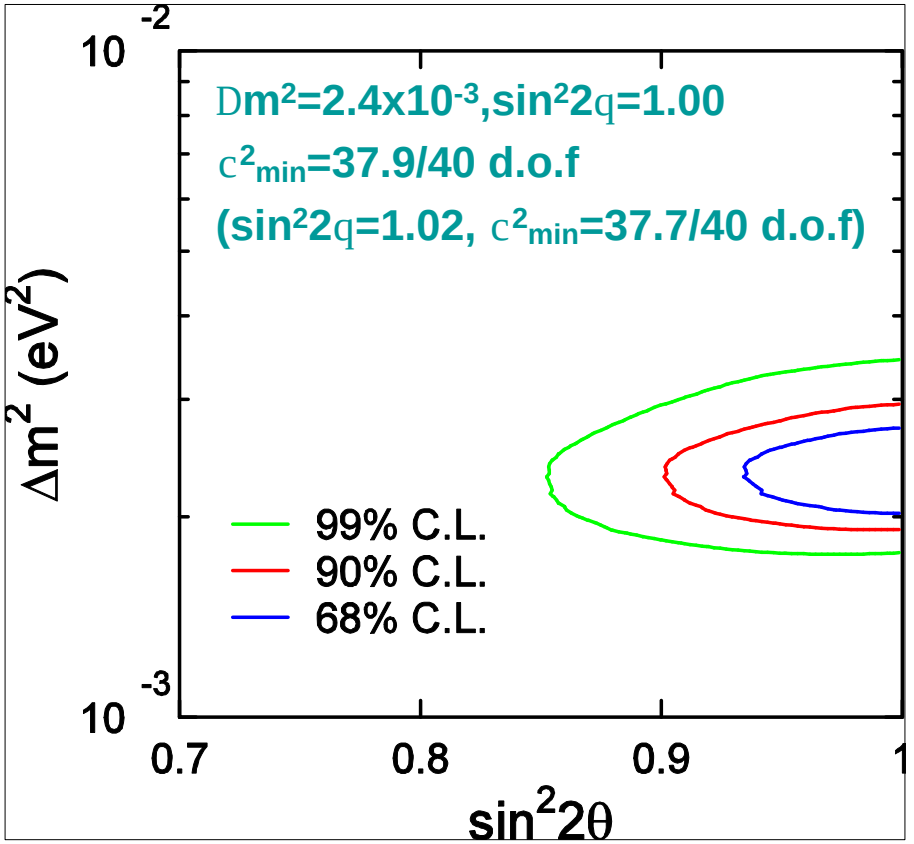
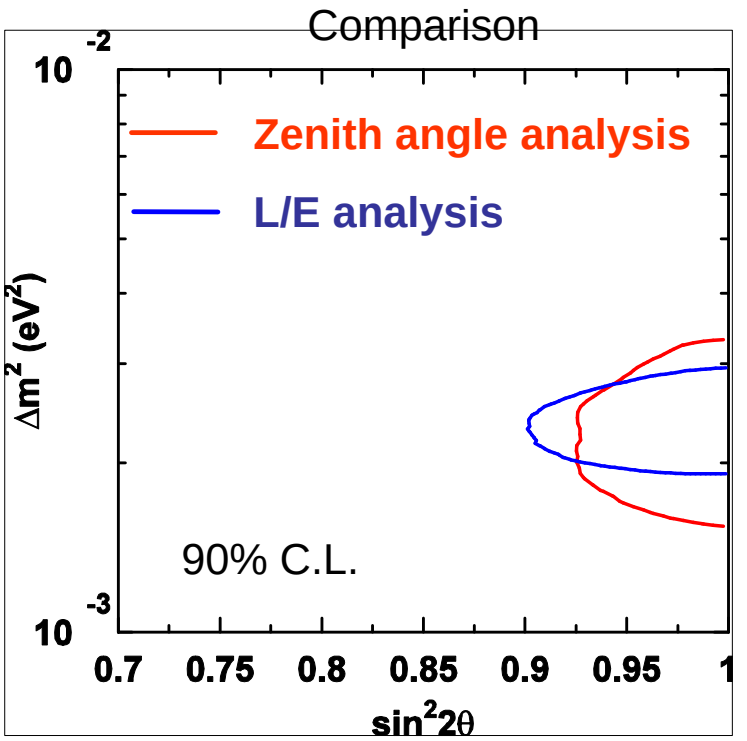
2 flavor neutrino oscillation in SK-1
-- L/E analysis --





$1.9\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}$ eV²
$0.90 < \sin^2 2\theta$ at 90% C.L.

June 15th, 2004
@NEUTRINO2004

New K2K Results

T. Nakaya (Kyoto University)
for K2K collaboration

K2K Collaboration

JAPAN: High Energy Accelerator Research Organization (KEK) / Institute for Cosmic Ray Research (ICRR), Univ. of Tokyo / Kobe University / Kyoto University / Niigata University / Okayama University / Tokyo University of Science / Tohoku University

KOREA: Chonnam National University / Dongshin University / Korea University / Seoul National University

U.S.A.: Boston University / University of California, Irvine / University of Hawaii, Manoa / Massachusetts Institute of Technology / State University of New York at Stony Brook / University of Washington at Seattle

POLAND: Warsaw University / Solton Institute

Since 2002

JAPAN: Hiroshima University / Osaka University **U.S.A.:** Duke University

CANADA: TRIUMF / University of British Columbia

ITALY: Rome **FRANCE:** Saclay **SPAIN:** Barcelona / Valencia **SWITZERLAND:** Geneva

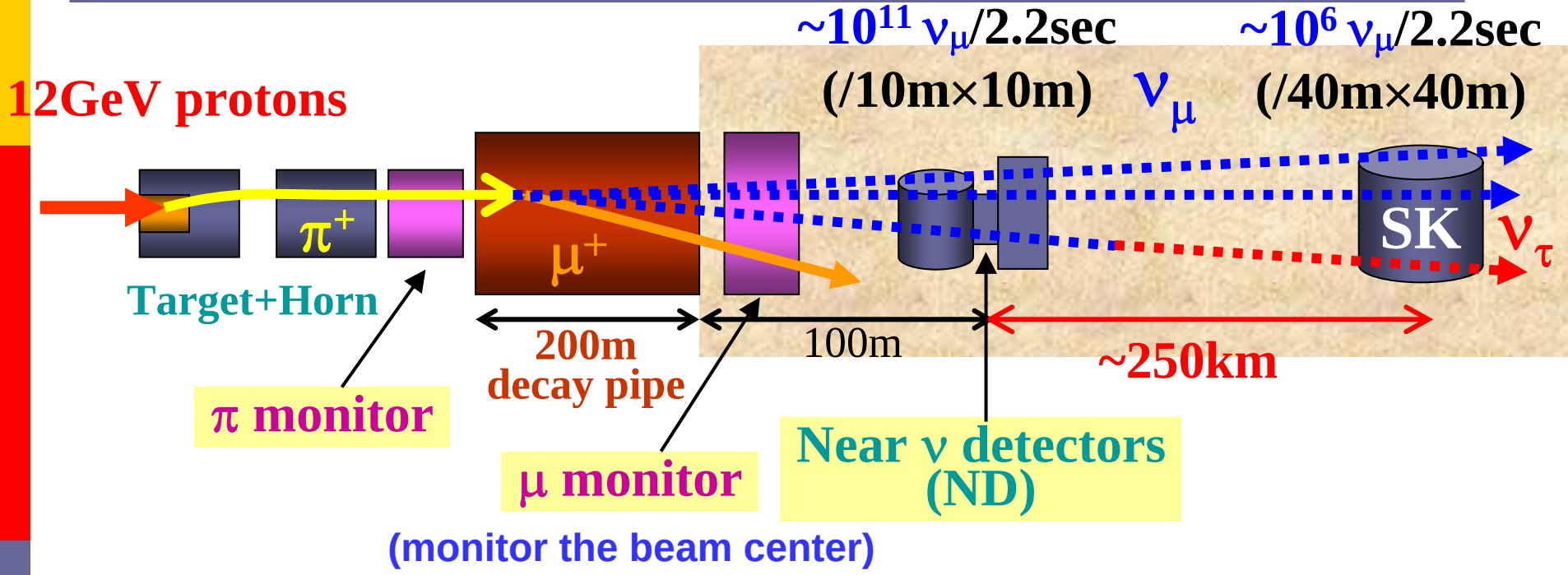
RUSSIA: INR-Moscow

1. Introduction and history of K2K

- 1995
  - Proposed to study neutrino oscillation for atmospheric neutrinos anomaly.
- 1999
  - Started taking data.
- 2000
  - Detected the less number of neutrinos than the expectation at a distance of 250 km. Disfavored null oscillation at the 2σ level.
- 2002
  - Observed indications of neutrino oscillation. The probability of null oscillation is less than 1%.
- 2004
  - *Confirm neutrino oscillation with both a deficit of ν_μ and the distortion of the E_ν spectrum.*

2. K2K experiment

~1 event/2days

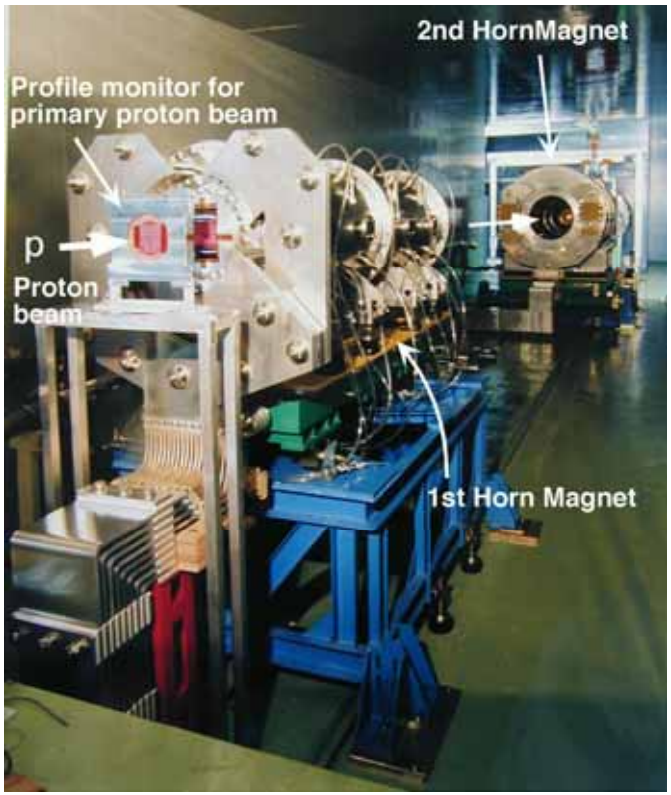


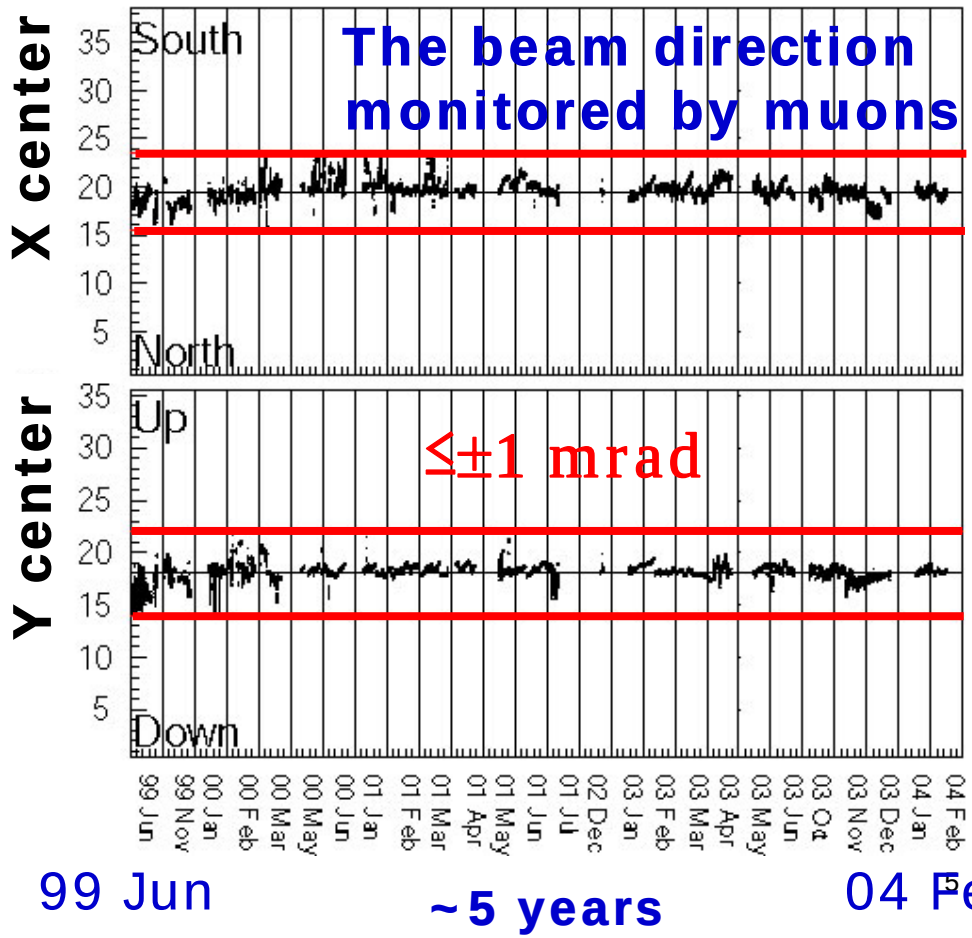
Signal of ν oscillation at K2K

- Reduction of ν_μ events
- Distortion of ν_μ energy spectrum

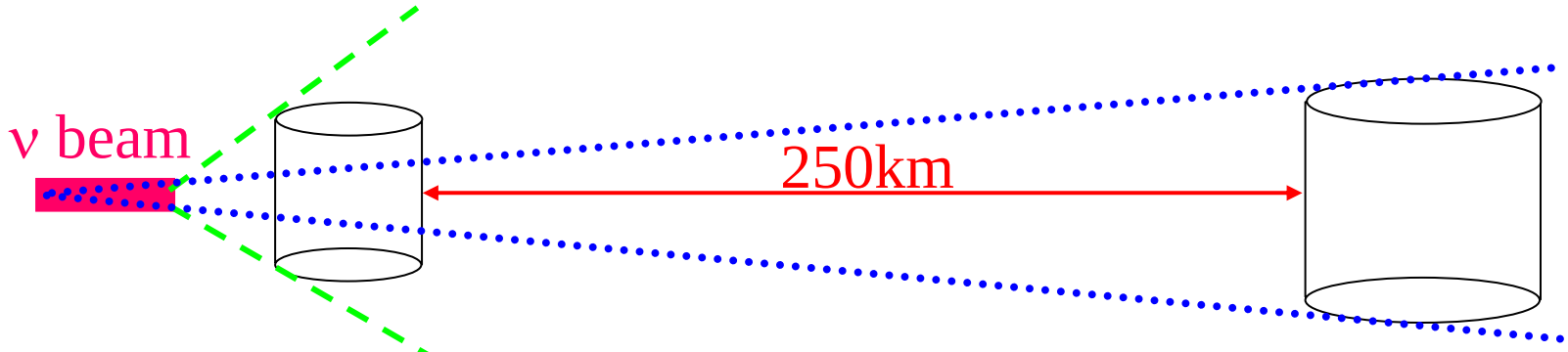
Neutrino beam and the directional control

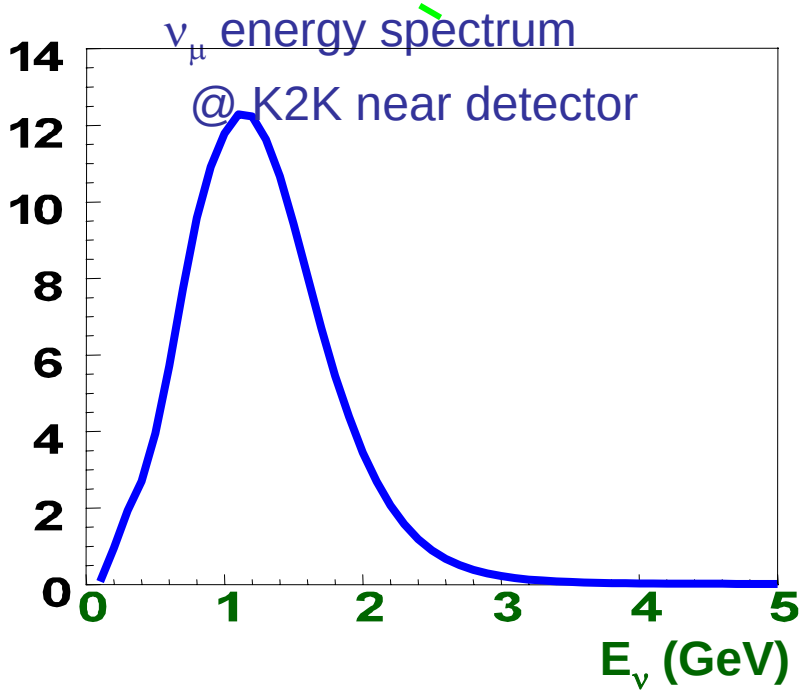
- ~1GeV neutrino beam by a dual horn system with 250kA.

