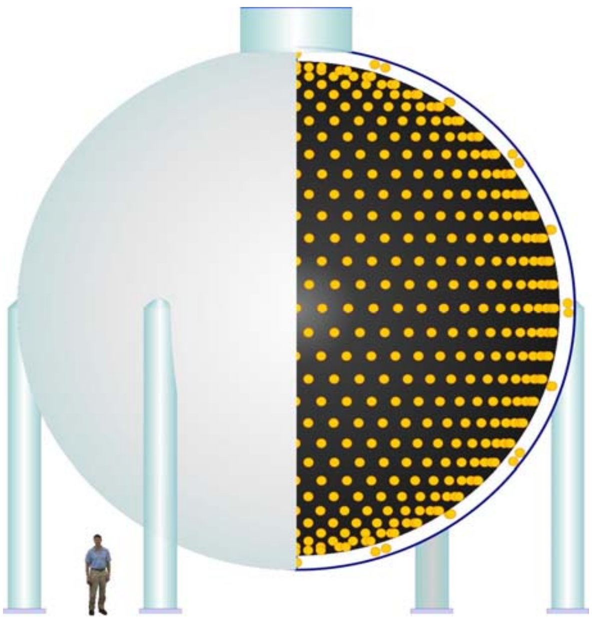
Summary of Neutrino Experiment Data and Expected Extensions to Sensitivity

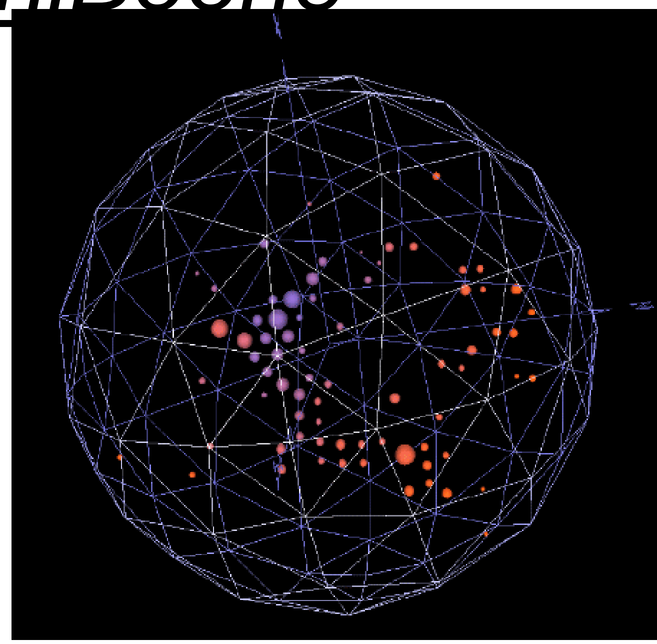


MINOS Simulation – statistical errors only

Currently MINOS > 2.5 E20 Protons

An appearance experiment using ν_μ at high values of Δm^2
- MiniBoone -





e from μ decay candidate.

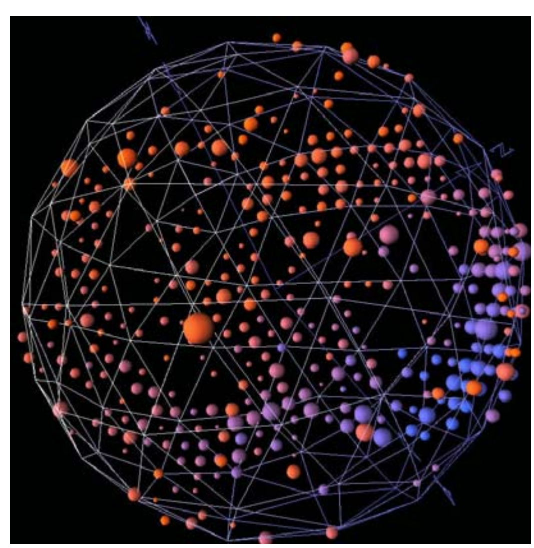
Ragged outer edge of ring
from scattering, brems

12 m sphere, 950 K liters of oil.

1280 PMT's - 8" diameter

Cerenkov and Scintillation light

π^0candidate –
overlapping rings,



An appearance experiment using ν_μ at high values of Δm^2

Check/confirm LSND oscillation signal at Fermilab Booster

Different systematics from previous experiment

– L=540 m ~10x LSND

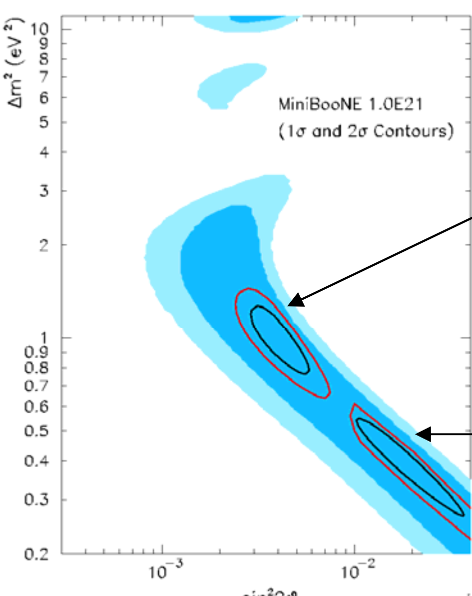
– E~500 MeV ~10x LSND

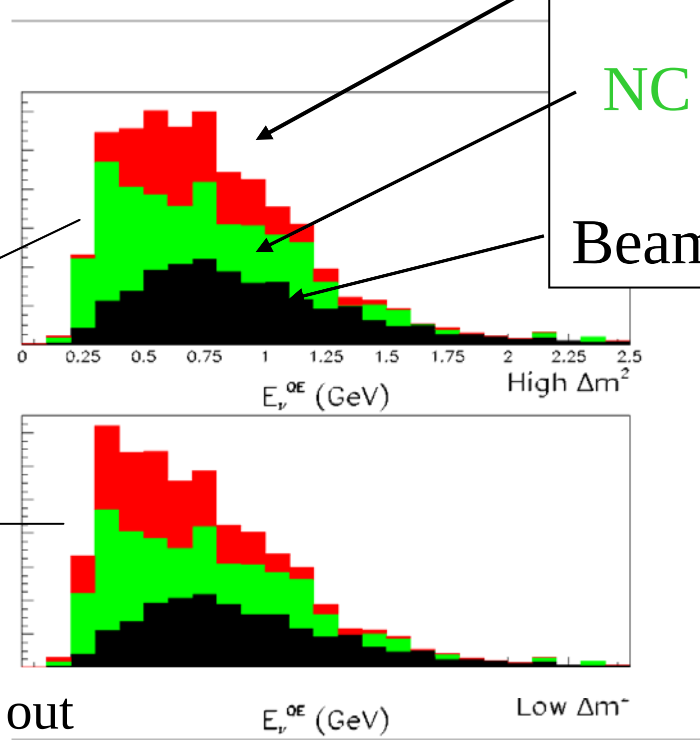
ν_e signal

NC π^0

Beam ν_e

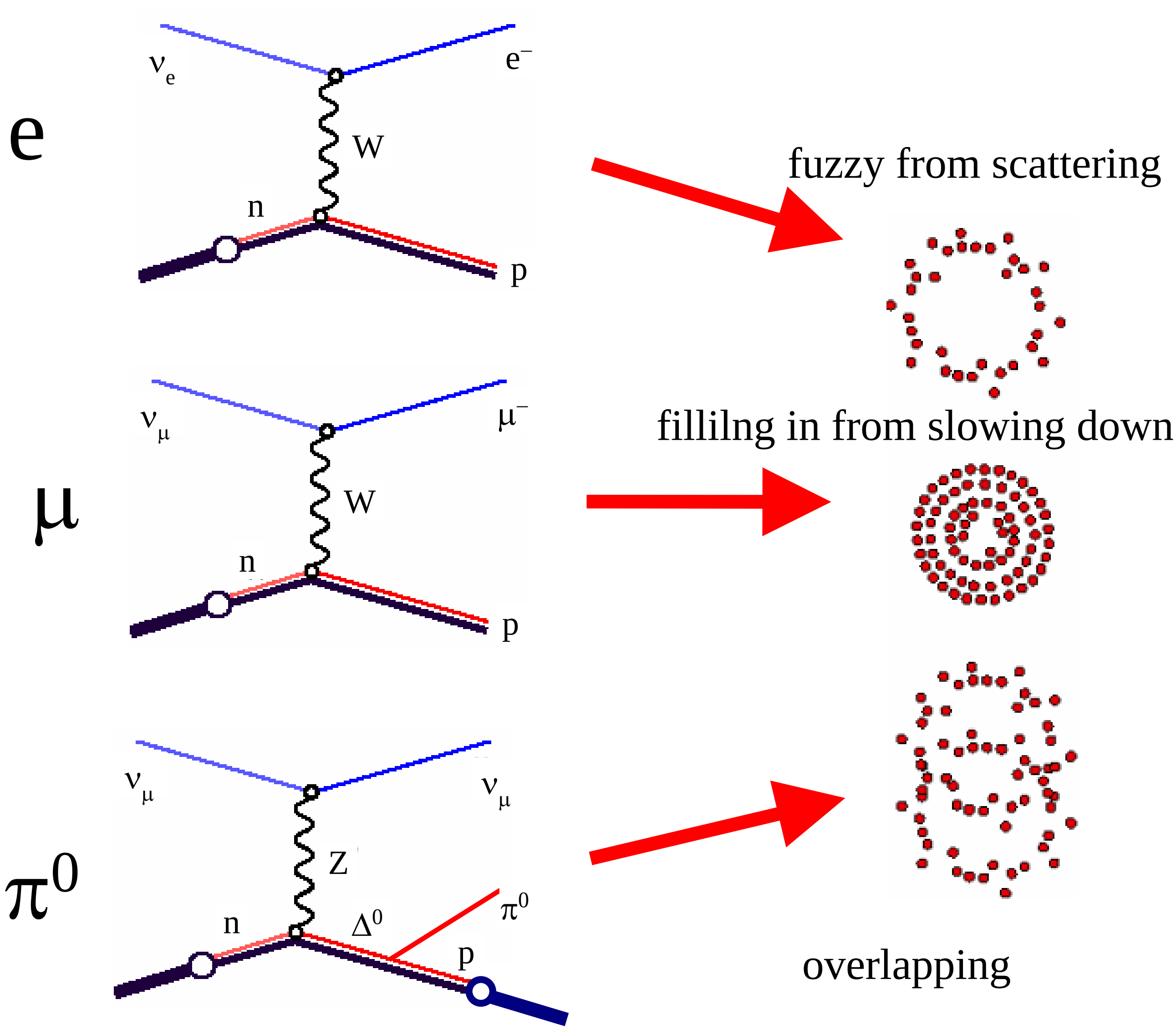
Sensitivity





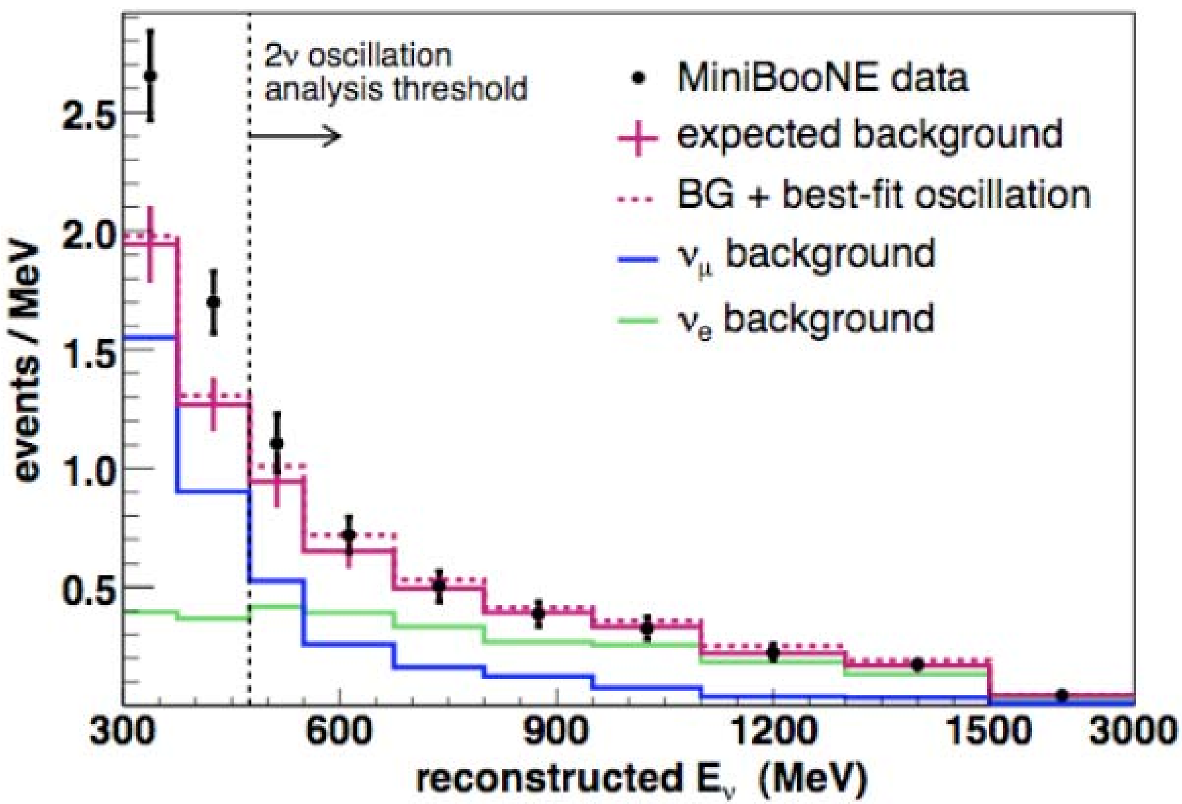
Larger mixing angles ruled out in the 80's

Event topologies in the MiniBoone detector



Graphic from S. Brice

MiniBoone Initial Result
Blind Analysis (April 2007)



data: 380 events

expectation: 358 ±19 (stat) ± 35 (sys) events

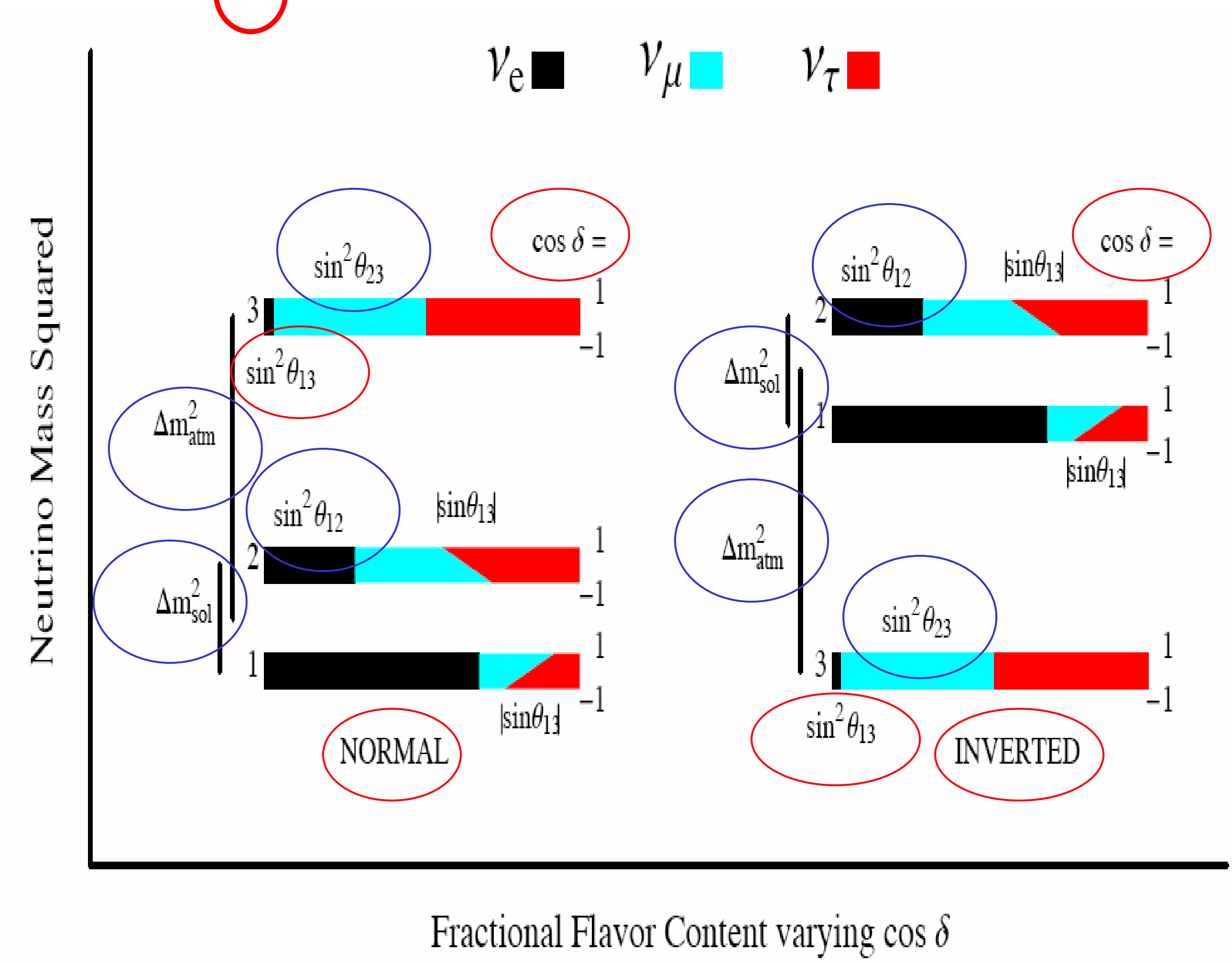
Inconsistent with ν_μ oscillation to ν_e as sole phenomenon (shape disagreement)

Disagreement at < 500 MeV still under investigation

Status of our Knowledge

Know to some extent

Don't know



O. Mena and S. Parke, hep-ph/0312131

ν_e Appearance and the Importance of θ_{13}

In our formalism, with $\Delta_{12} \cong 0$ (solar),

$$P_{\nu_\mu \to \nu_e} = 4\cos^2\theta_{13}\sin^2\theta_{13}\sin^2\theta_{23}$$

or finally to leading order and using

$$\cos\theta\sin\theta = \frac{\sin 2\theta}{2}$$

$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta_{13})$$

This small number will be seen again and again.

Currently $\sin^2 2\theta_{13} \le 0.14$

Reactor Experiments - sooner and later

Reactor experiments provide an alternative route to measurement of $\sin^2 2\theta_{13}$.

$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{atm} L/4E) + O(solar)$

Free from CP, hierarchy assymetries.

Disappearance experiments at modest baselines

Ballpark: *<E ν> ≃ 3 MeV at 1 km gives L/E = .003*

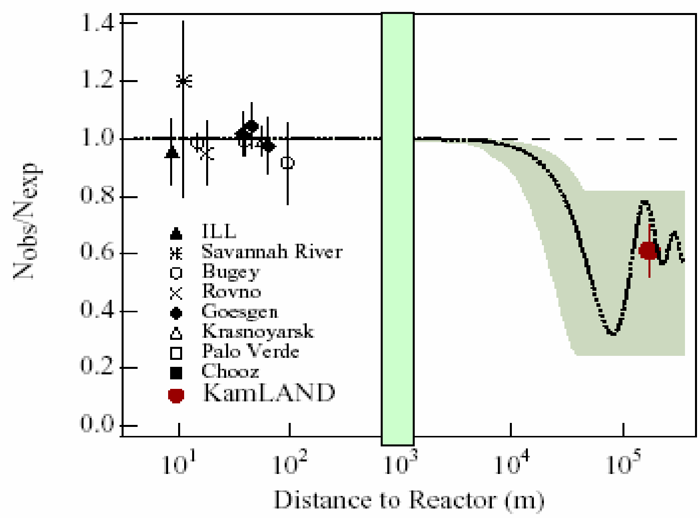
comparable to MINOS

Reaction

$$\bar{\nu}_e + p \rightarrow n + e^+$$

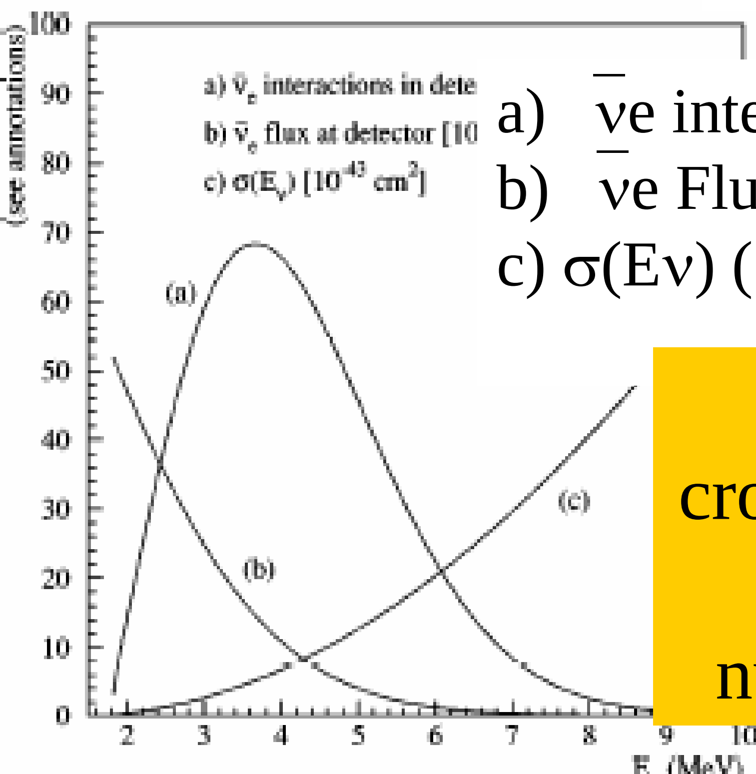
Detect via annihilation γ, followed by delayed γ from n-capture on nucleus

Reactor Experimental Landscape



KamLAND sees a 40% deficit/shape at 200km related to Δm^2_{12}

Search for a 1-5% deficit/shape at ~1 km related to Δm^2_{13}



a) $\bar{\nu}$e interactions/MeV-day

b) $\bar{\nu}$e Flux (10^8/MeV-s-cm^2)

c) $\sigma(E\nu)$ (10^{-43} cm^2)

High flux, low cross-section, results in acceptable numbers of events

Palo Verde

Courtesy KamLand, Palo Verde, Reyna

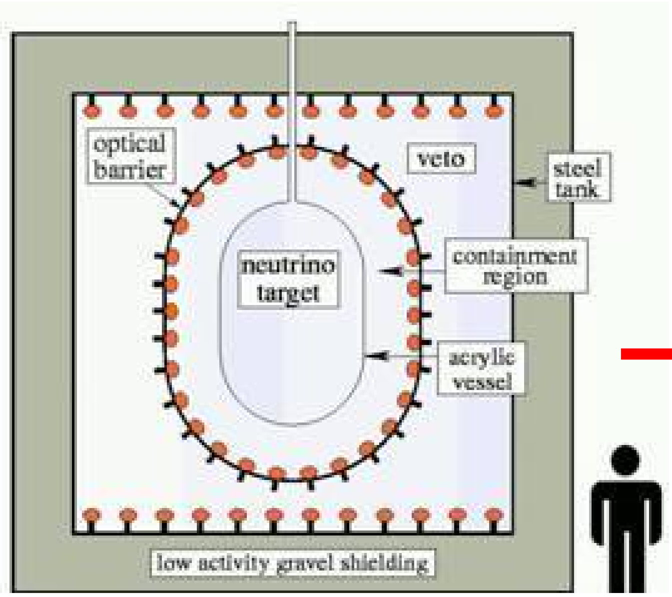
‡ from Palo Verde

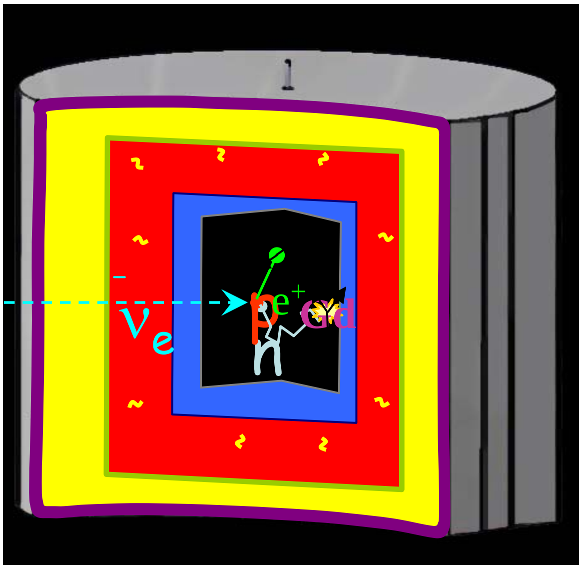
Near term for reactor θ_{13} Double Chooz

Currently world's best limit $\sin^2 2\theta_{13} < 0.14$

Improve by adding near detector, increasing mass of detector(s) 5T –> ~10T

Reactor Power substantially increased.





Distances : Near 100-200m Far: ~1 km

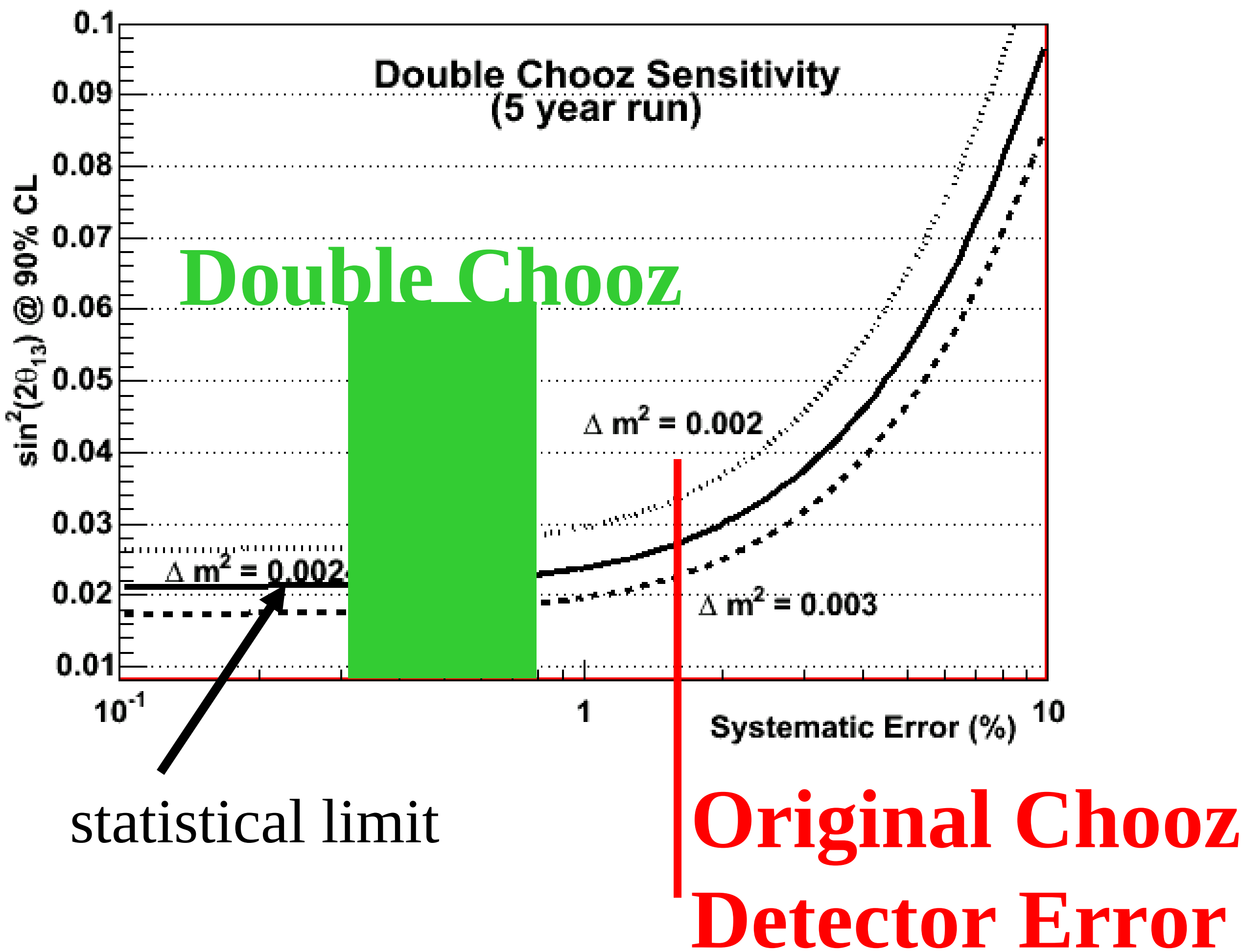
Depths: Near 30-40m Far: ~100 m

Exposure: 12 GW-T-year ==> 200-300 GW-T-year

Events: 2700 ==> 40K

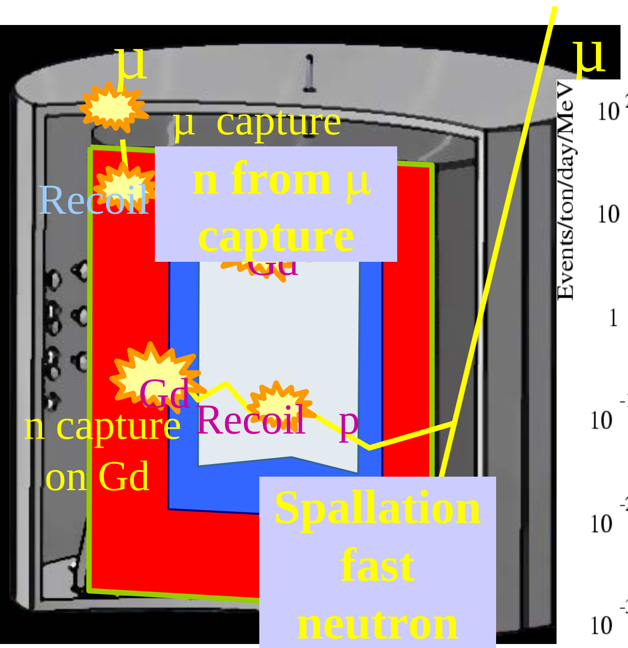
Courtesy Reyna, Goodman, Lasserre-NOvE-06

Double Chooz Sensitivity

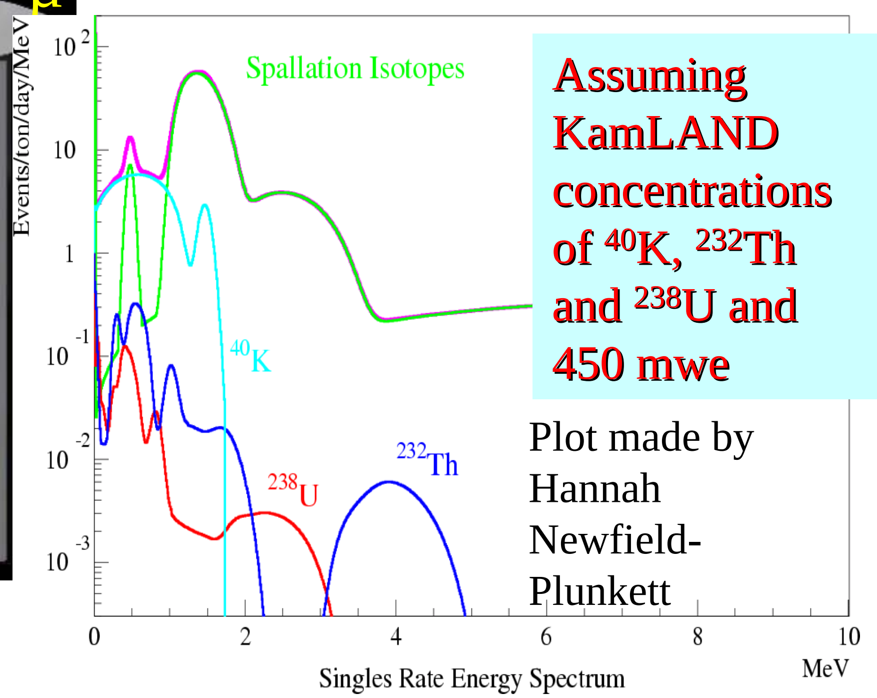


	Chooz	Double-Chooz
Reactor cross section	1.9 %	—
Number of protons	0.8 %	0.2 %
Detector efficiency	1.5 %	0.5 %
Reactor power	0.7 %	—
Energy per fission	0.6 %	—

Background reduction in DoubleChooz



Typical Spectra (Braidwood)



Background coming from radioactive materials, cosmic sources.

Spallation neutrons from μ, direct β-emitter creation

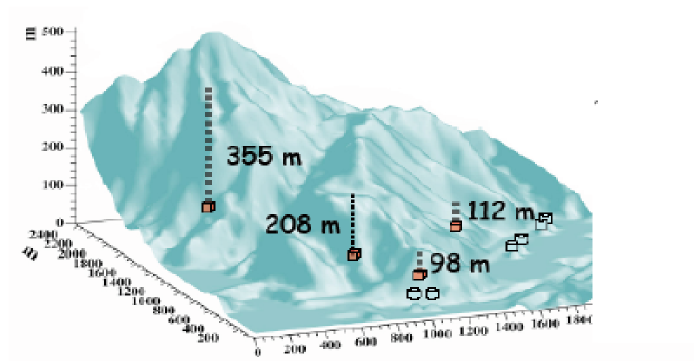
Control via detector design, reactor-off comparison with simulation

Expect total background subtraction systematic ~1%

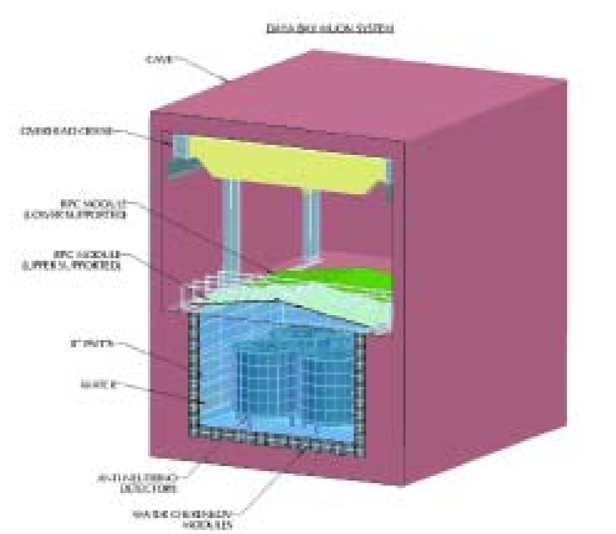
A Next Generation Reactor Experiment – Daya Bay (China)

Main avenues of improvement

- Increased Mass
- Depth



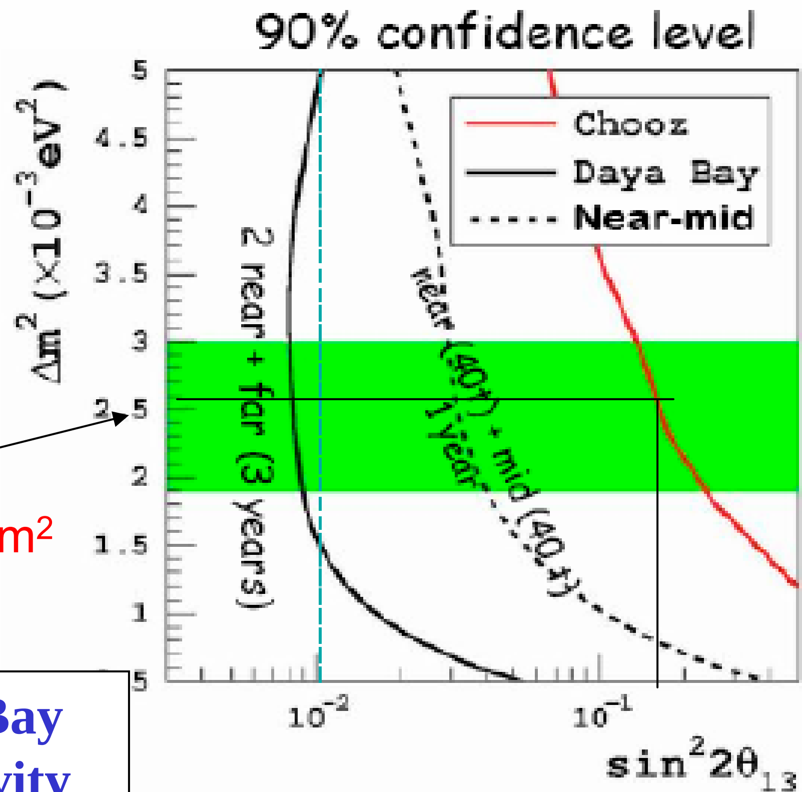
4 “Modules” at far position, 2 at each near.



Daya Bay, China
8 x 20 T detectors (fiducial)
1000 mwe (far)

Courtesy Daya Bay Collaboration

Sensitivity and Systematics



Atmospheric Δm^2

Expect background systematic of 0.3%

Daya Bay Sensitivity

- Use rate and spectral shape
- input relative detector systematic error of 0.38%

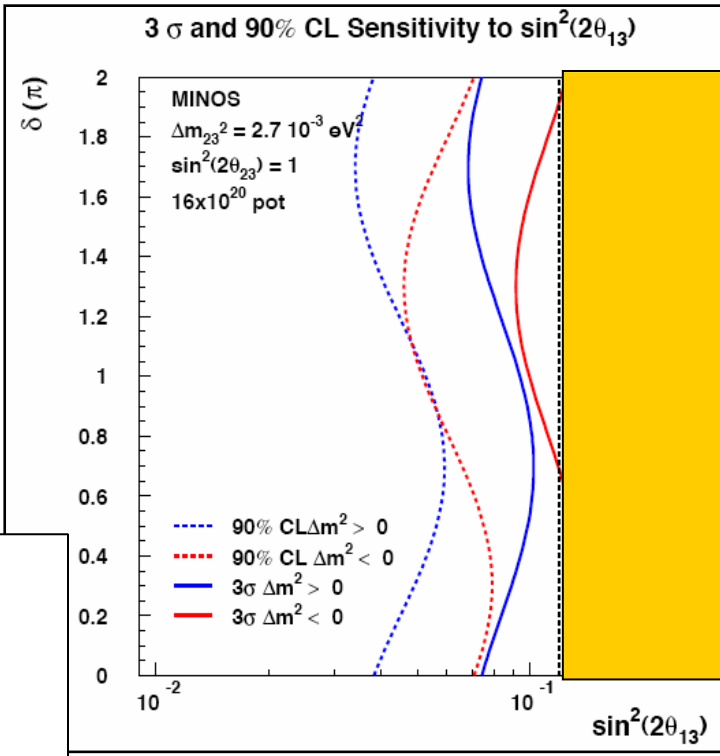
Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*) Baseline	Goal	Goal w/Swapping
# protons	H/C ratio	0.8	0.2	0.1	0
	Mass	-	0.2	0.02	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	< 0.01	< 0.01	< 0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

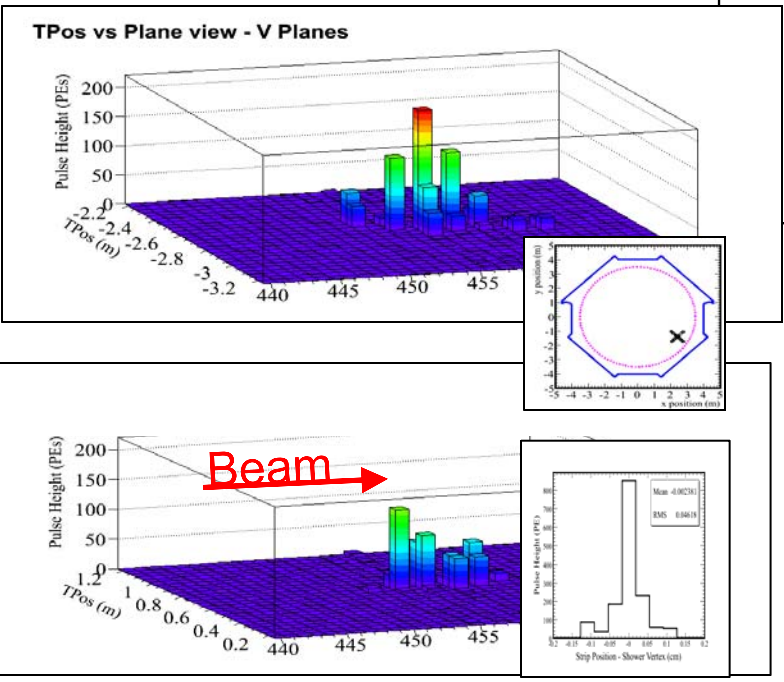
Overall detector + background about 0.5% systematics

MINOS electron sensitivity

Challenging because of detector granularity – typical electron is 8 planes long, 4 strips wide.

Background high – especially misidentified NC.

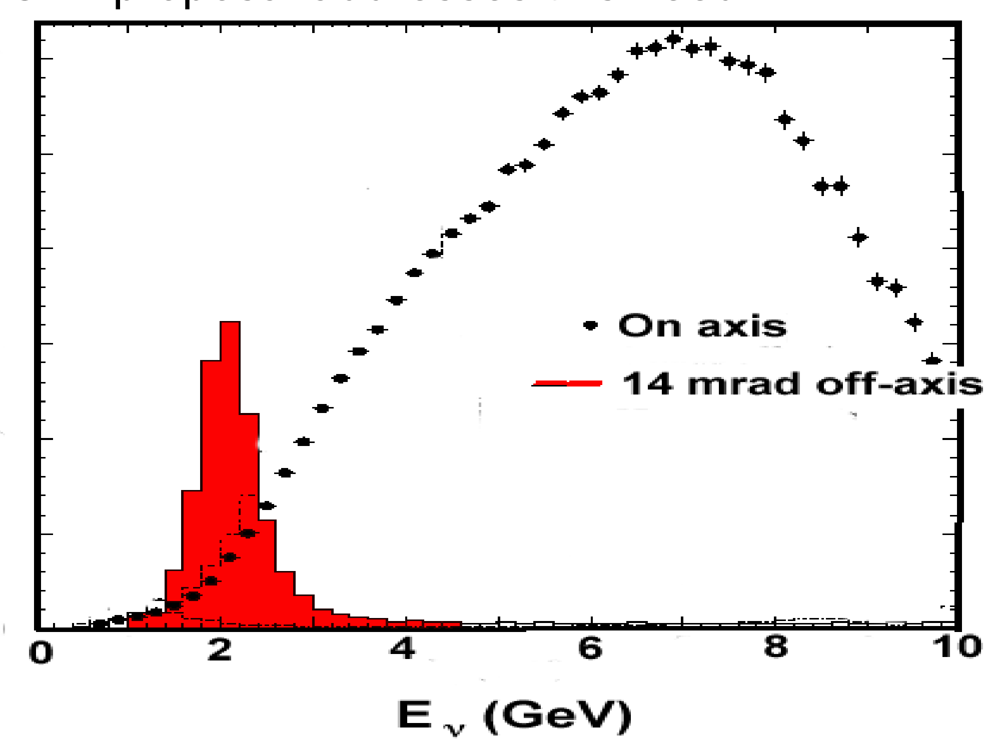




Multi-year run

Off-axis beams and NOvA

- Off-axis neutrino beams provide narrow-band kinematics
  - Reduces backgrounds
    - mis-id NC
    - ν_e's from K decay (wrong kinematics)
- Increases flux at oscillation maximum.
- This provides a good setting for ν_e appearance exeriments
  - Will be focus of Japanese T2K effort.
- NuMI beam already exists, can be exploited by construction of new detector.
  - NOvA proposal addresses this need.



