Atmospheric Neutrino Oscillations with the Super-Kamiokande detector

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On behalf of the Super-Kamiokande Collaboration

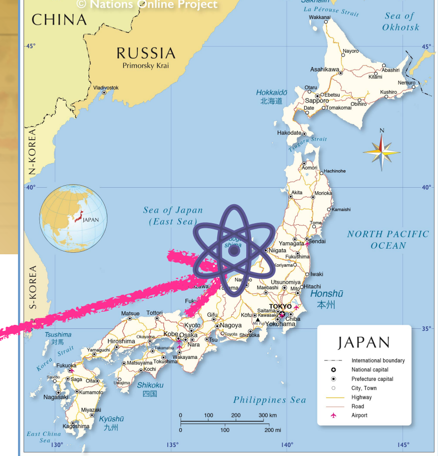
Photo Credit: Kamioka Observatory, ICRR

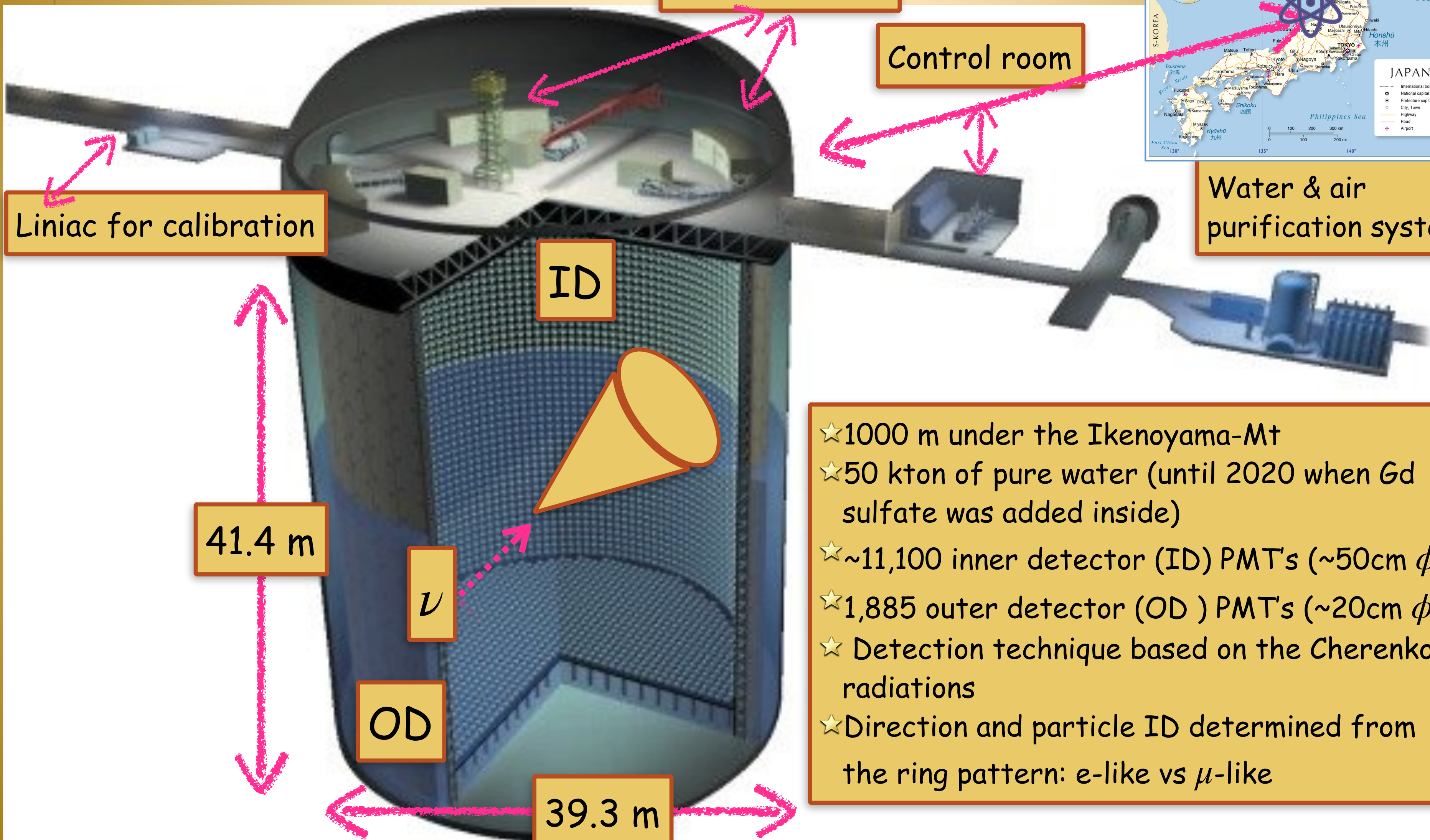
The Super-Kamiokande Collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tohoku University, Japan
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

~230 collaborators from 51 institutes in 11 countries

Super-Kamiokande detector

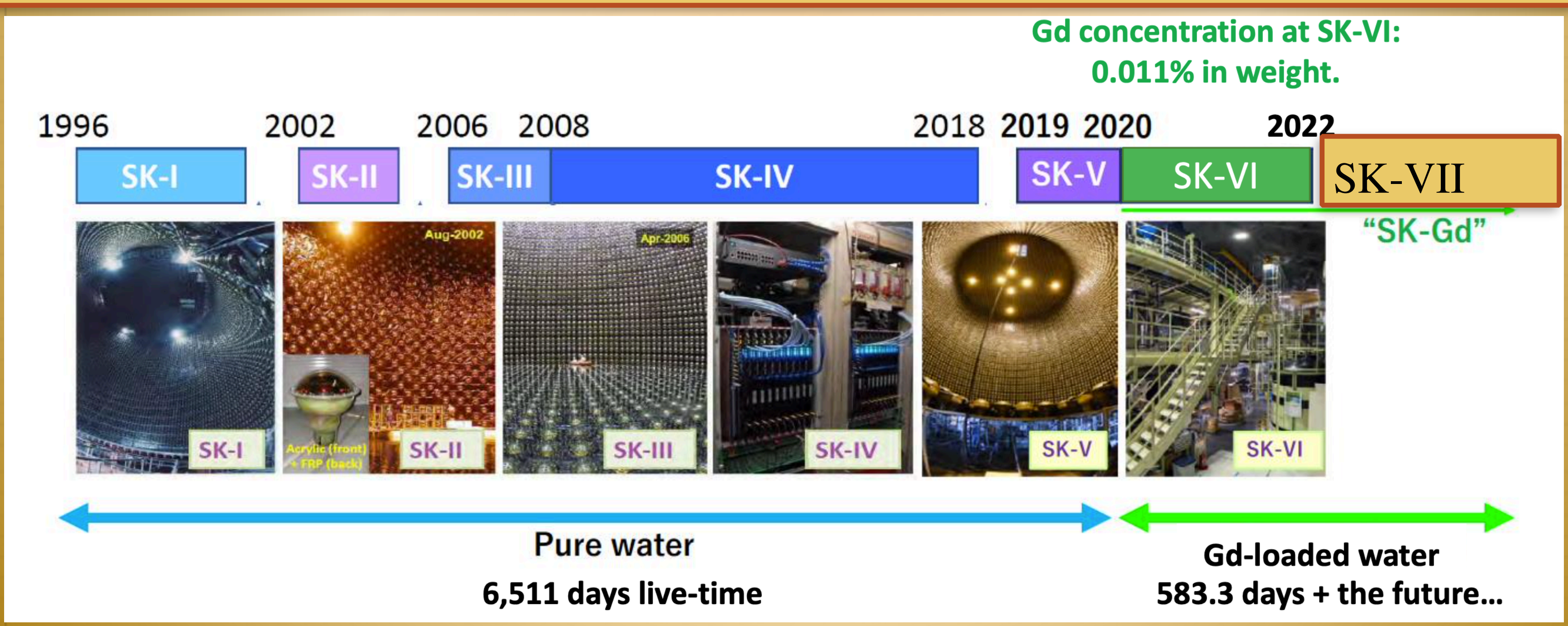




- ☆1000 m under the Ikenoyama-Mt
- ☆50 kton of pure water (until 2020 when Gd sulfate was added inside)
- ☆~11,100 inner detector (ID) PMT's (~50cm ϕ)
- ☆1,885 outer detector (OD) PMT's (~20cm ϕ)
- ☆ Detection technique based on the Cherenkov radiations
- ☆Direction and particle ID determined from the ring pattern: e-like vs μ-like

