The tau-neutrino oscillation measurements at Super-Kamiokande detector and future prospects

Magdalena Posiadała-Zezula

University of Warsaw,
Faculty of Physics

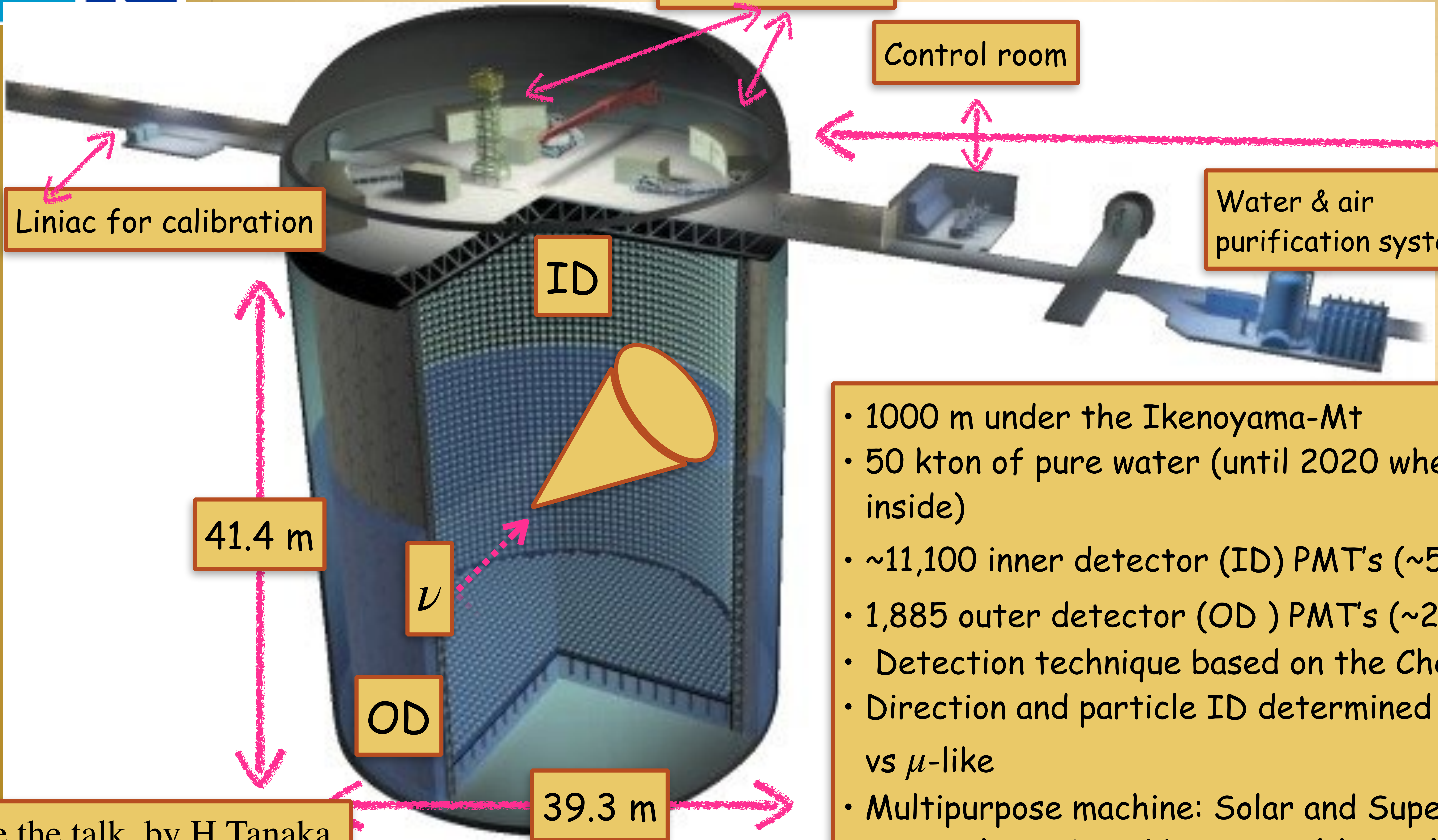
Photo Credit: Piotr Mijakowski

The Super-Kamiokande Collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
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
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Nihon University, Japan
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
Sungkyunkwan University, Korea
Stony Brook University, USA
Tohoku University, Japan
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

~230 collaborators from 53 institutes in 11 countries

Super-Kamiokande detector

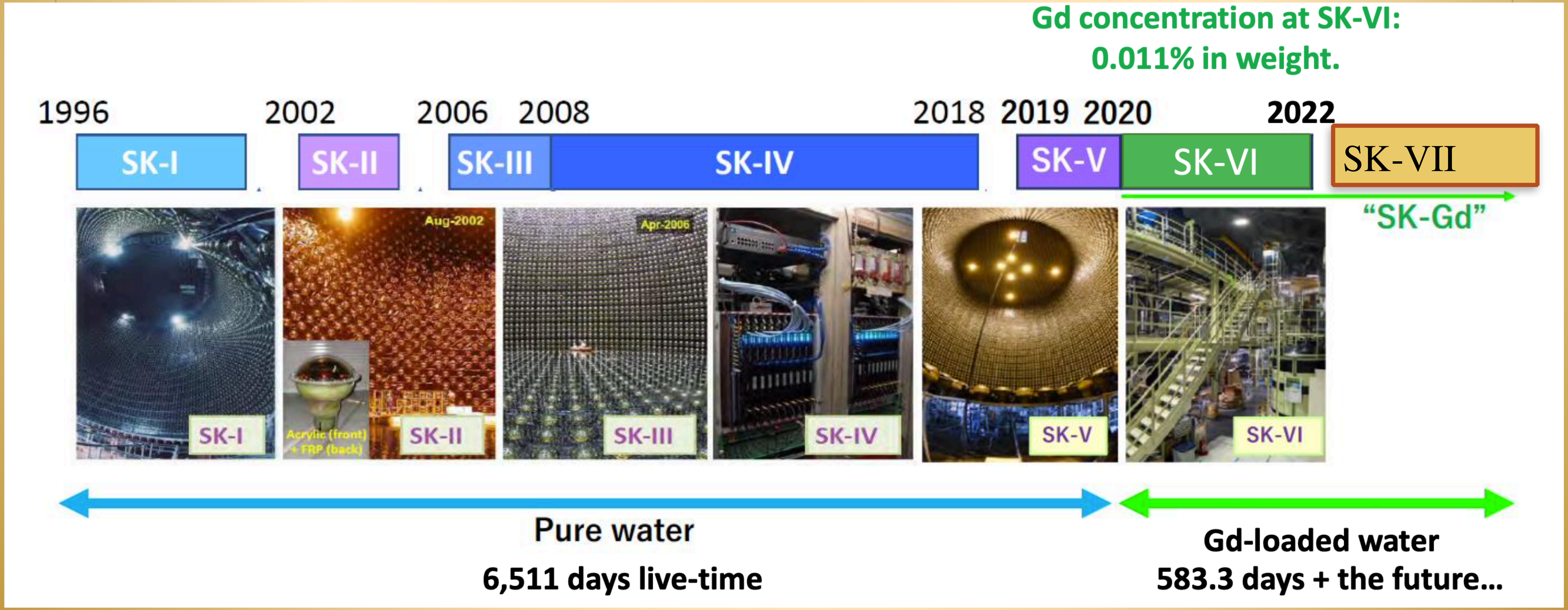


- 1000 m under the Ikenoyama-Mt
- 50 kton of pure water (until 2020 when Gd sulfate was added inside)
- ~11,100 inner detector (ID) PMT's (~50cm ϕ)
- 1,885 outer detector (OD) PMT's (~20cm ϕ)
- Detection technique based on the Cherenkov radiation
- Direction and particle ID determined from the ring pattern: e-like vs μ-like
- Multipurpose machine: Solar and Supernova Neutrinos, **Atmospheric Tau Neutrinos (this talk)**, Nucleon Decay, Far detector for T2K

See the talk by H.Tanaka

The Super-Kamiokande experiment

- ★ Super-Kamiokande (Super-K) has been taking data since 1996 and has come through seven run periods
- ★This tau analysis uses all pure water periods - SK -I - V.
- ★ 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 protons interact with the nuclei in the atmosphere:
  - $p, A + air \rightarrow \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}$
  - $\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$
  - $\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \nu_{\mu}(\bar{\nu}_{\mu})$
  - $K^{\pm}, K^{0}_{L} \rightarrow [\pi^{\pm}, \pi^{0}] + e^{\pm} + \nu_{e}(\bar{\nu}_{e})$
- Neutrinos with wide range of energy MeV- PeV produced isotropically about the Earth atmosphere

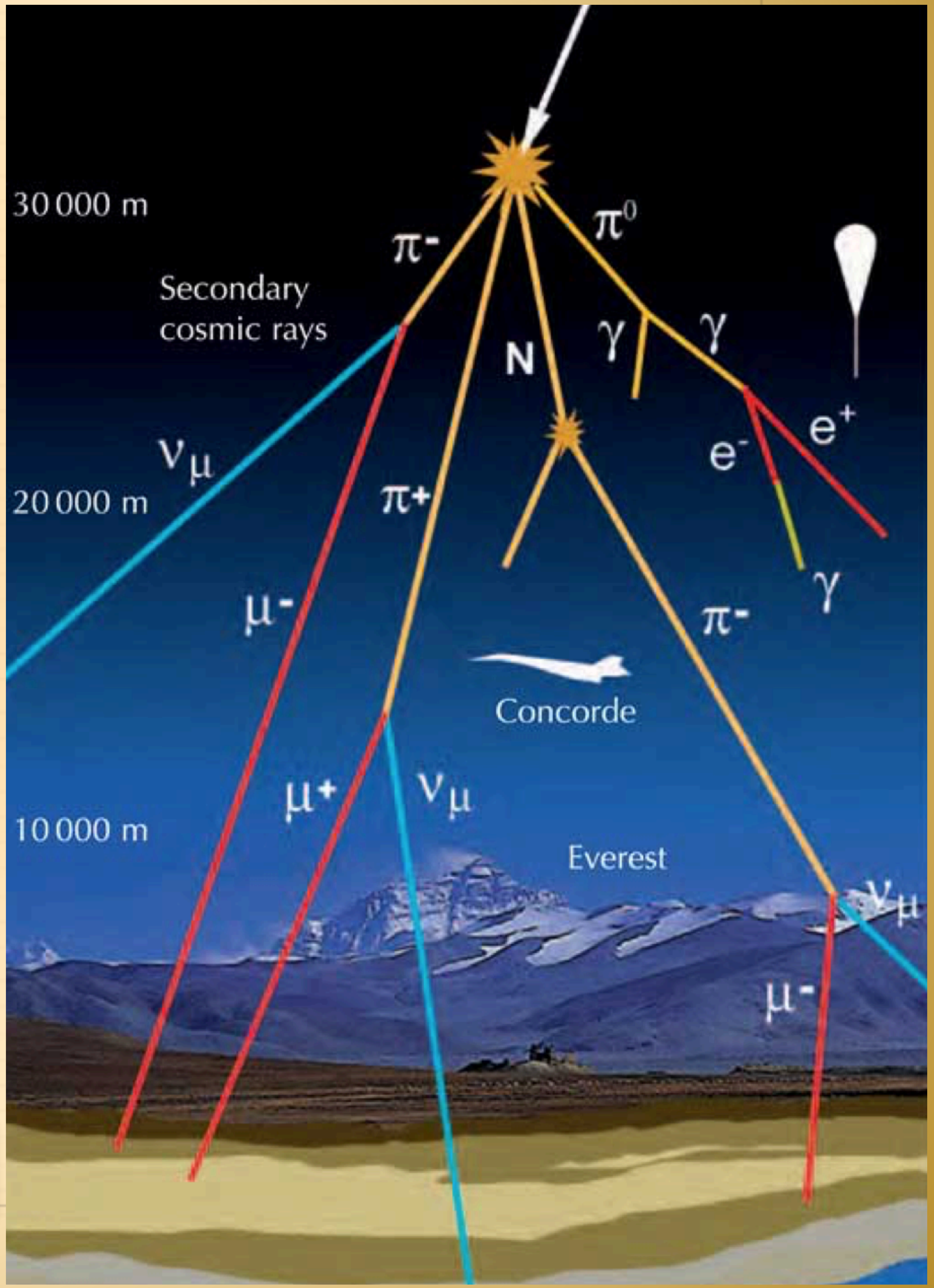
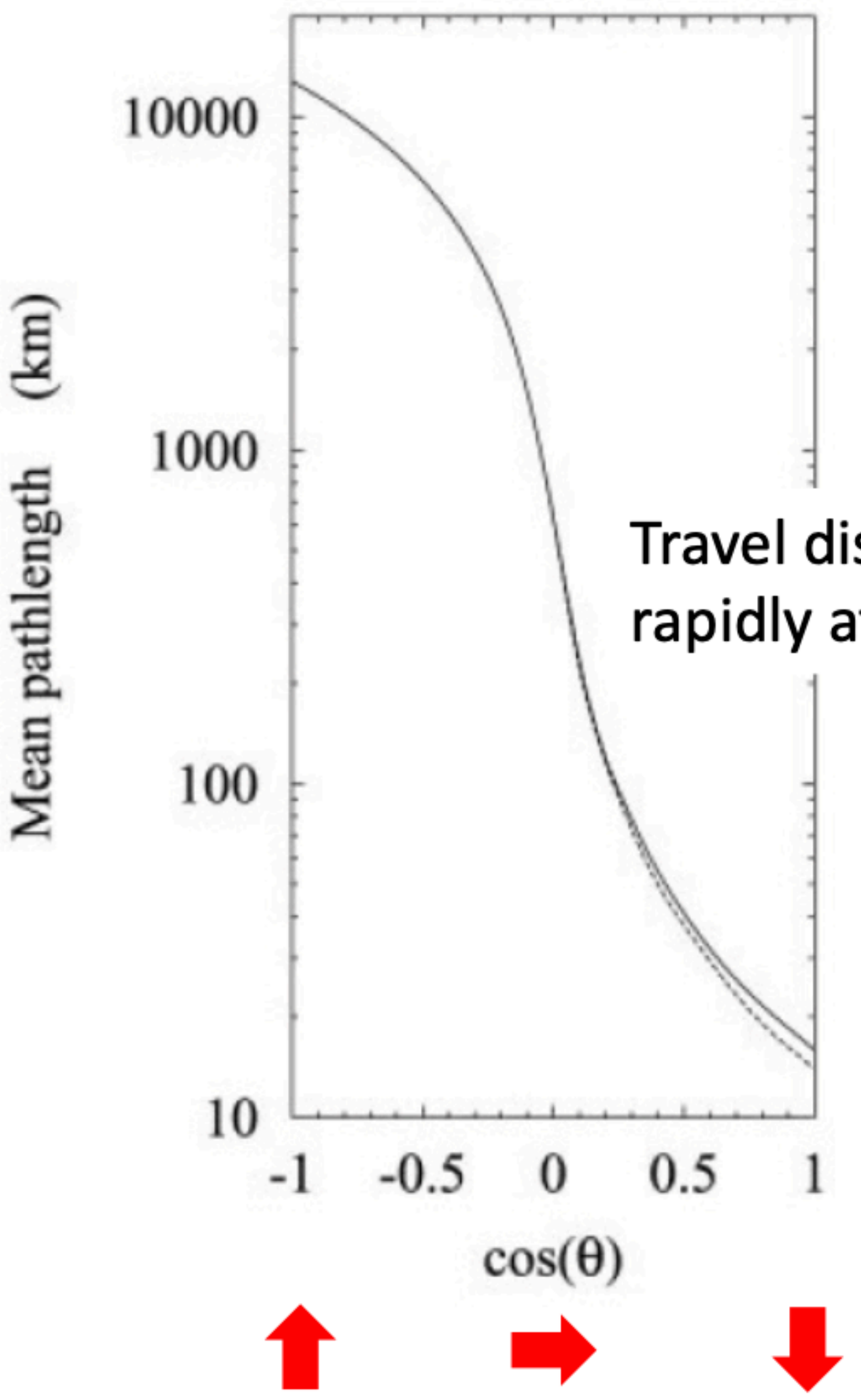


Photo: https://physicsopenlab.org/2016/01/10/cosmic-muons-decay/

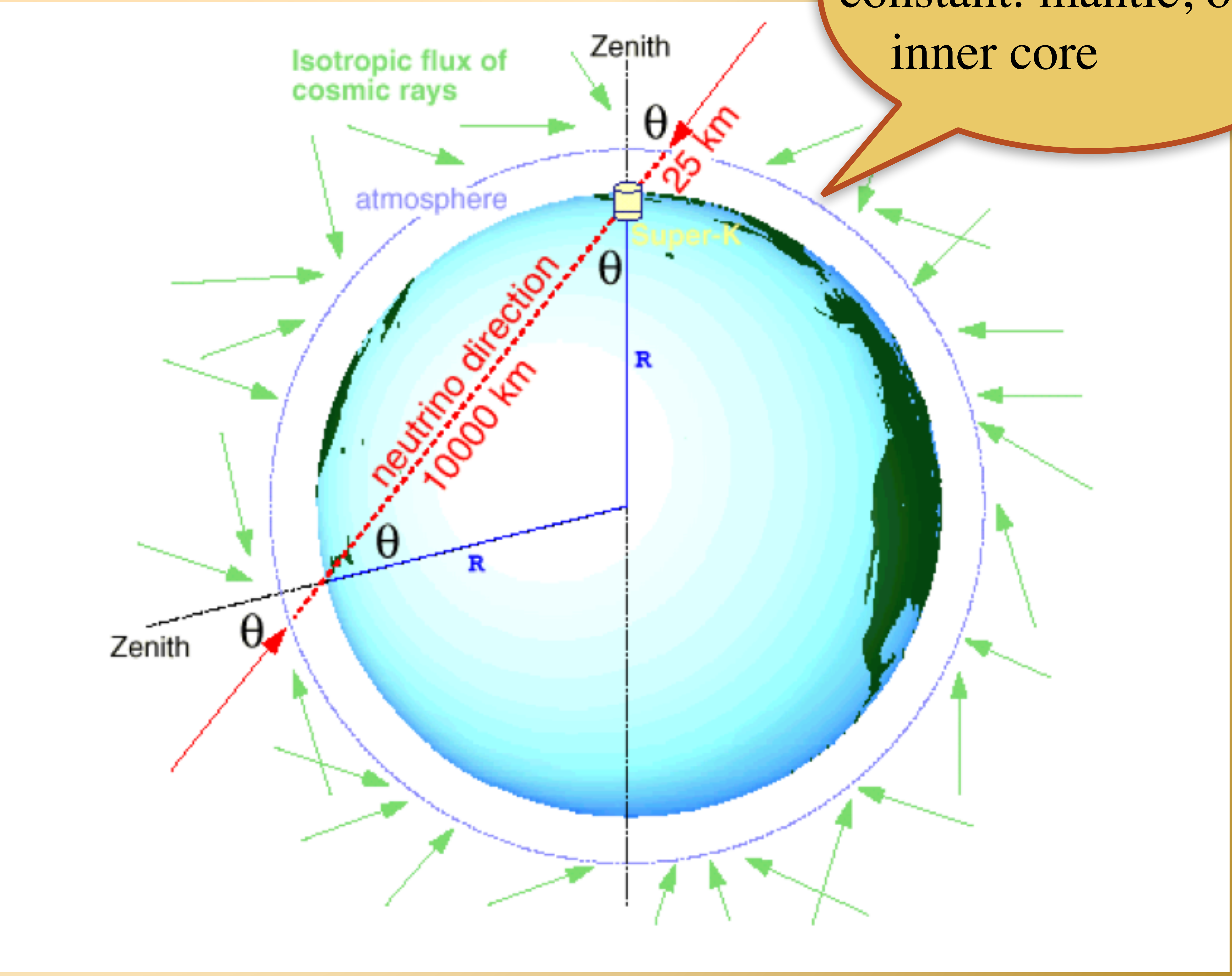
Travel distance

Atmospheric neutrinos travel 15 km to 13000 km.



