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Summary of Accelerator Neutrino Experiments

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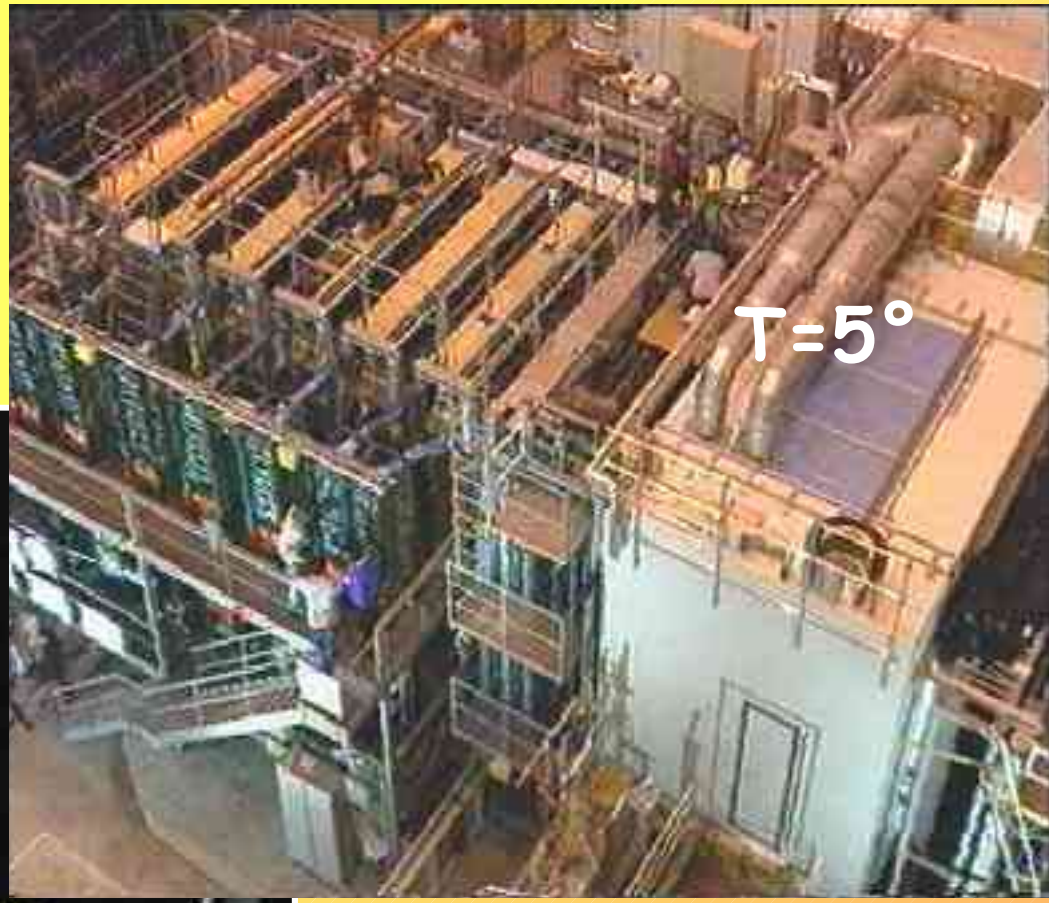
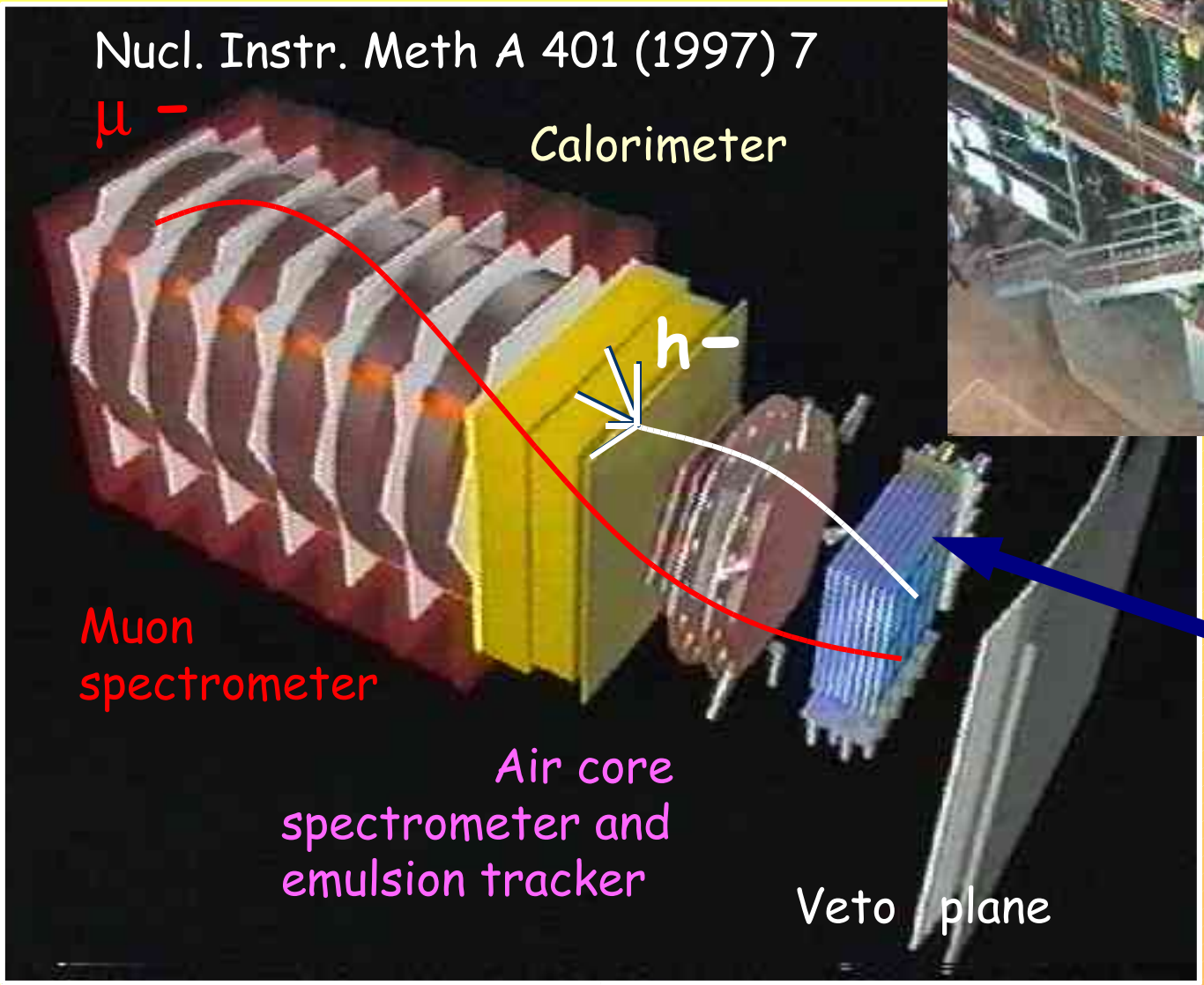
- Non-Oscillation Physics: CHORUS
- Oscillation Results
  - Current Experiments: CHORUS, K2K, MiniBooNE
  - Upcoming Experiments: MINOS, OPERA, T2K, Nova

CHORUS Detector





770 kg emulsion target and scintillating fibre tracker

Beam from '94-'97



Non-Oscillation Physics

So far, we have measured:

Trimuon events	Phys. Lett. B. 555 (2004) 44
Λ_c production	Phys. Lett. B. 555 (2003) 156
QE charm production	Phys. Lett. B. 575 (2003) 198
D^0 production	Phys. Lett. B. 527 (2002) 173
CC associate charm production	Phys. Lett. B. 539 (2002) 188
BR $\rightarrow \mu$	Phys. Lett. B. 549 (2002) 48
Diffractive D_s^* production	Phys. Lett. B. 435 (1998) 458

We are studying :

- **D^0 decay in neutrals**
- **$D^* \rightarrow D^0 + \pi^+$**
- **Associated charm production in CC and NC**
- **Charm fragmentation function**
- **Anti-neutrino charm production**
- **x distribution**
- **V_{cd}**

Fully neutral D^0 decay modes

Preliminary

BR4/BR2 – measured

BR4 = 0.1338 ± 0.0058 From PDG

BR($D^0 \longrightarrow$ neutrals)=1-BR4 x(1+ **BR2/BR4)=24.1 ± 4.5%(V6 negligible)**

Total production cross section

All D^0's = N_{V4}/BR4 = 2280 ± 151(stat.) ± 26(stat.eff.) ± 99(BR4 err.)

Relative detection efficiency D^0/CC = 0.88

$$\sigma(D^0)/\sigma(CC) = 2280/95450/0.88 =$$

$$= 2.71 \pm 0.22 \times 10^{-2}$$



Oscillation Analysis

Decay mode considered

i)τ^- --> $\mu^-\nu_\mu\nu_\tau$ ii) τ^- --> $h^-(n\pi^0)\nu_\tau$, iii) τ^- --> $3h^-(n\pi^0)\nu_\tau$

Pre-selection (data from electronic detector)

-vertex predicted in the emulsion

-At least one negative track

-1μ sample

-0μ sample

Emulsion Scanning

- Scanning has been completed

Final kinematic cuts

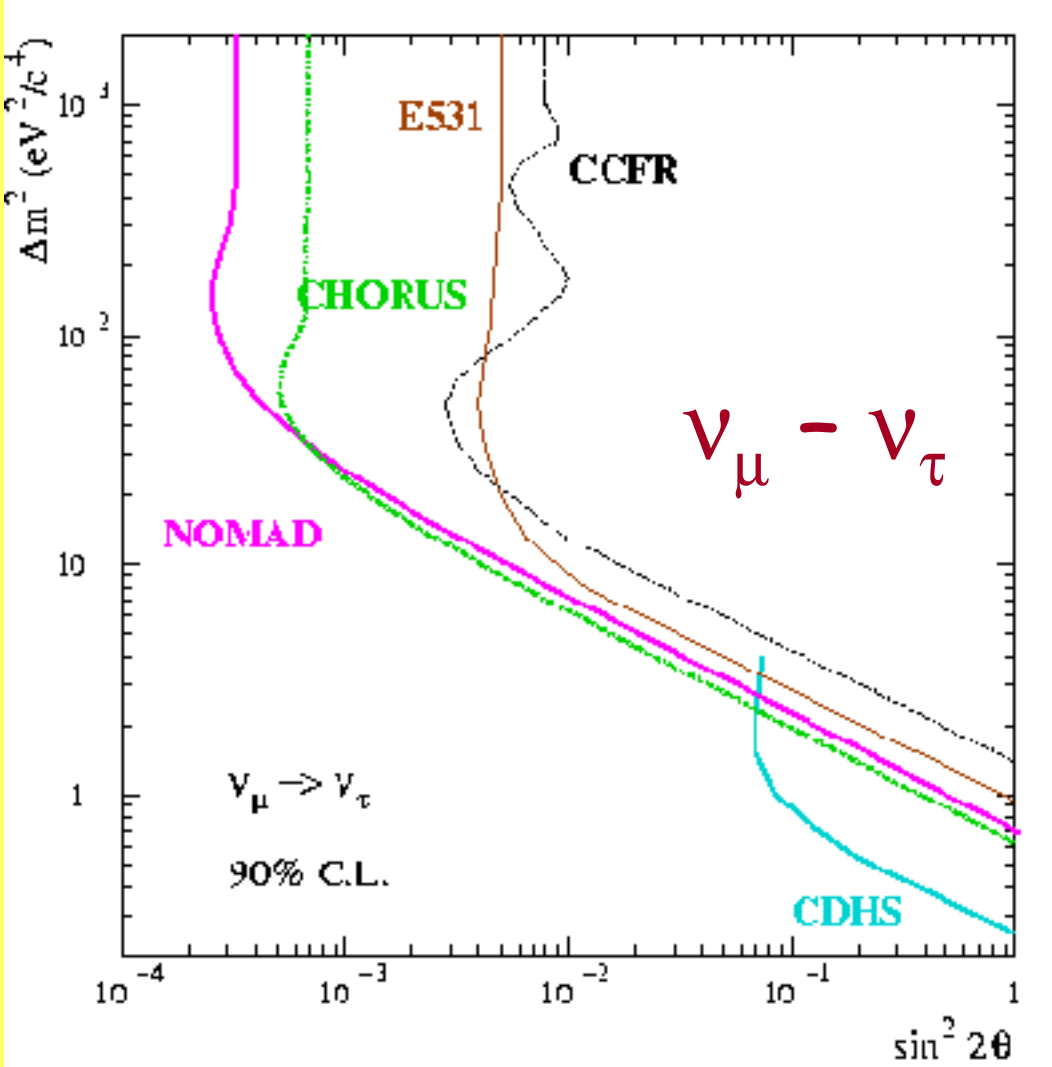
- decay length, kink angle, Pt at vertex

