Latest Atmospheric Neutrino Oscillation Results from Super-Kamiokande

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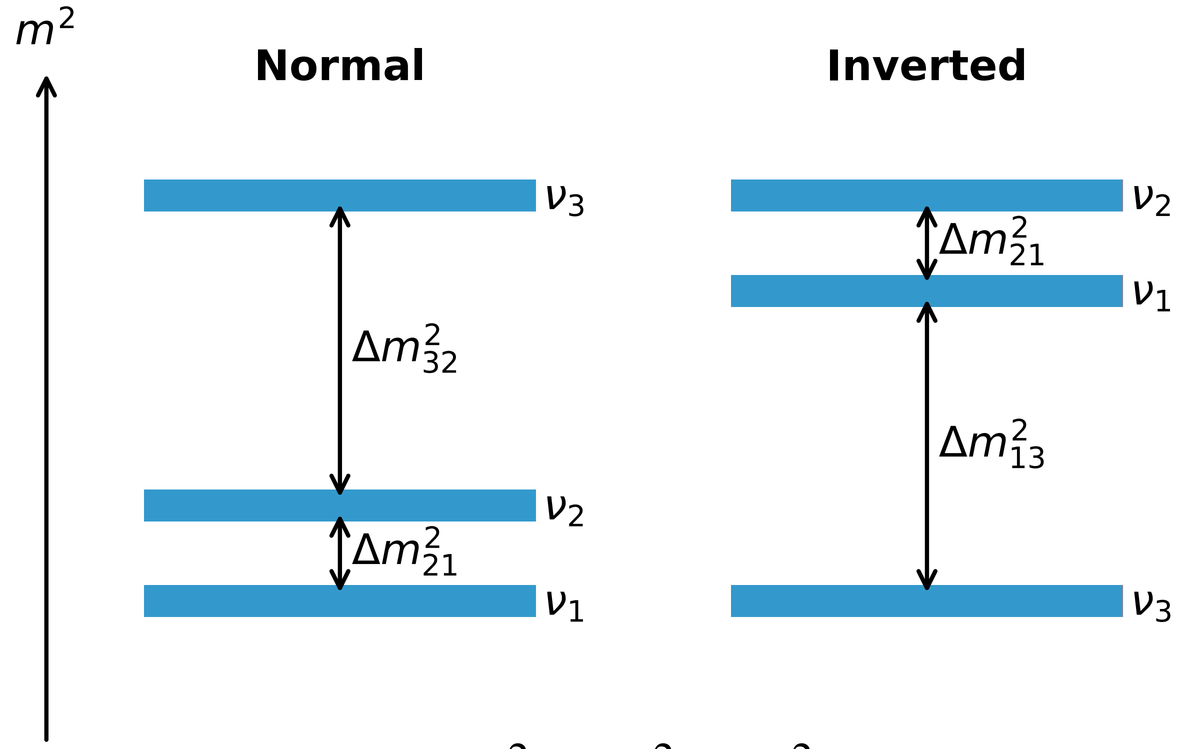
On behalf of the Super-Kamiokande Collaboration
Fermilab Wine & Cheese Seminar, 2024 Feb 09

*Now an SBND collaborator

BOSTON UNIVERSITY

Neutrino Mass Ordering

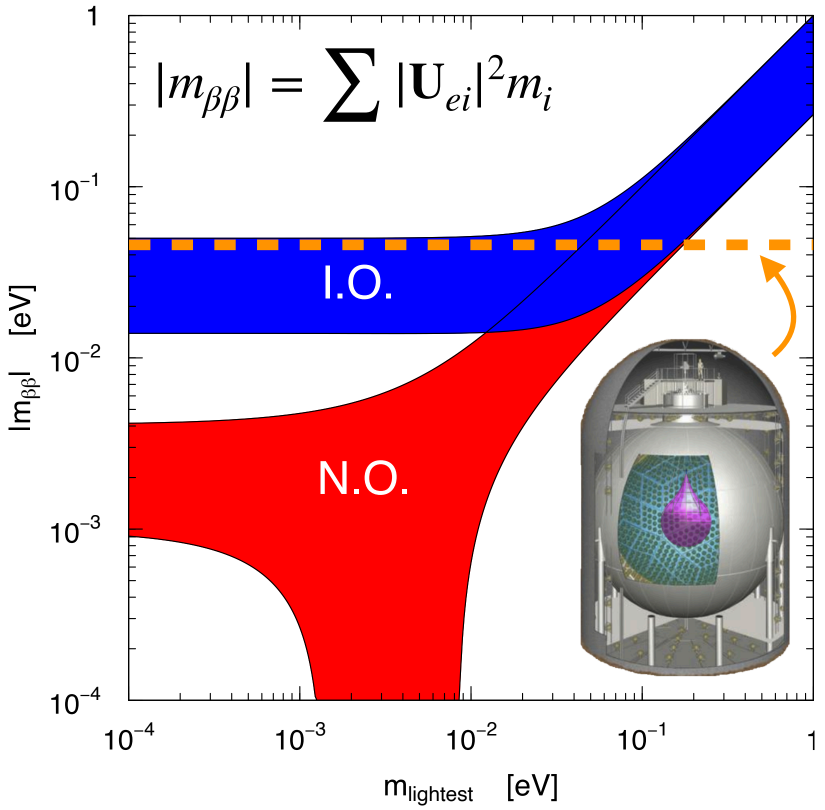
Two heavy & one light neutrino or the other way around?



$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Mass Ordering Connections

Neutrino-less
Double beta decay



de Salas et al. Front. Astron. Space Sci. **5** (2018)

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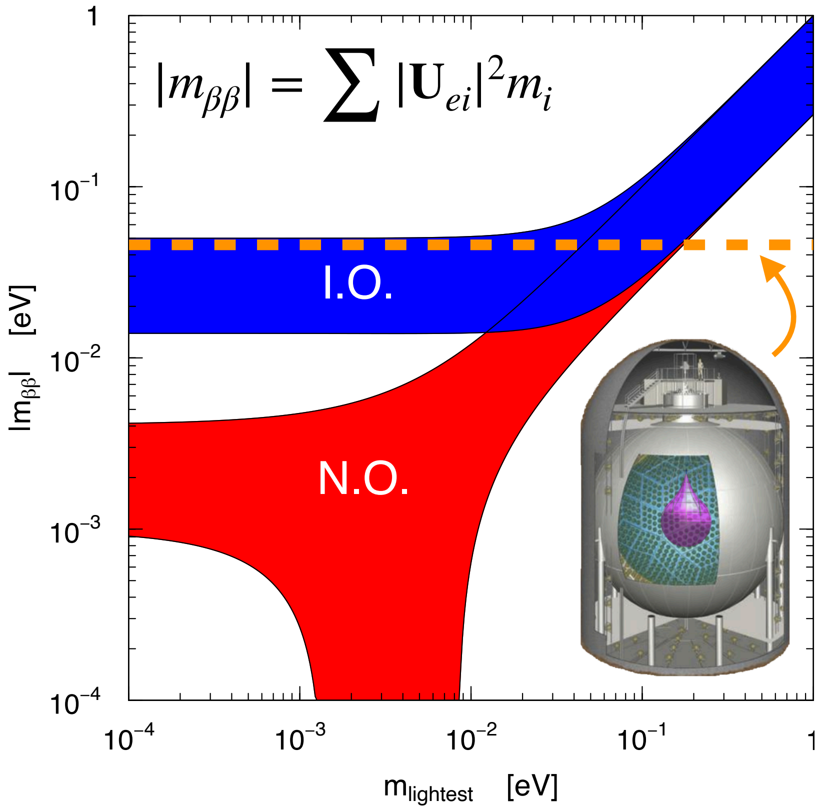

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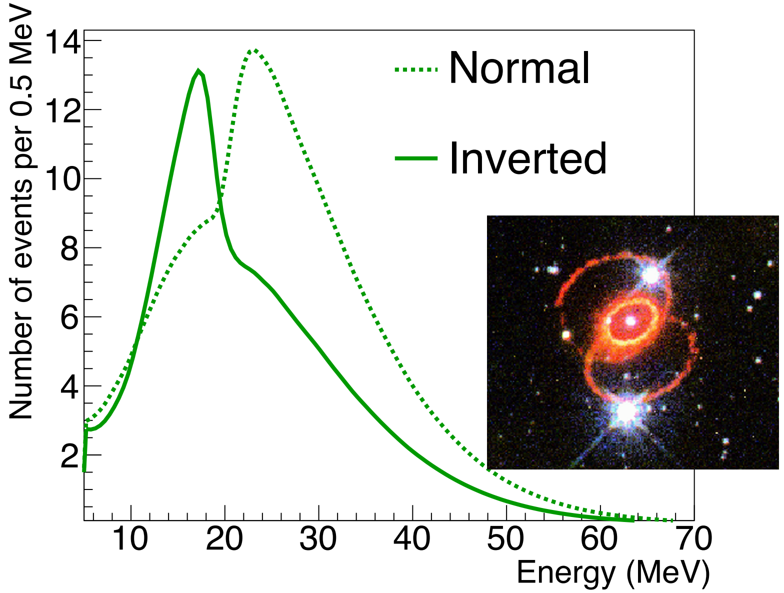
Supernova



K. Scholberg, J. Phys. G. Nucl. Part. **45** 014002 (2017)

Mass Ordering Connections

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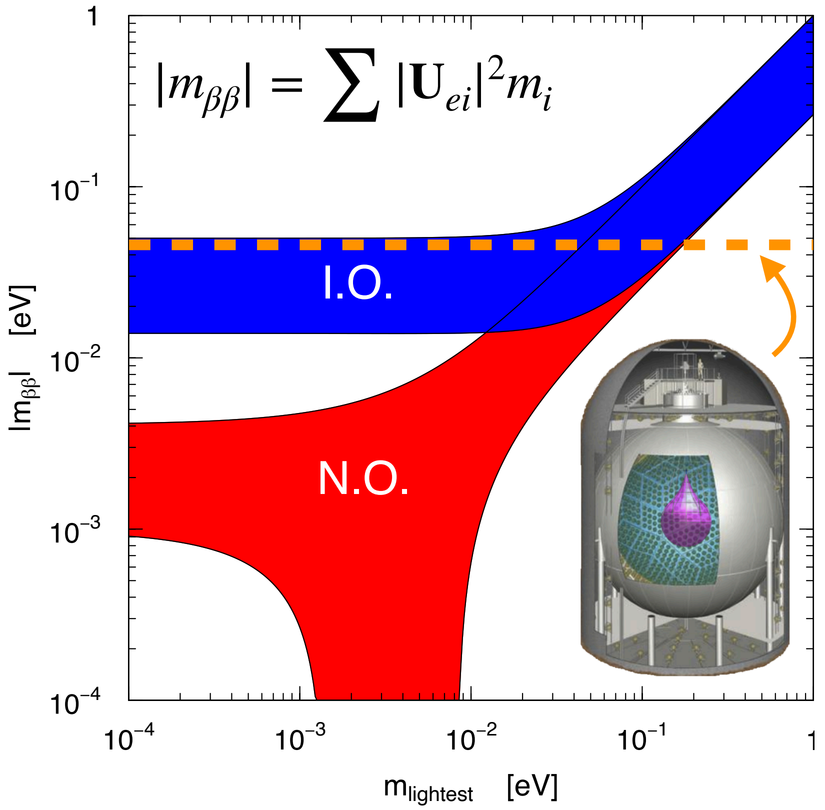

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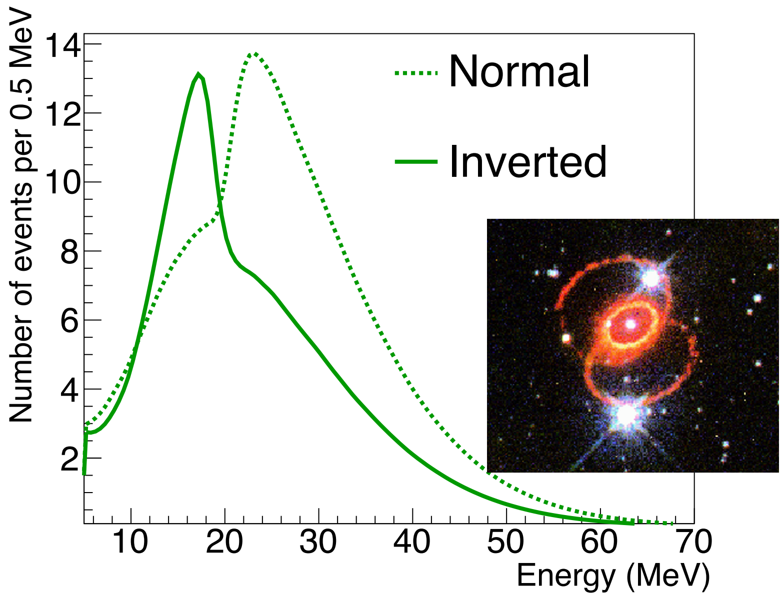
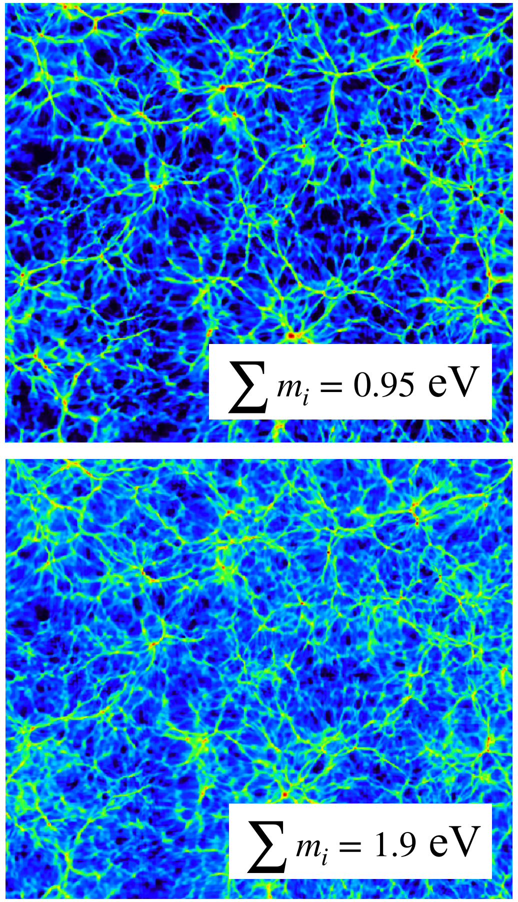


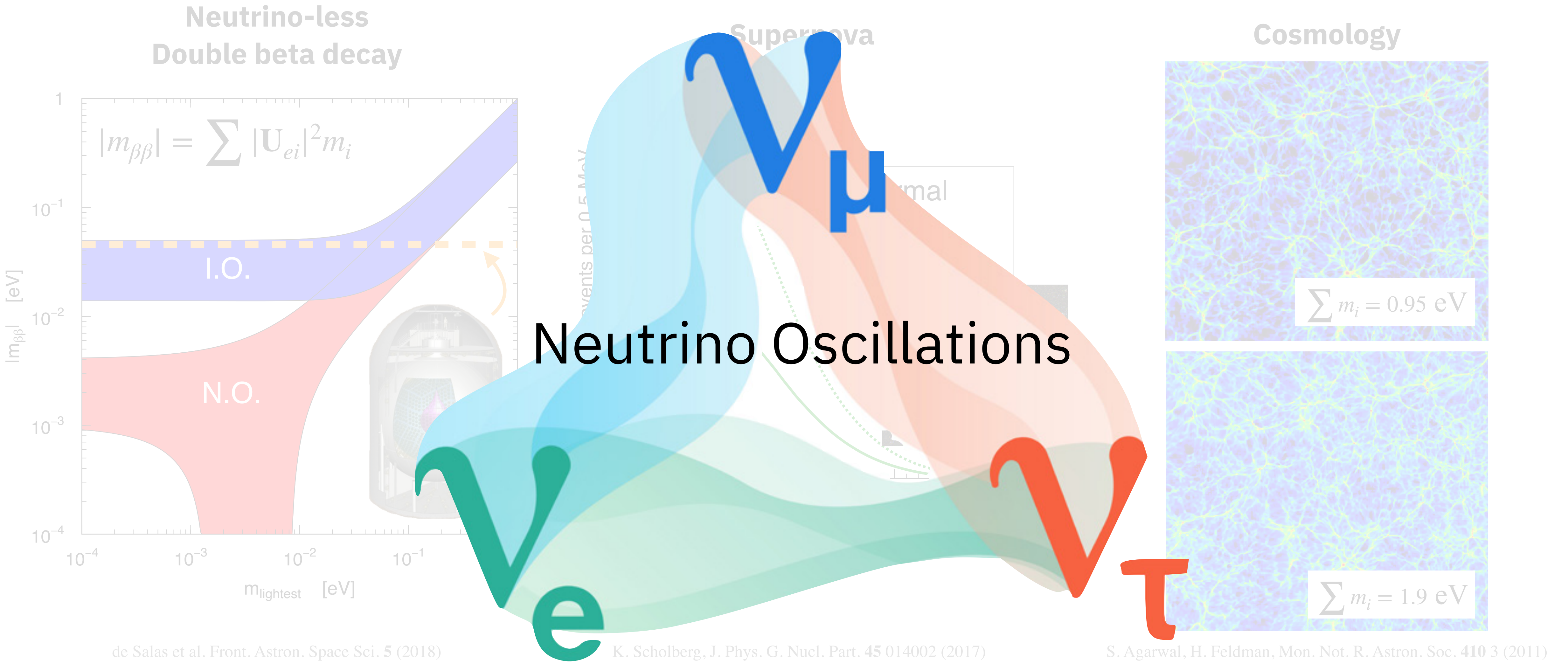
K. Scholberg, J. Phys. G. Nucl. Part. **45** 014002 (2017)

Cosmology



S. Agarwal, H. Feldman, Mon. Not. R. Astron. Soc. **410** 3 (2011)

Mass Ordering Connections



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Neutrino Mass & Oscillations

Neutrino flavor states ≠ mass states → Mixing

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Flavor states
(What we observe)

$\mathbf{U}$ = PMNS matrix

Mass states

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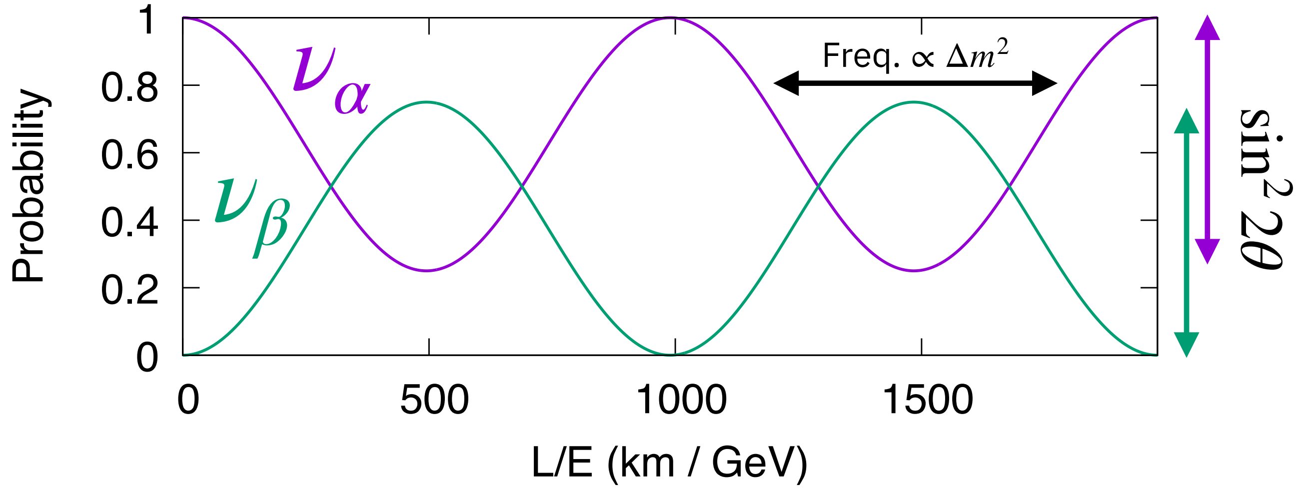

PDG 2023 World Averages

Parameter	Value	1σ	Uncertainty (%)
$\sin^2\theta_{12}$	0.307	0.013	4
$\sin^2\theta_{13}$	0.0220	0.0007	3
$\sin^2\theta_{23}$	0.547	0.021	4
δ_{CP}/π (Rad.)	1.23	0.21	17
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	0.18	2
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.437	0.033	1

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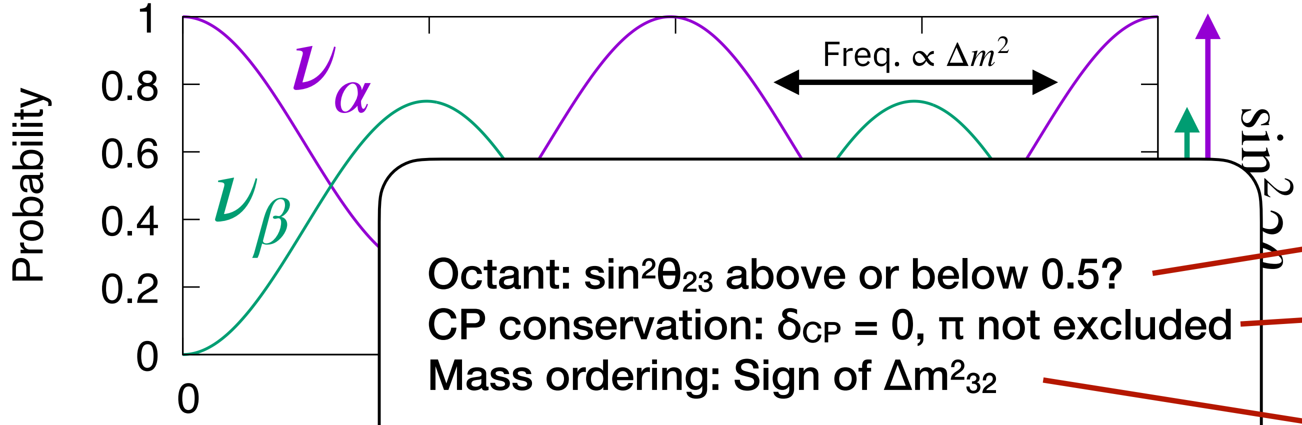
Flavor states (What we observe)

U = PMNS matrix

Mass states



Octant: $\sin^2\theta_{23}$ above or below 0.5?
CP conservation: δ_{CP} = 0, π not excluded
Mass ordering: Sign of Δm^2_{32}

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Mass Ordering in Neutrino Oscillations

Matter effect: Electron neutrino forward scattering introduces dependence on sign of Δm^2,

$$\sin^2 2\theta_{13,\text{Matter}} = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left(\pm 2\sqrt{2} G_F N_e E / \Delta m^2 - \cos 2\theta_{13}\right)^2}$$

G_F: Fermi constant
N_e: Electron density
$\pm$: ν / $\bar{\nu}$

RENO, Daya Bay, Double Chooz reactor neutrino experiments: $\theta_{13} \approx 8.5°$

$\Rightarrow \nu_\mu \to \nu_e$ or $\bar{\nu}_\mu \to \bar{\nu}_e$ resonance possible when $2\sqrt{2} G_F N_e E/\Delta m^2 \sim 1$

Mass Ordering Challenges

- Size of Matter Effect

- Degeneracy with δ_{CP}

Mass Ordering Challenges

- Size of Matter Effect

  Neutrino beams travel through earth's crust, $\rho \sim 3$ g/cm^3
  $\rightarrow 2\sqrt{2}G_F N_A E\rho/\Delta m^2 \sim 0.2$ for 1 GeV neutrino

  - Increase effect using longer L and higher E
  - Increase ρ? inner Earth layers 5–11 g/cm^3
    (more on this later)

- Degeneracy with δ_{CP}

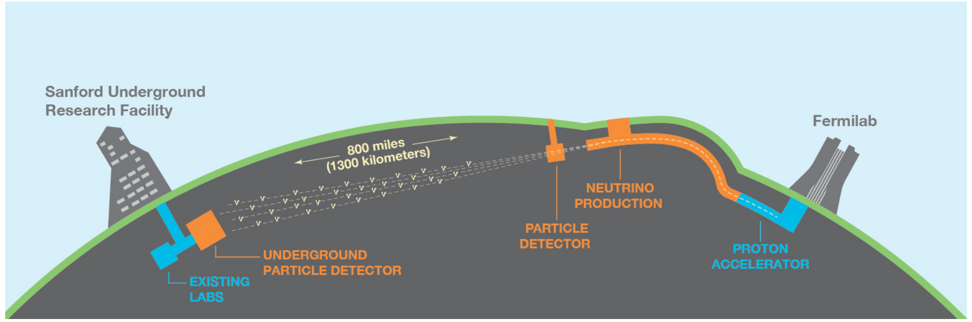

Image: Fermilab DUNE

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  - Increase effect using longer L and higher E
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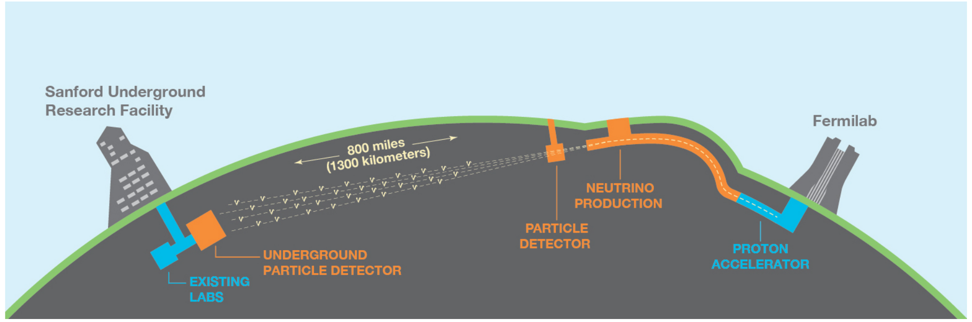
- Degeneracy with δ_{CP}
  - Mass ordering signal is enhanced $\nu_\mu \rightarrow \nu_e$ or $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, same signal for $\delta_{CP} \neq 0, \pi$
  - Maximum ν_e appearance is best-fit by normal ordering & $\delta_{CP} \sim -\pi/2$, but multiple combinations can explain other outcomes



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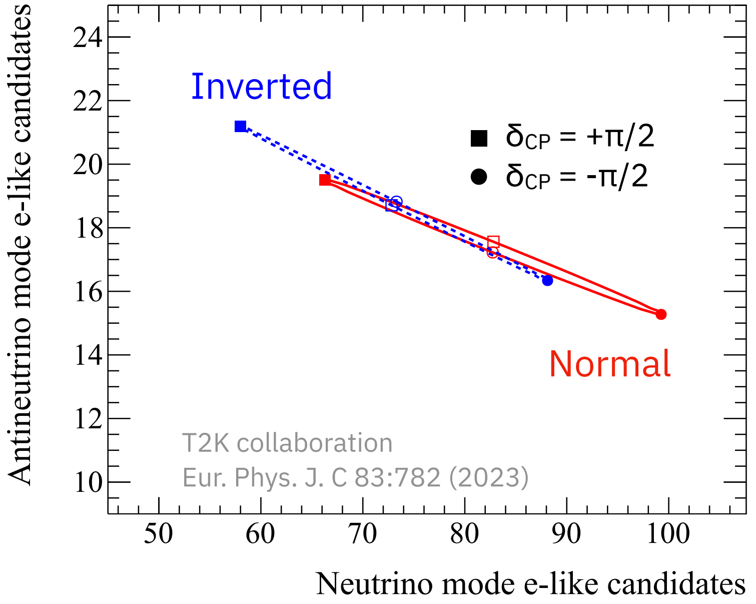
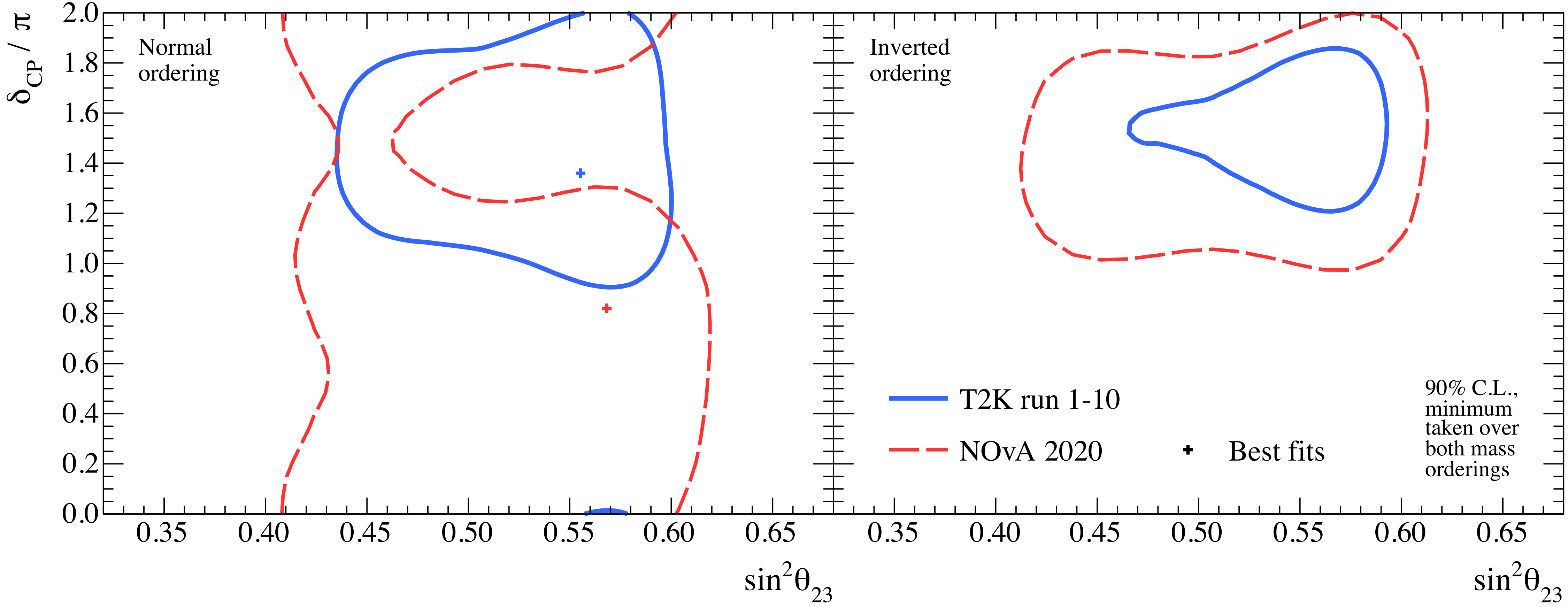


Present Status from Neutrino Beams



T2K Collaboration, Eur. Phys. J. C 83:782 (2023)
NOvA contour: Phys. Rev. D **106**, 032004 (2022)

Atmospheric Neutrino Oscillation Analysis

arXiv:2311.05105

Data release: 10.5281/zenodo.8401262

Atmospheric Neutrinos

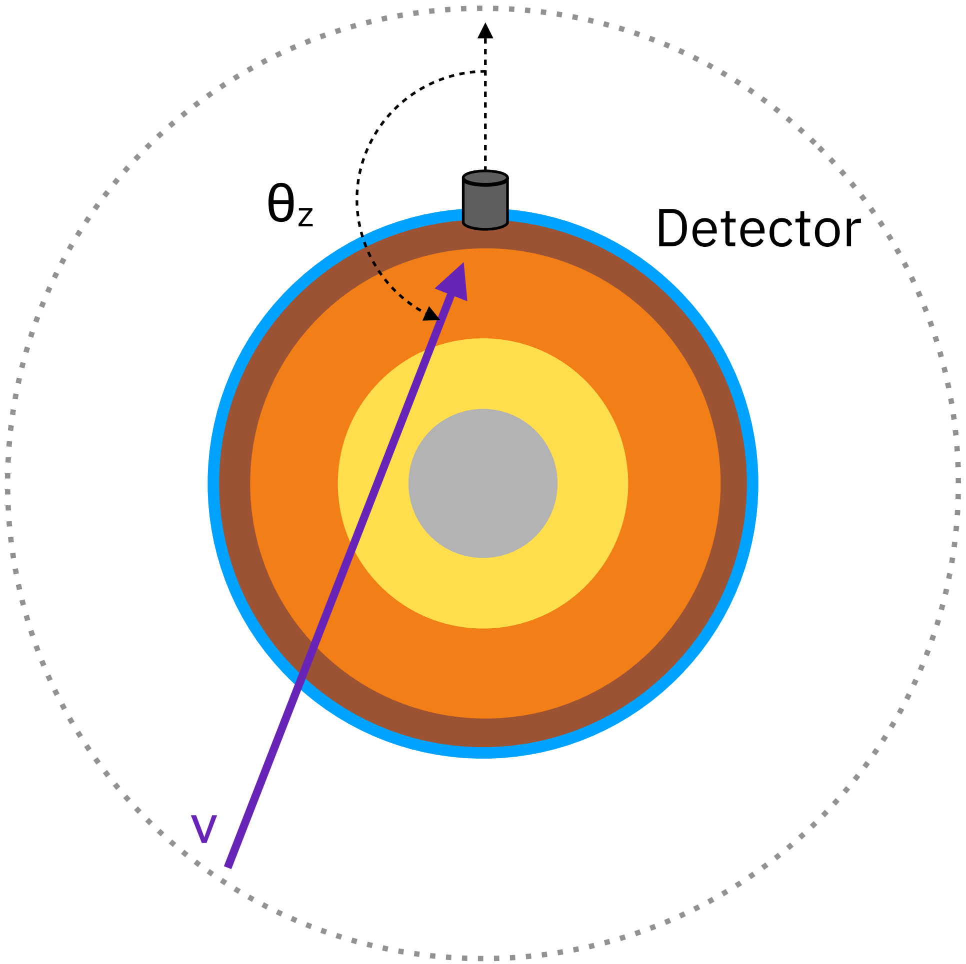
Production in particle showers from cosmic rays:

$$\pi^+ \to \mu^+ + \nu_\mu$$

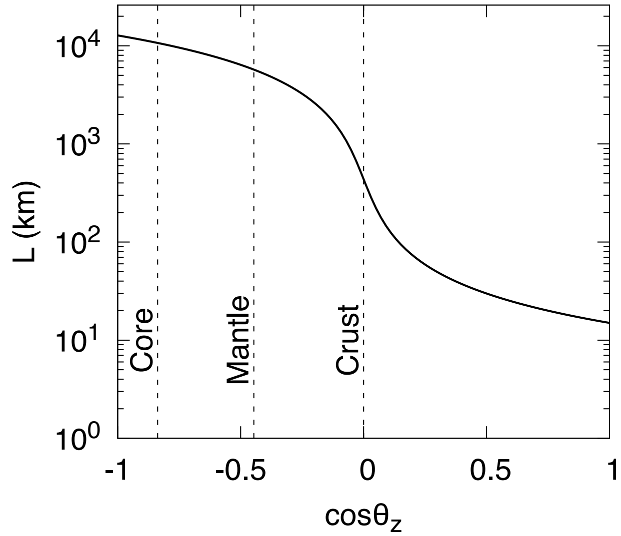
$$\quad \hookrightarrow \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