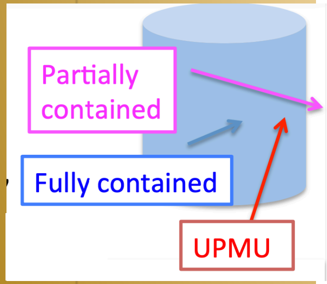
Super-Kamiokande experiment

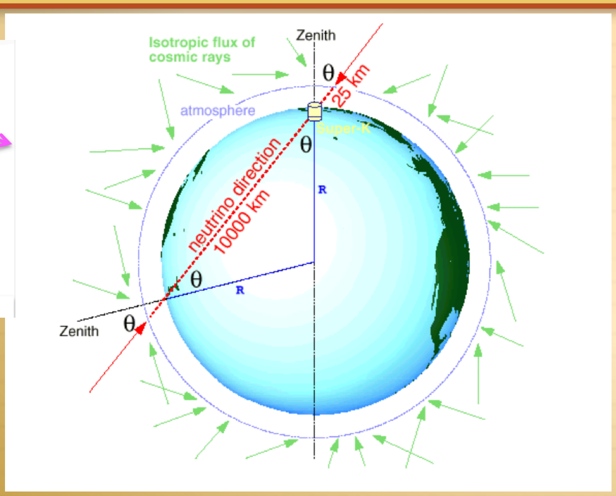
- ☆ Super-Kamiokande (SK) has been taking data since 1996 and has come through seven run periods
- ☆ Densely packed PMTs (40%/20% for SK-II) and good water quality provide excellent sensitivity for various physics targets.
- ☆ In 2020 we have added Gd sulfate to the water in order to increase the sensitivity for neutron capture; this improved tagging of the reaction IBD

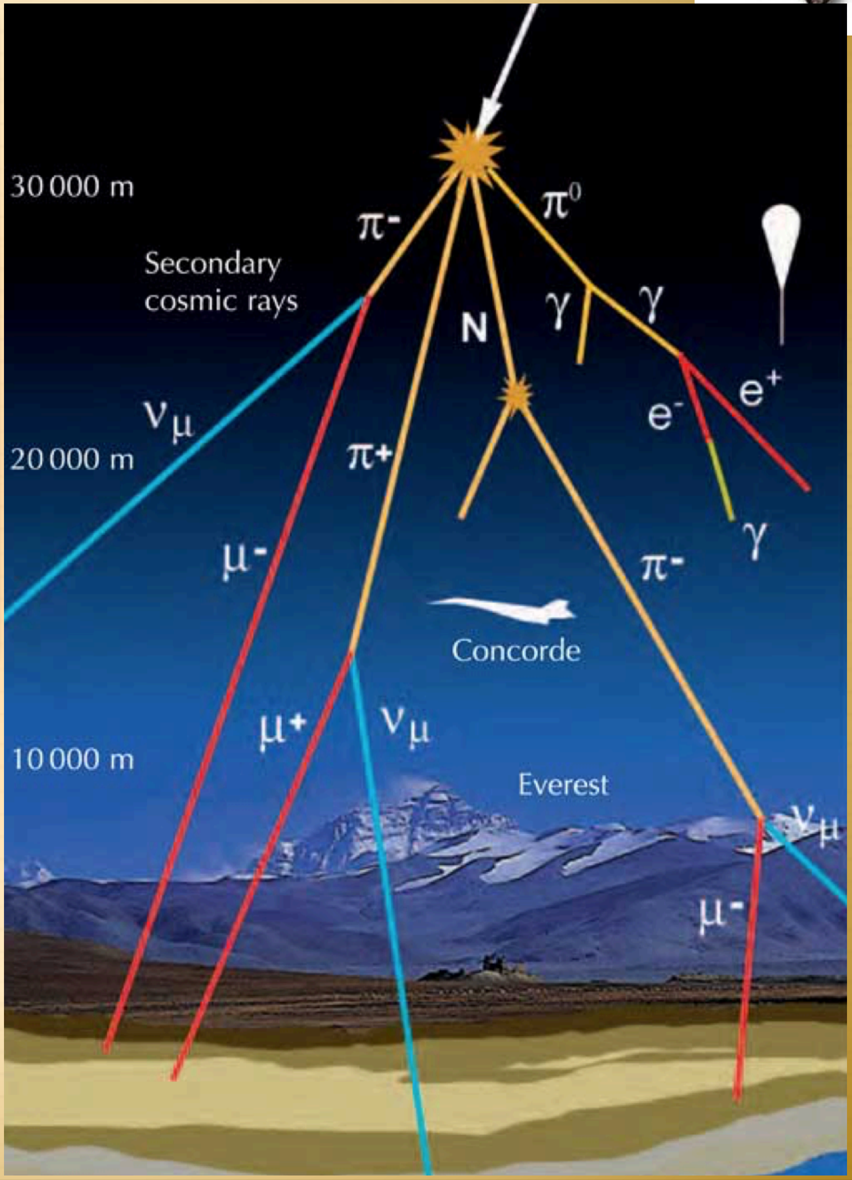


Atmospheric neutrinos

- Neutrinos are produced when cosmic protons interact with the nuclei in the atmosphere:
  - $p, A + air \rightarrow \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}$
  - $\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$
  - $\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \nu_{\mu}(\bar{\nu}_{\mu})$
  - $K^{\pm}, K_{L}^{0} \rightarrow [\pi^{\pm}, \pi^{0}] + e^{\pm} + \nu_{e}(\bar{\nu}_{e})$
- Neutrinos with vide range of energy MeV- PeV produced isotropically about the Earth atmosphere
- Path lengths 10- 13000 km



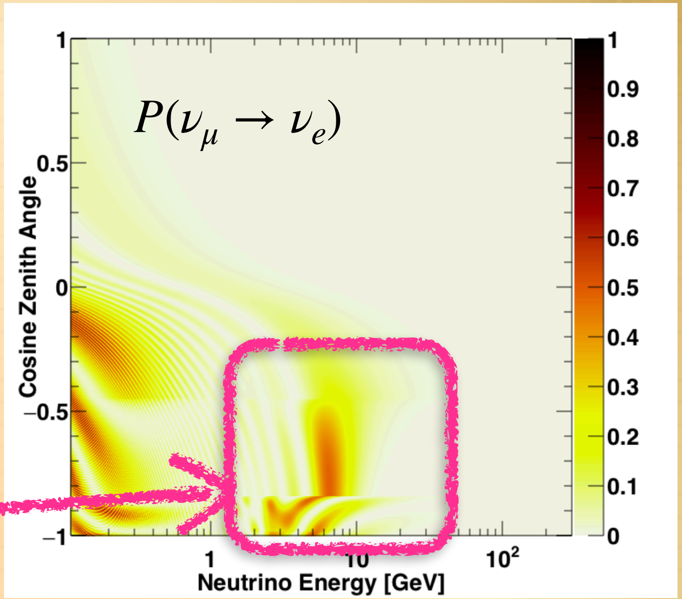




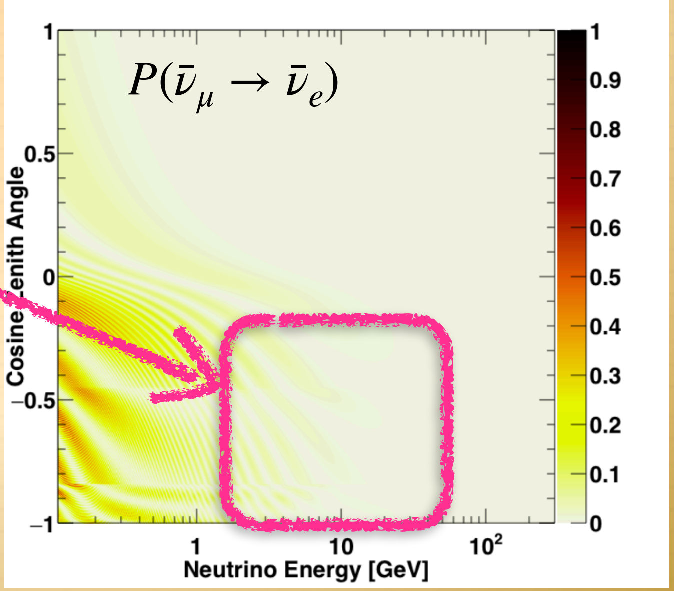
Atmospheric neutrino oscillations

- Oscillograms plotted for normal ordering (NO) with: $\Delta m^2_{21} = 7.7 \times 10^{-5}$, $\sin^2\theta_{23} = 0.50$, $\sin^2\theta_{12} = 0.30$, $\sin^2\theta_{13} = 0.0219$ and $\delta_{CP} = 0$

  Phys.Rev.D 97 (2018)



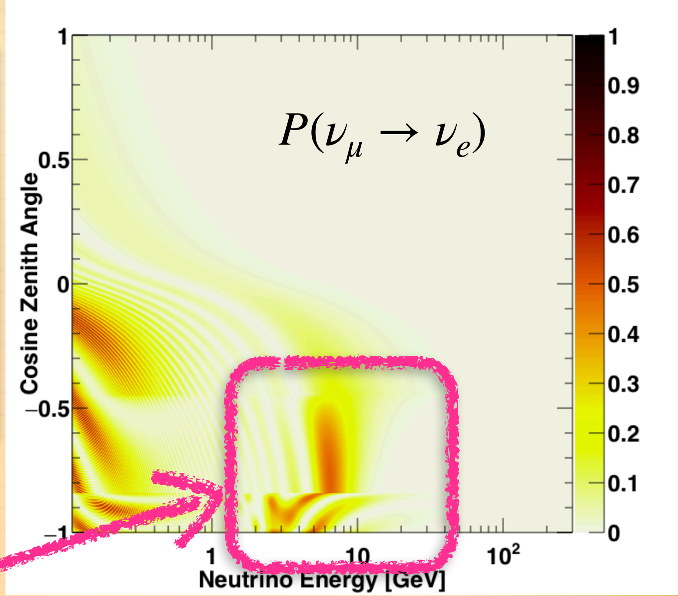
- **Impact of matter effects:**
  - **NO: enhancement of ν_e appearance**
  - **NO: effect is not present for $\bar{\nu}_\mu \to \bar{\nu}_e$**
  - **IO; situation is reversed**



