Super-Kamiokande
Latest atmospheric neutrino results

Flor de María Blaszczyk
on behalf of the Super-Kamiokande collaboration

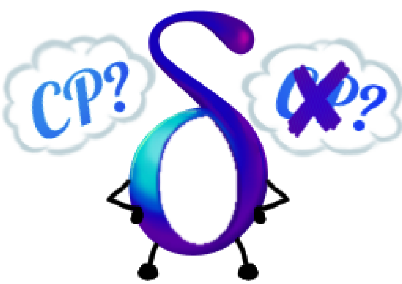
BOSTON UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

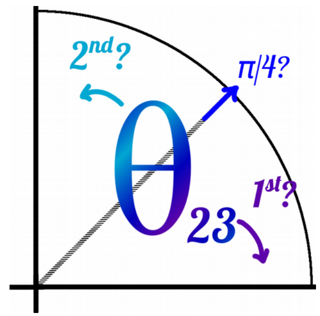
Outline

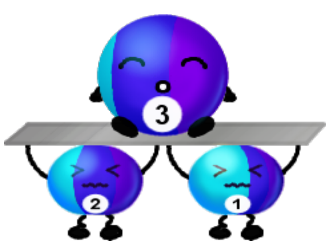
1^{st} analysis

δ_{CP} measurement

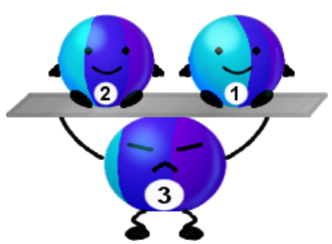


θ_{23} octant





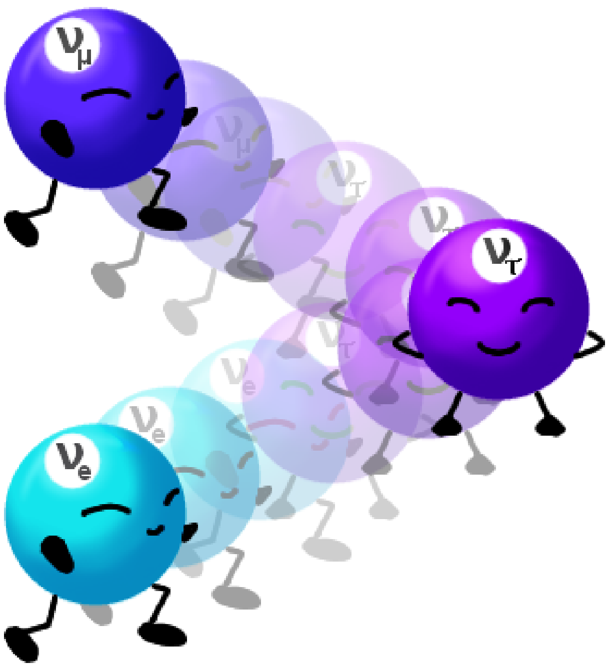
vs



Mass hierarchy

2^{nd} analysis

ν_τ appearance



Neutrino oscillations

- Flavour (interaction) eigenstates ≠ Mass (propagation) eigenstates, linked by the **PMNS mixing matrix**:

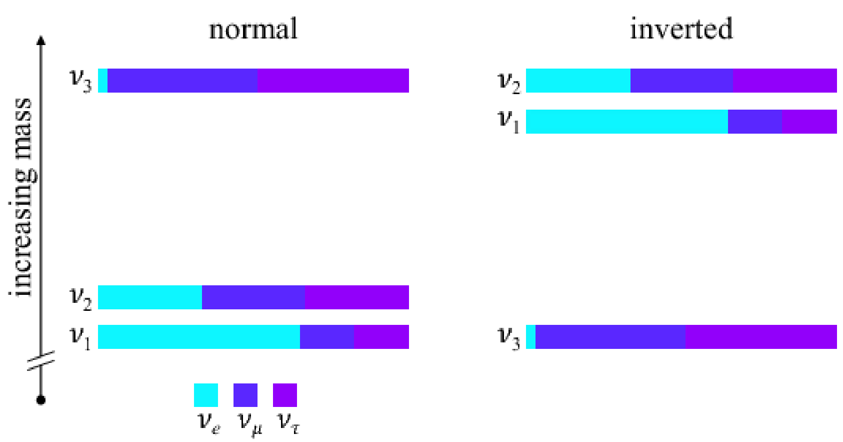
atmospheric — interference — solar

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

→ oscillation parameters: **2 Δm^2_{ij}** ($\Delta m^2_{ij} = m^2_i - m^2_j$), **3 mixing angles θ_{ij} and 1 phase.**

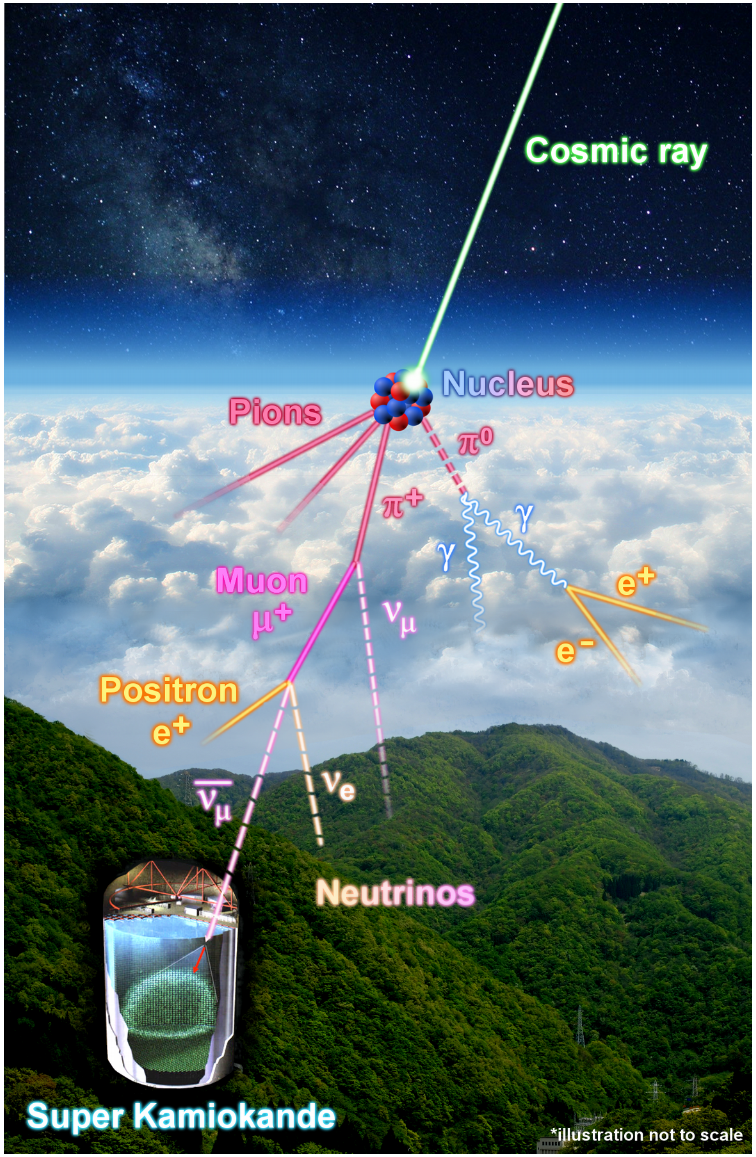
- To be solved:
  - **CP-violation phase δ**: are neutrino and antineutrino oscillation probabilities different?
  - **Mass hierarchy**: is it normal or inverted?

    → use matter effects
  - **θ_{23} octant**: is θ_{23} really π/4? Is it smaller or larger?

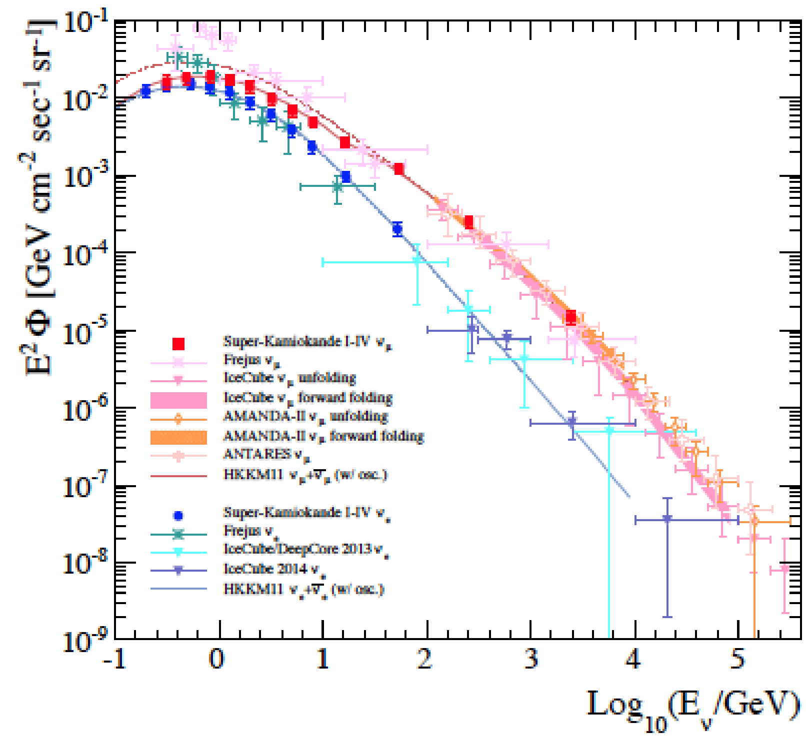


Atmospheric neutrinos can be used to study all of these questions!

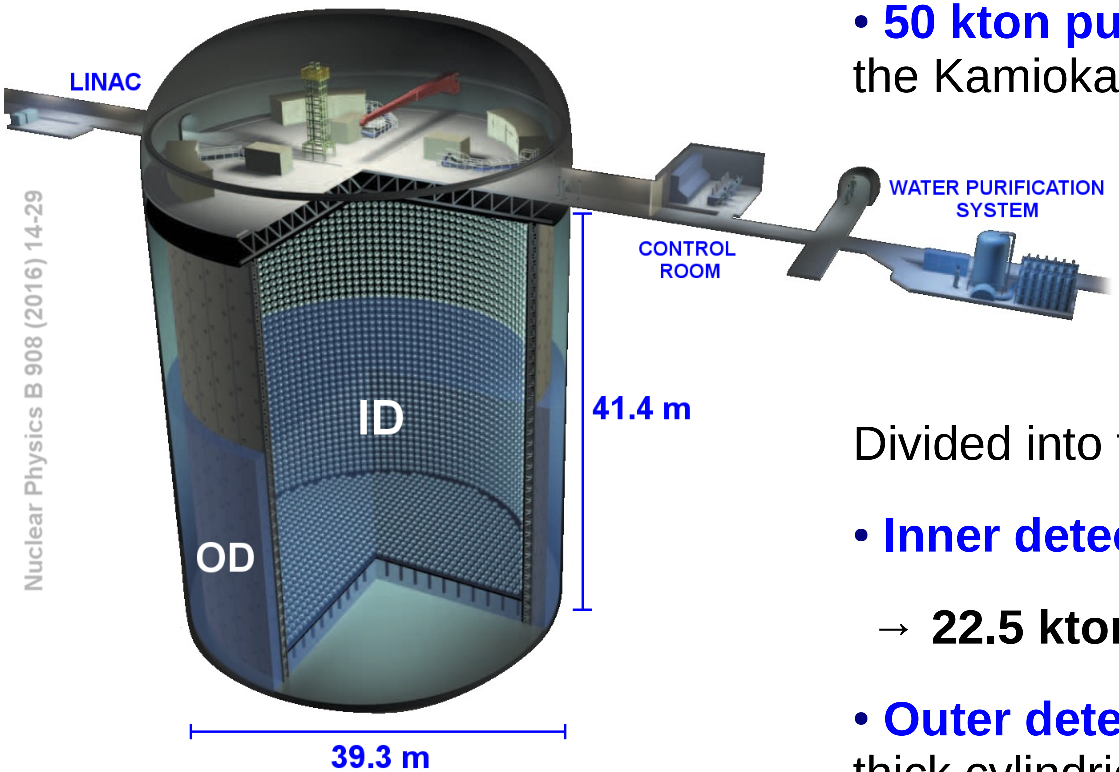
Atmospheric neutrino production



- Produced as decay products of secondary particles from cosmic ray interactions with the Earth's atmosphere
- Mix of ν_e, ν_μ, $\overline{\nu}_e$ and $\overline{\nu}_\mu$
- Power spectrum, ratios well predicted



The Super-Kamiokande detector



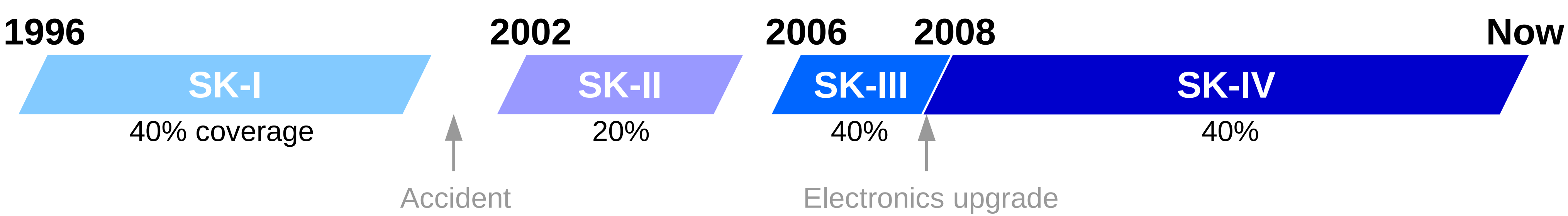
- **50 kton pure water Cherenkov detector** inside the Kamioka mine in Gifu, Japan.

