Detection of Tau Neutrinos at the Super-Kamiokande Experiment

Maitrayee Mandal

NCBJ ŚWIERK

Student Talk

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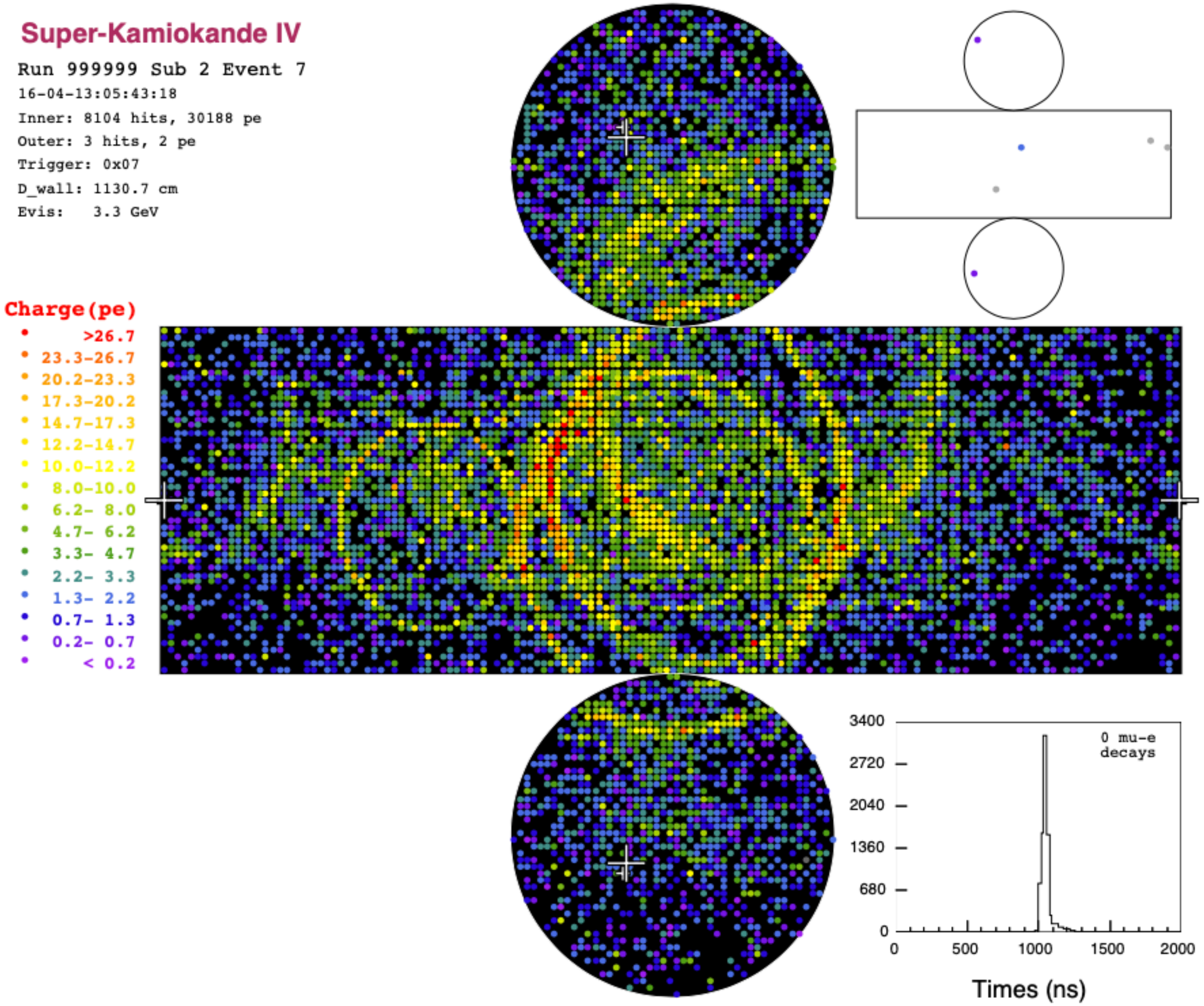
At the Super-Kamiokande experiment (SK),



SK event display of a typical event of tau neutrino charged current interaction showing multiple Cherenkov rings.

arXiv:1711.09436v1

the classification of the signal due to tau neutrino interactions from its respective background, is done **with a neural network - 7 input multi-layer perceptron.**

In 2018, SK excluded the hypothesis of no tau appearance from atmospheric neutrinos with a significance level of 4.6σ.

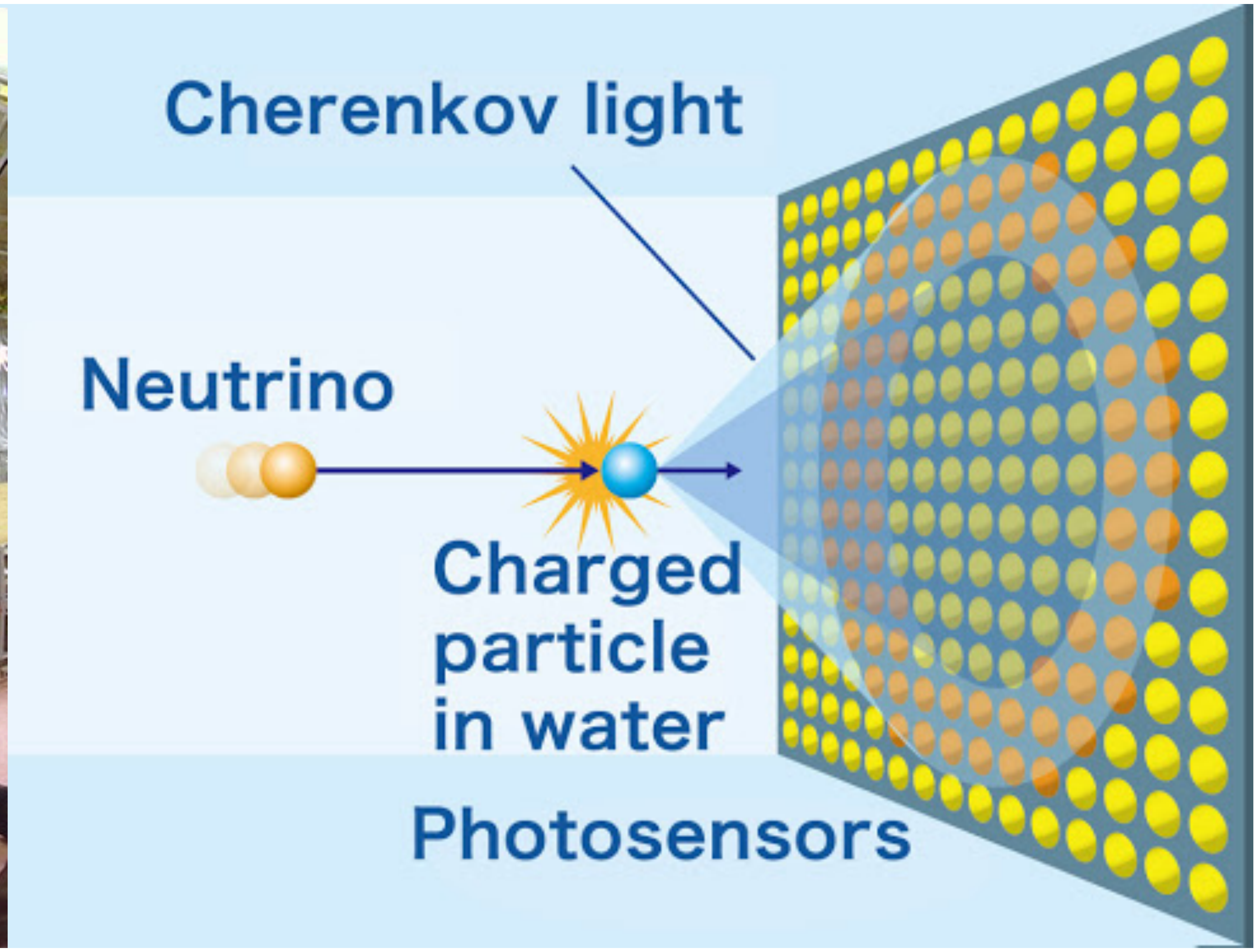
1. Super-Kamiokande Experiment
2. Neutrino Oscillations in Atmospheric Neutrinos
3. Detection of Tau Neutrinos at SK

Super-Kamiokande consists of stainless steel tank of 40 m diameter and 40 m height, filled with ultra-pure water. The walls of the tank are lined with **~13,000 photomultiplier tubes (PMT).**

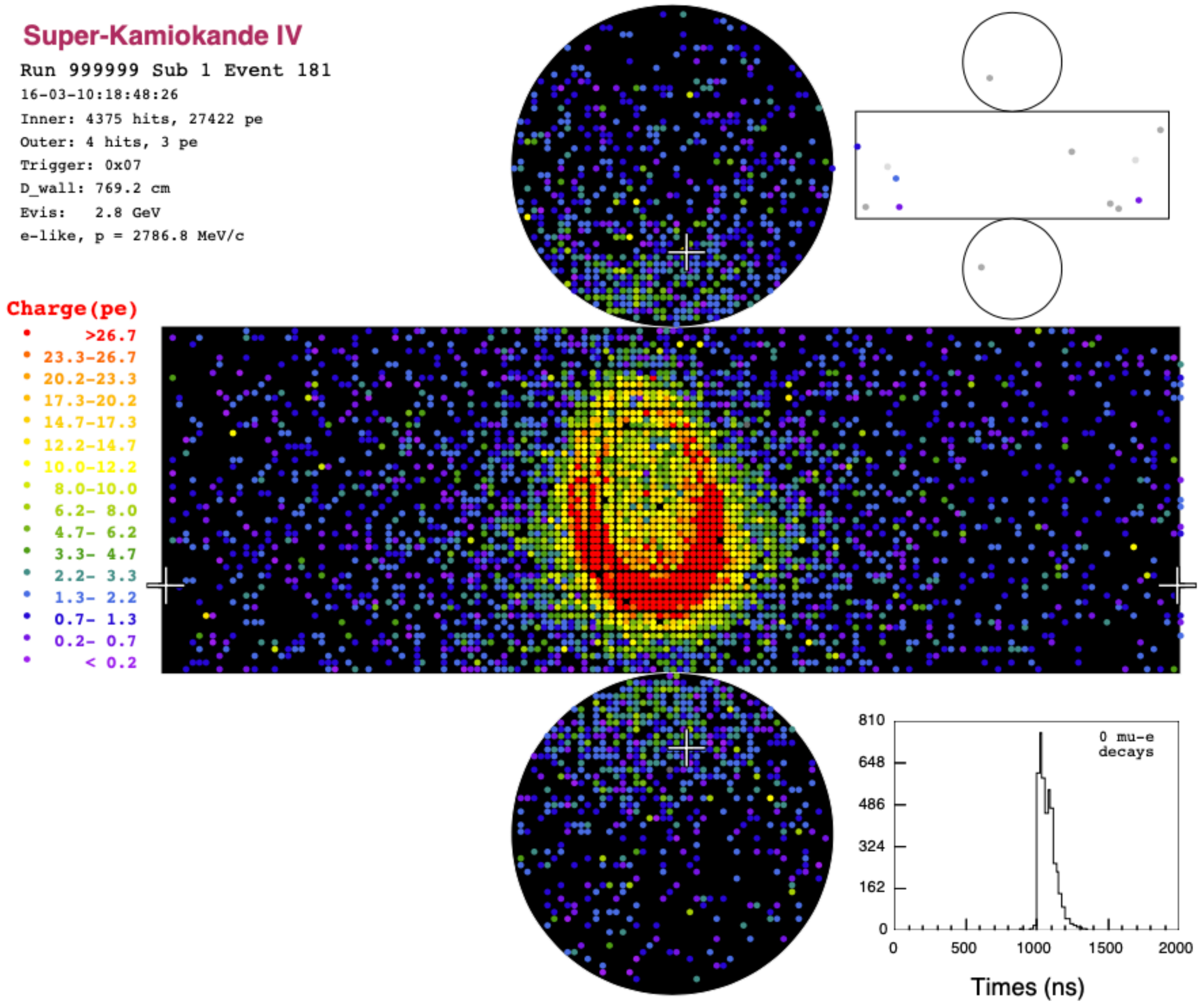
Super-Kamiokande Experiment

Installation of an SK inner detector PMT

http://www-sk.icrr.u-tokyo.ac.jp/sk/_images/photo/kensyutsuki/assemble-bottomPMT-m.jpg



