Oscillation analysis results using Super-Kamiokande atmospheric neutrino data

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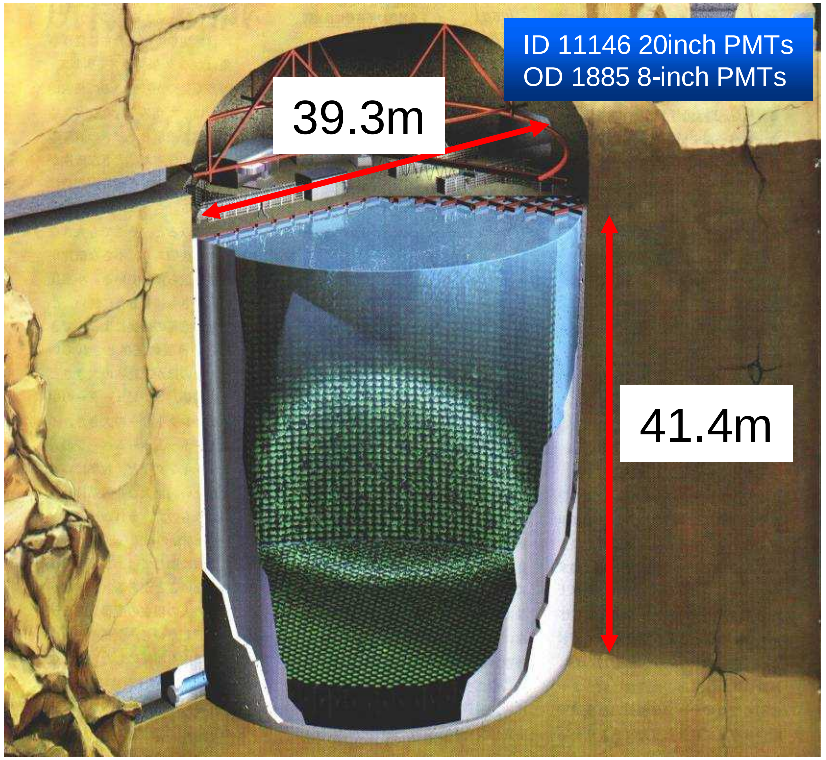
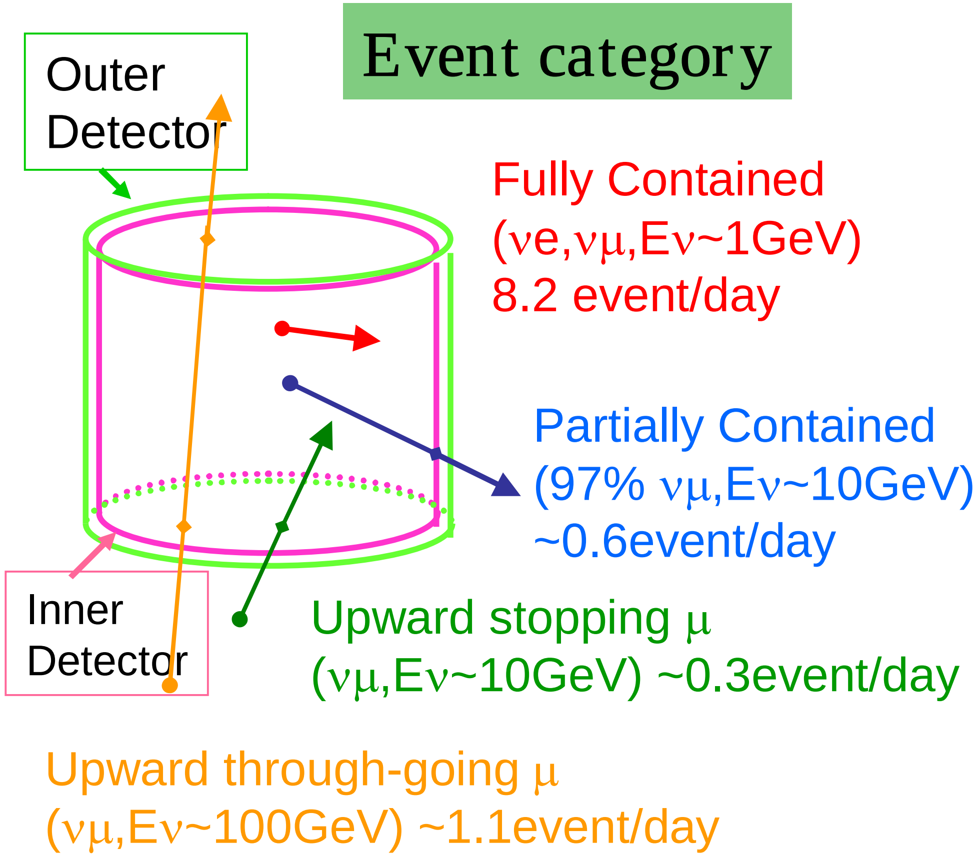
Super-Kamiokande



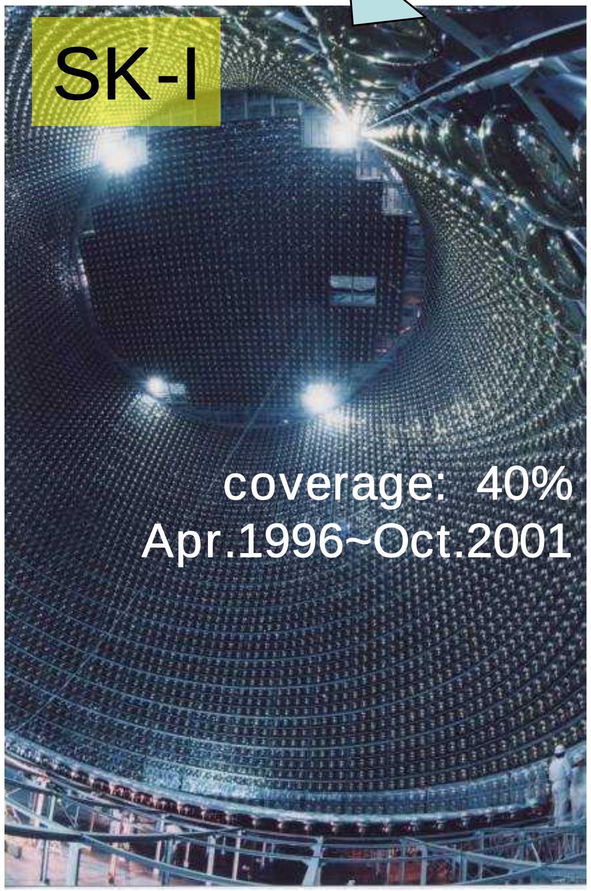
- Water Cherenkov detector
- 50kton (22.5 kton fid.), cylindrical shape
- Deep underground (2700 w.m.e)

