Latest Atmospheric Neutrino Oscillation Results from Super-Kamiokande

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CIPANP 2022

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Neutrino Oscillations

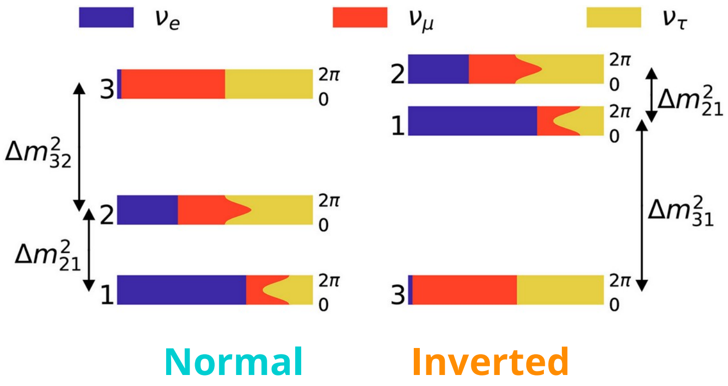
Neutrino flavor oscillations arise from differences in masses between mass states. Leading-order oscillations between two flavors in vacuum via:

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Unknowns:

- Value of δ_{CP}
- Octant of θ_{23}
- **Neutrino mass ordering**: One heavy and two light neutrinos, or the other way around? Sign of Δm^2_{31}

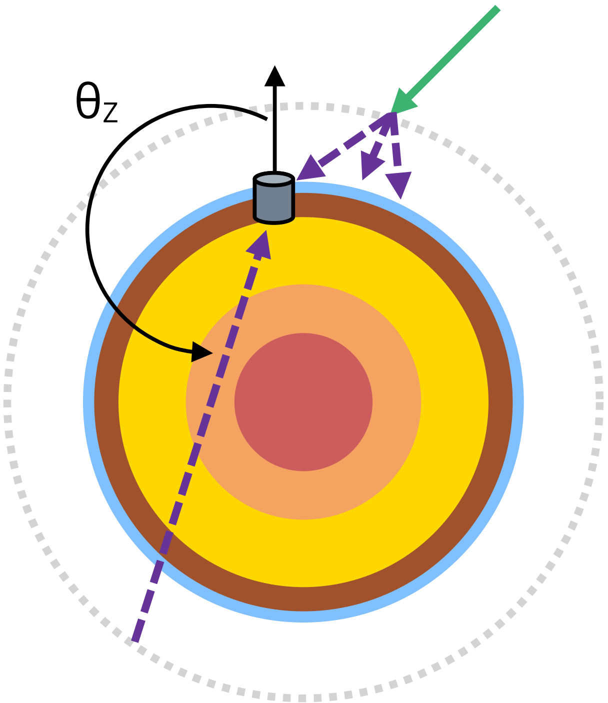
  → Implications for oscillations, 0νββ, supernova, cosmology



de Salas et al. 2018

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

Atmospheric Neutrinos



Neutrinos produced from particle showers in Earth's atmosphere

- Flavors: ν_μ, ν_e ~ 2:1 ratio, both neutrinos and anti-neutrinos
- E_ν: ~ few MeV - TeV range.
- Baseline: Parametrized by zenith angle θ_Z, ~15 km – 13,000 km

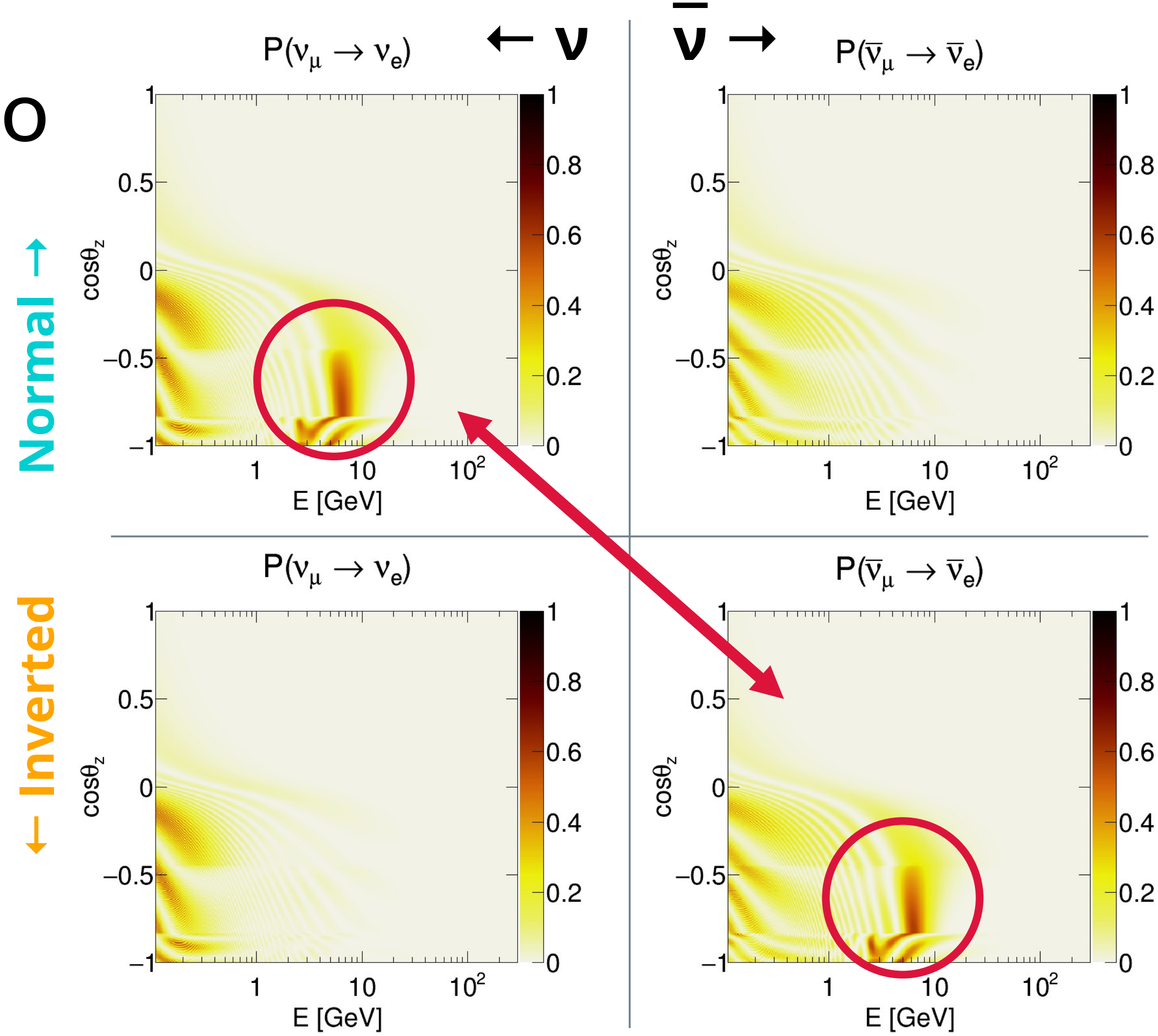
Matter effect: ν_e and $\bar{\nu}_e$ passing through dense inner layers of the earth experience modified potential, differs for neutrinos and anti-neutrinos

