Recent results and future prospects from Super-Kamiokande

Yasuhiro Nakajima (ICRR, the University of Tokyo)
on behalf of the Super-Kamiokande collaboration

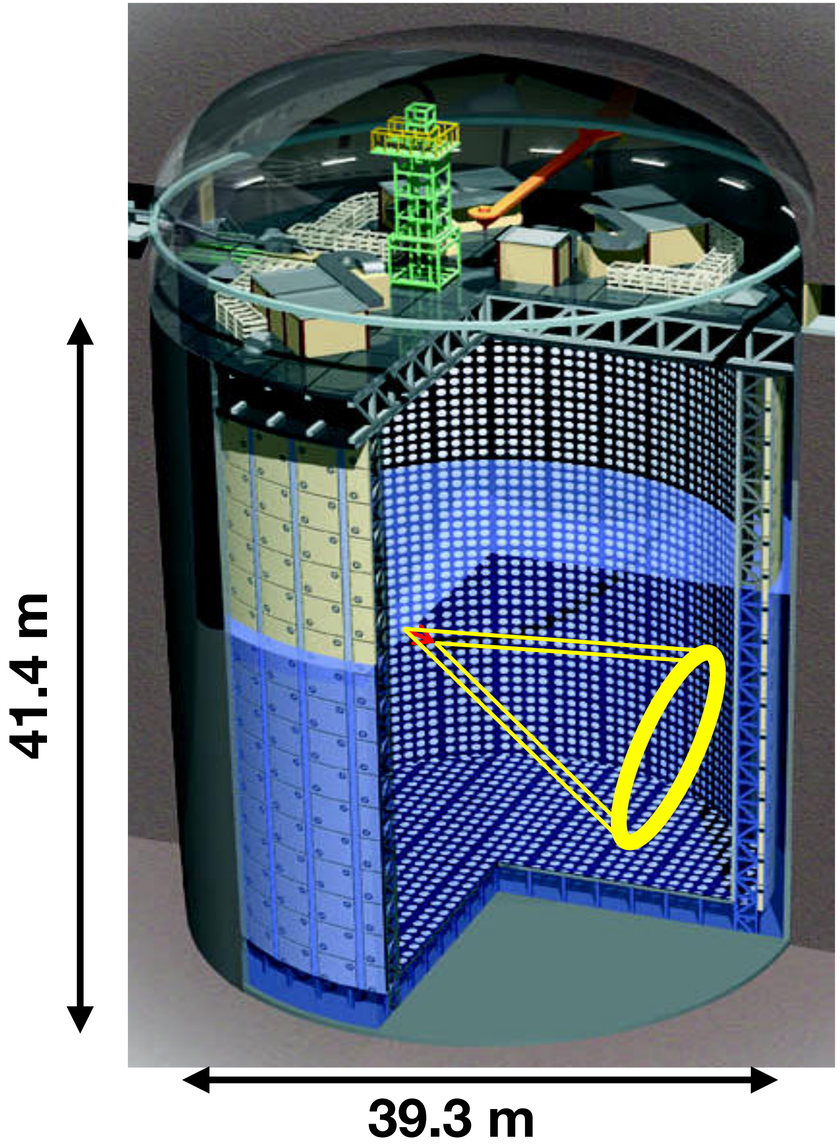
The XXIX International Conference on Neutrino Physics and Astrophysics (NEUTRINO2020)
June 30, 2020

The Super-Kamiokande Collaboration

~190 collaborators from 49 institutes in 10 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
Imperial College London, UK
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
Queen Mary University of London, 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
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

Super-Kamiokande

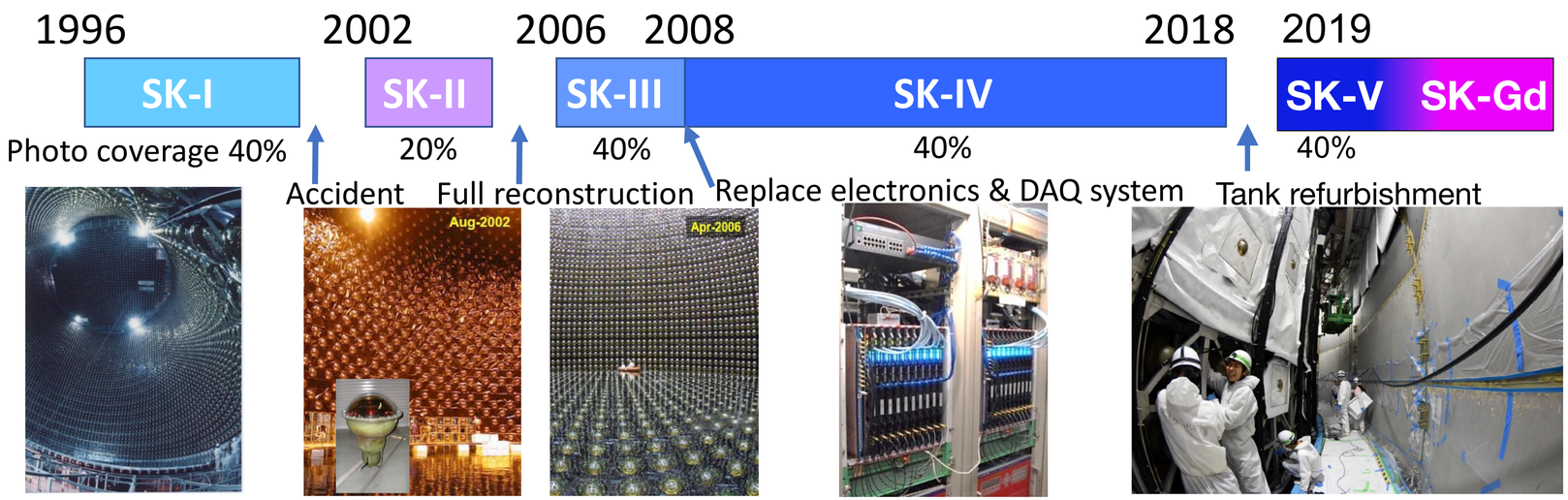


- 50-kton water Cherenkov detector located at Kamioka, Japan
- Overburden: 2700 mwe
- Inner Detector covered by > 11000 20-inch PMTs
- Studying neutrinos from wide variety of sources
  - Solar neutrinos
  - Supernova neutrinos
  - Atmospheric/Accelerator neutrinos

~ MeV

~ GeV

- Operational since 1996, transitioning to SK-Gd



Super-Kamiokande Gadolinium Project (SK-Gd)

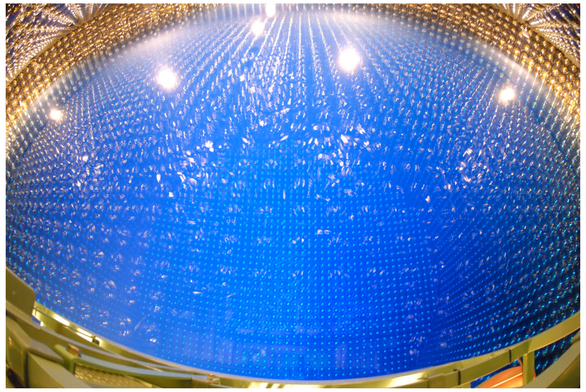
- Dissolving Gd to Super-Kamiokande to significantly enhance detection capability of neutrons from ν interactions

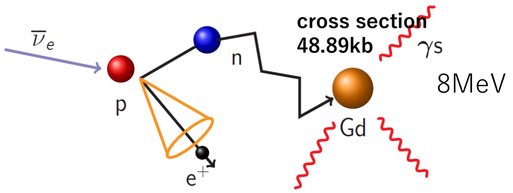
  J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. 93 (2004) 17110

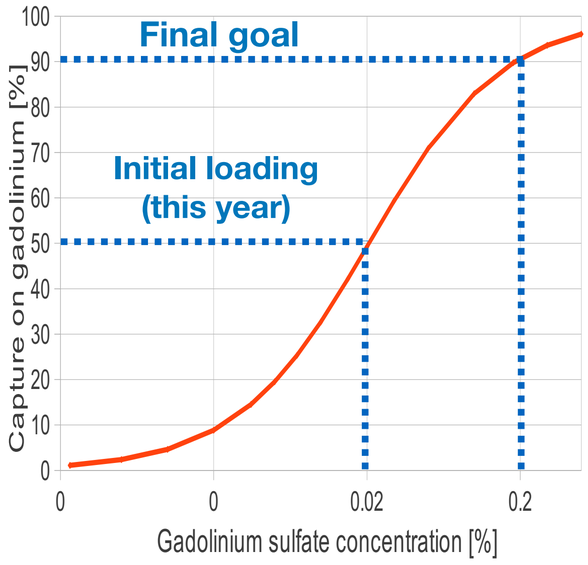
- Aiming for the **first observation of Diffuse Supernova Neutrino Backgrounds**
- Also aiming for:
  - Improving pointing accuracy for galactic supernova
  - Precursor of nearby supernova by Si-burning neutrinos
  - Reducing proton decay background
  - Neutrino/anti-neutrino discrimination (Long-baseline and atmospheric neutrinos)
  - Reactor neutrino measurements
- As the first step, loading 0.02% of $Gd_2(SO_4)_3$ in 2020