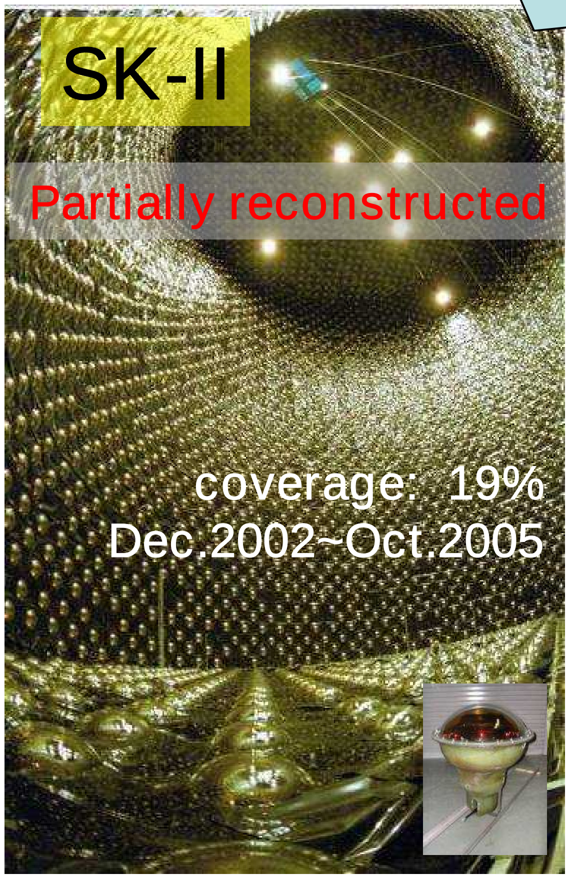


History of Super-Kamiokande

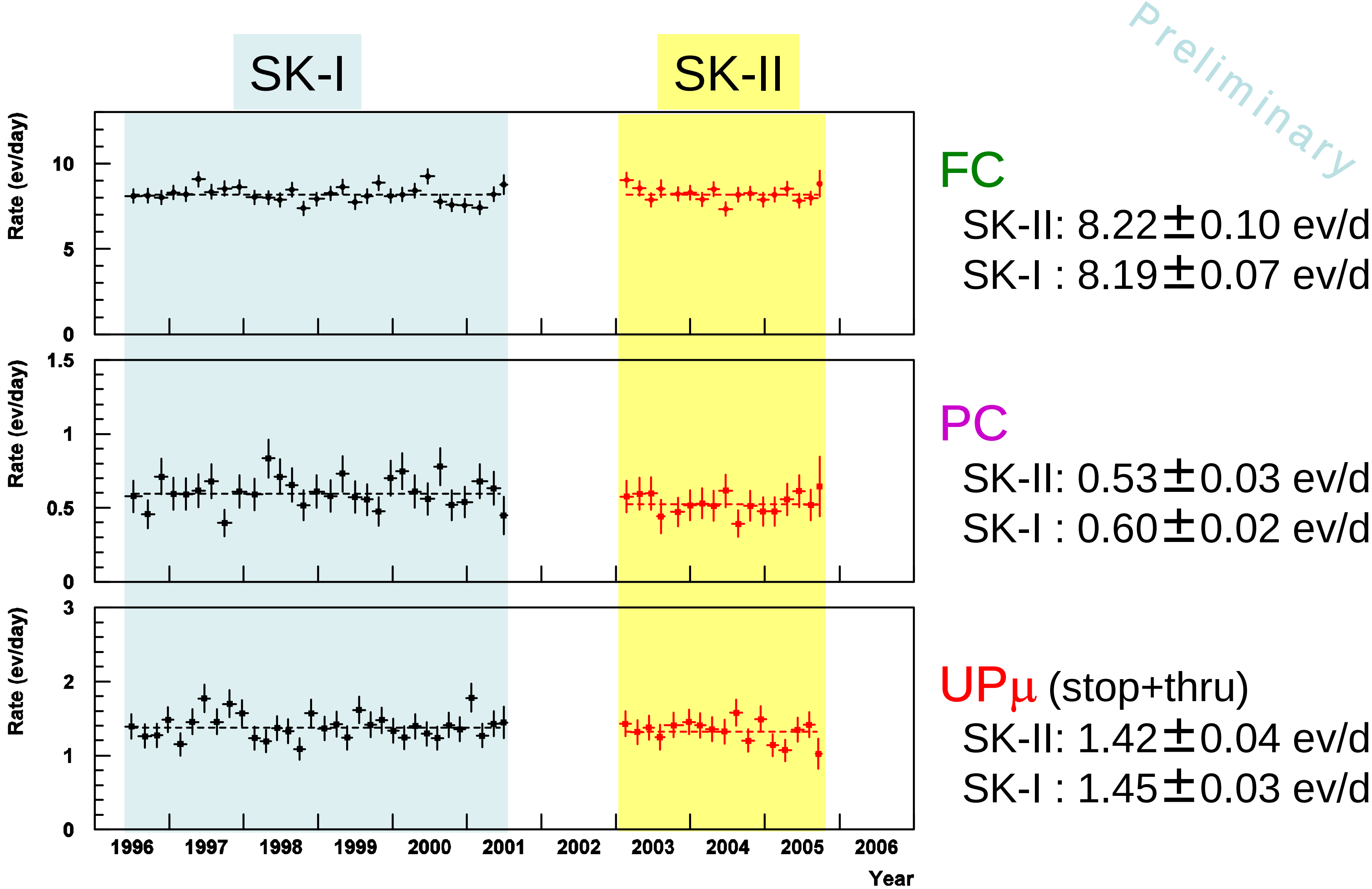
1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007

accident





Event rate



FC

SK-II: 8.22±0.10 ev/d

SK-I : 8.19±0.07 ev/d

PC

SK-II: 0.53±0.03 ev/d

SK-I : 0.60±0.02 ev/d

UPμ (stop+thru)

SK-II: 1.42±0.04 ev/d

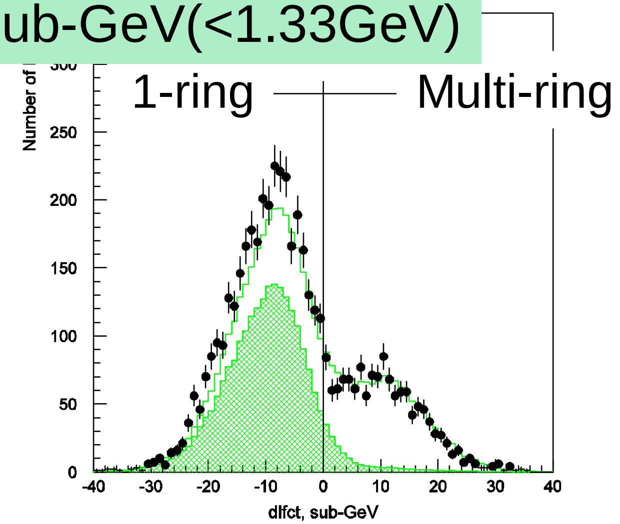
SK-I : 1.45±0.03 ev/d

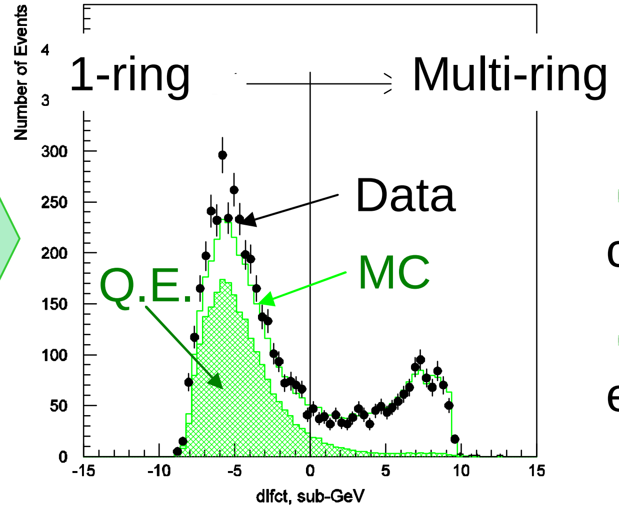
SK-II performance (Ring counting)