Travel distance changes rapidly at the horizon.

note definition of zenith angle



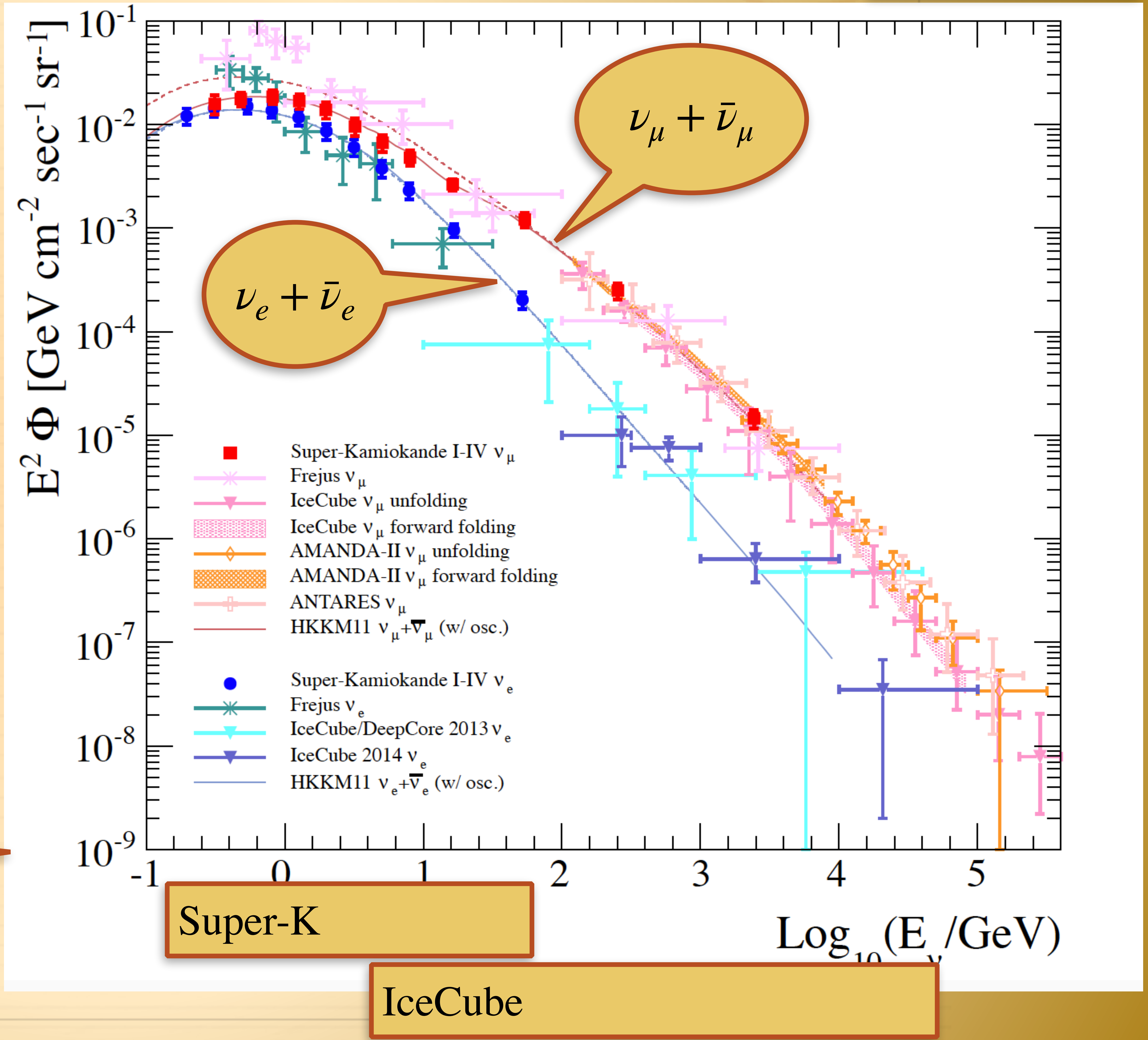
Earth density is not constant: mantle, outer, inner core

Atmospheric neutrino flux

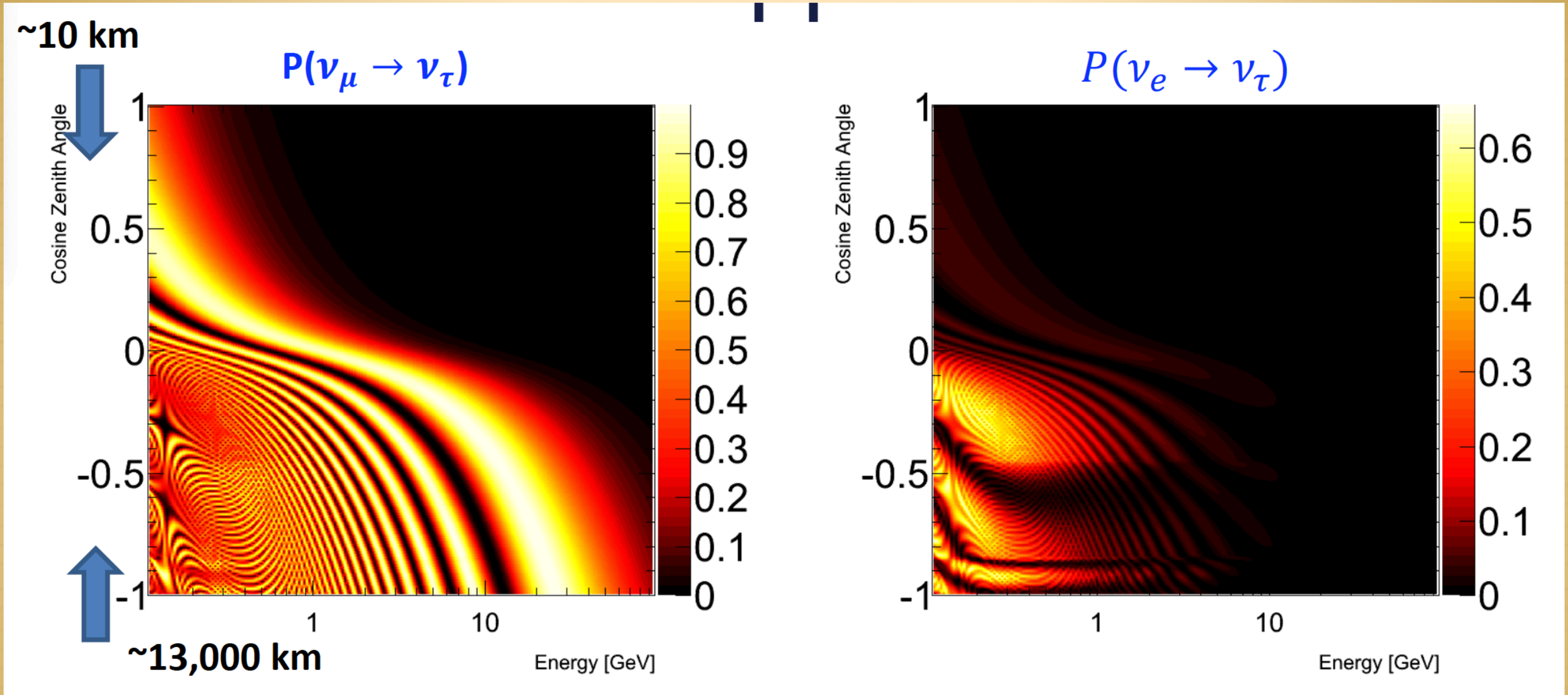
HONDA 2016

- ★ The simulation of atmospheric neutrinos is performed following the flux calculation of **Honda et. al** M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa (HKKM), and using the NEUT simulation software.
- ★ The HKKM11 flux model predictions (Phys. Rev. D **83**, 123001) for the Kamioka site are also shown in solid (with oscillation) and dashed (without oscillation) lines

Phys.Rev.D 94 (2016) 5, 052001



Tau neutrino appearance at Super-K

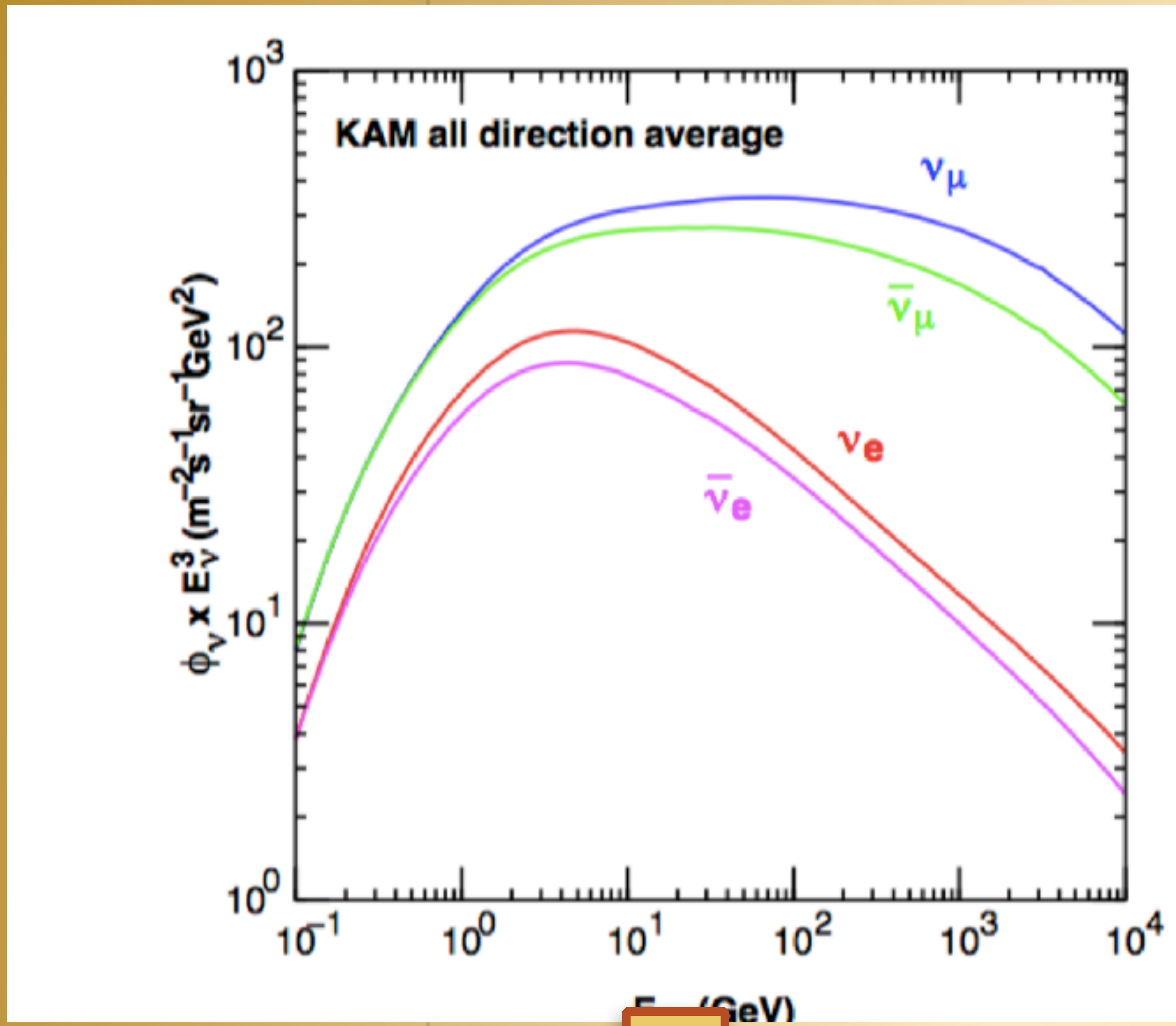


★ Probabilities are calculated with the assumption of : $\sin^2 2\theta_{23} = 1, \quad \Delta m^2_{32} = 2.1 \times 10^{-3} \text{eV}^2, \quad \sin^2 2\theta_{13} = 0.099, \quad NO$

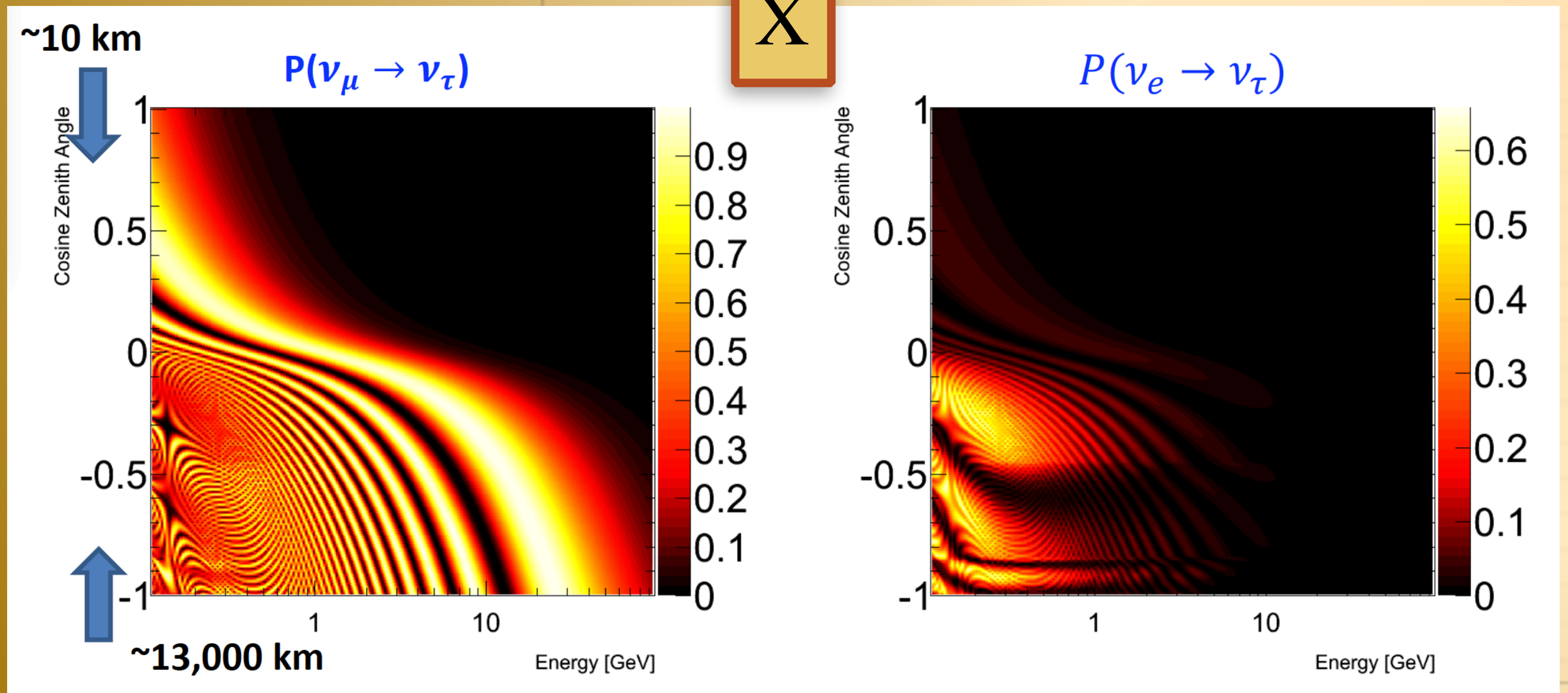
★ Clearly we see that most of the ν_τ appearance is coming from oscillations of a type $\nu_\mu \rightarrow \nu_\tau$