Understand Off-axis Mathematically

Model beam with $\theta^* = \pi/2$

$$P_T = P^* \sin\theta^*$$

$$P_L = \gamma P^* (1 + \cos\theta^*) \cong E_\nu$$

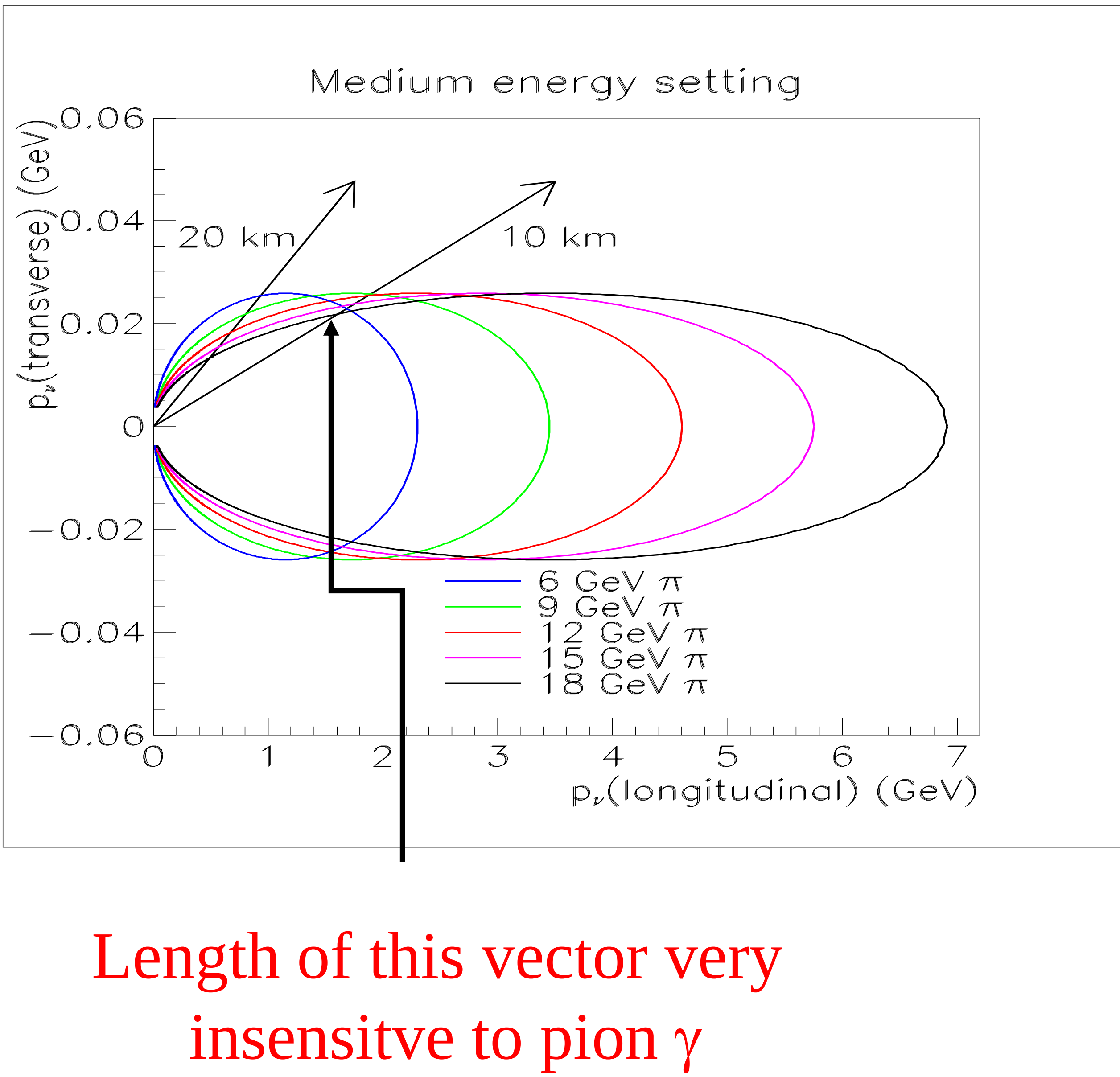
We fix $\theta_{lab} \equiv P_T / P_L$

At $\pi/2$ $\Delta P_T \cong 0$ as vary θ^*

$$\Delta P_L = \frac{\Delta P_T}{\theta_{lab}} \cong 0$$

Constraint on angle means γ compensates θ^* to fix P_L (at fixed θ_{lab})

Off Axis Beam Graphically

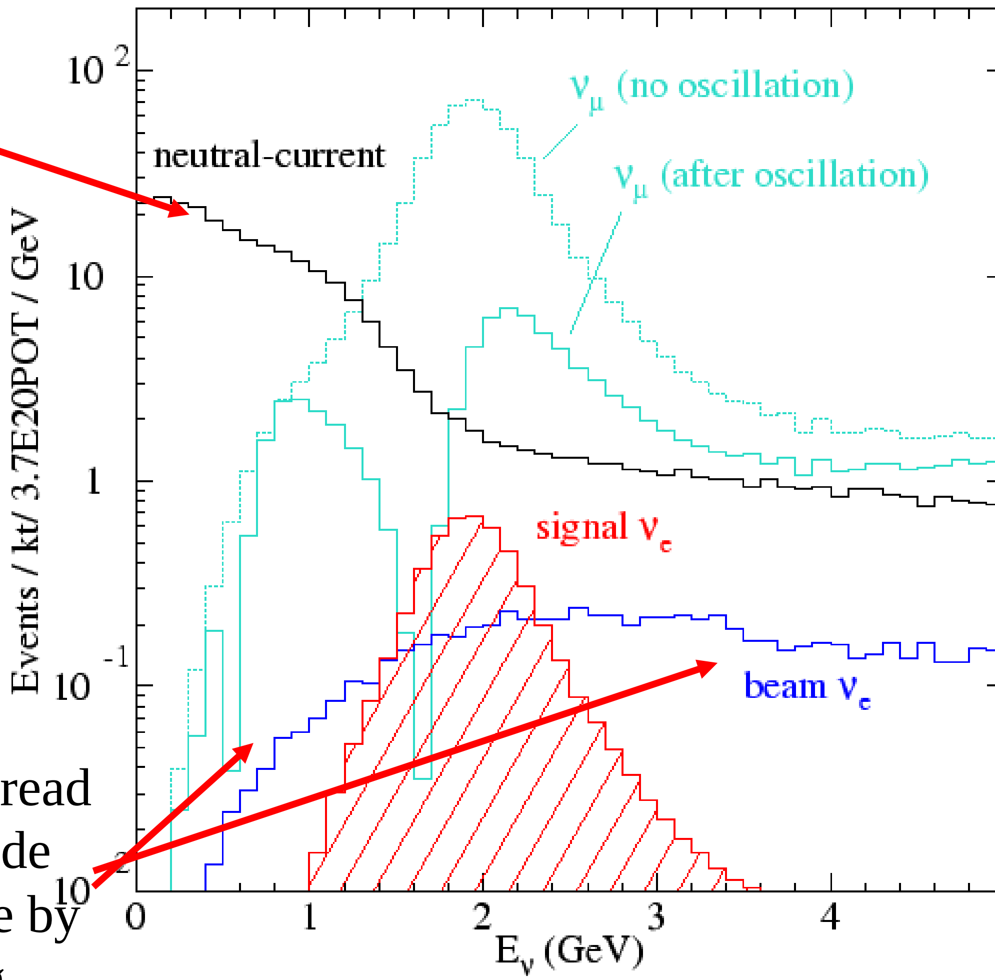


Length of this vector very insensitve to pion γ

$$E(\theta^* = \pi/2) \quad = \quad 1/2\, E(\theta^* = 0)$$

Combination of off-axis "narrow-band" beam and good energy resolution.

NC at low energy because no high energy tail

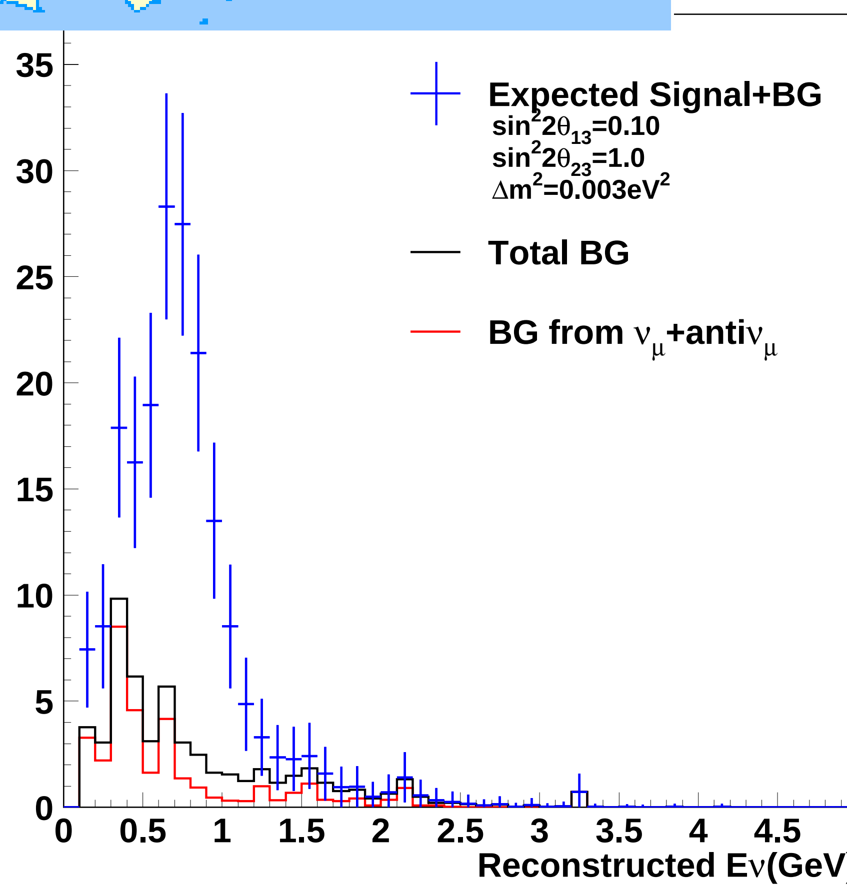


Beam ν_e are spread out over a wide range - remove by windowing

Backgrounds show a different energy spectrum and can be removed during analysis.

Sidebar - T2K Project at KEK

Hope for 2009 startup



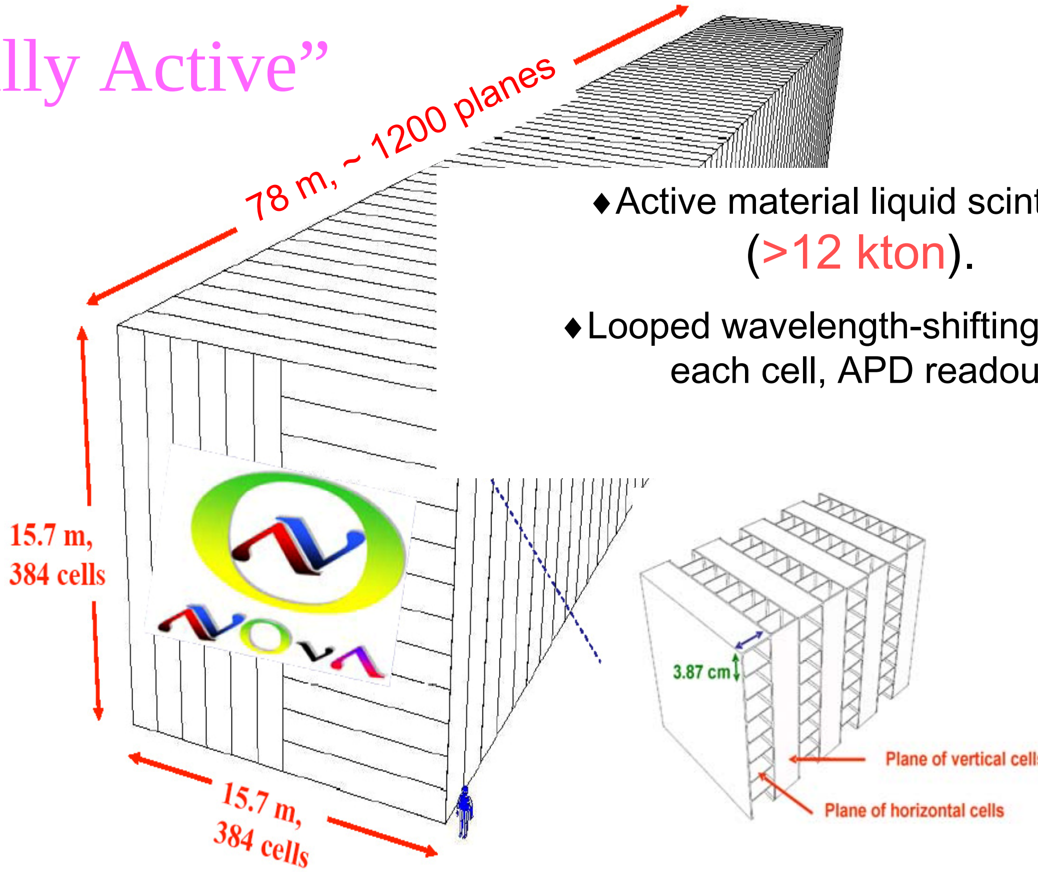
Results of 5 years running

NOvA, a large electron appearance experiment

"Totally Active"

♦Active material liquid scintillator (>12 kton).

♦Looped wavelength-shifting fiber in each cell, APD readout

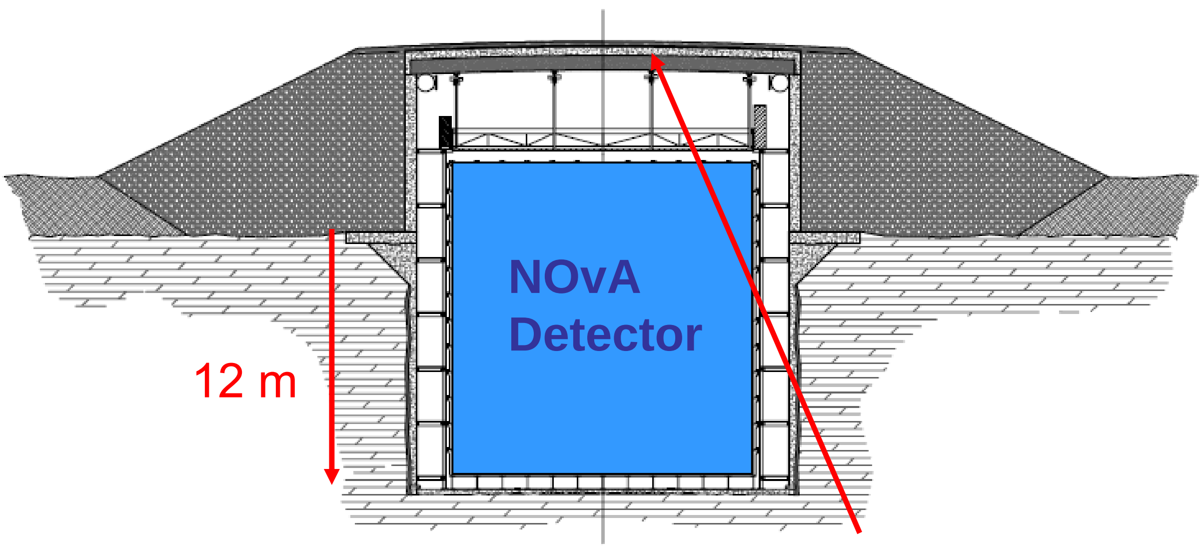


- 18 kton detector
- Baseline ~810 km

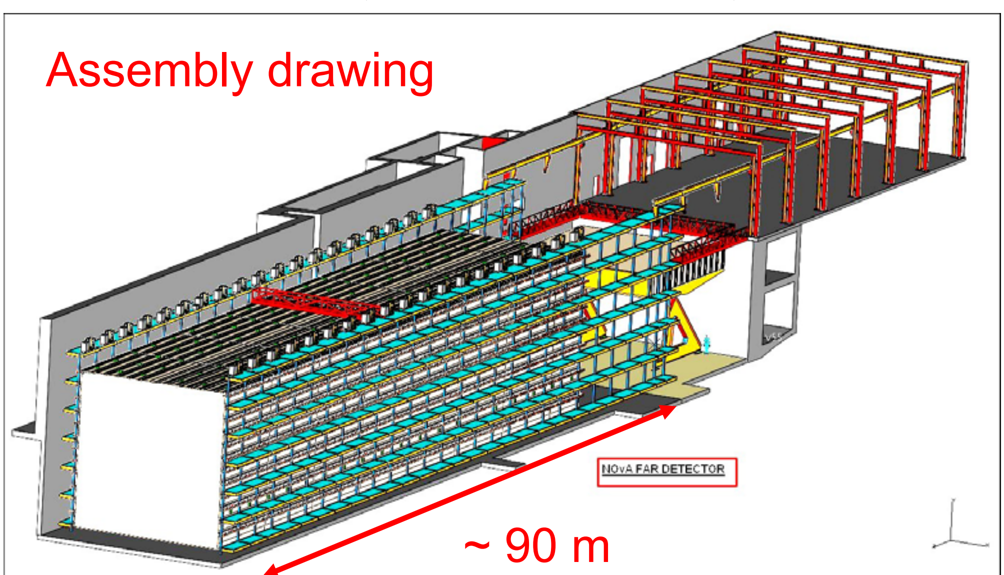
7
8

- ~1400 ν_μ CC events per 7e20 POT ($\Delta m^2 = 2.5 \times 10^{-3}$)
- Electron ID efficiency 24%
- For $\sin^2 2\theta_{13}$ ~ 0.1 would see ~100 ν_e interactions in 5 years

Large semi-underground building



Barite cover reduces background from cosmic γ (can fake electron)

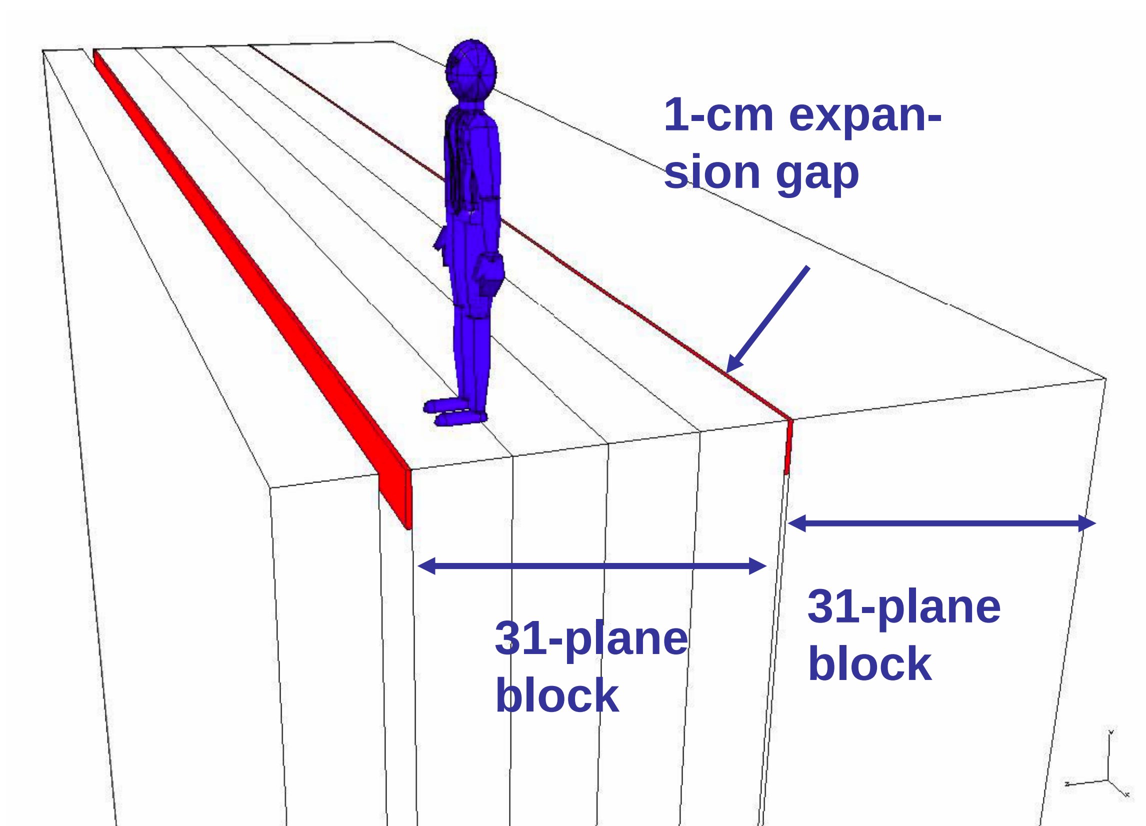


Probable location at Ash River, MN

14 mrad off axis

Trigger on timing –> surface location OK

For structural reasons, detector is built in 31 plane blocks



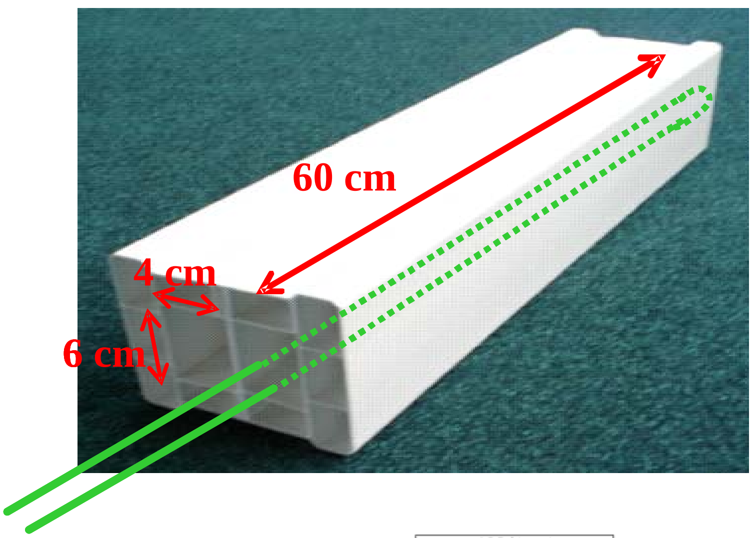
31 Plane blocks allow space for swelling at bottom of tubes.

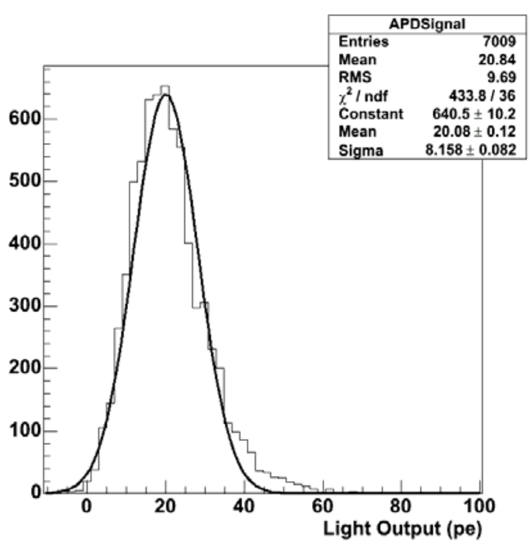
Structure erected block-by-block

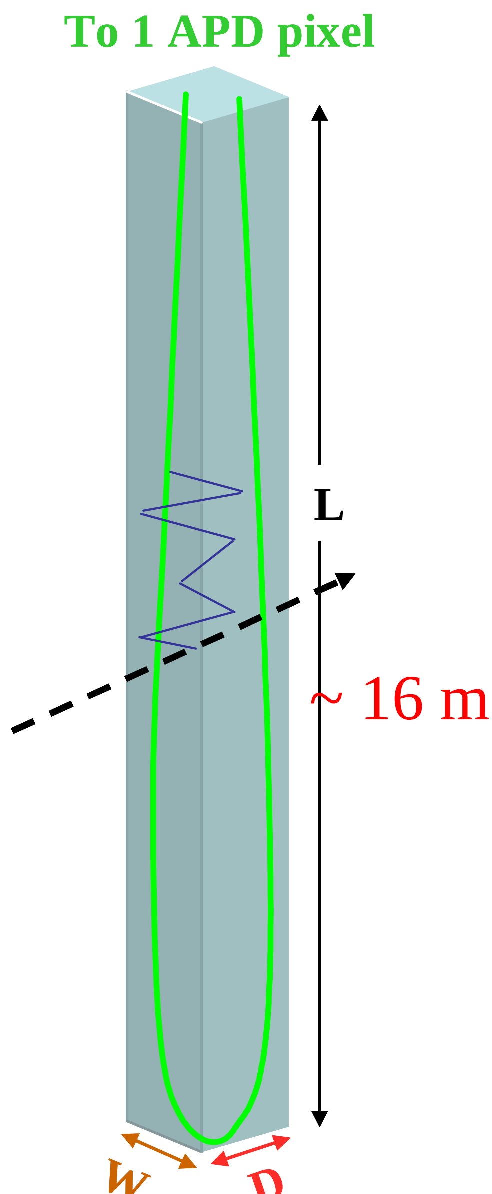
Weight of each block (empty): ~125 tons

Extruded PVC tubes filled with liquid scintillator

Prototype with full-length fiber
Readout cosmic muons







Prototype APD readout showing light output

Review of Oscillations in Matter

Recall ν_e + e scattering adds a potential

$$H_{matter} = H_{vac} + V_W \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Leading after some manipulation to

$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\Delta_{13}^2}{(\Delta_{13} \mp aL)^2} \sin^2(\Delta_{13} \mp aL)$$

new mixing strength

new effective mass

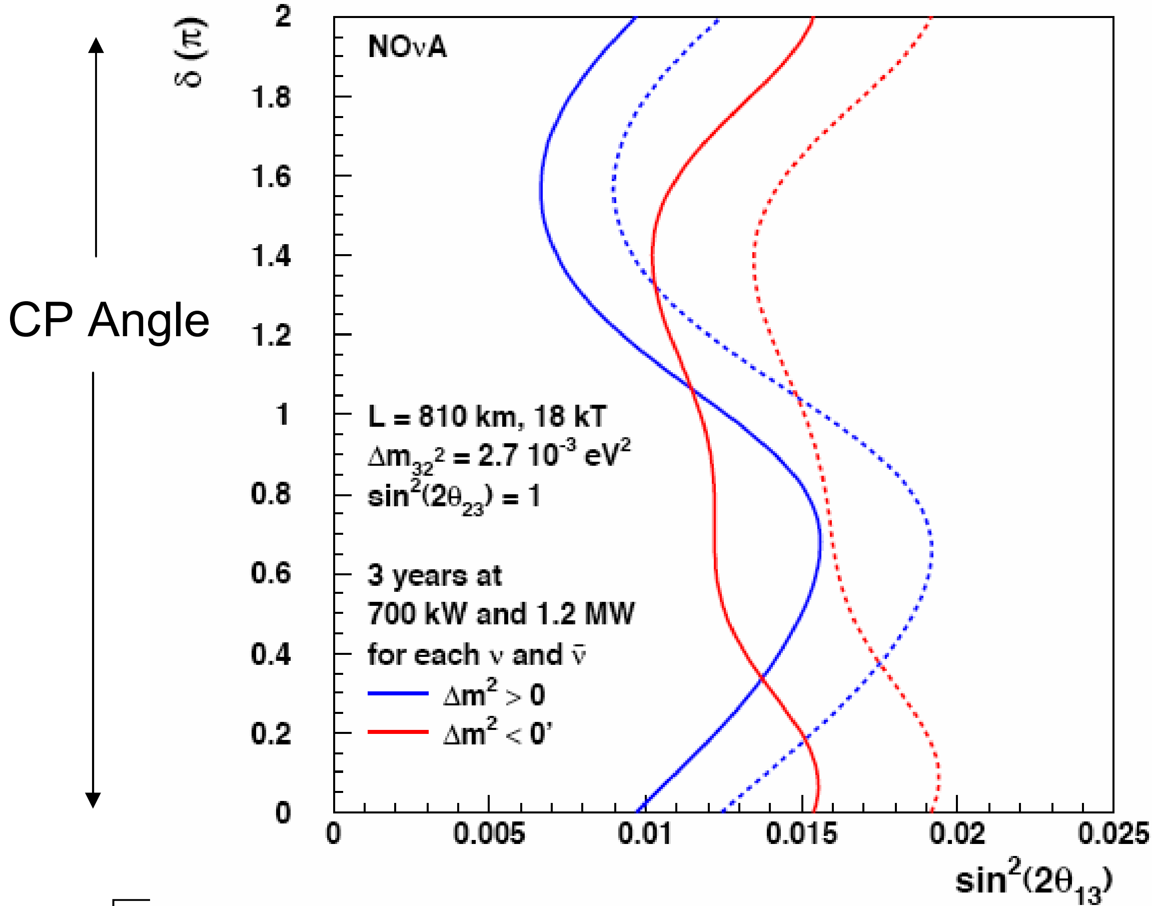
where a is

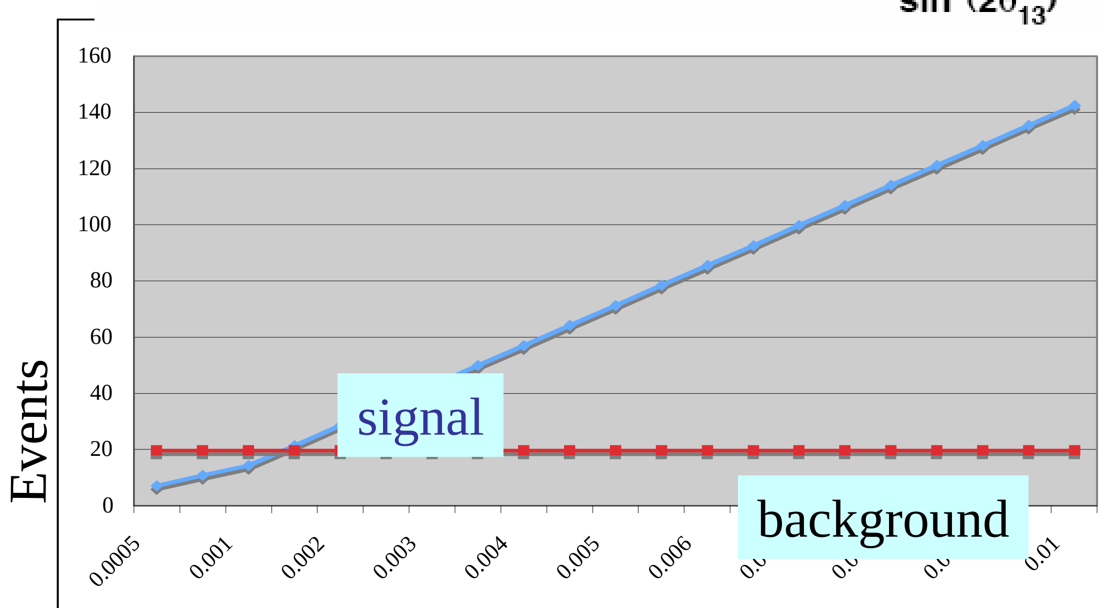
$$a = \frac{G_F N_e}{\sqrt{2}} \approx (3700\ \mathrm{km})^{-1} \left(\frac{\rho}{2.8\ \mathrm{g\ cm^{-3}}} \right)$$

and the sign changes between neutrinos and antineutrinos

3-ν's: Change is OK for all orders n of $\sin^n\Delta_{12}$ and $\sin^n\Delta_{13}$

NOvA Sensitivity to θ_{13}

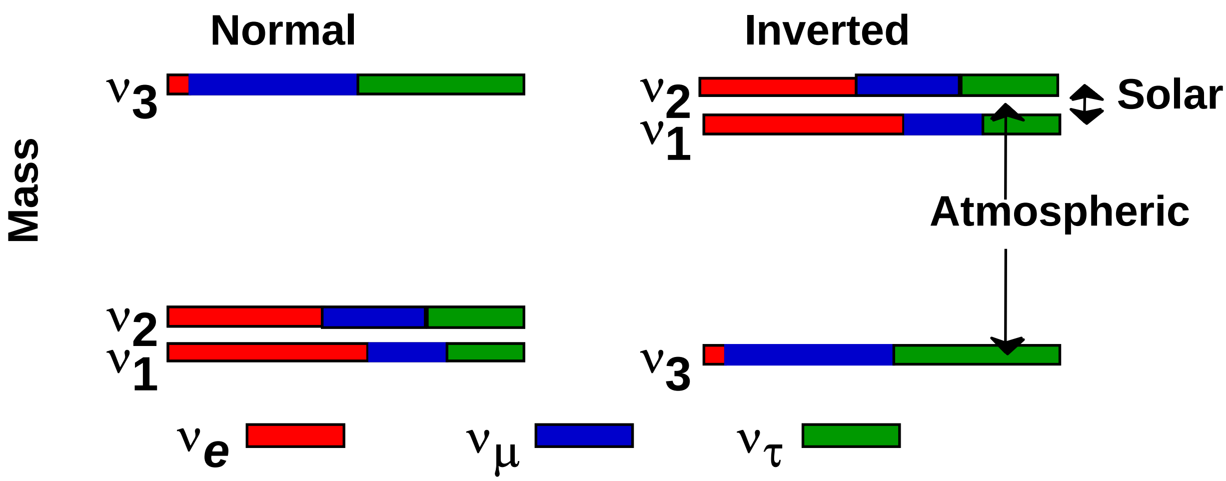




0.01 0.05 0.1

$\sin^2 2\theta_{13}$

Mass Hierarchy and NOvA



Major unsolved problem

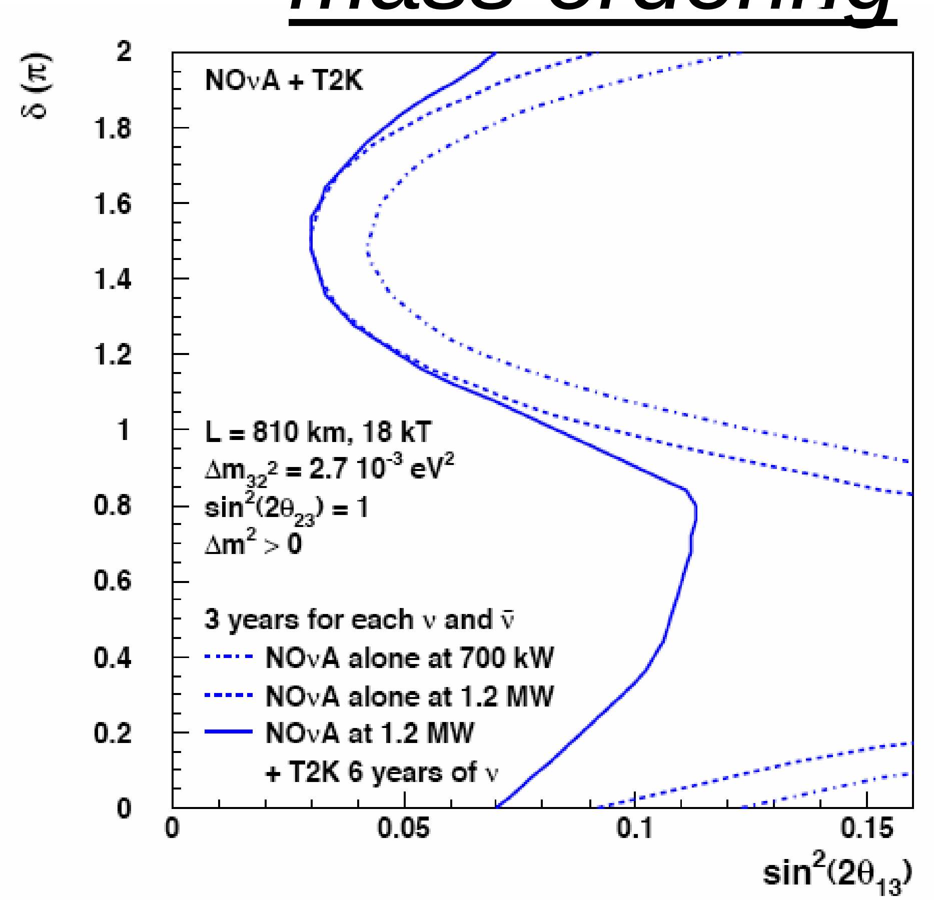
Requires matter effects to observe

Hence a real “target of opportunity” for a long baseline.

To leading order and zero CP violation, acts as if neutrinos and antineutrinos were interchanged.

CP violation makes it more complicated

NOvA Coverage range for mass ordering



Upgraded Fermilab complex could produce more beam, on order 1-2 MW

Best results from worldwide combinations

Next Order and CP Violation

- Do not neglect Δ_{12}
- Add back CP phase δ
- Terms group as

$$\left| e^{-i(\delta+\Delta_{32})} A_{atm} + A_{solar} \right|^2$$

(Before we looked only at $A_{atm}{}^2$)

Giving

$$P\left(\nu_\mu \rightarrow \nu_e\right) =$$

$$\sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{31}$$ ← Atmospheric

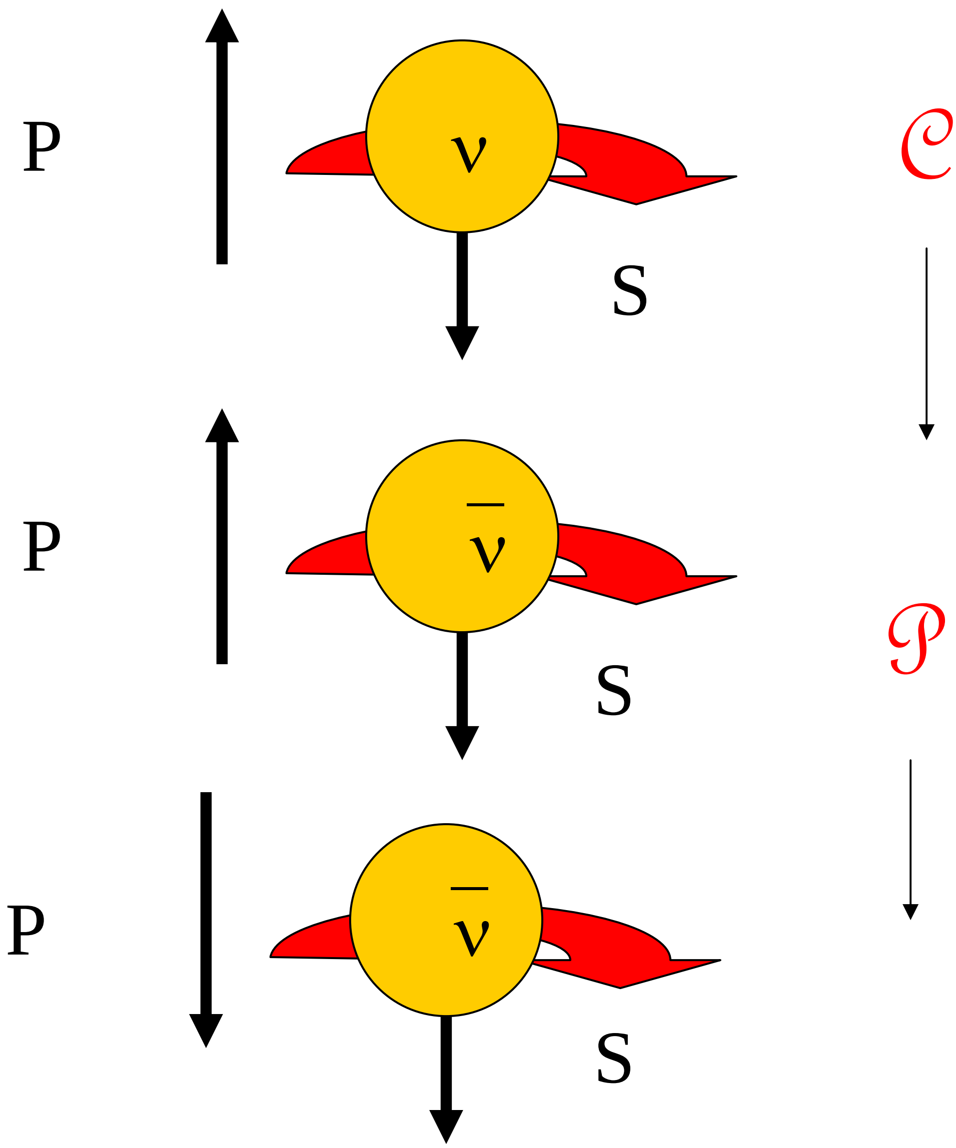
$$+\cos^2\theta_{13} \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$ ← Solar

$$+J_r \sin\Delta_{21} \sin\Delta_{31}$$ ← Interference

$$\left(\cos\Delta_{32} \cos\delta - \sin\Delta_{32} \sin\delta\right)$$

Note J_r a combination of angles $\simeq 0.9 \sin^2\theta_{13}$

CP and neutrinos



CP gives right-handed $\bar{\nu}$, Dirac partner of left-handed ν

These are the states created by the weak interaction

CP and Oscillation Experiments

$$P(\nu_\alpha \to \nu_\beta)$$

$$\mathcal{CP}$$

$$P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$$

$$\mathcal{T}$$

$$P(\overline{\nu}_\beta \to \overline{\nu}_\alpha)$$

CPT conservation gives

$$\Delta P^{T}_{\alpha\alpha} = 0$$

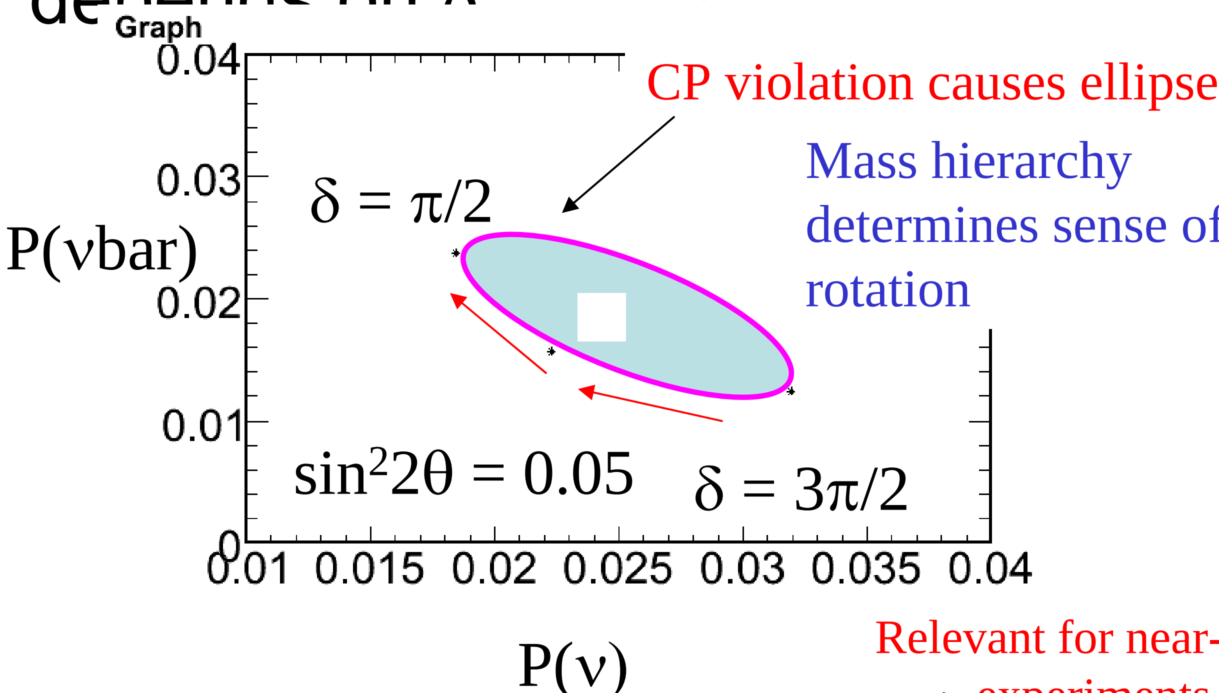
$$\Rightarrow \quad \Delta P^{CP}_{\alpha\alpha} = 0$$

Disappearance experiments can't see CP violation, only appearance experiments!

