# Tau neutrino appearance and the measurement of neutrino mass ordering in the flux of atmospheric neutrinos at Super-Kamiokande

Maitrayee Mandal

14 March 2024

# THE MOON AS THE SEARCHING GROUND FOR PROTON DECAY*

J. C. PATI

*Department of Physics and Astronomy*
*University of Maryland, College Park, MD 20742, USA*

ABDUS SALAM

*International Centre for Theoretical Physics*
*34100 Trieste, Italy*

and

B. V. SREEKANTAN†

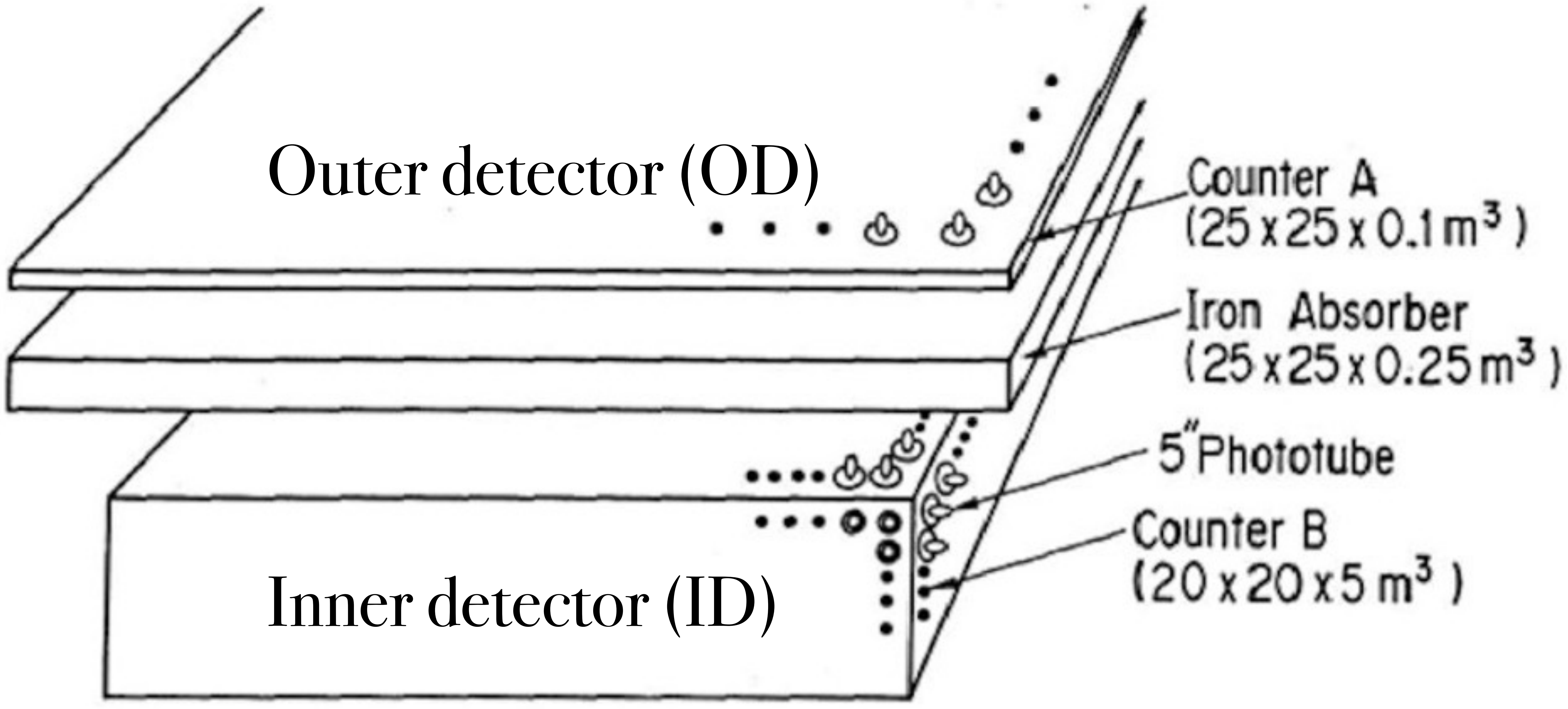
*Department of Physics and Astronomy*
*University of Maryland, College Park, MD 20742, USA*

Received 7 November 1985

The distinct advantage which a lunar detector would have over a terrestrial one in searching for proton decays corresponding to rather long nucleon lifetimes $\gtrsim 6 \times 10^{32}$ yrs is noted.

# Kamioka Nucleon Decay Experiment

## Initial plans of a water Cherenkov detector

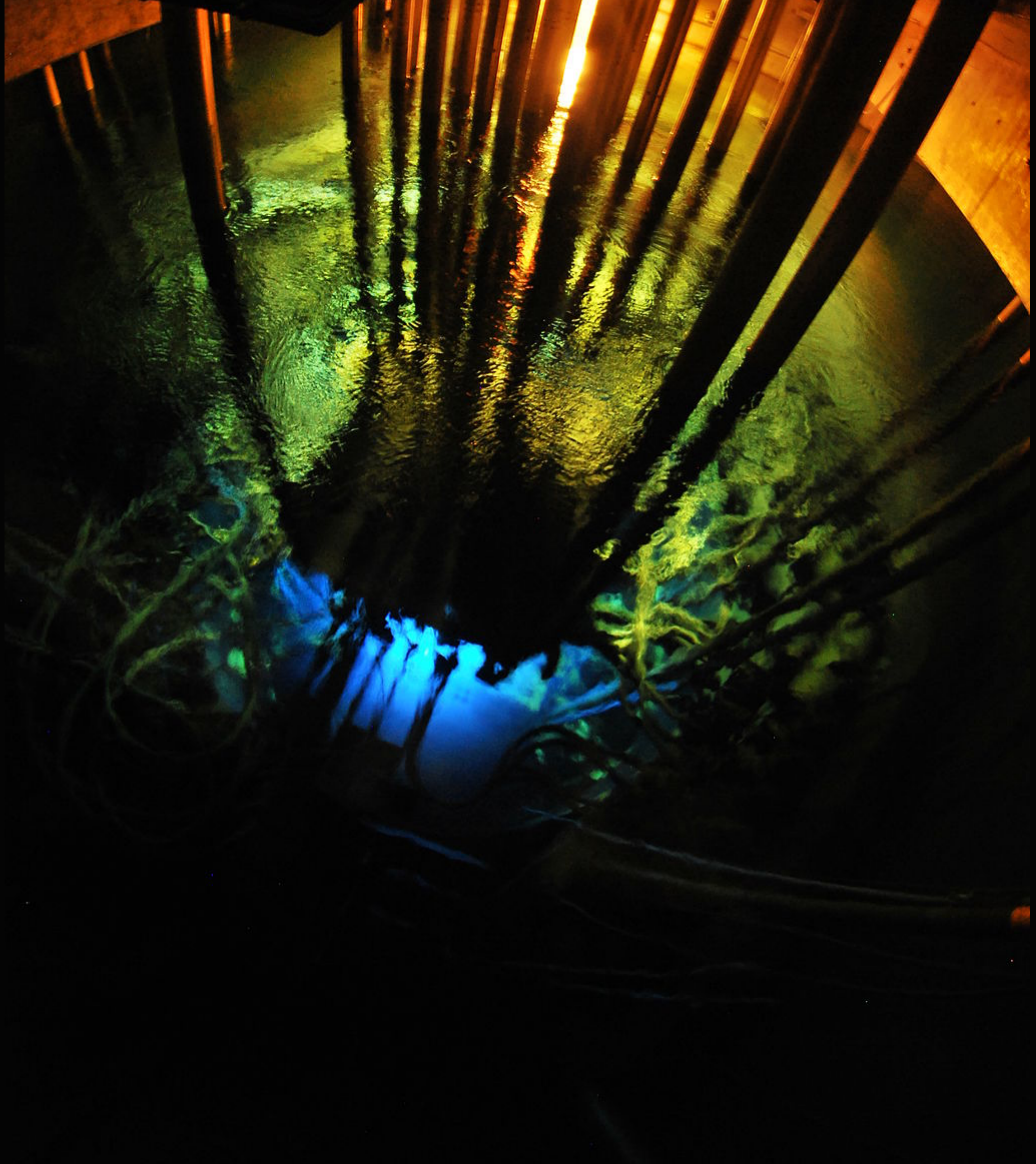



The start of things for Kamiokande: The Kamioka Nucleon Decay Experiment
Atsuto Suzuki arXiv:2203.10457

- ID filled with ultra-pure water.
- Detector lined with photon detectors.

MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

# Cherenkov radiation



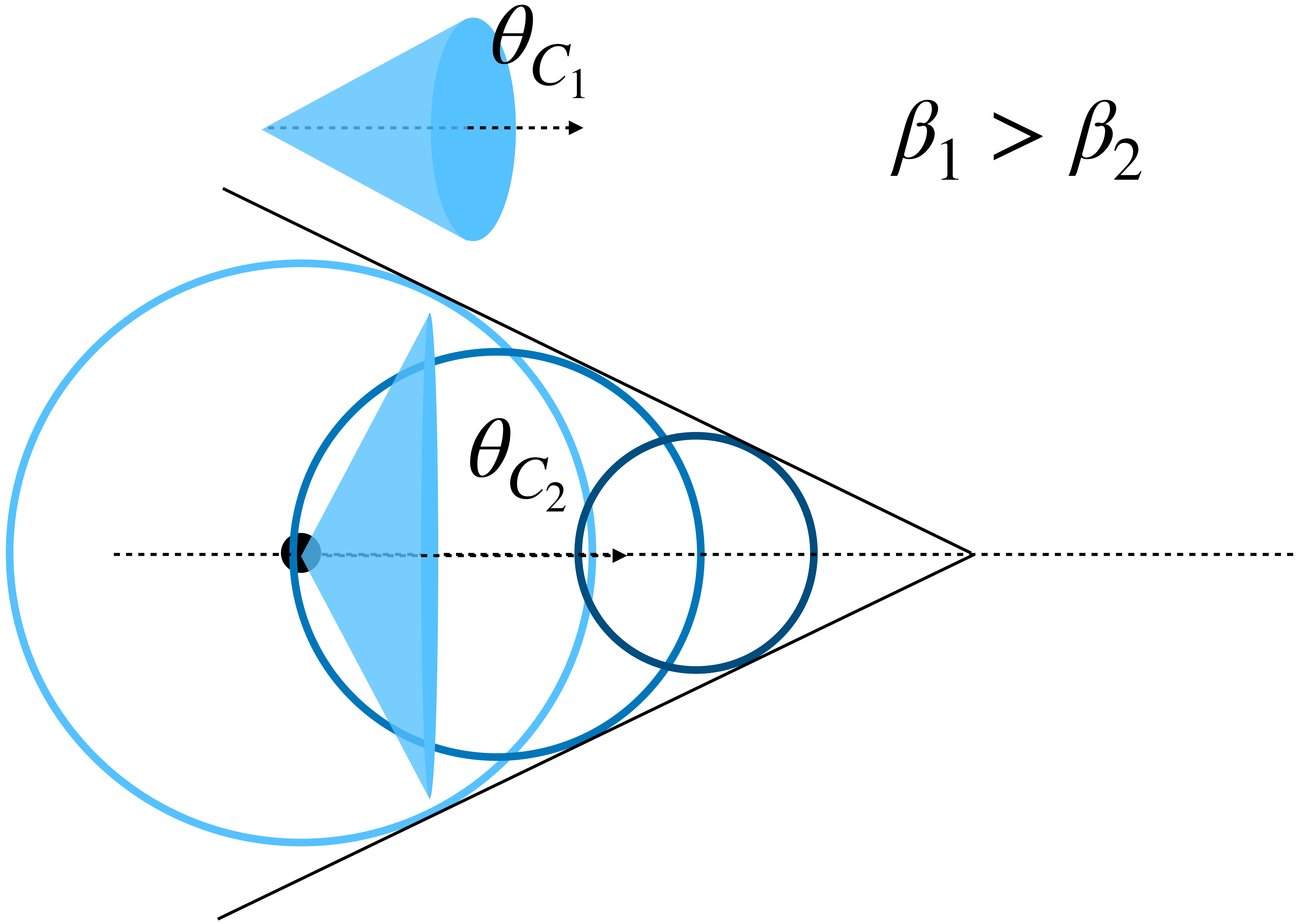
Maria reactor. (2023, January 27). In Wikipedia.
https://en.wikipedia.org/wiki/Maria_reactor

# Detecting charged particles

- Cherenkov radiation is produced for charged particle travelling faster than the speed of light in a dielectric material.

- For refractive index, n,

  Cherenkov angle, $\theta_C = \frac{1}{n\beta}$.

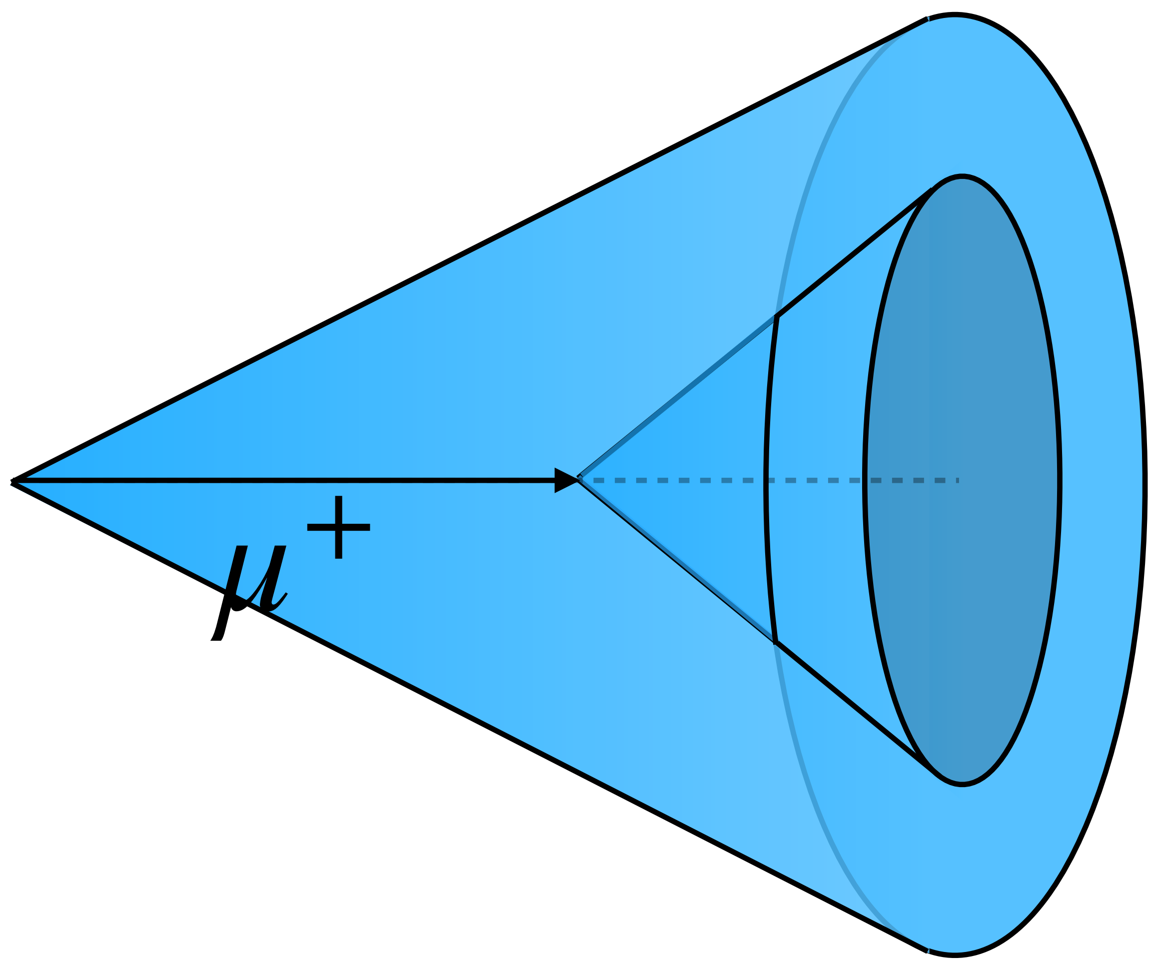




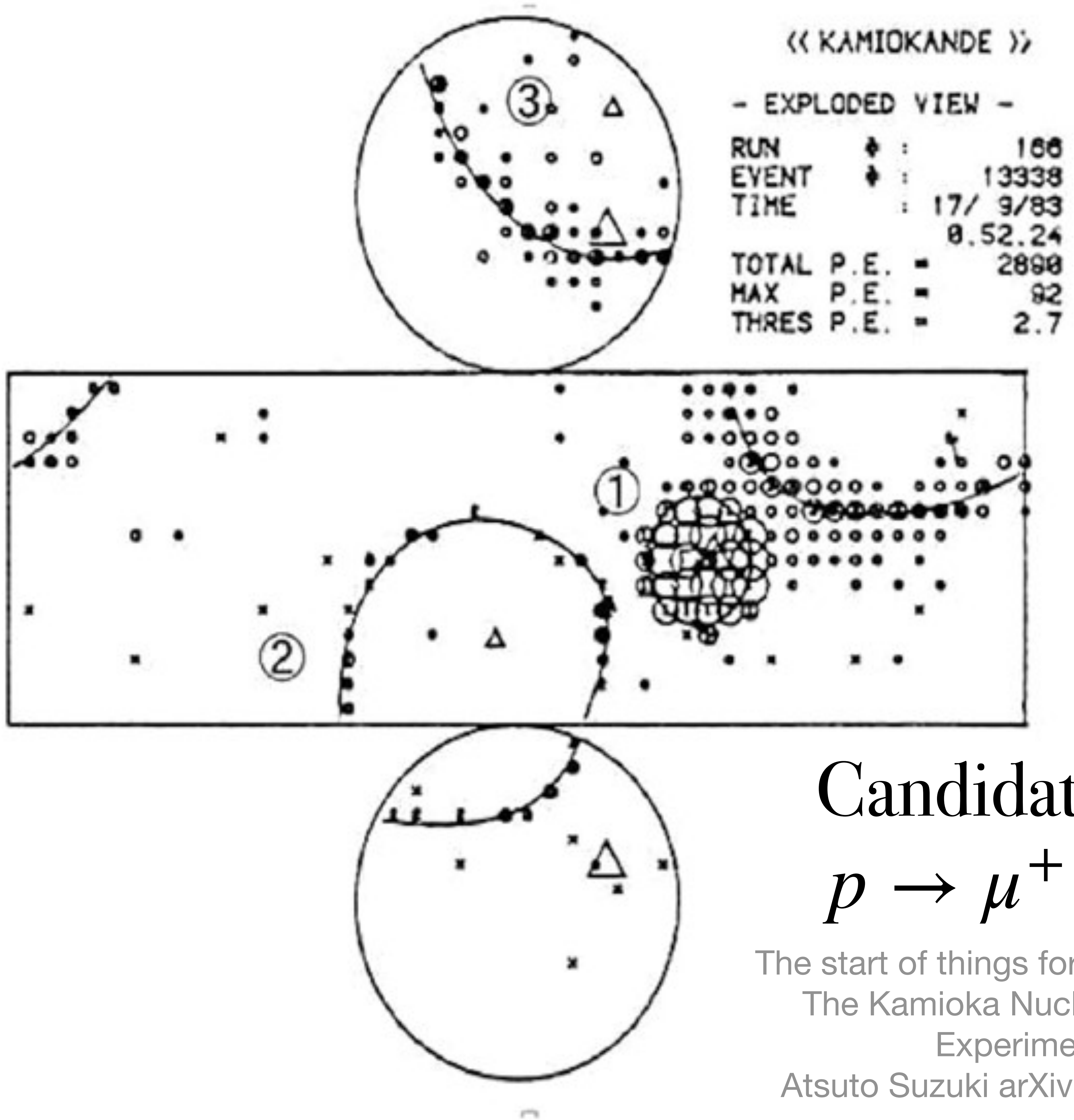
MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

# Working of a water Cherenkov detector

## Particle identification




Well defined muon ring.



