Results from Super Kamiokande

Naho Tanimoto

on behalf of Super Kamiokande collaborators

Duke University

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APS meeting at Jacksonville in FL

Super-Kamiokande Collaboration

- 140 collaborators from 35 institutes of 5 countries

K. Abe,[1] Y. Hayato,[1] T. Iida,[1] K. Ishihara,[1] J. Kameda,[1] Y. Koshio,[1] A. Minamino,[1] C. Mitsuda,[1] M. Miura,[1] S. Moriyama,[1] M. Nakahata,[1] Y. Obayashi,[1] H. Ogawa,[1] M. Shiozawa,[1] Y. Suzuki,[1] A. Takeda,[1] Y. Takeuchi,[1] K. Ueshima,[1] I. Higuchi,[2] C. Ishihara,[2] M. Ishitsuka,[2] T. Kajita,[2] K. Kaneyuki,[2] G. Mitsuka,[2] S. Nakayama,[2] H. Nishino,[2] K. Okumura,[2] C. Saji,[2] Y. Takenaga,[2] Y. Totsuka,[2] S. Clark,[3] S. Desai,[3] F. Dufour,[3] E. Kearns,[3] S. Likhoded,[3] M. Litos,[3] J. L. Raaf,[3] J. L. Stone,[3] L. R. Sulak,[3] W. Wang,[3] M. Goldhaber,[4] D. Casper,[5] J. P. Cravens,[5] W. R. Kropp,[5] D. W. Liu,[5] S. Mine,[5] C. Regis,[5] M. B. Smy,[5] H. W. Sobel,[5] M. R. Vagins,[5] K. S. Ganezer,[6] J. E. Hill,[6] W. E. Keig,[6] J. S. Jang,[7] J. Y. Kim,[7] I. T. Lim,[7] K. Scholberg,[8] N. Tanimoto,[8] C. W. Walter,[8] R. Wendell,[8] R. W. Ellsworth,[9] S. Tasaka,[10] E. Guillian,[11] J. G. Learned,[11] S. Matsuno,[11] M. D. Messier,[12] A. K. Ichikawa,[13] T. Ishida,[13] T. Ishii,[13] T. Iwashita,[13] T. Kobayashi,[13] T. Nakadaira,[13] K. Nakamura,[13] K. Nitta,[13] Y. Oyama,[13] A. T. Suzuki,[14] M. Hasegawa,[15] I. Kato,[15] H. Maesaka,[15] T. Nakaya,[15] K. Nishikawa,[15] T. Sasaki,[15] H. Sato,[15] S. Yamamoto,[15] M. Yokoyama,[15] T. J. Haines,[16] S. Dazeley,[17] S. Hatakeyama,[17] R. Svoboda,[17] G. W. Sullivan,[18] A. Habig,[19] R. Gran,[19] Y. Fukuda,[20] T. Sato,[20] Y. Itow,[21] T. Koike,[21] C. K. Jung,[22] T. Kato,[22] K. Kobayashi,[22] M. Malek,[22] C. McGrew,[22] A. Sarrat,[1,22] R. Terri,[22] C. Yanagisawa,[22] N. Tamura,[23] M. Sakuda,[24] M. Sugihara,[24] Y. Kuno,[25] M. Yoshida,[25] S. B. Kim,[26] J. Yoo,[26] T. Ishizuka,[27] H. Okazawa,[28] Y. Choi,[29] H. K. Seo,[29] Y. Gando,[30] T. Hasegawa,[30] K. Inoue,[30] H. Ishii,[31] K. Nishijima,[31] H. Ishino,[32] Y. Watanabe,[32] M. Koshiba,[33] D. Kielczewska,[34,5] J. Zalipska,[34] H. G. Berns,[35] K. K. Shiraishi,[35] K. Washburn,[35] and R. J. Wilkes[35]

(Super-Kamiokande Collaboration)

[1]*Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Kamioka, Gifu 506-1205, Japan*
[2]*Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[3]*Department of Physics, Boston University, Boston, Massachusetts 02215, USA*
[4]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[5]*Department of Physics and Astronomy, University of California, Irvine, Irvine, California 92697-4575, USA*
[6]*Department of Physics, California State University, Dominguez Hills, Carson, California 90747, USA*
[7]*Department of Physics, Chonnam National University, Kwangju 500-757, Korea*
[8]*Department of Physics, Duke University, Durham, North Carolina 27708, USA*
[9]*Department of Physics, George Mason University, Fairfax, Virginia 22030, USA*
[10]*Department of Physics, Gifu University, Gifu, Gifu 501-1193, Japan*
[11]*Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA*
[12]*Department of Physics, Indiana University, Bloomington, Indiana 47405-7105, USA*
[13]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan*
[14]*Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan*
[15]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[16]*Physics Division, P-23, Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA*
[17]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[18]*Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[19]*Department of Physics, University of Minnesota, Duluth, Minnesota 55812-2496, USA*
[20]*Department of Physics, Miyagi University of Education, Sendai, Miyagi 980-0845, Japan*
[21]*Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Aichi 464-8601, Japan*
[22]*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800, USA*
[23]*Department of Physics, Niigata University, Niigata, Niigata 950-2181, Japan*
[24]*Department of Physics, Okayama University, Okayama, Okayama 700-8530, Japan*
[25]*Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[26]*Department of Physics, Seoul National University, Seoul 151-742, Korea*
[27]*Department of Systems Engineering, Shizuoka University, Hamamatsu, Shizuoka 432-8561, Japan*
[28]*Department of Informatics in Social Welfare, Shizuoka University of Welfare, Yaizu, Shizuoka 425-8611, Japan*
[29]*Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea*
[30]*Research Center for Neutrino Science, Tohoku University, Sendai, Miyagi 980-8578, Japan*
[31]*Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan*
[32]*Department of Physics, Tokyo Institute for Technology, Meguro, Tokyo 152-8551, Japan*
[33]*University of Tokyo, Tokyo 113-0033, Japan*
[34]*Institute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland*
[35]*Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA*

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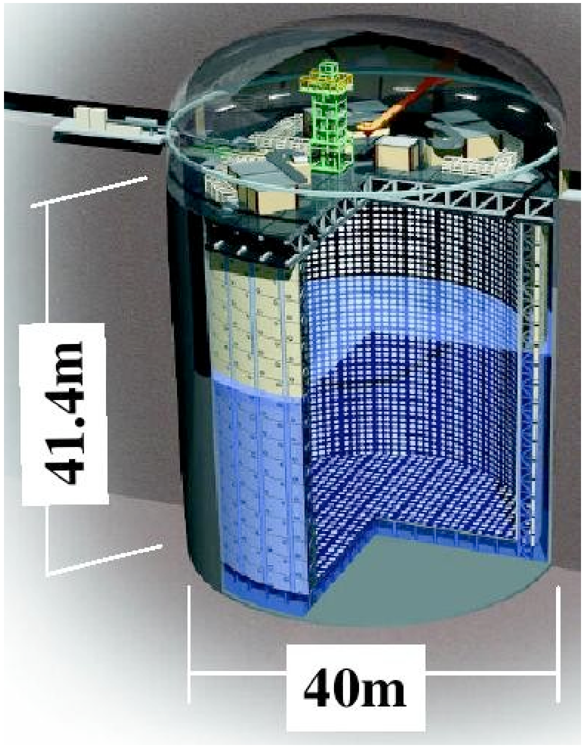
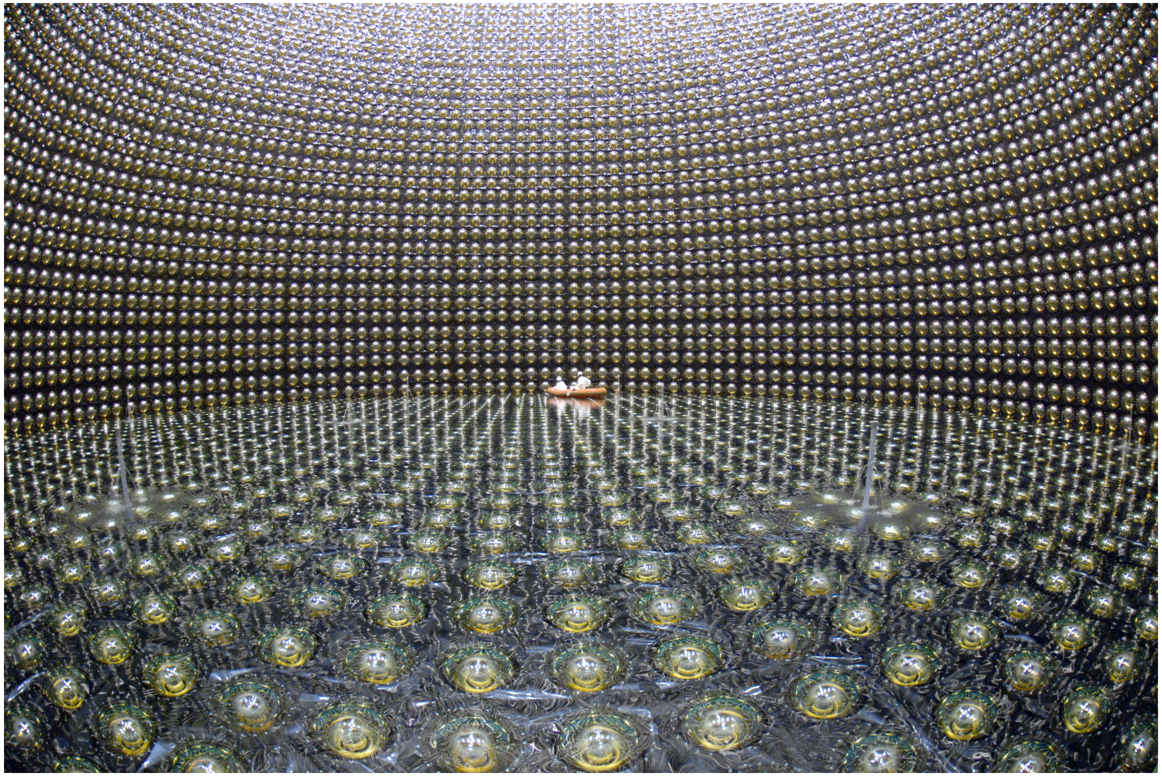
Super-Kamiokande Experiment

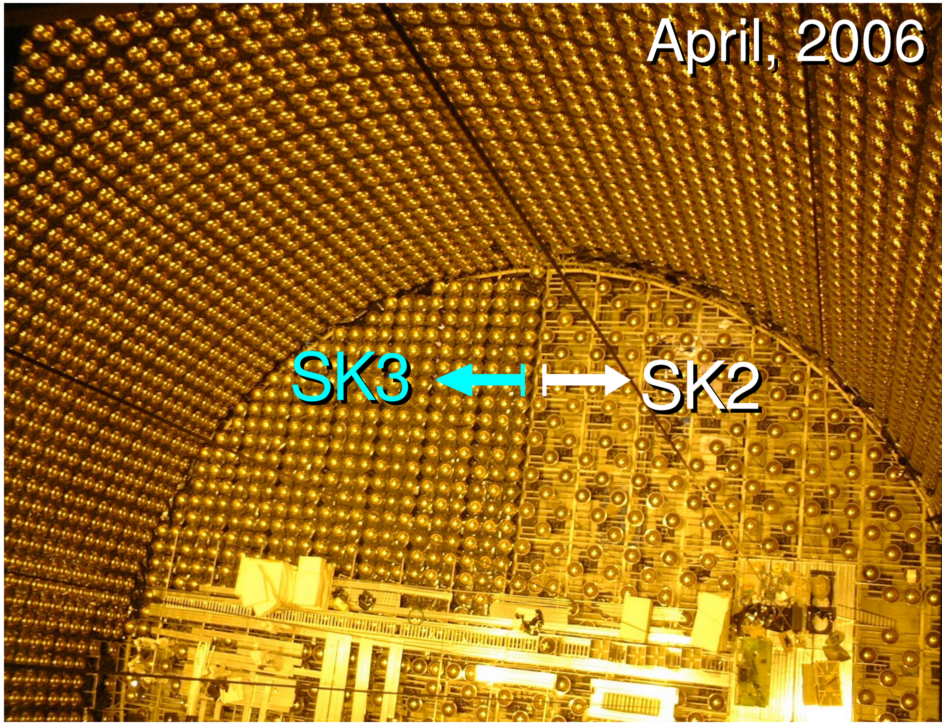




- A 50 kton Water Cherenkov detector
  - 1000m rock overburden (2600m w.e.)
  - 22.5 kton fiducial mass
  - Inner Detector (ID) : 11146 20-inch PMT tubes
  - Outer Detector(OD) : 1885 8-inch PMT tubes
  - Optical separation between inner and outer detector