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

$$\quad \hookrightarrow \mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

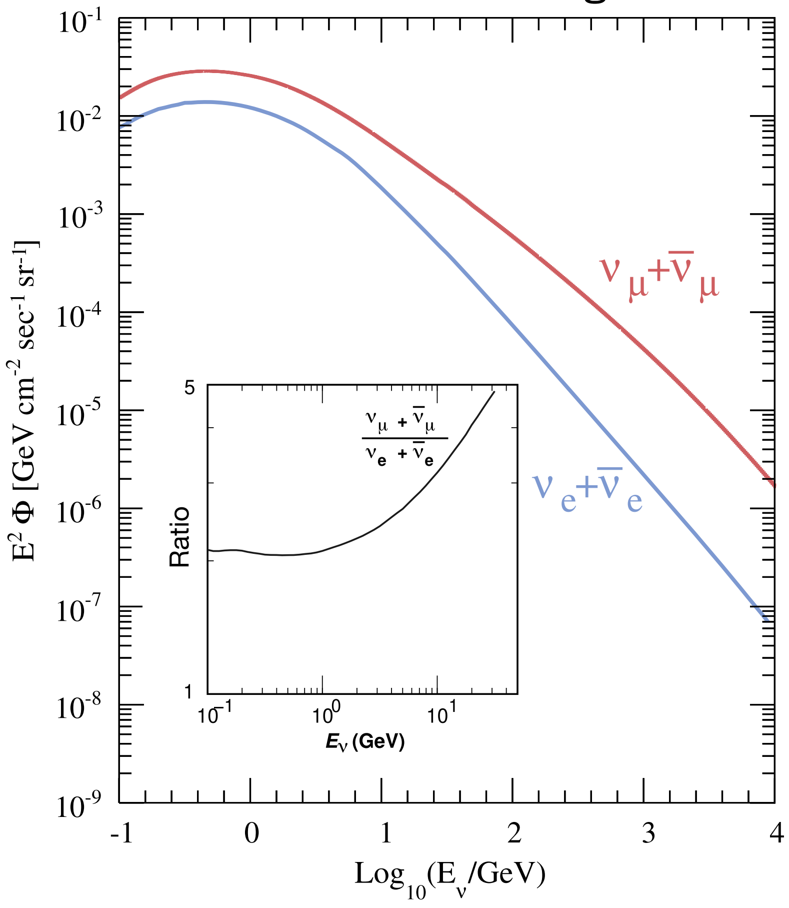


Zenith angle (neutrino direction) determines baseline ~15–13,000 km



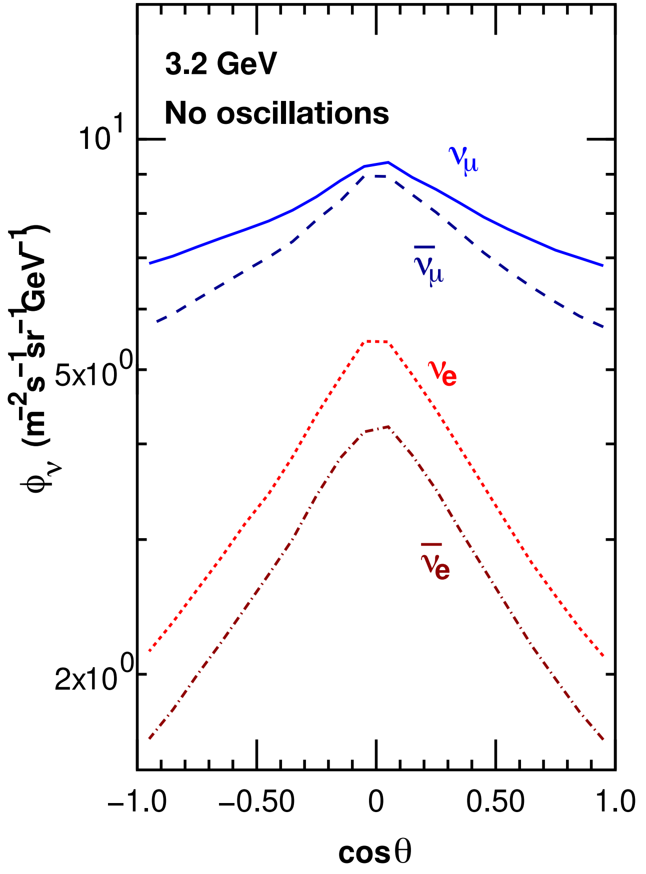
Atmospheric Neutrino Flux

MeV to TeV energies



Phys. Rev. D **94**, 052001 (2016)

Up/down symmetric flux for E_ν > few GeV



Phys. Rev. D **83**, 123001 (2011)

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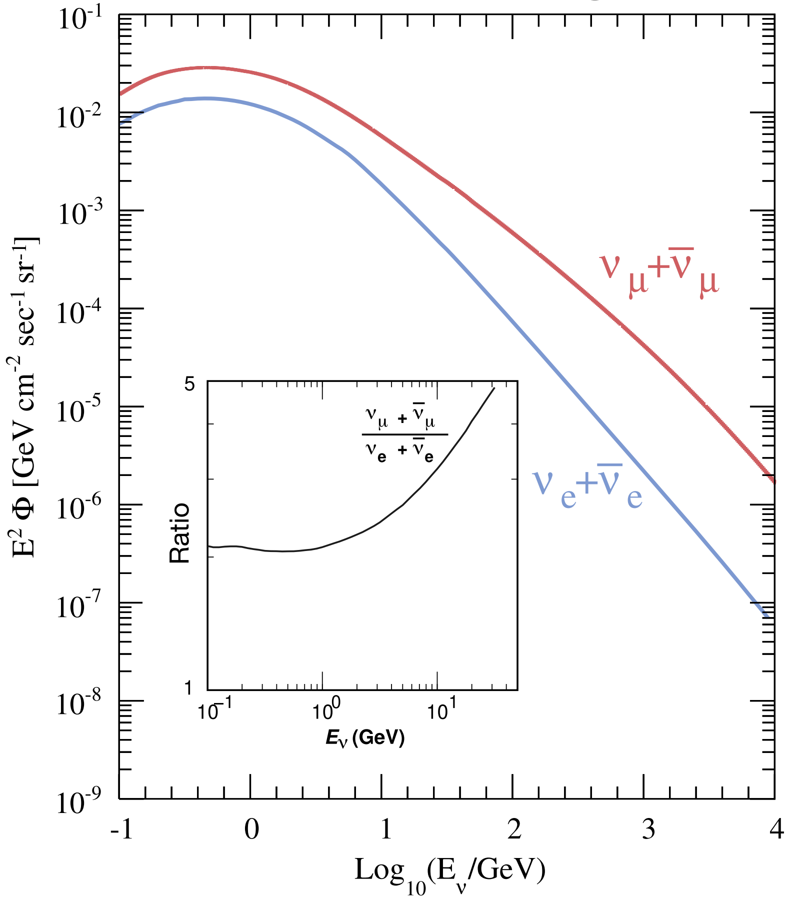

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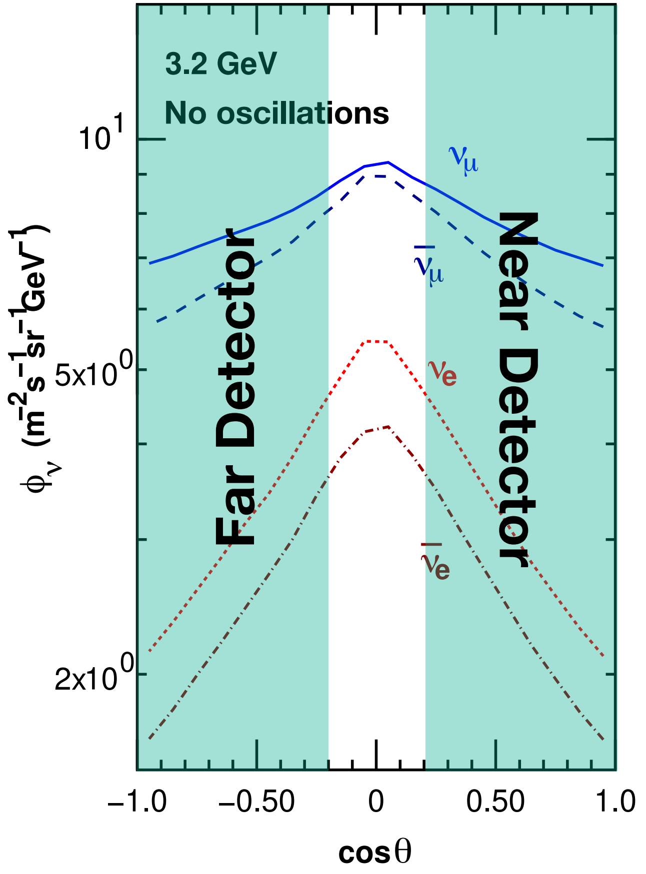
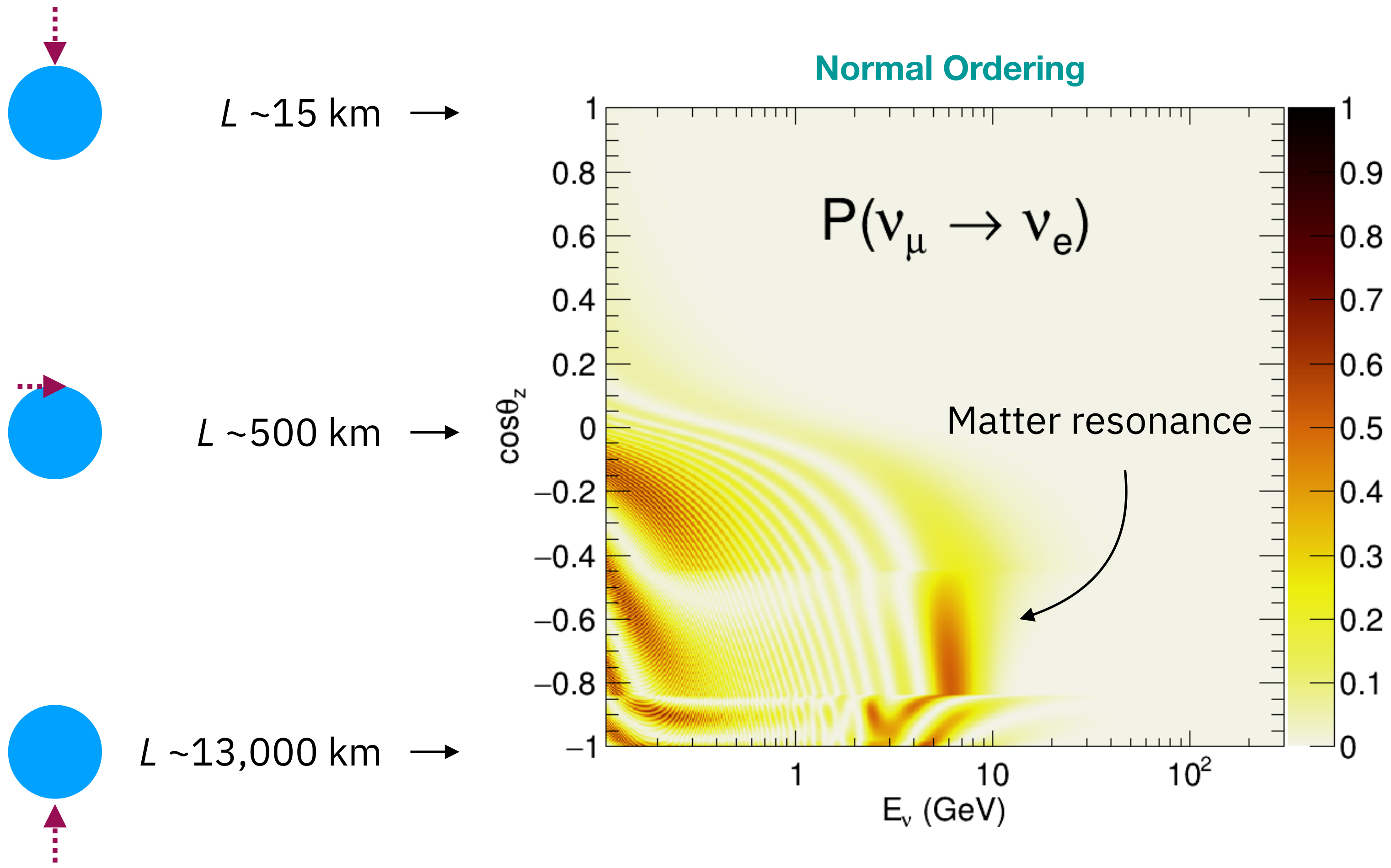
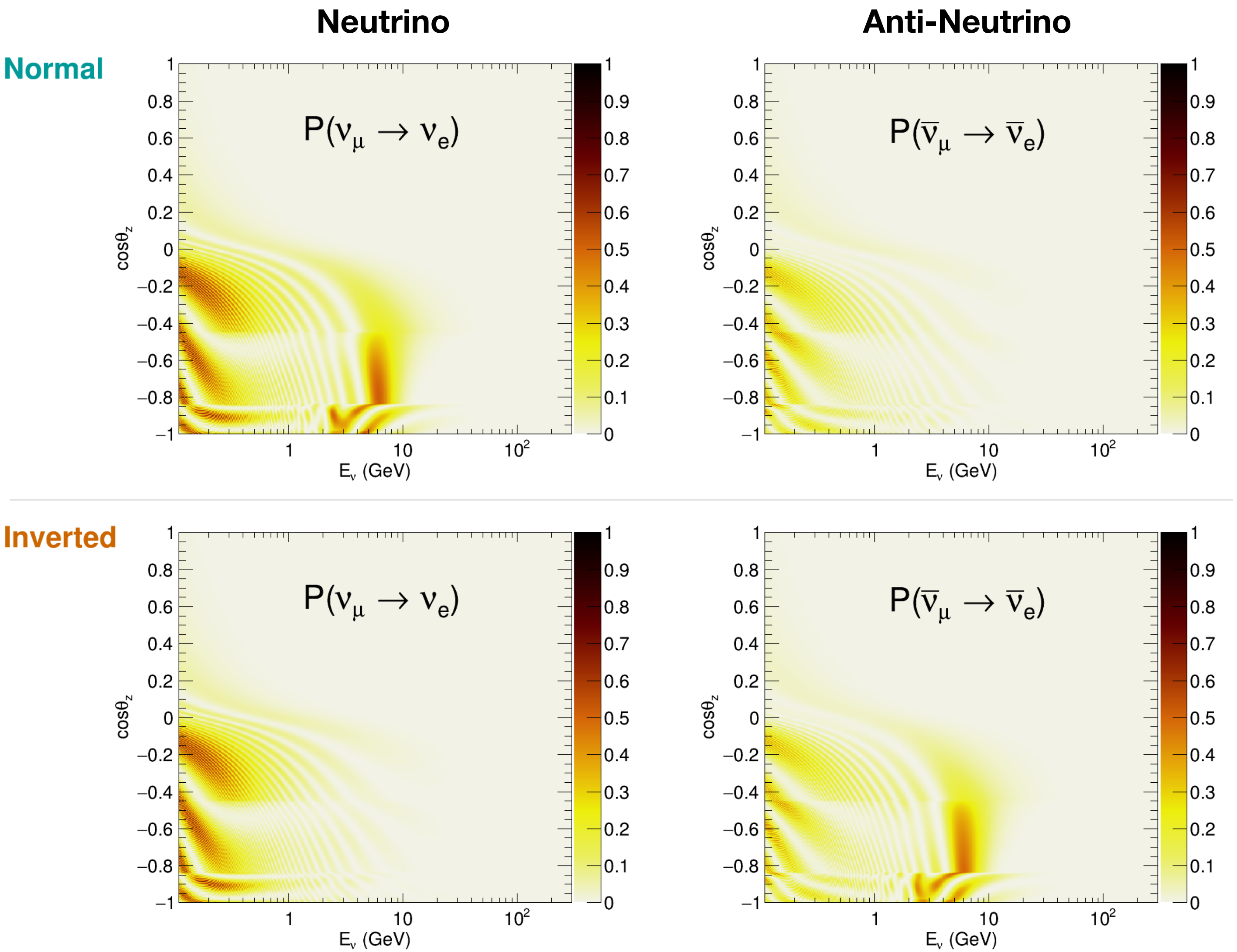


Phys. Rev. D **83**, 123001 (2011)

Mass Ordering in Atmospheric Neutrinos



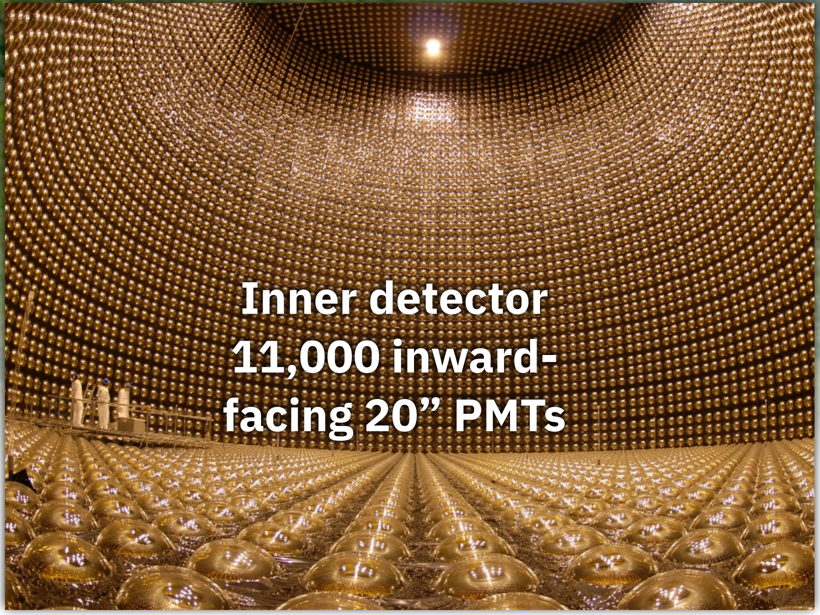
Mass Ordering in Atmospheric Neutrinos

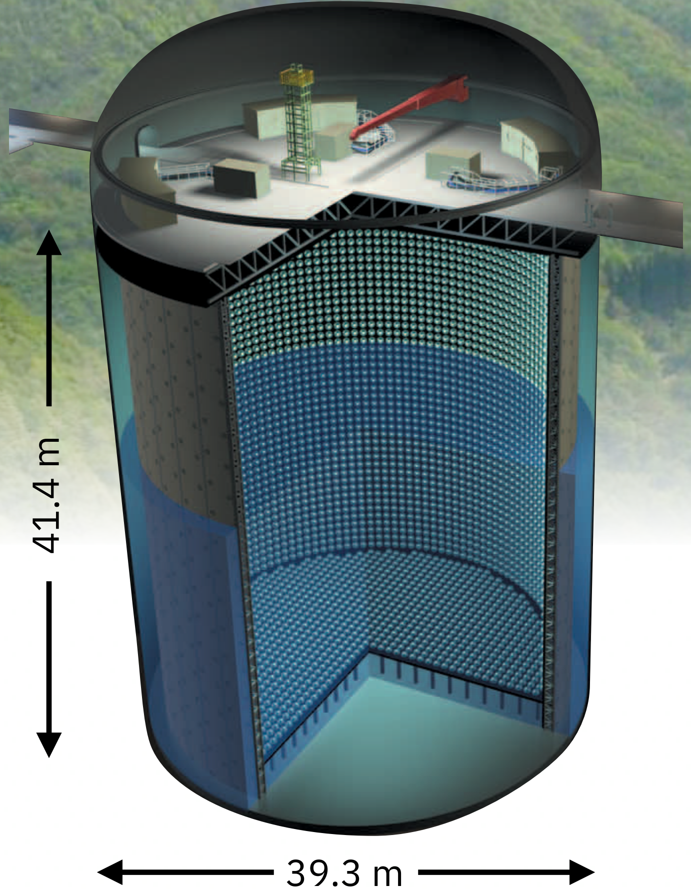


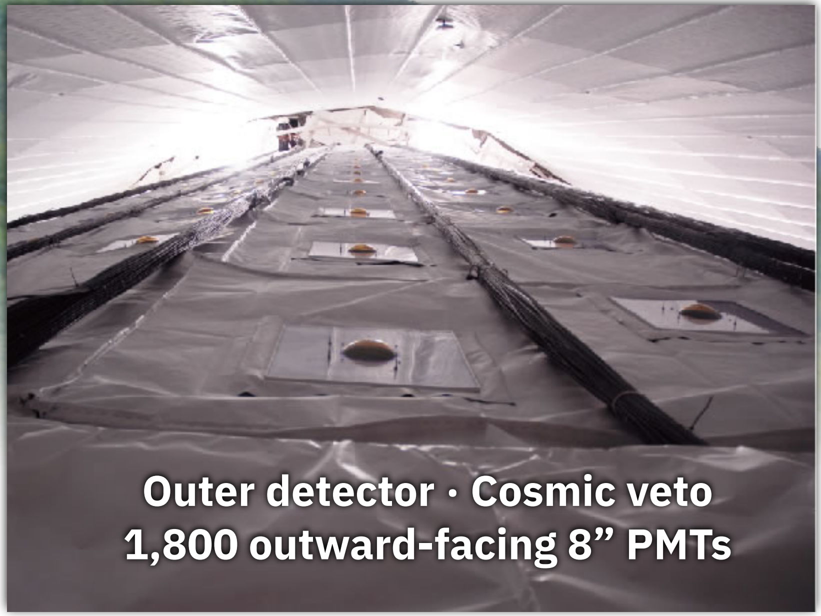
Parameters
$\sin^2\theta_{23} = 0.5$
$\Delta m^2_{32} = 2.4\times10^{-3}$
$\delta_{CP} = -\pi/2$
$\sin^2\theta_{13} = 0.022$

Super-K Experiment

Mt. Ikenoyama
(1 km overburden)

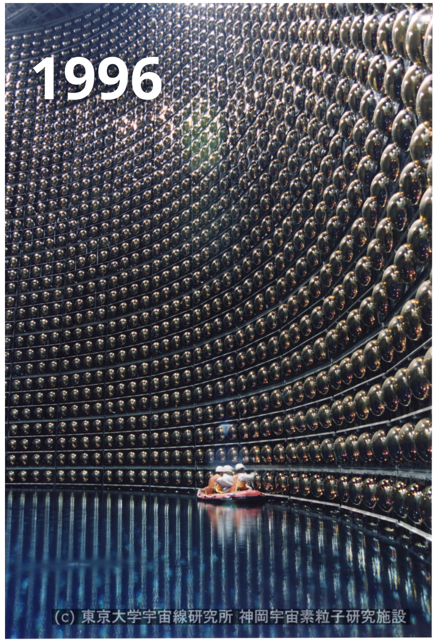


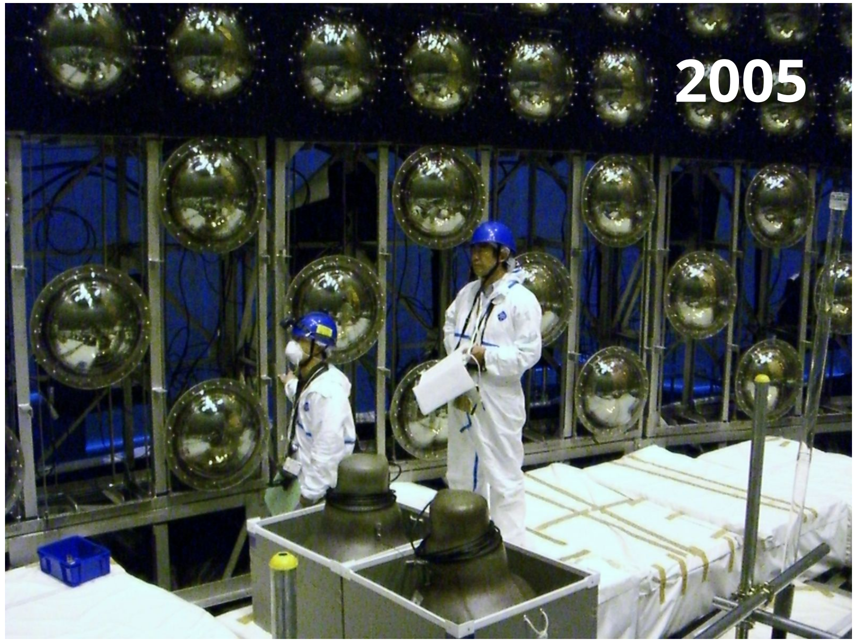


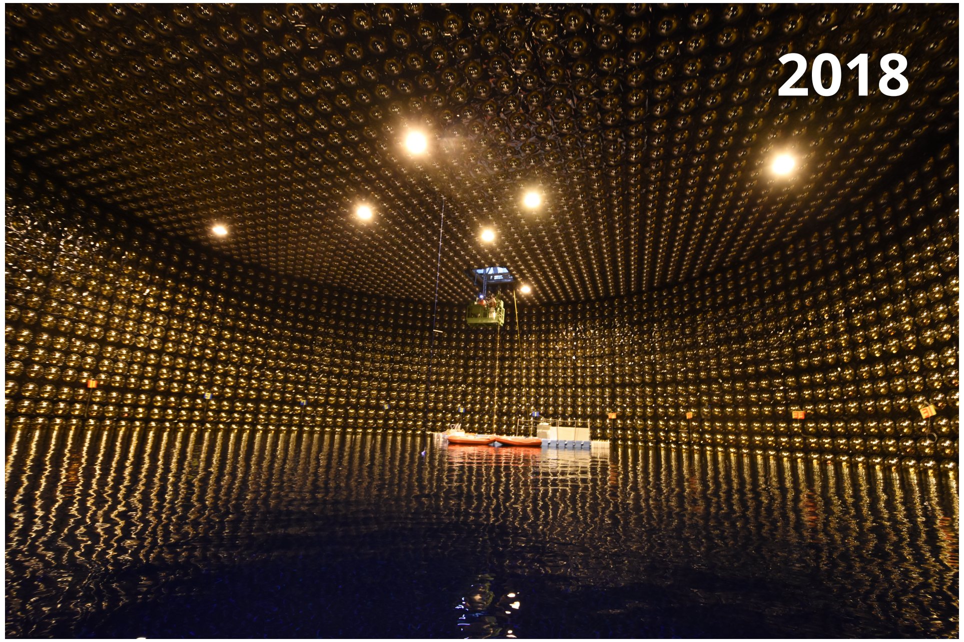


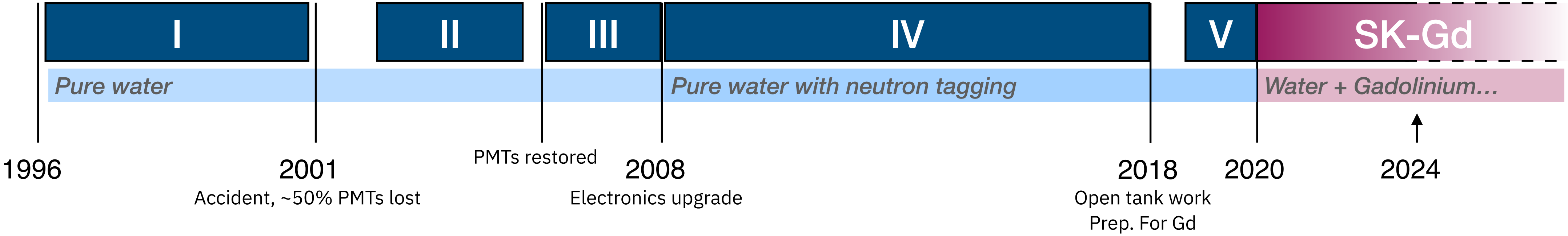
~2 ns resolution

Super-K Timeline



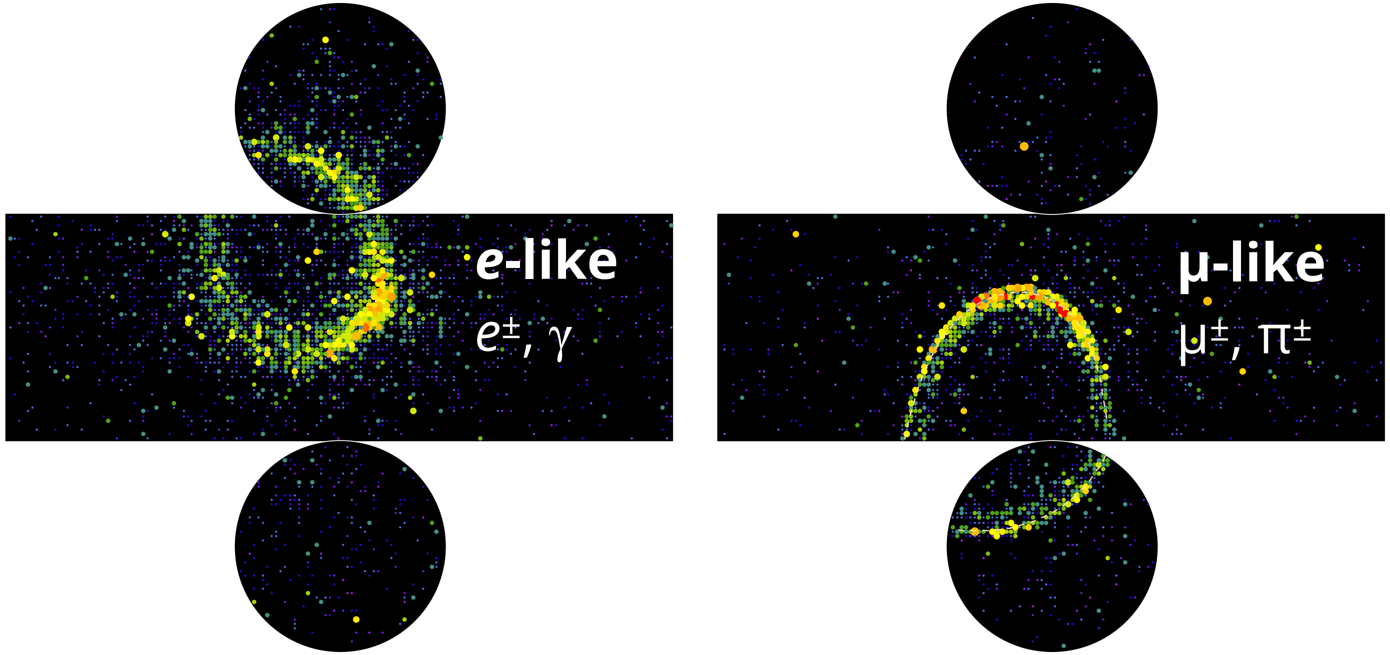






Super-K Events

Cherenkov rings for reconstructing particle type, direction, & momentum

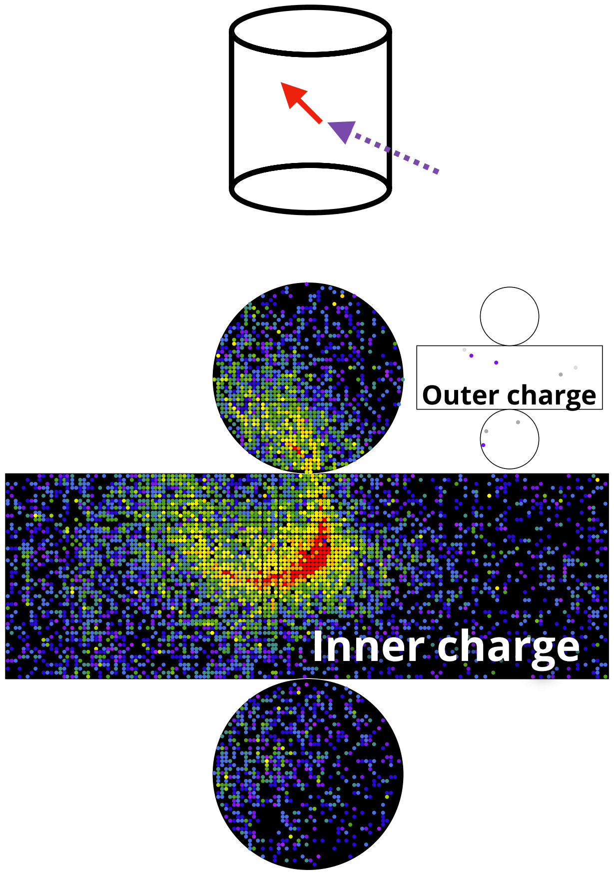


1 GeV μ *or* e (APFit)	
Vertex resolution	20 cm
Direction resolution	1.5°
Momentum resolution	3%
Mis-PID rate	0.7%

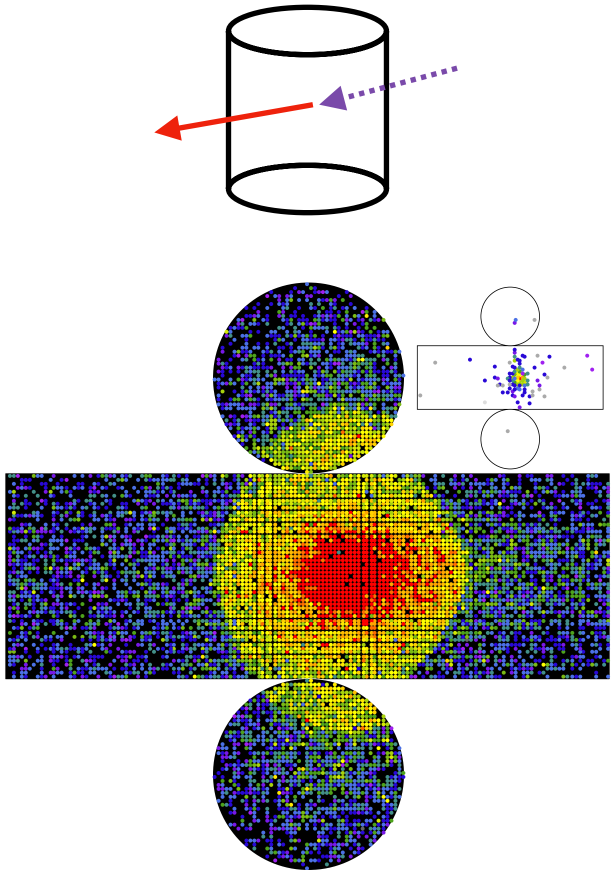
+ Also detect time-clustered hits from low-energy decay electrons & neutrons
- Can't distinguish charge, no event-by-event ν/ν̄ separation
- Miss low-momentum hadrons below Cherenkov threshold

Atmospheric Neutrino Events

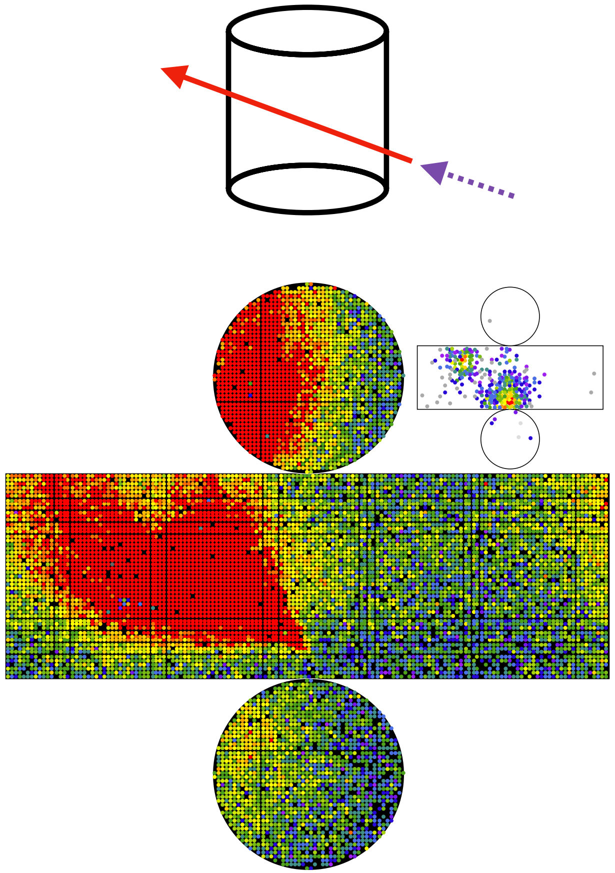
Fully Contained (FC)
Fiducial vertex, no exiting particles