- **Thanks to presence of matter effects we are sensitive to mass hierarchy**

Atmospheric neutrino oscillations

- Three flavour analysis with:
  - **Matter effects: - sensitive to mass hierarchy**
  - **Oscillations of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ are also sensitive to octant θ_{23}**
  -

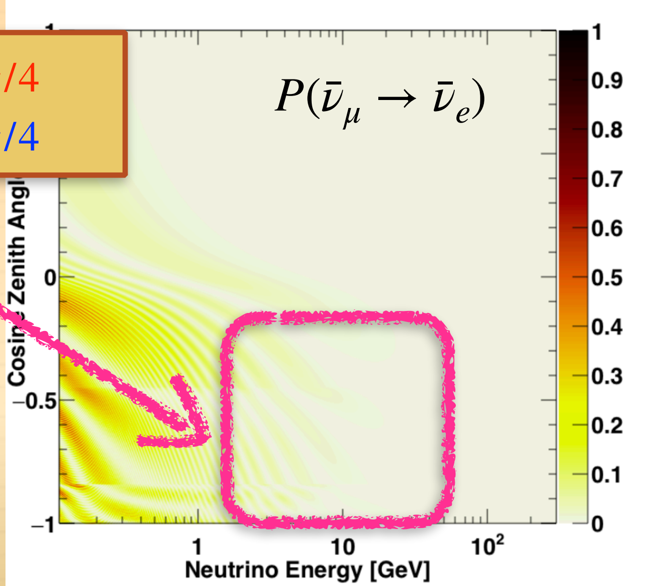


- **ν_e samples:**
  - **Multi-GeV e-like ν_e**
  - **Multi-Ring e-like ν_e**

More e^- for $\theta_{23} > \pi/4$

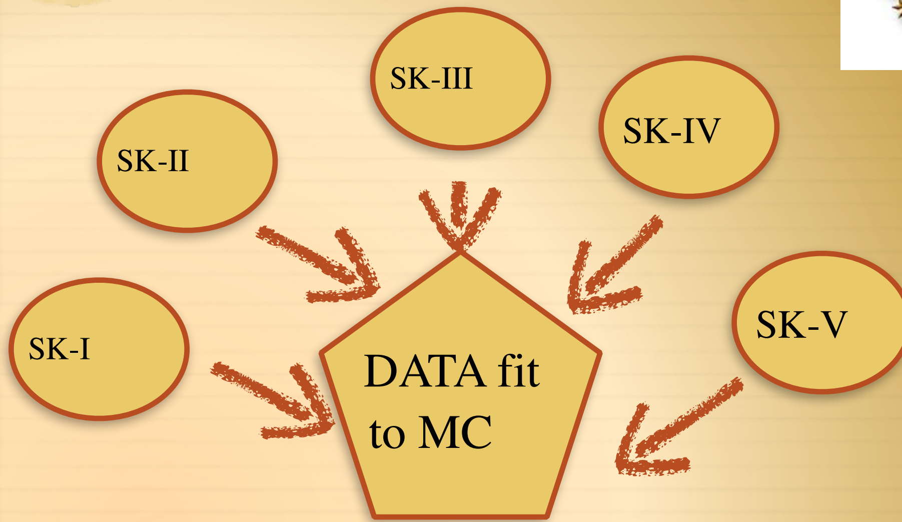
More e^+ for $\theta_{23} < \pi/4$

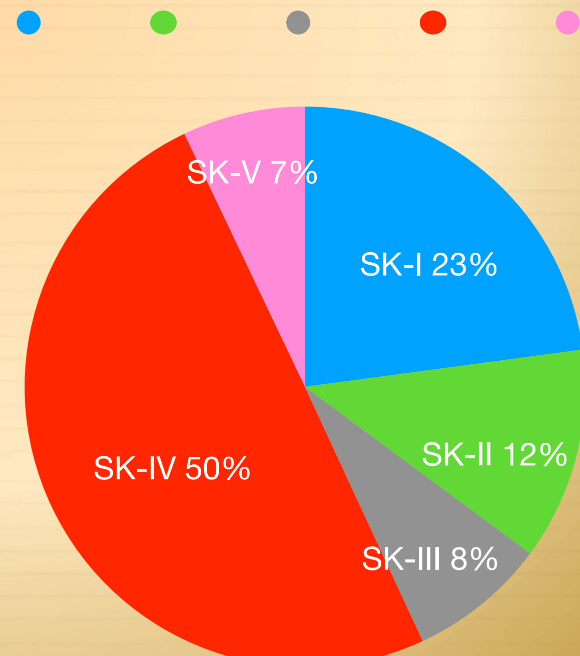
- **$\bar{\nu}_e$ samples:**
  - **Multi-GeV e-like $\bar{\nu}_e$**
  - **Multi-Ring e-like $\bar{\nu}_e$**



Oscillation analysis method at SK

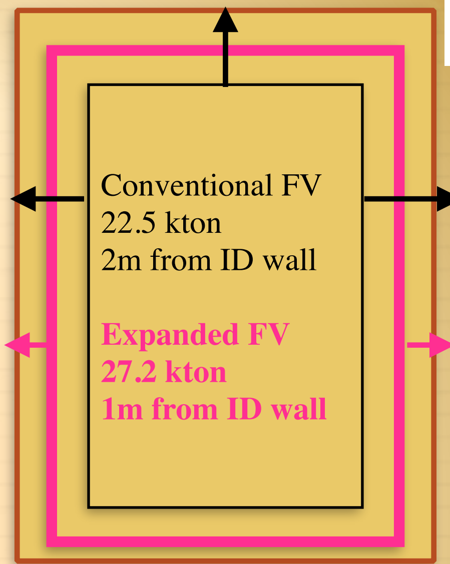
- Data are fit to the MC using χ^2 method assuming Poisson statistics and adding systematic errors as scaling factors on the MC in each bin (more in Phys.Rev.D 97 (2018))
- Reactor constraints on $\sin^2\theta_{13}: 0.0220 \pm 0.0007 (PDG2022)$
- Solar and Kamland: $\sin^2\theta_{12}, \Delta m^2_{21}$
- **Free to fit** : $\Delta m^2_{32}, \sin^2\theta_{23}, MO(NO/IO), \delta_{CP}$
- **What is new in this analysis !!!**
  - **SK-V data added**
  - **Enlarged FV region;**
  - New multi-ring selections
  - Systematics improvement

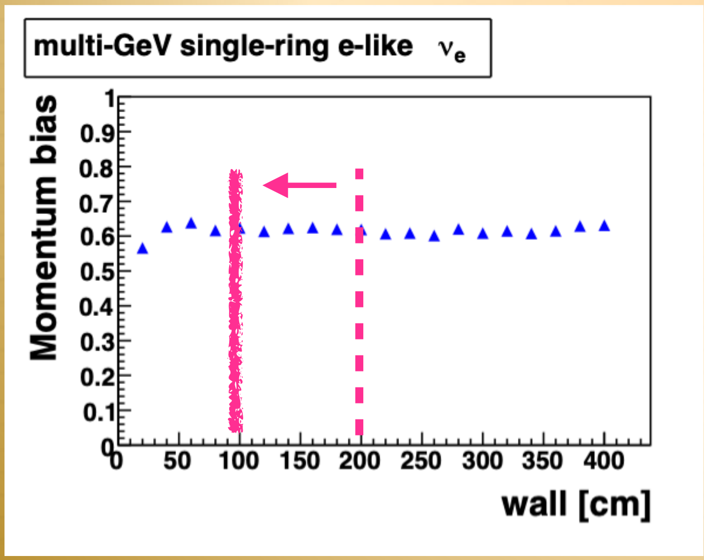


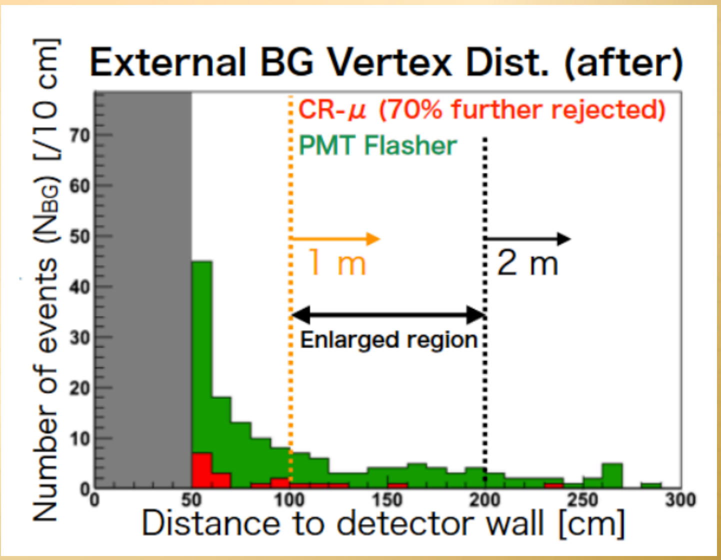


Enlarging the Fiducial Volume (1)