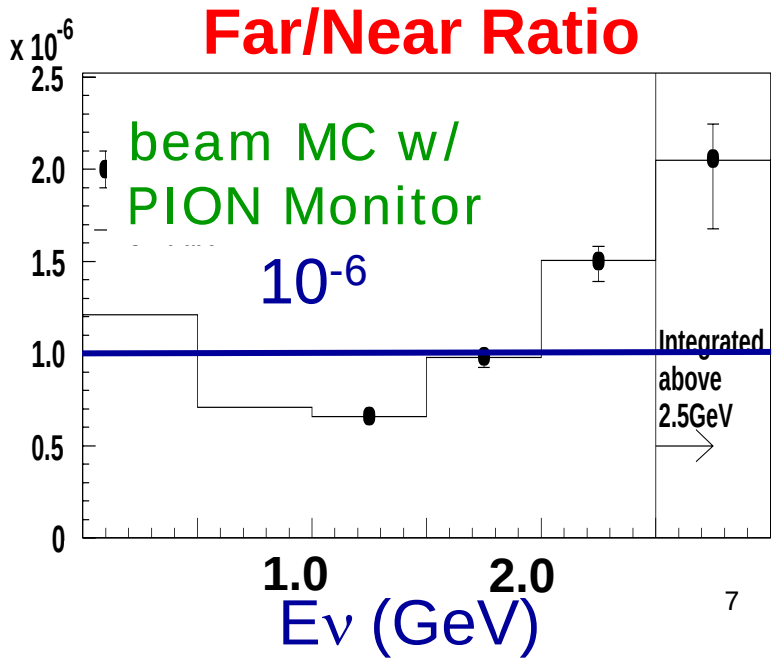




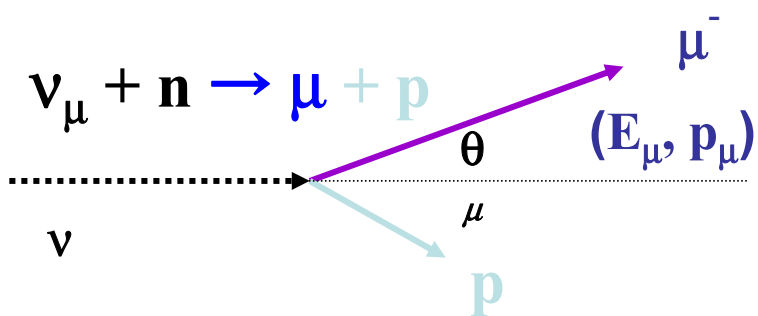
Neutrino spectrum and the far/near ratio







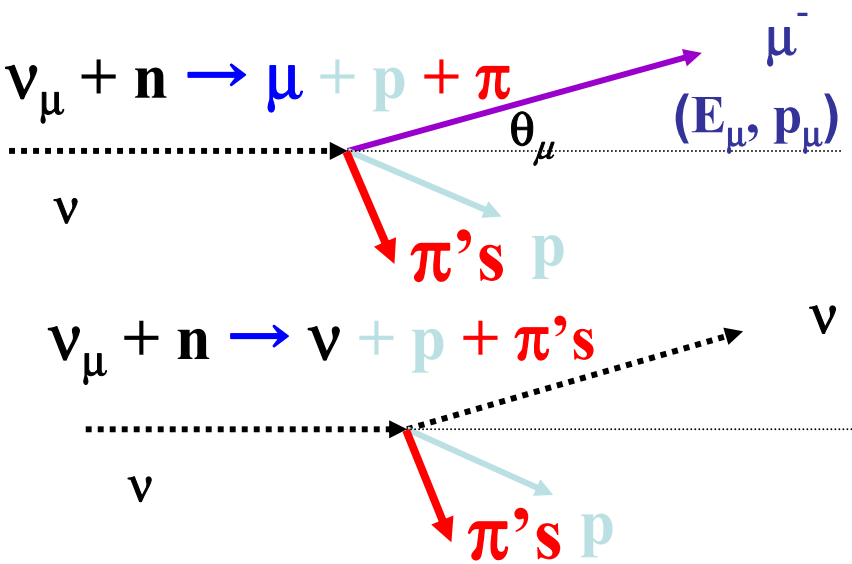
E_ν reconstruction at low energy



- CC QE
  - can reconstruct Eν ←(θ_μ, p_μ)

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

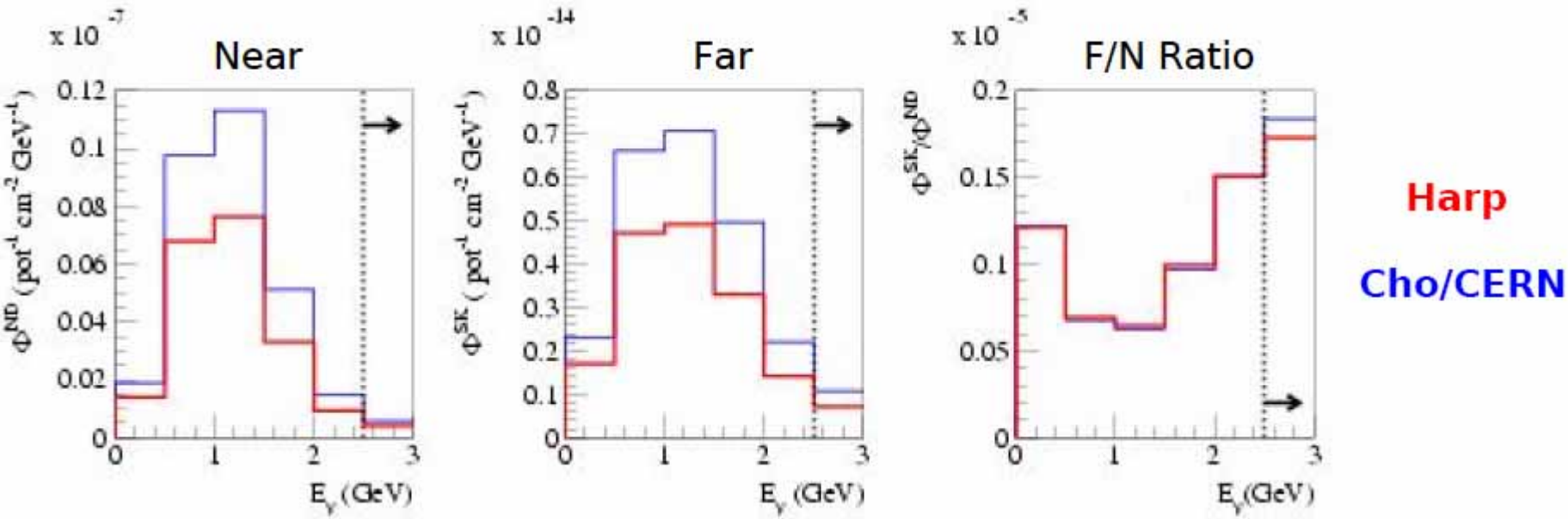
$\delta E \sim 60$ MeV $\delta E/E \sim 10\%$



- bkg. for E_ν measurement
- High energy part
- bkg.for e-appearance

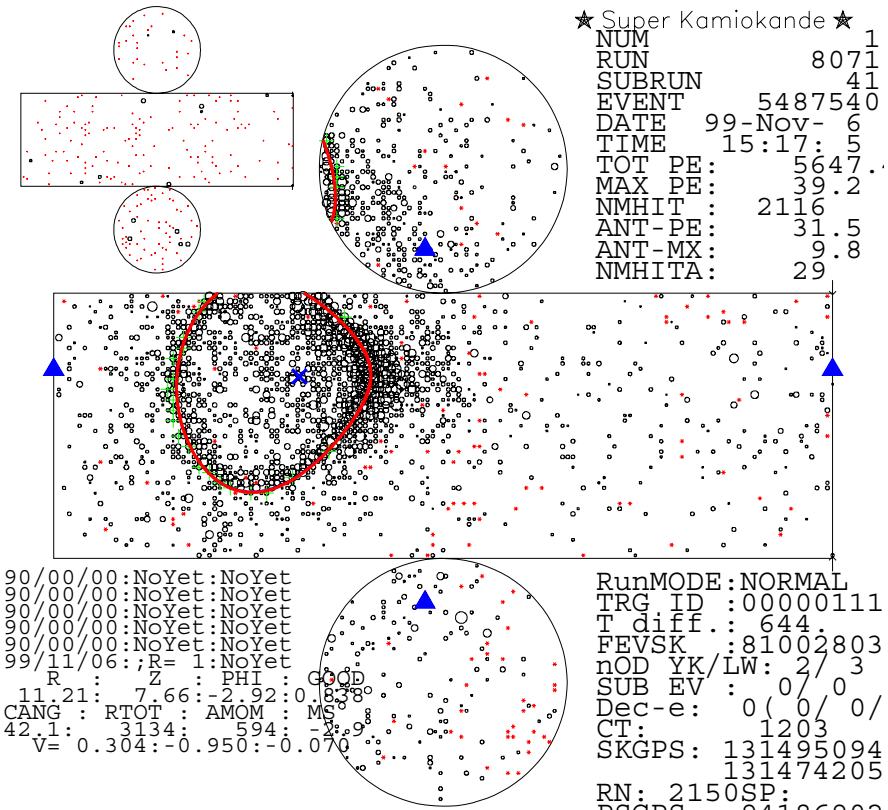
Experiences in K2K with Harp measurement

- Neutrino cross section cannot be trusted above GeV and below deep inelastic region –
- Proper near detectors to measure rate and Far/Near ratio should be used