preliminary

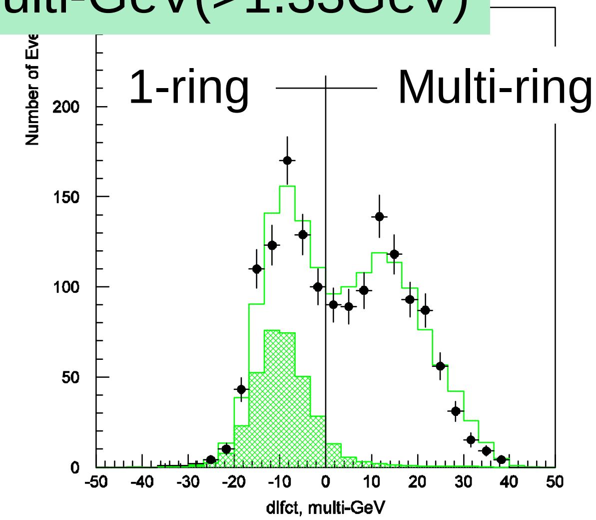
Old ring counting | **New ring counting**

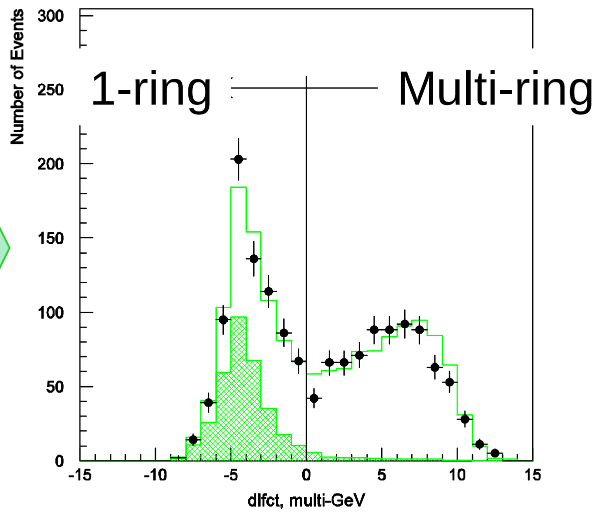
Sub-GeV(<1.33GeV)





Multi-GeV(>1.33GeV)





- improved ring-counting algorithm
- better separation, especially in multi-GeV
- reduced systematic error

SK-II data summary

Live time : 804 days (FC,PC)
828 days (UPμ)

Honda 2003, w/o oscillation

Preliminary

	FC sub-GeV		FC multi-GeV	
	Data	MC	Data	MC
1R	3565	3769.9	796	937.7
e-like	1842	1554.5	417	426.2
μ-like	1723	2215.4	379	511.5
2R	938	1033.8	318	377.1
>=3R	364	477.0	430	526.8
Total	4867	5280.8	1544	1841.5

	PC	
	Data	MC
Total	427	592.3

	UPμ	
	Data	MC
stop	228	350.8
thru	889	832.0

SK-II double ratio

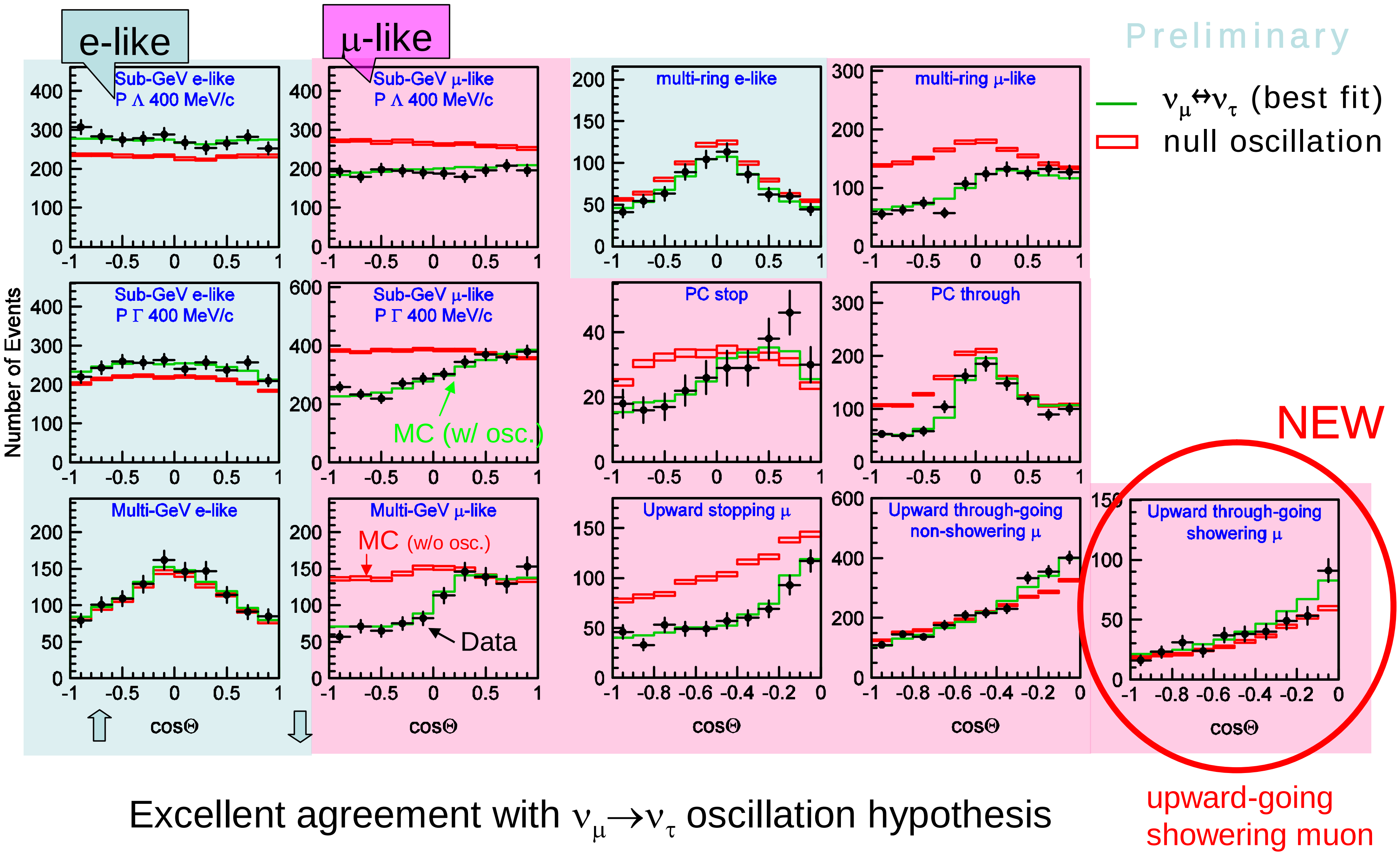
$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = \begin{cases} 0.656 \pm 0.022 \pm 0.033 & \text{(FC Sub-GeV)} \\ 0.746^{+0.047}_{-0.044} \pm 0.055 & \text{(FC Multi-GeV + PC)} \end{cases}$$

