ATMOSPHERIC NEUTRINO OSCILLATIONS

NEUTRINO OSCILLATION WORKSHOP

OSTUNI, ITALY

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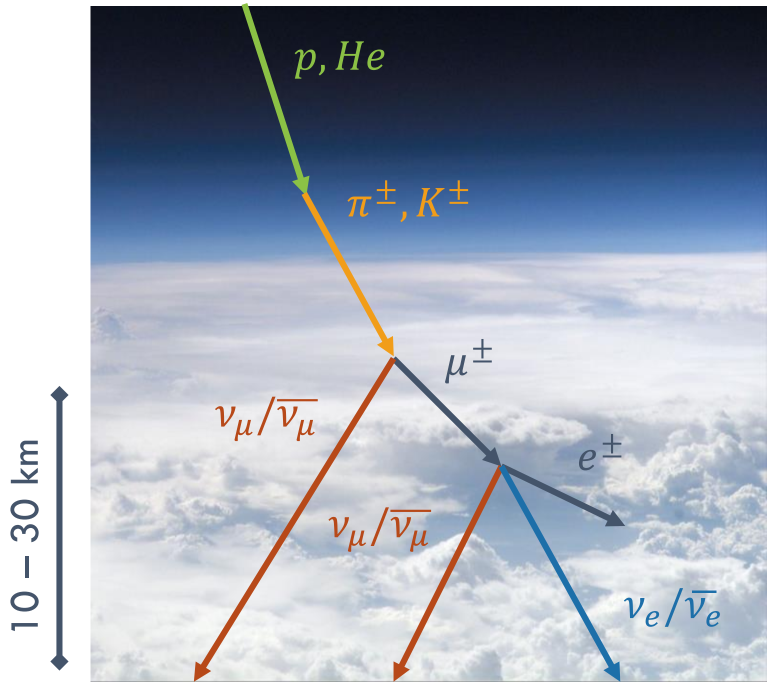
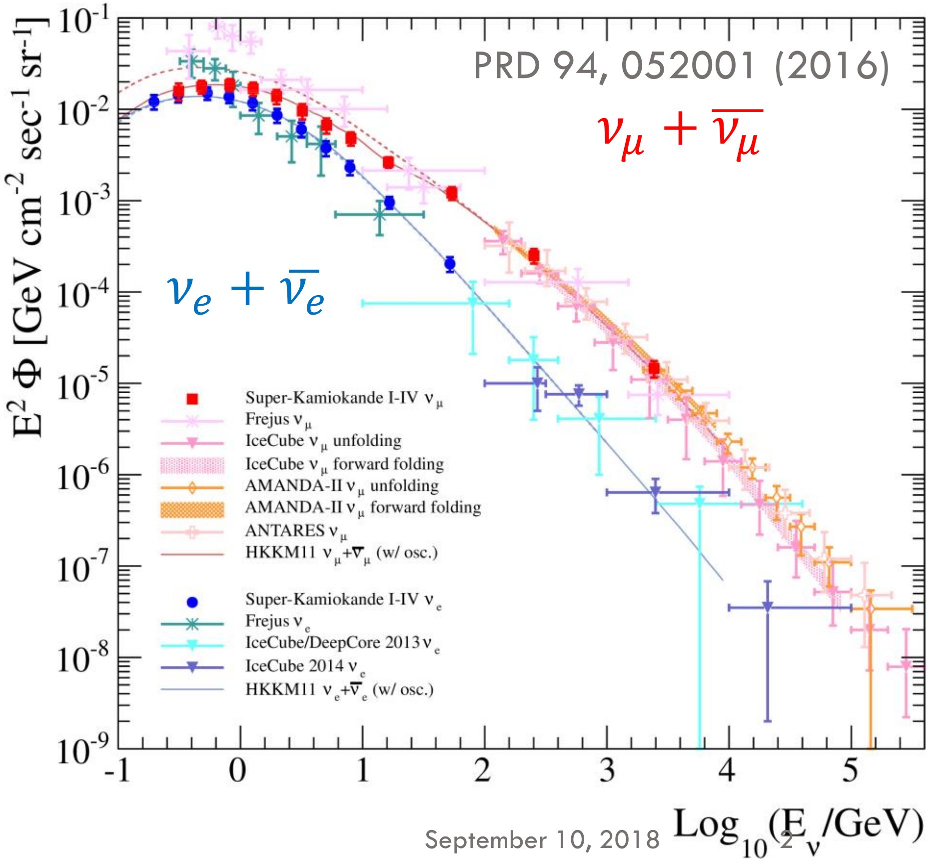
Stony Brook University

On behalf of the Super-Kamiokande Collaboration

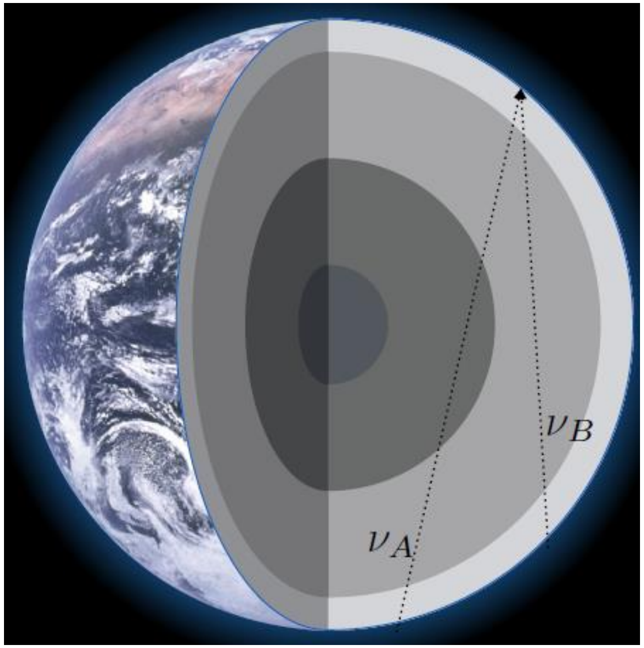
ATMOSPHERIC NEUTRINOS

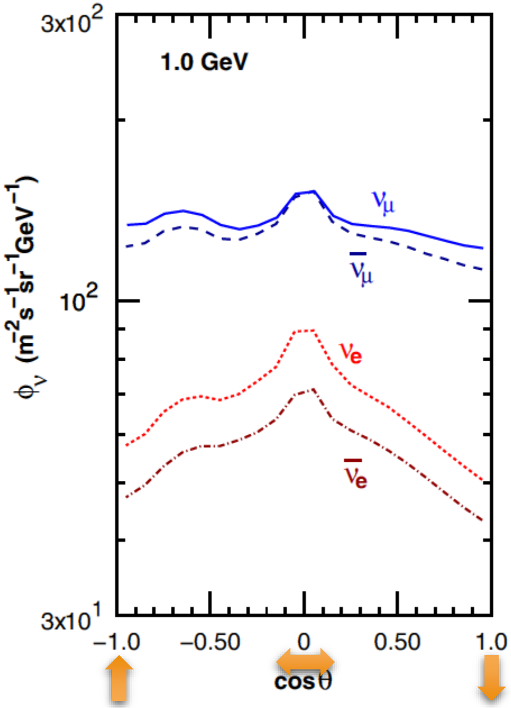
- Result from the interaction of primary cosmic rays with the Earth's atmosphere.
  - Below 1 GeV ${}^{\nu_\mu}/_{\nu_e} \approx 2$, at higher energies ${}^{\nu_\mu}/_{\nu_e} > 2$
  - Flux peaks in the hundreds of MeV and extends beyond TeV

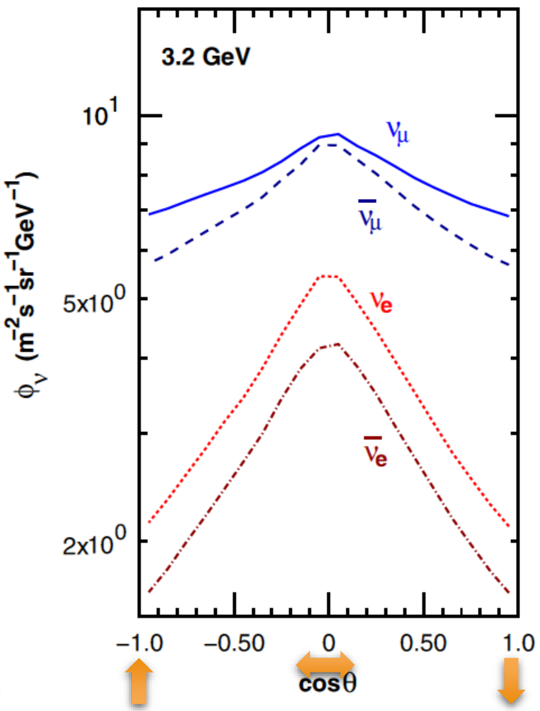




ATMOSPHERIC NEUTRINO DETECTION



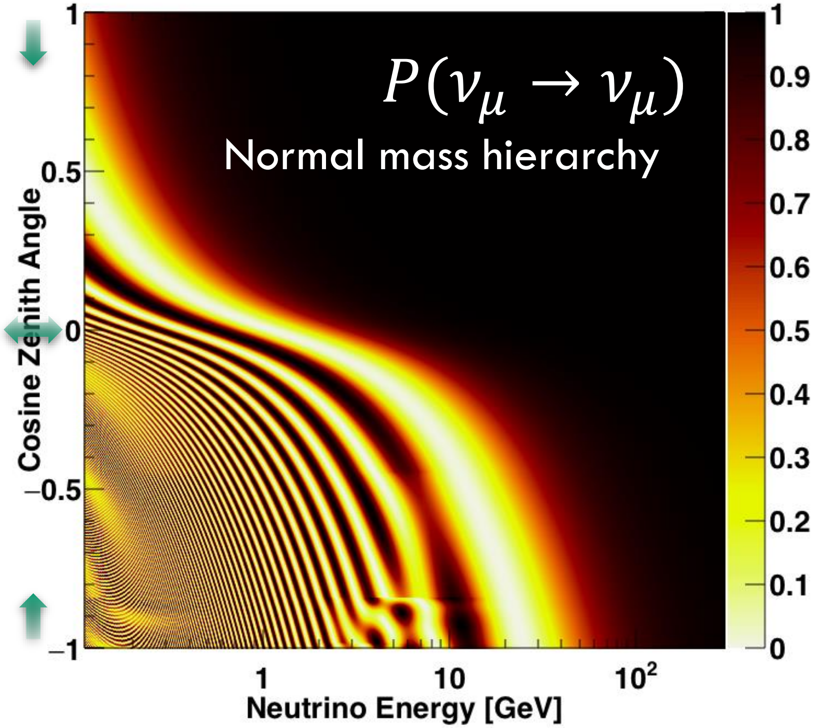


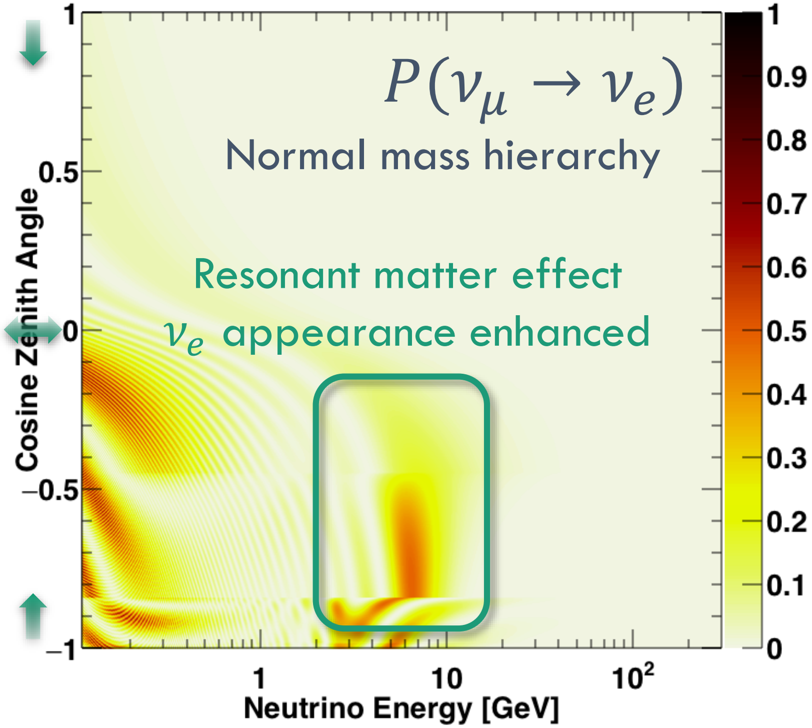


- Neutrinos detected at the surface of the Earth span a very wide range of baselines:
  - From around 10 – 30 km for down-going neutrinos, traversing only part of the atmosphere
  - Up to 13000 km for up-going neutrinos, traversing the Earth
  - The measured zenith angle correlates well with the baseline
- Study neutrino oscillations by measuring flux as a function of **zenith** angle and **energy**

ATMOSPHERIC NEUTRINO OSCILLATIONS

- Dominant effect is $\nu_\mu \rightarrow \nu_\tau$ oscillation ($\nu_\mu$disappearance)
    - Sensitive to $\boldsymbol{\Delta m^2_{32}}$ and $\boldsymbol{\theta_{23}}$
- Sub-leading effects in ν_e appearance
    - Resonant oscillation due to matter effect in the Earth, sensitive to **mass ordering**
    - Interference and solar-driven oscillations, sensitive to **CP violation phase** and $\boldsymbol{\theta_{23}}$ **octant**
- High-statistics data sets allow for sub-leading effects to be measured.