More than a Decade of SK

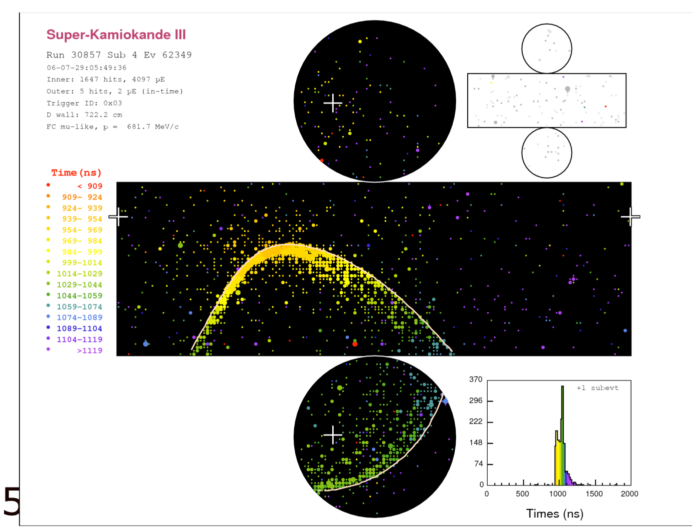
- SK1 (1996-2001)
  - 11146 inner(ID)/ 1885 outer(OD) PMT's; 40% of ID coverage
  - Solar ν, atmospheric ν, proton decay results; K2K I target
- SK2 (2003-2005)
  - Recovered 2001 accident with 19% ID coverage (shielded by acrylic covers), full OD
  - Nearly same sensitivity as SK1; K2K II target
- SK3 (2006-present)
  - Data taking since July 2006 with full coverage
  - Ready for T2K off-axis beam from J-PARC in 2009

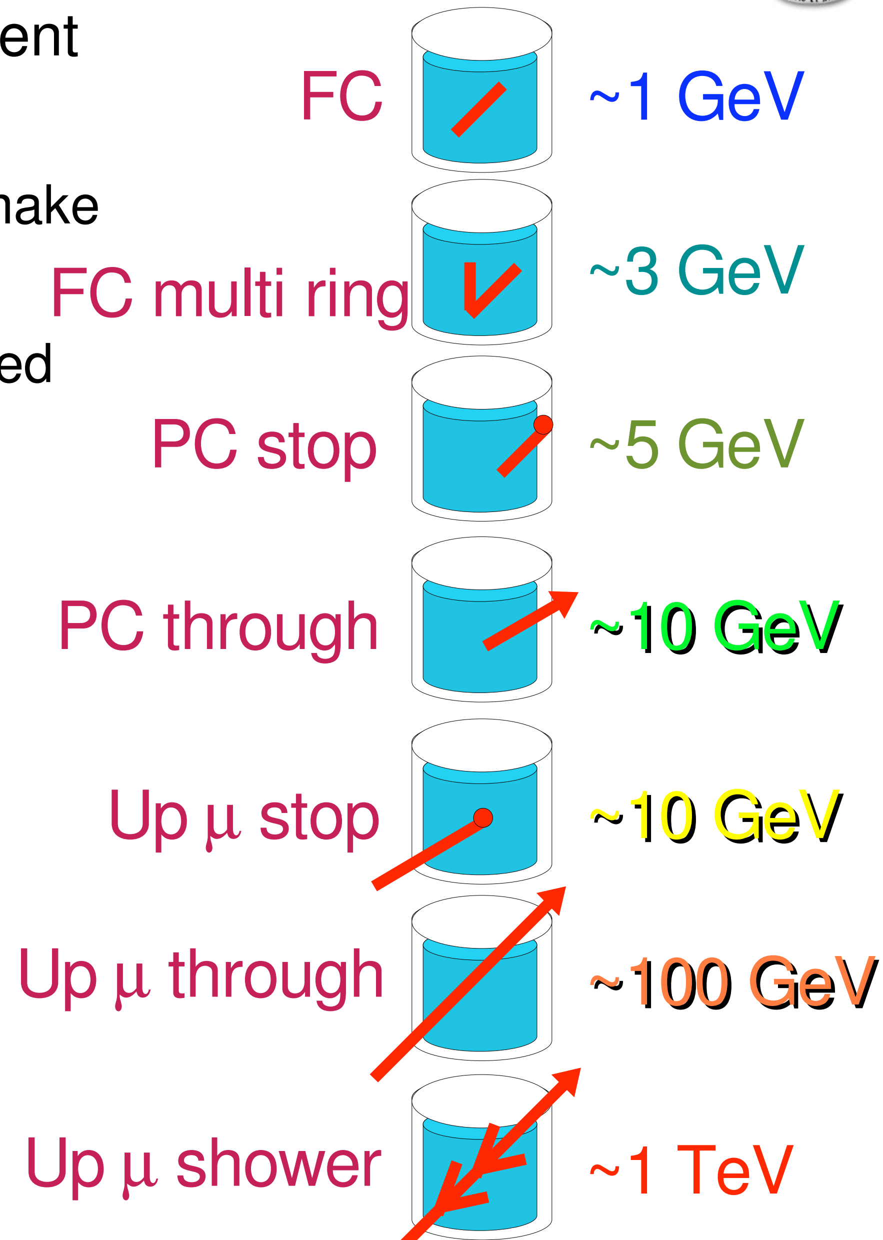


During SK3 reconstruction

SK Event Categories

- Neutrino observed via charged-current interactions with nuclei in water
  1. If lepton has enough energy it will make Cherenkov light
  2. Outgoing Cherenkov light is observed by the PMTs
  3. Energy and Position (vertex) of the event can be reconstructed
  4. Particle ID : e/μ like



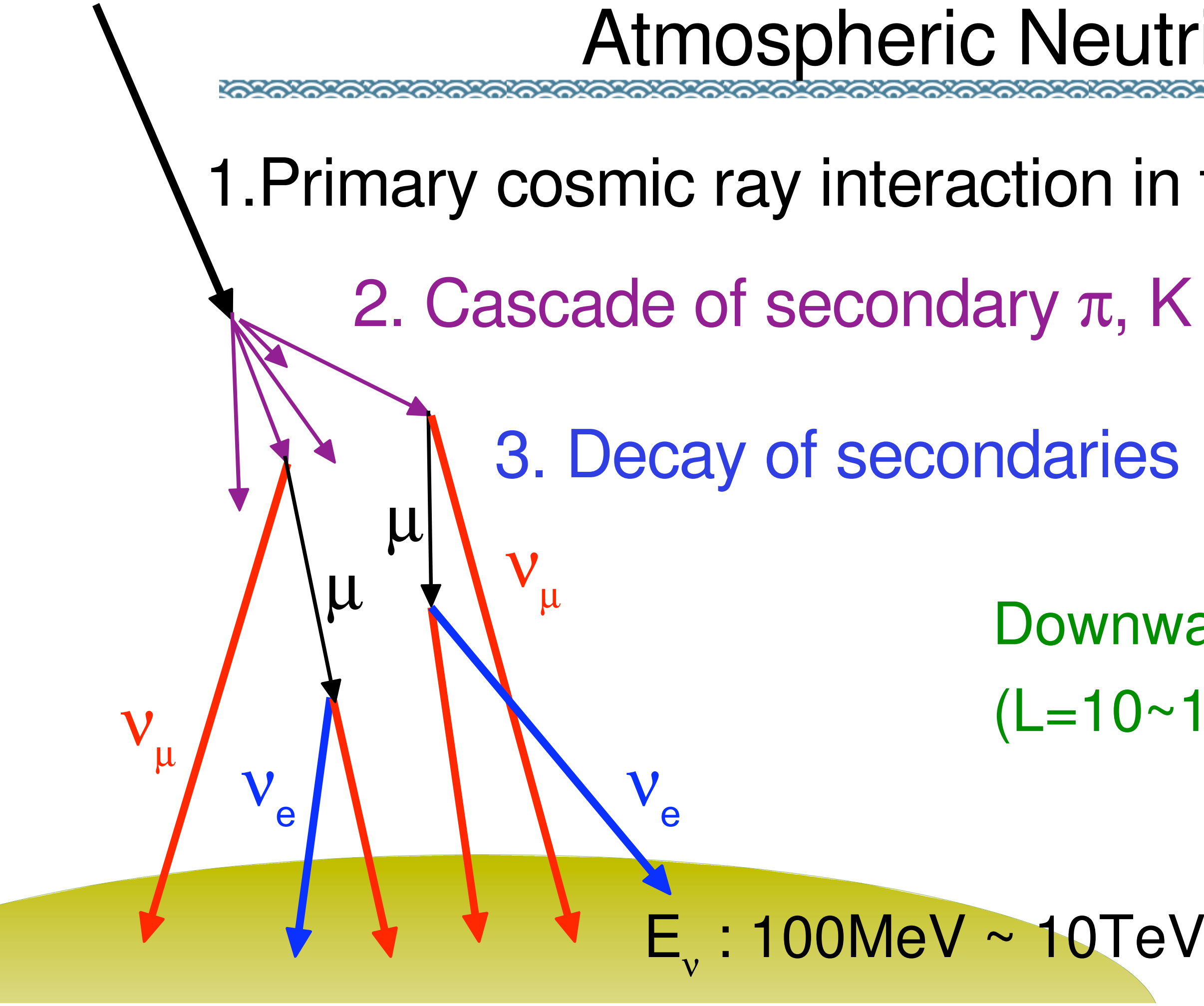


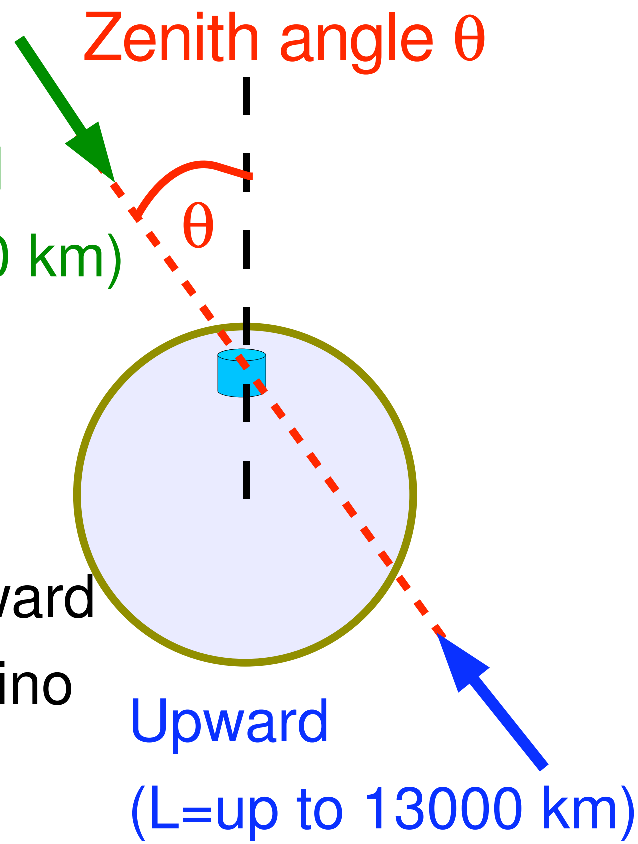
Atmospheric neutrino results

Recent atmospheric neutrino research at SK

- Search for neutral Q-balls in SK II (Phys. Lett. B 647, 18 (2007))
- Observation of the anisotropy of 10 TeV primary cosmic ray nuclei flux with the Super-Kamiokande-I detector (Phys. Rev. D75, 062003 (2007))
- A Measurement of Atmospheric Neutrino Flux Consistent with Tau Neutrino Appearance (Phys. Rev. Lett. 97, 171801 (2006))
- Search for Diffuse Astrophysical Neutrino Flux Using Ultra-High Energy Upward-Going Muons in Super-Kamiokande I (ApJ. 652,206 (2006))
- Three flavor neutrino oscillation analysis of atmospheric neutrinos in Super-Kamiokande (Phys. Rev. D 74, 032002 (2006))
- $\nu_\mu \rightarrow \nu_\tau$ oscillation is compared with alternative exotic models (sterile neutrino, neutrino decay and neutrino decoherence)

Atmospheric Neutrinos





- Flux up/down symmetric - differences in upward and downward going flux is a signal of neutrino physics

