NEUTRINO24 conference- selection of results

Magdalena Posiadala-Zezula
University of Warsaw

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

NEUTRINO 2024

XXXI International Conference on Neutrino Physics and Astrophysics

Milano (Italy) - June 16-22, 2024

Topics

Neutrino oscillations

Neutrino mass

Neutrinoless Double Beta Decay

Neutrino interactions

Accelerator neutrinos

Reactor neutrinos

Atmospheric neutrinos

Solar neutrinos

Supernova neutrinos

Astrophysical neutrinos

Geoneutrinos

Neutrino role in cosmology

Sterile neutrinos

Theory of neutrino masses and mixing, Leptogenesis

Beyond Standard Model searches in the neutrino sector

New technologies for neutrino physics

Conference chairs:

https://neutrino2024.org/

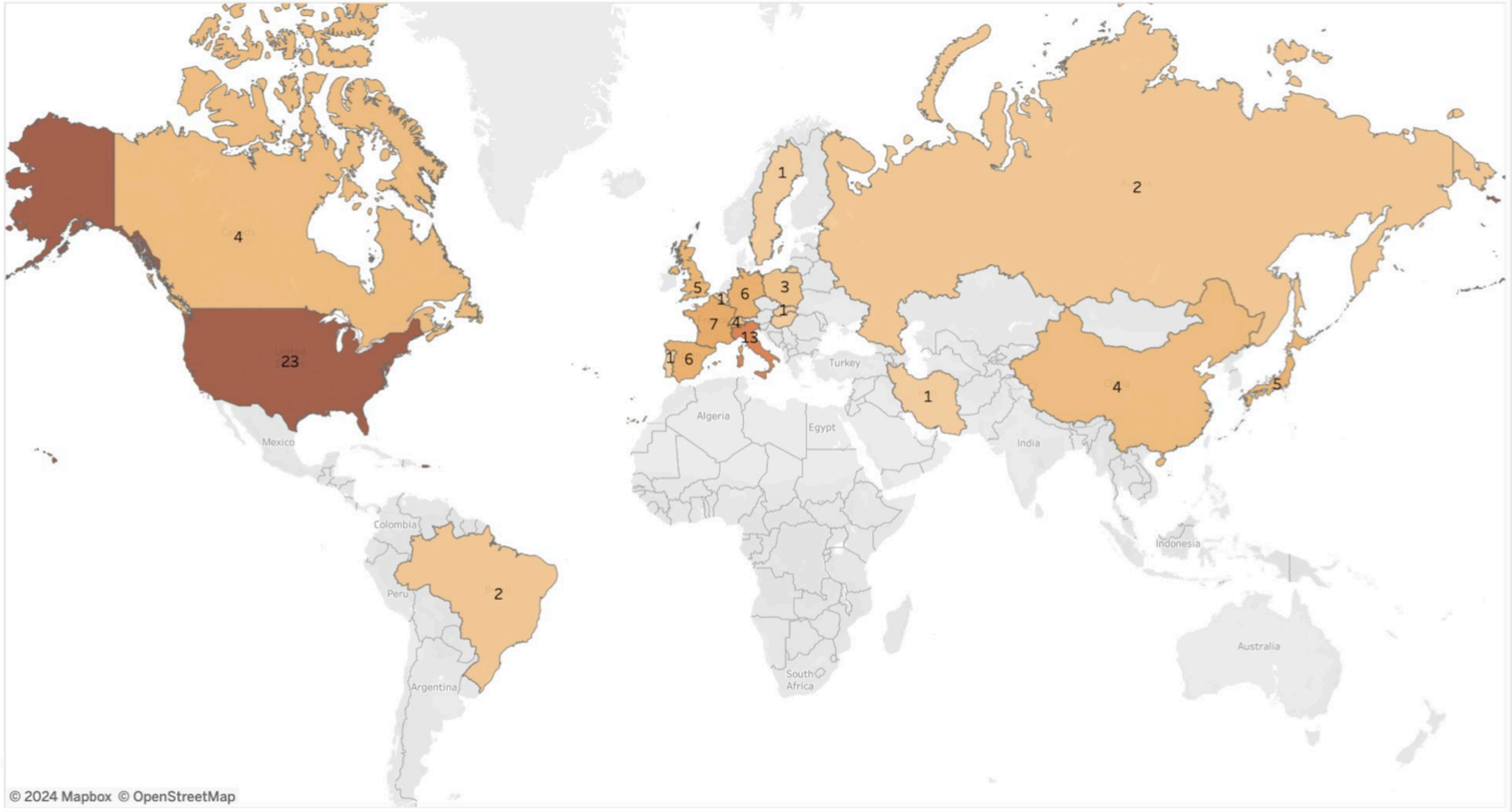
- The most important conference in Neutrino field
- 71 scientific talks plus 460 posters
- Polish contribution: my Super-Kamiokande talk +
- POSTERS: Katarzyna Kowalik (NCBJ), prof. Jan Sobczyk (University of Wroclaw), dr hab. Artur Ankowski (University of Wroclaw)

Neutrino speakers and chairs

91 people:
71 speakers (exp, reviews, reports)
20 chairs

F 25%

(F 19% ; F 33%)



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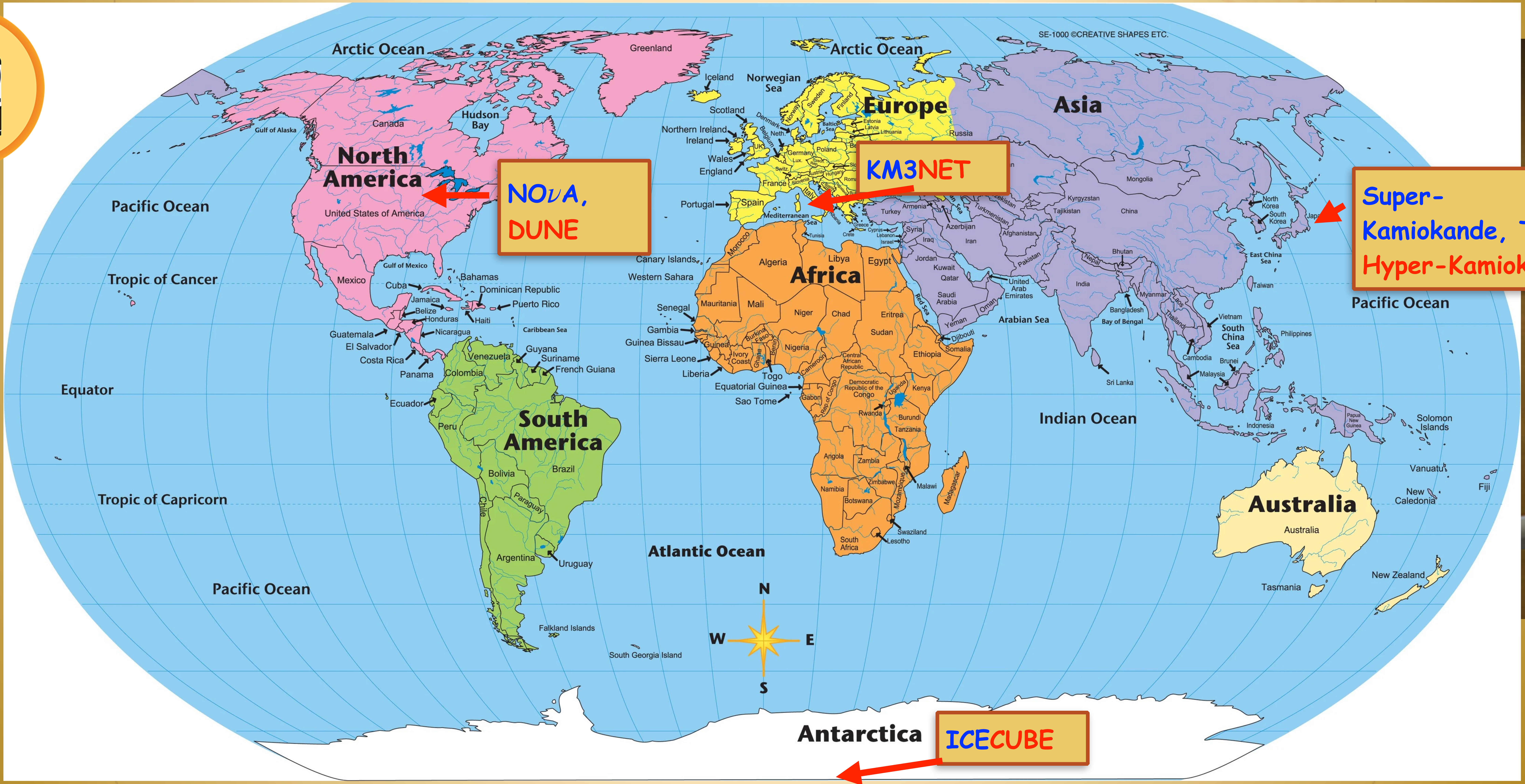
Recent and **future** prospects in atmospheric/accelerator neutrino searches- subjective selection



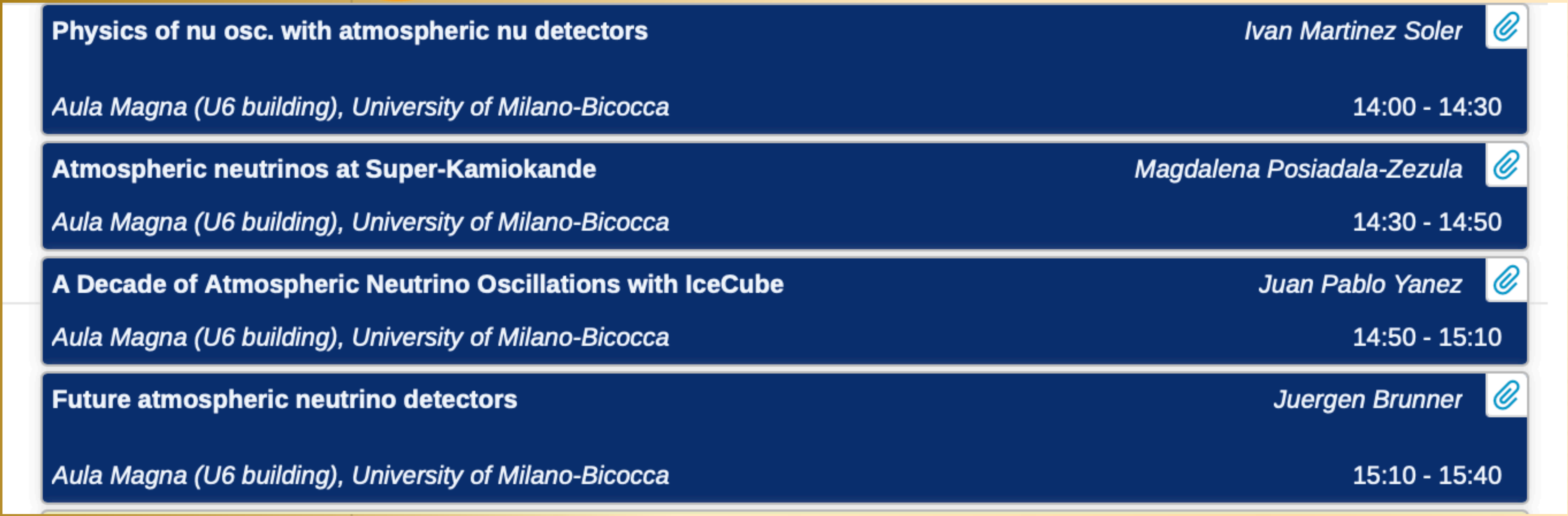
NOνA, DUNE

KM3NET

Super-Kamiokande, T2K
Hyper-Kamiokande

ICECUBE

Atmospheric neutrinos



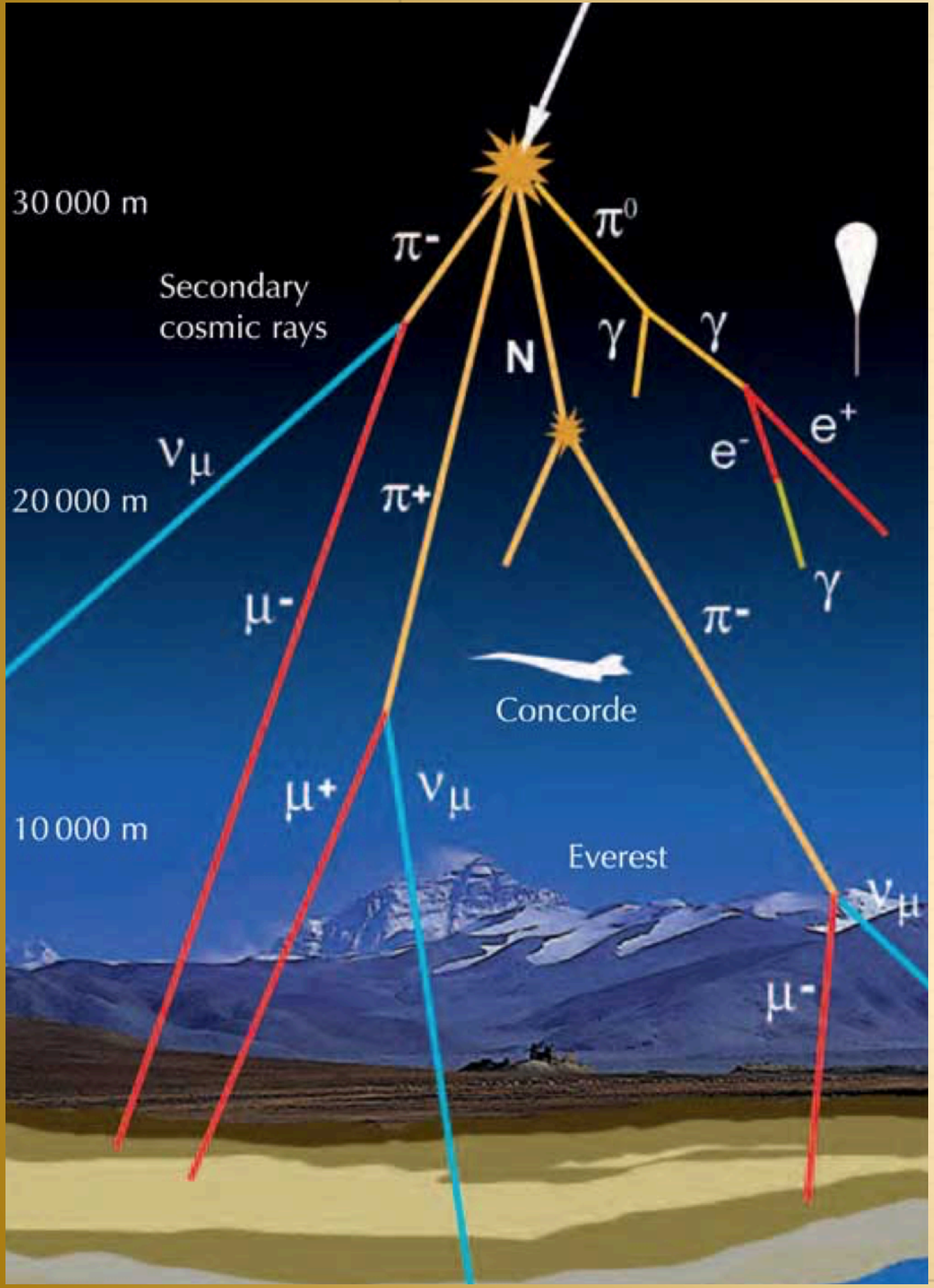
Physics of nu osc. with atmospheric nu detectors *Ivan Martinez Soler*
Aula Magna (U6 building), University of Milano-Bicocca 14:00 - 14:30

Atmospheric neutrinos at Super-Kamiokande *Magdalena Posiadala-Zezula*
Aula Magna (U6 building), University of Milano-Bicocca 14:30 - 14:50

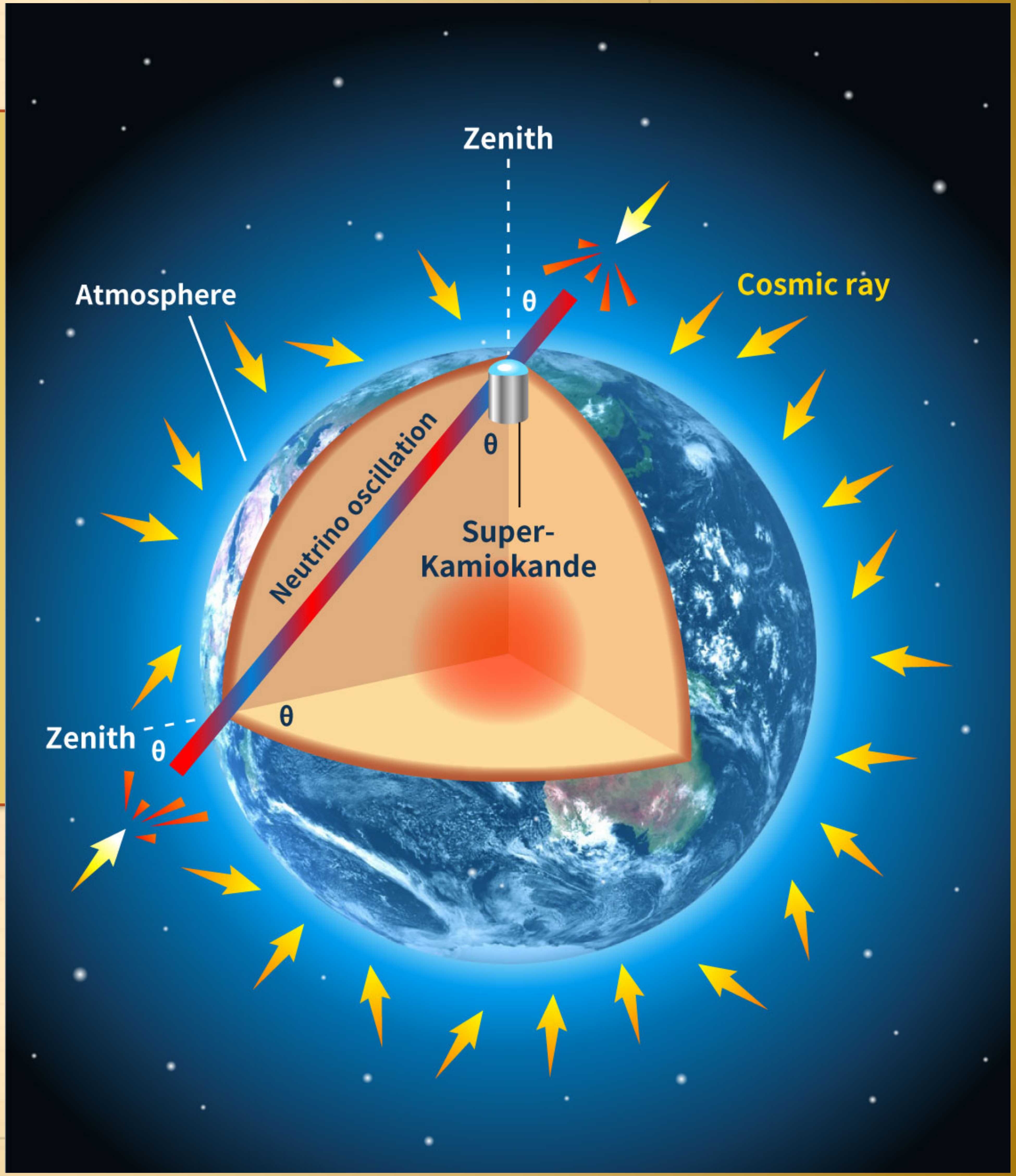
A Decade of Atmospheric Neutrino Oscillations with IceCube *Juan Pablo Yanez*
Aula Magna (U6 building), University of Milano-Bicocca 14:50 - 15:10

Future atmospheric neutrino detectors *Juergen Brunner*
Aula Magna (U6 building), University of Milano-Bicocca 15:10 - 15:40

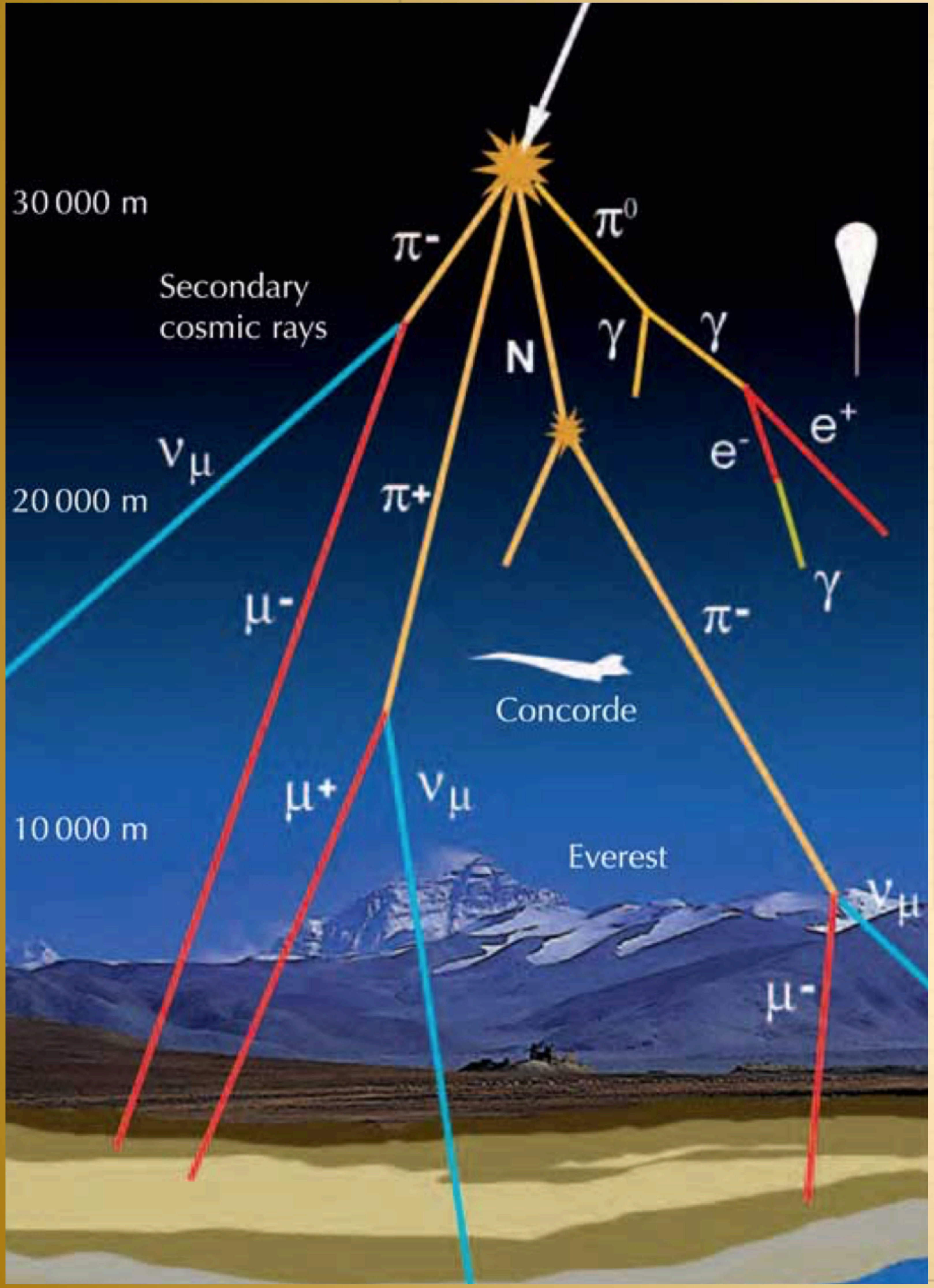
Atmospheric neutrinos



- 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 neutrinos



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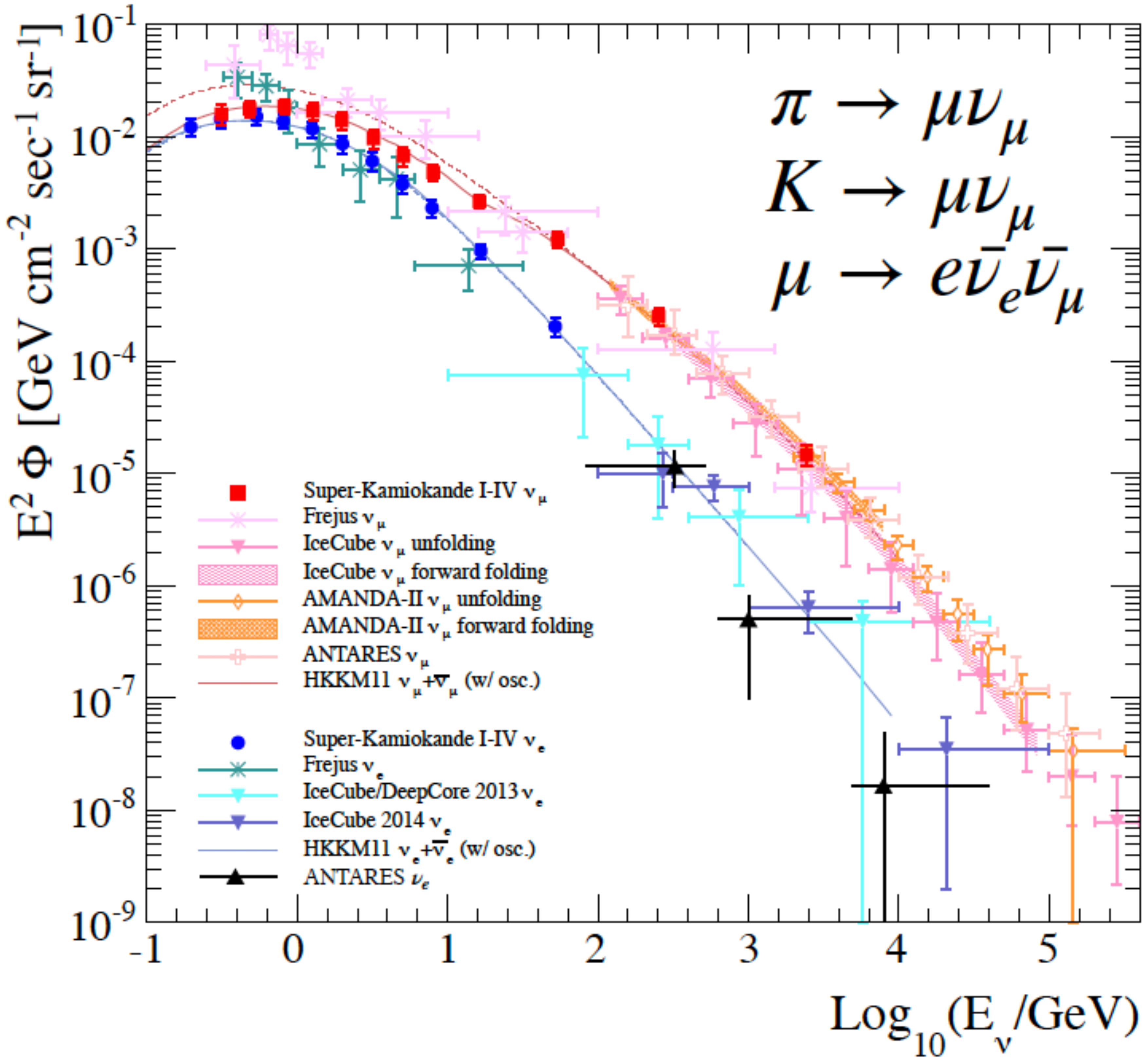
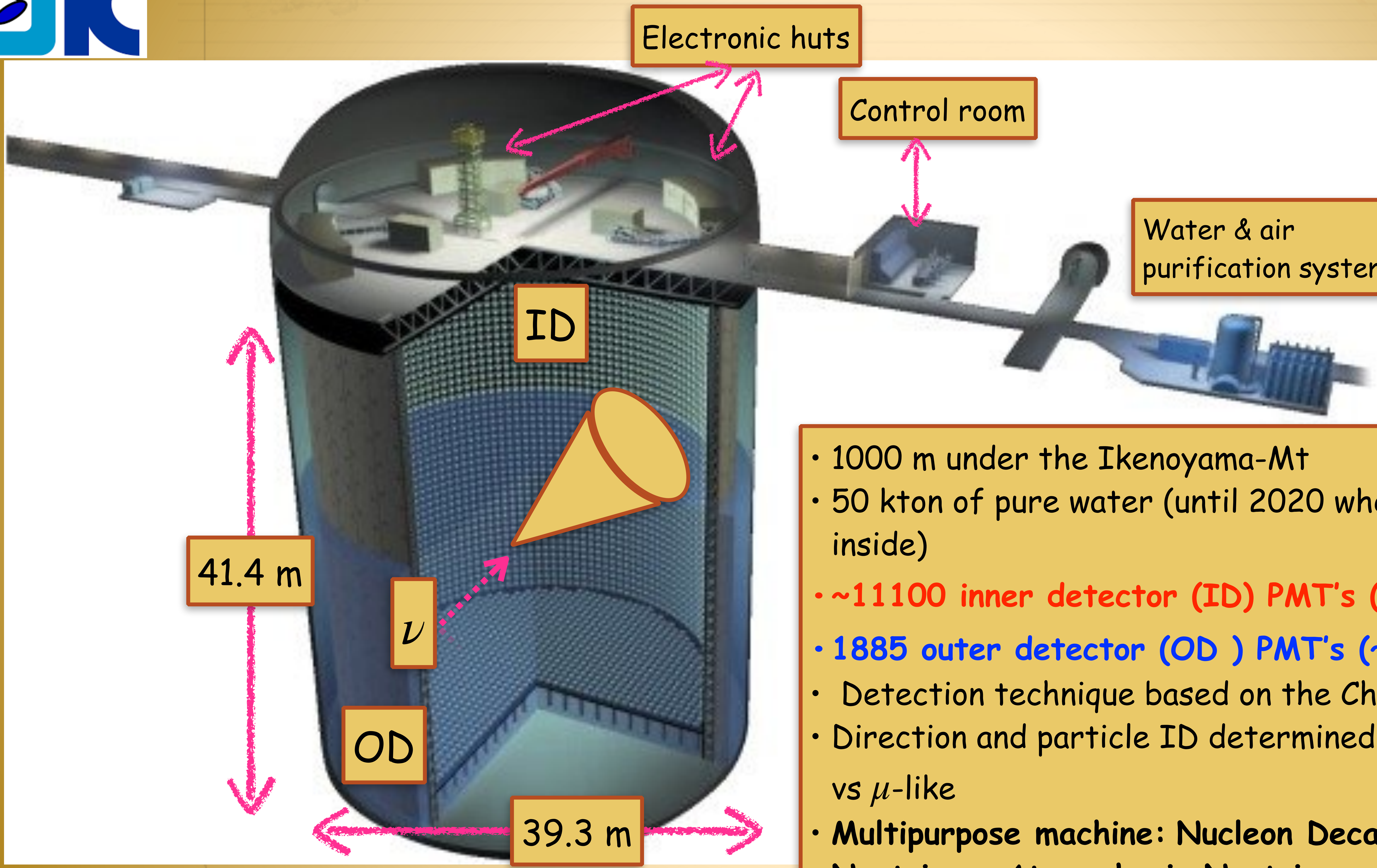


E. Richard et al. (SK), PRD 94 (2016) 5

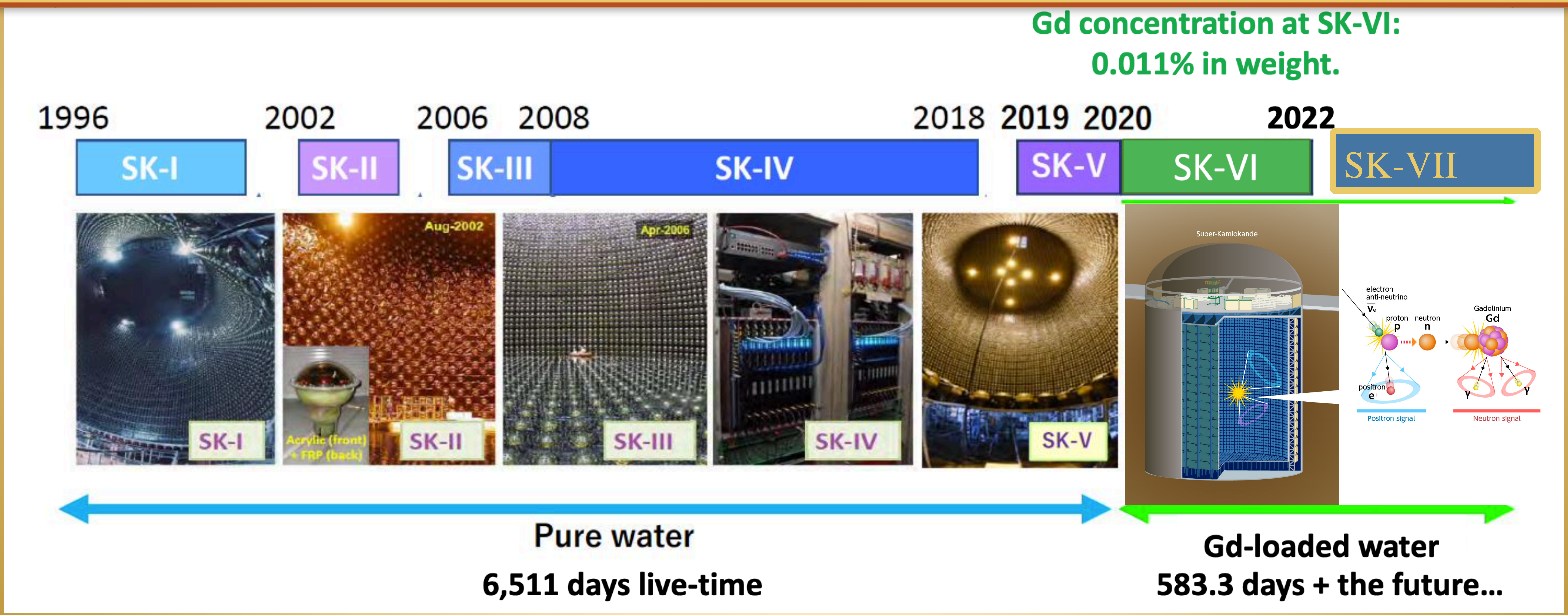
The Super-Kamiokande experiment



- 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.



Gd concentration at SK-VI:
0.011% in weight.

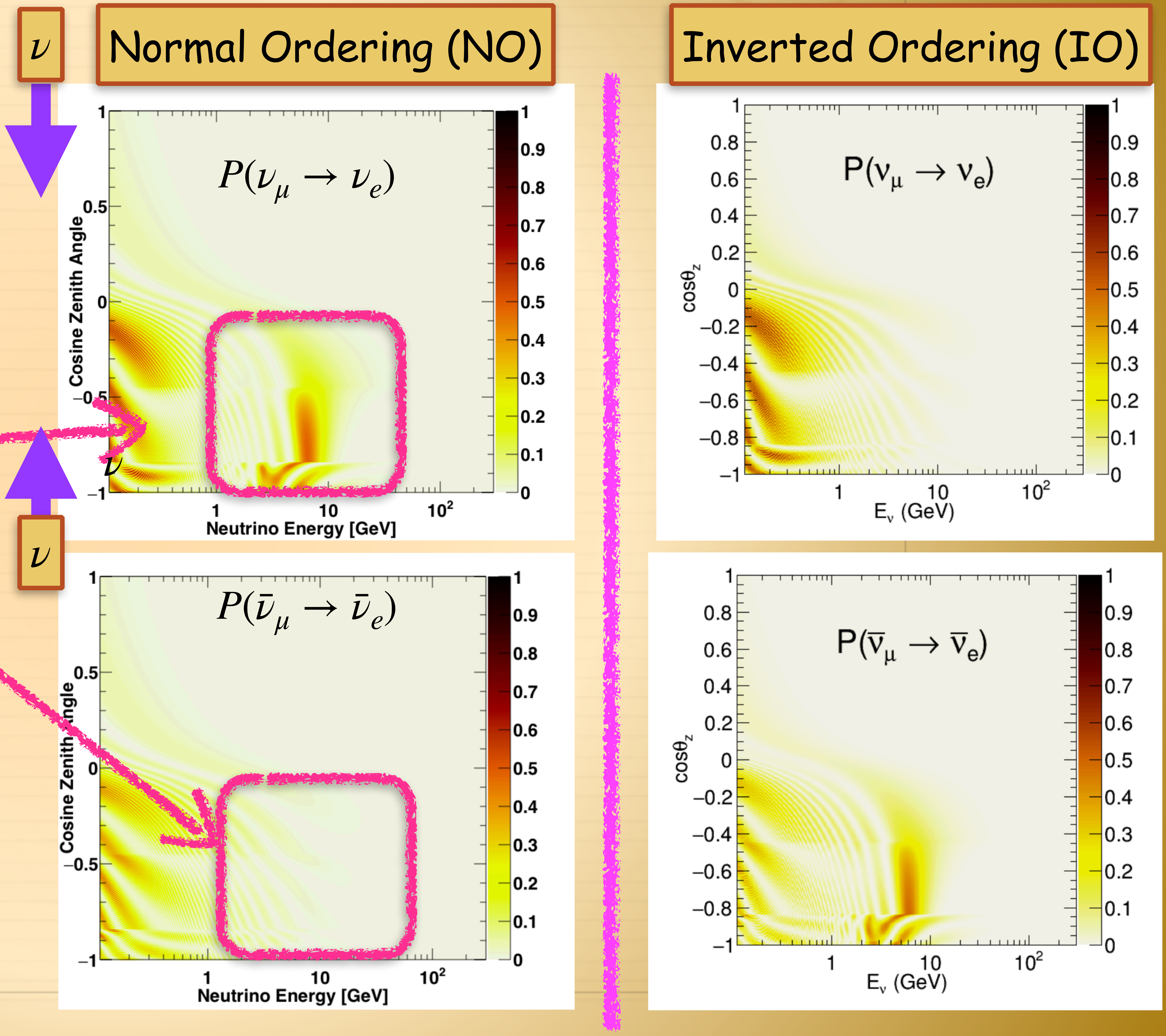
Pure water
6,511 days live-time

Gd-loaded water
583.3 days + the future...

