Super-Kamiokande: Neutrino Results & Gadolinium Status

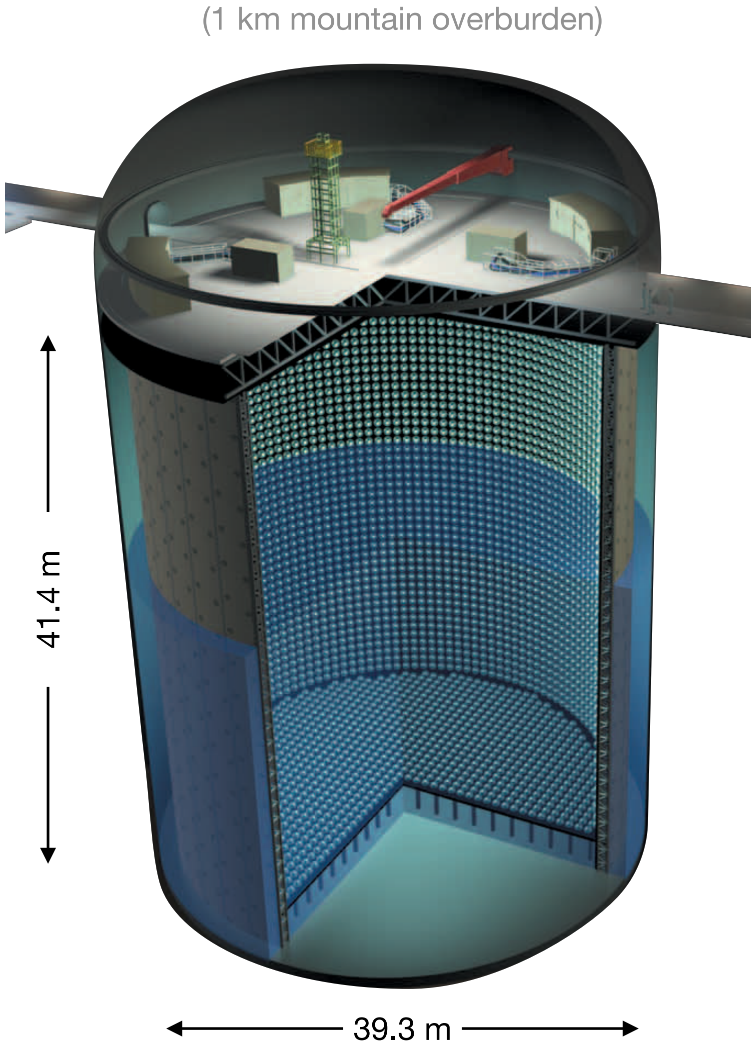
Thomas Wester, Boston University
On behalf of the Super-Kamiokande Collaboration
NNN2023, Procida

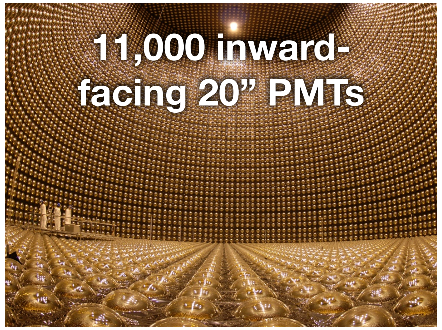
Outline

- Super-Kamiokande experiment
- Neutrino analyses
    - Atmospheric neutrino oscillations
    - Solar neutrinos
- SK-Gd
    - Gadolinium loading status
    - Diffuse Supernova Neutrino Background (DSNB) Search

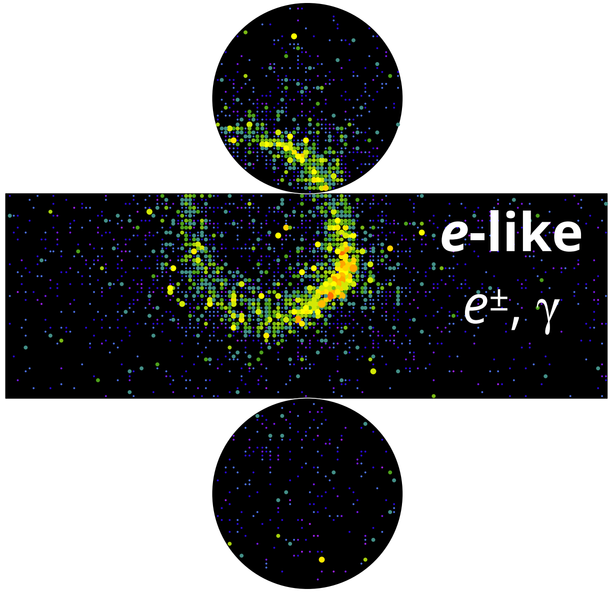
Super-K nucleon decay results:
See talk by S. Mine,
poster by J. Seo

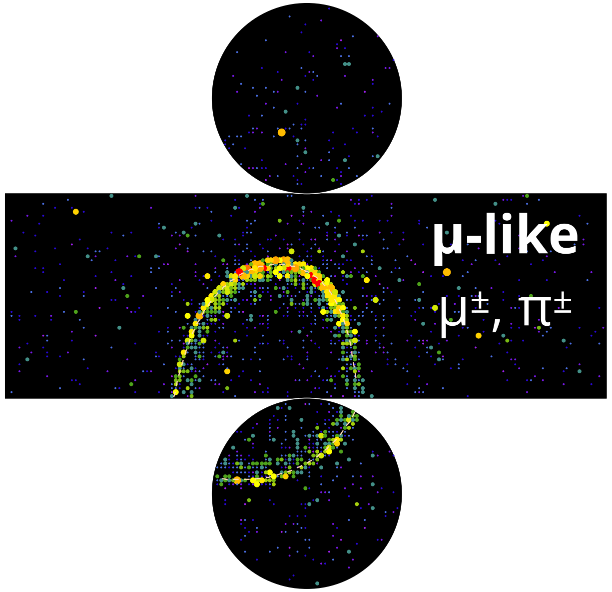
Super-K Experiment





Cherenkov rings for reconstructing particle type, direction, momentum



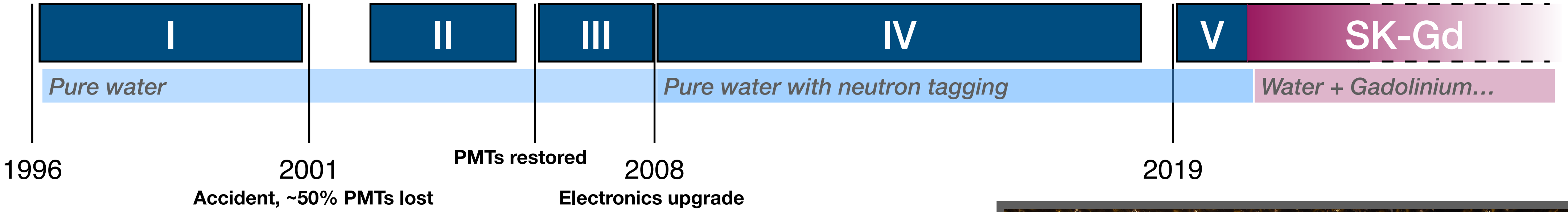


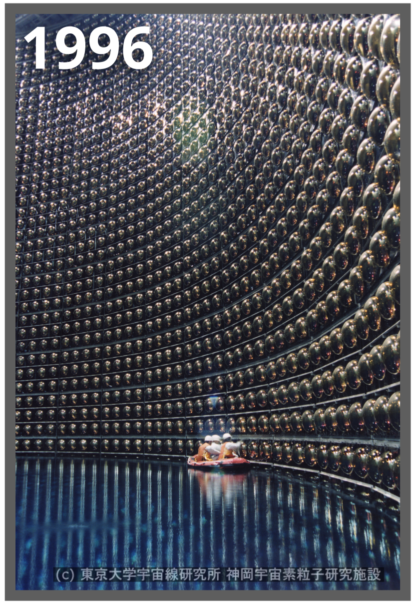
- Can’t distinguish charge, no event-by-event $\nu/\bar{\nu}$ separation

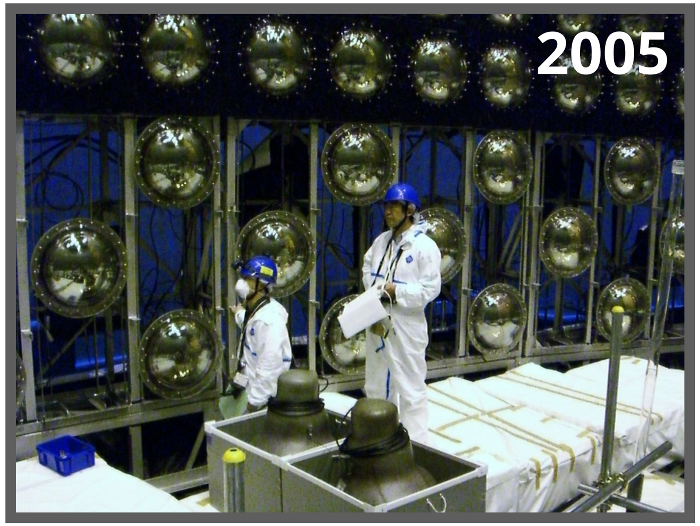
\+ **Hit clusters** from decay electrons & neutron captures for statistical separation of $\nu/\bar{\nu}$

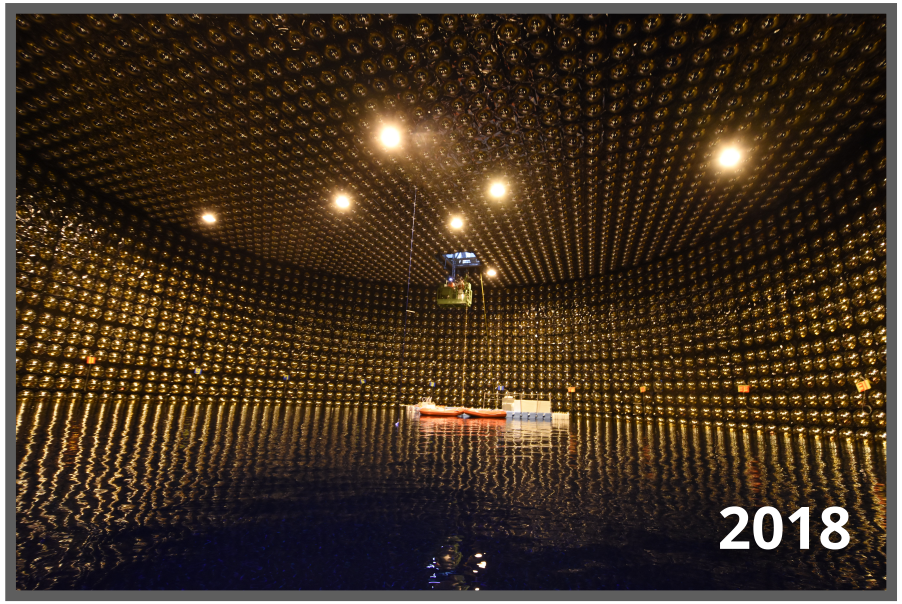
Super-K Timeline

SK I – SK V: Pure water phases
SK-Gd: Gadolinium added in 2020





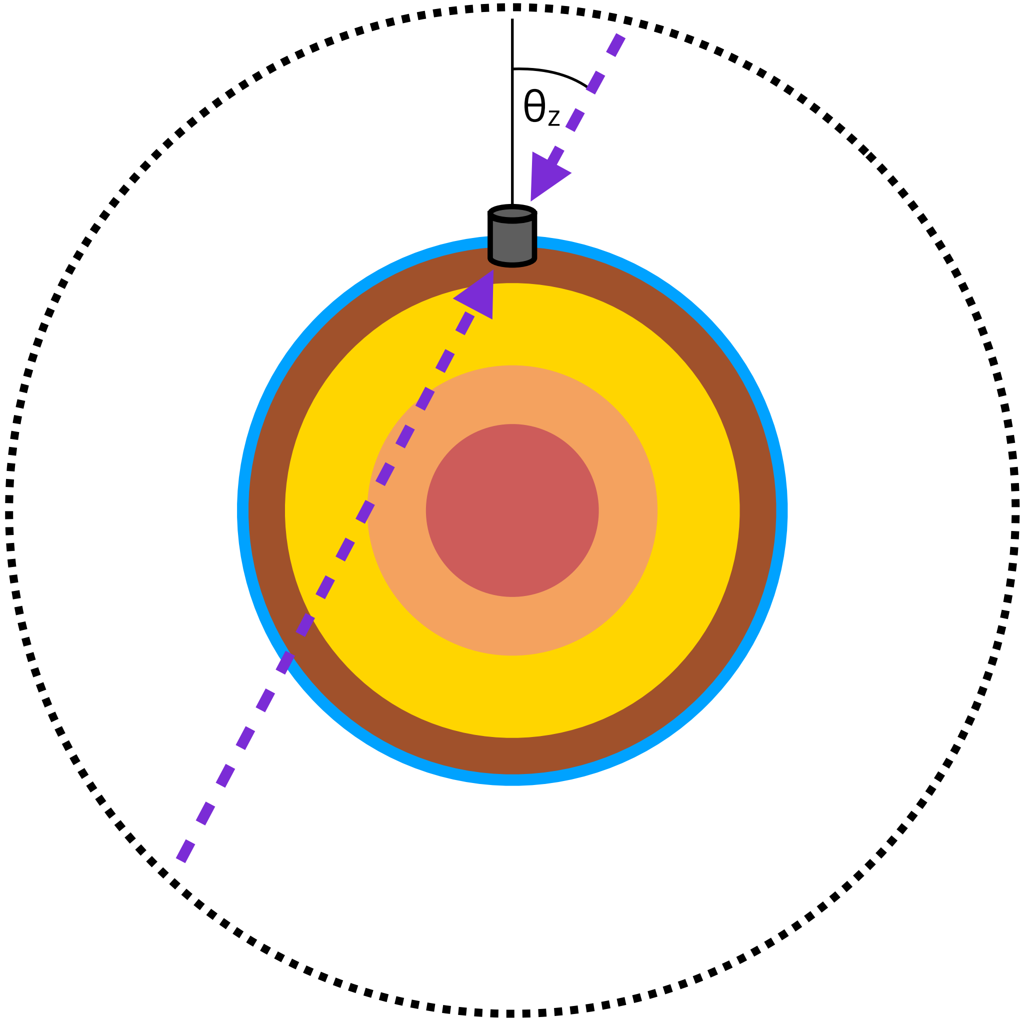




Atmospheric Neutrinos

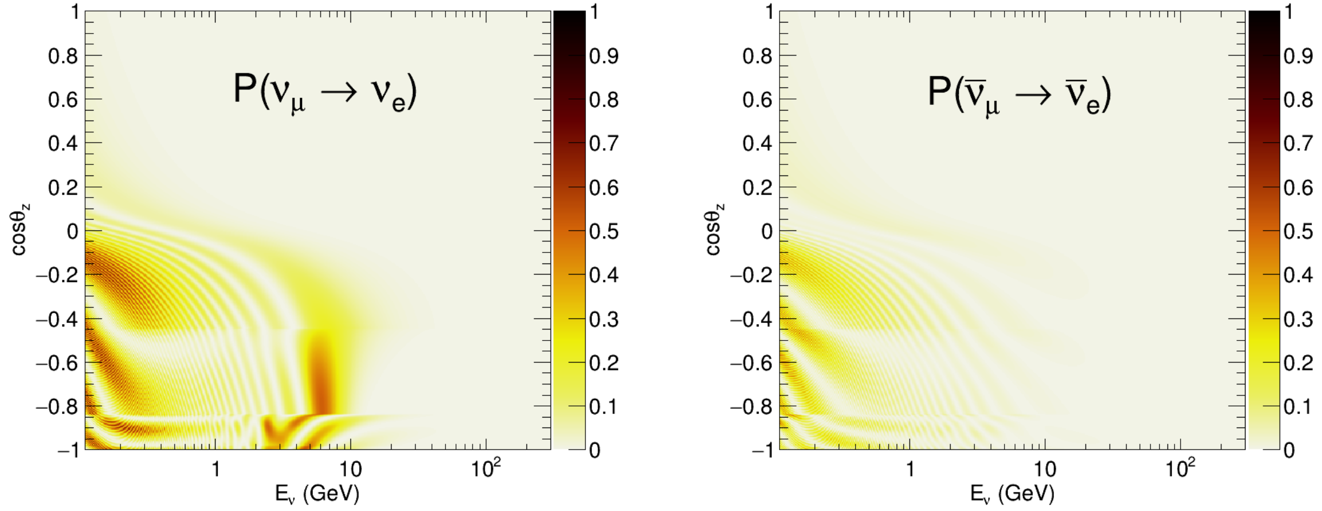
Atmospheric Neutrinos

- Baselines ~ 10–10,000 km,
  Energies ~ 100 MeV–100 TeV
- Atmospheric flux contains ν_μ, ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$
- Earth matter effect present for upward-going neutrinos
- Probe of neutrino oscillations:
  - ν_μ disappearance → $\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$
  - ν_e appearance → study δ_{CP}, θ_{23} octant, **unknown neutrino mass ordering**