Resonant matter effect

ν_e appearance enhanced

ATMOSPHERIC NEUTRINO OSCILLATIONS

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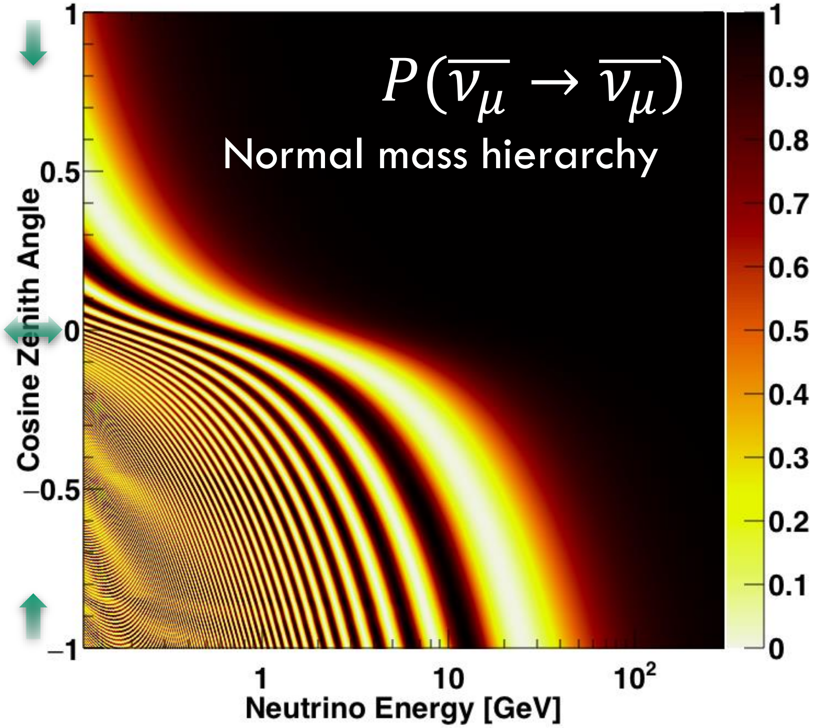
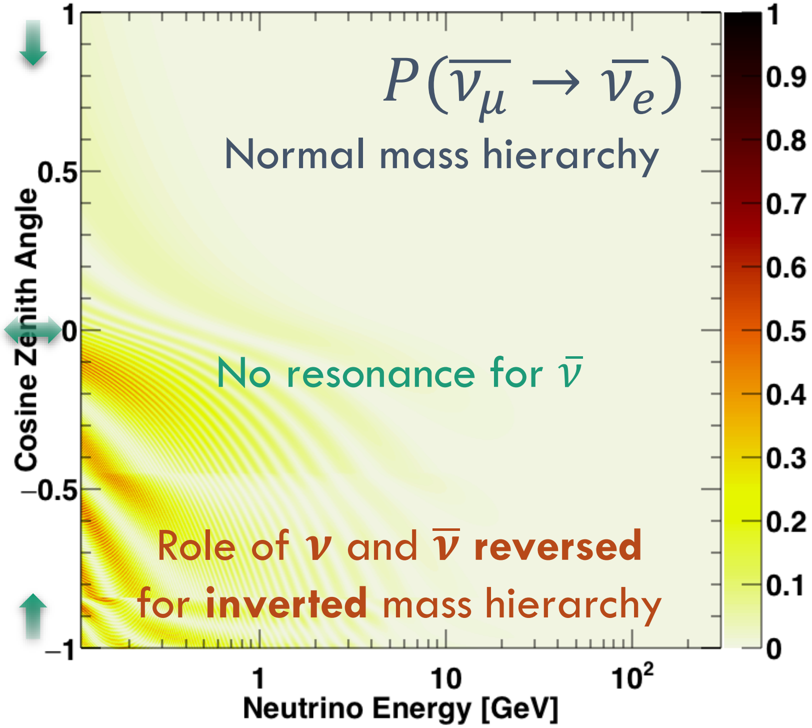


$P(\overline{\nu_\mu} \to \overline{\nu_\mu})$

Normal mass hierarchy



$P(\overline{\nu_\mu} \to \overline{\nu}_e)$

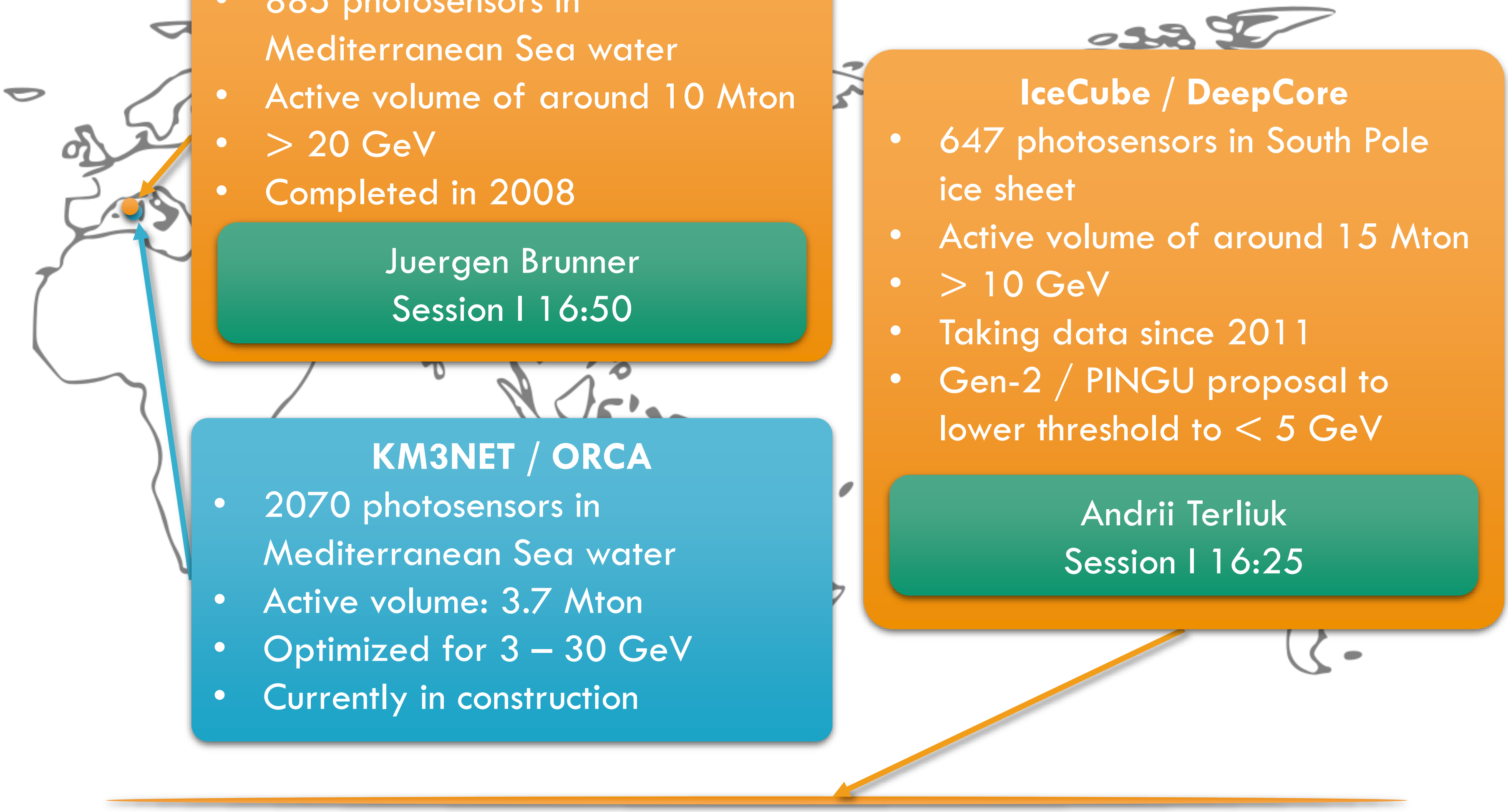
Normal mass hierarchy

No resonance for $\bar{\nu}$

Role of $\boldsymbol{\nu}$ and $\boldsymbol{\bar{\nu}}$ **reversed** for **inverted** mass hierarchy

CURRENT AND FUTURE EXPERIMENTS

CURRENT AND FUTURE EXPERIMENTS



ANTARES

- 885 photosensors in Mediterranean Sea water
- Active volume of around 10 Mton
- > 20 GeV
- Completed in 2008

Juergen Brunner
Session I 16:50

KM3NET / ORCA

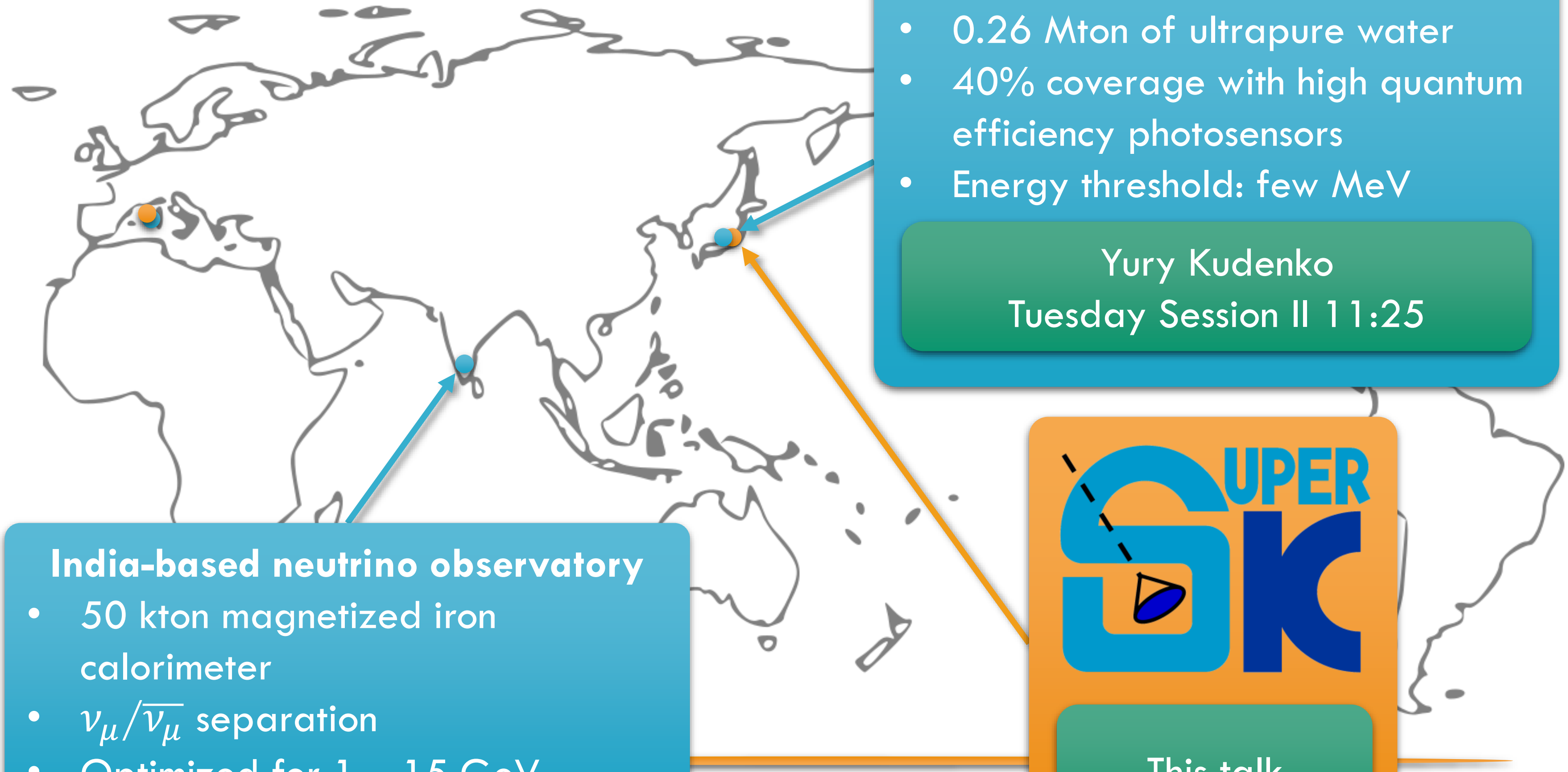
- 2070 photosensors in Mediterranean Sea water
- Active volume: 3.7 Mton
- Optimized for 3 – 30 GeV
- Currently in construction

