Super-Kamiokande: Atmospheric ν oscillation analysis

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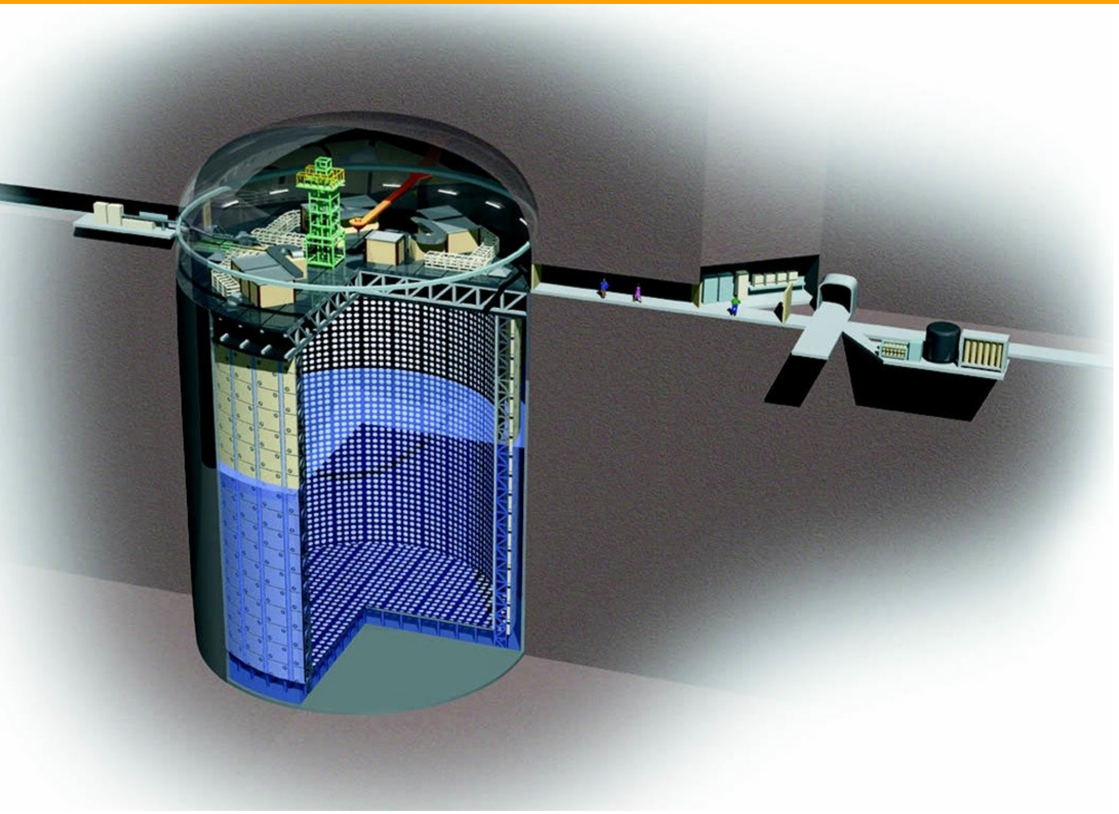
[UAM for the Super-Kamiokande Collaboration]

The Super-Kamiokande Collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
University of British Columbia, 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
Imperial College London, UK
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
KEK, Japan
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
Osaka University, Japan
University of Oxford, UK
Queen Mary University of London, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
The University of Winnipeg, Canada
Yokohama National University, Japan

A fully international collaboration of 45 institutions and 9 countries, and still growing

The Super-Kamiokande Experiment



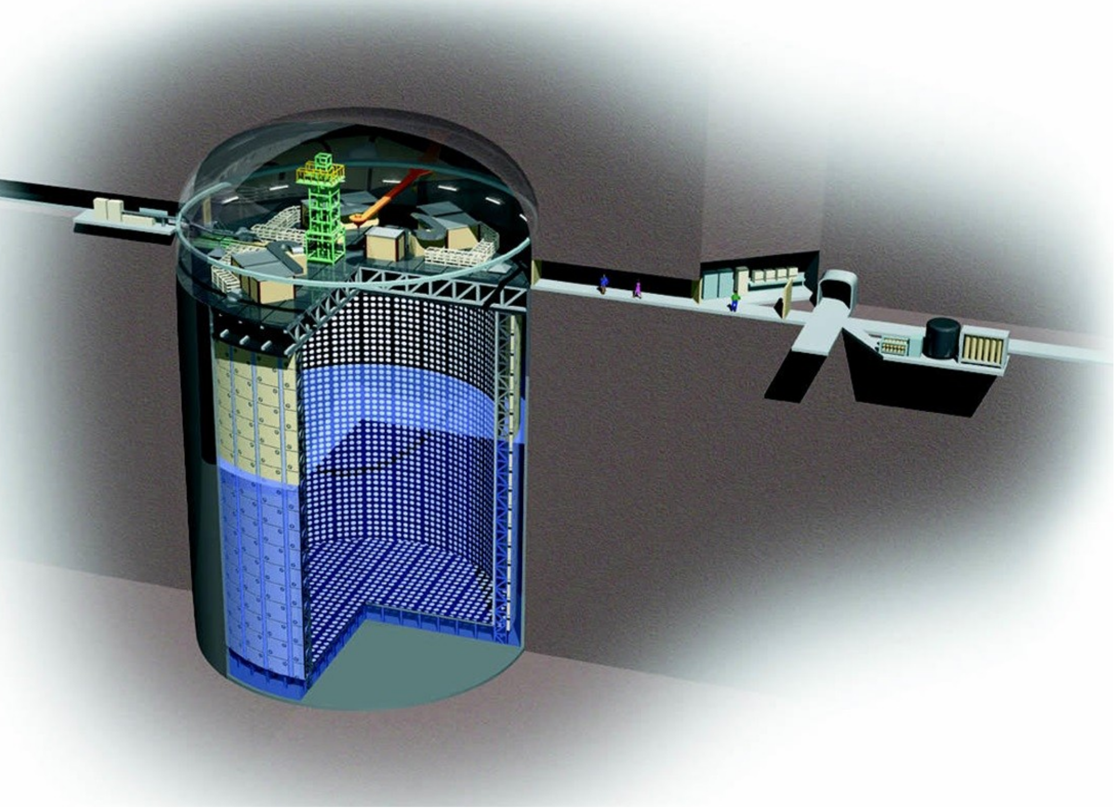
The SK is a **water-Cherenkov** detector located underground in the Kamioka mine with 1000 m of rock overburden

It is a **50 kton** tank filled with **ultra-pure water**

The detector is **optically divided in two** at 2 m from the detector walls:

- Inner detector: used for physics studies and instrumented with **11129 20”-PMTs** facing inwards
- Outer detector: vetoes cosmic rays and radioactivity signals from the rock, instrumented with **1885 8”-PMTs** facing outwards

The Super-Kamiokande Experiment



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Phase	Period	Number of PMTs		FRP case	Electronics
		ID (Coverage)	OD		
SK-I	Apr. 1996 - Jul. 2001	11146 (40%)	1884	no	ATM
SK-II	Oct. 2002 - Oct. 2005	5182 (19%)	1884	yes	ATM
SK-III	Jul. 2006 - Sep. 2008	11129 (40%)	1884	yes	ATM
SK-IV	Sep. 2008 - Today	11129 (40%)	1884	yes	QBEE

The Super-Kamiokande Experiment

SK began its operation already 22 years ago and has been providing key discoveries and measurements in a broad rage of physics (not only neutrino physics) ever since

- Discovery of neutrino oscillations and the massive character of neutrinos through atmospheric neutrinos (2015 Nobel Prize)
- Precise measurement of solar neutrinos, solving the solar neutrino problem
- As LBL far detector of KEK and T2K, confirming and improving the measurements of the oscillation parameters
- Best limits for the Diffuse Supernova Neutrino Background (DSNB)
- Best limits for proton decay in various channels
- Competitive bounds for new physics, dark matter, Lorentz violation, sterile neutrinos