$$i\frac{d}{dt}\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta \pm \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix}$$

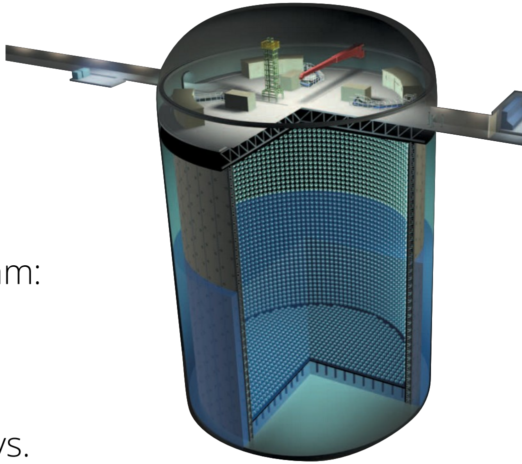
2 flavor example of adding matter potential to neutrino Hamiltonian

Atmospheric Neutrino Oscillations

Signature of mass ordering from either enhanced ν_e or $\bar{\nu}_e$ appearance with E_ν ~few GeV, due to matter effects



Super-Kamiokande



Particle observatory in Japan with broad physics program: Nucleon decay, neutrinos, dark matter…

- **20+ years of continued operation**

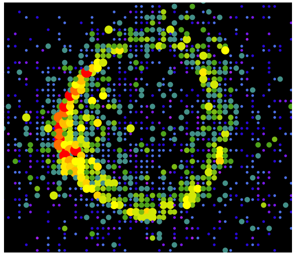
  5 pure water phases from 1996–2020, 6511 live days. Now running with dissolved gadolinium (SK-Gd)

- **50 kT water volume**

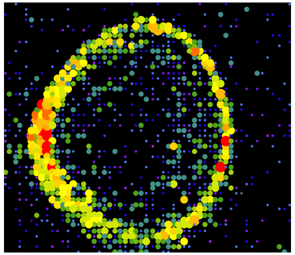
  >11,000 PMTs inner detector & >1,800 PMTs in outer detector

- **Cherenkov radiation**

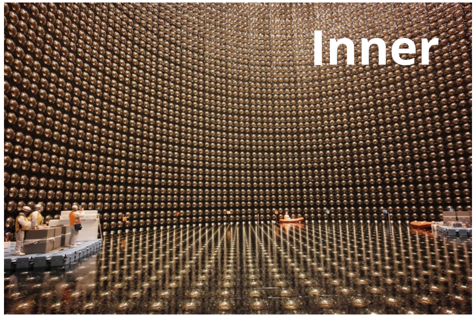
  Provides PID, energy & direction reconstruction of charged particles