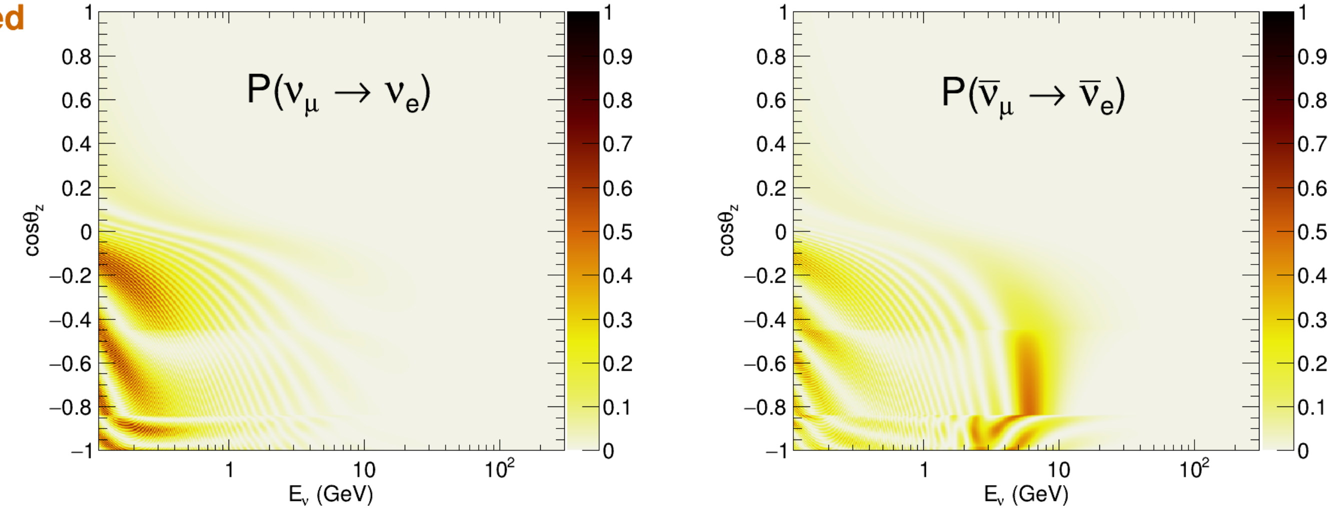


Mass Ordering in Atmospheric Neutrinos

Normal



Inverted



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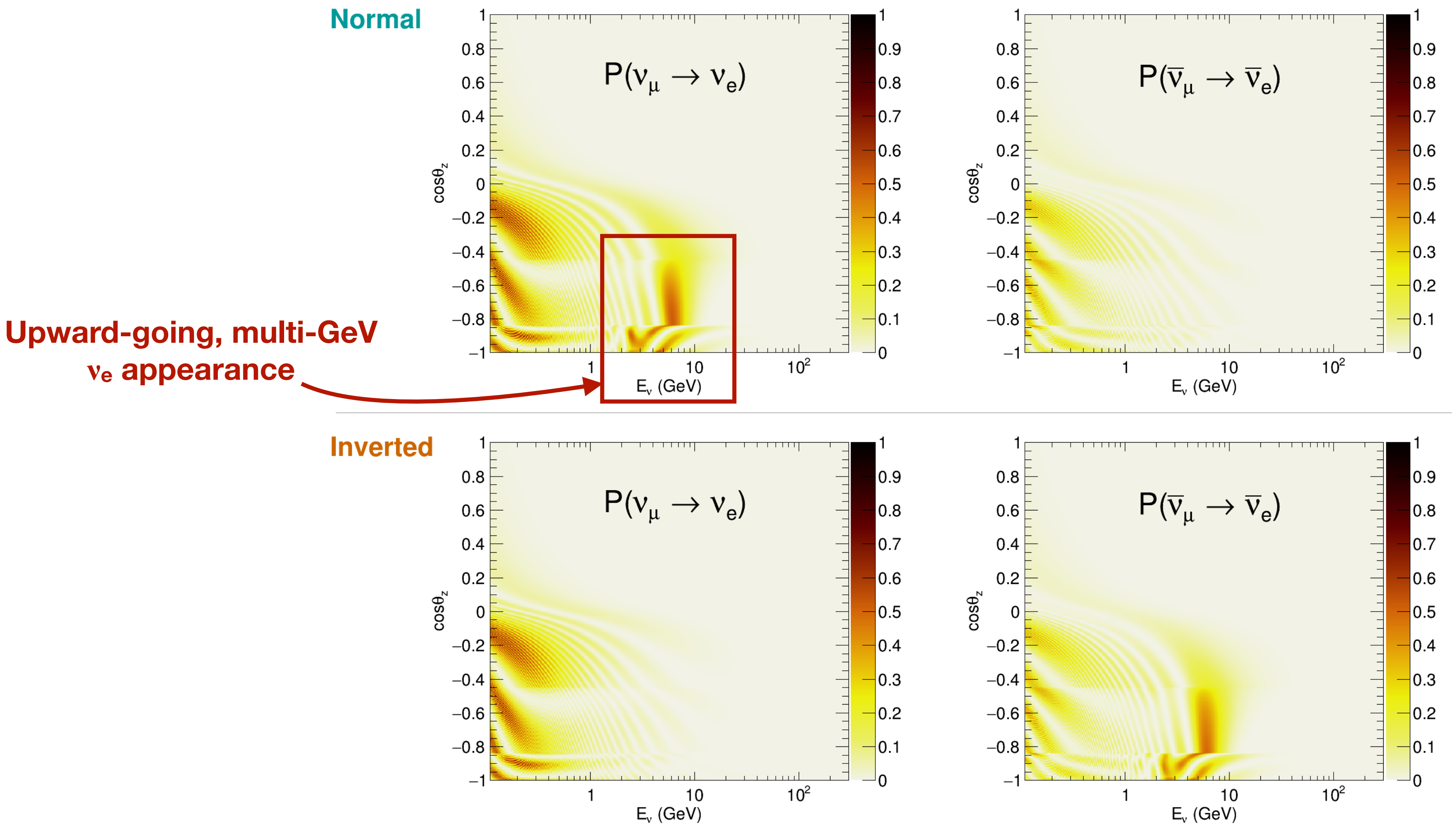
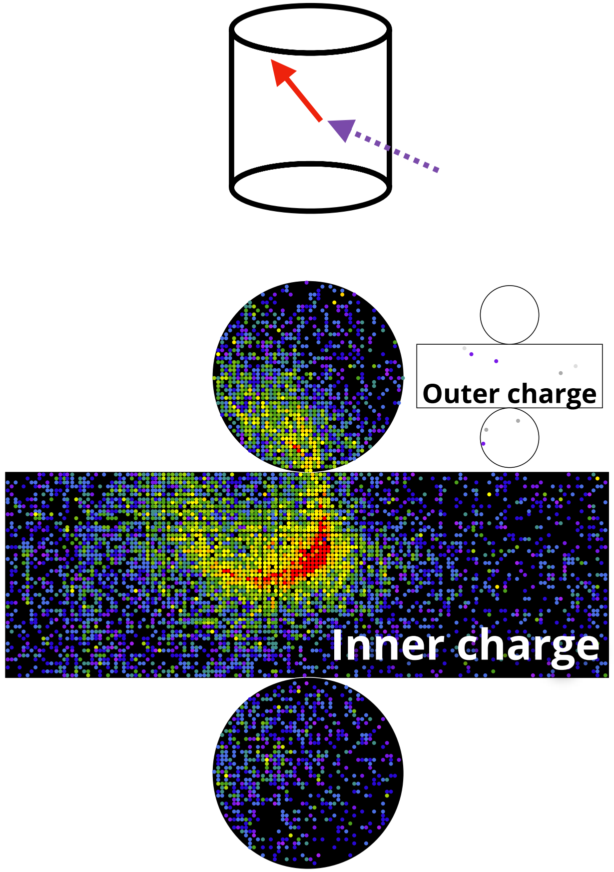


SK Atmospheric Neutrino Oscillation Analysis

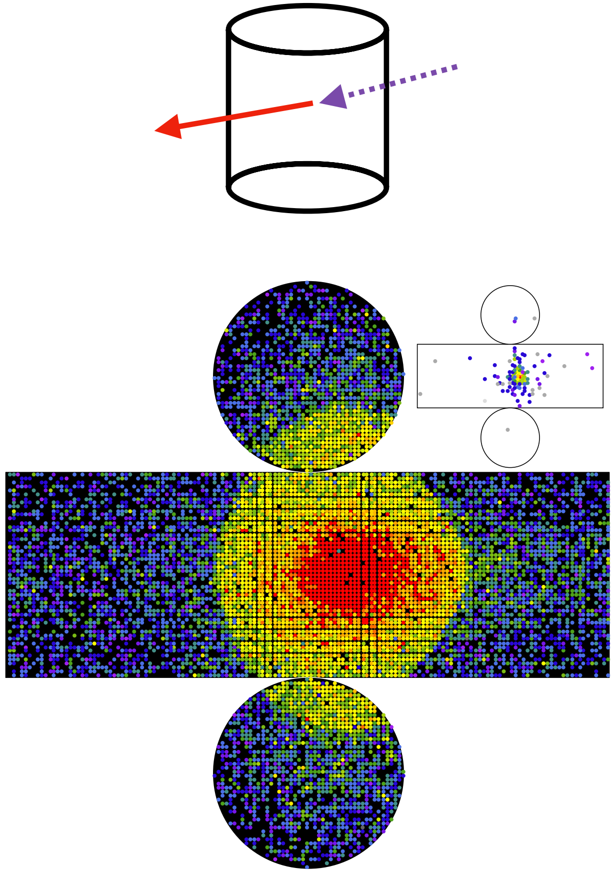
FC

Fiducial vertex, no exiting particles



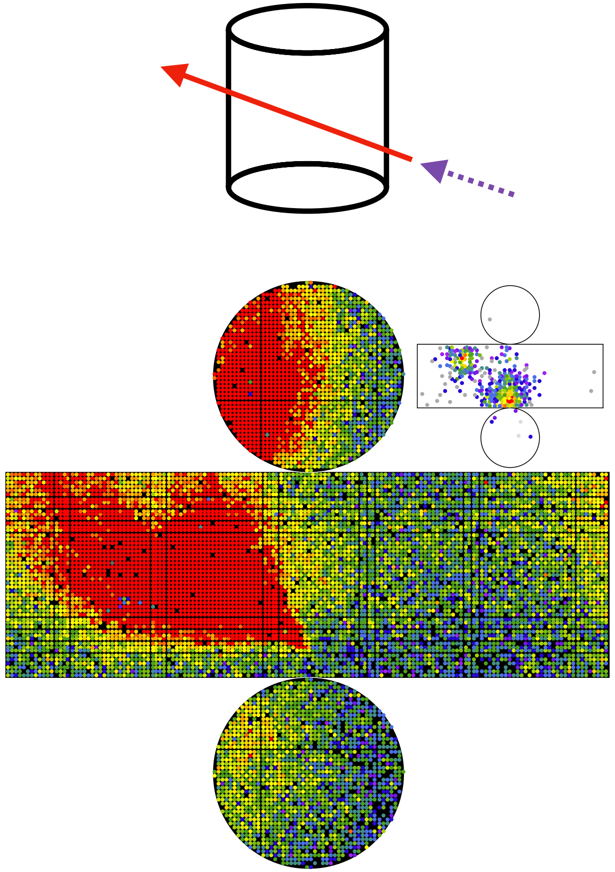
PC

Fiducial vertex, exiting particles



Up-μ

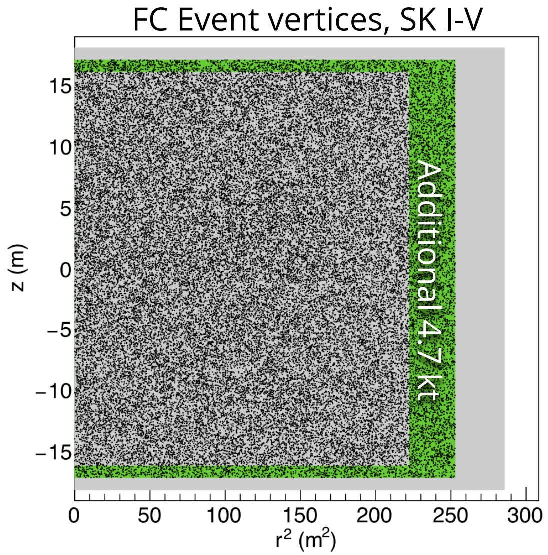
Outside vertex, upward-going



Analysis Improvements

New since our previous publication:

- Expanded fiducial volume & additional pure water livetime: **+48% statistics**



A. Takenaka et al. (SK Collaboration)
Phys. Rev. D **102**, 112011 (2020)

Analysis Improvements

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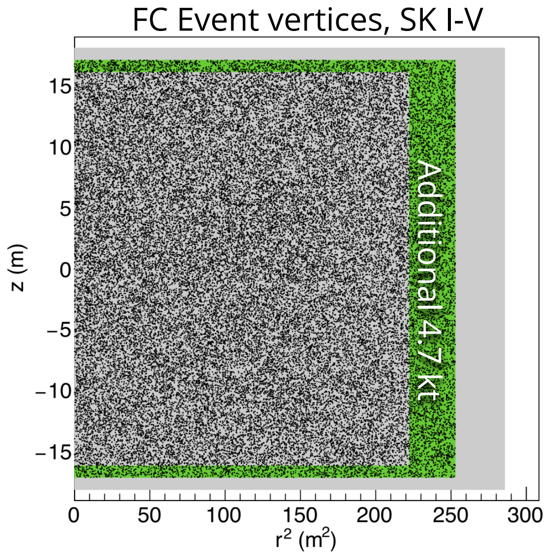

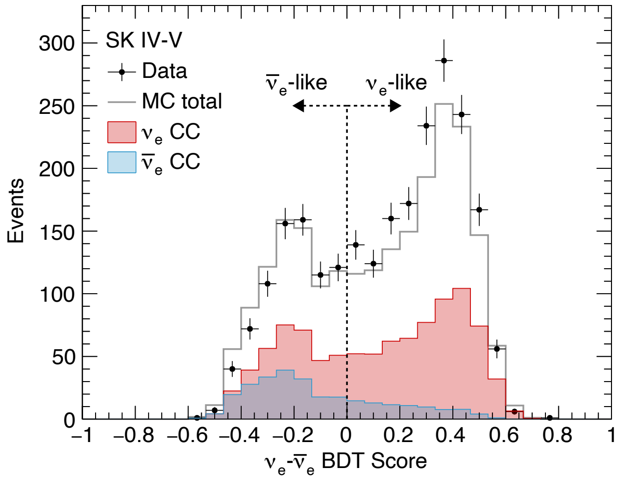

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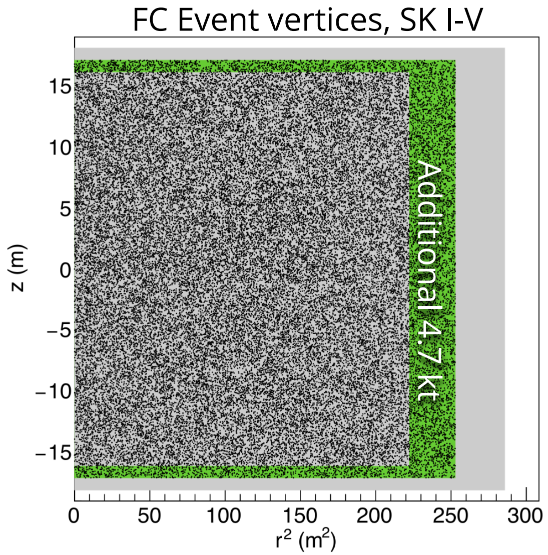

