Recent results on Atomospheric Neutrino Oscillation from Super-Kamiokande

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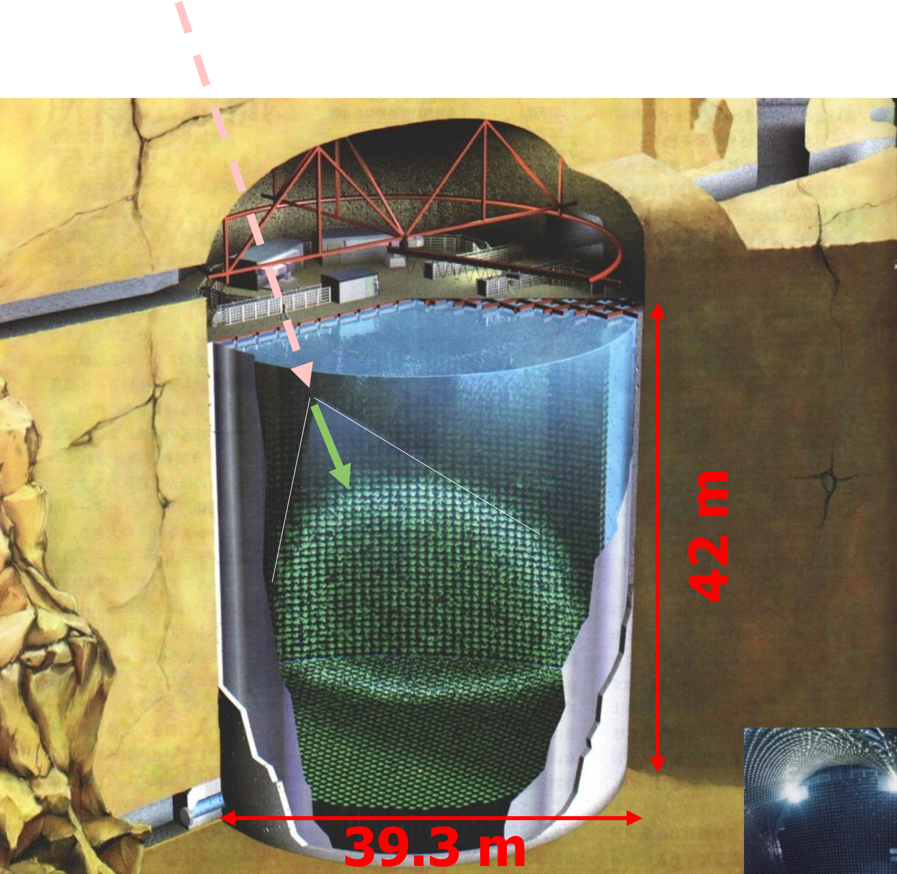
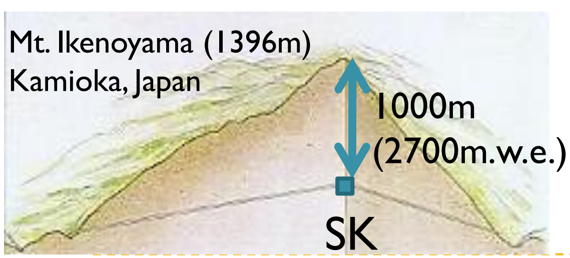
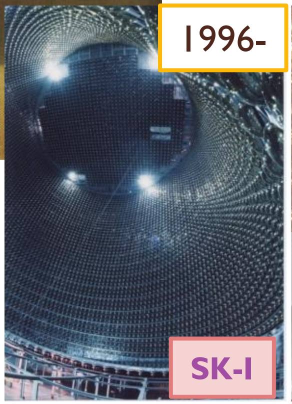
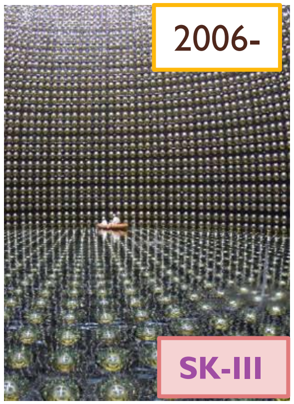
Super-Kamiokande

- Imaging Water Cherenkov detector
- 50kt Pure Water
- 32kt Inner Detector viewed by 20inch PMTs. Num of tubes: 11146(SK-I), 5200(-II), 11129(-III,IV)
- t~2m Outer Detector viewed by 1885 8inch PMTs



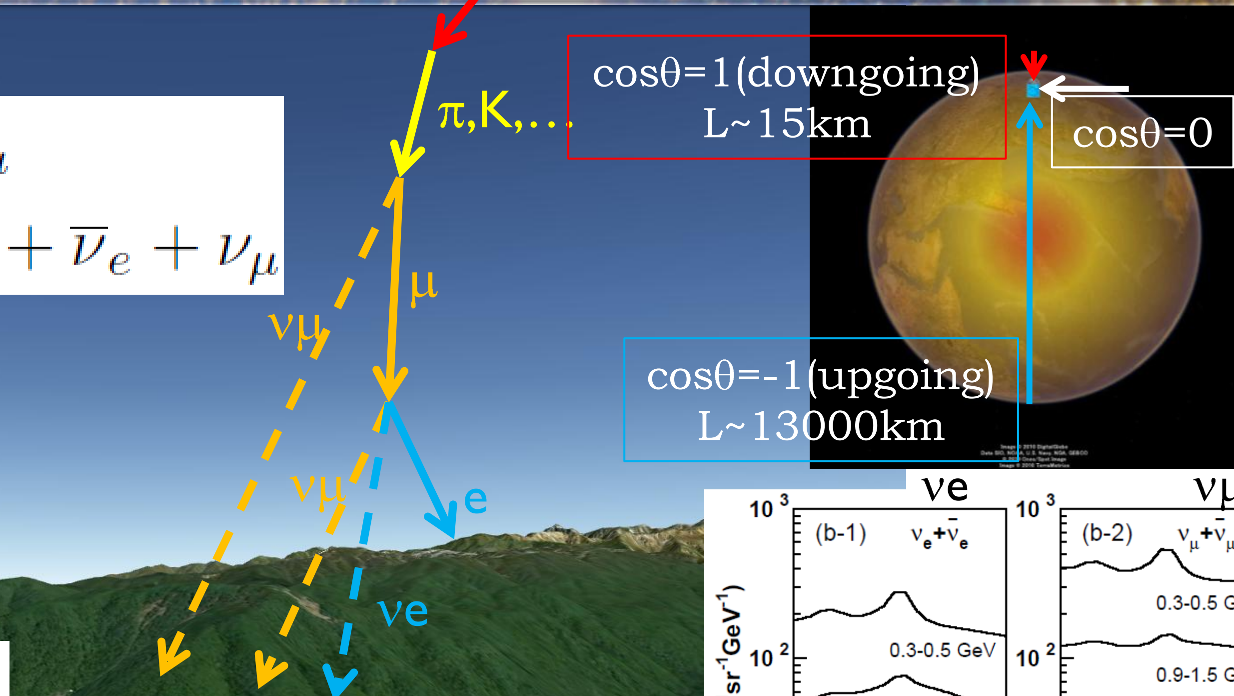


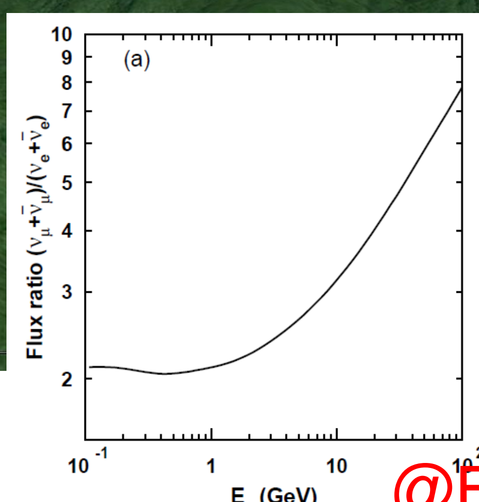




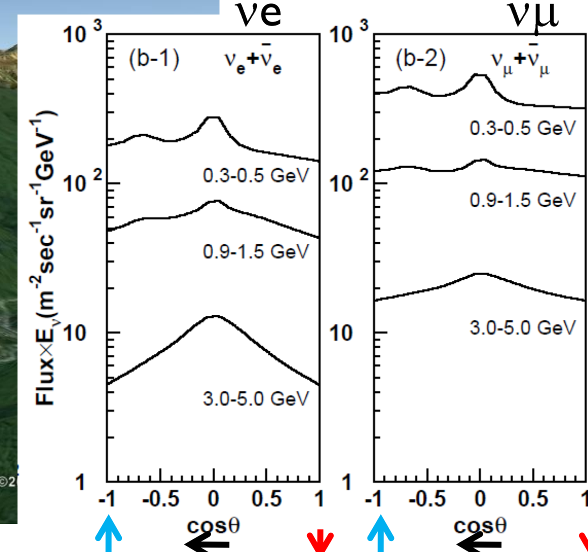
Atmospheric Neutrino

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$
$$\hookrightarrow e^- + \overline{\nu}_e + \nu_\mu$$