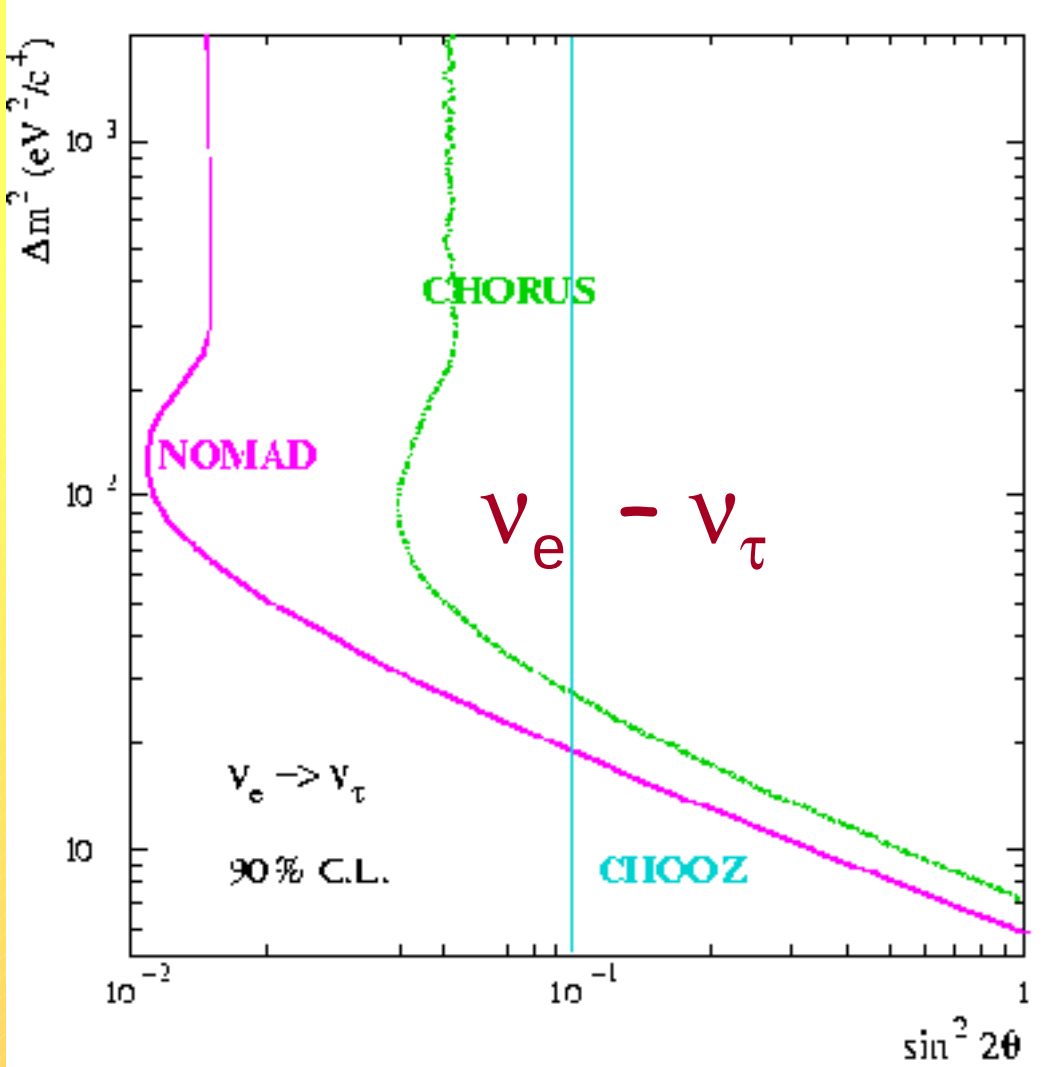
Estimating Efficiency

- expect results this year

No tau candidates found

Status of oscillation into ν_τ

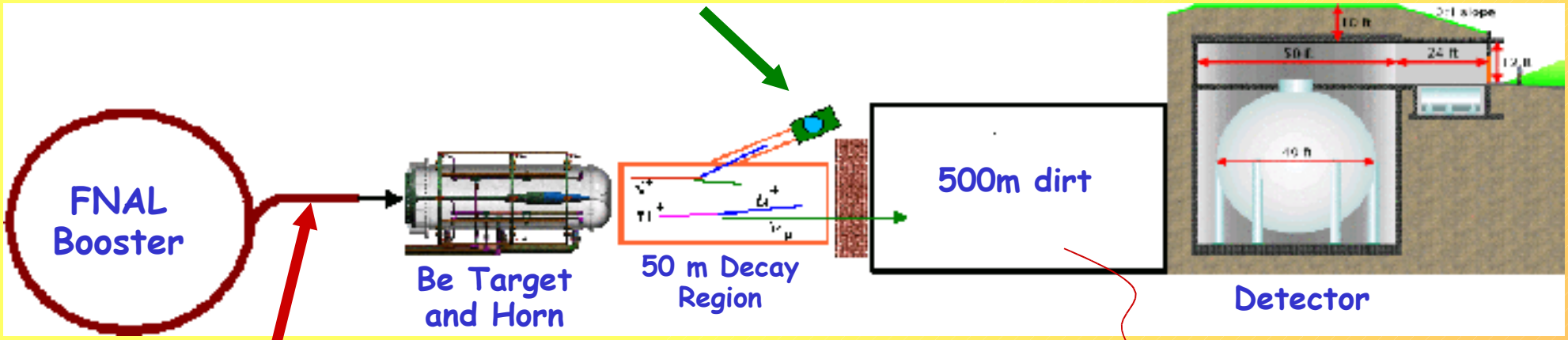




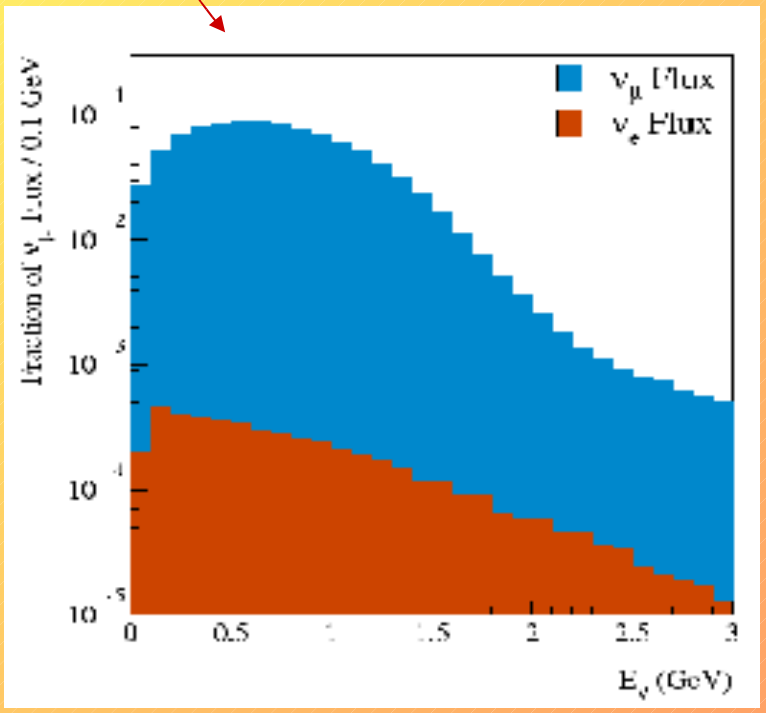
NOMAD data: final - CHORUS phase-II not yet finalized

MiniBooNE

"Little Muon Counter" (LMC): to understand K flux



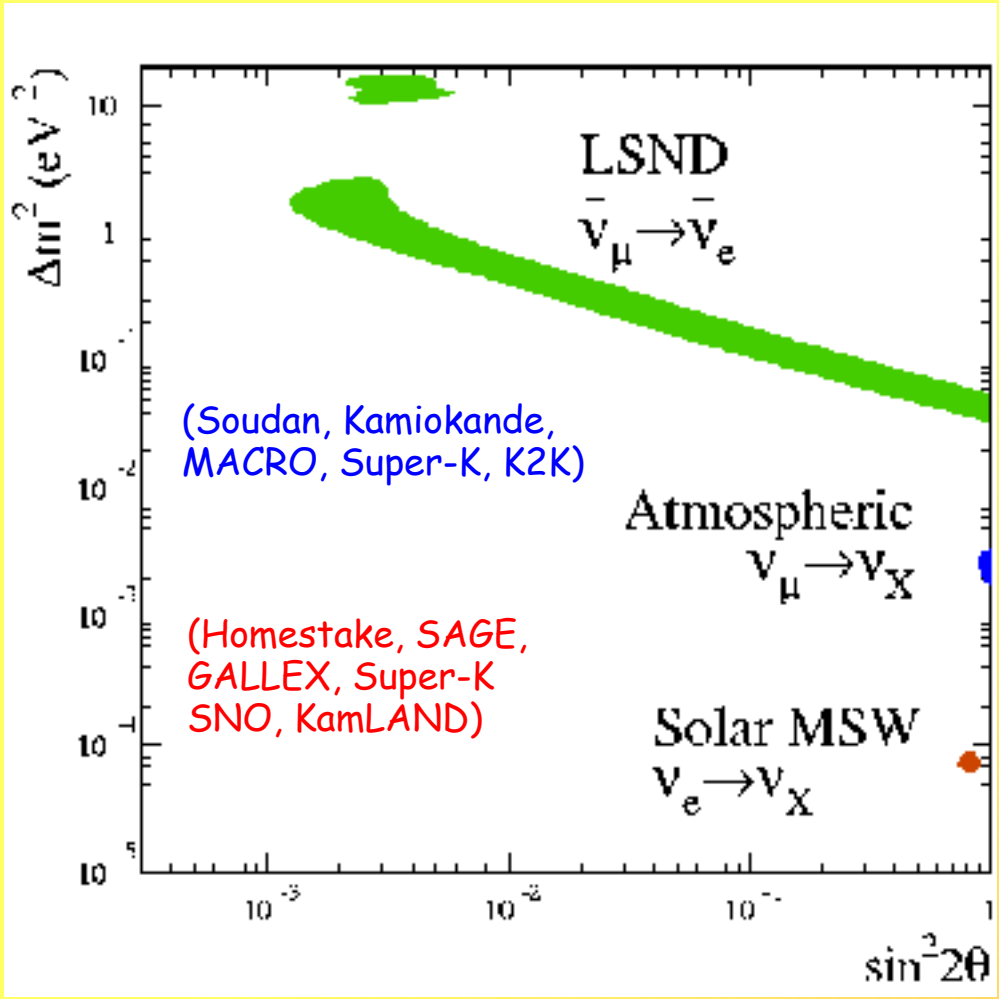
- Proton flux ~ 6×10^{16} p/hr (goal is 9×10^{16} p/hr)
  - ~ 1 detected neutrino/minute
  - L/E ~ 1



First beam in 2002

Motivation for MiniBooNE: LSND

State of the Oscillation Search



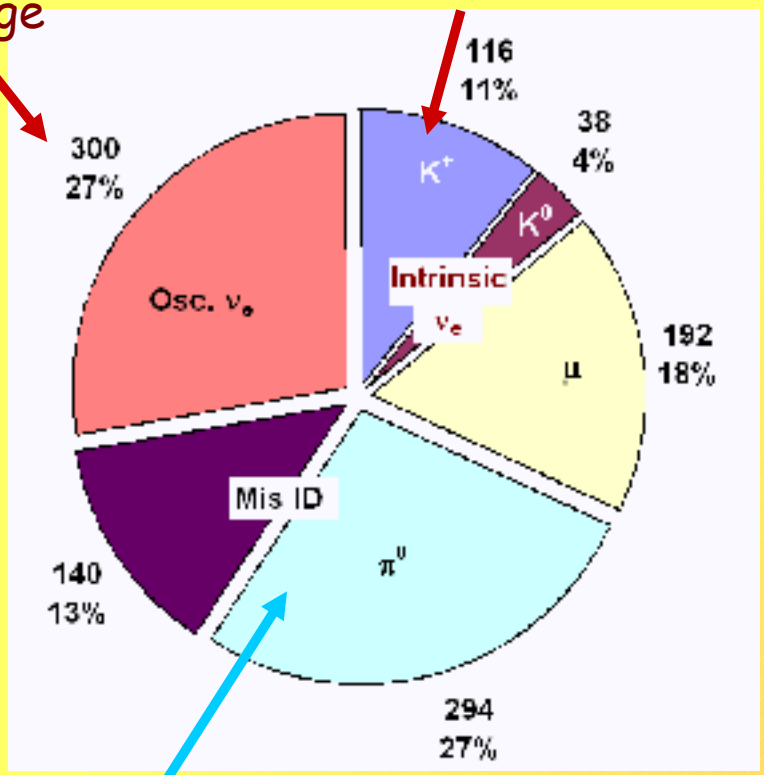
- Simplest model has three neutrino mass eigenstates, but…
- Data indicates 3 mass differences
  - $\Delta m^2_{atm} \sim 2\text{-}3 \times 10^{-3}$ eV^2
  - $\Delta m^2_{sol} \sim 7 \times 10^{-5}$ eV^2
  - $\Delta m^2_{LSND} \sim .1\text{-}10$ eV^2
- Must verify LSND
  - MiniBooNE

MiniBooNE Event Rates

Contributions to ν_e Signal

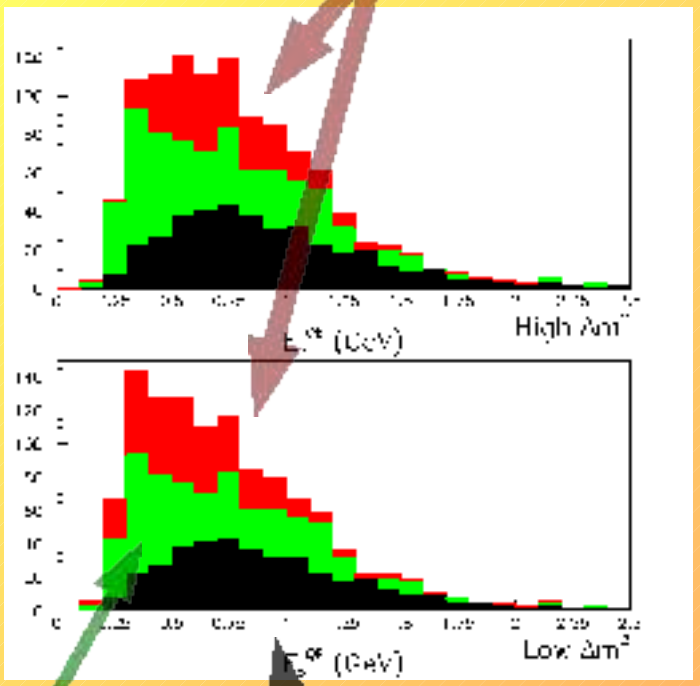
Hope LMC+HARP will help with K background

