Latest neutrino oscillation results from Super-Kamiokande

Hide-Kazu TANAKA
(Kamioka Obs., ICRR, University of Tokyo)

for Super-Kamiokande collaboration

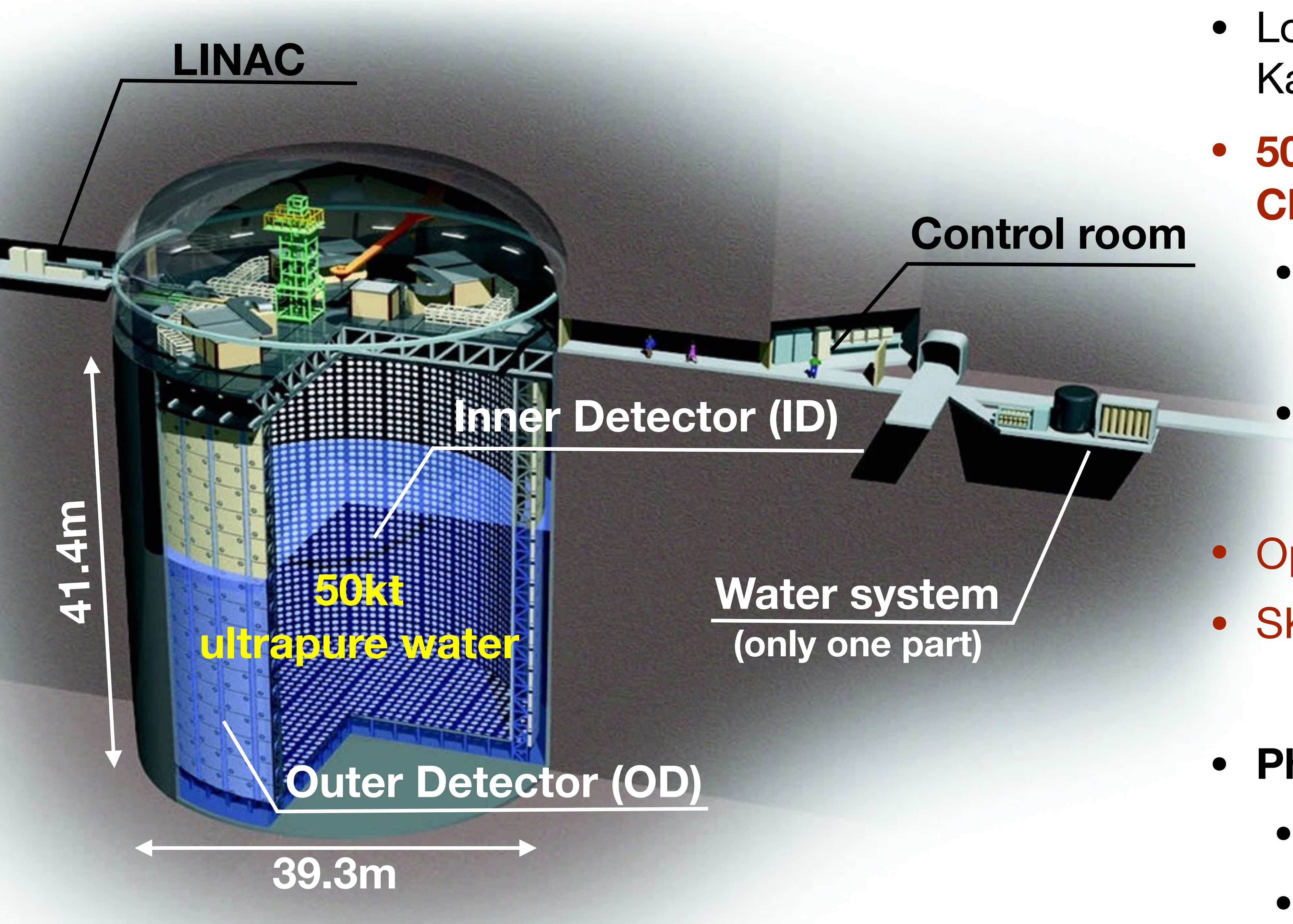
Neutrino Workshop at IFIRSE, July 17, 2023

The Super-Kamiokande collaboration

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

~230 collaborators from 51 institutes in 11 countries

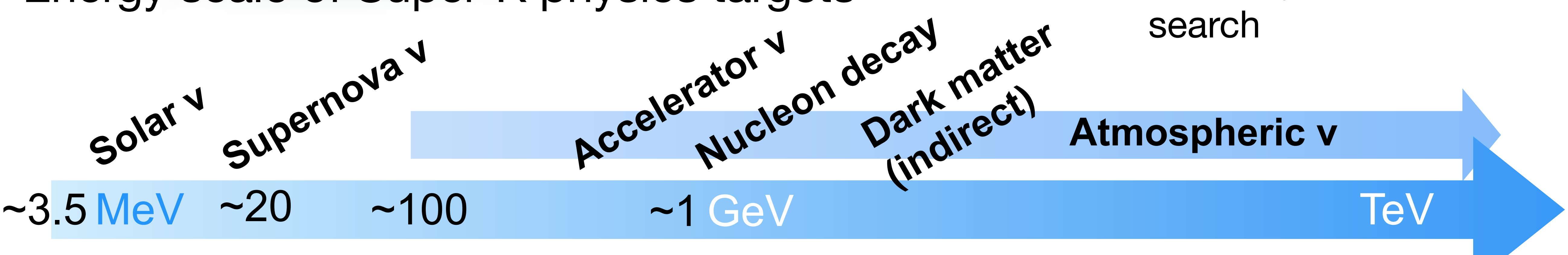
Super-Kamiokande



- Locates 1 km underground in Kamioka mine
- **50 kton ultra-pure water Cherenkov detector**
  - Inner Detector (ID)
    - 11,129 PMTs (20-inch)
  - Outer Detector (OD)
    - 1885 PMTs (8-inch)
- Operating since 1996 (SK-I)
- SK-VII is running

- **Physics targets:**
  - Nucleon decay search
  - Neutrino oscillation study
  - Astrophysical neutrino search

Energy scale of Super-K physics targets



SK data taking phases

96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28

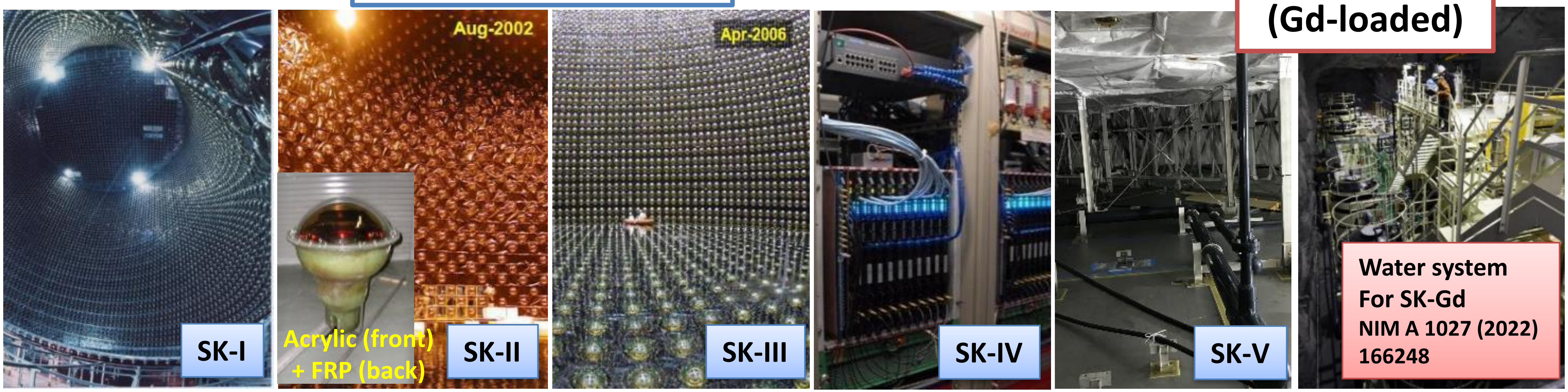
SK-I SK-II SK-III SK-IV SK-V SK-VI SK-VII

6,511 days live time

583.3 days live time ++

“SK” (pure water)

“SK-Gd” (Gd-loaded)



11146 ID PMTs (40% coverage)

5182 ID PMTs (19% coverage)

11129 ID PMTs (40% coverage)

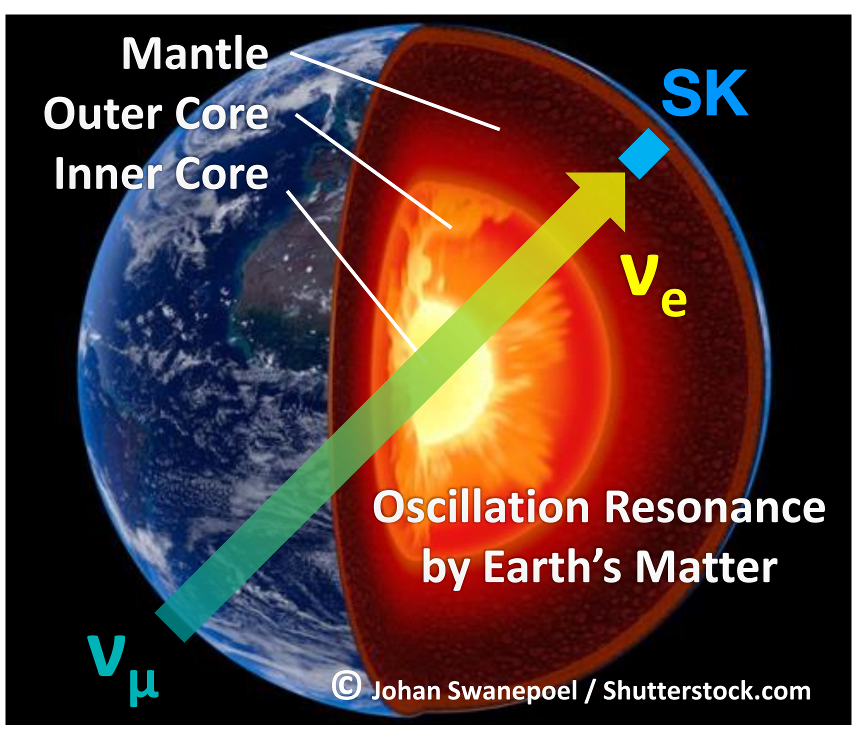
Electronics Upgrade

Refurbishment for SK-Gd

Neutron tagging with Gd

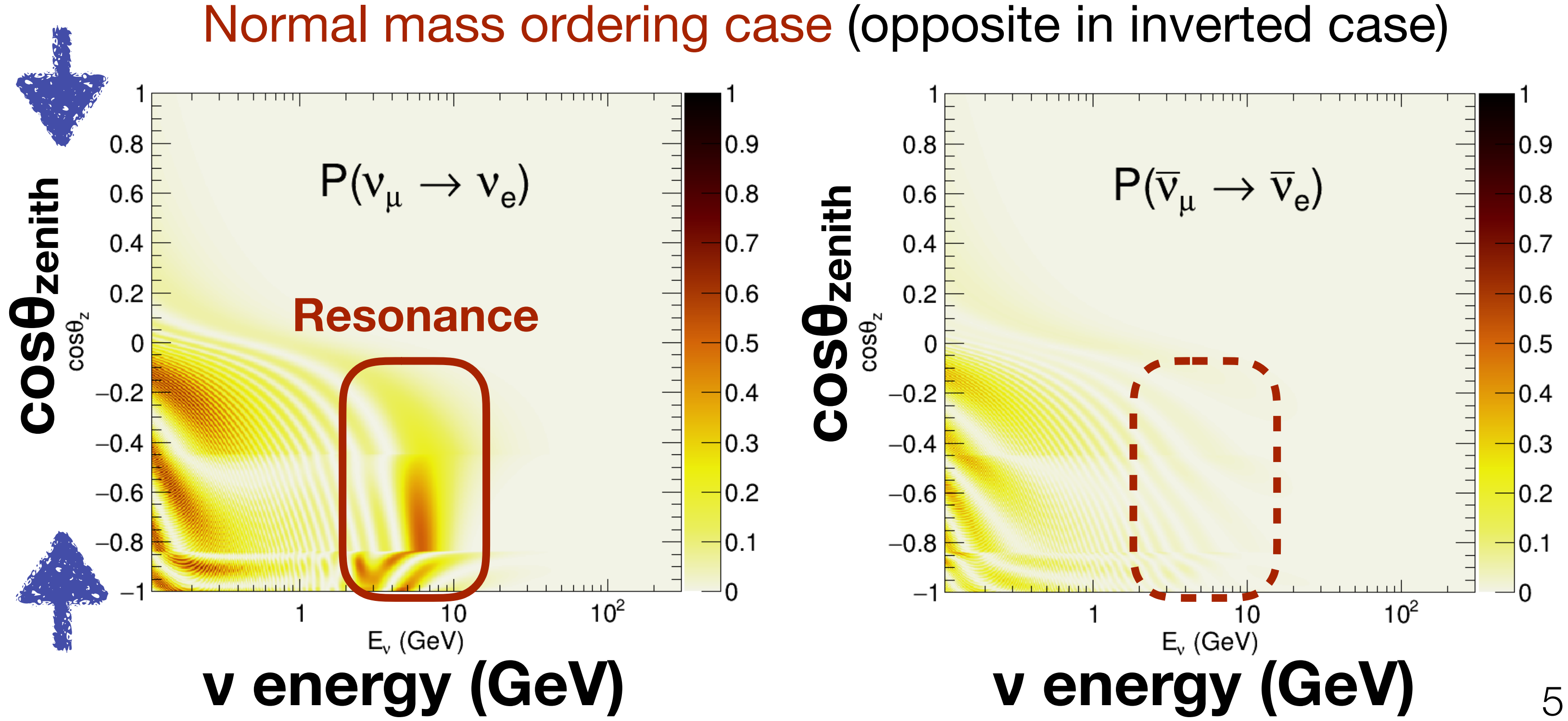
Atmospheric neutrinos

- Produced with cosmic-rays in Earth's atmosphere
- Atmospheric neutrinos produced in wide range of energy, MeV~TeV, and travel length varies 10km~1300km
- Neutrinos experience "matter effect" in Earth's core, which modifies $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probability depending on neutrino mass ordering (MO):
  - Normal mass ordering: $\nu_\mu \rightarrow \nu_e$ enhanced
  - Inverted mass ordering: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ enhanced
- Upward-going ν_e and $\bar{\nu}_e$ appearances in a few ~ several GeV sensitive to neutrino mass ordering