CP and Anti-Neutrinos

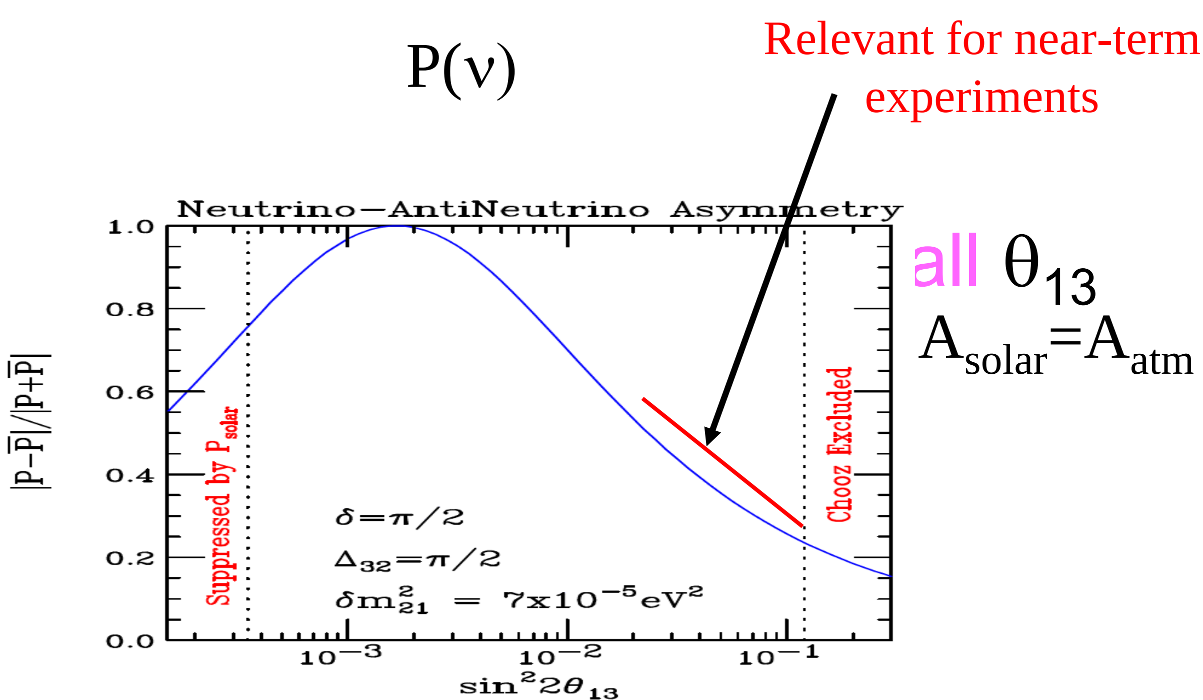
- CP δ changes sign between ν and ν–bar.
- As a result depends on δ

$$\frac{P_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e}}$$



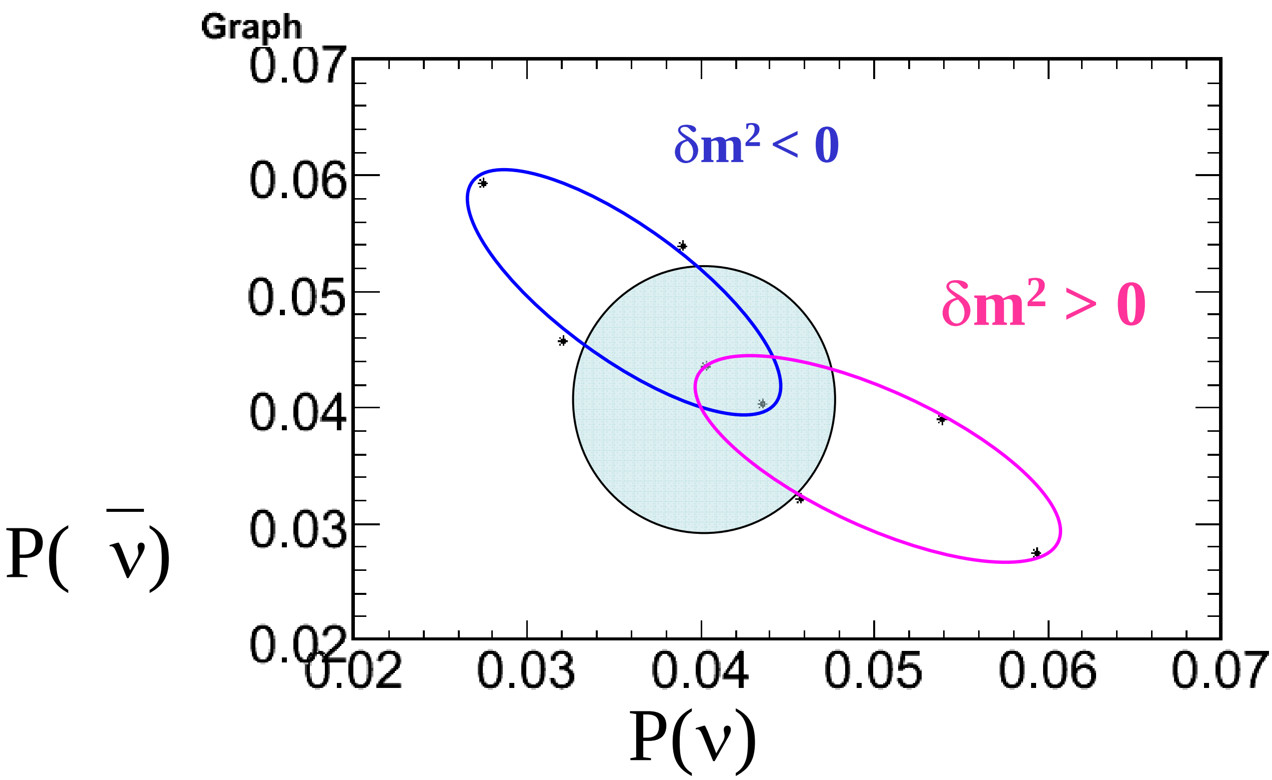
- Ef... all θ_{13}

$A_{solar}=A_{atm}$



Matter Effects Separate the CP Ellipses

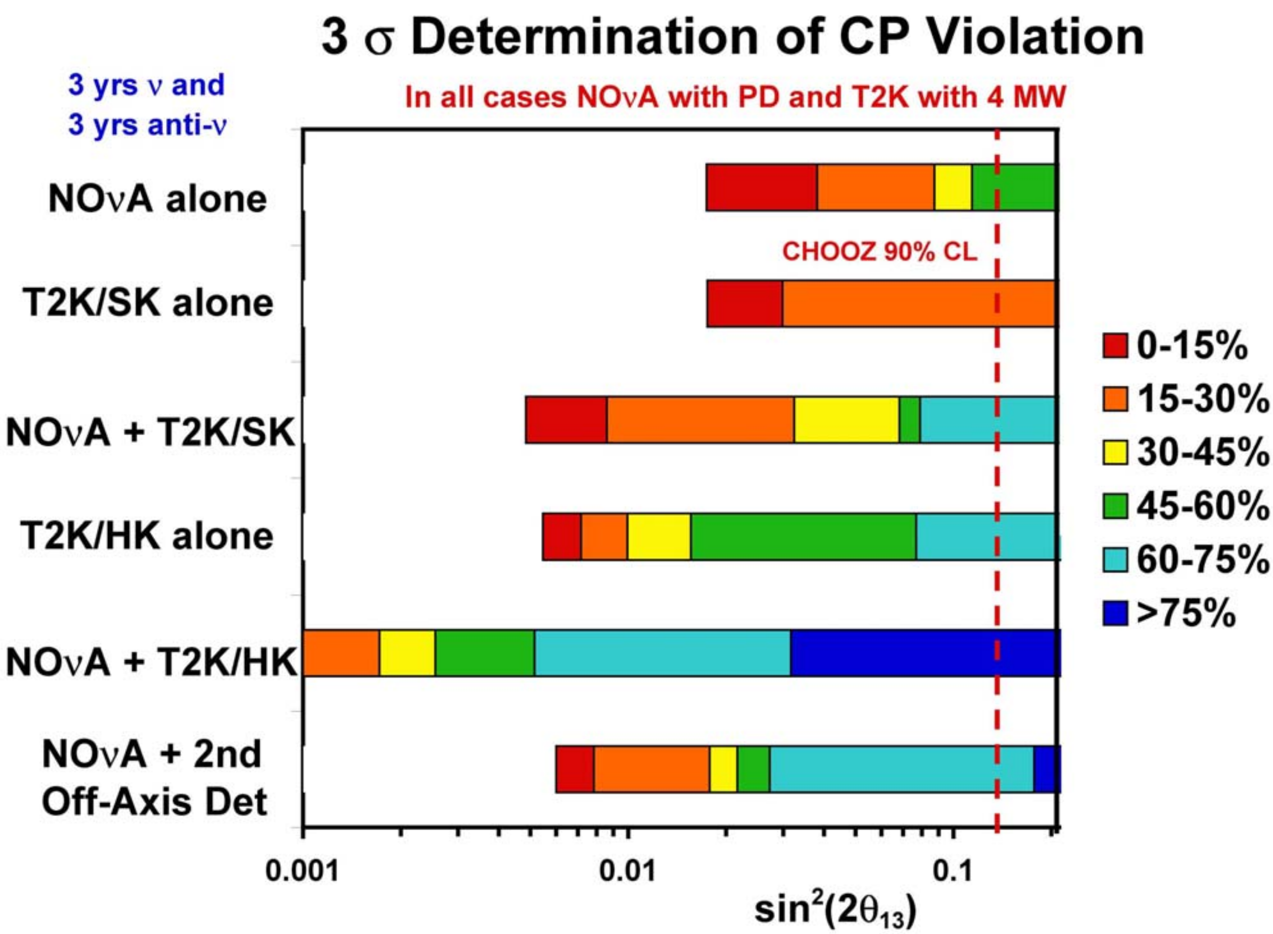
$\sin^2 2\theta_{13} = 0.10$



Typical data for multiple years of running

With adequate data, can distinguish mass hierarchy for some range of δ_{CP}, depending on strength of oscillation

To make progress on CP violation requires all the handles.



Need lots of protons ==> upgrades of beams

Great help from combining experiments!

The Next Stages

- The angle θ_{13} will be measured by the next generation of experiments
  - NoVA and T2K
  - Reactor Experiments
- For many values of δ, mass hierarchy will be resolved
  - For θ_{13} bigger than about 0.04
- Clues about CP violation
- Further progress will require additional detectors either
  - Bigger
  - Strategically placed.
- Large effort, potential big payoff

The scientific stakes could not be higher!

Leptogenesis and Cosmology

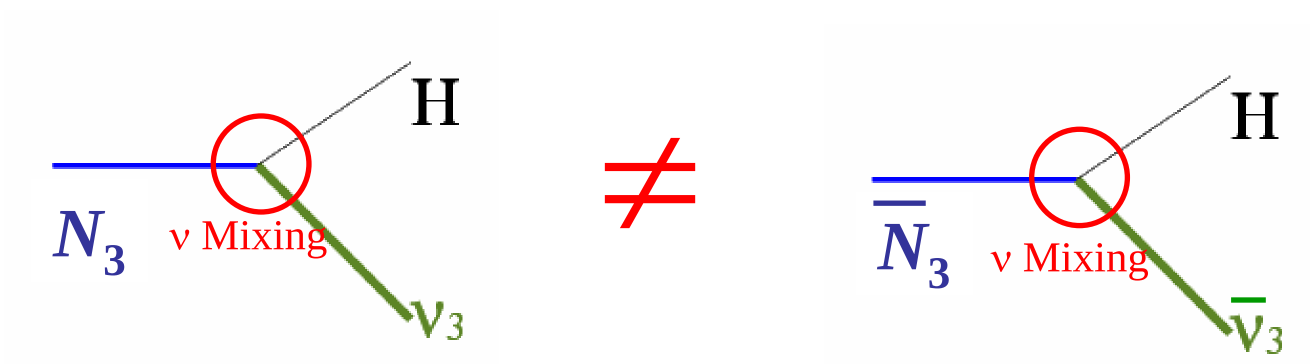
Universe has essentially no antimatter

BUT

Cosmology requires more CP-violation than the standard model provides to make this happen.

QCD can covert a lepton asymmetry to a quark one if there is enough CP violation in the neutrinos!

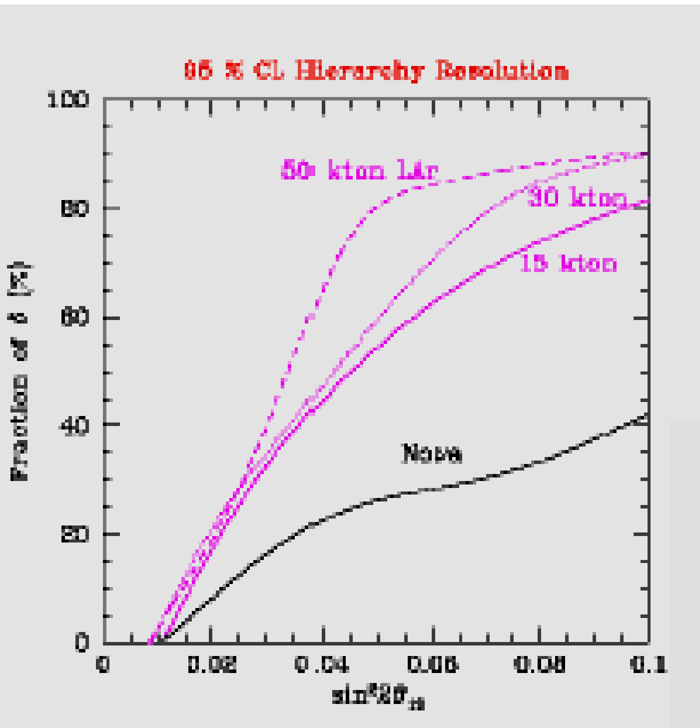
A heavy-mass partner of the neutrino is the most likely contributor. Recall see-saw.



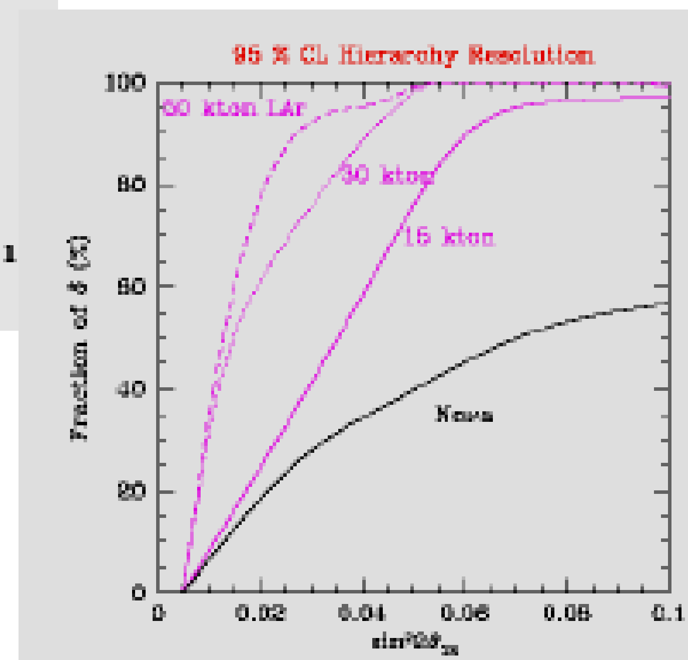
After Inflation at T ~ 10^{12} GeV

from M. Shaevitz

Advantages of a second detector



Upgraded Intensity (25 x 10^{20}/year)
6 years one detector + 4 years both

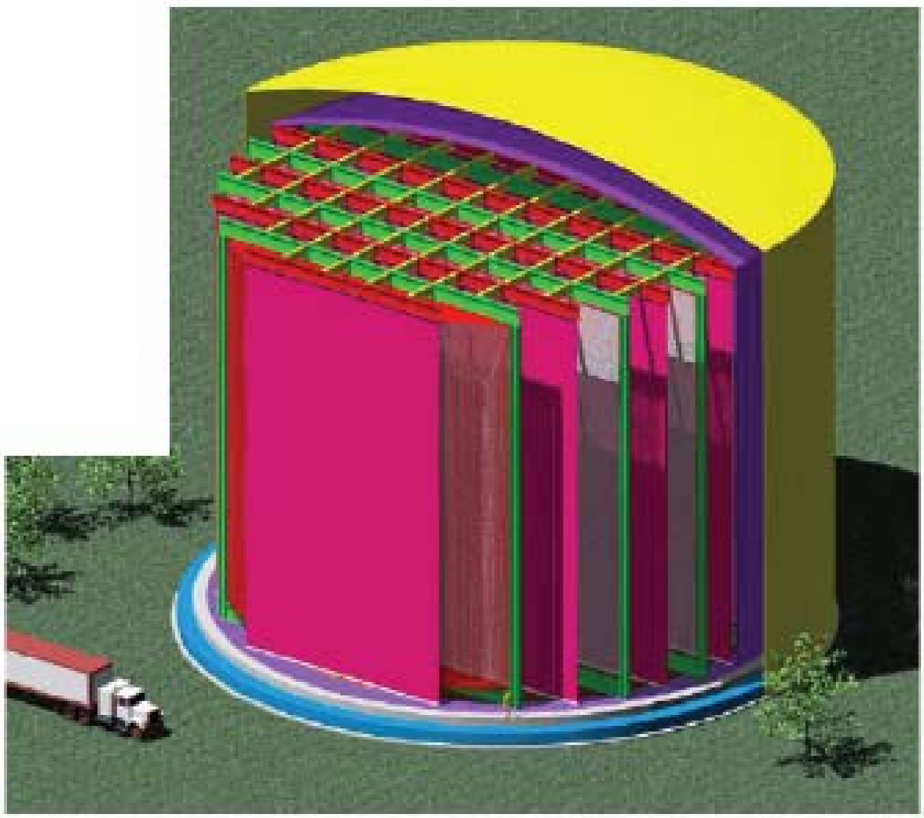


Nominal Intensity (6.5 x 10^{20}/year)
6 years one detector + 8 years both

One scenario with a second detector located at 200 km, with 0.7 GeV beam!

Mena, Palomares-Ruiz, and Pascoli, hep-ph/0510182

“For best results”, 2nd detector should be very efficient.

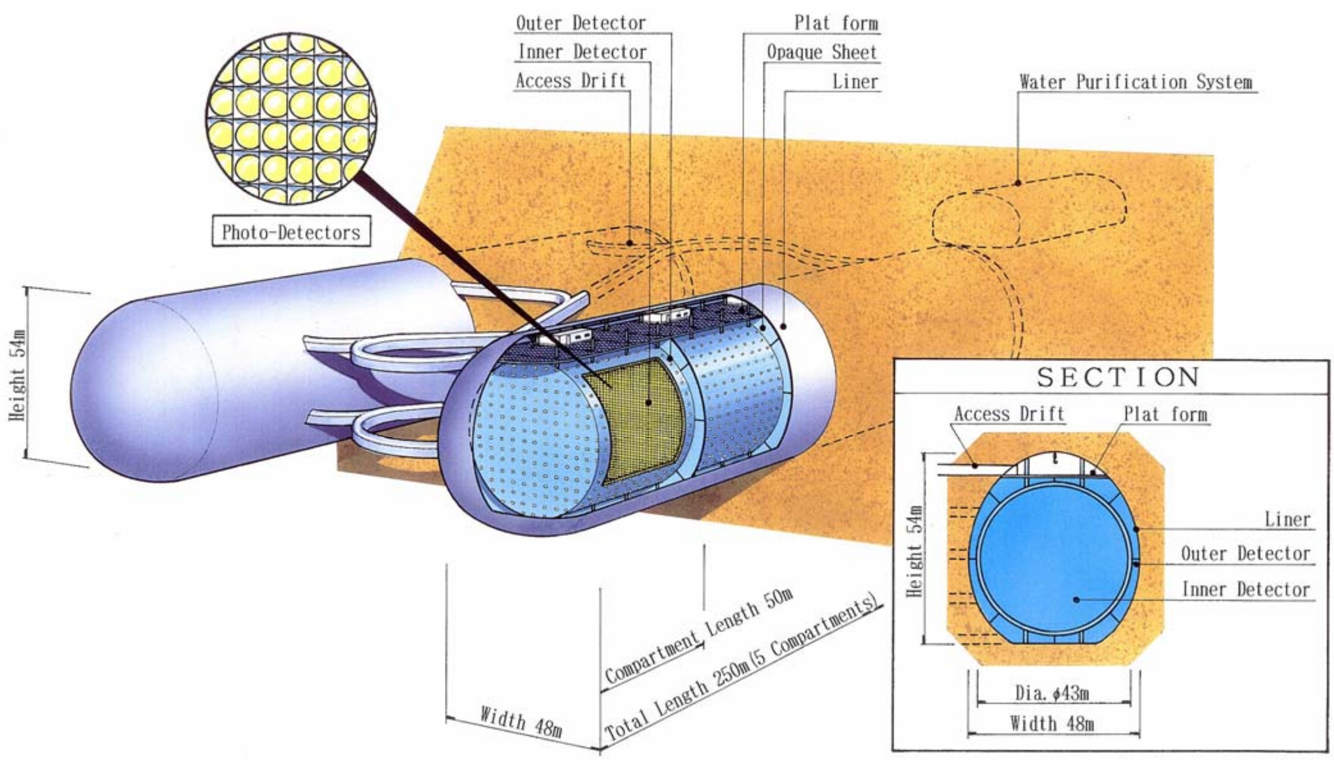


One potential technology is large liquid Argon (LAr) TPC

- Industrial size tanks
- Challenges from purity, noise, long drifts, cost
- Extremely high efficiency (claim ~90%)

Sidebar - Hyper-K megaton detector

1 MTon Water Cherenkov (like Super-K)
0.54 MTon fiducial volume
200 K PMT's



Tunnel shape cavity helps excavation and optimizes detector performance

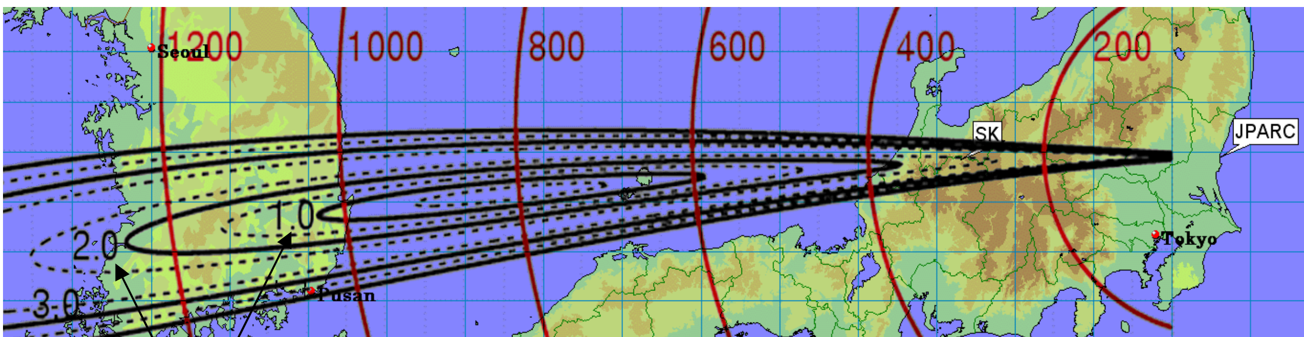
< 50 m deep for PMT's

Light path < 100 m

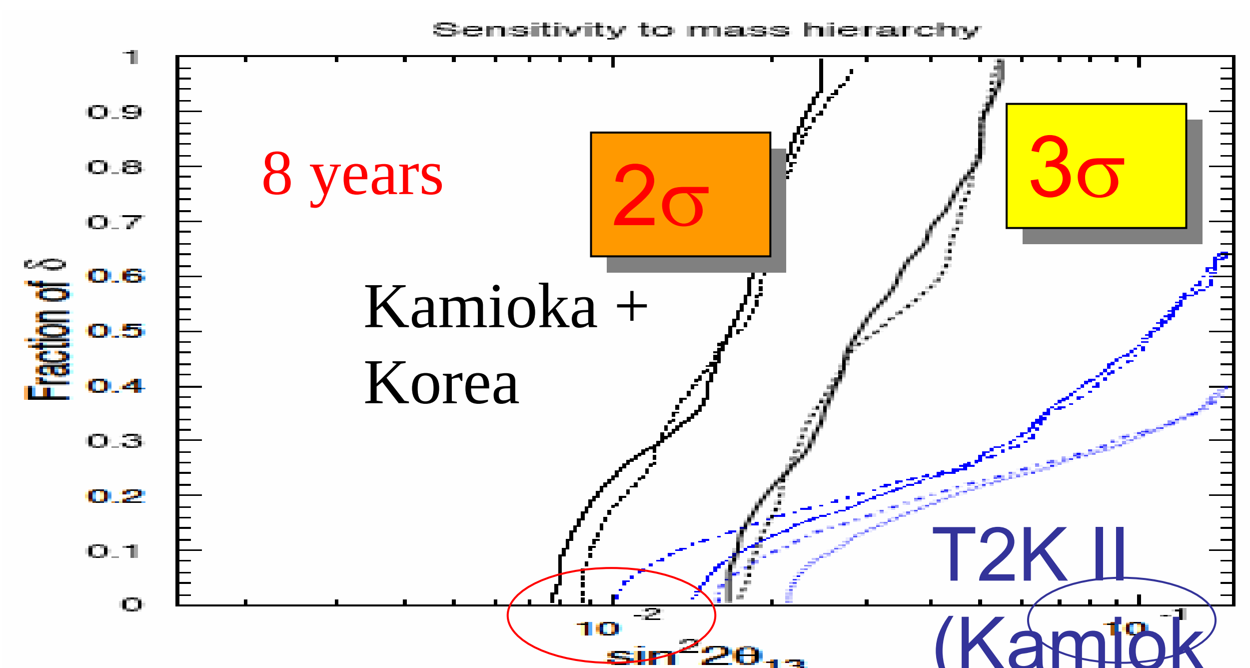
Dual cavities allows for staged construction, maintenance

Potential for Korean 2nd Detector

Split fiducial mass in 2 pieces (0.27 MTon each)



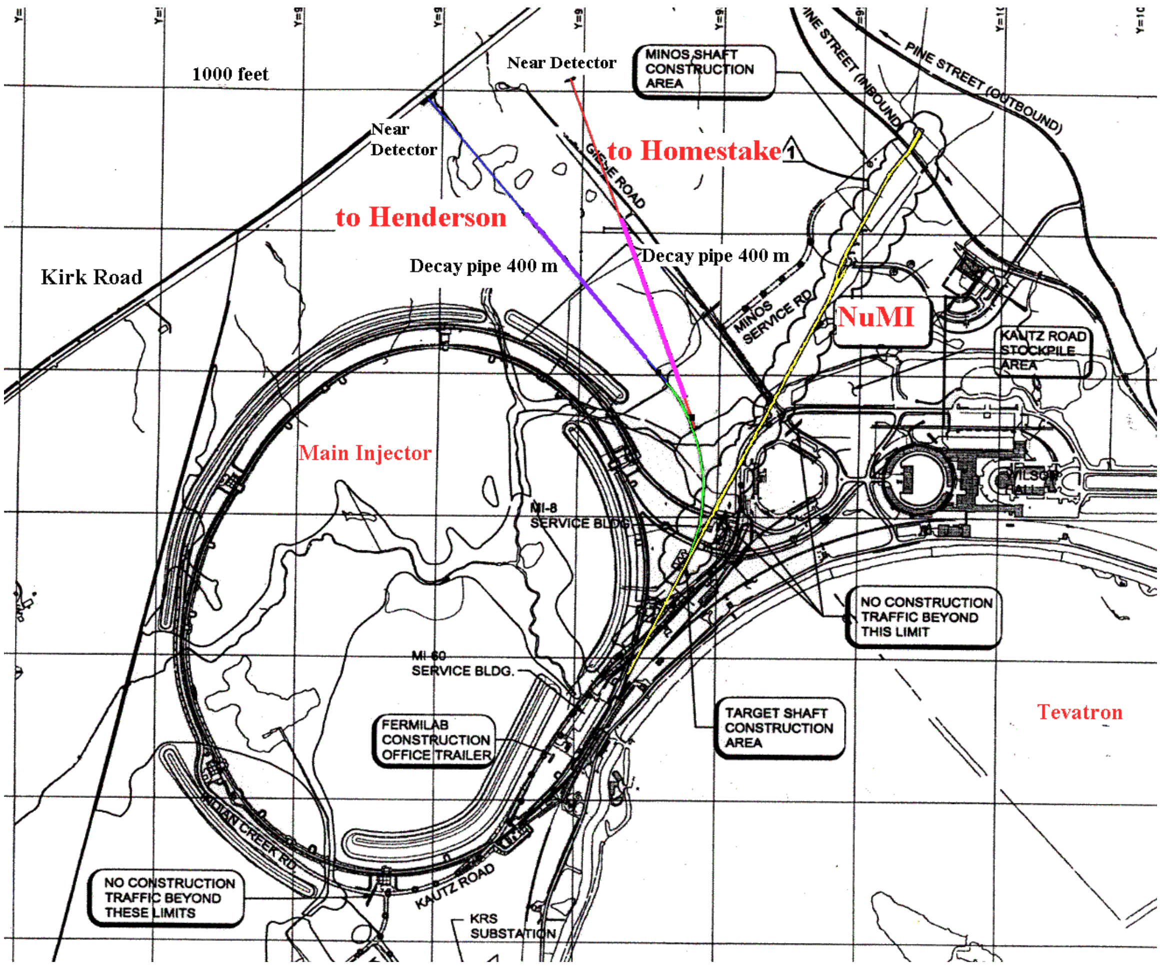
Off-axis angle (degrees) in 3 dimensions



Gives matter effect so that mass hierarchy can be studied

hep-ph/0504026

Can a beamline to a large DUSEL detector fit at Fermilab?

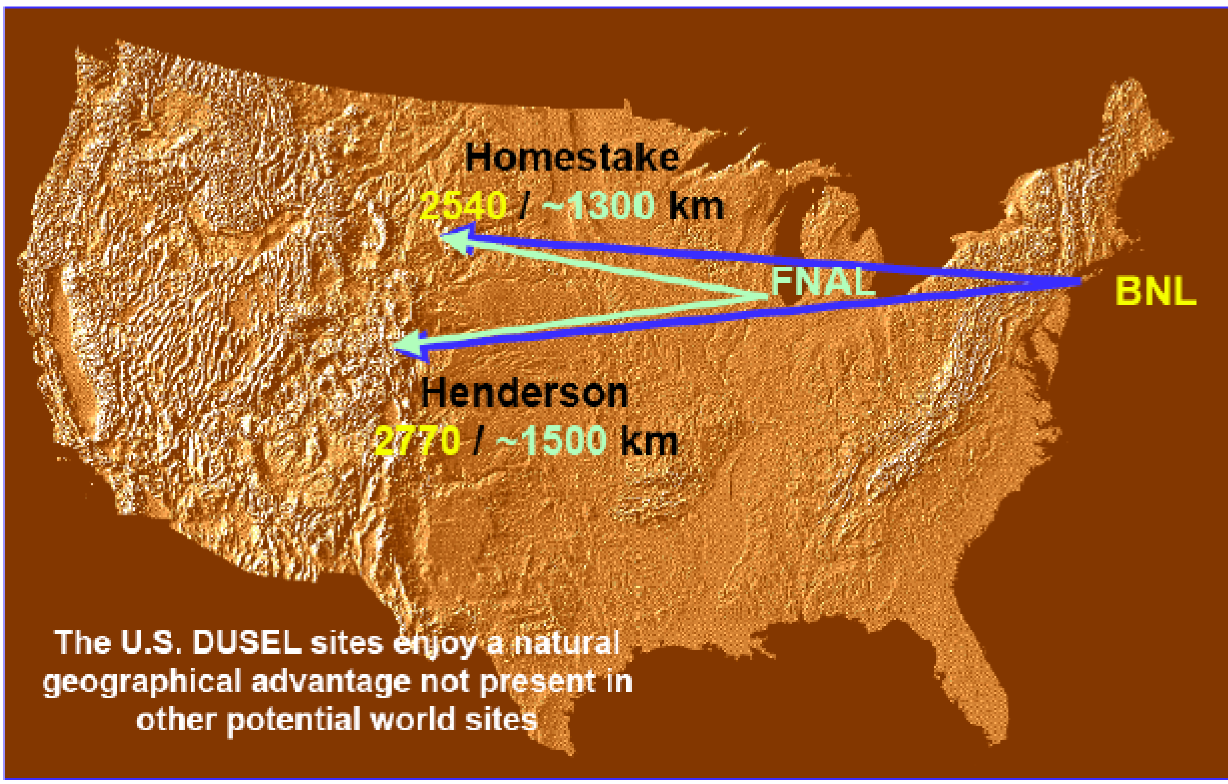


400 m decay pipe for use with low energy beam

Homestake (SD) 1289 km, ~ -6 degrees
Henderson (CO) 1495 km, ~ -7 degrees

W. Smart

Preferred DUSEL sites in the United States

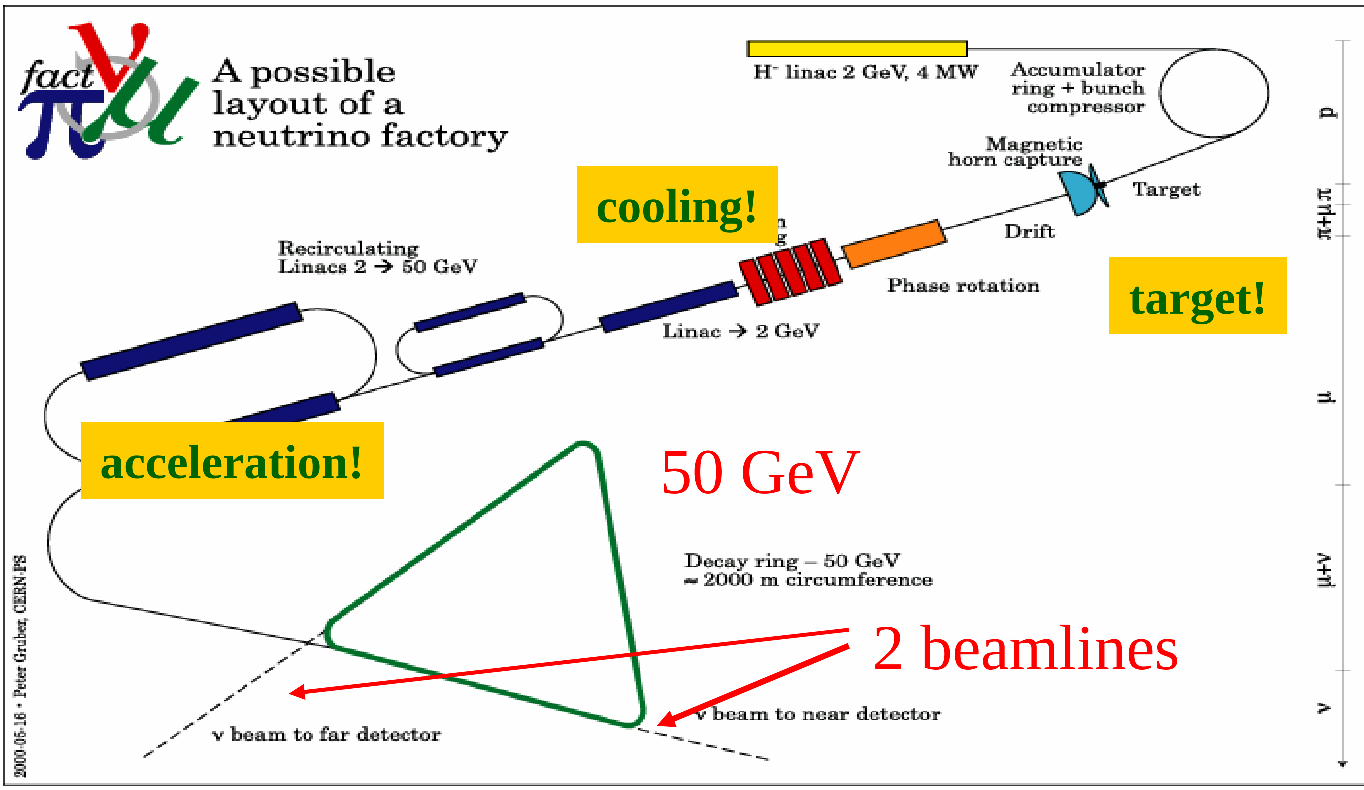


Ideal for long-baseline experiments

Focus now is on Fermilab as host

Lots of challenges, but lots of interest.

Advanced concepts- Neutrino Factory



Based on decays of stored muons. **After Blondel**

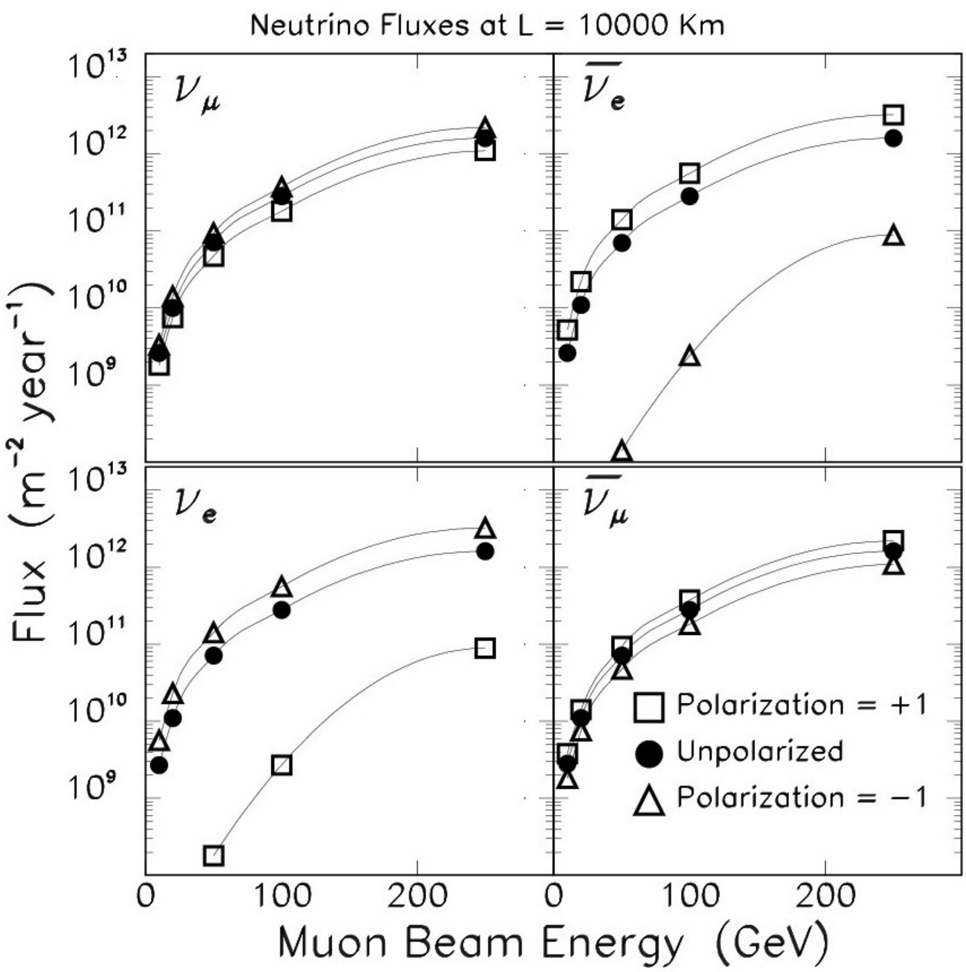
$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

Muon cooling schemes adopted from μ-collider designs.

Designs produce 1-5x10^{20} μ decays per year

Neutrino Factory Fluxes



In forward direction

$$F_{\nu_\mu}(x) \propto E_\mu{}^2 x^2 \left[(3-2x) + P_\mu(1-2x)\right]$$
$$F_{\overline{\nu}_e}(x) \propto E_\mu{}^2 x^2 \left[(1-x) + P_\mu(1-x)\right]$$

where $x = \dfrac{E_\nu}{E_\mu}$ and P is the μ polarization

Statistical power of Neutrino Factory

5 Years data taking

Expt	$\sin^2 2\theta_{13} = 0.1$ Signal	Bkg	$\sin^2 2\theta_{13} = 0.01$ Signal	Bkg
MINOS	49.1	108	6.7	109
ICARUS	31.8	69.1	4.5	70.3
OPERA	11.2	28.3	1.6	28.6
T2K	132	22.7	16.9	23.5
NOvA	186	19.7	23.0	20.7
NOvA+FPD	716	75.6	88.6	79.5
NuFact nu	29752	44.9	4071	44.9
NuFact nubar	7737	82.0	1116	82.0

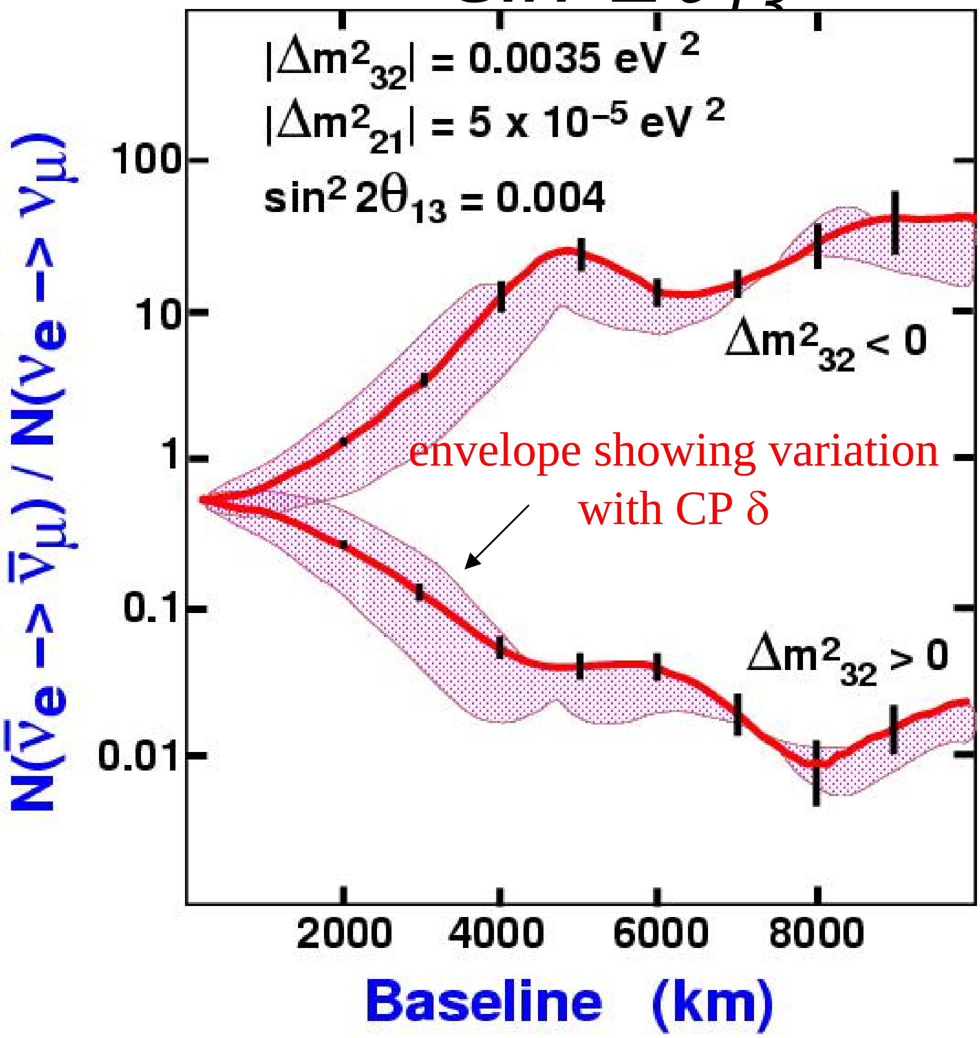
Calculations of W. Winter

Normal Hierarchy, $\delta = 0$

NUFACT: Beam = 3×10^{20} decays/yr,
E = 50 GeV, M_{det} = 100 kt, baseline 7300 km

Note this is a large magnetized detector because signal is “wrong-sign” μ

Neutrino Factory is sensitive to very low $\sin^2 2\theta_{13}$



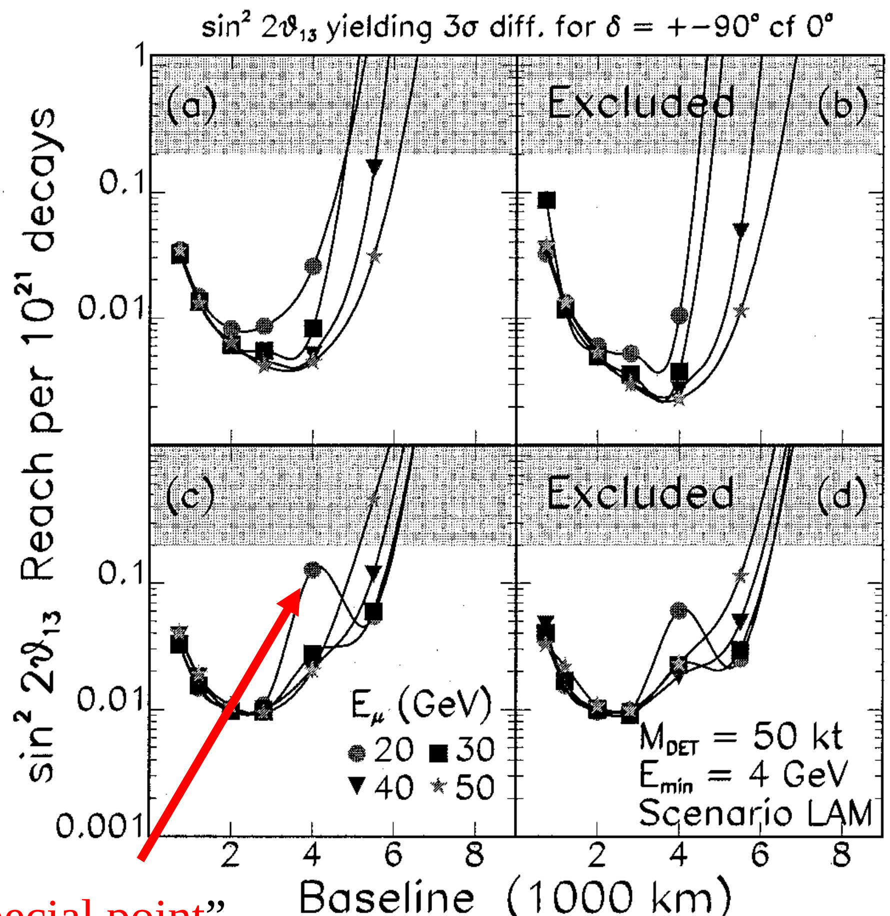
Ratio of oscillation rates from μ^- and μ^+ vs. baseline

Conditions: 10^{20} μ from 20 GeV ν-factory, 50 kT detector

Barger et al., PRD62, 073002, 2000; hep-ph/0003184

Interplay of mixing strength and baseline for CP determination at a ν-factory

$\sin^2 2\theta_{13}$ reach vs. baseline for CP discrimination



0, π/2 distinct

0, -π/2 distinct

1st “special point”

normal

inverted

Conditions: 10^{21} μ from 20 GeV ν-factory, 50 kT detector

Practicalities - cooling in two directions

μ^+ and μ^- from decays naturally require cooling both in P_T and P_L

Current thinking centers on *ionization cooling.*

TRANSVERSE COOLING

Reduce momentum uniformly in all coordinates by ionization in a liquid medium (liquid H_2).