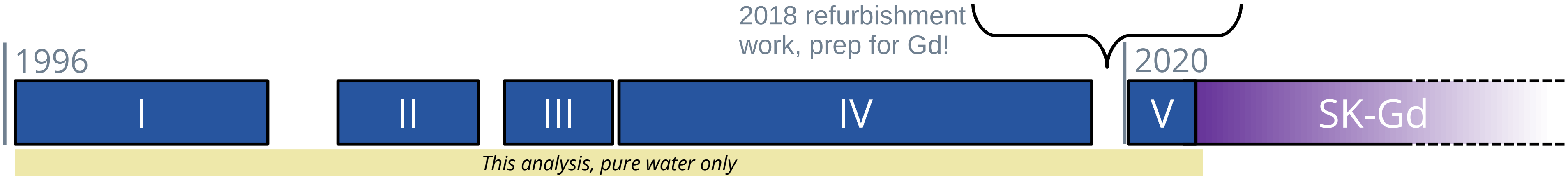


Fuzzy *e*-like ring



Sharp μ-like ring



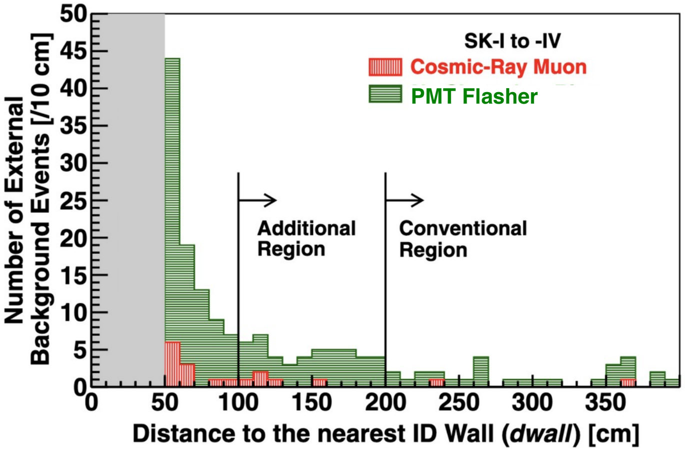


New for 2022: Expanded Fiducial Volume

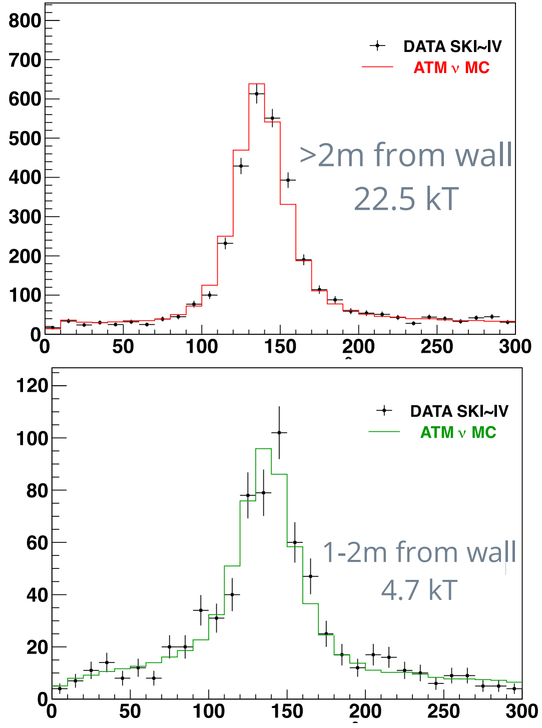
- Previous: vertex cut >2m from walls → 22.5 kT fiducial volume
- Events in 1-2m wall region studied, acceptable backgrounds, systematics & resolution established for all SK periods

+20% statistics, total exposure: 0.48 MT·Years

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



atmospheric neutrinos $NC\pi^0$



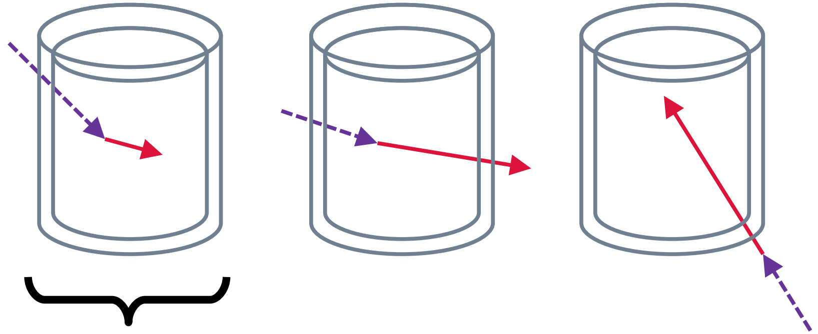
π^0 mass (MeV/c^2)

Oscillation Analysis Event Selection

Mostly ν_μ charged-current. Constrain other oscillation parameters

3 categories

Fully Contained | Partially Contained | Up-μ



Separate based on PID, # of rings, lepton momentum → Statistical $\nu/\bar{\nu}$ separation

Can't determine lepton charge event-by-event

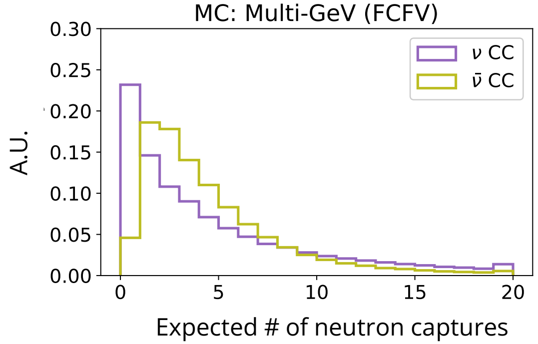
Decay electrons (d.e.) from pion-producing processes, $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$:

$$\nu_l + p \rightarrow p + l^- + \pi^+$$
$$\bar{\nu}_l + p \rightarrow p + l^+ + \pi^-$$

~70-90% efficiency to detect d.e.

Likely to be absorbed before decaying

Neutron production differs between ν and $\bar{\nu}$, correlated with hadronic activity:



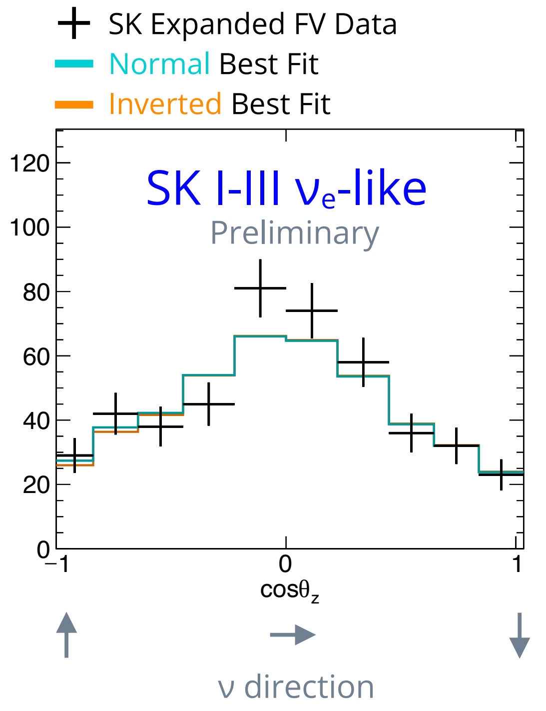
SK IV+ only
~25% efficiency

Multi-GeV ν_e Samples

d.e. = Decay electron

Fully contained 1 *e*-like ring Multi-GeV

- SK I-III
  - >0 d.e → ν_e-like: 58% ν_e, 9% $\bar{\nu}_e$
  - 0 d.e. → $\bar{\nu}_e$-like: 55% ν_e, 34% $\bar{\nu}_e$
- SK IV+
  - >0 d.e. → ν_e-like: 61% ν_e, 9% $\bar{\nu}_e$
  - 0 d.e.
    - >0 neutrons → $\bar{\nu}_e$-like: 43% ν_e, 46% $\bar{\nu}_e$
    - 0 neutrons → ν_e or $\bar{\nu}_e$-like: 64% ν_e, 28% $\bar{\nu}_e$