Atmospheric neutrino oscillations

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

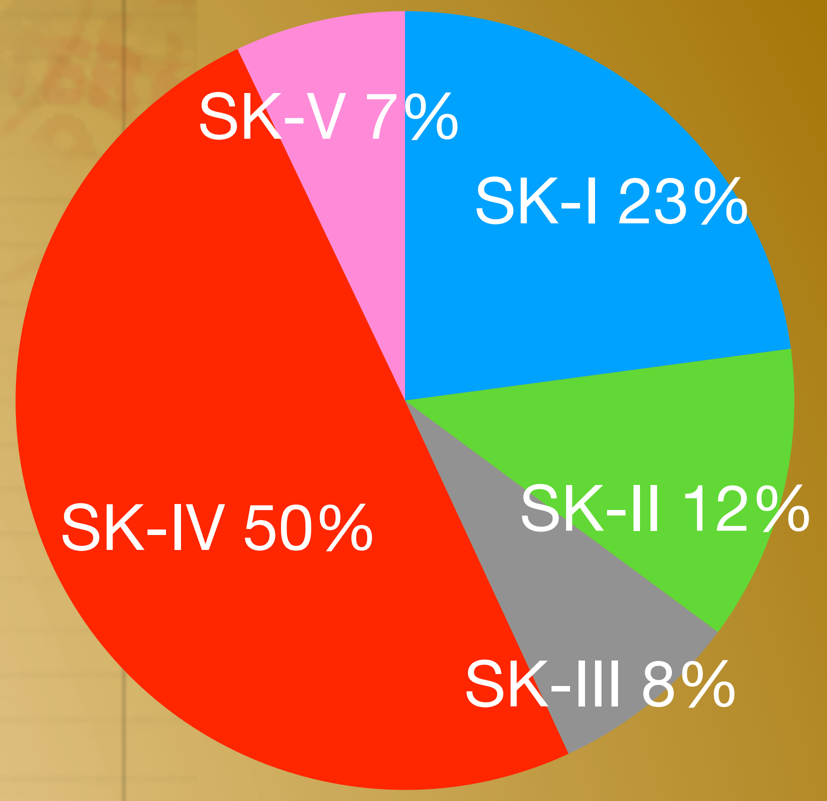
- Impact of matter effects:
  - NO: enhancement of ν_e appearance
  - NO: effect is not present for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - IO; situation is reversed



☆ 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 $\delta_{CP} = 0$

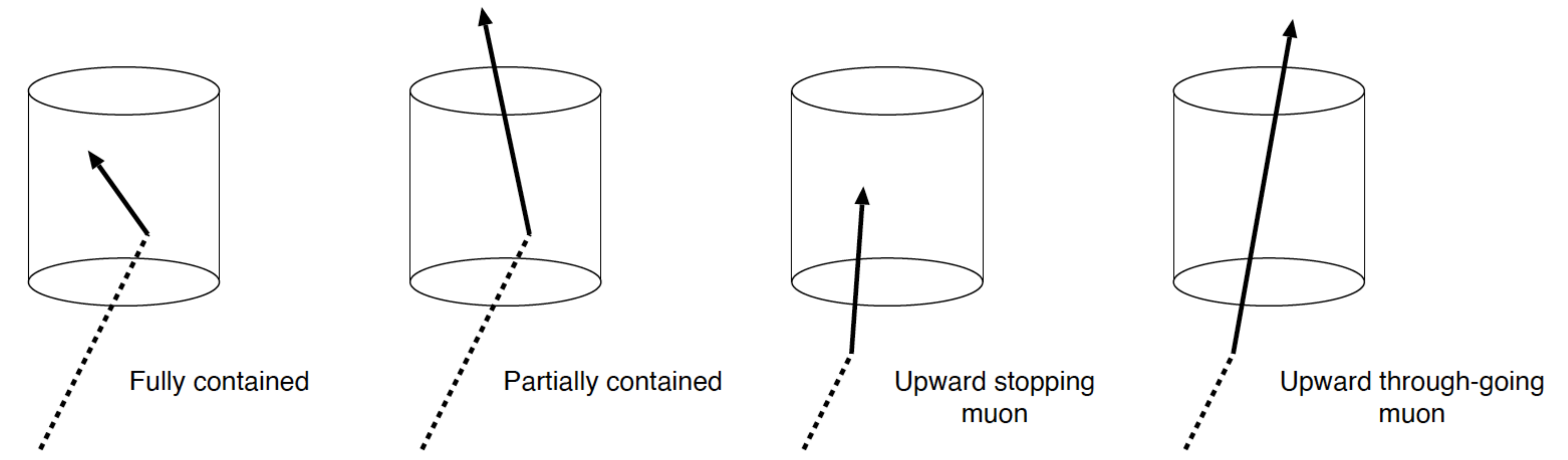
☆ Phys. Rev. D. 97 072001

Zenith angle atmospheric neutrino oscillation analysis

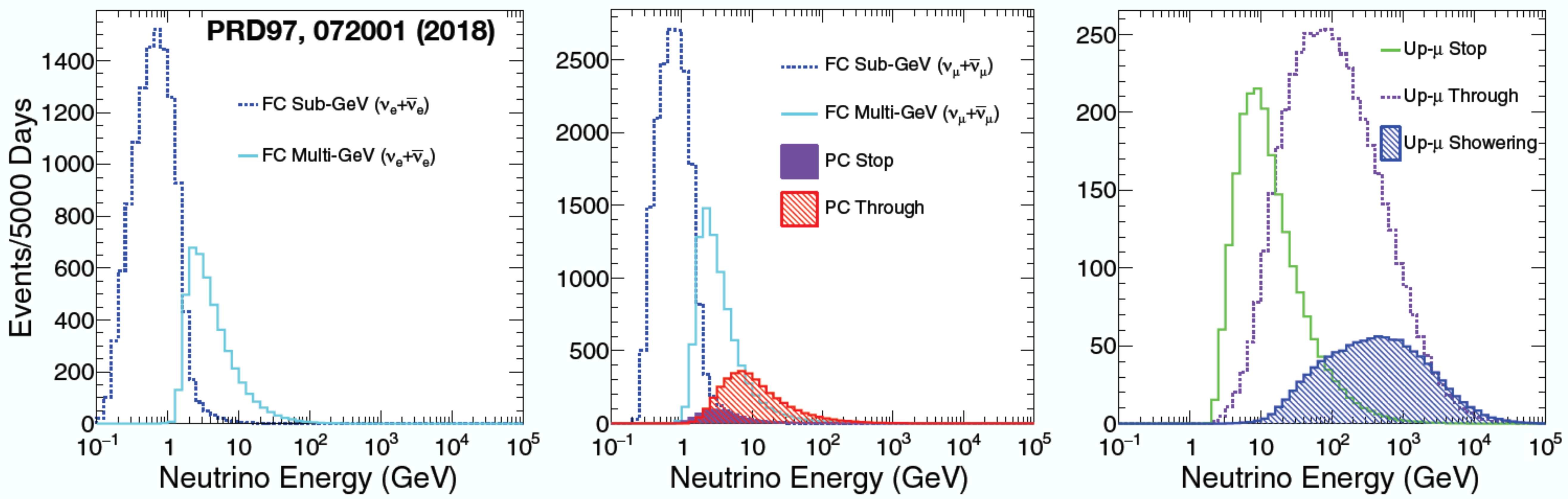


- Latest results with **full SK pure water phase (SK1-5)**:
  - Latest publication - **Phys. Rev. D 109, 072014 – Published on 24 April 2024**
  - Previously published results: Phys. Rev. D97, 072001 (2018)
- Updates since the previous analysis:
  - **Expansion of fiducial volume and more lifetime: 6511 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-v samples



Enlarging the Fiducial Volume

Phys. Rev. D 201, 112011 (2020)

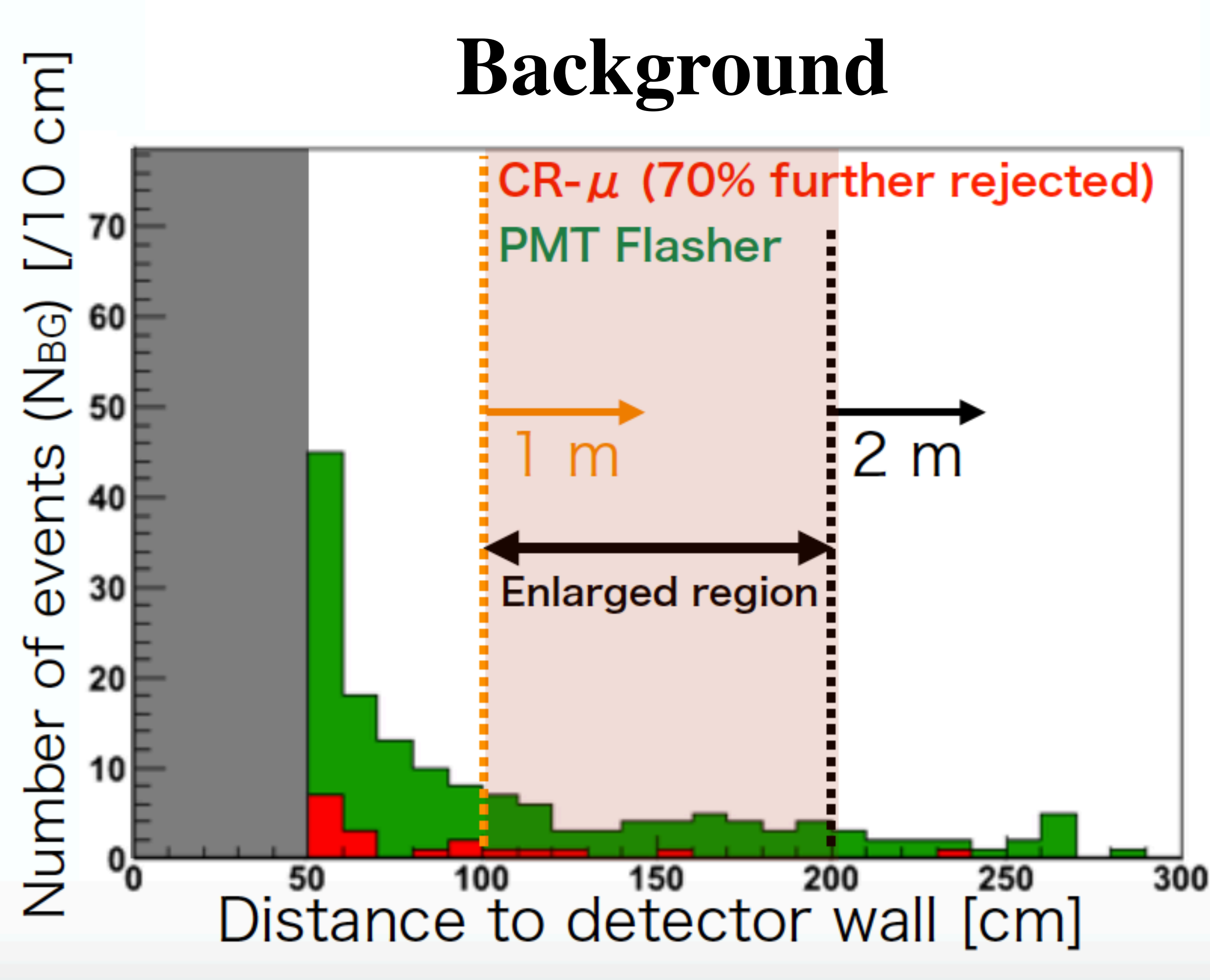
Distance btw vertex and nearest ID wall surface = "wall"

- 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)

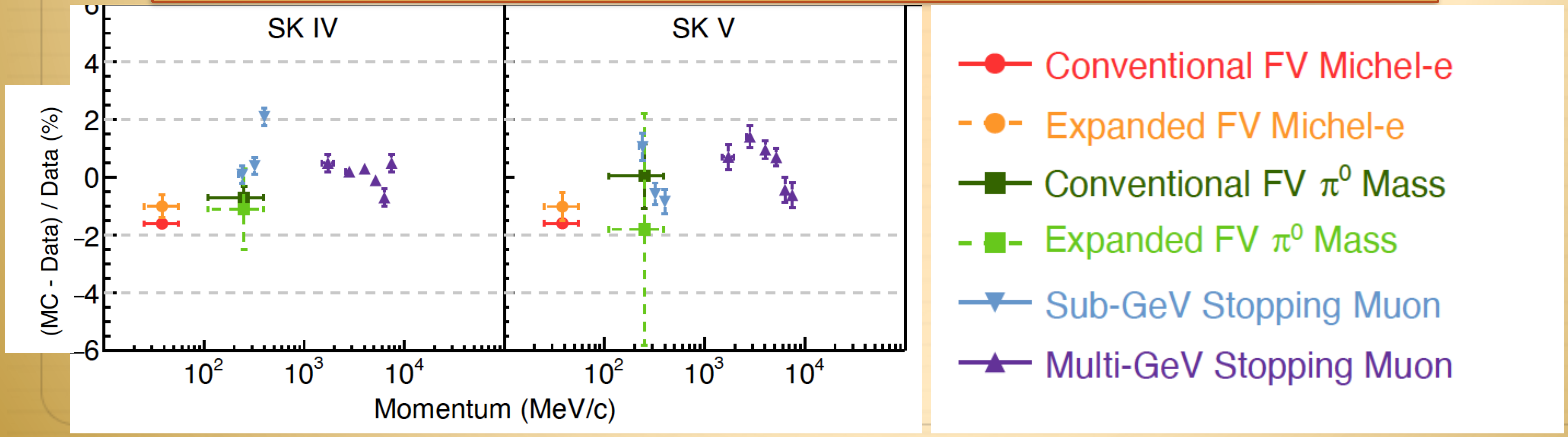
- Confirmed no significant increase of non-ν background and no significant bias in reconstruction (ex. energy scale)
- Systematics in the expanded region recalculated and under control

Conventional FV
22.5 kton
2m from ID wall

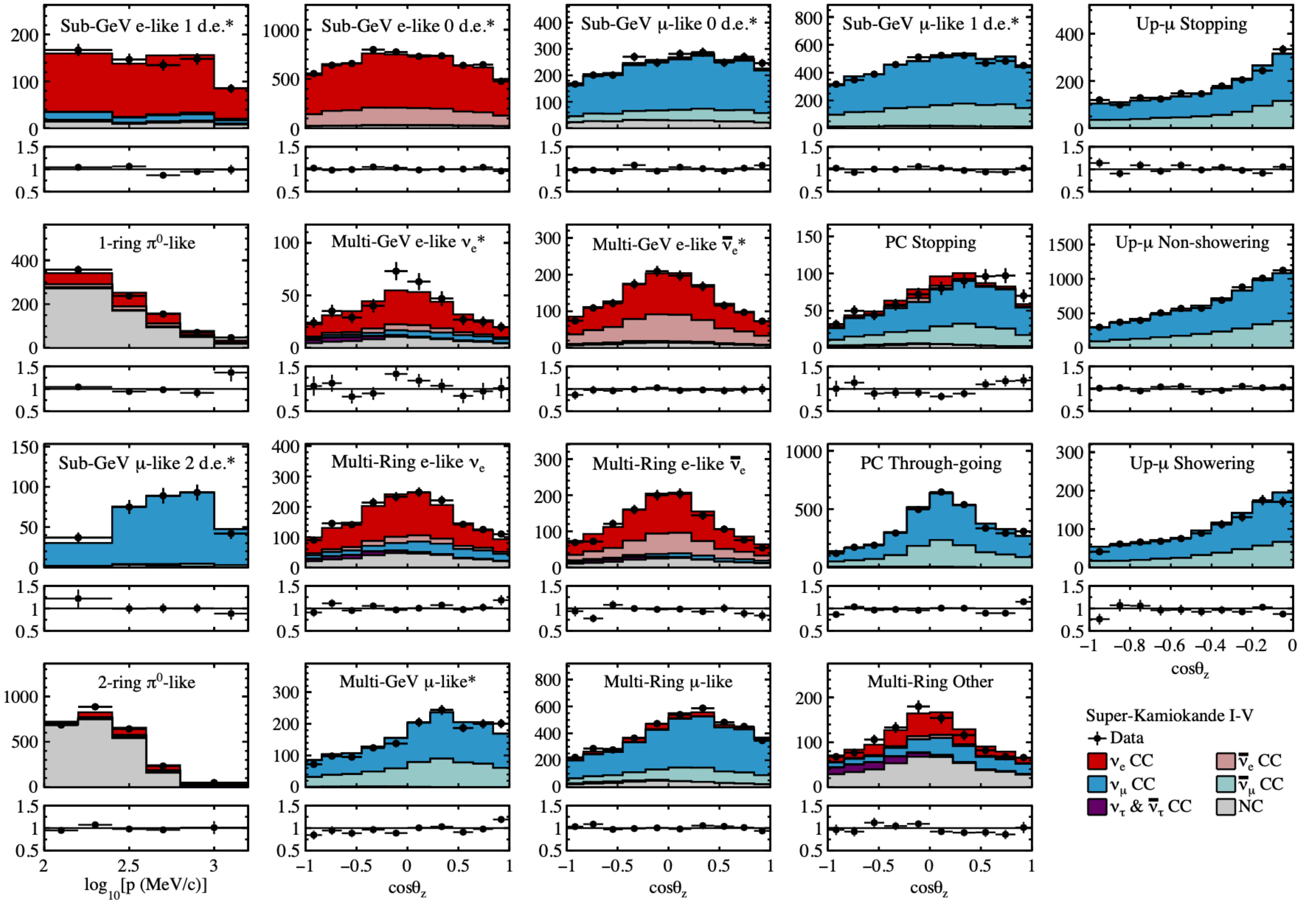
Expanded FV
27.2 kton
1m from ID wall



Energy reconstruction for various sources



Zenith angle or momentum distributions



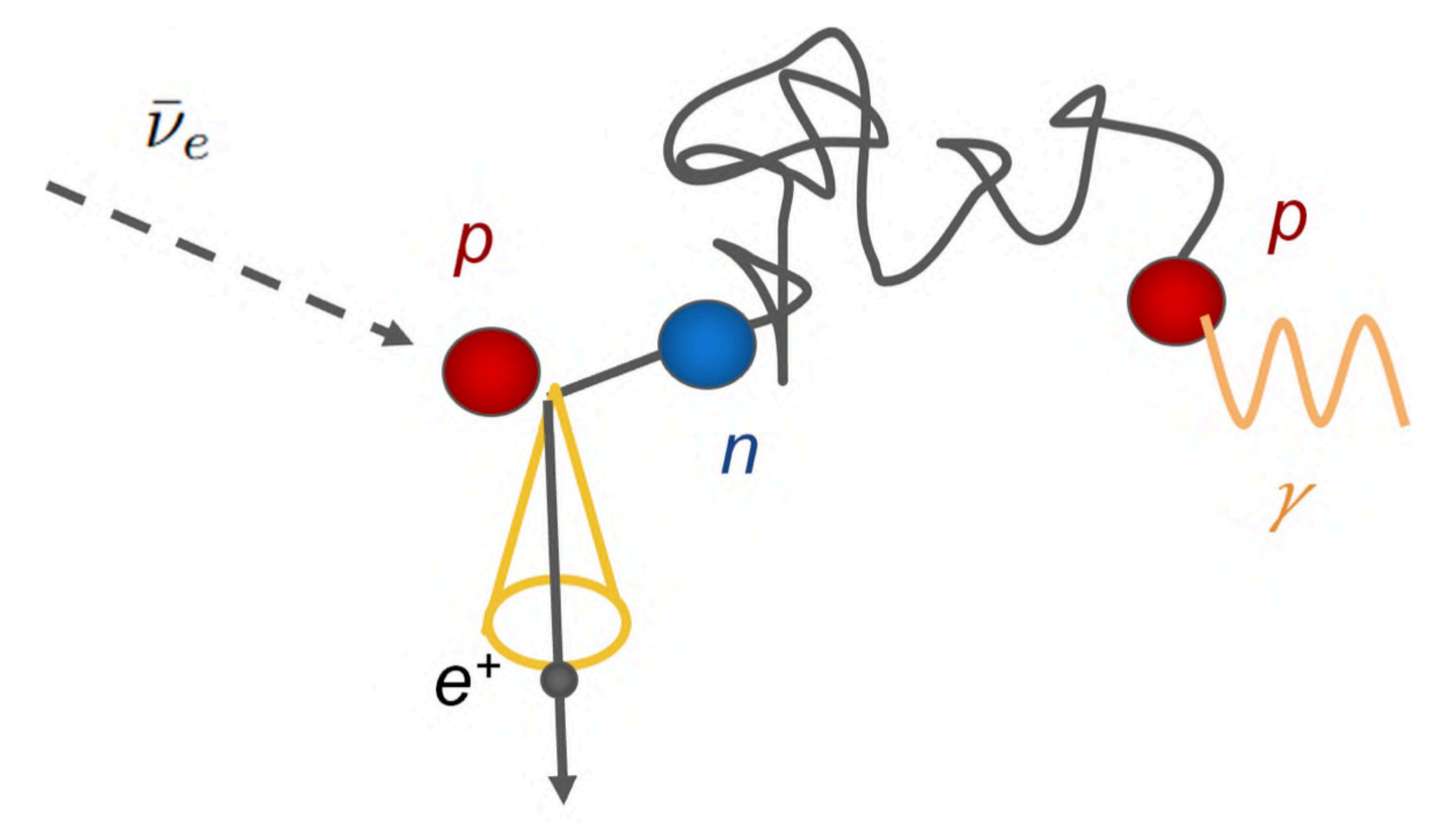
- Zenith angle or momentum distributions for the **19 analysis samples without neutron tagging.**
- FC: Sub-GeV and Multi-GeV samples with SK-I~III data, no neutron tagging included*
- PC, UPMU, FC π^0, FC Multi-Ring samples use SK-I~V data,

Neutron tagging on hydrogen at Super-K

Possible from SK-IV period

Reminder:
$\nu_e + n \rightarrow e^- + p$
$\bar{\nu}_e + p \rightarrow e^+ + n$

- IBD reaction: $\bar{\nu}_e + p \rightarrow n + e^+$
- Neutron tagging may happen on hydrogen.
  - $n + p \rightarrow d + \gamma(2.2MeV)$
  - The gamma ray may then scatter electrons (Compton scattering) in the water, accelerating some of them above the Cherenkov threshold.
  - Identifying the light from those electrons can be used to infer the presence of the gamma ray and hence its parent neutron.



Abe_2022_J._Inst._17_P10029.pdf

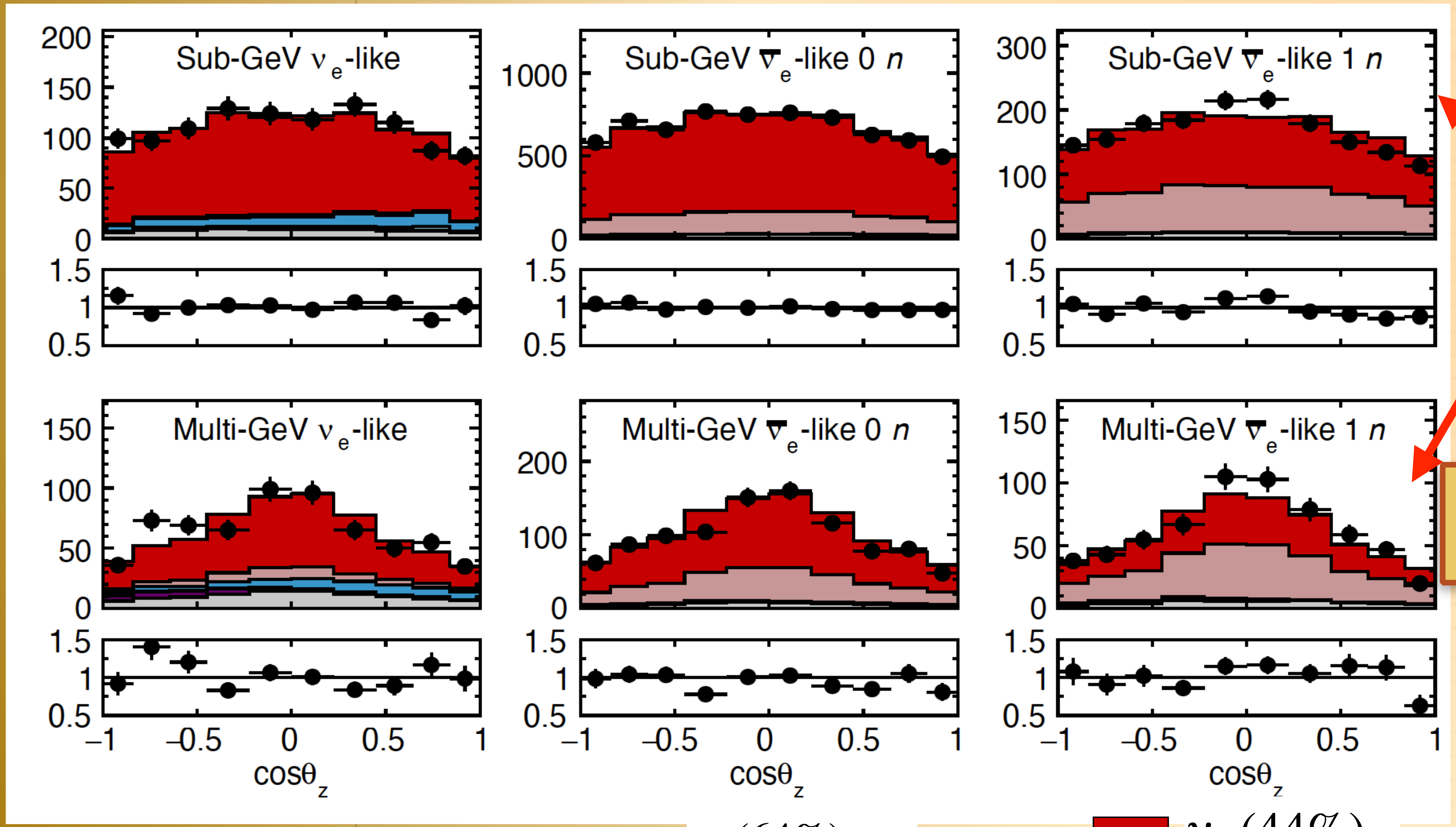
SK samples - impact of neutron tagging

- 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. $= 0$

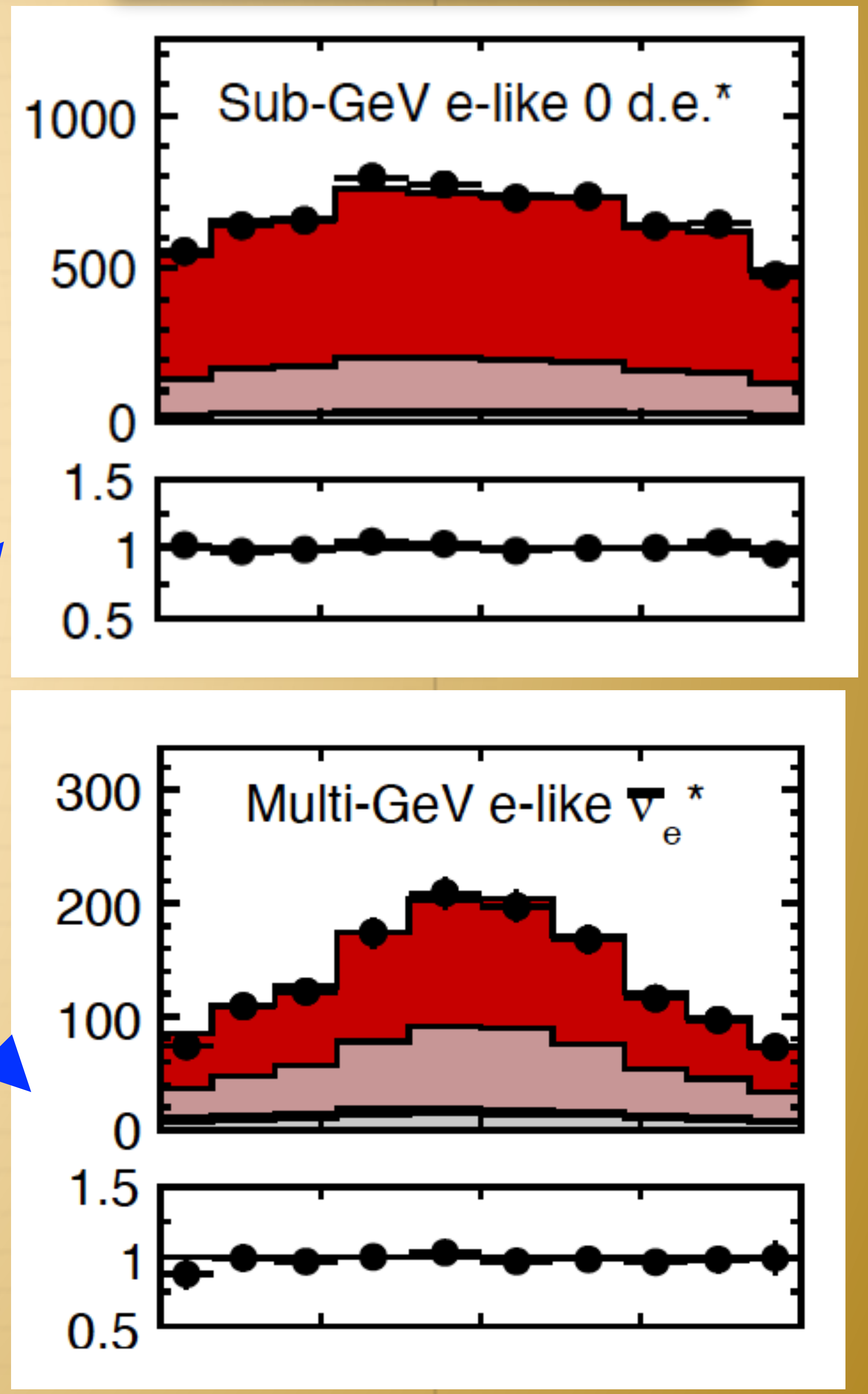
d.e.=0 + # of neut. ≥ 1



New selections with neutron tagging

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

d.e.=0



Super-Kamiokande I–V
- ● Data
- 🟥 ν_e CC
- ▨ $\bar{\nu}_e$ CC
- 🟦 ν_μ CC
- ▨ $\bar{\nu}_\mu$ CC
- 🟪 ν_τ & $\bar{\nu}_\tau$ CC
- ⬜ NC

🟥 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

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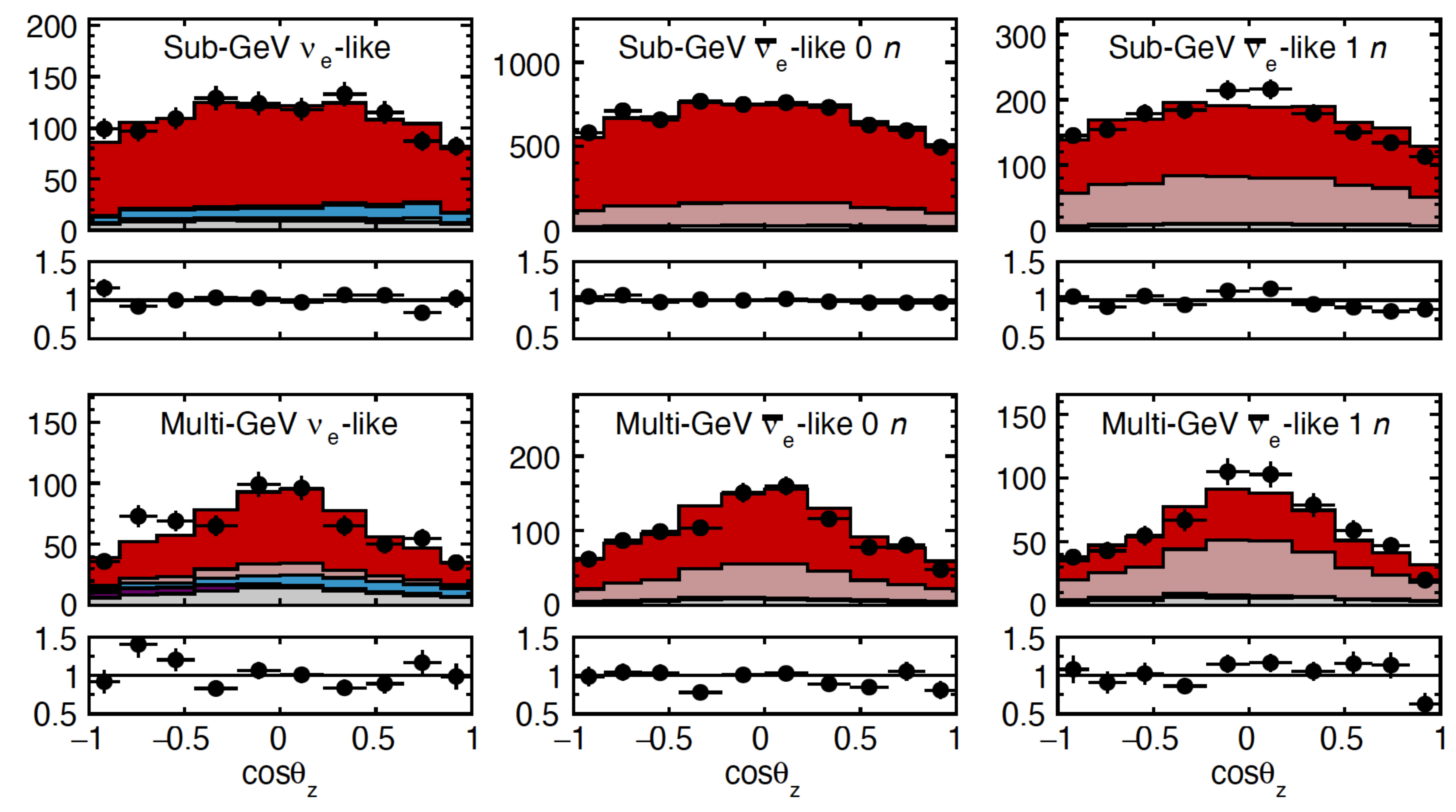
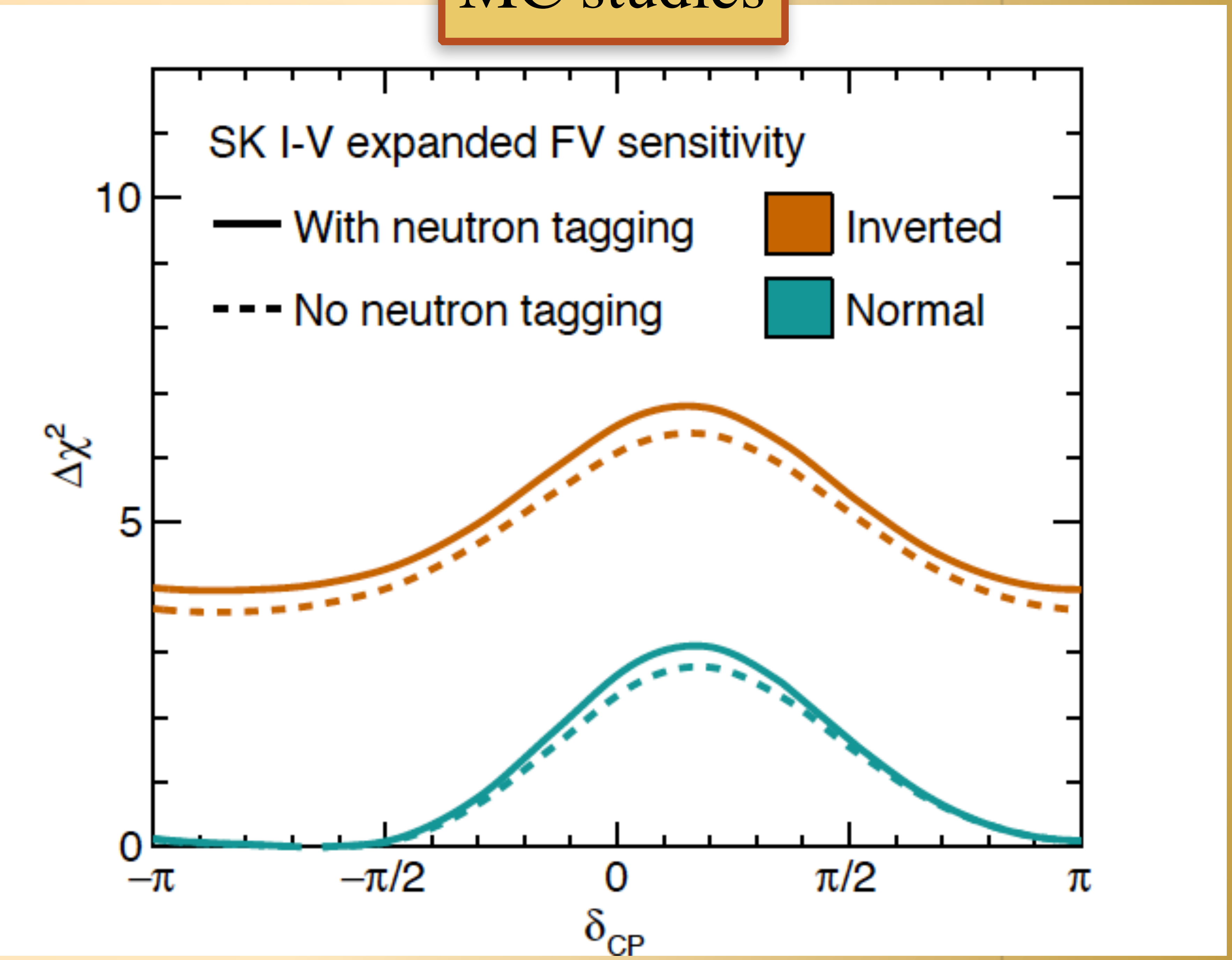


MC studies



SK atmospheric ν results

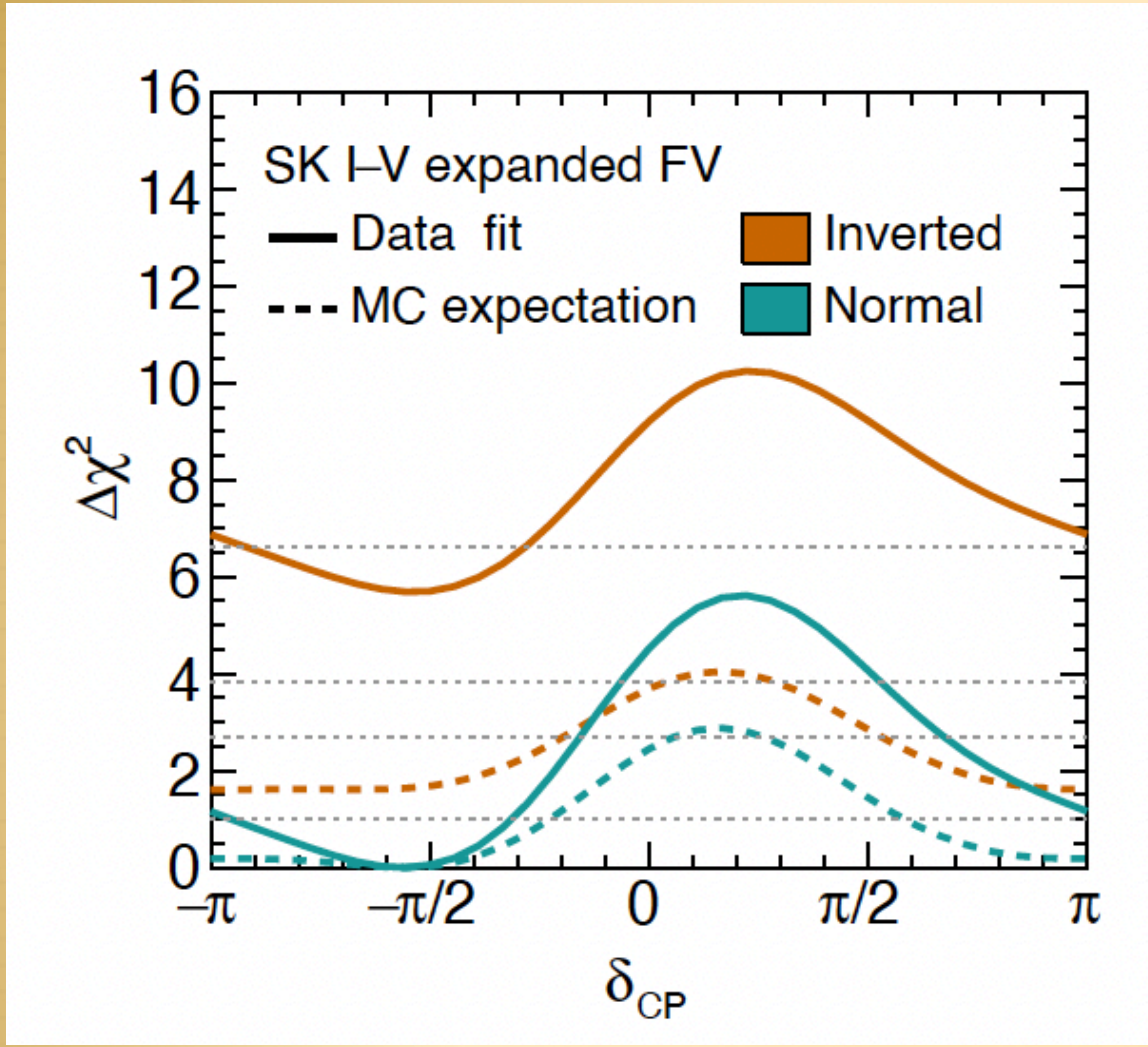
Phys. Rev. D 109, 072014, (2024)

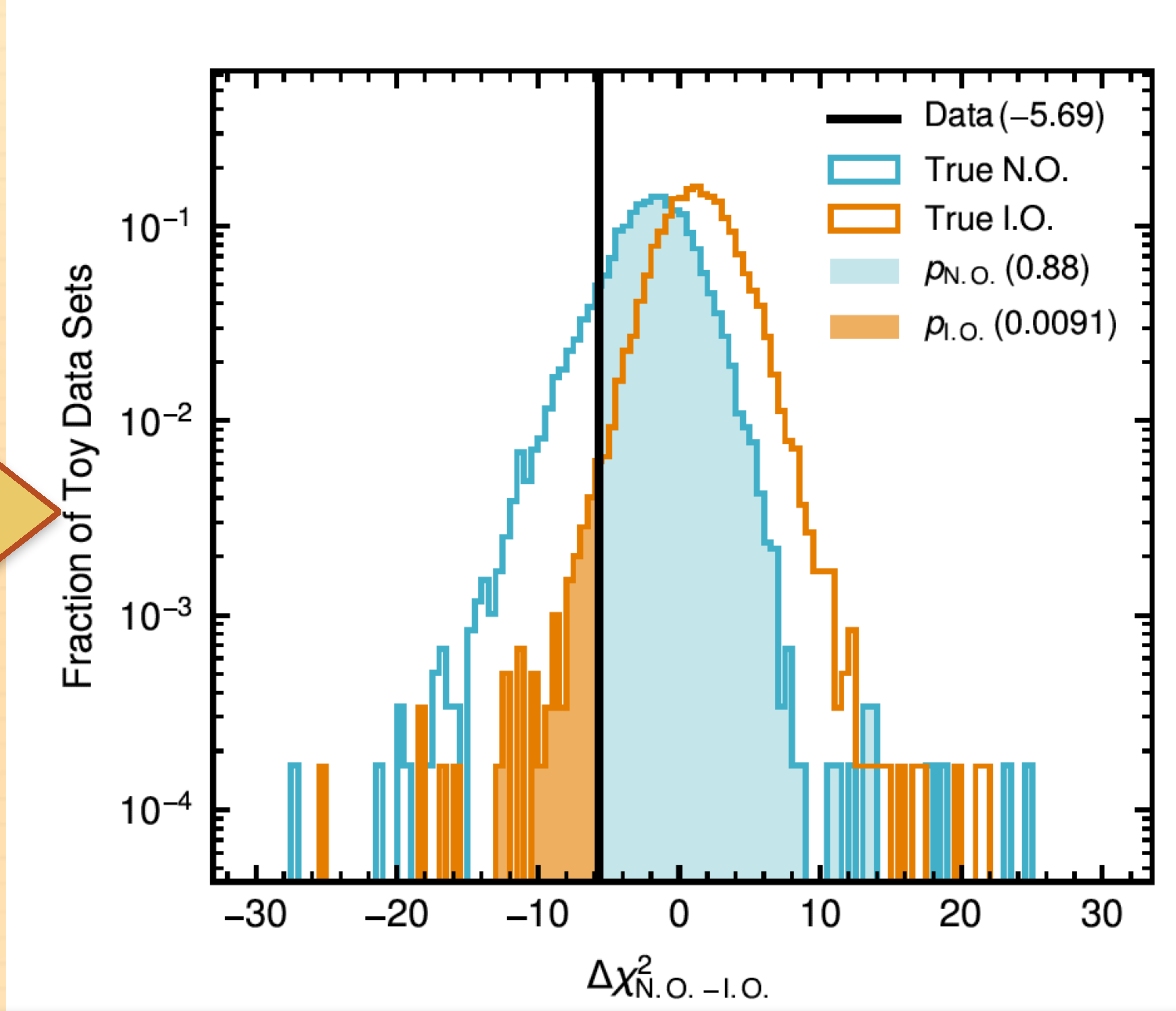
With $\sin^2\theta_{13}$ constrained

$sin^2\theta_{13} = 0.0220 \pm 0.0007$ [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** $92.3\,\% \simeq 1.4\sigma$

SK atmospheric ν results

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

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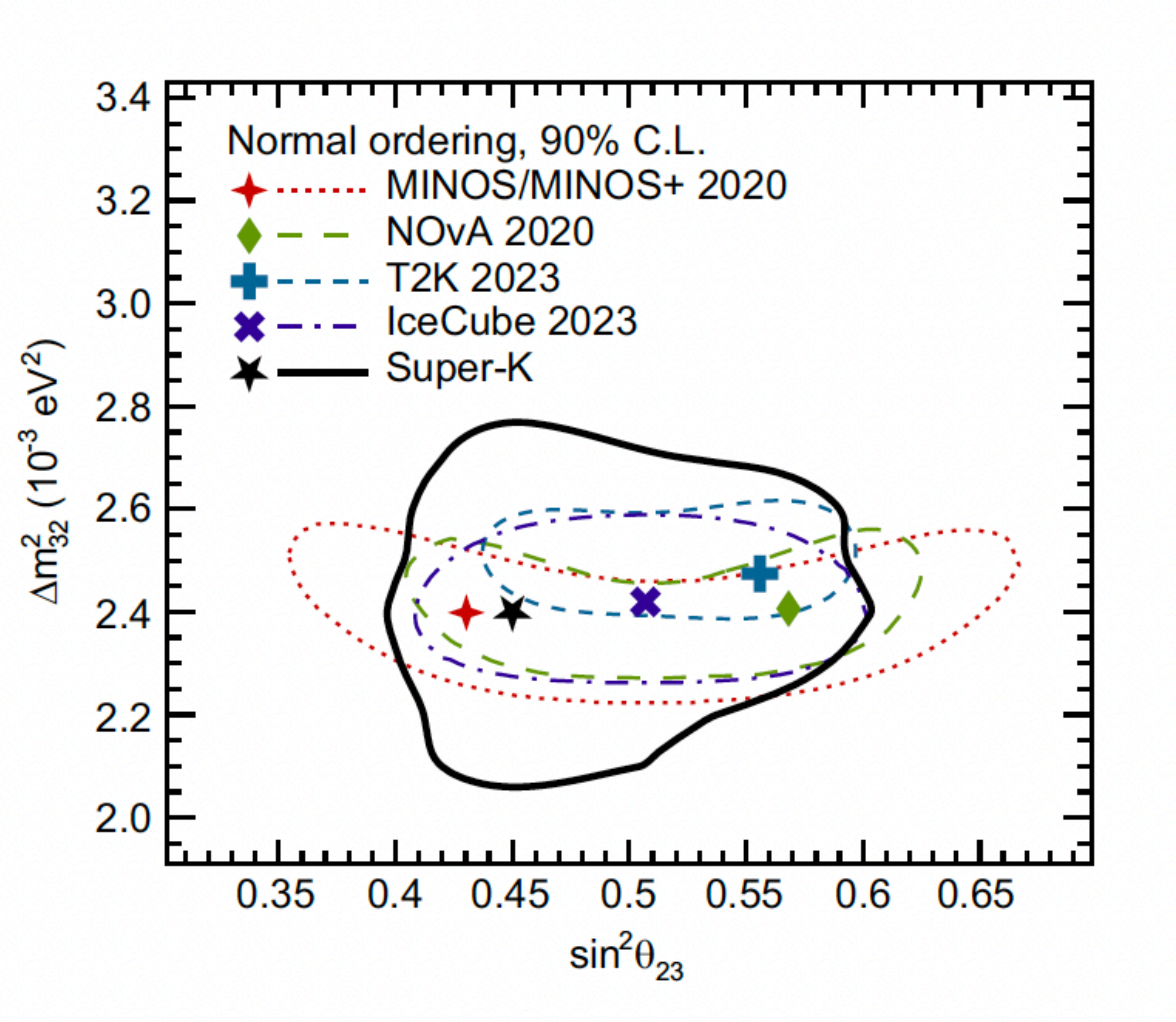

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L/E analysis @ Super - Kamiokande