IceCube / DeepCore

- 647 photosensors in South Pole ice sheet
- Active volume of around 15 Mton
- > 10 GeV
- Taking data since 2011
- Gen-2 / PINGU proposal to lower threshold to < 5 GeV

Andrii Terliuk
Session I 16:25

CURRENT AND FUTURE EXPERIMENTS



Hyper-Kamiokande
- 0.26 Mton of ultrapure water
- 40% coverage with high quantum efficiency photosensors
- Energy threshold: few MeV

Yury Kudenko
Tuesday Session II 11:25

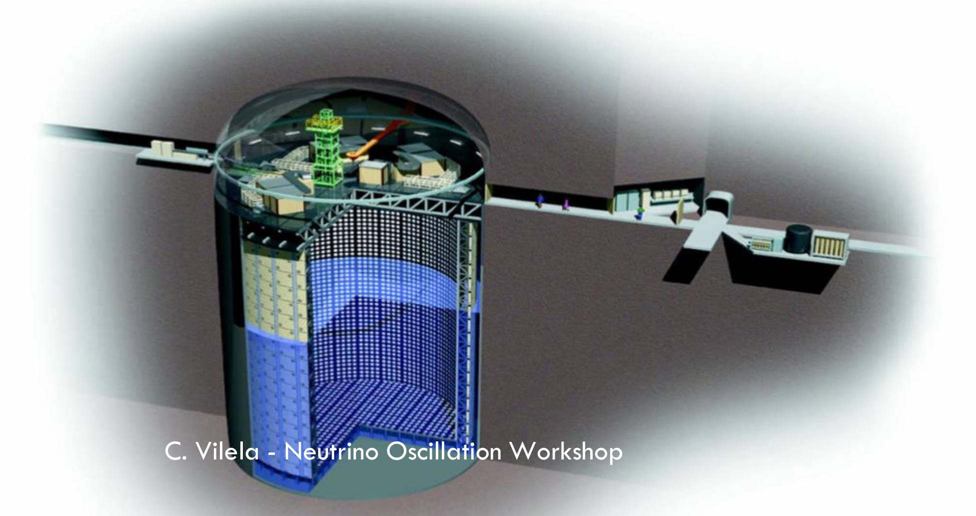
India-based neutrino observatory
- 50 kton magnetized iron calorimeter
- $\nu_\mu/\overline{\nu_\mu}$ separation
- Optimized for 1 – 15 GeV

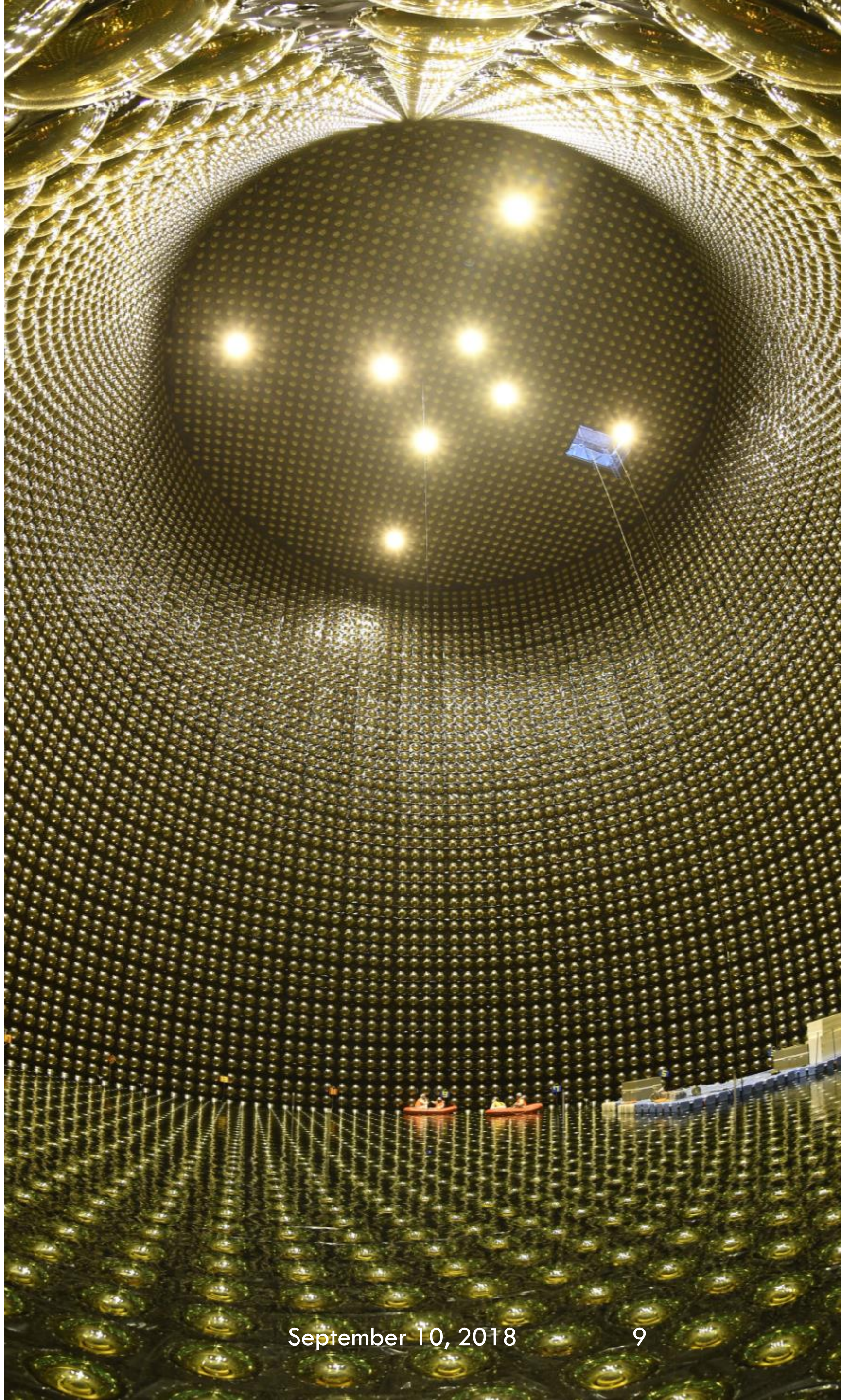
SUPER K

This talk

SUPER-KAMIOKANDE

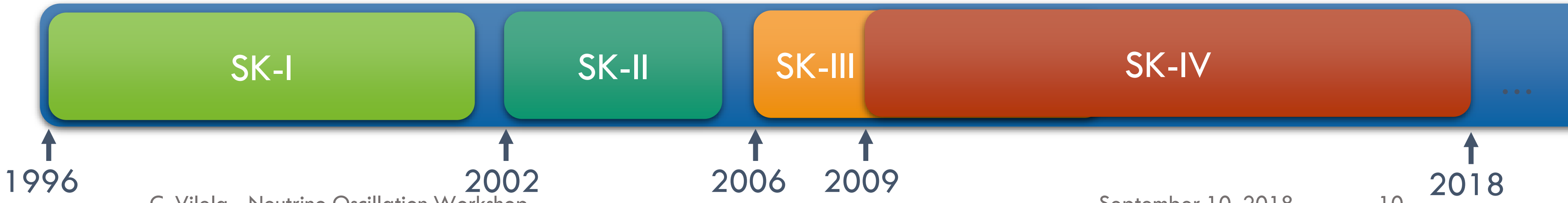
- 50 kiloton water-Cherenkov detector.
- Optically separated outer detector for tagging entering/escaping particles.
- ~11000 20” photomultiplier tubes (PMTs) facing the inner detector giving a photocathode coverage of 40%.
- ~2000 8” PMTs in the outer detector.
- Measure momentum and direction of particles above Cherenkov threshold.
  - Excellent $\mu^{\pm}/e^{\pm}$ separation.
  - No charge selection.





THE SUPER-KAMIOKANDE EXPERIMENT

- Detector has been operating for over twenty years.
- First phase of data taking ended when implosion accident led to loss of a large fraction of the PMTs.
    - Discovery of atmospheric neutrino oscillations in 1998!
- In 2002 the detector was rebuilt with roughly half of the coverage fraction.
    - Protective fiver reinforced plastic covers were added to the PMTs.
- Complete 40% coverage fraction is recovered in 2006.
- Front-end electronics upgrade in 2009
    - Better control of water conditions improves stability.
- Detector turned off in May 31st 2018 and is currently undergoing refurbishment.
    - Work towards gadolinium upgrade.
    - Failed PMTs are replaced.



SK-I

SK-II

SK-III

SK-IV

...

1996

2002

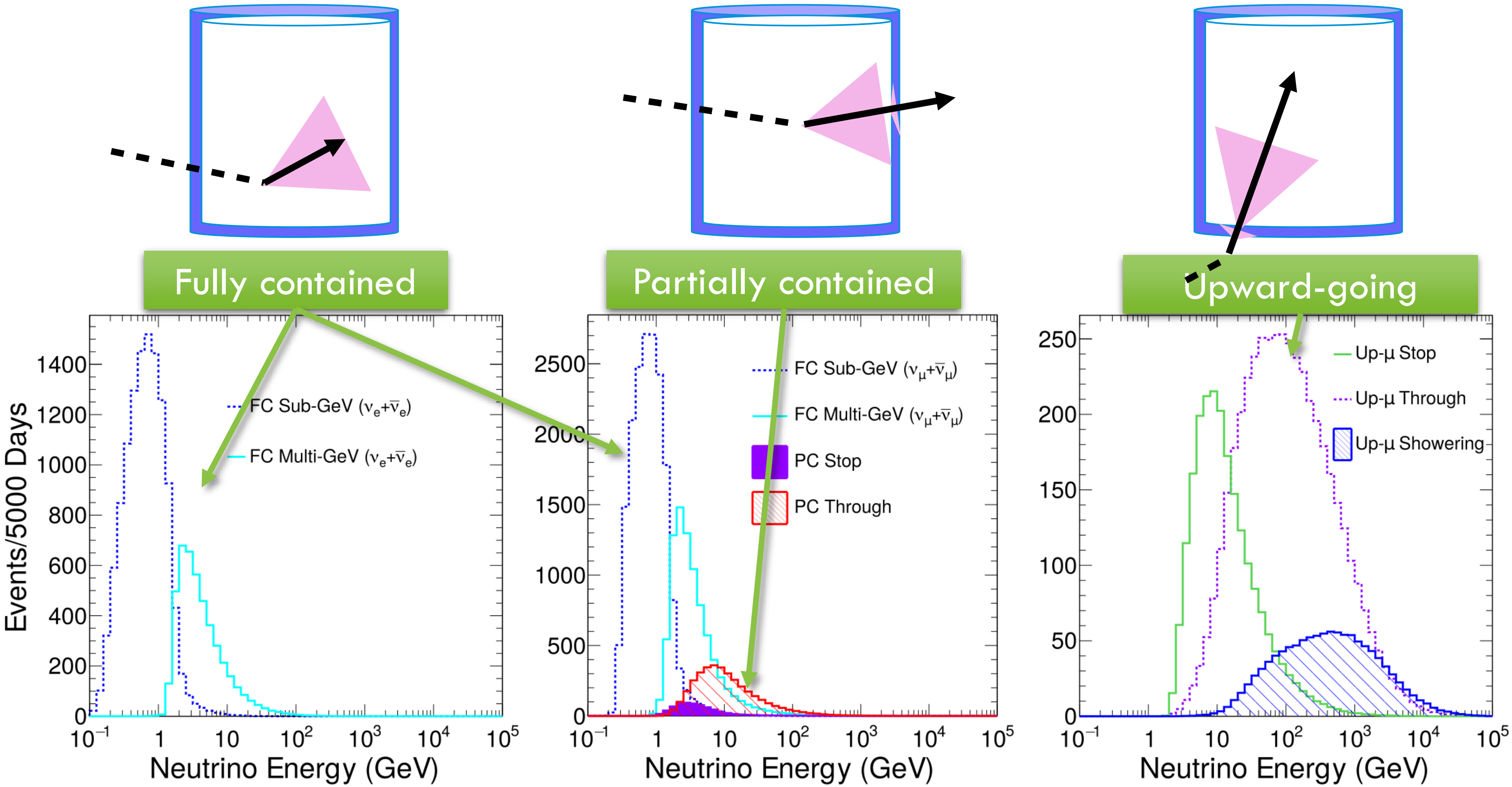
2006

2009

2018

ATMOSPHERIC NEUTRINO TOPOLOGIES

- Super-K events are broadly categorized according to outer detector activity.