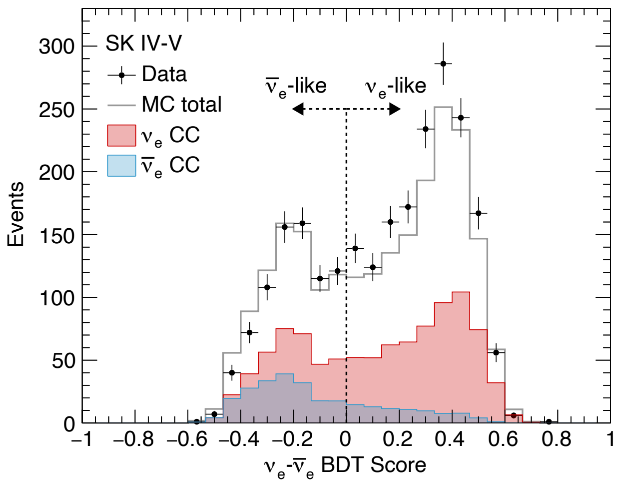

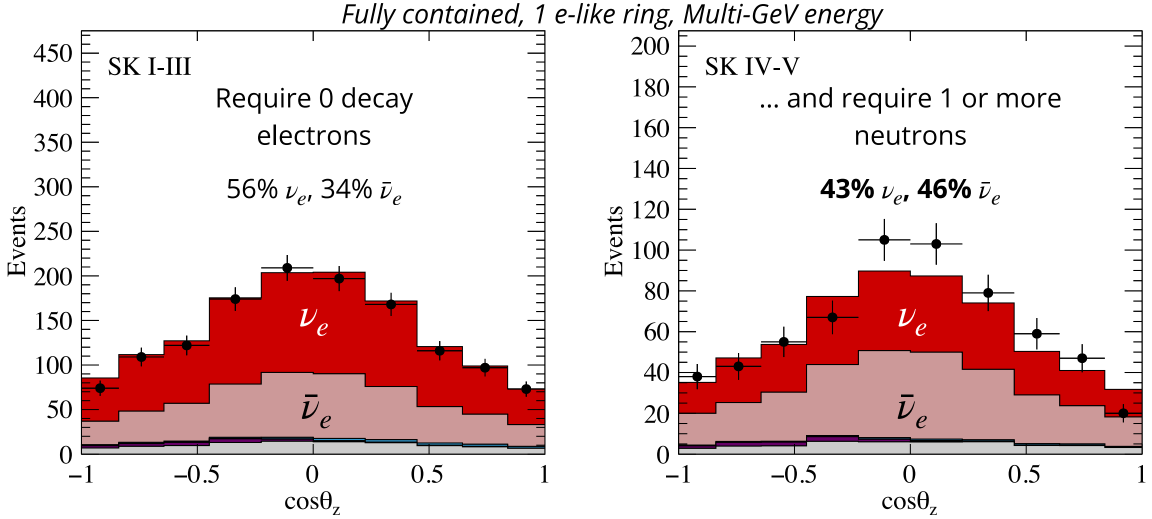

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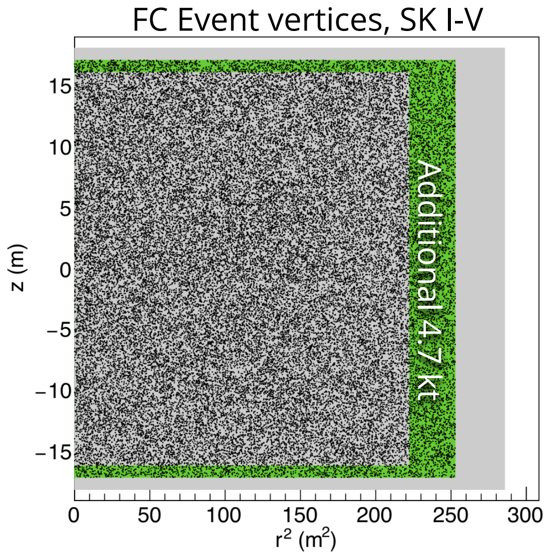
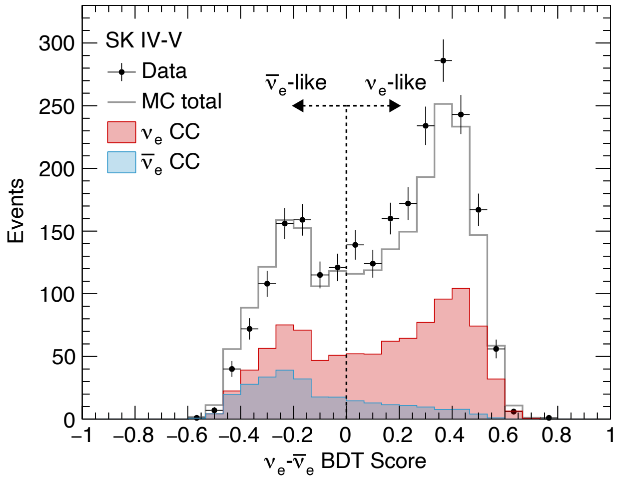
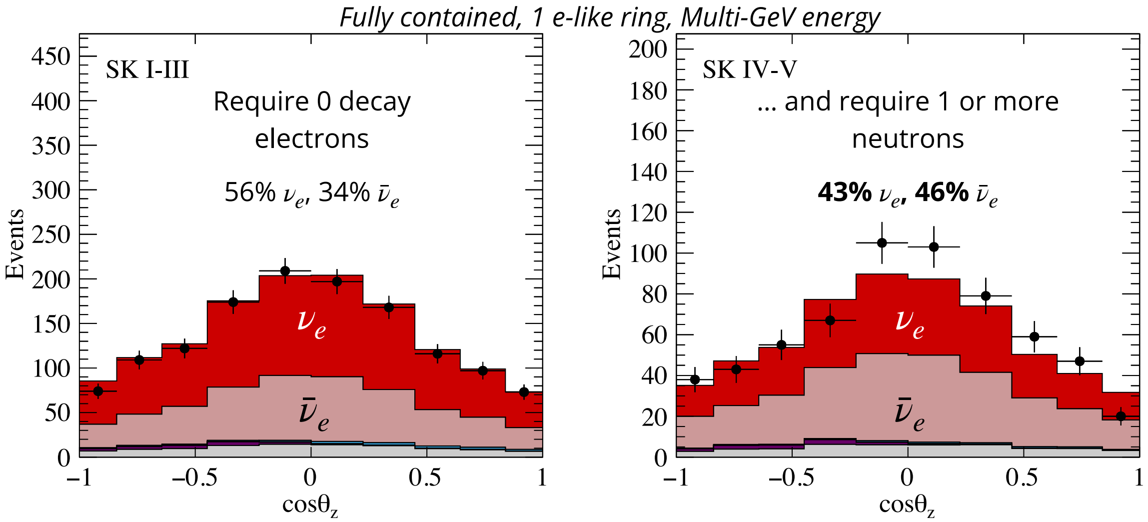
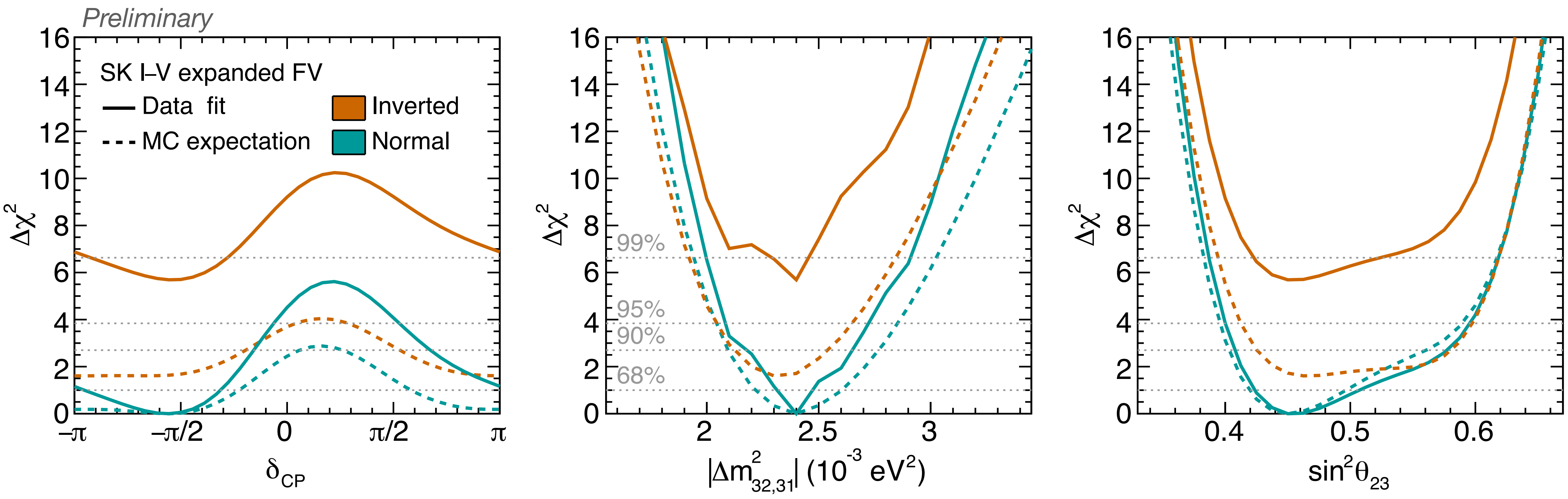
Preliminary results were presented at NEUTRINO2022. Minor improvements, & checks of mass ordering result now ready







SK I–V Atmospheric Oscillation Results

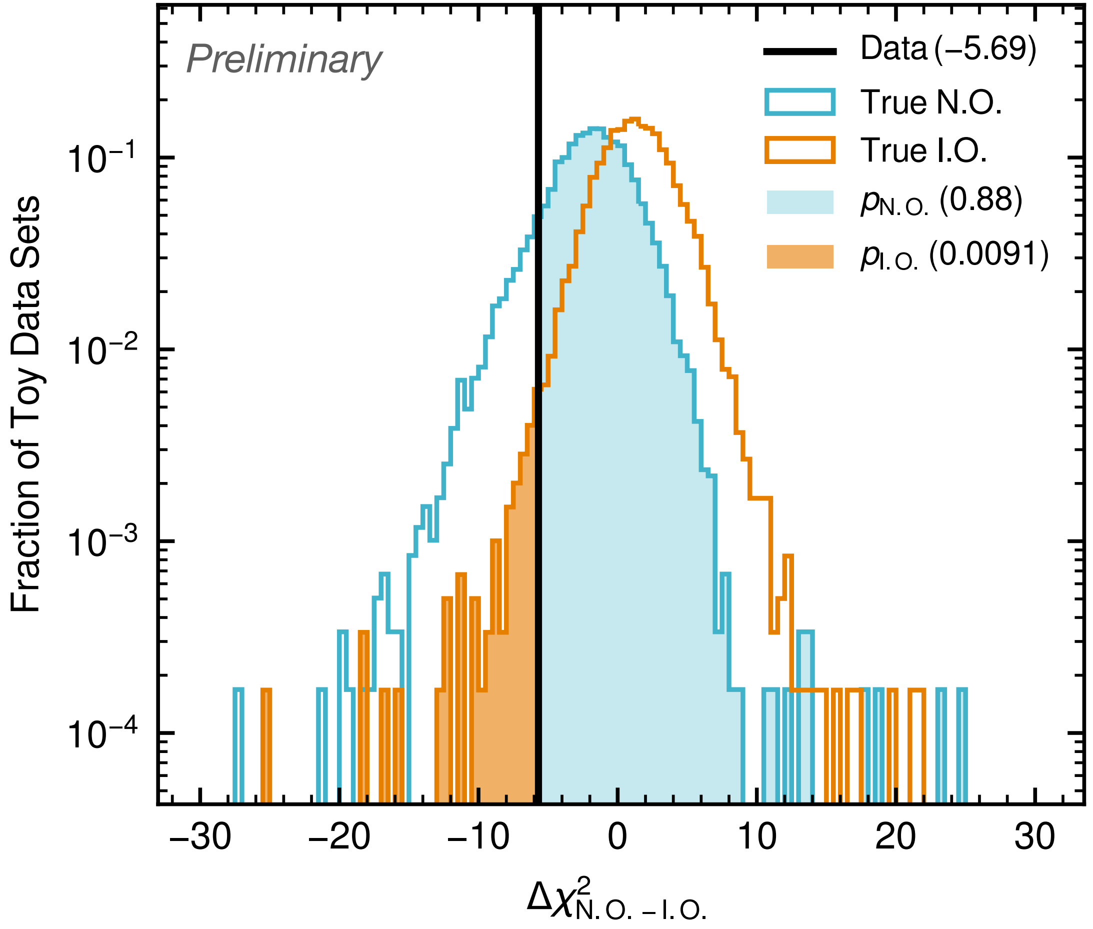


SK 2023 best fit: Normal ordering, δ_{CP} ~ $-\pi/2$, Δm^2_{32} ~ 2.4×10^{-3} eV^2, $\sin^2\theta_{23}$ ~ 0.45

Mass ordering: $\Delta\chi^2_{I.O.\ -\ N.O.}$ ~ 5.7*

With reactor constraint: $\sin^2\theta_{13} = 0.0220 \pm 0.0007$

*Mass Ordering Significance



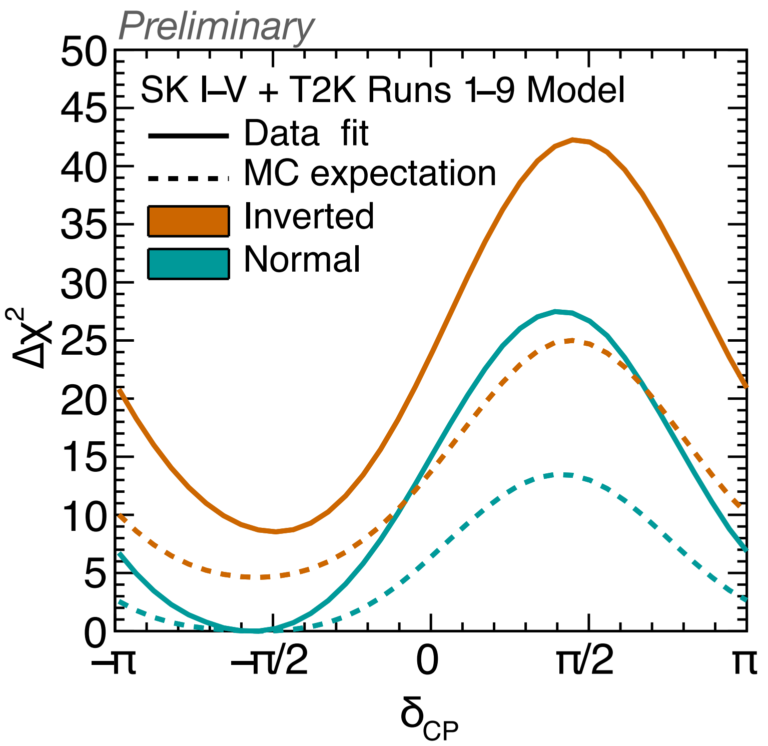
- Generate toy data sets to obtain distribution of $\Delta\chi^2_{NO\text{-}IO}$
- SK data fit result has lower probability of occurring for a true inverted ordering than normal, but is also more extreme than normal ordering median (exceeds sensitivity)
- Compute CL_S statistic to correct probability of rejecting the inverted ordering given simultaneous agreement with normal ordering:

$$\mathrm{CL}_S = \frac{p_{\mathrm{IO}}}{1 - p_{\mathrm{NO}}} \approx 0.077$$

Reject inverted ordering at the ~92% confidence level.

Constraints from T2K

SK + T2K Model



SK 2023 + T2K Runs 1–9 Model:

$\Delta\chi^2_{\text{I.O. - N.O.}}$ ~ 8.5, CL_S ~ 0.02

Reject inverted ordering at the ~98% confidence level

SK + T2K Model:

- External combination of SK & *published* T2K data by SK collaboration
- Tests effects of T2K constraints on Δm^2_{32}, $\sin^2\theta_{23}$, δ_{CP}, mass ordering on SK mass ordering result
- Previously done for SK 2018 oscillation analysis. Update for SK 2023 & T2K runs 1–9 was first shown at NEUTRINO 2022

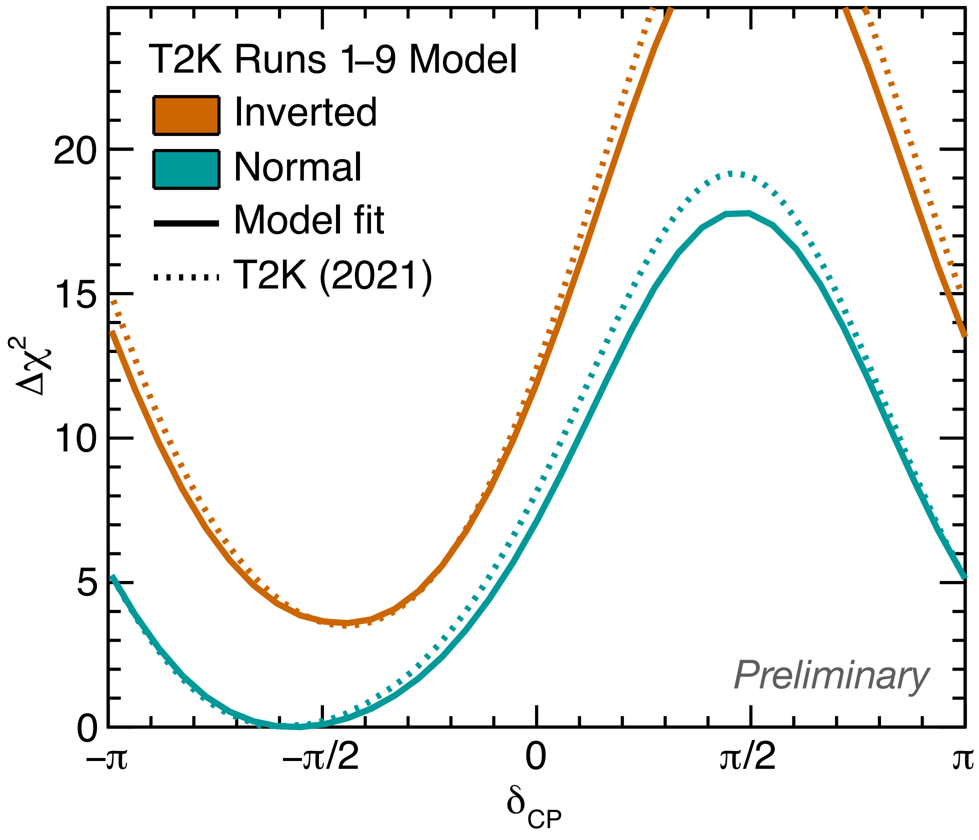
Methods:

- Re-weight atmospheric MC to T2K's nominal flux and cross section parameters and approximate T2K's systematic uncertainty with ND constraint from published information
- Fit model prediction to published T2K bin counts as additional bins in atmospheric fit

*Model based on on Phys. Rev. D **103**, 112008 (2021)*

T2K Model Compared to T2K Runs 1–9 Analysis

- T2K Model based on published information is overall conservative compare to the T2K Runs 1–9 analysis
- Few-% difference in mass ordering preference and δ_{CP} best-fit & allowed ranges
- T2K run 10 data only recently published, and so is not included



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Comparison with Joint Fit

	SK I–V + constraints from T2K Runs 1-9 Model External analysis by SK, update T2K Model from 2018 SK analysis	T2K+SK IV Joint fit New formal joint effort between T2K & SK *See talk by A. Eguchi*
Data products analyzed	Full atmospheric event info **Published T2K bin counts**	Full atmospheric event info **Full T2K event info**
Uncertainty model	Full atmospheric, **simplified beam** Correlated cross section uncertainties	Full atmospheric, **full beam** Correlated cross section **+ detector uncertainties, near detector included in correlation matrix**
Atm. exposure/ Beam POT	**6511.3 days** (SK I–V) **14.9e20 ν-mode**, 16.3e20 $\overline{\nu}$-mode (T2K runs 1–9)	**3244.4 days** (SK IV) **19.7e20 ν-mode**, 16.3e20 $\overline{\nu}$-mode (T2K runs 1–10)
Event selection	29 atmospheric samples, **neutron tagging** for SK IV–V 5 T2K single-ring samples	18 atmospheric samples, **no neutron tagging** 5 T2K single-ring samples
Analysis	**Profiled $\Delta\chi^2$**	**Frequentist & Bayesian results, cross validation between multiple fitters**

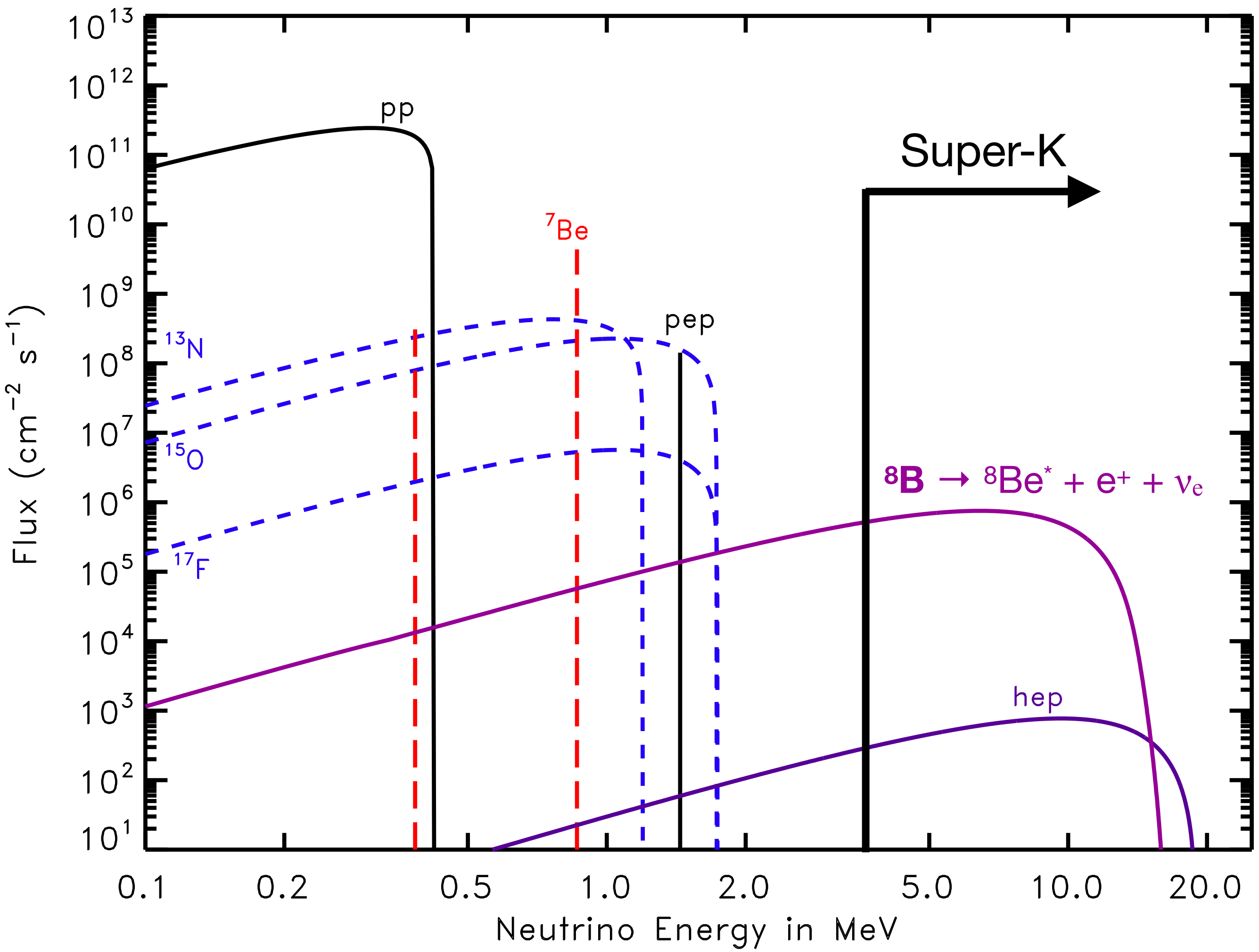
More details in backup. Previous SK publication: Phys. Rev. D **97**, 072001 (2018)

