Padova

5 settembre 2001

Neutrini @ LP01

Marco Laveder

Università & INFN, Padova

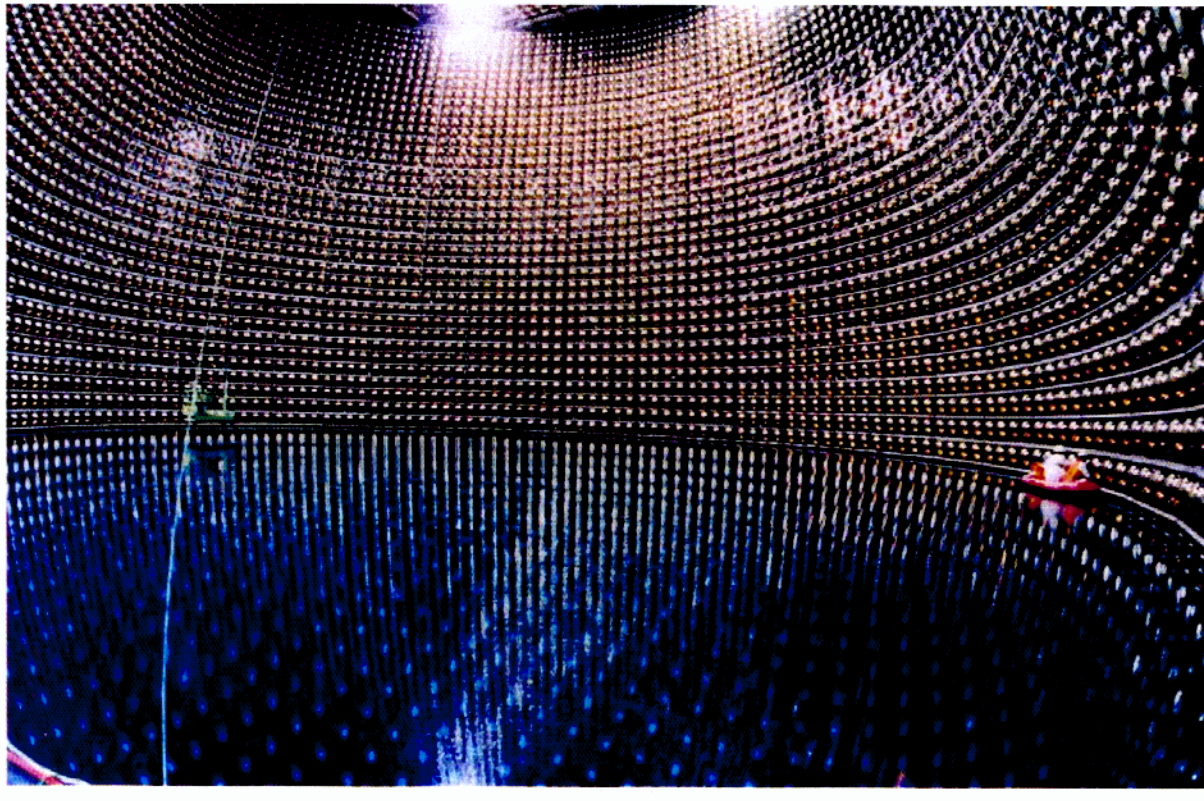
Outline

- Results from SK
- Results from K2K
- Results from SNO NEW
- Impact of SNO on Solar Neutrino Oscillations
- Results from NOMAD
- Interpretations of Neutrino Data
- Conclusions

Results from Super-K

Jordan A. Goodman
University of Maryland
LP01 – July 2001

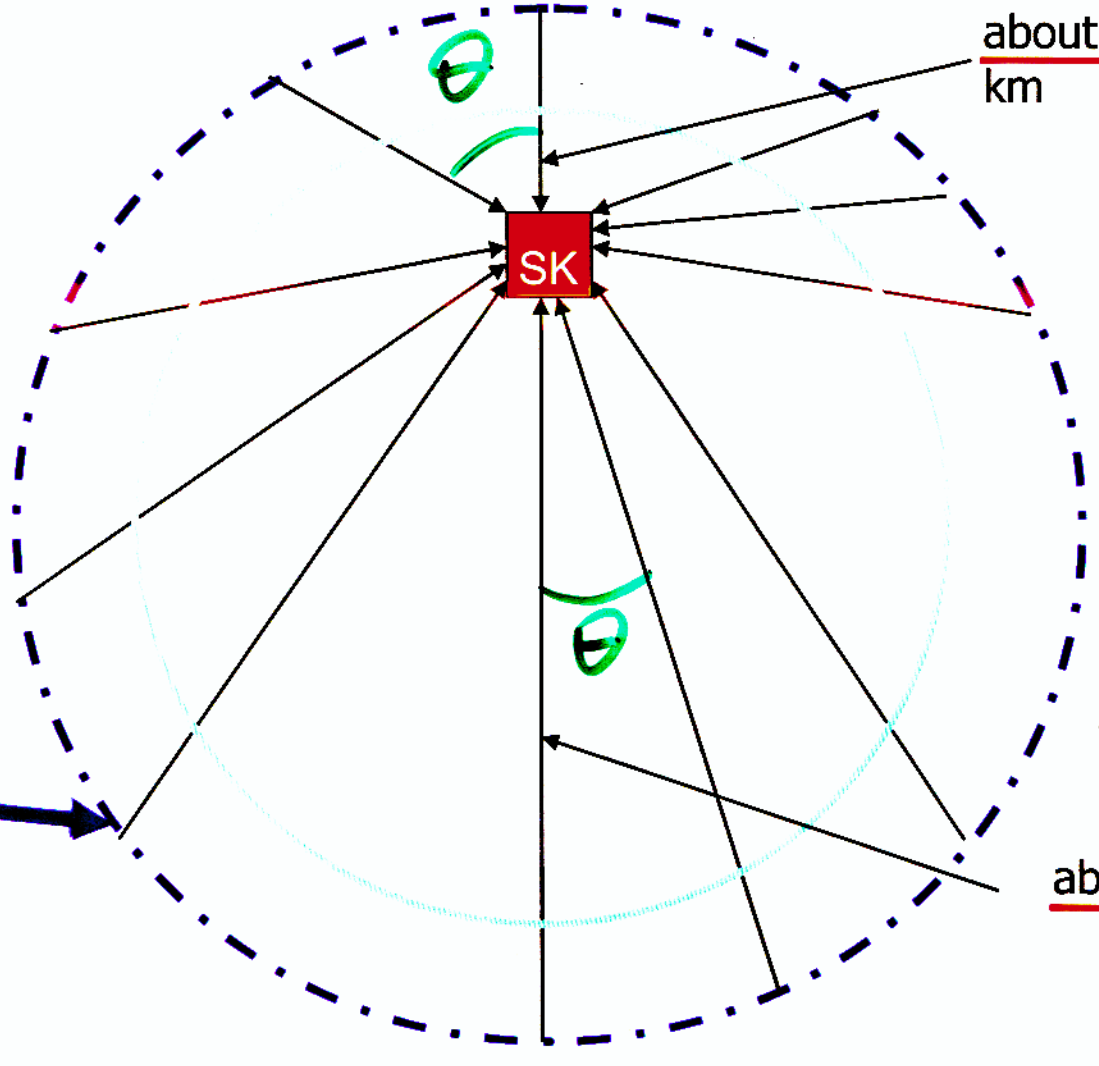
- Super-K
- Atmospheric ν's
  - Data & Results
- Solar ν's
  - Data & Results



Super-K is a 50,000 ton water Cherenkov detector. START data taking in April 1996.

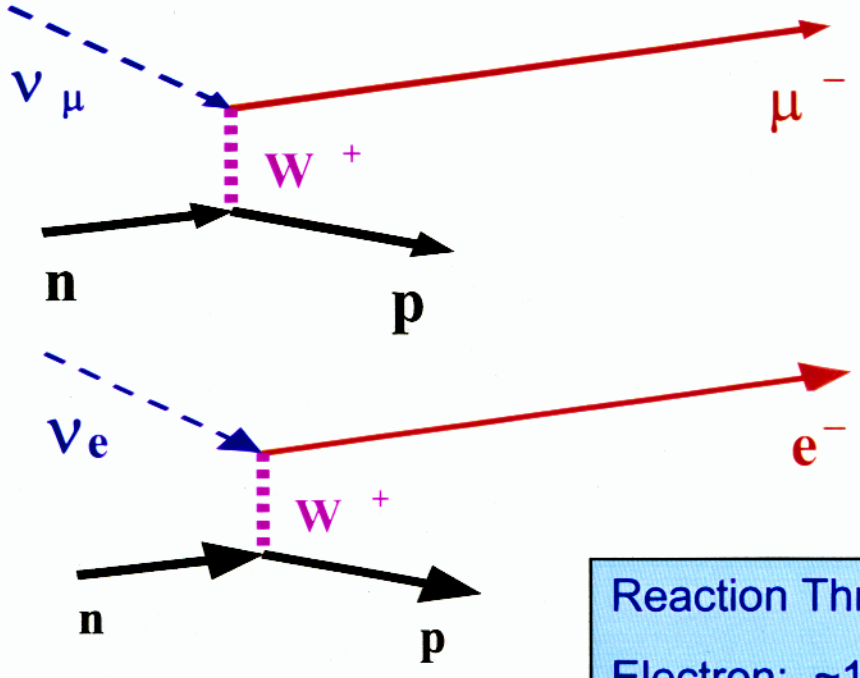
Atmospheric Oscillations

We look for ν transformations by looking at νs with different distances from production



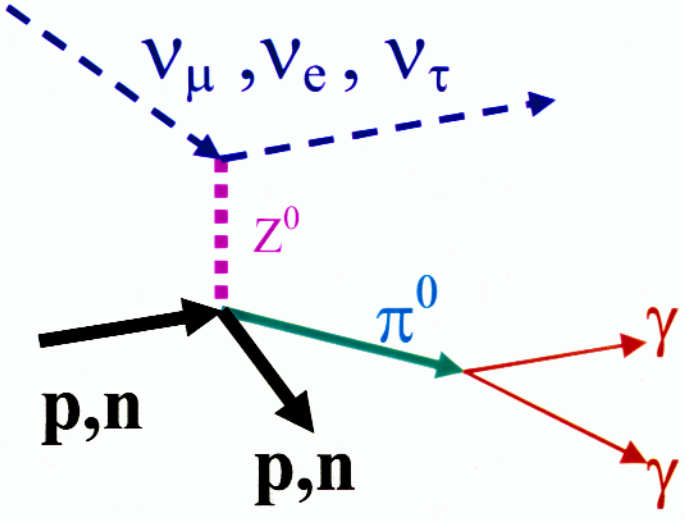
Neutrinos produced in the atmosphere

Atmospheric Neutrino Interactions



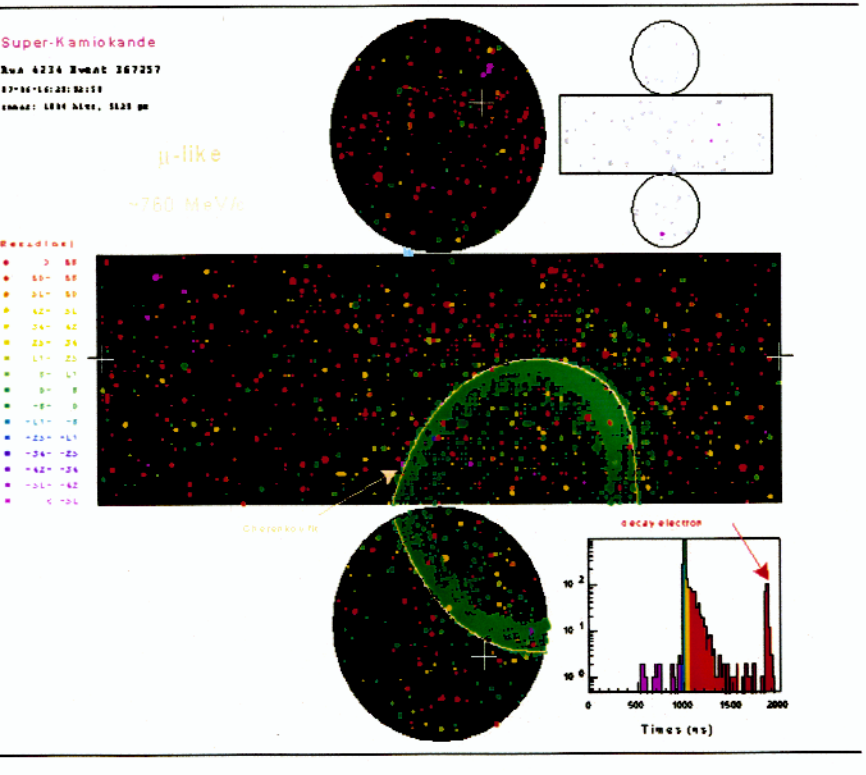
Charged Current

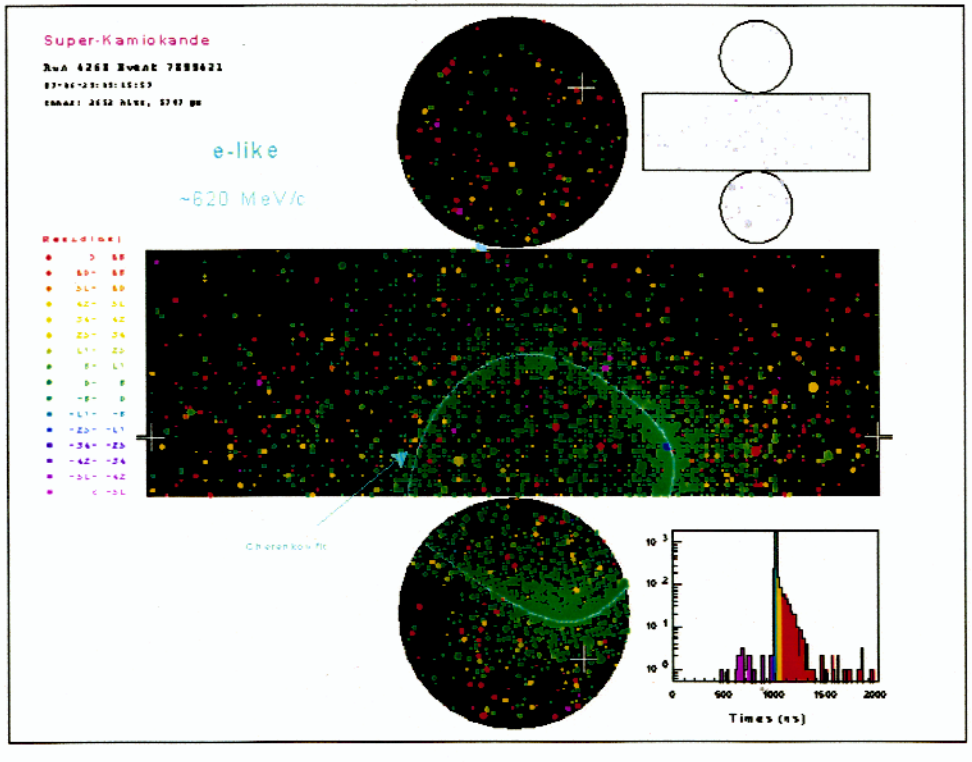
Reaction Thresholds	
Electron:	~1.5 MeV
Muon:	~110 MeV
Tau:	~3500 MeV



Neutral Current

Muon - Electron Identification





muon

electron

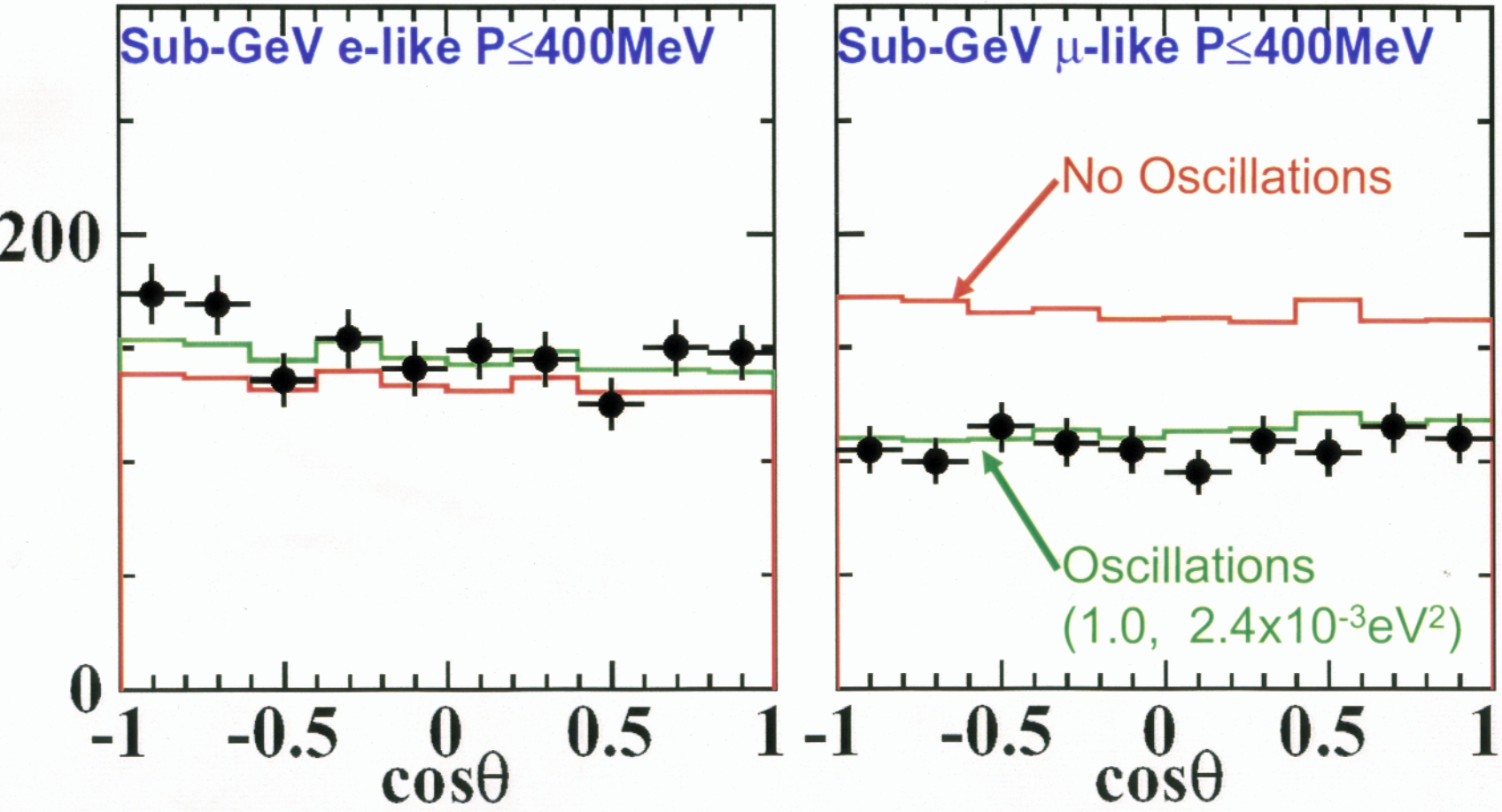
(e/π° separation)

$E_{vis} < 1.4$ GeV - Single Ring

89 days

Low Energy Sample

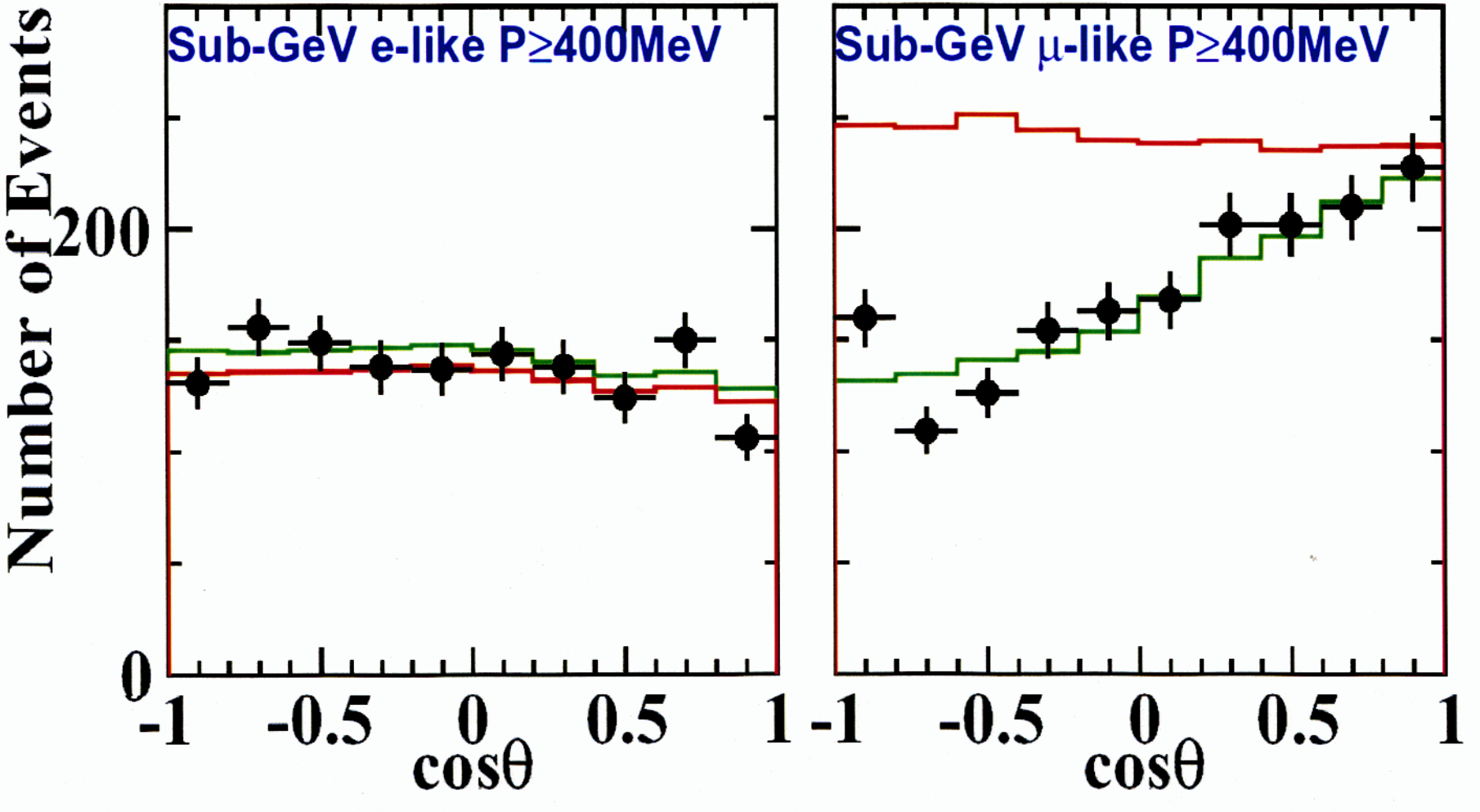
22.5 Kton fiducial



Global χ^{2}_{min} = 132.4 / 137 d.o.f for ν_μ to ν_τ

at ($\sin^2 2\theta$, Δm^2) = (1.00 , 2.4×10^{-3} eV^2)