★ ν_τ events have upward - going directions

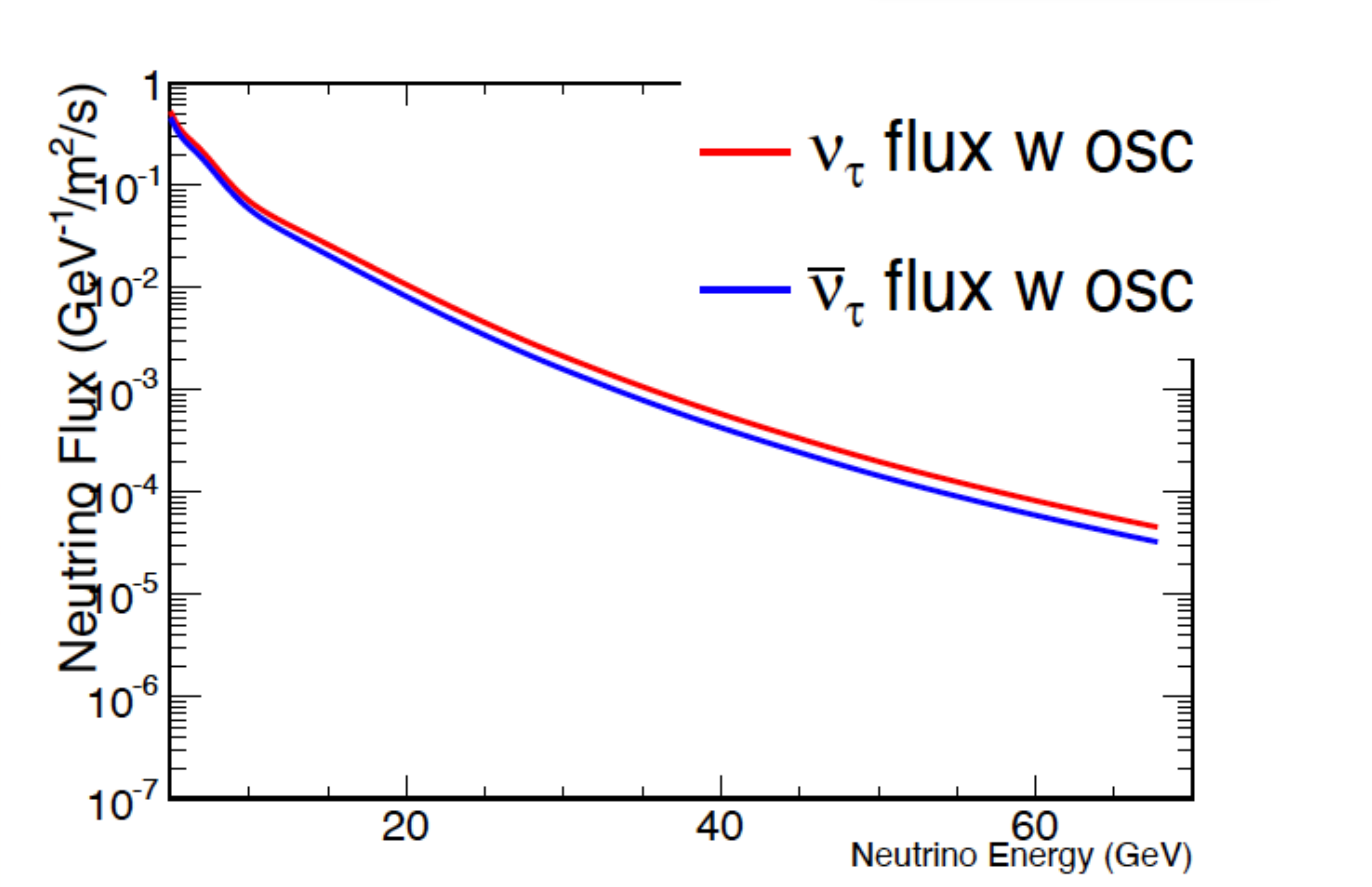
Flux of atmospheric ν_τ from neutrino oscillations at Super-K



X



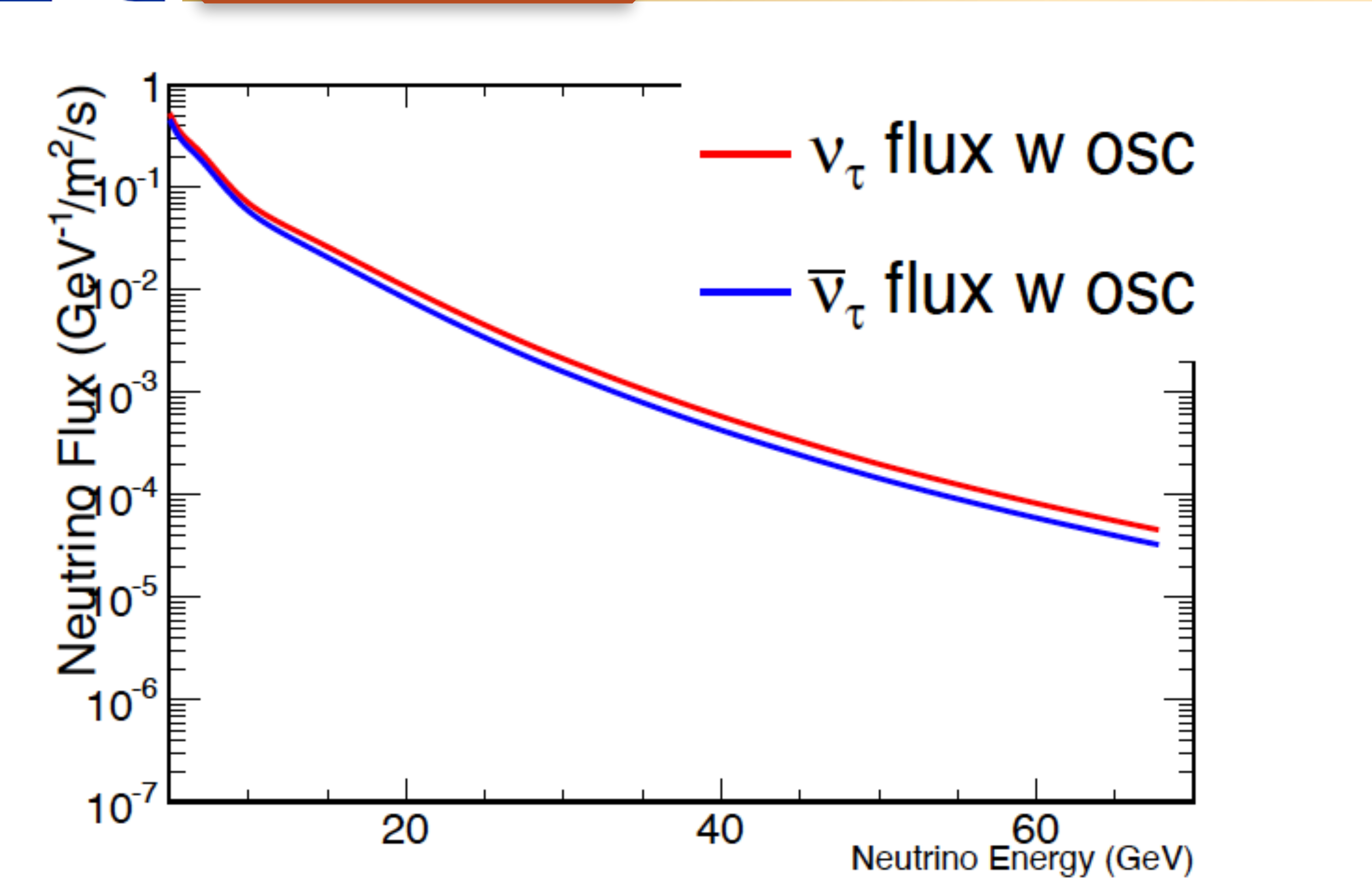
HONDA 2011



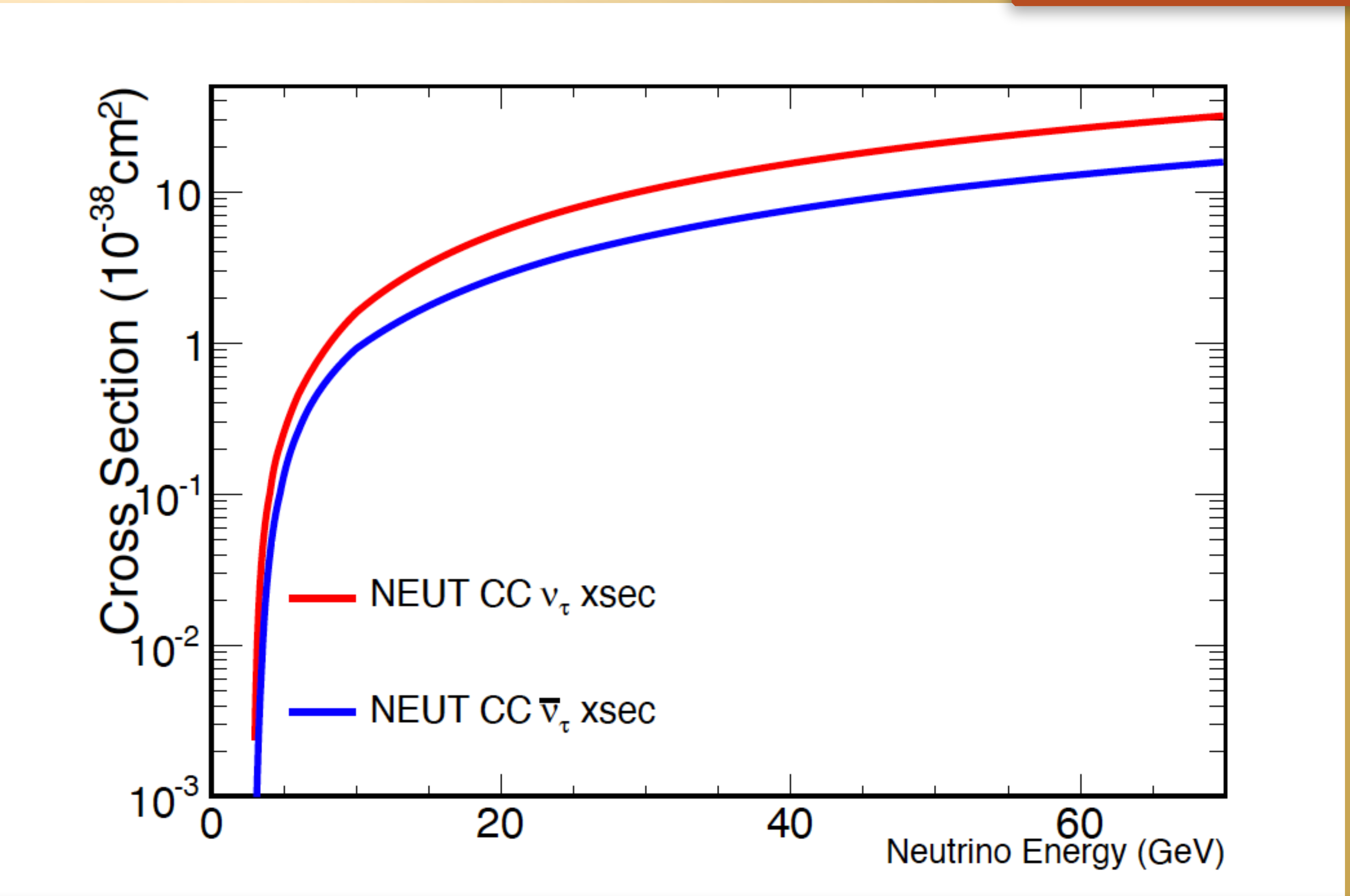
★Flux of atmospheric ν_τ (red) and (blue) from neutrino oscillations as a function of neutrino energy at Super-K

Tau neutrino appearance at Super -K

HONDA 2011



NEUT 5.3.6



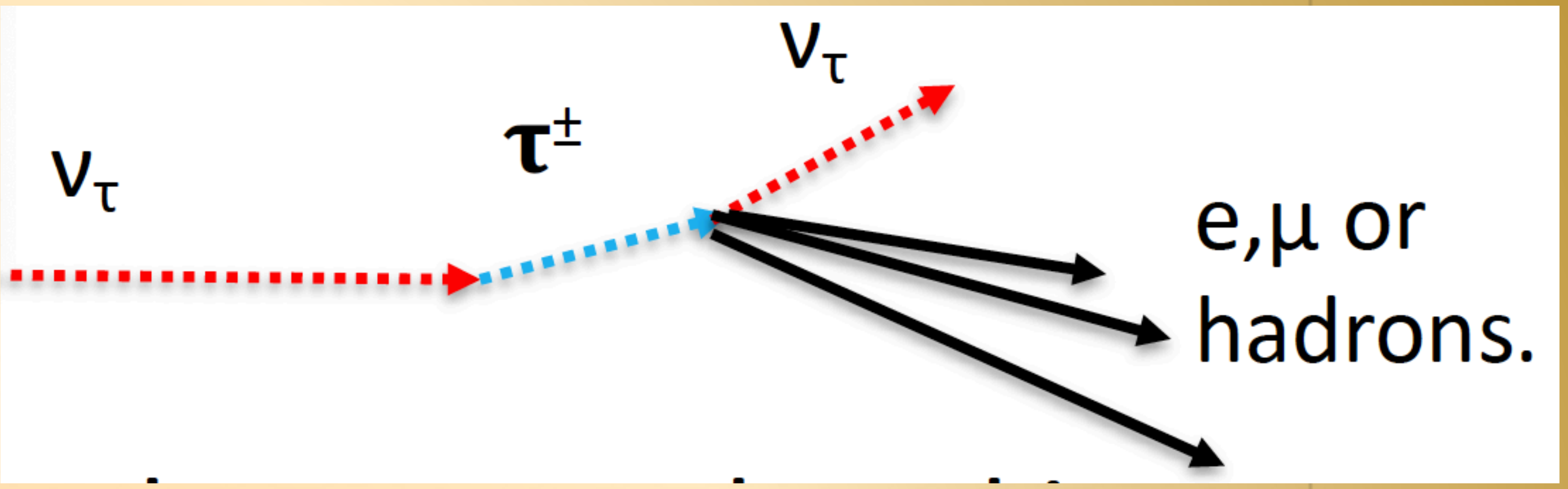
★ The τ **mass** is equal to 1.77 GeV/c^2 which **greatly suppresses the cross section of CCQE** τ interactions at low energies and results in NEUT a energy threshold of 3.5 GeV

★With current values of oscillation parameters we expect (CC) : $\Gamma_\tau \sim$ **1/yr/kton**

★Current Super-K data sets - 1996 -2020 - 484.9 kton-yrs,

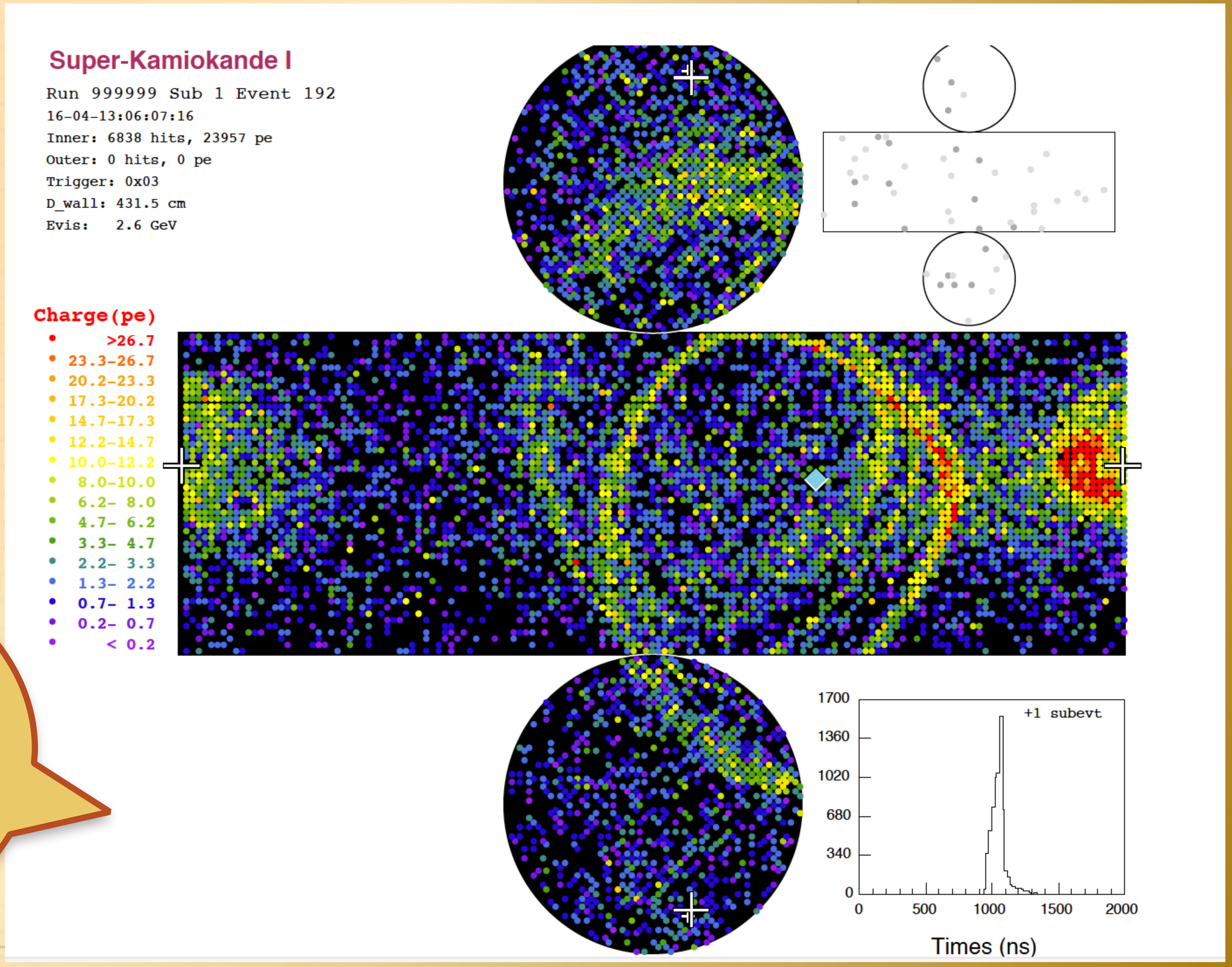
Extremely short lifetime of the τ

- ★ The tau lepton is not directly detected at the Super-K due to its short lifetime $\tau = 290 \times 10^{-15} s$
- ★ We have also many tau decay channels and in hadronic ones there are many additional particles produced that will generate Cherenkov radiation in the Super-K
- ★ As a consequence we will have many multi -ring events coming from the tau decays