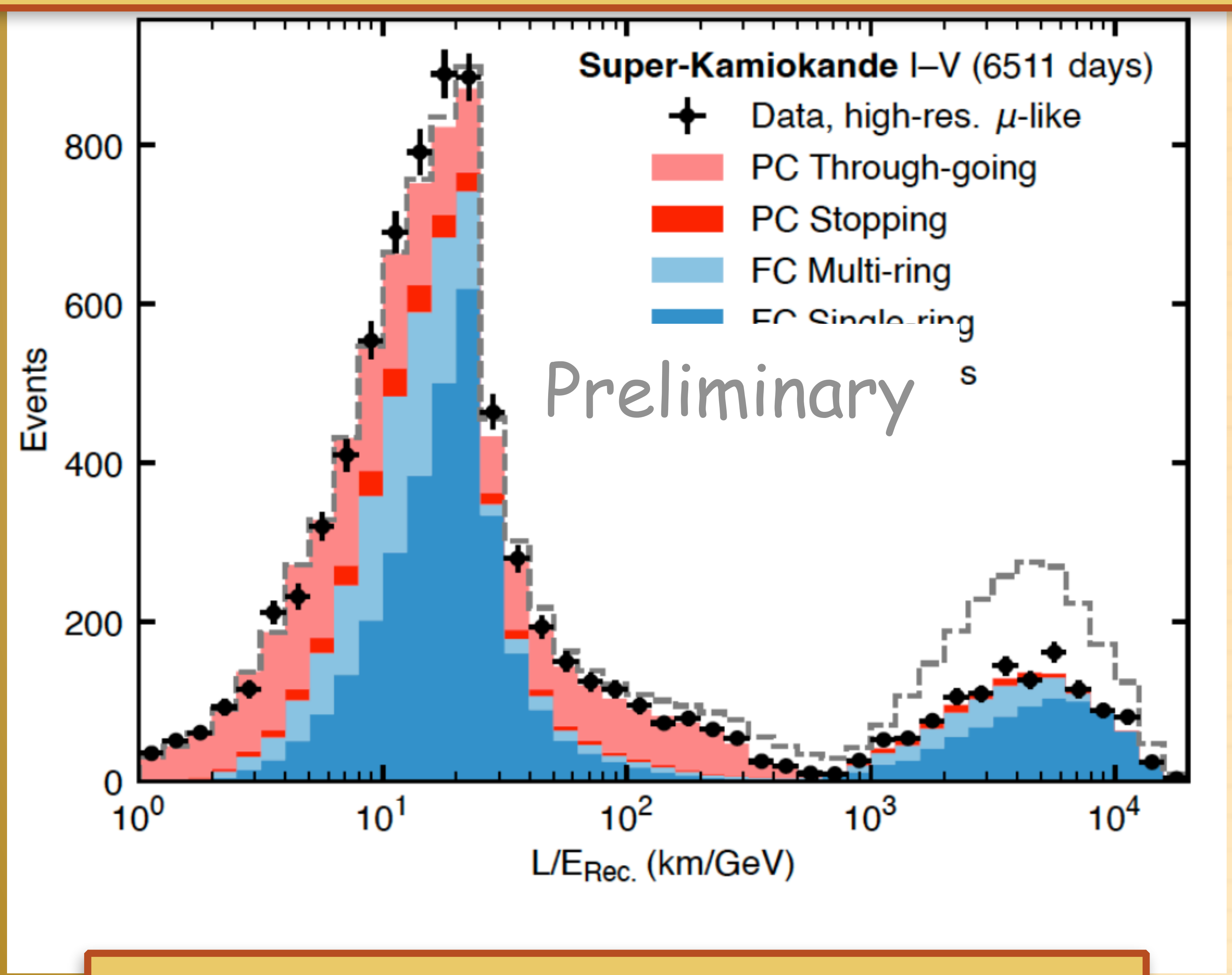
- Atmospheric neutrinos at SK span ~4 orders of magnitude in L/E, possible to see a complete oscillation of ν_μ **survival probability**
- Updates since the last published results in **2004 Phys. Rev. Lett. 93, 101801, SK1**:
  - Full SK pure water phases (SK-I~V data - 6511 days- $\sqrt{(}\Delta\chi^2$(decay,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

ν_μ and $\bar{\nu}_\mu$ disappearance

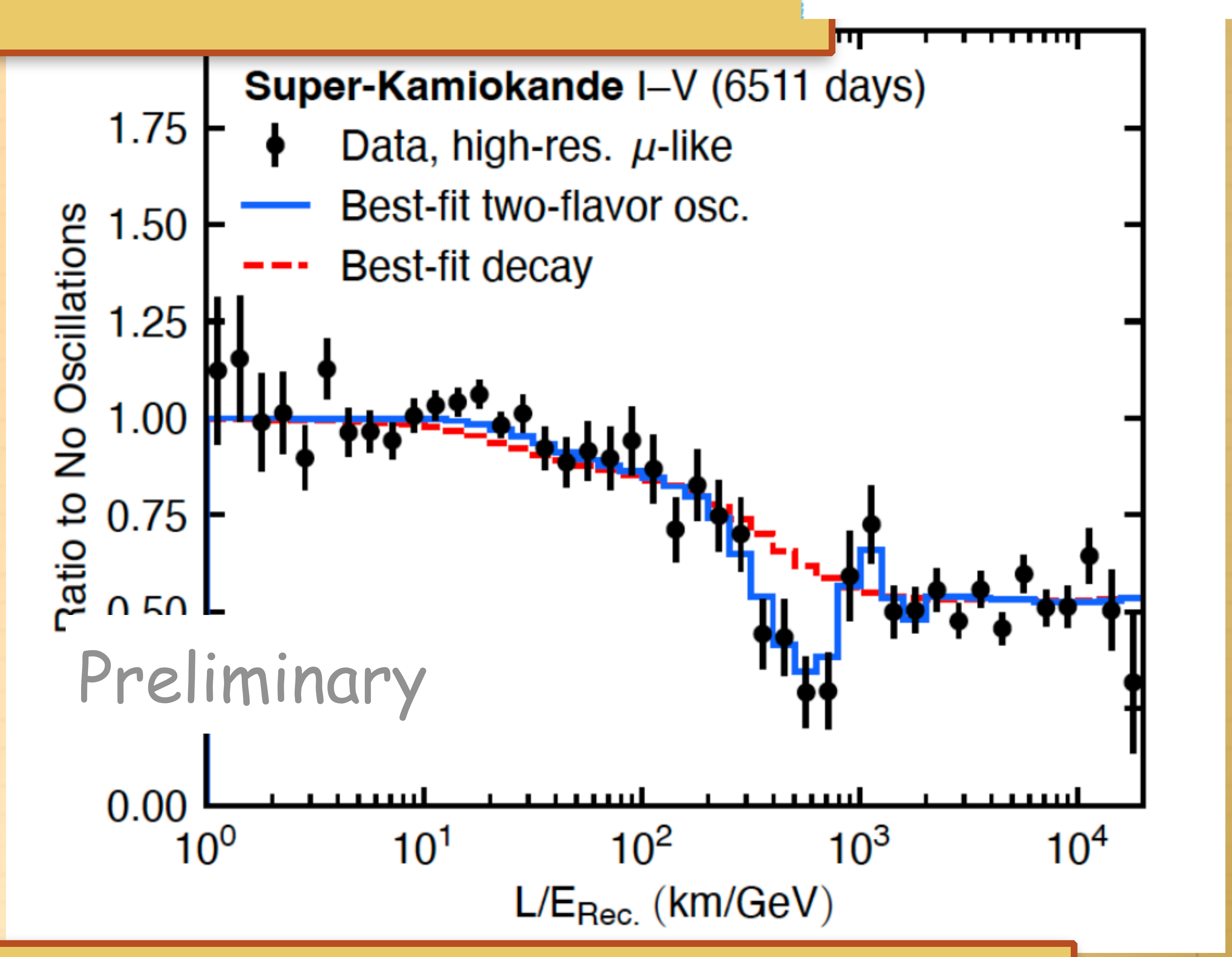
$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

Same oscillation probability for ν and $\bar{\nu}$

Sensitive to $|\Delta m^2_{32}|$ and to $\sin^2(2\theta_{23})$ → no sensitivity to mass ordering and δ_{CP}



High - resolution data/MC sample



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

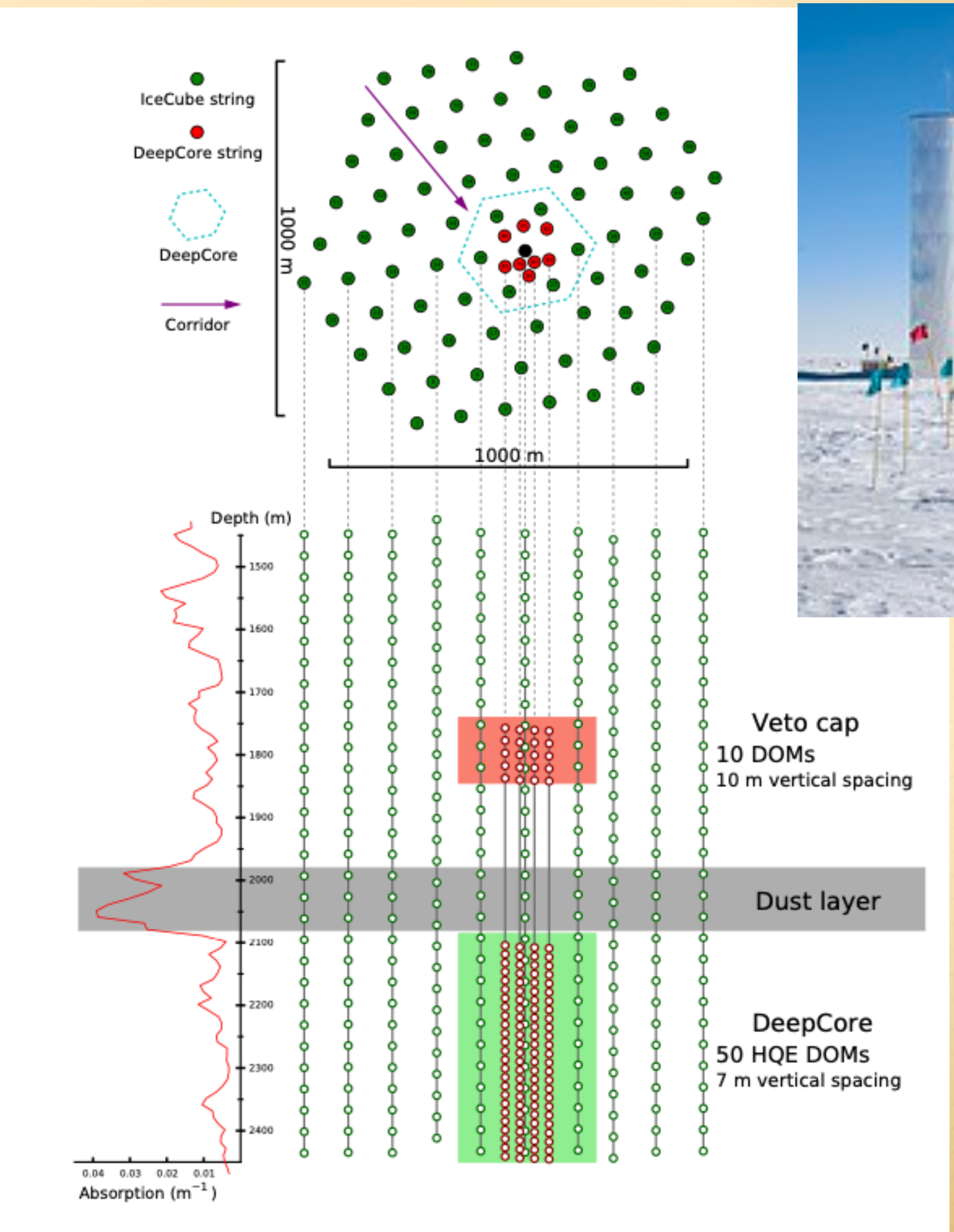
Atmospheric neutrinos

ICECUBE
NEUTRINO OBSERVATORY

Juan Pablo Yanez: "A Decade of Atmospheric ν Oscillations with IceCube" - For the IceCube Collaboration, Neutrino24

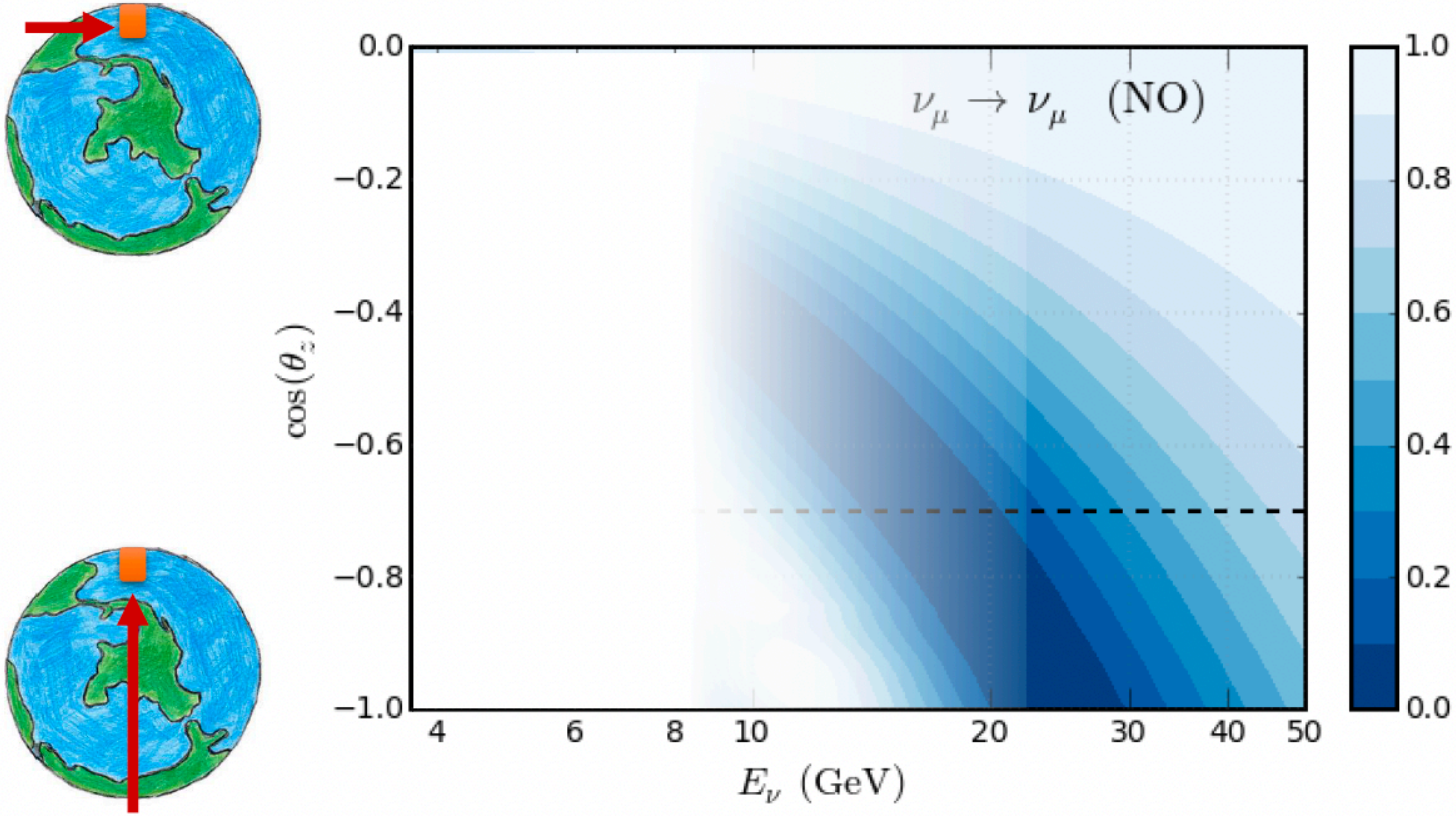
IceCube Neutrino Observatory

- The IceCube Neutrino Observatory is :
  - Ice Cherenkov telescope located at the geographic South Pole
  - It consists of **5,160 Digital Optical Modules (DOMs)** deployed in **86 boreholes** that were drilled with a high-pressure hot water drill
  - The bottom-center part of the array, referred to as **DeepCore** has a reduced horizontal spacing of 42-72 m and a vertical spacing of 7 m.



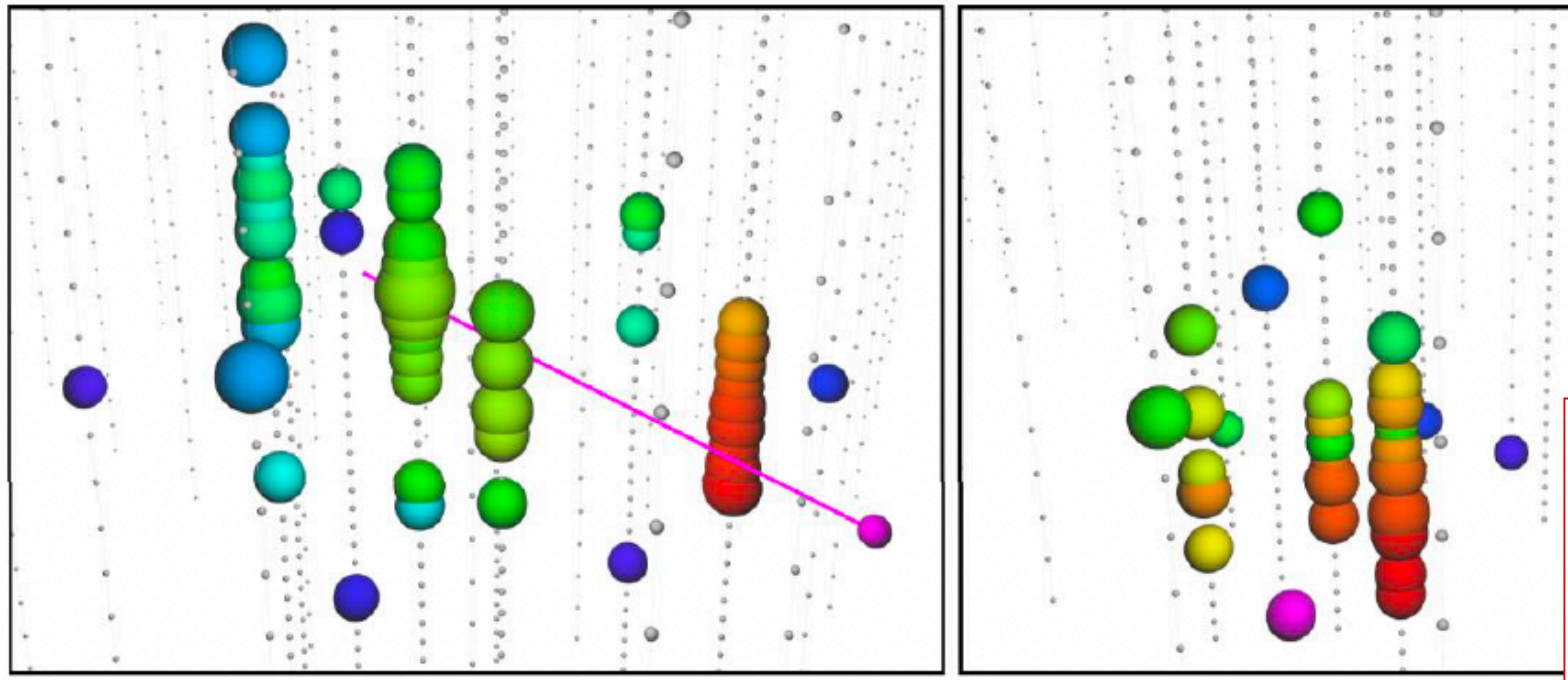
Measurements of neutrino oscillations (DeepCore)

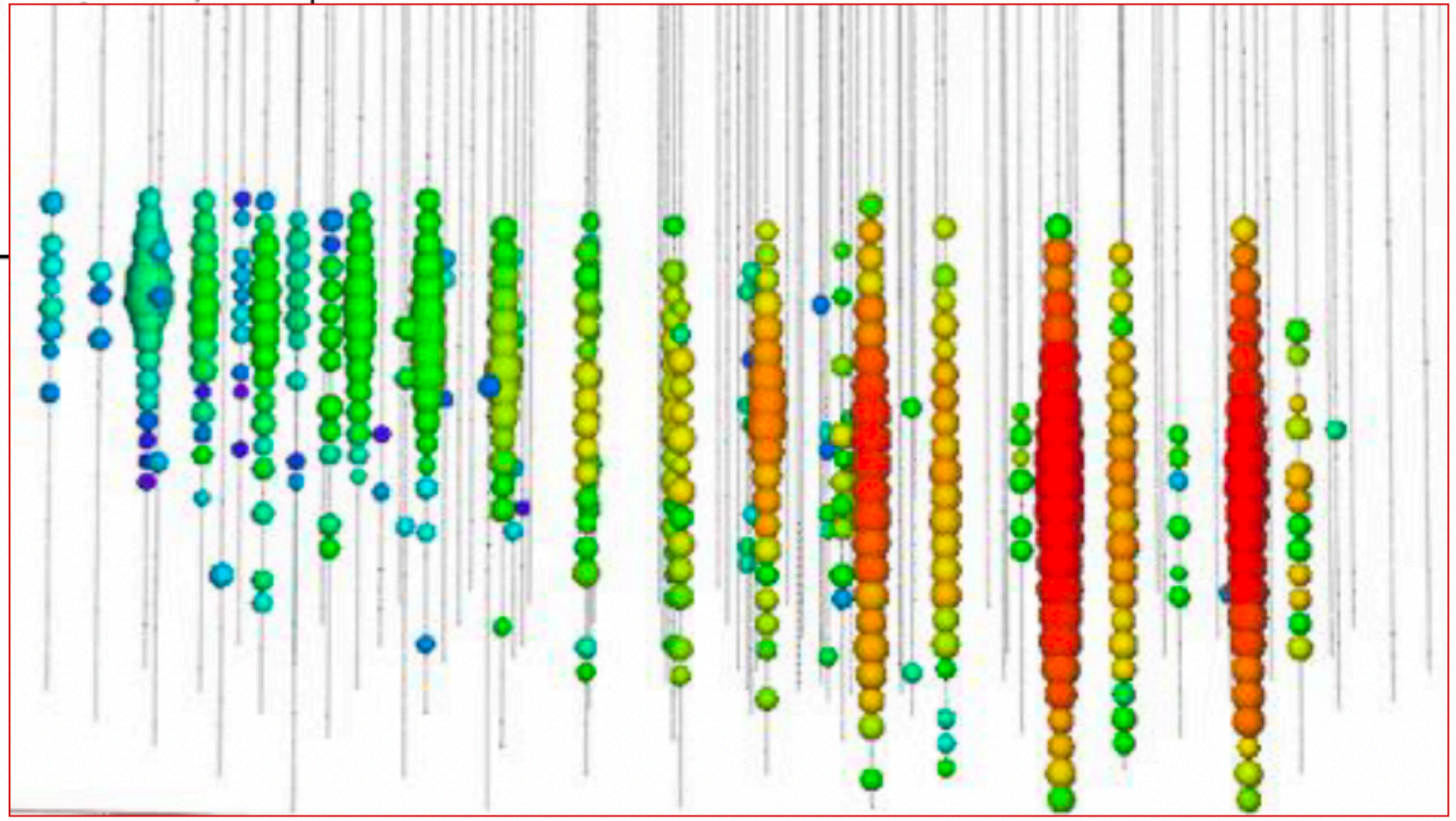
$$P\nu_\mu \to \nu_\mu \simeq 1 - \sin^2 2\theta_{23}\ \sin^2\left(\frac{\Delta m^2_{32}}{4E}L\right)$$



Events as seen by the detector

GeV events in DeepCore for ν oscillations



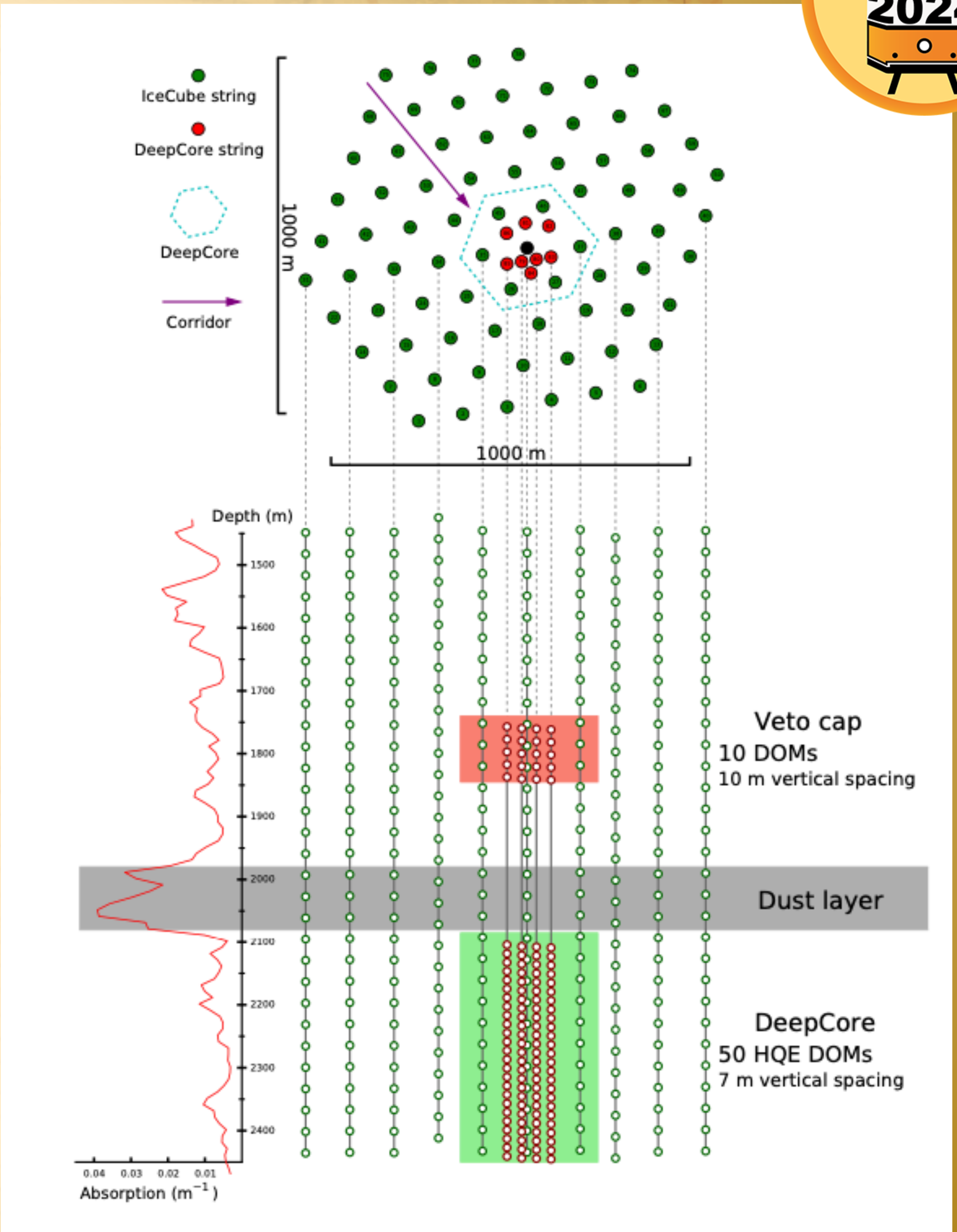


TeV event in IceCube for sterile ν searches

Color indicates time (red=early, blue=late).
Sphere size is proportional to number of photons observed.

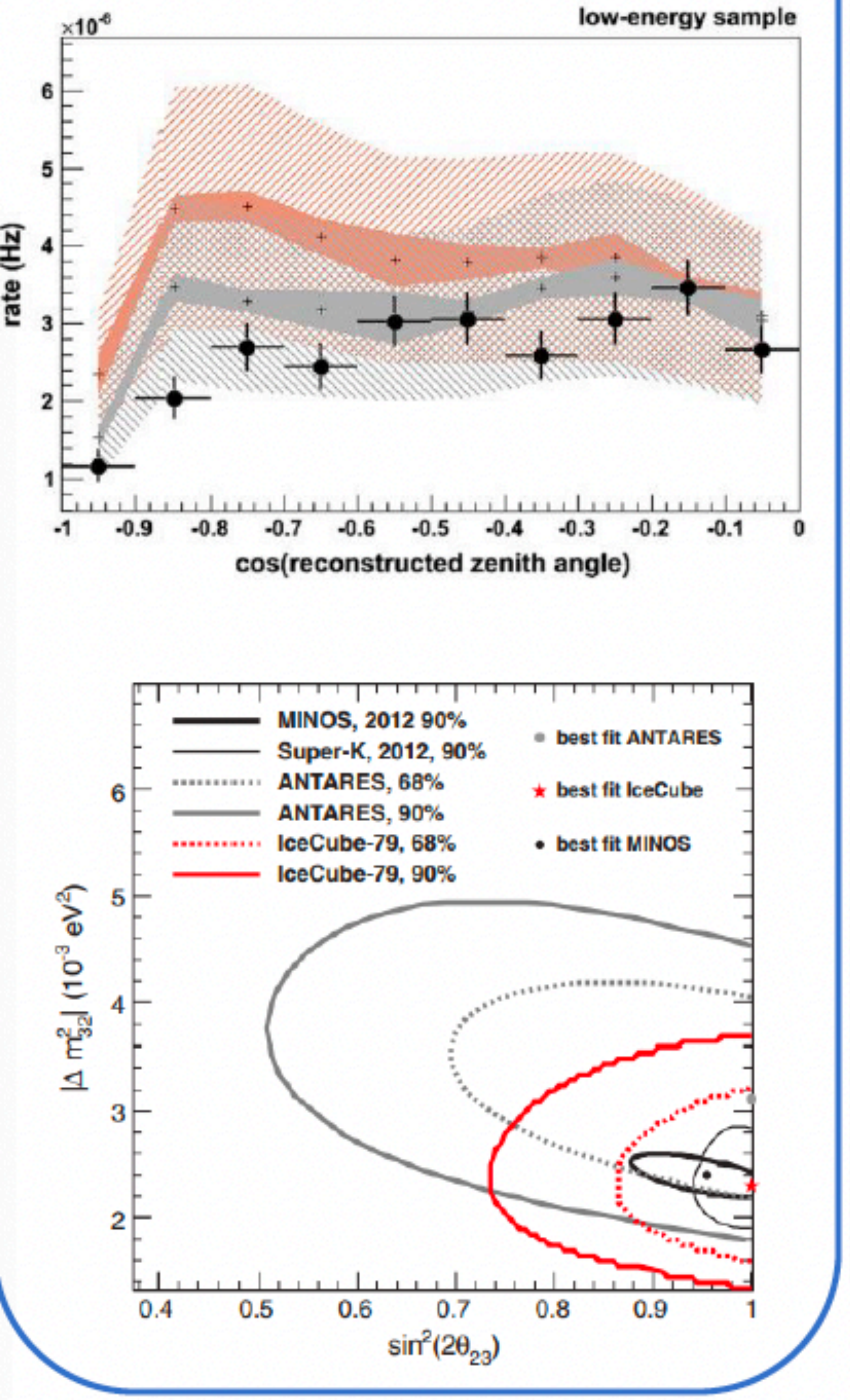
IceCube atmospheric neutrinos 2023 analysis

- A new data sample of collected by the DeepCore.
- Published in PHYSICAL REVIEW D 108, 012014 (2023)
- What is new?
  - **updated response of the optical modules calibrated** individually
  - **a more accurate description of the glacial ice**
  - **improved reconstructions an event selection** with higher background rejection efficiency,
  - the new sample includes 8 years of data collected from 2011-2019, which more than doubles the lifetime used in previously published analyses

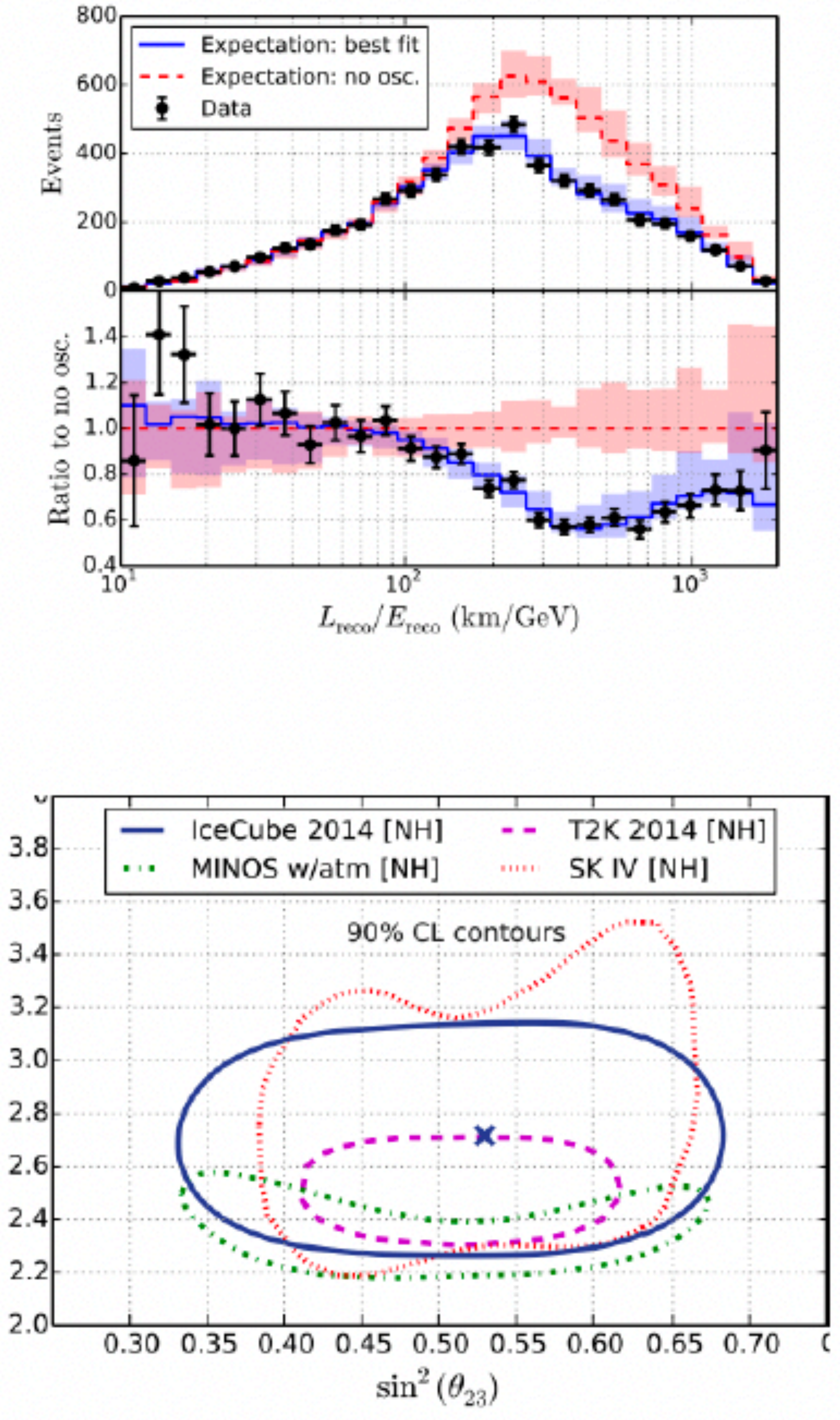


Atmospheric oscillations **progression**

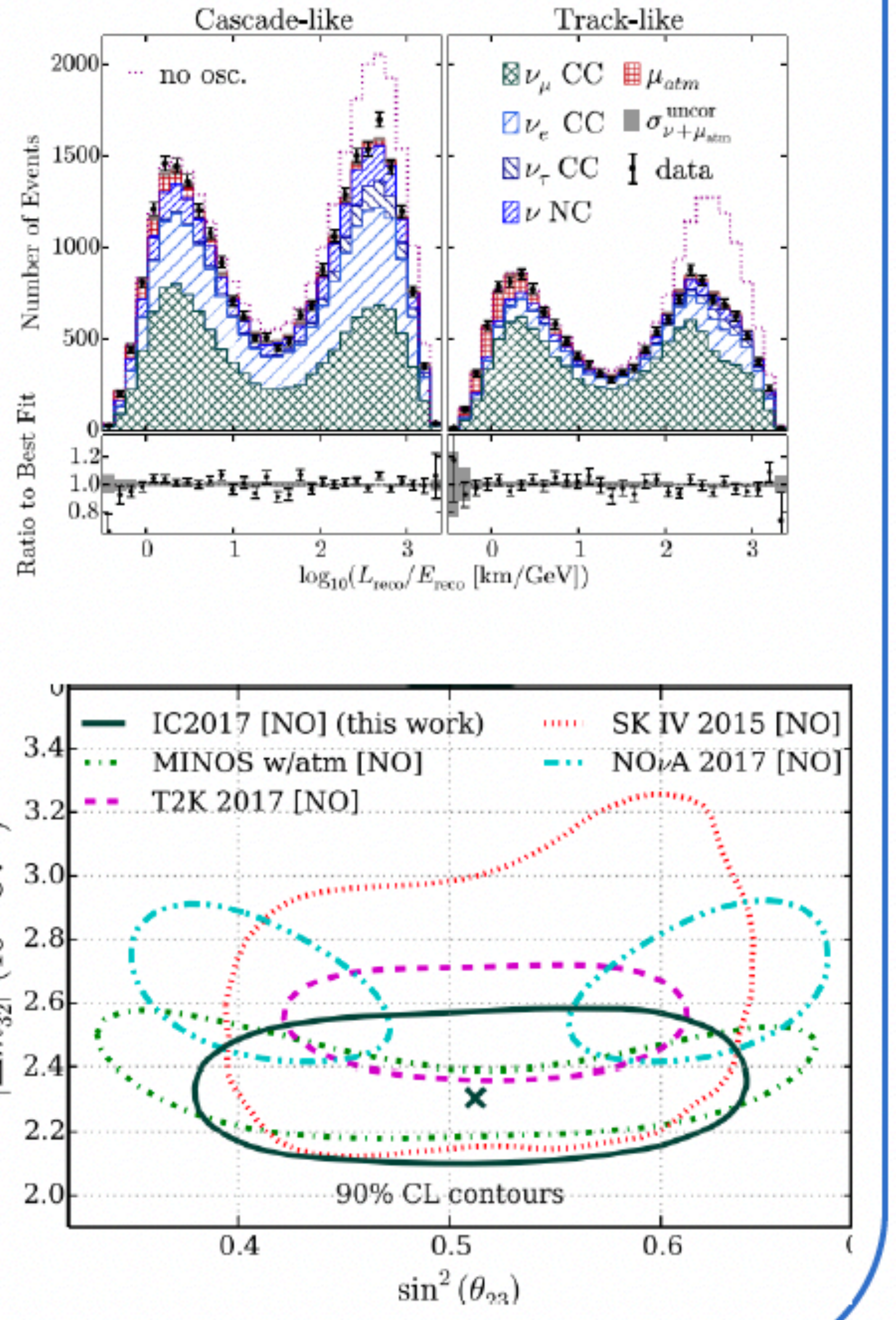
IceCube, PRL 111, 081801 **(2013)**
700 events



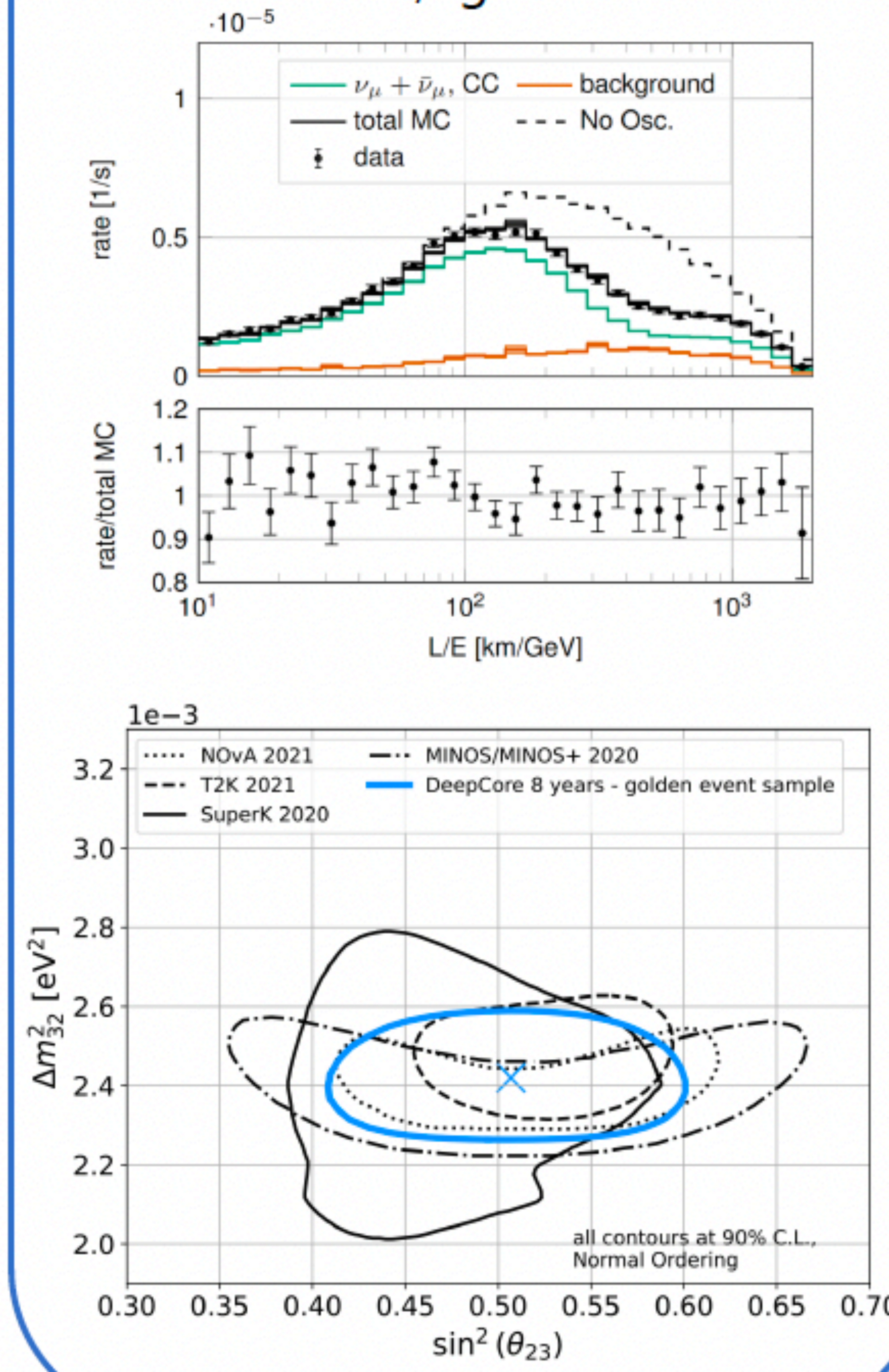
IceCube, PRD 91, 072004 **(2015)**
~5k events, "golden events"