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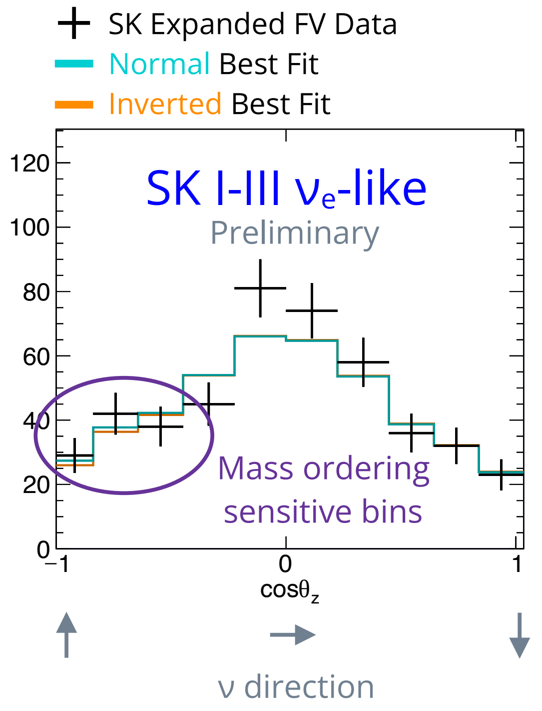
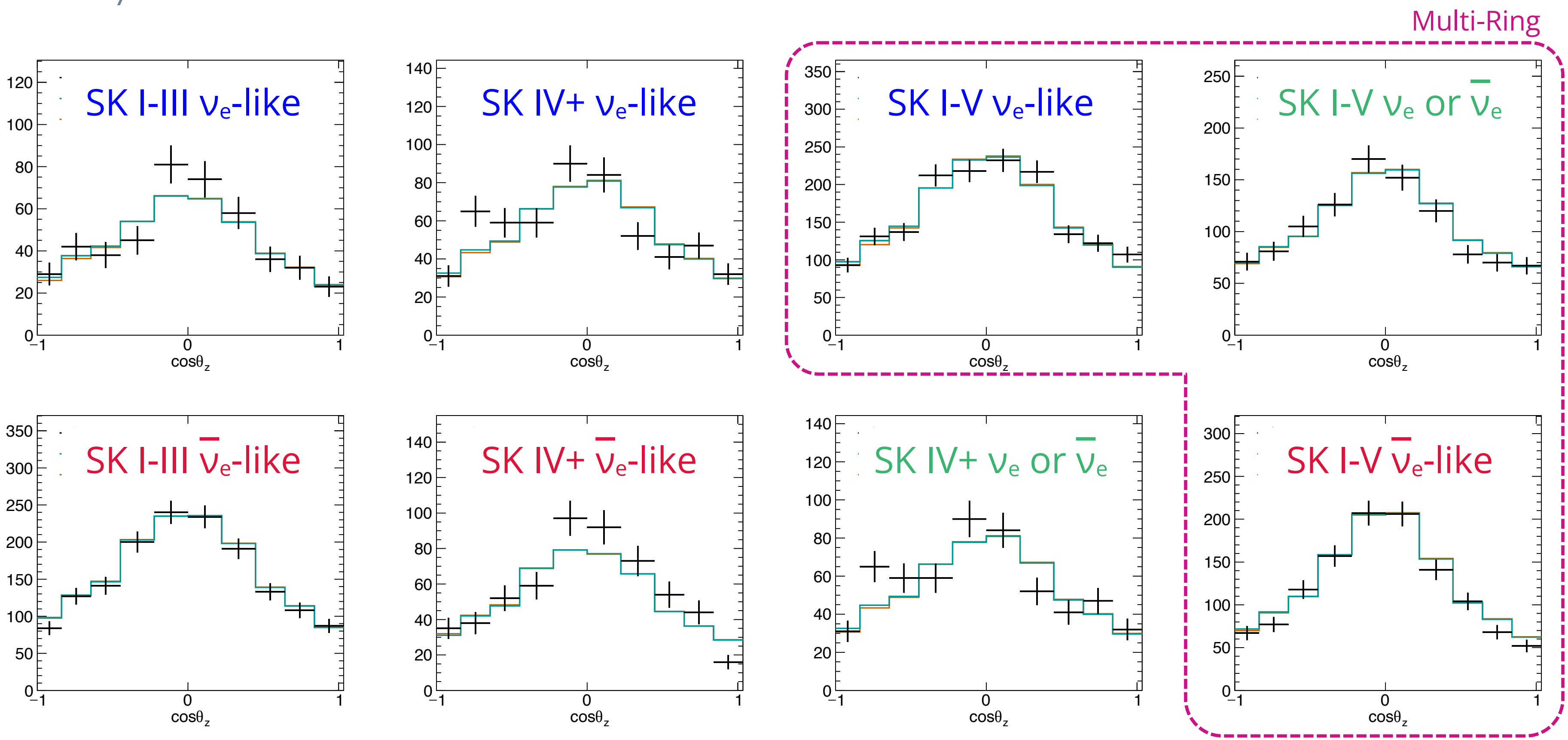