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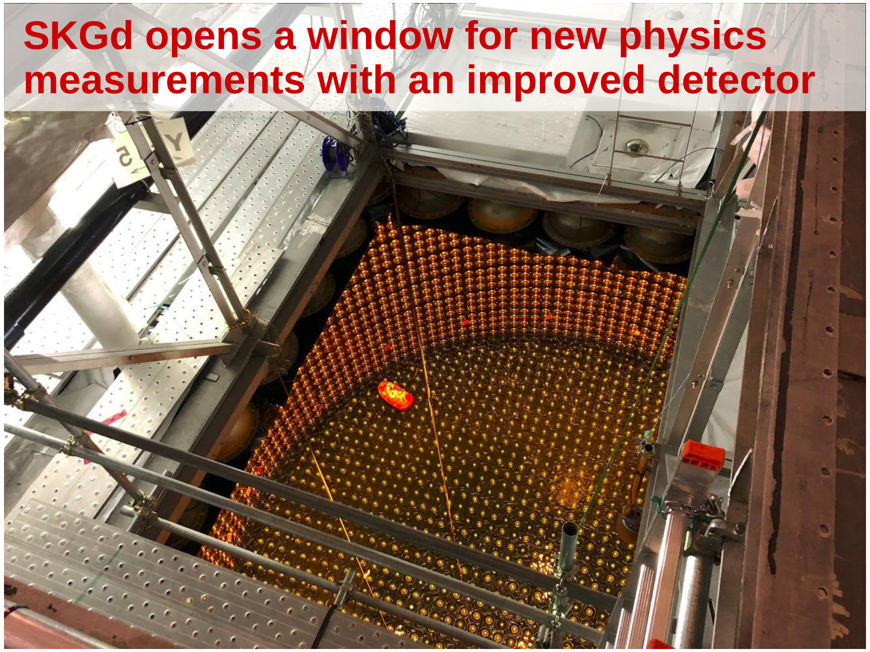
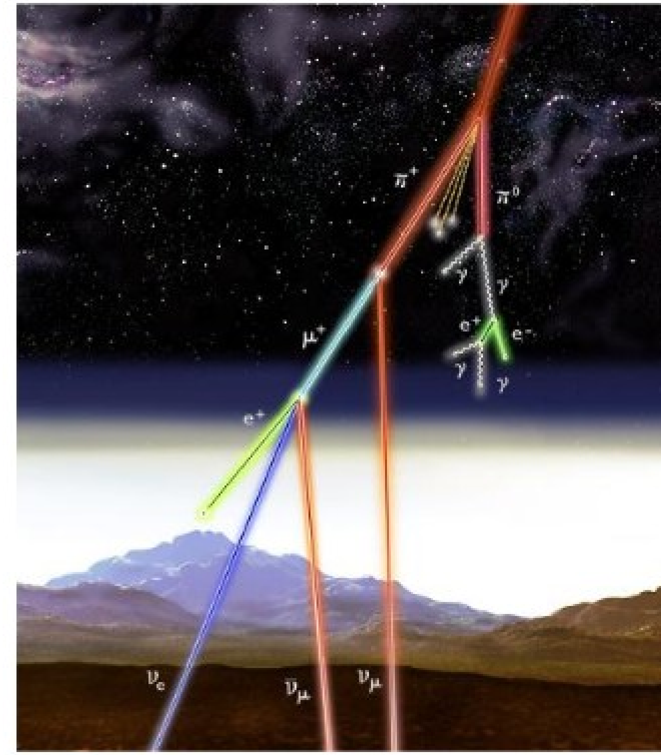
Currently, SK is getting ready to enter its next phase, **SKGd**, the addition of Gadolinium to enable very efficient neutron tagging keeping all the benefits of SK

- The detector has been drained, refurbished and some of the PMTs replaced
- SK-V will begin next year
- Operation with Gadolinium will start in 2020

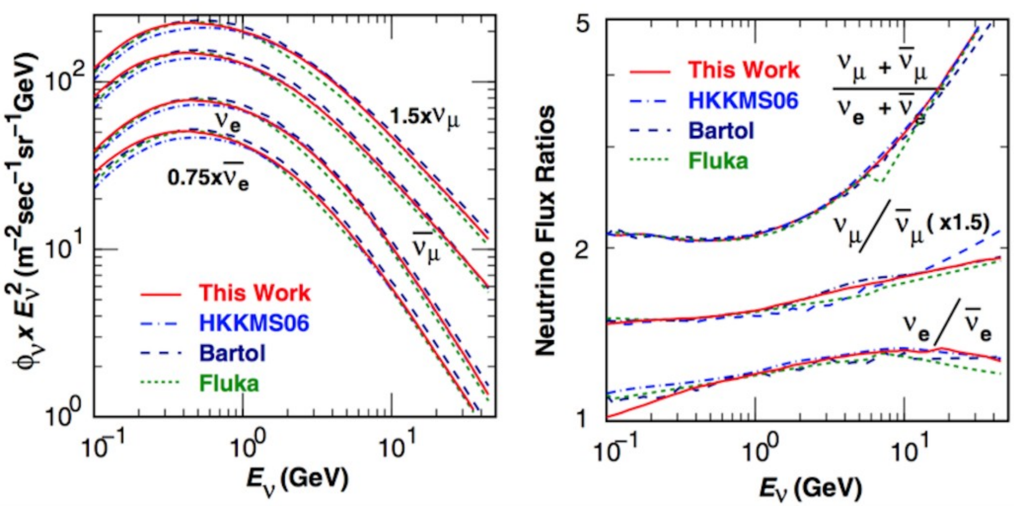


Atmospheric Neutrinos



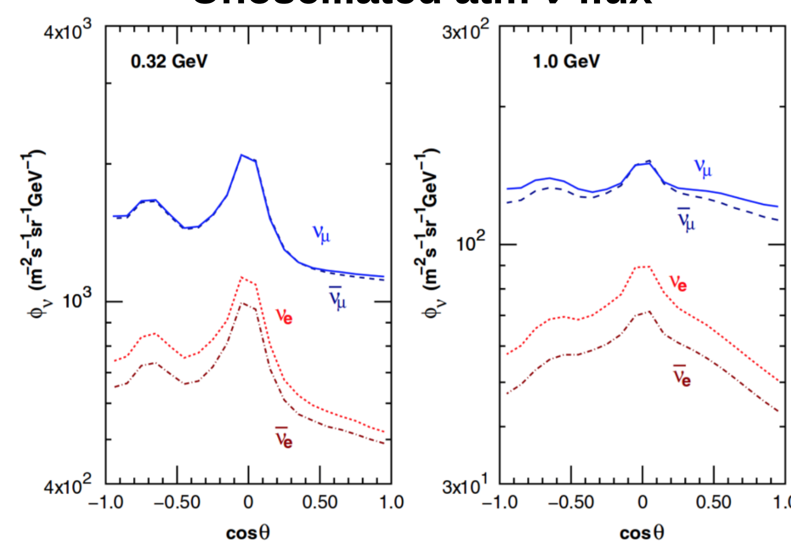
- Atmospheric neutrinos are produced in the interaction of cosmic rays with the Earth's atmosphere
- The neutrino energy spectrum strongly depends on that of the primary cosmic-ray flux, and decreases with energy, at a rate of $E^{-2.7}$, for energies larger than 1 GeV
- From the main production mechanisms one obtains that there will be twice as many ν_μ than ν_e

Unoscillated atm ν flux



- These are produced homogeneously in all the Earth's atmosphere, being any up-down-going asymmetries due to neutrino oscillations (MSW effect)

Unoscillated atm ν flux



Atmospheric ν Oscillations

Neutrino oscillations are directly related with their massive character
Neutrinos do not share the same mass (propagation) and weak (interaction) eigenstates

$$|\nu_l\rangle = \sum_l (U^{li}_{PMNS})^* |\nu_i\rangle$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

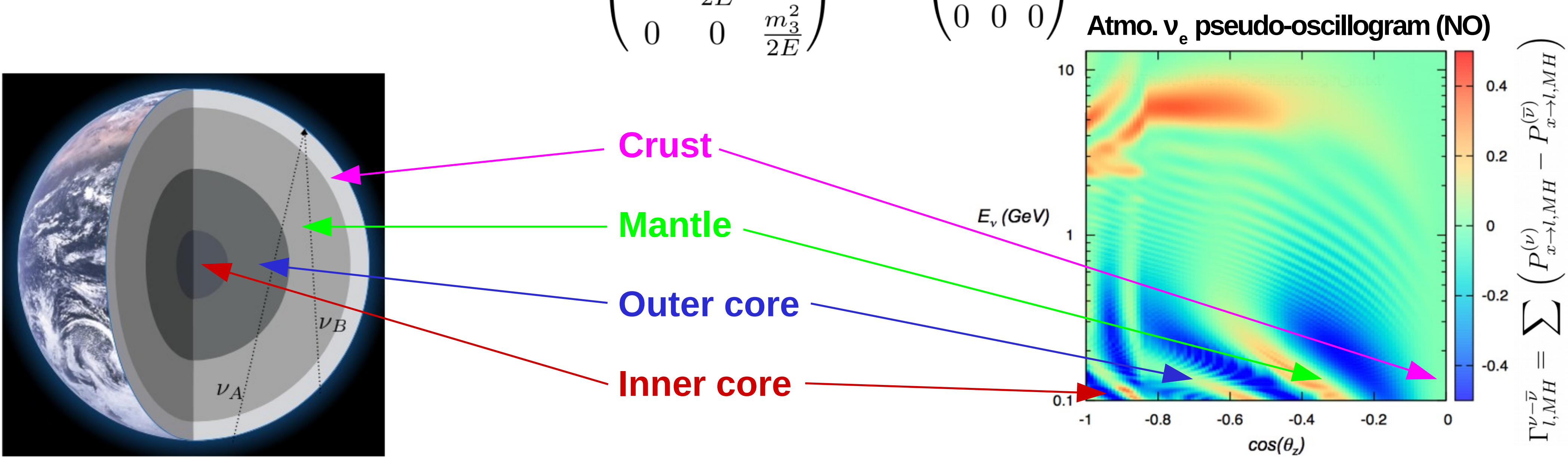
<u>Neutrino oscillations in vacuum:</u>

$$P_{\nu_l \to \nu_{l'}}(L/e) \approx \sum_{ij} U^{l',i}_{PMNS} (U^{l,i}_{PMNS})^* (U^{l',j}_{PMNS})^* U^{l,j}_{PMNS} e^{-i\frac{\Delta m^2_{ij}}{2}\frac{L}{E}}$$

