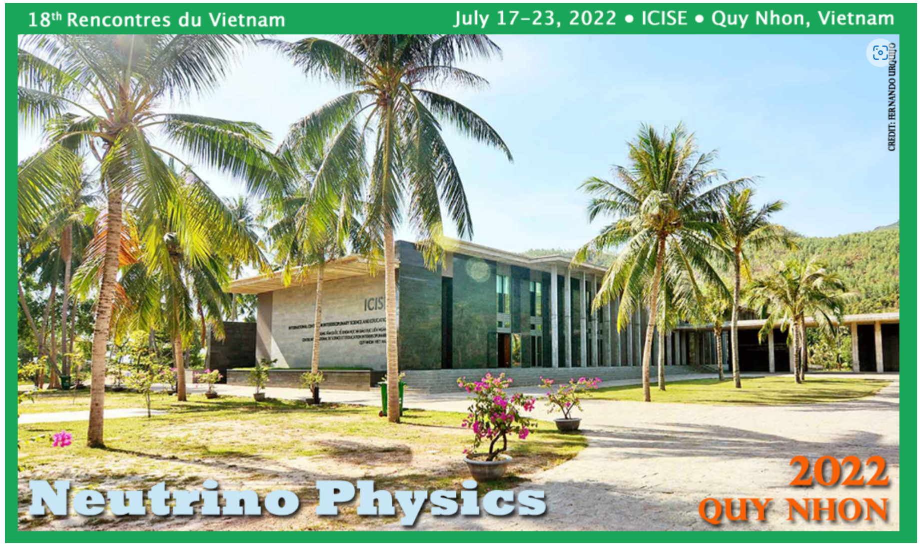
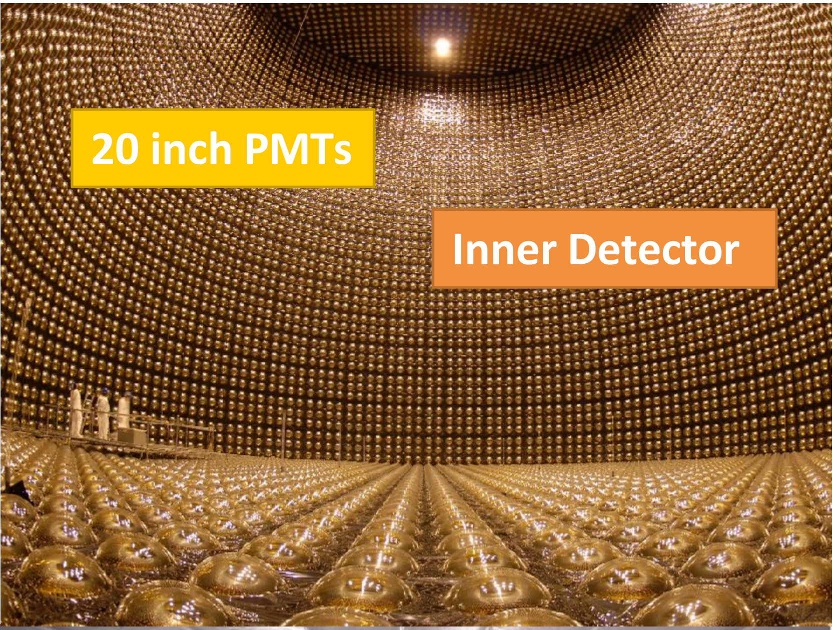
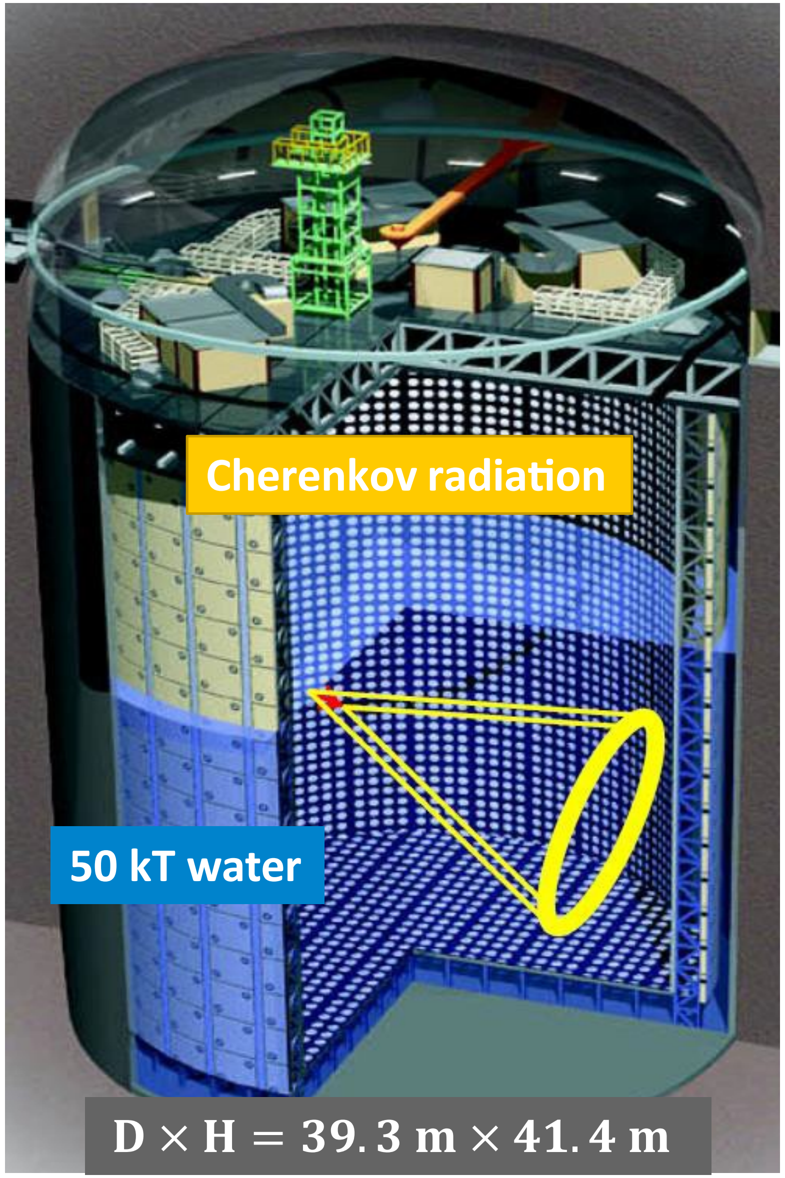
New Results with Atmospheric Neutrinos at Super-Kamiokande

Makoto Miura (Kamioka Observatory, ICRR)
on behalf of the Super-Kamiokande collaboration



The Super-Kamiokande Detector





The Super-Kamiokande Collaboration

~230 collaborators
from 51 institutes
in 11 countries

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France

INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
University of Oxford, UK

Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tohoku University, Japan
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

Since 2021

SK Data Taking Phases

Gd concentration at SK-VI:
0.011% in weight.

Pure water
6,511 days live-time

Gd-loaded water
583.3 days + the future...