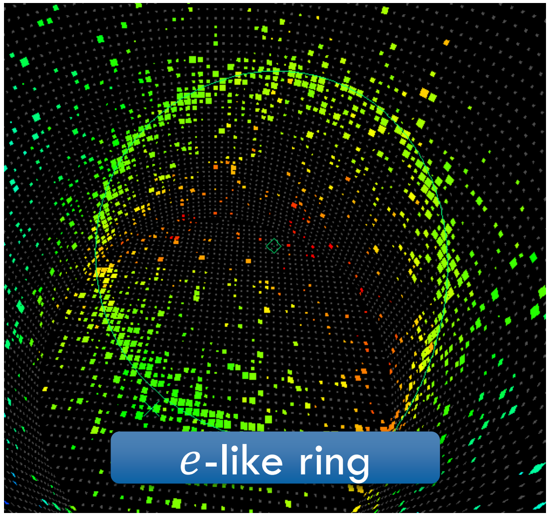


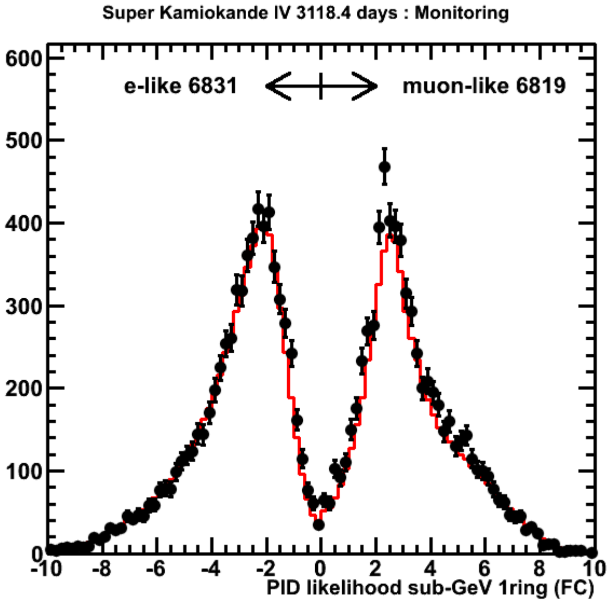
- Partially contained events are classified as stopping in the outer detector or exiting.
- Upward-going events are categorized as stopping in the inner detector, and showering or non-showering through-going.

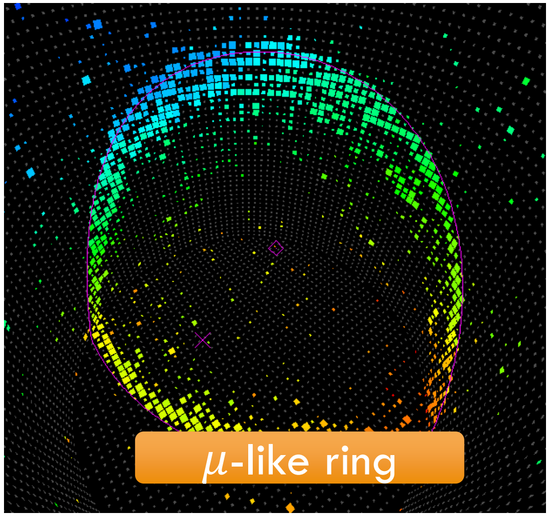
OSCILLATION ANALYSIS

ATMOSPHERIC ANALYSIS SAMPLES

- Fully contained events are required to be in a 22.5 kton fiducial volume 2 m from the detector walls and are further divided into **14** analysis samples according to:
  - Whether their visible energy is in the **sub-GeV** or **multi-GeV** range
  - Whether a **single** or **multiple** Cherenkov **rings** are reconstructed
  - The **particle identification** (e/μ) of the brightest ring
  - Additional classifiers such as number of muon **decay electrons** and likelihood of containing a $\boldsymbol{\pi^0}$

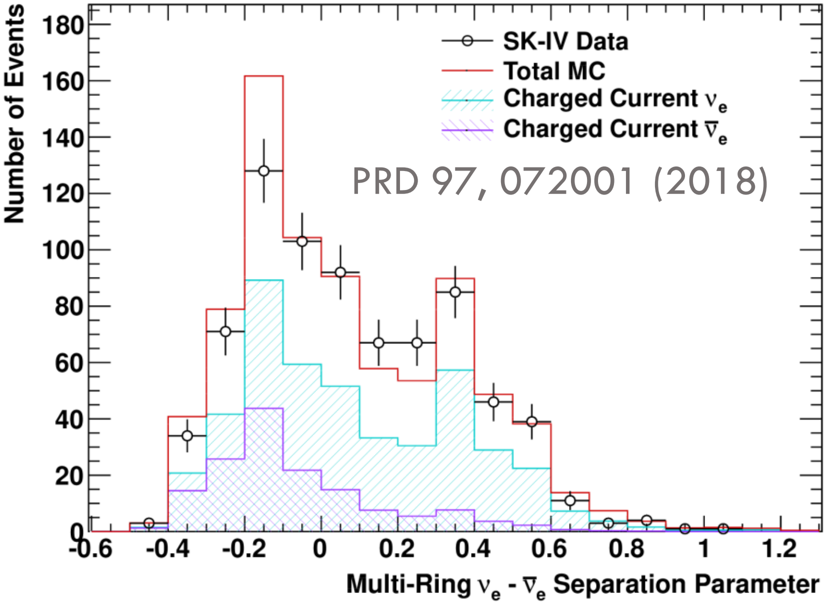






ν_eCC/$\overline{\nu_e}$CC SEPARATION

- Differences between ν_e and $\overline{\nu_e}$ oscillation probabilities provide the most direct handles on the neutrino mass ordering.
- Not possible to accurately classify individual events: improved sensitivity to oscillation parameters by statistically separating into ν_eCC-like and $\overline{\nu_e}$CC-like samples.
- For single-ring events, a $\overline{\nu_e}$-like sample is obtained by requiring that no decay electron exists in the event, with rejected events being assigned to the in ν_e-like sample.
- For multi-ring events, a likelihood is calculated based on number of rings, number of decay electrons and transverse momentum.



PRD 97, 072001 (2018)

	ν_eCC-like	$\overline{\nu_e}$CC-like
Number of rings	More	Fewer
Transverse momentum	Larger	Smaller
Number of decay electrons	More	Fewer
Signal efficiency	52.9%	71%
Signal purity	58.4%	27.5%

OBSERVED DATA AND BEST FIT PREDICTION

PRD 97, 072001 (2018)

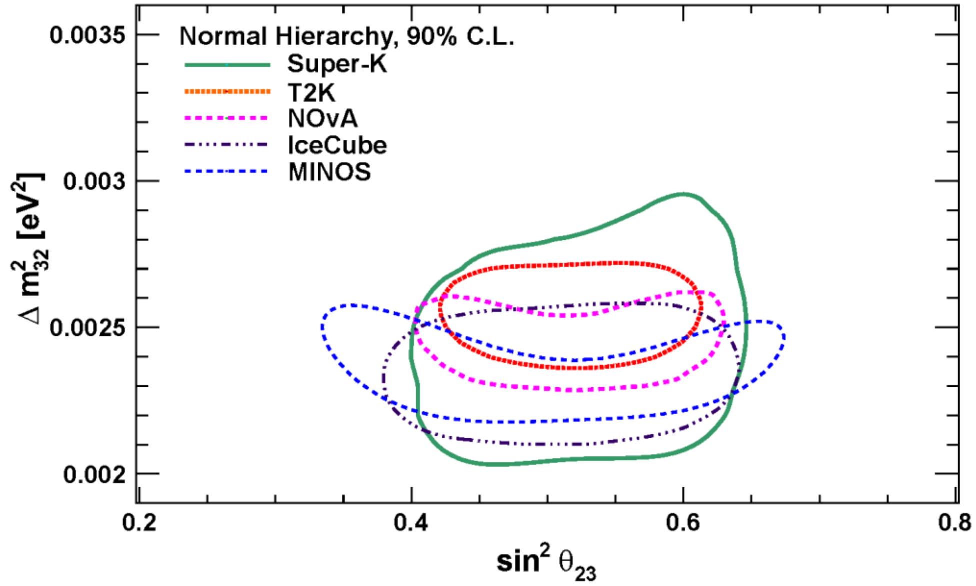
ATMOSPHERIC MIXING PARAMETERS

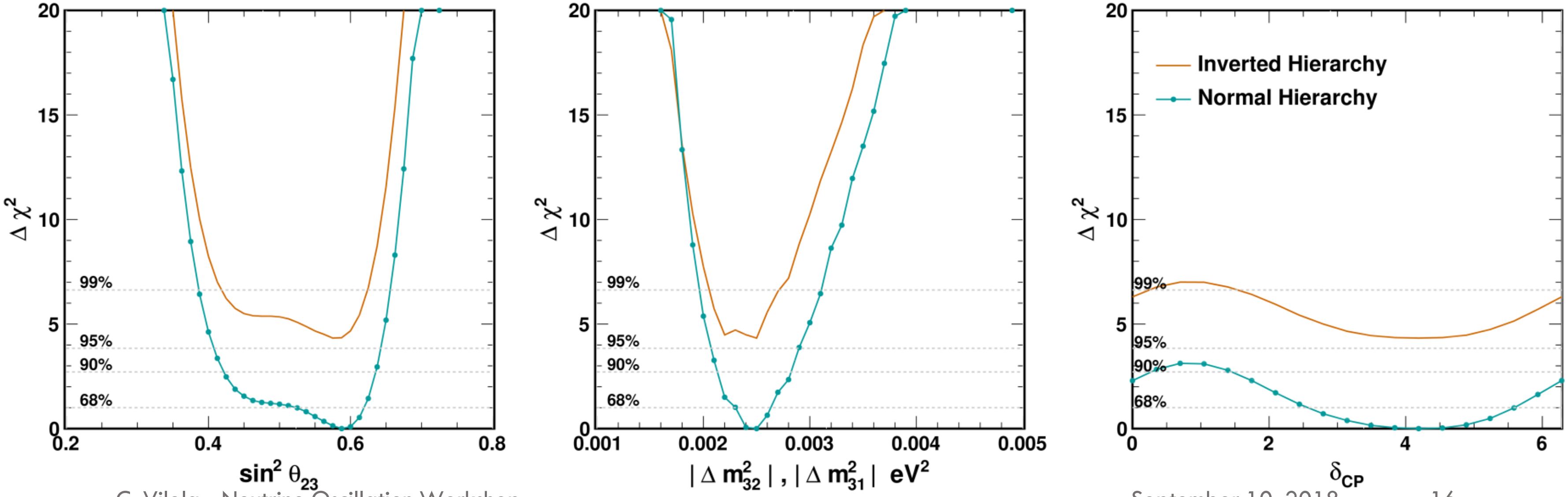
- Weak preference for the **upper θ_{23} octant** and **normal hierarchy**

$$|\Delta m^2_{32}| = 2.50^{+0.13}_{-0.20} \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.588 \pm^{0.031}_{0.067}$$

$$\chi^2_{NH} - \chi^2_{IH} = -4.34$$

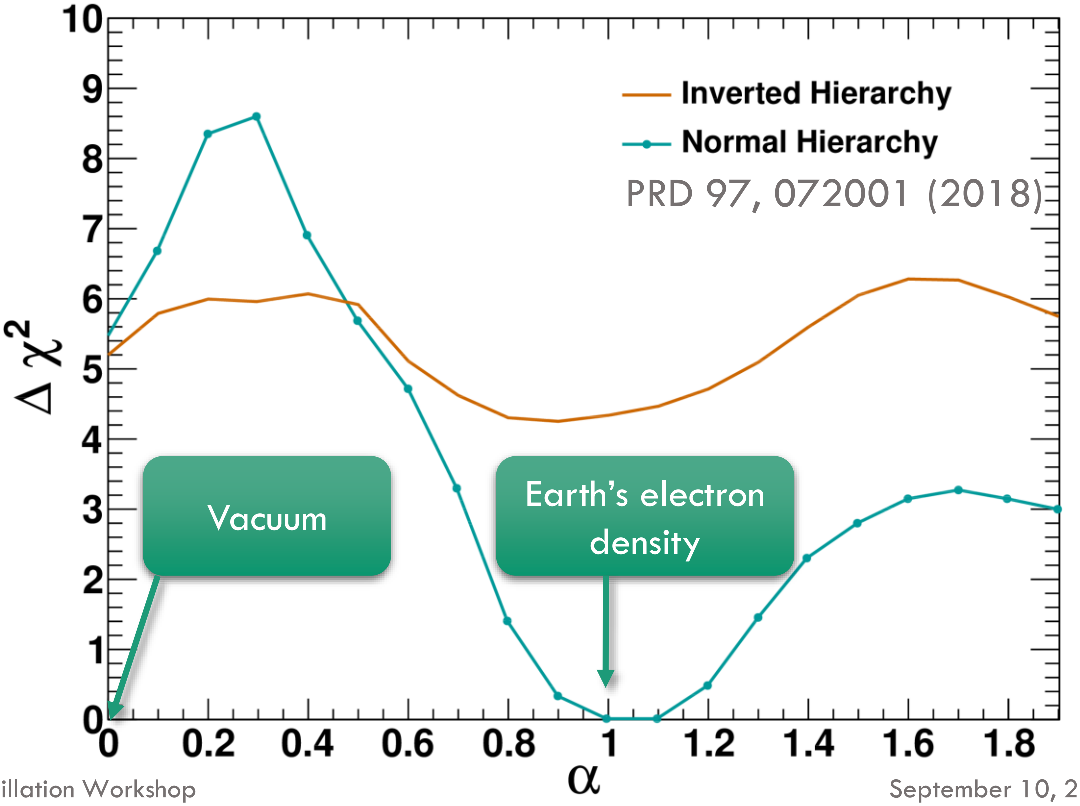




PRD 97, 072001 (2018)

OSCILLATIONS IN MATTER

- Test the consistency of the Super-K data with the matter effect hypothesis
- Modify oscillation probability with parameter α such that:
    - For vacuum oscillations, $\alpha = 0$
    - For matter effects with electron density consistent with standard matter, $\alpha = 1$
- Vacuum oscillations **excluded** at 1.6 σ, data prefers Earth's electron density.