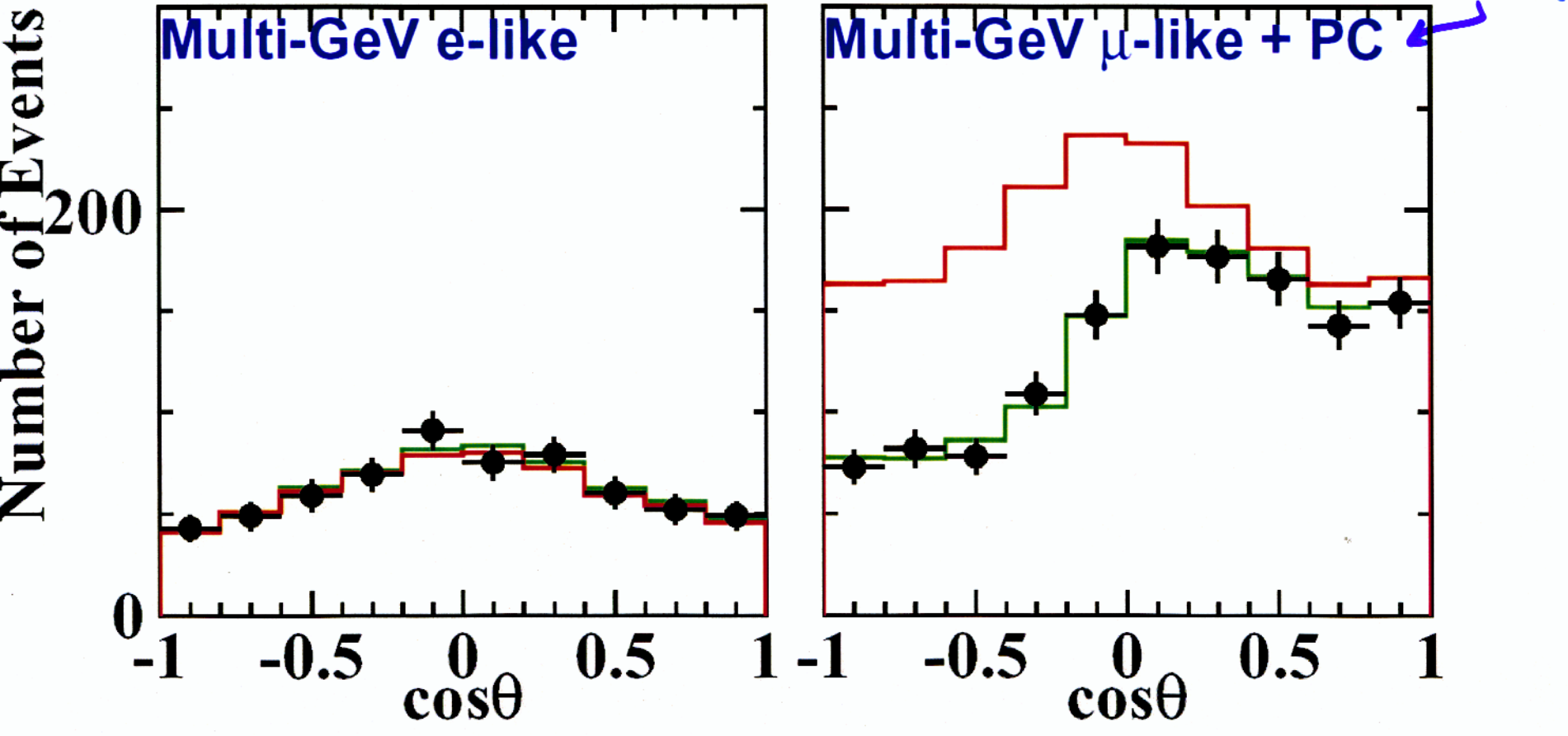
Moderate Energy Sample



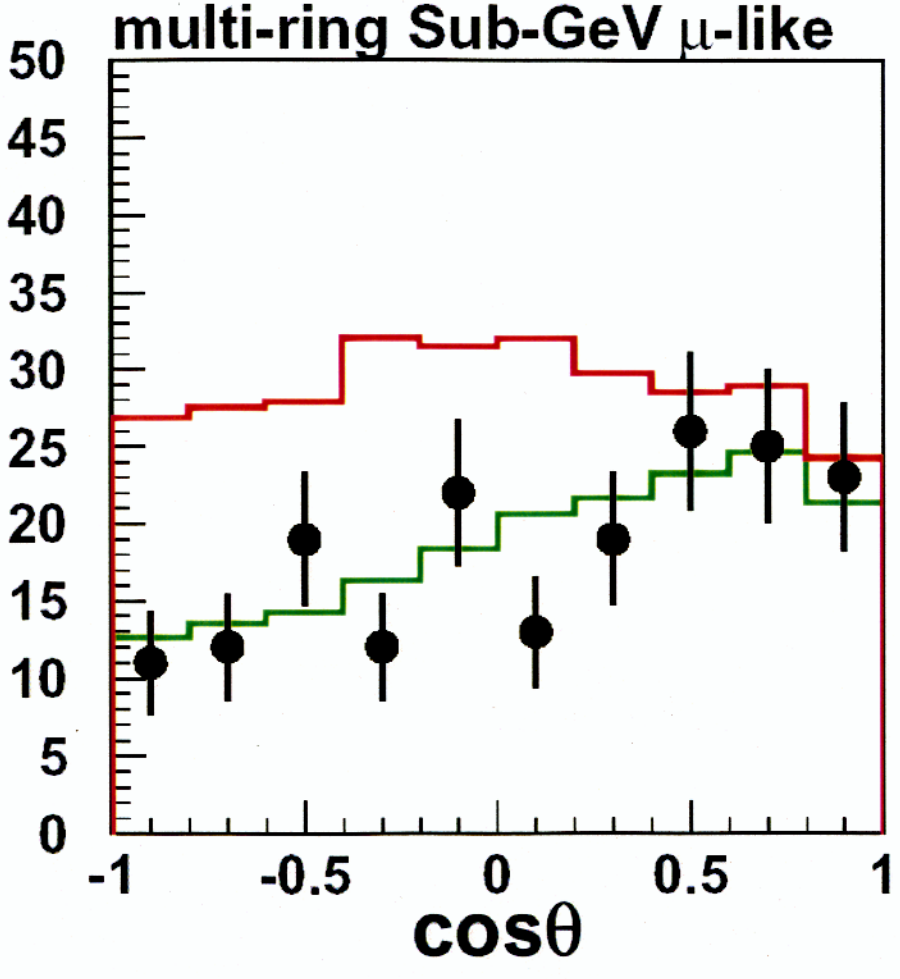
$E_{vis} > 1.4$ GeV - Single Ring

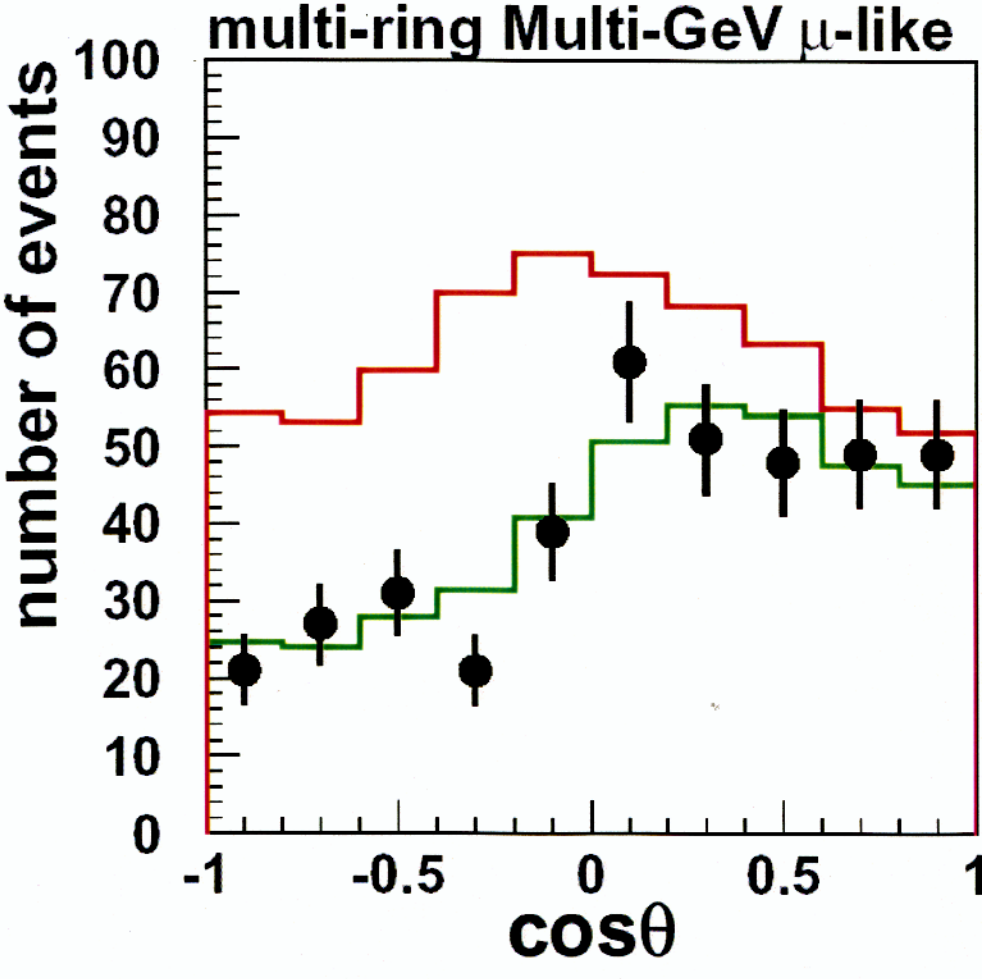
Multi-GeV Sample

Partially Contained

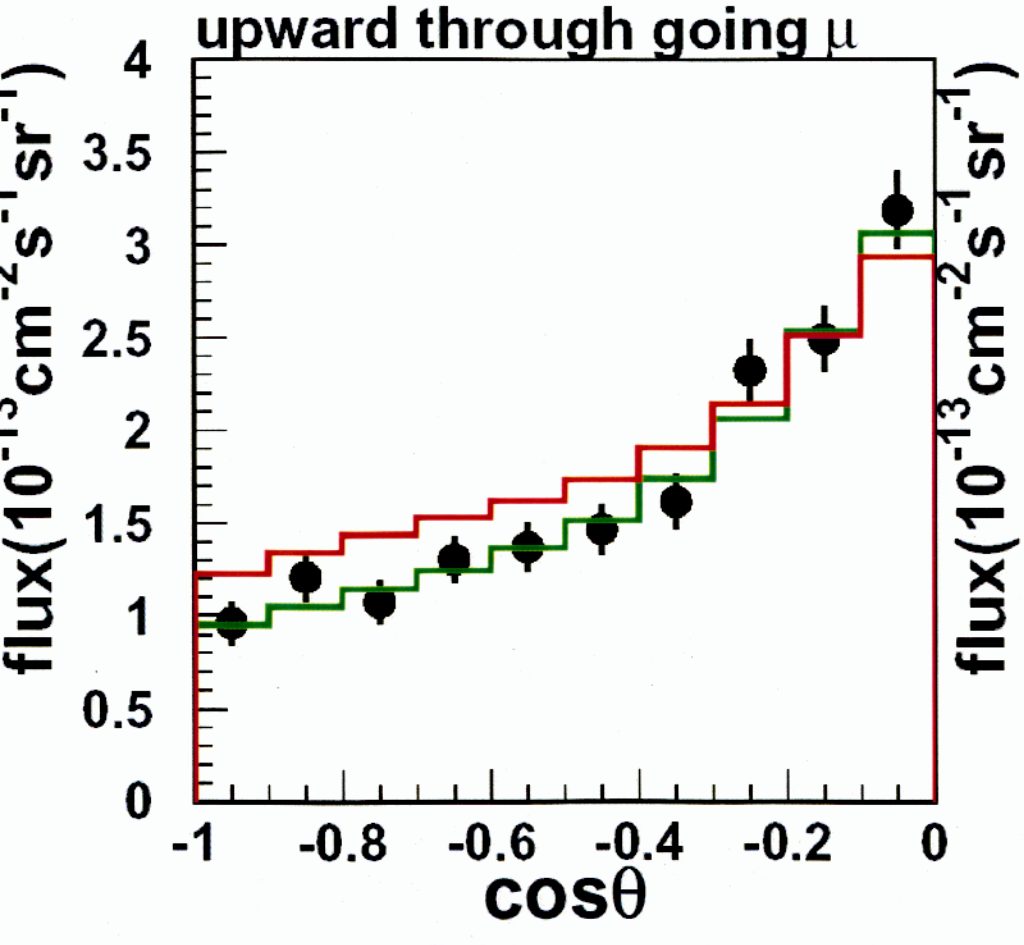


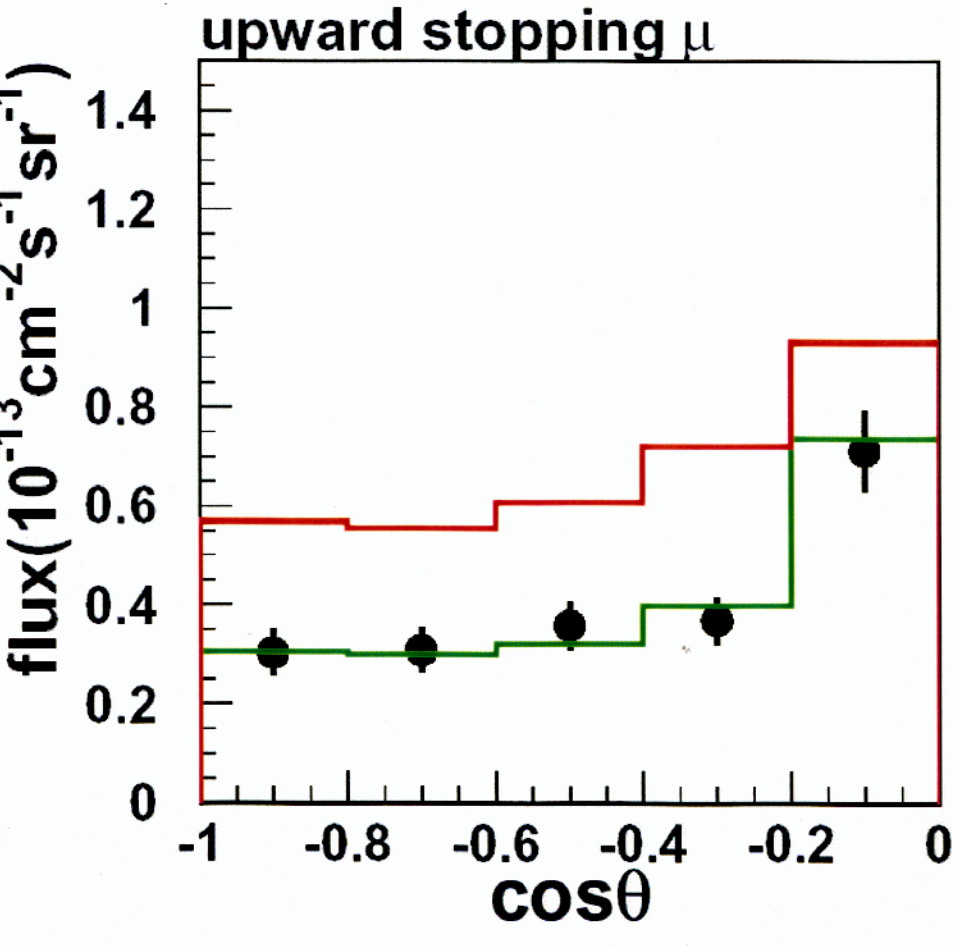
Multi-Ring Events



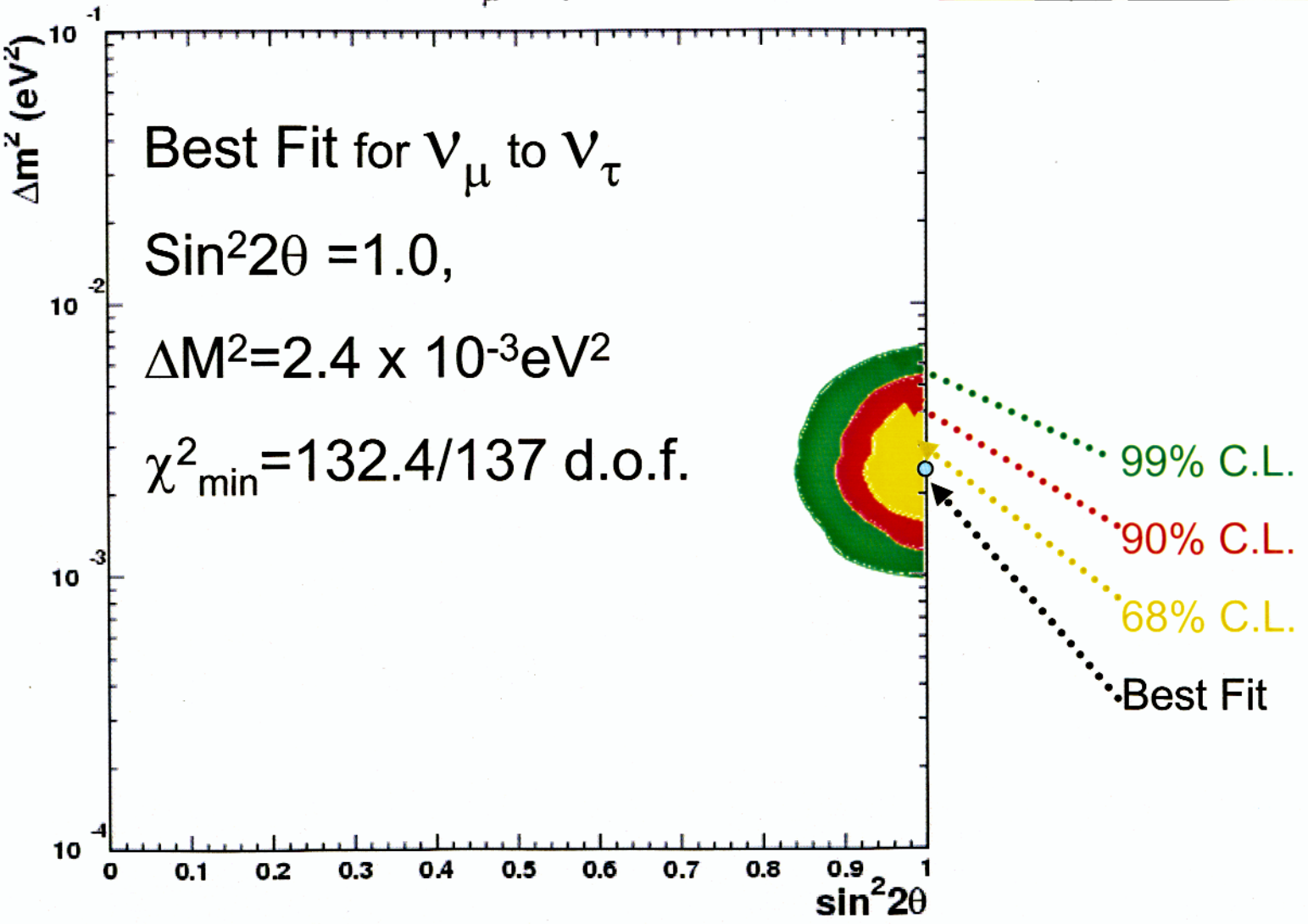


Upward Going Muons



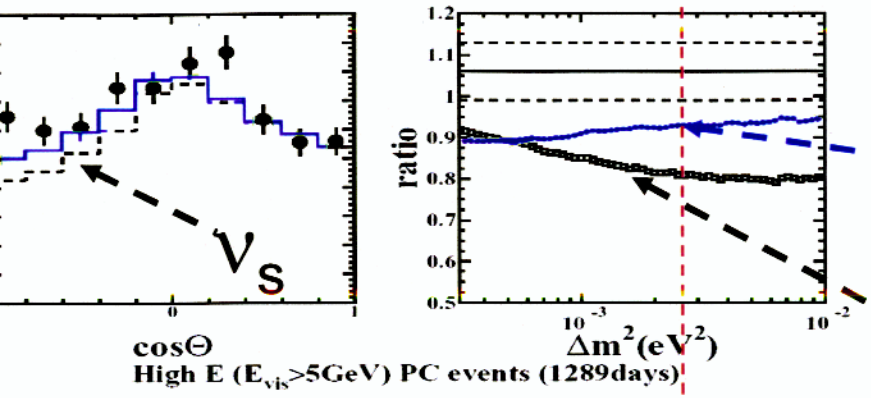


Summary of Atmospheric Results

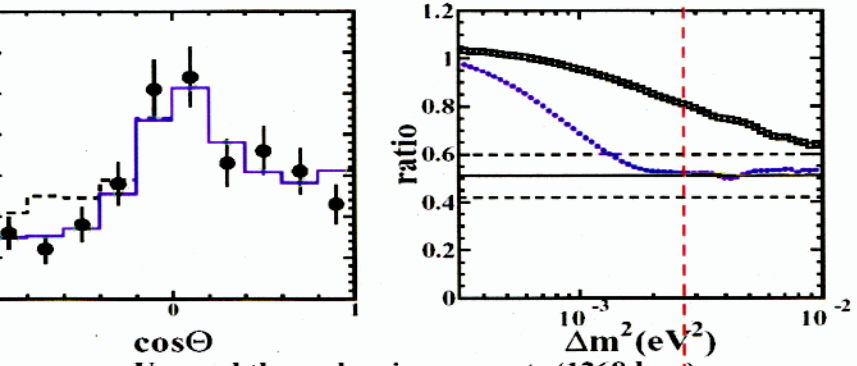


Tau vs Sterile Neutrino Analysis

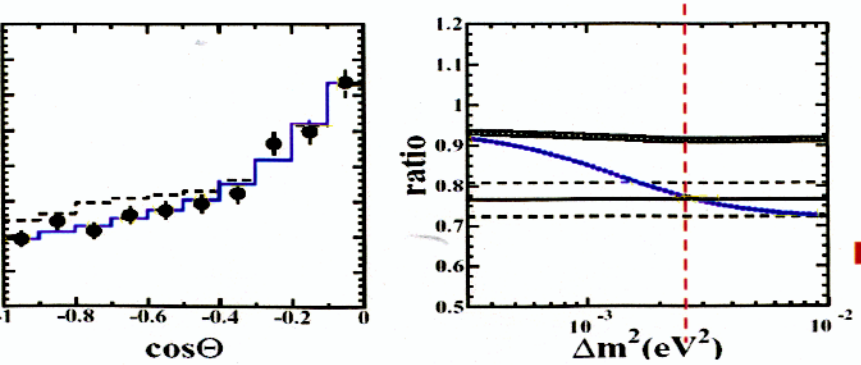
N.C. enriched multi-ring events (1289days)



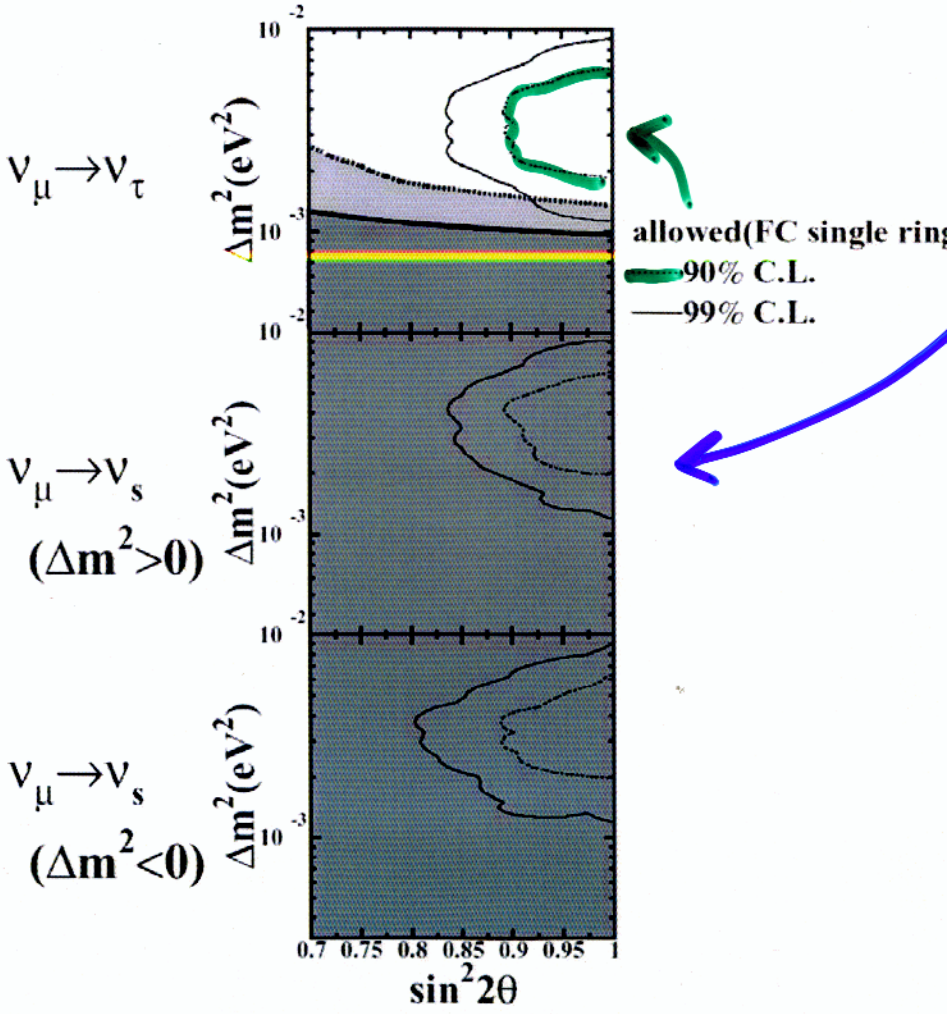
High E (E_{vis}>5GeV) PC events (1289days)



Upward through going μ events (1268days)



excluded region from combined analysis(multi+PC+upμ) (1289days)



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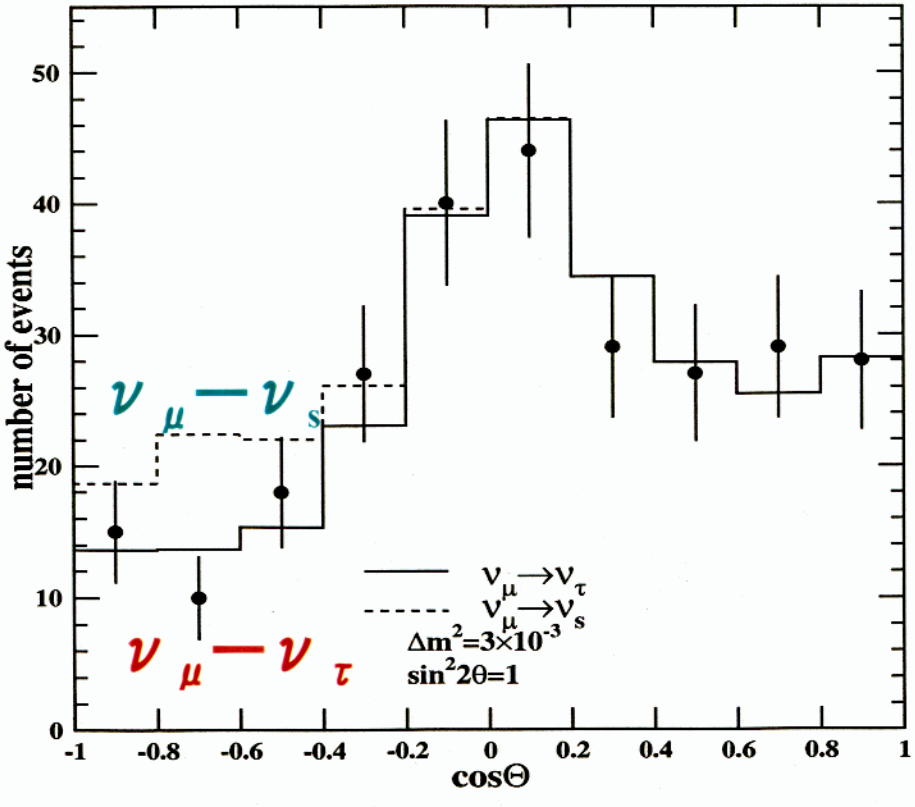
matter effect in the earth

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left(\frac{2VE_\nu}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

$\sin^2 2\theta \sim 1$, $E_\nu > 20$G

$\Rightarrow \sin^2 2\theta_m \ll 1$

zenith angle distribution of high E (E_{vis}>5GeV) PC events (1144days)