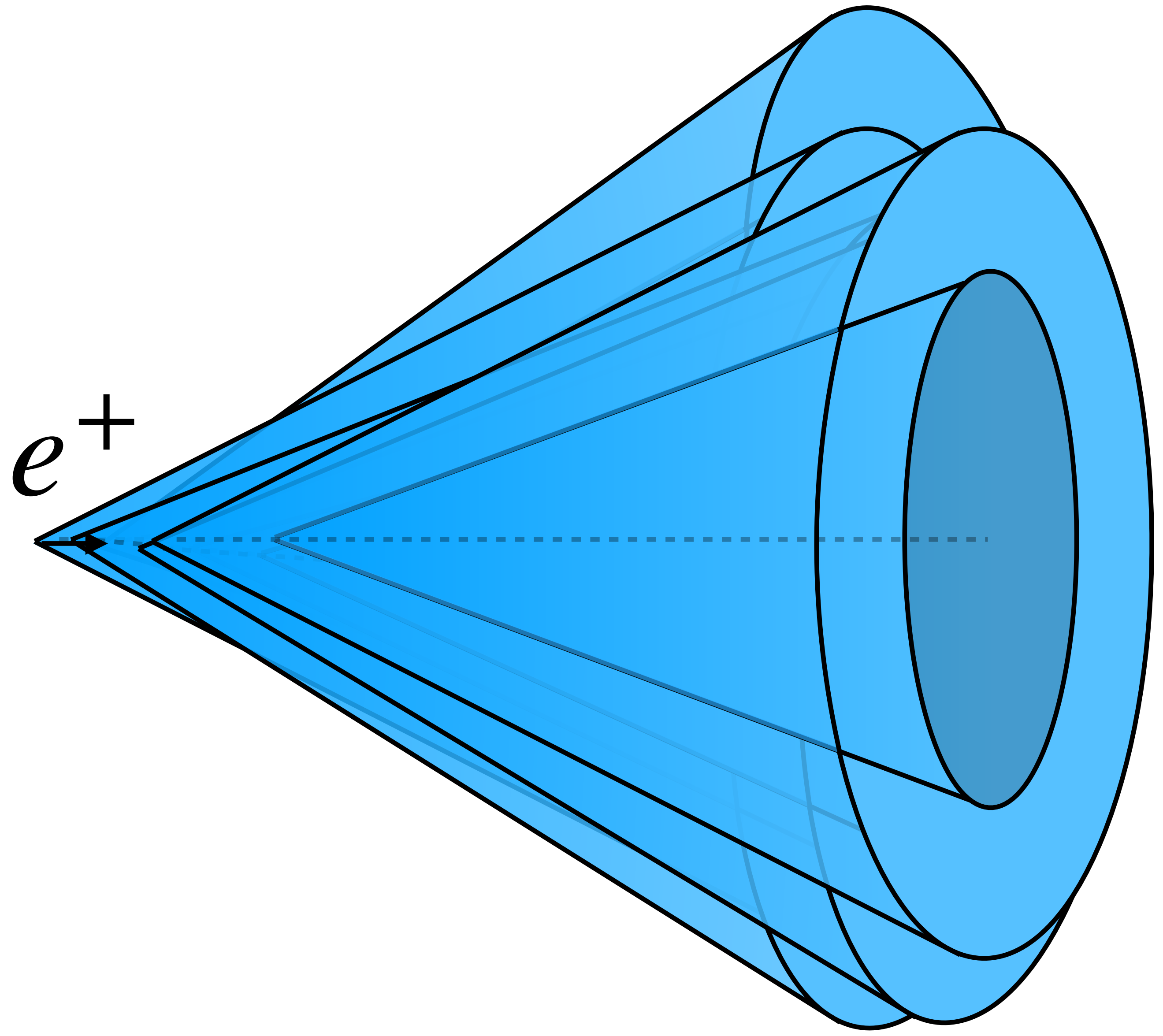

Candidate for

$$p \rightarrow \mu^+ + \eta^0$$

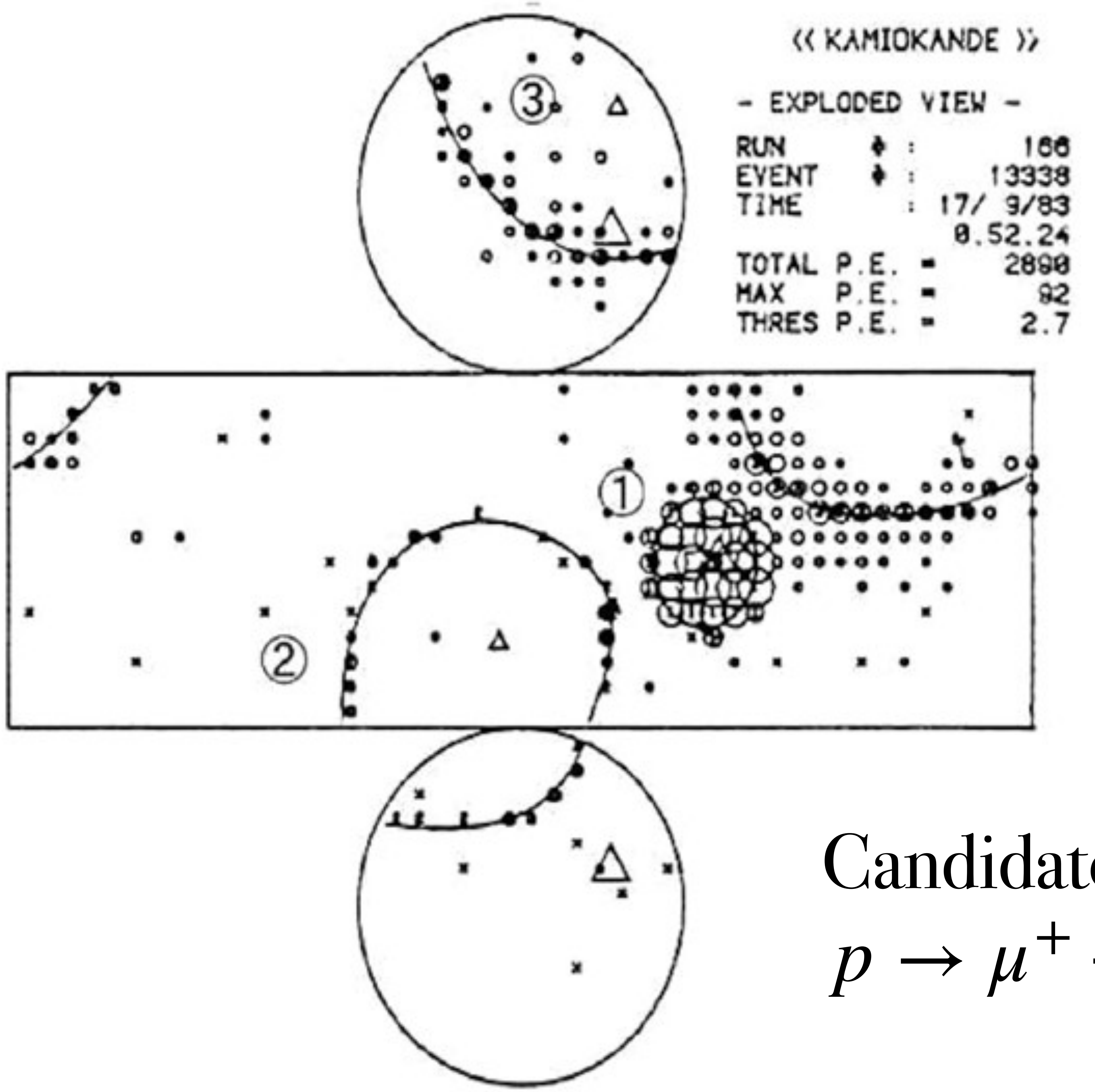
The start of things for Kamiokande: The Kamioka Nucleon Decay Experiment
Atsuto Suzuki arXiv:2203.10457

# Working of a water Cherenkov detector

## Particle identification

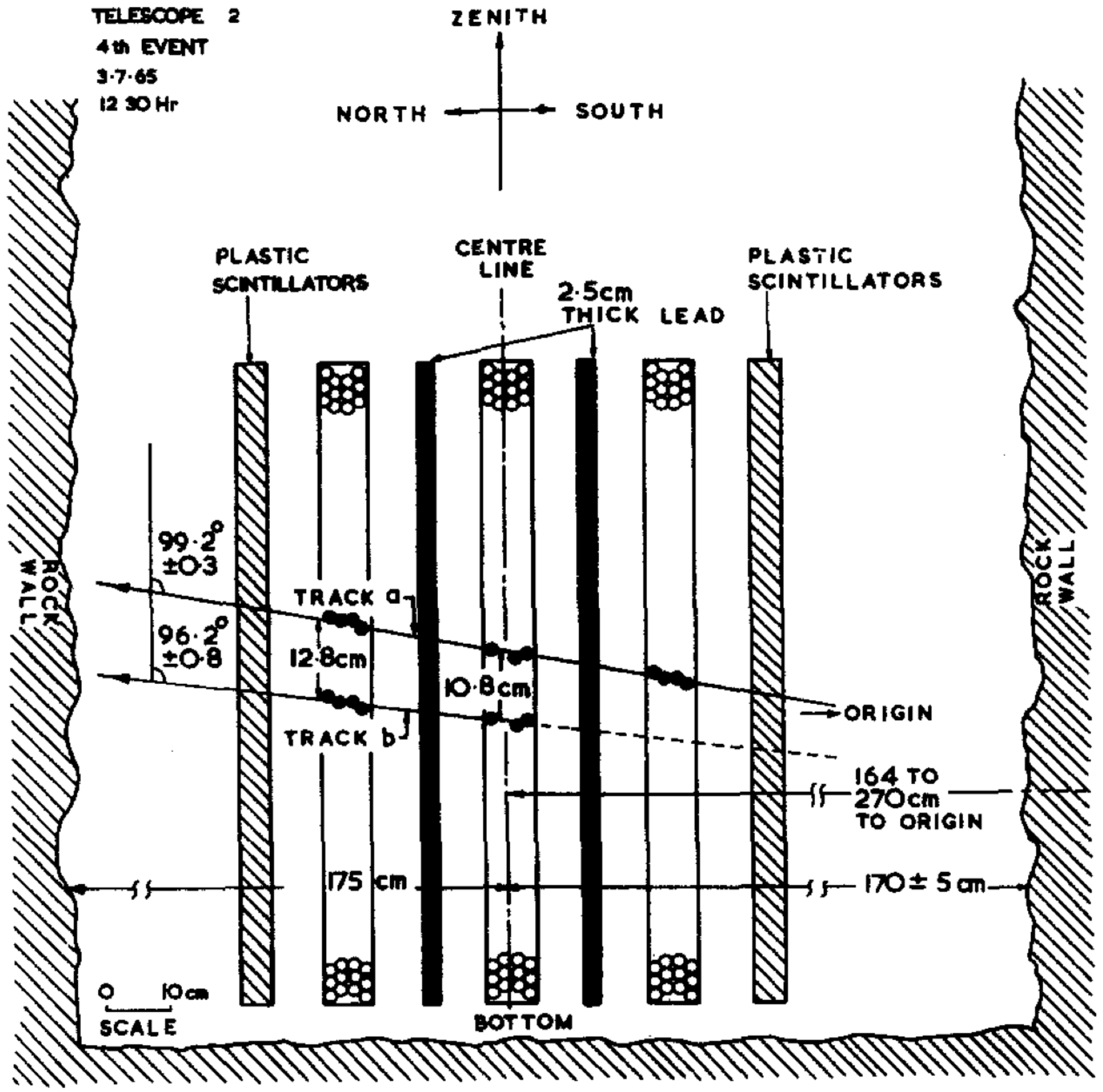


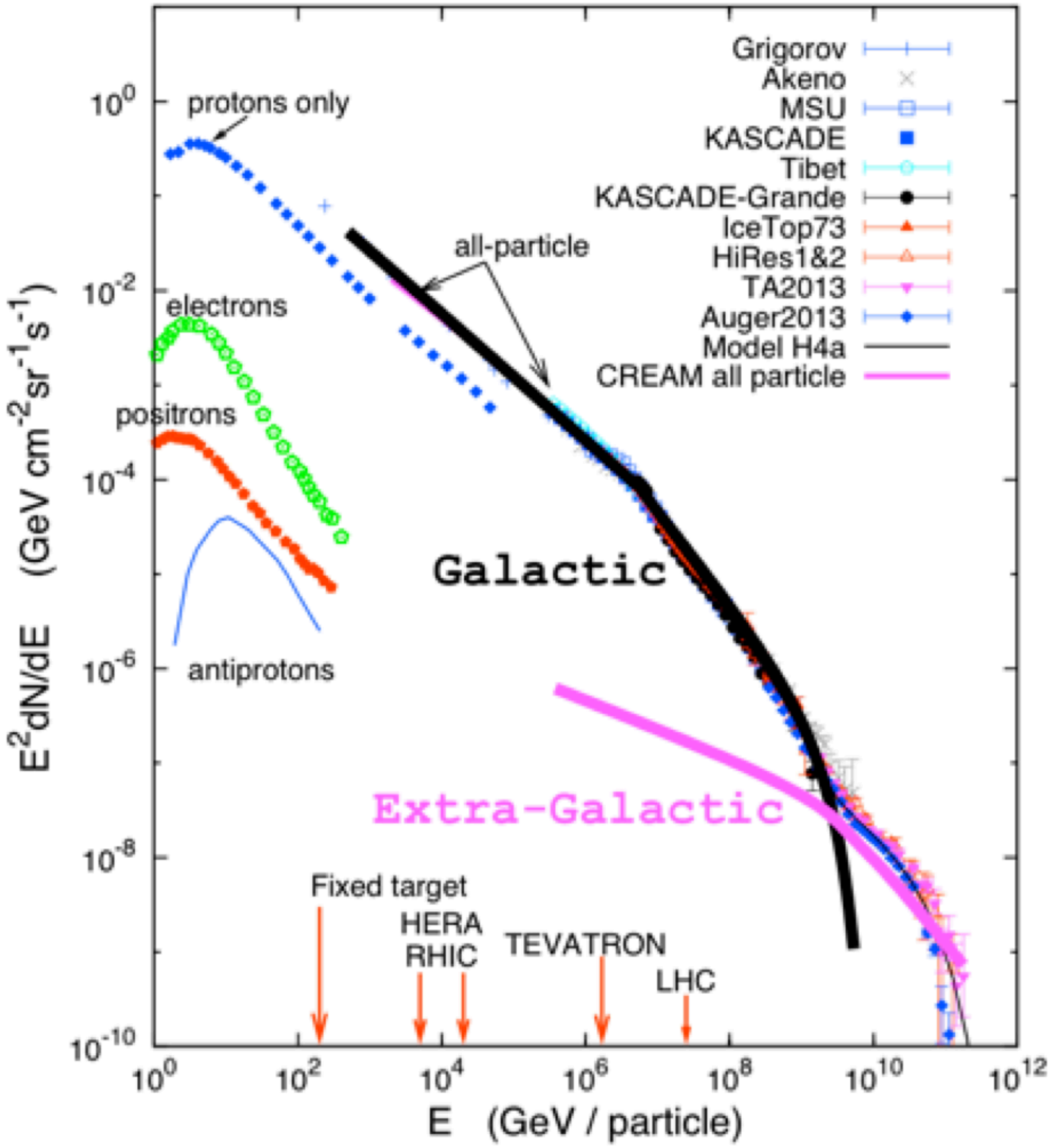

Fuzzy ‘electron ring’.




Candidate for
$p \to \mu^+ + \eta^0$

# Background to the proton decays: Interactions of atmospheric neutrinos




- Cosmic rays interact with the atmosphere and the secondaries produced lead to atmospheric neutrinos.

# Background to the proton decays: Interactions of atmospheric neutrinos

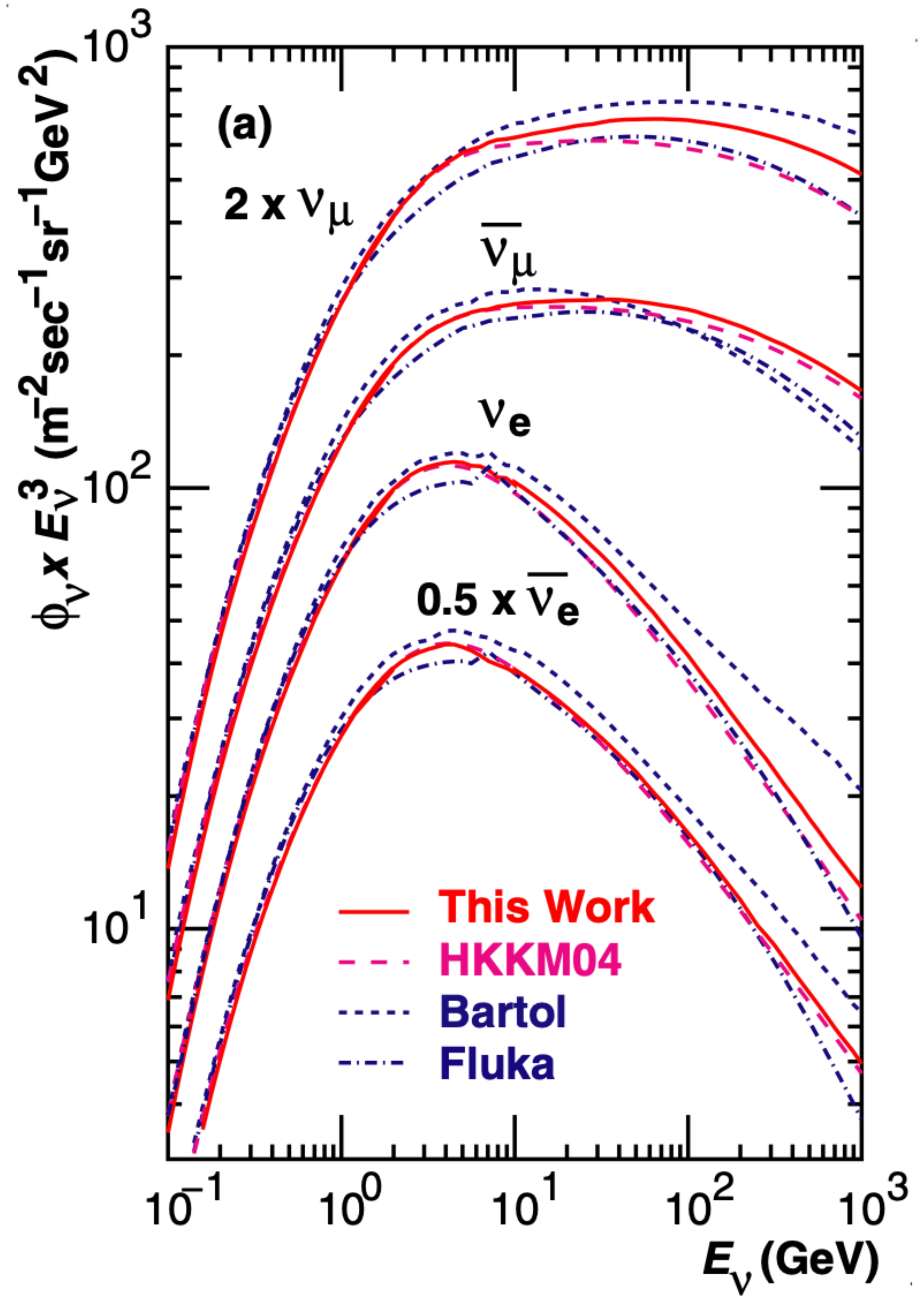
- Mostly muon neutrino and electron neutrinos.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu,$$

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+.$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu,$$

$$\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-.$$



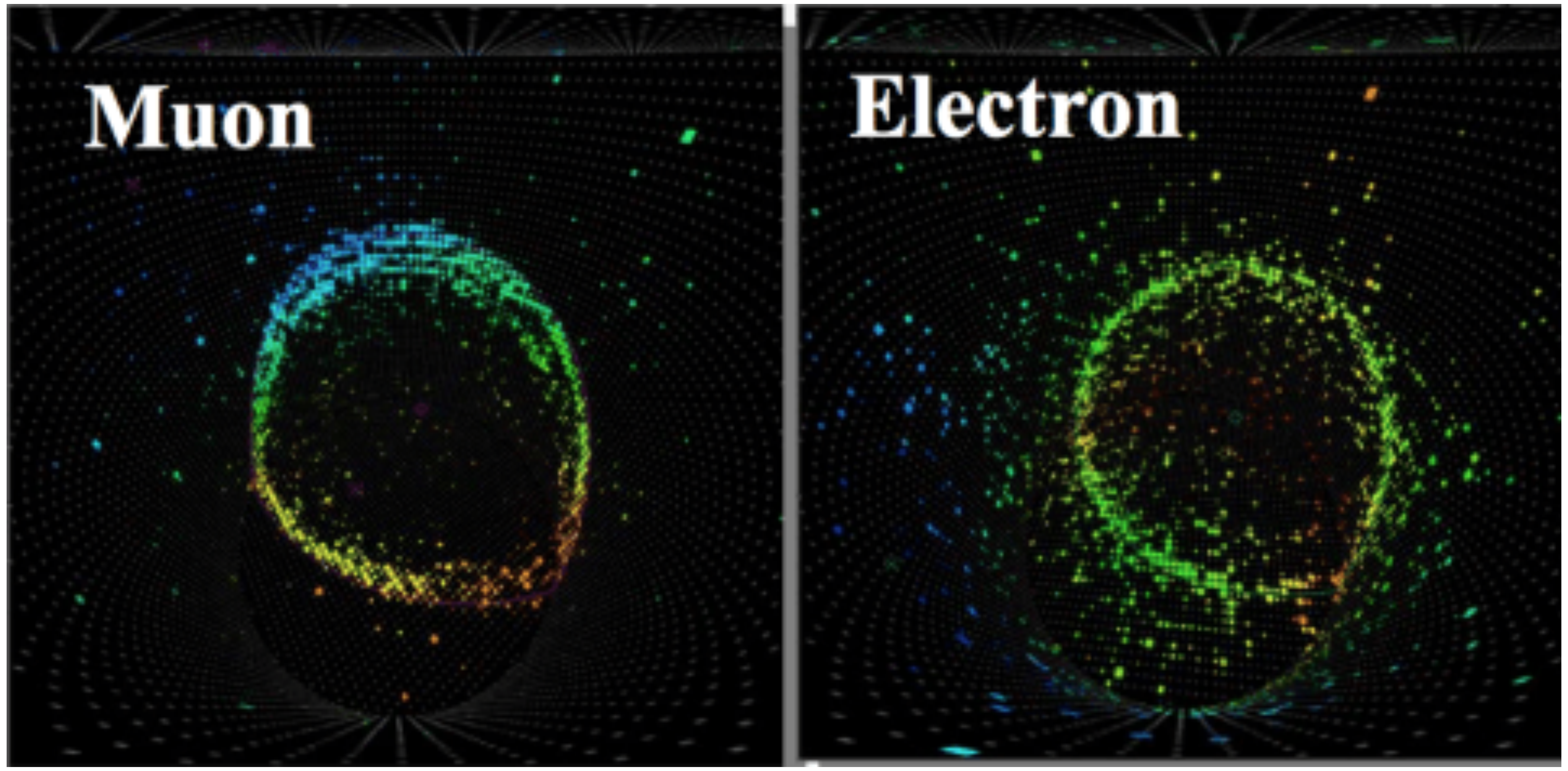

MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

# Interactions of atmospheric neutrinos

## Weak interactions

- Neutral Current (NC) Interactions:
  - $\nu_l + N \to \nu_l + X$
- Charged Current (CC) Interactions:
  - $\nu_l + N \to l^- + X$
  - $\bar{\nu}_l + N \to l^+ + X$

  where $l \in \{e, \mu\}$.
- Flavor of a neutrino identified from the charged lepton created.

