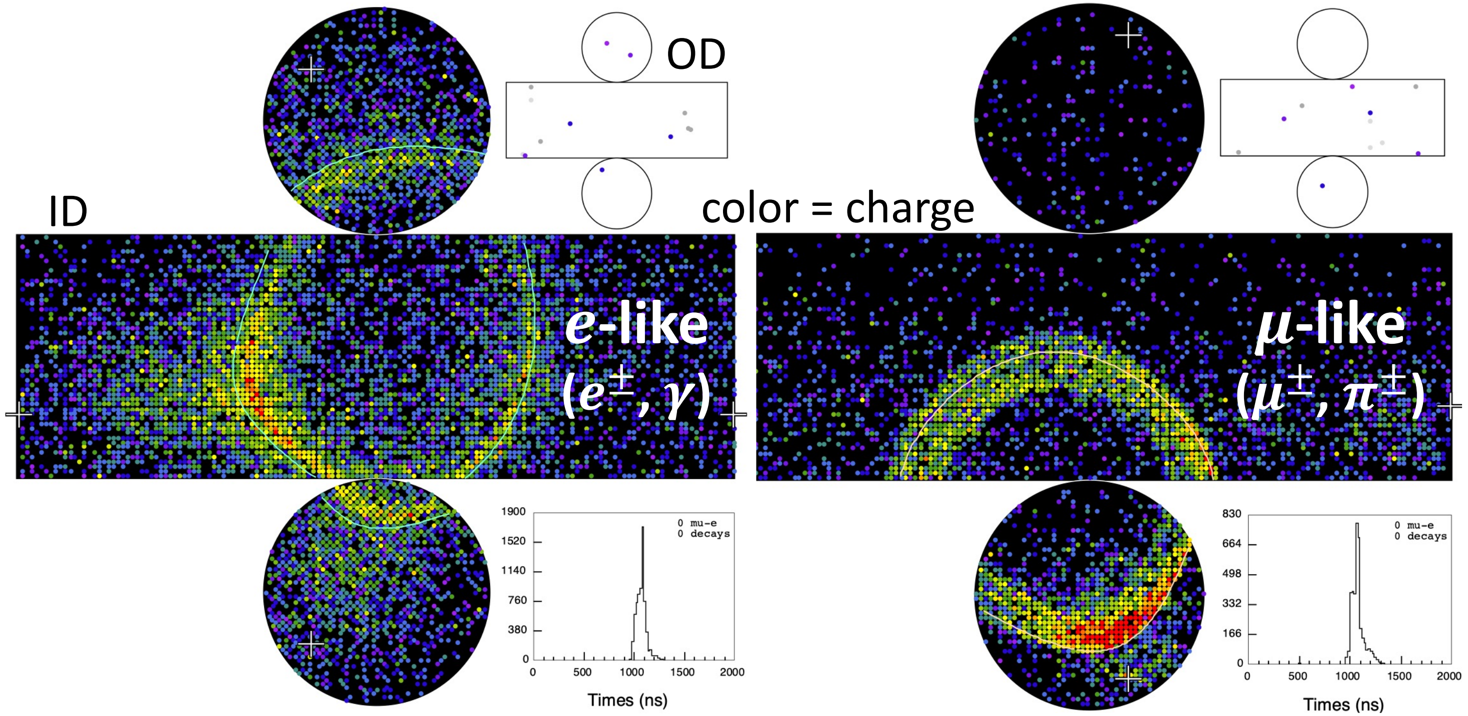
Super-K recent results and future perspectives

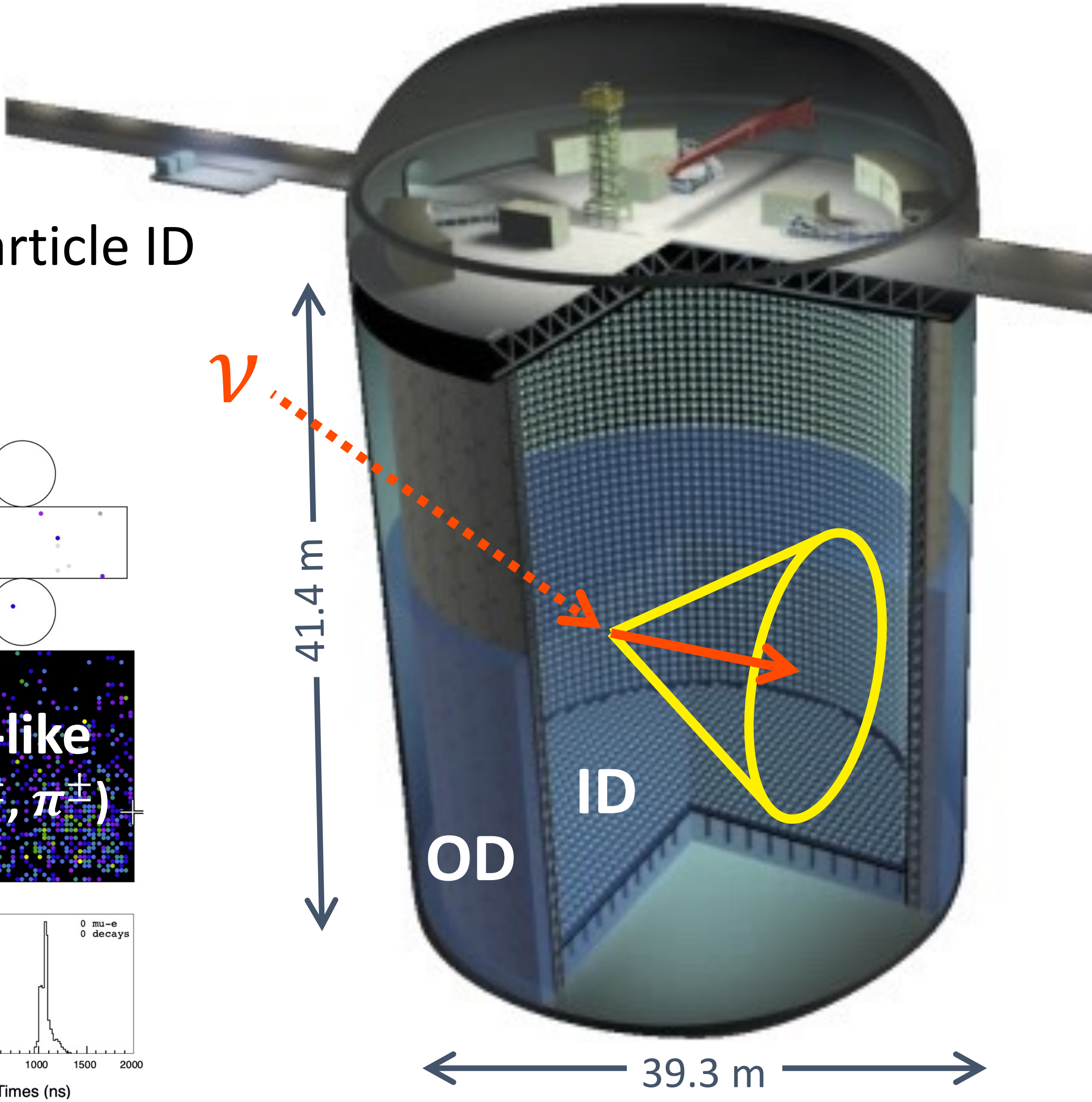
Shintaro Miki (ICRR, University of Tokyo)
on behalf of the Super-Kamiokande Collaboration

NNN24 @Rio de Janeiro, Oct. 28th 2024

Super-Kamiokande Detector

- 50 kton water Cherenkov detector
- 11,129 50cm PMT in ID
  → Reconstruct vertex, direction, momentum, particle ID
- 1,885 20cm PMT in OD → Muon veto



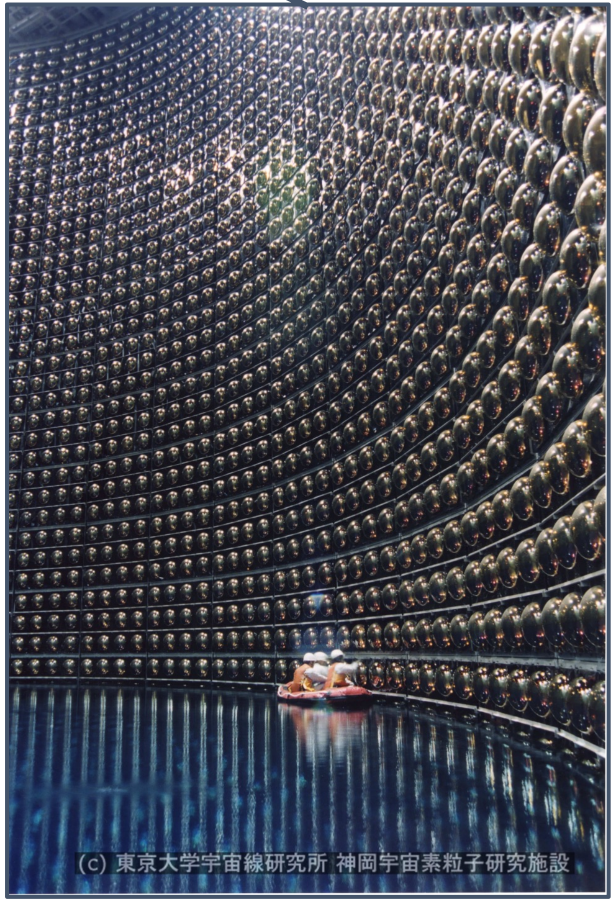


Experimental phases

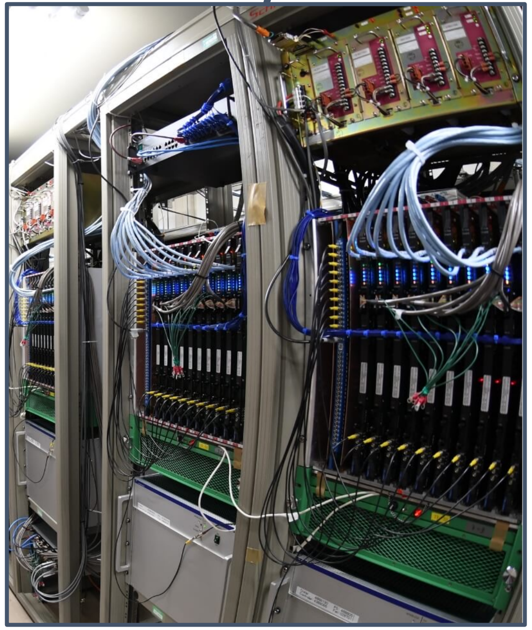
1996 | 2001 | 2008 | 2018 | 2020 | 2022

I | II | III | IV | V | VI | VII | VIII

Neutron tag



Electronics upgrade



IEEE TNS.57.2.428 (2010)