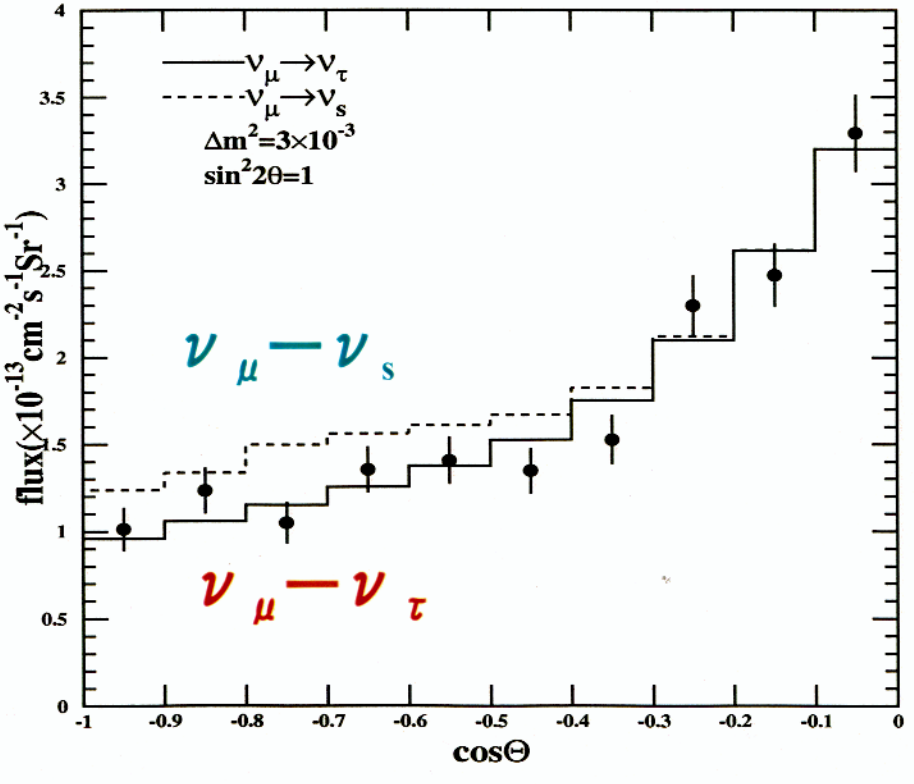


PC, Evis>5GeV

<E ν >$\sim$25GeV

up/down ratio

zenith angle distribution of upward through going μ events (1138days

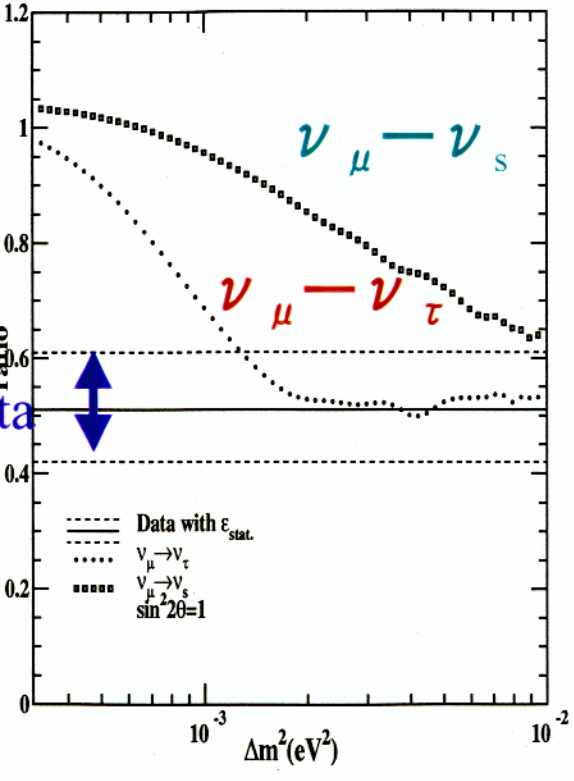


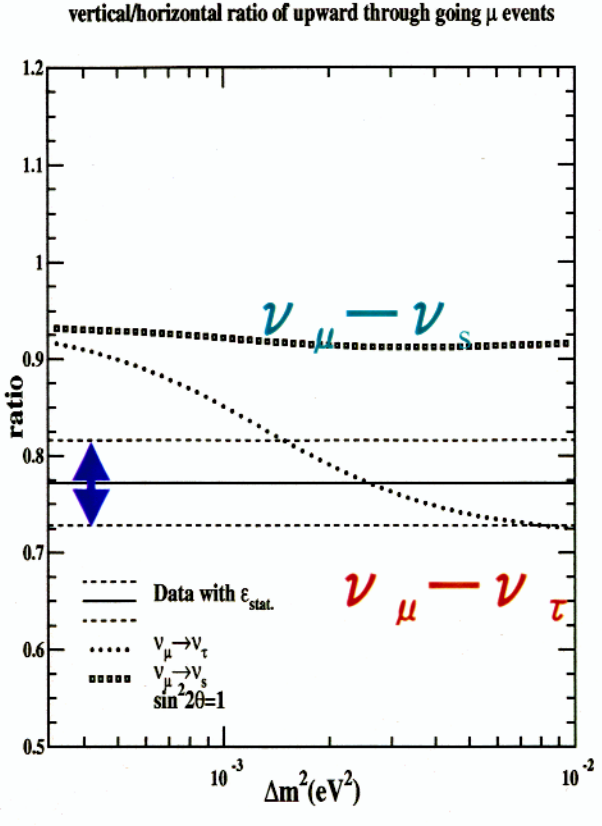
up through going μ

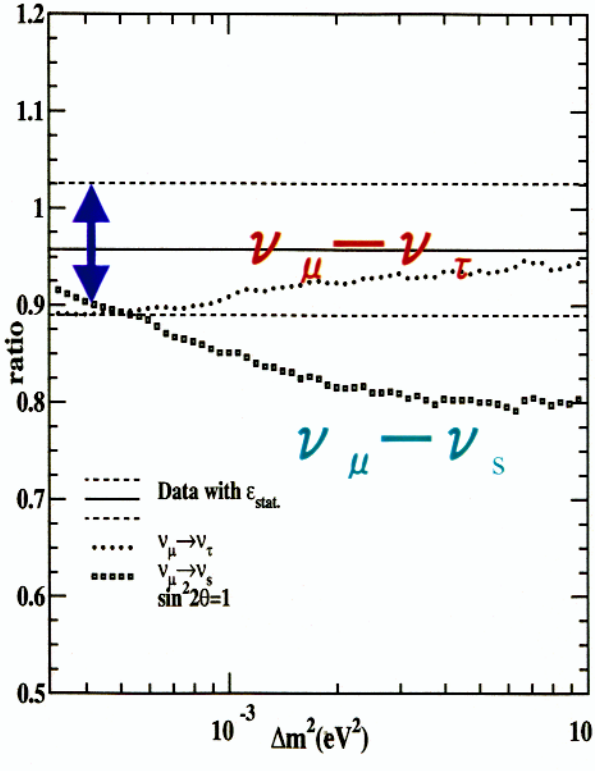
<E ν >$\sim$100GeV

vertical/horizontal ratio

$\nu_\mu - \nu_\tau$ v.s. $\nu_\mu - \nu_s$







high energy PC up/down ratio

up through μ vertical/horizontal ratio

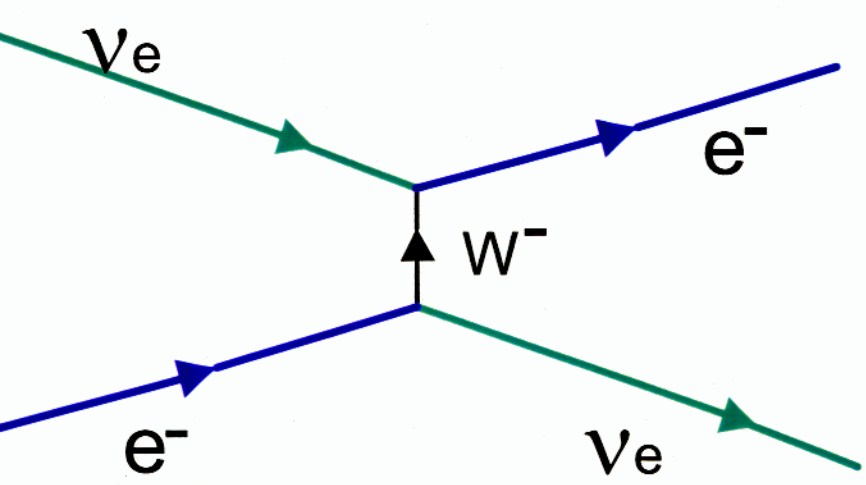
NC enrigh multi ring event up/down ratio

Tau Appearance?

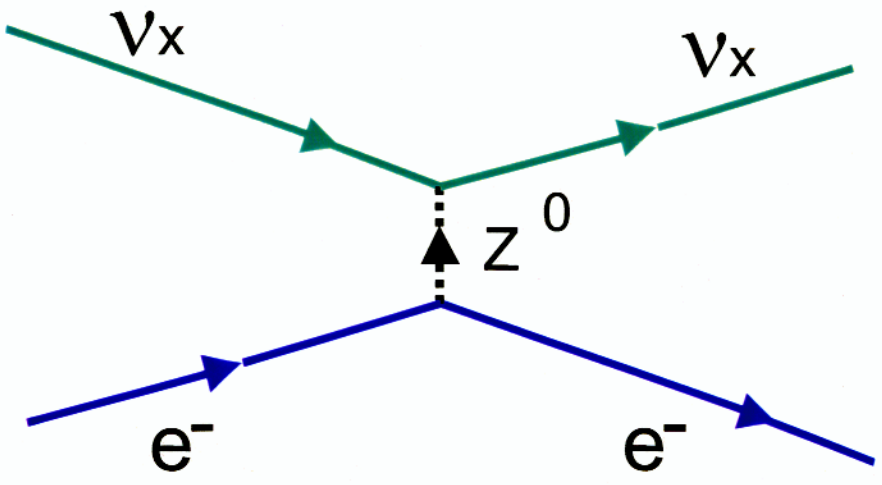
- Tau's require greater than 3 GeV in neutrino energy
  - This eliminates most events
- Three correlated methods were used
  - All look for enhanced upward going multi-ring events
- All show slight evidence for Tau appearance
- None are statistically significant

Analysis	ε_τ	fit #τ	σ_{exp}	σ
Likelihood	43%	$66 \pm 41_{stat}\,^{+25}_{-18}$	2.0	1.5
Neural Net	51%	$92 \pm 35_{stat}\,^{+17}_{-23}$	2.0	2.2
Energy Flow	32%	$79^{+44}_{-40}(stat+sys)$	1.9	1.8

Solar Neutrinos in Super-K



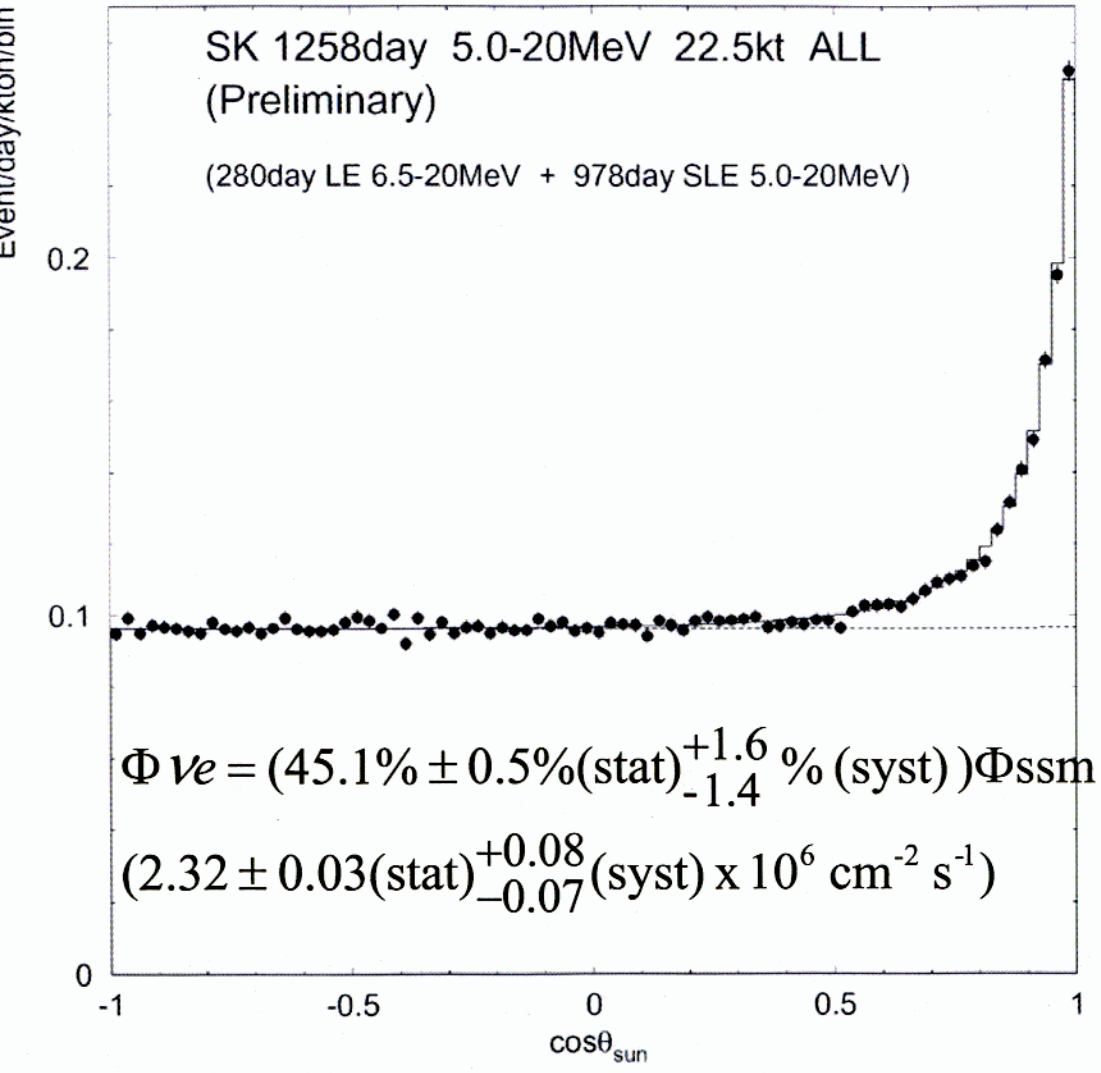
Charged Current
(electron ν's only)

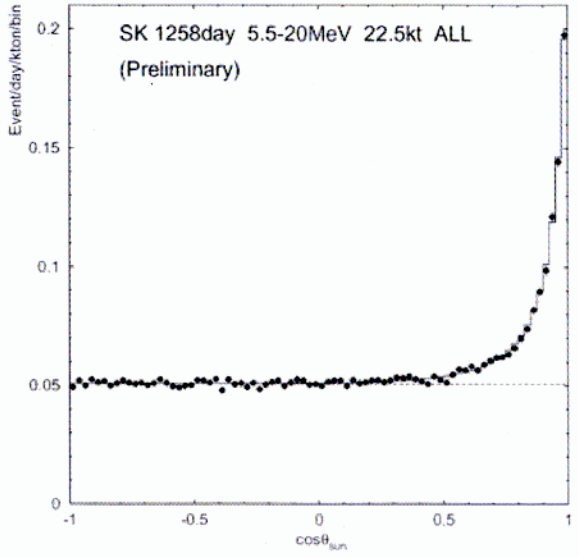


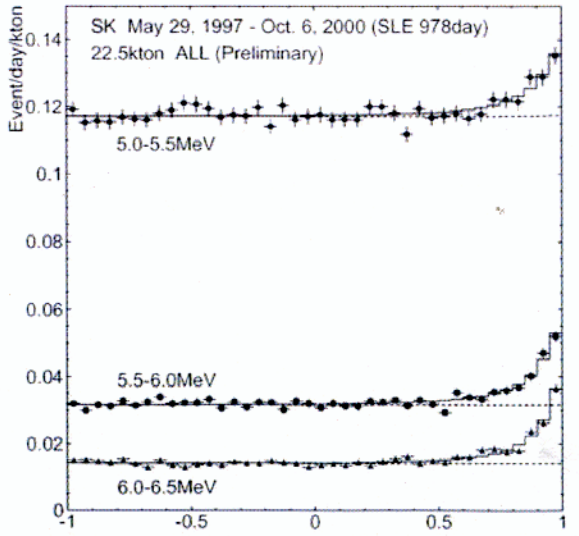
Neutral Current
(all ν flavors)

- The ratio of NC/CC cross section is ~1/6.5

Solar Neutrinos

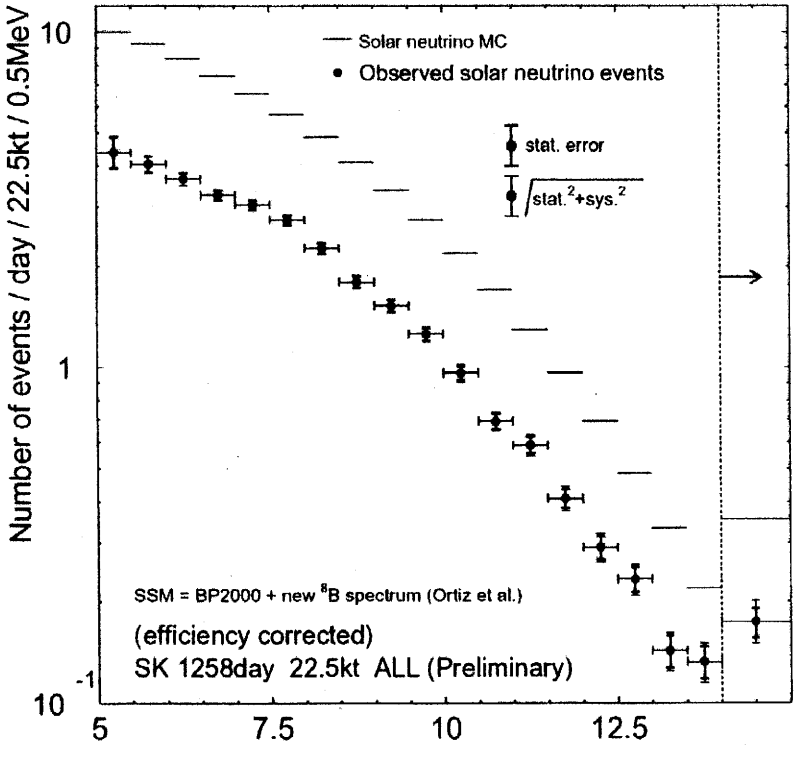


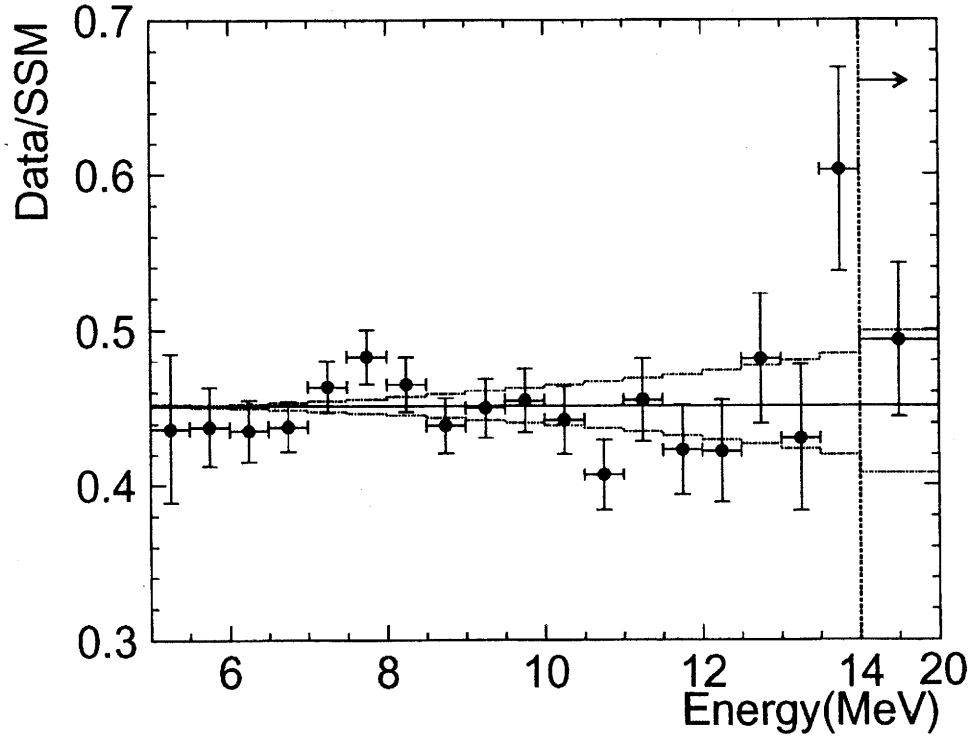




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Energy Spectrum

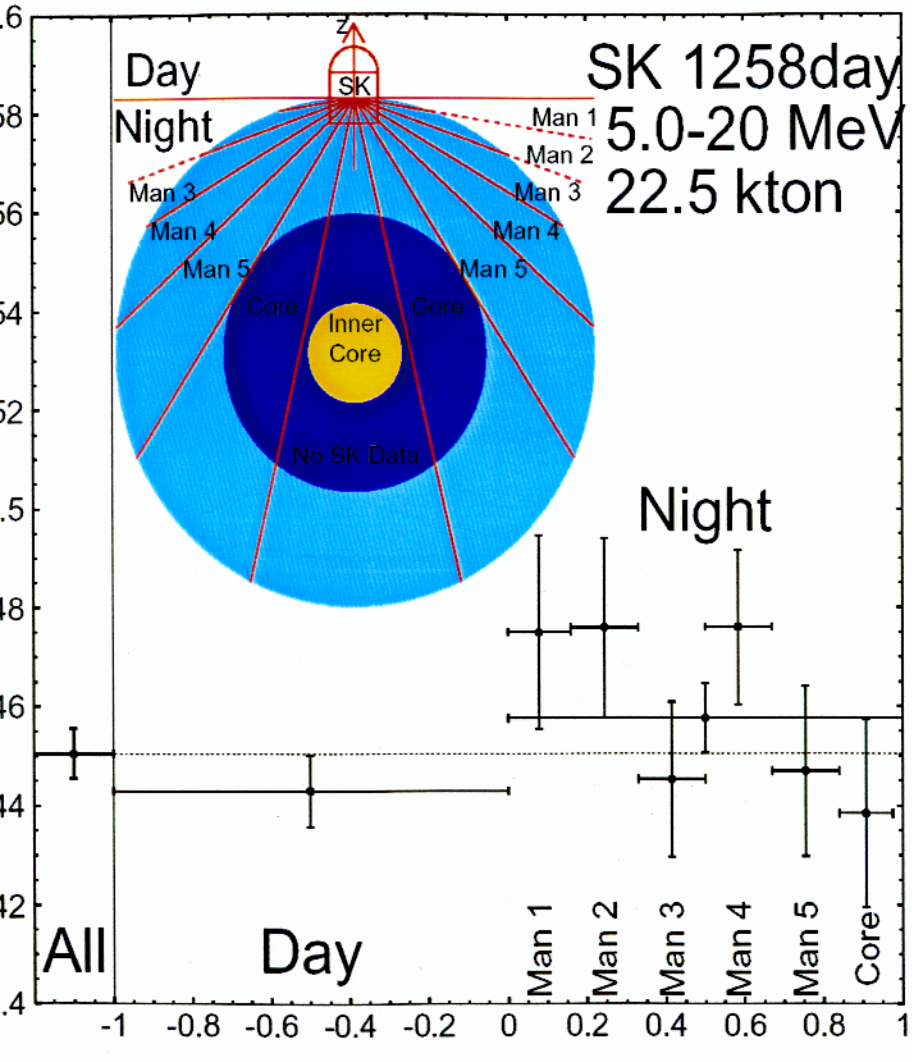


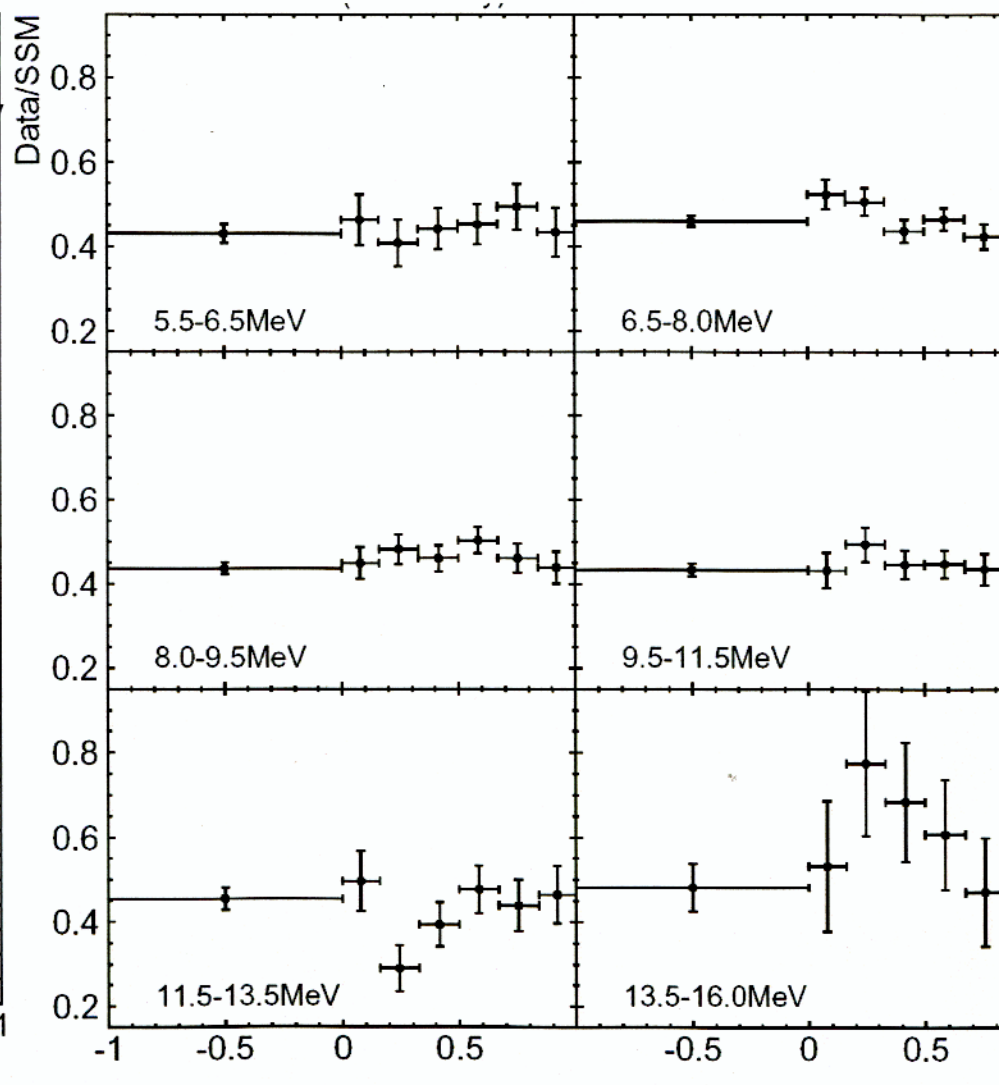


Energy Spectrum is consistent with flat

Day / Night - BP2000+New ^{8}B Spectrum

Preliminary





$$\frac{\Phi_n - \Phi_d}{\frac{1}{2}(\Phi_n + \Phi_d)} = 0.033 \pm 0.022(\text{stat.})^{+0.013}_{-0.012}(\text{sys.})$$