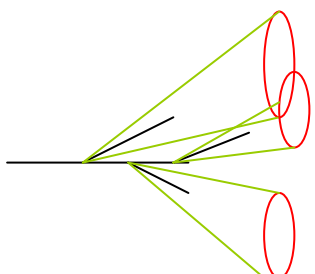


3. PID in SK

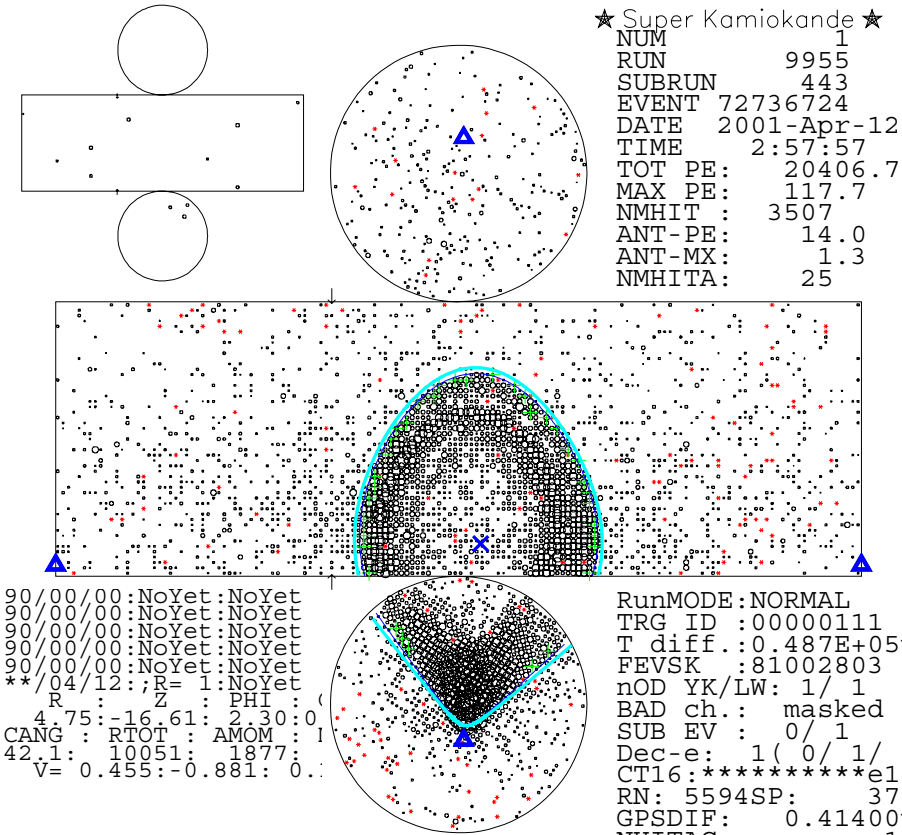
e-like



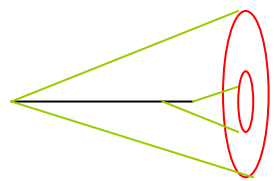
e



μ-like

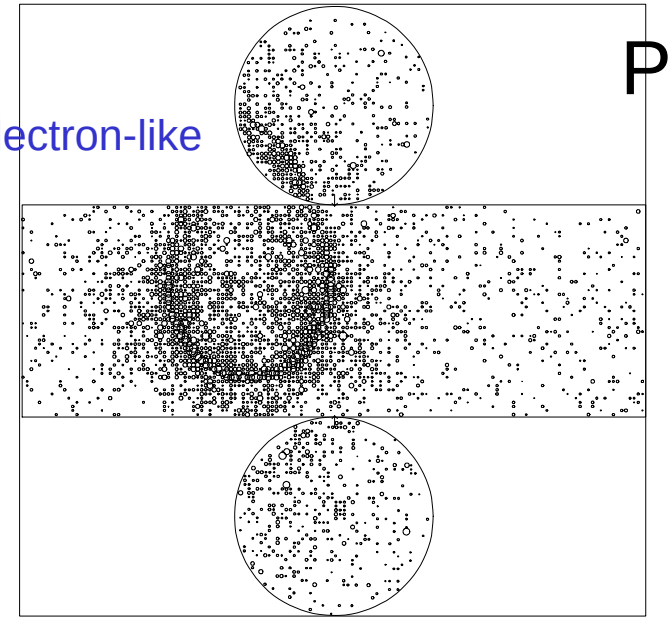


μ

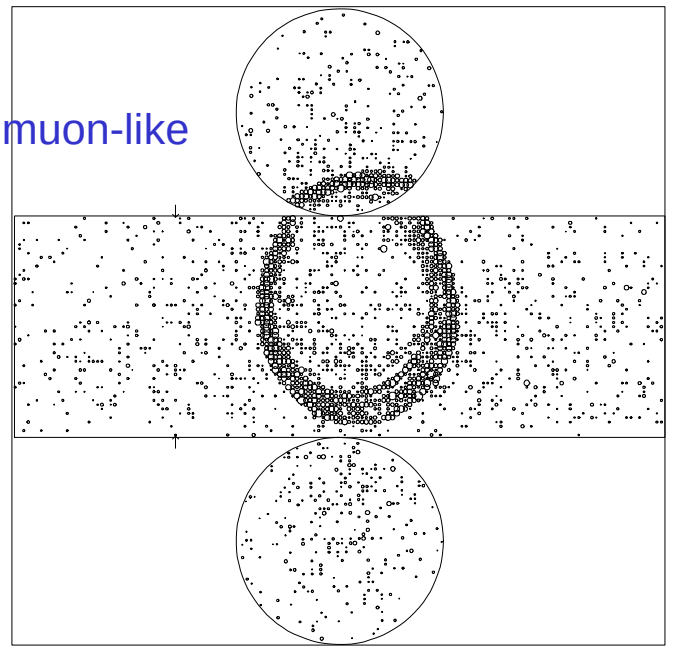


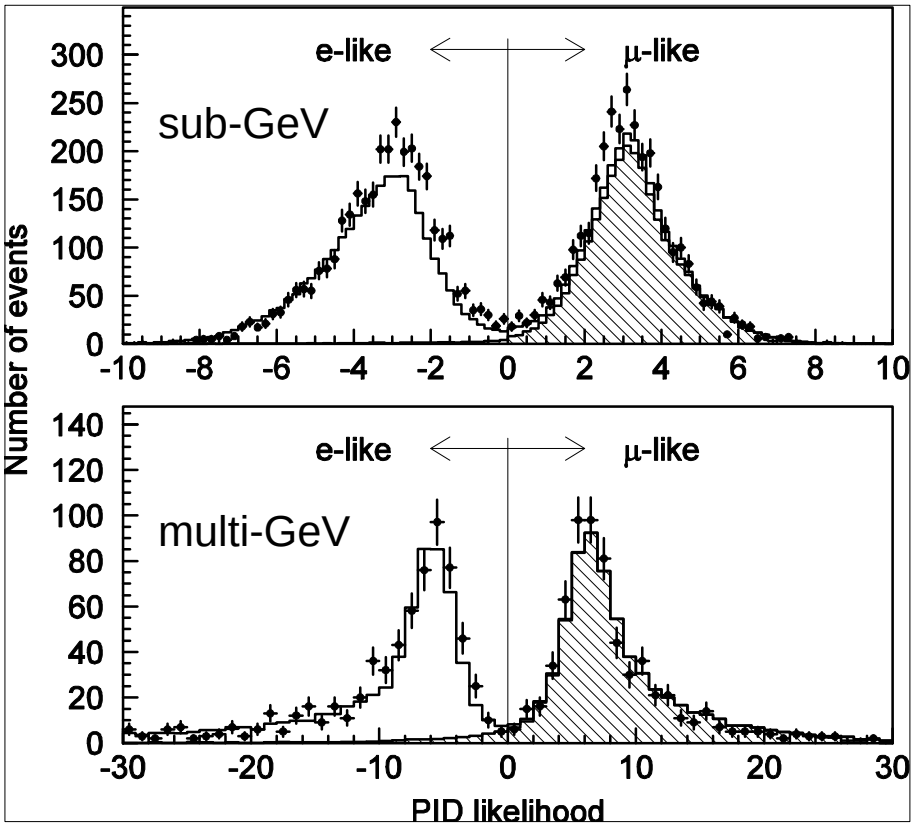
Particle ID

electron-like

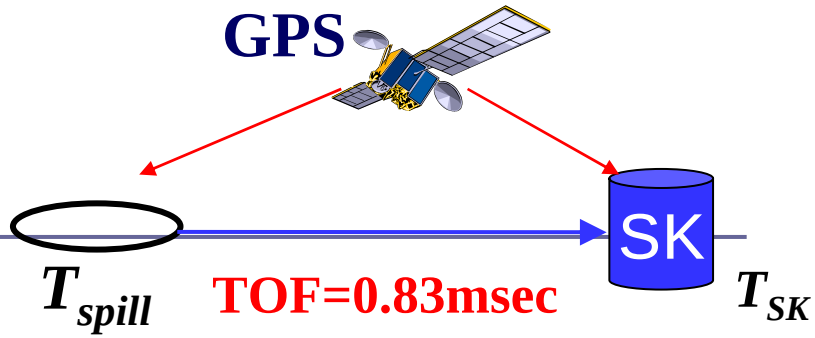


muon-like

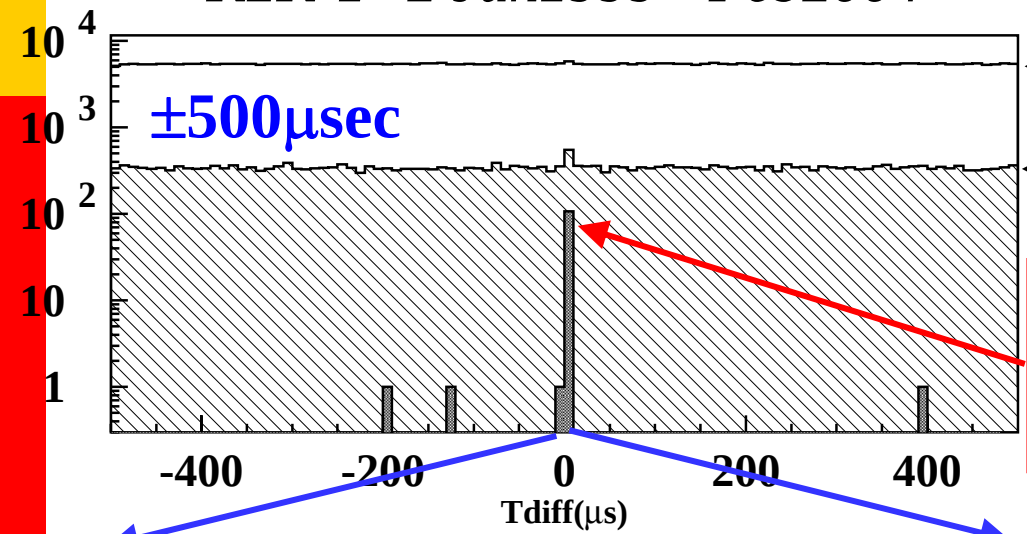




SK Events



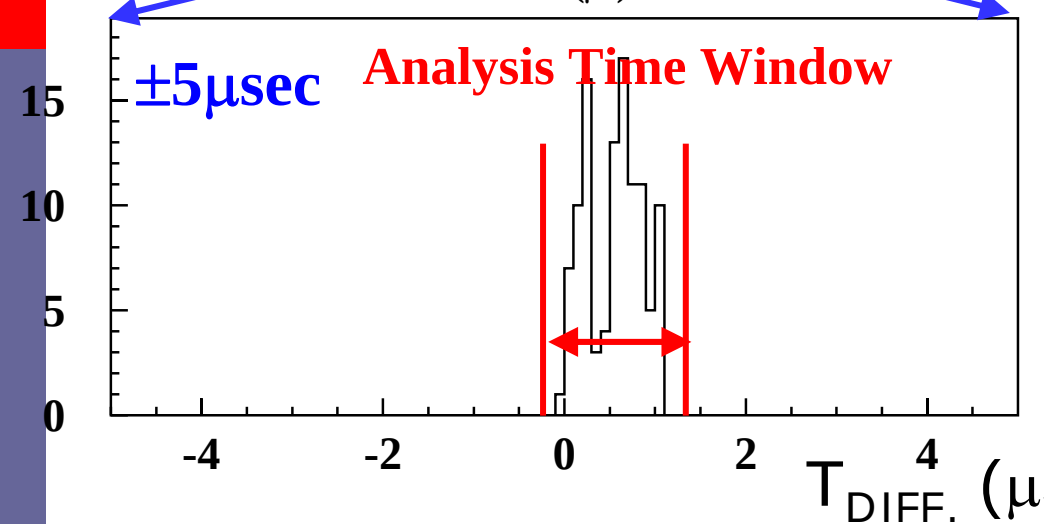
K2K-1+2 Jun1999 - Feb2004



Decay electron cut.

≥20MeV Deposited Energy

No Activity in Outer Detector
Event Vertex in Fiducial Volume
More than 30MeV Deposited Energy

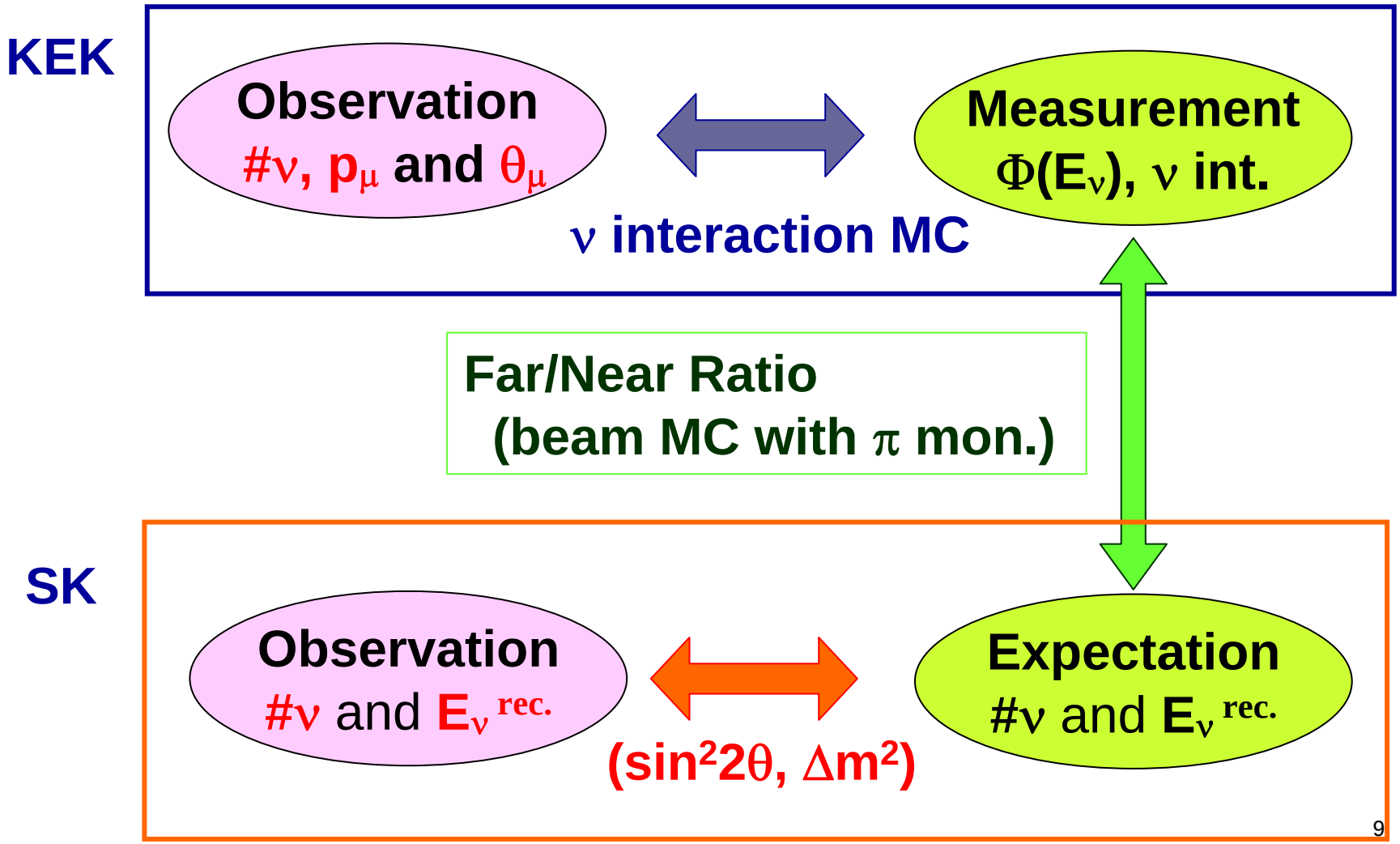


108 events

$-0.2 < T_{SK} - T_{spill} - TOF < 1.3\mu sec$

(BG: 1.6 events within ±500μs
2.4×10^{-3} events in 1.5μs)

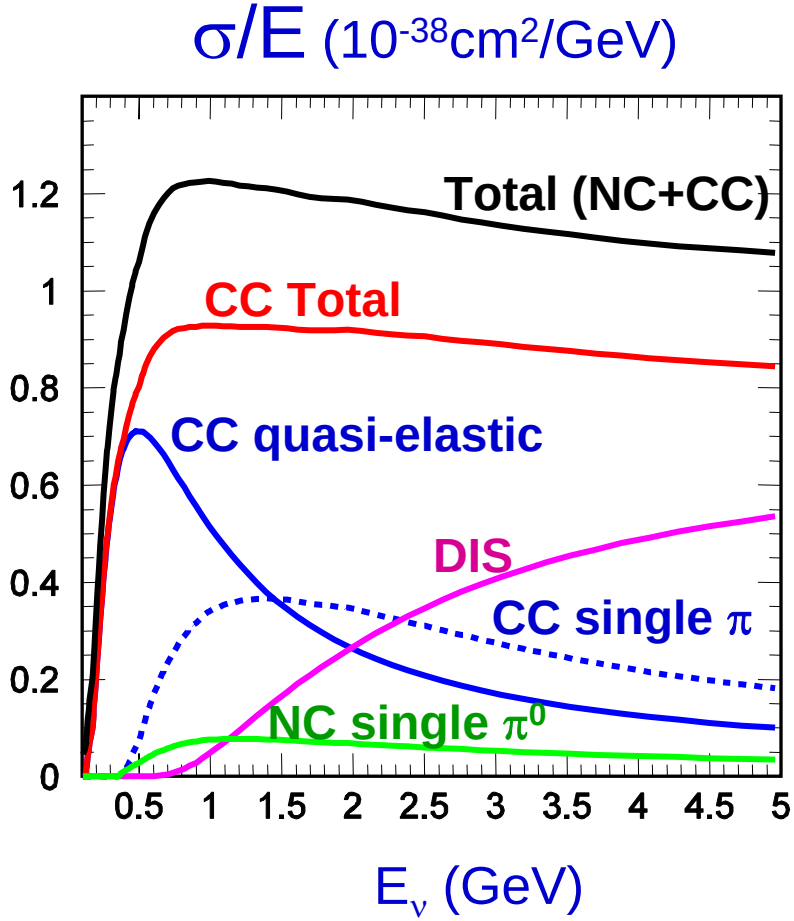
3. Analysis Overview



NEUT: K2K Neutrino interaction MC

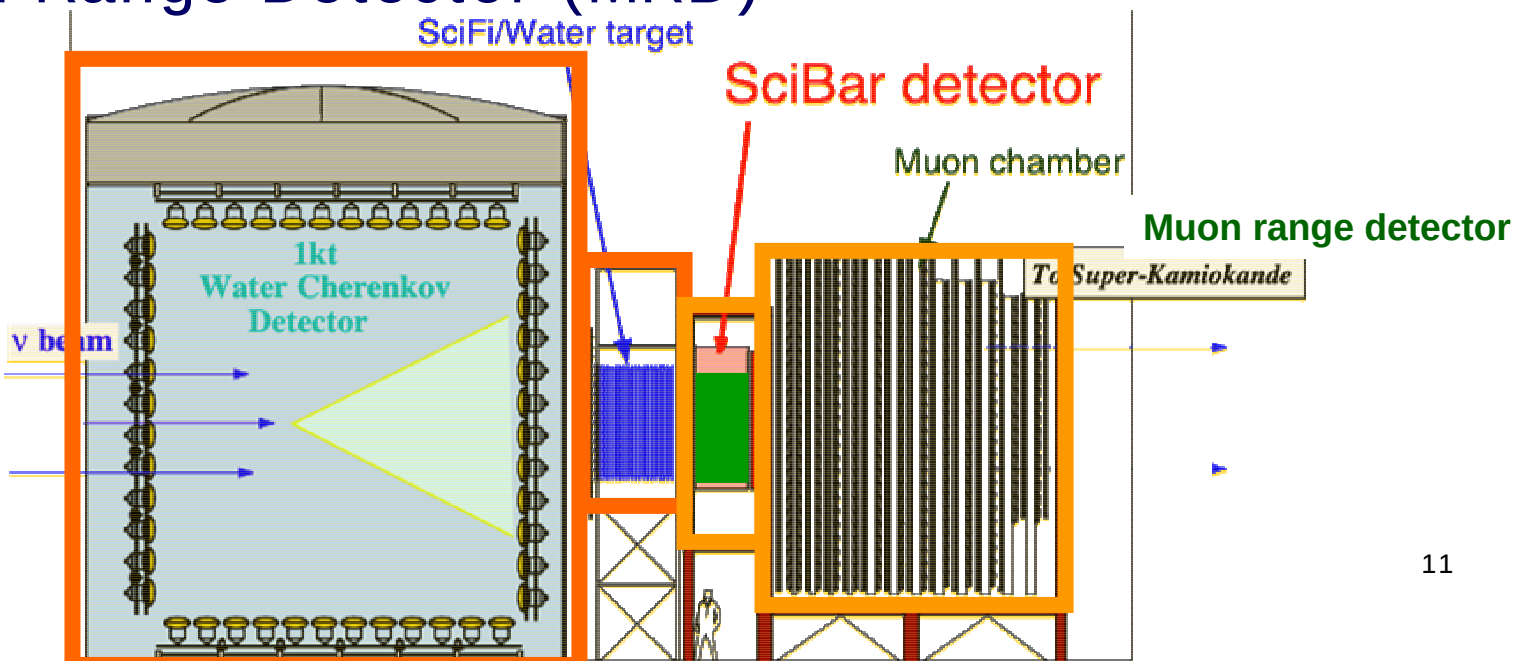
- **CC quasi elastic (CCQE)**
  - Smith and Moniz with $M_A = 1.1$GeV
- **CC (resonance) single π (CC-1π)**
  - Rein and Sehgal's with $M_A = 1.1$GeV
- **DIS**
  - GRV94 + JETSET with Bodek and Yang correction.
- **CC coherent π**
  - Rein&Sehgal with the cross section rescale by J. Marteau
- **NC**

+ Nuclear Effects



4. Near detector measurements

- 1KT Water Cherenkov Detector (1KT)
- Scintillating-fiber/Water sandwich Detector (SciFi)
- Lead Glass calorimeter (LG) before 2002
- Scintillator Bar Detector (SciBar) after 2003
- Muon Range Detector (MRD)



4.1 1KT Flux measurement

- The same detector technology as Super-K.
- Sensitive to low energy neutrinos.

$$N_{SK}^{\exp} = N_{KT}^{obs} \bullet \boxed{\frac{\int \Phi_{SK}(E_\nu)\sigma(E_\nu)dE_\nu}{\int \Phi_{KT}(E_\nu)\sigma(E_\nu)dE_\nu}} \bullet \frac{M_{SK}}{M_{KT}} \bullet \frac{\varepsilon_{SK}}{\varepsilon_{KT}}$$

≡Far/Near Ratio (by MC) ~ 1×10^{-6}

M: Fiducial mass M_{SK} = 22,500ton, M_{KT} = 25ton

ε: efficiency $\varepsilon_{SK\text{-}I(II)}$ = 77.0(78.2)%, ε_{KT} = 74.5%

$$N_{SK}^{exp} = 150.9^{+11.6}_{-10.0} \quad \Leftrightarrow \quad N_{SK}^{obs} = 108$$

4.4 Near Detectors combined measurements

(p_μ,θ_μ) for 1track, 2trackQE and 2track nQE samples
$\rightarrow \Phi(E\nu)$, nQE/QE

- Fitting parameters
  - $\Phi(E_\nu)$, nQE/QE ratio
  - Detector uncertainties on the energy scale and the track counting efficiency.
  - The change of track counting efficiency by nuclear effect uncertainties; proton re-scattering and π interactions in a nucleus ...
- Strategy
  ① Measure $\Phi(E_\nu)$ in the more relevant region of $\theta_\mu \geq 20°$ for 1KT and $\theta_\mu \geq 10°$ for SciFi and SciBar.
  ② Apply a low q^2 correction factor to the CC-1π model (or coherent π).
  ③ Measure nQE/QE ratio for the entire θ_μ range.