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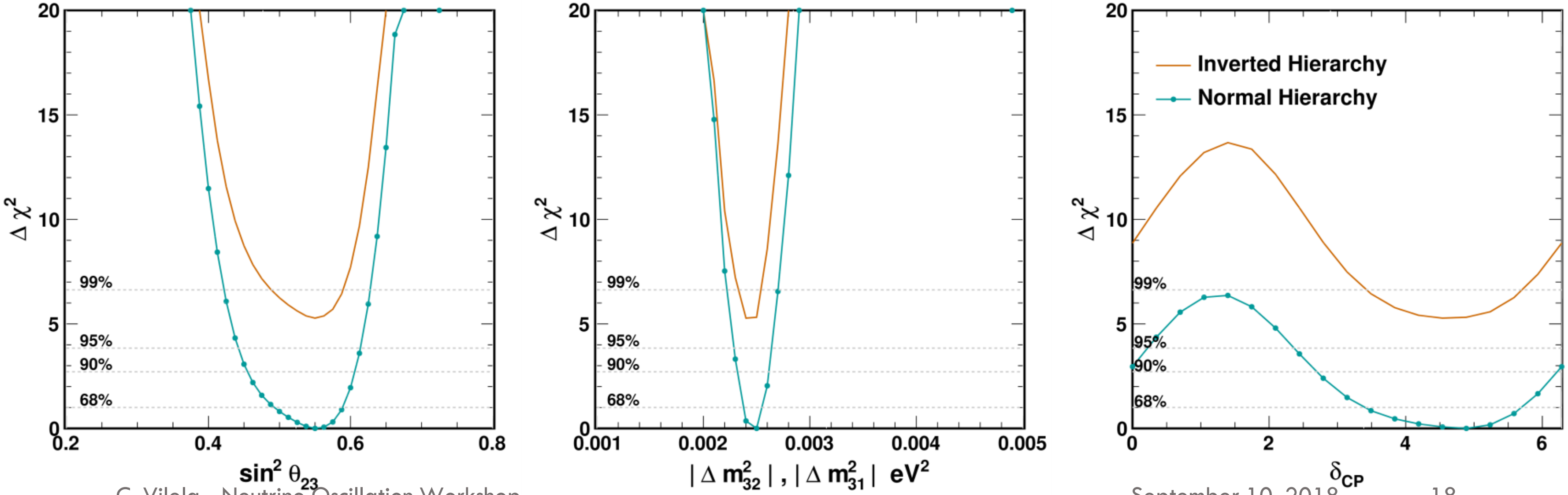
COMBINATION WITH T2K DATA

- T2K and Super-K share cross-section and detector modelling tools and their data sets are complementary
- Add T2K samples to oscillation analysis with data made publicly available by T2K and model using common software tools

	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32,31}\rvert$ [eV^2]	δ_{CP}
Normal	$0.550\,\pm^{0.040}_{0.059}$	$2.50^{+0.05}_{-0.13}\times 10^{-3}$	$4.89\,\pm^{0.84}_{1.45}$
Inverted	$0.550\,\pm^{0.037}_{0.049}$	$2.40^{+0.13}_{-0.06}\times 10^{-3}$	$4.54\,\pm^{0.99}_{0.96}$



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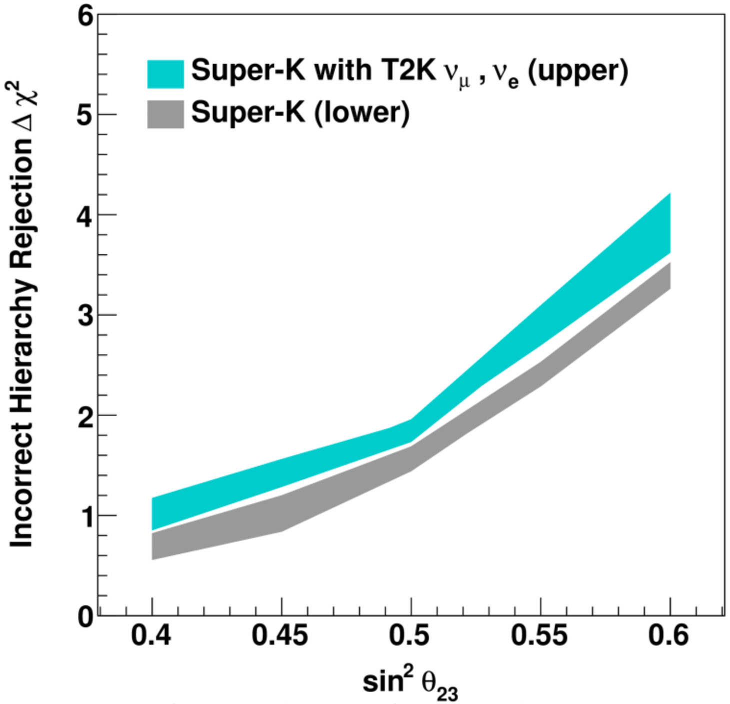
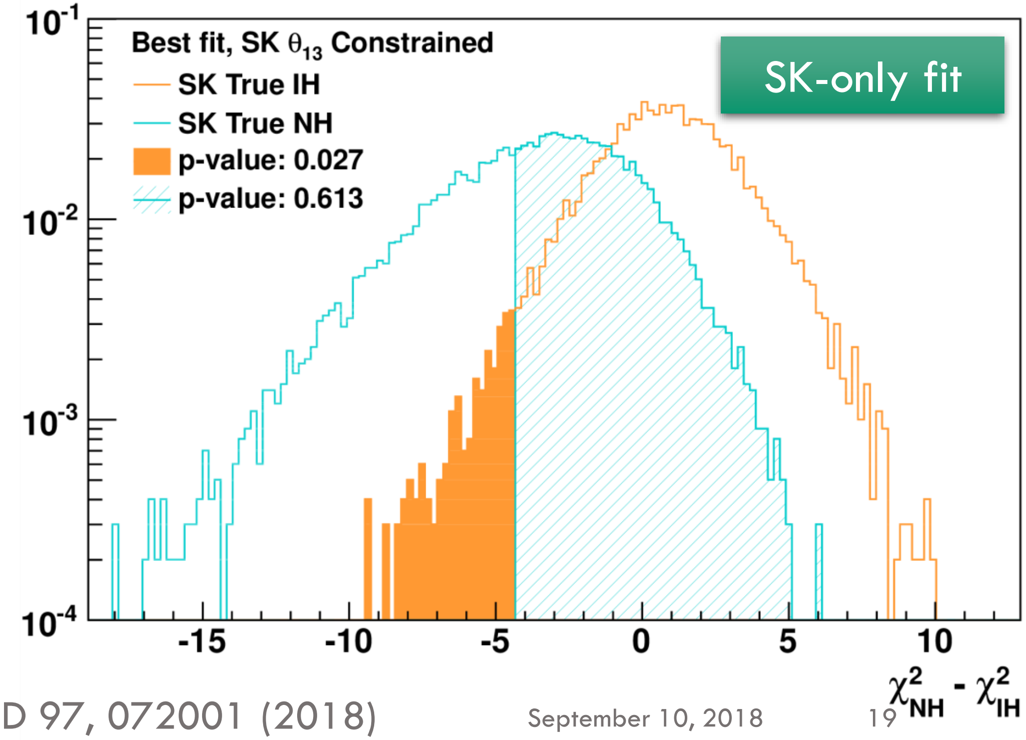
MASS ORDERING CONSTRAINT

- The constraint on the mass ordering is strongly correlated with the value of $\sin^2\theta_{23}$ which benefits from the additional T2K data.
- Calculate p-values for rejecting both hierarchy hypothesis by running toy experiments with statistical fluctuations, Gaussian fluctuations for the systematic uncertainties and oscillation parameters ranging their 90% CL bounds
  - Super-K and θ_{13} constraint: $\mathbf{CL_s}\ (\text{exclude IH}) = \mathbf{81.9\ - 96.7}\%$
  - With T2K model: $\mathbf{CL_s}\ (\text{exclude IH}) = \mathbf{91.9\ - 94.4}\%$



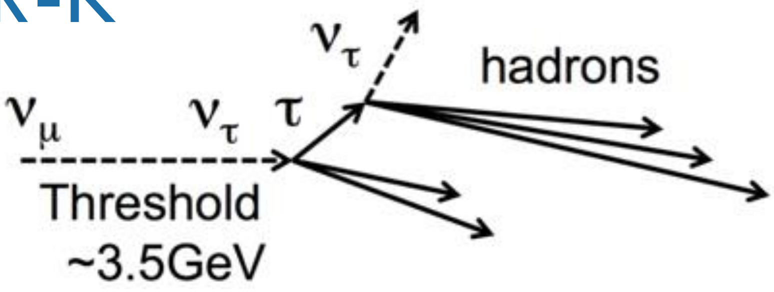


SK-only fit

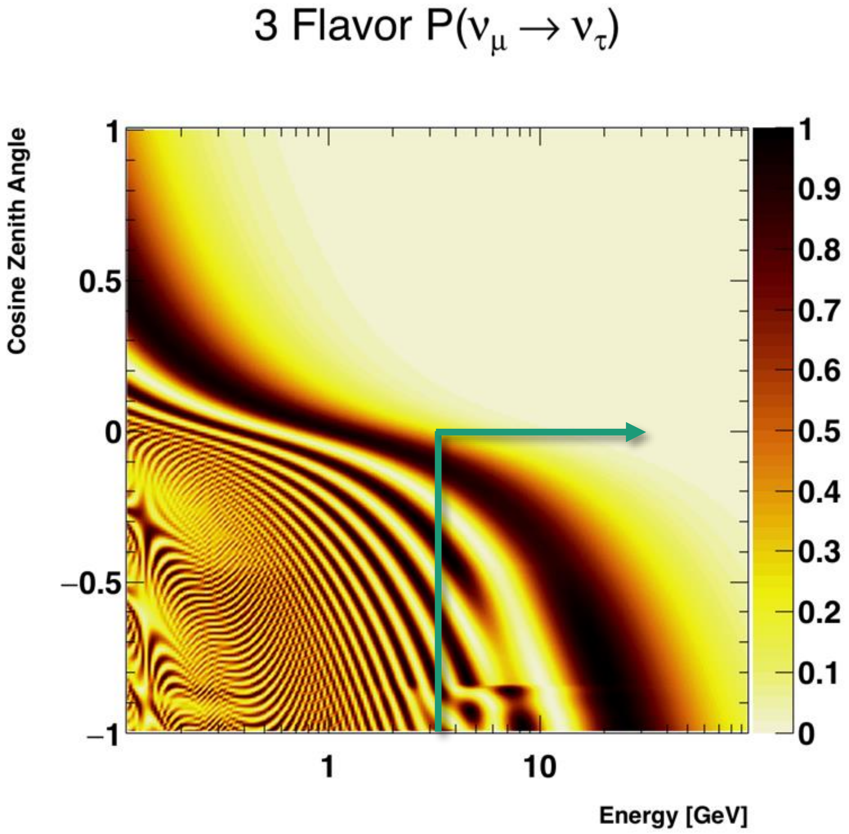
PRD 97, 072001 (2018)

ν_τ APPEARANCE AND CROSS SECTION

ν_τ DETECTION AT SUPER-K



- The primary ν_τ flux is negligible, any ν_τ's seen will have oscillated from the ν_μ flux.
  - Must be upward-going.
- Threshold for τ production is very high, rare at Super-K.
- Hadronic τ decays give complex multi-ring event topologies.
- Difficult to distinguish from DIS backgrounds.
- Train artificial neural network to select ν_τCC events.

