# Review of Atmospheric ν Data

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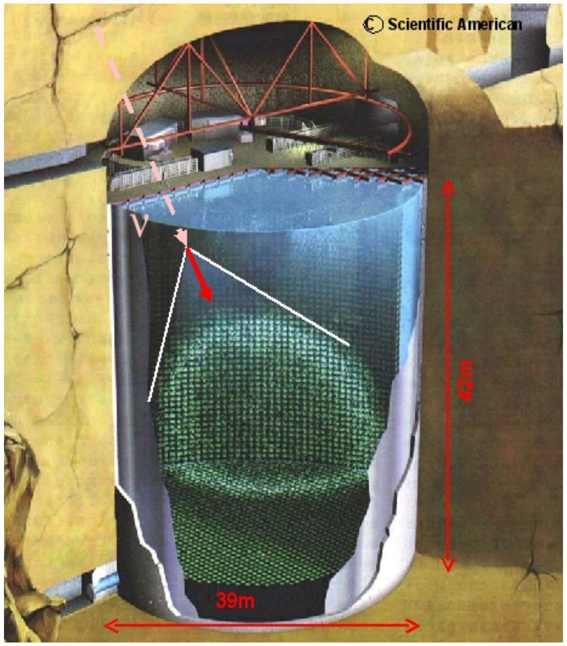
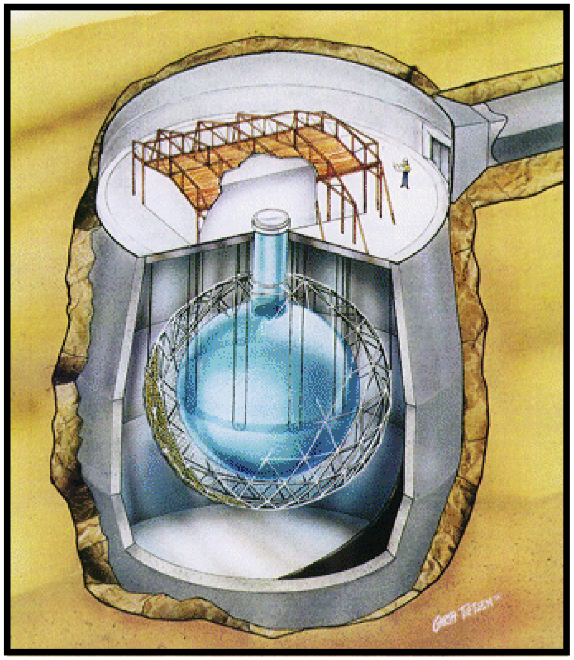


# Atmospheric $\nu$ - Yesterday's news?

- Atmospheric neutrinos and the Super-K experiment were the smoking gun which finally gained acceptance for neutrino mass and oscillations
  - Neutrinos had been seen to disappear since 1968 when Ray Davies first reported his results on solar neutrinos
    - Nobody believed it until….
  - 1998, Super-K unambiguously demonstrated a different rate of upward and downward going atmospheric $\nu_\mu$
- First beyond-the-standard-model results
- Neutrinos became news, a new industry was born
- But by 2006 beam neutrino oscillation experiments, first K2K, now MINOS have taken over as controlled, potentially precise, experiments
- What can atmospheric neutrino experiments still contribute?

# Three Underground Experiments

## Super-K

- Results from Super-K I and II, two flavour and three flavour analyses (poster)
- Search for $\nu_\tau$ appearance (SK-I)(poster)
- Search for sterile neutrinos (SK-I) (poster)
- Test of Mass Varying neutrino models (SK-I) (poster)

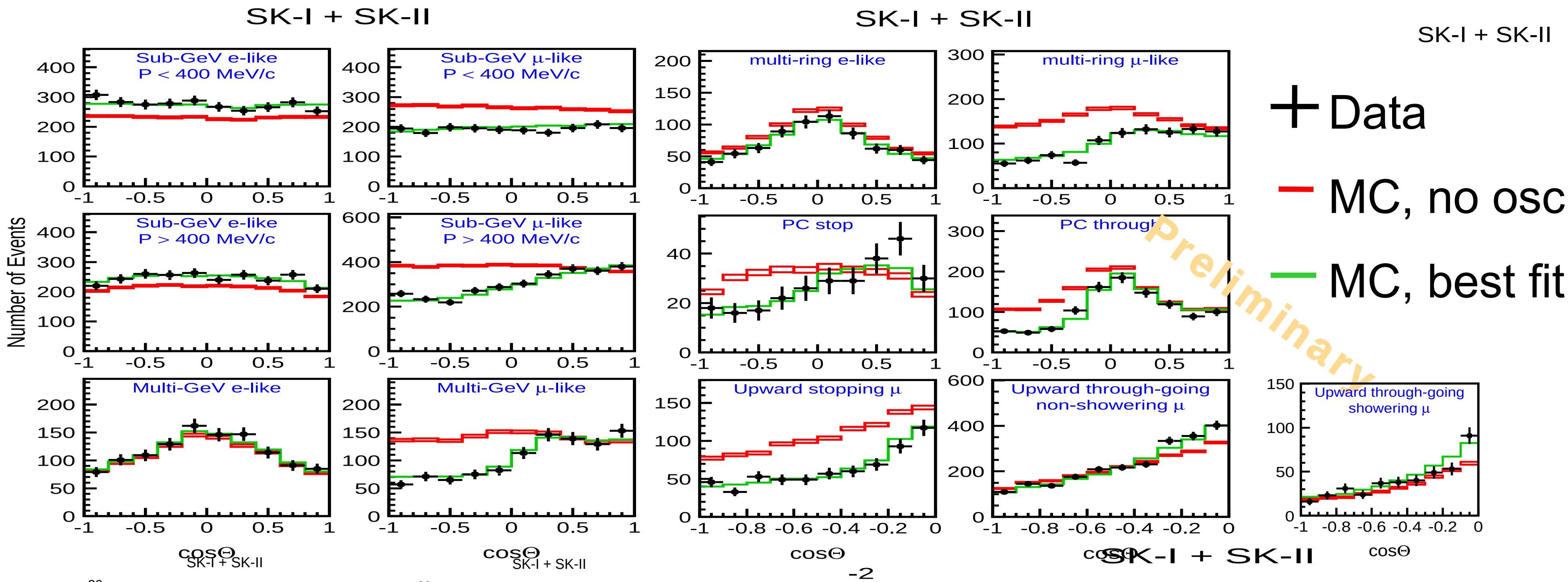
## MINOS

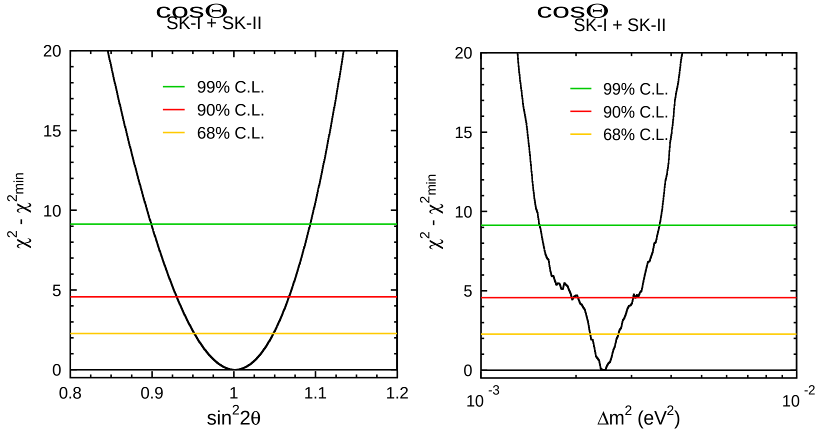
- Charge separated ( $\nu_\mu$ and $\bar{\nu}_\mu$ ) results from contained vertex events (poster) and neutrino induced incoming $\mu$ events