SK-I

$$0.658 \pm 0.016 \pm 0.035$$

$$0.702^{+0.032}_{-0.030} \pm 0.099$$

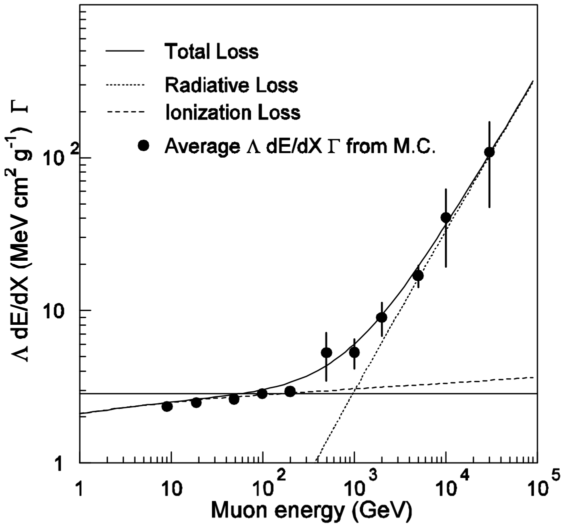
Zenith Angle Distributions (SK-I+SK-II)



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

Upward showering muon

muon dE/dx in water

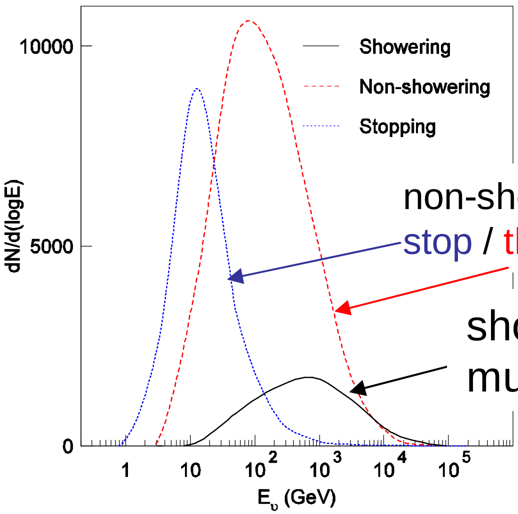


(Radiation loss) > (Ionization loss) @ Pμ>~1TeV

<Eν> ~ 1 TeV

Separation using charge profile

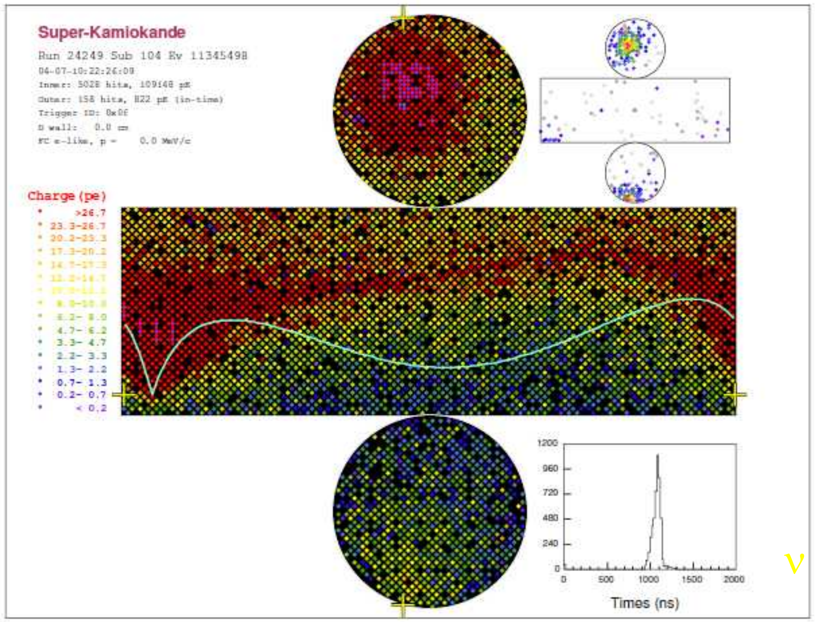
309 (91) events observed in SK-I (SK-II)



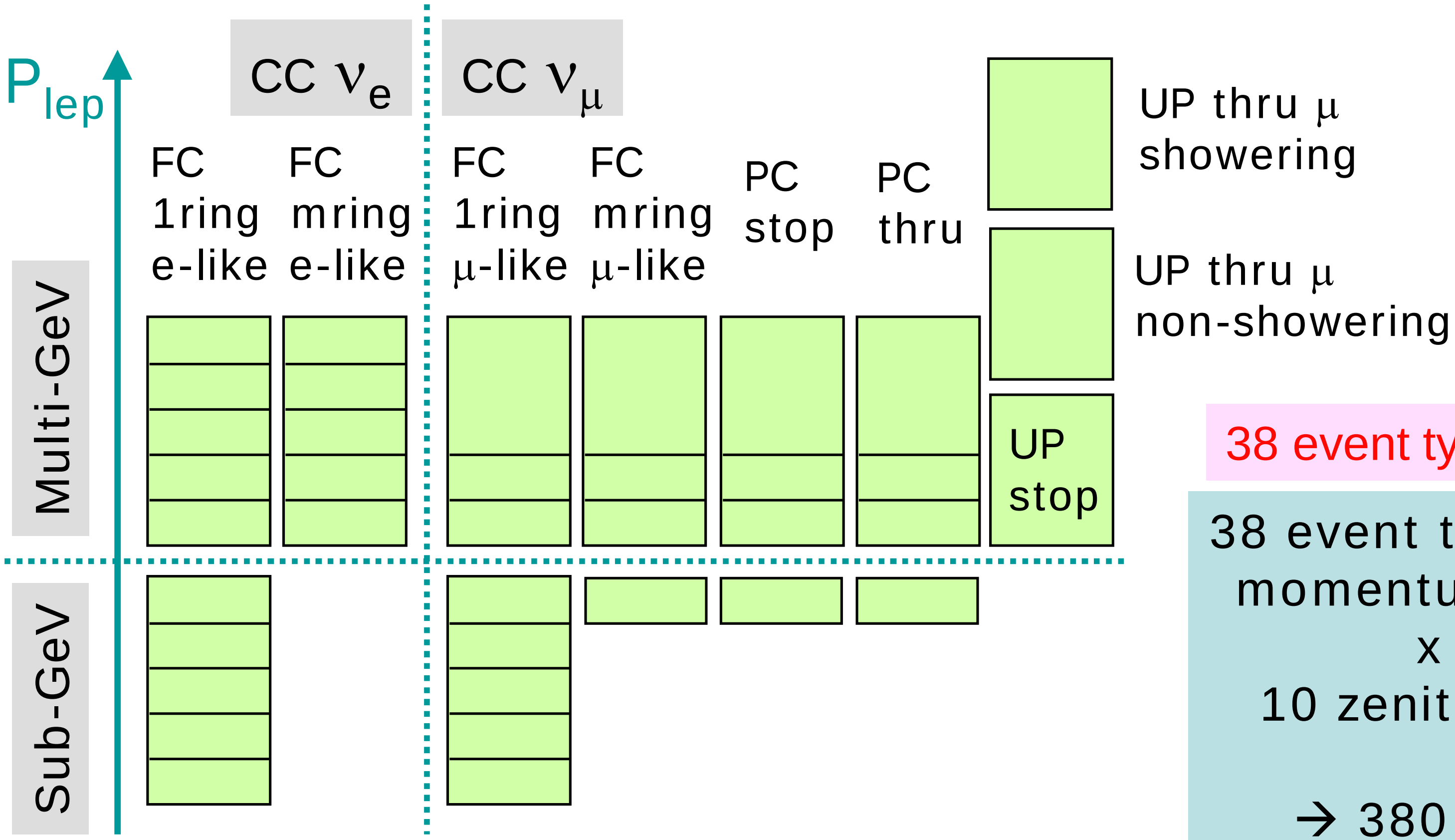
non-showering muon
stop / through

showering
muon

typical showering muon (SK-II)



