Atmospheric neutrino observations in Super-Kamiokande I

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SK I における大気ニュートリノの観測 (最終結果に近い段階の解析の現状)

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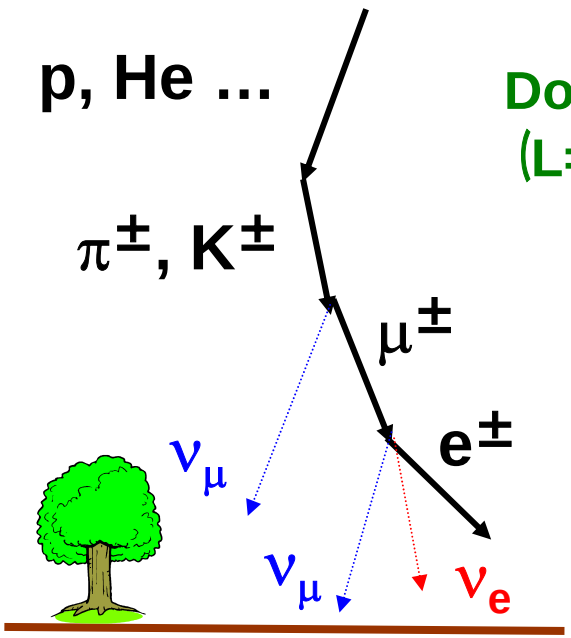
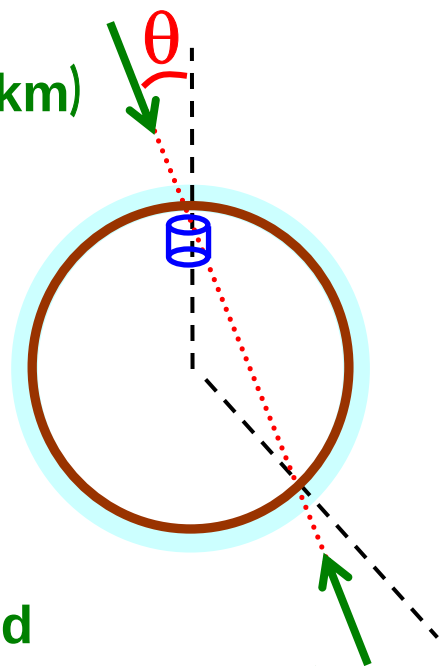
Atmospheric neutrino

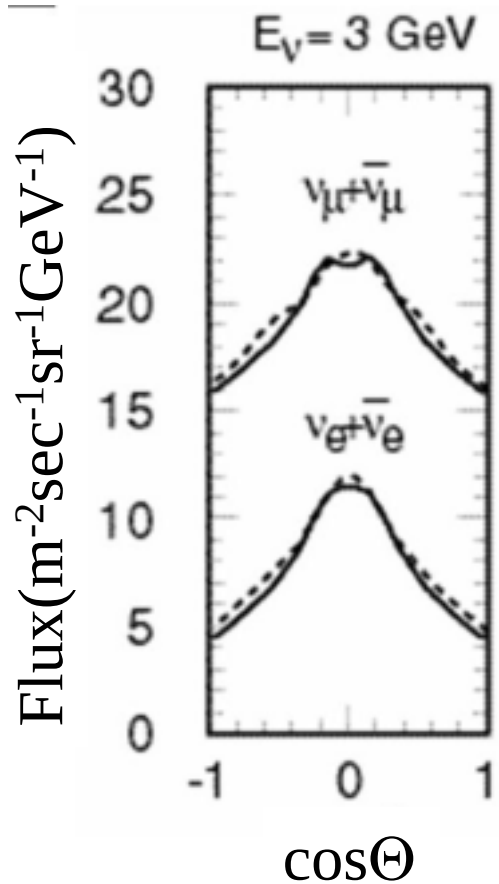


Zenith angle

Downward
(L=10~100 km)



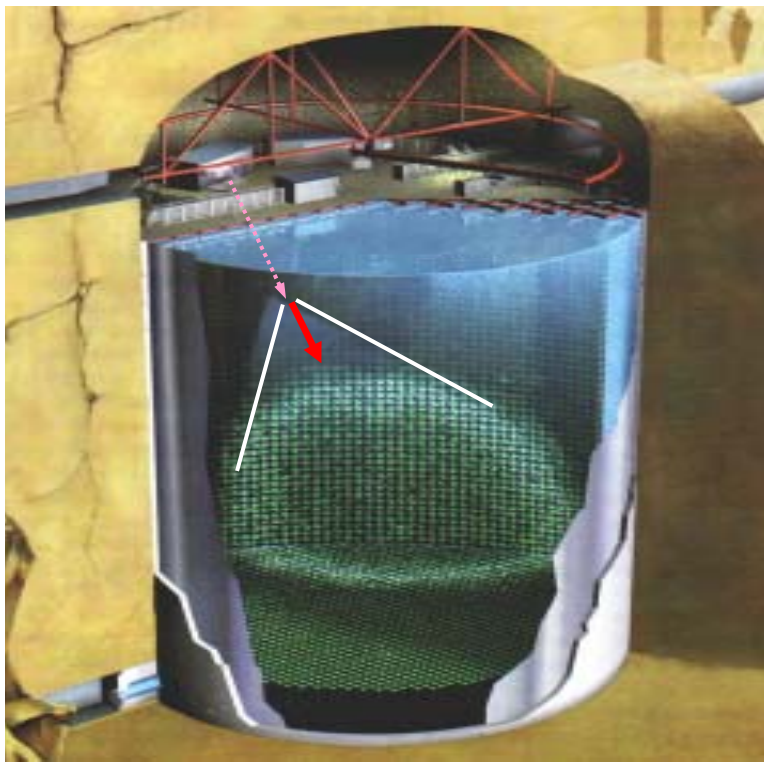
Upward
(L=up to 13000 km)



Up/Down Symmetry

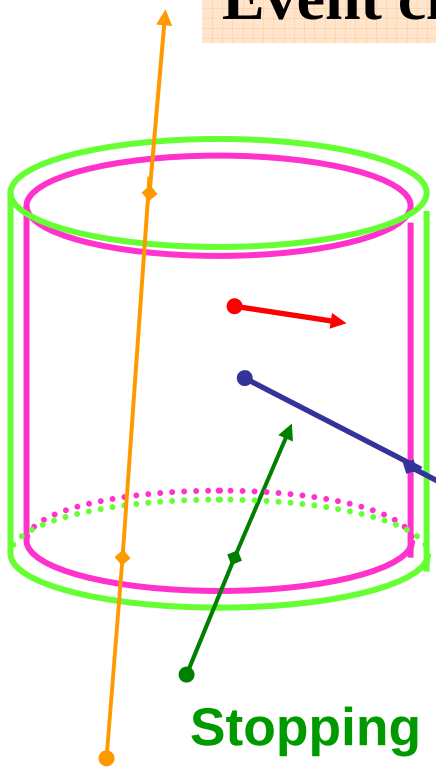
Super-Kamiokande detector & atmospheric neutrino data