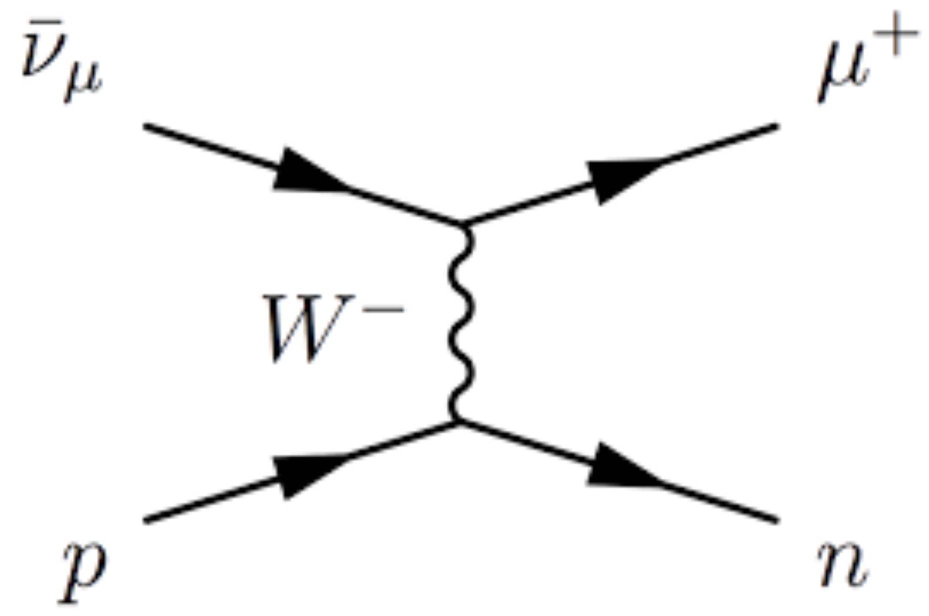


# Neutrino-nucleon interactions

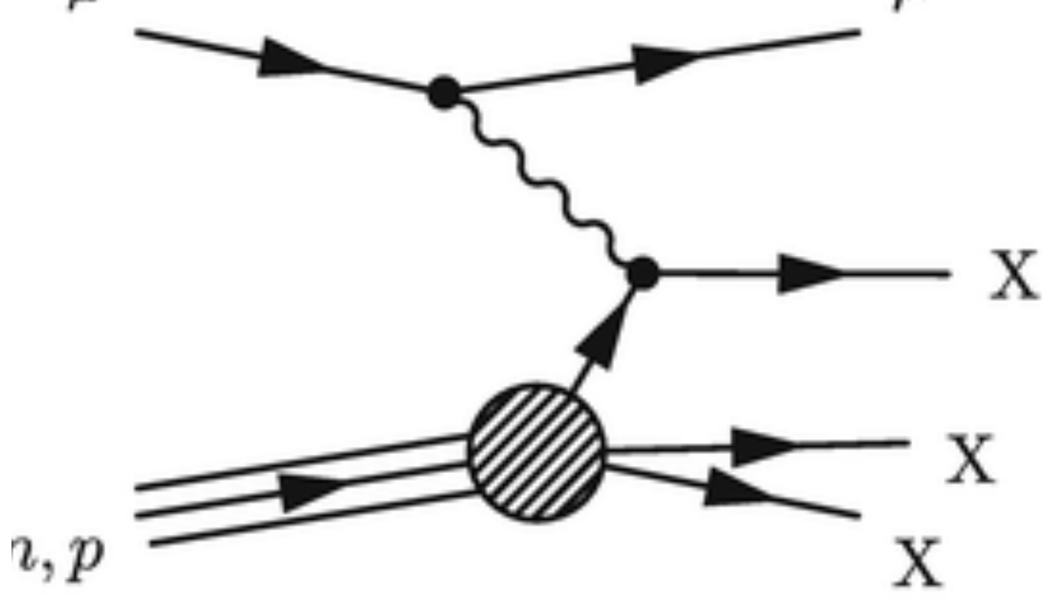
## Weak interactions

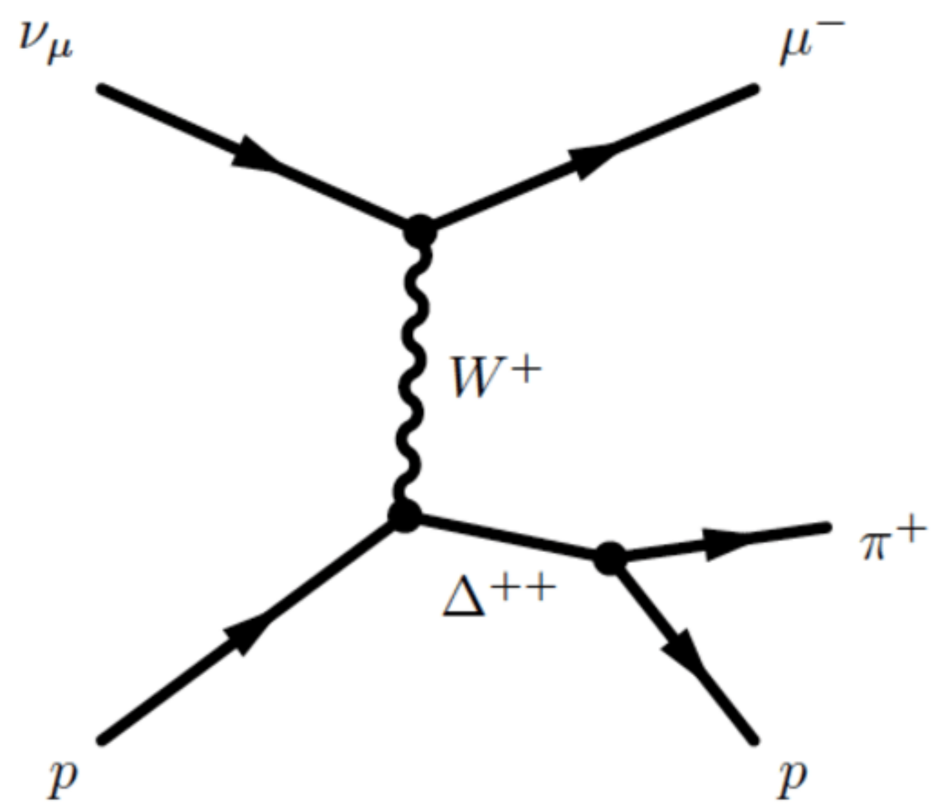
- Neutral Current (NC) Interactions:
    - $\nu_\mu + N \rightarrow \nu_\mu + X$
- Charged Current (CC) Interactions:
    - $\nu_\mu + N \rightarrow \mu^- + X$
    - $\bar{\nu}_\mu + N \rightarrow \mu^+ + X$
    - In order to produce a charged lepton, the neutrino must have sufficient energy - threshold energy.

Quasi-inelastic (QE)




Deep-inelastic scattering (DIS)



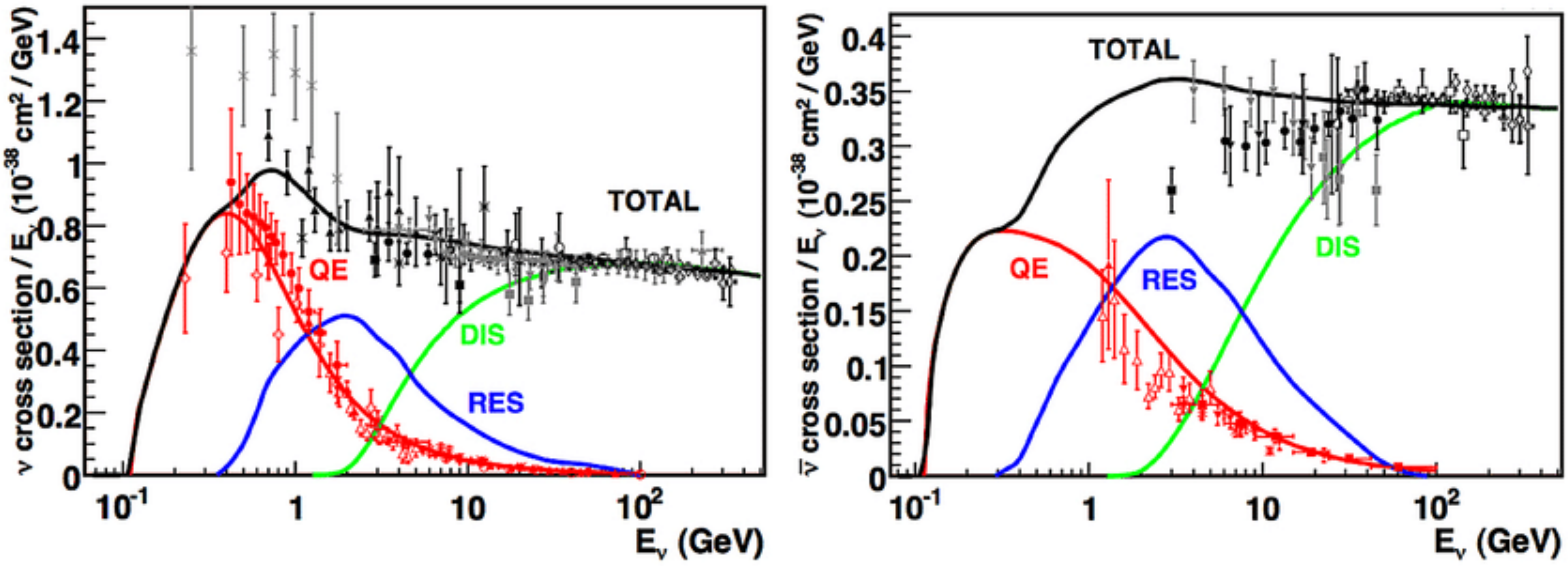




Resonant pion production (RES)

MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

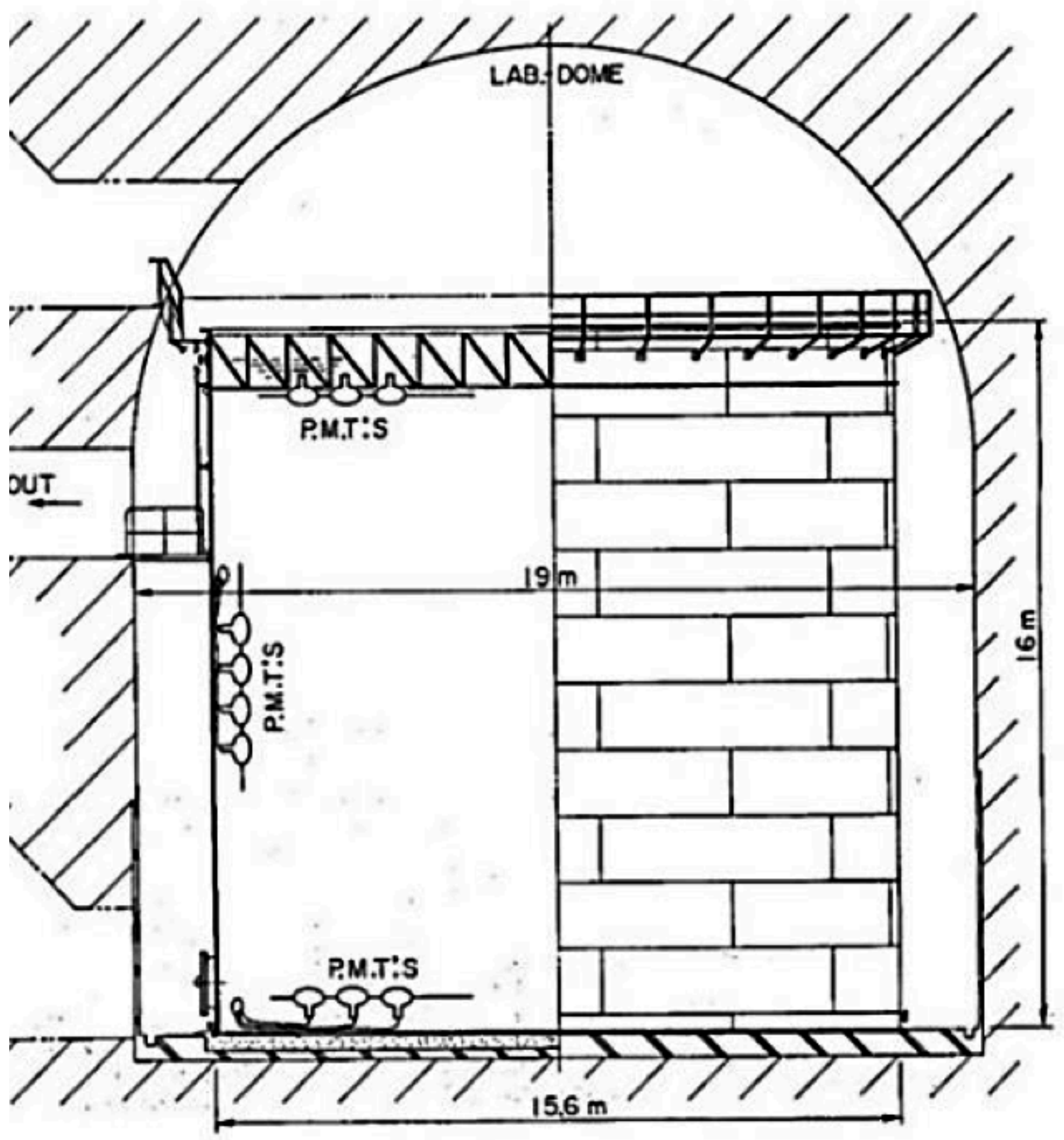
# Neutrino-nucleon interactions

## Weak interactions



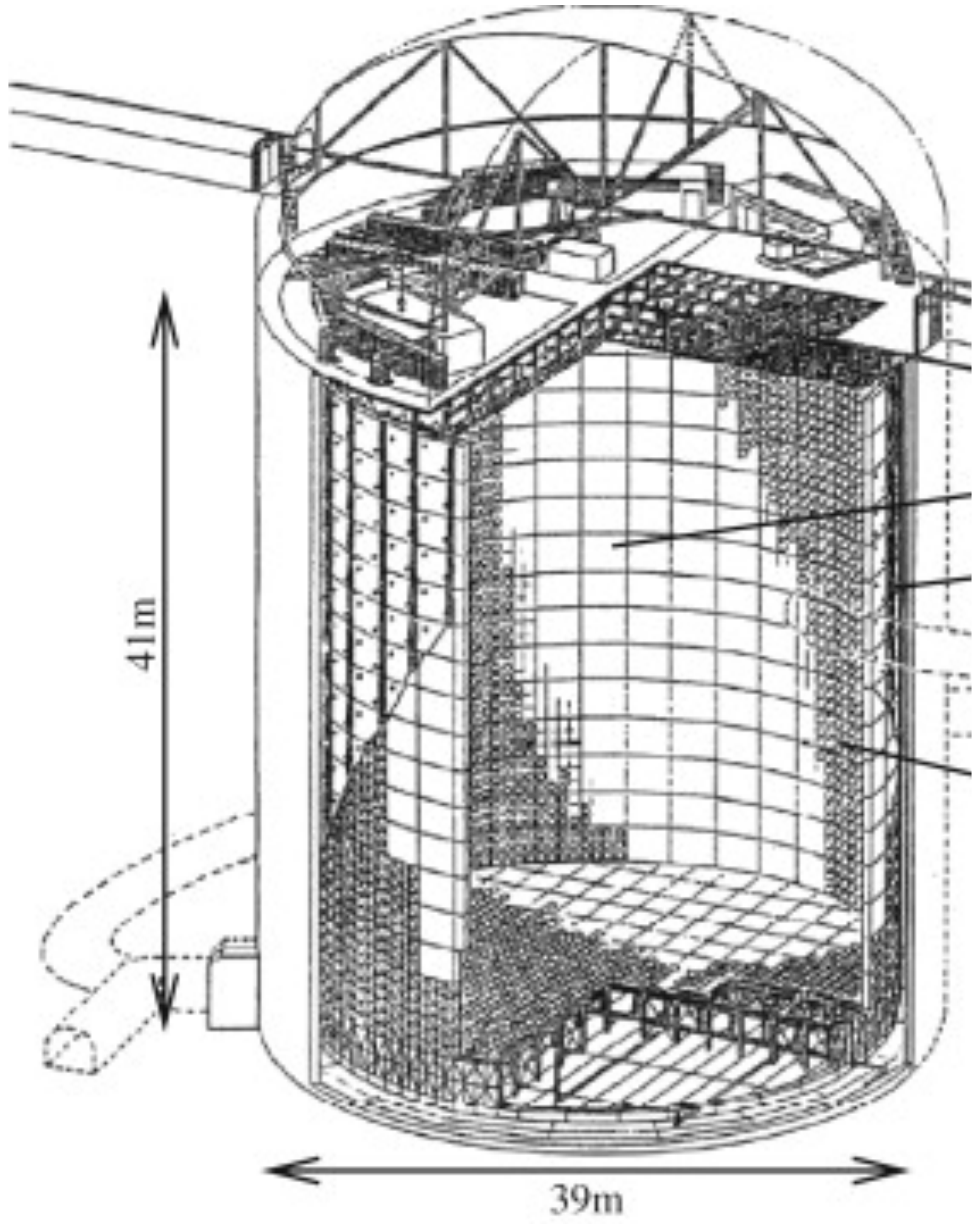
# Generations of experiments in the Kamioka Mine