SK-I + SK-II combined analysis (data binning)



38 event type

38 event type and momentum bins
x
10 zenith bins

→ 380 bins

380 bins for SK-I + 380 bins for SK-II → 760 bins in total

Statistical Treatment of Binned Data

- " Pull Approach " G.L.Fogli et al. PRD66 (2002) 053010
- χ^2 incorporates Poissonian uncertainties.

number of p, Θ, event-type bins

number of sys. effects (normalization is free)

$$\chi^2 \equiv \sum_{i=1}^{760} \left(2(N_i^{\exp} - N_i^{\rm obs}) + 2N_i^{\rm obs} \ln \frac{N_i^{\rm obs}}{N_i^{\exp}} \right) + \sum_{j=1}^{68} \left(\frac{\varepsilon_j}{\sigma_j} \right)^2$$

$$N_i^{\exp} = N_i^0 \cdot P(\nu_\alpha \rightarrow \nu_\beta) \cdot (1 + \sum_{j=1}^{70} f_j^i \cdot \varepsilon_j)$$

fractional change in predicted event rate due to variation in systematic param. ε

At each point on a ($\sin^2 2\theta$, Δm^2) grid, χ^2 is minimized by varying systematic parameters ε_j .

Systematic errors

used in previous analyses

hep-ex/0501064

- neutrino flux (14)
- neutrino interaction (12)

Identical for SK-I and SK-II

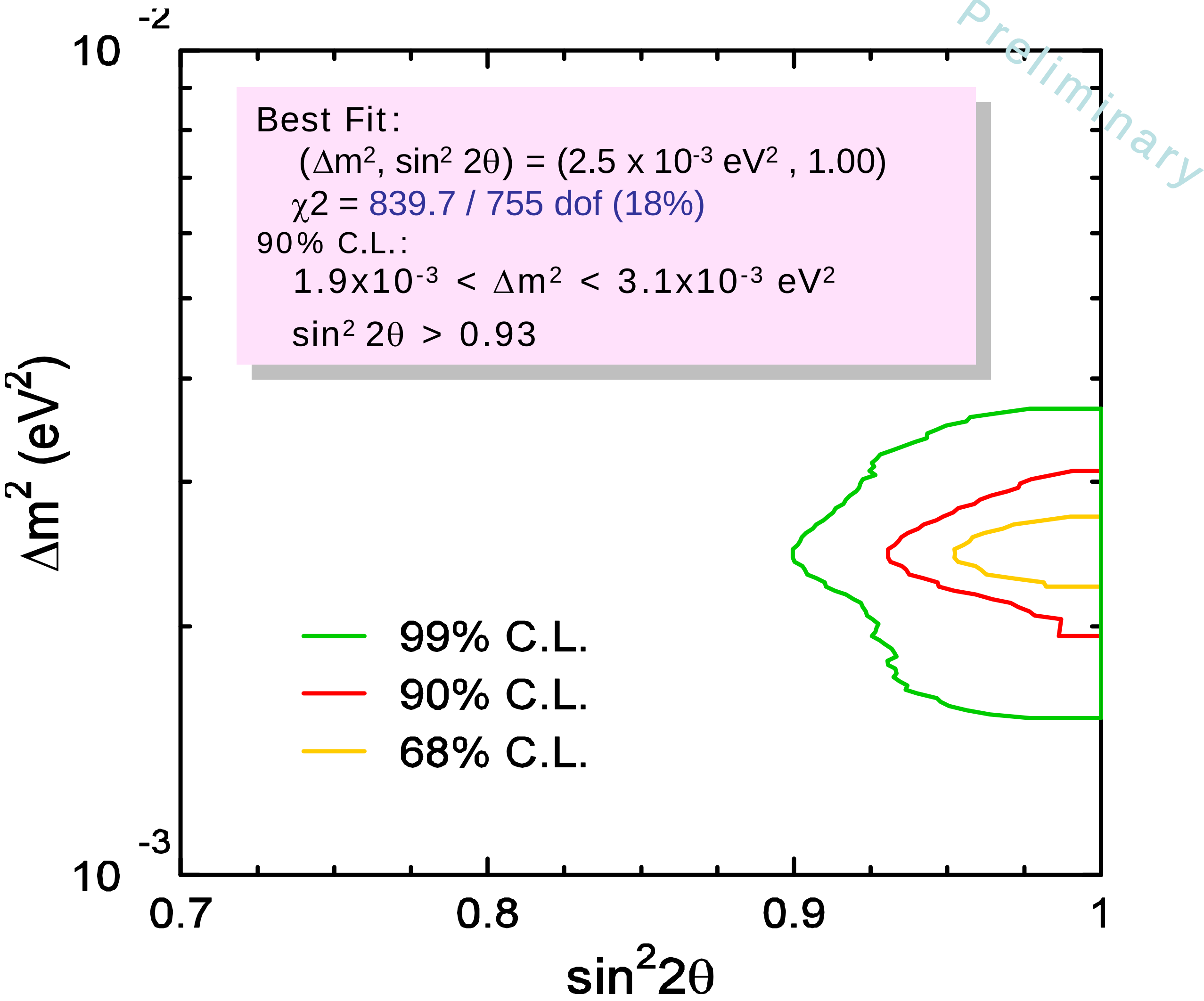
- solar activity (1)
- event selection and reconstruction (19)
- BG sub. from showering (1)
- shower / non-shower sep.(1)

Regarded as independent between SK-I and SK-II

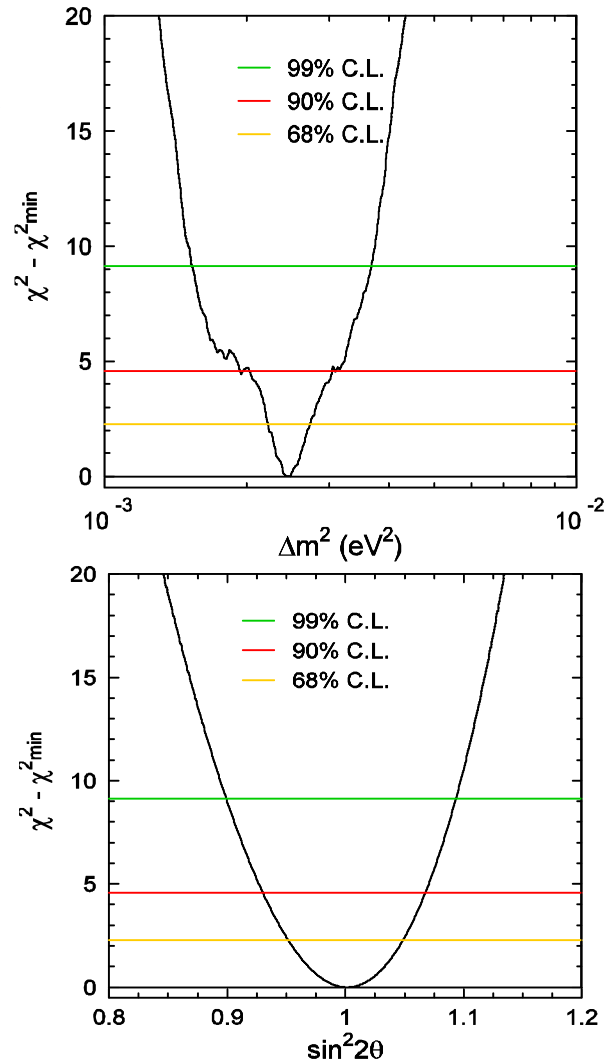
The total number of systematic errors is :