Partially Contained (PC)
Fiducial vertex, exiting particles

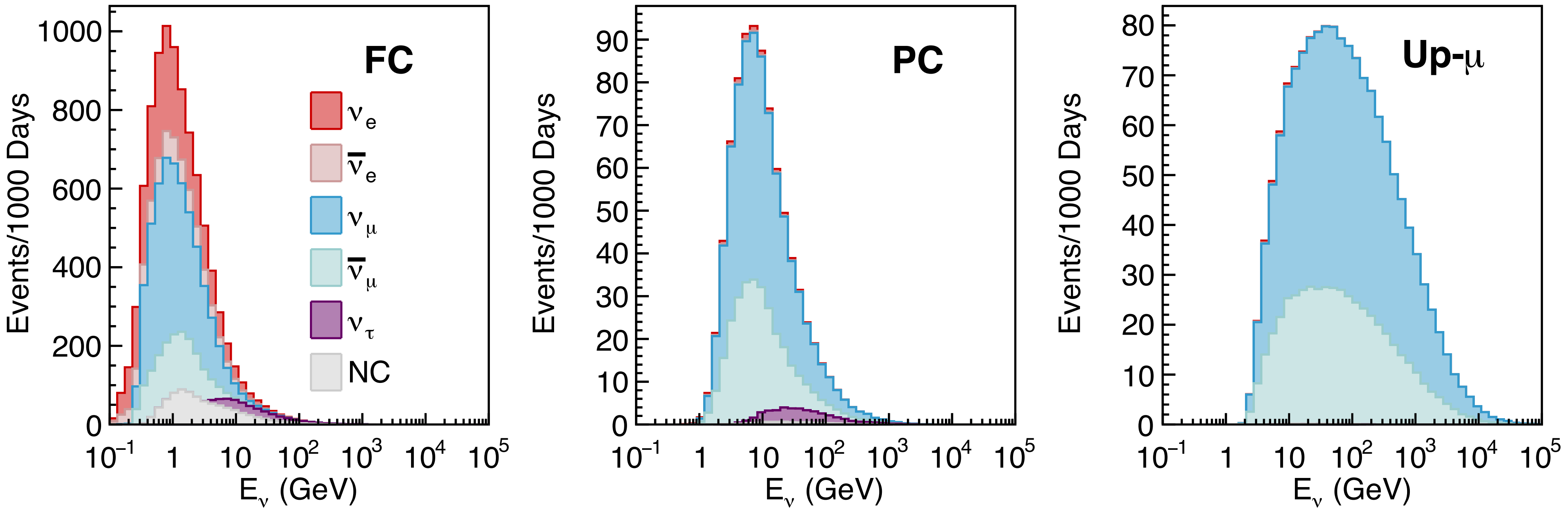


Up-μ
Outside vertex, upward-going



SK Atmospheric Neutrinos

Oscillated event rate @ SK



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}

Neutrino/Anti-Neutrino Separation

$$\nu_e + N \rightarrow N + e^- + \pi^+ \longrightarrow$$

$$\bar{\nu}_e + N \rightarrow N + e^+ + \pi^- \longrightarrow$$

Neutrino/Anti-Neutrino Separation

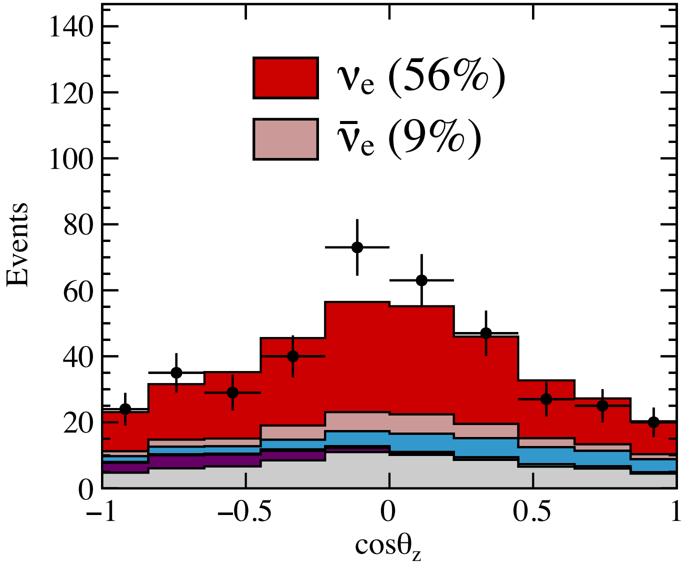
$$\nu_e + N \rightarrow N + e^- + \pi^+ \longrightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$$

Delayed decay *e*

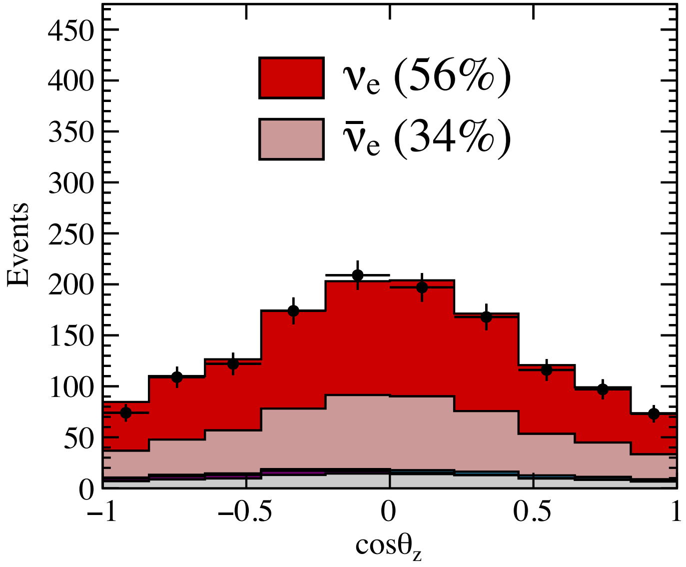
$$\bar{\nu}_e + N \rightarrow N + e^+ + \pi^- \not\longrightarrow$$

Absorbed in H_2O
before decay

Multi-GeV, single *e*-like ring
1 decay electron



Multi-GeV, single *e*-like ring
0 decay electrons

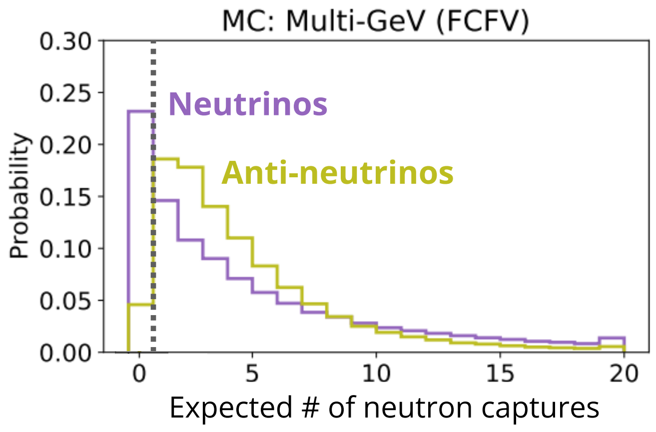


Neutrino/Anti-Neutrino Separation

Neutron tagging in SK: JINST **17** P10029 (2022)

Neutrons: More produced for anti-neutrino interactions

- 2008 upgrade: Tagged 2.2 MeV gammas from neutron capture on hydrogen during SK IV–V phases (57% of total exposure)
- 26% tagging efficiency with neural network



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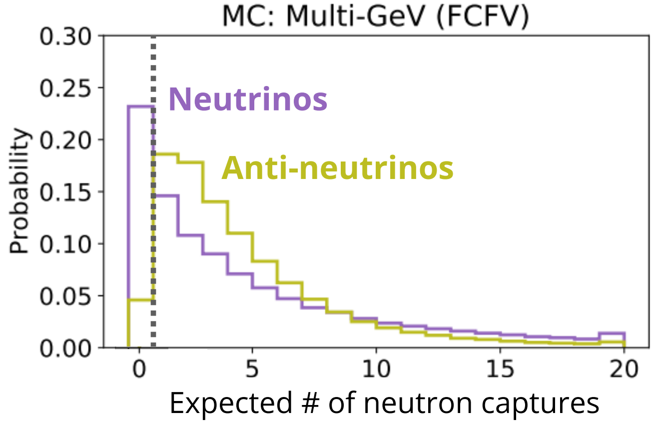
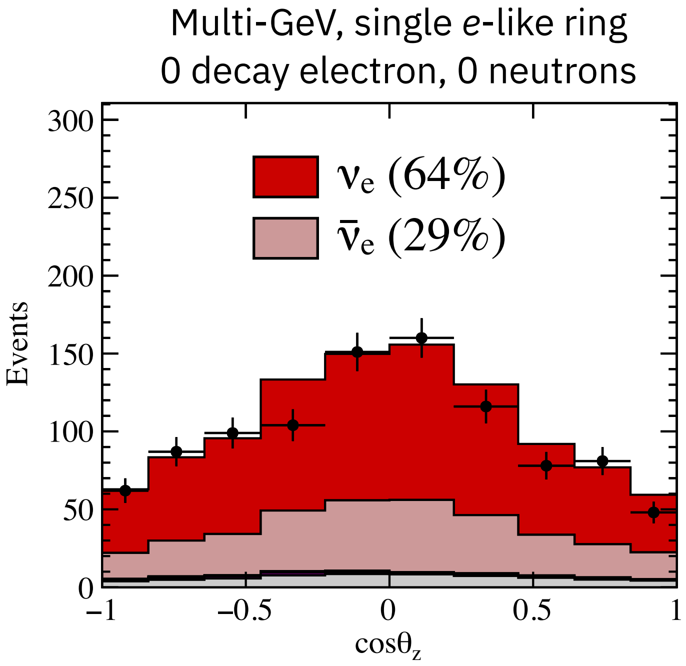
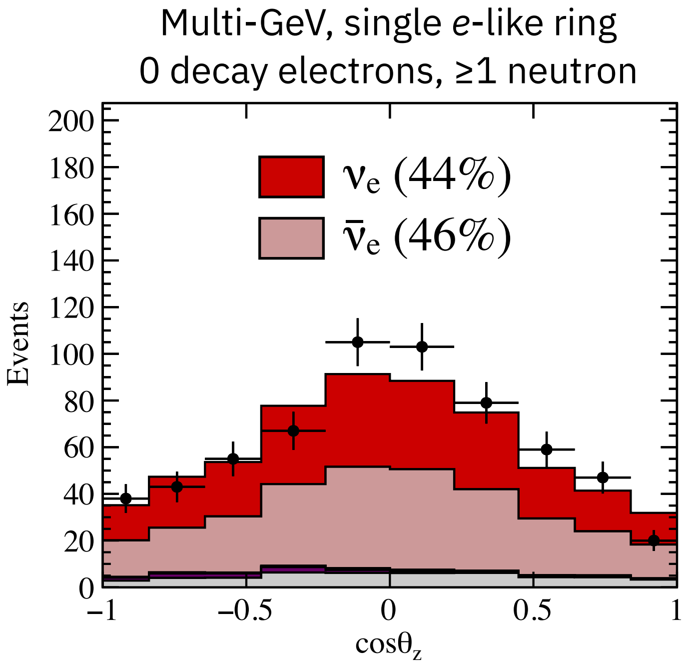
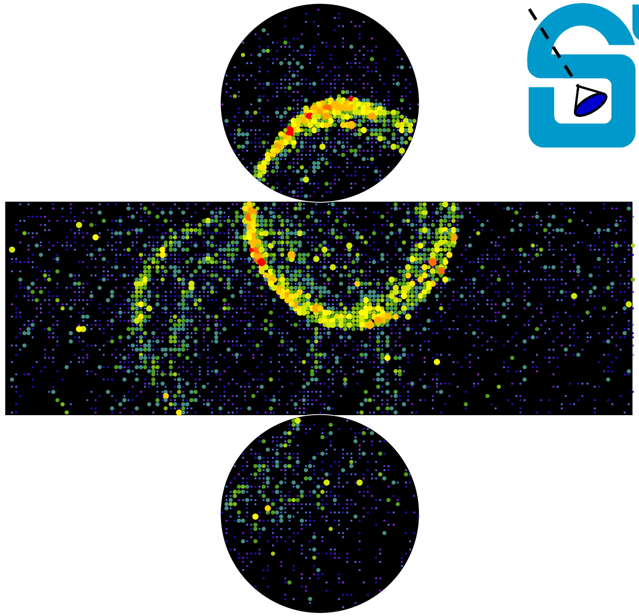




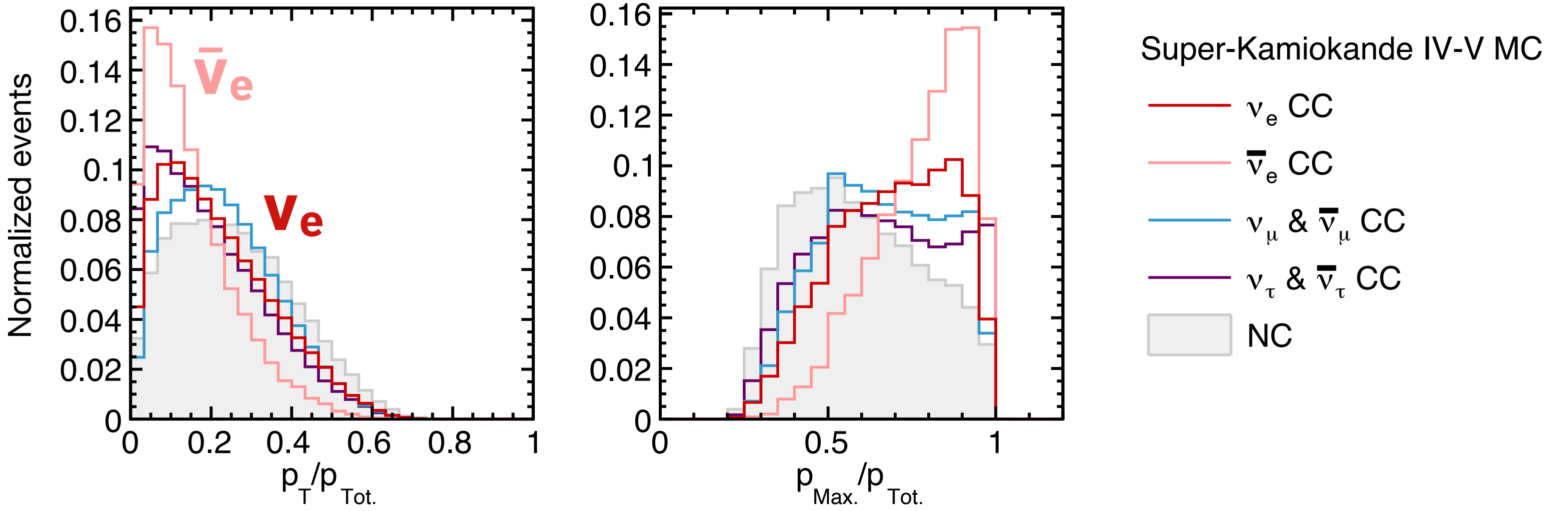


Multi-Ring BDT



Multi-ring events are more complicated to reconstruct, but offer more information

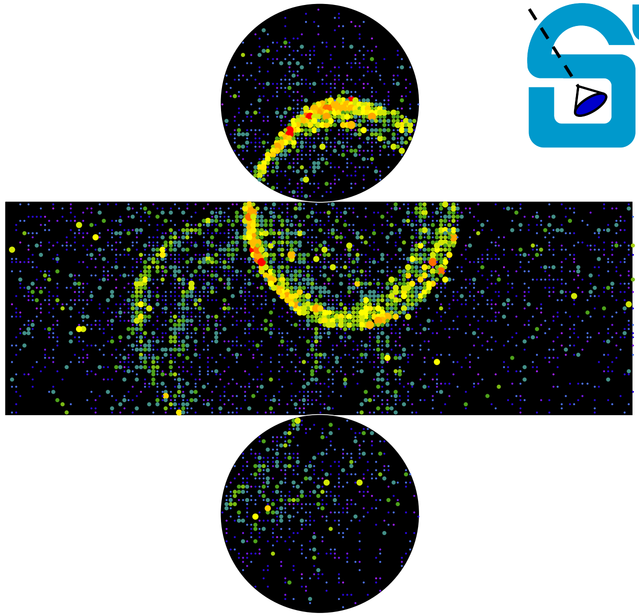
- Distribution of ring momenta to improve ν_e-$\bar{\nu}_e$ separation in addition to the number of decay electrons
- Boosted decision tree (BDT) classifier with 7 input variables implemented in SK I–V analysis, replacing previous likelihood method



Transverse momentum fraction

Leading ring momentum fraction

Multi-Ring BDT



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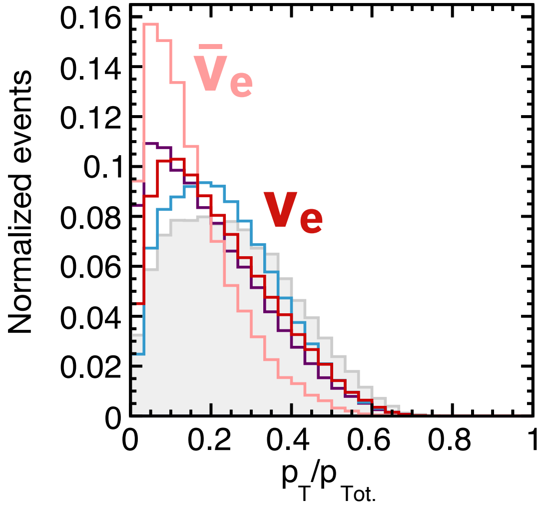

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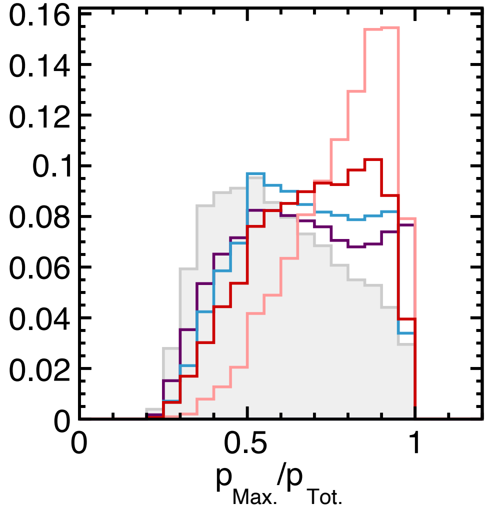
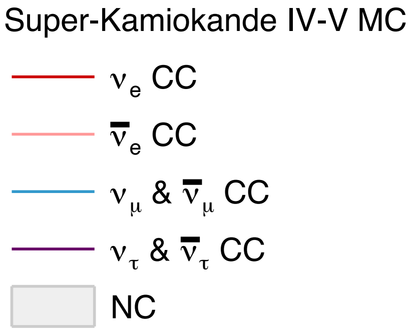
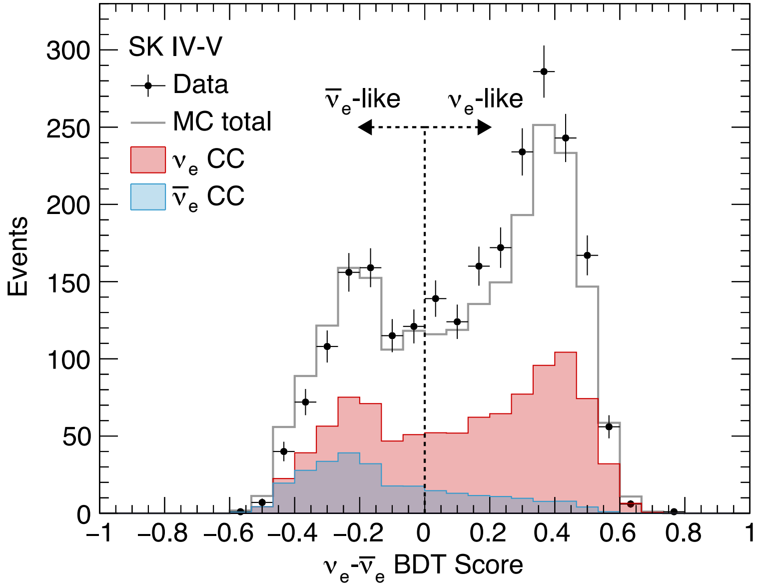


Leading ring momentum fraction

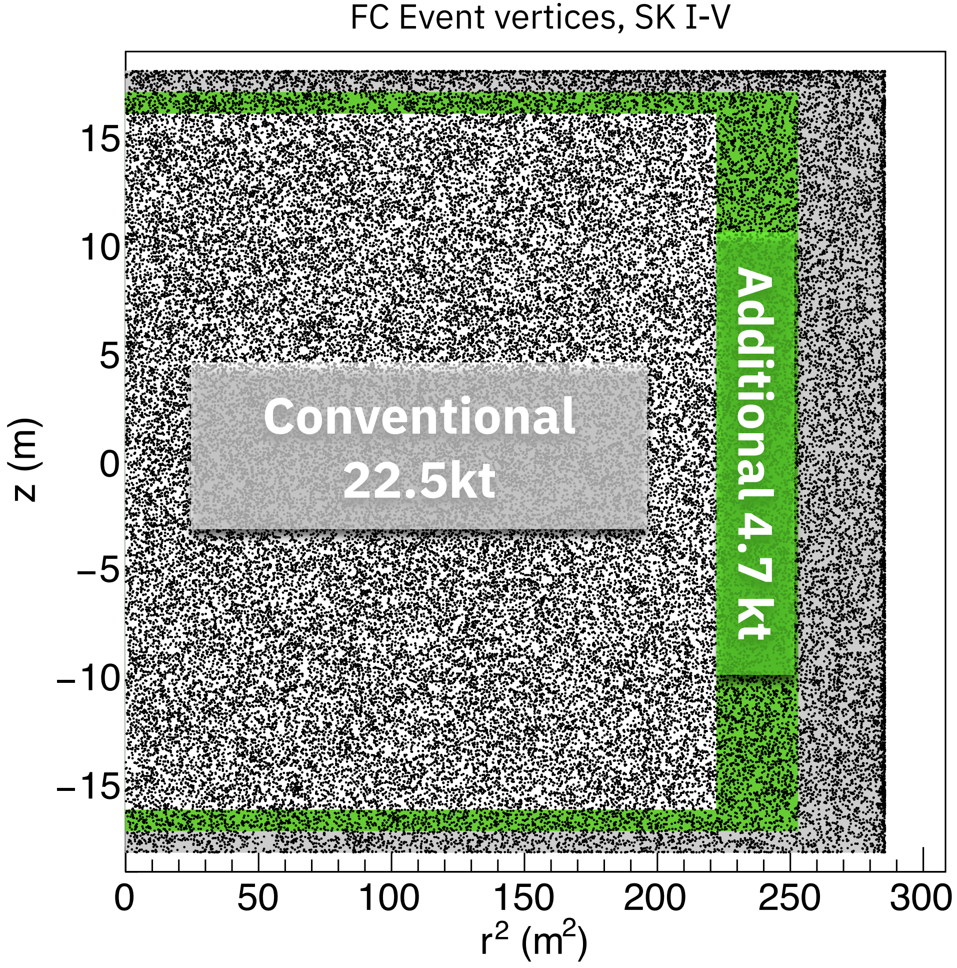




Expanded Fiducial Volume

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

New for SK I–V analysis: Increased fiducial volume for FC events from 22.5 kt → 27.2 kt for all SK phases



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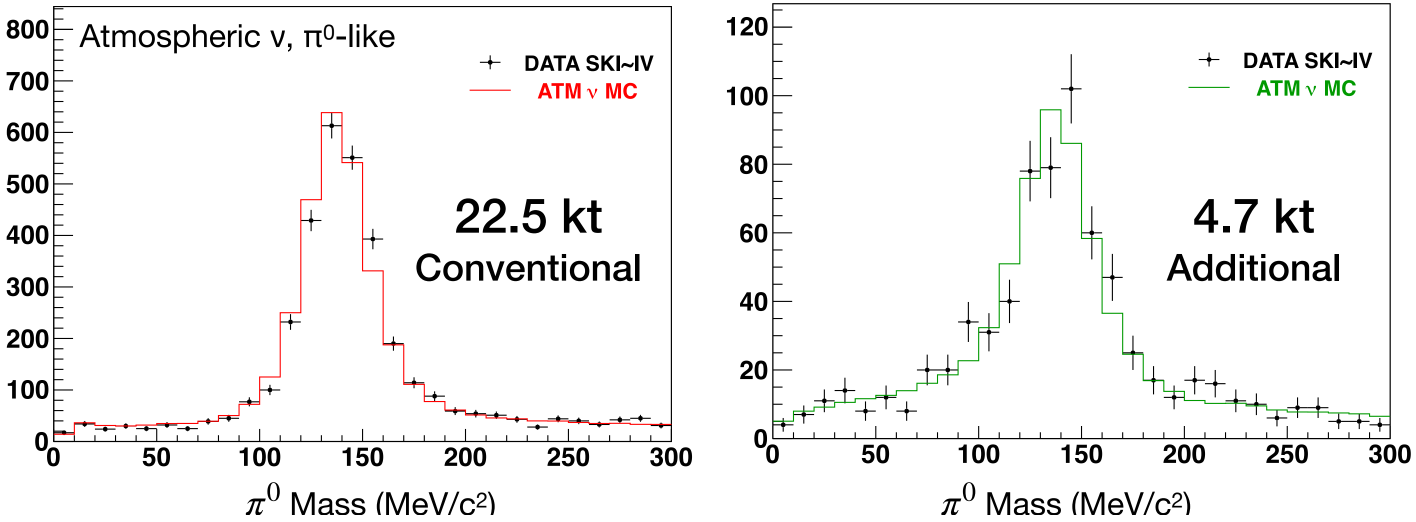

Expanded Fiducial Volume

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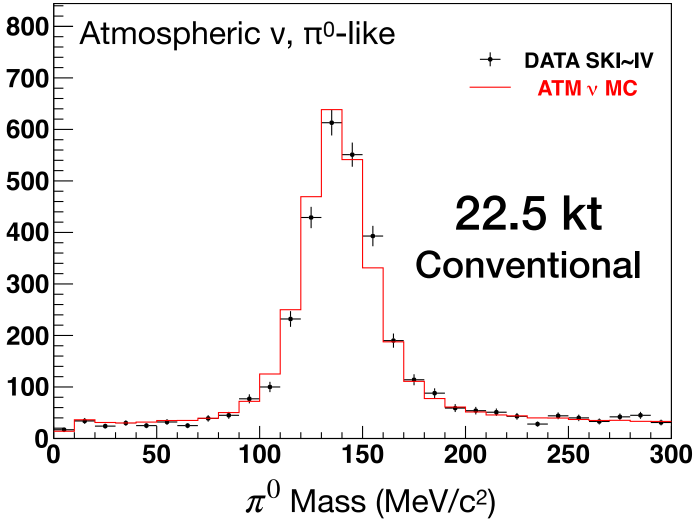
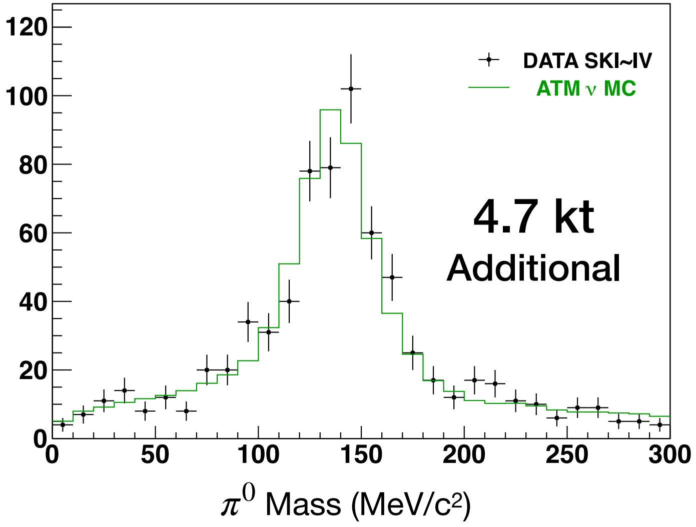
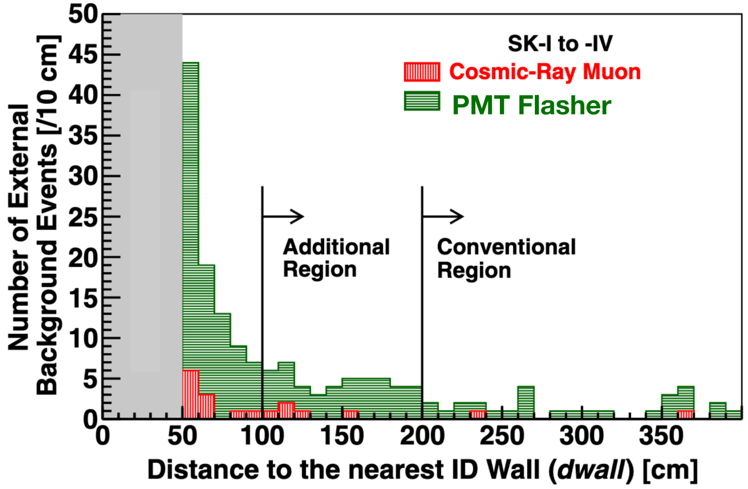
New for SK I–V analysis: Increased fiducial volume for FC events from 22.5 kt → 27.2 kt for all SK phases

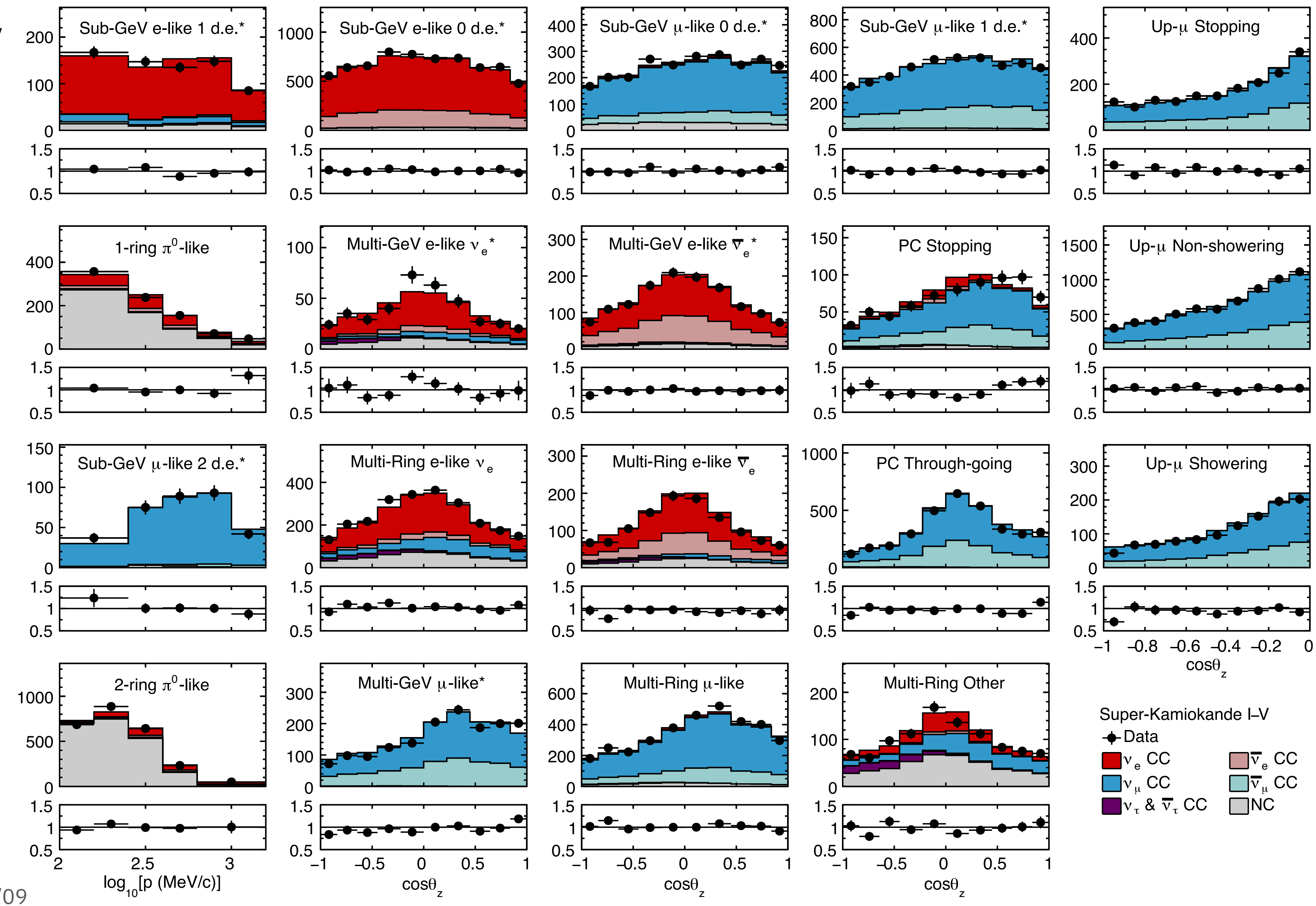
- Reconstruction: Likelihoods used in PID & vertex fitters updated with dependence on distance to wall
- Background: New reduction cuts added to reject entering cosmic muons. Background in additional volume is 0.5% (0.1% in conventional volume)