  ~50% n-capture on Gd

+







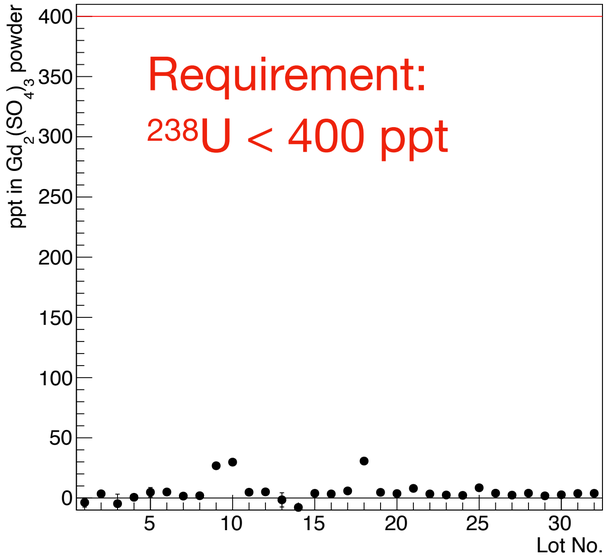
R&D Challenges (RI in Gd powder)

- Radio impurities in Gd power could introduce additional backgrounds to solar and supernova neutrinos
- Stringent requirement for RI imposed
- Developed methods to evaluate low concentration RI
  - PTEP 2017 (2017) 11, 113H01
  - PTEP 2018 (2018) 9, 091H01
  - arXiv: 2006.09664
- Screened at multiple sites
  - ICP-MS: Kamioka
  - HPGe: Canfranc, Boulby and Kamioka
- Worked with production companies and achieved the required purity

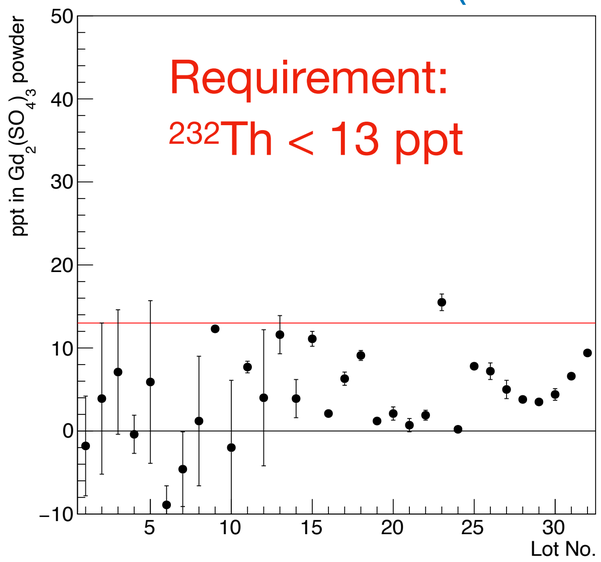
Radioactive impurities for $Gd_2(SO_4)_3$ powder [mBq/kg]

Chain	Isotope	SK-Gd requirements	
		For solar	For DSNB
^{238}U	^{238}U	—	< 5
	^{226}Ra	< 0.5	—
^{232}Th	^{228}Ra	< 0.05	—
	^{228}Th	< 0.05	—
^{235}U	^{235}U	< 30	—
	^{227}Ac/^{227}Th	< 30	—

U contamination (ICP-MS)



Th contamination (ICP-MS)



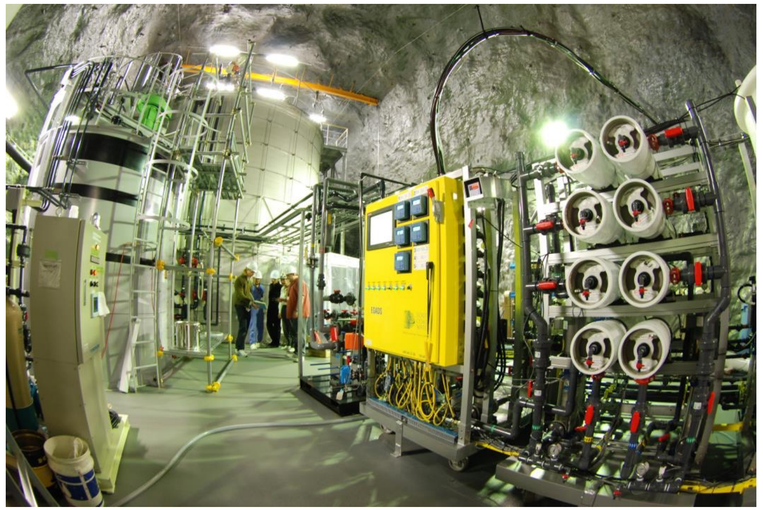
R&D Challenges (water purification)

- Challenge: remove impurities *without* removing Gd
- Two systems developed and tested with a 200 m^3 tank (EGADS)
  - "Band-pass" system with nano-filter
  - Special resin-based system

Both successfully kept water transparency at the current SK level without losing Gd

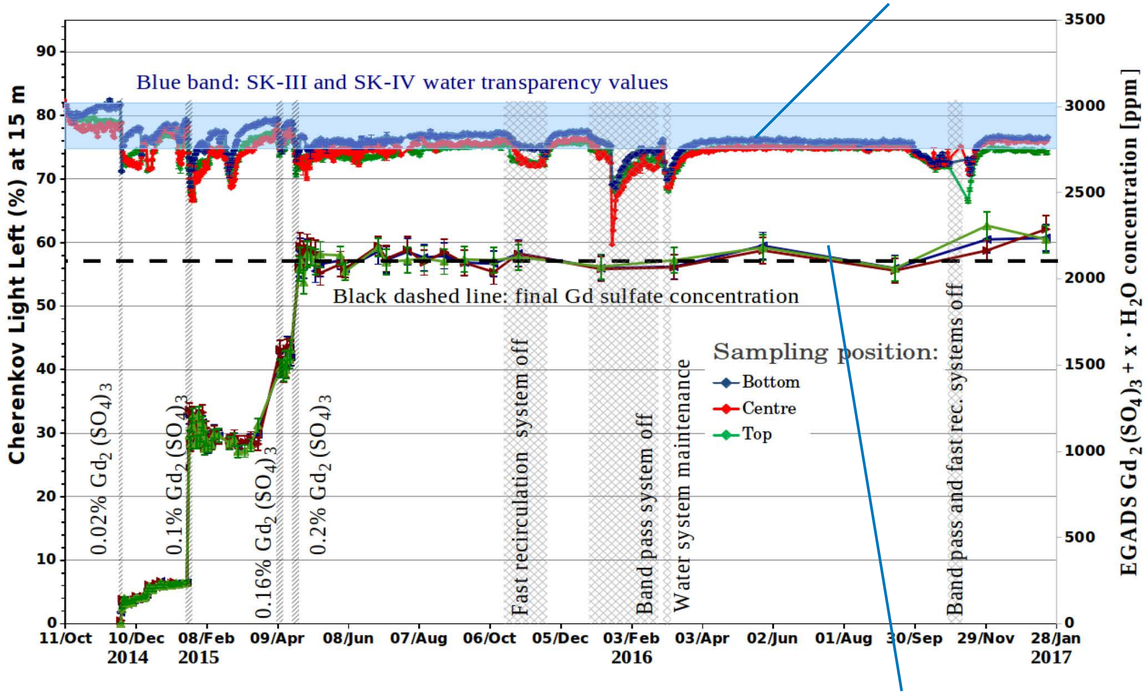
Nucl.Instrum.Meth.A 959 (2020) 163549

- Constructed a dedicated Gd-dissolving and Gd-water purification system for Super-Kamiokande



200 m^3 tank (EGADS)