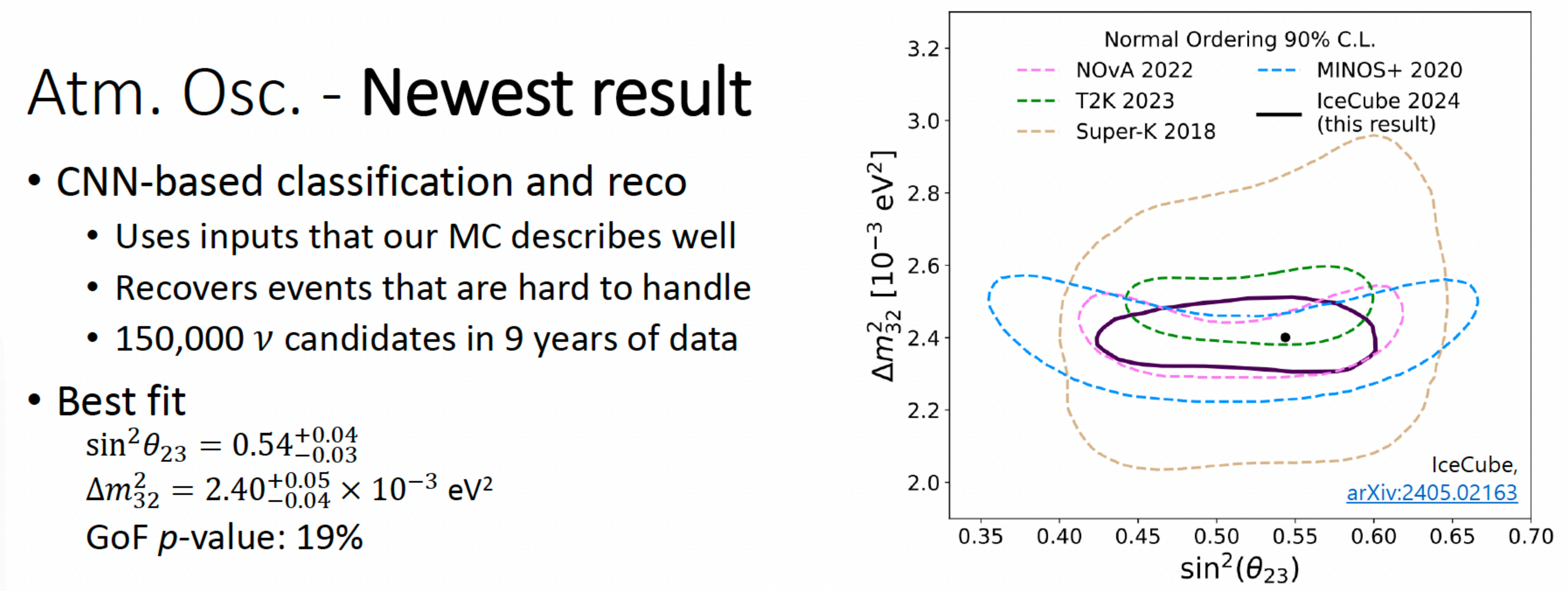
IceCube, PRL 120, 071801 **(2018)**
~35k events, inclusive sample



IceCube, PRD 108, 012014 **(2023)**
~22k events, "golden events"



IceCube result from 2024



Atm. Osc. - **Newest result**

- CNN-based classification and reco
  - Uses inputs that our MC describes well
  - Recovers events that are hard to handle
  - 150,000 ν candidates in 9 years of data
- Best fit

$$\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}$$

$$\Delta m^2_{32} = 2.40^{+0.05}_{-0.04} \times 10^{-3}\ \mathrm{eV}^2$$

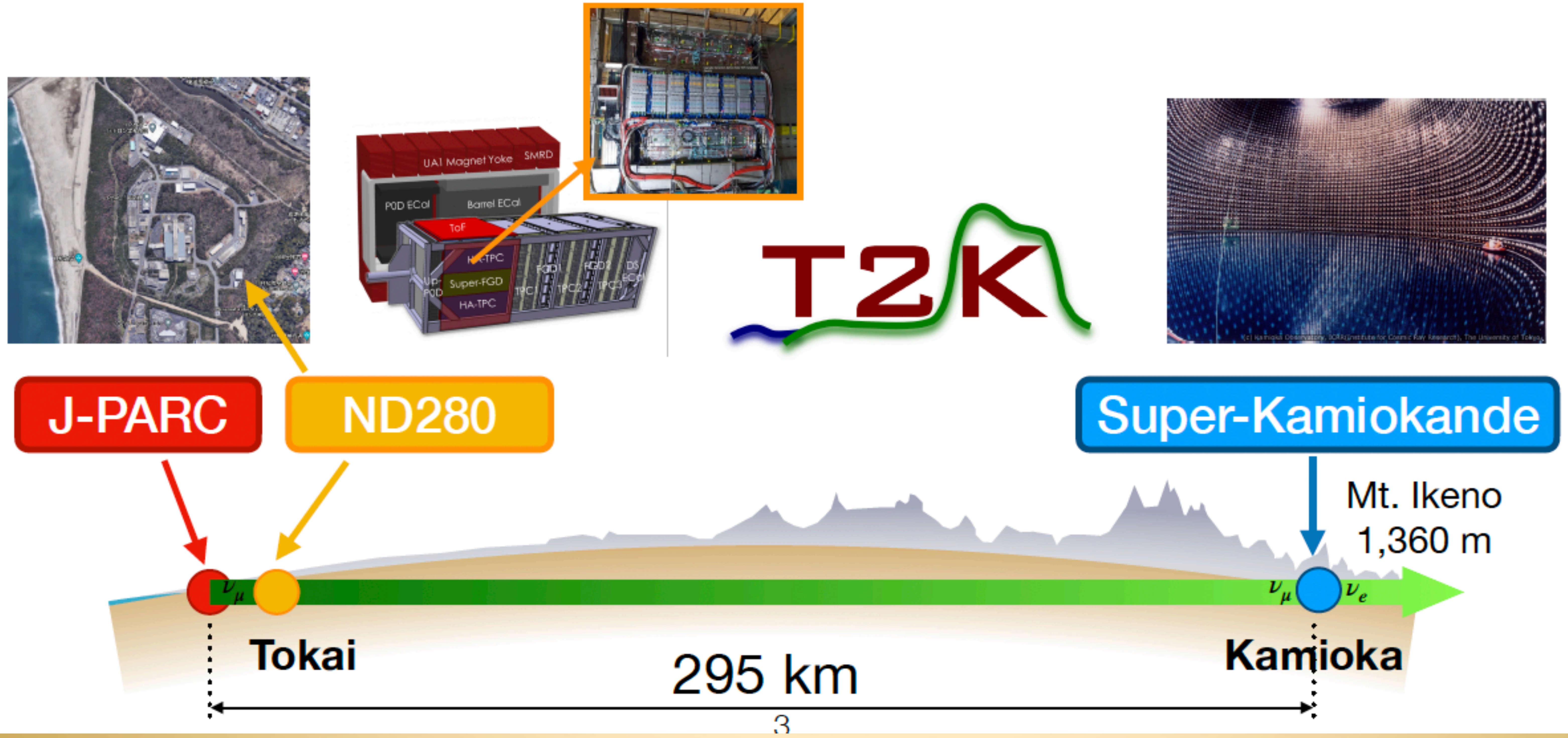
GoF *p*-value: 19%

Joint fits (1):
Accelerator + atmospheric neutrinos

T2K experiment

REMINDER

- High intensity ~600 MeV ν_μ or $\bar{\nu}_\mu$ beam produced at J-PARC (Tokai)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande)
  - ν_e and $\bar{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ disappearance → θ_{23} and $|\Delta m^2_{32}|$



Physics case

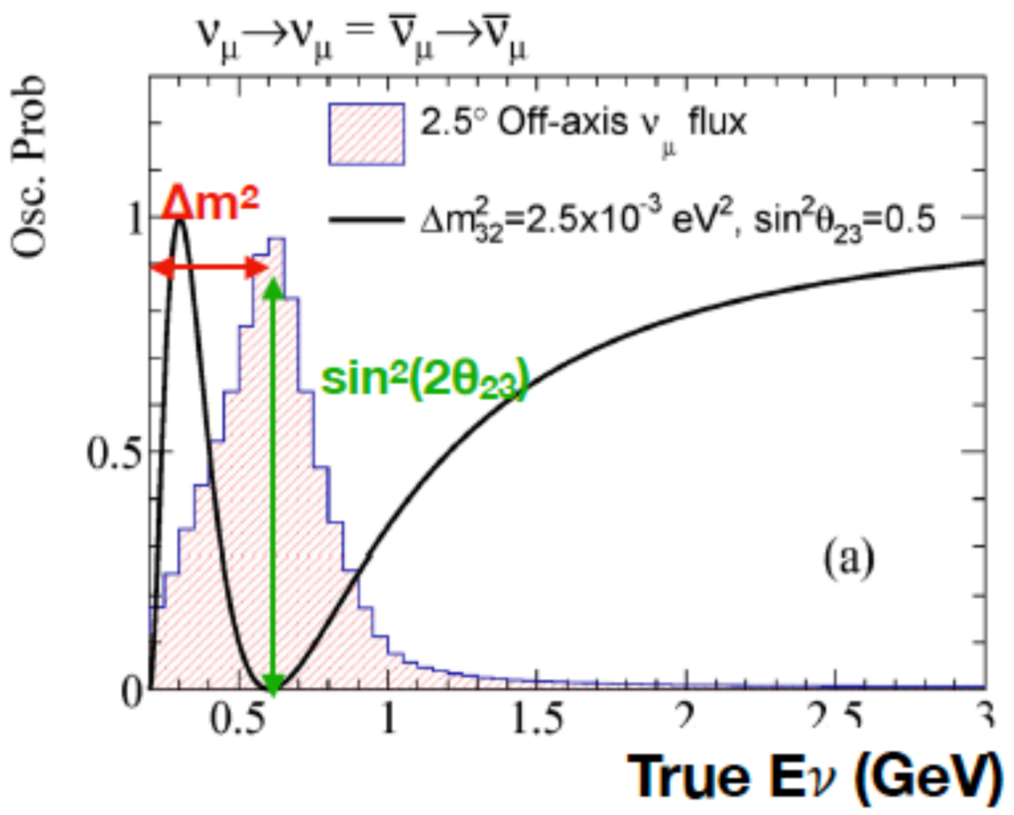
REMINDER

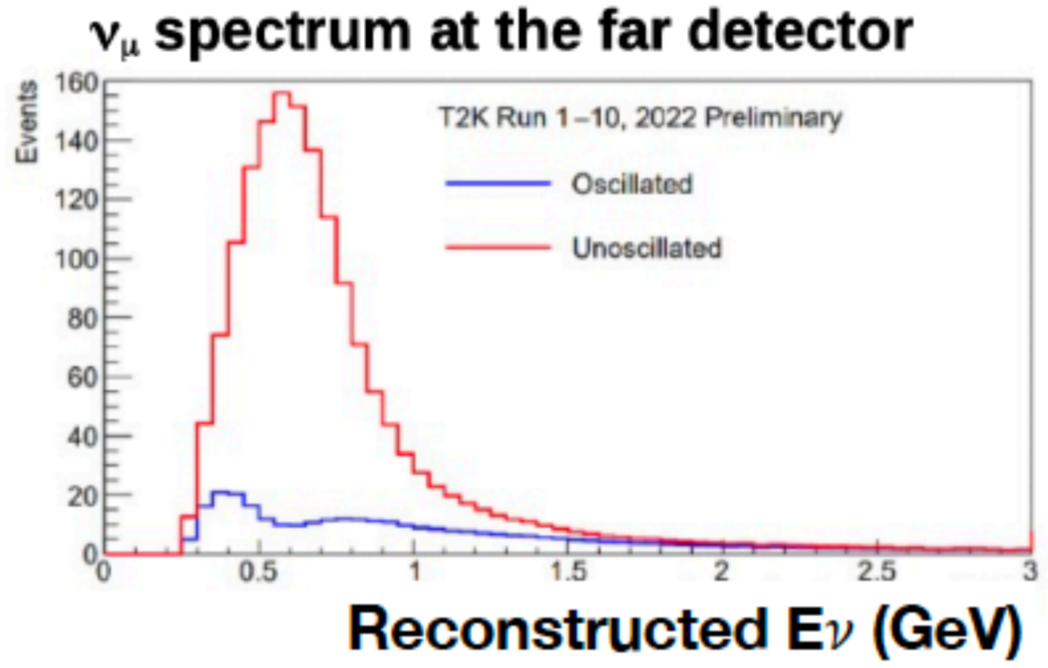
ν_μ and $\bar{\nu}_\mu$ disappearance

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

Same oscillation probability for ν and $\bar{\nu}$

Sensitive to $|\Delta m^2_{32}|$ and to $\sin^2(2\theta_{23})$ → no sensitivity to mass ordering and δ_{CP}





ν_e and $\bar{\nu}_e$ appearance

$$P(\overline{\nu_\mu} \to \overline{\nu_e}) \simeq sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}$$

$$(\mp)\alpha\frac{J_0\sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}]$$

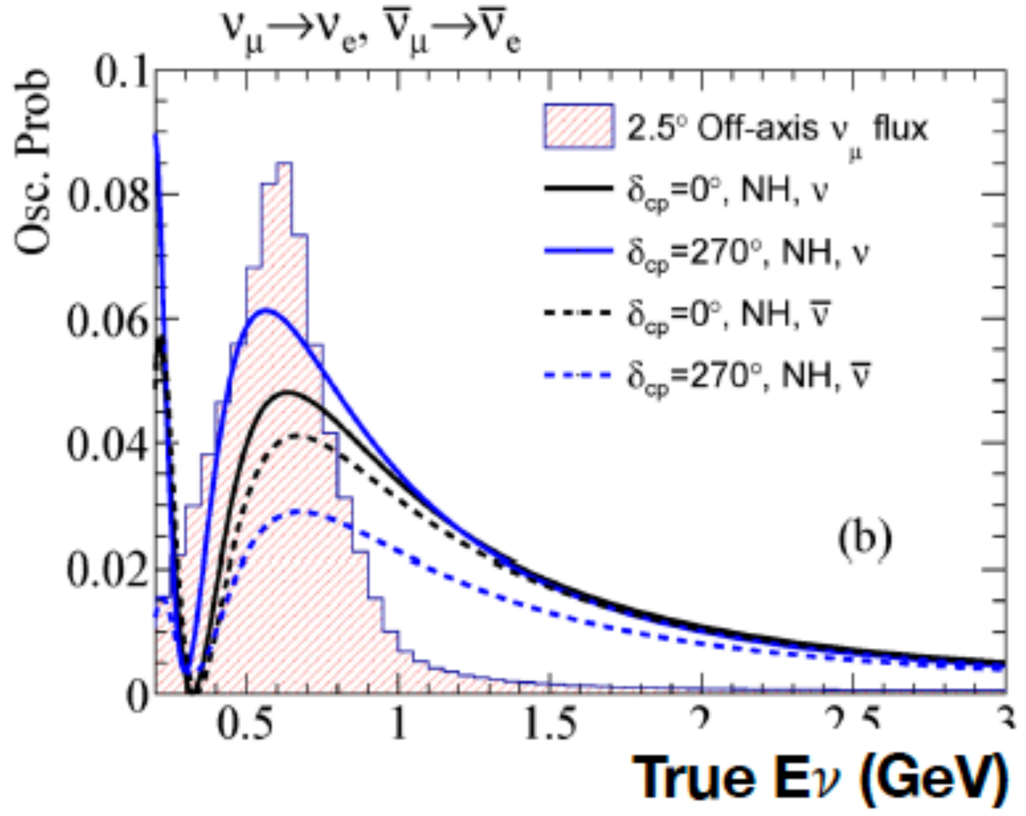
$$+\alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30$$

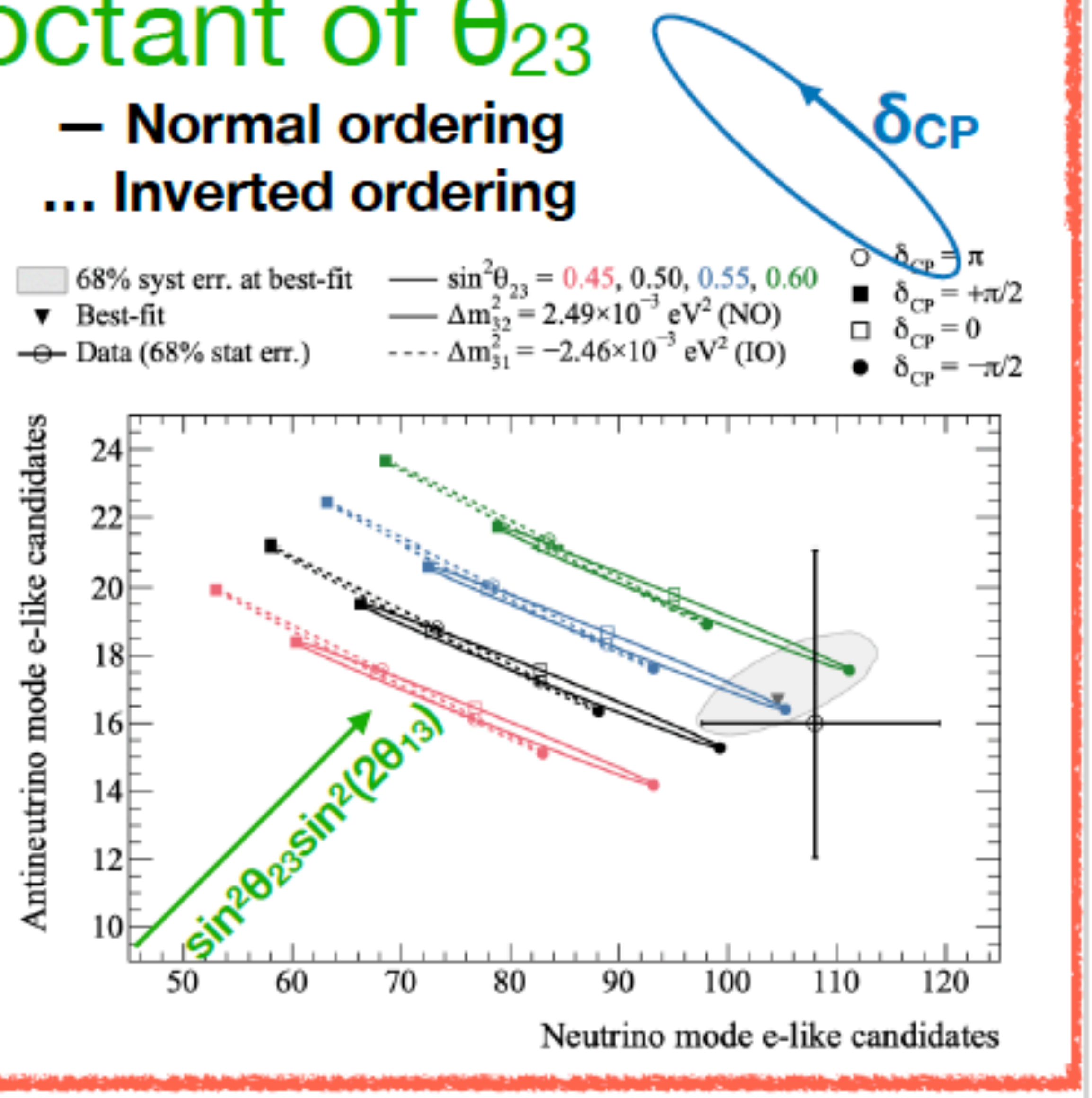
$$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$

$$A = (\mp)2\sqrt{2}G_F n_e E/\Delta m^2_{31}$$

Sensitivity to δ_{CP}, to the mass ordering and to the octant of θ_{23}

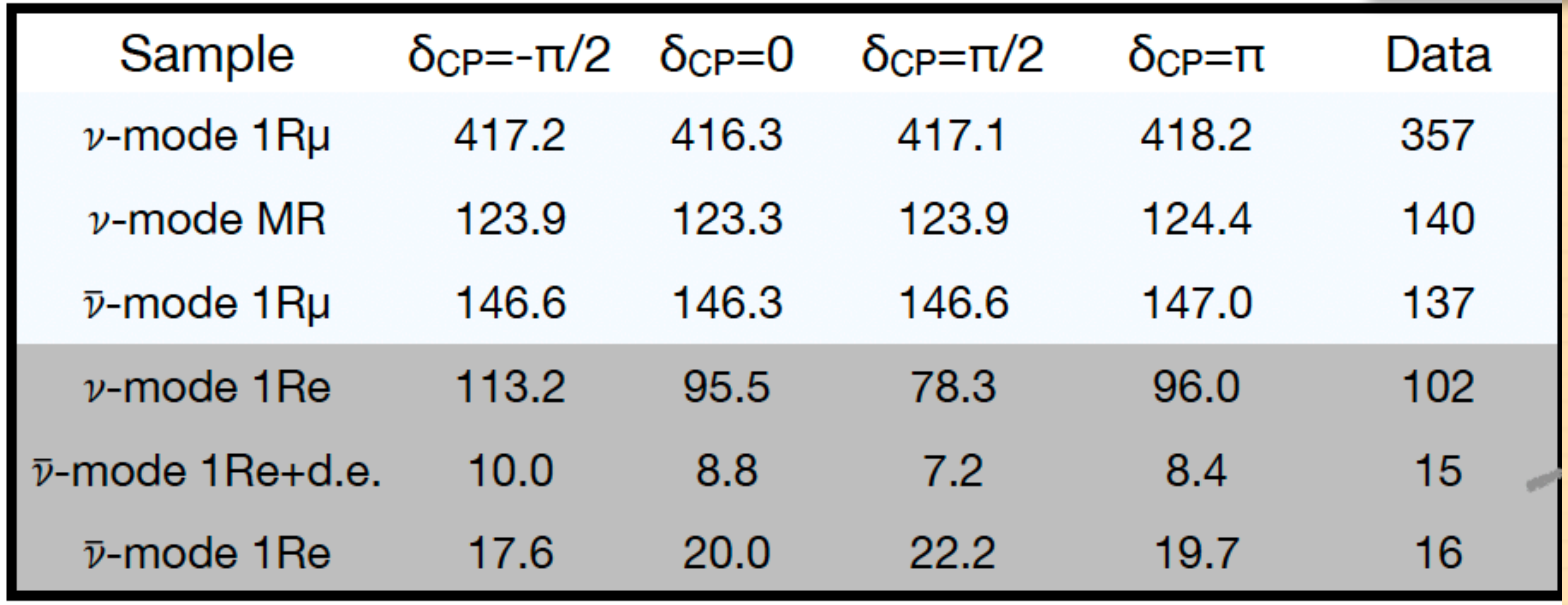


— Normal ordering
… Inverted ordering

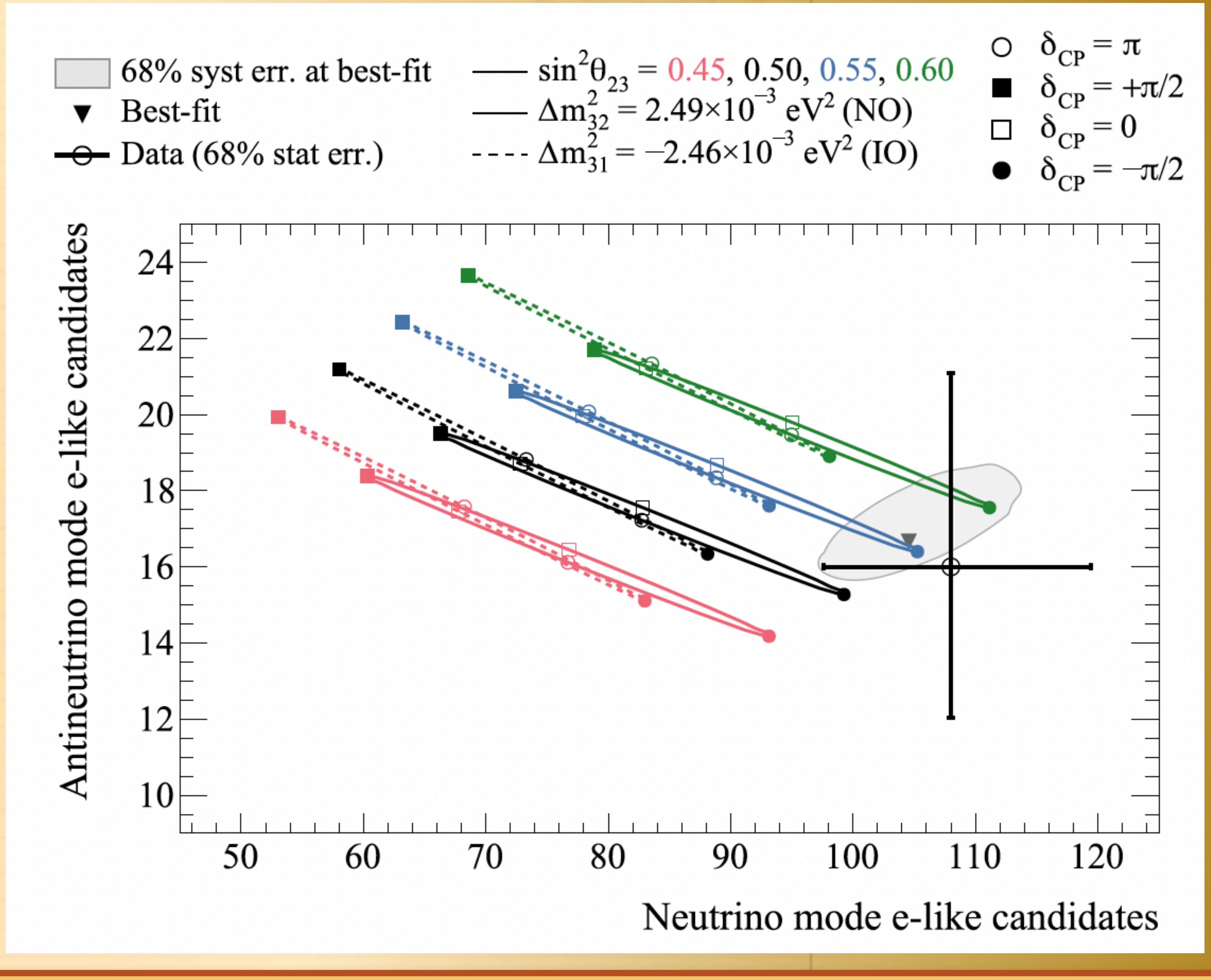


T2K only oscillation analysis results

DATA



Sample	δCP=-π/2	δCP=0	δCP=π/2	δCP=π	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
$\bar{\nu}$-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
$\bar{\nu}$-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
$\bar{\nu}$-mode 1Re	17.6	20.0	22.2	19.7	16



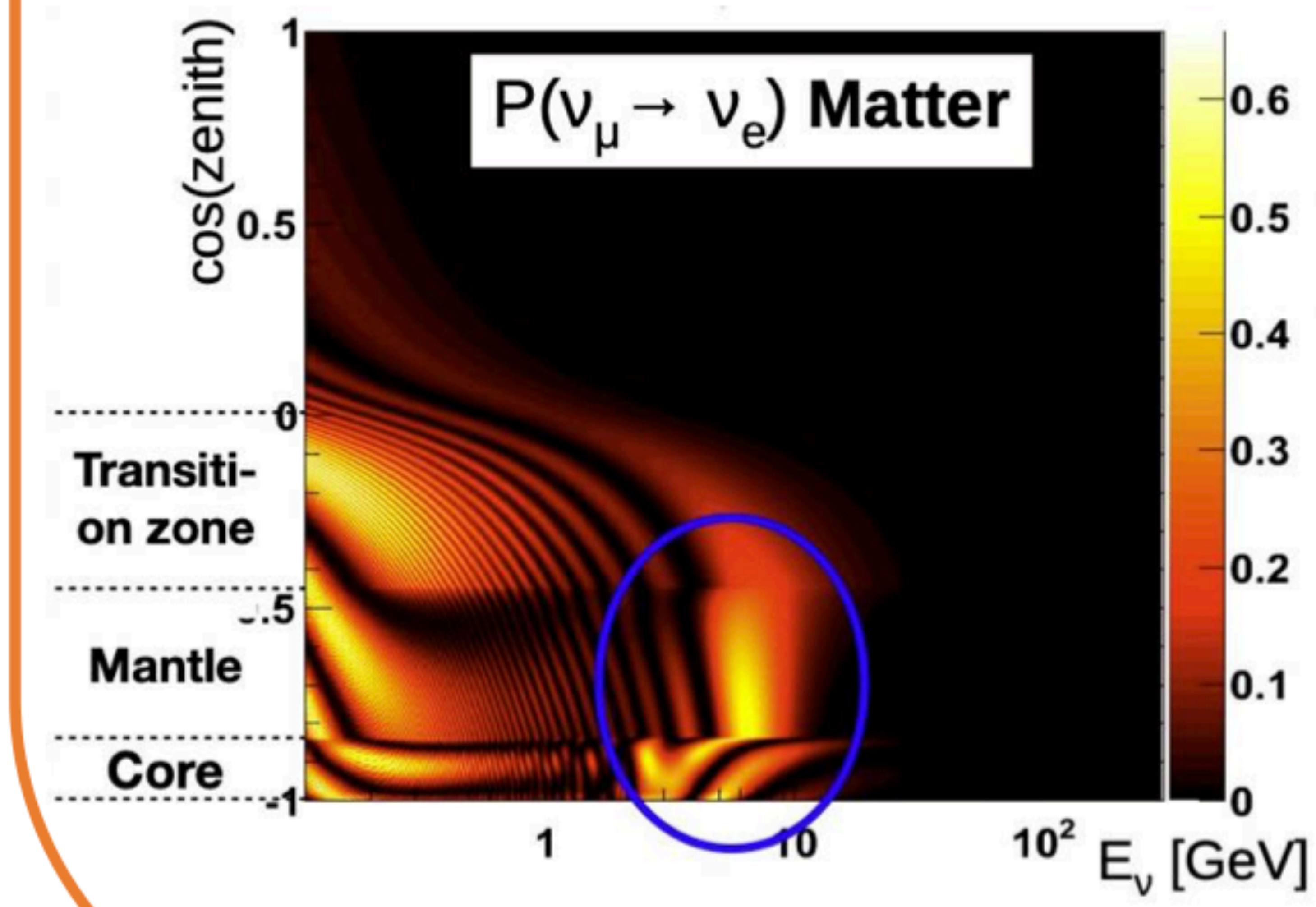
In T2K δ_{CP} and mass ordering have similar effect on $\nu_e/\bar{\nu}_e$ event rates - so called degeneracy of oscillation parameters .

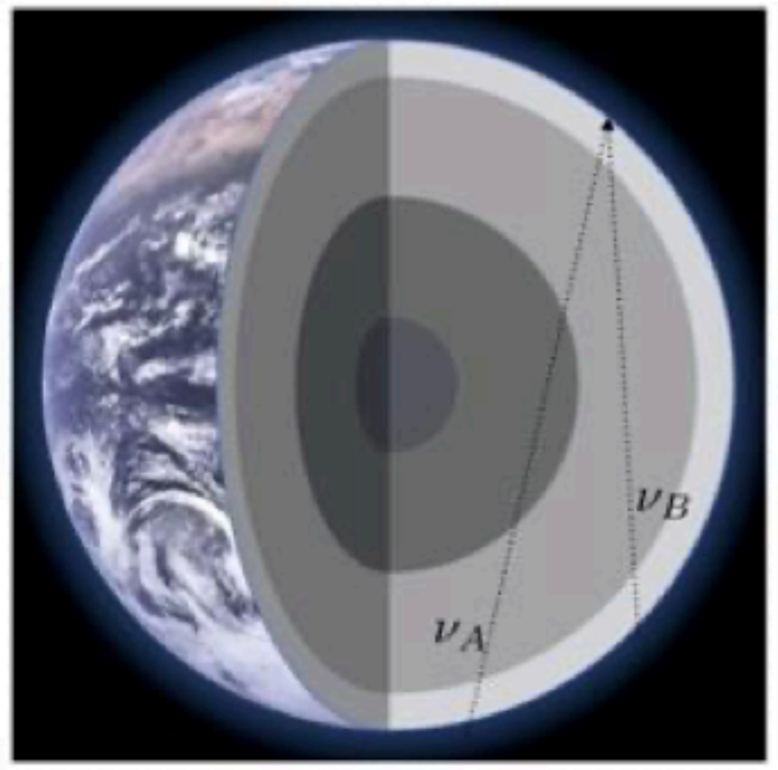
Claudio Giganti: “T2K experiment status and plans” - For the T2K Collaboration, Neutrino24

Motivation of the joint fit between Super-K atmospheric and T2K data

Atmospheric neutrinos in Super-K

- Resonance in earth mantle and core in Multi-GeV region, only for neutrinos in normal and anti-neutrinos in inverted mass ordering (MO)
- SK Atmospheric neutrinos are sensitive to MO

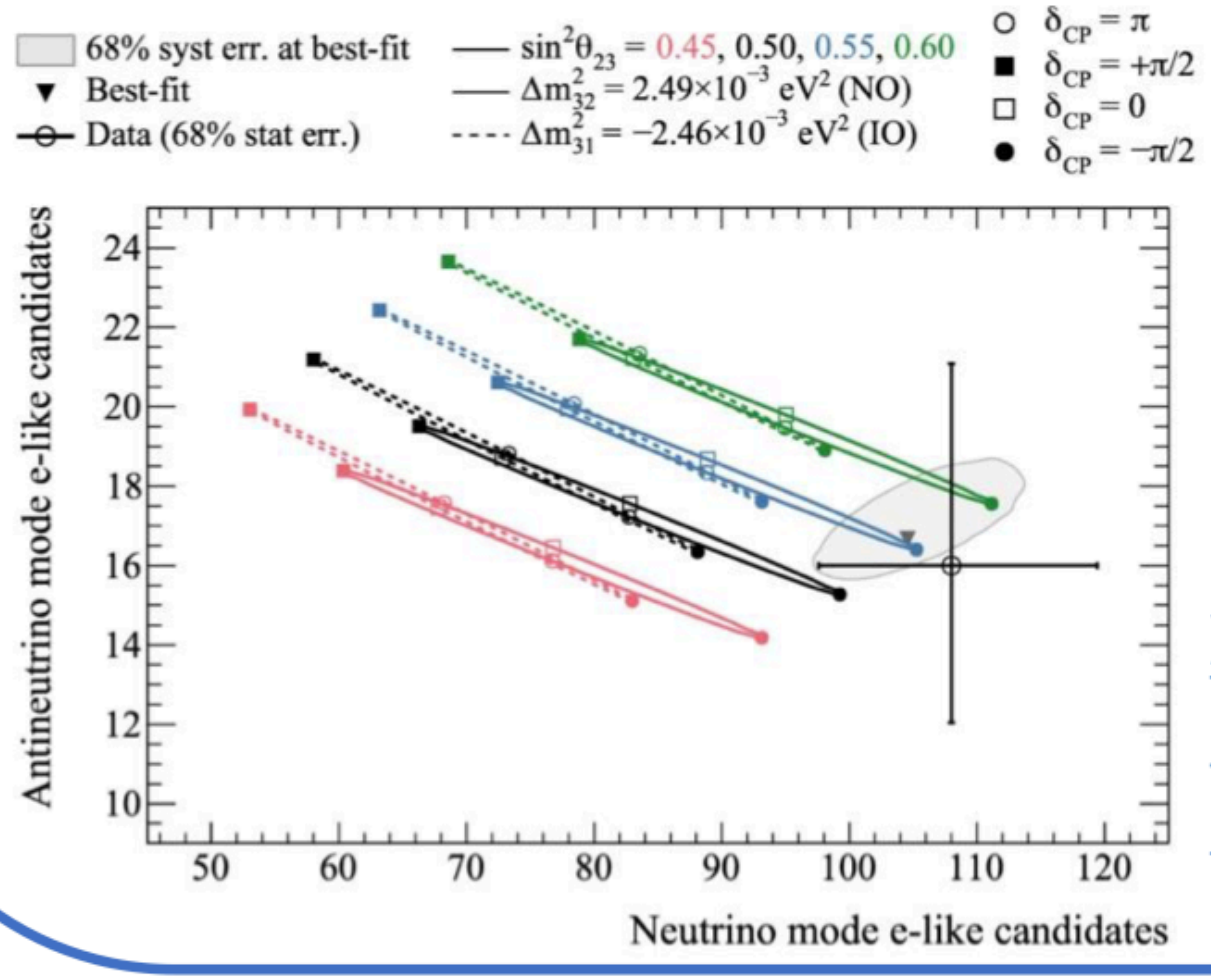




*Plots from C. Bronner @ PANE 2018

Accelerator neutrinos in T2K

- T2K has better sensitivity to δ_{CP} from ν_e appearance channel, and to $\Delta m^2_{32}, \theta_{23}$ from ν_μ disappearance channel
- In T2K, δ_{CP} and MO have similar effect on the $\nu_e/\bar{\nu}_e$ event rates (degeneracy of oscillation parameters)



*Plots from Eur.Phys.J. C 83 (2023) 9, 782

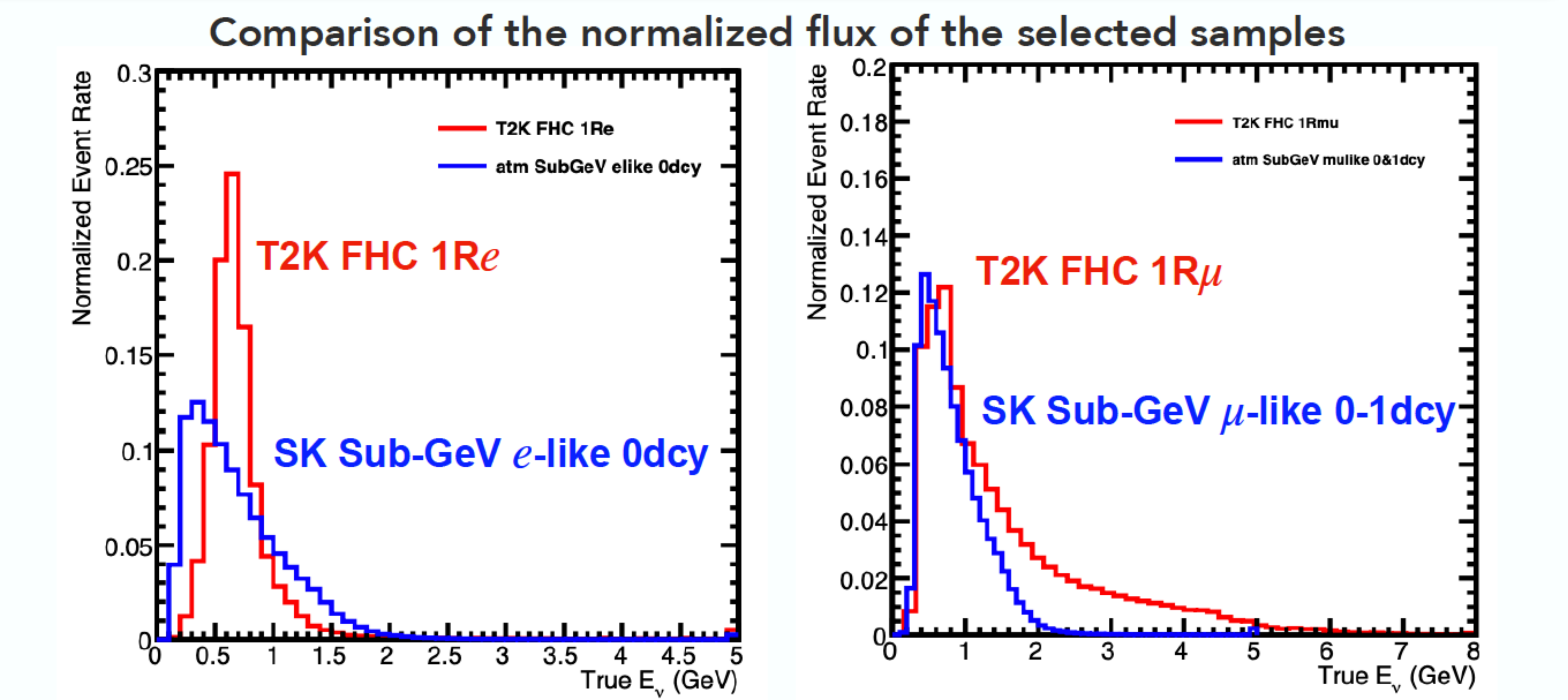
Zhenxiong Xie: “Joint analysis of the Super-Kamiokande atmospheric and T2K data” - For the T2K Collaboration, HEPP 2024

SK +T2K joint fit analysis

- 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

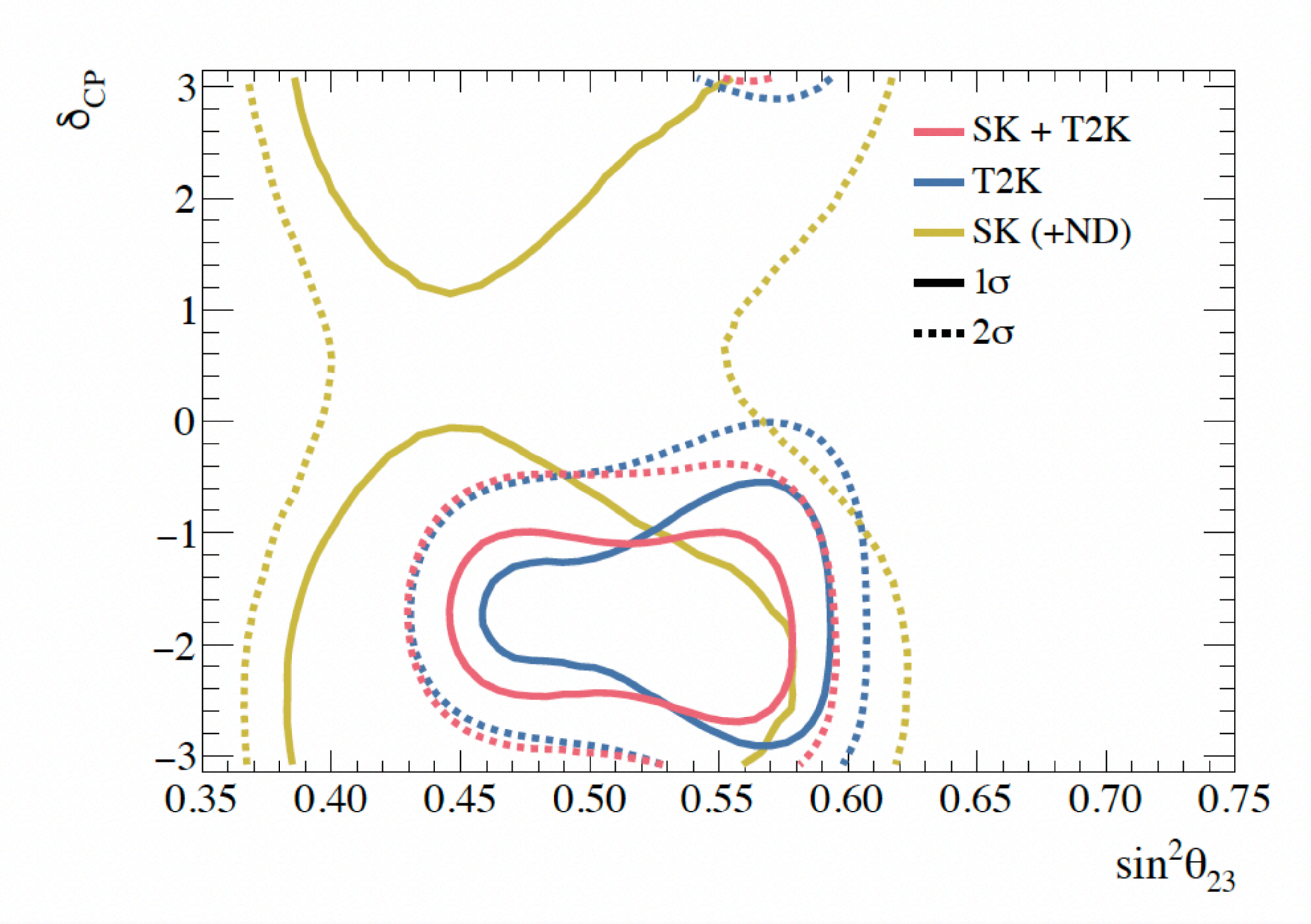
Paper is now on the arXiv [2405.12488]

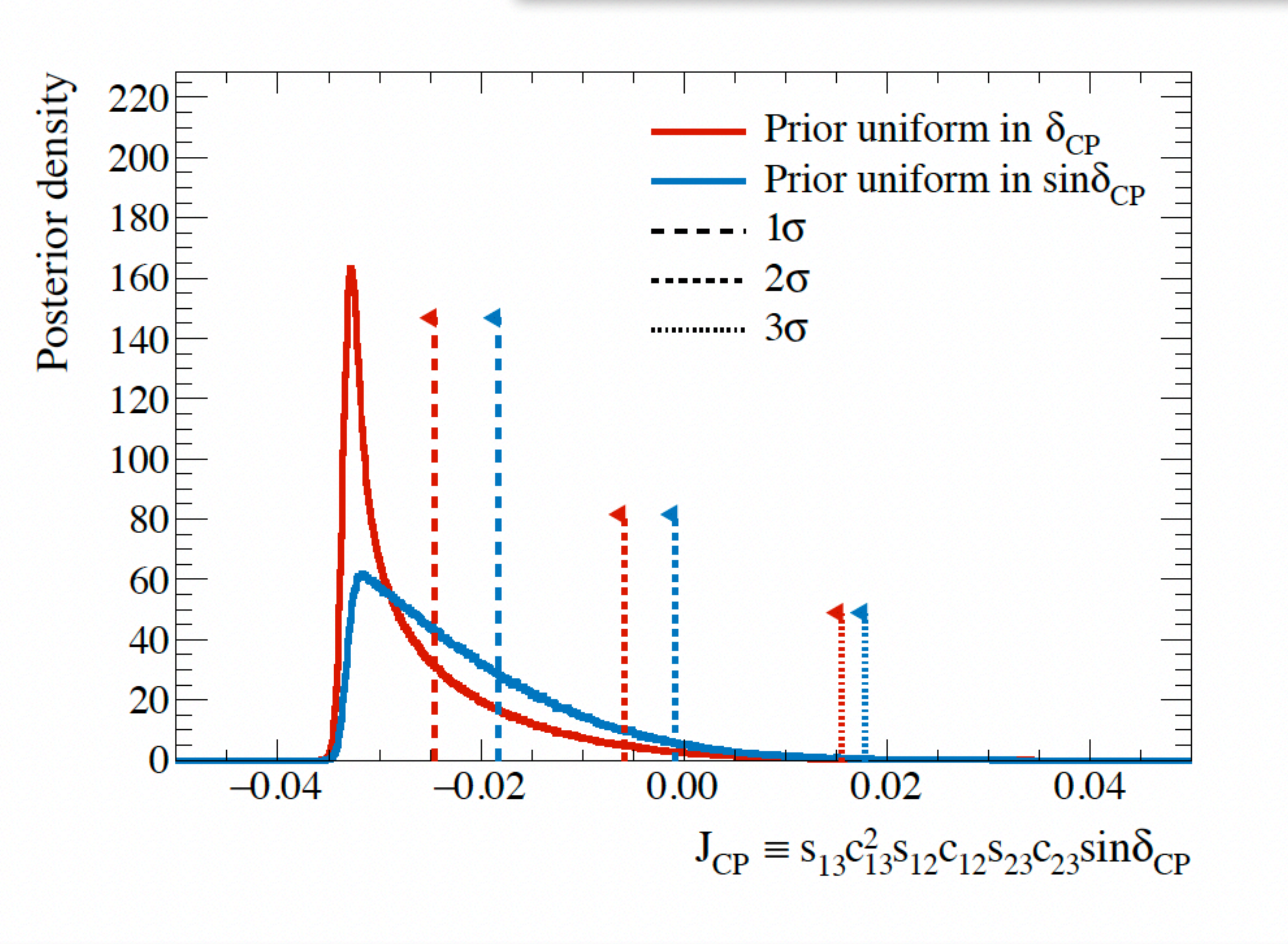
- SK4 data - 3244 days (2008-2018) - PTEP, 5, 053F01, (2019)
- T2K data published in Phys. Rev. D 108, 7, 072011, (2023)
- Future updates will include full SK atm statistics at least 50% more data and more data from T2K


Comparison of the normalized flux of the selected samples

SK +T2K joint fit results

https://arxiv.org/pdf/2405.12488 (2024)





The results show:

- Jarlskog invariant J_{CP}=0 is excluded at 2.0 σ (1.9 σ) for prior in flat δ_{CP} (for prior in flat $\sin\delta_{CP}$)
- a limited preference for the normal ordering,
- and no strong preference for the θ_{23} octant.