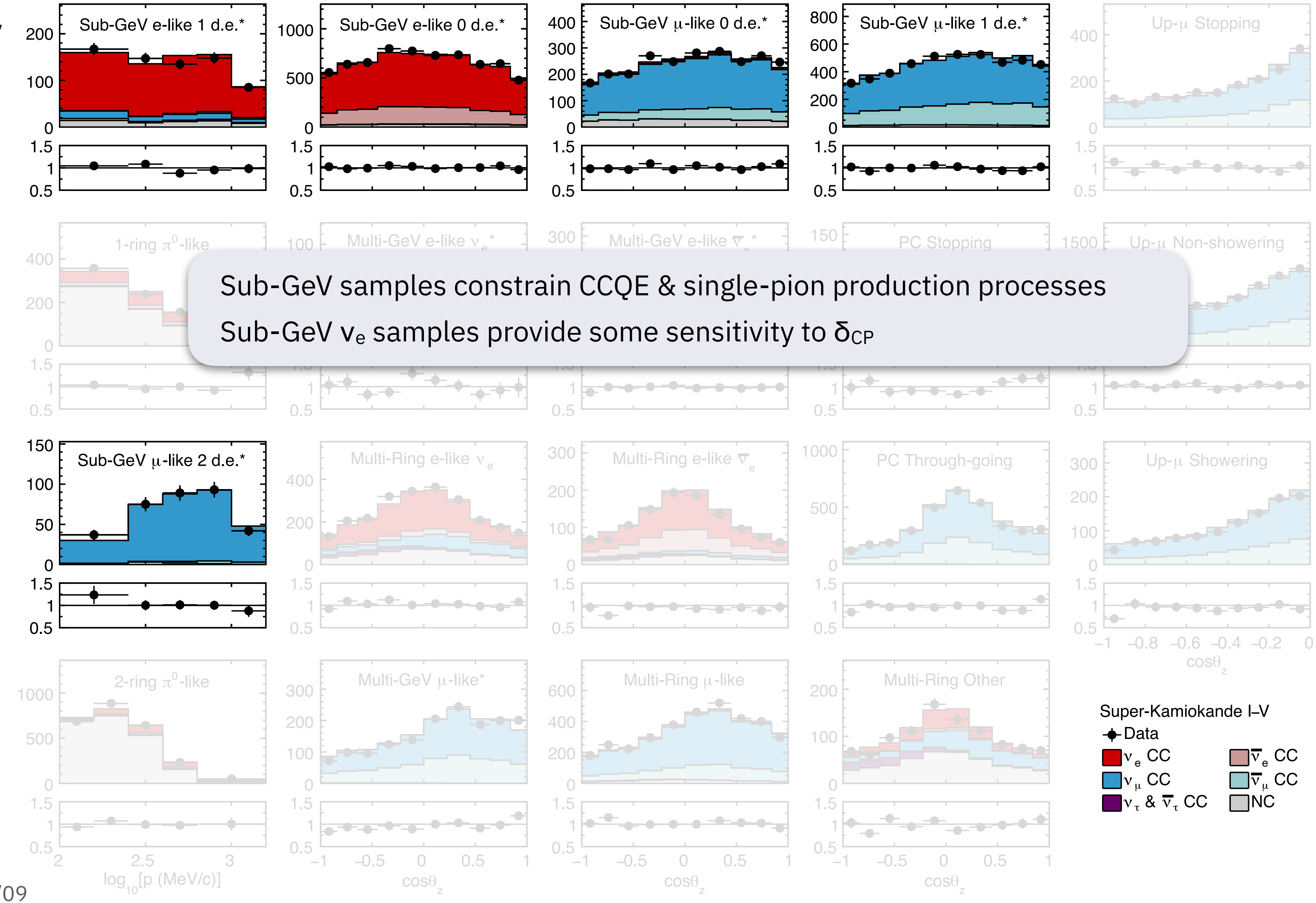




SK I–V pure-water data set



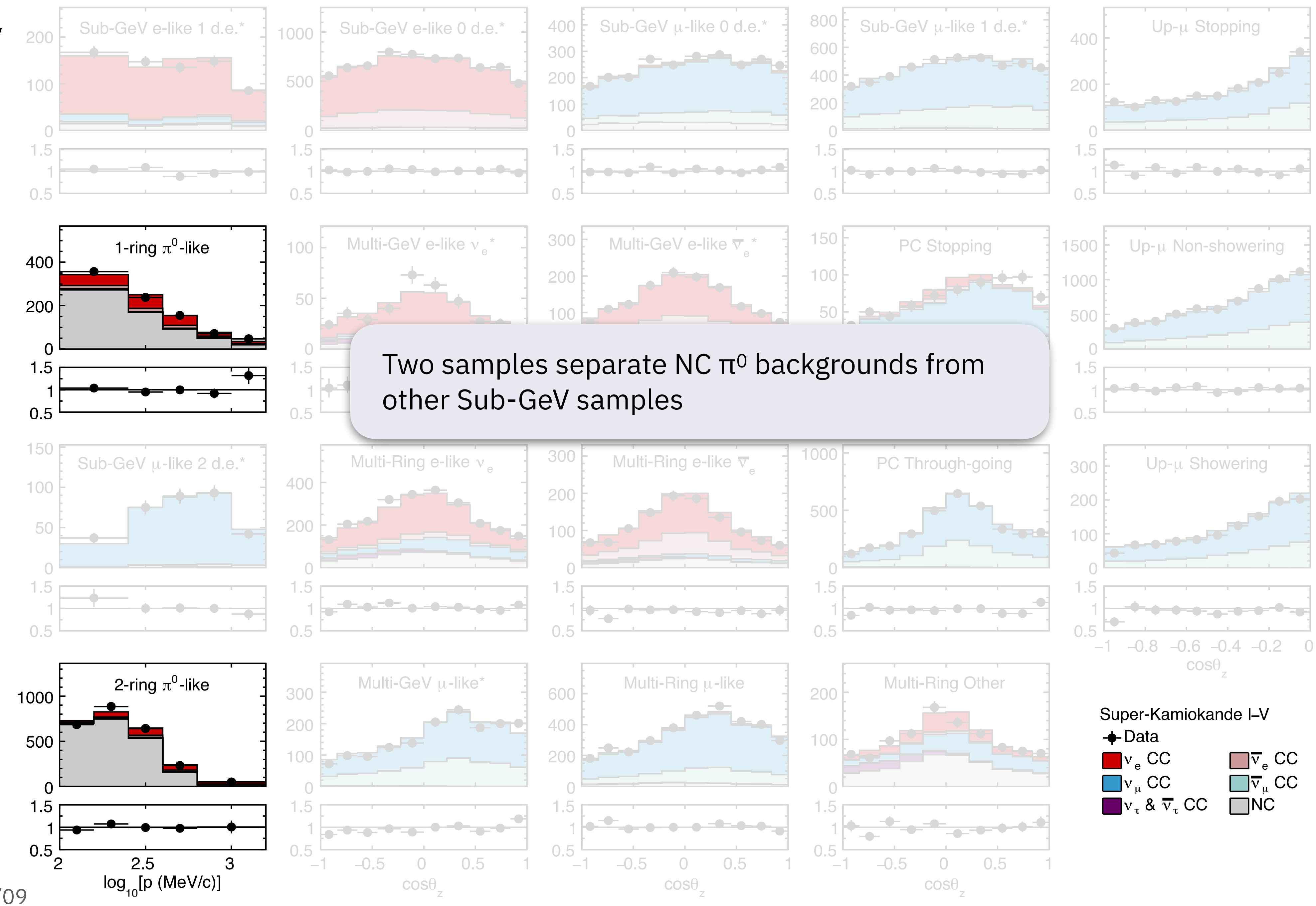
SK I–V pure-water data set



Sub-GeV samples constrain CCQE & single-pion production processes

Sub-GeV ν_e samples provide some sensitivity to δ_{CP}

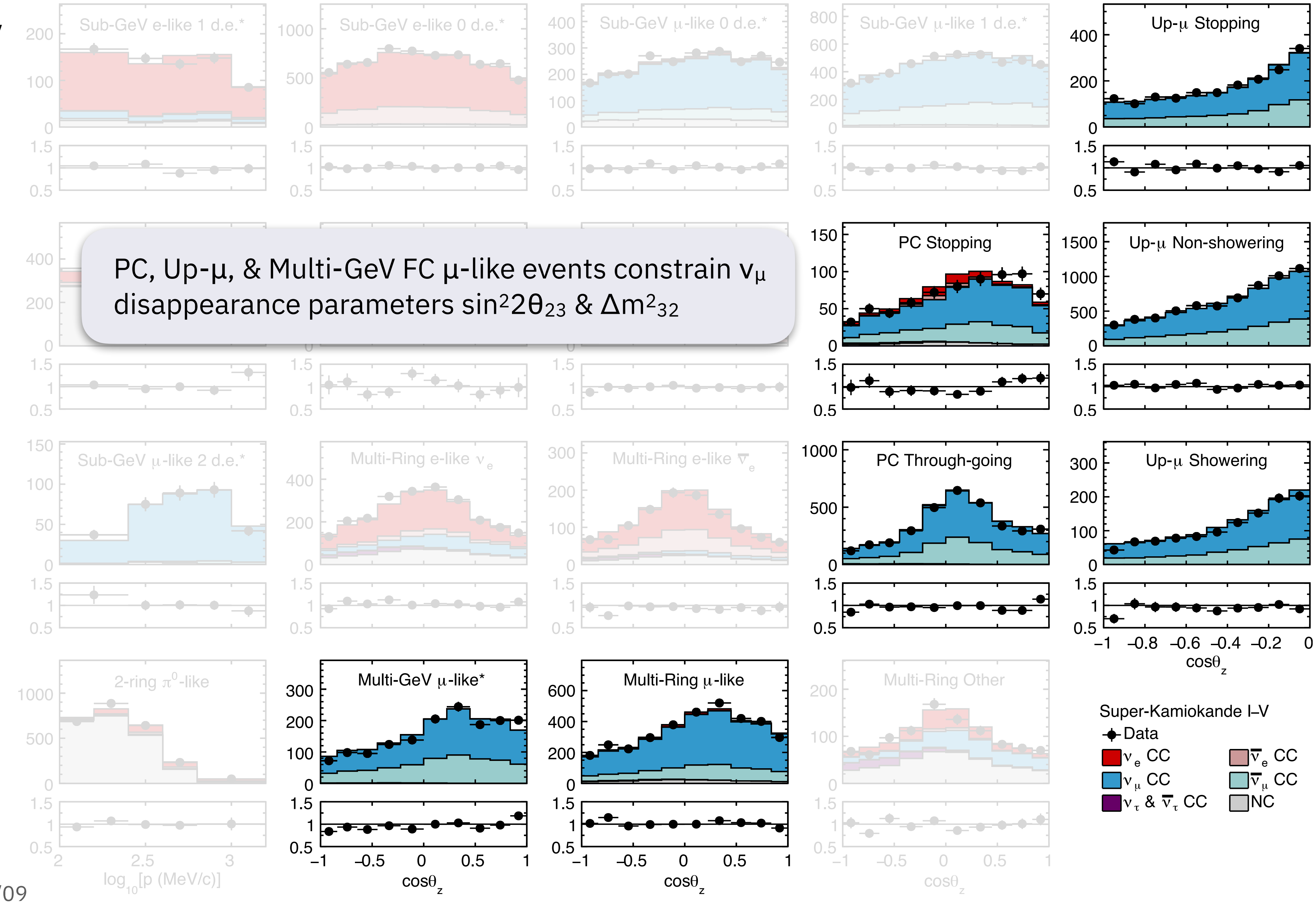
SK I–V pure-water data set



Two samples separate NC π^0 backgrounds from other Sub-GeV samples

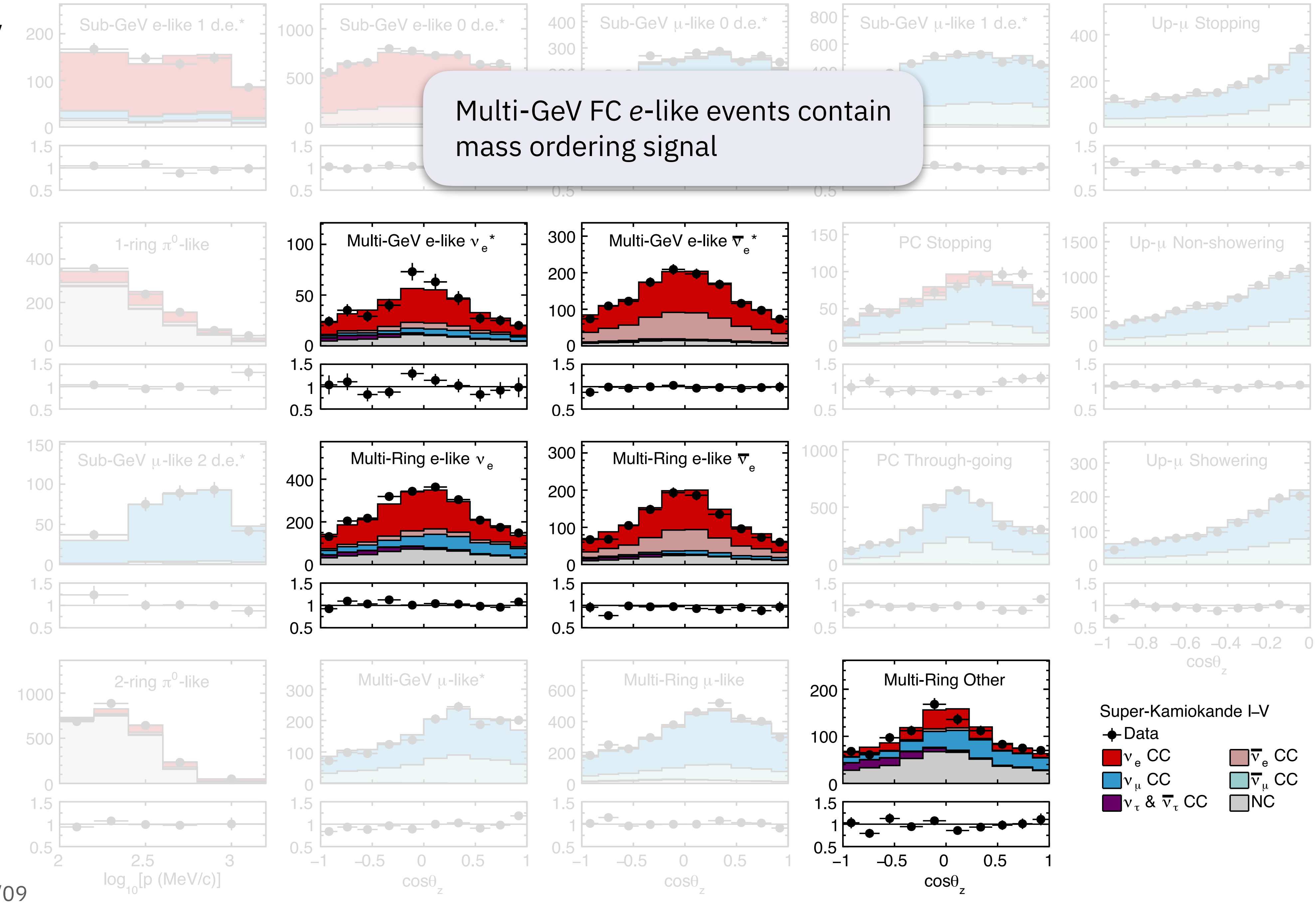
SK I–V pure-water data set

PC, Up-μ, & Multi-GeV FC μ-like events constrain ν_μ disappearance parameters $\sin^2 2\theta_{23}$ & Δm^2_{32}

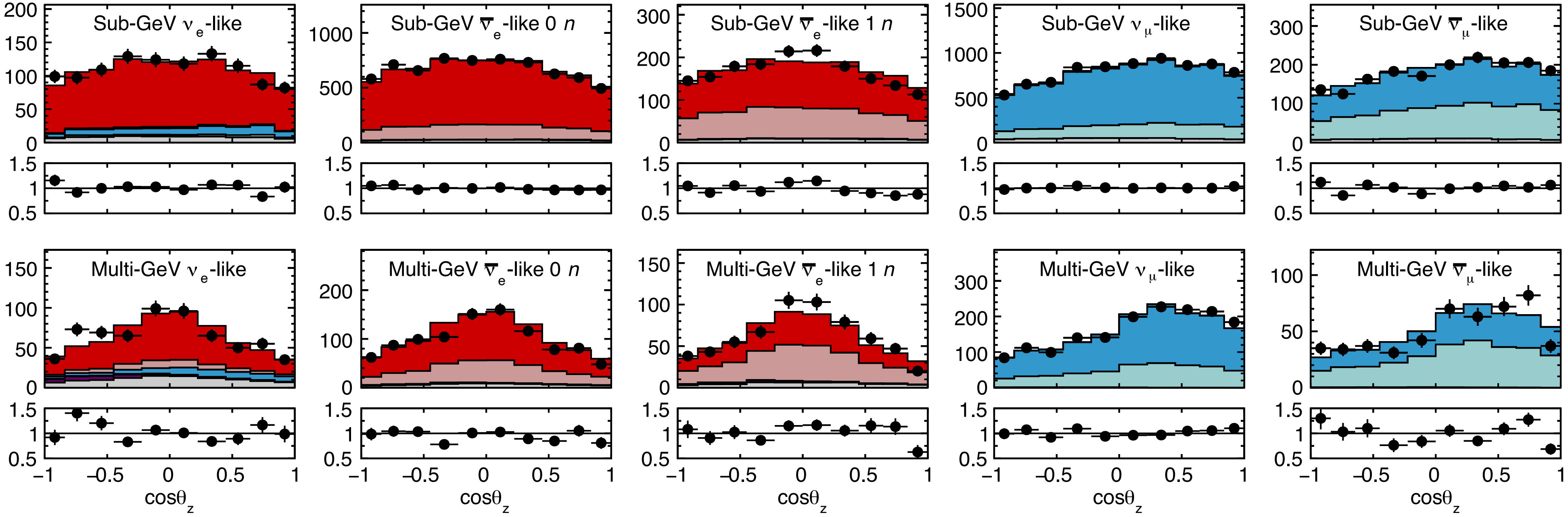


SK I–V pure-water data set

Multi-GeV FC *e*-like events contain mass ordering signal



+ SK IV–V samples with neutron tagging



SK IV–V single-ring samples with neutron tagging selection included as additional samples in SK I–V analysis

χ^2 Calculation

Expected counts

Observed counts

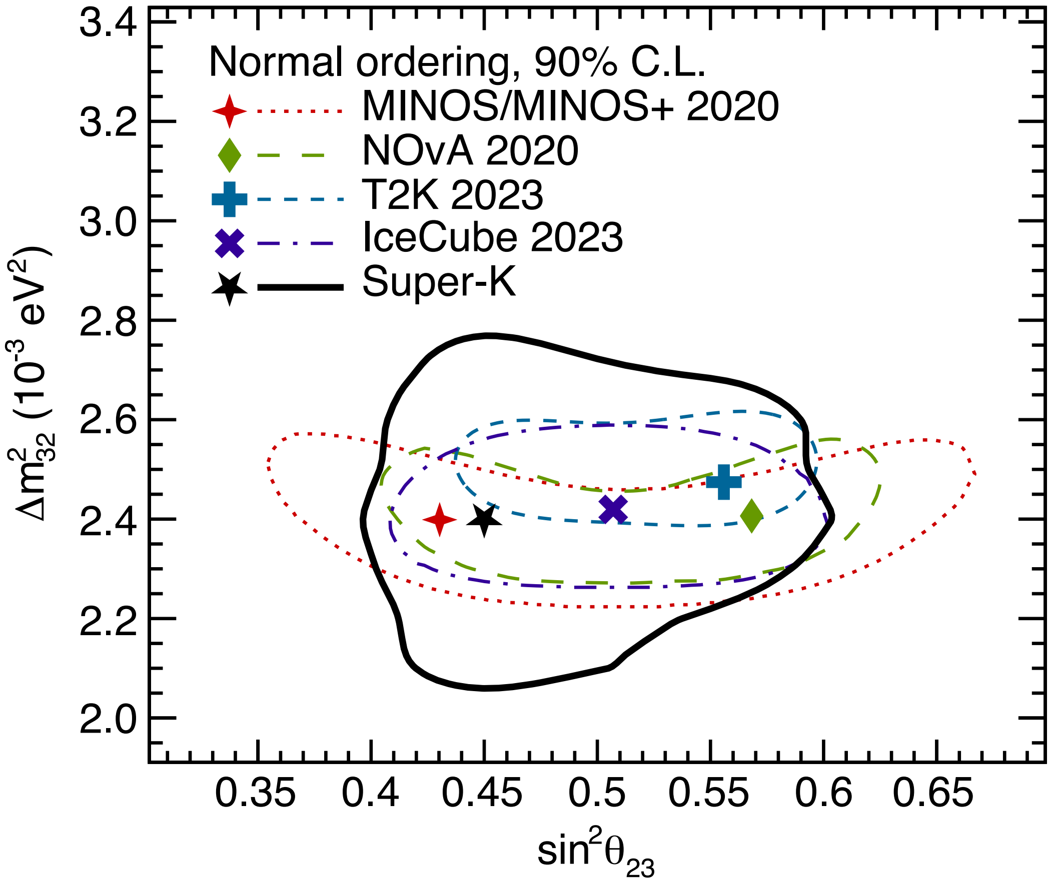
$$\chi^2 = \sum_n \left(E_n - O_n + O_n \ln \frac{O_n}{E_n} \right) + \sum_i \epsilon_i^2$$

Sum over n bins

Systematic error pull terms

Data set	Samples	Bins	Systematic uncertainties	Free parameters	Minimization
6511 live days 0.48 Mton·years	29	930 2D $\cos\theta_z$ vs. momentum	194 Detector: 29×5 phases Flux & xsec: 49	$\sin^2\theta_{23}$, Δm^2_{32}, δ_{CP}, ordering Also perform fit with θ_{13} free	Grid scan

Results: Δm^2_{32} & $\sin^2\theta_{23}$



SK I–V best fit

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

$\sin^2\theta_{23}$ ~ 0.45 (lower octant)

Δm^2_{32} ~ 2.4×10^{-3} eV^2

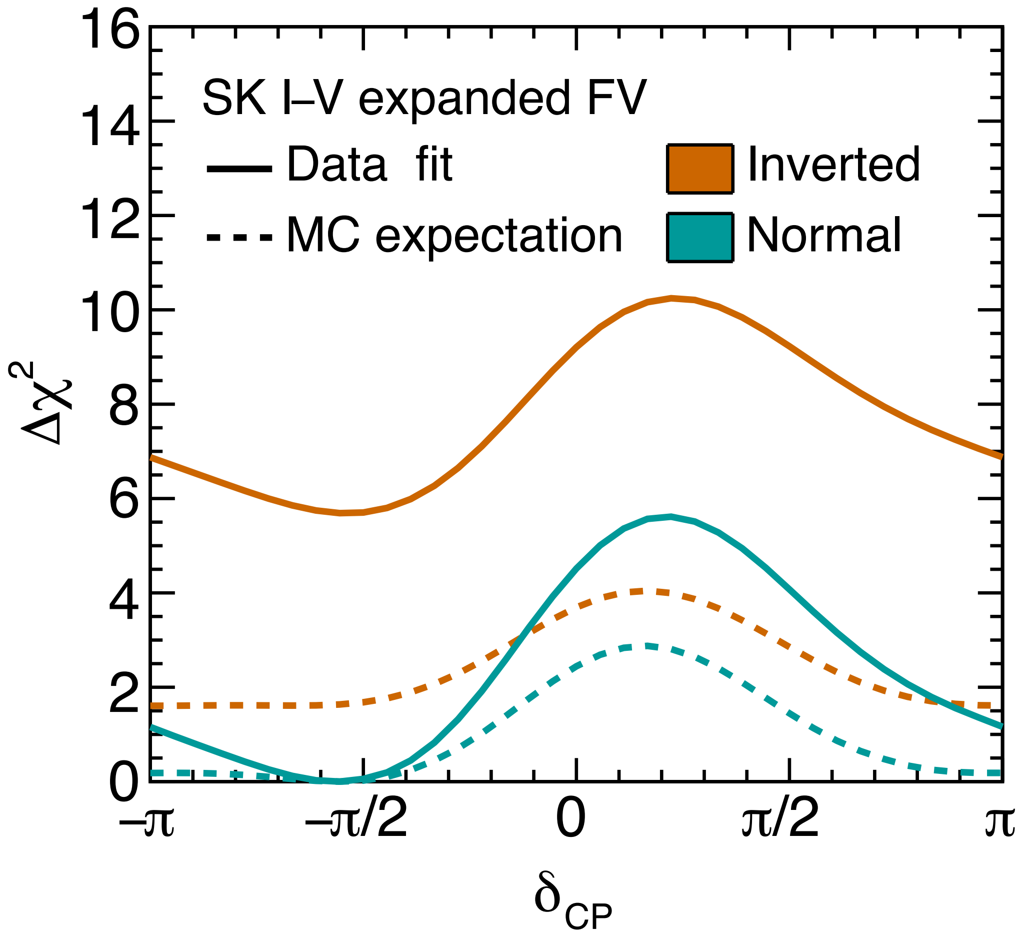
MINOS: Phys. Rev. Lett. **125**, 131802 (2020)

NOvA: 10.5281/zenodo.4142045 (2020)

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

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

Results: Mass Ordering & δ_{CP}



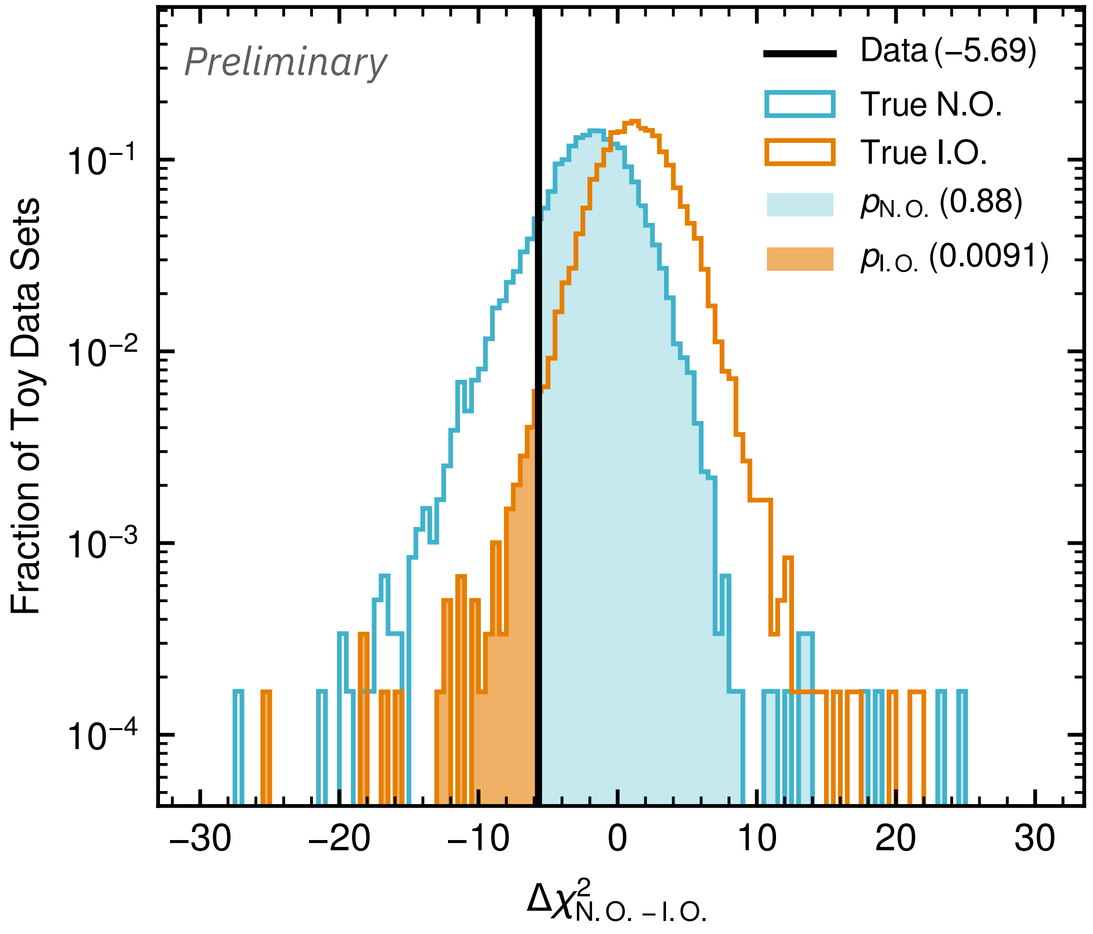
SK I–V best fit

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

Normal ordering, $\Delta\chi^2_{I.O.\,-\,N.O.} \sim 5.7$*

$\delta_{CP} \approx -\pi/2$

*Mass Ordering Significance

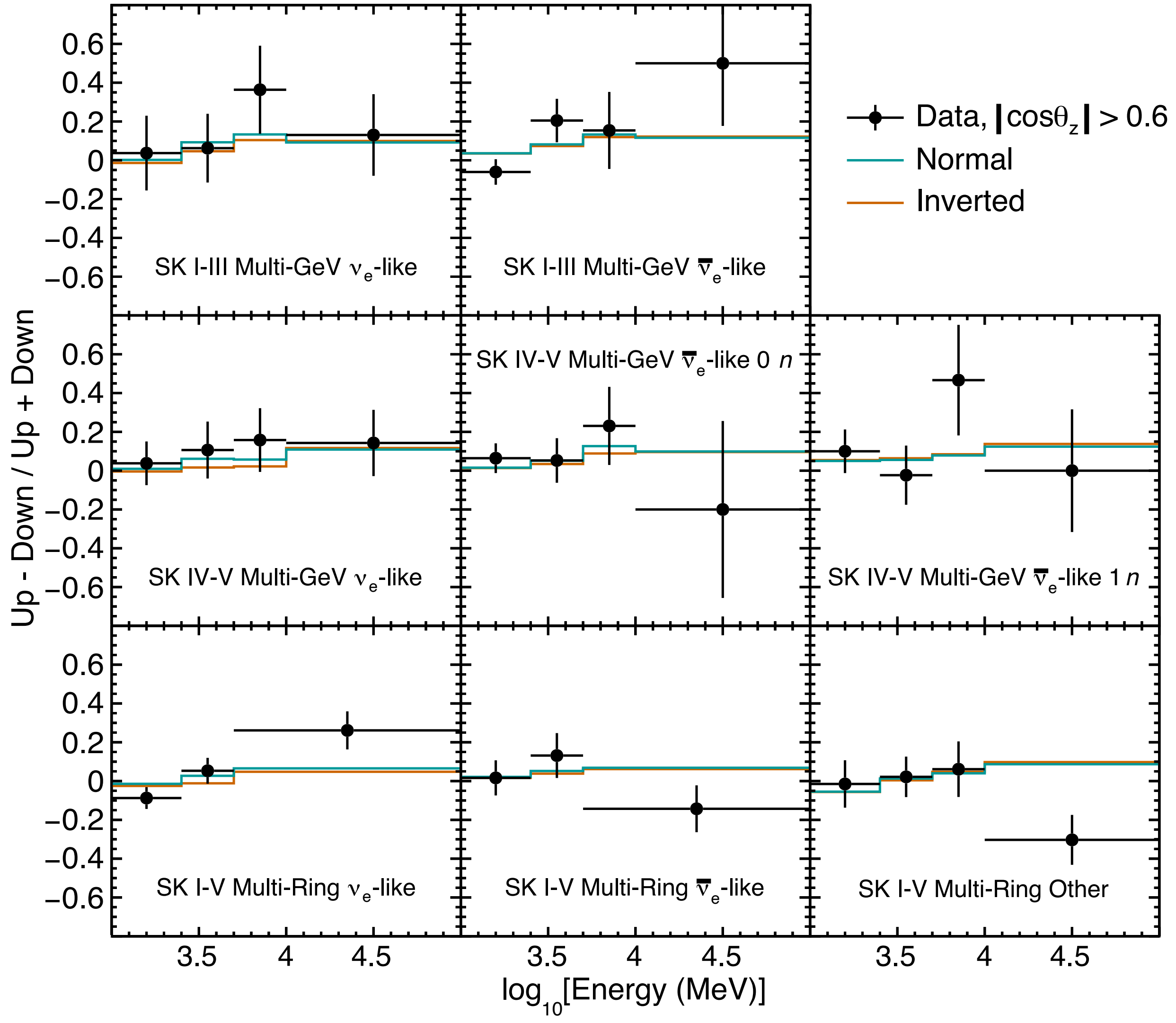


- Generate toy data sets to obtain distribution of $\Delta\chi^2_{\text{NO-IO}}$
- **CL_S statistic** corrects probability of rejecting the inverted ordering by probability of rejecting normal ordering

$$CL_S = \frac{p_{IO}}{1 - p_{NO}} \approx 0.077$$

Reject inverted ordering at the ~92% confidence level.

Mass Ordering in the Data



Upward-going / downward going ratio in multi-GeV *e*-like samples shows consistent excess in mass ordering-sensitive bins

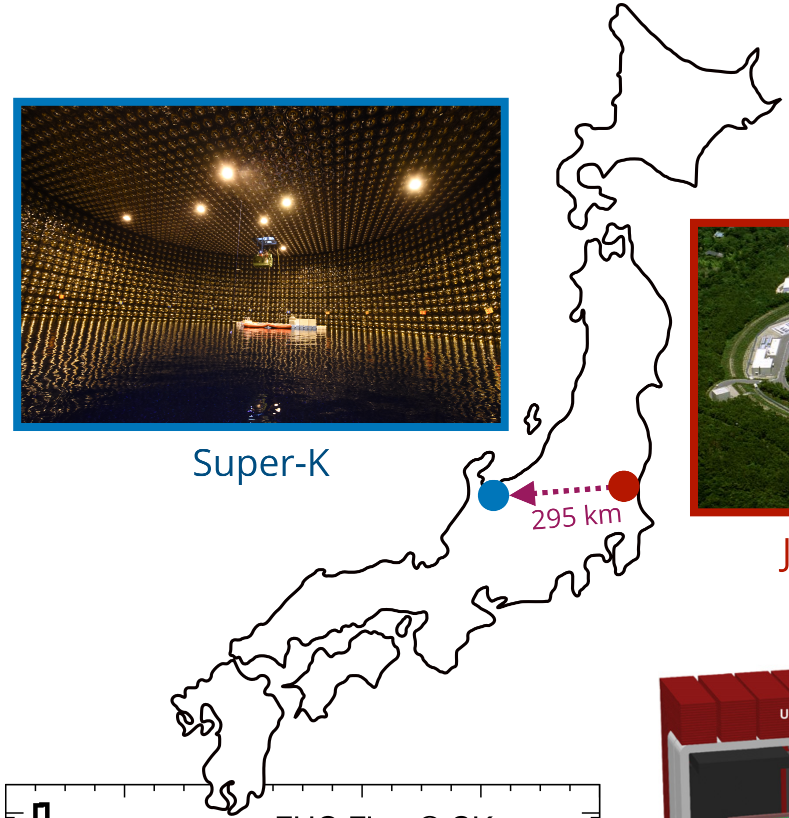
SK+T2K Joint Fit

First report: A. Eguchi, NNN23 Procida
L. Berns, KEK-JPARC Seminar

T2K Experiment

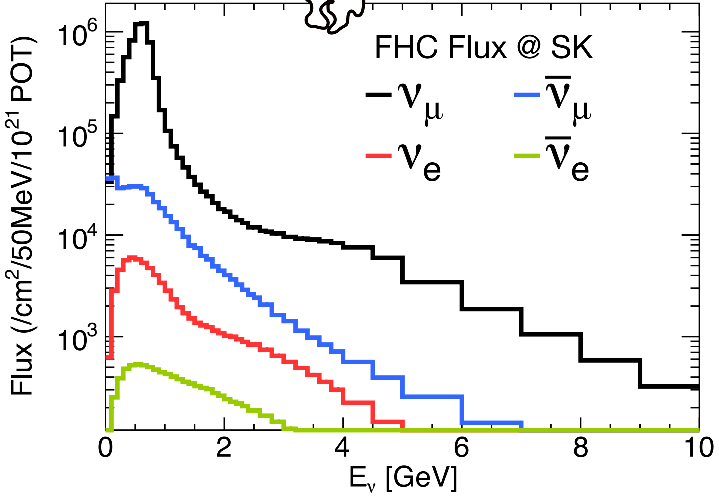
Precision long-baseline experiment measuring Δm^2_{32}, $\sin^2\theta_{23}$, δ_{CP}

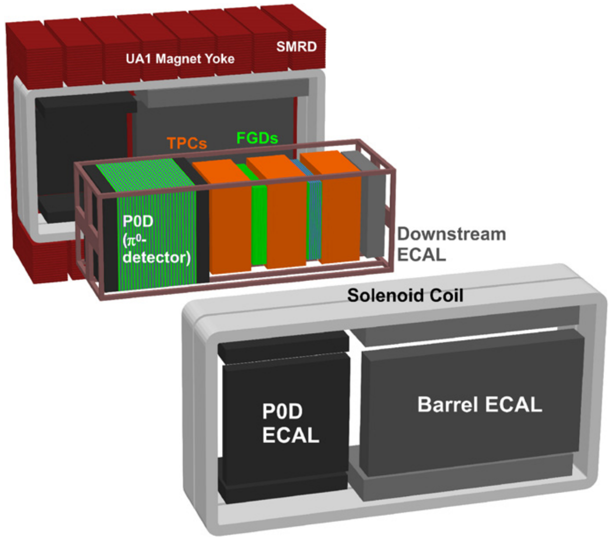
- Neutrino flux peaked at 600 MeV, CC Quasi-elastic (CCQE) primary interaction channel
- ND280 near detector constrains flux & cross section uncertainties
- >3.6×10^{21} POT accumulated since 2010:
  - FHC (ν-mode) 1.97×10^{21} POT
  - RHC ($\bar{\nu}$-mode) 1.64×10^{21} POT



Super-K

JPARC accelerator





ND280 near detector

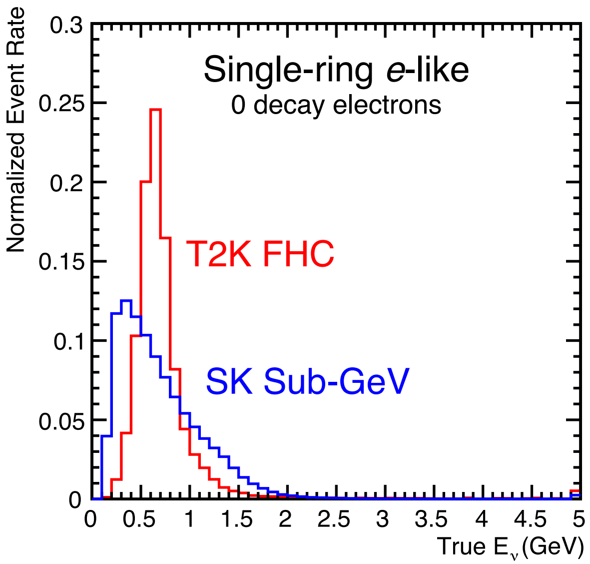
Joint Fit Overview

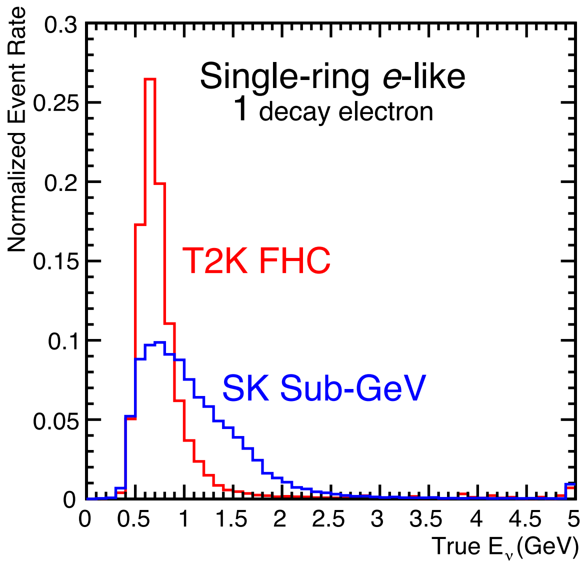
Joint fit combines existing SK & T2K analyses into single framework

Joint fit goals:

- **Demonstrate complementarity** of precision accelerator measurement & large matter effect in atmospheric neutrinos
- **Combined cross section model** for accelerator & atmospheric events
  ↳ T2K near detector constraints applied to atmospheric samples
- **Correlated detector systematics**