Gd loading

13 tons Gd sulfate in 2020

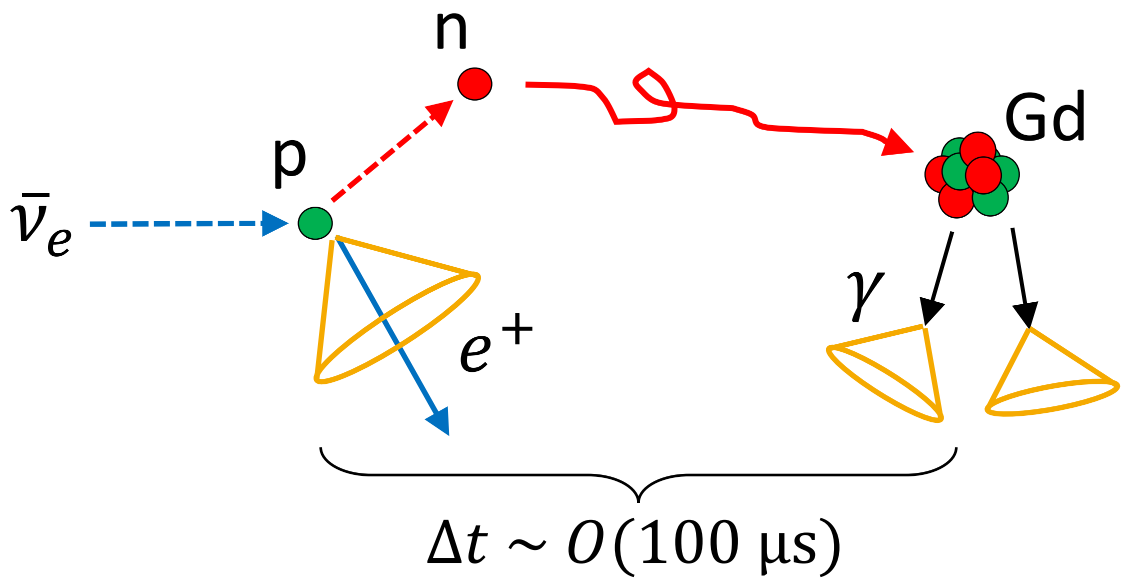
+26 tons Gd sulfate in 2022

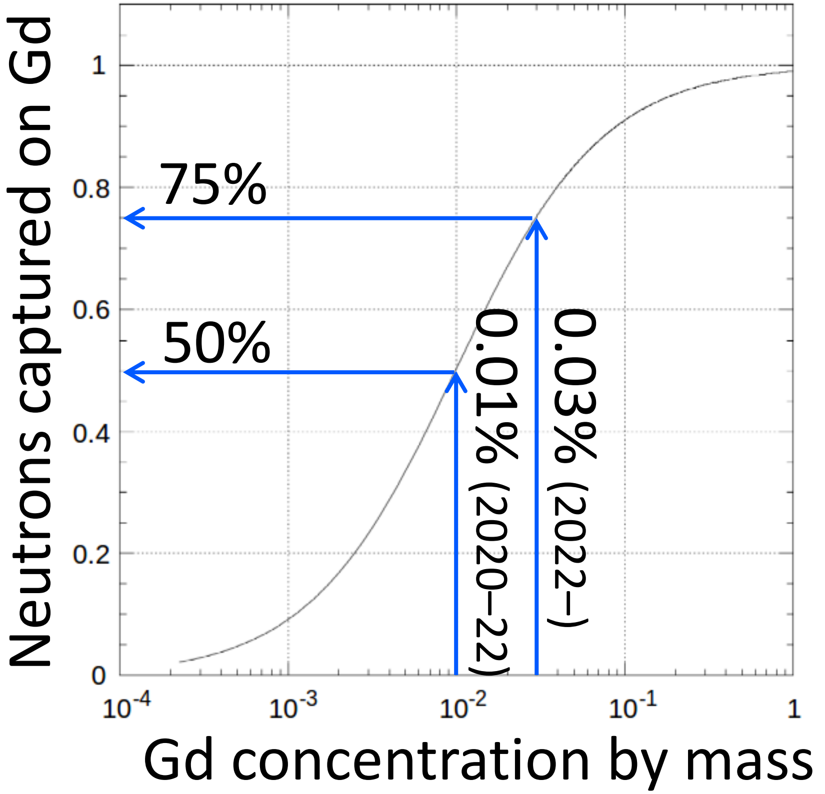
NIM A.1027.166248 (2022)

NIM A.1065.169480 (2024)

SK-Gd: Physics motivation

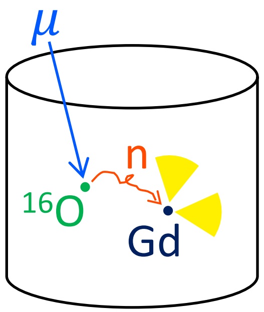
- Gd improves neutron tagging by:
  - **Large cross section** to capture neutrons + **High energy γ's** (total 8 MeV)



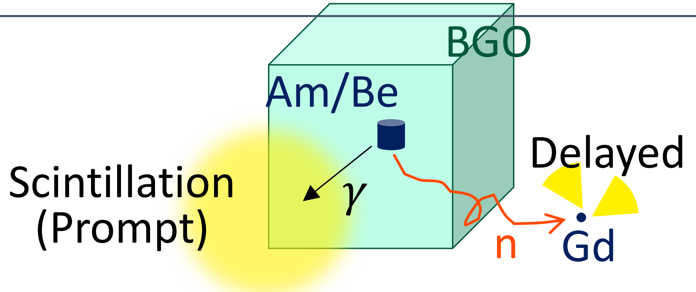


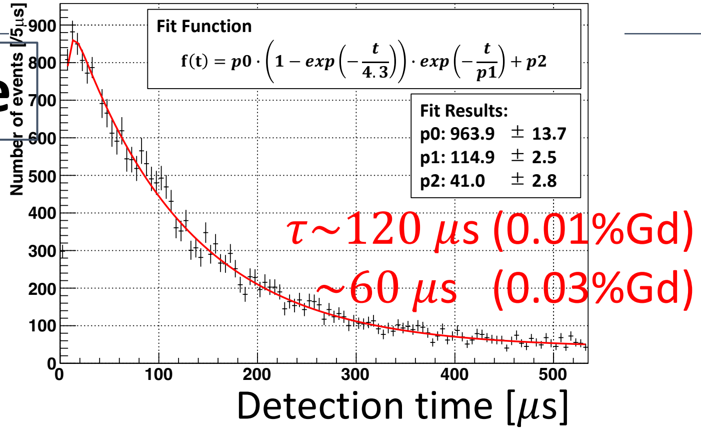
- Neutron tagging helps to…
  - reject backgrounds for IBD events and nucleon decays
  - improve $\nu/\bar{\nu}$ separation in O(GeV) ν events
  - improve event reconstruction assuming hadron momentum

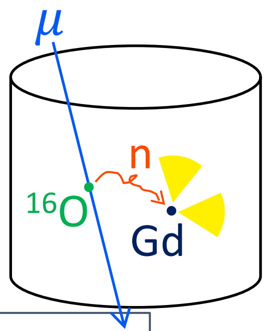
Neutron monitoring



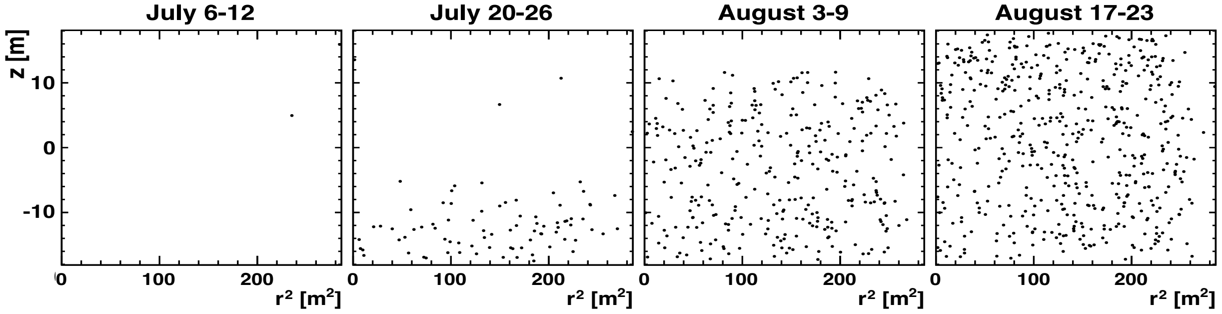
Calibration with **Am/Be source**



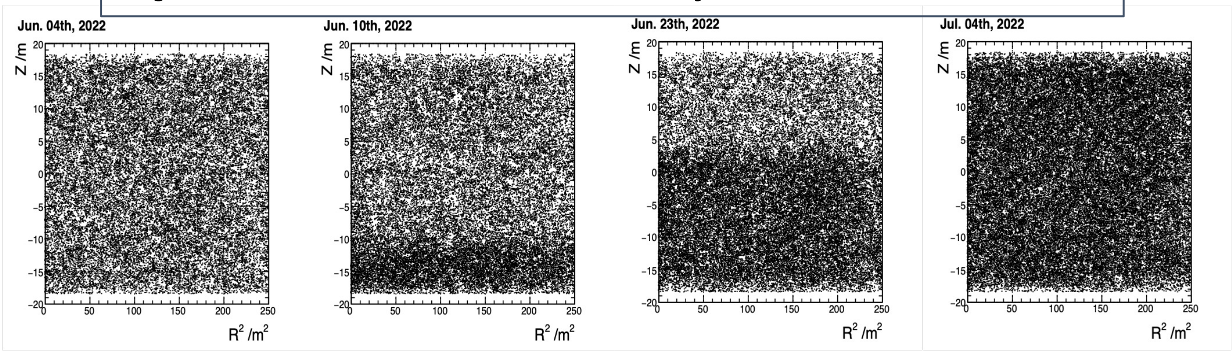


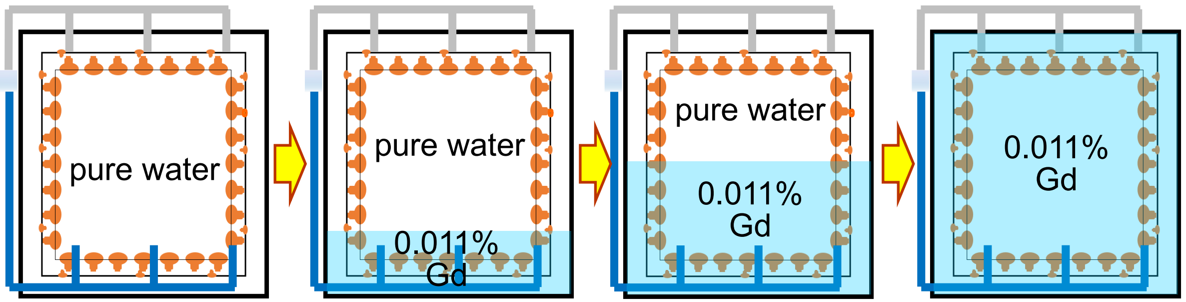


Neutrons from cosmic **muon capture**

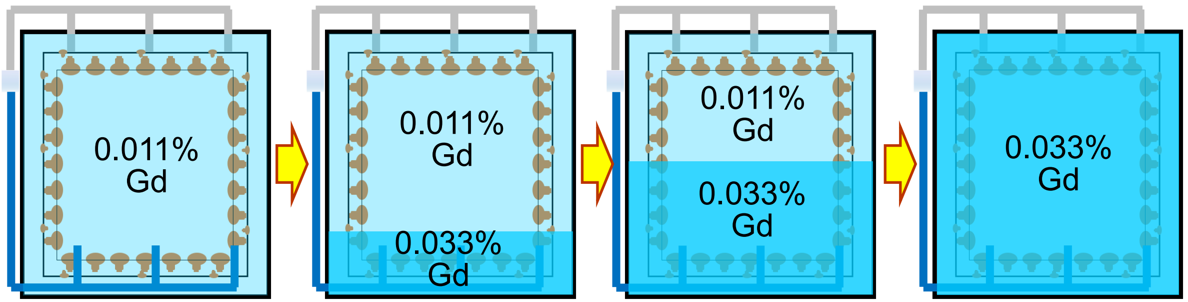


Spallation neutrons by cosmic muons





First loading in 2020



Second loading in 2022

Recent physics highlights

- Atmospheric neutrinos:
    - Oscillation results from full pure-water phases [PRD.109.072014 (2024)]
    - Neutron multiplicity result in SK-Gd
    - Expected oscillation improvements in SK-Gd
- Diffuse Supernova Neutrino Background (DSNB):
    - Latest search in SK-Gd [ApJL.951.L27 (2023)]+New results
- Reactor neutrinos:
    - First positive observation in SK-Gd
- Nucleon decays:
    - $n \rightarrow \nu\pi^0$ in pure-water phases
    - $p \rightarrow e^+X$ in pure-water phases

