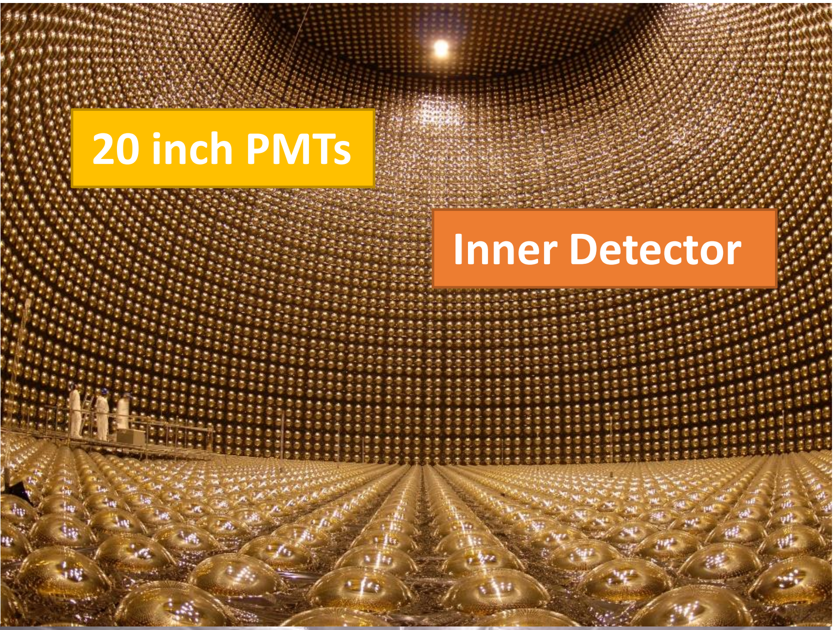
New Results with Atmospheric Neutrinos at Super-Kamiokande

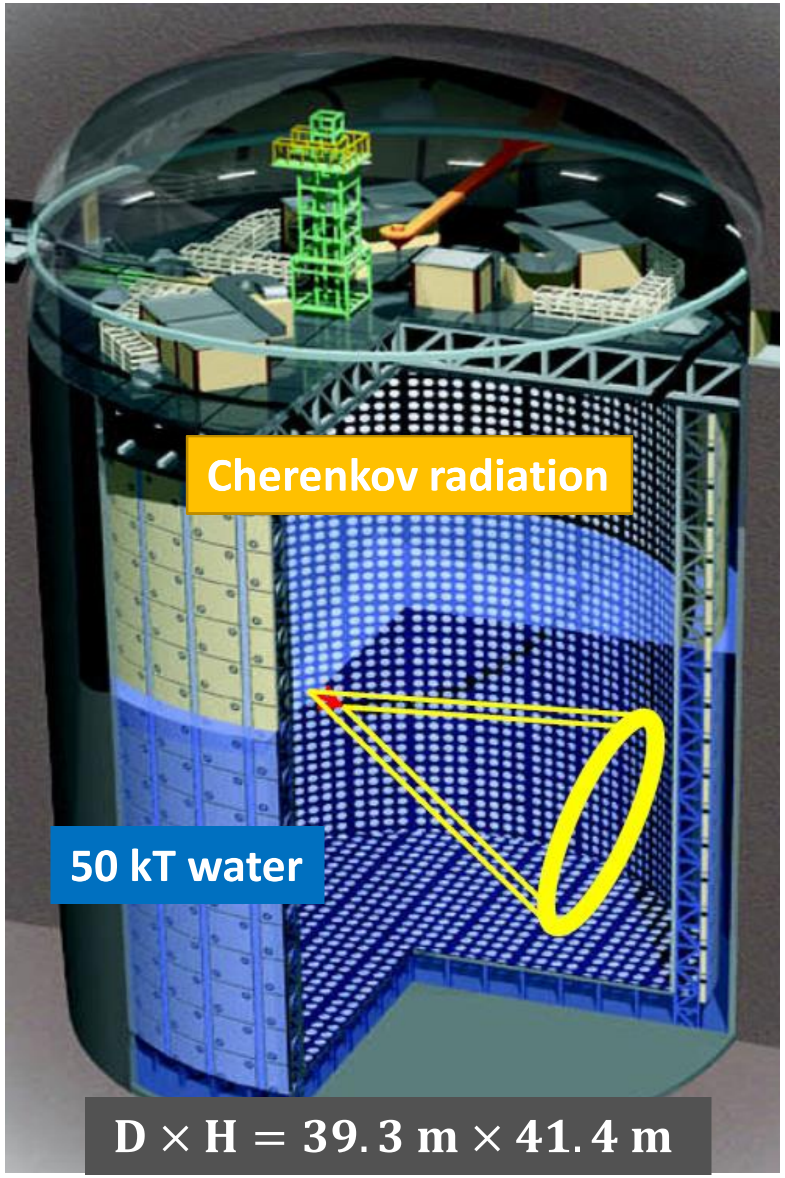
Linyan Wan, Boston University

on behalf of the Super-Kamiokande collaboration

The 50th Anniversary
NEUTRINO 2022
Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

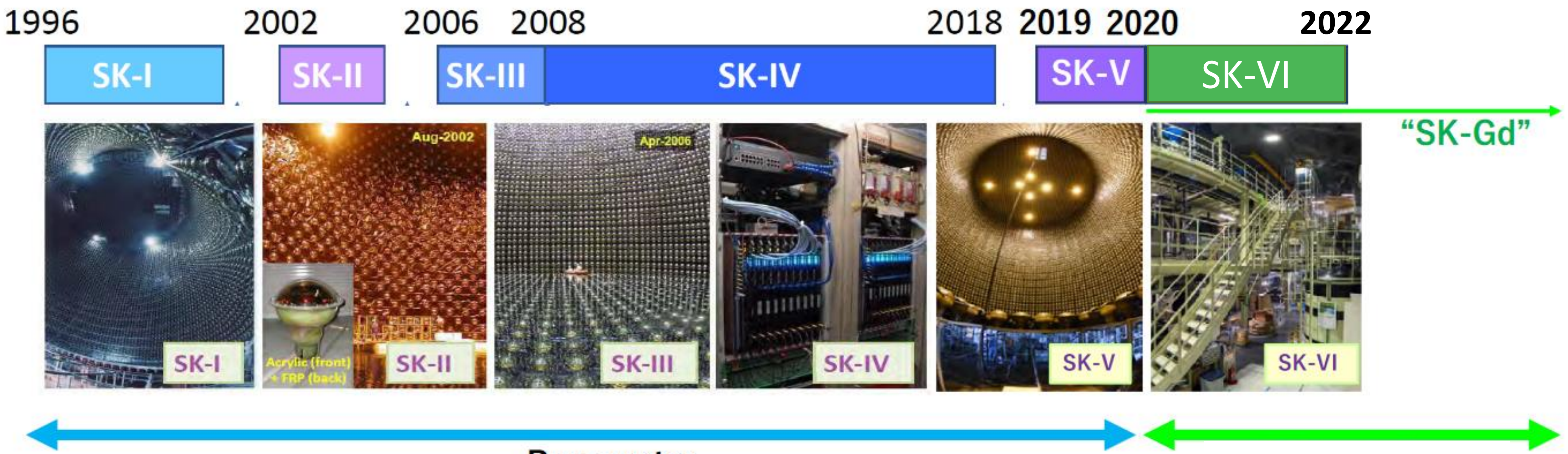
The Super-Kamiokande Detector





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…

The Super-Kamiokande Collaboration

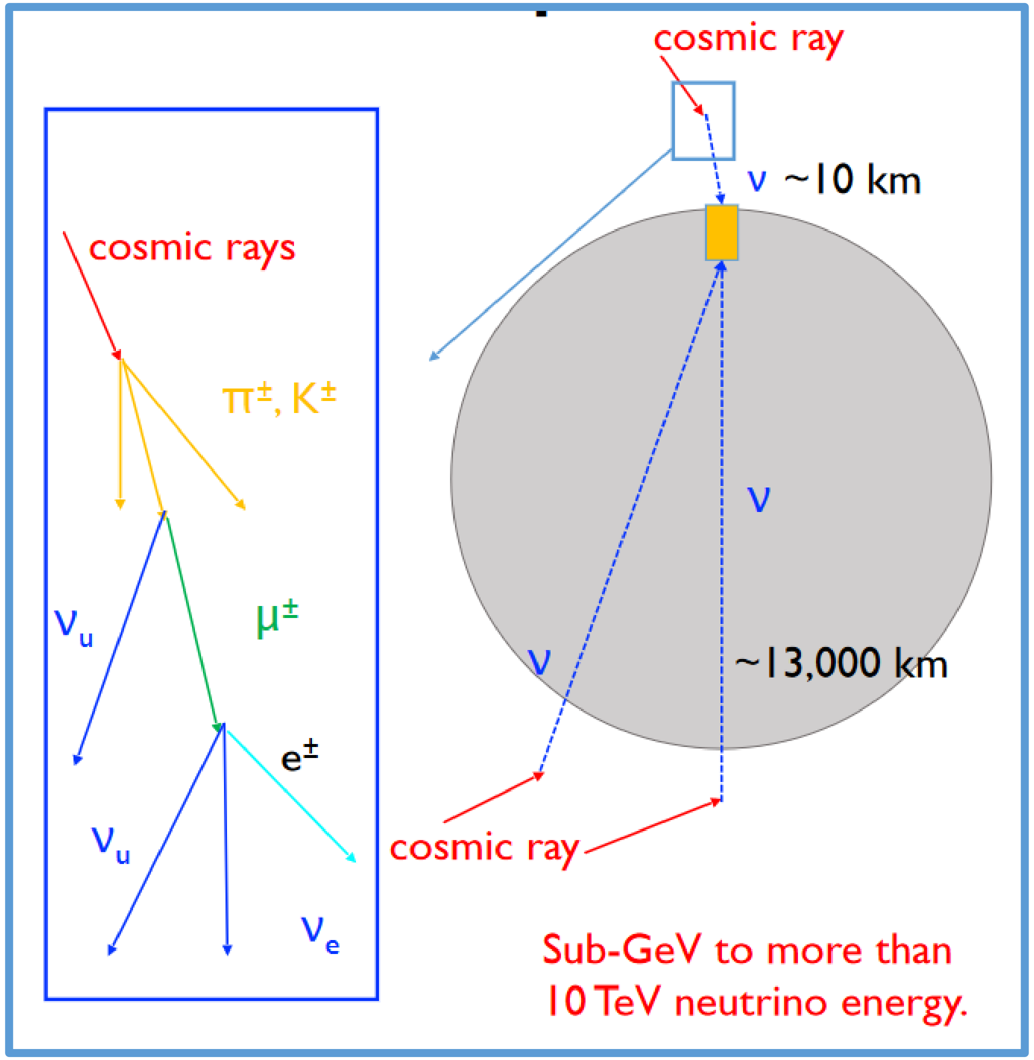
~230 collaborators
from 51 institutes
in 11 countries