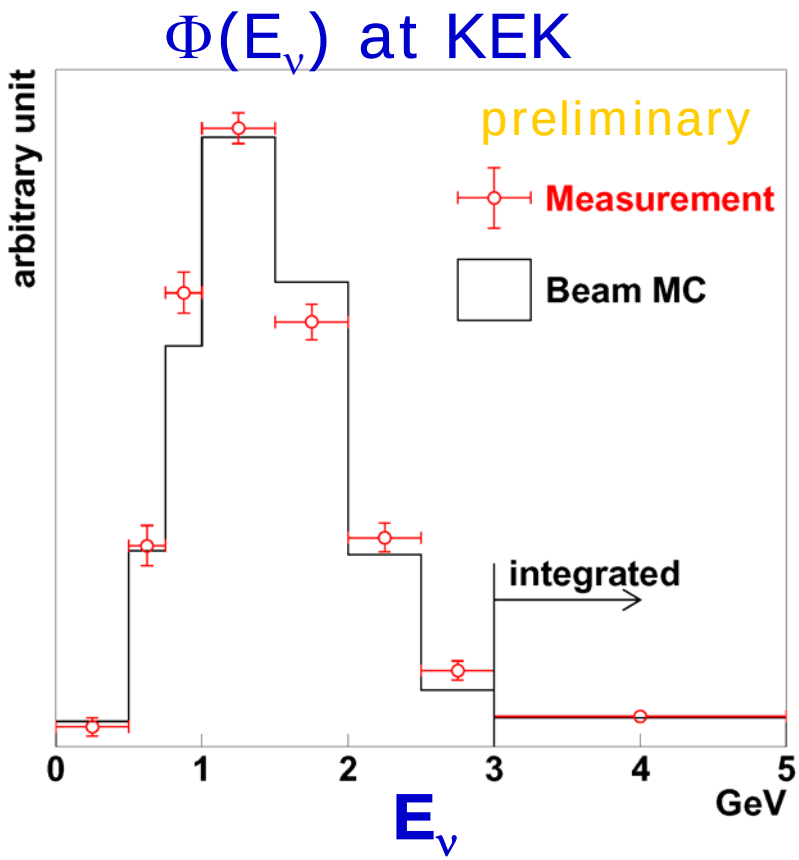
Flux measurements

χ^2=638.1 for 609 *d.o.f*

- Φ1 (Eν < 500) = 0.78 ± 0.36
- Φ2 (500≤ Eν < 750) = 1.01 ± 0.09
- Φ3 (750≤ Eν <1000) = 1.12 ± 0.07
- Φ4 (1000≤ Eν <1500) = 1.00
- Φ5 (1500≤ Eν <2000) = 0.90 ± 0.04
- Φ6 (2000≤ Eν <2500) = 1.07 ± 0.06
- Φ7 (2500≤ Eν <3000) = 1.33 ± 0.17
- Φ8 (3000≤ Eν) = 1.04 ± 0.18
- nQE/QE = 1.02 ± 0.10

The nQE/QE error of 10% is assigned based on the sensitivity of the fitted nonQE/QE value by varying the fit criteria.

- θ>10°(20 °) cut: nQE/QE=0.95 ±0.04
- standard(CC-1π low q^2 corr.): nQE/QE=1.02 ±0.03
- No coherent: π=nQE/QE=1.06 ±0.03



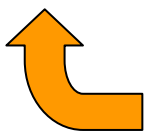
5. Super-K oscillation analysis

- Total Number of events
- E_ν^{rec} spectrum shape of FC-1ring-μ events
- Systematic error term

$$L(\Delta m^2, \sin 2\theta, f^x)$$
$$= L_{norm}(\Delta m^2, \sin 2\theta, f^x) \cdot L_{shape}(\Delta m^2, \sin 2\theta, f^x) \cdot L_{syst}(f^x)$$

f^x : Systematic error parameters

Normalization, Flux, and nQE/QE ratio are in f^x



Near Detector measurements, Pion Monitor constraint, beam MC estimation, and Super-K systematic uncertainties.

K2K-SK events

preliminary

K2K-alll (K2K-I, K2K-II)	DATA (K2K-I, K2K-II)	MC (K2K-I, K2K-II)
FC 22.5kt	**108** (56, 52)	**150.9** (79.1*, 71.8)
1ring	**66** (32, 34)	**93.7** (48.6, 45.1)
μ-like for E_ν^{rec}	**57 (56)** (30, 27)	**84.8** (44.3, 40.5)
e-like	**9** (2, 7)	**8.8** (4.3, 4.5)
Multi Ring	**42** (24, 18)	**57.2** (30.5, 26.7)

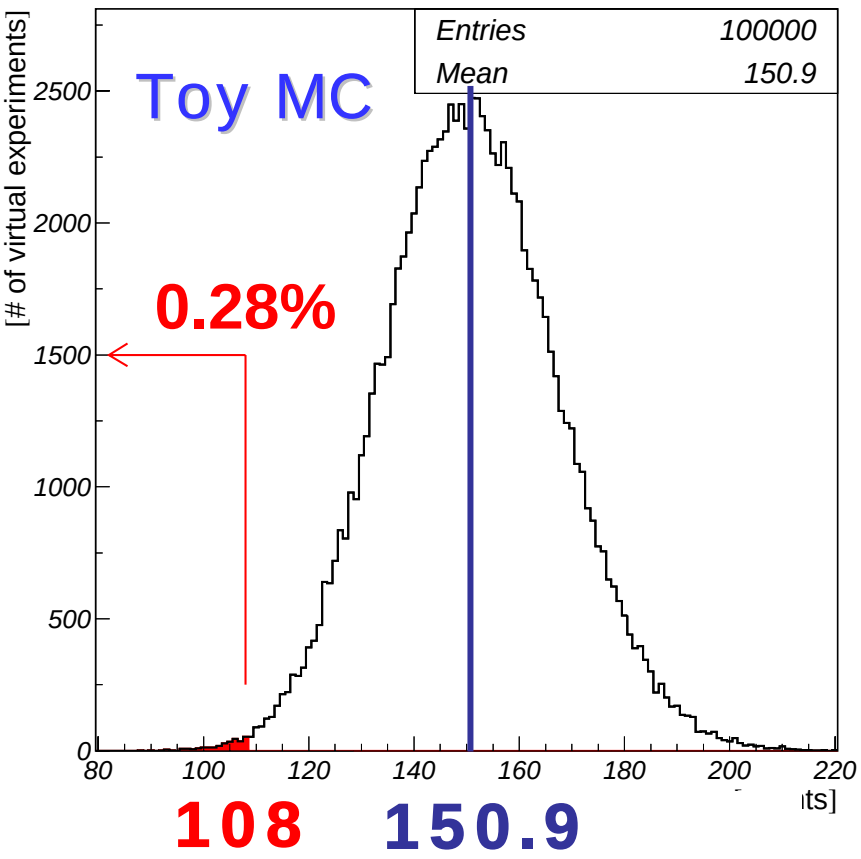
Ref; K2K-I(47.9×10^{18}POT), K2K-II(41.2×10^{18}POT)

*: The number is changed from the previous one.

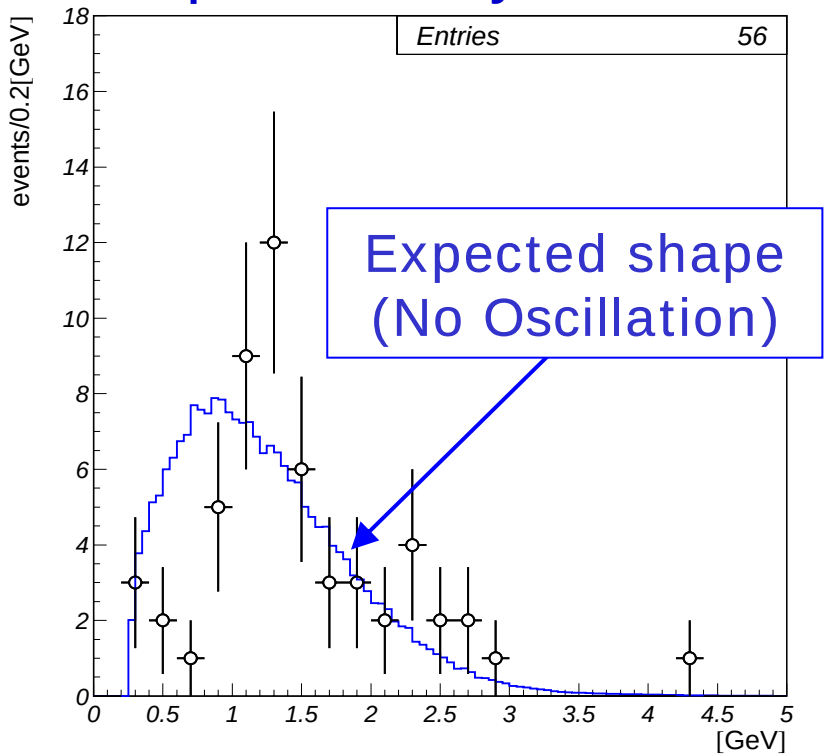
$L_{norm}(f^x)$

$L_{shape}(f^x)$

#SK Events



KS probability=0.11%



$E\nu^{rec}$[GeV]

CC-QE assumption

$$E_\nu^{rec} = \frac{(m_N - V)E_\mu - m_\mu^2/2 + m_N V - V^2/2}{(m_N - V) - E_\mu + p_\mu \cos\theta_\mu}$$

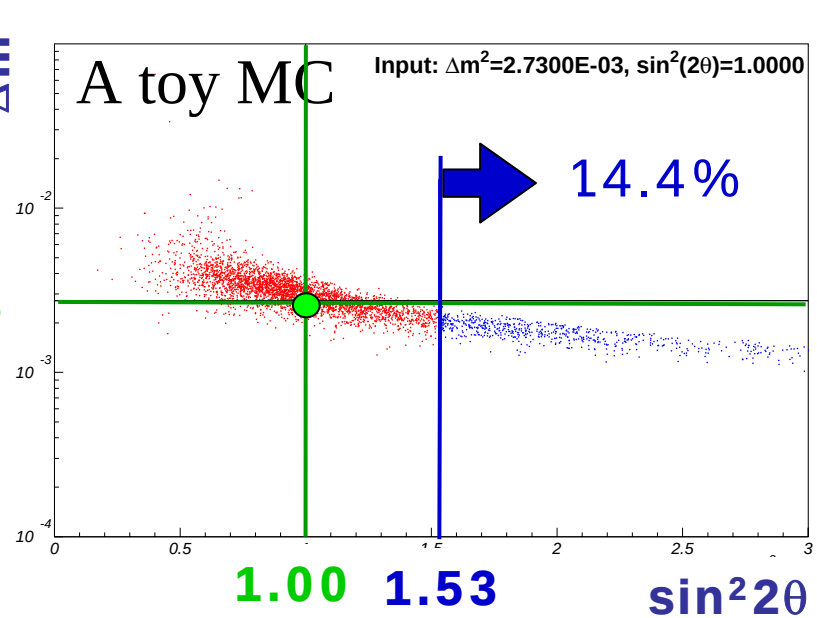
V: Nuclear potential

6. Results preliminary

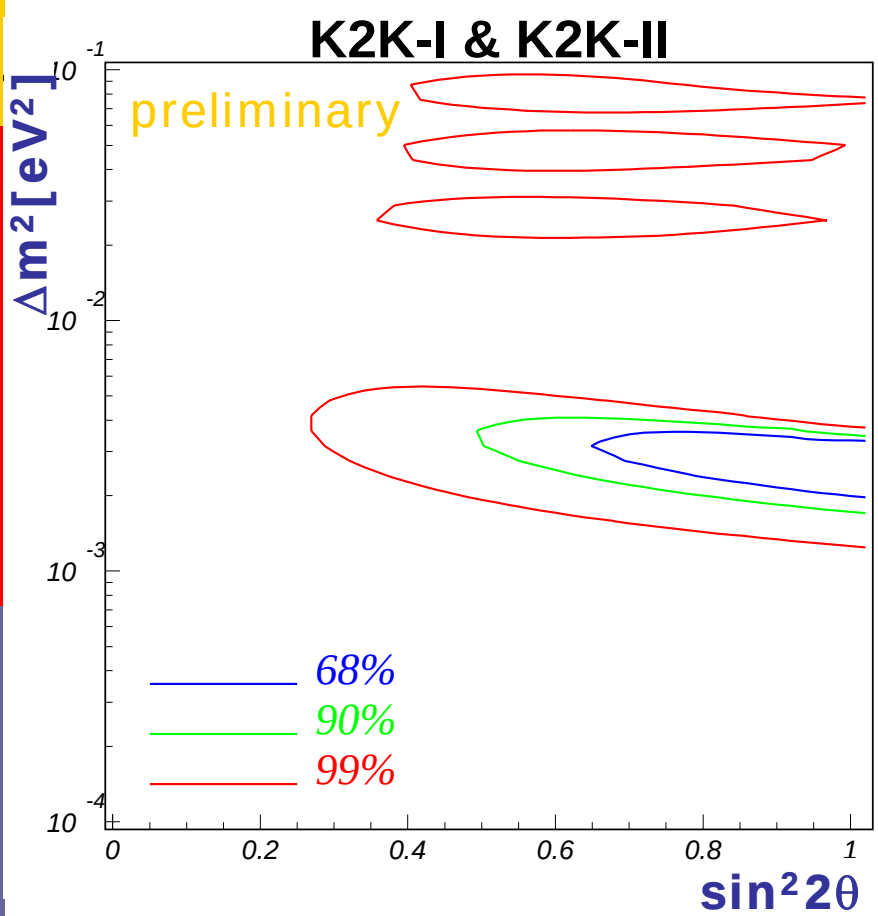
- Best fit values.
  - $\sin^2 2\theta = 1.53$
  - $\Delta m^2\ [eV^2] = 2.12 \times 10^{-3}$
- Best fit values in the physical region.
  - $\sin^2 2\theta = \mathbf{1.00}$
  - $\Delta m^2\ [eV^2] = \mathbf{2.73 \times 10^{-3}}$

$\Delta \log L = 0.64$

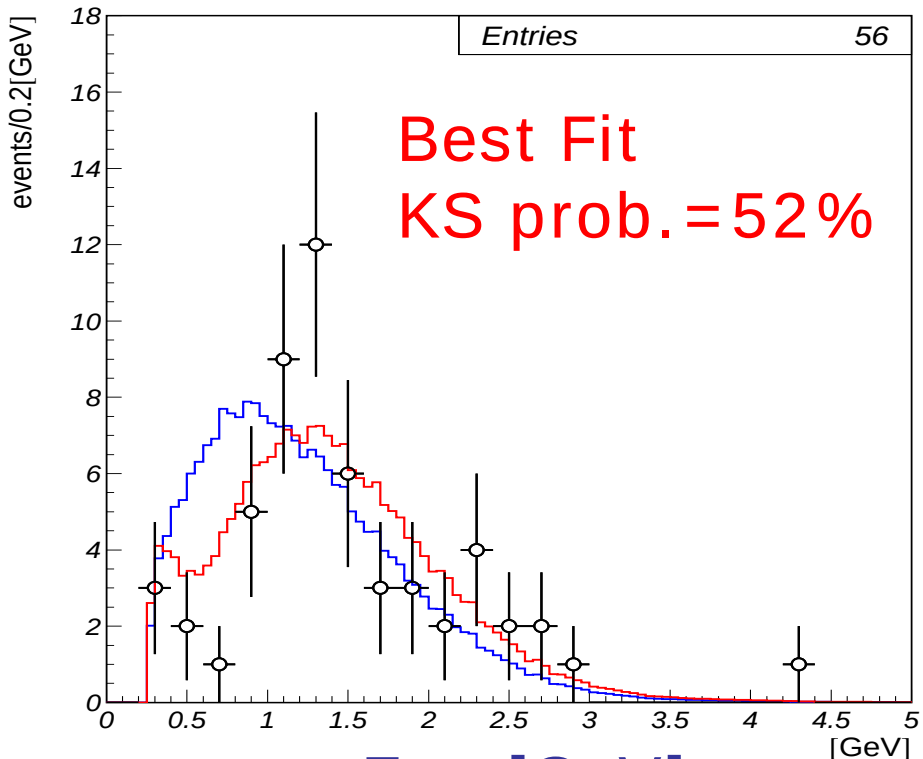
$\sin^2 2\theta = 1.53$ can occurr due to a a statistical fluctuation with 14.4%.



Data are consistent with the oscillation.