Creation of Cherenkov Ring at SK

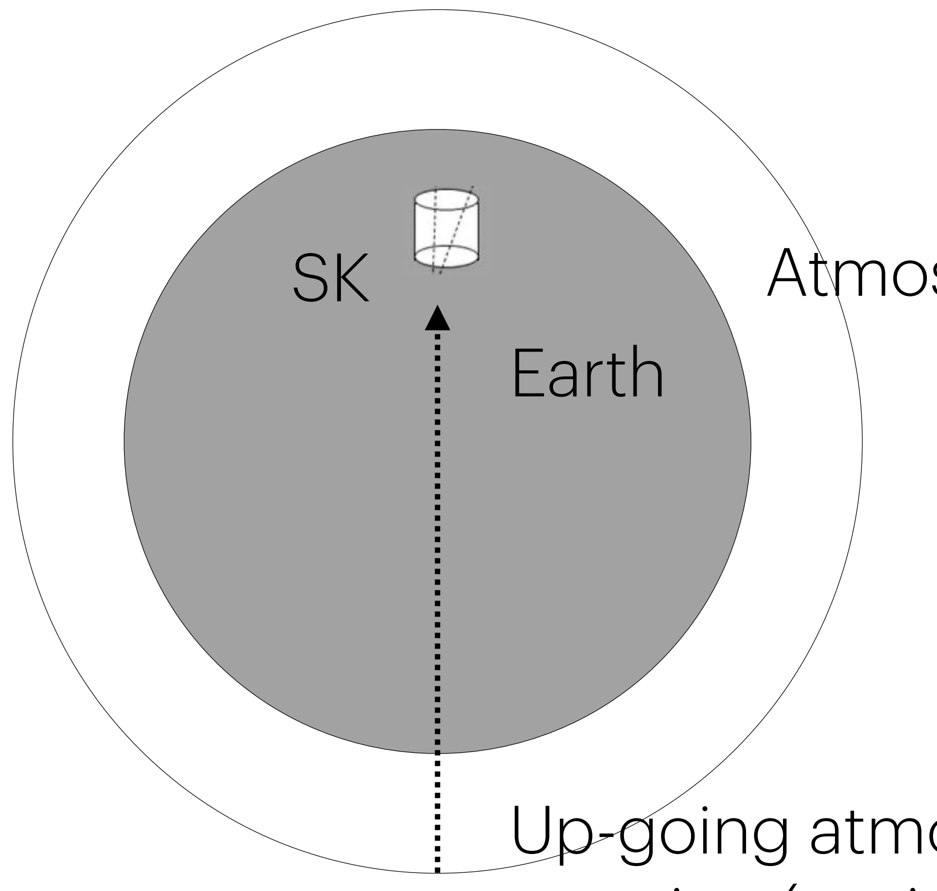


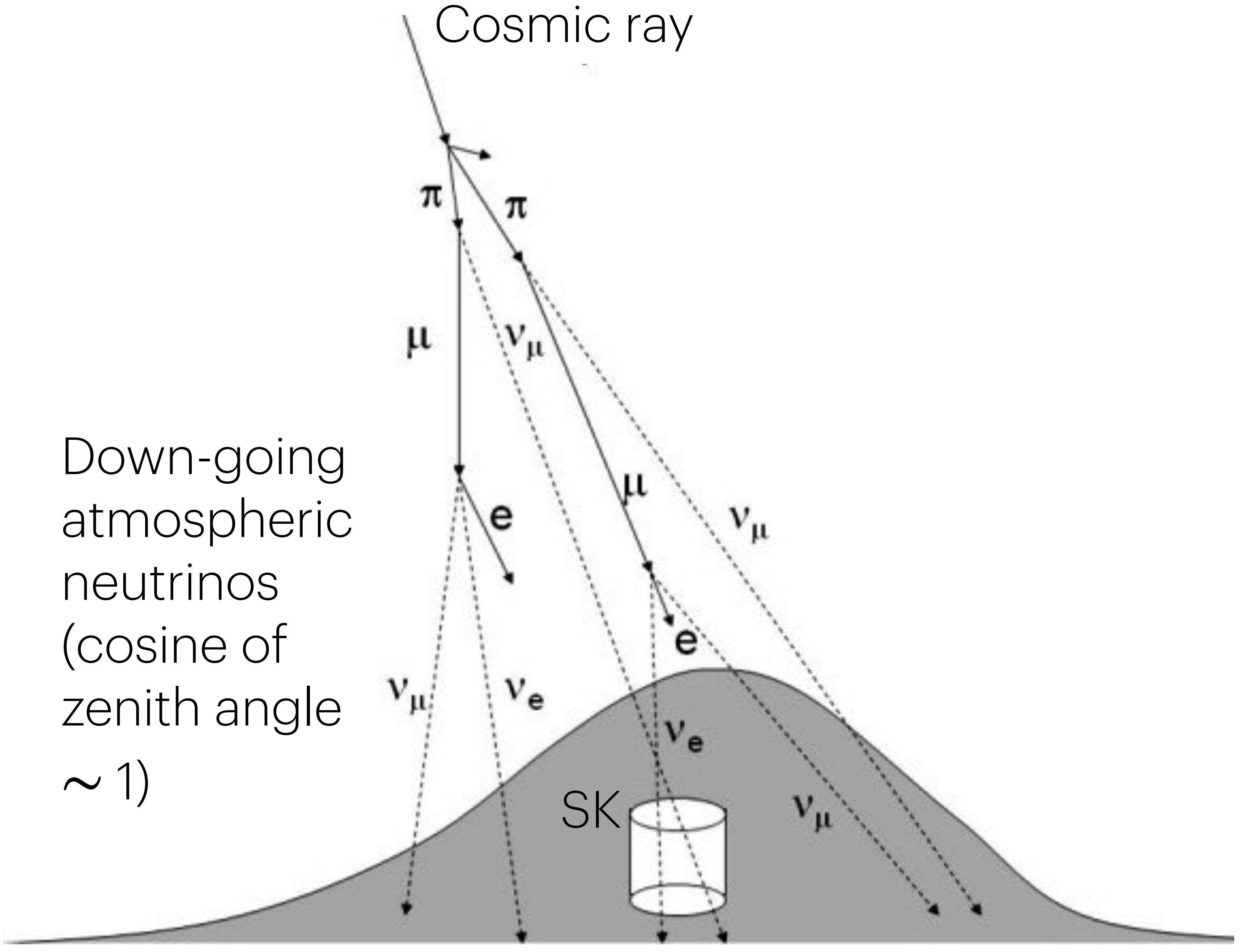
SK Event Display of a Cherenkov ring produced by e-like event, indicating ν_e CC interaction. arXiv:1711.09436v1

- Charged particles produce **Cherenkov radiation**, when traveling faster than the speed of light in a medium (refractive index, n).

$$\beta = \frac{v_{\text{particle}}}{c} > \frac{1}{n}.$$

- The radiation can be detected by photomultiplier tubes.
- The presence of a charged particle in an event, corresponds to the observation of a “Cherenkov ring”. We observe multiple rings for many charged particles in an event.





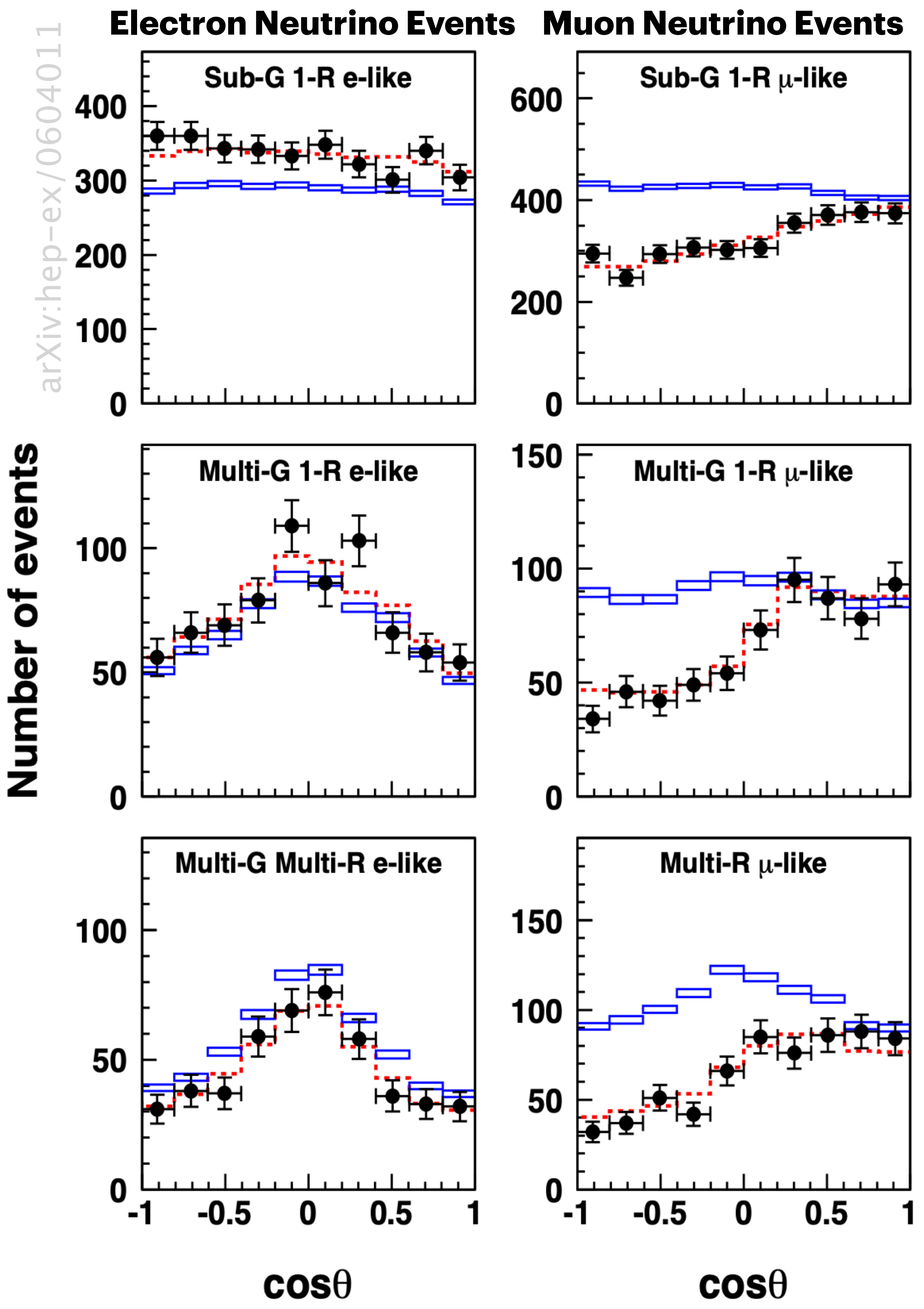
Atmospheric Neutrinos

- Cosmic rays (protons and nuclei from outer space) produce hadronic showers of pions and kaons, that decay to muons.

$$\pi^+ \to \mu^+ + \nu_\mu,$$
$$\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+.$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu,$$
$$\mu^- \to \nu_\mu + \bar{\nu}_e + e^-.$$

- Muon neutrino and electron neutrino are thus, produced in the upper atmosphere.
- We denote the zenith angle by θ.
- Super-Kamiokande observes a deficit of up-going muon neutrinos, $\cos\theta < 0$.
- The deficit is explained by neutrino oscillations.

Zenith angle distributions for



Blue boxes show simulated distribution assuming no oscillations, red dotted lines show best-fit of data, black dots are the observed data points.