Solar Conclusions

SK measures elastic scattering $\Phi_{es} = (\Phi\nu_e + (\Phi\nu_e + \Phi\nu_{\mu,\tau})/6.5)$

Assuming no oscillations – i.e. $\Phi_{es} = \Phi\nu_e + \Phi\nu_e/6.5$

$$\Phi\, \nu e = (45.1\% \pm 0.5\%(\text{stat})^{+1.6}_{-1.4}\,\%\,(\text{syst}))\Phi\text{ssm}$$

$$(2.32 \pm 0.03(\text{stat})^{+0.08}_{-0.07}(\text{syst}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1})$$

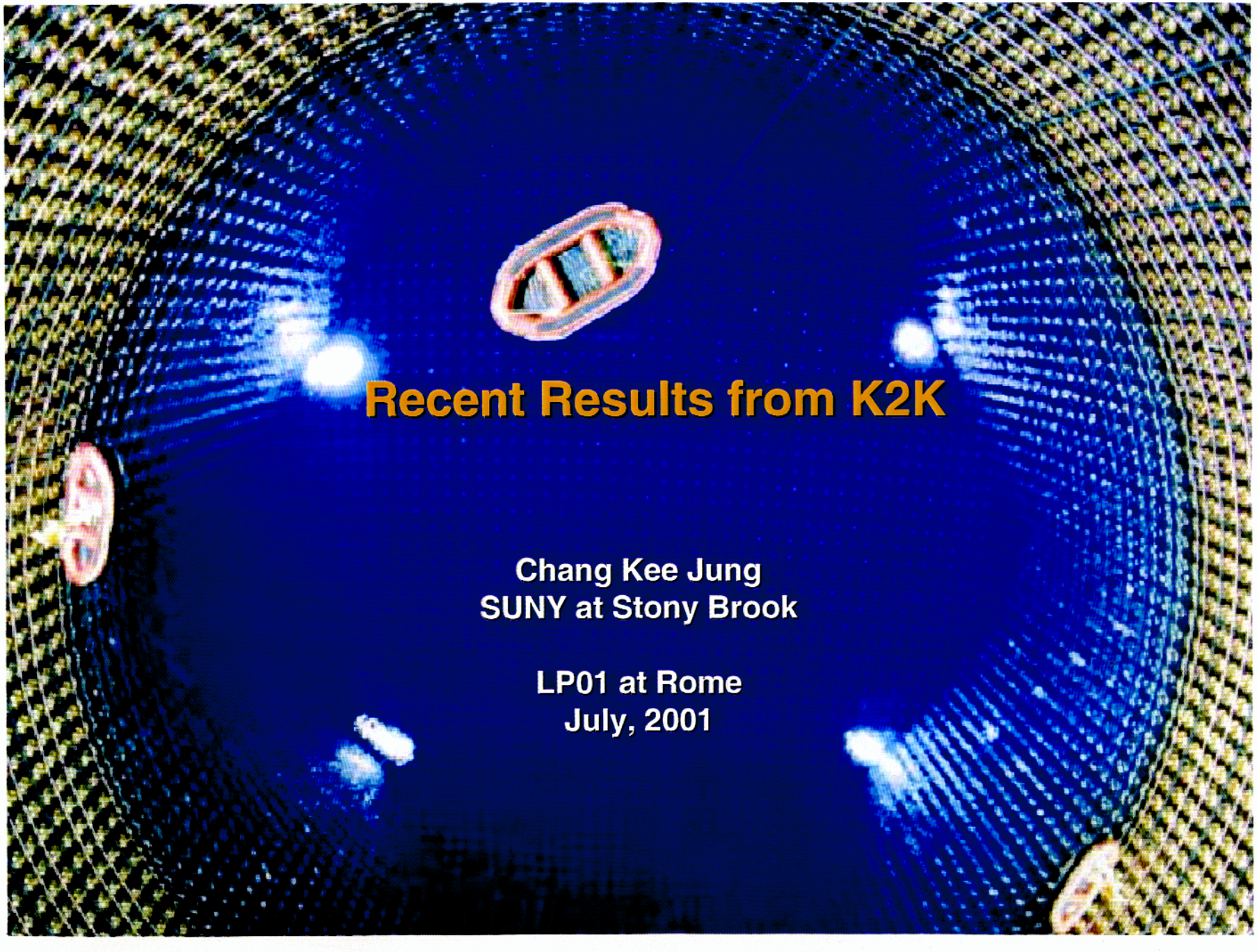
If the full Φ_{ssm} is present and there are oscillations to active flavors then $\Phi_{ssm} = \Phi\nu_e + \Phi\nu_{\mu,\tau}$

SK measures $\Phi_{es} = 0.45(1+1/6.5)\Phi_{ssm} = \Phi\nu_e + (\Phi\nu_e + \Phi\nu_{\mu,\tau})/6.5$

This implies that $\Phi\nu_e = 0.45\Phi_{ssm} - (1-0.45)/6.5\ \Phi_{ssm}$

Which yields $\Phi\nu_e = (36\% \pm \sim 1.7\%(\text{sys+stat}))\Phi_{ssm}$

SNO reports $\Phi\nu_e = (35\% \pm 3\%)\Phi_{ssm}$



Recent Results from K2K

Chang Kee Jung
SUNY at Stony Brook

LP01 at Rome
July, 2001

K2K Overview



- ν_μ (99%) beam
- $\langle E_\nu \rangle \sim$ 1.3GeV
- **Near detector**

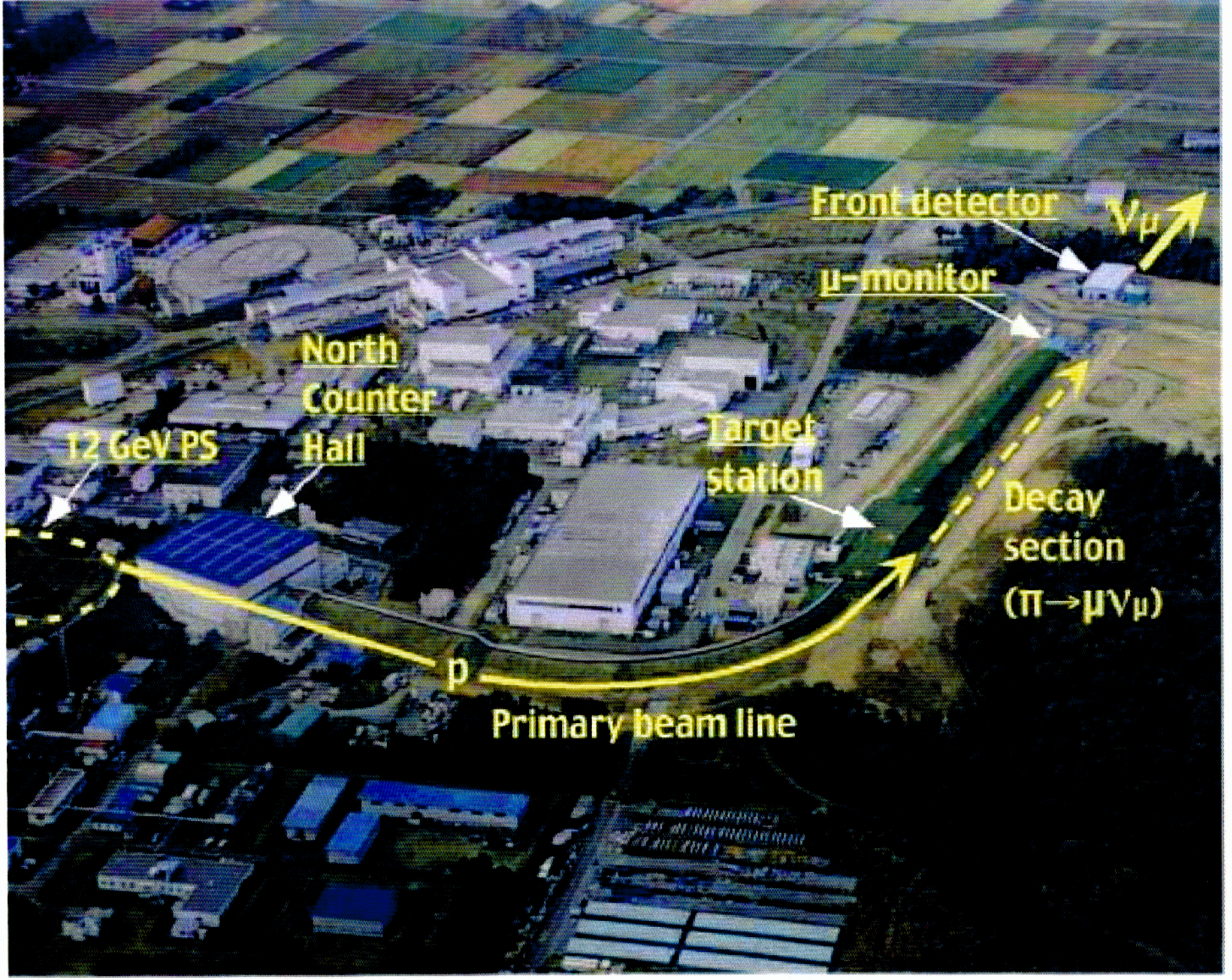
  @300m
- **Far detector**:

  Super Kamiokande(SK)

  @250km
- Sensitive for

  $\Delta m^2 > 2 \times 10^{-3}$ eV^2
- ν_μ disappearance

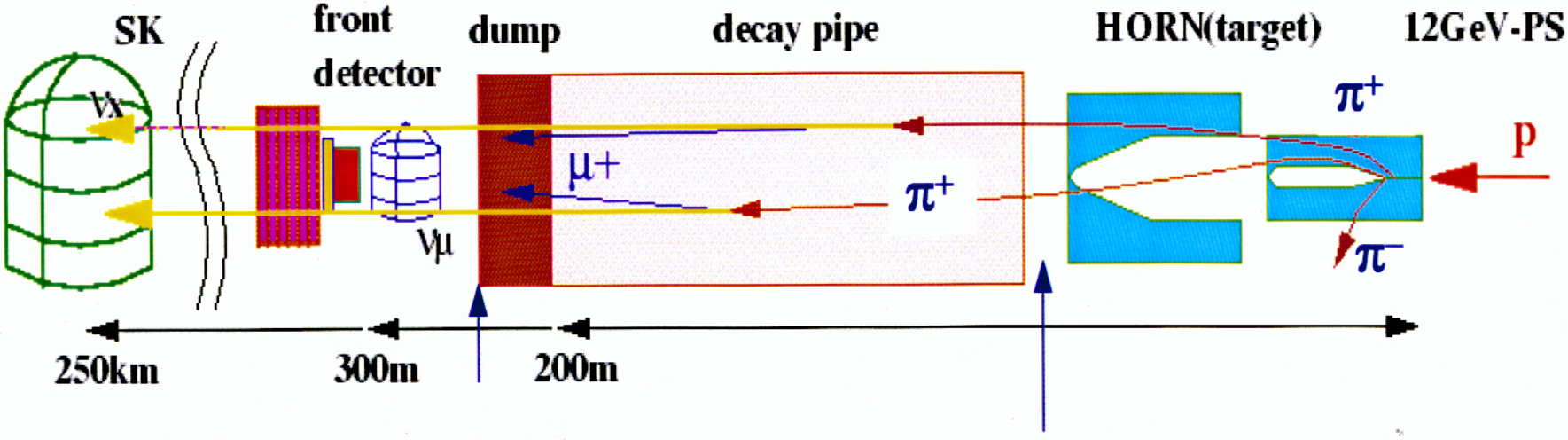
  ν_e appearance


Front detector
ν_μ
μ-monitor
North
Counter
Hall
12 GeV PS
Target
station
Decay
section
($\pi \rightarrow \mu\nu_\mu$)
p
Primary beam line

K2K Neutrino Beamline

monitor

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



Muon Profile Monitors

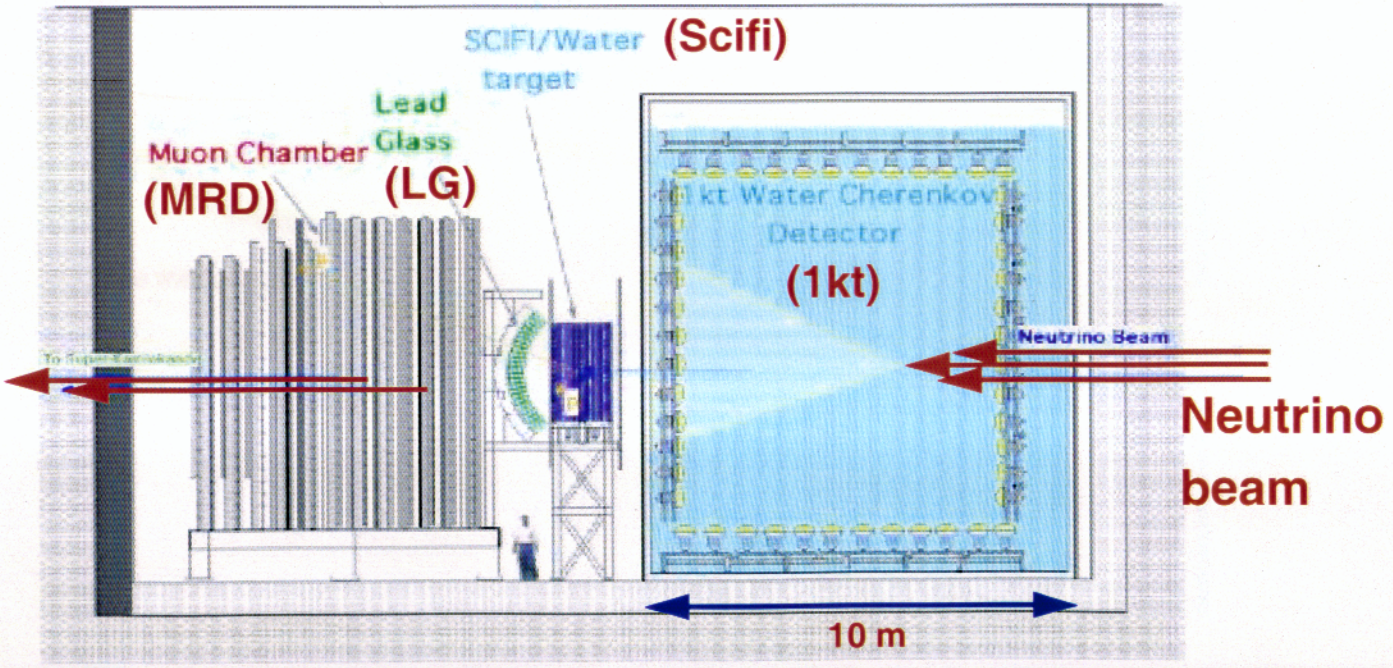
'MUMON' ≡ silicon pads

Beam Monitors: pion, proton

'PIMON' ≡ gas Č

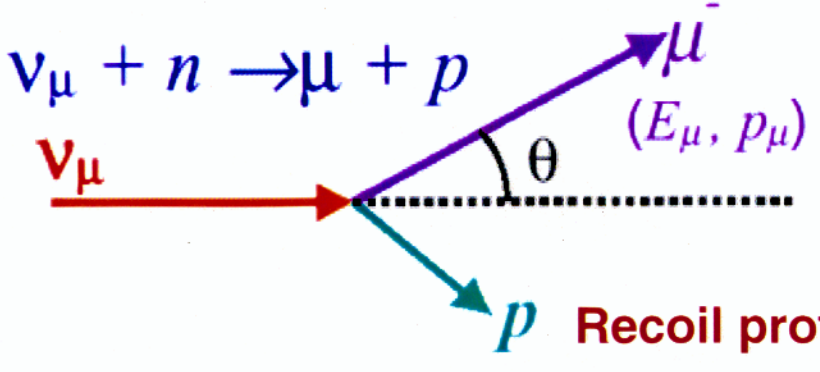
K2K Near Detector Complex

- 1kt (mini-SuperK): similar systematics as SuperK
- Scifi (scintillating fiber tracker): 19 layers of 6 cm thick water target w/ 20 layers of scifi (x,y), precision tracking => QEL/INEL diso.
- LG (Lead Glass calorimeter): Measure ν_e contamination
- MRD (muon range detector): 12 layers of iron plates w/ D.C.s => (E_μ, θ_μ) of ν_μ CC



K2K Strategy for Observation of Neutrino Oscillation

1. Monitor the Beam Direction
   - muon monitor: spill by spill ($E_\mu > 5$GeV)
   - MRD: day by day ($E_\mu > 1$GeV)
   - 1 kton: day by day ($E_\mu > 0.2$GeV)
2. Measure neutrino beam flux and energy spectrum by utilizing CC QE events ($\nu_\mu + n \rightarrow \mu^- + p$) at near detectors



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

Recoil proton

--> not seen in 1kt: below Cherenkov threshold

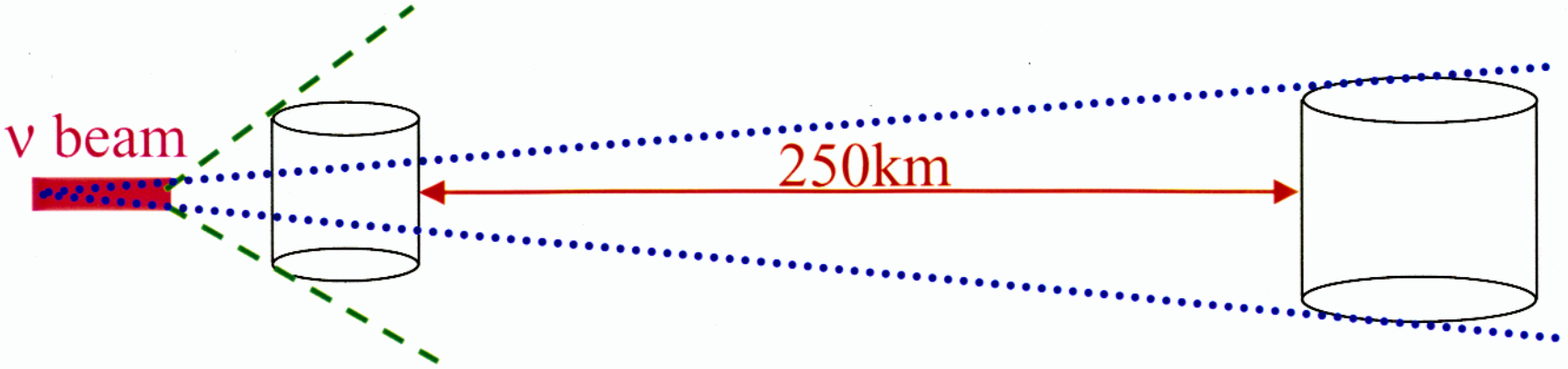
--> can be seen in Scifi

3. Extrapolate the measured flux and the energy spectrum at the near detector to the far detector
   - pion monitor
   - beam MC
4. Compare the observed number of events with the predicted and Look for distortion in the measured E_ν at SuperK

	July 1999	Feb. 2000	June 2000	July 2000	July 2001
#Observed	1	3	17	28 (27)	???
#Expected	~5*	12*	29*	38 (40*)	64

hep-ex/0103001
(accepted for publication in PLB)

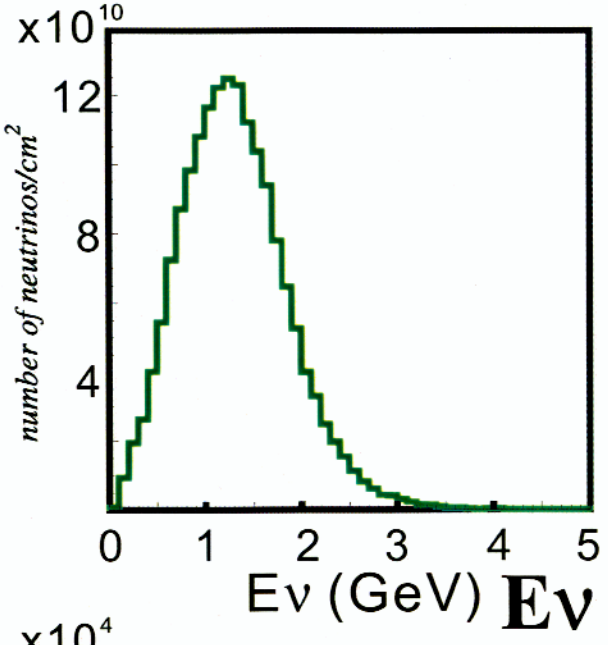
Extrapolation from Near to Far sites

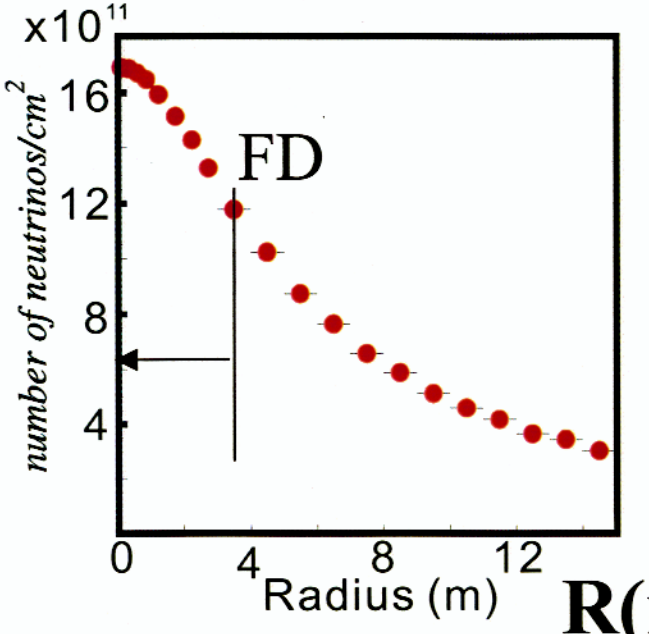


How we extrapolate the measurement at the near site to that at the far site?

