Atmospheric neutrinos at Super-Kamiokande

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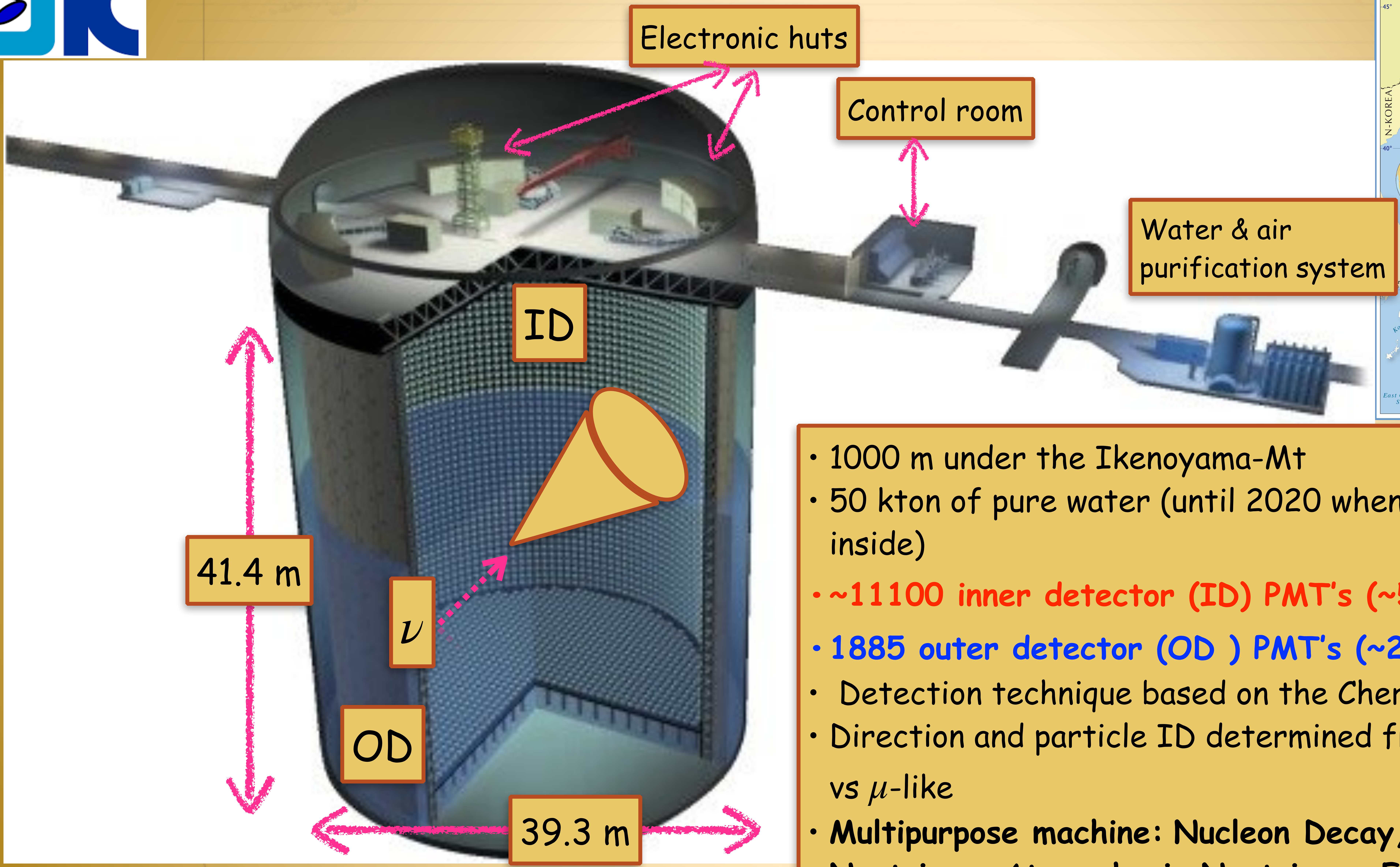
XXXI International Conference on Neutrino Physics and Astrophysics
(Neutrino24)
Milan, Italy, 17-22 June 2024

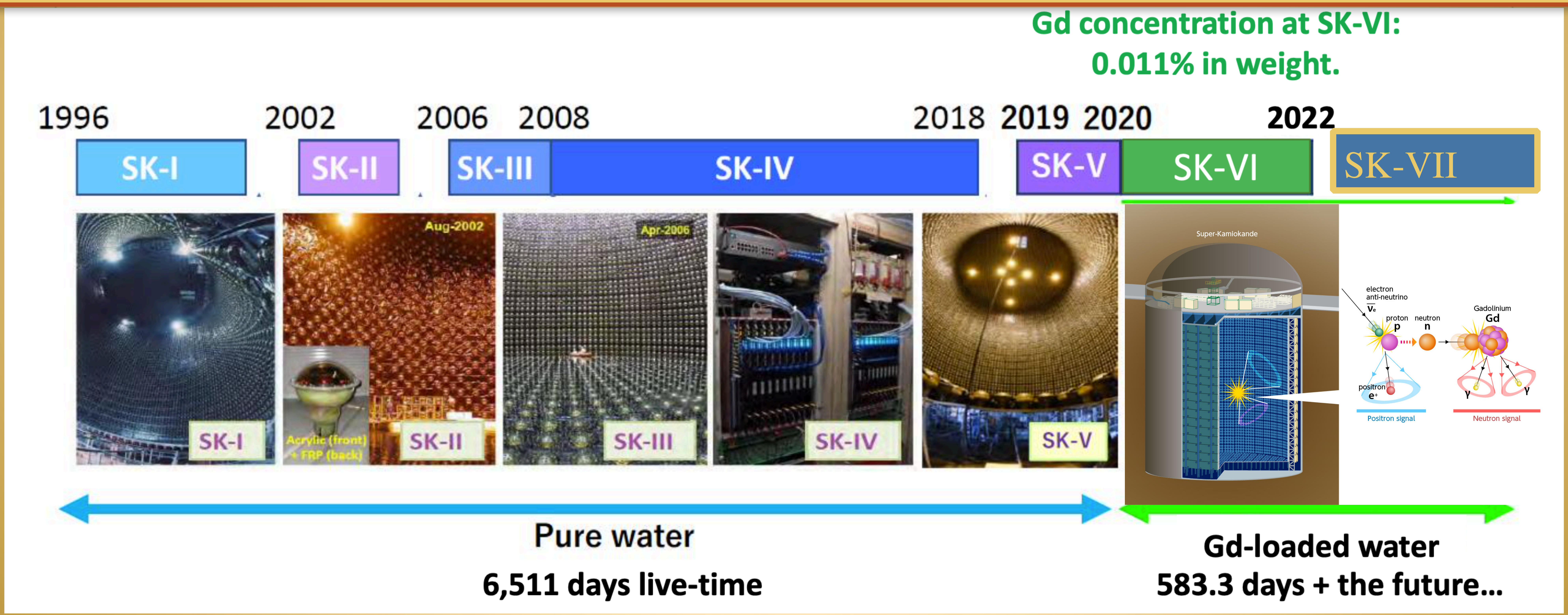
The Super-Kamiokande experiment



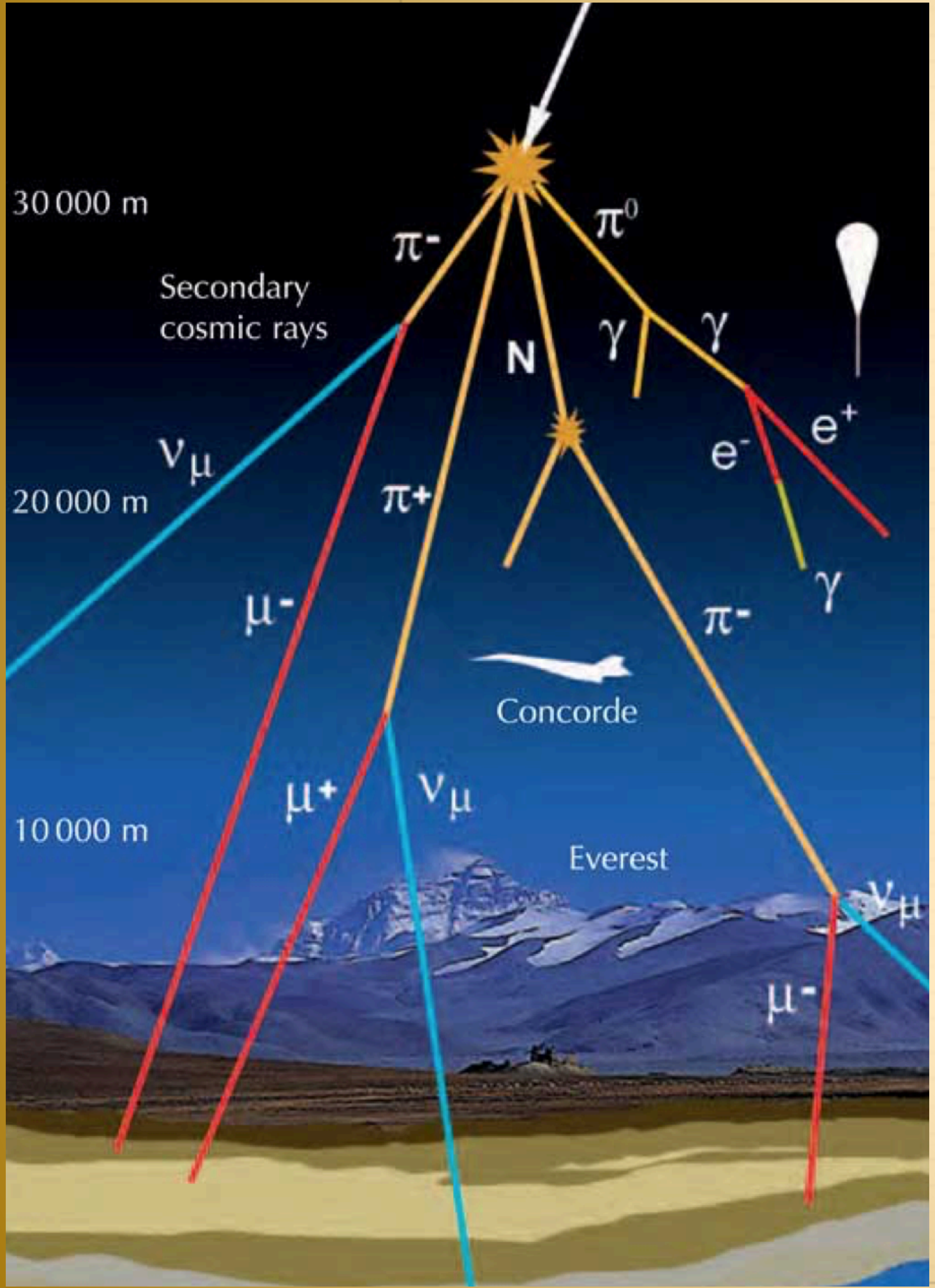
- 1000 m under the Ikenoyama-Mt
- 50 kton of pure water (until 2020 when Gd sulfate was added inside)
- ~11100 inner detector (ID) PMT's (~50cm ϕ)
- 1885 outer detector (OD) PMT's (~20cm ϕ)
- Detection technique based on the Cherenkov radiation
- Direction and particle ID determined from the ring pattern: e-like vs μ-like
- **Multipurpose machine: Nucleon Decay, Solar and Supernova Neutrinos, Atmospheric Neutrinos, Far detector for T2K**

The Super-Kamiokande experiment

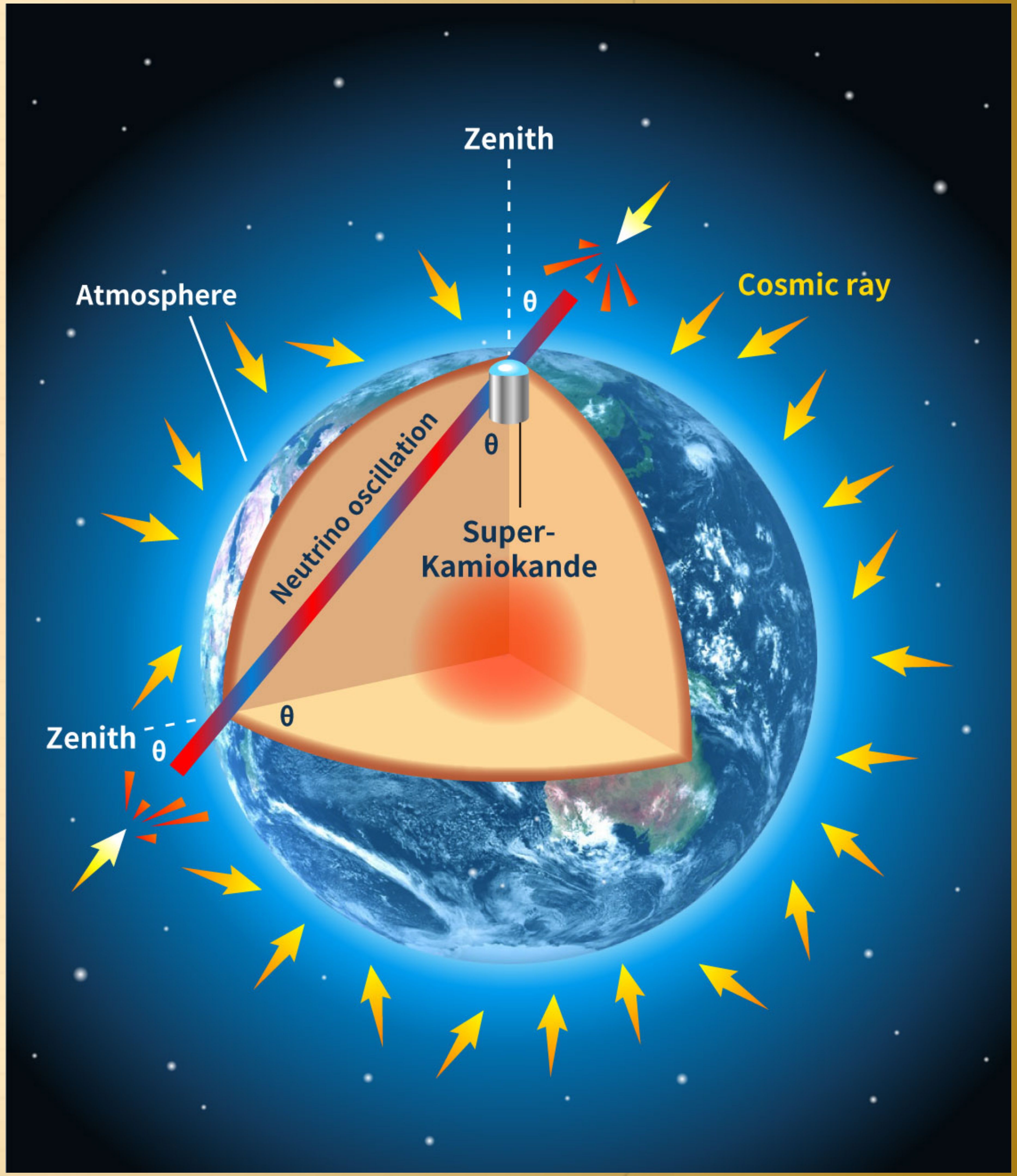
- Super-Kamiokande has been taking data since 1996 and has come through seven run periods
- Densely packed PMTs (40% / 20% for SK-II) and good water quality provide excellent sensitivity for various physics targets.
- In 2020 we have added Gd sulfate to the water in order to increase the sensitivity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



Atmospheric neutrinos



- Neutrinos are produced when cosmic particles, mainly protons, interact with the nuclei in the atmosphere:
  - with wide range of energy MeV- TeV produced isotropically about the Earth atmosphere
  - travel length varies 10km ~13000 km



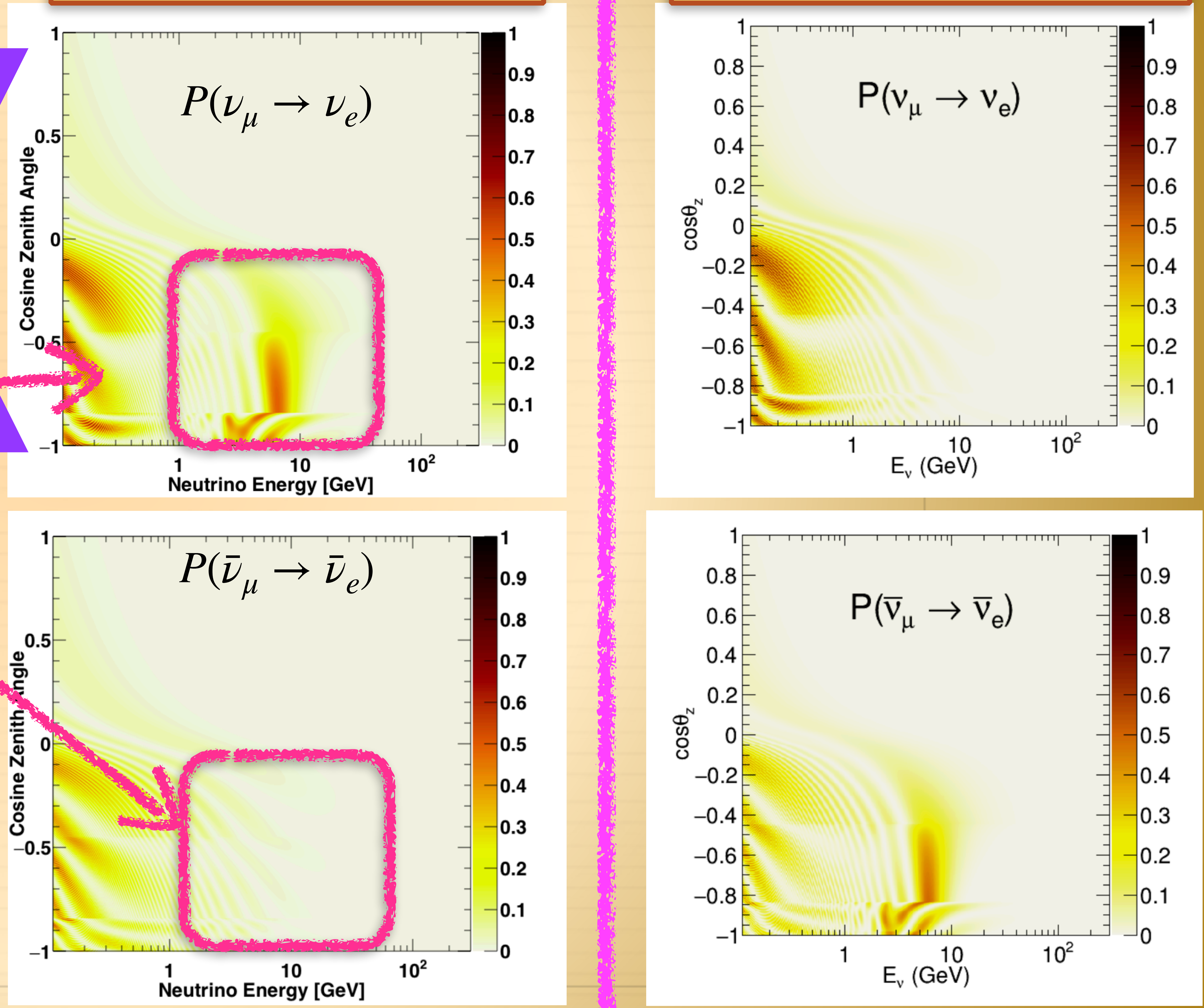
Atmospheric neutrino oscillations

- Thanks to presence of matter effects we are sensitive to neutrino mass ordering

- 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

Normal Ordering (NO)

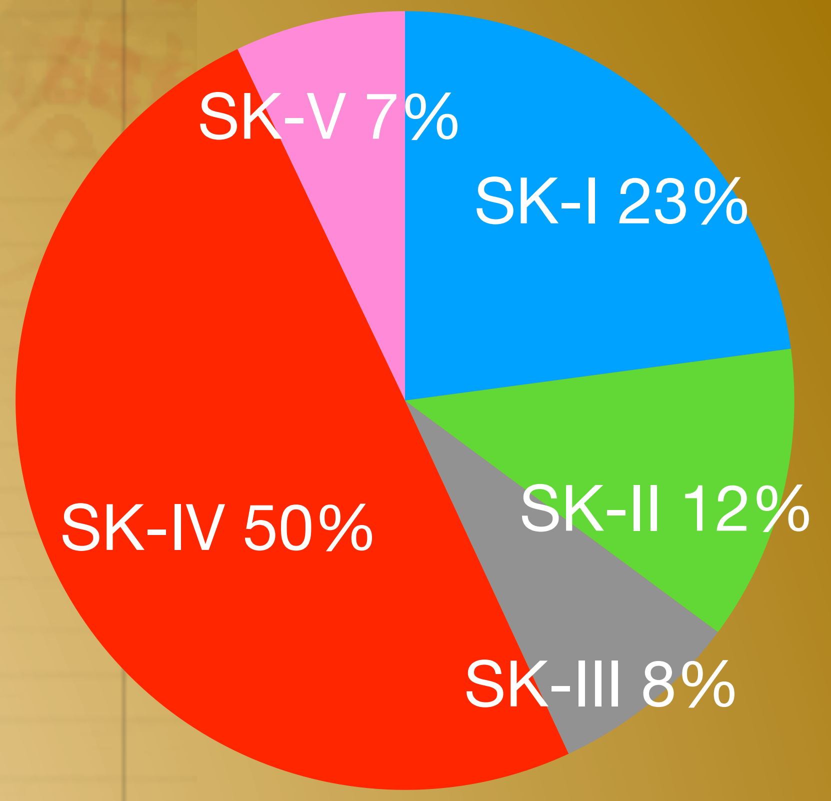
Inverted Ordering (IO)



☆ Oscillograms plotted with: $\Delta m^2_{21} = 7.7 \times 10^{-5} \mathrm{eV}^2$, $\sin^2\theta_{23} = 0.50$, $\sin^2\theta_{12} = 0.30$, $\sin^2\theta_{13} = 0.0219$ and $\delta_{CP} = 0$