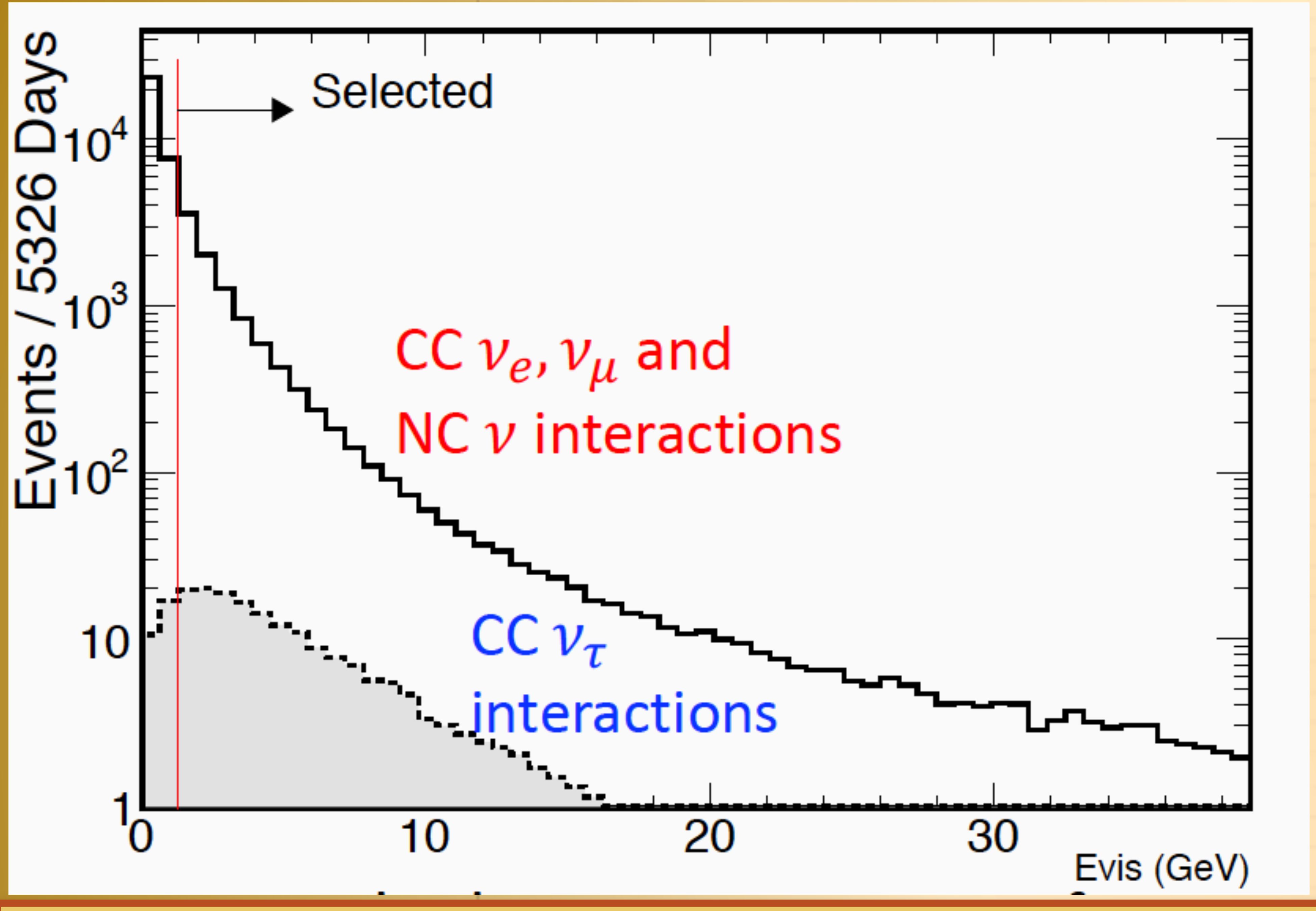


Decay mode	Branching ratio (%)
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.41 ± 0.04
$e^-\bar{\nu}_e\nu_\tau$	17.83 ± 0.04
$\pi^-\nu_\tau$	10.83 ± 0.06
$\pi^-\pi^0\nu_\tau$	25.52 ± 0.09
$\pi^-2\pi^0\nu_\tau$	9.3 ± 0.11
$\pi^-3\pi^0\nu_\tau$	1.05 ± 0.07
$\pi^-\pi^+\pi^-\nu_\tau$	8.99 ± 0.06
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$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

Example of the τ MC event at Super-K



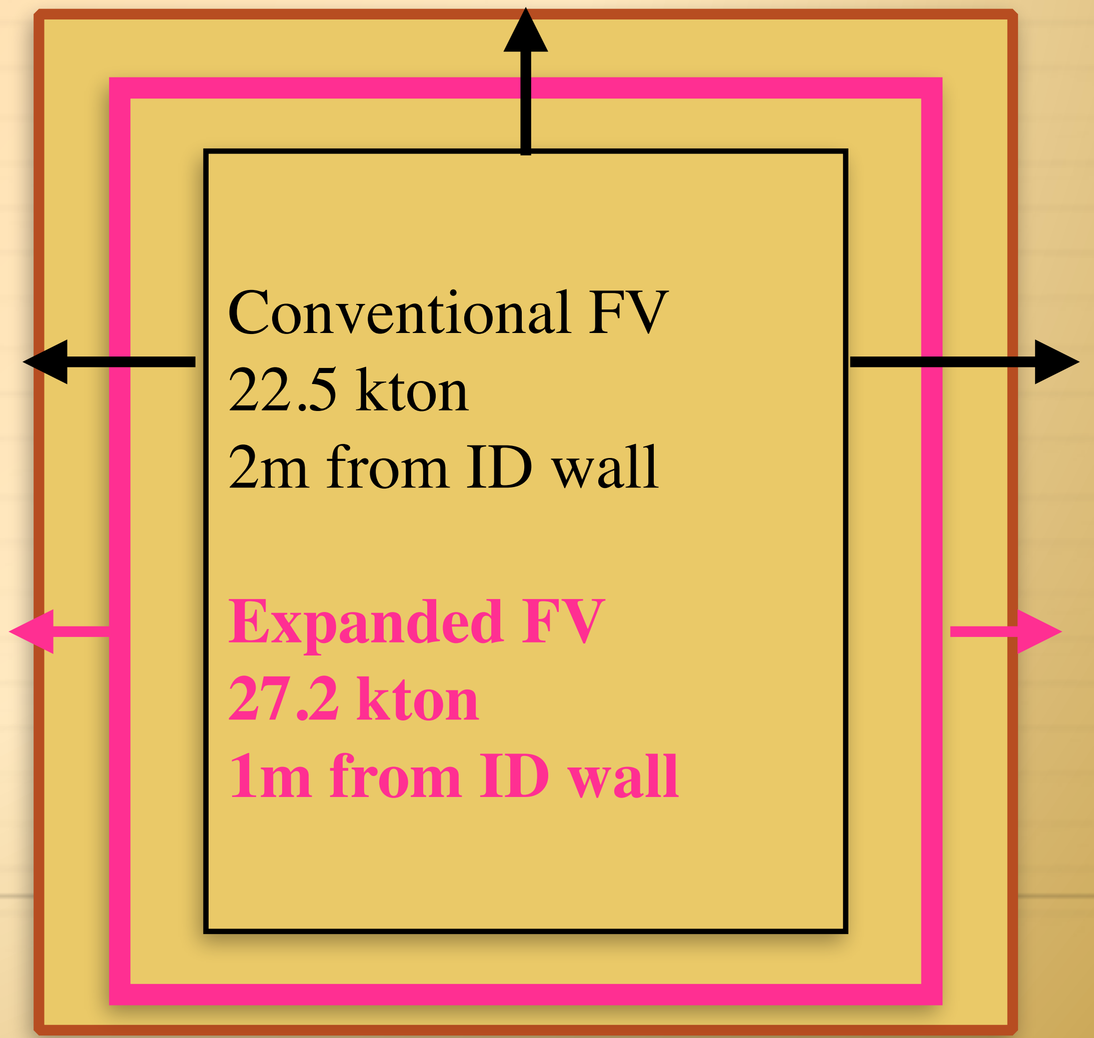
Tau neutrino selections at Super-K



★ The large target mass of Super-K, coupling with the wide energy range of atmospheric neutrinos, makes it possible to detect CC tau interactions. Fully contained events

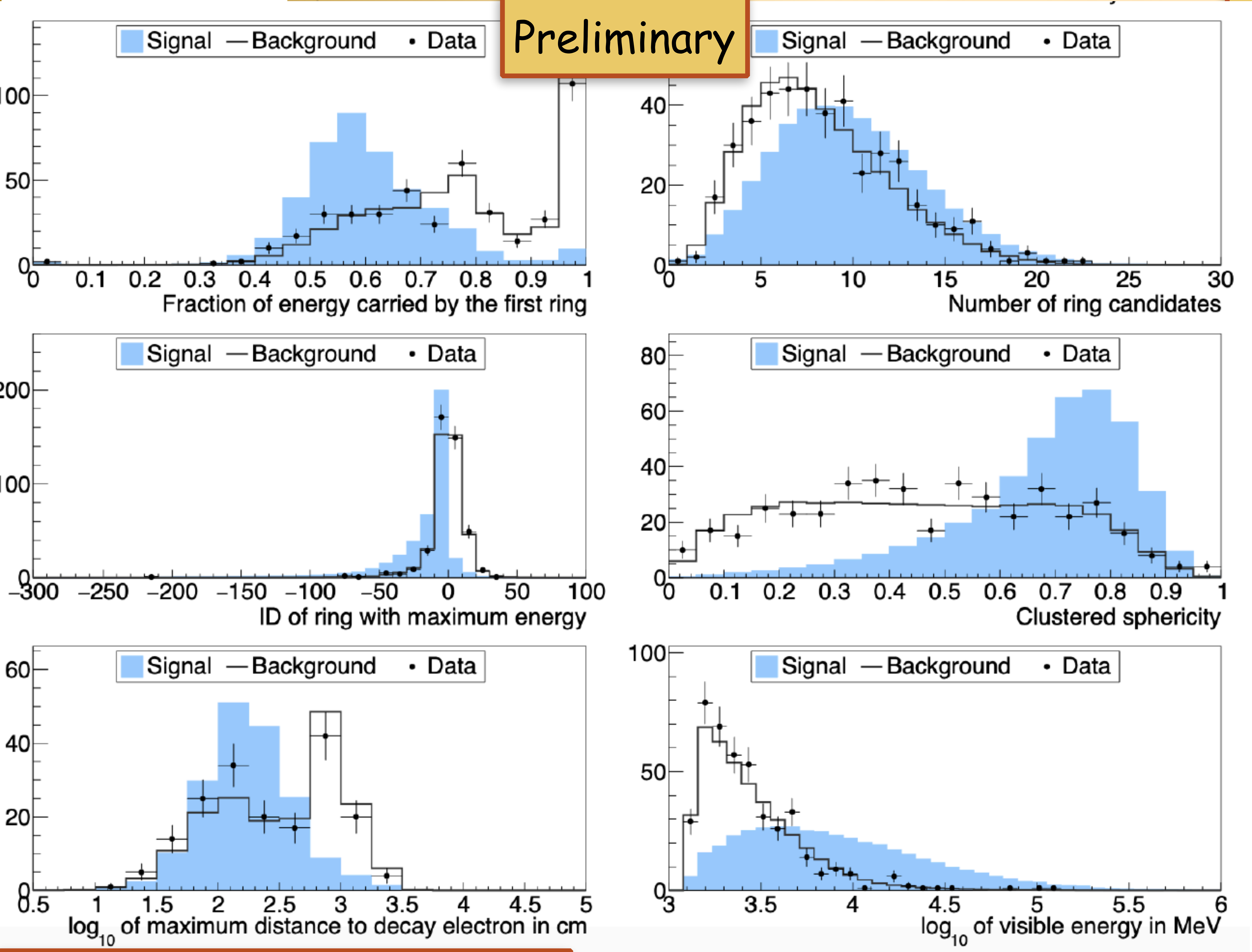
★ The ν_τ selections at Super-K:
- ★Fully contained events
- ★**Vertex reconstructed 1 m from the nearest wall (expanded FV region)**
- ★$E_{vis} > 1.33$ GeV - multi-ring events

- **What is new in 2023 tau analysis ?**
  - **50% more data statistics added by:**
    - **SK- IV added - 2016-2018 - full SK-V period**
    - **Expanded Fiducial Volume region**
    - **Reconstruction and PID algorithms have been improved for expanded region.**



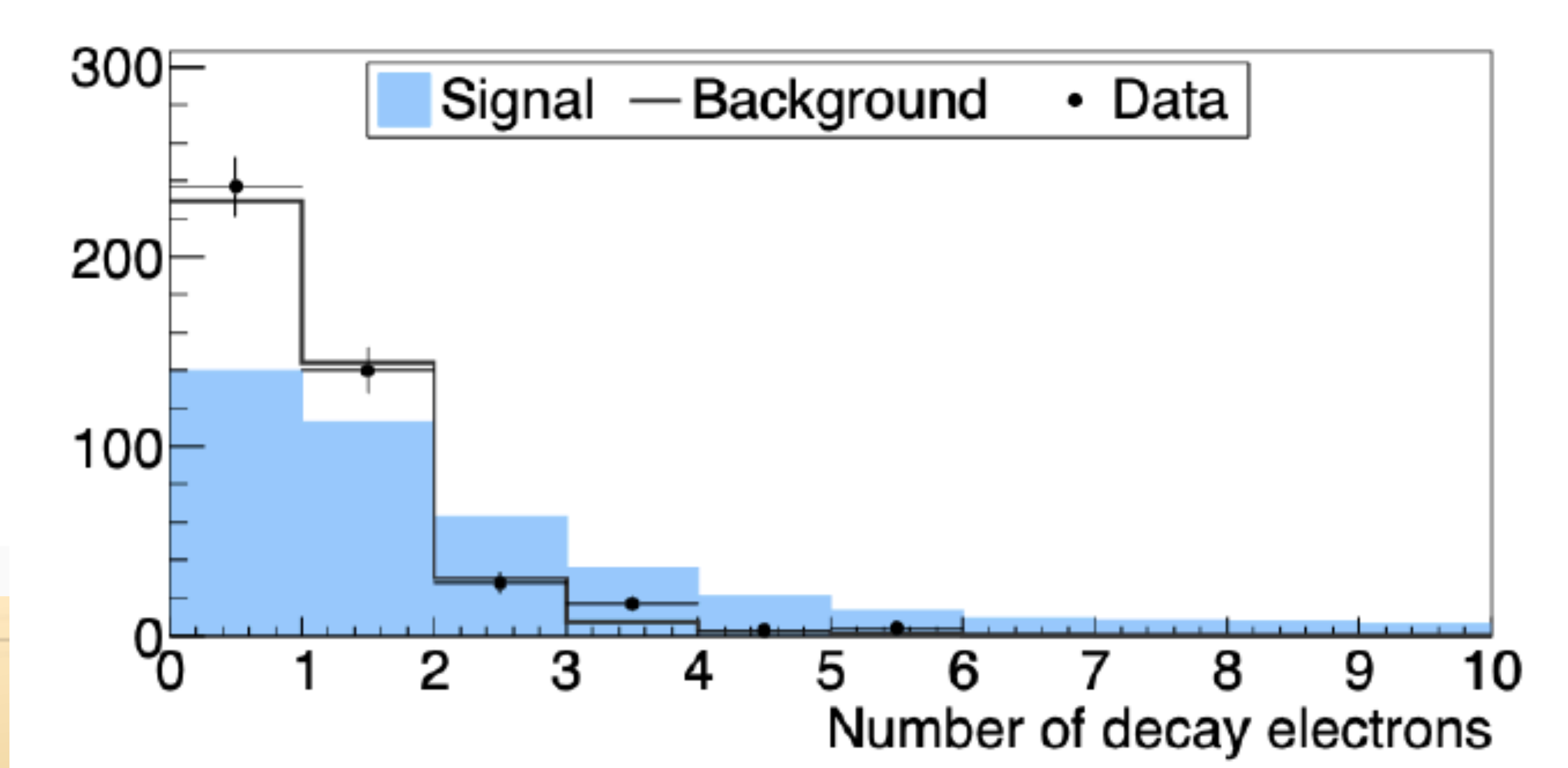
A neutral network algorithm to identify ν_τ interactions