Kamiokande
1983-1996
4.5 kton

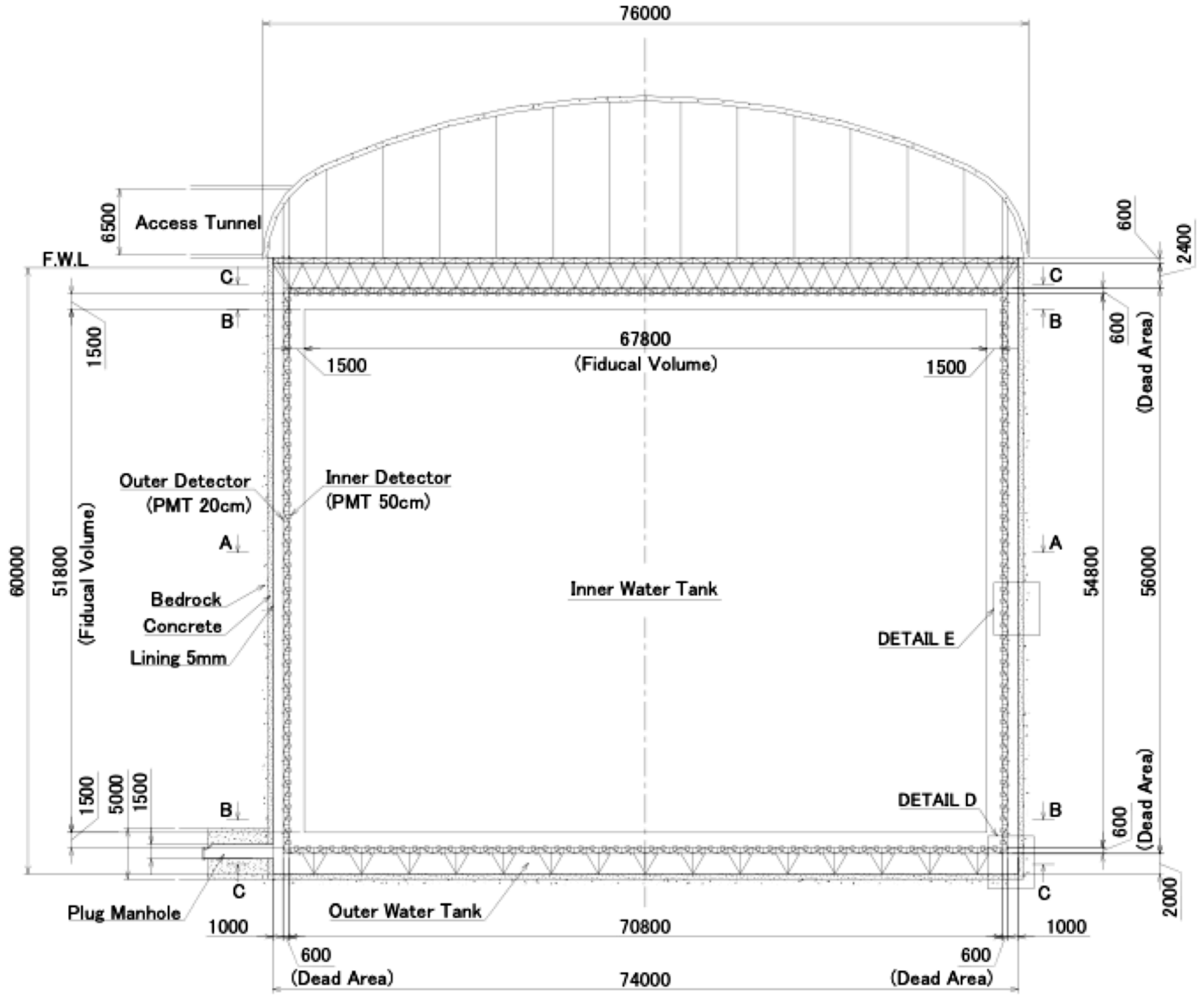



arXiv:2203.10457

Super-Kamiokande
1996-present
50 kton




Hyper-Kamiokande
2026 onwards
258 kton




[Hyper-Kamiokande design report](#)
arXiv:1805.04163, 2018

# Super-Kamiokande photomultiplier tubes

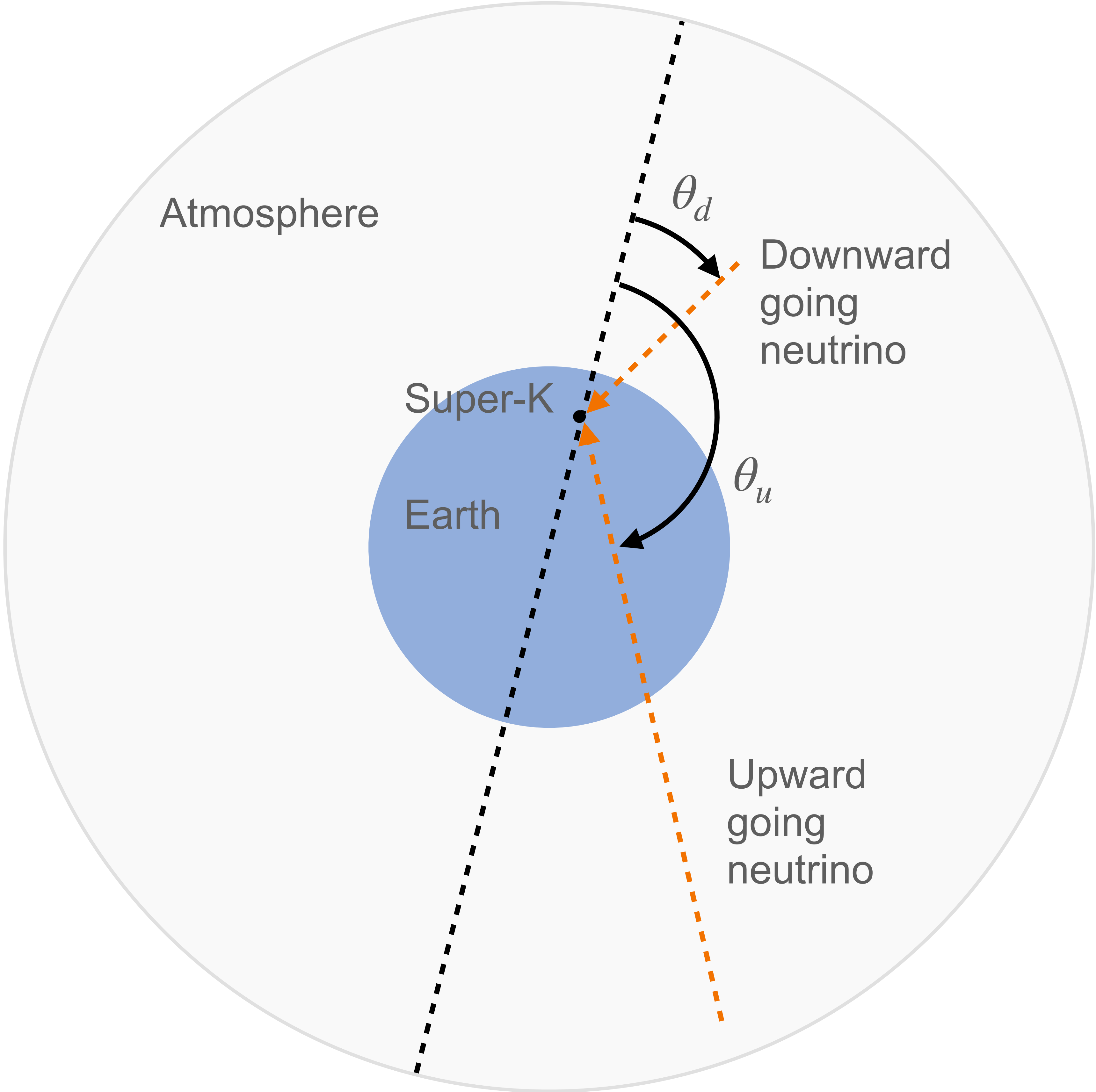
OD: 50 cm PMTs

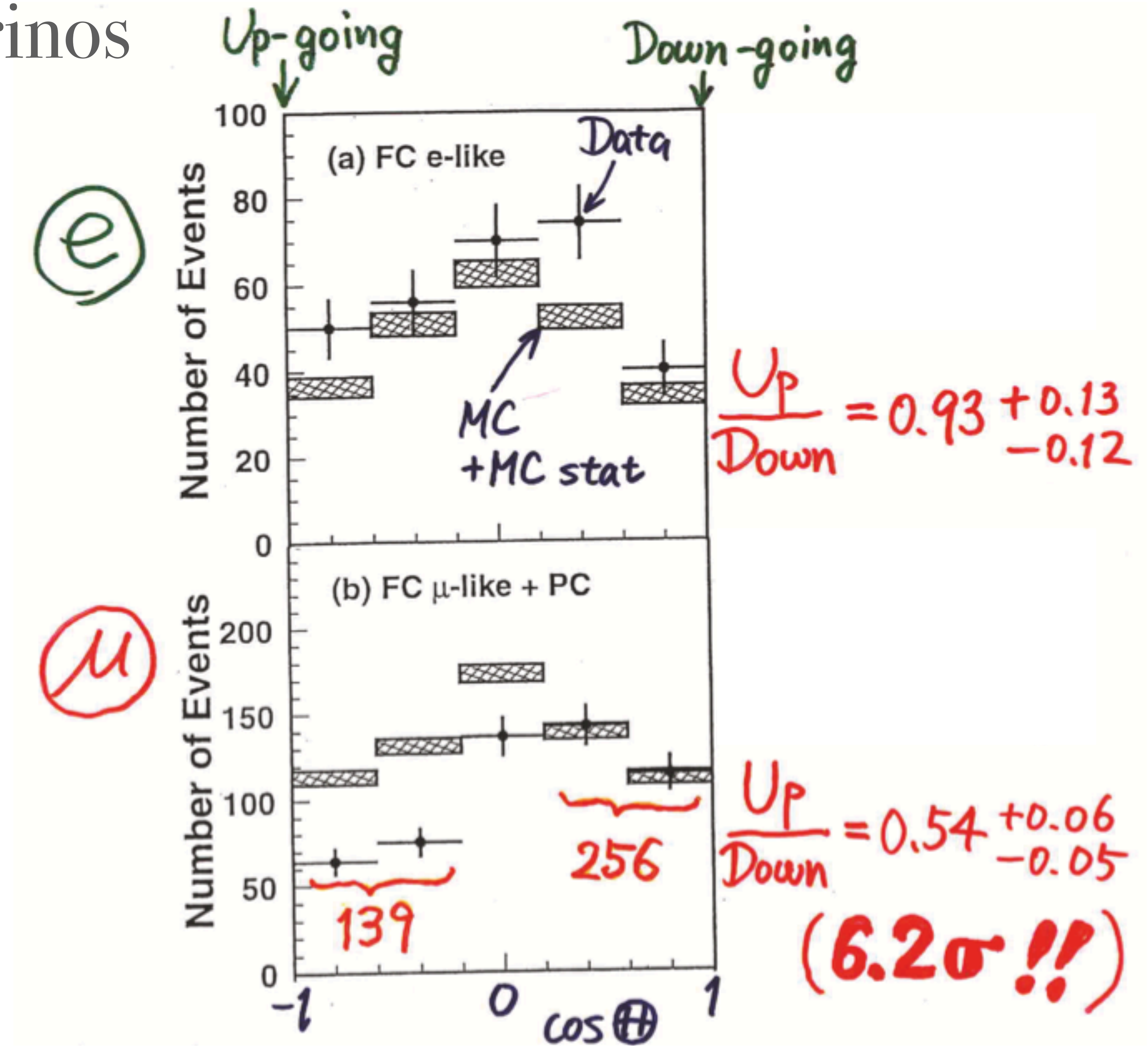
ID: 8 inch PMTs

MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

# A discovery for the atmospheric neutrinos

## Deficit of upward going muon neutrinos




# 2015 Nobel Prize

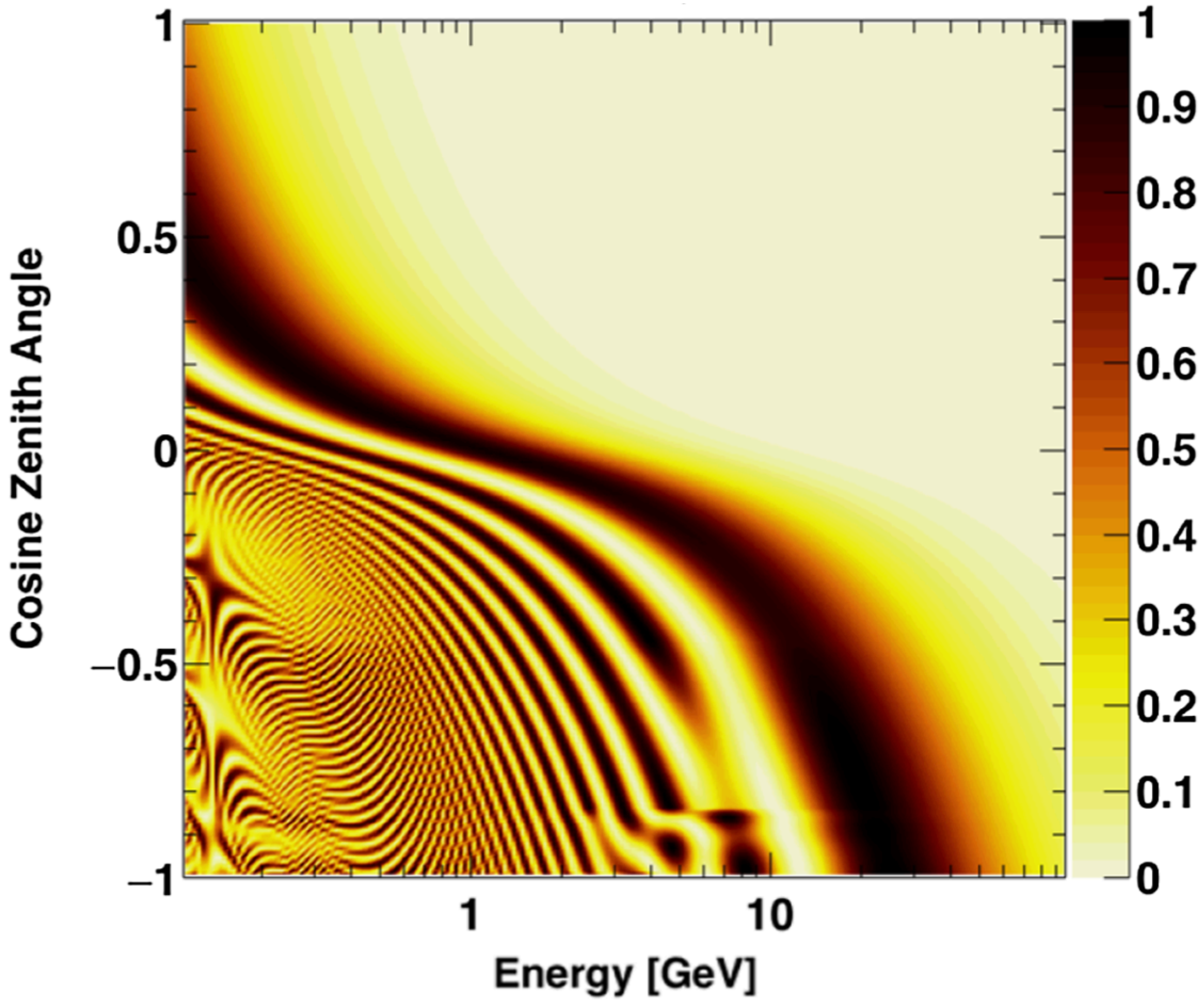
From 18th International Conference on Neutrino Physics and Astrophysics (Neutrino '98) by the Super-Kamiokande collaboration (edited)

# Neutrino oscillations

## Muon neutrinos oscillate to tau neutrinos

Oscillation probabilities for the appearance of tau neutrinos from muon neutrinos,

assuming normal ordering.

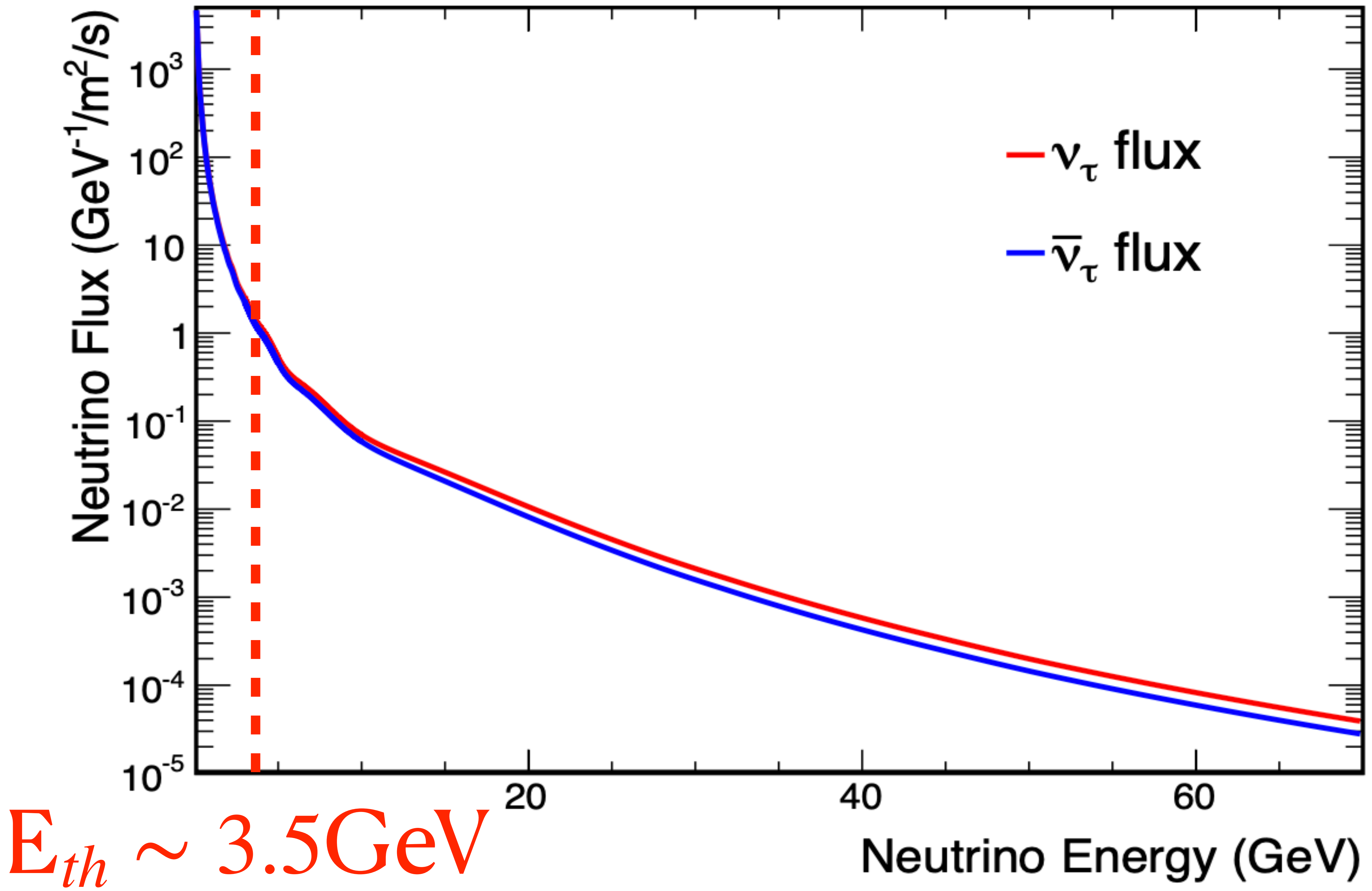



MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

# Can SK detect tau neutrinos?

Detecting oscillated tau neutrinos is an unambiguous proof of neutrino oscillations

- Expected at SK at the rate of 1 tau neutrino CC interaction per kt fiducial volume (active mass of the detector) per livetime year.
- Not explicitly designed for tau neutrinos.



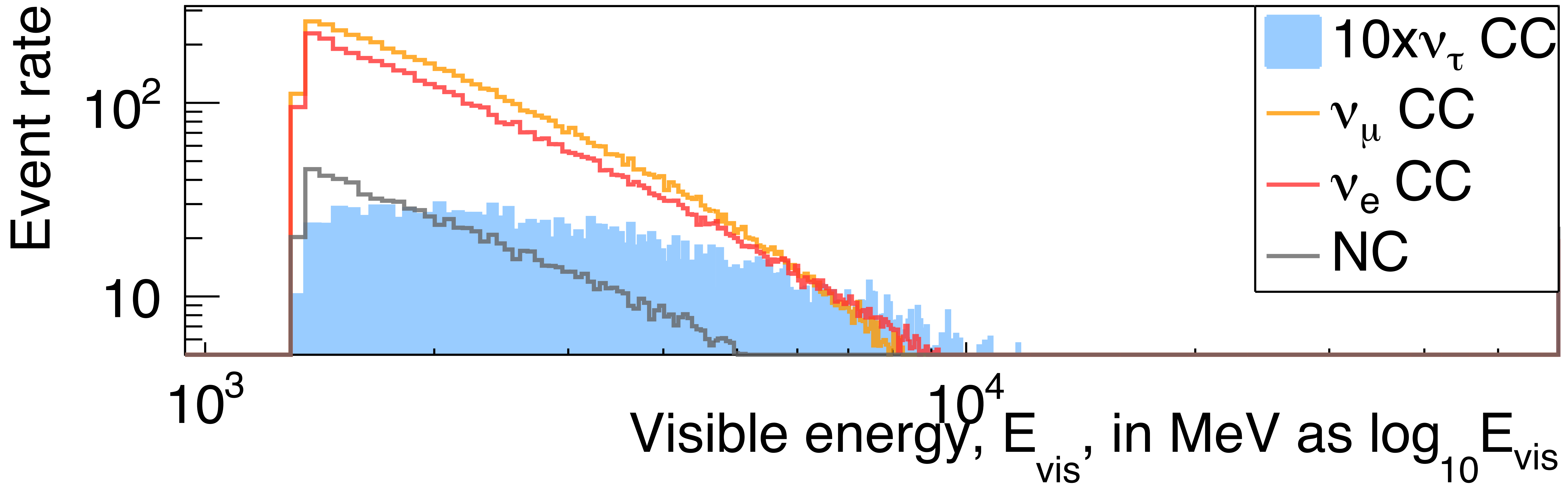

10.1103/PhysRevD.98.052006

# Can SK detect tau neutrinos?

## Challenges due to the short lifetime and large mass of the tau lepton

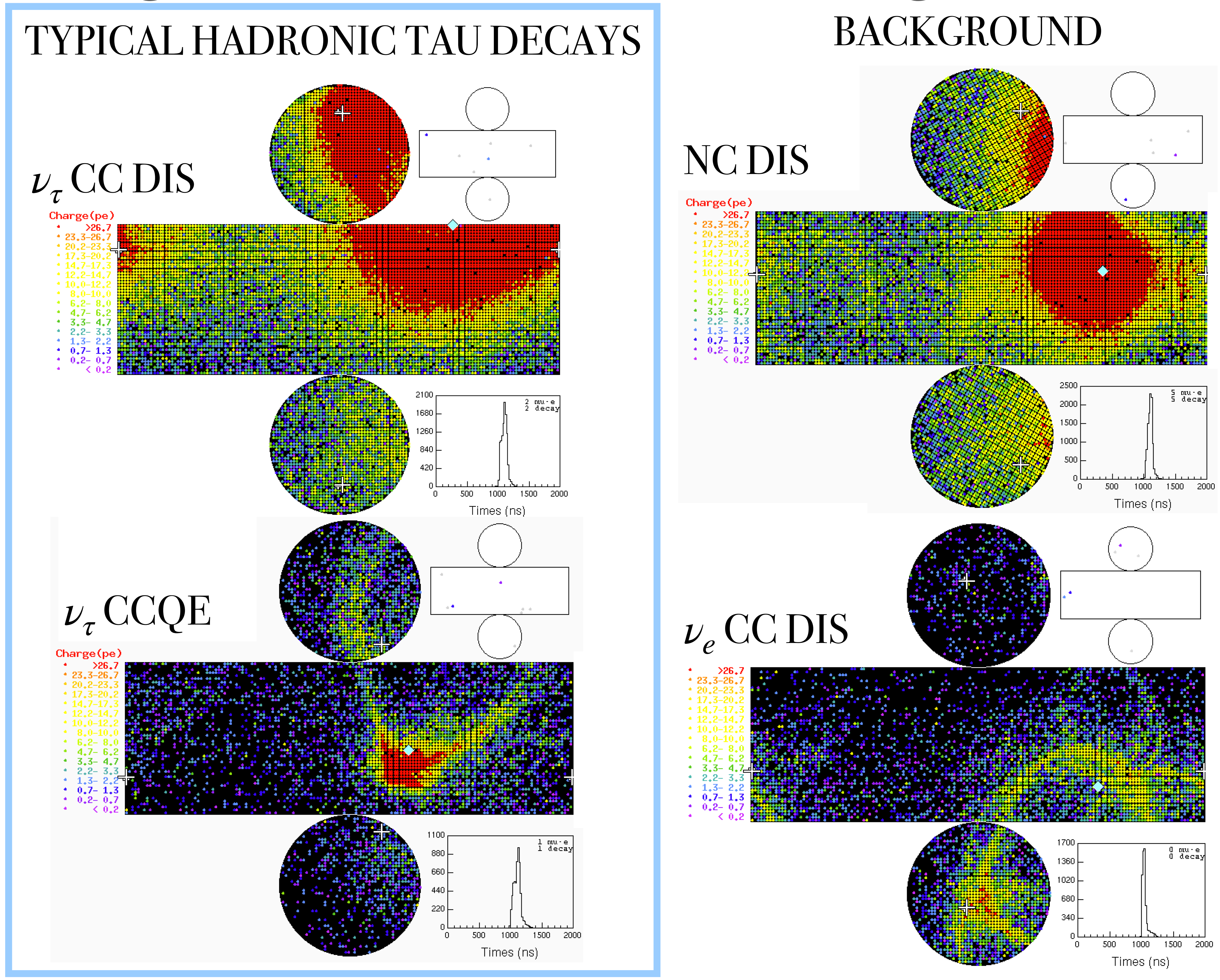
| Tau (mass1.8GeV, lifetime10-13s) decay mode | B.R. % |
|---|---|
| $\tau^- \rightarrow h^-\pi^0\nu_\tau$ | 26.0 |
| $\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau$ | 17.8 |
| $\tau^- \rightarrow \mu^-\bar{\nu}_e\nu_\tau$ | 17.4 |
| $\tau^- \rightarrow h^-\nu_\tau$ | 11.5 |
| $\tau^- \rightarrow h^-h^+h^-\nu_\tau$ | 9.8 |
| $\tau^- \rightarrow h^-\pi^0\pi^0\nu_\tau$ | 9.5 |
| Other hadronic modes | 8.0 |

- Background to $\nu_\tau$ CC interaction events: $\nu_\mu$ CC, $\nu_e$ CC and NC interactions of all flavors



# Can SK detect tau neutrinos?

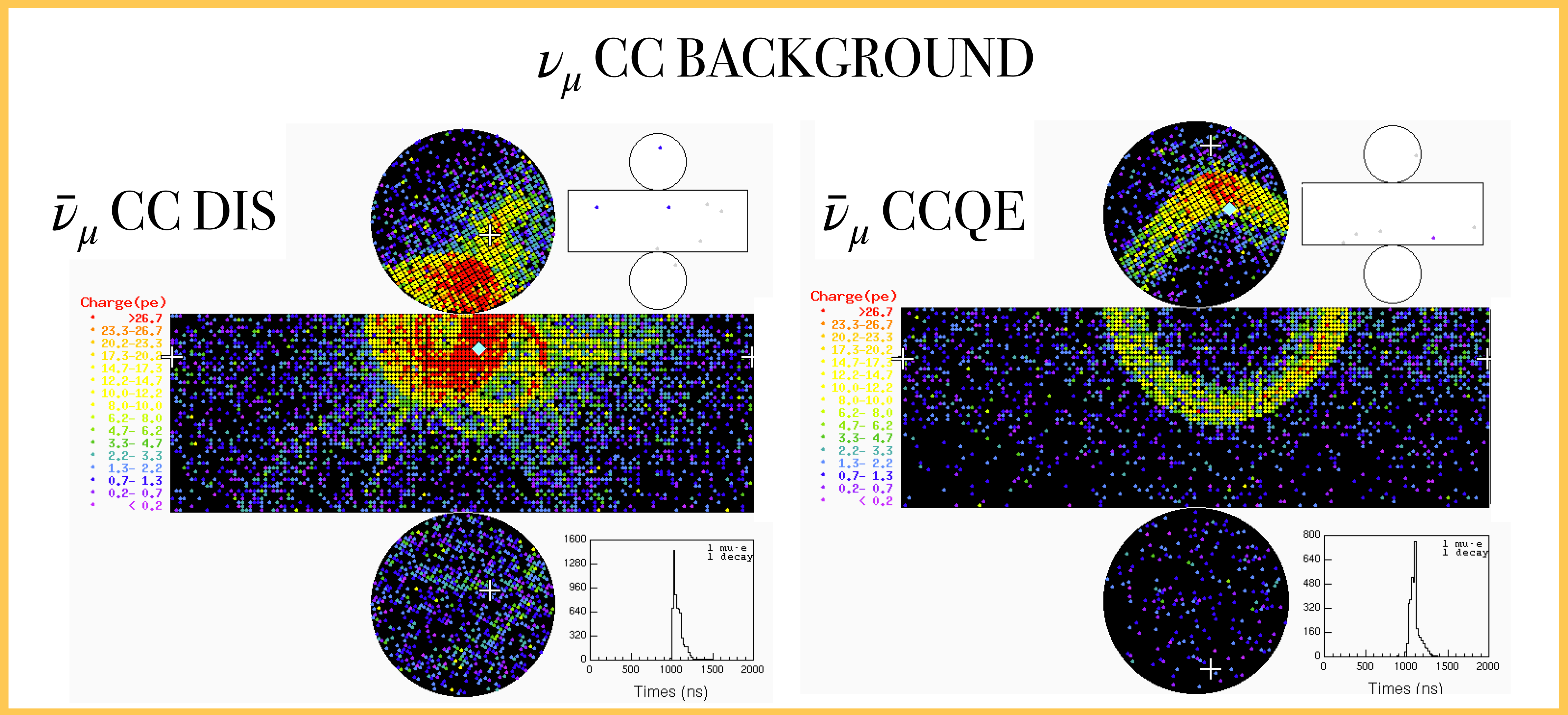
## Background-like events in the signal

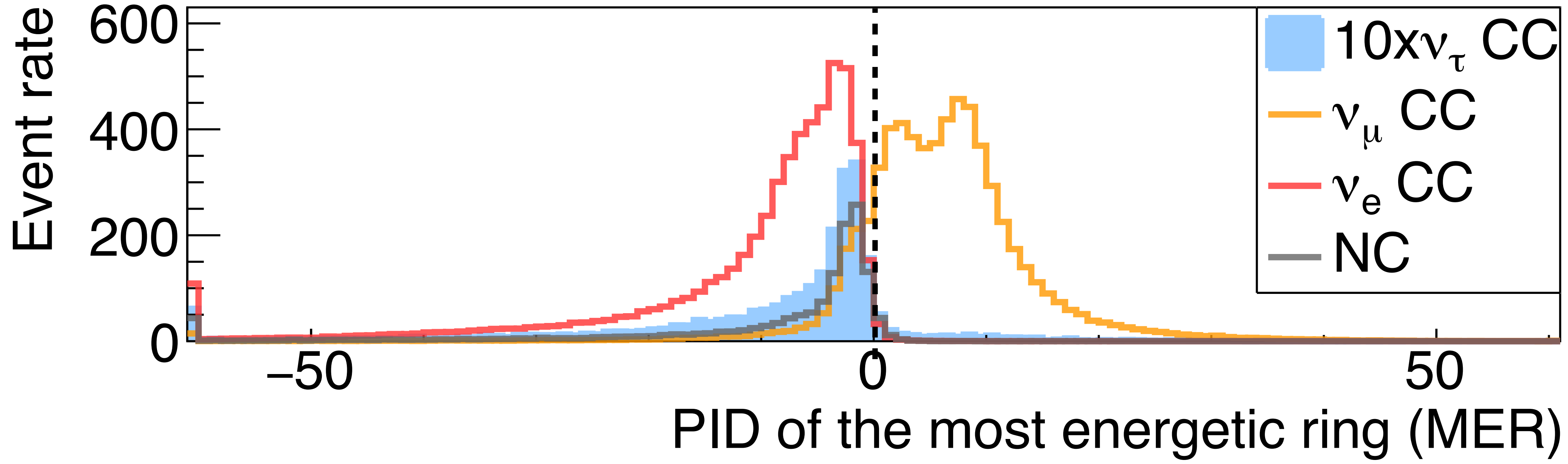



- Showering events present in both background and signal.

