Latest Results – Tau Neutrino Appearance Measurements at Super-Kamiokande

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14 June 2024

Super-KamiokaNDE

- Water Cherenkov detector, active since 1996.

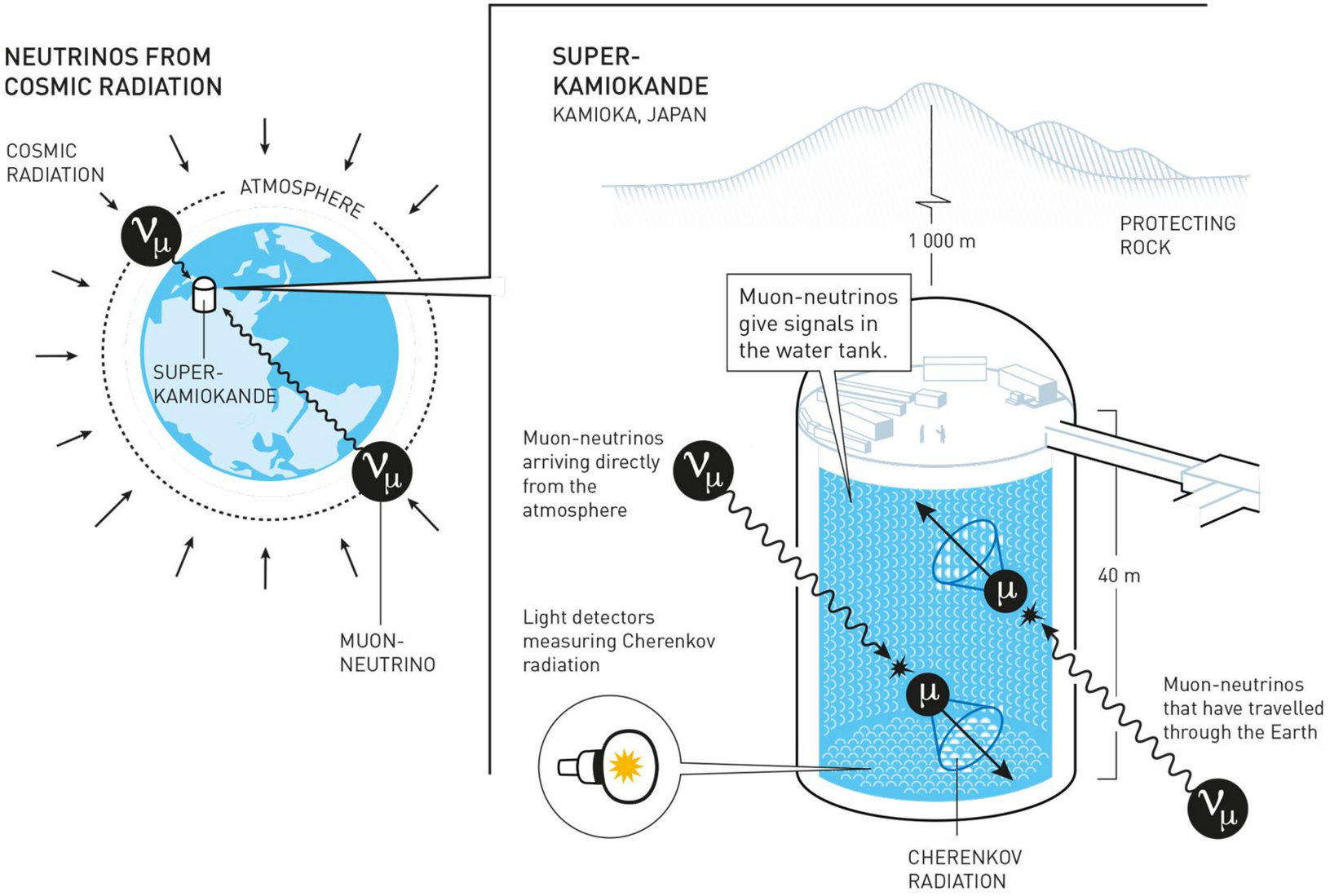
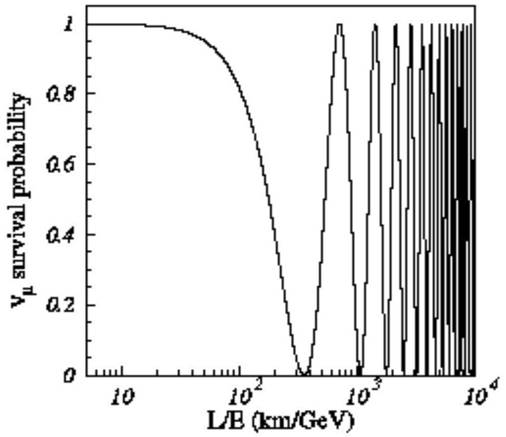
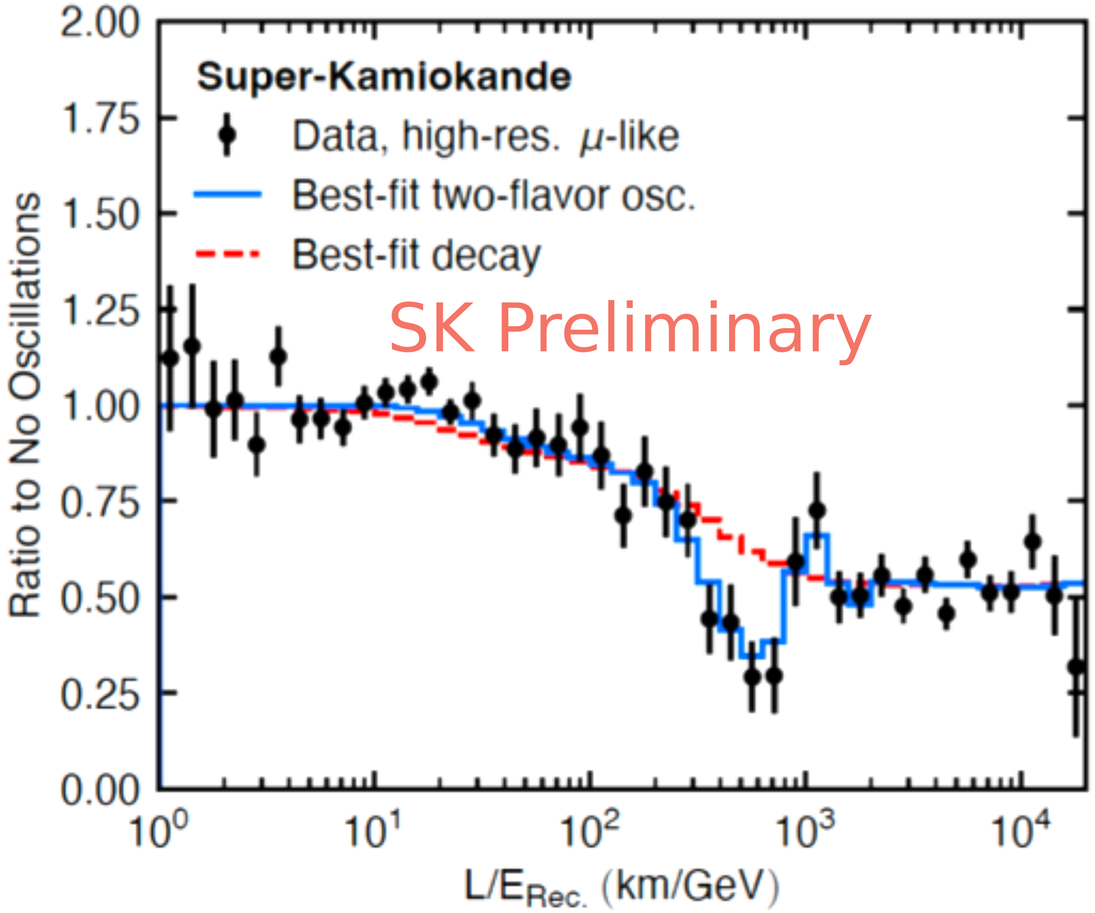


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrino oscillations
(SK 2024!)

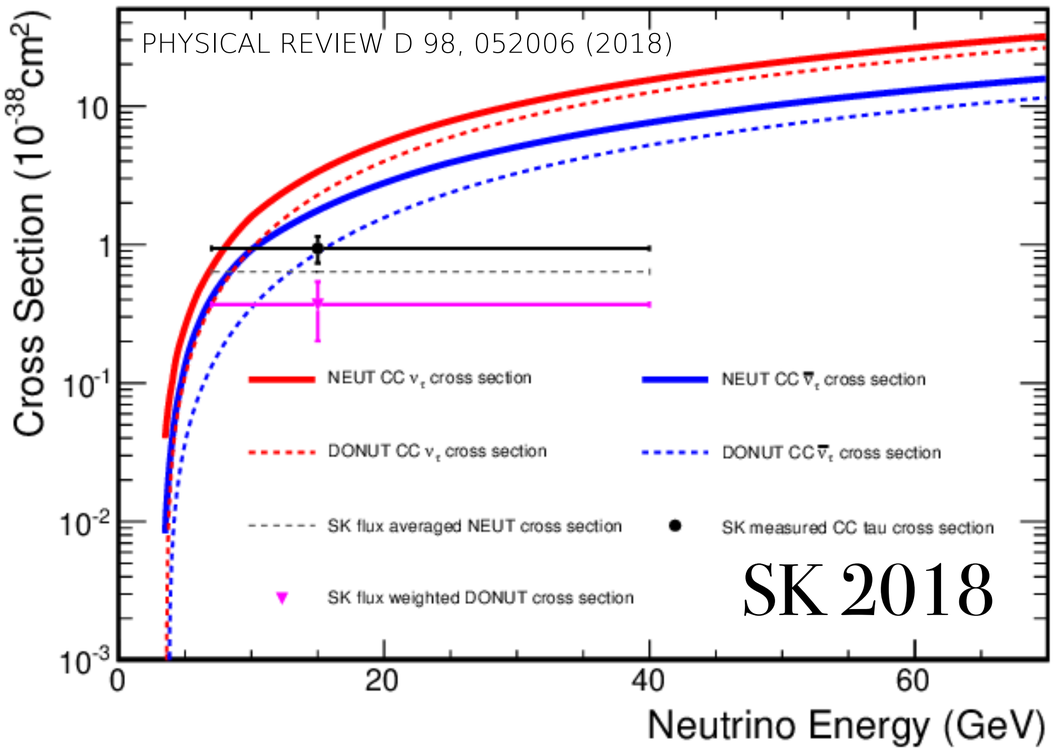




- Muon neutrinos oscillate to tau neutrinos.

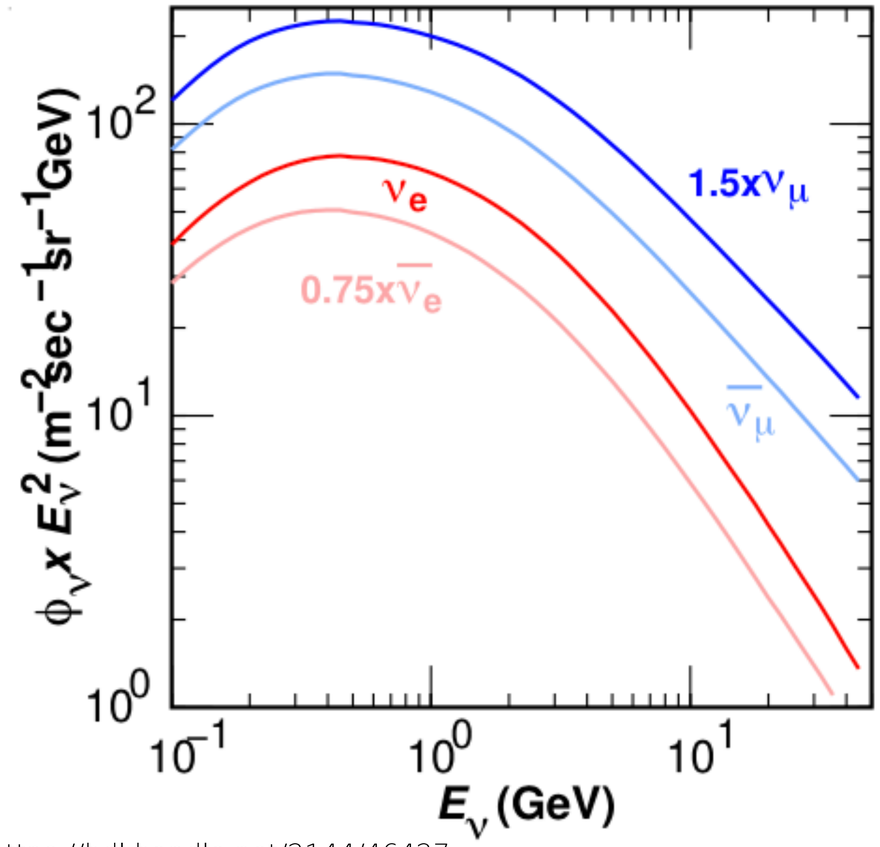
Unambiguous proof of neutrinos oscillations

Oscillated tau neutrinos at SK

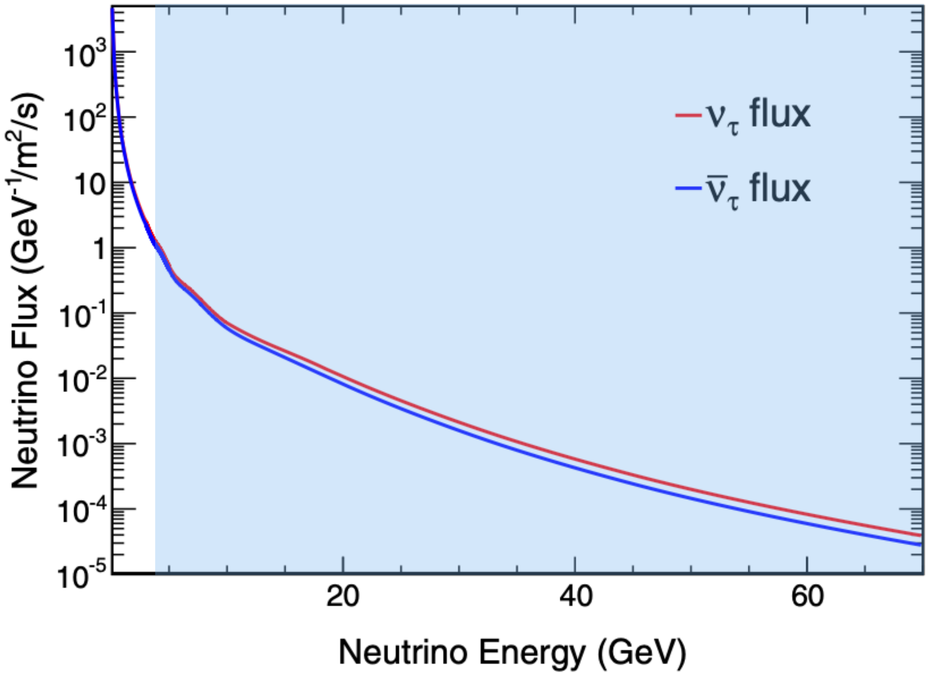


- Challenging to identify.
  1. Low tau neutrino interaction cross-section.
  2. Limited resolution from the background.