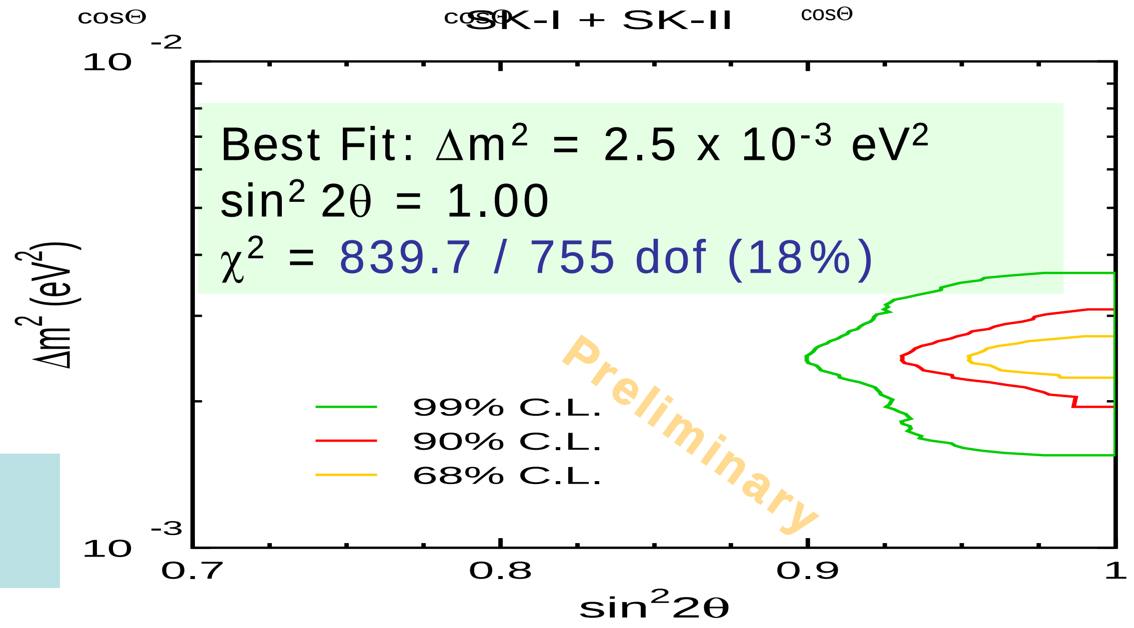
## SNO

- Neutrino induced incoming $\mu$ events

# Super-K Two-flavour analysis




$1.9 \times 10^{-3}$ $eV^2 < \Delta m^2_{23} < 3.1 \times 10^{-3}$ $eV^2$
$\sin^2 2\theta_{23} > 0.9$ at 90% CL

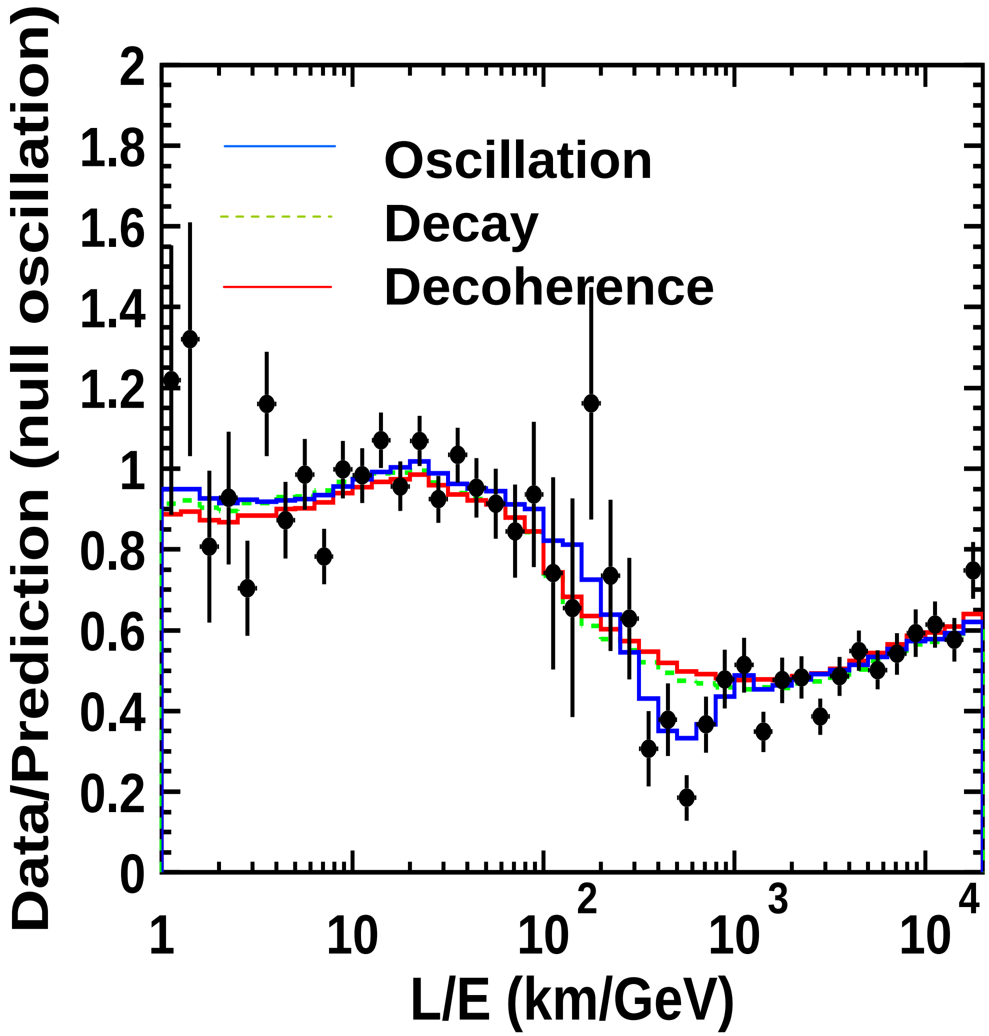
# L/E Analysis

❖L/E analysis uses a restricted sample of higher resolution events

❖Dip corresponding to the first oscillation minimum

❖Oscillation, decay and decoherence models tested

$\chi^2_{osc}$ = 83.9/83
$\chi^2_{dcy}$ = 107.1/83, $\Delta\chi^2$ = 23.2(**4.8σ**)
$\chi^2_{dec}$ = 112.5/83, $\Delta\chi^2$ = 27.6(**5.3σ**)




❖Best fit parameters

**$\Delta m^2_{23}$=2.3x$10^{-3}$ $eV^2$ (2.0x$10^{-3}$<$\Delta m^2$<2.8x$10^{-3}$ $eV^2$ at 90%C.L.)**
**$\sin^2 2\theta_{23}$=1.00 ($\sin^2 2\theta_{23}$>0.93 at 90%C.L.)**

# Sub Dominant $\nu_\mu \rightarrow \nu_e$ Oscillations

- At very long baselines through the earth oscillations driven by $\Delta m^2_{12}$ can be significant at low energies
- Then the $\nu_e$ flux will change with oscillations
  - $\nu_e$ *flux decreases* by $\nu_e$ oscillation : $1 - P(\nu_e \rightarrow \nu_e) = P_2$
  - $\nu_e$ *flux increases* by $\nu_\mu$ oscillation : $r\,P(\nu_\mu \rightarrow \nu_e) = r \cos^2\theta_{23} P_2$
  - where $r = (\nu_\mu \text{ flux}) / (\nu_e \text{ flux}) \sim 2$ at low energy
- For $\theta_{23} \sim 45^0$ the two effects approximately cancel