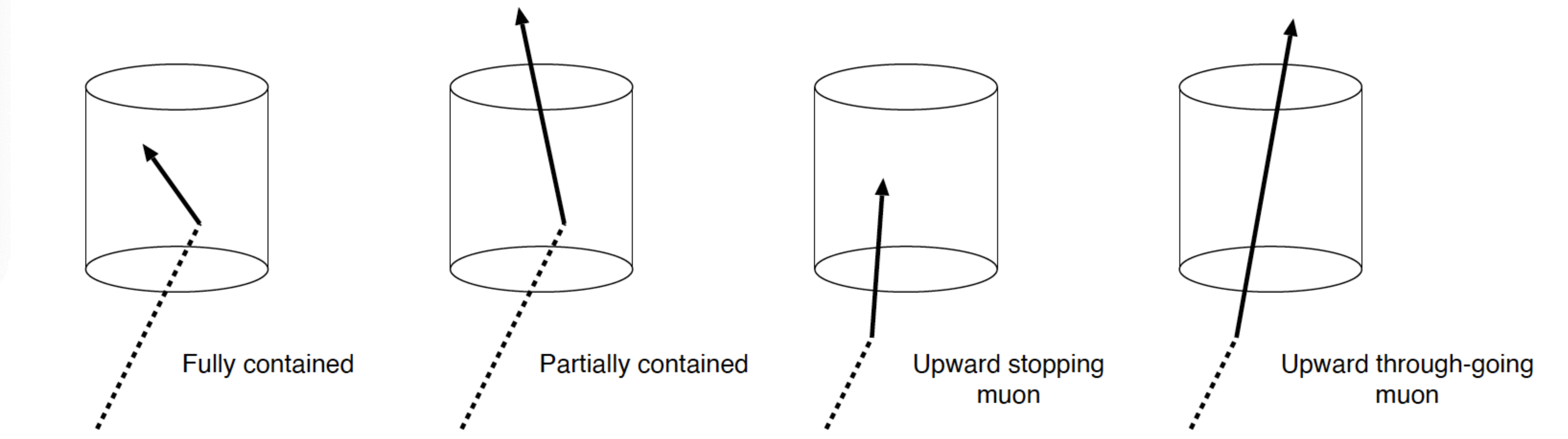
☆ Phys. Rev. D. 97 072001

Zenith angle atmospheric neutrino oscillation analysis

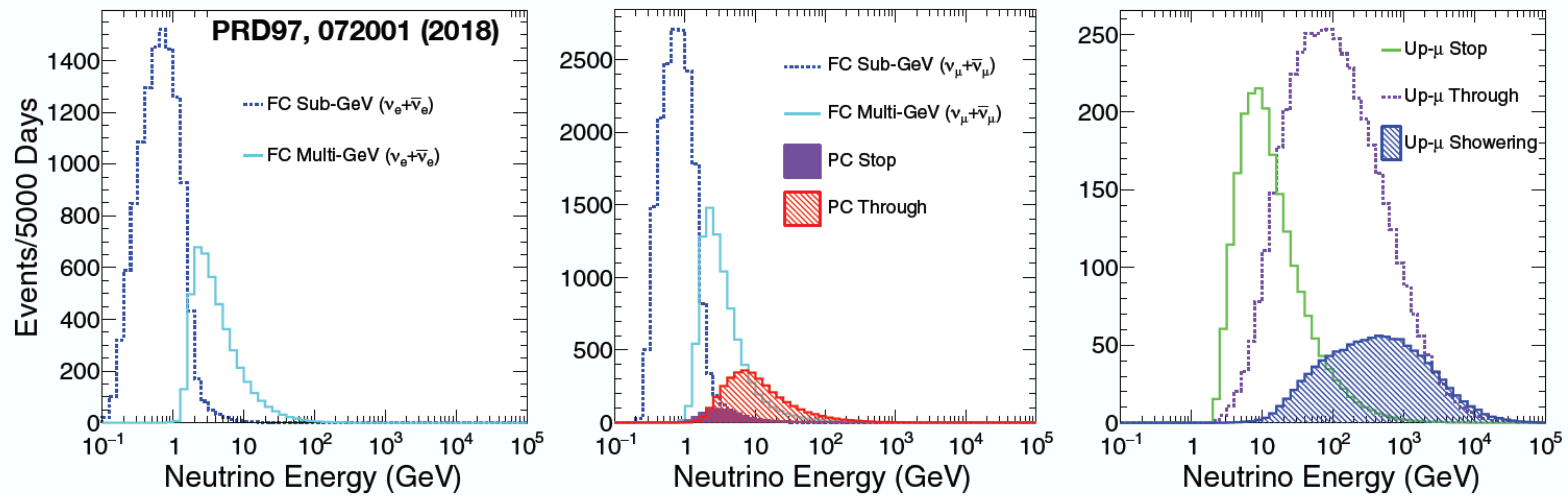


- Latest results with **full SK pure water phase (SK1-5)**:
  - Latest publication - Phys. Rev. D 109, 072014 – Published on 24 April 2024
  - Previously published results: Phys. Rev. D97, 072001 (2018)
- Updates since the previous analysis:
  - **Expansion of fiducial volume and more lifetime: 6511 days, 484 kt·yr in total +50% of statistics**
  - **Event selection with neutron tagging on hydrogen (SK4-5)**
  - New multi-ring event classification using a Boosted Decision Tree (BDT)
    - Improved charged current/neutral current separation
- Atmospheric ν oscillation fit with external constrains
  - θ_{13} from reactors

★ Atmospheric neutrino events at Super-K are classified into several categories:



Expected energy spectra of atm-ν samples



Enlarging the Fiducial Volume

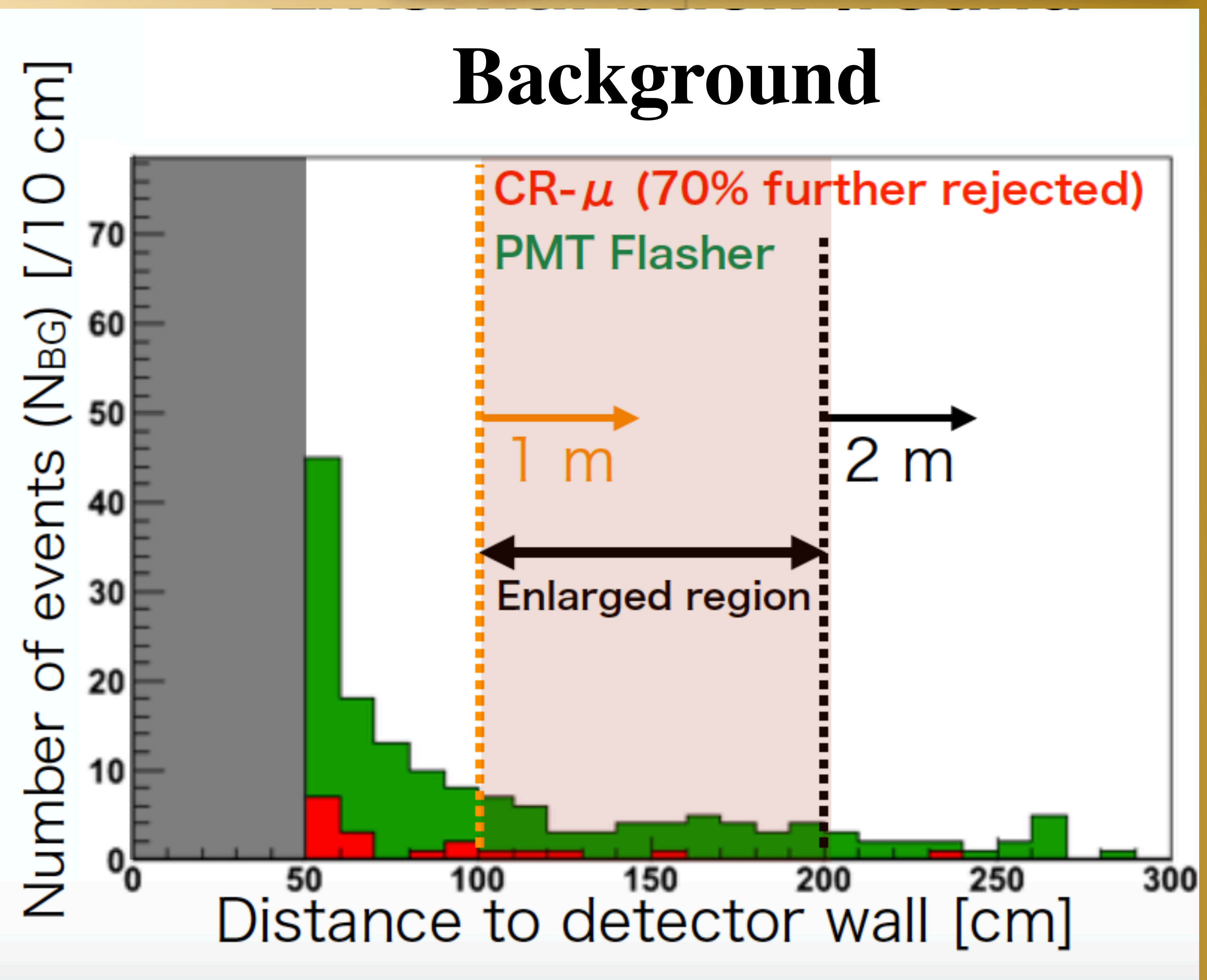
Phys. Rev. D 201, 112011 (2020)

Distance btw vertex and nearest ID wall surface = “wall”

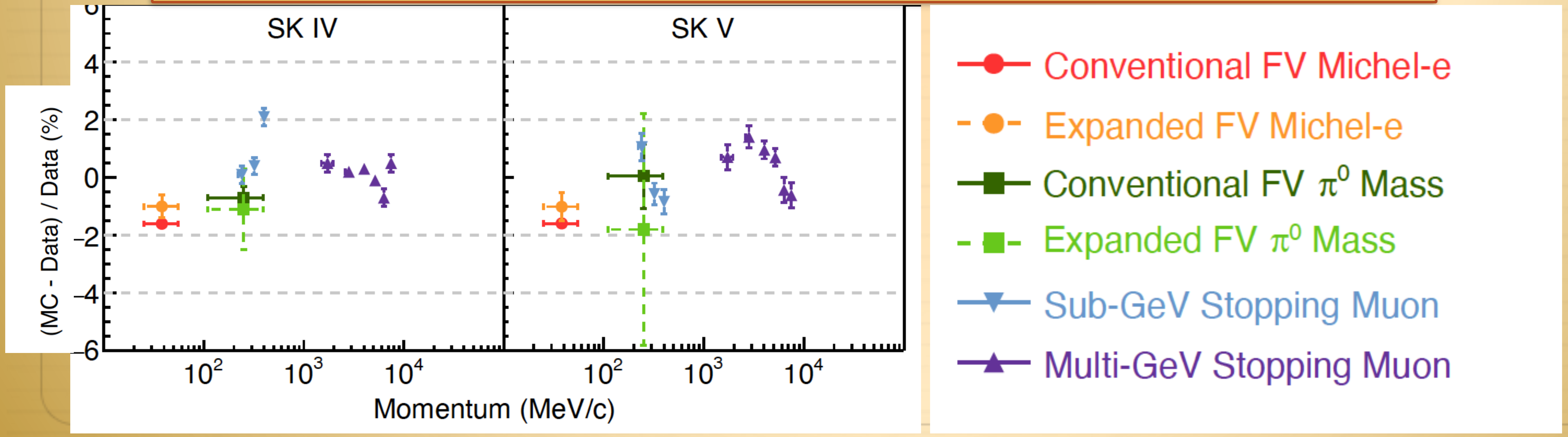
- Conventional fiducial volume defined as wall > 2m
- Expanded fiducial volume to wall > 1m (for all SK periods)

  ★Increased fiducial volume by 20% (22.5kt → 27.2kt)

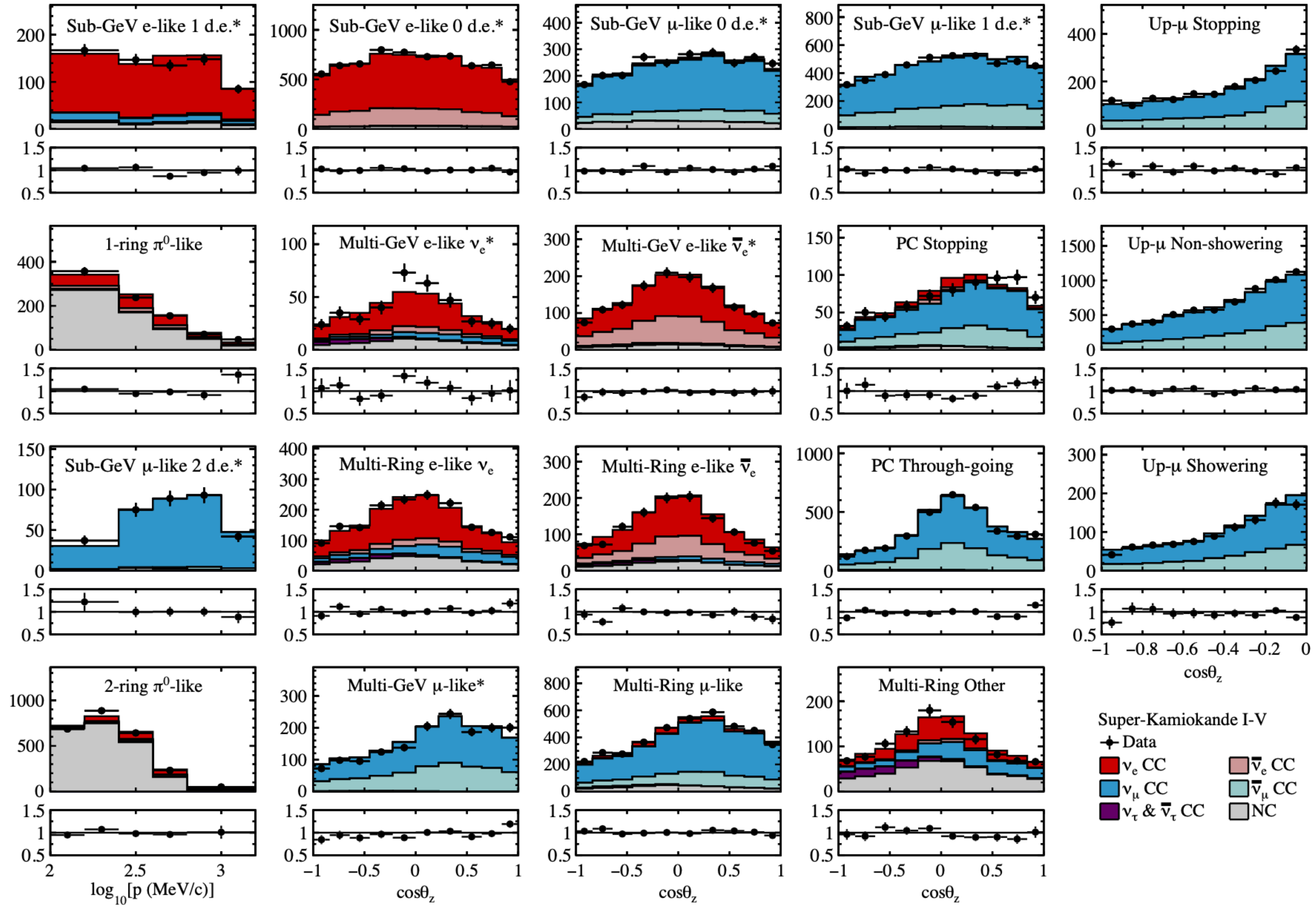
- Confirmed no significant increase of non-ν background and no significant bias in reconstruction (ex. energy scale)
- Systematics in the expanded region recalculated and under control



Energy reconstruction for various sources



Zenith angle or momentum distributions



- Zenith angle or momentum distributions for the 19 analysis samples **without neutron tagging**.
- FC: Sub-GeV and Multi-GeV samples with SK-I~III data, no neutron tagging included*
- PC, UPMU, FC π^0, FC Multi-Ring samples use SK-I~V data,

SK samples - impact of neutron tagging

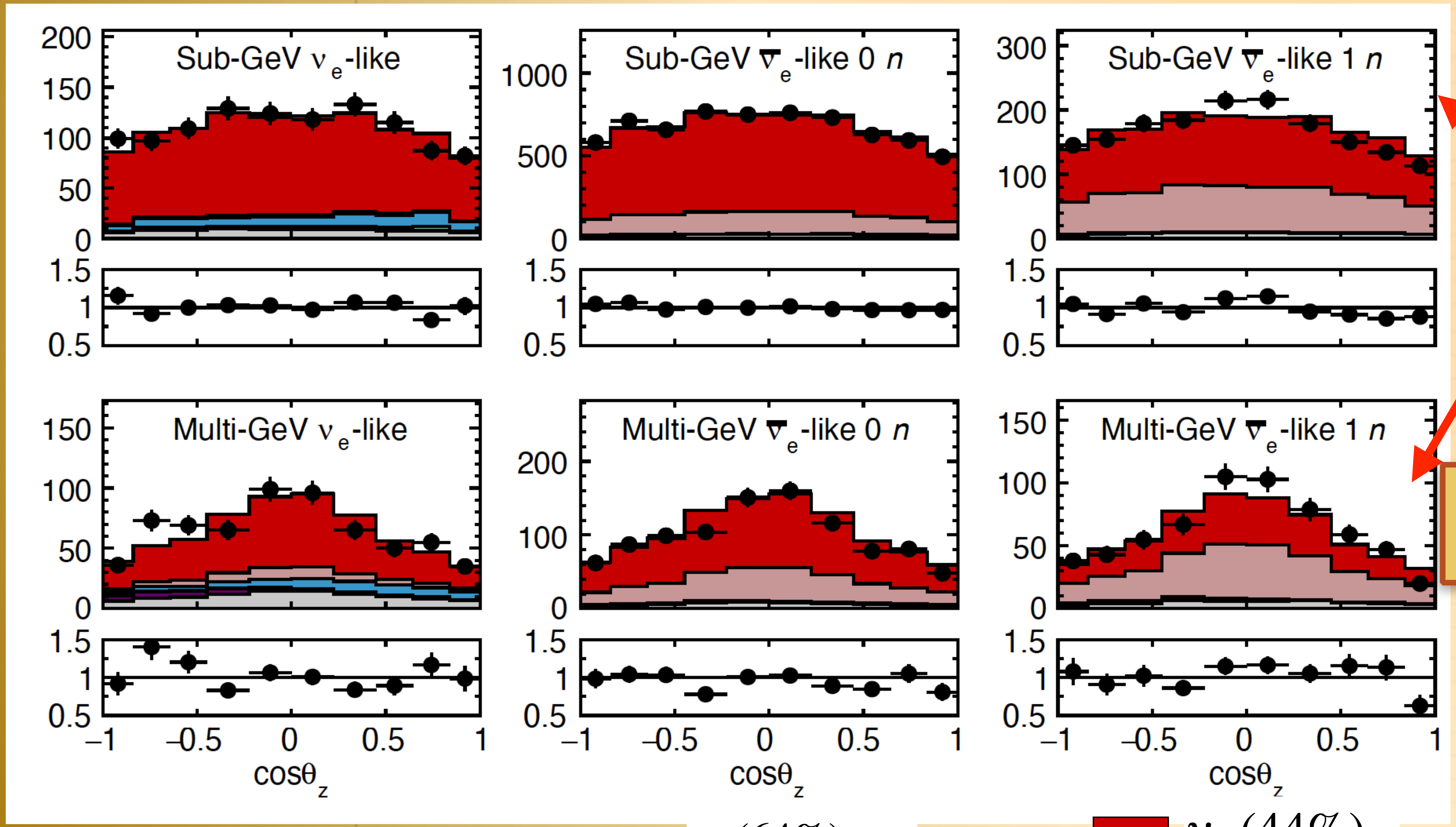
- Additional selections done for SK4 and SK5 data period, **with neutron tagging on Hydrogen.**
- Improves separation between ν and $\bar{\nu}$ events

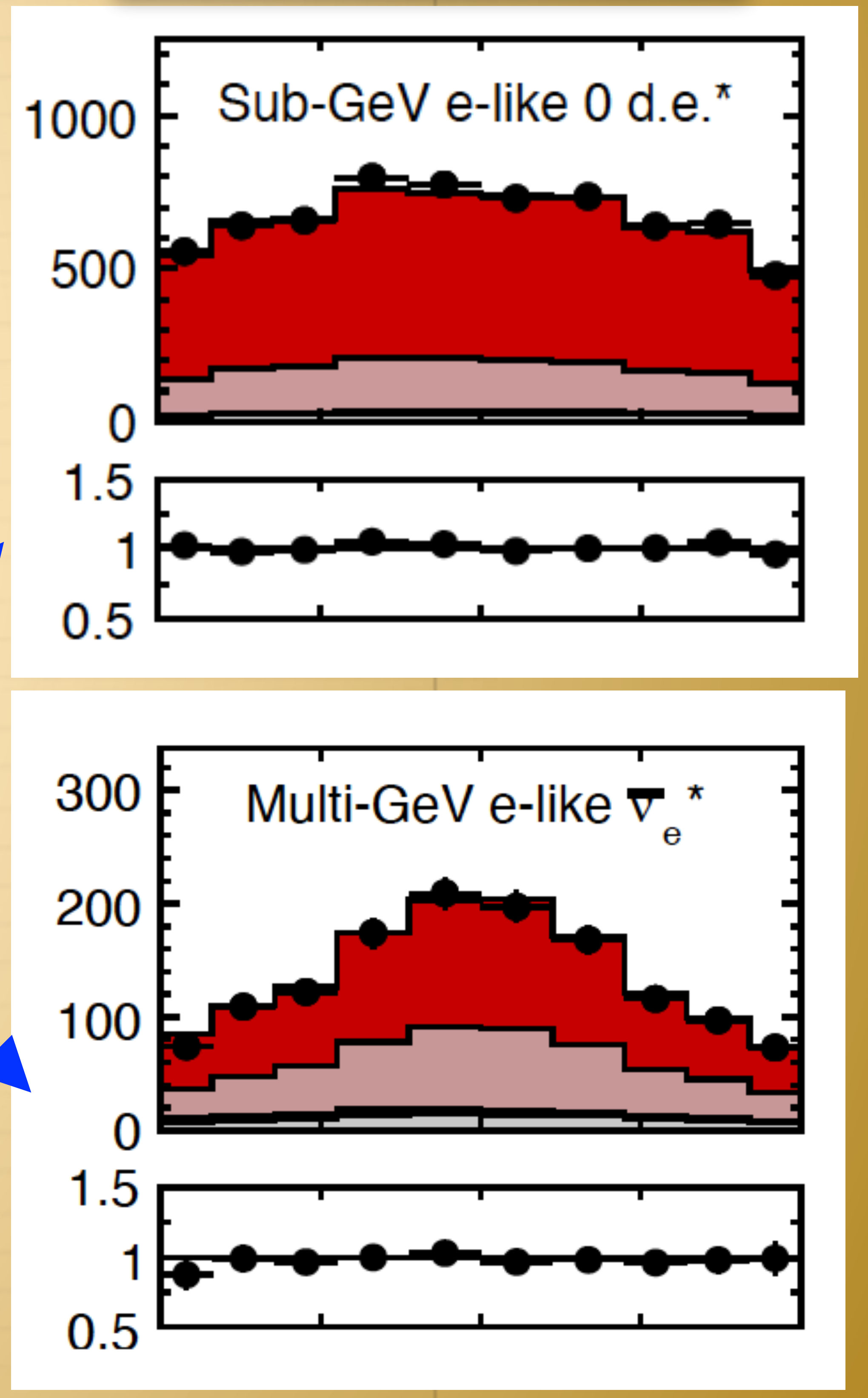
d.e. ≥ 1 + any # of neut.