Multi-GeV ν_e Data

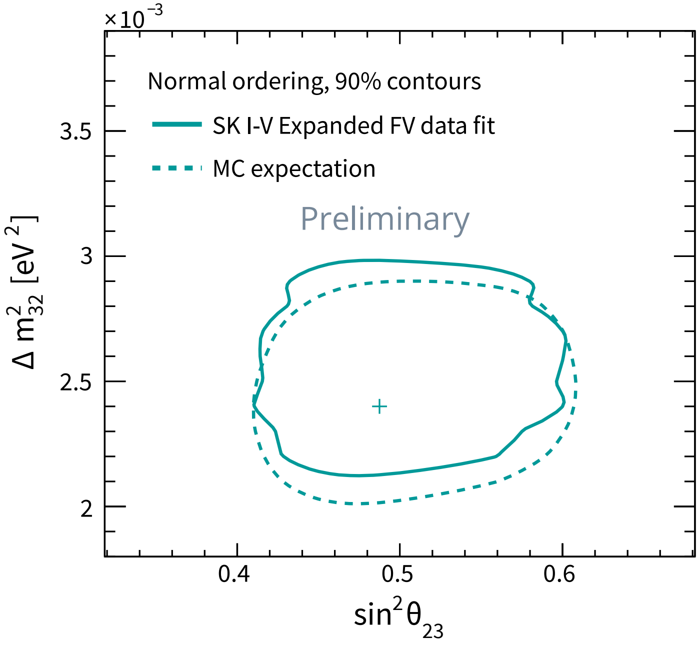
Preliminary

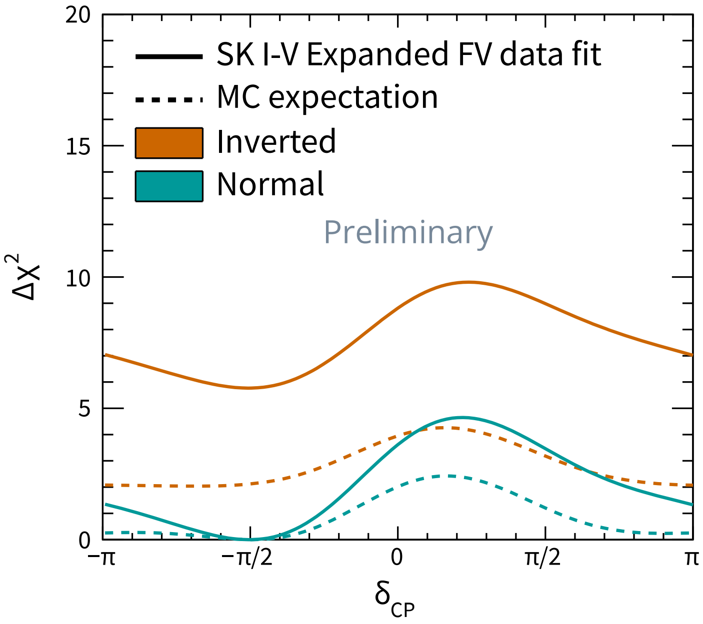
SK I-V, expanded FV: ~5.5k ν_e and $\bar{\nu}_e$



Super-Kamiokande 2022 Results

χ^2 minimization with pull terms
930 bins, $\sin^2\theta_{23}$, Δm^2_{23}, δ_{CP} free
With reactor constraint:
$\sin^2\theta_{13}=0.0220\pm0.0007$





Best fits	χ^2	$\|\Delta m^2_{31}\|$ [eV²]	$\sin^2\theta_{23}$	δ_{CP}
Normal	1000.42	2.4×10^{-3}	0.49	4.71
Inverted	1006.19	2.4×10^{-3}	0.49	4.71

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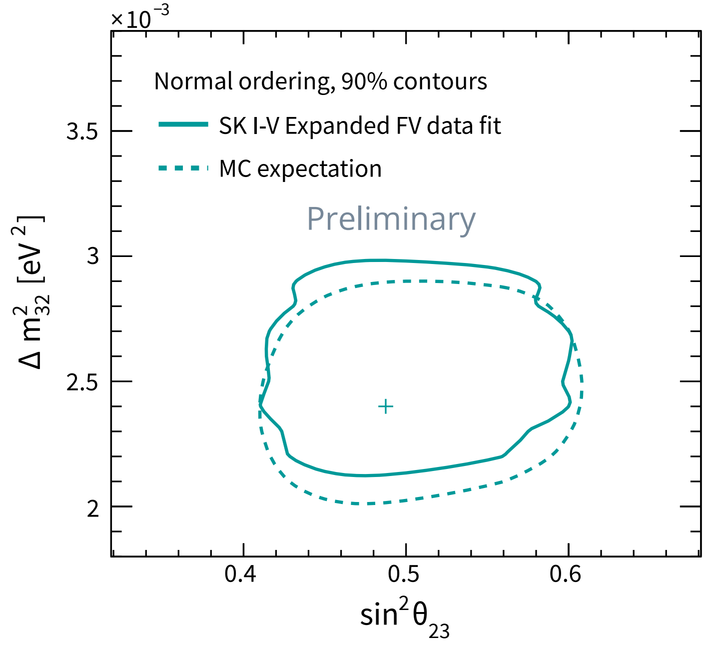

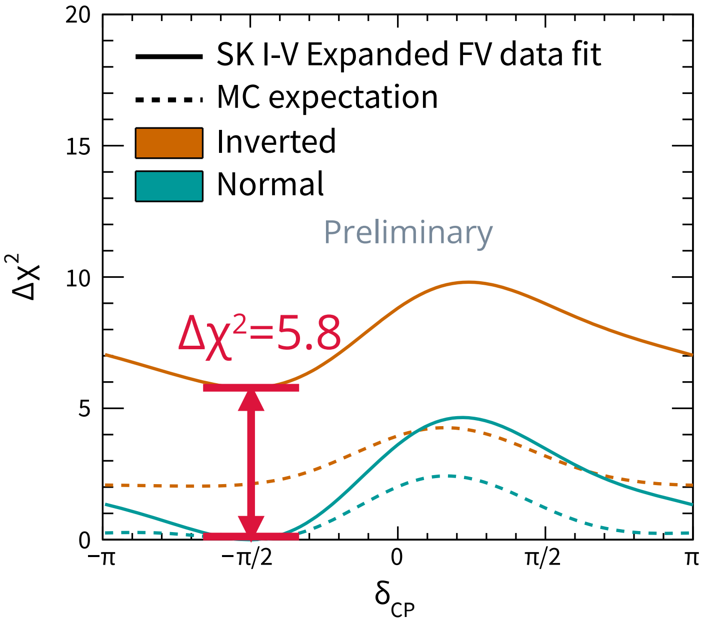

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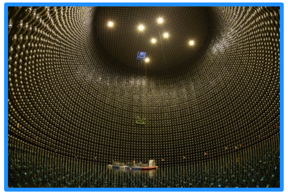
Constraints from T2K

Mass ordering analysis improves with constraints on other oscillation parameters $|\Delta m^2_{31}|$, $\sin^2\theta_{23}$, δ_{CP}...