<u>Neutrino oscillations through matter:</u>

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

→ matter interaction

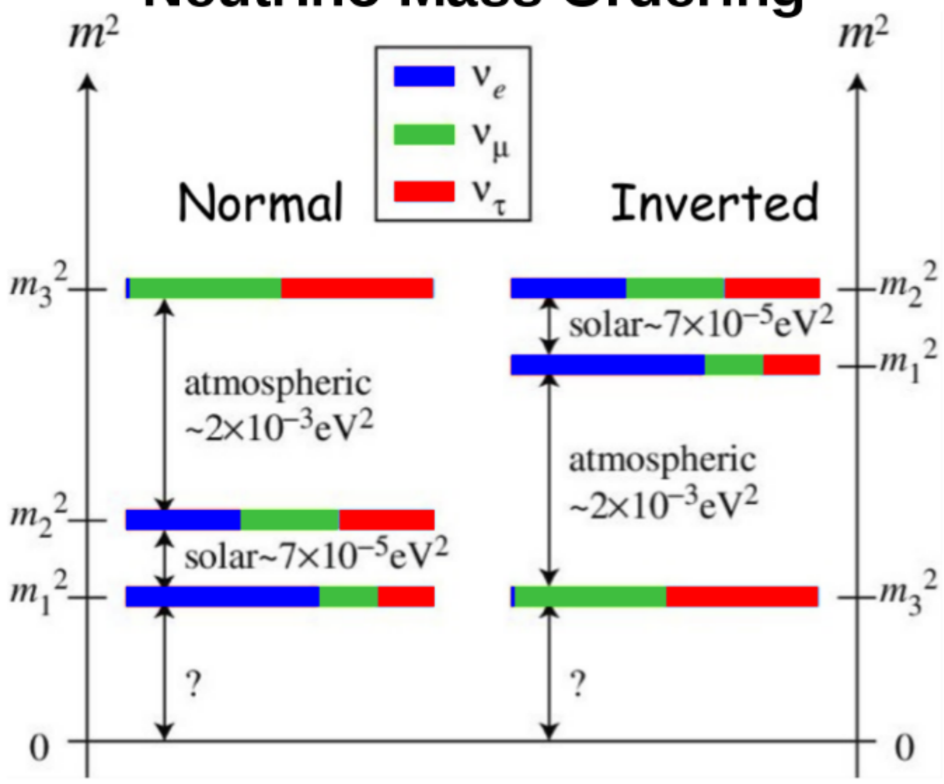


Atmospheric ν Oscillations and SuperK

Neutrino oscillations are parametrized by **6 independent neutrino oscillation parameters**:

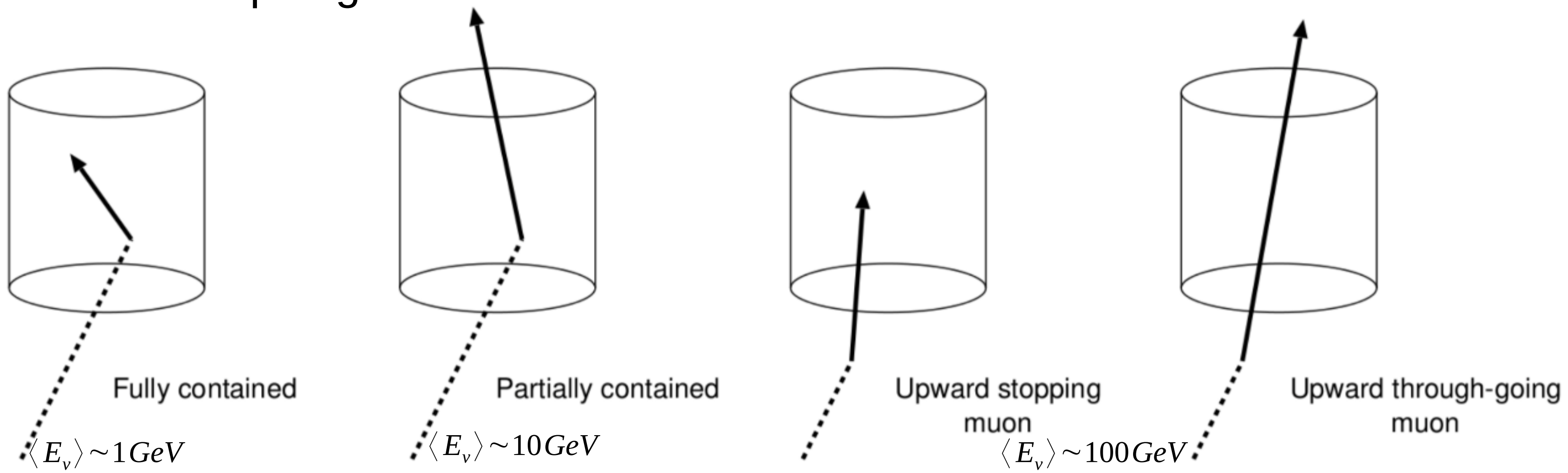
- Neutrino mixing angles, $\boldsymbol{\theta_{12}}$, $\boldsymbol{\theta_{13}}$, $\boldsymbol{\theta_{23}}$
  - *Atmospheric neutrinos at SK are sensitive to the last two, mainly to θ_{23} and through the μ-like samples of several GeVs*
- A CP-violating phase, $\boldsymbol{\delta_{CP}}$
  - *SK has a moderate sensitivity to δ_{cp} through the lower energy samples, sub-GeV*
- Neutrino squared mass differences, $\boldsymbol{\Delta m^2_{21}, \Delta m^2_{31} (\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21})}$
  - *SK provides good constraints on Δm_{32}, and specially to its sign (the **neutrino mass ordering**, MO) with ~GeV samples and through the Earth's matter effects*