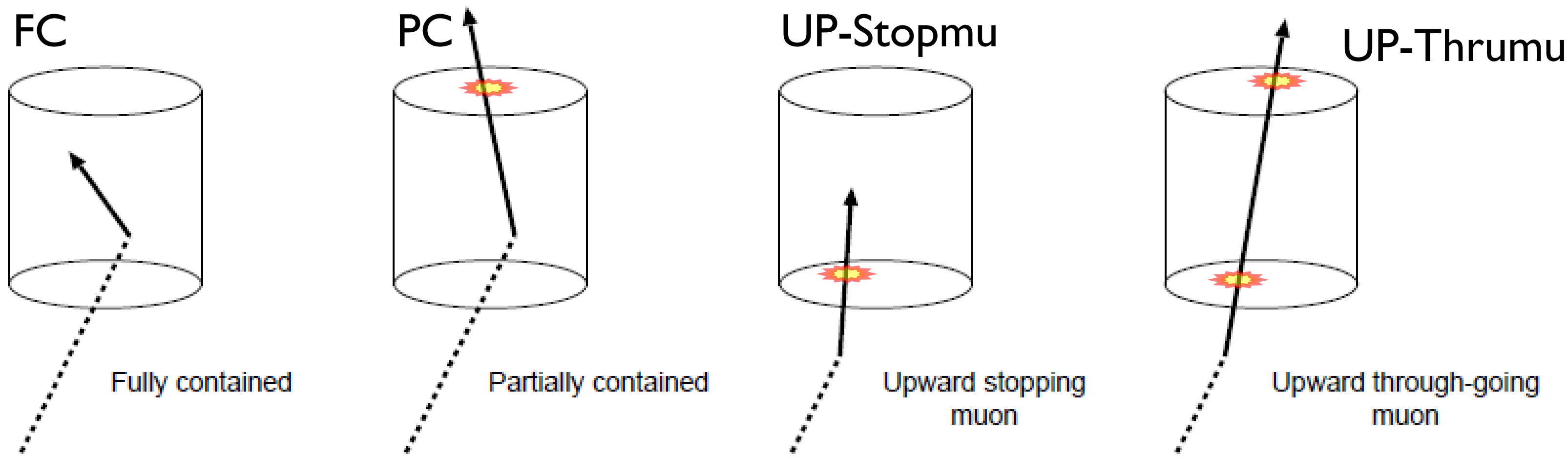


νμ/νe ~ 2
@Eν<a few GeV

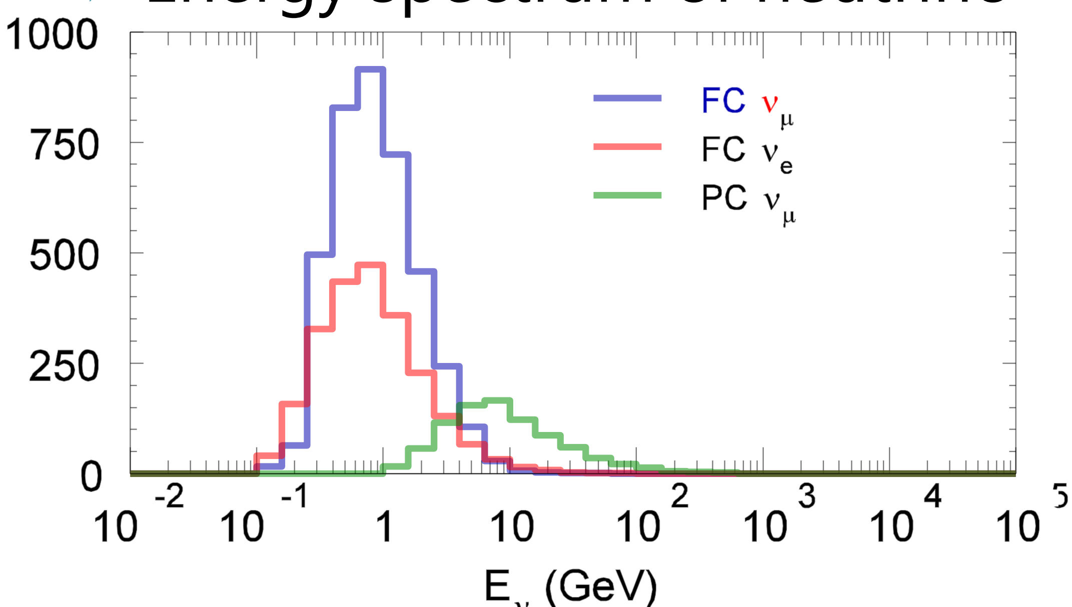


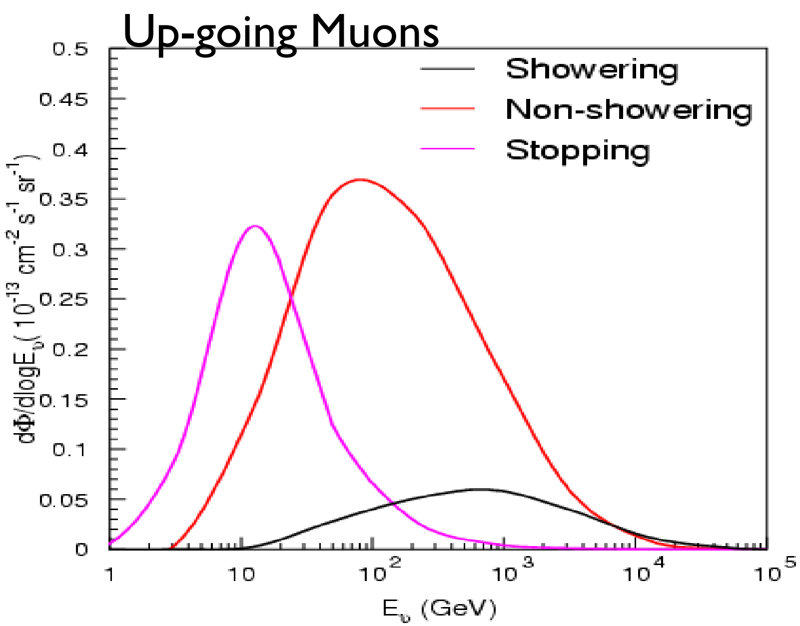
Zenith angle distribution
~Up/Down symmetric
(In the case of NO oscillation)

Event Topology

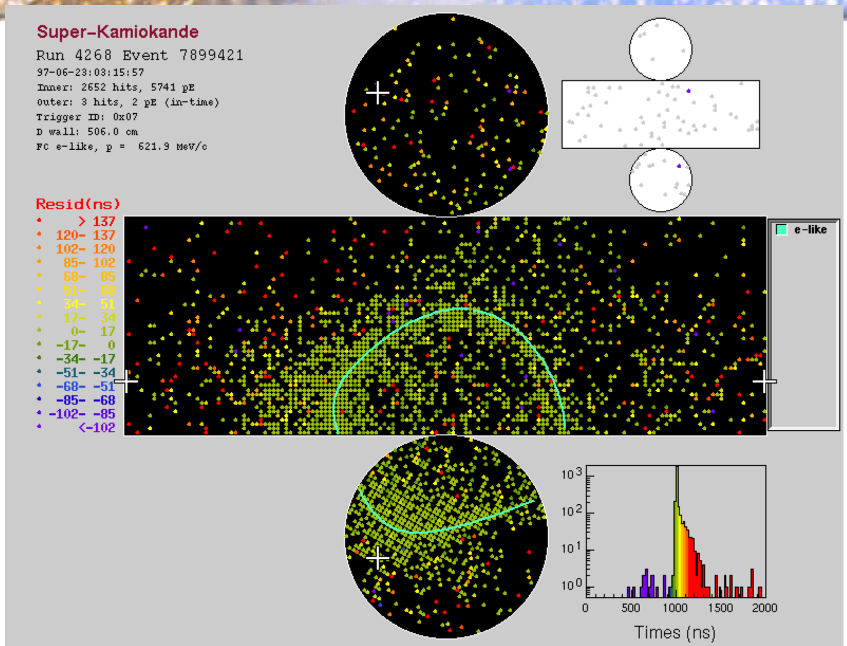


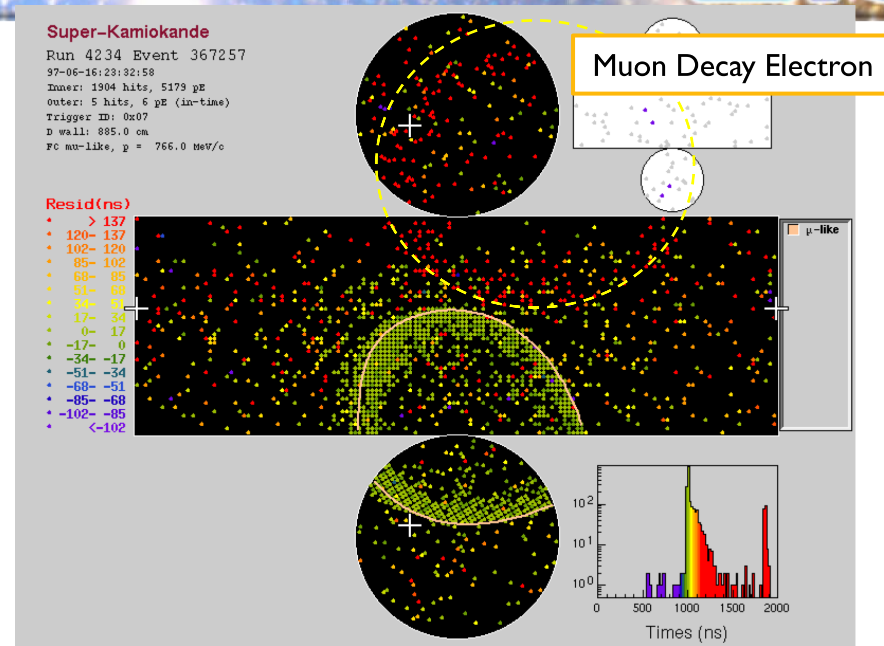
- Energy spectrum of neutrino



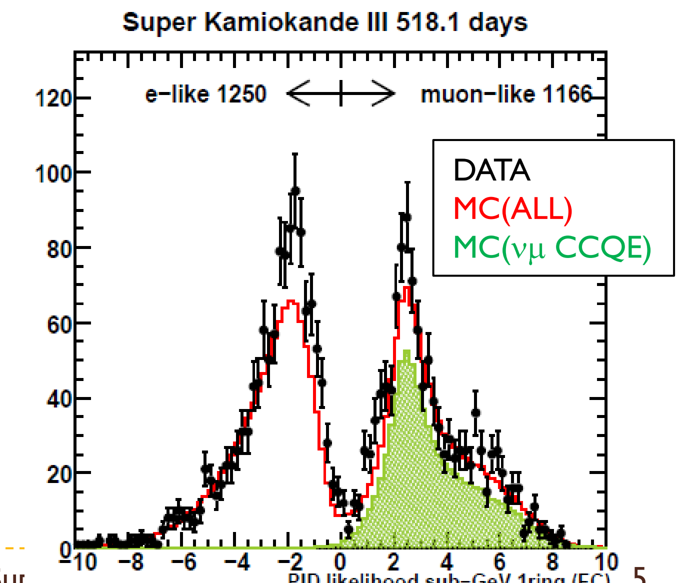


Particle Identification





- Identify Electron-like(Showering) particles and Muon-like particles using Cherenkov ring <u>Pattern</u> and <u>Angle</u> likelihood