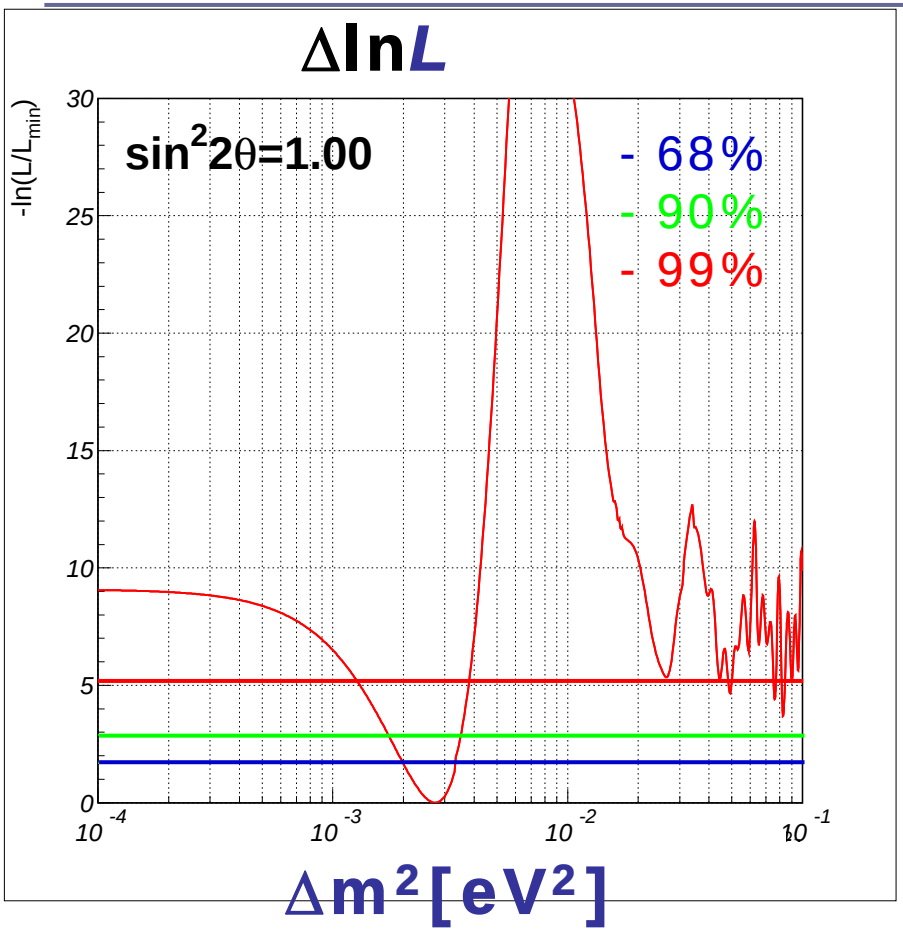


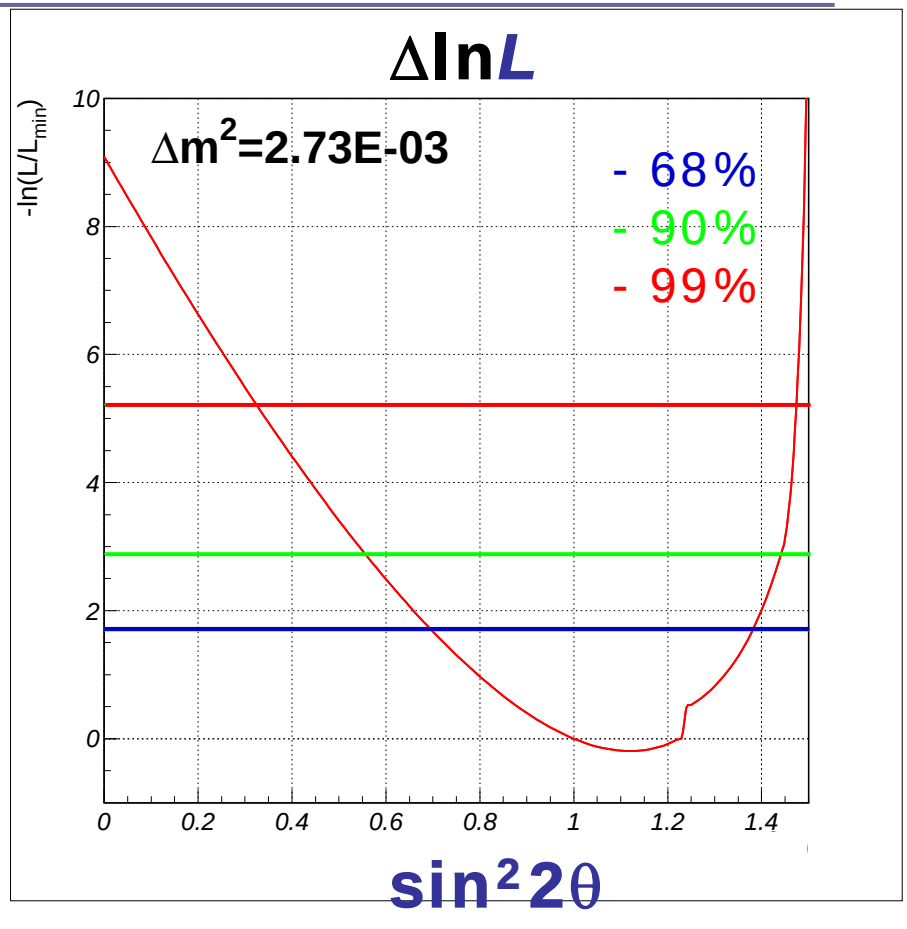
- $N_{SK}^{obs} = 108$
- N_{SK}^{exp} (best fit) = 104.8



Based on $\Delta \ln L$

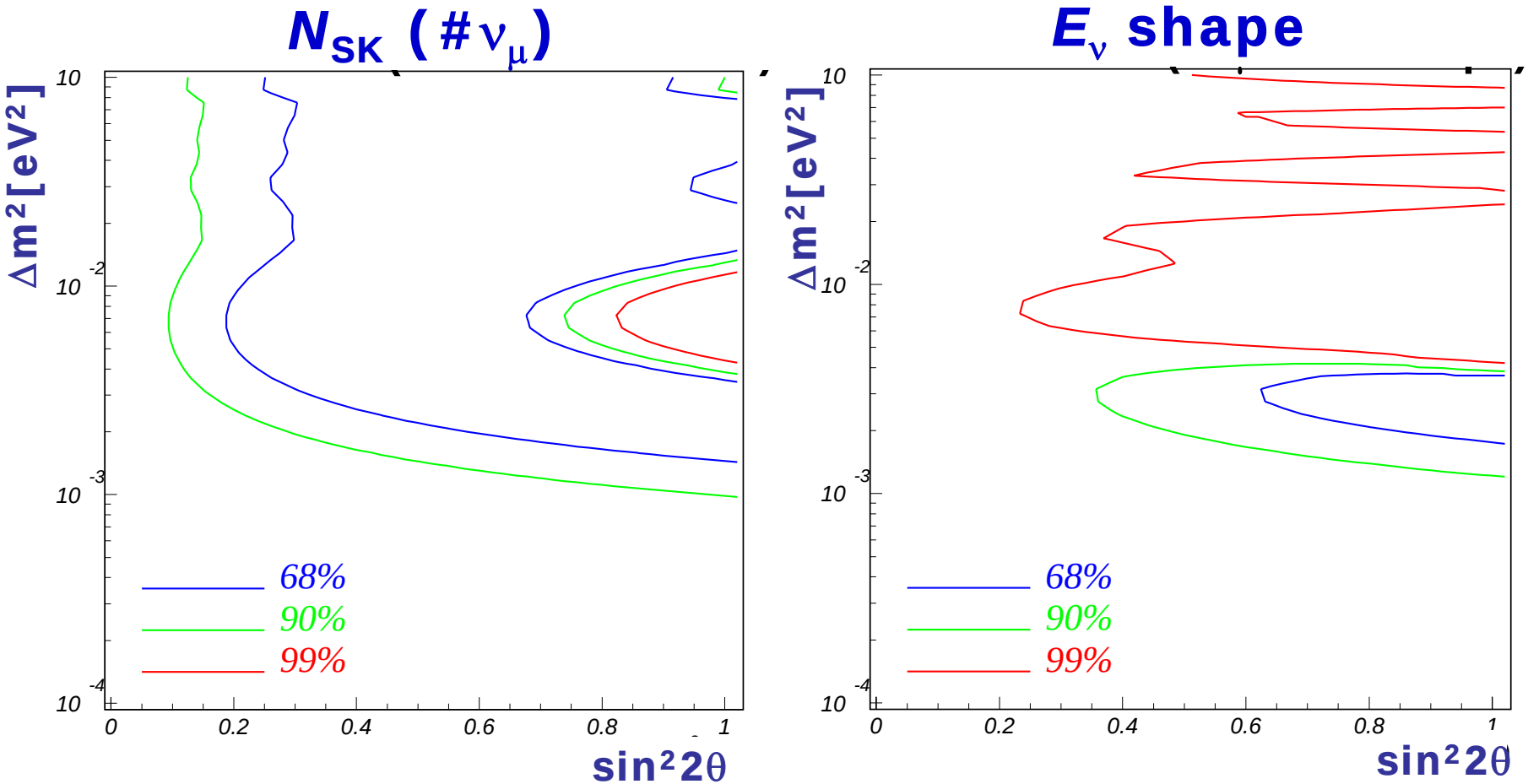
Log Likelihood difference from the minimum.





- $\Delta m^2 < (1.7 \sim 3.5) \times 10^{-3}$ eV^2 at $\sin^2 2\theta = 1.0$ (90% C.L.)

ν_μ disappearance versus E_ν shape distortion



Both disappearance of ν_μ and the distortion of E_ν spectrum have the consistent result.

Null oscillation probability

preliminary

The null oscillation probabilities are calculated based on $\Delta \ln L$.

	K2K-I	K2K-II	K2K-all
ν_μ disappearance	2.0%	3.7%	0.33% (2.9σ)
E_ν spectrum distortion	19.5%	5.4%	1.1% (2.5σ)
Combined	1.3%* (2.5σ)	0.56% (2.8σ)	**0.011%** (3.9σ)

*: The value is changed from the previous one.

Disappearance of ν_μ and distortion of the energy spectrum as expected in neutrino oscillation.

K2K confirms ***neutrino oscillation*** *discovered in Super-K atmospheric neutrinos.*

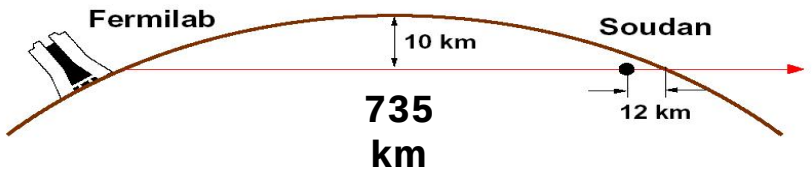
First MINOS Results from the NuMI Beam

D. A. Petyt, University of Minnesota
For the MINOS Collaboration

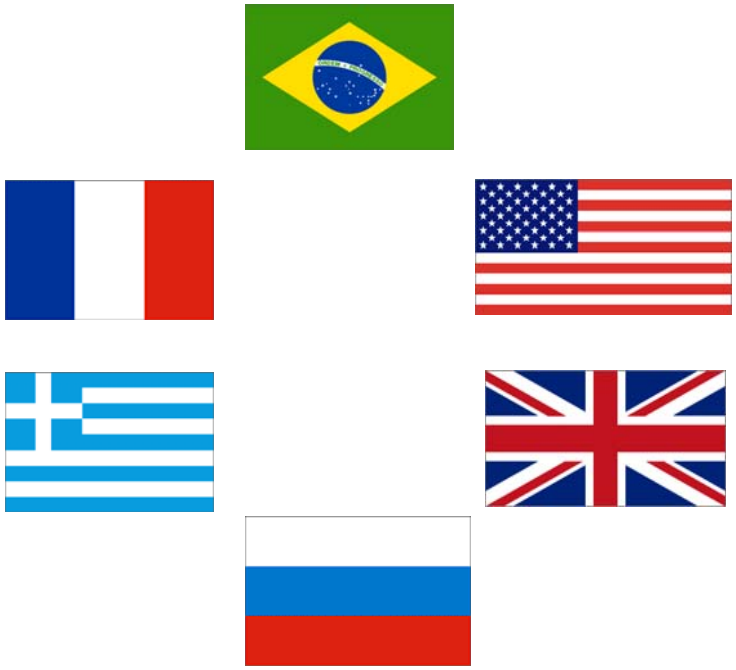
Joint Experimental/Theoretical Physics Seminar
Fermilab March 30th 2006

The MINOS Experiment

- **MINOS (Main Injector Neutrino Oscillation Search)** – a long-baseline neutrino oscillation experiment:
  - Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector.
  - A Near detector at Fermilab to measure the beam composition and energy spectrum
  - A Far detector deep underground in the Soudan Mine, Minnesota, to search for evidence of oscillations



The MINOS Collaboration



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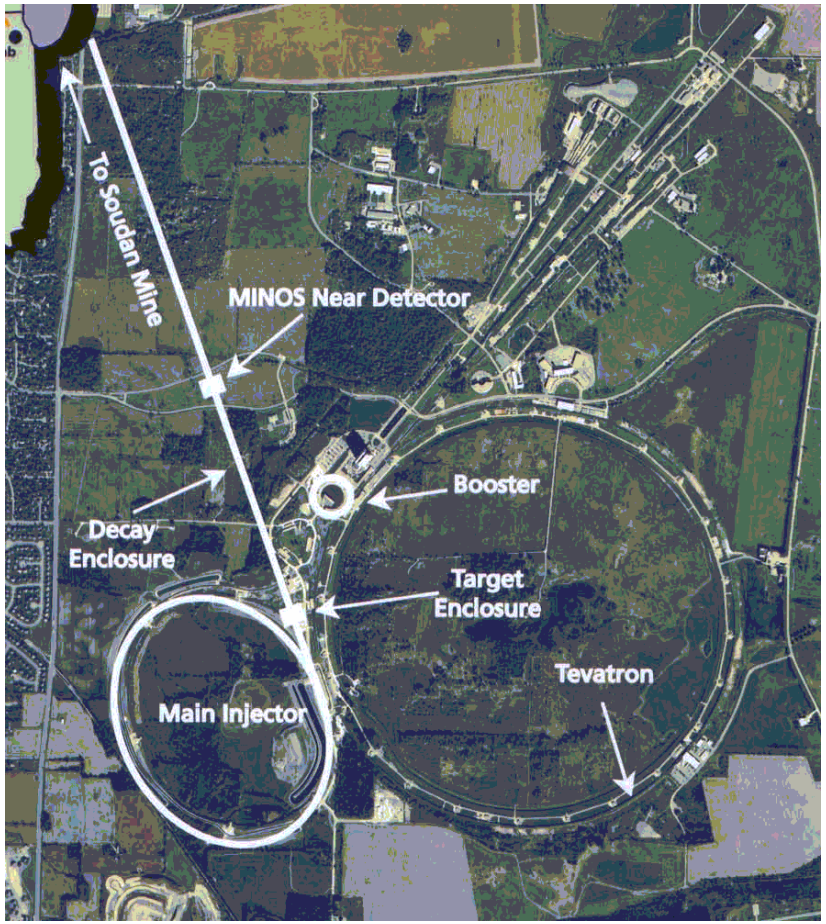
175 scientists

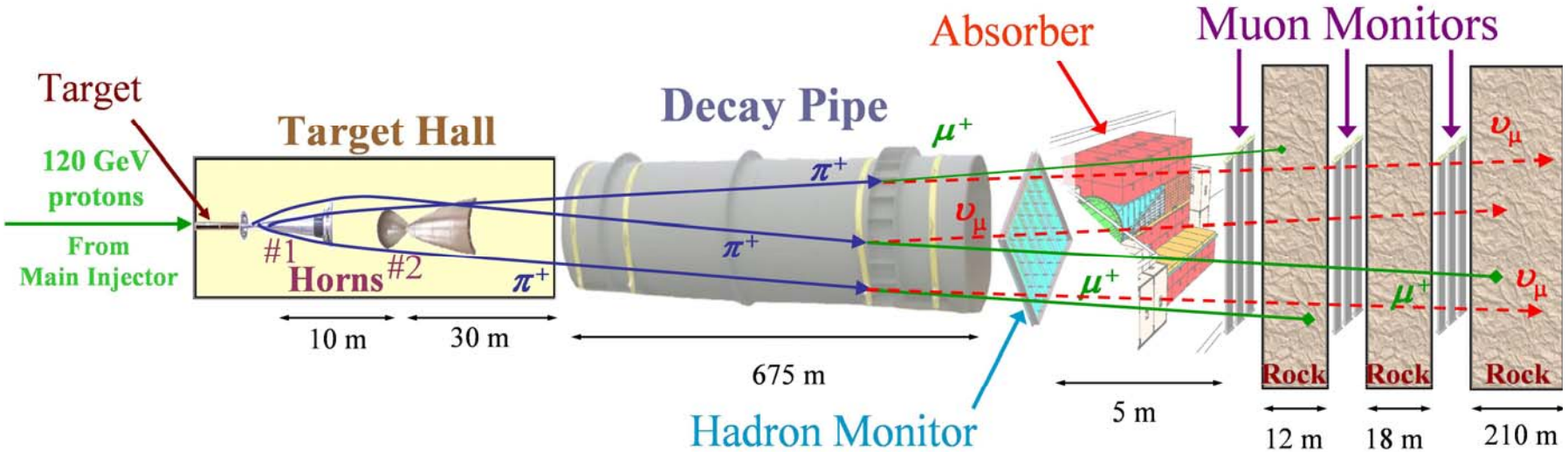
Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
College de France • Harvard • IIT • Indiana • ITEP-Moscow • Lebedev • Livermore
Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Protvino • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • Western Washington • William & Mary • Wisconsin

The NUMI facility



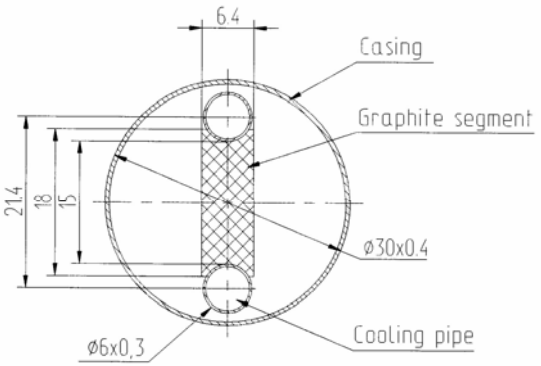
- **Design parameters:**
  - 120 GeV protons from the Main Injector
  - Main Injector can accept up to 6 Booster batches/cycle,
  - Either 5 or 6 batches for NuMI
  - 1.867 second cycle time
  - 4×10^{13} protons/pulse
  - 0.4 MW
  - Single turn extraction (10μs)