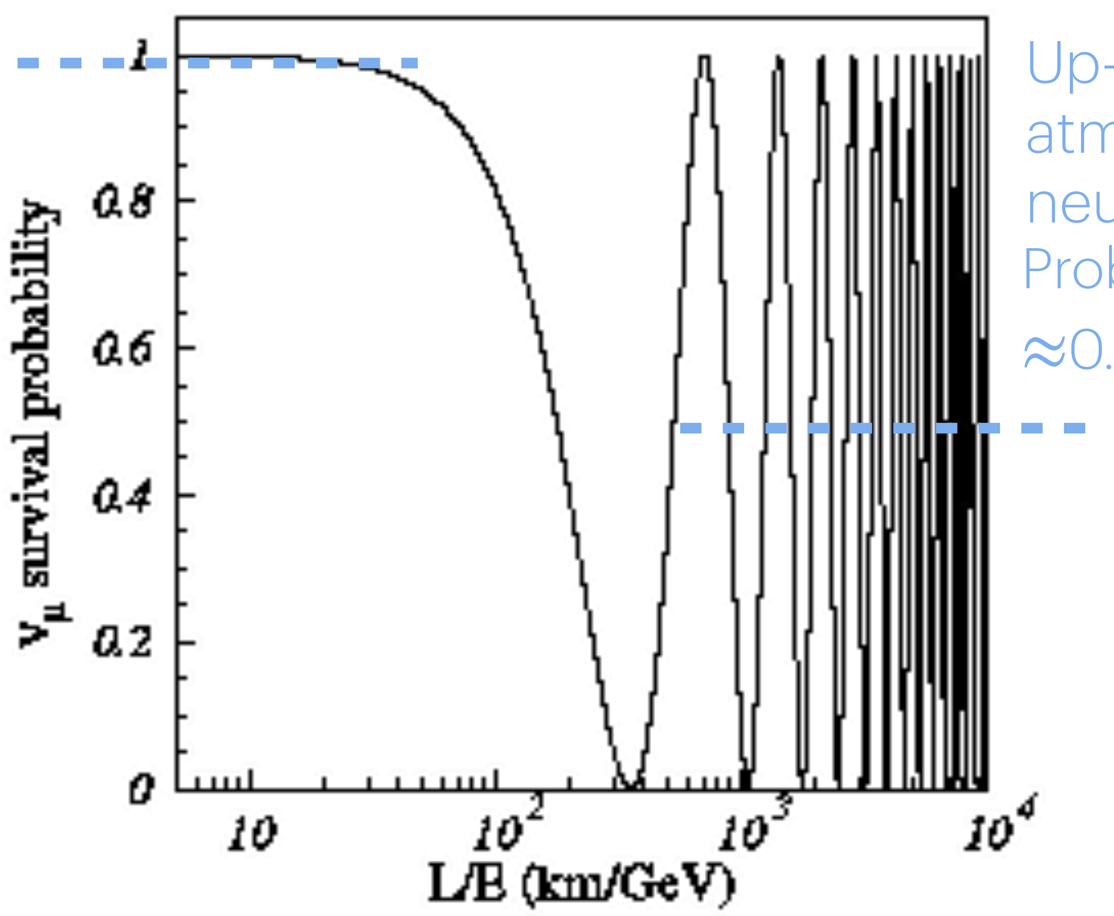
Neutrino Oscillations

arXiv:hep-ex/0404034

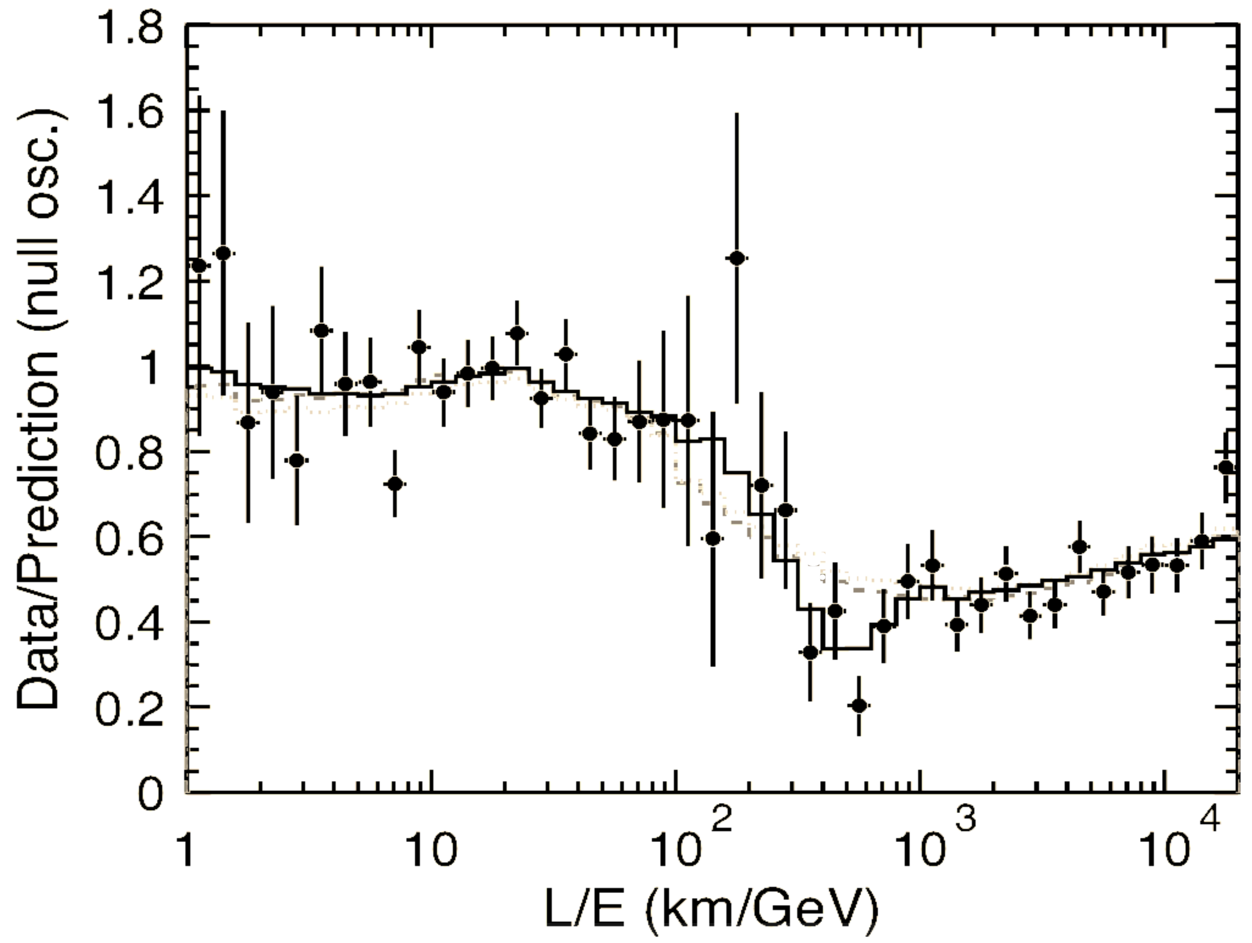
Muon neutrino survival probability assuming two neutrino approximation

Down-going atmospheric neutrino

Probability =1



Up-going atmospheric neutrino Probability ≈0.5



Ratio of the data to the simulated events without neutrino oscillation (points) and the best-fit expectation for 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations (solid line).

2015 Nobel Prize for Physics

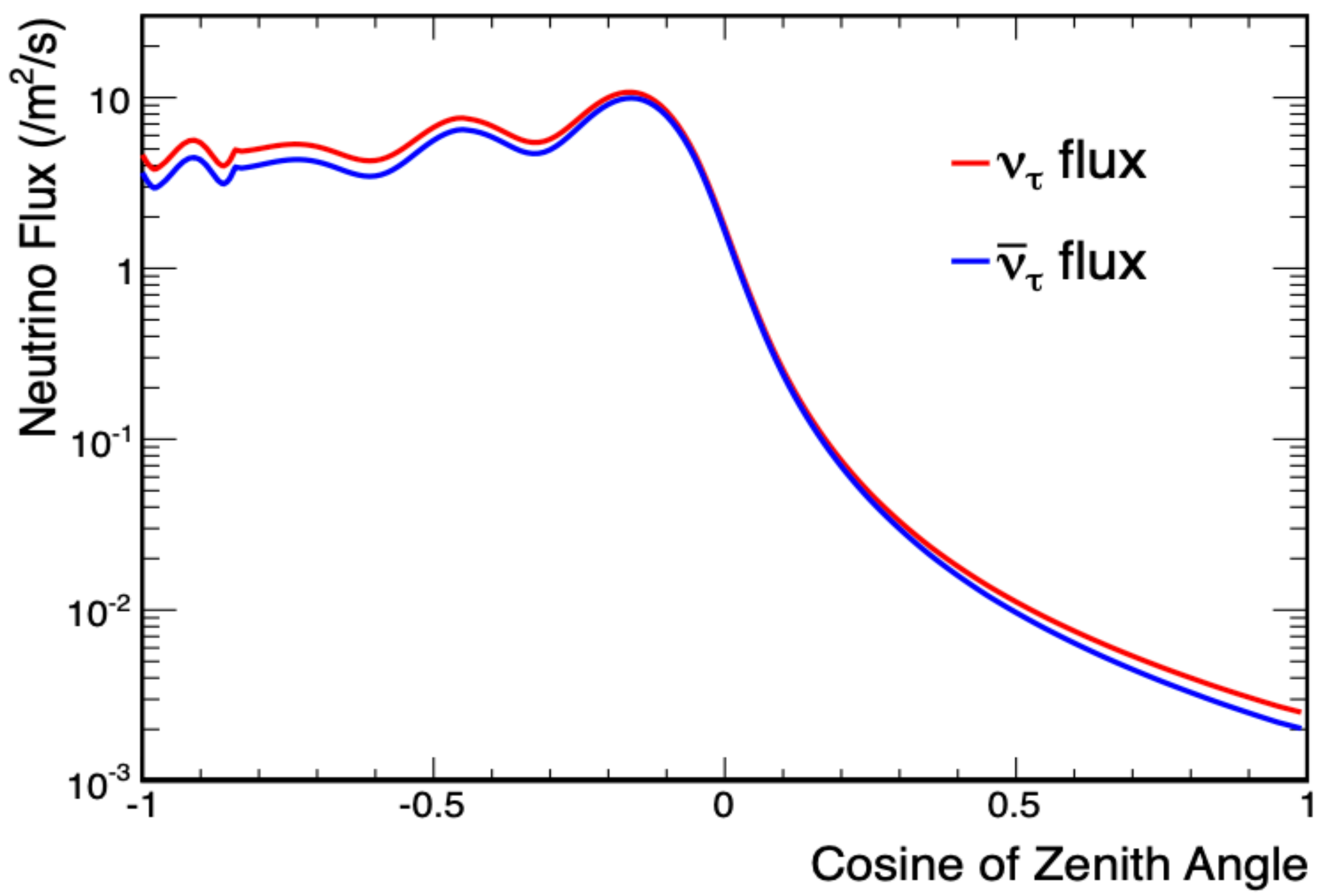
- Neutrinos have mass - experimental proof that Standard Model is incomplete.
- Mass states, ν_i , $i \in \{1,2,3\}$ are mixed with the flavour states through the PMNS matrix.

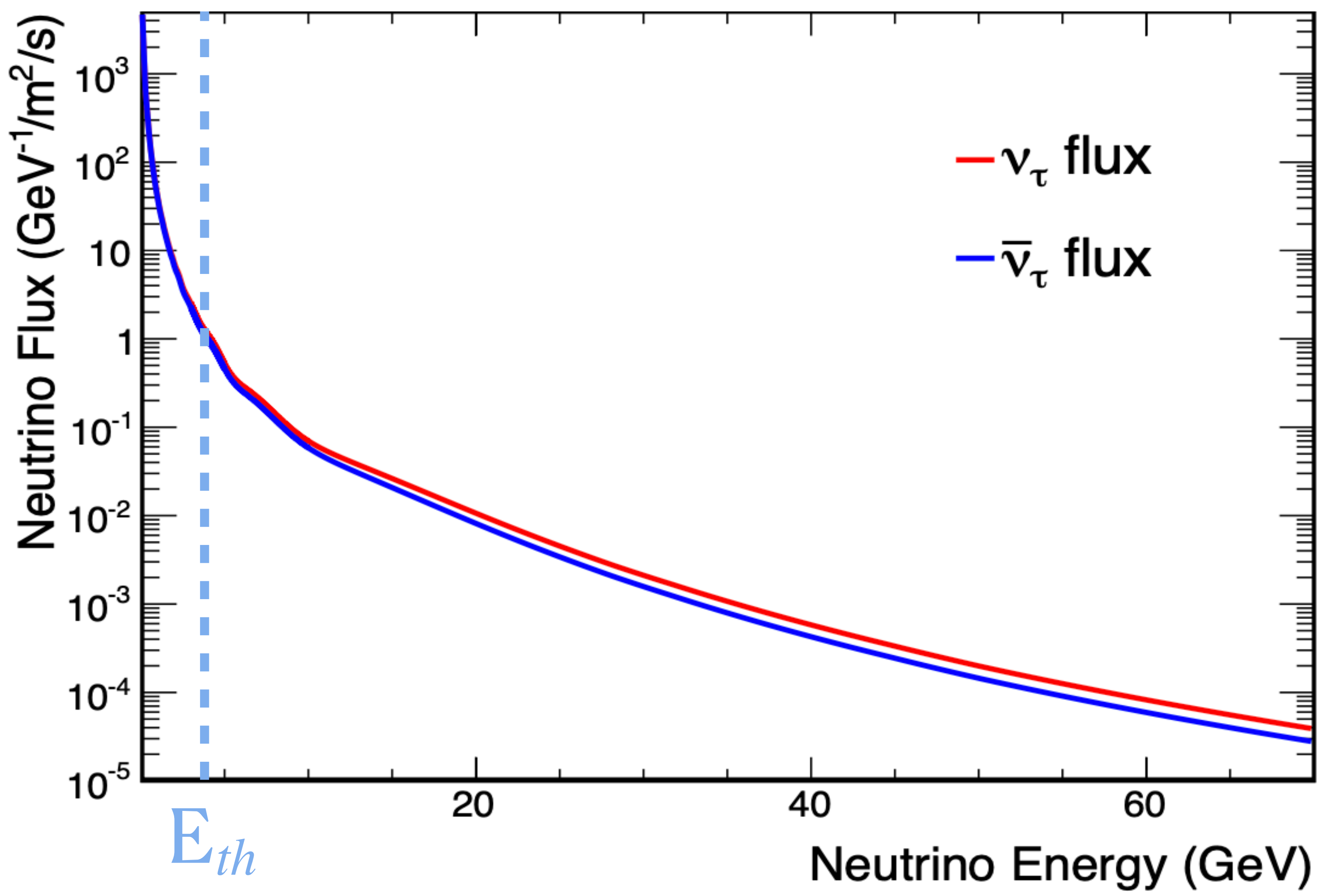
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

- The probability of detecting a neutrino in a particular flavor changes as it propagates.
- Muon neutrinos oscillate maximally to tau neutrinos, which can be detected at SK.