Blue from pure-water phases
Red from SK-Gd

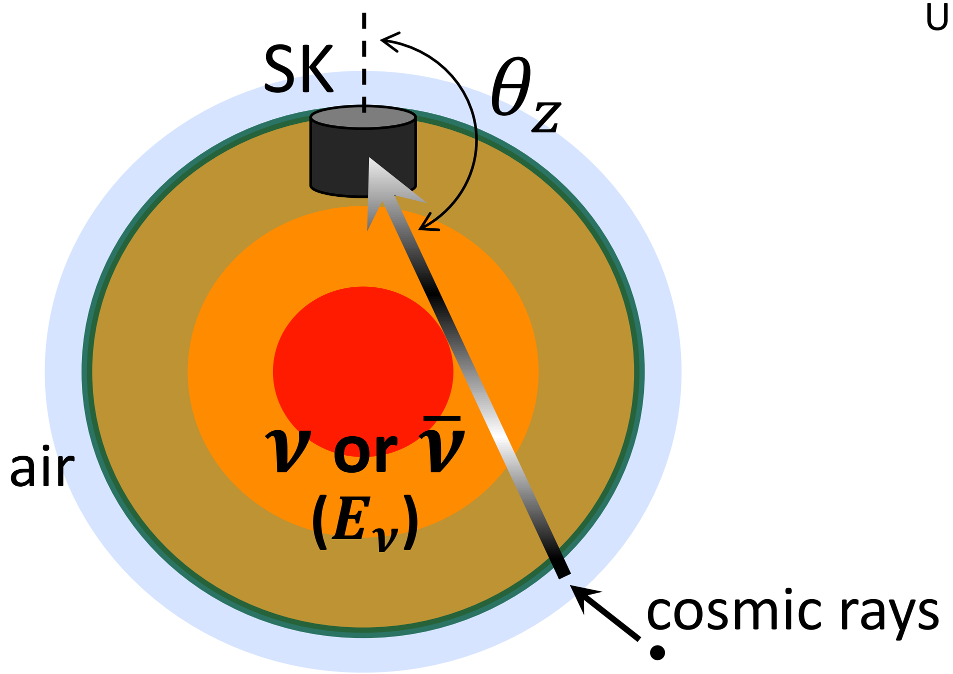
Papers published since NNN23

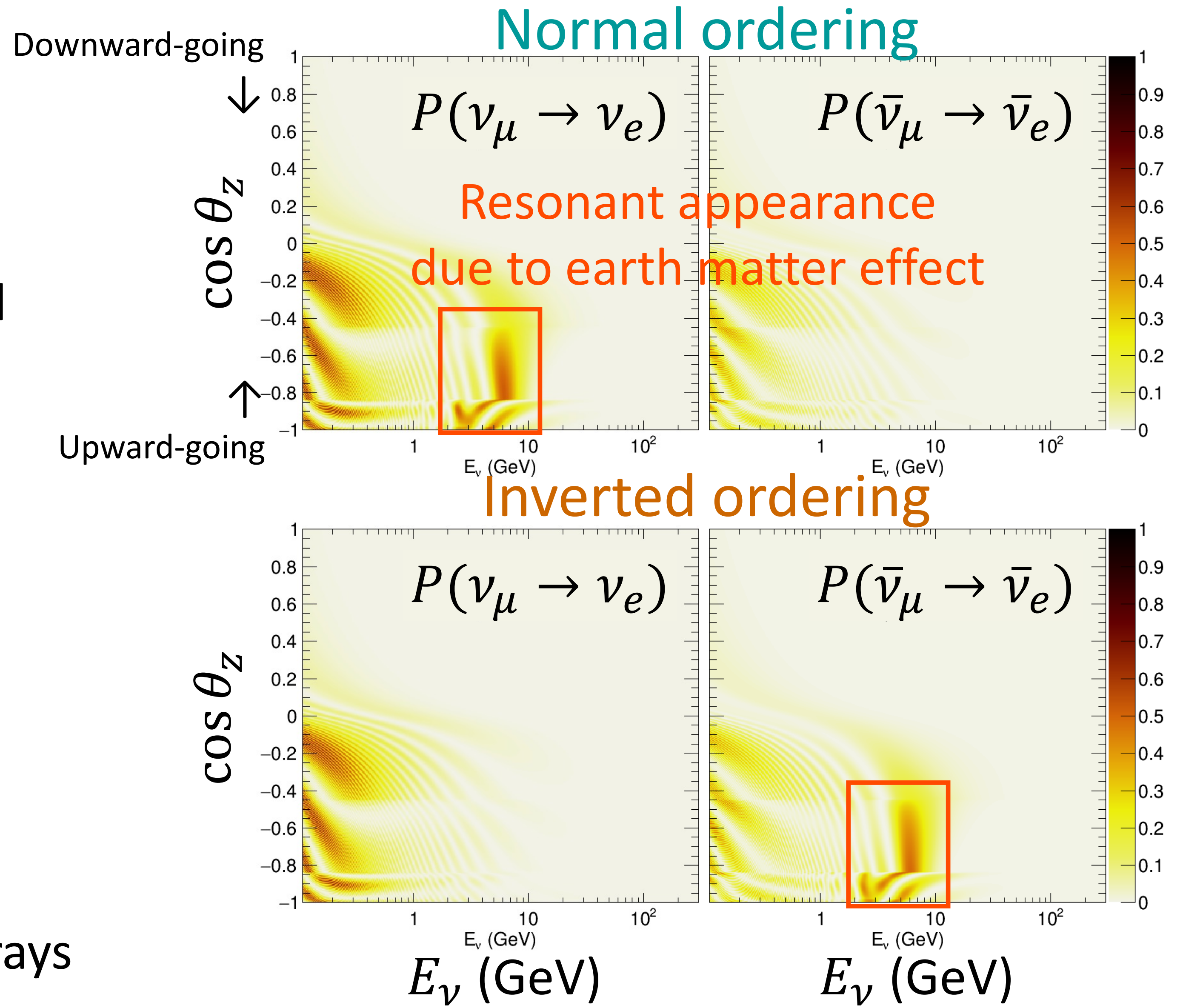
- Measurement of NCQE cross section in SK-Gd [PRD.109.L011101 (2023)]
- Atmospheric neutrino oscillation analysis in SK I–V [PRD.109.072014 (2024)]
- Solar neutrino measurements in SK-IV [PRD.109.092001 (2024)]
- Second gadolinium loading [NIMA.1065.169480 (2024)]
- Search for periodic time variations of solar neutrino [PRL.132.241803 (2024)]
- Real-time supernova monitoring system in SK-Gd [ApJ.970.93 (2024)]
- Cosmogenic induced spallation removal in SK-IV [PRD.110.032003 (2024)]
- Combined pre-supernova alert with KamLAND and SK [ApJ.973.140 (2024)]
- Data overflow protection system for nearby supernovae [PTEP.2024.ptae128 (2024)]
- Charge ratio and polarization of cosmic-ray muons [PRD.110.082008 (2024)]

Atmospheric neutrinos

Atmospheric neutrino analysis

- Wide ranges of
  - Energy ~ 100 MeV to >TeV
  - Baseline ~ 10 – 10,000 km
- Powerful probe for mass ordering, and sensitive to θ_{23}, Δm^2_{32}, and δ_{CP}.

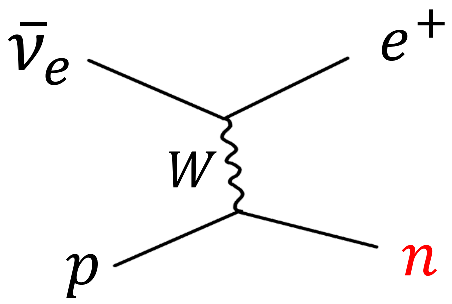


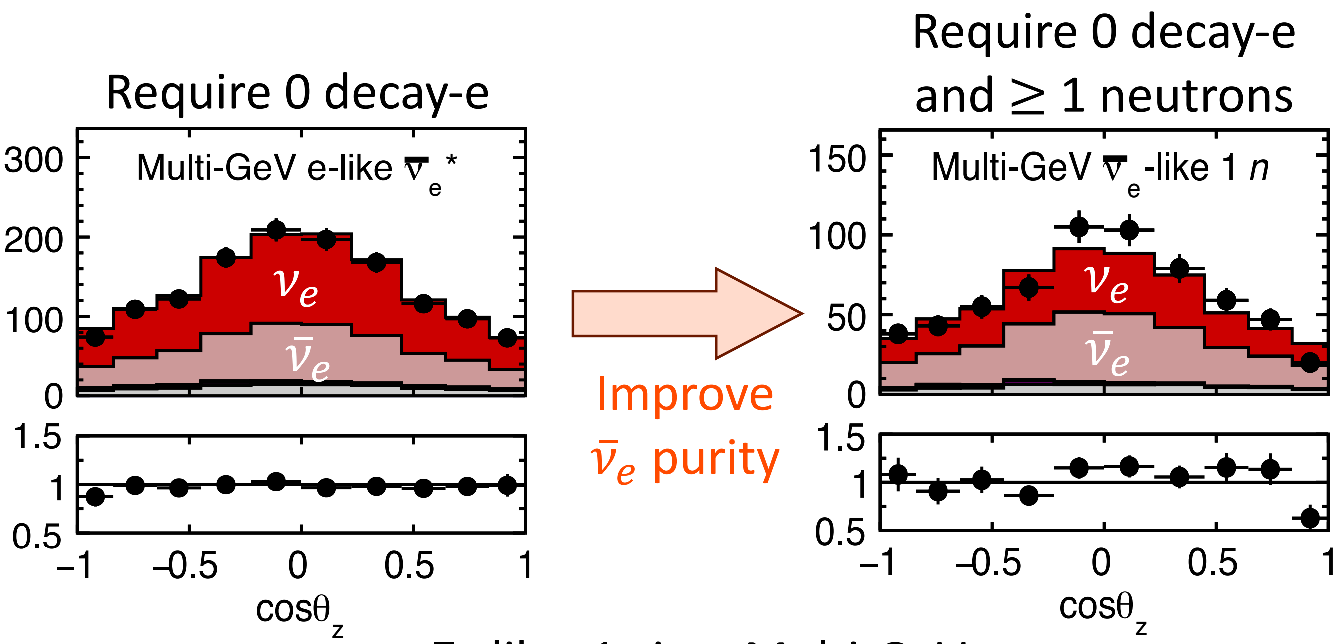


Latest analysis with pure-water

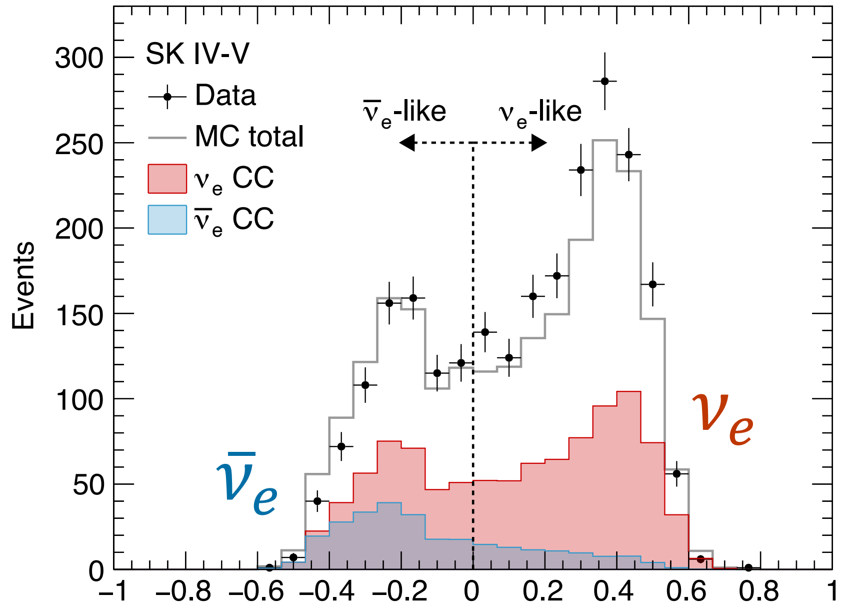
❖ Analysis from full pure-water phases, SK I-V. [PRD.109.072014 (2024)]

- Expand fiducial volume: 22.5 kton → 27.2 kton
- Neutron tagging on hydrogen to separate $\nu_e/\bar{\nu}_e$
- Boosted decision tree (BDT) for multi-ring event classification