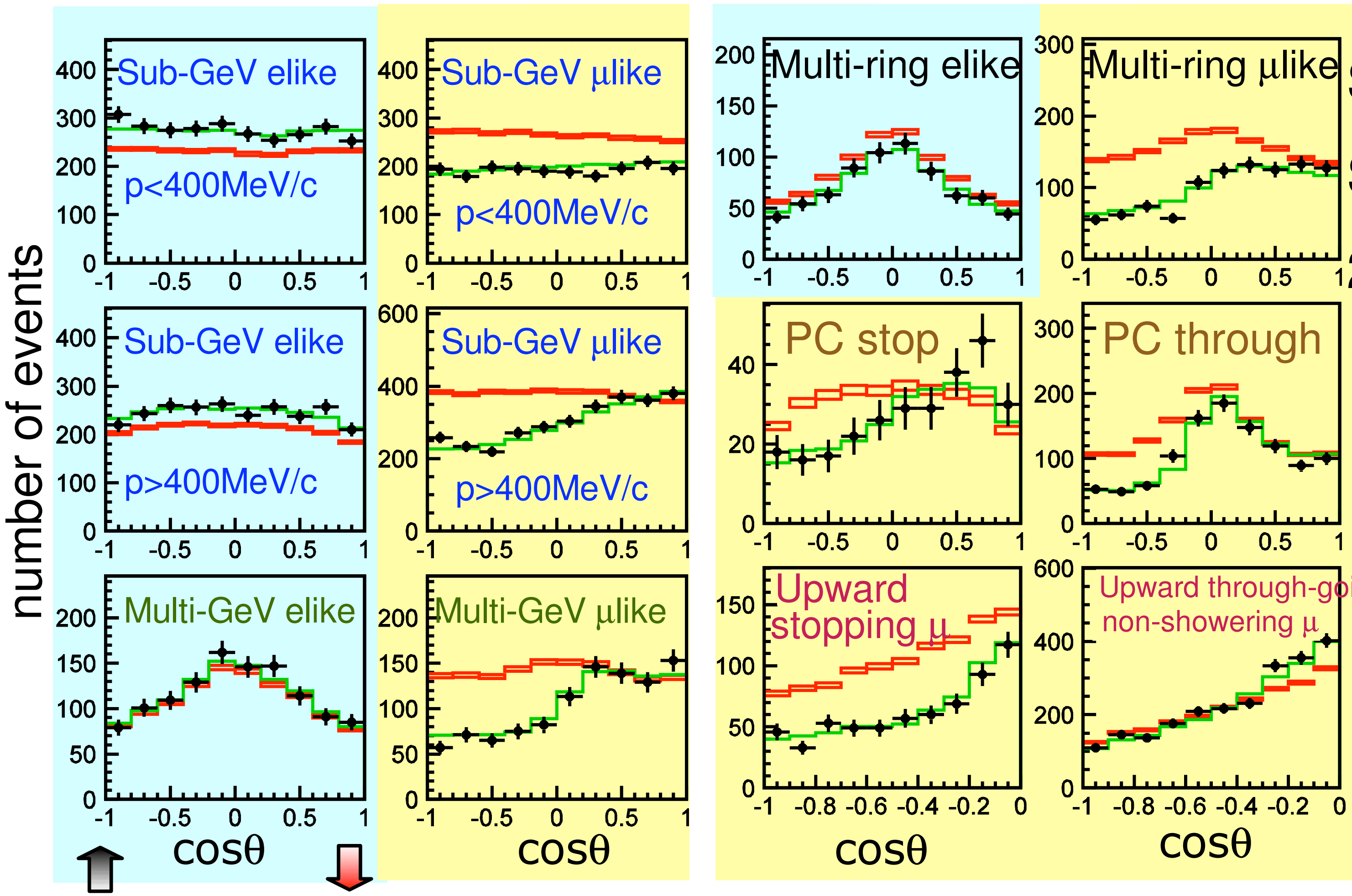
Zenith angle distributions (SK1+SK2)

— ν_μ-ν_τ oscillation(at best fit point)

— null oscillation

e-like | μ-like

$$P_{\mu\rightarrow\tau} = \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$$



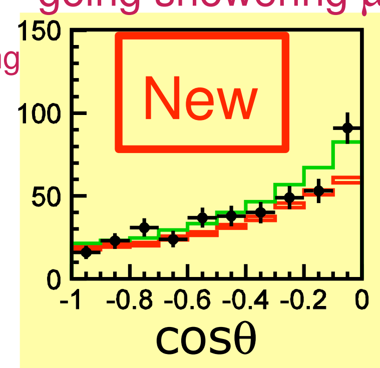
SK1: 1489days

SK2: 804days

23,000 ν's

100MeV-10TeV

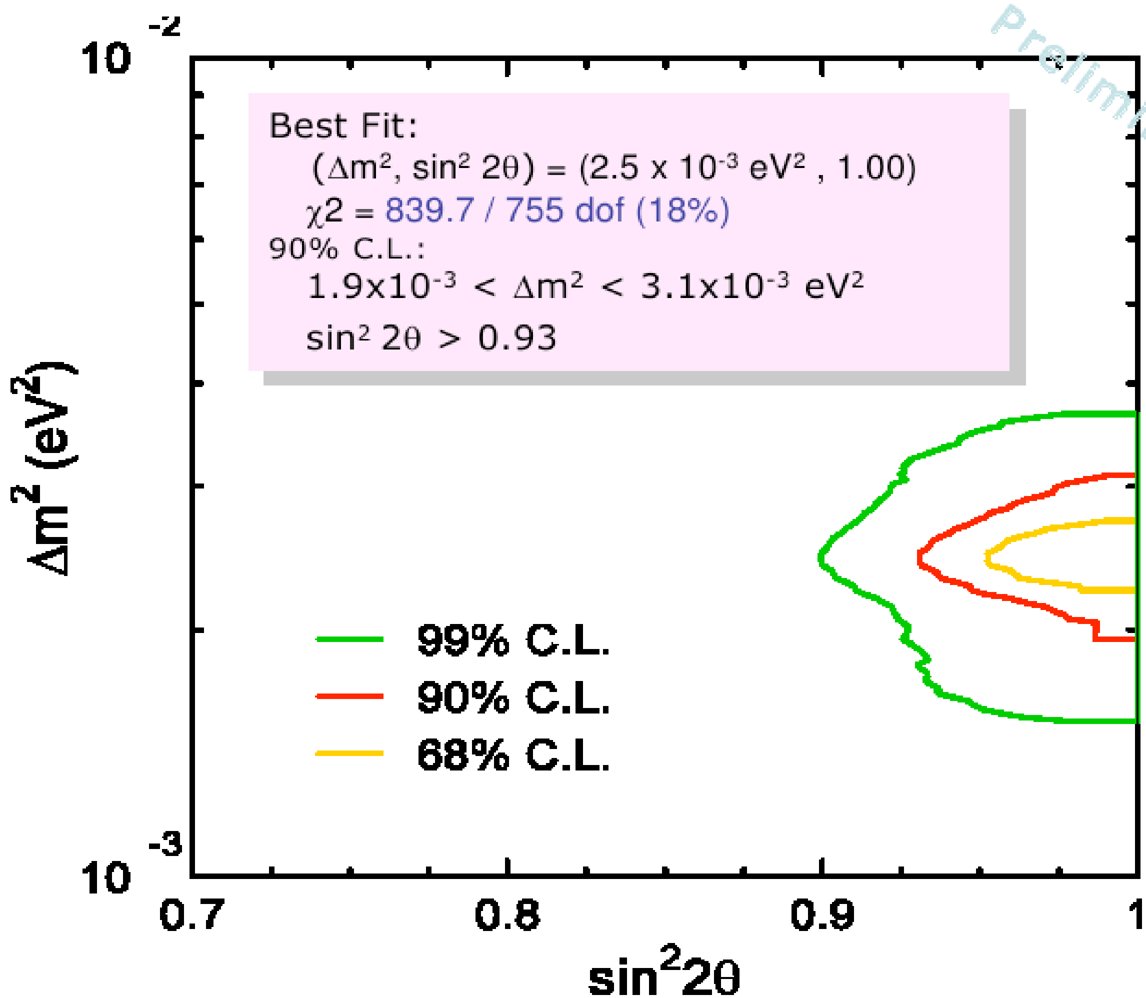
Upward through-going showering μ



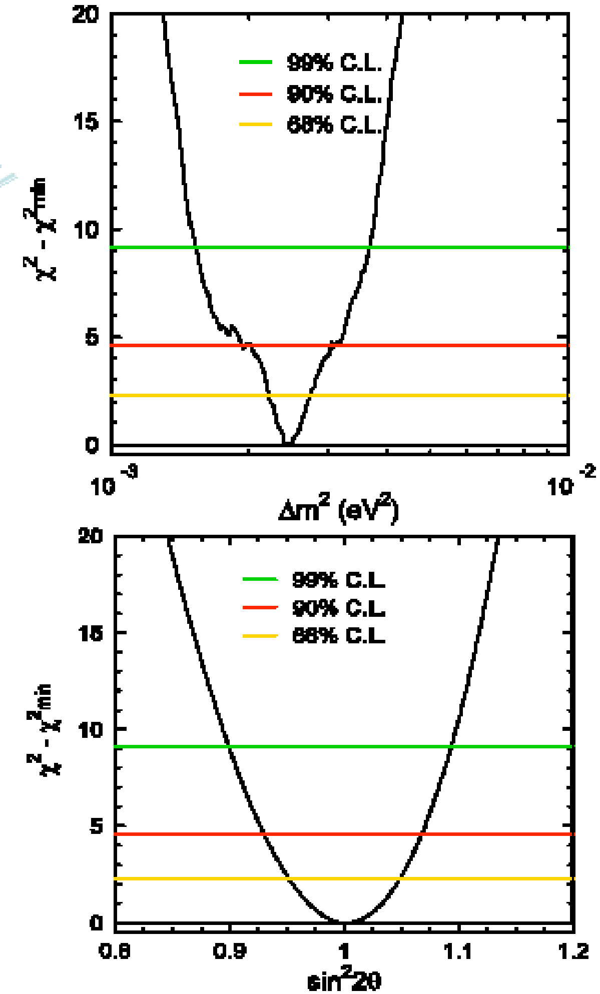
Excellent agreement with $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis

Allowed Oscillation Parameters(SK1+SK2)

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

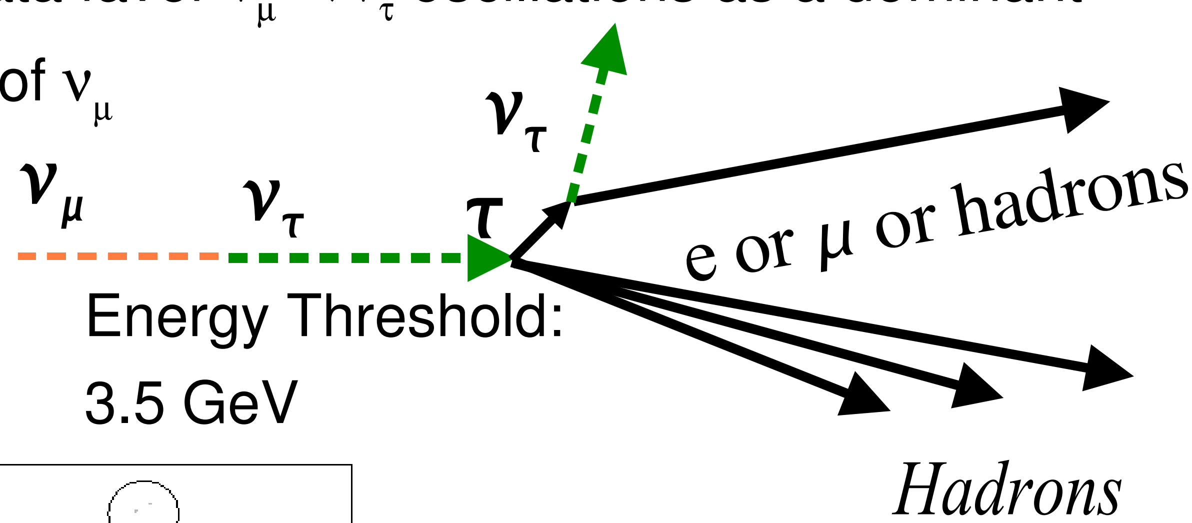


Δχ² distribution



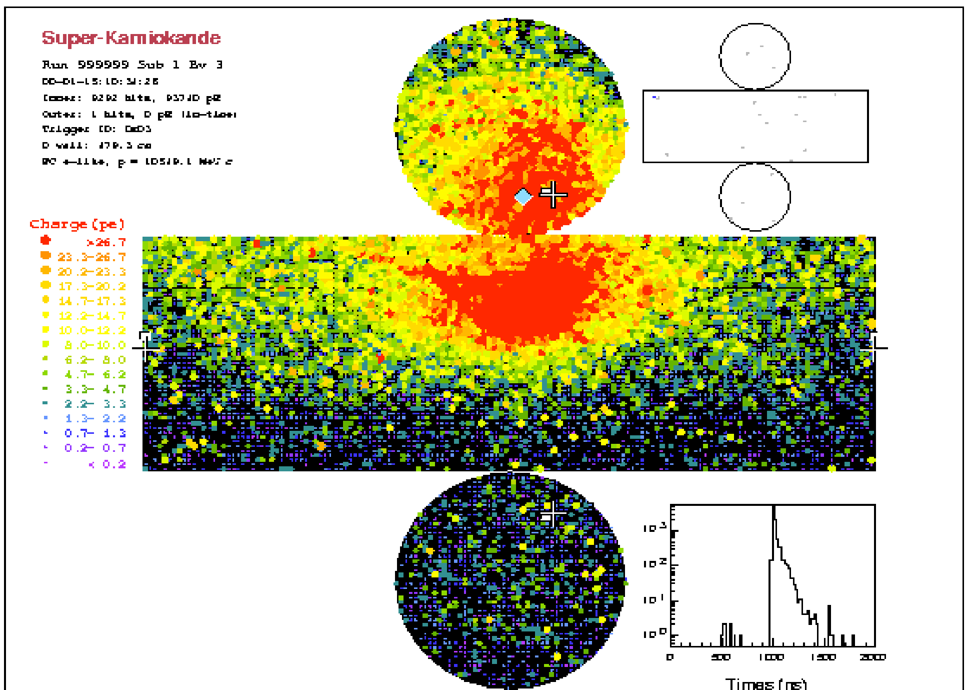
Tau neutrino appearance (SK1)