10.1103/PhysRevD.98.052006

Fluxes of atmospheric tau neutrinos from neutrino oscillations at SK based on Honda flux calculation and tau neutrino appearance

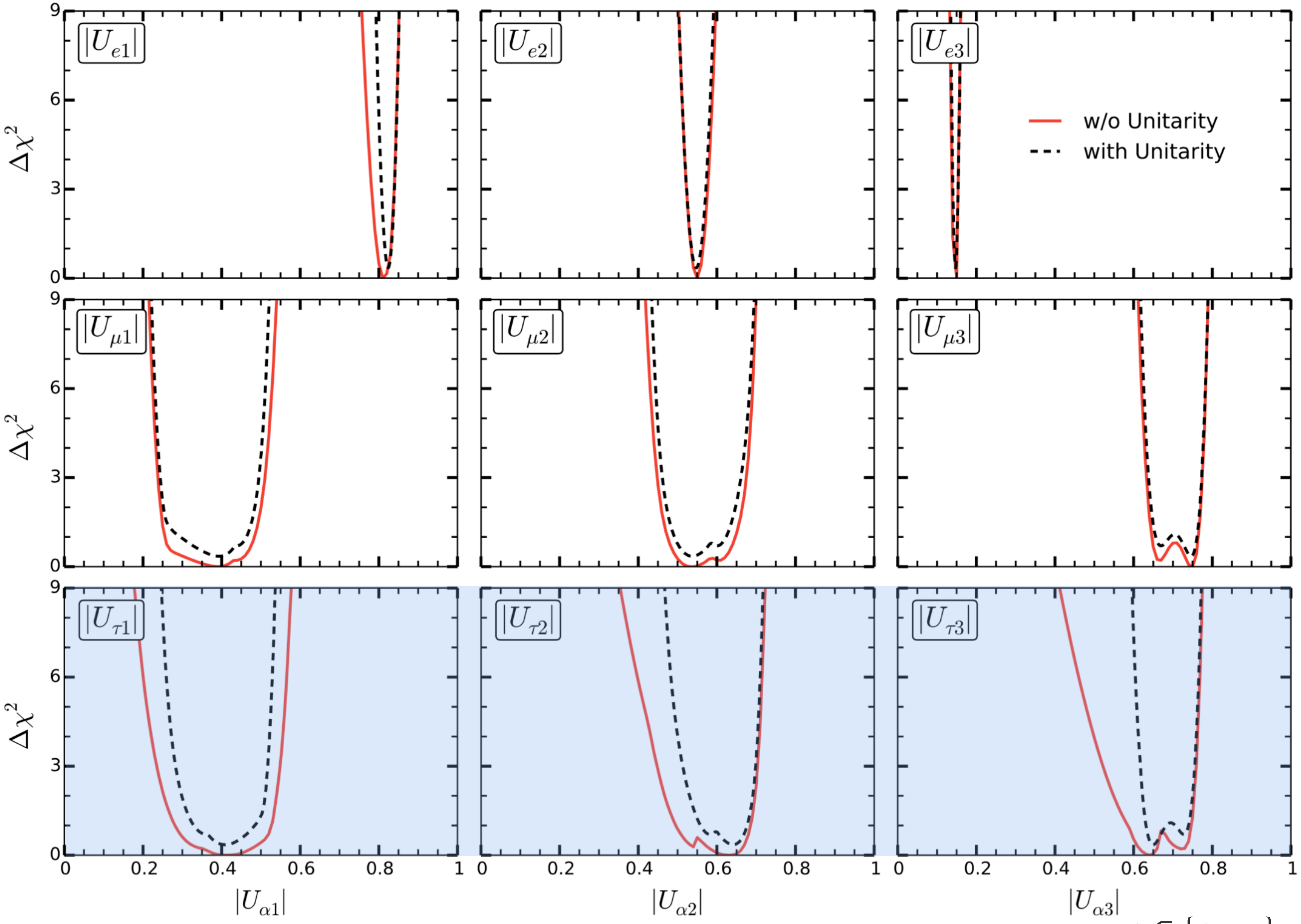




In 2018, SK excluded the hypothesis of no tau appearance from atmospheric neutrinos with a significance level of 4.6σ.

1. Super-Kamiokande Experiment
2. Neutrino Oscillations in Atmospheric Neutrinos
3. Detection of Tau Neutrinos at SK
   - Motivation
   - Present method
   - Preliminary studies for possible upgrades

Neutrino Oscillations



$\alpha \in \{e, \mu, \tau\}$.

arXiv:1508.05095

- Direct detection of tau neutrinos in the atmosphere provides unambiguous confirmation of the phenomenon of neutrino oscillation.
- PMNS matrix is assumed to be unitary.
- Refits of global oscillation results without assuming unitarity allow **significant room for new physics particularly in the tau sector.**
- In case of non-unitarity, the PMNS matrix would be a smaller subset of a unitary extended PMNS matrix.

$$\mathrm{U}_{\mathrm{PMNS}}^{\mathrm{Extended}} = \begin{pmatrix} \overbrace{\begin{pmatrix} \mathrm{U}_{e1} & \mathrm{U}_{e2} & \mathrm{U}_{e3} \\ \mathrm{U}_{\mu1} & \mathrm{U}_{\mu2} & \mathrm{U}_{\mu3} \\ \mathrm{U}_{\tau1} & \mathrm{U}_{\tau2} & \mathrm{U}_{\tau3} \end{pmatrix}}^{\mathrm{U}_{\mathrm{PMNS}}^{3\times3}} & \begin{matrix} \cdots & \mathrm{U}_{en} \\ \cdots & \mathrm{U}_{\mu n} \\ \cdots & \mathrm{U}_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ \mathrm{U}_{s_n1} & \mathrm{U}_{s_n2} & \mathrm{U}_{s_n3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & \mathrm{U}_{s_nn} \end{matrix} \end{pmatrix} .$$

- The additional flavors, s_n, could hint at the existence of sterile neutrinos - there is a need for precise measurement in the tau neutrino sector.

- Lifetime of tau, $\tau_\tau = 2.9 \times 10^{-7} \mu s$. It is detected through its decay products.
- Tau leptons decay to produce hadronic or electromagnetic showers - tau-like events are multiple ring event.
- Predominant mis-classified background - NC events (can also be multiple ring events).

Multivariate methods are required to separate the two types of multi-ring events.

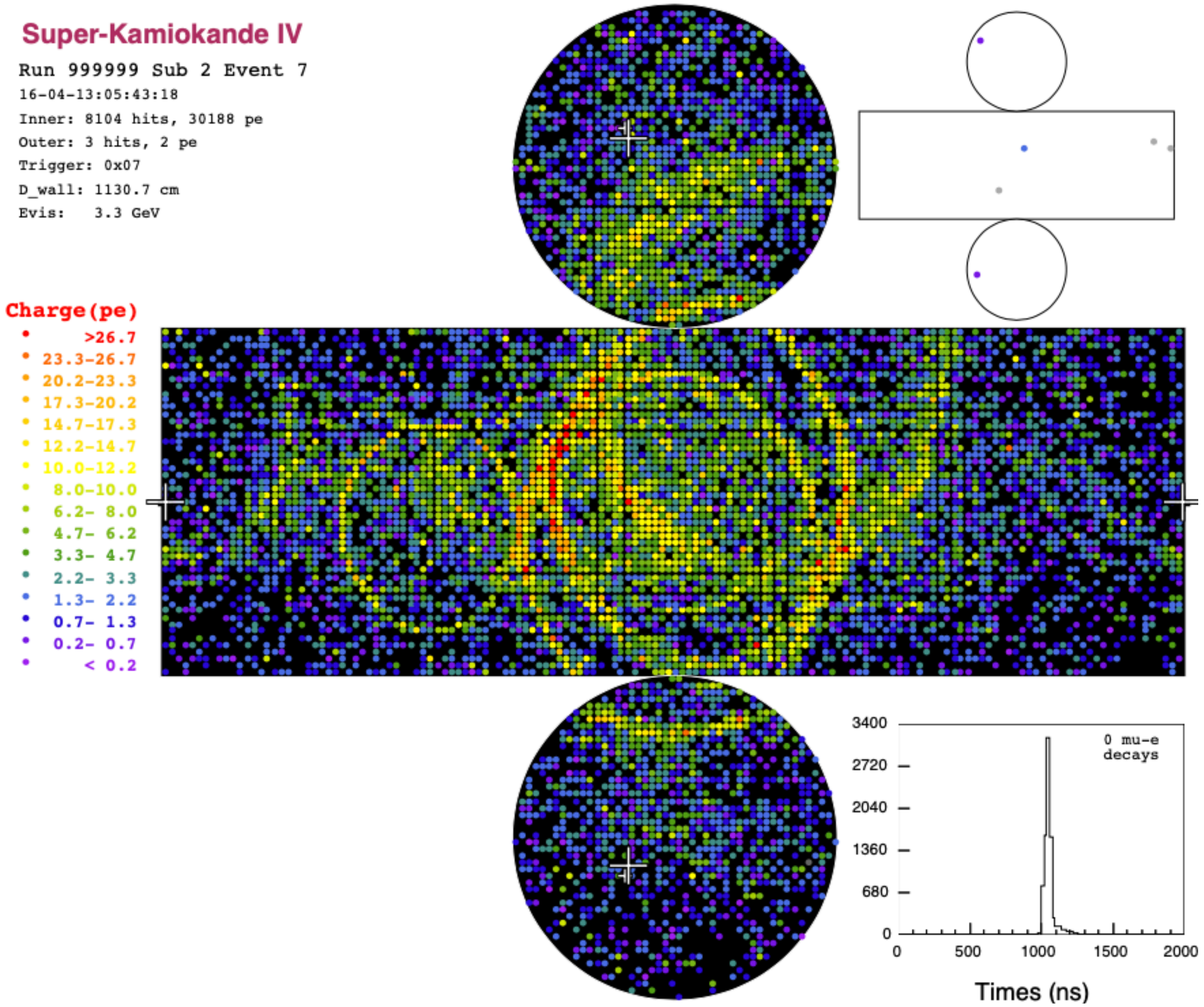
Charged Current (CC) Interactions:

$$\nu_l + N \rightarrow l^- + X$$
$$\bar{\nu}_l + N \rightarrow l^+ + X$$
where $l \in \{e, \mu, \tau\}$

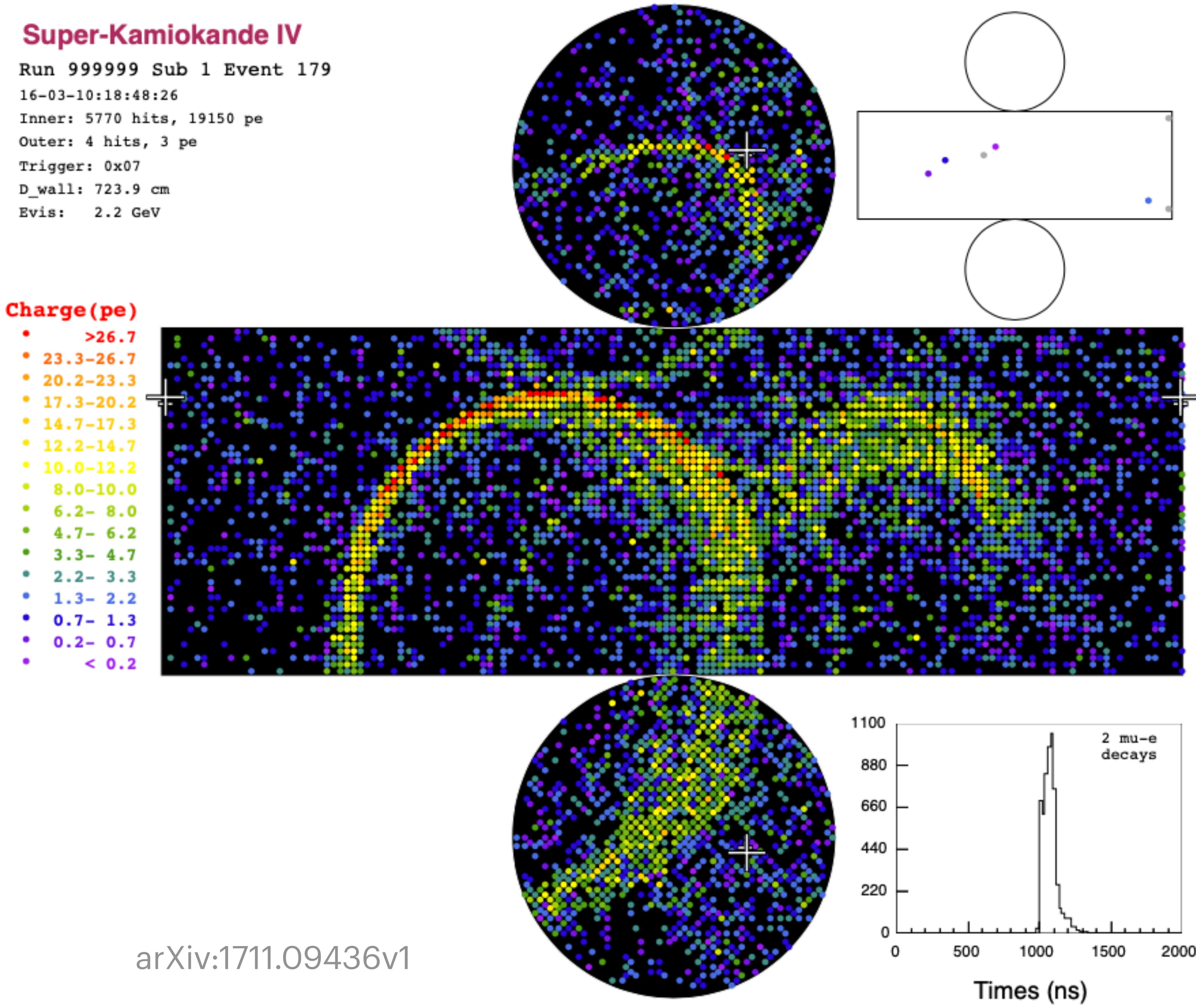
Neutral Current (NC) Interactions:

$$\nu_l + N \rightarrow \nu_l + X$$

Tau CC event



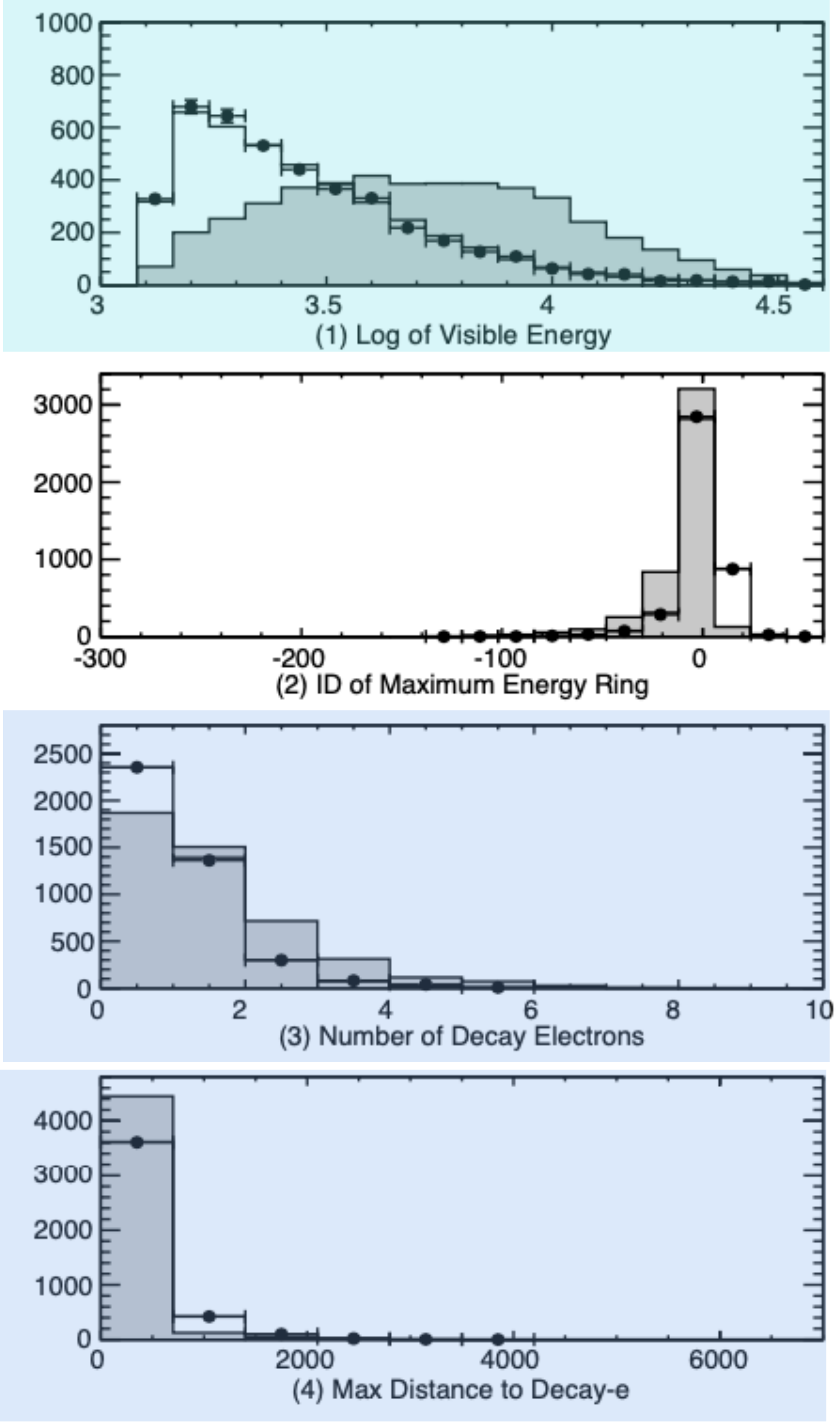
NC event



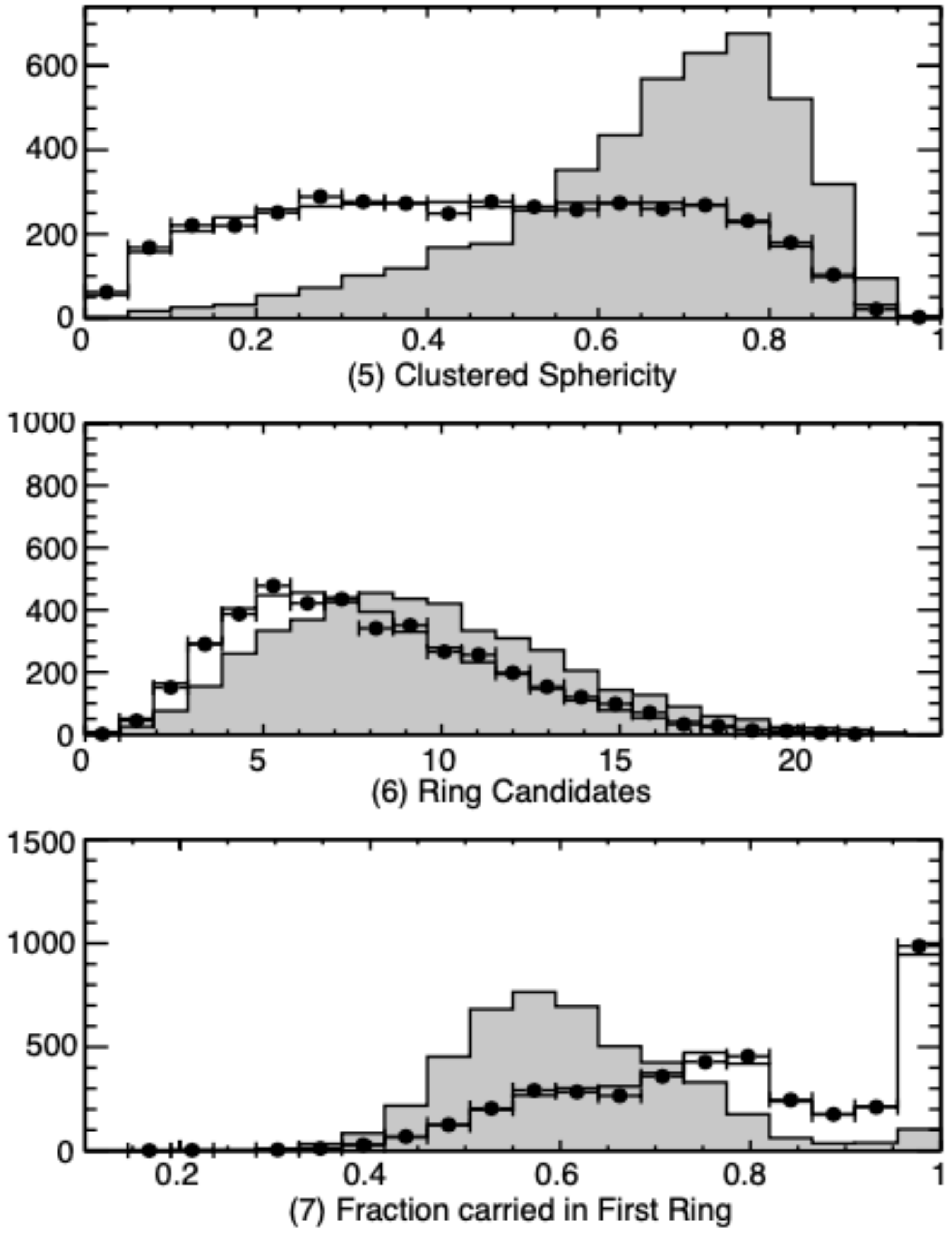
arXiv:1711.09436v1

Misclassification of NC background

- Machine learning algorithm of a 7 input MLP separates the tau signal from the background.

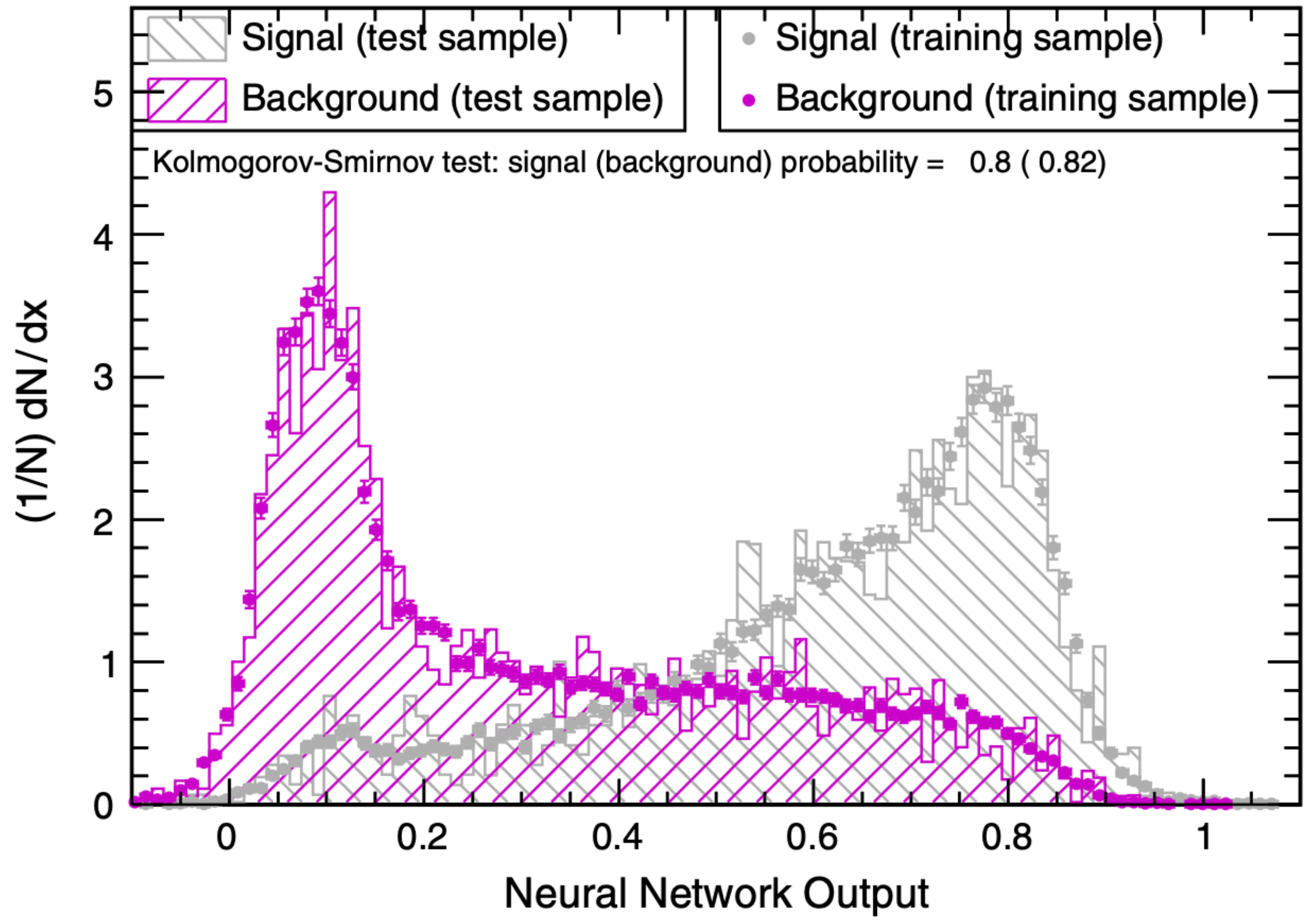


Input Variables → Neural network (NN) → **Output tag [0,1]**



Background MC (black histogram) and data (black dots) to tau MC (gray shaded

arXiv:1711.09436v1



- Output cut off at 0.5:

  53% NC background misidentified as tau-signal like.

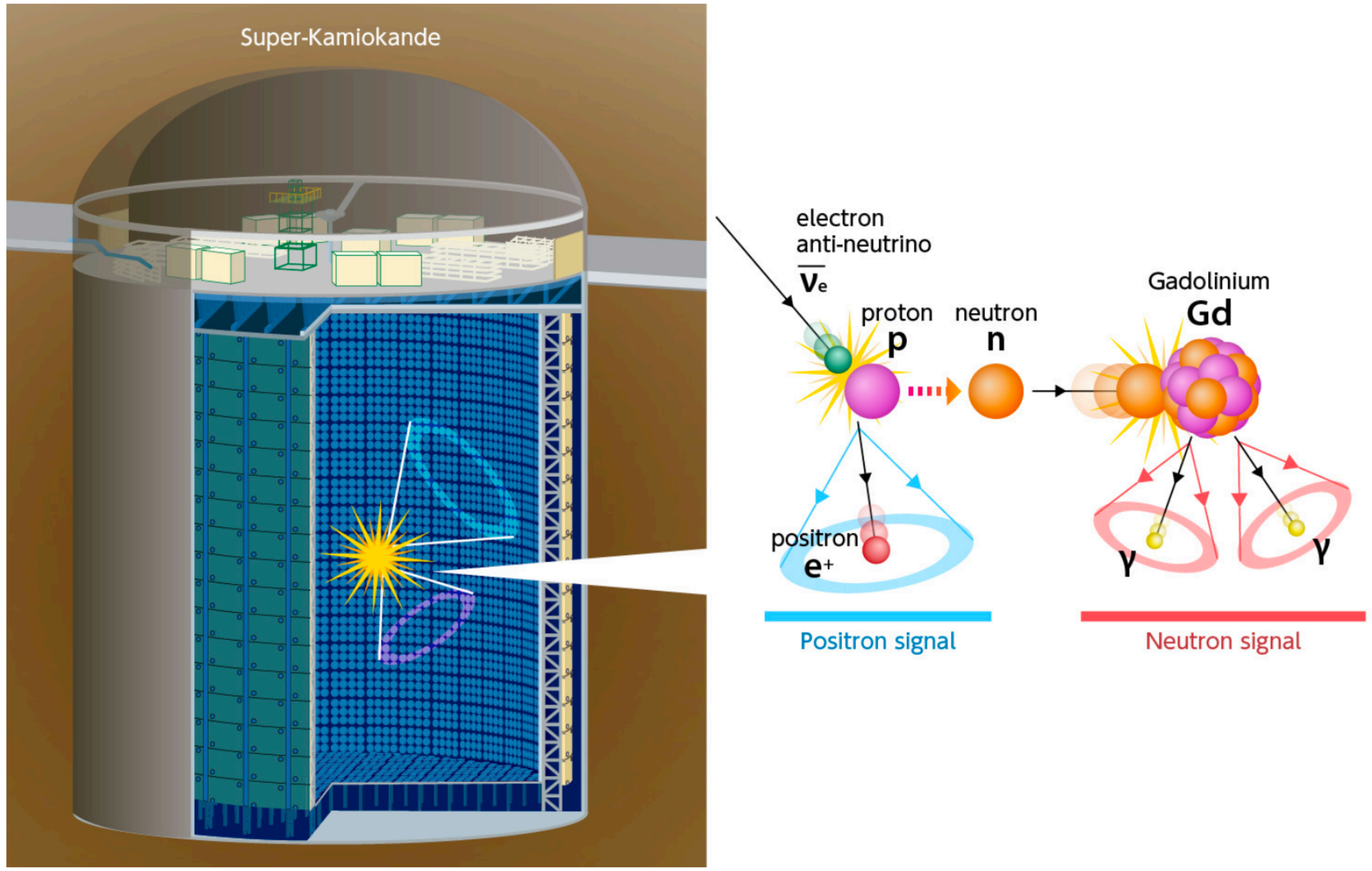
- The SK MLP does not contain neutron capture information.