d.e.=0 + # of neut. $= 0$

d.e.=0 + # of neut. ≥ 1

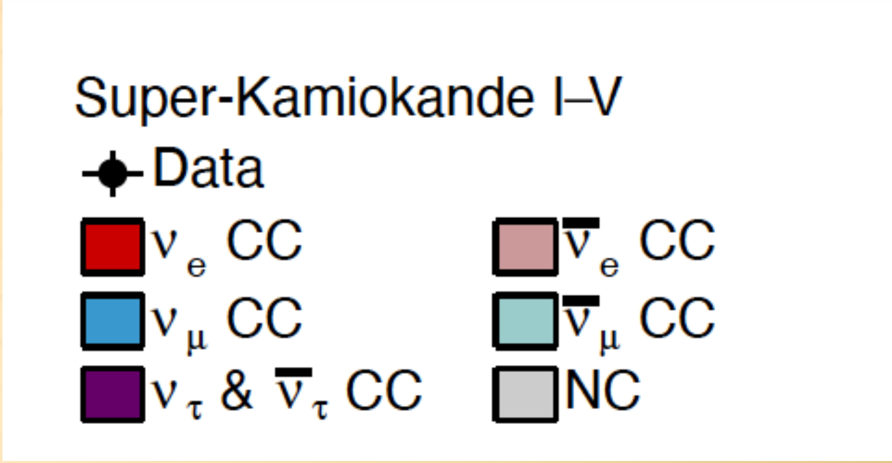
d.e.=0





New selections with neutron tagging

Old selections
Phys. Rev. D97, 072001 (2018)



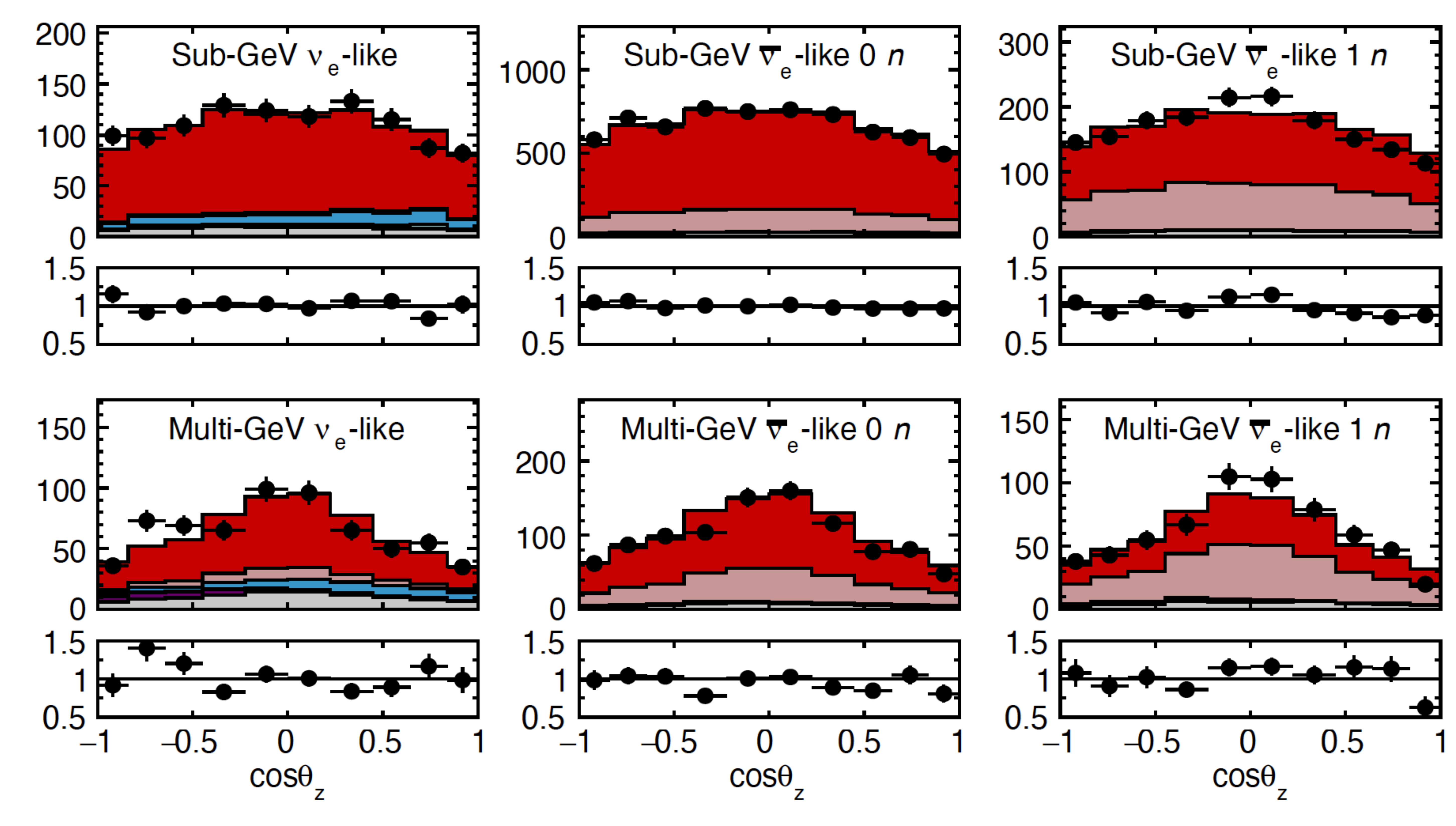
ν_e (64%)
$\bar{\nu}_e$ (29%)

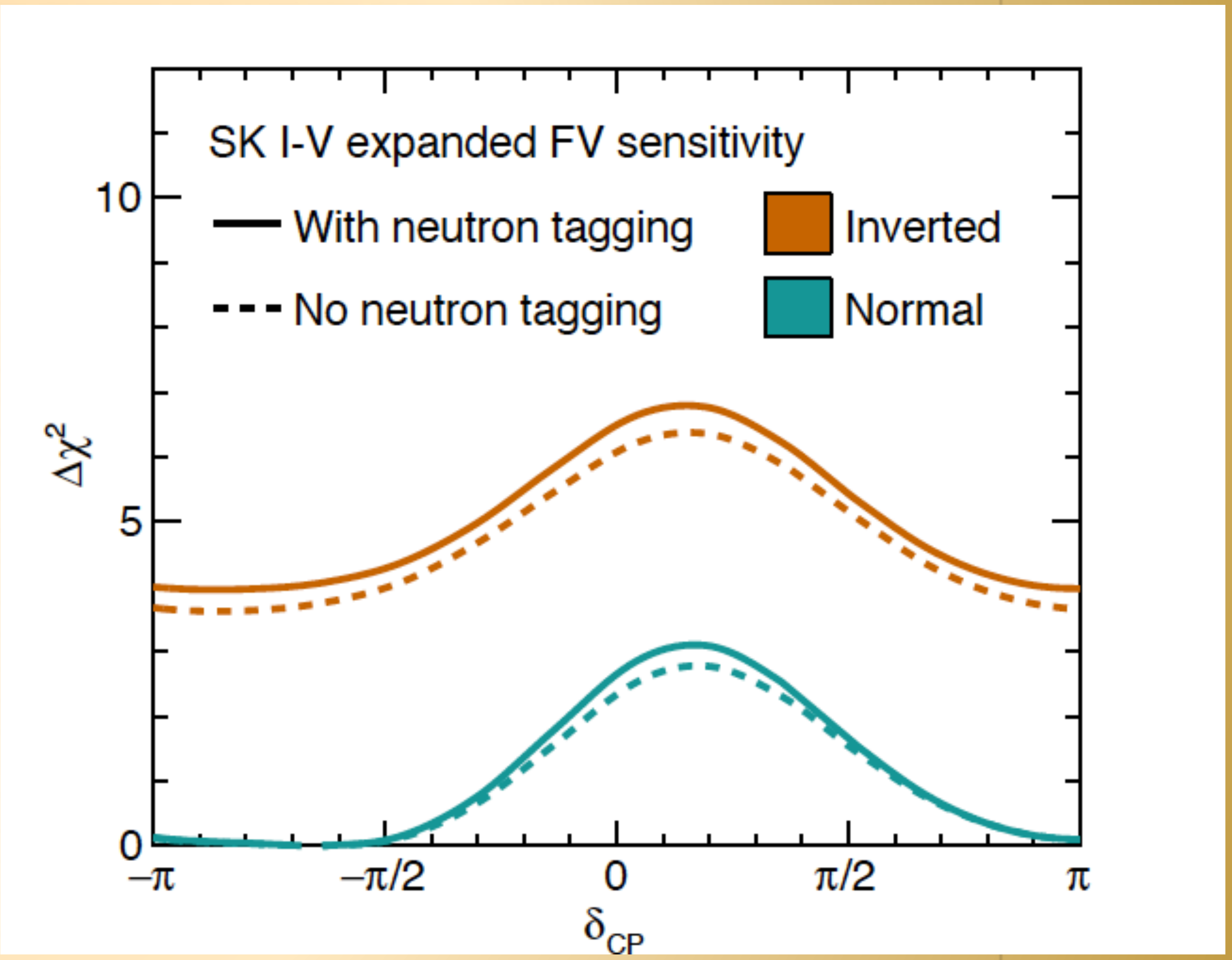
ν_e (44%)
$\bar{\nu}_e$ (46%)

ν_e (56%)
$\bar{\nu}_e$ (34%)

SK samples - impact of neutron tagging

- Additional selections done for SK4 and SK5 data period, **with neutron tagging on Hydrogen.**
- Improves separation between ν and $\bar{\nu}$ events





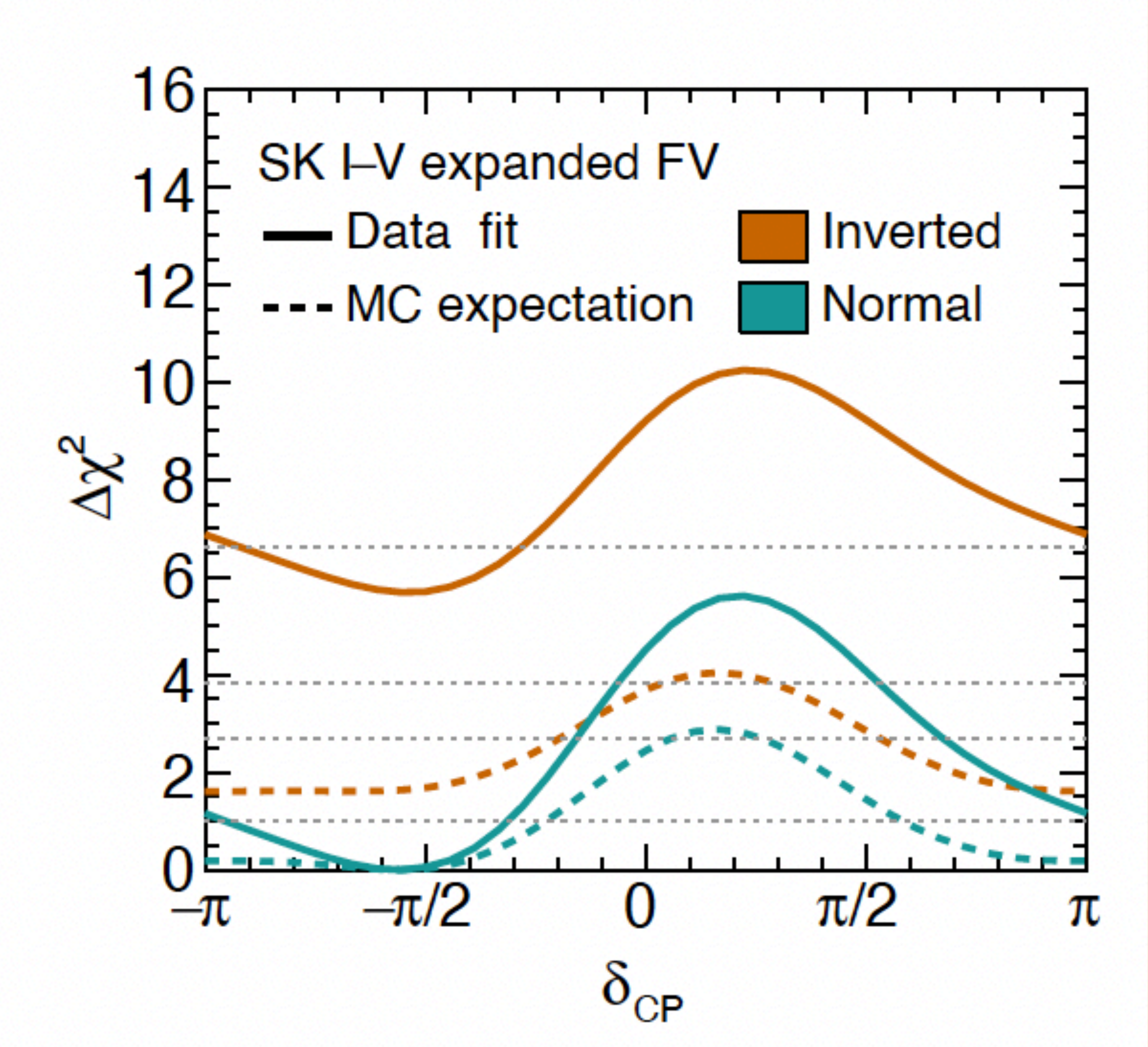
SK atmospheric ν results

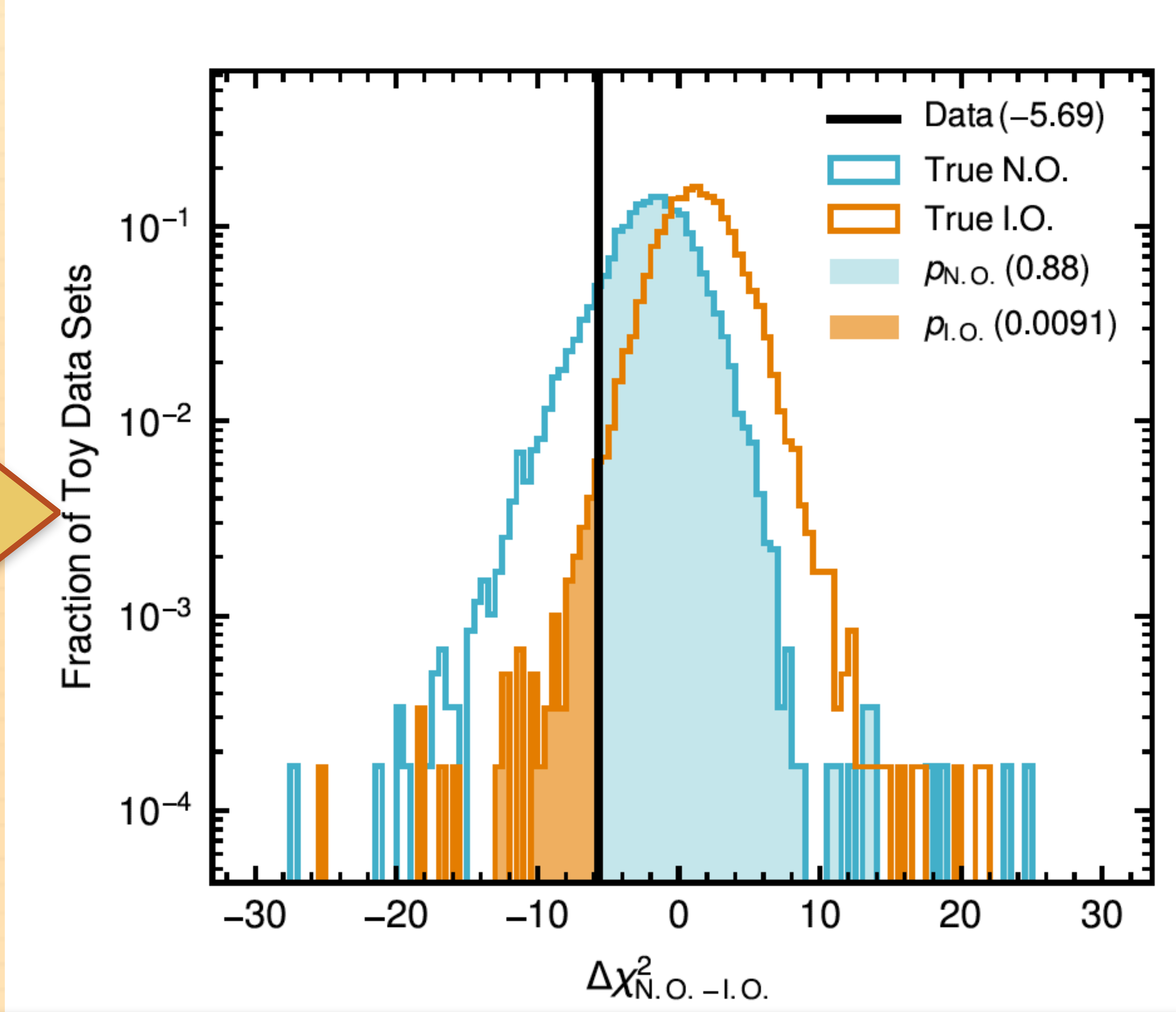
Phys. Rev. D 109, 072014, (2024)

With $\sin^2\theta_{13}$ constrained
$sin^2\theta_{13} = 0.0220 \pm 0.0007$
[PTEP 2022, 083C01 (2022])

SK data release on Zenodo page:

https://zenodo.org/records/8401262





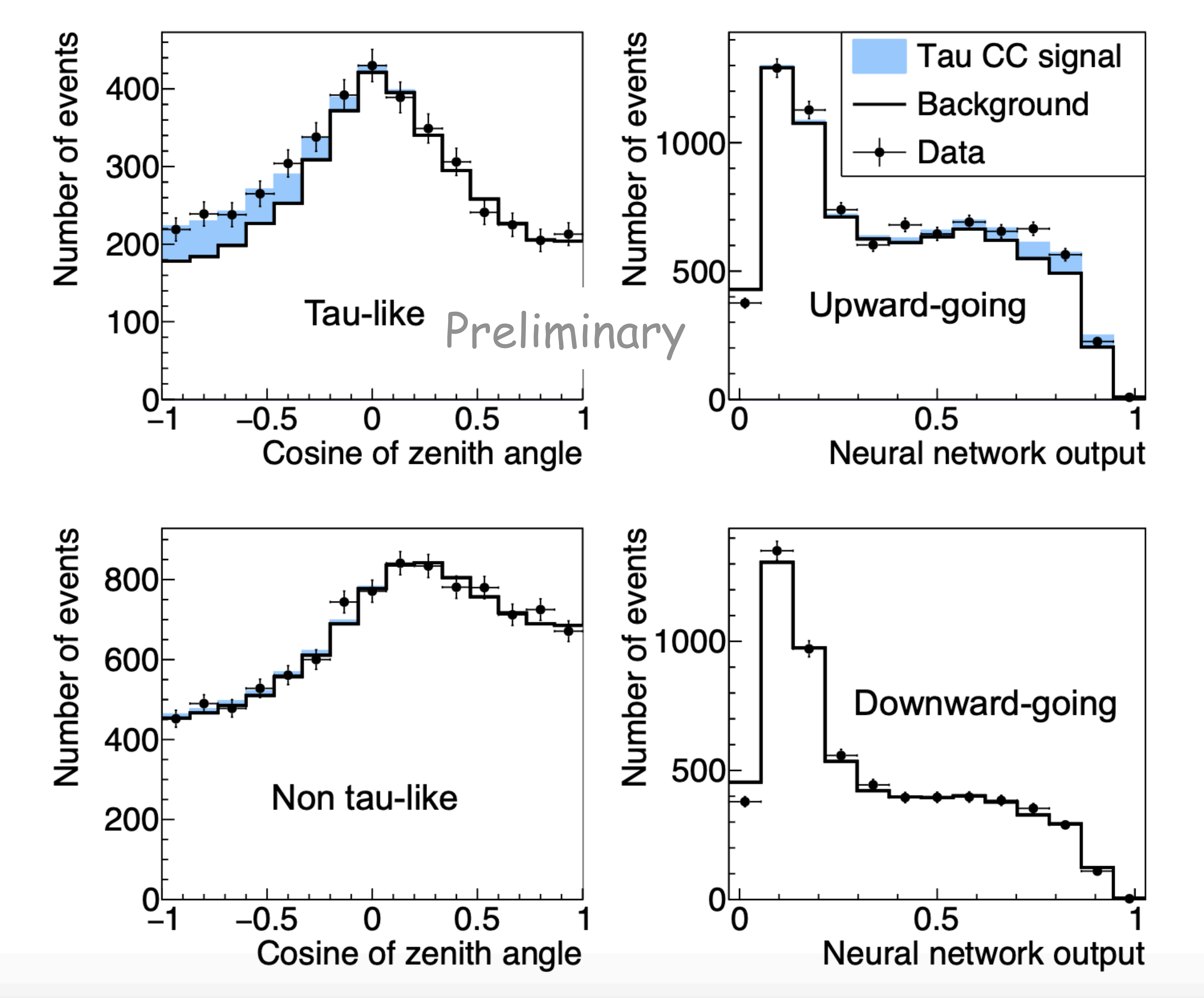
Full SK pure water phase (SK1-5) best fit results:

- Normal ordering, $\delta_{CP} \simeq -\pi/2$,
- $\Delta m^2_{32} \simeq 2.4 \cdot 10^{-3}$eV^2, $\sin^2\theta_{23} \simeq 0.45$ (Lower octant)
- Mass ordering: $\Delta\chi^2_{I.O-N.O} \simeq 5.69$

- Generate toy data sets to obtain distribution of $\Delta\chi^2_{NO-IO}$ and usage of CL_s method.
- **Conclusion: rejection of the inverted mass ordering is at** $92.3\,\% \simeq 1.4\sigma$