Re-accelerate longitudinally –> net decrease in P_T/P_L

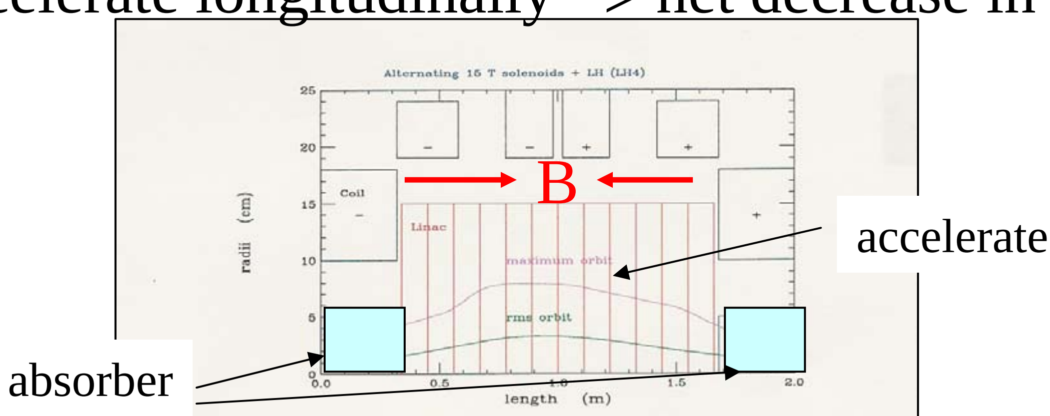


Figure 2: Schematic of a 2 m section (one period) of the alternating solenoid transverse cooling lattice described in the text.

Reduction in transverse emittance ε_T

Note ε_T ~ Area of phase ellipse in x, angle space

Longitudinal Cooling

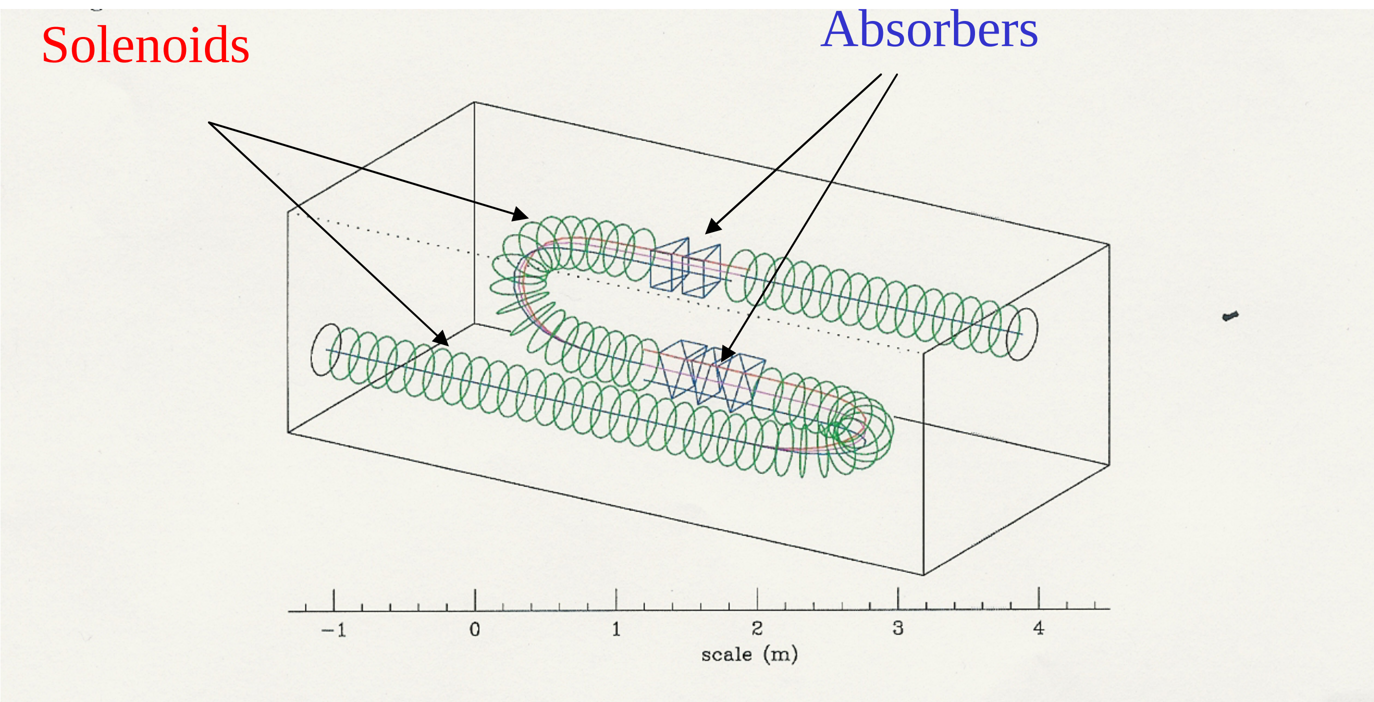
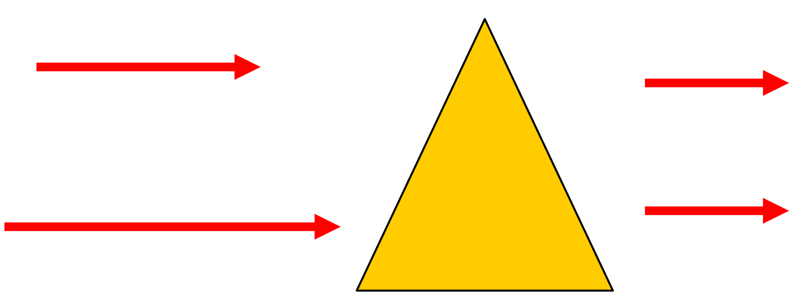


Figure 3: Schematic of the bent solenoid longitudinal emittance exchange section.

Curved solenoids introduce dispersion, e.g.

$$y = f(E)$$



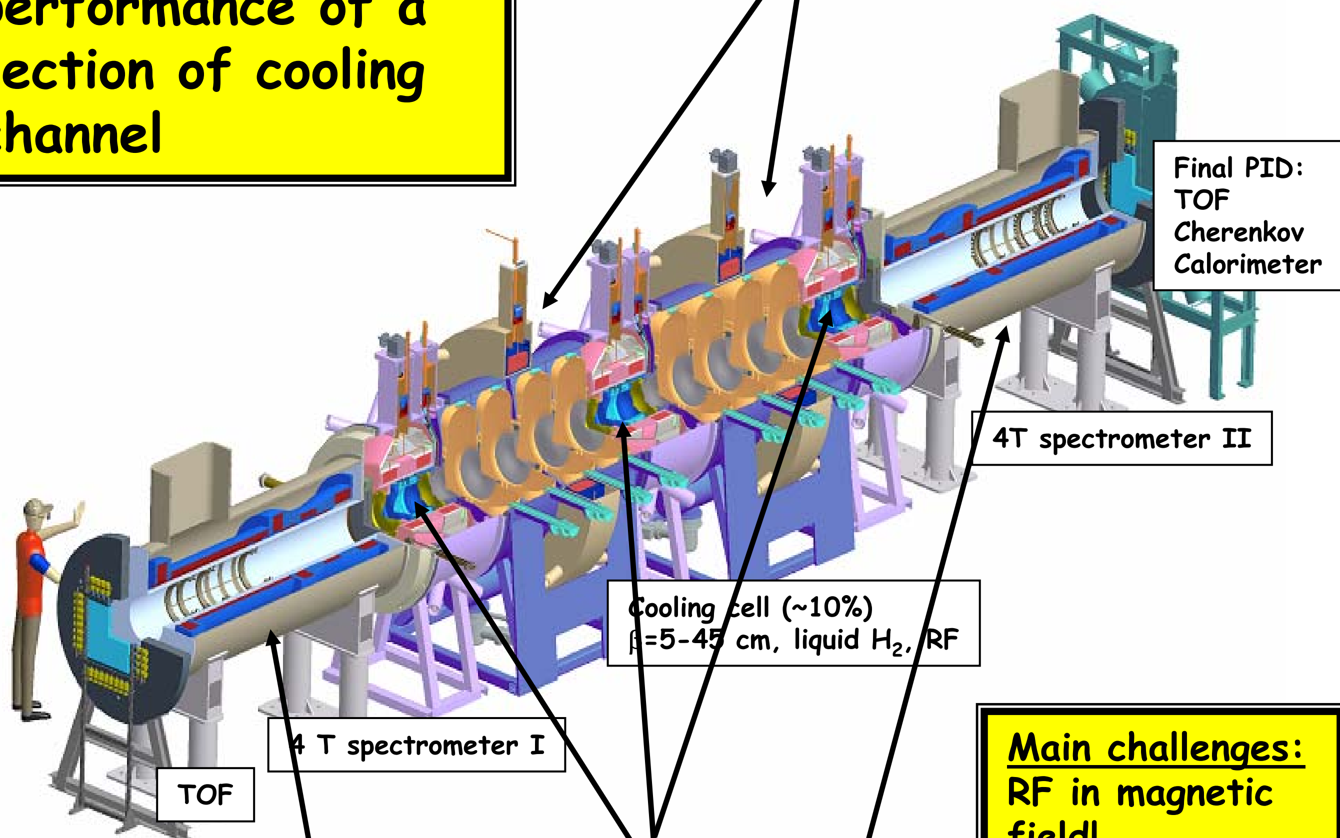
High energy sees more material than low

==> spread reduced

MICE Experiment at RAL

Aims: demonstrate feasibility & performance of a section of cooling channel

RF Cavities



LH_2 "targets"

"In" and "out" spectrometers

Main challenges:
RF in magnetic field!
10^{-3} meas. of emittance
Safety issues

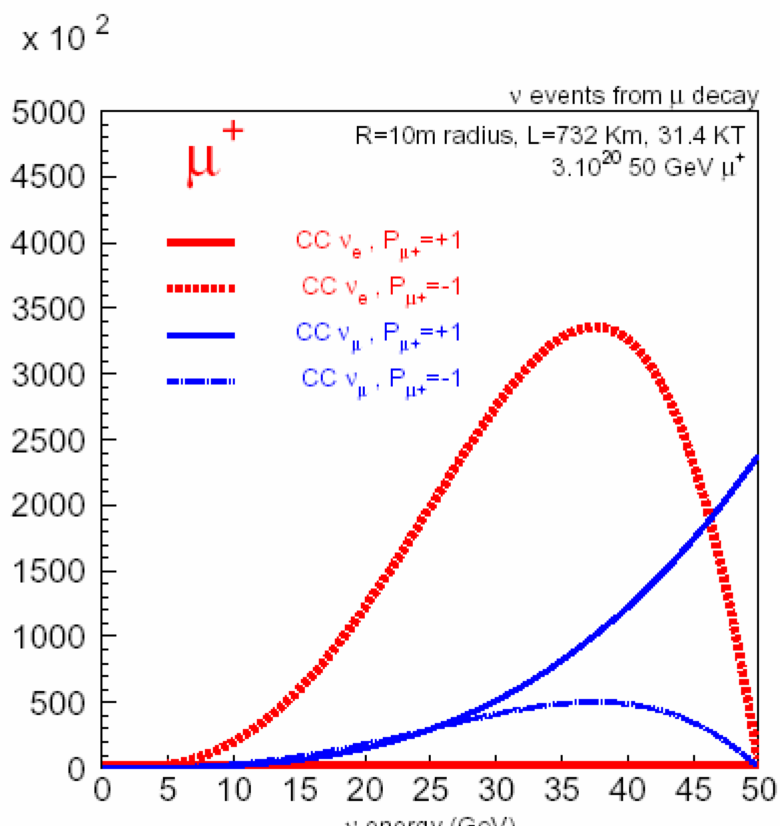
Build a prototype cooling channel

Cool 200 MeV beam by 10%

Useful or just for fun?

A.Blondel, "Muon Polarisation in the Neutrino Factory"

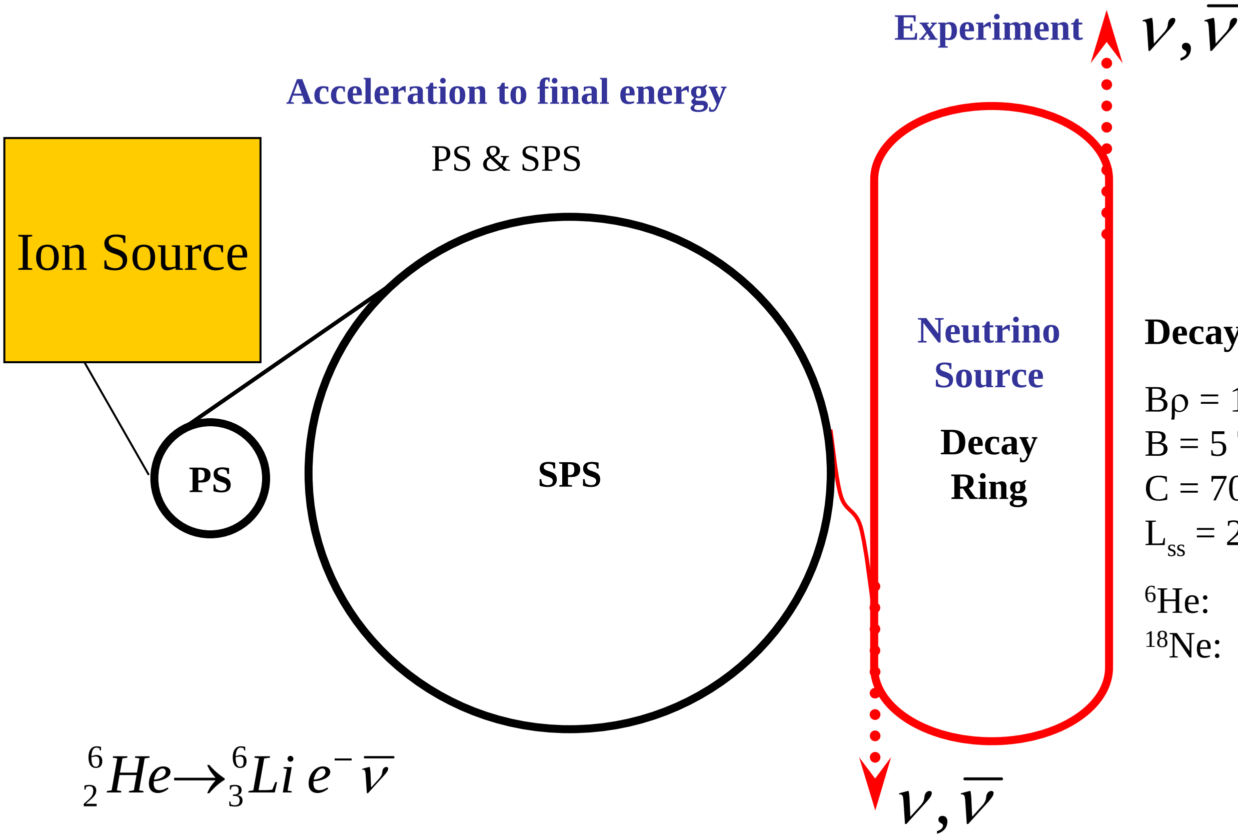
. By switching from negative muons with 50% negative polarisation to positive muons with 50% negative polarisation, one can change the ratio of CC ν_e to CC ν_μ by a factor 20, this ratio is only 5 in absence of polarisation. This must be useful.



Too early to say!

Beta-beams - an alternative source of clean ν_e and $\bar{\nu}_e$ beams

Acceleration **Neutrino source**



Decay ring

$B\rho$ = 1500 Tm
B = 5 T
C = 7000 m
L_{ss} = 2500 m
^{6}He: γ = 150
^{18}Ne: γ = 60

$${}^{6}_{2}He \rightarrow {}^{6}_{3}Li\, e^{-}\, \bar{\nu}$$

Average $E_{cms} = 1.937$ MeV

$${}^{18}_{10}Ne \rightarrow {}^{18}_{9}Fe\, e^{+}\, \nu$$

Average $E_{cms} = 1.86$ MeV

About 10^{18} decays/year

Need high γ because energy low.

CERN concept
(for Frejus, 130 km)
(from Lindross, NUFACT 05)

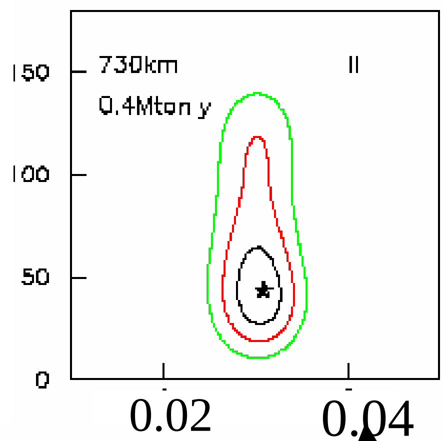
Any relevance of this β-beam concept for Fermilab?

Extraordinarily difficult if it can be done at all

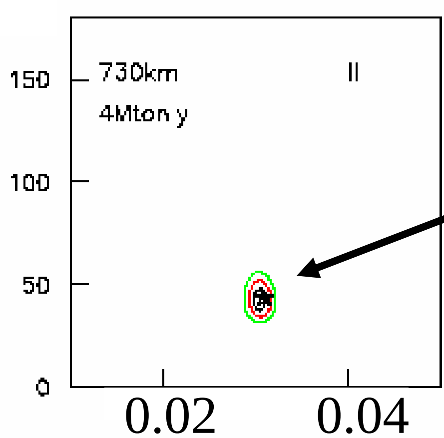
- Build ion source
- Rigourous control of losses (quenching)
- Tunnel activation

Discussed in literature, conferences

Distinguish δ from (0,π)



$\sin^2 2\theta_{13}$



$\sin^2 2\theta_{13}$

Soudan distance with 2 different (large) exposures

High γ gives an advantage that improves competitiveness with combination of conventional "superbeam" experiments

Conclusions – Neutrinos are Critical Physics

- Since about 1998, the neutrino has been demanding extension of the Standard Model.
- Many experiments feeding on the new phenomena already.
- Many more in the pipeline.
- Lots of basic physics, lengthy hard work required, geological distances

- All this must be telling us something important!

BACKUP SLIDES

Final Sidebar - Polarization at a neutrino factory

Polarization is defined as $max < \sigma \cdot e > = P$

(e is direction of polarization vector)

In the reaction $\pi^+ \to \mu^+ \nu_\mu$

the muon polarization is $- v/c = - P_\mu^*/E_\mu^* = - 0.27$

Spin rotation in the magnetic and electric fields of an accelerator has been shown to decrease this to ~18%, unless special steps are taken.

Why interesting? Recall that

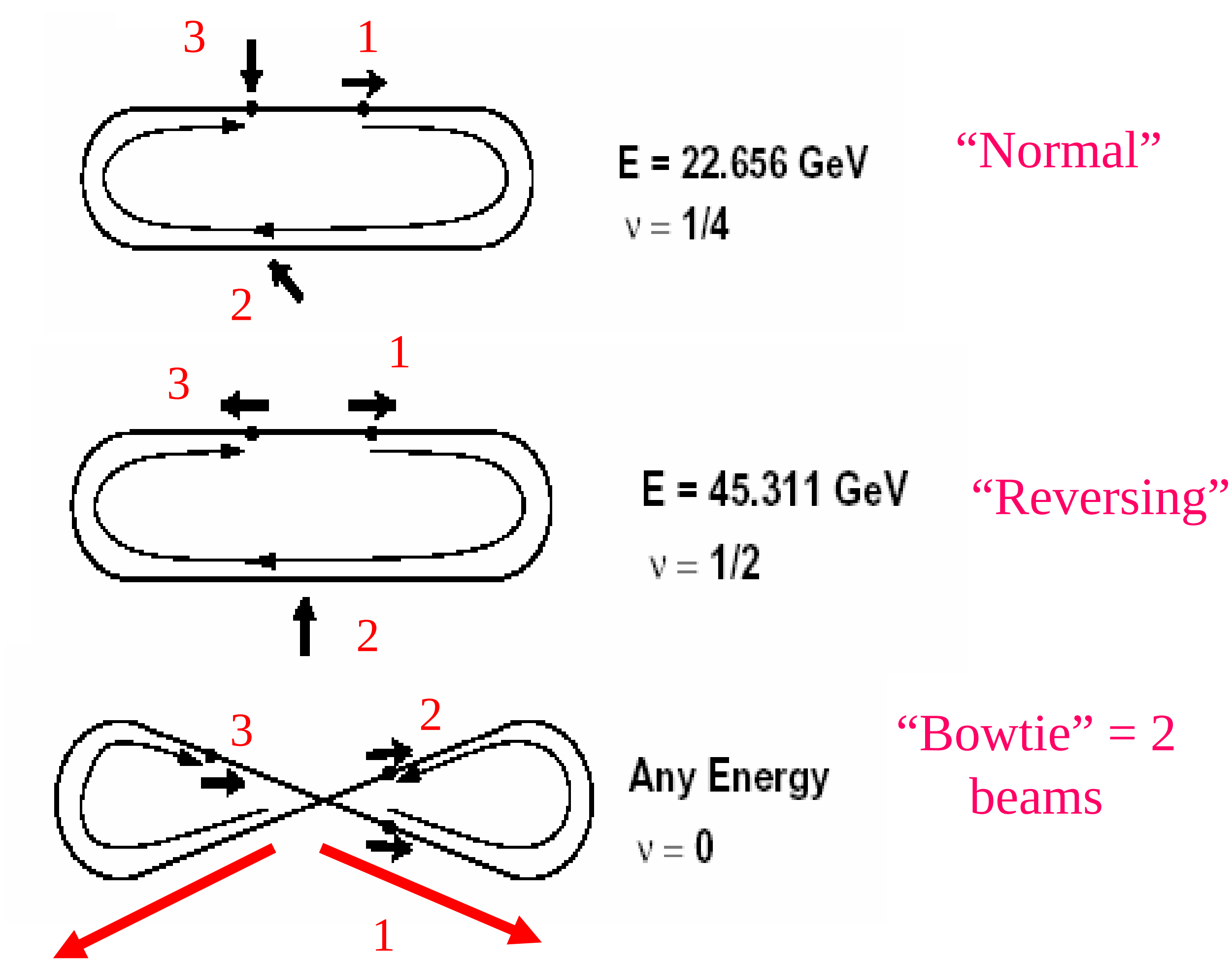
$$F_{\bar{\nu}_e}(x) \propto E_\mu^{\ 2} x^2 \left[(1-x) + P_\mu (1-x)\right]$$

If $P_\mu = 1$, the flux of $\bar{\nu}_e$ vanishes!

Preserving polarization at a storage ring

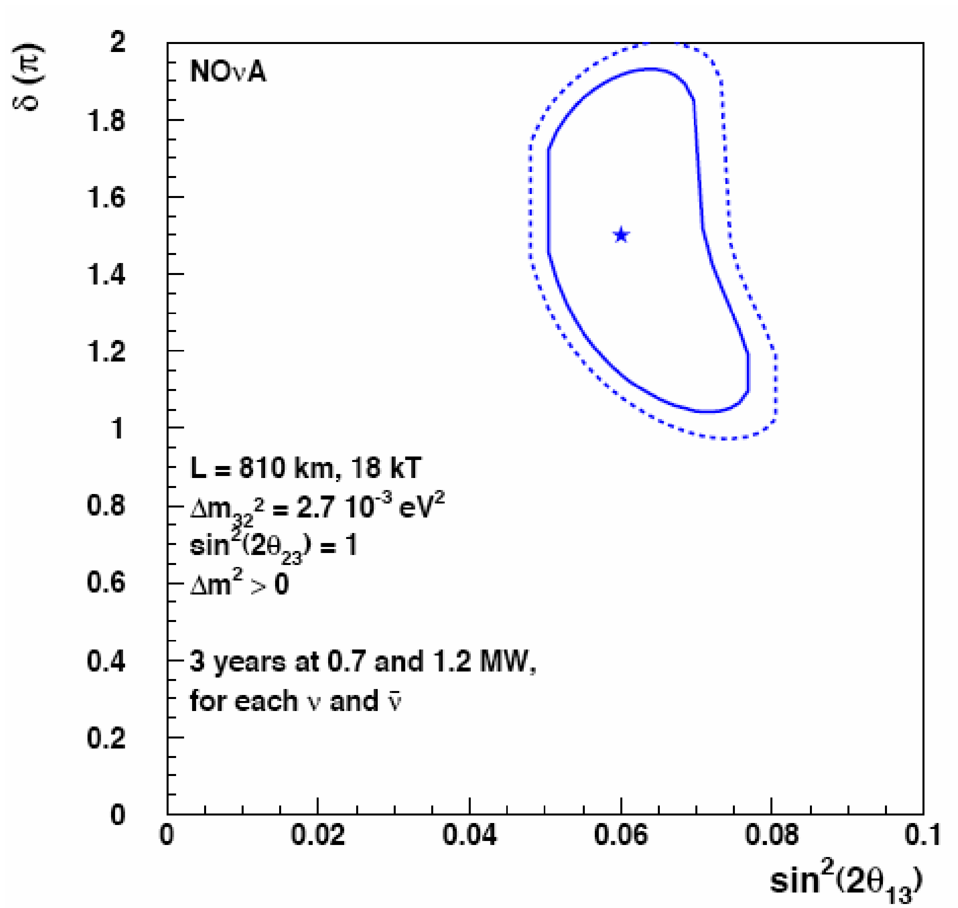
Spin tune depends on magic energy (princple of g-2 experiment)

$$\nu = a_\mu \gamma = \frac{g_\mu - 2}{2}\frac{\mathrm{E_{beam}}}{m_\mu} = \frac{\mathrm{E_{beam}(GeV)}}{90.6223(6)} \; .$$



Graphic: A. Blondel

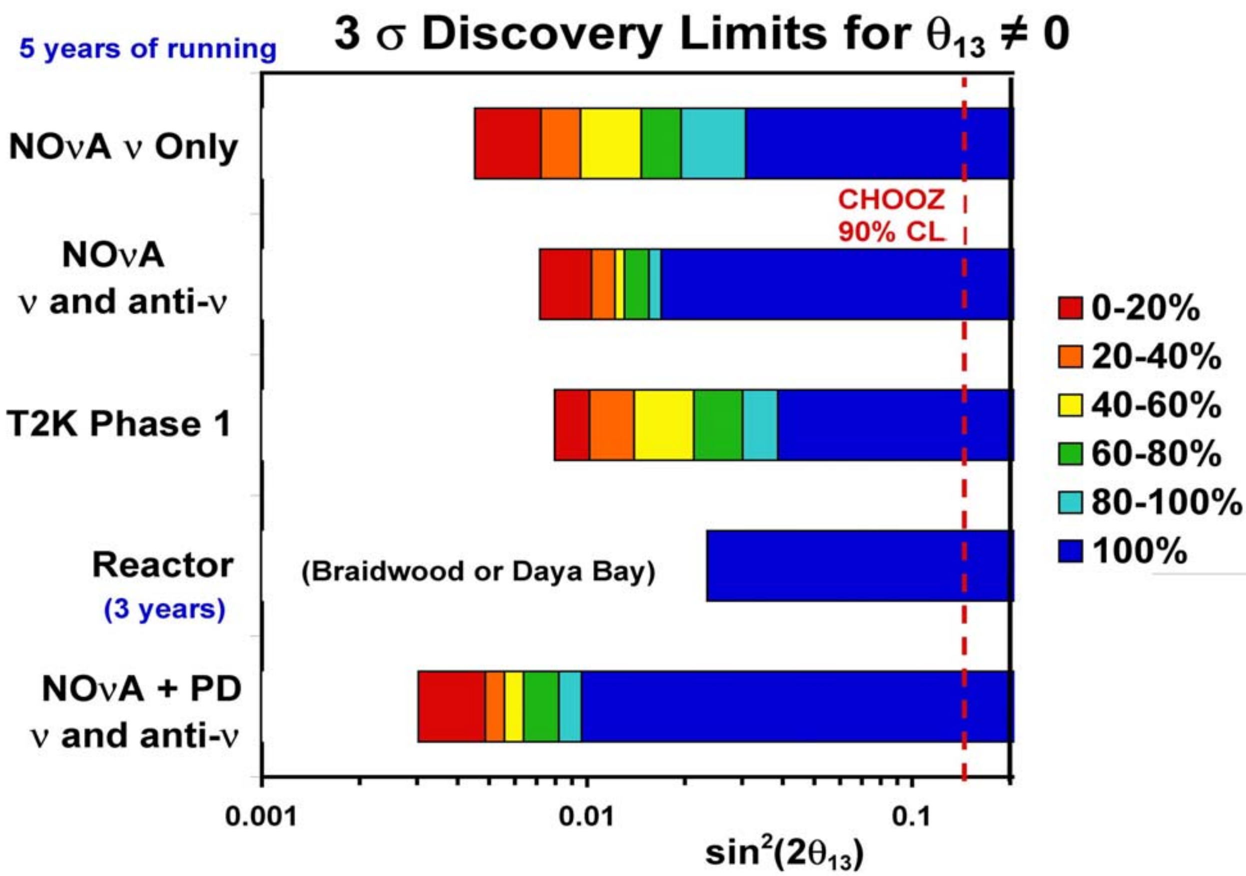
NOvA Coverage range for mass ordering

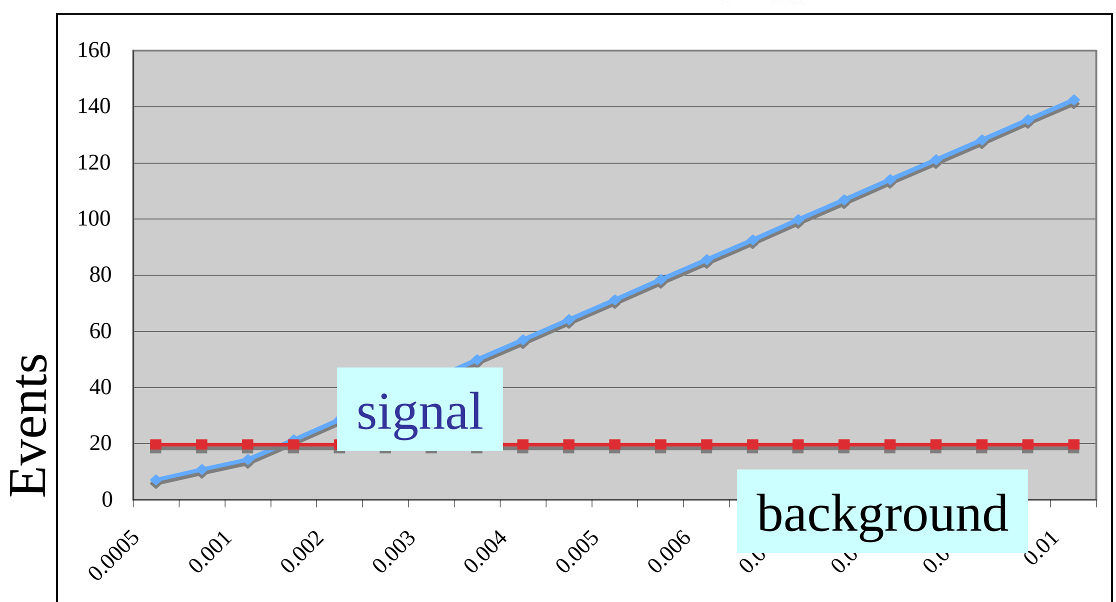


Upgraded Fermilab complex could produce more beam, on order 1-2 MW

Best results from worldwide combinations

NOvA Sensitivity to θ_{13}





0.01 0.05 0.1

$\sin^2 2\theta_{13}$

Sidebar - magic baseline removes degeneracies (that second "special" point)

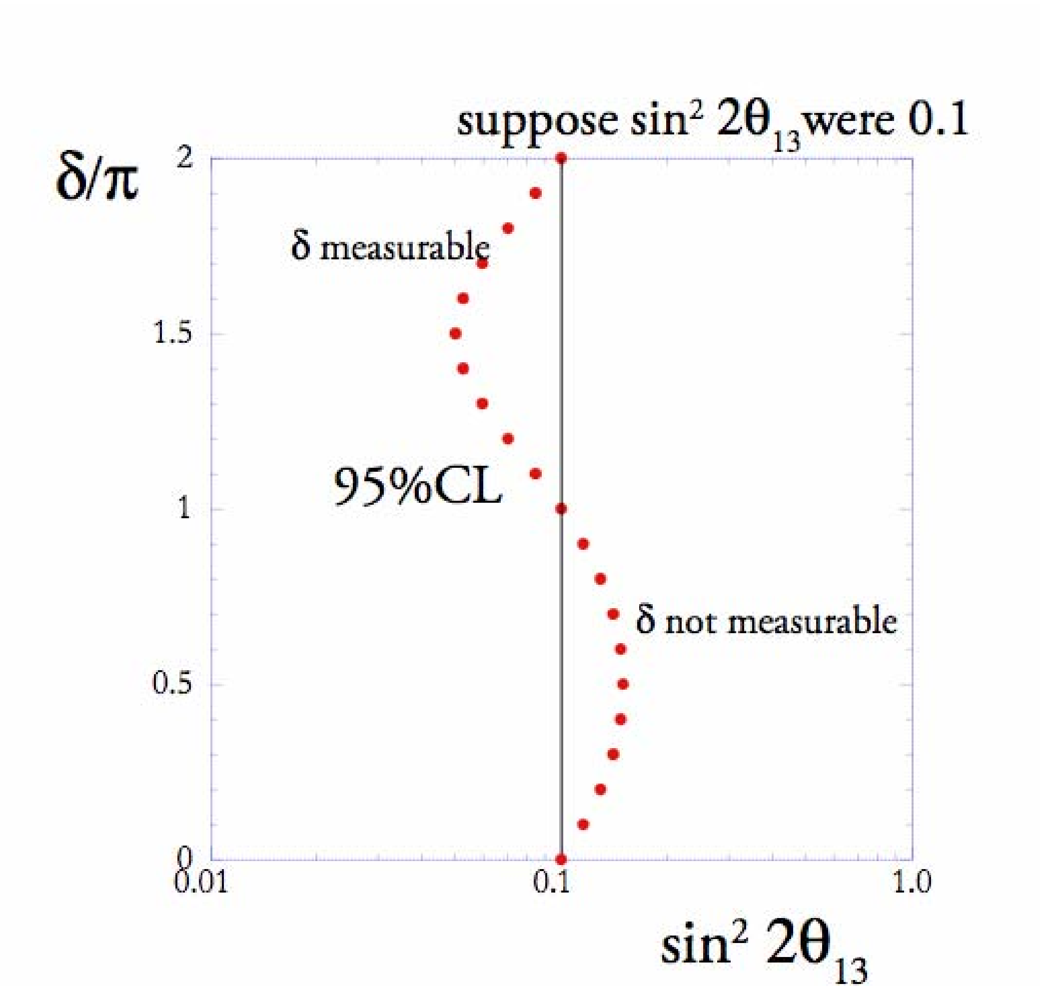
$$P_{\rm app} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$
$$\pm\ \alpha \sin 2\theta_{13}\, \xi \sin\delta_{\rm CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$
$$+\ \alpha \sin 2\theta_{13}\, \xi \cos\delta_{\rm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

$$\Leftrightarrow\ \sin(\hat{A}\Delta) = 0$$
$$\Leftrightarrow\ \sqrt{2} G_F n_e(L) L = 2\pi$$
$$\Leftrightarrow\ L \sim 7\,500\ \mathrm{km}$$

Removes CP dependence at this baseline, regardless of conditions.

Best for $\sin^2 2\theta_{13} < 0.01$, where CP degeneracies are largest

Can discuss measurements of quantities in terms of what fraction of CP-space they can see

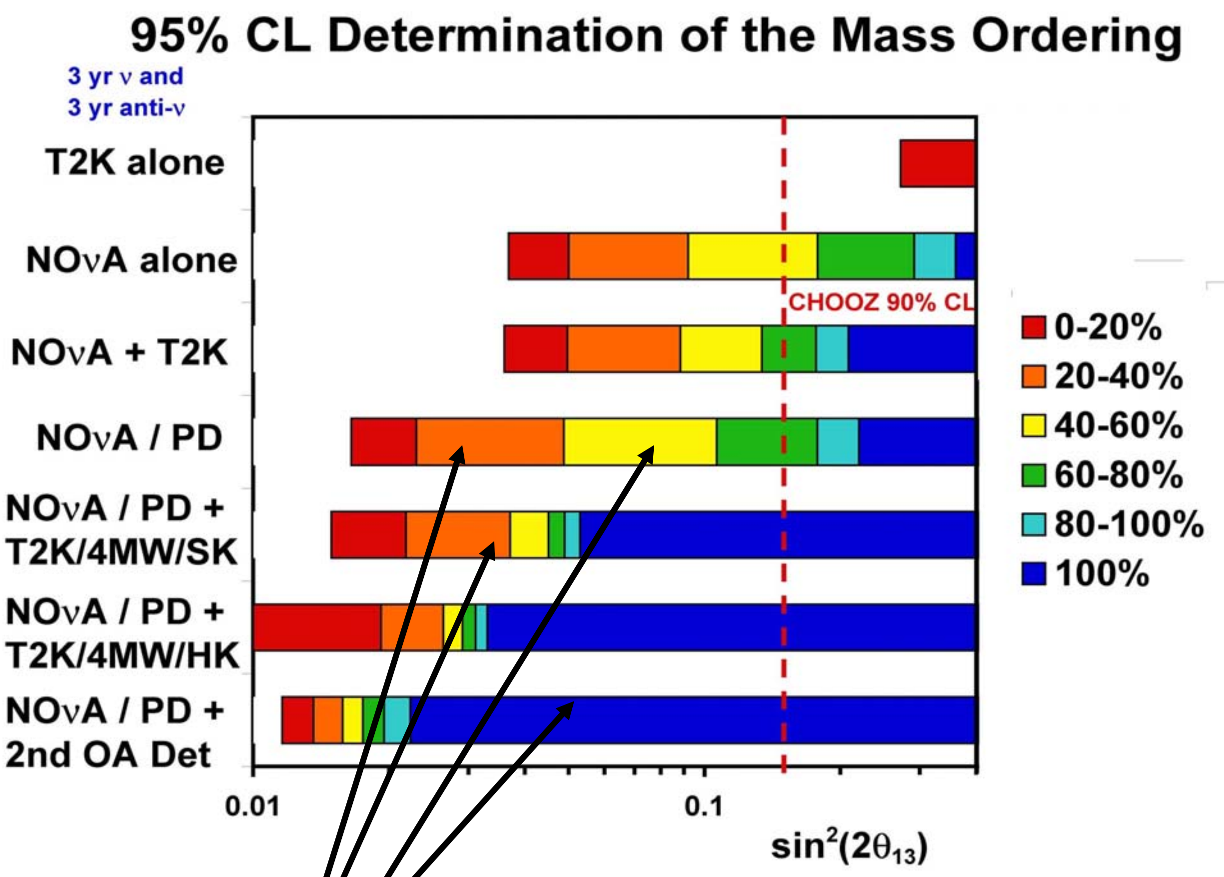


This is just a guide-the-eye example to illustrate the following plots.

In reality, overlaps, degeneracies can make situation quite complicated.

Graphic - after R. Bernstein

NOvA Coverage range for mass ordering



Upgraded Fermilab complex could produce more beam, on order 1-2 MW

Best results from worldwide combinations

Flux Comparison between Off-Axis and Forward Beams

$$P_T(\pi/2) = P^* \sin(\pi/2) = P^*$$

$$P_L(\pi/2) = \gamma P^* = \frac{1}{2} P_L(0)$$

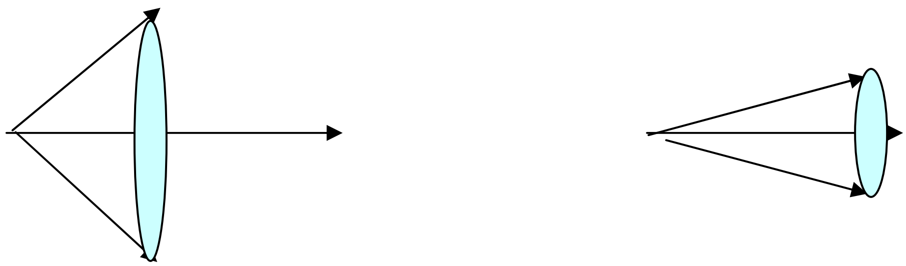
$$\frac{P_L}{P_T} = \gamma \quad \Rightarrow \quad \gamma_{\pi/2}\theta_{lab} = 1$$

Compare solid angle between fully forward beam ($\theta = 0$) and model off-axis beam.

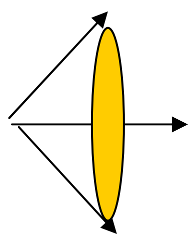
$$\Delta\Omega_{\pi/2} \propto \left(\frac{2\gamma_{\pi/2}}{1+\gamma_{\pi/2}{}^2 \theta_{lab}{}^2} \right)^2 = (2\gamma_0)^2 = \Delta\Omega_0$$

Hence flux can stay constant or even increase in region of interest.