Water transparency

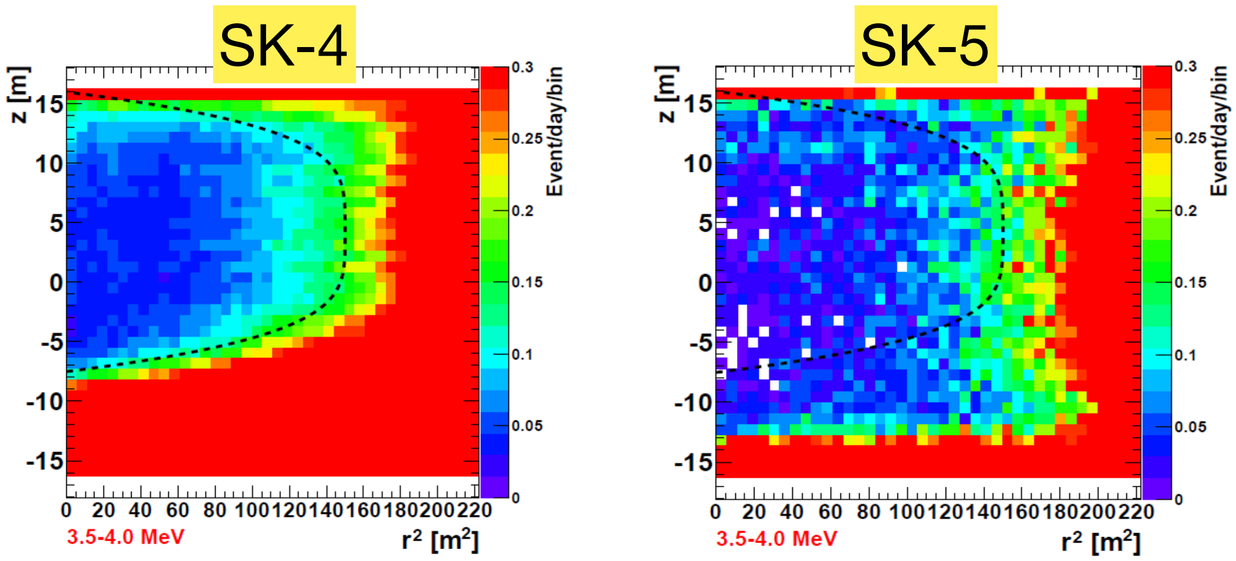


Gd concentration

SK detector preparation

- Major refurbishment work 2018-2019:
  - Stopped water leak: < 1/200 of before (~1 m^3/d)
  - Many other improvements and cleaning
- SK-V operation (2019-):
  - The new Gd-water purification system tested with the real SK detector
    - Successfully kept water transparency at a level similar to previous phases
  - Water flow tuning: Suppressed convection and expanded low-background region

Event rate at 3.5-4.0 MeV

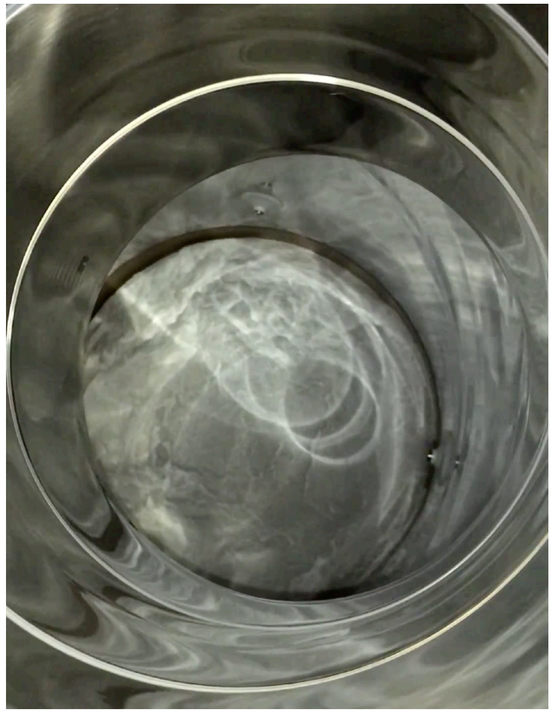


Ready, Set, …

- 14 tons of $Gd_2(SO_4)_3$ ($8H_2O$) powder for initial loading produced and screened
- The new water system is ready to process Gd-loaded water

Gd dissolving

- Commissioning of the new Gd dissolving system just started!
- Gd loading to Super-K will start *VERY* soon!



Recent results from Super-Kamiokande

New results at Neutrino 2020

- **Search for Diffuse Supernova Neutrino Backgrounds**
- **Solar neutrino oscillation measurements**
- **Atmospheric neutrino oscillation measurements**
- Multi-messenger astronomy:
  - Gravitational-wave event follow-up [Poster #161: M. Lamoureux]
  - Gamma-ray bust follow-up [Poster #85: M. Harada]
- Search for supernova bursts [Poster #136: M. Mori]
- Search for neutron-antineutron oscillation [Poster #43: L. Wan]

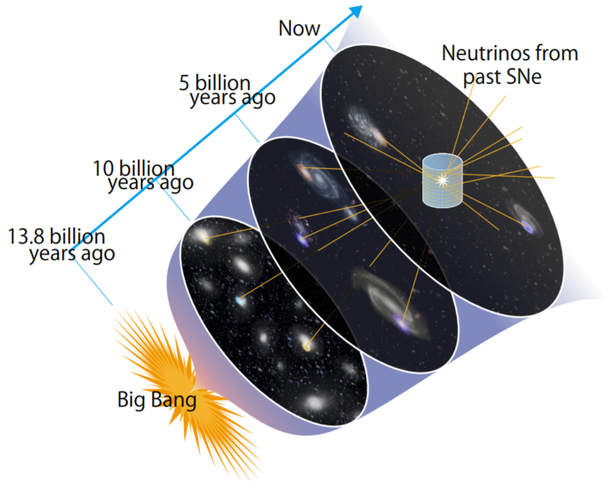
Recent publications (2019-)

- Phys. Rev. D 101, 052011 (2020), “Search for proton decay into three charged leptons in 0.37 megaton-years exposure of the Super-Kamiokande”
- Astrophys. J. Lett. 887, L6 (2019), “Search for Astronomical Neutrinos from Blazar TXS0506+056 in Super-Kamiokande"
- Astrophys. J. 885, 2 (2019), “Sensitivity of Super-Kamiokande with Gadolinium to Low Energy Antineutrinos from Pre-supernova Emission”
- Phys. Rev. D 99, 032005 (2019), “Measurement of the neutrino-oxygen neutral-current quasielastic cross section using atmospheric neutrinos at Super-Kamiokande”
- Prog. Theor. Exp. Phys. 2019, 053F01, “Atmospheric Neutrino Oscillation Analysis With Improved Event Reconstruction in Super-Kamiokande IV”

Supernova Neutrinos

Diffuse Supernova Neutrino Backgrounds

a.k.a Supernova Relic Neutrinos (SRN)



- Supernova burst neutrinos:
  - Rich physics observables once detected
  - No detection since 1987A. Most recent search in [Poster #136: M. Mori]
- **Diffuse Supernova Neutrino Backgrounds (DSNB)**:
  - Neutrinos produced from all the SN bursts and diffused in the current universe.

    ~ a few SN explosions every second

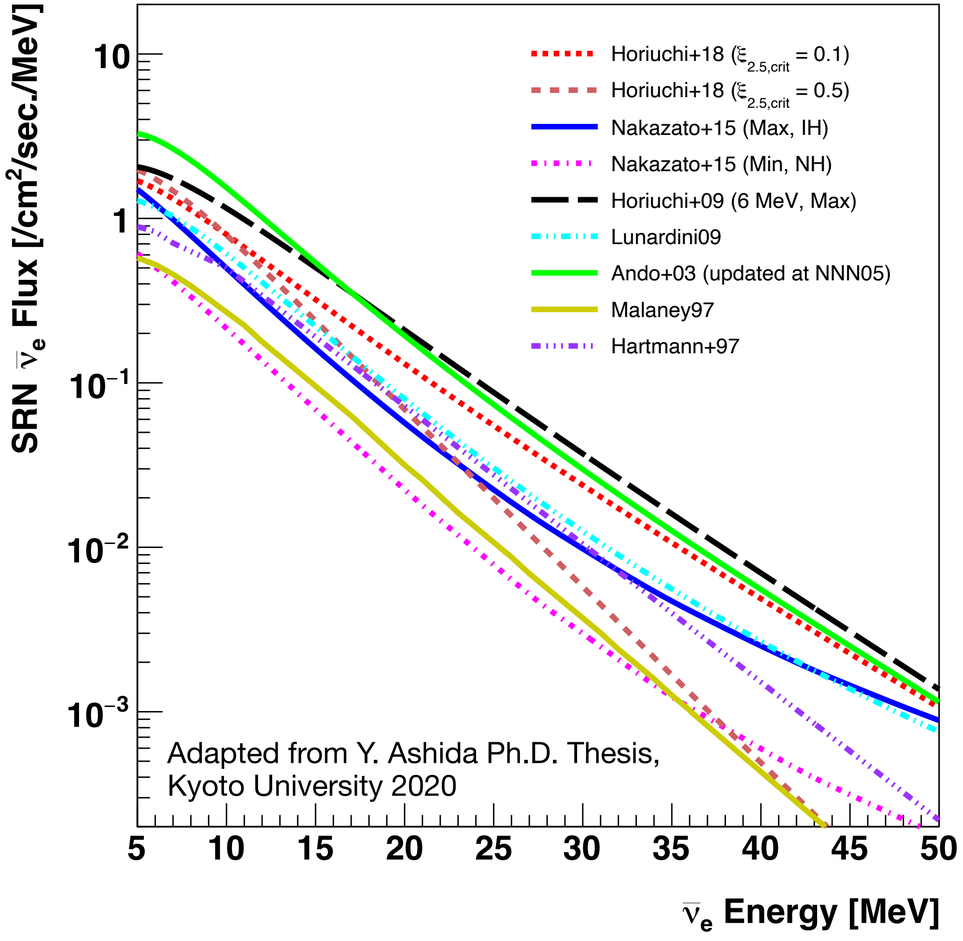
    O(10^{18}) SNe so far in this universe