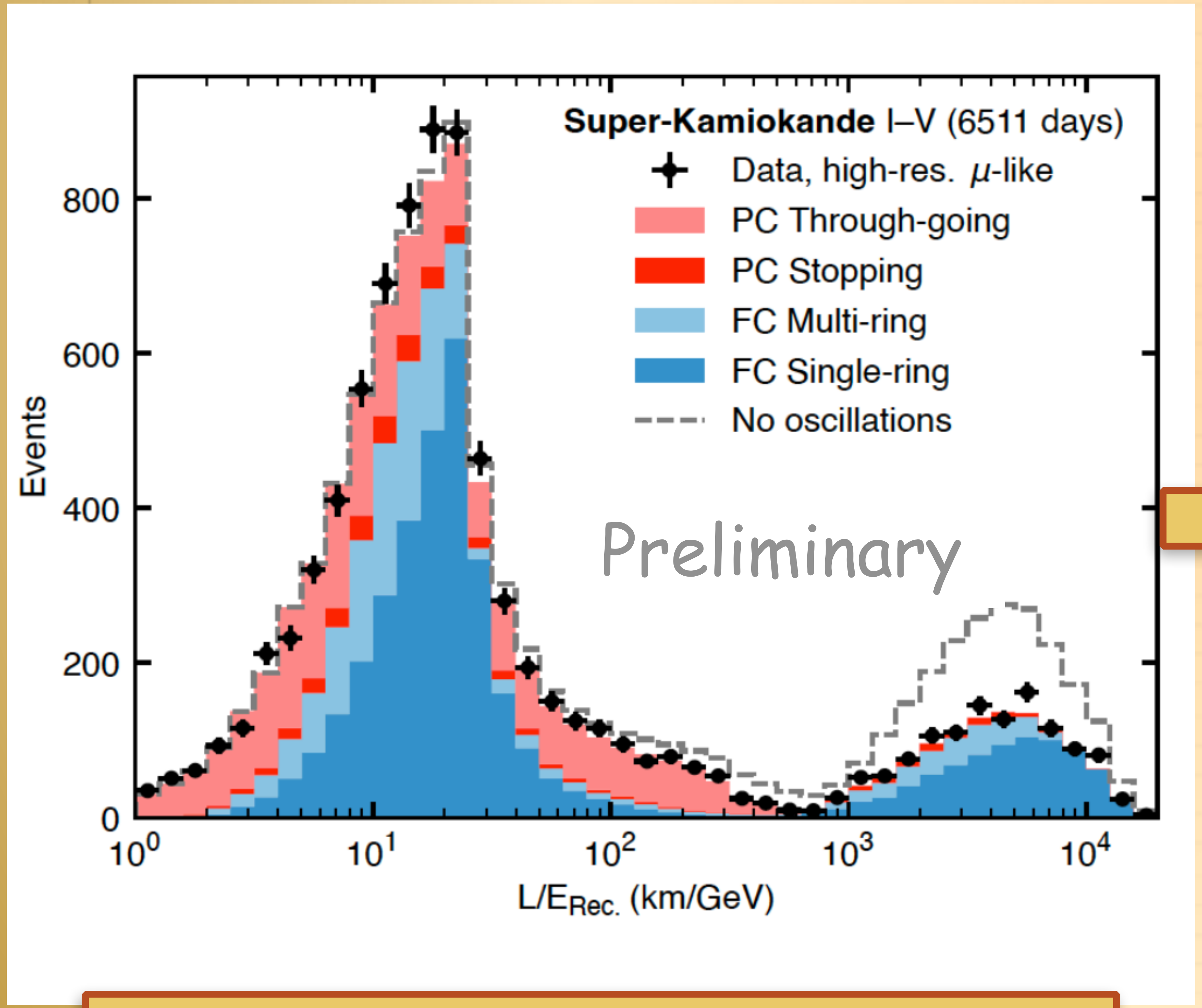
ν_τ appearance searches

- Updates since the last publication in Phys. Rev. D 98 052006 (2018)
  - Full SK pure water phases (SK1-5 data)
    - Additional 2 years of SK-IV and SK-V data added
  - Expanded fiducial volume - overall 50% more data added
- Best fit of ν_τ normalisation parameter: $\alpha = 1.359 \pm 0.289$
- **Excluding no ν_τ appearance ($\alpha = 0$) at 4.8σ significance,** p-value= $7.5 \cdot 10^{-7}$
- Observed # of ν_τ CC events: 428 ± 92 (normal MO)

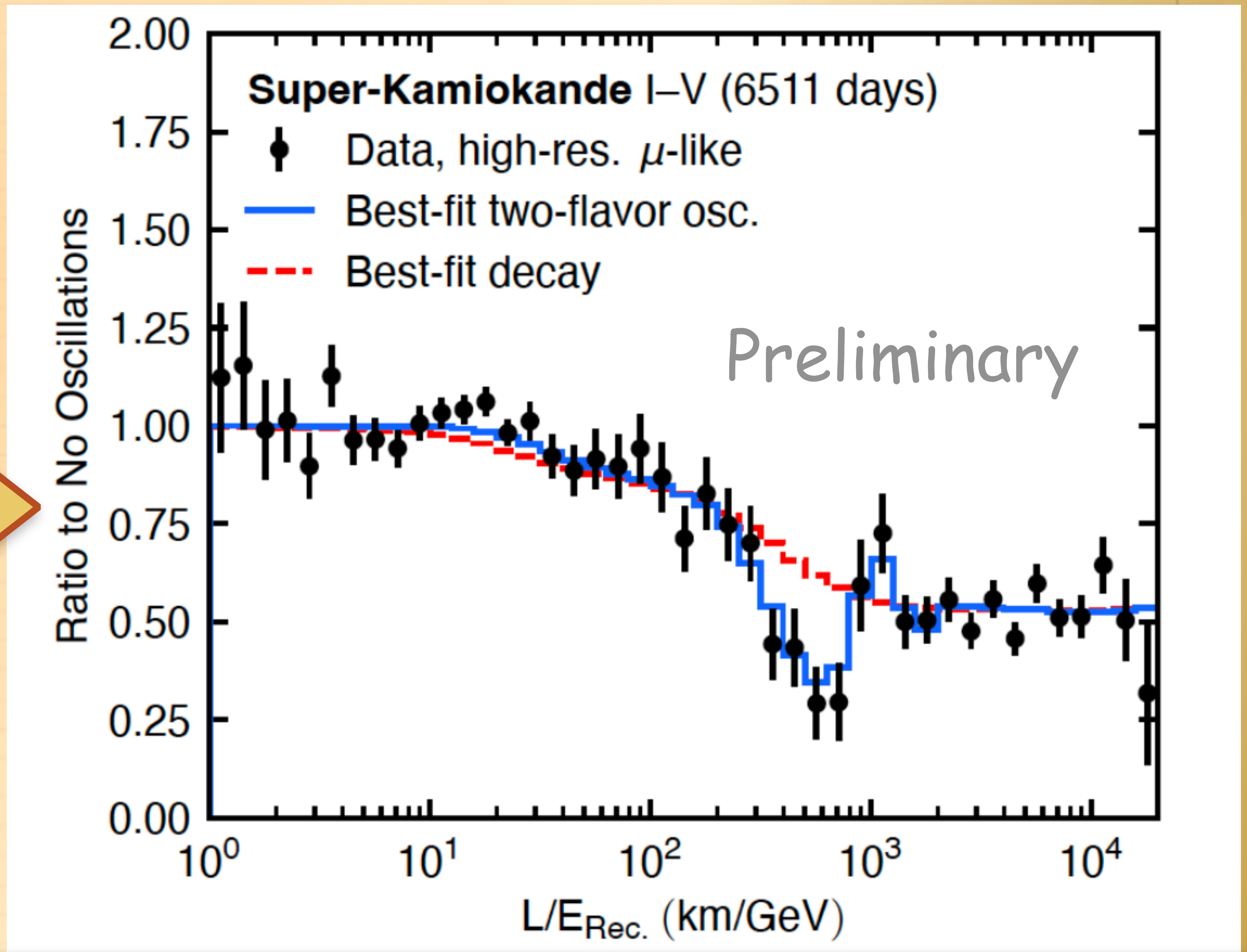


L/E analysis @ Super - Kamiokande

- Atmospheric neutrinos at SK span ~4 orders of magnitude in L/E, possible to see a complete oscillation of ν_μ **survival probability**
- Updates since the last published results in **2004 Phys. Rev. Lett. 93, 101801, SK1**:
  - Full SK pure water phases (SK-I~V data - 6511 days- $\sqrt{(}\Delta\chi^2$(decay, 2 fl. osc.) $= 6.0\sigma$))
  - New L/E estimator, high- and low-resolution samples



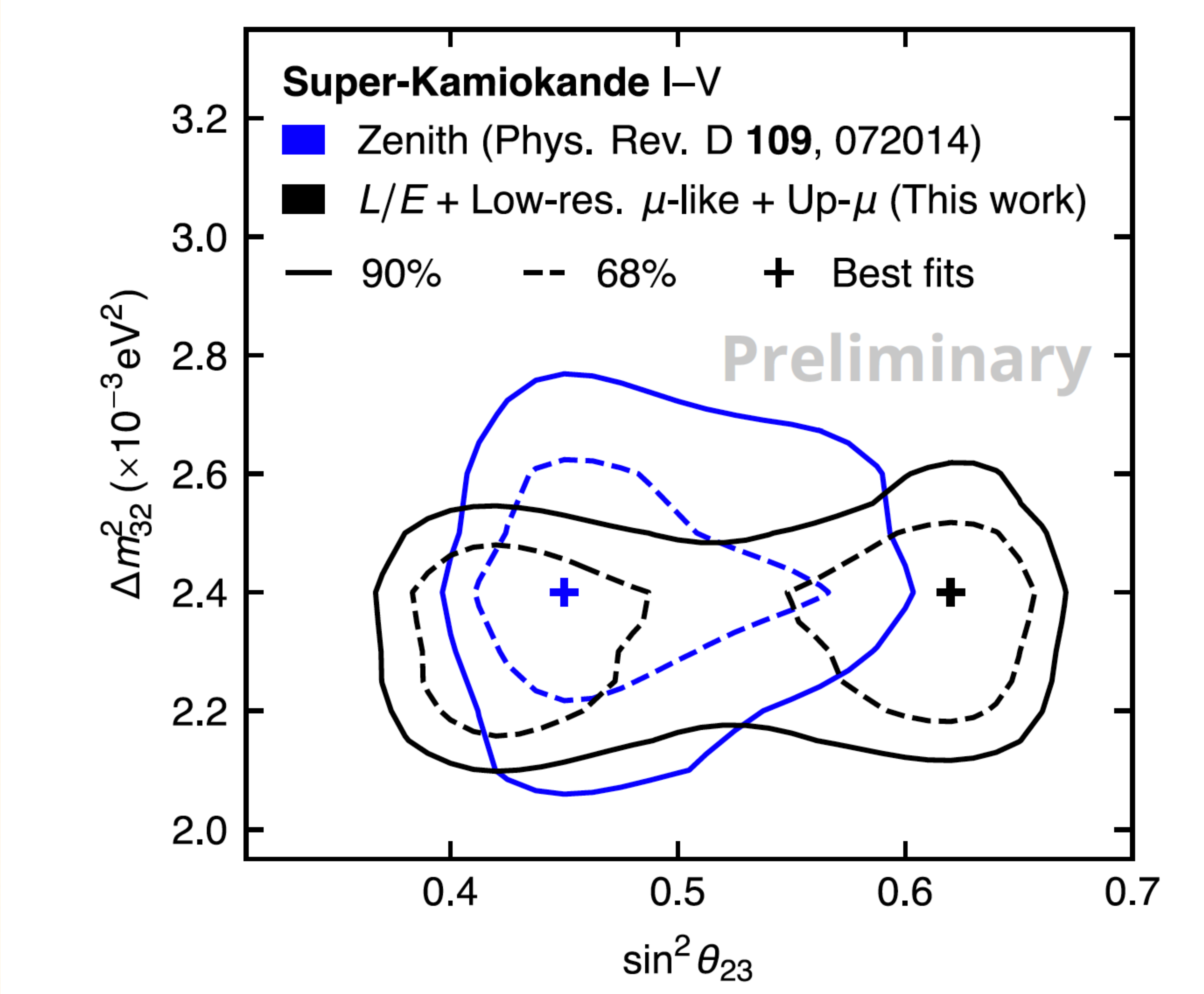
High - resolution data/MC sample



High resolution data: best fit for two flavour oscillations vs. neutrino decay

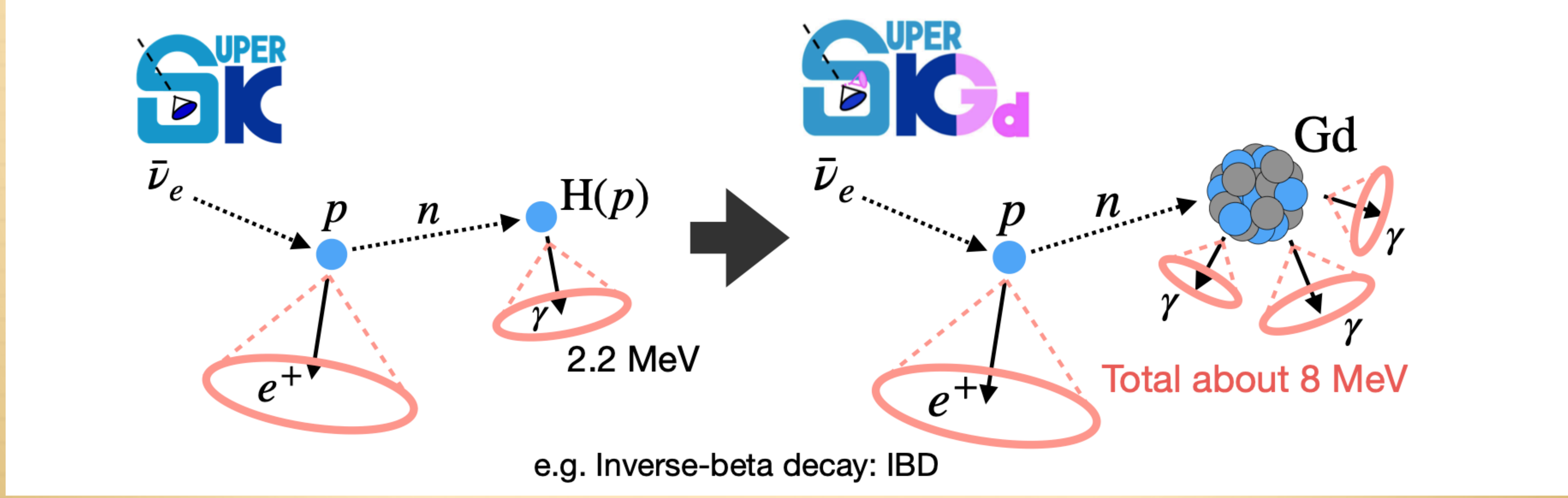
L/E analysis @ Super - Kamiokande

- Atmospheric mixing contours
  - Normal ordering is assumed
  - See the poster by Thomas Wester: Neutrino oscillation analysis with Super-Kamiokande's highest-resolution events



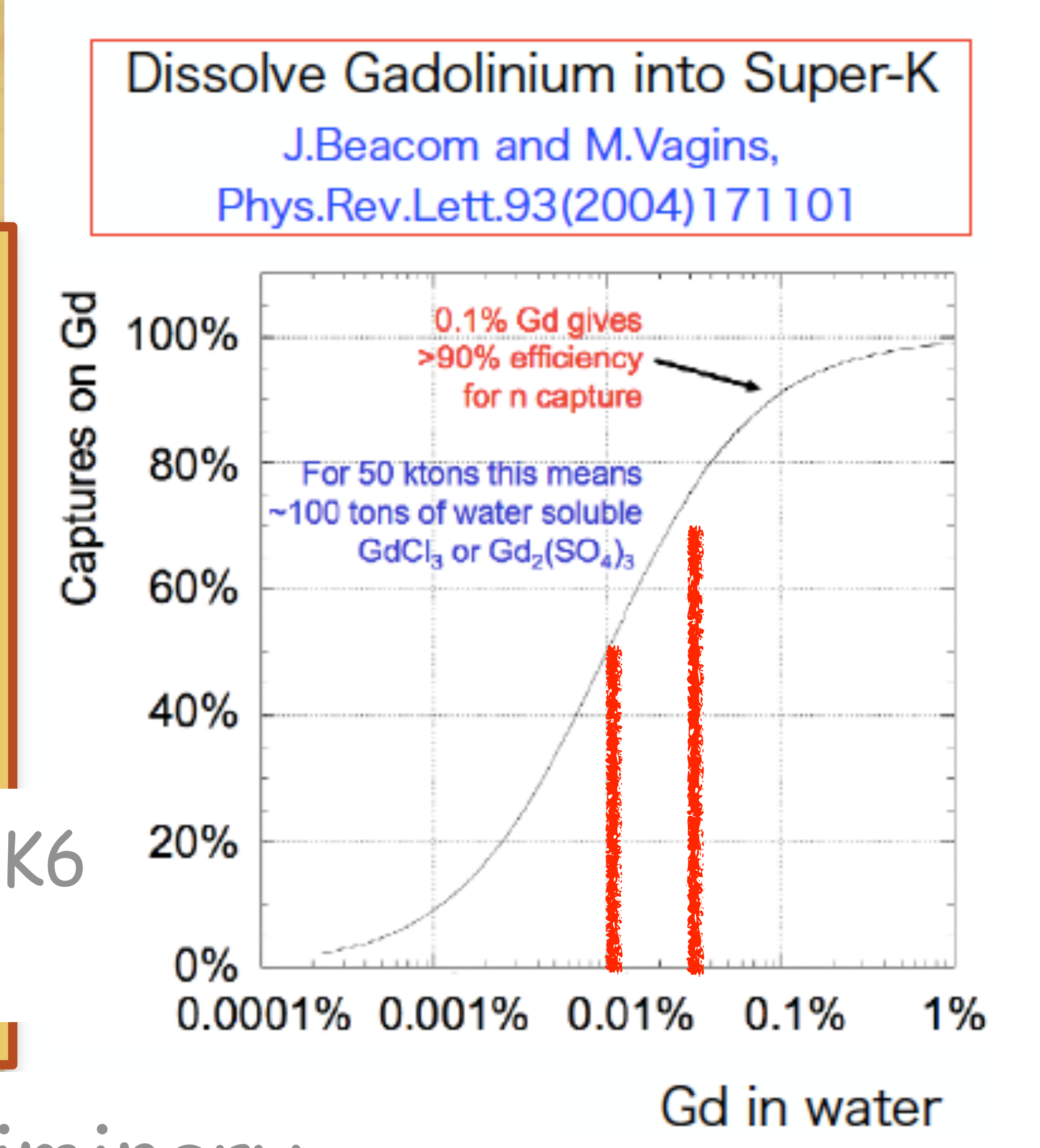
SK-Gd era

Gadolinium project at Super-K: SK-Gd



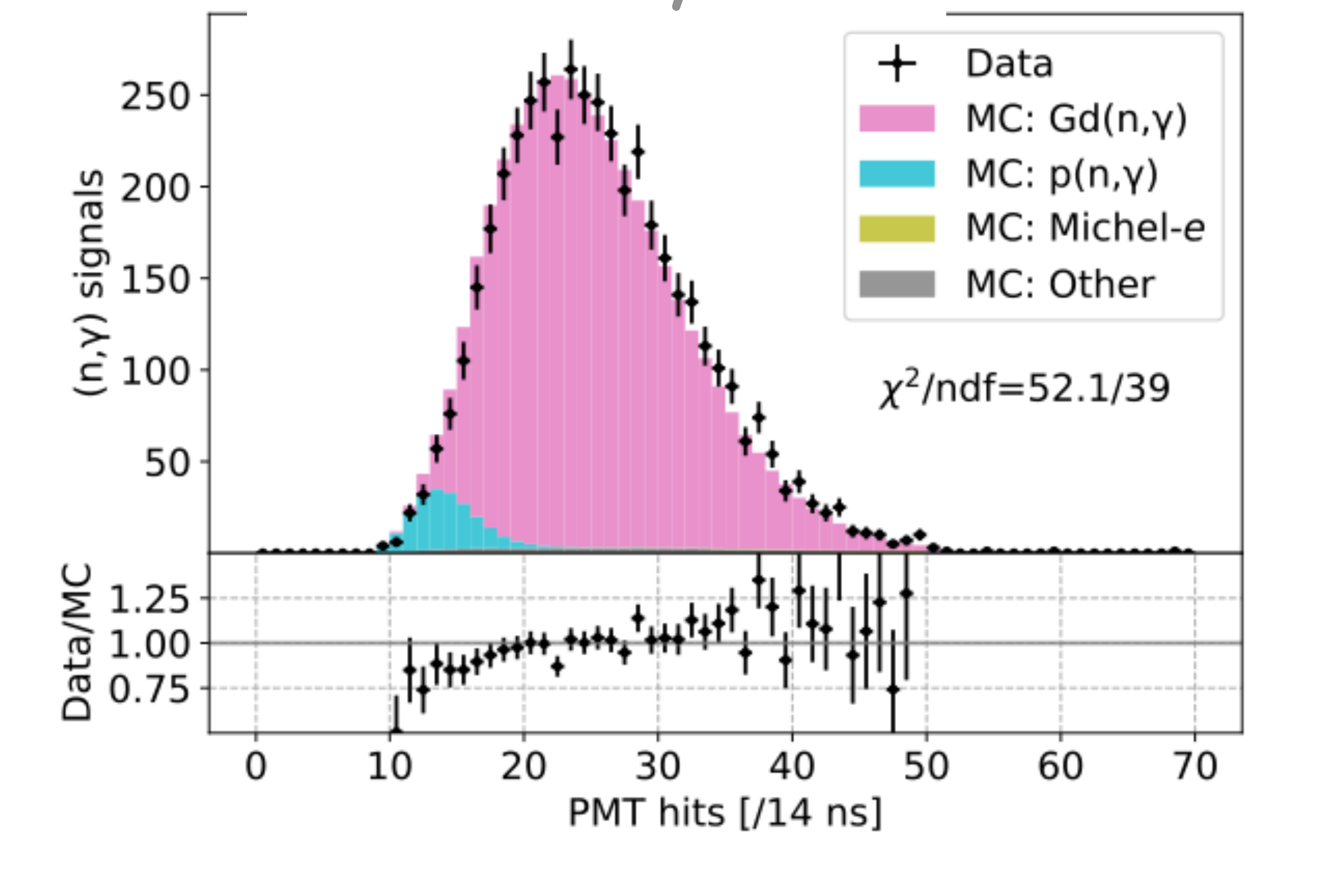
Why Gd salt was added ?