Example of simple detector analysis - μ/e discrimination



Muon - long range (late hits), cone fills in as muon slows.

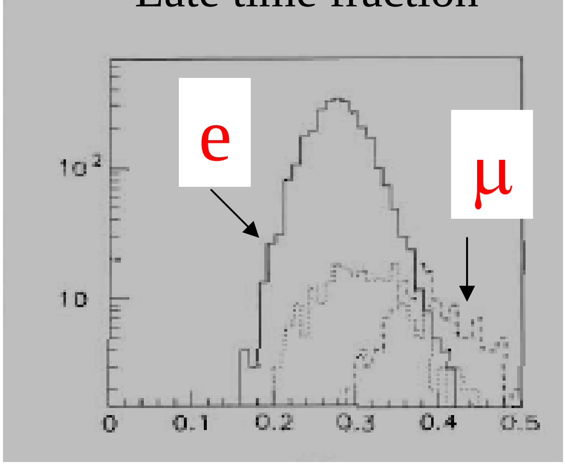


recall Chernkov angle

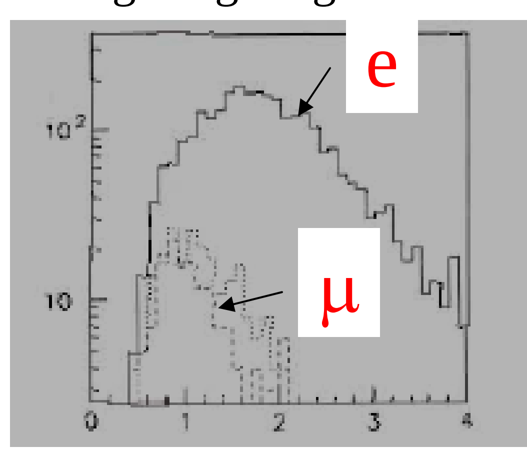
$$\cos\theta = \frac{1}{\beta n}$$

Electron - short range (prompt), most light in outer part

Late time fraction



Large angle light fraction



Note: this is a very old illustration of how this can be done. MiniBoone now uses likelihood analysis techniques

Neutrinos North! The MINOS Project at Fermilab

MINOS

Presented by Rob Plunkett

Fermi National Accelerator Laboratory

- What's so special about neutrinos?
- Ways and means of small masses
- Neutrinos from a mix
- A glimpse at the data
- A real stretch - the MINOS long baseline experiment
- The truth is out there...soon.

The International Neutrino World

A short summary of the neutrino history

Large History of the neutrino

1898
Discovery of the radioactivity
The first car's races (70 km/h maximum!)

1926
Problem with beta radioactivity
Between two wars, people dance the Charleston and the Boston

1930
Pauli invents the neutrino particle
Crisis of 1929...

1933
Fermi baptizes the neutrino and builds his theory of weak interaction
Hitler gets power in Germany

1956
First discovery of the neutrino by an experiment ν_e
Riots in Budapest. Indochina. Cold war. Atmospheric tests of thermonuclear bombs.

1962
Discovery of an other type of neutrino: the ν_μ
Missiles of Cuba, not far from the End!

1974
Discovery of neutral currents thanks to the neutrinos
Energy crisis... first oil problem

1977
Discovery of the tau (co-particle of ν_τ)
Energy crisis... second oil problem

1985-1989
Pseudo-discovery of a neutrino at 17 keV
The man on the moon 20 years ago. Mutations in European East countries

1990
The mystery of dark matter comes again
Berlin wall finally falls!

1991
LEP experiments show that there are only three light neutrinos
Eltsine is the new President of Russia. Iraq invades Koweit

1994
First proclamation of possible neutrinos oscillations seen by LSND experiment

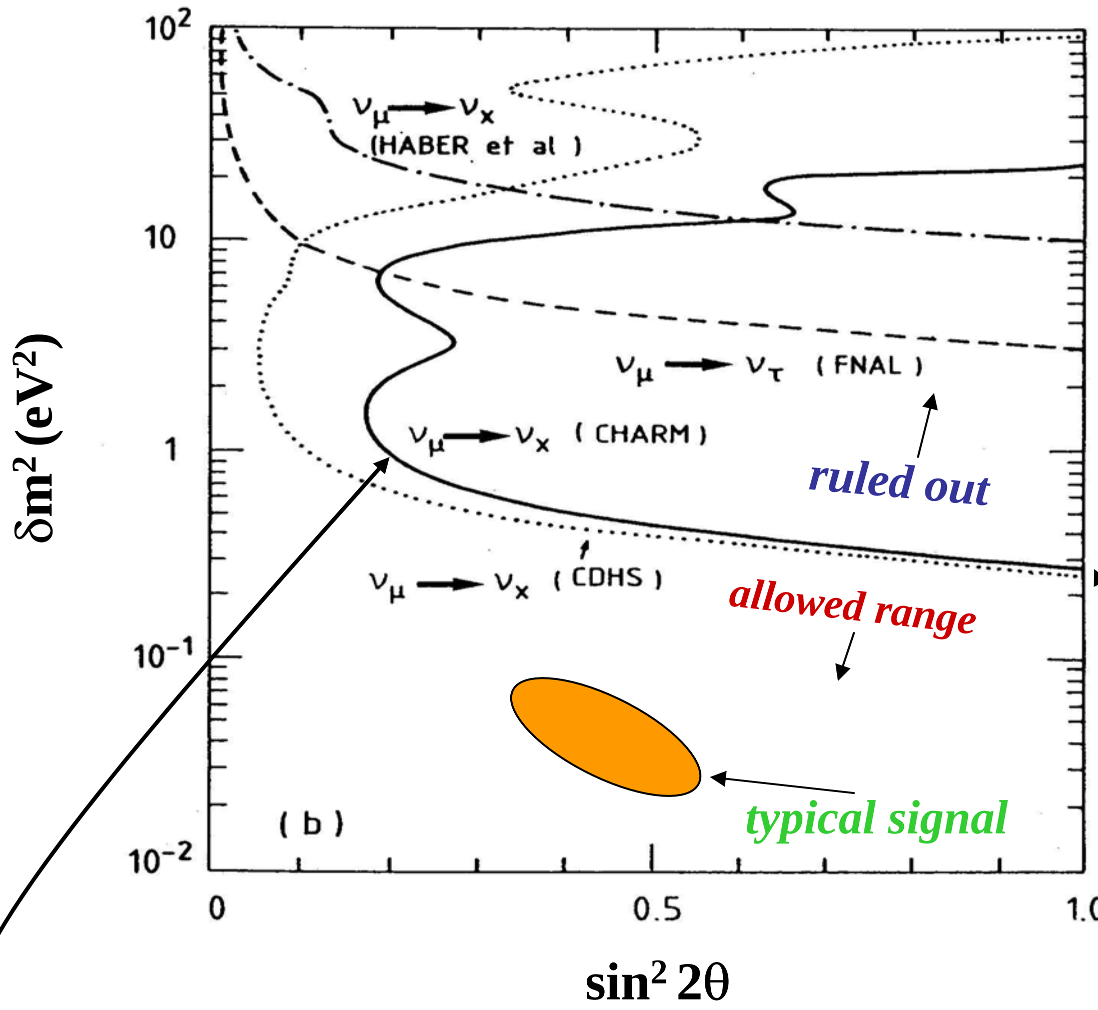
1995
Missing solar neutrinos confirmed by GALLEX
Internet and its WWW explode... and LAPP is 19 years old

1998
May be neutrinos oscillations seen in LSND and Super-Kamiokande
Human rights declaration is 50 years old, 1968 is 30 years old

Last update: 04/11/1999 : http://wwwlapp.in2p3.fr/neutrinos/aneut.html

Didier Verkindt

How to Read an Oscillations Plot



$\sin^2 2\theta$ boundary ~ N

δm^2 boundary ~ E, $N^{1/2}$

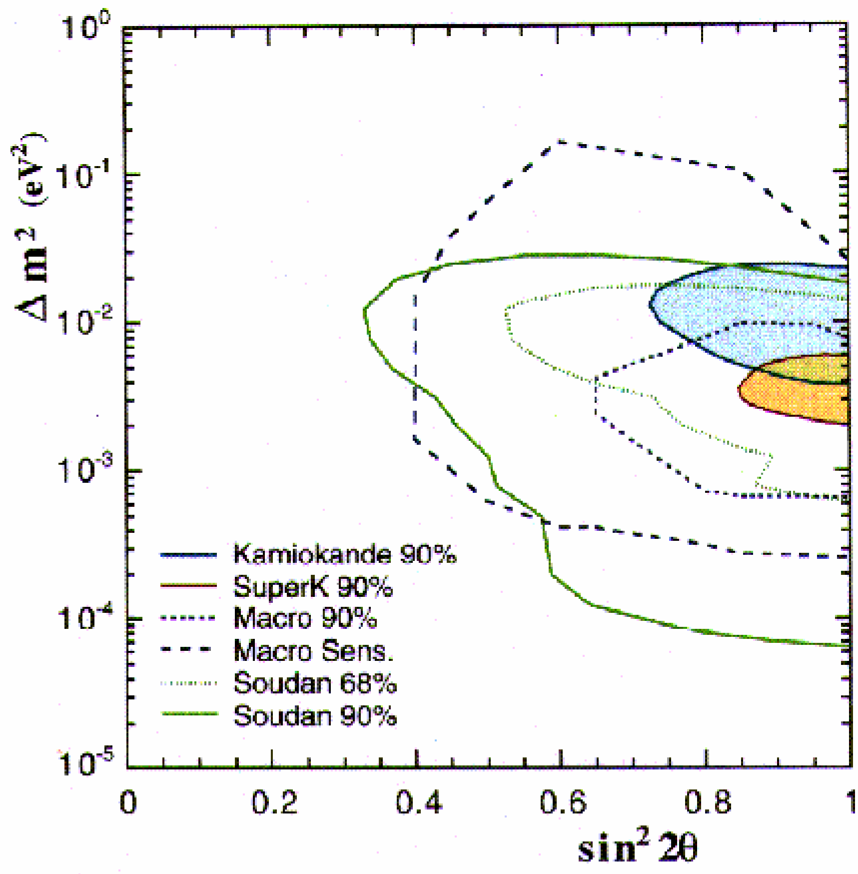
Fits to Oscillation Hypothesis from Atmospheric Experiments

SuperK Best Fit:

$\Delta m^2 = 3.5 \times 10^{-3}$ eV^2

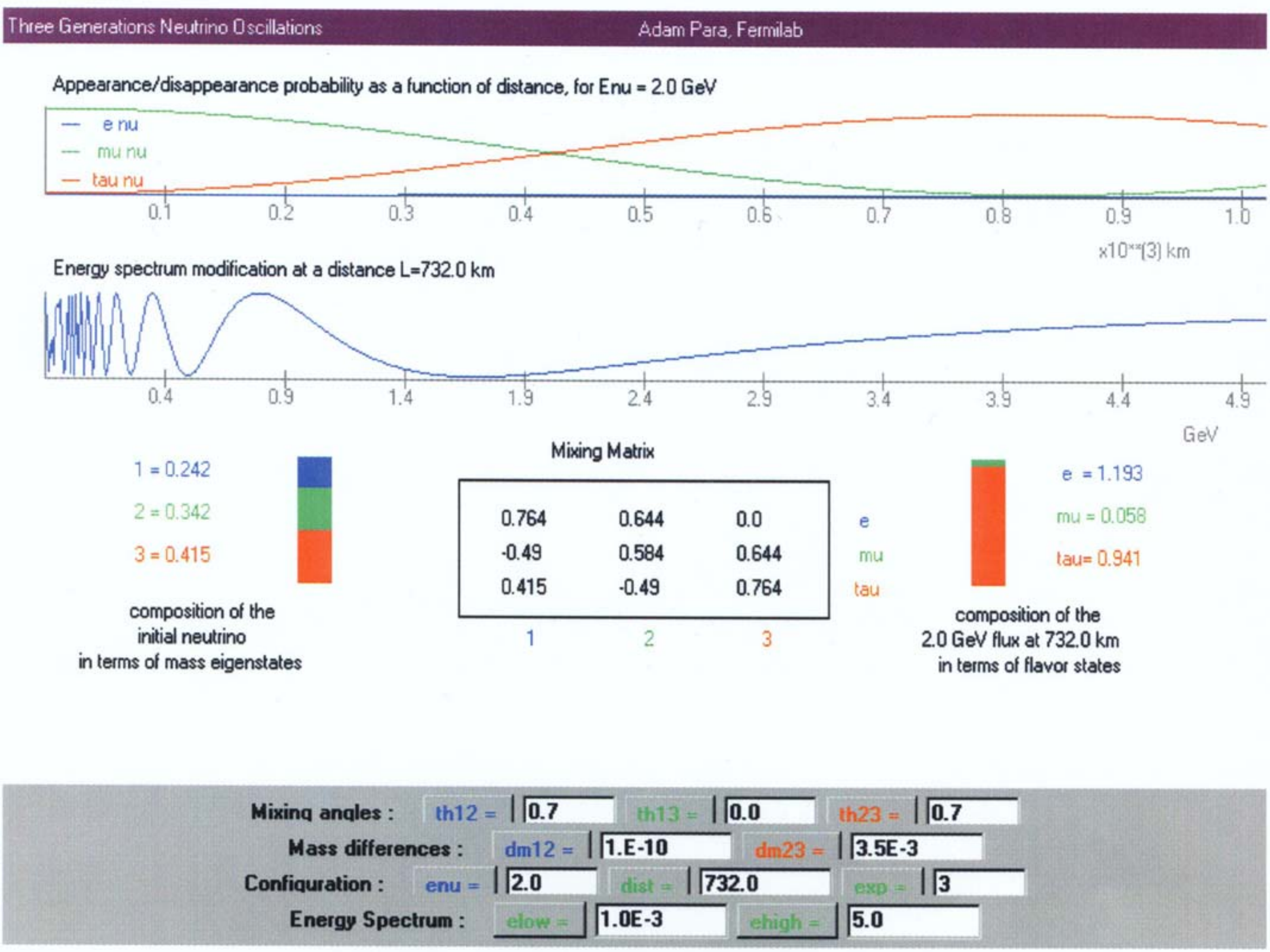
$\sin^2 2\theta = 1.0$

$\alpha = 0.06$



3 Families of Neutrinos Mixing

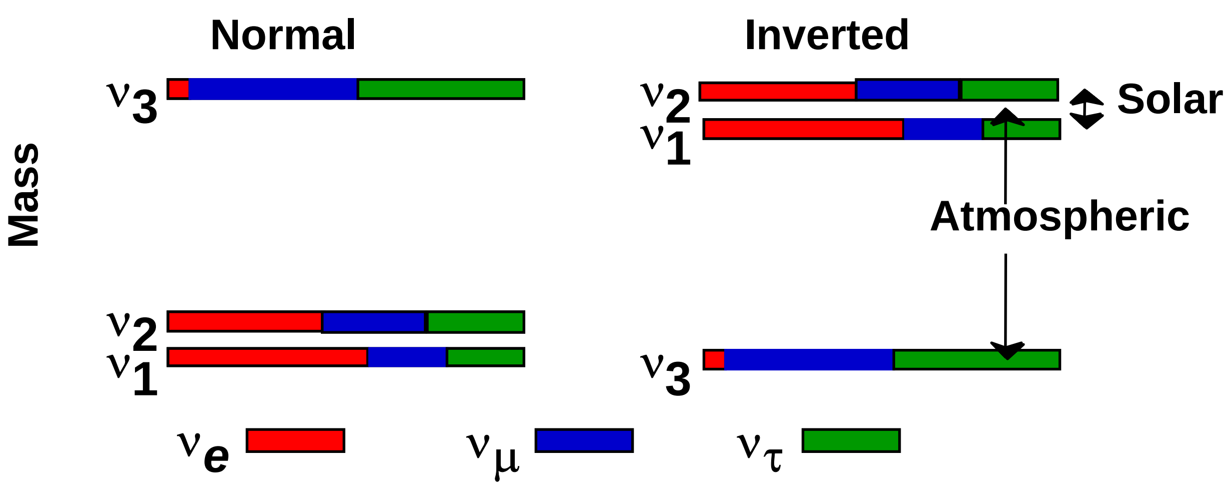
Web-based tool... (courtesy A. Para)



Implementing general model...

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass Hierarchy and NOvA



Major unsolved problem

Requires matter effects to observe

Hence a real "target of opportunity" for a long baseline.

To leading order and zero CP violation, acts as if neutrinos and antineutrinos were interchanged.

CP violation makes it more complicated

Review of Oscillations in Matter

Recall ν_e + e scattering adds a potential

$$H_{matter} = H_{vac} + V_W \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Leading after some manipulation to

$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\Delta_{13}^2}{(\Delta_{13} \mp aL)^2} \sin^2(\Delta_{13} \mp aL)$$

new mixing strength

new effective mass

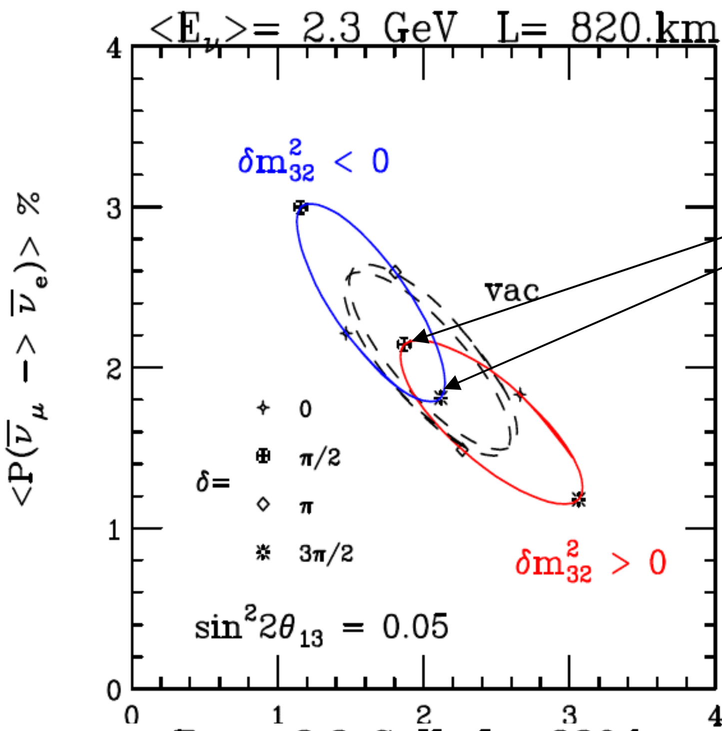
where a is

$$a = \frac{G_F N_e}{\sqrt{2}} \approx (3700 \text{ km})^{-1} \left(\frac{\rho}{2.8 \text{ g cm}^{-3}} \right)$$

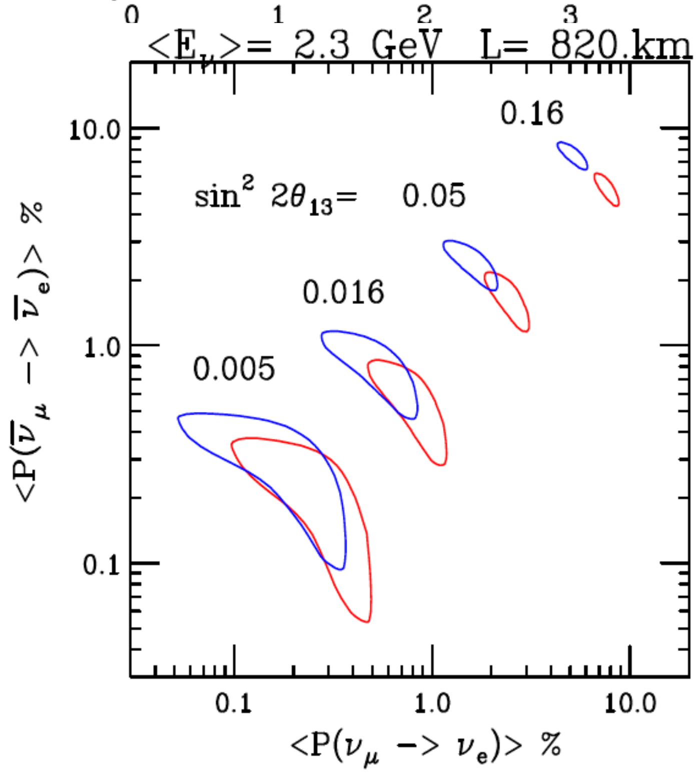
and the sign changes between neutrinos and antineutrinos

3-ν's: Change is OK for all orders n of $\sin^n\Delta_{12}$ and $\sin^n\Delta_{13}$

Matter effects split the CP ellipses



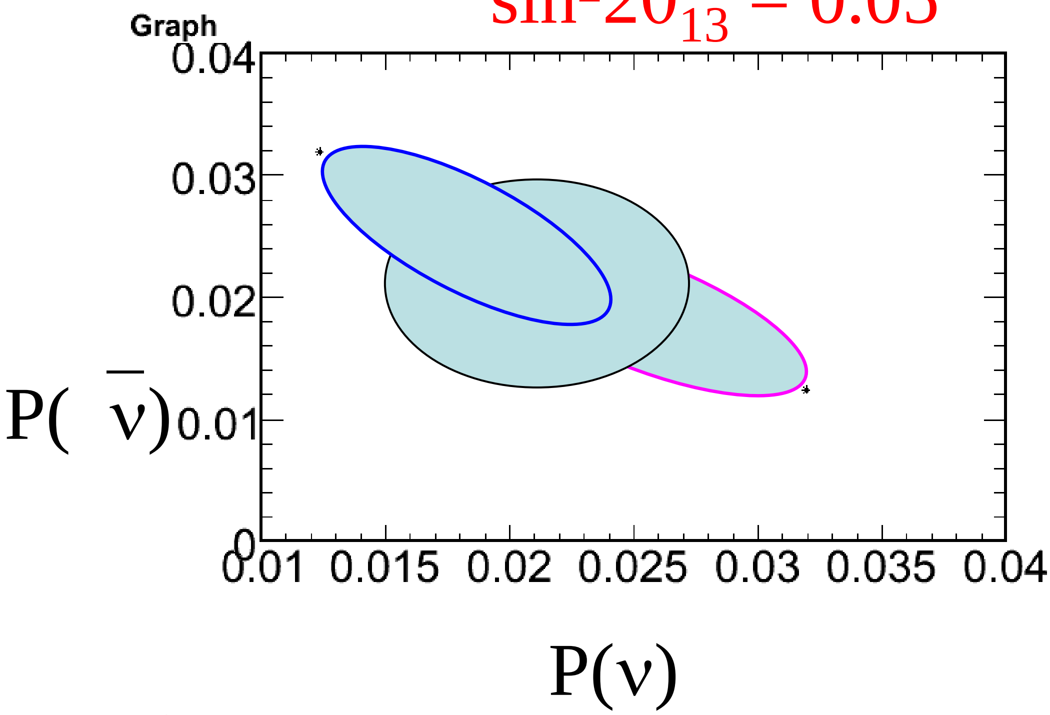
Opposite rotation senses can increase overlap



Ellipse separation is leading order effect, grows with $\sin^2 2\theta$

2-σ data estimate superimposed on CP-ellipses

$\sin^2 2\theta_{13} = 0.05$

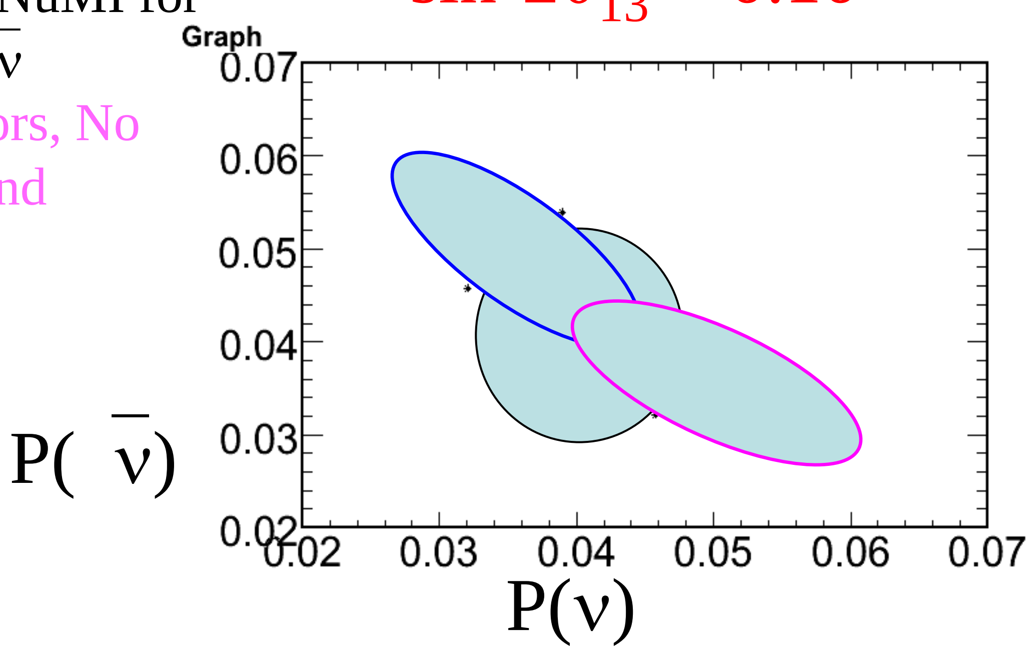


Scale from NOvA proposal for $\sin^2 2\theta_{13}$

3 years nominal NuMI for both ν, $\bar{\nu}$

Statistical errors, No background

$\sin^2 2\theta_{13} = 0.10$



MINOS Beam Event Characteristics

Simple event selections for both detectors.

Far Detector

- 50 μs window around beam spill
- Reconstructed track within fiducial volume (70% for CC)
- Track angle along beam direction.
- Data and beam quality cuts (96%)

Only an unknown fraction of the far detector data is used for checks and testing.

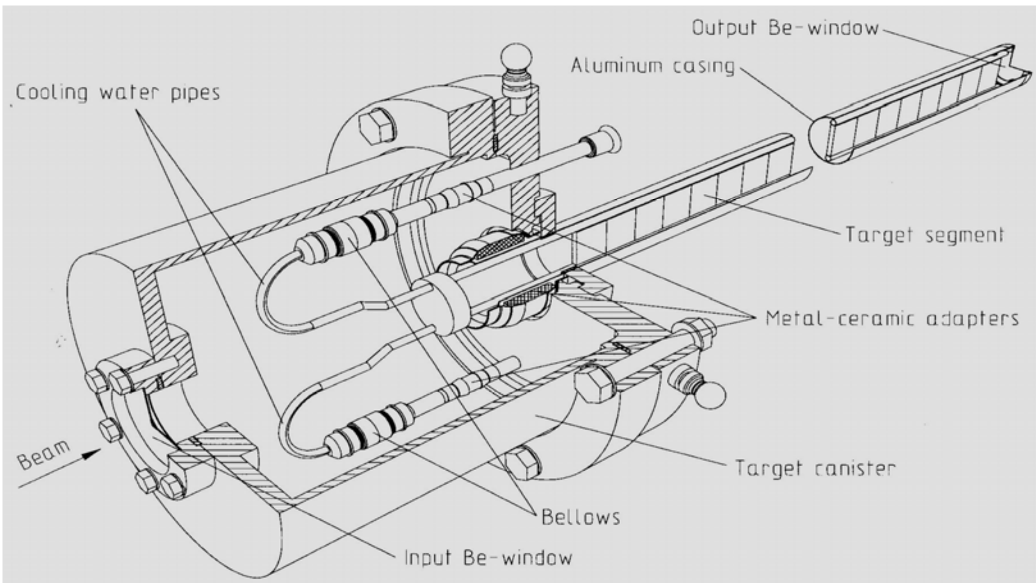
Near Detector

- Fiducial cuts using track or event vertex for candidate neutral currents
- Track quality cuts for events with tracks
- Beam quality cuts

A Tanalizing but Scattered Outlook

- Plausible evidence from 3 sources for the oscillation phenomenon
  - No show-stoppers uncovered in any of the channels
- Unfortunately, all point in different directions!
  - $\Sigma\ \delta m_i^2 = 0$ by definition
  - Can't accomodate atmospheric, solar, and LSND
- Non-standard physics solution would be required
  - Like a 4th, "sterile" neutrino, ν_s , with no standard model interactions.
- Definitive resolution will require a new generation of accelerator experiments ==> Fermilab

NuMI Target - where the decaying particles start



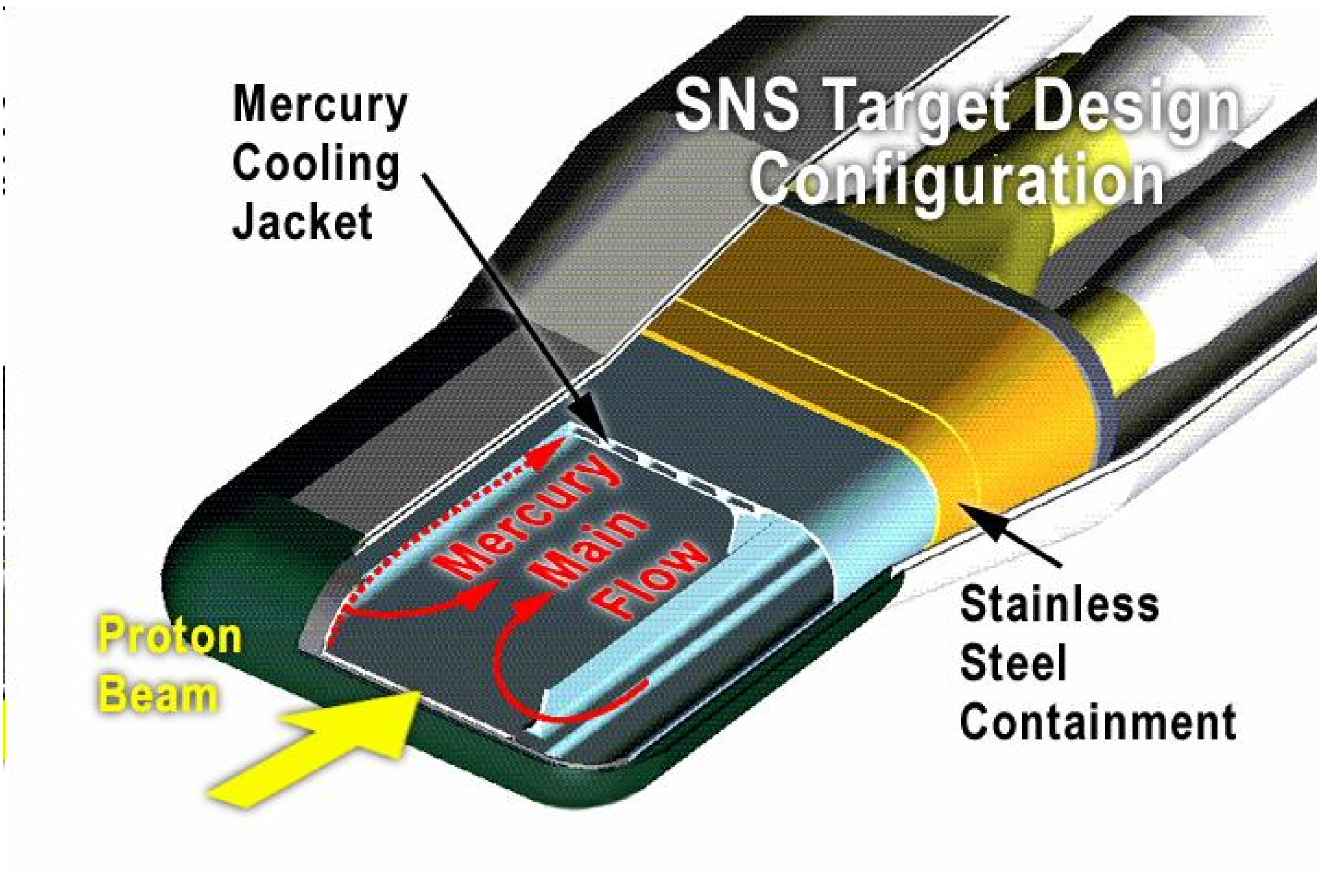
60 cm graphite fins - water cooled
Be windows at either end
Absorbs 40 KW of power at design intensities.
Careful modeling because distribution of particles coming out affects ν flux

Sidebar- advanced targeting

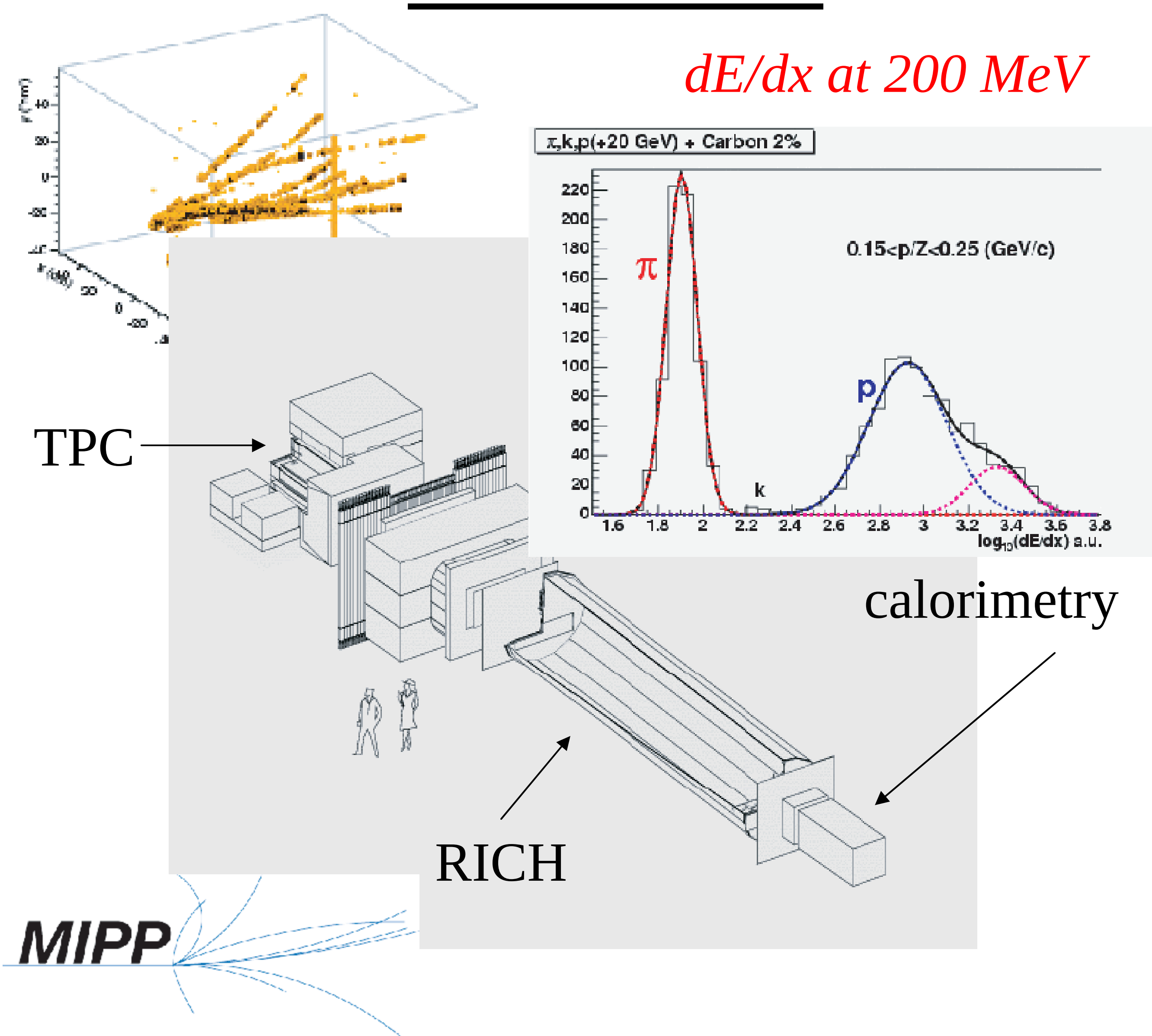
At very high beam powers, targeting becomes more difficult.

Radiation, heat transfer, shock issues.

SNS flowing liquid mercury target absorbs 2 MW!



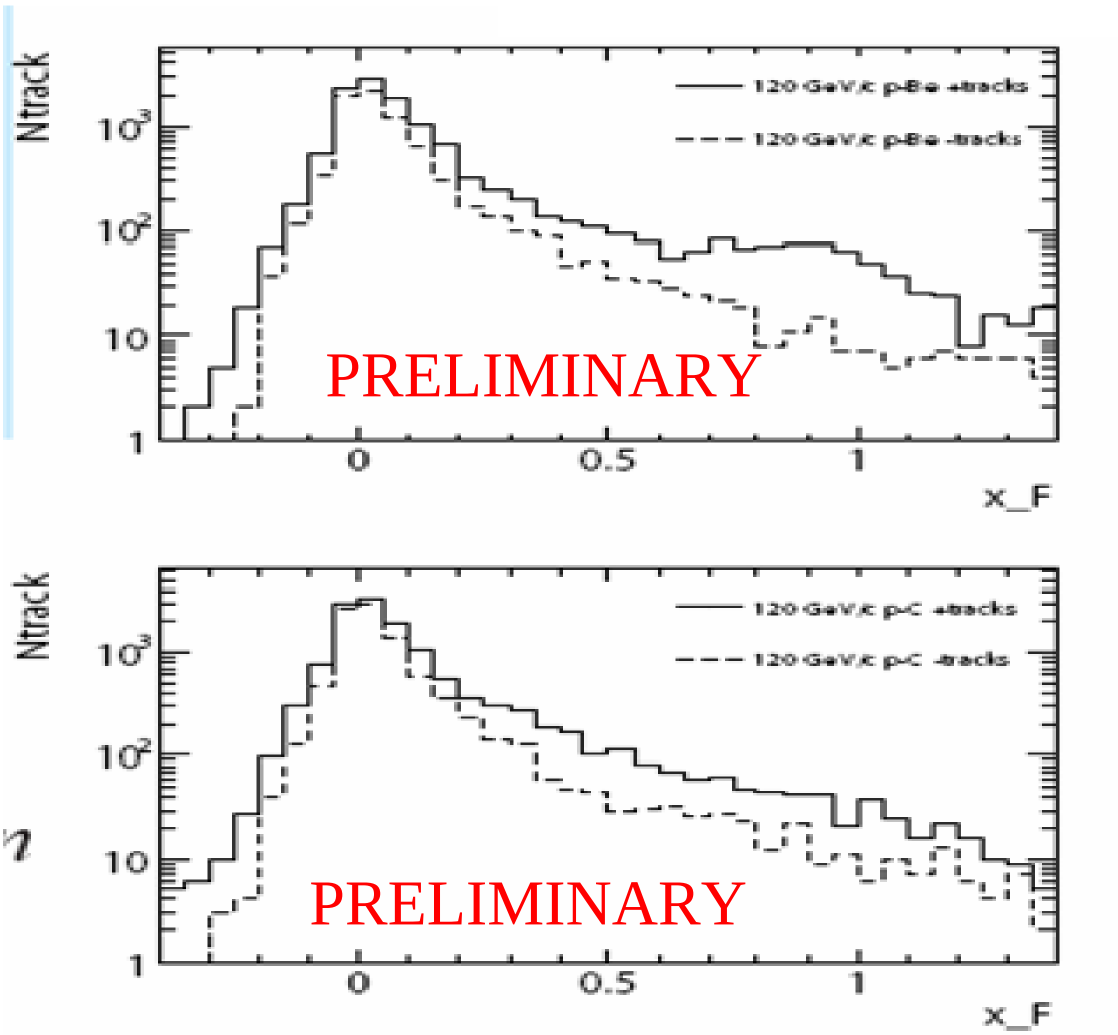
Example of experimental program- MIPP experiment at Fermilab



Study p,K + A interactions from 5-85 GeV
Study p + A interactions at 120 GeV
Measurements on H, Be, C, various metals

Typical MIPP Preliminary Data

MIPP

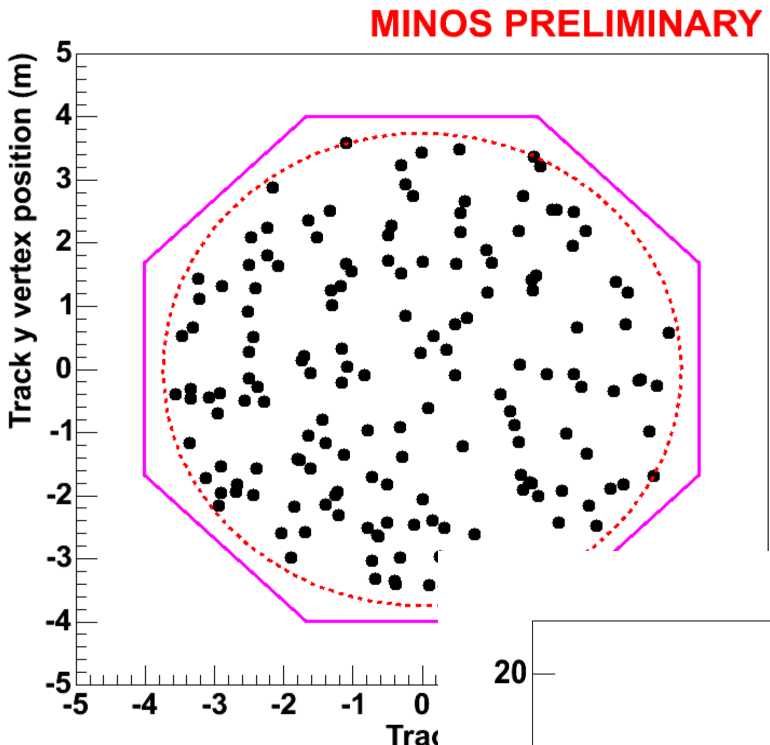


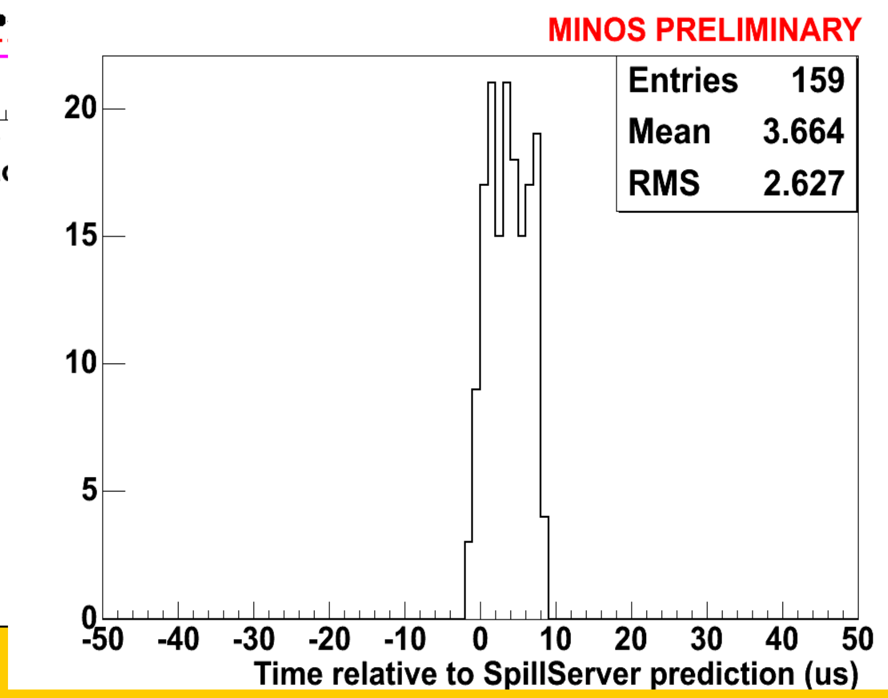
Inclusive x_F distributions for Be (top) and C (bottom) targets

Working through target list including NuMI target

Coutesy Messier, NOVE-06

Vertex and Timing Distribution of Far Detector Events



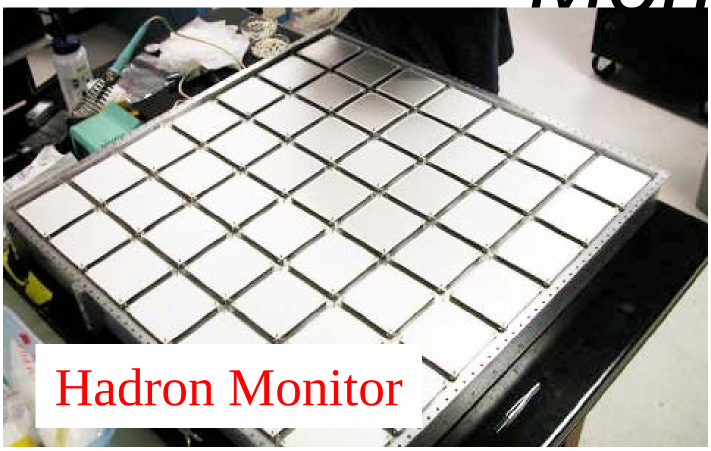


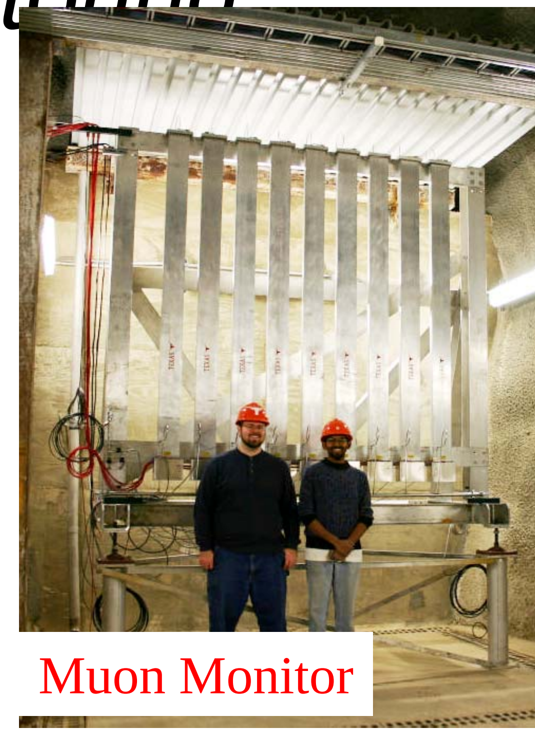
The cuts described result in 159 neutrino events.