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

New Results from SK

- **Atmospheric neutrino oscillation measurements**
  - SK-I through SK-V + Expanded FV
  - Three Flavor Oscillation with T2K Constraints
  - Tau appearance study [Poster by Maitrayee Mandal @ III-a, 2F. Majorana, MT09-216]
- **Boosted dark matter search**
- Proton decay [Poster by Ryo Matsumoto @ IV-a, 8F. Majorana, MT17-156]
- Cross-section measurement [Poster by Baran Bodur @ IV-b, 7F. Majorana, MT05-371]
- **Neutron capture on Gd in SK-VI**

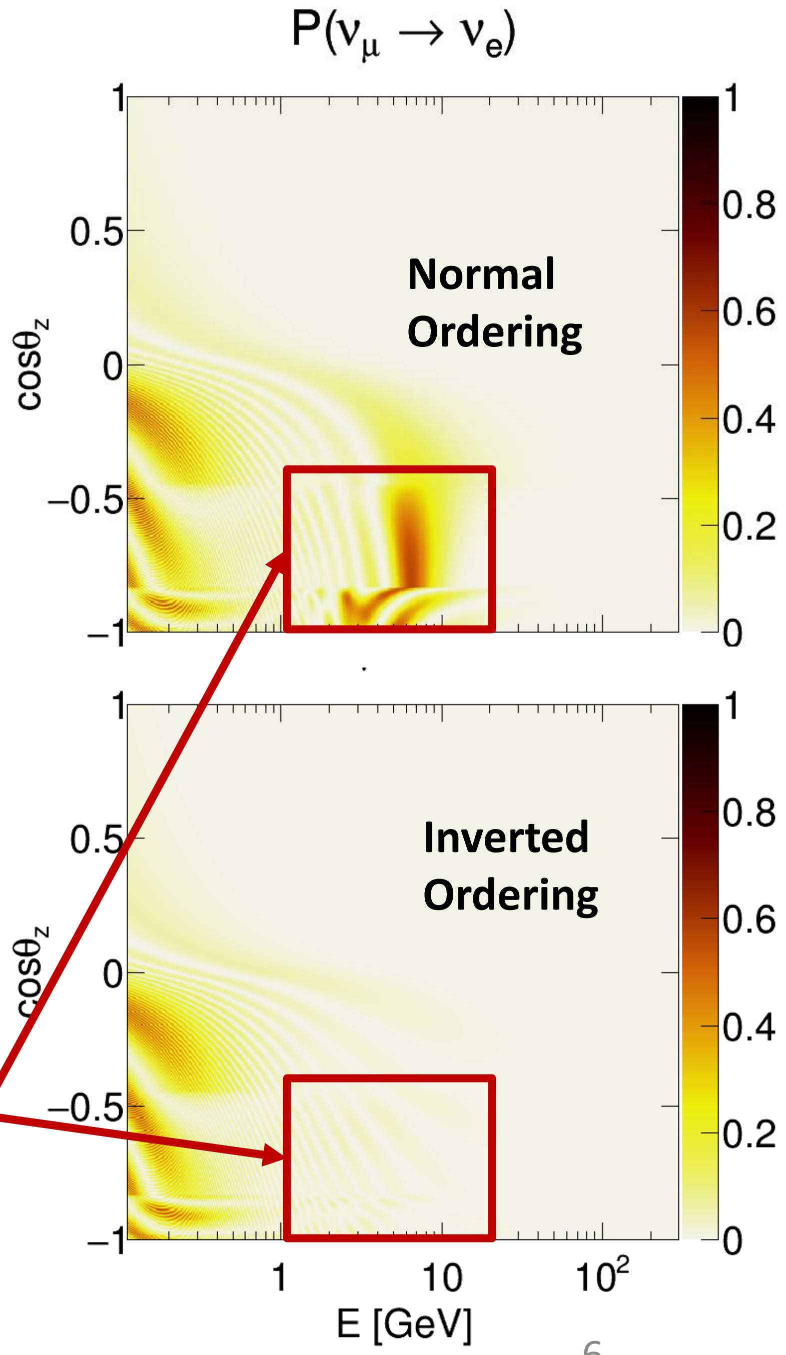
Atmospheric Neutrino Oscillation



Key measurements:

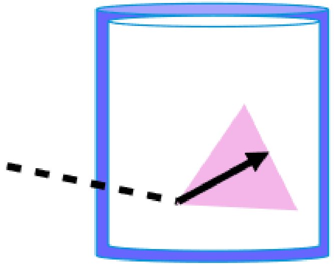
- ν_μ disappearance
  - Δm^2_{32}
  - $\sin^2\theta_{23}$
- ν_e appearance
  - CP violation δ
  - Mass-ordering

Matter Effect

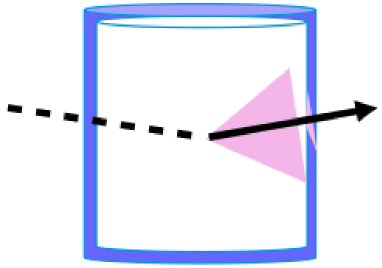


Atmospheric Neutrino Analysis at SK

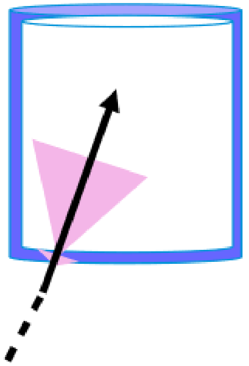
Fully Contained (FC)



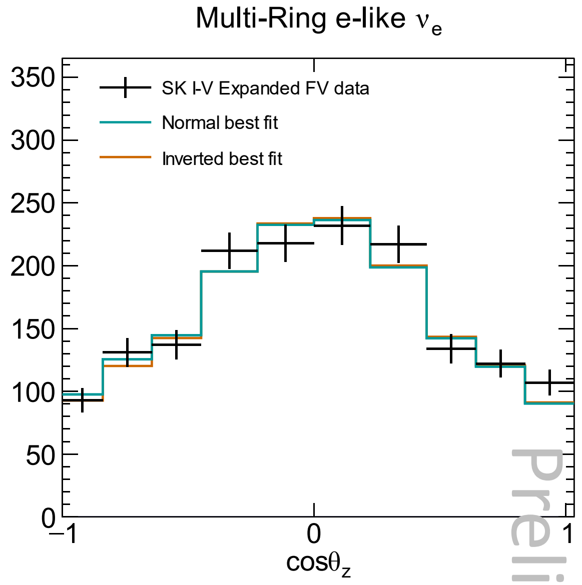
Partially Contained (PC)

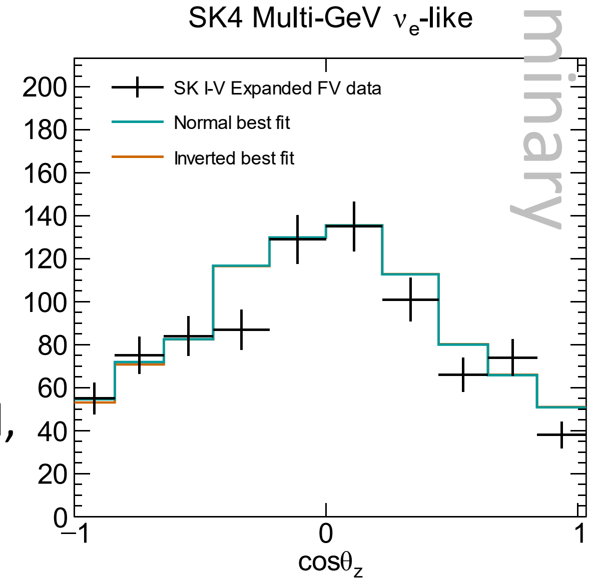


Upward-going Muons (Up-μ)



Reconstructed, Classified, and Binned





Total exposure: 484.2 kiloton-years

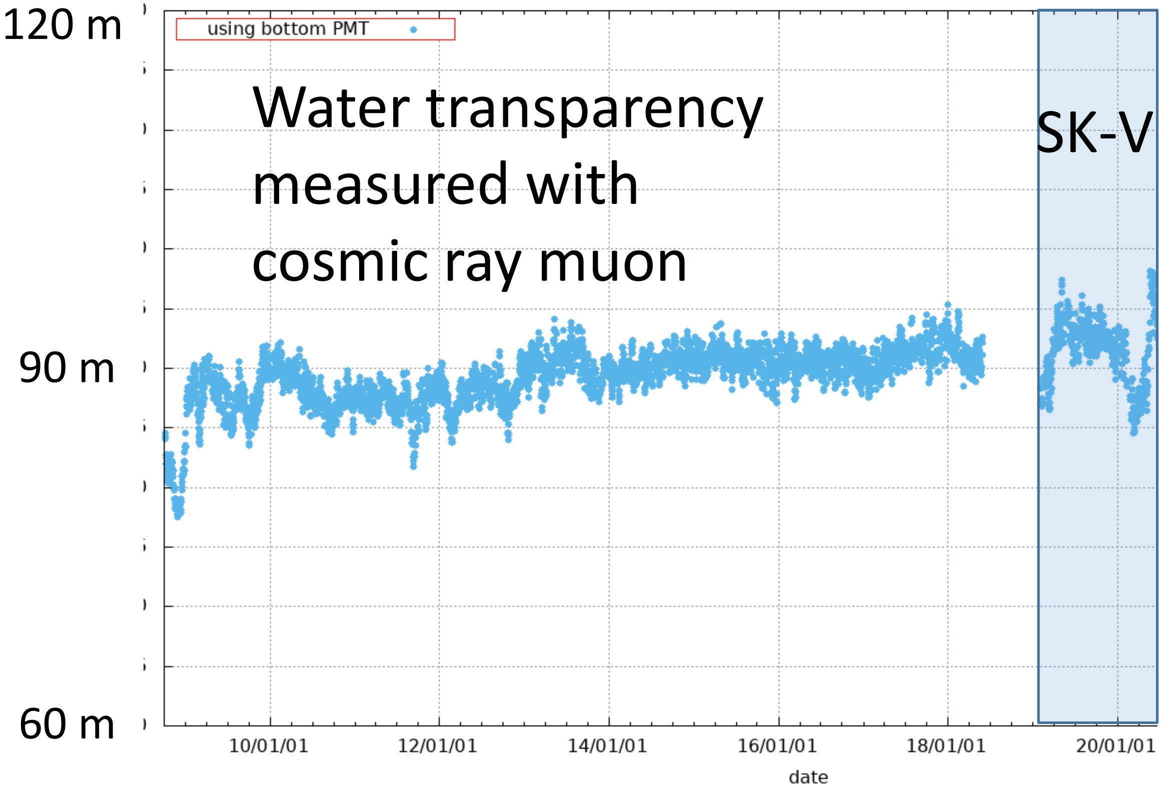
30% more data than 2020 analysis
Using all of pure water data at SK