Signal: Based on LSND average



Can be constrained with data

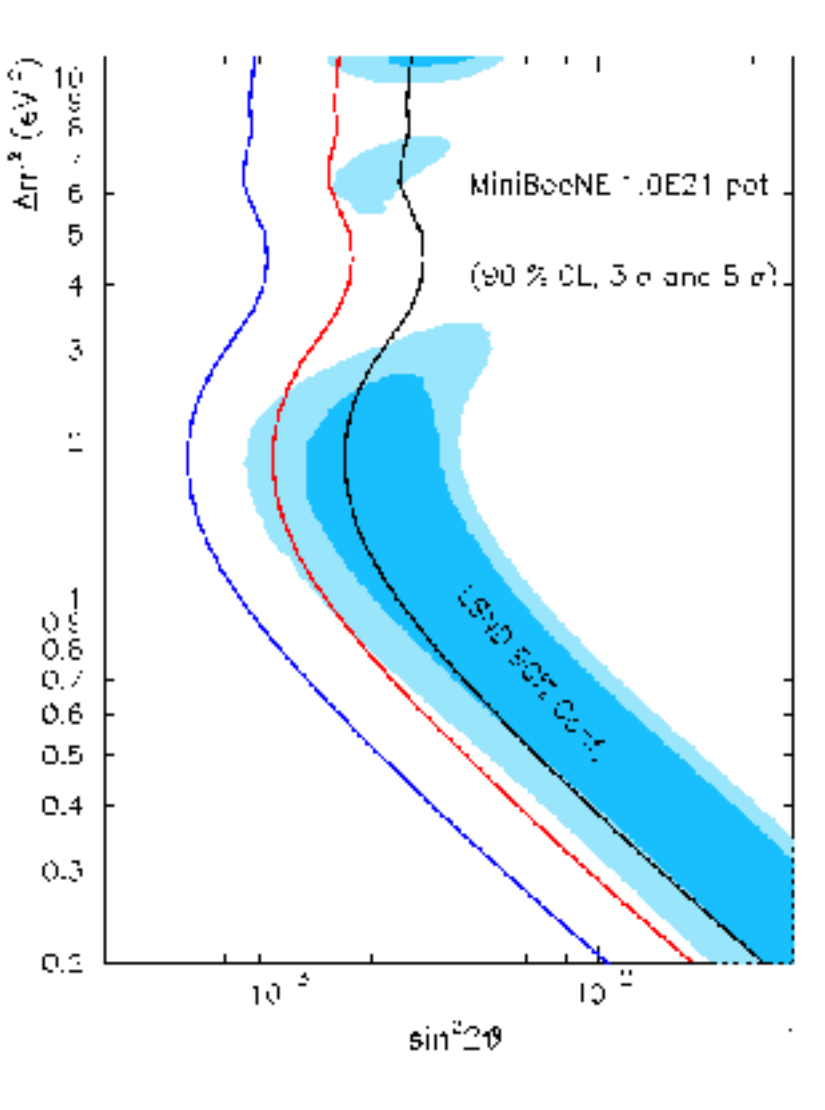
ν_e Signal

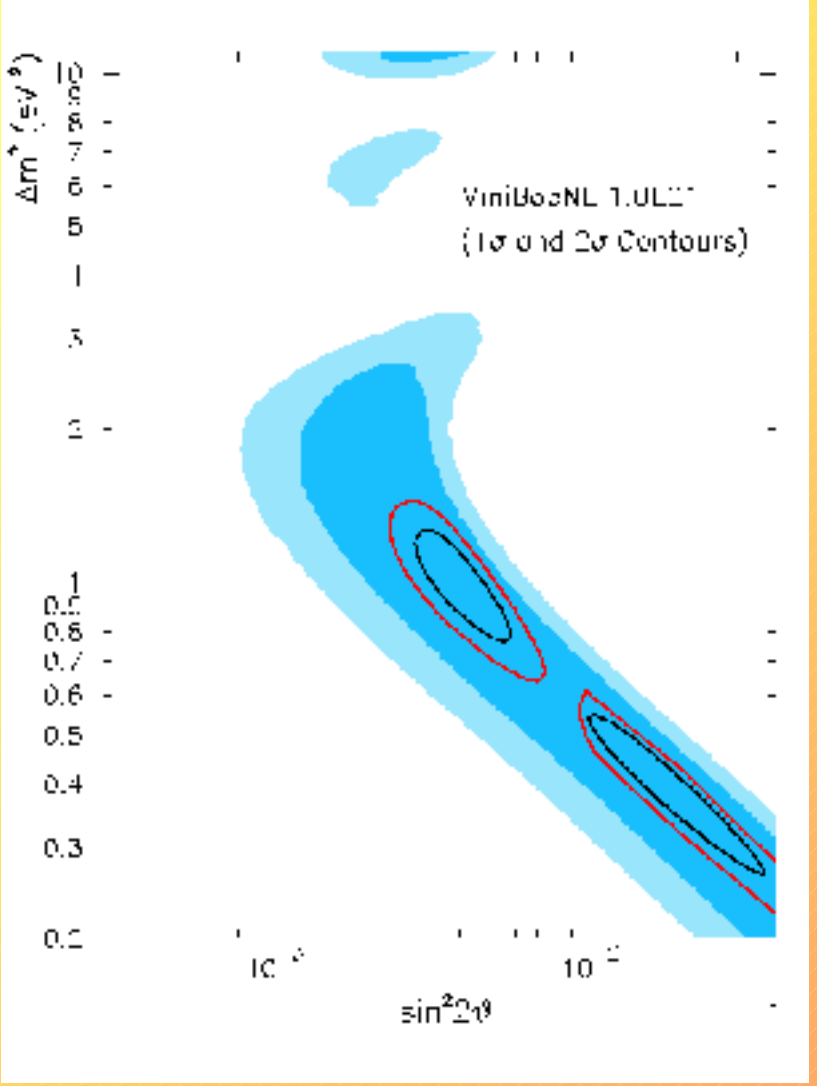


intrinsic ν_e background

π0 background

MiniBooNE Sensitivity (1 x 10^{21} POT)





- No signal
  - Can exclude most of LSND at 5σ
- Signal
  - Can achieve good Δm^2 separation

The MiniBooNE Horn

- Horn failed after almost 100 million pulses
  - Previous horn records .5Hz and 12M pulses
- ✸ March, 2004: Horn developed an internal water leak
  - Collected water and continued to run
- ✸ July 24th, 2004: Horn began to ground-fault
  - ~600 Amps (out of 170,000) to ground
- ✸ Conclusion
  - Cannot safely run horn in this state.
  - Horn (way) too hot to repair.
  - Will run with horn OFF until Fall shutdown (starts August 23rd)
    - Useful for systematics
  - Will replace horn with a spare during shutdown.

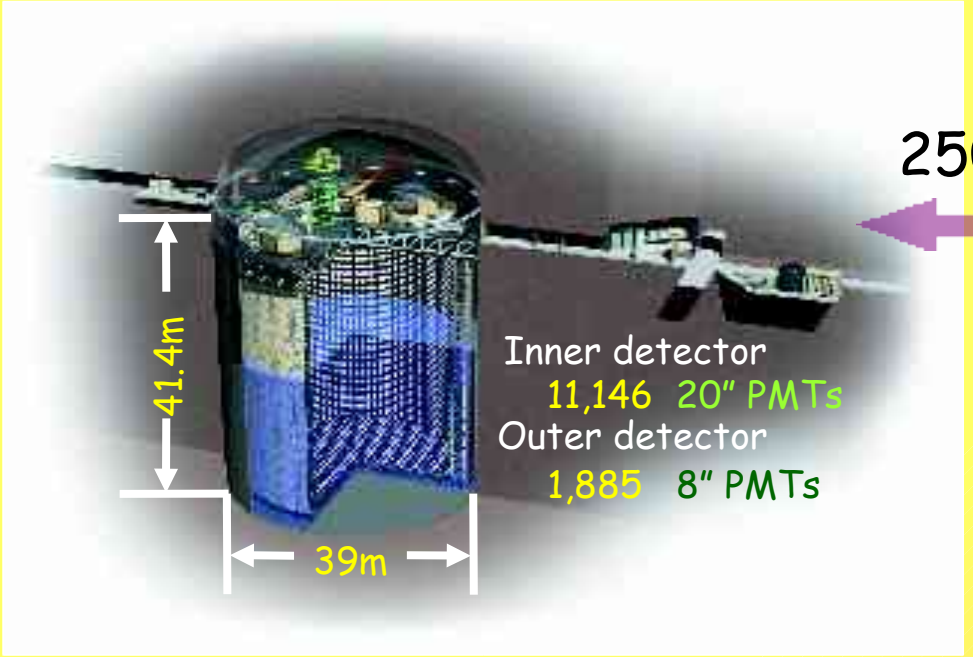
MiniBooNE Summary

- ★ MiniBooNE has collected 3.5 x 10^{20} protons
- The experiment has made impressive progress in understanding both the detector and the data.
- Fermilab is about to go into a 13 week shutdown, during which…
  - The MiniBooNE horn will be replaced.
  - Improvements will be made to the Booster, which should allow it to achieve the MiniBooNE intensity goals
- NuMI will start in early 2005, BUT MiniBooNE should be able to continue taking data, albeit at a reduced intensity
  - 5 x 10^{20} proton by early 2005
  - 1 x 10^{21} somewhere between mid-2006 and mid-2007
- Will not release ν_e appearance result before 5 x 10^{20}, but other physics along the way, e.g.
  - NC π^0 cross-section
  - ν_μ disappearance result

K2K-I Mar.1999 ~ Jul.2001

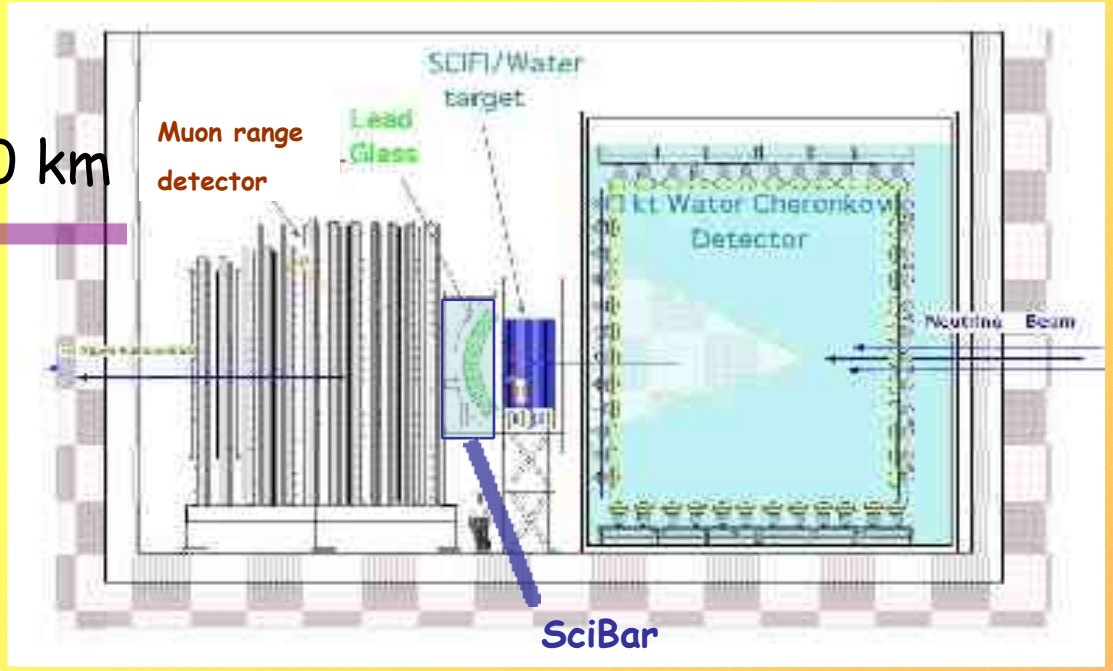
First Long Base-line Experiment

Super-Kamiokande I



250 km

Near neutrino detectors



K2K-II After the successful resume of the experiment Dec.21,2002~

Super-Kamiokande II

- Inner detector

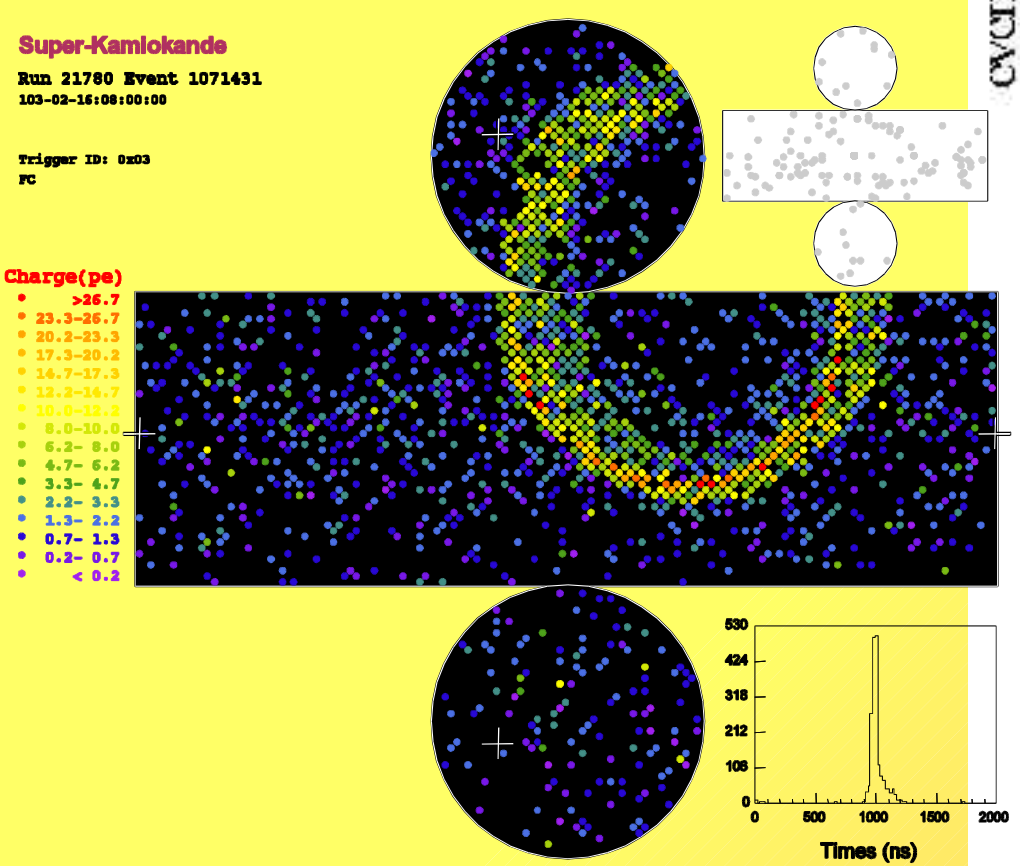
  5,182 PMTs with FRP+Acrylic cover
- Outer detector :1,885 PMTs

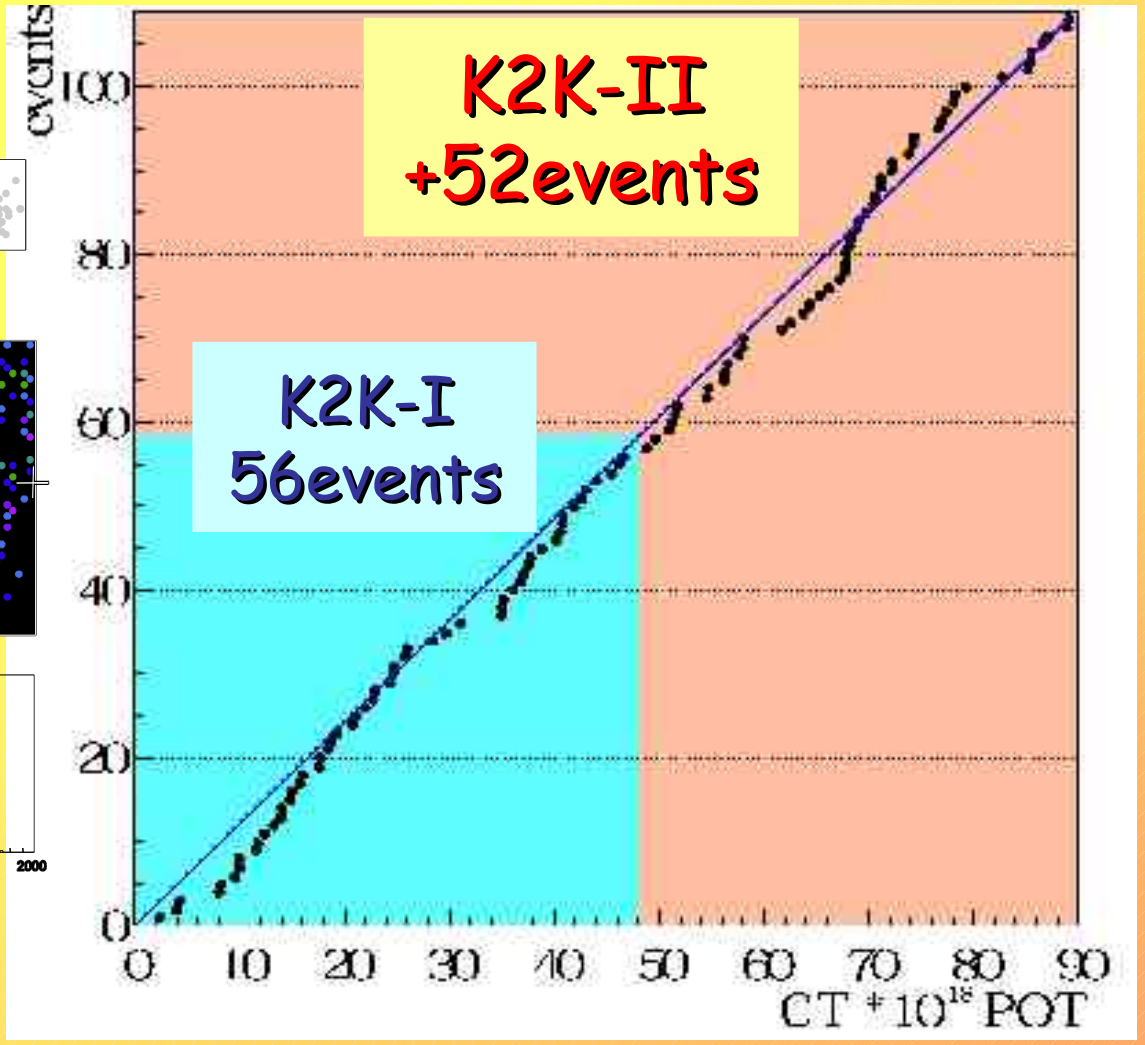
Upgraded near neutrino detectors

- Remove Lead Glass detector to explore lower energy region
- **SciBar** , full-active Scinti. detector (Sept.2003~)