  - Can study history of SN bursts with neutrinos

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\mathrm{SN}}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

z_{max} ~ 1 for SK energy range

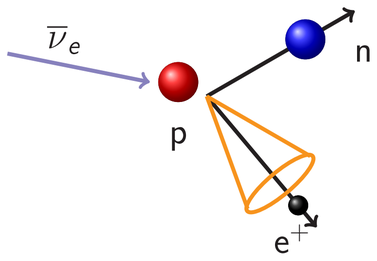
  - Many astrophysics and particle physics implications:
    - Contribution of failed supernova
    - Neutrino oscillation effect in dense medium
    - Galaxy evolution
    - Supernova burst mechanism



DSNB: Signal and Backgrounds

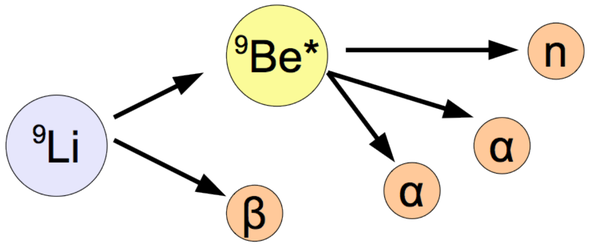
Rare event search: a few interactions / year / SK

- Primary signal: Inverse Beta Decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)

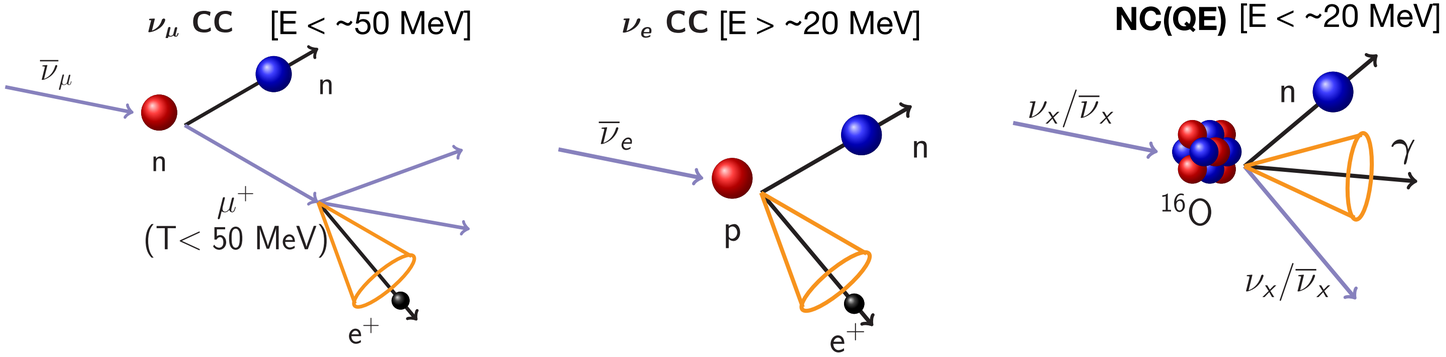


Detecting both position and neutron is the key to reduce backgrounds

- Backgrounds that mimic e^+ + n pair:
  - **^{9}Li (from cosmic μ spallation)** [E < ~15 MeV]



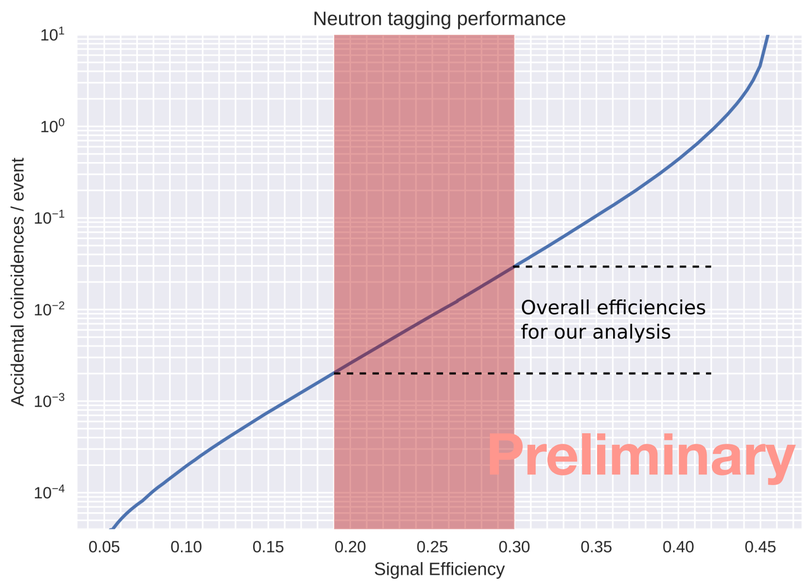
  - **Atmospheric neutrinos** [Poster #175: S. Sakai]

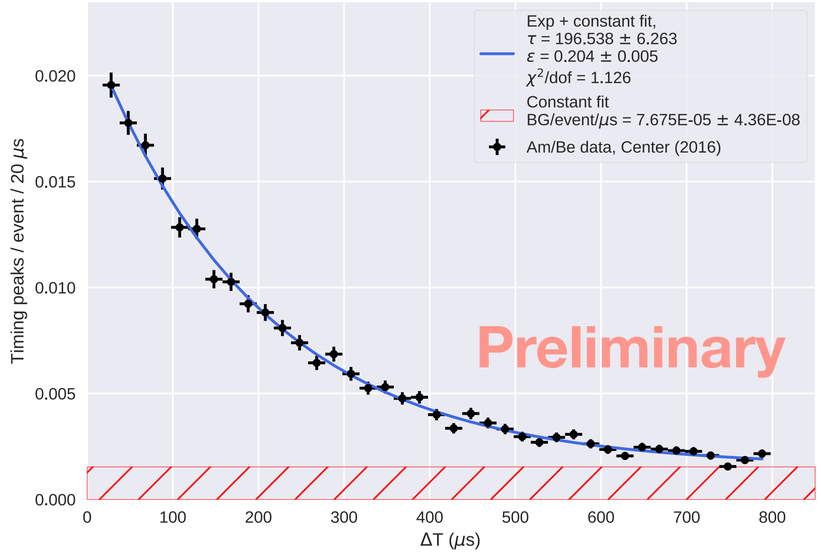


  - **Accidental coincidence (mostly spallation products + fake-neutrons)** [E < ~15 MeV]
  - **Reactor neutrinos** [E < ~10 MeV] [Poster #221: A. Goldsack]

Analysis method

- Employed neutron tagging:
  - Neutron signal in SK (pure water): 2.2 MeV γ from n-H capture
    - Very small (typically ~ 7 PMT hits) signal
    - Buried in radioactivity from the detector
  - Developed a neutron selection algorithm based on Boosted Decision Tree
    - 20-30% signal efficiency with 0.2-3% fake-tag rate
- Two methods for testing DSNB signal
  - Spectrum fit: Fit spectrum shape assuming a DSNB model
  - DSNB-model independent search: Test event excess for each reconstructed energy bin