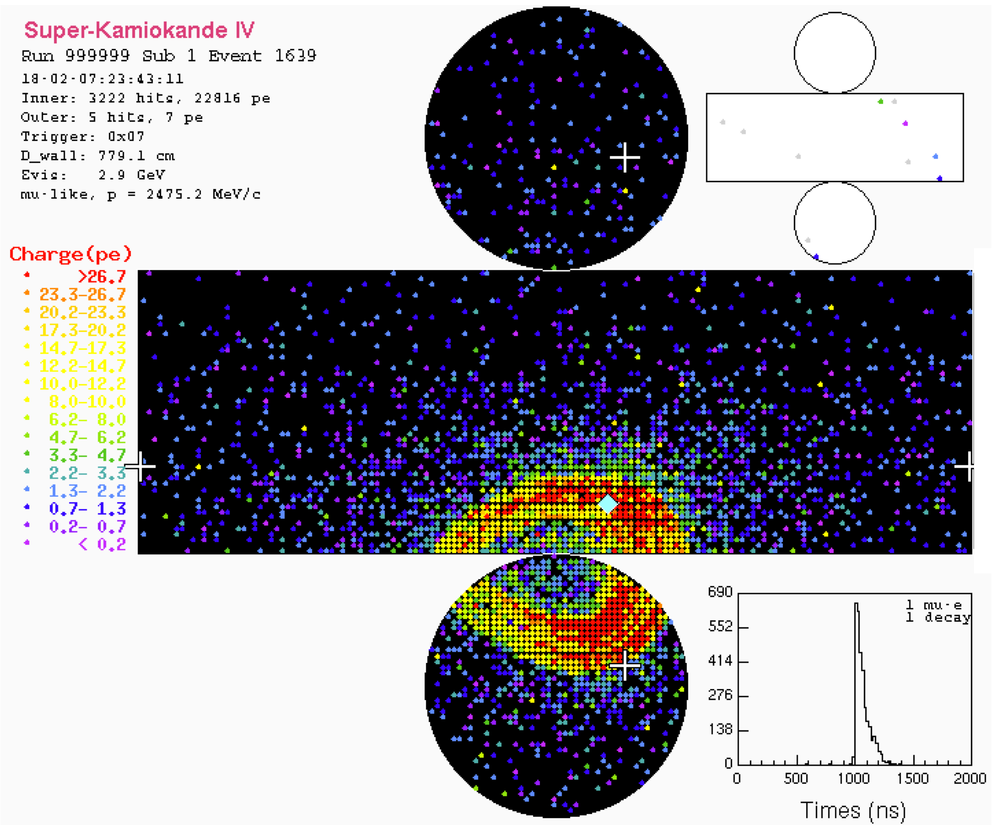
# Can SK detect tau neutrinos?

## Non-showering background-like events in the signal




TYPICAL LEPTONIC
$\nu_\tau$ CCQE TAU DECAY
($\tau^- \to \nu_\tau \bar{\nu}_\mu \mu^-$, 17% B.R.)



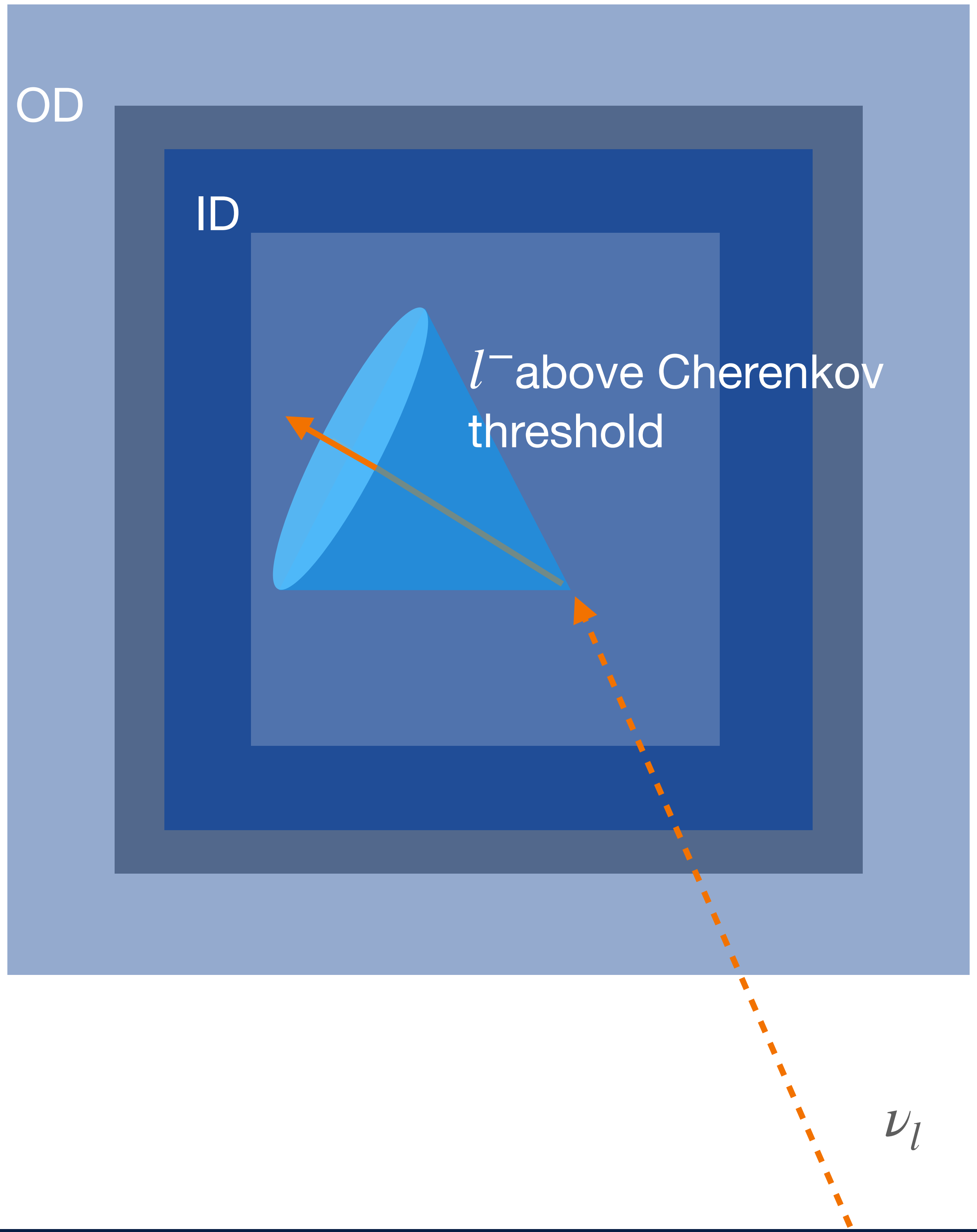

- No single variable that completely differentiates the signal from the background.

# Can SK detect tau neutrinos?

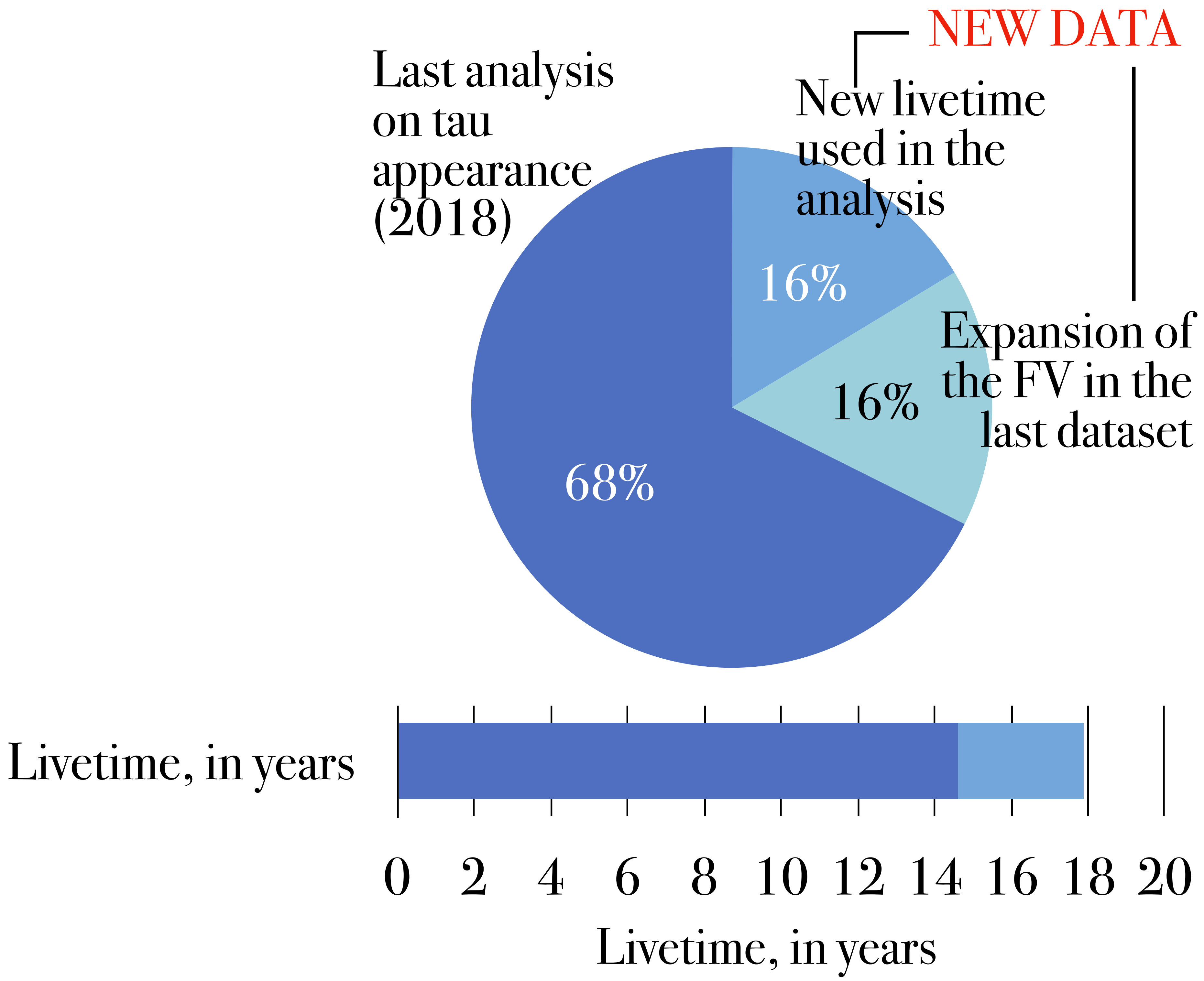
Yes.

- We use multi-variate methods of classification.

FULLY CONTAINED (FC) EVENT



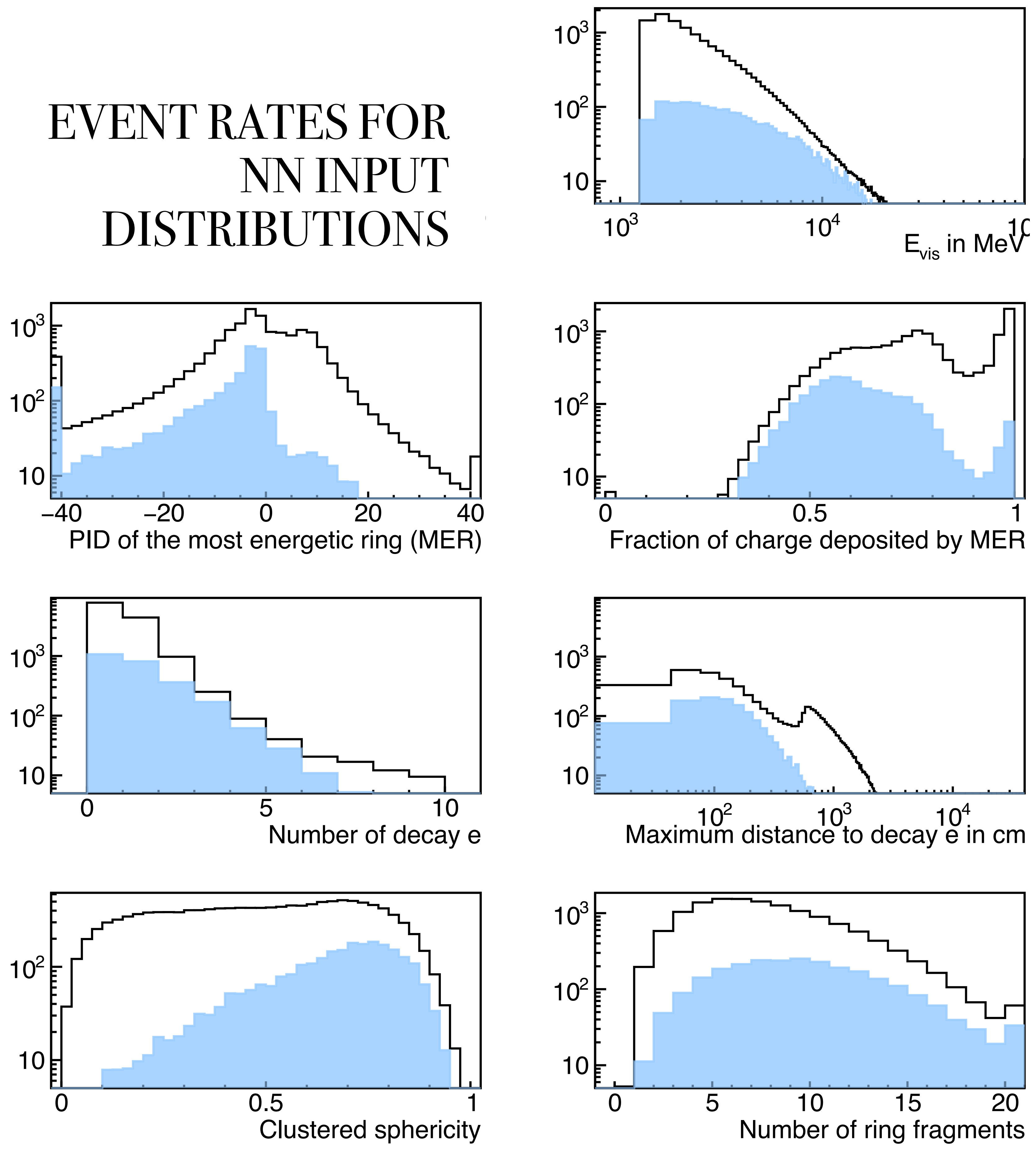

50% MORE EXPOSURE (Livetime x FV)