- SK-Gd: add Gd sulphate to ultra pure water to enhance neutron tagging efficiency.
- Physics targets:
  - Detection of the world's first (DSNB) -see Harada-san talk
  - Improvement of supernova direction pointing accuracy
  - Enhancement of ν and $\bar{\nu}$ identification and improvement of E_ν reconstruction in atmospheric ν and T2K analyses
  - Reduction of background in nucleon decay search

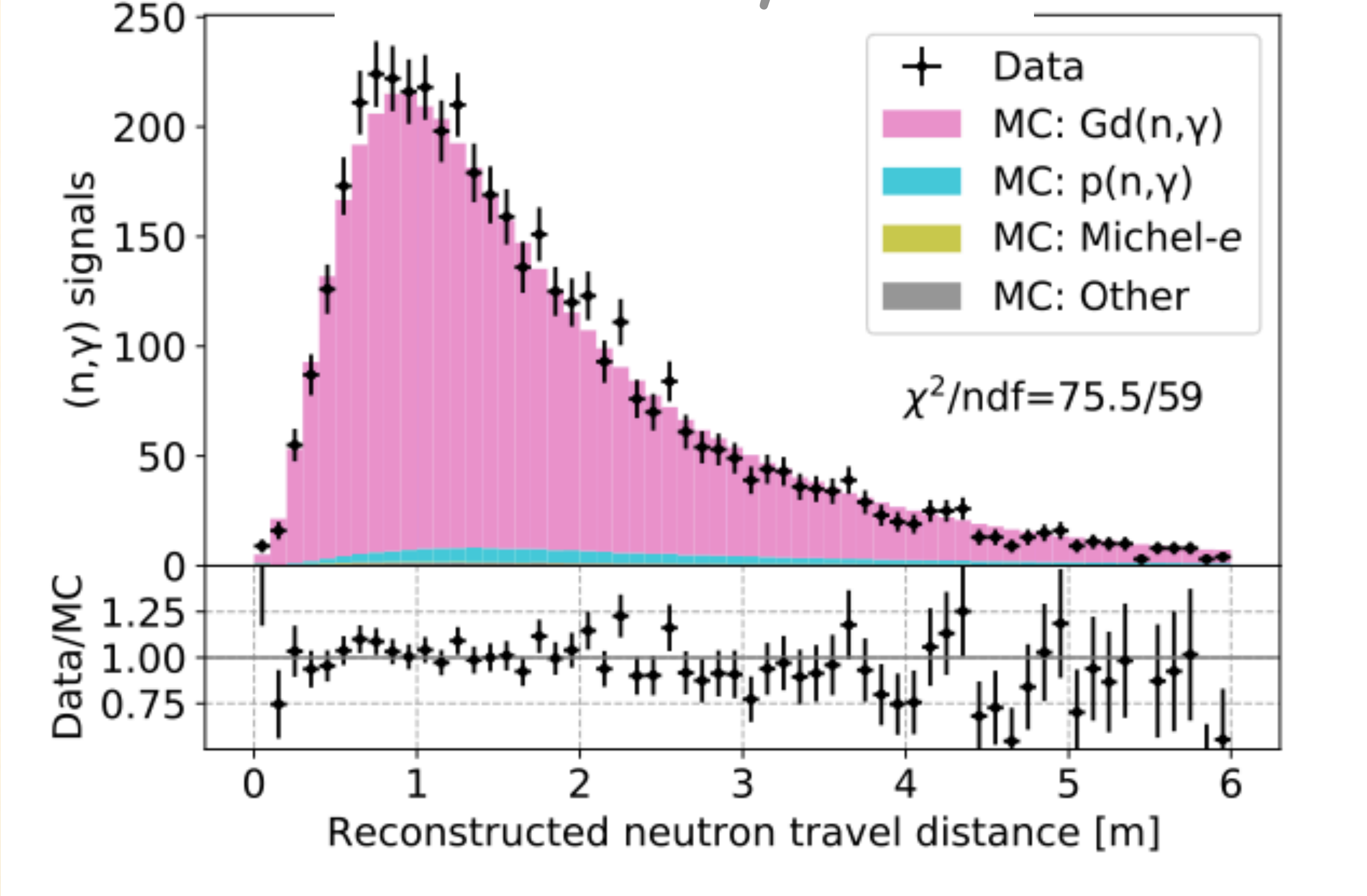


Gd: 0.01% SK6
0.03% SK7

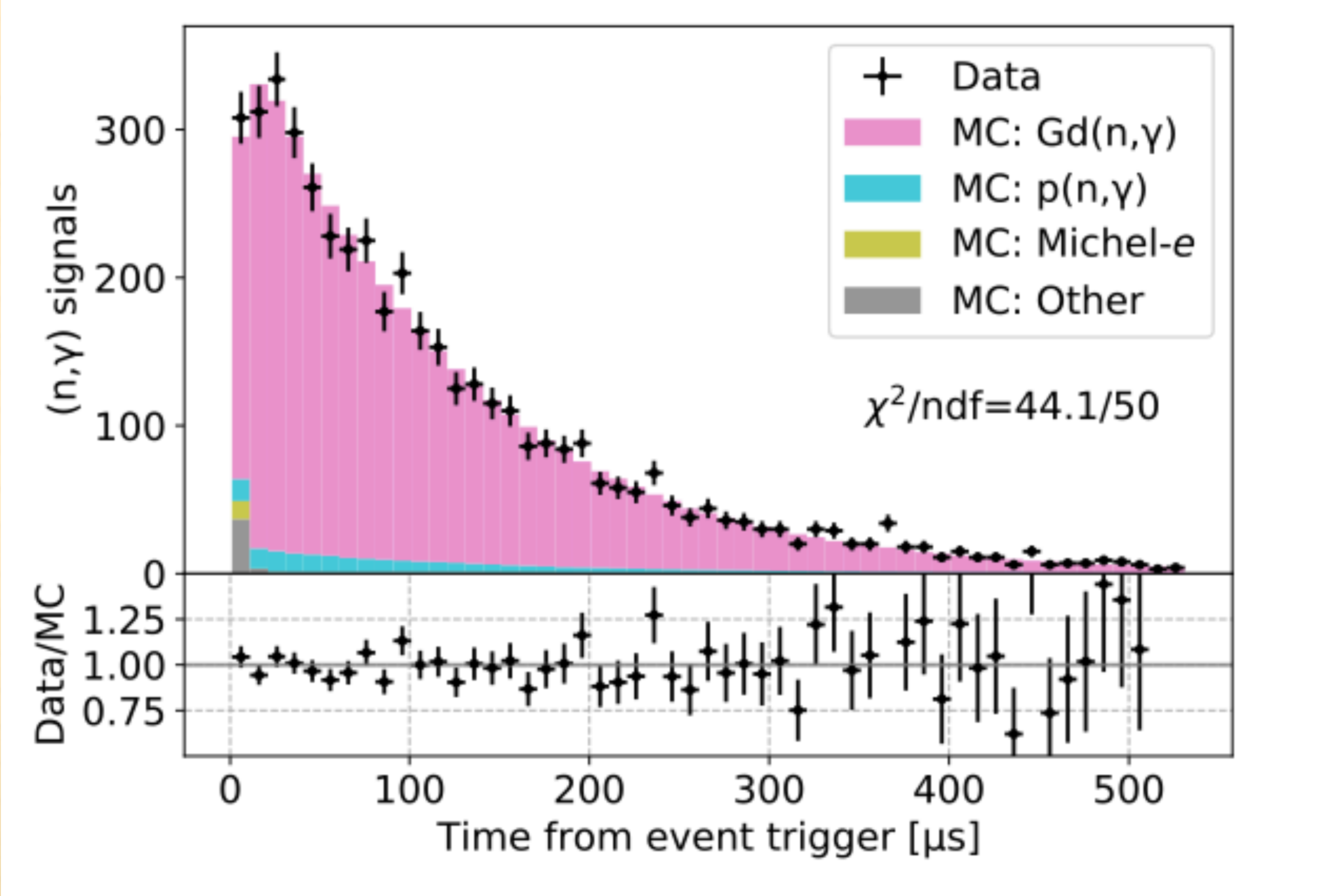
Preliminary



Preliminary



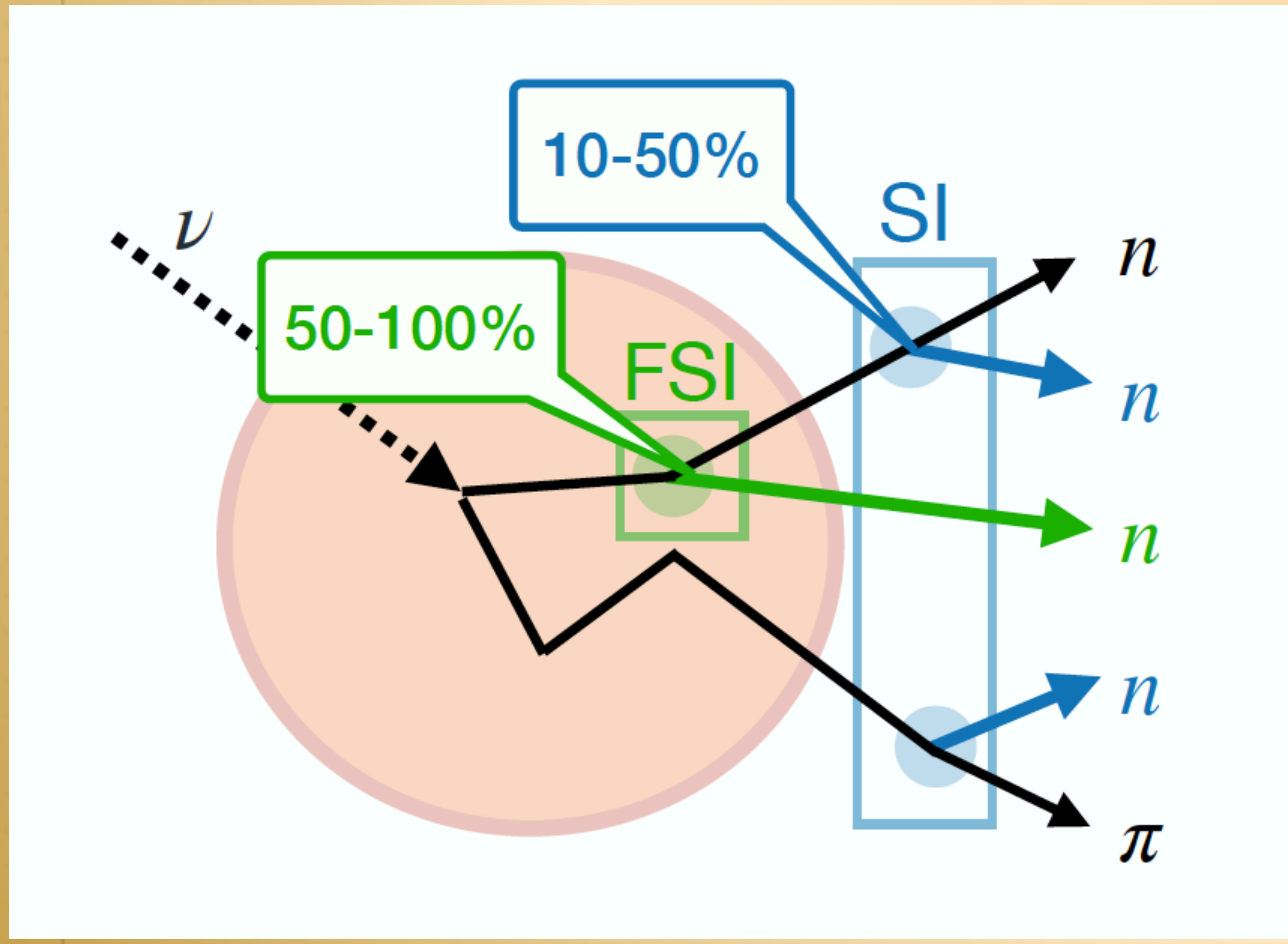
Preliminary

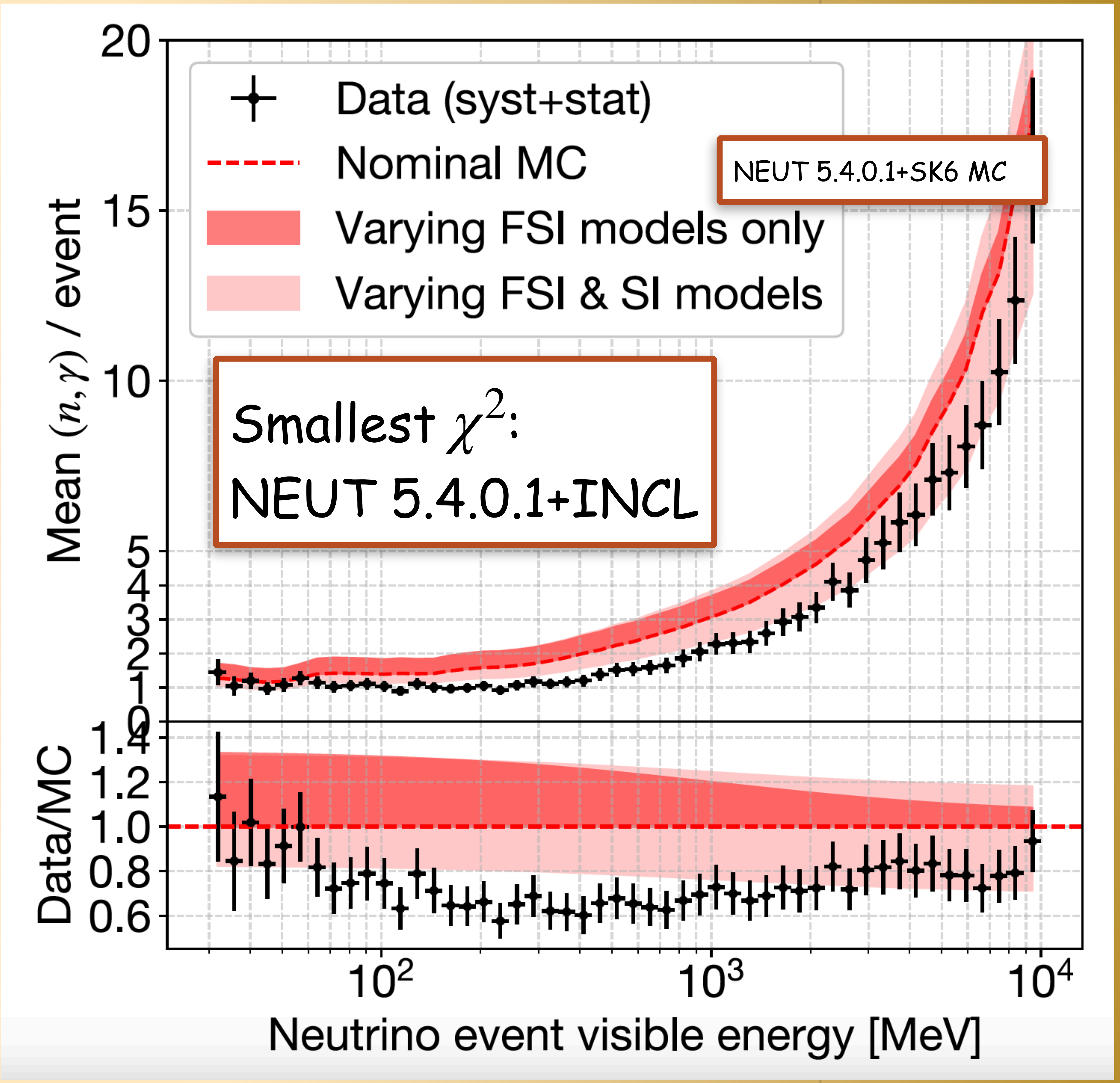


Neutrons in atmospheric ν interactions

- SK-Gd: neutron multiplicity measurements
  - Large uncertainty in "neutron smearing"
  - Huge differences between models

Neutron multiplicity = $\frac{\text{measured neutrons}}{\text{detec eff.}}$

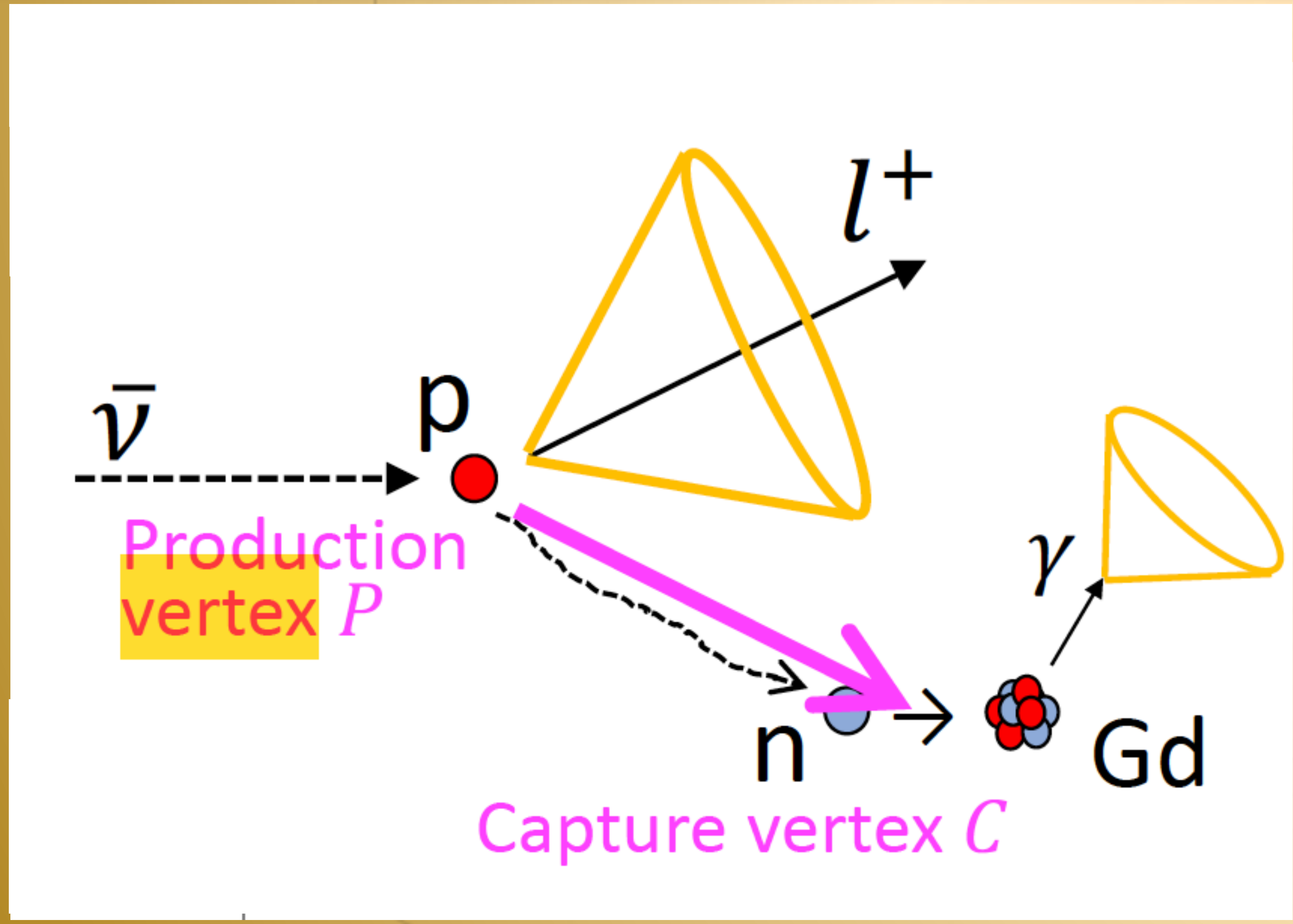


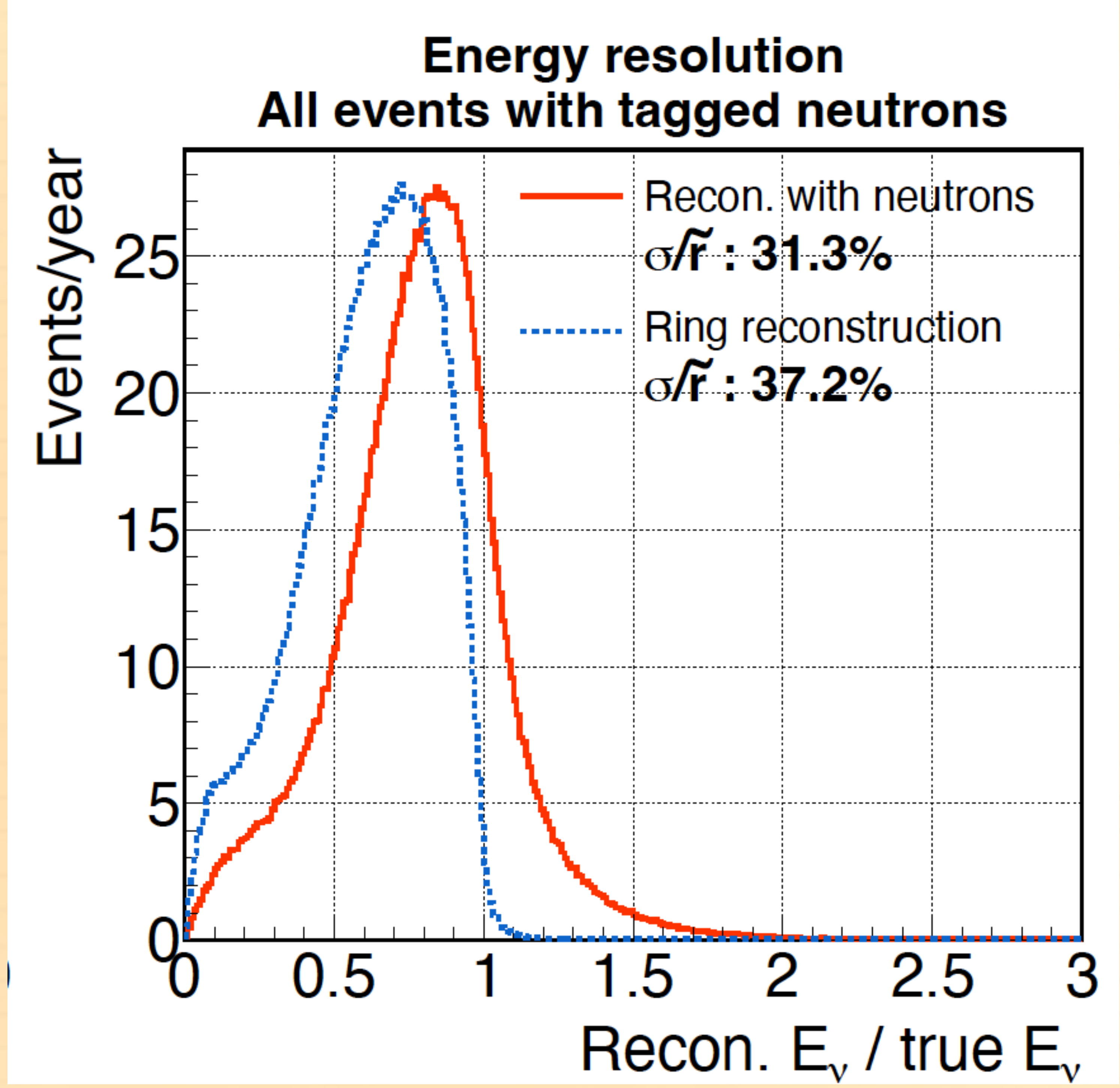


- SK4+5+6 atm. (FCFV ~12 years of data)