Journey of a tau neutrino at SK



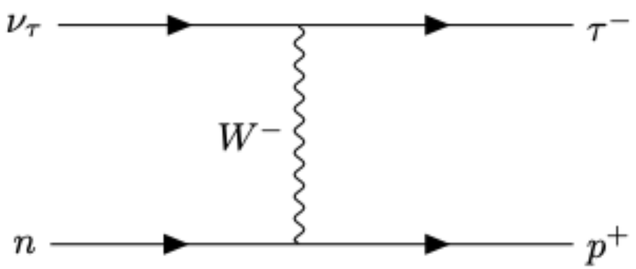
https://hdl.handle.net/2144/46427



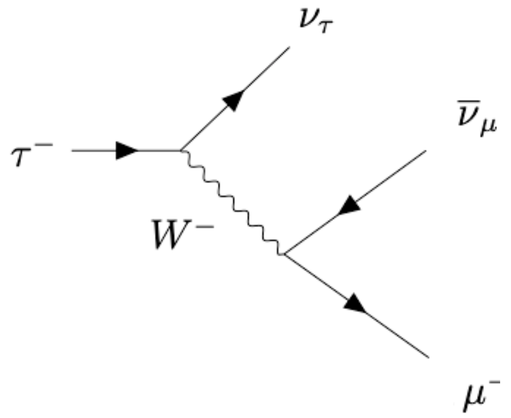
- Threshold for tau neutrino CC interaction is 3.5 GeV.

Journey of a tau neutrino at SK

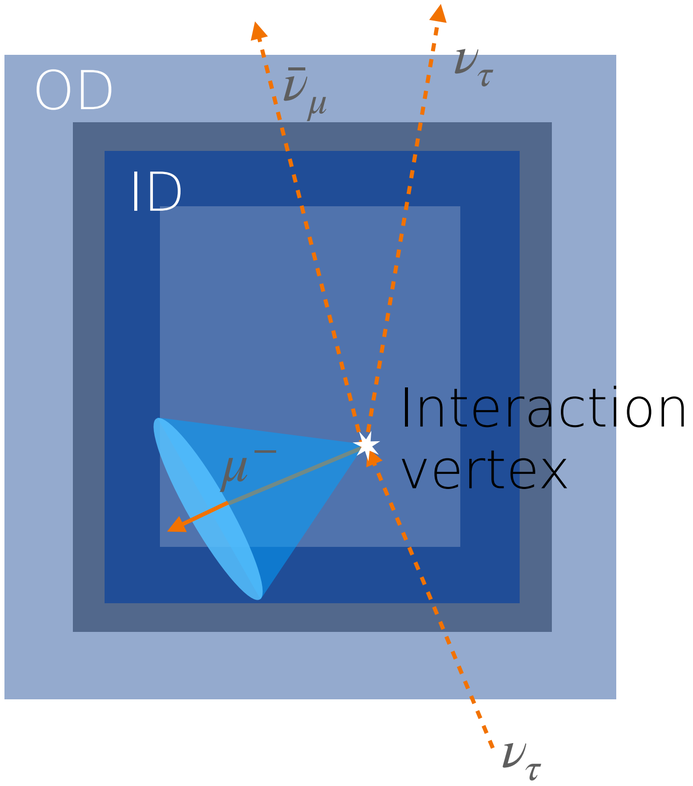
- 1 tau neutrino CC interaction at SK per kton-year.
- Eg:
  ν_τ CCQE

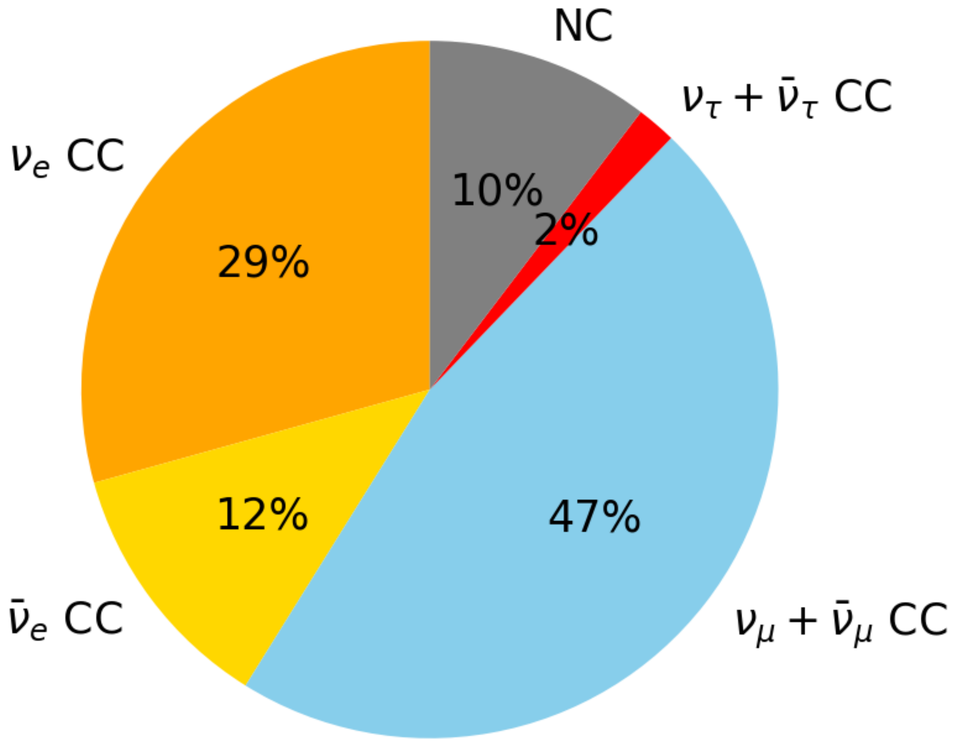


Tau (mass=1.8GeV, lifetime=10^{-13}s)	B.R. %
$\tau^- \to h^- \pi^0 \nu_\tau$	26.0
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	17.8
$\tau^- \to \mu^- \bar{\nu}_e \nu_\tau$	17.4
$\tau^- \to h^- \nu_\tau$	11.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	9.8
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	9.5
Other hadronic	8.0



1 tau neutrino CC interaction expected per kton-year

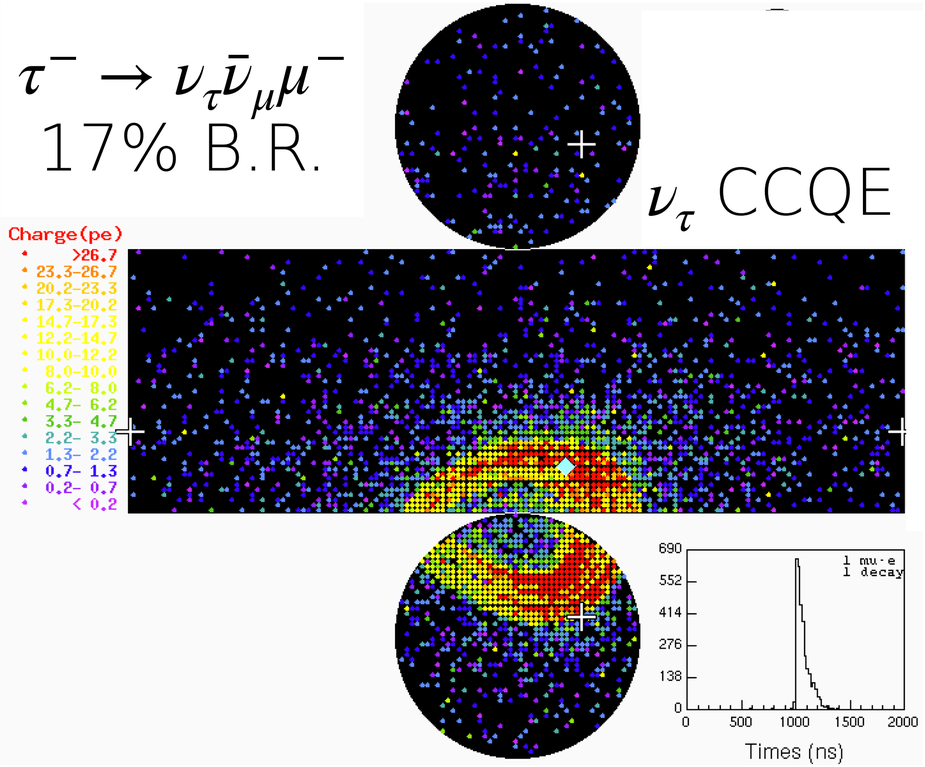




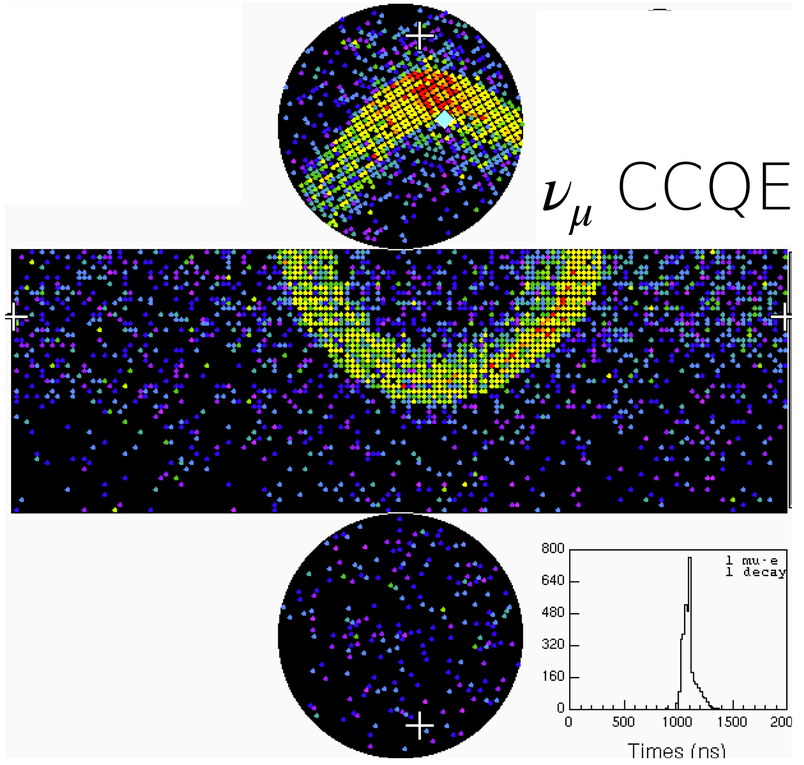
Identification of tau neutrinos at SK

Signal

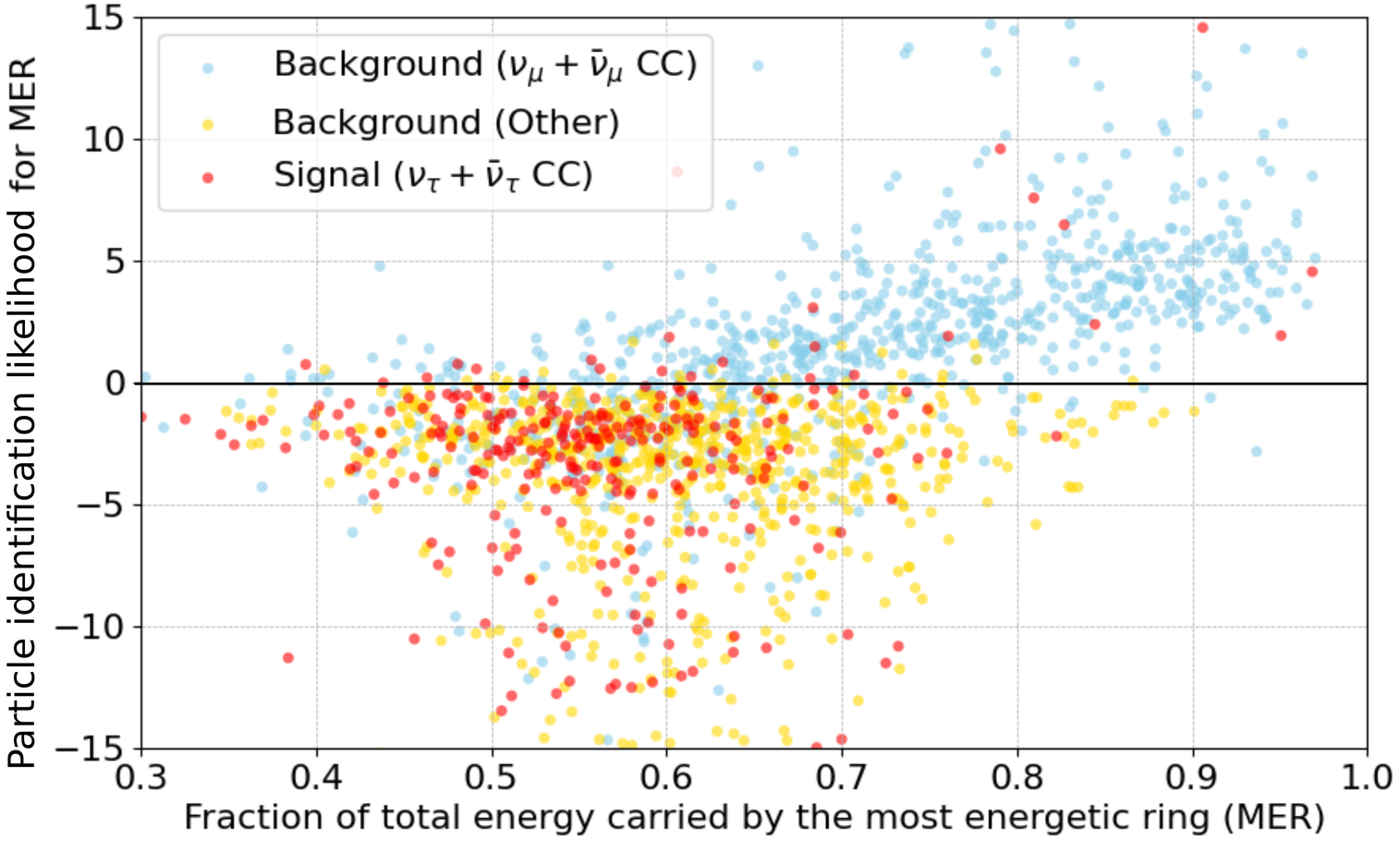
$\tau^- \rightarrow \nu_\tau \bar{\nu}_\mu \mu^-$
17% B.R.