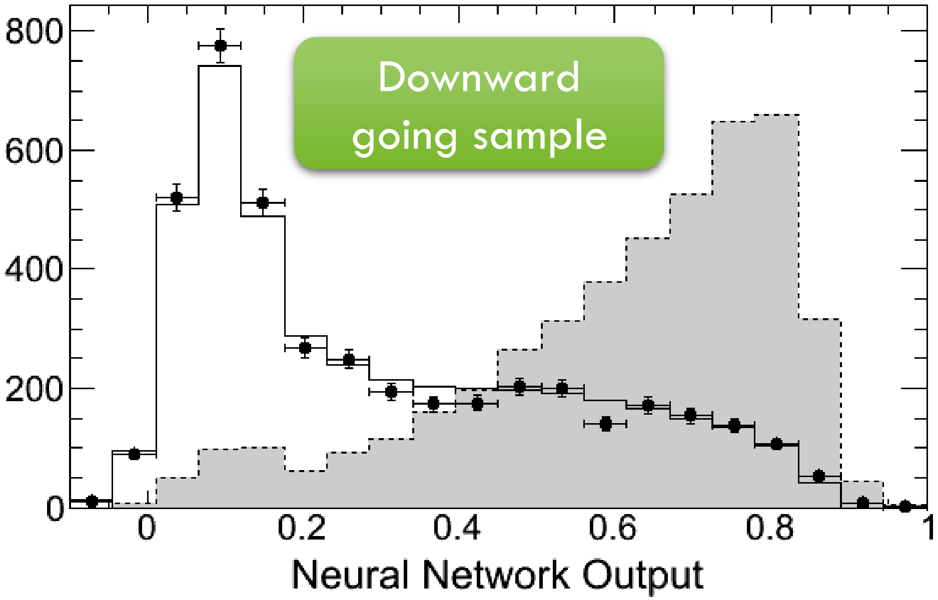


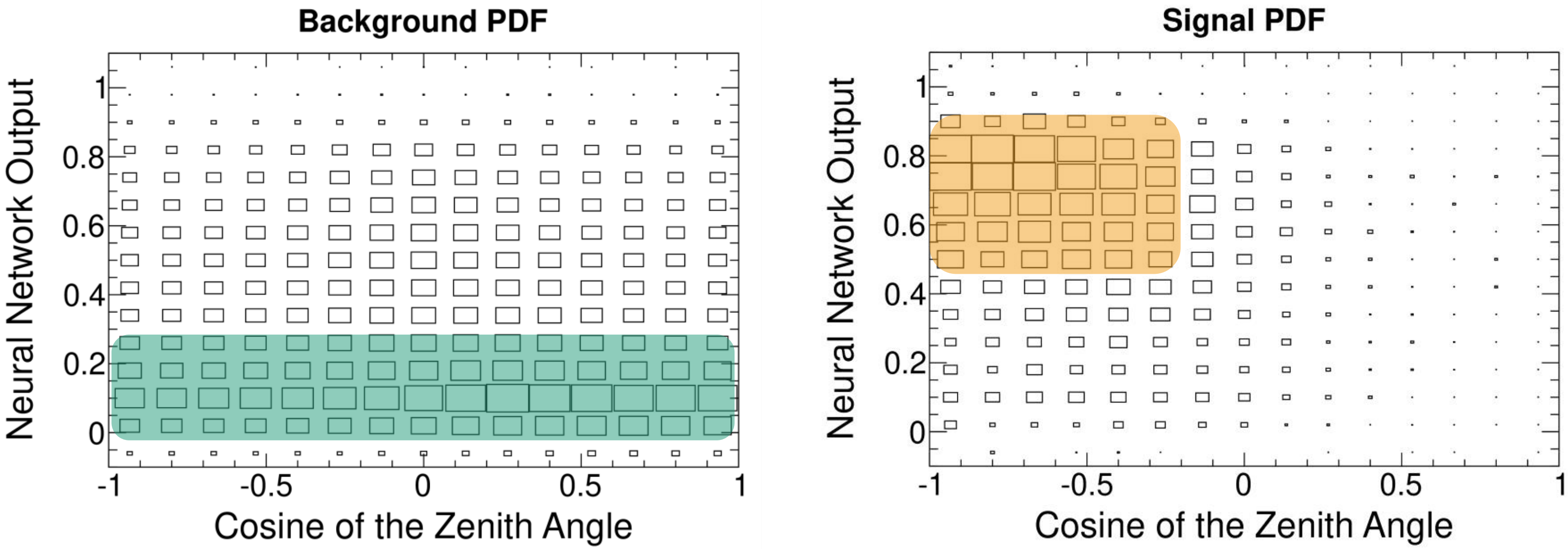
ν_τ APPEARANCE

- Fit 2D pdfs to the data:

$$Data = PDF_{BG} + \alpha PDF_{\nu_\tau} + \Sigma \epsilon_i PDF_i$$

- α is a normalization constant for the signal and $\epsilon_i PDF_i$ take into account systematic variations.



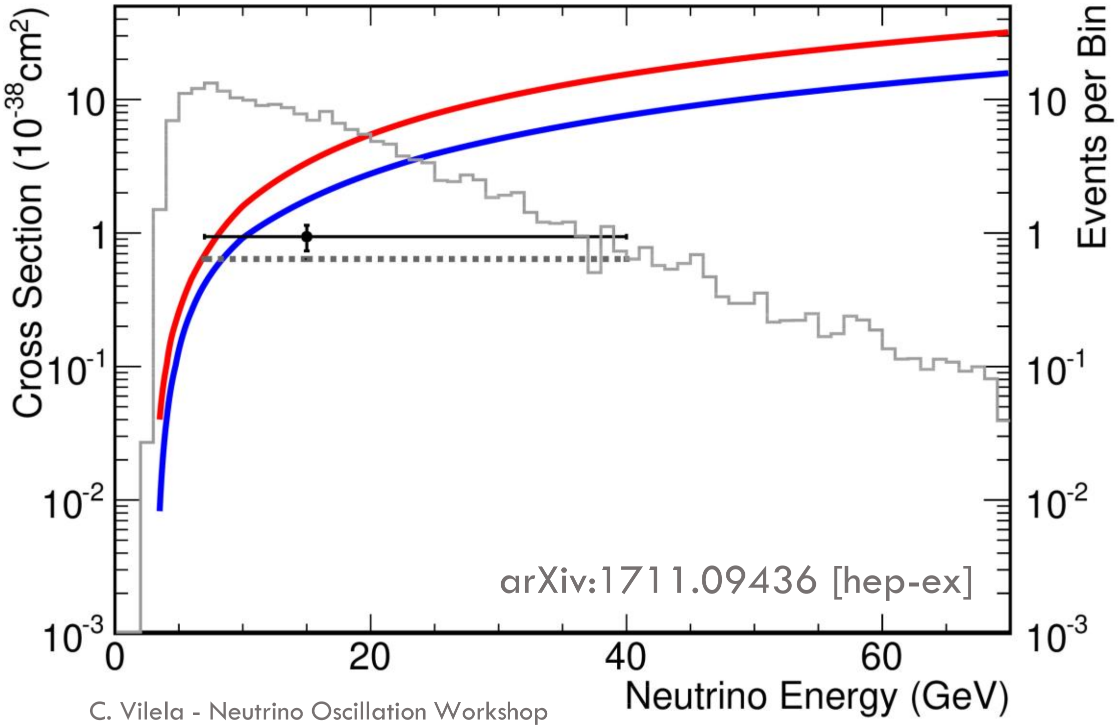


arXiv:1711.09436 [hep-ex]

ν_τ APPEARANCE AND CROSS SECTION

- Exclude $\alpha = 0$ at **4.6σ**
  - Sensitivity with $\alpha = 1$ is 3.3σ
- Measured cross section consistent with prediction.
- Flux averaged cross section between 3.5 and 70 GeV:

$$\sigma = (0.94 \pm 0.20) \times 10^{-38}\text{cm}^2$$



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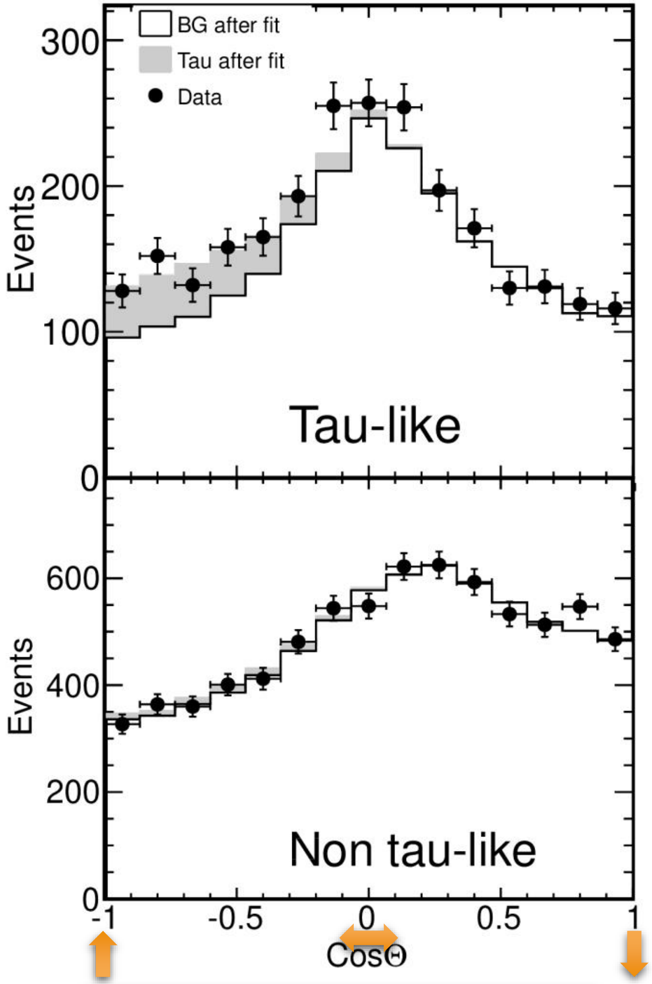
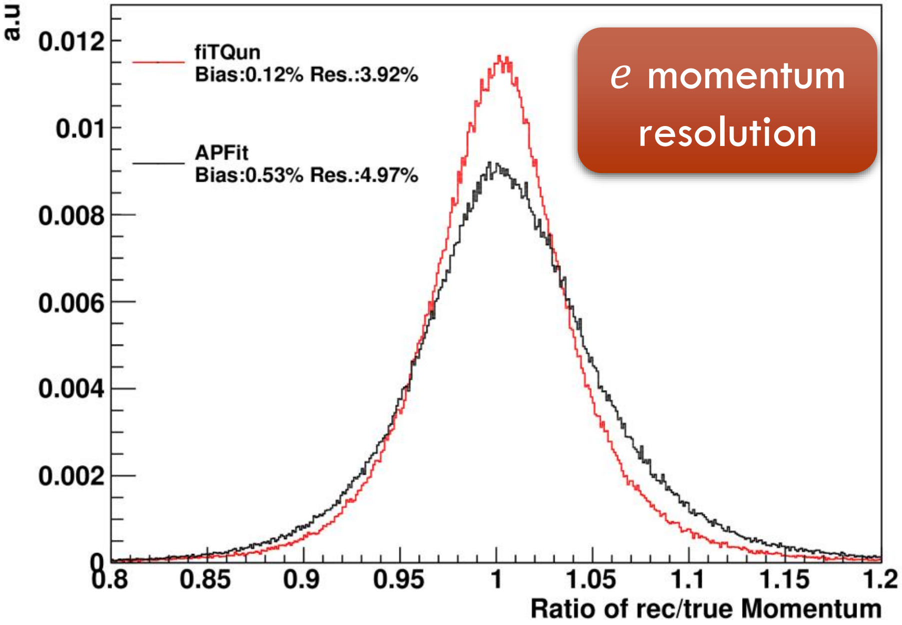


0.33 Mton years
338.1 ± 72.7 ν_τ events

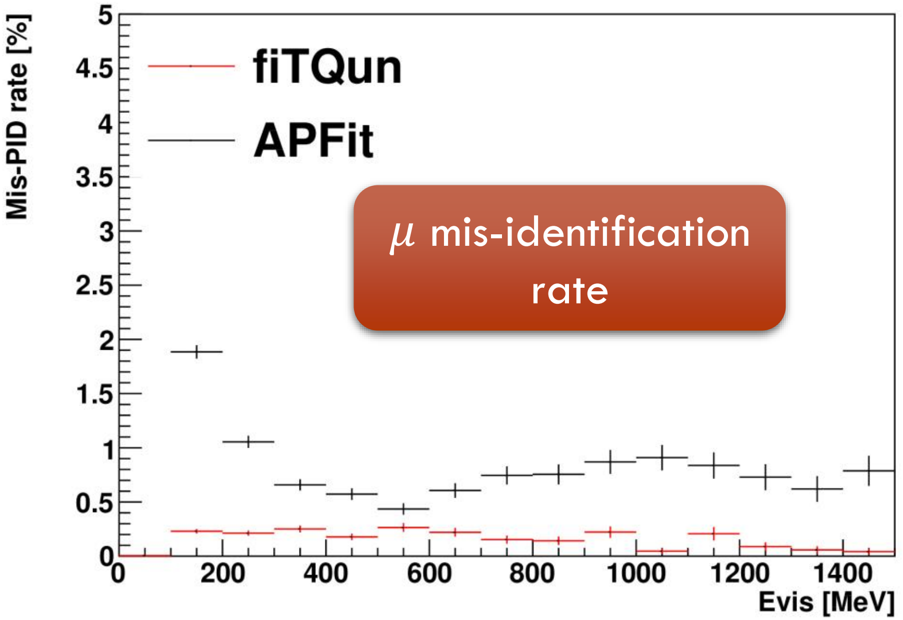
FUTURE IMPROVEMENTS

NEW RECONSTRUCTION ALGORITHM

- A new reconstruction algorithm for Super-K, previously used in T2K analyses provides improvements across the board.
  - e/μ, e/π^0 and μ/π^+ separation
  - Ring identification
  - Vertex, momentum and direction resolutions
- Maximum likelihood estimator making full use of the charge and hit time information in the event, including non-hit PMTs