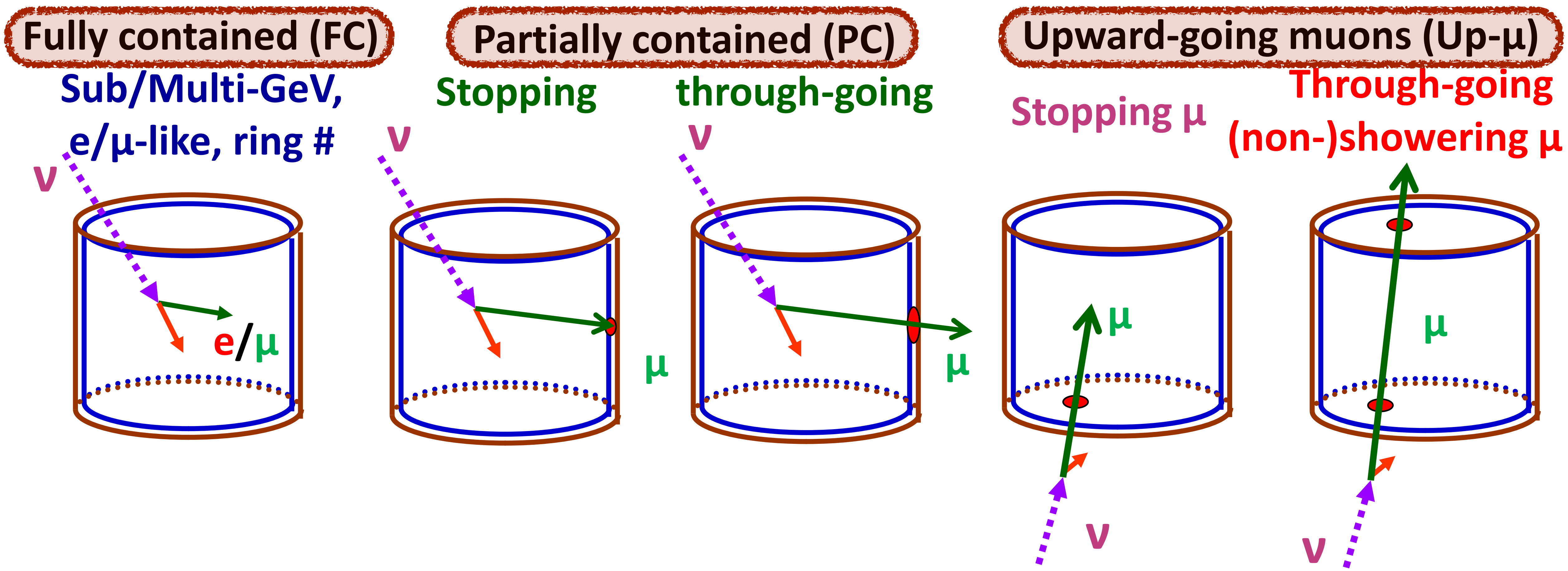


Oscillation probability

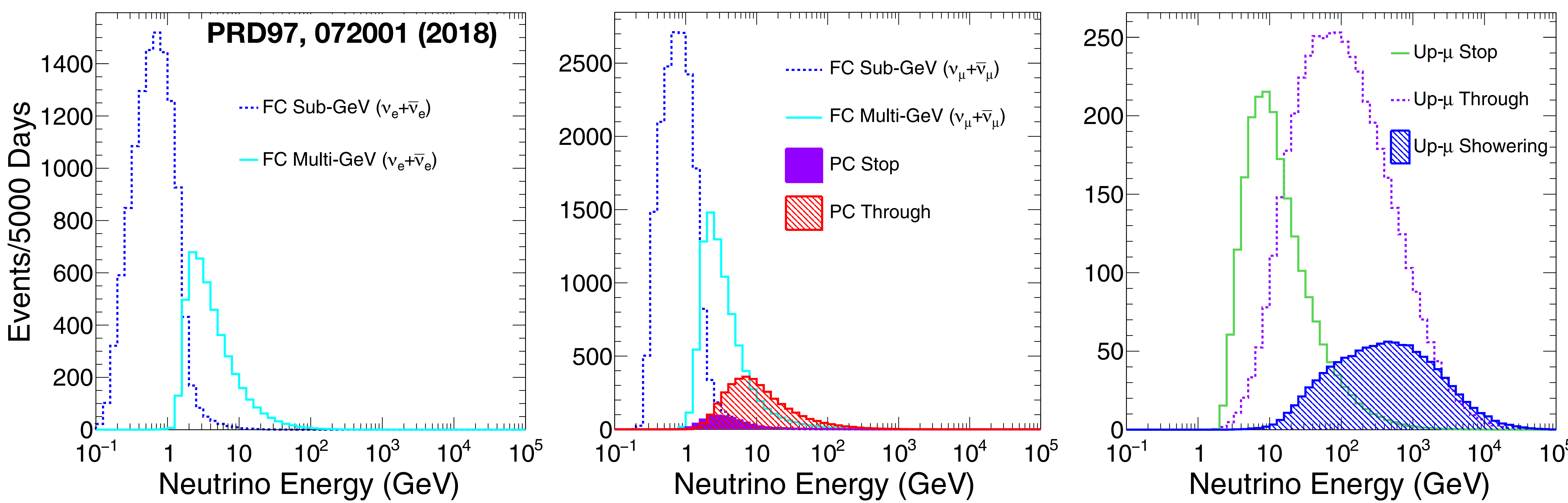
Normal mass ordering case (opposite in inverted case)



Atmospheric ν event classification in SK



Expected energy spectra of atm-ν samples

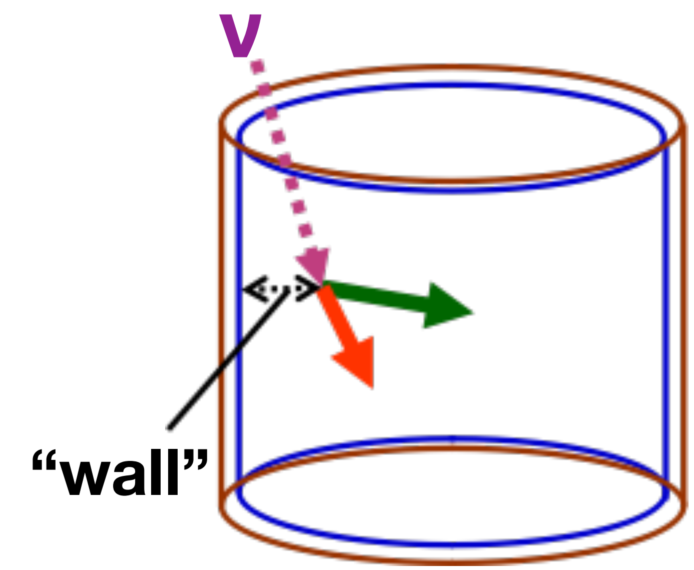


SK atm-ν oscillation analysis improvements

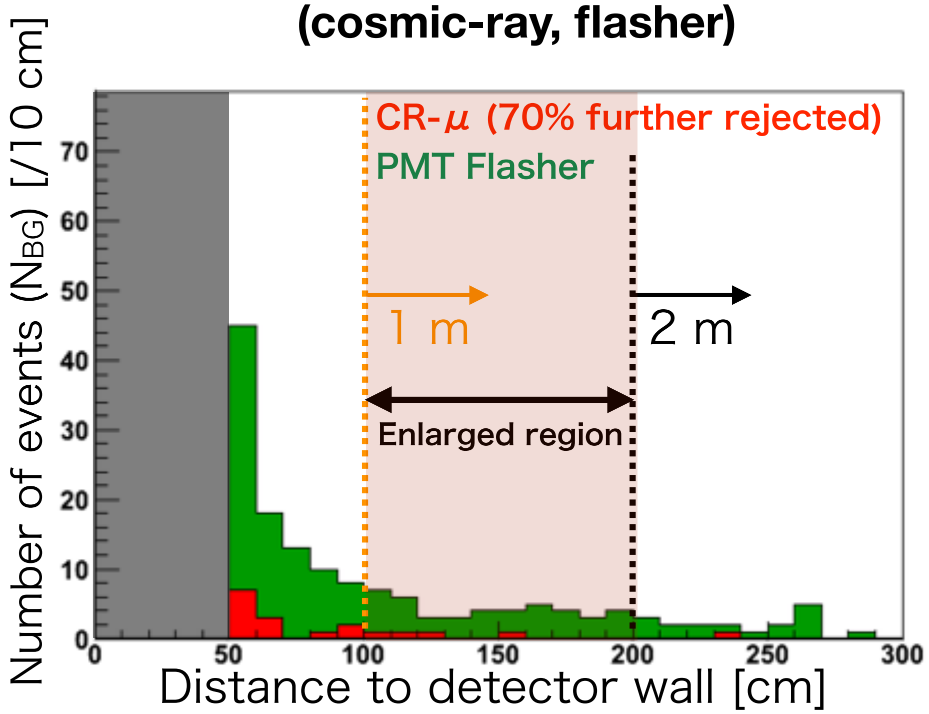
- New results with **full SK 'pure water' phase data (SK-I~V data)** with several updates
  - **New publication in preparation**
    - cf. previously published: PRD97, 072001 (2018): SK 5326 days, 328 kt·yr
- Updates since the previous analysis
  - **Expanded fiducial volume: +20% statistics (SK-I~V)**
  - More livetime: 6511 days, 484 kt·yr in total
  - Event selection with neutron tagging (SK-IV~V)
    - Enhance the separation ν events from $\bar{\nu}$ events
  - New multi-ring event classification using a Boosted Decision Tree (BDT)
  - **Atmospheric ν oscillation fit with external constraints**
    - **θ_{13} from reactors**
    - **"T2K model" and T2K runs 1-9 data**
      - Include antineutrino mode sample

Enlarged fiducial volume

- Distance btw vertex and nearest ID wall surface = “wall”
- Conventional fiducial volume defined ‘wall > 2m’
  ➜ Expand to ‘wall > 1m’ (for all SK periods)
  ➜ Increase fiducial volume by 20% (22.5kt → 27.2kt)
- Confirmed no significant increase of non-ν background and no significant bias in reconstruction (ex. energy scale)
  - Systematics in the expanded region under control

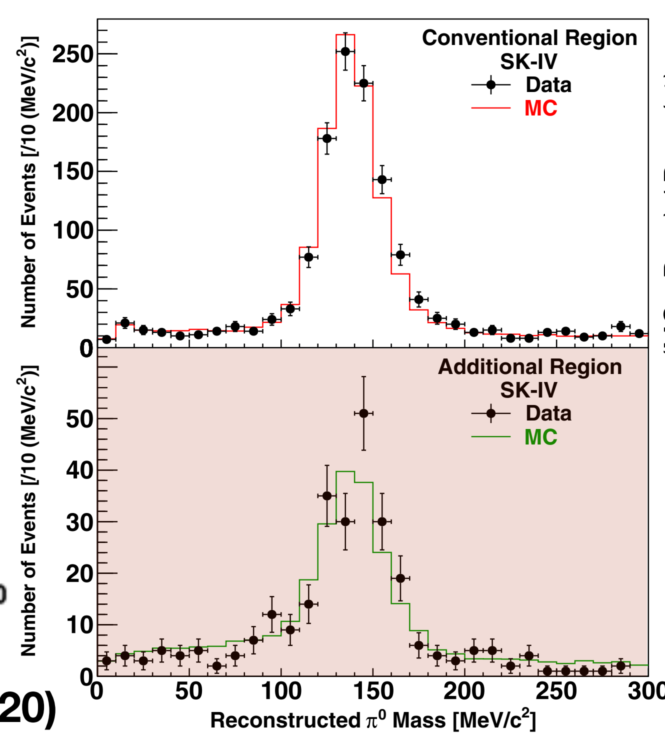


External background
(cosmic-ray, flasher)

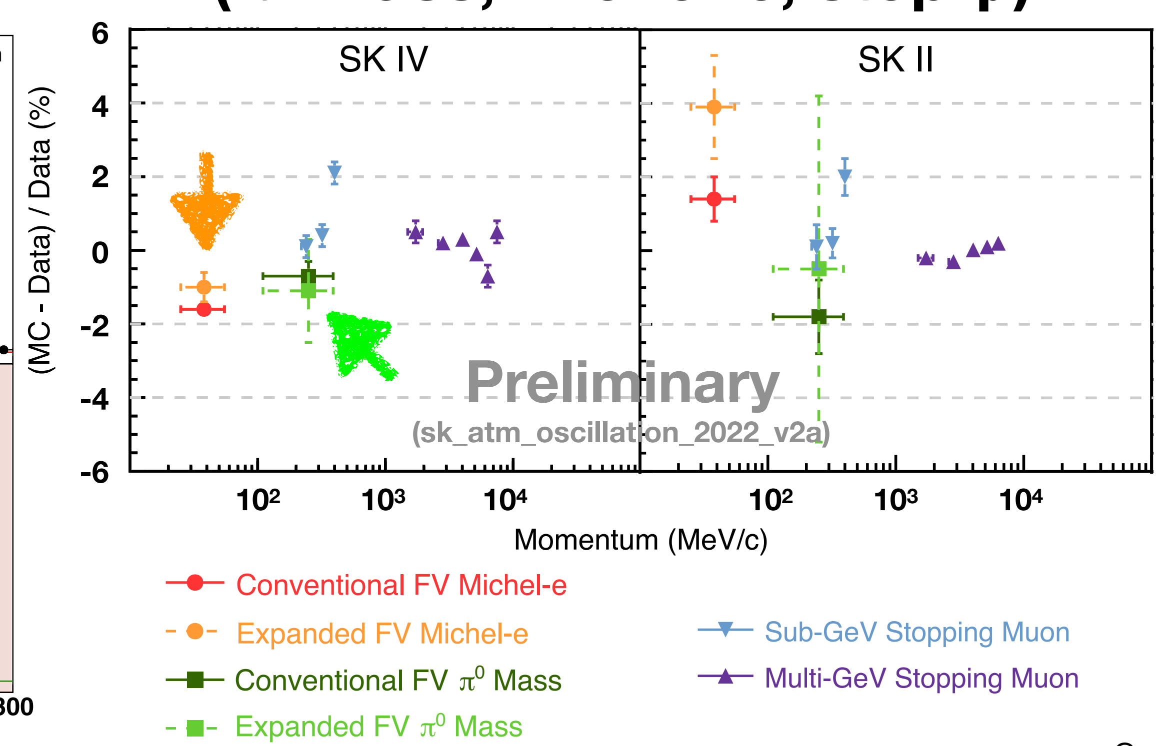


PRD 201, 112011 (2020)