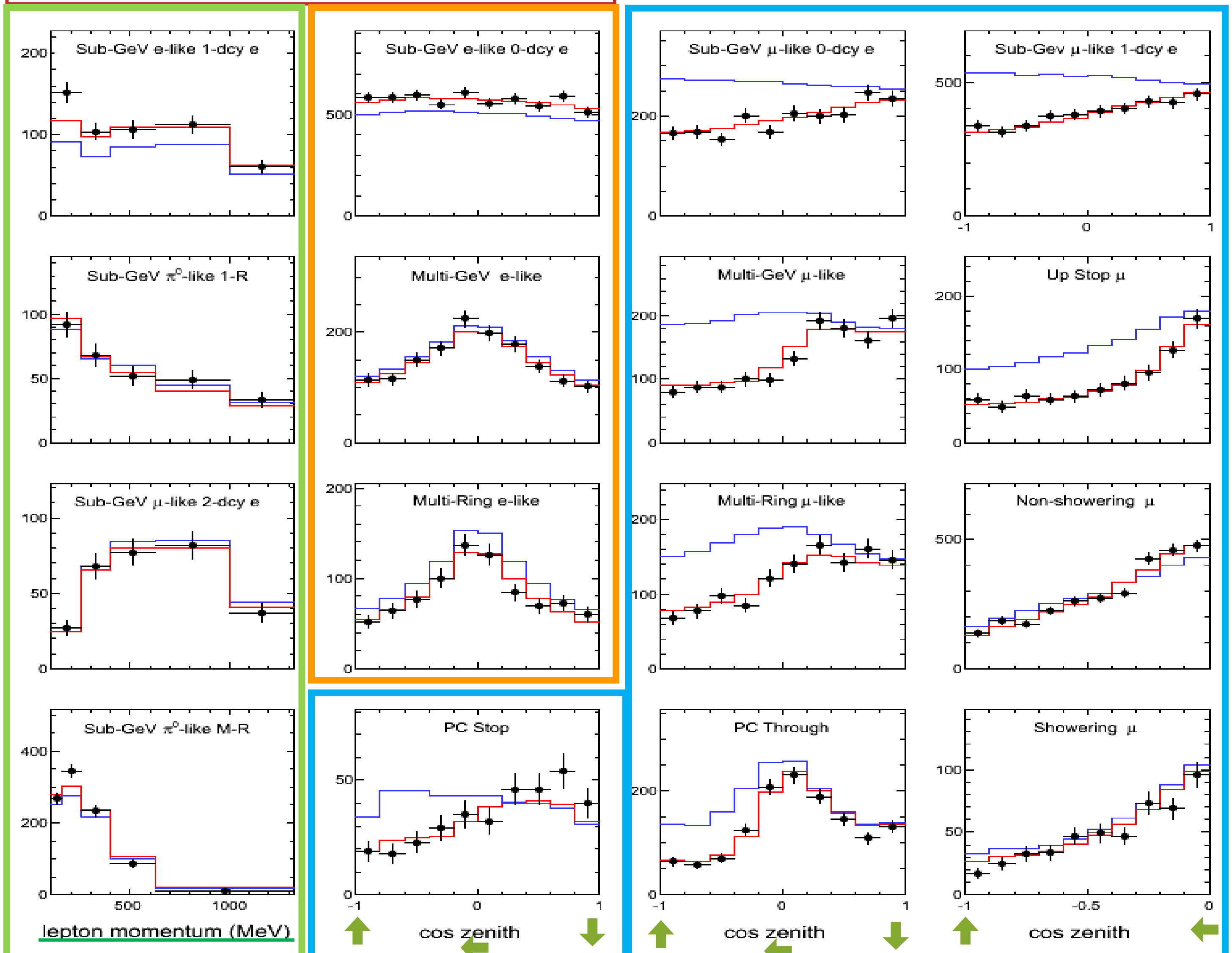


Zenith angle & lepton momentum distributions

SK-I+II+III
Preliminary

— (red) $\nu_\mu - \nu_\tau$ **oscillation (best fit)**
— (blue) **null oscillation**

momentum | **e-like** | **μ-like**



Live time:

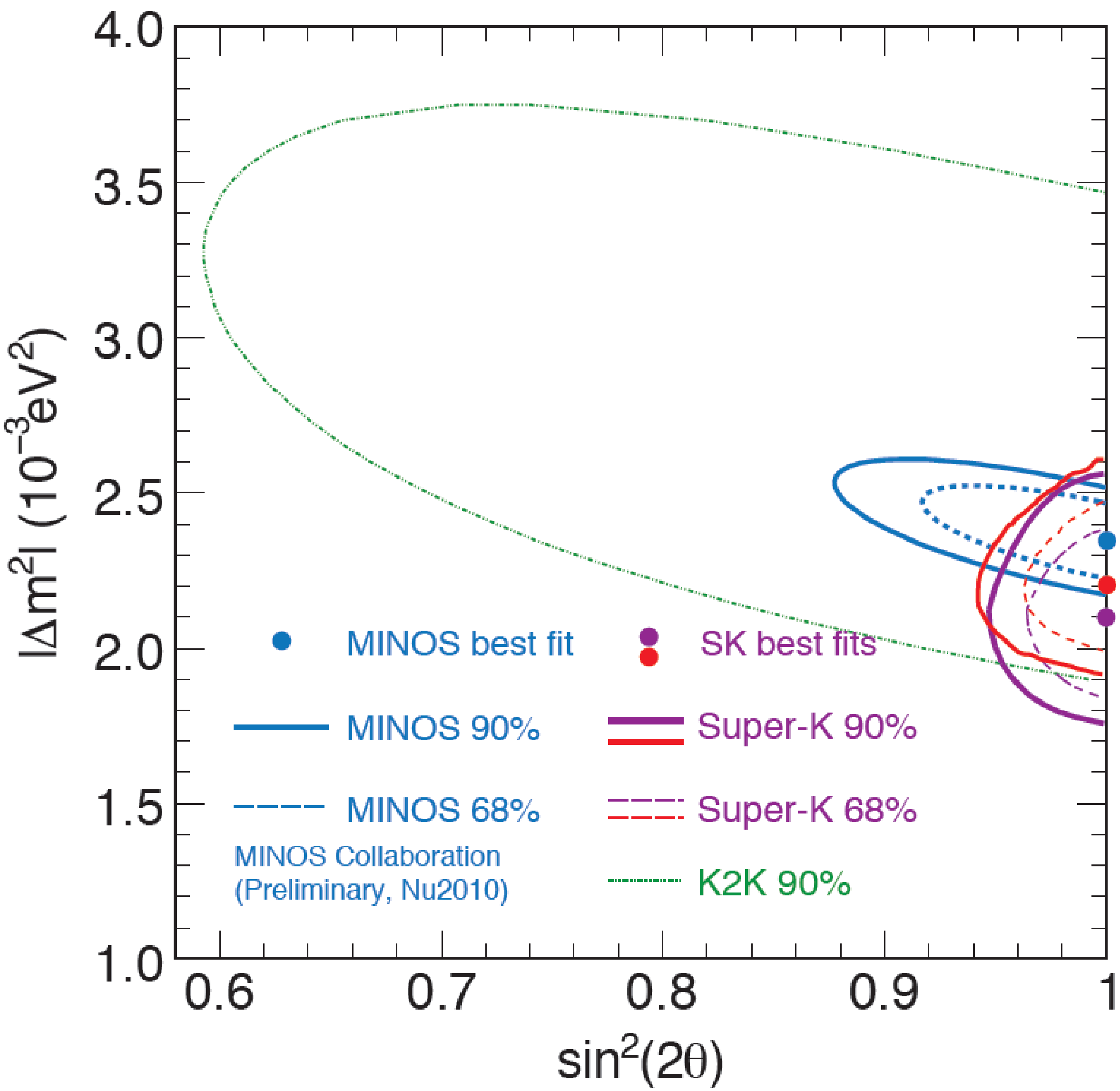
SK-I
1489d (FCPC)
1646d (Upmu)

SK-II
799d (FCPC)
827d (Upmu)

SK-III
518d (FCPC)
636d (Upmu)

Sub-GeV samples are divided to improve sensitivity to low-energy oscillation effects

2-flavor oscillation analysis results



SK-I+II+III *Preliminary*

Zenith Physical Region (1σ)
$\Delta m_{23}^2 = 2.11 + 0.11/-0.19 \times 10^{-3}$
$\sin^2 2\theta_{23} > 0.96$ (90%C.L.)