First beam in 1999

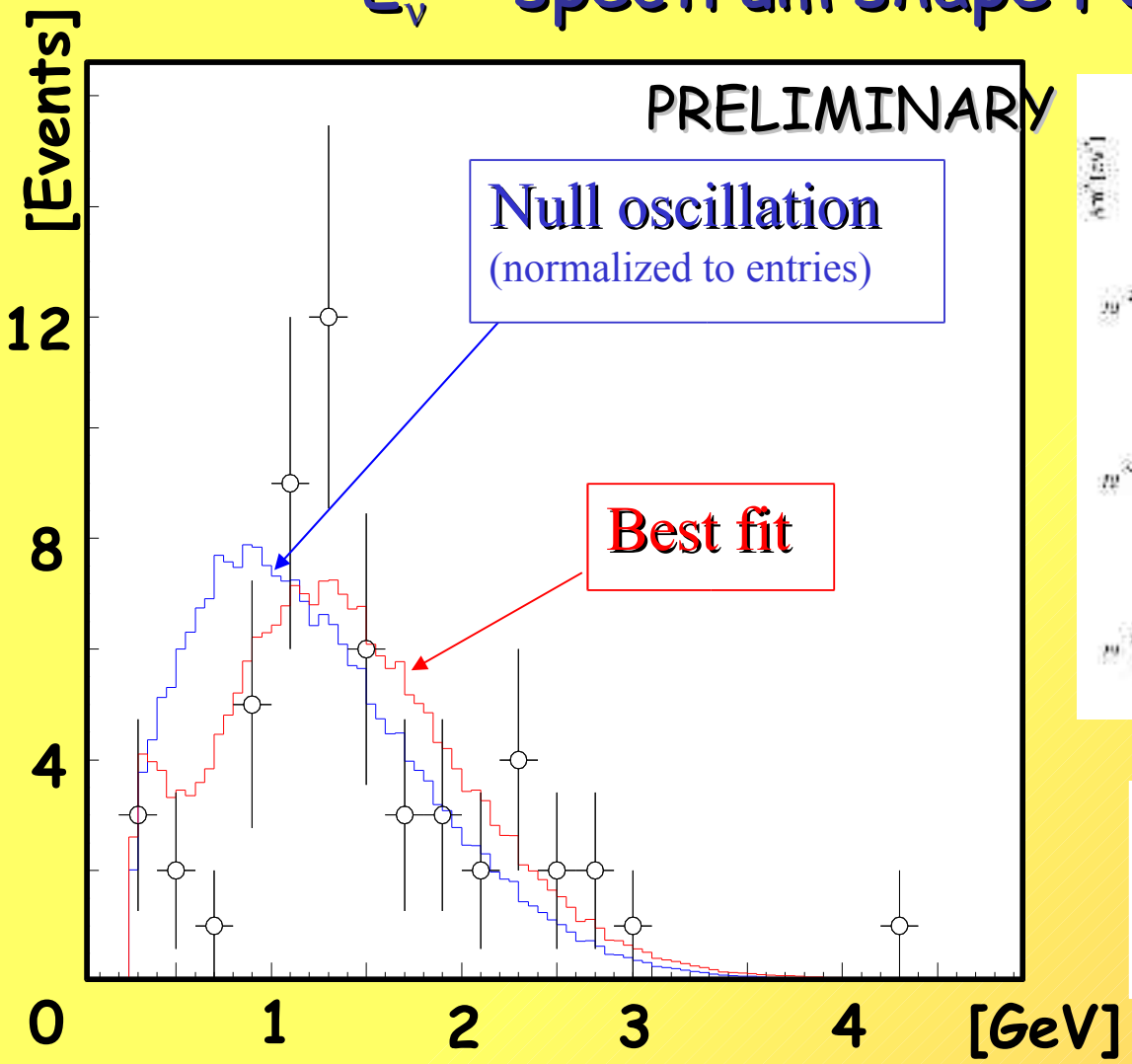
Super-Kamiokande In-Fiducial Events
(Jun.1999~Feb.2004)

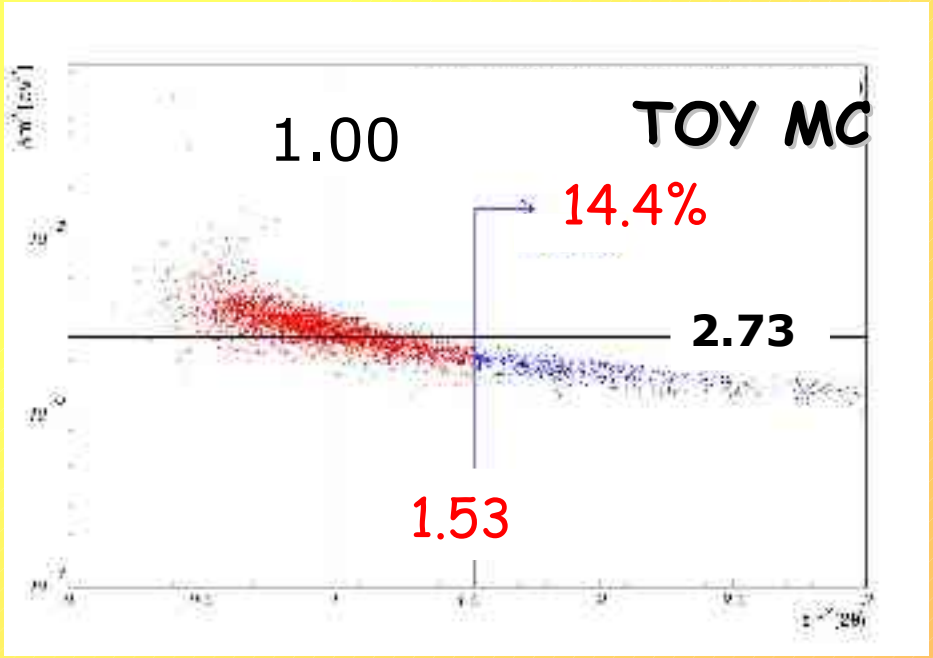




Event rate ([Observed # of events] / [POT]) for K2K-II consistent with K2K-I

E_ν^{rec} spectrum shape FC-1Rμ events





- N_{SK}^{exp} (best fit)=104.8
- N_{SK}^{obs}=108

Best fit in physical region

$(\sin^2 2\theta, \Delta m^2) = (1.00, 2.73 \times 10^{-3})$

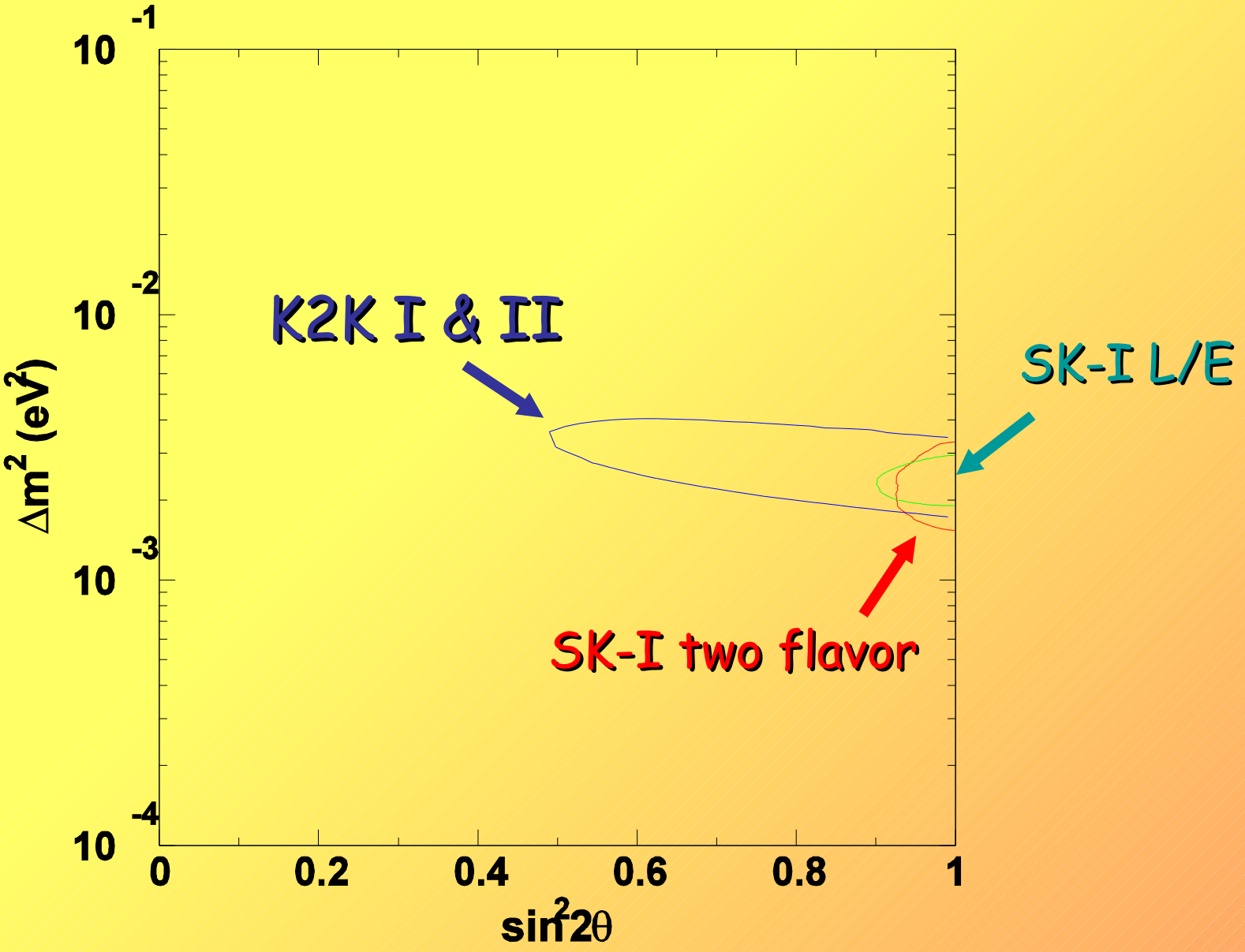
global best fit = $(1.53, 2.12 \times 10^{-3})$

$\Delta \log L = 0.64$

Best fit matches data

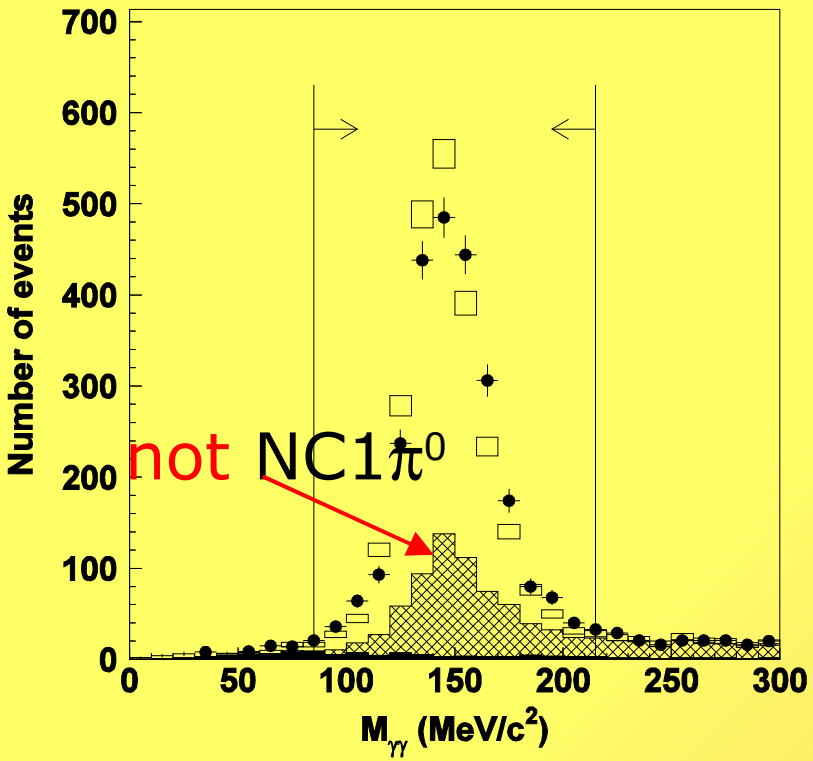
[KS prob.=52%] (shape)

ν_μ-ν_τ oscillation 90% C.L. regions

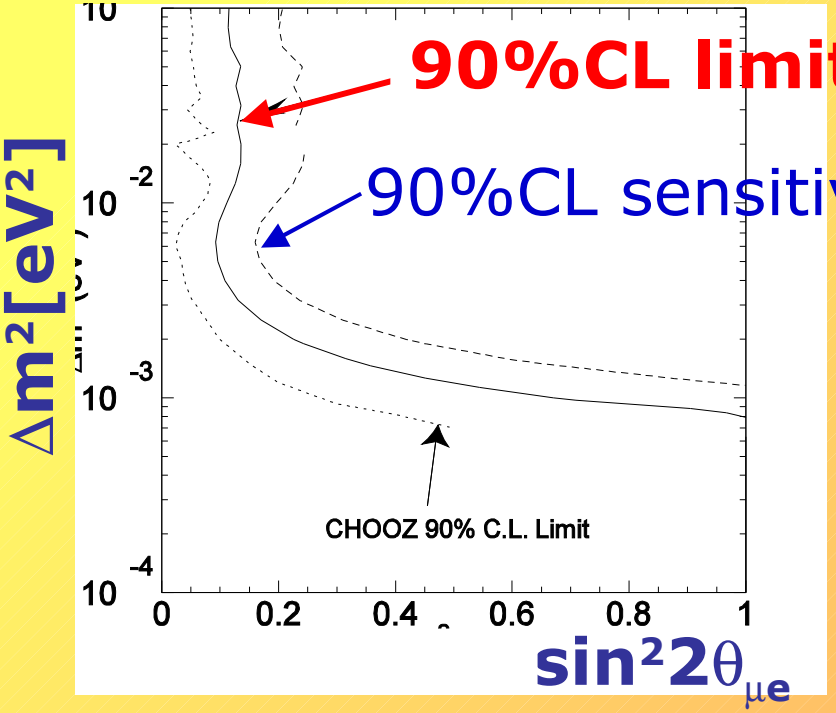


Other K2K Physics

$\nu_\mu + H_2O \rightarrow NC1\pi^0$



$\nu_\mu \rightarrow \nu_e$ **search**



$$\frac{\sigma\left(\nu_\mu \rightarrow NC\,1\,\pi^{\,0}\right)}{\sigma\left(\nu_\mu \rightarrow CCall\right)} = 0.065 \pm 0.001 \pm 0.007$$