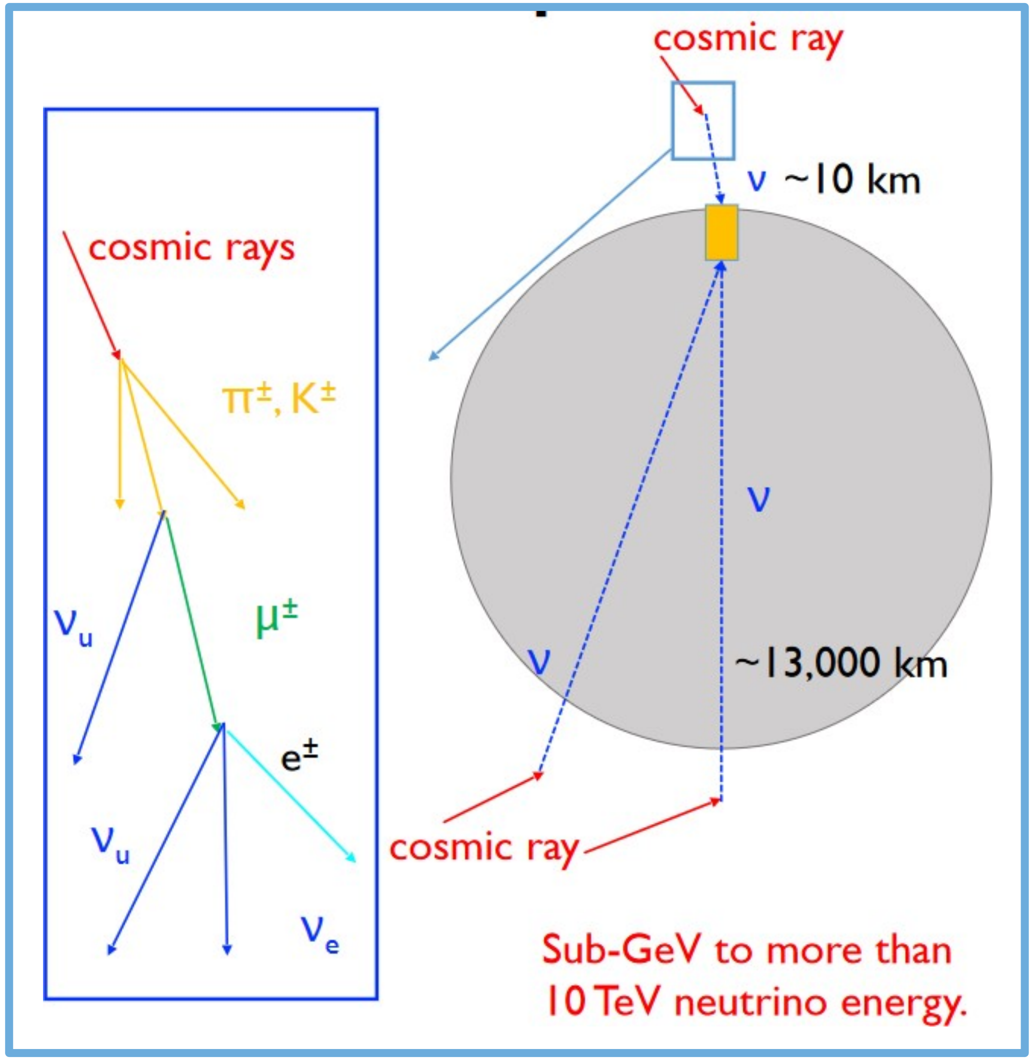
New Results from SK

- **Atmospheric neutrino oscillation measurements**
  - SK-I through SK-V + Expanded FV
  - Three Flavor Oscillation with T2K Constraints

- **Proton decay: p→ μ^+K^0**

- **Neutron capture on Gd in SK-VI**

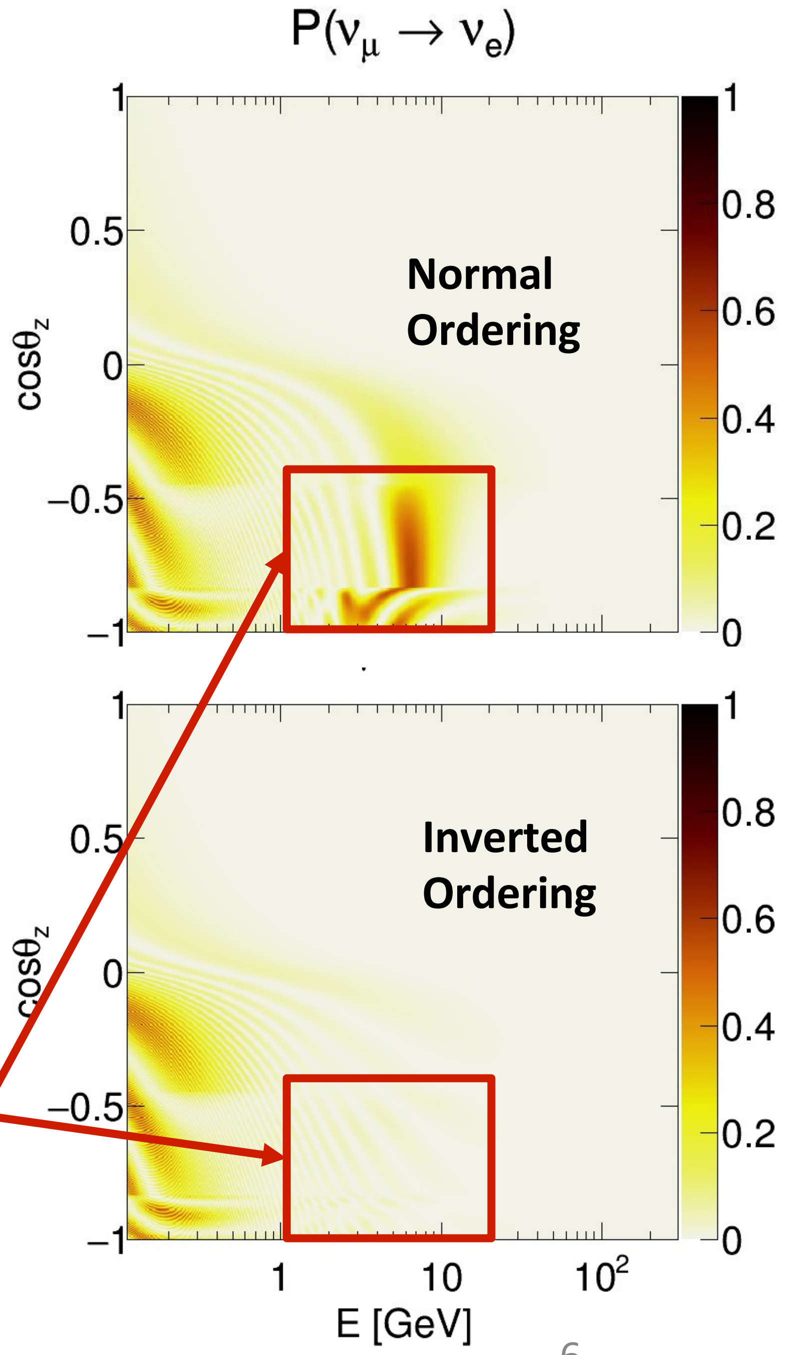
Atmospheric Neutrino Oscillation



Key measurements:

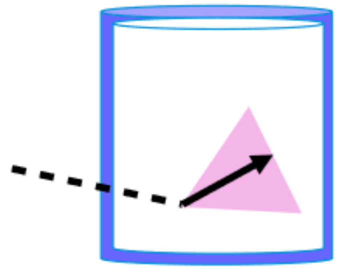
- ν_μ disappearance
  - Δm^2_{32}
  - $\sin^2\theta_{23}$
- ν_e apearance
  - CP violation δ
  - Mass-ordering

Matter Effect

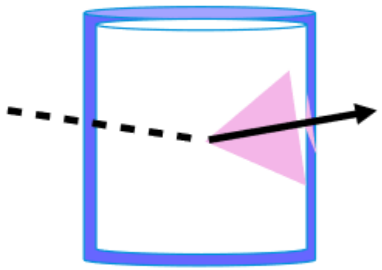


Atmospheric Neutrino Analysis at SK

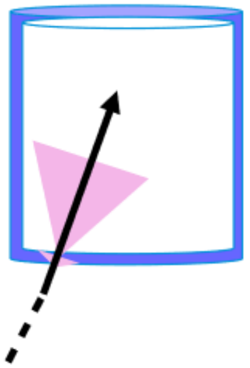
Fully Contained (FC)



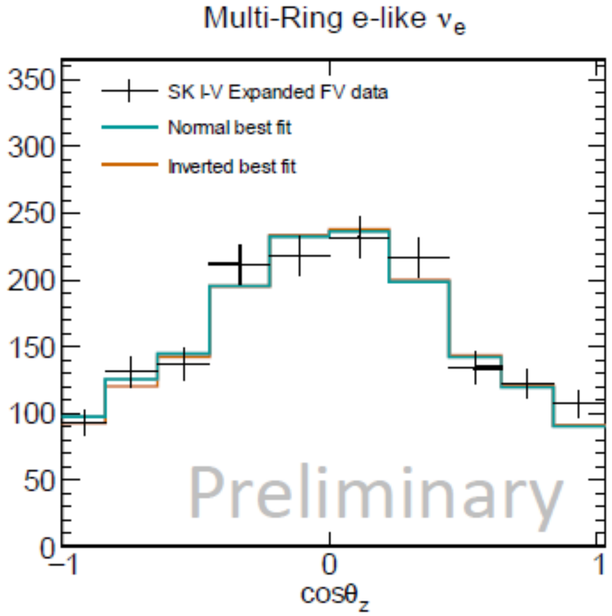
Partially Contained (PC)

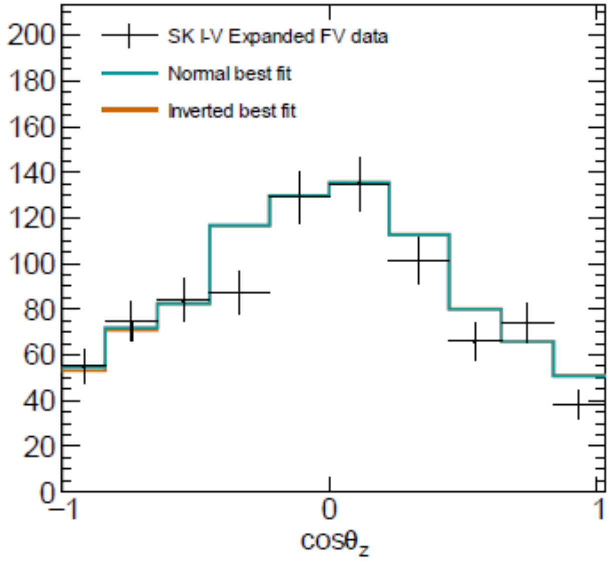


Upward-going Muons (Up-μ)