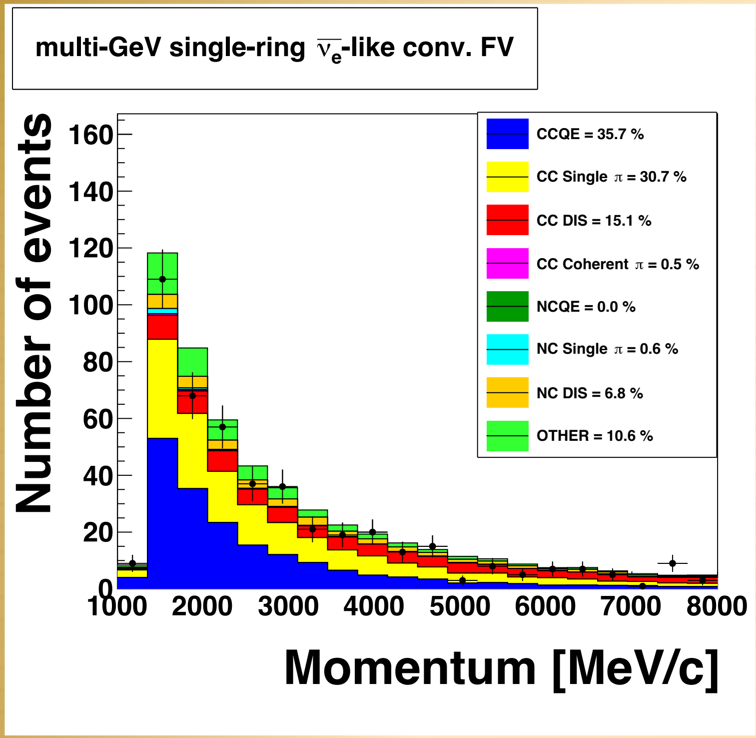
- So far only events with vertex reconstructed within 2m from the nearest wall have been used for the analysis (Conventional FV of 22.5kt)
- Systematic uncertainties have been evaluated in expanded FV region.

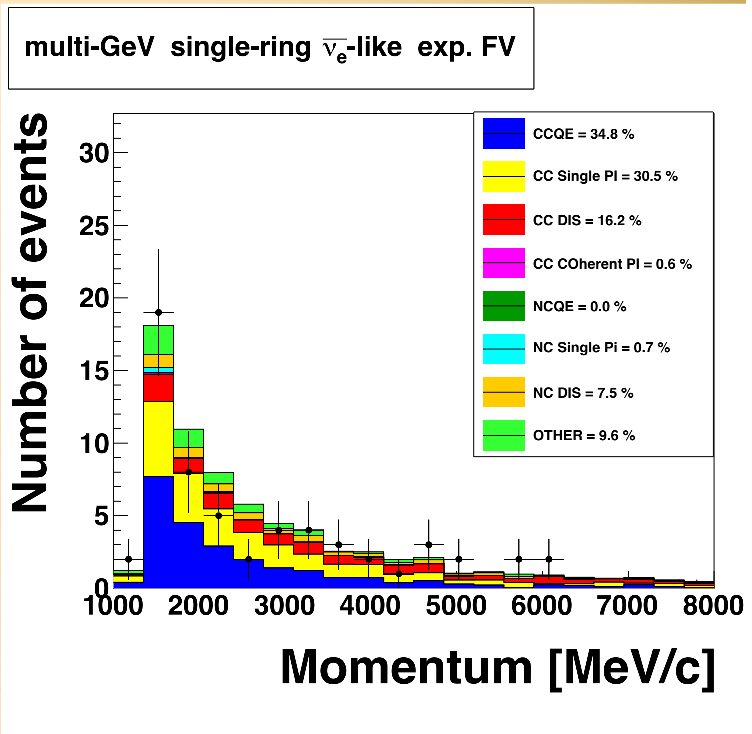






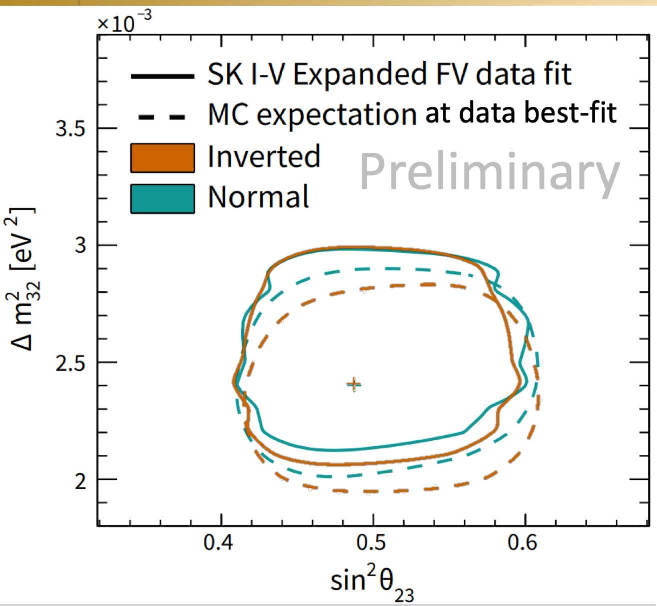
Enlarging the Fiducial Volume (2)

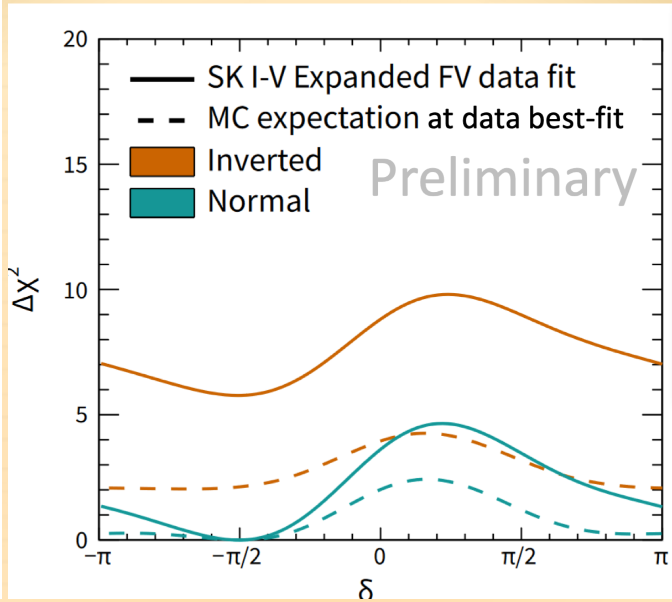




☆ Expansion of FV region allow us to **increase the statistics by 20%** keeping systematic uncertainties still satisfactory

SK only: parameters determination





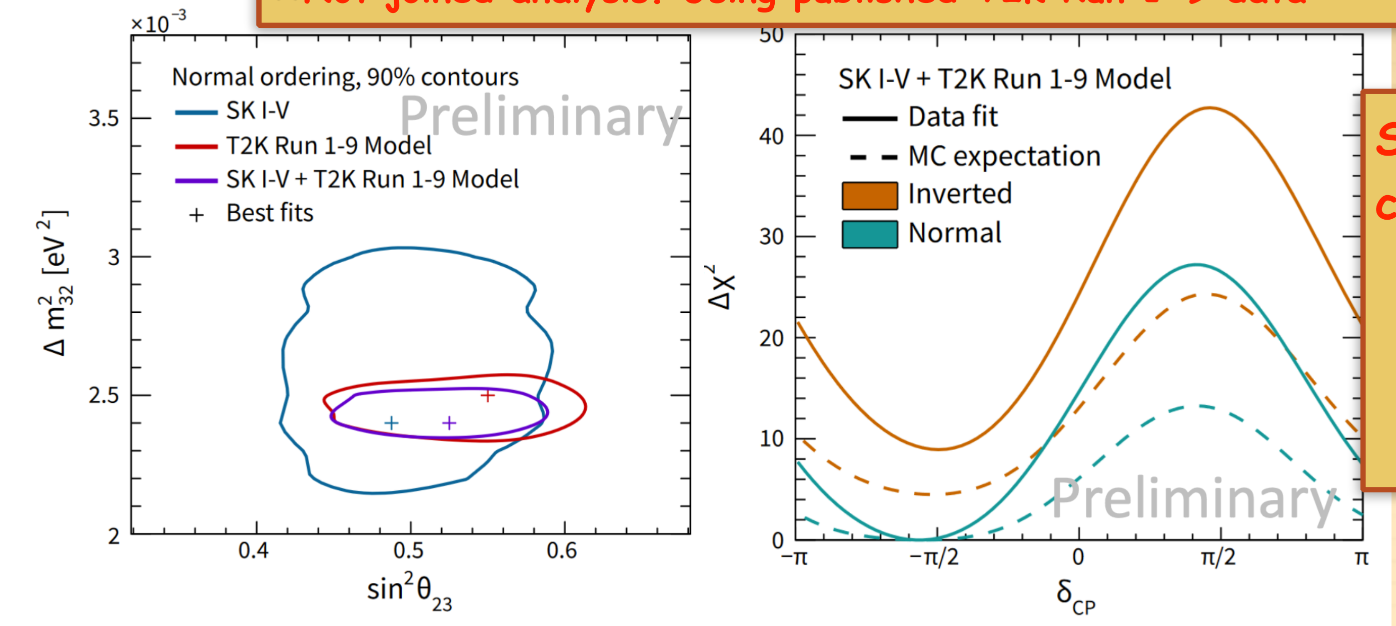
SK atmospheric neutrino data favours:

- ☆**Maximal mixing**
- ☆**NO ($\Delta\chi^2 = 5.8$)**
- ☆$\delta_{CP} \simeq -\dfrac{\pi}{2}$

930 bins	χ^2	$\delta_{CP} \in [0,2\pi]$	$\sin^2\theta_{23}$	Δm^2_{23}
SK NO	**1000.42**	**4.71**	**0.49**	$2.4 \times 10^{-3}\mathrm{eV}^2$
SK IO	**1006.19**	**4.71**	**0.49**	$2.4 \times 10^{-3}\mathrm{eV}^2$

SK + T2K - parameters determination

☆Not joined analysis. Using published T2K Run 1-9 data



SK + external T2K constrains favour:

- ☆Maximal mixing
- ☆NO ($\Delta\chi^2 = 8.9$)
- ☆$\delta_{CP} \simeq -\frac{\pi}{2}$

930 bins	χ^2	$\delta_{CP} \in [0,2\pi]$	$\sin^2\theta_{23}$	Δm^2_{23}
SK+T2K NO	**1086.33**	**4.54**	**0.53**	$2.4 \times 10^{-3}\mathrm{eV}^2$
SK +T2K IO	**1095.25**	**4.71**	**0.53**	$2.4 \times 10^{-3}\mathrm{eV}^2$

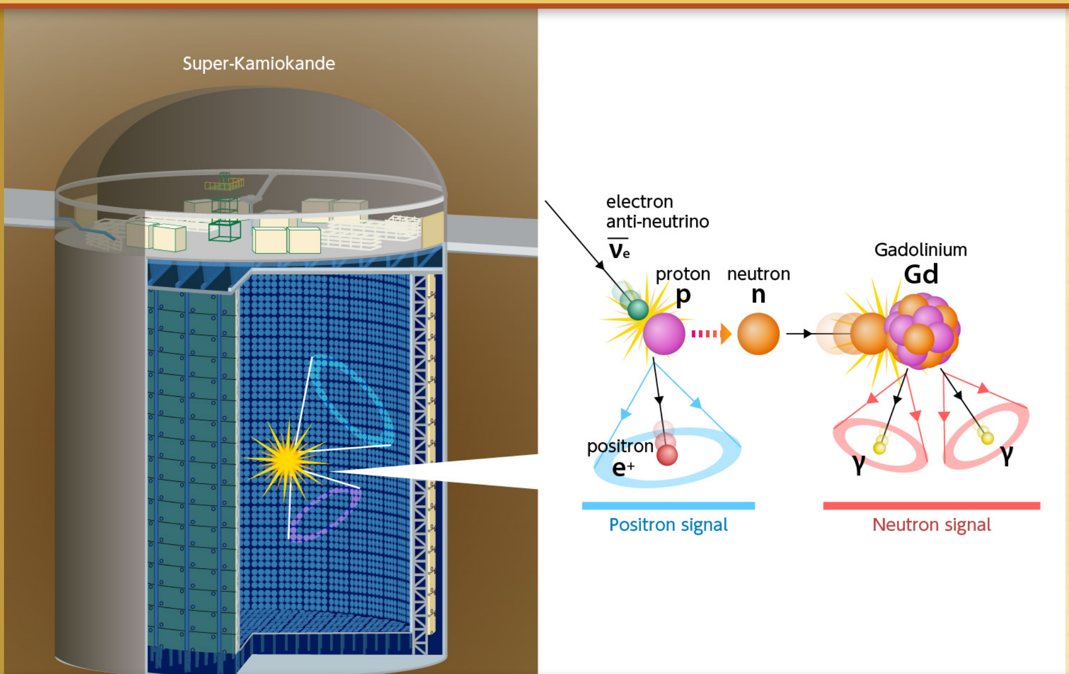
☆SK is sensitive to mass ordering; T2K sensitive to δ_{CP}

SK-Gd era

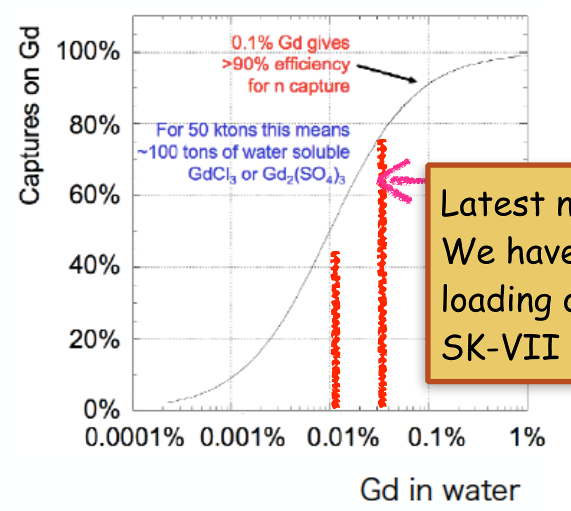
Gadolinium project at Super-K: SK-Gd

Why Gd salt was added ?

MAIN AIM: improves SK's ability to observe the sea of neutrinos, known as "supernova relic neutrinos"
For atmospheric neutrino oscillations: we may be able to improve neutrino-antineutrino separation

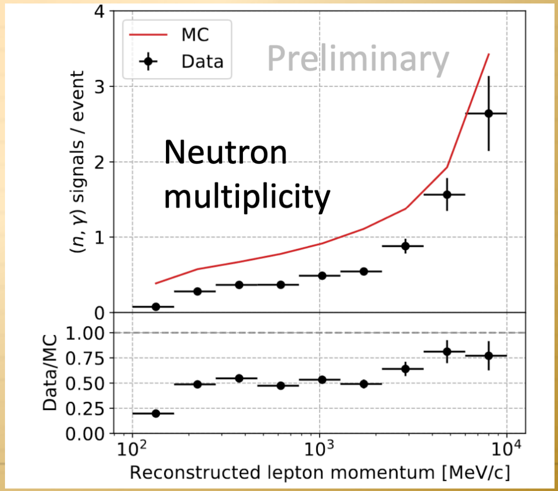


Dissolve Gadolinium into Super-K
J.Beacom and M.Vagins, Phys.Rev.Lett.93(2004)171101



Latest news:
We have finished Gd loading on July 5th!!
SK-VII era

Cross section for neutron capture for Gd is 49000 barns, while for protons is only 0.3 barn.



Problems:
Measured neutron multiplicity is lower than present MC prediction.

Summary

- Atmospheric neutrino oscillation analysis is:
  - **favouring NO,** $\delta_{CP} \simeq -\frac{\pi}{2}$ **and maximal** $\sin^2\theta_{23}$
  - with all pure water data sets (SK-I ~V),
  - with expanded fiducial volume.
- SK-Gd
  - SK-VI (Gd~0.01%) analysis is ongoing
  - SK-VII (Gd~0.03%) just started!