$=0.064$ (prediction)

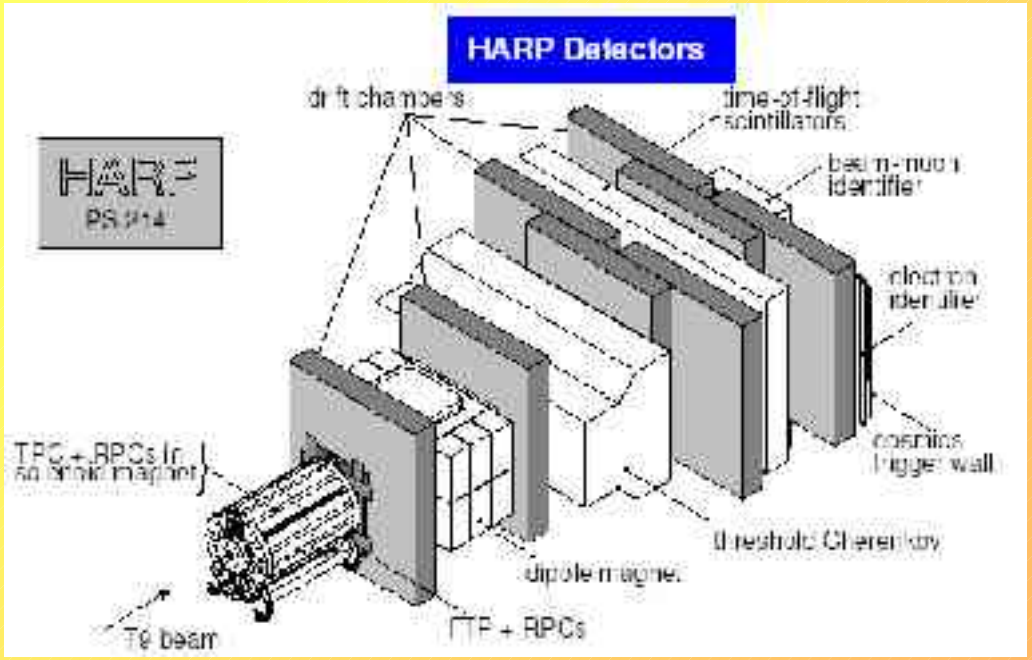
preliminary

K2K Status

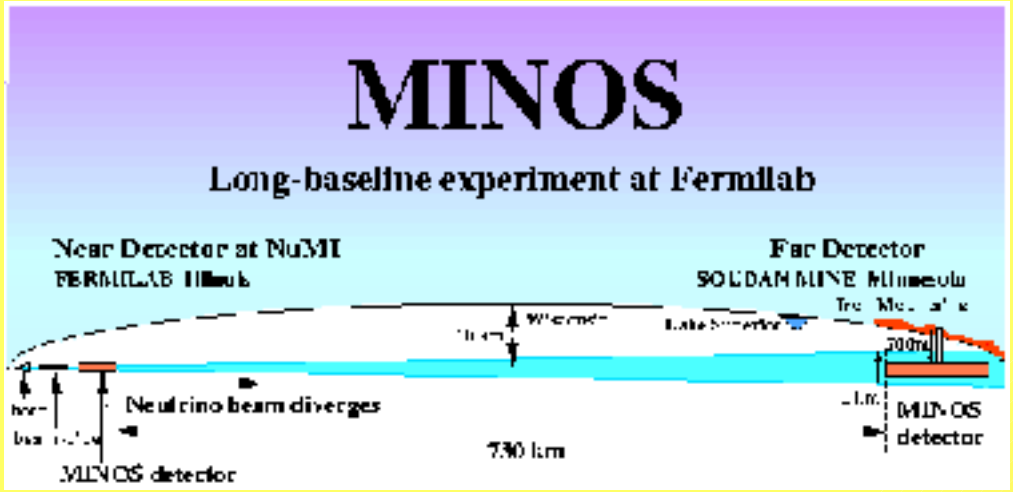
- K2K results include data through February '04 (8.9×10^{19} p.o.t.)
  - 108 FCFV events at SK.
- Oscillation analysis
  1. Both SK rate and E_ν^{rec} shape are consistent oscillation parameter region.
  2. Null oscillation probability = **0.011%** (3.9σ significance)
  3. $\Delta m^2 = 1.7 \sim 3.5 \times 10^{-3} eV^2$ for $\sin^2 2\theta = 1$ @ 90%CL
  4. $\sin^2 2\theta$, Δm^2 consistent with atmospheric neutrino results.
- Data taking will resume in October
  - 10^{20} protons on target for analysis

The HARP Experiment

- A systematic study of secondary hadron production (P_{beam} = 1.5 – 15 MeV/c)
- Goals are to provide
  - input to predict the neutrino fluxes for K2K and MiniBooNE
  - input for the prediction of atmospheric neutrino fluxes
  - π/K yield for design of neutrino factory



MINOS : Overview





High intensity ν_μ beam from Fermilab to Soudan (Mn)

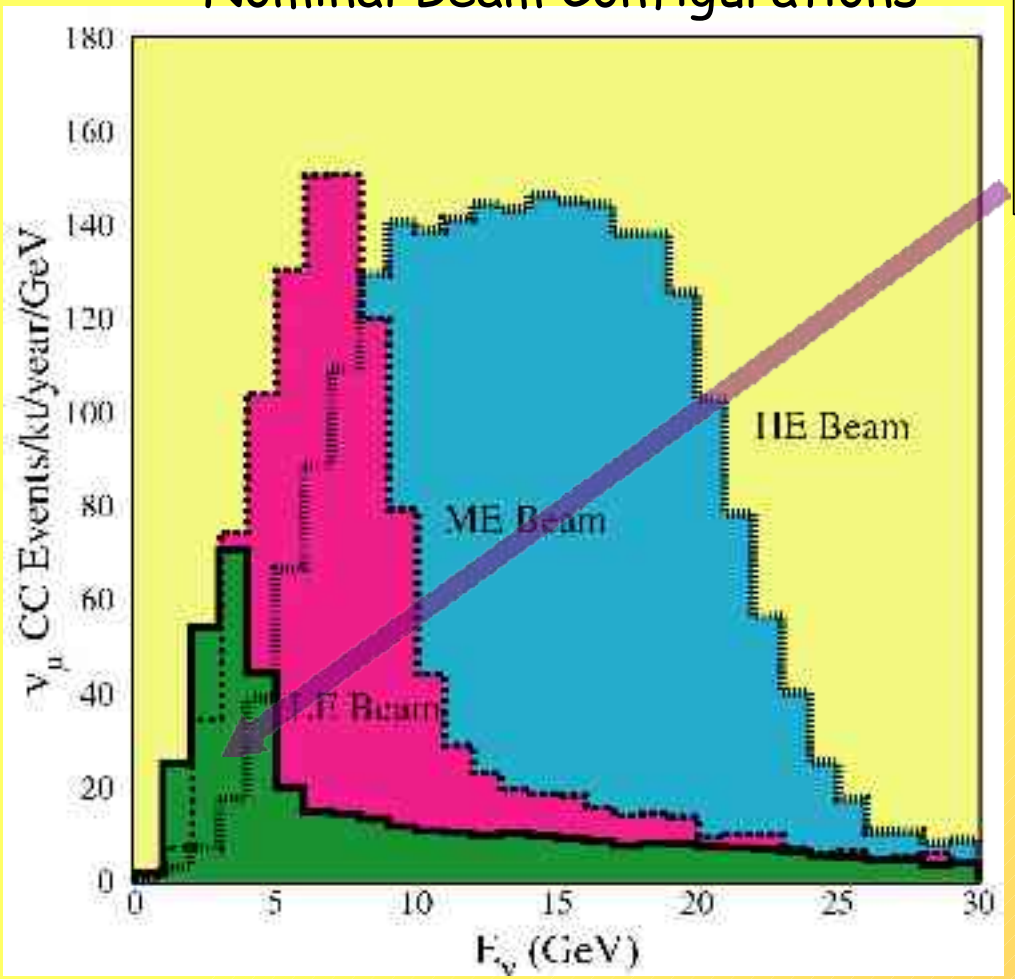
Two detectors, Near (1kT) and Far (5.4kT)

Primary measurement : Compare ν energy spectrum in the Far Detector to the un-oscillated expectation from the Beam and Near Detector

- Observe oscillation minimum
- Confirm oscillatory behaviour in ν_μ sector
- Measure Δm_{23}^2 to ~10%
- Look for evidence of $\nu_\mu \rightarrow \nu_e$ oscillations

NUMI Beam - Configurations

Nominal Beam Configurations



Beam energy can be tuned by adjusting position of 2nd horn relative to target

LE beam best match for $\Delta m^2 \sim 2\text{-}3\ 10^{-3}\ eV^2$

Both ν_μ and $\overline{\nu}_\mu$ beams - $\overline{\nu}_\mu$ later running

First beam will be in December 2004

Beam turns on with $2.5\ 10^{20}$ protons/year

Studies in progress to improve on this

ν_μ CC Events/year

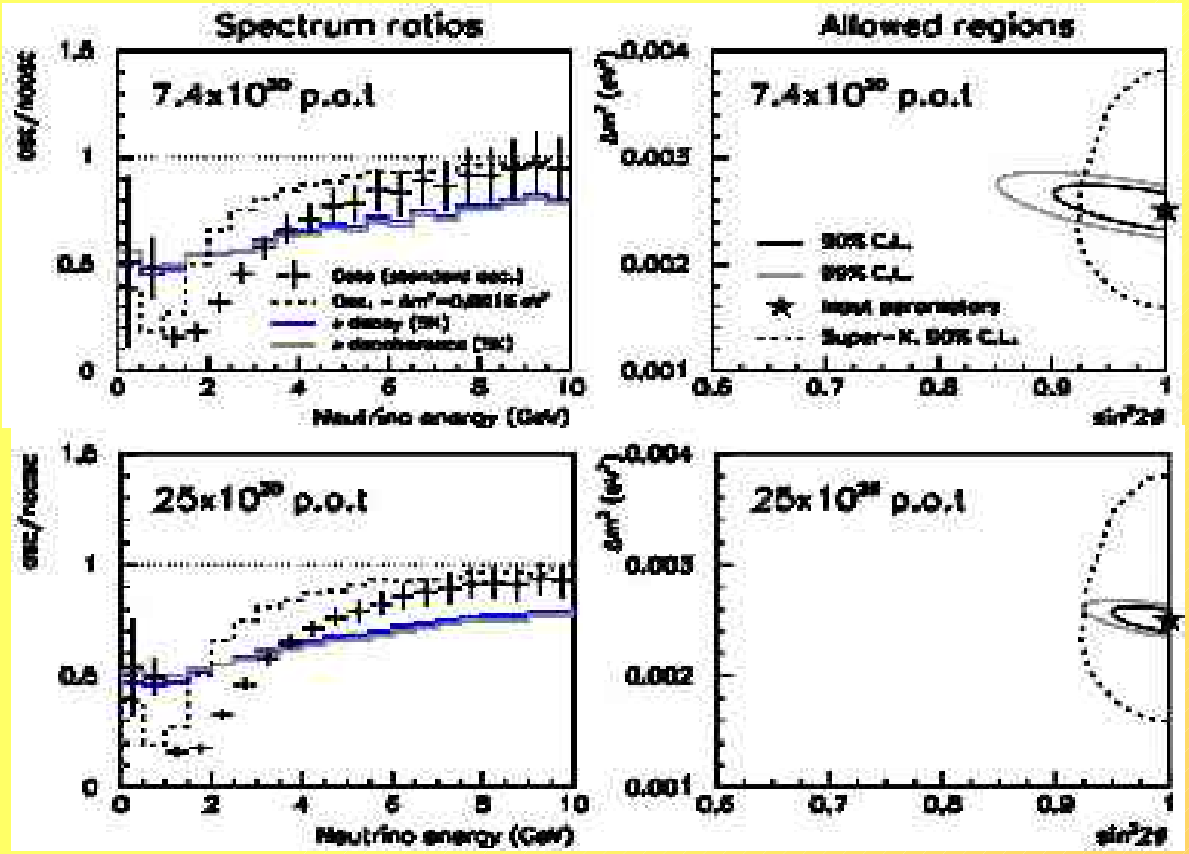
(with no oscillations)

Low	Medium	High
1,600	4300	9250

MINOS Sensitivity

Sensitivity for two exposures

($\Delta m^2 = 2.5\ 10^{-3} eV^2$, $\sin^2 2\theta = 1.0$)



ν_μ CC events

Reconstruct ν_μ energy

$E_\nu = p_\mu + E_{had}$

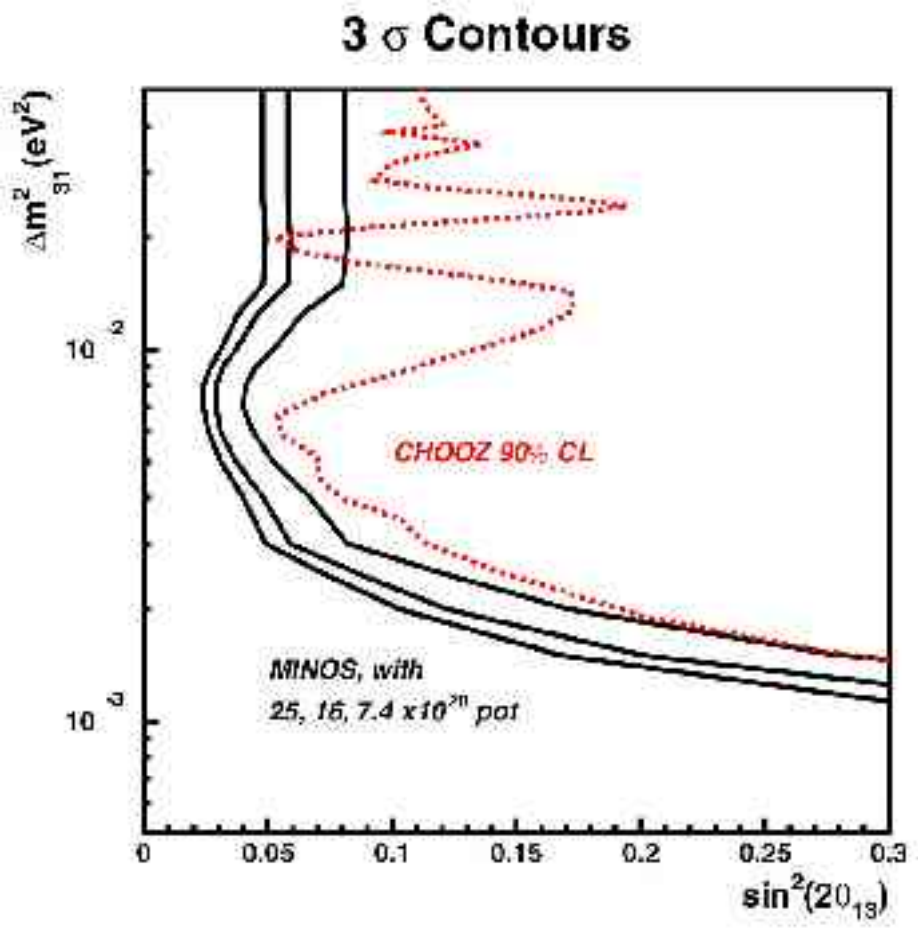
Compare observed energy spectrum at Far Detector with un-oscillated expectation from Near Detector and Beam.