Divided into two volumes:

- **Inner detector (ID)**: 11 126 x 20 inch PMTs,

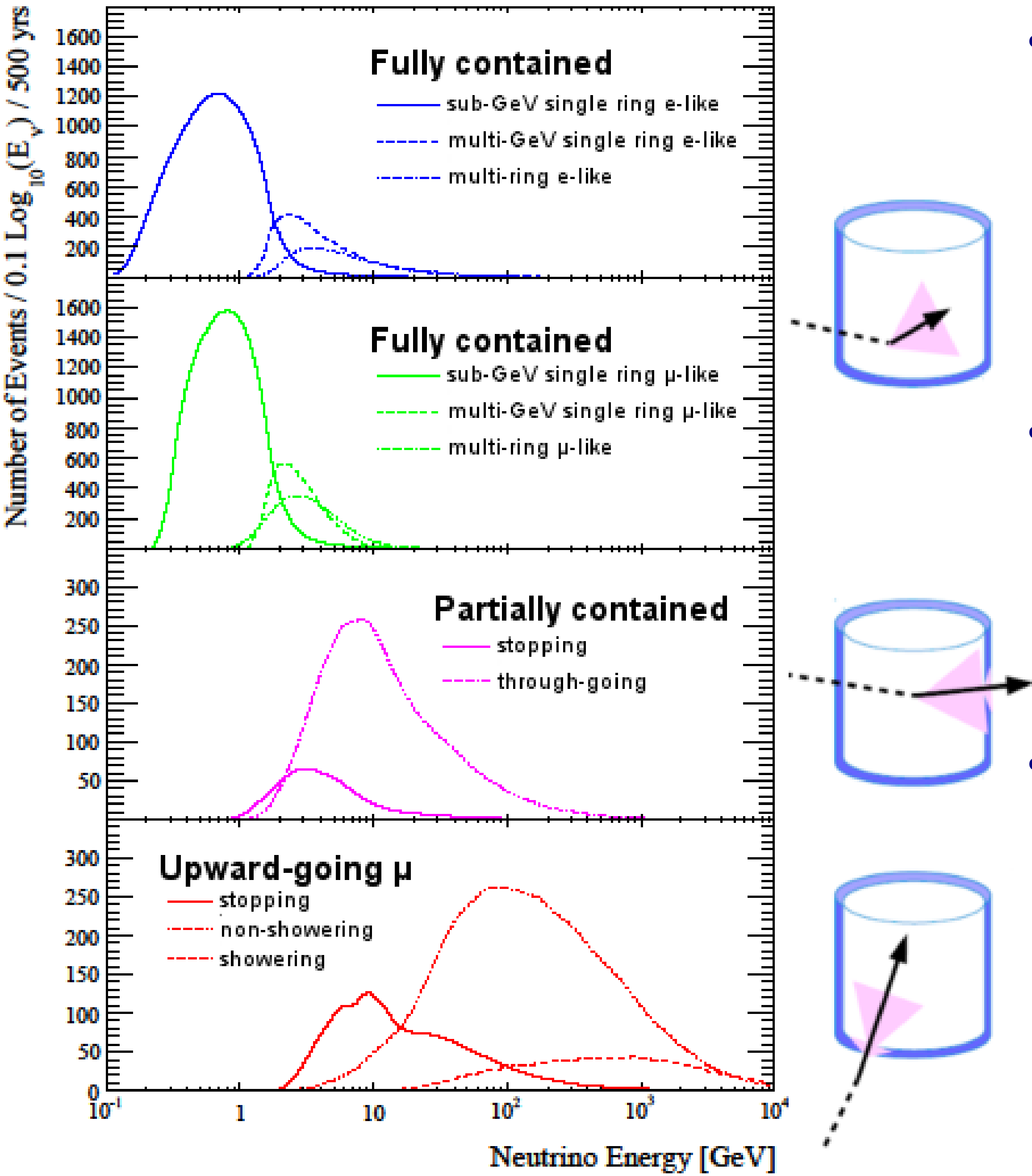
  → **22.5 kton fiducial volume**

- **Outer detector (OD)**: 1 885 x 8 inch PMTs, 2m thick cylindrical shell around ID



→ Results shown include data from all 4 periods (5326 days)

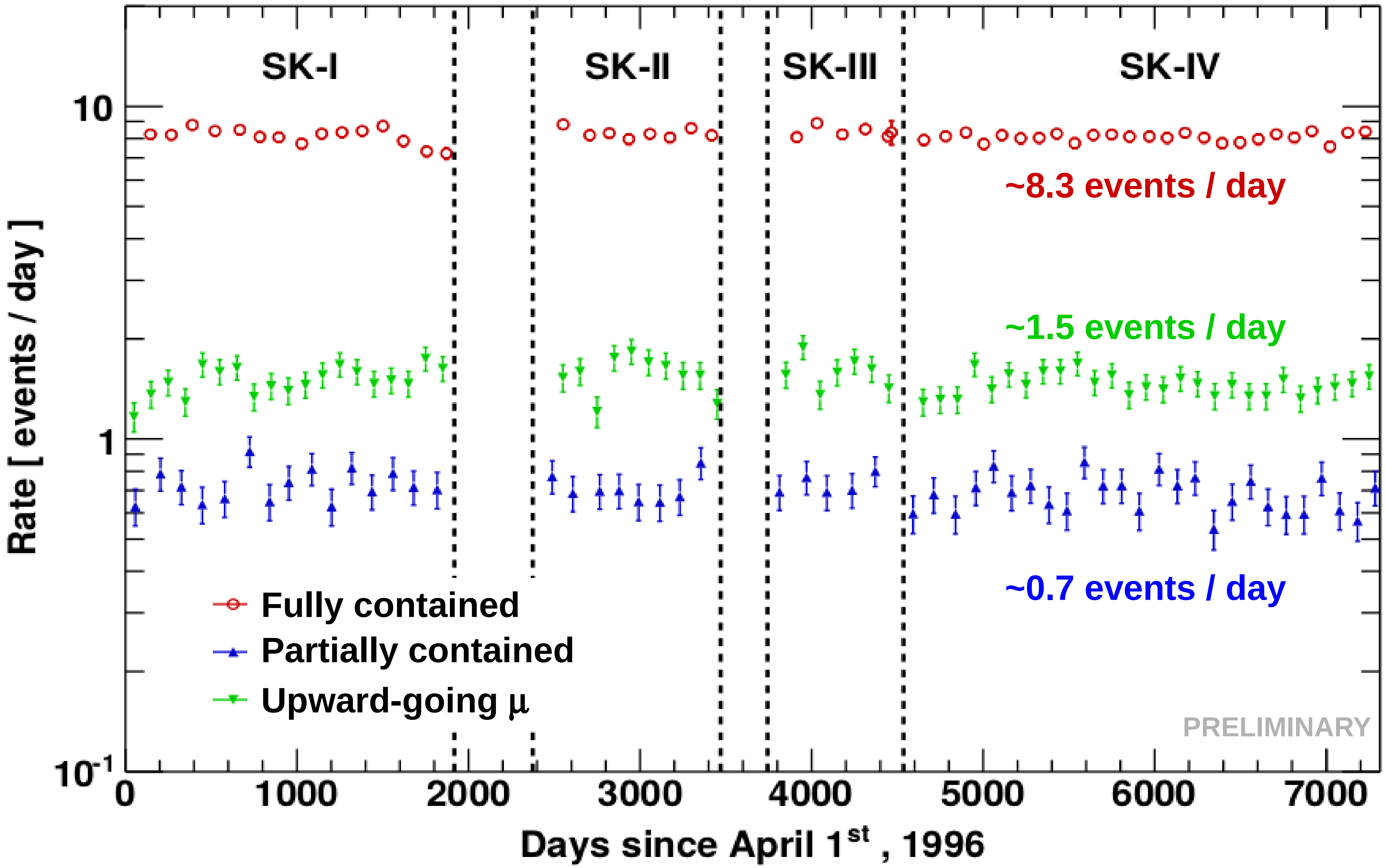
Atmospheric neutrino samples



- **Fully contained** (FC):
  - Reconstructed vertex inside FV
  - No OD activity
  - Sub-divided into 14: e-like, μ-like, π^0-like, nb. of rings, energy, nb. of decay electrons
- **Partially contained** (PC):
  - Vertex in FV
  - With OD activity
  - Sub-divided into 2: stopping and through-going
- **Upward going muon** (Upmu):
  - Produced by neutrinos in rock around SK or OD
  - Sub-divided into 3: stopping, through-going non showering and through-going showering

→ **energy range from ~100 MeV to ~10 TeV**

Event rates



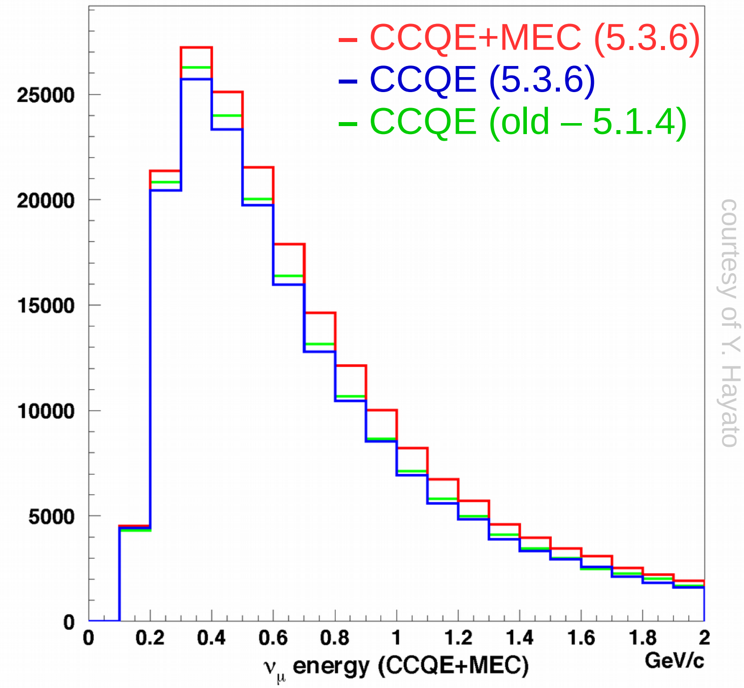
→ **Stable data taking for over 20 years!**

Monte Carlo samples

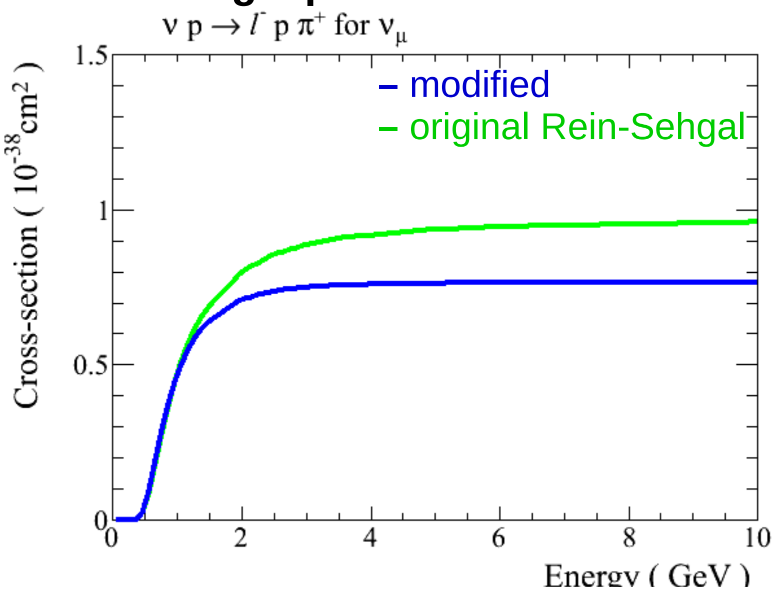
- Uses Honda et al. 2011 flux calculation (arXiv:1102.2688 [astroph.HE])
- Neutrino interactions simulated with updated NEUT 5.3.6
  - CCQE: Fermi gas, M_A=1.2 GeV/c^2, dipole form factor changed to BBBA05 (extracted from e^- scattering experiments)
  - Include meson exchange currents (Nieves et al.)
  - CC/NC 1π form factor change (Graczyk & Sobczyk)

    → M_A = 1.21 GeV/c^2 → 0.95 GeV/c^2
  - DIS (multi-π) improvement, formation zone correction

Neutrino energy comparisons



Single pion cross-section



Atmospheric neutrino oscillation analysis

Matter effects

- Matter effects due to ν_e-electron scattering

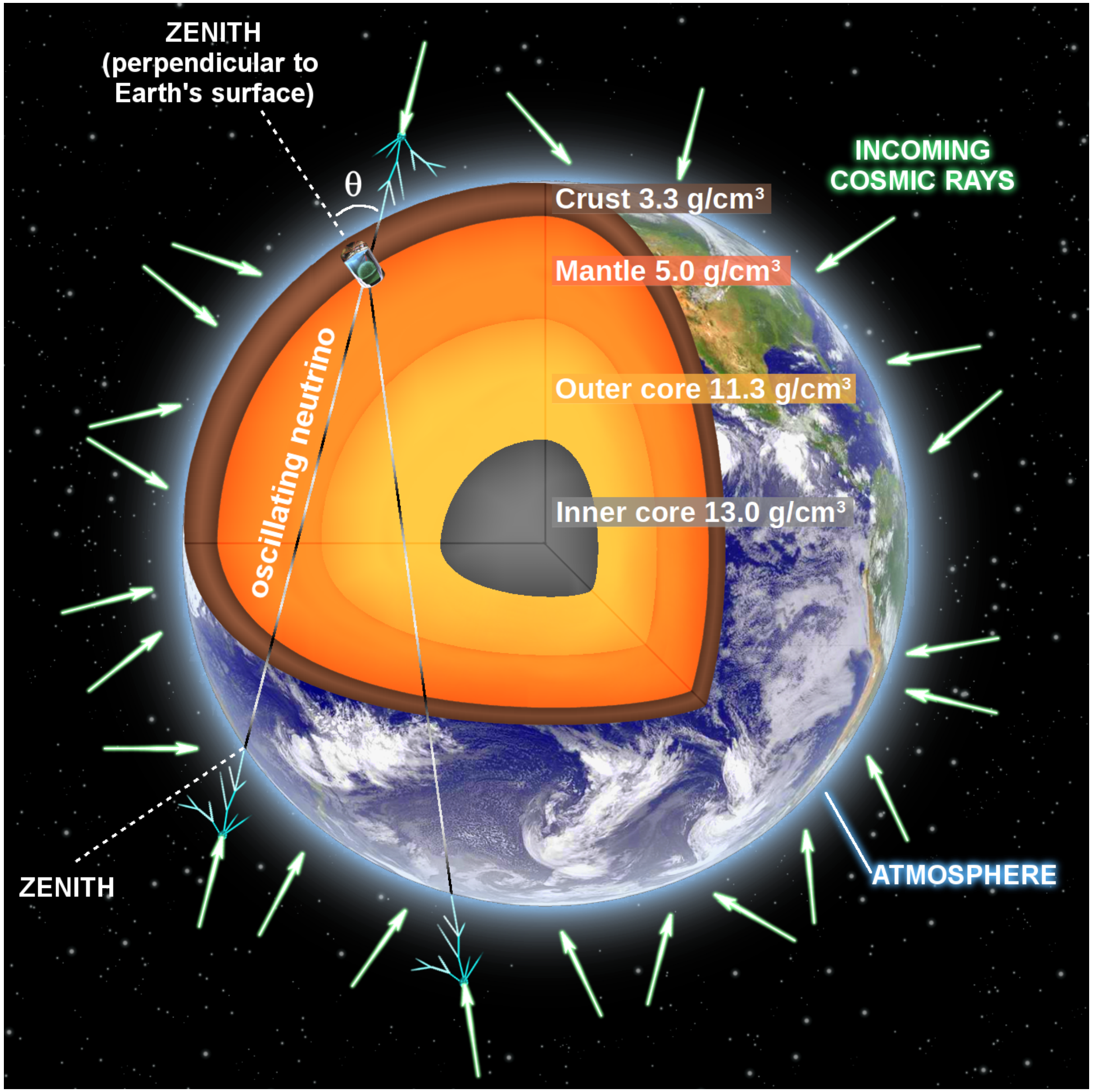
$$H_{\text{matter}} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix} + U^\dagger \begin{pmatrix} a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U$$

where $a = \sqrt{2} G_F N_e$ ($-a$ for $\bar{\nu}$), G_F is the Fermi constant, and N_e the electron density

- Earth modelled with 4 layers

→ simplified preliminary reference Earth model (PREM)