L/E Physical Region (1σ)
$\Delta m_{23}^2 = 2.19 + 0.14/-0.13 \times 10^{-3}$
$\sin^2 2\theta_{23} > 0.96$ (90%C.L.)

- Results of both zenith angle analysis and L/E analysis are consistent.
- SK provides the most stringent limit for $\sin^2(2\theta_{23})$.

- **Consider both matter effect and solar term simultaneously.**
- **Matter effect: possible enhancement of ν_e is expected in several GeV energy region and in Earth core**
  - ➡ **θ_{13} and mass hierarchy could be studied.**
- **Solar term: possible enhancement of ν_e in sub-GeV region**
  - ➡ **θ_{23} octant degeneracy could be studied.**
- **Interference: CP phase could be studied. (when $\sin^2\theta_{13}$ >~0.05).**

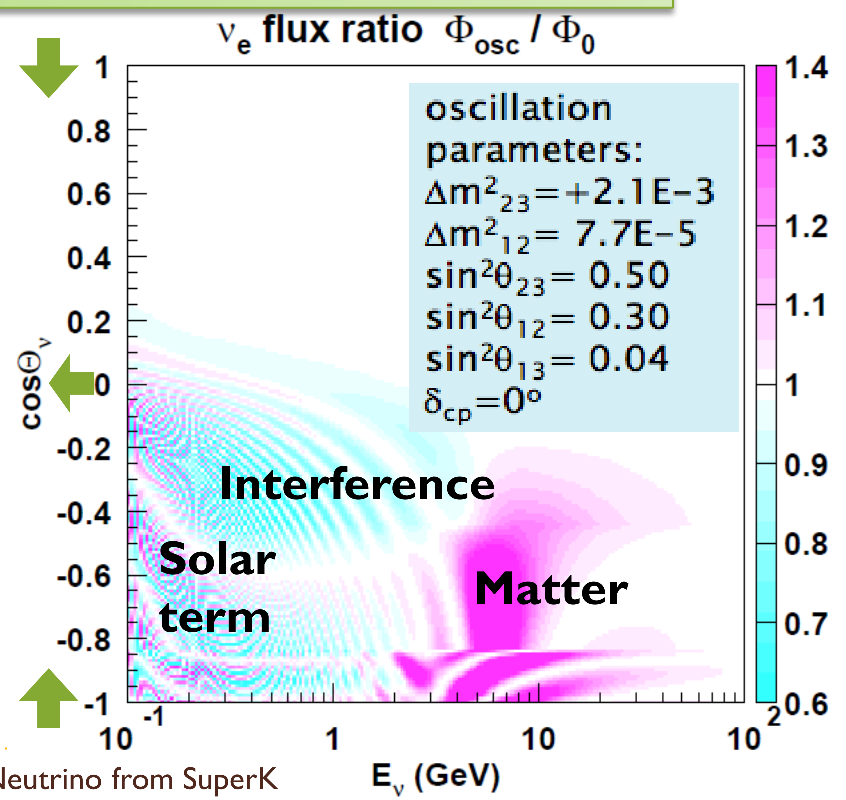
Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \quad \leftarrow \text{Matter effect}$$
$$+\Delta_2(\Delta m_{12}^2) \quad \leftarrow \text{Solar term}$$
$$+\Delta_3(\theta_{13}, \Delta m_{12}^2, \delta) \quad \leftarrow \text{Interference}$$

(The ν_μ flux difference is also expected.)

Full 3-f osc. analysis: all parameters are considered simultaneously.

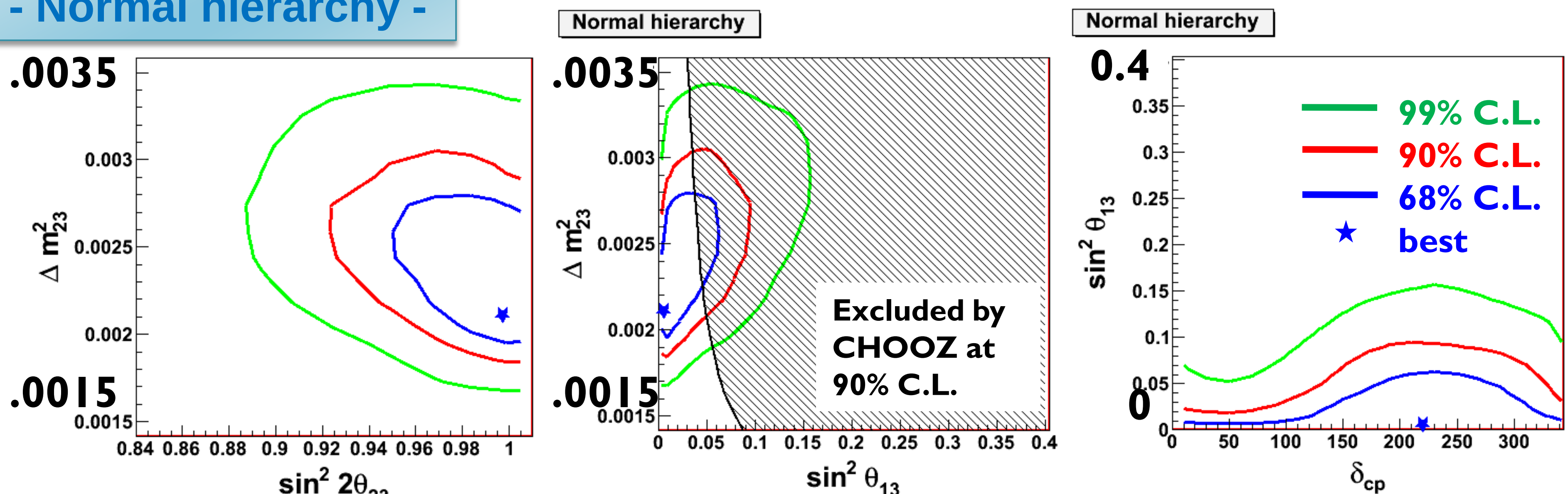
PRD81, 092004: either matter effect or solar term is considered with approximations (cannot test the interference part)



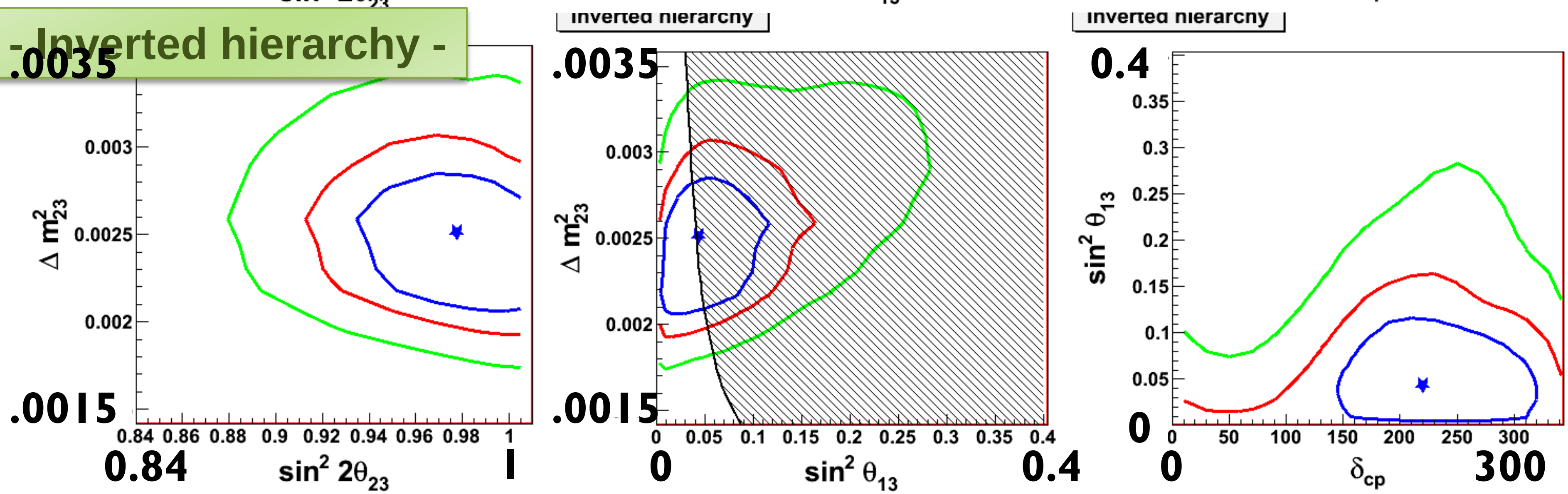
Full 3−flavor oscillation results

SK-I+II+III *Preliminary*

- Normal hierarchy -



- Inverted hierarchy -



Full 3-flavor oscillation results

- Normal hierarchy -

SK-I+II+III *Preliminary*

χ^2_{min} = 469.94 /416dof

Parameter	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10³)	2.11 eV^2	1.88 - 2.75 eV^2	1.99 - 2.54 eV^2
$\sin^2\theta_{23}$	0.525	0.406 - 0.629	0.441 - 0.597
$\sin^2\theta_{13}$	0.006	< 0.066	< 0.036
CP-δ	220°	-	140.8 - 297.3°