Joint fits (2):
Accelerator + accelerator neutrinos

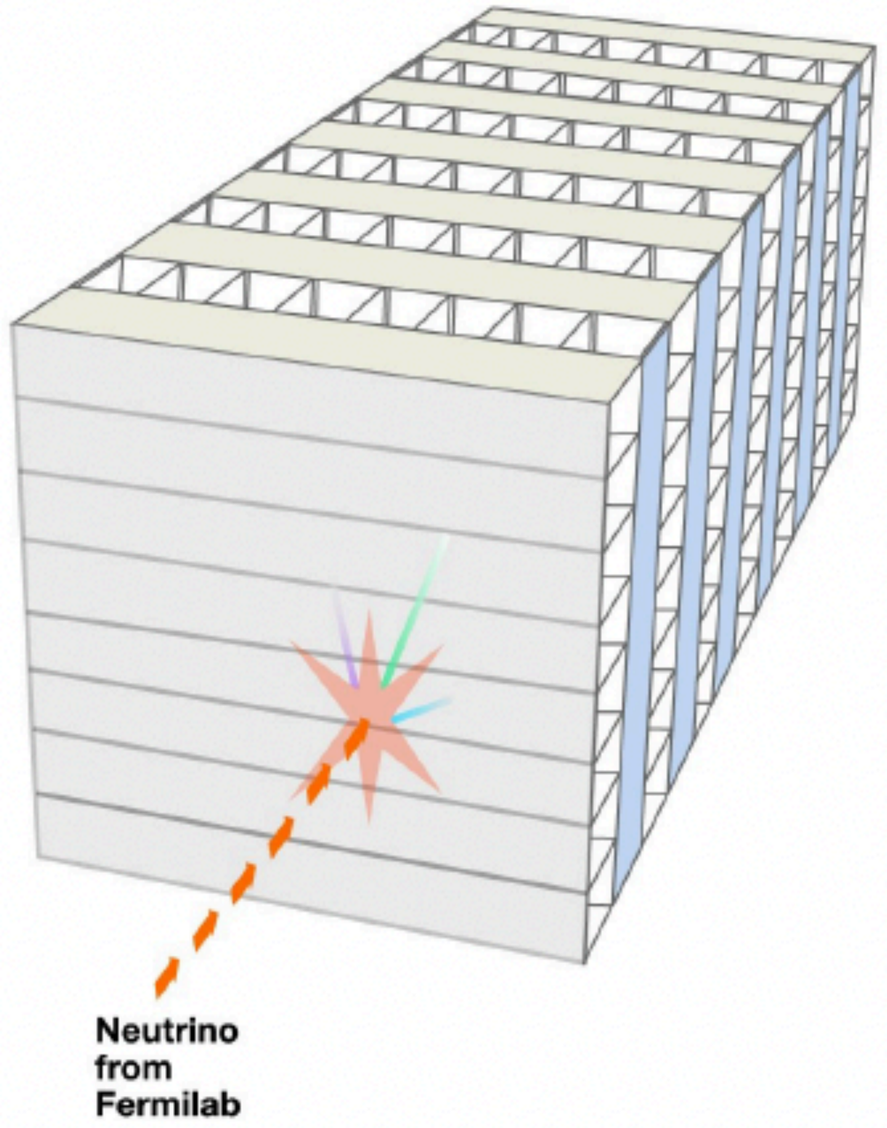
NOvA and T2K are complementary

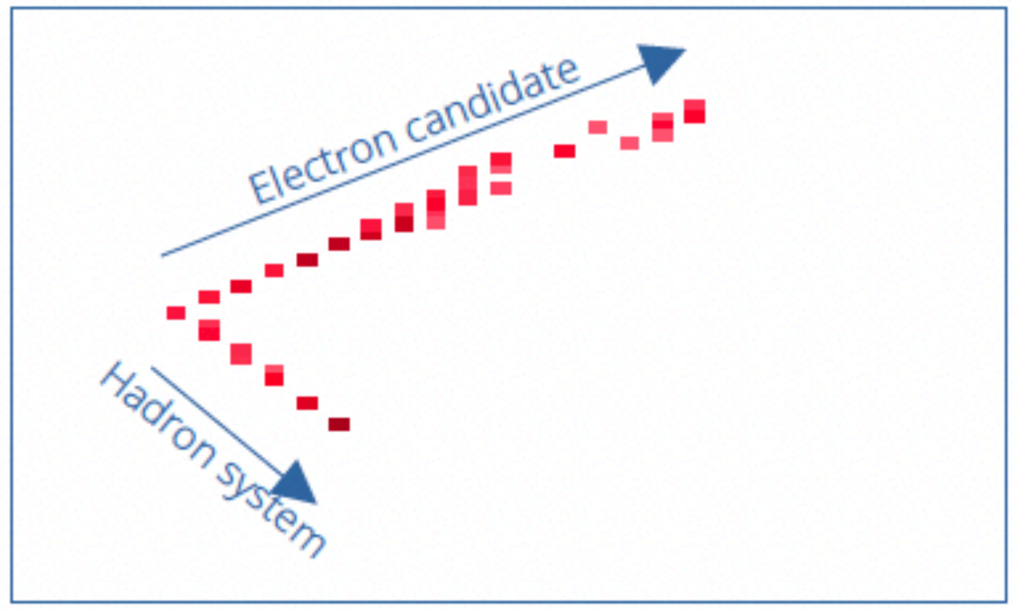
Compared to T2K*, NOvA uses

a different experimental approach

NOvA

active scintillator calorimeters





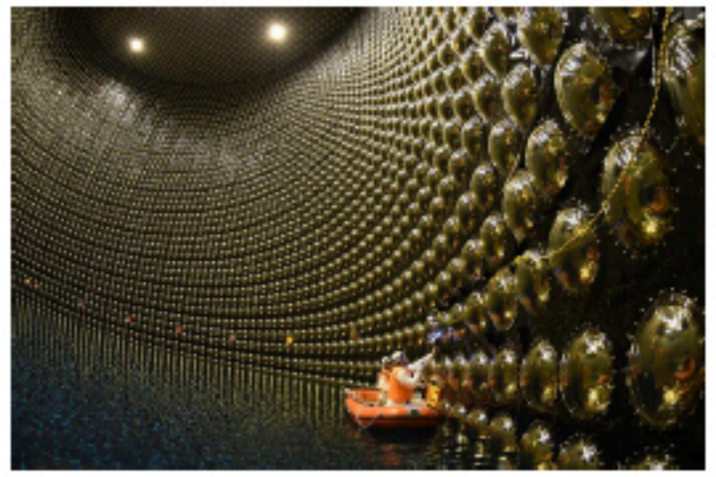
see significant energy from both lepton and hadron systems: "calorimetric" E_ν reconstruction

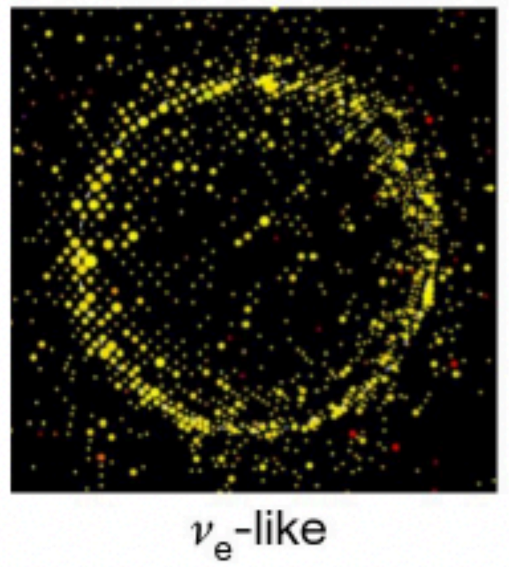
& functionally equivalent detectors

shared uncertainties mostly cancel

T2K

water Cherenkov FD





see only lepton energy: "kinematic" E_ν reconstruction

Hybrid gas TPC & scintillator tracker ND

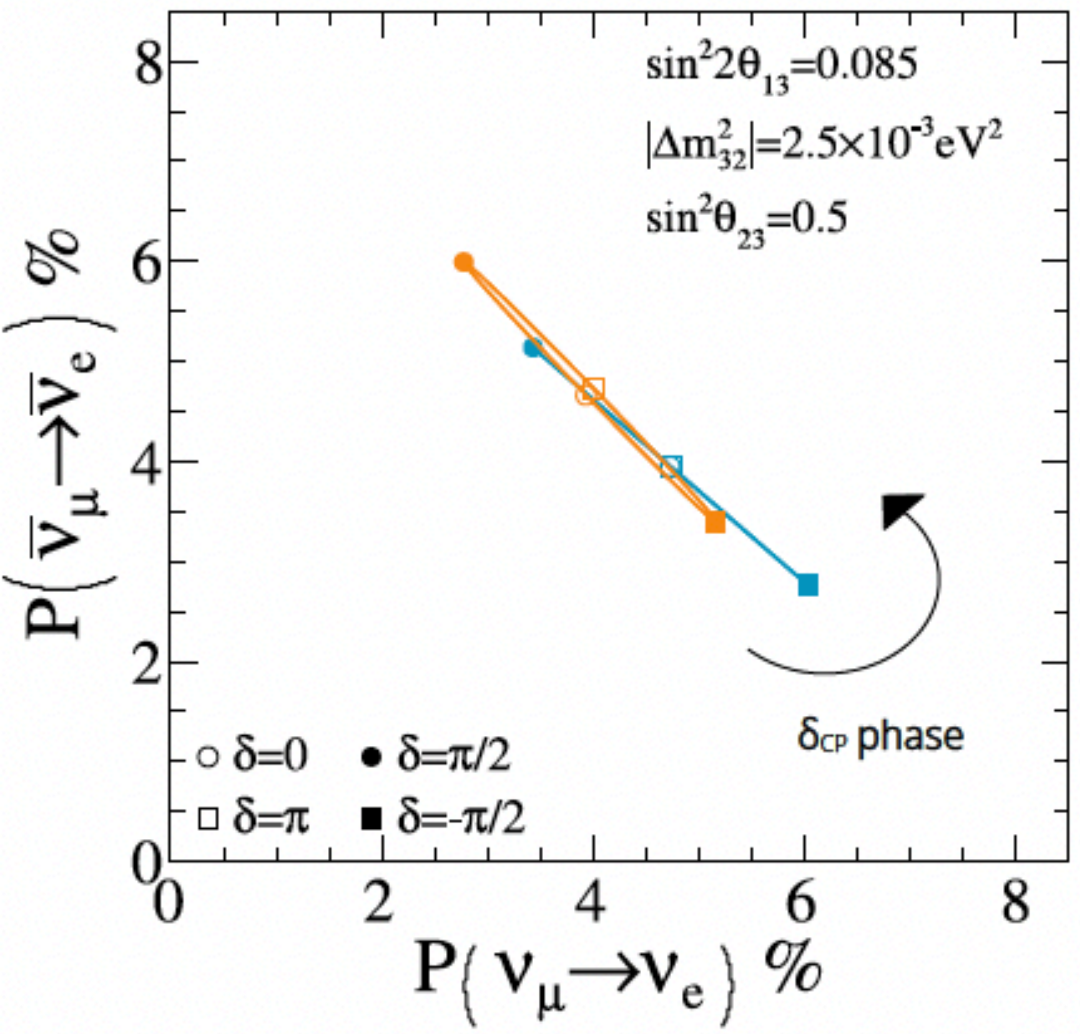
ND+FD shared uncertainties explicitly fitted & constrained via model

Jeremy Wolcott "New NOvA Resultswith 10 Years of Data" - For the Nova Collaboration, Neutrino24

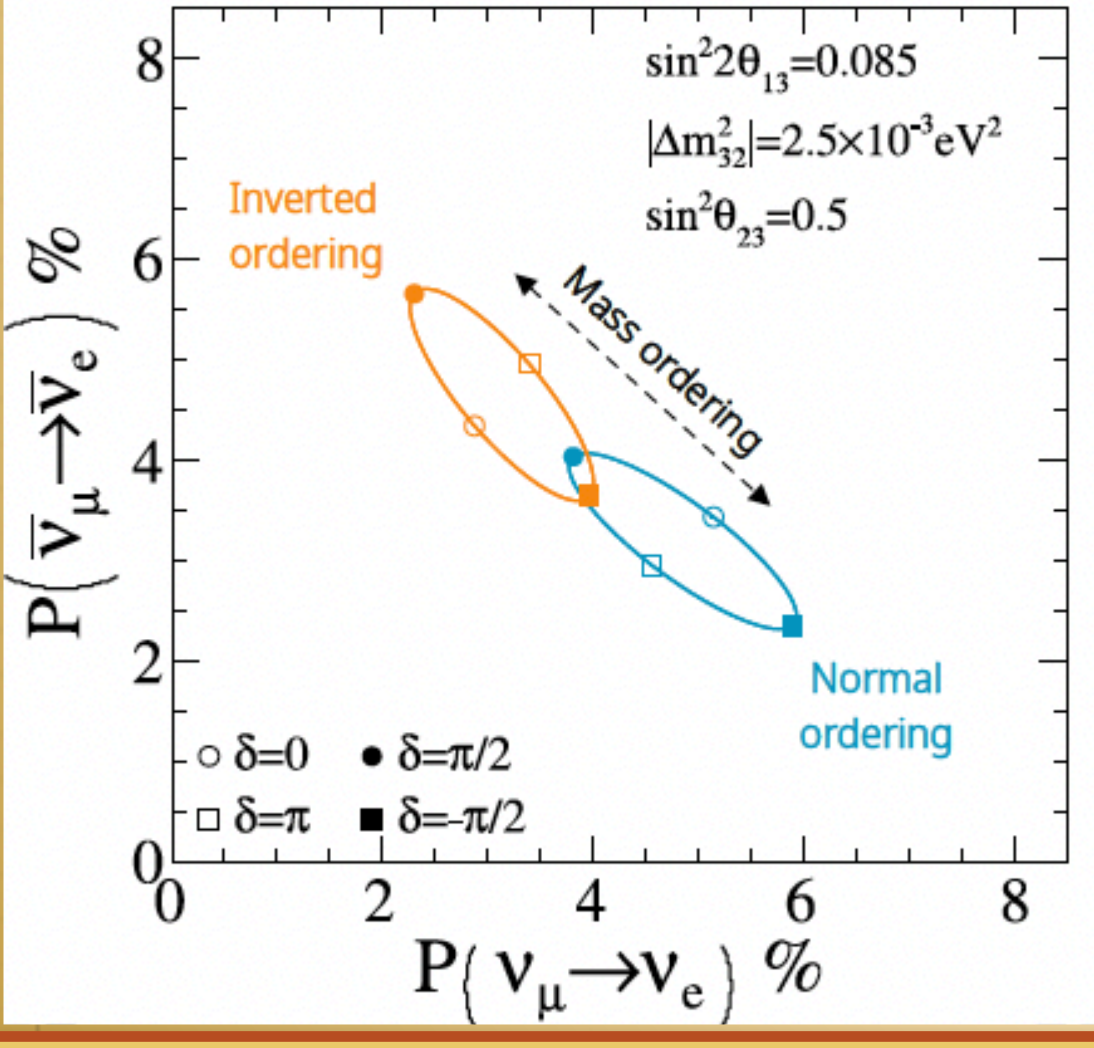
NOvA/T2K E$_\nu$ differences: implications

NOvA has larger matter effects

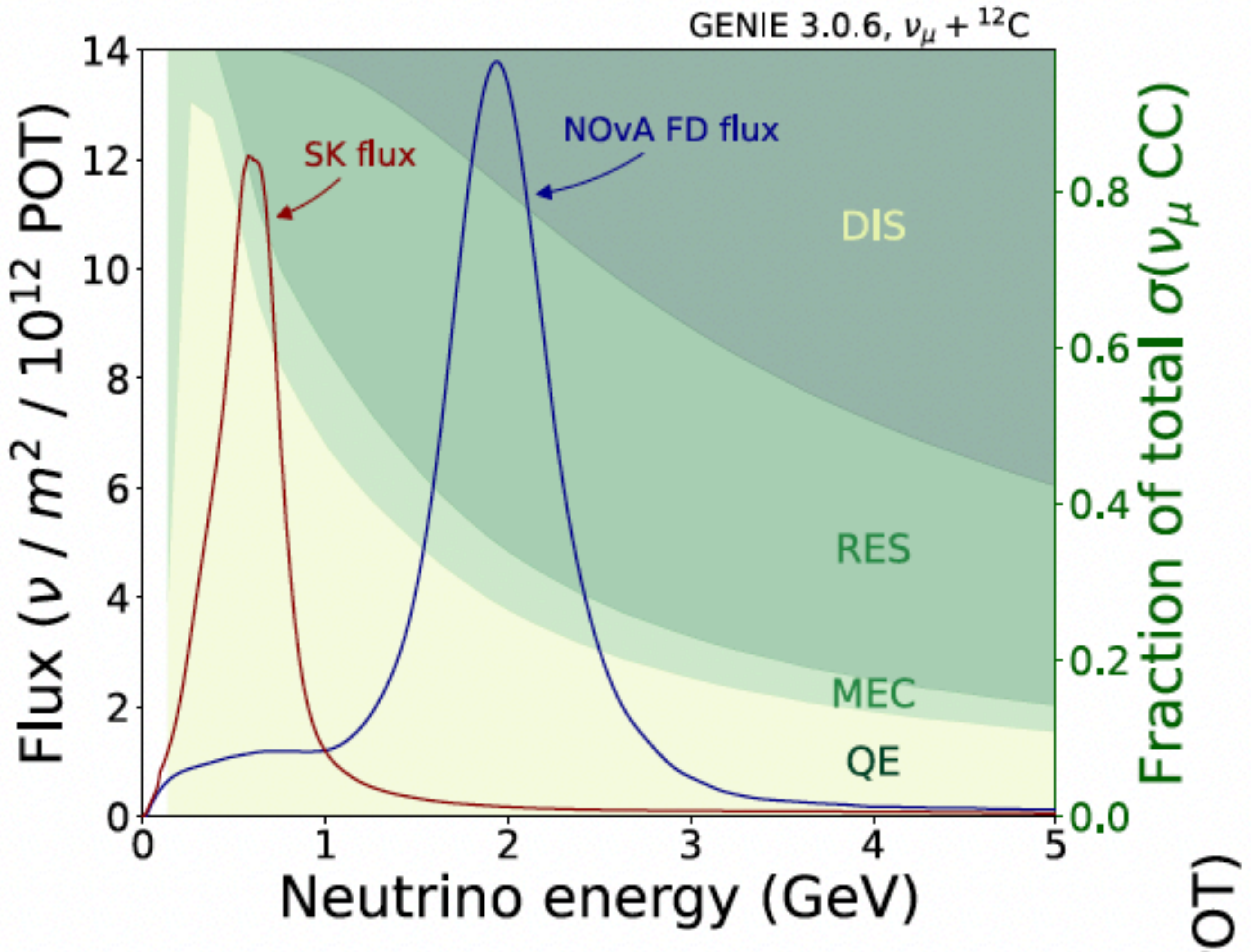
T2K: L=295 km, E=0.6 GeV



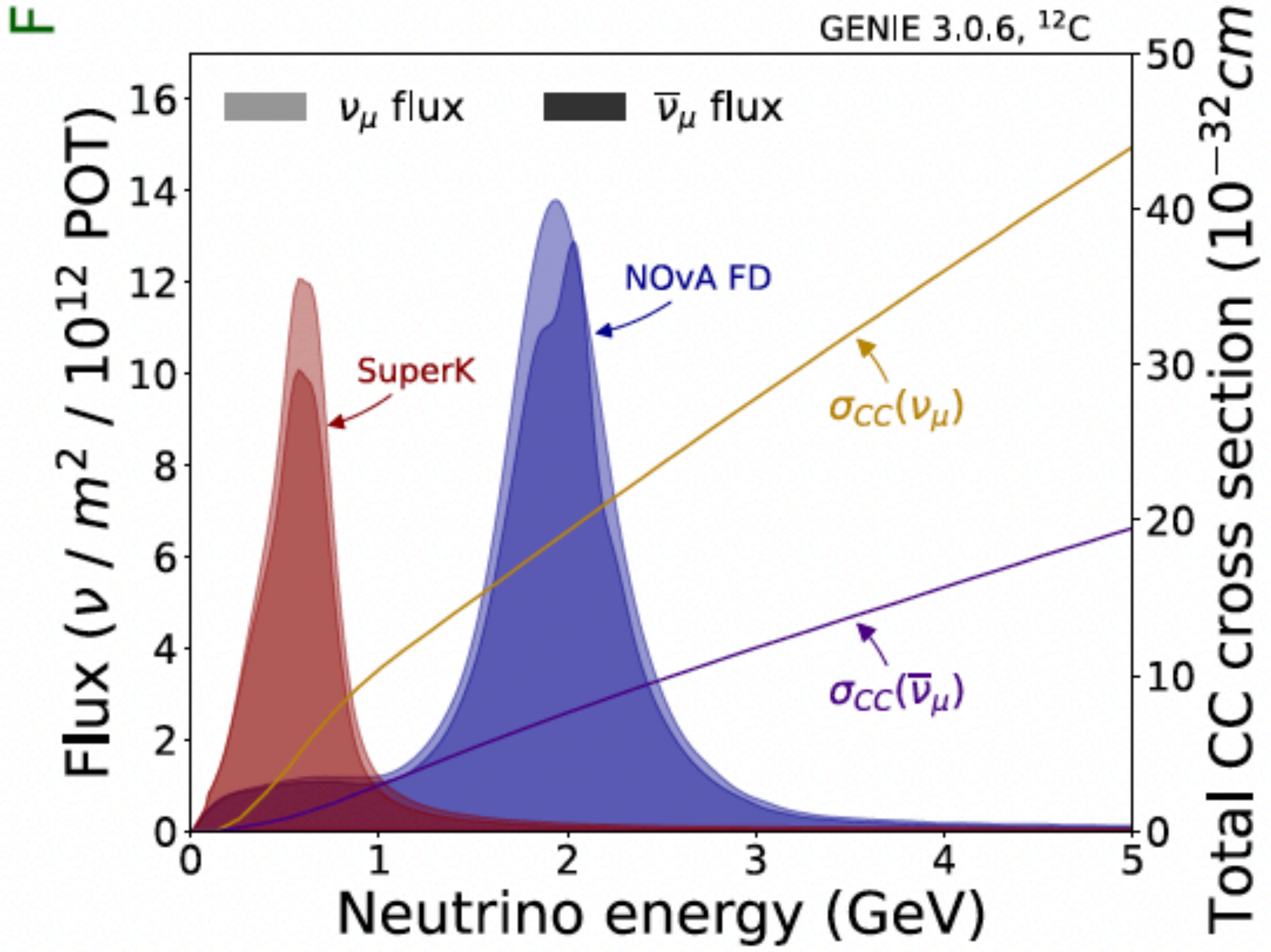
NOvA: L=810 km, E=2.0 GeV



NOvA has more final-state pions



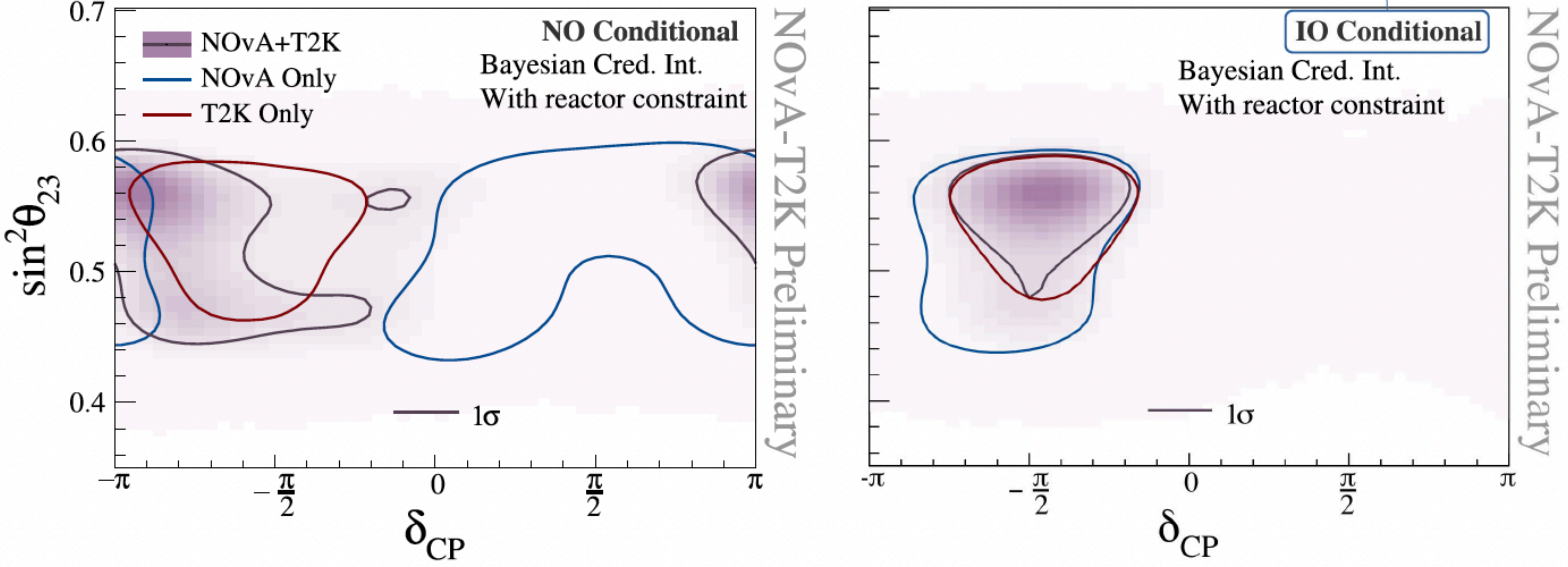
NOvA sees more antineutrinos



NOvA-T2K joint fit: PMNS parameters

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)

“assuming IO is true”
(does not include relative probability of IO vs. NO)

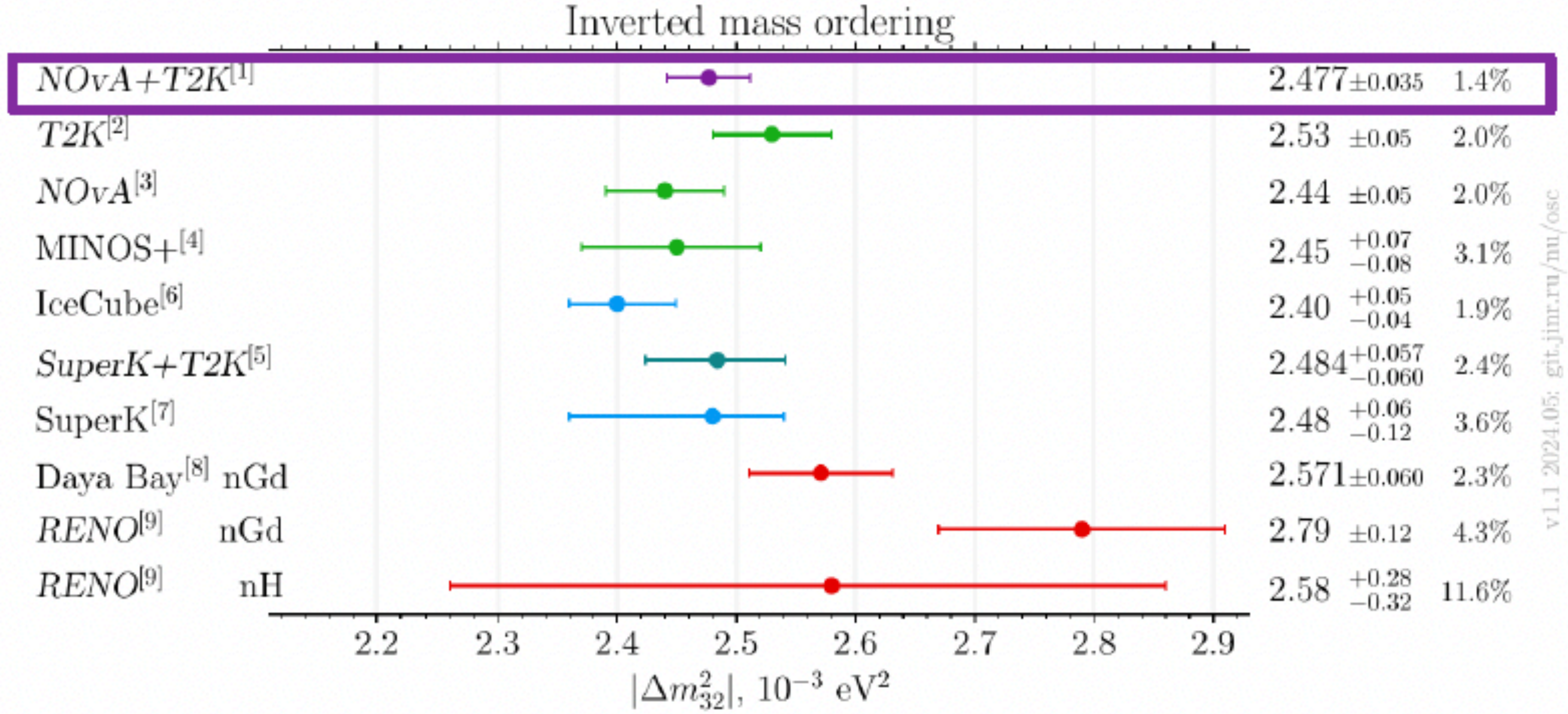


Joint fit splits the difference b/w NOvA-only & T2K-only in NO; improves constraint in IO

NOvA-T2K joint fit: takeaways

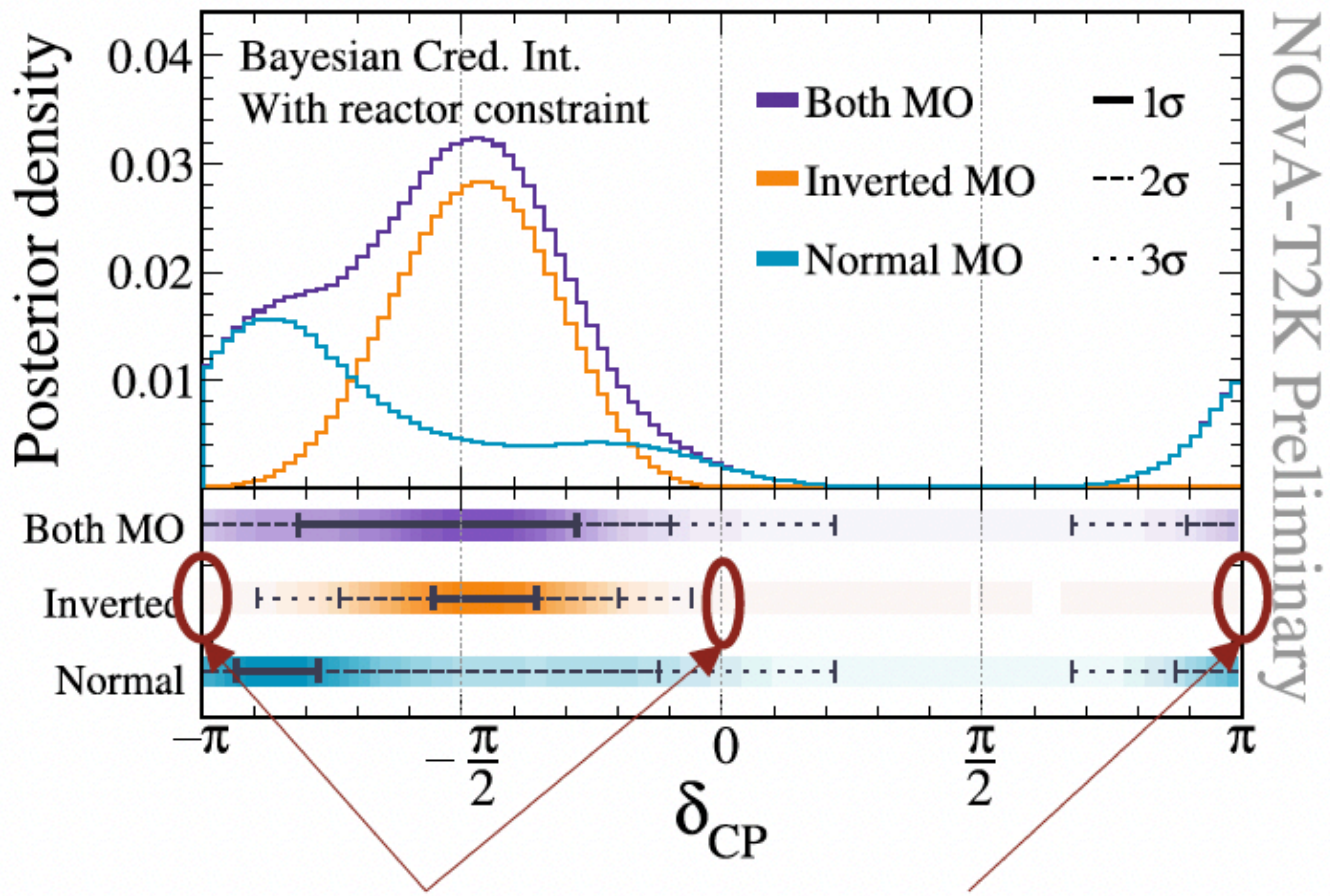
Advancing the precision frontier on $|\Delta m^2_{32}|$

<2% measurement!



Mild preference for Inverted Ordering but **influenced by θ₁₃ constraint**

NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)



CP-conserving points are *outside* 3σ intervals in IO

Expect CPV *if* ordering is inverted

Astrophysical neutrino(s)

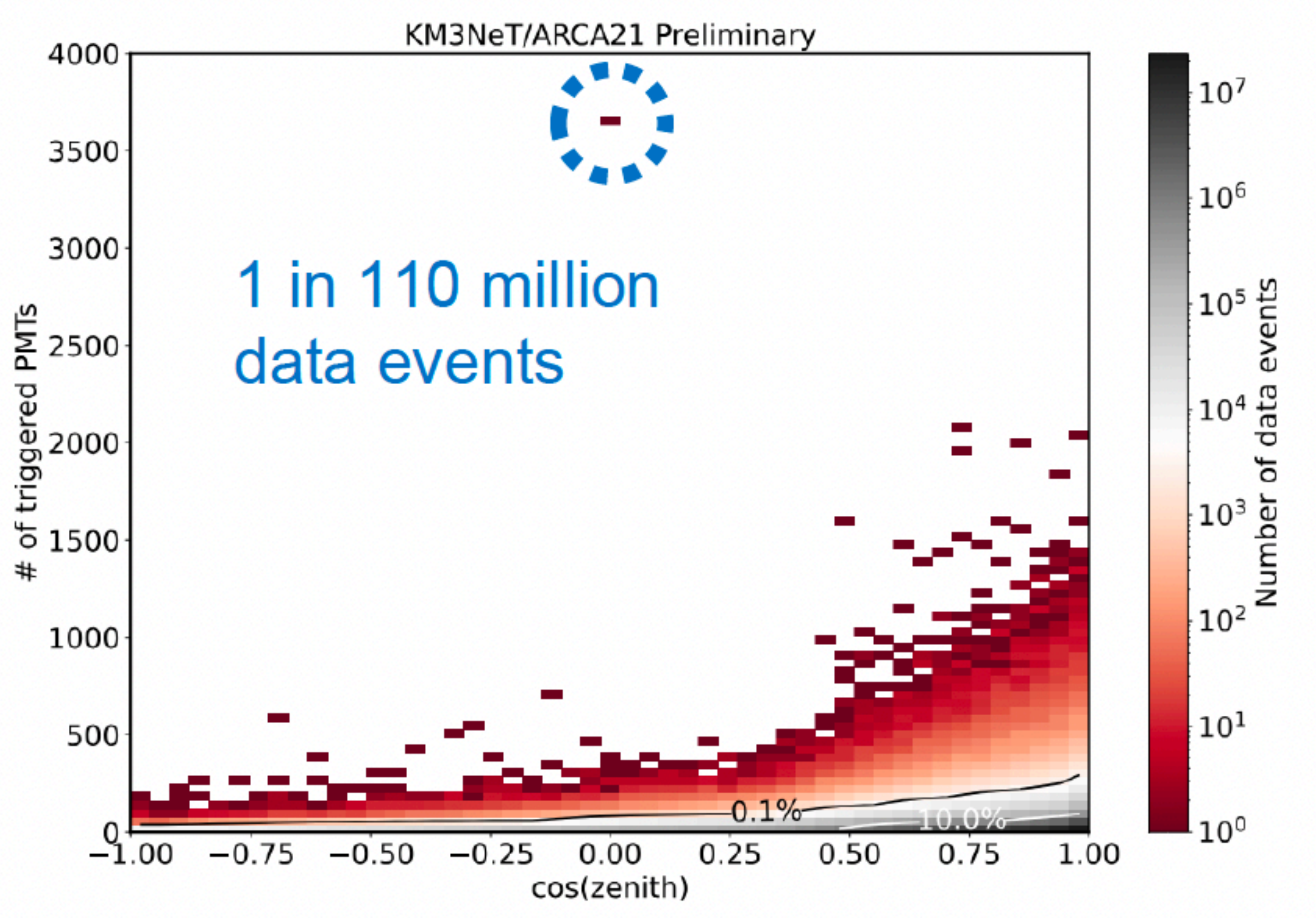
Uncharted Territory

At the highest energies, there's darkness…

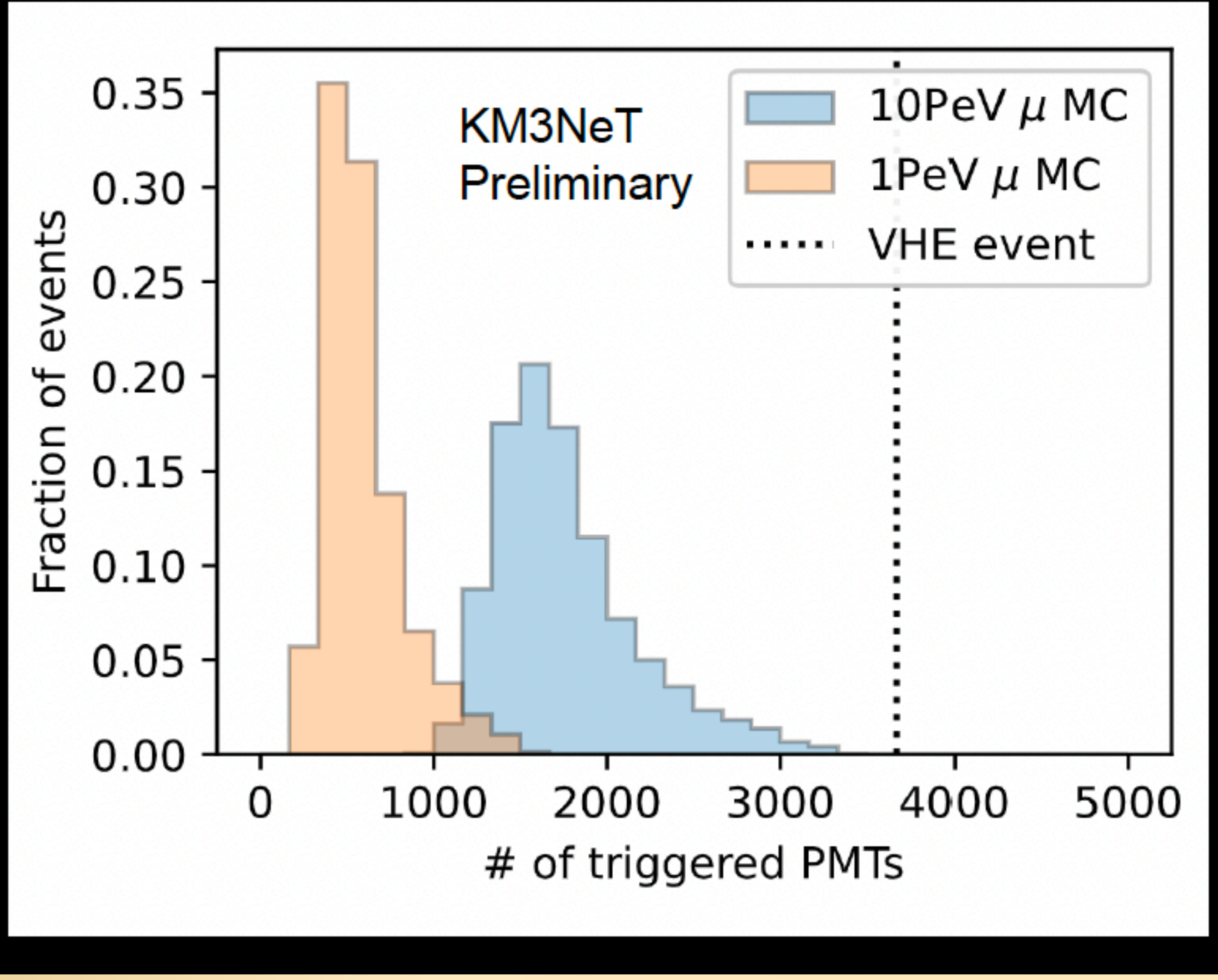
Astrophysical neutrino(s)