Solar Neutrinos

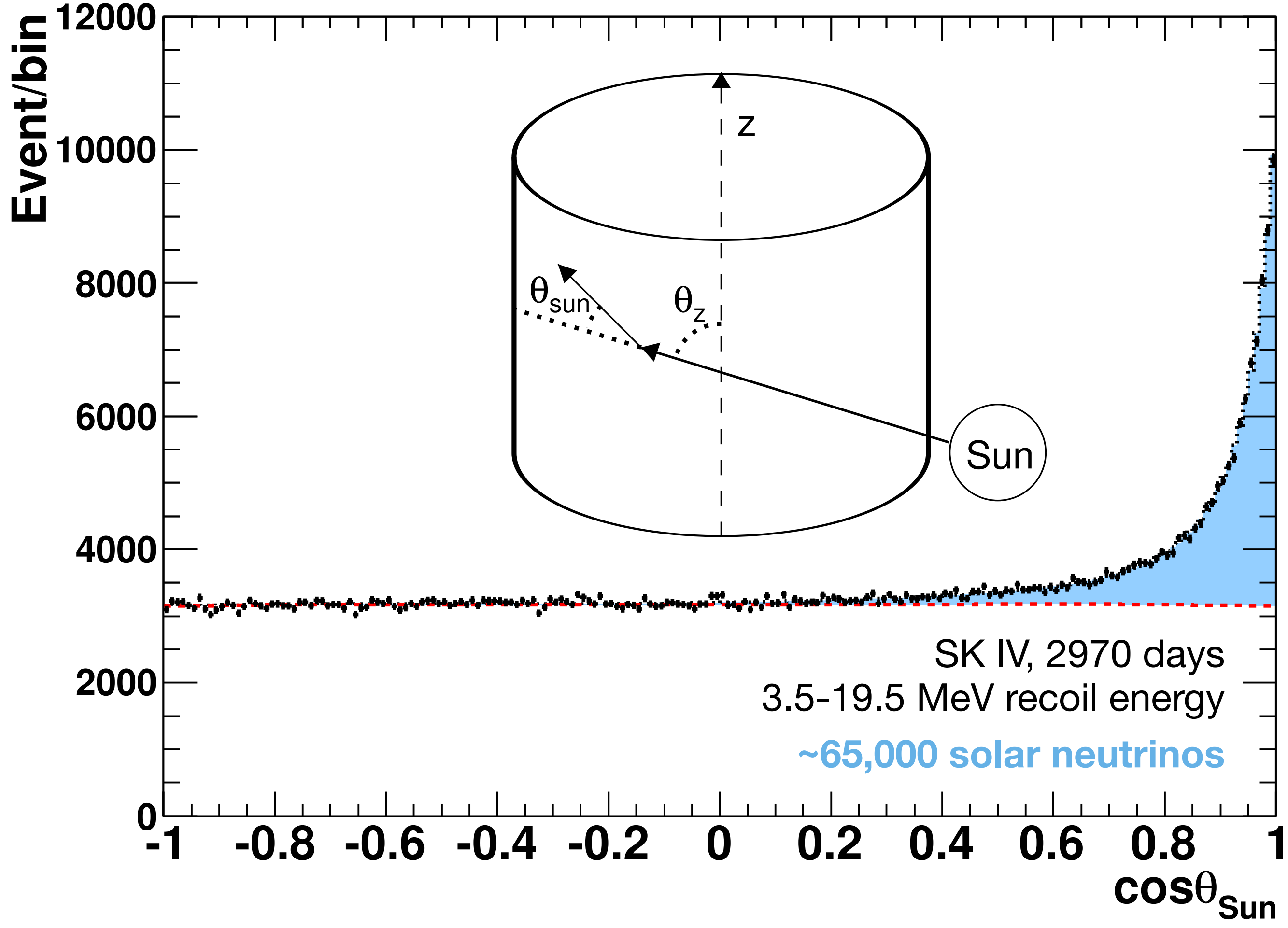
Solar Neutrinos

Neutrinos produced in the sun through fusion processes

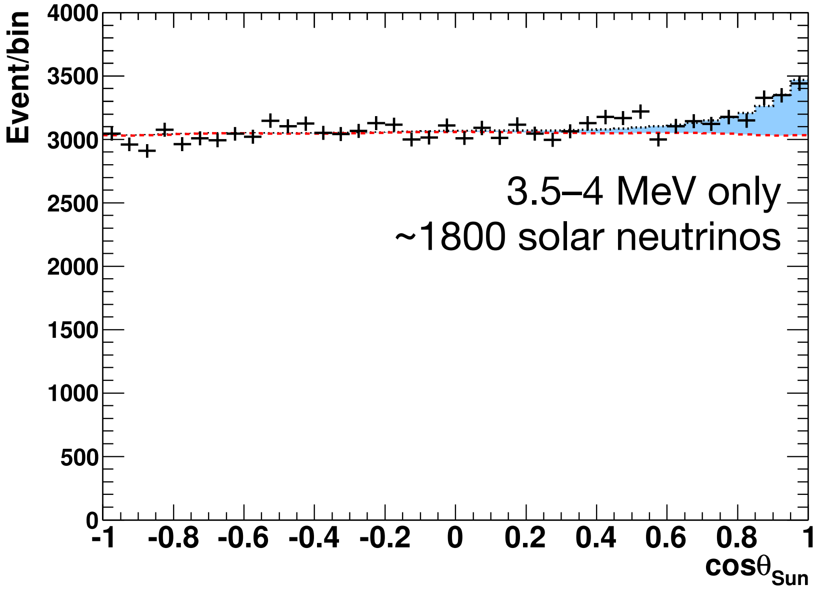
- **^{8}B neutrinos** recorded by SK with direction and energy information
- Oscillation topics:
  - Oscillation parameters θ_{12}, Δm^2_{21}
  - Day/night effect: Regeneration of solar neutrinos in earth matter
  - Solar upturn: MSW oscillations between ~1-5 MeV
- Other solar neutrino topics:
  - Flux modulation
  - Anti-neutrino search



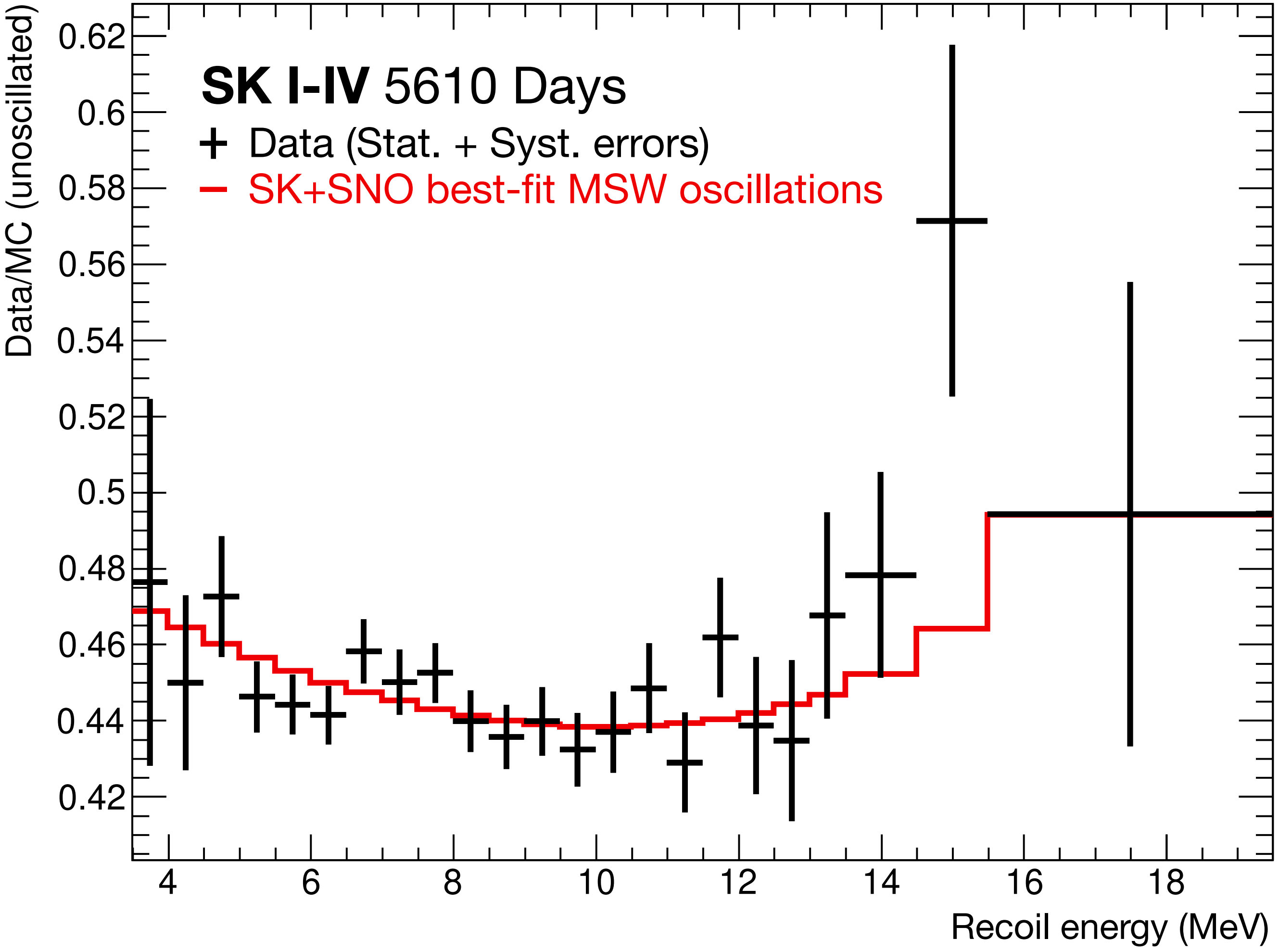
SK Solar Neutrino Measurements



- Solar ν recoil electrons point back to sun
- Rate extracted from solar peak after background subtraction
- Bin into energy ranges & goodness scores to minimize systematic uncertainties

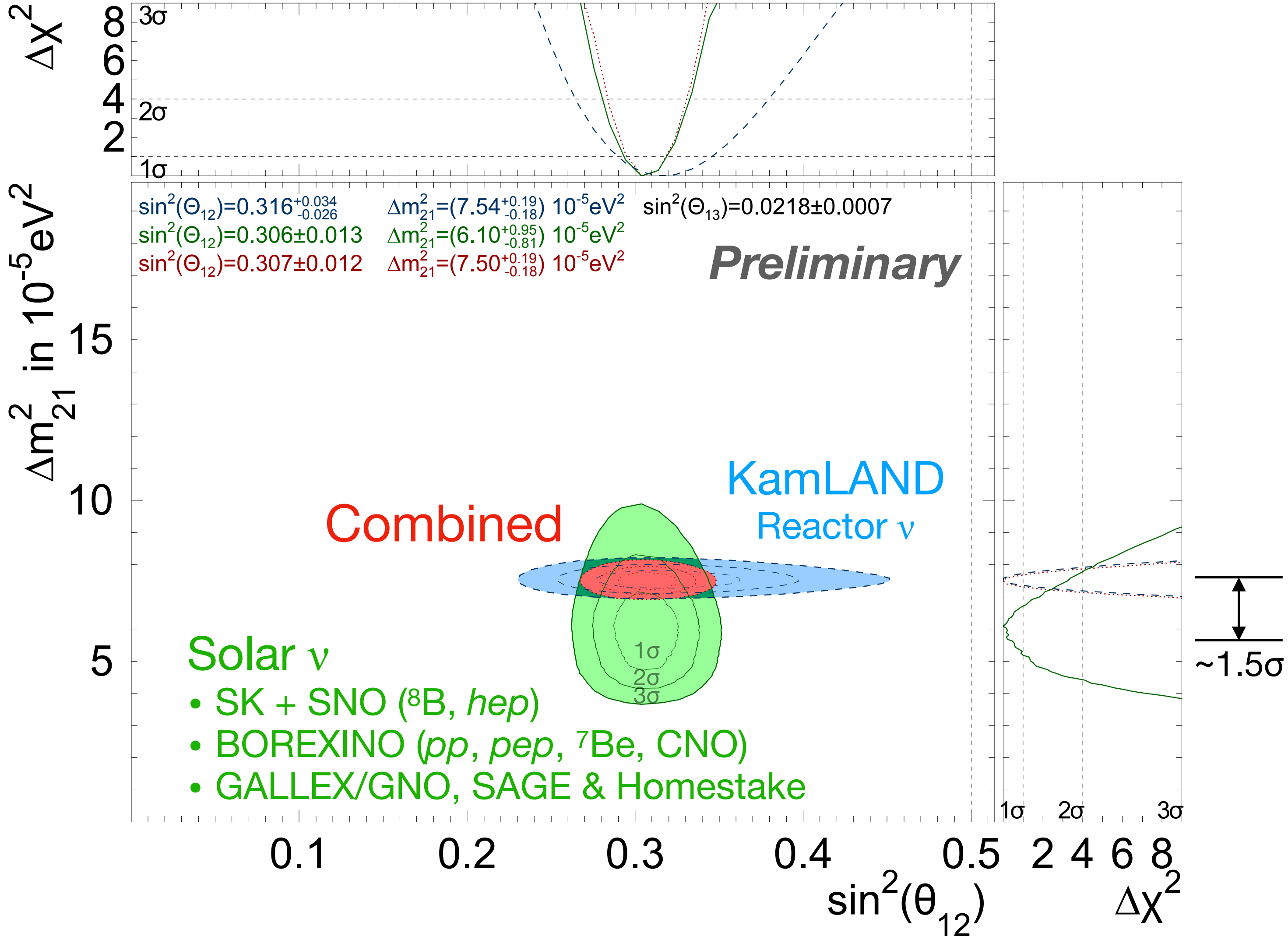


SK Solar Neutrino Oscillations



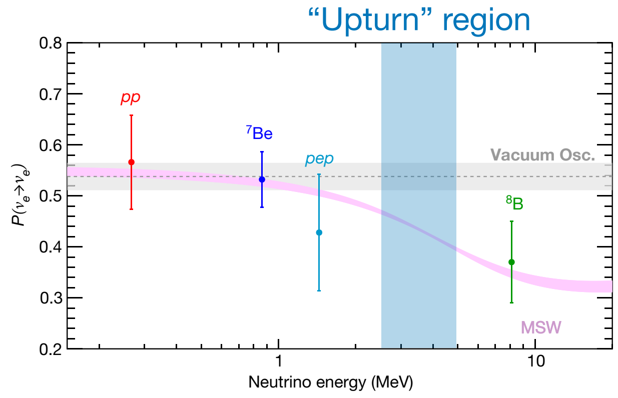
- SK data favors up-turn scenario below 5 MeV, but < 3.5 MeV data needed
- Recoil energy spectrum consistent with MSW oscillations

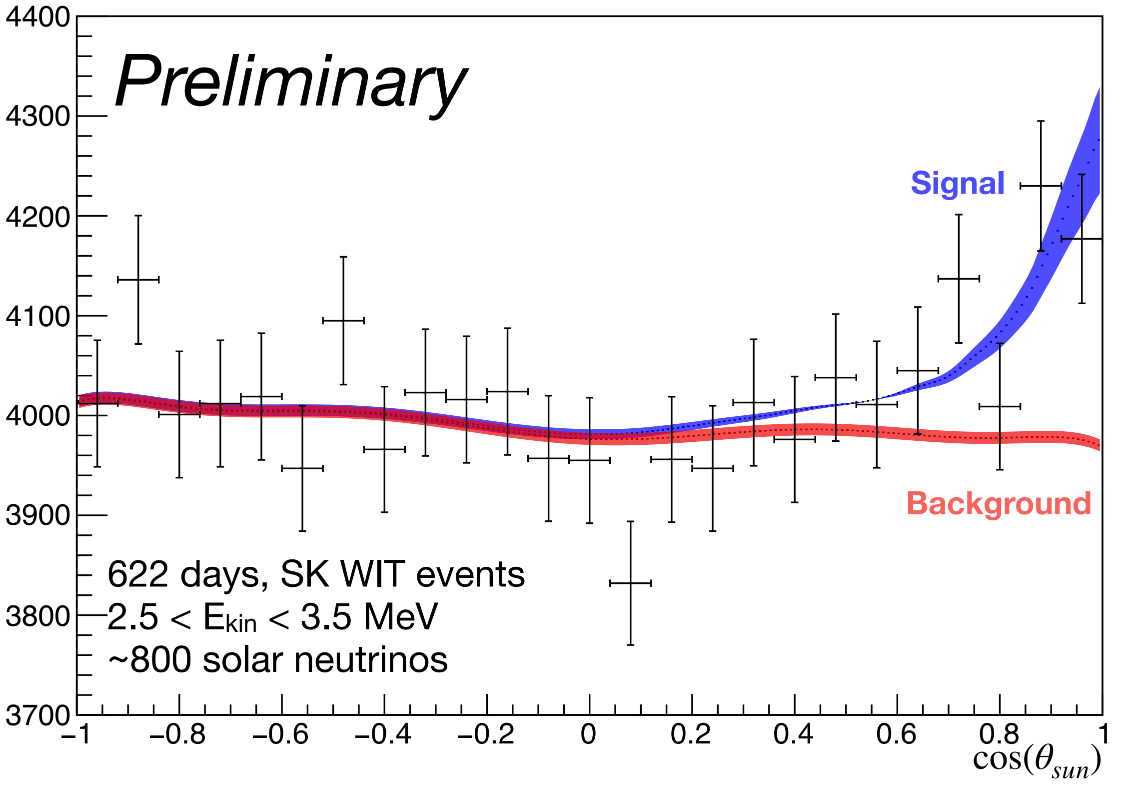
Solar Neutrino Global Fit Status



Progress Towards Upturn

- Need to lower current SK solar neutrino energy threshold to observe transition between matter and vacuum oscillations in solar neutrinos. Background-limited
- Dedicated hardware (WIT) searches un-triggered data for low-energy events & fits for fiducial vertex in real-time
- Some efficiency for solar neutrino identification down to 2.5 MeV recoil energy using BDT & WIT data

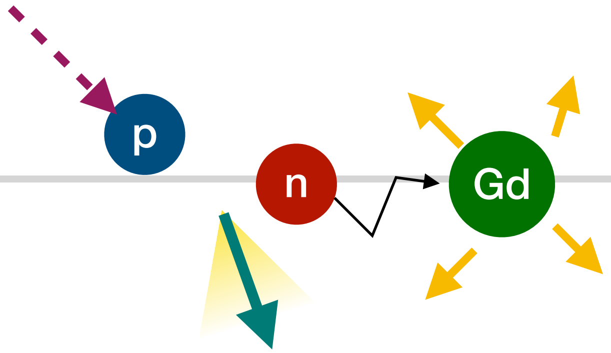




A. Yankelevich. (2022). Machine Learning Methods for Solar Neutrino Classification. (NEUTRINO2022 Poster)

SK-Gd: Super-K with Gadolinium

Introduction to SK-Gd



Why add gadolinium? Improved neutron tagging:

Neutron captures	**H**	**0.01% Gd**	**0.03% Gd**
Gamma energy	2.2 MeV	**8 MeV, multiple γ**	
Capture time	200 μs	120 μs	**60 μs**
Tagging efficiency	25%	50%	**75%**

SK-Gd proposal: Phys. Rev. Lett. **93**, 171101 (2003)

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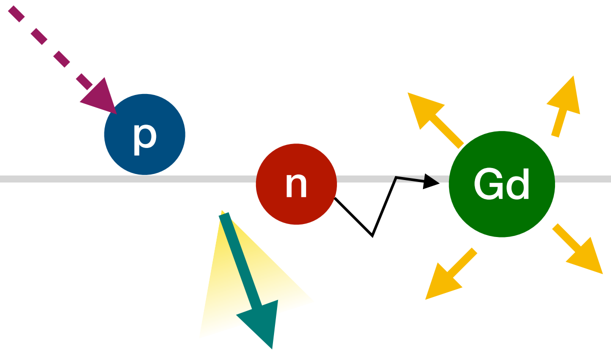

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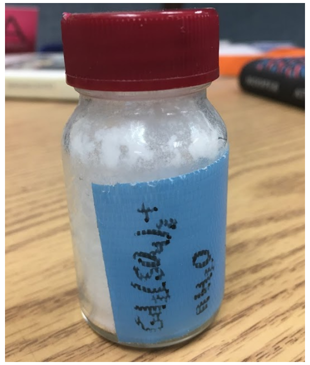
Knowing the number of neutrons...