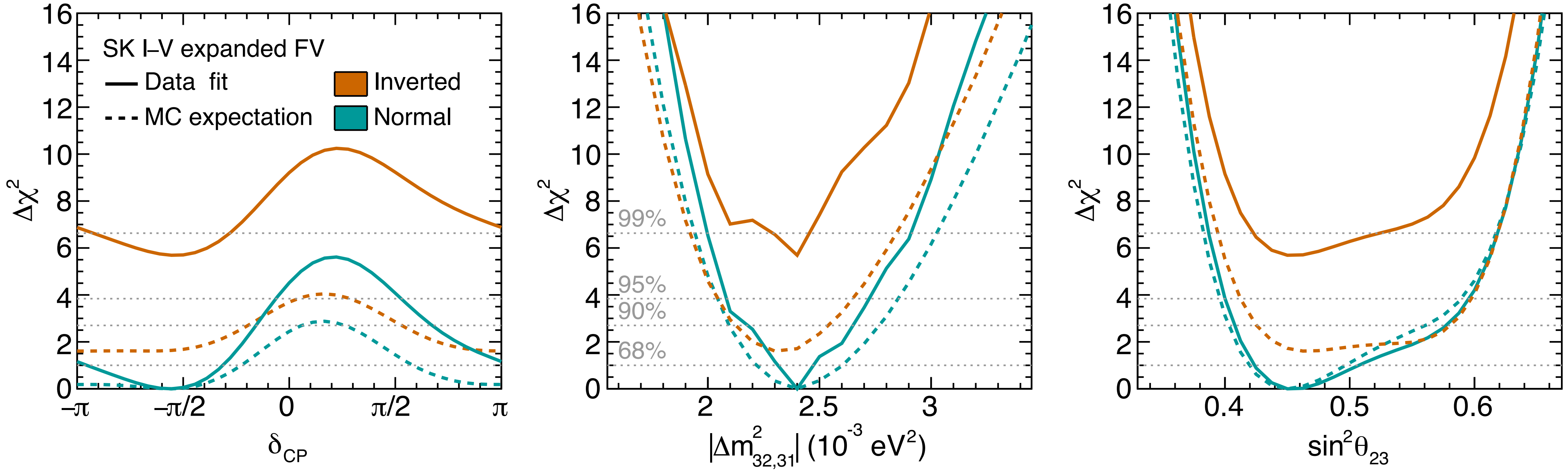
$\bar{\nu}_e$-like, 1-ring, Multi-GeV



ν_e-$\bar{\nu}_e$ BDT score

Results from pure-water phases

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

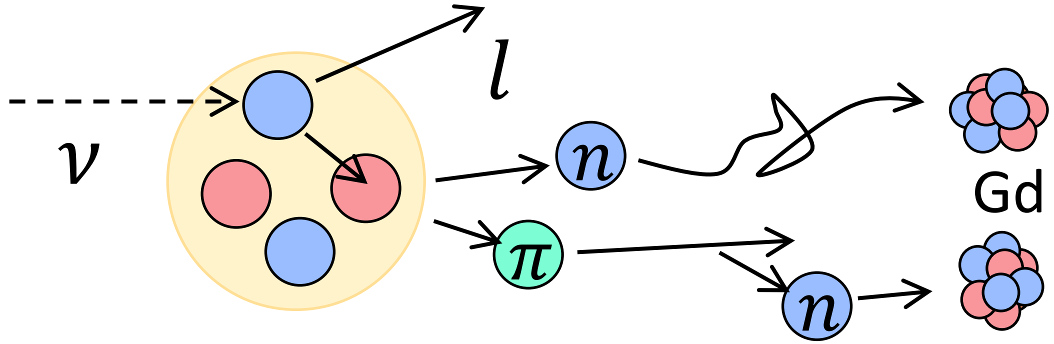


- Best fit at: Normal ordering, $\delta_{CP} \sim -\pi/2$, $\Delta m^2_{32} = 2.4\times10^{-3}$ eV², $\sin^2\theta_{23} = 0.45$
- Mass ordering $\Delta\chi^2_{\mathrm{IO-NO}} = 5.69$

  → Converted to $\mathrm{C.L.}_s = \frac{p_{\mathrm{IO}}}{1-p_{\mathrm{NO}}} = 0.077$, with **92.3% confidence level to reject IO**.

Neutron multiplicity

- Provides constraints for neutrino event generators and O(100) MeV hadronic interaction models.
- Less neutrons observed than the least predicting model in Sub-GeV.

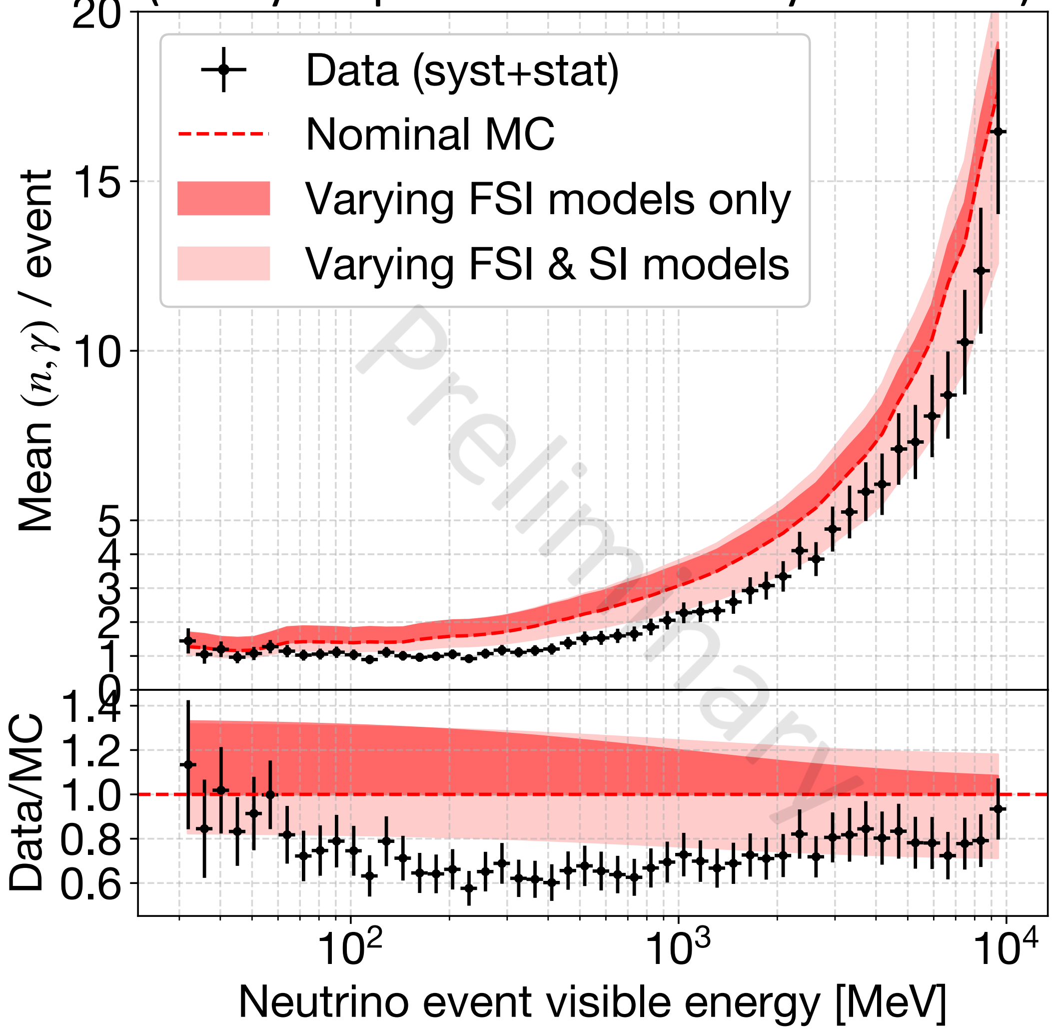


Neutrino Interaction
+
Final State Interaction

×

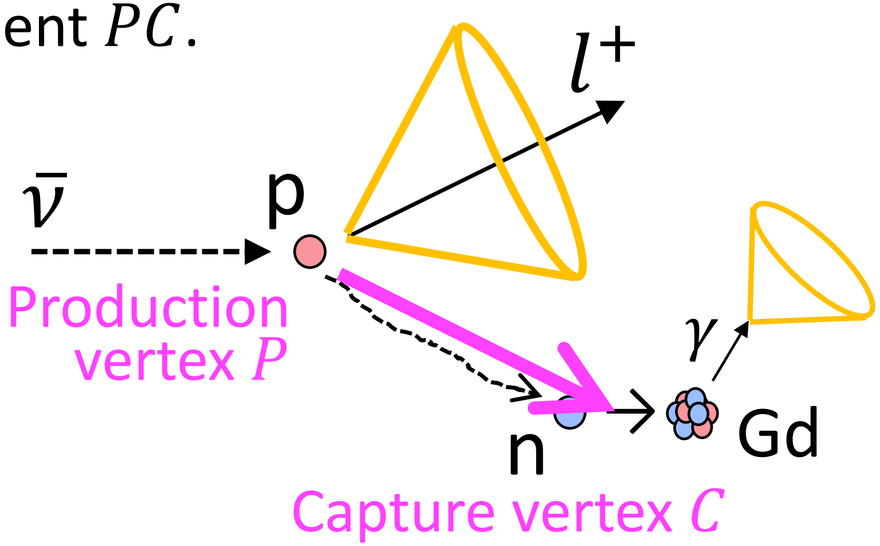
Secondary
Interaction

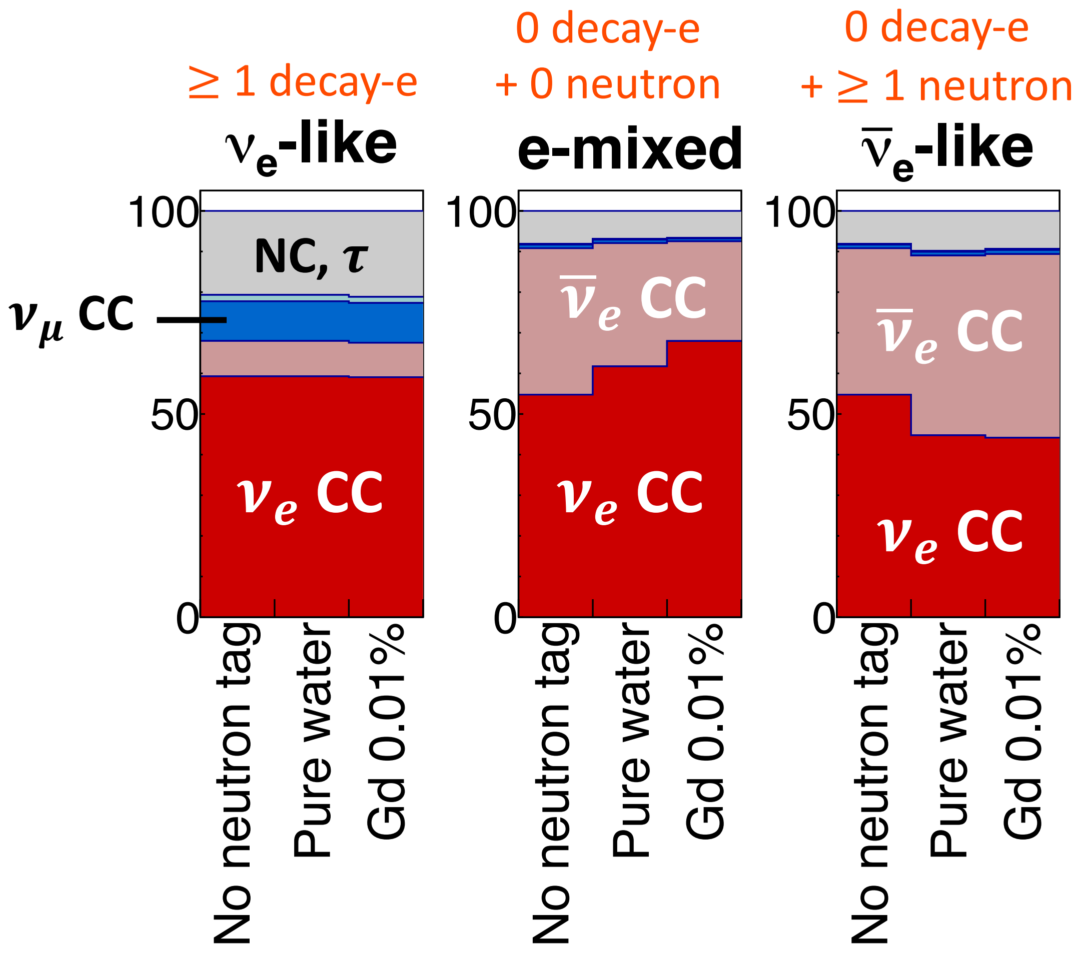
Measurement in SK IV–VI
(∼10 year pure-water + ∼1.5 year SK-Gd)



Gd for oscillation analysis

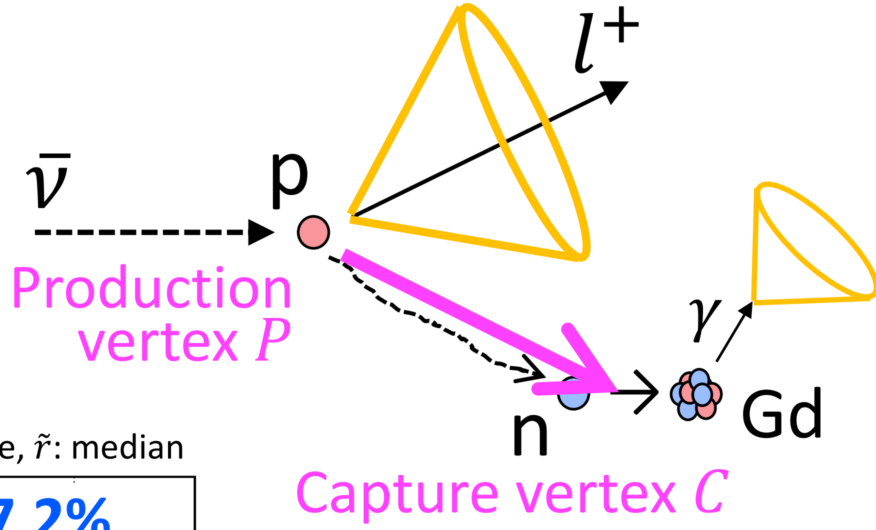
- Improve $\nu/\bar{\nu}$ separation.
  - Same criteria as in pure-water phases so far: $\bar{\nu}$-like if ≥ 1 neutrons tagged
- Reconstruct neutrino energy and direction assuming neutron momenta.
  - Neutron momentum is estimated from its displacement $\overrightarrow{PC}$.