Uncharted Territory

- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV

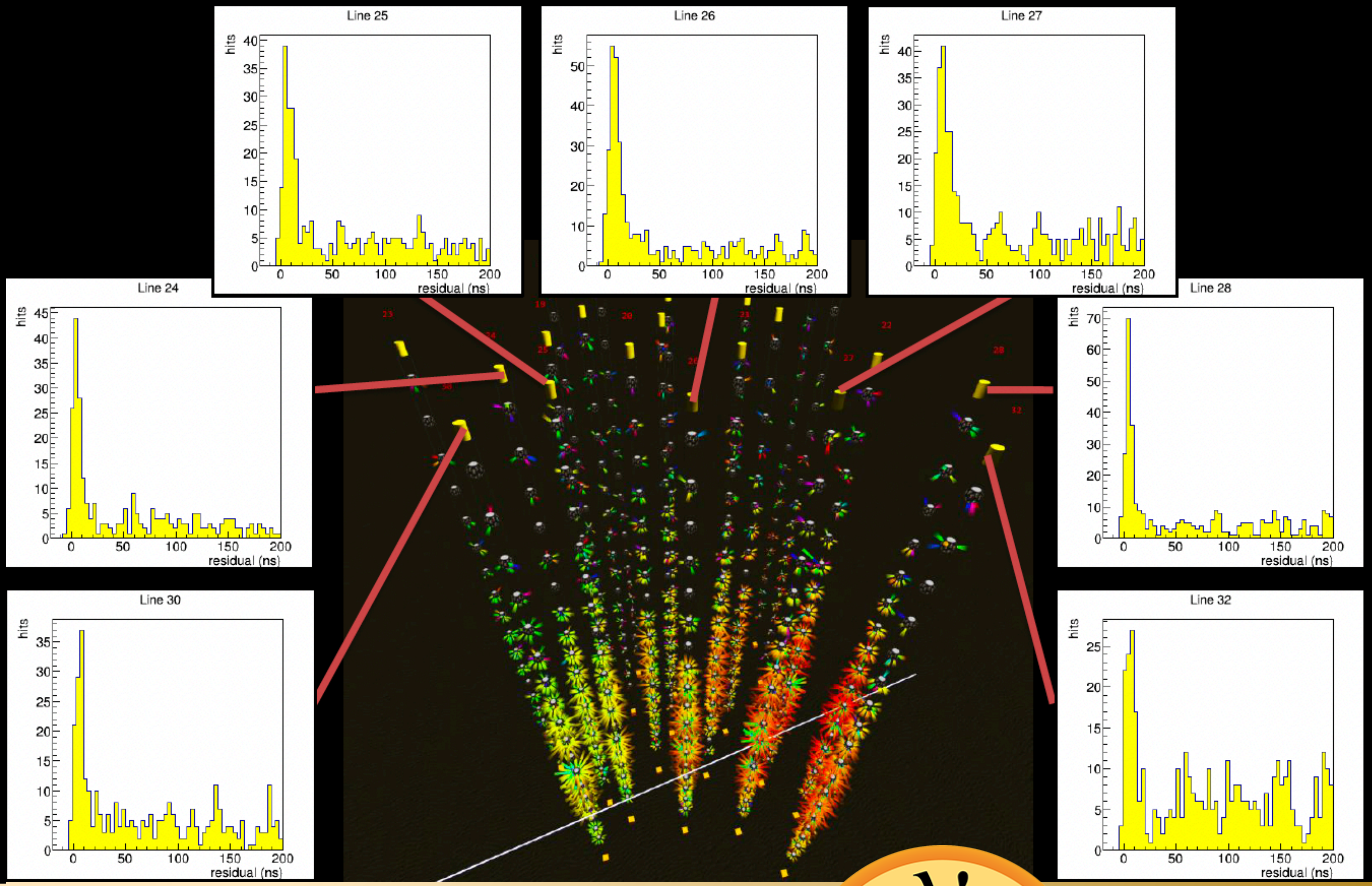


1 in 110 million data events



Uncharted Territory

- Event is well reconstructed as a high energy muon crossing entire ARCA21 detector



Summary slides

SUMMARY OF OSCILLATION RESULTS FOR THREE ACTIVE ν TYPES

Particle Data Group

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$

Solar, Reactor

$\sin^2(\theta_{23}) = 0.539 \pm 0.022 \quad (S = 1.1) \quad$ (Inverted order)

$\sin^2(\theta_{23}) = 0.546 \pm 0.021 \quad$ (Normal order)

$\Delta m^2_{32} = (-2.536 \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Inverted order)

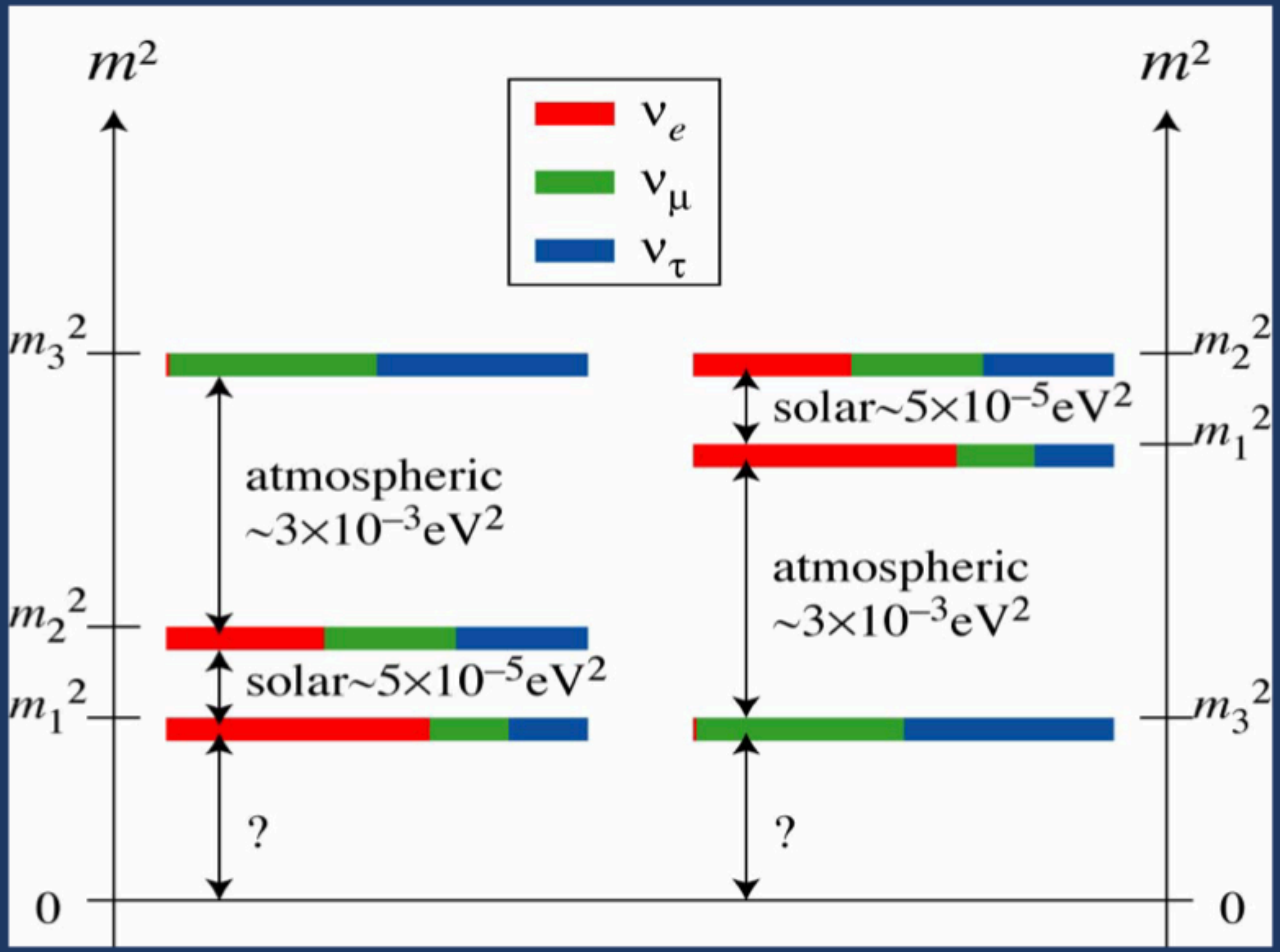
$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Normal order)

Atmospheric,Accelerator

$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

Reactor, Accelerator

Mass Hierarchies



Normal Inverted

Future objectives:

- δ_{CP}
- θ_{23} max?
- Hierarchy?
- Majorana ν?
- Absolute mass
- Sterile ν?

Accelerator,Reactor, Atmospheric

0νββ, Cosmology, Electron spectrometers,

Accelerator,Reactor, Atmospheric

Art McDonald “Where are we and where are we going?” - Neutrino24

FUTURE :)

- Wideband (anti)neutrino beamline with
- Underground, modular LArTPC Far Det
- Movable LArTPC Near Detector with mu separate on-axis det
- Global collaboration

5 DUNE - Neut

The

- KM3NeT is building a s
- The KM3NeT DOMs ar

Jiangmen Underground Neutrino Observatory (JUNO)

- Proposed as a reactor neutrino experiment for **mass ordering** in 2008 (PRD78:111103,2008; PRD79:073007,2009)
  - ⇨ driving the design specifications: location, 20 kton LS, 3% energy resolution, 700 m underground
- Rich physics program in solar, supernova, atmospheric, geo-neutrinos, proton decay, exotic searches
- Approved in 2013. Construction in 2015-2024

74 institutions, >700 collaborators

Asia: China (34), Taiwan,China (3) Thailand (3), Pakistan, Armenia
Europe: Italy (8), Germany (7), France (5), Russia (3), Belgium, Czech, Finland, Latvia, Slovakia, UK
America: Brazil (2), Chile (2), USA (2)

Hyper-Kamiokande Project

Rich physics & discovery potential
Construction started in 2020
Operation will start in 2027

Two host institutes:

Fully funded (NSF+partners)
Deployment to occur 2025-2026

Thank you!

Photo Credit: Piotr Mijakowski

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

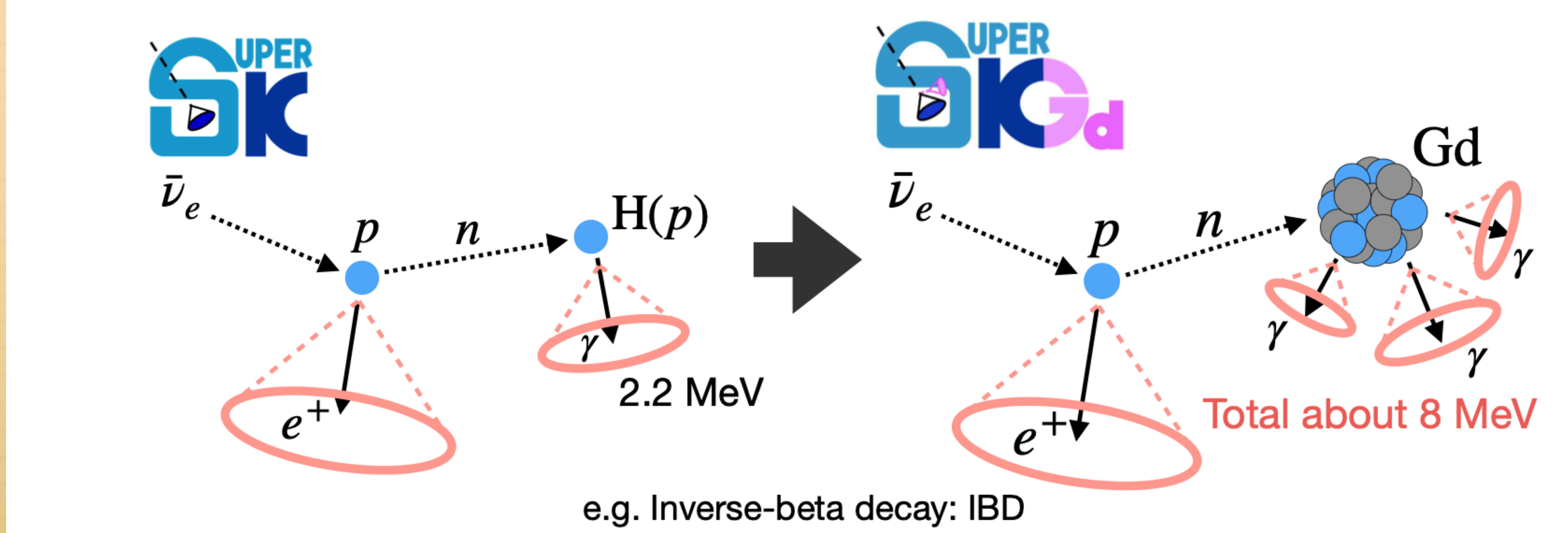
INFN Bari, Italyl
NFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
University of Minnesota, 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

SK-Gd era

Gadolinium project at Super-K: SK-Gd



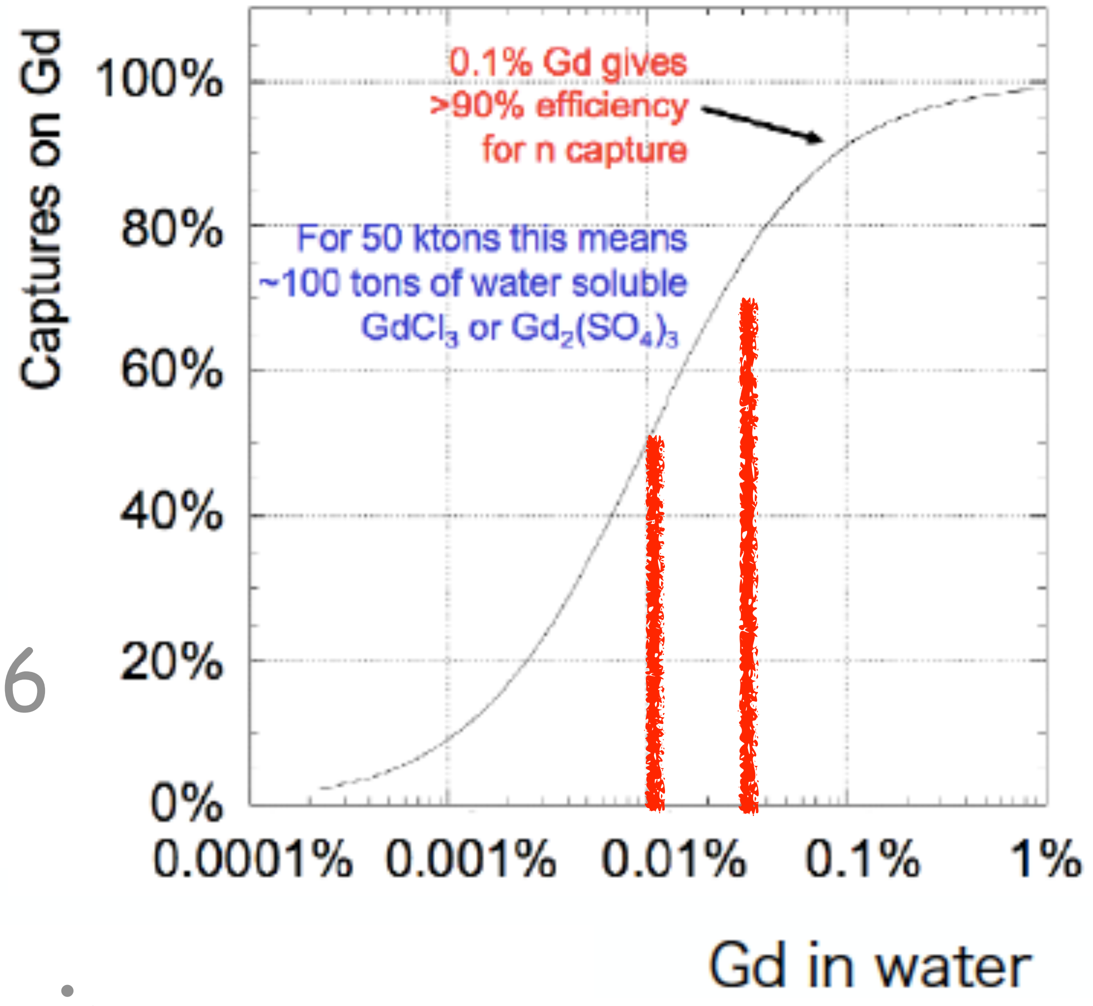
e.g. Inverse-beta decay: IBD

Why Gd salt was added ?

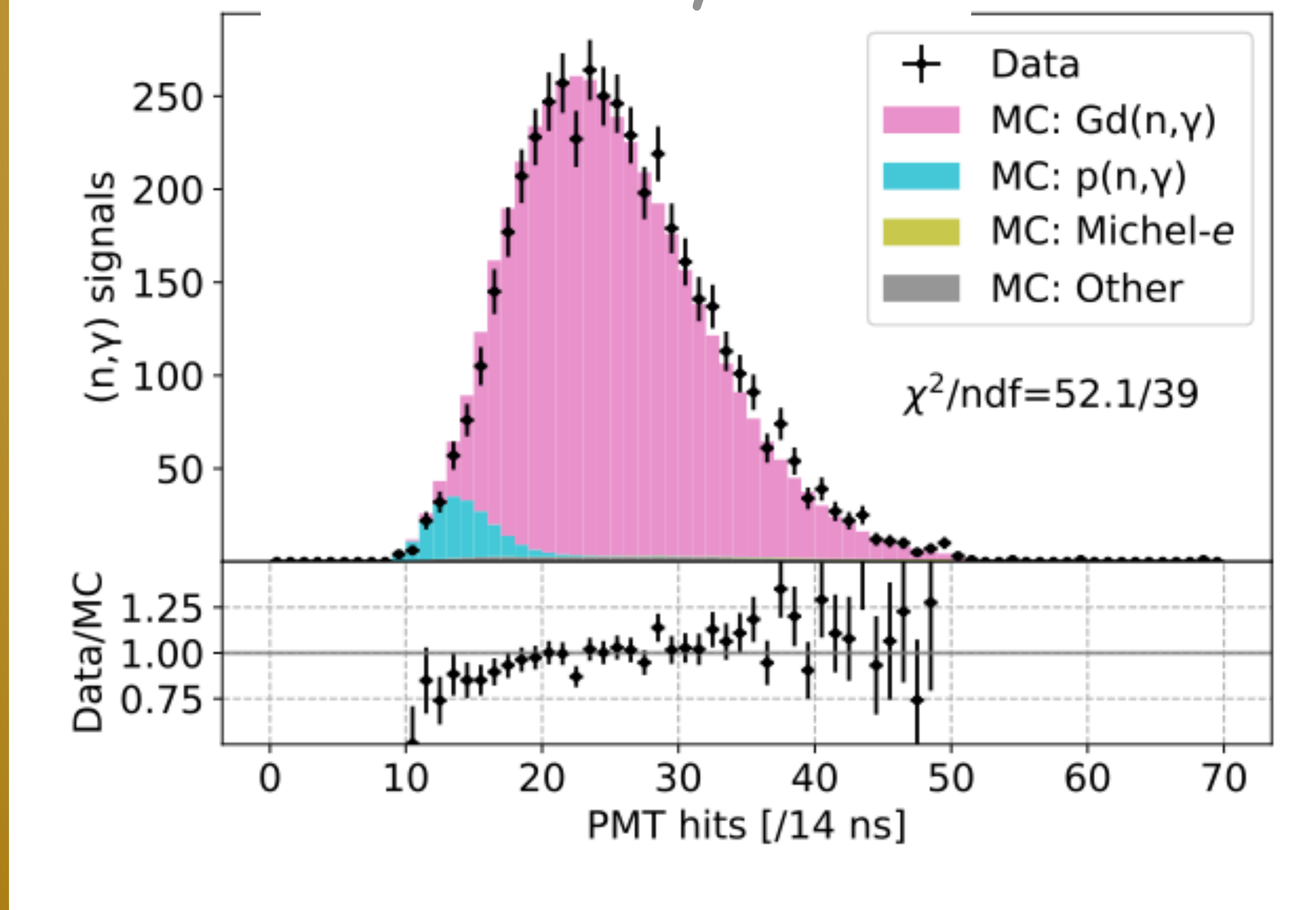
- SK-Gd: add Gd sulphate to ultra pure water to enhance neutron tagging efficiency.
- Physics targets:
  - Detection of the world's first (DSNB) -see Harada-san talk
  - Improvement of supernova direction pointing accuracy
  - Enhancement of ν and $\overline{\nu}$ identification and improvement of E_ν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

Gd: 0.01% SK6
0.03% SK7

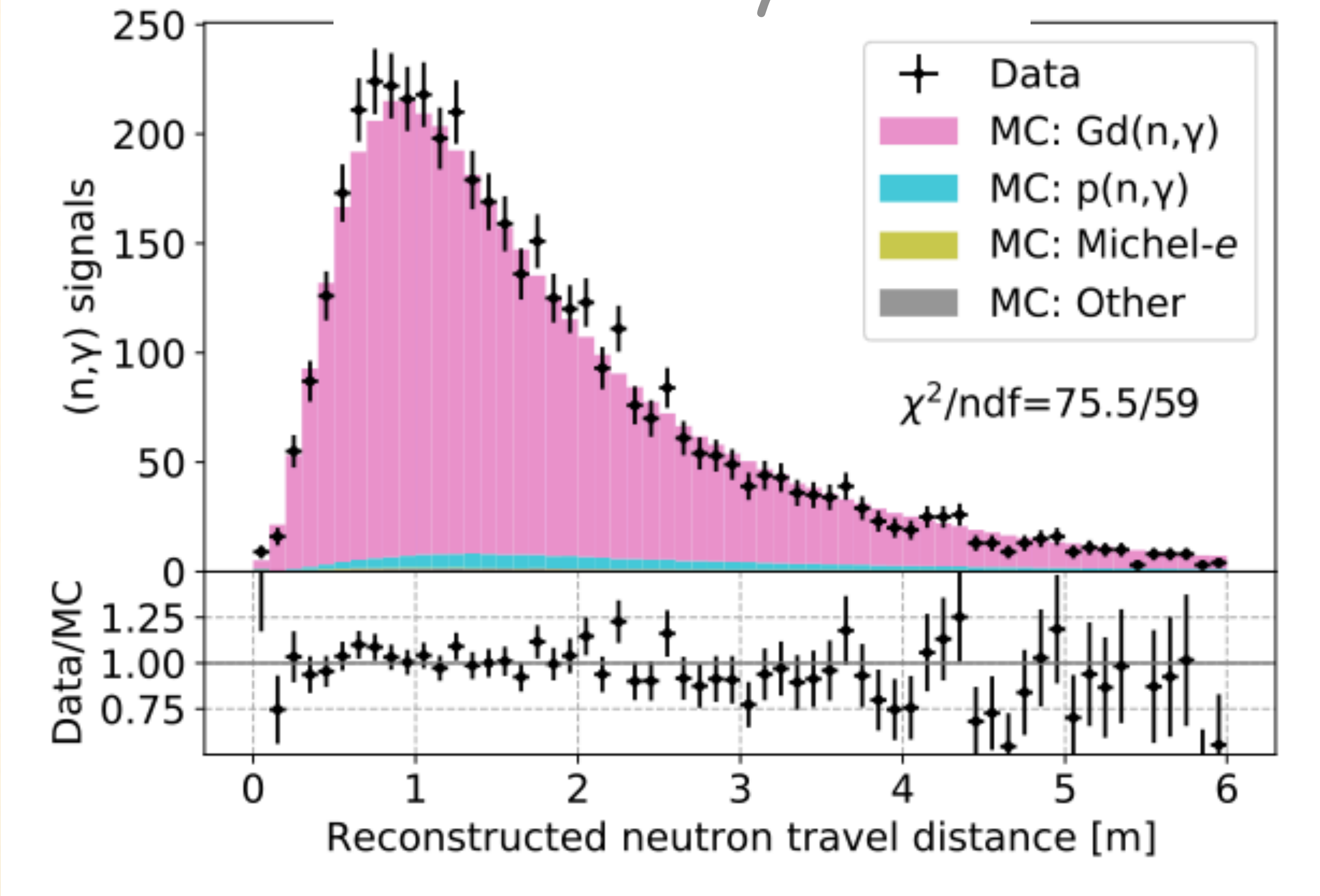
Dissolve Gadolinium into Super-K
J.Beacom and M.Vagins,
Phys.Rev.Lett.93(2004)171101



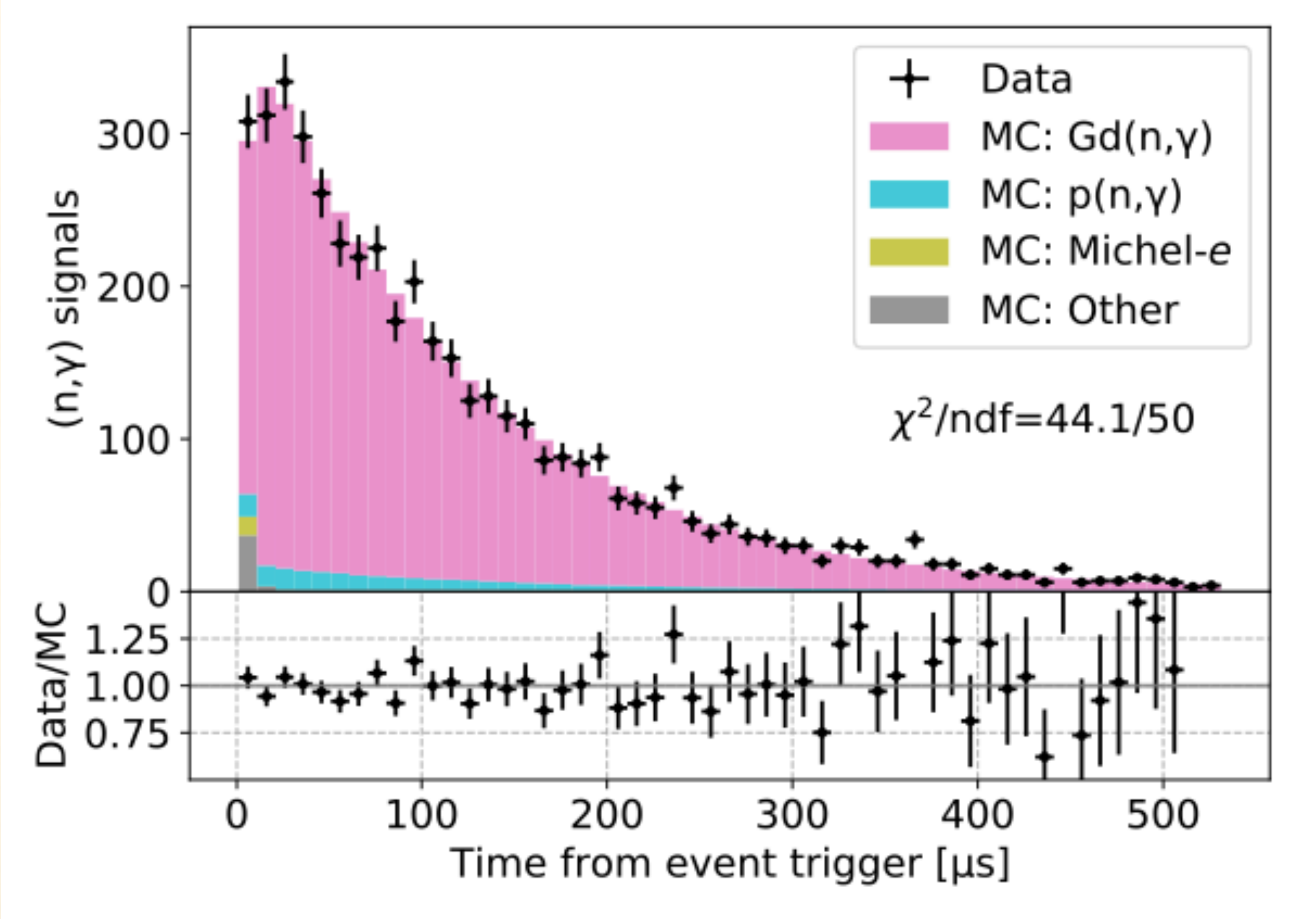
Preliminary



Preliminary



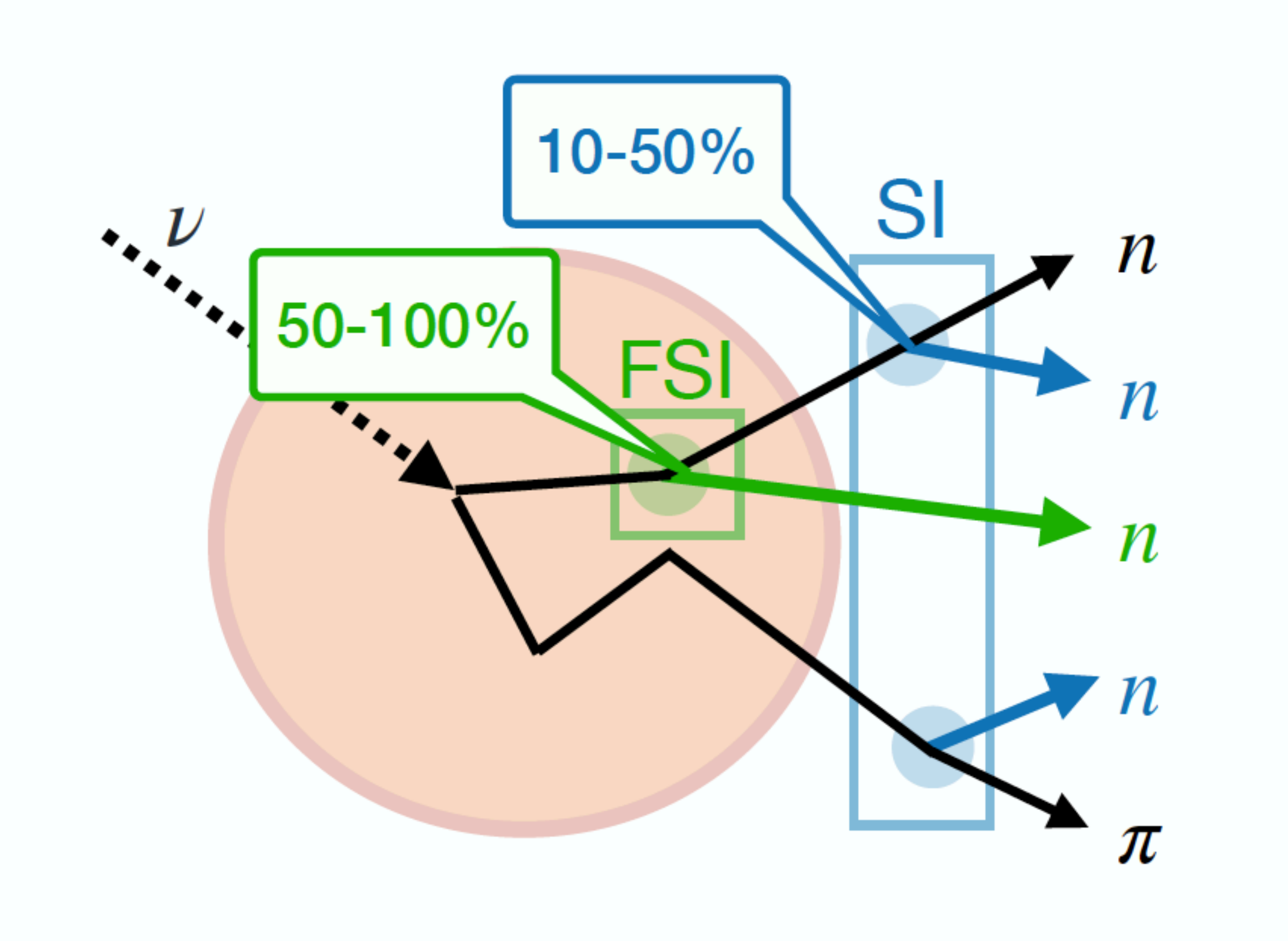
Preliminary

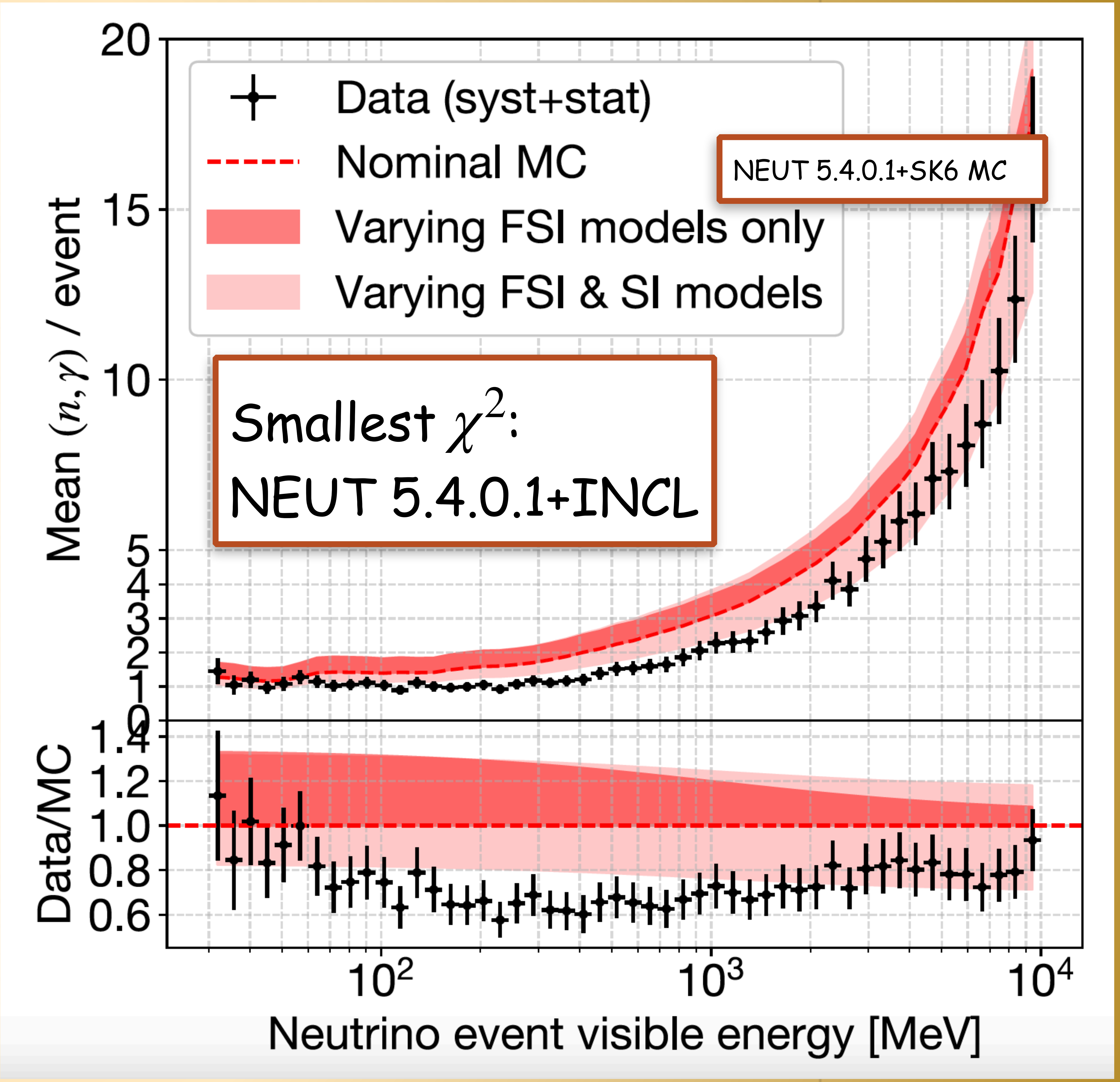


Neutrons in atmospheric ν interactions

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

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



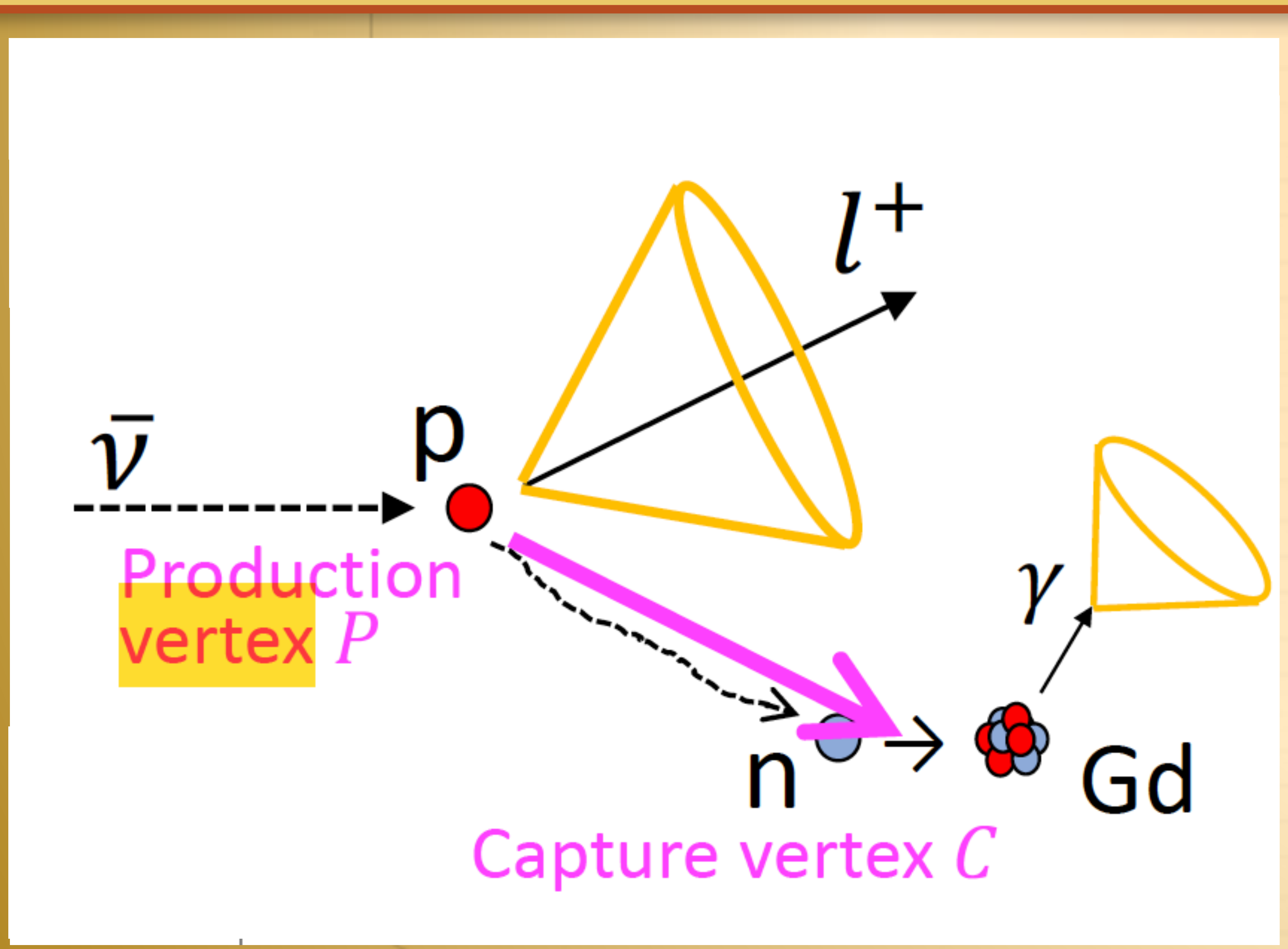


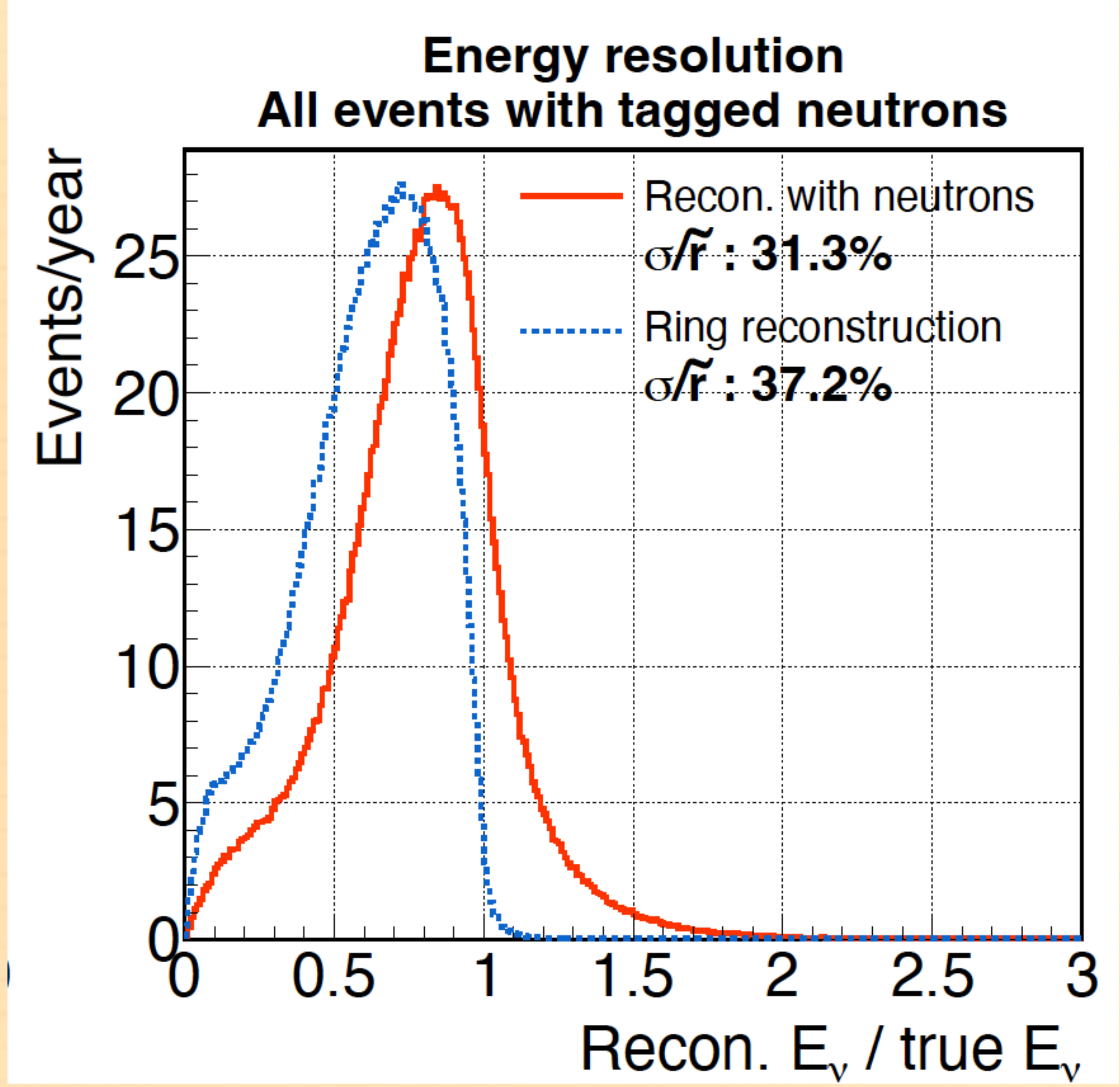
Smallest χ^2:
NEUT 5.4.0.1+INCL

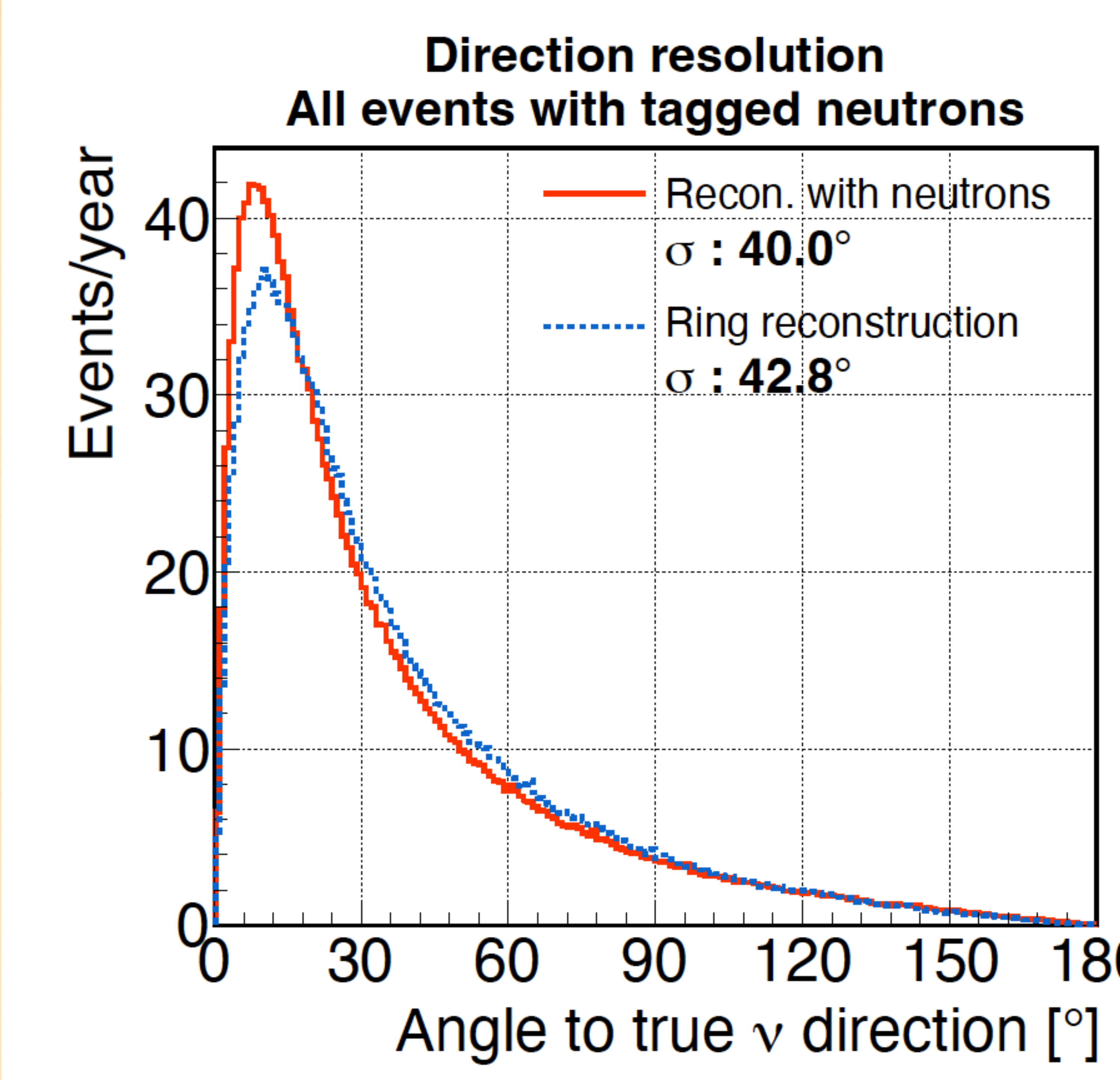
- SK4+5+6 atm. (FCFV ~12 years of data)