Reconstructed, Classified, and binned





Total exposure:
484.2 kiloton-years

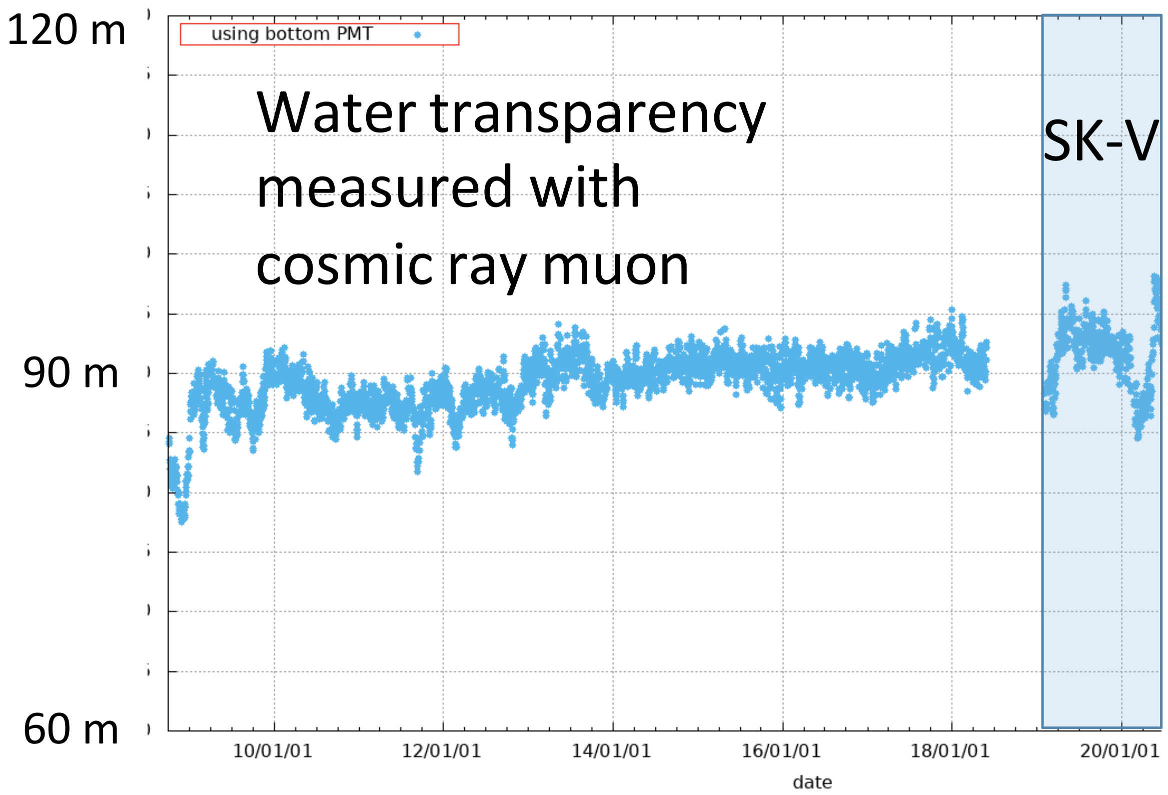
30% more data than 2020 analysis
Using all of pure water data at SK

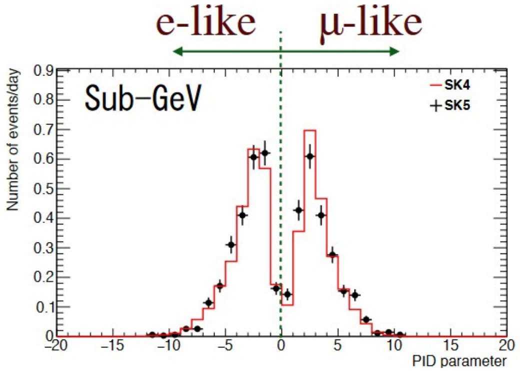
New in this analysis:

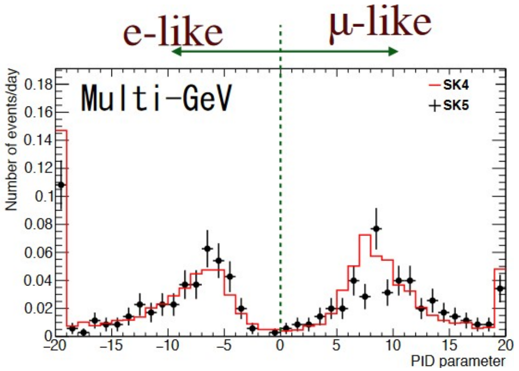
- SK-V data
- Expanded fiducial volume
- T2K model including $\bar{\nu}$ mode
- New multi-ring selection
- Systematics improvements