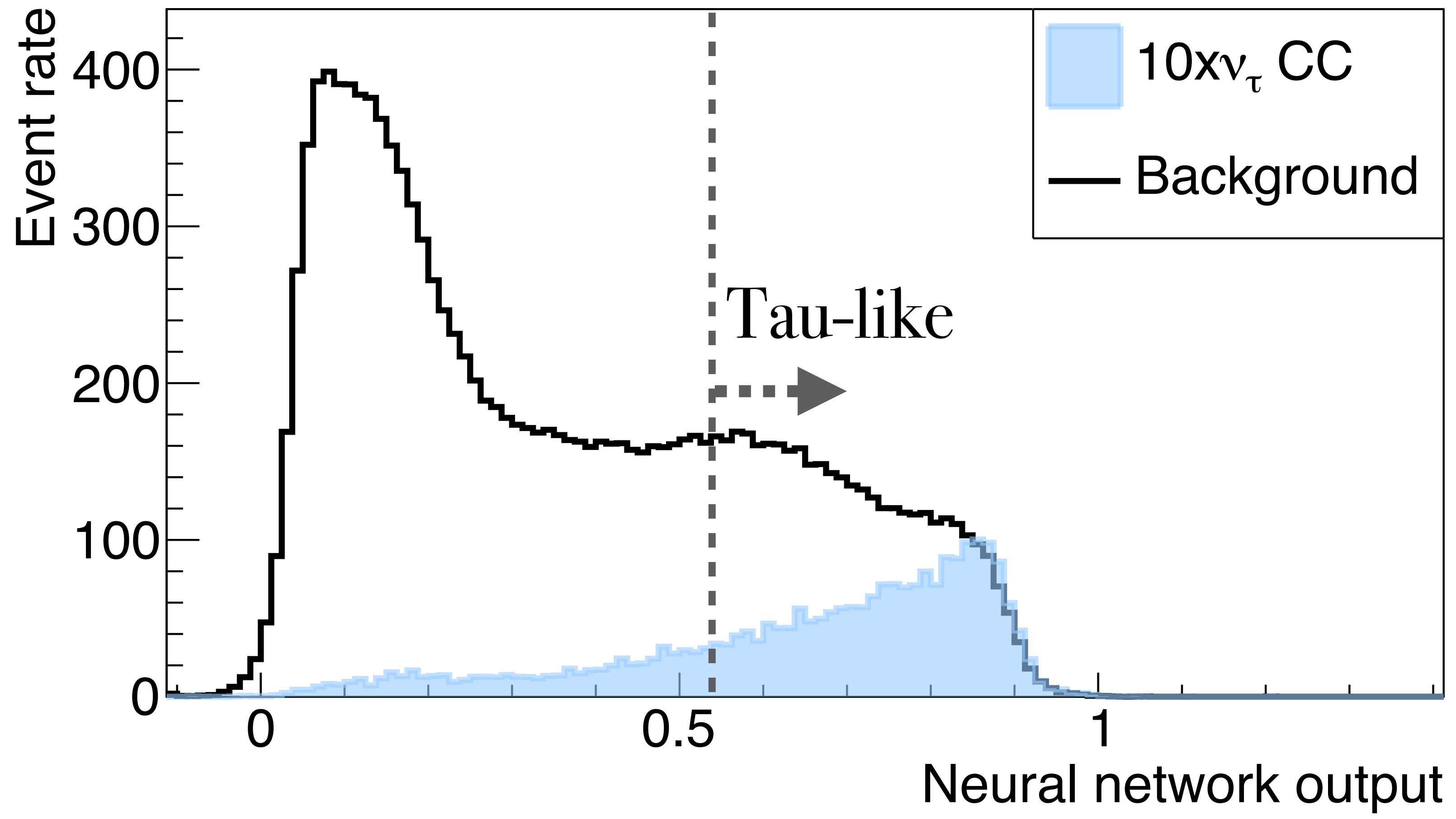

MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

# Neural network to detect tau neutrinos

EVENT RATES FOR NN INPUT DISTRIBUTIONS




NN OUTPUT

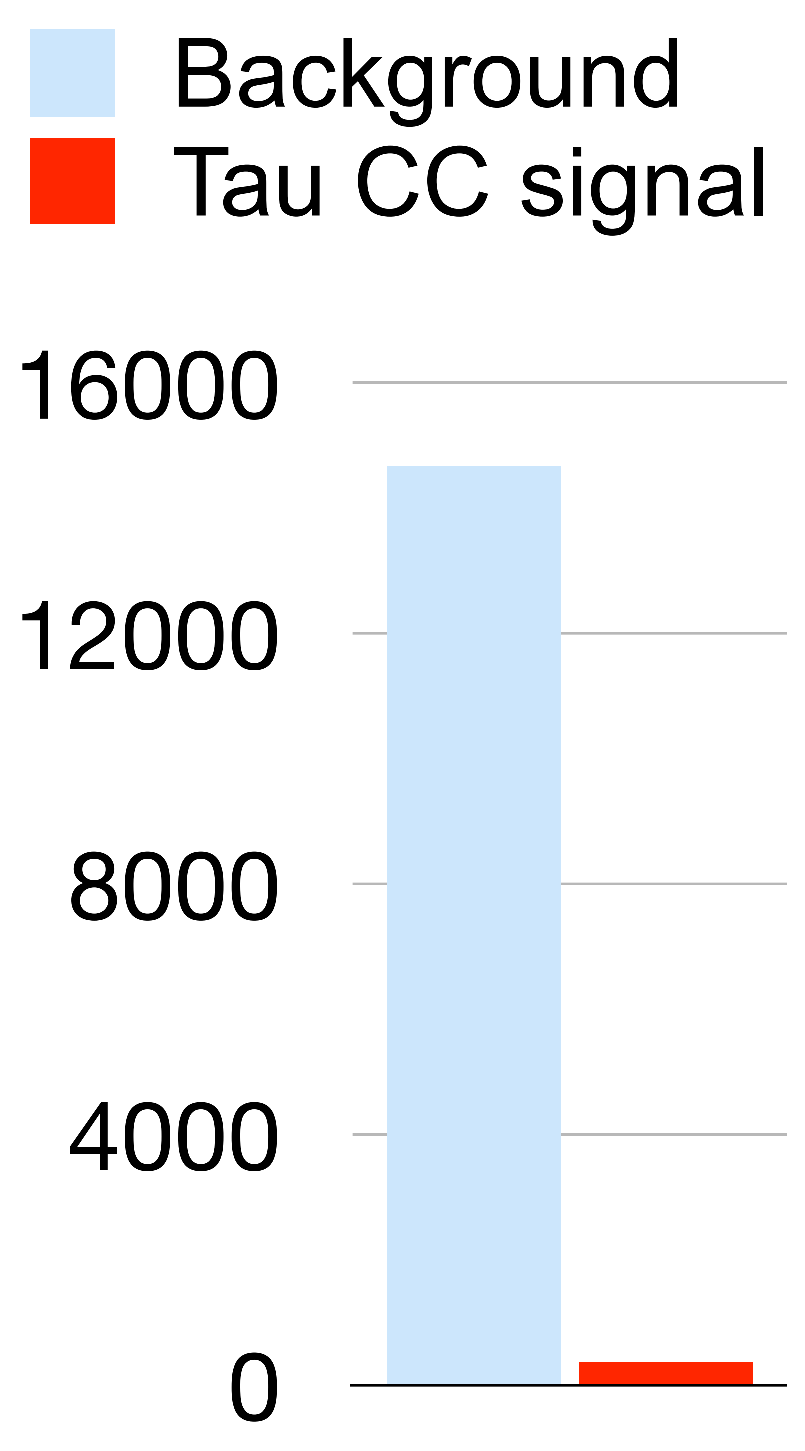


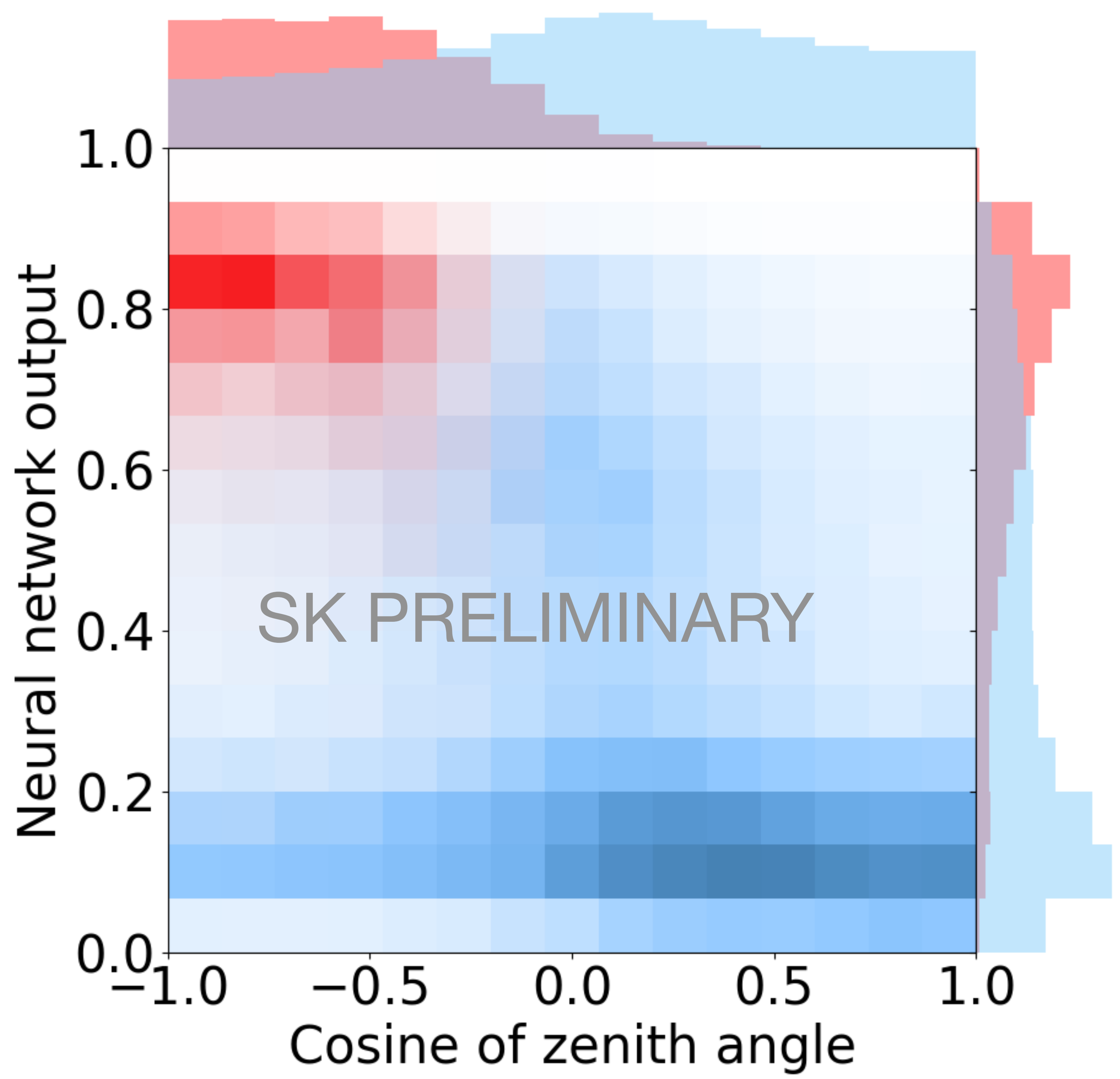

- Cut at the threshold of 0.54 results in a 5% pure tau neutrino sample.

- Nearly 20 times more background picked out as compared to $\nu_\tau$ CC signal, no cut made on the NN output.

# Extended likelihood fit

Data $= \alpha$Signal + Background + $\Sigma_i \epsilon_i$(Fluctuations in the nominal distributions due to +/-1$\sigma$ change in systematic uncertainties)



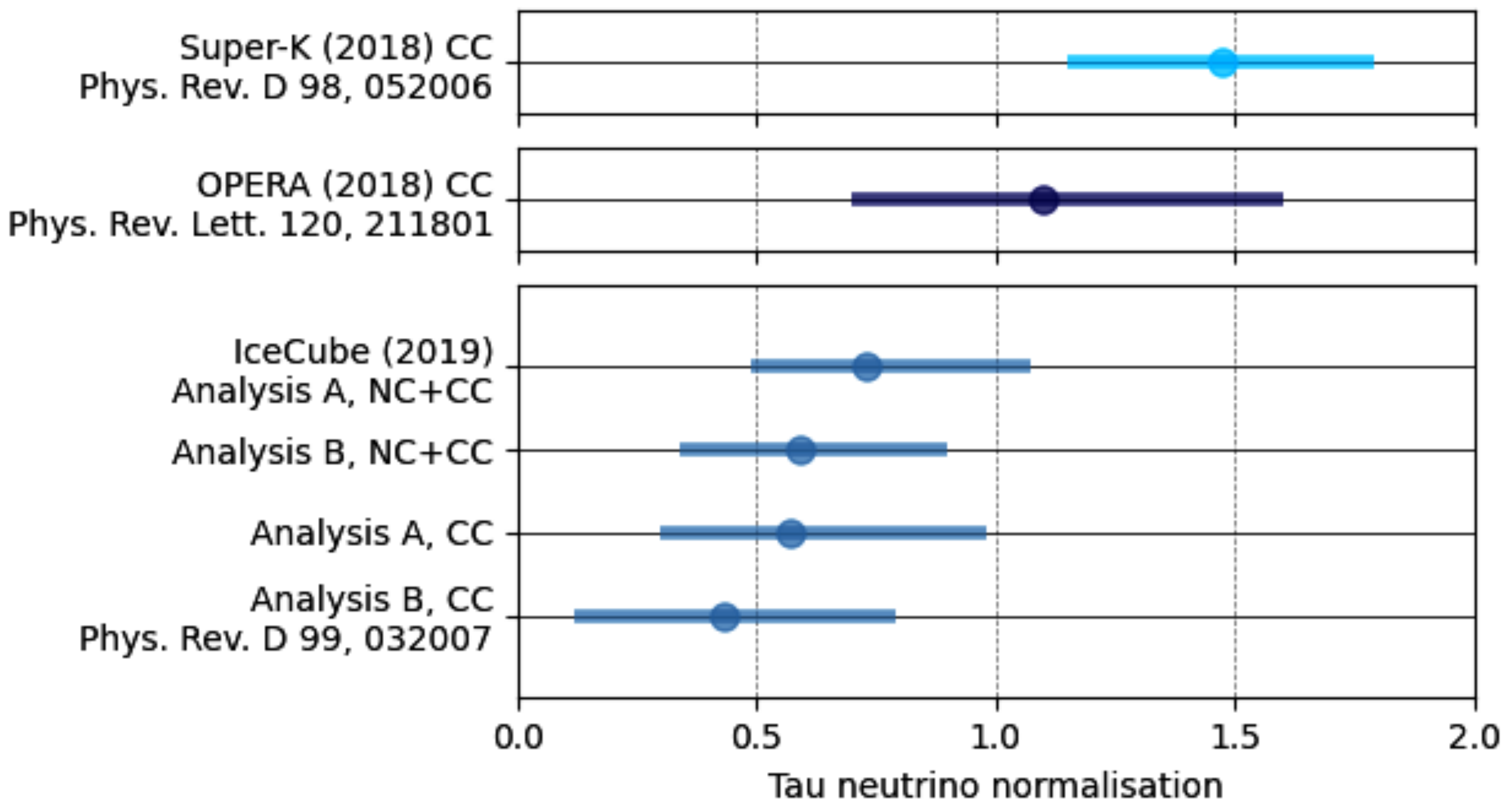



# Extended likelihood fit

Data = $\alpha$Signal + Background + $\Sigma_i \epsilon_i$(Fluctuations in the nominal distributions due to +/-1$\sigma$ change in systematic uncertainties)

## $\nu_\tau$ normalisation

$$\alpha = \frac{\text{Number of } \nu_\tau \text{ events observed}}{\text{Number of } \nu_\tau \text{ events expected under the standard 3-flavor oscillation formalism}}.$$




MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

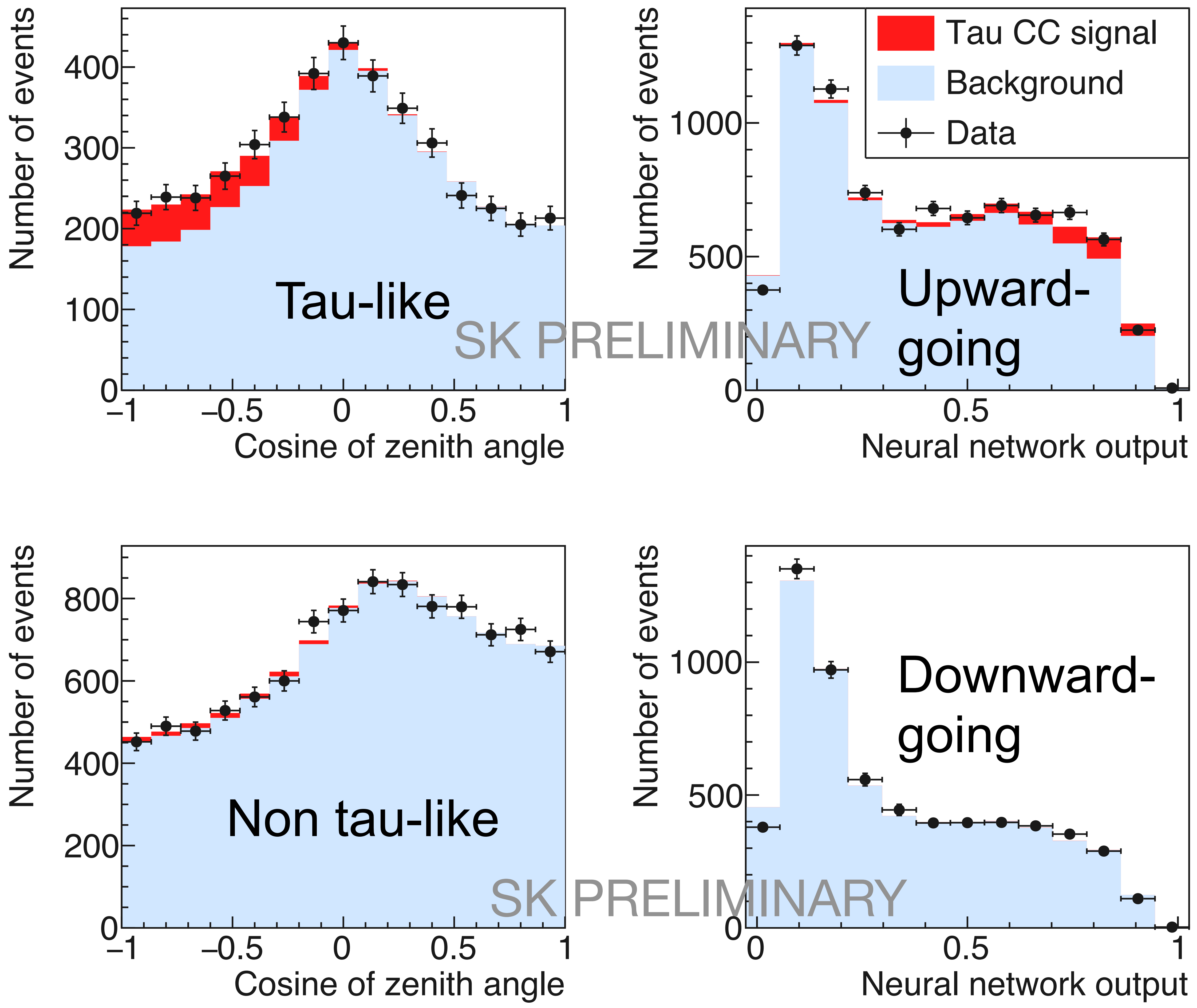
# Tau neutrino appearance

SK 2023 results on data from 1996 to 2020 (exposure of 485 kT.y)

- $\alpha_{\text{fitted}}$=1.36+/-0.29

  under normal ordering.

- 428+/-92 observed $\nu_\tau$ CC events.




MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

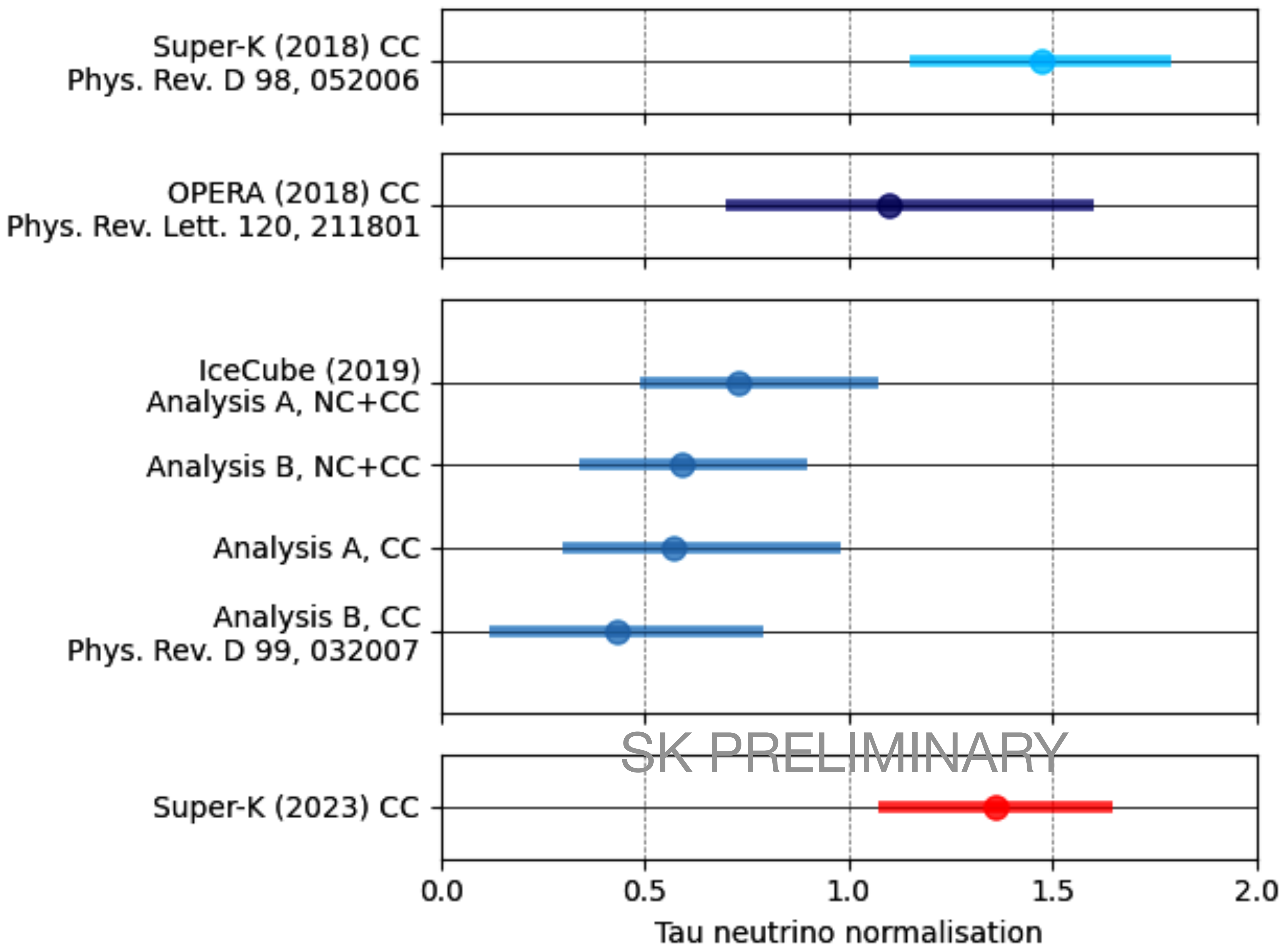
# Tau neutrino appearance

SK 2023 results on data from 1996 to 2020 (exposure of 485 kT.y)

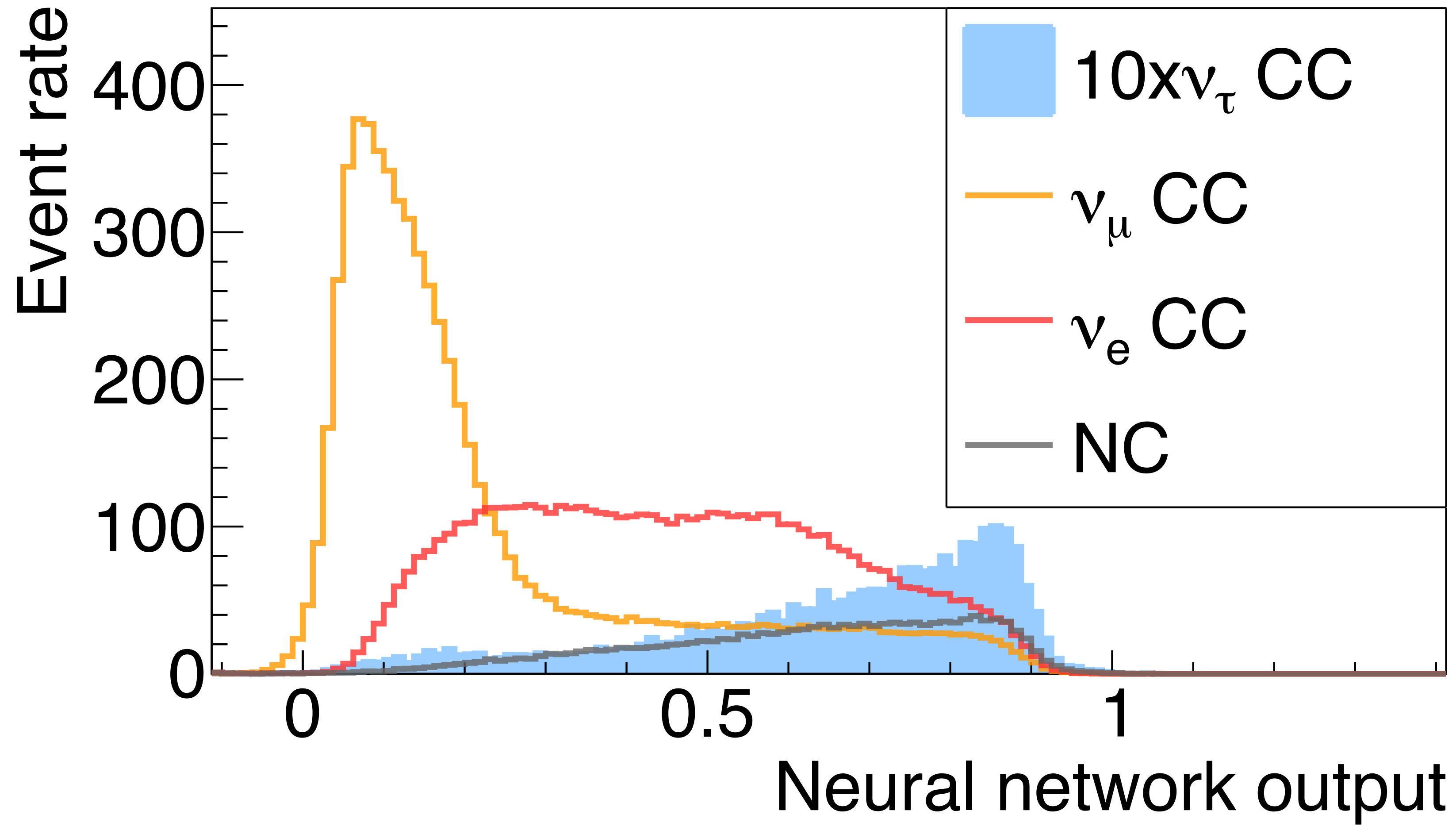
- $\alpha_{\text{fitted}}$=1.36+/-0.29

  under normal ordering.

- 428+/-92 observed $\nu_\tau$ CC events.