Reconstructed π⁰ mass

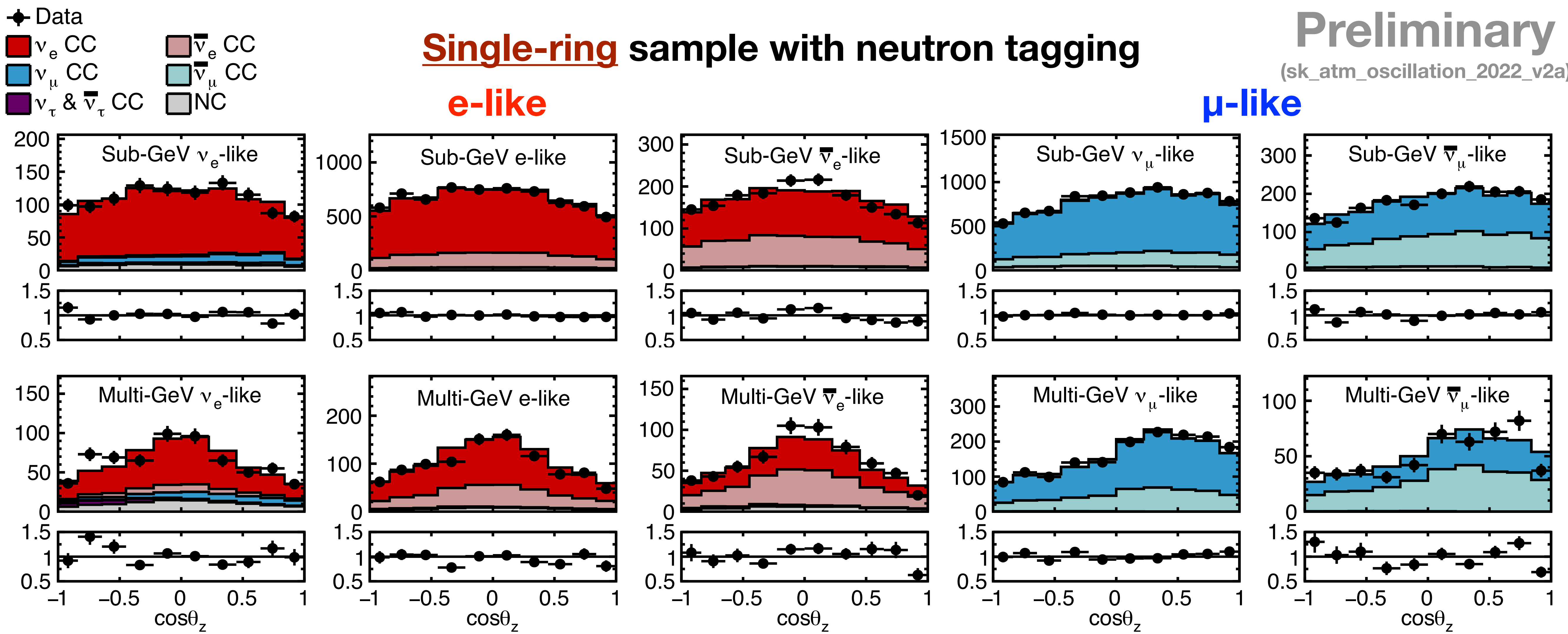


Energy scale
(π⁰ mass, Michel-e, stop-μ)

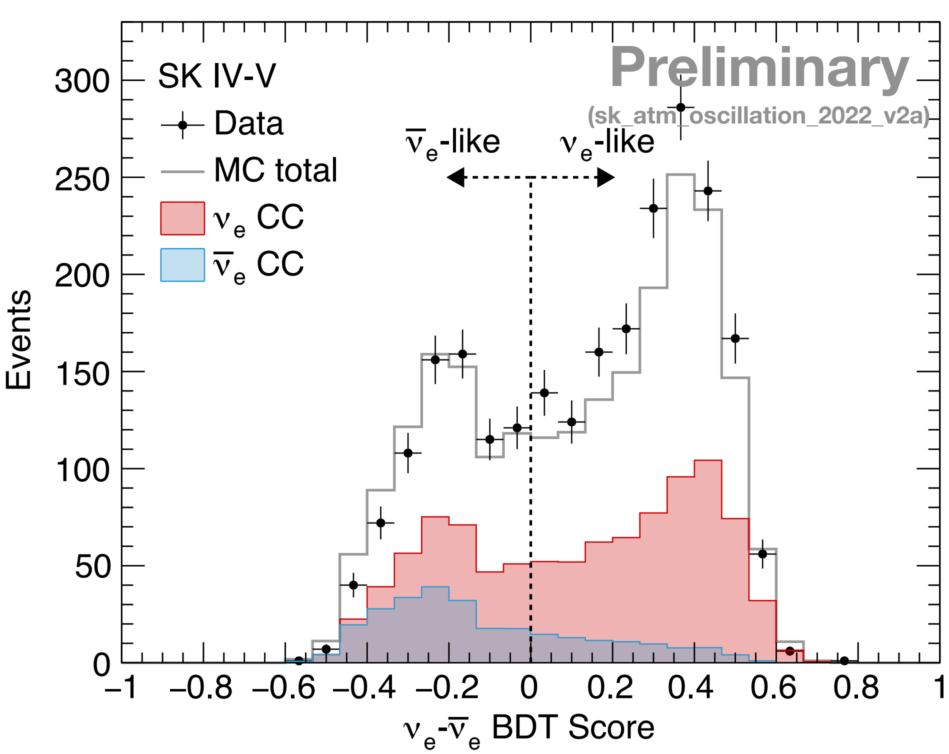


Neutron tagging and multi-ring BDT classification

Single-ring sample with neutron tagging



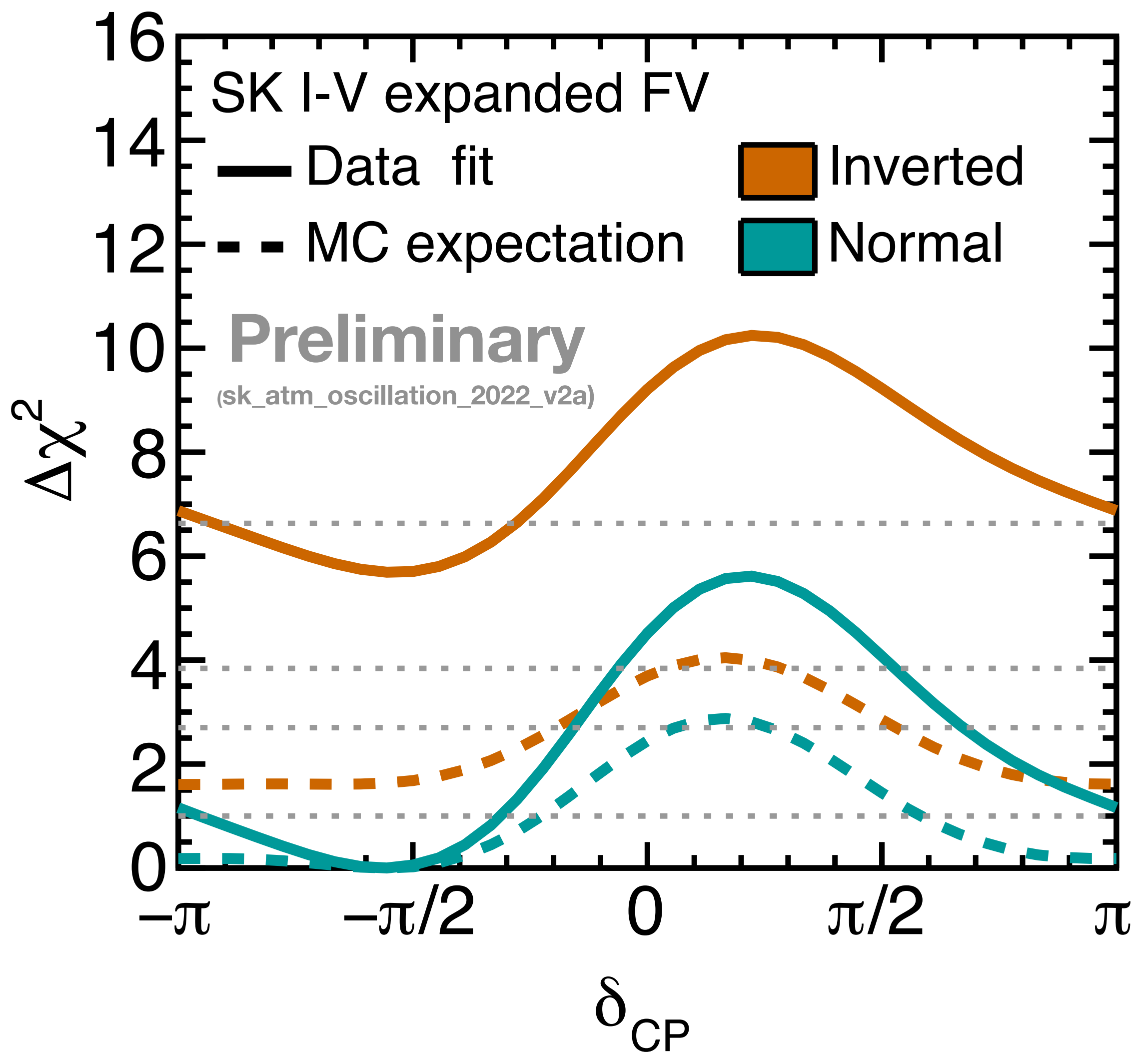
Multi-ring sample with BDT

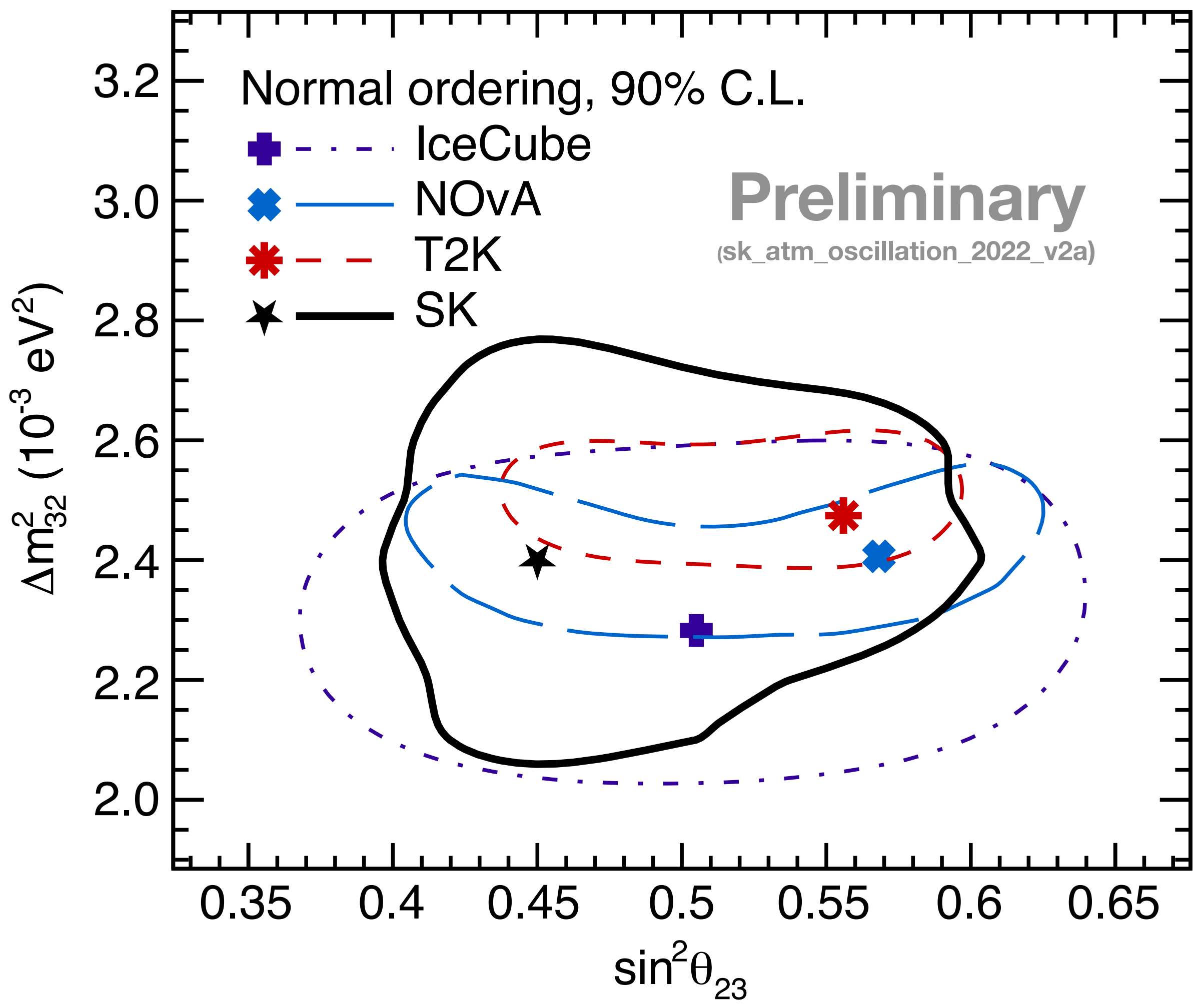


- **Single-ring neutron tagging and multi-ring BDT event classification enhance the separation btw ν and $\bar{\nu}$ events**

SK atm-ν oscillation results

with θ13 constraint from reactors $\sin^2\theta_{13} = 0.0220 \pm 0.0007$ [PTEP 2022, 083C01 (2022)]





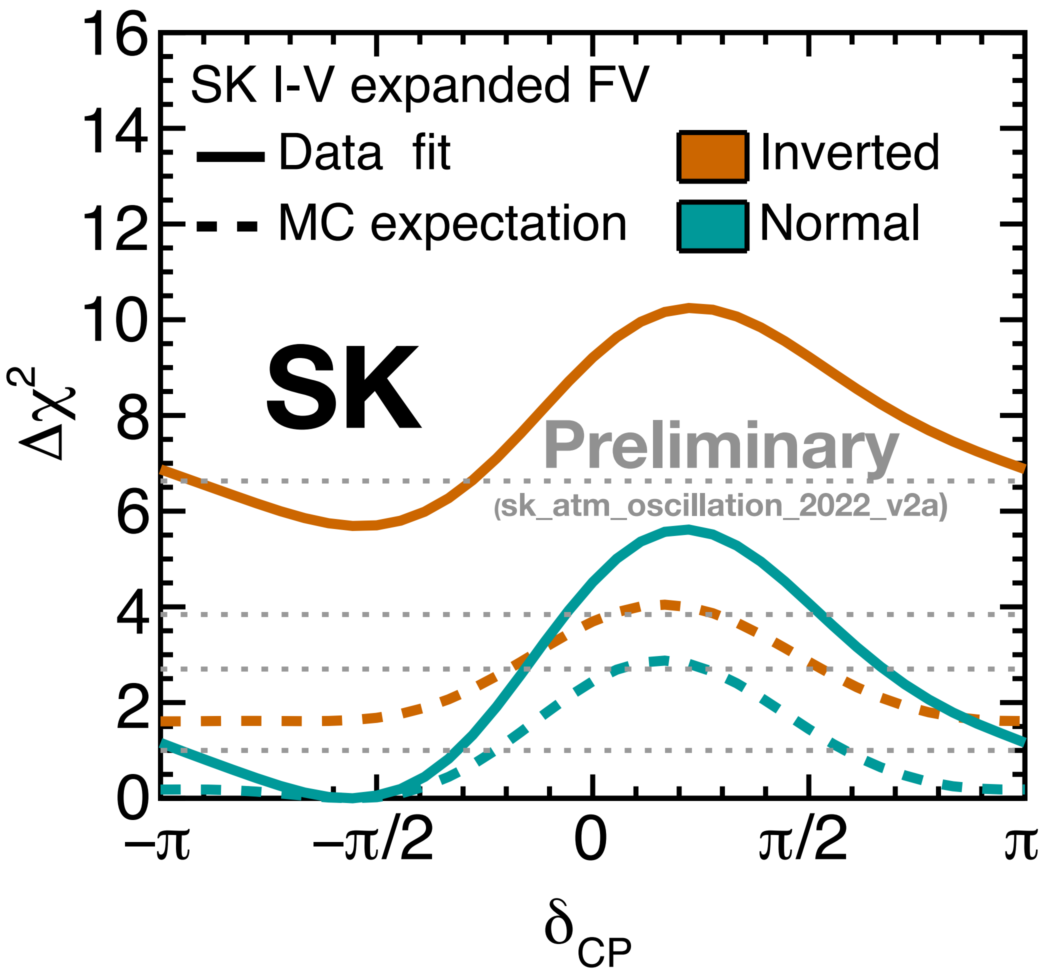
- **Best-fit results**
  (for both normal and inverted MO)
  - $\delta_{CP} = -1.75$
  - $\sin^2\theta_{23} = 0.45$
  - $\Delta m^2_{32} = 2.4 \times 10^{-3} eV^2$