SK6 oscillation analysis with neutron tagging

- Why neutrons are useful in the atmospheric oscillation analysis?
  - they **improve the $\nu/\bar{\nu}$ separation,**
  - they **improve the reconstruction of E_ν and neutrino direction $\vec{d_\nu}$** with information on neutron momentum $\vec{p_n}$ (estimated from neutron travel distance @ the SK- assuming $\vec{p_n} \propto |\vec{PC}|$)





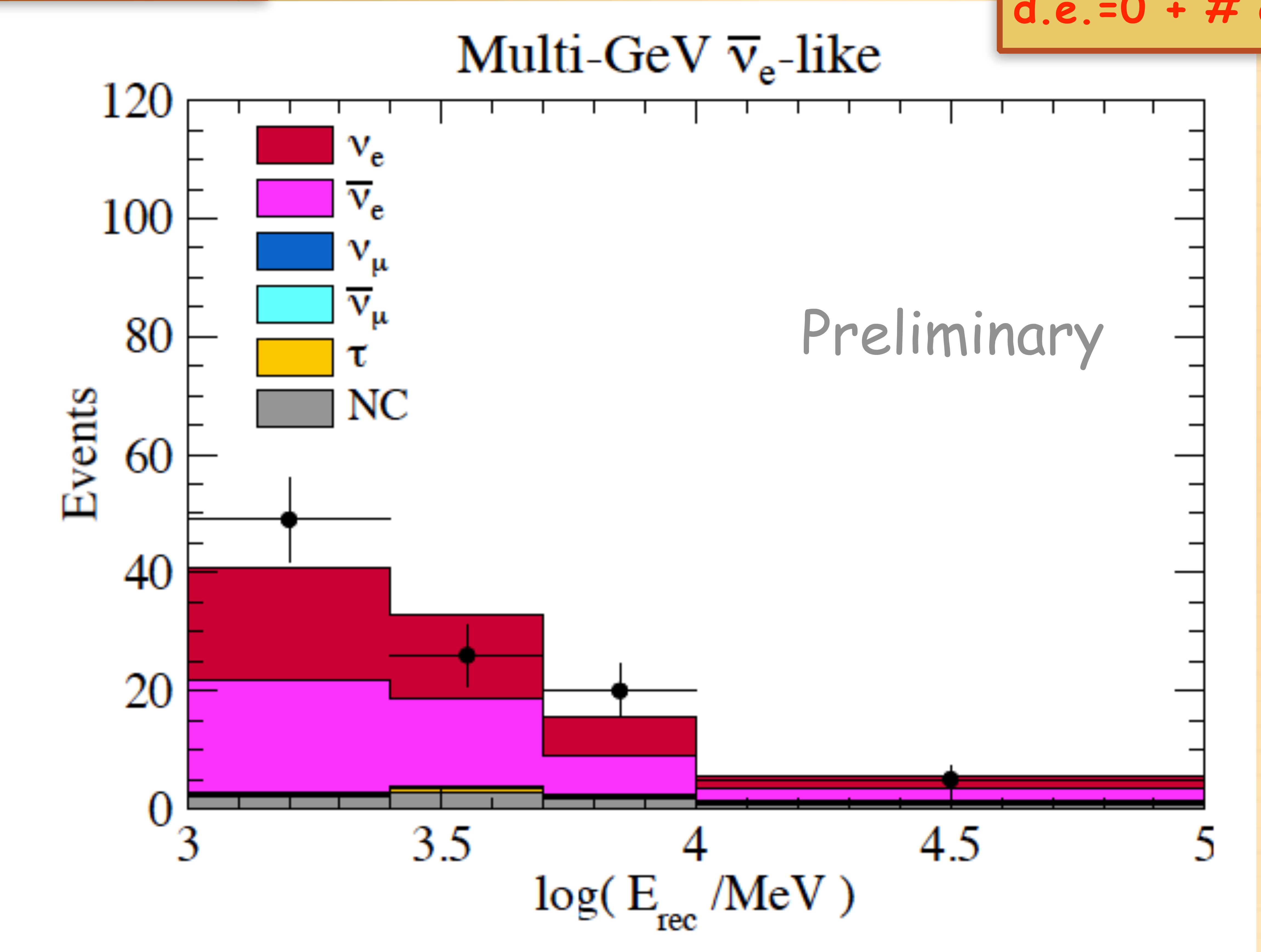
- *See the poster #112 by Shintaro Miki: Atmospheric Neutrino Oscillations in SK-Gd*

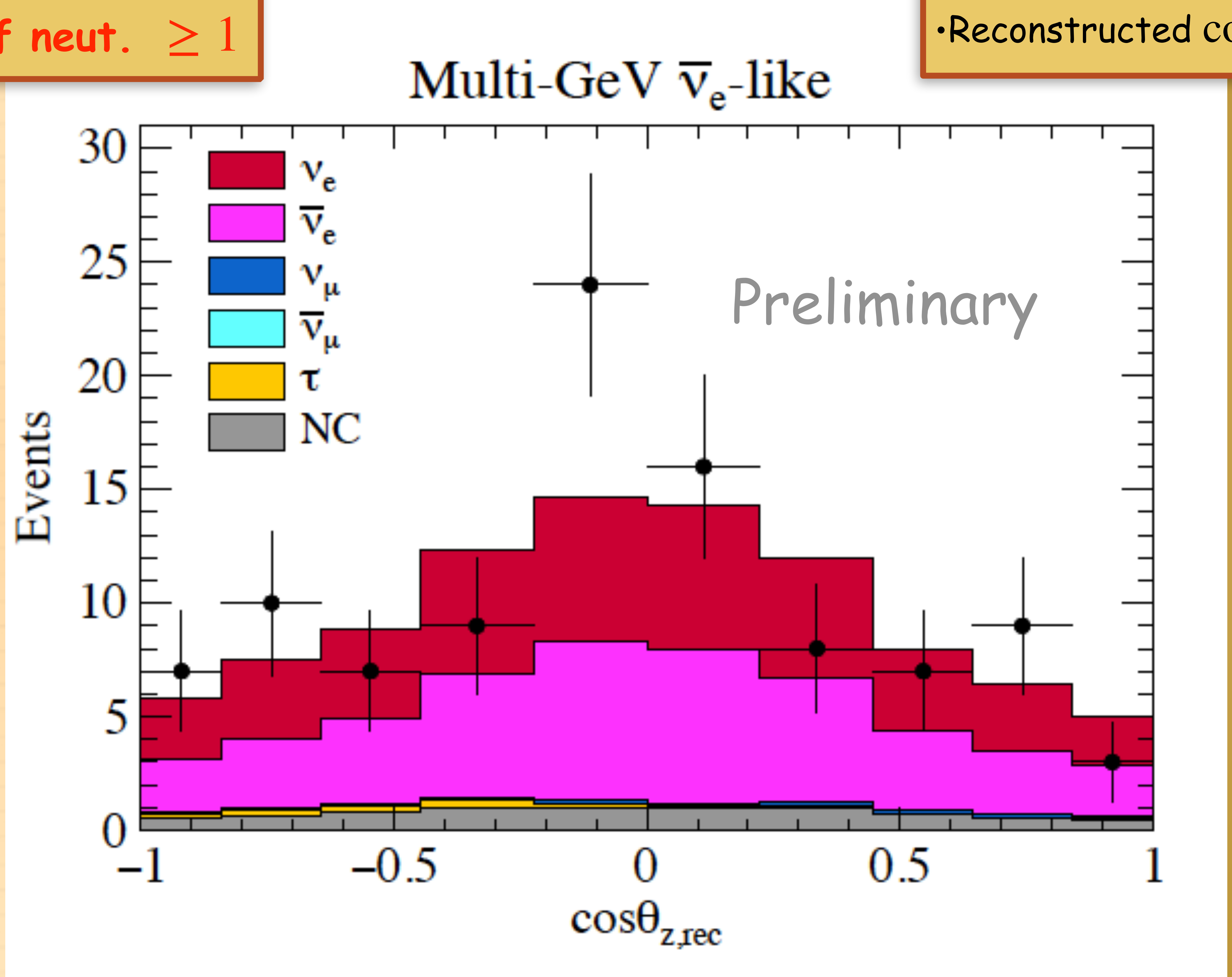
SK6 reconstruction with neutrons

•Reconstructed E_ν

d.e.=0 + # of neut. ≥ 1

•Reconstructed $\cos\theta_\nu$





• See the poster #112 by Shintaro Miki: Atmospheric Neutrino Oscillations in SK-Gd

Summary

Atmospheric neutrinos full pure SK1-5 data:

- Analysed all pure water data sets (SK1 -5) and with expanded fiducial volume (total 27.2kton) and using information on neutron tagging on hydrogen - new paper **Phys. Rev. D 109, 072014 – Published 24 April 2024**
- Latest results on ν_τ appearance searches
- Latest results on L/E analysis - high- and low-resolution samples

Atmospheric neutrinos - SK4 data:

- SK+T2K joint fit results - see the talk of Claudio Giganti on T2K on this conference - **results published on arXiv:2405.12488**

SK- Gd:

- Neutron tagging is working, observing many more captures
- Latest results on neutron multiplicity measurements
- Studies with SK6 data and reconstruction with neutrons

The Super-Kamiokande Collaboration

Toyama meeting 2024

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
BMCC/CUNY, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Gifu University, Japan
GIST, Korea
University of Glasgow, UK
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France/Japan

INFN Bari, ItalyI
NFN 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
University of Minnesota, USA
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan

Osaka Electro-Communication Univ.,Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
University of Silesia in Katowice, Poland
Sungkyunkwan University, Korea
Tohoku University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, Japan
University of Toyama, 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 54 institutes in 11 countries

Thank you!

Photo Credit: Piotr Mijakowski

Other SK talks@ Neutrino24:

1. Masayuki Harada: Review of diffuse SN neutrino background

SK posters @ Neutrino24:

1. Z. Xie, L. Berns: First joint analysis of Super-Kamiokande atmospheric and T2K accelerator neutron data
2. Natsumi Ogawa: Search for proton decay via $p \to e^+ + \eta$ and. $p \to \mu^+ + \eta$ in Super-Kamiokande
3. Thomas Wester: Neutrino oscillation analysis with Super-Kamiokande's highest-resolution events
4. Maitrayee Mandal: Tau neutrino appearance and the measurement of the neutrino mass ordering at Super-Kamiokande
5. Shintaro Miki: Atmospheric Neutrino Oscillations in SK-Gd
6. Antoine Beauche: Diffuse Supernova Neutrino Background: Insights from Super-K & prosecutes with Hyper-K
7. Rudolph Rogly: Overview of the model-dependent approach for the Diffuse Supernova Neutrino Background search with SK-Gd
8. A.Santos, Y.Kanemura, M.Harada: New limits on the low-energy astrophysical electron antineutrinos at SK-Gd experiment
9. Yuuki Nakano: Solar neutrino measurement using the Super-Kamiokande detector
10. S. Izumiyama et al.: Observation of distant reactor neutrino in Super-Kamiokande with gadolinium- loaded water
11. Fumi Nakanishi: Search for "mini - burst" supernova neutrinos in Super-Kamiokande
12. Tomoaki Tada: Constraint on the atmospheric neutrino flux models using the cosmic-ray muon data in the Super-Kamiokande
13. Barry Pointon: HEALPix-based Analysis of Burst Neutrinos for Supernova Direction Reconstruction at Super-Kamiokande
14. Saki Fujita Energy: Scale Calibration of the Super-Kamiokande Detector using the Decay of Nitrogen-16
15. Guillaume Provost: Supernova burst monitoring in Super-Kamiokande
16. Alejandro Yankelevich: Measurement of below 3.49 MeV solar neutrinos at Super-Kamiokande
17. Lucas Nascimento Machado: Combined KamLAND and Super-Kamiokande Presupernova Alarm

Data release

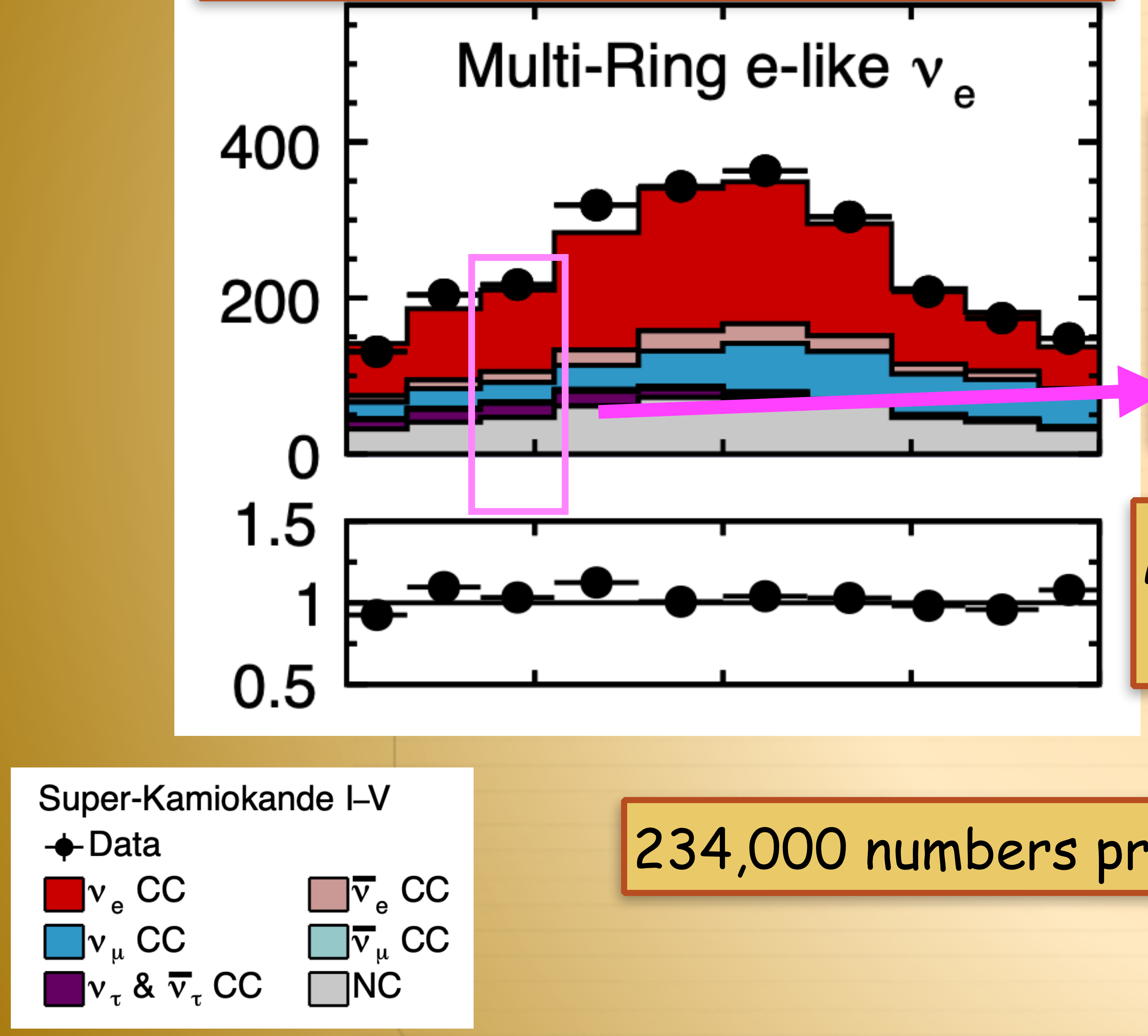
Open Access

Atmospheric neutrino oscillation analysis with neutron tagging and an expanded fiducial volume in Super-Kamiokande I–V

T. Wester *et al.* (The Super-Kamiokande Collaboration)
Phys. Rev. D **109**, 072014 – Published 24 April 2024

[57] Data release: Atmospheric neutrino oscillation analysis with neutron tagging and an expanded fiducial volume in Super-Kamiokande I–V, 10.5281/zenodo.8401262 (2023).

information from all 930 2DIM $\cos_\theta$ vs p_l bins provided



Data counts
Unoscillated MC
Oscillated best fit MC for N.O.
Oscillated best fit MC for I.O.

$\nu_e CC$
$\bar{\nu}_e CC$
$\nu_\mu CC$
$\bar{\nu}_\mu CC$
NC
$\nu_\tau CC\ (osc)$

Average
median
RMS
$\pm 1\sigma, \ \pm 2\sigma$
quantiles for
$E_{\nu,true}$
$\theta_{\nu,true}$

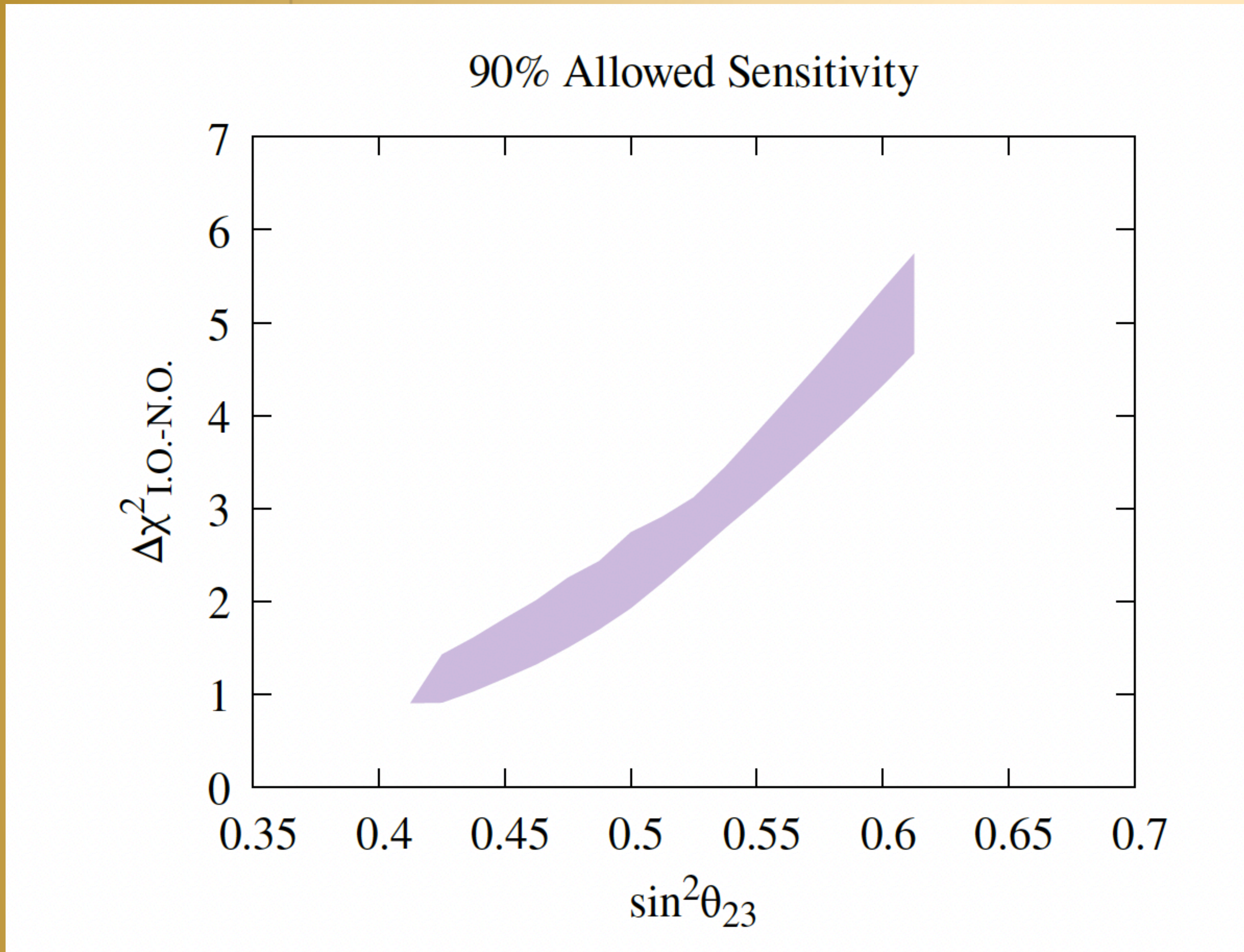
Modeling multi-GeV ν interactions is non-trivial

234,000 numbers provided

+

χ^2 map and digitized contours provided

The mass ordering sensitivity

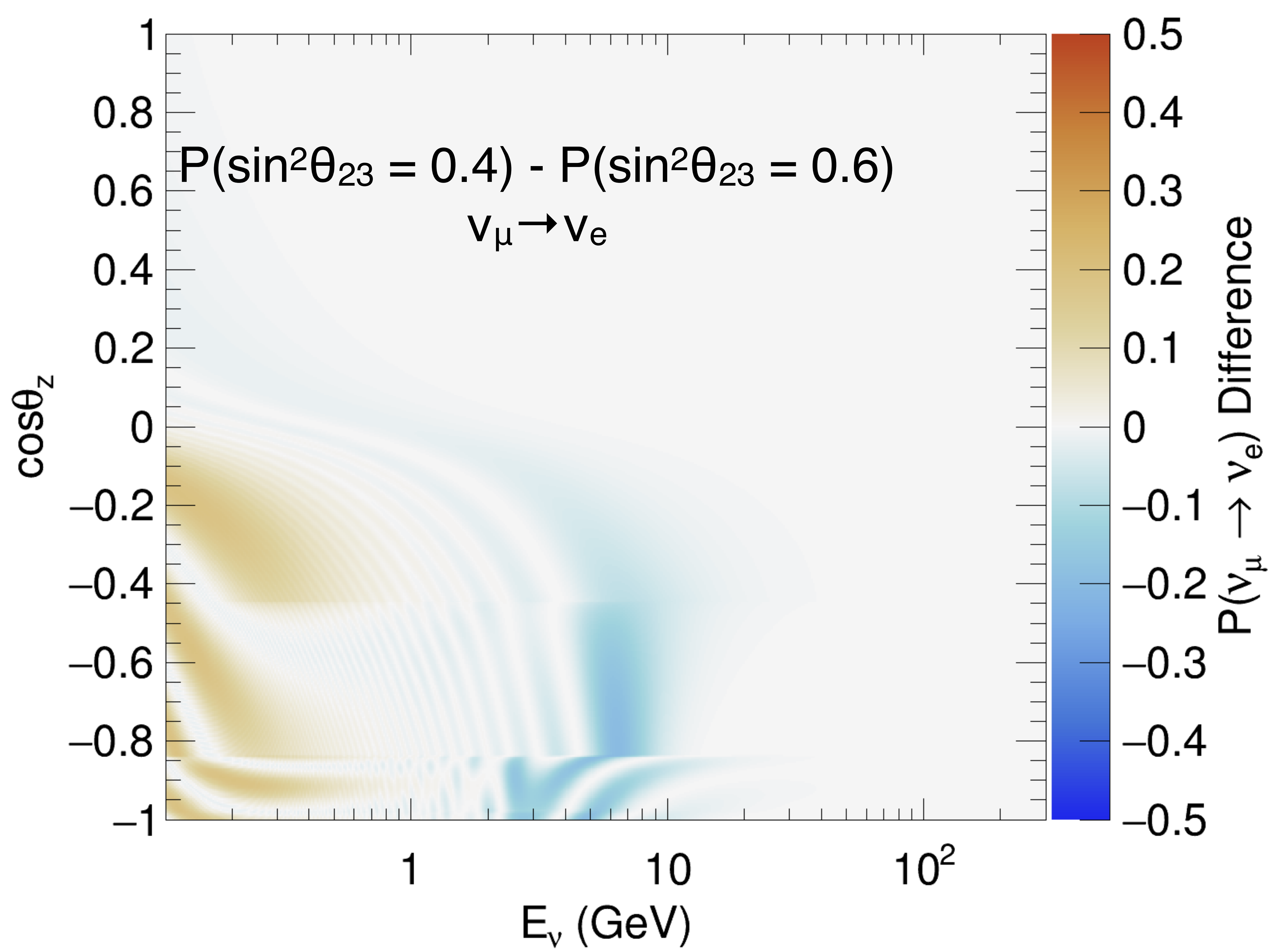


- The mass ordering sensitivity is highly dependent on the values of $\sin^2\theta_{23}, \sin^2\theta_{13}$ and δ_{CP}
- This figure shows the sensitivity for the mass ordering **assuming different values of the oscillation parameters followed by the fit at 90%**
- **The largest ν_e appearance signal - the highest sensitivity to reject the inverted mass ordering - is for:**
  - **the higher values of $\sin^2\theta_{23}$**
  - **values of $\delta_{CP} = -\pi/2$**