Background



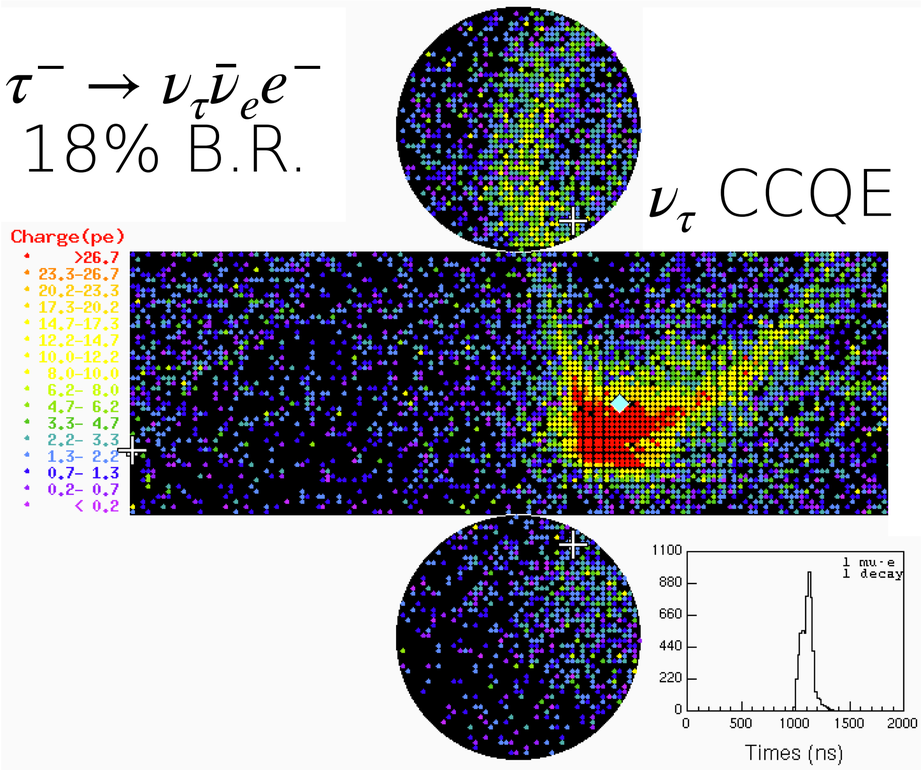
Identification of tau neutrinos at SK



Identification of tau neutrinos at SK

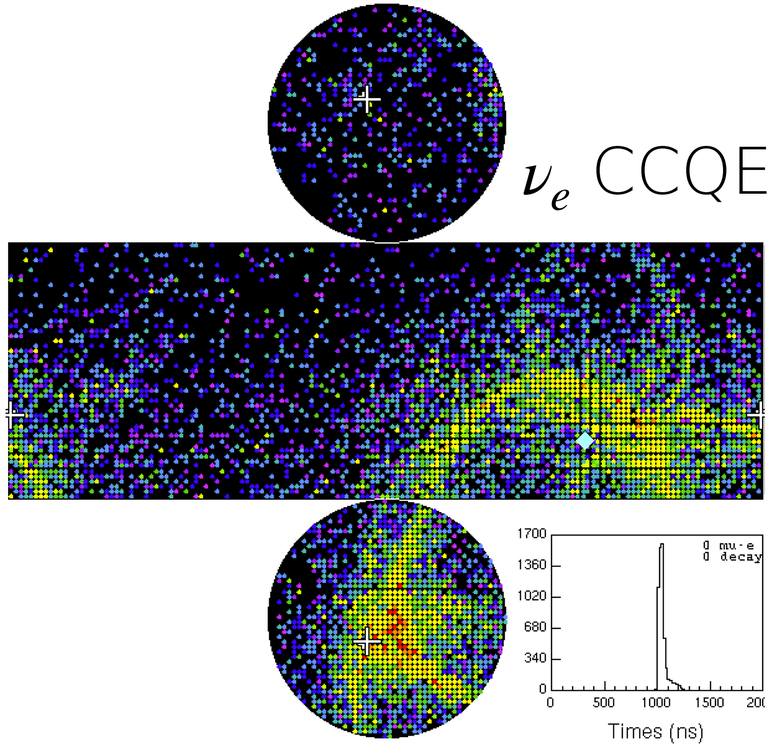
Signal

$\tau^- \rightarrow \nu_\tau \bar{\nu}_e e^-$
18% B.R.



ν_τ CCQE

Background

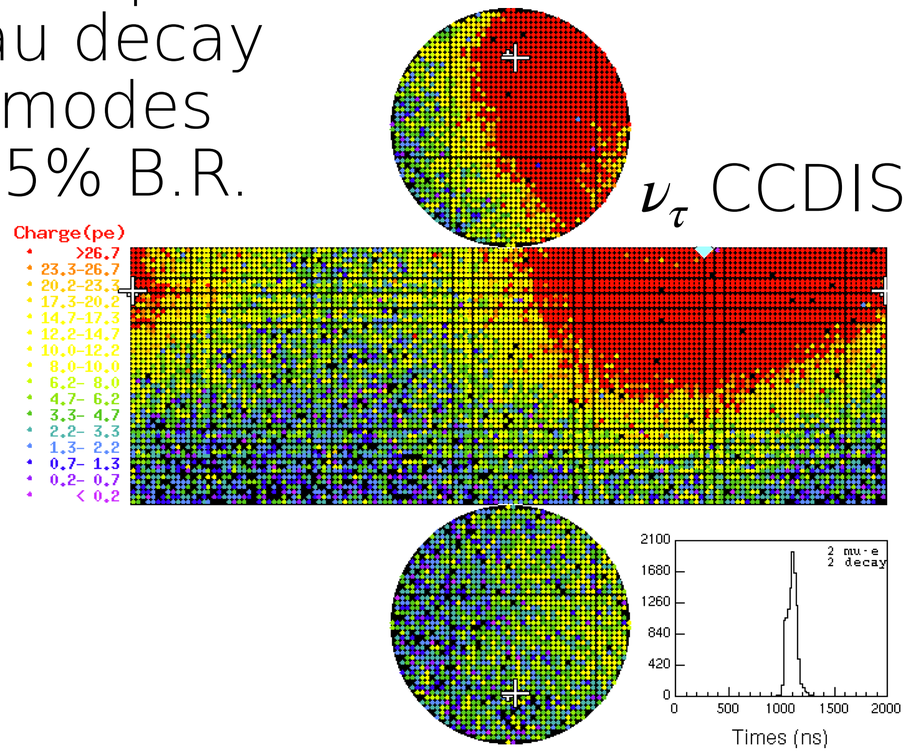


ν_e CCQE

Identification of tau neutrinos at SK

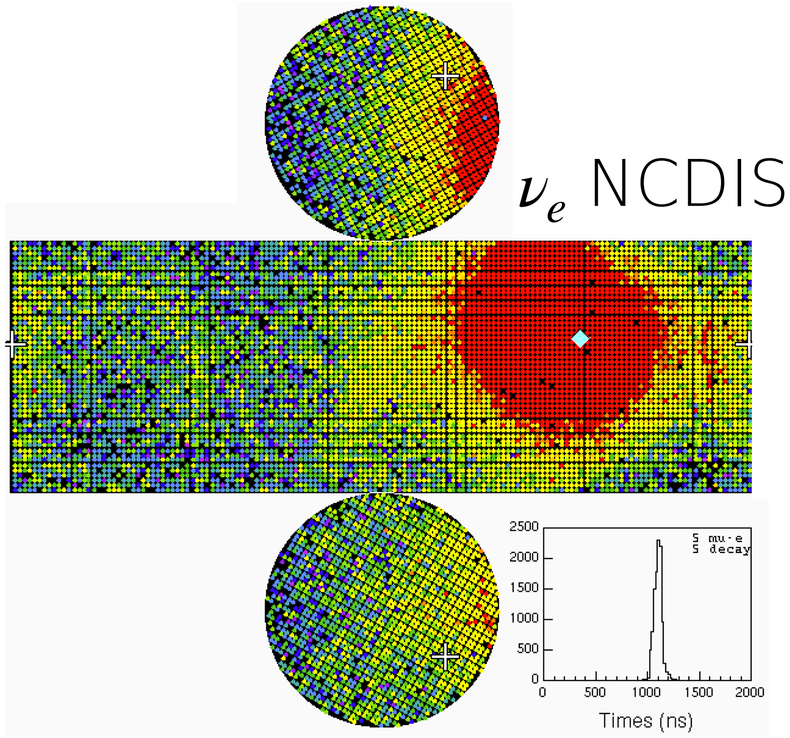
Semi-leptonic tau decay modes 65% B.R.