Neutrino Mass Ordering



Atmospheric Neutrinos in SuperK

There are four event topologies in SK



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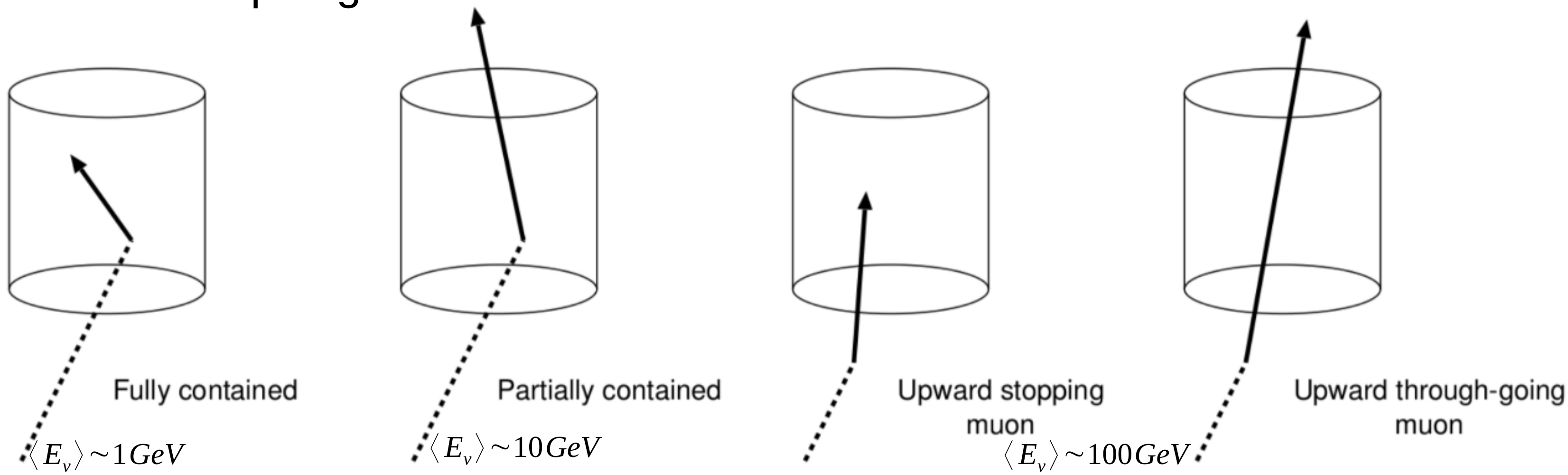
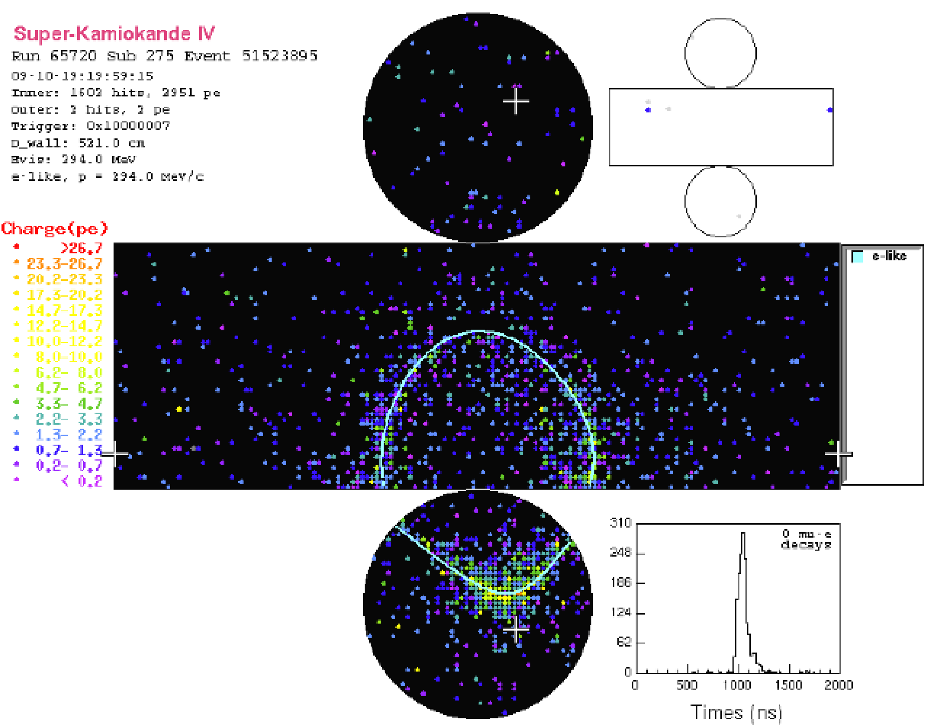
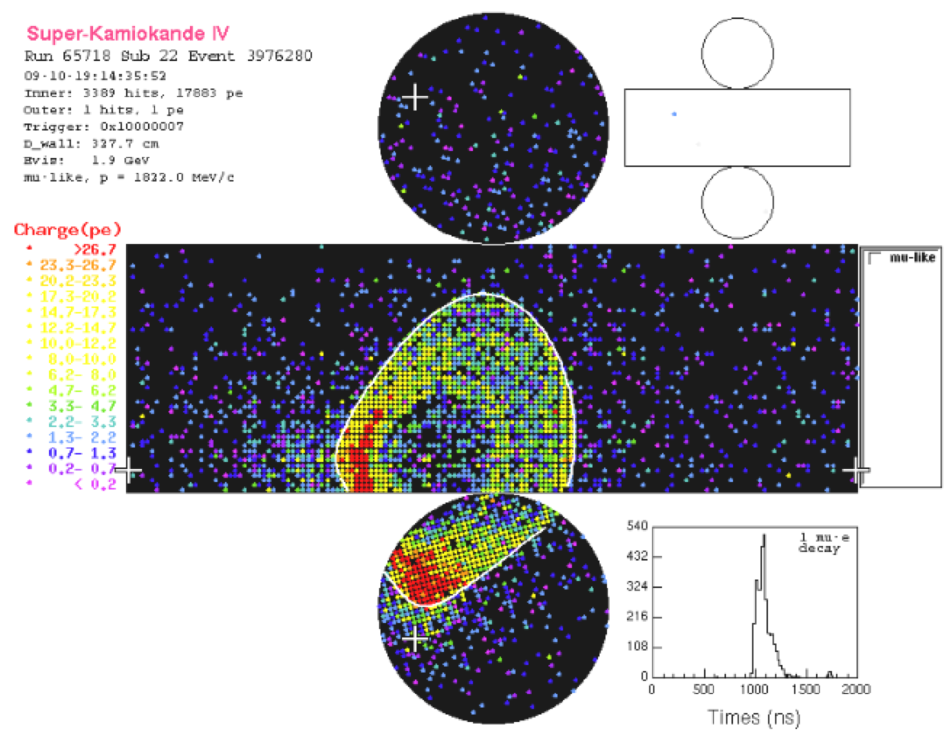


And two types of ring patterns





SuperK Atm. ν Oscillation Analysis

Analysis strategy

For the atmospheric neutrino analysis, the data are compared to the Monte Carlo simulations under the oscillation hypothesis and using a binned (lepton momentum and zenith angle) χ^2 method

The analysis assumes Poisson statistics and takes into account systematic errors as scaling factors on the MC bin by bin

$$\chi^2 = 2\sum_{i=1}^{n}\left(N_i^{exp}\left(1+\sum_{j=1}^{m} f_j^i \epsilon_j\right) - N_i^{obs} + N_i^{obs}\ln\frac{N_i^{obs}}{N_i^{exp}\left(1+\sum_{j=1}^{m} f_j^i \epsilon_j\right)} + \sum_{j=1}^{m}\left(\frac{\epsilon_j}{\sigma_j}\right)\right)$$

expected number of events at bin i^{th}

relative change at bin i^{th} due to 1σ of systematic j^{th}

observed number of events at bin i^{th}

fitting parameter of the j^{th} systematic error

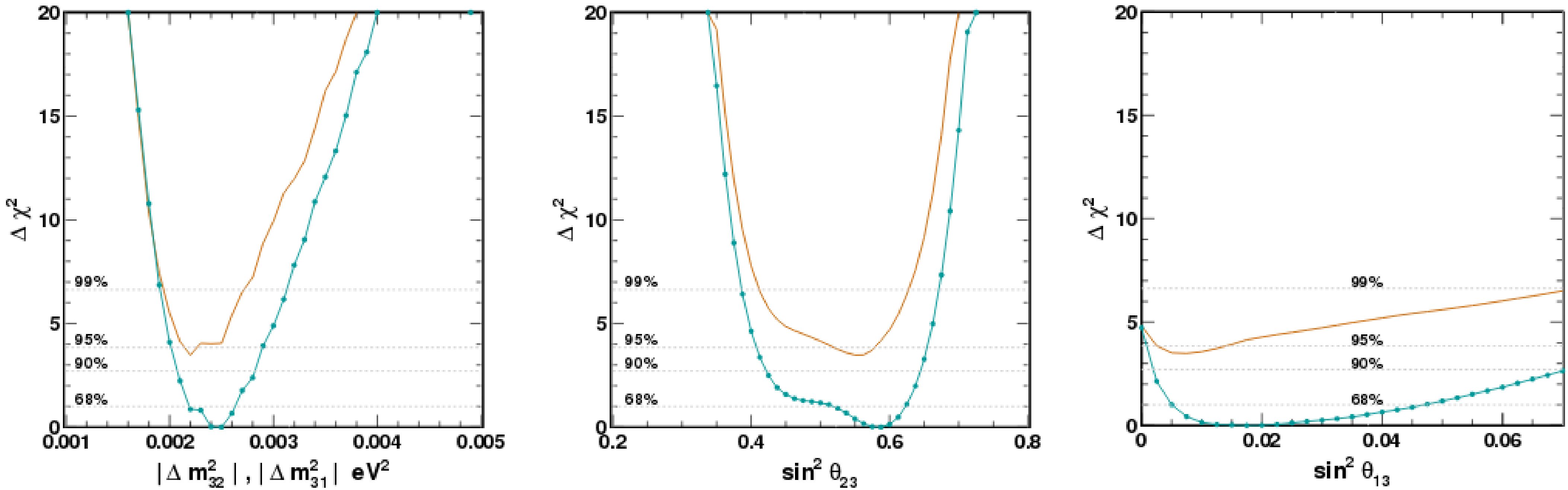
1σ error of the j^{th} systematic error

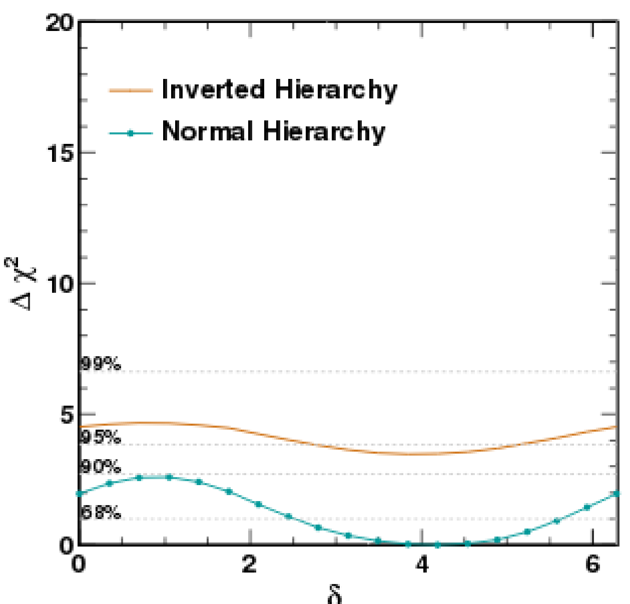
- For each MC simulation the χ^2 and ε_j are obtained by solving the $\partial\chi^2/\partial\epsilon_j = 0$ system of equations
- The best fit is obtained at those oscillation parameters corresponding with the simulation with smaller χ^2 value