SK-V

2019.2 ~ 2020.7, 461 days



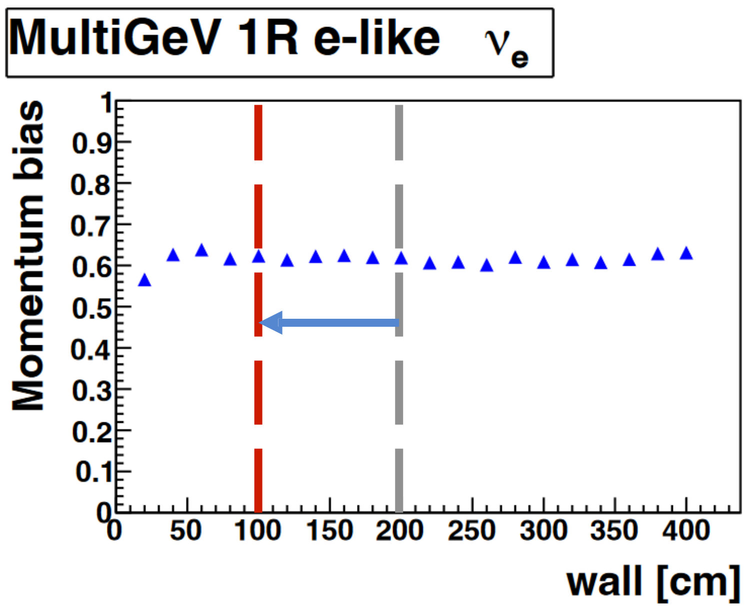


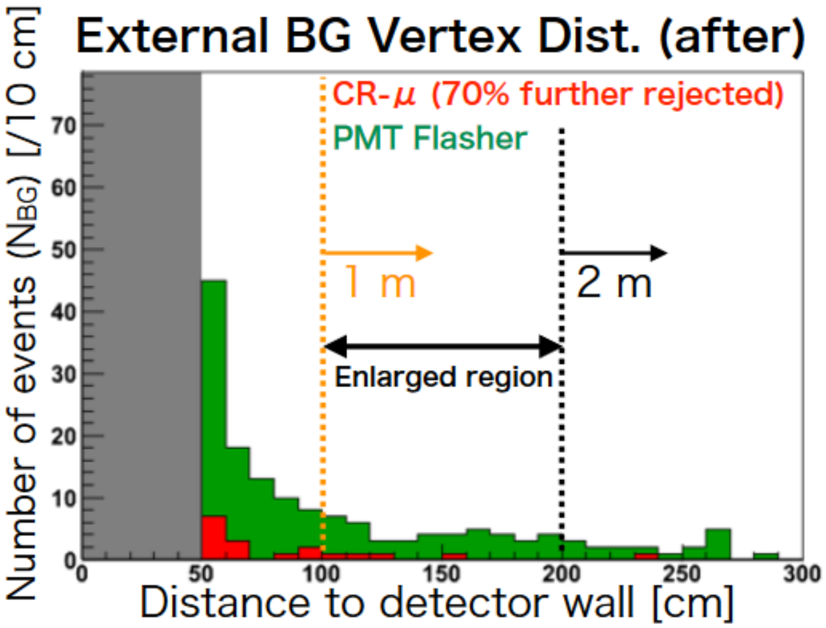


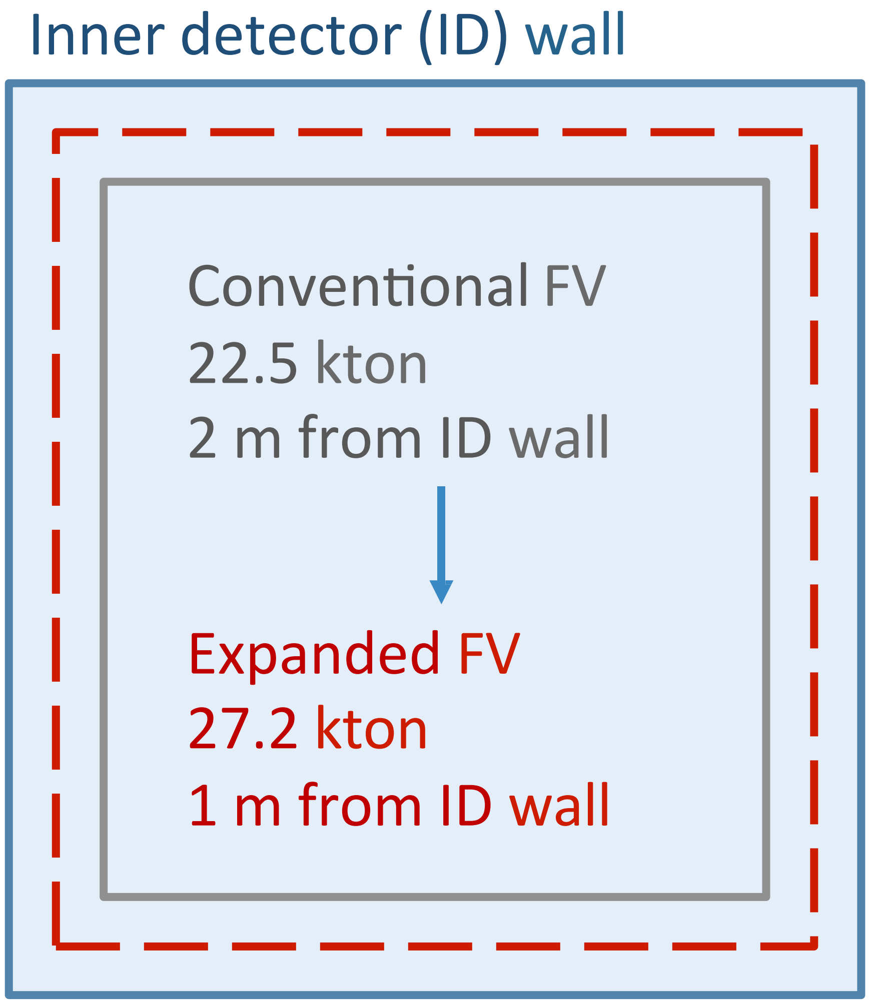
- The last SK phase with pure water
- Upgraded water system, replaced PMT, cleaned detector… Getting ready for Gd loading!
- Consistent data quality with SK4

Expanded Fiducial Volume

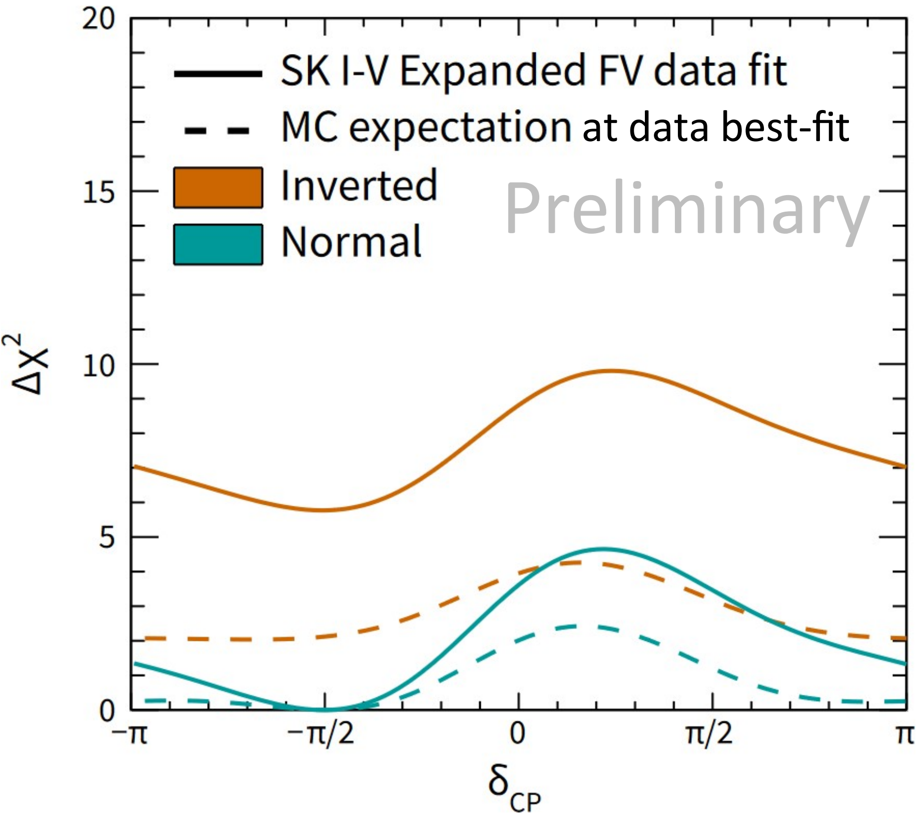
- Expanded fiducial volume
  - 22.5 kton → 27.2 kton, 20% increase
- No significant increase of external background
- No significant bias in reconstruction
- Systematics re-estimated for expanded FV

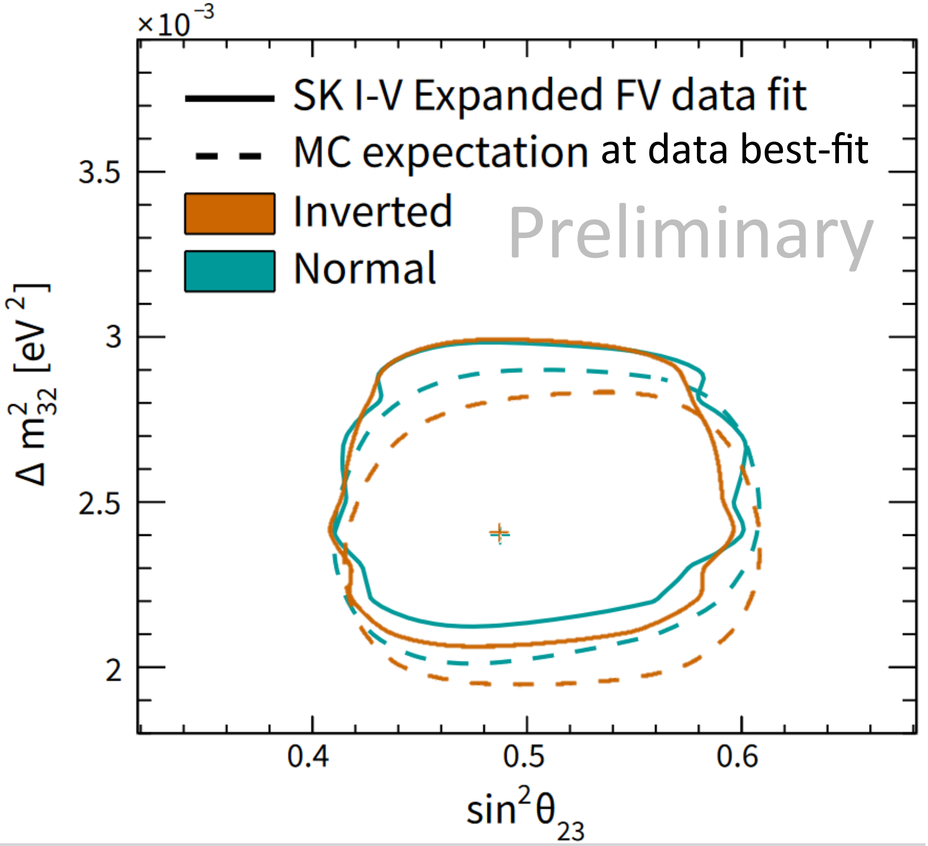






Oscillation Measurements (SK only)





SK atmospheric neutrino data favors:

- maximal mixing
- NO ($\Delta\chi^2 = 5.8$)
- $\delta_{\mathrm{CP}} \approx -\frac{\pi}{2}$

930 bins	χ^2	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23}
SK NO	1000.42	4.71	0.49	2.4×10^{-3} eV^2
SK IO	1006.19	4.71	0.49	2.4×10^{-3} eV^2

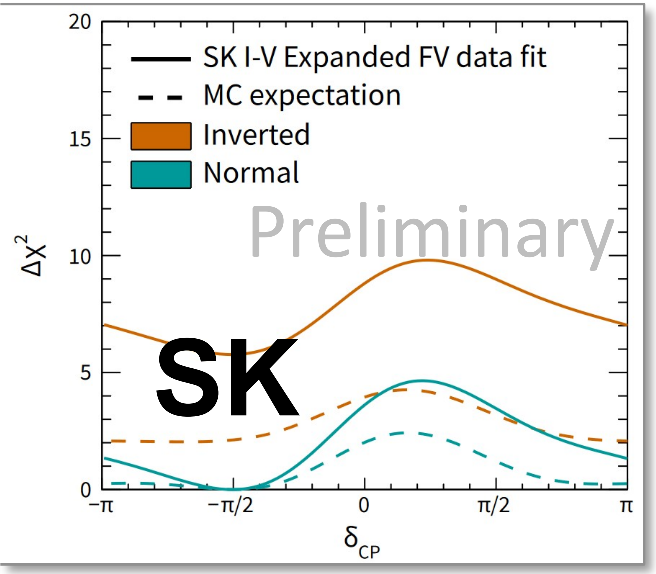
Prelim inary

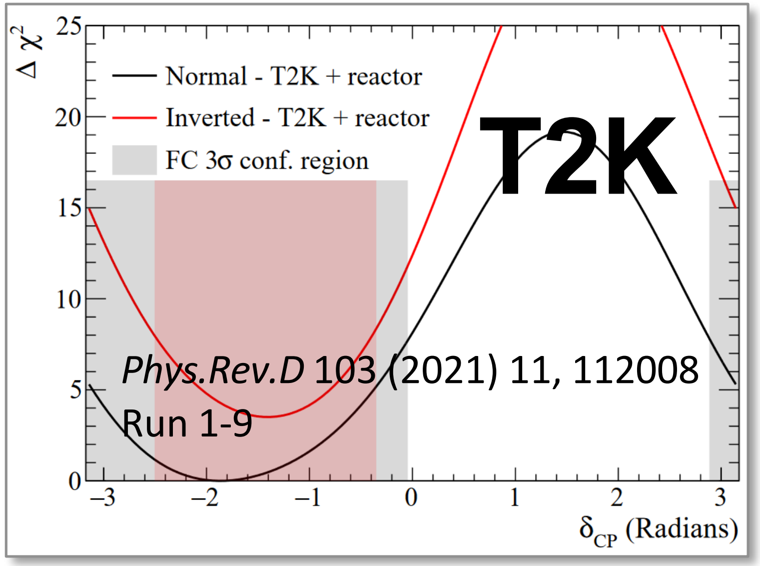
*Results on MO and δ_{CP} exceed sensitivity.