Joint Fit	T2K Eur. Phys. J. C 83:782 (2023)	SK PTEP 2019 5, 053F01
Data set	Runs 1-10	SK IV
Exposure	3.6×10^{21} POT	254 kt·yr (~50% of pure-water data set)
Samples	5 single ring	18 (no neutron tagging)

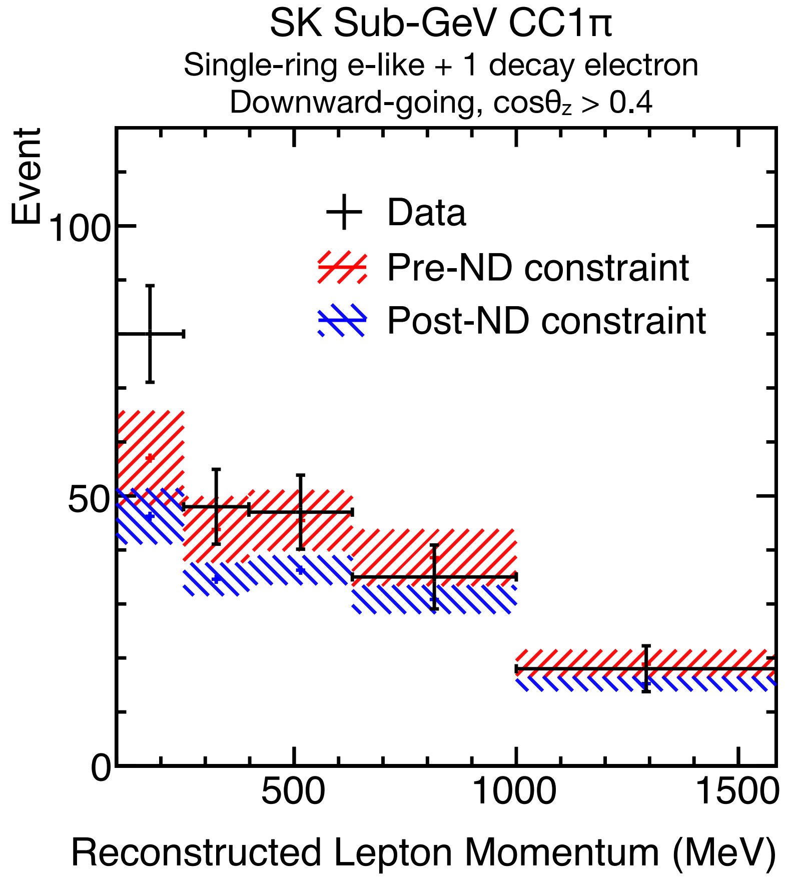




SK + T2K Near Detector Constraints

Near detector constraint found to cause excess in SK atmospheric CC1π sample from study of downward-going (un-oscillated) control data

- Excess can potentially bias δ_{CP} measurement

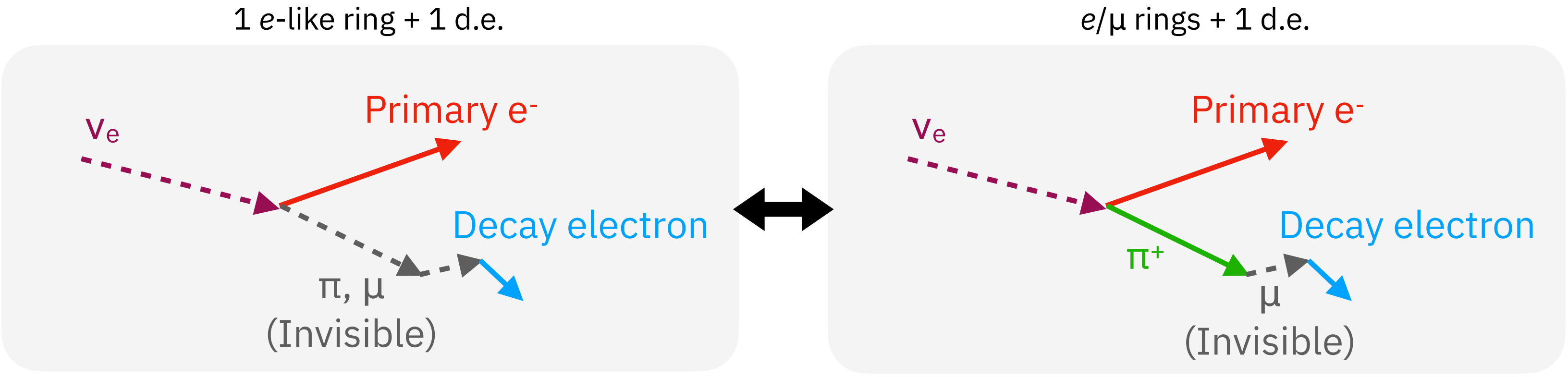


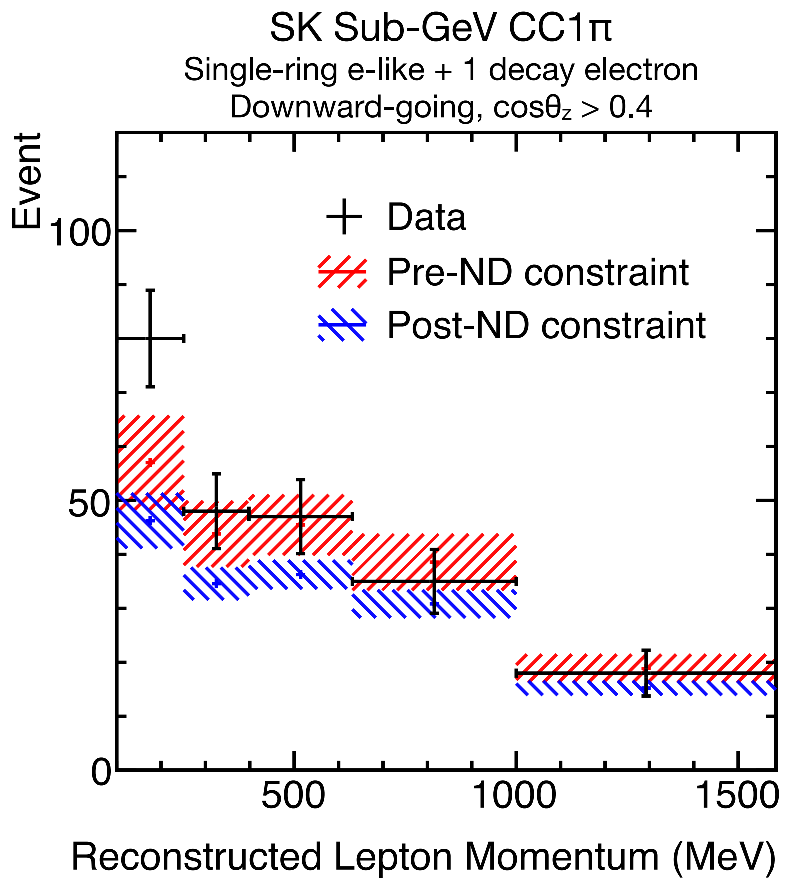
SK + T2K Near Detector Constraints

Near detector constraint found to cause excess in SK atmospheric CC1π sample from study of downward-going (un-oscillated) control data

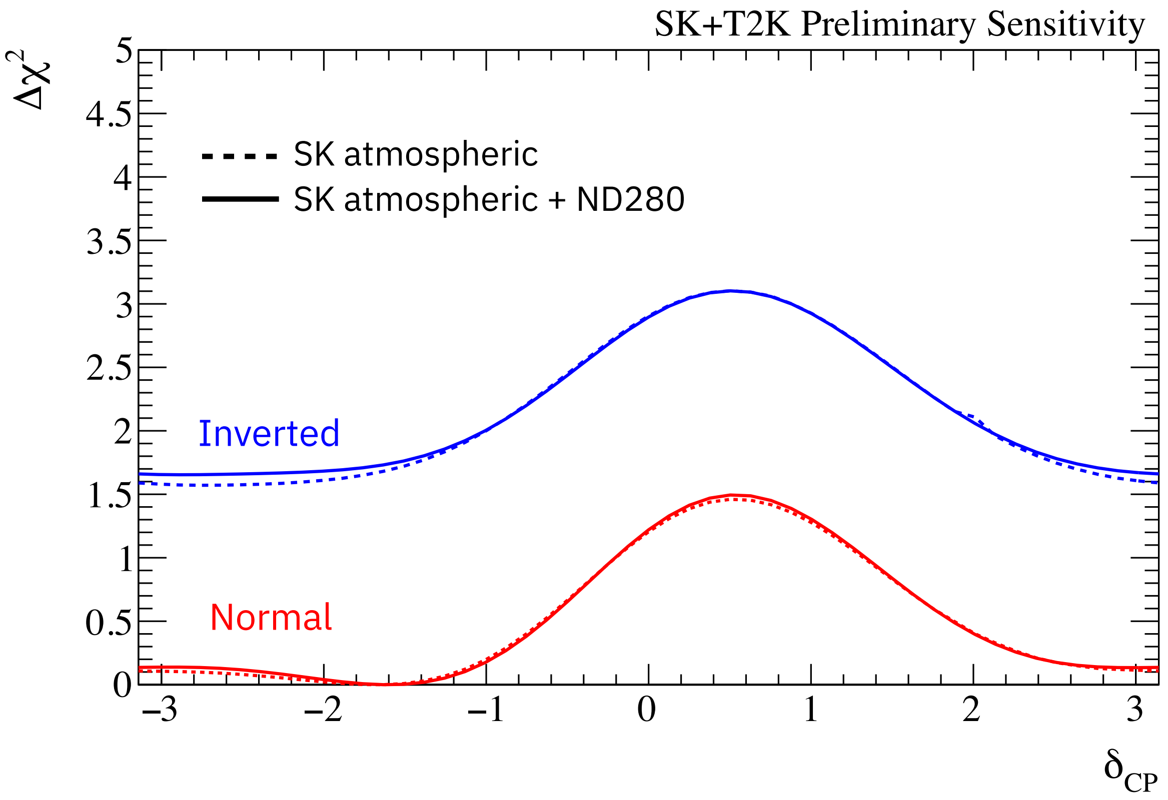
- Excess can potentially bias δ_{CP} measurement
- Add new uncertainty on pion momentum: Changes number of pions above/below Cherenkov threshold in SK, small effect on near detector

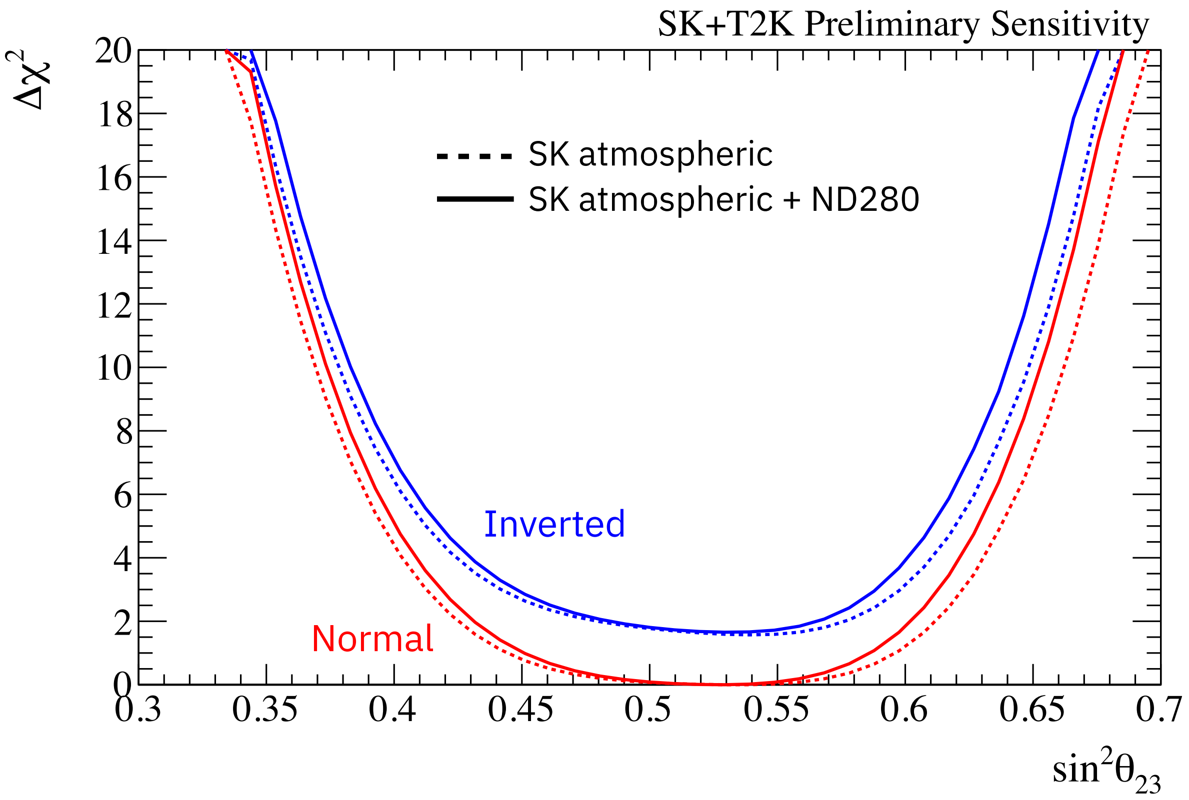
π momentum uncertainty





SK + T2K Near Detector Constraints



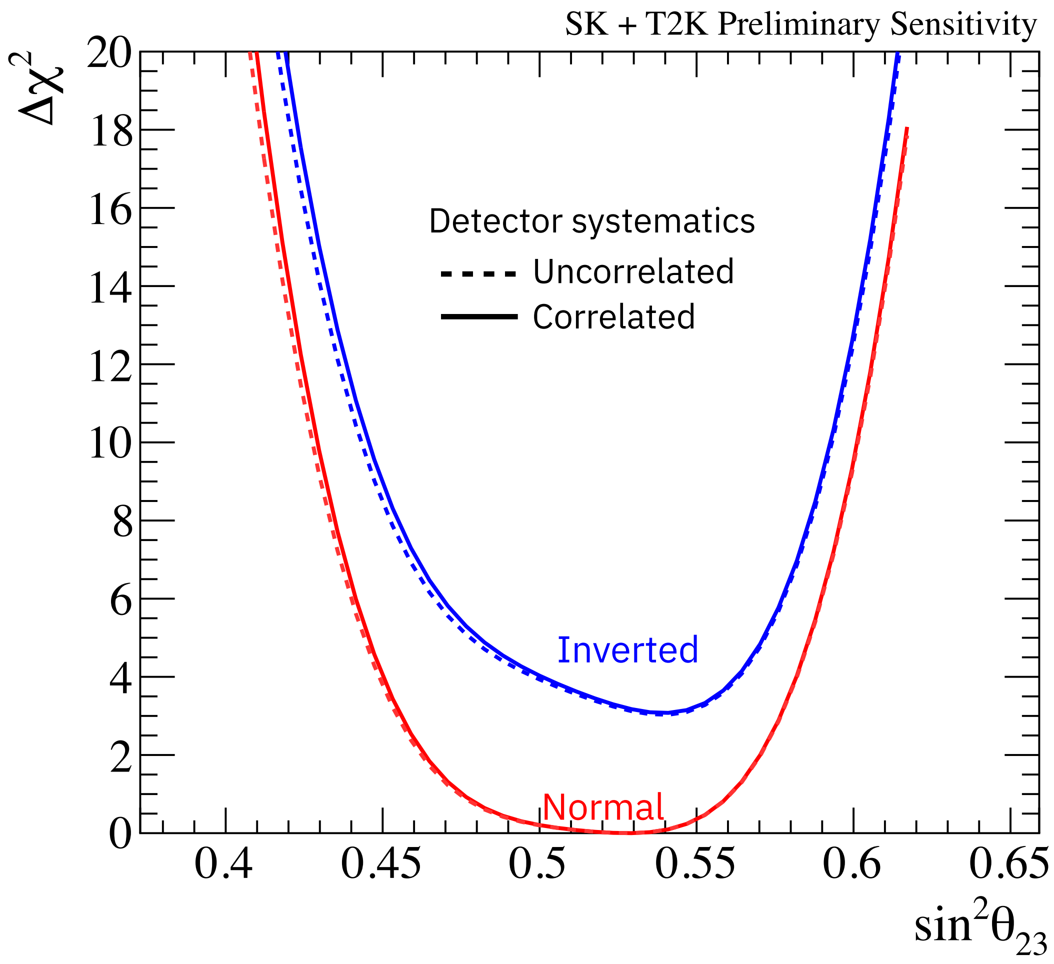


Improvement in SK $\sin^2\theta_{23}$ sensitivity from T2K ND constraint

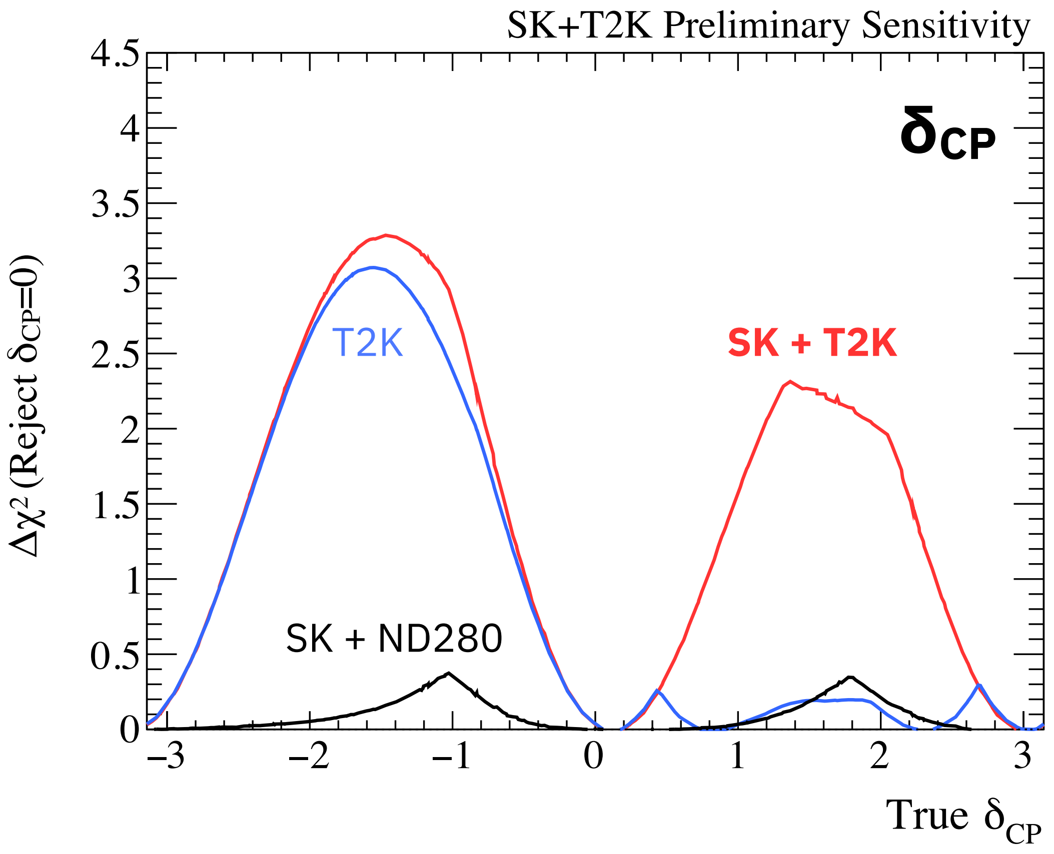
Detector Systematics

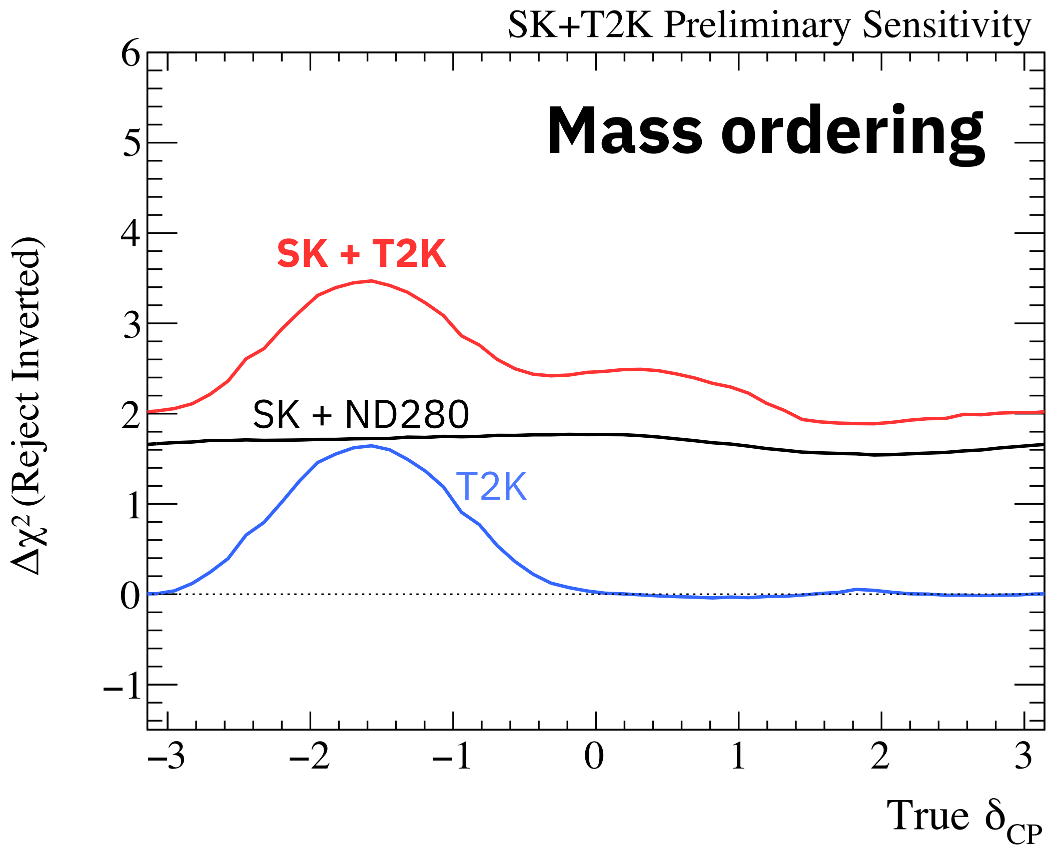
- Same reconstruction is applied to SK & T2K events
  → Detector systematics are fully correlated

- Overall small effect on oscillation parameter sensitivities. Expect to become more relevant with higher statistics



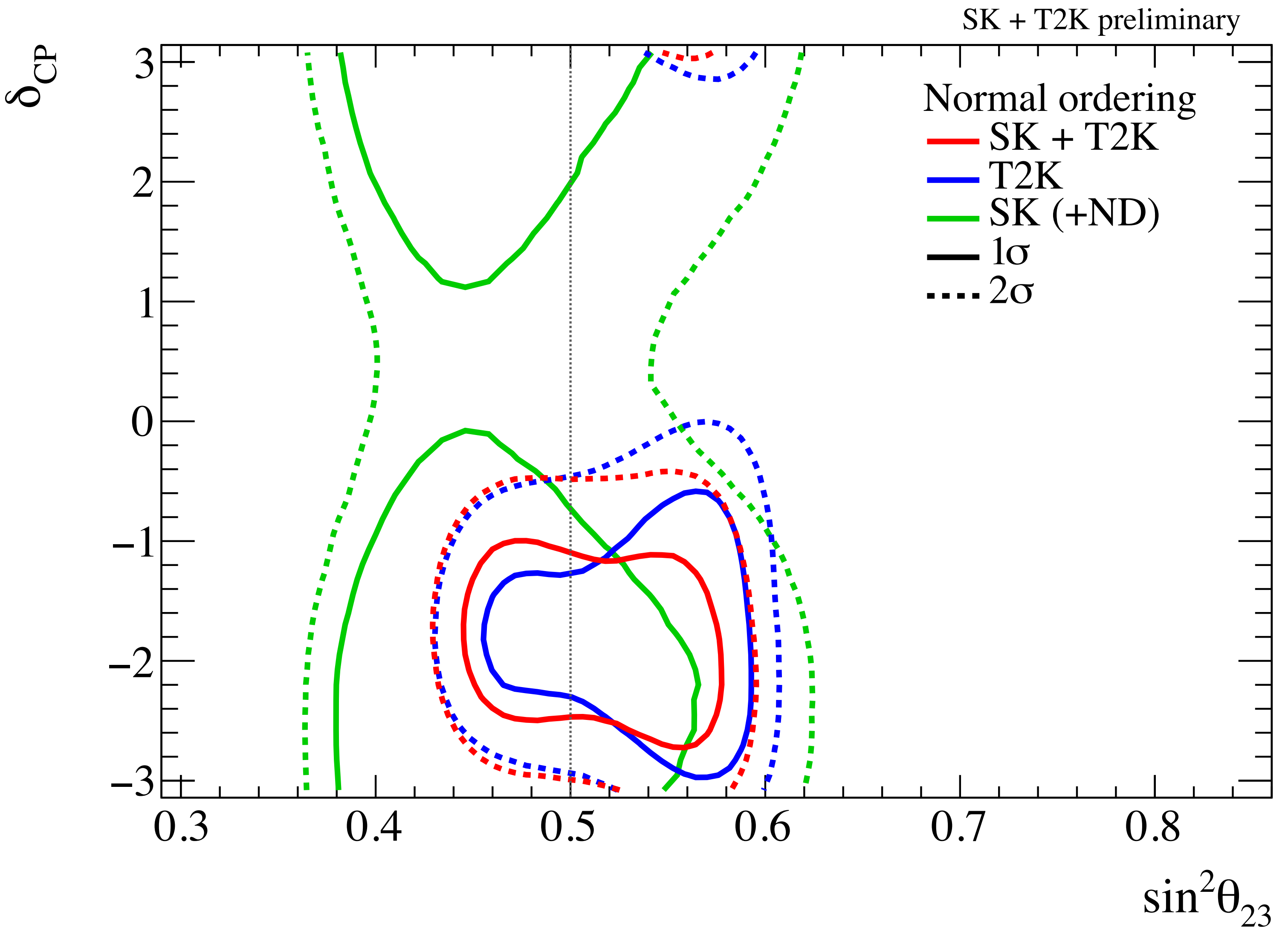
T2K + SK IV Joint Fit Sensitivities





- Mass ordering-δ_{CP} degeneracy broken for $0 < \delta_{CP} < \pi$
- Gains in sensitivity beyond simple likelihood sum

T2K + SK IV Joint Fit Results: δ_{CP} & Octant

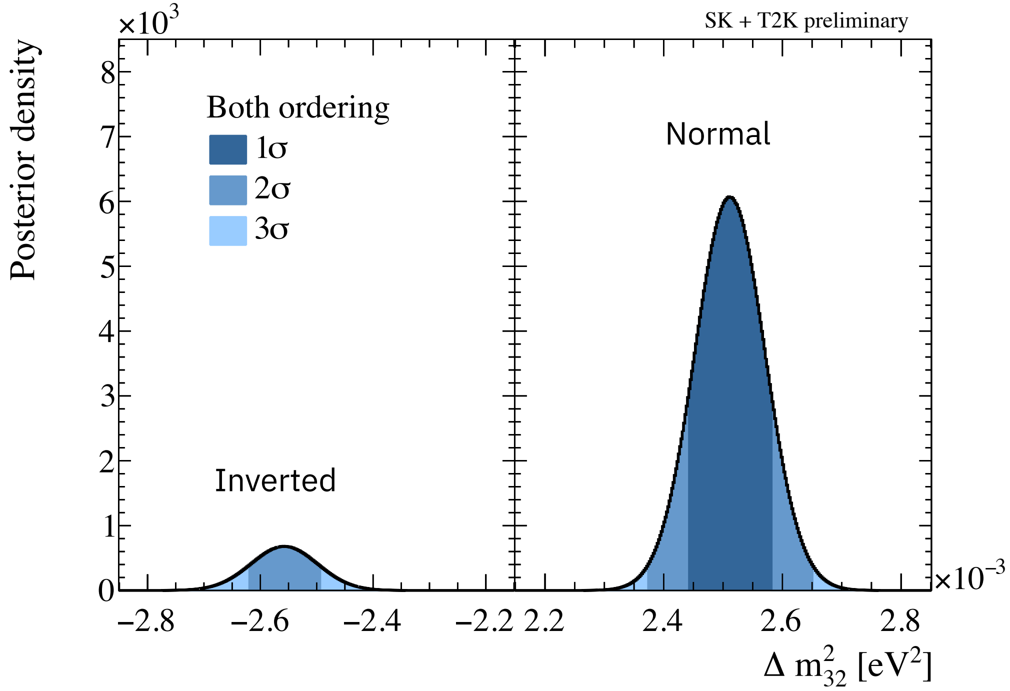


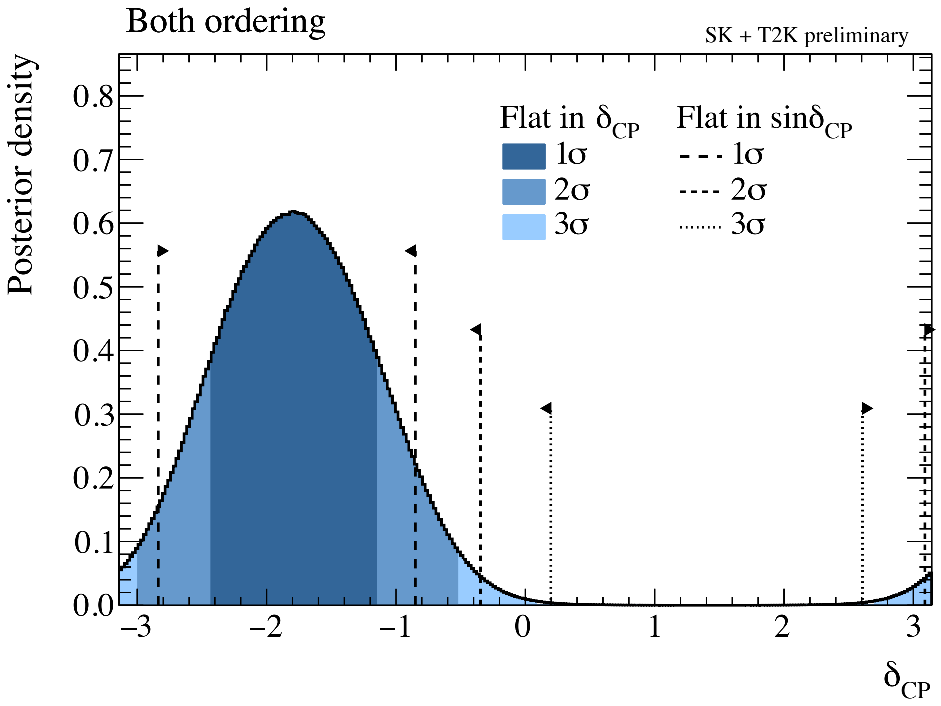
Bayesian results, frequentist results in preparation

Best fit in the normal ordering, $\delta_{CP} \sim -\pi/2$

SK & T2K data slightly prefer different octants for $\sin^2\theta_{23}$, joint fit has no strong preference

Joint Fit Results: Mass Ordering & CP conservation





NO/IO Bayes factor 8.98±0.06

(~1.6σ assuming Gaussian)

CP conservation rejected at 90%-2σ level

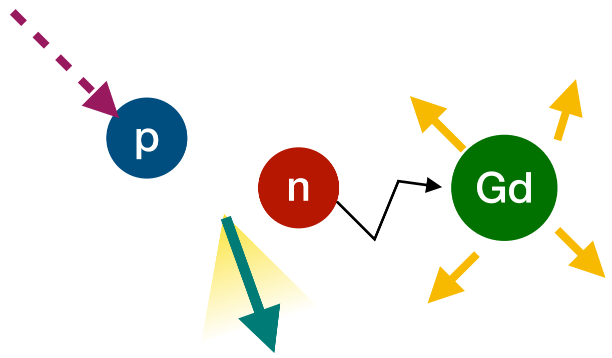
Depending on prior choice & out-of-model effects

Coming soon: Comparisons between multiple fitting groups & frequentist results

SK-Gd: Super-K with Gadolinium

SK-Gd Idea

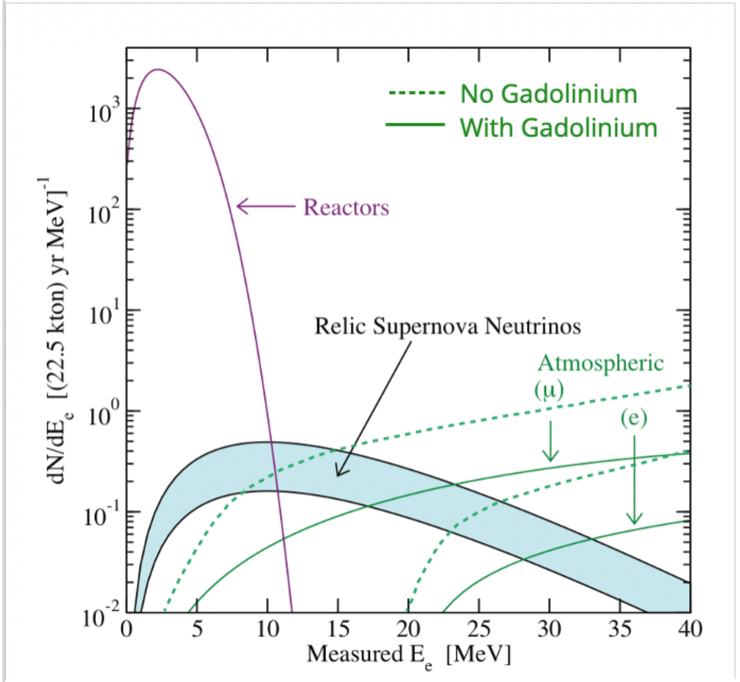
SK-Gd proposal: Phys. Rev. Lett. **93**, 171101 (2003)



Neutron captures	Gamma energy (MeV)	Capture time (µs)	Tagging efficiency (%)	Capture vertex resolution (cm)
H (pure water)	2.2	200	26	–
0.01% Gd	8	120	50	~100
0.03% Gd	8	60	75	~100

Gd Neuton Tagging in SK

Diffuse supernova neutrino background (DSNB)



Inverse beta decay (IBD) signal, reduce atmospheric ν background

Gd Neuton Tagging in SK

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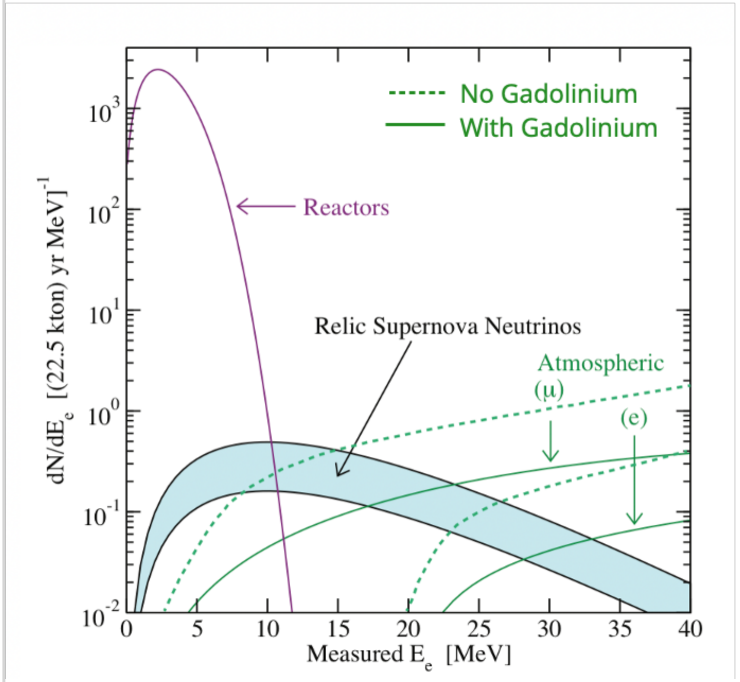
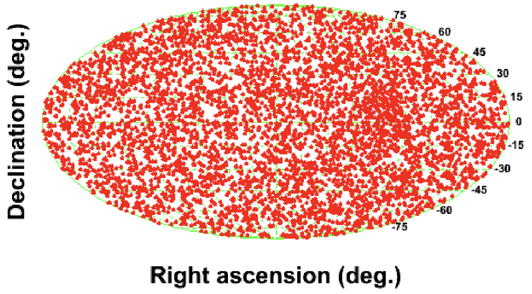