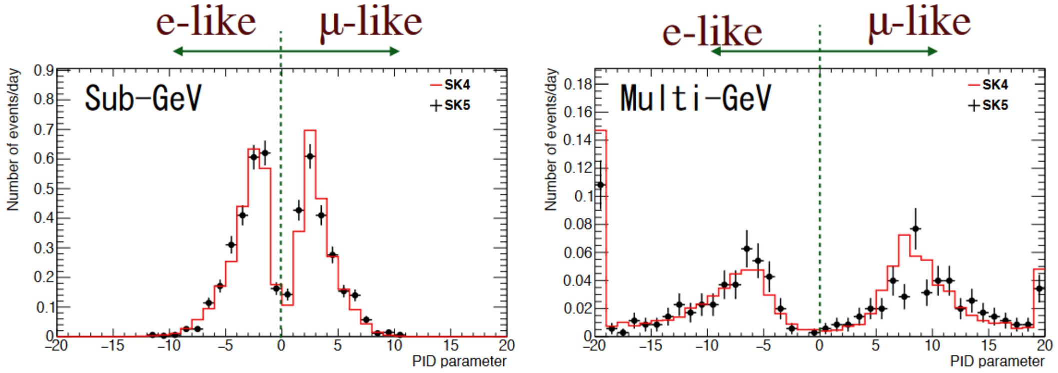
New in this analysis:

- 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

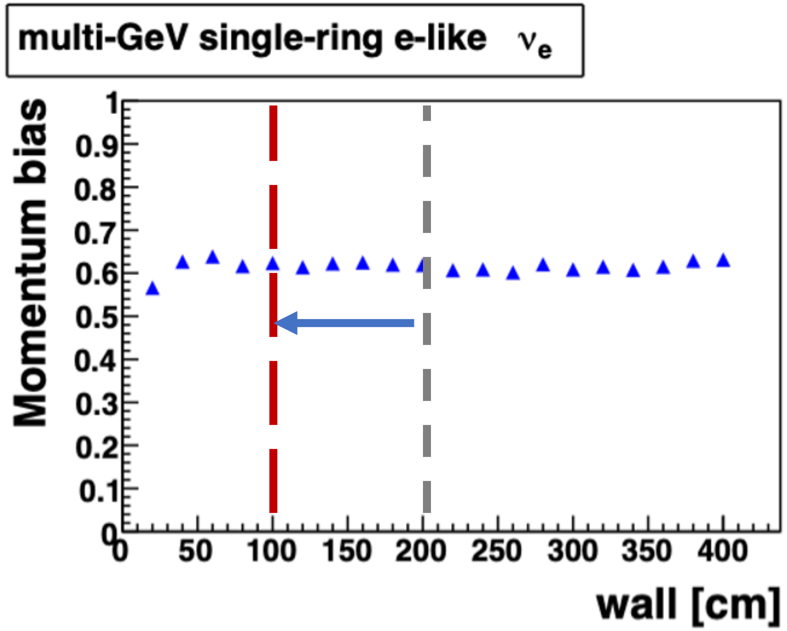


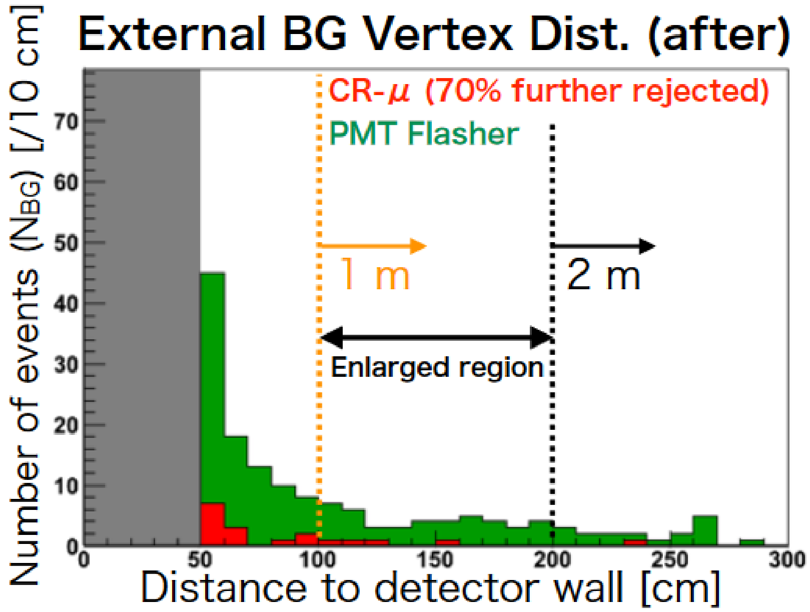


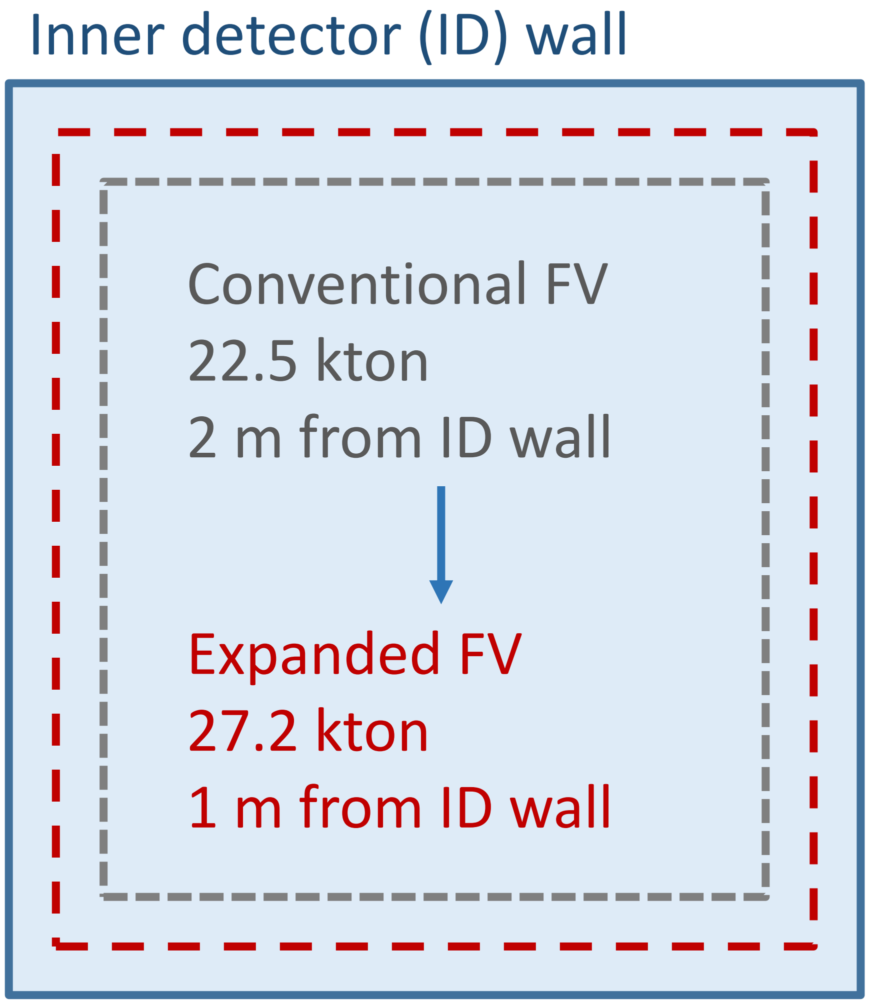
- The last SK phase with pure water
- Upgraded water system, replaced PMT, cleaned detector… Getting ready for Gd loading!
- Consistent data quality with SK4

Expanded Fiducial Volume

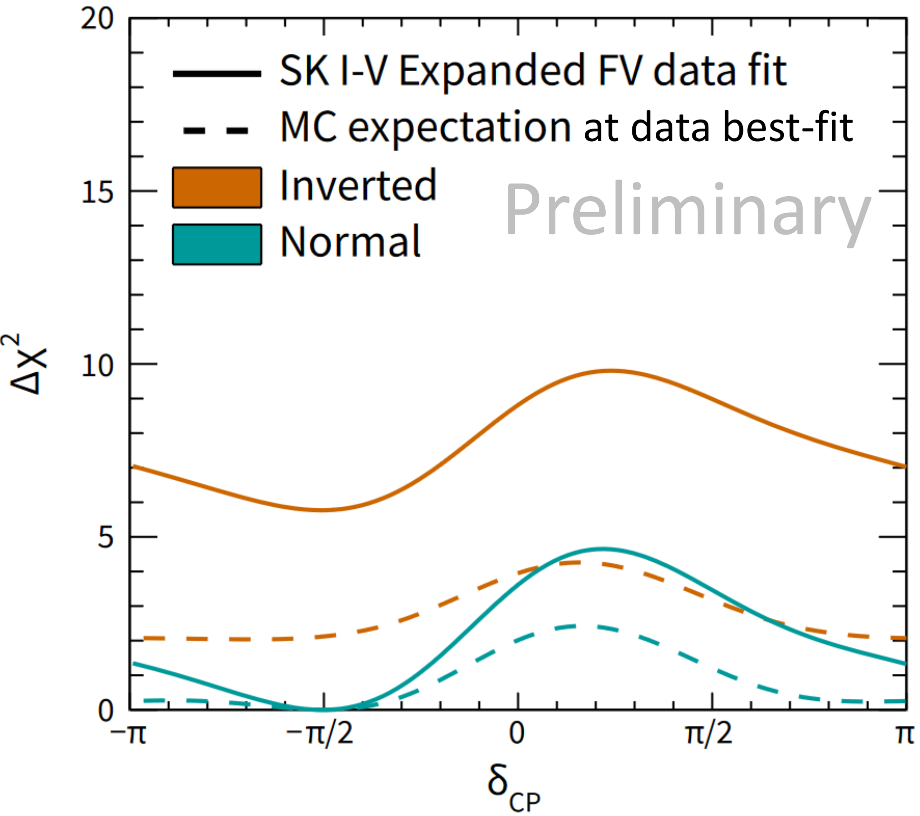
- Expanded fiducial volume
  - 22.5 kton → **27.2 kton**, 20% increase
- No significant increase of external background
- No significant bias in reconstruction
- Systematics re-estimated for expanded FV