- SK atmospheric ν data favor $\nu_\mu \rightarrow \nu_\tau$ oscillations as a dominant source of the deficit of ν_μ



Energy Threshold:
3.5 GeV

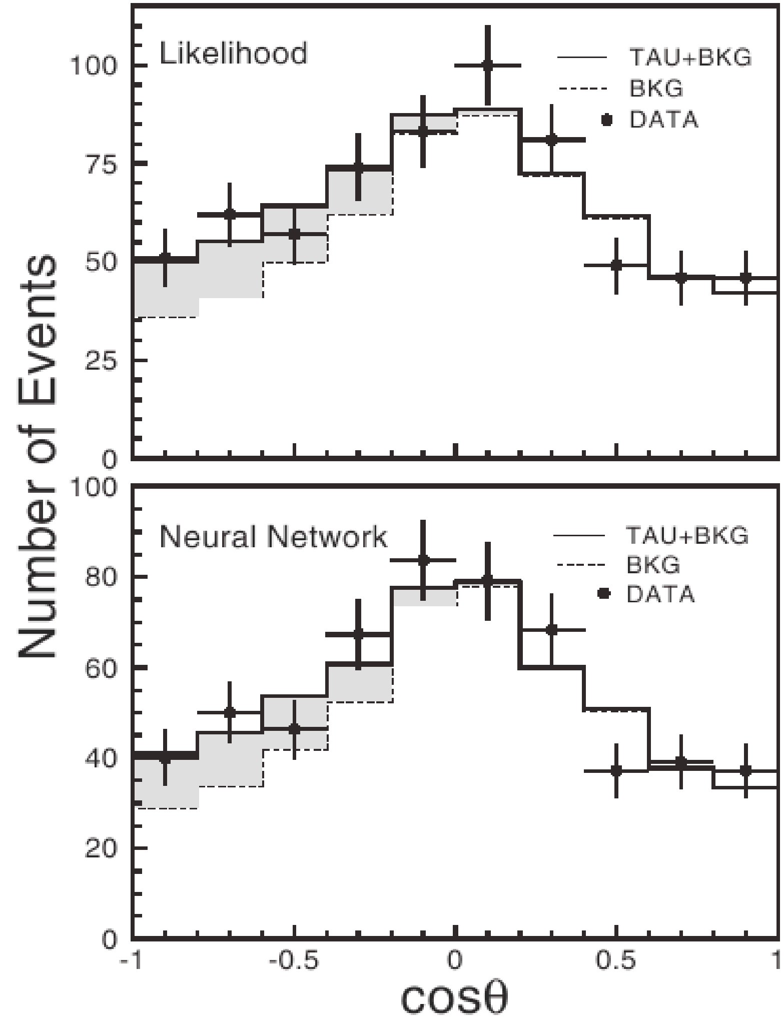
Typical MC τ event



According to MC,expect about 80 τ's in current sample... but they are hard to distinguish from other multi-ring ν interaction events

Select Tau Neutrino like events (SK1)

- Two analyses (Likelihood and Neural Network) yield consistent answers
- A best fit ν_τ appearance signal (shaded area)
  - 138±48(stat.) +14.8/-31.6(syst.)
  - significance : 2.4σ
- Consistent with the expected number of ν_τ from MC (Δm^2=2.4x10^{-3} eV^2)
  - 78.4±26(sys)

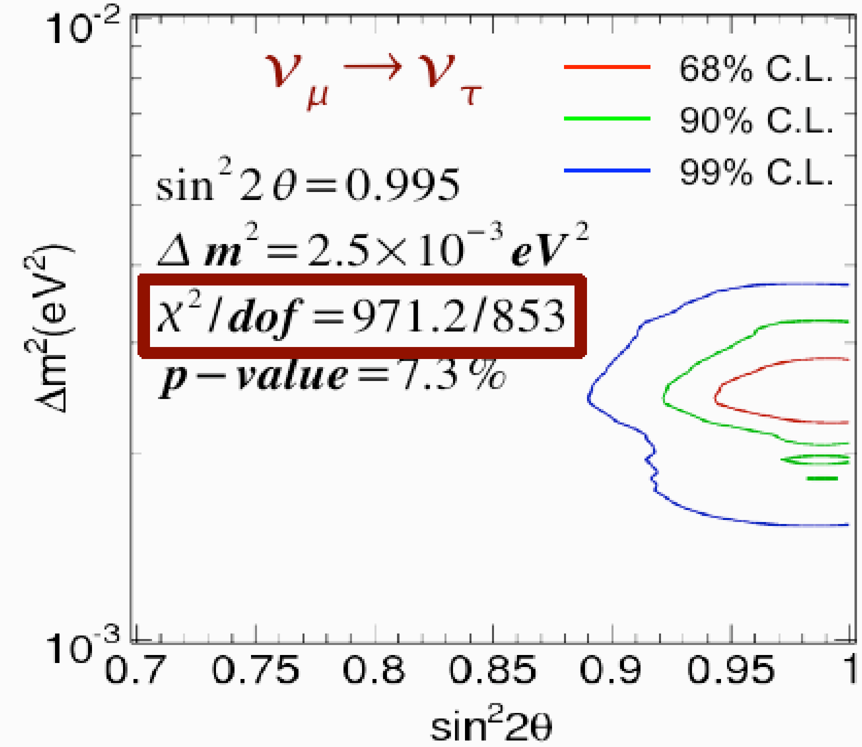


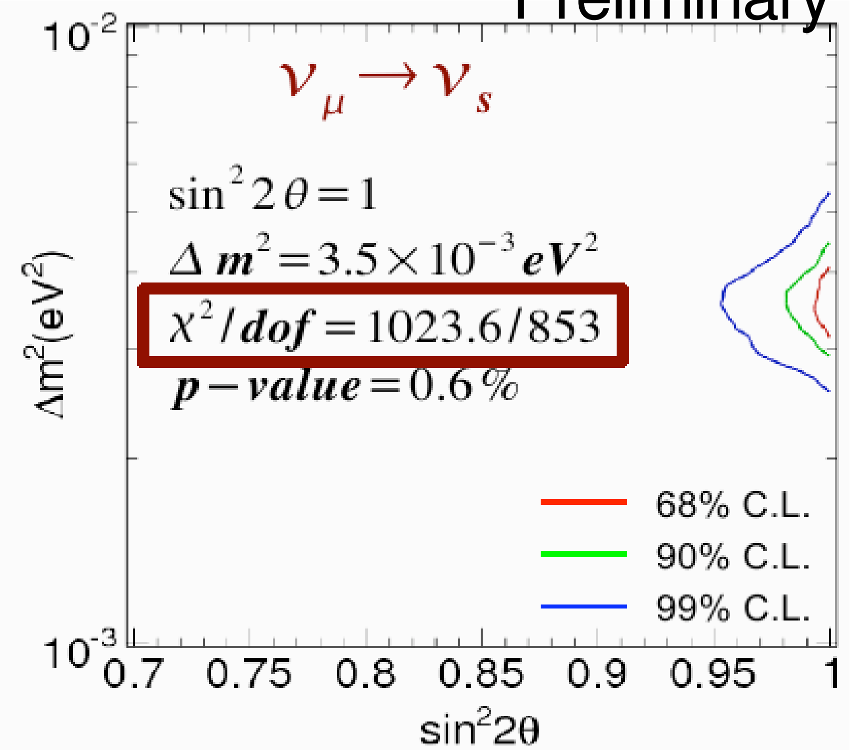
Does it have to be tau neutrino?

- LEP experiments : Z decay cross section indicates there are only three active neutrino flavors, $N_\nu=2.992\pm0.020$
- If only three flavors of neutrinos, it has to be tau neutrino
  - $\nu_\mu \rightarrow \nu_e$ oscillation does not explain the SK data
- Sterile neutrino (ν_s: no electric, strong or weak charge) is a potential candidate of Atmospheric neutrino disappearance
  - Some theoretical models predict the existence of ν_s
- So, Compare $\nu_\mu \rightarrow \nu_\tau$ oscillation and $\nu_\mu \rightarrow \nu_s$ oscillation
  - Inside detector : Less NC events
  - During the propagation : Has Matter Effect ($\nu_\mu \rightarrow \nu_\tau$ doesn't have)

Tau neutrino vs Sterile neutrino

Preliminary

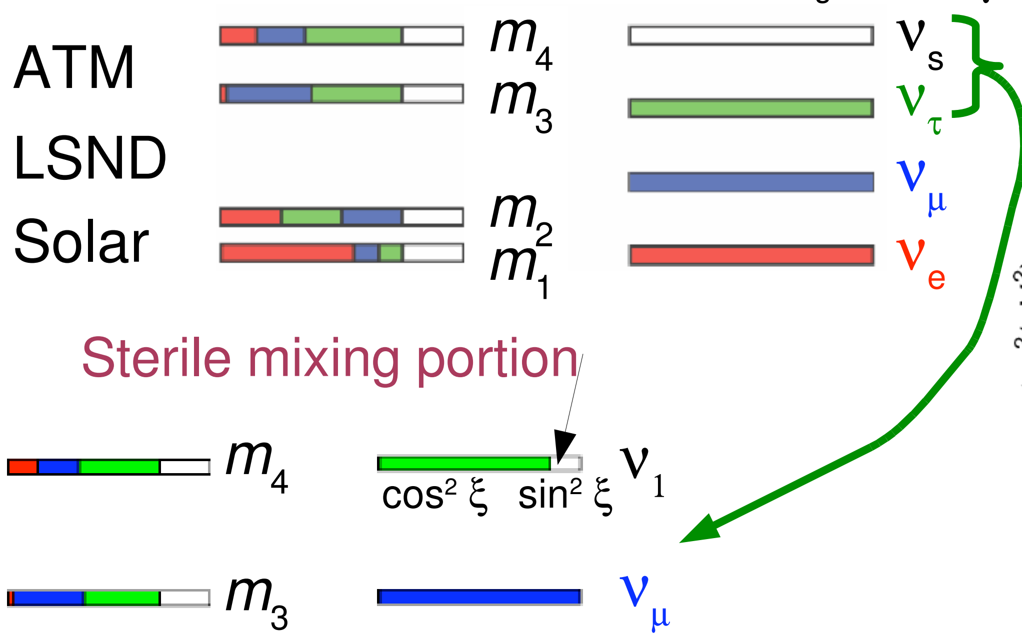


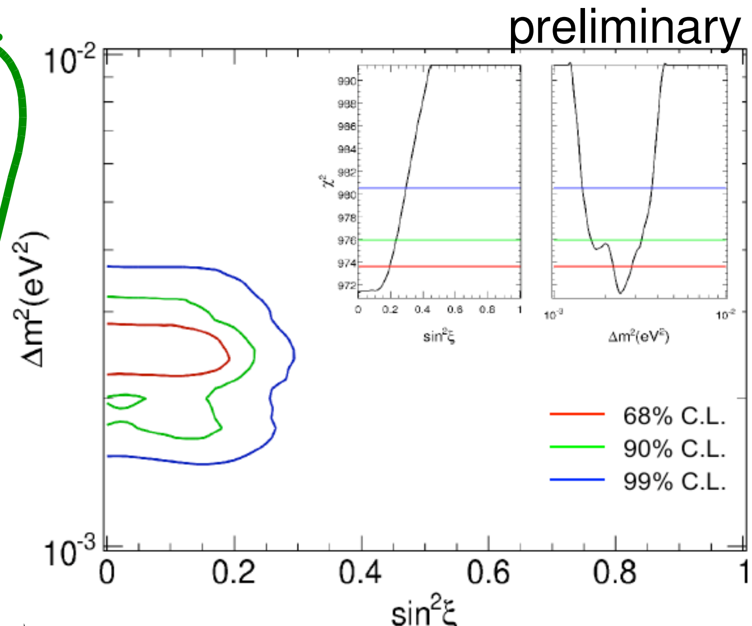


- Exclusion level : 7.2σ

What about admixtures?