Producing the neutrino beam



- Moveable target relative to horn 1 – continuously variable neutrino spectrum

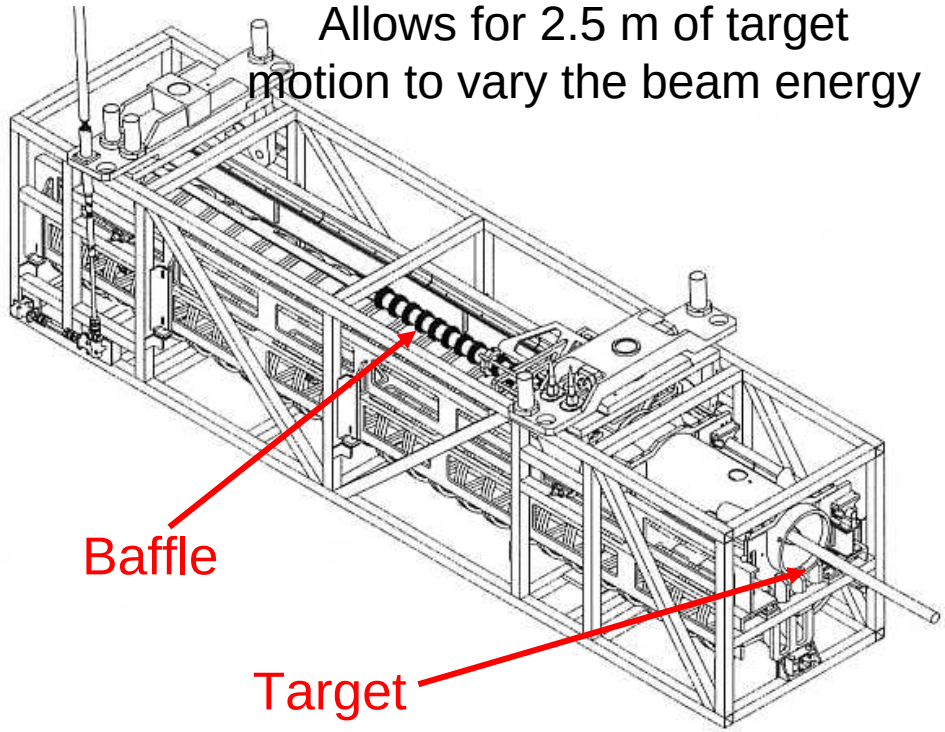
NuMI target



- Target:
  - 47 segments of graphite of 20 mm length and 6.4×15 mm^2 cross section
  - 0.3 mm spacing between segments, for a total target length of 95.4 cm
- Baffle:
  - protects beamline components from beam mis-steering
  - 150 cm long graphite rod with 11mm diameter hole

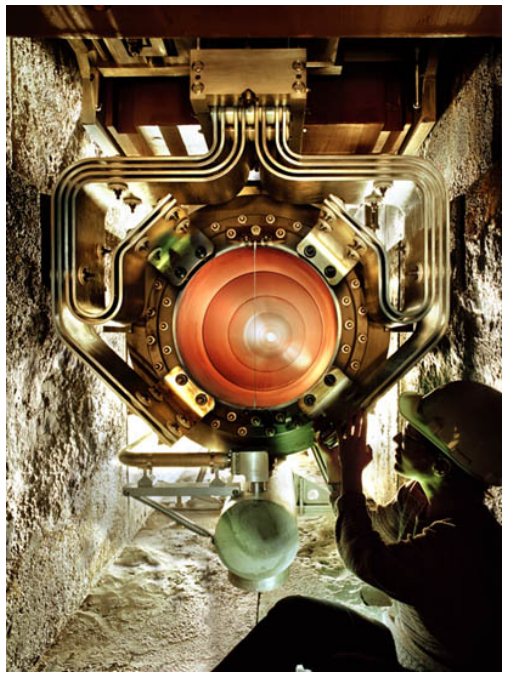
Target/Baffle carrier

Allows for 2.5 m of target motion to vary the beam energy



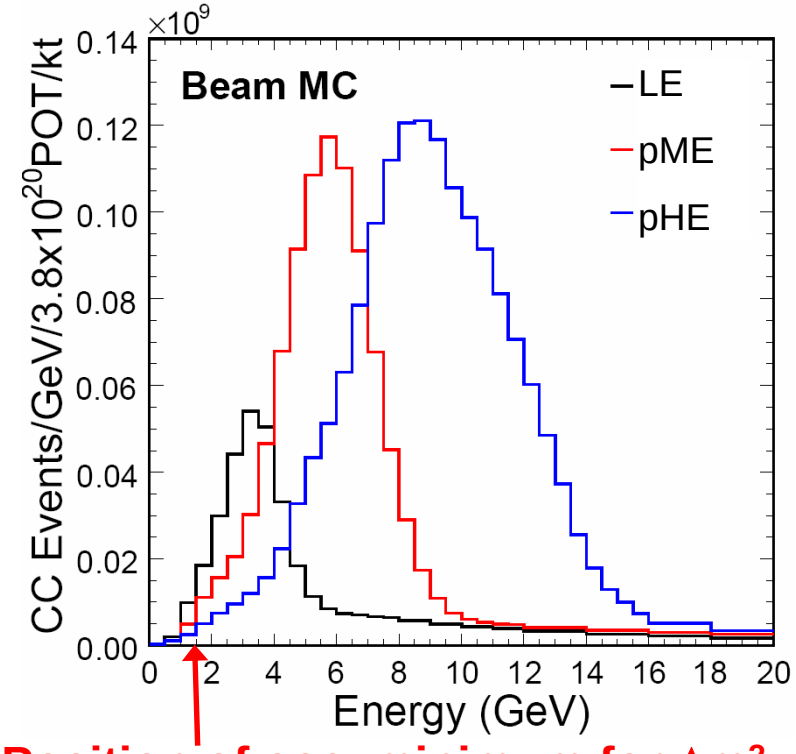
Focussing horns

- Two parabolic focussing horns connected in series.
- Nominal horn current at 200 kA
- Produces 3.0 Tesla peak field



The NuMI neutrino beam

- **Currently running in the LE-10 configuration**
- Beam composition (events in low energy configuration): **98.5% $\nu_\mu+\bar{\nu}_\mu$ (6.5% $\bar{\nu}_\mu$), 1.5% $\nu_e+\bar{\nu}_e$**
- Took ~1.5e18 pot in pME and pHE configurations early in the run for commissioning and systematics studies



Position of osc. minimum for Δm^2=0.0025 eV²

Expected no of events (no osc.) in Far Detector

Beam	Target z position (cm)	FD Events per 1e20 pot
LE-10	-10	390
pME	-100	970
pHE	-250	1340

Events in fiducial volume

Detector Technology

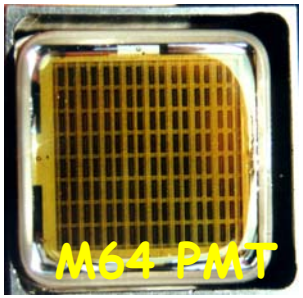
MINOS Near and Far detectors are functionally identical: share same detector technology and granularity:

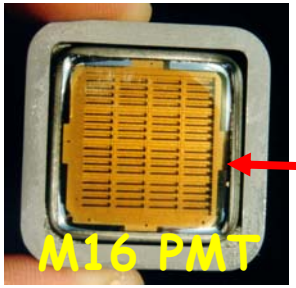
2.54 cm thick magnetised steel plates

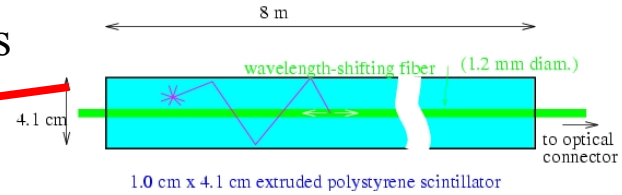
4.1x1cm co-extruded scintillator strips (MINOS-developed technology)

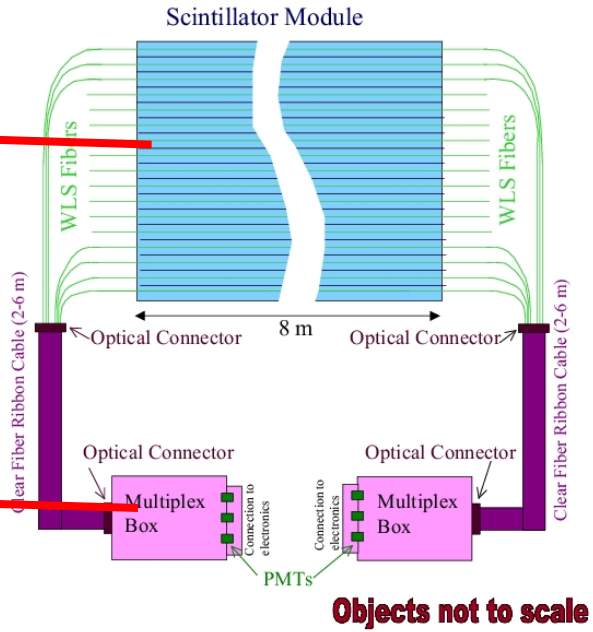
orthogonal orientation on alternate planes – U,V

optical fibre readout to multi-anode PMTs









The MINOS Detectors

Far Detector

Near Detector

5.4 kton mass, 8×8×30m	1 kton mass 3.8×4.8×15m
484 steel/scintillator planes	282 steel and 153 scintillator planes
(x 8 multiplexing)	(x 4 multiplexing after plane 120)
VA electronics	Fast QIE electronics

B ~1.2T

Multi-pixel (M16,M64) PMTs

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

Continuous *untriggered* readout of whole detector (only during spill for the ND)

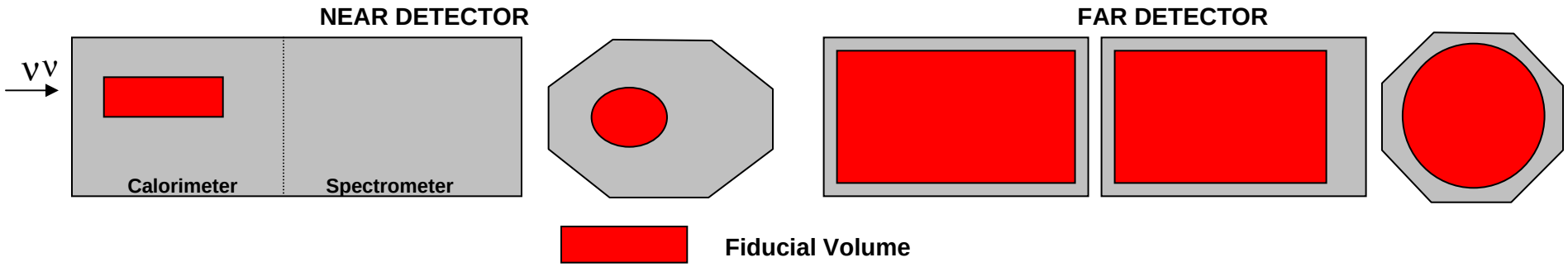
Interspersed light injection (LI) for calibration

Software triggering in DAQ PCs (Highly flexible : plane, energy, LI triggers in use)

Spill times from FNAL to FD trigger farm

Event selection cuts – Near and Far

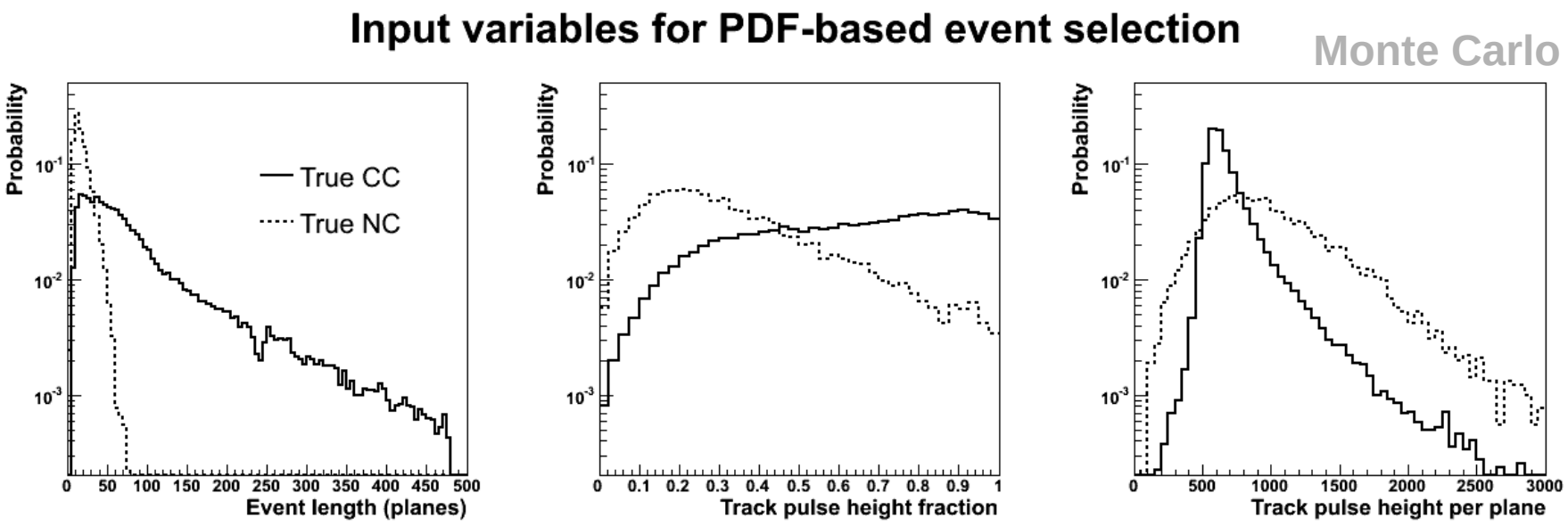
- ν_μ CC-like events are selected in the following way:
  1. Event must contain at least one good reconstructed track
  2. The reconstructed track vertex should be within the fiducial volume of the detector:
     - NEAR: 1m < z < 5m (z measured from the front face of the detector), R< 1m from beam centre.
     - FAR: z>50cm from front face, z>2m from rear face, R< 3.7m from centre of detector.



  3. The fitted track should have negative charge (selects ν_μ)
  4. Cut on likelihood-based Particle ID parameter which is used to separate CC and NC events.

Selecting CC events

- Events are selected using a likelihood-based procedure, with three input Probability Density Functions (PDFs) that show differences for True CC and NC interactions:
  - **Event length in planes** (*related to muon momentum*)
  - **Fraction of event pulse height in the reconstructed track** (*related to the inelasticity of CC events*)
  - **Average track pulse height per plane** (*related to dE/dX of the reconstructed track*)
- The probability that a event with particular values of these three variables is CC or NC (P_μ and P_{NC} respectively) is then the product of the three CC PDFs and the three NC PDFs at those values

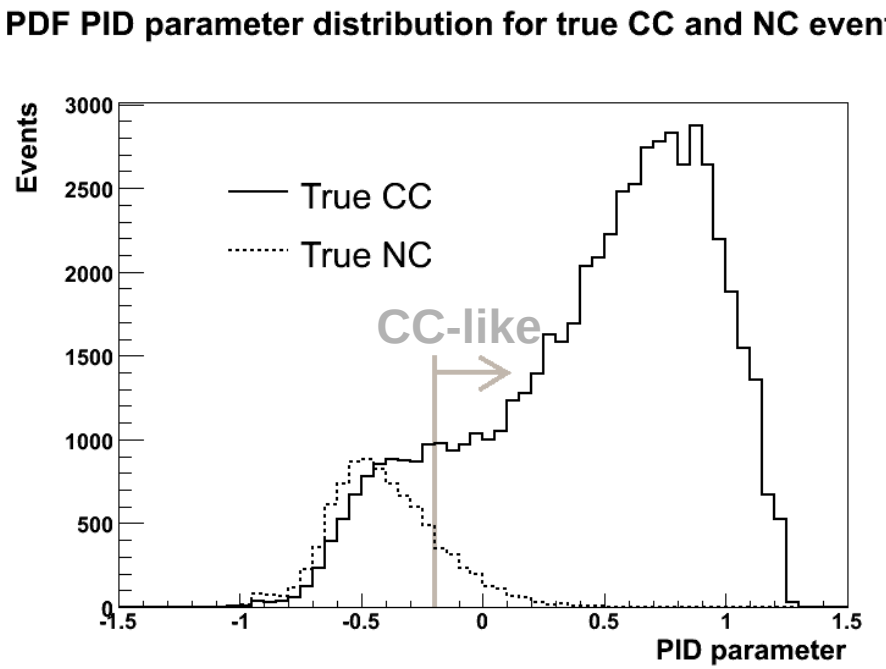


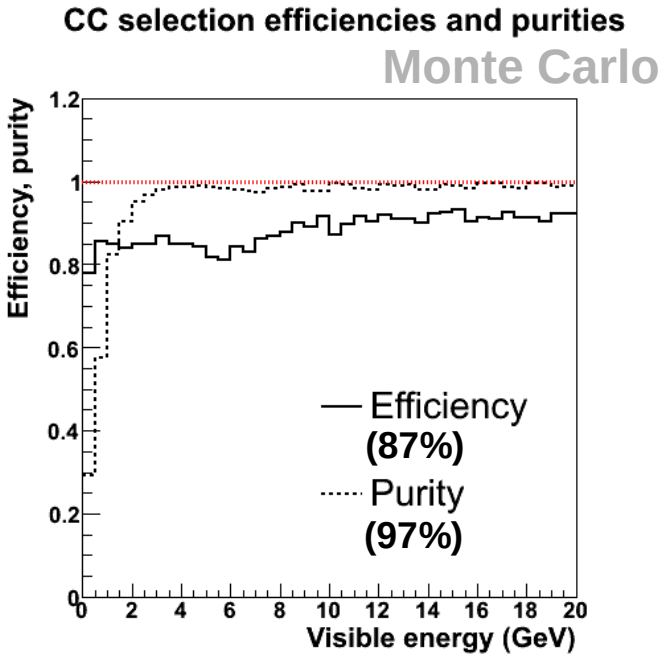
CC selection efficiencies

- The Particle ID (PID) parameter is defined thus:

$$PID = -(\sqrt{-\log(P_\mu)} - \sqrt{-\log(P_{NC})})$$

- CC-like events are defined by the cut PID>-0.2 in the FD (>-0.1 in the ND)
  - NC contamination is limited to the lowest visible energy bins (below 1.5 GeV)
  - Selection efficiency is quite flat as a function of visible energy





Far detector Oscillation Analysis with 0.93e20 pot

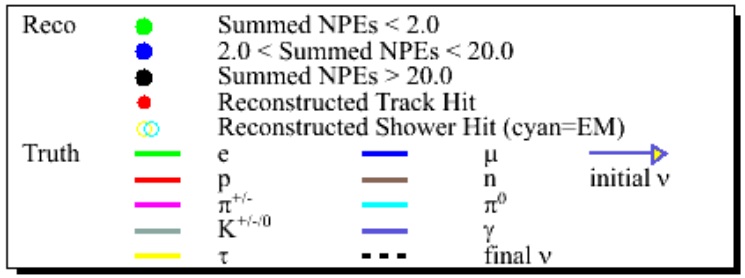
Performing a blind analysis

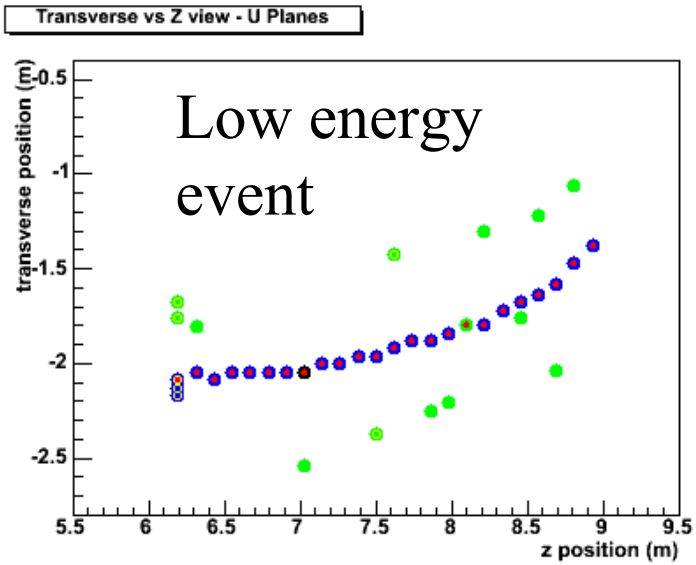
- The MINOS collaboration decided to pursue a "blind" analysis policy for the first accelerator neutrino results
  - **The blinding procedure hides an unknown fraction of our events based on their length and total energy deposition**.
- Unknown fraction Far Detector Data was "open" - used them to perform extensive data quality checks.