Next, the results from SK atmospheric neutrino analysis are shown and discussed

SuperK Atm. ν Oscillation Analysis

SK atmospheric neutrino results with no external constraints





- Significant preference for normal neutrino mass ordering (***$\Delta\chi^2$(NO-IO) = -3.5***)
- Data slightly favours the ***second octant of the θ_{23}*** mixing angle
- Slight indication of ***large values of δ_{CP}***

Hierarchy	χ^2	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32,31}\rvert$ [$\times10^{-3}$ eV^2]	δ_{CP}
NH	571.29	$0.018^{+0.029}_{-0.013}$	$0.587^{+0.036}_{-0.069}$	$2.50^{+0.13}_{-0.31}$	$4.18^{+1.45}_{-1.66}$
IH	574.77	$0.008^{+0.017}_{-0.007}$	$0.551^{+0.044}_{-0.075}$	$2.20^{+0.33}_{-0.13}$	$3.84^{+2.38}_{-2.12}$

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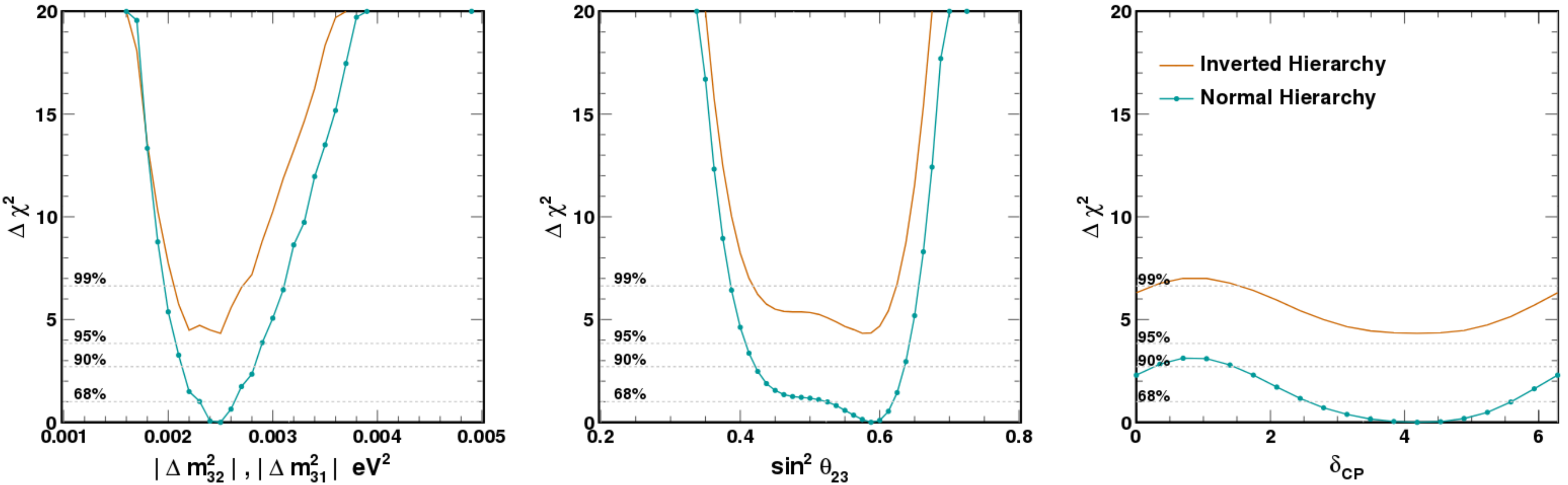
SuperK Atm. ν Oscillation Analysis

SK atmospheric neutrino results with reactor (θ_{13}) constraints

$$\sin^2\theta_{13} = 0.0219 \pm 0.0012$$ *(Daya Bay, RENO, and Double Chooz)*



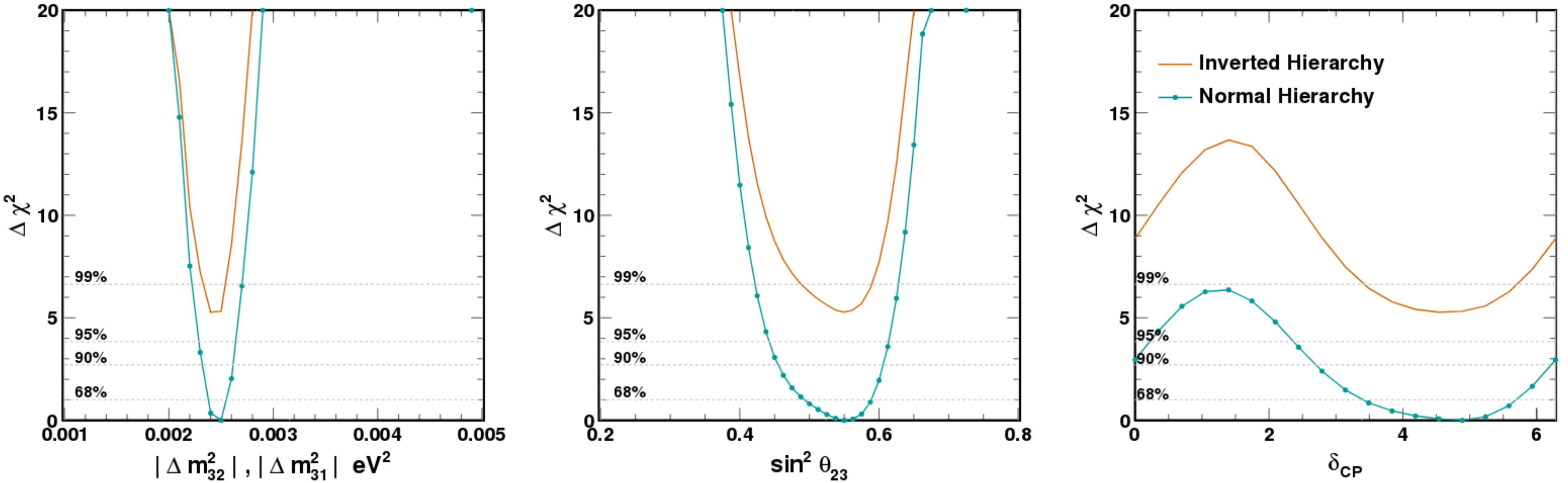
- Slight improved in the significance for the normal neutrino mass ordering (***Δχ²(NO-IO) = -4.3***)
- Enhanced preference for lepton CP-violation with ***large values of δ_{CP}***

Hierarchy	χ^2	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32,31}\rvert$ [$\times 10^{-3}$ eV^2]	δ_{CP}
NH	571.33	–	$0.588^{+0.031}_{-0.064}$	$2.50^{+0.13}_{-0.20}$	$4.18^{+1.41}_{-1.61}$
IH	575.66	–	$0.575^{+0.036}_{-0.073}$	$2.50^{+0.08}_{-0.37}$	$4.18^{+1.52}_{-1.66}$

Phys. Rev. D 97, 072001 (2018)

SuperK Atm. ν Oscillation Analysis

Joint analysis of SK atmospheric neutrino and T2K model with reactor (θ_{13}) constraints



- Improvement in the preference for normal neutrino mass ordering (***Δχ²(NO-IO) = -5.3***)
- More precision measurement of the $\boldsymbol{\Delta m^2_{32}}$ and $\boldsymbol{\theta_{23}}$
- Very significant enhancement for the sensitivity to the ***CP-violating phase***

Hierarchy	χ^2	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32,31}\rvert$ [$\times 10^{-3}$ eV^2]	δ_{CP}
NH	639.43	–	$0.550^{+0.039}_{-0.057}$	$2.50^{+0.05}_{-0.12}$	$4.88^{+0.81}_{-1.48}$
IH	644.70	–	$0.550^{+0.035}_{-0.051}$	$2.40^{+0.13}_{-0.05}$	$4.54^{+1.05}_{-0.97}$

Phys. Rev. D 97, 072001 (2018)

Understanding SK Atm. ν Osc. Analysis

Matter Effects

The data is consistent with the matter effects
Data prefer the normal hierarchy with an electron density consistent with that of standard matter ($\alpha = 1.0$)
Pure vacuum oscillations ($\alpha = 0.0$) are disfavored by the fit by $\boldsymbol{\chi^2[\alpha=0]-\chi^2_{min} = 5.2}$
Based on toy Monte Carlo studies, this corresponds to a rejection of vacuum oscillations of 1.6σ