Water Cherenkov detector



- 1000 m underground
- 50,000 ton (22,500 ton fid.)
- 11,146 20 inch PMTs
- 1,885 anti-counter PMTs

Event classification



Fully Contained
(E_ν ~1GeV)

Partially Contained
(E_ν ~10GeV)

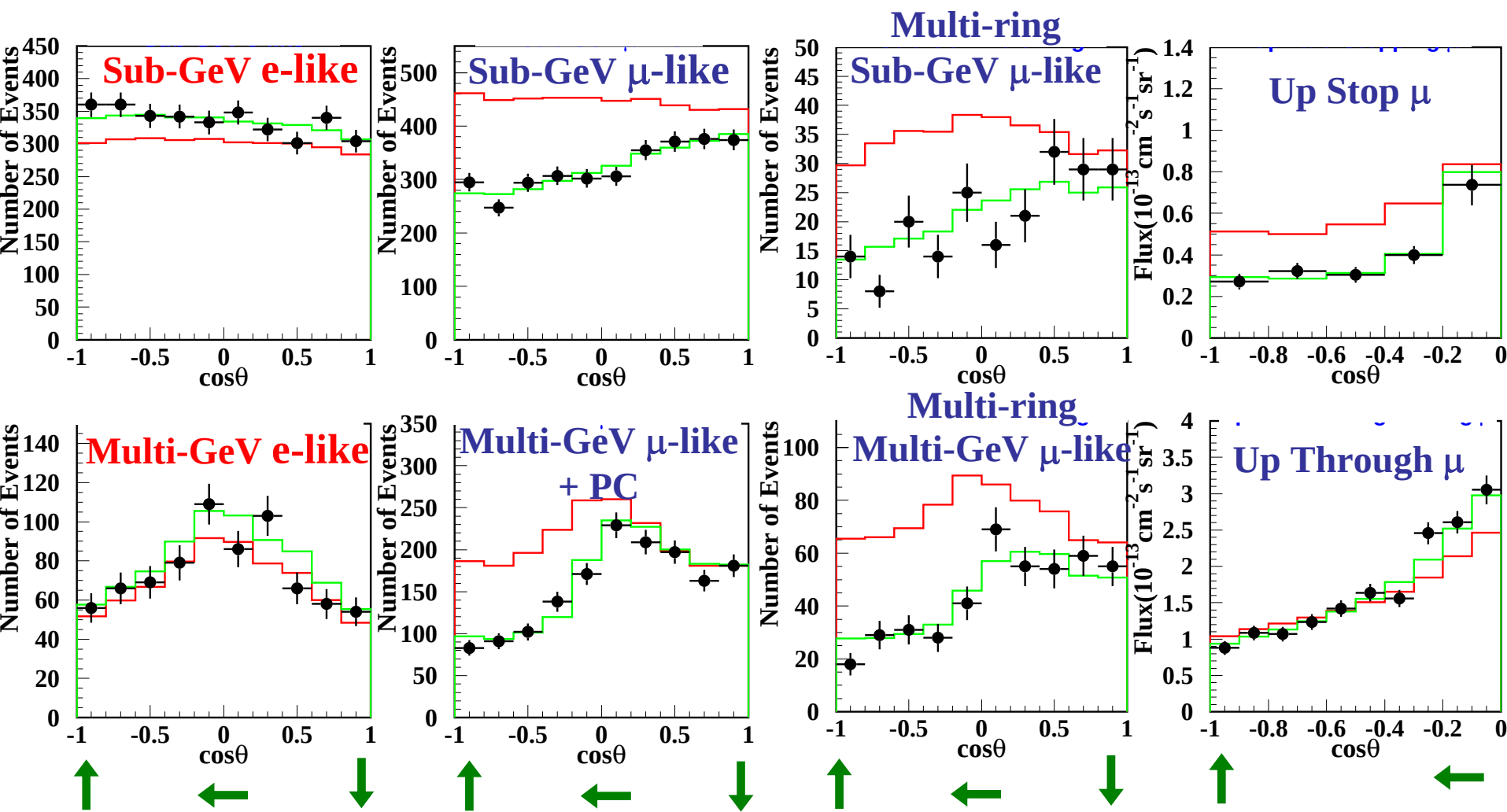
Stopping μ (E_ν ~10GeV)

Through-going μ (E_ν ~100GeV)

Zenith angle distributions (FC+PC+up-μ)

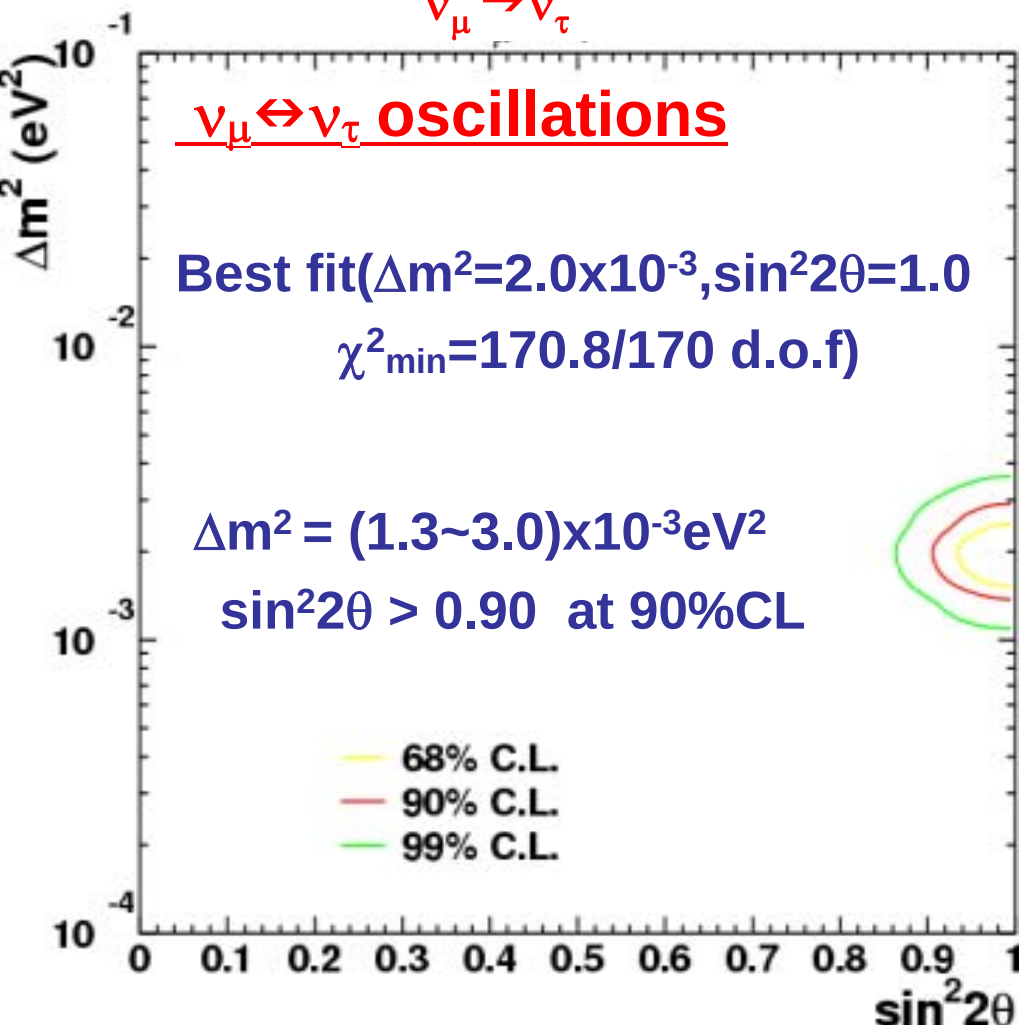
No oscillation

Oscillation best fit ($\Delta m^2=2.0\times10^{-3}eV^2$, $\sin^2 2\theta=1.00$)