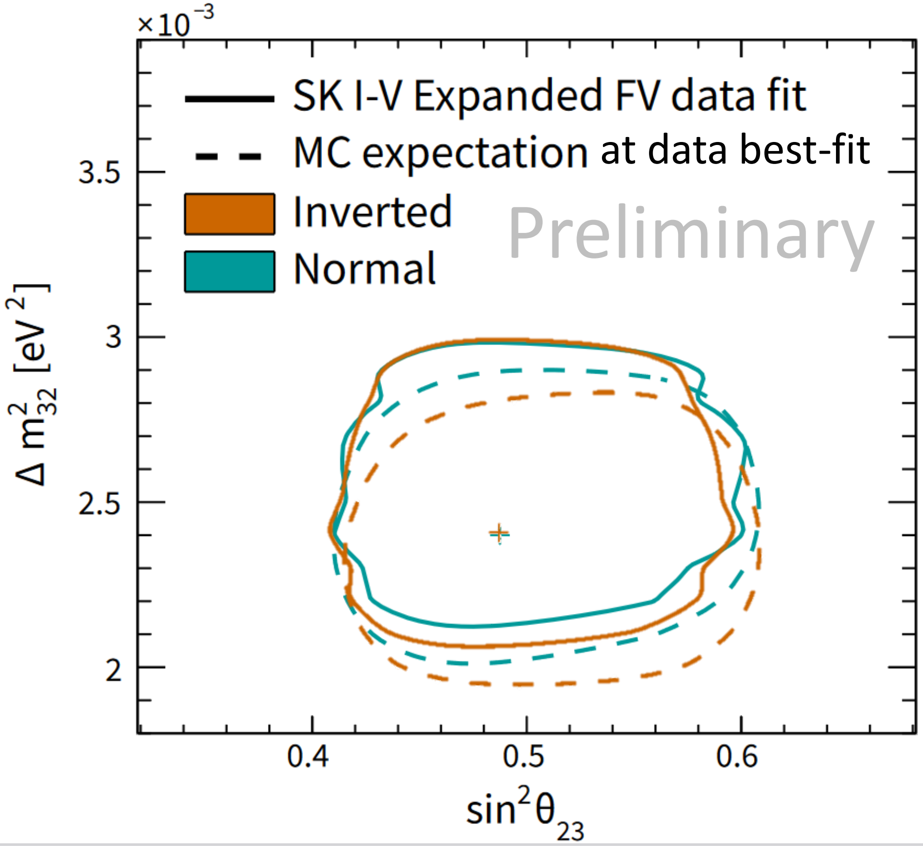






Oscillation Measurements (SK only)





SK atmospheric neutrino data favors:

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

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

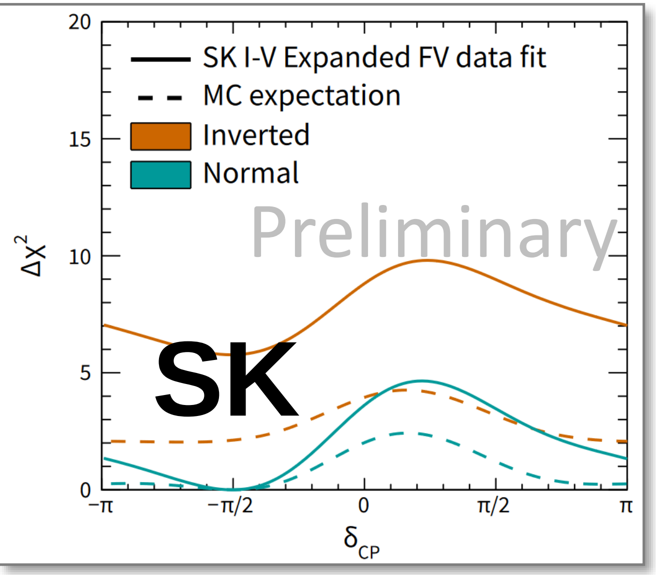
Preliminary

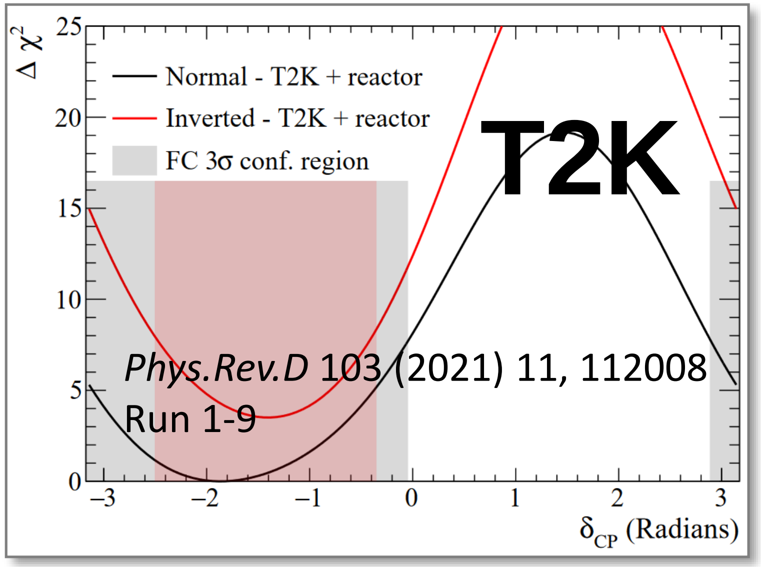
*Results on MO and δ_{CP} exceed sensitivity.

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

Combining SK and External T2K Constraints

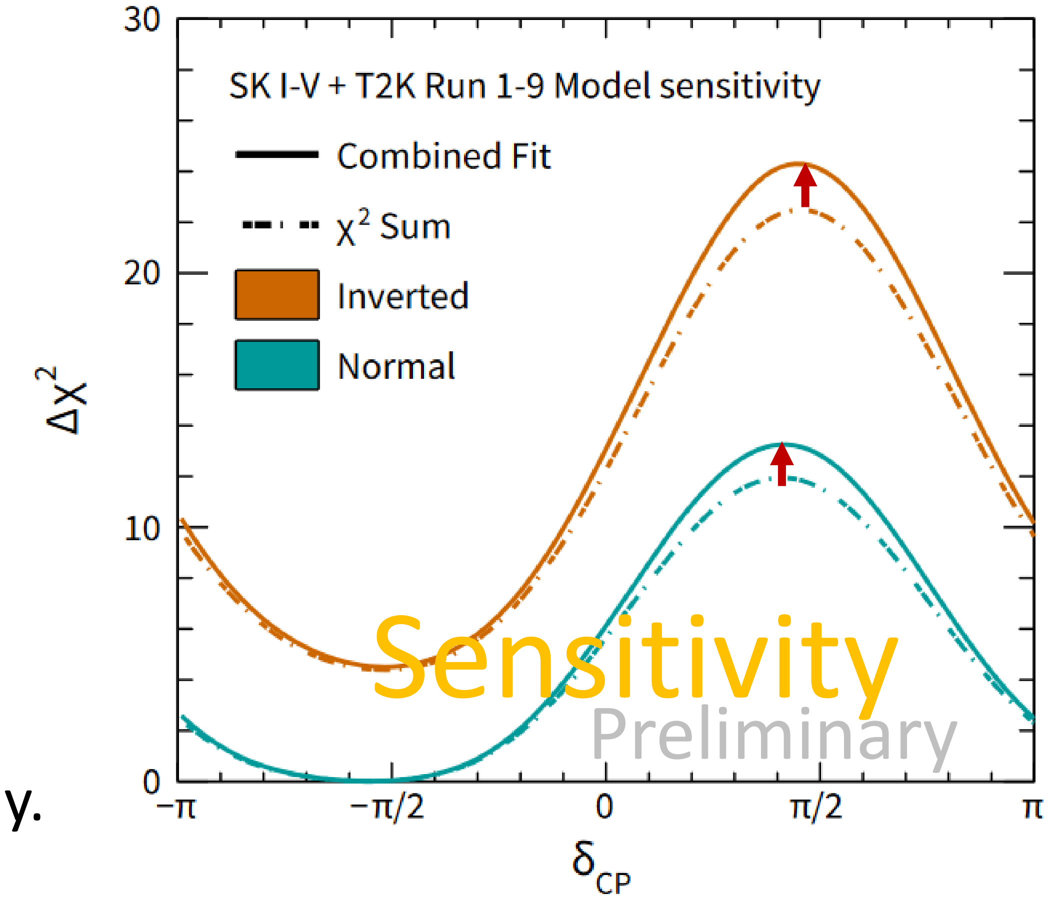
- SK sensitive on mass ordering, T2K sensitive on δ_{CP}





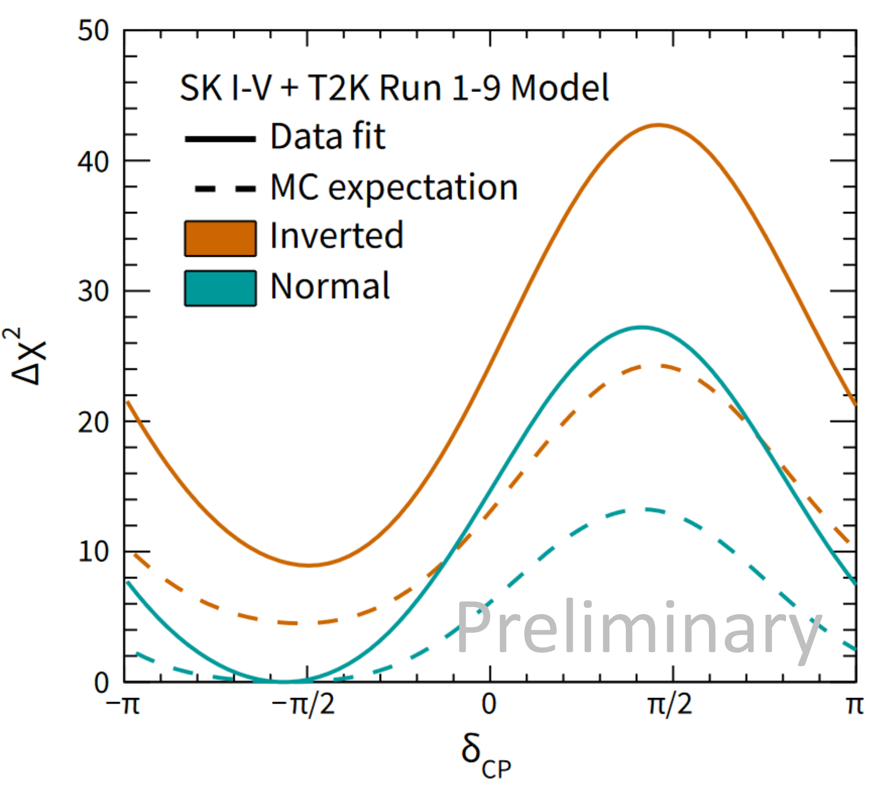
This is an SK analysis, and we have no access to T2K data.
The combination is performed by modelling T2K externally.