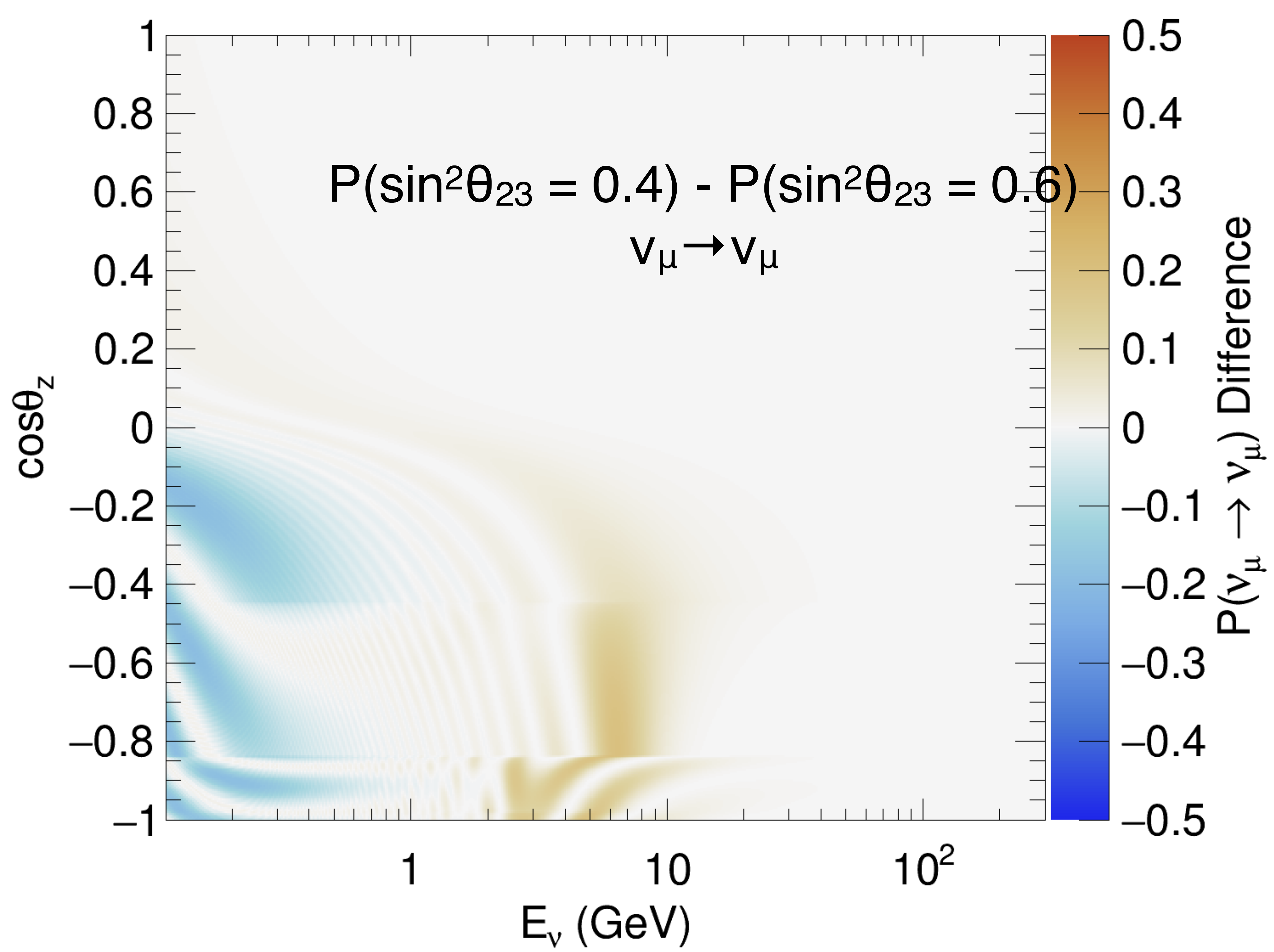
Conclusion: the difference between DATA and MC expectations is much smaller for upper-octant values of $\sin^2\theta_{23}$

Octant effect on oscillations

$P(\nu_\mu \to \nu_e)$ difference



$P(\nu_\mu \to \nu_\mu)$ difference

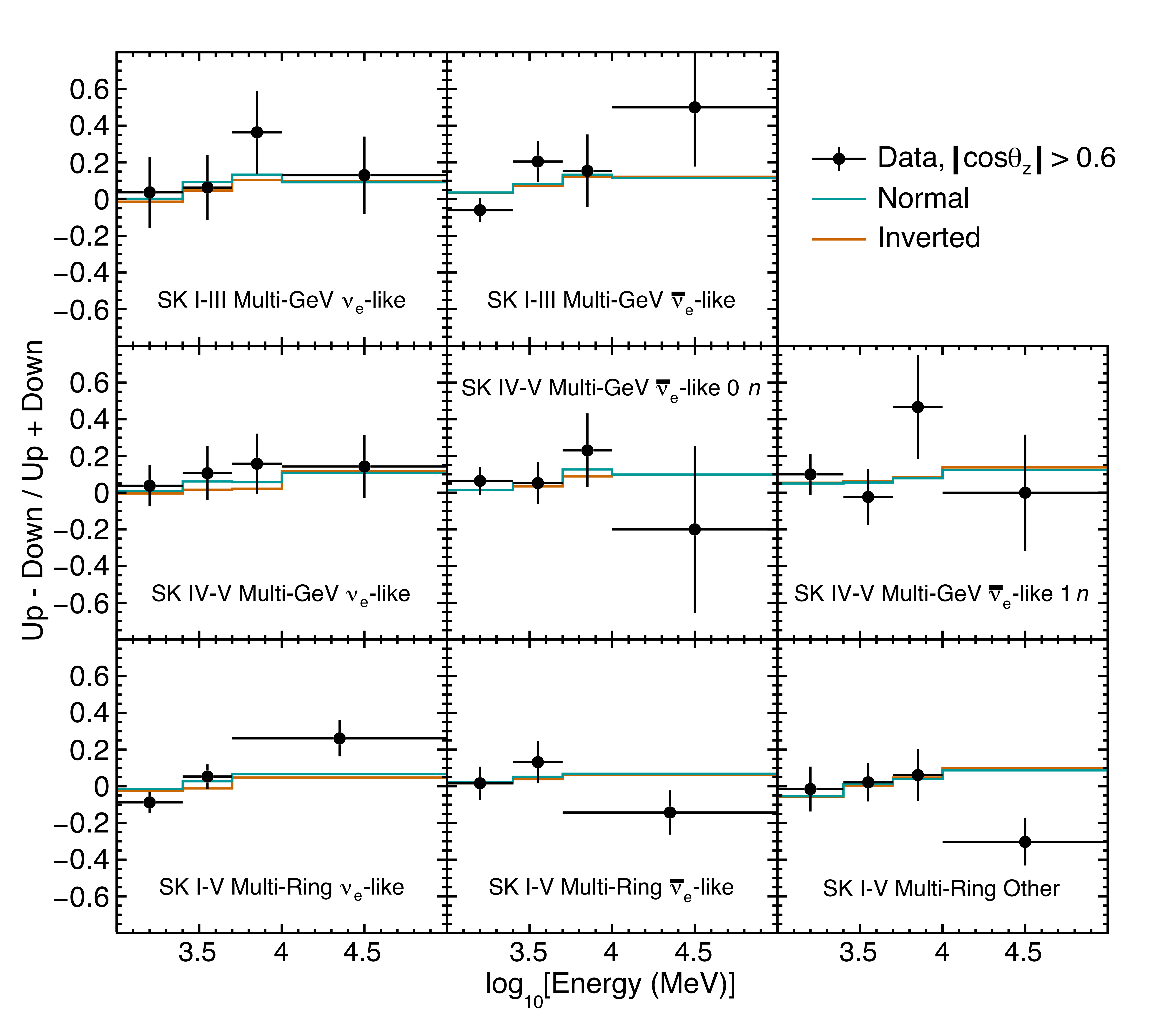


Thomas Wester's studies

Assumptions:

- Normal ordering, $\delta_{CP} \simeq -\pi/2$,
- $\Delta m^2_{32} \simeq 2.4 \cdot 10^{-3} \mathrm{eV}^2$
- $sin^2\theta_{13} = 0.0220 \pm 0.0007$ from reactor measurements

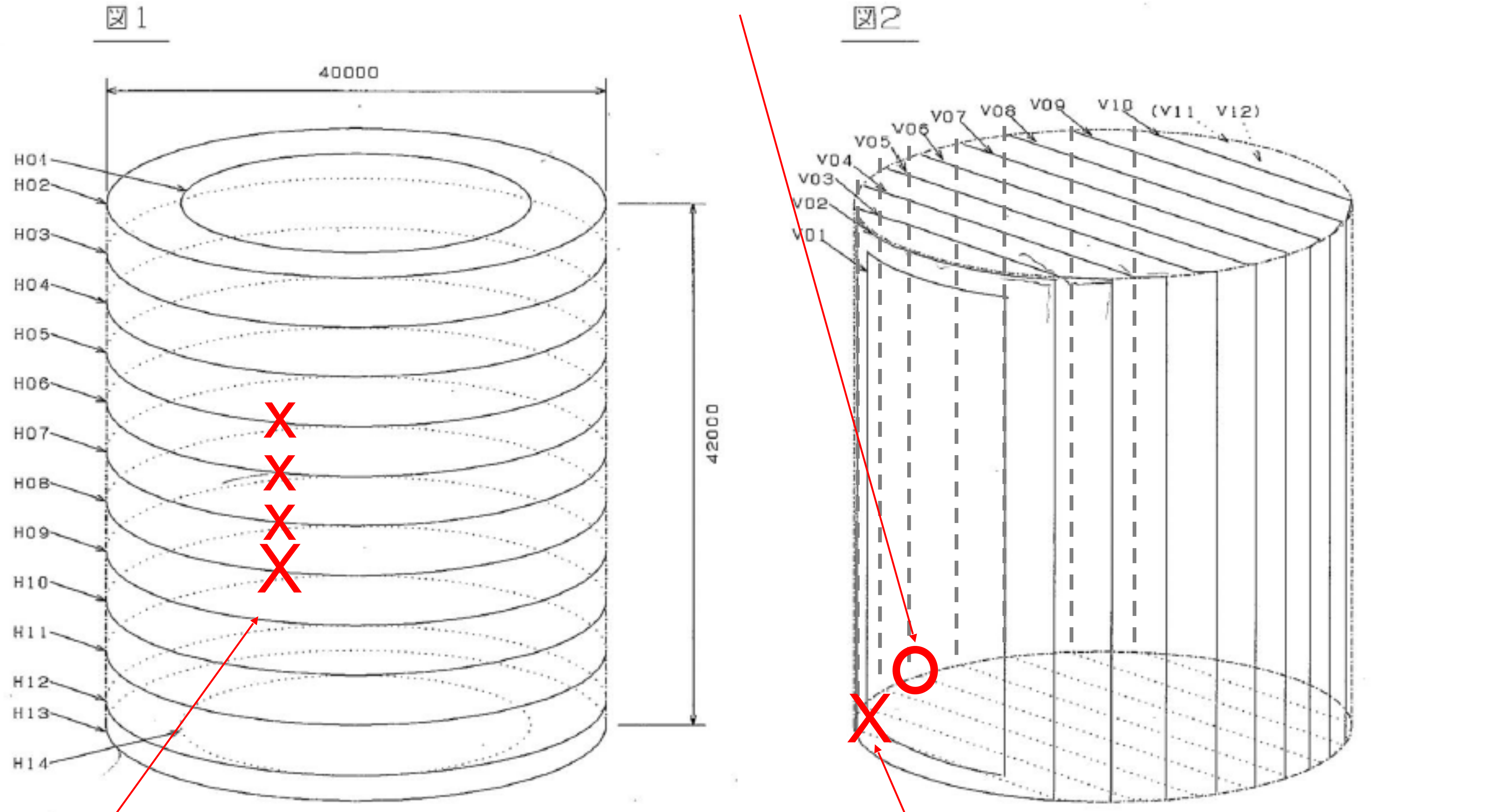
Mass ordering in the data



Upward-going / downward going ratio in **multi-GeV e-like samples shows some excess** in mass ordering-sensitive bins

SK's geomagnetic compensation coil problems and countermeasures

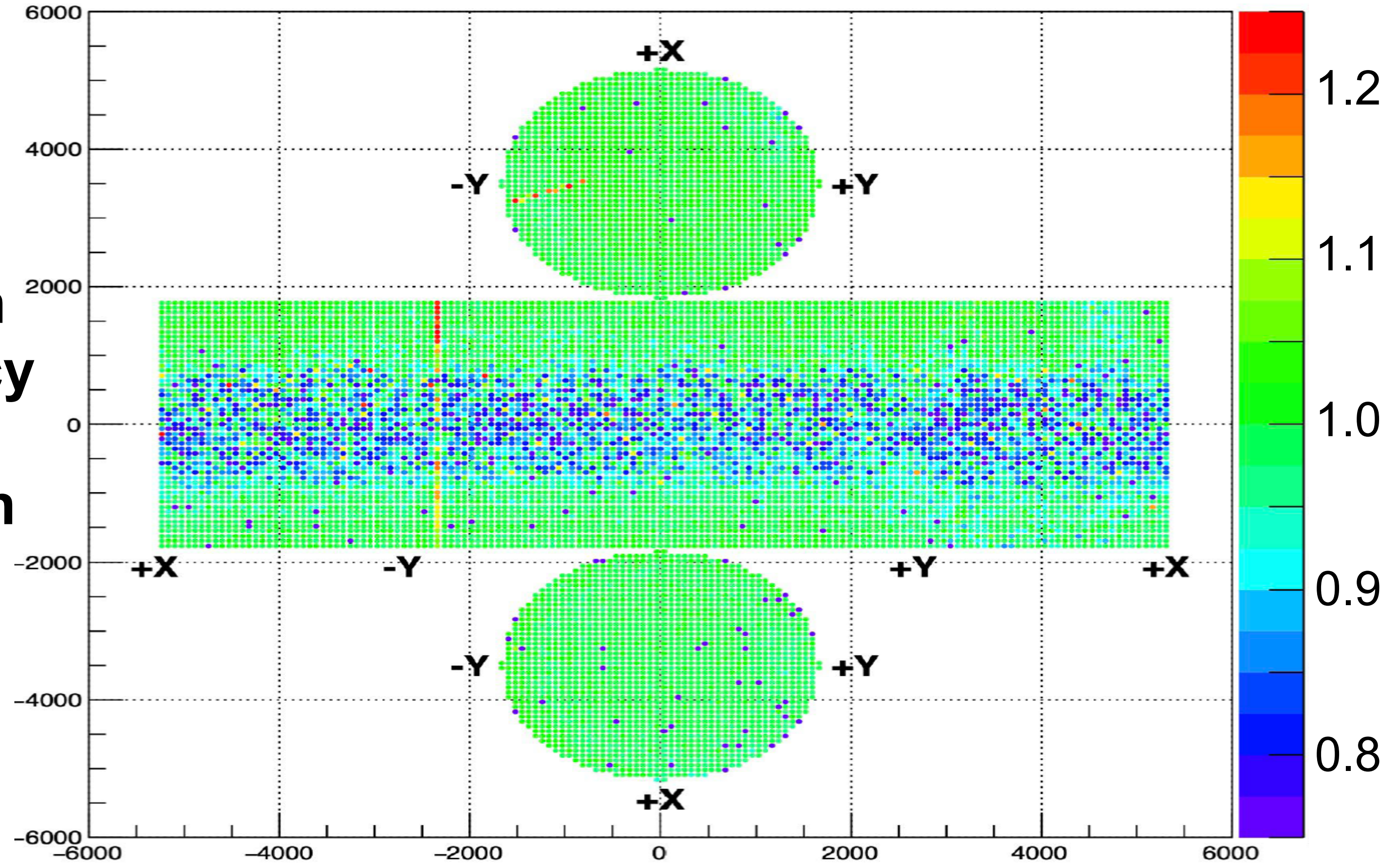
V06 disconnected on Oct.25, 2023.
Damaged sub-cable was bypassed on Dec.1, 2023. [recovered]



H09 disconnected on Dec.8, 2023.
Due to power supply configuration, H06, H07, and H08 are also off.

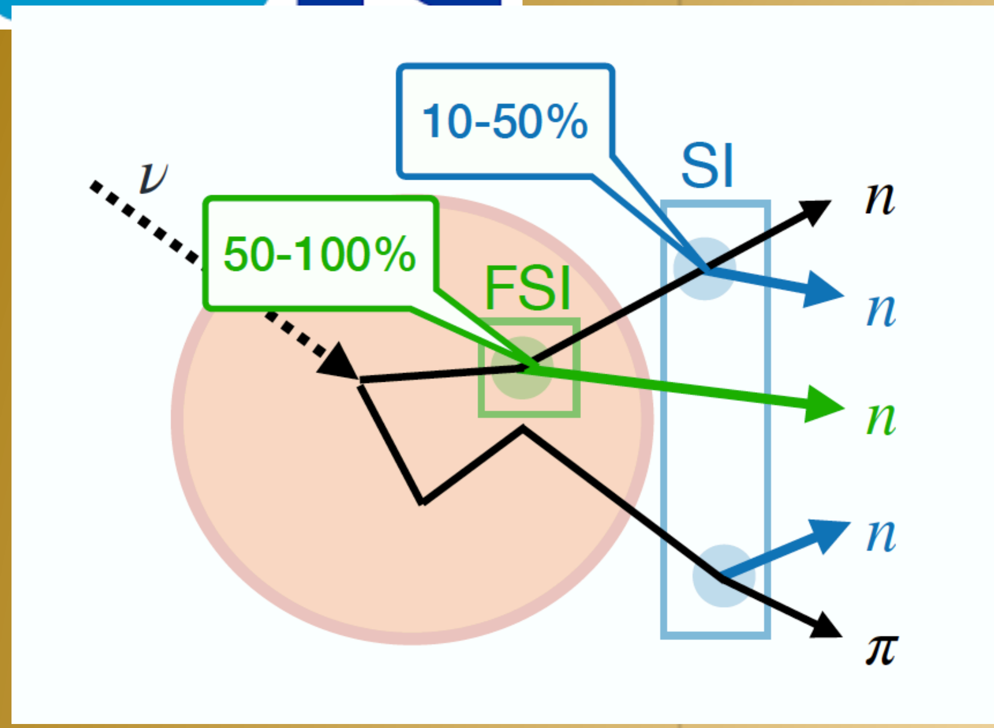
V01 disconnected on Nov.15, 2023.
V01 was bypassed from the power supply on Dec.2, 2023.

PMT photoelectron collection efficiency ratio, comparing May 2024 condition to nominal



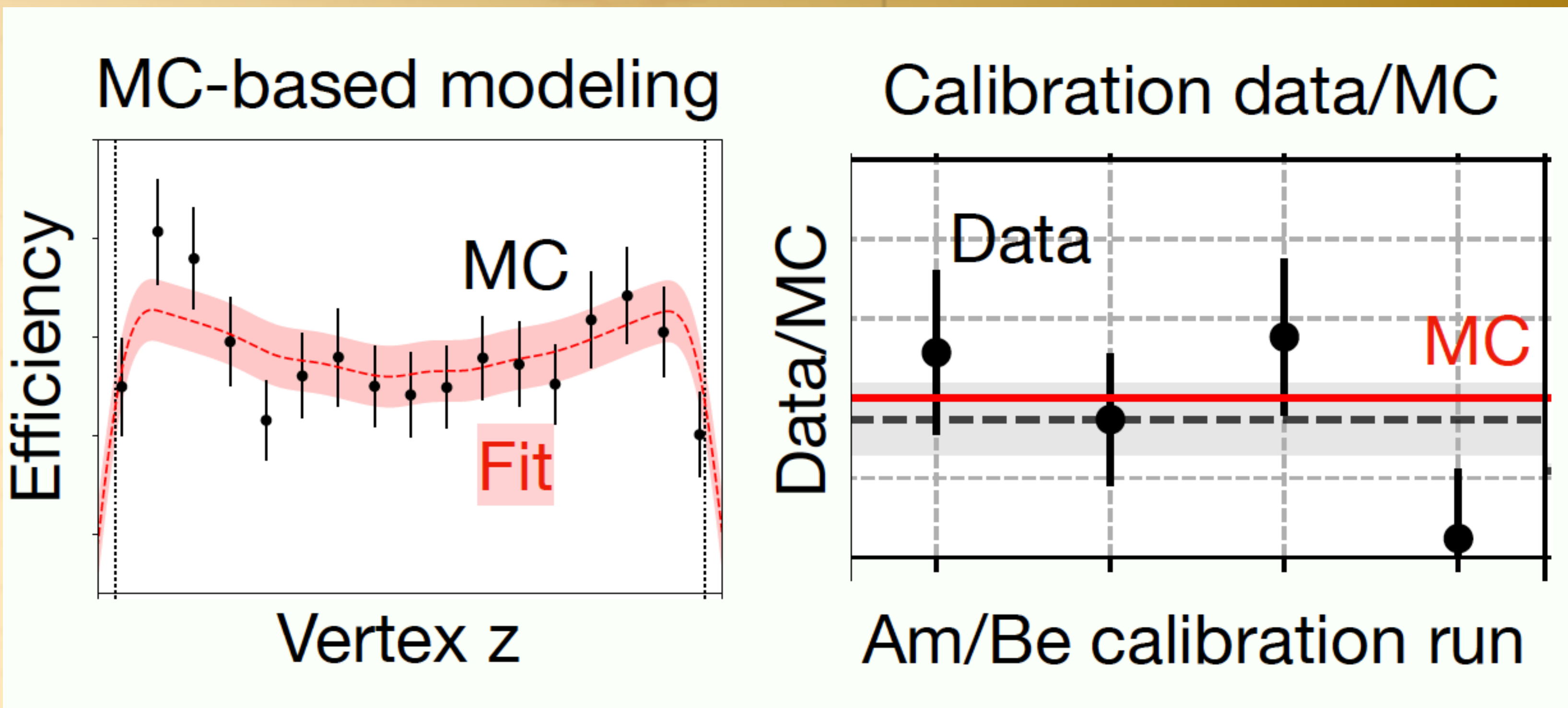
- SK geomagnetic compensation coil cables have failed in three locations.
- At two of locations, part of the coil was successfully bypassed to restore functionality. The other location is entirely underwater, resulting in the entire cable group being turned off.
- A 10-20% decrease in collection efficiency is observed for about 20% of PMTs in the barrel.
- Efficiency for detecting neutron capture on Gd has also decreased by about 3%.
- The physics impact can be compensated by calibration and simulation.
- The likely cause is corrosion of wire connections due to ionized water seeping in under heat shrink insulation.
- SK plans to install six new horizontal coils in summer 2024 to restore the geomagnetic field cancellation.