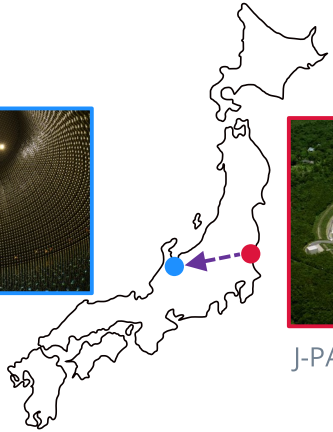
T2K long-baseline experiment is a natural choice:

- **Precise measurement of $|\Delta m^2_{31}|$ & $\sin^2\theta_{23}$**, and sensitive to δ_{CP} due to known ν direction, fixed baseline, narrow energy spectrum & pure ν or $\bar{\nu}$ beam
- **Shared systematics with SK**: Cross section uncertainties can be correlated

→ Large matter effect in atmospheric νs is complementary to precision measurements from beam νs for studying mass ordering

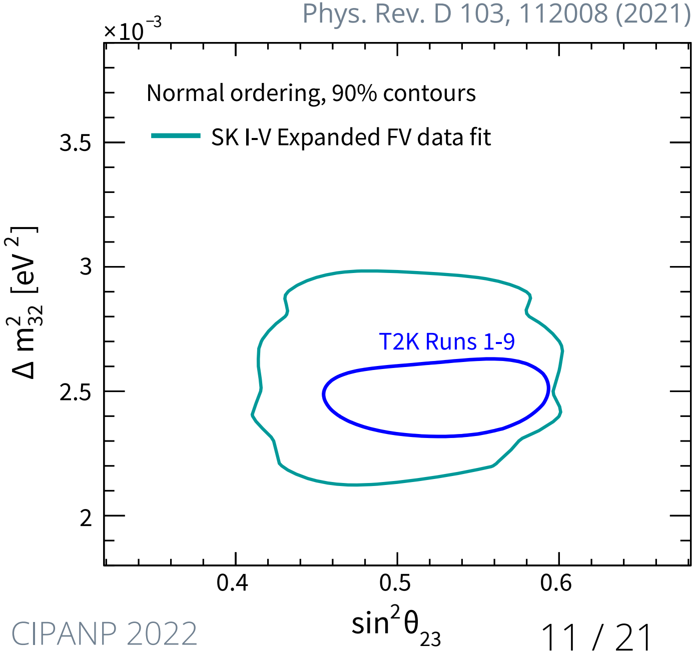


SK



J-PARC accelerator complex

Runs 1-9: T2K Collaboration. Phys. Rev. D 103, 112008 (2021)



Result with T2K Constraints

χ^2 minimization with pull terms
1020 bins, $\sin^2\theta_{23}$, Δm^2_{23}, δ_{CP} free
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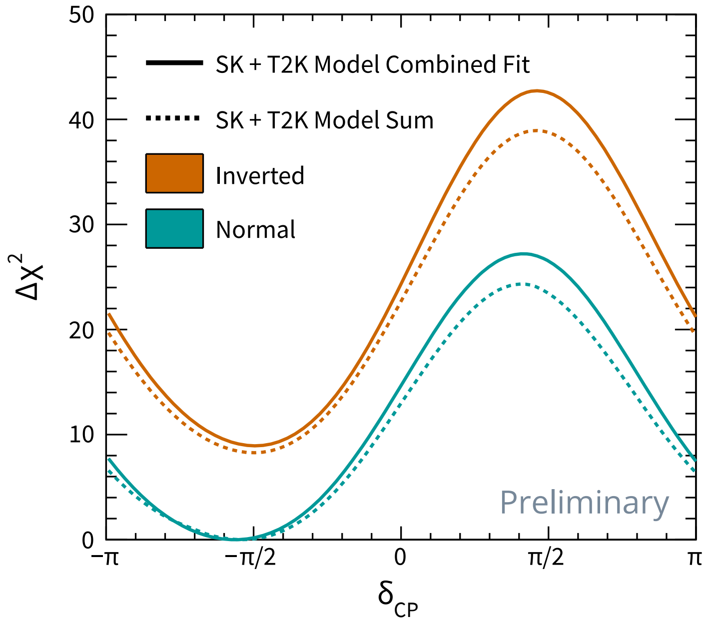
Note: External modeling of T2K by SK, using published runs 1-9 data and SK MC re-weighted to T2K flux & xsec. inputs.



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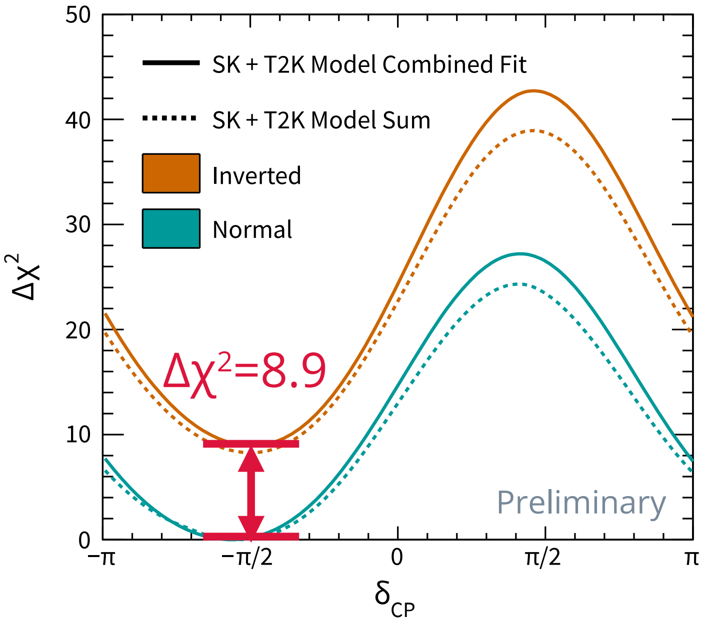