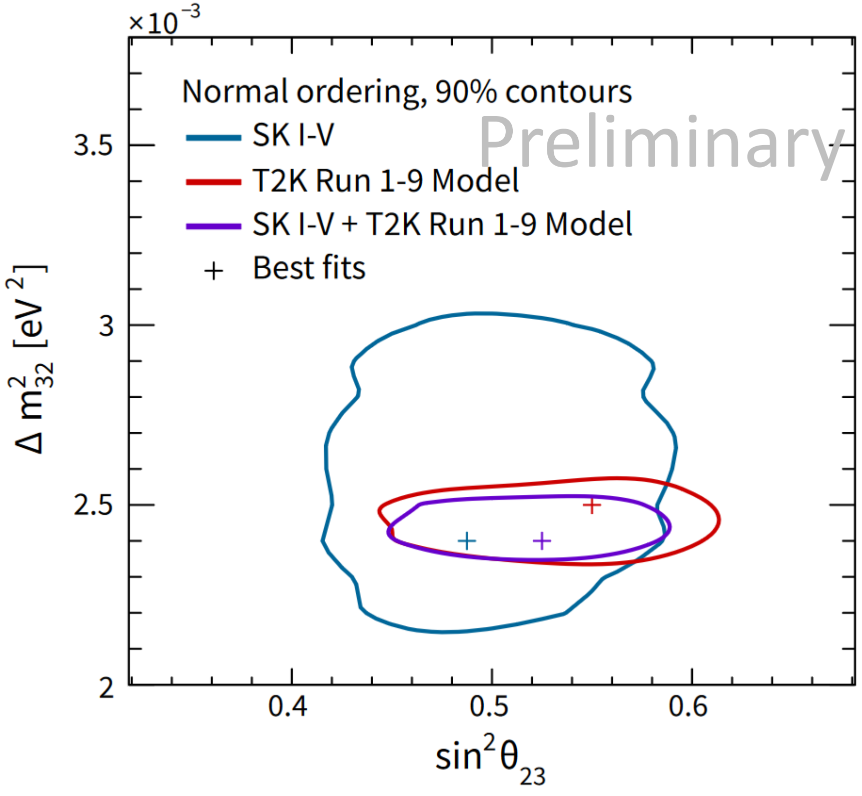
- Reweight SK MC to T2K flux
- Construct cross-sections models
  - SK = T2K far detector→ correlated cross-section
- Simultaneously fit SK data and T2K published data



Additional sensitivity gained from combined fit with correlated cross-section uncertainty

Oscillation Measurements (SK+T2K)





SK + external T2K constraints favor:

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

*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

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

More on SK-T2K Joint Analyses

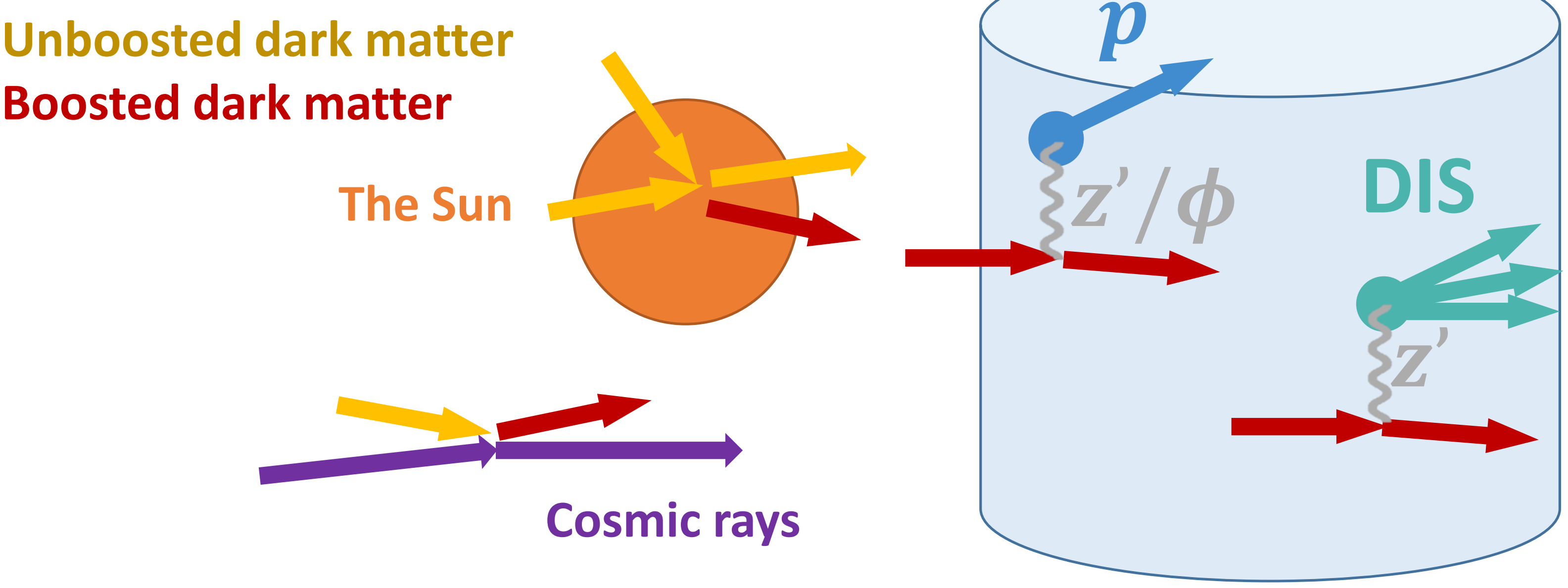
SK-T2K joint oscillation analysis group

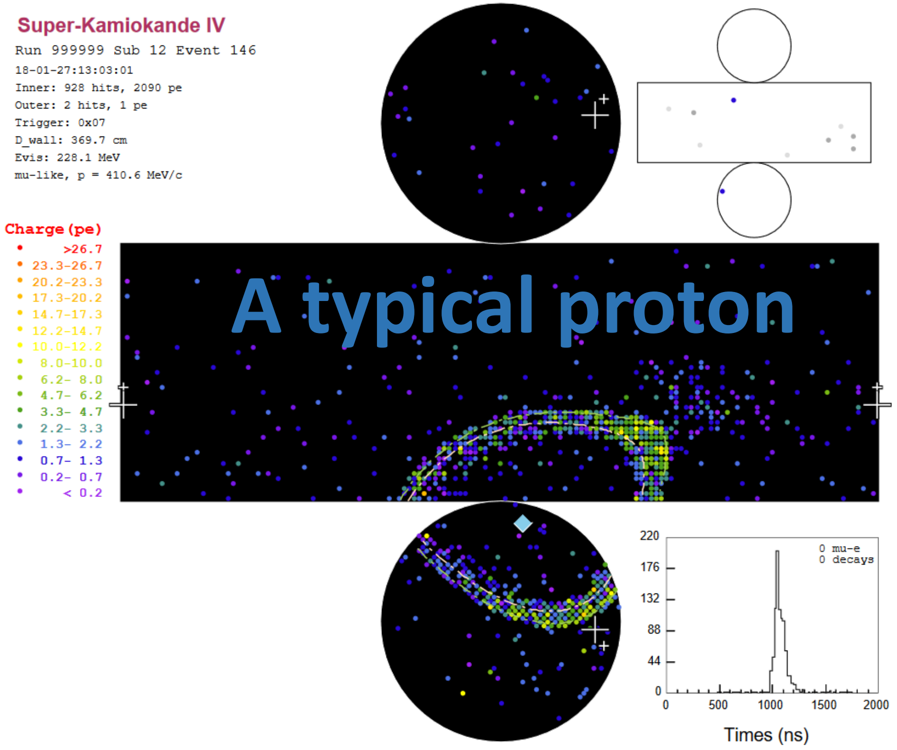
This result (SK + external T2K constraints)		Sensitivity only
Thomas Wester @ II-b, 7F. Dirac		Daniel Barrow @ II-a, 8F. Dirac Lukas Berns @ II-b, 8F. Dirac Junjie Xia @ II-b, 7F. Dirac
SK + published T2K binned data	Data sources	T2K + SK event data
SK-I to SK-V (1996-2020) 484.2 kiloton-year	Atmospheric data	SK-IV only (2008-2019) 253.9 kiloton-year
Run 1-9 (2009-2017) 1.5×10^{21} POT for ν mode 1.6×10^{21} POT for $\bar{\nu}$ mode	Beam data	Run 1-10 (2009-2020) 2.0×10^{21} POT for ν mode 1.6×10^{21} POT for $\bar{\nu}$ mode
Yes	Neutron samples	Not yet
Cross-section + energy scale	Correlated systematics	Cross-section + energy scale (with full detector syst. in progress)
SK + modelling T2K	Analysis frame	Full SK + T2K analysis

New Results from SK

- **Atmospheric neutrino oscillation measurements**
- **Boosted dark matter search**
- **Neutron capture on Gd in SK-VI**

Boosted Dark Matter





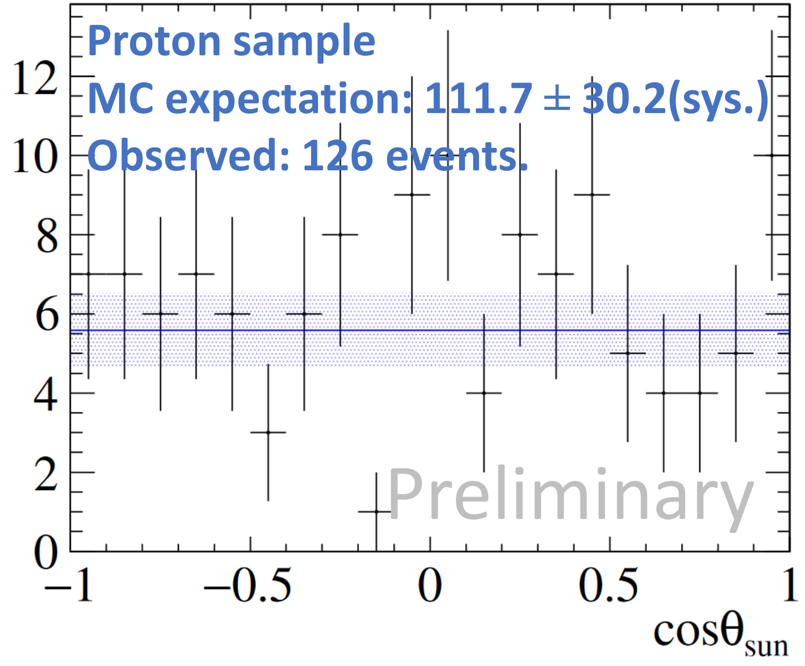
- **Cold heavy dark matter** can be boosted by **galactic cosmic rays** or in dense astrophysics objects such as **the Sun** by 2-component processes.
- **Boosted dark matter** can produce observable signals at SK.
- Signals: recoil electrons [1], **recoil protons**, **deep inelastic events (DIS)**.
- Backgrounds: atmospheric neutrinos.