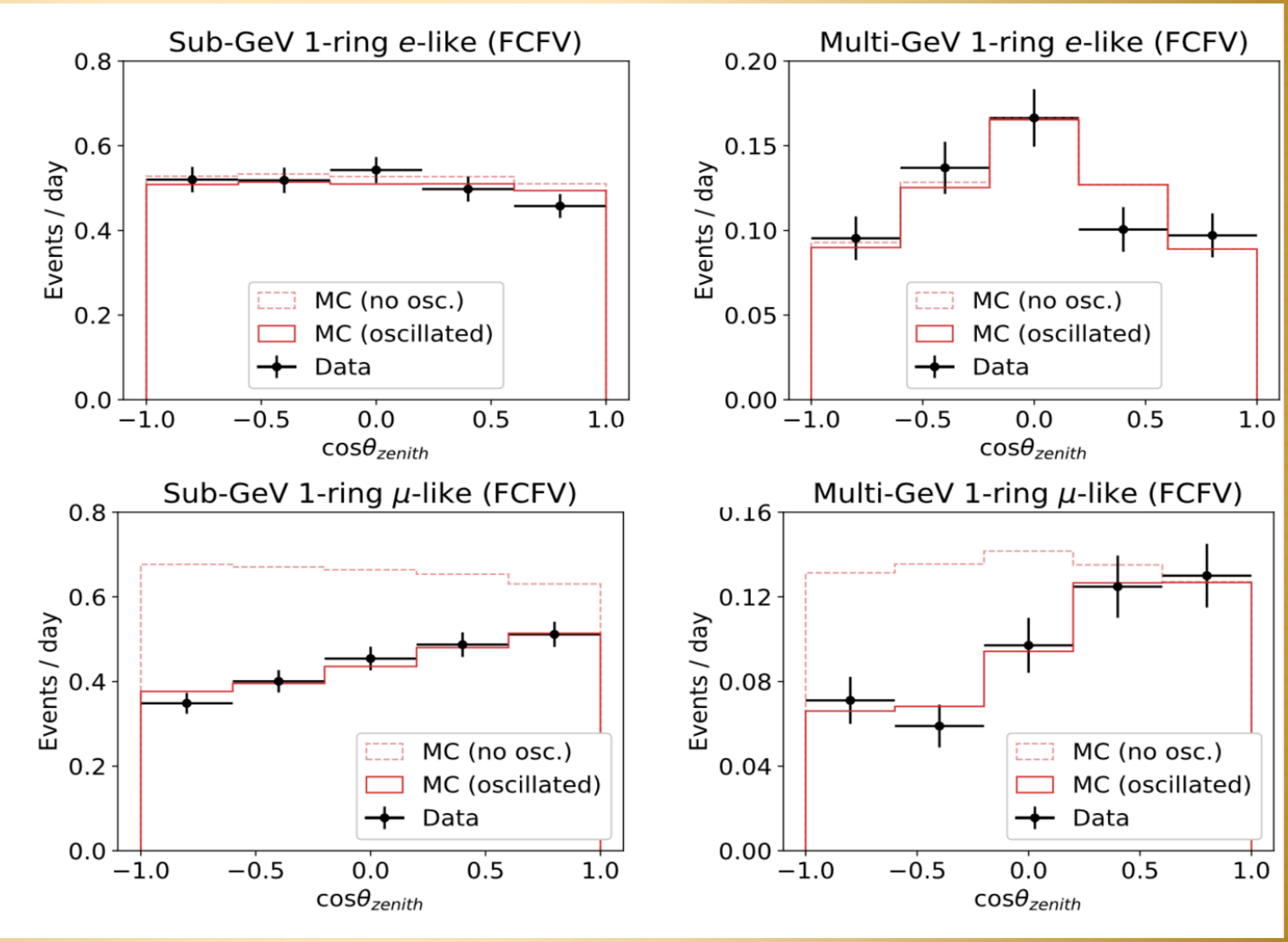
SK posters @ ICHEP22

- **Maitrayee Mandal: "Tau neutrinos appearance in the flux of atmospheric neutrinos at the Super-Kamiokande"**, poster #774
- **Masayuki Harada, "Evaluation of neutron tagging for SK-Gd experiment"**, poster #1218
- **Ji-Woong Seo, "Sensitivity study for the proton decay via $p \to \mu^+\pi^0\pi^0$ in the Super-Kamiokande detector"**, poster #597

Thank you !

SK - VI performance

- At SK- VI Gd loading has exceeded the 0.011% which corresponds to 50% of neutron tagging efficiency
- On **June 1st 2022** we have started SK-VII period with more Gd being added to SK tank!
- Stay tuned !



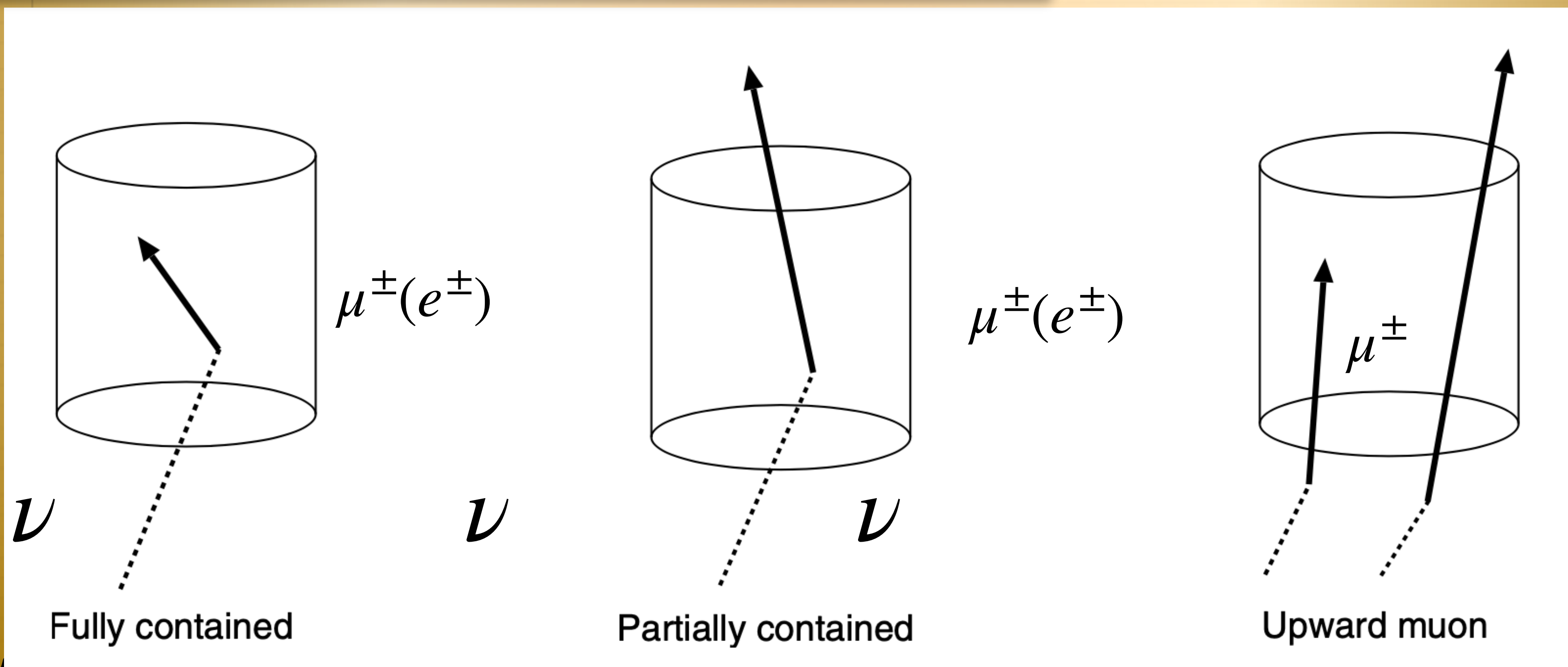
HE−ν samples

Fully contained (FC):
- Reconstructed vertex in ID
- OD hits<16

Partially contained (PC):
- Reconstructed vertex in ID
- OD hits>=16

Upward-going muons (UPMU):
- Through-going with requirement of track length >7 m
- Stopping in the detector

For events classified as FC and PC, the neutrino interacts within the fiducial volume, defined as the region located more than 100 cm from the ID wall

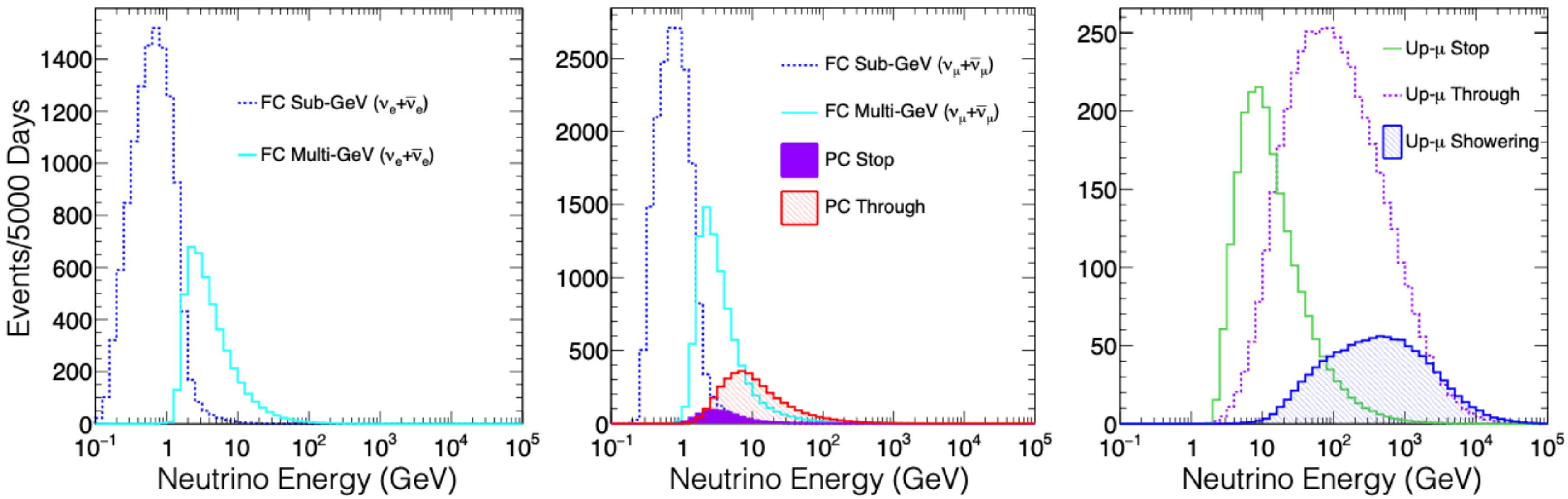


HE−ν samples

Fully contained (FC)

Partially contained (PC)

Upward-going muons (UPMU):