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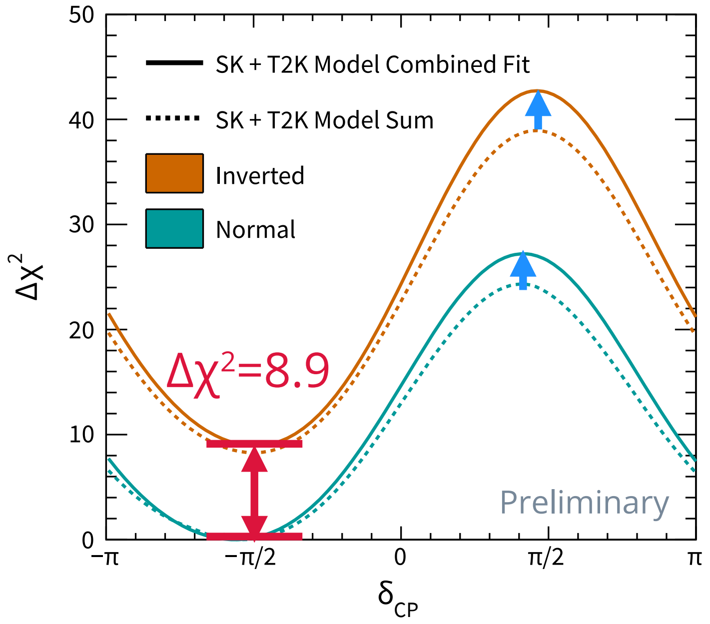

Shared systematics improve sensitivity over separate fits combined with $\Delta\chi^2$ sum

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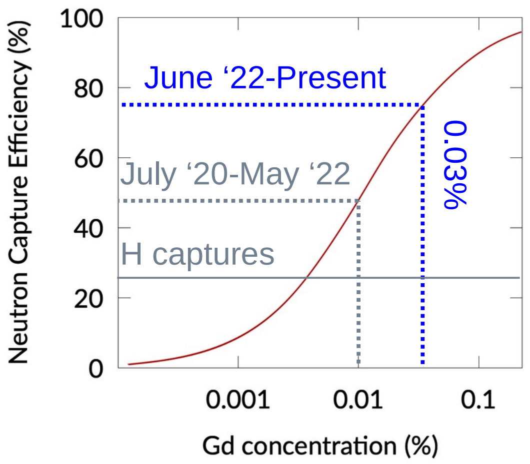
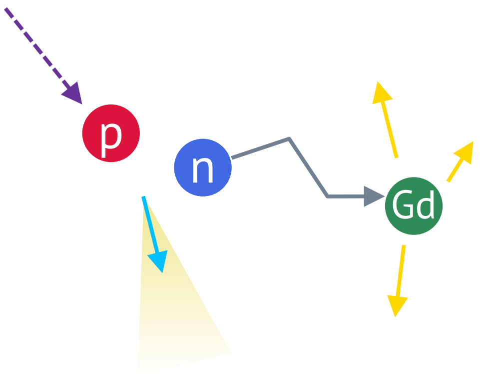
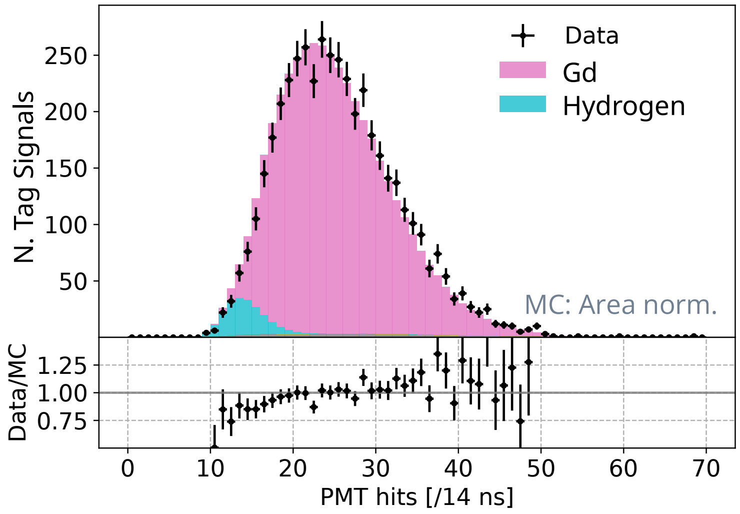
Happening Now: SK-Gd



High-efficiency neutron capture with gadolinium thanks to large neutron capture cross section, higher total gamma energy & faster capture time than hydrogen