- Admixtures are model dependent
- SK analysis is based on Fogli et al PRD 63 (053008) 2001
  - A 2+2 mass hierarchy model
  - Construct a superposition of ν_s and ν_τ states → 2 flavor mixing



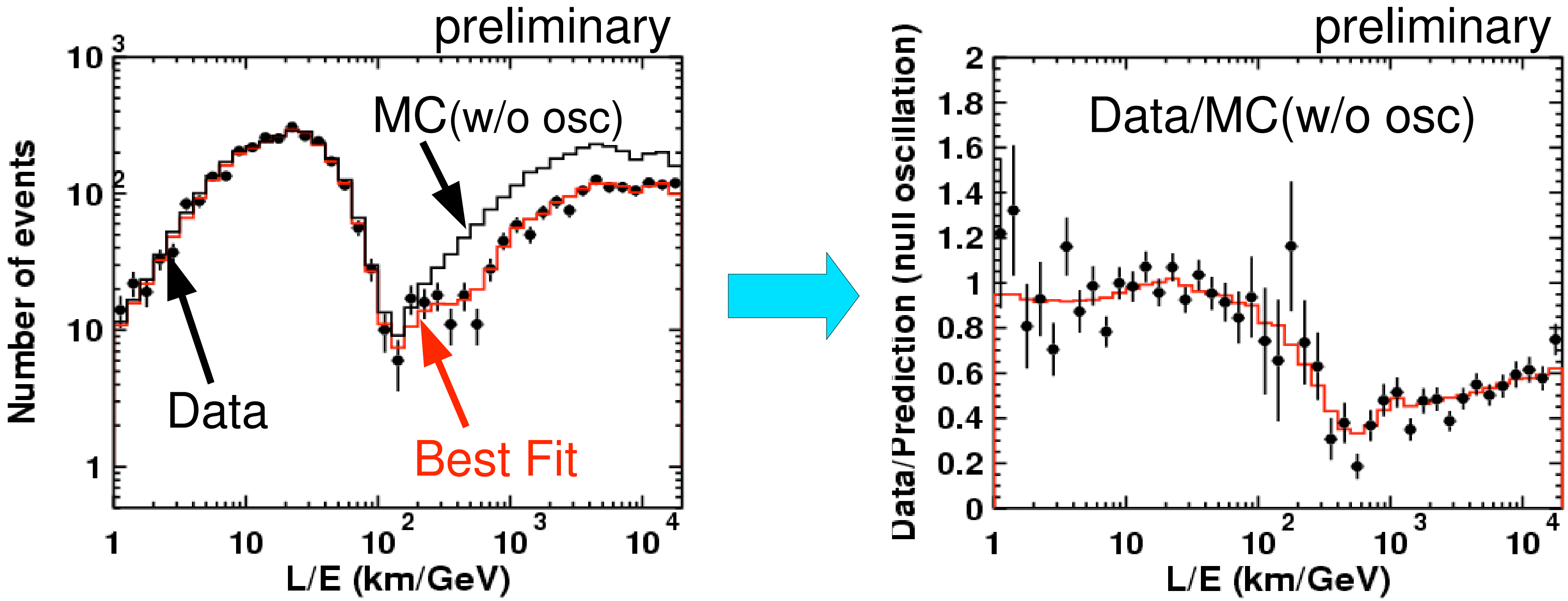


$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos(\xi) & \sin(\xi) \\ -\sin(\xi) & \cos(\xi) \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \nu_s \end{pmatrix}$$

- Allowed sterile neutrino admixture limit at 90% C.L. : $\sin^2\xi < 0.23$

Neutrino disappearance : L/E (SK1+SK2)

- Survival probability of ν_μ is a function of L/E for 2 flavor oscillation : $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{4E})$



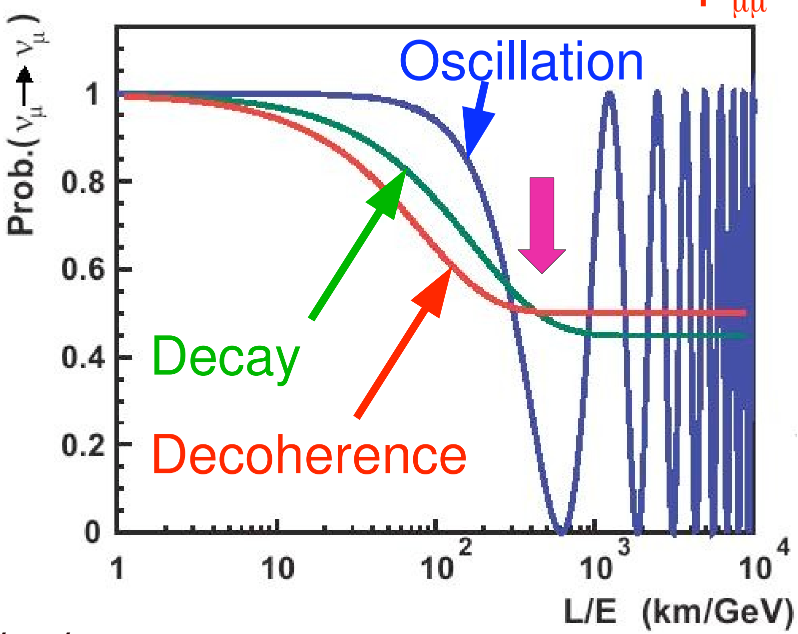
Best fit: $\Delta m^2 = 2.3 \times 10^{-3}$, $\sin^2 2\theta = 1.00$

$\chi^2_{min} = 83.9/83$ d.o.f.

Alternative models of Neutrino Disappearance

- What about other possibilities?
  - Neutrino Decay
    - Assuming the dominant component of ν_μ, i.e., ν_2, to be the only unstable state with a lifetime τ_0
    - $\nu_\mu \approx \cos\theta\, \nu_2 + \sin\theta\, \nu_3$, $\nu_e \approx \nu_1$ $\quad P_{\mu\mu} = \sin^4\theta + \cos^4\theta \times \exp\left(-\frac{m_2}{2\tau}\frac{L}{E}\right)$
  - Neutrino Decoherence effect induced by new physics

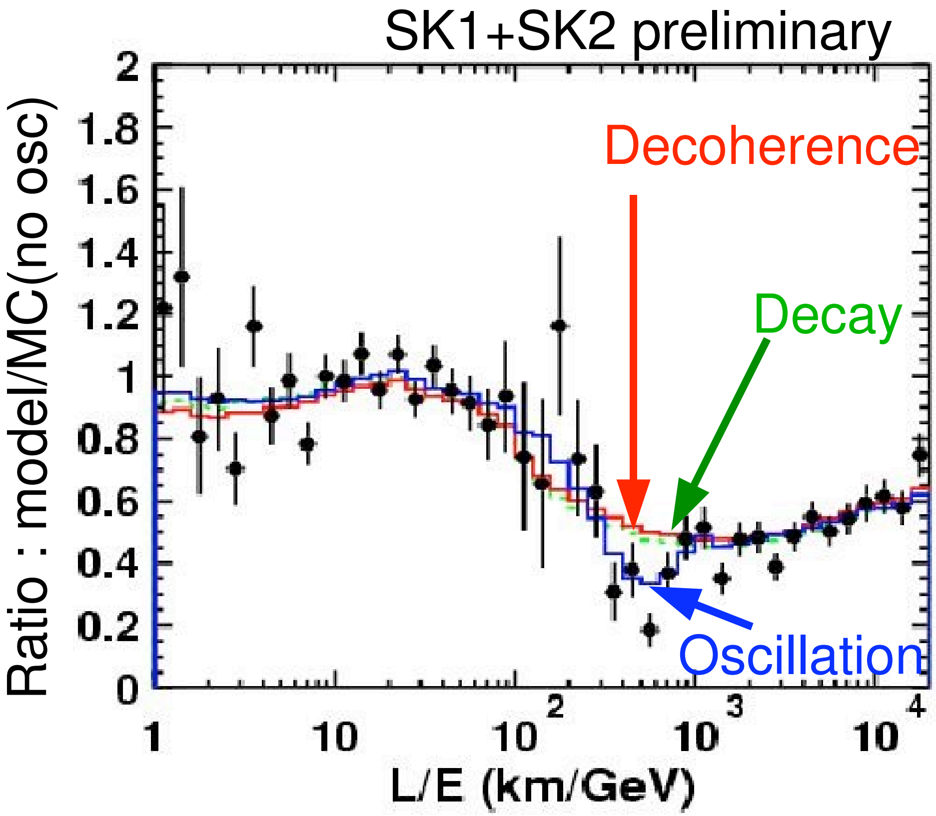
$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times \left(1 - \exp(-\gamma_0 L) \times \cos\left(\frac{\Delta m^2 L}{2E}\right)\right)$$



- Can test the first dip in L/E

Test of other modes with L/E of SK1+SK2

- The data/prediction for 3 models as a function of L/E



χ^2(decoherence)=112.5/82 d.o.f., $\Delta\chi^2$=27.6 (5.3σ)

χ^2(decay)=107.1/82 d.o.f., $\Delta\chi^2$=23.2 (4.8σ)

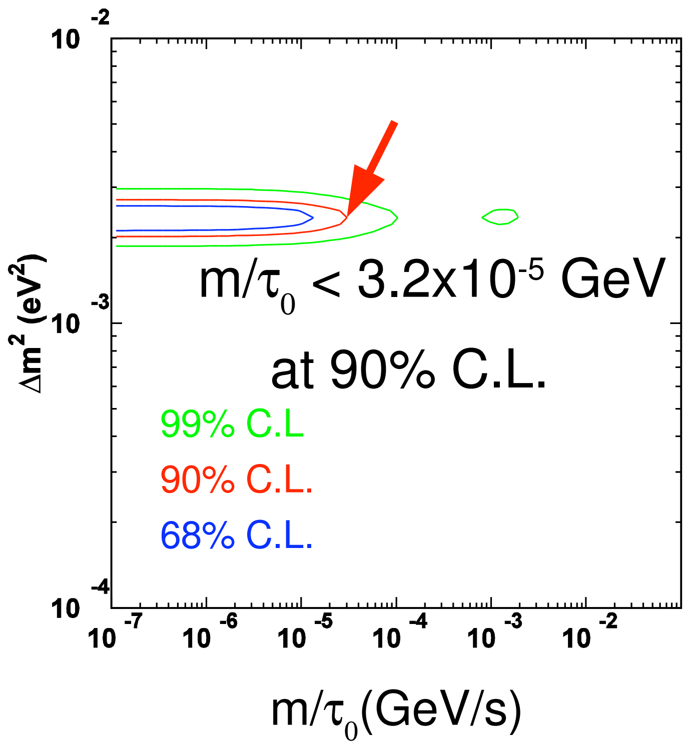
χ^2(osc)=83.9/82 d.o.f.