Allowed region (FC+PC+up-μ)

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

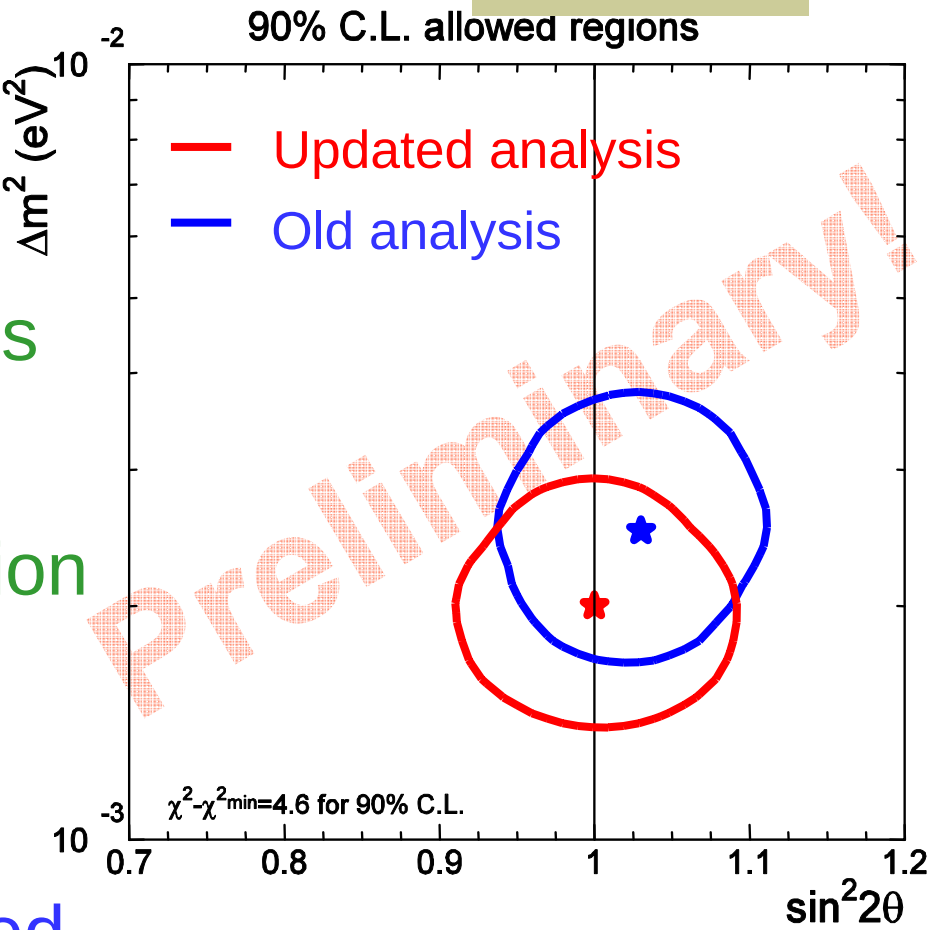


Combined Systematic Errors

		σ_i	best fit
α	Absolute Normalization Uncertainty	Free	8.70 %
α_L	SubGeV Multi-ring Absolute Normalization Uncertainty	Free	-23.8 %
α_H	MultiGeV Multi-ring Absolute Normalization Uncertainty	Free	-26.1 %
δ	Eν Spectrum Index	0.05	0.005
β_L	SubGeV μ/e Ratio	8 %	-6.1 %
β_H	MultiGeV μ/e Ratio	12 %	-12.5 %
ρ	FC/PC Relative Normalization	8 %	4.3 %
η_L	SubGeV Up/Down Asymmetry	2.4 %	-2.2 %
η_H	MultiGeV Up/Down Asymmetry	2.7 %	-1.1 %
β_1	FC+PC/Stop ↑μ Relative Normalization	7 %	-2.8 %
β_2	Through ↑μ/Stop ↑μ Relative Normalization	7 %	8.2 %
	FC+PC Horizontal/Vertical Uncertainty	4 %	0.2 %
	↑μ Horizontal/Vertical Uncertainty	3 %	1.5 %
	L/E Uncertainty	15 %	-5.8 %