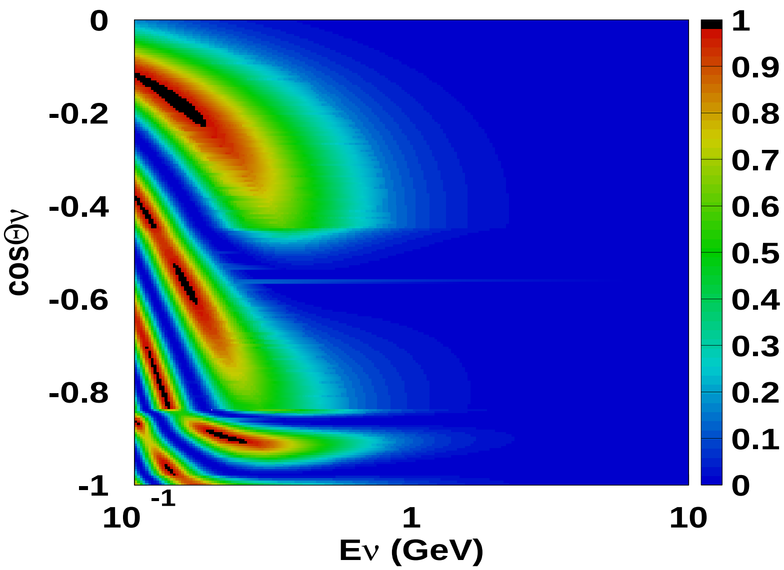
  $\cos^2\theta_{23} = 0.5$ ($\theta_{23} = 45$ deg.) : $\nu_e$ increase ~ decrease

  $\cos^2\theta_{23} > 0.5$ ($\theta_{23} < 45$ deg.) : $\nu_e$ increase > decrease

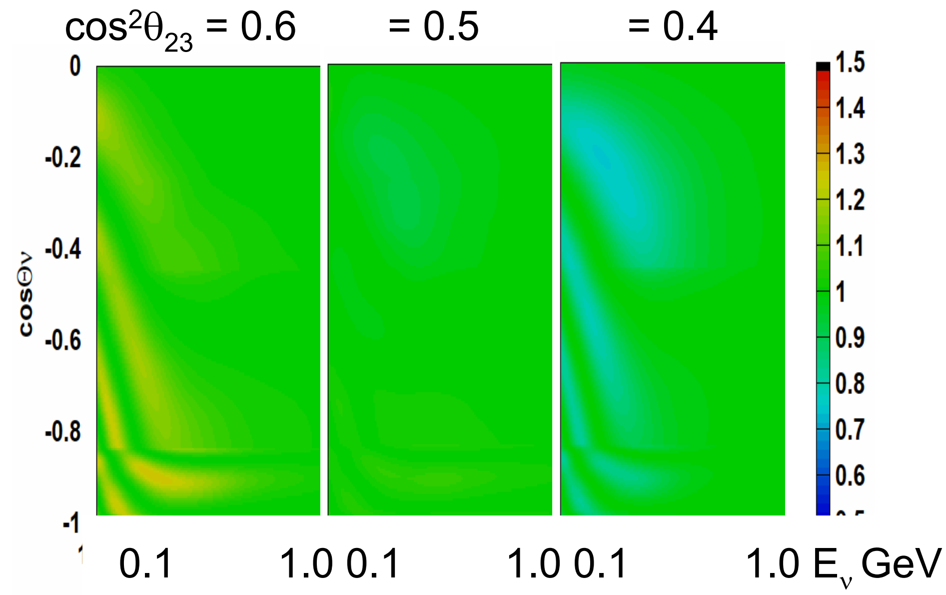
  $\cos^2\theta_{23} < 0.5$ ($\theta_{23} > 45$ deg.) : $\nu_e$ increase < decrease
- In principle possible to tell if $\theta > 45^0$ or $< 45^0$
- Matter effects may also play a part

# Sub Dominant $\nu_\mu \rightarrow \nu_e$ Oscillations

2ν transition probability $\nu_e \rightarrow \nu_{\mu,\tau}$
in matter driven by $\Delta m^2_{12}$




$\nu_e$ flux with oscillation / $\nu_e$ flux without oscillation



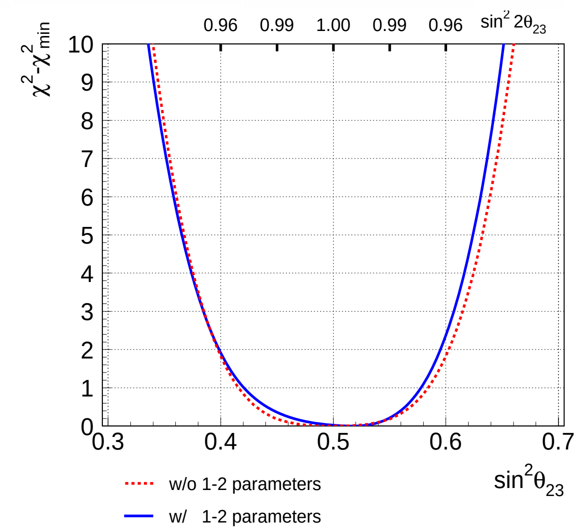

❖Effects in low energy events with negative zenith angles

❖Fit shows no significant evidence for deviation from $\sin^2 2\theta_{23}=1$

❖For more details see the poster of Moriyama

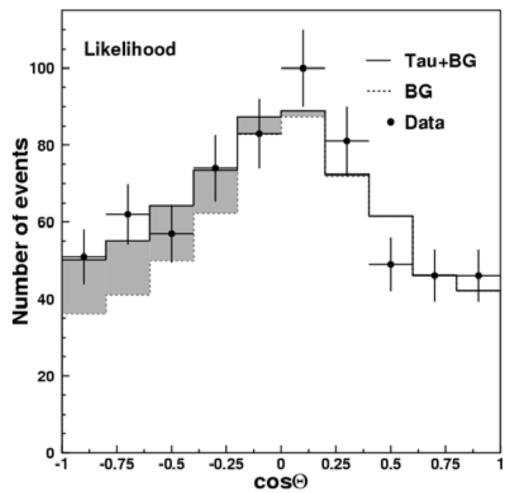
Solar terms off

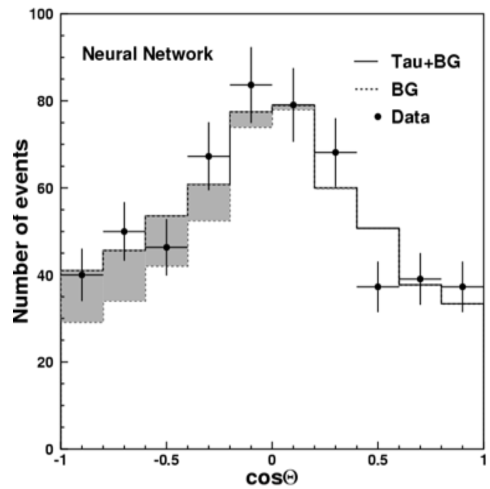
Solar terms on



# $\nu_\tau$ Appearance

- Events with a $\tau$ decay look like high multiplicity neutral current events
- Select Multi-GeV events with their most energetic ring e-like
- Perform Likelihood and Neural Net analyses to separate $\tau$ events