- Neutrino decoherence and decay models are excluded at ~5σ

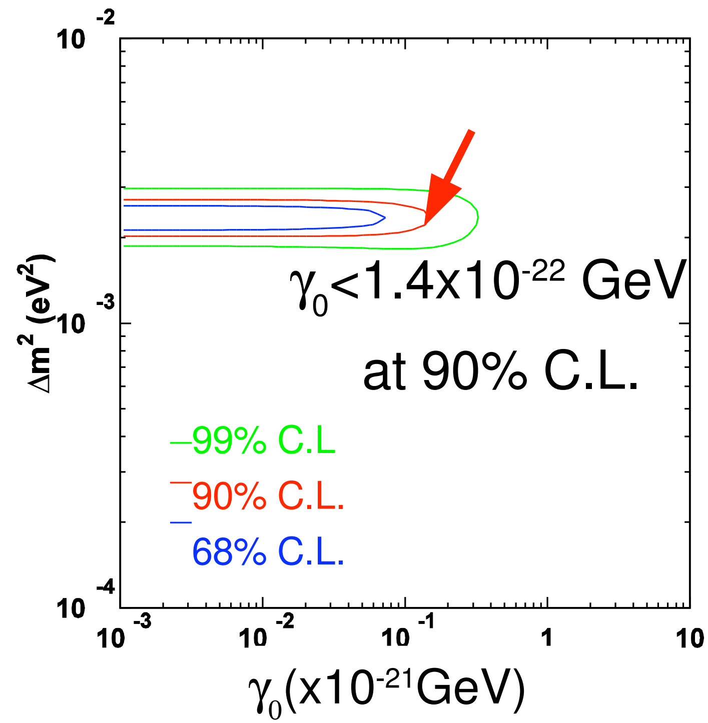
ν osc. and decoherence(decay) coexistence

- In addition, we compared two models :

1) Neutrino Oscillation + Neutrino Decay



2) Neutrino Oscillation + Neutrino Decoherence



Three flavor oscillation analysis (SK1)

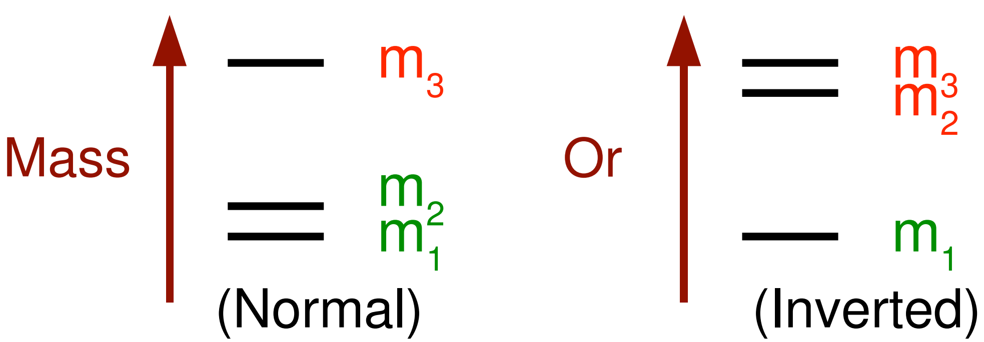
- 3 flavor mixing looks like this :

$$\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = U \times \begin{pmatrix} m_1\\ m_2\\ m_3\end{pmatrix}, \quad U = \begin{pmatrix}1 & 0 & 0\\ 0 & C_{23} & S_{23}\\ 0 & -S_{23} & C_{23}\end{pmatrix}\begin{pmatrix}C_{13} & 0 & S_{13}e^{i\delta}\\ 0 & 1 & 0\\ -S_{13}e^{i\delta} & 0 & C_{13}\end{pmatrix}\begin{pmatrix}C_{12} & S_{12} & 0\\ -S_{12} & C_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

atmospheric ??? solar

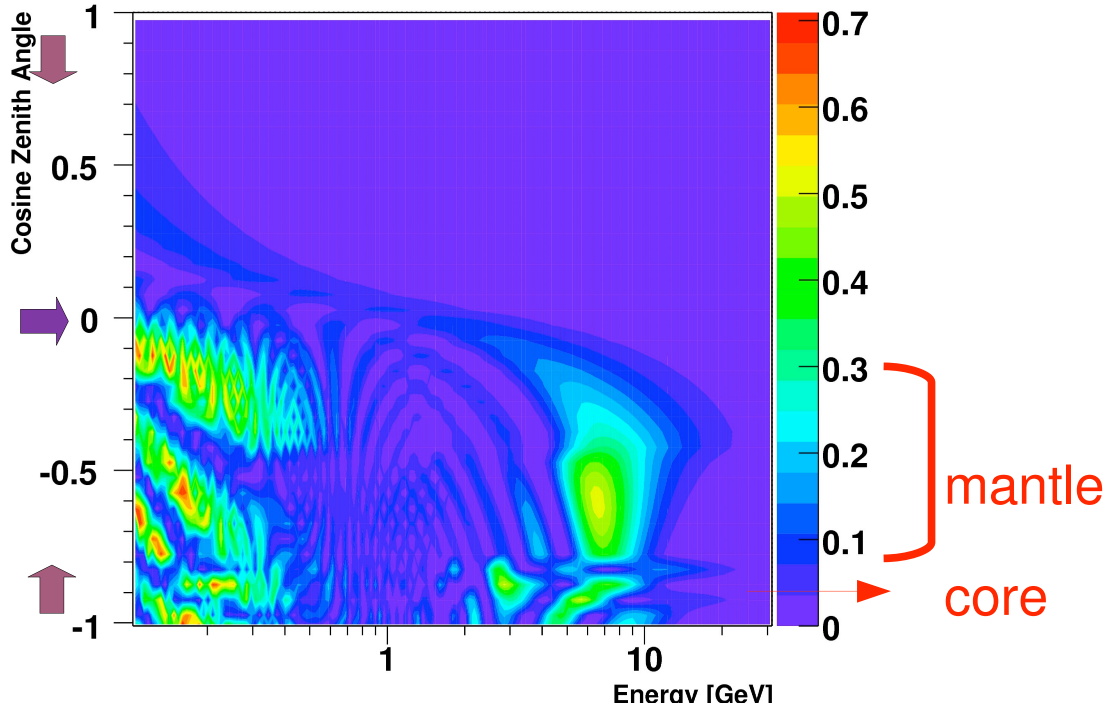
$$c_{ij} = \cos(\theta_{ij}), \quad s_{ij} = \sin(\theta_{ij})$$

  - In the full expression of *U*, we have 6 parameters
    - $\theta_{12}, \theta_{13}, \theta_{23}$, $\Delta m^2_{12}, \Delta m^2_{23}$, where $\Delta m^2_{ij} \equiv m^2_j - m^2_i$, and δ_{CP}
- Open question in neutrino physics :
  - θ_{13}, δ_{CP} are nonzero?
  - What is the mass hierarchy?



SK approach to these problems are

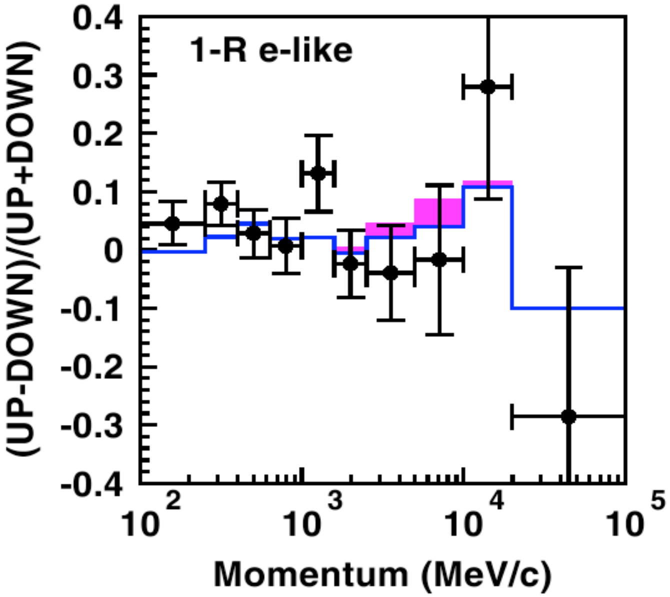
$\nu_\mu \rightarrow \nu_e$

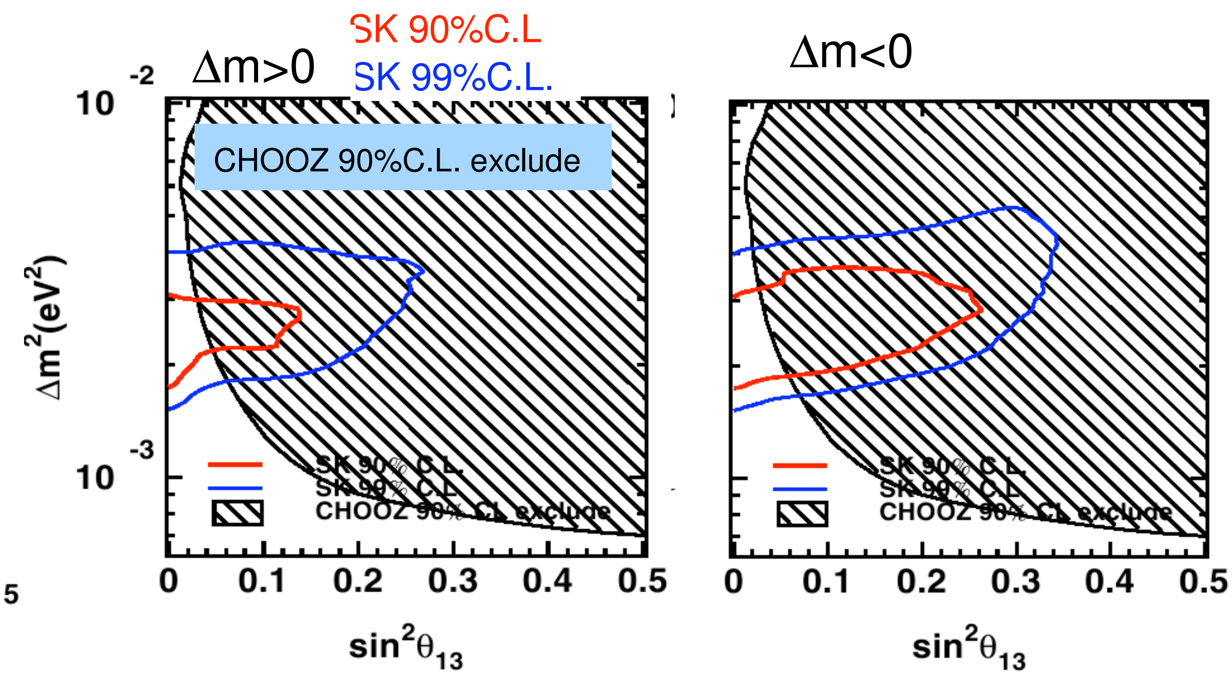


- The effect on $P(\nu_\mu \rightarrow \nu_e)$ for nonzero θ_{13} can be large.
  - We can look for extra e-like events at high energy as an indication of θ_{13}
- SK can not discriminate between ν and $\bar{\nu}$ on an event-by-event basis.
- However, the amount of e-like excess depends on the magnitude of θ_{13}, and on the sign of the hierarchy.
  - For inverted hierarchy anti-ν's experience this resonance

Three flavor oscillation Results(SK1)

- The up-down asymmetry as a function of momentum is consistent with expectation of $\theta_{13}=0$.
- No significant e-like excess has been seen.
- Both normal and inverted mass hierarchy hypothesis are tested and both are consistent.
- Obtained upper limits on θ_{13} is consistent with CHOOZ limit.