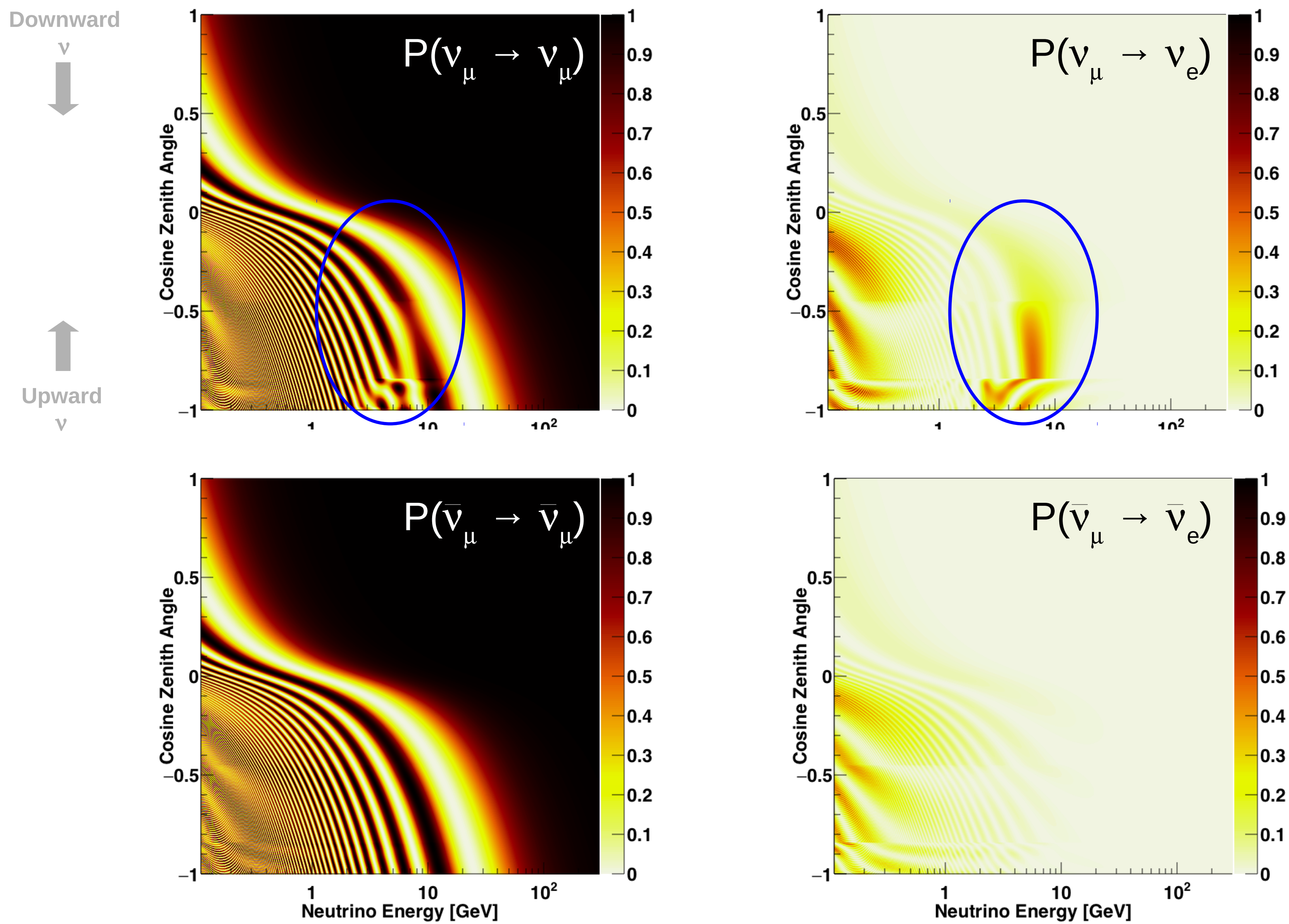
- Spherical symmetry so neutrino path only depends on:
  - production height
  - zenith angle



Matter effects

Oscillation probabilities

Normal hierarchy, $\Delta m_{32}^2 = 2.5 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.5$, $\sin^2\theta_{13} = 0.0219$, $\delta_{CP} = 0$



→ **Resonant enhancement visible only in neutrinos for normal hierarchy** (antineutrinos for inverted)

Analysis

- Three different fits are done:
  1) Super-K atmospheric only (θ_{12} and Δm^2_{12} fixed), θ_{13} free
  2) Super-K atmospheric only, $\sin^2\theta_{13}$ = 0.0219 (Daya Bay + RENO + Double Chooz)
  3) Super-K atmospheric + T2K model, $\sin^2\theta_{13}$ = 0.0219
- Binned χ^2 method using systematic errors as scaling factors on the simulation:

$$\chi^2 = 2\sum_n \left(E_n - \mathcal{O}_n + \mathcal{O}_n \ln \frac{\mathcal{O}_n}{E_n} \right) + \sum_i \left(\frac{\epsilon_i}{\sigma_i} \right)^2$$

Expected from MC

$$E_n = \sum_j E_{n,j} (1 + \sum_i f^i_{n,j} \epsilon_i)$$

Observed in data

$$\mathcal{O}_n = \sum_j \mathcal{O}_{n,j}.$$

n → nth analysis bin (520 analysis bins)

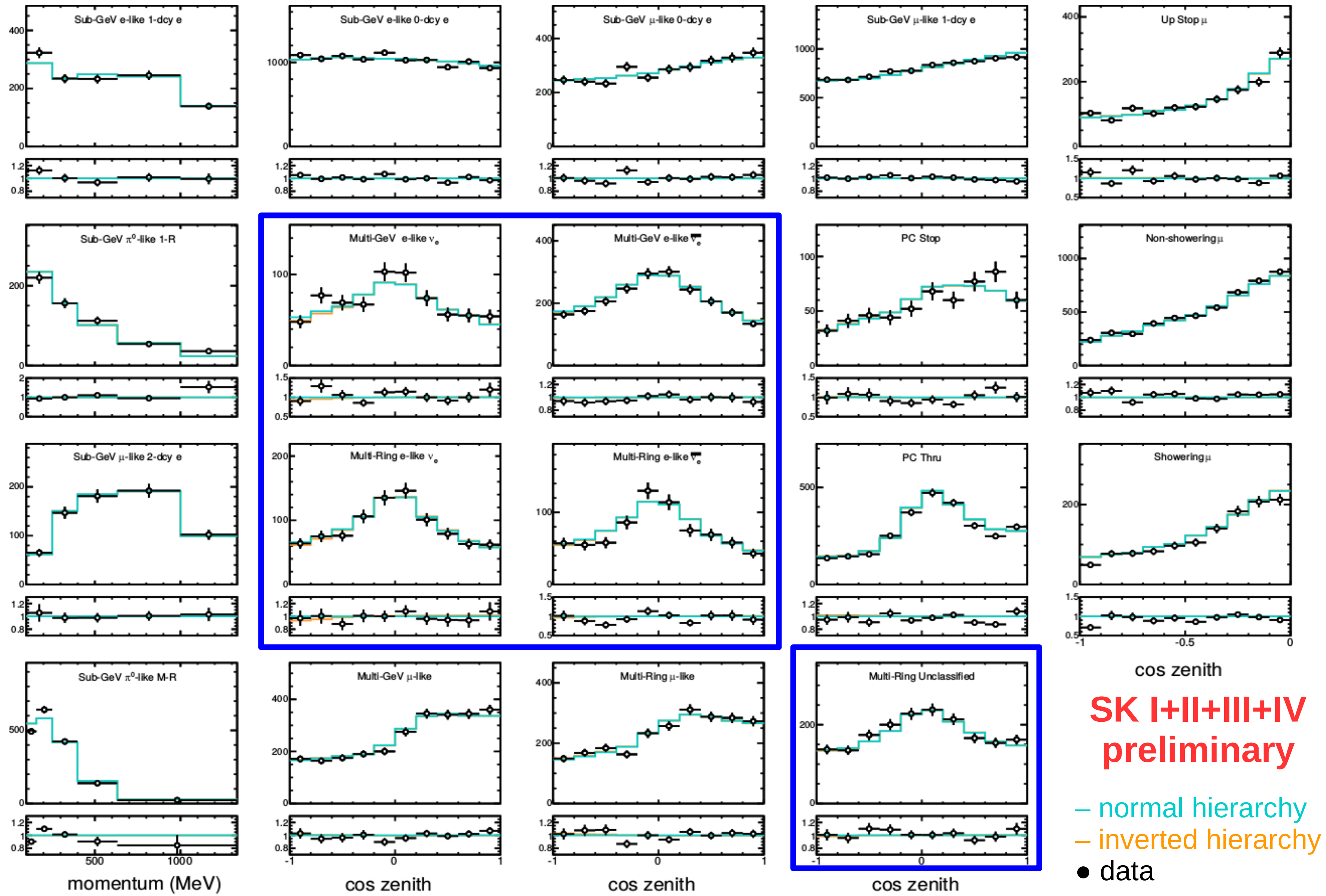
j → jth Super-K period (I to IV)

i → ith systematic error (155 error sources)

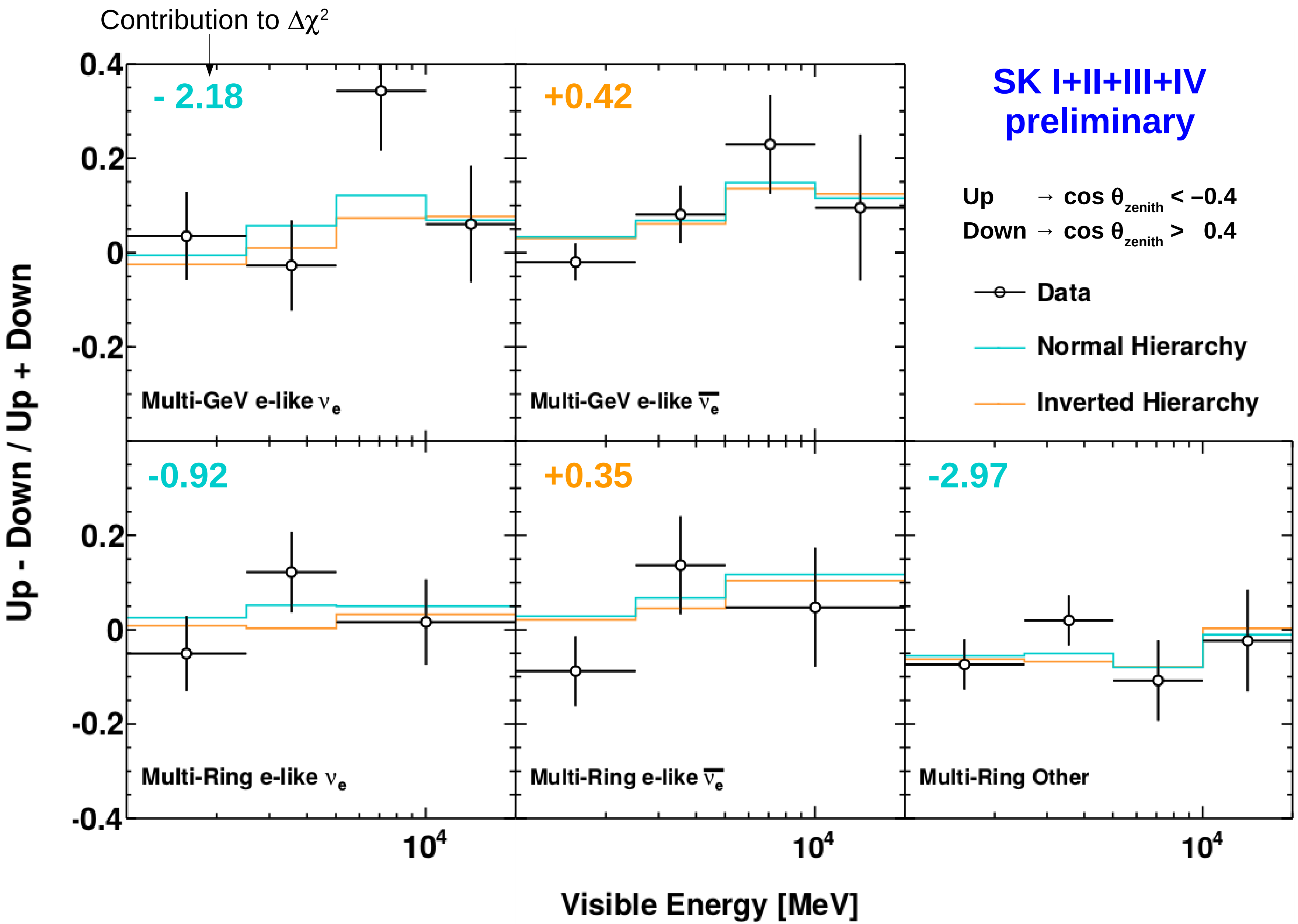
$f^i_{n,j}$ → fractional change in nth MC bin for a $1 - \sigma^i$ variation on ith systematic error

ε_i → ith systematic error fitting parameter

Data vs MC with hierarchy



Hierarchy sensitive samples



1) Super-K atm. with θ_{13} free

- θ_{12} and Δm^2_{12} fixed, θ_{13} is not constrained

χ^2_{min} (NH) = 571.7

χ^2_{min} (IH) = 575.2

→ **better data-MC agreement for normal hierarchy**

- Best fit $\sin^2\theta_{23}$ = $0.584^{+0.039}_{-0.069}$ ($0.550^{+0.043}_{-0.078}$)

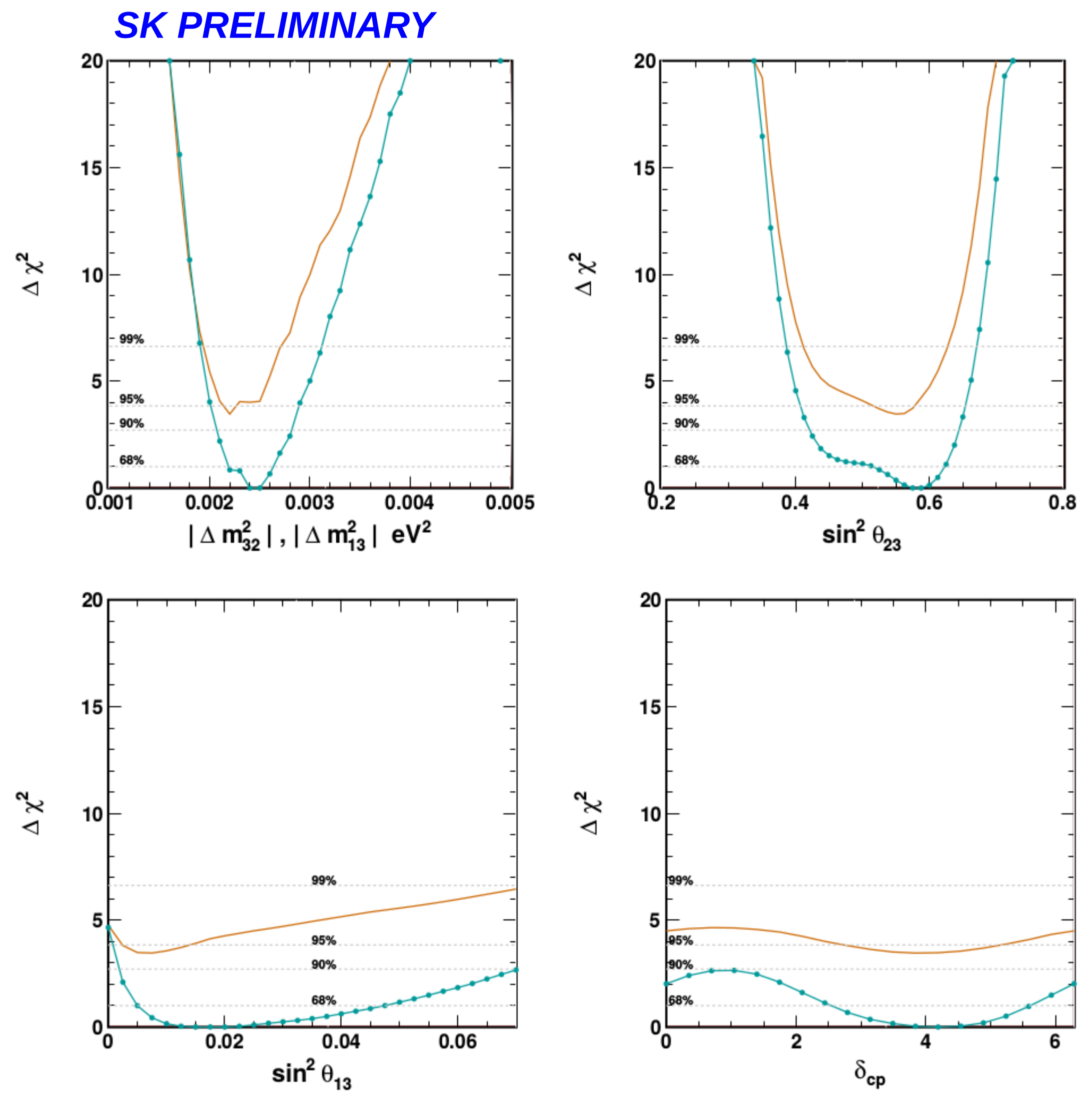
→ **2nd octant preferred**

- Best fit $\delta_{CP} = 4.18^{+1.43}_{-1.64}$ ($3.85^{+2.35}_{-2.15}$)