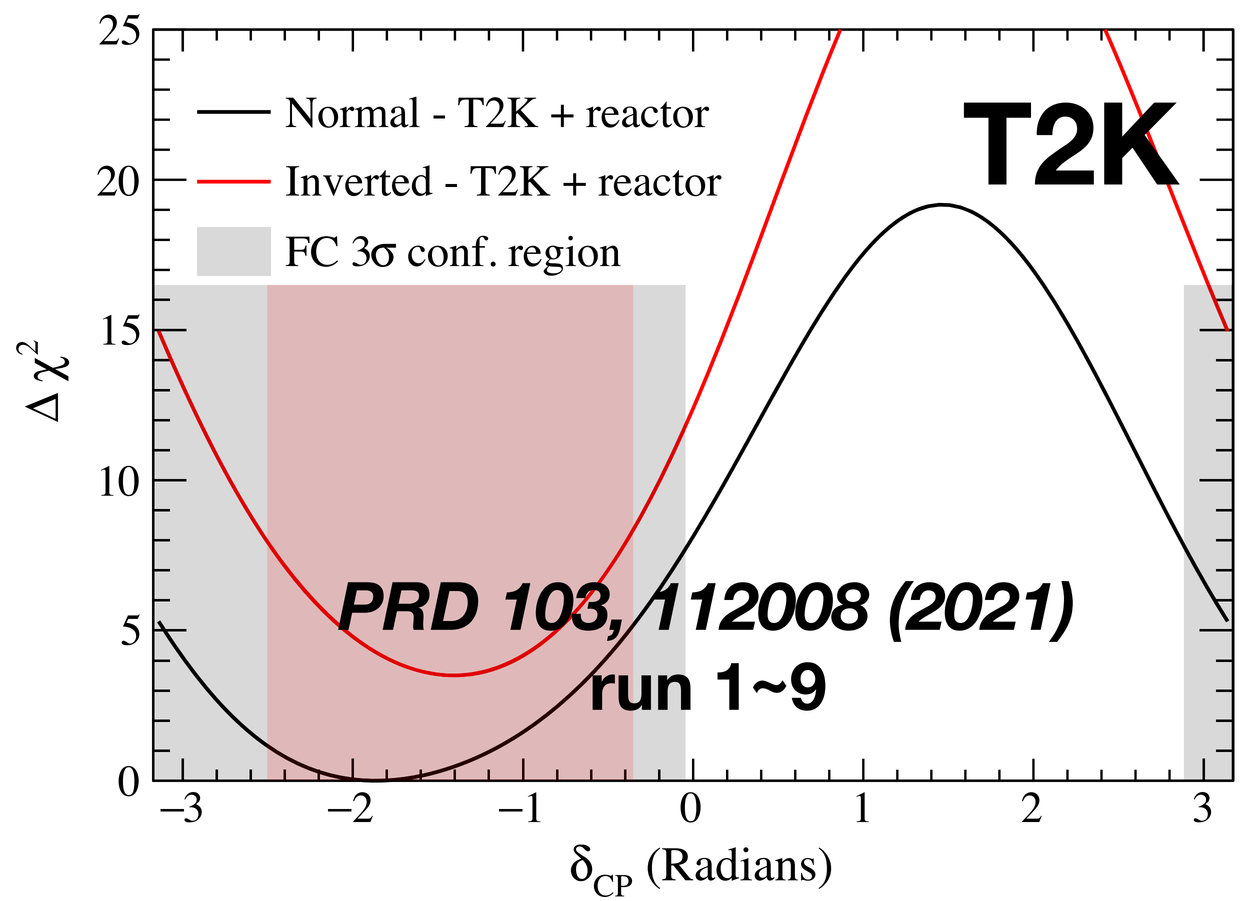
Preliminary
(sk_atm_oscillation_2022_v2a)

- **SK atm-ν data favors:**
  - Maximal mixing
  - δ_{CP} ~ -π/2
  - Normal mass ordering
    - $\Delta\chi2_{(IO-NO)} = 5.69$

Preliminary
(sk_atm_oscillation_2022_v2a)

Constraints from T2K

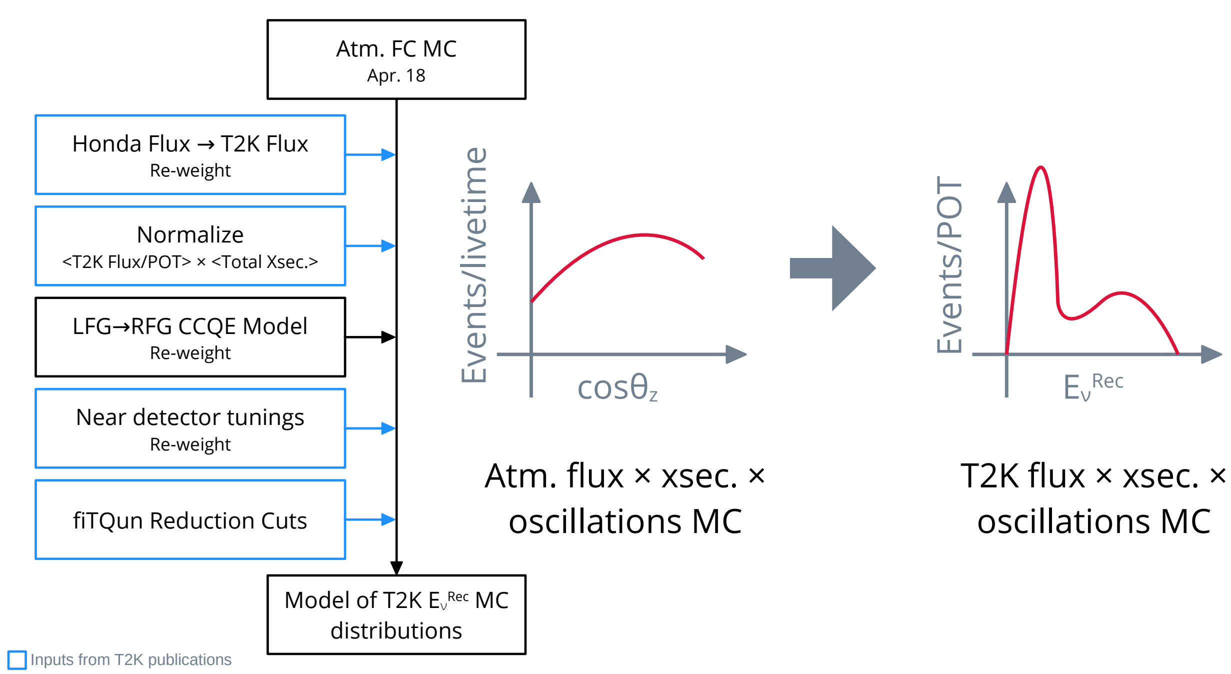




SK sensitive to Mass Ordering, T2K sensitive to δ_{CP}

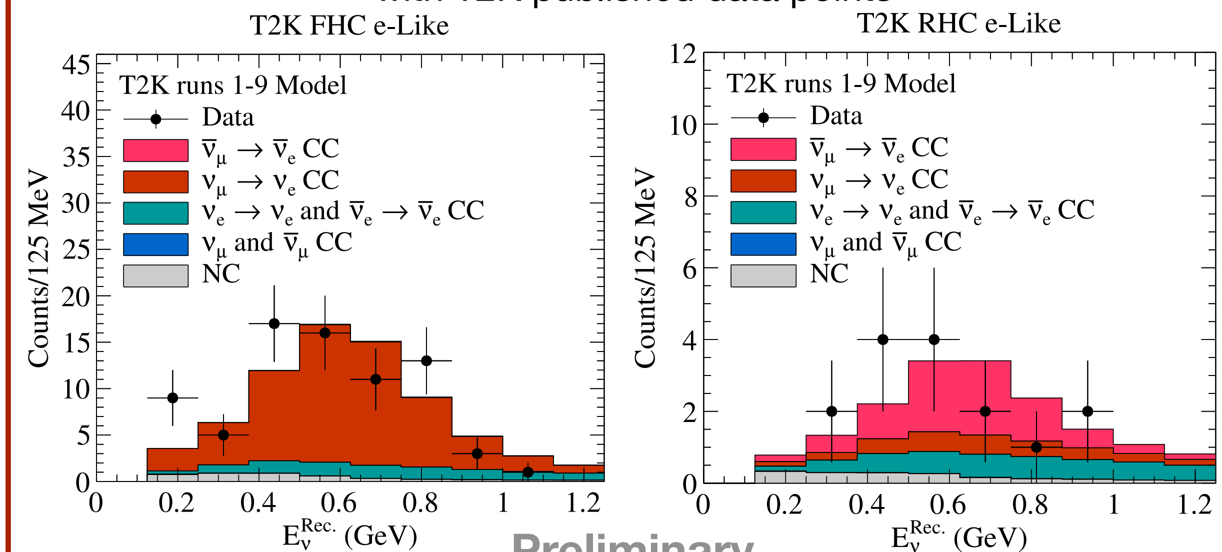
Constraints from T2K

- SK and T2K are independent collaborations and there is no formal sharing of data, MC, analysis tools, etc, **(yet)**
- **Constraints with "T2K model"**
    - Re-weight SK atm-ν MC to reproduce a model for T2K MC following the T2K publications
        - Reweight SK MC to T2K flux
        - Construct cross section models (include model tunings by T2K Near Detector)
        - Apply T2K event selection criteria after all re-weighting
    - Simultaneously fit SK data and T2K published data



ex. T2K model

with T2K published data points



Preliminary

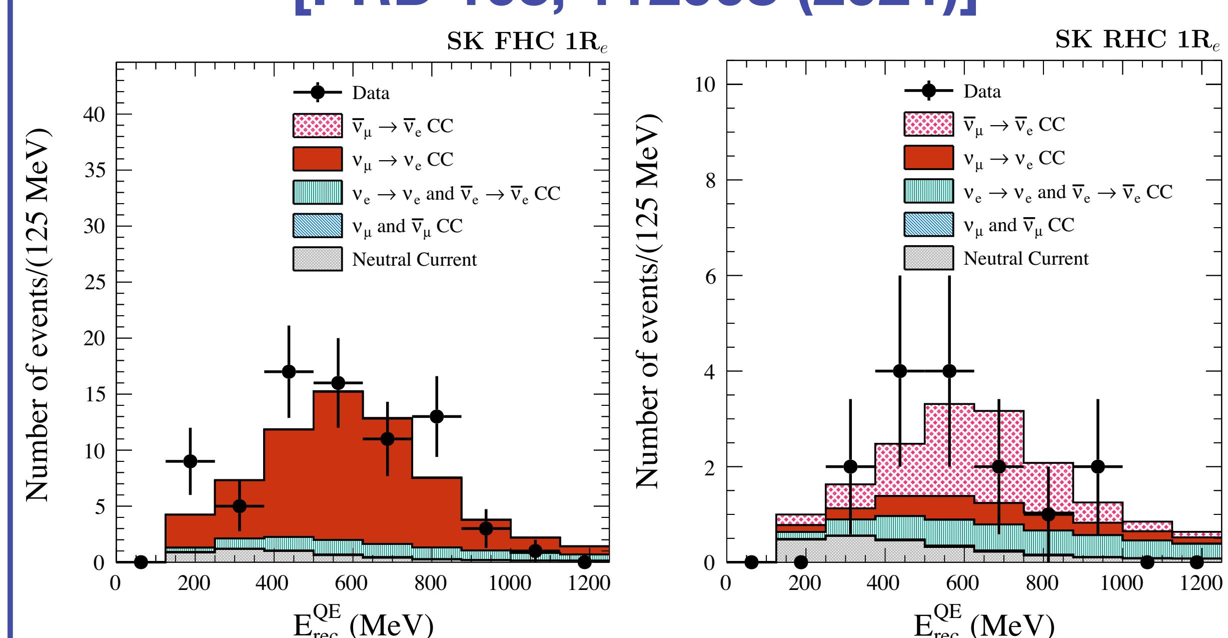
(Figures adopted from T. Wester Ph.D. thesis 2023)

Generally see good agreement with T2K distributions

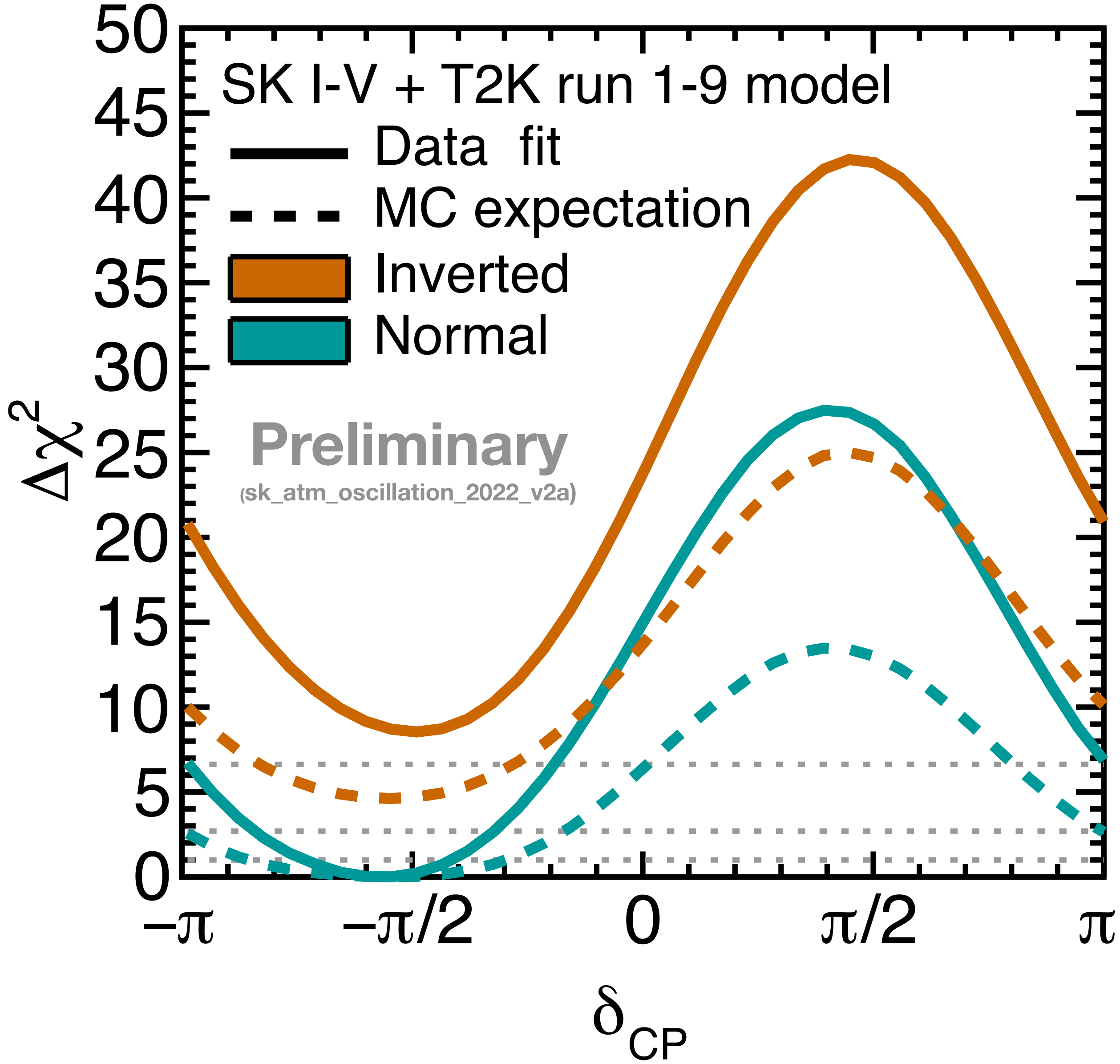
(include μ-like samples)