Preliminary



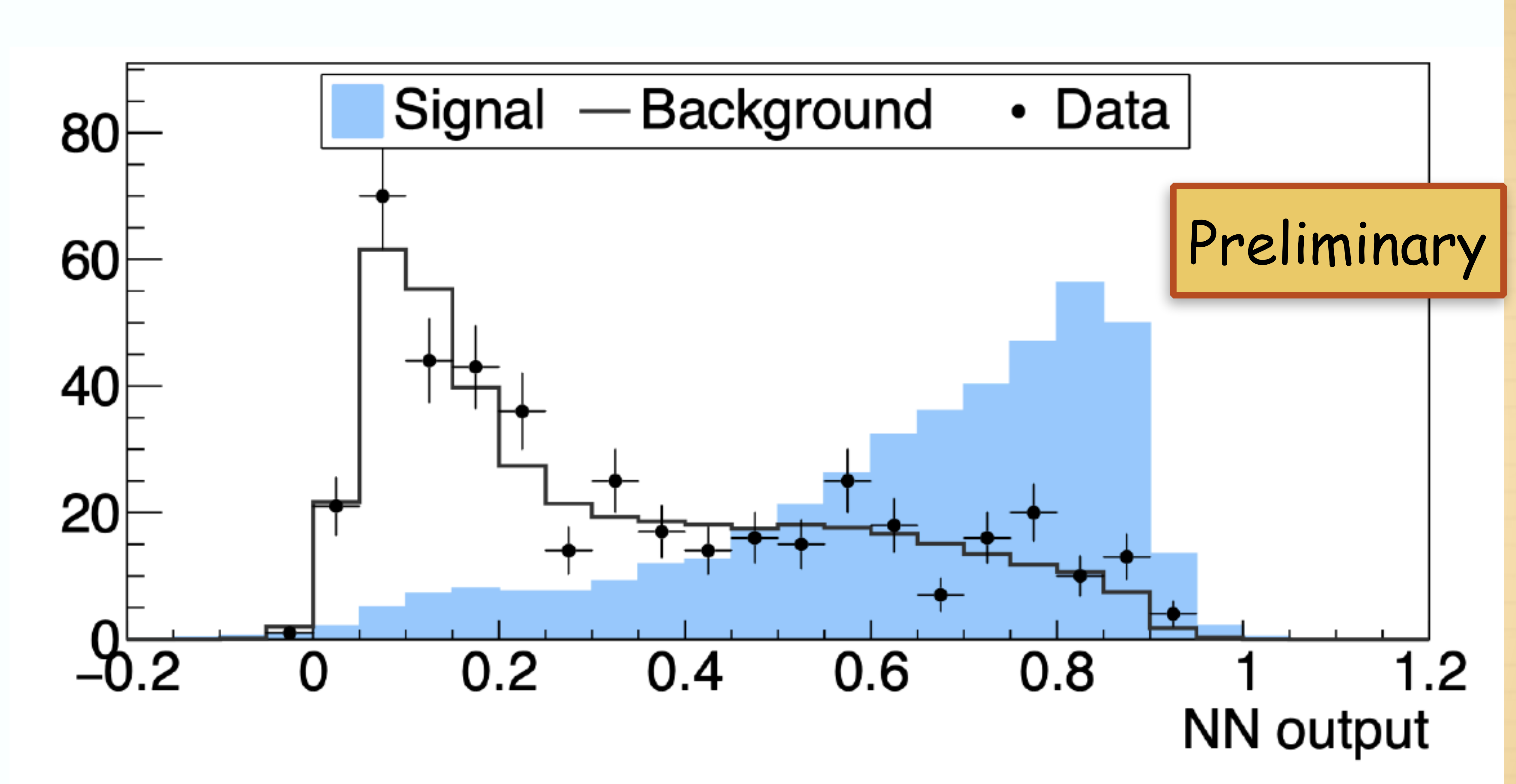
★ We use **seven input variables** for the tau identification to the neural network (NN) algorithm:

- ★Log E_{vis} - total visible energy in the event
- ★The particle identification of the most energetic ring
- ★Number of decay electron candidates ($\pi \rightarrow \mu \rightarrow e$ or $\mu \rightarrow e$)
- ★The maximum distance between the primary interaction point and any decay electron
- ★Number of ring candidates
- ★The clustered sphericity of the event
- ★The fraction of total number of photoelectrons in the event carried by the first ring



Maitrayee Mandal, NCBJ, Warsaw

A neutral network algorithm to identify ν_τ interactions



Preliminary

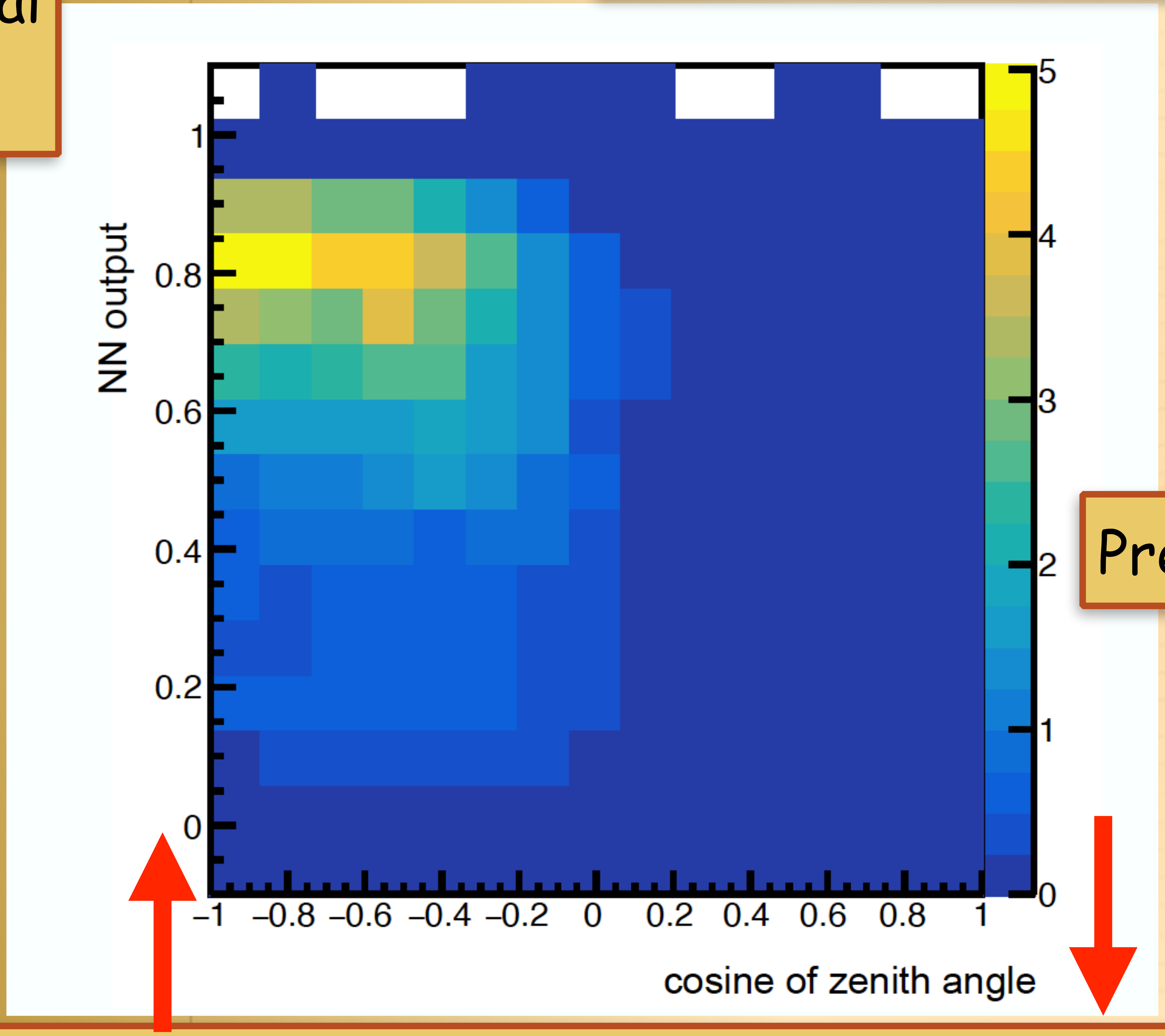
☆ MC and DATA plots showing the output distribution for the tau CC signal and the background for SK I-V.

Maitrayee Mandal, NCBJ, Warsaw

Search for tau neutrino appearance

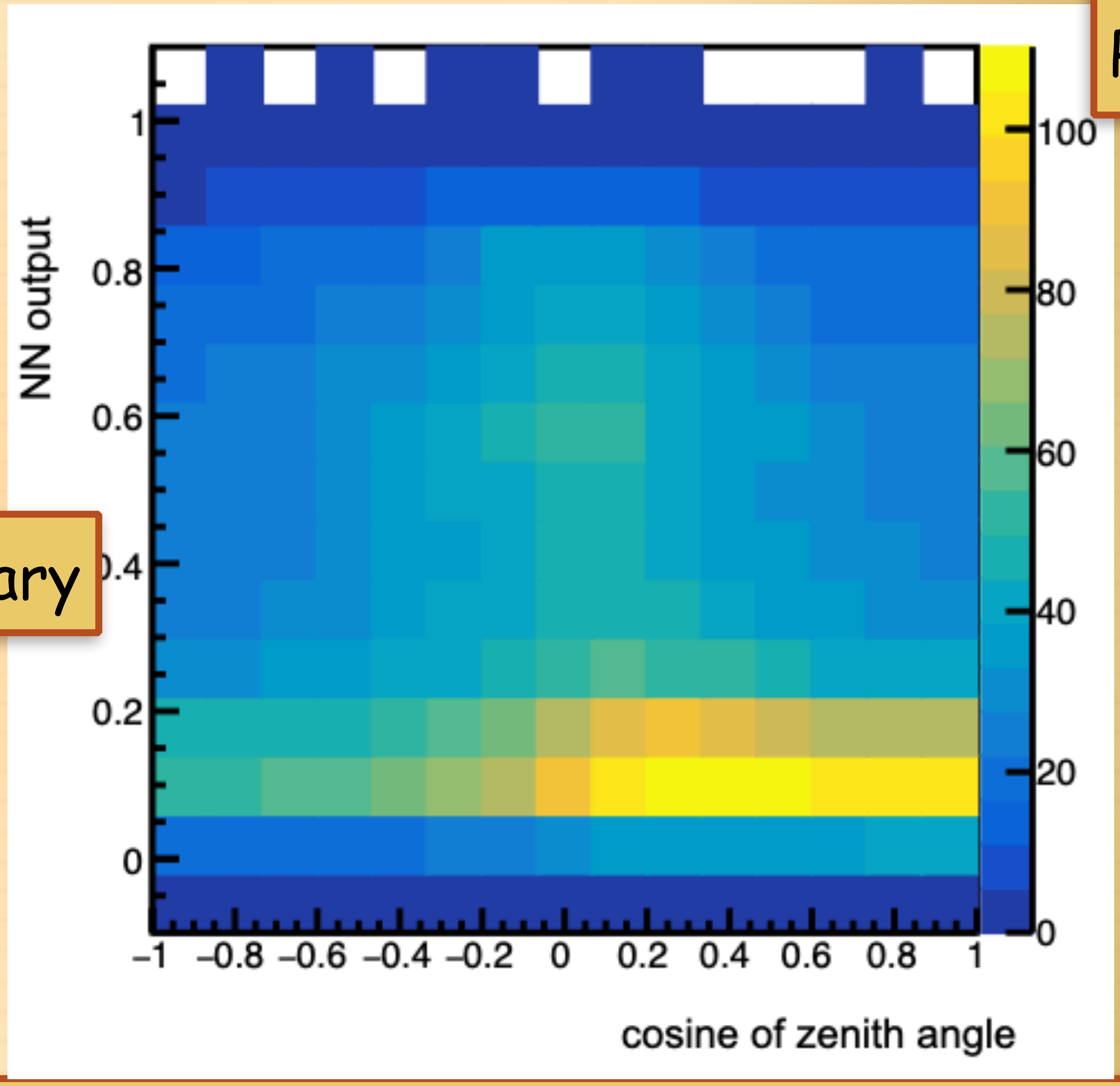
$$\mathrm{DATA} = \mathrm{PDF_{BG}} + \alpha \times \mathrm{PDF_{tau}} + \sum \epsilon_i \times \mathrm{PDF_i}$$

Tau signal PDF$_{tau}$



Preliminary

Background PDF$_{tau}$



★ Fit two-dimensional likelihood PDFs with event direction and neural network output for signal and background and simultaneously varying systematic error templates

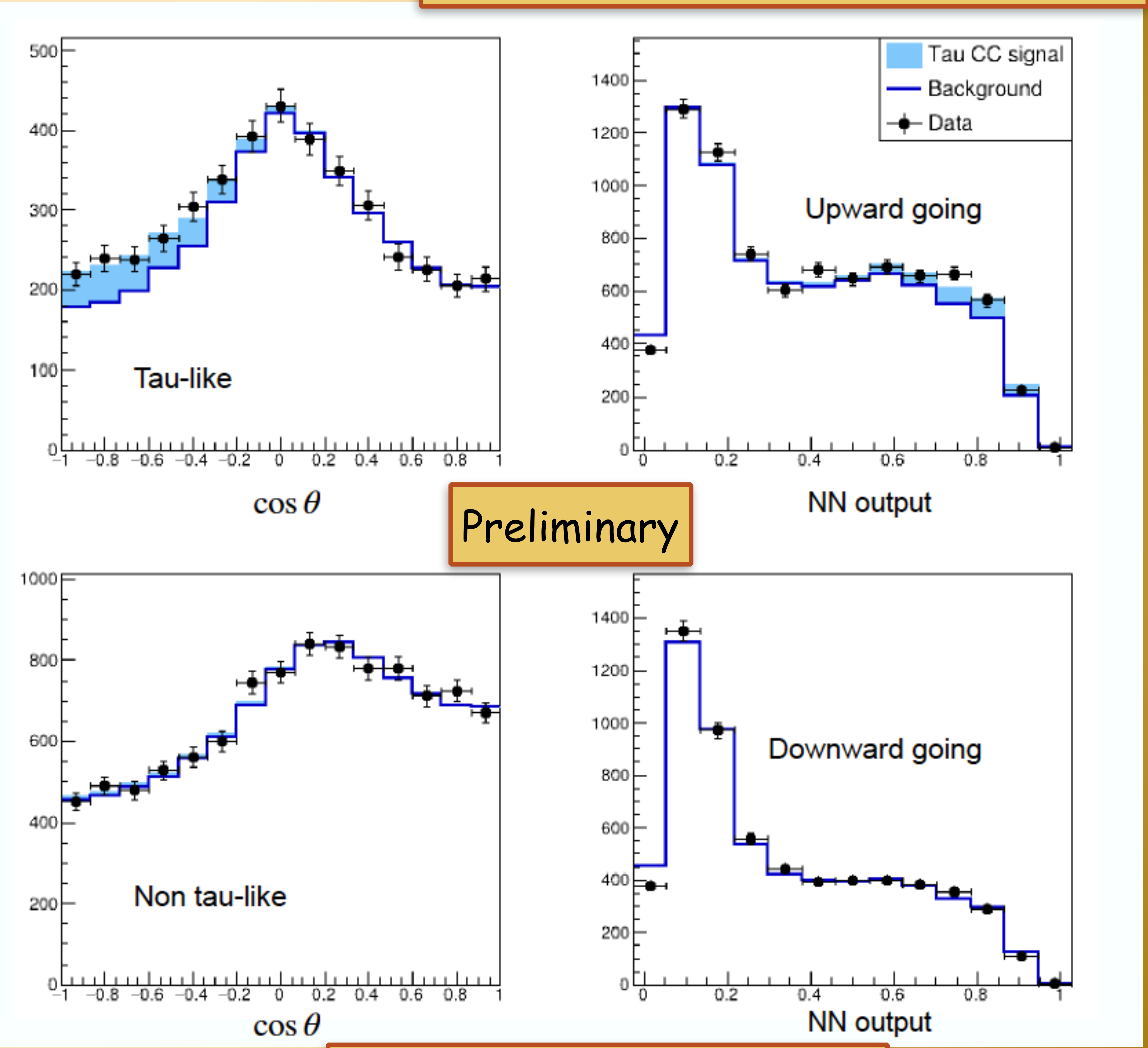
Maitrayee Mandal, NCBJ, Warsaw

New tau appearance results

2023 tau appearance result!!!!

$$\text{DATA} = \text{PDF}_{\text{BG}} + \alpha \times \text{PDF}_{\text{tau}} + \sum \epsilon_i \times \text{PDF}_{\text{i}}$$

- ★ $\alpha = 1.36 \pm 0.29$(stat. + syst.)
- ★ 4.8σ rejection of no tau appearance
- ★ 428 ± 92 observed tau events at Super-K pure water periods