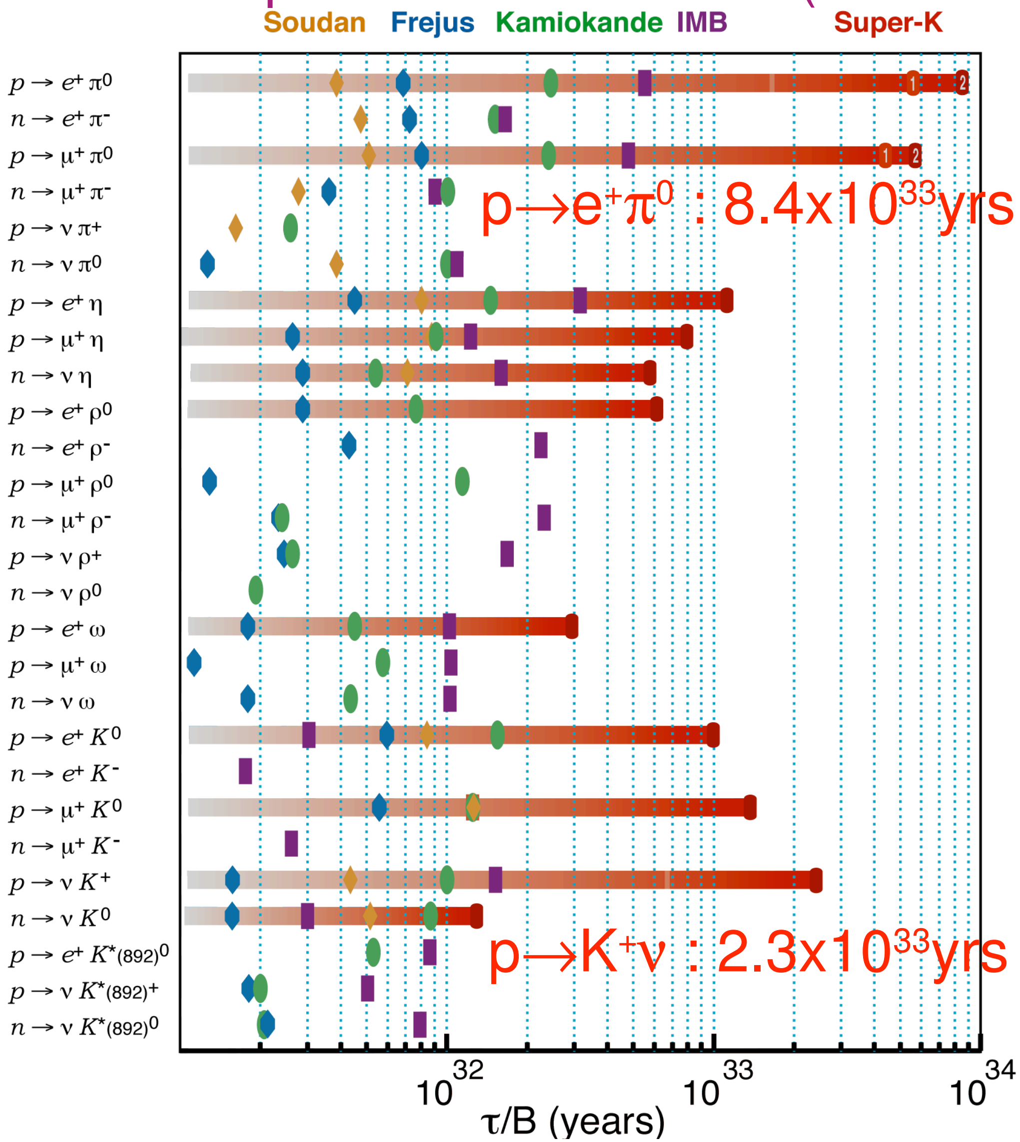




Nucleon Decay Search

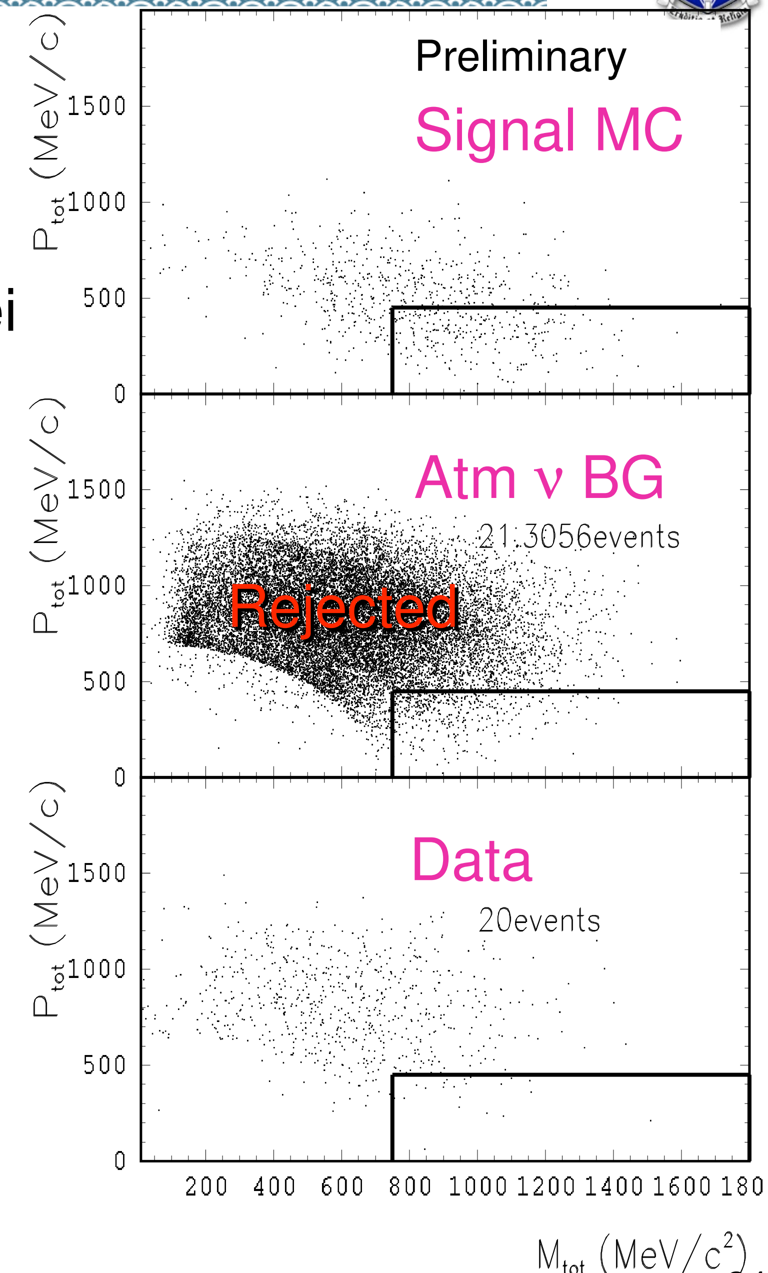
- Past experiments and SK have set severe constraints on viable GUTs. Minimal SU(5), Minimal SUSY SU(5) are ruled out.
- New modes are being tested.

Nucleon Lifetime with antilepton+meson modes (90%C.L.)



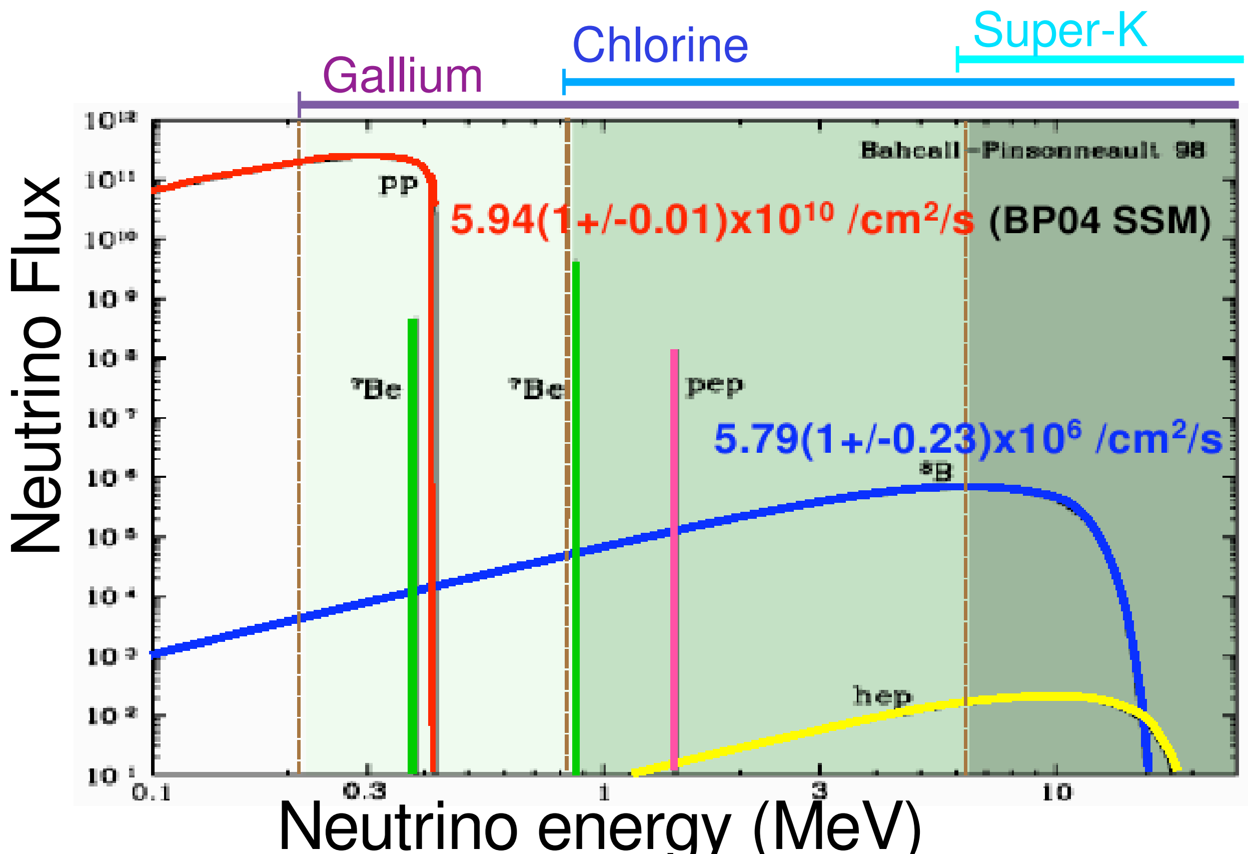
n-$\bar{n}$ oscillation (SK1)

- Other models of GUTs predict Δ(B-L)=2 processes, such as n-$\bar{n}$ oscillation.
- $\bar{n}$N annihilation arising from n$\bar{n}$ oscillation which occur in the H2O nuclei produce multiple particles. →multi-rings
  - Detection efficiency = 10.4%
- Main source of BG is from atm.ν
- Observed: 20, Expected BG: 21.31
- 1.77x10^{32} yr at 90% C.L. with SK1 data



Solar neutrino

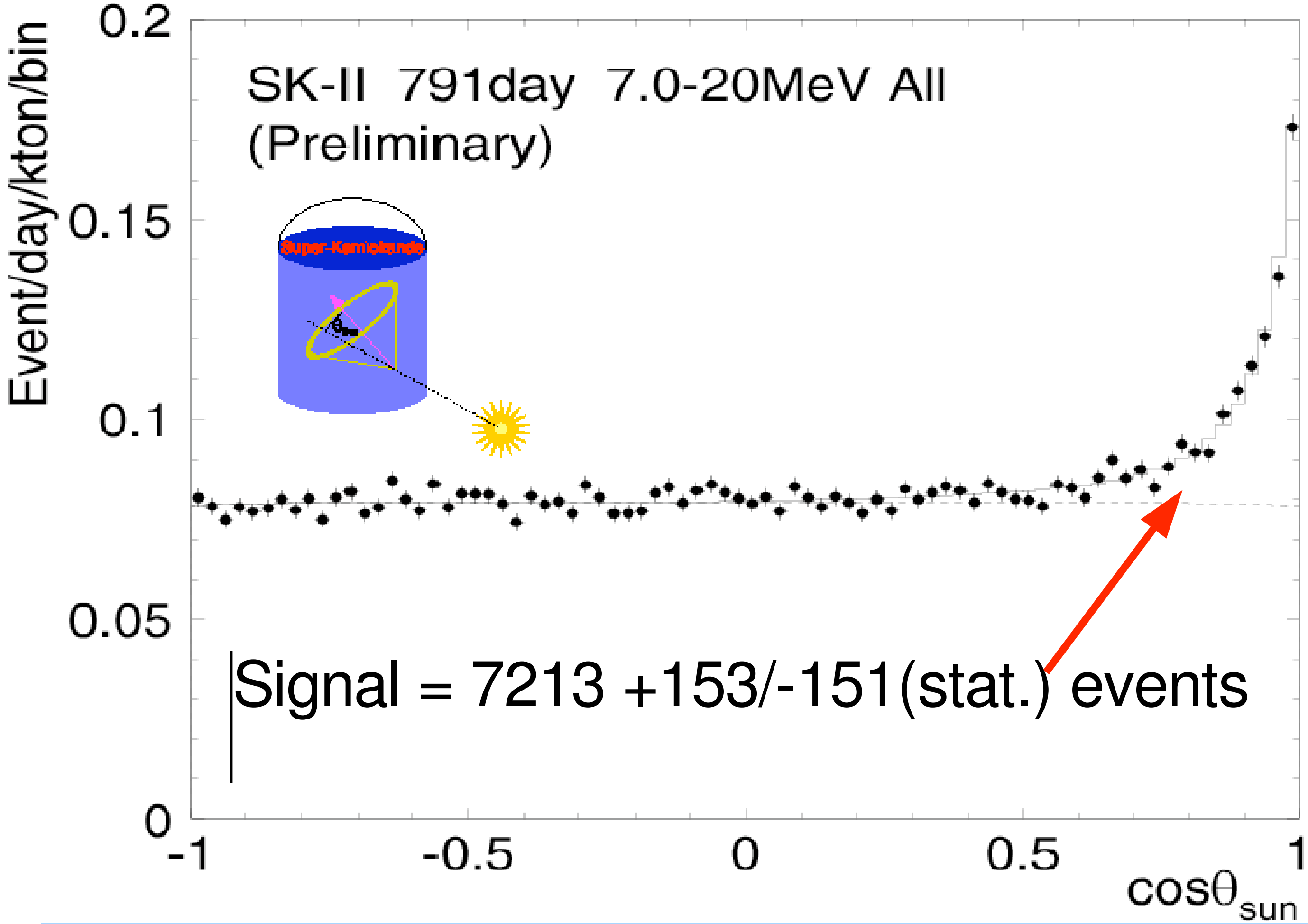
- SK observes ^8B neutrino scattering on electrons
- Event Reconstruction energy threshold ~6MeV