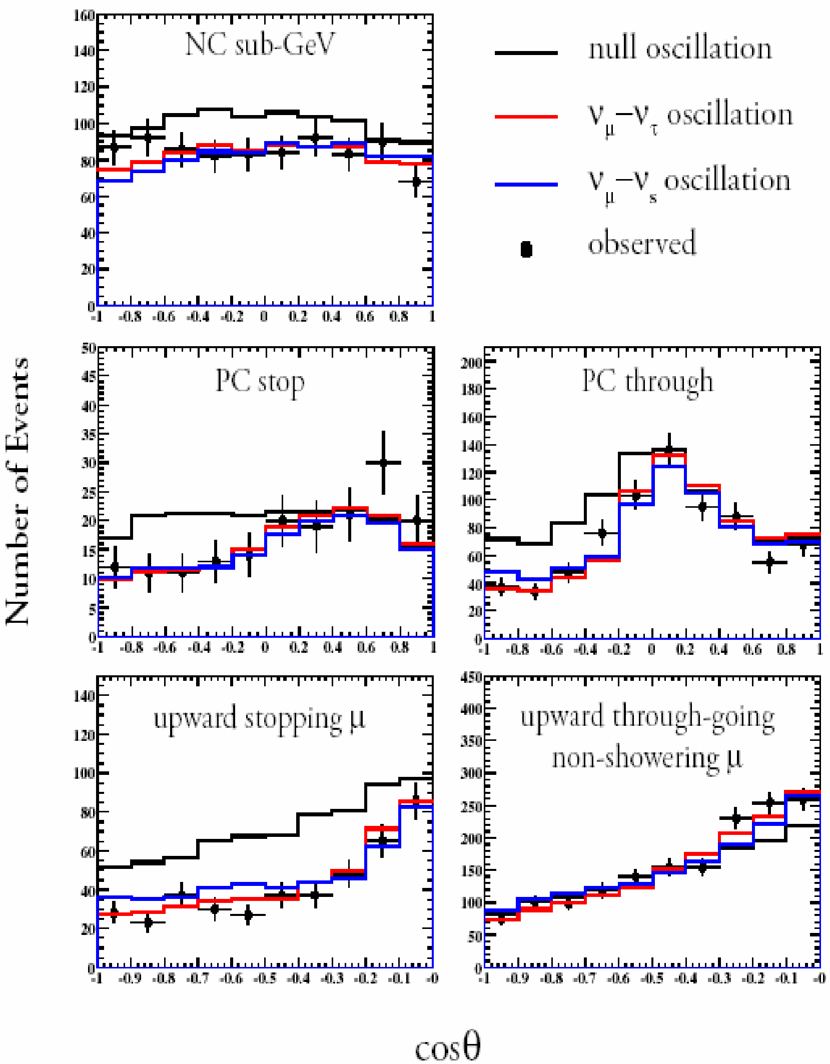



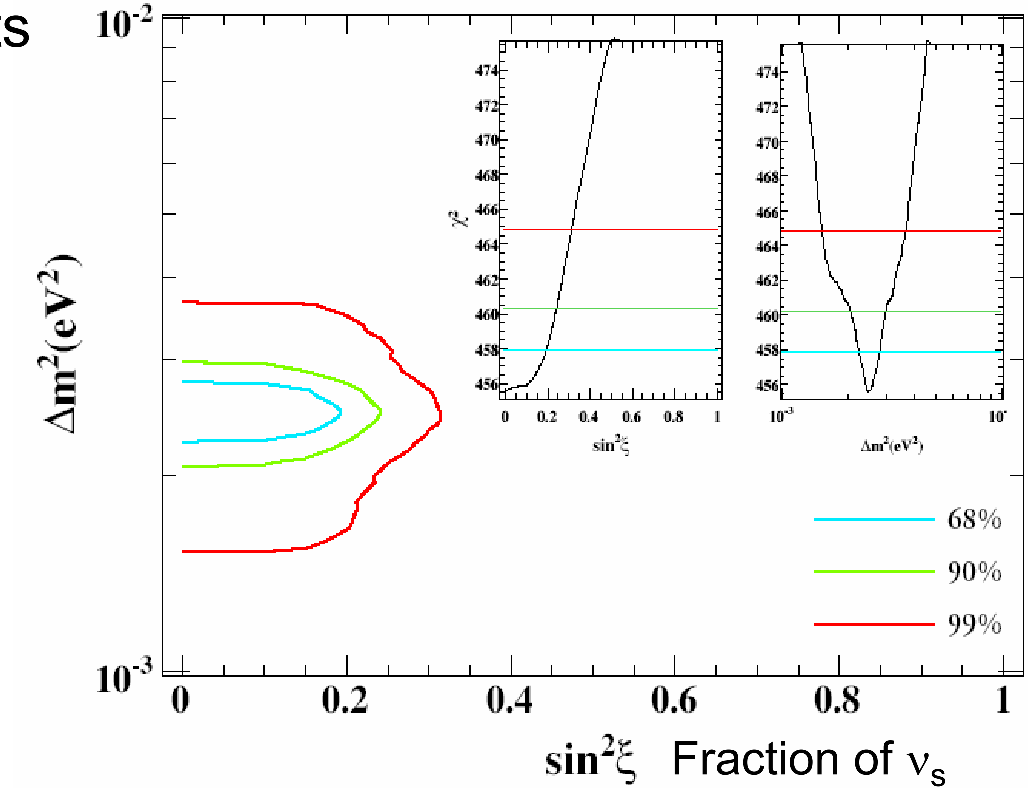

For more details see the poster of Tokufumi Kato

- Likelihood analysis:
  - Total $\tau$ excess: 138 ± 48(stat.) + (+14.8/-31.6)(sys.) ( 2.4 sigma)
    - Expected $\tau$ excess: 78.4 ± 26(sys.)
- Neural Net analysis:
  - Total $\tau$ excess: 134± 48(stat.) + (+16/-27.2)(sys.) (2.4sigma)
    - Expected $\tau$ excess: 78.4 ± 27(sys.)

# Sterile Neutrinos

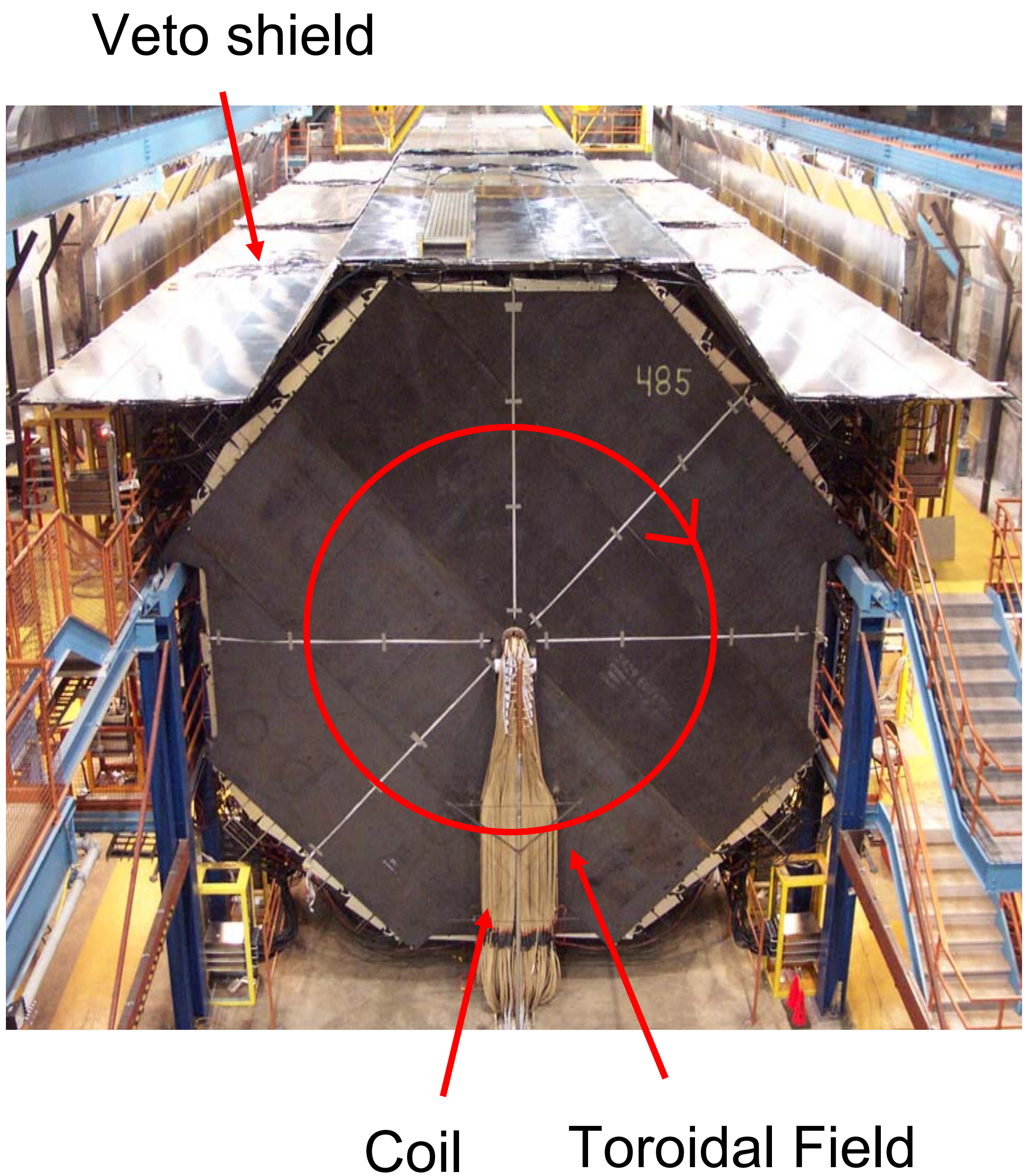
- Search for sterile neutrinos in a 2+2 mass hierarchy (Fogli et al)
- Oscillations to $\nu_s$ reduce nc events