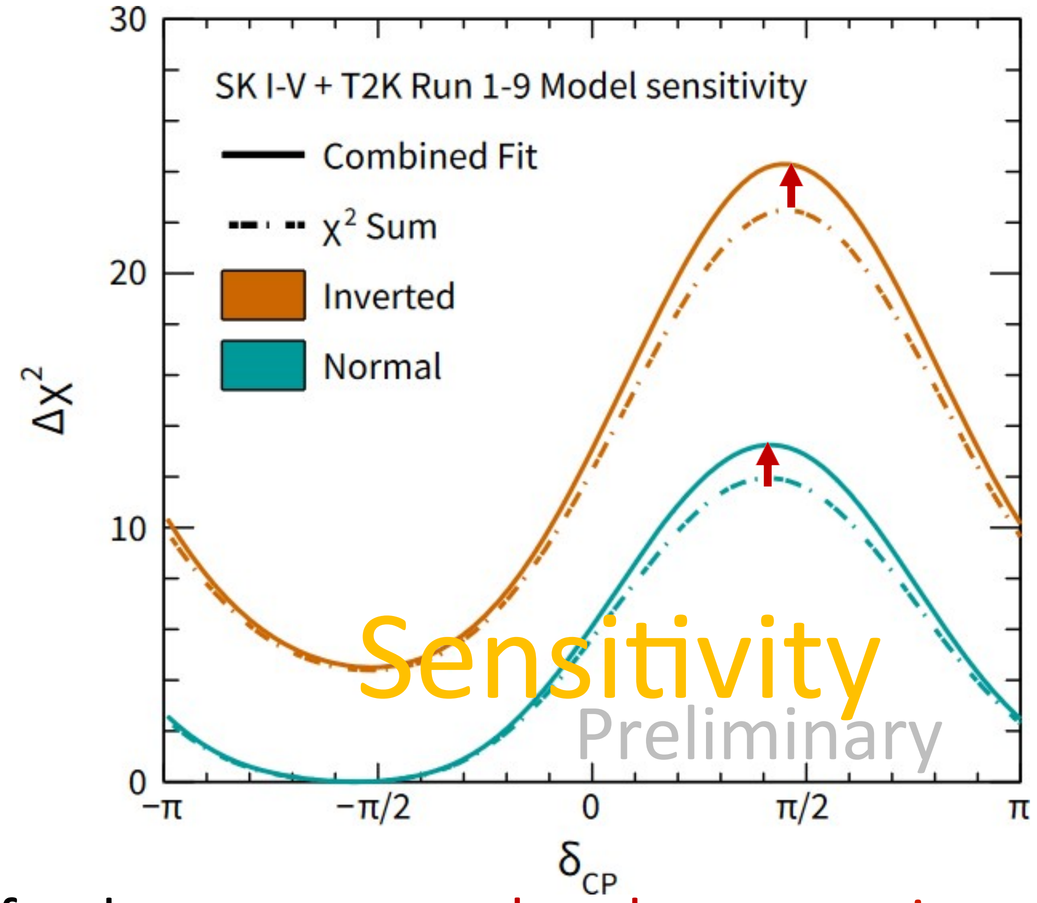
$\sin^2\theta_{13} = 0.0220 \pm 0.0007$

Combining SK and External T2K Constraints

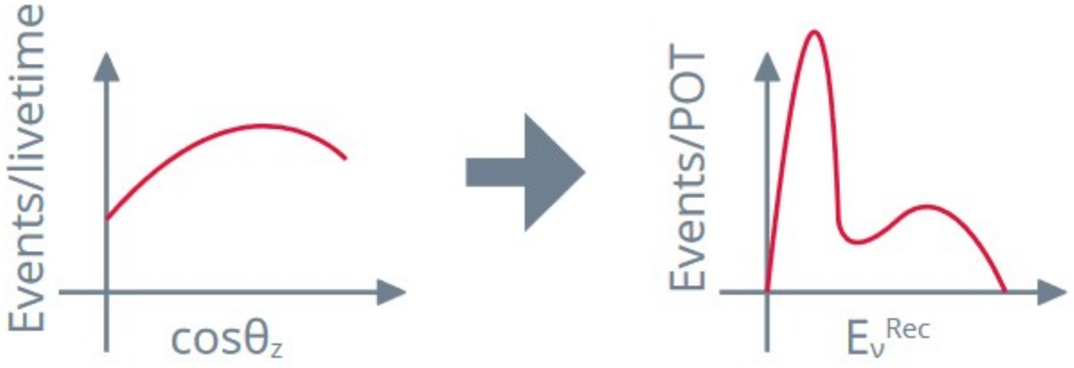
- SK sensitive on mass ordering, T2K sensitive on δ_{CP}





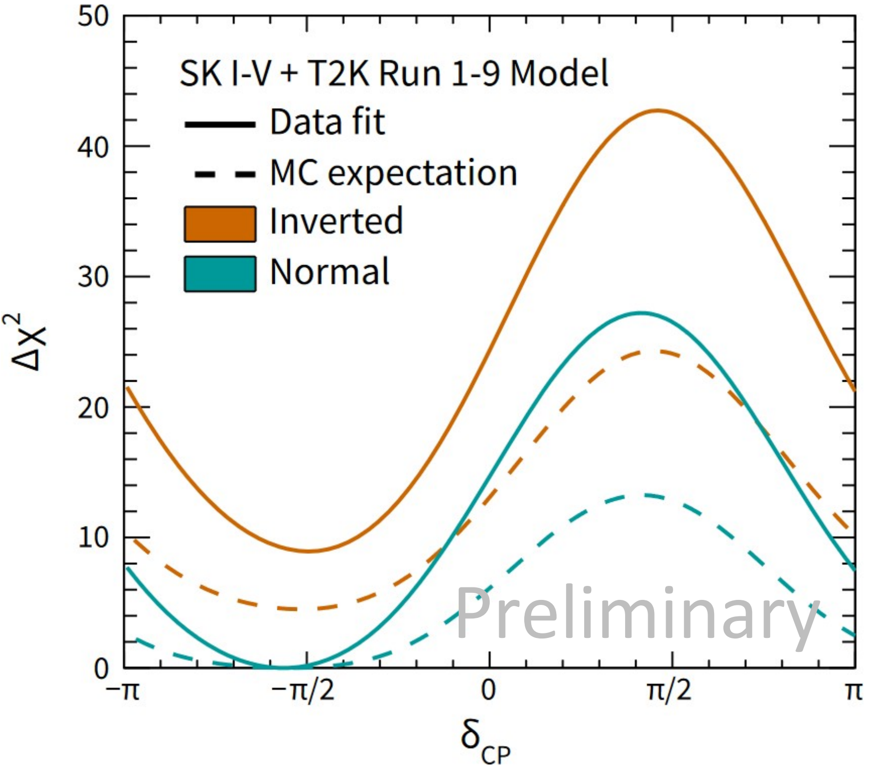


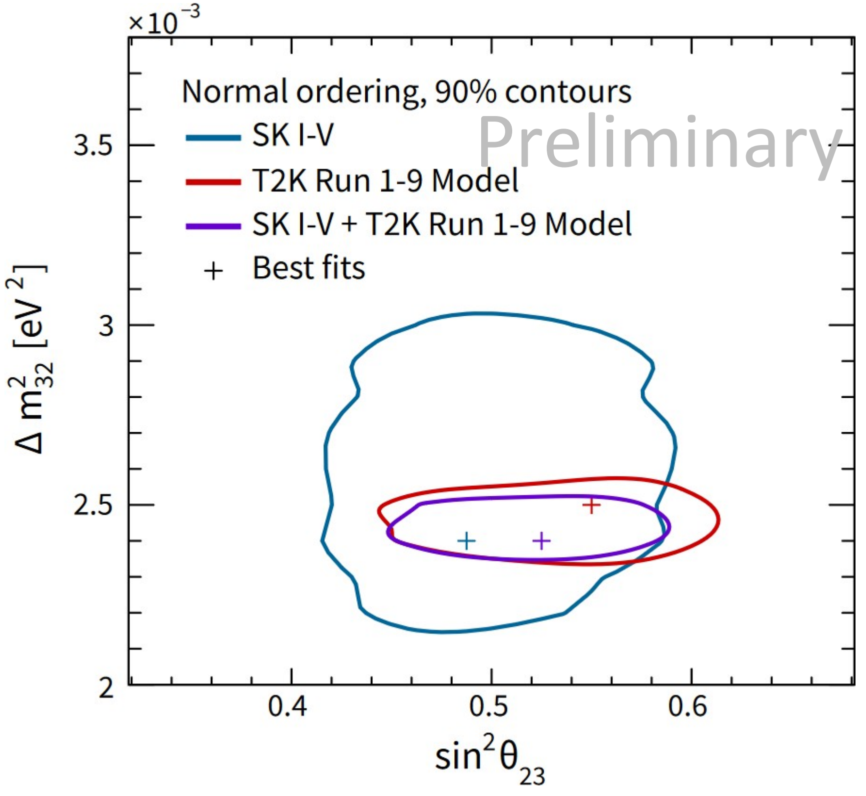
- To combine, reweight SK MC to T2K published data