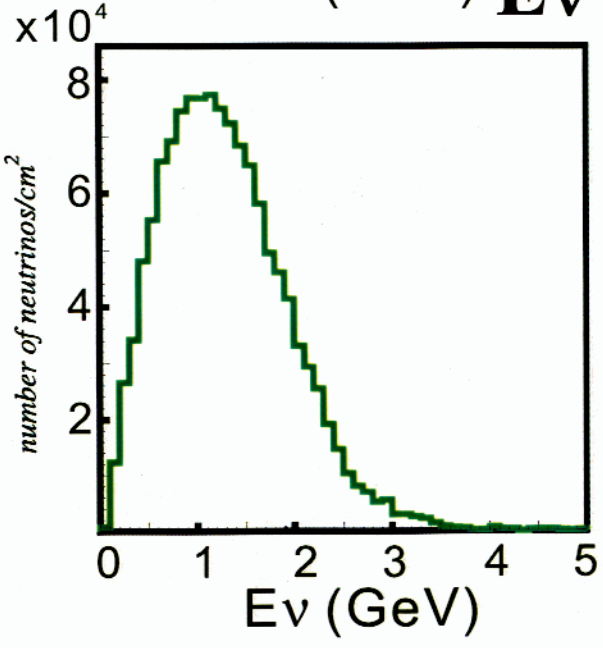
Neutrino Spectra and Radial Distributions at 300m/250km (MC)

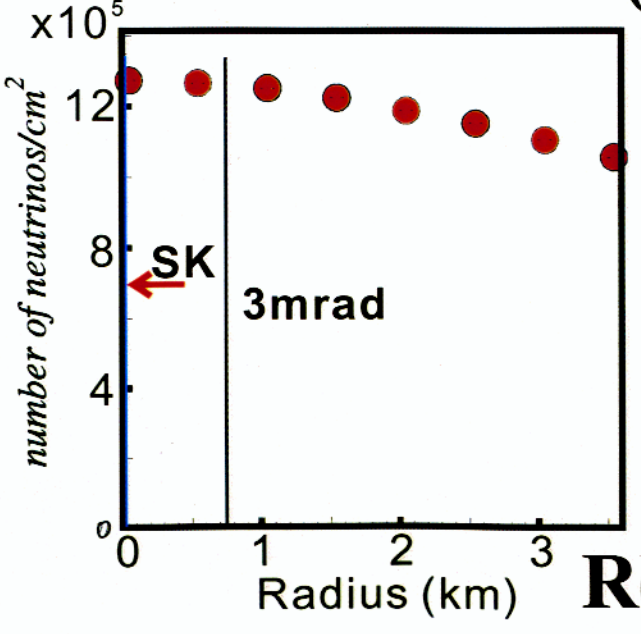
1km(4mr)
@ SK
no change





300m



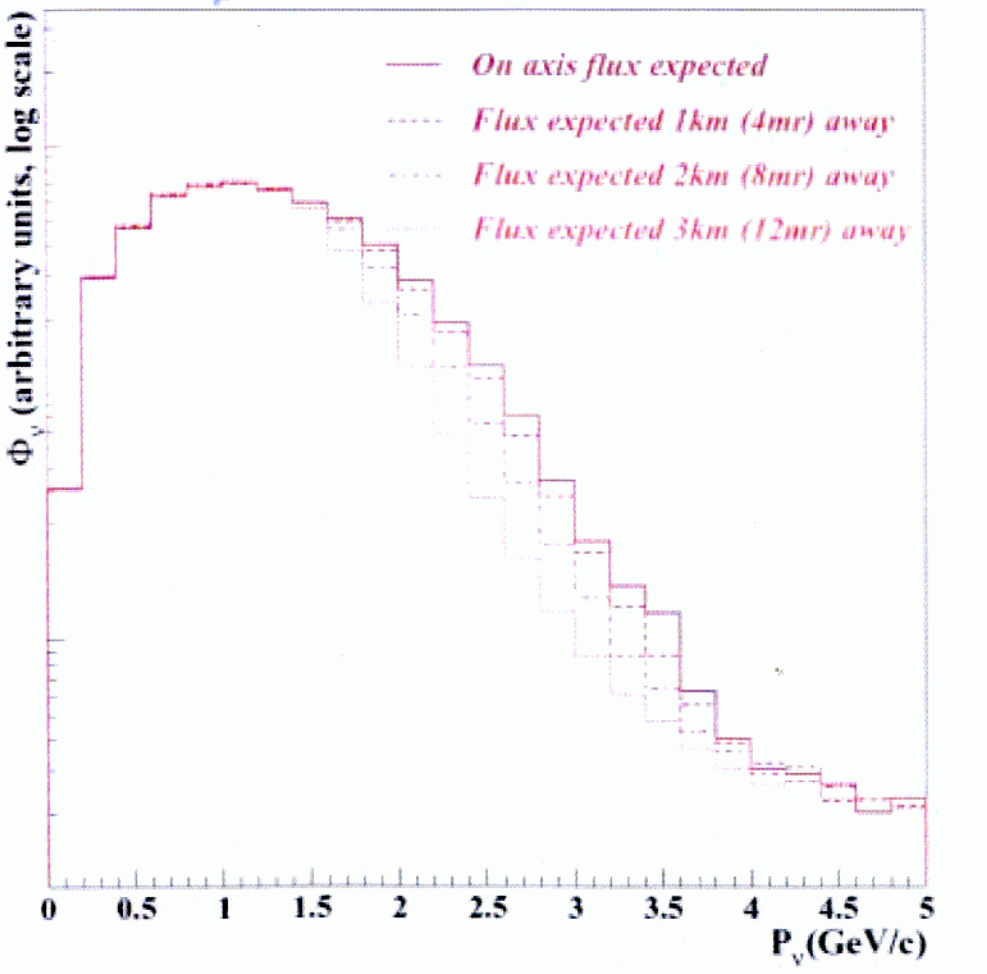


250km

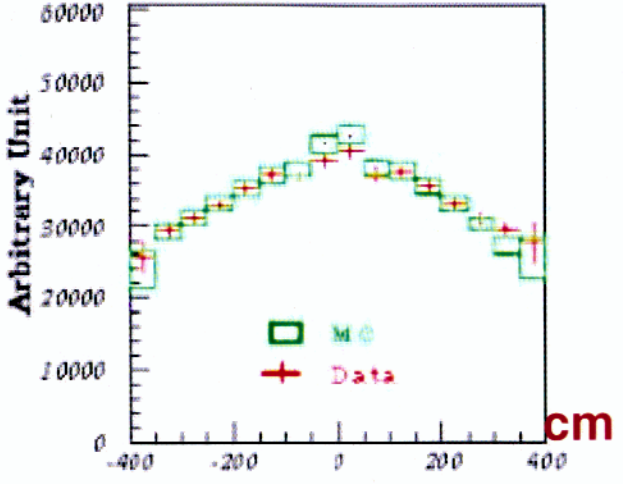
Beam Aiming

- Survey Accuracy using GPS
  ~0.01 mrad
- Civil Construction Accuracy
  ~0.1 mrad
- Beam Aiming Requirement
  < 3-5 mrad
- Monitored Accuracy
  < 1 mrad

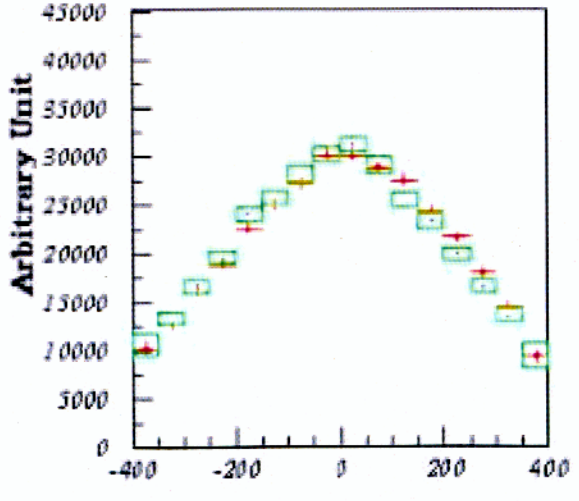
Expected ν_μ flux at 250 km, on axis and far from it



Beam Direction Monitoring: Neutrino

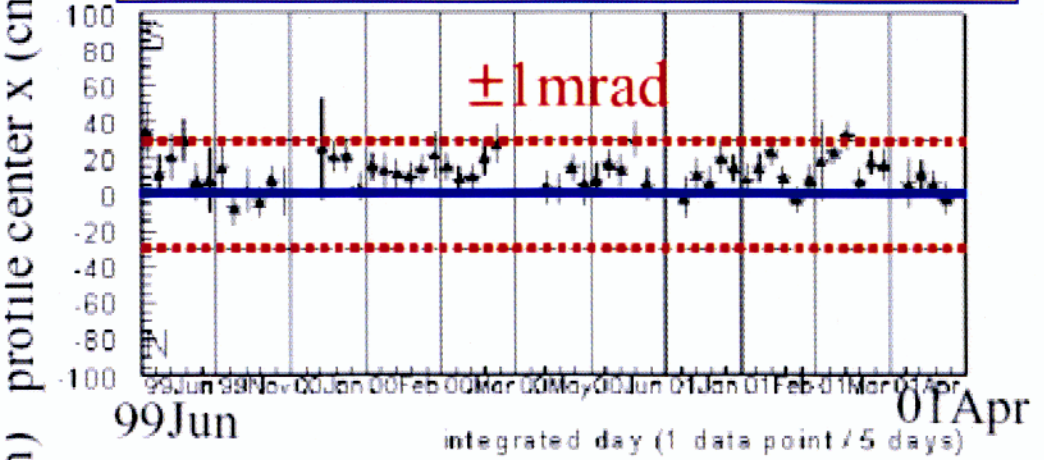


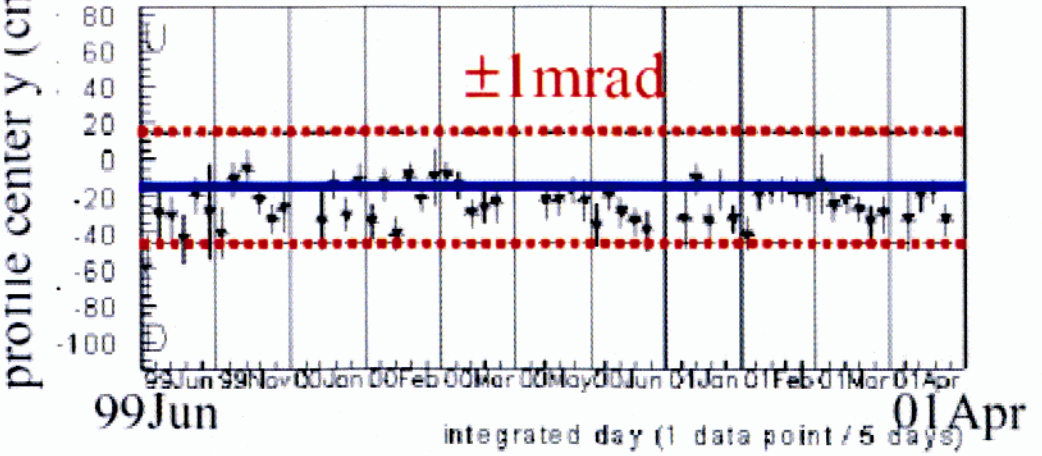
profile x ($0.5GeV < E_\mu < 1.0GeV$)



profile x ($1.0GeV < E_\mu < 2.5GeV$)

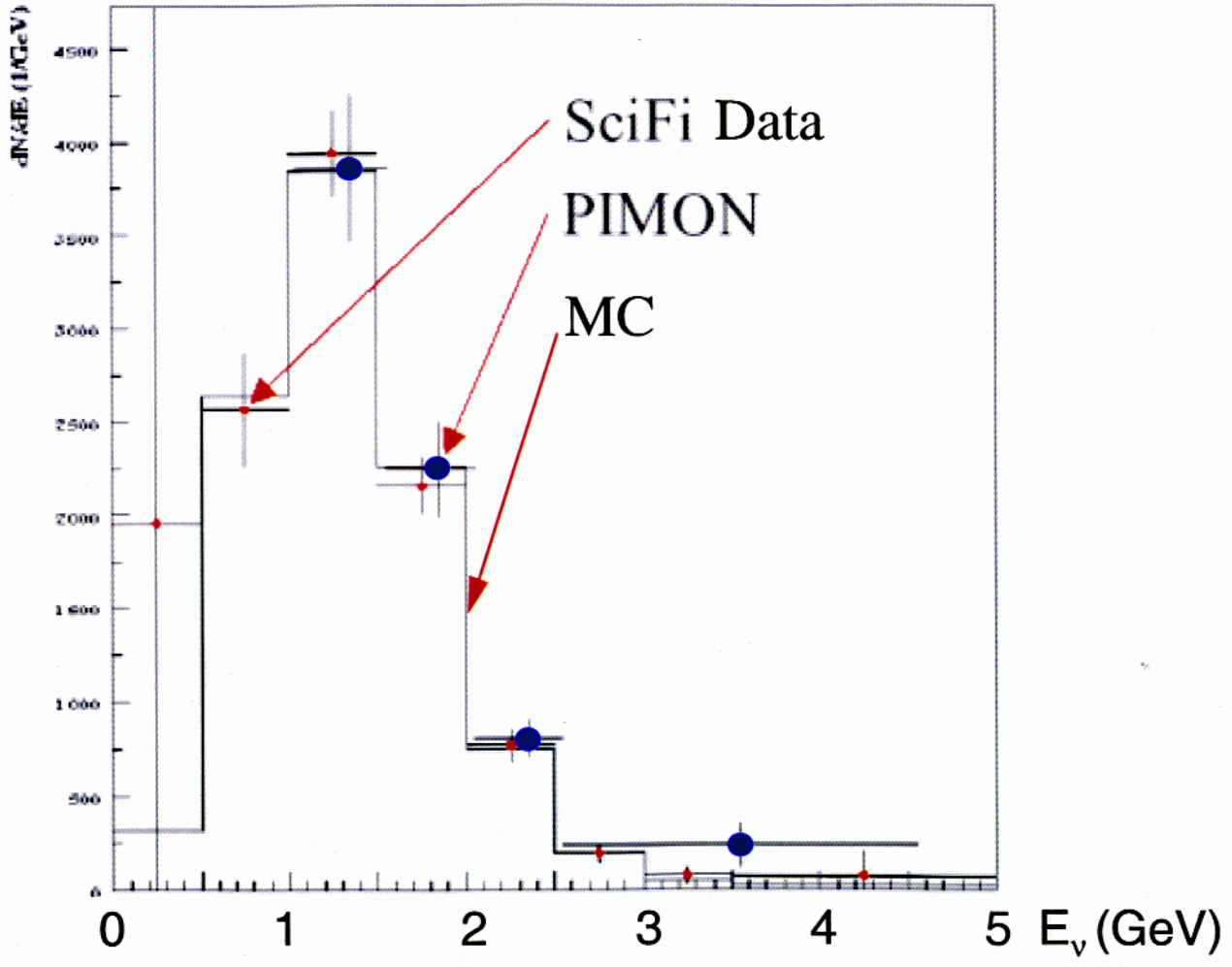
Neutrino beam profile center in MRD at 300 m from the target





Reconstructed Energy Spectrum at Scifi

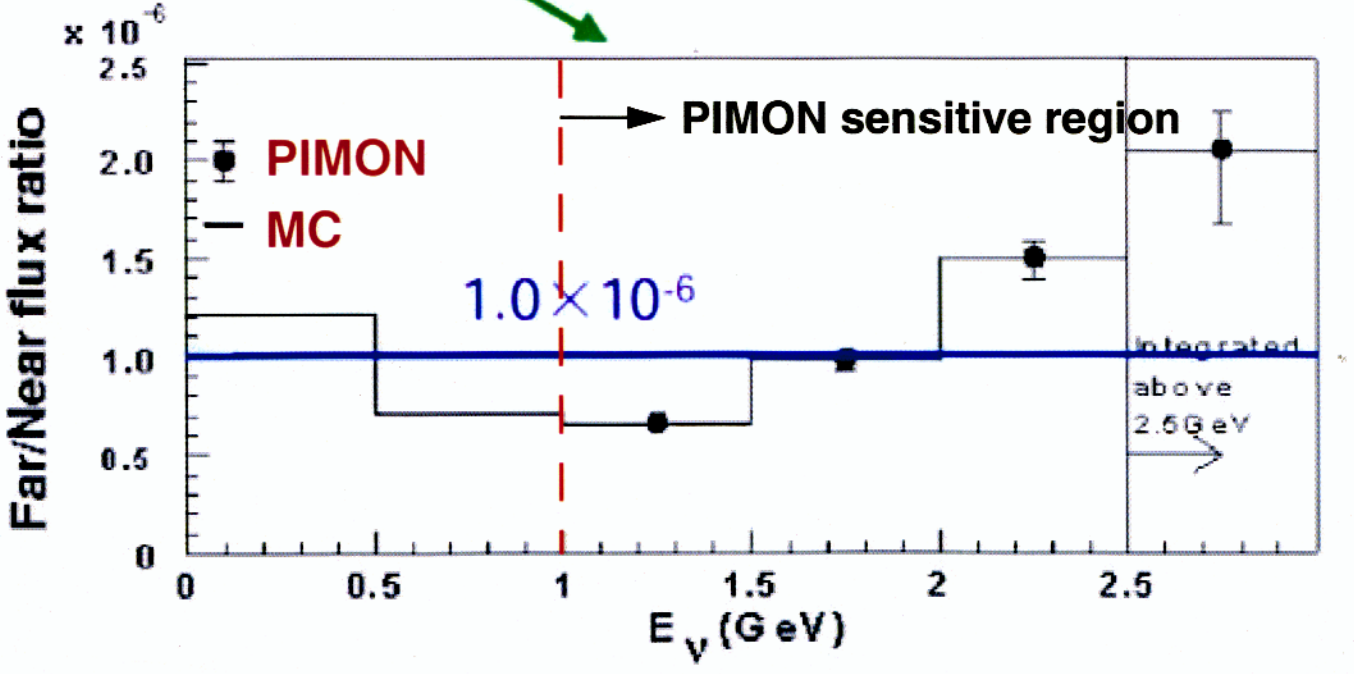
CC QE E_ν spectrum after BG subtraction.



Extrapolation to SuperK

$$N_{SK}^{expected} = N_{KEK}^{measurement} \times R\ (Far/Near)$$

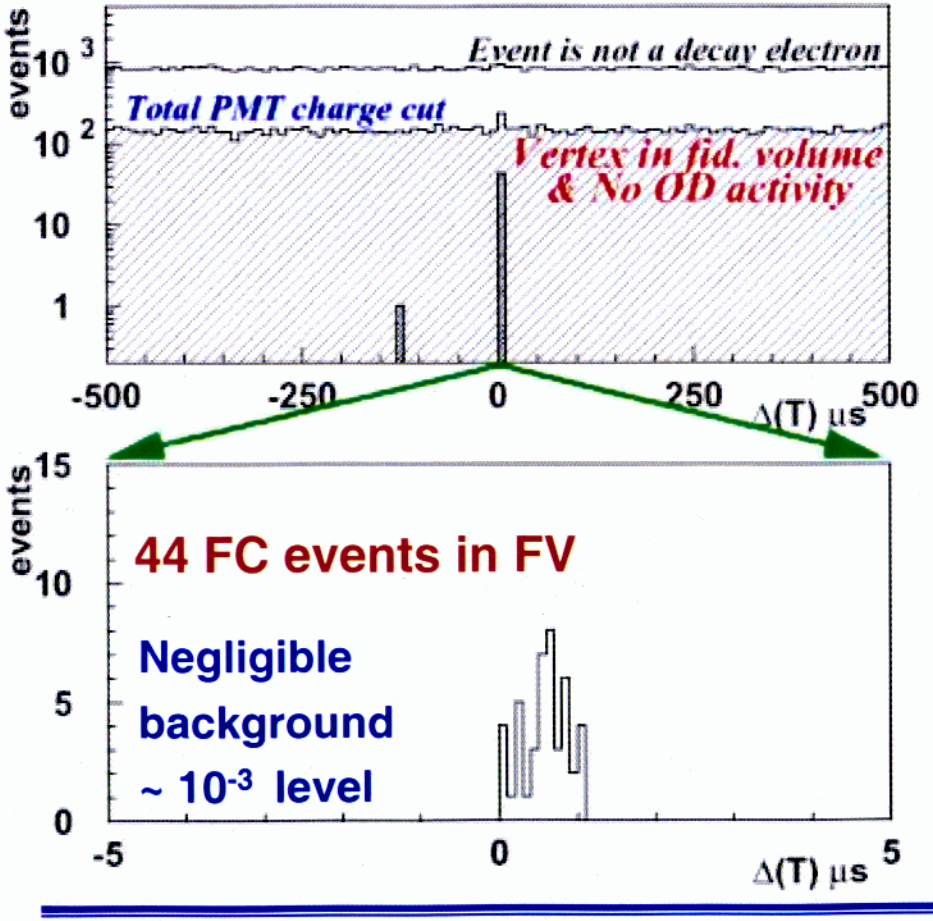
$$R = \frac{\int \Phi_{SK}(E_\nu)\sigma(E_\nu)dE_\nu}{\int \Phi_{KEK}(E_\nu)\sigma(E_\nu)dE_\nu} \cdot \frac{N_{SK}^{Target\ mass}}{N_{KEK}^{Target\ mass}}$$

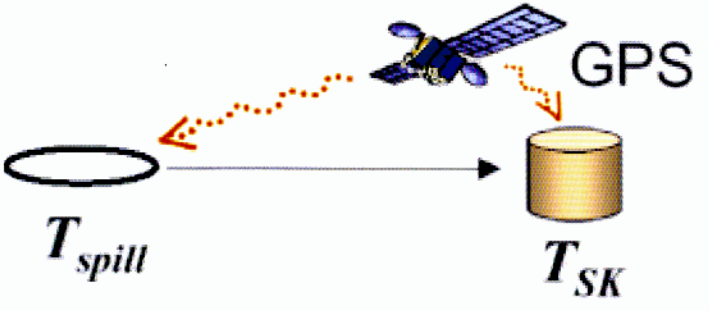


K2K Events Observed in SuperK

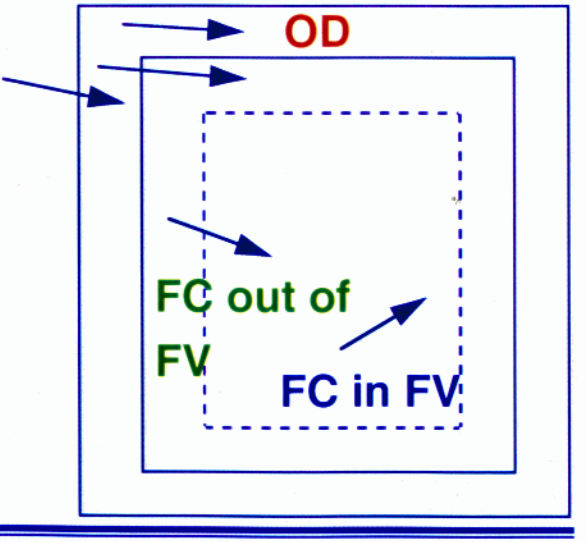
$$-0.2 \le \Delta T \equiv T_{SK} - T_{Spill} - \mathrm{TOF} \le 1.3 \mu\,\mathrm{sec}$$

Fully Contained Event Analysis

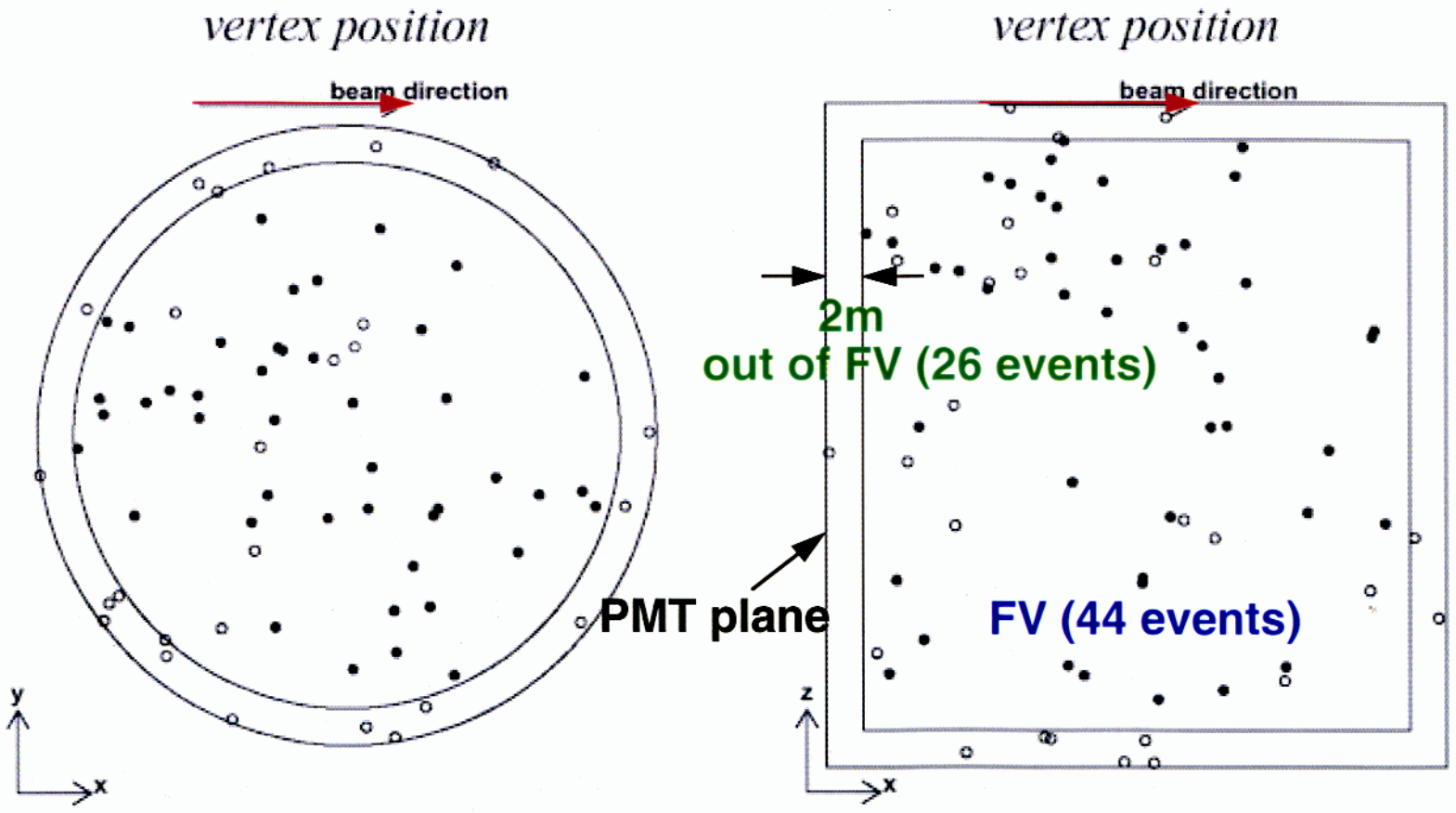




T_{Spill}: Abs. time of spill start
T_{SK}: Abs. time of SK event
TOF: 0.83ms (KEK to Kamioka)



Vertex Distribution of the K2K Events in SuperK

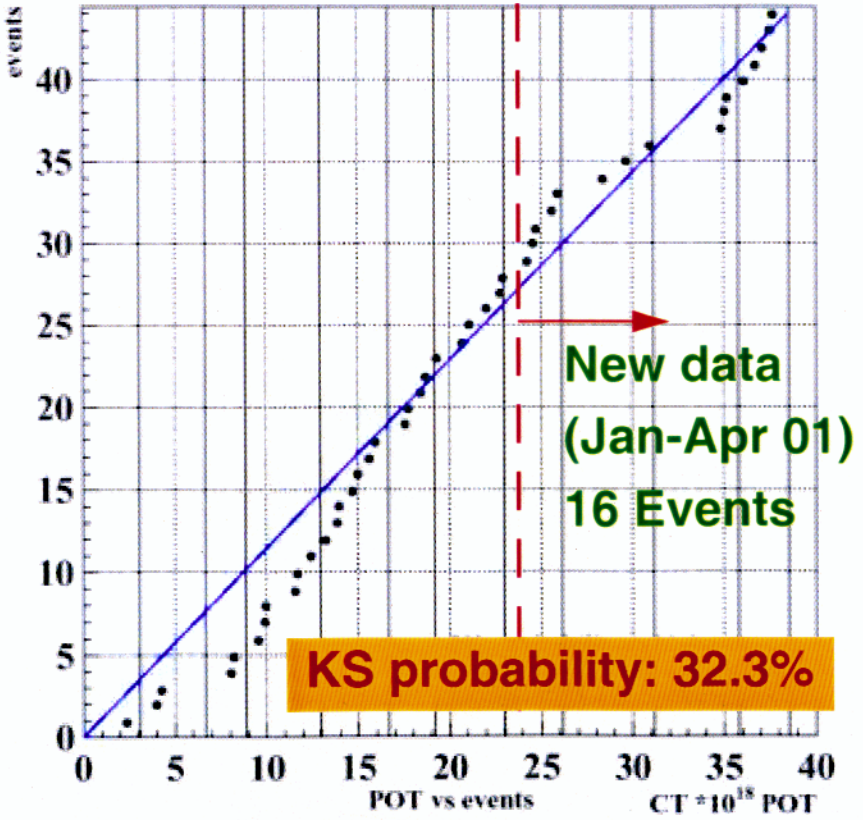


(Solid dots are events with vertices in the fiducial volume; open are outside.)