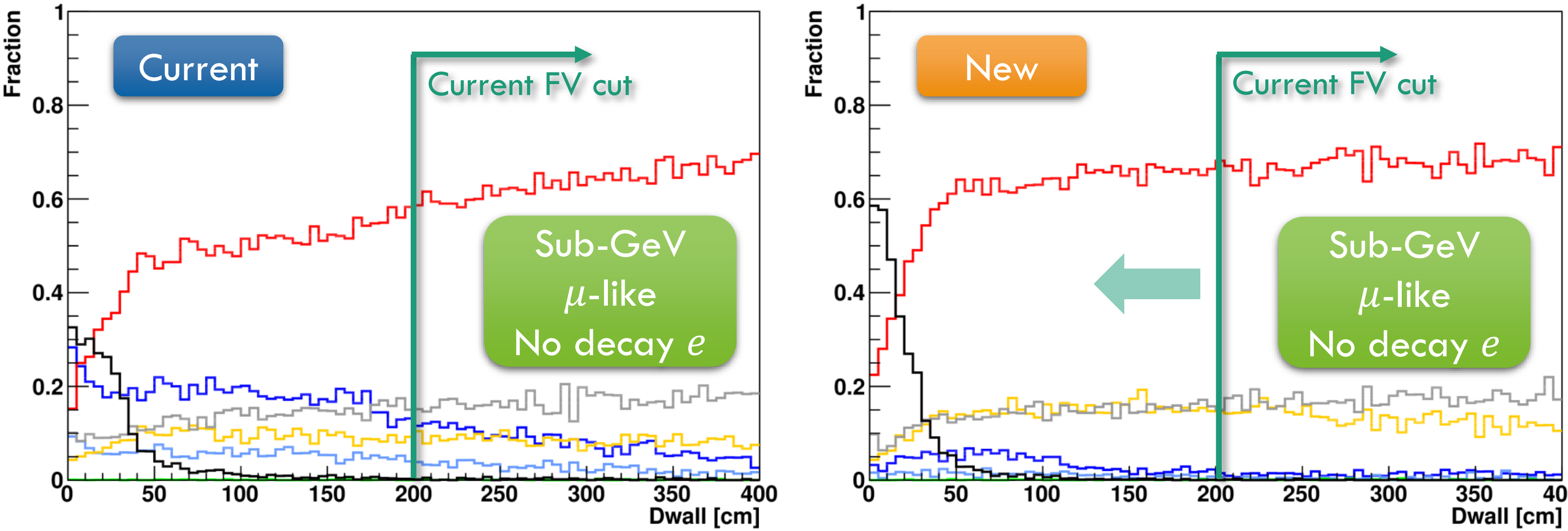
e momentum resolution



μ mis-identification rate

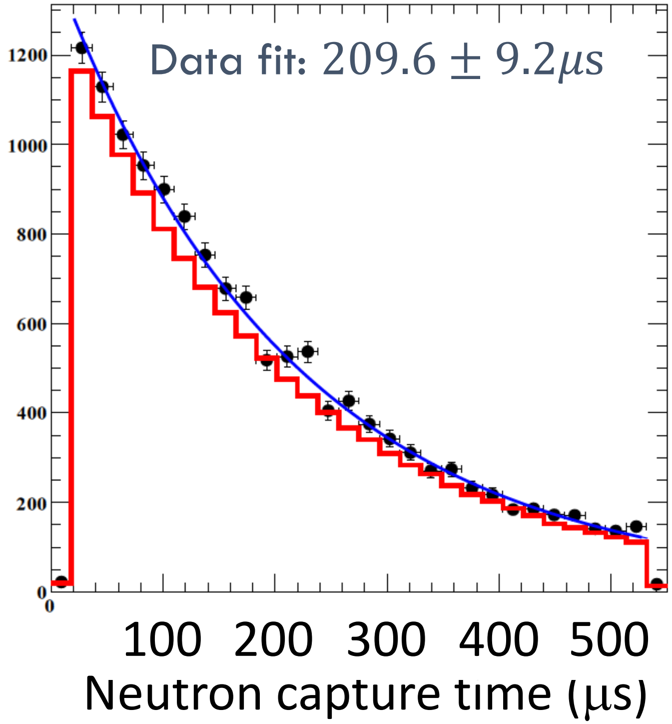
FIDUCIAL VOLUME EXPANSION

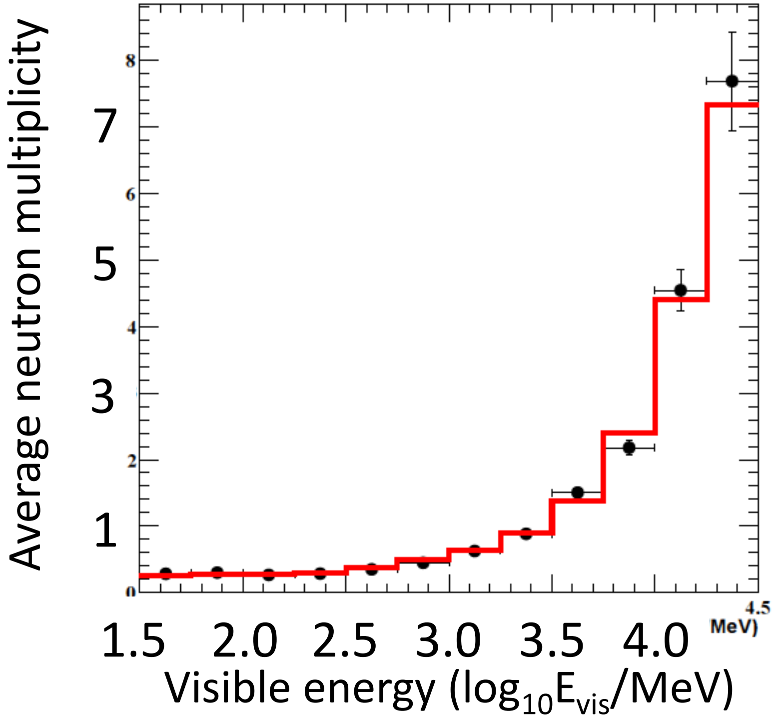
- Current Super-K analyses require reconstructed vertices to be at least **2 m** away from the closest wall
  - An additional ≈ 10 kton of water exists in the unused region
  - Some of it might be usable, in particular with the capabilities of the new reconstruction algorithm
  - Latest T2K oscillation results featured 30% effective statistical gains from the new reconstruction and an expanded fiducial volume



NEUTRON TAGGING

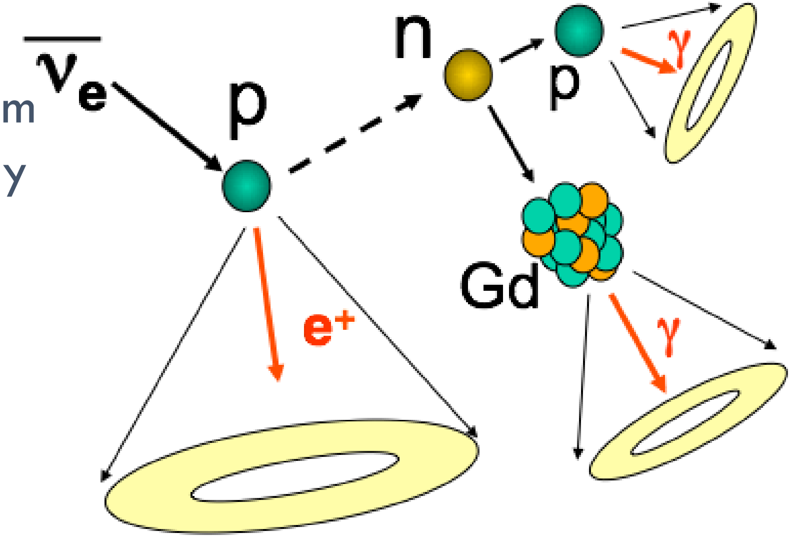
- Neutron captures on hydrogen are detected at Super-K with around 20% efficiency.
- Counting neutrons emitted in neutrino interactions can provide an additional handle on neutrino energy and $\nu/\bar{\nu}$ separation





GADOLINIUM UPGRADE

- Loading the Super-K water with gadolinium will increase the neutron tagging efficiency to 90%
- Detector is currently undergoing refurbishment work necessary for gadolinium loading



SUMMARY

- The analysis of 5326 days of Super-K atmospheric data significantly constrains neutrino oscillation parameters, especially when combined with publicly available T2K data.

	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32,31}\rvert\ [\mathrm{eV}^2]$	$\boldsymbol{\delta_{CP}}$
Normal	$0.550\ \pm^{0.040}_{0.059}$	$2.50^{+0.05}_{-0.13}\times 10^{-3}$	$4.89\ \pm^{0.84}_{1.45}$
Inverted	$0.550\ \pm^{0.037}_{0.049}$	$2.40^{+0.13}_{-0.06}\times 10^{-3}$	$4.54\ \pm^{0.99}_{0.96}$

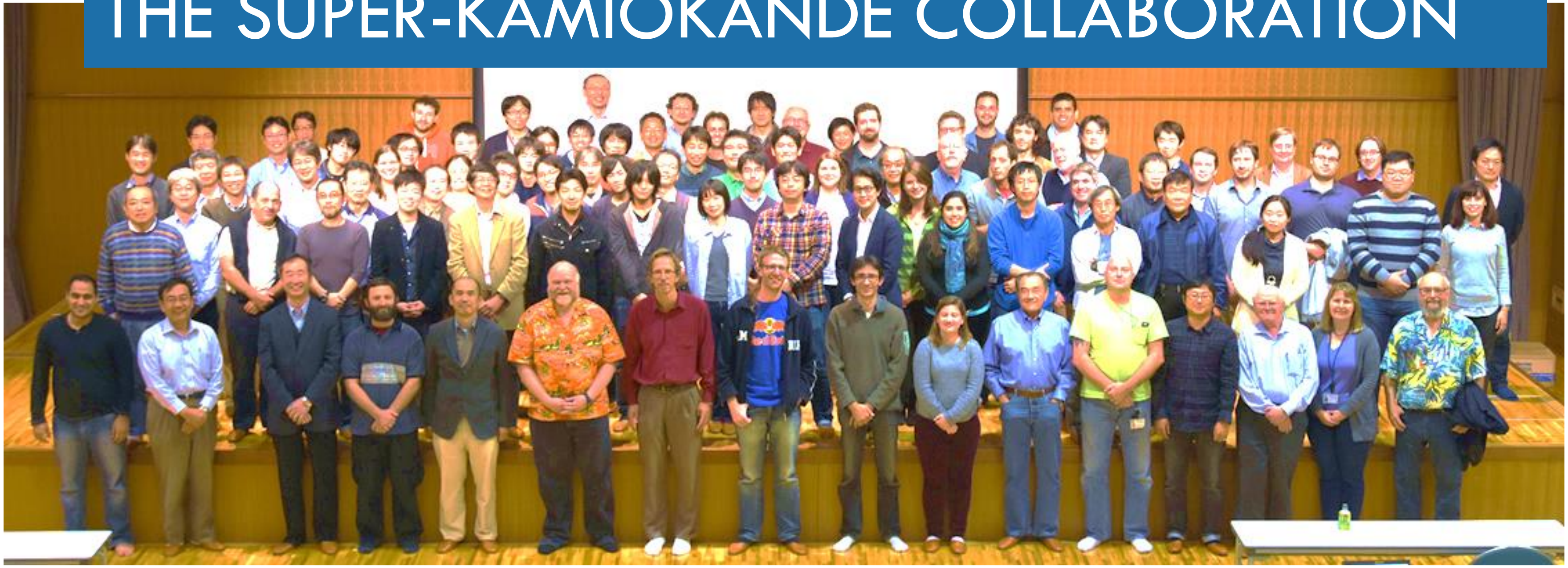
- Mass ordering constraints:
  - Super-K and θ_{13} constraint: $\mathbf{CL}_s$ (exclude IH) $= \mathbf{81.9\ -96.7}\%$
  - With T2K model: $\mathbf{CL}_s$ (exclude IH) $= \mathbf{91.9\ -94.4}\%$

- Super-K observes ν_τ appearance with a significance of 4.6σ and measures the ν_τ cross section to be in agreement with model predictions.

$$\sigma = (0.94 \pm 0.20)\times 10^{-38}\mathrm{cm}^2$$

- Significant analysis improvements are foreseen in the near future, with a new reconstruction algorithm, an expanded fiducial volume and neutron tagging capability.