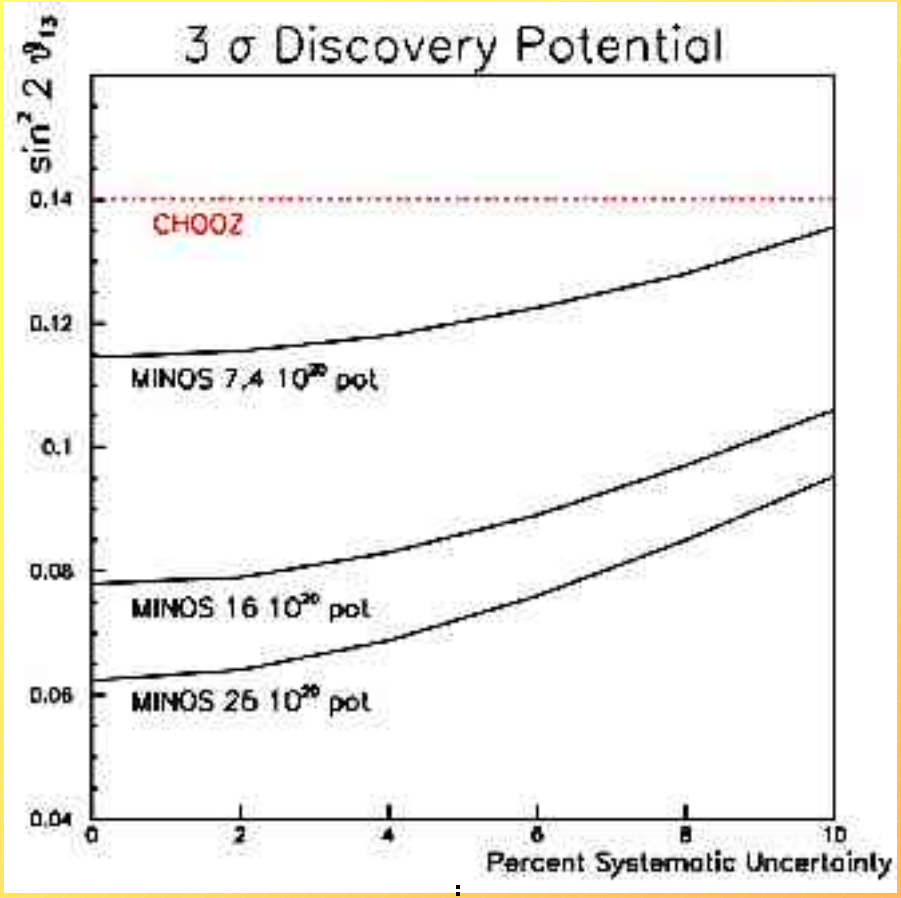
Direct measurement of L/E dependence

Observe oscillation minimum

sin22θ , Δm2 measurement from depth and position of oscillation minimum

MINOS ν_e Appearance



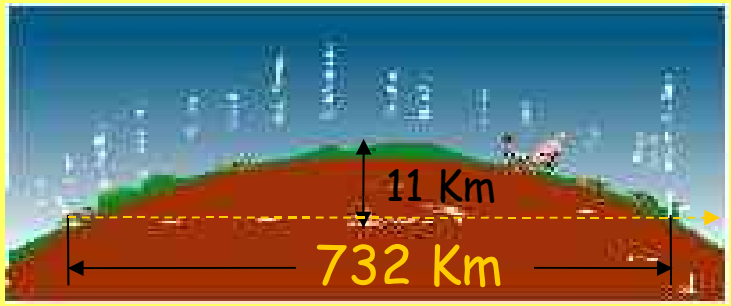


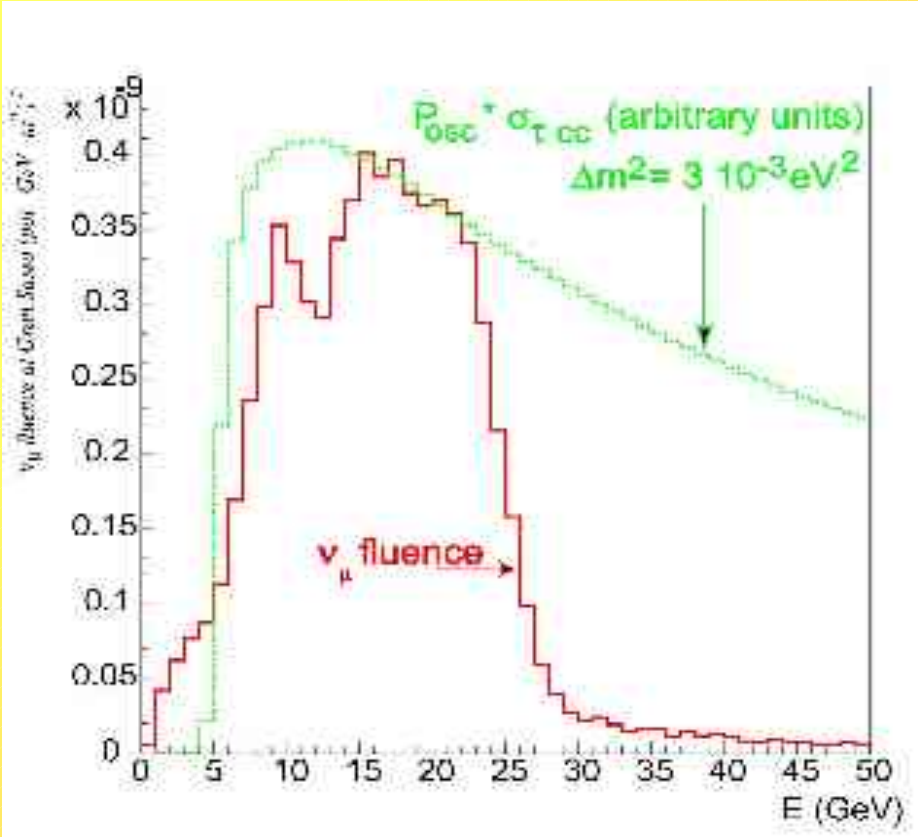
- Can improve on CHOOZ limit
- Chance of measuring θ_{13} !
- Reach is much improved with more protons

MINOS Summary

- NUMI beam installation well advanced and on schedule
- Minos Near Detector nearing completion
  - Final plane of detector installed Aug 11, 2004!
- Minos Far Detector fully operational
  - Data taking since first planes installed, August 2001
  - Routine physics quality data taking since mid 2003
  - Cosmic ray / atmospheric neutrino studies under way
  - First direct observation of separated atmospheric neutrinos
- MINOS in good shape
  - Protons on target in December 2004
  - First beam physics runs early 2005

CERN Neutrinos to Gran Sasso





400 GeV proton beam

4.5 x 10^{19} protons/year

(7.6 x 10^{19} dedicated mode)

200 days/year, ε = 55%

$(\nu_e+\overline{\nu_e}) / \nu_\mu$	0.85 %
$\overline{\nu_\mu} / \nu_\mu$	2.1 %
ν_τ negligible	

CNGS beam optimized for τ appearance:

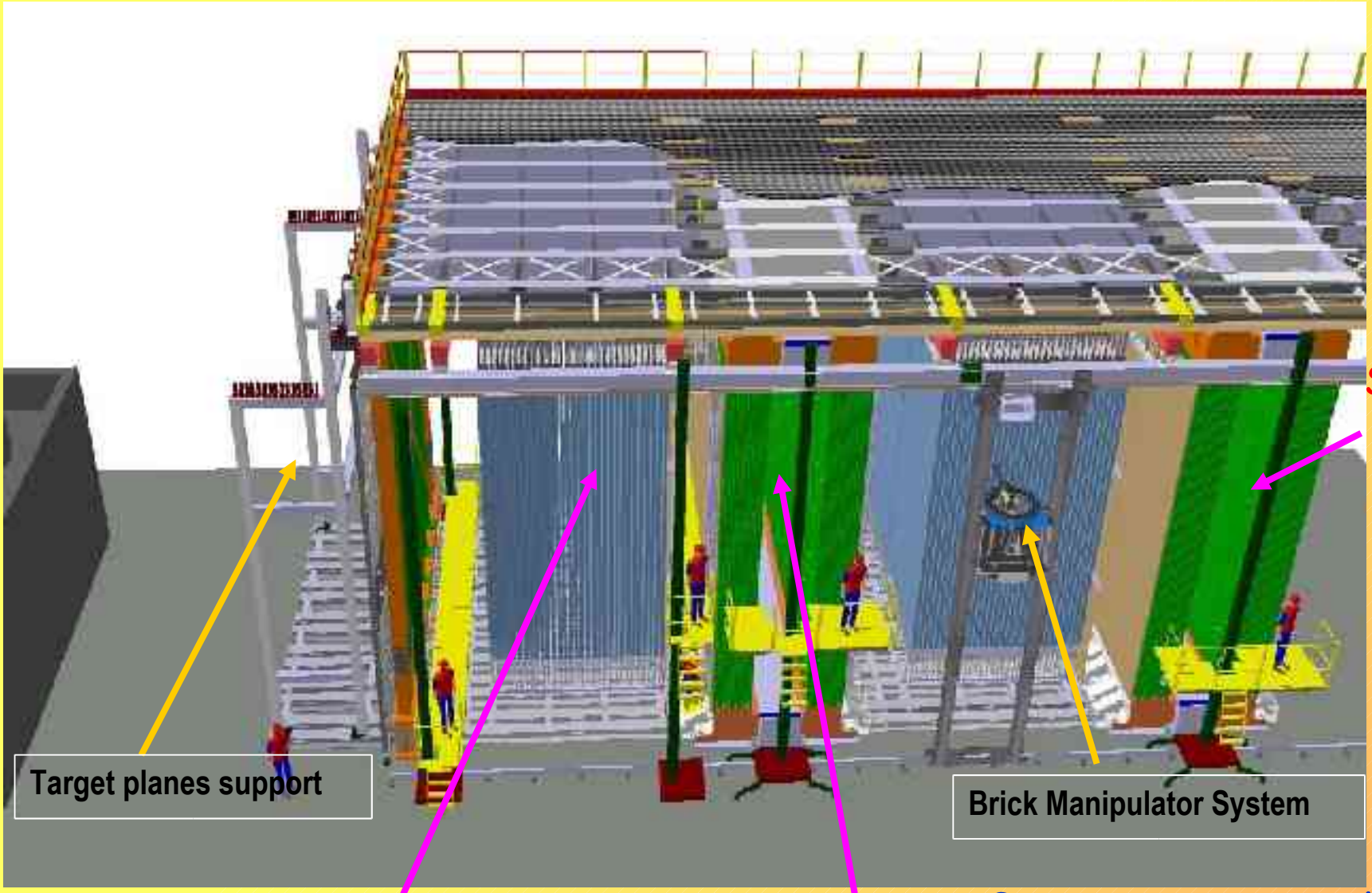
$\langle E_\nu \rangle$ = 17 GeV



CNGS horns (Orsay)

At 732 km in OPERA: 6200 ν_μ CC+NC /year expected + 27 ν_τCC/year (Δm^2= 2.4 10^{-3} eV^2)

The OPERA Detector



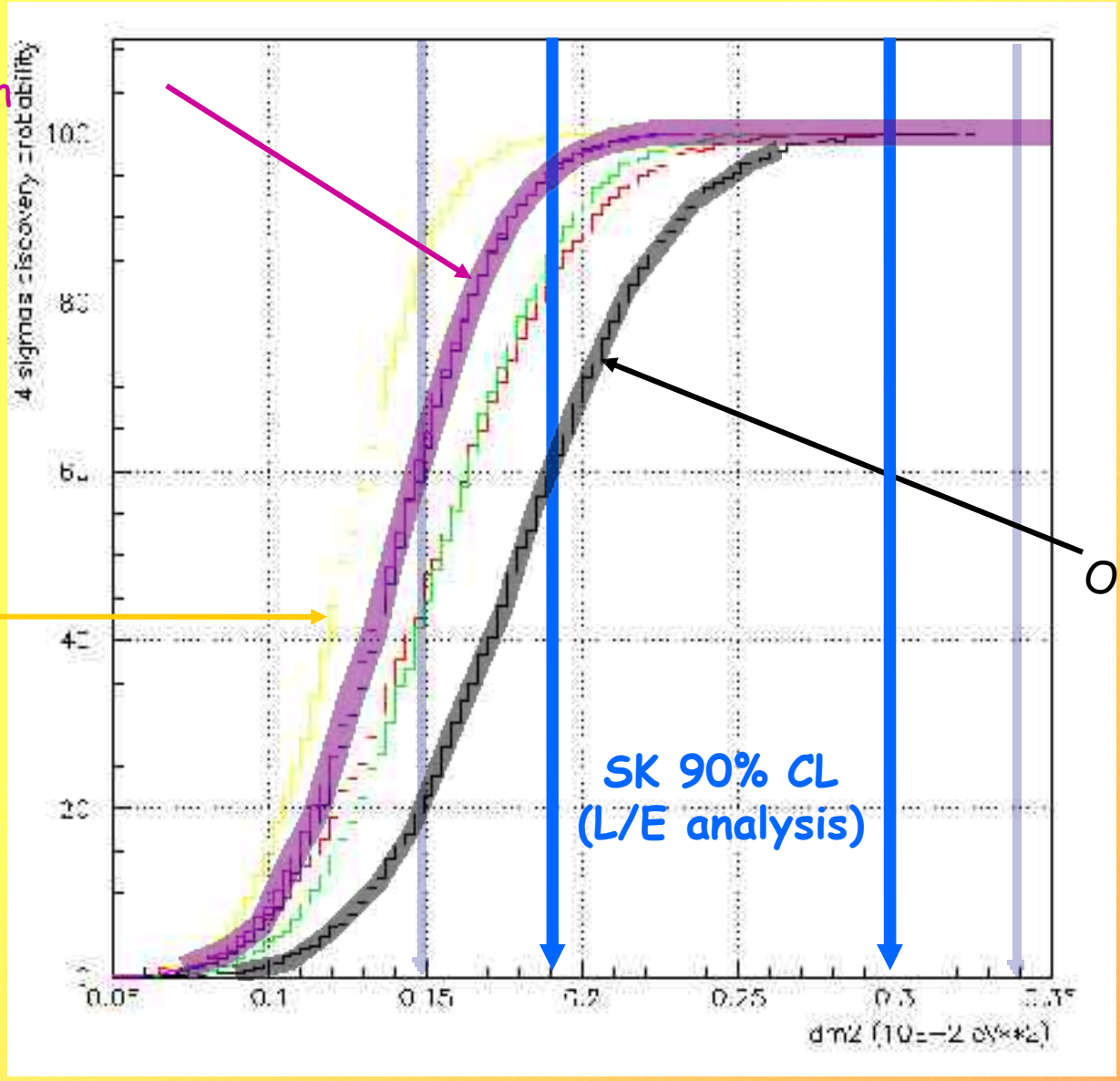
SM2 magnet complete in April 2005

Target sections: installation starts September 2004

Spectrometer sections: installation started May 2003
SM1 magnet complete June 2004