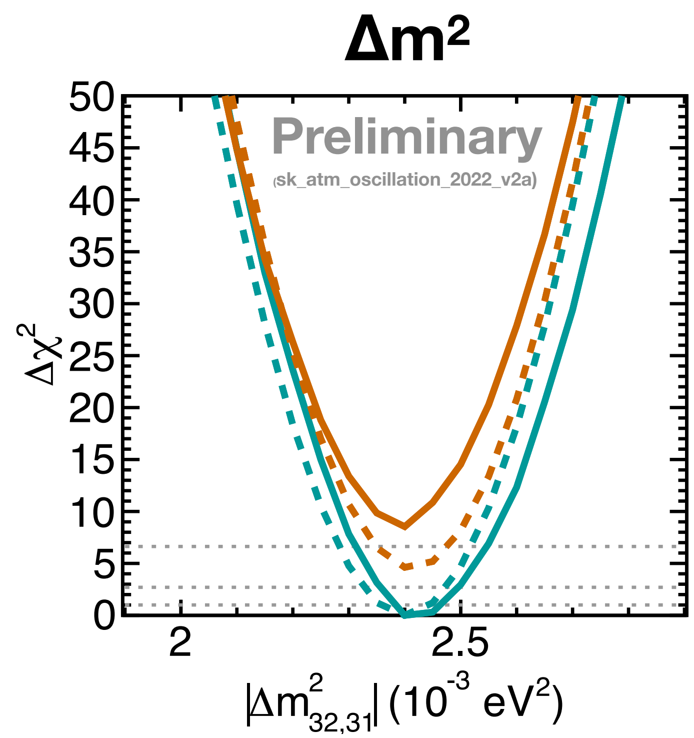
T2K run1-9

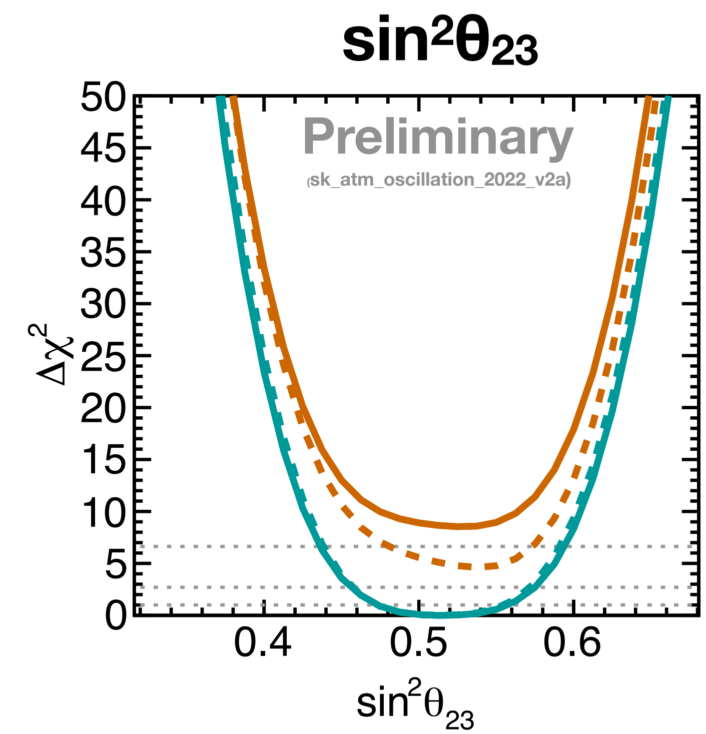
[PRD 103, 112008 (2021)]



Atm-ν oscillation analysis with T2K model







- **Best-fit results (for normal MO)**
  - $\delta_{CP} = -1.75$
  - $\sin^2\theta_{23} = 0.51$
  - $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

Preliminary
(sk_atm_oscillation_2022_v2a)

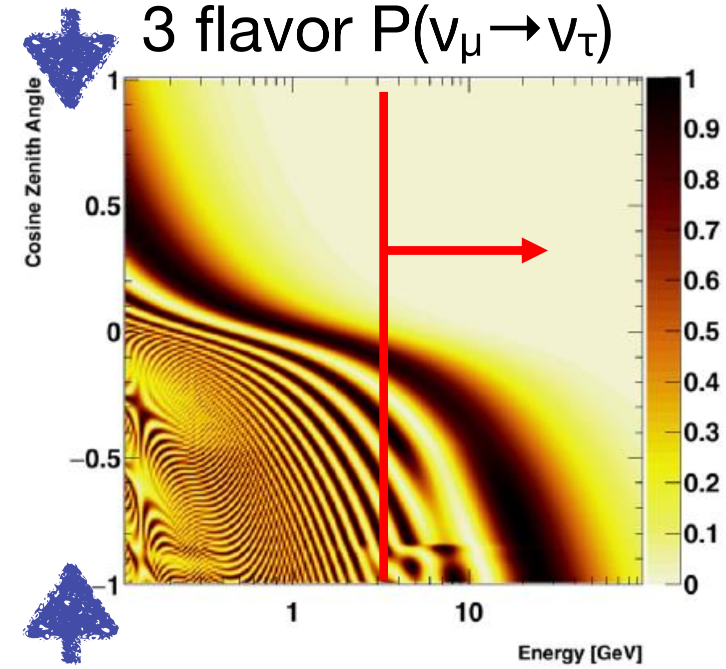
- **SK atm-ν + T2K model favors:**
  - Maximal mixing
  - $\delta_{CP} \sim -\pi/2$
  - Normal mass ordering
    - $\Delta\chi 2_{\text{(IO-NO)}} = 8.54$
    - cf. SK alone $\Delta\chi 2 = 5.69$

Preliminary
(sk_atm_oscillation_2022_v2a)

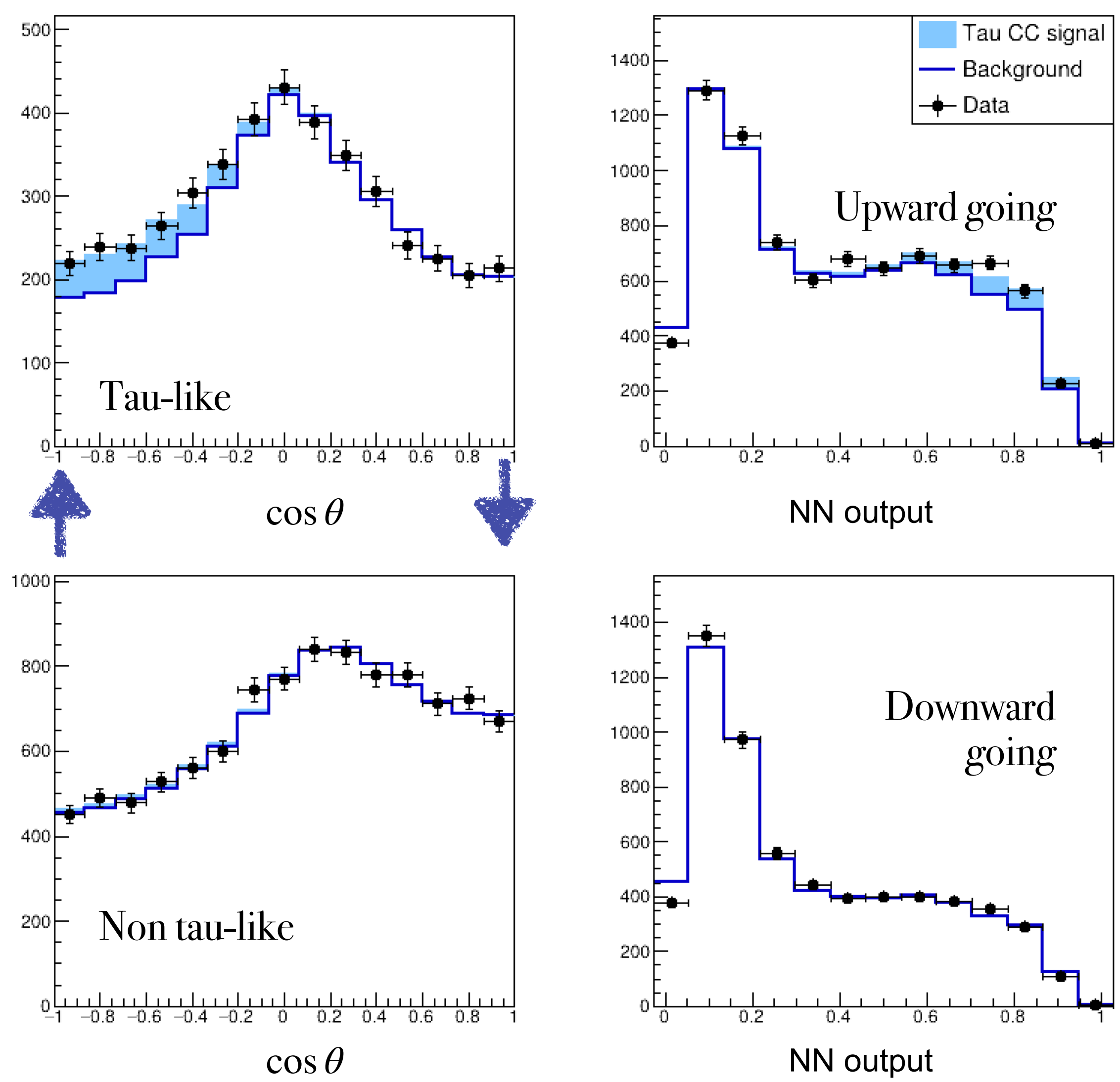
Formal joint SK+T2K analysis on-going

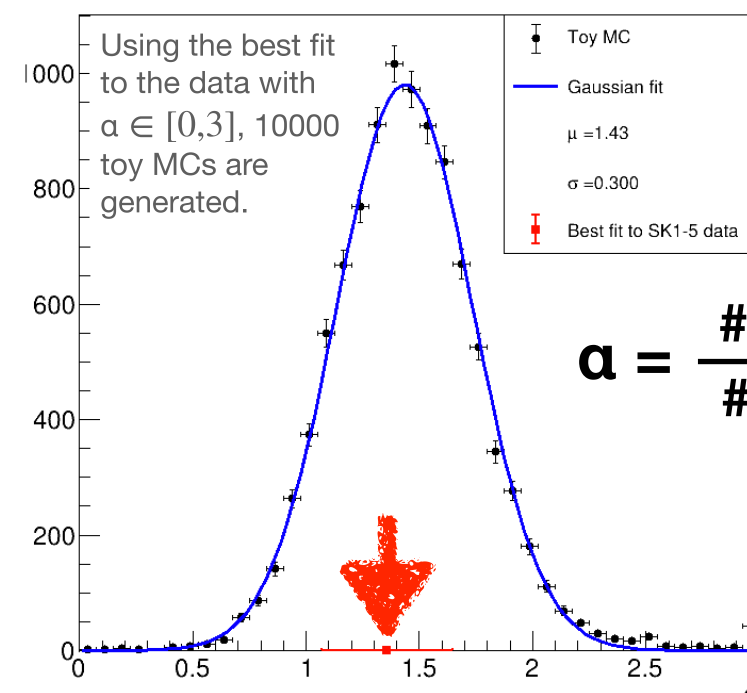
ν_τ appearance search

- Updates since the previous publication: Pays. Rev. D98, 052006 (2018)
  - **Full SK 'pure water' phase data (SK-I~V data)**
    - ~2 years of SK-IV and SK-V data added
  - **Expanded fiducial volume**
  - **➜** ~50% more data added
- Best fit of ν_τ normalization parameter: $\alpha = 1.359 \pm 0.289$
  - cf. α=1 means consistent with prediction
- **Exclude no ν_τ appearance (α=0) at 4.8σ significance, p-value: 7.5×10^{-7}**
- Observed # of ν_τ CC events: 428 ± 92 events (normal MO)



ν_τ appearance signal:
Upward going, $E_\nu \geq$3.5GeV





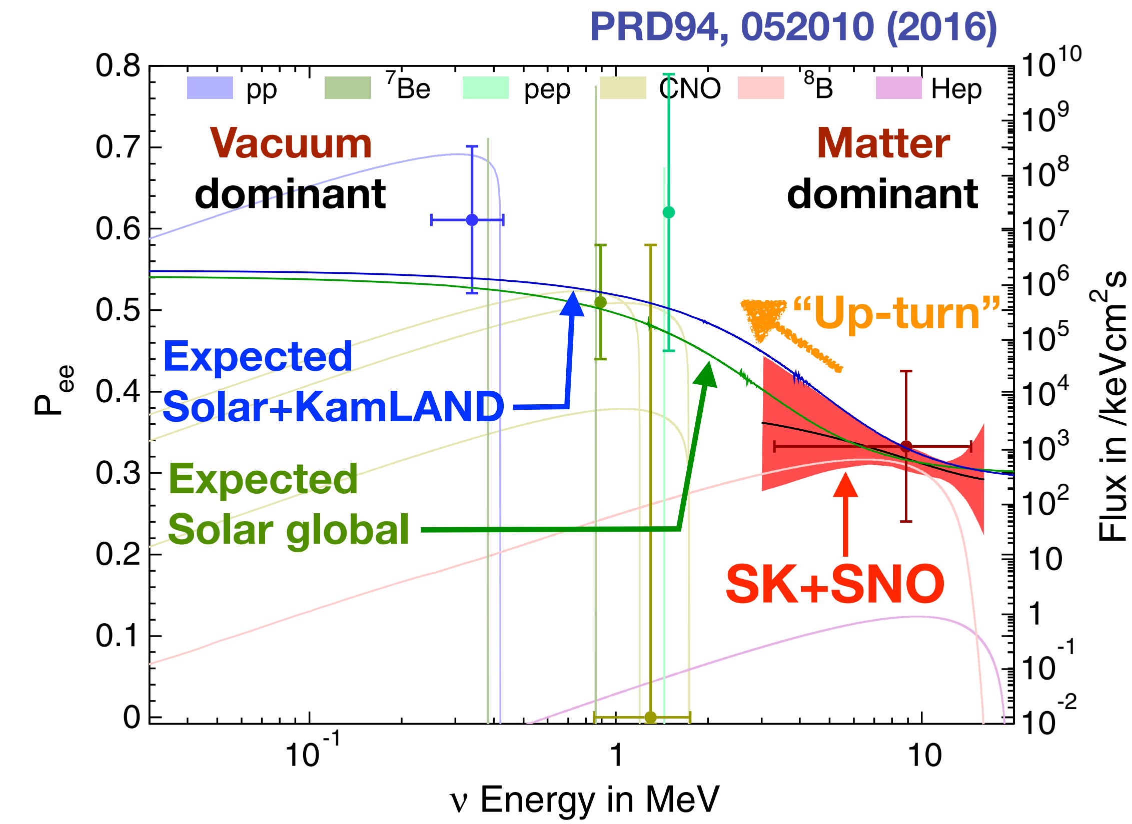
$$\alpha = \frac{\#\text{ of observed } \nu_\tau}{\#\text{ of expected } \nu_\tau}$$