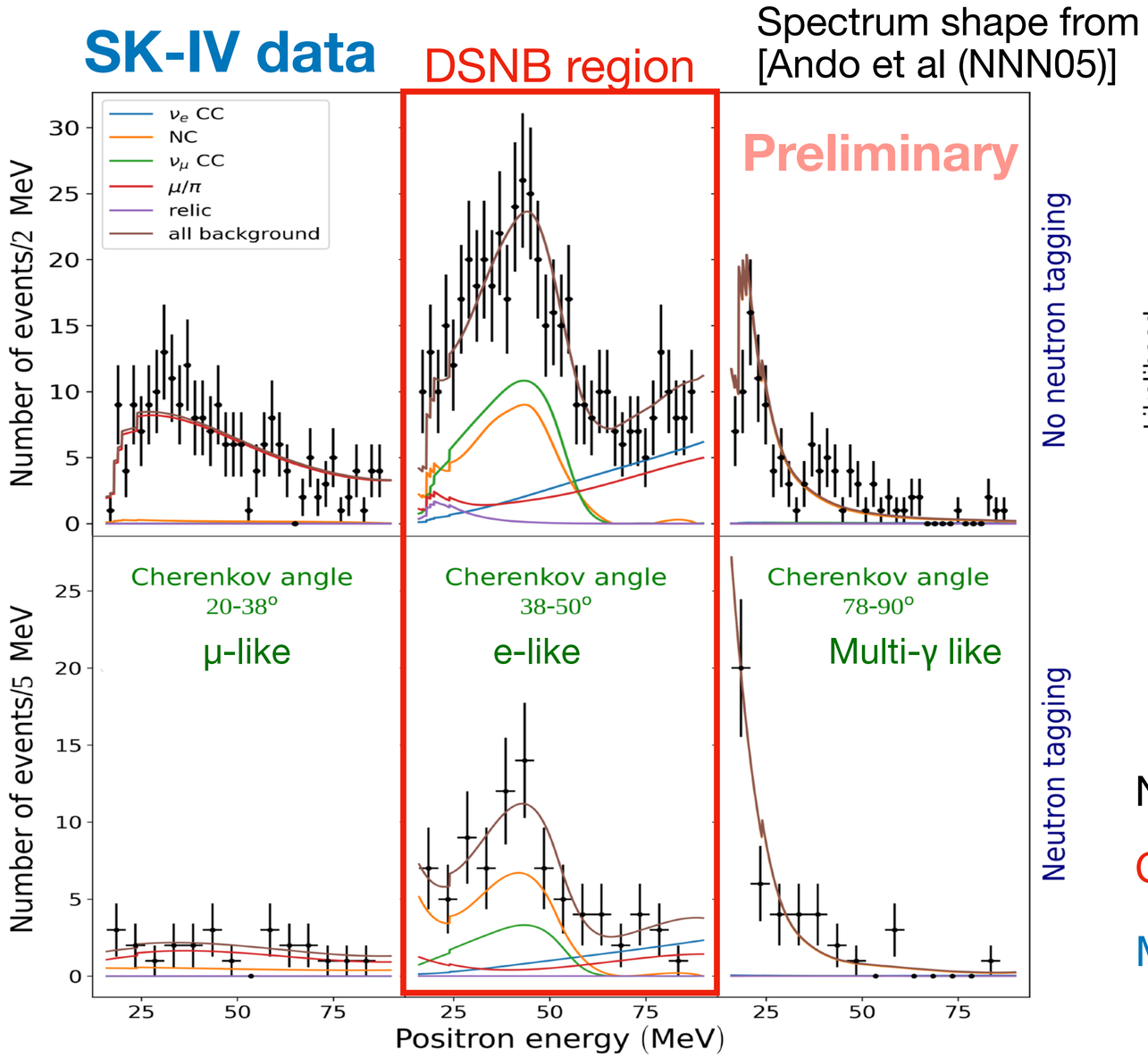




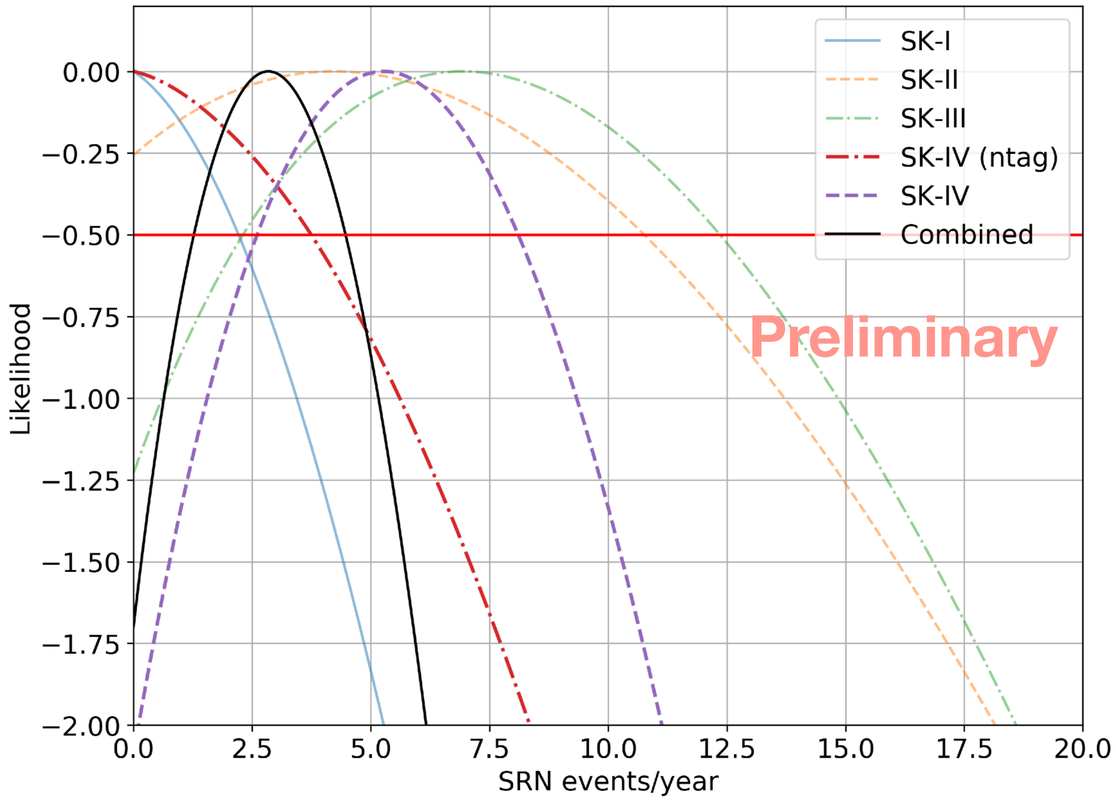
[Poster #231: S. El Hedri]

[Poster #231: S. El Hedri]

Spectrum fit result



E_p > 16 MeV



No significant excess observed

Combined limit: **ϕ < 2.7 cm^{-2}/s (90% CL) for E_p > 16 MeV**

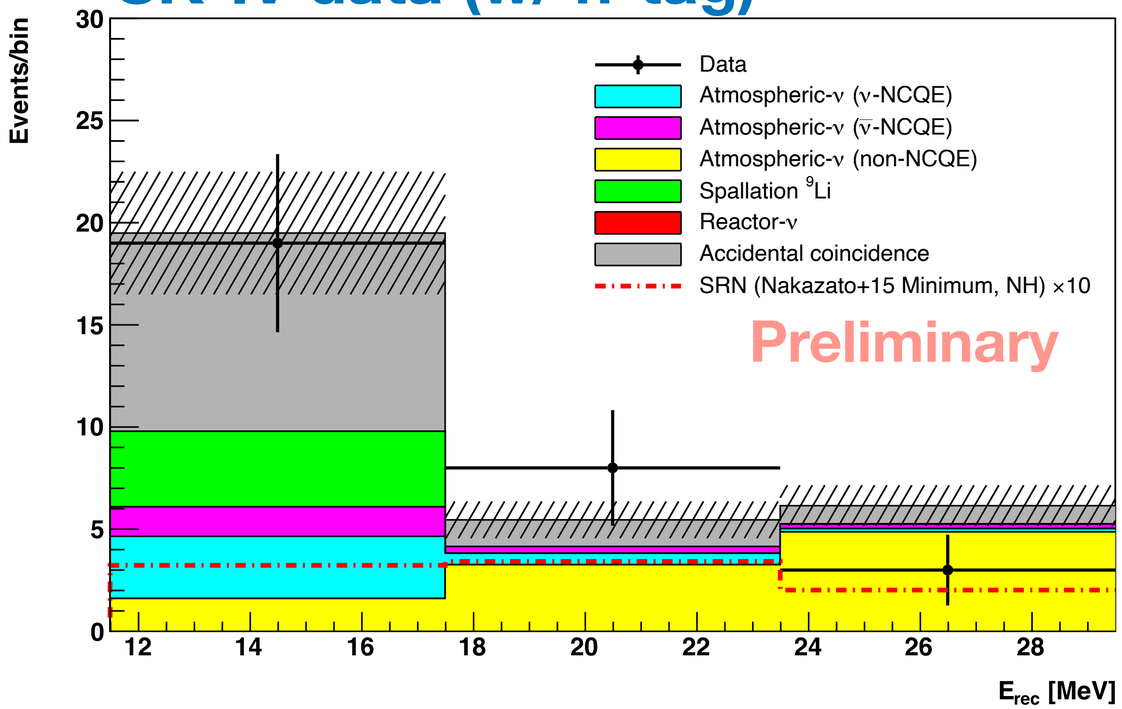
Model prediction: ϕ = 1.7 cm^{-2}/s [Ando et al (NNN05)]

Limit within a factor two of this prediction!