Signal



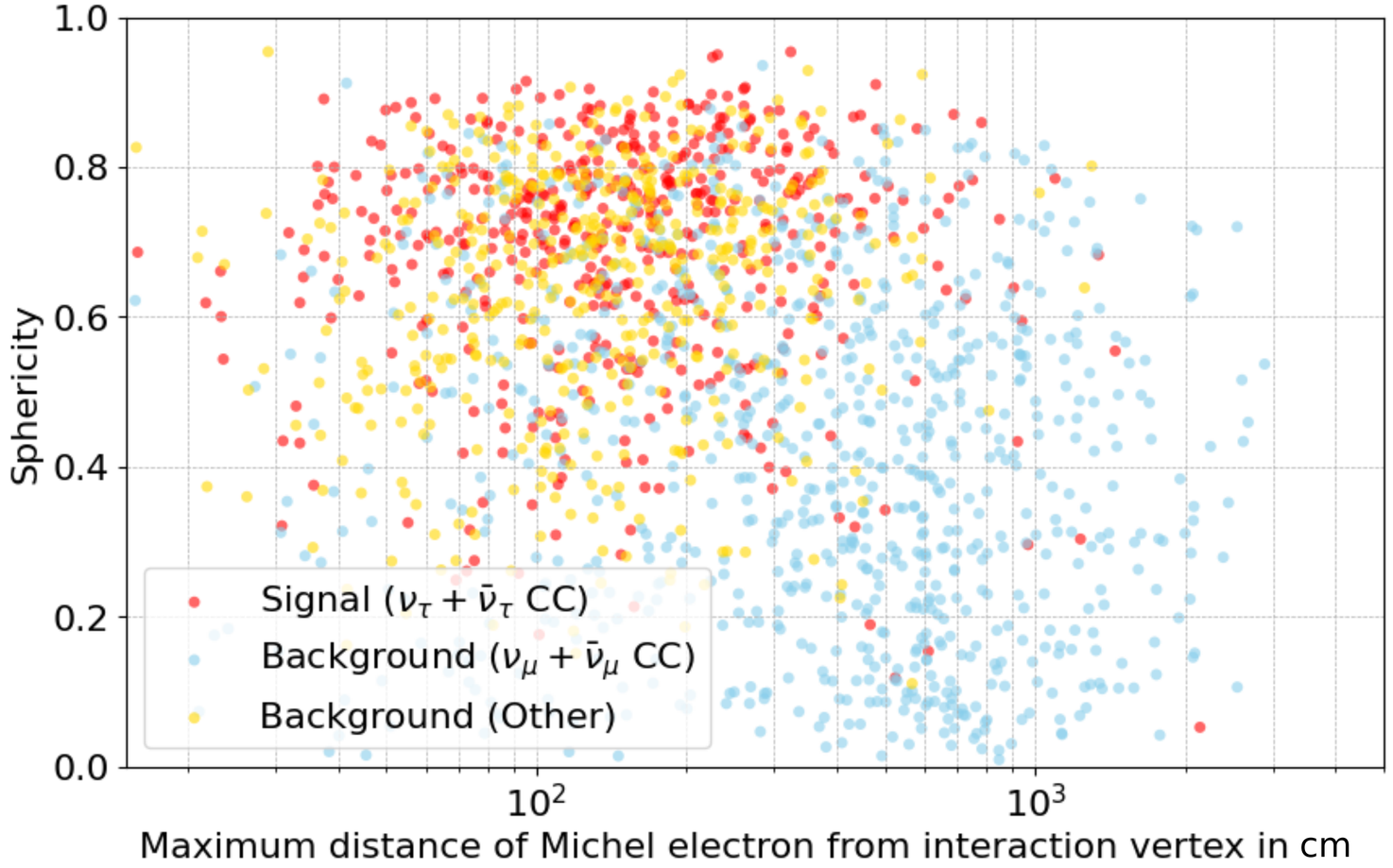
ν_τ CCDIS

Background



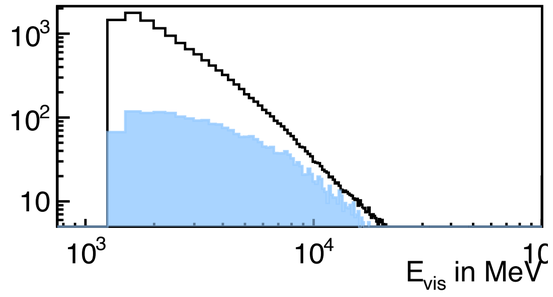
ν_e NCDIS

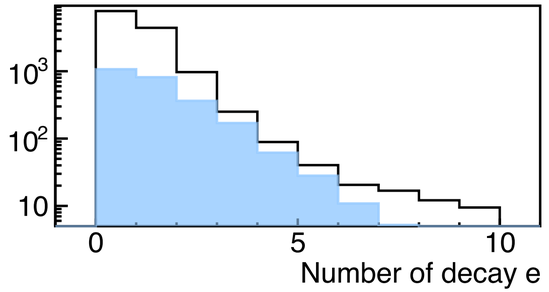
Identification of tau neutrinos at SK

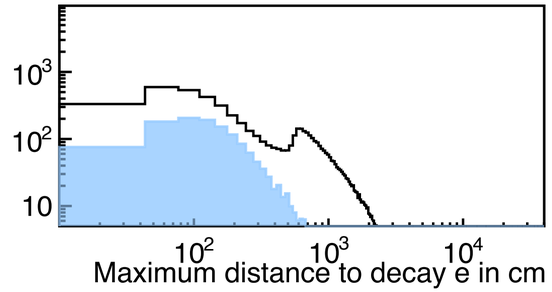


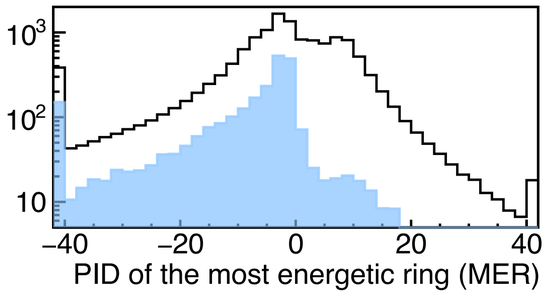
Identification of tau neutrinos at SK

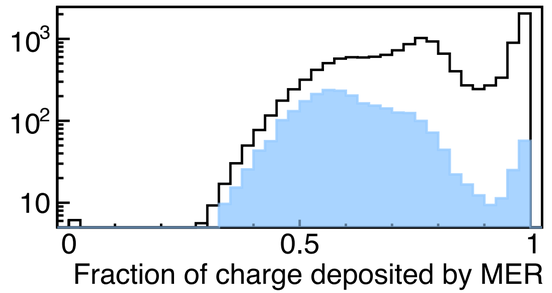
- Inputs to a multi-layer perceptron

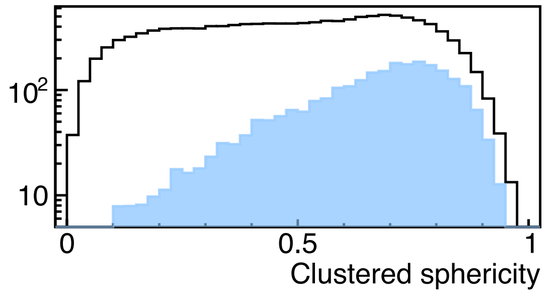


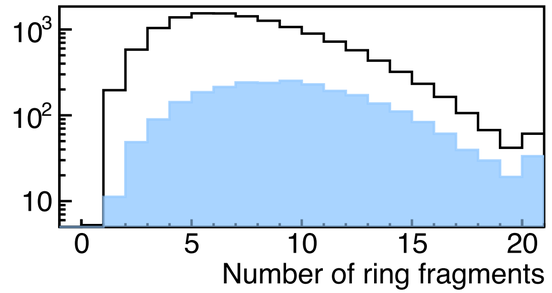




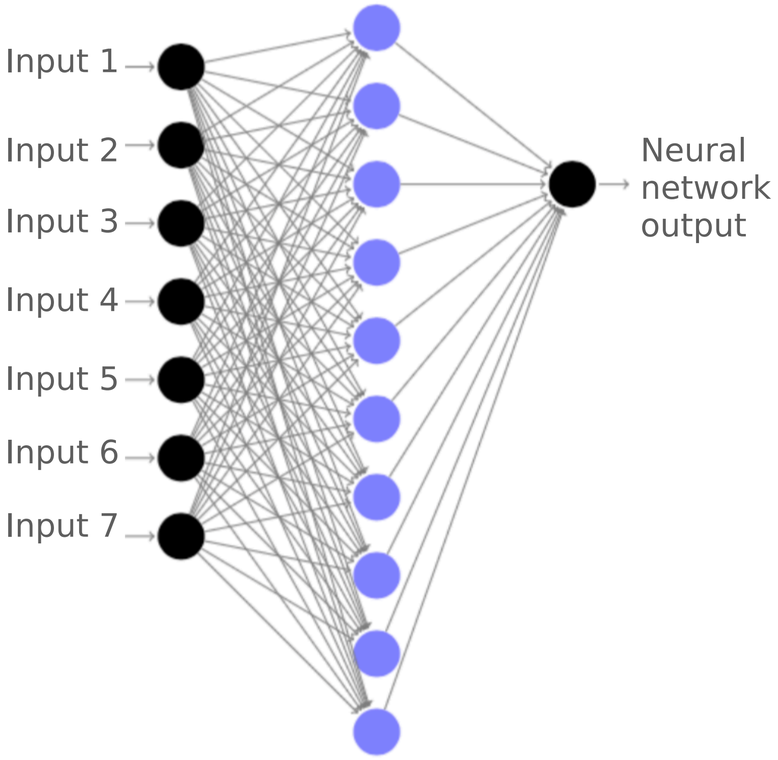


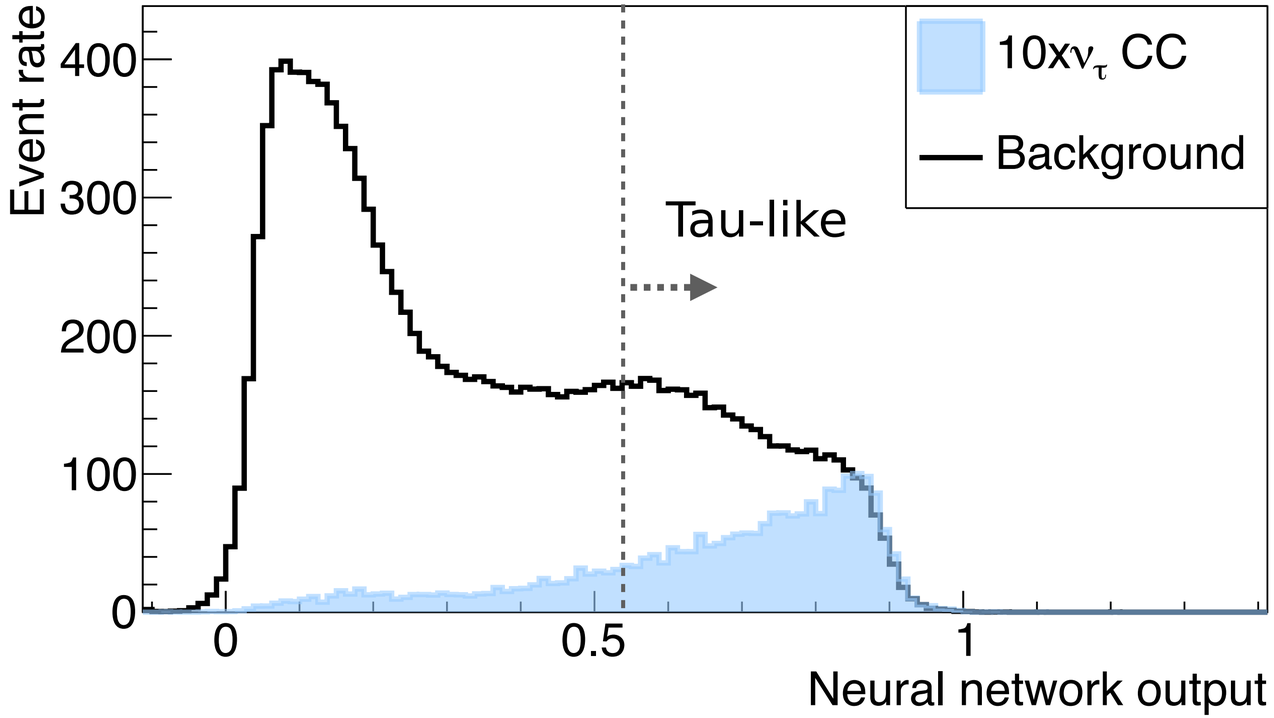




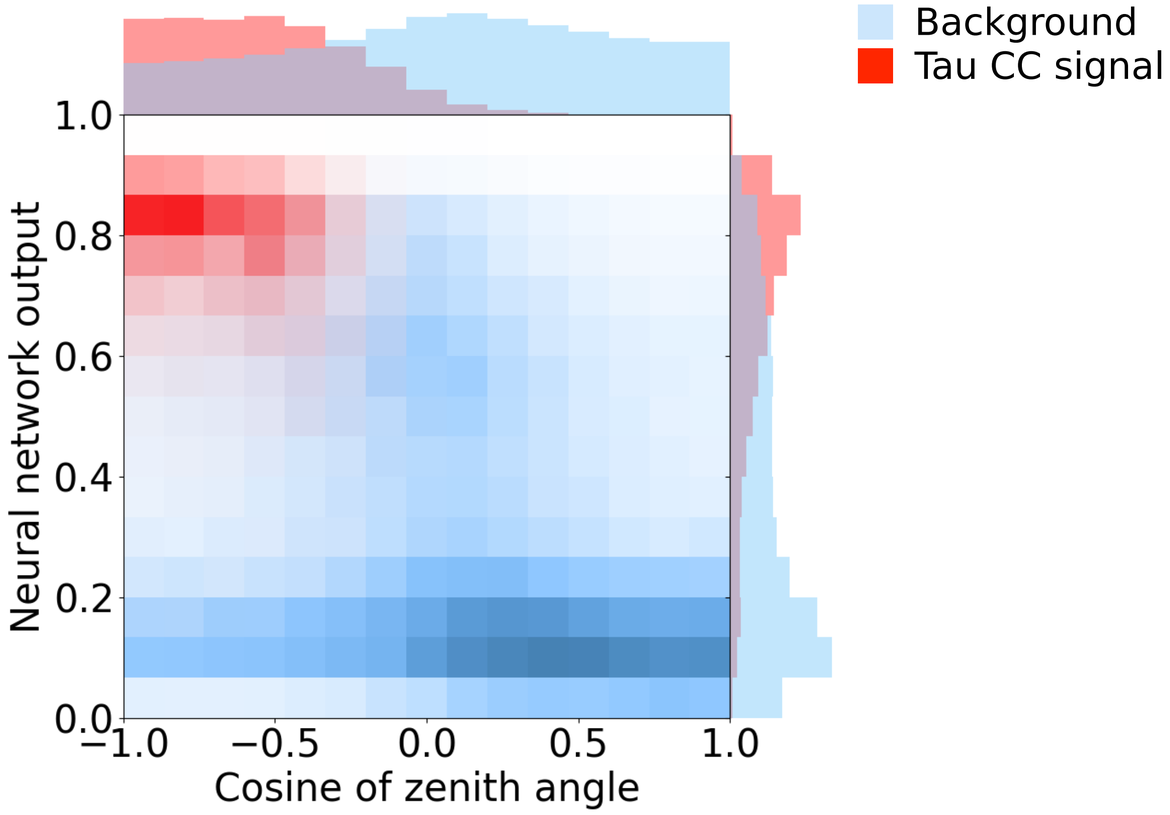


Binary classifier





Unbinned extended maximum likelihood fit



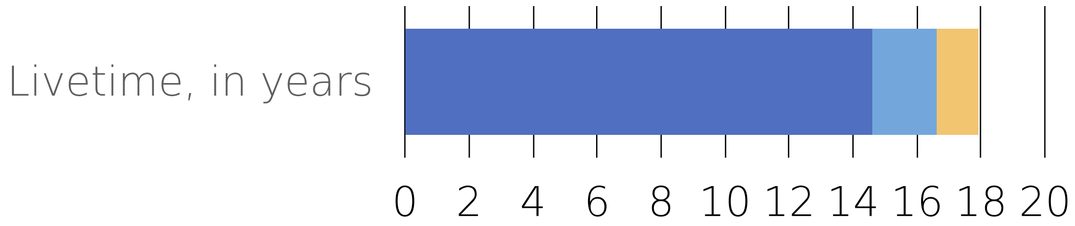
Data = Background + α.Signal

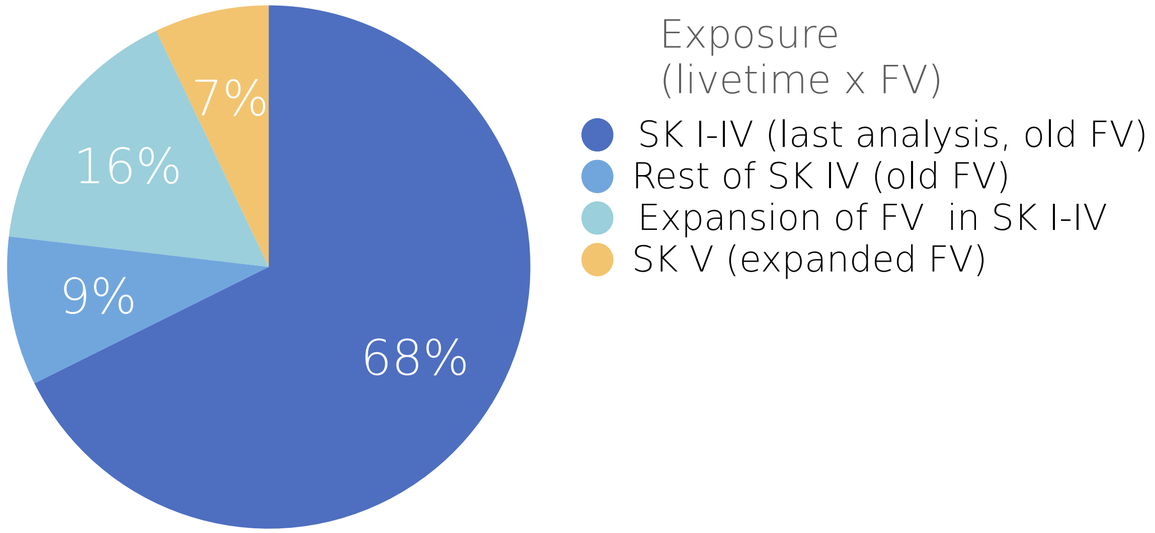
$+ \Sigma_i \epsilon_i$.Fluctuations in the nominal distributions due to ±1σ change in systematic uncertainties).