Expected neutrino energy spectra of different event categories

Multi-GeV samples @ SK-IV

$\bar{\nu}_\mu$ like
- Number of decay electrons=1
- Number of tagged neutrons>0

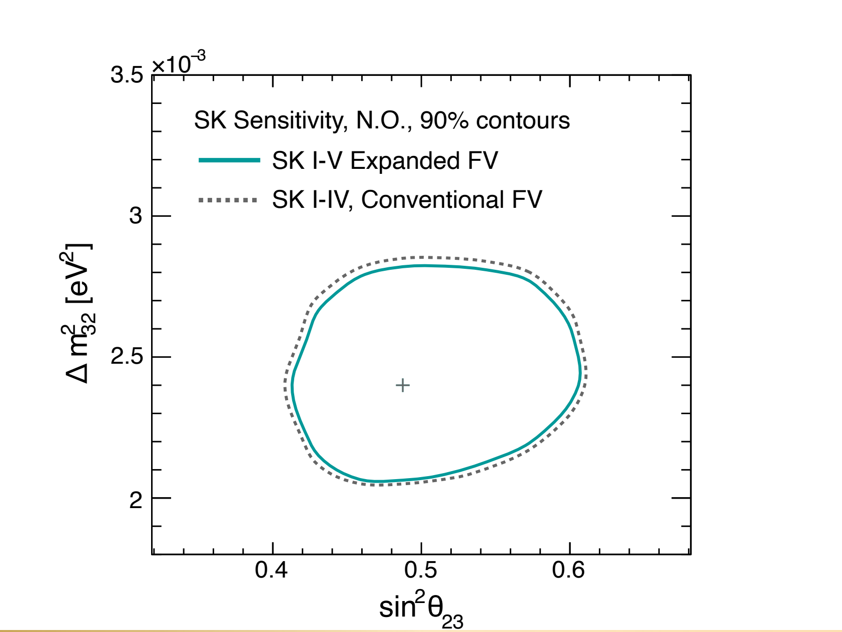
ν_μ like:
- Number of decay electrons $\neq$1
- Number of decay electrons =1 and number of tagged neutrons=0

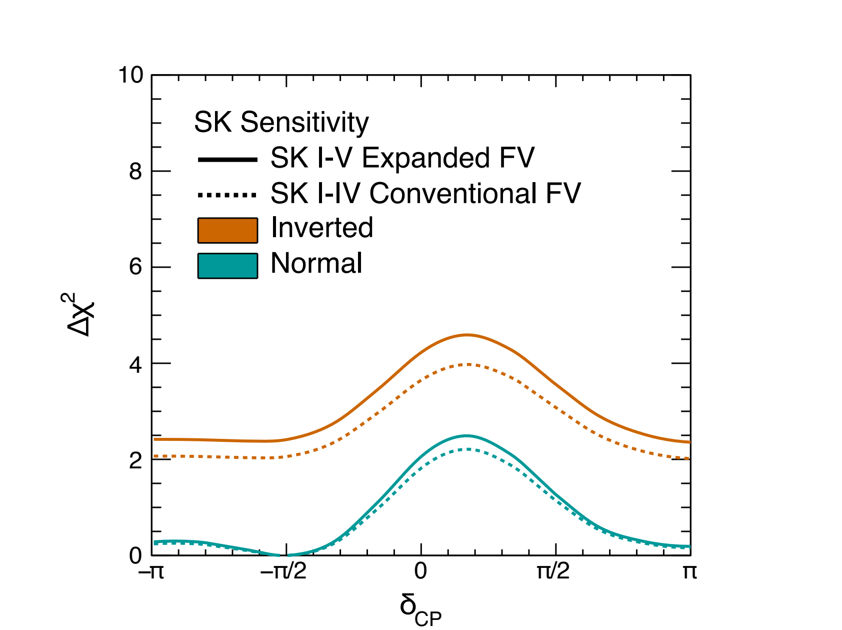
$\bar{\nu}_e$ like
- Number of decay electrons=0
- Number of tagged neutrons>0

$\nu_e + \bar{\nu}_e$ like
- Number of decay electrons=0
- Number of tagged neutrons=0