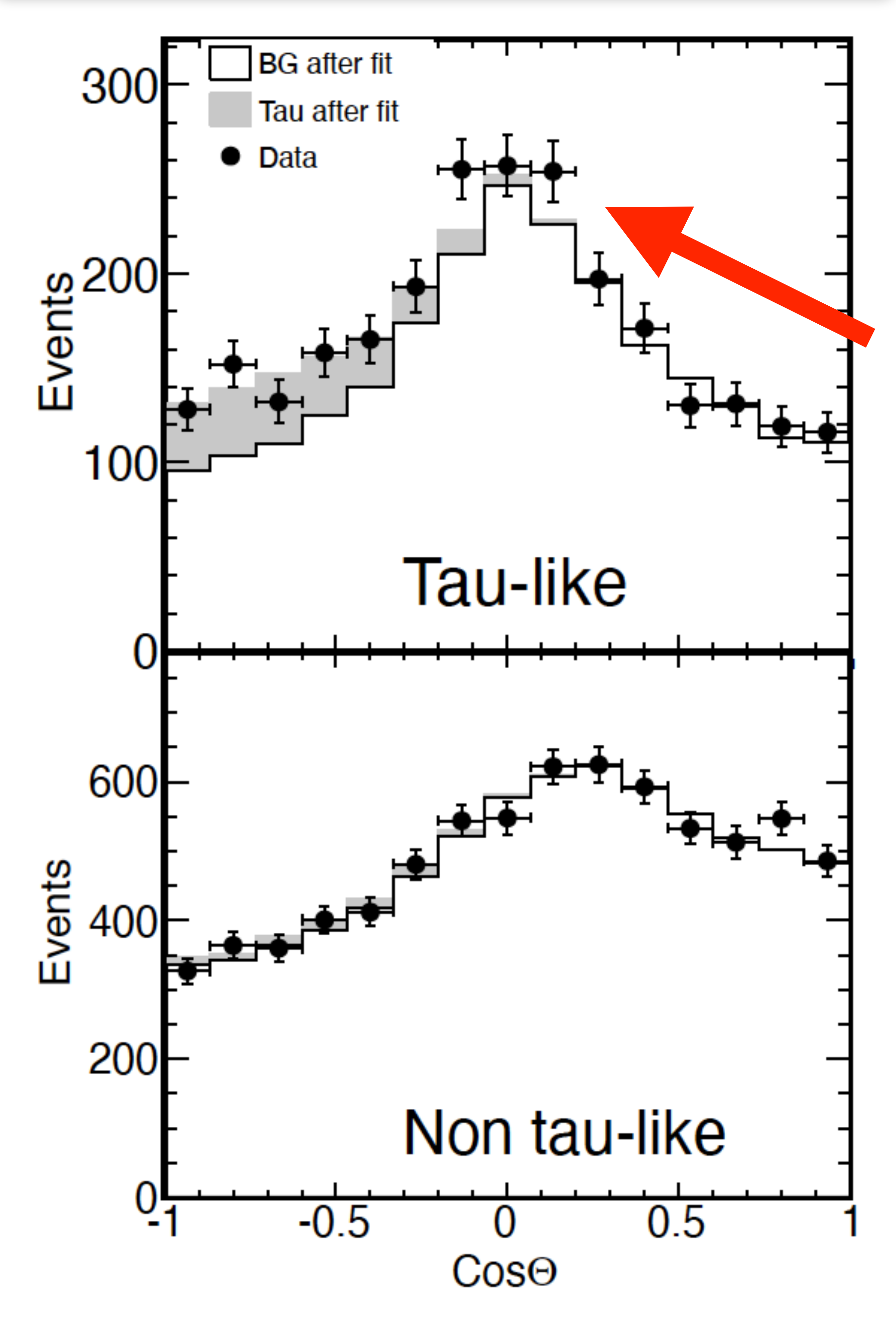


Preliminary

Maitrayee Mandal, NCBJ, Warsaw

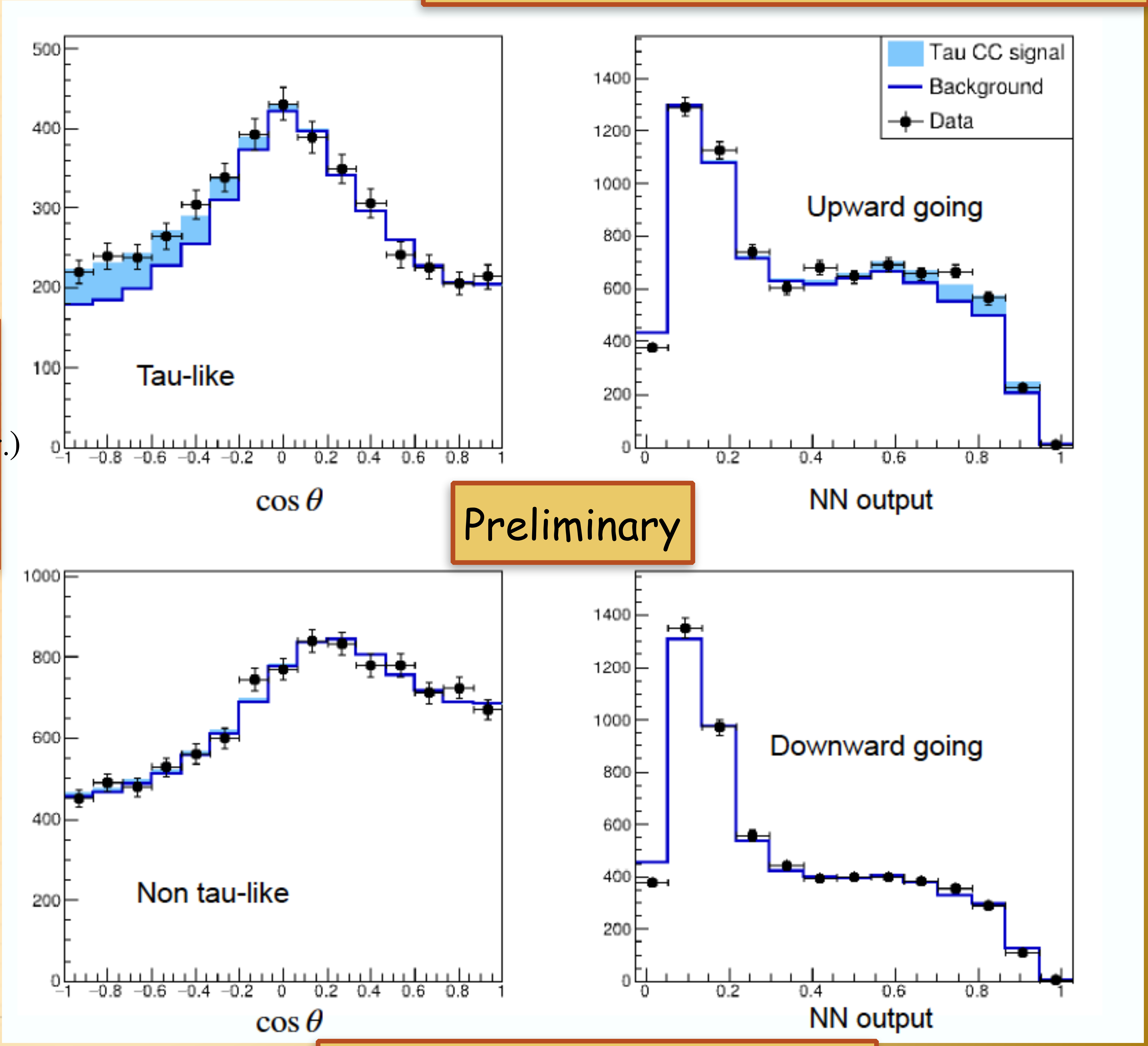
New tau appearance results

PHYS. REV. D 98 052006 (2018)



- ★ Last published result from 2018:
- ★ $\alpha = 1.47 \pm 0.32$(stat. + syst.)
- ★ 4.6σ rejection of no tau appearance

2023 tau appearance result!!!!



Preliminary

Maitrayee Mandal, NCBJ, Warsaw

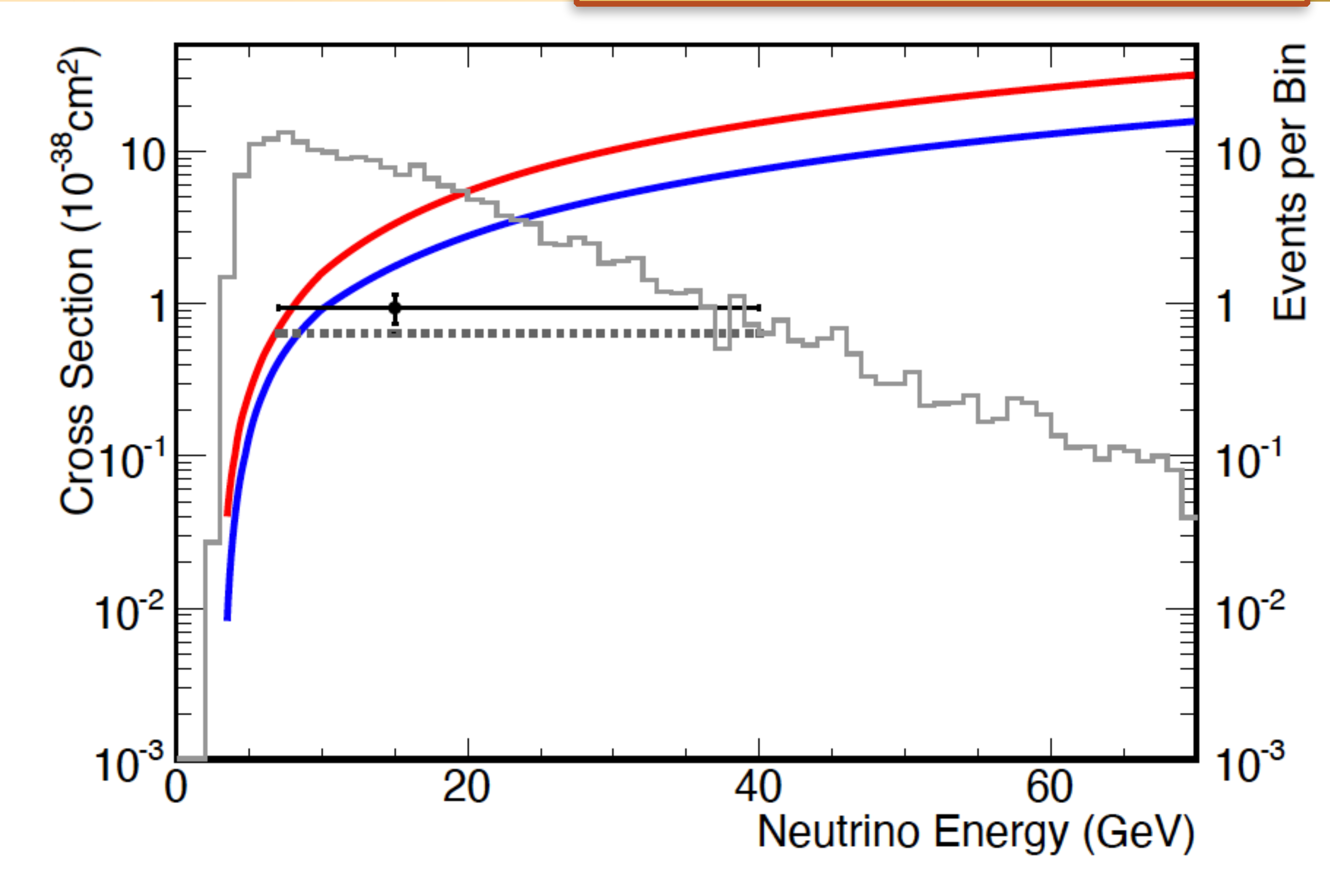
ν_τ CC interaction cross -section

- ★ ν_τ CC interactions observed in Super-K give the opportunity to measure the CC cross section.
- ★ By scaling the theoretical cross section in the MC simulations to match the data, we can measure the inclusive charged-current tau neutrino cross section in water:

$$\sigma_{measured} = \alpha \times \sigma_{theory}$$

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

PHYS. REV. D 98 052006 (2018)

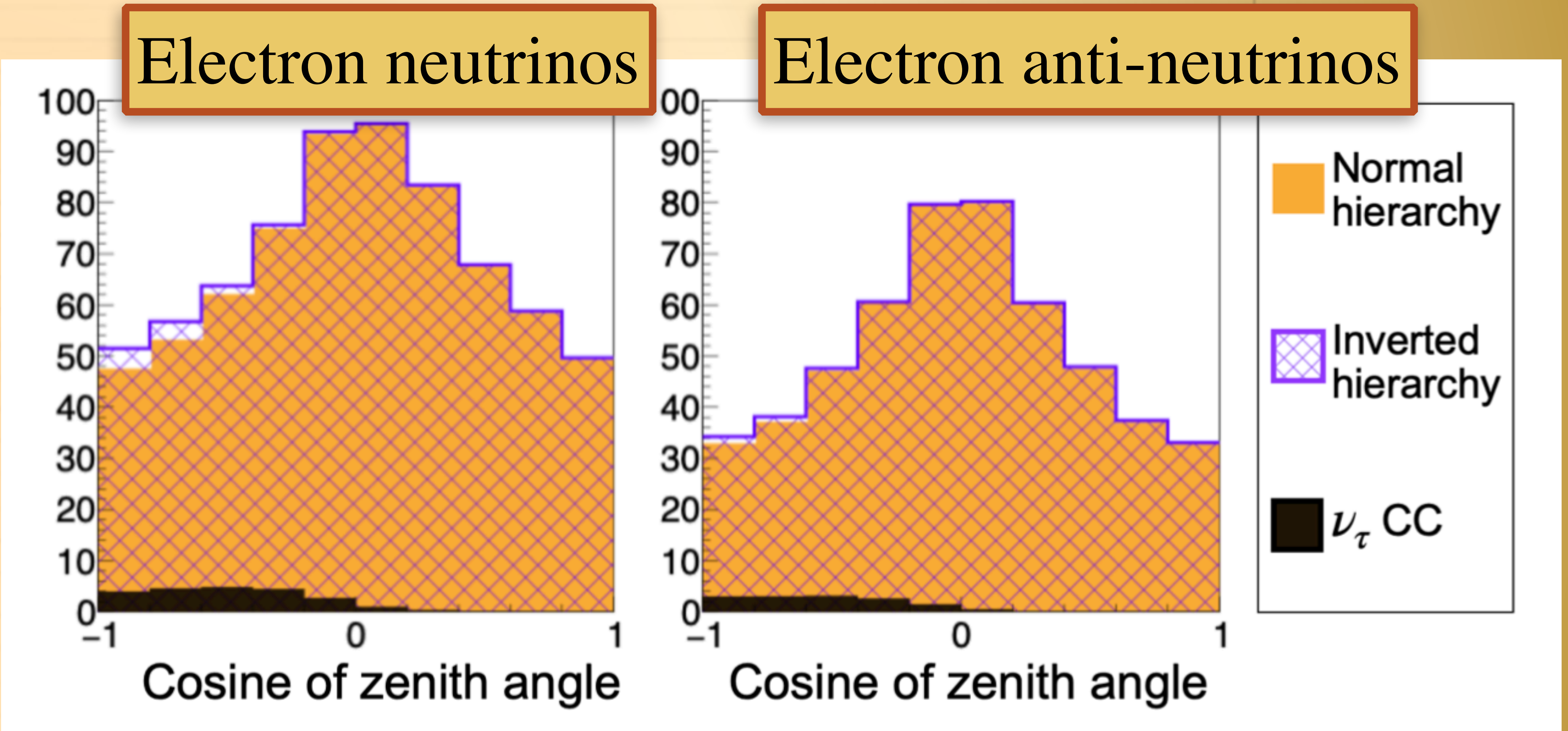


The uncertainty on the tau cross-section is large (25%) and not well measured !!!!

Tau neutrino background in the atmospheric neutrino samples

- What are the next steps ?
  - removing **tau neutrino background from the multi-ring ν_e-like and $\bar{\nu}_e$ - like** samples at Super-K which are used to study mass hierarchy.