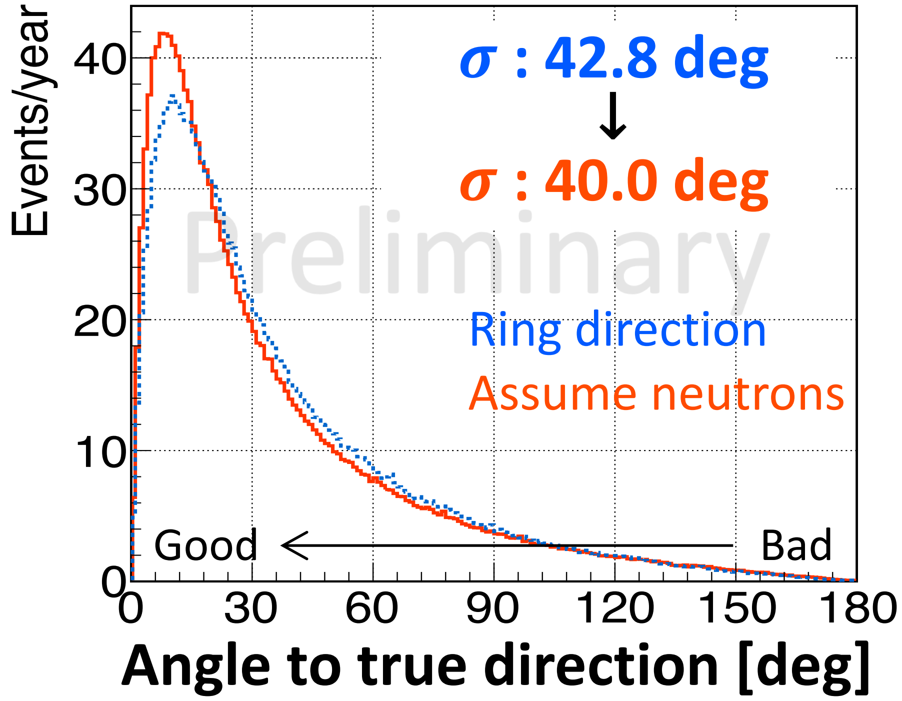


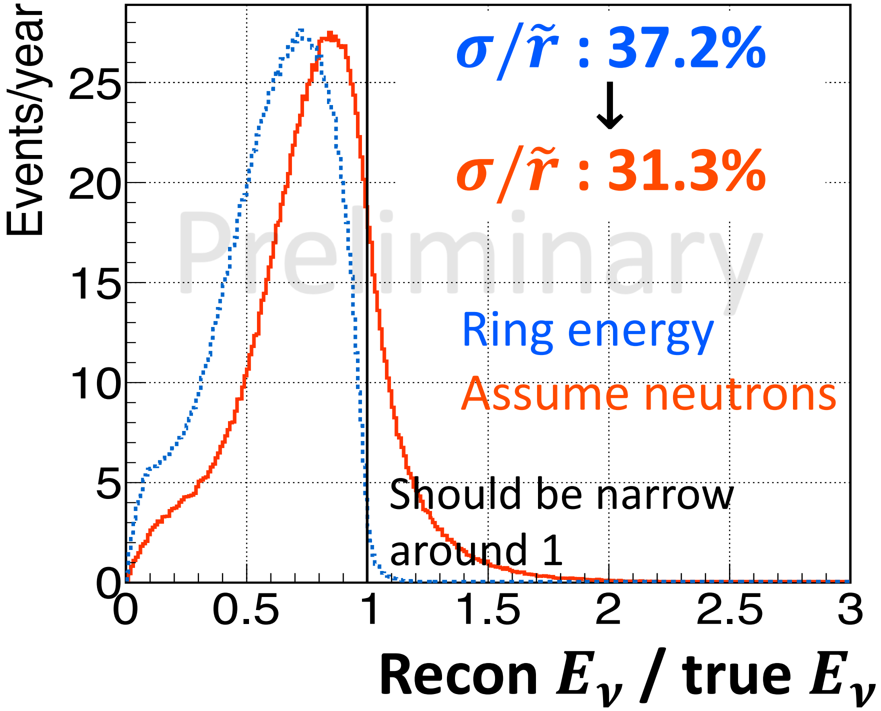
ν reconstruction using neutrons

- Assuming $\overrightarrow{p_n} \propto \overrightarrow{PC}$, reconstruct neutrino variables as
  - Direction: $\overrightarrow{d_\nu} \propto \overrightarrow{p_l} + \overrightarrow{p_n}$
  - Energy: $E_\nu = E_l + K_n$



σ: 68% percentile, $\tilde{r}$: median



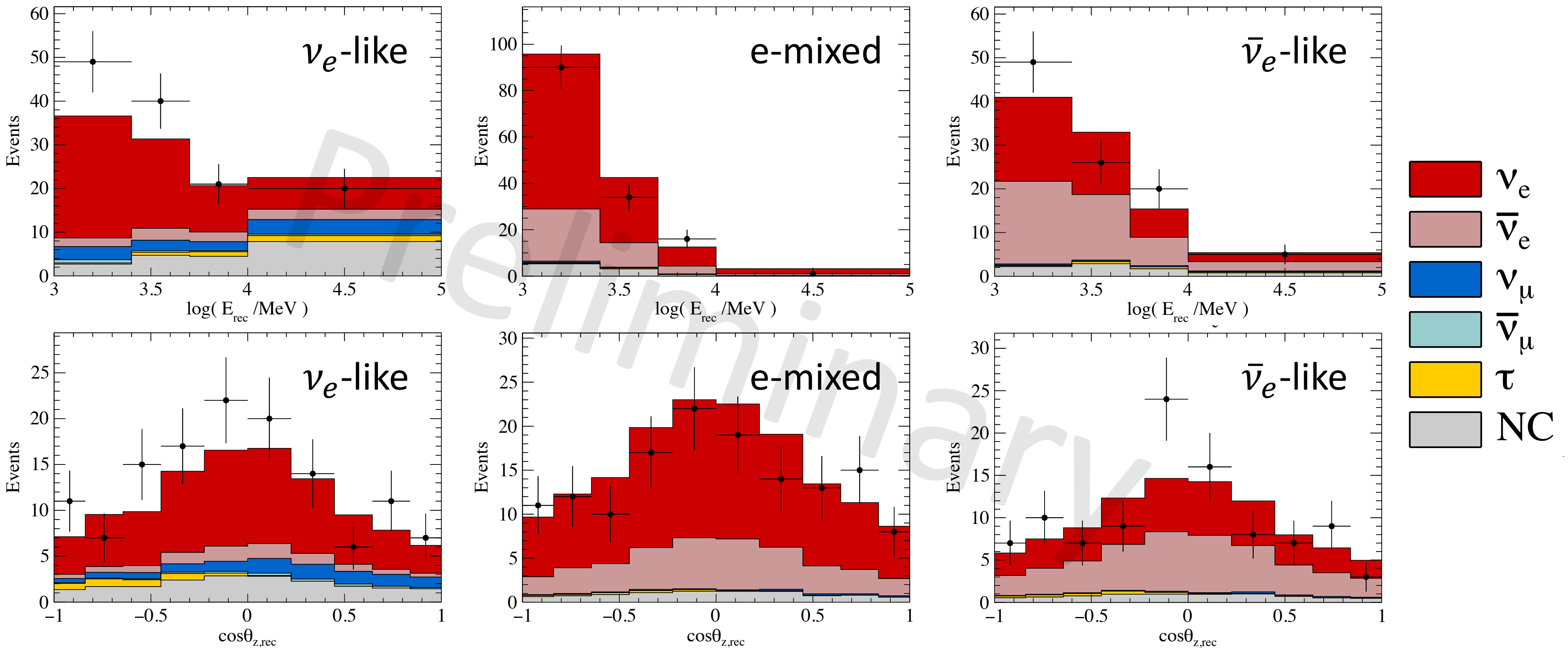


Observed distributions in SK-Gd

- The observed neutrino energy and direction agree with the predicted distributions.
- The first measurement of **neutrino** dynamics, not outgoing leptons.

Neutrino energy
E_ν

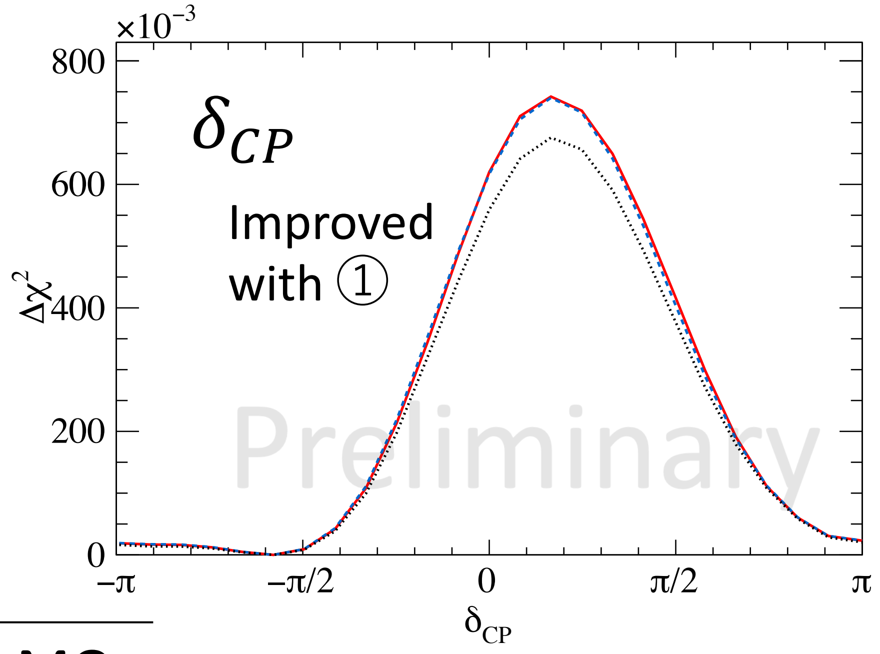
Zenith angle
$\cos\theta_\nu$



1-ring, $E_{\mathrm{visible}} > 1.3$ GeV
After fitting oscillation and systematic uncertainties

Oscillation sensitivity in SK-Gd

- Sensitivity to MO is improved by 21% with Gd, and by another 10% with new reconstruction using neutrons.
- Sensitivity to δ_{CP} is also improved with Gd.
- Data fit is ongoing.



	Target	Reconstruction using neutrons	Sensitivity to MO $\Delta\chi^2(\mathrm{IO}-\mathrm{NO})$
A	Pure water	×	0.169
B	Gd 0.01%	×	0.204
C	Gd 0.01%	✓	0.225

① Improve by $\nu/\bar{\nu}$ separation (21%)

② Improve by new reconstruction (10%)

*Event classification using neutrons is adapted in all the cases.