ν_e like:
- Number of decay electrons >0

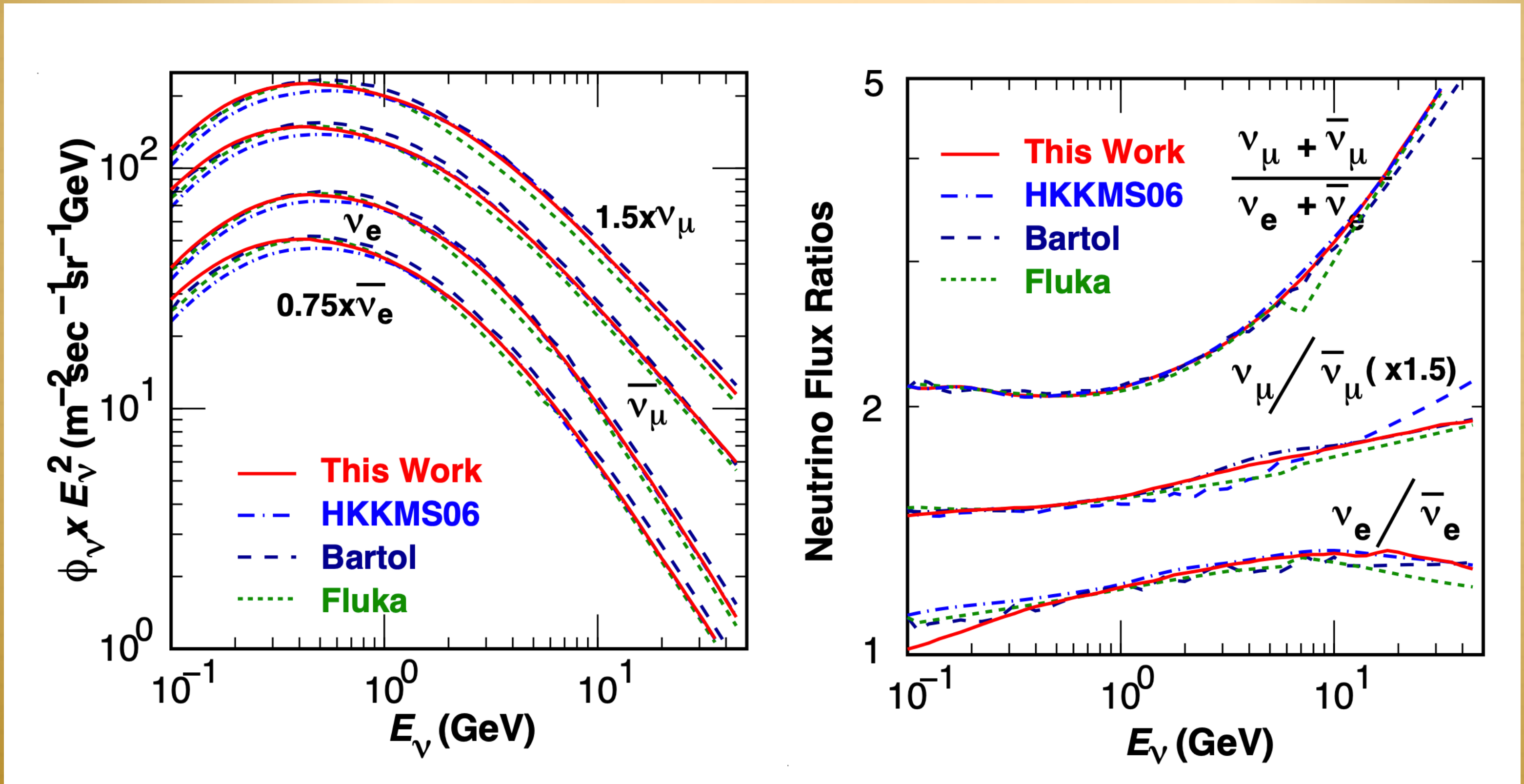
SK only - parameters determination





Atmospheric neutrino flux

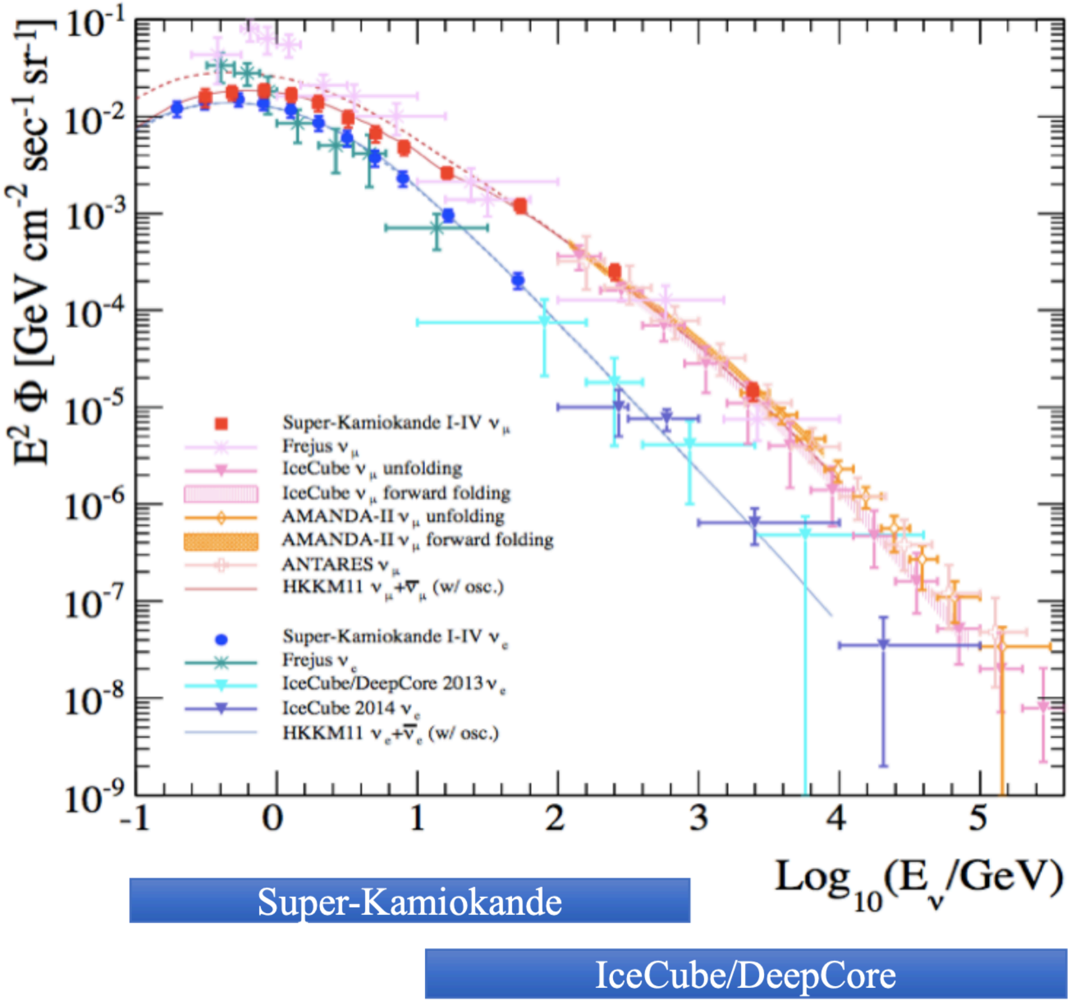
- The simulation of atmospheric neutrinos is performed following the flux calculation of Honda et. al M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa, Phys.Rev. D83, 123001 (2011), arXiv:1102.2688 [astro-ph.HE] and using the NEUT simulation software.



Atmospheric neutrino flux

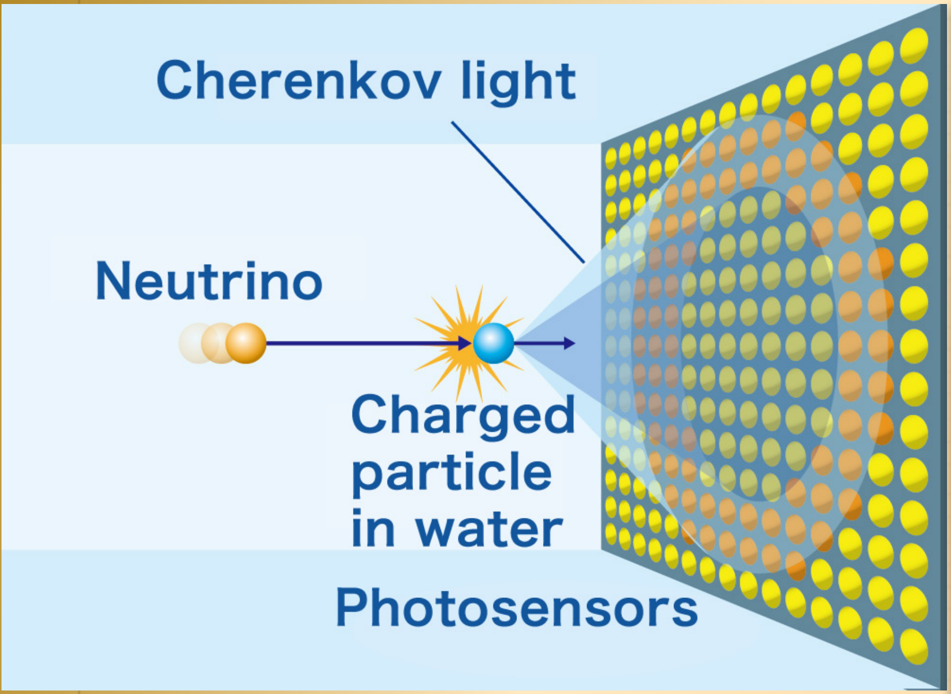
Atmospheric Neutrino Flux:

PHYSICAL REVIEW D 94, 052001 (2016)



R. Wendell talk at:
29th International Symposium on Lepton Photon Interactions at High Energies 2019

Detection technique



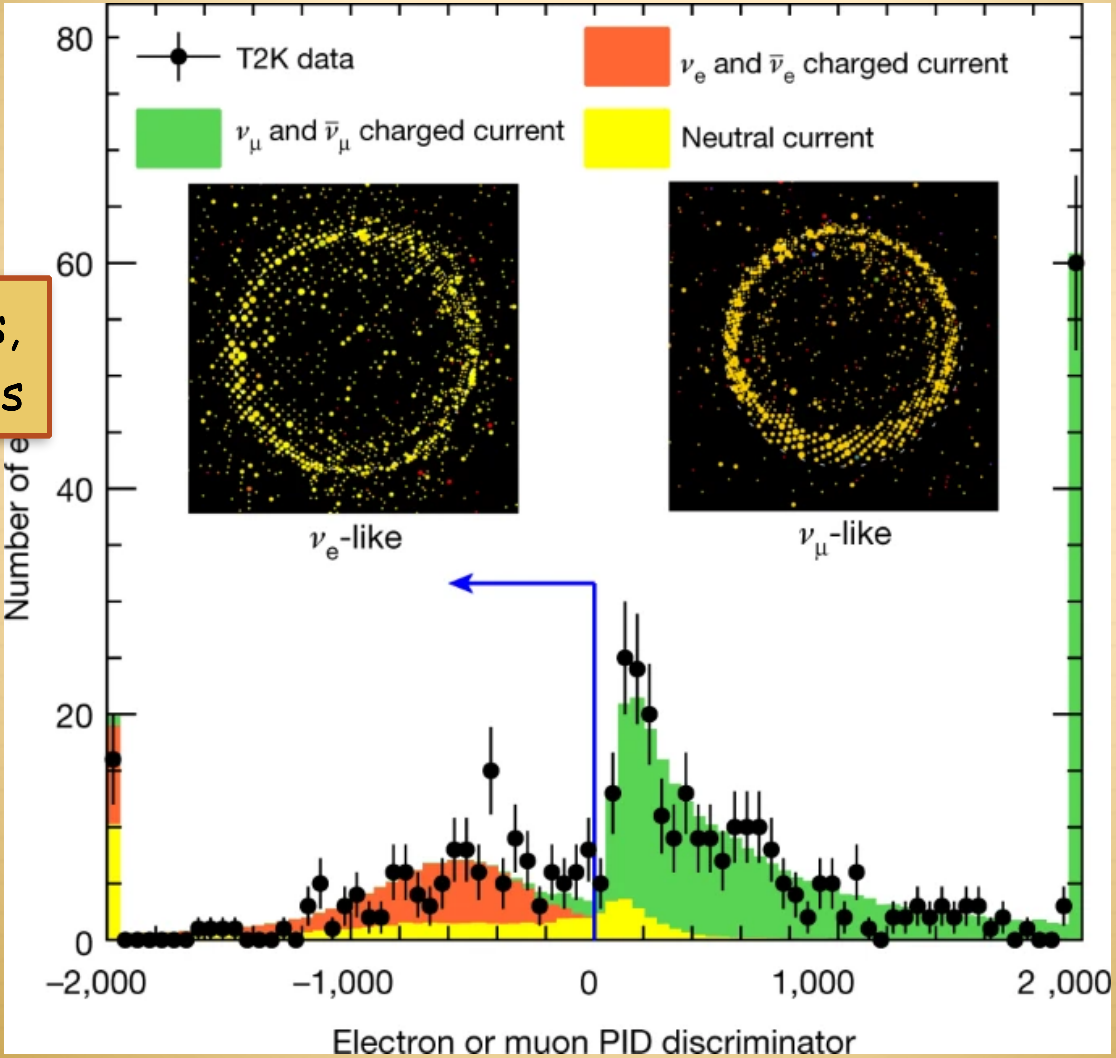
- **In water, light travels about 25% slower** than it does in a vacuum and it is possible for an energetic particle to travel faster than light.
- A **blue light** called **Cherenkov light** is emitted by charged particle.
- This light is detected by an array of light sensitive PMT's
- By measuring **the brightness, shape, and direction of the ring** we can figure out how much energy the particle had, whether it is a muon or electron, and which way it was going.

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\nu_e + n \rightarrow e^- + p$$

Separation between μ and e in Cherenkov detectors

Fuzzy edges, blurred rings



Sharp edges of the ring