- SK = T2K far detector→ correlated cross-section
- Additional sensitivity gained from combined fit with correlated cross-section uncertainty

Oscillation Measurements (SK+T2K)





SK + external T2K constraints favor:

- maximal mixing
- NO ($\Delta\chi^2 = 8.9$)
- $\delta_{CP} \approx -\frac{\pi}{2}$

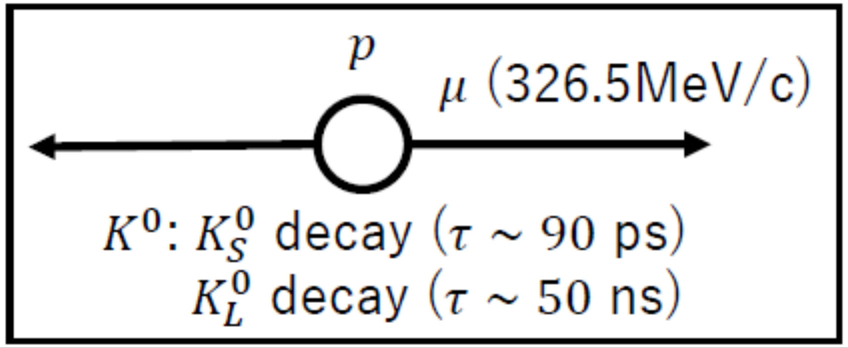
*Results from both experiments exceed sensitivity.

1020 bins	χ^2	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23}
SK+T2K NO	1086.33	4.54	0.53	2.4×10^{-3} eV^2
SK+T2K IO	1095.25	4.71	0.53	2.4×10^{-3} eV^2

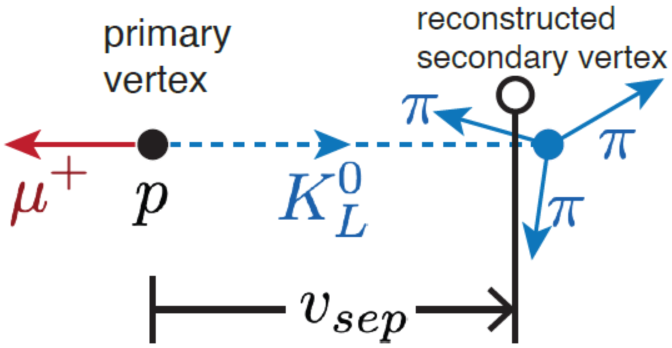
Preliminary

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

Proton decay search: p→ μ^+K^0



- Favored by SUSY GUTs.
- K^0 is a mixing state of K^0_S and K^0_L
- Results of SK-I~III (178 kt*yrs) have been published, (Phys.Rev.D85 (2012)112001)
- SK-IV data (200 kt*yrs) is newly analyzed with neutron tagging.
- Target K^0 decays
  - K^0_S → $\pi^0\pi^0$, $\pi^+\pi^-$ (~70 ps)
    - ✓ All final particles can be detected in SK
      → Reconstruct K^0, proton mass & momentum
  - K^0_L → $\pi^0\pi^0$, $\pi^+\pi^-\pi^0$, $\pi^\pm l^\mp \nu$ (~50 ns)
    - ✓ (Challenging!) Have multiple vertices.
      → Newly developed reconstruction tool for multi-vertex events.

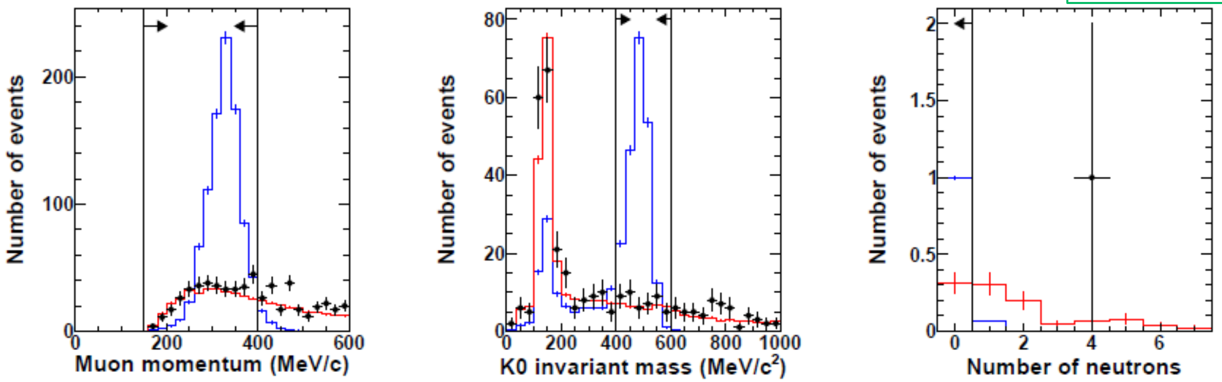


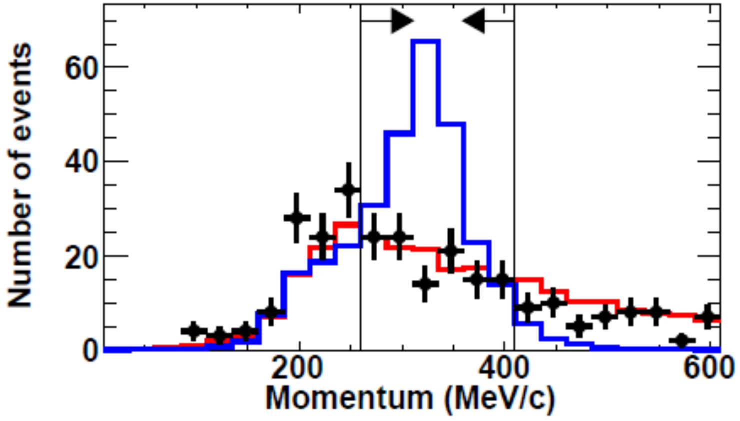
Proton decay search: p→ μ^+K^0

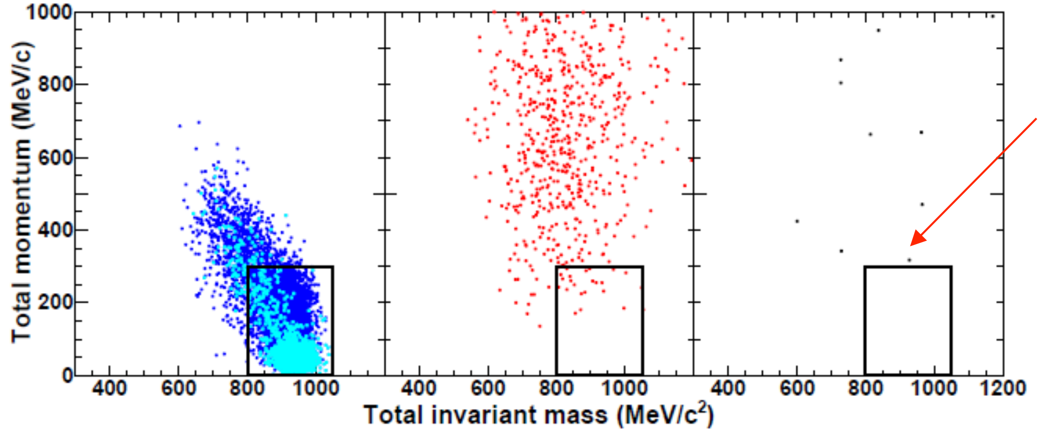
K^0_S ($\pi^0\pi^0$)

Blue: Signal MC
Red; Atm.ν MC
Black: Data

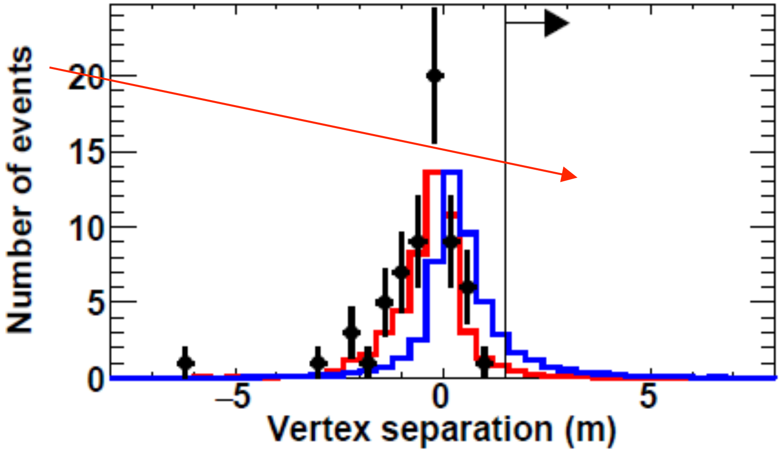
K^0_L







No candidates found.