- Inverted hierarchy -

χ^2_{min} = 468.34 /416dof

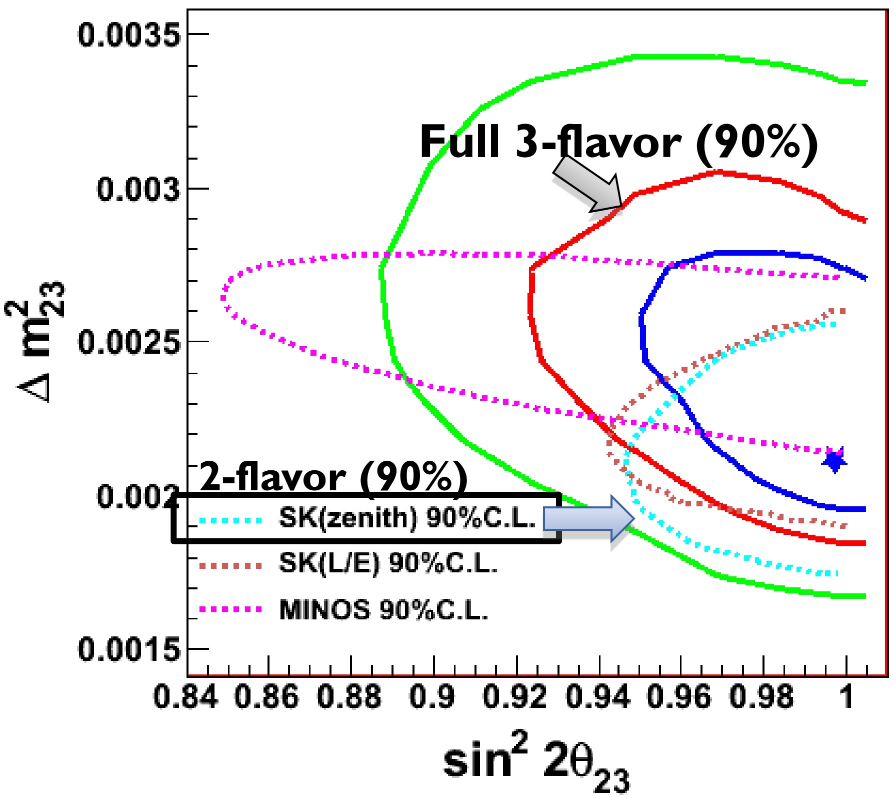
Parameter	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10³)	2.51 eV^2	1.98 - 2.81 eV^2	2.09 - 2.64 eV^2
$\sin^2\theta_{23}$	0.575	0.426 - 0.644	0.501 - 0.623
$\sin^2\theta_{13}$	0.044	< 0.122	0.0122 - 0.0850
CP-δ	220°	121.4 - 319.1°	165.6 - 280.4°

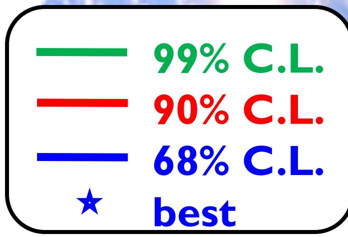
- No significant preference on hierarchy.
- No significant constraint on CP phase at 90% C.L.

($\sin^2\theta_{12}$, Δm^2_{12}) are fixed at (0.304, 7.66×10^{-5} eV^2)

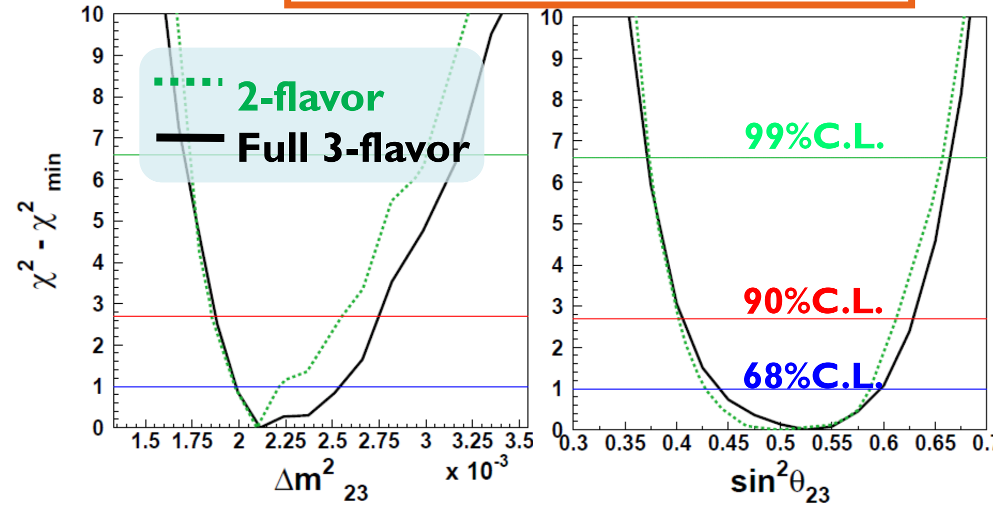
Comparison with 2−flavor analysis

Normal hierarchy





$\chi^2 - \chi^2_{min}$ distributions

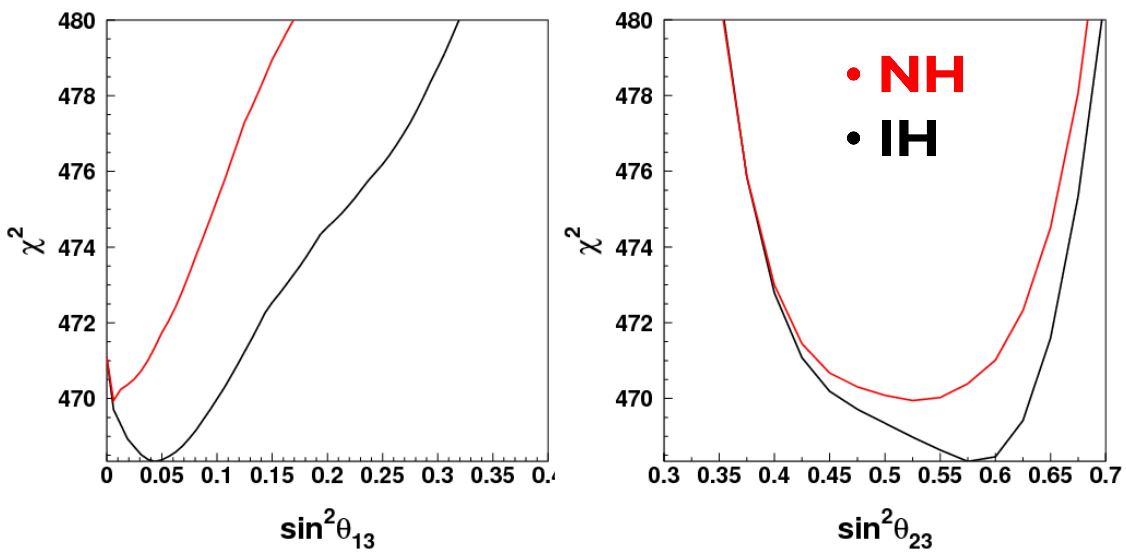


Consistent results are obtained.
No deviation of $\sin^2\theta_{23}$ from 0.5.
Allowed region of Δm^2_{23} is a bit larger than that of the 2-flavor analysis as the effect of CP phase is also taken into account.

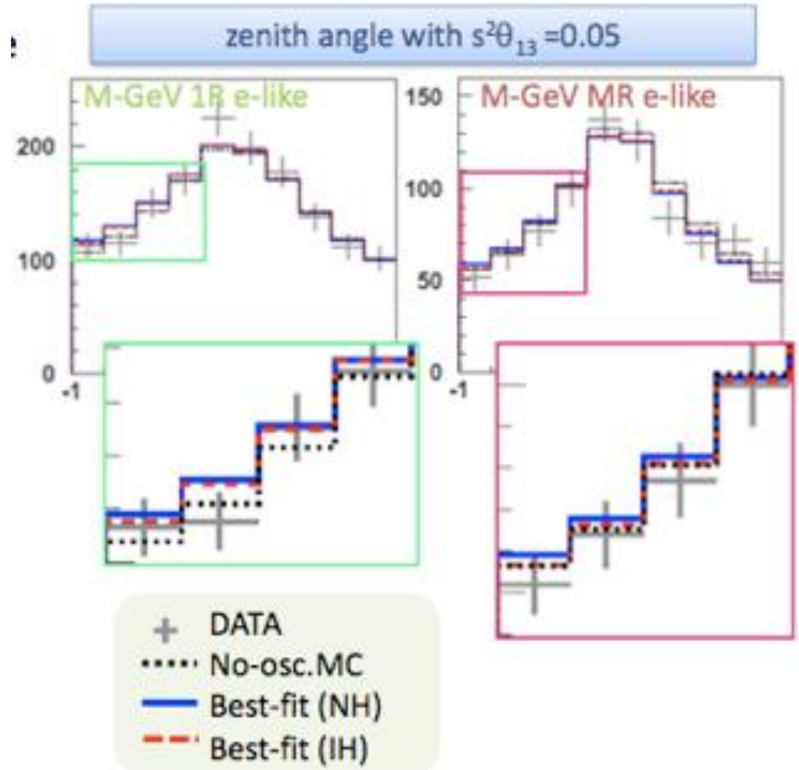
90%C.L. allowed region (1dof, $\chi^2 = \chi^2_{min} + 2.71$)

Full 3-flavor (NH)	*Global-best*
$(1.88 < \Delta m^2_{23} < 2.75)$ e-3	$(2.22 < \Delta m^2_{23} < 2.60)$ e-3
$0.406 < \sin^2\theta_{23} < 0.629$	$0.401 < \sin^2\theta_{23} < 0.615$
$(0.93 < \sin^2 2\theta_{23})$	$(0.95 < \sin^2 2\theta_{23})$

Best fit is in the inverted hierarchy case
Normal hierarchy (NH): χ^2_{min} = **469.94**/416dof
Inverted hierarchy (IH): χ^2_{min} = **468.34**/416dof
→ $\Delta\chi^2 = 1.6$
No significant difference