Best fit: $\alpha = 1.359 \pm 0.289$

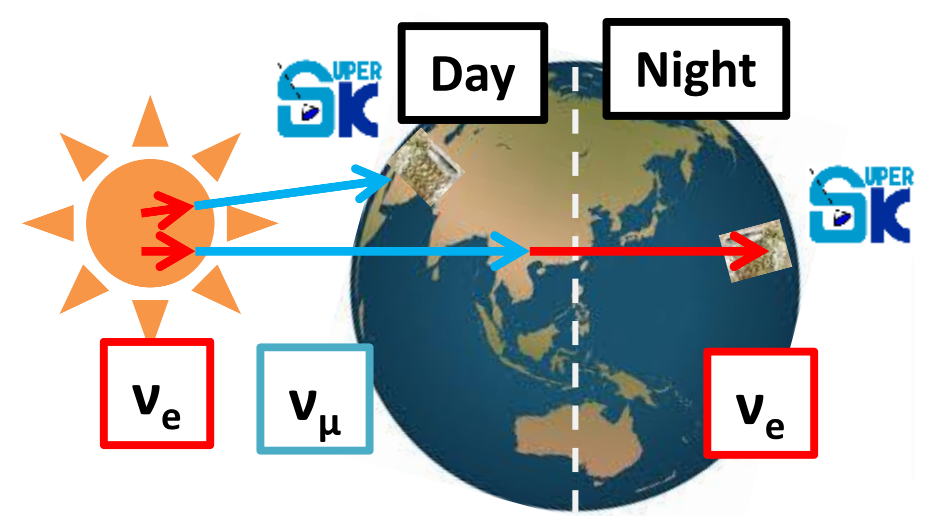
Solar neutrinos

- Intense neutrinos from nuclear fusion in the Sun's core
  - High statistics measurements
- Sensitive to θ_{12} and Δm^2_{21}
- Precision test of the MSW oscillation model
  - Precise measurement of spectrum at the vacuum-to-matter transition "up-turn"
    - Matter effect in the sun
  - Measurement of Day/Night flux asymmetry
    - Matter effect in the earth's core

Solar ν_e survival probability



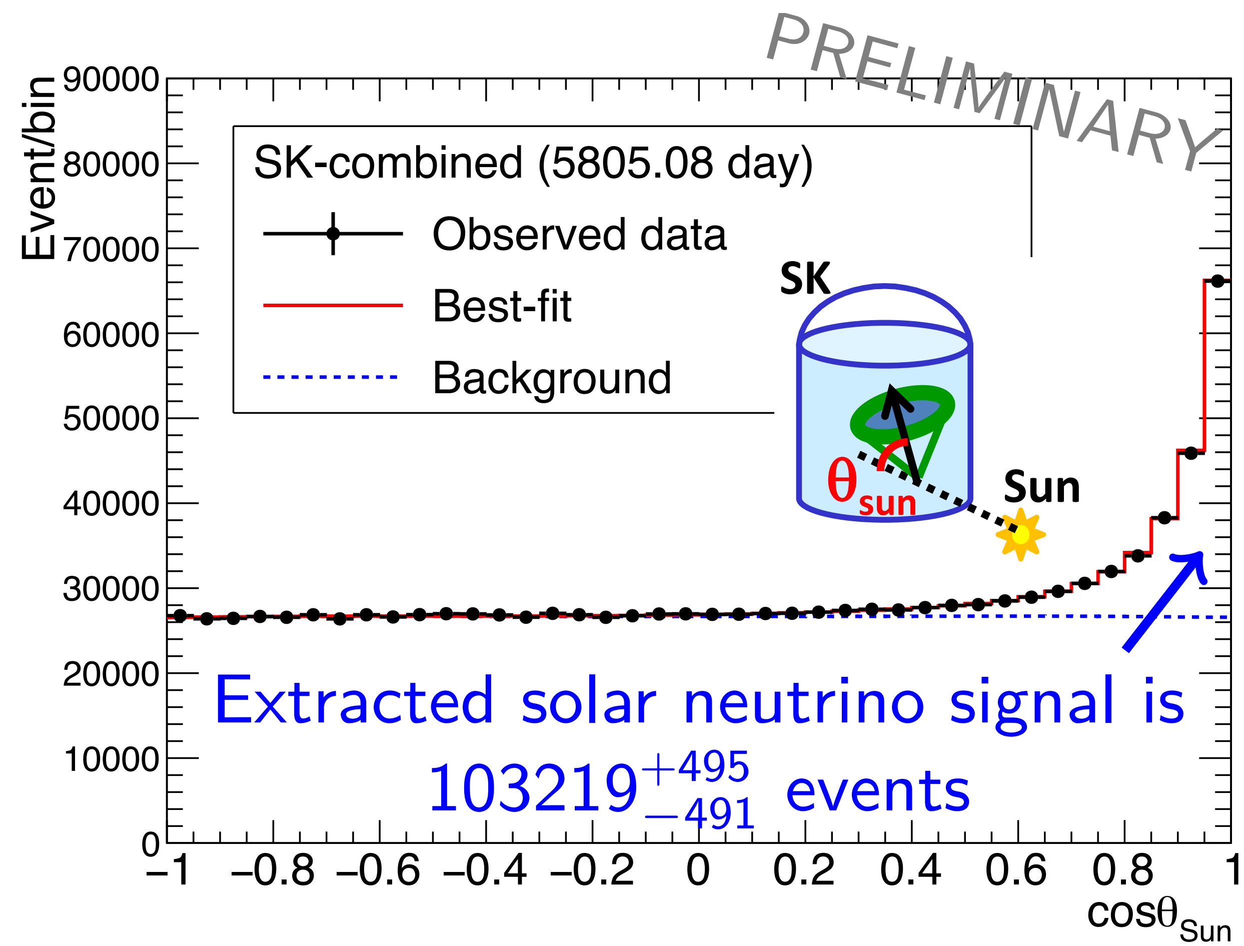
Day-Night flux asymmetry

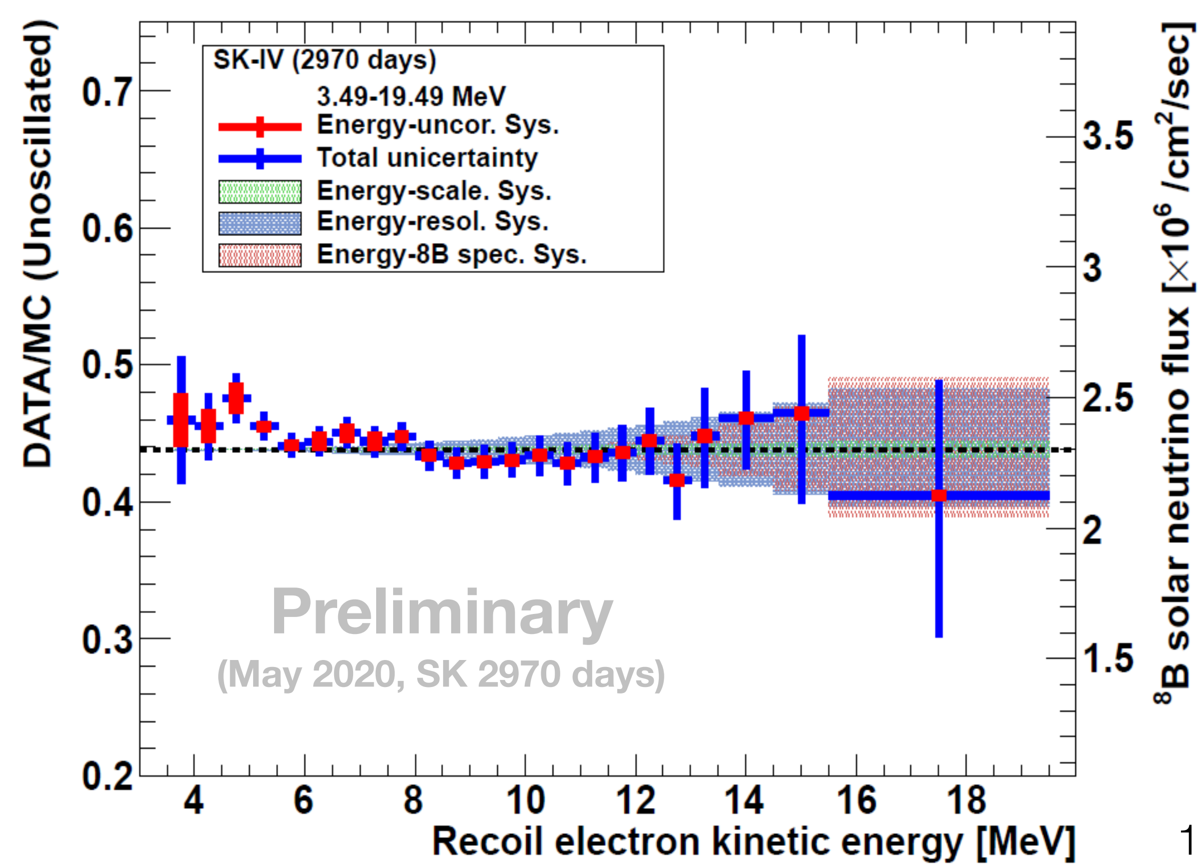


Regenerate ν_e with Earth's matter effect

Solar ν observation in SK

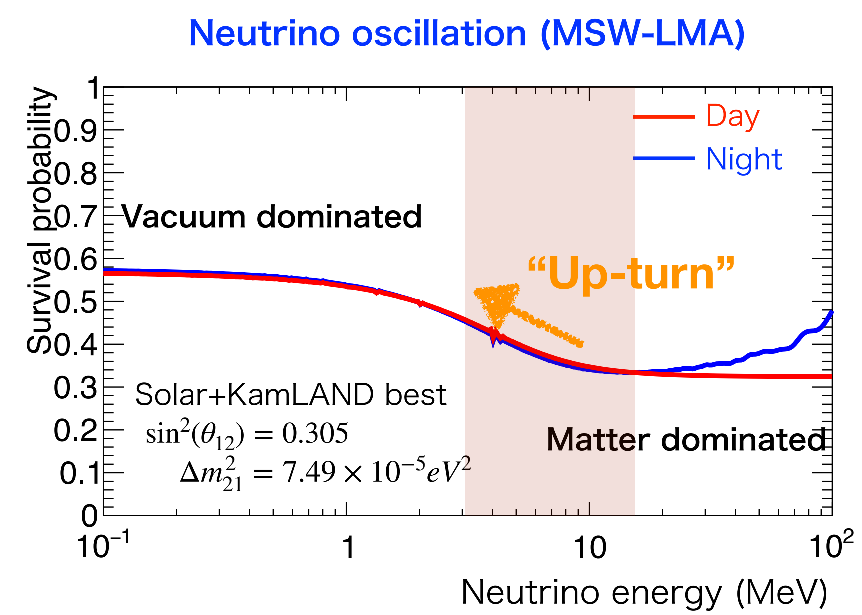
- Super-K's measurement of solar neutrinos
  - Detecting recoil electron from elastic scattering
  - Robust signal extraction using angular correlation with the Sun
- Total # of observed solar ν events: >10^5 in SK-I~IV (5805 days)