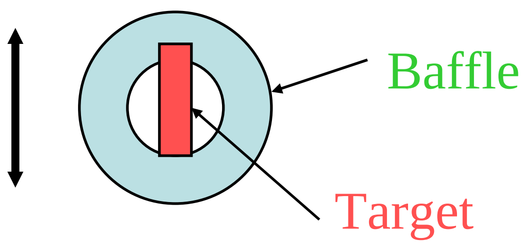
Protons used for this work 9.3 x 10^{19}

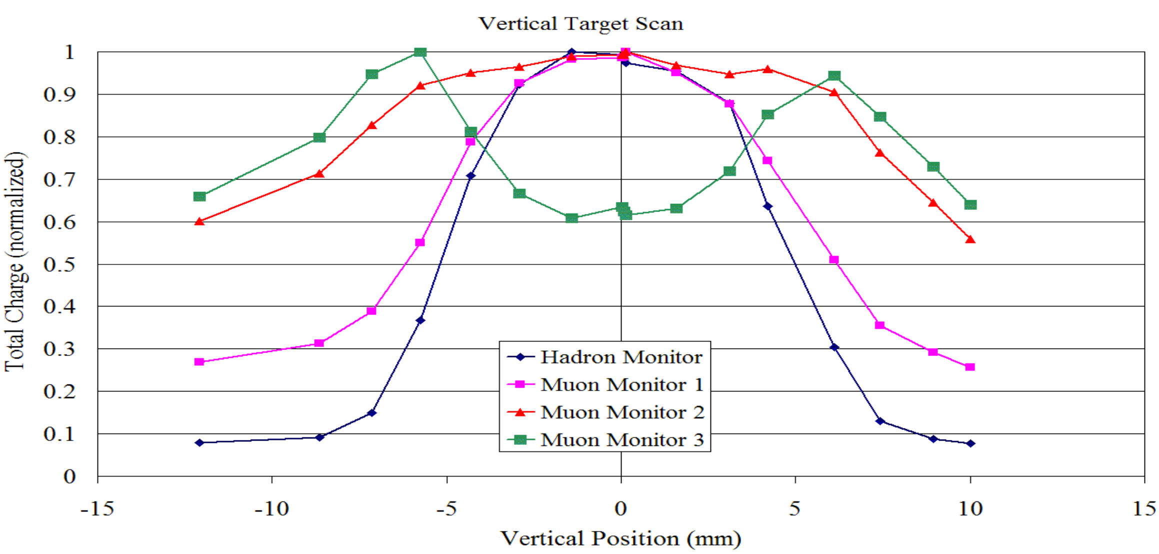
Caution: This is MINOS open sample only

Secondary Beam Monitoring









Scan of beam across target shows edges, increased production in outer baffle - real detail!

Neutrinos from π, K Decay - Spectrum

Two-body decay $\pi \rightarrow \mu\nu$ of CM energy E*

Lorenz Transformation of P_L, E

$$M = \gamma(1 + \beta \cos\theta^*)$$
$$M \cos\theta = \gamma(\cos\theta^* + \beta)$$

using
$$M \equiv E_{lab} / E^*$$

$$M = \frac{1}{\gamma(1 - \beta\cos\theta)}$$
$$\cong \frac{1}{\gamma(1 - \cos\theta)} \cong \frac{2\gamma}{1 + \gamma^2\theta^2}$$

Spectrum depends on angle

Sharper for increased π energy

Neutrinos from π, K Decay - Flux

Lorenz transform P_T this time

$$E \sin\theta = E^* \sin\theta^*$$

$$\downarrow$$

$$M \sin\theta = \sin\theta^*$$

for small angles

$$\sin\theta \cong \theta \Rightarrow \quad M\theta = \theta^*$$

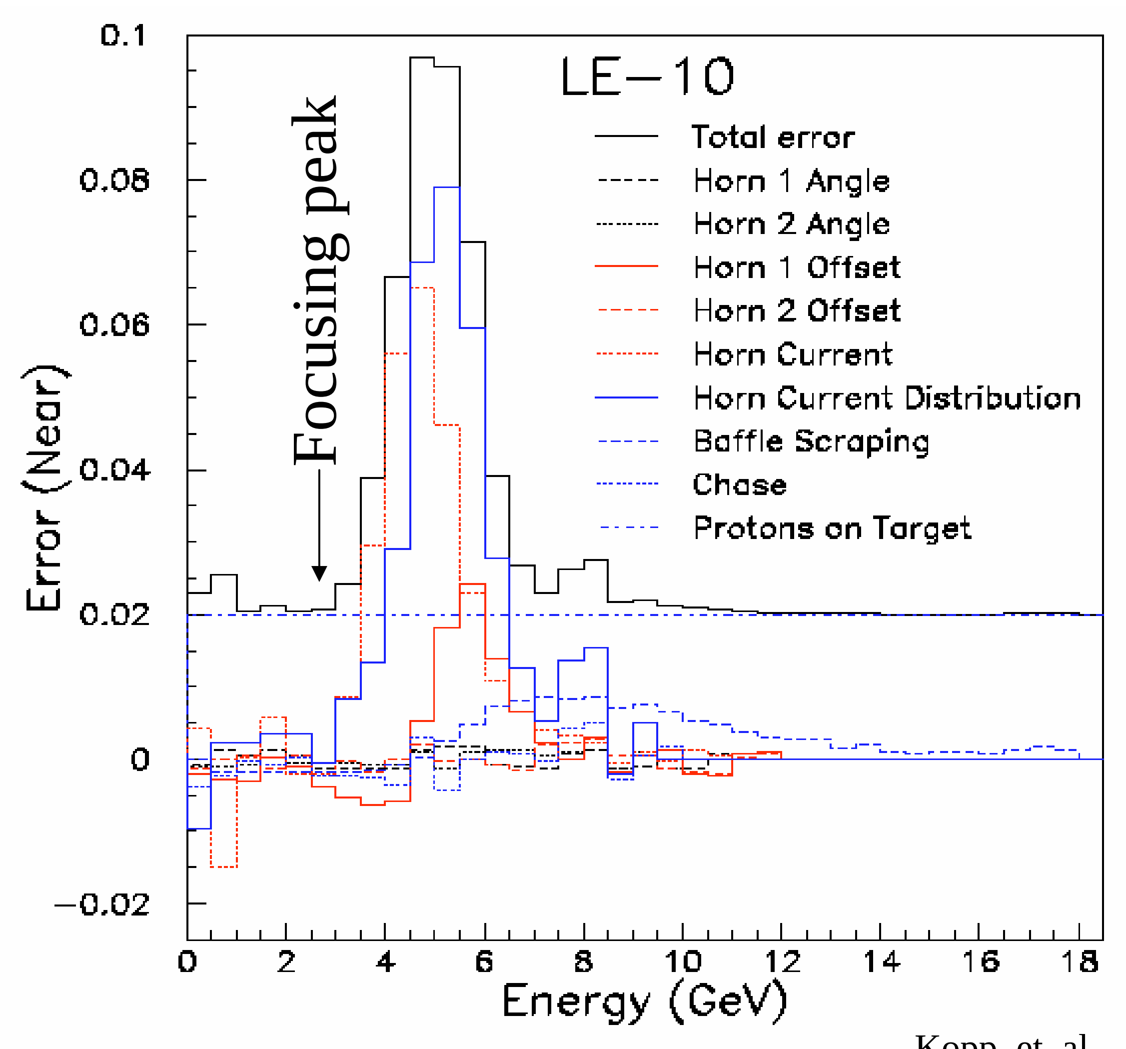
$$\Rightarrow \quad \frac{d\theta^*}{d\theta} = M$$

*actually, this is valid for all values of θ**

giving flux compression factor

$$\frac{d\Omega^*}{d\Omega} = \frac{\sin\theta^* d\theta^*}{\sin\theta \, d\theta} = M^2 = \frac{4\gamma^2}{(1+\gamma^2\theta^2)^2}$$

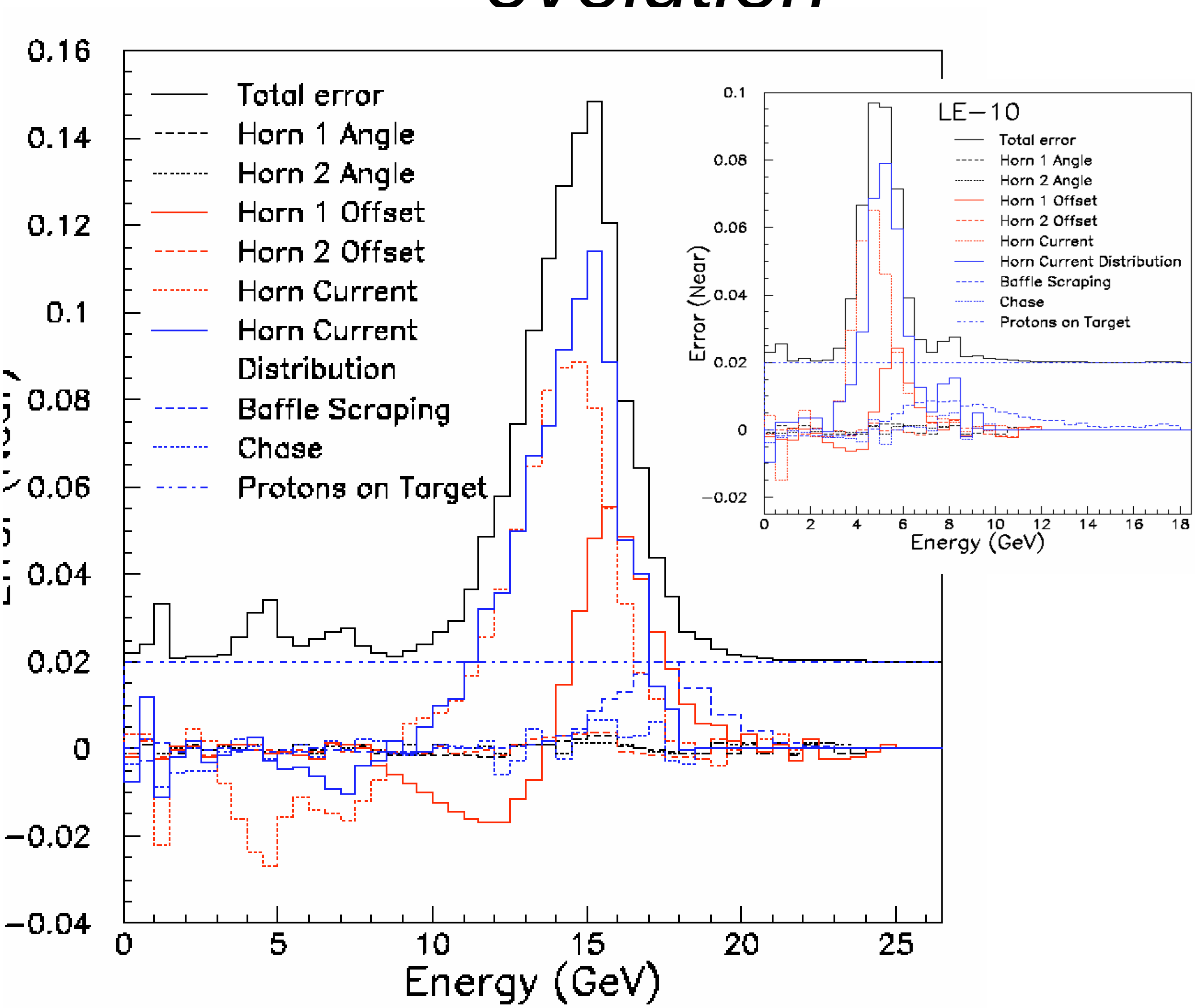
Beamline Flux Fractional Uncertainties in NuMI Beam



Kopp, et. al

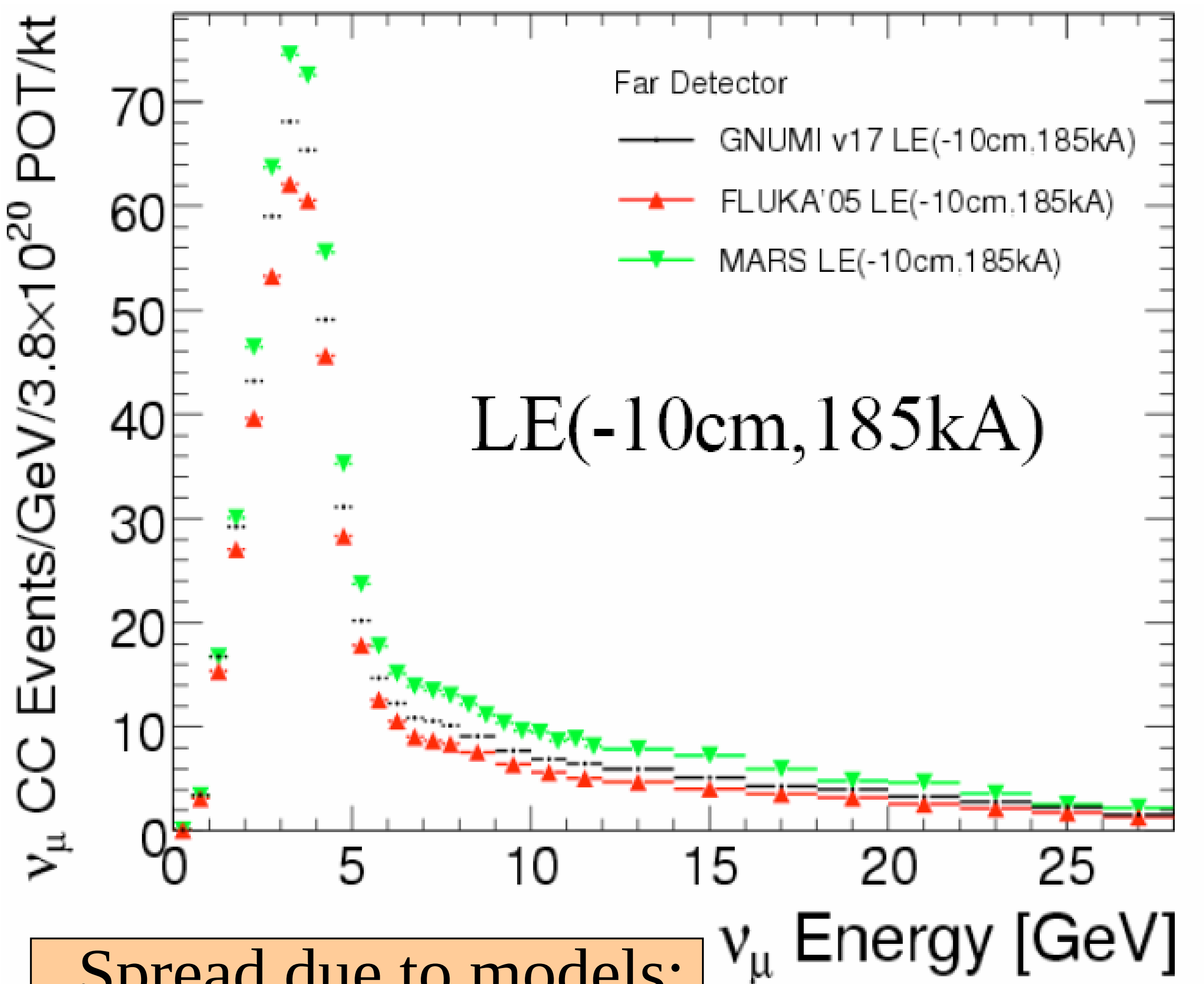
Does not include errors from hadron production model

Study typical uncertainties with beam energy evolution



NuMI high energy beam at near location (inset repeats the low energy plot)

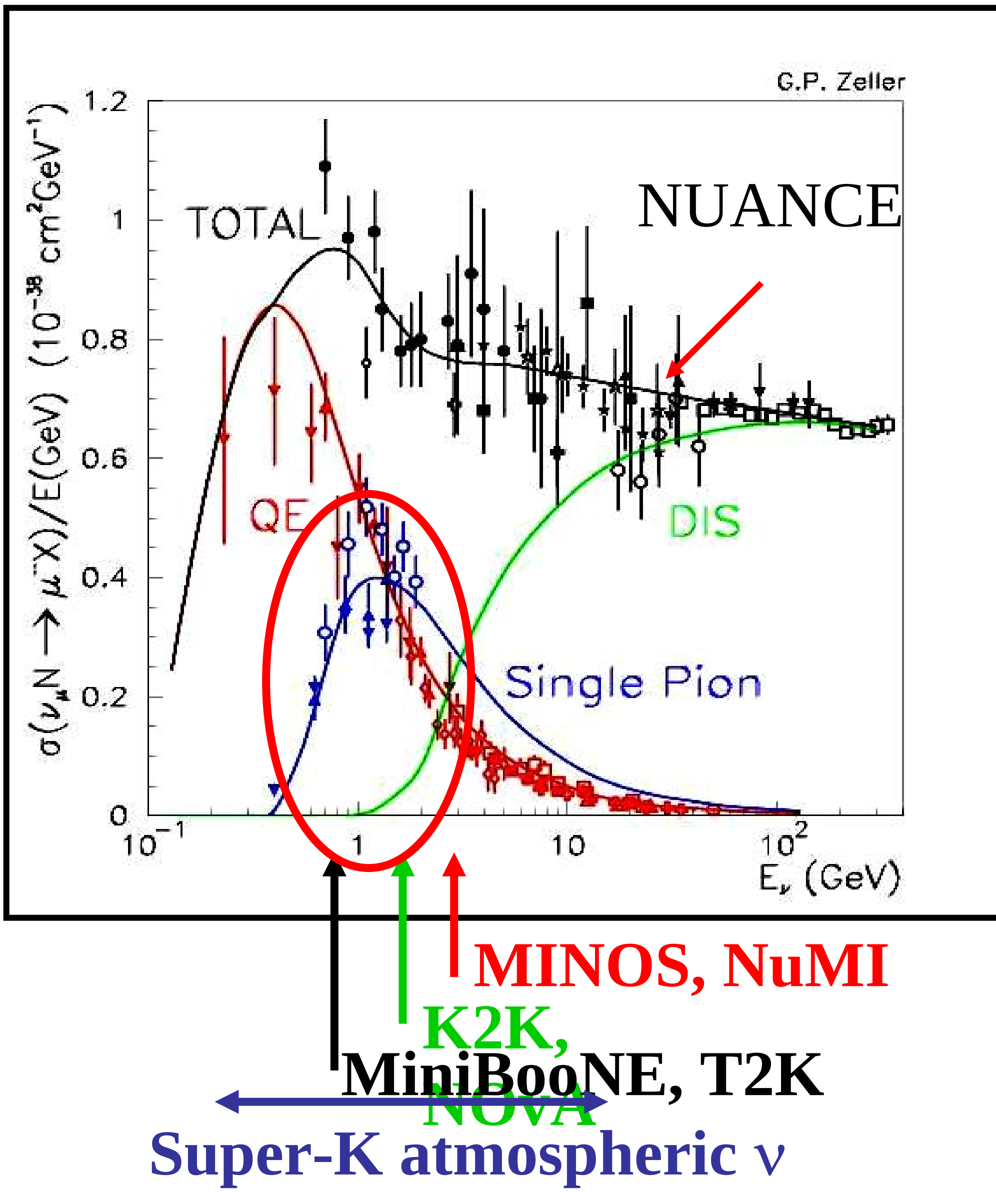
Spread of a neutrino spectrum due to parent hadron uncertainties



Spread due to models:
8% (peak)
15% (tail)

Kopp, et. al.

Interlude - the physics of 0.5-5 GeV Neutrino Interactions



Complex physics modeled as a combination of low-multiplicity processes

Pions are produced via intermediate resonant states

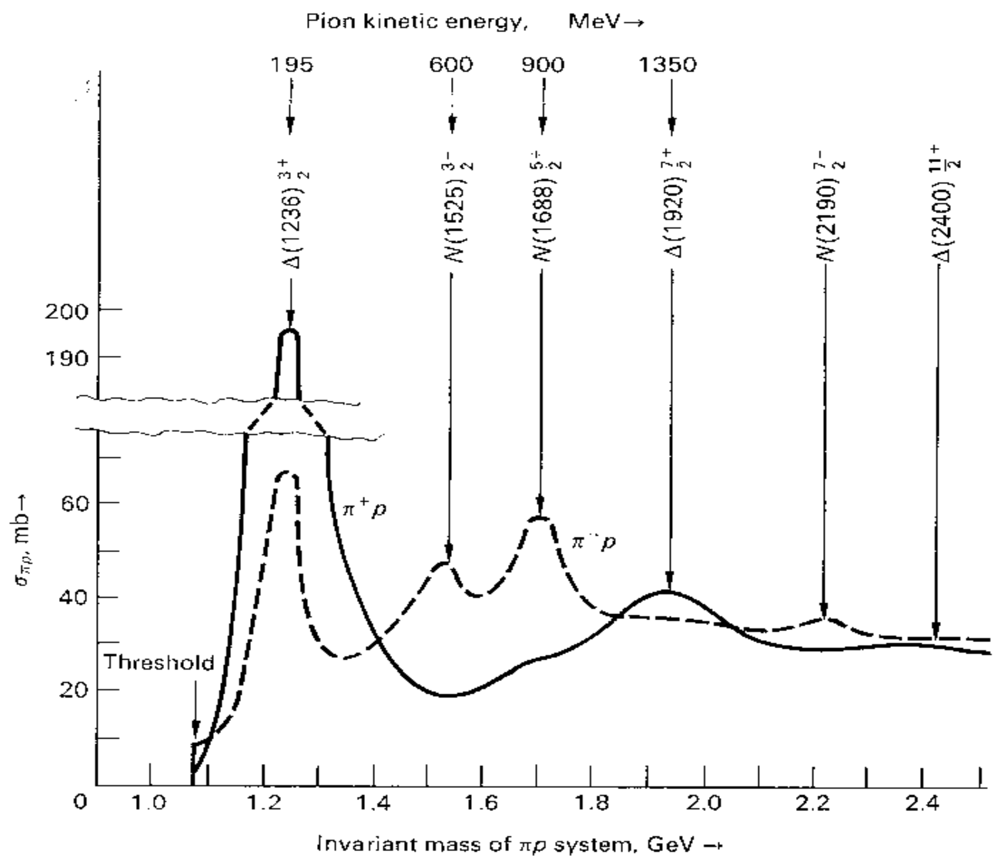
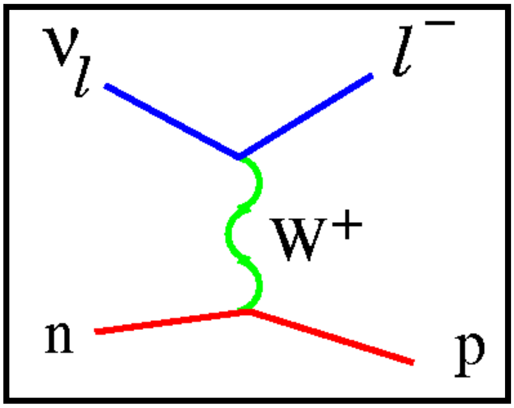


Fig. 4.6 Variation of total cross section for π^+ and π^- mesons on protons, with incident pion energy. The symbol Δ refers to resonances of $I = \frac{3}{2}$; N refers to $I = \frac{1}{2}$. The positions of only a few of the known states, together with their spin-parity assignments, are given.

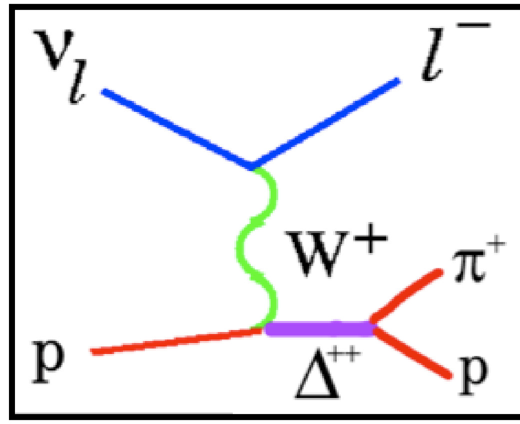
Resonances as observed in πn scattering experiments

(Figure from Perkins, Introduction to High Energy Physics

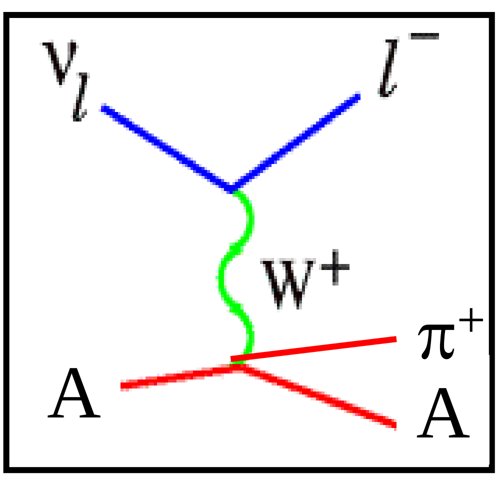
Different models have underlying physics in common



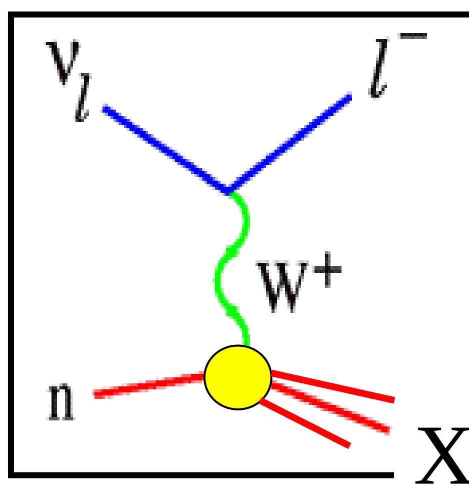
Quasi-elastic



Resonant π production



Coherent production



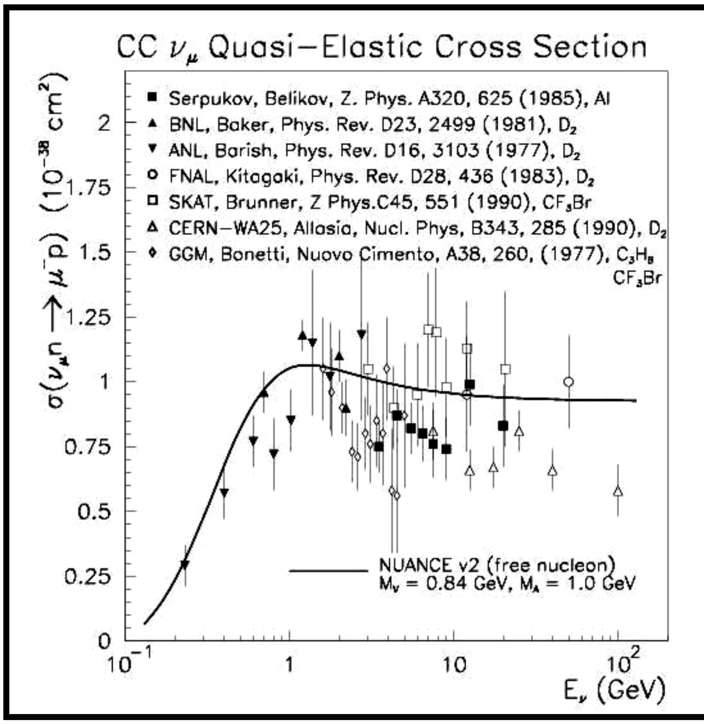
DIS

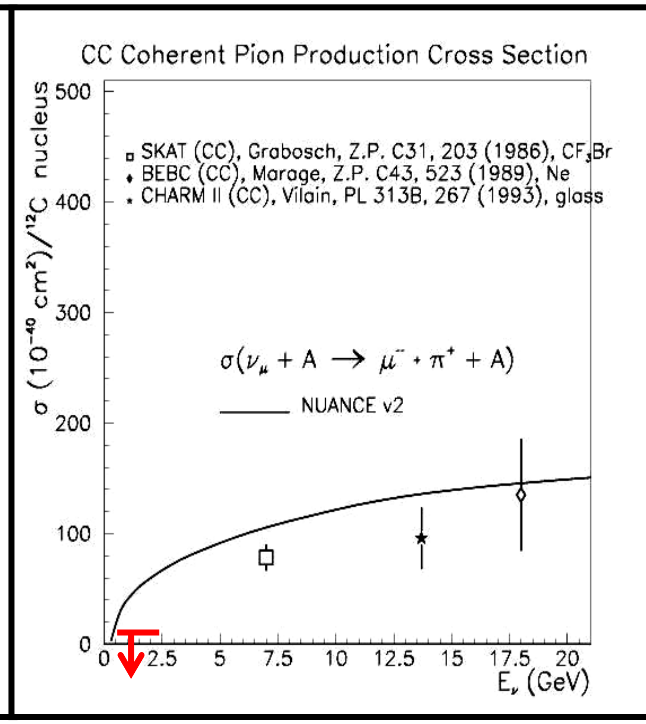
Different models combine channels differently.

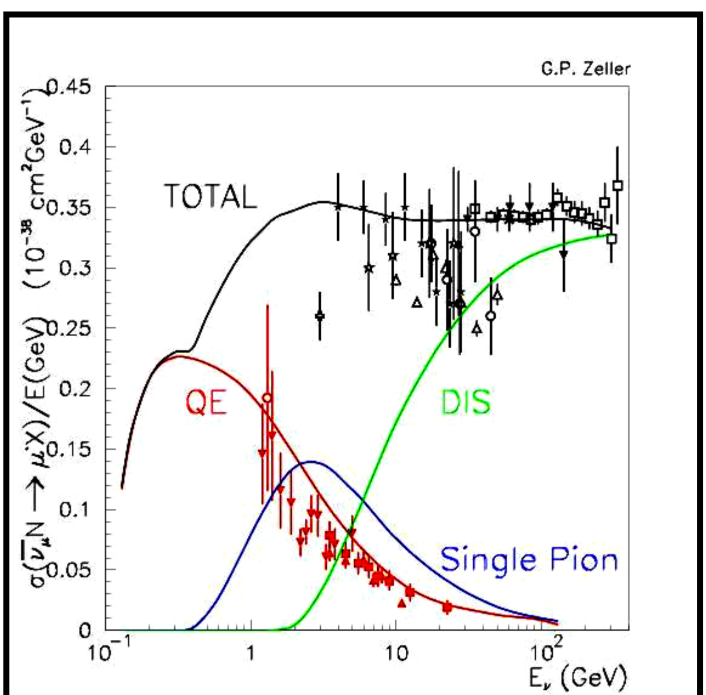
e.g. NUANCE - coherent addition of resonances

NEUGEN - incoherent addition

Existing data not strongly constraining



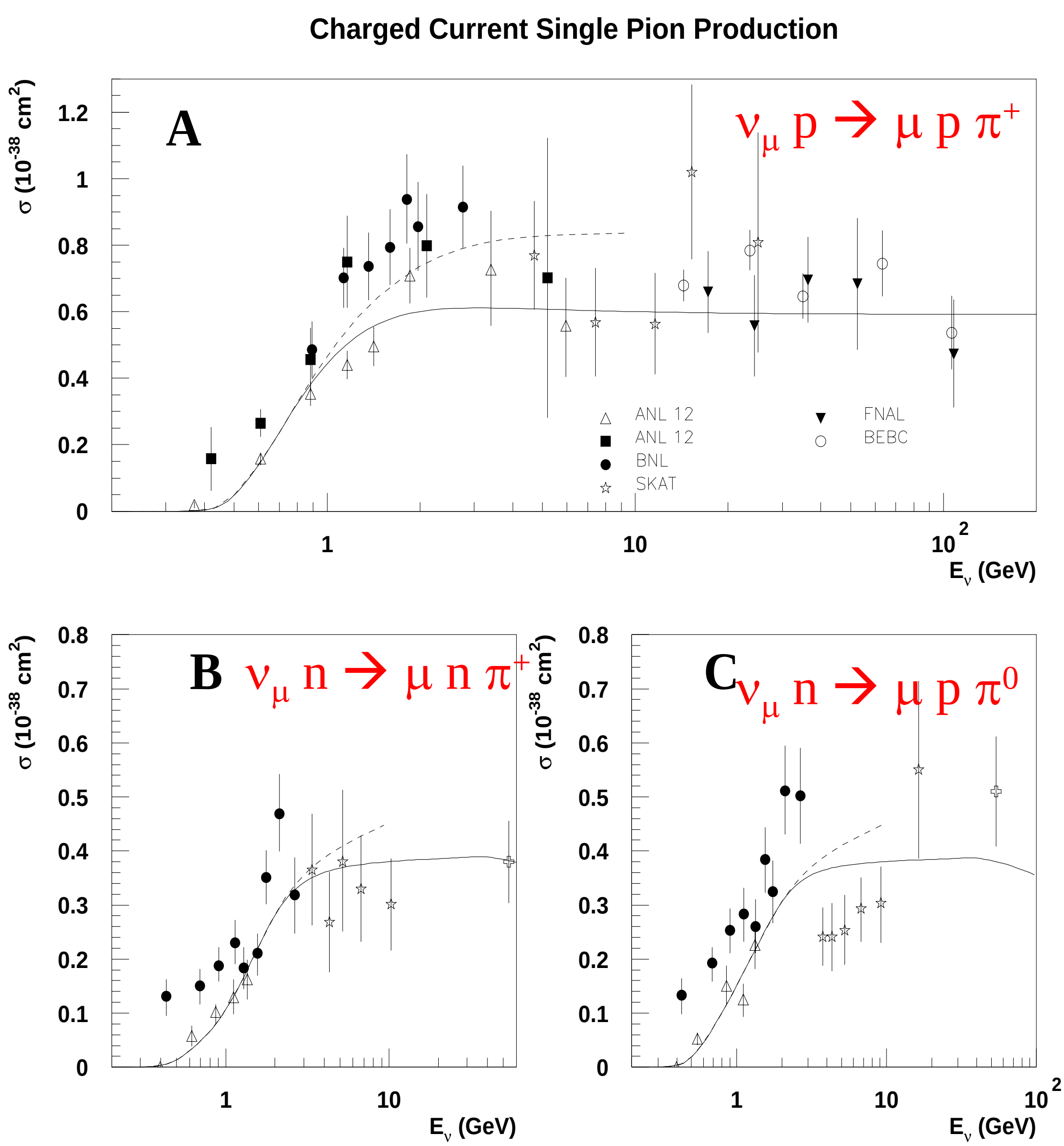




Coherent, ν–bar data basically nonexistent in region of interest.

Parameters in the models are tuned to exclusive channel cross sections.

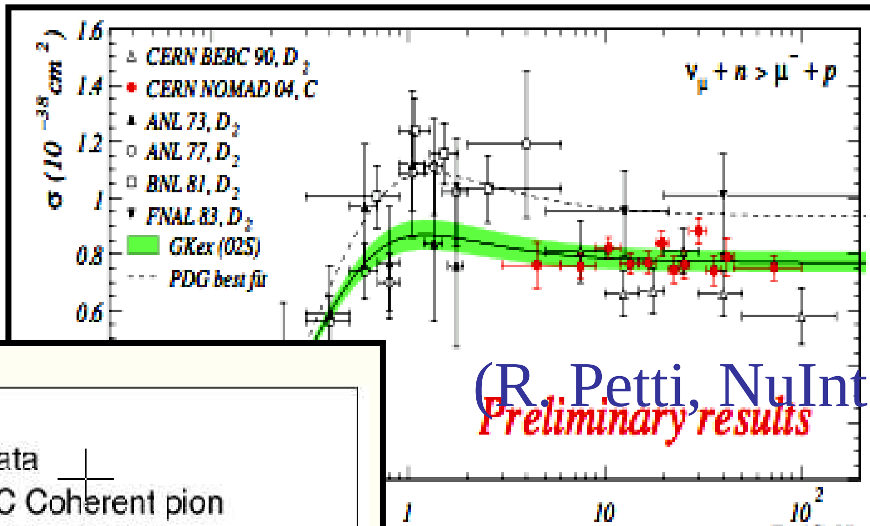
$$\sigma_{tot} = \sigma_{QE} + \sum_i (\sigma^i_{res} + f_i \sigma^i_{DIS})$$



Examples from NEUGEN courtesy H. Gallagher

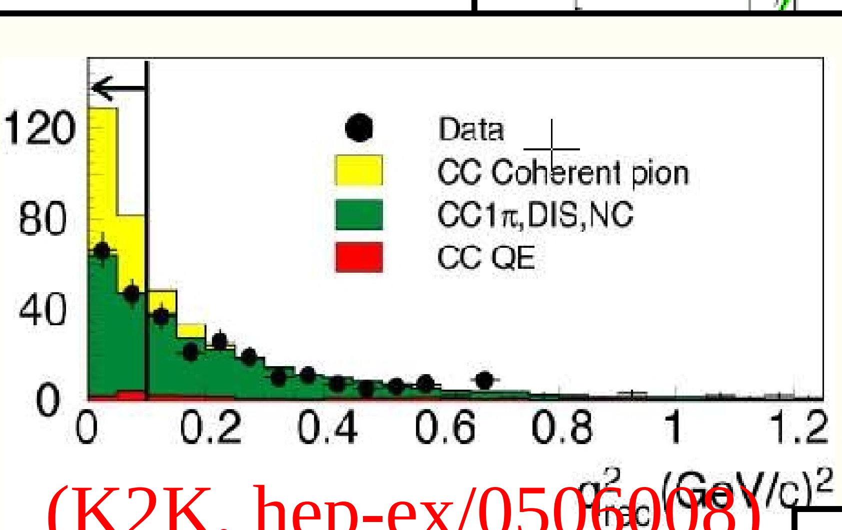
Worldwide effort to improve knowledge

•NOMAD, ^{12}C



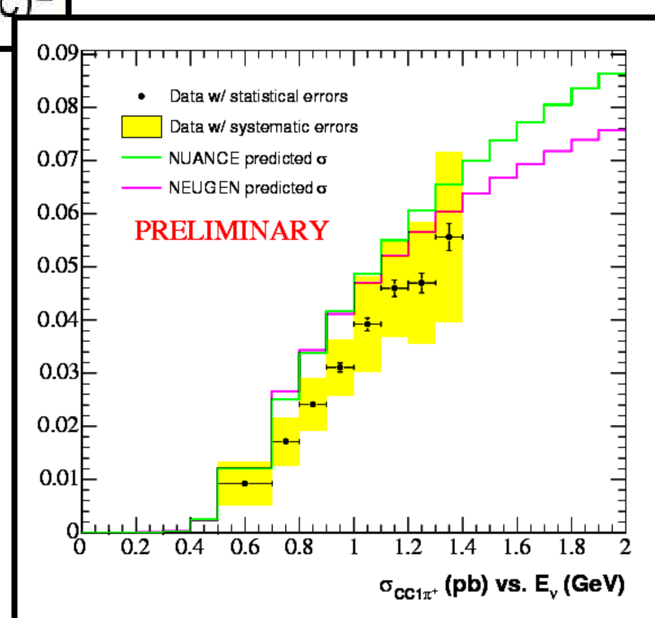
(R. Petti, NuInt05)

K2K,
coherent π+



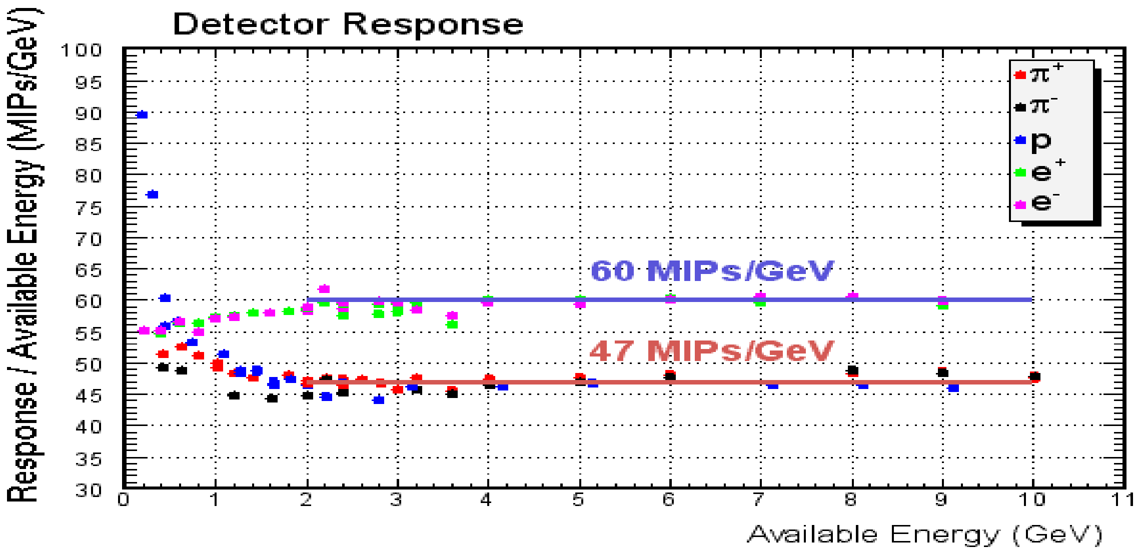
(K2K, hep-ex/0506008)