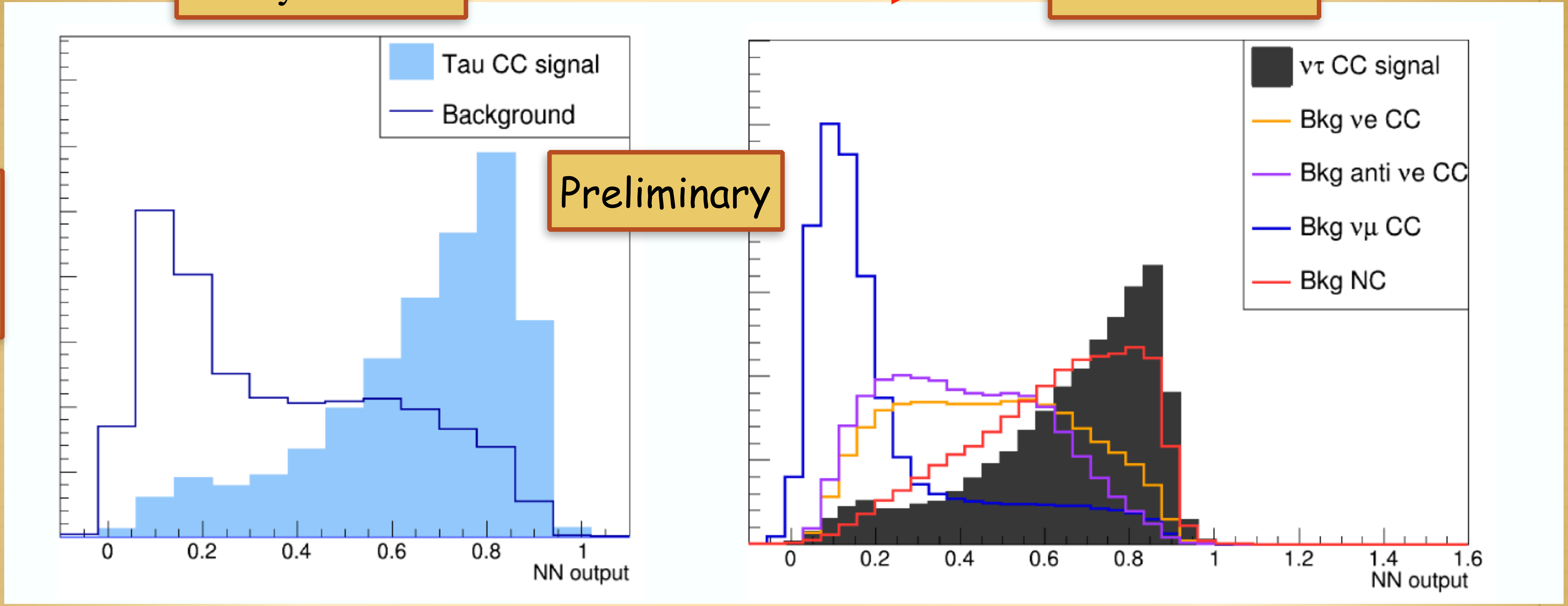
Event rates of multi-ring e-like samples at Super-K



DOI: https://doi.org/10.22323/1.414.1074

Future prospects in tau searches

Binary classifier → Multi classifier



Shorter time scale

Work in progress!

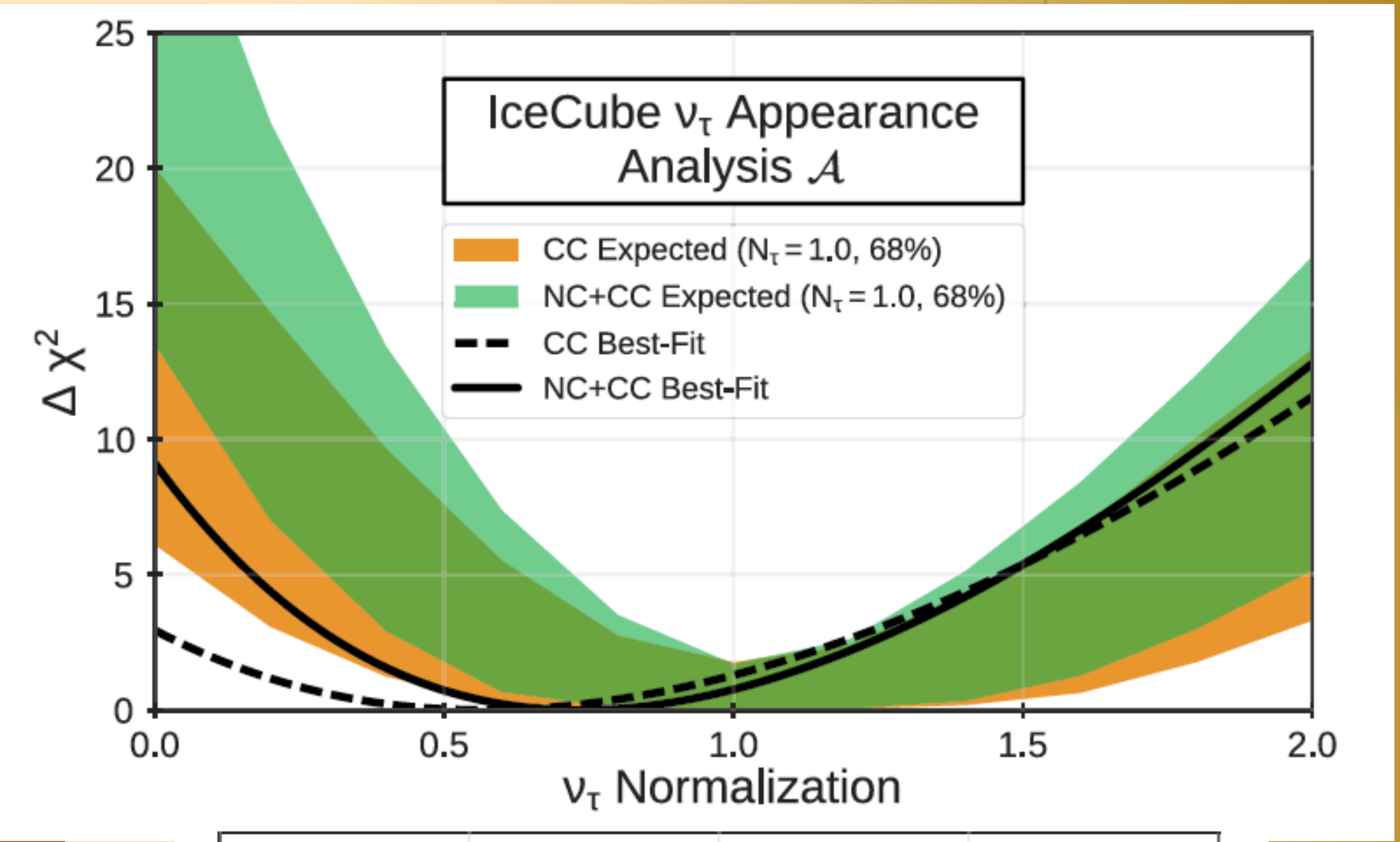
- ★ Moving from binary classifier to multi classifier.
- ★ Adding new information as input to the machine learning tools: using information on neutron capture - work ongoing, problems with neutron multiplicities

★ **AIM** : To extract tau like events from multi-ring e-like samples which are sensitive to mass ordering searches.

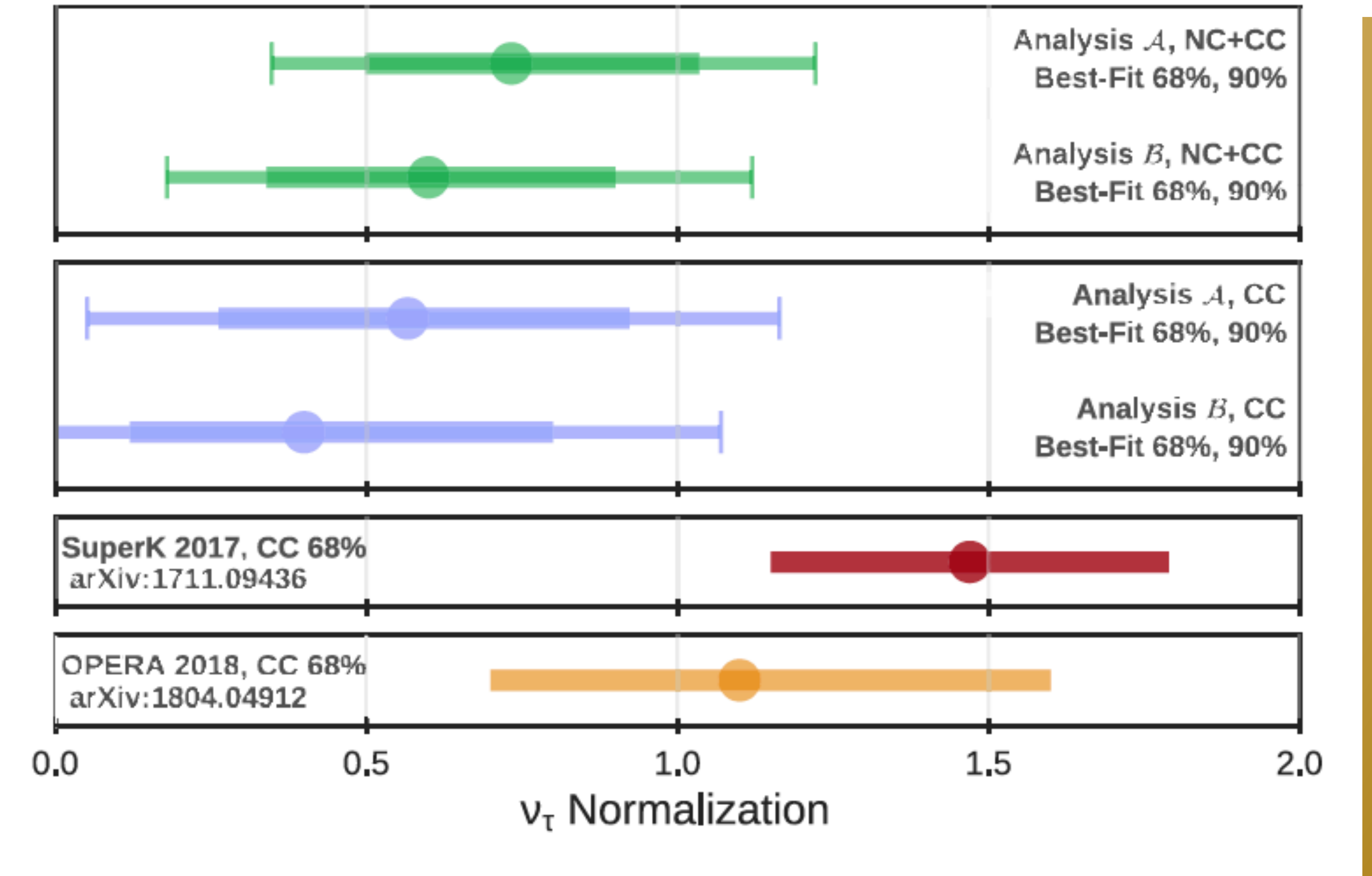
Recent and future prospects in tau searches

Low-energy tau neutrinos in IceCube

- ★**Tau neutrino candidates in the detector appear from atmospheric muon neutrino oscillations $\nu_\mu \rightarrow \nu_\tau$**
  - ★For CC ν_τ interactions in GeV energy region we immediate tau decays which produce single cascades in the detector
  - ★By allowing for a ν_τ appearance contribution to all cascade events, the so-called tau normalisation can be fitted



- ★**Analysis A** targets high acceptance of all flavour neutrino events and its bkg estimation is simulation driven
- ★**Analysis B** is optimised for higher rejection of non-neutrino events and its atmospheric muon bkg estimation is data driven



Phys. Rev. D 99, 032007 (2019)

High-energy tau neutrinos in IceCube

★**Tau neutrino candidates in the detector:**

★For CC ν_τ interactions we have so called "**double cascade**" event when two showers are separated by the tau decay distance.

★7.5 years of high energy events were scanned - two candidates for tau events were found

Eur. Phys. J. C (2022) 82

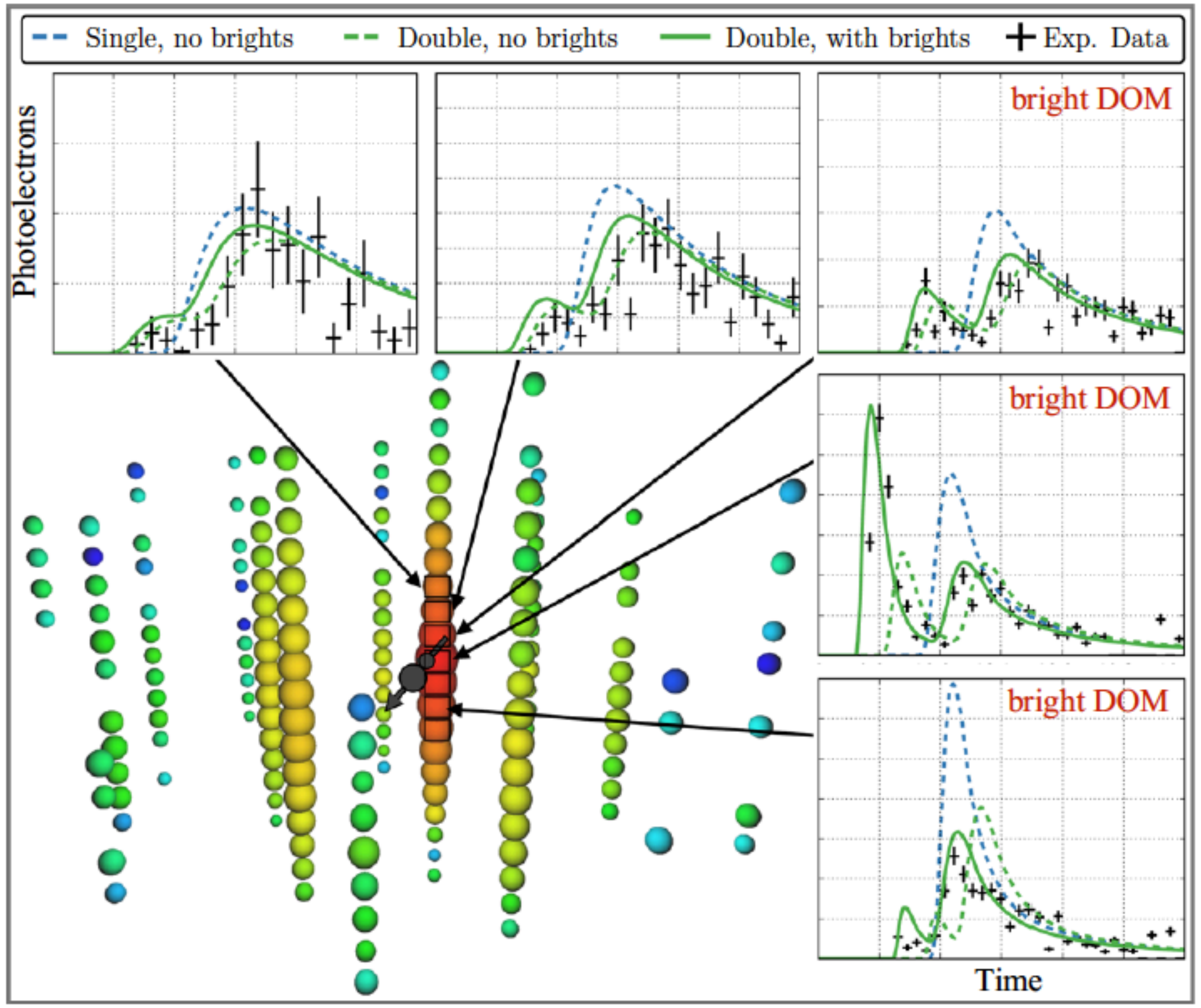
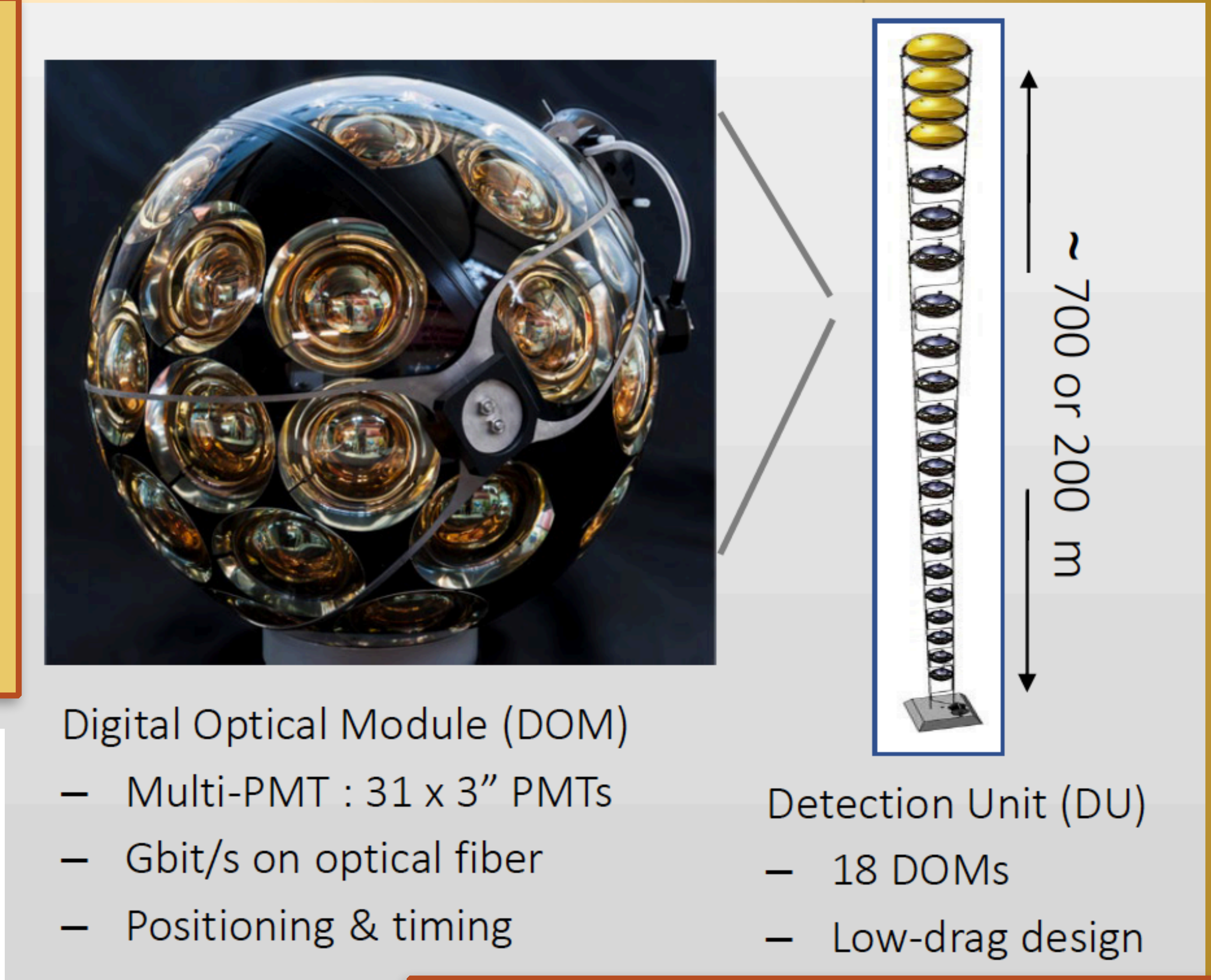