- … helps **reject backgrounds** for IBD events & proton decay searches
- … improves **statistical separation of neutrinos & anti-neutrinos**
- … provides estimate of **hadronic activity**

SK-Gd proposal: Phys. Rev. Lett. **93**, 171101 (2003)

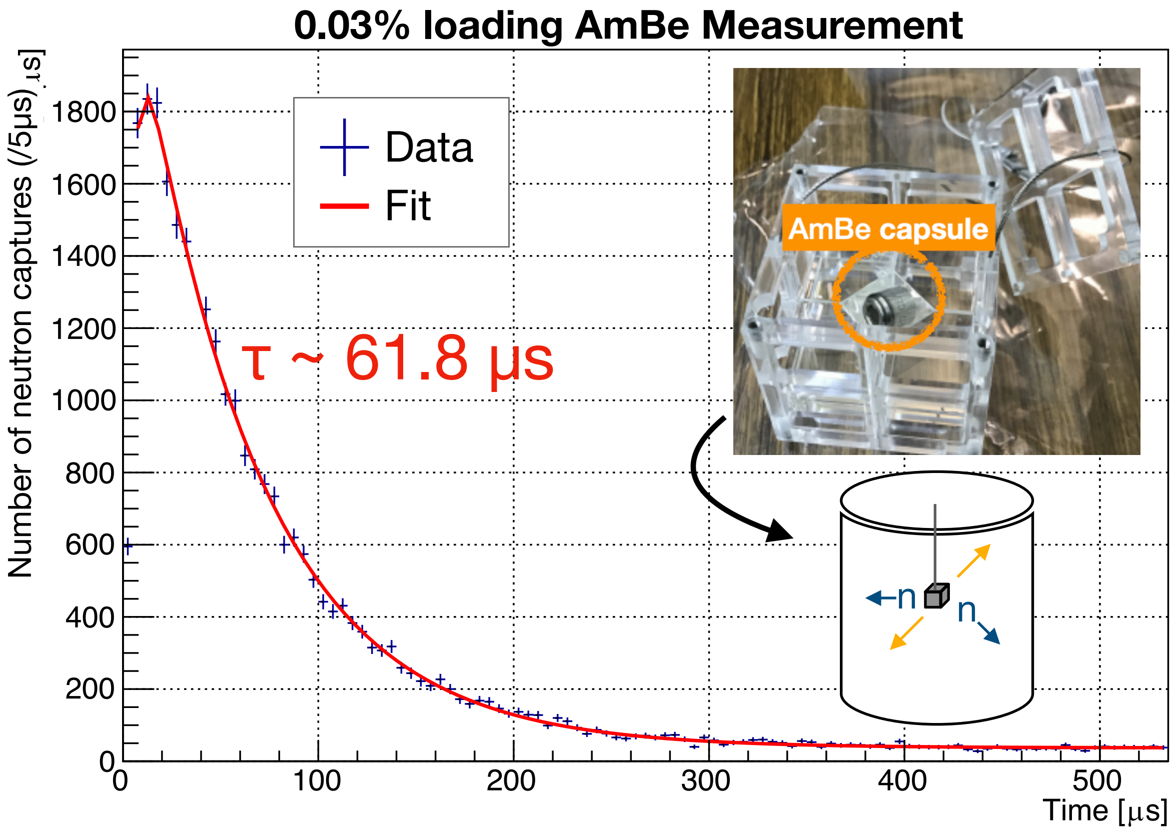
Gadolinium Loading Timeline

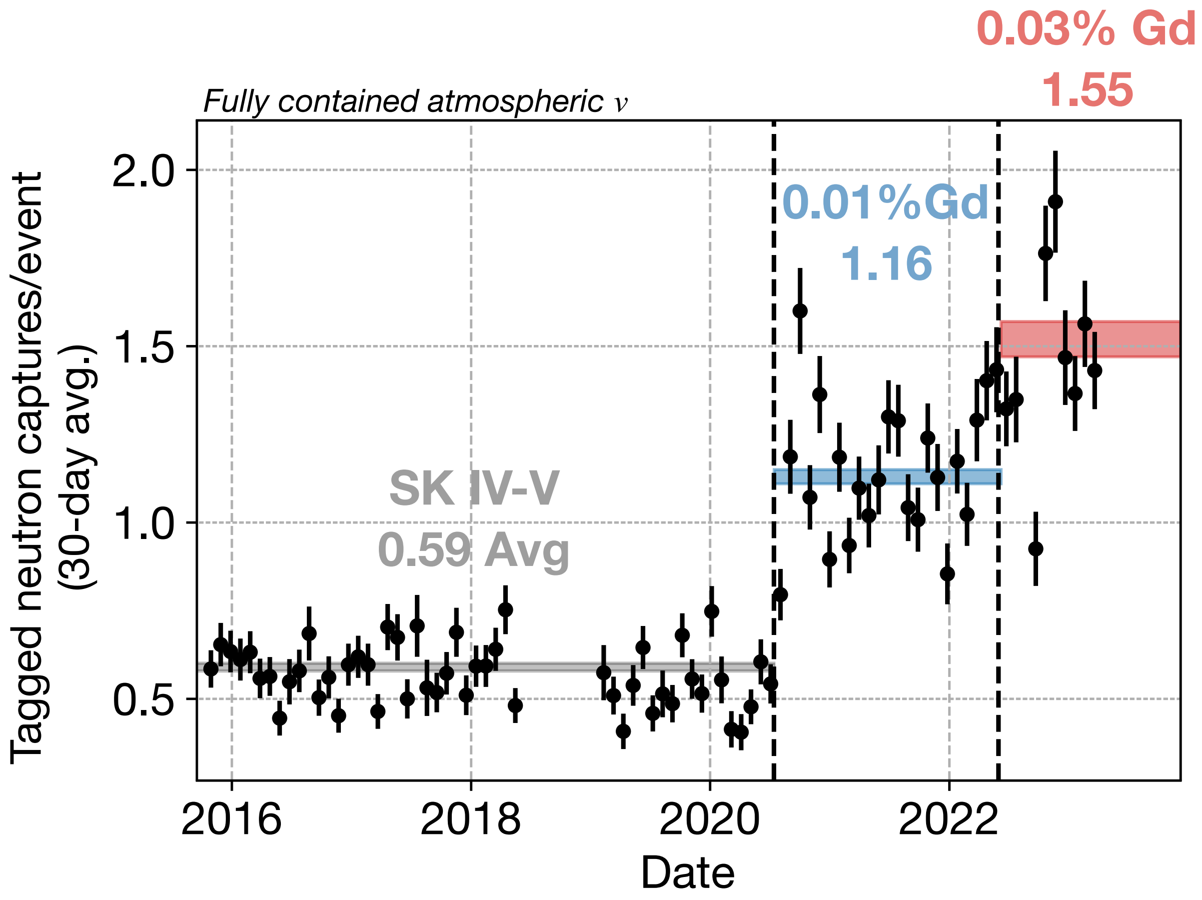
+



- Gd water system installed summer 2018, commissioned with pure water 2019-2020
- 0.01% loading completed summer 2020
- 0.03% loading completed summer 2022
- Gd data being analyzed now!

SK-Gd Neutron Capture Measurements



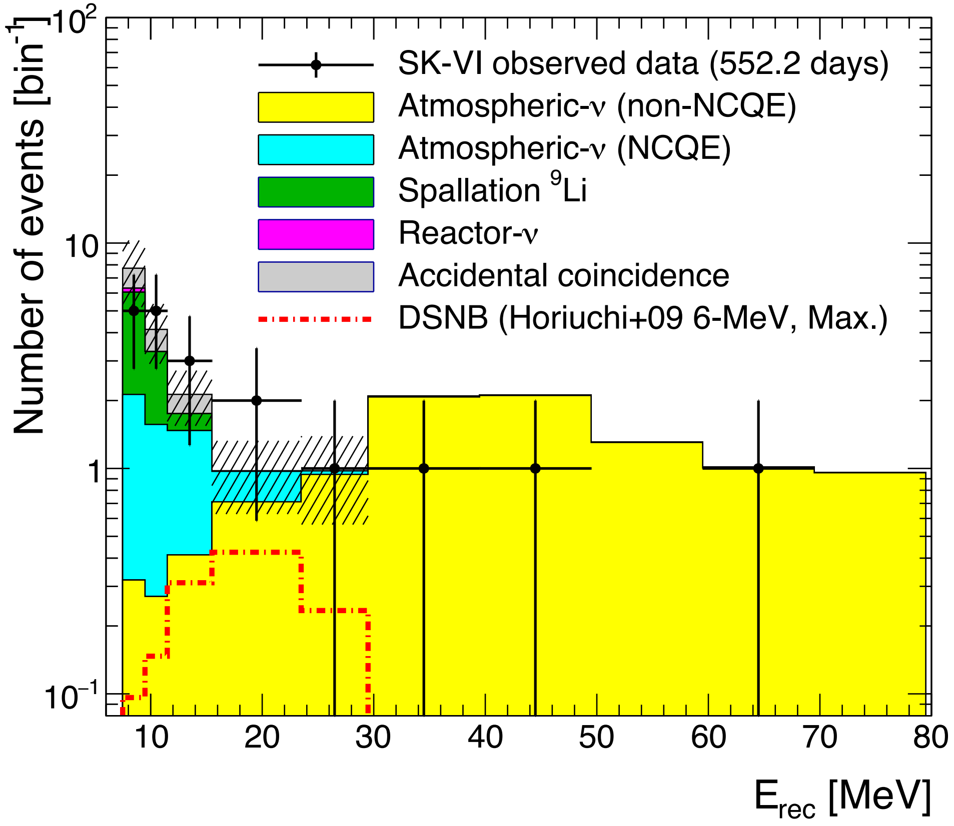


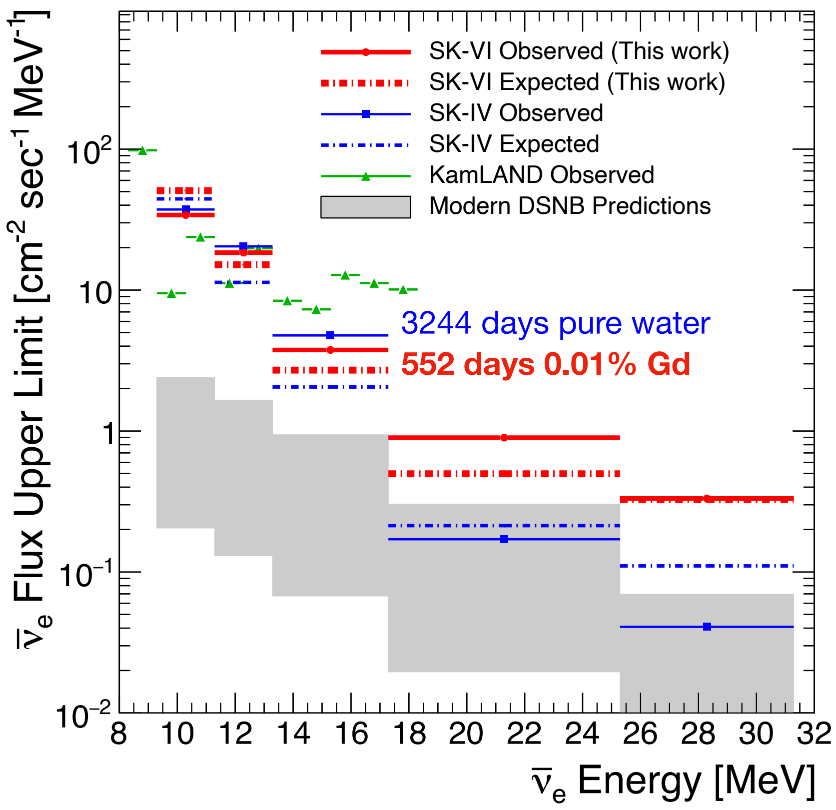
SK-Gd DSNB analysis

(See poster by M. Harada)

Diffuse Supernova Neutrino Background: Not-yet observed neutrino source expected from all past supernova

- ~7.5–30 MeV IBD signal window avoids reactor neutrinos & atmospheric background
- 0.01% SK-Gd data analyzed: Sensitivity is close to theoretical predictions, competitive with pure water phases





APJ Lett. **951**:L27

Summary

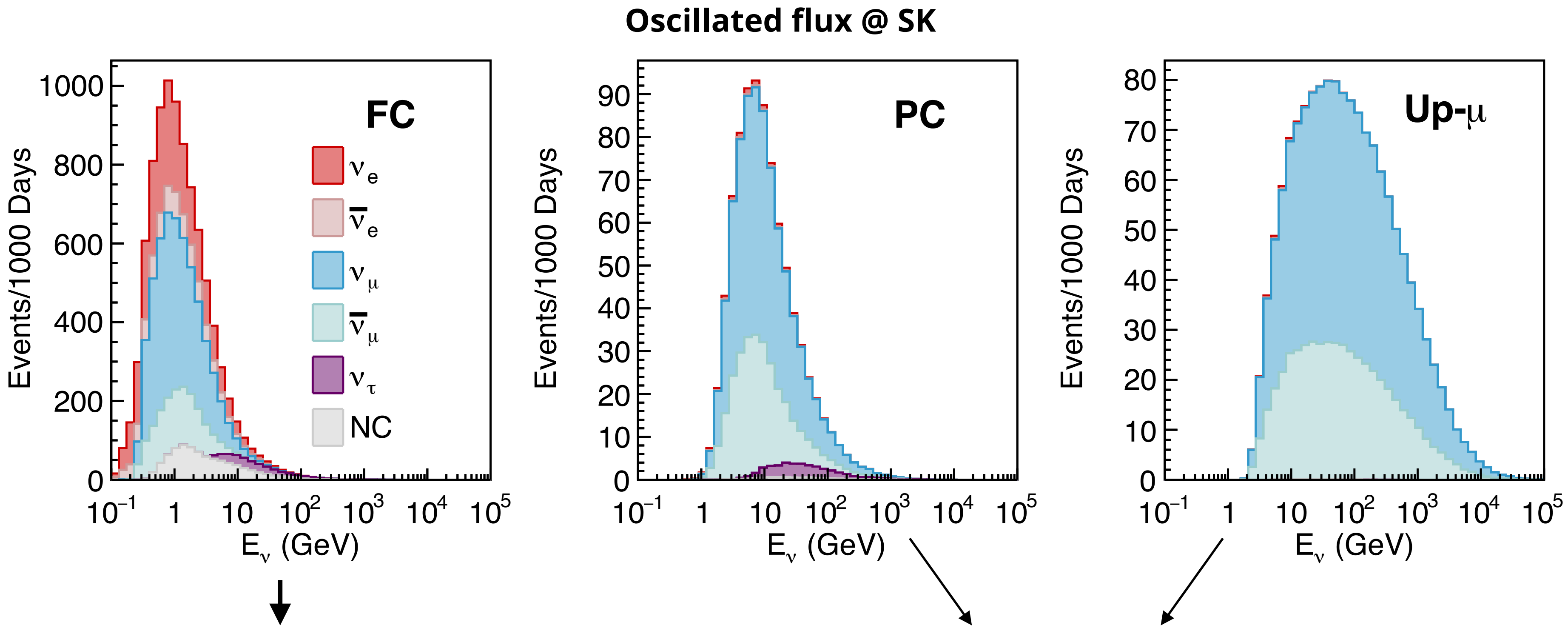
Atmospheric neutrinos
- Analyzed full pure water data set, prefer normal mass ordering, inverted CL_s ~ 0.07
- SK in agreement with T2K on mass ordering & δ_{CP}.

Solar neutrinos
- Global analysis including SK I-IV is compatible with KamLAND
- We are leveraging high solar ν statistics for sub-leading oscillation effects & BSM searches

SK-Gd
- Neutron tagging is working, observing many more captures, first Gd data is analyzed, more soon!