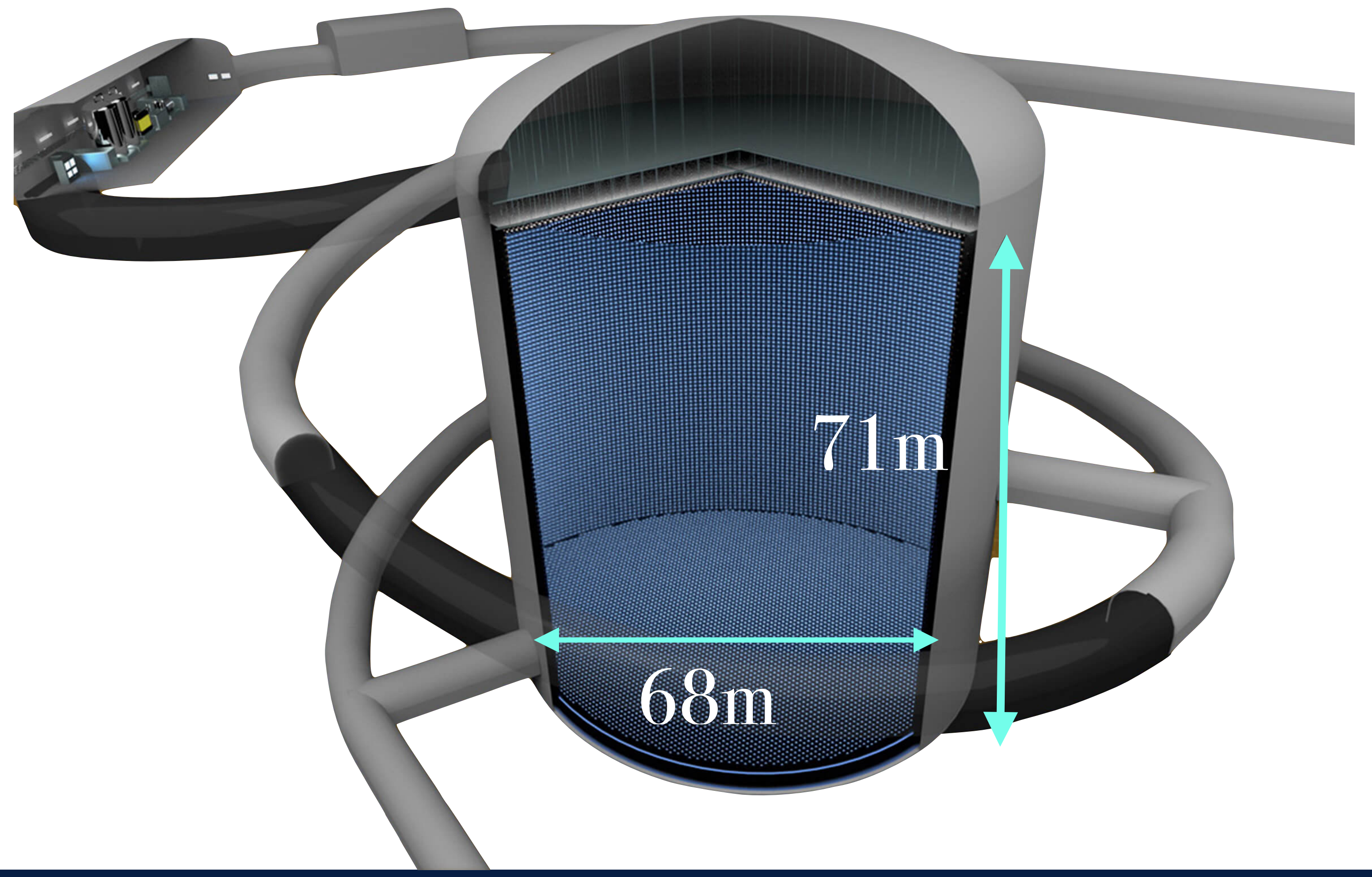


# What next?




| % of background misclassified | $\nu_\mu$ CC | $\nu_e$ CC | NC |
|---|---|---|---|
| | 13% | 37% | 70% |

- On-going efforts to remove mis-classified background by introduction of neutron capture information (for NC) from the Sk-Gd upgrade.
- Upgrading the neural network by the usage of better classification methods.
- Hyper-Kamiokande.



# What next?

## Three flavor neutrino oscillation

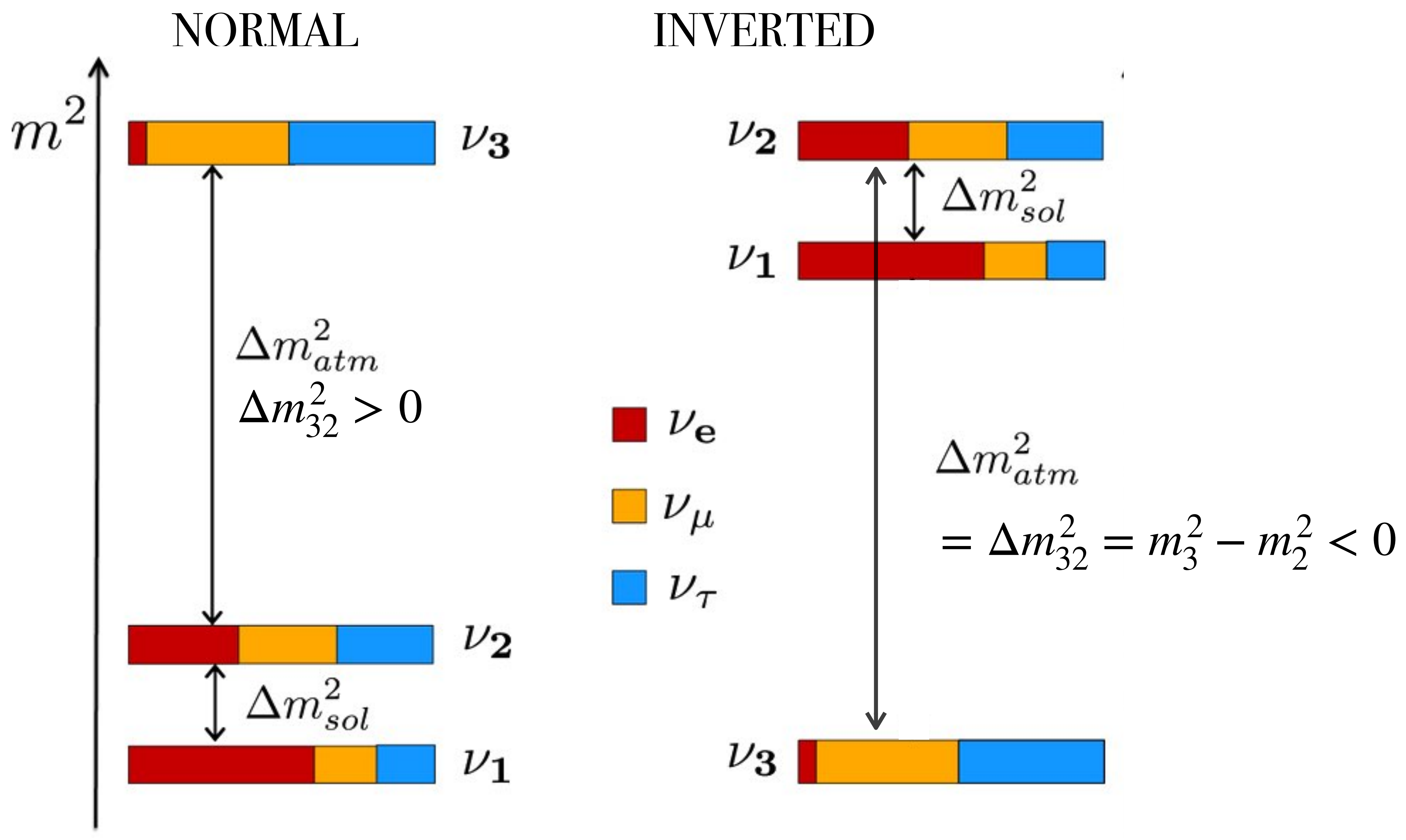
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}_{e1} & \mathrm{U}_{e2} & \mathrm{U}_{e3} \\ \mathrm{U}_{\mu 1} & \mathrm{U}_{\mu 2} & \mathrm{U}_{\mu 3} \\ \mathrm{U}_{\tau 1} & \mathrm{U}_{\tau 2} & \mathrm{U}_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

- Era of precision measurements.
- 3 open questions remain.

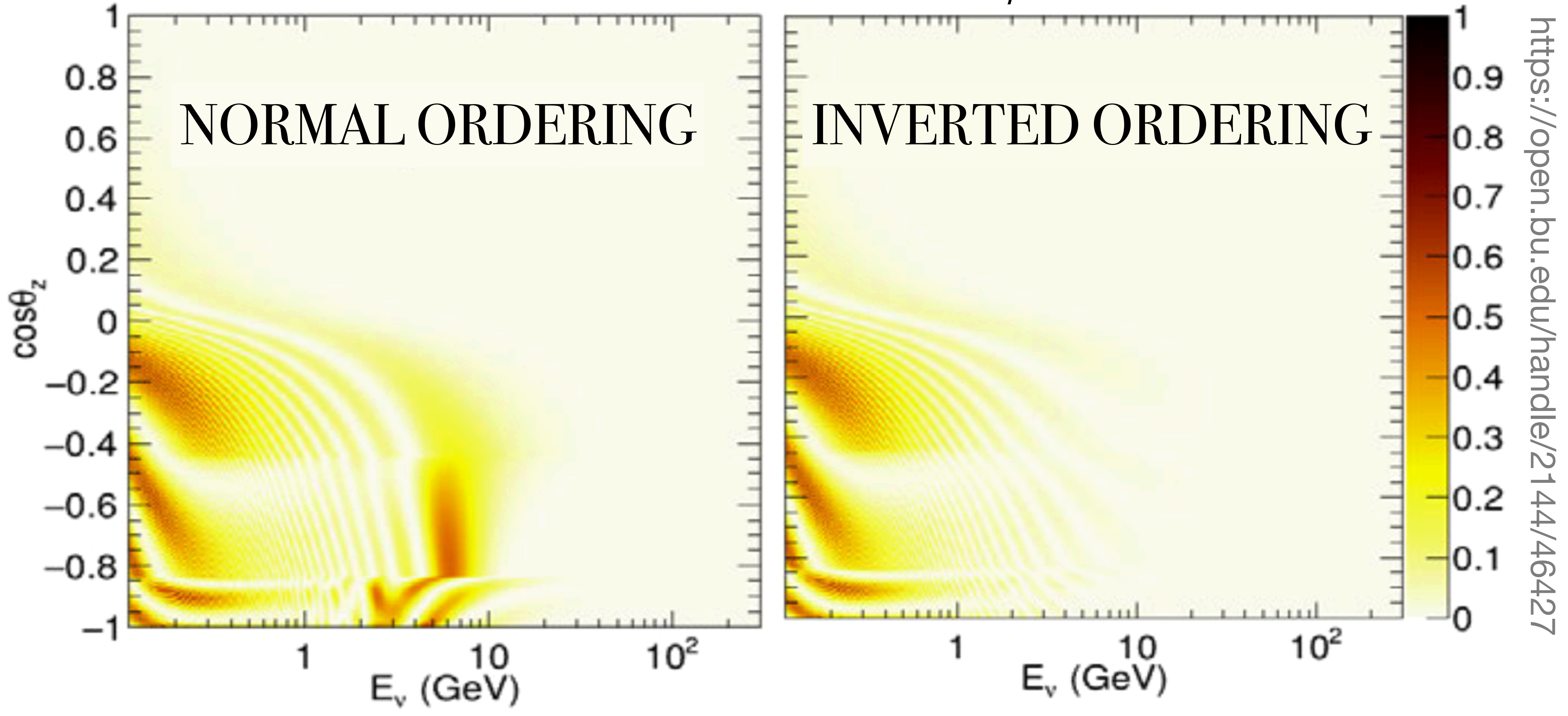
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \mathrm{c}_{23} & \mathrm{s}_{23} \\ 0 & -\mathrm{s}_{23} & \mathrm{c}_{23} \end{pmatrix} \begin{pmatrix} \mathrm{c}_{13} & 0 & \mathrm{s}_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\mathrm{s}_{13} e^{i\delta_{CP}} & 0 & \mathrm{c}_{13} \end{pmatrix} \begin{pmatrix} \mathrm{c}_{12} & \mathrm{s}_{12} & 0 \\ -\mathrm{s}_{12} & \mathrm{c}_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

# Neutrino mass ordering

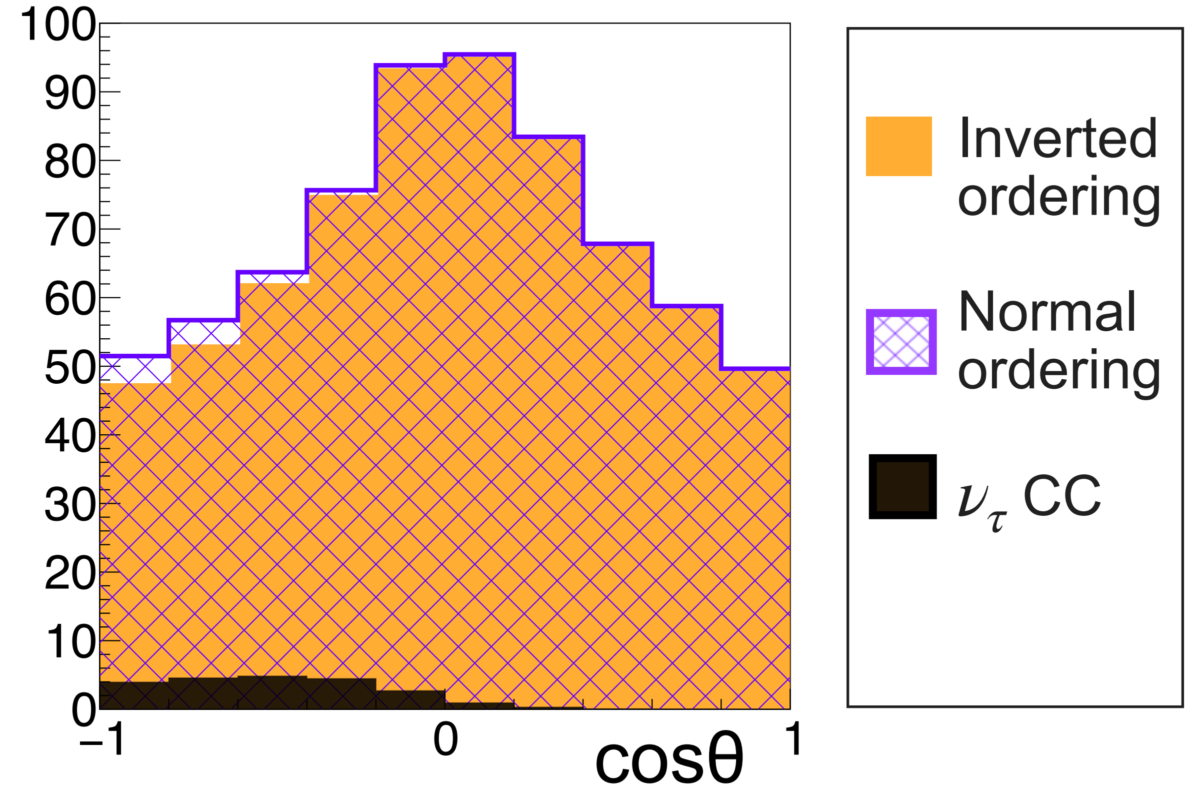



OSCILLATION PROBABILITIES OF $\nu_\mu \rightarrow \nu_e$ UNDER




EVENT RATES FOR AN $\nu_e$ SAMPLE AT SUPER-K

$\nu_e$-like events that produce multiple Cherenkov rings and visible energy $E_{vis}$>1.33 GeV selected by a BDT





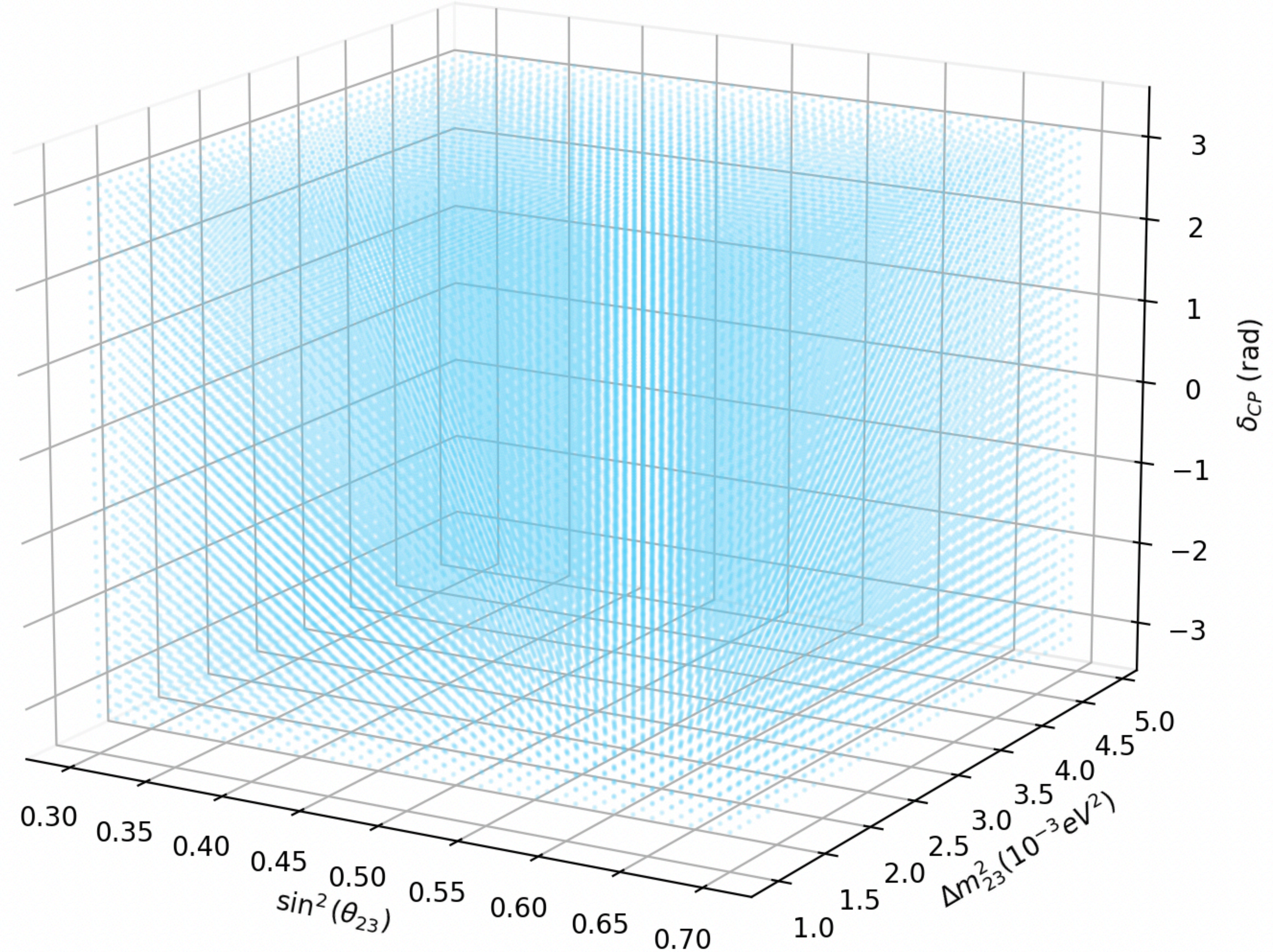
MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

# Three flavor neutrino oscillation

SK 2023 paper

| Parameter | Min. | Max. | Points |
|---|---|---|---|
| SK, $\sin^2\theta_{13}$ Constrained | | | |
| $\sin^2\theta_{23}$ | 0.3 | 0.7 | 35 |
| $\Delta m^2_{32}$ $(10^{-3}\,\mathrm{eV}^2)$ | 1.0 | 4.9 | 40 |
| $\delta_{\mathrm{CP}}$ (rad) | $-\pi$ | $\pi$ | 37 |
| $\sin^2\theta_{13}$ | $0.0220 \pm 0.0007$ | | 1 |