[1] Phys. Rev. Lett. 120, 221301 (2018)

Proton Sample and DIS Sample

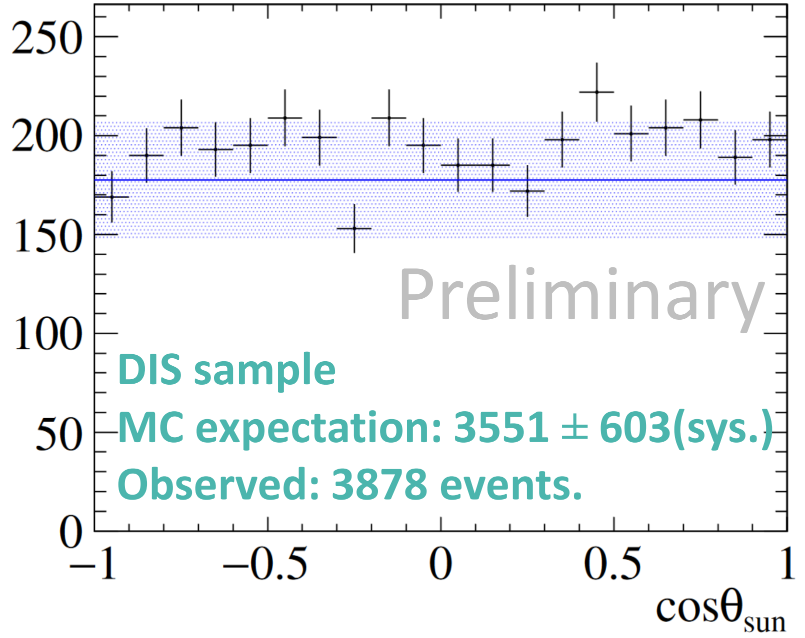
Proton sample:

- **Pattern fitting** based reconstruction.
- A **multi-variate analysis (MVA)** to select **protons** over **low energy muons** from atmospheric neutrinos.
- A neutral current sample (77% proton purity).
- Detection limited within **1.2 GeV/c** $< p_p <$ **2.3 GeV/c**.



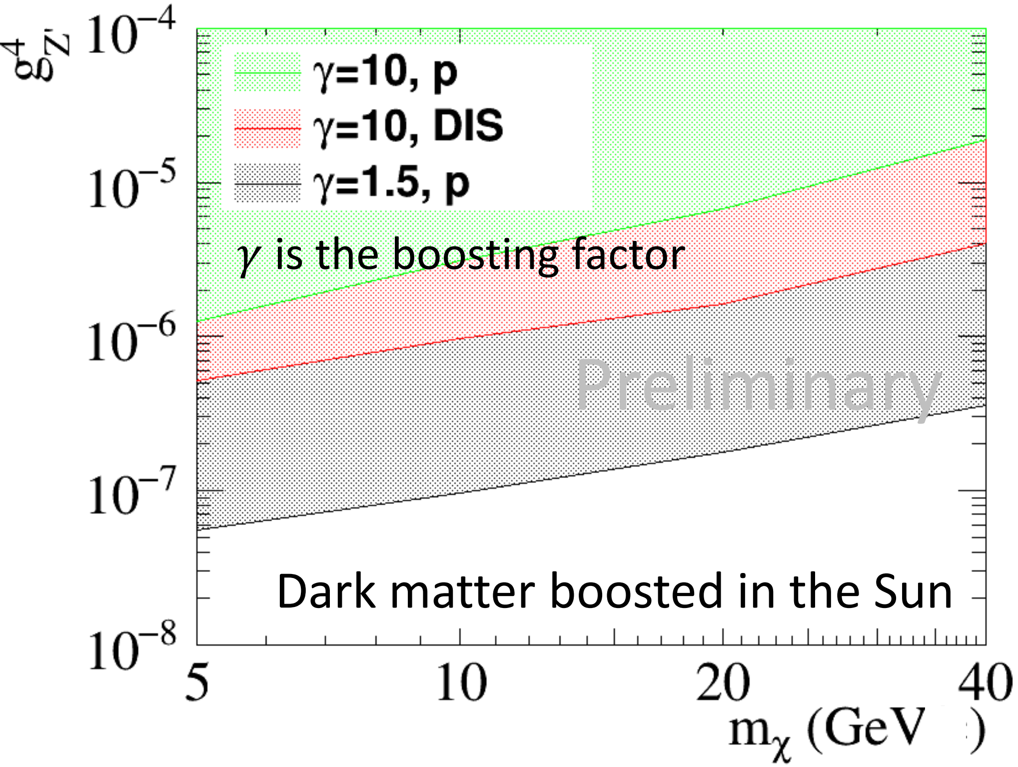
Deep inelastic scattering (DIS) sample:

- $E_{vis} > 1.33$ **GeV** with **more than 1 ring.**
- PID cuts to remove $\nu_\mu/\overline{\nu}_\mu$ **CC backgrounds** from atmospheric neutrinos
- Sensitive to higher dark matter mass / boosting parameters.

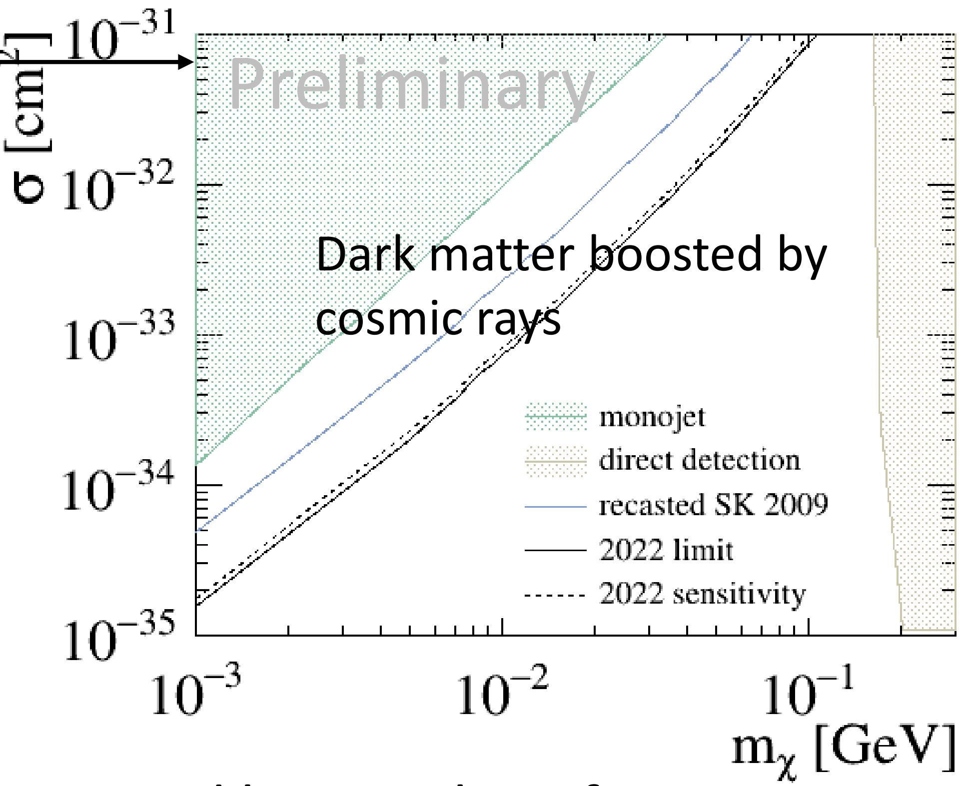


No excess observed in the direction of **the Sun** or **galactic center** in either samples.

Constraints on Boosted Dark Matter Models



PandaX-II
Phys. Rev. Lett. 128, 171801



Constrained by searching for proton and DIS sample excess in the direction of the Sun.

Scalar DM, mediator $m_{Z'} = 1$ GeV
Flux from Phys. Rev. D 103, 095012 (2021)
Cross-section by GENIE r3.00.06, Berger et al.

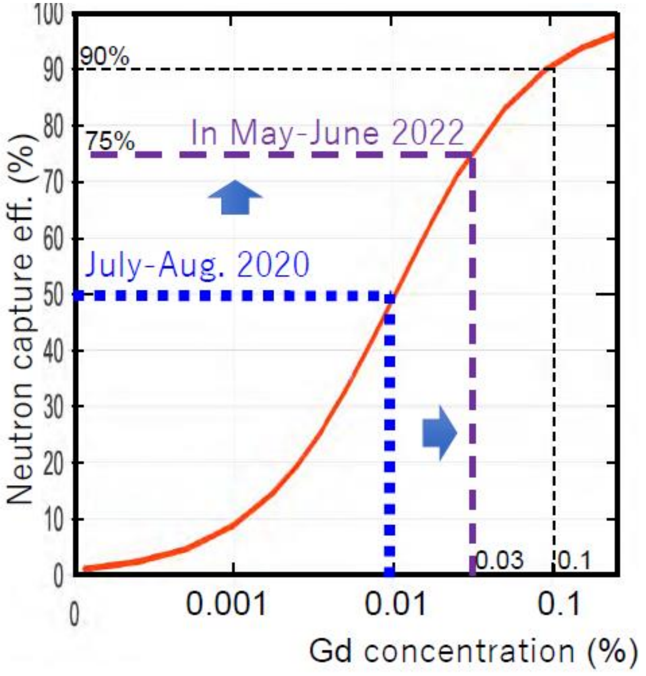
Constrained by searching for proton excess in the direction of the galactic center.

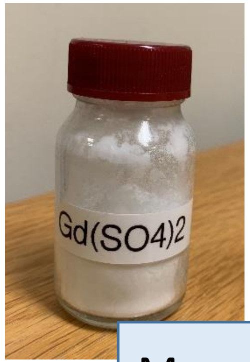
Fermionic DM, scalar mediator $m = 1$ GeV
Flux & cross-section from Ema et al., SciPost Phys. 10, 072 (2021)