Flux (14) + Interaction (12) + SK-I (22) + SK-II (22) = 70

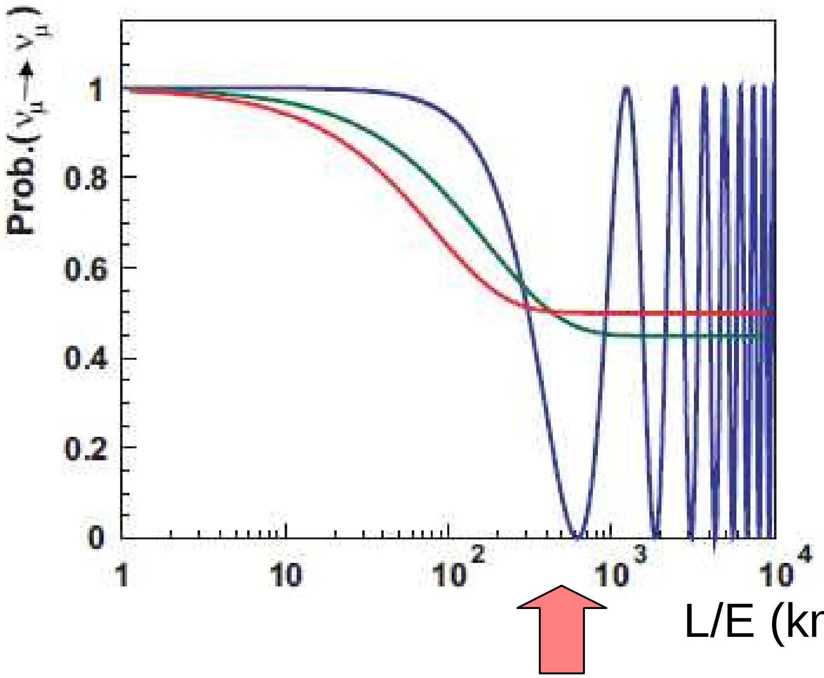
Allowed region

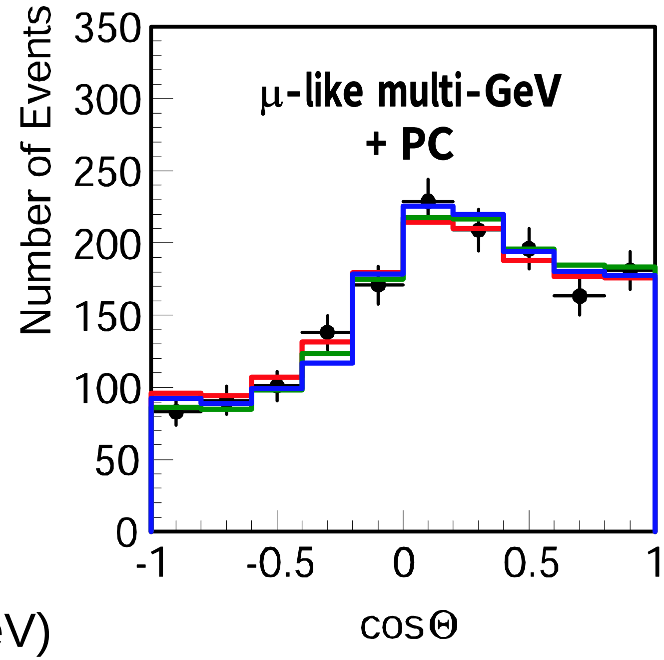


$\Delta\chi^2$ distribution



L/E analysis





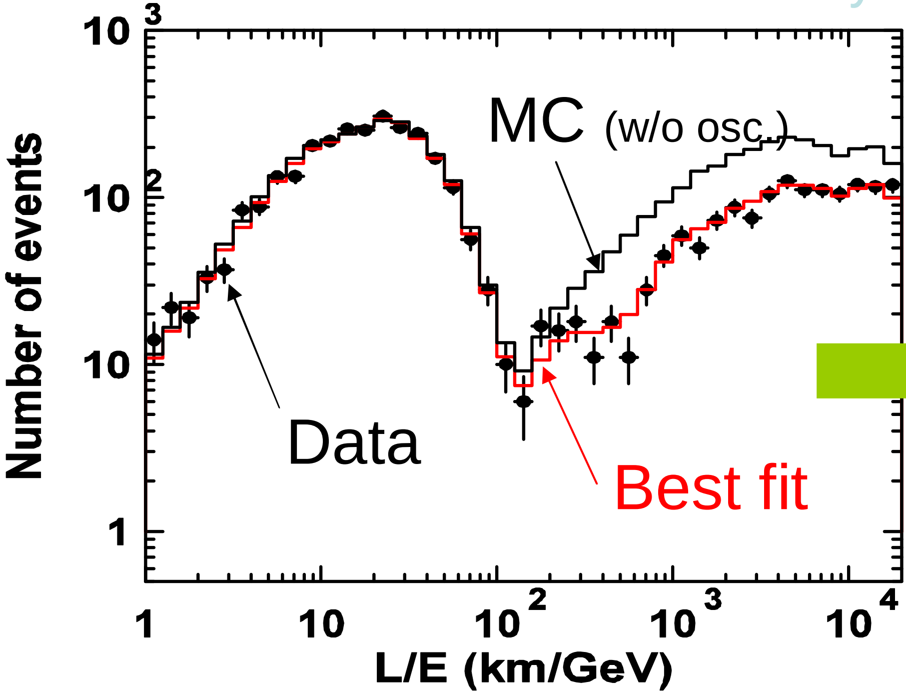
this dip should be observed

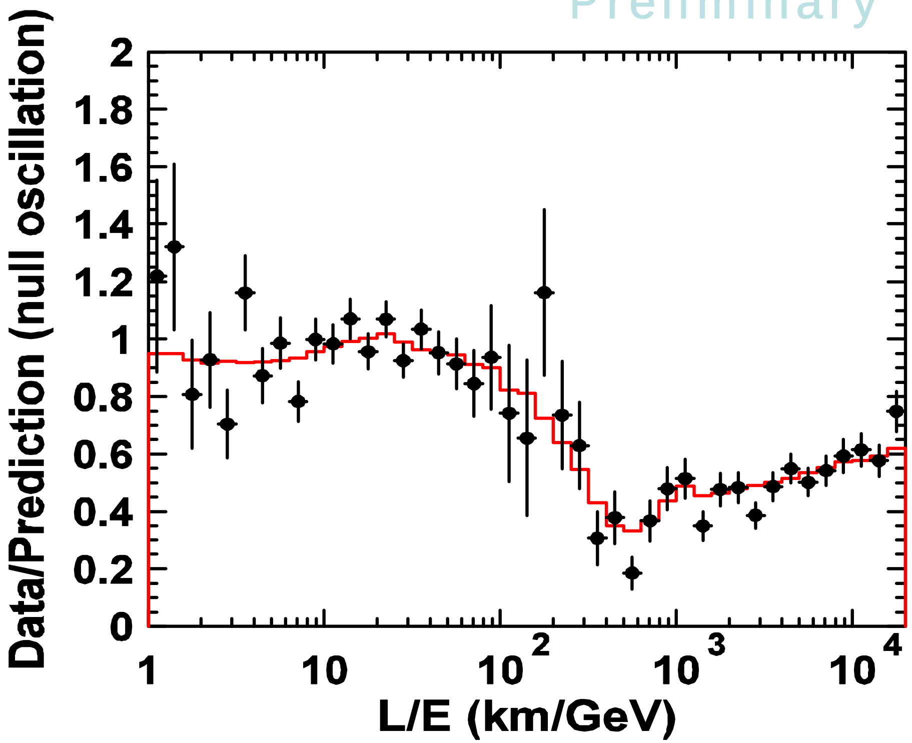
Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$