- Best fit is with no sterile neutinos, all sterile excluded at 7.0σ
- Up to a 25% admixture is allowed
- For more details see poster of Wei Wang

# MINOS Atmospheric ν

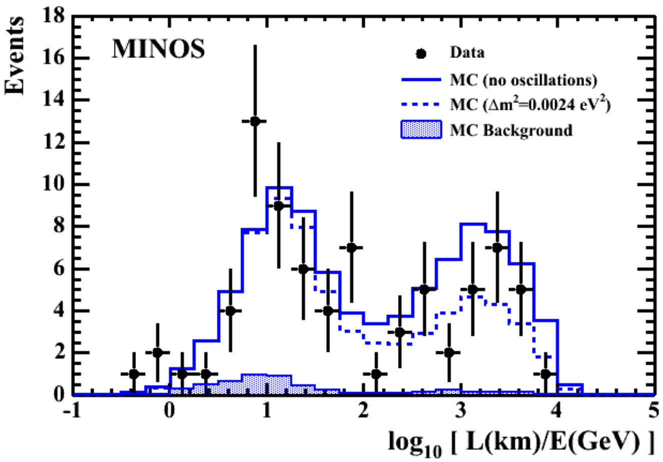


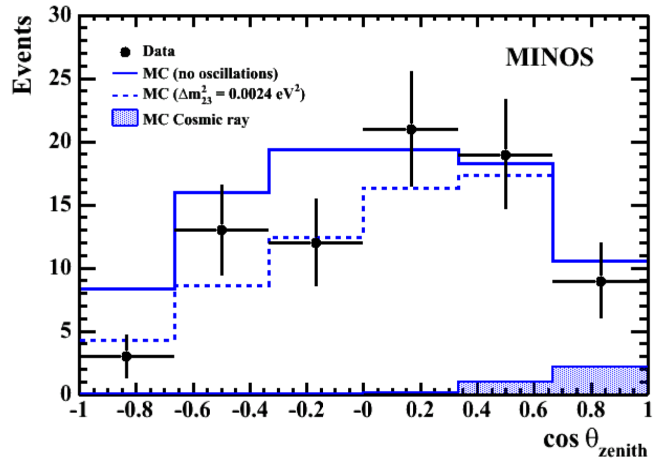

- First underground experiment equipped with a magnetic field
- Can separate $\nu_\mu$ from $\bar{\nu}_\mu$
- 5.4 kilotons total mass
- Alternating planes of 2.5cm steel and 4cm wide scintillator strips
- Not designed as an atmospheric neutrino detector – active planes are vertical
- Veto shield necessary to eliminate cosmic ray background

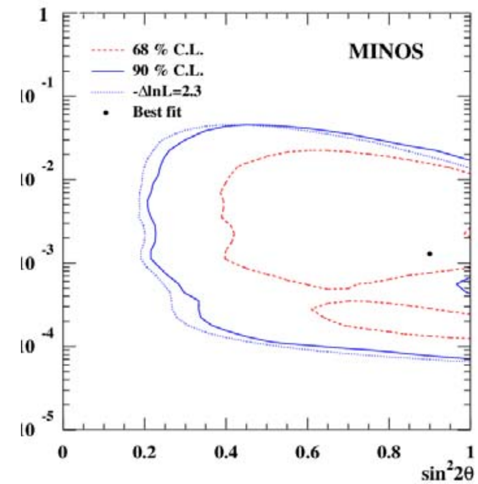
# MINOS analyses

- Contained vertex events
  - Analysis of 418 live days (6.18 kiloton years)
  - Published in **Phys. Rev. D73, 072002 (2006)**
  - More data and an improved analysis will give nearly three times the statistics, watch this space
- Neutrino induced muon events (Preliminary, new at this conference)
  - Muons coming from neutrino interactions in the rock surrounding the detector
  - Data from 842 live days
- Each analysis performs an all event and a charge separated analysis
- To come, a combined analysis of all data

# Contained Vertex Analysis




❖ 107 data events compared with 127±13 expected for no oscillations

❖ Event direction measured by timing

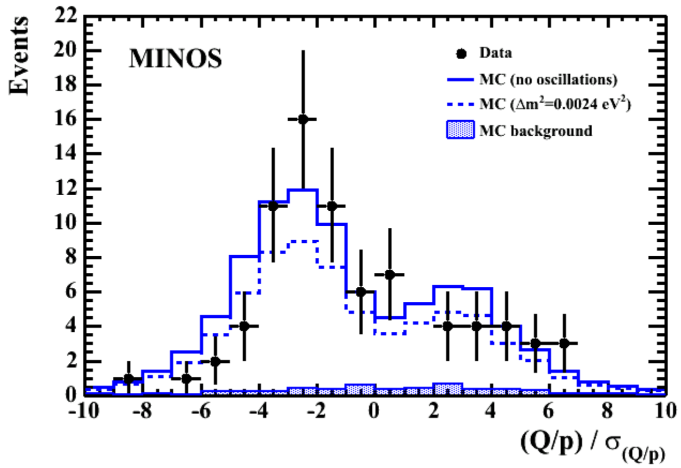
❖ 77 events with a well measured direction, 49 downward going, 28 upward going

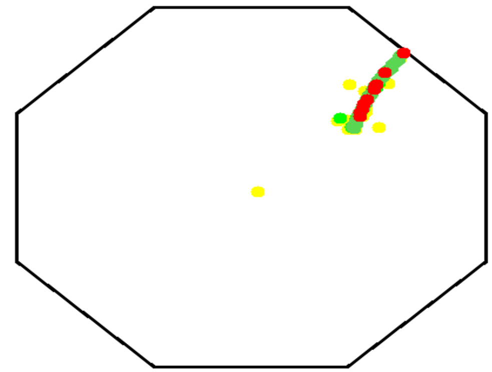
$$\mathbf{R^{data}_{up/down} / R^{MC}_{up/down} = 0.62^{+0.19}_{-0.14}(stat.) \pm 0.02(sys.)}$$

❖ An extended maximum likelihood analysis with Feldman-Cousins style error analysis yields the above allowed regions