Diffuse Supernova Neutrino Background (DSNB)

Physics motivation of DSNB

- Supernova neutrinos provide a lot of physics, but nearby supernovae are very rare.
- DSNB: "Relic" neutrinos from past all distant SNe will also provide SN information.

$$\Phi_{\mathrm{DSNB}}(E) \propto \int \boxed{R_{\mathrm{SN}}(z)} \boxed{\frac{\mathrm{d}F_{\bar{\nu}}(E,z)}{\mathrm{d}E}} \boxed{\left|\frac{\mathrm{d}t}{\mathrm{d}z}\right|} \mathrm{d}z$$

SN rate

Cosmic expansion

SN ν emission

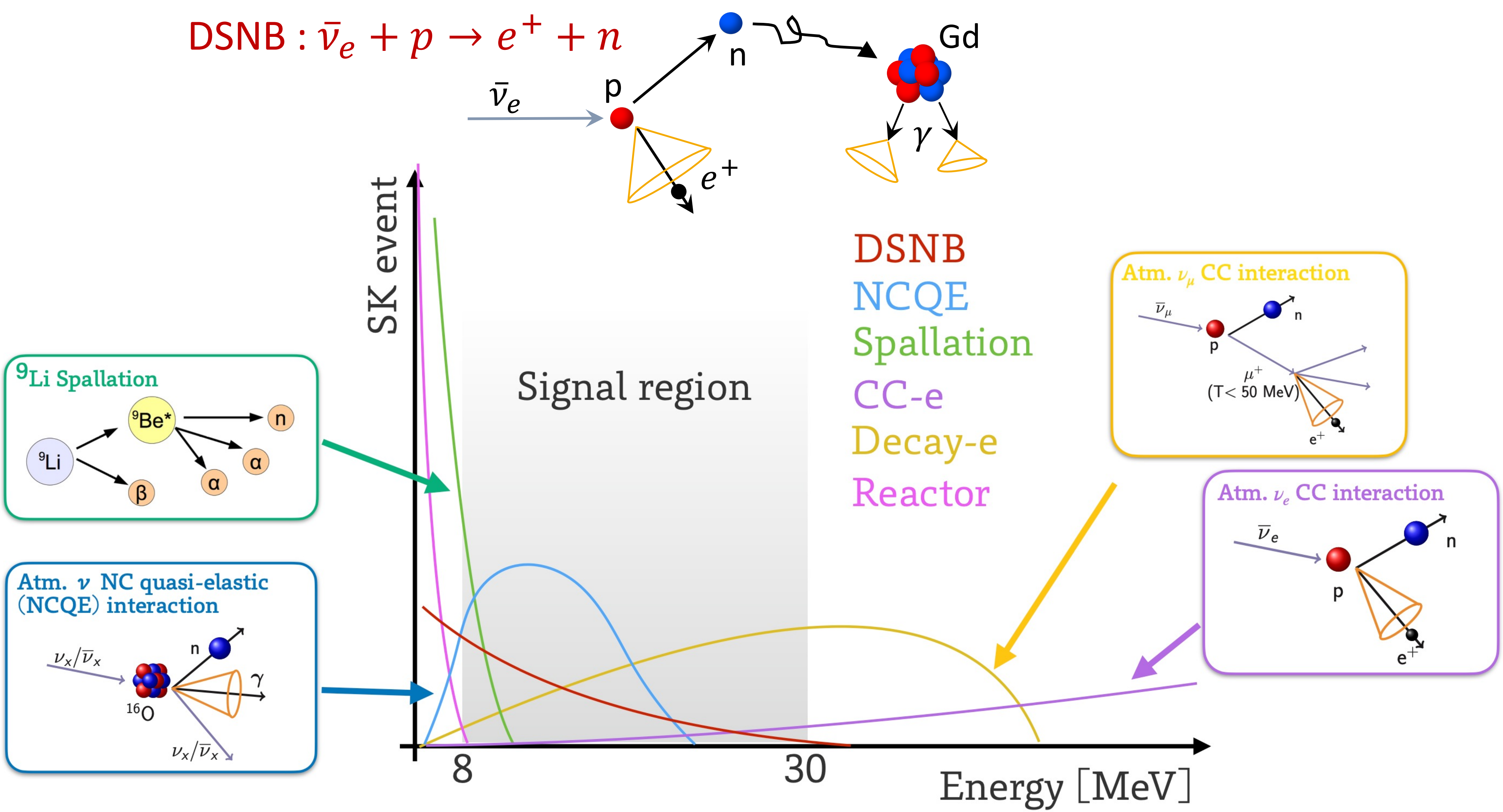
Depends on star formation history

- Star formation rate
- Black hole formation rate

Depends on…

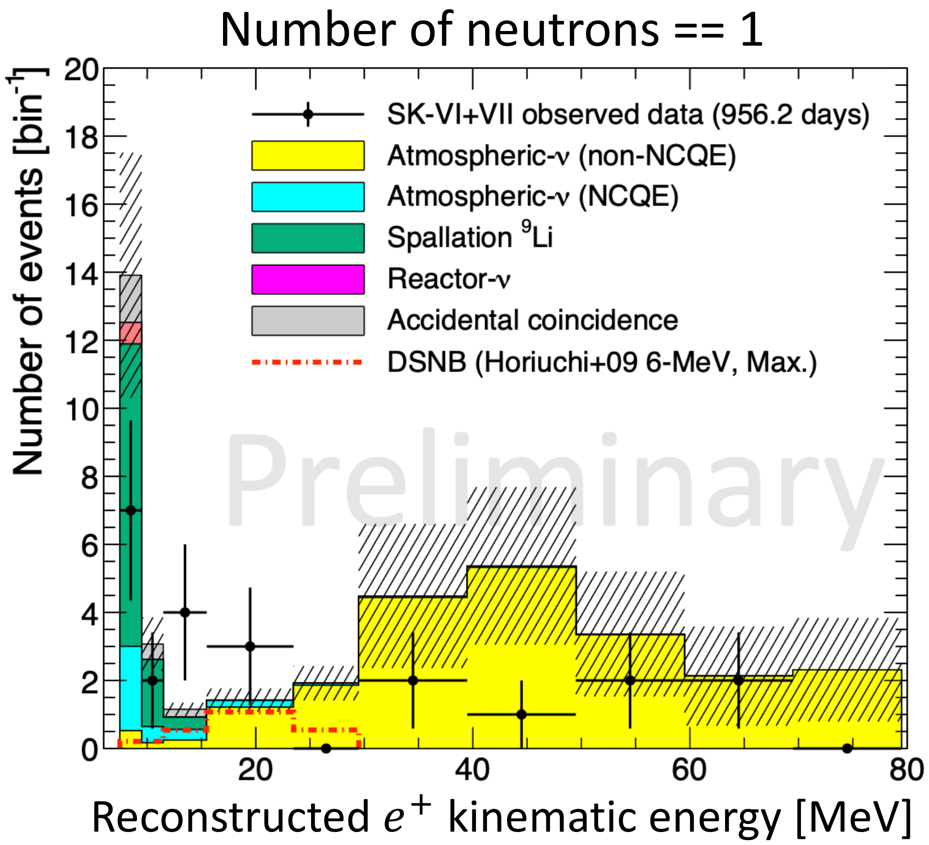
- SN neutrino spectrum
- Oscillation inside stars
- NSI, e.g. neutrino decay

DSNB signal and backgrounds

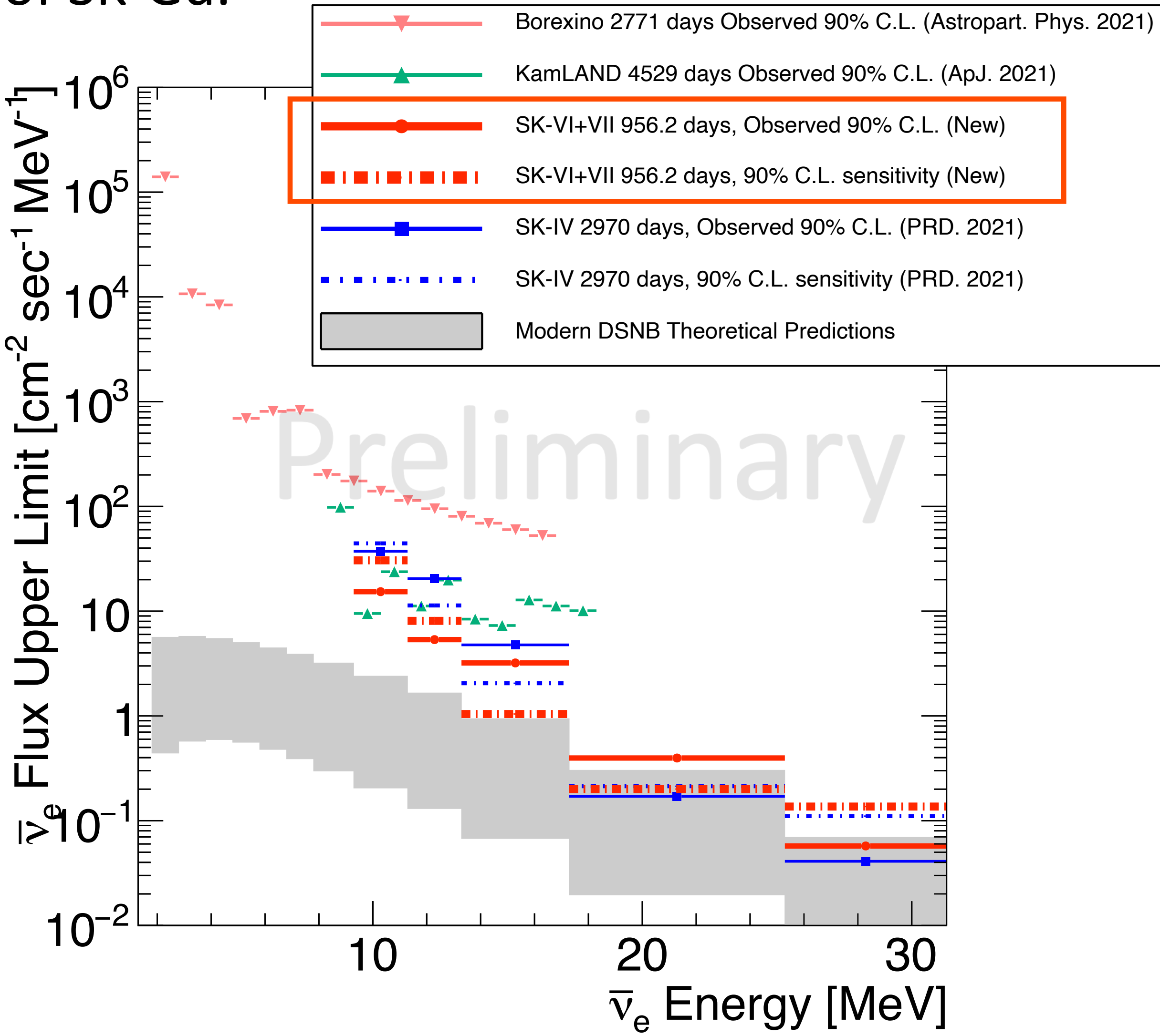


Flux limits from binned analysis

- Spectrum independent analysis with 956 days of SK-Gd.
- Update the world stringent sensitivity for almost all bins.