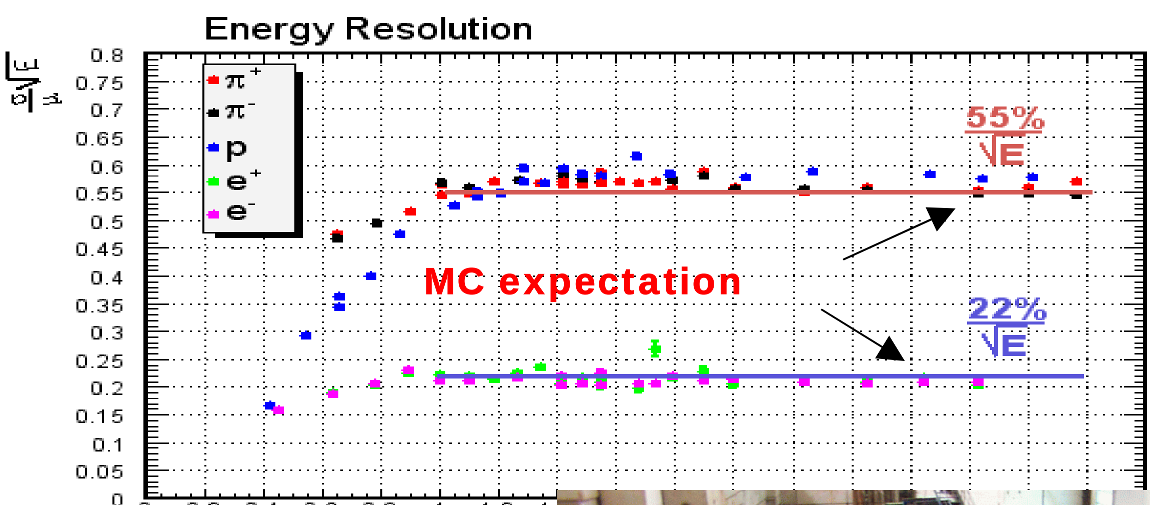
MiniBoone single π
(Monroe,Wasco)



Plots courtesy G. Zeller, NOvE-06

MINOS Calibration Detector at CERN

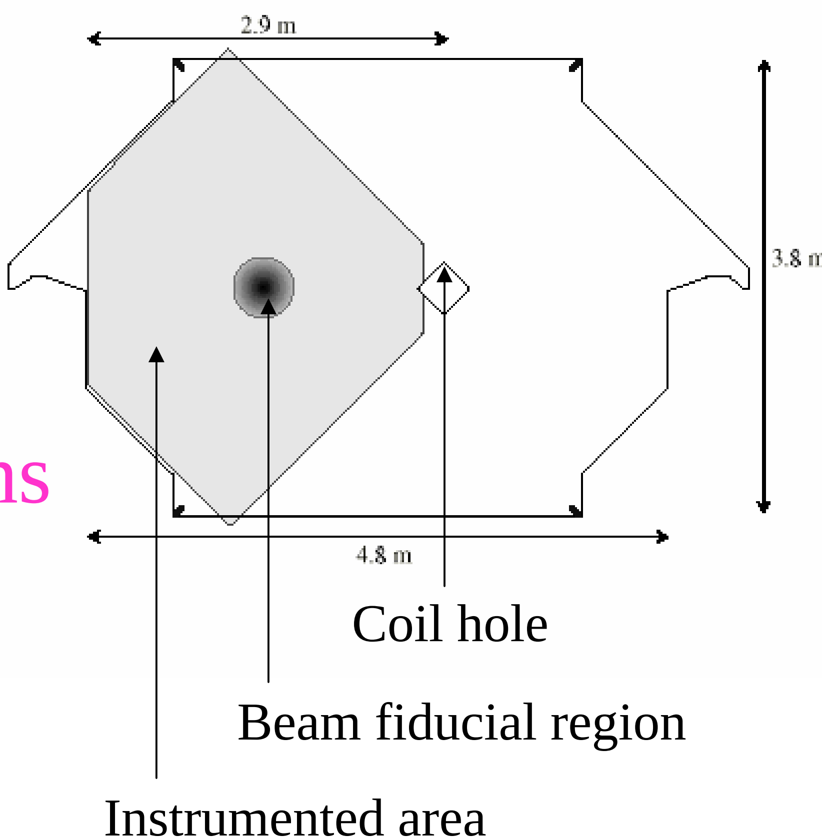




60-plane 'micro - MINOS'
Also checked near/far electronics

Minos Near Detector Architecture

980 tons

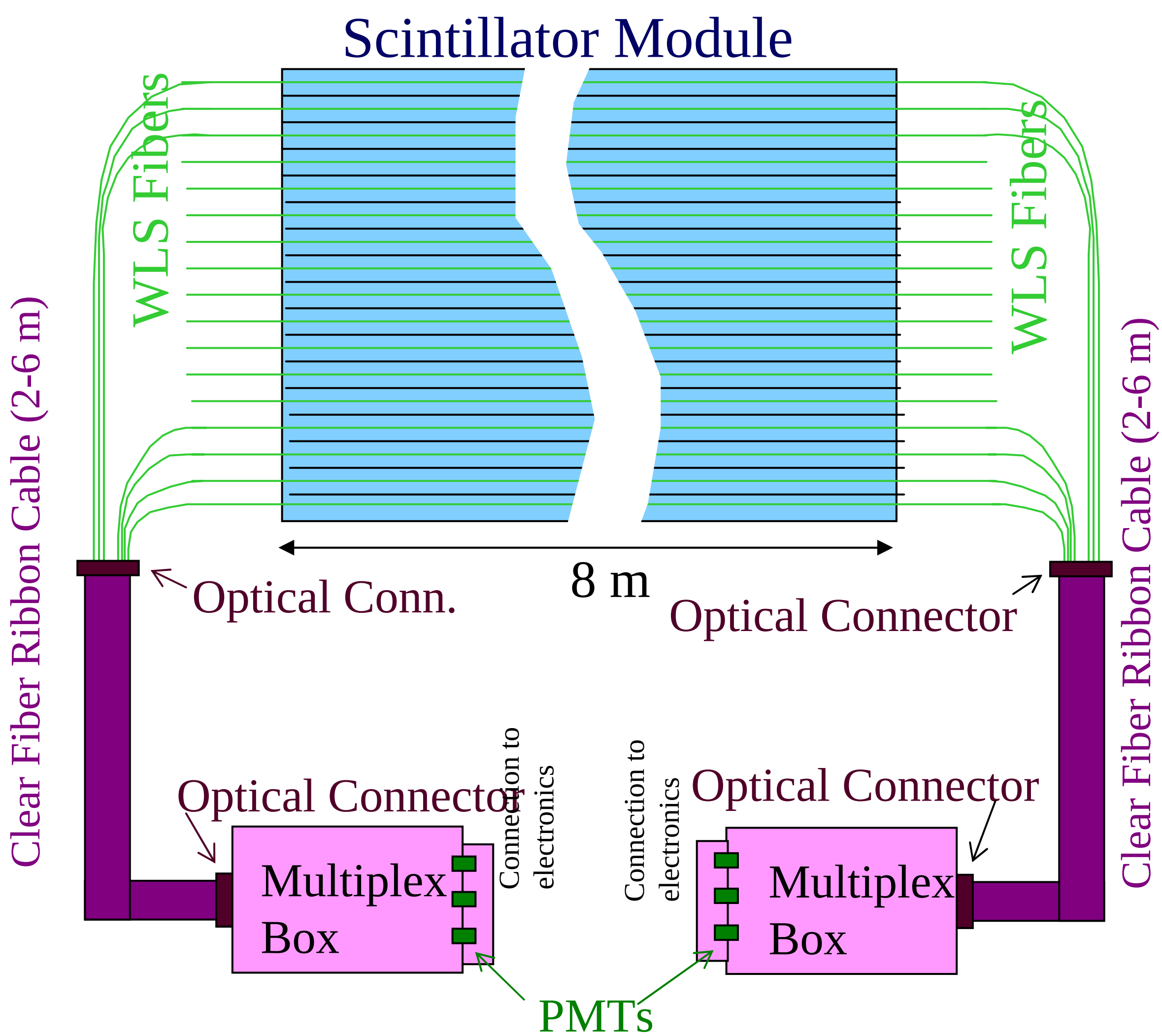


Single steel plates (280) , shorter modules

Calorimeter (1st 3/7) is partially instrumented except for 1/5 of planes with full coverage

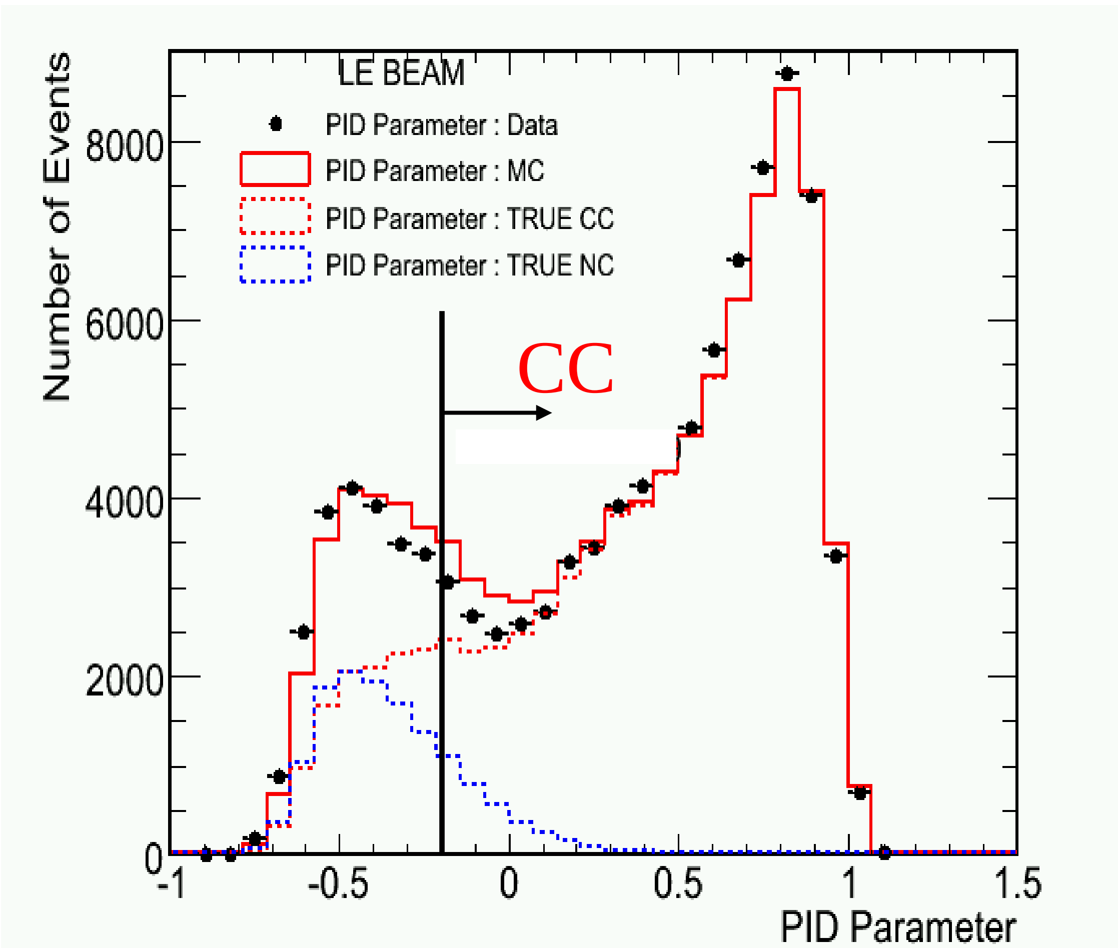
Muon Spectrometer section has only every 5th plane instrumented

MINOS Detector Technology



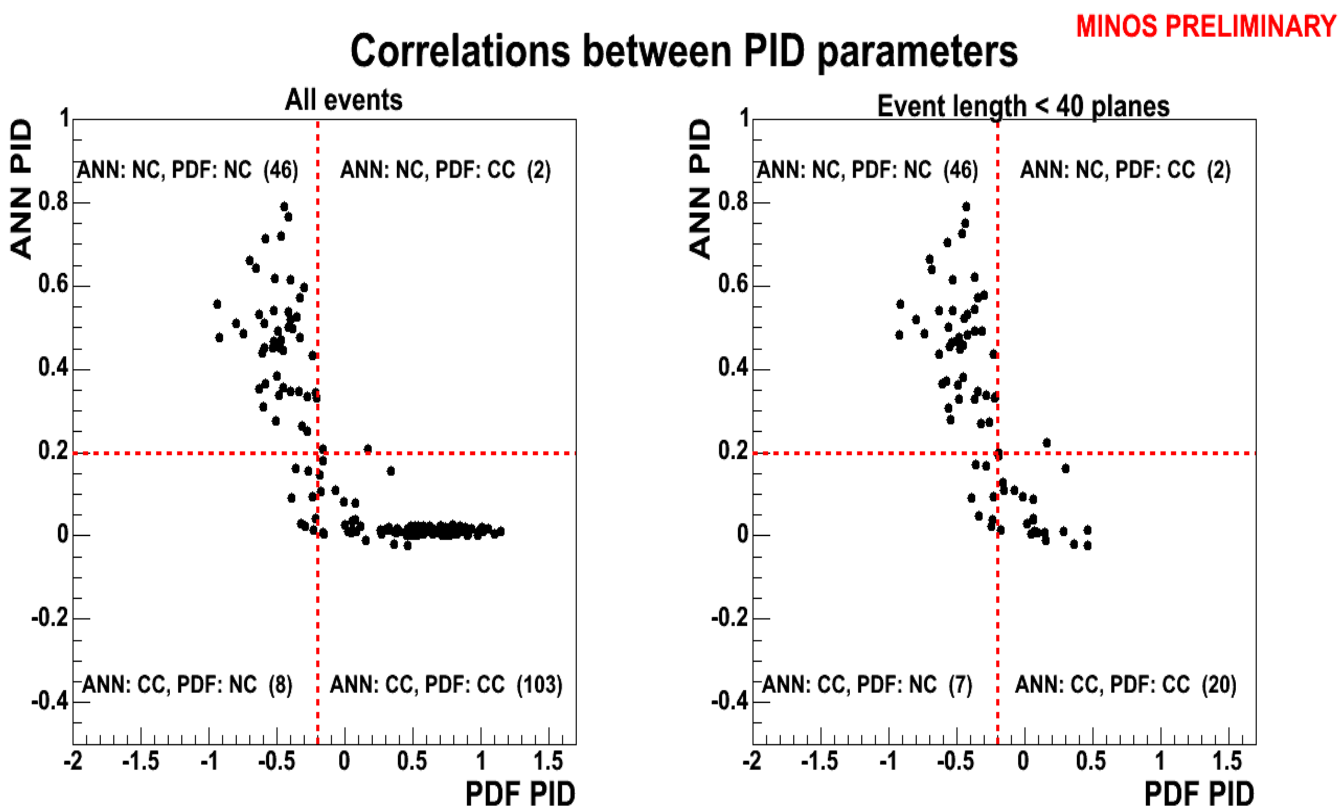
Objects not to scale

Performance of Charged Current Selection Algorithm



With cut at -0.2, MC estimate of efficiency is 87%, with purity 98%

Stability of CC Selection Algorithms



Likelihood-Based

Likelihood-Based

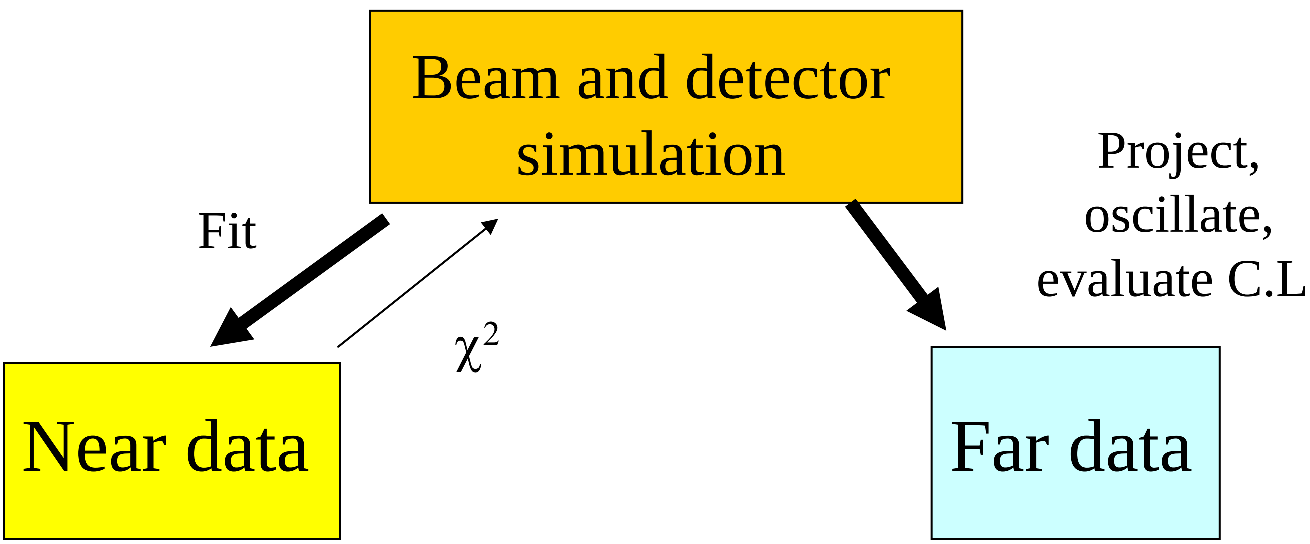
Excellent overlap between algorithms for charged-current selection.

Extrapolations and use of near detector data

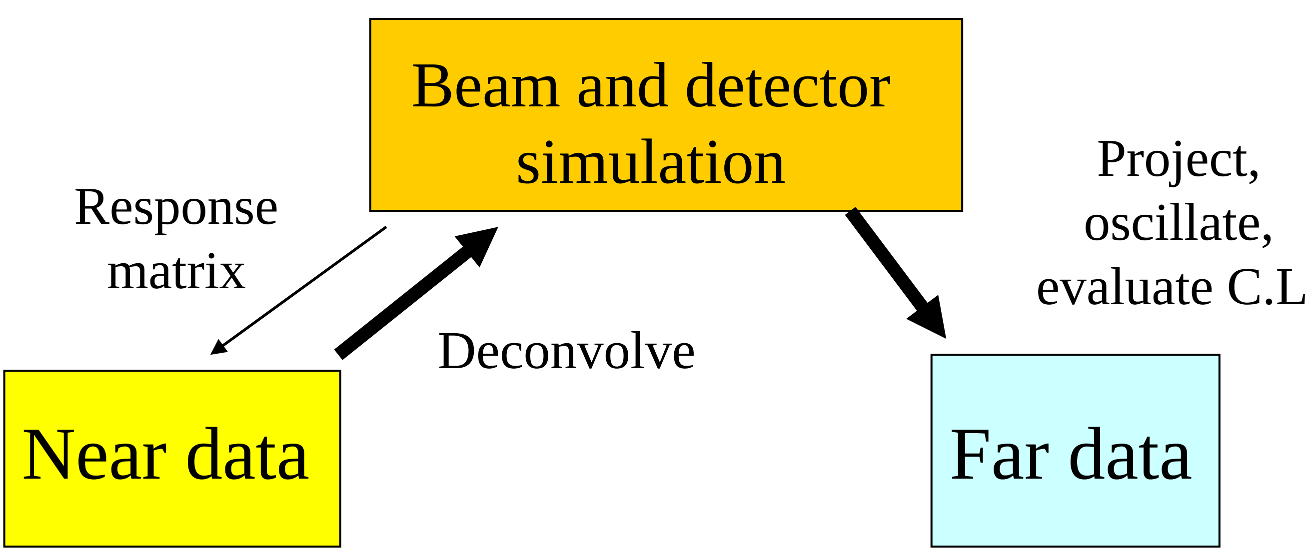
Two representative techniques

many common inputs

I) Fitting the near data



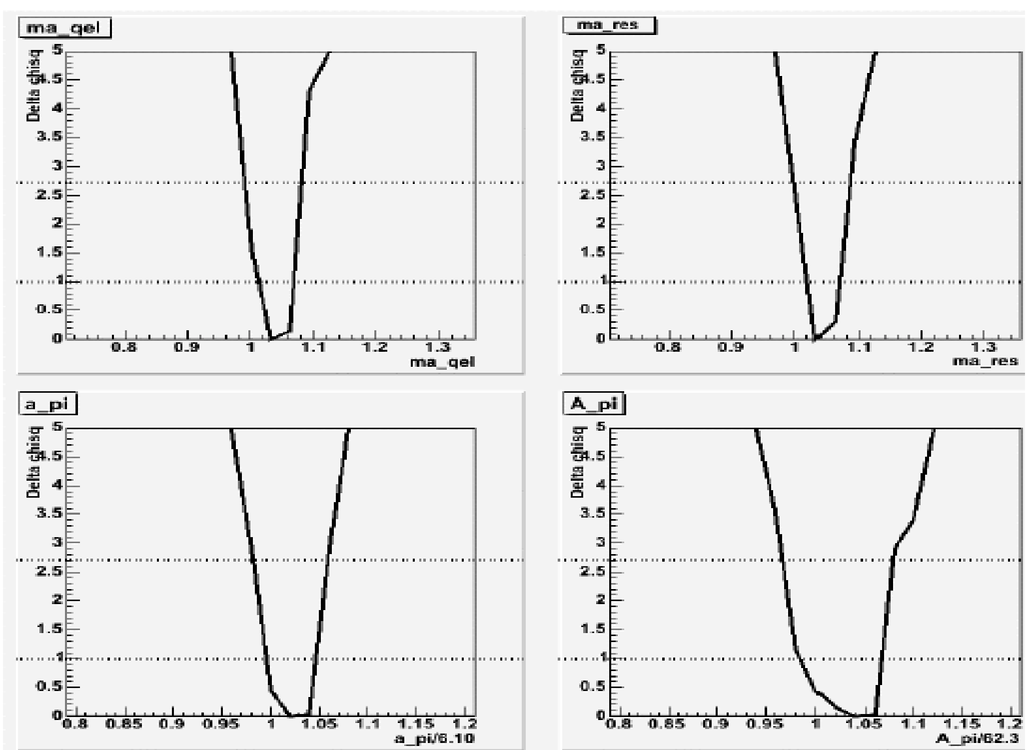
II) Deconvoluting the near data



Example of typical fitting procedure - MINOS Mock Data Challenge

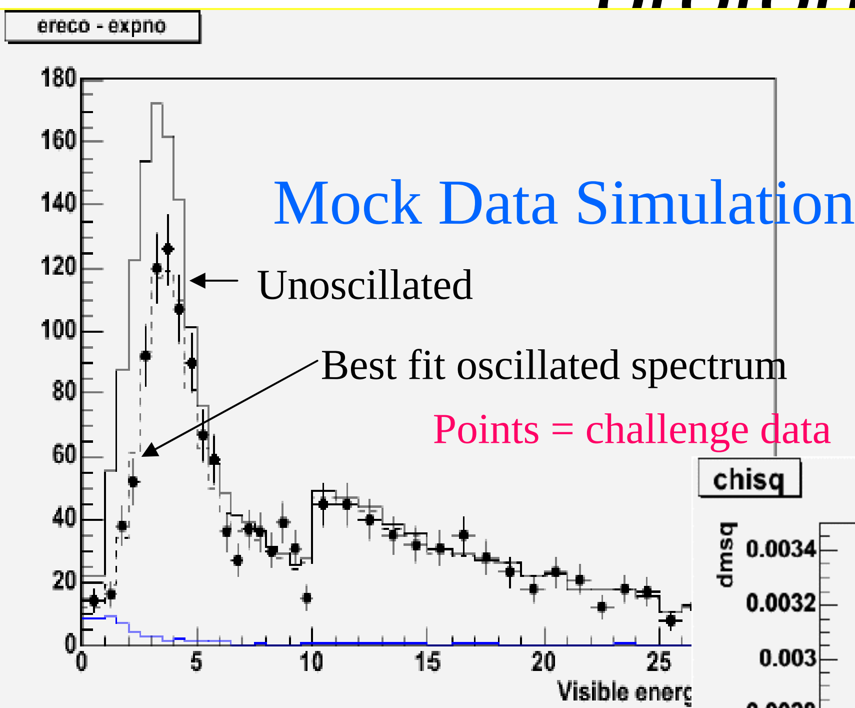
$$\chi^2(\vec{\alpha}) = \sum_{i=1}^{nbins} \frac{[n_i - m_i(\vec{\alpha})]^2}{\sigma_i^2} + \sum_{j=1}^{nsyst} \frac{\varepsilon_j^2}{\sigma_j^2}$$

where $\vec{\alpha}$ is a vector of parameters and ε is a fractional (uncorrelated) systematic error.

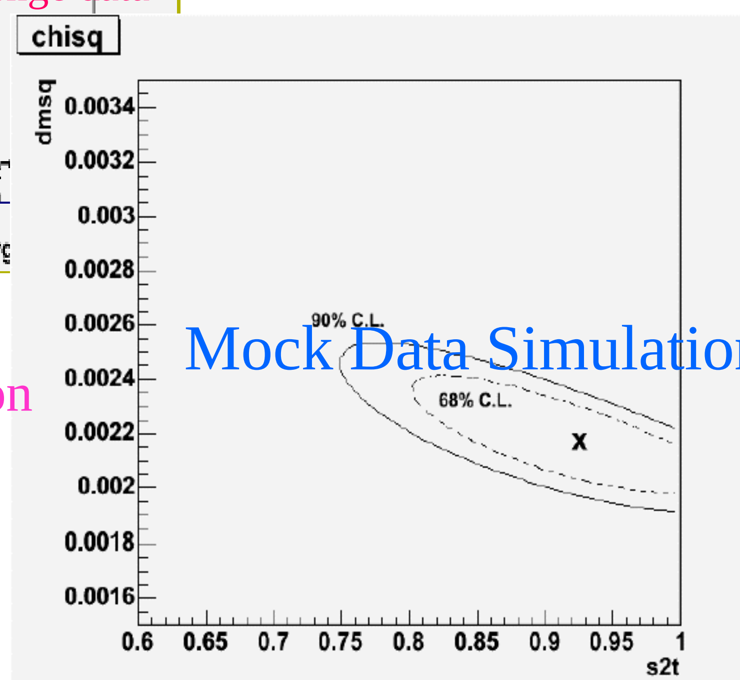


Typical $\Delta\chi 2$ plots for BMPT and cross-section parameters

Results of Mock Data Challenge (simulated 7.4 x 10^{20} protons)



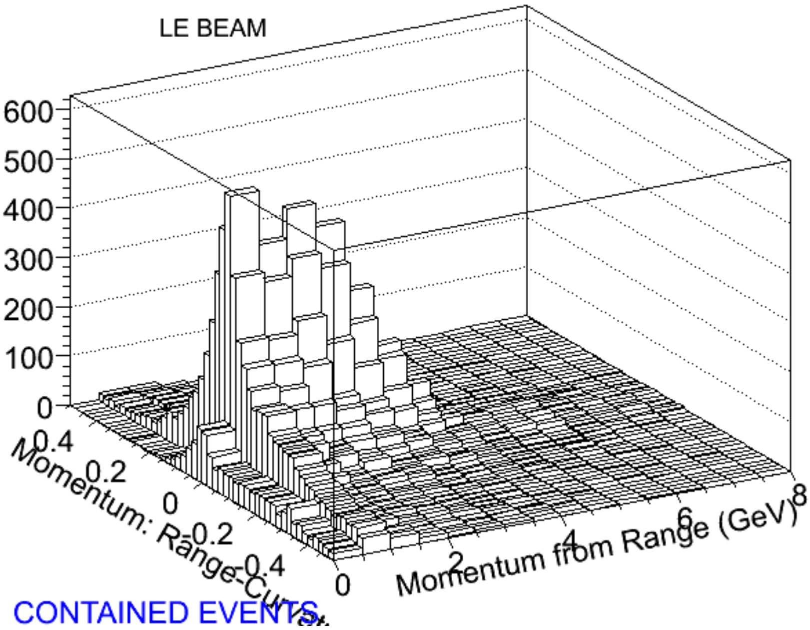
Fit to reconstructed far energy spectrum



Best fit results for oscillation parameters

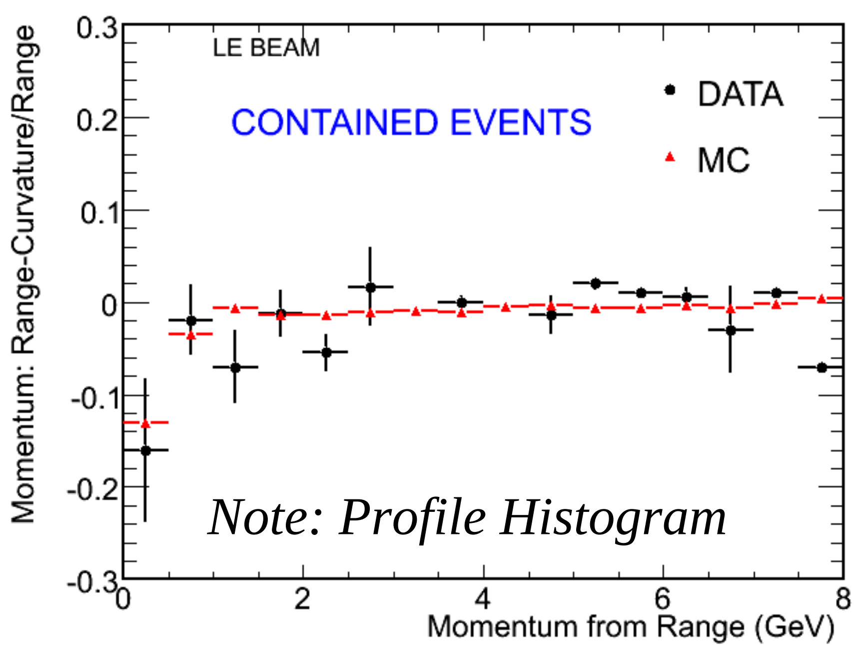
	Challenge Value	Fitted Value
Δm^2	2.1 x 10^{-3}	2.2 x 10^{-3}
$Sin^2(2\theta_{23})$	0.88	0.93

Range and Curvature Momentum Comparison



Near Detector

Far Detector



Note: Profile Histogram

Comparison in momentum regime where events are contained.

Builds confidence in magnetic field map and calibration

Example -MINOS CC Disappearance Analysis

Blind analysis - only <50% of data in open sample for comparisons.

Remainder modified by “blinding function”.

Steps in analysis

Select neutrino events

Classify as CC events

Likelihood-based procedure using pulse height, event length.

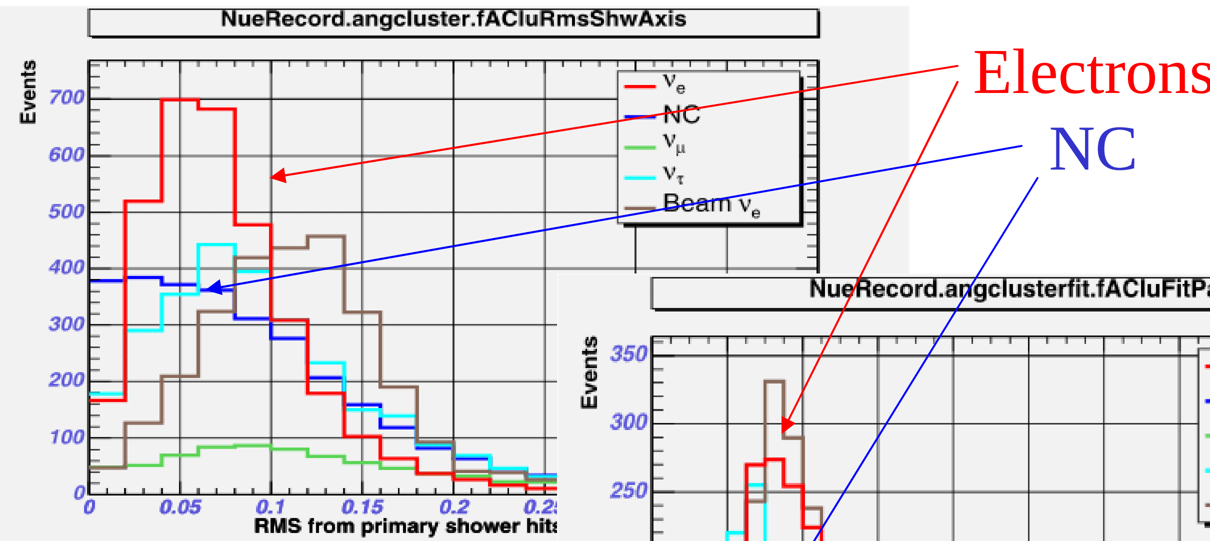
Check with neural net based procedure - good agreement. Also controlled scanning checks.

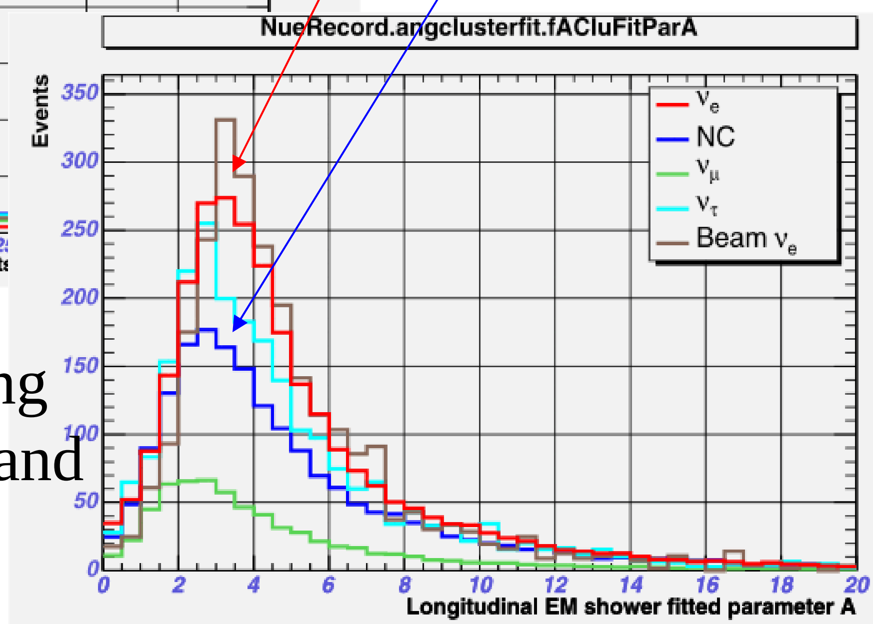
Extrapolate (using near) to far CC spectra to extract oscillation parameters.

Notes: NuMI/MINOS MC used to extrapolate far/near

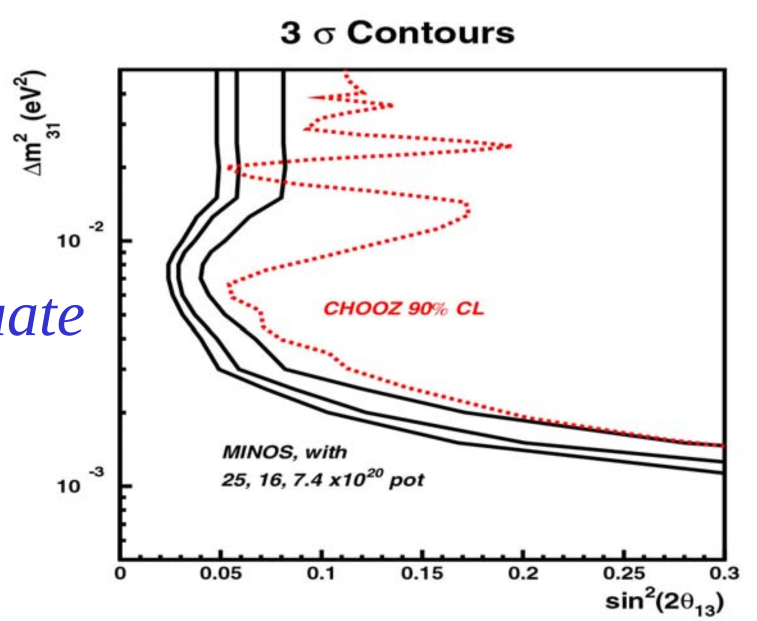
Fit χ^2 will include systematic errors.

MINOS electrons and their sensitivity





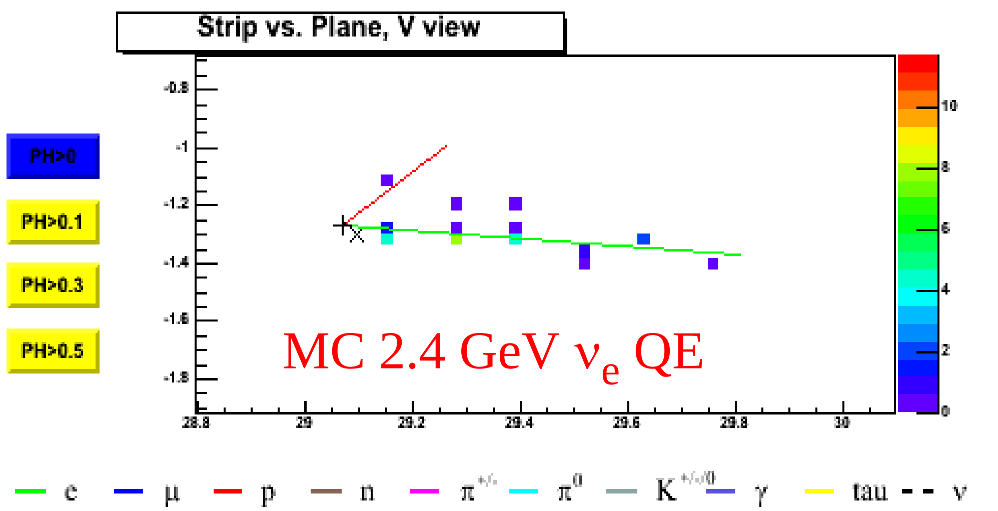
Typical discriminating variables:transverse and longitudinal shower shapes



Can improve CHOOZ limit by ~2 with adequate protons

Electrons and $\sin^2 2\theta_{13}$ in MINOS

As an iron calorimeter, MINOS is not optimized for low-energy e^- detection (1-3 GeV)



With appropriate attention, progress can be made on limits for $\sin^2 2\theta_{13}$

Principal background (~2/3) is from mis-identified π^0 NC events:

$$\nu_\mu + N \to \nu_\mu + N' + \pi^0, \quad \pi^0 \to \gamma\gamma$$

Understand Off-axis Mathematically

Model beam with $\theta^* = \pi/2$

$$P_T = P^* \sin\theta^*$$

$$P_L = \gamma P^* (1 + \cos\theta^*) \cong E_\nu$$

We fix $\theta_{lab} \equiv P_T / P_L$

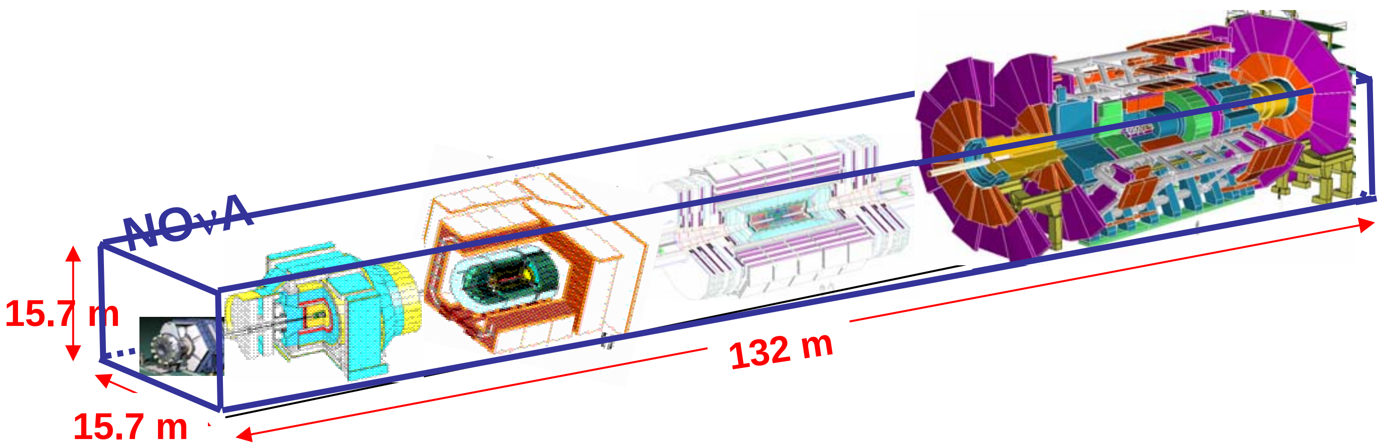
At $\pi/2$ $\Delta P_T \cong 0$ as vary θ^*

$$\Delta P_L = \frac{\Delta P_T}{\theta_{lab}} \cong 0$$

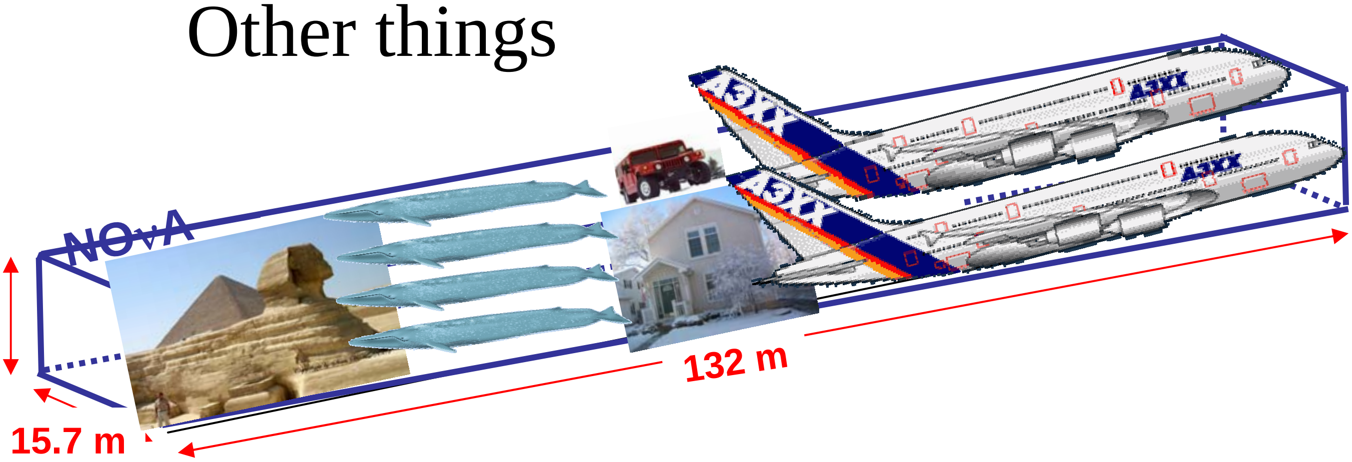
Constraint on angle means γ compensates θ^* to fix P_L (at fixed θ_{lab})

Two Views of the very Large

BaBar, CDF, D0, CMS, & ATLAS



Other things



Next Order and CP Violation

- Do not neglect Δ_{12}
- Add back CP phase δ
- Terms group as

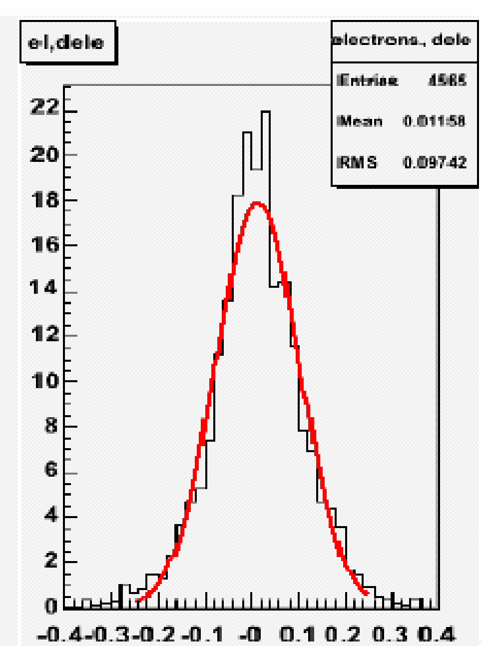
$$\left| e^{-i(\delta+\Delta_{32})} A_{atm} + A_{solar} \right|^2$$

(Before we looked only at A_{atm}^2)