→ weak constraint, CP-conserving value π included at ~1σ

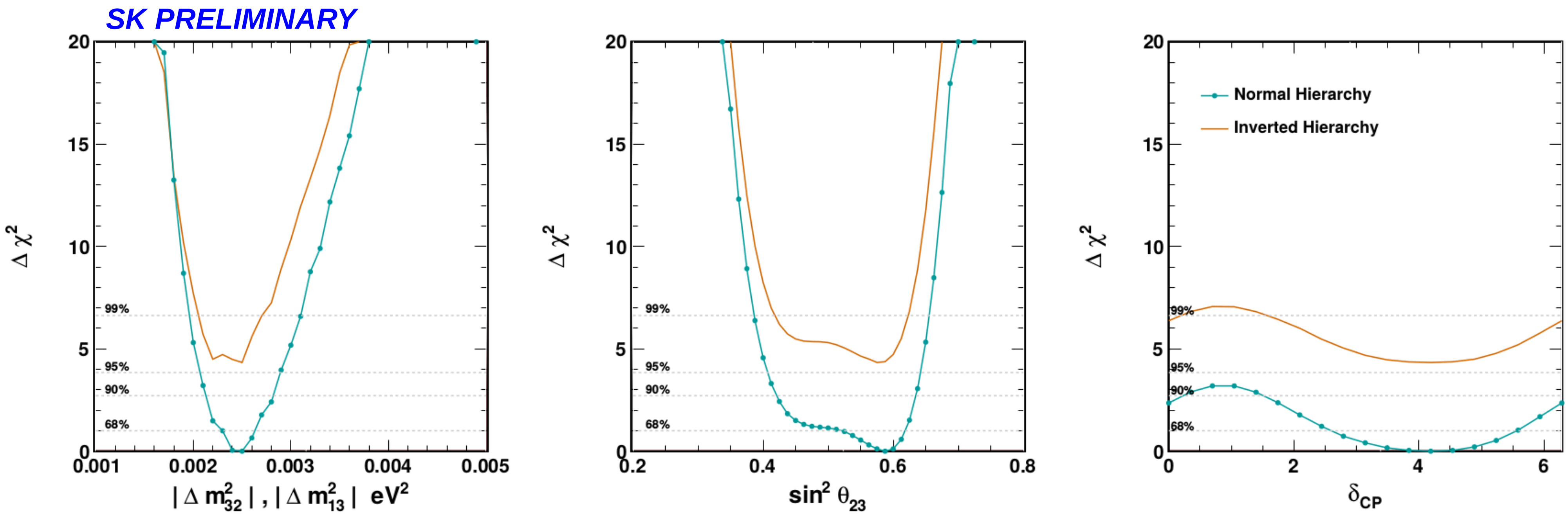
- Best fit $\sin^2\theta_{13}$ = $0.019^{+0.028}_{-0.014}$ ($0.008^{+0.017}_{-0.007}$)

→ Non-zero θ_{13} can also be seen with atmospheric neutrinos (weak constraint)



– normal hierarchy
– inverted hierarchy

2) Super-K atm. + θ_{13} fixed ($\sin^2\theta_{13} = 0.0219 \pm 0.0012$)



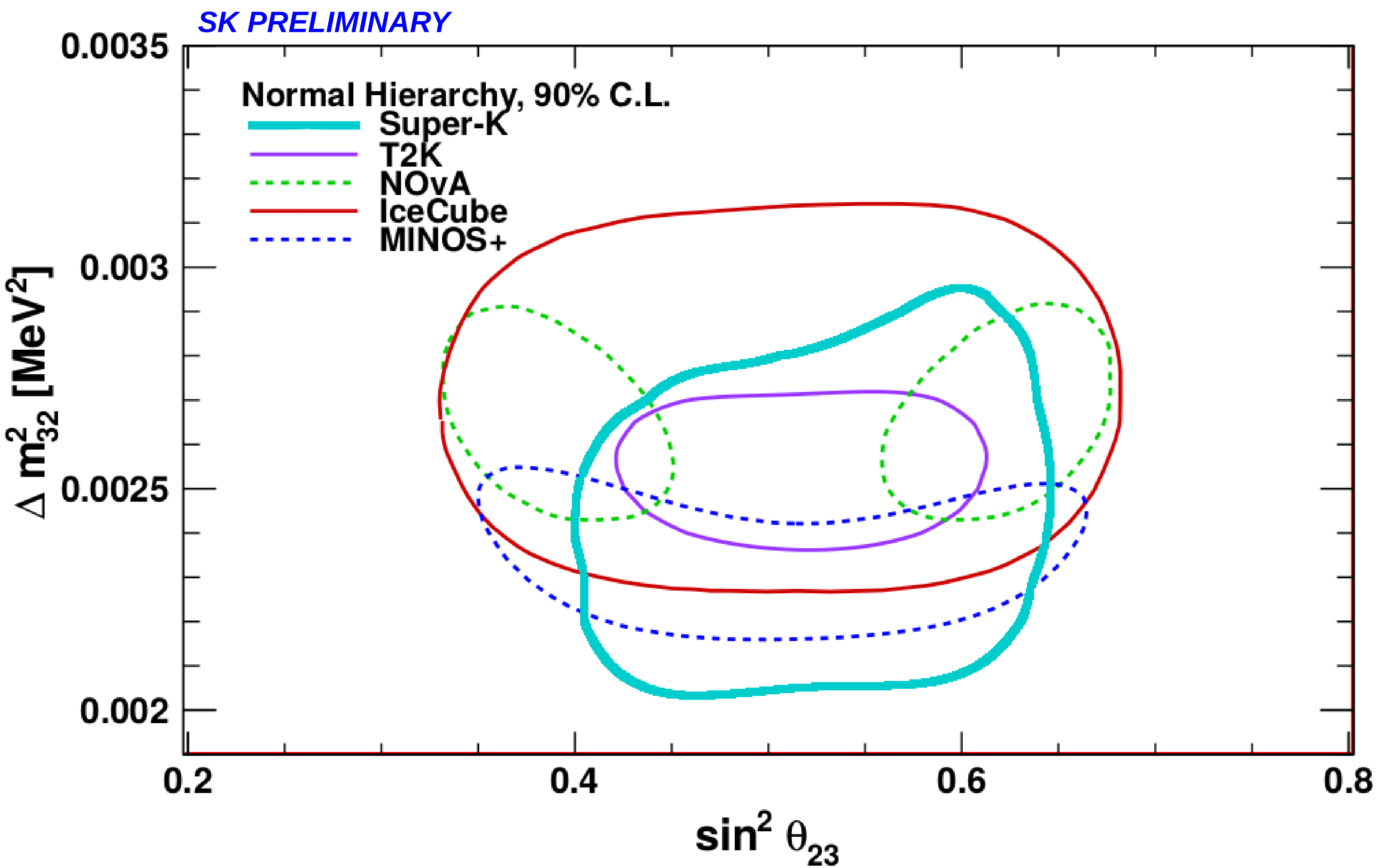
$\Delta\chi^2 \equiv \chi^2_{min}(NH) - \chi^2_{min}(IH) = -4.4$ → **normal hierarchy favored**

- Best fit $\sin^2\theta_{23} = 0.588^{+0.031}_{-0.067}$ $\left(0.575^{+0.035}_{-0.085}\right)$ → **2nd octant preference strengthened**
- Best fit $\delta_{CP} = 4.19^{+1.37}_{-1.59}$ $(4.19^{+1.49}_{-1.63})$ → ~$3\pi/2$, weak constraint
- Additional scaling parameter on electron density α ($\alpha = 0$ is vacuum, $\alpha = 1$ is standard e^- density)
- Normal hierarchy preferred with electron density consistent with standard matter

$$\Delta\chi^2 \equiv \chi^2_{\alpha=0} - \chi^2_{min} = 5.2$$

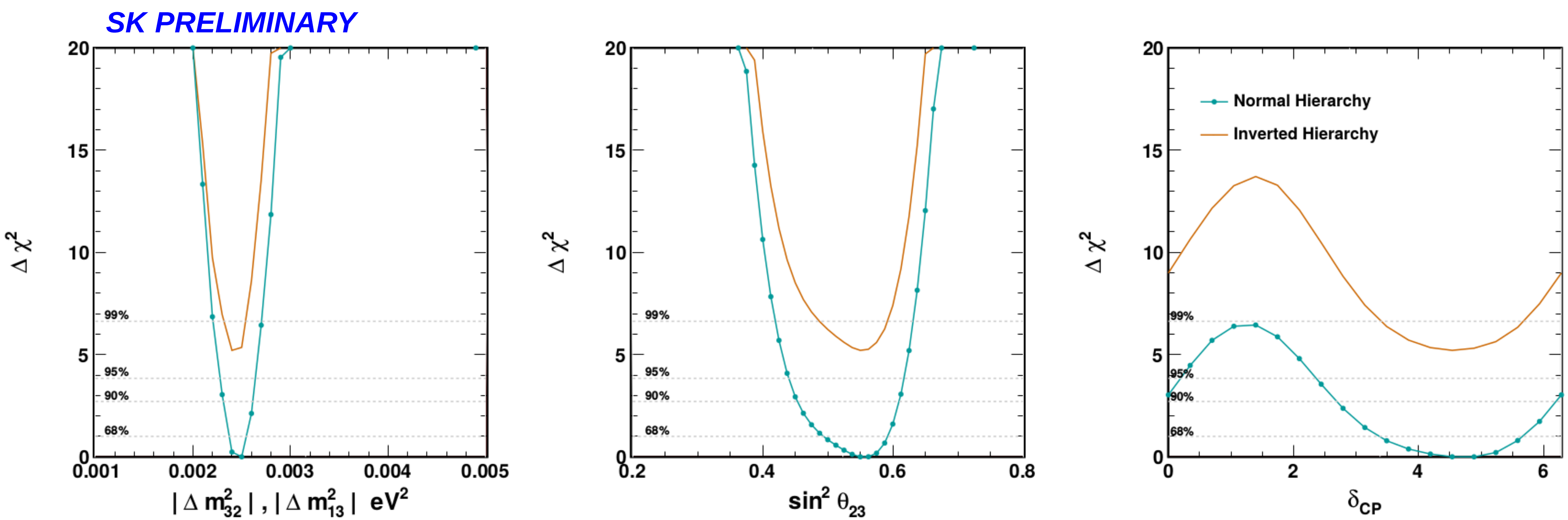
→ exclude vacuum oscillations at 1.6 σ level

2) Super-K atm. + θ_{13} fixed ($\sin^2\theta_{13} = 0.0219 \pm 0.0012$)



→ **Good agreement with other experiments**

3) Super-K atm. + θ_{13} fixed + T2K constraint



- Super-K is T2K far detector so only neutrino source differs: common reconstruction and NEUT-based simulation

- **Use only published T2K beam flux bins** : reweight atmospheric ν MC using T2K beam flux

$\Delta\chi^2 = -5.2$ → normal hierarchy preference strengthened

- Best fit **$\sin^2\theta_{23}$= $0.550^{+0.040}_{-0.059}$** (**$0.550^{+0.040}_{-0.059}$**) → closer to maximal but still **2nd octant**

- Best fit **δ_{CP} = $4.89^{+0.84}_{-1.45}$** (**$4.54^{+0.99}_{-0.96}$**) → still ~3π/2, stronger constraint

Mass hierarchy results significance

- CL_s method [A.L. Read J. Phys. G28 2693 (2002)]

$$\mathrm{CL}_s = \frac{p_0(IH)}{1 - p_0(NH)}$$

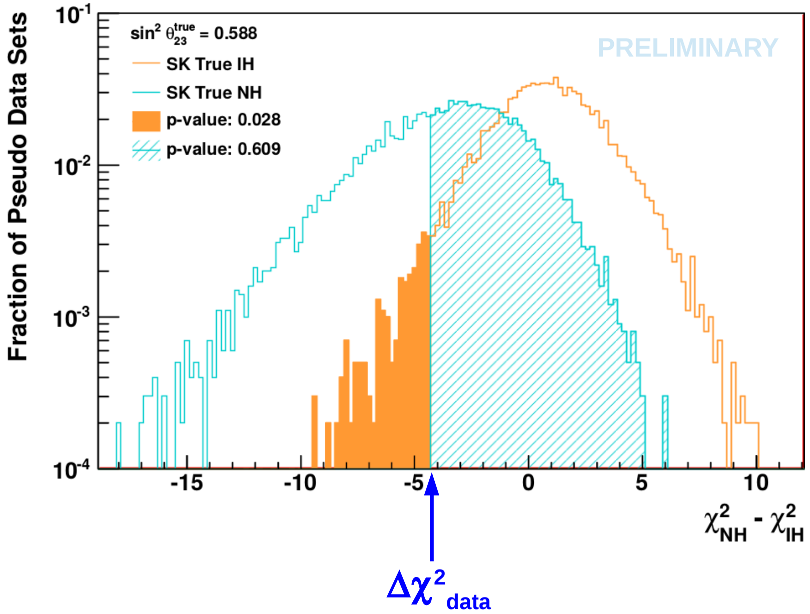
- p_0(IH) is the p-value to obtain, assuming IH is true:

$$\Delta\chi^2\ (\mathrm{NH} - \mathrm{IH}) < \Delta\chi^2_{\mathrm{data}}$$

- Oscillation parameters allowed to vary within 90% C.L.
- **Inverted hierarchy rejected** with
  - $81.4\% < 1\text{-}CL_s < 94.9\%$ for SK, θ_{13} constrained
  - $91.5\% < 1\text{-}CL_s < 94.5\%$ for SK+T2K, θ_{13} constrained

CLs calculation

(best fit values in SK θ_{13} constrained analysis)



Fit	CL_s Lower 90% C.L.	Best Fit	Upper 90% C.L.
SK θ_{13} Constrained	0.186	0.071	0.051
SK+T2K θ_{13} Constrained	0.085	0.074	0.055