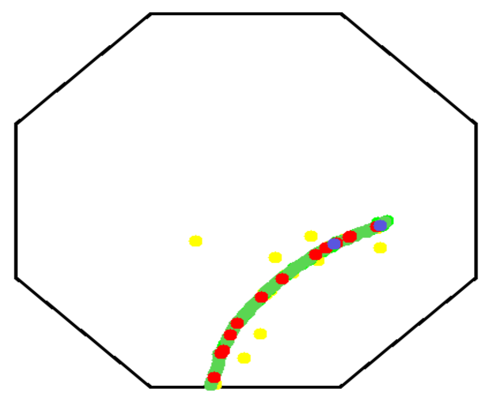
# Charge sign measurement

- In the magnetic field we measure $Q/p$, the charge divided by momentum and its error $\sigma\left(Q/p\right)$



Upward going partially contained event



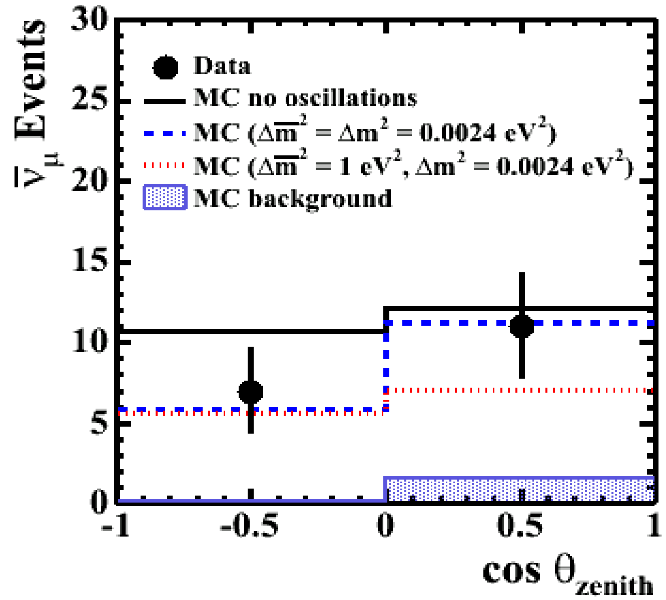
Downward going partially contained event

- Charge sign is defined well measured if $|(Q/p)/(\sigma(Q/p))|>2$.

- 52 well measured events, 34 $\nu_\mu$ , 18 $\bar{\nu}_\mu$

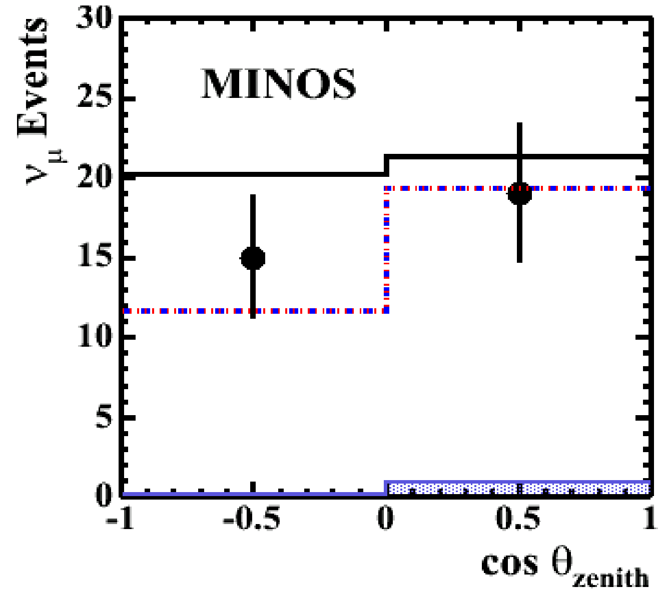
$$R^{data}_{\bar{\nu}_\mu/\nu_\mu} = 0.53^{+0.21}_{-0.15}(\text{stat.}) \pm 0.03(\text{sys.})$$

# Charge Separation



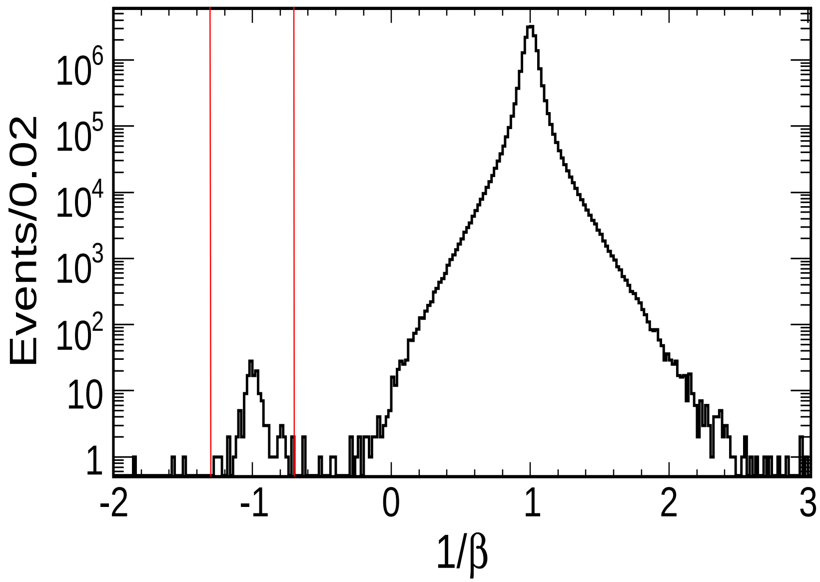

- Up versus down charge separated angular distributions are plotted
- Both $\nu_\mu$ and $\bar{\nu}_\mu$ are consistent with standard oscillations
- $\bar{\nu}_\mu$ oscillations with $\Delta m^2$ of 1ev$^2$ are less favoured

$$R^{data}_{\bar{\nu}/\nu} / R^{MC}_{\bar{\nu}/\nu} = 0.96^{+0.38}_{-0.27}(\text{stat.}) \pm 0.15(\text{sys.})$$



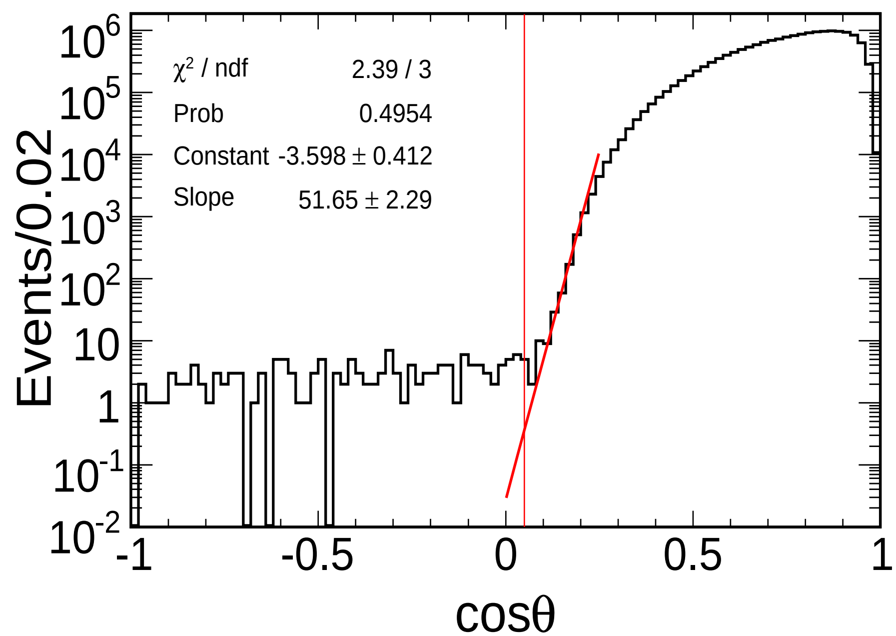

- For more details see poster of Andy Blake

# Neutrino induced μ Analysis




- Upward going μ are produced by ν interactions in the surrounding rock
- μ direction determined by timing
- Single hit timing resolution 2.3ns
- 131 upward going μ selected