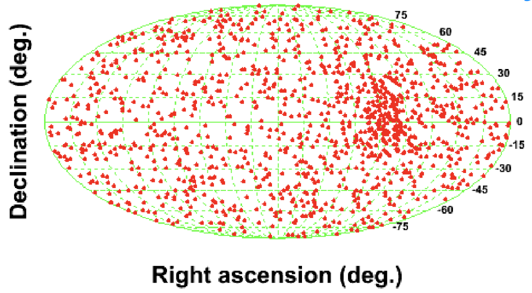
Inverse beta decay (IBD) signal, reduce atmospheric ν background

Supernova Pointing

10 kpc SN, All events



IBD removed with 80% efficiency



Efficiently tag IBD events
Elastic scatters point back to SN location

Gd Neuton Tagging in SK

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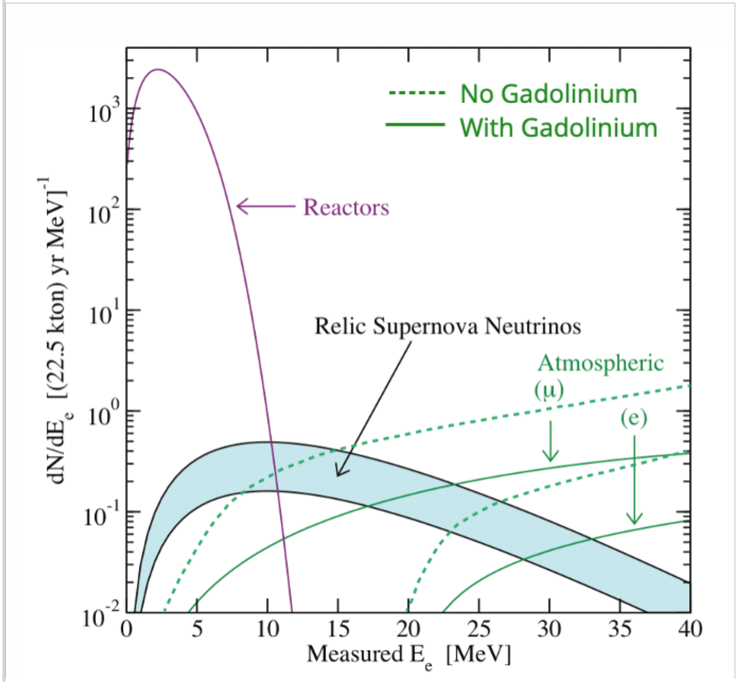

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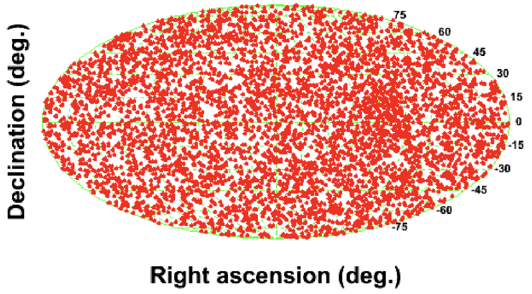

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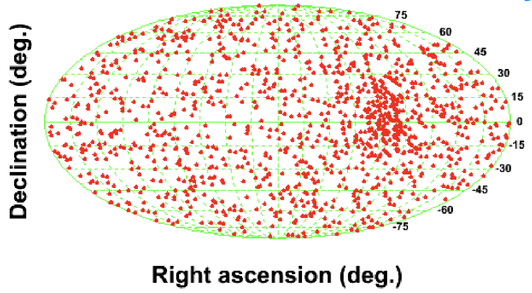
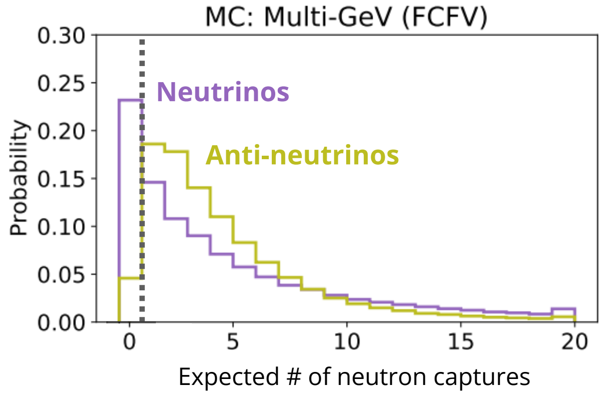
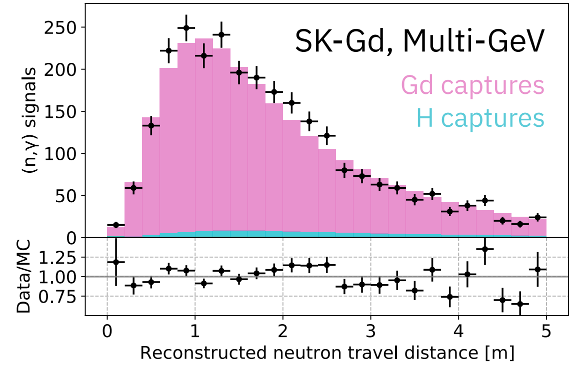


Efficiently tag IBD events
Elastic scatters point back to SN location

Atmospheric ν





Neutrino/anti-neutrino separation
Neutron vertex used in reconstruction

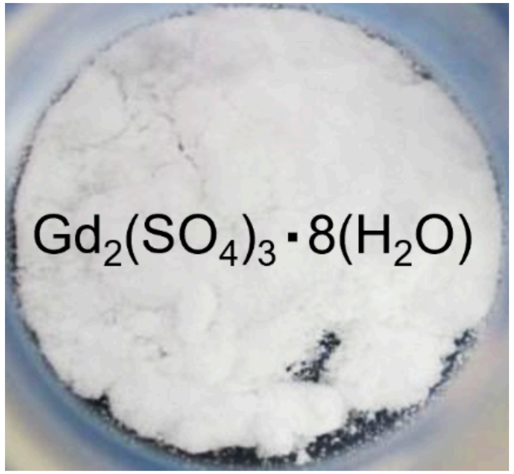
Gadolinium Timeline

2014–: EGADS detector ~ mini-SK, ongoing Gd R&D

2018: SK-Gd water system installed, commissioned with pure water during 2019-2020

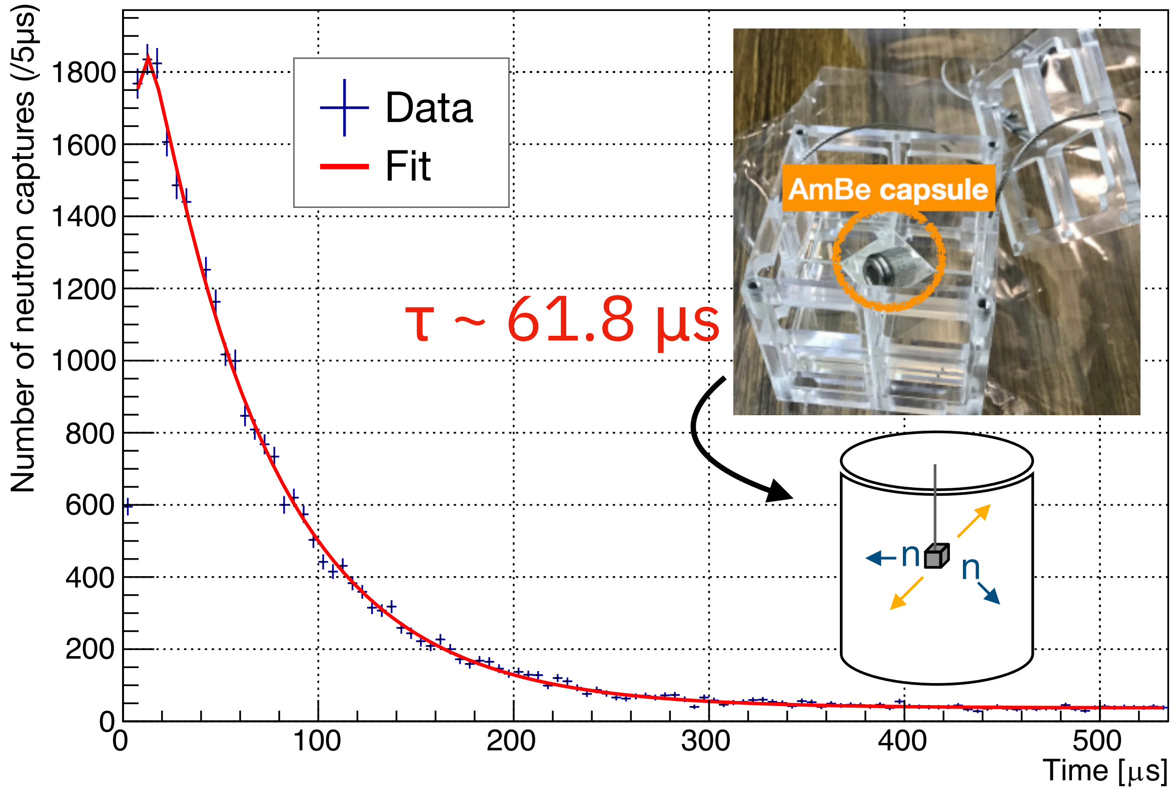
2020: 0.01% loading completed

2022: 0.03% loading completed

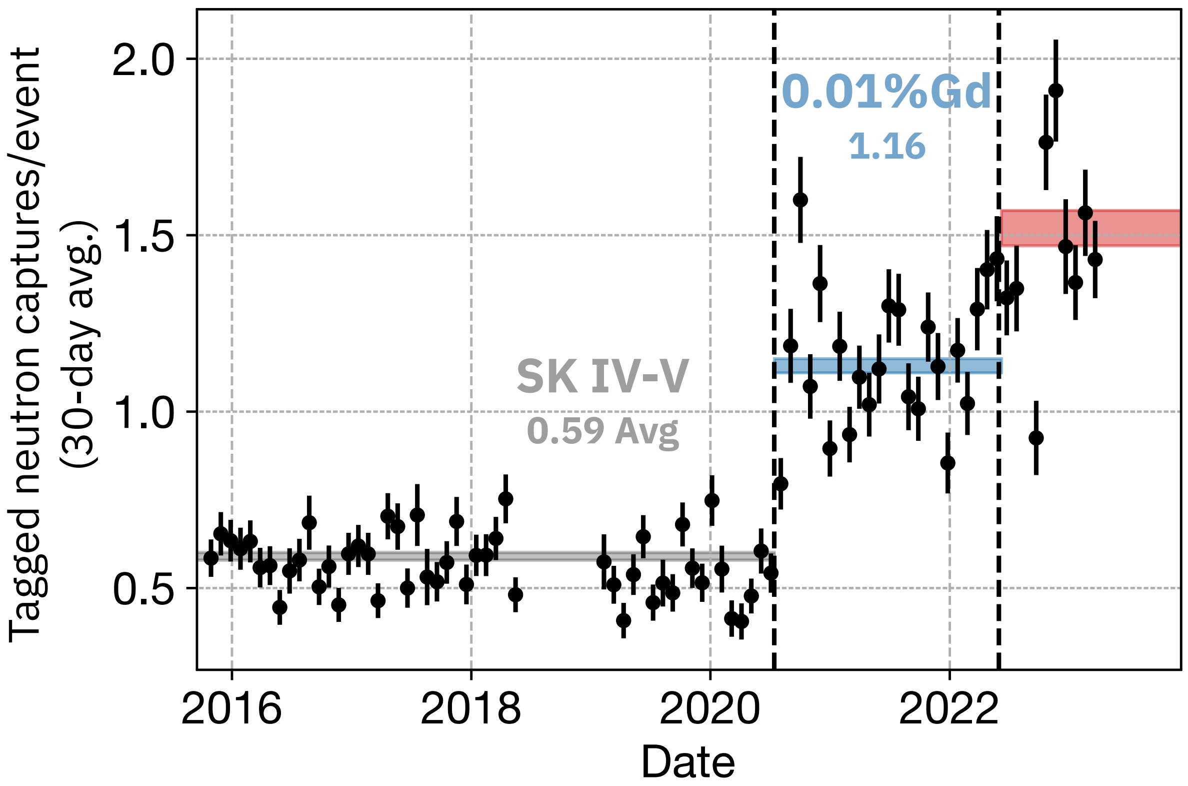


SK-Gd Neutron Capture Measurements

0.03% loading AmBe Measurement



Fully contained atmospheric ν

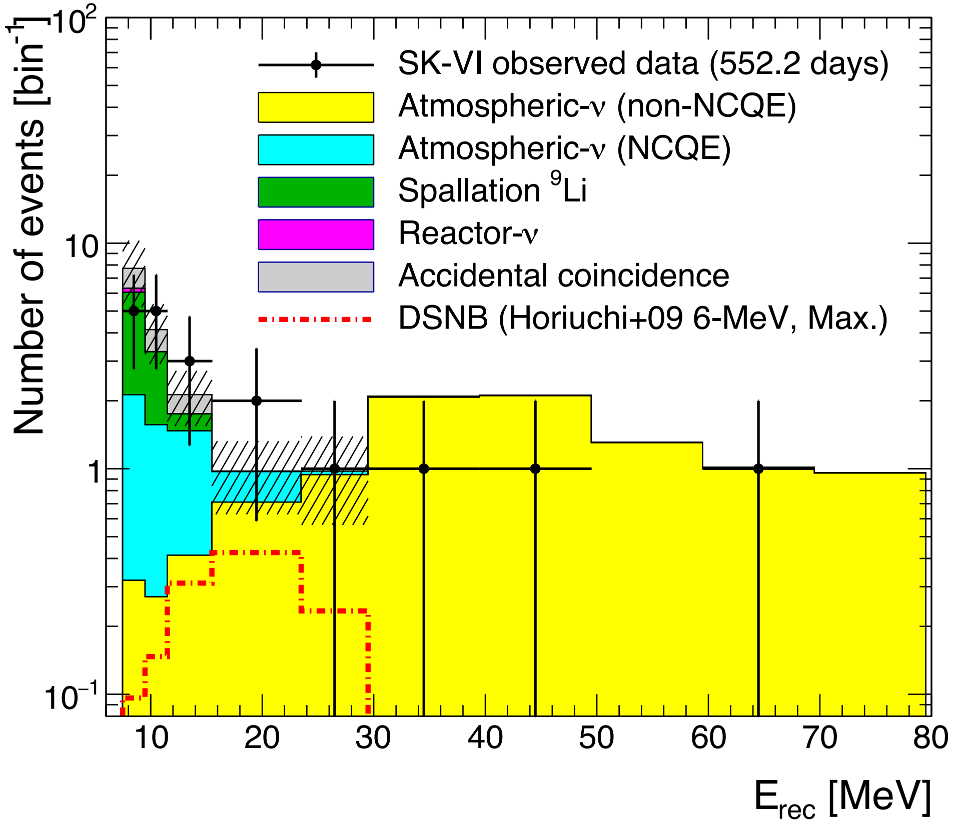


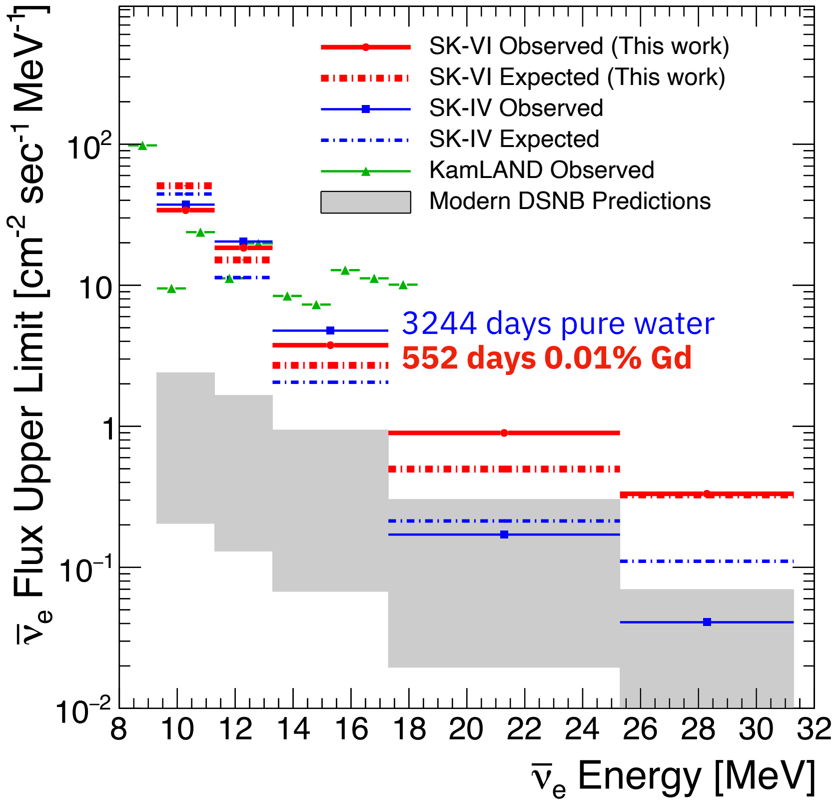
SK-Gd DSNB analysis

APJ Lett. **951**:L27 (2023)

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 if neutron is tagged
- 0.01% SK-Gd data analyzed: Sensitivity is close to theoretical predictions, competitive with pure water phases





Summary

Atmospheric neutrinos
- Analyzed full pure water data set
- Prefer normal mass ordering, reject inverted ordering CL_s ~ 0.077

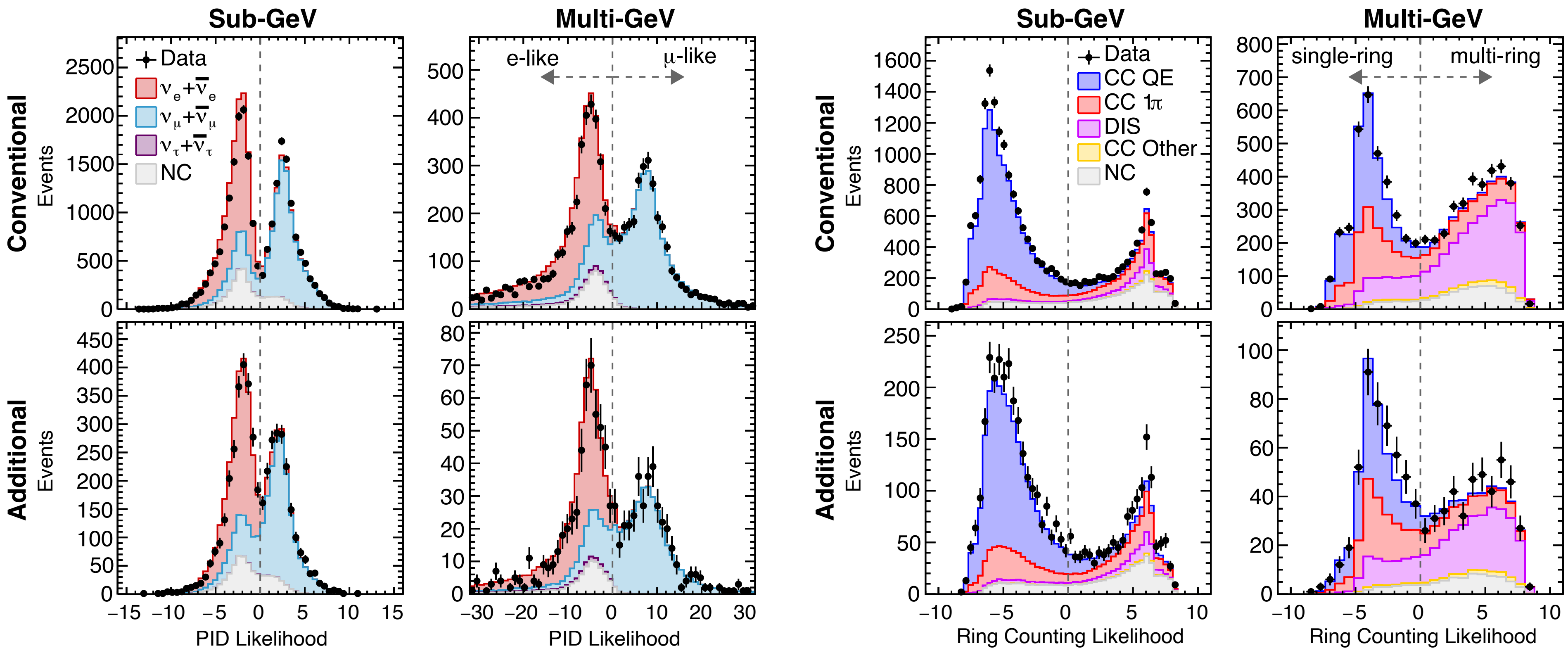
Joint Analysis with T2K
- Developed robust analysis framework for combining SK atmospheric and T2K beam data sets
- Reject CP conservation at ~2σ level using ~50% of pure-water atmospheric data set

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

Extra

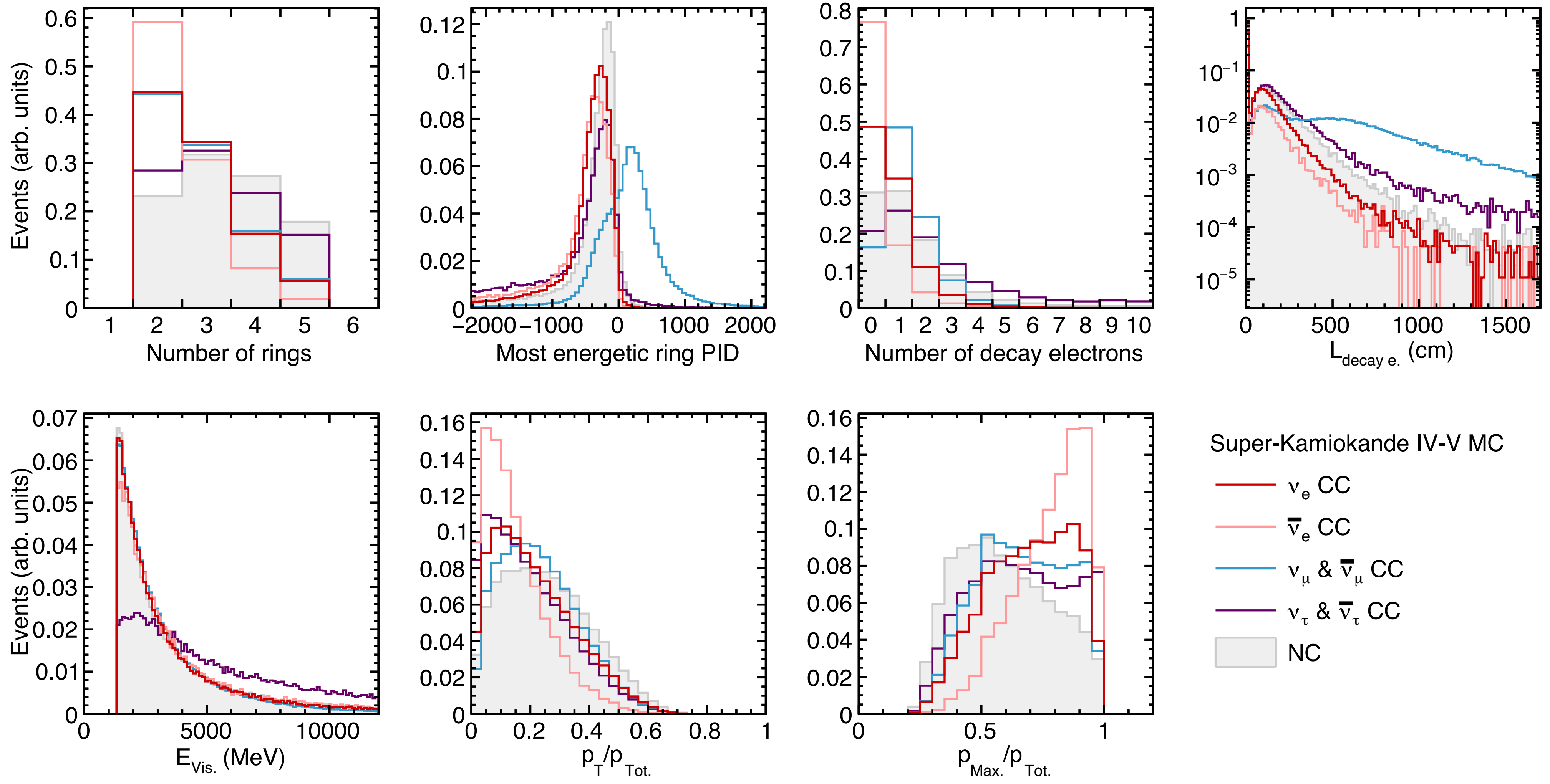
SK I–V Atmospheric Neutrino Oscillation Analysis

Comparison of Fiducial Volume Reconstruction Performance



Distributions show data/MC agreement before the application of any systematic uncertainties. Dashed lines show cut for e/μ or single/multi-ring classification.

All Multi-ring BDT Input Distributions

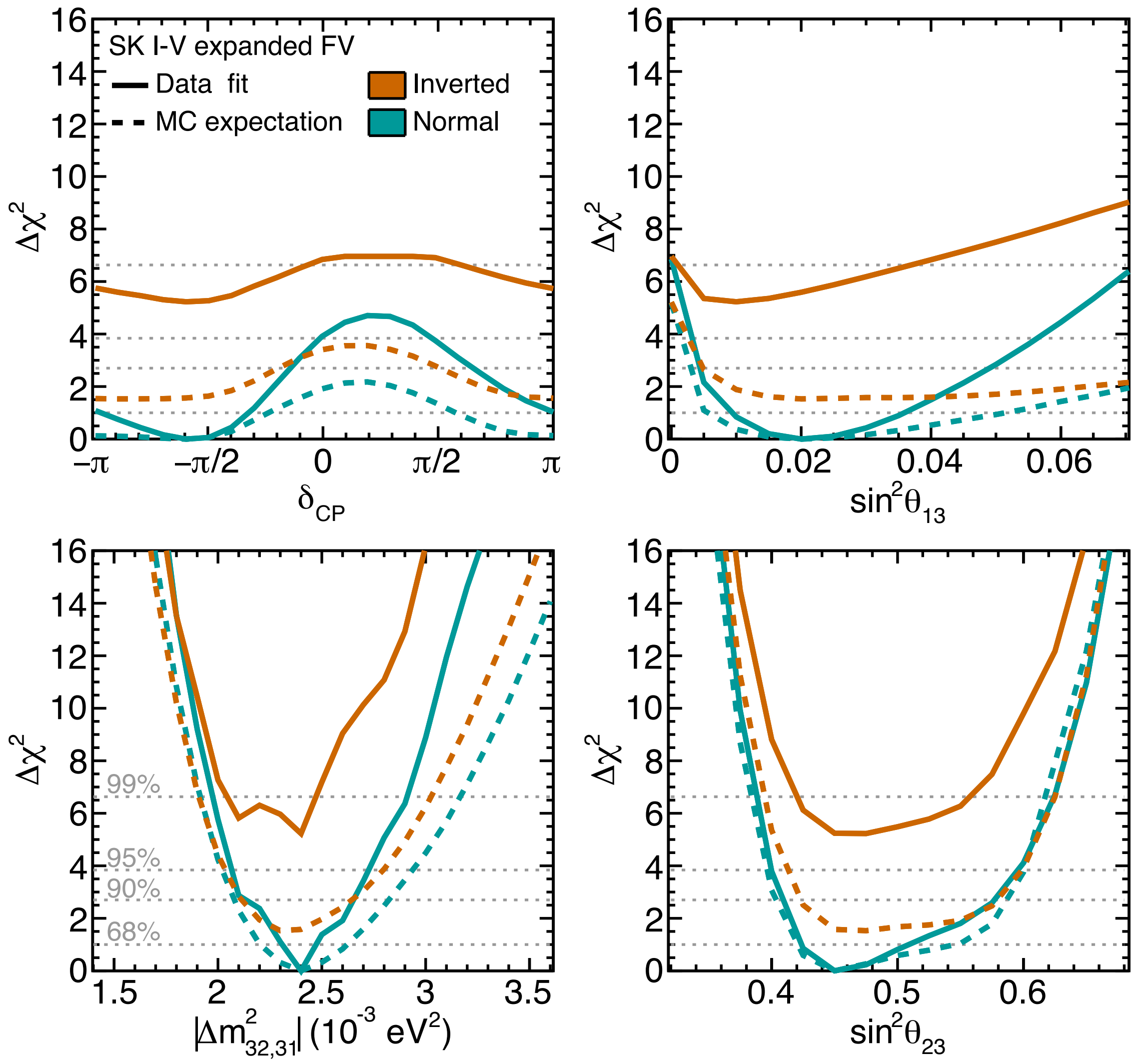


Multi-ring BDT Efficiencies & Purities

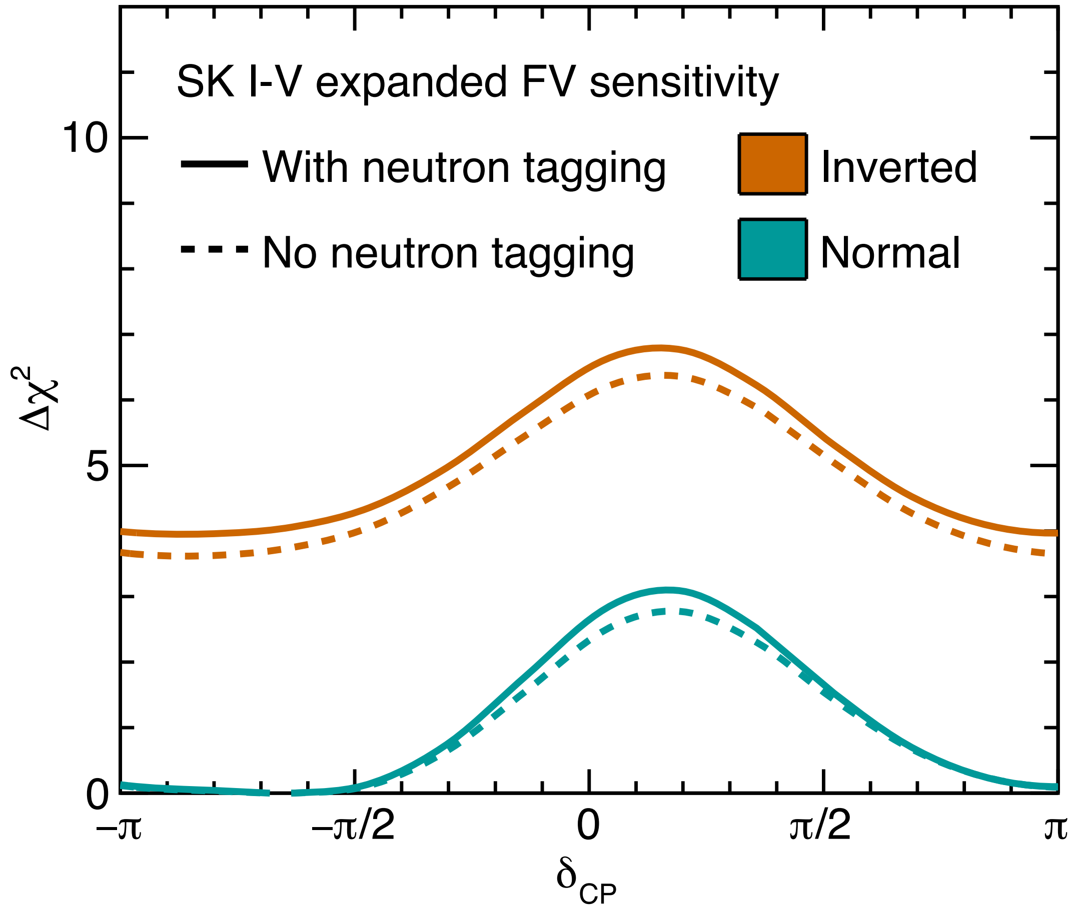
Multi-ring sample	Likelihood (Previous SK analyses)		BDT (SK I–V analysis)	
	Efficiency (%)	Purity (%)	Efficiency (%)	Purity (%)
ν_e	35	56	55	50
$\bar{\nu}_e$	58	27	65	26
ν_μ & $\bar{\nu}_\mu$	74	92	81	91
Other (NC)	57	30	31	43

Results with θ_{13} Free

- Prefer **normal** ordering, $\Delta\chi^2_{IO\text{-}NO} \approx$ **5.2**
- Prefer **$\sin^2\theta_{13} \approx 0.02$**, consistent with world-average reactor measurements



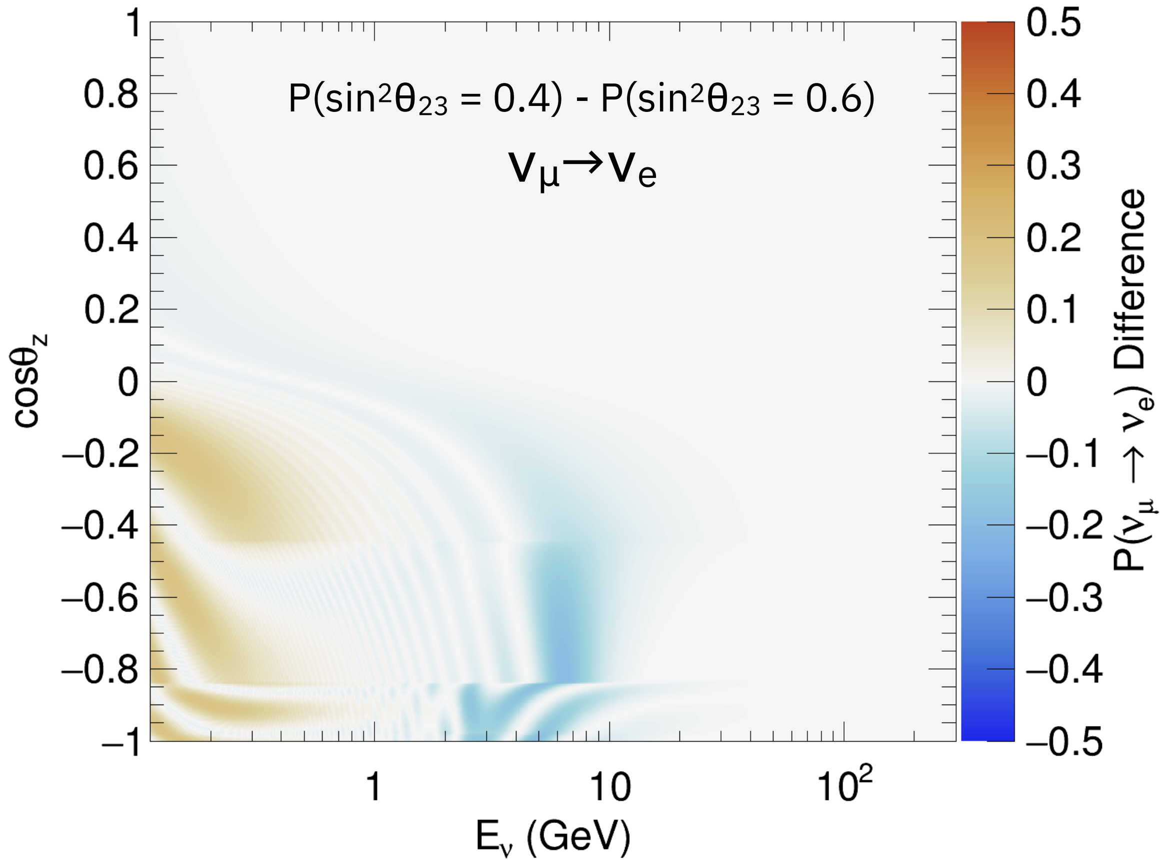
Neutron Tagging & Mass Ordering

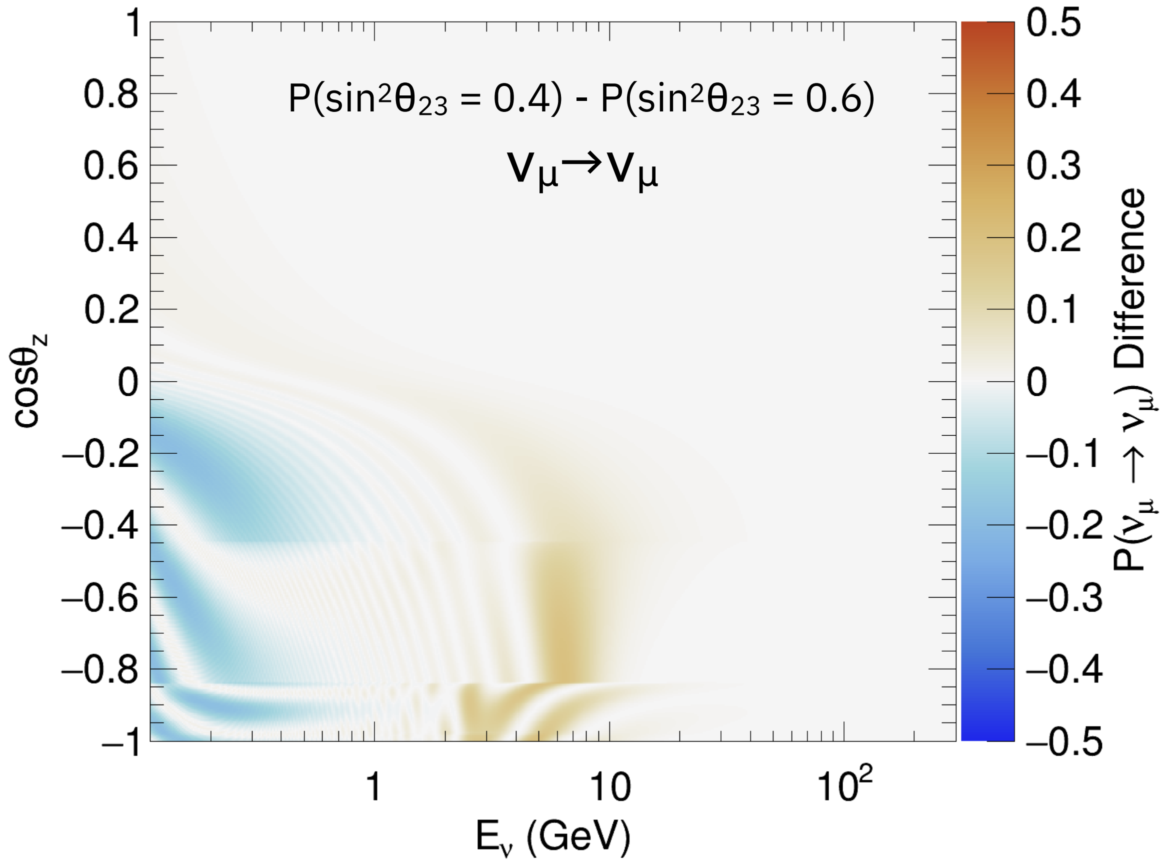


Comparison between event selection from previous SK atmospheric neutrino oscillation publication & event selection using neutron tagging for SK IV-V (57% of total livetime) fully contained single-ring data