THE SUPER-KAMIOKANDE COLLABORATION



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RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
University of British Columbia, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
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Imperial College London, UK
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Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
The University of Winnipeg, Canada
Yokohama National University, Japan

~165 collaborators from
45 institutes and 9 countries

SUPPLEMENTARY

DATASET AND OSCILLATION ANALYSIS

- Use **5326** days of all Super-K eras, corresponding to a total exposure of **328** kton years
  - Data taken in SK-IV corresponds to 2519 days
- Events are binned in lepton **momentum**, visible **energy** and/or **zenith** angle, depending on the sample
- A grid in the oscillation parameter space is scanned, with the χ^2 minimized with respect to the nuisance parameters at each point

$$\chi^2 = 2\sum_n \left(E_n - O_\mathrm{n} + O_n \ln\frac{O_n}{E_n}\right) + \sum_i \left(\frac{\epsilon_i}{\sigma_i}\right)^2$$

Poisson term and Gaussian systematic parameter constraints

$$E_n = \sum_j E_{n,j}\left(1 + \sum_i f^i_{n,j}\epsilon_i\right)$$

Expectation with systematic variations

$$O_n = \sum_j O_{n,j}$$

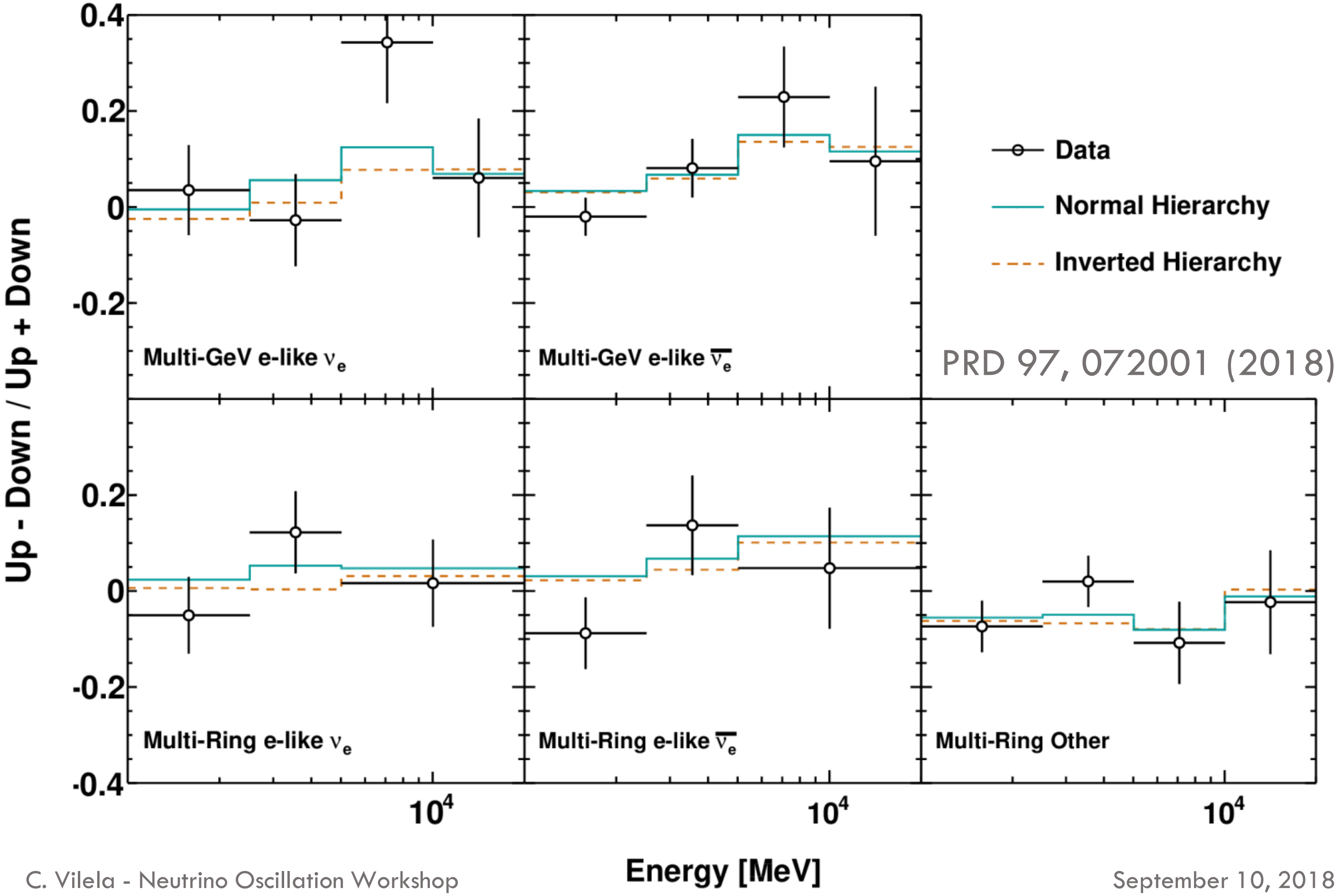
Observed data over all Super-K eras

j: Super-K era
n: Analysis bin
i: Systematic uncertainty parameter

External constraints:
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\mathrm{ev}^2$
$\sin^2\theta_{12} = 0.304 \pm 0.014$
$\sin^2\theta_{13} = 0.0219 \pm 0.012$

MASS ORDERING CONSTRAINT

- Up/Down asymmetry using upward-going ($\cos\theta < -0.4$) and downward going ($\cos\theta > 0.4$) fully contained multi-GeV samples.
  - Weak mass ordering preference arises from small fluctuations in the few GeV range.



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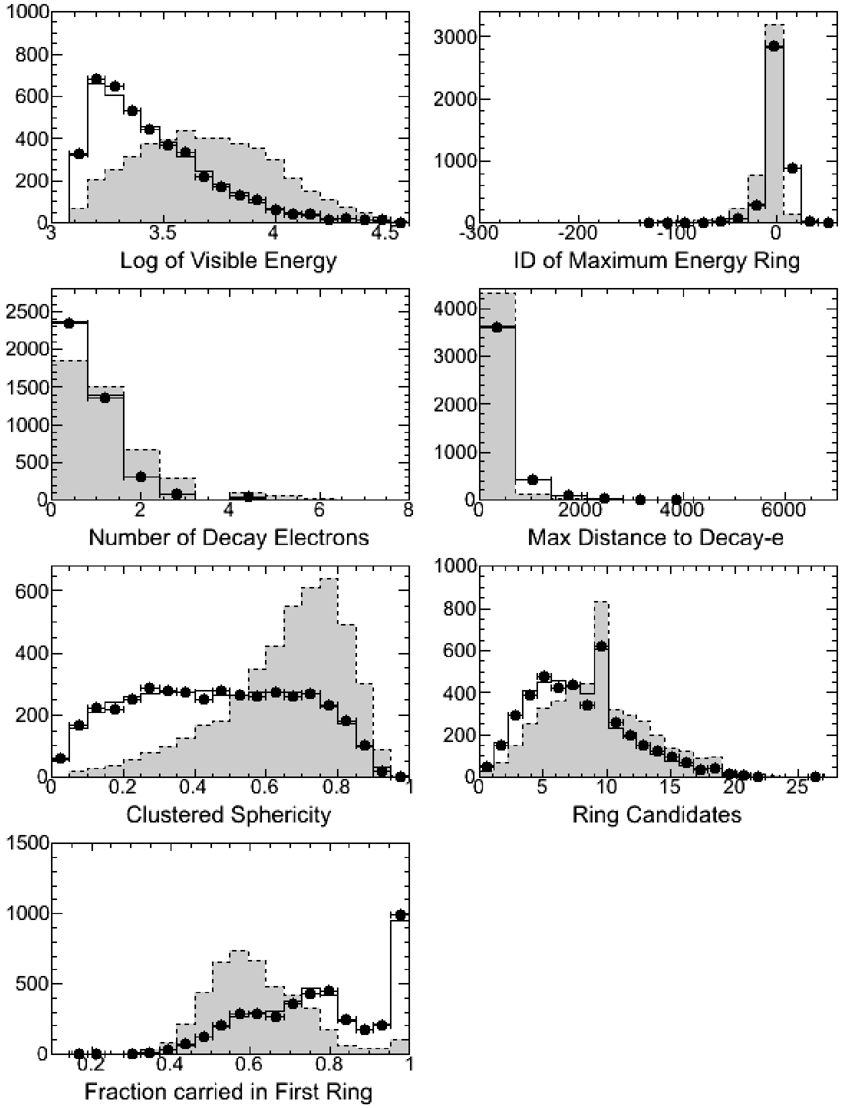
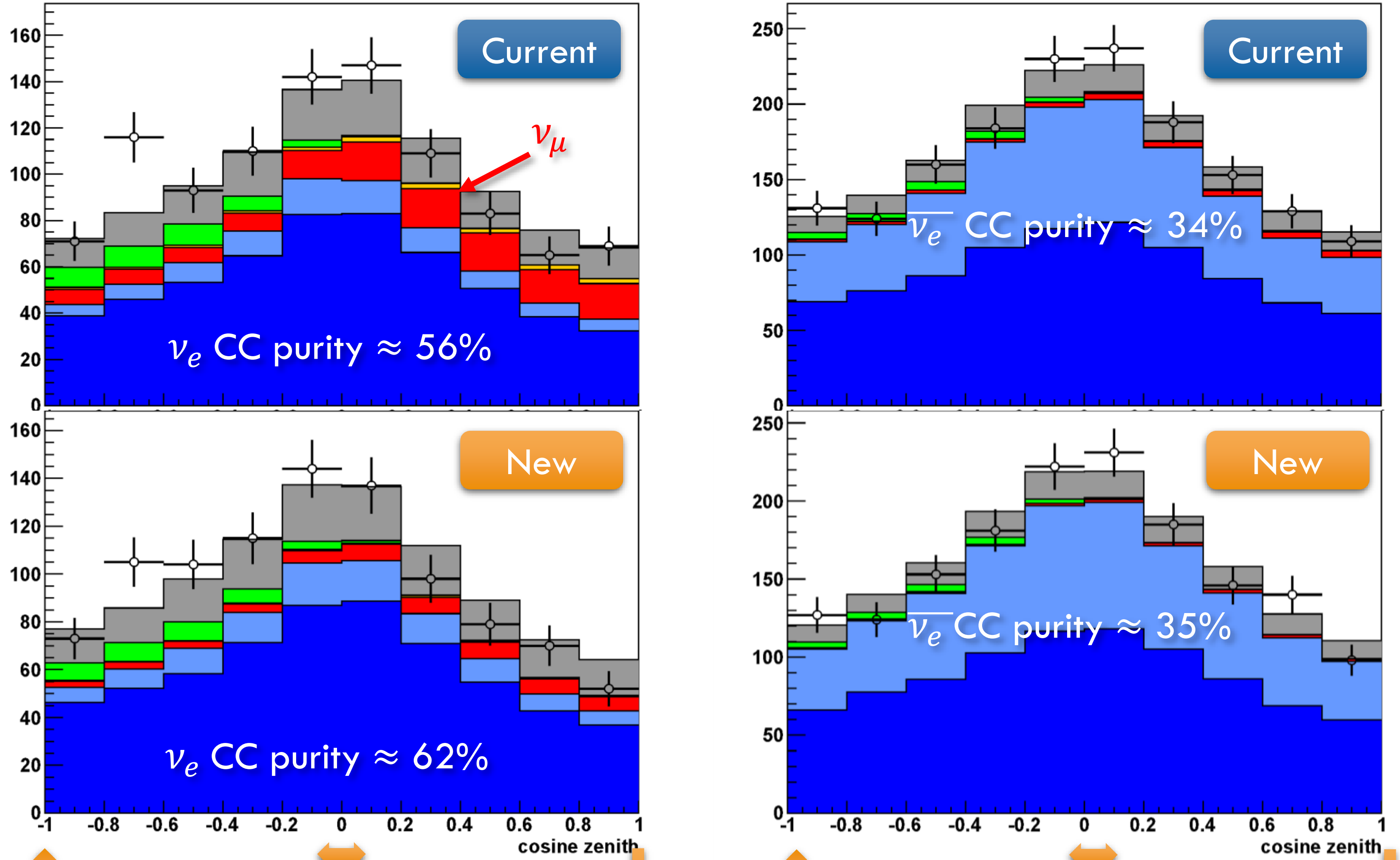
ν_τ NEURAL NETWORK INPUTS



NEW RECONSTRUCTION ALGORITHM

- Multi-ring ν_eCC and $\overline{\nu_e}$CC samples



ν_e CC purity ≈ 56%

$\overline{\nu_e}$ CC purity ≈ 34%

ν_e CC purity ≈ 62%

$\overline{\nu_e}$ CC purity ≈ 35%