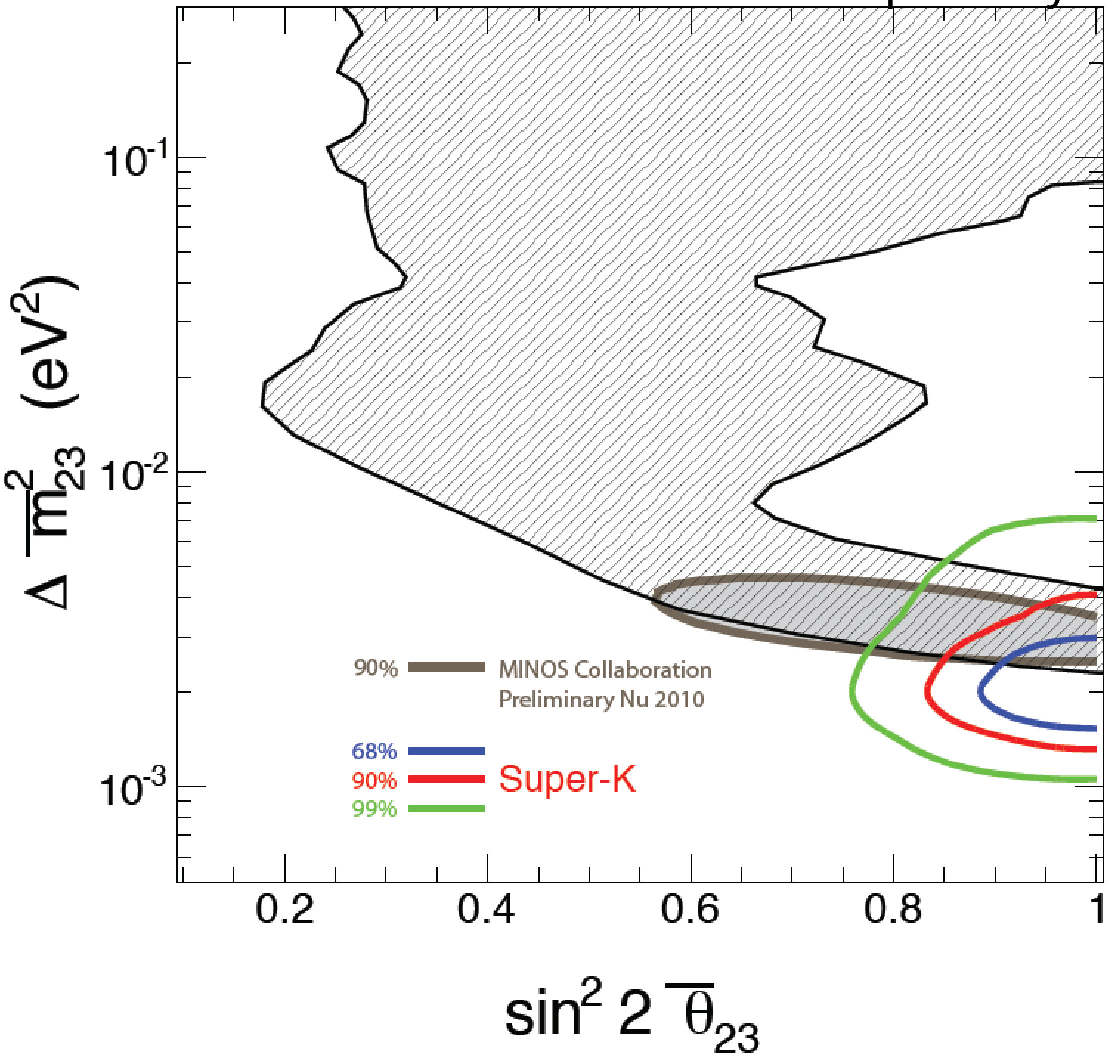
Multi-GeV samples tend to favor inverted hierarchy.



There are also some contributions from Multi-GeV μ-like samples favoring IH to NH.

Search for CPT violation in atm. ν

- Under the CPT theorem, P(ν→ ν) and P($\overline{\nu}$→$\overline{\nu}$) should be same.
- Test ν oscillation or $\overline{\nu}$ oscillation separately.



SK-I+II+III

Preliminary

Neutrino:

$\Delta m_{23}^2 = 2.2\times10^{-3}\,eV^2$

$\sin^2 2\theta_{23} = 1.0$

Anti-neutrino:

$\Delta \overline{m}_{23}^2 = 2.0\times10^{-3}\,eV^2$

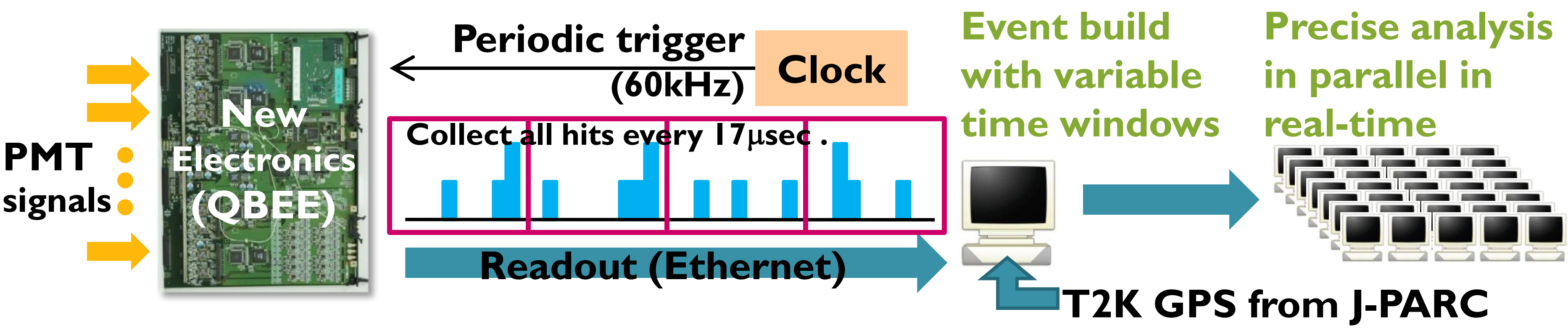
$\sin^2 2\overline{\theta}_{23} = 1.0$

No evidence for CPT violating oscillations is found

Improvements of the DAQ system

IEEE Trans. Nucl. Sci. 57 (2010) 428

SK-I,II,III: partial data above threshold (Num. of hits) were read (1.3μsec window x3kHz)
SK-IV: All hits above pulse height threshold are read, then apply complex triggers by software.



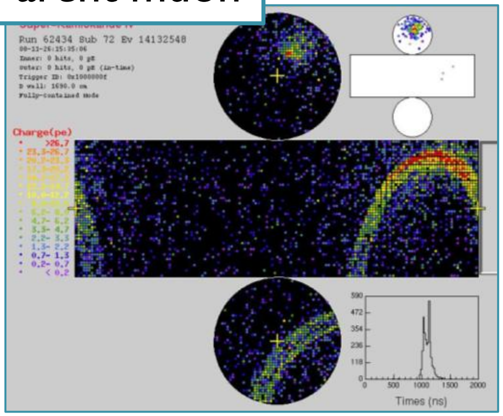
Typical event time windows:

- **Super-Low-Energy (SLE) events (<~6.5MeV): -0.5/+1.0μsec** — high rate (~3kHz)
- **Normal events(>~6.5MeV): -5/+35μsec** — decay electrons
- **Supernova Relic ν (SRN) candidates(>~10MeV, No OD): -5/+535μsec** — neutrons
- **T2K events: -512/+512μsec at T2K beam spill timing**

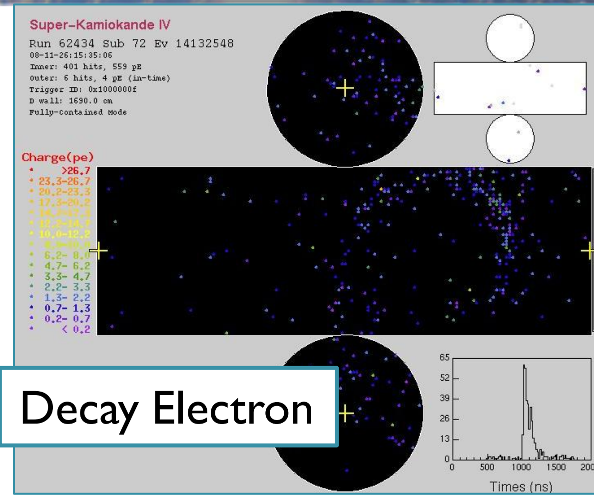
Wider dynamic range for charge measurement of each channel (>2000pC) x5
No dead time up to ~6MHz/10sec for Supernova burst neutrinos x100
Apply precise event reconstruction to remove more low-e BG events in real-time