Observed # of K2K Events vs. POT in SuperK

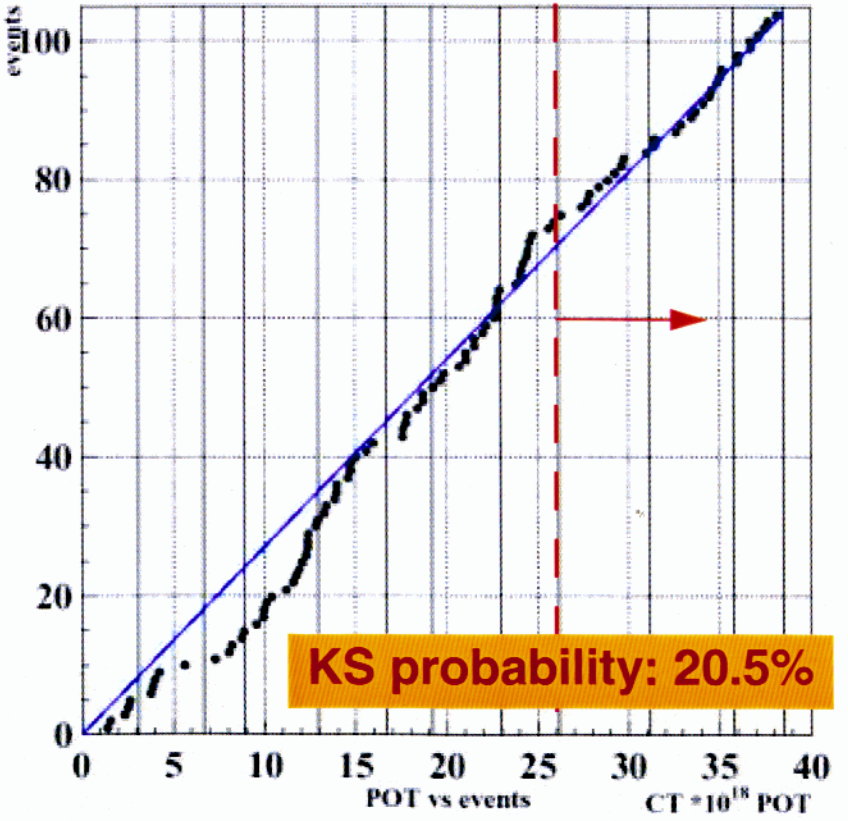
Events within FV

FC 22.5kt **44 Events/3.85 x 10^{19} POT**



All Events

FC+OD **104 Events**



of Observed Events vs. the Expected at SuperK

June 1999 - April 2001

FC Events in FV

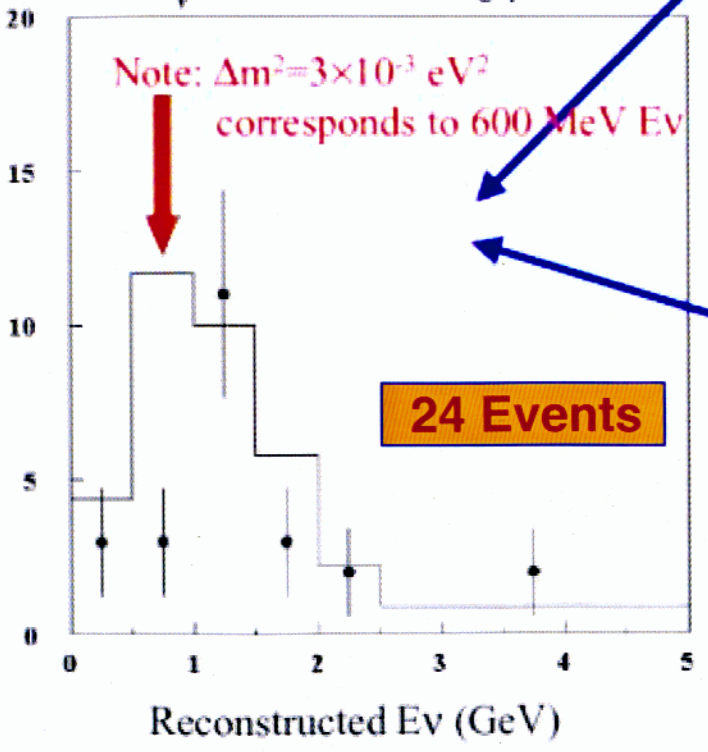
	Obs.	No Osci. (1kton)	$\Delta m^2(\times 10^{-3} eV^2)$ 3 (sin²2θ =1)	5	7
FC 22.5kt	44	$63.9^{+6.1}_{-6.6}$	41.5	27.4	23.1
1-ring	26	38.4±5.5	22.3	14.1	13.1
μ-like	24	34.9±5.5	19.3	11.6	10.7
e-like	2	3.5±1.4*	2.9	2.5	2.4
multi ring	18	25.5±4.3**	19.3	13.3	10.0

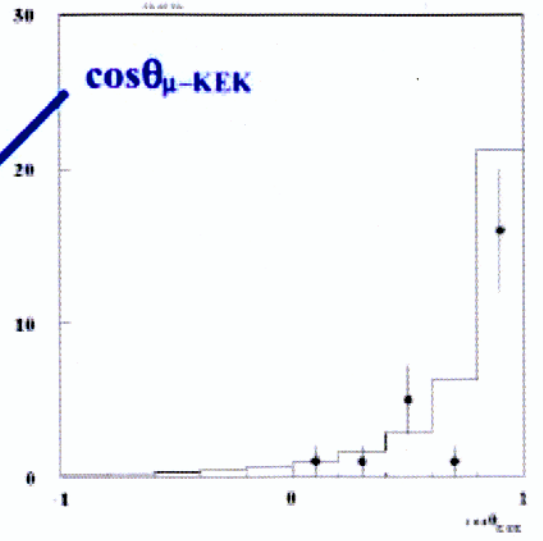
* Mostly π^0 single RING from NC not ν_e CC

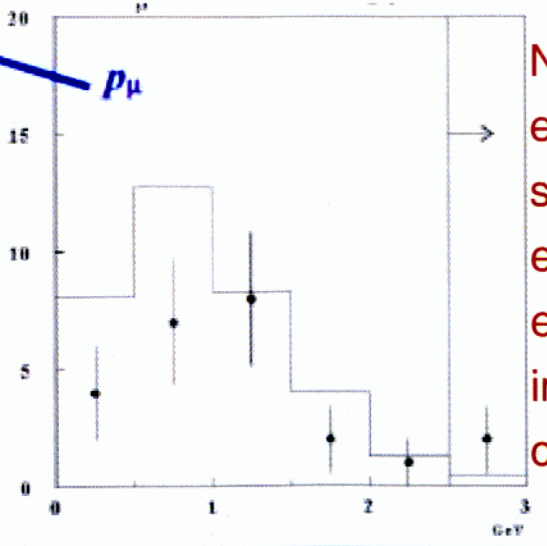
** CC : NC = 2 : 1

Observed Energy Spectrum at SuperK

Reconstructed Ev







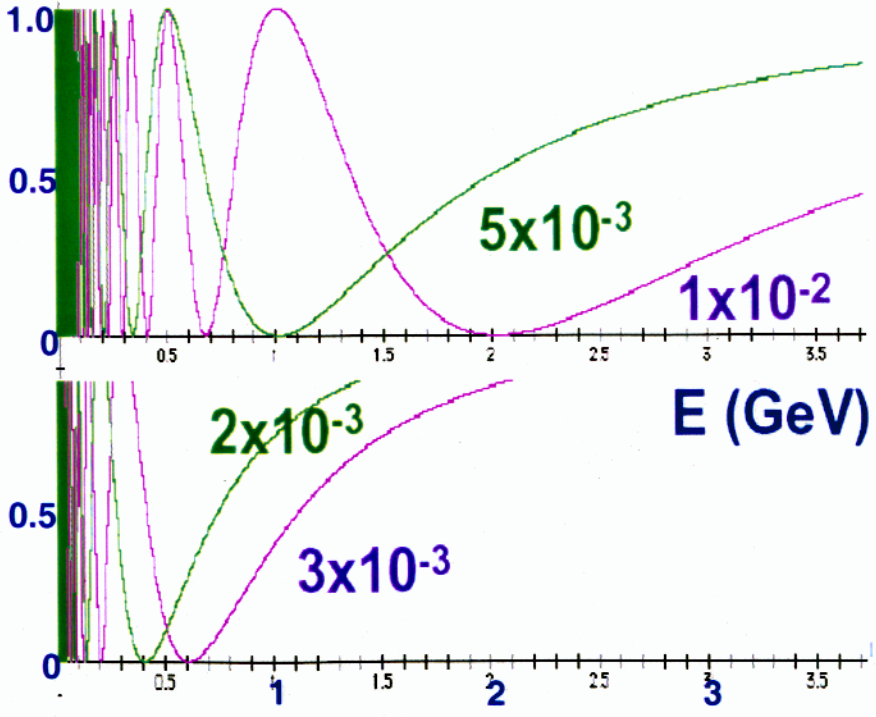
Data
MC w/o osc.

Note no error bars for expected energy spectrum: Detailed evalution of systematic errors underway, including bin-by-bin correlation

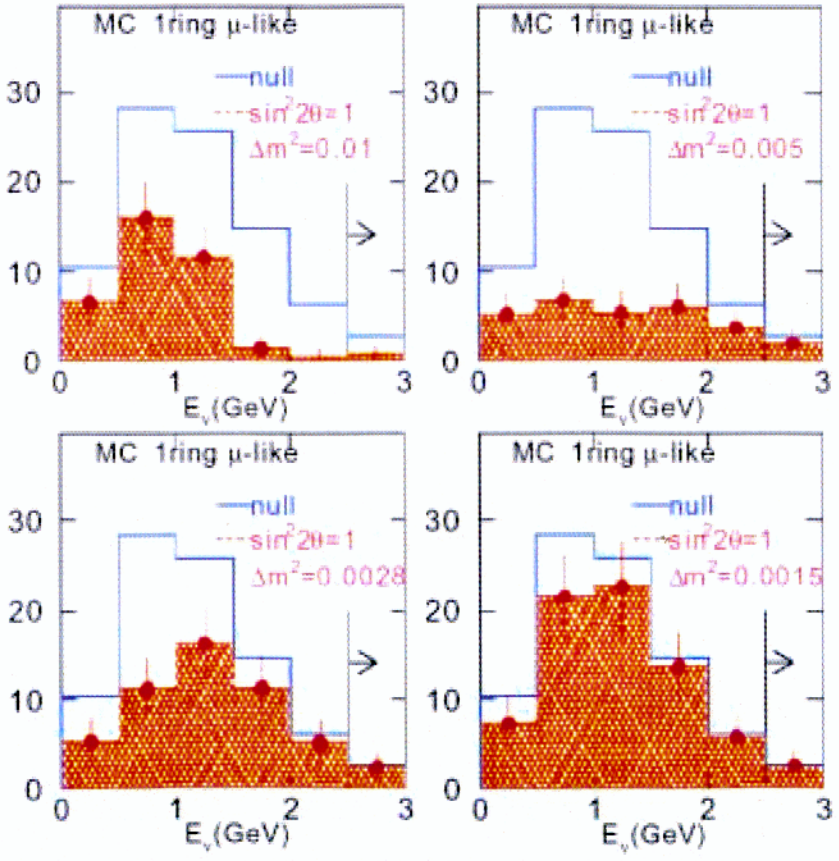
Neutrino Energy Spectrum at SuperK

$P_{\nu\to\nu} = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$
with $\sin^2 2\theta = 1.0$, $L = 250$km

88 μ candidates @ 10^{20} POT



Reconstructed Neutrino Energy (MC)



Conclusion

- K2K is running very well
  - Beam intensity at the design level
  - June 1999 - April 2001 data:
    3.85 (4.58) x 10^{19} POT SuperK live (delivered)

    ==> additional data (May - July 2001) being analyzed

    ==> Goal: accumulate 10^{20} POT (~untill 2004)
  - 44 observed events compared to $63.9^{+6.1}_{-6.6}$ (sys) expected from null oscillation

    ==> null oscillation probability < 3%
  - Energy spectrum analysis is underway

    ==> qualitatively the observed energy spectrum consistent w/ the SuperK atm best fit parameters

    ==> quantivative results to come in spring 2002

Solar Neutrino Results from SNO

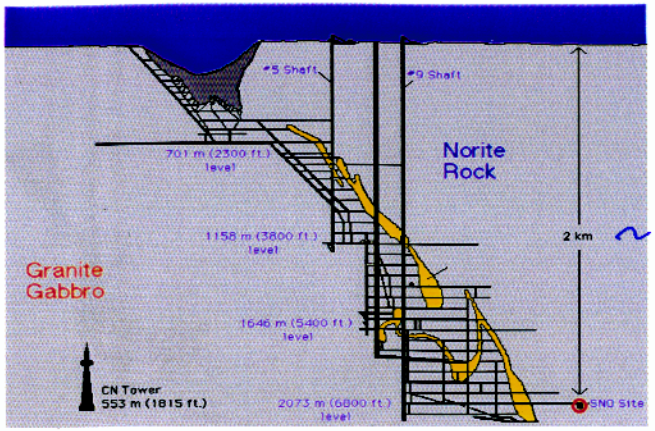
Joshua Klein
for the SNO Collaboration

Talk Outline

- SNO Detector
- CC Analysis
- Future Prospects



Sudbury Neutrino Observatory



~6000 mwe

1000 tonnes D_2O

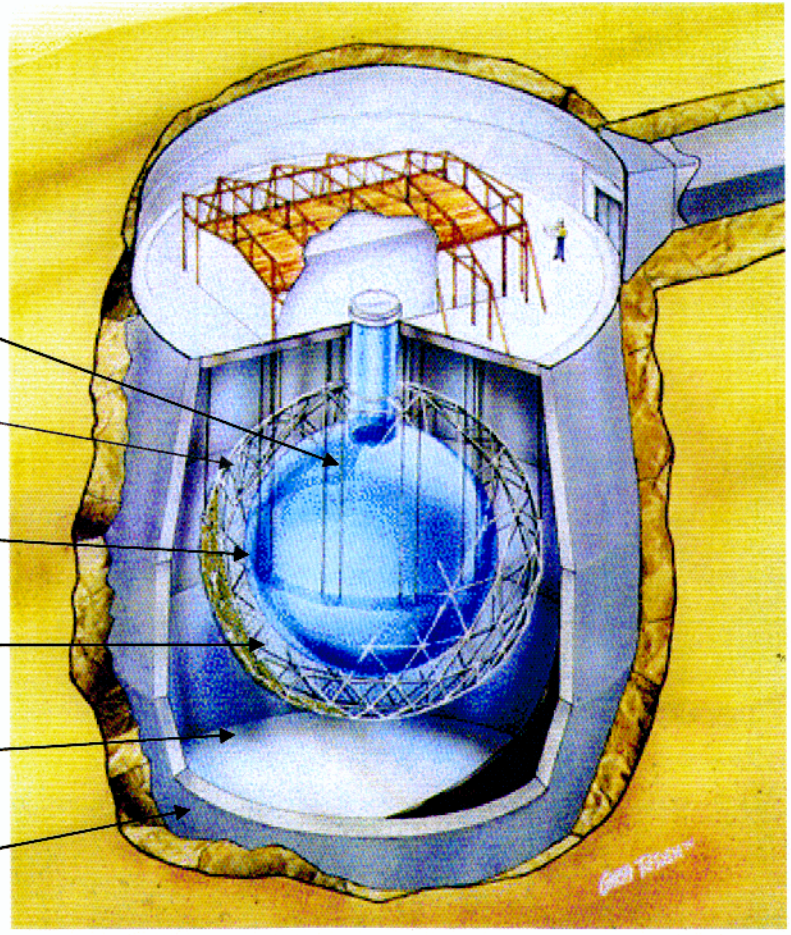
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



ν Reactions in SNO

CC $\nu_e + d \Rightarrow p + p + e^-$

- Good measurement of ν_e energy spectrum
- Weak directional sensitivity $\propto 1 - 1/3\cos(\theta)$

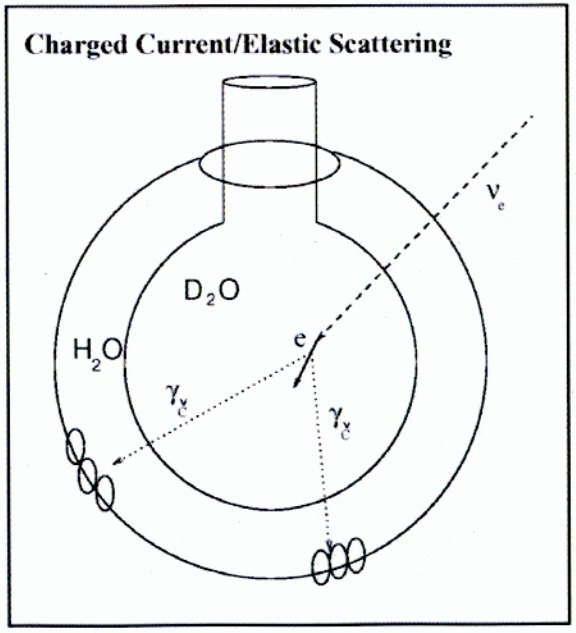
NC $\nu_x + d \Rightarrow p + n + \nu_x$

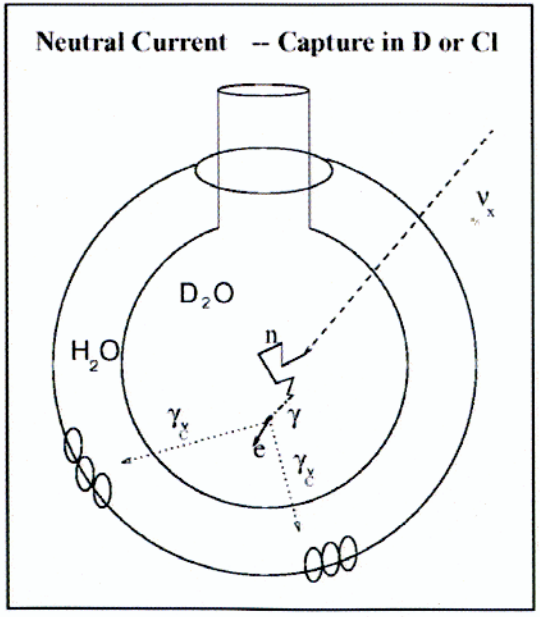
- Measure total ^8B ν flux from the sun.
- Equal cross section for all ν types

ν Energy Thresholds { CC : 1.44 MeV
NC : 2.22 MeV

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

- Mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ
- Strong directional sensitivity





Sudbury Neutrino Observatory

Main goal:



Direct observation of solar neutrino flavor change via inclusive appearance

If ν_e's from the Sun change into other active flavors, then

$$\phi^{CC}(\nu_e) < \phi^{ES}(\nu_x)$$

$$\phi^{CC}(\nu_e) < \phi^{NC}(\nu_x)$$

Inclusive $\nu_{\mu\tau}$ Appearance

Two possibilities:

$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

Advantages:

- NC gives total flux directly
- Cross section uncertainties cancel

$$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.14(\nu_\mu + \nu_\tau)}$$

Advantages:

- ES excess points to Sun
- Can match energy regimes
- Super-K precision measurement

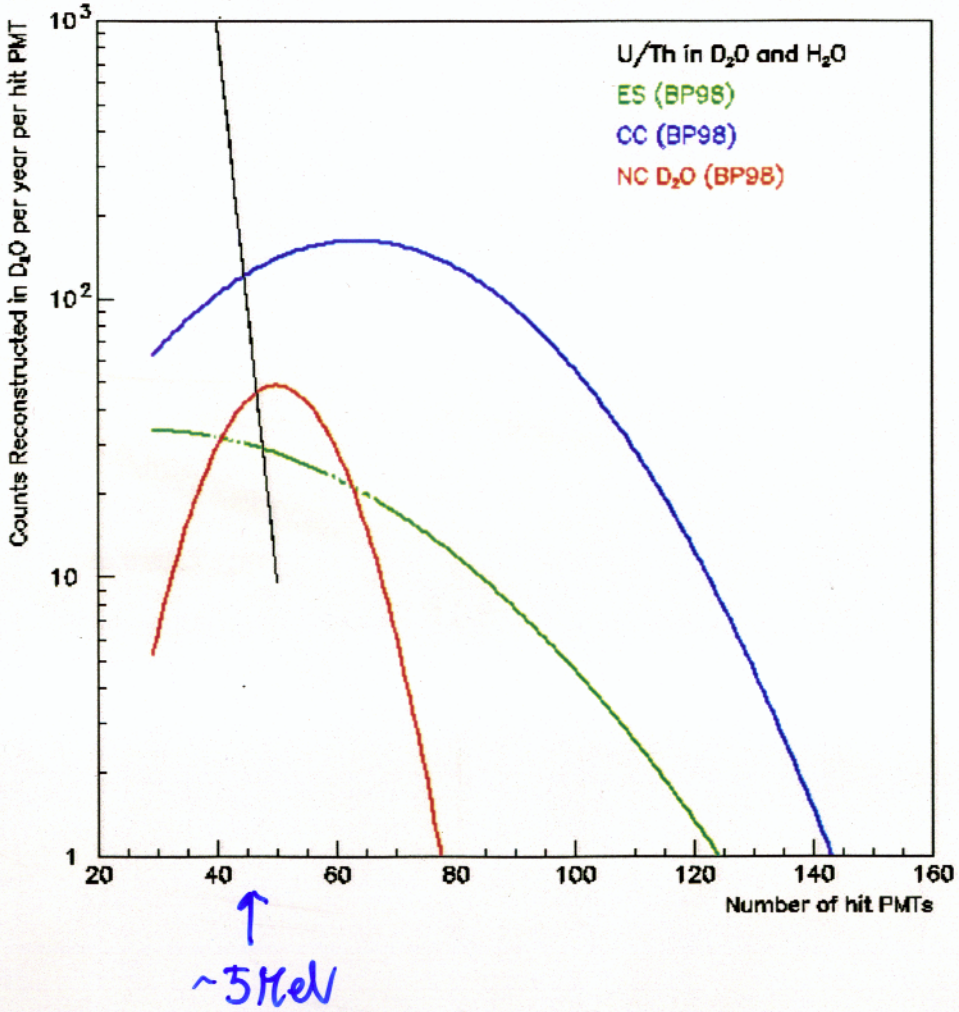


CC/ES used in this analysis

Signal/Background Spectra

Monte Carlo Predictions

(pure ^{8}B only)

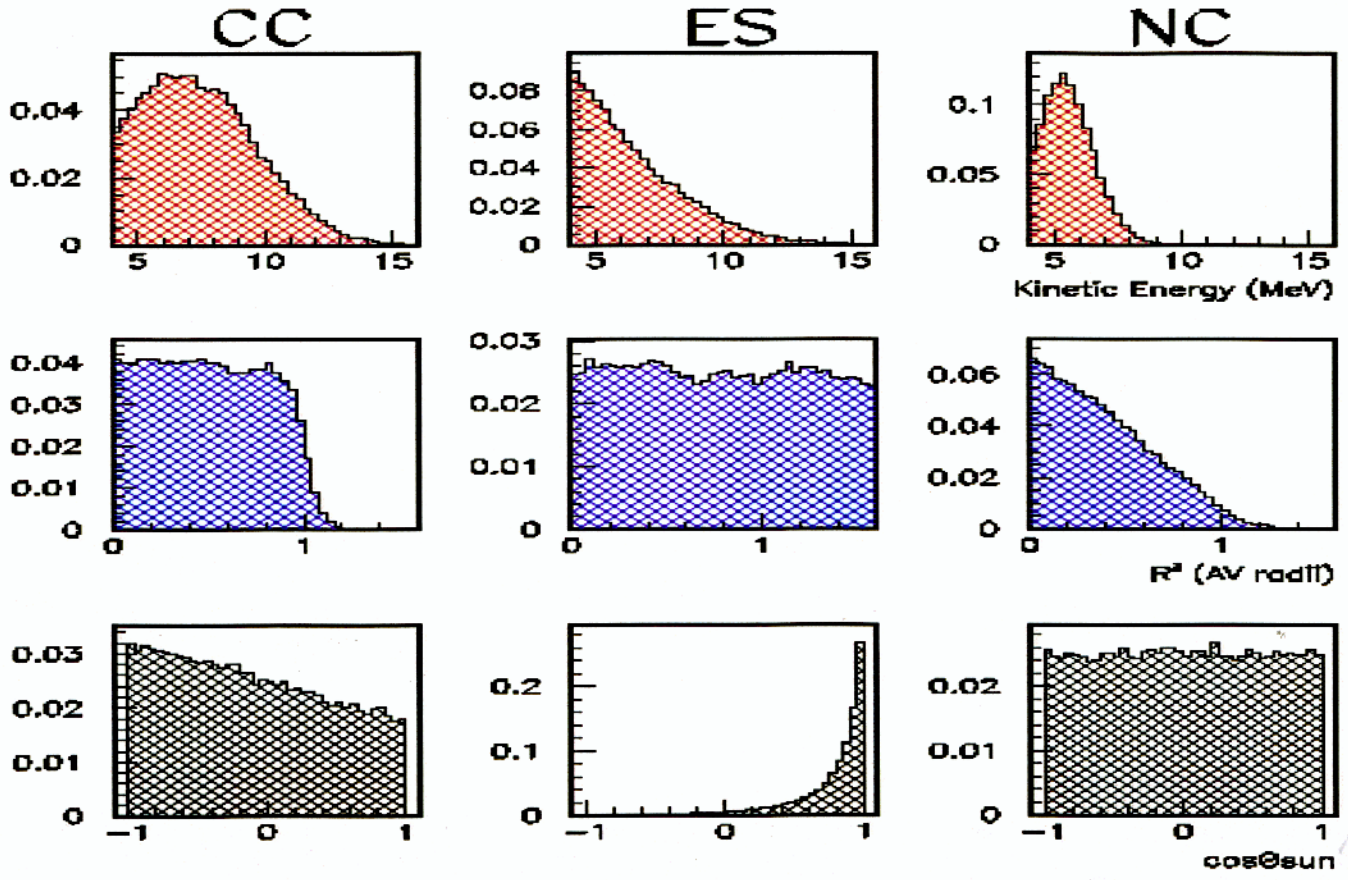


$T_e \geq 6.75$ MeV

9 PMT hits ~ 1 MeV

Extracting Signals

Can use derived observables (R^3, $\cos\theta_{sun}$, and E) to produce pdfs.