New Results from SK

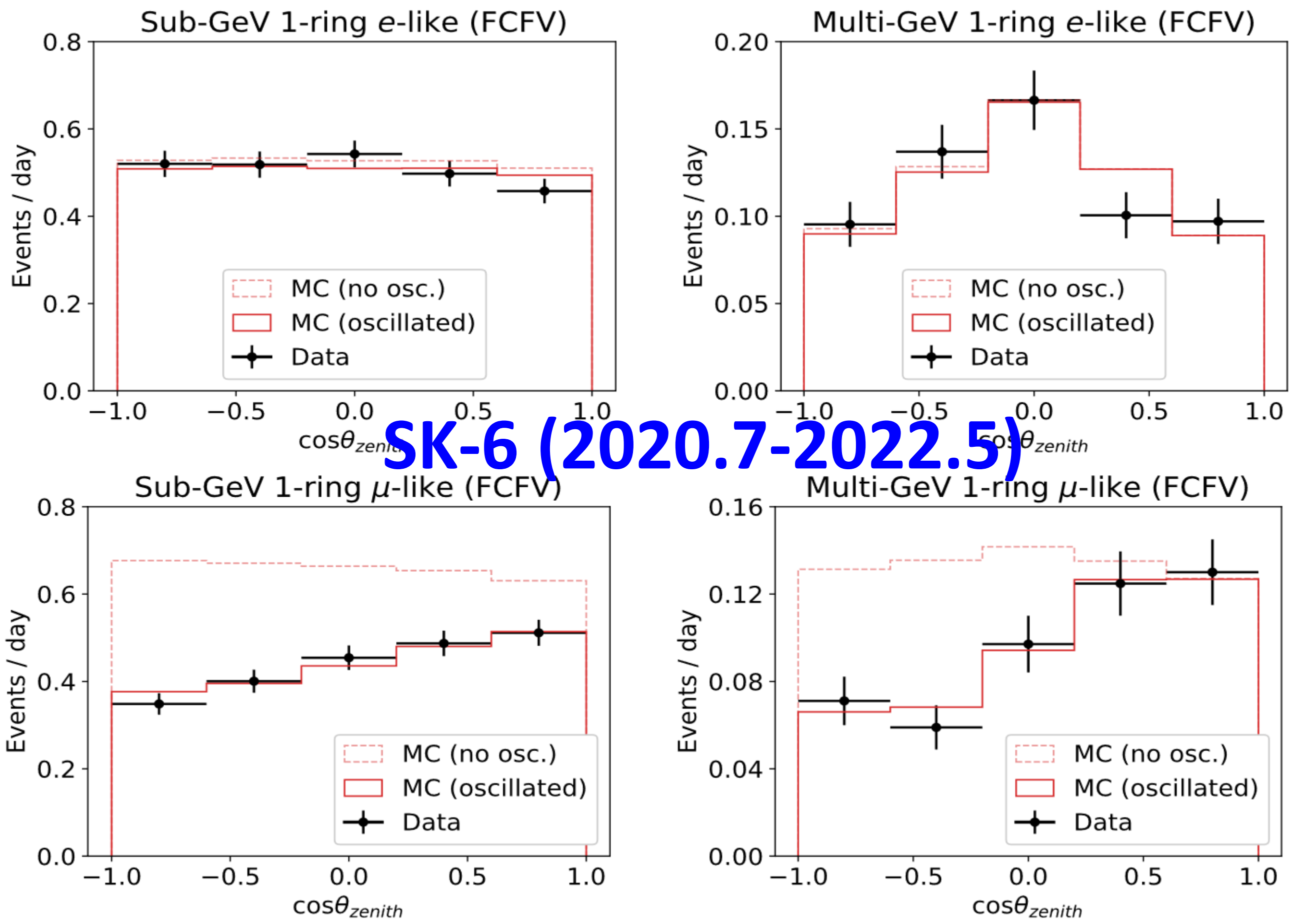
- Atmospheric neutrino oscillation measurements
- Boosted dark matter search
- Neutron capture on Gd in SK-VI

- Gd loading started in 2020.
- At **SK-6**, the Gd concentration is **0.011%**, corresponding to **~50%** neutron tagging efficiency.
- More Gd being loaded NOW!





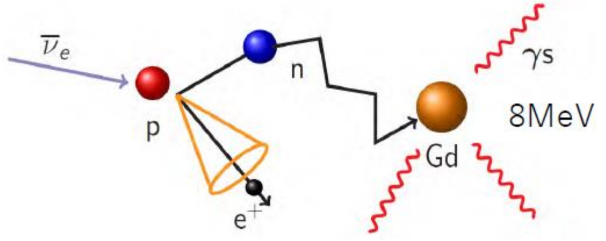
More on SK-Gd:
Mark Vagins
June 2nd,
23:00 KST



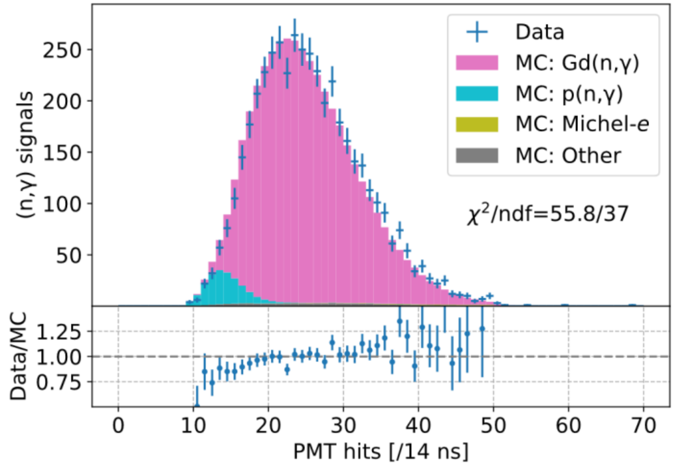
SK-6 (2020.7-2022.5)

- With 577 days of **data** in **SK-6**, the data quality is as expected in **MC**, and event rate is consistent with pure water phase.

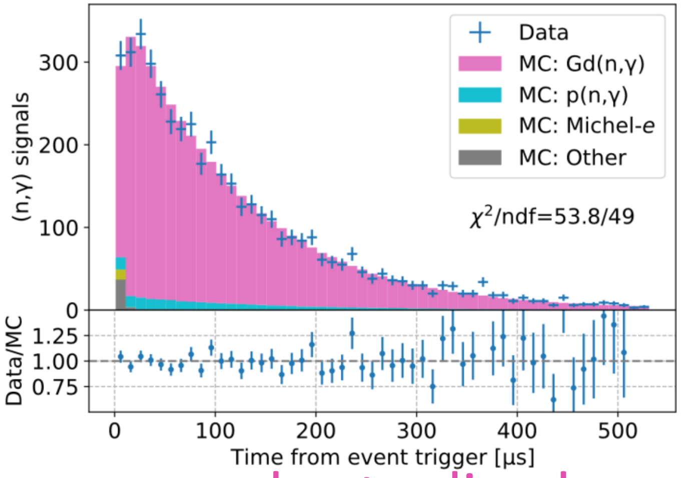
SK-6 Neutron Capture Signal on Gd



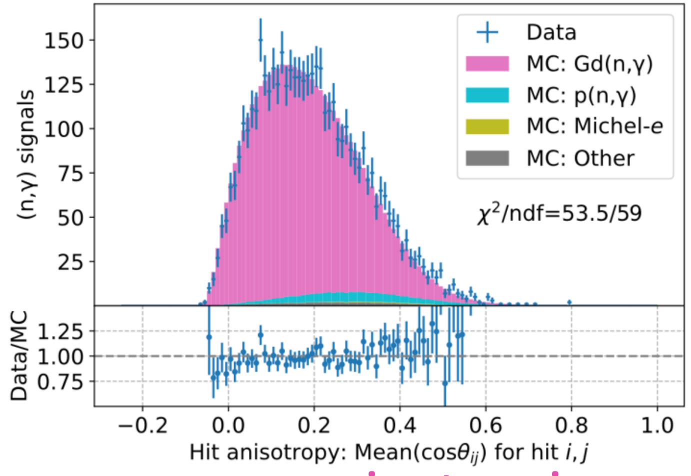
- Compared to H, neutron captures on Gd are:



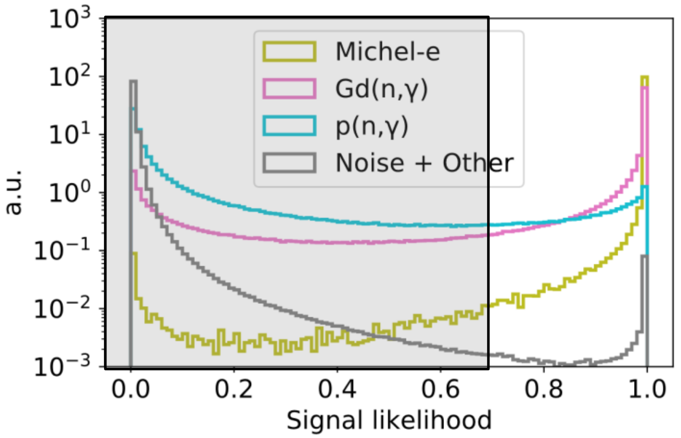
more energetic



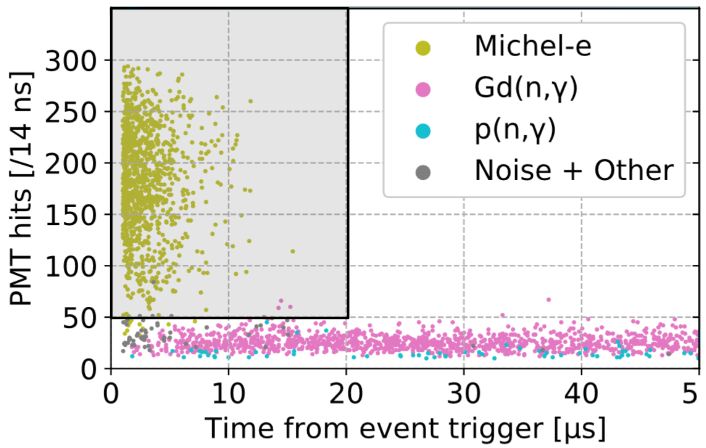
shorter lived



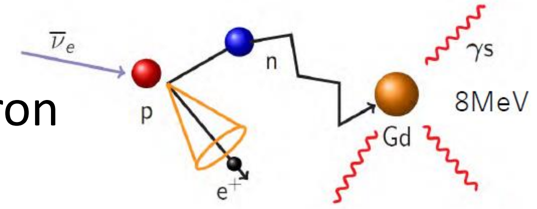
more isotropic



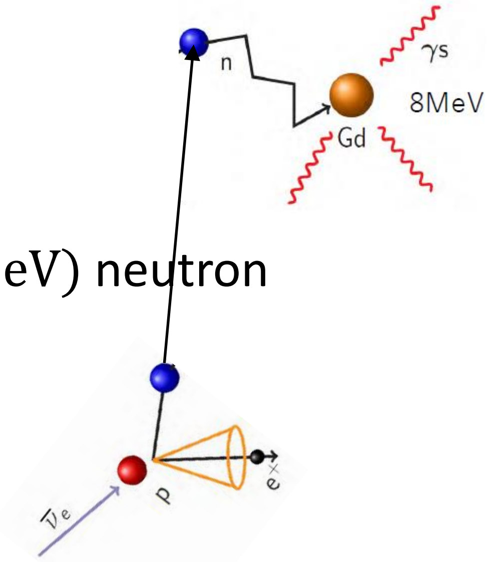
- Neural network to select neutron candidates
- Cuts to remove remaining Michel electrons