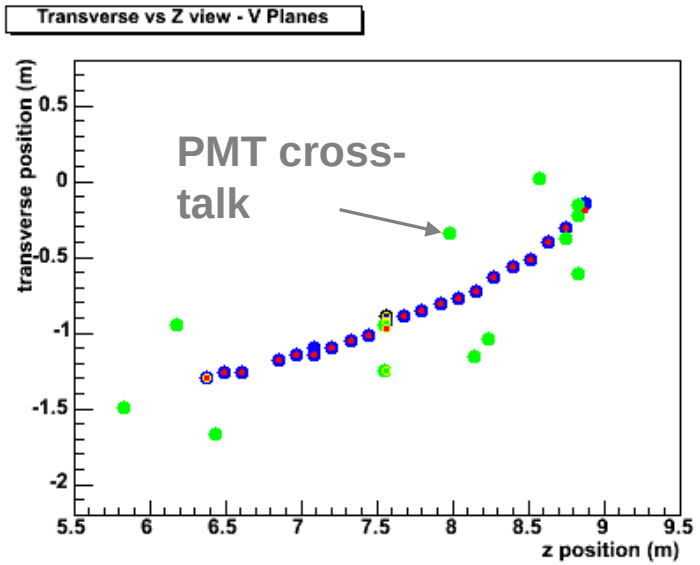
- Remaining fraction was "hidden". Final analyses were performed on total sample once Box was opened**.** Box opening criteria were:
  - **Checks on open sample should indicate no problems with the FD beam dataset (missing events, reconstruction problems etc.)**
  - **Oscillation analysis (cuts and fitting procedures) should be pre-defined and validated on MC. No re-tuning of cuts allowed after box opening**

Example event – 2 GeV ν_μ CC

Run: 32133, Snarl: 97235, Slice: 1(/1), Event 1(/1)
Reco
#Trks: 1
#Shws: 2
q/p: -0.517 +/- 0.034, p/q: -1.935
TrkRangeEnergy: 2.042 RecoShwEnergy: 0.196
Vtx: -0.52, -2.42, 6.20

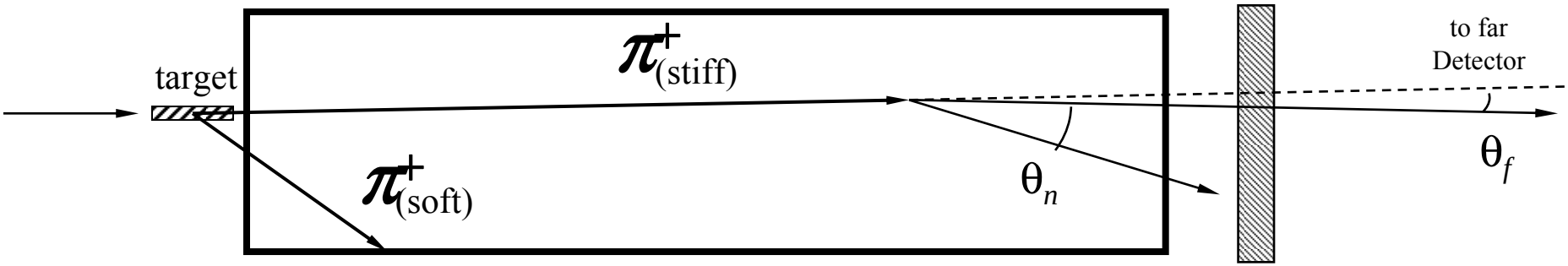






Predicting the unoscillated FD spectrum

- Directly use the Near detector data to perform the extrapolation between Near and Far, **using our Monte Carlo to provide necessary corrections due to energy smearing and acceptance.**
- Use our knowledge of **pion decay kinematics and the geometry of our beamline** (extended neutrino source, seen as point-like from the Far Detector) **to predict the Far detector energy distribution from the measured Near detector distribution**



$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2 \qquad E_\nu = \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

- This method is known as the "**Beam Matrix**" method.

Schematic Description of the "Beam Matrix"Method

A) $E^{\text{Reconstructed}}_{Near\ \text{CC-like}} \Rightarrow E^{True}_{Near\ \text{CC}}$

Correction for purity, Reconstructed =>True, Correction for efficiency

B) $E^{True}_{Near\ \text{CC}} \Rightarrow E^{True}_{Far\ \text{CC}}$

BEAM MATRIX

C) $E^{True}_{Far\ \text{CC}} \Rightarrow E^{\text{Reconstructed}}_{Far\ \text{CC-like}}$

i) Oscillation, True => Reconstructed, Correction for efficiency to obtain CC oscillated spectrum

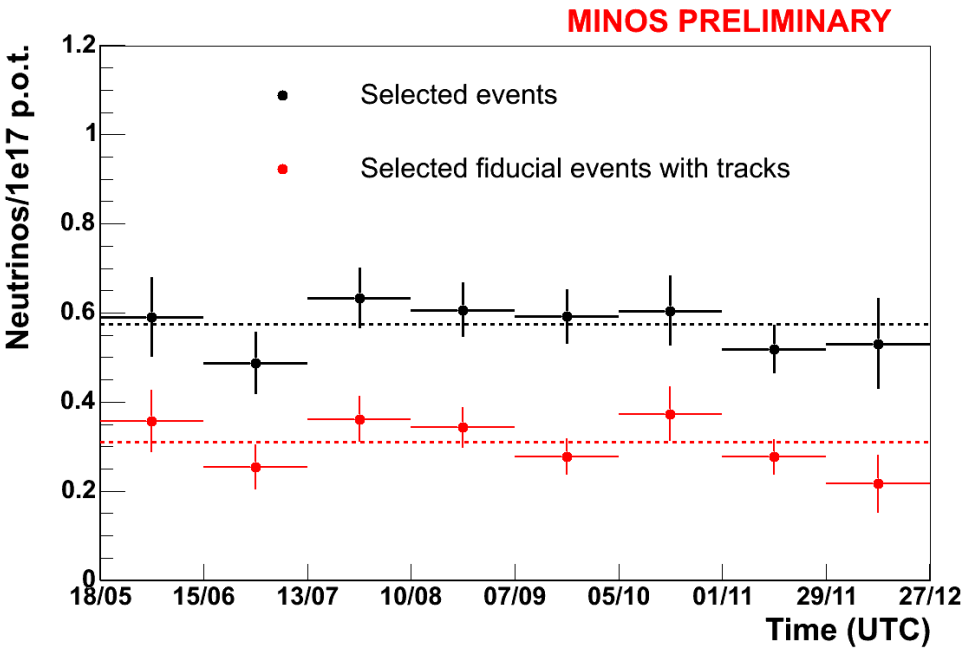
ii) Unoscillated True => Reconstructed, Use purity to obtain NC background

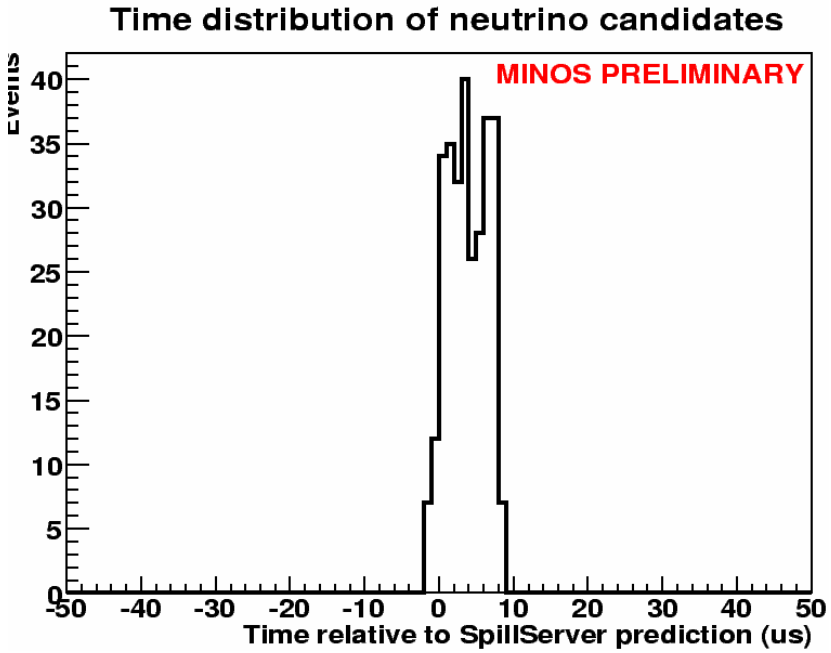
Box opening

- **After extensive checks on the open dataset, the collaboration decided that we had sufficient confidence in the FD data.**
- **Our analysis methods had been fully validated on MC datasets.**
- **Therefore we could proceed to open the box and look at the full dataset (March 4th 2006)**

Full dataset

Far Detector Data





Breakdown of selected events

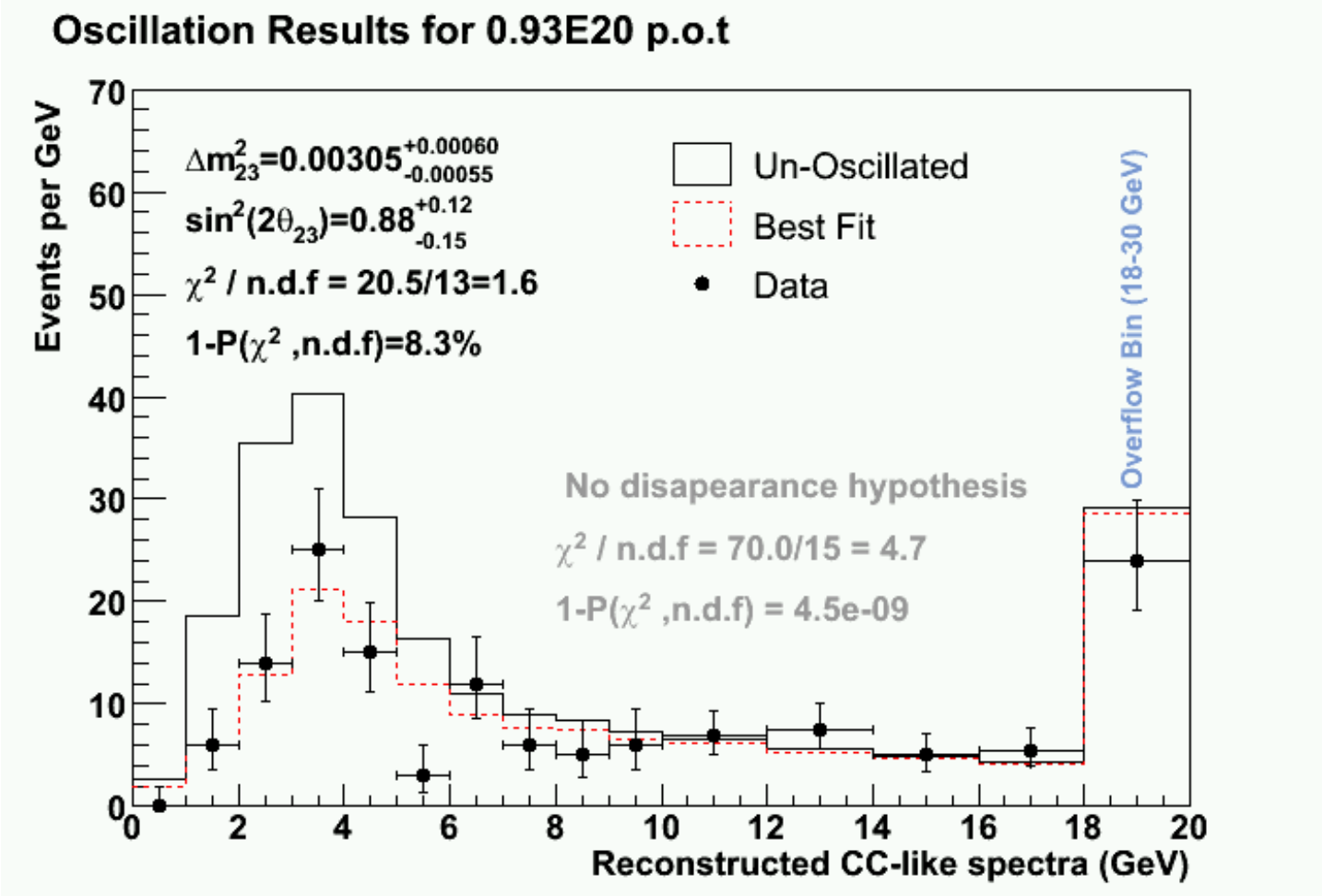
Cut	Events	efficiency
All events in fiducial vol	331	-
Events with a track	296	89.1%
Track quality cuts	281	95.3%
PID cut (CC-like)	204	72.9%
Track charge sign cut (negative muons only)	186	91.2%
Reconstructed energy < 30 GeV	166	89.2%

Numbers of observed and expected events

Data sample	observed	expected	ratio	significance
All CC-like events ($\nu_\mu+\bar{\nu}_\mu$)	204	298±15	0.69	4.1σ
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10 GeV)	92	177±11	0.52	5.0σ

- We observe a 33% deficit of events between 0 and 30 GeV with respect to the no oscillation expectation.
  - Numbers are consistent for $\nu_\mu+\bar{\nu}_\mu$ sample and for the ν_μ-only sample
- **The statistical significance of this effect is 5 standard deviations**

Best-fit spectrum

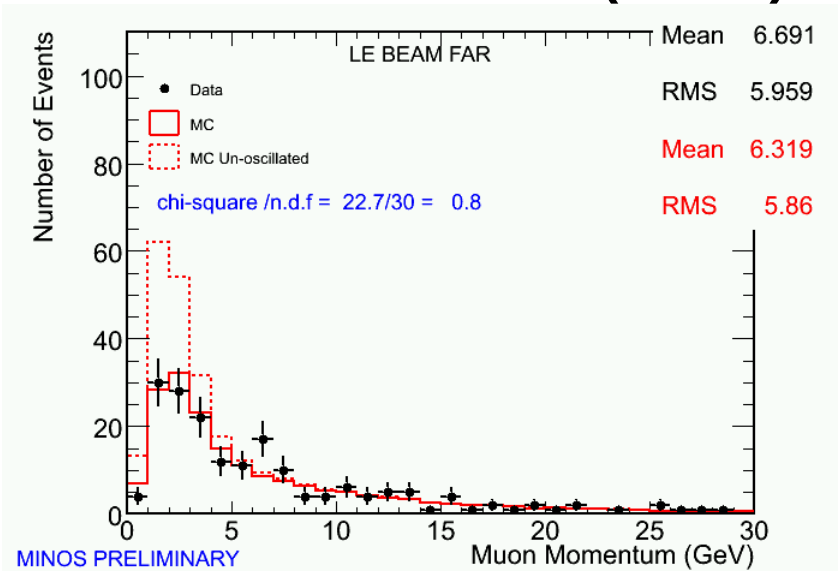


$$\chi^2(\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i / e_i)$$

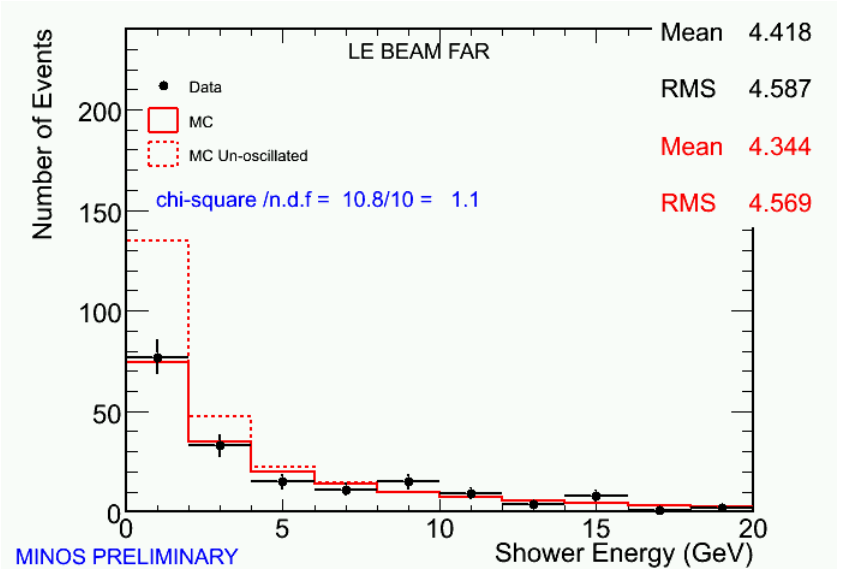
- Measurement errors are 1 sigma, 1 d.o.f.