DSNB-model independent search

[Poster #231: S. El Hedri]

SK-IV data (w/ n-tag)



Search Results & Integrated SRN Electron Antineutrino Flux [/cm²/sec.]

E_ν region [MeV]	13.3–19.3	19.3–25.3	25.3–31.3
SK-IV 2970 days (Expected)	**9.48**	**1.35**	**0.82**
SK-IV 2970 days (Observed)	**9.08**	**2.22**	**0.35**
Horiuchi+18 ($\xi_{2.5,crit} = 0.1$)	1.583	0.553	0.173
Horiuchi+18 ($\xi_{2.5,crit} = 0.5$)	1.108	0.252	0.050
Nakazato+15 (Maximum, IH)	0.798	0.236	0.081
Nakazato+15 (Minimum, NH)	0.337	0.089	0.026
Horiuchi+09 (6 MeV, Maximum)	2.534	0.887	0.314
Lunardini09	1.032	0.321	0.098
Ando+03 (updated at NNN05)	2.652	0.796	0.261
Malaney97	0.469	0.125	0.034
Hartmann+97	0.947	0.297	0.093

: Models within a factor of 3

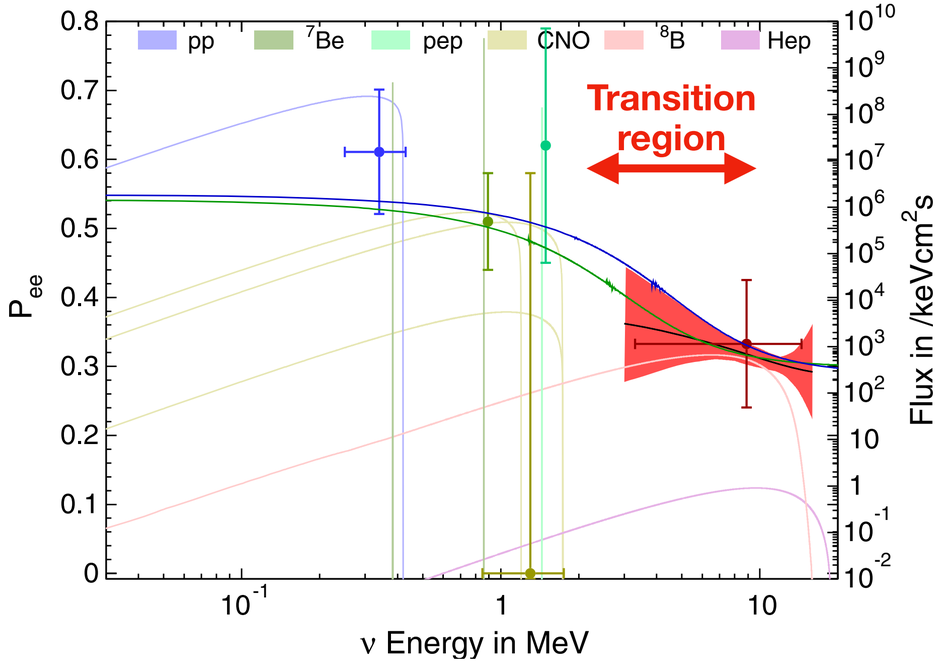
- No significant excess found
- Set one of the most stringent limits above 13.3 MeV
- Many model predictions are within several factors from the current limit
- Sensitivity limited by small statistics and backgrounds

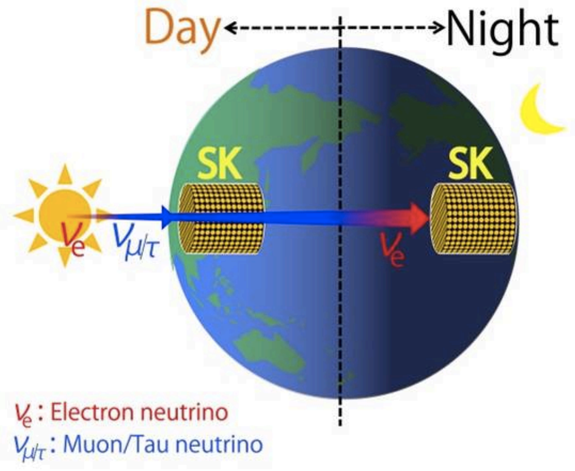
→Will be significantly improved with better neutron tagging in SK-Gd

Solar Neutrinos

Solar Neutrinos

- Intense neutrinos from nuclear fusion in the Sun's core
  - Majority (99%) from pp-chain with subdominant contribution from CNO cycle
- What's left in solar neutrinos?
  - Help understanding solar interior
  - **Precision test of the MSW oscillation model**
    - Precise measurement of spectrum at the vacuum-to-matter transition region
    - Measurement of Day/Night asymmetry
- Super-K's measurement of solar neutrinos
  - Detecting recoil electrons from elastic scattering
  - Robust signal extraction using angular correlation with the Sun
  - Current threshold for analysis: $E_{kin} > 3.5$ MeV





Super-K has been continuously improving analysis with more statistics

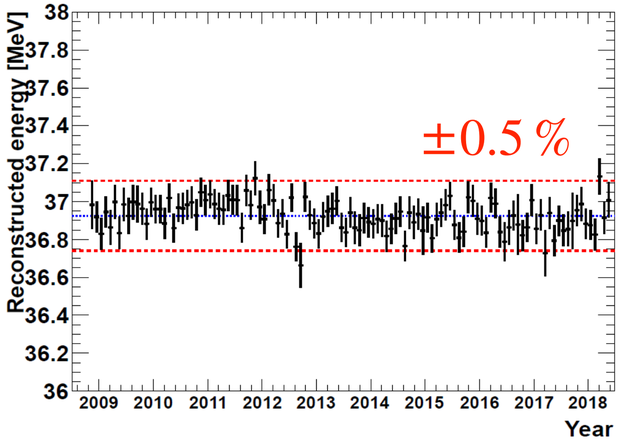
Analysis Improvements

- Detector simulation improvements [Poster #350: Y. Nakano]
  - Improved PMT hit timing simulation
  - Improved modeling of water quality non-uniformity
- Analysis improvements [Poster #350: Y. Nakano]
  - Correction for PMT gain drift (introduced in 2017)
  - Improved correction for non-uniform energy response

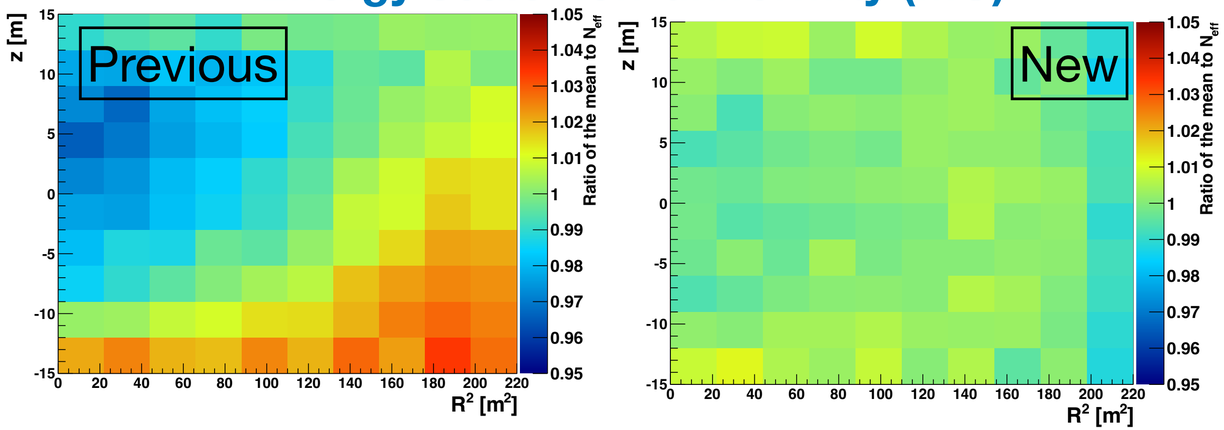
    E-scale non-uniformity (MC) 1.7% → 0.5%
- Improved spallation cut [Poster #166: S. Locke]
  - 12% more signal efficiency while keeping spallation rejection efficiency at a similar level (~90%)

    Gained ~1 year worth statistics

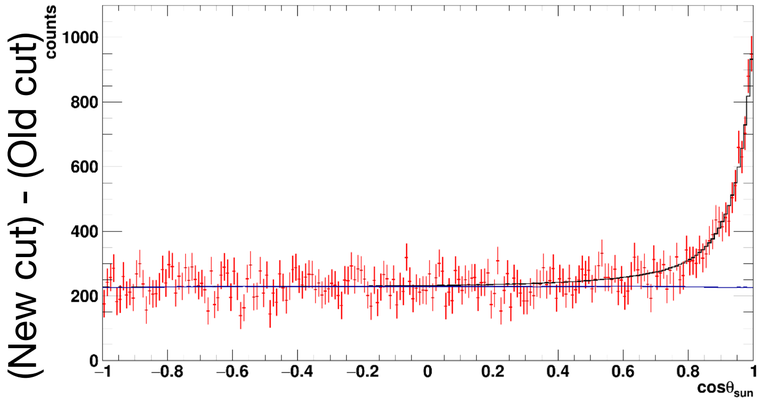
Energy scale stability (decay-e from cosmic μ)