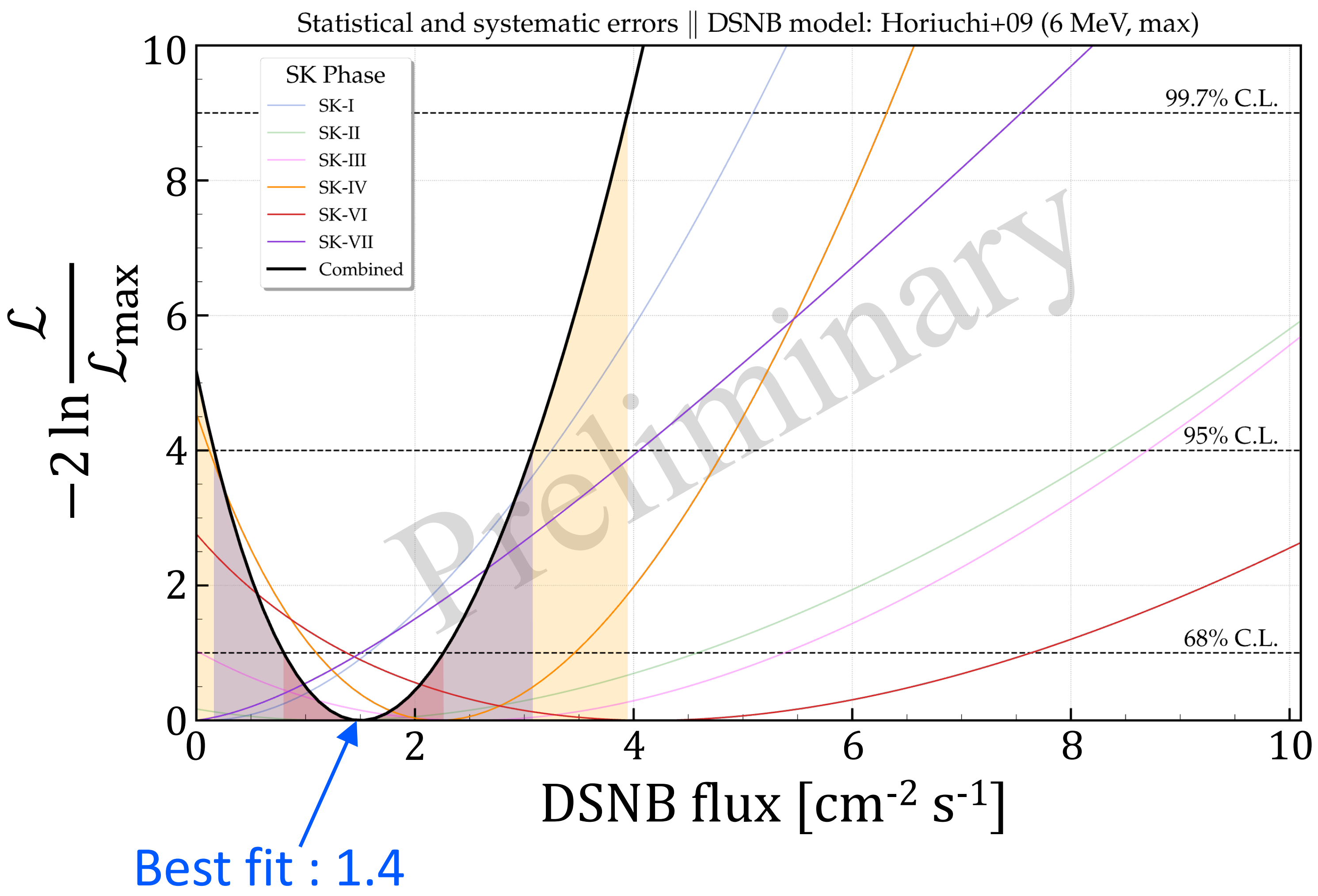
M. Harada, Neutrino2024



Result from spectral fit

- 6779 days of SK
  (5823 d pure-water + 956 d SK-Gd)
- $17.3 < E_\nu < 31.3$ MeV
- Use both $N_n = 1, \neq 1$ separately to suppress uncertainty of background prediction.

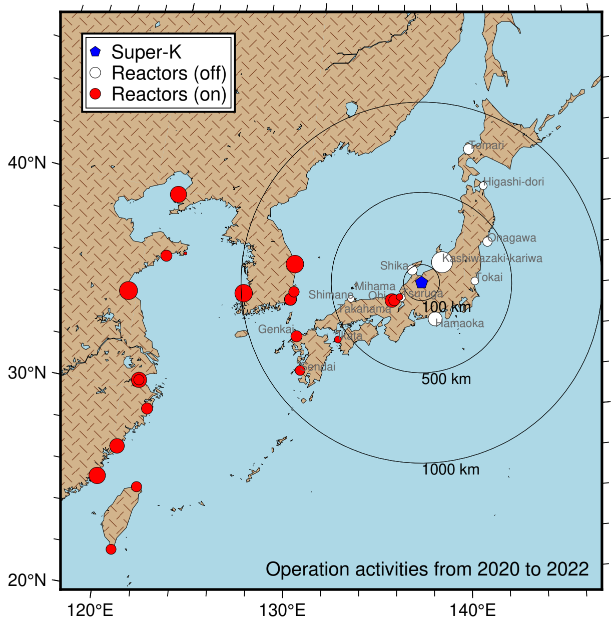
- **Exhibits 2.3σ excess from null assumption.**



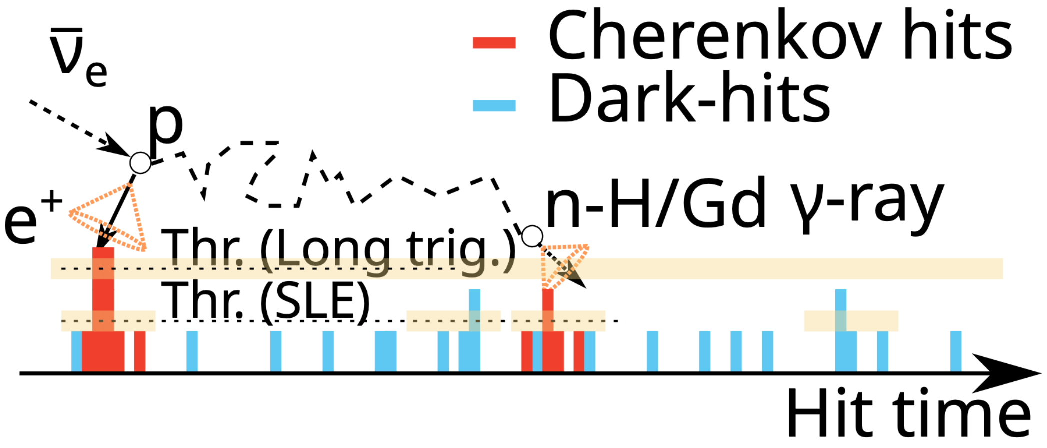
Reactor neutrinos

Reactor neutrinos at SK

- Very low energy: Peak at ~4 MeV
- No measurement in water-Cherenkov detectors.
  - Except for evidence from SNO+



- Target interaction is IBD, same as DSNB search.
- Lowered energy threshold thanks to higher energy neutron signals.
  - Conventional: **Long trigger after large hit cluster**
    - Threshold : ~8 MeV
  - New: **Individual super-low-energy (SLE) trigger**
    - Threshold : ~3 MeV

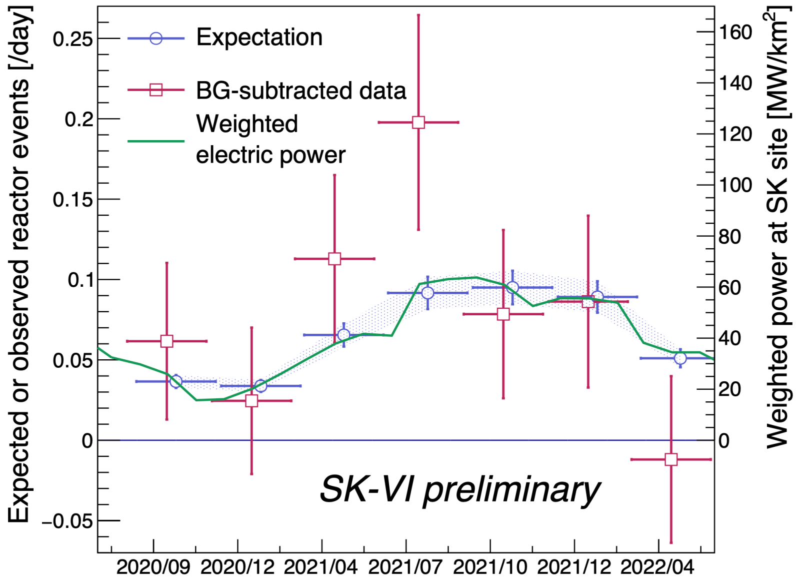


First observation in SK

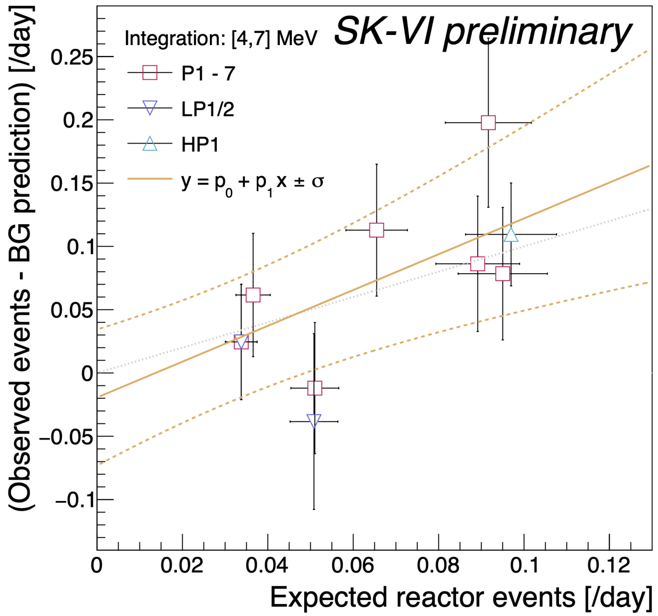
- Found excess in the signal region.
  →First positive observation of reactor $\bar{\nu}$ in SK.
- Correlated with reactor power.
- Statistics are limited to discuss oscillation.