Fig. 4 Double-cascade event #2 (2014). The reconstructed double-cascade vertex positions are indicated as grey circles, the direction indicated with a grey arrow. The size of the circles illustrates the relative deposited energy, the color encodes relative time (from red to blue). Bright DOMs are excluded from this analysis

Other prospects in tau searches - Km3Net

- ★ KM3NeT will be constructed at two separate geographical locations:
  - ★ a densely instrumented detector called **Km3Net ORCA** will be built off the French coast and will study **low-energy atmospheric neutrino** oscillations
  - ★ a more sparsely instrumented detector called **Km3Net ARCA** will be built off the Italian coast near **Sicily** for the study of **high-energy astrophysical neutrinos**



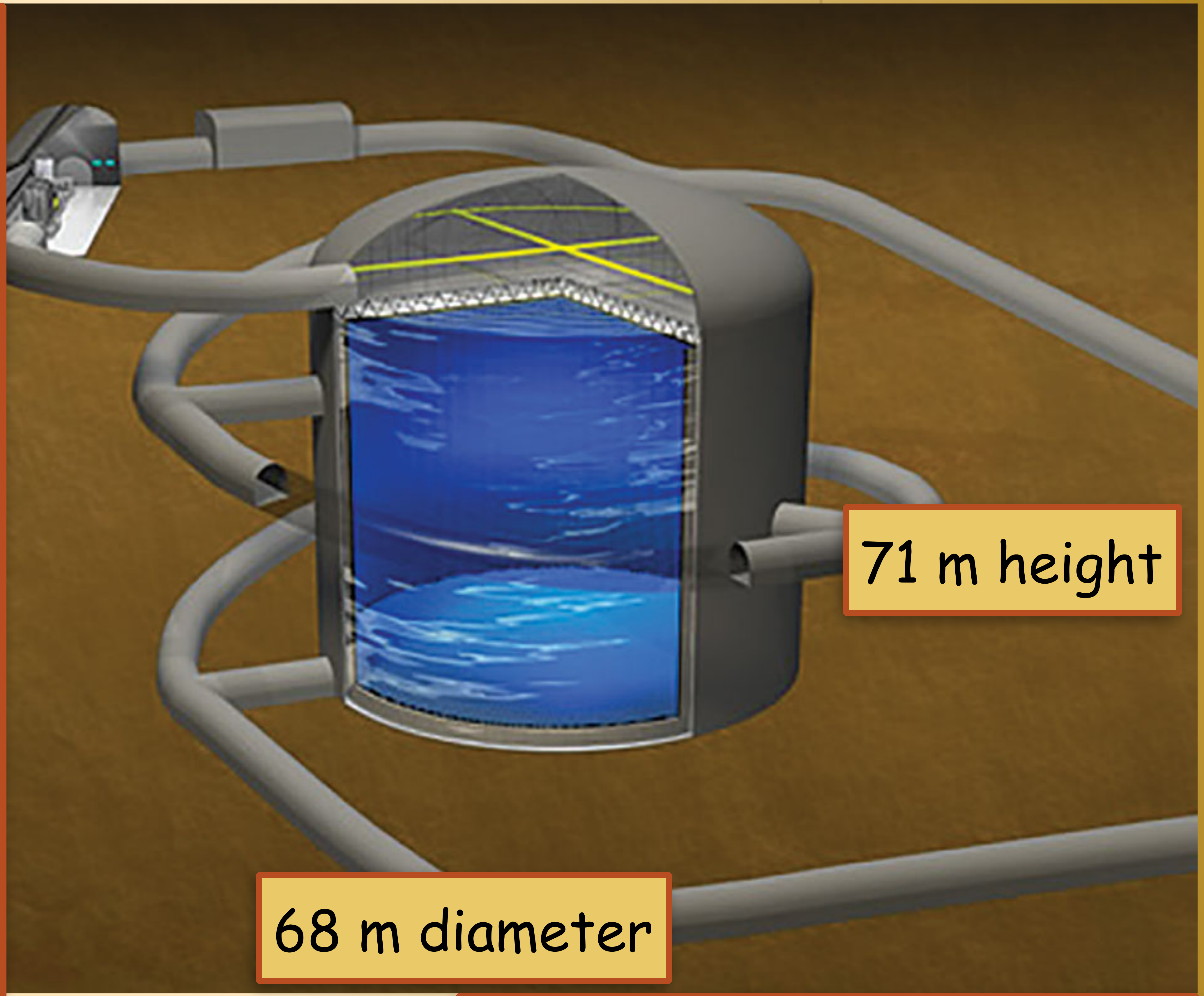
	IceCube Upgrade	**KM3NeT ORCA**
Completion	2022-2023 [12]	2023 [13]
Tau normalisation	13% constrained	20% constrained at 3σ after 1 year
Neutrino mass ordering (*)	3σ in 3-8 years	3-6σ in 3 years
Δm^2_{32} relative uncertainty (RU)	3%	3%
$\sin^2(\theta_{23})$ RU at maximal mixing	14%	13%
$\sin^2(\theta_{23})$ RU off-maximal mixing	8%	4%

Aart Heijboer, Neutrino 2022

https://arxiv.org/pdf/1812.01036.pdf

Future prospects in tau searches - Hyper Kamiokande

- ★**Hyper-Kamiokande experiment - starts data taking in 2027**
  - ★Tank will have 260 kton with FV of ~186 kton which is **~6.8 times larger than Super-K expanded FV 27.2 kton)**
  - ★ **Hyper-K** will be able to accumulate atmospheric neutrinos at a rate more than **10 times as fast as Super-K**, significantly reducing the statistical uncertainty in atmospheric neutrino analyses.
  - ★Current Hyper-K analysis uses the same methodology as Super-K
  - ★**In 10 years of data in Hyper-K we expect** ~2000 ν_τ CC events - no improvements assumed in systematic errors or detector performance
  - ★Expect improvements with the CC ν_τ cross-section measurements



See the talk by prof. T. Nakaya

Summary

★ **New 2023 tau neutrino appearance results** were presented using complete Super-K I-V pure water data sets:

- ★ we get $\alpha = 1.36 \pm 0.29$(stat. + syst.) **with 4.8σ rejection of no tau appearance**
- ★this corresponds to 428 ± 92 observed tau events at Super-K.
- ★What next ?
  - ★ extract tau like events from multi-ring e-like samples which are sensitive to mass ordering searches

★Other interesting tau searches: IceCube, Km3Net and future Hyper-Kamiokande - stay tuned !

Thank you!

Photo Credit: Piotr Mijakowski

Systematic uncertainties in the tau analysis

★ The uncertainty in the tau normalisation was most affected by the change in the event rates due to the uncertainty in the NC/CC ratio when looking at the systematics' sources without correlations.

★ Dominant systematics are cross section related but flux errors also play a role

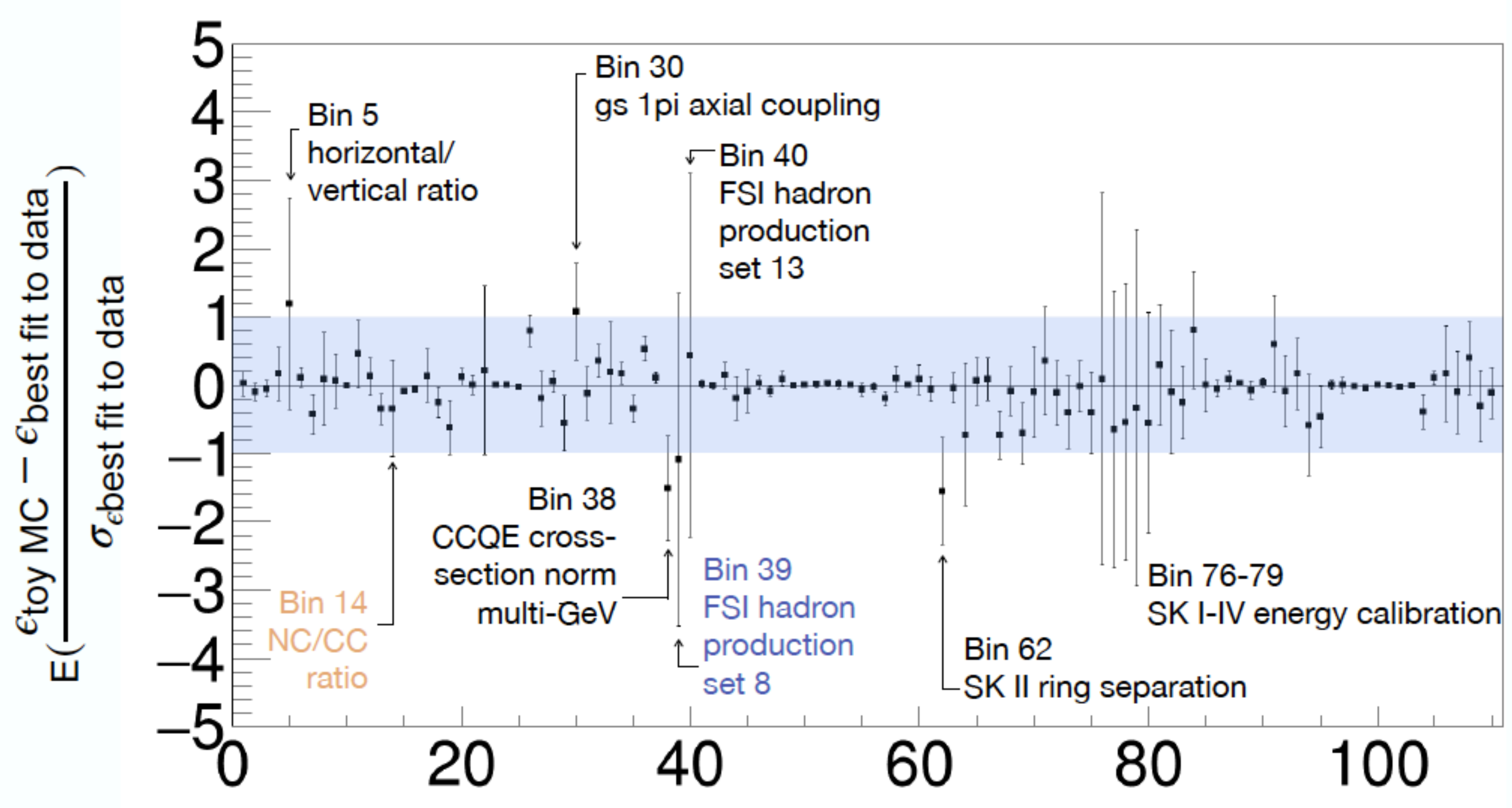


Figure 8: Post-fit pulls for the different systematic uncertainties showing the uncertainty in nearly all sources is within the 1σ range.

	Key name of the systematic uncertainty in the Fij root files	Tau normalisation in the case of introducing a single systematic error in the study	Uncertainty in tau normalisation
1	NC_CC_ratio	0.97 +/- 0.23	24%
2	DIS_xsec	0.98 +/- 0.22	22%
3	fsi_hadprod_up_set8	1.05 +/- 0.23	22%
4	dis_q2_high_W	0.97 +/- 0.21	21%
	DIS_model_difference	1.02 +/- 0.20	20%
5	dis_had_mult	1.04 +/- 0.19	19%
6	gs_1pi_axial_coupling	1.05 +/- 0.19	19%
7	dis_norm_low_W	1.04 +/- 0.19	18%
8	dis_q2_vec_low_W	1.04 +/- 0.19	18%
9	fsi_hadprod_down_set13	1.04 +/- 0.19	18%
10	nubar_nu_1pi_ratio	1.05 +/- 0.19	18%
11	dis_q2_axi_low_W	1.04 +/- 0.19	18%
12	mec_on_off	1.06 +/- 0.19	18%
13	gs_1pi_bkg	1.05 +/- 0.19	18%
14	neut_axial_mass	1.06 +/- 0.19	18%
15	gs_1pi_CA5	1.06 +/- 0.19	18%
16	CCQE_xsec_shape	1.04 +/- 0.19	18%
17	CCQE_nu_nubar_ratio	1.04 +/- 0.19	18%
18	CCQE_numu_nue_ratio	1.04 +/- 0.19	18%
19	coherent_pi_xsec	1.05 +/- 0.19	18%
20	pi0_qpi_ratio	1.06 +/- 0.19	18%
21	CCQE_xsec_norm_mult	1.06 +/- 0.19	18%

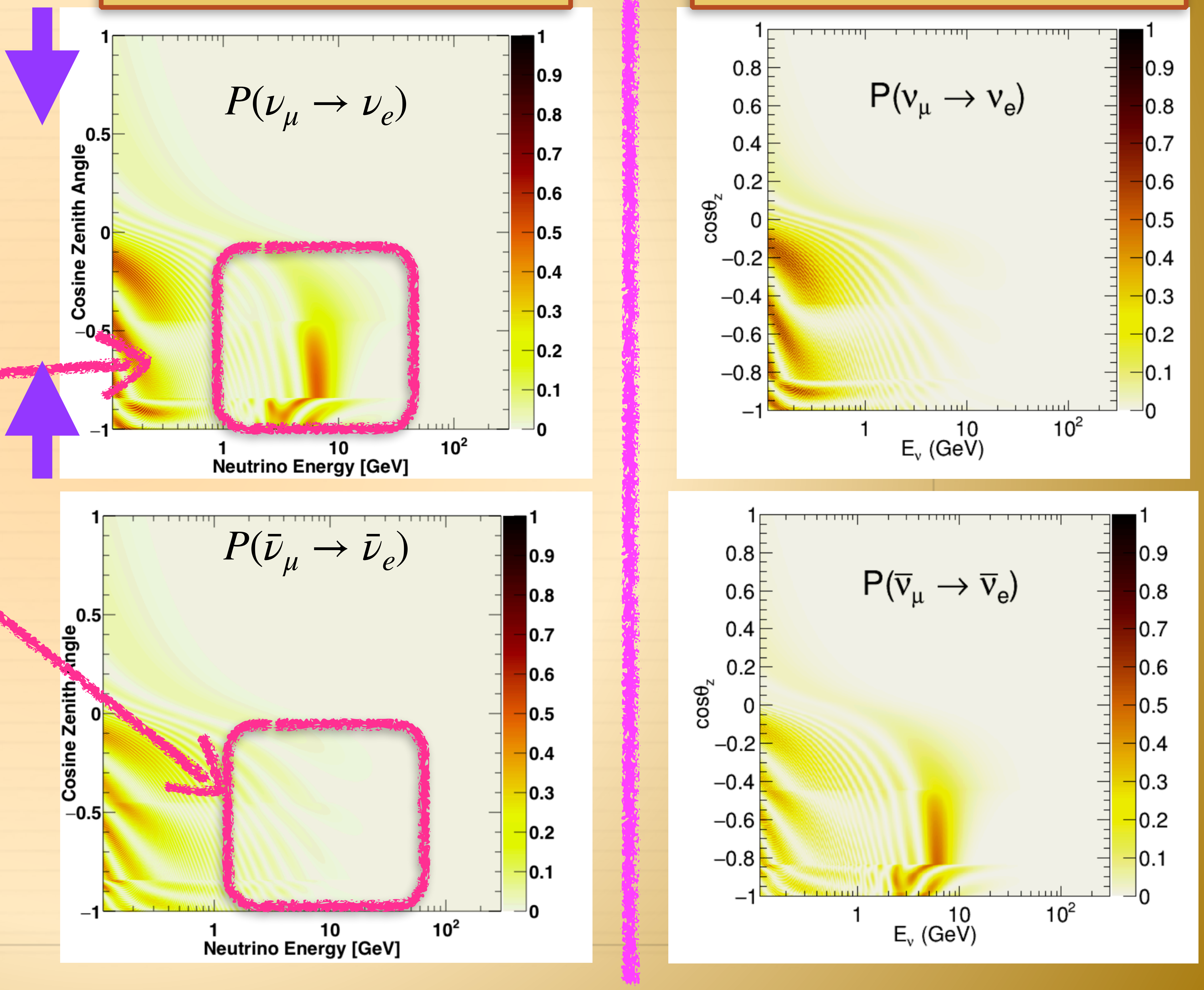
Atmospheric neutrino oscillations

- Oscillograms plotted with: $\Delta m^2_{21} = 7.7 \times 10^{-5}$, $\sin^2\theta_{23} = 0.50$, $\sin^2\theta_{12} = 0.30$, $\sin^2\theta_{13} = 0.0219$ and $\delta_{CP} = 0$
- Phys. Rev. D. 97 072001

- 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

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

Normal Ordering (NO) | Inverted Ordering (IO)



Atmospheric neutrino oscillations

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

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

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

Normal Ordering (NO)

Inverted Ordering (IO)