Neutrons in atmospheric ν interactions



- SK-Gd: neutron multiplicity measurements
  - Large uncertainty in "neutron smearing", Huge differences between models

$$\text{Neutron multiplicity} = \frac{\text{measured neutrons}}{\text{detec eff.}}$$



- Hadronic interaction models to compare with data

NEUT 5.4.0.1+SK6 MC

PI
- NEUT 5.4.0
- NEUT 5.6.3
- GENIE

FSI
- hA
- hN
- INCL
- Bertini

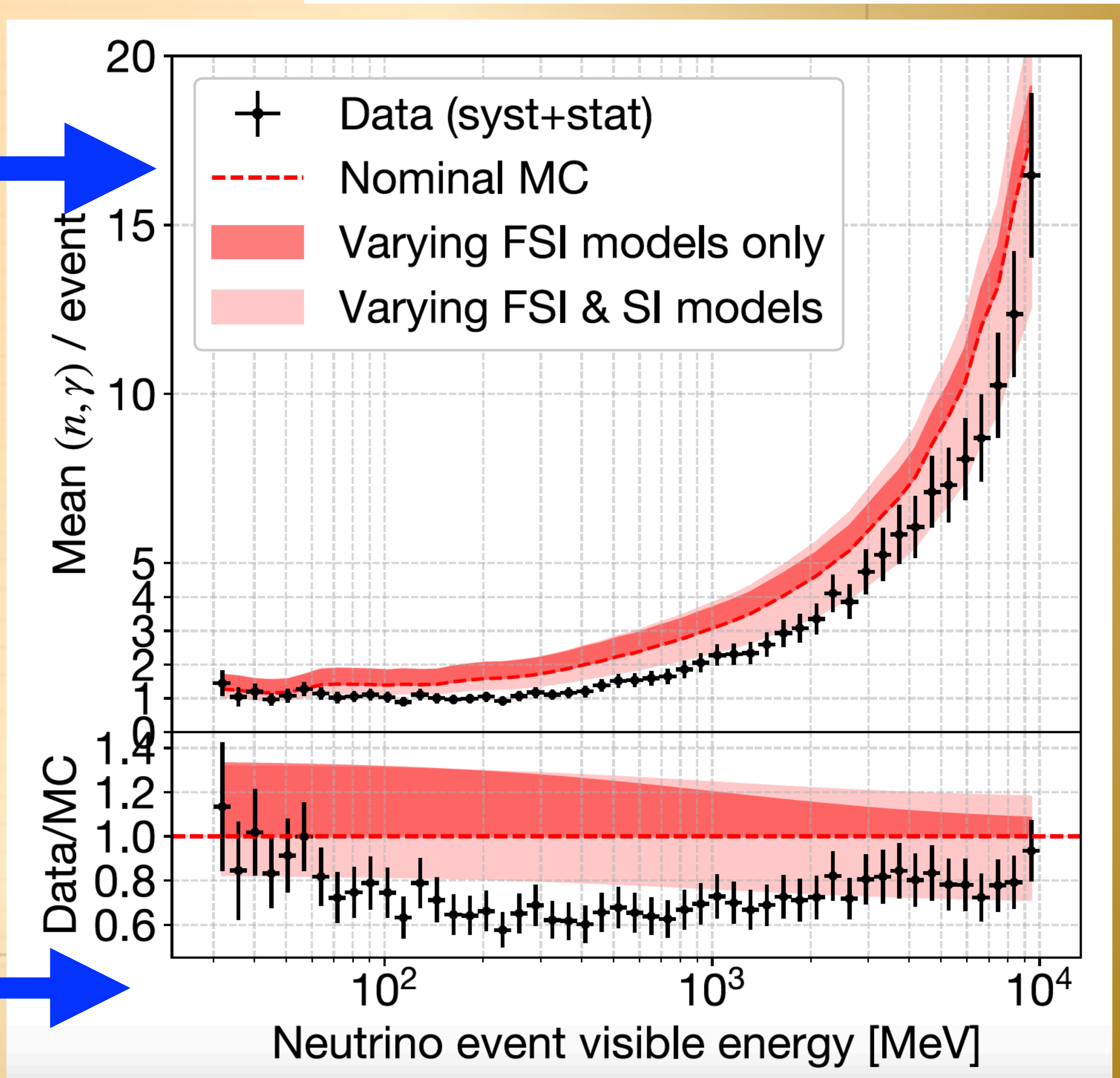
6 models

SI
- SK4/5 default
- SK6 default
- GCALOR
- Bertini
- INCL

5 models

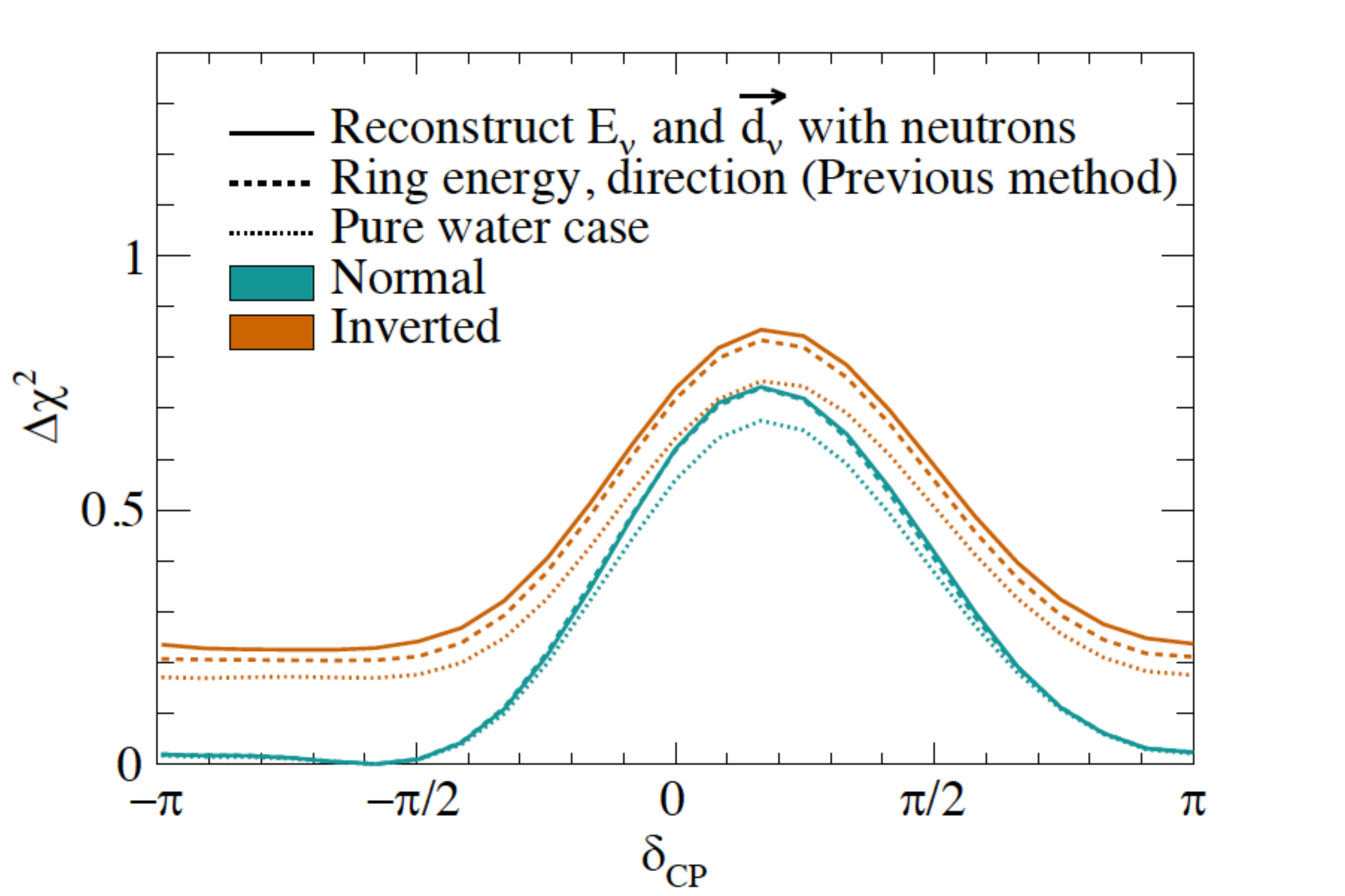
Flux: Honda flux (2011)
GENIE 3.4.0 G18_10b_02_11b

Smallest χ^2:
NEUT 5.4.0.1+INCL



- SK4+5+6 atm. (FCFV ~12 years of data)

SK6 atmospheric neutrino reconstruction with neutrons



Assumed oscillation parameters:
Normal ordering, $\Delta m^2_{32} = 2.4\times10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.45$, $\delta_{CP} = 4.45$
(Best fit point in SK1-5 data fit with θ_{13}-constrained)

Sensitivity (SK6: 564.4 live-days)

Conclusion: MO sensitivity is improved by 21% with Gd, and by another 10% with new E_ν reconstruction using neutron information.

$\nu/\bar{\nu}$ separation @ SK before neutron tagging

$$\nu_e + N \rightarrow N + e^- + \pi^+$$

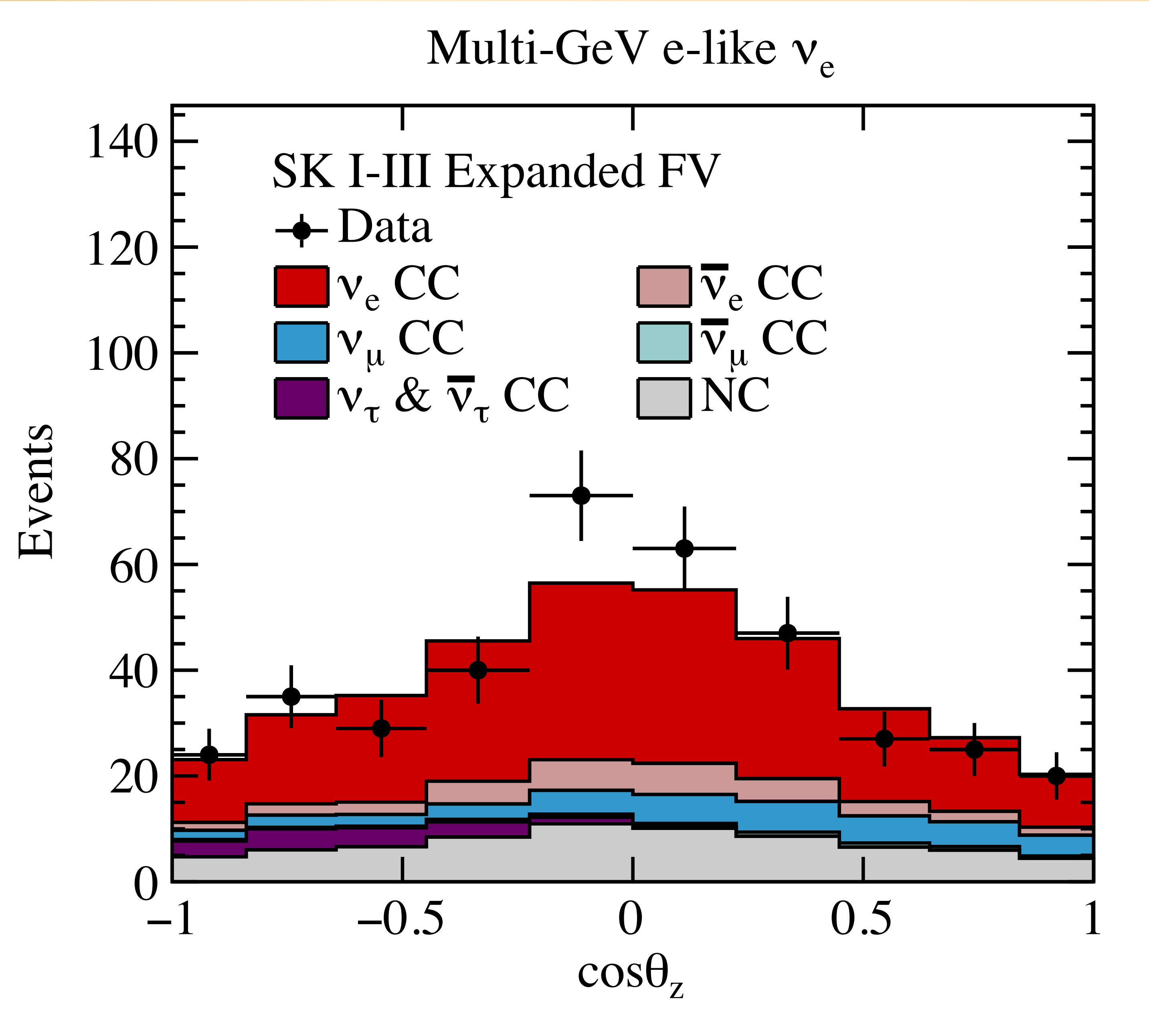
$$\pi^+ \rightarrow \mu^+ \rightarrow e^+$$

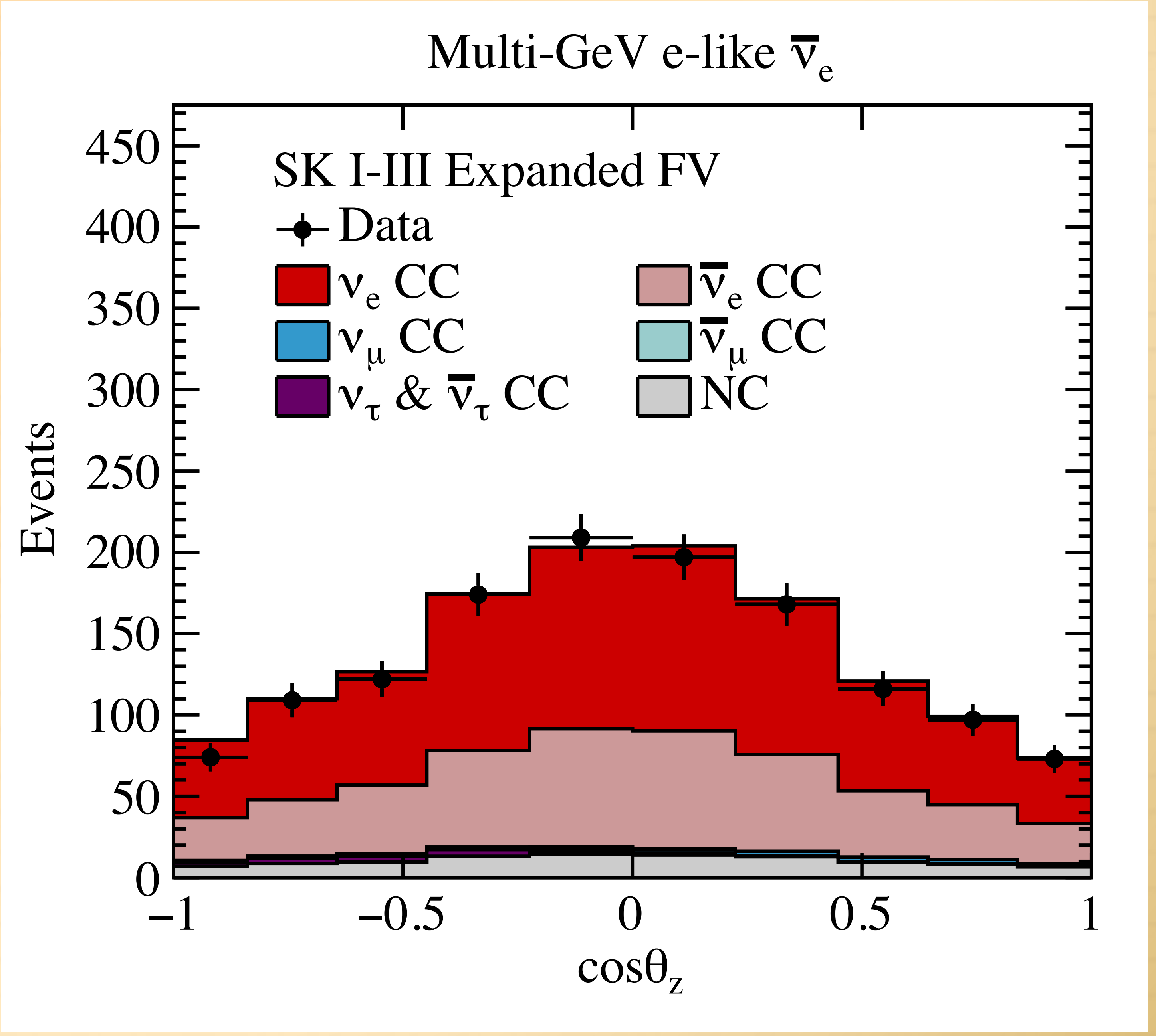
Delayed "decay electron"

$$\bar{\nu}_e + N \rightarrow N + e^+ + \pi^-$$

π^- mostly absorbed by Oxygen

ν_e (56%)
$\bar{\nu}_e$ (9%)



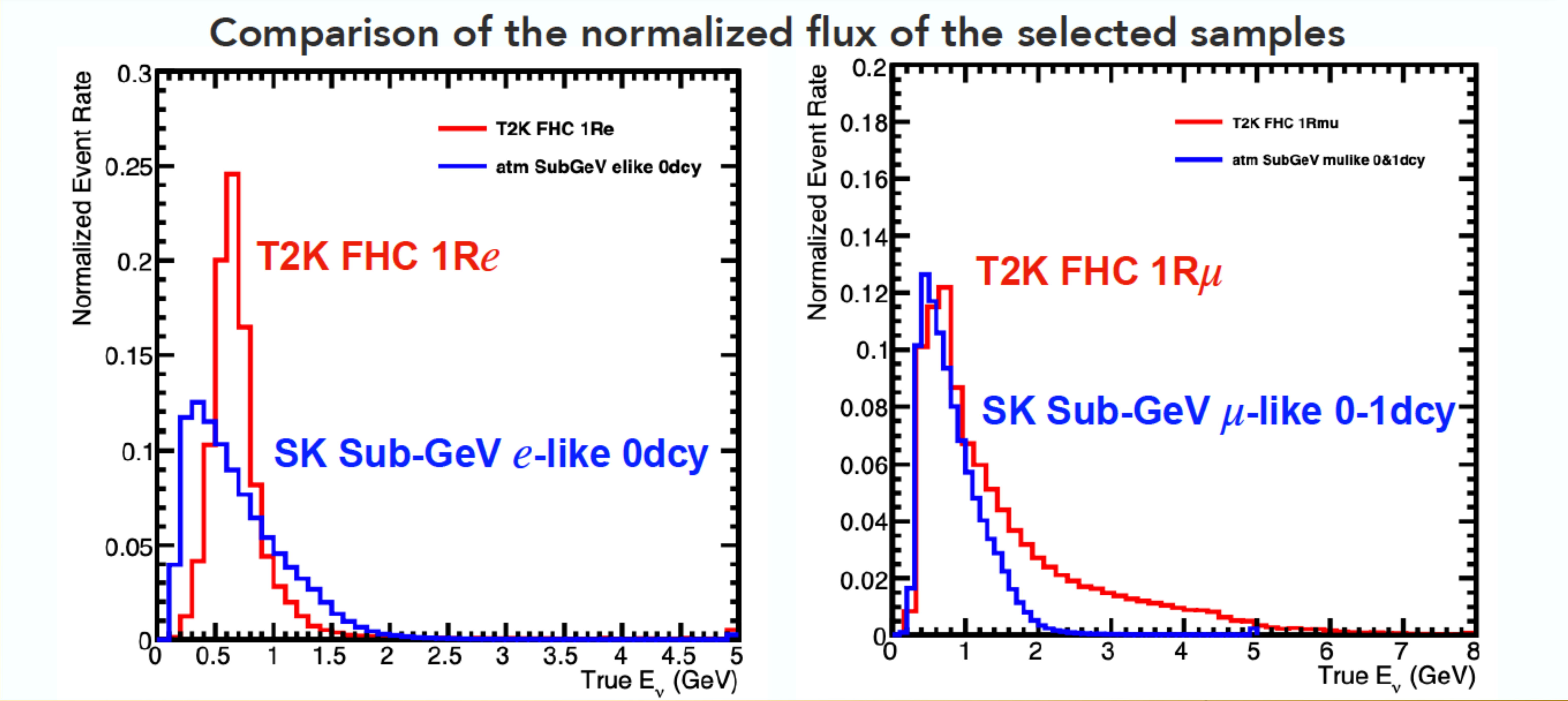


ν_e (56%)
$\bar{\nu}_e$ (34%)

SK +T2K joint fit analysis

- SK4 data - 3244 days (2008-2018) - PTEP, 5, 053F01, (2019)
- T2K data published in Phys. Rev. D 108, 7, 072011, (2023)
- Future updates will include full SK atm statistics at least 50% more data and more data from T2K

- Motivation of the Joint Analysis:
  - T2K and SK use the same detector and have samples with similar energy ranges and similar selections.
  - We can take into account **the correlations of the systematic uncertainties**
  - T2K near detector can be used to constrain the cross-section uncertainties for the low -energy atmospheric samples as well



Paper is now on the arXiv [2405.12488]

See the talk on this conference from Claudio Giganti - T2K report