Sensitivity versus Beam Intensity

Opera with beam x1.5, possible ε improvements and BKGD reduction



Opera with beam x3

Opera $\nu_\mu \rightarrow \nu_e$ sensitivity

Expected signal and backgrounds assuming **5 years** data taking, nominal CNGS beam and $\Delta m^2_{23}=2.5\times10^{-3}$ **eV**^{2}, $\sin^2 2\theta_{23}=1$

θ_{13}	signal	$\tau\rightarrow e$	ν_μCC	ν_μNC	ν_eCC beam
9°	9.3	4.5	1.0	5.2	18
8°	7.4	4.5	1.0	5.2	18
7°	**5.8**	4.6	1.0	5.2	**18**
5°	3.0	4.6	1.0	5.2	18
Efficiency	0.31	0.032	0.34×10^{-4}	7.0×10^{-4}	0.082

Simultaneous use of $E_{visible}$, $E_{electron}$ and missing P_t

$\sin^2 2\theta_{13}$ limit	θ_{13} limit 90% CL
< 0.06	< **7.1°**
< 0.05 (beam x1.5)	< 6.4°

Sensitivity to θ_{13} has a dependence on δ_{CP} complementary to T2K

OPERA Conclusions

- OPERA is looking for $\nu_\mu \rightarrow \nu_\tau$ oscillations (ν_τ appearance) and $\nu_\mu \rightarrow \nu_e$ oscillations (measurement of θ_{13}) as part of the European long baseline Neutrino program

- The OPERA collaboration since the approval in 2000 accomplished great progress towards the realisation of this large and delicate detector

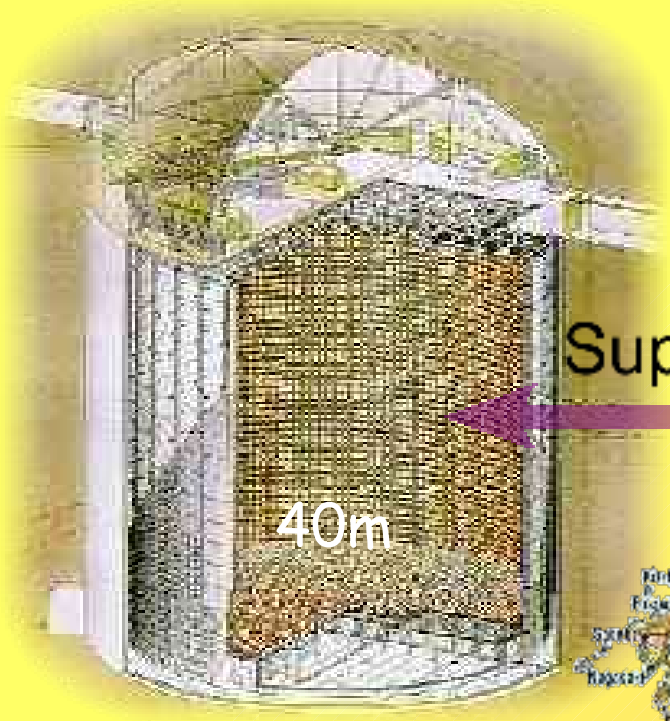
- Work is going on to improve the sensitivity by reducing the background and increasing the efficiency. The expected increase of the beam intensity will have a similar effect to secure the ν_τ appearance observation.

- The CNGS beam and the OPERA experiment will start in 2006

Tokai To Kamioka

295 km from target to SK

J-PARC

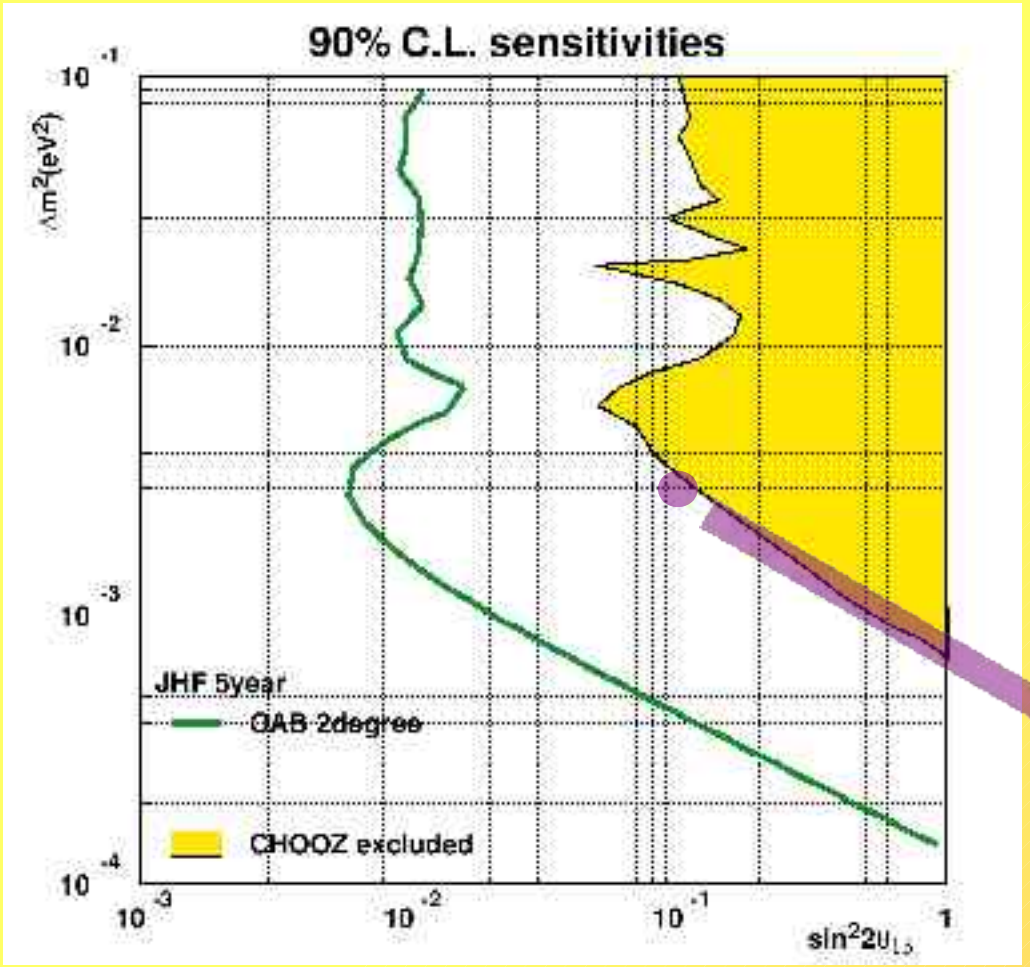




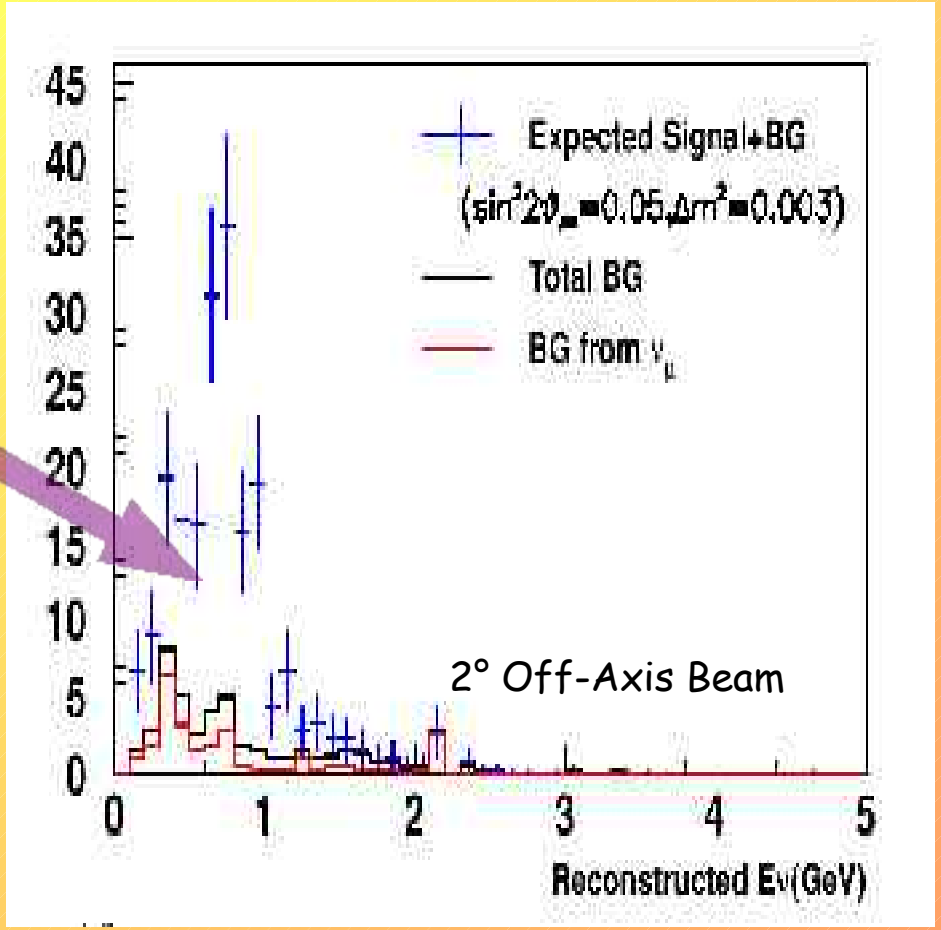


Beam 1° to 3° off axis

T2K ν_e Appearance Sensitivity (θ_{13})



- 10^{21} protons on target
- Background Rejection
- Control Systematics to 10%



- $\sin^2 2\theta_{13} \sim 0.006$ @ $\Delta m^2 = 0.003$
  - @ $\delta = 0$
- $\sin^2 2\theta_{\mu e} \sim 0.003$

NOvA Program

(Off-axis Detector at NuMI)

Goals

- $\sin^2 2\theta_{13}$ sensitivity a factor of 10 better than MINOS (~0.01)
- $\delta(\sin^2 2\theta_{23})$ measured to 2%
- Resolve or contribute to understanding of mass hierarchy via matter effects
- Begin to study CP violation in the neutrino sector

Summary

- First terrestrial confirmation of neutrino oscillations
- More oscillation results expected soon
  - MiniBooNE (~2005)
  - CHORUS oscillation (later this year)
- The next round of experiments starting
  - MINOS: first data very early next year
  - CNGS: first data early next year
- The next generation of experiments are well into the planning stages
  - NOvA, T2K
- Also a strong non-oscillation program (see NUINT)

The End



CHORUS Phase II

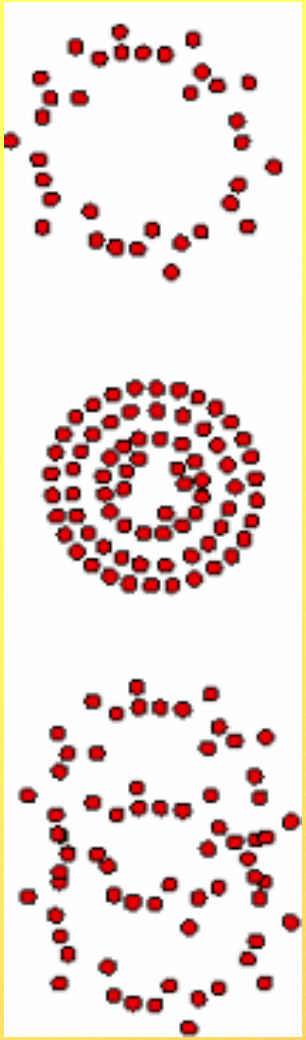
- ✔ New EMULSION data-taking and analysis for
  - Increased sensitivity oscillation search
  - Charm physics
  - Emulsion scanning is complete
- ✔ IMPROVEMENTS:
  - Multi-track predictions (and Scanback) without kinematic cuts
  - Full vertex emulsion data taking (on located vertices)
  - Offline Emulsion Analysis