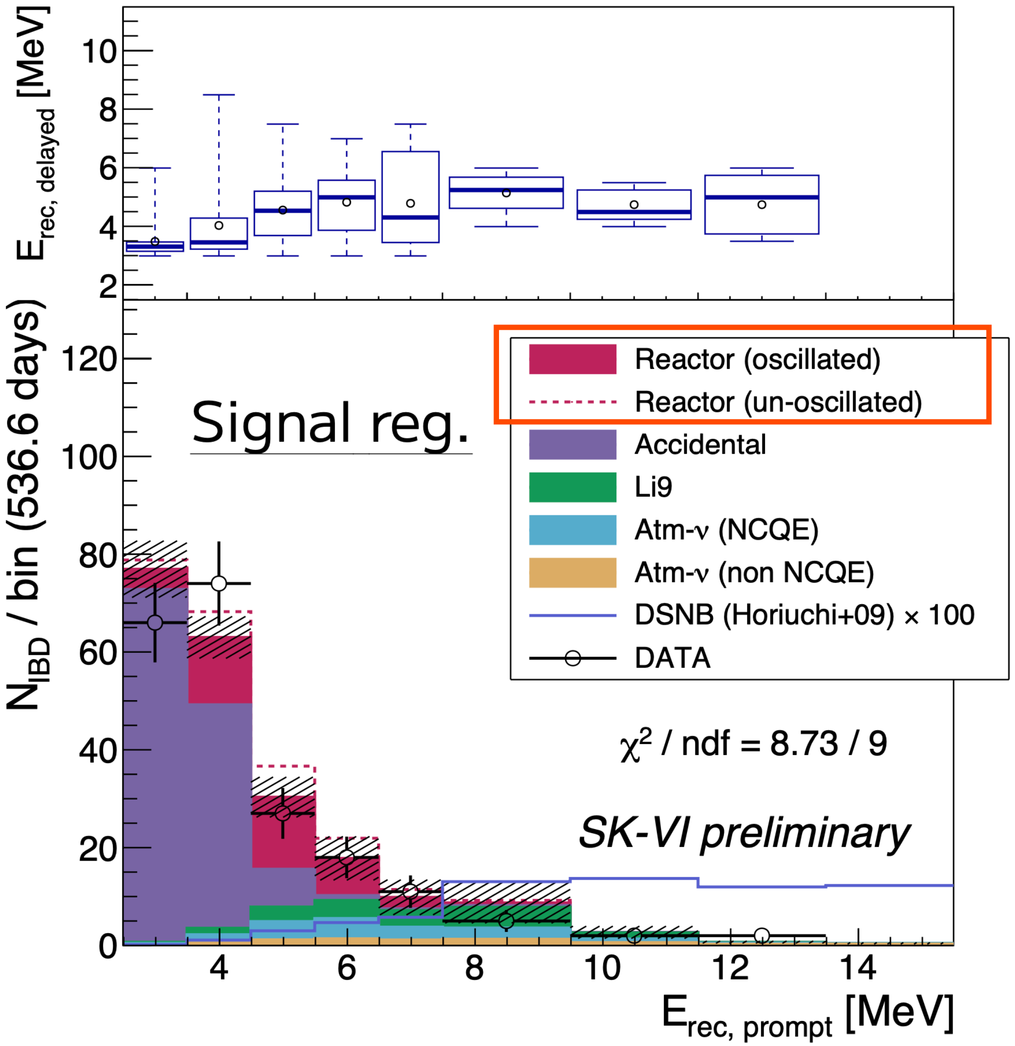
S. Izumiyama, Neutrino2024

History



Correlation to expectation

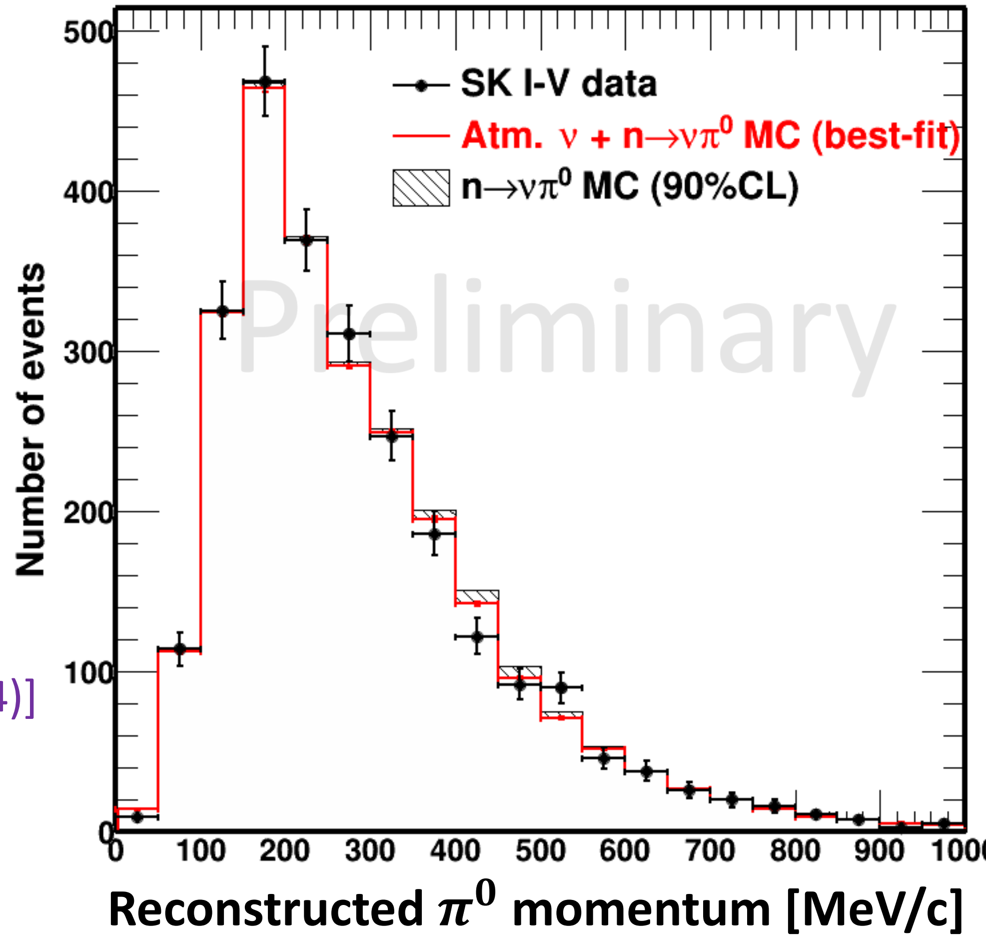




Nucleon decays

$n \to \nu\pi^0$

- Favored in a minimal SUSY SO(10) model. [PhysLettB.587.105 (2004) etc.]
- Analyzed full pure-water phases with expanded fiducial volume.
- Neutron tagging on hydrogen to reject background.
- No signal excess found.
- $\tau(n \to \nu\pi^0) > 1.1\times10^{33}$ years (90% C.L.)
- Same limit as in our previous search [PRL.113.121802 (2014)] because estimated signal efficiency decreased due to simulation model upgrade.

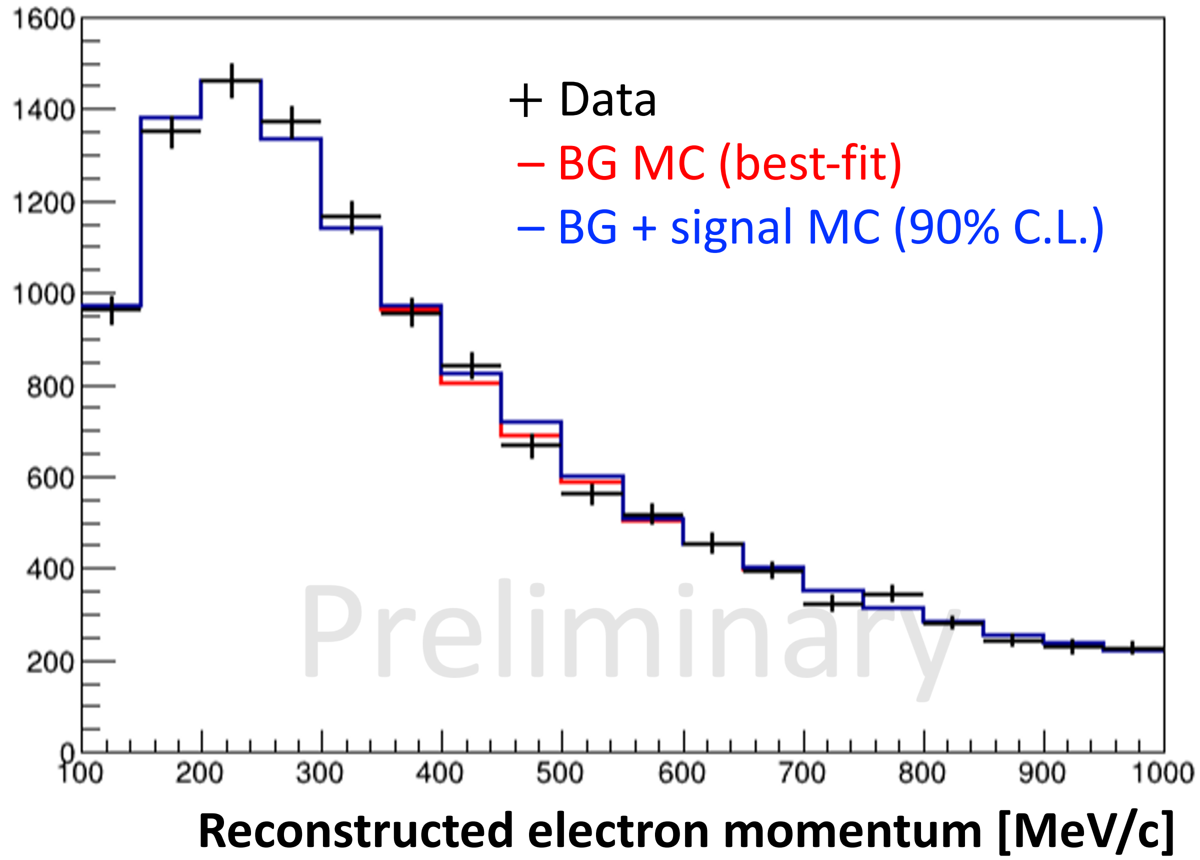


$p \to e^+X$

- X is a massless, invisible particle.
- Model inclusive search.
- Analyzed full pure-water phases with expanded fiducial volume.

- No signal excess found.
- $\tau(p \to e^+X) > 1.6{\times}10^{33}$ years (90% C.L.)
  - Previous result: $> 7.9{\times}10^{32}$ years
  [PRL.115.121803 (2015)]

- For other modes, see the talk by S. Mine in NNN23.



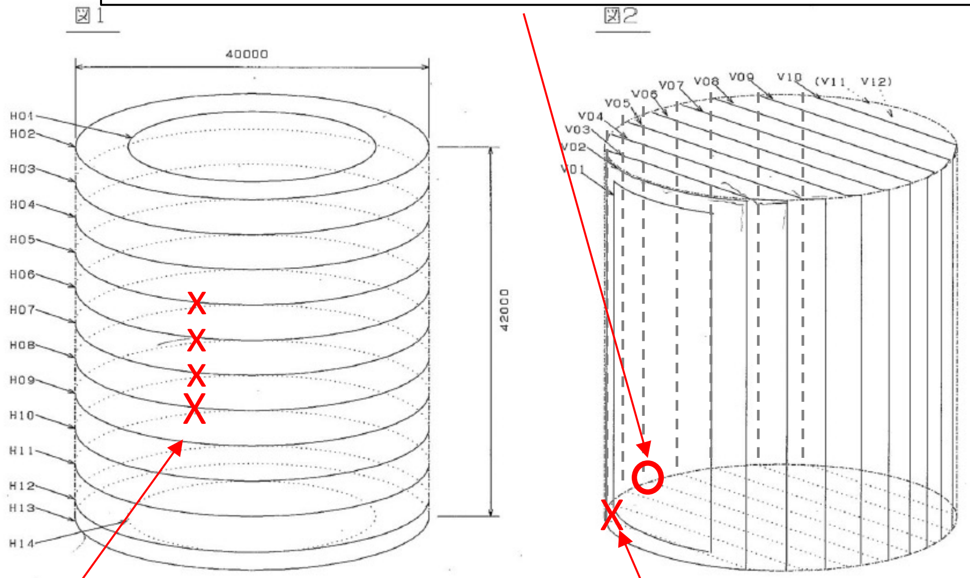
Summary

- **Atmospheric neutrinos**:
  - Analyzed full pure-water data set. Prefer normal ordering with CL_s=0.077.
  - SK-Gd data analyses ongoing. Sensitivity to MO is improved by 33%.
- **DSNB**: Update the flux limit with SK-Gd data. Spectral fit shows 2.3σ excess to null.
- **Reactor**: First positive observation in SK, correlated with reactor power.
- **Nucleon decays**: Updates in two modes: $n \to \nu\pi^0$ and $p \to e^+X$.

Back up

SK's geomagnetic compensation coil problems and countermeasures

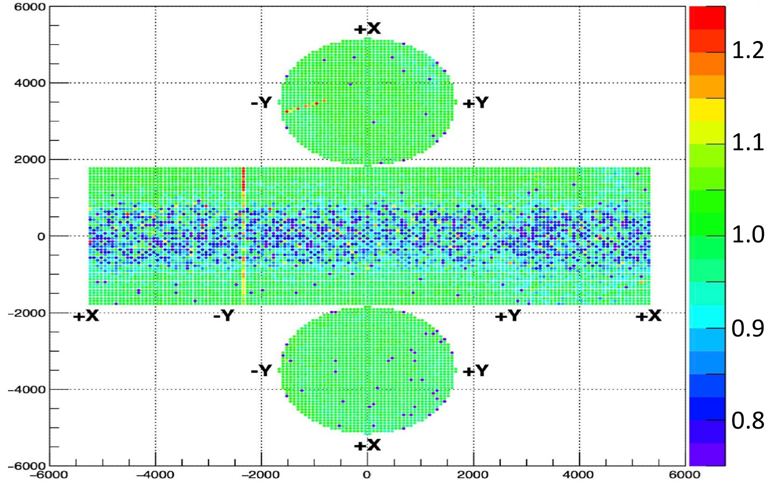
V06 disconnected on Oct.25, 2023.
Damaged sub-cable was bypassed on Dec.1, 2023. [recovered]



H09 disconnected on Dec.8, 2023. Due to power supply configuration, H06, H07, and H08 are also off.

V01 disconnected on Nov.15, 2023. V01 was bypassed from the power supply on Dec.2, 2023.

PMT photoelectron collection efficiency ratio, comparing May 2024 condition to nominal



- SK geomagnetic compensation coil cables have failed in three locations.
- At two of locations, part of the coil was successfully bypassed to restore functionality. The other location is entirely underwater, resulting in the entire cable group being turned off.
- A 10-20% decrease in collection efficiency is observed for about 20% of PMTs in the barrel.
- Efficiency for detecting neutron capture on Gd has also decreased by about 3%.
- The physics impact can be compensated by calibration and simulation.
- The likely cause is corrosion of wire connections due to ionized water seeping in under heat shrink insulation.
- SK plans to install six new horizontal coils in summer 2024 to restore the geomagnetic field cancellation.