Extra

SK Atmospheric Neutrino Oscillation Analysis



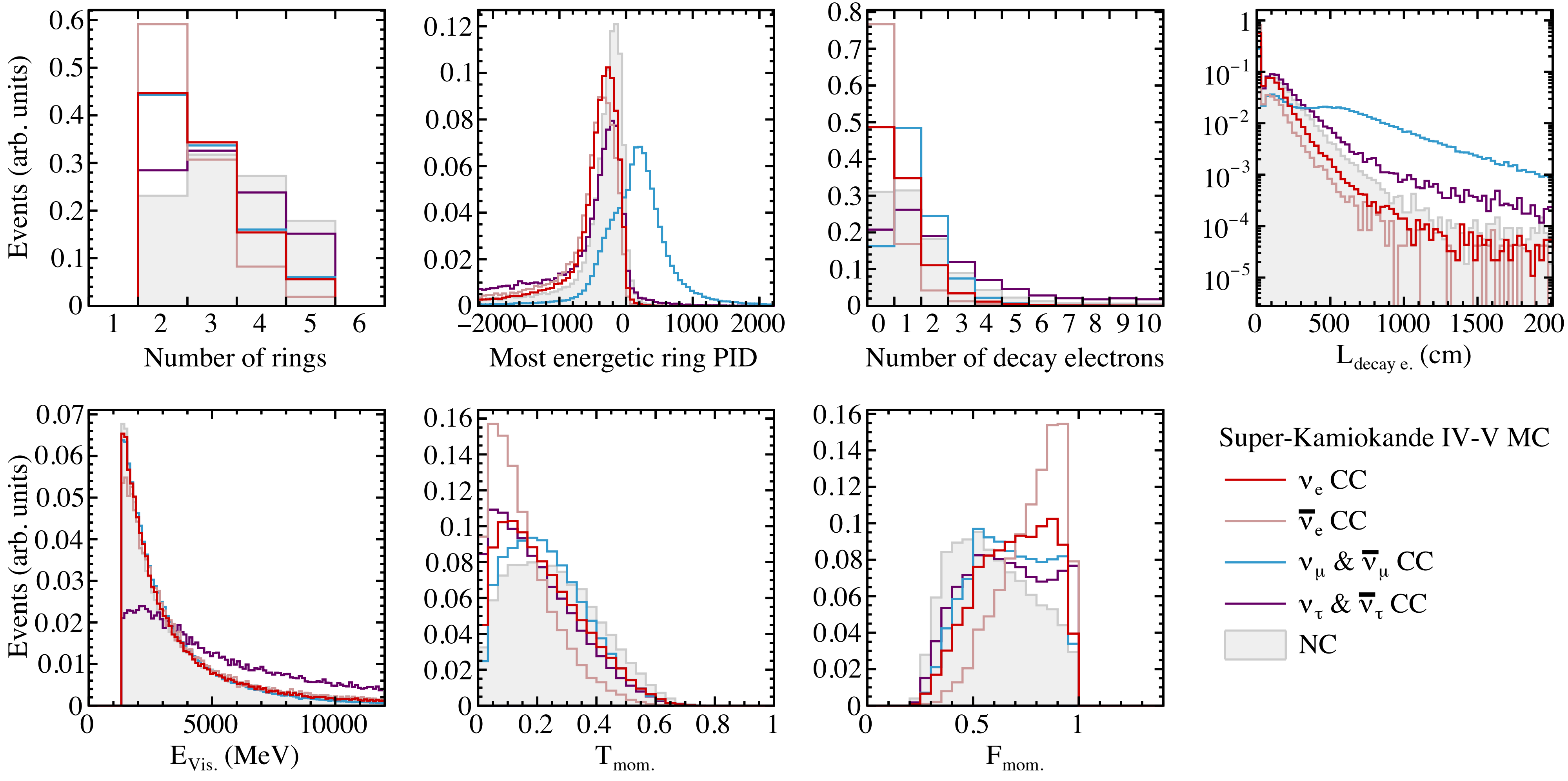
MeV - GeV, all flavors

Mass ordering, θ_{23} octant, δ_{CP}

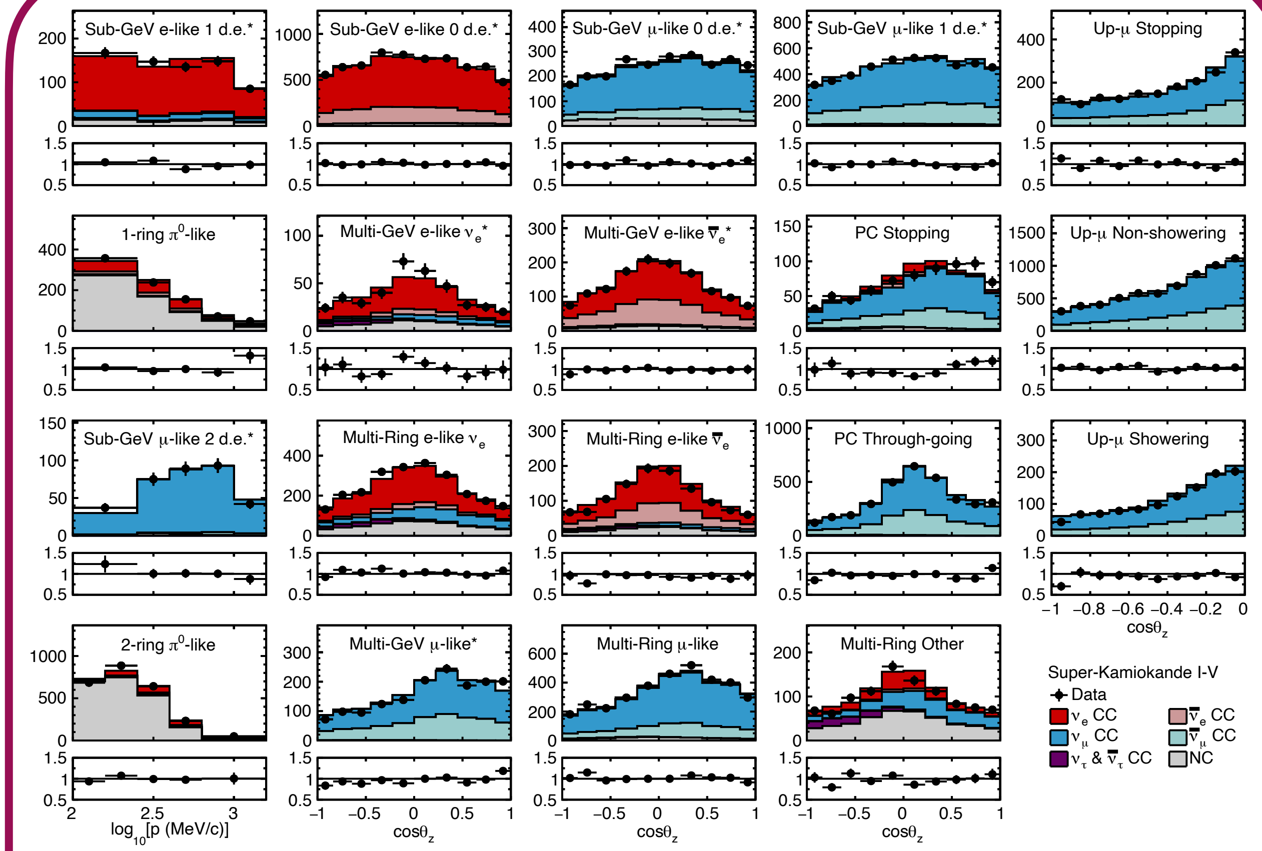
>GeV, almost all ν_μ

Constrain $\sin^2 2\theta_{23}$, Δm^2_{32}

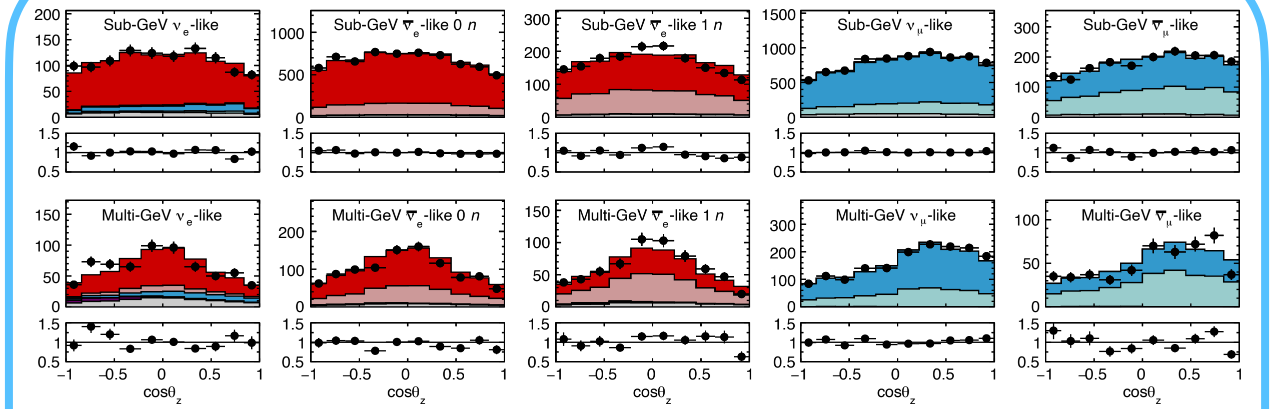
Multi-Ring BDT Input Distributions



Atmospheric Neutrino Event Selection



19 samples: SK I-III fully contained single-ring samples
+ SK I-V PC, Up-μ, FC multi-ring, & π0-like samples



10 SK IV-V fully contained single ring samples
with neutron tagging

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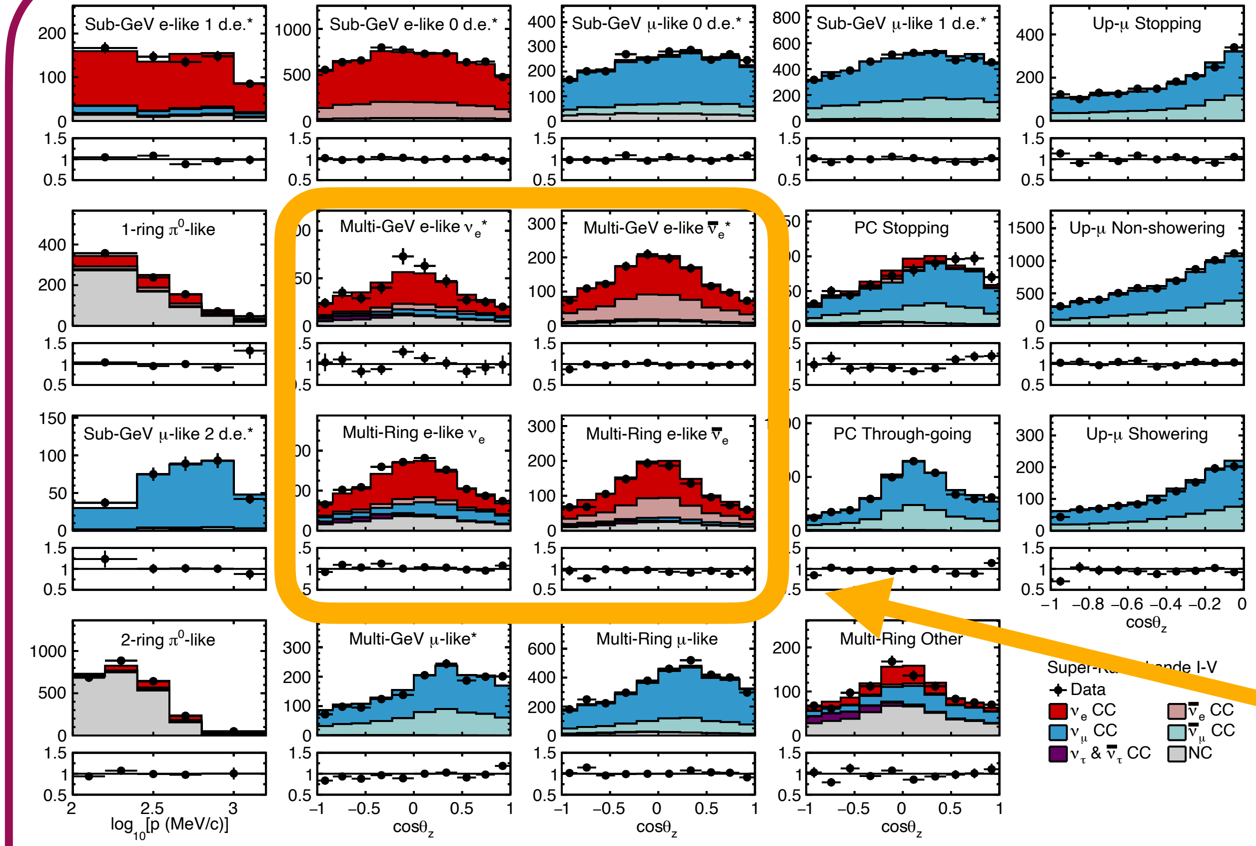

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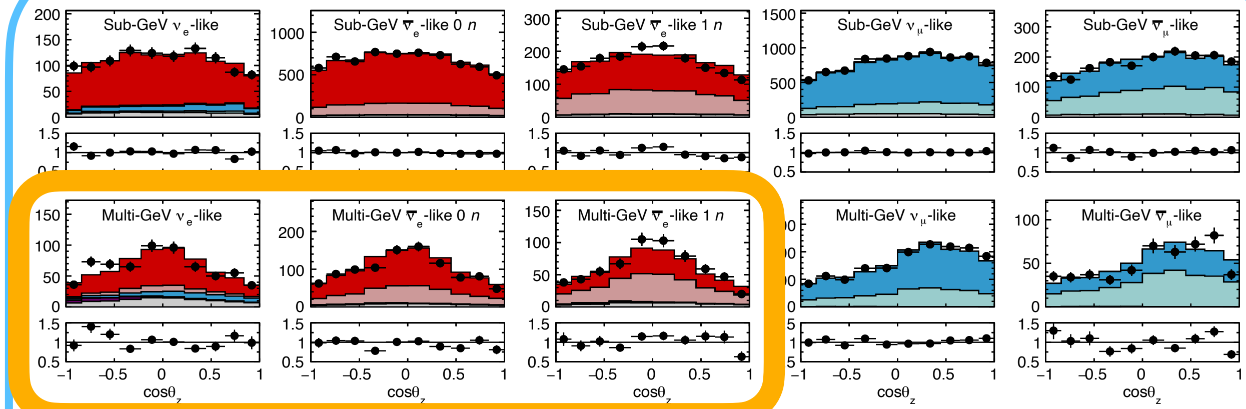


10 SK IV-V fully contained single ring samples
with neutron tagging

~6,000 Multi-GeV ν_e- or $\bar{\nu}_e$-like events

Normal MC: ~200 $\nu_\mu \rightarrow \nu_e$

Inverted MC: ~50 $\nu_\mu \rightarrow \nu_e$

χ^2 Calculation

Minimize χ^2 statistic for data versus MC given set of oscillation parameters & systematics:

Expected counts — Observed counts

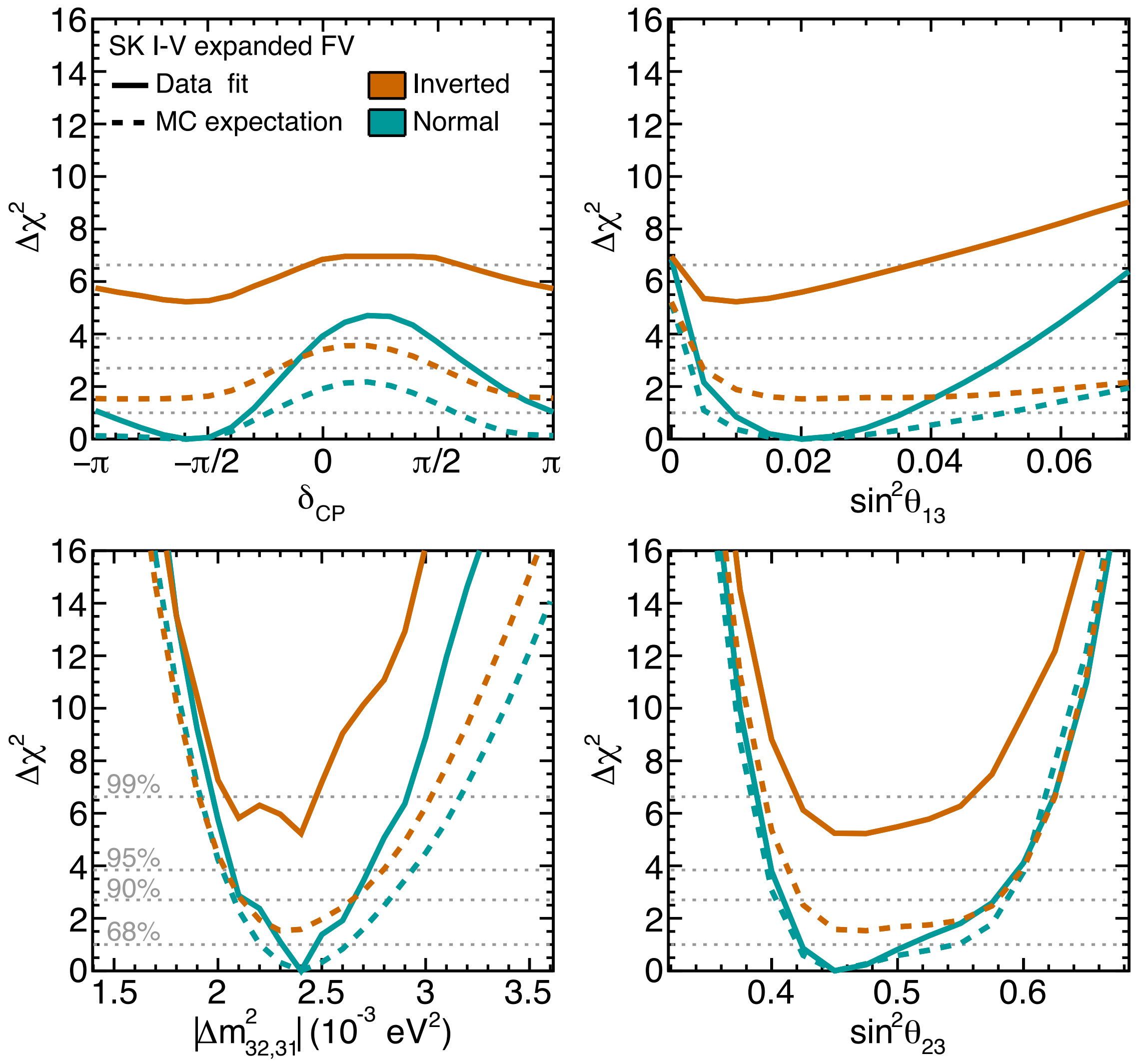
$$\chi^2 = \sum_n \left(E_n - O_n + O_n \ln \frac{O_n}{E_n} \right) + \sum_i \epsilon_i^2$$

Sum over *n* bins — *i* Systematic error pull terms

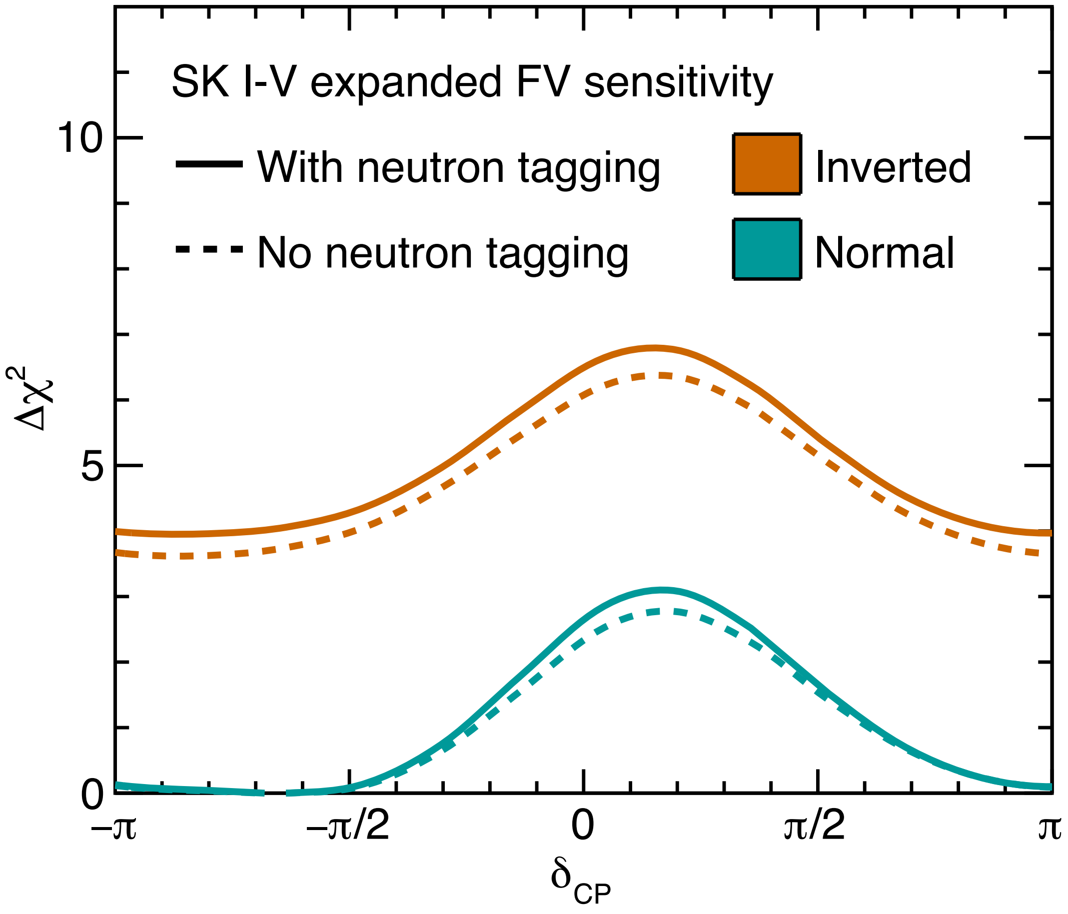
	Data set	Samples	Bins	Systematic errors	Free parameters	Minimization
SK I-V, expanded FV	6511 live days (0.48 Mton·years)	29	930 (2D $\cos\theta_z$ vs. momentum)	194	$\sin^2\theta_{23}$, Δm^2_{32}, δ_{CP}, ordering	Grid scan