- Soudan overburden is flat
  - Horizontal cosmic ray μ have to traverse a large column of rock and are absorbed.
- Cut at a zenith angle of 0.05
- 10 extra neutrino induced μ not selected by the timing cut



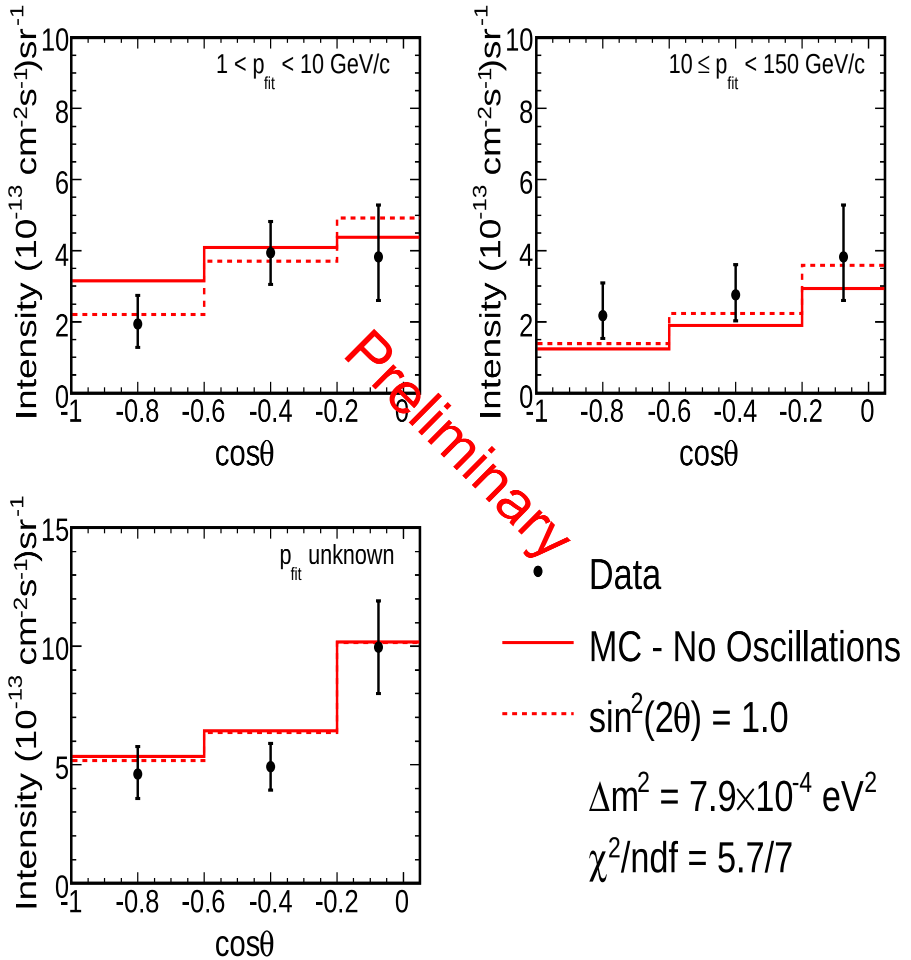
# Combined Charge Analysis

- Divide data into three categories
  - $1<p_\mu<10$GeV/c (low)
  - $10<p_\mu<150$GeV/c with well measured momentum (high)
  - Poorly measured momentum and charge sign (mostly high momentum)

| | $\mu^+$ | $\mu^-$ |
|---|---|---|
| $1<p_\mu<10$Gev/c | 22(39.5) | 16(20.9) |
| $10<p_\mu<150$GeV/c | 20(18.8) | 13(9.7) |
| Unknown charge | 70(81.4) | |

Data (MC no oscillations)

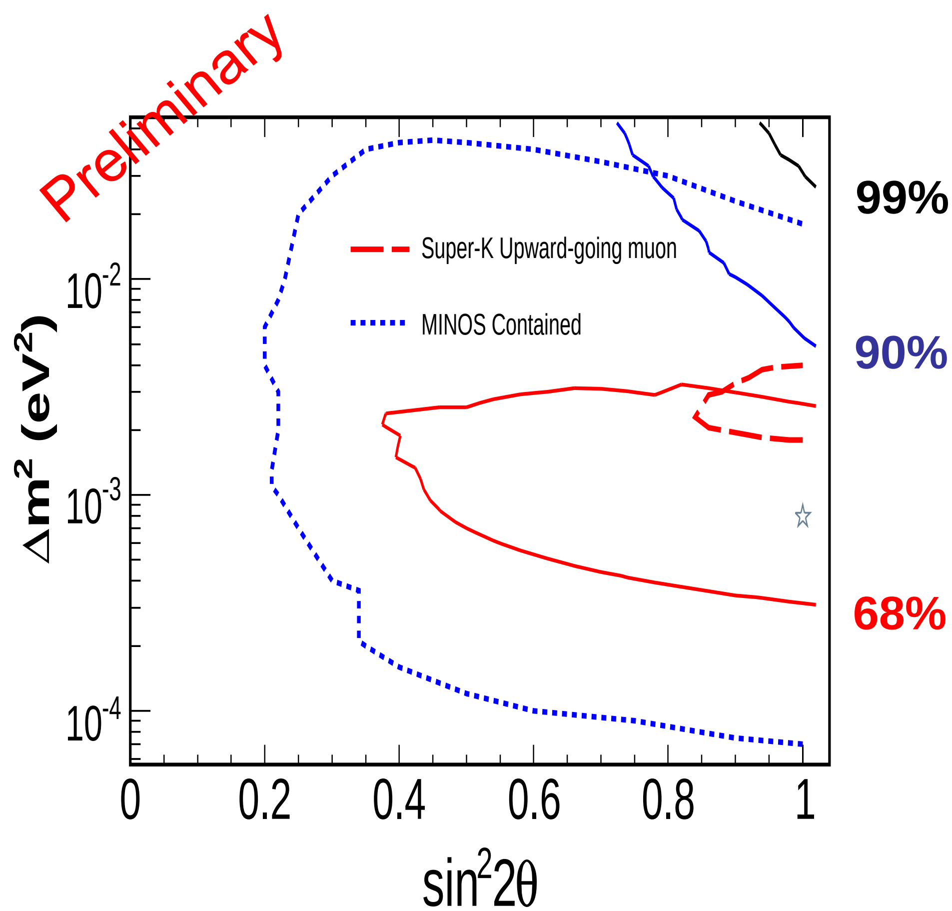
- Expect low momentum ν to oscillate more than high momentum




$$\frac{R^{data}_{\frac{low}{high}}}{R^{MC}_{\frac{low}{high}}} = 0.54^{+0.17}_{-0.13}(stat) \pm 0.10(syst)$$

# Oscillation analysis

- Oscillation fit to the momentum separated zenith angle distribution
- Five systematic errors included as nuisance parameters in the fit
  - Reconstruction
  - Cross sections
- Oscillation analysis, best fit point
  - $\Delta m^2 = 7.9 \times 10^{-4}$ eV$^2$
  - $\sin^2 2\theta = 1.0$
  - $\chi^2/ndf = 5.7/7$
- No oscillations excluded at the 87% confidence level