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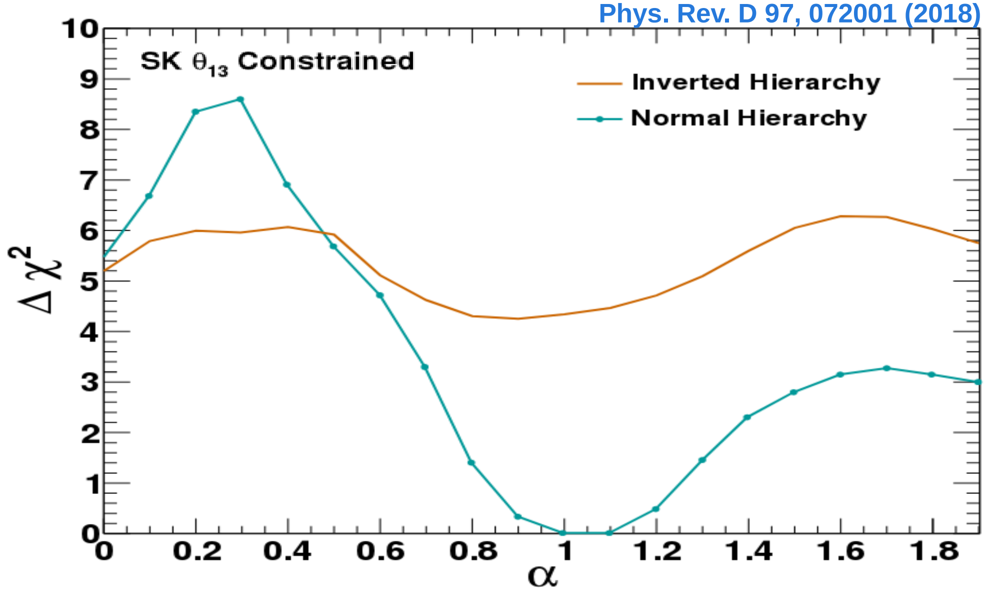
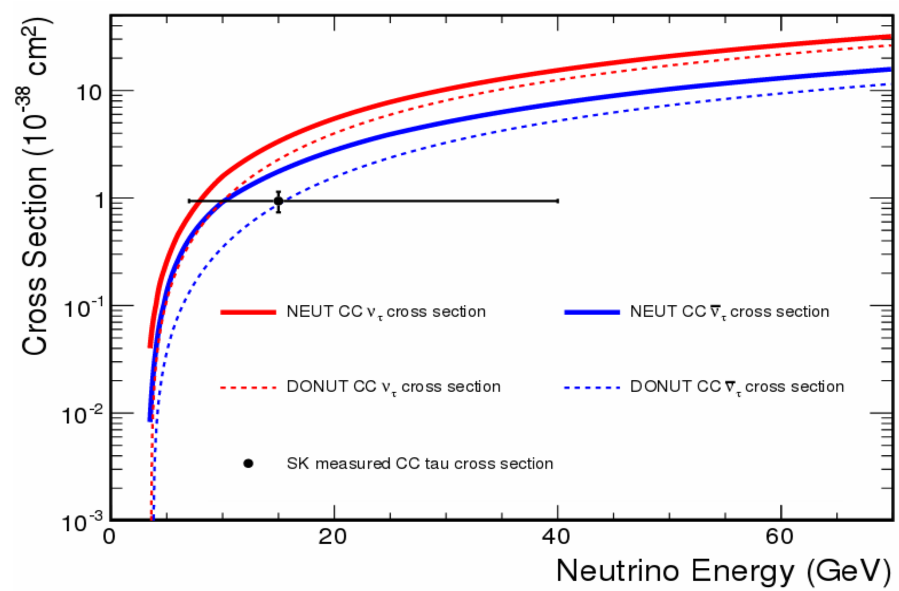


Tau Appearance

The search for τ-like events is done separating the event topologies for tau decay products and the DIS interactions through a neural network

The efficiency of this method is ~76%

- Measured **338.1 ± 72.7 (stat+syst) events**
- Rejecting ***no-τ-appearance at 4.6σ***
- Averaged cross-section of **$(0.94\pm0.20)\times10^{-38}$ cm²** between 3.5 and 70 GeV



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Understanding SK Atm. ν Osc. Analysis

Neutrino Mass Ordering

The significance of the preference for the neutrino normal mass ordering is not necessarily given by the χ^2 difference of the two ordering hypothesis because Wilk's theorem does not apply

Pseudo-data sets are generated to estimate the *p-values* for obtaining a difference in terms of χ^2

- νMO highly depends on the rest of the oscillation parameters
  - → this is taken into account by using the 90% C.L. intervals obtained from the analysis
- SK is currently limited by the level of statistics so the CLs method is used to avoid an overestimation of the significance by the *p-value*

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

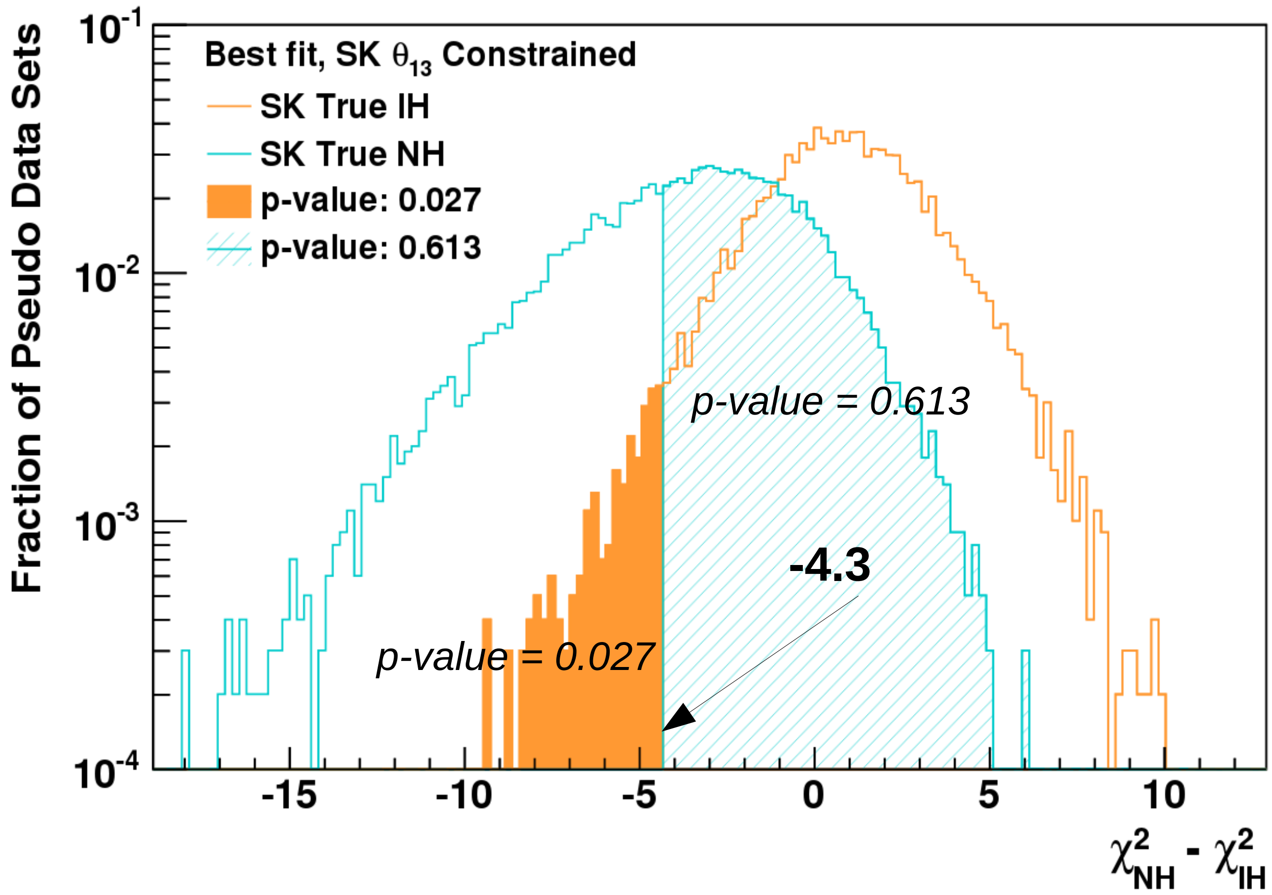
  - → *p0(IH): p-value for obtaining a difference in the minimum χ^2 between both hierarchy hypotheses, smaller than that from the data assuming the truth is inverted MO*
  - → *p0(NH): p-value for obtaining a difference in the minimum χ^2 between both hierarchy hypotheses, larger than that from the data assuming the truth is normal MO*

Understanding SK Atm. ν Osc. Analysis

Neutrino Mass Ordering

This analysis shows the following results:

- SK only: inverted mass ordering is disfavored by between **81.9%** and **96.7%**
- SK with θ_{13} constraints: disfavours the inverted ordering at **93.0%** assuming the analysis best fit oscillation parameters
- SK and T2K model joint fit with θ_{13} constraints: inverted mass ordering is disfavour between **91.9% and 94.5%**