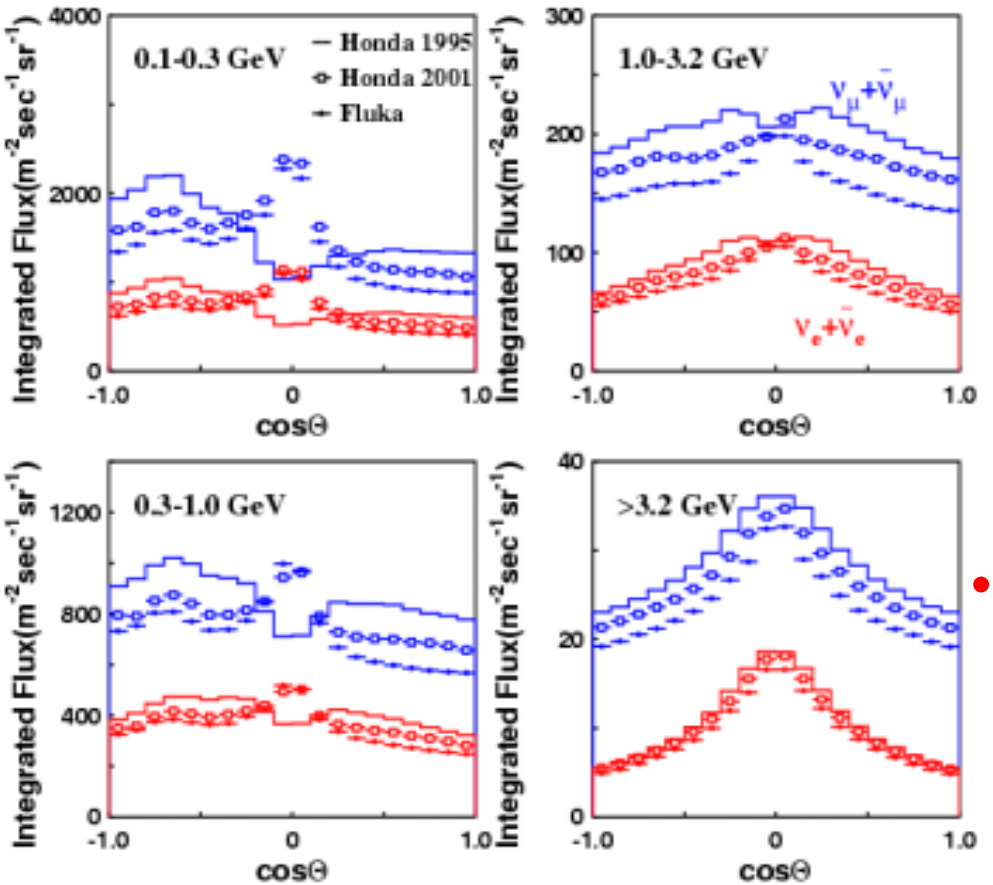
Comparison with old result

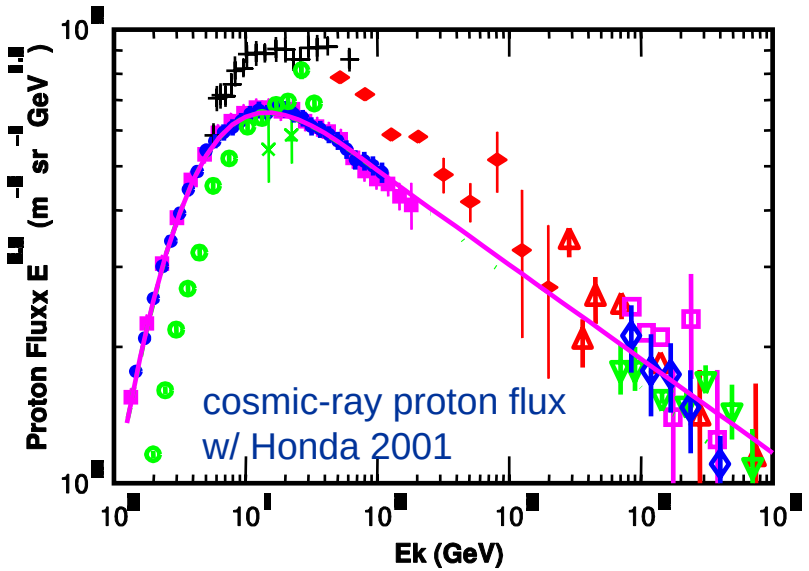
- Neutrino flux
  (Honda 1995 Honda 2001)
- Neutrino interaction models
  (several improvements,
  agree with K2K near data)
- Improved detector simulation
- Improved event
  reconstruction tools



Each changes slightly shifted
the allowed region to lower Δm^2

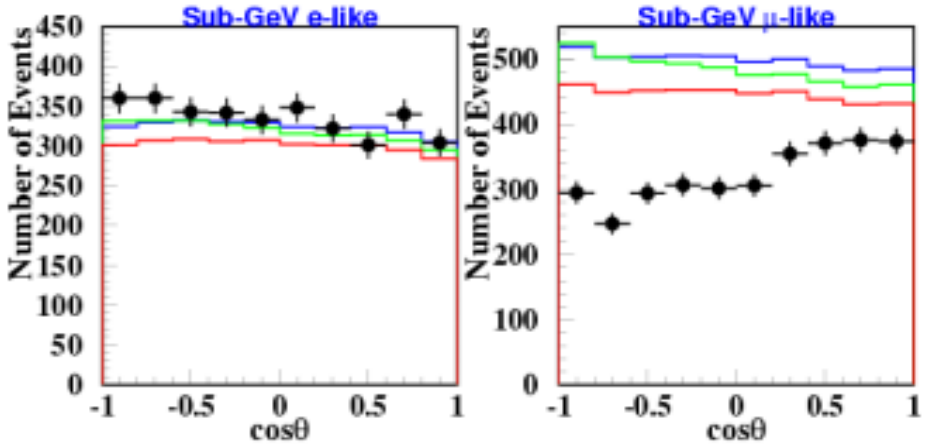
Flux changes

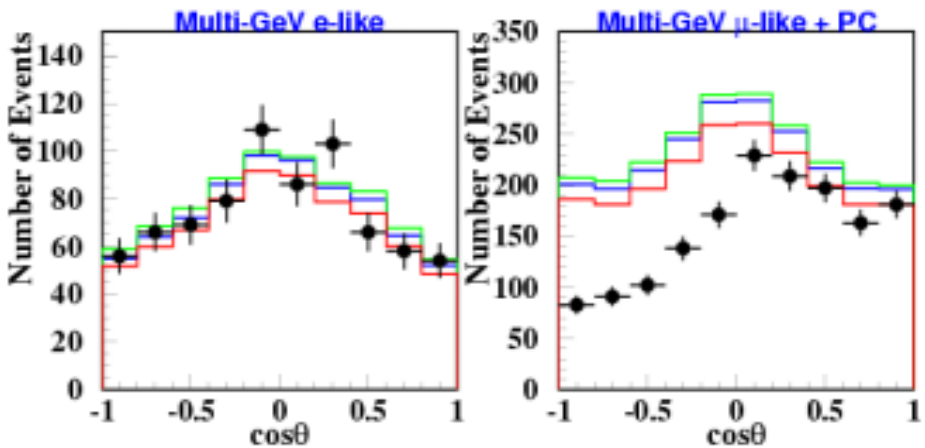


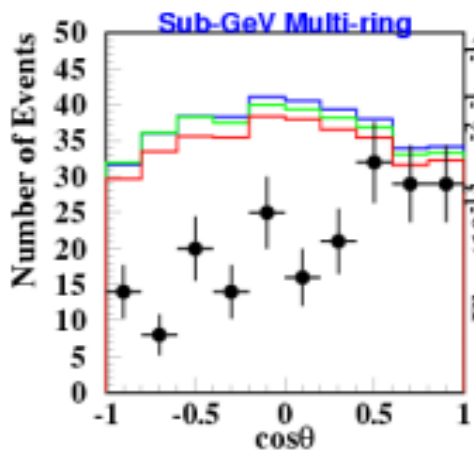


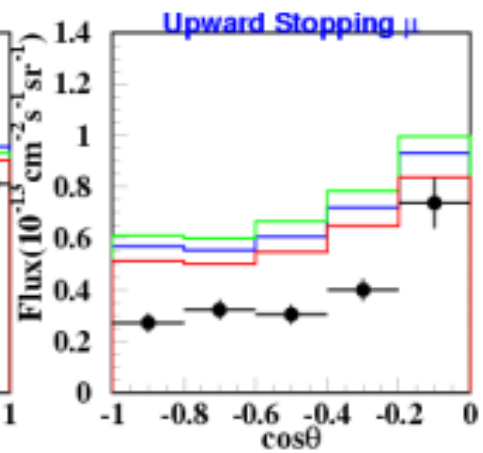
- Honda1D → Honda 3D
  - Absolute normalization lower
  - "3D" enhancement
    - At low energies
    - Near the horizon