PRL92(2004)121301

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

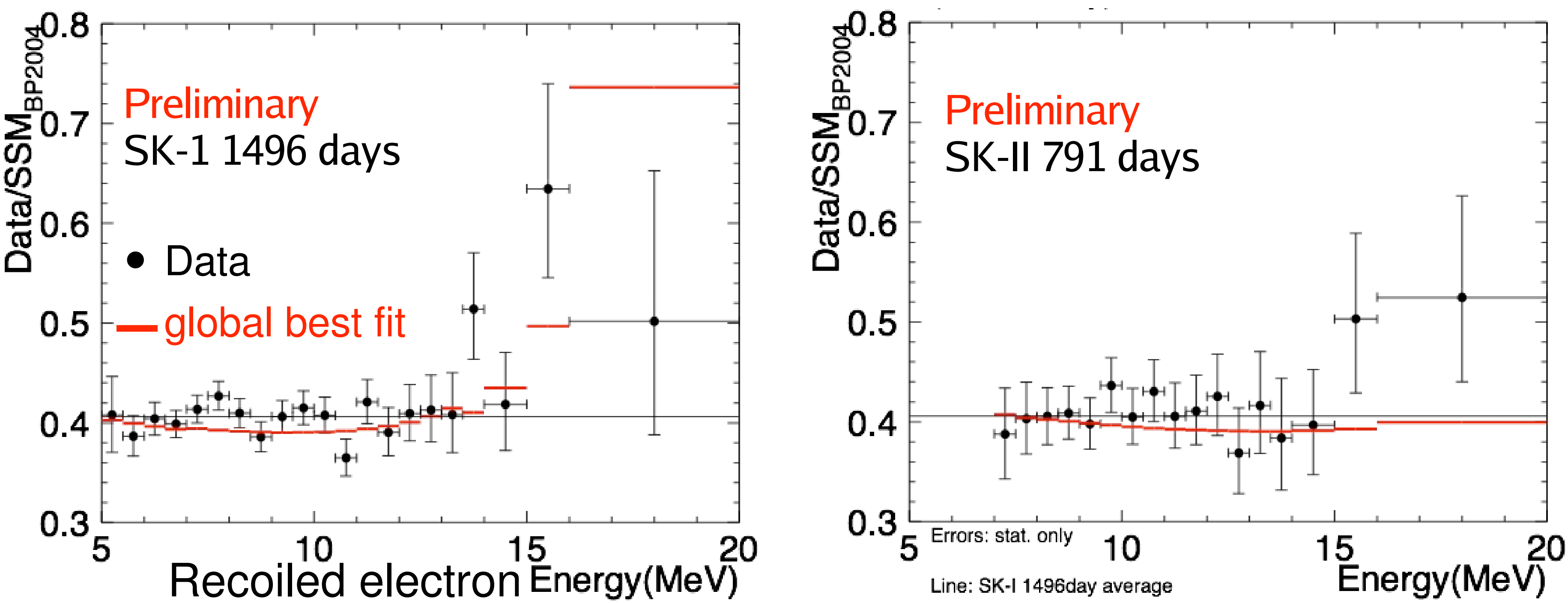
^8B flux



^8B Flux for SK1 and SK2 : [$cm^{-2}s^{-1}$]

- 2.35 ± 0.02 (stat.) ± 0.08(syst.) (SK1)
- 2.38 ± 0.05 (stat.) +0.16/-0.15(syst.) (SK2)

Energy distribution of Solar Neutrino at SK



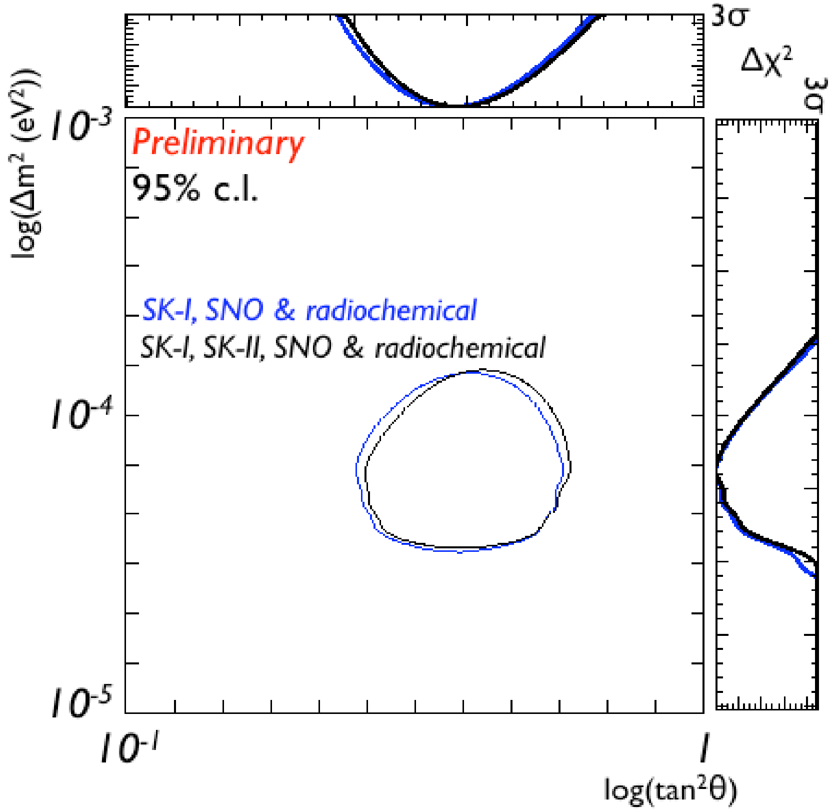
^{8}B *flux = 0.90 x SSM =* **5.21x10^{6}** cm^{-2}s^{-1}

hep flux = 8.62 x SSM = **6.79x10^{4}** cm^{-2}s^{-1}

Combined results from SK + other experiments

- Solar neutrino oscillation analysis combining SK,SNO and radio chemical experiments(Gallex/SNO/SAGE)

$$\chi^2_{global}(\beta,\eta) = \chi^2_{SK}(\beta,\eta) + \chi^2_{SNO}(\beta,\eta) + \chi^2_{radiochem}(\beta,\eta)$$



Favors the large mixing angle solution

$\tan^2\theta=0.40$

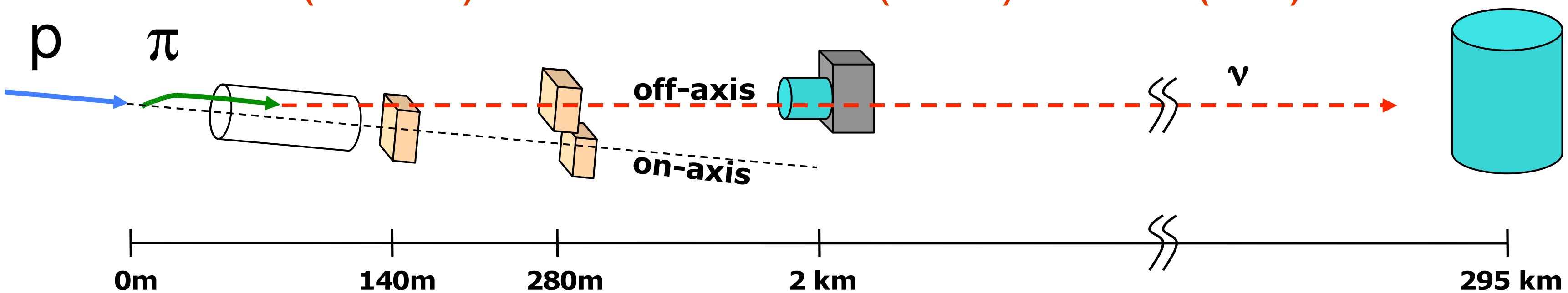
$\Delta m^2=6.03\times10^{-5}\ eV^2$

The Future of SK : T2K(Tokai to Kamioka)

295 km, 0.75 MW beam, 2.5 degrees of off-axis, start in 2009

- Upgrade of new electronics, DAQ, GPS systems at SK

Near (280m) + Intermediate(2km) + Far (SK)



Summary

- SK3 started taking data on June 2006 with full PMT coverage
- $\nu_\mu \rightarrow \nu_\tau$ oscillation is compared with alternative models
  - Mass induced $\nu_\mu \rightarrow \nu_s$ oscillation : excluded at 7.2σ level
  - Admixture of ν_s is allowed $\sin^2 \xi < 0.23$ at 90% C.L.
- ν_τ excess events have been observed in upward-going FC ν.
- SK1 Three Flavor analysis is consistent with both mass hierarchies and the CHOOZ limit
- n-$\bar{n}$ oscillation with SK1 : 1.77×10^{32} yr at 90% C.L.
- Solar neutrino oscillation analysis combining SK,SNO and radio chemical experiments(Gallex/SNO/SAGE) favor the LMA solution ($\tan^2\theta=0.40$, $\Delta m^2=6.03\times10^{-5}$ eV^2)
- Upgrades for T2K experiment are underway

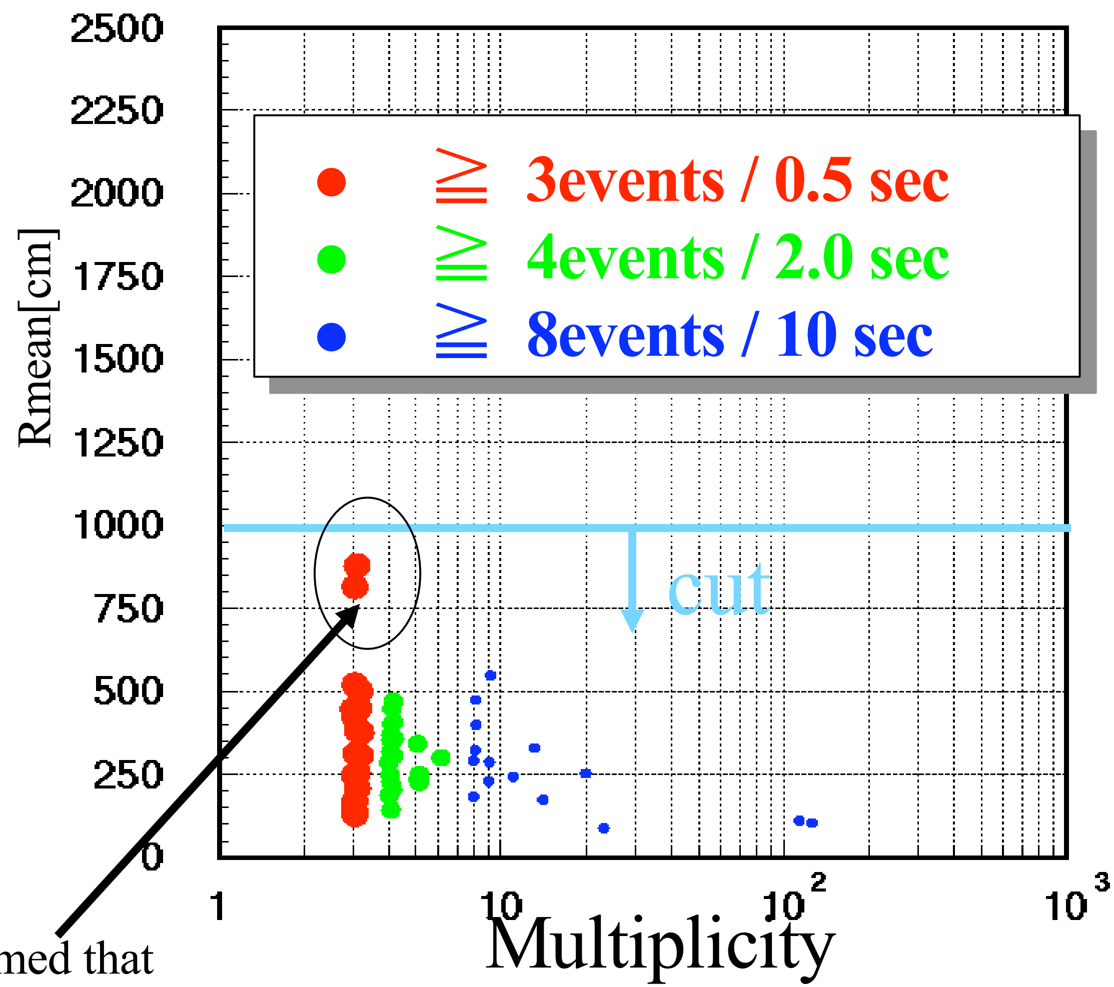
Supernova Burst Search

- Kamiokande, IMB, Baksan experiments observed the neutrino burst from SN1987A on Feb 23,1987. Since then, neutrino astronomy was started.
- SK typical core collapse SN explosion emits all types of neutrinos and has a total energy output of ~3x1053 ergs, i.e. generate 10,000 events (9,000 without n oscillation) at SK in the case of SK at 10 kpc.
- SK is sensitive to ??? (distance?)
- 2589.2 live-days of data (SK1+SK2)

To investigate SN clusters in lower energy (<17 MeV) events ,

Set the criteria of Higher multiplicity and Shorter timewindow

≧ 3events / 0.5 sec
or ≧ 4events / 2.0 sec
or ≧ 8events / 10 sec



I confirmed that
one of them is flasher events
the other one is spallation events

Oscillation induced by LIV and CPTV

- Neutrino oscillation without mass
- Pure Lorentz Invariant Violation effect
- CPT violation

CPT violation