Proton decay search: p→ μ^+K^0

Results (SK-IV)

Search mode	Efficiency (%)	Background (events)	Candidates (events)	Lower limit (10^{33} years)
$K_S^0 \to 2\pi^0$	9.7 ± 1.0	0.31 ± 0.14	0	2.7
$K_S^0 \to \pi^+\pi^-$	4.98 ± 0.54	0.8 ± 0.2	0	1.4
$K_L^0 \to \pi^\pm l^\mp \nu$	0.91 ± 0.17	1.0 ± 0.3	0	0.2
$K_L^0 \to 3\pi^0$	0.36 ± 0.06	0.12 ± 0.06	0	0.1
$K_L^0 \to \pi^+\pi^-\pi^0$	0.18 ± 0.04	0.16 ± 0.07	0	0.05

Proton lifetime (90 % CL, SK-I~IV combined): > 3.6 x 10^{33} years

(Previous paper: >1.6 x 10^{33} years)

Published soon !

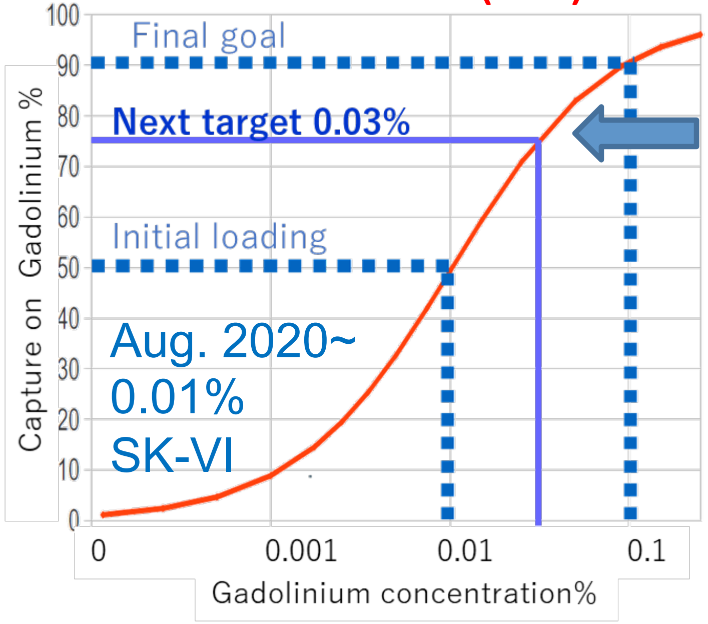
Evolution of Super-K: SK-Gd

$\bar{\nu}_e + p \rightarrow e^+ + n$

Gadolinium captures neutron and emit **~ 8 MeV γ**

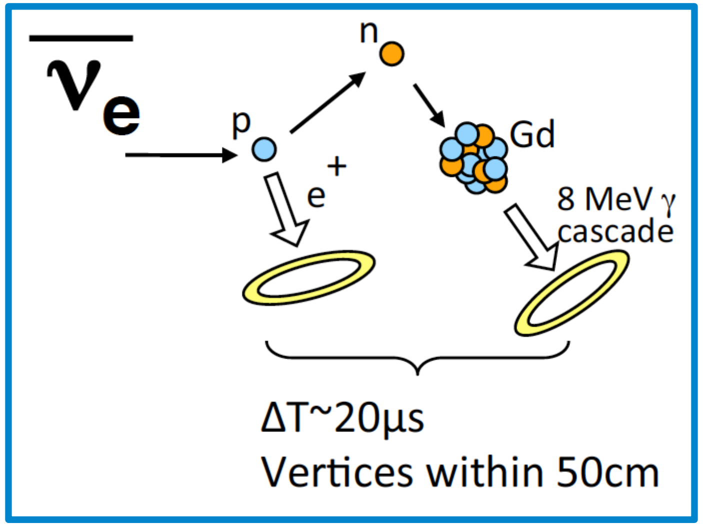
Detection efficiency of 8MeV γ ~ 100%

Add Gadolinium (Gd) to the SK water.



The latest news:
We finished dissolving on July 5th !

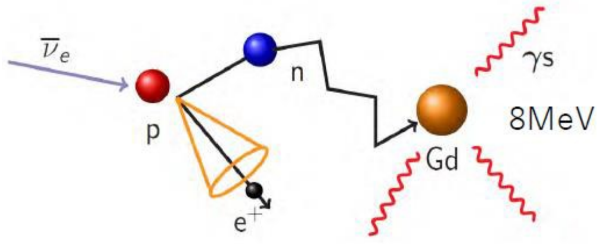
SK-VII started !



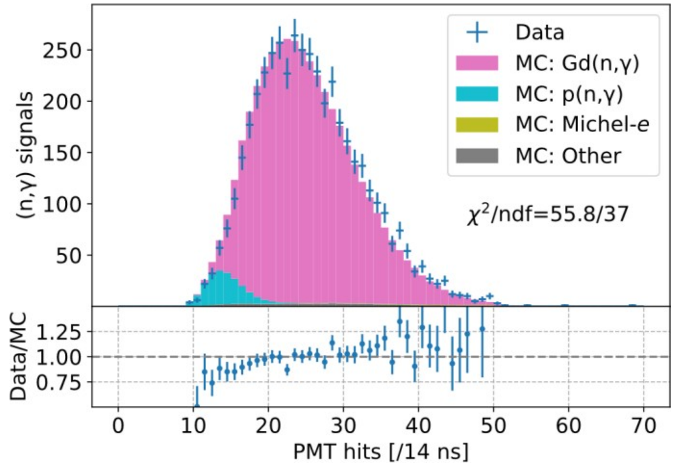
Neutrino / anti-neutrino discrimination

- Discovery of supernova(SN) diffuse ν search and pointing accuracy improvement for SN burst
- Improve Discrimination power of ν and ν in T2K and atmospheric neutrino analyses
- Nucleon decay background rejection

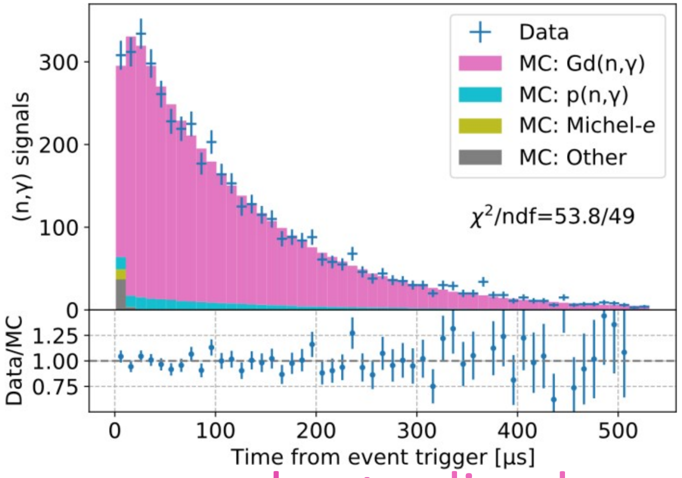
SK-VI Neutron Capture Signal on Gd



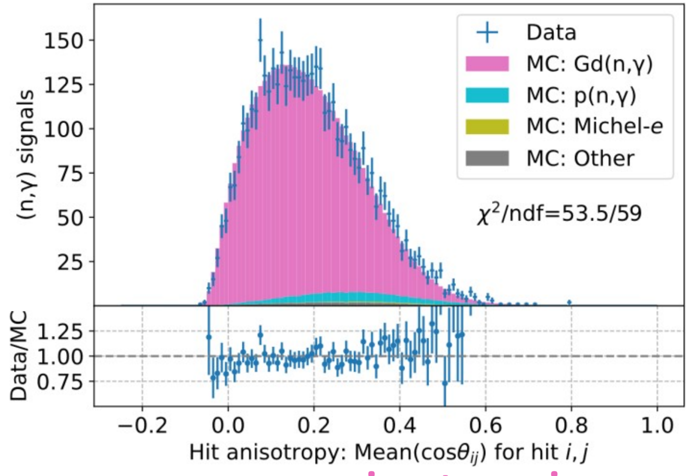
- Compared to H, neutron captures on Gd are:



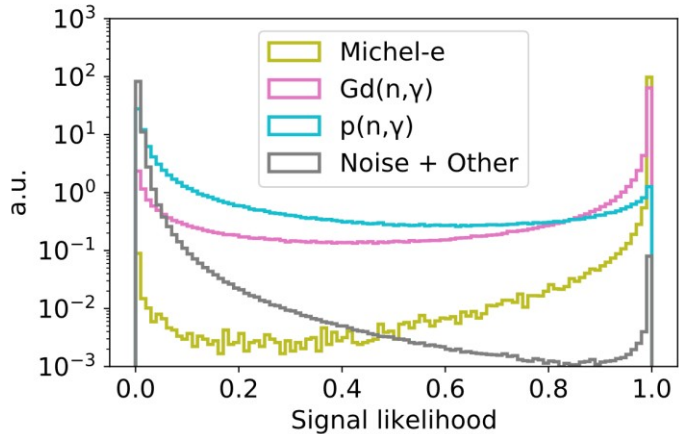
more energetic



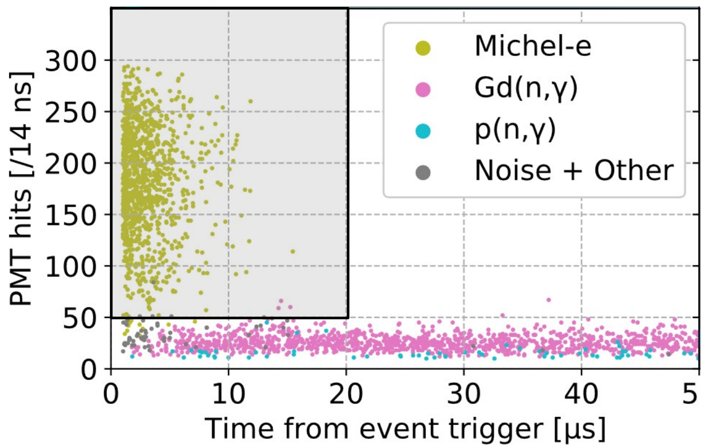
shorter lived



more isotropic

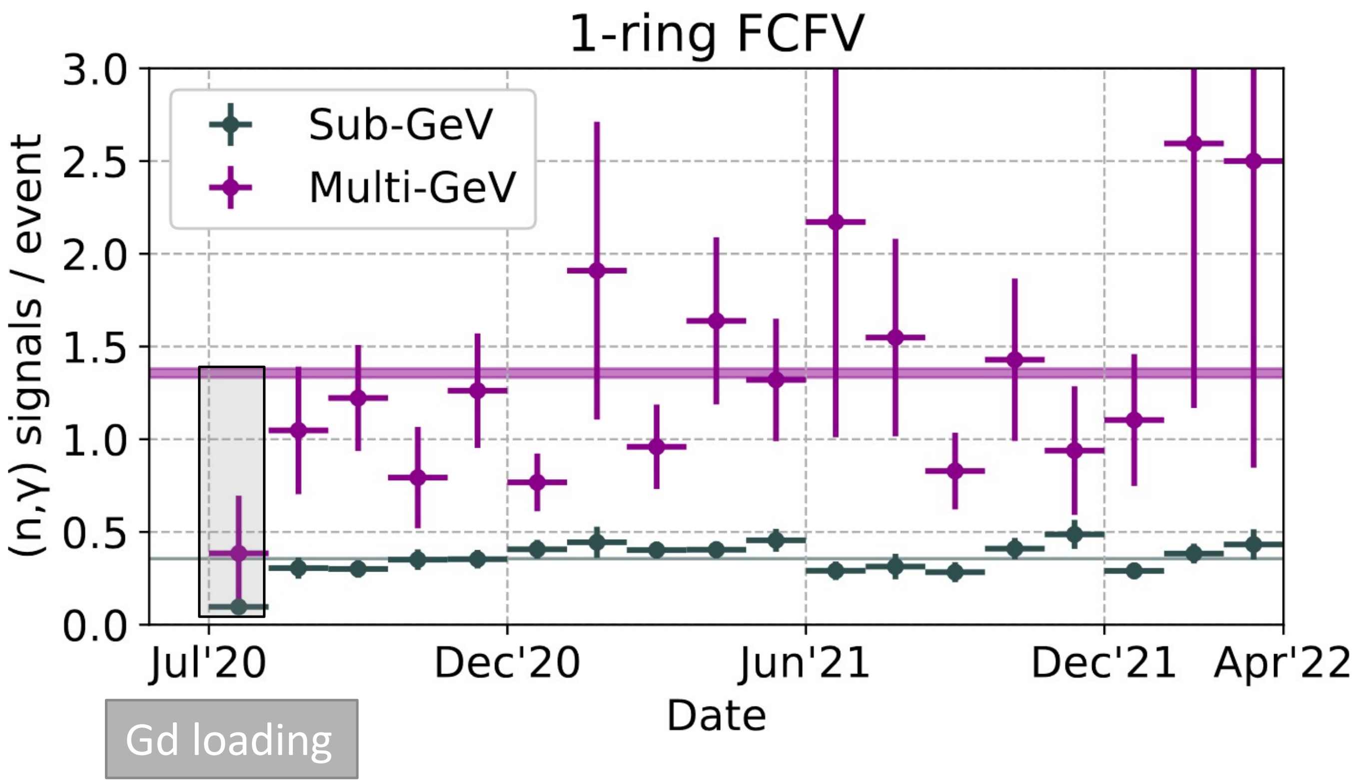


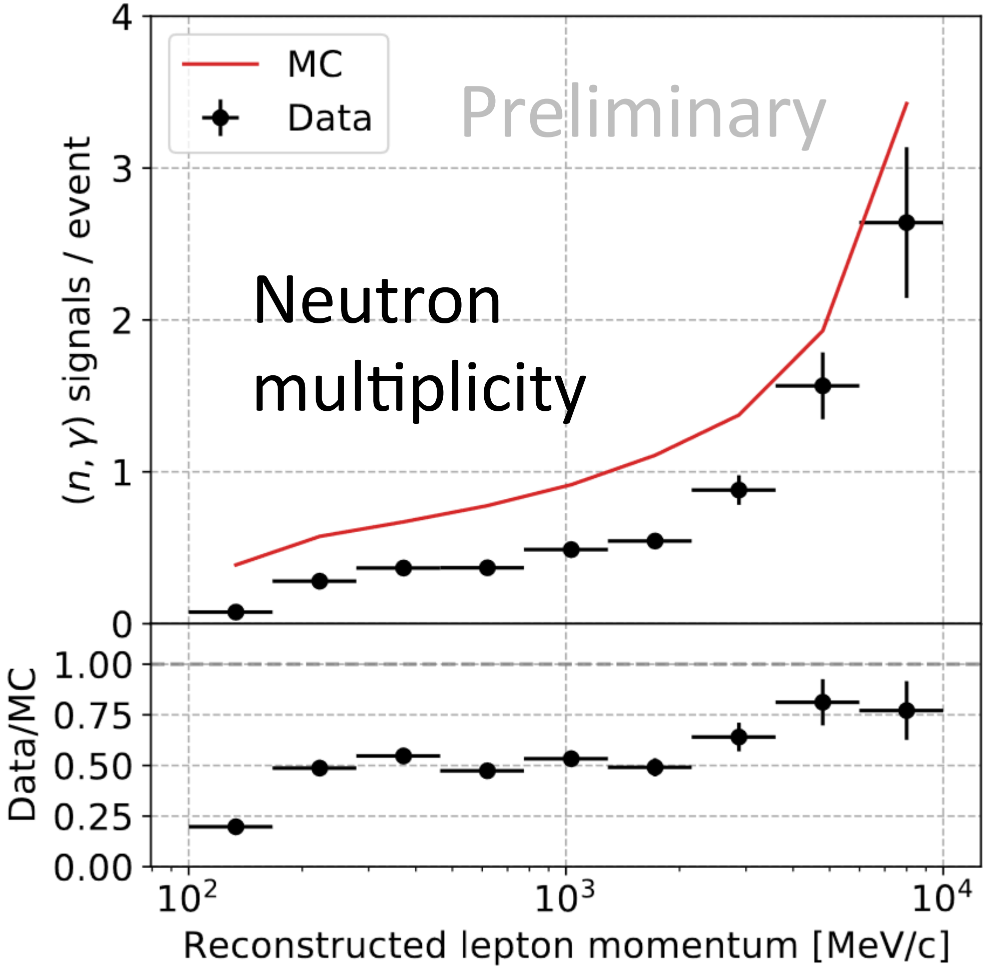
- Neural network to select neutron candidates
- Cuts to remove remaining Michel electrons



SK-VI Neutron Measurement

- Stable neutron rate since Gd loading.
- Higher neutron multiplicity at higher energy events, as expected.





- Measured neutron multiplicity is lower than present MC prediction.
- Neutron production needs model development and improvement.

Summary

- Atmospheric neutrino oscillation:
  - Analyze all pure water phase (SK-I ~ V).
  - Expand fiducial volume.
  - favoring NO, $\delta_{CP} \approx -\frac{\pi}{2}$, and maximal $\sin^2\theta_{23}$
- Proton decay search p→ μ^+K^0:
  - SK-IV data is newly analyzed (372 kton*yrs from SK-I ~ IV).
  - No signals observed beyond atmospheric ν BG.
  - Set proton lifetime limits as > 3.6×10^{33} years
- SK-Gd
  - SK-VI (Gd ~0.01 %) analysis is on going.
  - SK-VII (Gd ~0.03%) just started from this July !