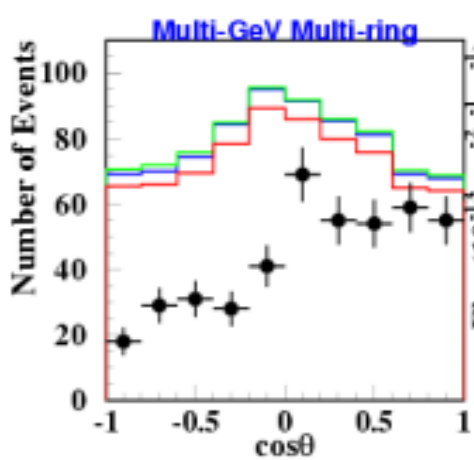
Different flux in Super-Kamiokande

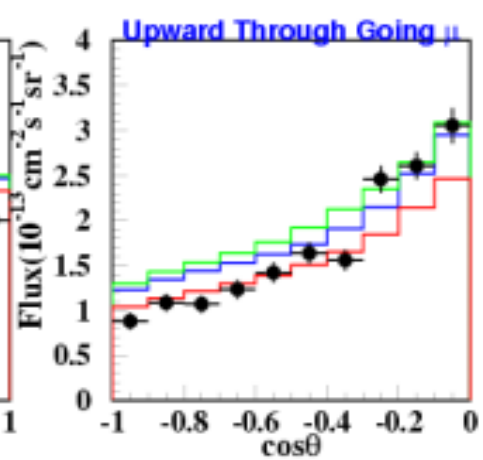












— **Honda 2001 (3D)**
— **Honda 1995 (1D)**

— **Bartol 1996**
+ **Data**

Other improvements

Neutrino interactions

Agree with K2K near data

Q.E.	M_A=1.0	→	1.1
Single π	M_A=1.0	→	1.1

Analysis tools

SK detector simulator

Light scattering parameters in water (laser measurement)

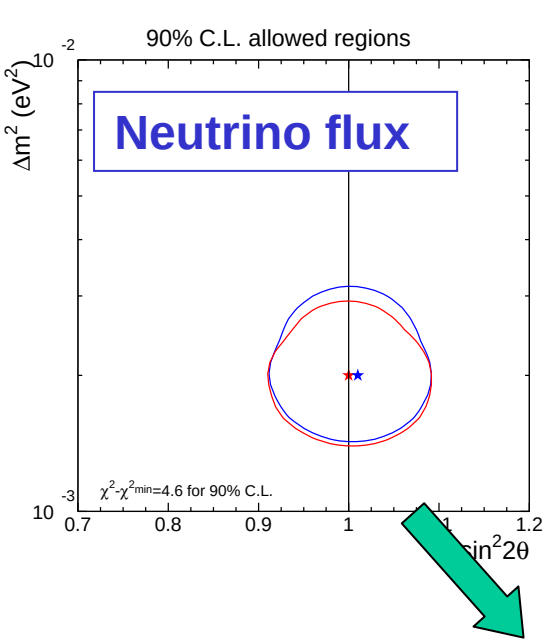
Outer detector PMT gain parameter (single p.e. distribution)

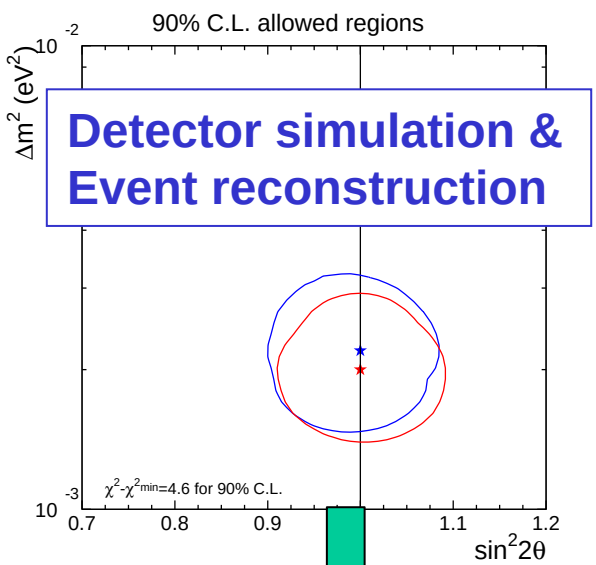
dE/dx in water → decrease 3% for μ (>300MeV/c)

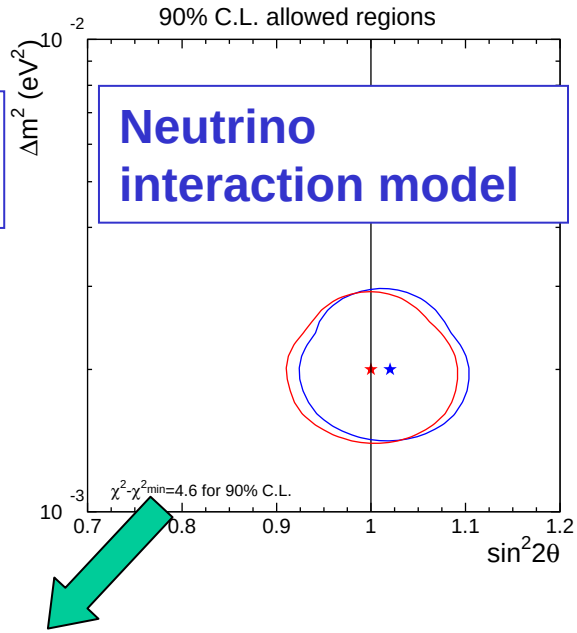
Data reduction

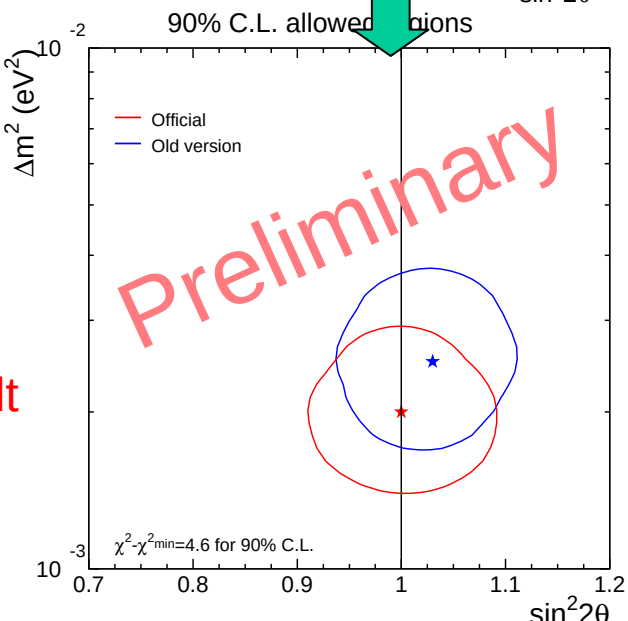
Fully automated FC and PC data reduction