Results with θ_{13} Free

- Prefer **normal** ordering, $\Delta\chi^2_{IO\text{-}NO} \approx$ **5.2**
- Prefer **$\sin^2\theta_{13}\approx0.02$**, consistent with world-average reactor measurements



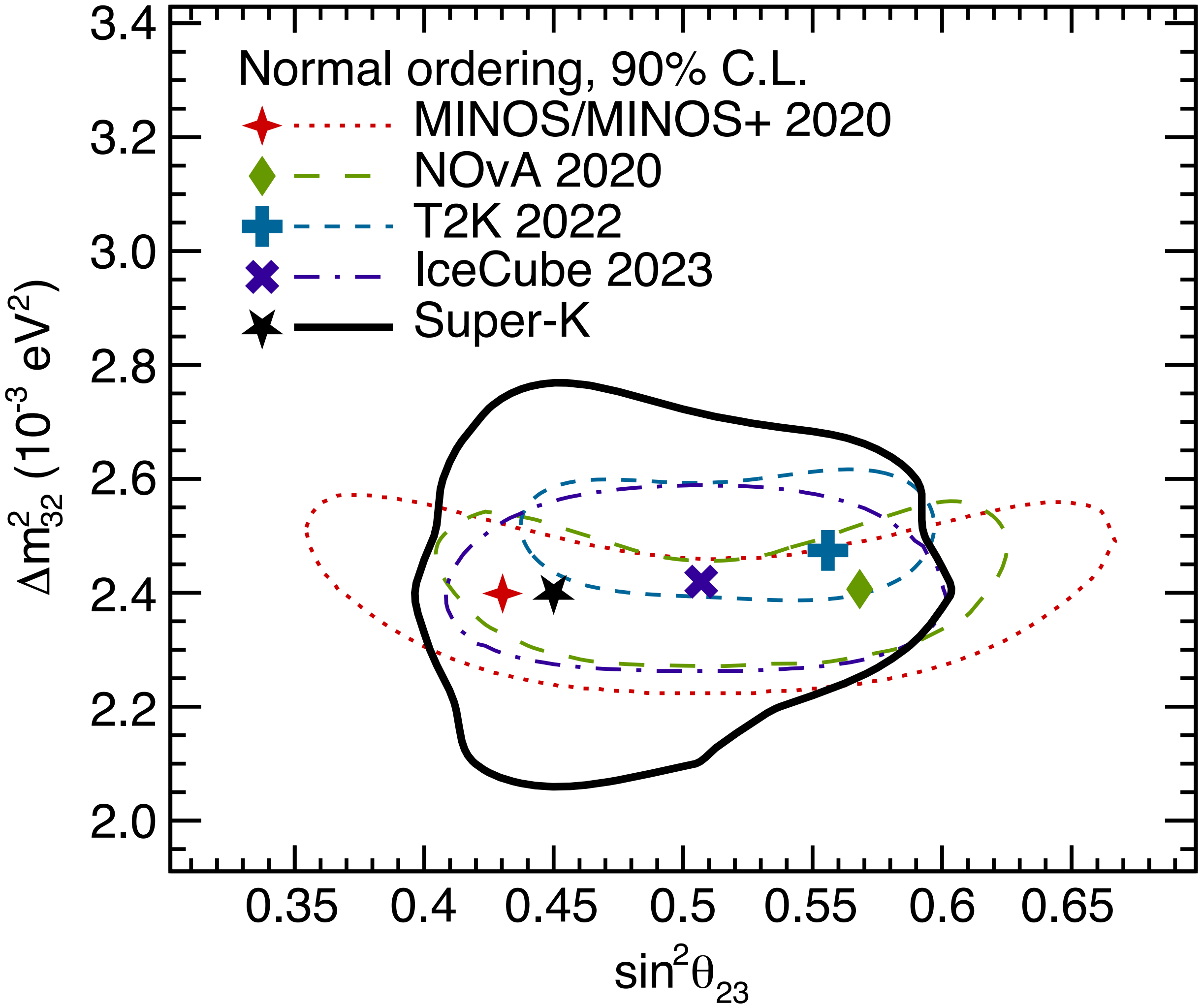
Neutron Tagging & Mass Ordering



Comparison between event selection from previous SK atmospheric neutrino oscillation publication & event selection using neutron tagging for SK IV-V (57% of total livetime) fully contained single-ring data

Oscillation parameters assumed: PDG 2022

Status of Atmospheric Mixing Parameters



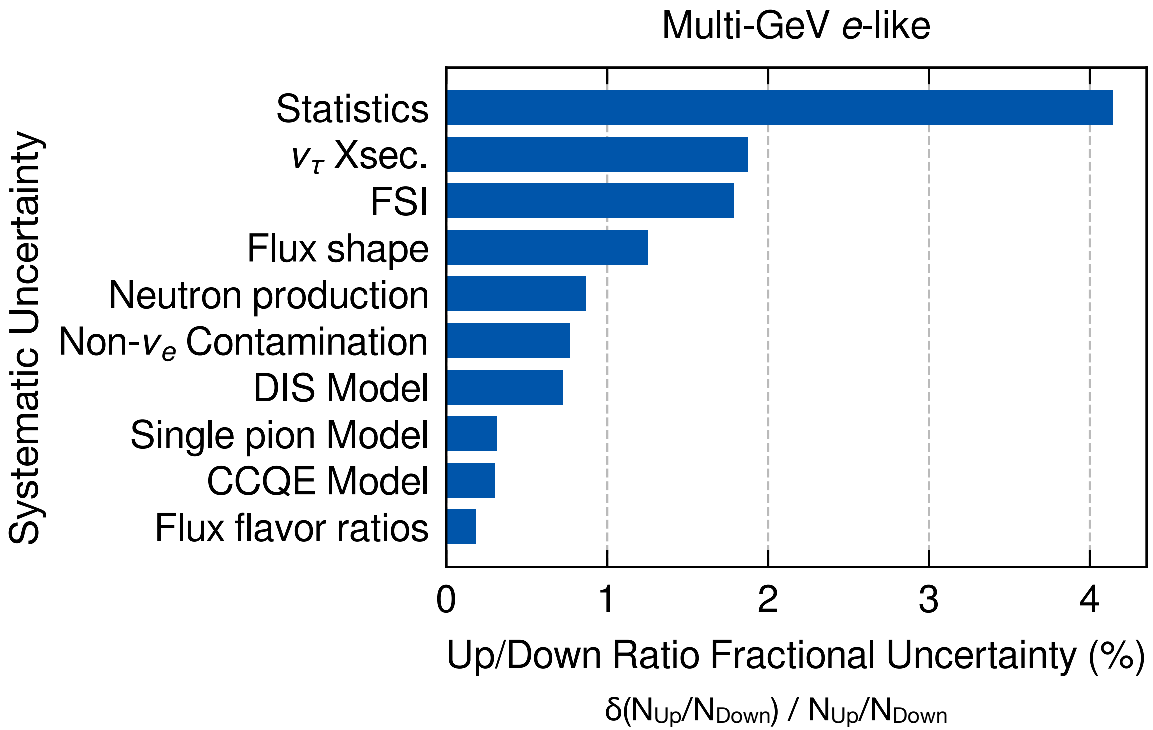
MINOS: Phys. Rev. Lett. **125**, 131802 (2020)

NOvA: 10.5281/zenodo.4142045 (2020)

T2K: Eur. Phys. J. C **83**, 782 (2023)

IceCube: Phys. Rev. D **108**, 012014 (2023)

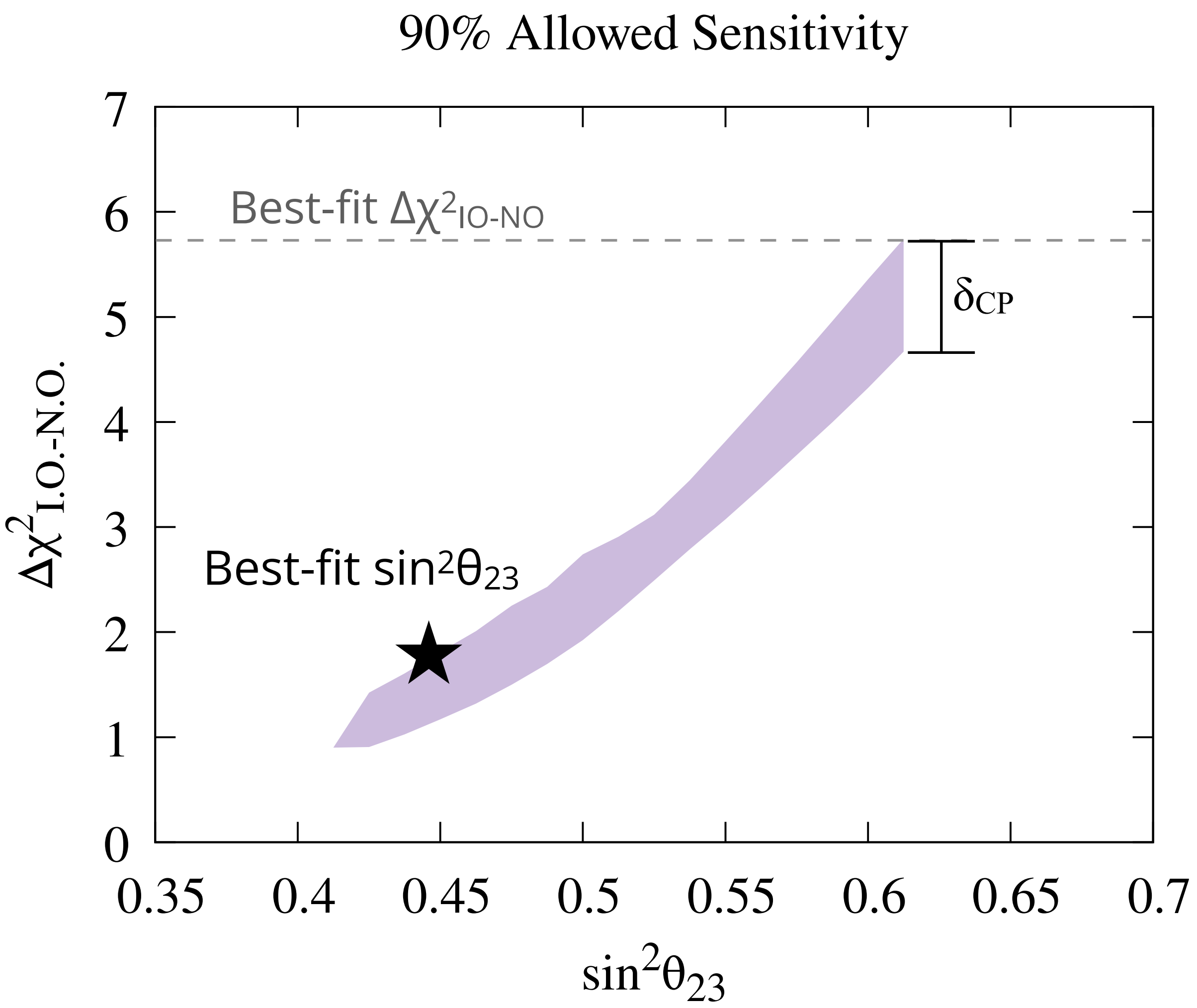
Systematic Uncertainty Importance



- Mass ordering analysis: Look for electron neutrino appearance in upward-going neutrinos
- Downward-going neutrinos constrain many flux and cross section uncertainties
- Systematic uncertainties with asymmetric zenith angle dependence have the largest effect on mass ordering analysis
- SK analysis is still statistics-limited

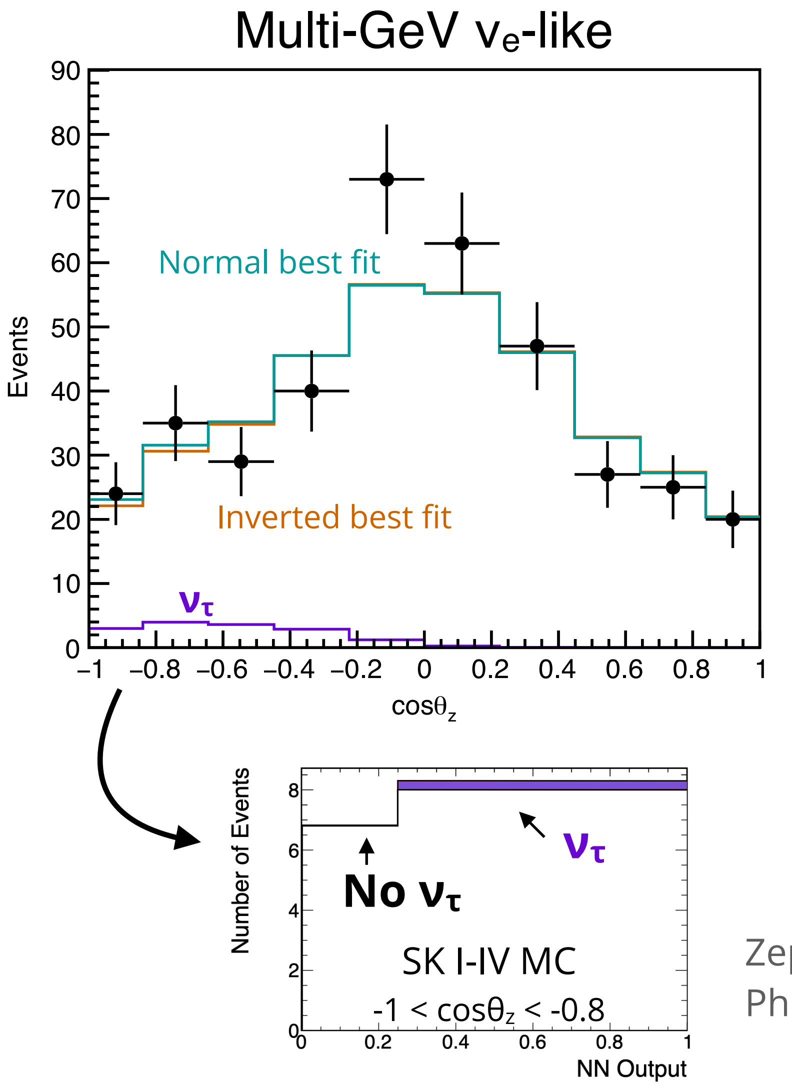
Mass Ordering Sensitivity vs. Octant

- Octant is constrained by sub-GeV events & multi-GeV ν_μ events with small mass ordering sensitivity
- Figure: Sensitivity for combinations of oscillation parameters allowed at 90% confidence level
- Upper-octant values of θ_{23} are closer to observed $\Delta\chi^2_{IO-NO}$, wide range



Reducing ν_τ Contamination

- ν_τ due to $\nu_\mu \rightarrow \nu_\tau$ oscillations appears in upward-going multi-GeV signal region for mass ordering
- No constraint from downward-going atmospheric neutrinos
- Developing neural network selection to divide Multi-GeV *e*-like events by ν_τ probability to reduce impact of cross section uncertainty



Zepeng Li
PhD Thesis, 2017

Constraints from T2K Model

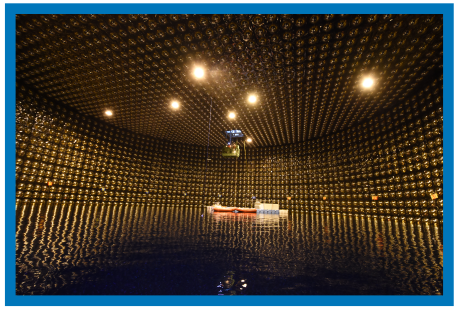
Why combine SK and T2K data?

- Synergy between atmospheric neutrino matter effect & precision measurements of θ_{23}, Δm^2_{32}, δ_{CP} from beam neutrinos
- Same H_2O target: Treat cross section uncertainties as correlated. Potential for improvements beyond likelihood sum

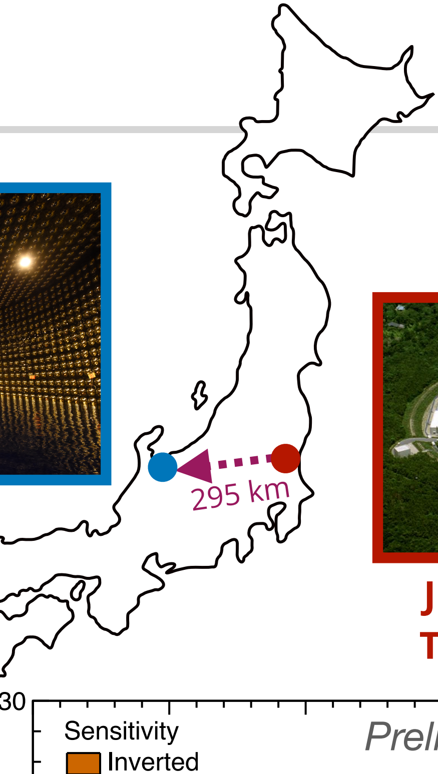
T2K Modeling approach:

- Re-weight atmospheric MC to T2K's nominal flux and cross section parameters and approximates T2K's systematic uncertainty treatment from published information
- Fit model to published T2K bin counts as additional bins in atmospheric fit

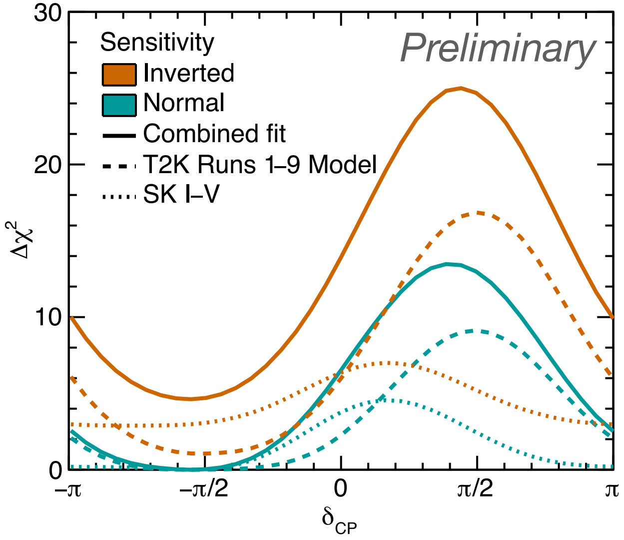
*Model based on on Phys. Rev. D **103**, 112008 (2021)*