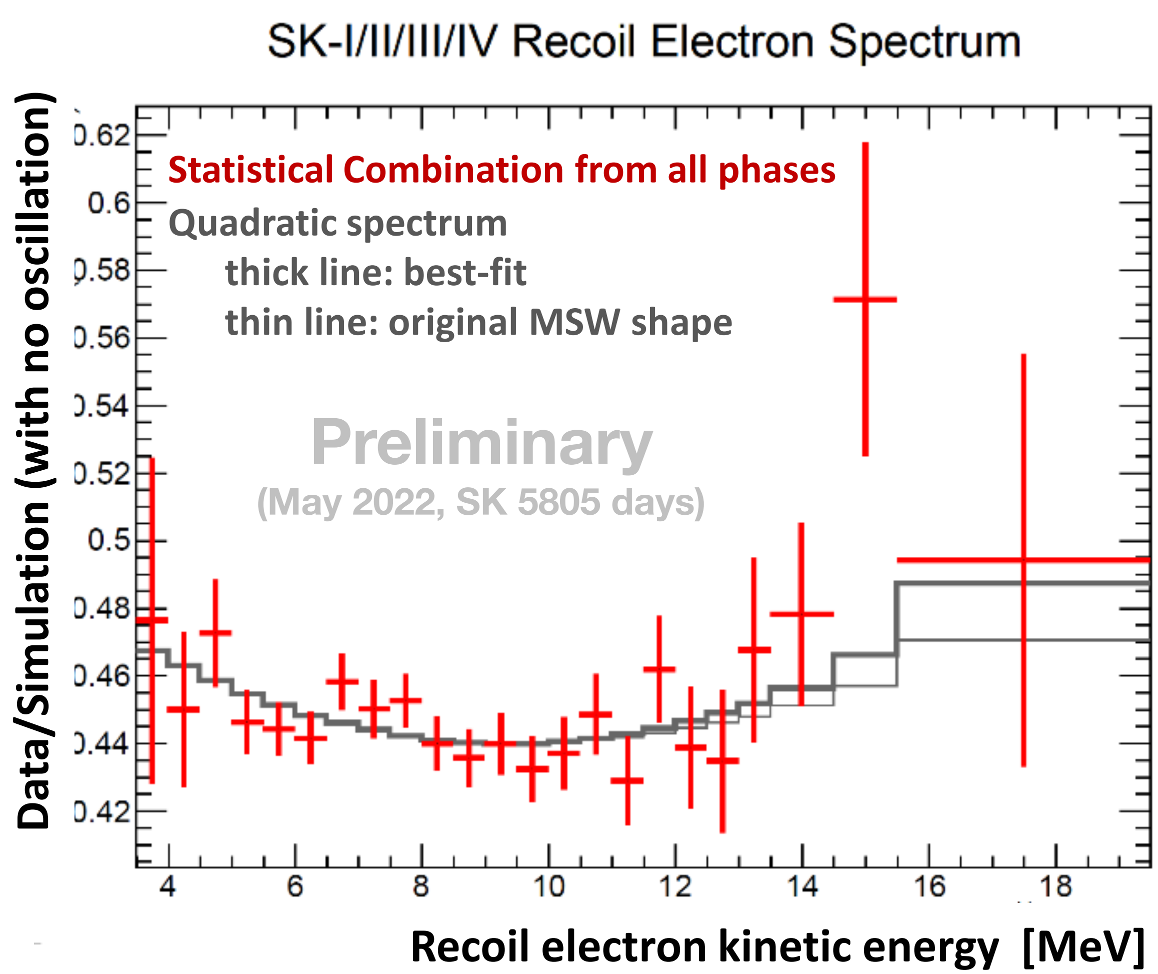


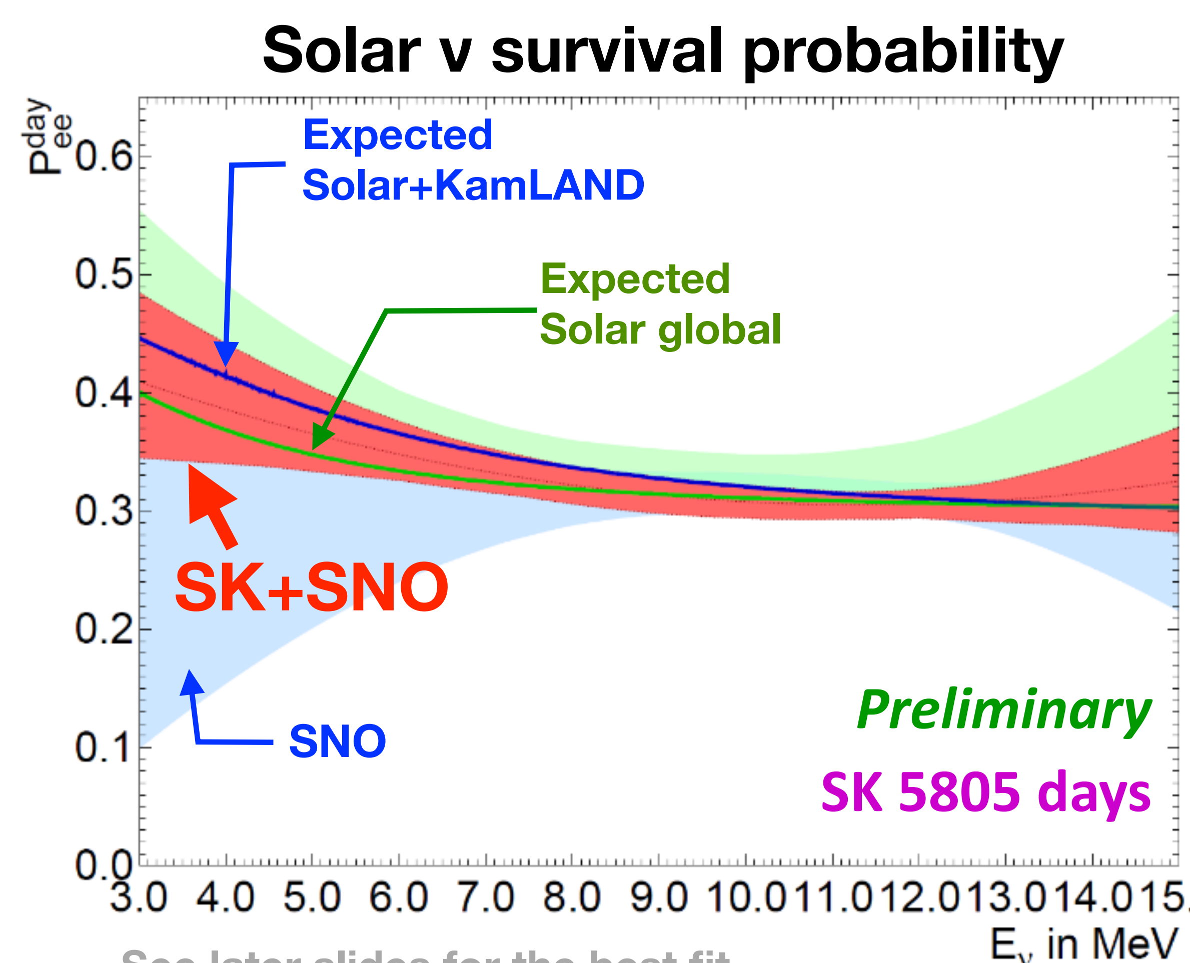


Solar ν spectral fitting

- SK-I~IV 5,805 live days data
  - Include several analysis improvements, e.g. improved systematics, etc.
- Energy spectrum slightly favors "up-turn"
  - though need more data
- Trying to lower the energy threshold (see next slide)



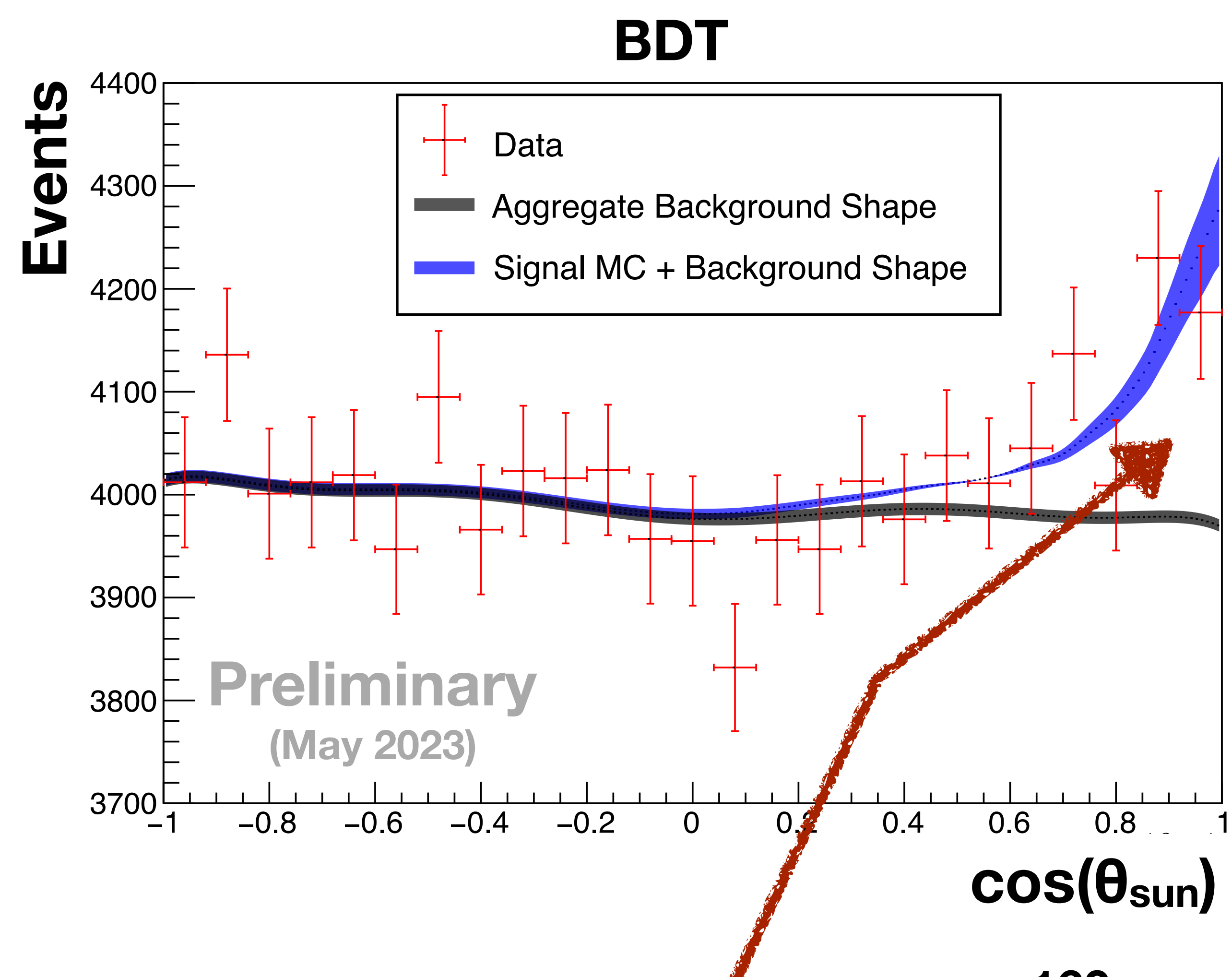




See later slides for the best fit oscillation parameters

Solar ν signal with lowest energy in SK

- An attempt to further lower the energy threshold
- Use Wideband Intelligent Trigger (WIT) data in SK-IV
    - 622 live days data
    - Recoil electron kinetic energy 2.49 MeV - 3.49 MeV
- Applied a boosted decision tree (BDT) event selection
    - Fed standard reconstruction variables used in the traditional solar analysis
    - ~6 times better background rejection comparing to the traditional solar analysis
- A clear peak pointing to the Sun

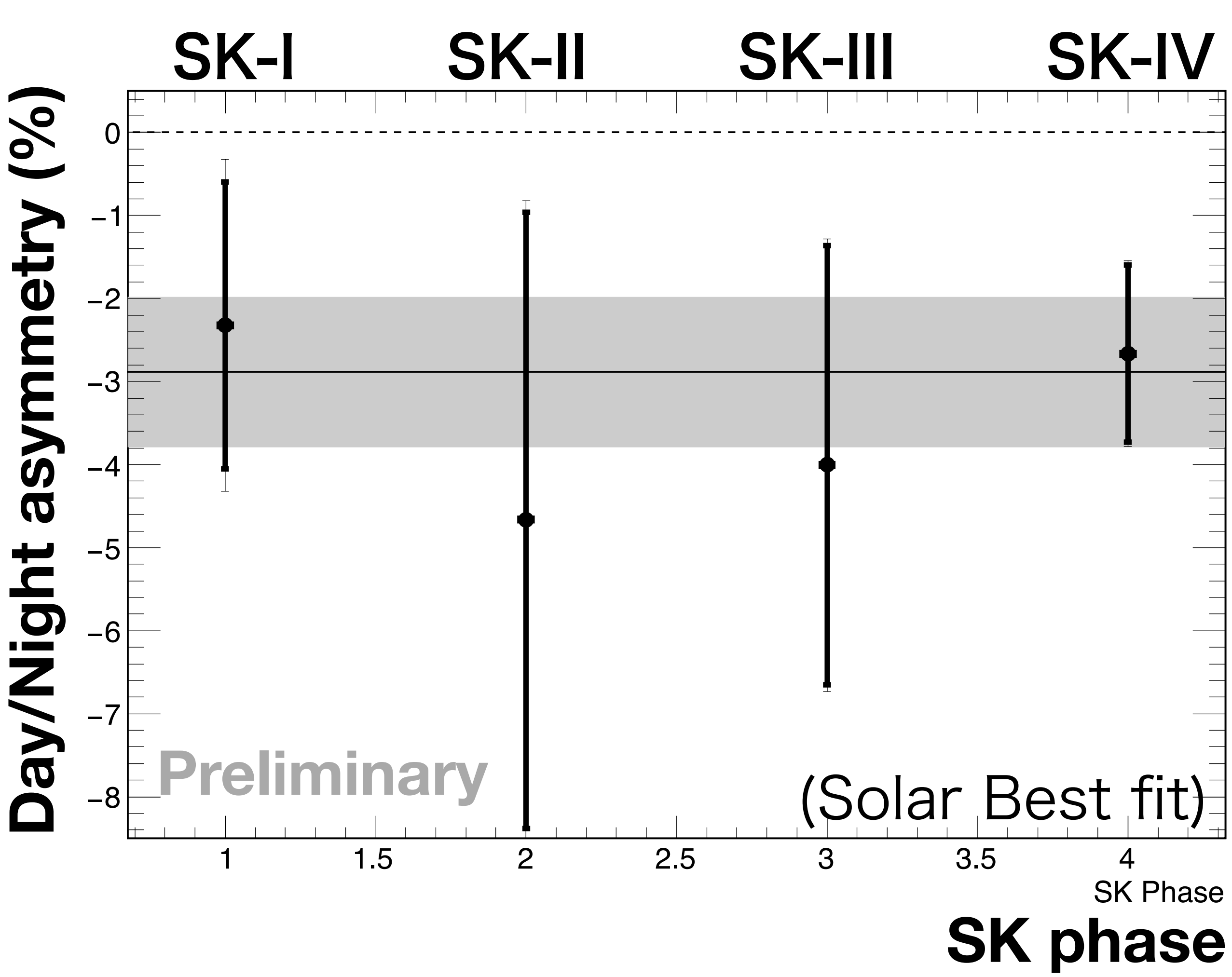


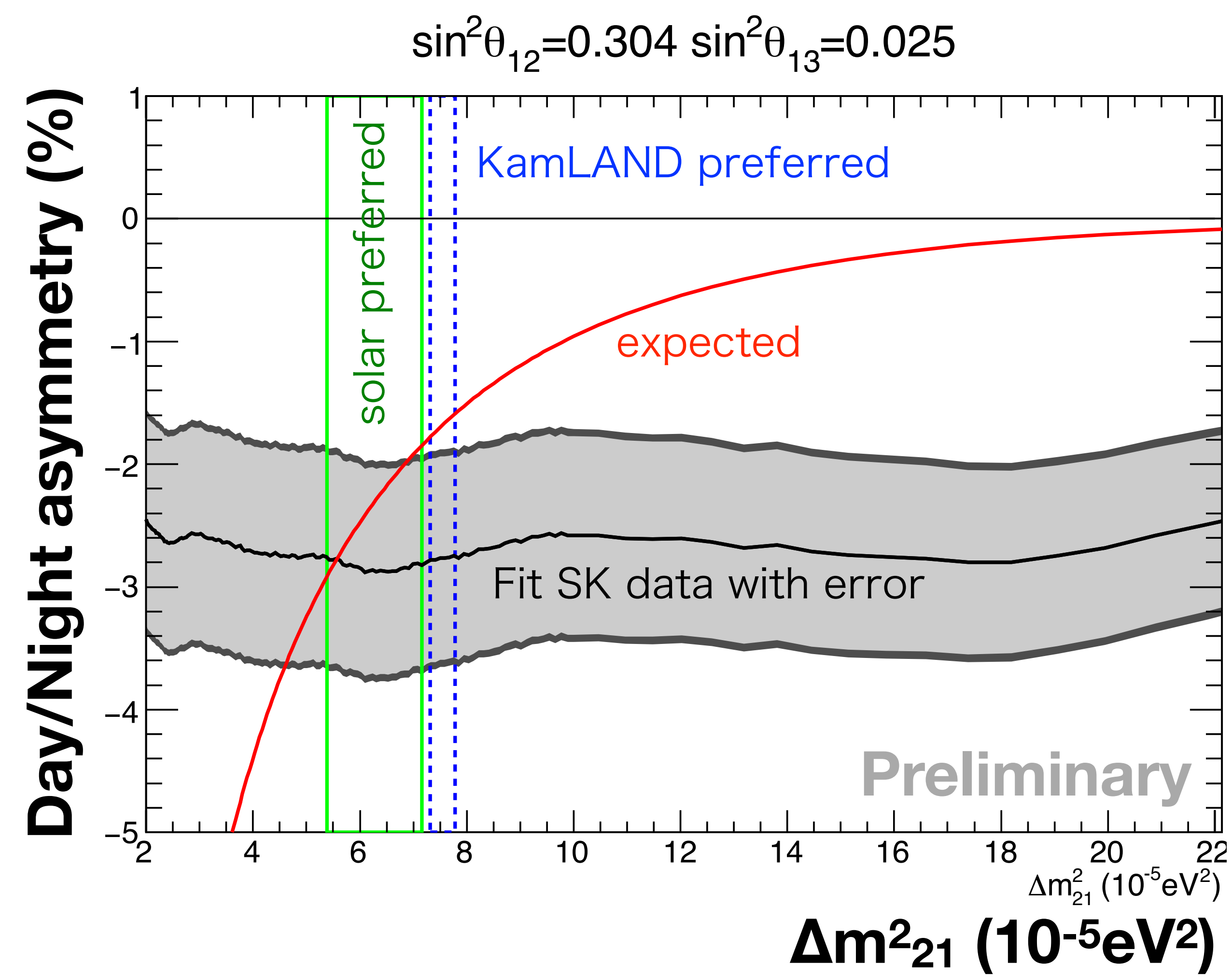
# of signal events: 790 $^{+160}_{-150}$