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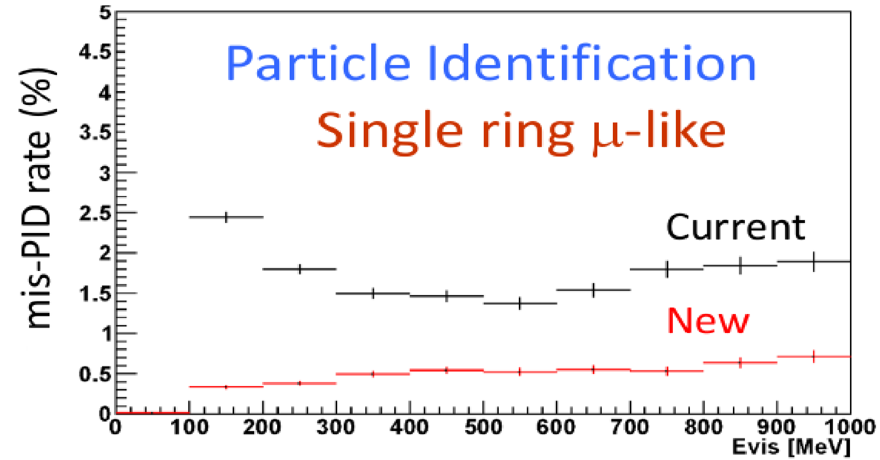
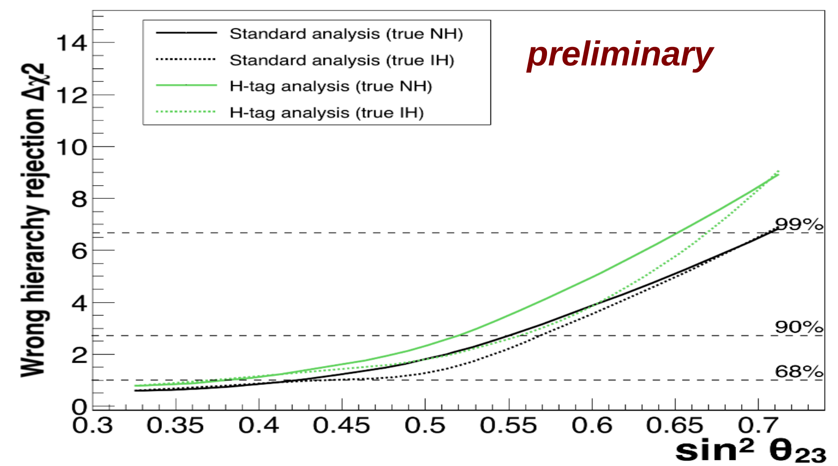
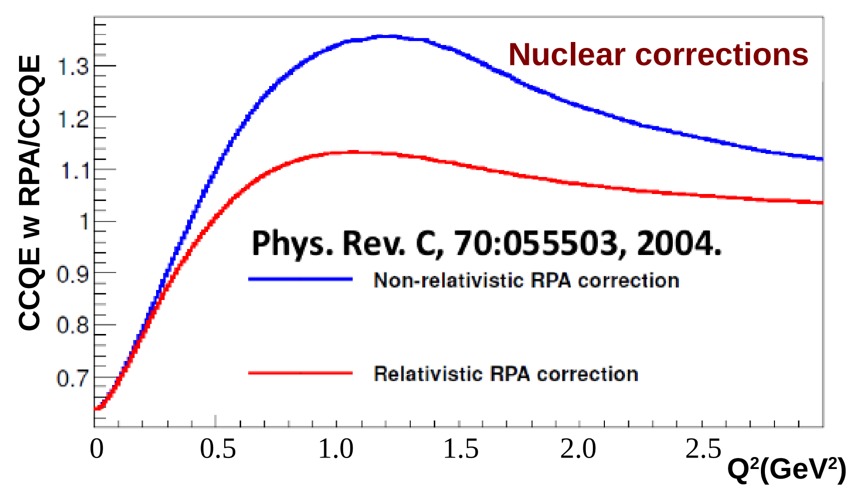
Future Improvements of SK Atm. ν Analysis

- Studying to **expand SK's fiducial volume** from 2 m from (22.5 kton) to 0.5 m from the wall, by adapting a reconstruction tool from T2K (fiTQun)
  - ➔ More statistics
  - ➔ Better ring finding and identification performance
- Application of **neutron tagging** (via Hydrogen capture, ~20% efficiency)
  - ➔ Better neutrino-antineutrino and interaction mode identification
  - ➔ Improved energy reconstruction through its information about the hadronic state
- **Improved neutrino-nucleus interaction** models thanks to updated models and new data







Upcoming SKGd Atm. ν Osc. Analysis

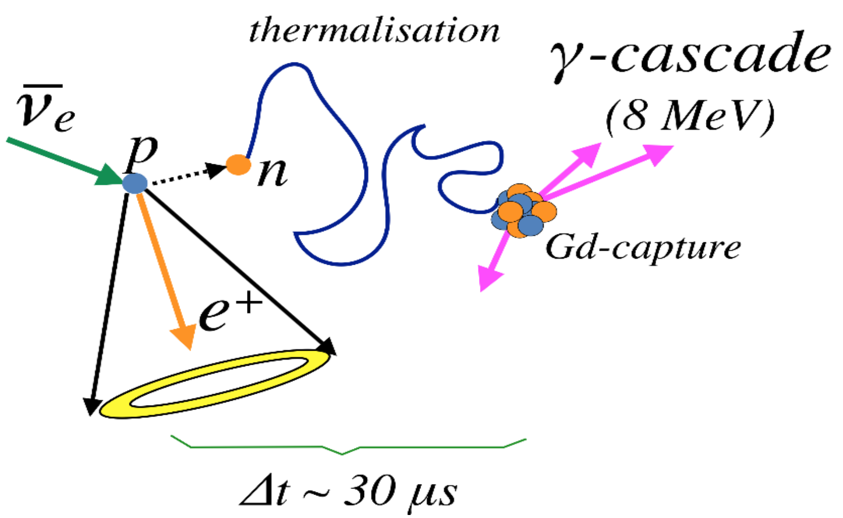
For the **SKGd** project, SuperK will be loaded with **0.2% by mass of $Gd_2(SO_4)_3$**

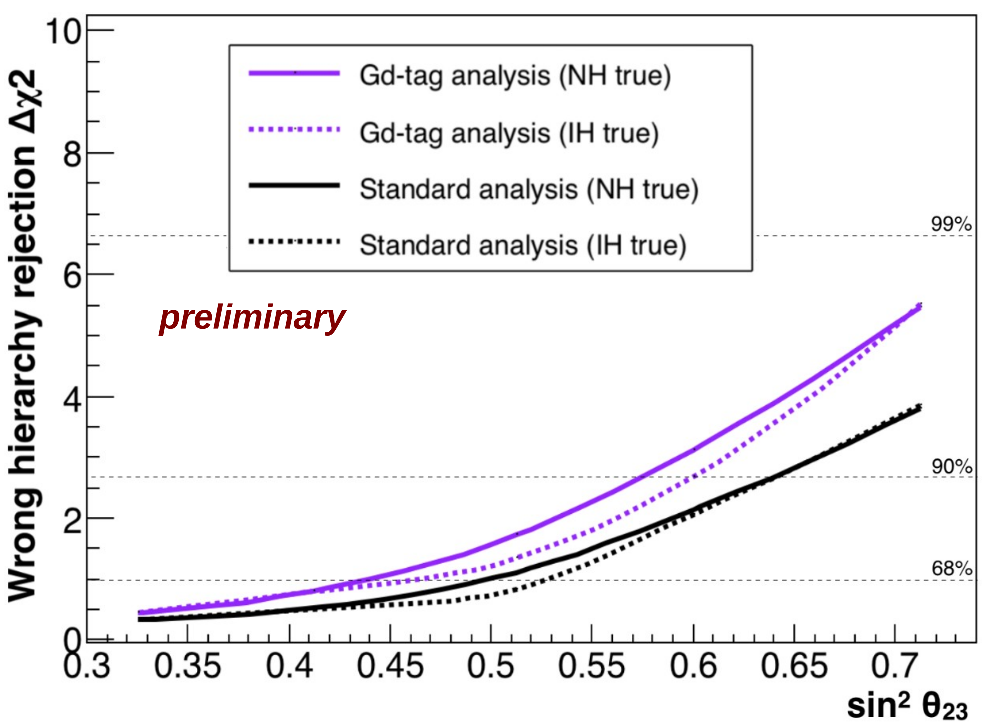
This enables that 90% of neutrons are captured by Gd and with an efficiency over 90%