Sensitivity for tau normalisation, α

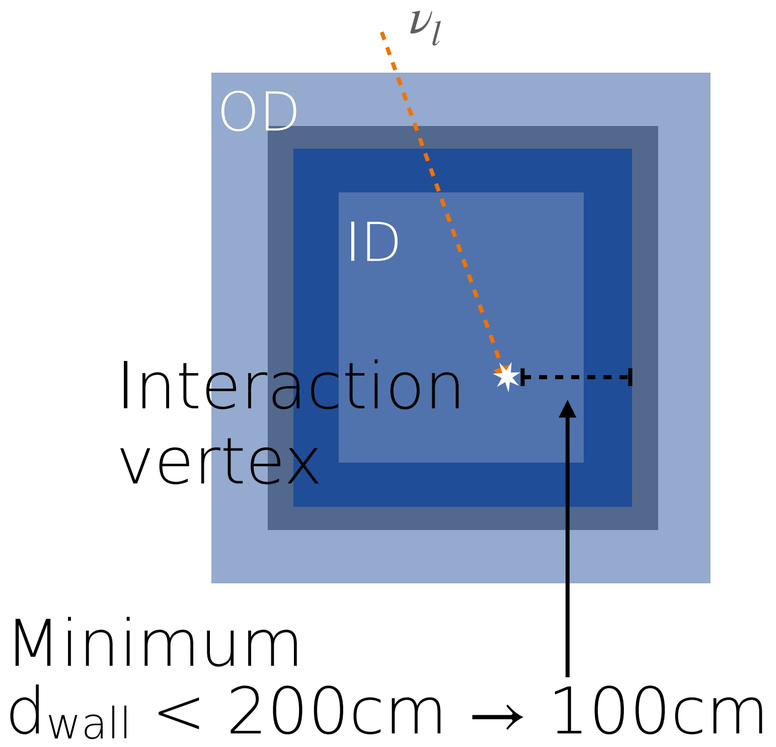
		Tau normalisation			% uncertainty	Exclusion of null hypothesis (α=0) Significance in σ
Nominal event rates (no systematics)		1.012	+/-	0.189	18%	5.4
All systematics (54 in total)		1.063	+/-	0.294	28%	3.6
Selected systematic uncertainties added to the fit depending on source	Flux related	1.051	+/-	0.223	21%	
	Oscillation theory related	1.028	+/-	0.200	19%	
	Neutrino interaction cross-section related	1.012	+/-	0.237	23%	
	Detector response and reconstruction related	1.010	+/-	0.239	24%	

Increased exposure since SK 2018

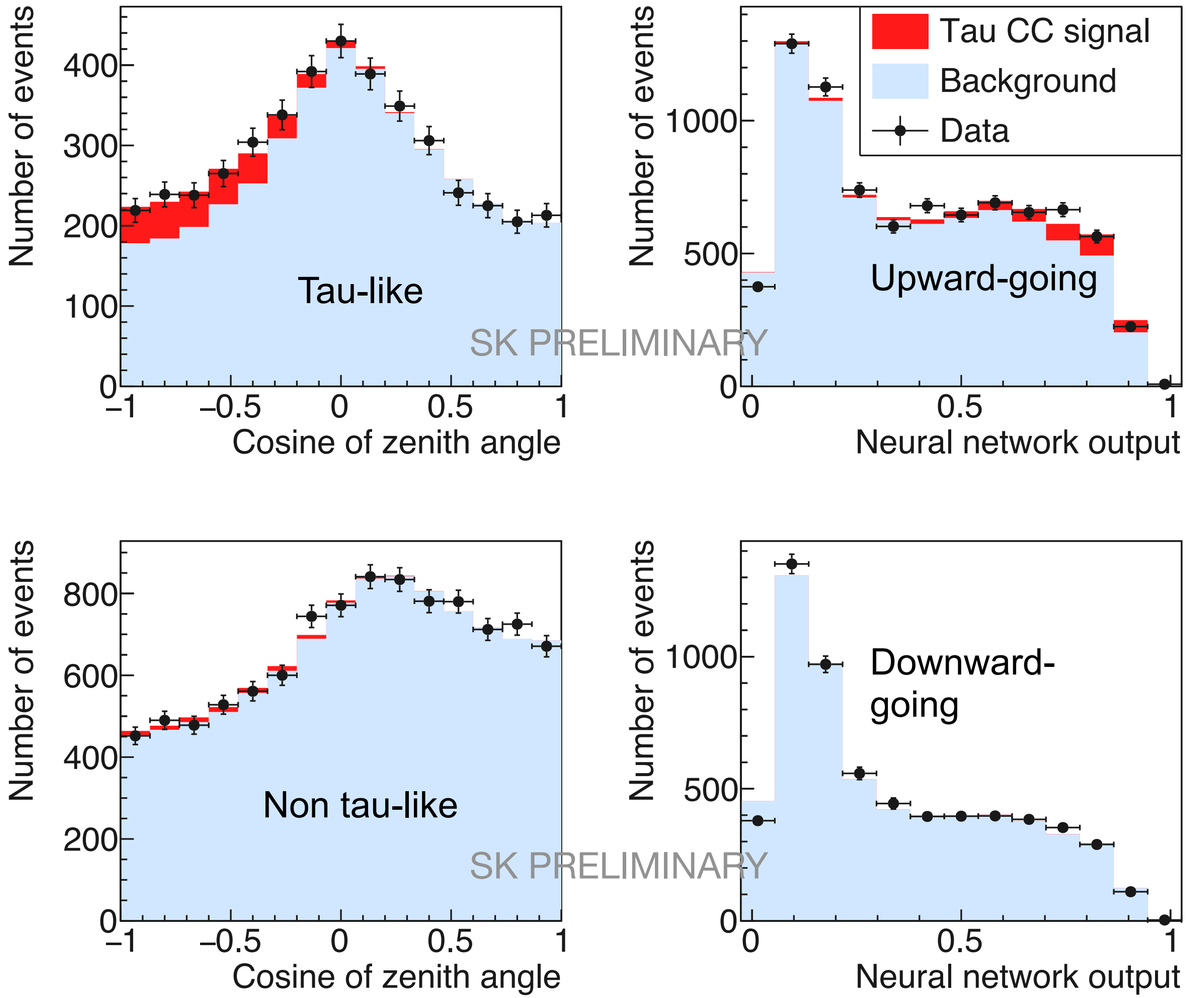




- 30% more data.

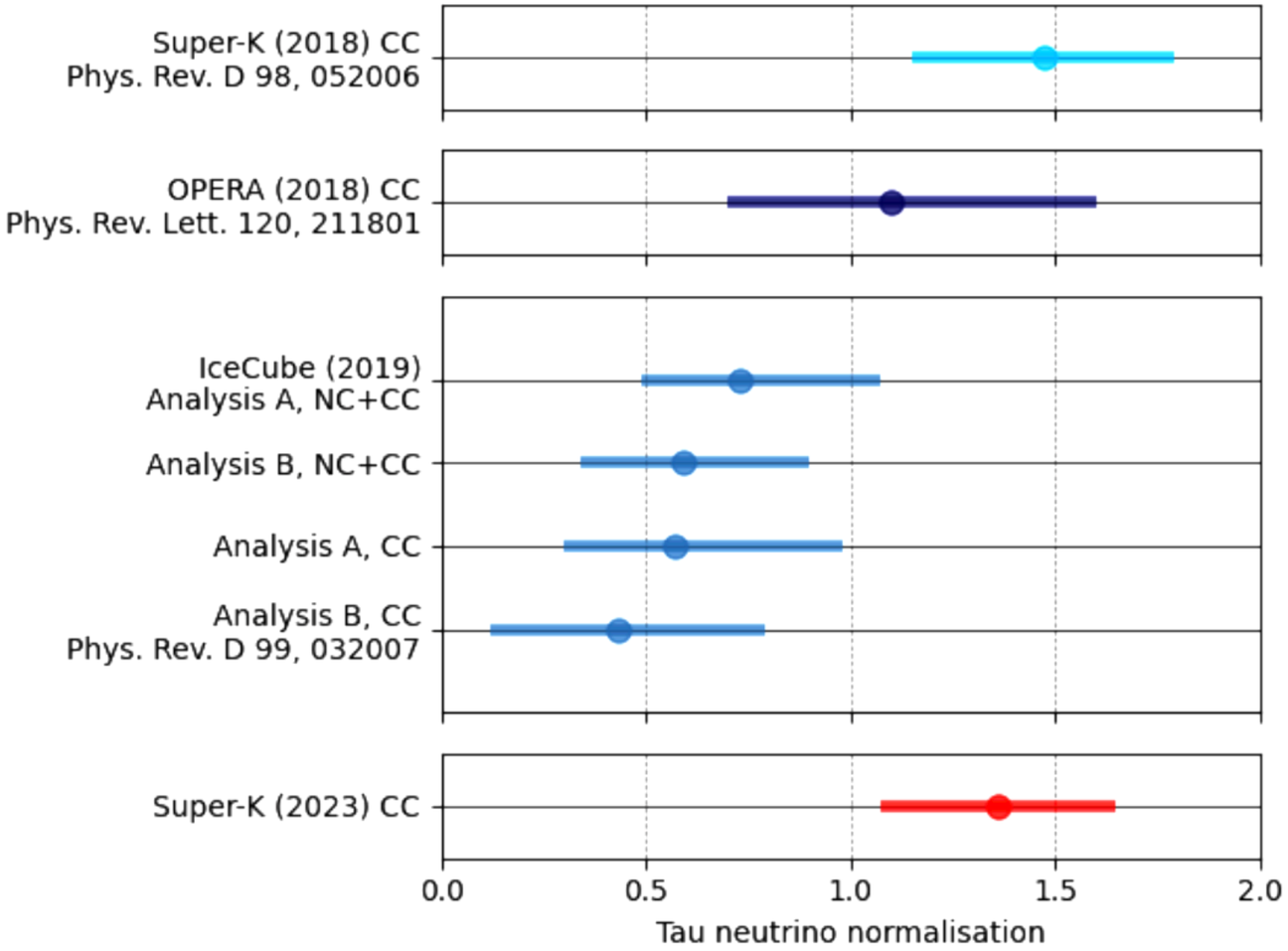


Latest results



- In 484 kton-year exposure,
  - α =1.36+/-0.29,
  - 428+/-92 tau neutrino CC events observed.