Muon Decay Electron Tagging

Parent muon

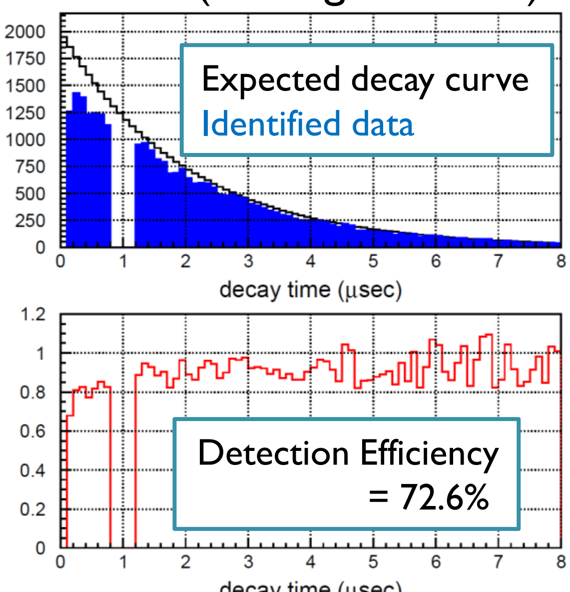


τ~2us

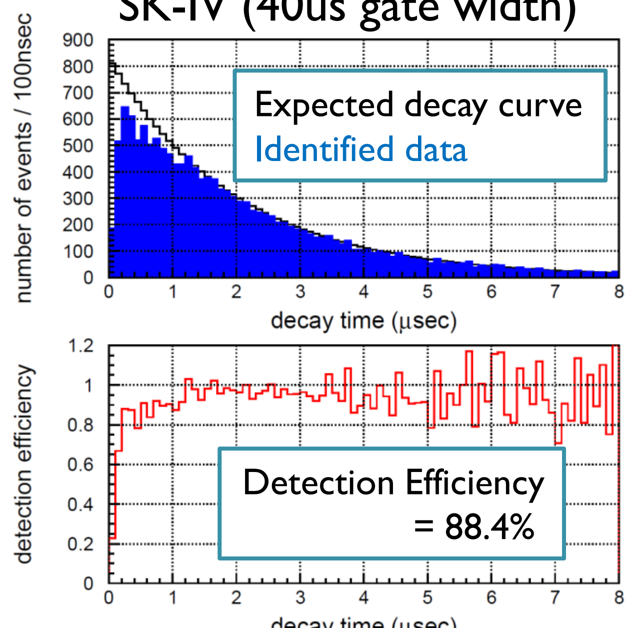


Decay Electron

SK-III (1.3us gate width)



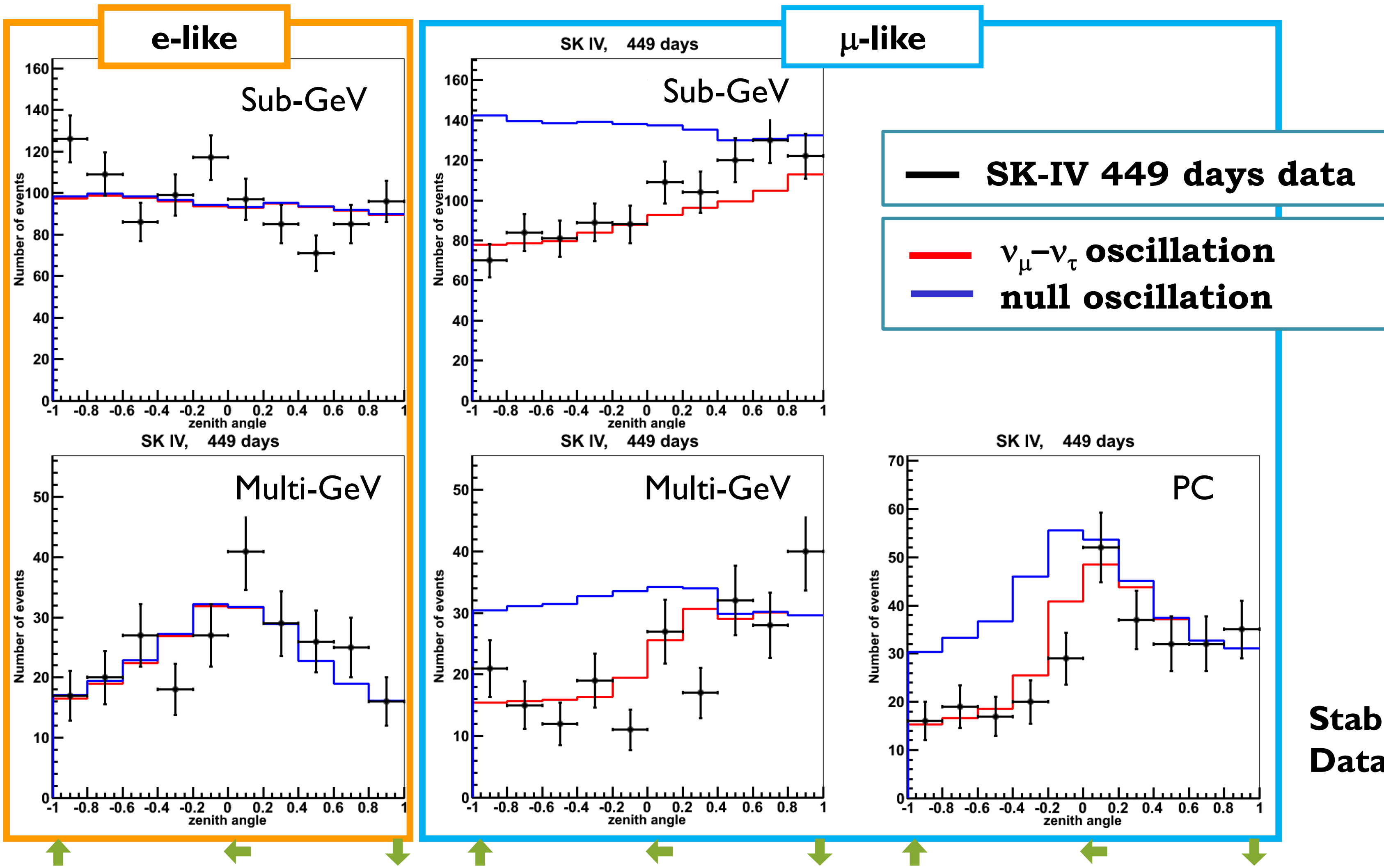
SK-IV (40us gate width)



Wider gate width of SK-IV enables detection of muon decay electrons at T~1us efficiently

Zenith angle distributions of SK-IV atm. ν

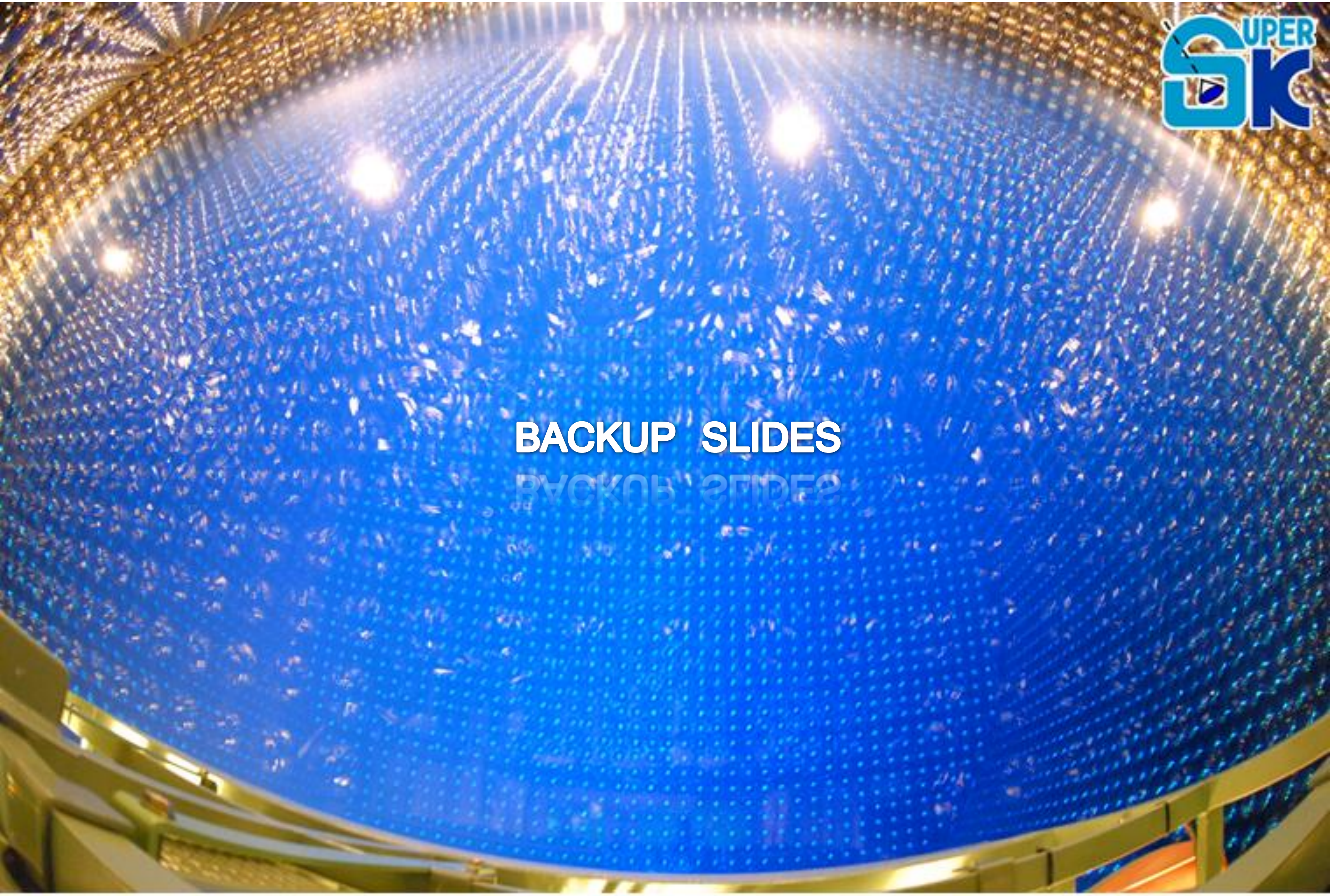
SK-IV



Stable Data taking!