Max. Likelihood fit for relative signal amplitudes

Signal Extraction

➢Event Numbers

Now have:

- Data sample
- Calibrated model for pdfs
- Negligible backgrounds

Maximum likelihood fit to R^3, $\cos\theta_{sun}$, and E yields:

$$\Rightarrow \begin{cases} \text{CC} = 975.4 \pm 39.7 \text{ events} \\ \text{ES} = 106.1 \pm 15.2 \text{ events} \\ \text{neutrons} = 87.5 \pm 24.7 \text{ events} \end{cases}$$

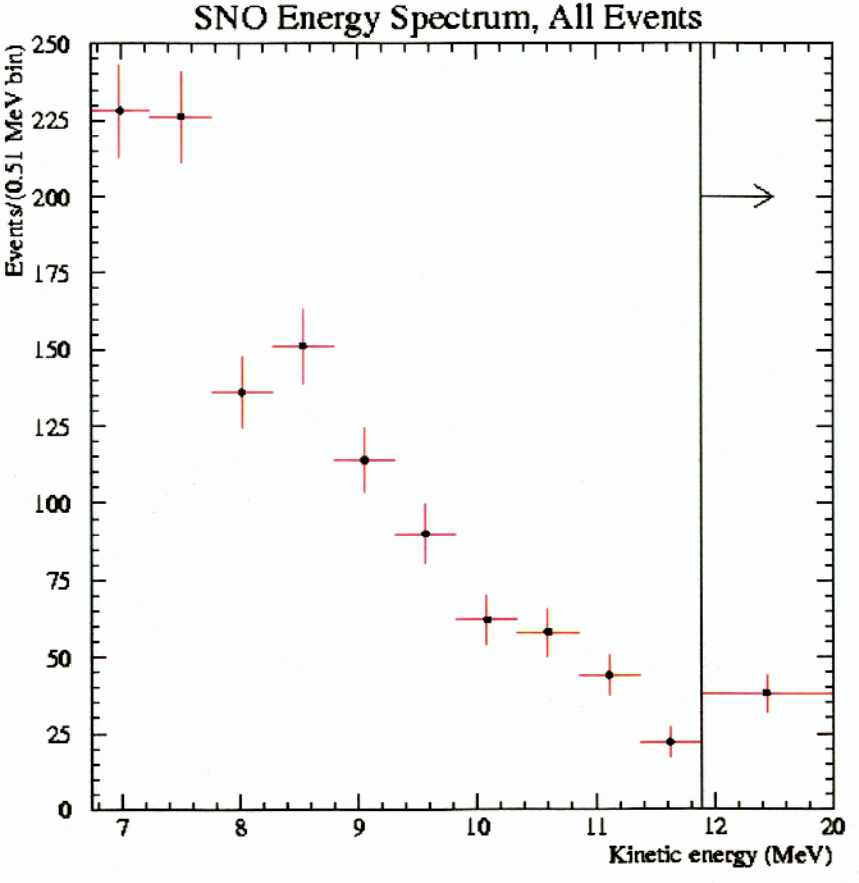
(statistical uncertainties only, no hep)

Data Processing

➢Final data sample

Require

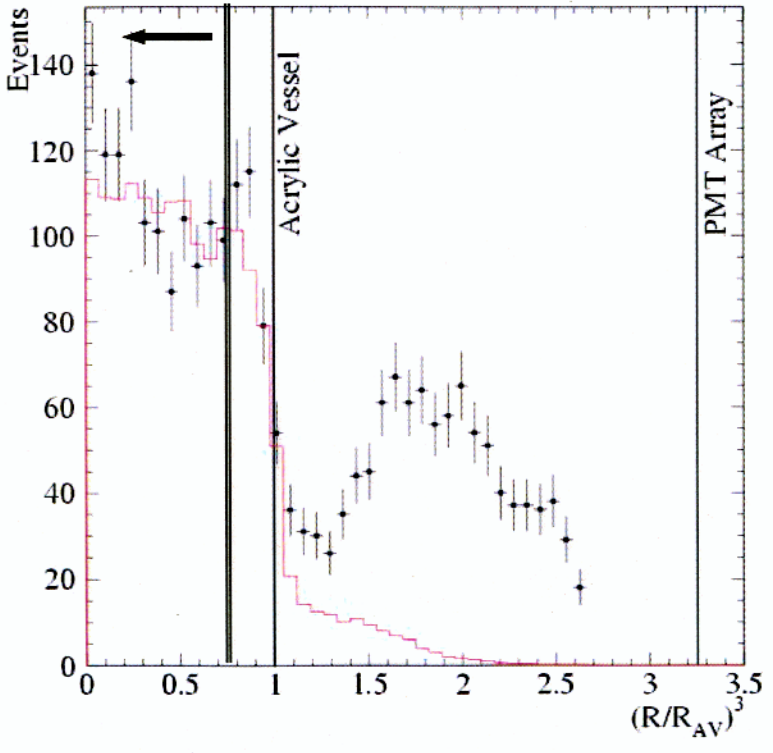
- R < 550 cm (well understood response, away from AV backgrounds)
- T > 6.75 MeV (away from neutrons and radioactive backgrounds)



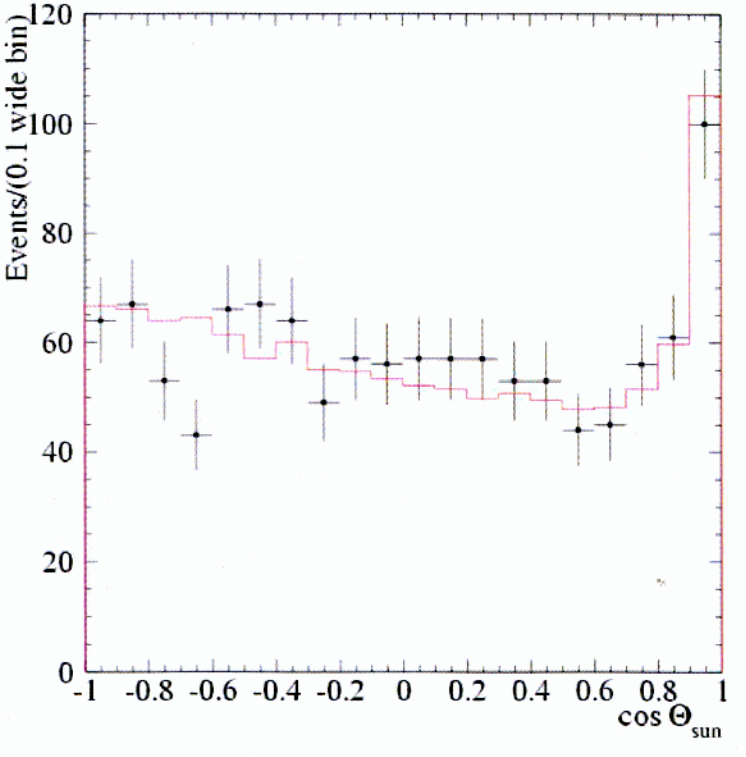
Signal Extraction

- Signal Distributions

Radial Distribution



Solar Direction Distribution



Signal Extraction

➢ Flux Measurements

- SNO measurements: (units 10^6 cm^{-2} s^{-1})

$$\Phi^{CC}\,(^8B) = 1.75 \pm 0.07\ (\text{stat})\ {}^{+0.12}_{-0.11}\ (\text{sys.})\ \pm 0.05\ (\text{theor})$$

$$\Phi^{ES}\,(^8B) = 2.39 \pm 0.34\ (\text{stat})\ {}^{+0.16}_{-0.14}\ (\text{sys.})$$

- Super-Kamiokande finds*

$$\Phi^{ES}\,(^8B) = 2.32 \pm 0.03\ (\text{stat})\ {}^{+0.08}_{-0.07}\ (\text{sys.})$$

*S. Fukuda, et al., hep-ex/0103032

Signal Extraction

➢ES-CC Differences

- **SNO:** CC vs ES (Units $10^6\,cm^{-2}\,s^{-1}$)

$$\Phi^{ES}_{SNO} - \Phi^{CC}_{SNO} = 0.64 \pm 0.40 \Rightarrow 1.6\sigma \text{ from zero}$$

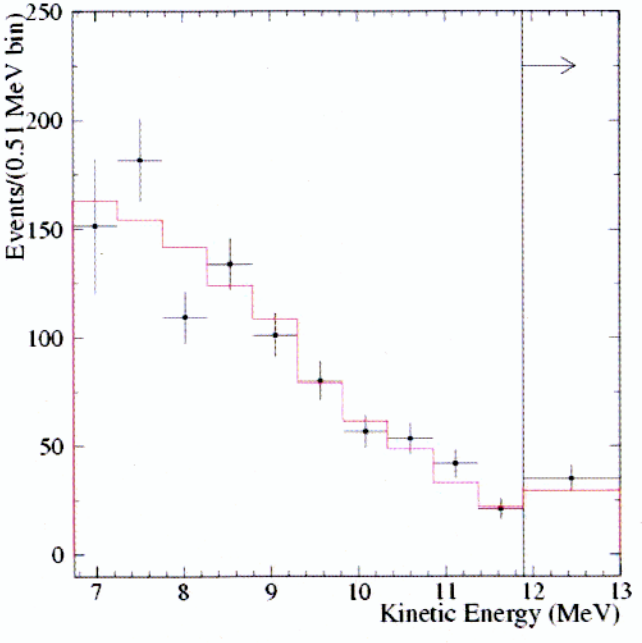
- CC at **SNO** vs ES at **SK**

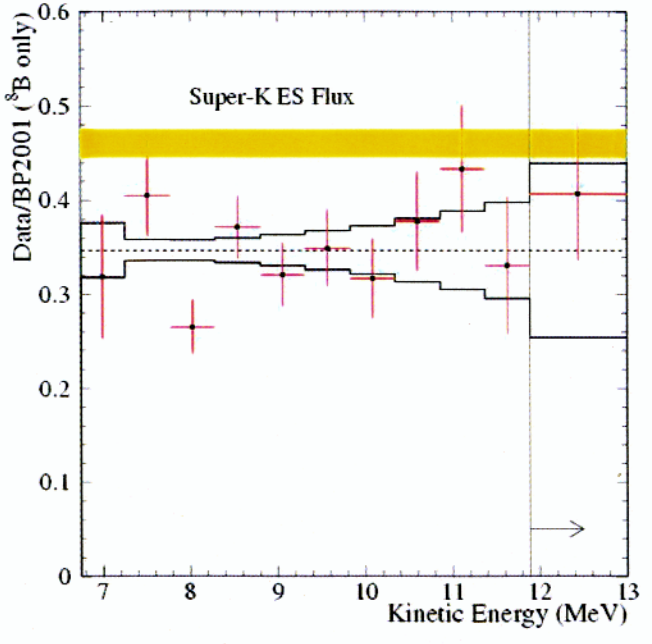
$$\Phi^{ES}_{SK} - \Phi^{CC}_{SNO} = 0.57 \pm 0.17 \Rightarrow 3.3\sigma \text{ from zero}$$

Direct evidence for non-ν_e active component to ^8B

Signal Extraction

➢Charged Current Spectrum





CC spectrum derived from fit ***without*** constraint on shape of ^{8}B spectrum

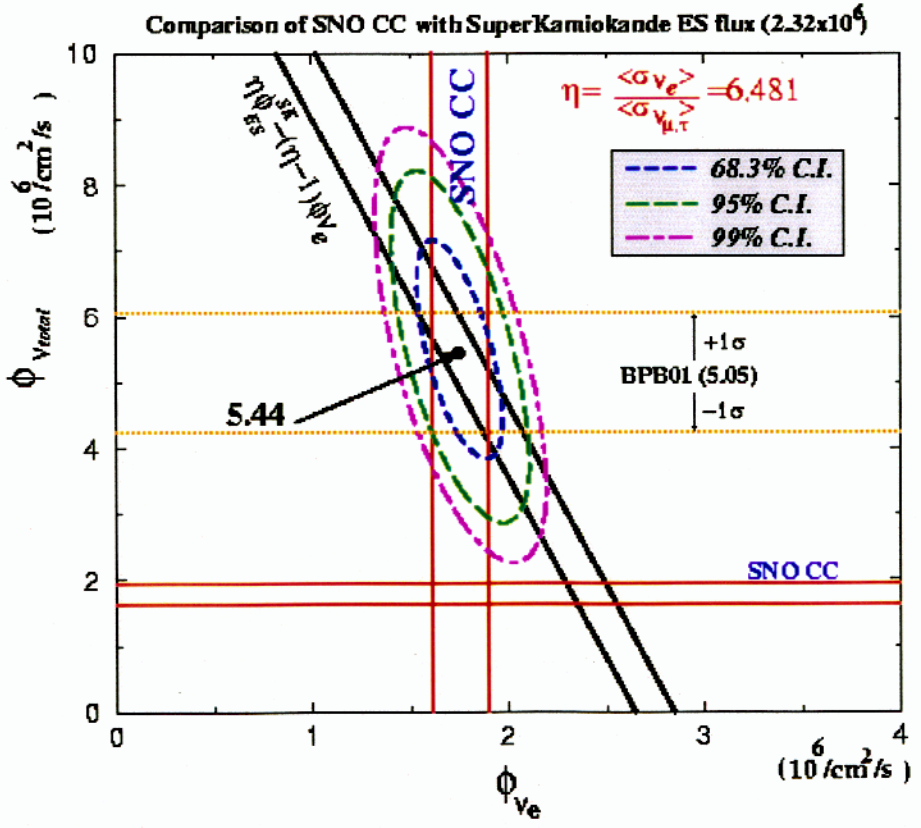
CC spectrum normalized to predicted ^{8}B spectrum.

➥ no evidence for shape distortion.

Physics Implications

➢ Flavor Content and Total Flux

Neutrino Flavor Composition of B8 Flux

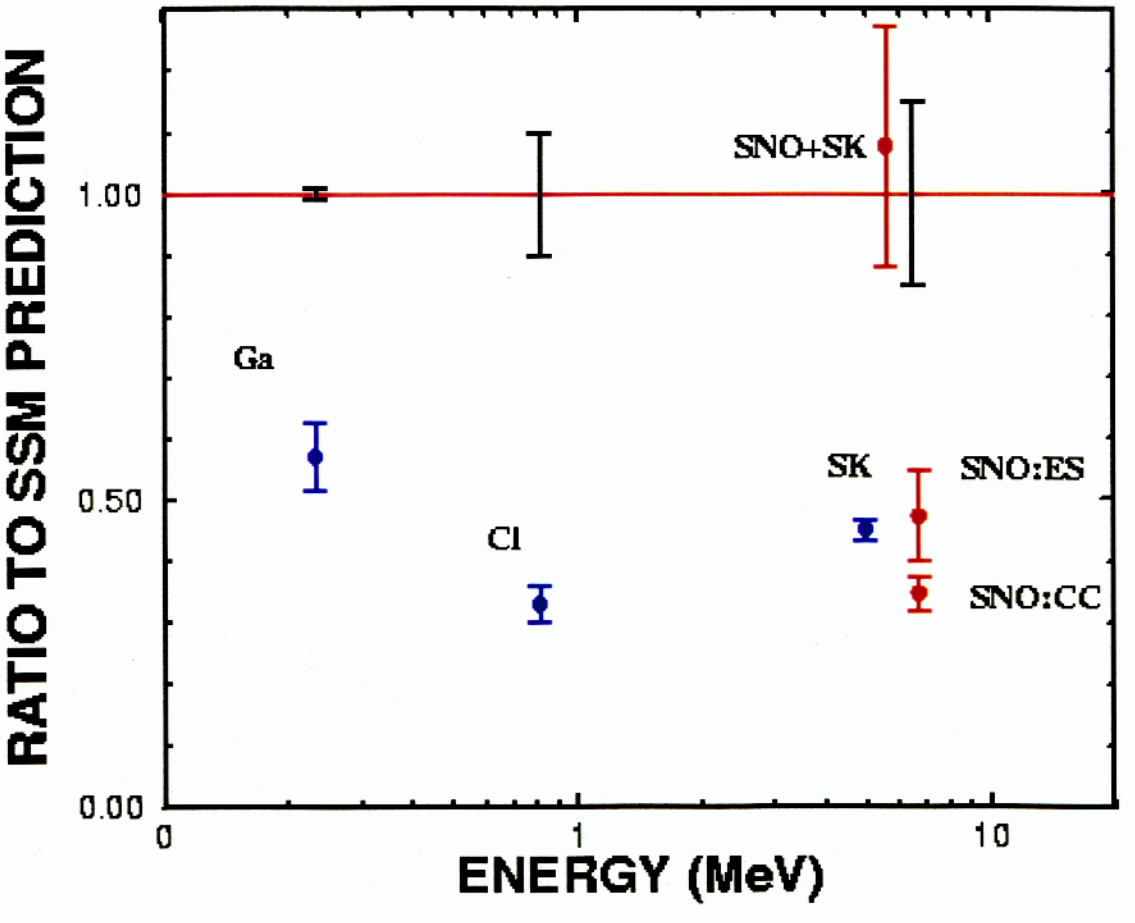


Total ^{8}B of
$5.44 \pm 0.99 \times 10^{6}\ cm^{-2}s^{-1}$
In good agreement with
BPB01 prediction of
$5.05^{+0.1}_{-0.8} \times 10^{6}\ cm^{-2}\ s^{-1}$

Ratio of Φ^{CC} to BPB01
$= 0.347 \pm 0.029$

Physics Implications

➢ SNO Compared to Other Solar Experiments



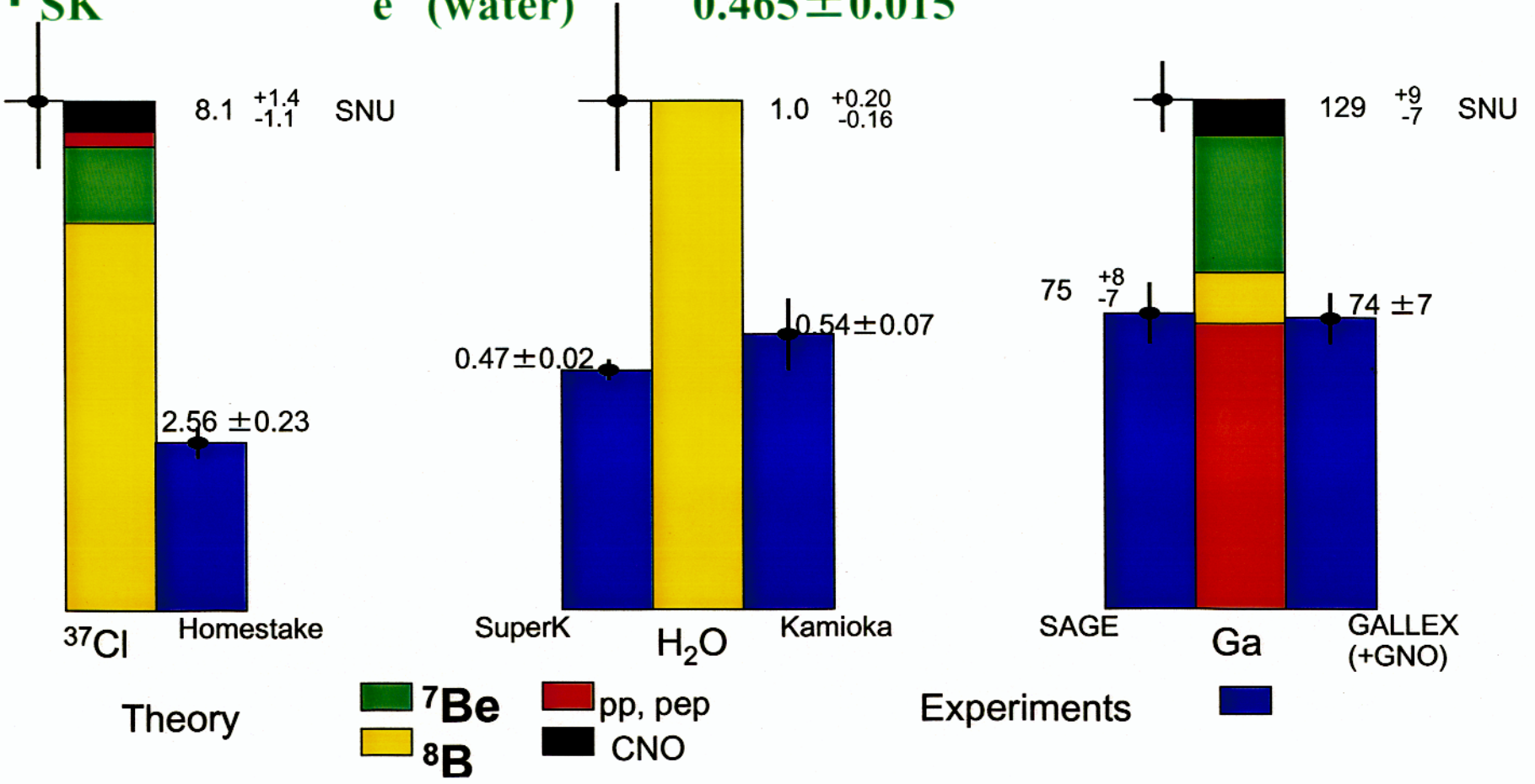
Solar Neutrino Experiments (as of ν2000)

	Target	Data / SSM (BP2000)
· Homestake	^{37}Cl	0.32 ± 0.03
· Kamiokande	e^- (water)	0.54 ± 0.07
· SAGE	^{71}Ga	0.58 ± 0.06
· GALLEX+GNO	^{71}Ga	0.57 ± 0.05
· SK	e^- (water)	0.465 ± 0.015

Be ⇒ 0

B ⇒ 0.5

then….no need of osc.