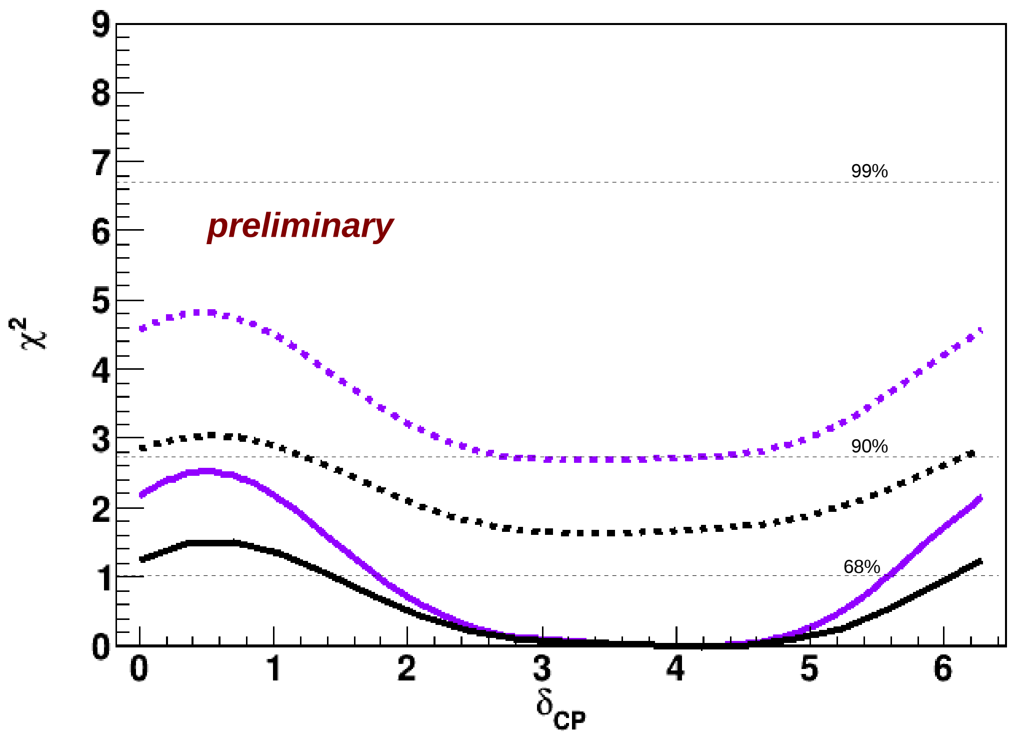
- **80% of final-state neutrons will be detected**

Improving the benefits already seeing with H-neutron tagging:

- **neutrino-antineutrino separation**
- **energy reconstruction**



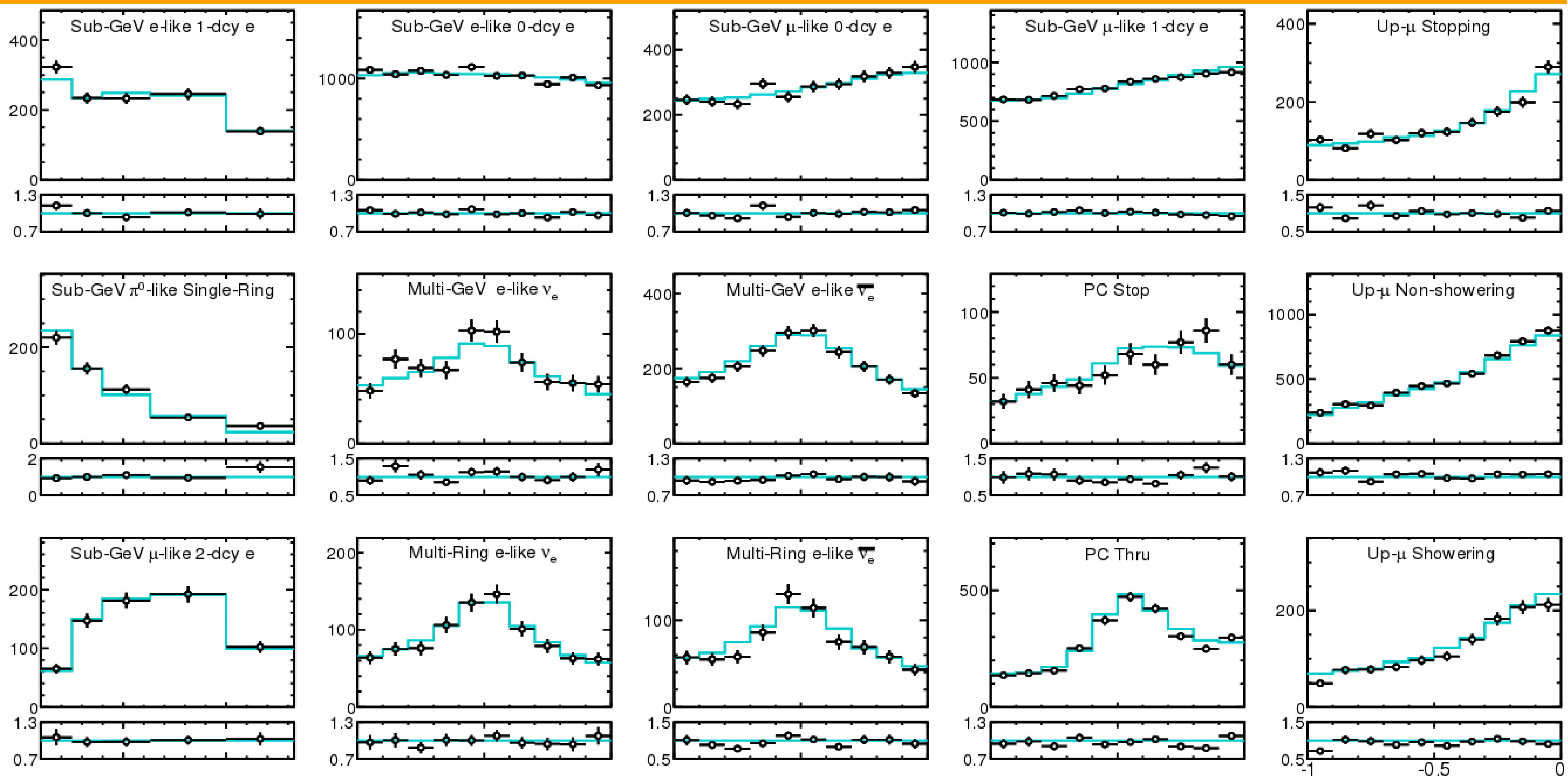


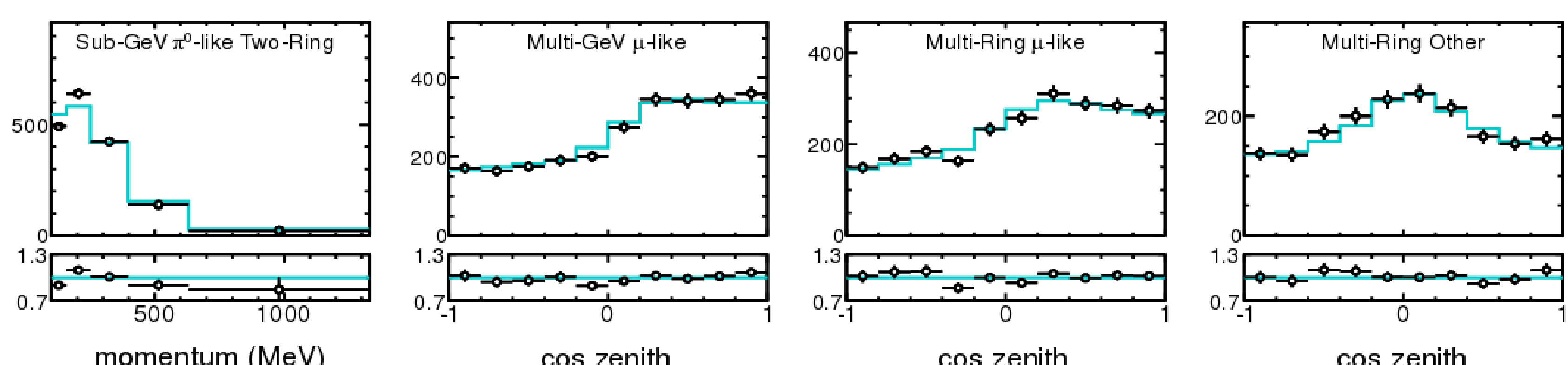


Summary

- Results shown for **SK-I to SK-IV, 5326 days** (2519 days from SK-IV), 328 kt·year
- Three different atmospheric neutrino oscillation results have been presented
  - **SK only**
  - **SK with reactors constraint**
  - **SK and T2K model joint analysis with reactor constraints**
- In addition, Earth's matter effects and tau appearance analyses are performed showing
  - **preference for standard matter effects**
  - **rejecting no-τ-appearance at 4.6σ**
- Additional care is taken for providing a consistent and realistic statistical interpretation for the **preference for normal neutrino mass ordering**
  - Inverted ordering is rejected between 91.9% and 94.5% for the SK and T2K model joint fit with θ_{13} constraints
- Several independent studies are being developed to improved the atmospheric oscillation analysis
- Currently, SK is being refurbished and prepared for loading Gd for the next phase, **SKGd**
  - enhancement **neutron tagging to more than 80% efficiency**, improving the sensitivity for the neutrino oscillation parameters

SuperK atmospheric ν data and results





Data results:
http://www-sk.icrr.u-tokyo.ac.jp/sk/publications/result-e.html