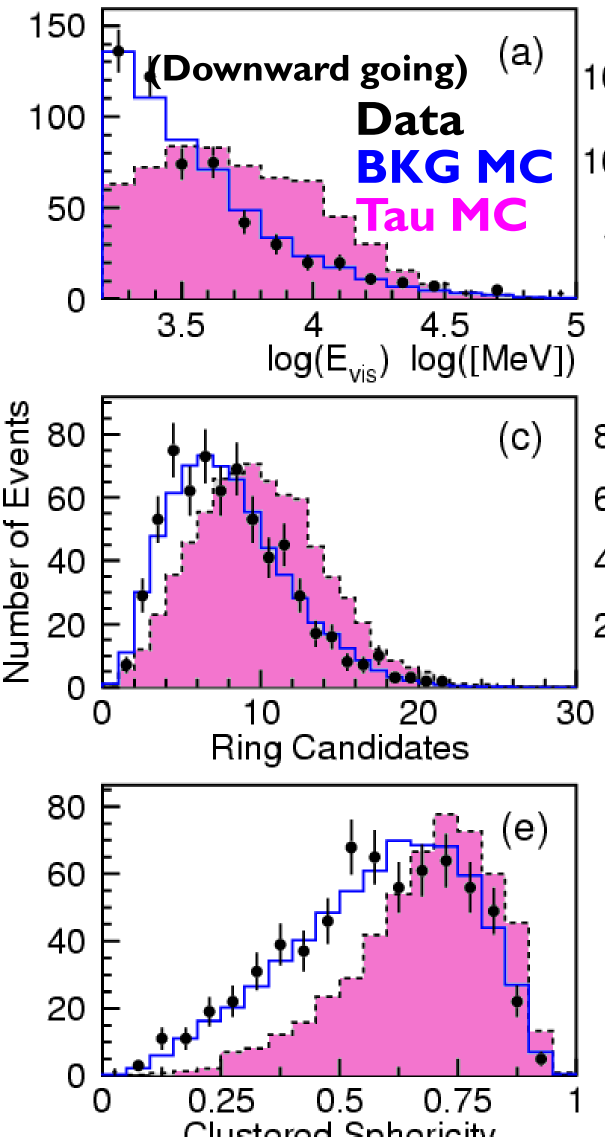
SUMMARY

- Recent update on Atmospheric neutrino oscillation from SK-I,II,III
  - 2 Flavor nm-nt oscillation result
  - Full 3 Flavor including Solar term & CP, Mass Hierarchy
    → "Consistent with 2 flavor result, No preference of Hierarchy
  - CPT violations search → "No evidence"
- Electronics Upgrade (SK-IV)
  - Improvement on Decay-electron tagging efficiency
  - Stable Atmospheric neutrino data taking
- Super-Kamiokande Talk/Posters
  - M. Miura(Nucleon decay) 24-Jul-2010 09:20; BSM Session
  - H. Sekiya(Solar neutrino) Poster
  - M. Smy (Low-energy anti neutrino detection) Poster


BACKUP SLIDES

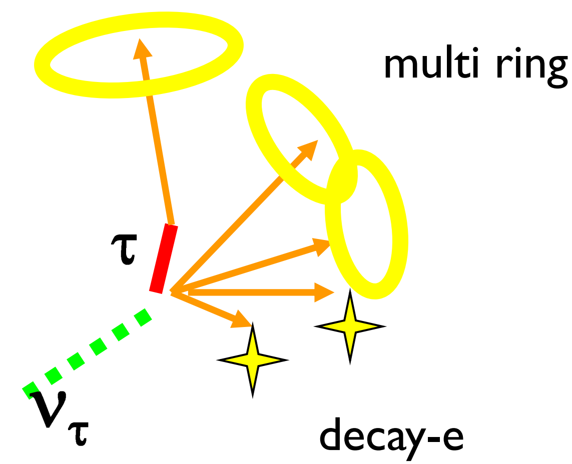
ν_τ appearance search

Likelihood variables



PRL97,171801 (2006)

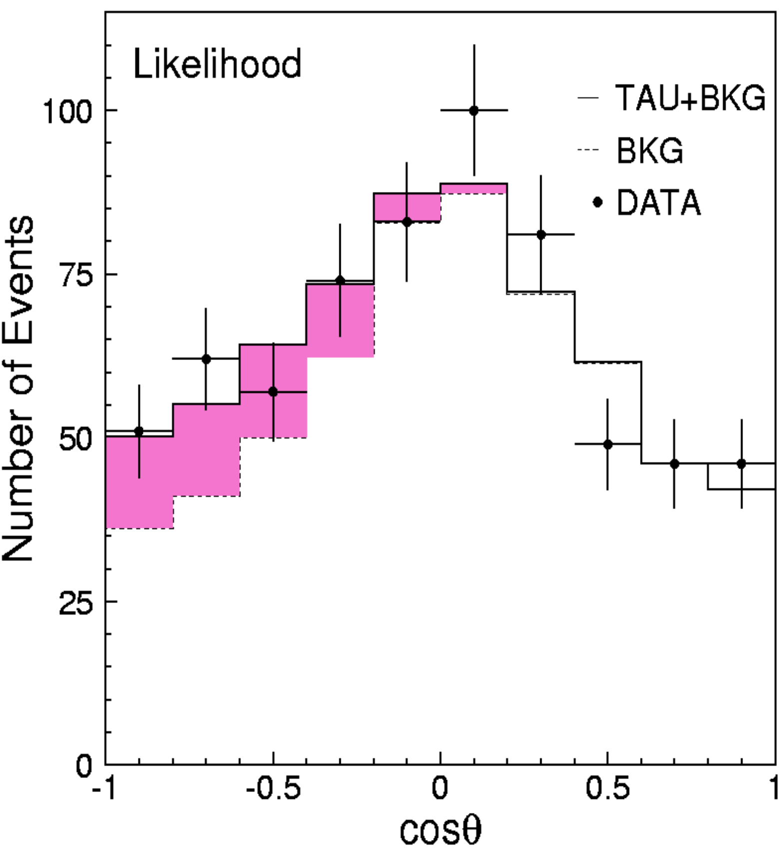
τ–like selection;
effτ=43%,
S/N=5%



(a) Visible Energy
(b) Max. decay-e distance from vertex
(c) Ring Candidates
(d) Sphericity in the lab frame
(e) Clustered sphericity in COM frame

ν_τ appearance search

zenith angle distribution of tau enrich sample



PRL97,171801 (2006)

	Data	BKG MC	Tau MC
Generated in fiducial volume	-	17135 (100%)	78.4 (100%)
Evis > 1.33 GeV	2888	2943 (17.2%)	51.5 (65.7%)
Most Energetic ring e-like	1803	1765 (10.3%)	47.1 (60.1%)
Likelihood > 0.0	649	647 (3.79%)	33.8 (43.1%)
Neural network > 0.5	603	577 (3.36%)	30.6 (39.0%)

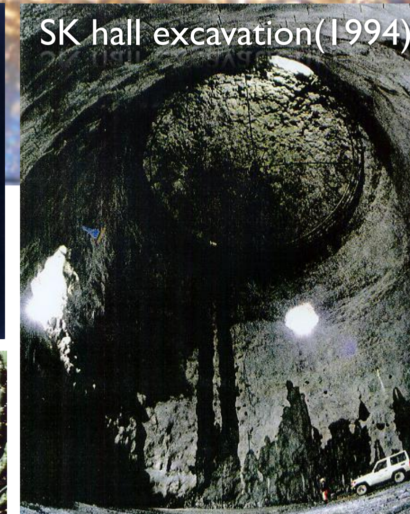
- Best-fit tau excess:
  138+/-48(stat.)+15/-32(syst.)
- Expected: 78+/-26(syst.)

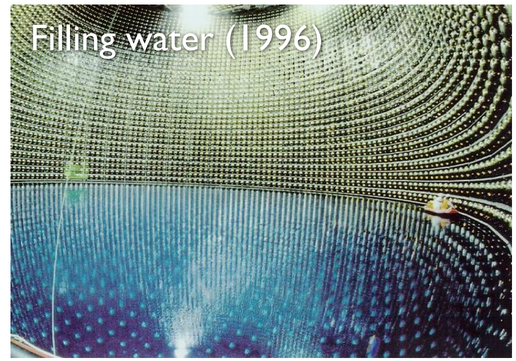
(Likelihood)

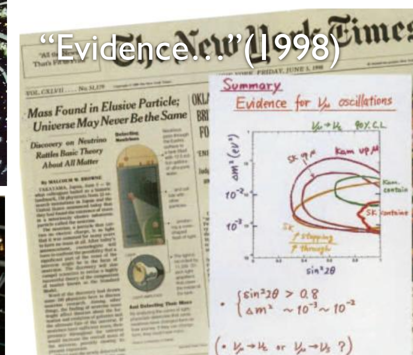
tau enrich sample is consistent with $\nu_\mu - \nu_\tau$ oscillation

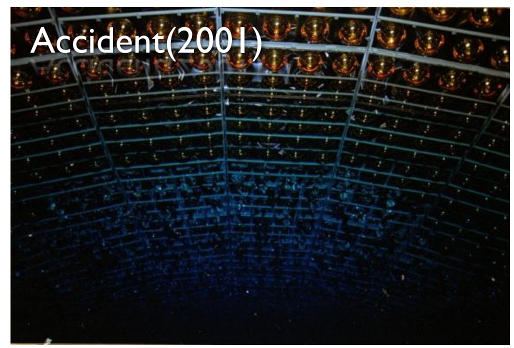
History

- 1983 Kamiokande started observation to search for Proton decay
- 1987 Kamiokande observed SN1987a
- 1991 Construction of SK started
- 1996 SK started observation
- 1998 "Evidence for oscillation of atmospheric neutrinos"
- 1999 K2K started
- 2001 Accident
- 2002 Partial reconstruction
  SK-II started
  K2K-II started (-2004)
- 2006 Full reconstruction
  SK-III started
- 2008 Replacement of DAQ electronics
  SK-IV Started
- 2009 T2K started









Kamioka Underground Site