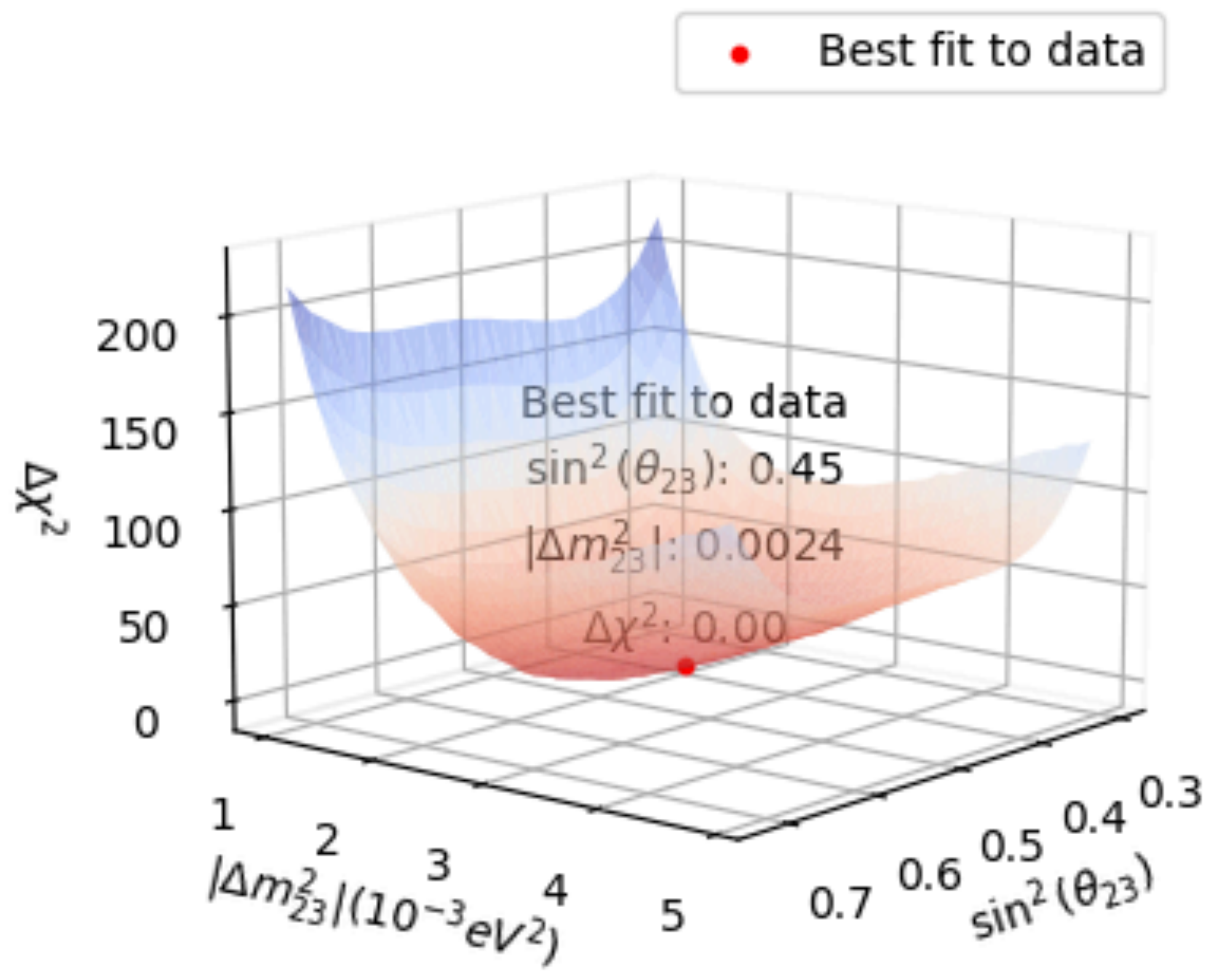
51800 points for each ordering

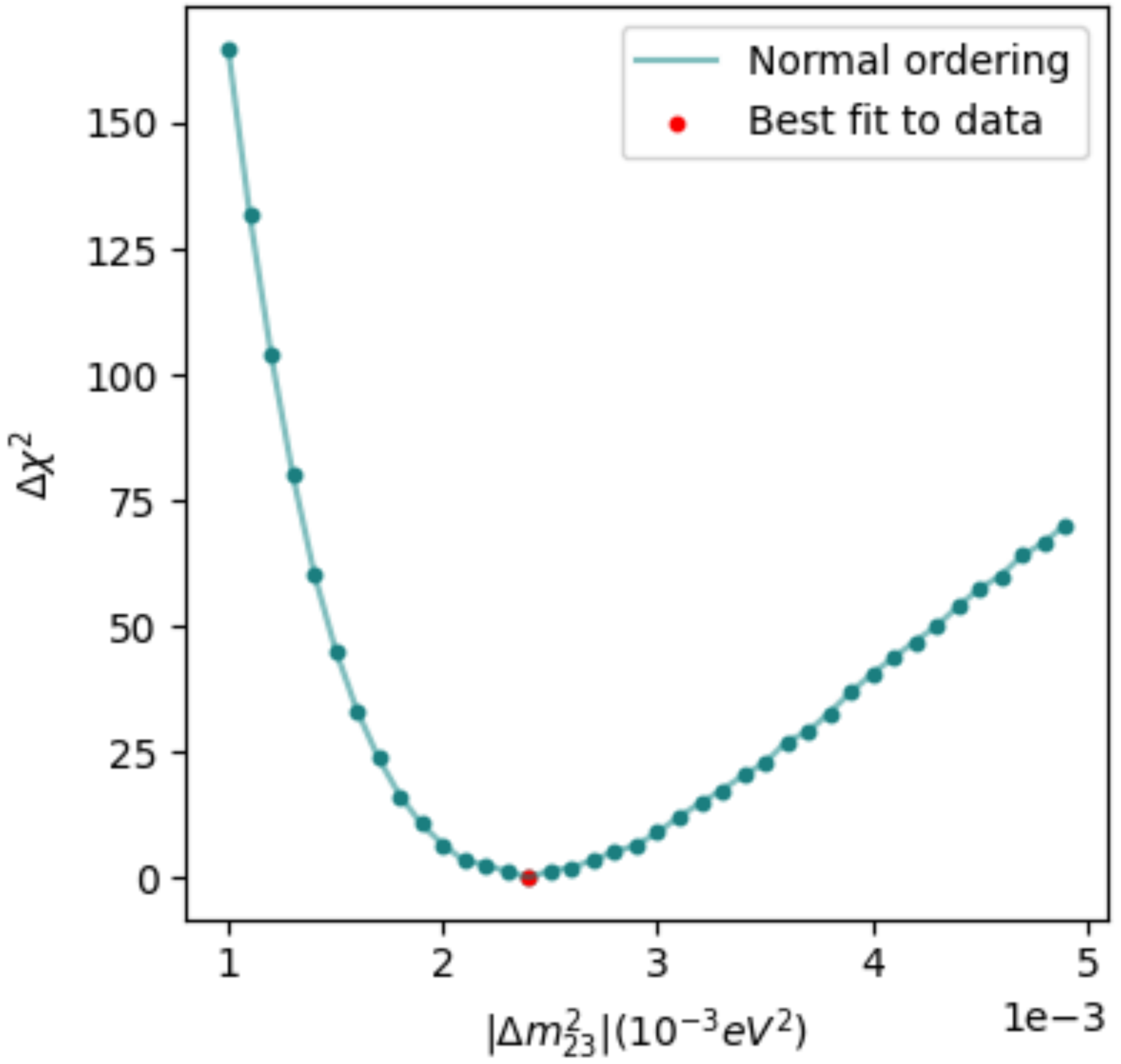


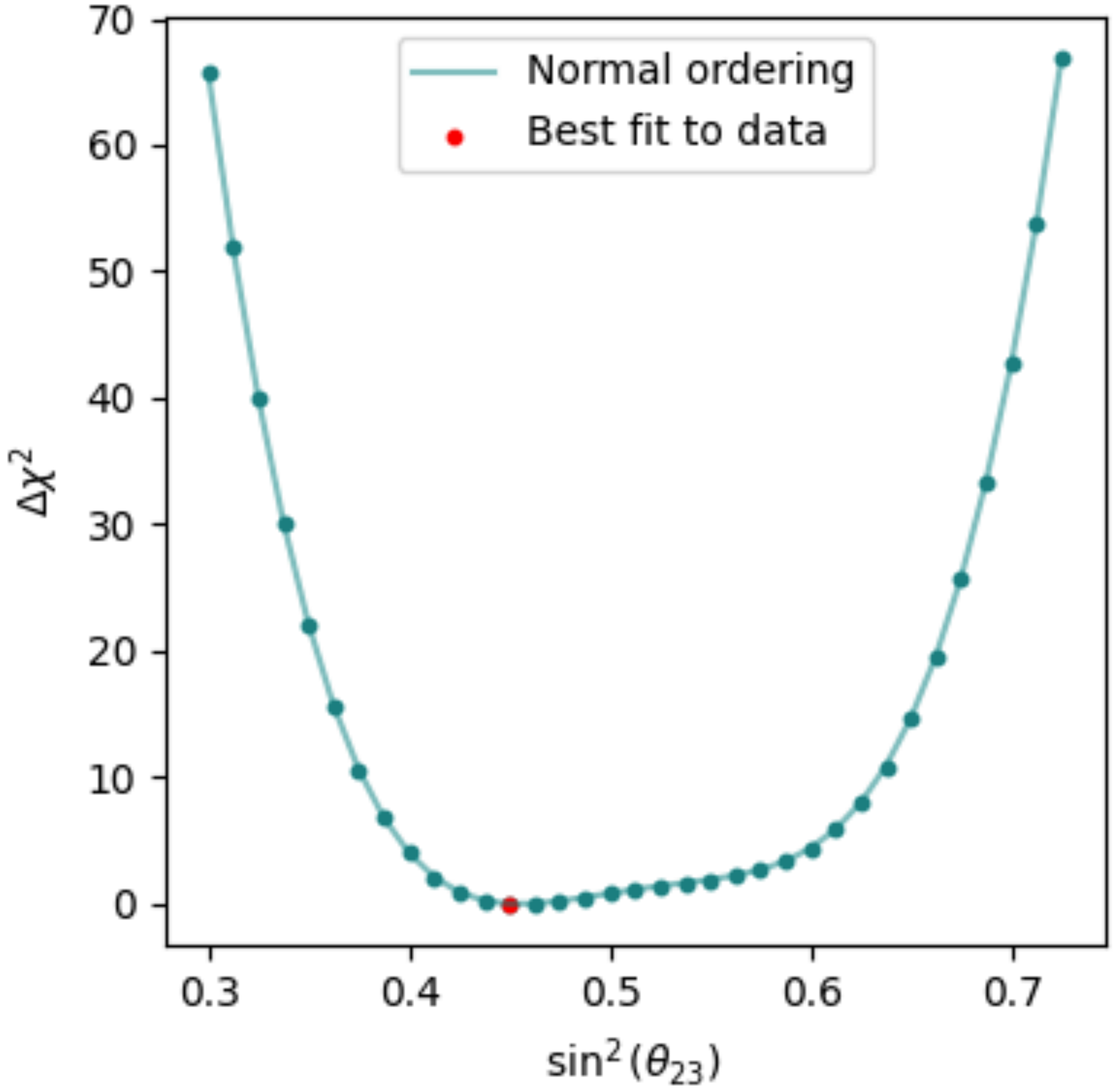
# Present data fit

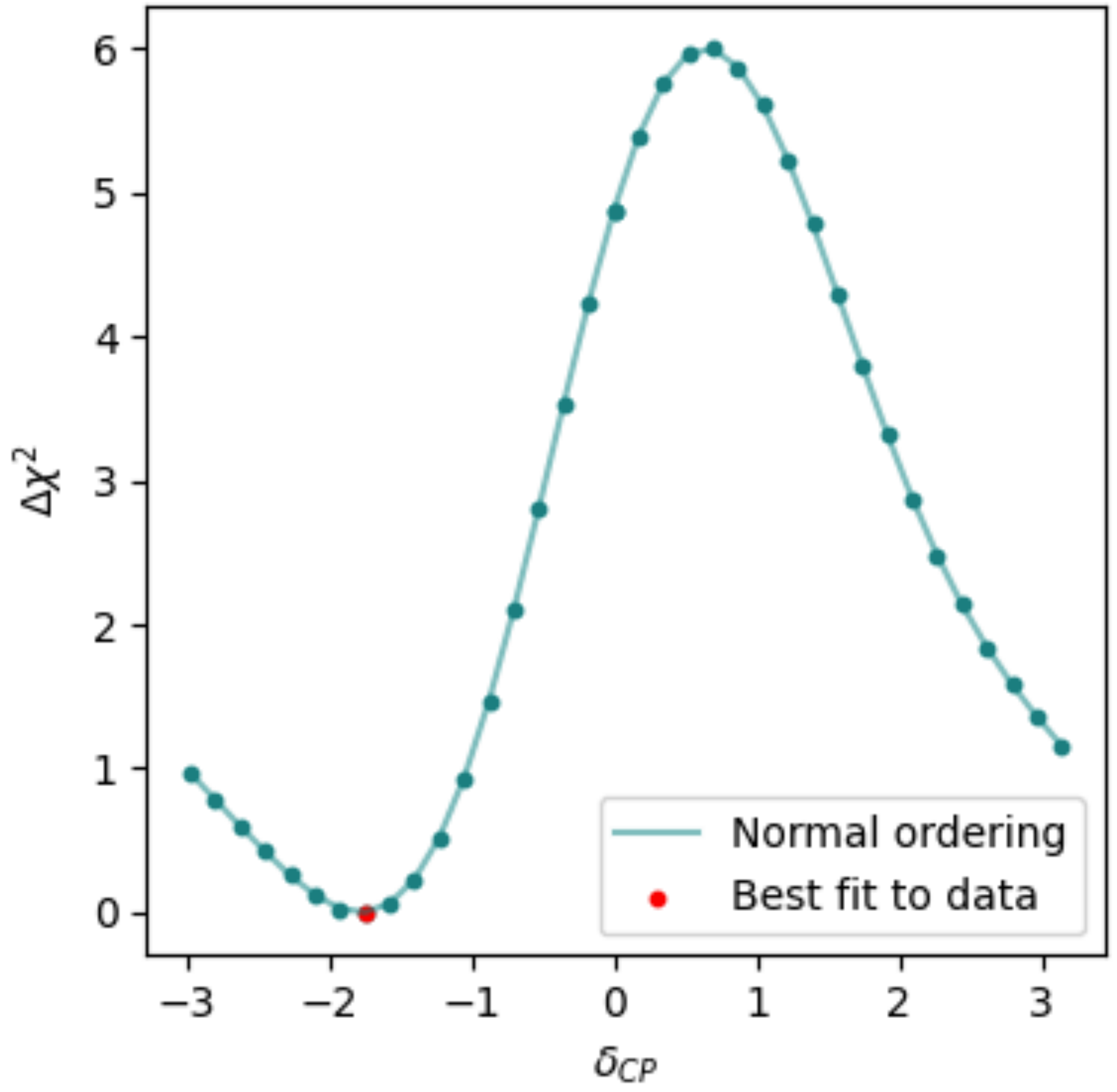
| Fit result | Ordering | $\chi^2$ | $\Delta\chi^2_{\mathrm{I.O.-N.O.}}$ |
|---|---|---|---|
| SK, $\sin^2\theta_{13}$ Constrained | Normal | 1022.06 | 5.69 |
| | Inverted | 1027.75 | |

| Ordering | $\sin^2\theta_{23}$ |
|---|---|
| Normal | $0.45^{+0.06}_{-0.03}$ |
| Inverted | $0.45^{+0.08}_{-0.03}$ |
| **Ordering** | **$\lvert\Delta m^2_{32,31}\rvert$ $(10^{-3}\,\mathrm{eV}^2)$** |
| Normal | $2.40^{+0.07}_{-0.09}$ |
| Inverted | $2.40^{+0.06}_{-0.12}$ |
| **Ordering** | **$\delta_{\mathrm{CP}}$ $(-\pi,\pi)$** |
| Normal | $-1.75^{+0.76}_{-1.25}$ |
| Inverted | $-1.75^{+0.89}_{-1.22}$ |

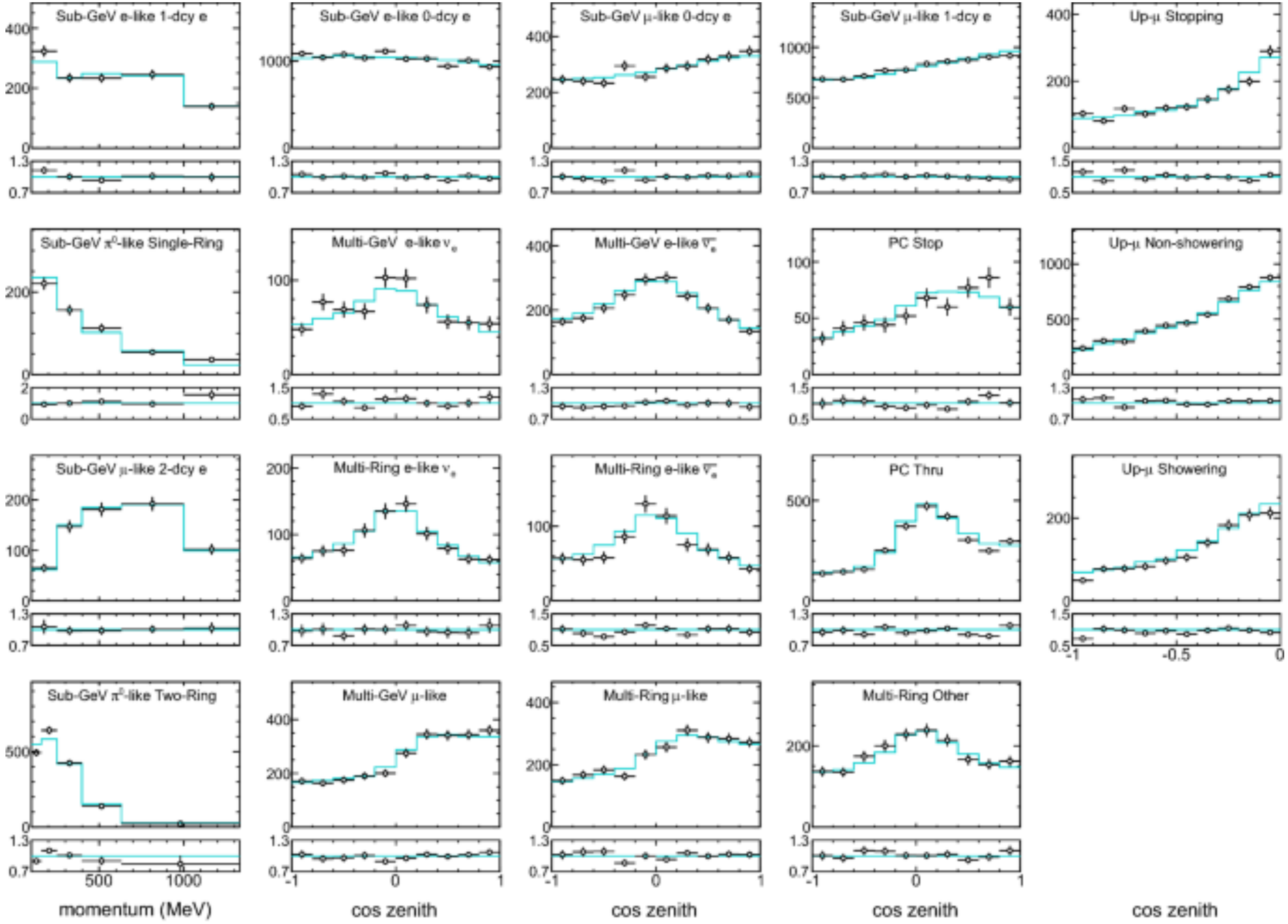


# SK samples




MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

Multi-class classifier development removed from online copy.

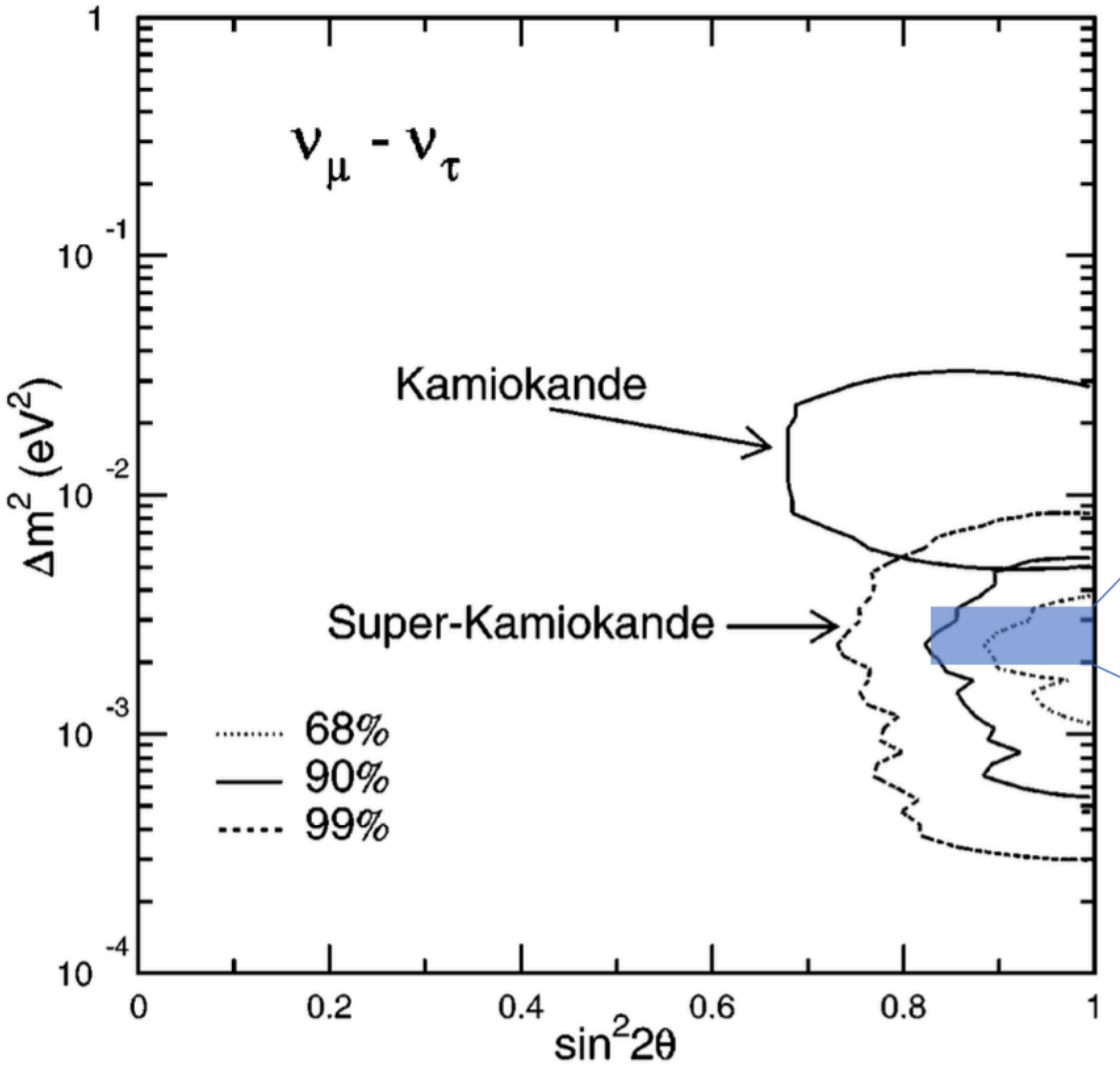
MAITRAYEE MANDAL
Maitrayee.Mandal@ncbj.gov.pl

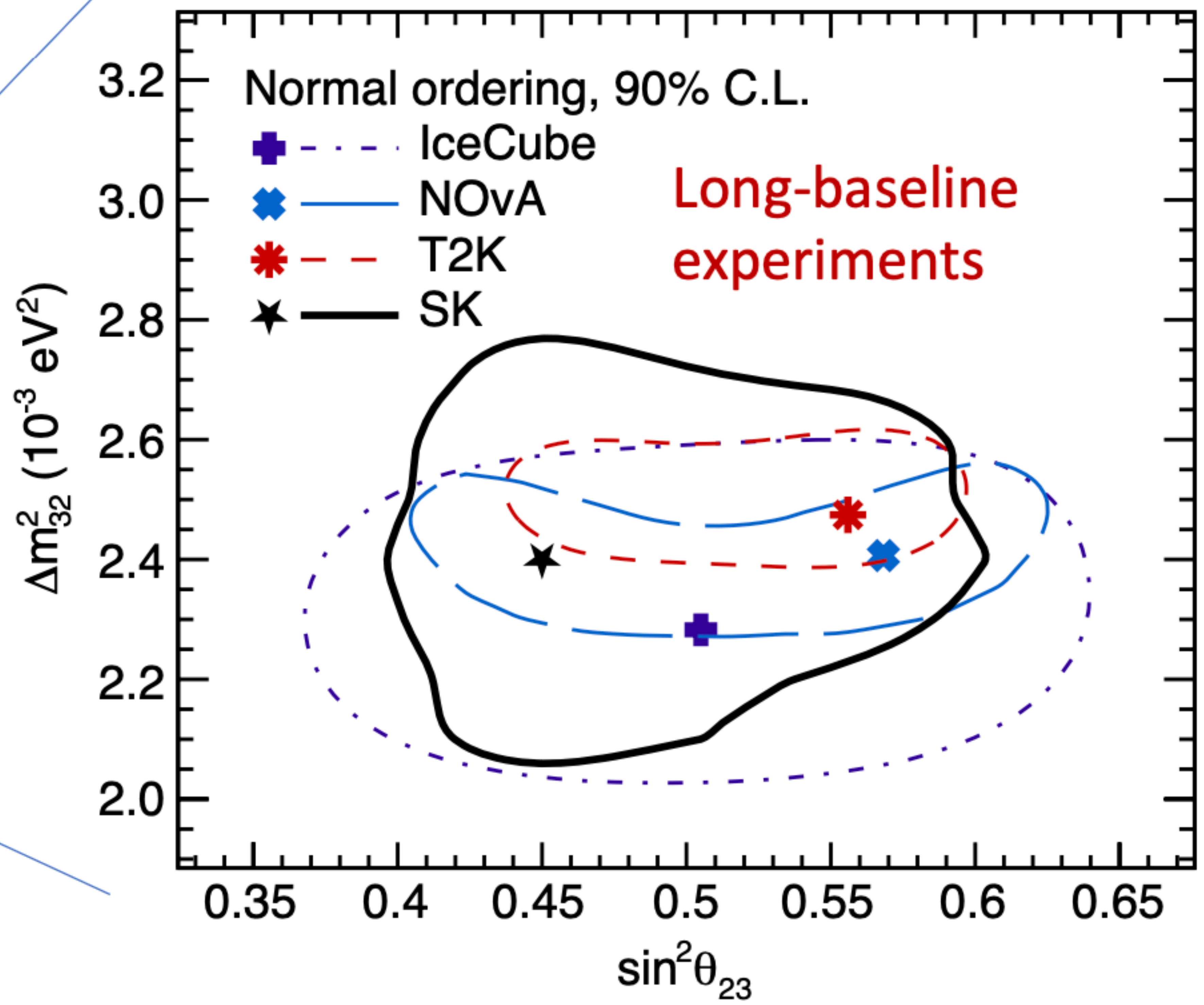
Multi-class classifier development removed from online copy.

# Summary

1998

2023




Taken from slide by Ed Kearns
14th International Neutrino Summer School 2023 at Fermilab NPC