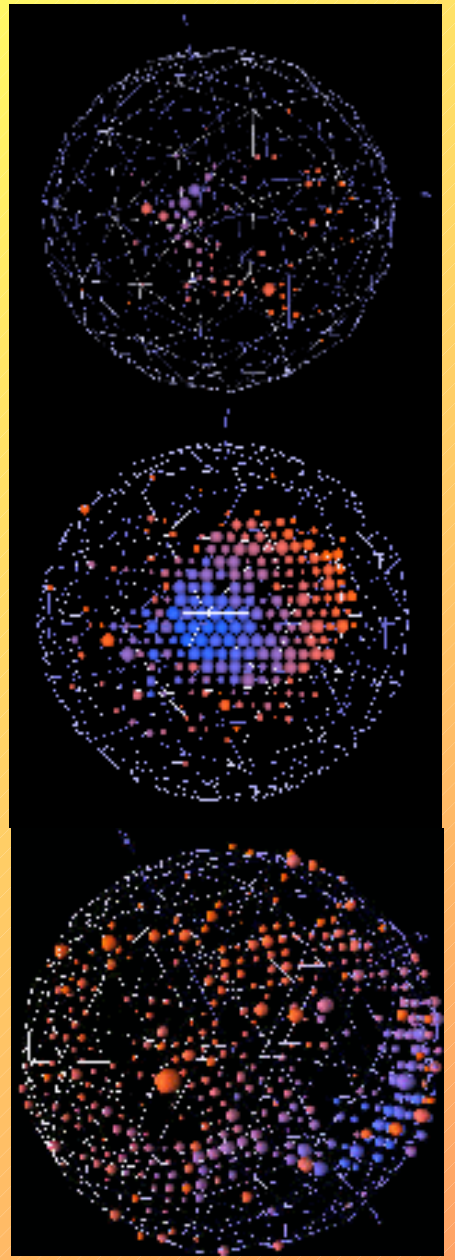
Neutrino Detection/Particle ID

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

$\nu_\mu + n \rightarrow \mu^- + p$

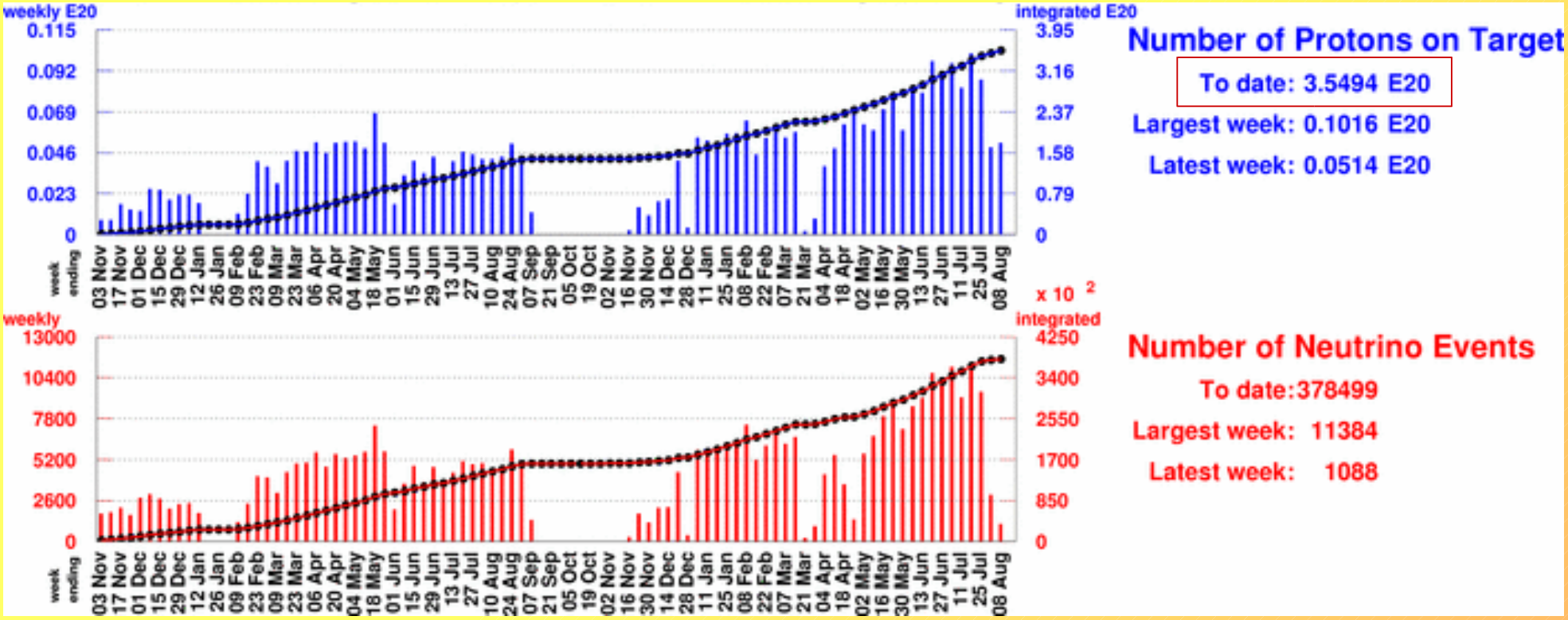
$\nu_\mu + n \rightarrow \pi^0 + n$





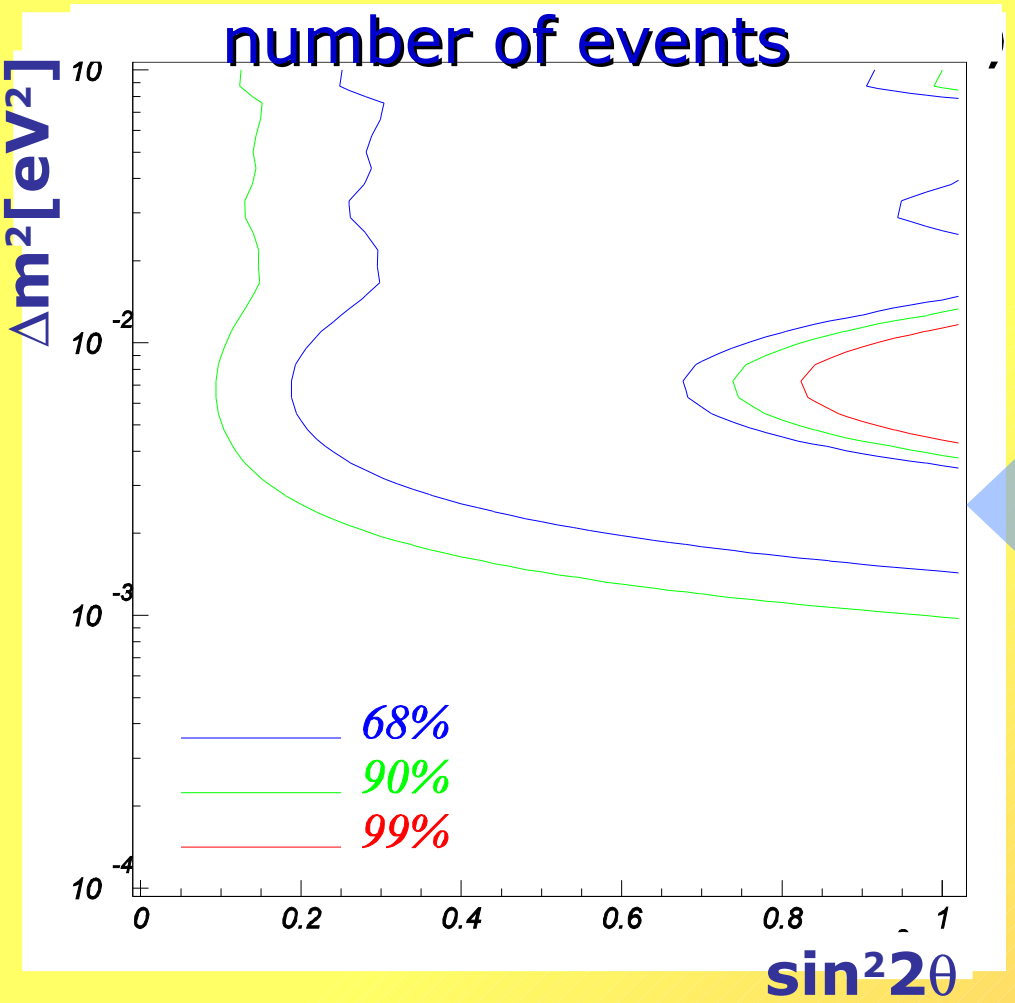
Important Background!!!

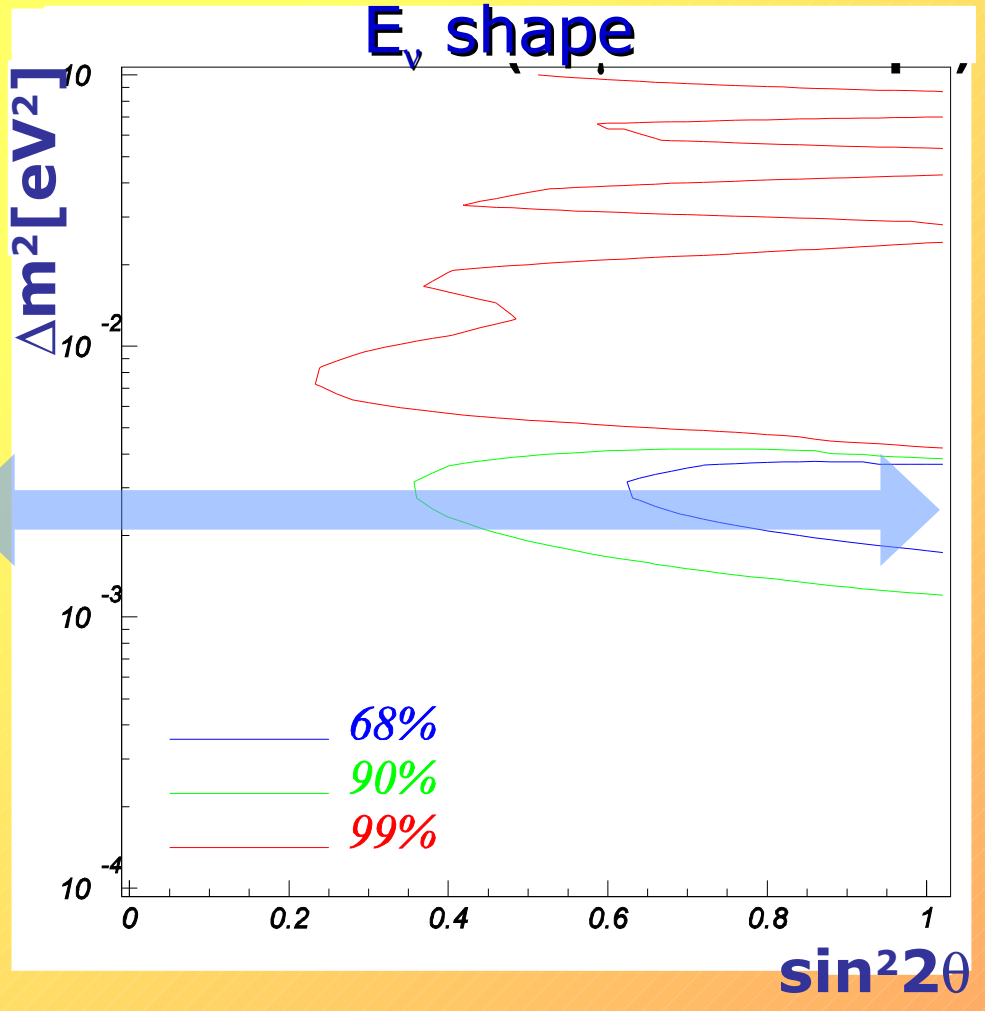
MiniBooNE Progress



- To date: 3.5 x 10^{20} protons on target
- Will collect at least 5 x 10^{20}
- Hope for 1 x 10^{21}

Number of events v.s. E_ν shape

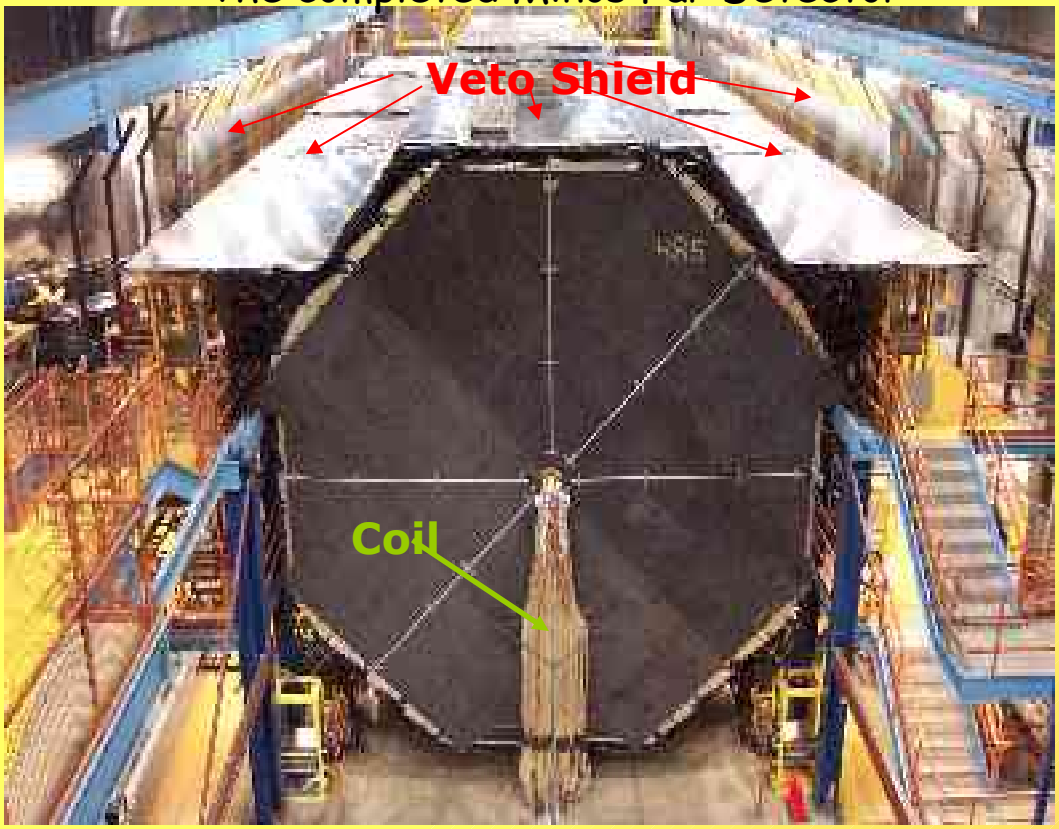




Oscillation analysis results based on number of events and the E_ν spectrum distortion are consistent.

MINOS Far Detector

The completed Minos Far Detector



Data taking since ~ September 2001
Installation fully completed in July 2003.
Atmospheric ν / cosmic μ data sample

5.4 kton magnetised tracking calorimeter, B ~1.5T

484 steel/scintillator planes built in 2 supermodules

2.54cm thick steel, 192 4x1cm scint. strips per plane

- orthogonal orientation on alternate planes – U,V
- optical fibre *readout*

Veto shield covers top/sides for atmospheric ν

Multi-pixel (M16) PMTs read out with VA electronics

- 8-fold optical multiplexing
- chips individually digitised, sparsified & read out when dynode above a threshold
- excellent time resolution – 1.56ns timestamps

Continuous untriggered readout of whole detector

Interspersed light injection (LI) for calibration

Software triggering in DAQ PCs (independent of ND)

- highly flexible : plane, energy, LI triggers in use
- spill times from FNAL to FD trigger farm under dev.

GPS time-stamping to synch FD data to ND/Beam

MINOS Near Detector

Site: Fermilab, ~ 1 km

Minos Near Detector as installation neared completion



Plane installation fully completed on Aug 11, 2004

1 kton (total mass) magnetised tracking calorimeter

Same basic design as Far Detector

Partially instrumented

- 282 steel planes, 153 scintillator planes
- reduced sampling in rear planes (121-281) "spectrometer section" used for muon tracking

High instantaneous ν rate, ~ 20ev/spill in LE beam

No multiplexing except in spectrometer region (4x)

Fast "QIE" electronics

- continuous digitisation on all channels during spill (19ns time-slicing). Mode enabled by spill signal.
- dynode triggered digitisation out of spill (cosmics)

GPS time-stamping / Software triggering in DAQ

- all in spill hits written out by DAQ
- standard cosmics triggers out of spill