Super-K



JPARC accelerator, T2K near detectors



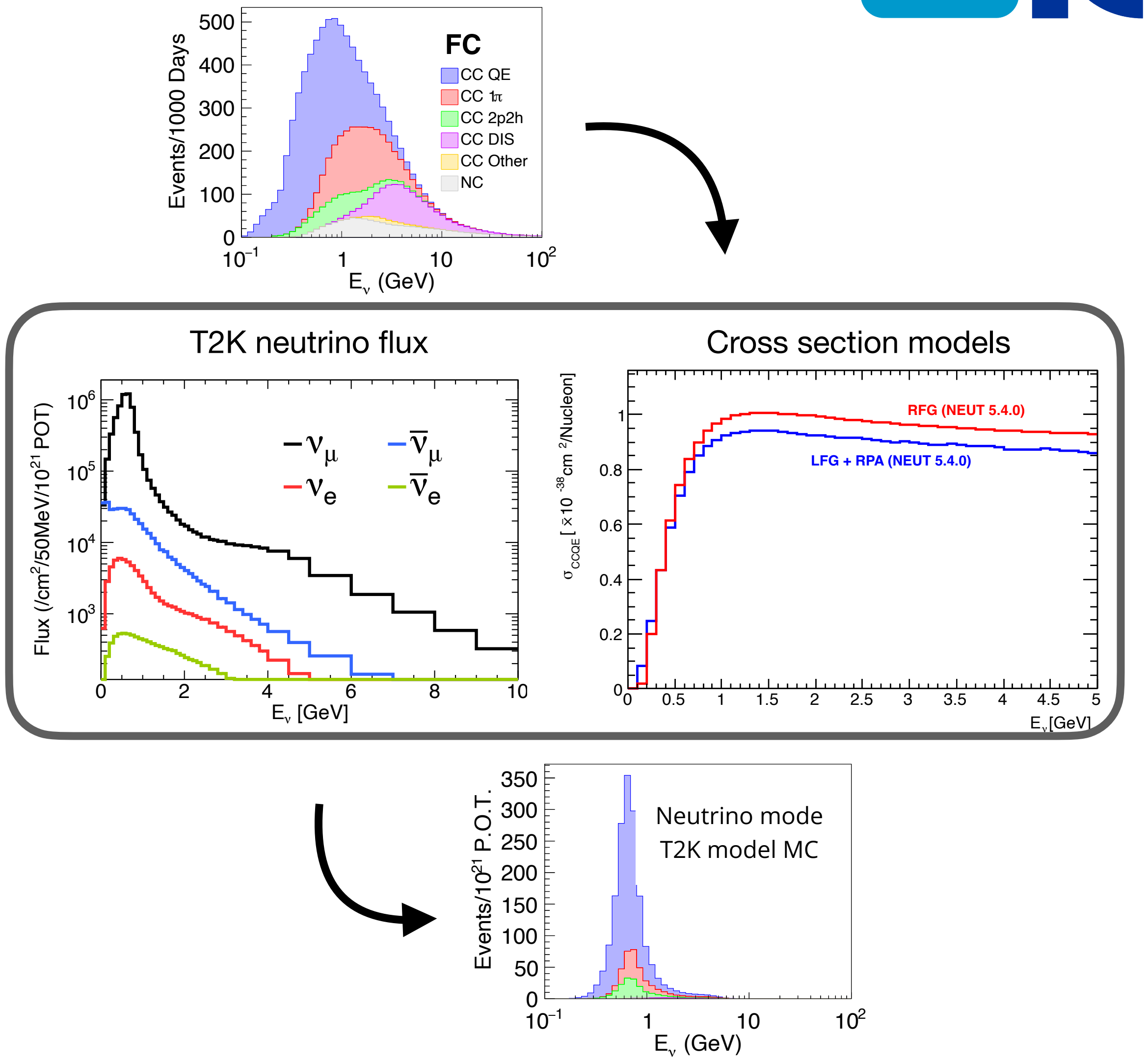
T2K Model

T2K Model re-weights atmospheric MC to the nominal cross section and flux models from the T2K runs 1–9 analysis

- CCQE model: RFG+RPA, M_A^{QE}=1.13±0.08 GeV/c^2
- Single pion model: Rein-Seghal, C_A^5=0.98±0.06, $I_{½}$=1.31±0.26, M_A^{Res}=0.81±0.04 GeV/c^2
- SK models and uncertainties used for 2p2h, DIS, FSI processes

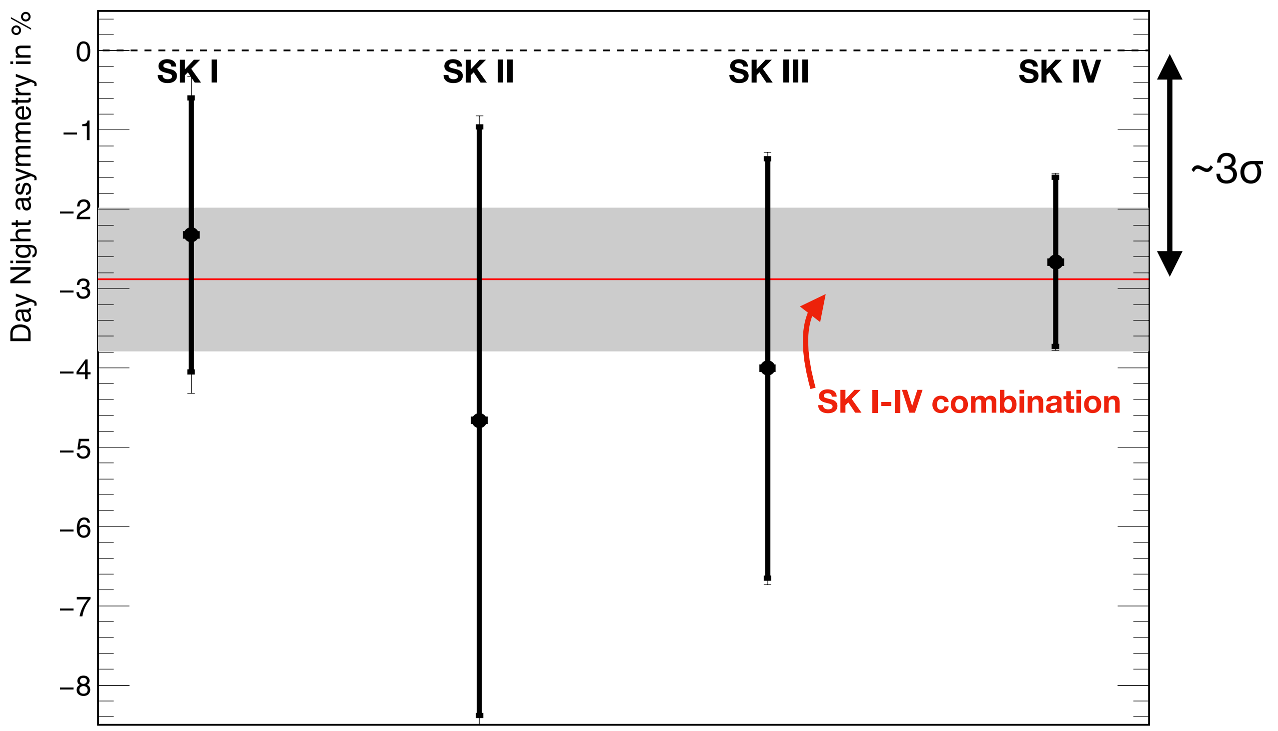
Flux and cross section central values and uncertainties are taken to be post-ND280 fit from Phys. Rev. D **103**, 112008 (2021)

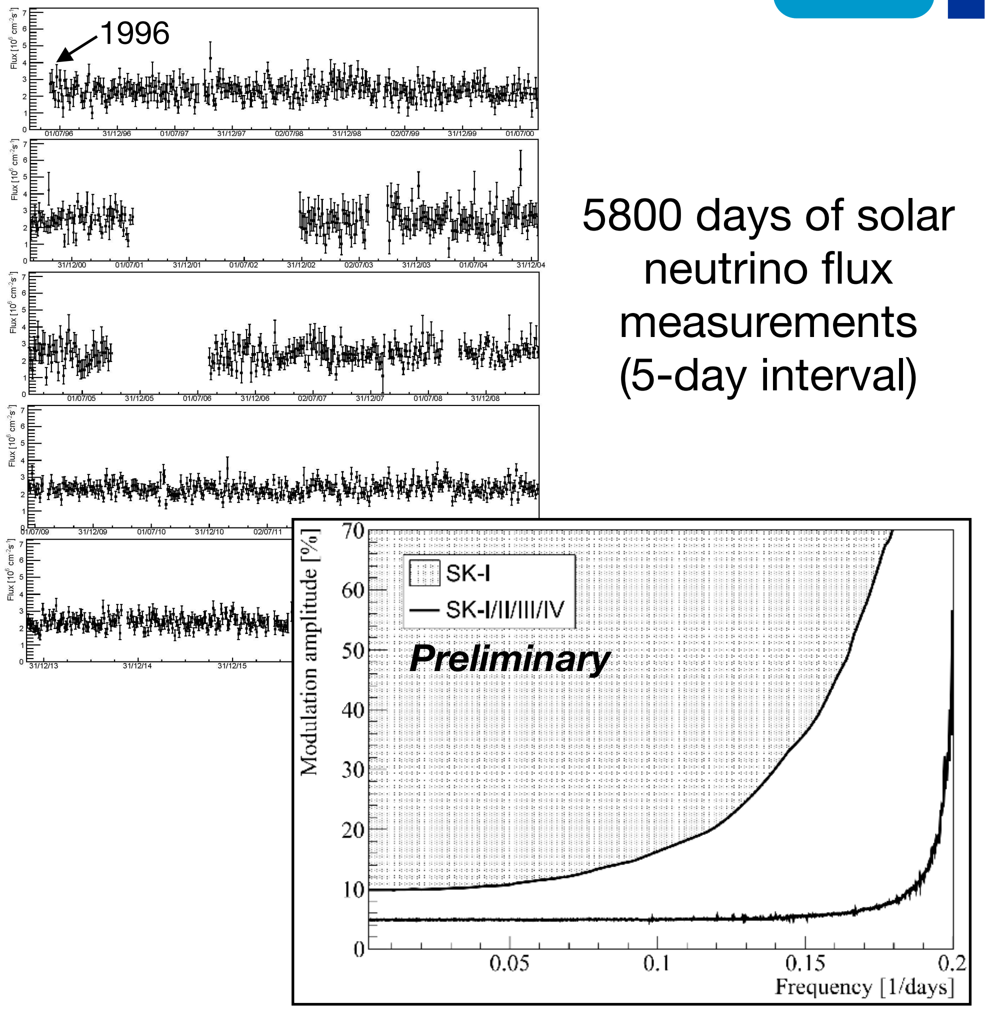
More details: SK 2018 PRD, T. Wester PhD thesis



Other Solar Neutrino Results

Day/Night Asymmetry in Solar Neutrino Flux

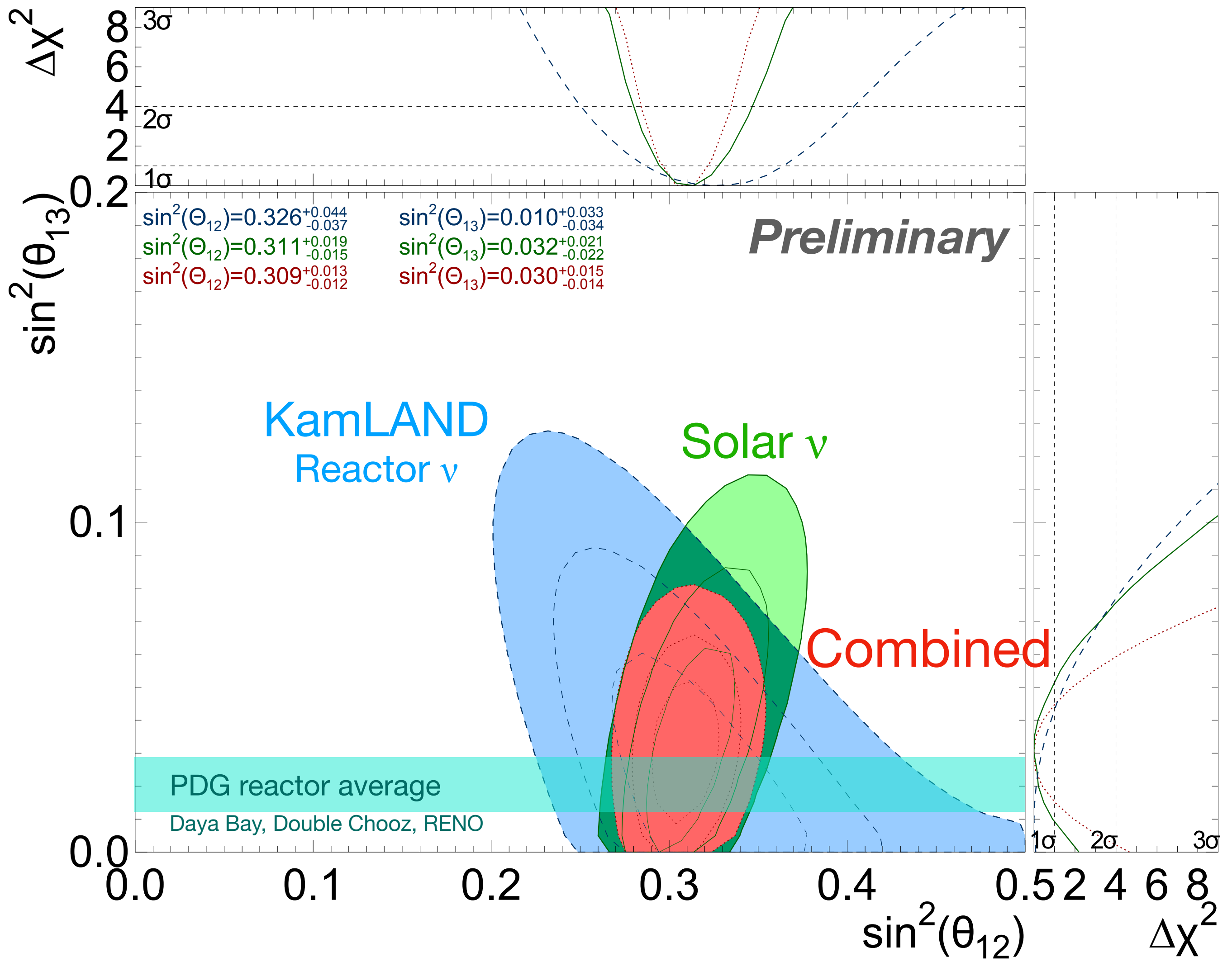




5800 days of solar neutrino flux measurements (5-day interval)

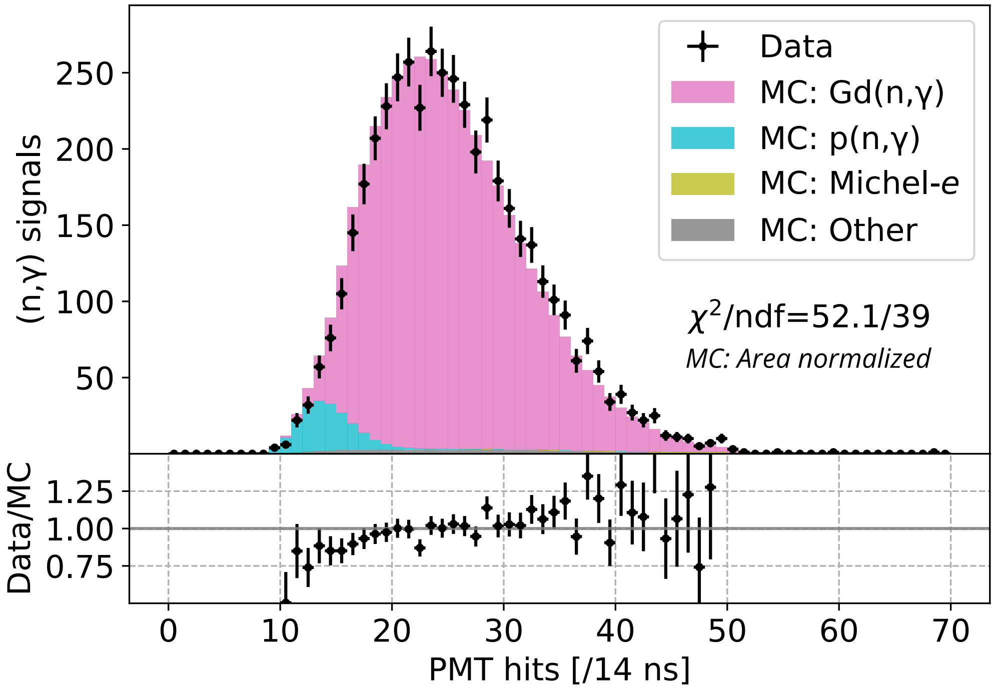
Solar ^{8}B ν flux modulation < 5% @ 95% C.L.

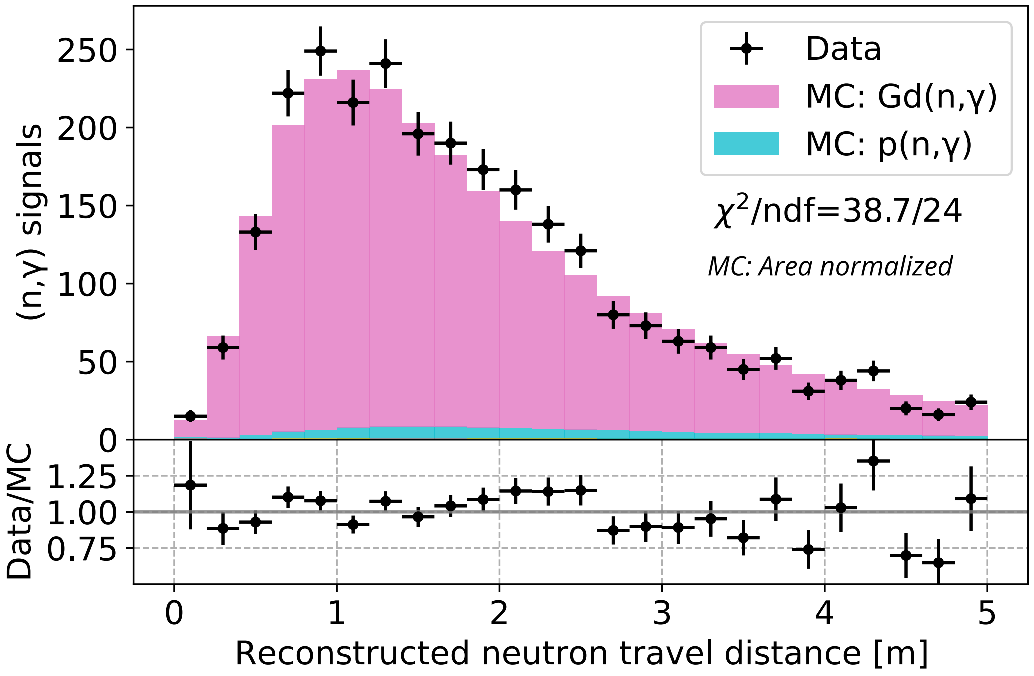
Solar Neutrino Global Fit of θ_{13}



SK-Gd for Atmospheric Neutrinos

SK-Gd data, 0.01% Gd loading. Atmospheric neutrino events





Improved ν-ν̄ separation expected from higher neutron tagging efficiency with Gd captures. Many more captures per event

Improved neutrino reconstruction expected using capture vertex. Neutrino energy correlates with neutron travel distance.