Oscillation parameters assumed: PDG 2022

Octant Effect on Oscillations

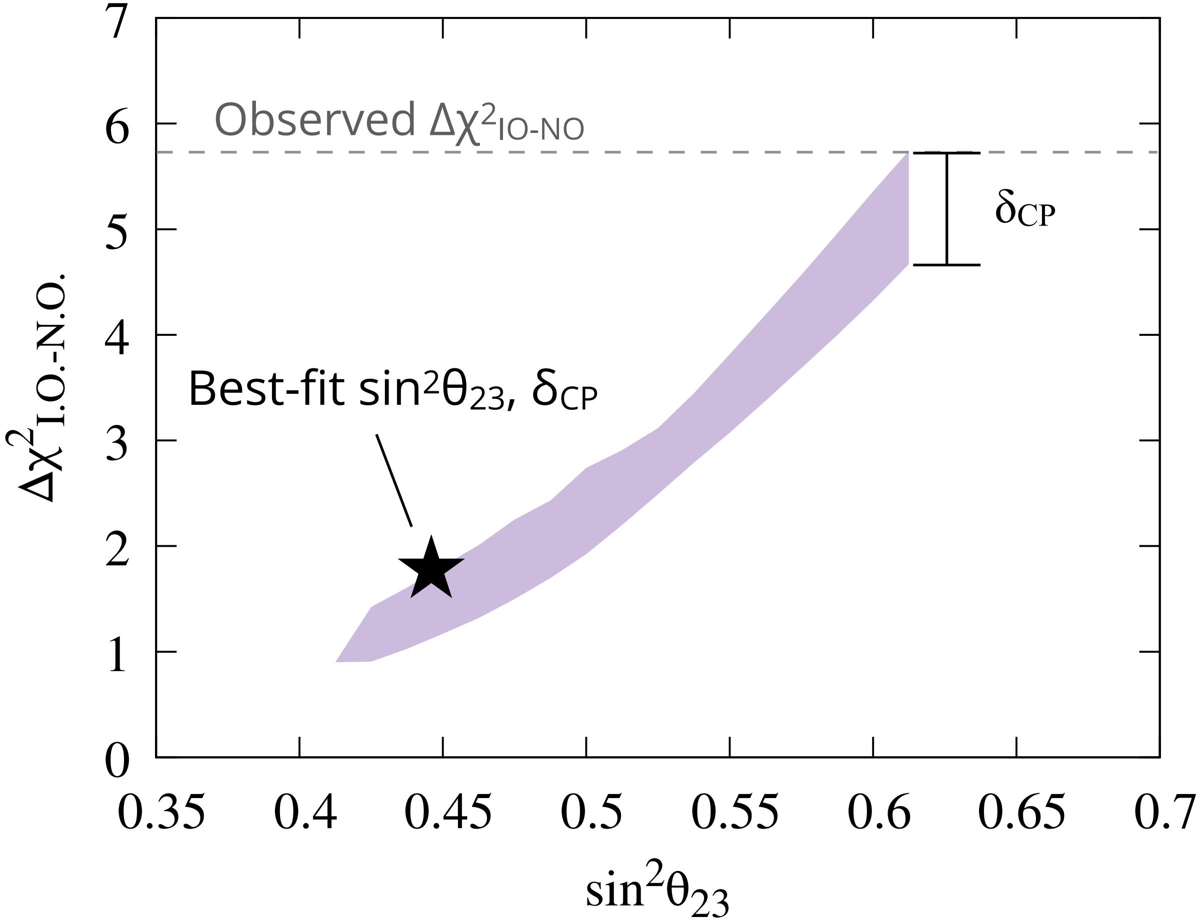




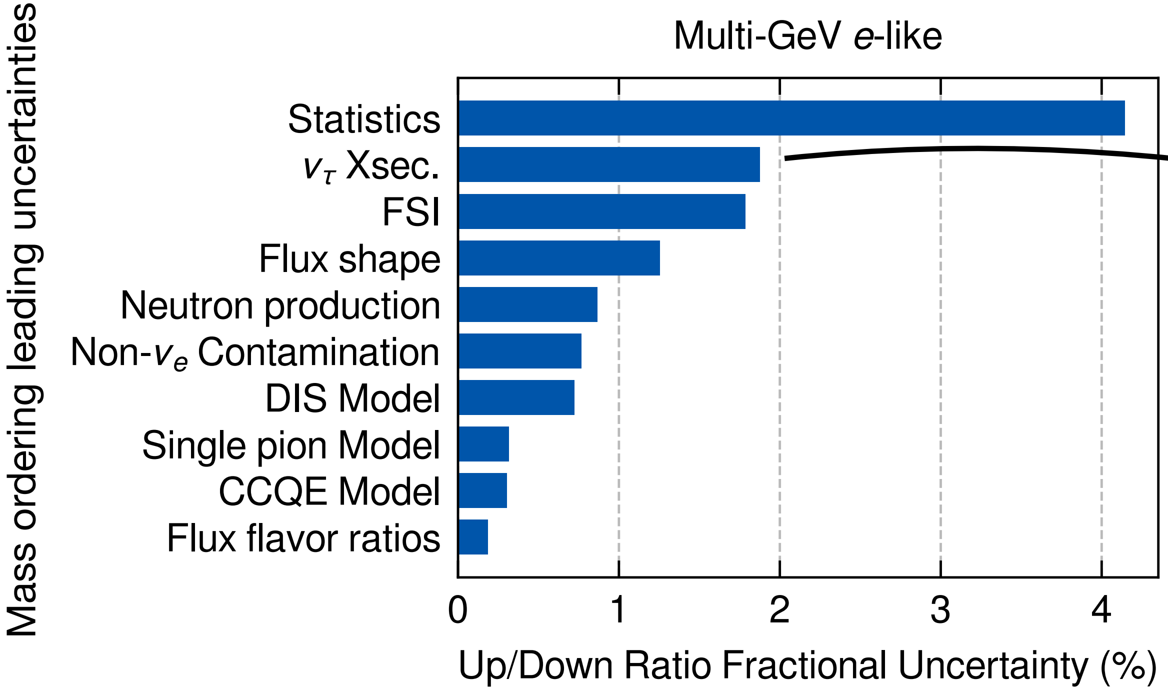
Mass Ordering Sensitivity vs. Octant

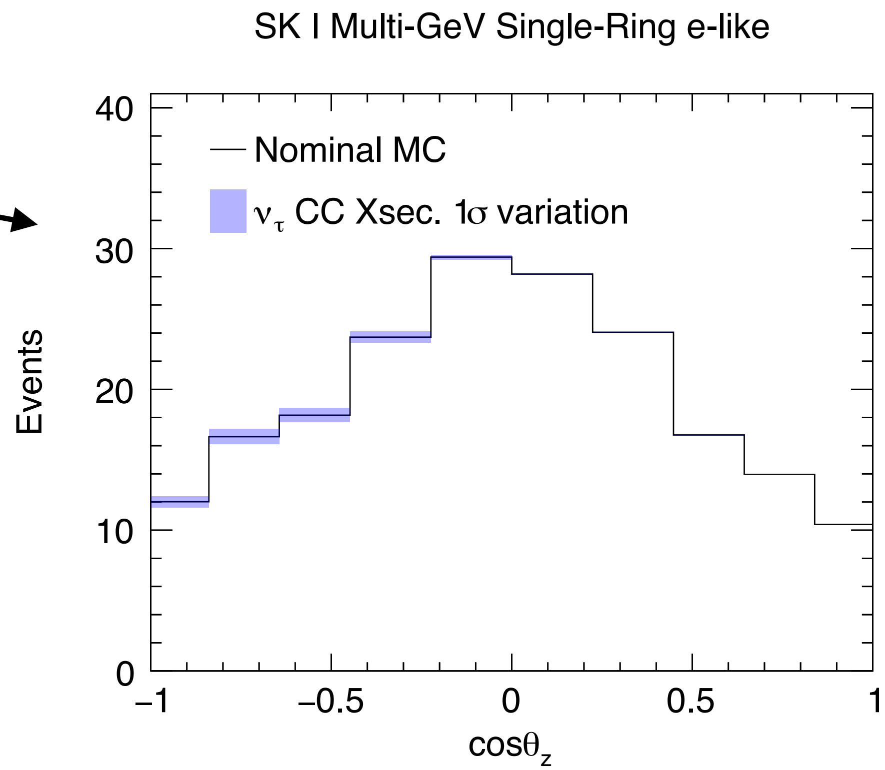
- Octant is constrained by sub-GeV events & multi-GeV ν_μ events with small mass ordering sensitivity
- Figure: Sensitivity for combinations of oscillation parameters allowed at 90% confidence level
- Upper-octant values of θ_{23} are closer to observed $\Delta\chi^2_{IO-NO}$, wide range

Mass ordering sensitivity for oscillation parameters allowed at 90% confidence level



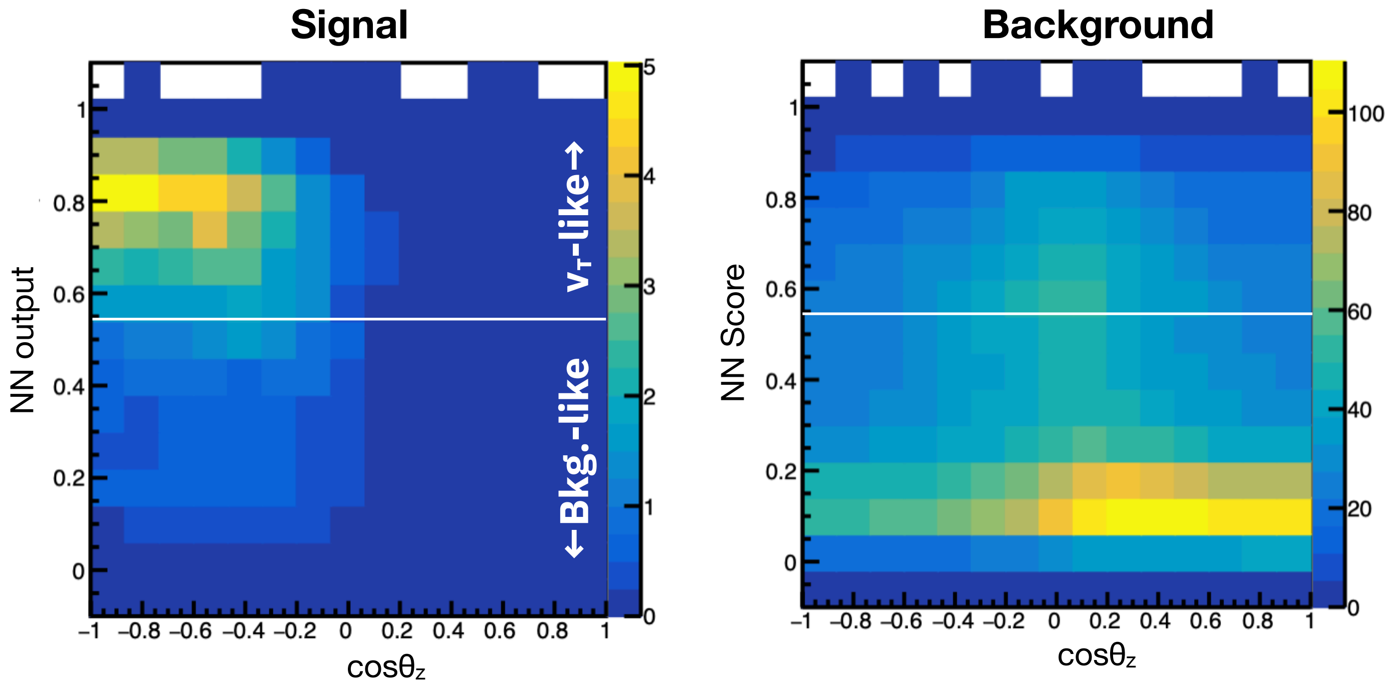
Tau Neutrinos: What's Next



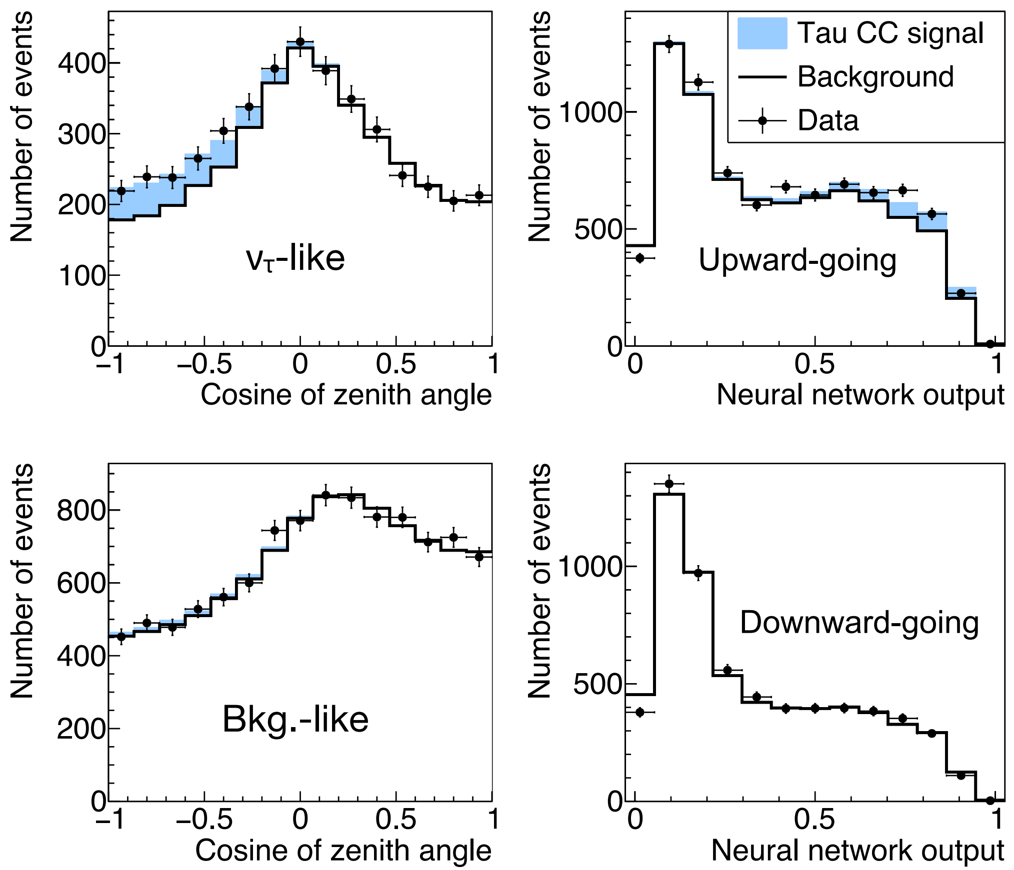


SK ν_τ Appearance with Neural Network

- Neural network based on Multi-ring BDT inputs + sphericity measure
- Fit 2D signal & background PDFs to data, >4σ ν_τ appearance signal
- Planned incorporation into oscillation analysis

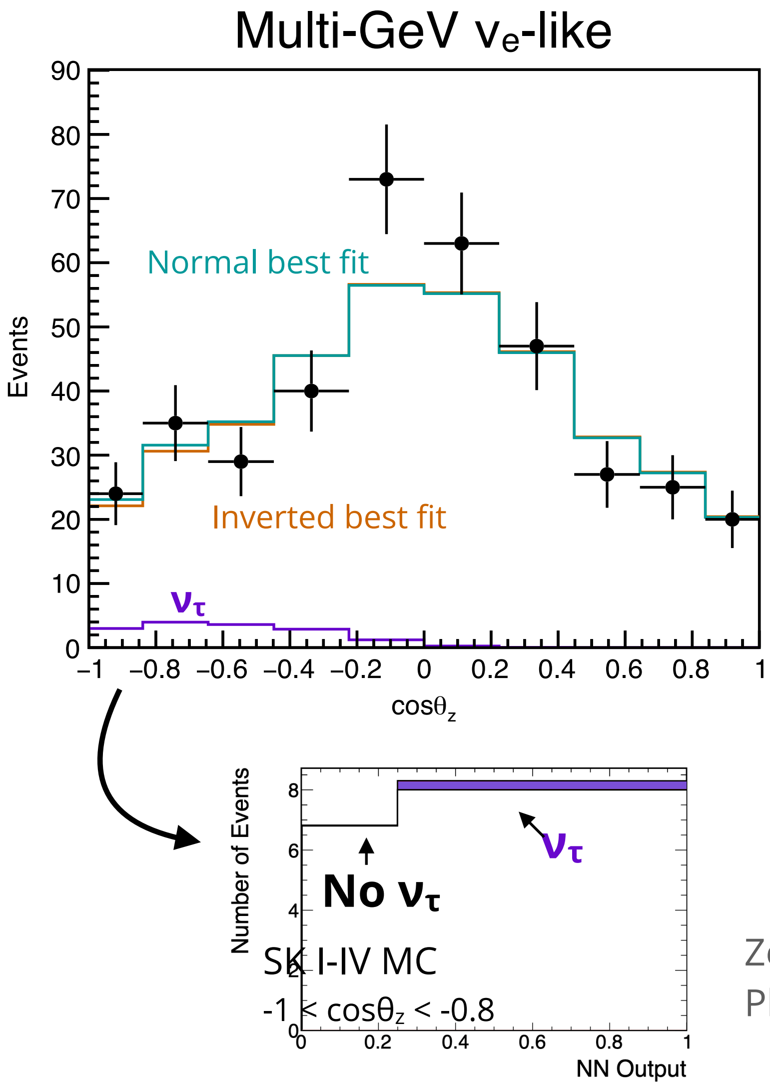


1D projections of PDF fit to data



Reducing ν_τ Contamination

- ν_τ due to $\nu_\mu \to \nu_\tau$ 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



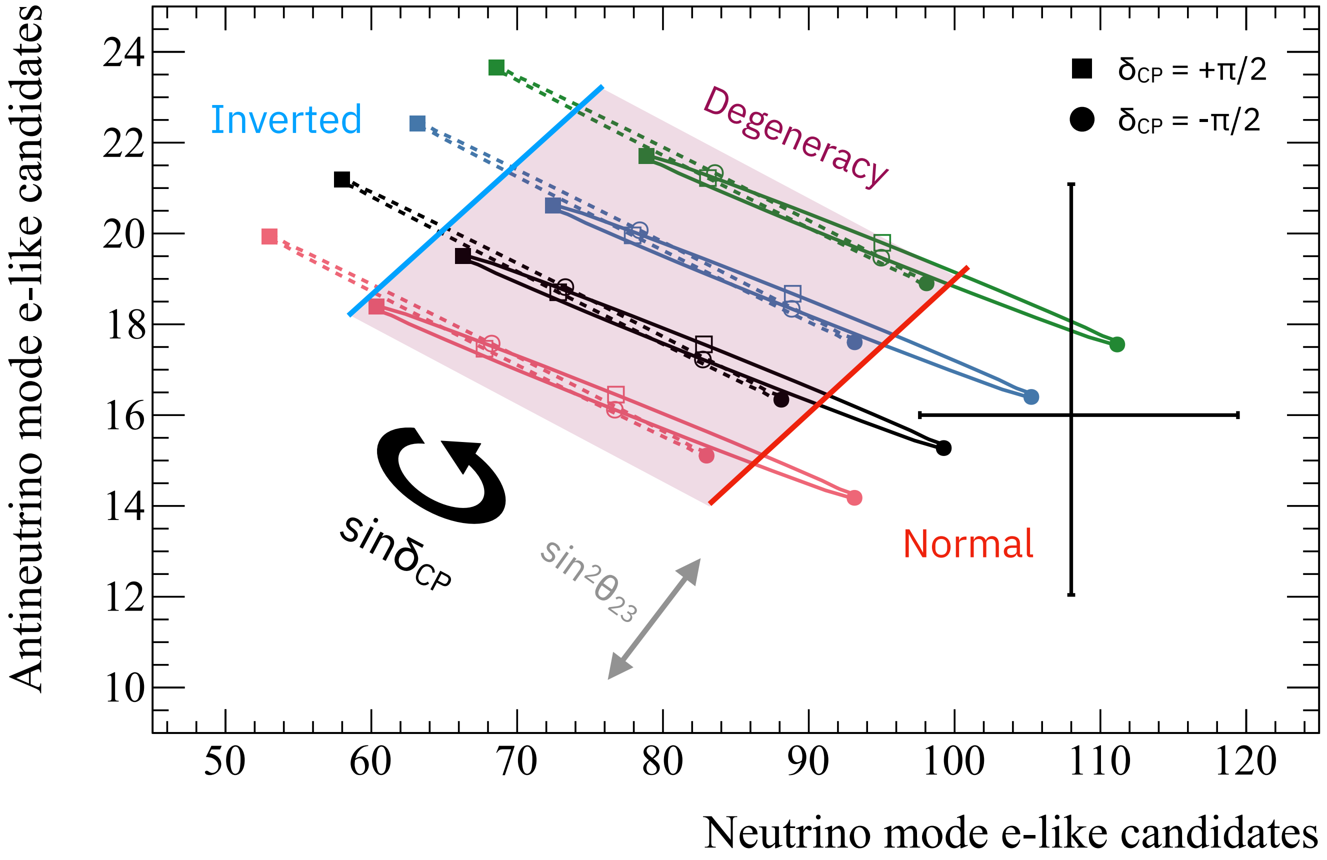
Zepeng Li
PhD Thesis, 2017

More on SK + T2K Joint Fit

T2K Oscillation Measurement

T2K uses $\nu_\mu \rightarrow \nu_e$ appearance to measure δ_{CP} & mass ordering

- Maximum ν_e appearance for normal ordering & $\delta_{CP} \sim -\pi/2$, can exclude inverted ordering
- Degeneracy between mass ordering & δ_{CP} for non-maximal values due to small matter effect



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

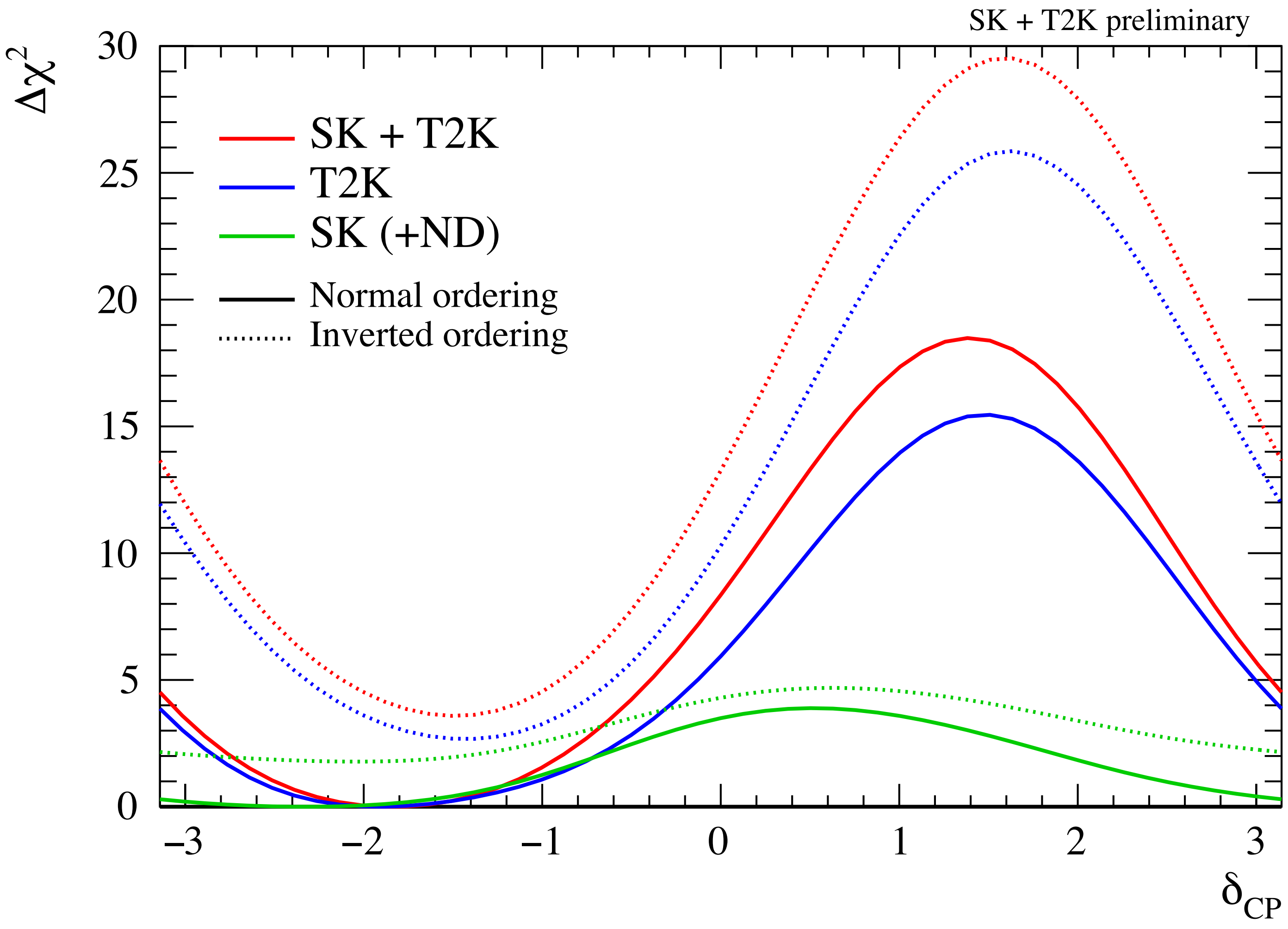
Cross Section Model Overview

	Low-energy sub-GeV atm + beam	**High-energy** multi-GeV atm
CCQE	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	add ν_e/ν_μ ratio unc. (CRPA)	
2p2h	T2K model w/ND280	SK model (100% error) + T2K-style shape
Resonant	T2K model w/ND280 + new pion momentum dial + NC1π^0 uncertainties	SK model for 3 dials common with T2K, use more recent larger T2K priors
DIS	T2K model w/ND280	SK model
$\nu\tau$	SK model (25% norm on top of other syst) for other systematics checked that we have no numerically unstable values	
FSI	T2K model w/ND280	T2K model w/o ND280 should be mostly same as SK model
SI	T2K model, correlated in low-E/high-E only applied to FC and PC for atm, PN not applied to atm	

98

L. Berns, KEK-JPARC Seminar

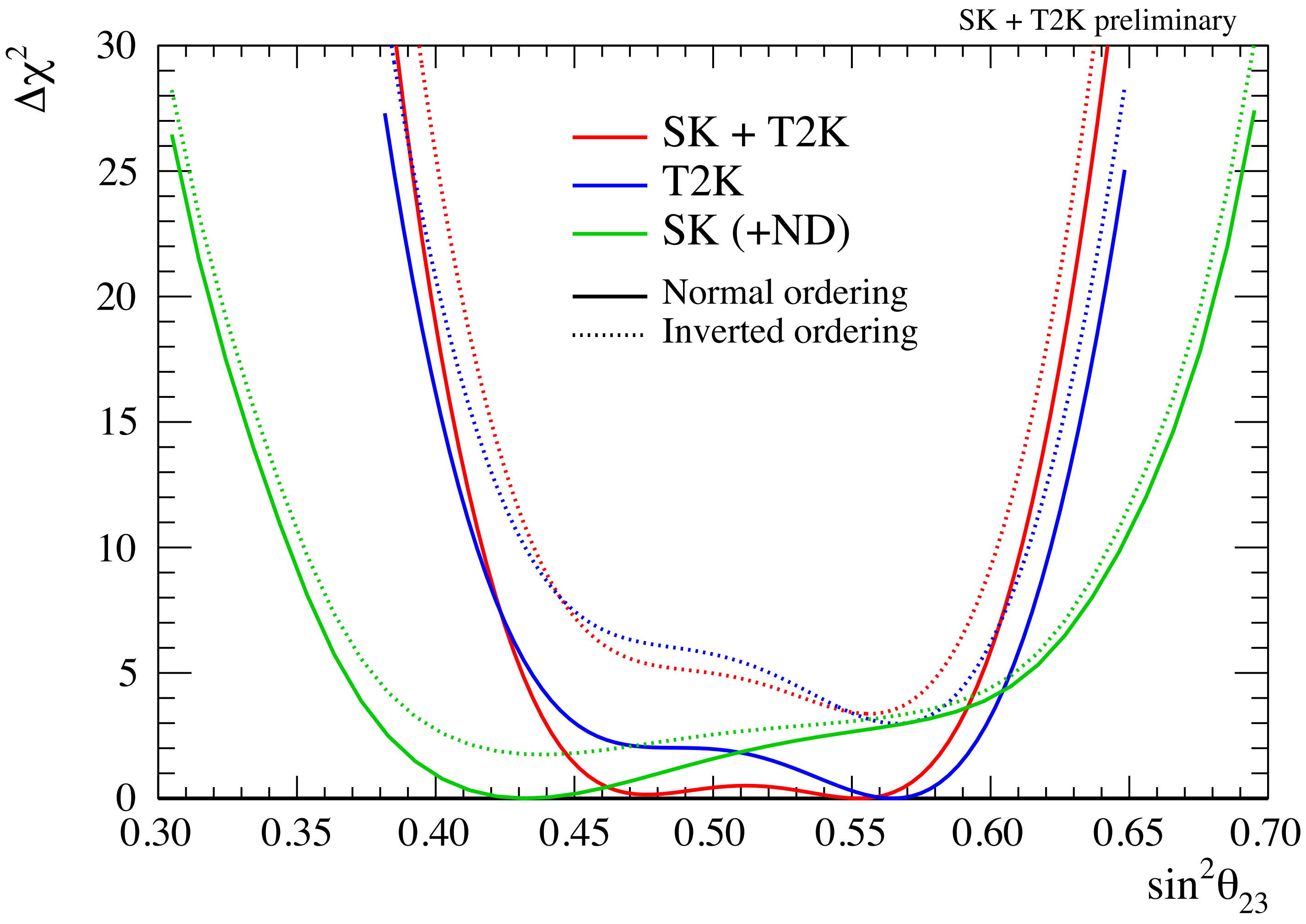
T2K + SK IV Joint Fit Results 1D



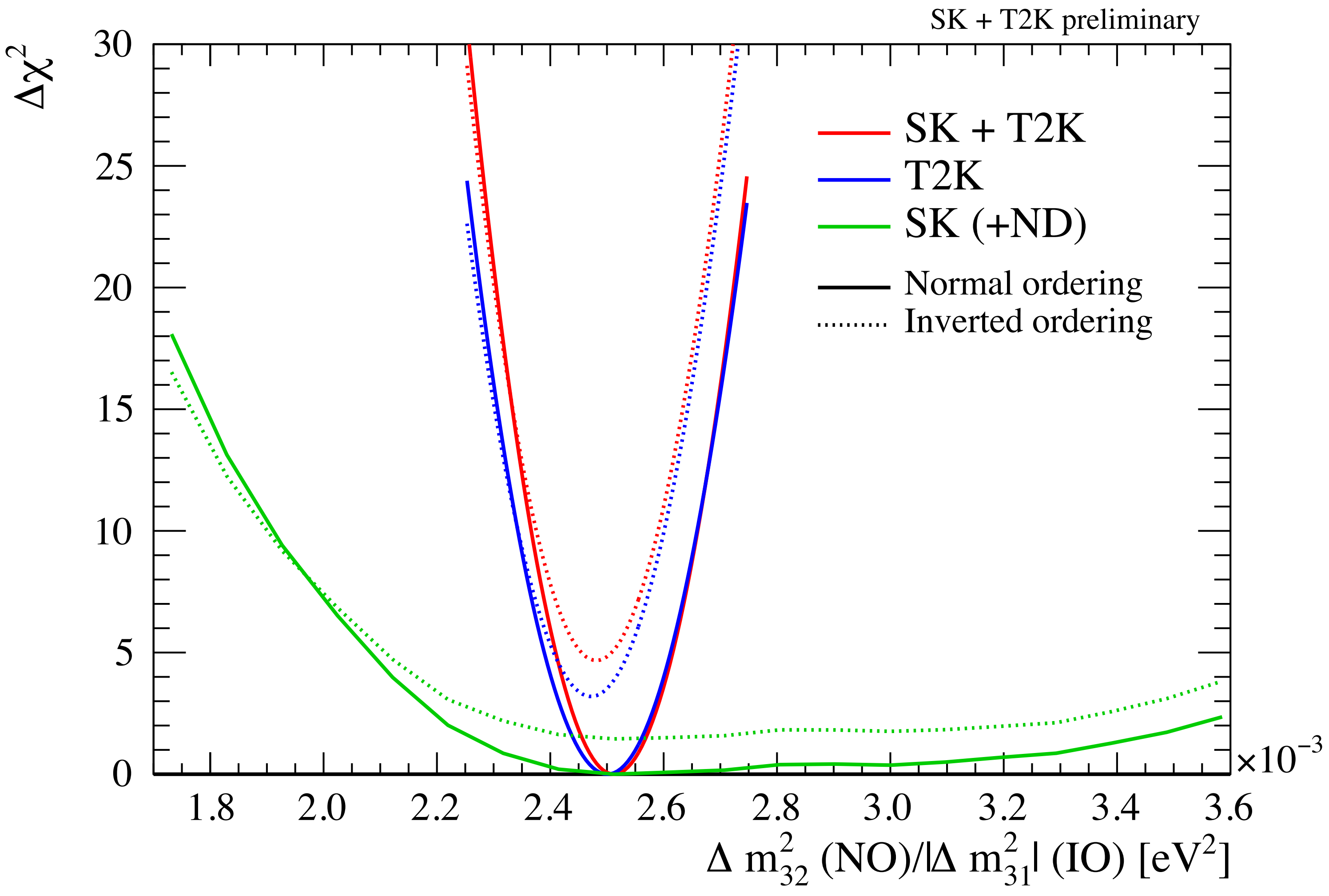
$\Delta\chi^2$ obtained from the numerical marginalization based on the importance sampling method.