Effect from each change









Old result

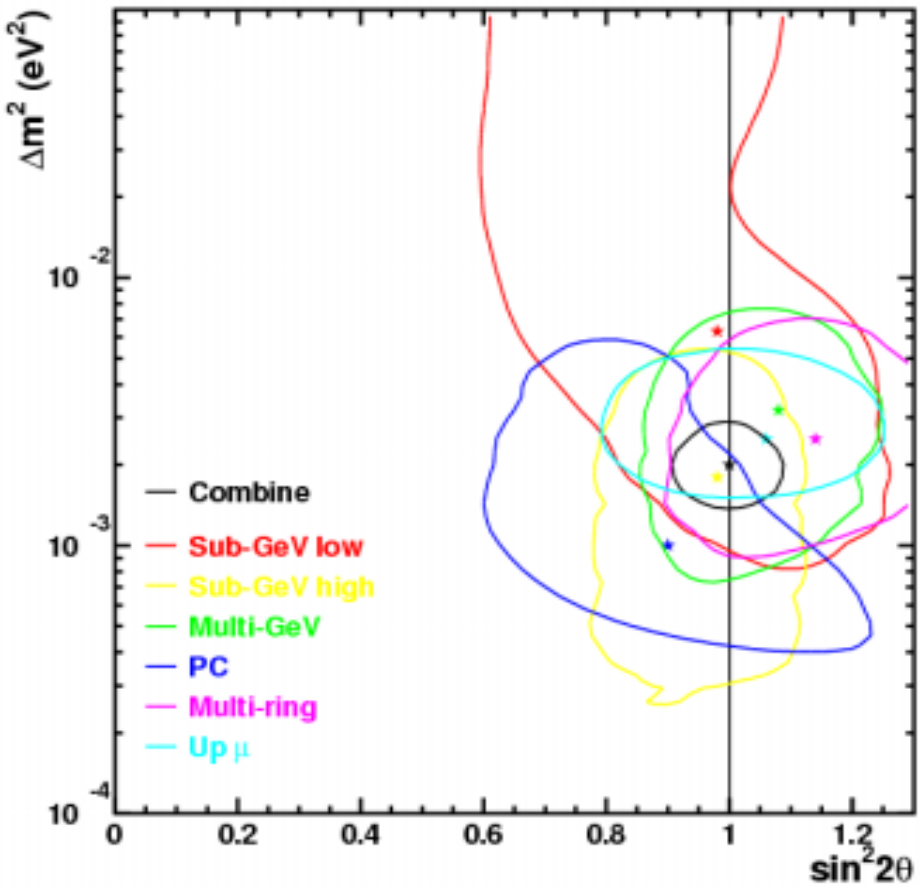
Updated result

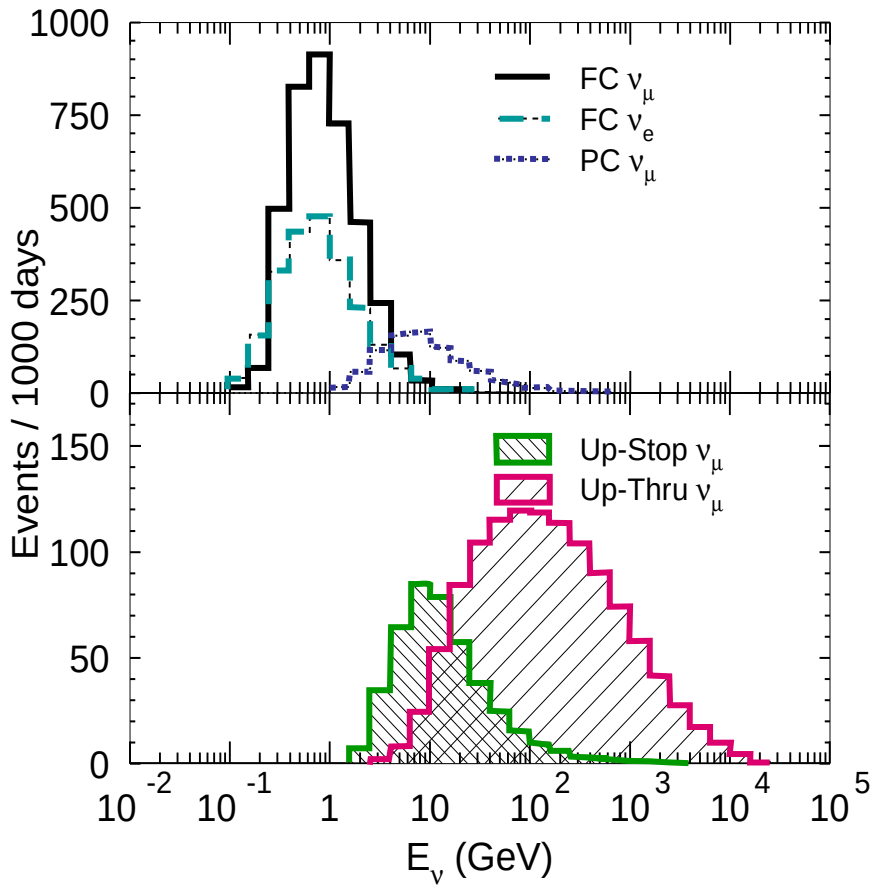
Each change contributes to the shift in the allowed (Δm^2) region.

Sub-sample consistency

Check the result using different types of data

→ all allowed regions overlap best fit





Further improvement for SK I final result

✓ Honda flux updated

Dipole approximation → Multi pole for geomagnetic field

✓Upward going muon prediction

Analytical calculation → Monte Carlo method

- Consider angular correlation ν → μ

✓ re-estimation of systematic errors

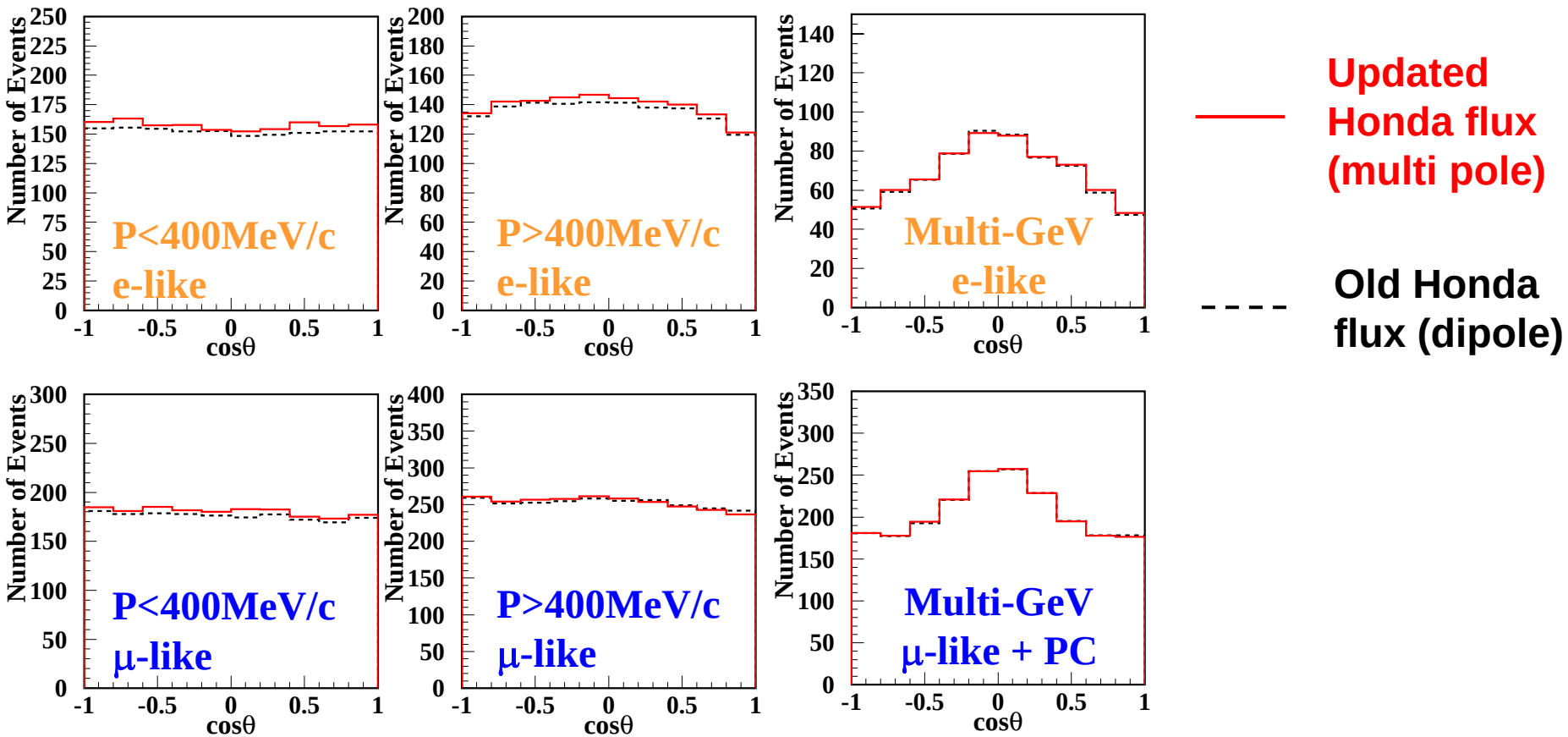
→ more fundamental components with mathematical method