Neutrino decay : $P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \times \exp(-\frac{m}{2\tau}\frac{L}{E}))^2$

Neutrino decoherence : $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times (1 - \exp(-\gamma_0 \frac{L}{E}))$

L/E distribution

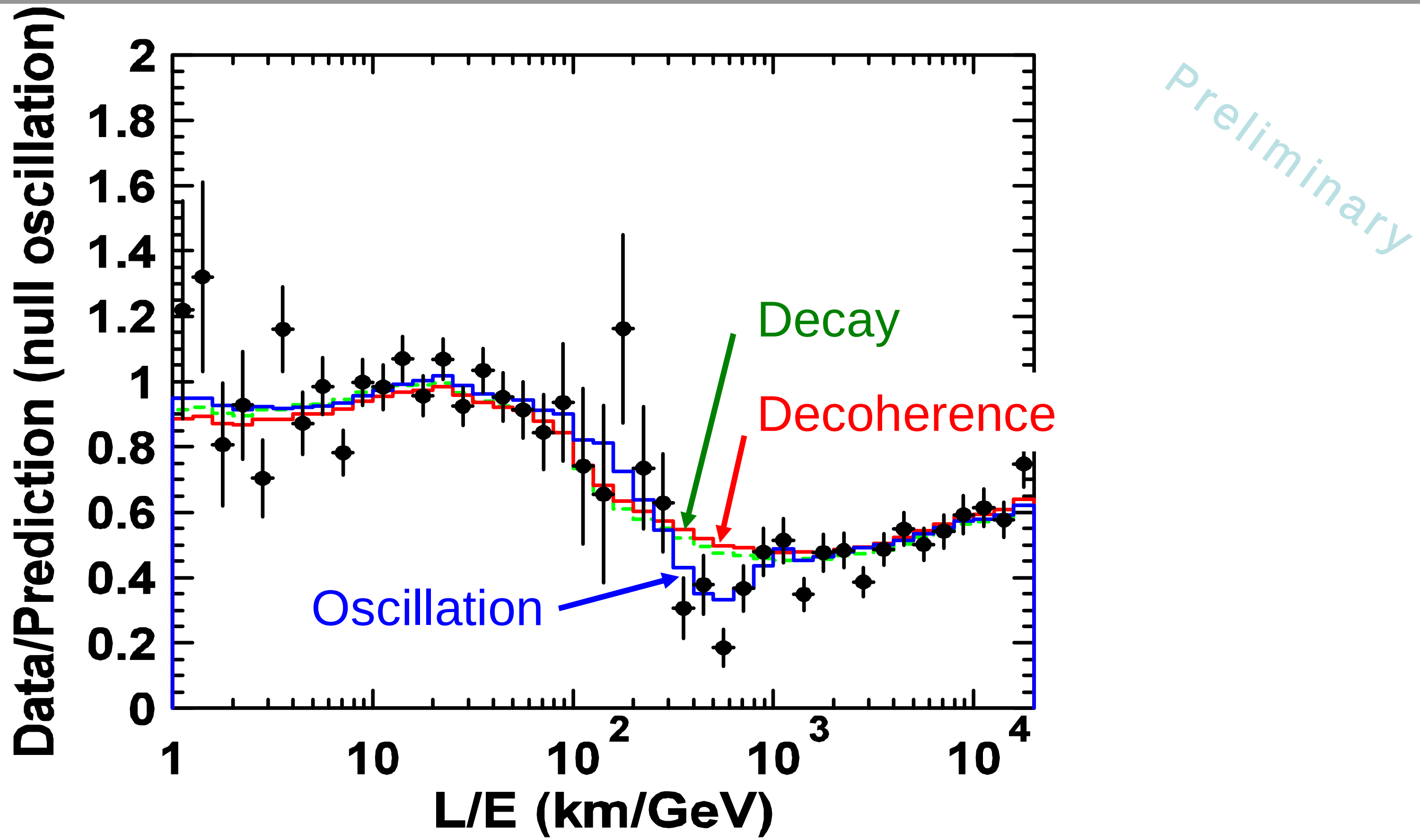




Event sample:
SK1+SK2 FC μ-like, PC
w/ resolution cut

Best fit: $\Delta m^2=2.3\times10^{-3}, \sin^2 2\theta=1.00$
$\chi^2_{min}=83.9/83$ d.o.f
($\sin^2 2\theta=1.03$, $\chi^2_{min}=83.4/83$ d.o.f)

L/ E analysis result



χ^2_{osc} = 83.9/83 d.o.f SK-I

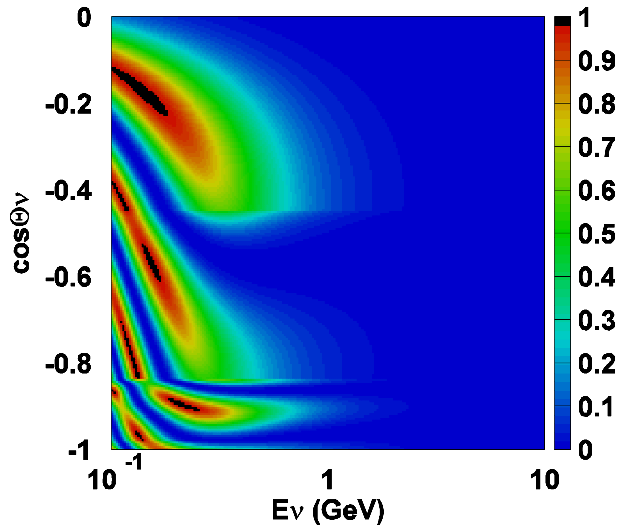
χ^2_{dcy} = 107.1/83 d.o.f, $\Delta\chi^2$ = 23.2 (4.8 $\boldsymbol{\sigma}$) ← 3.4σ

χ^2_{dec} = 112.5/83 d.o.f, $\Delta\chi^2$ = 27.6 (5.3 $\boldsymbol{\sigma}$) ← 3.8σ

Solar term effect to atmospheric neutrinos

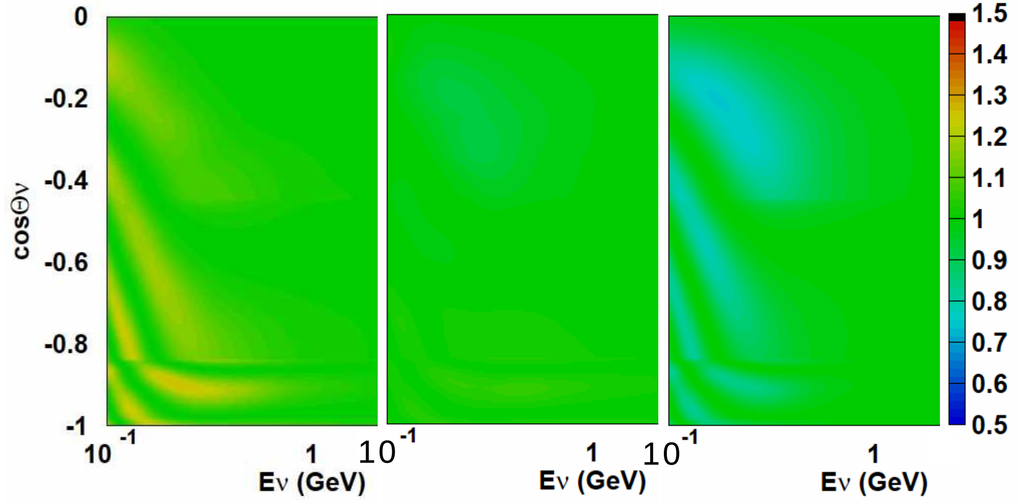
Due to the LMA solution, atmospheric neutrinos should also oscillate by (θ_{12} , Δm^2_{12}).