Energy scale non-uniformity (MC)

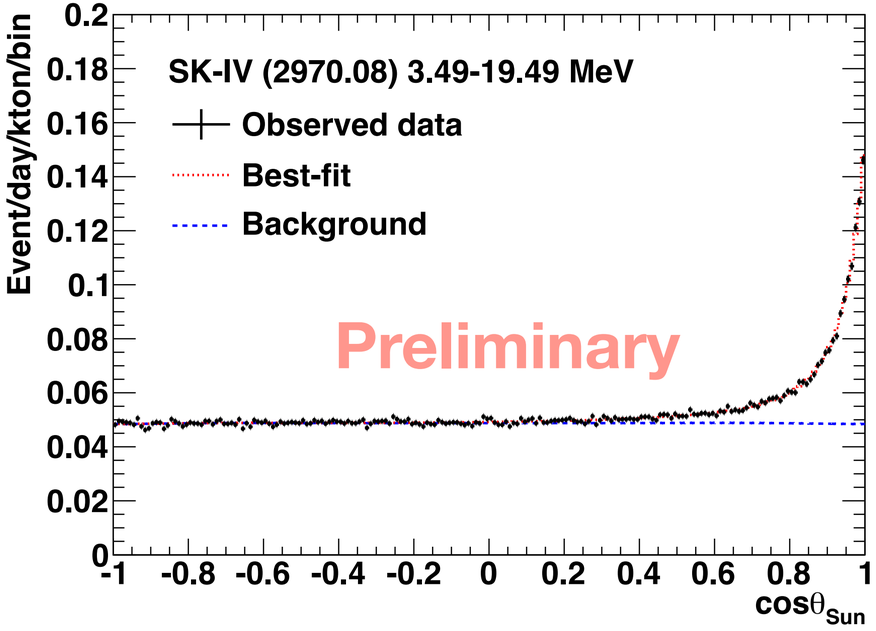


Additional events w/ new spallation cut

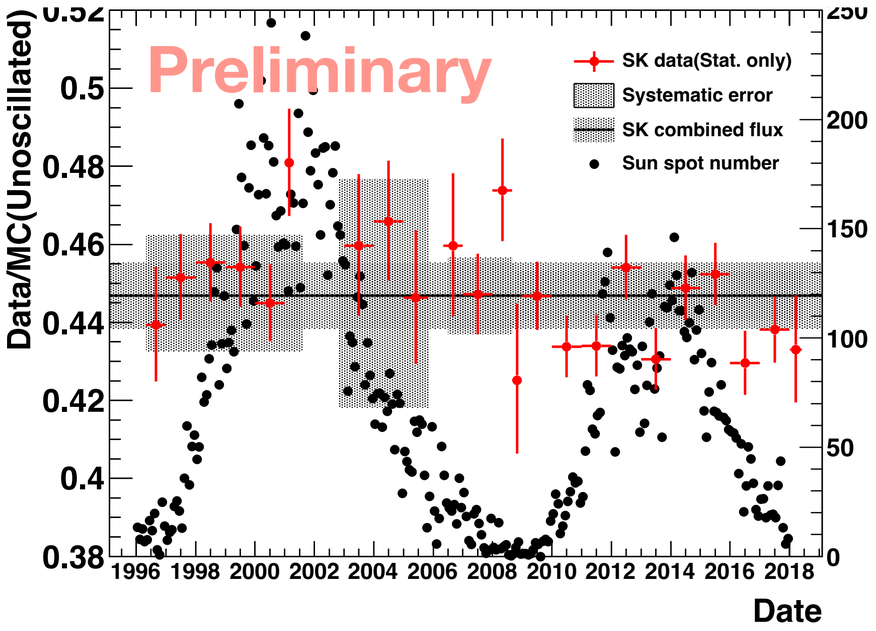


Solar neutrino flux

- Analysis using all the data up through SK-IV presented today
- 5805 live days from all (SK-I ~ SK-IV) period (2970 days in SK-IV)
- More than 100k ^{8}B (and HEP) solar neutrino interactions collected

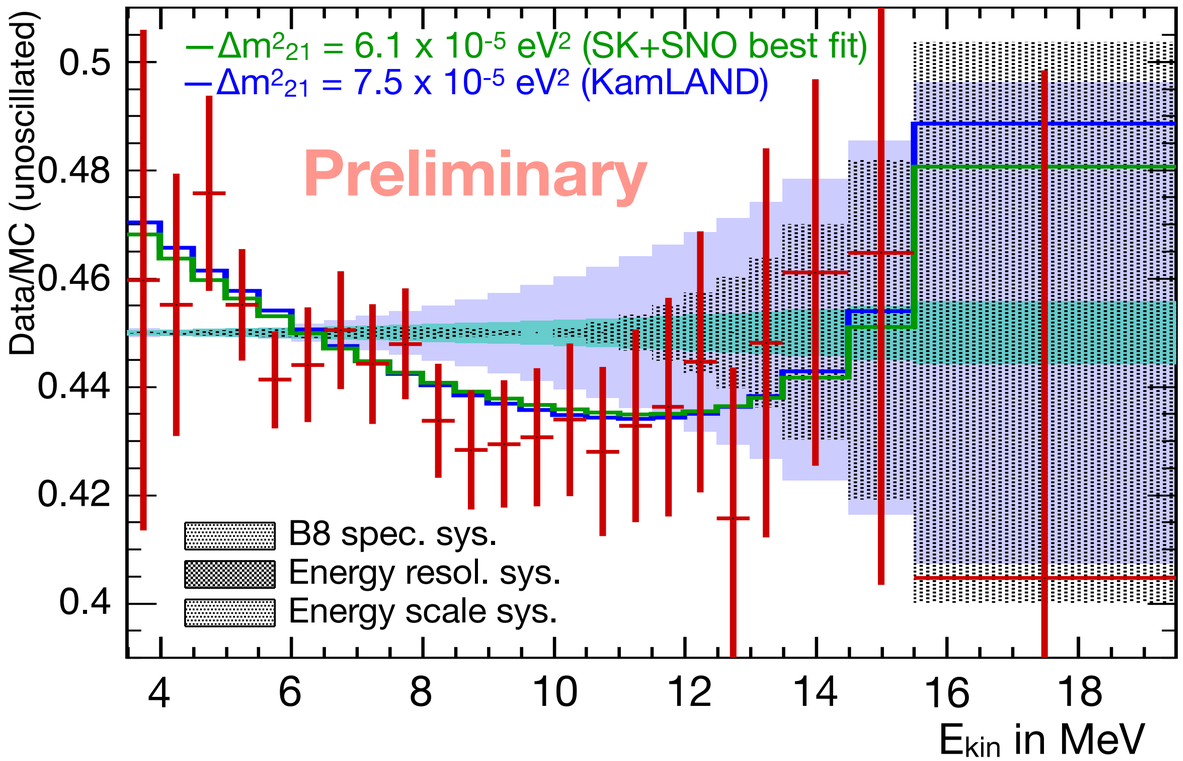


Phase	Livetime [days]	Energy [MeV]	DATA/MC	Flux w/ systematic error [*10⁶ /cm²/sec]	Extracted Signal (Statistical only)
SK-I	1496	4.5-19.5	$0.453 \pm 0.005\ ^{+0.016}_{-0.014}$	$2.38 \pm 0.02 \pm 0.08$	$22443\ ^{+227}_{-225}$
SK-II	791	6.5-19.5	$0.459 \pm 0.010 \pm 0.030$	$2.41 \pm 0.05\ ^{+0.16}_{-0.15}$	$7210\ ^{+153}_{-151}$
SK-III	548	4.0-19.5	$0.458 \pm 0.008 \pm 0.010$	$2.40 \pm 0.04 \pm 0.05$	$8148\ ^{+133}_{-133}$
SK-IV (Updated)	2970.08	3.5-19.5	$0.443 \pm 0.003 \pm 0.006$	$2.33 \pm 0.01 \pm 0.03$	63890^{+381}_{-379}
Combined	5805	–	$0.447 \pm 0.002 \pm 0.008$	$2.35 \pm 0.01 \pm 0.04$	More than 100k events