SK-Gd Upgrade

Increased Neutron Tagging Efficiency

- 64.8% branching ratio the tau neutrinos decay through **hadronic decay modes**, these result in hadron showers which produce many neutrons, similar to hadronic showers from NC events.
- The neutrons, once thermalised, are captured.
- More neutron captures are expected in the predominant NC background than in the tau-signal.

Decay mode	Branching ratio (%)
$e^-\bar{\nu}_e\nu_\tau$	17.83
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.41
$\pi^-\nu_\tau$	10.83
$\pi^-\pi^0\nu_\tau$	25.52
$3\pi\nu_\tau$	18.29
others	10.12



- In 2020, gadolinium was dissolved in the SK water.

Neutron capture on free protons

- 2.2 MeV gamma produced
- σ_n=0.33 barns
- 13.1 - 24.5% position dependant neutron tagging efficiency.

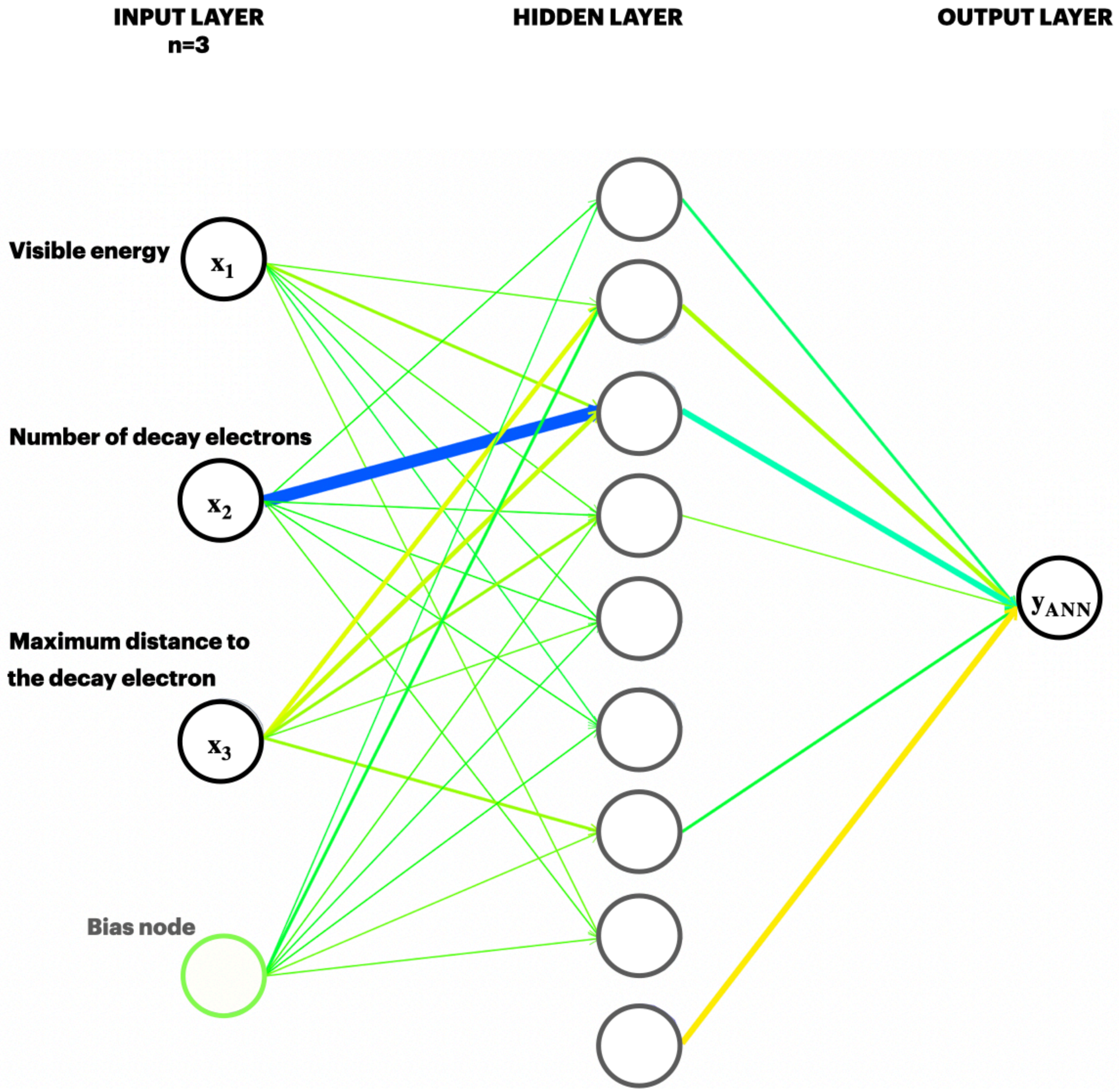
Neutron capture on Gadolinium by mixing 0.2% by mass of $GdCl_3$ in water

- 8 MeV gamma cascade
- σ_n=49,700 barns, 90% of neutron captures are on Gd, with 0.1% Gd concentration by mass. (Present concentration 50% efficiency.)
- 66.7% efficiency for events above 3 MeV.

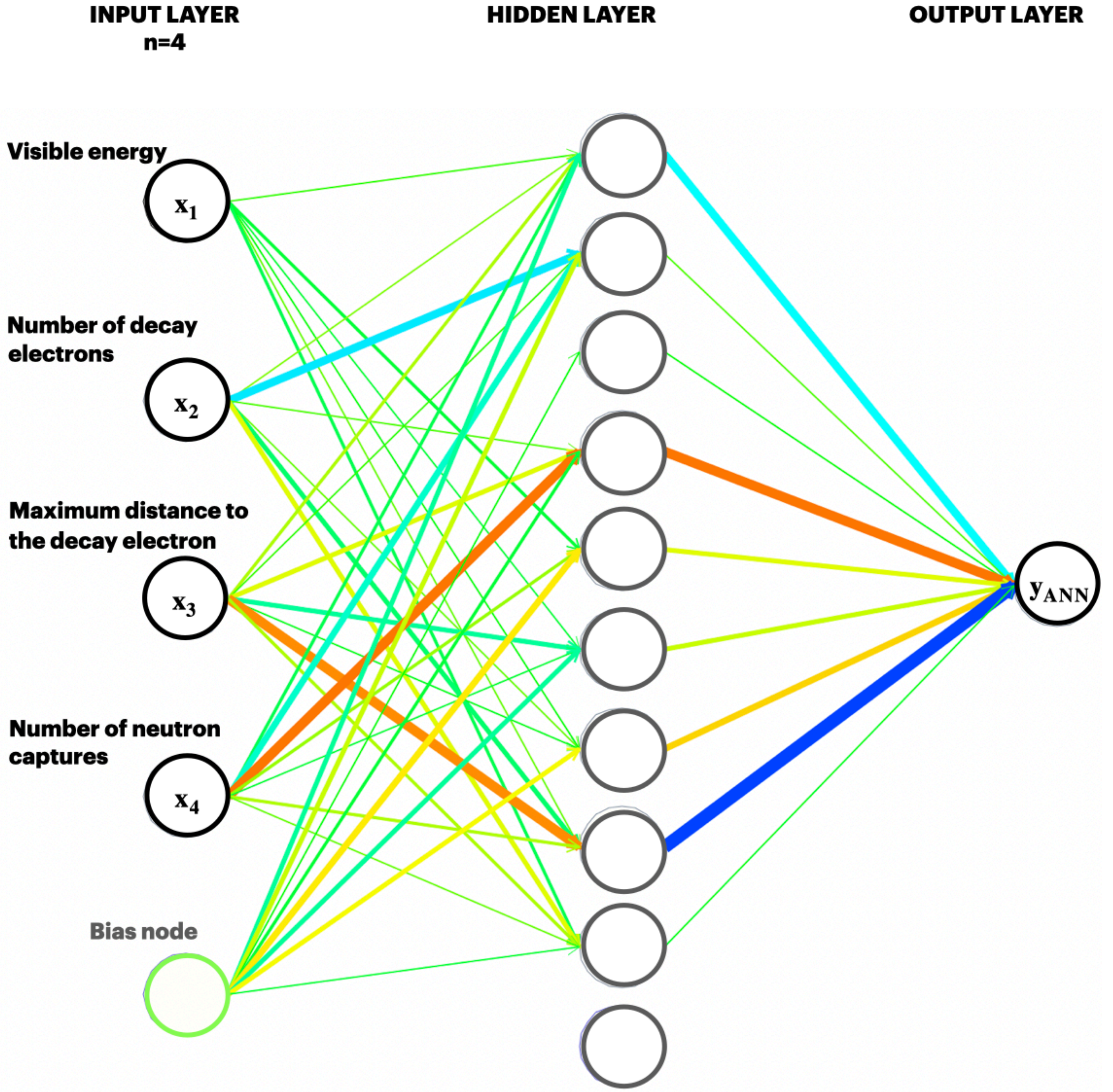
Comparison between MLP with and without neutron capture information

- M.Sc. Thesis, 2020
- Simulation of the inputs on GEANT4, considering a simplified SK setting.
- Comparisons of the generated inputs on ROOT TMVA.

3 input MLP without neutron capture information (Variables common with the classification analysis of the Super-Kamiokande Experiment)



4 input MLP with additional variable of neutron capture information

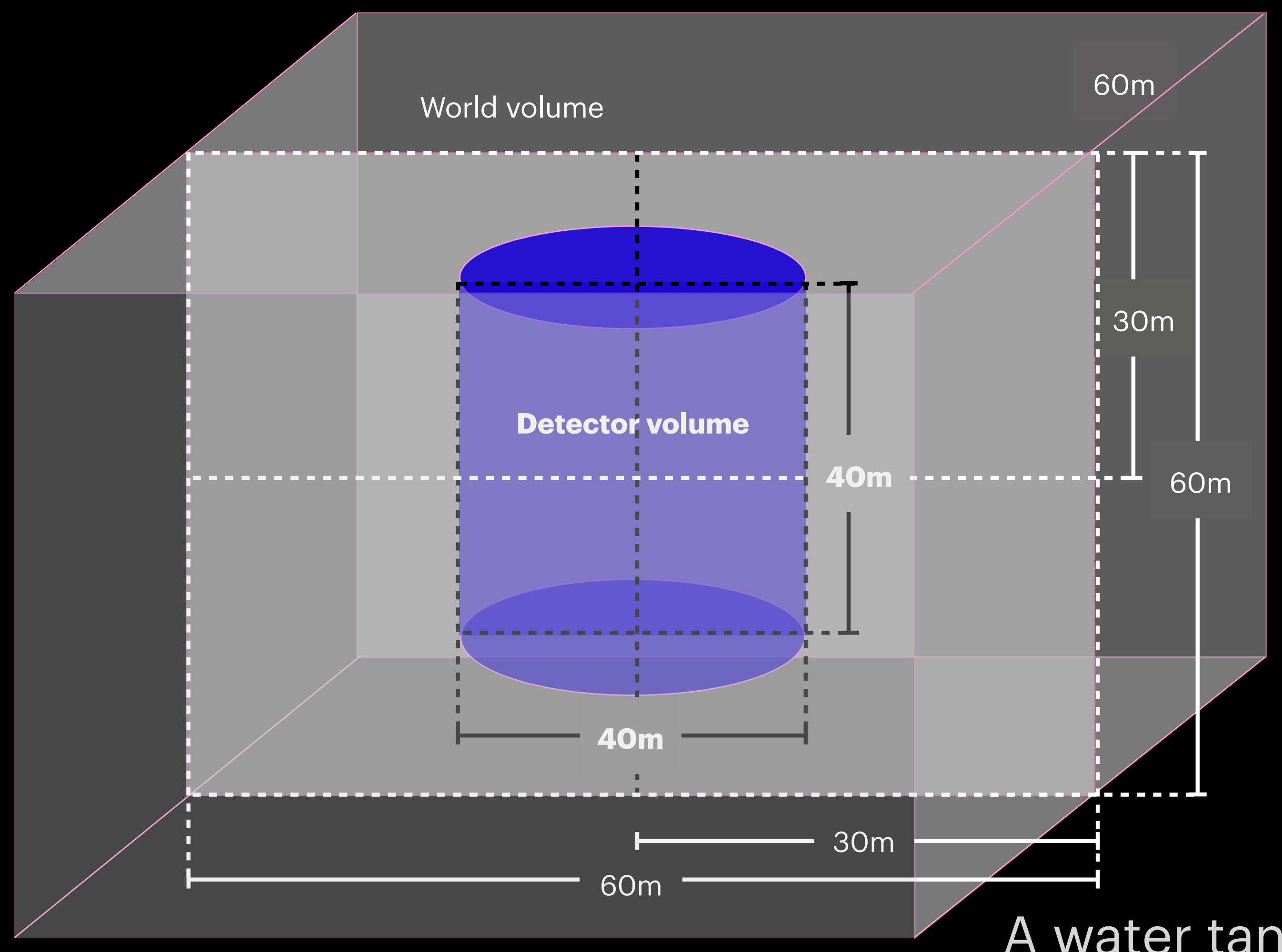


Question: Does information about neutron captures in an event improve the tau signal classification?