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 $\overrightarrow{d_\nu}$** with information on neutron momentum $\overrightarrow{p_n}$ (estimated from neutron travel distance @ the SK- assuming $\overrightarrow{p_n} \propto |\overrightarrow{PC}|$)





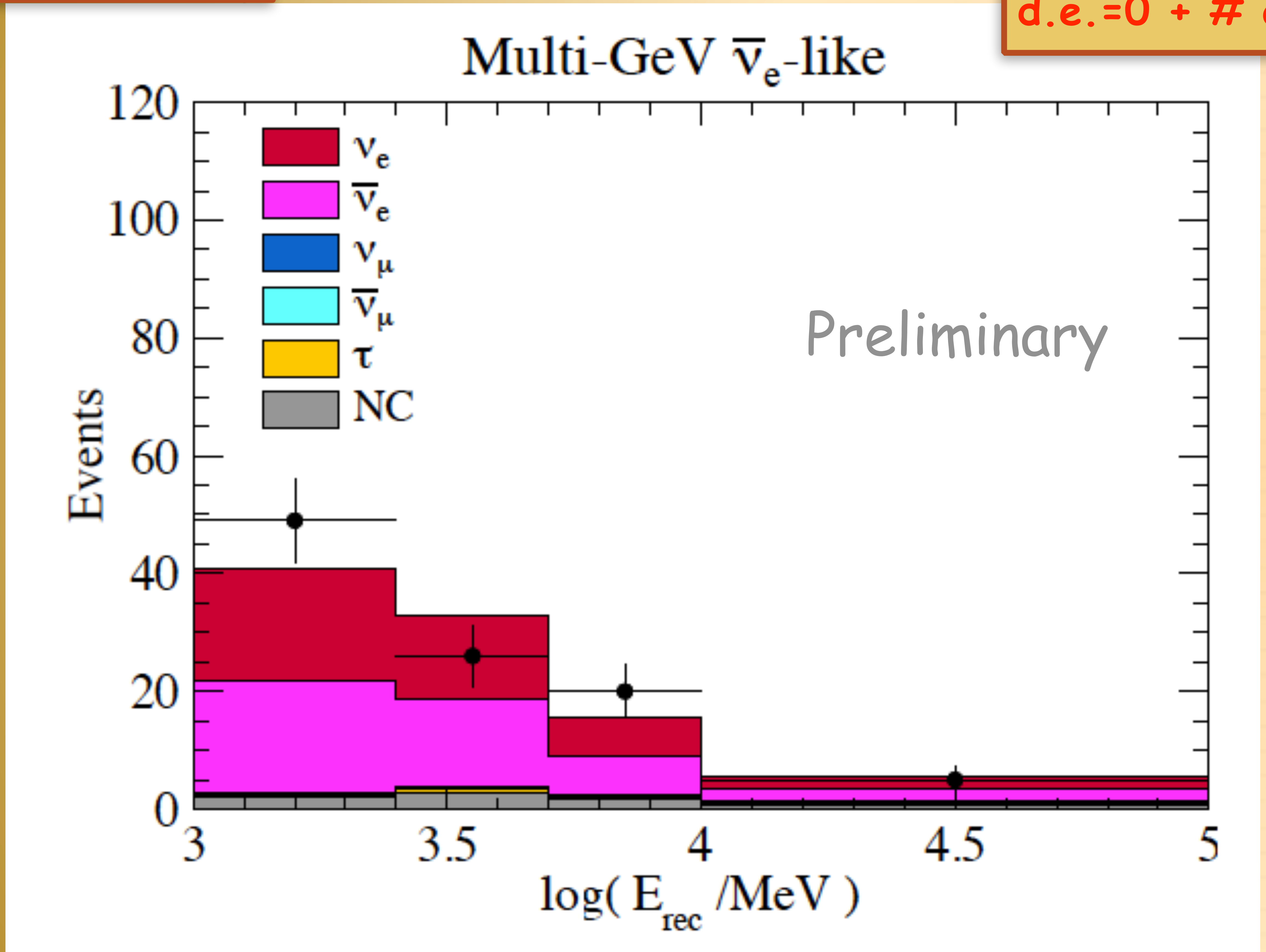


- *See the poster #112 by Shintaro Miki: Atmospheric Neutrino Oscillations in SK-Gd*

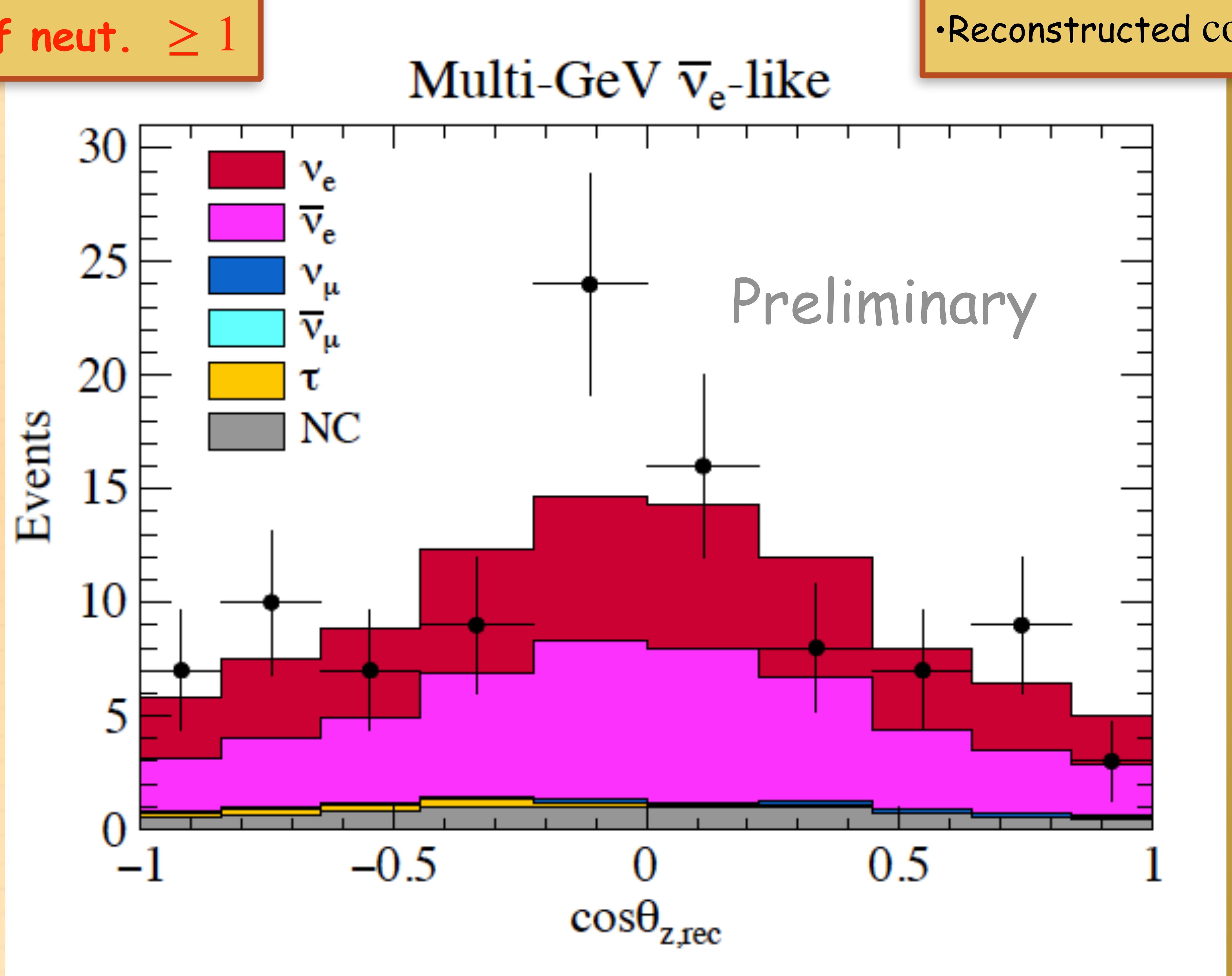
SK6 reconstruction with neutrons

- Reconstructed E_ν

d.e.=0 + # of neut. ≥ 1

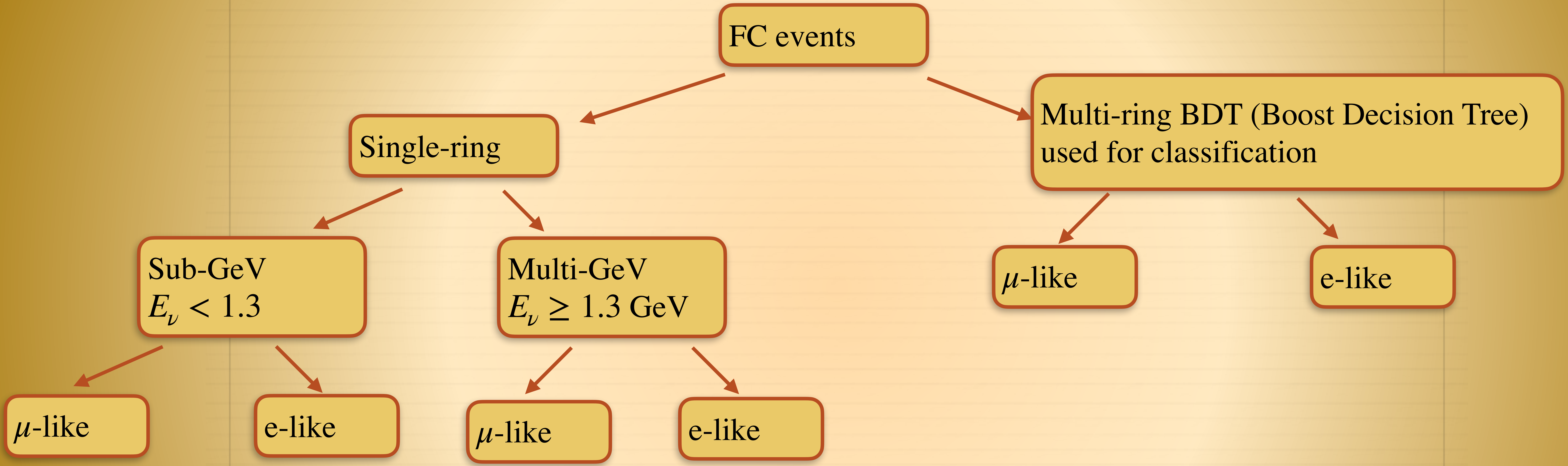


- Reconstructed $\cos\theta_\nu$



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

FC events- selections



FC events

Single-ring

Multi-ring BDT (Boost Decision Tree) used for classification

Sub-GeV
$E_\nu < 1.3$

Multi-GeV
$E_\nu \geq 1.3$ GeV

μ-like

e-like

μ-like

e-like

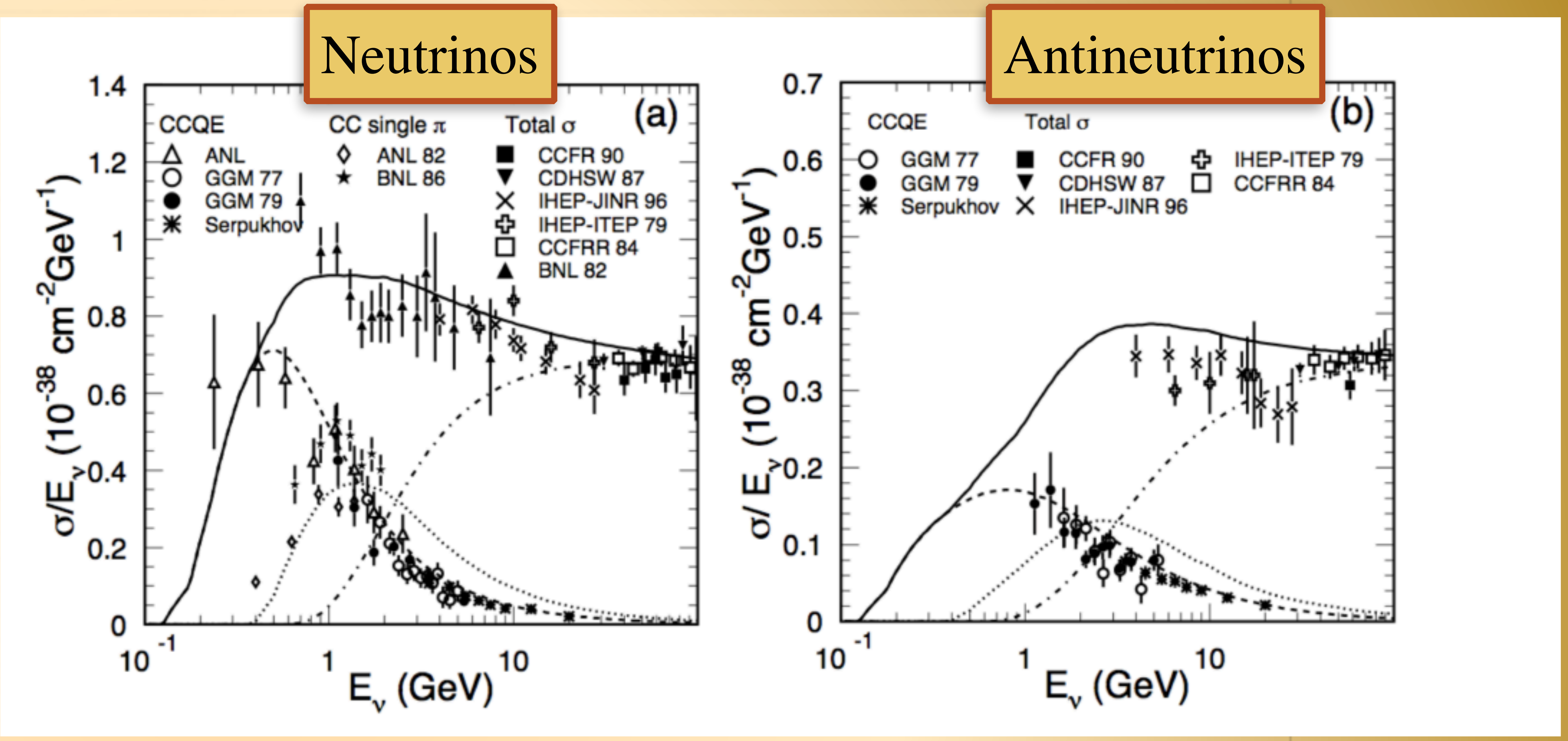
μ-like

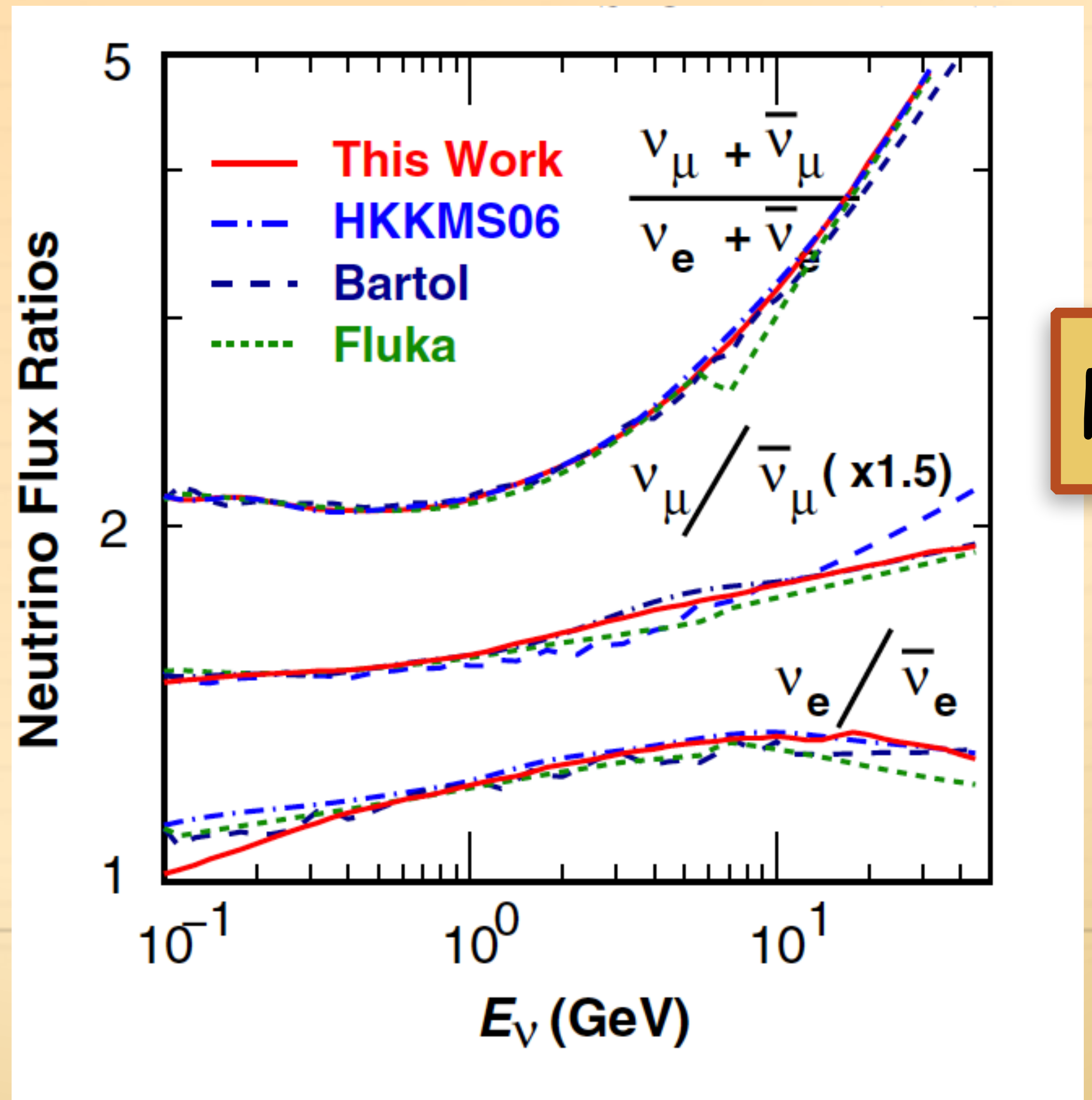
e-like

- The number of decay electrons is used to separate events into neutrino or antineutrino enhanced samples
- From SK-IV period it was possible to search for neutron captures on hydrogen to increase neutrino-antineutrino separation.

Separation of ν_e and $\bar{\nu}_e$

- **Separation of ν_e and $\bar{\nu}_e$ is important for mass ordering searches**
- No magnetic filed in the Super-K detector to do that
- However we have larger cross-section and flux for ν_e than $\bar{\nu}_e$ which results in **twice more ν_e interactions than $\bar{\nu}_e$ in the Super-K detector**





Phys. Rev. D 83 123001 (2011)

Separation of ν_e and $\bar{\nu}_e$

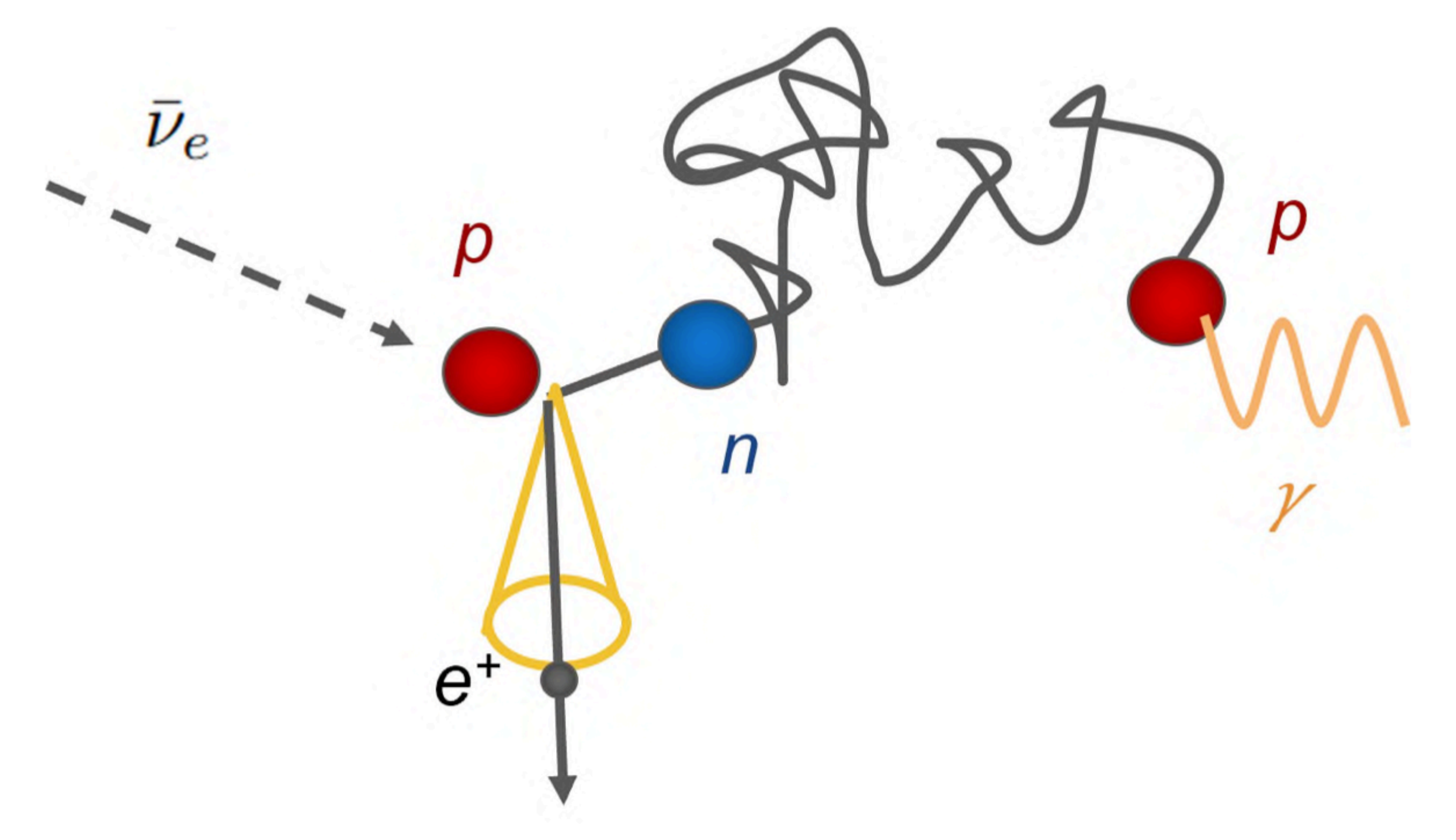
- The number of decay electrons is used to separate events into neutrino or antineutrino enhanced samples.
  - **Single-ring Multi-GeV class:**
    - $\bar{\nu}_e + n \to e^+ + n + \pi^-$ and π^- will often be captured on oxygen nucleus leaving the e^+ as the only Cherenkov light emitting particle. No decay electron will be seen in that event
    - $\nu_e + n \to e^- + n + \pi^+$ where π^+ does not capture and can decay to μ^+ and later produce delayed electron

Neutron tagging on hydrogen at Super-K

Possible from SK-IV period

Reminder:
$\nu_e + n \rightarrow e^- + p$
$\bar{\nu}_e + p \rightarrow e^+ + n$

- IBD reaction: $\bar{\nu}_e + p \rightarrow n + e^+$
- Neutron tagging may happen on hydrogen.
  - $n + p \rightarrow d + \gamma(2.2MeV)$
  - The gamma ray may then scatter electrons (Compton scattering) in the water, accelerating some of them above the Cherenkov threshold.
  - Identifying the light from those electrons can be used to infer the presence of the gamma ray and hence its parent neutron.



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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 $p \rightarrow e^+ + \eta$ and. $p \rightarrow \mu^+ + \eta$ 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

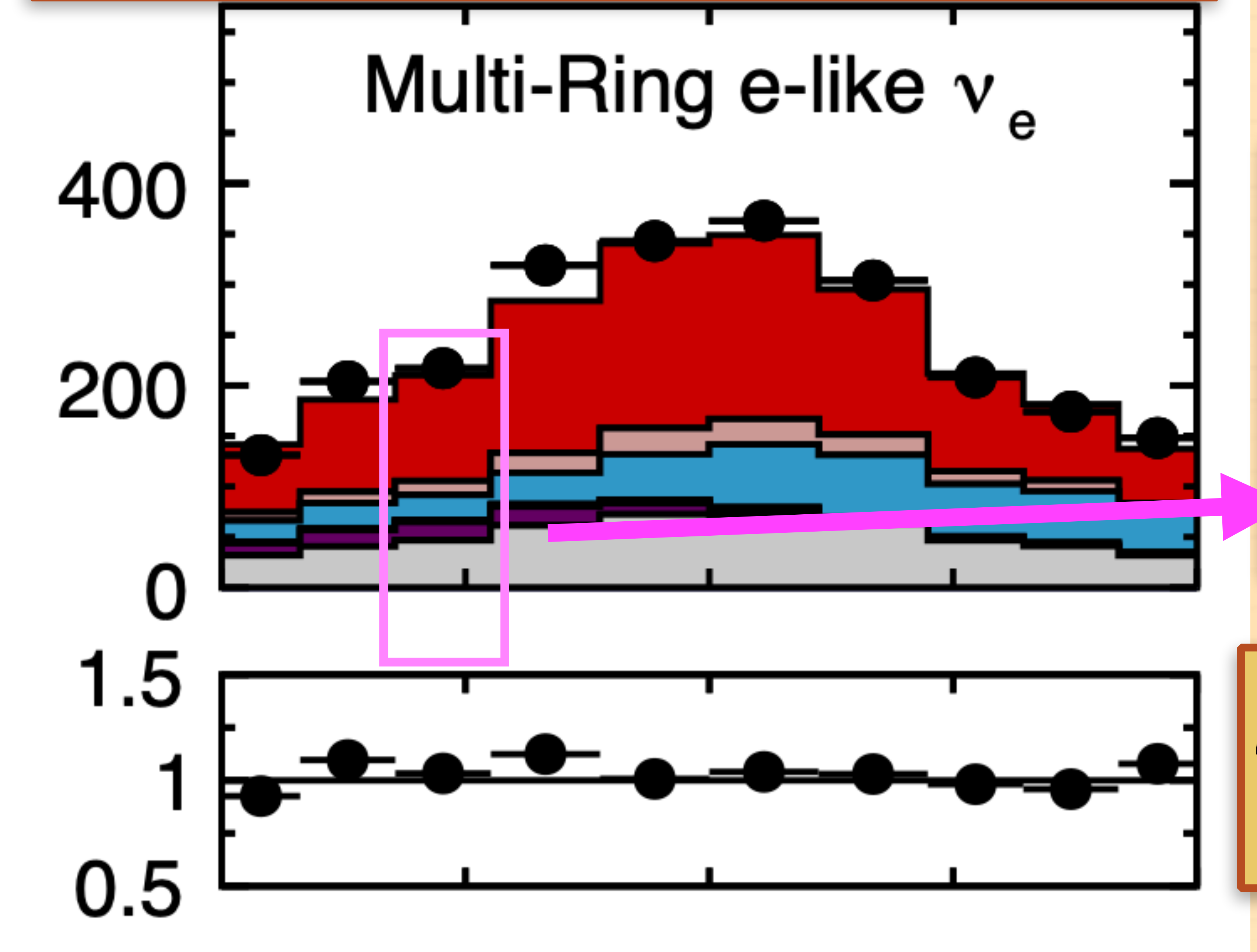
Atmospheric neutrino oscillation analysis with neutron tagging and an expanded fiducial volume in Super-Kamiokande I–V

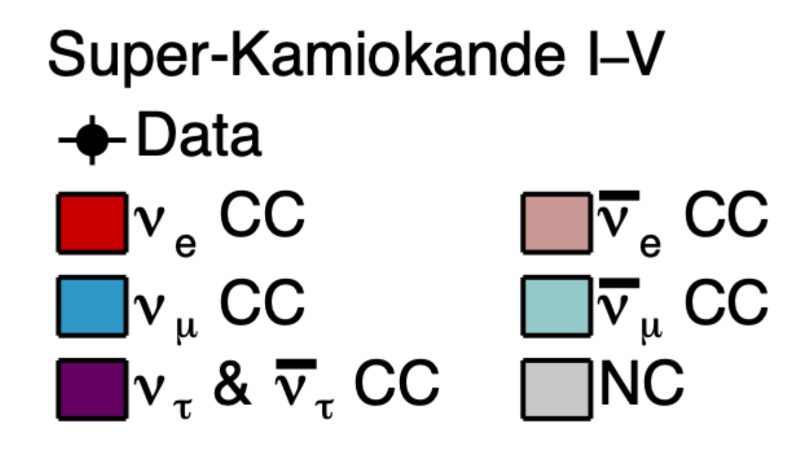
T. Wester *et al.* (The Super-Kamiokande Collaboration)

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

$E_{\nu,true}$

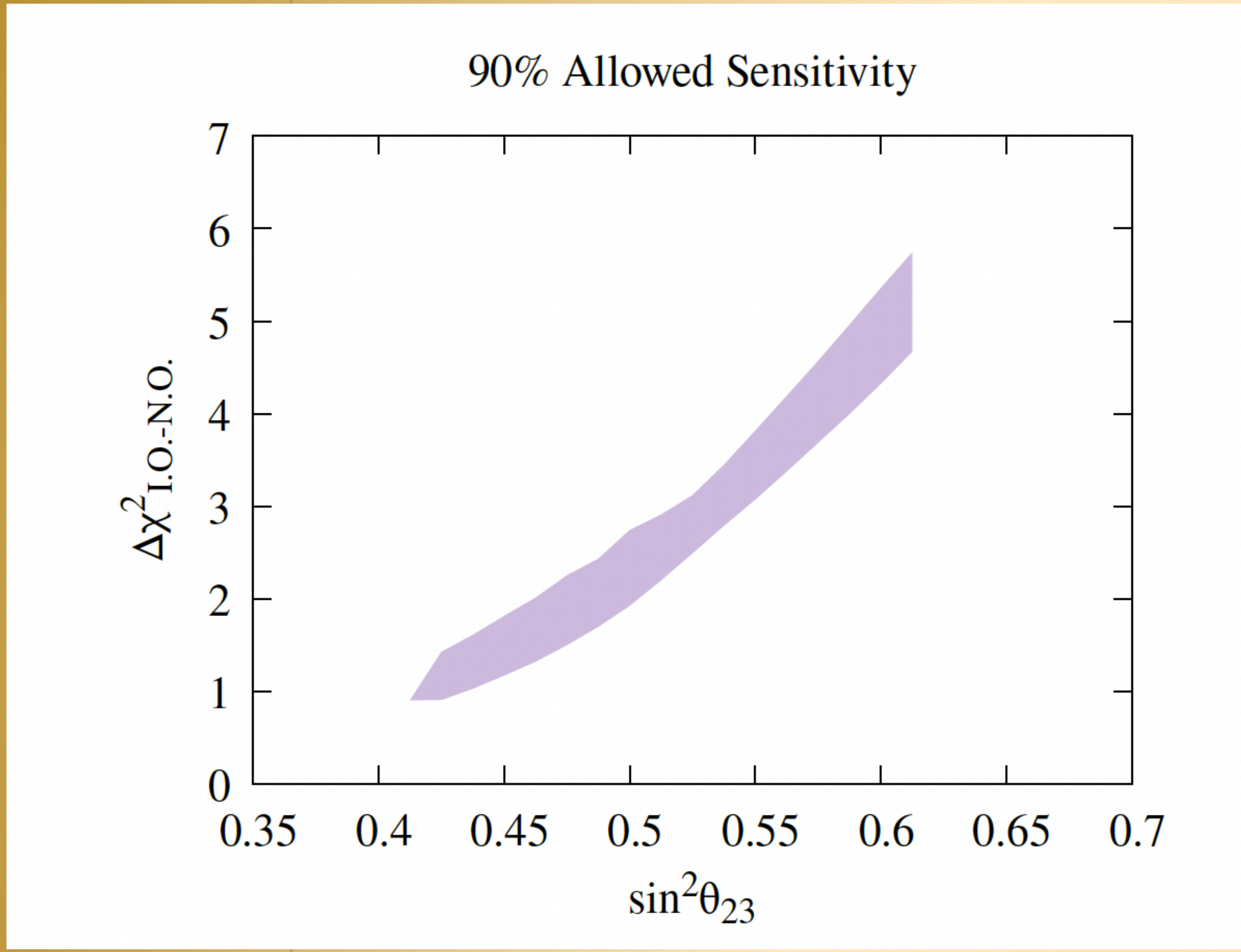
$\theta_{\nu,true}$

Modeling multi-GeV ν interactions is non-trivial

234,000 numbers provided

χ^2 map and digitized contours provided

The mass ordering sensitivity

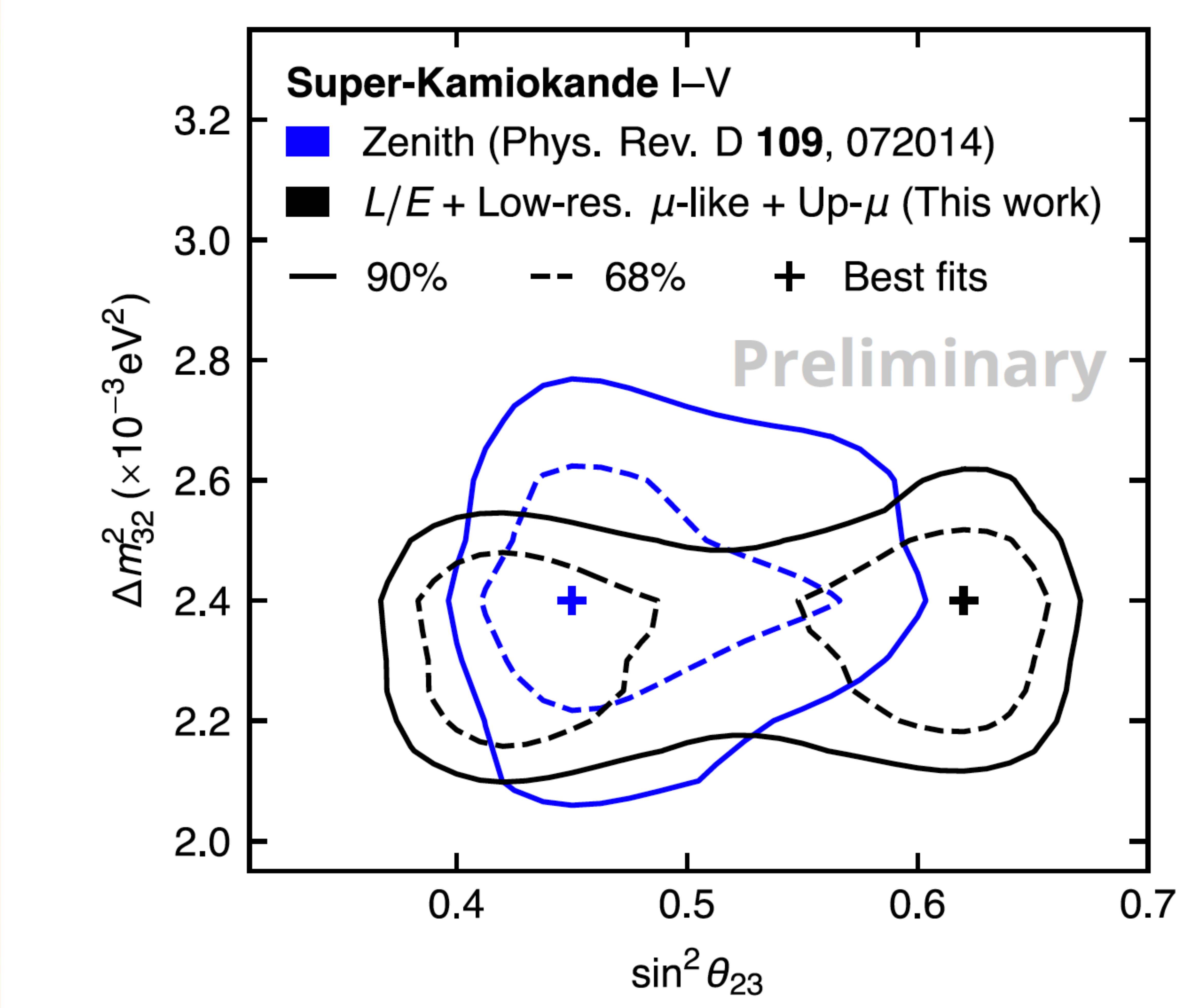


- The mass ordering sensitivity is highly dependent on the values of $\sin^2\theta_{23}, \sin^2\theta_{13}$ and δ_{CP}
- This figure shows the sensitivity for the mass ordering **assuming different values of the oscillation parameters followed by the fit at 90%**
- **The largest ν_e appearance signal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