# Charge Separated Analysis

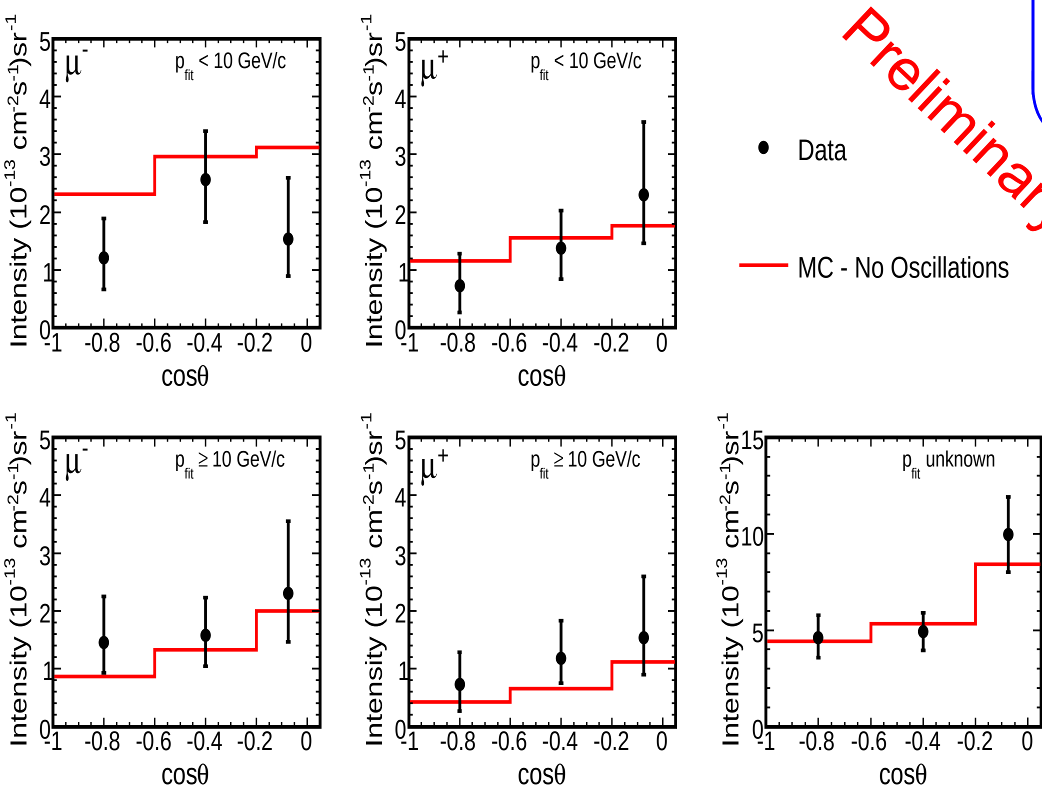
- Both $\nu_\mu$ and $\bar{\nu}_\mu$ show a deficit with respect to the prediction
- Ratio consistent with 1.0 but with a large uncertainty

$$\left(\frac{R^{data}_{\frac{low}{high}}}{R^{MC}_{\frac{low}{high}}}\right)_{\nu} = 0.53^{+0.22}_{-0.16}(stat) \pm 0.10(syst)$$

$$\left(\frac{R^{data}_{\frac{low}{high}}}{R^{MC}_{\frac{low}{high}}}\right)_{\bar{\nu}} = 0.57^{+0.32}_{-0.20}(stat) \pm 0.10(syst)$$

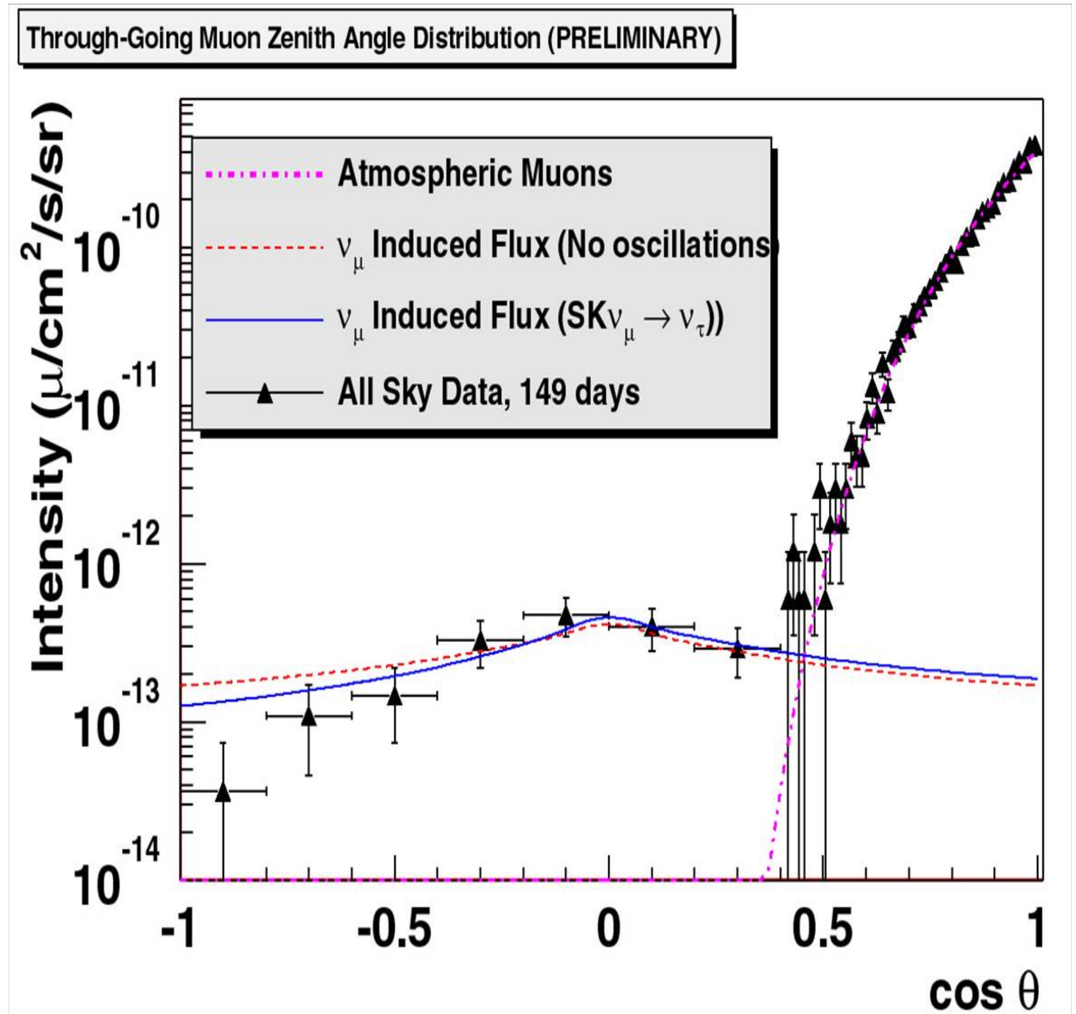
Preliminary

$$R_\nu \Big/ R_{\bar{\nu}} = 0.91^{+0.64}_{-0.42}(stat) \pm 0.05(syst)$$



# SNO Atmospheric ν

- SNO is a very deep experiment
- Cosmic μ are absorbed a long way above the horizontal
- Neutrino induced μ from the surrounding rock are visible well above the horizon
- See the transition region where the oscillation dip is maximal
- Data from the first 149 days exposure is available
- Remaining data is still in a blinded analysis
- For more details see poster of Formaggio and Poon



# The Future of Atmospheric $\nu$

- What can atmospheric neutrino experiments do that beams cannot?
  - Measurement of $\Delta m^2$ depends on the resolution on L/E
    - Beam experiments better, L fixed
  - Measurement of $\sin^2 2\theta_{23}$ depends on statistical precision
    - Depends on $\nu$ flux $\times$ mass, present beam experiments worse
    - Future experiments (NO$\nu$A, T2K) will do better
- Atmospheric neutrino experiments have an unbeatably long baseline
  - Large matter effects in principle
    - Determine mass hierarchy + resolve $\sin^2 2\theta_{23}$ ambiguity
- Room for one more large magnetised atmospheric neutrino detector
  - INO, next talk