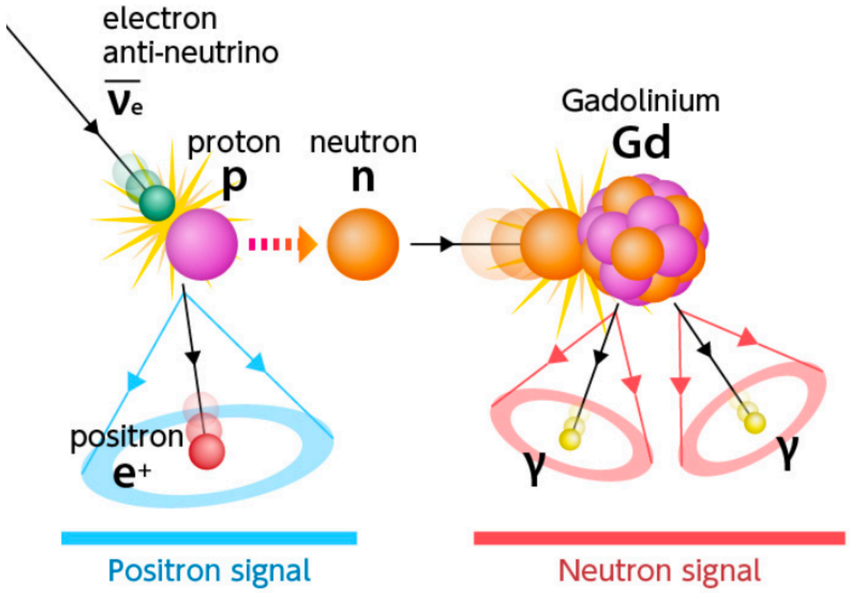
Latest results



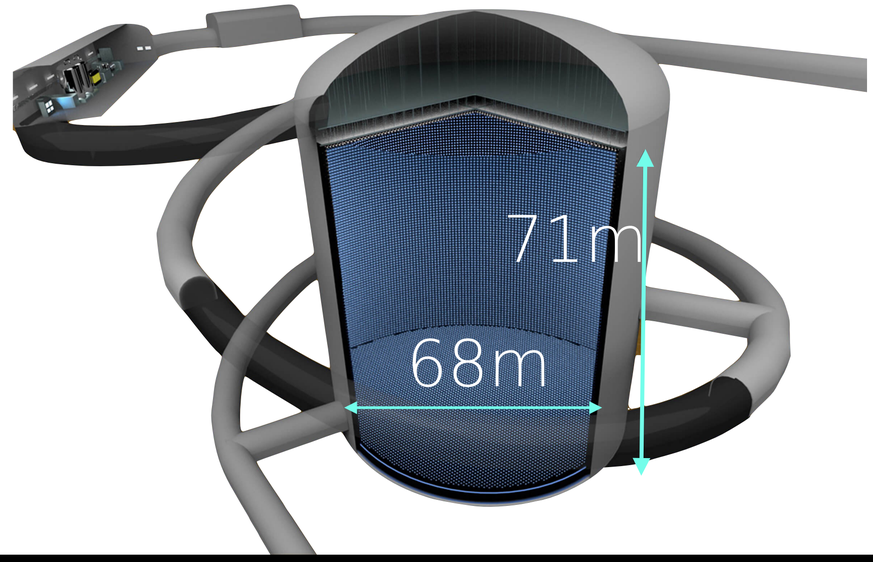
- 4.8σ significance of excluding the no tau neutrino appearance.

Way forward

2020: SK-Gd phase started.

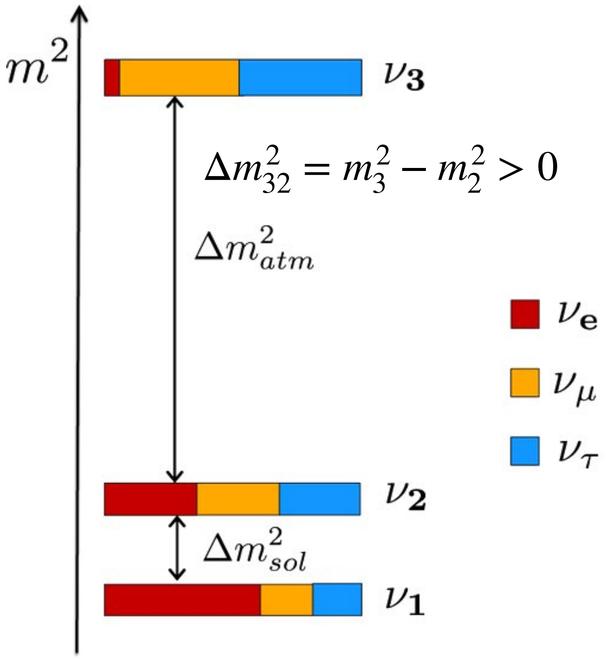


- 2024: 2 years of SK-Gd phase - 41 kton-year exposure ready for analysis!
- 2027: Hyper-Kamiokande data-taking projected (186.5 kton/year).

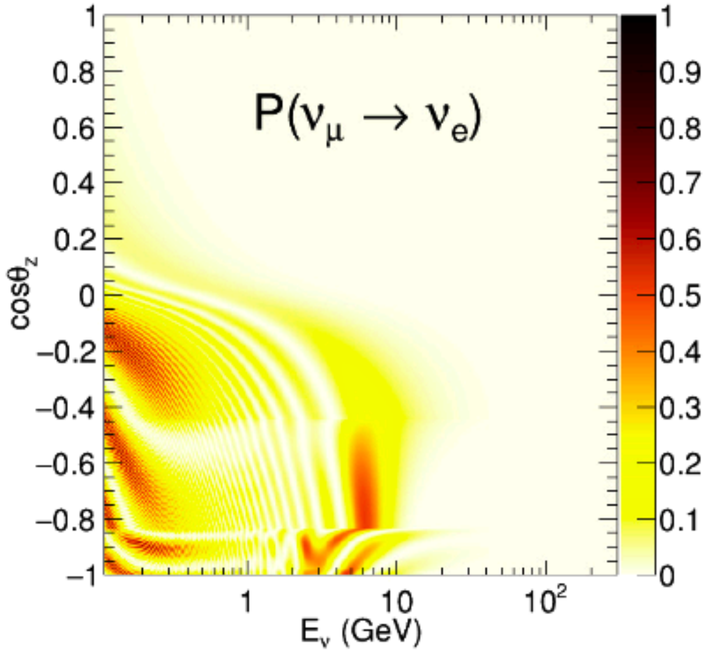


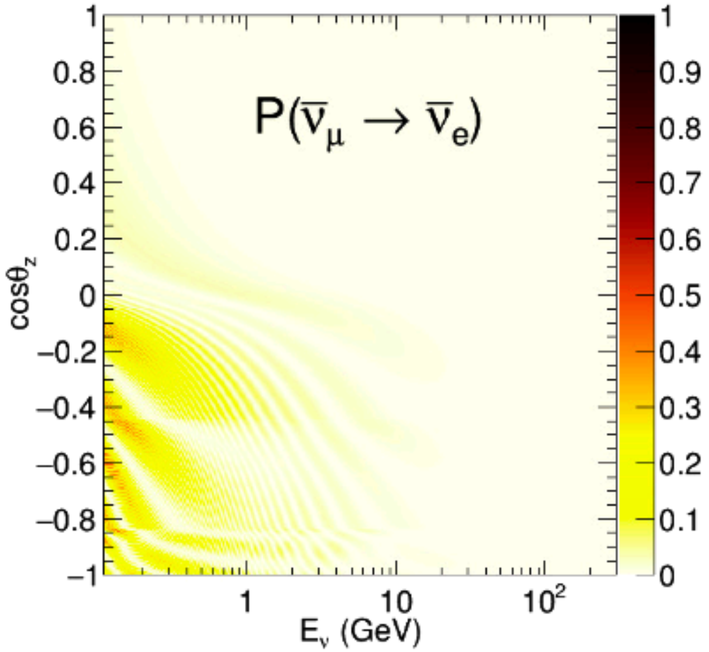
Tau neutrinos and 3-flavor oscillation

Is the mass-ordering normal?



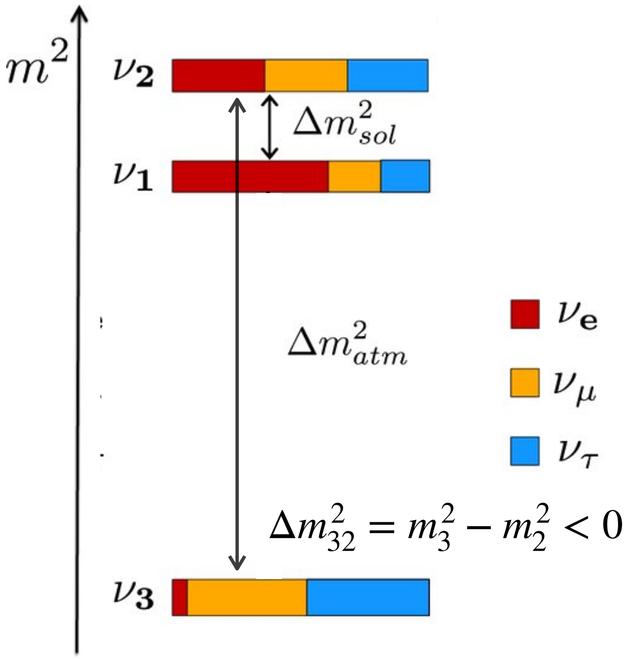
PHYSICAL REVIEW D 109, 072014 (2024)



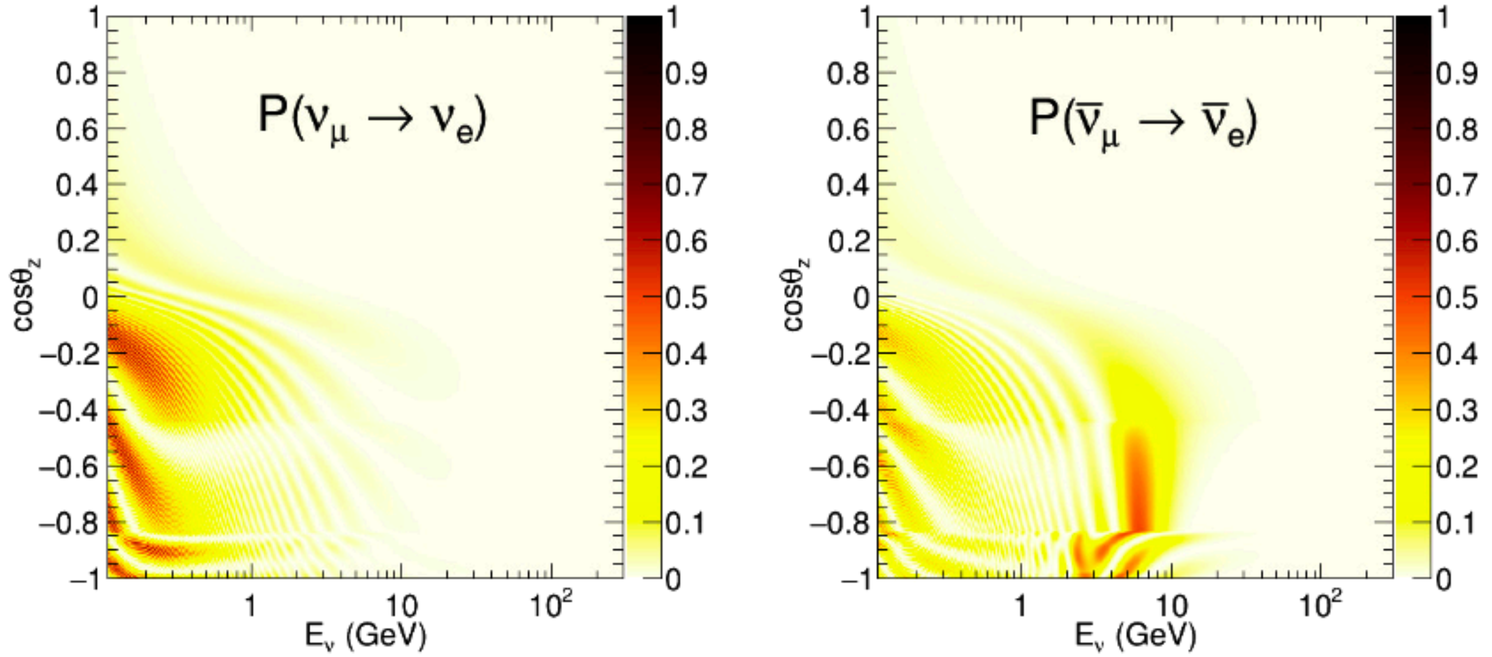


Tau neutrinos and 3-flavor oscillation

Or is it inverted?

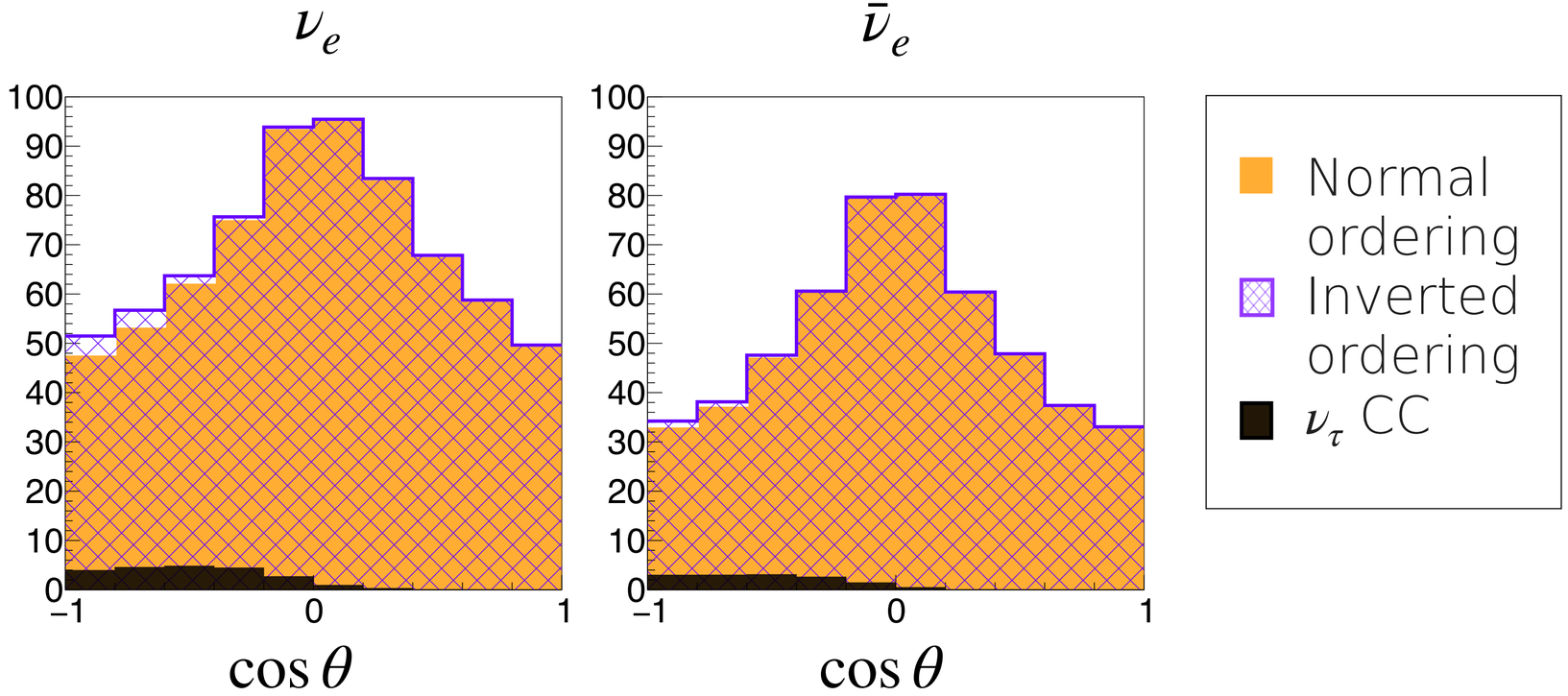


PHYSICAL REVIEW D 109, 072014 (2024)



Tau neutrinos and the 3-flavor oscillation

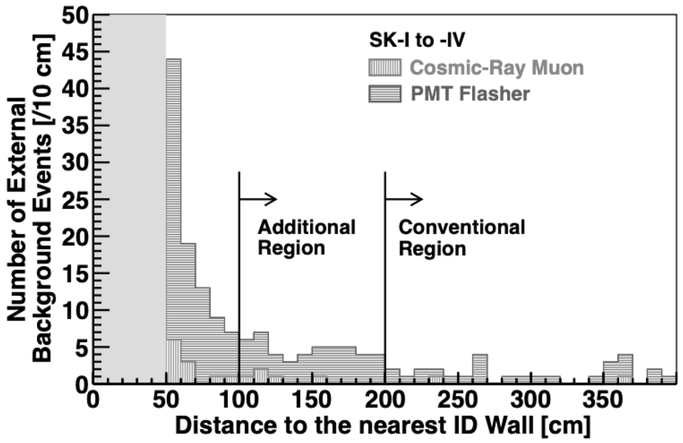
- Multi-GeV multi-ring SK samples as classified by a boosted decision tree.