Giving

$$A_{atm}^2 + A_{solar}^2 + P_{\text{interference}}$$

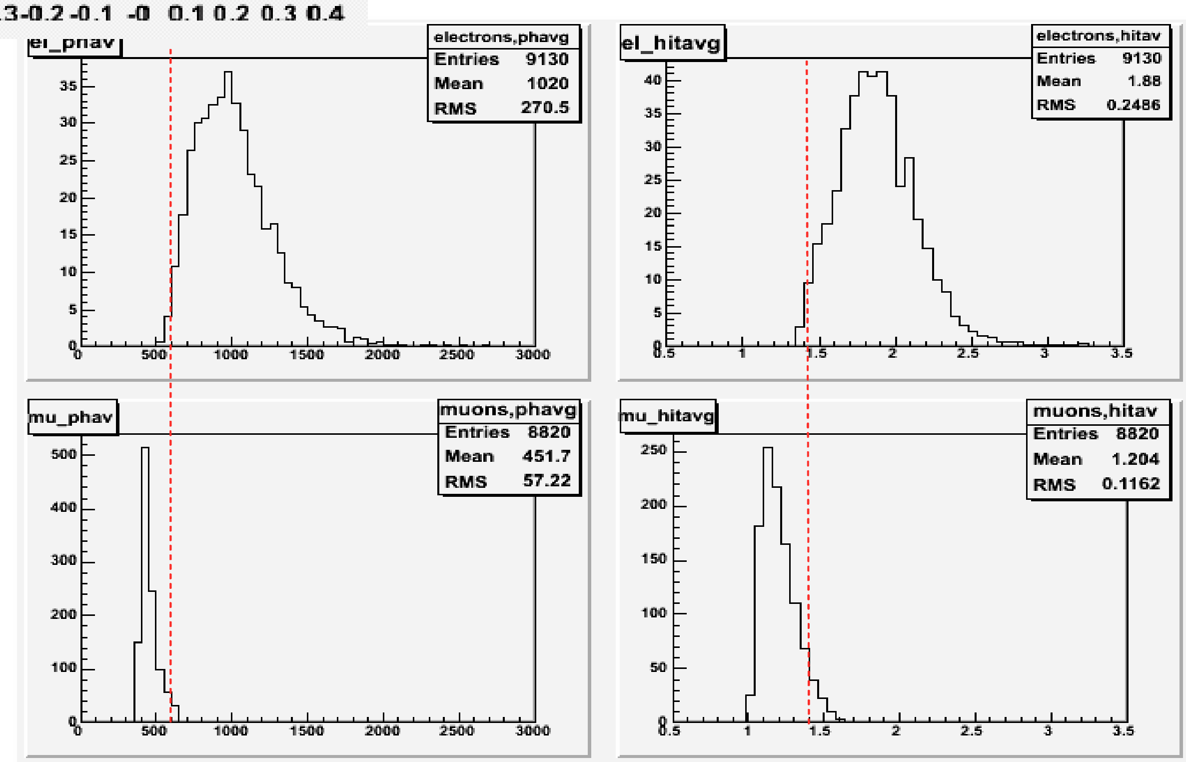
NOvA performance and event classification variables



Active detector gives good resolution

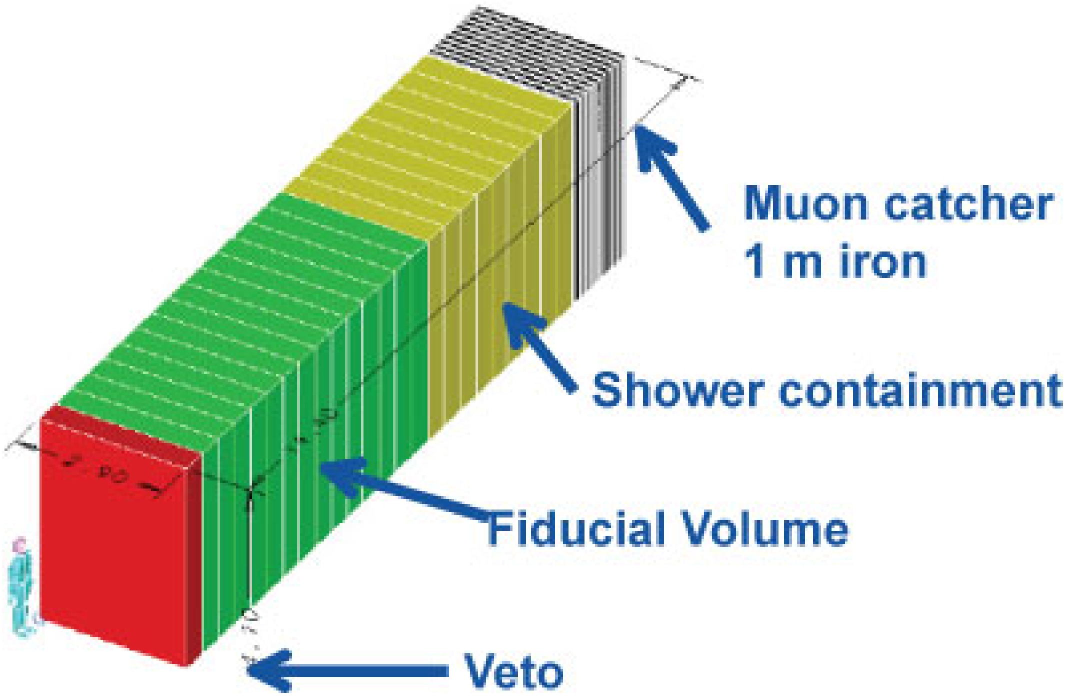
$$\frac{\Delta E}{E} = \frac{9\%}{\sqrt{E}}$$

Overall $\nu_\mu \rightarrow \nu_e$ efficiency ~24%

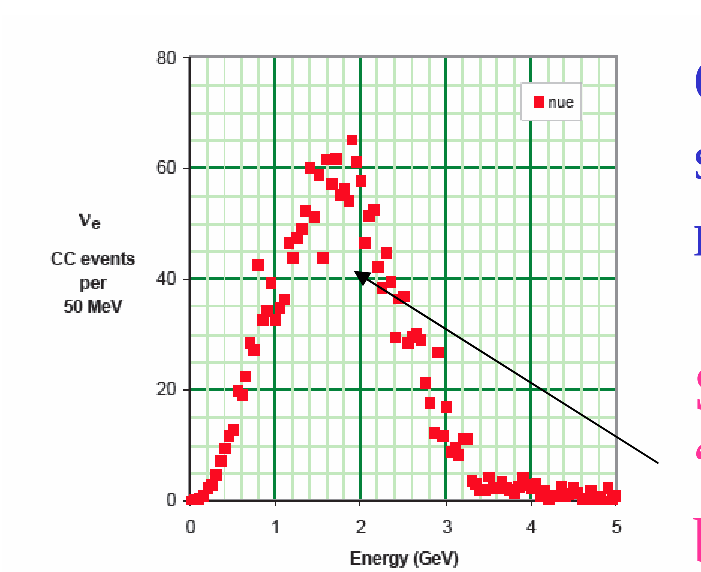


e-μ discrimination using average pulse height/plane and <hits>/plane

NOvA also has a near detector as a crucial component



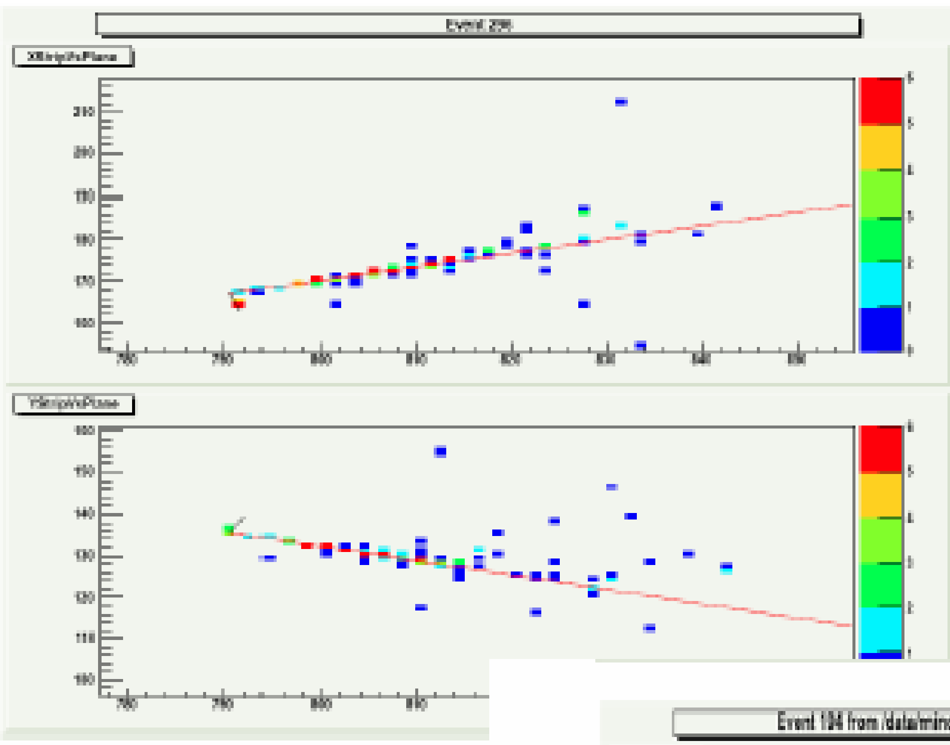
Can move to different locations in underground tunnel to measure off-axis effects and calibrate far spectra



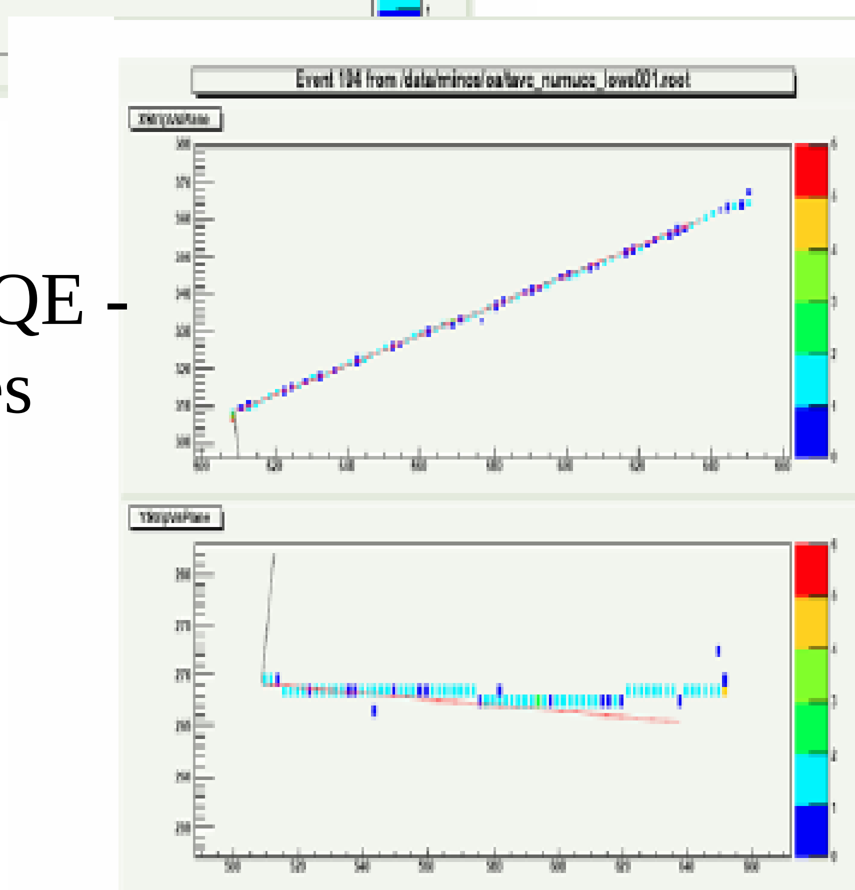
Can also operate early on surface to understand response

Sample ν_e spectrum from "off-axis neutrino test beam"

Representative NOvA MC Events



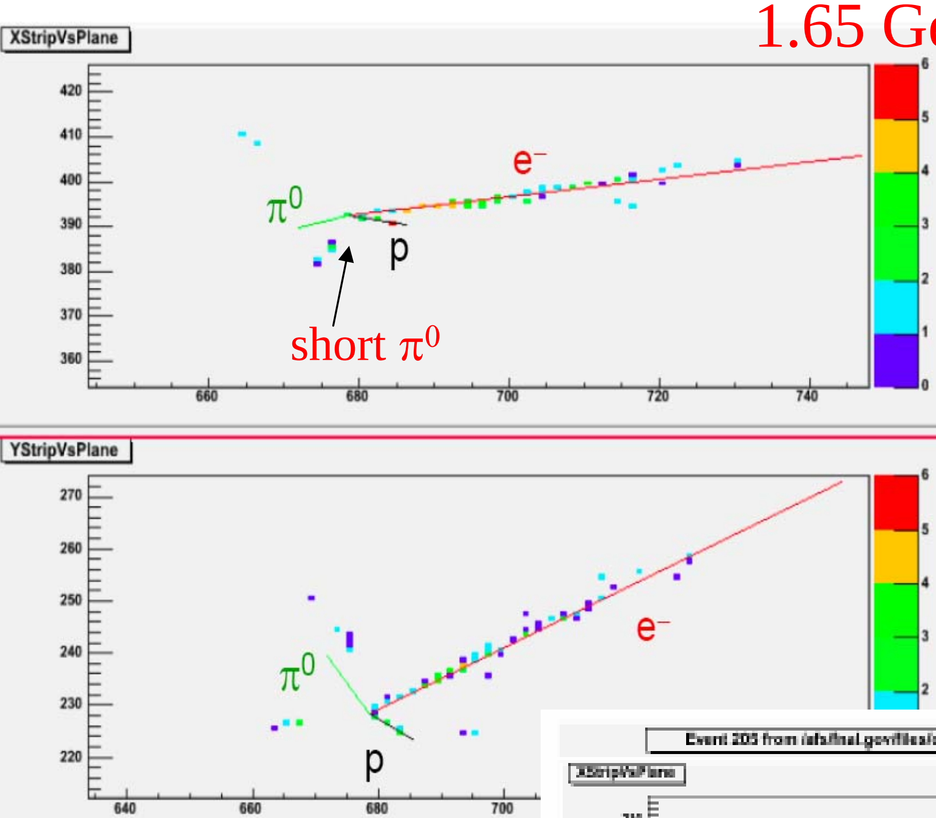
2 GeV ν_e QE - 60 planes



2.2 GeV ν_μ QE - 140 planes

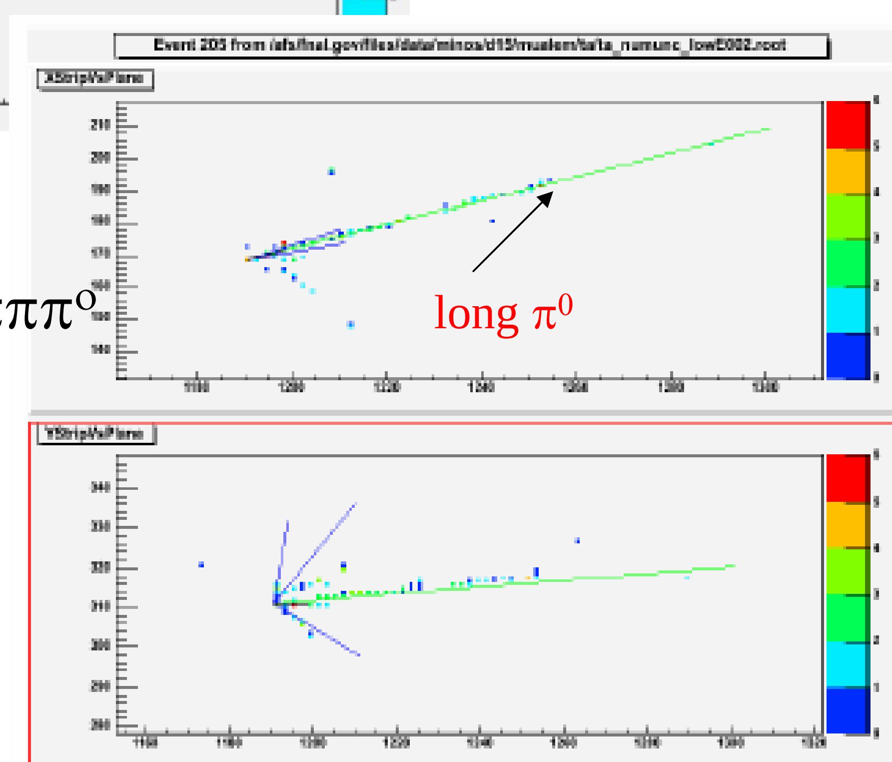
NOvA MC events showing successful and unsuccesful π^0 rejection.

1.65 GeV $\nu_e N \rightarrow e p \pi^0$



55 planes
Success!!

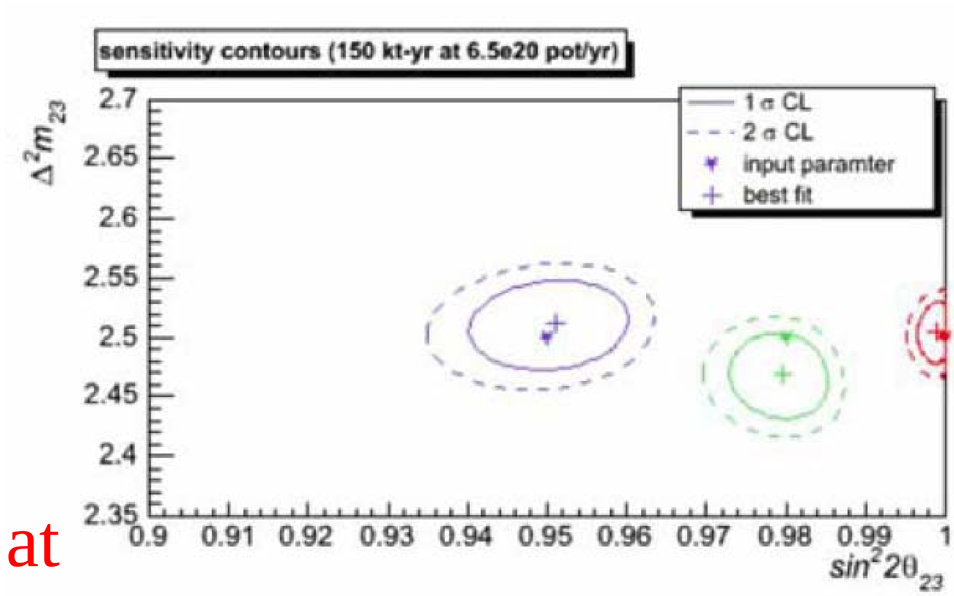
4.95 GeV $\nu N \rightarrow \nu \pi \pi \pi^0$

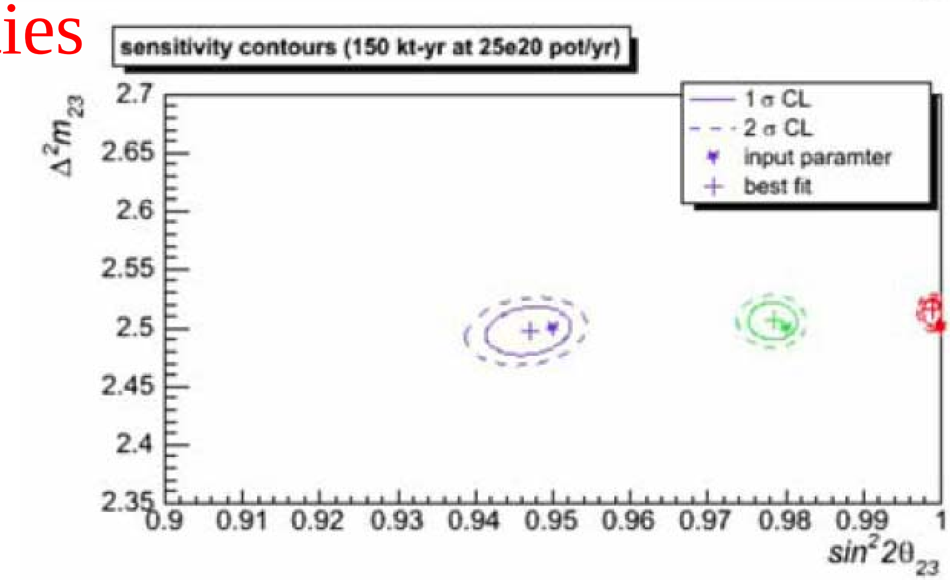


70 planes
Failure!!

Sufficient running of NOvA can make do other precision measurements.

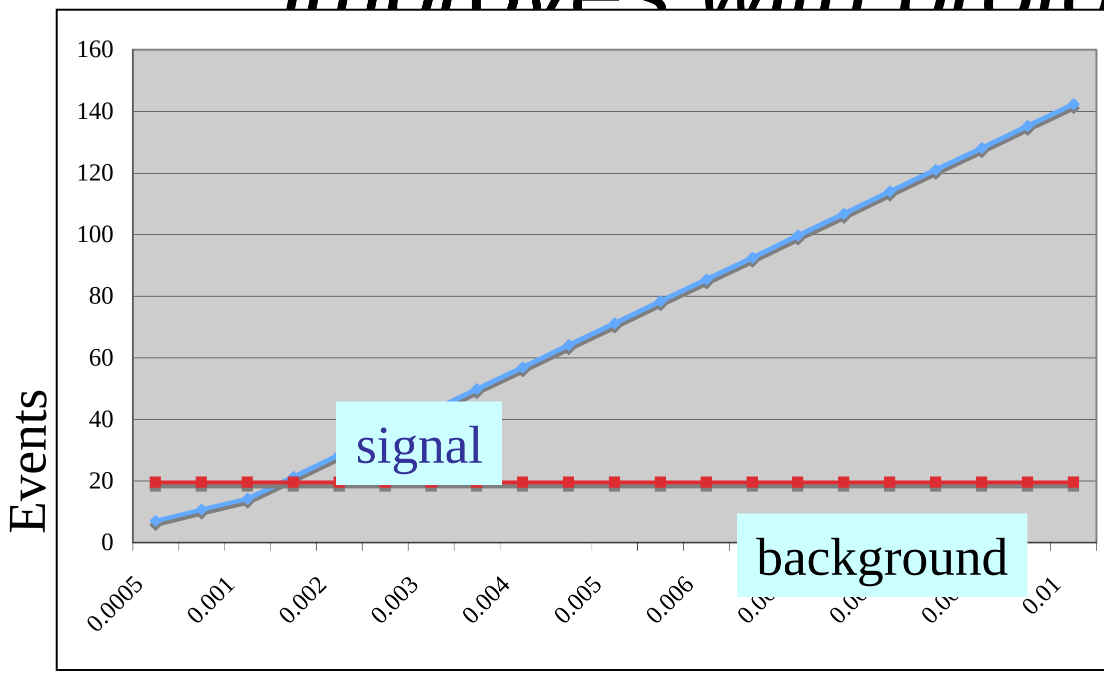
5-year run at two intensities





Excellent results for $\sin^2\theta_{23}$ with expected intensities.

Measurement is limited by statistics - experiment improves with protons



0.01 0.05 0.1

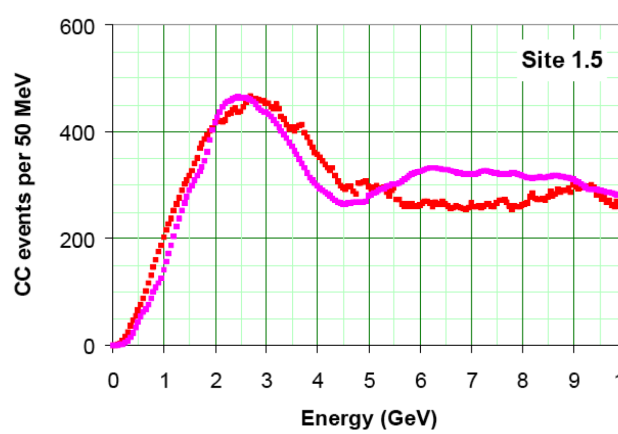
$\sin^2 2\theta_1$

For $\sin^2 2\theta_{13} = 0.1$:

ν: S=142.1, B=19.5

ν: S= 71.8, B=12.1

5 yrs at 6.5E20 pot/yr, efficiencies included



Background ν_e from near detector

Graphic - R. Bernstein

The Fine Art of Small Masses

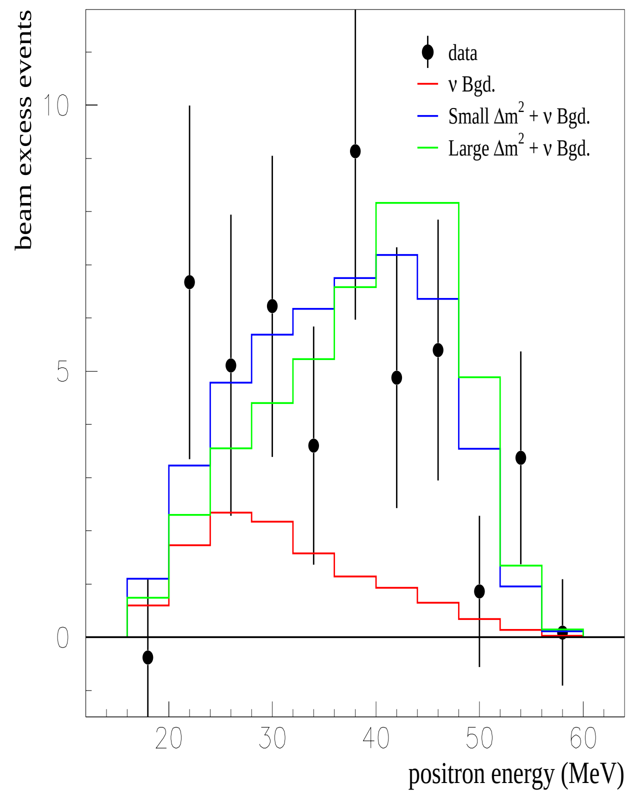
- Direct searches
  - Look for deviations at very end of β-decay spectrum.
  - Time-of-flight spread in Supernova !
  - Cosmological "constraints"
    - **Don't exceed allowed density**
  - Accelerator-based studies of π, τ decays.
- Current state is limits only.
- Resort to indirect techniques
  - Oscillations and mixing!

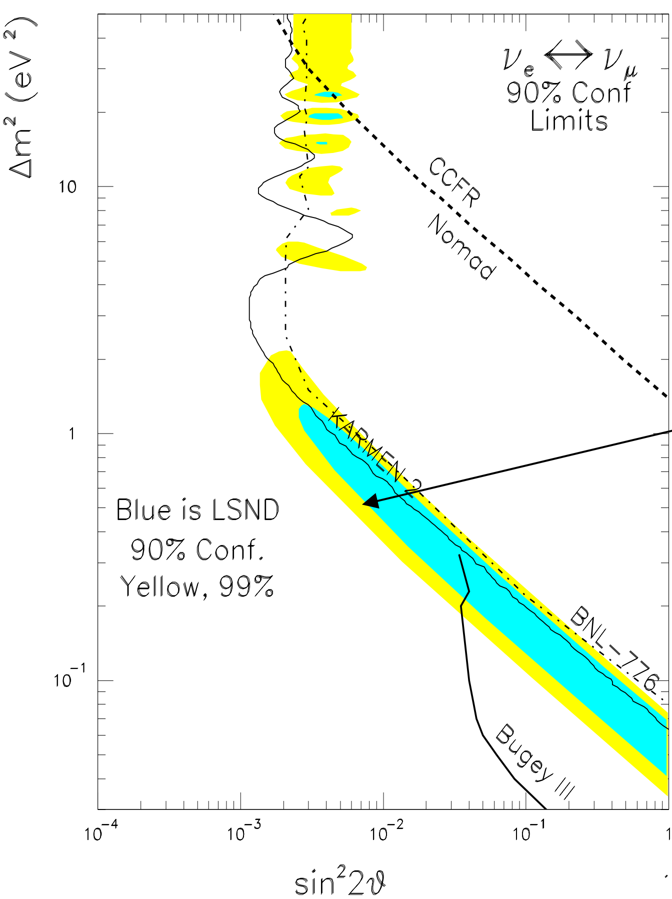
	Decays	*Astronomy*
ν_e	**< 3 - 7 eV**	**< 20 eV (SN 1987A)**
	< 1 eV ("double-β", model-dependent)	
ν_μ	**< 0.170 MeV**	$\Sigma m_\nu < 8$ **eV (cosmology)**
ν_τ	**< 24 MeV**	

Hints of Oscillations # 3
LSND - Stopped Pion Decay

Use stopped π,μ decays
as source of anti - ν_μ

Detect positron
and neutron from CC.



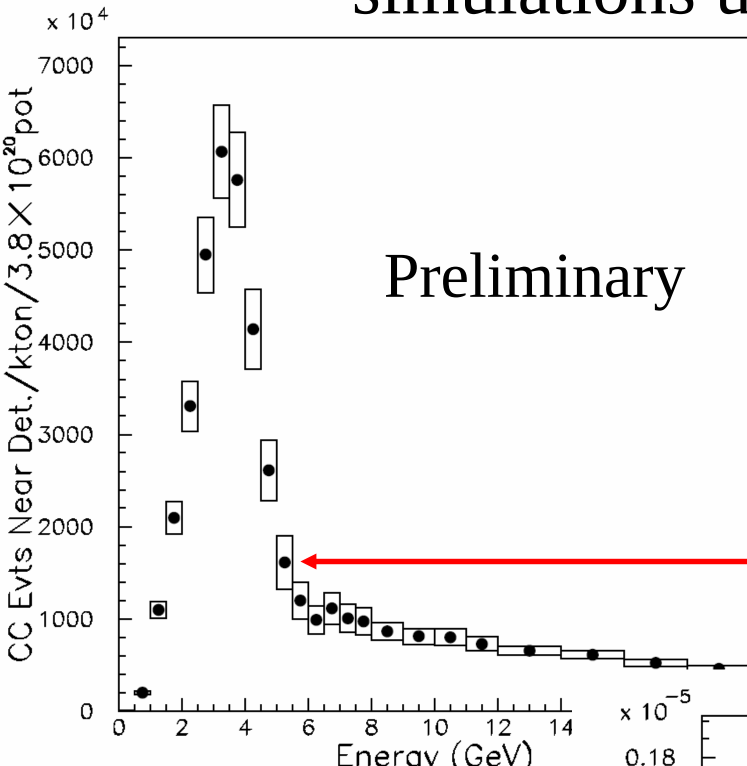


Recent analysis shows compatible with other experiments - but close.

Fermilab MiniBOONE
experiment is checking.

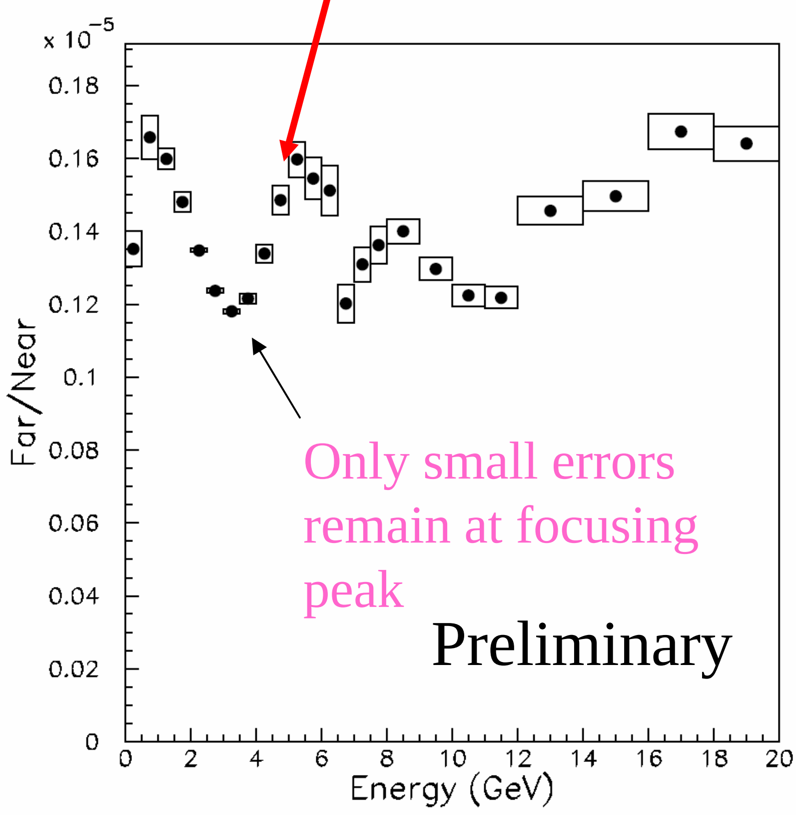
Two detectors to reduce uncertainty

Examples from MINOS simulations using FLUKA



Hadron production uncertainty dominates this plot

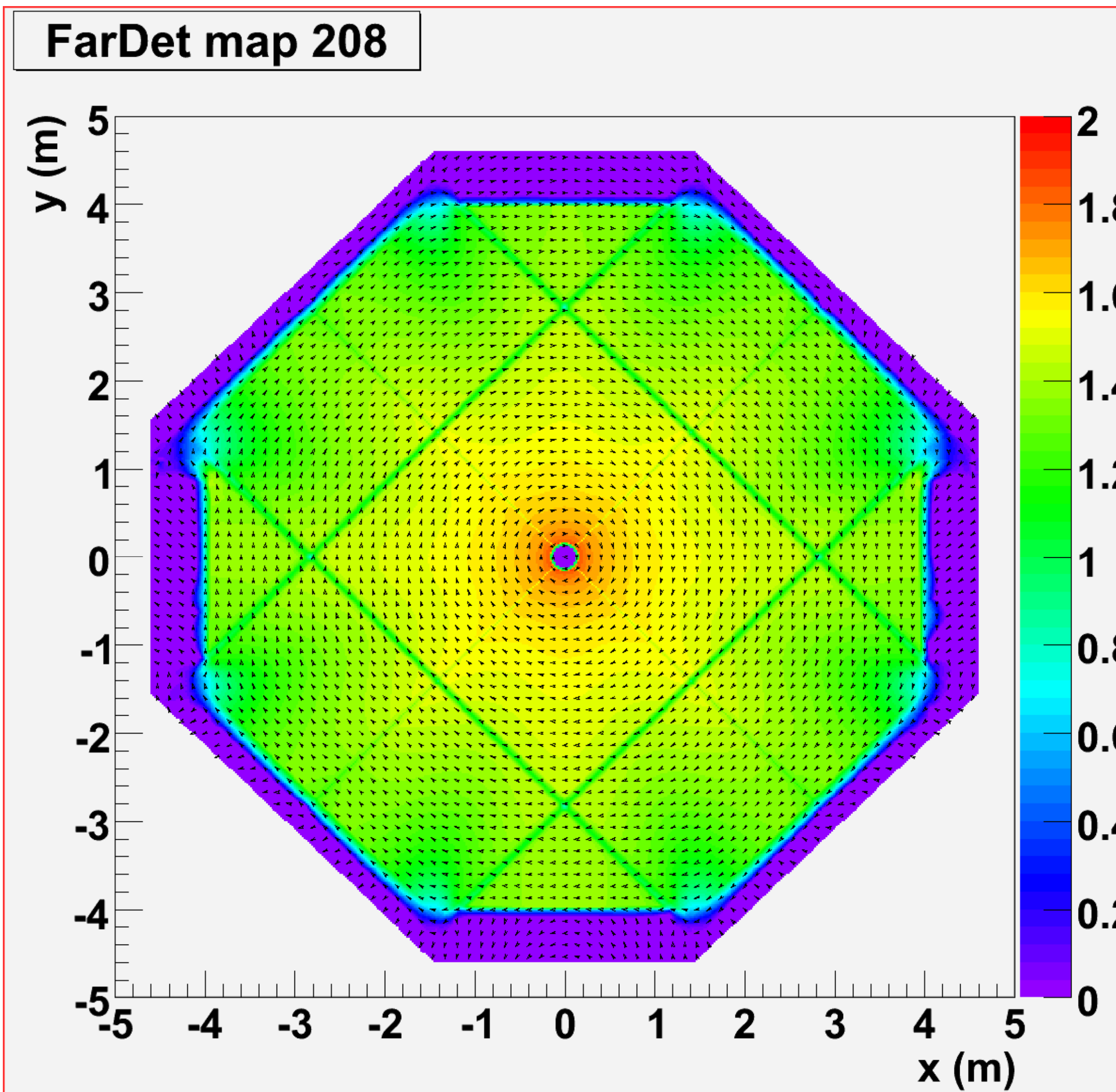
At 5 GeV, uncertainty of ~15% —-> ~ 4%



In far/near ratio, hadron uncertainty largely cancels

Tracking must go on in magnetized iron

Determine field map by finite element analysis, steel properties.



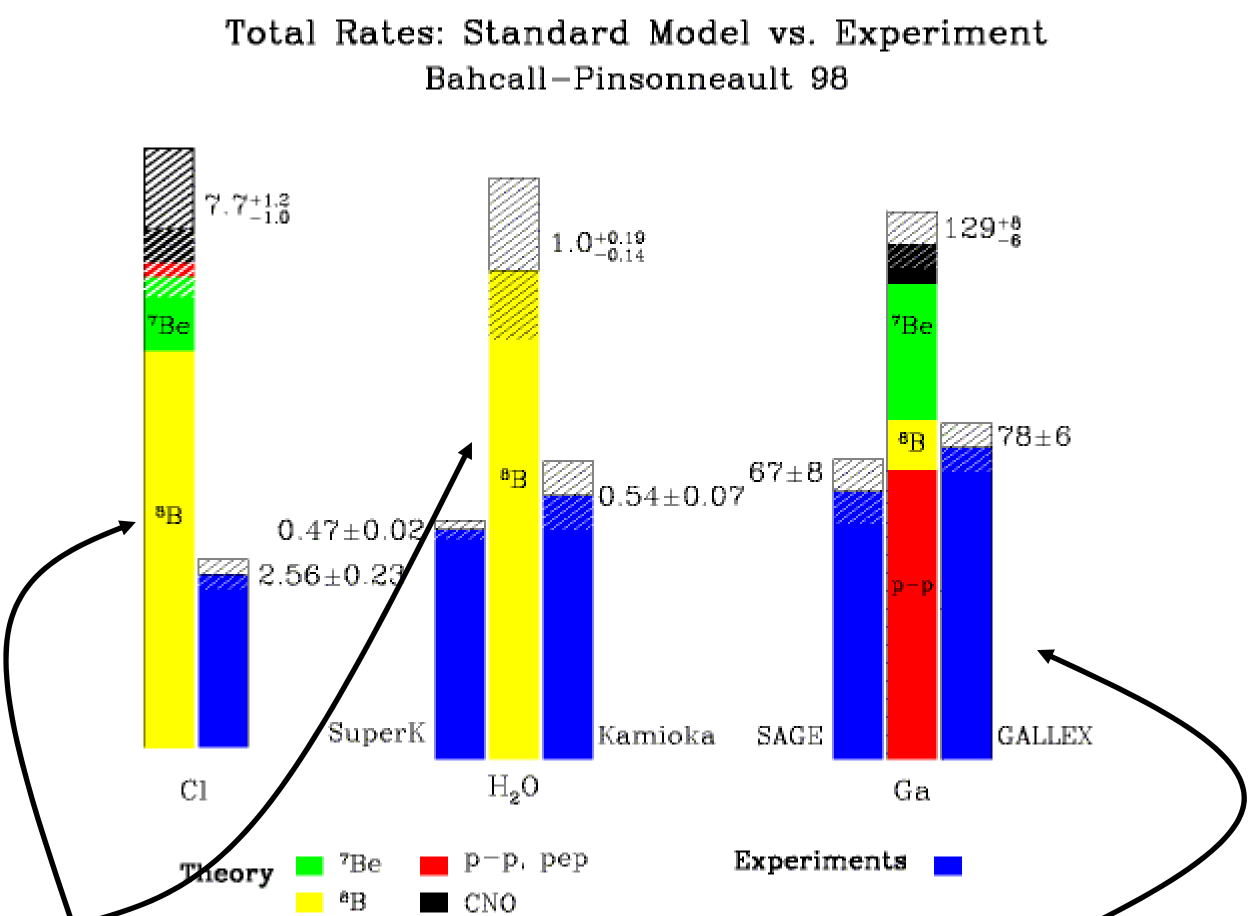
MINOS Far Detector B-field (Tesla)

Solar Neutrinos - Observations

Difficult experiments using 3 different technologies have detected the solar neutrino radiation

Sensitive to different mixes of channels

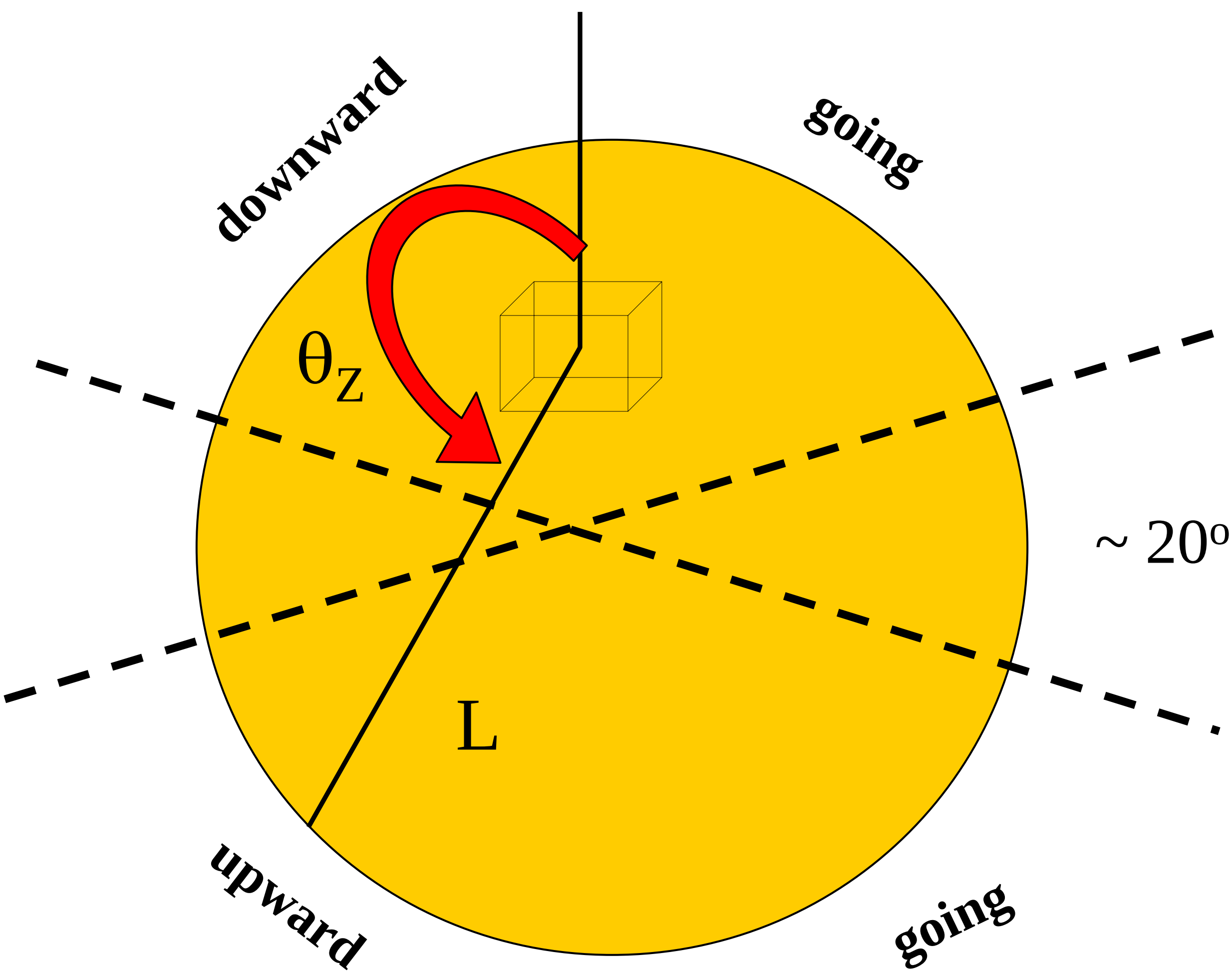
All have reported significant deficits



Correcting B increases Be - not seen.

pp alone, no room for Be

Zenith Angle as a Clue to Oscillation



ν path lengths vary from 20 - 13,000 km.

Wide energy ν energy spectrum with
~1 GeV "typical"