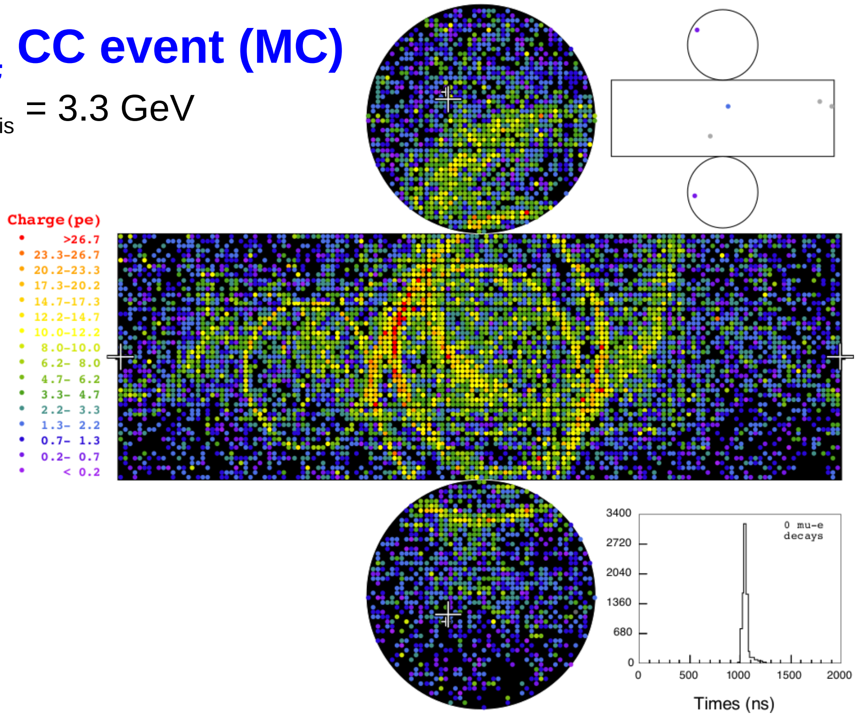
SK PRELIMINARY

Tau appearance analysis and cross-section measurement

ν_τ in Super-Kamiokande

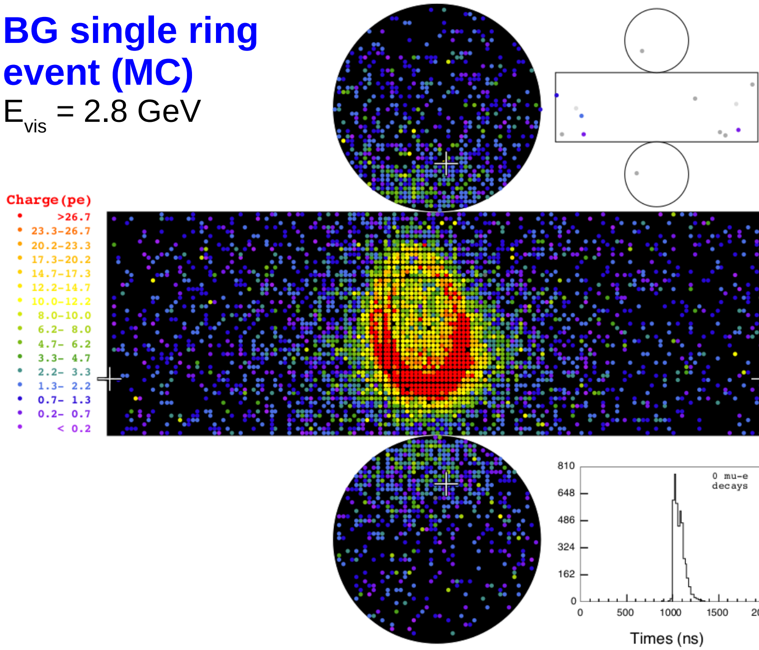
ν_τ CC event (MC)

E_{vis} = 3.3 GeV



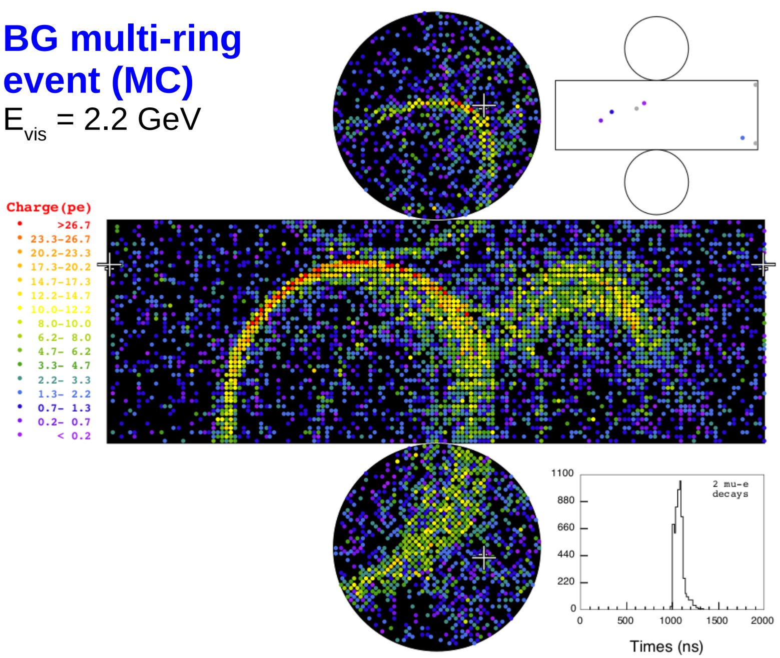
BG single ring event (MC)

E_{vis} = 2.8 GeV



BG multi-ring event (MC)

E_{vis} = 2.2 GeV



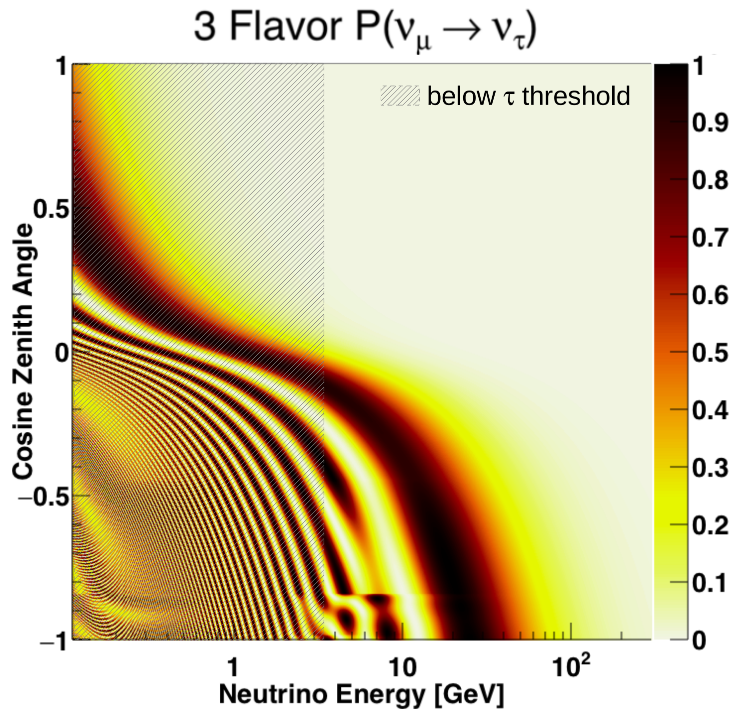
- τ leptons, produced by ν_τ CC interactions, have a short lifetime (~ 10^{-13} s) → **indirect detection** in Super-K
- Decay into multiple particles → **multi-ring events**
- Main background : other neutrino interactions with multiple outgoing charged particles

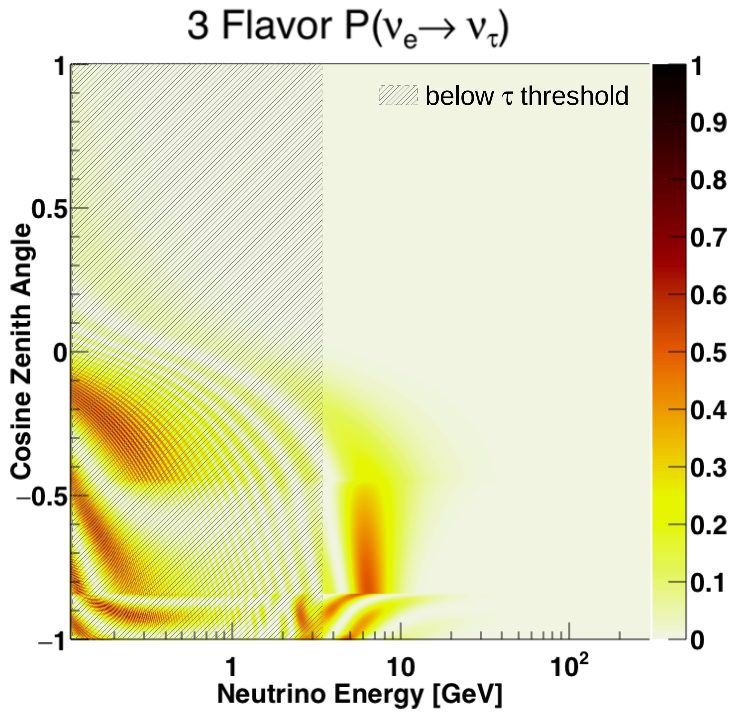
  → single ring events are easily rejected

ν_τ selection

ν_τ appearance probabilities

Normal hierarchy, $\Delta m_{32}^2 = 2.1 \times 10^{-3}$ eV^2, $\Delta m_{21}^2 = 7.6 \times 10^{-5}$ eV^2, $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0.099$, $\delta_{CP} = 0$



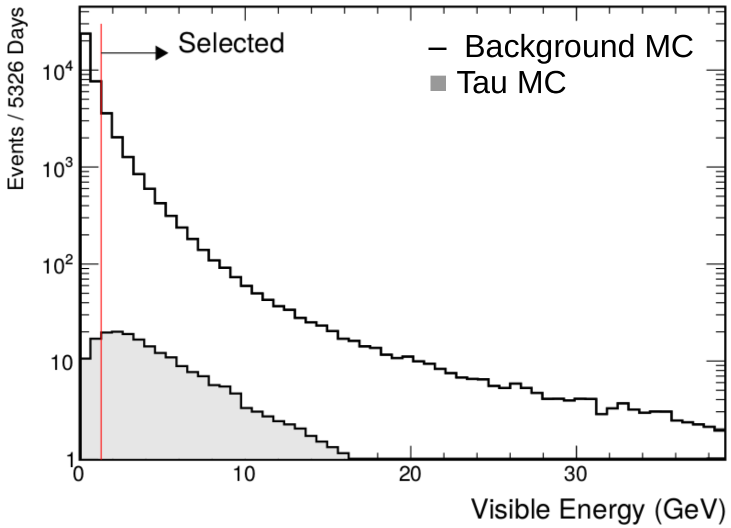


- ν_τ expected only from **upward-going ν** oscillations

→ downward-going sample used for background MC validation

- **Fully contained** events only
- **Visible energy (E_{vis}) > 1.3 GeV**

→ ν_τ CC signal efficiency = 86 % (BG rejection 77%)



ν_τ selection

- Neural network algorithm, using 7 discriminating variables:

1) Visible energy

→ *energy threshold for CC ν_τ appearance and large τ mass*

2) Maximum energy ring particle ID

→ *τ events have showering particles ≡ ID < 0*

3) Number of decay electrons

→ *expect more, from pion decays*

4) Maximum distance between primary vertex and decay electron

→ *μ from ν_μ interaction are more energetic*

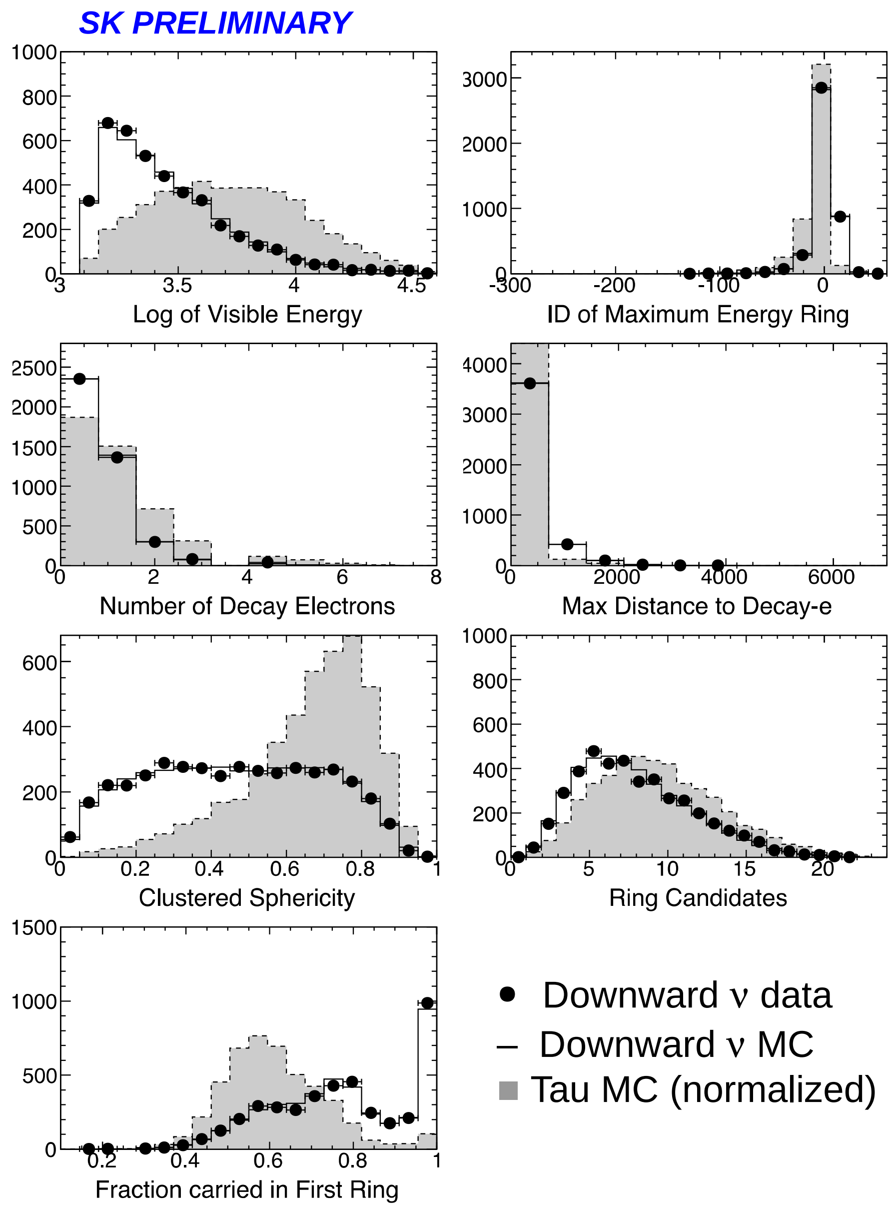
5) Event sphericity

→ *τ hadronic decays more isotropic, S → 1*

6) Number of ring and ring fragment candidates

7) Fraction of total photoelectrons in the most-energetic ring

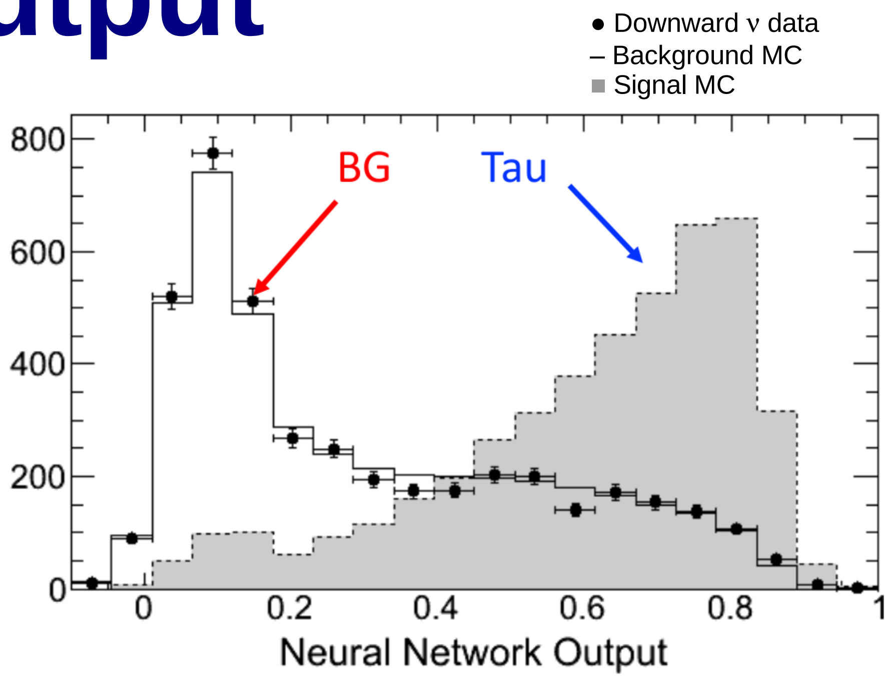
→ *expected to be smaller*



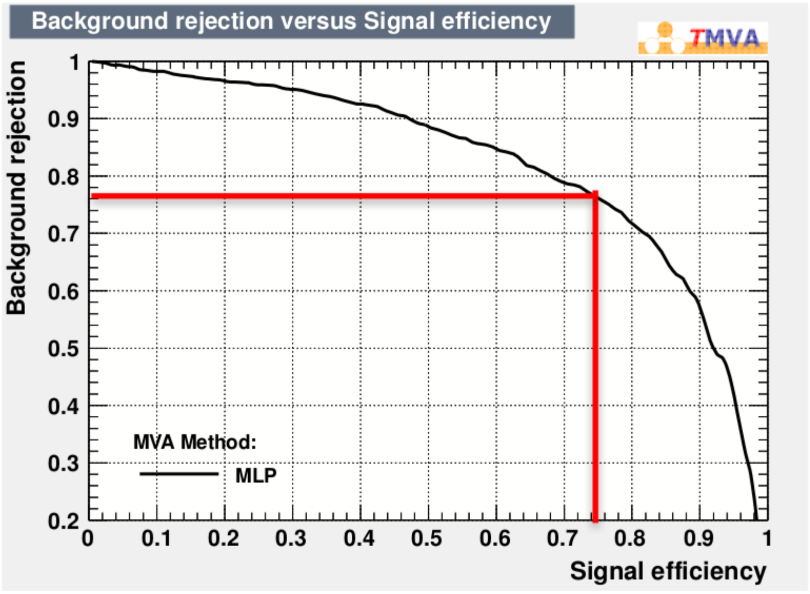
Neural network output

- Good separation between background and signal
- Good agreement between background simulation and downward going data

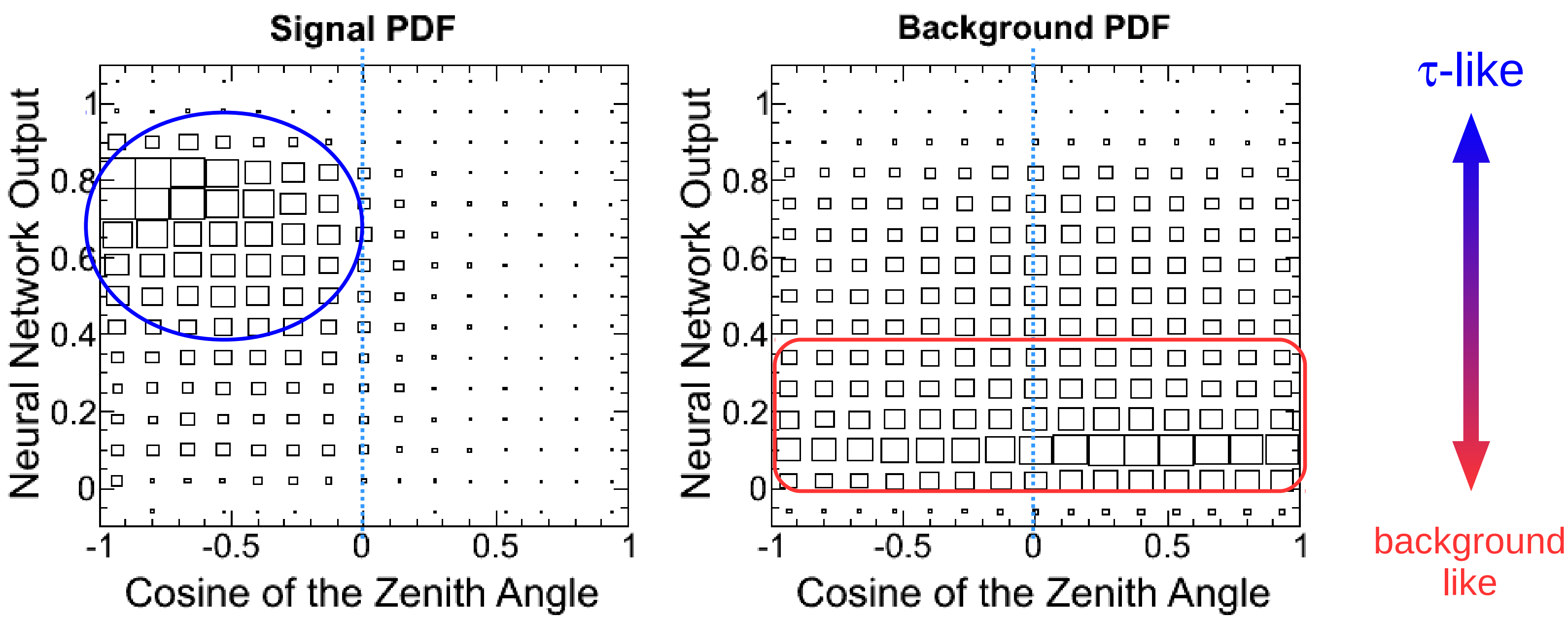
→ no tau expected in the downward sample



- Performance example: for $NN_{output} > 0.5$, 76% of the signal is selected and 72% of the background is rejected



ν_τ appearance search



- Two-dimensional unbinned maximum likelihood fit:

Tau signal normalization

Syst. error magnitude

$$\text{Data} = \alpha \times \text{Signal} + \text{Background} + \Sigma\, \varepsilon_i \times (\text{PDF}_i^{\text{signal}} + \text{PDF}_i^{\text{BG}})$$

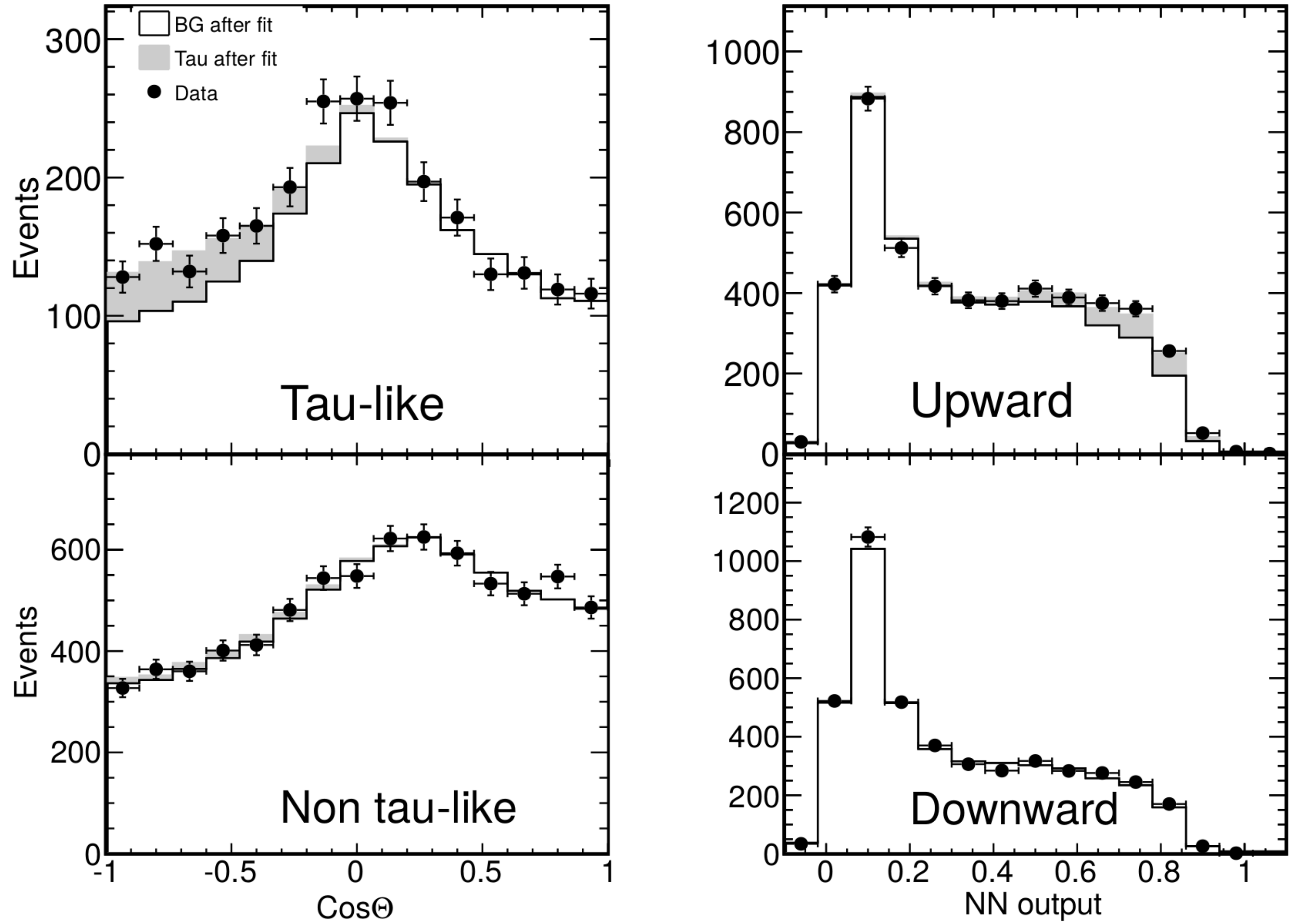
Built from the NN output and event direction

Systematic PDFs

Built from the atmospheric neutrino analysis systematic errors that change the 2D signal / BG histograms by at least 2.5% when applying a 1σ shift (28 systematic errors)

ν_τ appearance search results

SK PRELIMINARY



PRELIMINARY RESULTS (NH)

α = 1.47 ± 0.32 (stat + syst)

[1.41 ± 0.28 stat only]

- No-tau appearance rejection at 4.6 σ level for normal hierarchy (3.3 σ expected)
- 338.1 ± 72.7 fully contained CC ν_τ events

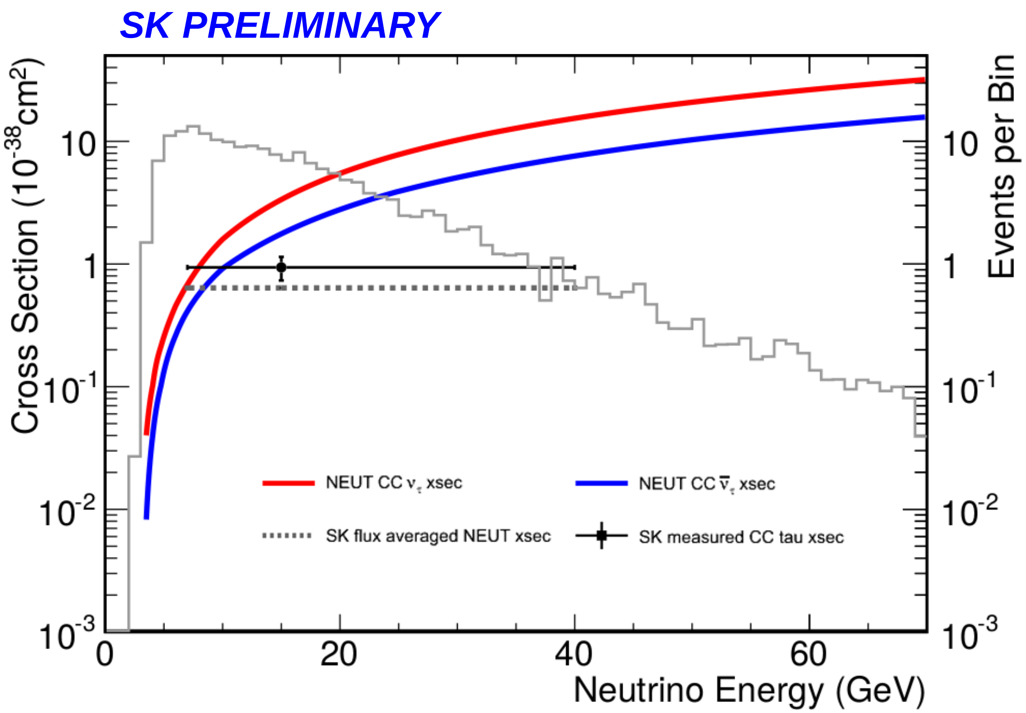
CC ν_τ cross-section measurement

$$\sigma_{measured} = S_\tau \times \langle \sigma_{theory} \rangle$$

- S_T is a scaling factor and $\langle \sigma_{theory} \rangle$ is the flux-averaged theoretical CC ν_τ cross-section used in NEUT
- In this case $\mathbf{S_T = \alpha}$ so

$$\sigma_{measured} = (1.47 \pm 0.32) \times \langle \sigma_{theory} \rangle$$

- The flux-averaged theoretical cross-section is calculated to be **0.64×10^{-38} cm^2 between 3.5 GeV and 70 GeV**