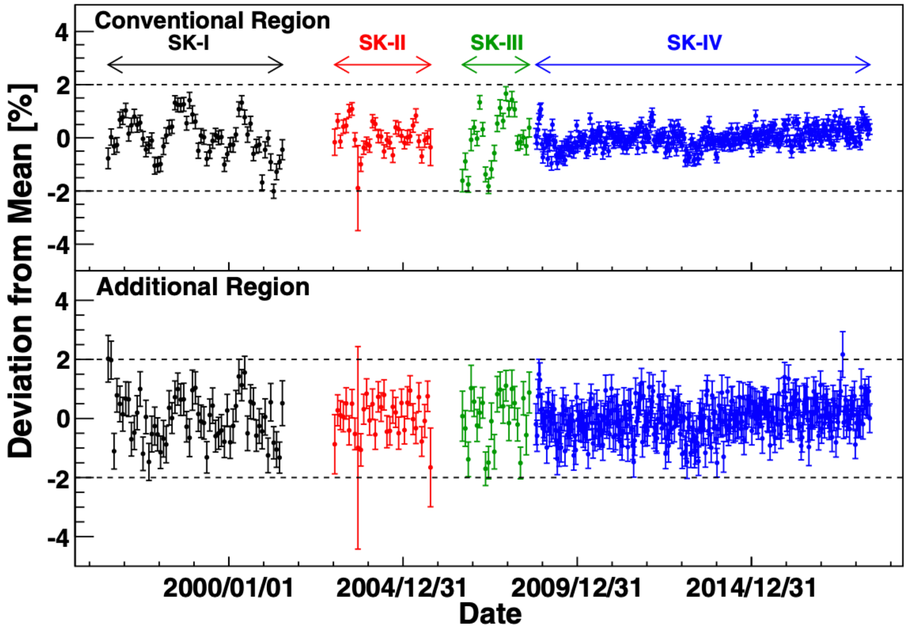
Summary

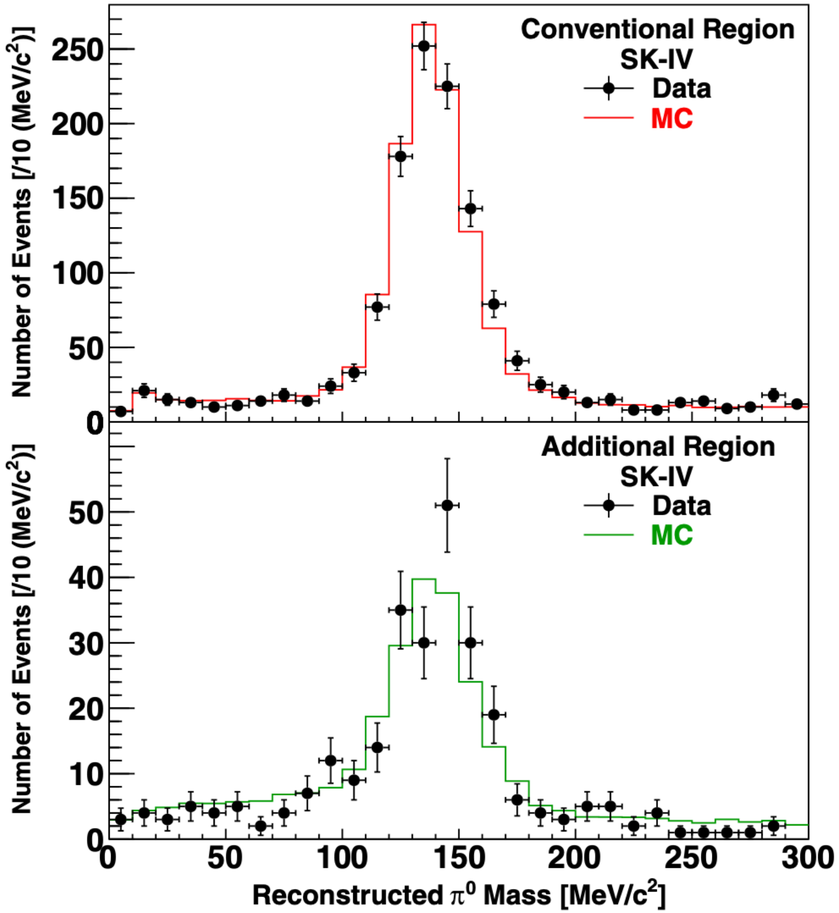
- Results from the analysis of the data recorded in all the pure water runs at SK (485 kton-year):
  - Observed 428+/-92 tau CC events.
  - Tau neutrino normalisation, α=1.4+/-0.3.
- Expect further improvements and potential increase in the sensitivity towards determining neutrino mass-ordering at SK.

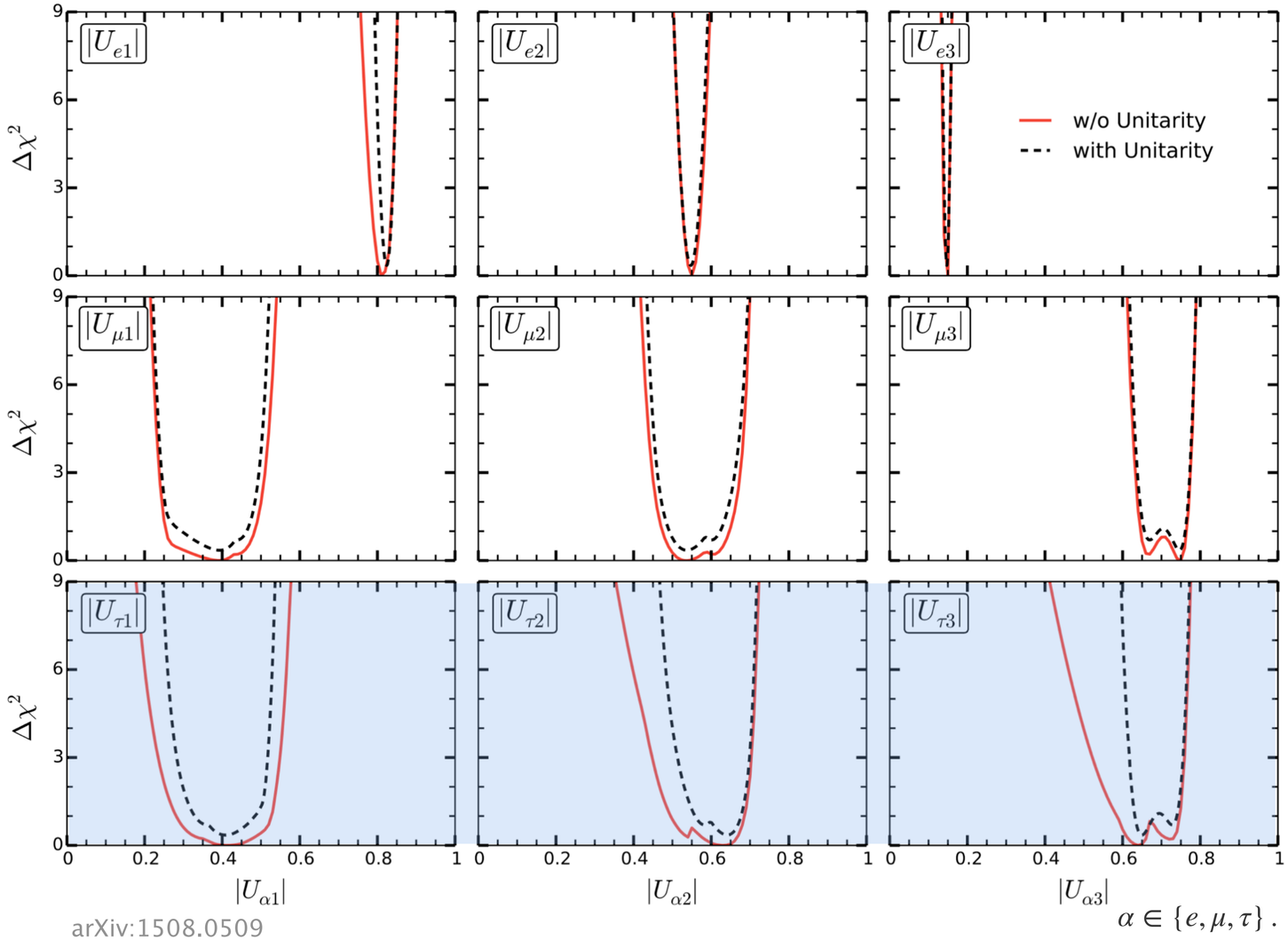
Back-up



Phys. Rev. D 102, 112011 (2020)