P_2 : 2ν transition prob. $\nu_e \rightarrow \nu_{\mu,\tau}$ in matter driven by Δm^2_{12}



$\sin^2 2\theta_{12} = 0.83$
$\Delta m^2_{12} = 8.3 \times 10^{-3}$ eV^2
$\sin^2 \theta_{13} = 0$

$\sin^2 2\theta_{23}$	= 0.96	= 1.0	= 0.96
$\sin^2 \theta_{23}$	= 0.4	= 0.5	= 0.6



$$\frac{\nu_e \text{ flux (osc.)}}{\nu_e \text{ flux (no osc.)}}$$

Discrimination between $\theta_{23} < \pi/4$ and $> \pi/4$ might be possible by studying low energy atmospheric ν_e and ν_μ events.

Oscillation analysis with solar terms

- Data set : SK-I (1489 days) + SK-II (804 days)

- Oscillation maps :

Δm^2_{12}	$= 10^{-4.16} \sim 10^{-4.04}$ eV^2	(5 points)
$\sin^2\theta_{12}$	$= 0.22 \sim 0.40$	(7 points)
$\sin^2\theta_{13}$	$= 0$	(fixed)
Δm^2_{23}	$= 10^{-3} \sim 10^{-2.2}$ eV^2	(41 points)
$\sin^2\theta_{23}$	$= 0.3 \sim 0.7$	(41 points)

→ 4 dimensional analysis

- Calculate the minimum χ^2 : projection to the $\sin^2\theta_{23}$ axis

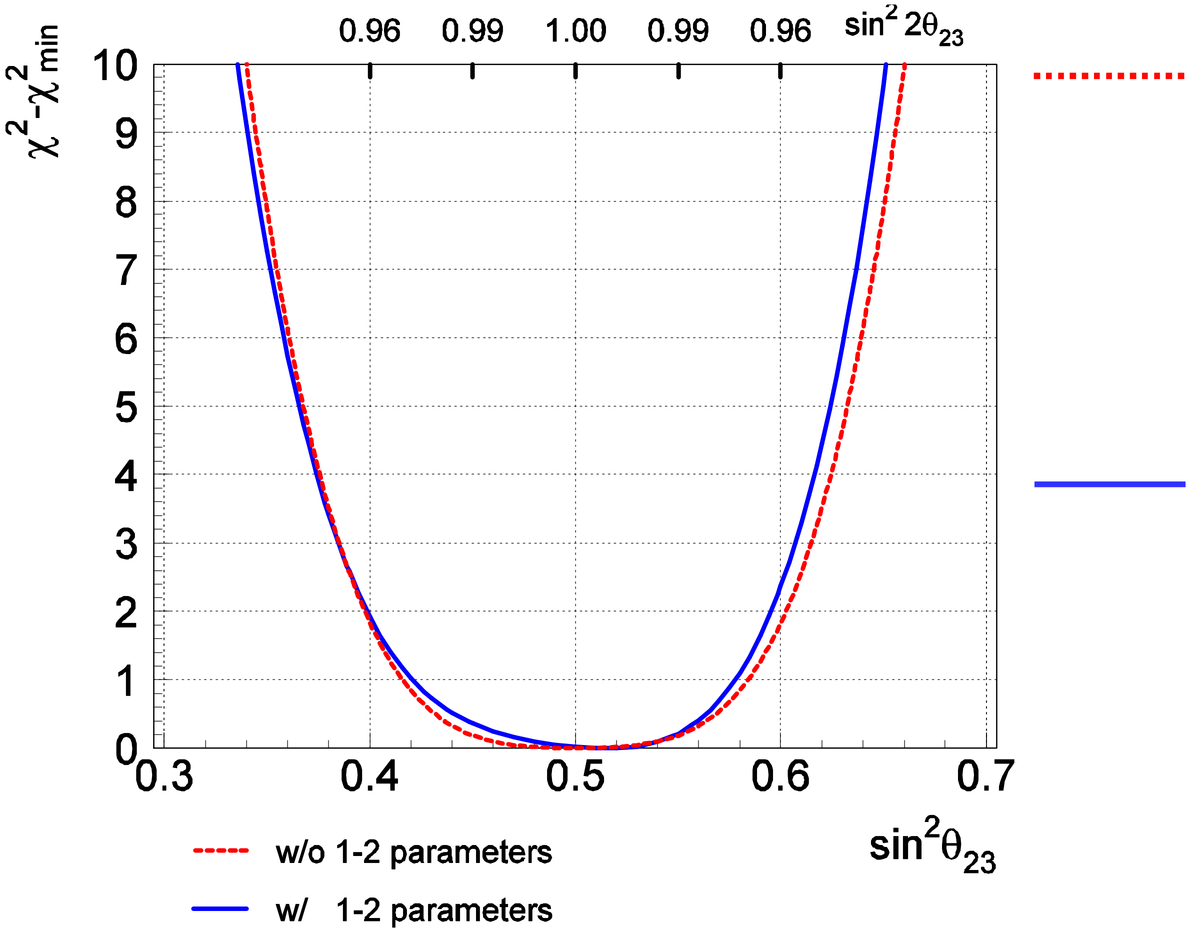
χ^2_{sol} from Solar-ν+KamLAND results are added in each (Δm^2_{12} , $\sin^2\theta_{12}$) point.

↓

deviation from the 2-3 full mixing ?

Result of $\sin^2\theta_{23}$ determination

$\chi^2 - \chi^2_{min}$ distribution as a function of $\sin^2\theta_{23}$ where the other oscillation parameters are chosen to minimize χ^2



Preliminary

Solar terms off :

The 1-2 parameters (Δm^2_{12} , $\sin^2\theta_{12}$) are fixed at zero.

best-fit : $\sin^2\theta_{23}$ = 0.50

Solar terms on :

The 1-2 parameters are scanned.

best-fit : $\sin^2\theta_{23}$ = 0.52 ($\sin^2 2\theta_{23}$ = 0.9984)

Summary

- We have analyzed SK-I + SK-II atmospheric neutrino data in Super-Kamiokande
- Two-flavor oscillation analysis and L/E analysis were performed by these method:
  - Two-flavor oscillation without solar terms
    - $\sin^2 2\theta > 0.93$, 1.9×10^{-3} eV^2 < Δm^2 < 3.1×10^{-3} eV^2 at 90 % C.L.
  - Oscillation with solar terms
    - No clear evidence for deviation of θ_{23} from $\pi/4$
  - L/E analysis
    - neutrino decay and decoherence hypotheses are excluded more significantly.