Physics distributions

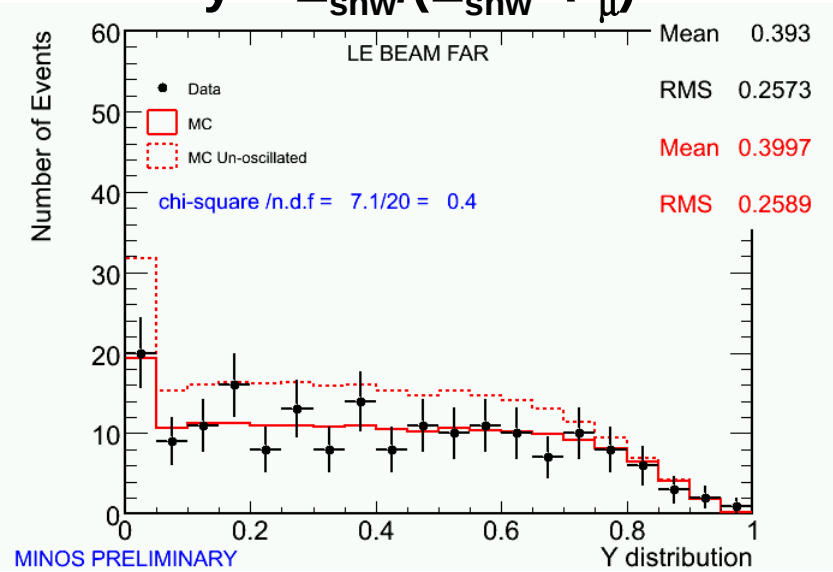
Muon Momentum (GeV/c)



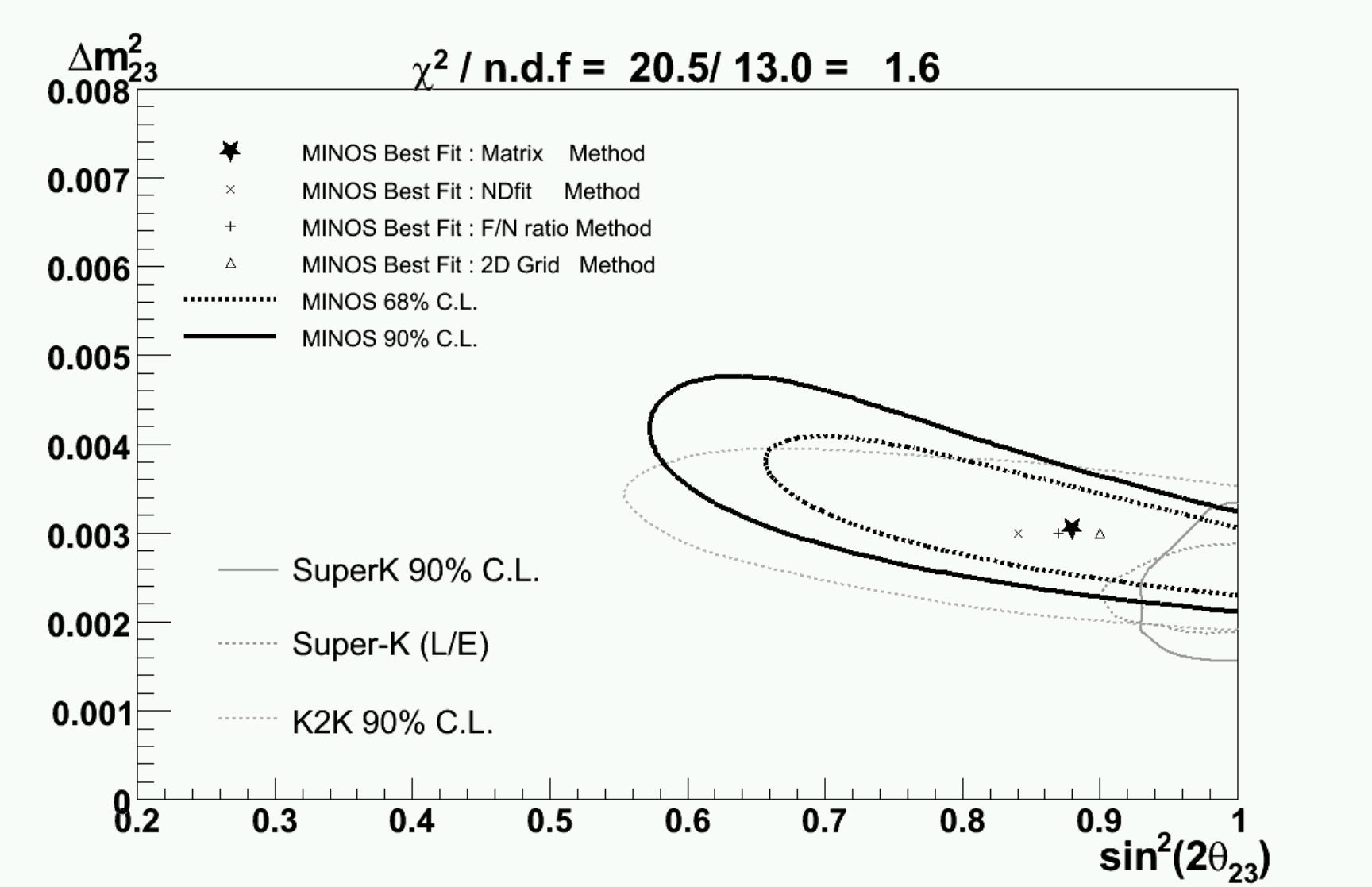
Shower Energy (GeV)



$y = E_{shw}/(E_{shw}+P_{\mu})$

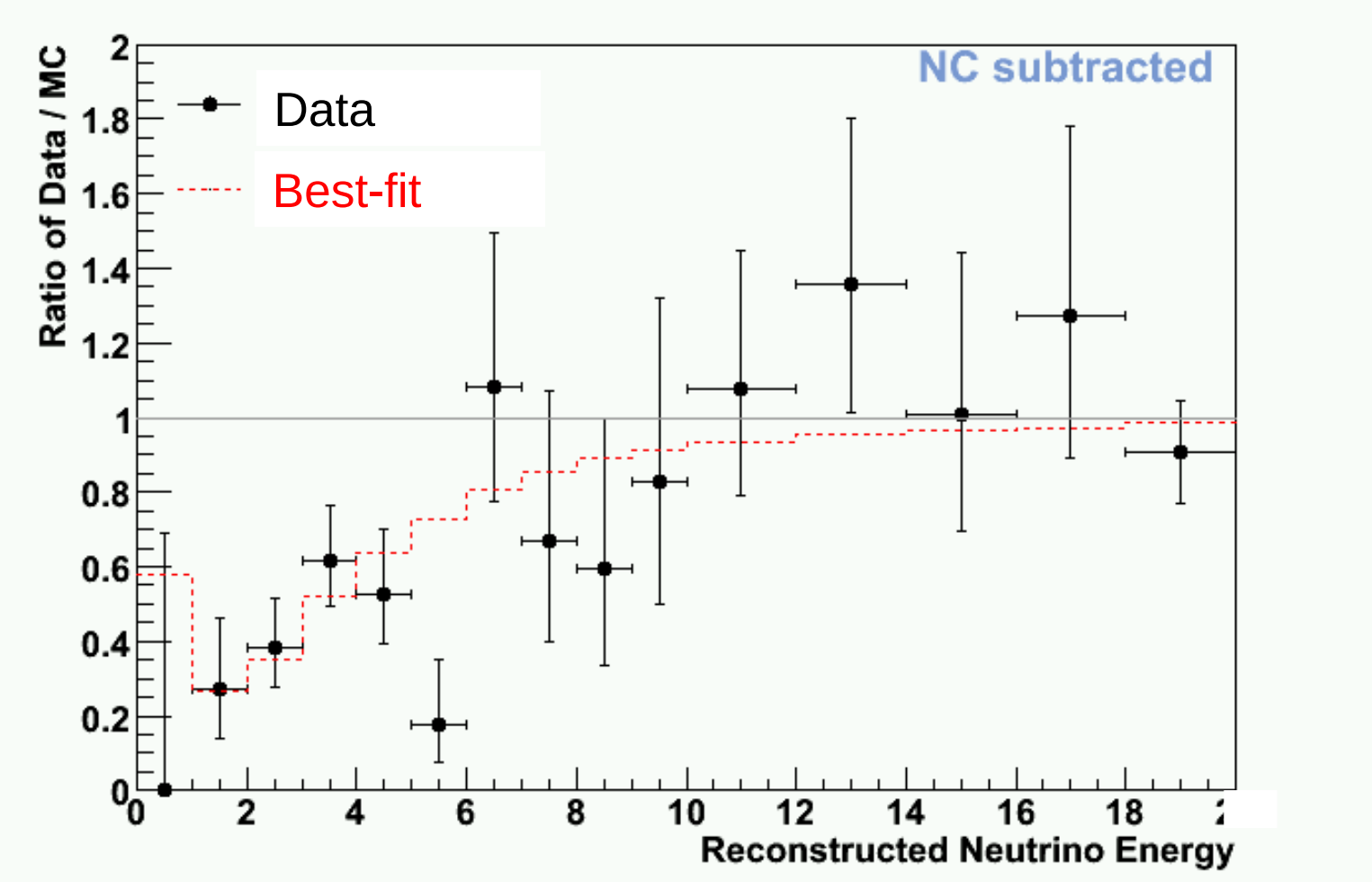


Allowed regions



- **The results of the four different extrapolation methods are in excellent agreement with each other.**

Ratio of Data/MC



- Data is quite well-described by the best-fit oscillation hypothesis

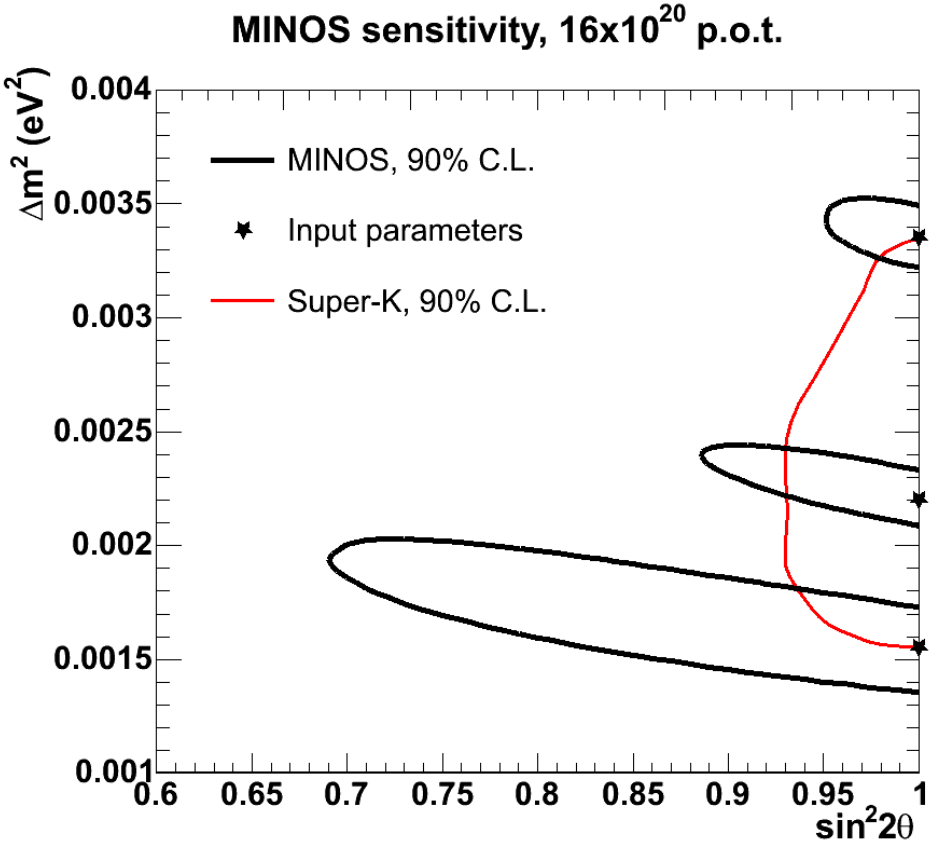
Systematic errors

- Systematic shifts in the fitted parameters have been computed with MC "fake data" samples for $\Delta m^2=0.003$ eV^2, $\sin^2 2\theta=0.9$ for the following uncertainties:

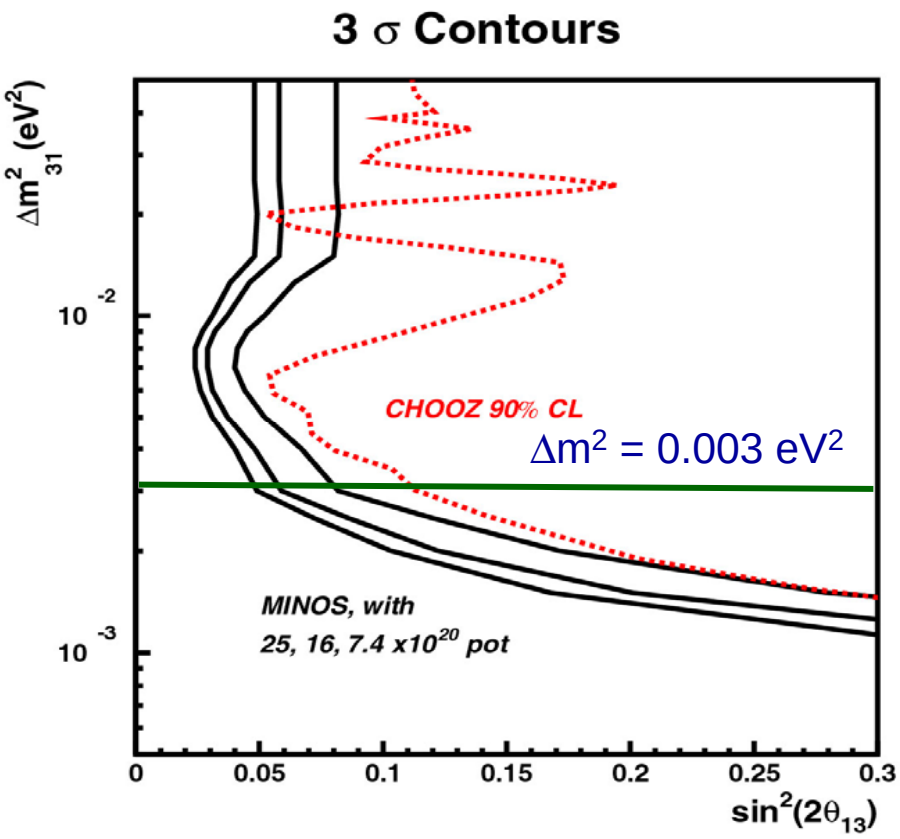
Uncertainty	Δm^2 shift (eV^2)	$\sin^2 2\theta$ shift
Normalisation +/- 4%	0.63e-4	0.025
Muon energy scale +/- 2%	0.14e-4	0.020
Relative Shower energy scale +/- 3%	0.27e-4	0.020
NC contamination +/- 30%	0.77e-4	0.035
CC cross-section uncertainties	0.50e-4	0.016
Beam uncertainty	0.13e-4	0.012
Intranuclear re-scattering	0.27e-4	0.030
Total (sum in quadrature)	**1.19e-4**	**0.063**
Statistical error (data)	**6.4e-4**	**0.15**

Projected sensitivity of MINOS

ν_μ disappearance



$\nu_\mu \rightarrow \nu_e$

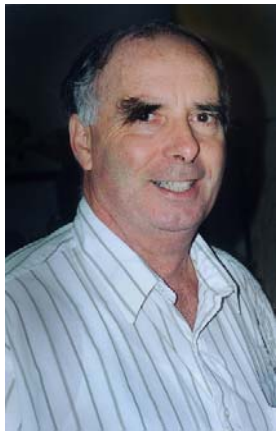


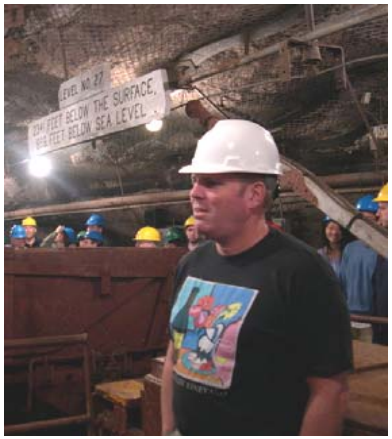
- With increased statistics, we should be able to make a very precise measurement of Δm^2_{23} and also search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations well-below the current exclusion limit
- In addition, by making a precise measurement of the CC spectrum, we should be able to test/rule out alternate models such as neutrino decay.

Dedication

Lynn Miller

Michael Murtagh



Julia Thompson

Doug Michael