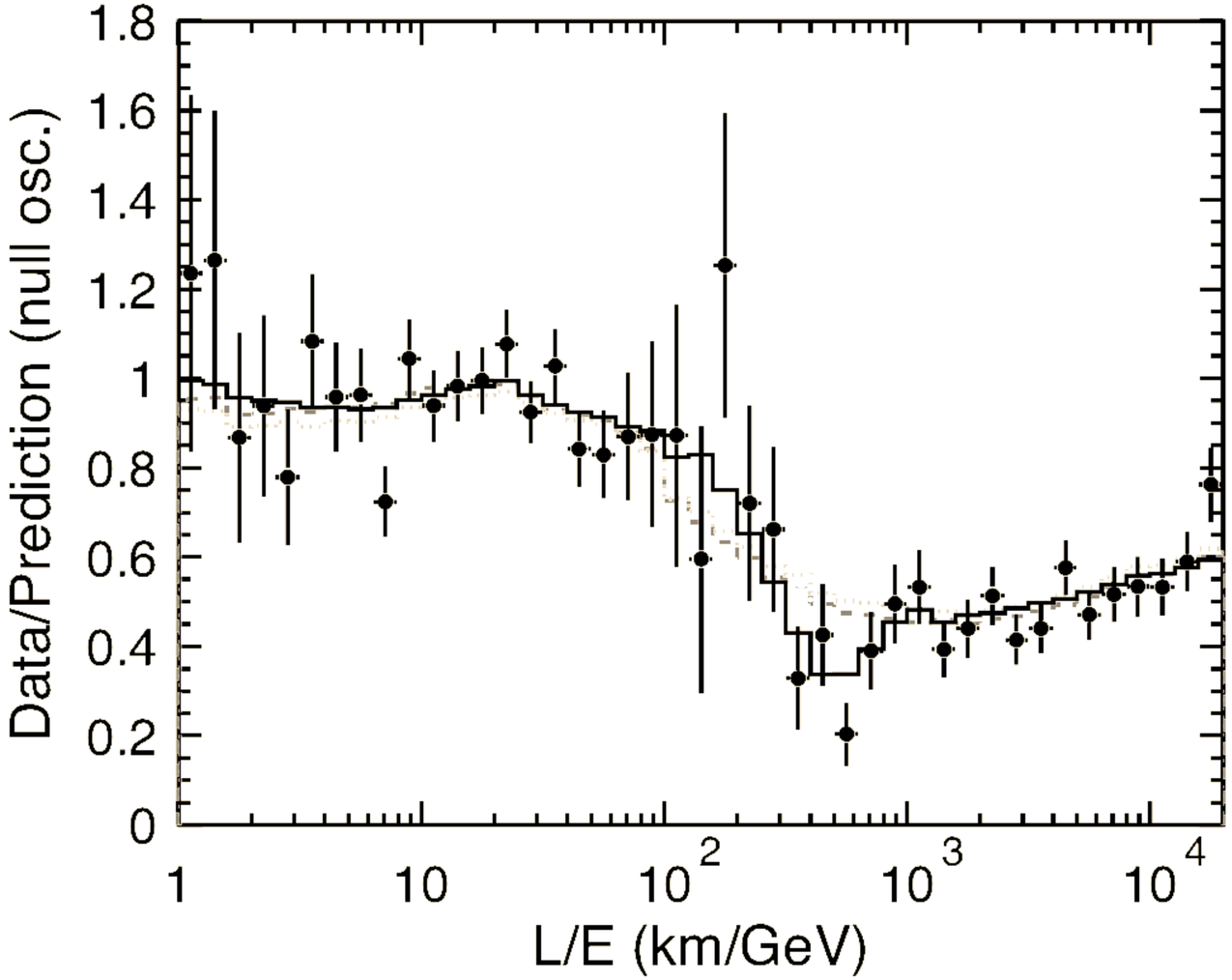




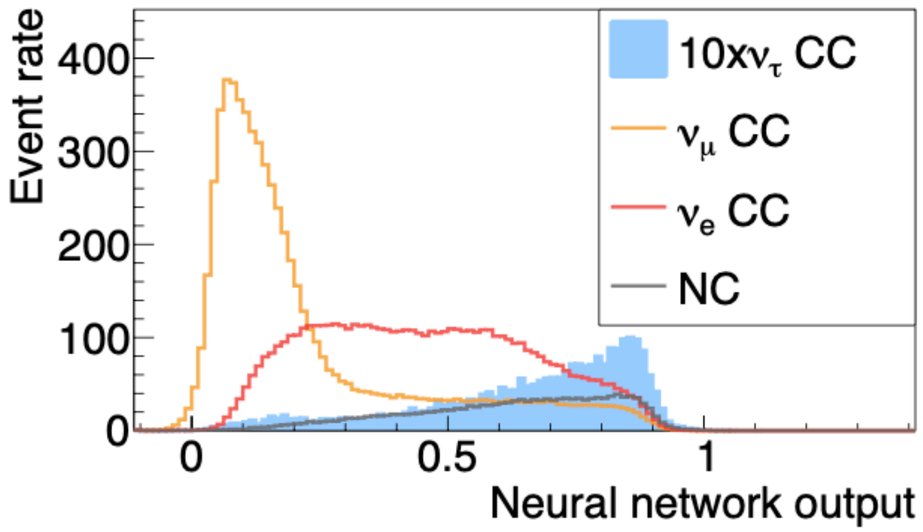


arXiv:1508.0509

$$\mathrm{U}^{\mathrm{Extended}}_{\mathrm{PMNS}} = \begin{pmatrix} \overbrace{\begin{pmatrix} \mathrm{U}_{e1} & \mathrm{U}_{e2} & \mathrm{U}_{e3} \\ \mathrm{U}_{\mu 1} & \mathrm{U}_{\mu 2} & \mathrm{U}_{\mu 3} \\ \mathrm{U}_{\tau 1} & \mathrm{U}_{\tau 2} & \mathrm{U}_{\tau 3} \end{pmatrix}}^{\mathrm{U}^{3\times 3}_{\mathrm{PMNS}}} & \cdots & \mathrm{U}_{en} \\ \vdots & \ddots & \vdots \\ \mathrm{U}_{s_n 1} & \mathrm{U}_{s_n 2} & \mathrm{U}_{s_n 3} & \cdots & \mathrm{U}_{s_n n} \end{pmatrix} .$$



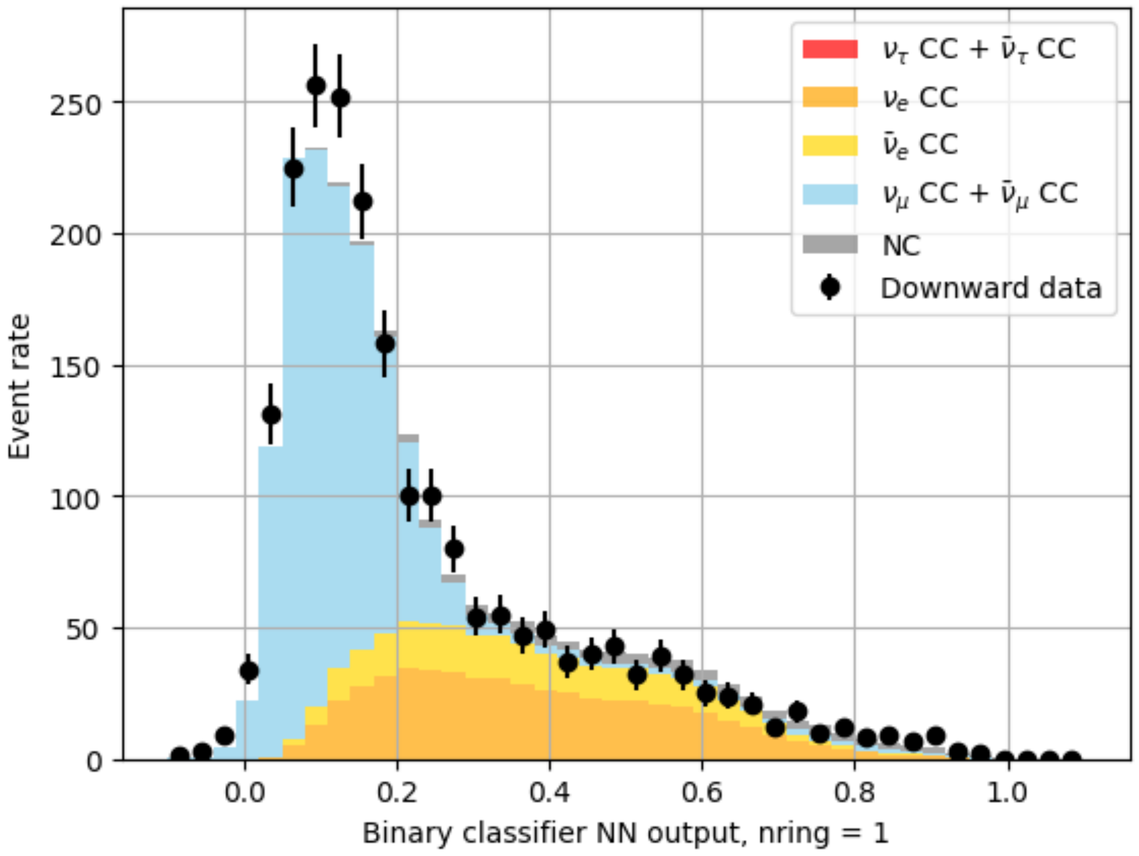
Phys. Rev. Lett. 93, 101801 (2004)



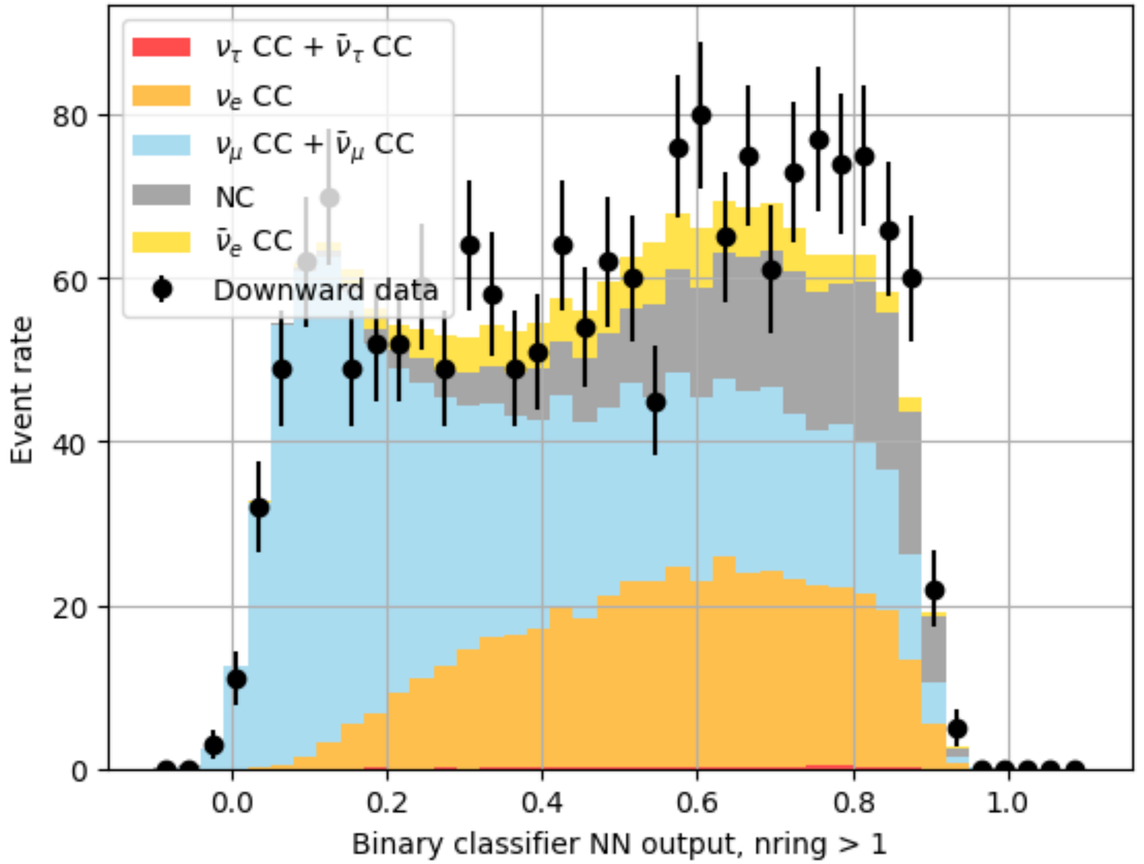
	ν_μ CC	ν_e CC	NC
% of background misclassified	13%	37%	70%

	α (stat. +syst.)	Uncertainty	Significance
SK I	1.4 +/- 0.5	39%	2.4
SK II	0.9 +/- 0.7	85%	1.0
SK III	2.6 +/- 0.8	31%	2.9
SK IV	1.6 +/- 0.4	24%	4.0
SK V	0.5 +/- 0.7	146%	0.1

SK4 single ring events

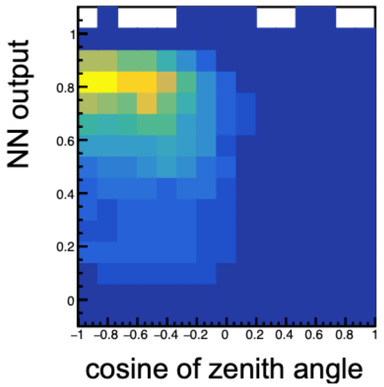


SK4 multi-ring events

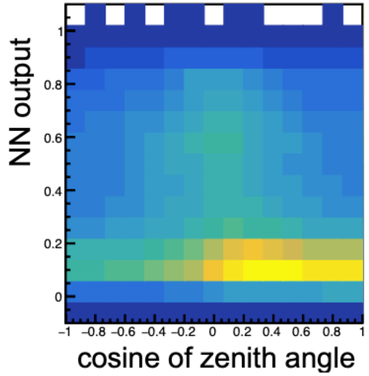


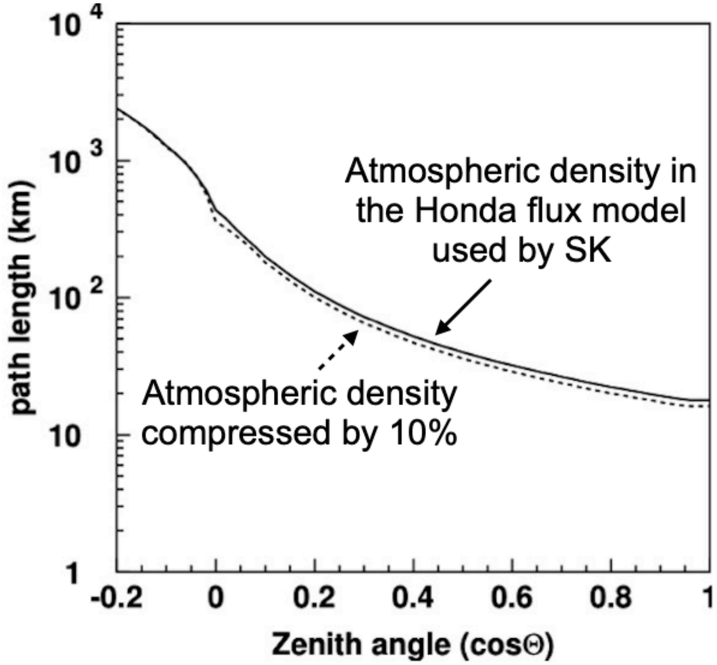
Nominal

Signal



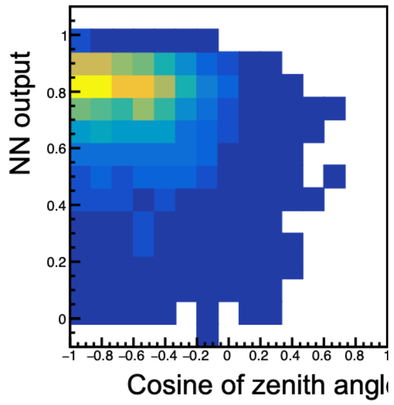
Background





DIS xsec

Signal



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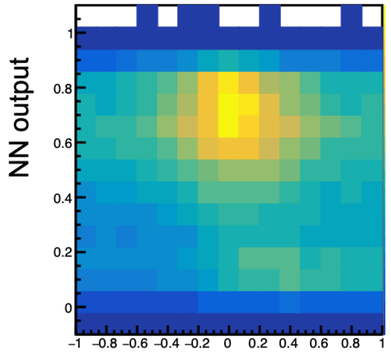

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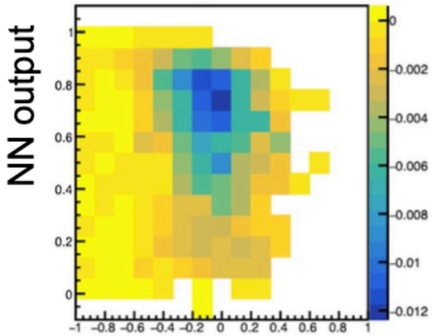

Background