The fixed $\Delta\chi^2$ does not guarantee the correct coverage, and therefore, the significance of CP symmetry exclusion is not given by the values of $\Delta\chi^2$ at $\delta CP = 0, \pi$.

T2K + SK IV Joint Fit Results 1D



T2K + SK IV Joint Fit Results 1D



Joint Fit CP Conservation Summary

Summary of two fitting groups, third group results in preparation

Criteria for exclusion:
δ_{CP} → Exclude 0 & π
J_{CP} → Exclude 0

Analysis	Variable	Prior	1σ	90%	2σ	3σ
Analysis 1	$\delta_{\rm CP}$	Flat in $\delta_{\rm CP}$	✓	✓	✓	×
		Flat in $\sin\delta_{\rm CP}$	✓	✓(×)	×	×
	$J_{\rm CP}$	Flat in $\delta_{\rm CP}$	✓	✓	✓	×
		Flat in $\sin\delta_{\rm CP}$	✓	✓	✓	×
Analysis 2	$\delta_{\rm CP}$	Flat in $\delta_{\rm CP}$	✓	✓	✓	×
		Flat in $\sin\delta_{\rm CP}$	✓	✓(×)	×	×
	$J_{\rm CP}$	Flat in $\delta_{\rm CP}$	✓	✓	✓	×
		Flat in $\sin\delta_{\rm CP}$	✓	✓	✓(×)	×

✓: excluded ×: not excluded

✓(×): excluded but may not be robust against the possible bias from an out-of-model effect

Joint Fit Results Table

SK+T2K Preliminary

Prior flat in δ_{CP}			
Normal ordering	δ_{CP}	$\sin\delta_{CP}$	J_{CP}
Most probable value	-1.872	-1.000	-0.033
1σ	[-2.464, -1.205]	[-1.000, -0.776]	[-0.034, -0.026]
2σ	[-3.021, -0.556]	[-1.000, -0.261]	[-0.034, -0.008]
3σ	[-3.142, 0.085] and [2.682, 3.142]	[-1.000, 0.344]	[-0.035, 0.012]
Inverted ordering	δ_{CP}	$\sin\delta_{CP}$	J_{CP}
Most probable value	-1.476	-1.000	-0.033
1σ	[-2.003, -0.976]	[-1.000, -0.870]	[-0.034, -0.029]
2σ	[-2.528, -0.506]	[-1.000, -0.523]	[-0.034, -0.017]
3σ	[-3.048, -0.023]	[-1.000, -0.052]	[-0.035, -0.002]
Both ordering	δ_{CP}	$\sin\delta_{CP}$	J_{CP}
Most probable value	-1.797	-1.000	-0.033
1σ	[-2.417, -1.159]	[-1.000, -0.787]	[-0.034, -0.026]
2σ	[-2.985, -0.552]	[-1.000, -0.281]	[-0.034, -0.009]
3σ	[-3.142, 0.072] and [2.704, 3.142]	[-1.000, 0.325]	[-0.035, 0.011]

Out-of-Model Effects Considered

List of Robustness Test

- 14 simulated data studies have been performed to test a possible bias in the analysis.

- The first six studies are taken from Appendix B of Eur.Phys.J.C 83 (2023) 9, 782.
- Two alternative nuclear models are tested (our baseline model is SF)
  - LFG+RPA [ref]
  - HF+CRPA [ref]

SF: Spectral Function
LFG: Local Fermi Gas
RPA: Random Phase Approximation
HF: Hartree-Fock
CRPA: Continuum Random Phase Approximation

- The last six studies were included to test possible problems that would come with the joint fit.

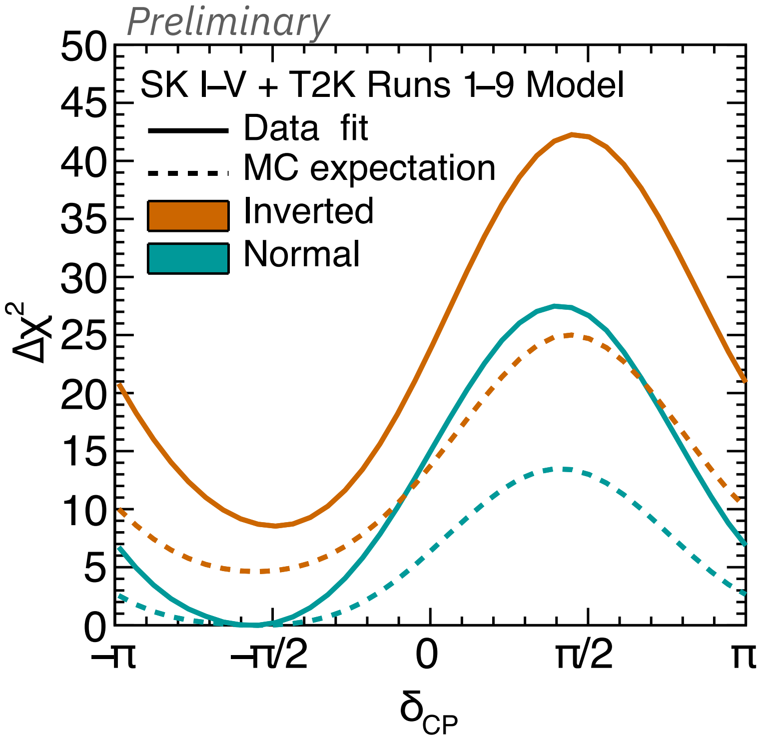
	Model component
Martini 2p2h	2p2h
ND280 data-driven pion kinematics	CC1π
CC0π non-QE alteration	CC0π
Removal energy	Nuclear Model
Axial form factors	CCQE
Pion SI bug fix	CC1π, CC$n\pi$
LFG	Nuclear model
CRPA	Nuclear model
Pion multiplicity	CC$n\pi$
Energy-dependent $\sigma_{\nu_e}/\sigma_{\nu_\mu}$	$\sigma_{\nu_e}/\sigma_{\nu_\mu}$
Xsec-only fit	Fit
Atmospheric down-going CC1π	CC1π
Atmospheric full-zenith CC1π	CC1π
No-migration energy scale fit	Fit

A. Eguchi SK+T2K joint analysis NNN23 @ Procida Wednesday, 11th October, 2023 70

A. Eguchi, NNN23 Procida

SK + T2K Model

SK + T2K Model



SK 2023 + T2K Runs 1–9 Model:

$\Delta\chi^2_{I.O.\ -\ N.O.}$ ~ 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)*

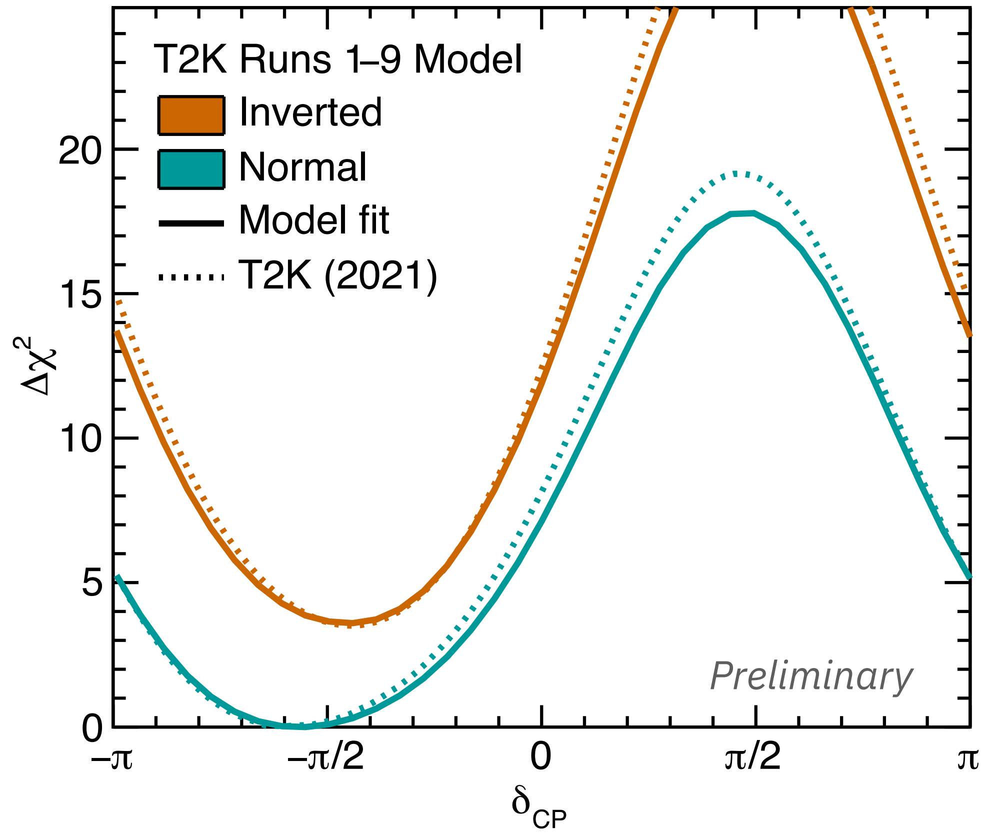
Comparison with Joint Fit

	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
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 $\bar{\nu}$-mode (T2K runs 1–9)	**3244.4 days** (SK IV) **19.7e20 ν-mode**, 16.3e20 $\bar{\nu}$-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)

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



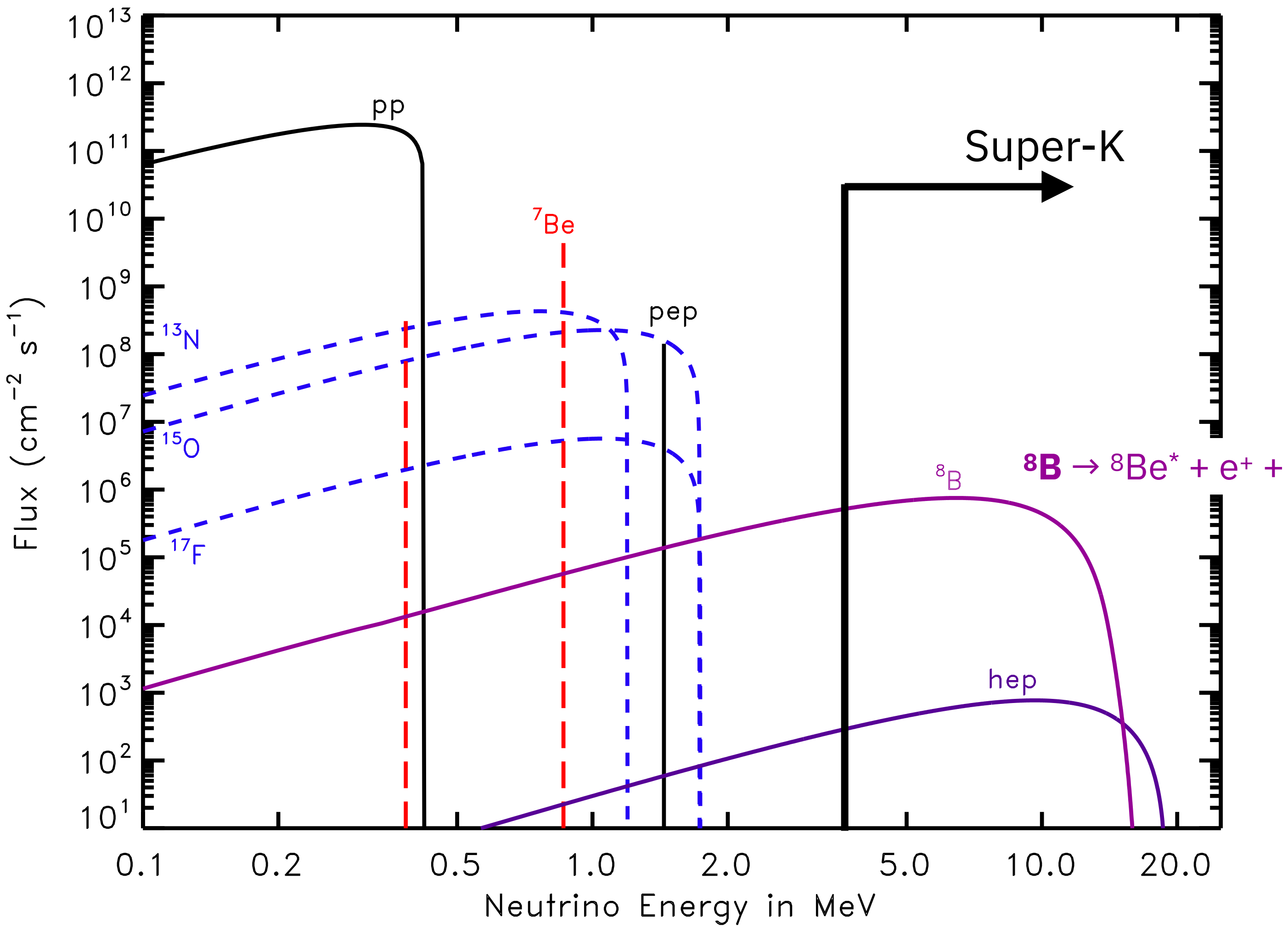
*Model based on on Phys. Rev. D **103**, 112008 (2021)*

Solar Neutrinos

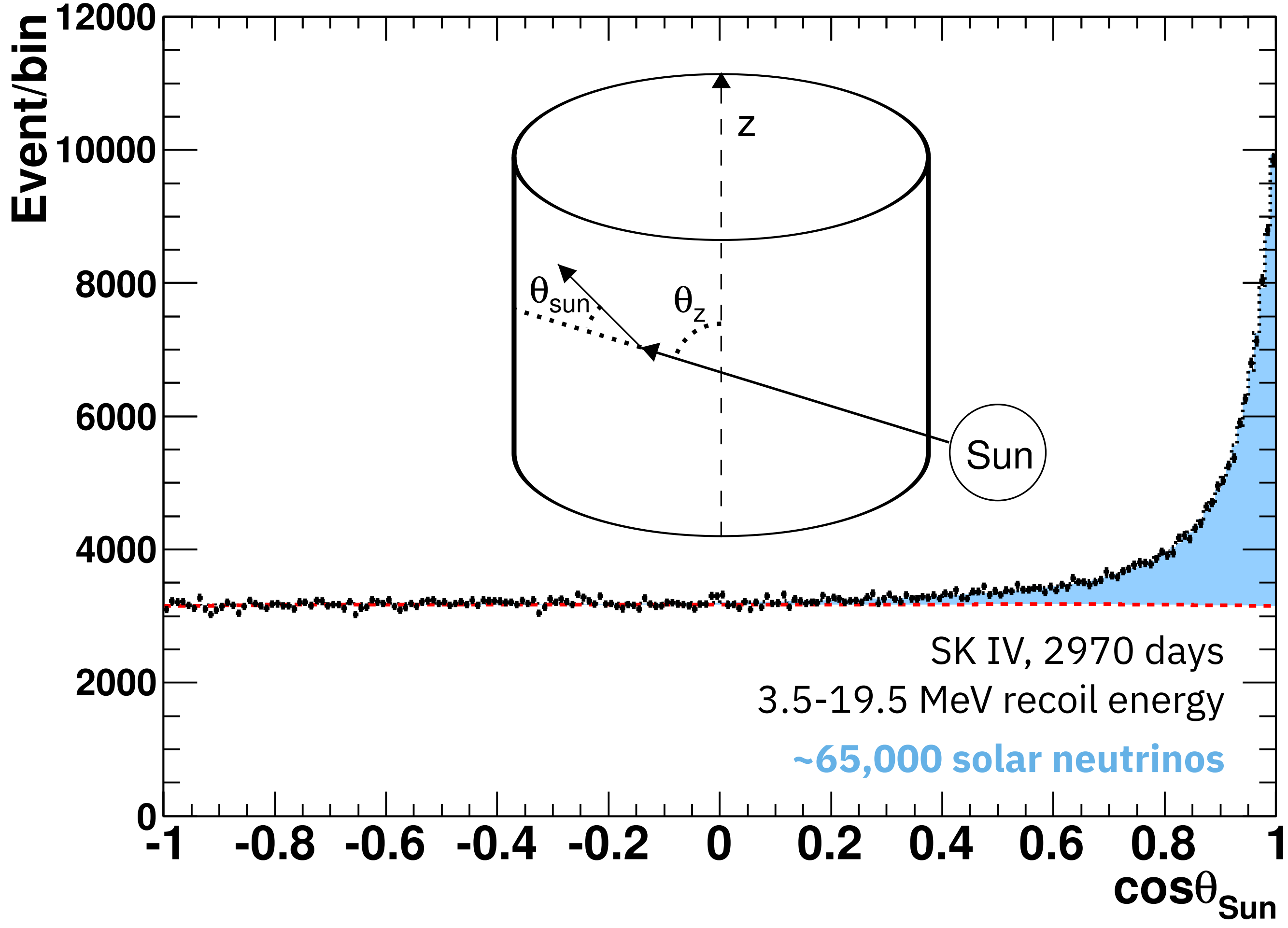
Solar Neutrinos

Neutrinos produced in the sun through fusion processes

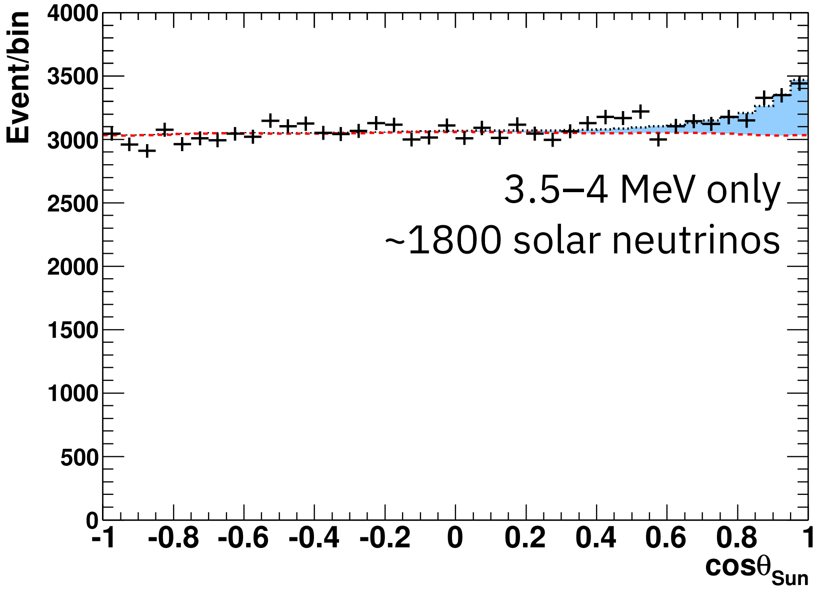
- ^{8}**B neutrinos** recorded by SK with direction and energy information
- Oscillation topics:
  - Oscillation parameters θ_{12}, Δm^2_{21}
  - Day/night effect: Regeneration of solar neutrinos in earth matter
  - Solar upturn: MSW oscillations between ~1-5 MeV
- Other solar neutrino topics:
  - Flux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



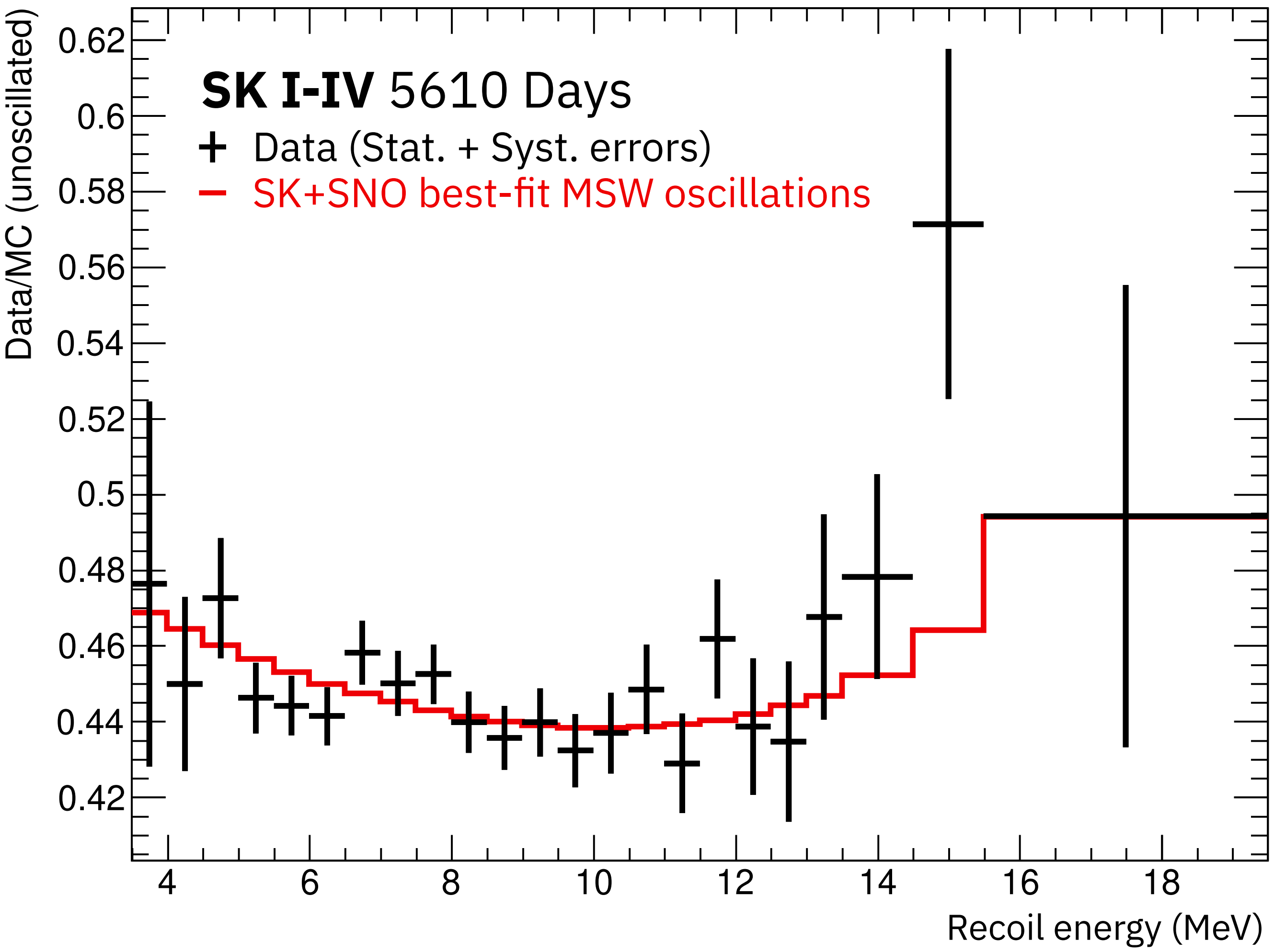
SK Solar Neutrino Measurements



- 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

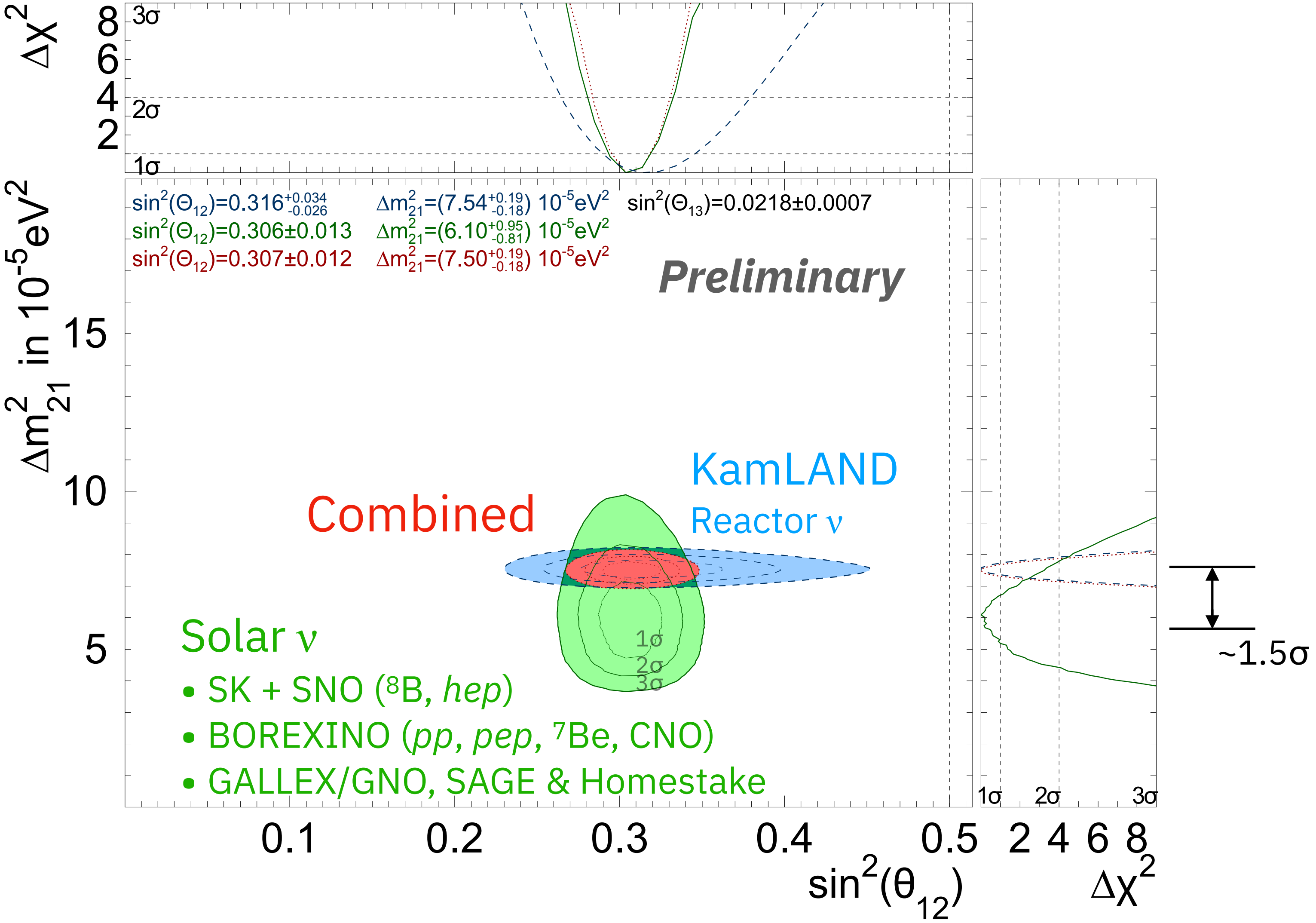


SK Solar Neutrino Oscillations

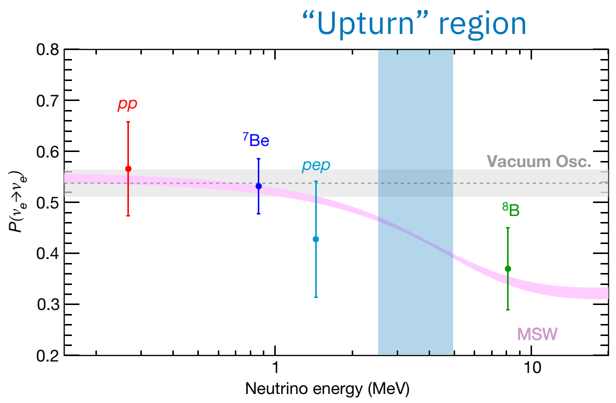


- SK data favors up-turn scenario below 5 MeV, but < 3.5 MeV data needed
- Recoil energy spectrum consistent with MSW oscillations

Solar Neutrino Global Fit Status



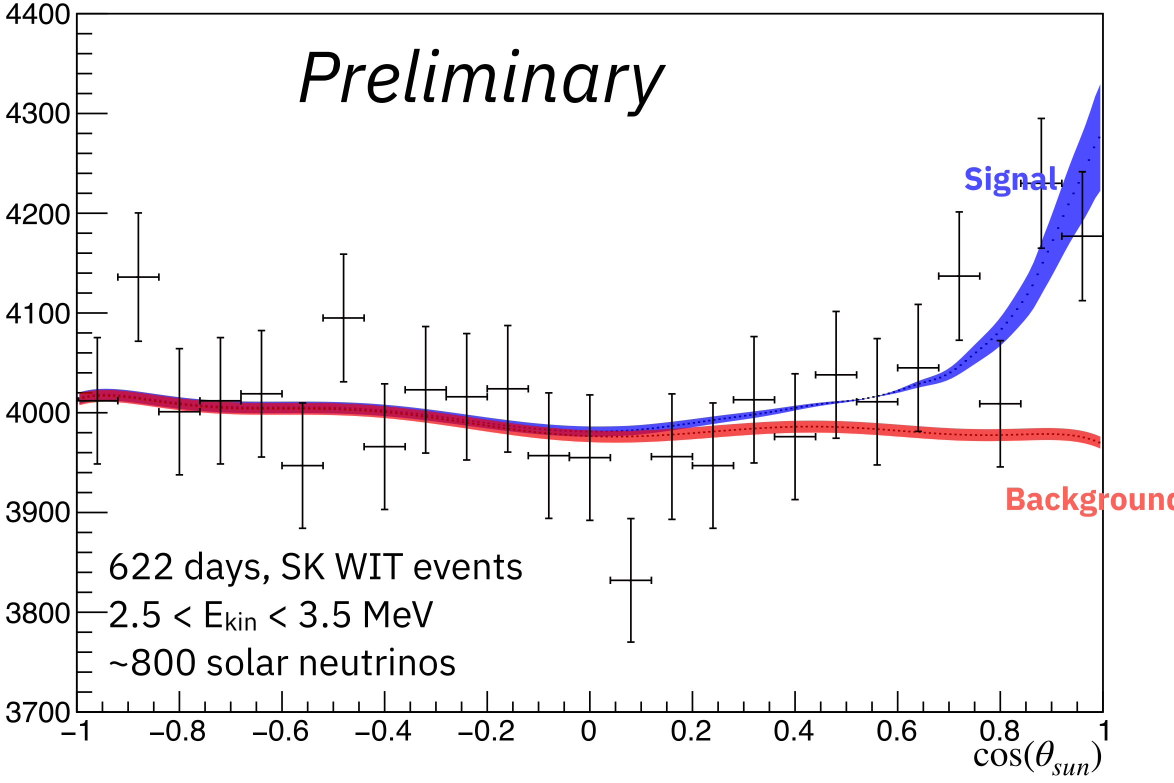
Progress Towards Upturn



- 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

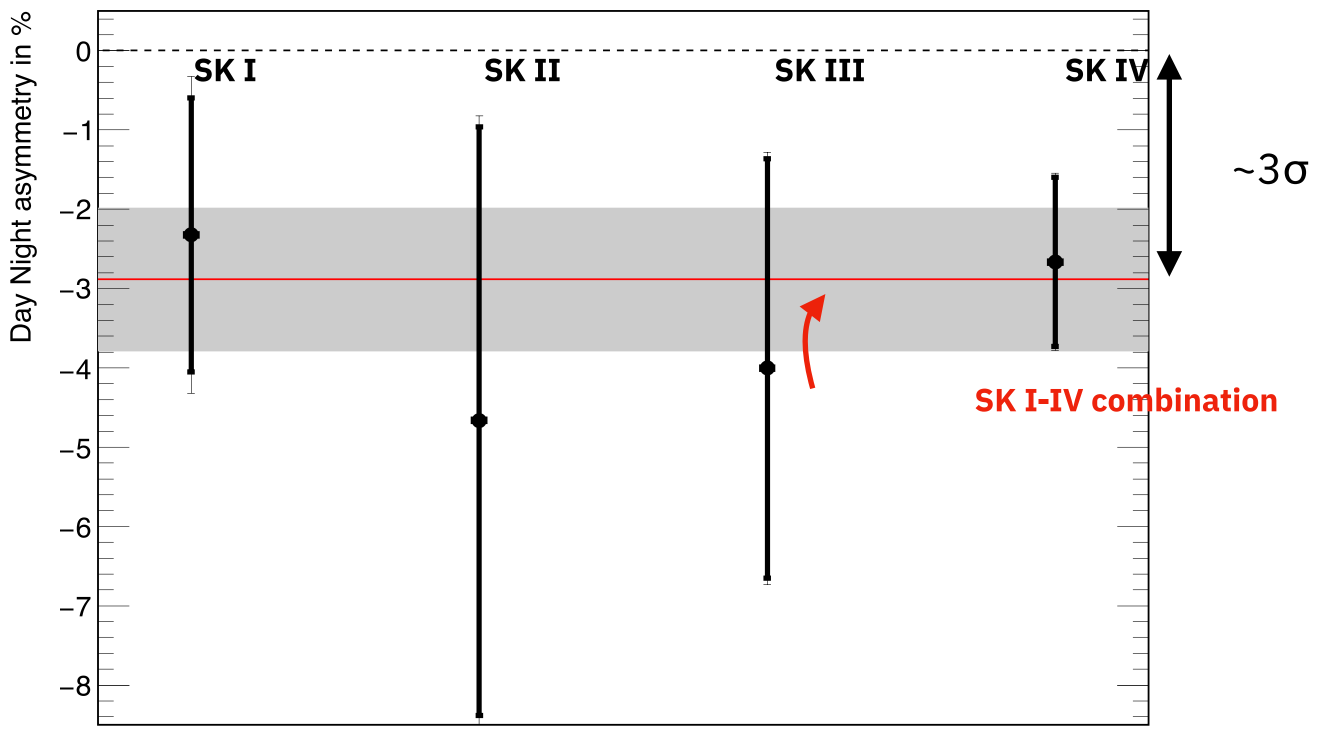
- Some efficiency for solar neutrino identification down to 2.5 MeV recoil energy using BDT & WIT data

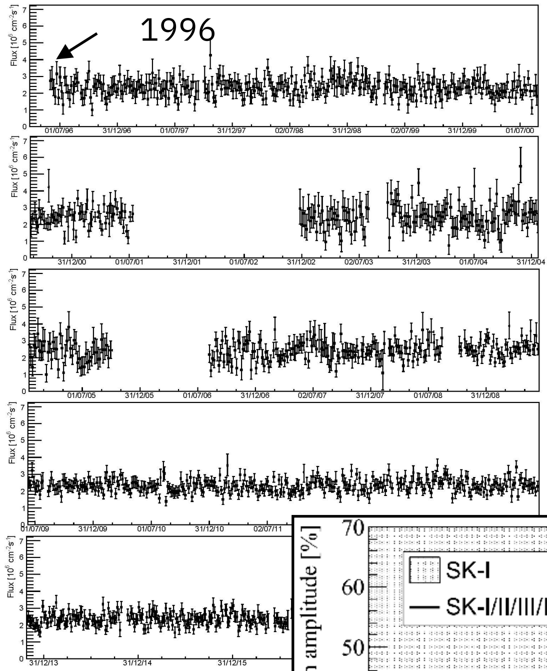


A. Yankelevich. (2022). Machine Learning Methods for Solar Neutrino Classification. (NEUTRINO2022 Poster)

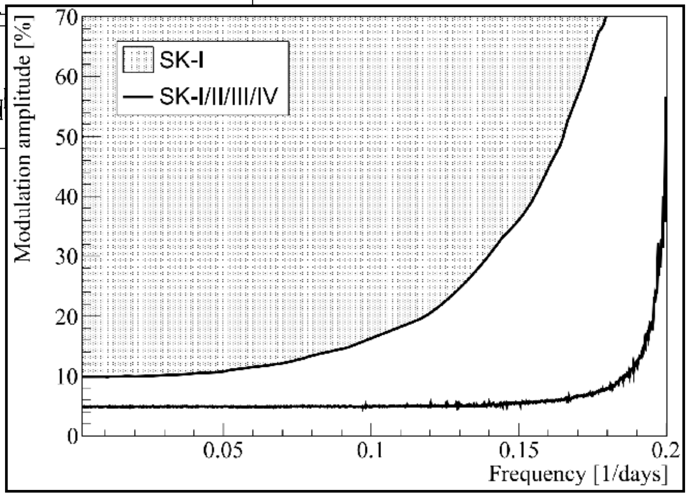
Other Solar Neutrino Results

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}