Generation of Inputs to the MLP

Generated with a software toolkit - GEANT4 (GEometry ANd Tracking)

Simplified picture of the Super-Kamiokande detector

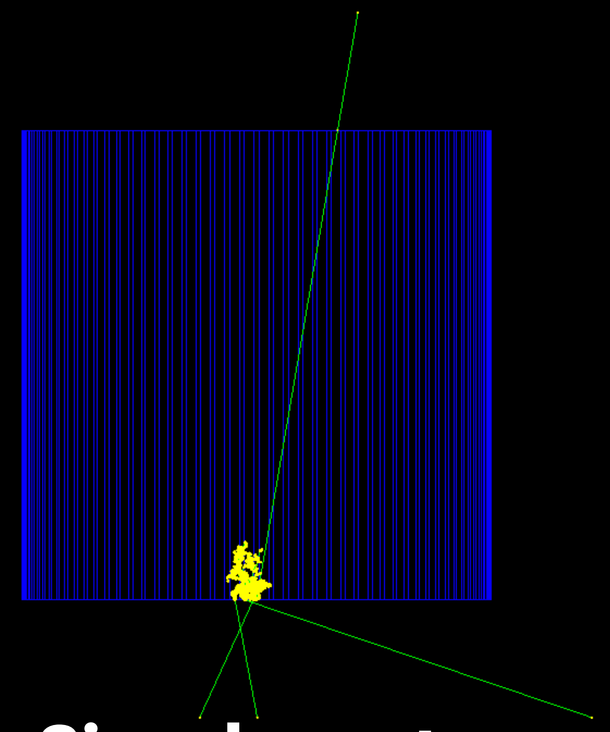


A water tank (detector volume) in vacuum (world volume)

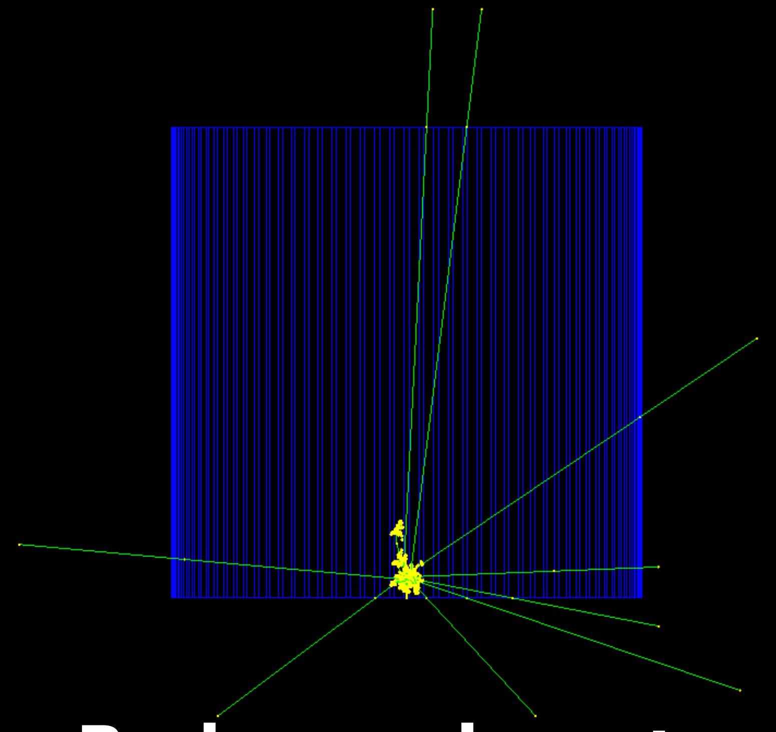
- We generated interactions as per the physics list FTFP_BERT_HP in GEANT4, which simulates neutrons to thermal energies.
- 3 cases of initial kinetic energy of the particles are considered: 4 GeV, 8 GeV and 12 GeV.
- 10,000 events each for signal and background.

- Since we do not model detector response, recreate 3 neural network inputs
  - Log of visible energy as the kinetic energy lost along the track of the particle while $\beta > \frac{1}{n}$.
  - Number of decay electrons as the number of electrons from muon decays/captures.
  - Maximum distance to decay electron.
- Additional input: Number of neutron captures per event.

Primary particles and interactions in GEANT4



Signal events:
Tau neutrino charged current interactions (initial particle : Tau-)

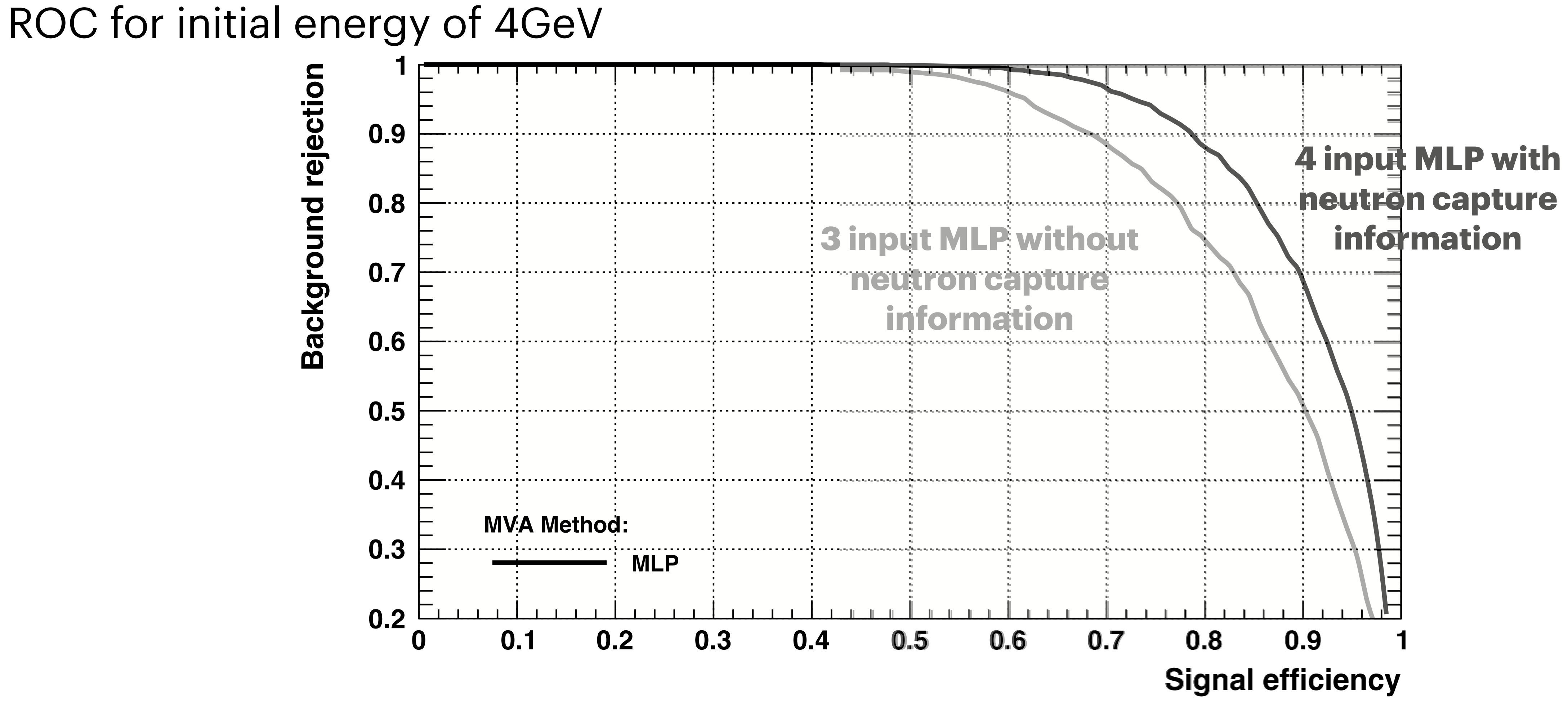


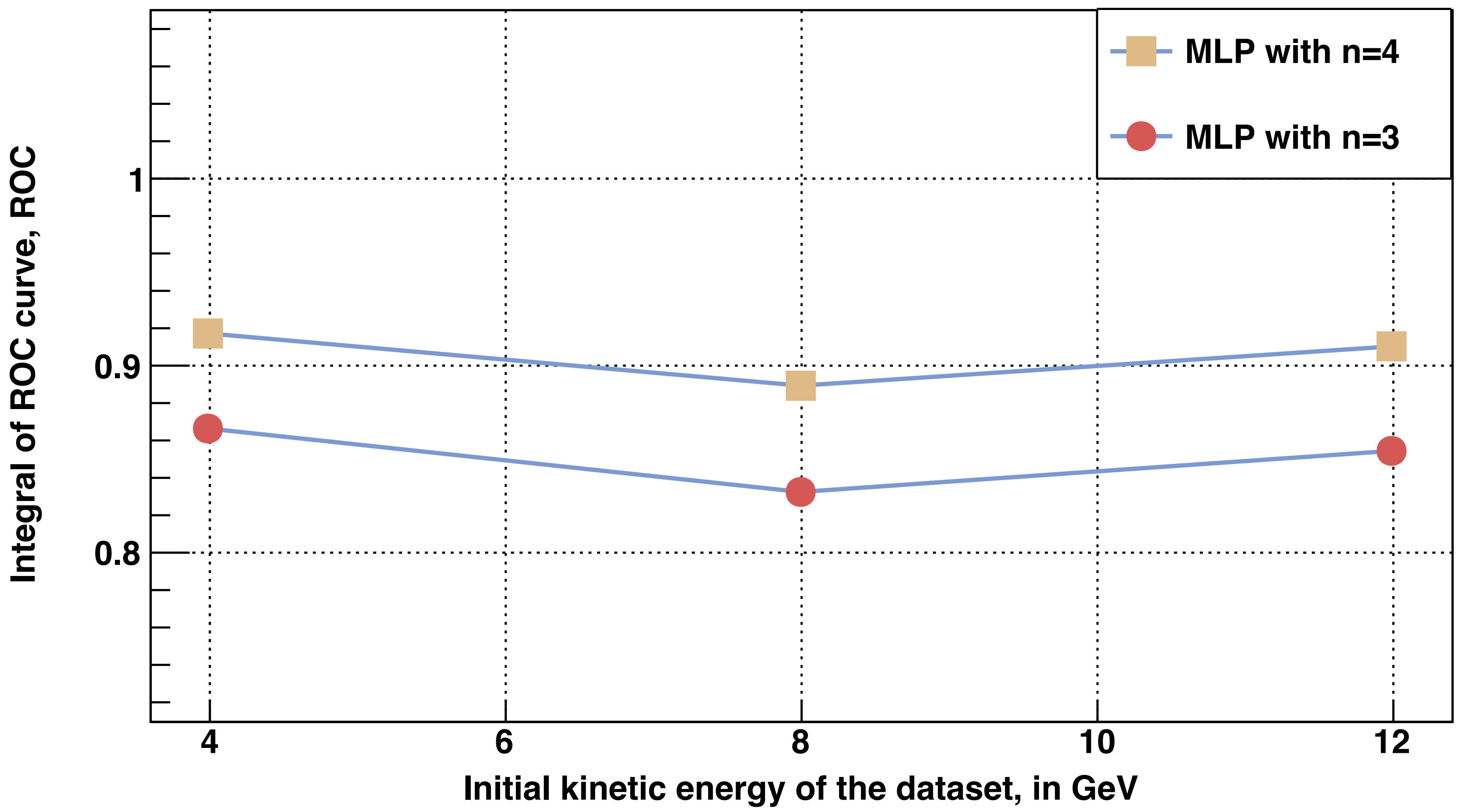
Background events:
Hadron shower from neutral current interactions of neutrinos of all flavors (initial particle: proton)

Question: **Does information about neutron captures in an event improve the tau signal classification?**
Answer: **Yes.**