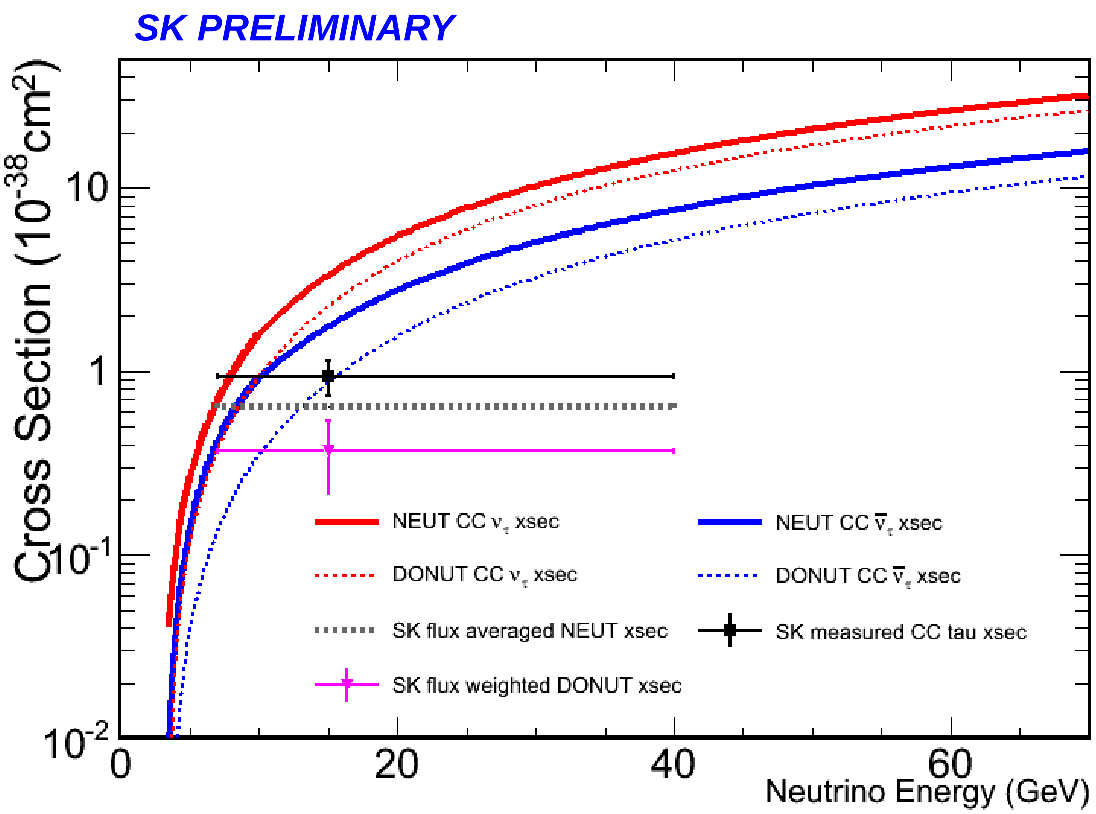


$\langle\sigma_{measured}\rangle = (0.94 \pm 0.20) \times 10^{-38}$ cm^2

for flux averaged between 3.5 GeV and 70 GeV

→ Agreement between theoretical and measured cross-sections at 1.5 σ level

Comparison to DONUT



- DONUT observed 9 CC ν_τ events (1.5 BG)
- Mean energy is 111 GeV

→ CC deep-inelastic scattering is dominant

- Assume CC ν_τ cross-section has linear dependence on neutrino energy

$$\sigma(E) = \sigma_{const} \cdot E \cdot K(E)$$

→ extrapolate to SK energies

$$\langle\sigma_{SK\text{-}DONUT}\rangle = (0.37 \pm 0.18) \times 10^{-38}\ \mathrm{cm}^2$$

- Lower than Super-K measurement

$$\langle\sigma_{SK}\rangle = (0.94 \pm 0.20) \times 10^{-38}\ \mathrm{cm}^2$$

→extrapolation missing contribution from other CC cross-sections

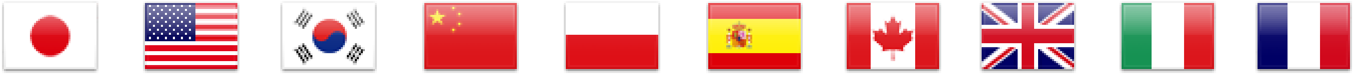
Summary

- Atmospheric neutrinos can be used to study several unresolved neutrino questions...
  - θ_{13} non-zero observed
  - Measured oscillation parameters in good agreement with other experiments
  - All analyses show slight preference for **normal mass hierarchy** and for the **second octant of θ_{23}**

- **No-tau appearance hypothesis excluded at 4.6σ** level assuming normal hierarchy
- $CC\nu_\tau$ cross-section is $(0.94 \pm 0.20) \times 10^{-38}$ cm^2 between 3.5 GeV and 70 GeV
- Results will be published soon, two papers in preparation

The collaboration

~160 members, ~45 institutes

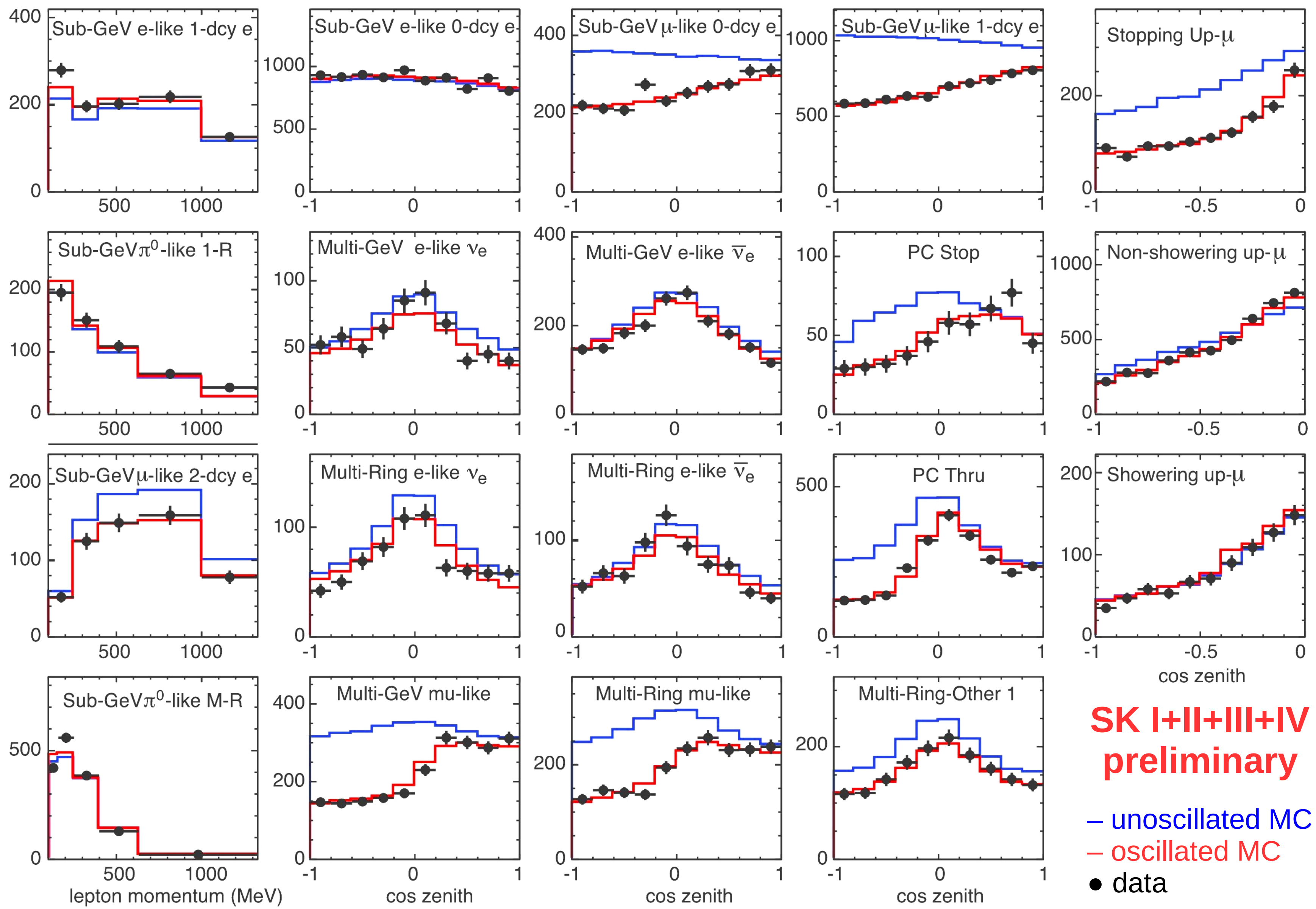


Back up

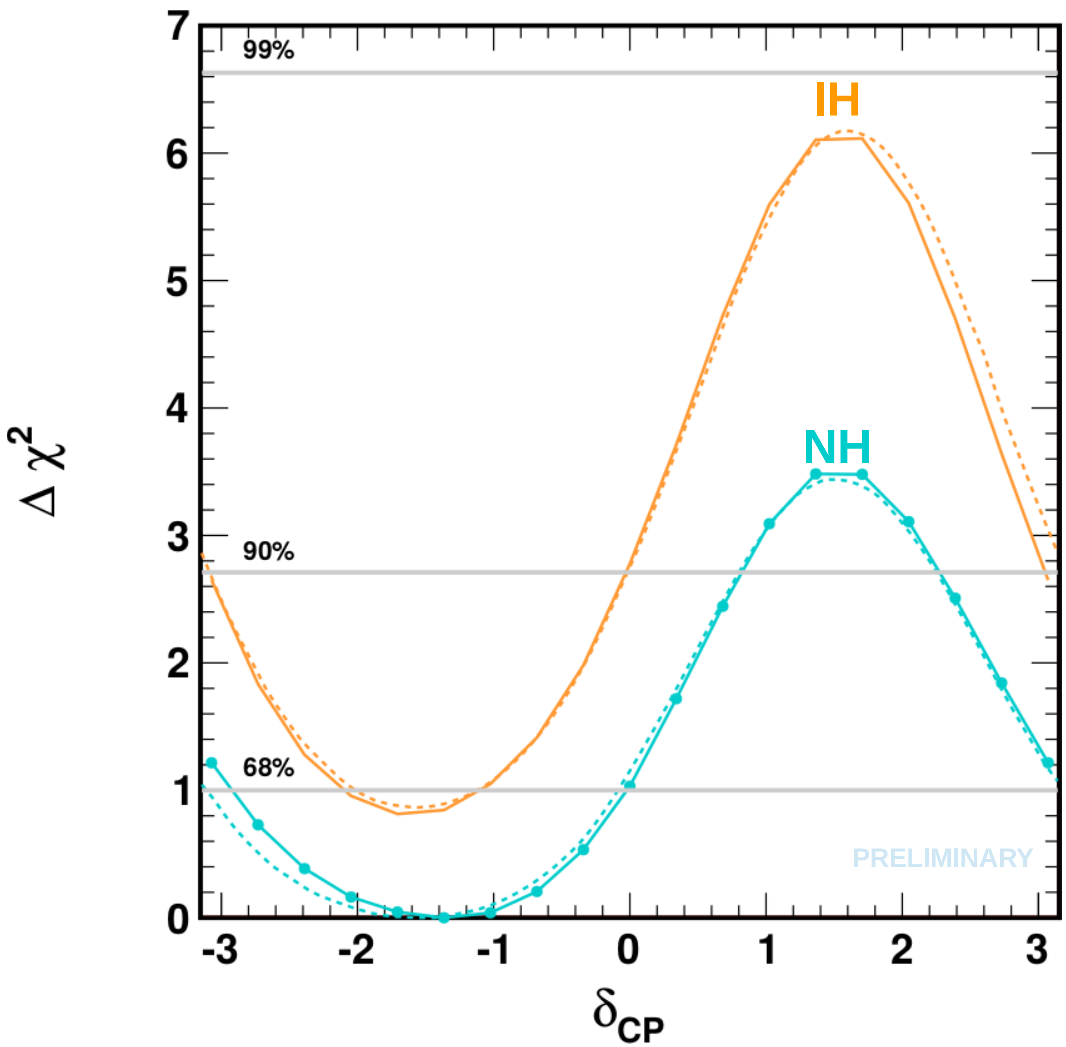
FC samples purities

Sample	Energy bins	$\cos\theta_z$ bins	CC ν_e	CC $\bar{\nu}_e$	CC $\nu_\mu + \bar{\nu}_\mu$	CC ν_τ	NC	Data	MC
Fully Contained (FC) Sub-GeV									
e-like, Single-ring									
0 decay-e	5 $e^\pm$ momentum	10 in $[-1,1]$	0.717	0.248	0.002	0.000	0.033	10294	10266.1
1 decay-e	5 $e^\pm$ momentum		0.805	0.019	0.108	0.001	0.067	1174	1150.7
μ-like, Single-ring									
0 decay-e	5 $\mu^\pm$ momentum	10 in $[-1,1]$	0.041	0.013	0.759	0.001	0.186	2843	2824.3
1 decay-e	5 $\mu^\pm$ momentum	10 in $[-1,1]$	0.001	0.000	0.972	0.000	0.027	8011	8008.7
2 decay-e	5 $\mu^\pm$ momentum		0.000	0.000	0.979	0.001	0.020	687	687.0
π^0-like									
Single-ring	5 $e^\pm$ momentum		0.096	0.033	0.015	0.000	0.856	578	571.8
Two-ring	5 π^0 momentum		0.067	0.025	0.011	0.000	0.897	1720	1728.4
Multi-ring			0.294	0.047	0.342	0.000	0.318	1682	1624.2
Fully Contained (FC) Multi-GeV									
Single-ring									
ν_e-like	4 $e^\pm$ momentum	10 in $[-1,1]$	0.621	0.090	0.100	0.033	0.156	705	671.3
$\bar{\nu}_e$-like	4 $e^\pm$ momentum	10 in $[-1,1]$	0.546	0.372	0.009	0.010	0.063	2142	2193.7
μ-like	2 $\mu^\pm$ momentum	10 in $[-1,1]$	0.003	0.001	0.992	0.002	0.002	2565	2573.8
Multi-ring									
ν_e-like	3 visible energy	10 in $[-1,1]$	0.557	0.102	0.117	0.040	0.184	907	915.5
$\bar{\nu}_e$-like	3 visible energy	10 in $[-1,1]$	0.531	0.270	0.041	0.022	0.136	745	773.8
μ-like	4 visible energy	10 in $[-1,1]$	0.027	0.004	0.913	0.005	0.051	2310	2294.0
Other	4 visible energy	10 in $[-1,1]$	0.275	0.029	0.348	0.049	0.299	1808	1772.6
Partially Contained (PC)									
Stopping	2 visible energy	10 in $[-1,0]$	0.084	0.032	0.829	0.010	0.045	566	570.0
Through-going	4 visible energy	10 in $[-1,1]$	0.006	0.003	0.978	0.007	0.006	2801	2889.9
Upward-going Muons (Up-μ)									
Stopping	3 visible energy	10 in $[-1,0]$	0.008	0.003	0.986	0.000	0.003	1456.4	1448.9
Through-going									
Non-showering		10 in $[-1,0]$	0.002	0.001	0.996	0.000	0.001	5035.3	4900.4
Showering		10 in $[-1,0]$	0.001	0.000	0.998	0.000	0.001	1231.0	1305.0