- Check the sources clearly
- Treat the correlations of errors correctly

→ re-estimate systematic uncertainties
estimate additional errors

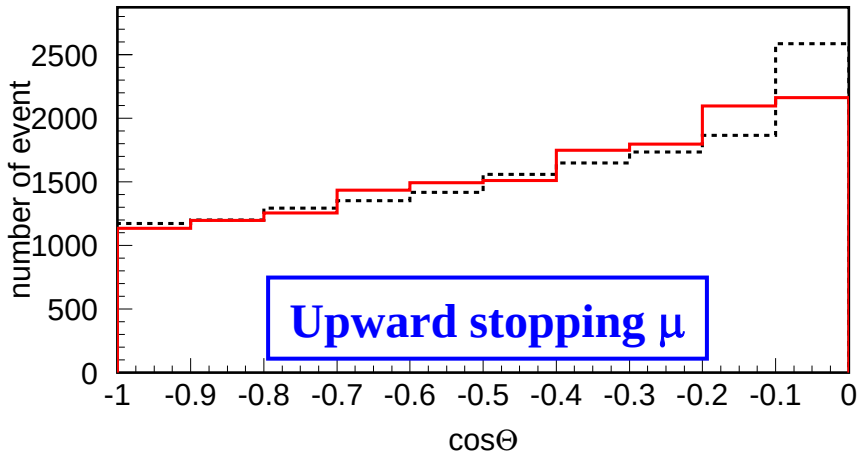
SK I oscillation analysis will be finalized soon (with full paper)

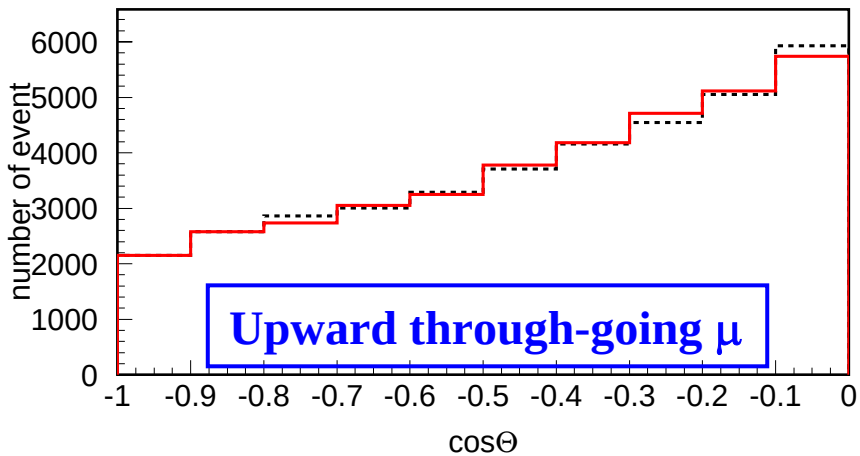
Updated Honda flux



The difference is small

Upward-going μ Monte Carlo



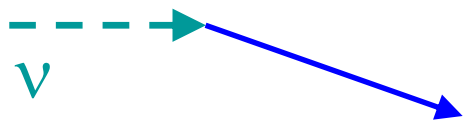


Neutrino direction

Muon direction

Analytical calculation

MC



μ → fitter

The difference is small in upward stopping μ 5 bin analysis

→ becomes large in 10 bin analysis

Calculation methods, basic idea

(based on Fogli et al., hep-ph/0206162)

Definition of χ^2

$$\chi^2 = \sum_{n=1} \frac{\left(N^n_{obs} - N^n_{exp}\left(1 + \sum_{k=1}^{K} f^n_k \cdot \varepsilon^k\right)\right)^2}{\sigma_n^2} + \sum_{k=1}^{K}\left(\frac{\varepsilon^k}{\sigma_k}\right)^2$$

$$N^n_{obs}: \text{observed},\ N^n_{exp}: \text{expected},\ \varepsilon^k: \text{systematics}$$

In our current analysis, minimum χ^2 is obtained by optimizing ε_j (j = 1,2,..) for each ($\sin^2 2\theta$, Δm^2) point.

But, mathematically,

χ^2 is minimum $\Leftrightarrow$ $\dfrac{\partial \chi^2}{\partial \varepsilon_j} = 0$ **for any j .**

Minimizing χ^2 $\Leftrightarrow$ Solving n_{sys} linear equation.

Re-estimation of systematic errors

	Sub-GeV	Multi-GeV
Reduction	<<1	3
Neutrino flux	<5	<5
$E^{-\gamma}$	0.6	1.6
PID	2	3
Ring counting	3	6
Vertex position	0.6	2.4
Energy calibration	1.0	4.1
Non-ν BG		
flasher	<0.5	<0.1
cosmic m	<0.1	<0.2
neutron BG	<0.1	<0.2
Neutrino interaction		
CC	3.5	4.3
NC	3	4
Hadron simulator	0.5	1.0
FC/PC separation	<0.1	0.5
Error in μ/e ratio	7.8%	11.8%

Treat as independent error term and re-estimate the values

List of updated systematic errors

(A) Neutrino flux

① flux absolute normalization
② ν_e/ν_μ ratio
③ anti-neutrino/neutrino ratio
④ geomagnetic effect(up-down ratio)
⑤ horizontal-vertical ratio (3D effect)
⑥ horizontal-vertical ratio (K/pi)
⑦ Neutrino flight length (production height)
⑧ Energy spectrum
⑨ Sample-by-sample normalization