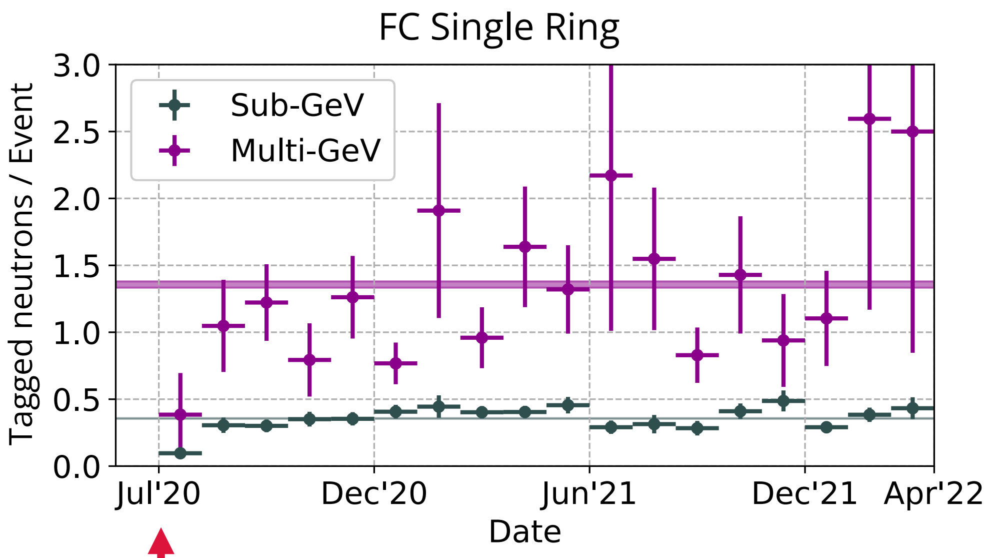




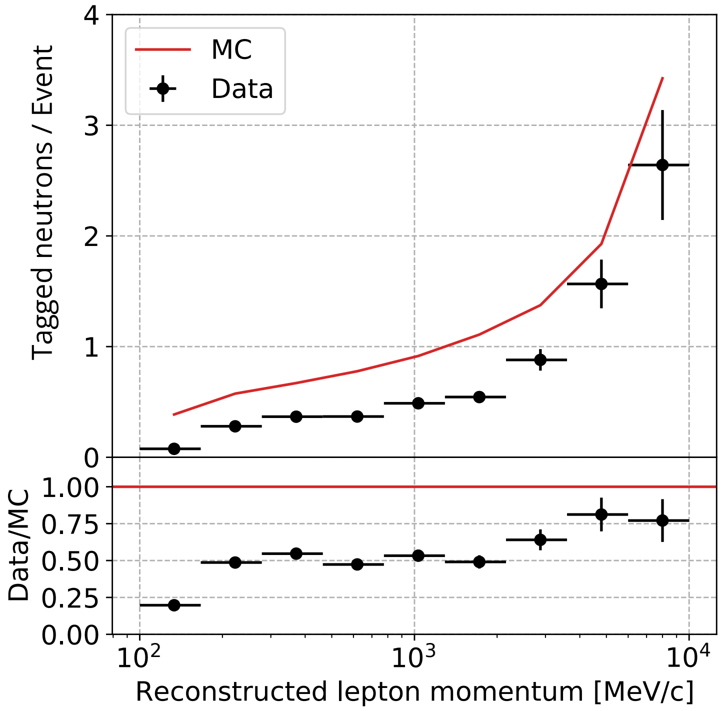
Oscillation analysis improvements:

- Better $\nu_e/\bar{\nu}_e$ separation: observe many more neutron captures than on hydrogen
- Improved direction & energy reconstruction: Incorporate neutron vertex & multiplicity

Multi-GeV Events in SK-Gd



Start Gd loading



Working to understand MC, disagreement in multiplicity

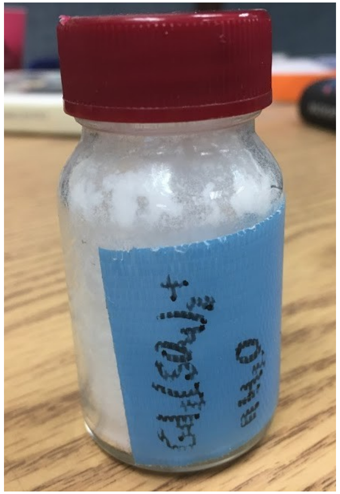
Summary

- Atmospheric neutrinos are an important data set for determining the neutrino mass ordering

SK 2022: $\Delta\chi^2_{\text{I.O.-N.O.}} \approx 5.8$

- Atmospheric neutrinos are complementary to long baseline experiments

- SK is better than ever. New data after refurbishment & running with gadolinium NOW!



Thank you!

Super-Kamiokande collaboration @ Toyama, Japan. November 2019

Backup Slides

SK Analysis History

Result	Livetime (Days)	Fiducial Volume (kT)	# of Bins	Neutron tagging?	Multi-Ring Selection	NEUT Version	*$\sin^2\theta_{13}$-Constrained Results*			
							$\sin^2\theta_{23}$	Δm^2_{32} $\times 10^{-3}$ eV^2	δ_{CP}	$\Delta\chi^2$ I.O. - N.O.
2018 PRD	5326	22.5	520	No	Likelihood	5.3.6	0.59	2.5	4.18	4.3
2020 Preliminary	6050	22.5	930	Yes	BDT	5.4.0	0.45	2.4	4.54	3.4
2022 Preliminary	6511	27.2	930	Yes	BDT	5.4.0	0.49	2.4	4.71	5.8

More on the SK Mass Ordering Result

Excess in ν_e signal region drives the preference for normal ordering

- Previously observed, excess mainly in SK IV conventional fiducial volume events
- CL_s-corrected *p*-value from 2018 result (5326 days, conventional FV) set preference for normal ordering at 93% level, less than simple $\sqrt{\Delta\chi^2}$ ~ 98% from fit

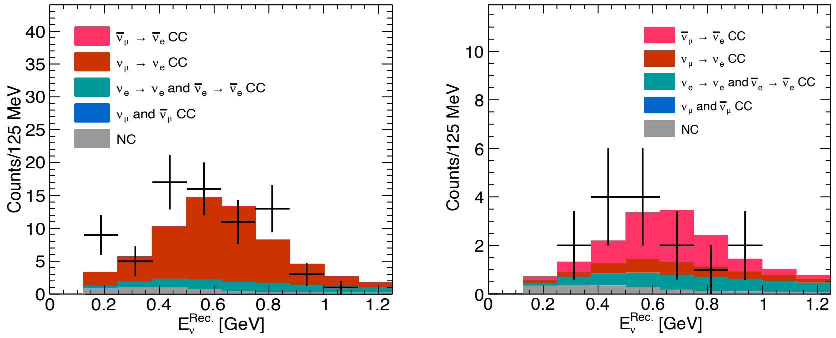
Stay tuned for final *p*-value in progress & paper in prep.

T2K Modeling

Use published T2K Run 1-9 data & SK MC re-weighted to T2K flux and cross sections for this analysis

- Re-weighting provides flexibility to check impact of cross section models on final result
- Can apply some T2K near detector cross section constraints to SK atmospheric data
- – Compromises: Use more conservative systematic errors for pion final state interactions & 2p2h process due to differences in treatment between SK & T2K

A SK+T2K analysis group with members from both collaborations is working to unify cross section modeling for a formal joint fit



T2K ν_e data & SK MC. MC has T2K fluxes & cross section models applied as re-weighting factors

SK+T2K Model Individual Fits