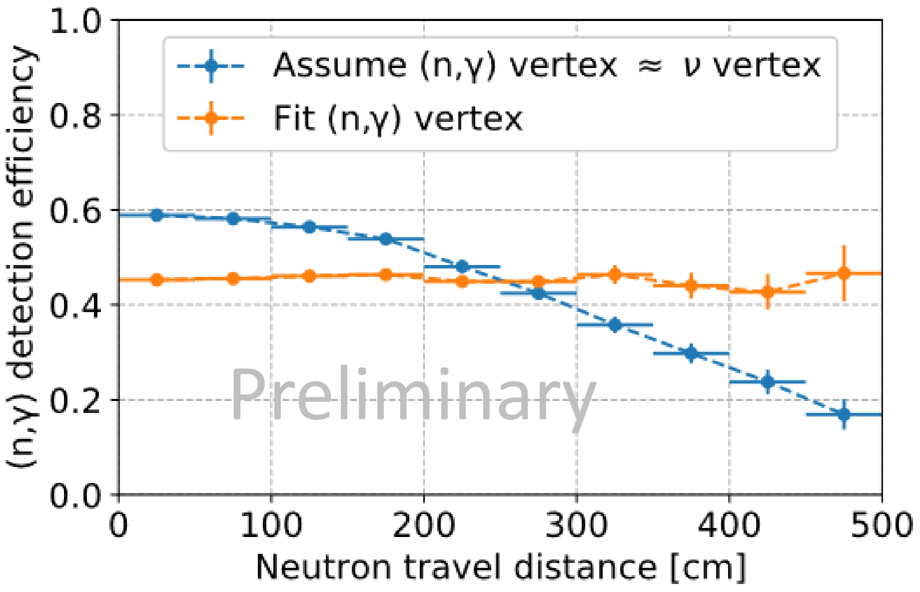


Neutron Vertex Reconstruction

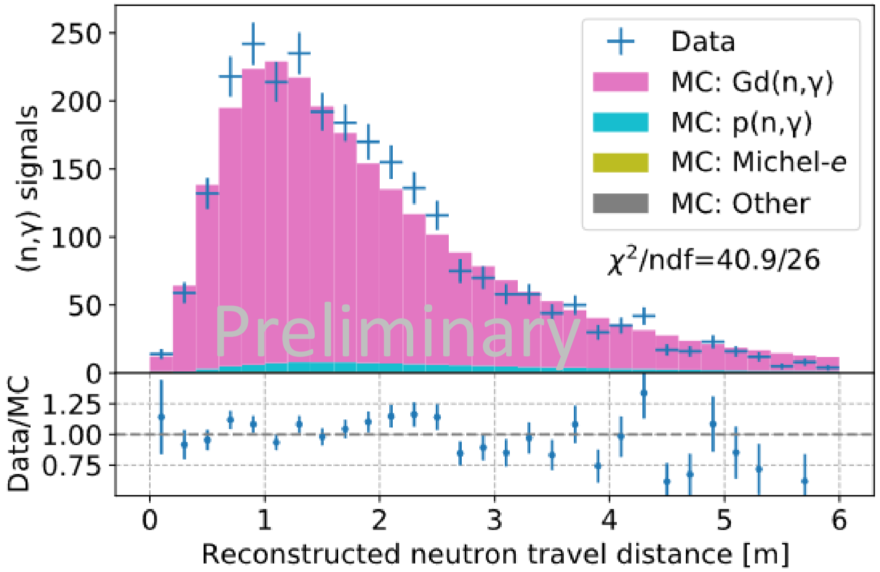


- In SK pure water phase, neutrons were tagged at the primary event vertex.
- Neutron captures on Gd yield higher number of hits, enabling independent neutron vertex reconstruction.
- Displacement between neutron vertex and primary vertex helps neutrino reconstruction.





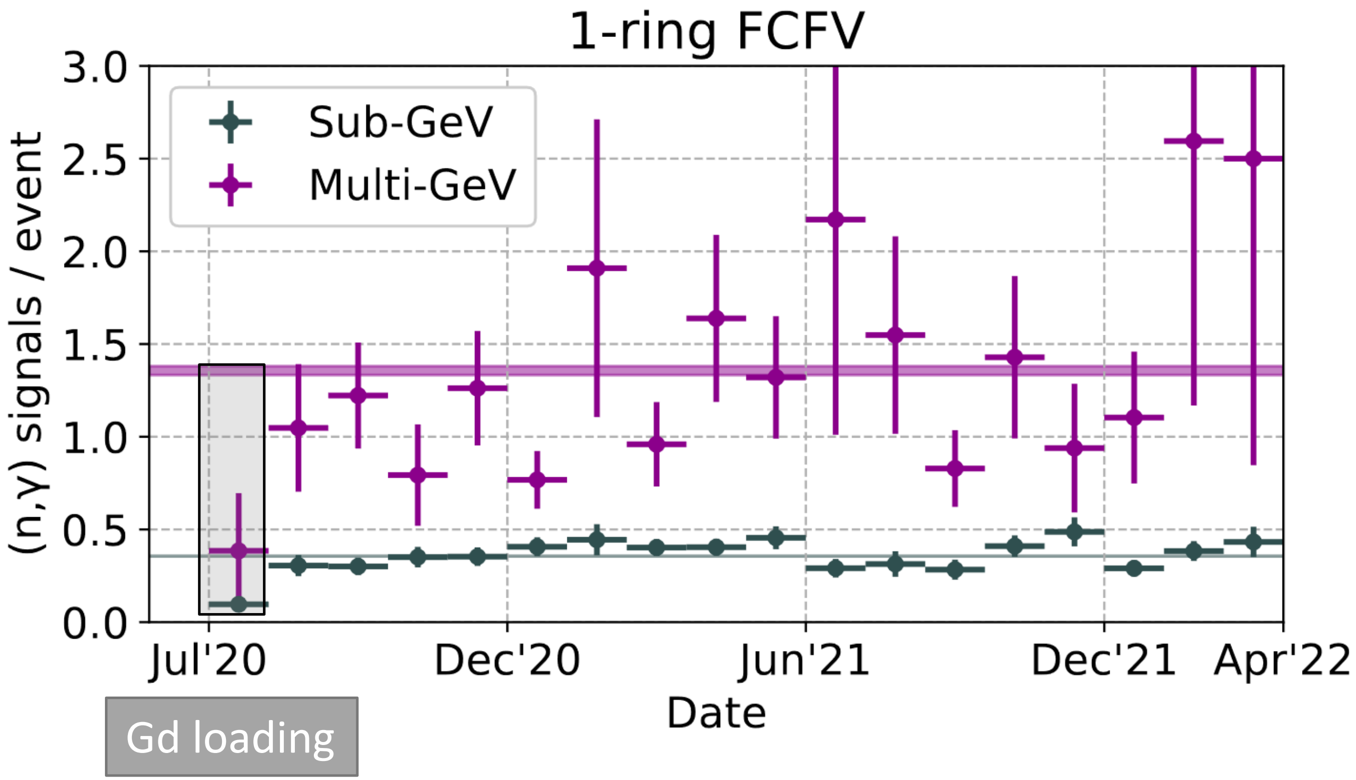
Multi-GeV neutrino



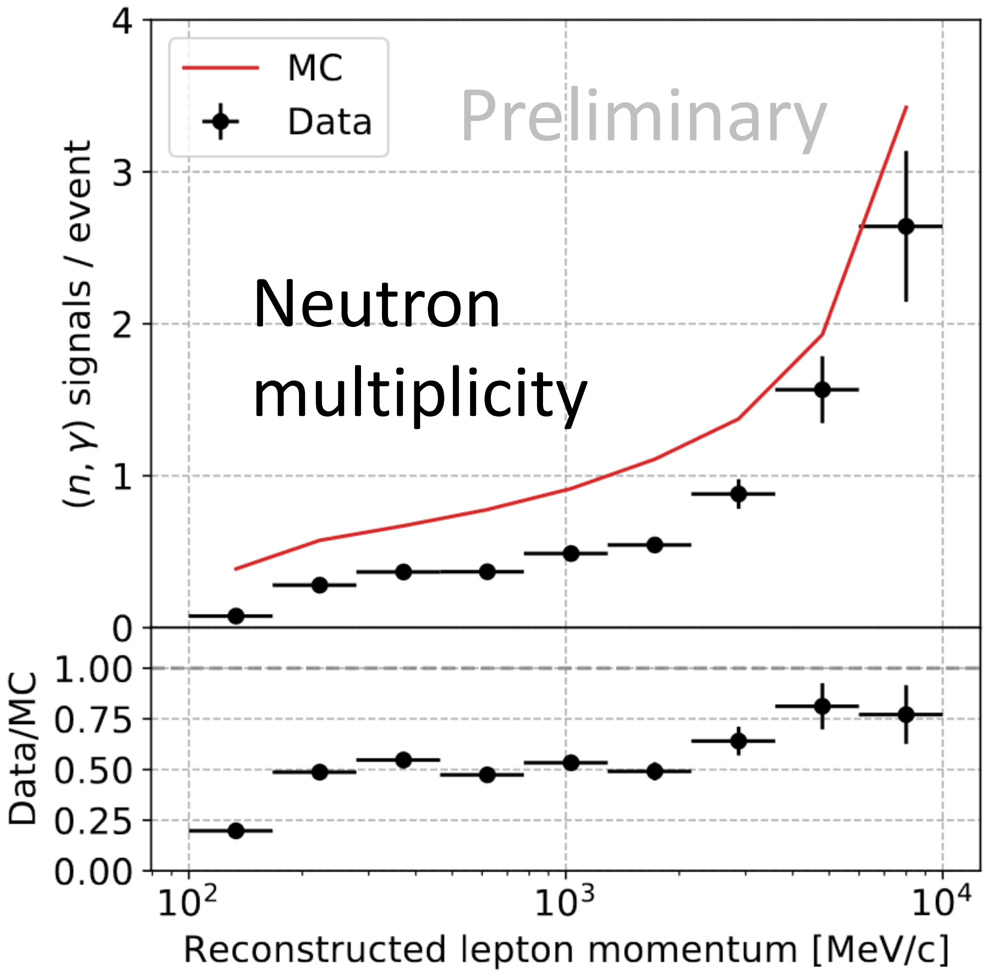
High energy neutrons travel longer before being captured.

SK-6 Neutron Measurement

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



[Poster by Seungho Han @ III-b, 2F. Majorana, MT09-370]



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

Summary

- **Atmospheric neutrino oscillation:** favoring NO, $\delta_{CP} \approx -\frac{\pi}{2}$, and maximal $\sin^2\theta_{23}$
- **Boosted dark matter search:** proton and DIS sample, constraints on models
- **Neutron measurement in SK-VI:** observed neutron capture on Gd
- **More in poster sessions and in following talks:**

Seungho Han	Sensitivity improvements via neutron detection in SK-Gd atmospheric neutrino oscillation analysis	II-a, 8F. DT01-372
Thomas Wester	Atmospheric Neutrino Oscillation Analysis with SK	II-b, 7F. DT01-251
Maitrayee Mandal	ν_τ appearance in atmospheric neutrinos at SK	III-a, 2F. MT09-216
Linyan Wan	Boosted dark matter search with hadrons at SK	III-b, 2F. MT09-046
Seungho Han	Neutron signals from atmospheric neutrino interactions in SK-Gd	III-b, 2F. MT09-370
Ryo Matsumoto	Search for proton decay into muon and neutral Kaon in SK	IV-a, 8F. MT17-156
Baran Bodur	ν_e - ^{16}O cross-section with atmospheric neutrinos in SK	IV-b, 7F. MT05-371

More on SK solar ν's:
Yusuke Koshio
June 2nd,
21:30 KST

More on SK-Gd:
Mark Vagins
June 2nd,
23:00 KST