(B) Neutrino cross section & kinematics

① Quasi elastic scattering
② low energy neutrino scattering in QE
③ single-pion production
④ multi-pion production
⑤ Bodek correction in DIS
⑥ coherent pion
⑦ NC/CC ratio
⑧ neutrino-lepton angular correlation

(D) Event selection

① FC reduction
② PC reduction
③ Up-μ detection efficiency
④ 1.6 GeV cut (→ 2% energy calibration)
⑤ Through-going/stopping μ separation

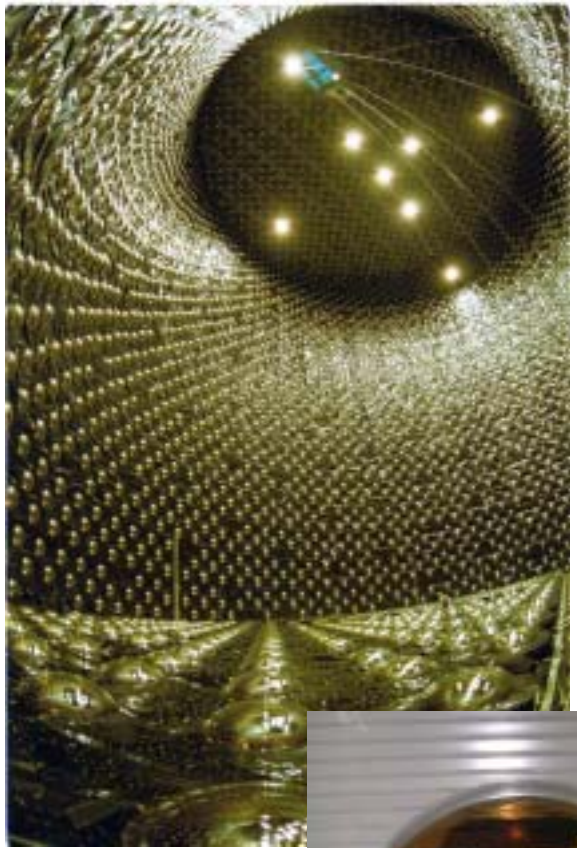
(E) Event reconstruction

① 1-ring/multi-ring separation
② Particle ID
③ Energy calibration
④ Up-down asymmetry of energy calibration

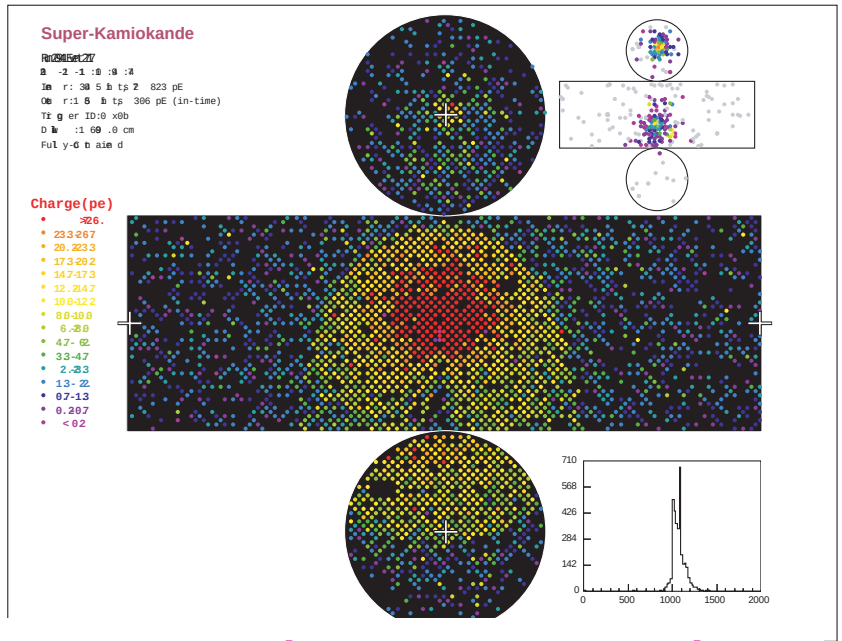
(F) Other sources

① m/e ratio
② up/down ratio
③ FC/PC relative normalization
④ τ from oscillation

SK-II is working



20inch PMT with
Acrylic + FRP vessel

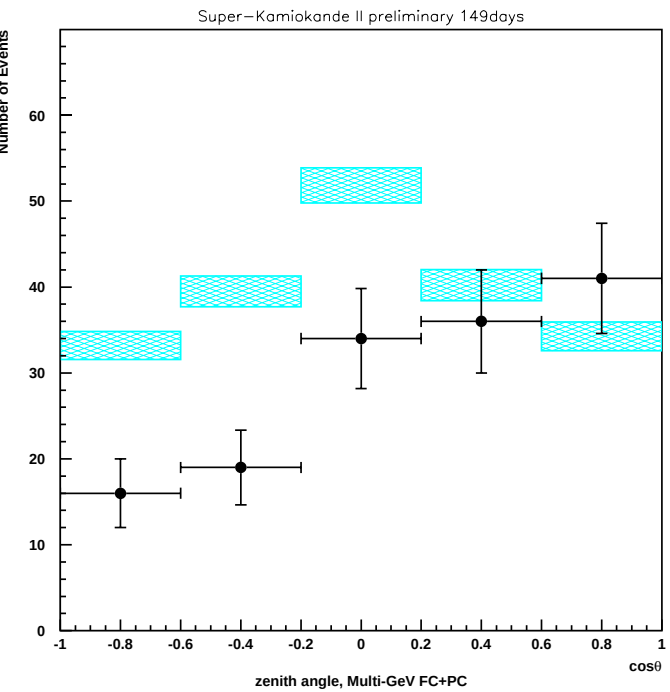


SK-II Cosmic ray muon sample

With about half of original ID PMTs

- **20-inch PMTs in acrylic shells to prevent future chain implosions**
- **OD at full complement (1885) of 8-inch PMTs**

First report from SK-II



SK-II zenith angle for
Multi-GeV μ-like + PC

Number of Events / Event rate in SK-II

	SK-II 149 days	SK-I 1489 days
Fully-contained events	1245 (8.33±0.24)	12180 (8.18±0.07)
Partially-contained events	80 (0.54±0.06)	911 (0.62±0.02)

The event rate is consistent with SK-I

Clear deficit in upward-going events

Summary

- **$\nu_\mu \leftrightarrow \nu_\tau$ 2 flavor oscillations**
  - **Updated result**
    - Best fit value is ($\Delta m^2 = 2.0 \times 10^{-3}$ eV^2, $\sin^2(2\theta) = 1.0$)
    - $1.3 < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2, $\sin^2(2\theta) > 0.90$ @ 90% C.L.
    - Each change contributes to the shift of allowed region
  - **final SK-I result**
    - To be published soon with SK-I paper after modifications
      - updated Honda flux calculation
      - prediction of upward-going μ by Monte Carlo method
      - re-estimated systematic errors
- **Status of SK-II**
  - **SK-II analysis has started**
    - Event rate is consistent with SK-I
    - deficit in upward-going event in Multi-GeV μ-like + PC sample