Data and MC comparisons

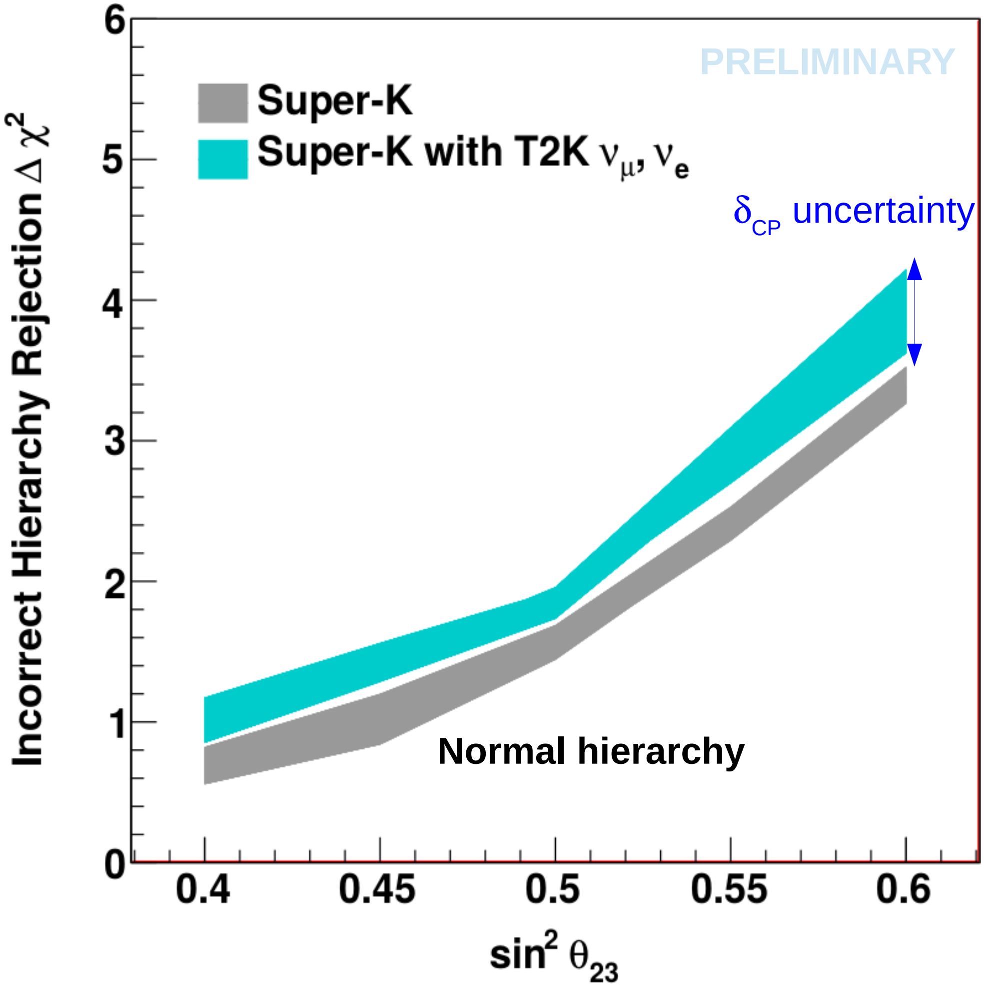


T2K vs Super-K T2K model



– T2K model
-- T2K published data
(arXiv:1502.01550 [hep-ex])

Sensitivity to mass hierarchy



Summary

Fit	Hierarchy	χ^2	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32,13}\rvert$ [eV^2]	δ_{CP}
SK θ_{13} Free	NH	571.7	$0.019^{+0.028}_{-0.014}$	$0.584^{+0.039}_{-0.069}$	$2.47^{+0.17}_{-0.28}$	$4.18^{+1.43}_{-1.64}$
	IH	575.2	$0.008^{+0.017}_{-0.007}$	$0.550^{+0.043}_{-0.078}$	$2.20^{+0.33}_{-0.13}$	$3.85^{+2.35}_{-2.15}$
SK θ_{13} Constrained	NH	571.7	–	$0.588^{+0.031}_{-0.067}$	$2.50^{+0.13}_{-0.20}$	$4.19^{+1.37}_{-1.59}$
	IH	576.1	–	$0.575^{+0.035}_{-0.085}$	$2.50^{+0.08}_{-0.37}$	$4.19^{+1.49}_{-1.63}$
SK+T2K θ_{13} Constrained	NH	639.6	–	$0.550^{+0.040}_{-0.059}$	$2.50^{+0.05}_{-0.13}$	$4.89^{+0.84}_{-1.45}$
	IH	644.8	–	$0.550^{+0.037}_{-0.049}$	$2.40^{+0.13}_{-0.06}$	$4.54^{+0.99}_{-0.96}$

Systematics detail

Systematic Error			Fit Value (%)	σ (%)
Flux normalization	$E_\nu < 1$ GeV[a]		14.3	25
	$E_\nu > 1$ GeV[b]		7.8	15
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$	$E_\nu < 1$ GeV		0.06	2
	$1 < E_\nu < 10$ GeV		−1.1	3
	$E_\nu > 10$ GeV[c]		1.6	5
$\bar{\nu}_e/\nu_e$	$E_\nu < 1$ GeV		1.7	5
	$1 < E_\nu < 10$ GeV		3.4	5
	$E_\nu > 10$ GeV[d]		−1.6	8
$\bar{\nu}_\mu/\nu_\mu$	$E_\nu < 1$ GeV		0.23	2
	$1 < E_\nu < 10$ GeV		2.9	6
	$E_\nu > 10$ GeV[e]		−2.9	15
Up/down ratio	< 400 MeV	e-like	−0.026	0.1
		μ-like	−0.078	0.3
		0-decay μ-like	−0.286	1.1
	> 400 MeV	e-like	−0.208	0.8
		μ-like	−0.13	0.5
		0-decay μ-like	−0.442	1.7
	Multi-GeV	e-like	−0.182	0.7
		μ-like	−0.052	0.2
	Multi-ring Sub-GeV	e-like	−0.104	0.4
		μ-like	−0.052	0.2
	Multi-ring Multi-GeV	e-like	−0.078	0.3
		μ-like	−0.052	0.2
	PC		−0.052	0.2
Horizontal/vertical ratio	< 400 MeV	e-like	0.019	0.1
		μ-like	0.019	0.1
		0-decay μ-like	0.058	0.3
	> 400 MeV	e-like	0.271	1.4
		μ-like	0.368	1.9
		0-decay μ-like	0.271	1.4
	Multi-GeV	e-like	0.62	3.2
		μ-like	0.446	2.3
	Multi-ring Sub-GeV	e-like	0.271	1.4
		μ-like	0.252	1.3
	Multi-ring Multi-GeV	e-like	0.543	2.8
		μ-like	0.291	1.5
	PC		0.330	1.7
K/π ratio in flux calculation[f]			−9.3	10
Neutrino path length			−2.17	10
Sample-by-sample	FC Multi-GeV		−6.5	5
	PC + Stopping UP-μ		0.19	5
Matter effects			0.52	6.8

[a] Uncertainty decreases linearly with $\log E_\nu$ from 25 %(0.1 GeV) to 7 %(1 GeV).
[b] Uncertainty is 7 % up to 10 GeV, linearly increases with $\log E_\nu$ from 7 %(10 GeV) to 12 %(100 GeV) and then to 20 %(1 TeV)
[c] Uncertainty linearly increases with $\log E_\nu$ from 5 %(30 GeV) to 30 %(1 TeV).
[d] Uncertainty linearly increases with $\log E_\nu$ from 8 %(100 GeV) to 20 %(1 TeV).
[e] Uncertainty linearly increases with $\log E_\nu$ from 6 %(50 GeV) to 40 %(1 TeV).
[f] Uncertainty increases linearly from 5% to 20% between 100GeV and 1TeV.

Systematics detail

Systematic Error		Fit Value (%)	σ (%)
M_A in QE		-0.56	10
Single π Production, Axial Coupling		-4.5	10
Single π Production, C_{A5}		-3.0	10
Single π Production, BKG		-8.7	10
CCQE cross section[a]		6.6	10
CCQE $\bar{\nu}/\nu$ ratio[a]		9.3	10
CCQE μ/e ratio[a]		0.71	10
DIS cross section		-4.4	5
DIS model comparisons[b]		3.0	10
DIS Q^2 distribution (high W)[c]		8.2	10
DIS Q^2 distribution (low W)[c]		-5.8	10
Coherent π production		-8.6	100
NC/CC		12.1	20
ν_τ cross section		-13.9	25
Single π production, $\pi^0/\pi^\pm$		-20.2	40
Single π production, $\bar{\nu}_i/\nu_i$ (i=e,μ)[d]		-11.1	10
NC fraction from hadron simulation		-0.54	10
π^+ decay uncertainty Sub-GeV 1-ring	e-like 0-decay	-0.18	0.6
	μ-like 0-decay	-0.24	0.8
	e-like 1-decay	1.2	4.1
	μ-like 1-decay	0.71	0.9
	μ-like 2-decay	1.7	5.7
Meson exchange current[e]		-1.8	10
Δm^2_{21} [27]		0.022	2.4
$\sin^2(\theta_{12})$ [27]		0.34	4.6
$\sin^2(\theta_{13})$ [27]		0.11	5.4

[a] Difference from the Nieves [24] model is set to 1.0
[b] Difference from CKMT [42] parametrization is set to 1.0
[c] Difference from GRV98 [43] is set to 1.0
[d] Difference from the Hernandez[44] model is set to 1.0
[e] Difference from NEUT without model from [24] is set to 1.0

Systematics detail

Systematic Error			SK-I Fit Value	SK-I σ	SK-II Fit Value	SK-II σ	SK-III Fit Value	SK-III σ	SK-IV Fit Value	SK-IV σ
FC reduction			−0.008	0.2	0.005	0.2	0.068	0.8	0.68	1.3
PC reduction			0.007	2.4	−3.45	4.8	−0.012	0.5	−0.78	1
FC/PC separation			−0.10	0.6	0.077	0.5	−0.13	0.9	0.0004	0.02
PC stopping/through-going separation (bottom)			−15.8	23	−2.4	13	−0.31	12	−1.5	6.8
PC stopping/through-going separation (barrel)			3.8	7	−5.7	9.4	−13.9	29	−0.40	8.5
PC stopping/through-going separation (top)			8.5	46	−3.0	19	−12.6	87	−24.1	40
Non-ν background	Sub-GeV μ-like		0.010	0.1	0.065	0.4	0.106	0.5	−0.011	0.02
	Multi-GeV μ-like		0.037	0.4	0.065	0.4	0.106	0.5	−0.011	0.02
	Sub-GeV 1-ring 0-decay μ-like		0.010	0.1	0.049	0.3	0.085	0.4	−0.052	0.09
	PC		0.019	0.2	0.114	0.7	0.381	1.8	−0.282	0.49
	Sub-GeV e-like (flasher event)		0.069	0.5	0.000	0.2	−0.004	0.2	−0.000	0.02
	Multi-GeV e-like (flasher event)		0.013	0.1	0.000	0.3	−0.013	0.7	−0.000	0.08
	Multi-GeV 1-ring e-like		3.6	13	−5.2	38	−1.0	27	2.4	18
	Multi-GeV Multi-ring e-like		3.8	12	3.8	11	0.74	11	0.40	12
Fiducial Volume			−0.86	2	0.10	2	0.22	2	−1.5	2
Ring separation	$<$ 400 MeV	e-like	0.45	2.3	−1.08	1.3	0.80	2.3	0.95	1.6
		μ-like	0.14	0.7	−1.91	2.3	1.04	3	1.79	3
	$>$ 400 MeV	e-like	0.078	0.4	−1.41	1.7	0.45	1.3	−0.60	1
		μ-like	0.14	0.7	−0.582	0.7	0.208	0.6	−0.36	0.6
	Multi-GeV	e-like	0.72	3.7	−2.16	2.6	0.45	1.3	−0.60	1
		μ-like	0.33	1.7	−1.41	1.7	0.35	1	0.72	1.2
	Multi-ring Sub-GeV	e-like	−0.68	3.5	3.16	3.8	0.45	1.3	1.13	1.9
		μ-like	−0.88	4.5	6.82	8.2	−0.90	2.6	1.37	2.3
	Multi-ring Multi-GeV	e-like	−0.60	3.1	1.58	1.9	−0.38	1.1	0.54	0.9
		μ-like	−0.80	4.1	0.666	0.8	−0.73	2.1	−1.43	2.4
Particle identification (1 ring)	Sub-GeV	e-like	0.039	0.23	0.229	0.66	0.053	0.26	−0.123	0.28
		μ-like	−0.031	0.18	−0.173	0.5	−0.038	0.19	0.097	0.22
	Multi-GeV	e-like	0.032	0.19	0.083	0.24	0.062	0.31	−0.155	0.35
		μ-like	−0.032	0.19	−0.090	0.26	−0.060	0.3	0.155	0.35
Particle identification (multi-ring)	Sub-GeV	e-like	−0.22	3.1	−3.43	6	3.50	9.5	−2.26	4.2
		μ-like	0.046	0.66	1.43	2.5	−1.92	5.2	0.86	1.6
	Multi-GeV	e-like	0.45	6.5	5.56	9.7	−1.80	4.9	−1.78	3.3
		μ-like	−0.20	2.9	−2.23	3.9	1.00	2.7	0.86	1.6
Energy calibration			−0.76	3.3	−0.89	2.8	0.06	2.4	0.09	2.1
Up/down asymmetry energy calibration			0.26	0.6	0.24	0.6	0.74	1.3	−0.15	0.4
UP-μ reduction	Stopping		−0.091	0.7	−0.090	0.7	0.162	0.7	0.087	0.5
	Through-going		−0.065	0.5	−0.094	0.5	0.115	0.5	0.053	0.3
UP-μ stopping/through-going separation			0.003	0.4	−0.004	0.6	0.030	0.4	−0.102	0.6
Energy cut for stopping UP-μ			−0.043	0.9	−0.122	1.3	0.957	2	−0.122	1.7
Path length cut for through-going UP-μ			−0.416	1.5	−0.825	2.3	0.993	2.8	1.47	1.5
Through-going UP-μ showering separation			7.53	3.4	−4.68	4.4	2.89	2.4	−3.30	3
Background subtraction for UP-μ	Stopping[a]		10.0	16	−3.1	21	−4.9	20	−6.7	17
	Non-showering[a]		−3.6	18	−3.6	14	1.4	24	2.1	17
	Showering[a]		−12.3	18	−15.7	14	0.1	24	−0.9	24
$\nu_e/\bar{\nu}_e$ Separation			−0.98	7.2	7.02	7.9	0.43	7.7	2.50	6.8
Sub-GeV 1-ring π^0 selection	$100 < P_e < 250$ MeV/c		1.7	9	6.9	10	0.96	6.3	5.23	4.6
	$250 < P_e < 400$ MeV/c		1.7	9.2	9.7	14	0.75	4.9	3.4	3
	$400 < P_e < 630$ MeV/c		1.1	16	7.6	11	3.7	24	13.7	13
	$630 < P_e < 1000$ MeV/c		2.6	14	11.1	16	1.3	8.2	19.4	17
	$1000 < P_e < 1330$ MeV/c		2.2	12	6.8	9.8	1.7	11	27.3	24
Sub-GeV 2-ring π^0			1.3	5.6	−2.7	4.4	1.6	5.9	−0.72	5.6
Decay-e tagging			−3.3	10	−1.0	10	0.9	10	1.3	10
Solar Activity			−1.8	20	20.0	50	2.7	20	0.6	10

[a] The uncertainties in BG subtraction for upward-going muons are only for the most horizontal bin, $-0.1 < \cos\theta < 0$.

Tau decay modes

Decay mode	Branching ratio (%)
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.41 ± 0.04
$e^- \bar{\nu}_e \nu_\tau$	17.83 ± 0.04
$\pi^- \nu_\tau$	10.83 ± 0.06
$\pi^- \pi^0 \nu_\tau$	25.52 ± 0.09
$\pi^- 2\pi^0 \nu_\tau$	9.3 ± 0.11
$\pi^- 3\pi^0 \nu_\tau$	1.05 ± 0.07
$\pi^- \pi^+ \pi^- \nu_\tau$	8.99 ± 0.06
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	8.99 ± 0.06
$h^- \omega \nu_\tau$	2.00 ± 0.08

Flux averaged cross-section

$$\langle \sigma_{theory} \rangle = \frac{\sum_{\nu_\tau,\bar{\nu}_\tau} \int \frac{d\Phi(E_\nu)}{dE_\nu} \sigma_{theory} E_\nu dE_\nu}{\sum_{\nu_\tau,\bar{\nu}_\tau} \int \frac{d\Phi(E_\nu)}{dE_\nu} dE_\nu}$$