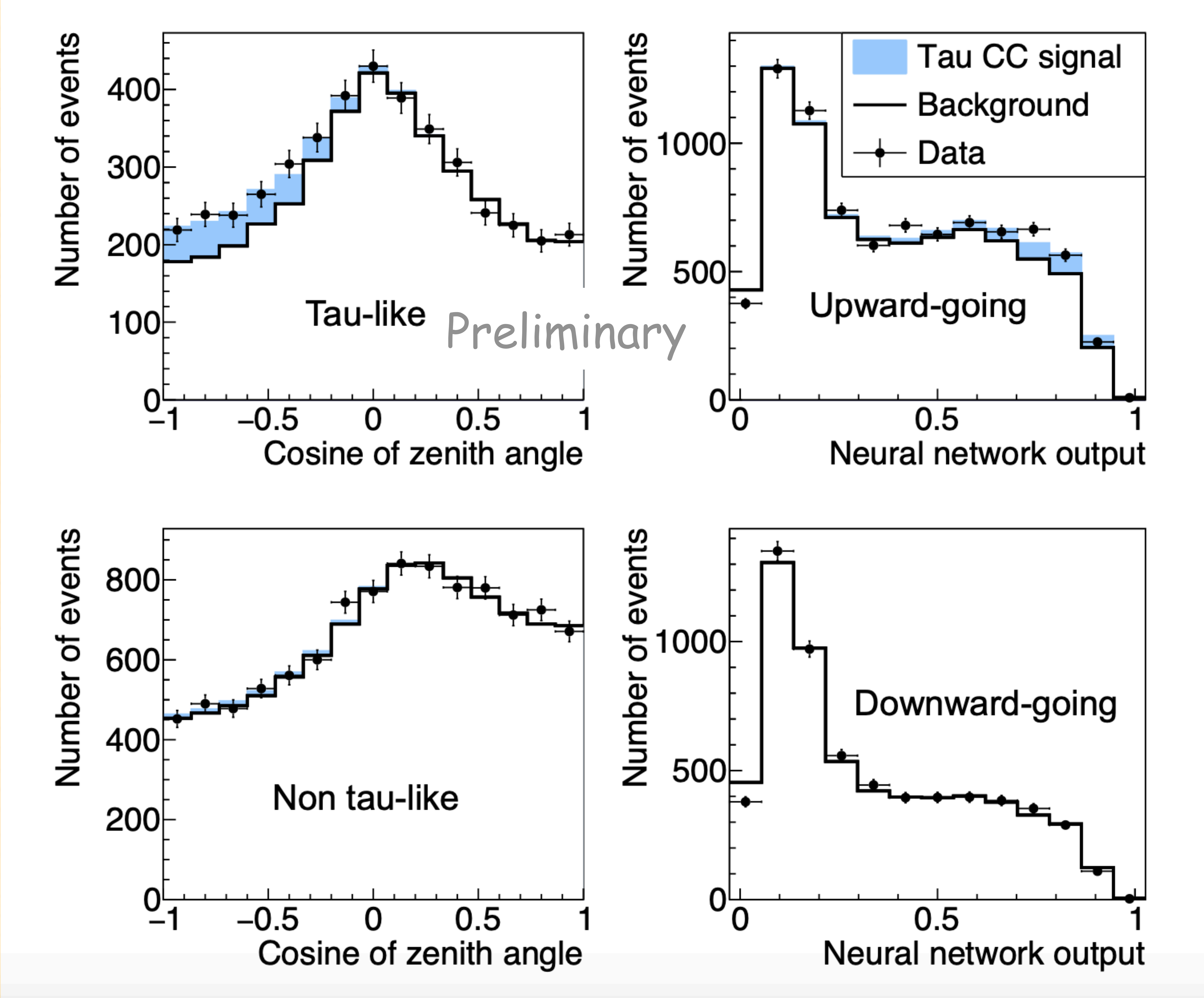
L/E analysis @ Super - Kamiokande

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



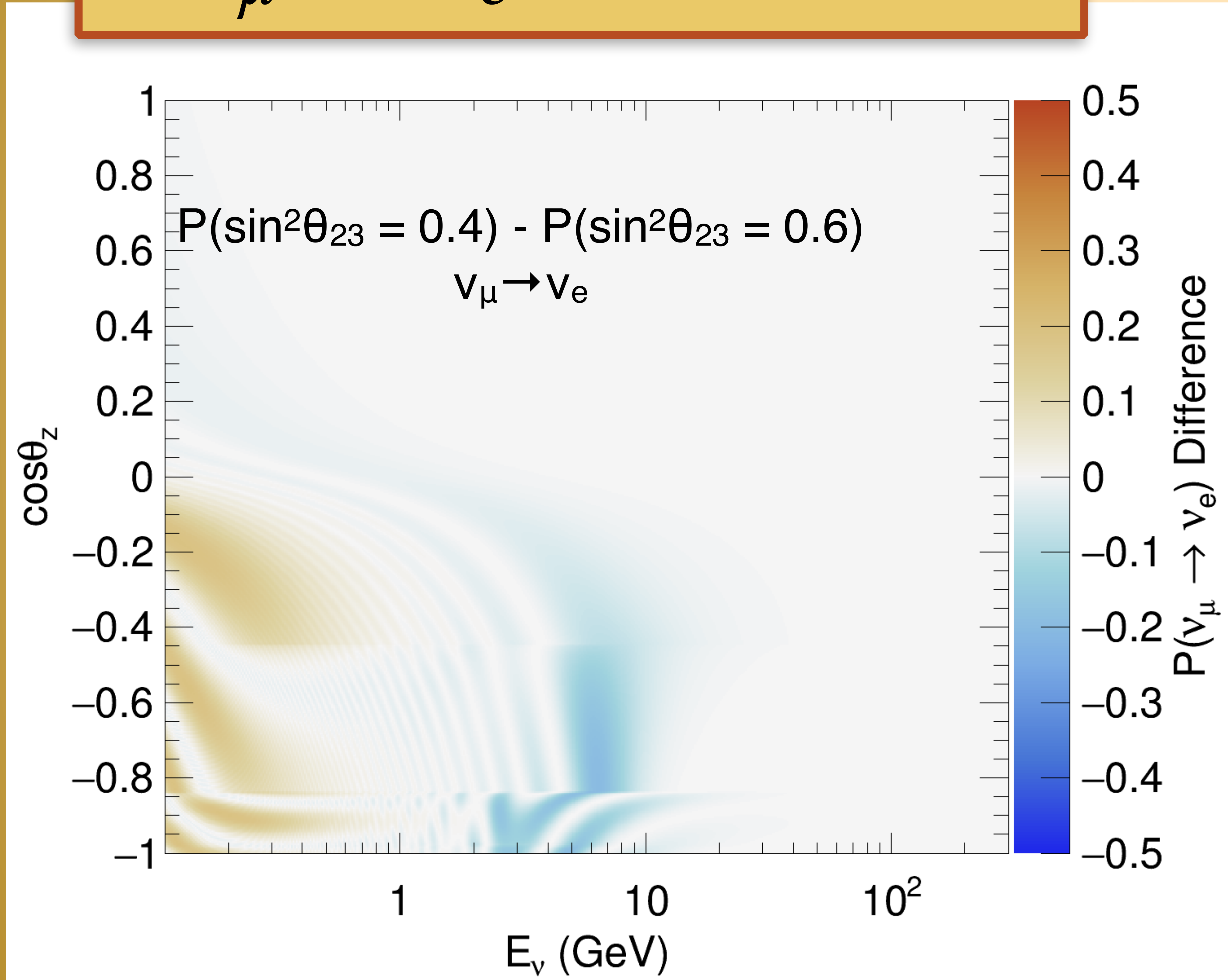
ν_τ appearance searches

- 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)

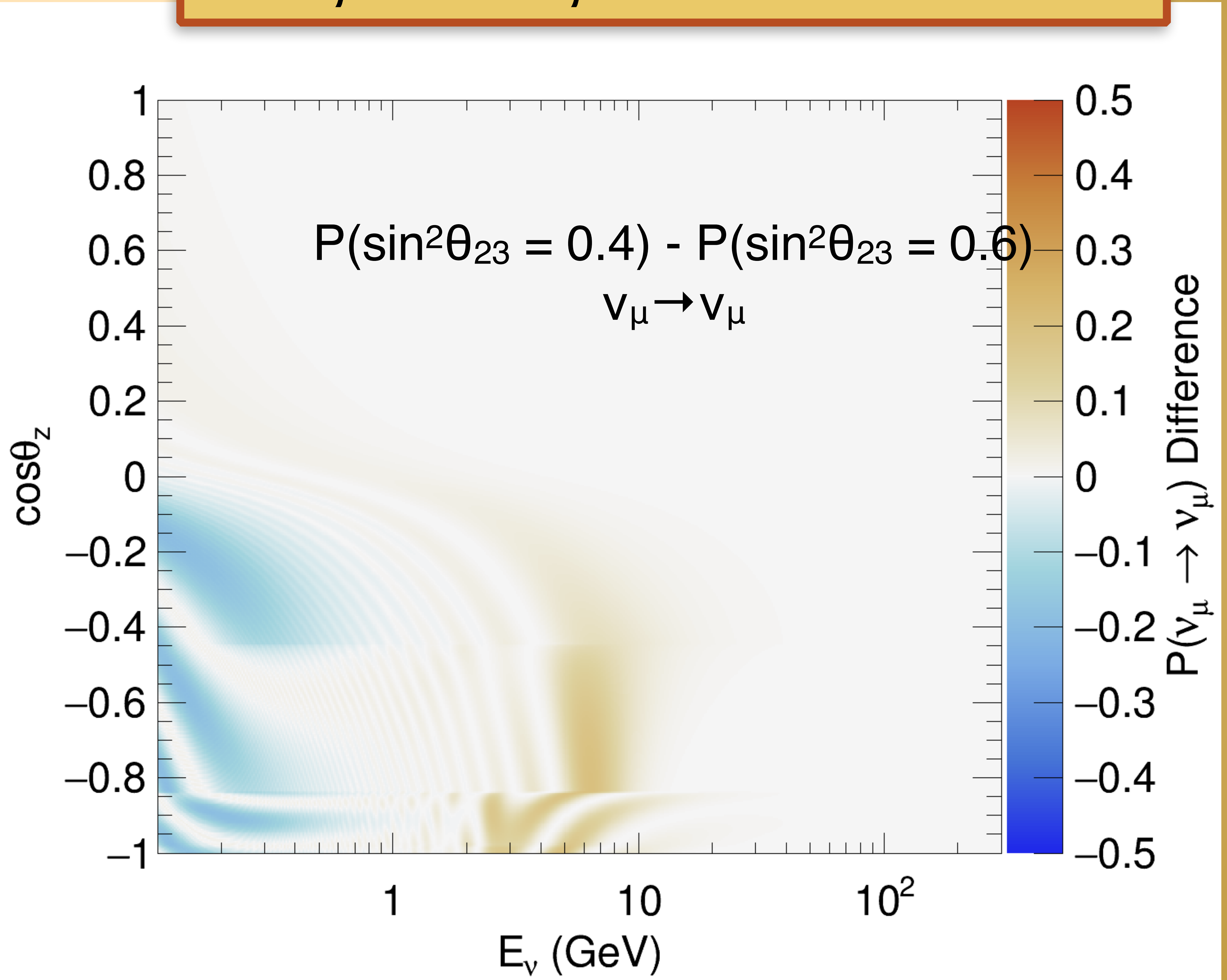


Octant effect on oscillations

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



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

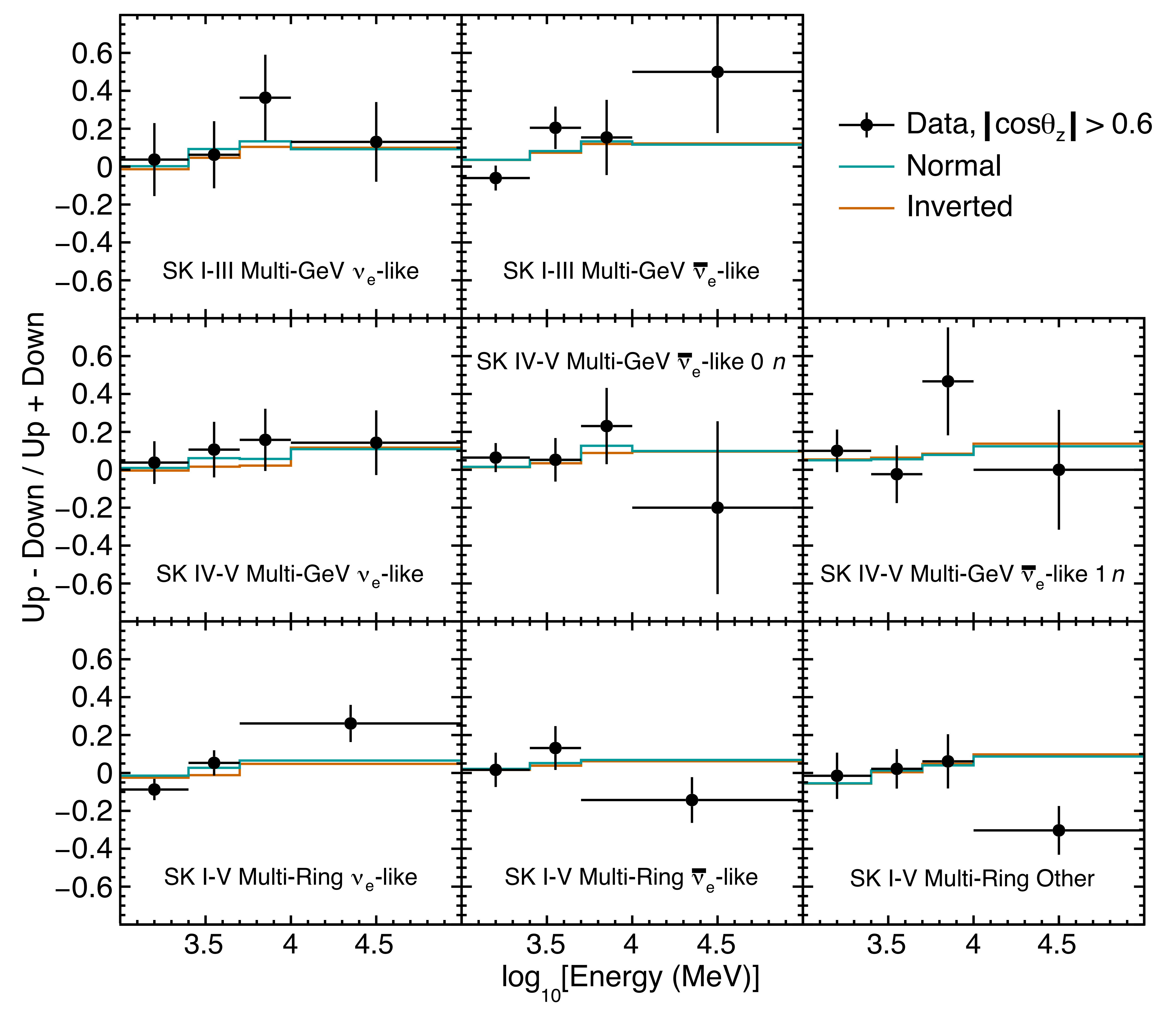


Thomas Wester's studies

Assumptions:

- Normal ordering, $\delta_{CP} \simeq -\pi/2$,
- $\Delta m^2_{32} \simeq 2.4 \cdot 10^{-3}$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]

図1

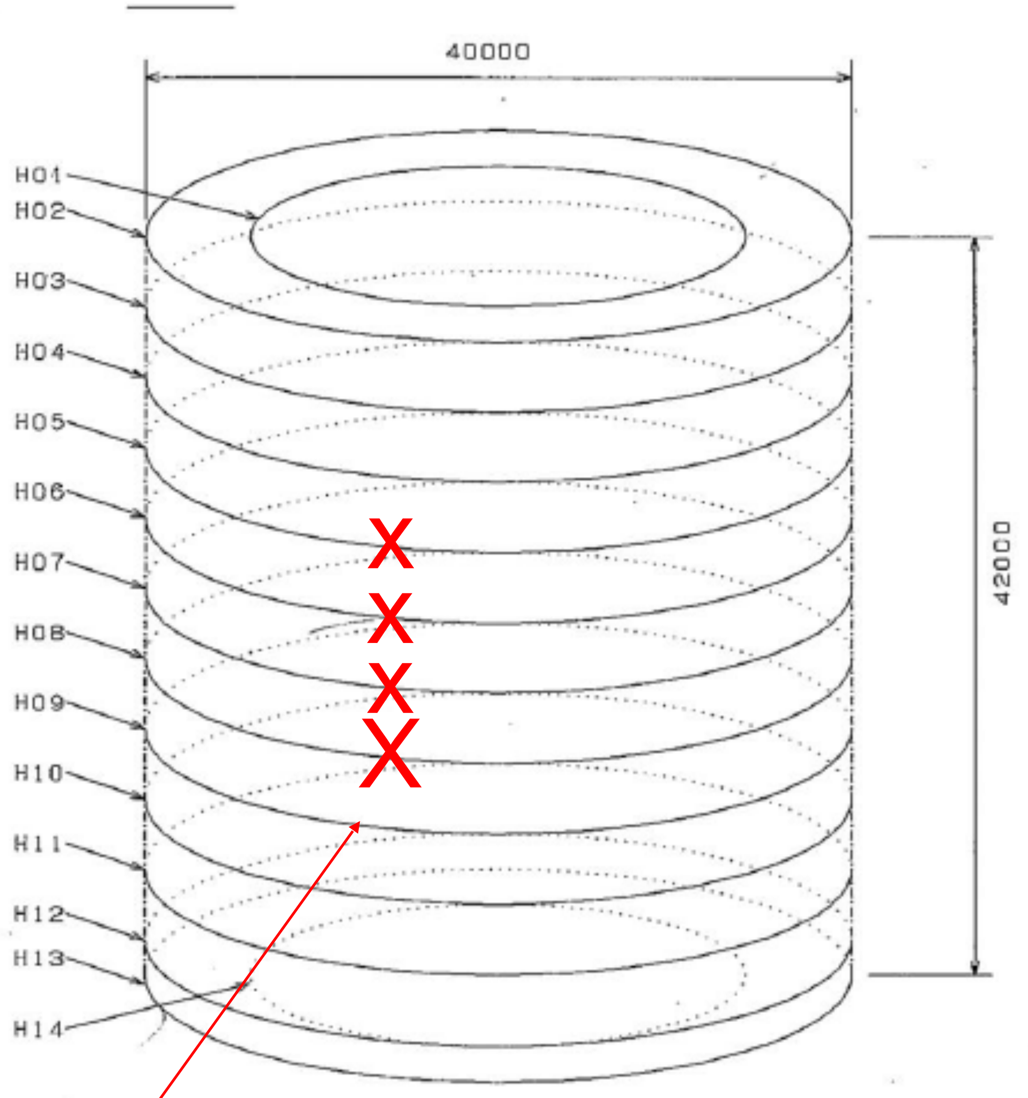
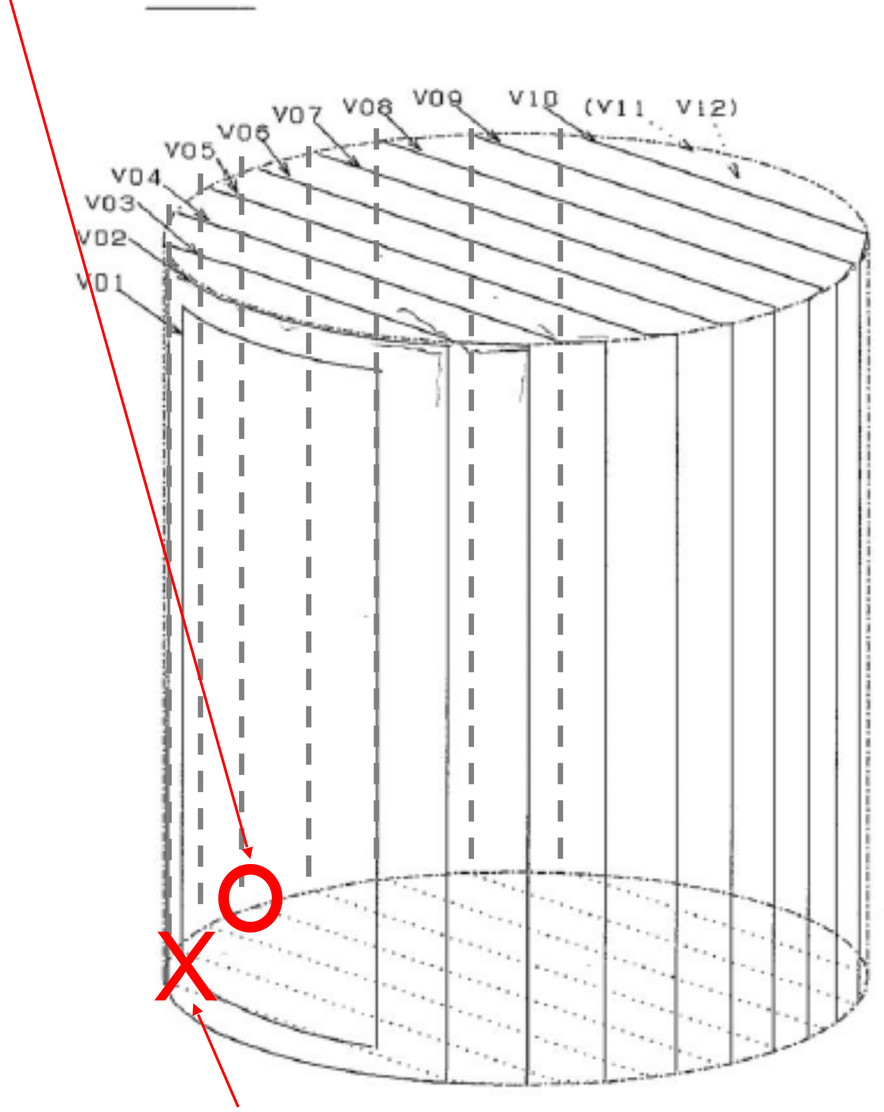


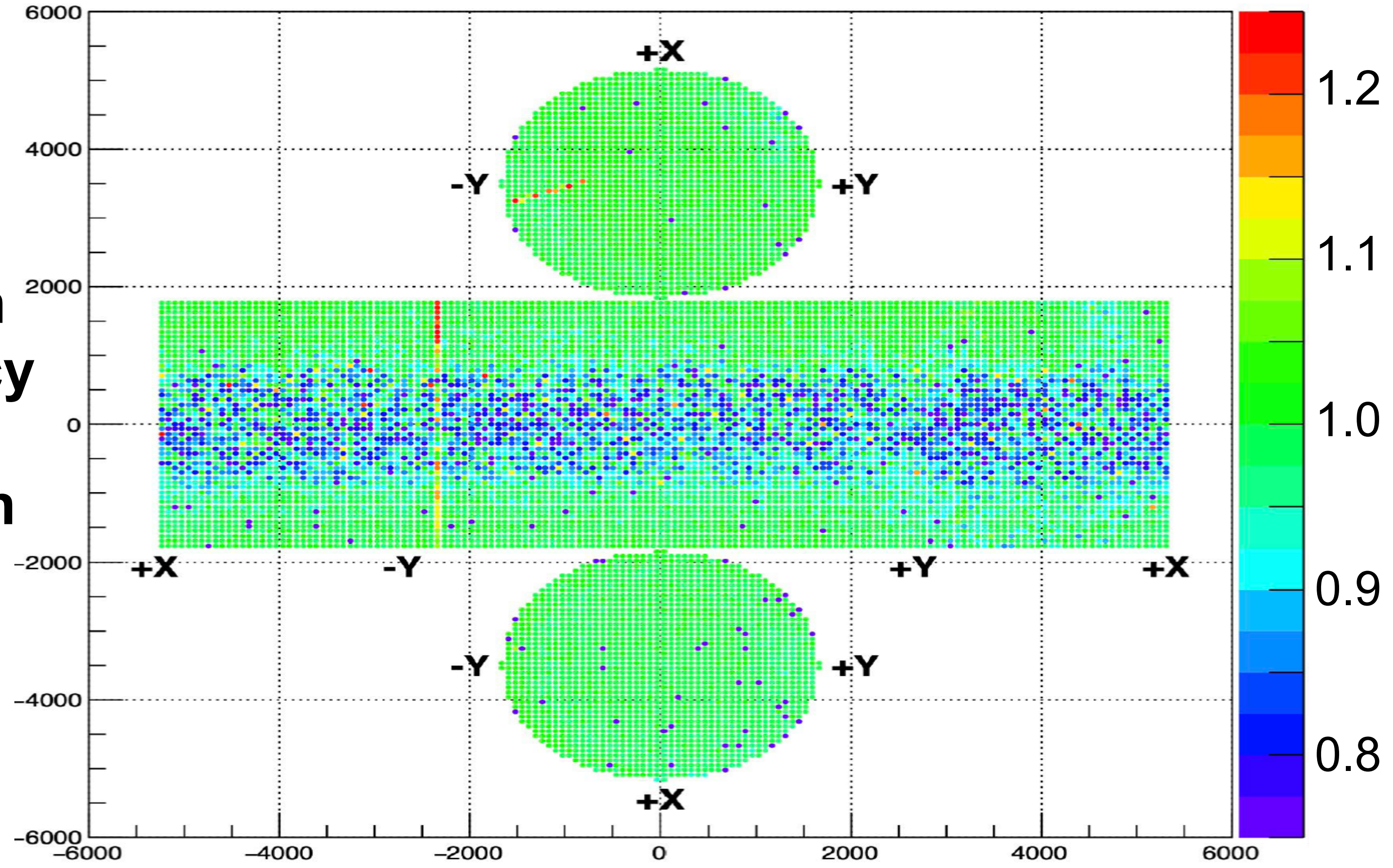
図2



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

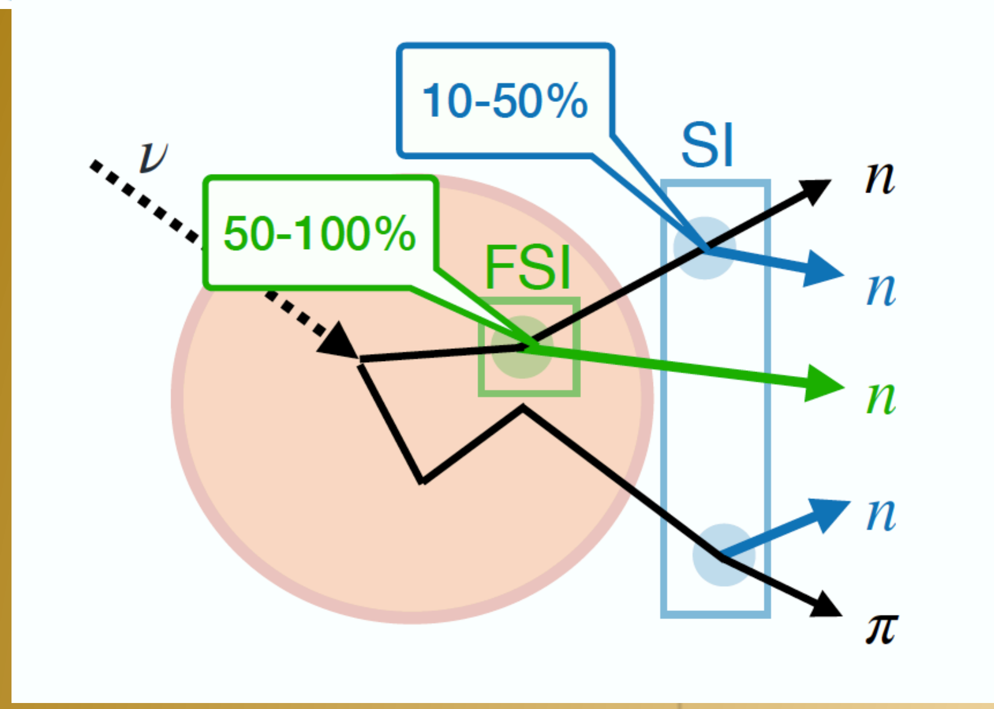
V01 disconnected on Nov.15, 2023.
V01 was bypassed from the power
supply on Dec.2, 2023.

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



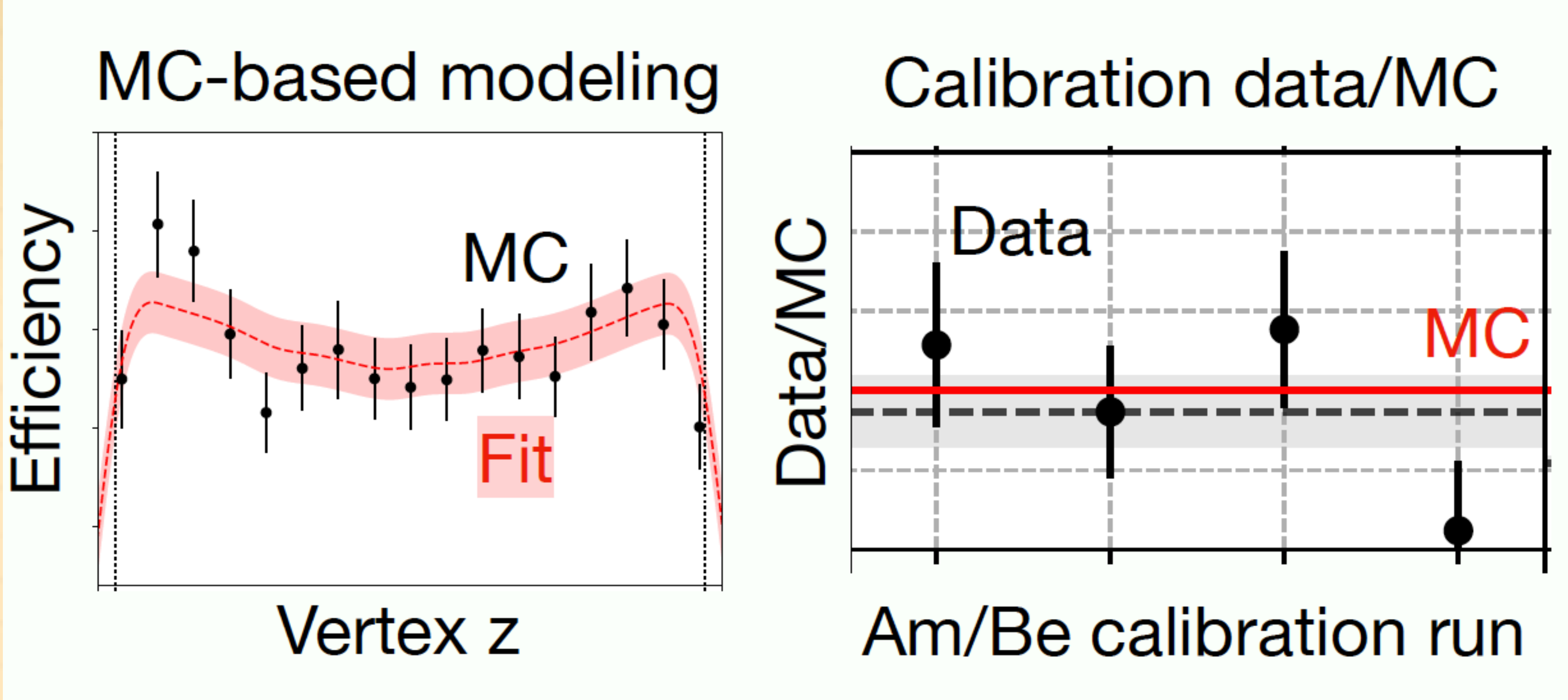
- SK geomagnetic compensation coil cables have failed in three locations.
- At two of locations, part of the coil was successfully bypassed to restore functionality. The other location is entirely underwater, resulting in the entire cable group being turned off.
- A 10-20% decrease in collection efficiency 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

PI
- NEUT 5.4.0
- NEUT 5.6.3
- GENIE

FSI
- hA
- hN
- INCL
- Bertini

Flux: Honda flux (2011)
GENIE 3.4.0 G18_10b_02_11b

6 models

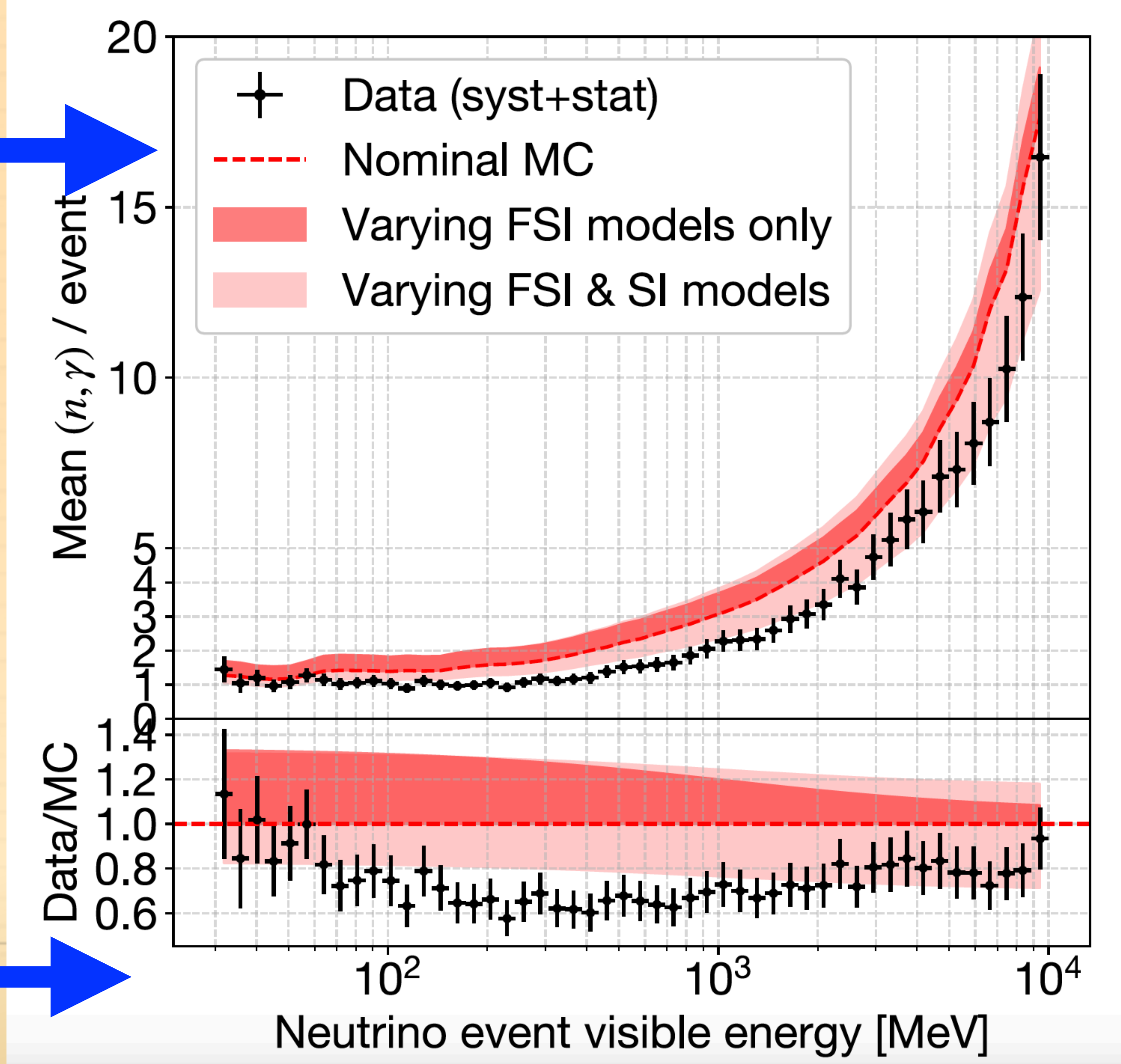
SI
- SK4/5 default
- SK6 default
- GCALOR
- Bertini
- INCL

5 models

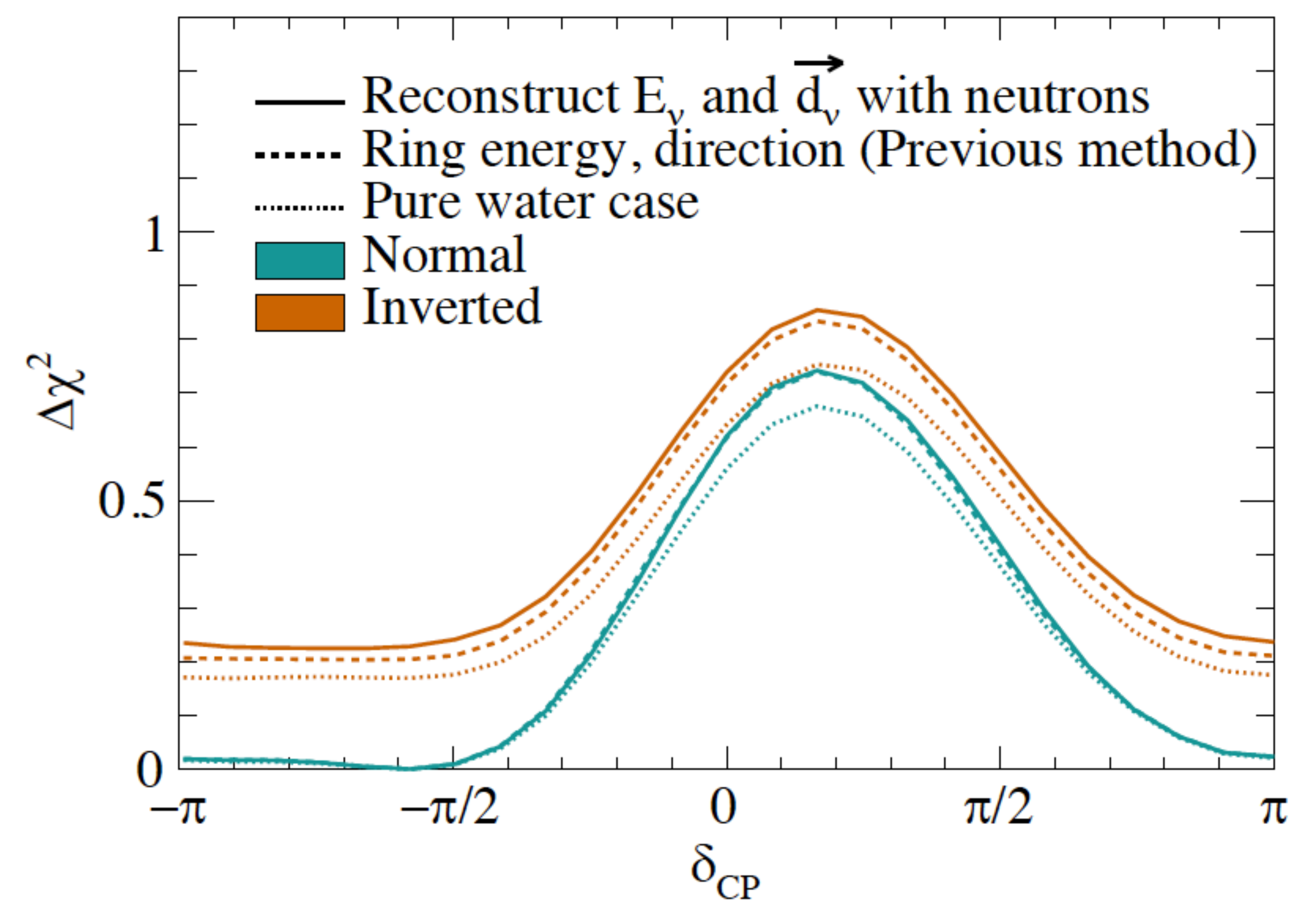
NEUT 5.4.0.1+SK6 MC

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

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

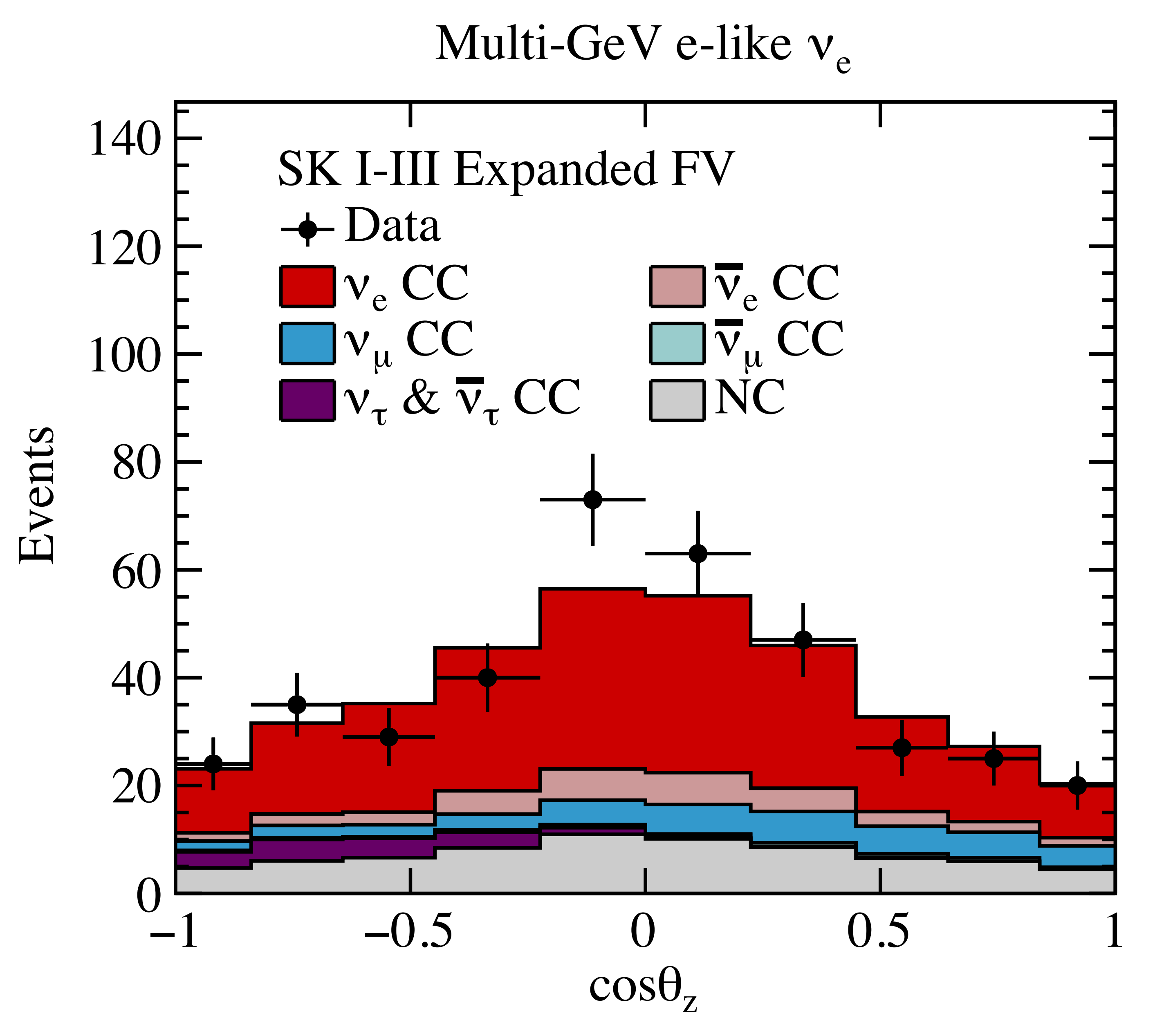
$$\pi^+ \rightarrow \mu^+ \rightarrow e^+$$

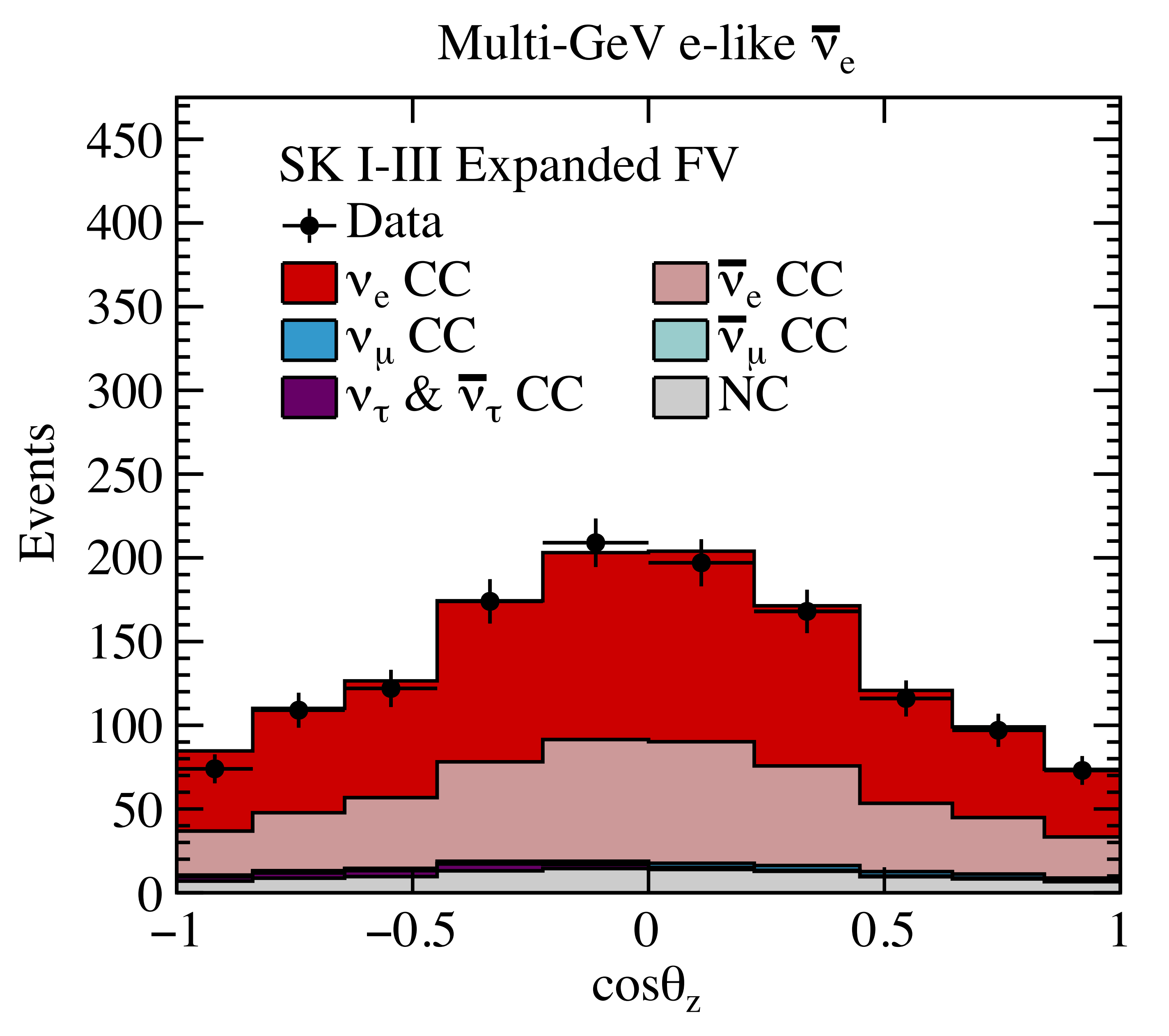
Delayed "decay electron

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

π^- mostly absorbed by Oxygen

🟥 ν_e (56%)
▨ $\bar{\nu}_e$ (9%)





🟥 ν_e (56%)
▨ $\bar{\nu}_e$ (34%)