- **References:**
    - 10.5281/zenodo.6759244
    - J. Phys. Conf. Ser. 888, 012189 (2017)

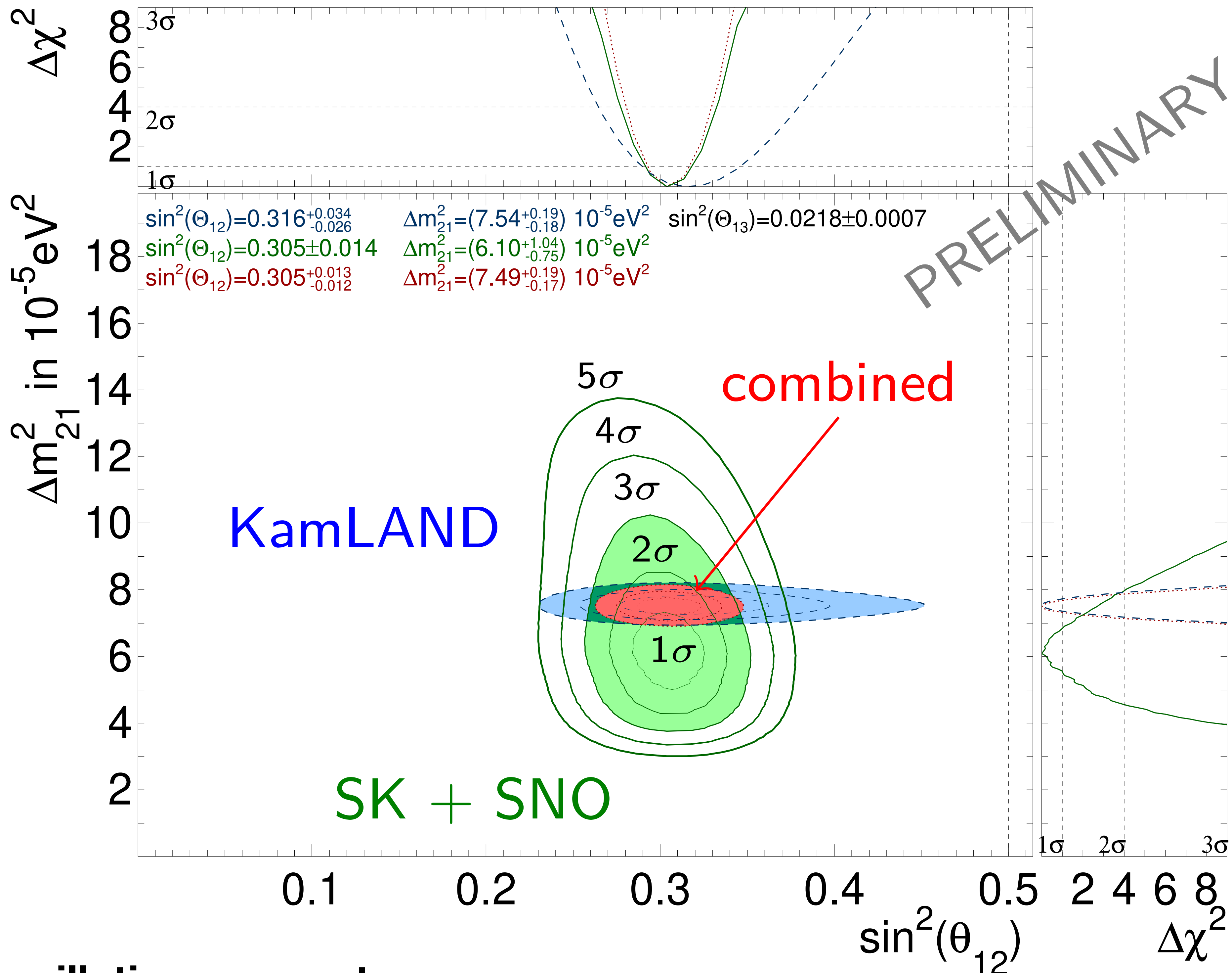
Day/Night flux asymmetry

- Day/Night flux asymmetry: $A_{D/N} = \frac{\Phi_{day} - \Phi_{night}}{0.5(\Phi_{day} + \Phi_{night})}$
  - Expected D/N asymmetry ~3% in the SK energy region
- SK confirmed a higher solar ν flux at night than that at daytime with **significance of 3.2σ for the Solar best fit, 3.1σ for the Global best fit**





Solar ν oscillation parameter extraction

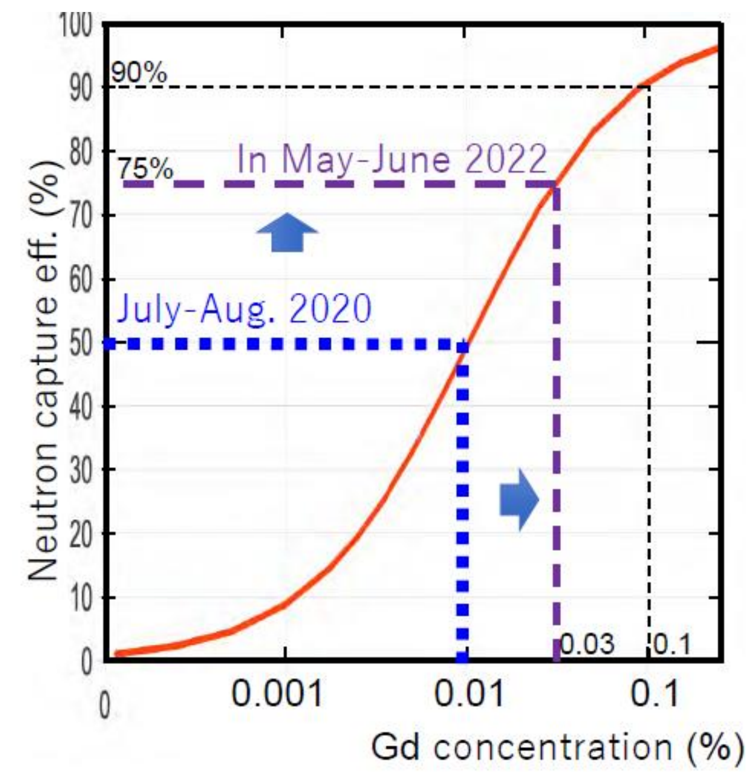


Best fit oscillation parameters

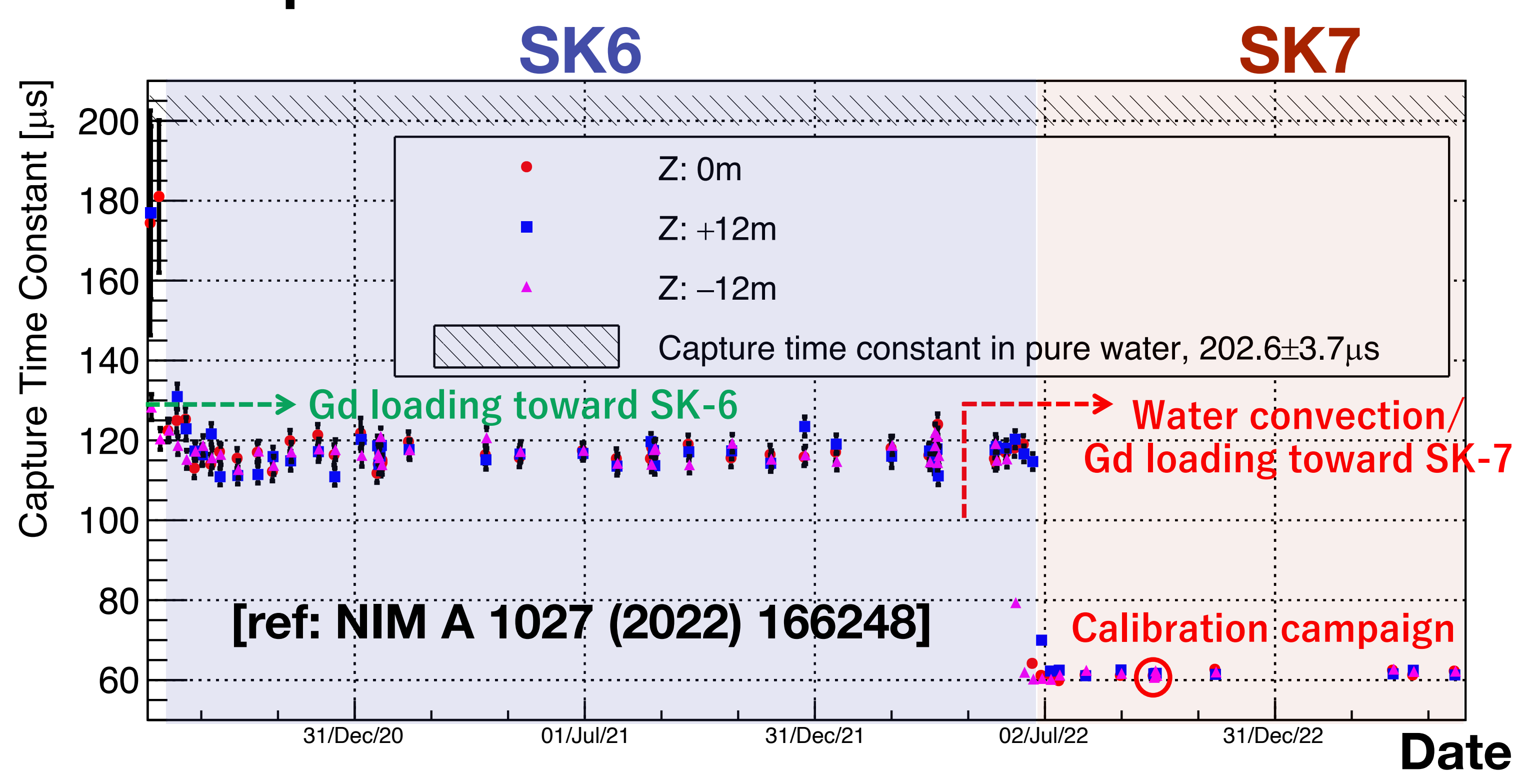
Experiment	$\sin^2\theta_{12}$	Δm^2_{21}
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18} \times 10^{-5}$ eV^2
SK + SNO	0.305 ± 0.014	$6.10^{+1.04}_{-0.75} \times 10^{-5}$ eV^2
Combined	$0.305^{+0.013}_{-0.012}$	$7.49^{+0.19}_{-0.17} \times 10^{-5}$ eV^2

- There is ~1.5σ tension between SK+SNO and KamLAND in Δm^2_{21}

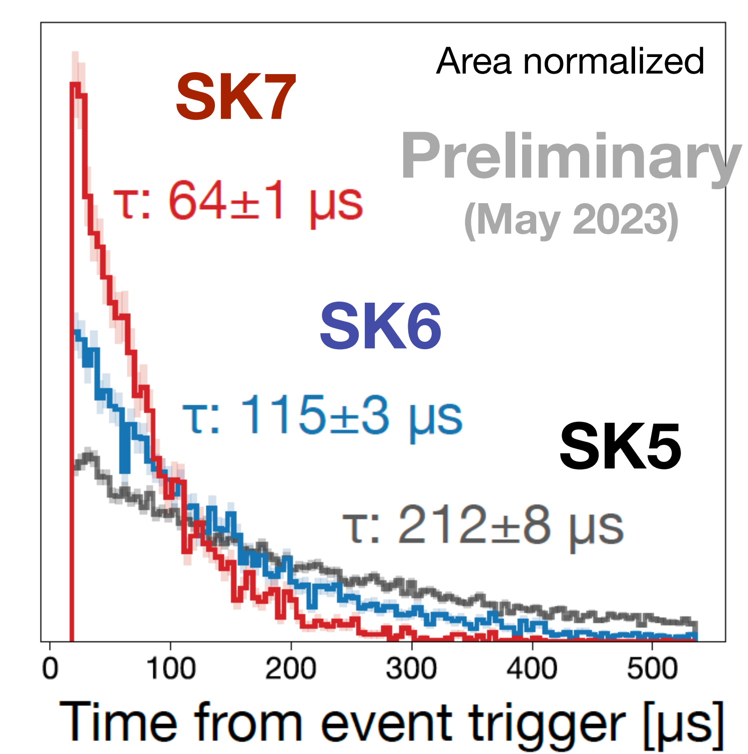
- SK-Gd: add Gd to ultrapure water to enhance neutron tagging efficiency
- Physics targets:
  - Detect the world's first Supernova Relic Neutrino (SRN)
  - Enhance ν and ν̄ identification in atmospheric ν and T2K analyses
  - Reduce background in nucleon decay search
- Gd concentration in each SK phase
  - **SK-6** (Aug. 18, 2020~): 0.011%→ **~50% n-Gd capture eff.**
  - **SK-7** (July 5, 2022~): 0.03%→ **~75% n-Gd capture eff.**
- Observed clear increase of neutron candidates and shorter capture time
- Confirmed uniformity of Gd concentration over SK detector and its stability over time



n-capture time with AmBe calibration source



n-capture time in atm-ν events



Summary

- SK atmospheric and solar neutrino oscillation analyses keep improving
  - **Atmospheric neutrino**: new results with full SK pure water phase data (SK-I~V) and with expanded fiducial volume — new paper in preparation
  - **Solar neutrino**: lowering the energy threshold to 2.49MeV (kinetic energy) aiming to see the “up-turn”

- SK-Gd phase began in 2020, and SK continues the stable operation
  - Expect several improvements in oscillation analyses and nucleon decay search
  - Observed clear signal of neutron capture on Gd in SK-VI and SK-VII
  - Many analysis developments on-going