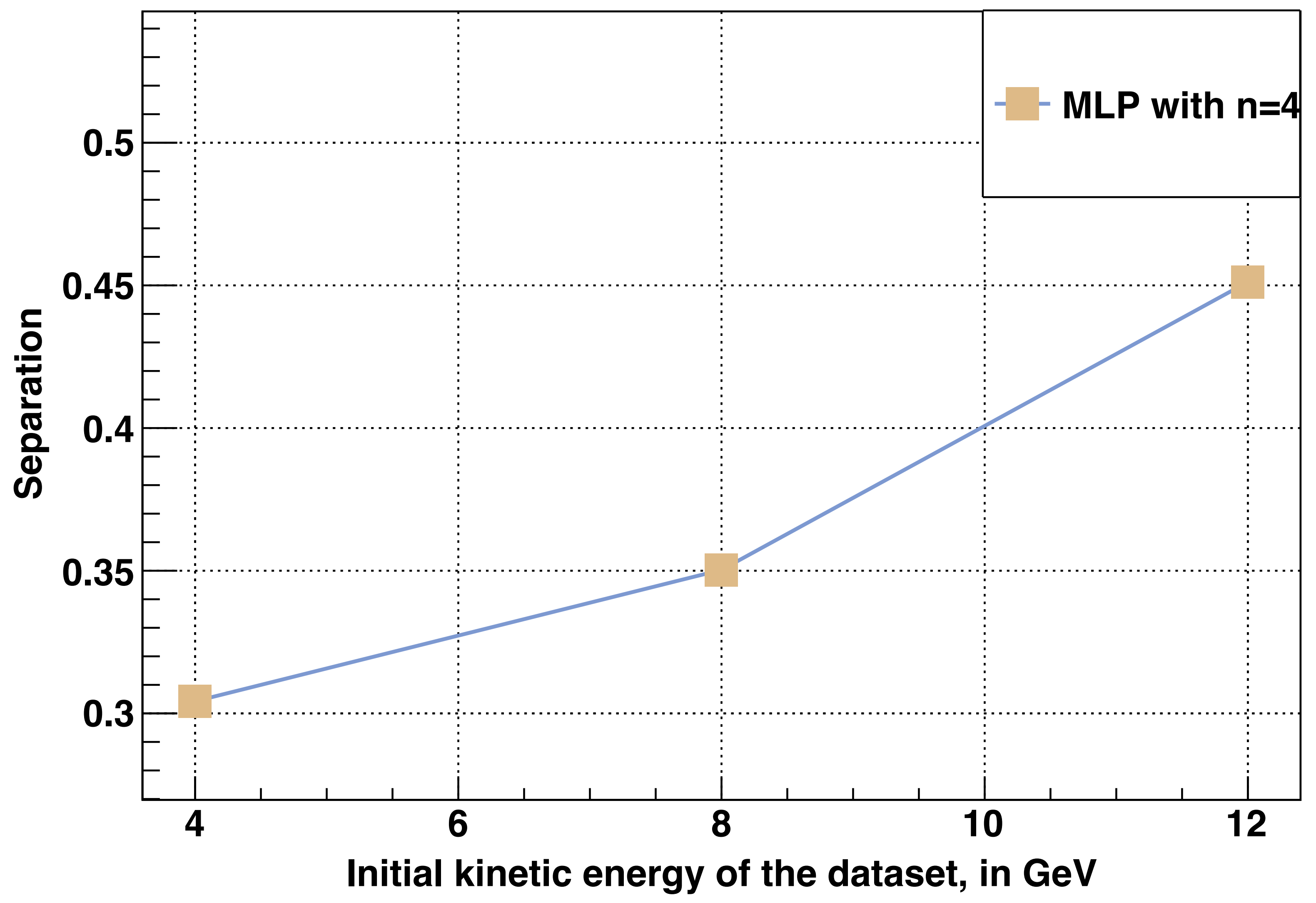
- MLP with 4 inputs performs better than the MLP with 3 inputs.
- Positive correlation between the initial energy of the event and separation of the tau signal PDF from background due to input of the number of neutron captures.
- Note the best separation coming from the neutron capture variable as compared to the other three variables.

ROC curve: Background Rejection versus Signal Efficiency of the MLP





Separation using Neutron Capture Information



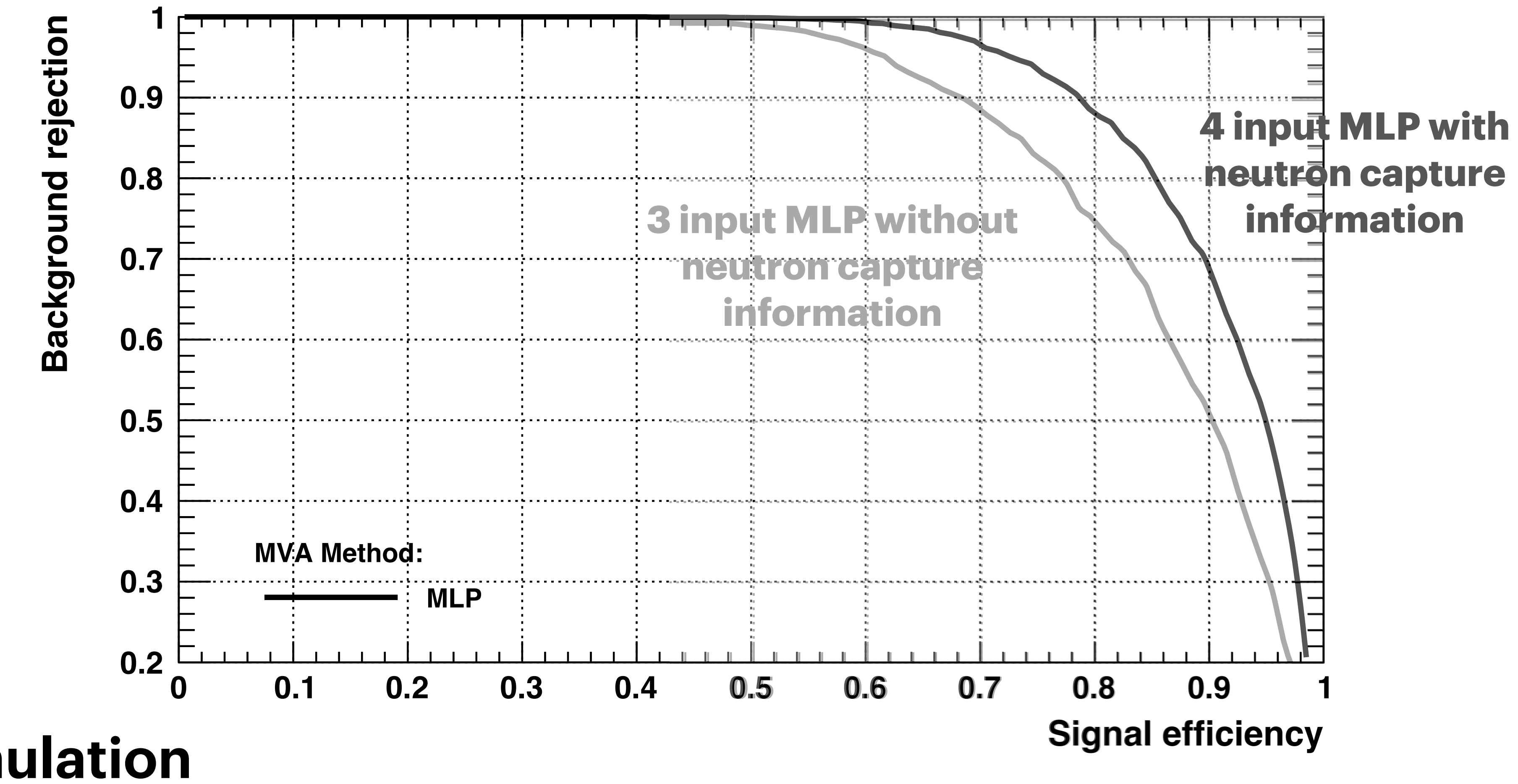
Dataset with Initial Kinetic Energy	Ranking of variables (Separation)			
	1	2	3	4
4 GeV	Number of Neutron Captures (3.041e-01)	Visible Energy (1.897e-01)	Distance to Decay Electron (1.535e-01)	Number of Decay Electrons (6.816e-02)
8 GeV	Number of Neutron Captures (3.503e-01)	Number of Electron (1.727e-01)	Distance to to Decay Electron (1.591e-01)	Visible Energy (1.568e-01)
12 GeV	Number of Neutron Captures (4.512e-01)	Number of Decay Electron (2.534e-01)	Visible Energy (2.409e-01)	Distance to Decay Electron (1.651e-01)

Comparison with the Super-Kamiokande MLP

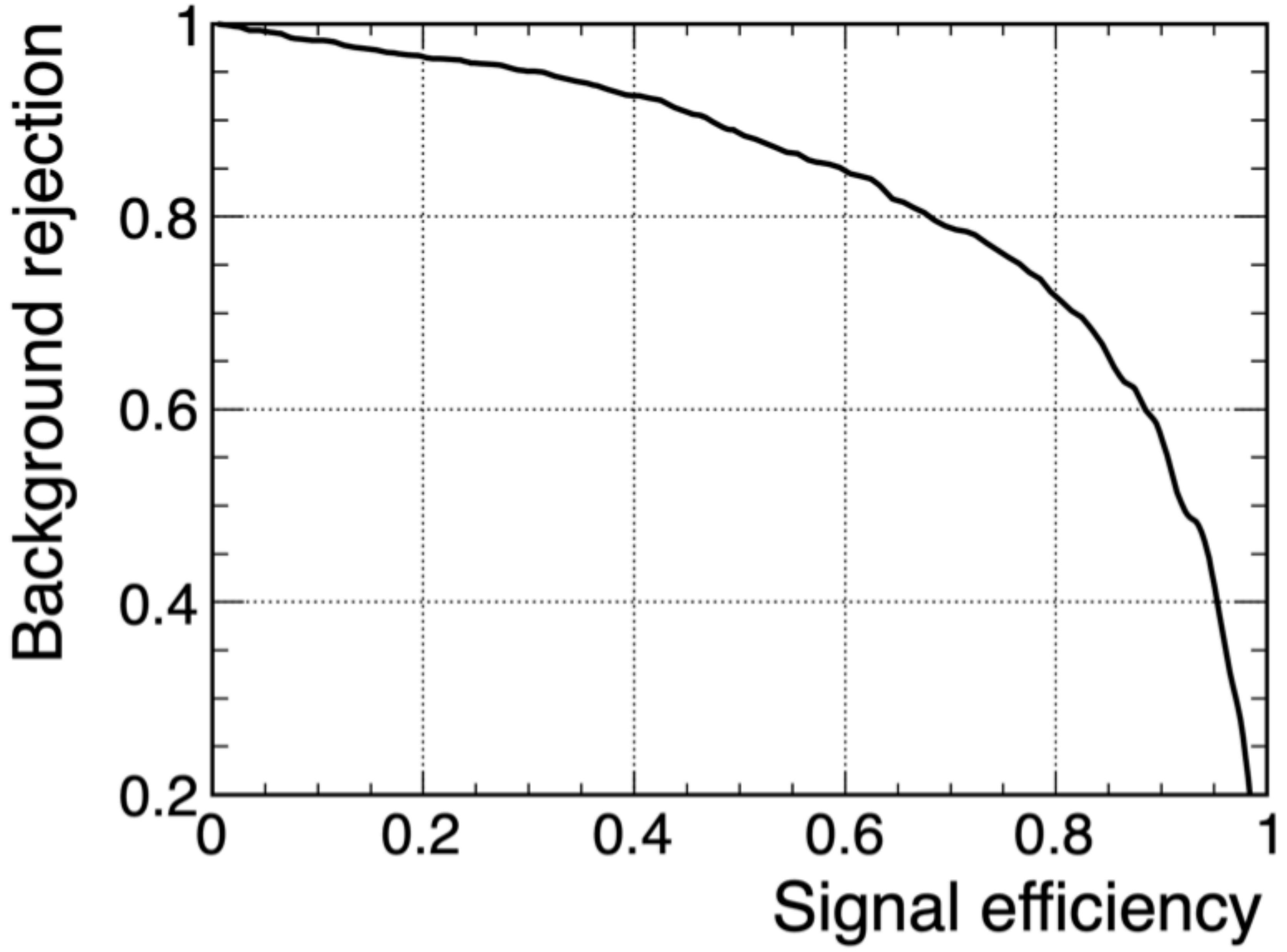
Neutron capture information seems to improve the tau signal classification, especially for higher energy events.

ROC curve: Background Rejection versus Signal Efficiency of the MLP

ROC for initial energy of 4GeV



ROC in SK simulation



- Preliminary studied considered only NC interaction background in the simulations, and observed an average of only 12% of the NC background being misidentified as tau-like with the inclusion of neutron capture information, as compared to the 25% misidentification seen without neutron capture information.
- The prospect of expanding the SK NN with new inputs about neutron captures is under consideration.
- Possible implementation of the classification with more sophisticated algorithms of convoluted NNs.

- The Super-Kamiokande experiment (SK) allows for the direct detection of tau neutrinos from atmospheric neutrinos.
- SK used machine learning techniques of neural networks (NNs) to classify the tau charged- current interactions from the interactions of the atmospheric muon and electron neutrinos.
- The present NN of SK is a multilayer perceptron. My research involves upgrading the NN for better classification.
- The prospect of expanding the NN with new inputs about neutron captures is under consideration, owing to the enhanced detection of neutrons with the addition of gadolinium in SK.
- Preliminary results show that this additional information shall improve the NN classification, and hence, the detection of tau neutrinos.