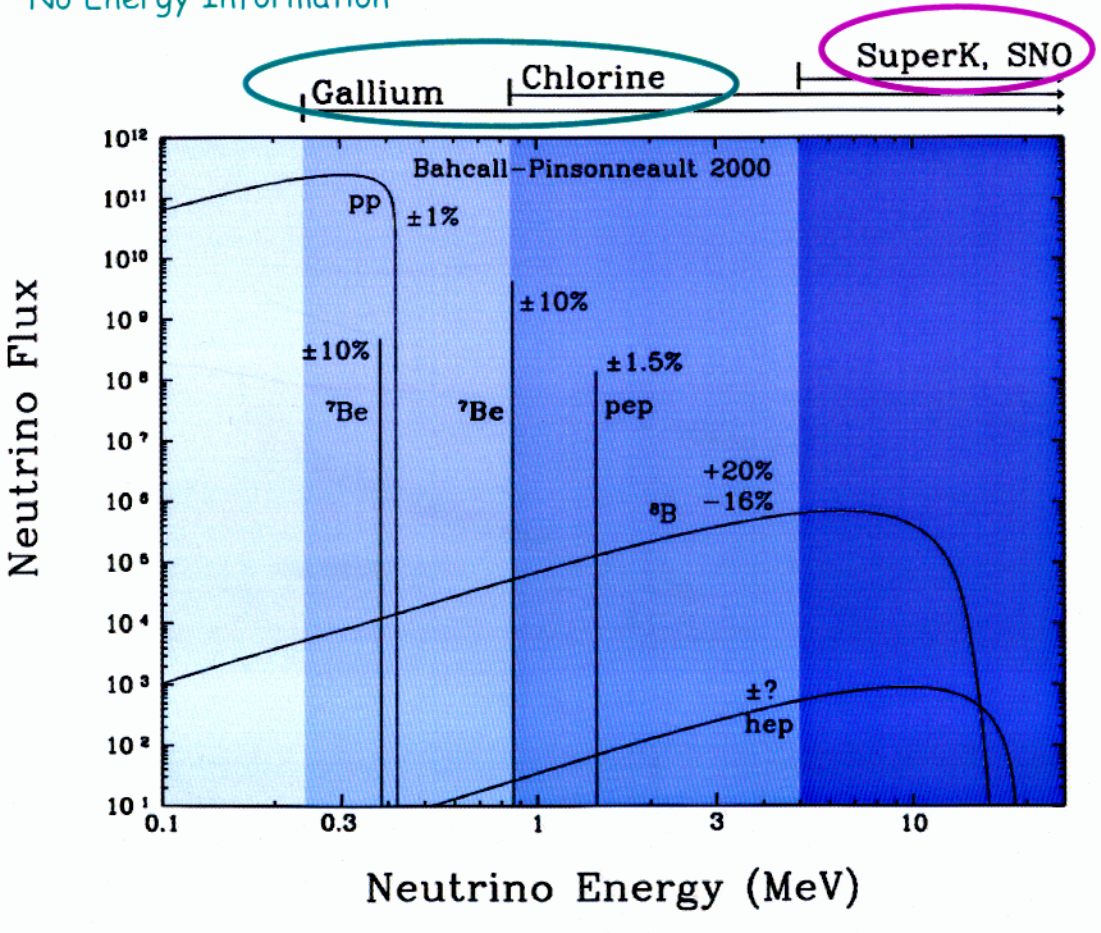
Solar Neutrino

adiochemical Experiment

No Energy Information

Real-Time Experiment

Timing & Energy Information



http://www.sns.ias.edu/~jnb/

Gallium (SAGE, Gallex + GNO)

$$\nu e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

Chlorine (Homestake)

$$\nu e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

H_2O (Kamioka, Super-K), **D_2O** (SNO)

ES $\nu e + e^- \rightarrow \nu e + e^-$

D_2O (SNO)

CC $\nu e + d \rightarrow p + p + e^-$

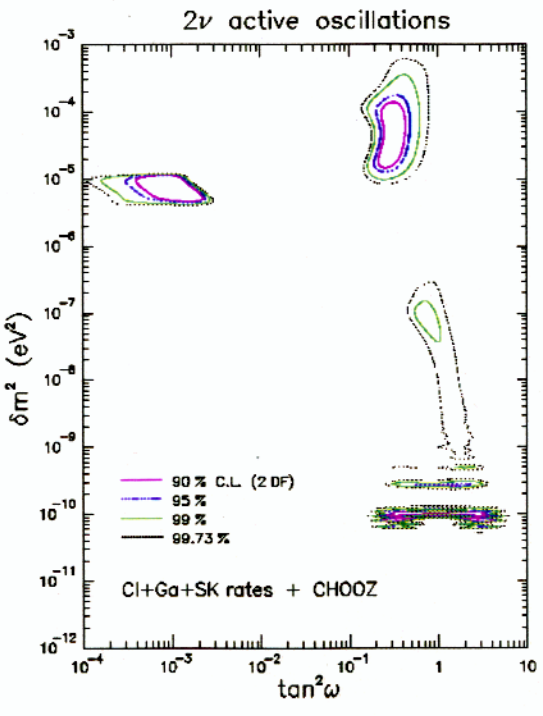
NC $\nu x + d \rightarrow p + n + e^-$

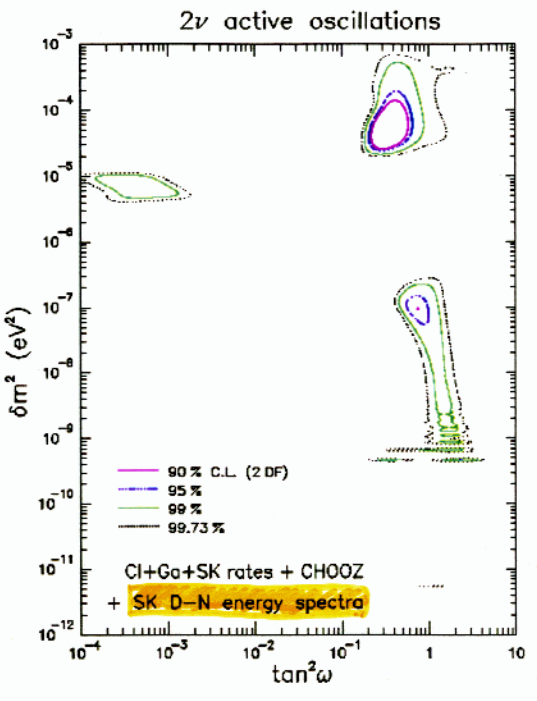
(Equal cross-section for all flavors)

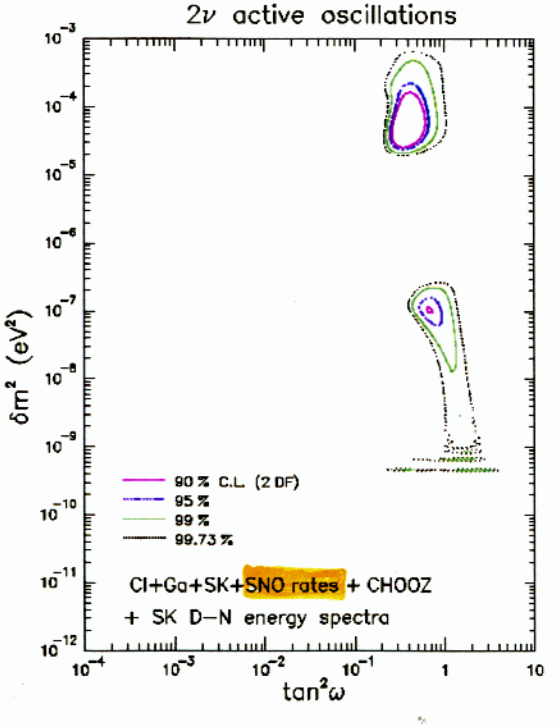
New Input !

Physics Implications

➢Mixing Angles







Fogli, Lisi, Montanino, and Palazzo, hep-ph/0106247

Also: Bahcall, Gonzalez-Garcia, Pena-Garay, hep-ph/0106258

Creminelli, Signorelli, and Strumia, hep-ph/0102234 v2

Garzelli, Giunti, hep-ph/0108191 v1

Krastev, Smirnov, hep-ph/0108177

Neutrino Oscillation - Near term

In the next few years we expect important results from both SuperKamiokande and SNO. Two new experiments will give important contributions to the unravelling of the solar neutrino problem:

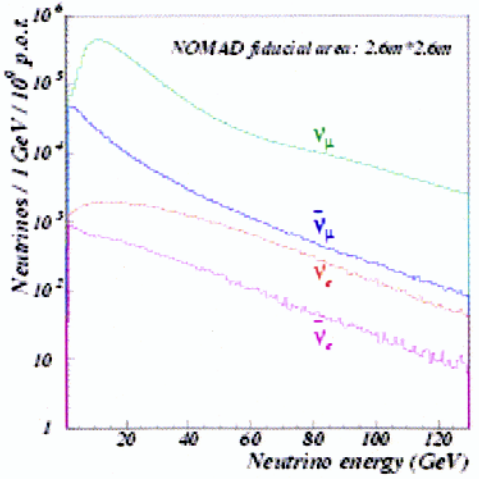
- KamLand will study oscillations in reactor neutrinos with a sensitivity sufficient to confirm or exclude the — now favoured — LM solution for neutrino oscillations.
- Borexino will be able to observe in real time the flux of the low-energy Be^7 solar neutrinos. This will allow refined studies of day/night and seasonal effects.

NOMAD νμ→νe analysis

Search for $\nu_\mu \rightarrow \nu_e$ Oscillations in NOMAD

- Appearance experiment; based on powerful electron identification in NOMAD
- Exploits low ν_e contamination in CERN neutrino beam

Neutrino fluxes at NOMAD:



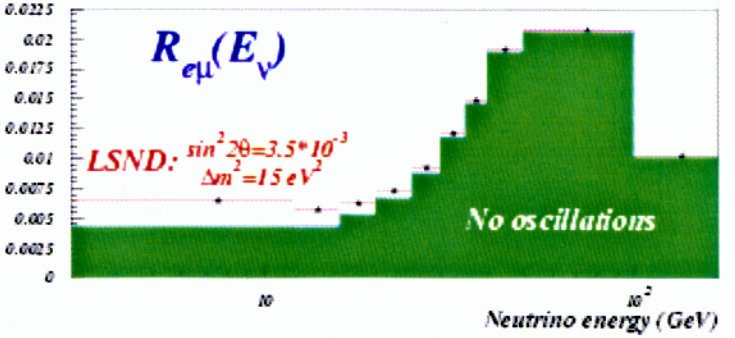
	ν_x/ν_μ	$\langle E_\nu \rangle$, GeV
ν_μ	1.0	24.2
$\bar{\nu}_\mu$	0.064	18.5
ν_e	0.010	36.6
$\bar{\nu}_e$	0.003	28.7

- Relative ν_e/ν_μ abundance in CERN SPS beam $\sim$ 1%
  $\Rightarrow$ $\nu_\mu \rightarrow \nu_e$ oscillations at a 10^{-3} level would increase the expected ν_e flux by $\sim$ 10%
- Different energy spectra for ν_e and ν_μ
  $\Rightarrow$ oscillation effect is enhanced at low ν_e energies
- Radial distribution of ν_e is broader than that of ν_μ
  $\Rightarrow$ oscillation effect is enhanced at the center of detector

The General Analysis Procedure

To reduce systematic uncertainties, we study the ratio $R_{e\mu}$ of the number of charged current interactions $(\nu_e \text{ CC})/(\nu_\mu \text{ CC})$, as a function of E_ν and r:

$$R_{e\mu} = \frac{\text{"}\nu_e \text{ CC"}}{\text{"}\nu_\mu \text{ CC"}}(E_\nu, r) = \frac{e^-(\nu_e \text{ CC}) + e^-(bkg) + e^-(\nu_e^{osc} \text{ CC})}{\mu^-(\nu_\mu \text{ CC}) + \mu^-(bkg)}$$

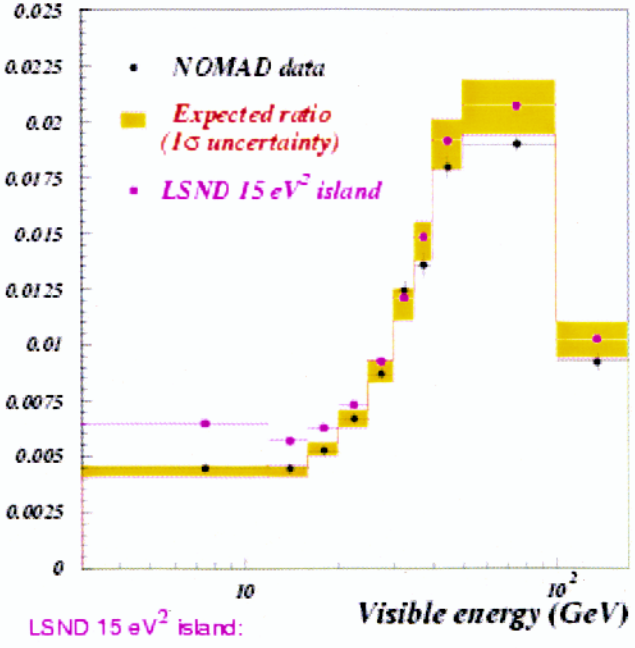


- Select ν_μ CC and ν_e CC interactions (applying lepton ID and kinematic criteria optimised on MC samples).
- Estimate remaining 'non-prompt' μ^- and e^- backgrounds.
- Reconstruct neutrino energy E_ν and radial position r on event-by-event basis.
- Estimate systematic uncertainties.
- Compare measured and predicted $R_{e\mu}(E_\nu, r)$.

NOMAD νμ→νe analysis

Preliminary Results

- Dominant systematic errors are due to uncertainties in π^+, K^+ and K^0_L yields (4-6%)
- $R_{e\mu}$ ratio as a function of neutrino energy:



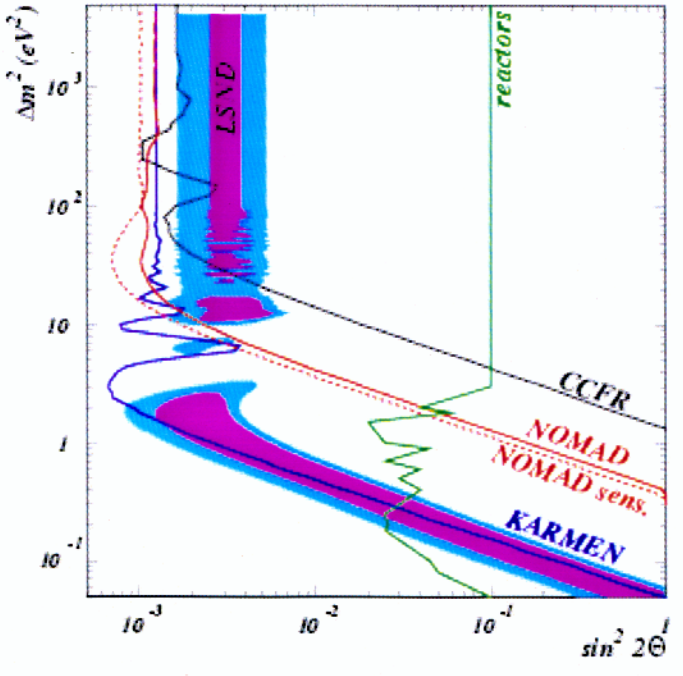
LSND 15 eV^2 island:
$\sin^2 2\theta = 3.5 \cdot 10^{-3}$ $\Delta m^2 = 15$ eV^2

- χ^2 in the absence of oscillations: 19.7 / 29 d.o.f.
- $\chi^2_{\min}$ with oscillation hypothesis: 18.6 / 27 d.o.f.

No evidence for oscillations

Exclusion Region (Preliminary)

(full NOMAD data sample)



At large Δm^2: $\sin^2 2\theta < 1.2 \times 10^{-3}$ @ 90% C.L.

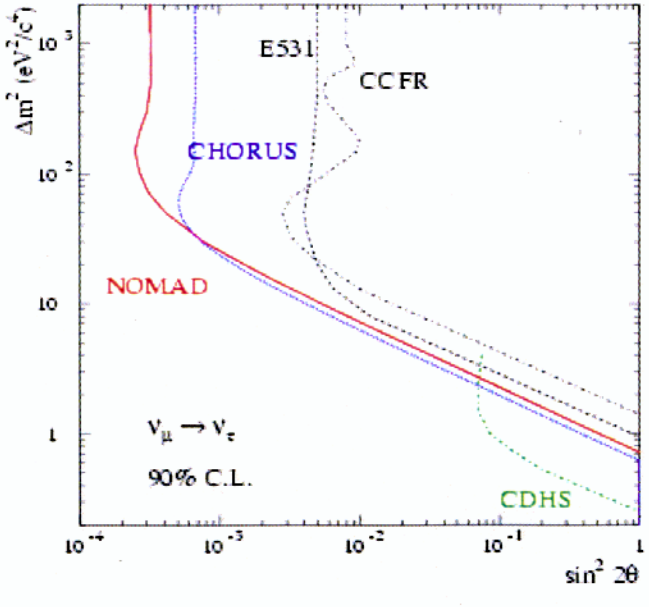
(Feldman-Cousins method)

- Exclude high Δm^2 region of oscillation parameters from LSND down to ~ 10 eV^2
- NOMAD is not sensitive to low Δm^2 LSND solutions (limited by beam energy and source–detector distance)

NOMAD νμ→ντ, νe→ντ analysis

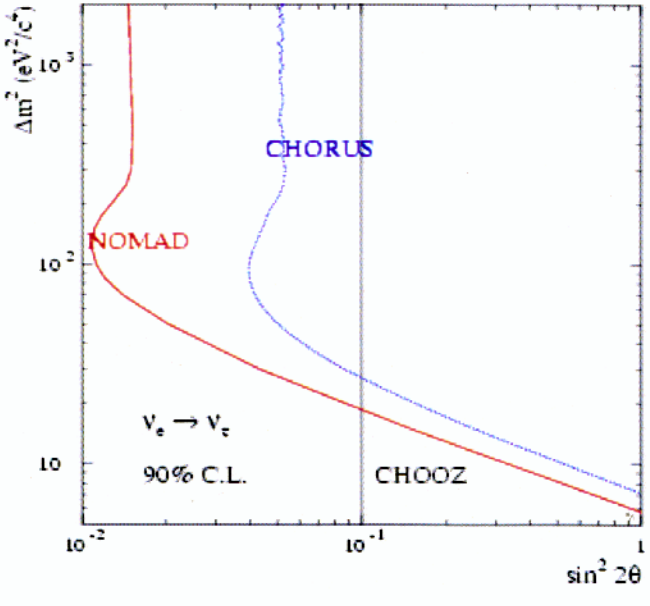
Final Results of the ν_τ Search

- $\nu_\mu \rightarrow \nu_\tau$



$$\begin{cases} S_{\nu_\mu \to \nu_\tau} = 2.50 \times 10^{-4} \\ L_{\nu_\mu \to \nu_\tau} = 1.63 \times 10^{-4} \\ P(\leq L) = 37\% \end{cases} \quad (90\%\,\text{C.L.})$$

- $\nu_e \rightarrow \nu_\tau$



$$\begin{cases} S_{\nu_e \to \nu_\tau} = 1.10 \times 10^{-2} \\ L_{\nu_e \to \nu_\tau} = 0.74 \times 10^{-2} \\ P(\leq L) = 39\% \end{cases}$$

Interpretations of ν DATA - 1

ATMOSPHERIC, SOLAR } ν OSCILLATIONS

LSND } NOT ν OSC (anomalous μ decay) LFV

} 3 ν MIXING matrix

MNS matrix

- Standard parameterization of Maki-Nakagawa-Sakata matrix for 3 generations

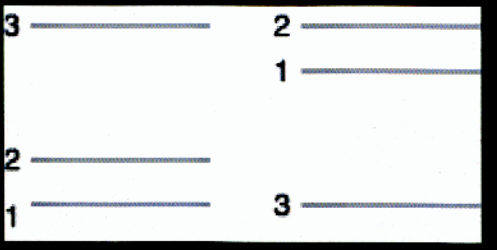
$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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

atmospheric ??? solar

Three-generation

- Solar & atmospheric ν oscillations easily accommodated within three generations
- $\sin^2 2\theta_{23}$ near maximal, $\Delta m^2_{\rm atm} \sim 3\times10^{-3}{\rm eV}^2$
- $\sin^2 2\theta_{12}$ large, $\Delta m^2_{\rm solar} \sim 3\times10^{-5}{\rm eV}^2$?
- $\sin^2 2\theta_{13} < 0.05$ from CHOOZ, Palo Verde
- Because of small $\sin^2 2\theta_{13}$, solar & atmospheric ν oscillations almost decouple
- Need to know the solar situation,
- $\sin^2 2\theta_{13}$, and mass hierarchy



Question of Flavor

- What distinguishes different generations?
  - Same gauge quantum numbers, but different
- Probably a hidden *flavor quantum number*
  - If LMA, all mixing except U_{e3} large

$$(e \quad \mu \quad \tau)\begin{pmatrix} big & big & small \\ big & big & big \\ big & big & big \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$\frac{\Delta m^2_{solar}}{\Delta m^2_{atm}} \sim 0.01 - 0.2$$

  - Two mass splittings not *very* different
  - Any new symmetry or structure behind it?

State of Art Models

- Albright-Babu-Barr (LMA)
- Altarelli-Feruglio (LOW)
- Many others *(apology!)*
  - Lam, Alexandre, Sato, McKellar
- Essence: break naïve relations from SU(5) or SO(10) in a clever way
- Interesting possible connection to proton decay (Babu-Pati-Wilczek)

More Fossils: Lepton Flavor Violation

- Neutrino oscillation

  $\Rightarrow$ lepton family number is not conserved!

  – Any tests using charged leptons?

  – Use $\Delta m^2_{\text{atm}} \sim 3\times10^{-3}\text{eV}^2$ to estimate

  $\Rightarrow B(\tau\rightarrow\mu\gamma)\sim10^{-41}$

  – However, many supersymmetric models predict $B(\tau\rightarrow\mu\gamma)$, $B(\mu\rightarrow e\gamma)$, $\mu\rightarrow e$ at interesting levels

  – Even overall lepton number violation

(Bueno, Campanelli, Rico, Rubbia, Laveder)

A. Bueno, M. Campanelli, S. Rico, A. Rubbia & M. Laveder
JHEP 06 (2001) 032 – hep-ph/0010308

	decay	interaction
standard	$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$	$\nu_e N \to e^- X$ $\bar{\nu}_\mu N \to \mu^+ X$
LFV	$\mu^+ \to e^+ \bar{\nu}_e \nu_\mu$	$\bar{\nu}_e N \to e^+$ $\nu_\mu N \to \mu^-$ WRONG SI MUON DETECTOR with charge
NV	$\mu^+ \to e^+ \bar{\nu}_\mu \bar{\nu}_e$ $(\mu^- \to e^- \nu_\mu \nu_e)$ more convenient	$\bar{\nu}_\mu N \to \mu^+$ $\bar{\nu}_e N \to e^+$ WRONG SIGN DETECTOR with e charge di

Interpretations of ν DATA - 2

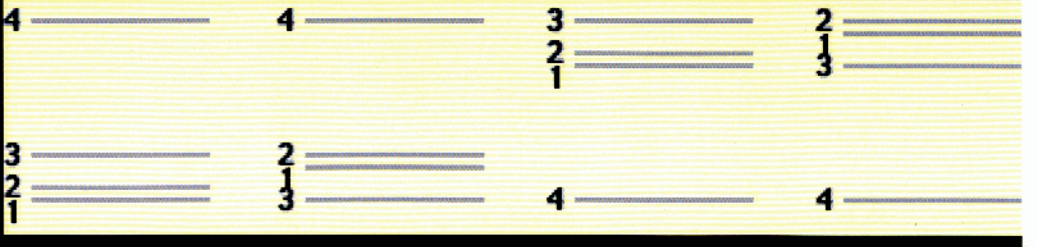
ATMOSPHERIC
SOLAR
LSND

} ν OSCILLATIONS { 4 ν MIXING (3 active + 1 sterile)
3 different Δm^2

Sterile Neutrino

- LSND, atmospheric and solar neutrino oscillation signals
  - $\Delta m^2_{\mathrm{LSND}} \sim \mathrm{eV}^2$
  - $\Delta m^2_{\mathrm{atm}} \sim 3\times10^{-3}\mathrm{eV}^2$
  - $\Delta m^2_{\mathrm{solar}} < 10^{-3}\mathrm{eV}^2$
  - $\Rightarrow$ Can't be accommodated with 3 neutrinos
  - $\Rightarrow$ Need a sterile neutrino

- 3+1 or 2+2 spectrum?



Sterile Neutrino

- 3+1 spectrum: $\sin^2 2\theta_{\mathrm{LSND}} = 4|U_{4e}|^2|U_{4\mu}|^2$
  - $|U_{4\mu}|^2$ can't be big because of CDHS, SK U/D
  - $|U_{4e}|^2$ can't be big because of Bugey
  - Marginally allowed (90% excl. vs 99% allw'd)
- 2+2 spectrum: past fits preferred
  - Atmospheric mostly $\nu_\mu \leftrightarrow \nu_\tau$
  - Solar mostly $\nu_e \leftrightarrow \nu_s$ (or vice versa)
  - Now solar sterile getting tight?

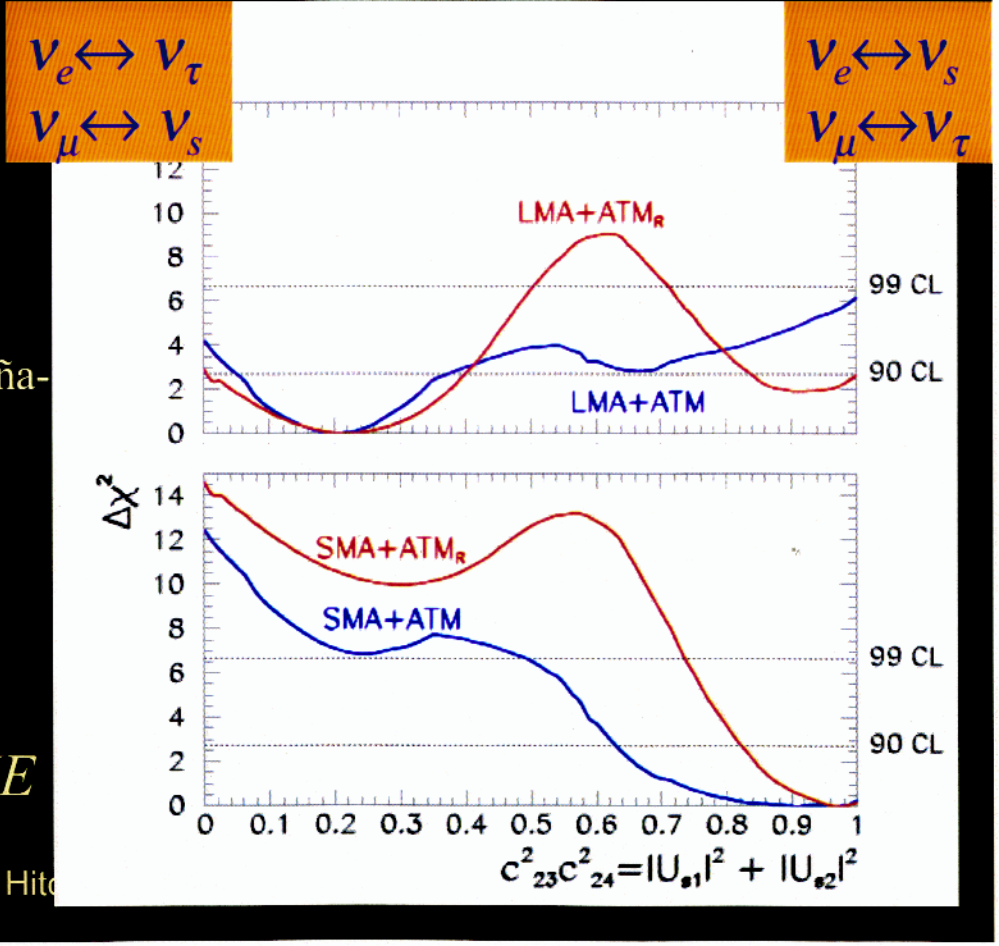
    (Barger et al, Giunti et al, Gonzalez-Garcia et al)

But Not Excluded Yet!

- Global fit to four-neutrino oscillation
  - Solar, Atmospheric, LSND

  (Gonzalez-Garcia, Maltoni, Peña-Garay@EPS01)
- One can still find a reasonable fit with 2+2

  ⇒ *Wait for Mini-BooNE*



CONCLUSIONS

Oscillation of Solar Neutrinos

The SNO/SK result

For a long time neutrino oscillations (Bruno Pontecorvo) were suspected to be the cause of the solar neutrino deficit. Now we know!

A combination of the Charged Current measurement presented by SNO and the Neutrino-Electron scattering measurements at SuperKamiokande demonstrates (to 3σ) that the solar neutrino deficit in the high energy part of the spectrum is due to the trasformation of electron neutrinos into other active neutrinos, presumably a combination of ν_μ, ν_τ.

This result is a real milestone and opens the way for a detailed exploration of the neutrino mixing matrix and mass spectrum, which will occupy our community in the next decades.

What an exciting time!