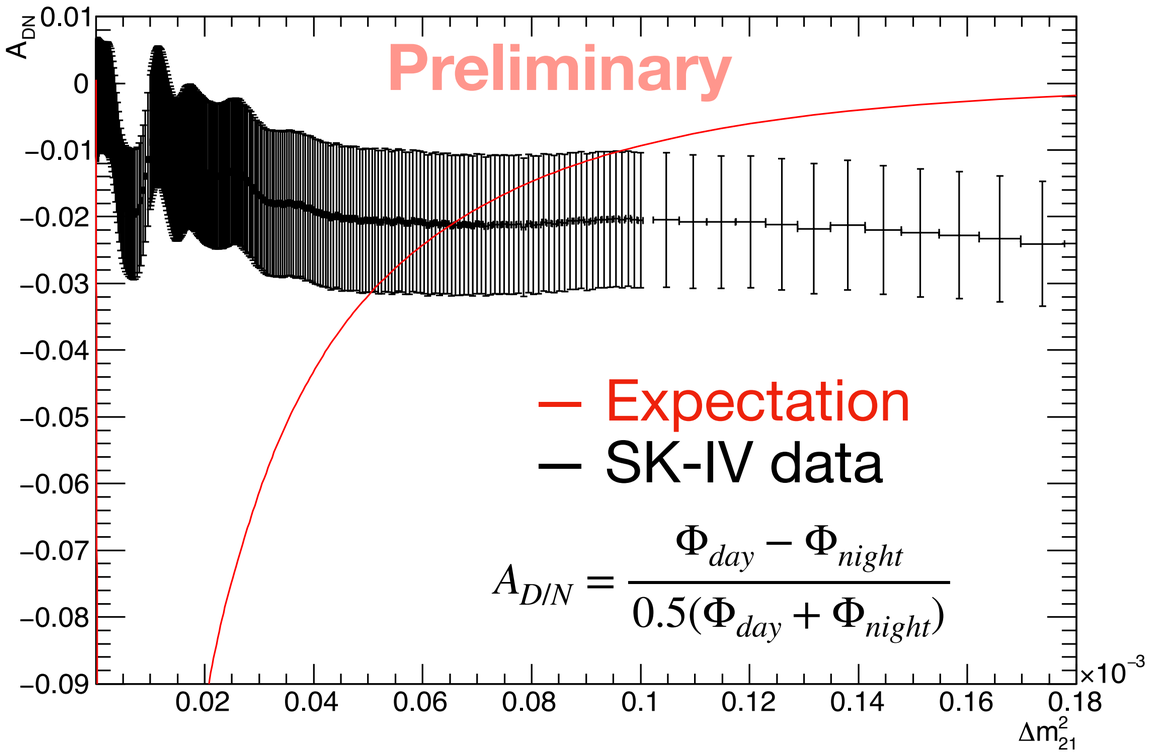


Oscillation analysis

Energy spectrum fit (SK-IV)



Day/Night amplitude fit (SK-IV)



$A_{DN}^{Fit} = (-2.1 \pm 1.1)\,\%$ $[3.5 < E < 19.5$ (MeV)]

Disfavors flat oscillation probability by ~1σ

Spectrum shape compatible with KamLAND Δm^2_{21} (< 1σ)

~2σ preference of non-zero Day/Night asymmetry

Difference from the previous results

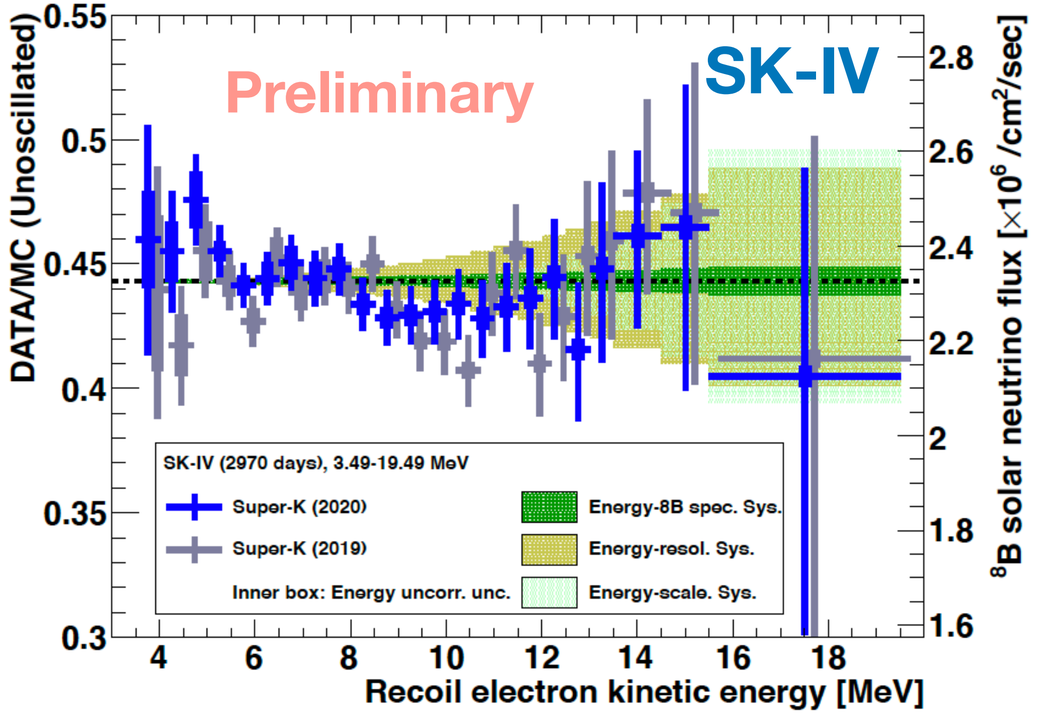
- Best fit value of solar Δm^2_{21} changed from 4.8 x 10^{-5} eV^2 (2019) to 6.1 x 10^{-5} eV^2
- Spectrum analysis:

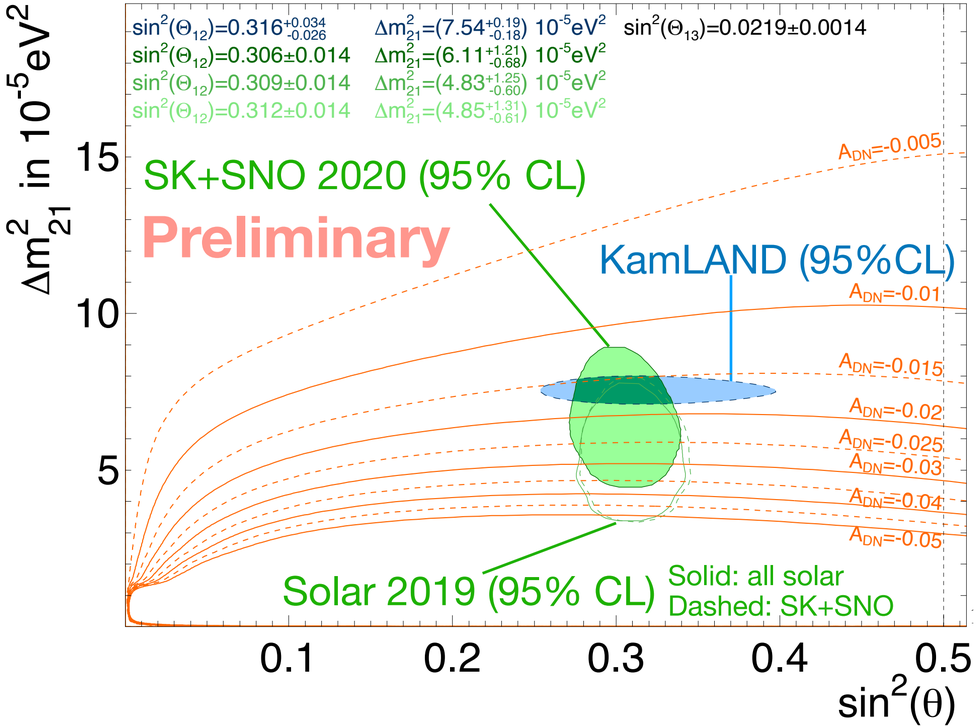
  Data/MC ratio at E < 6 MeV slightly shifted upward

  - Shift of prediction due to improved detector simulation
  - Added statistics due to improved spallation cut
  - Event migration due to new reconstruction tool
- Day/Night asymmetry:

  $A_{DN}^{Fit} = (-3.6 \pm 1.6(stat) \pm 0.6(syst))\,\% \rightarrow A_{DN}^{Fit} = (-2.1 \pm 1.1)\,\%$

  - Event migration due to new reconstruction
  - Previous analysis used data up to Feb 2014 (SK-IV: 1664 days)
  - Added ~1300 days of data fluctuated towards smaller D/N asymmetry
- Both impacted to the shift of best fit Δm^2_{21} value by roughly equal amount (in term of change of $\Delta\chi^2$)





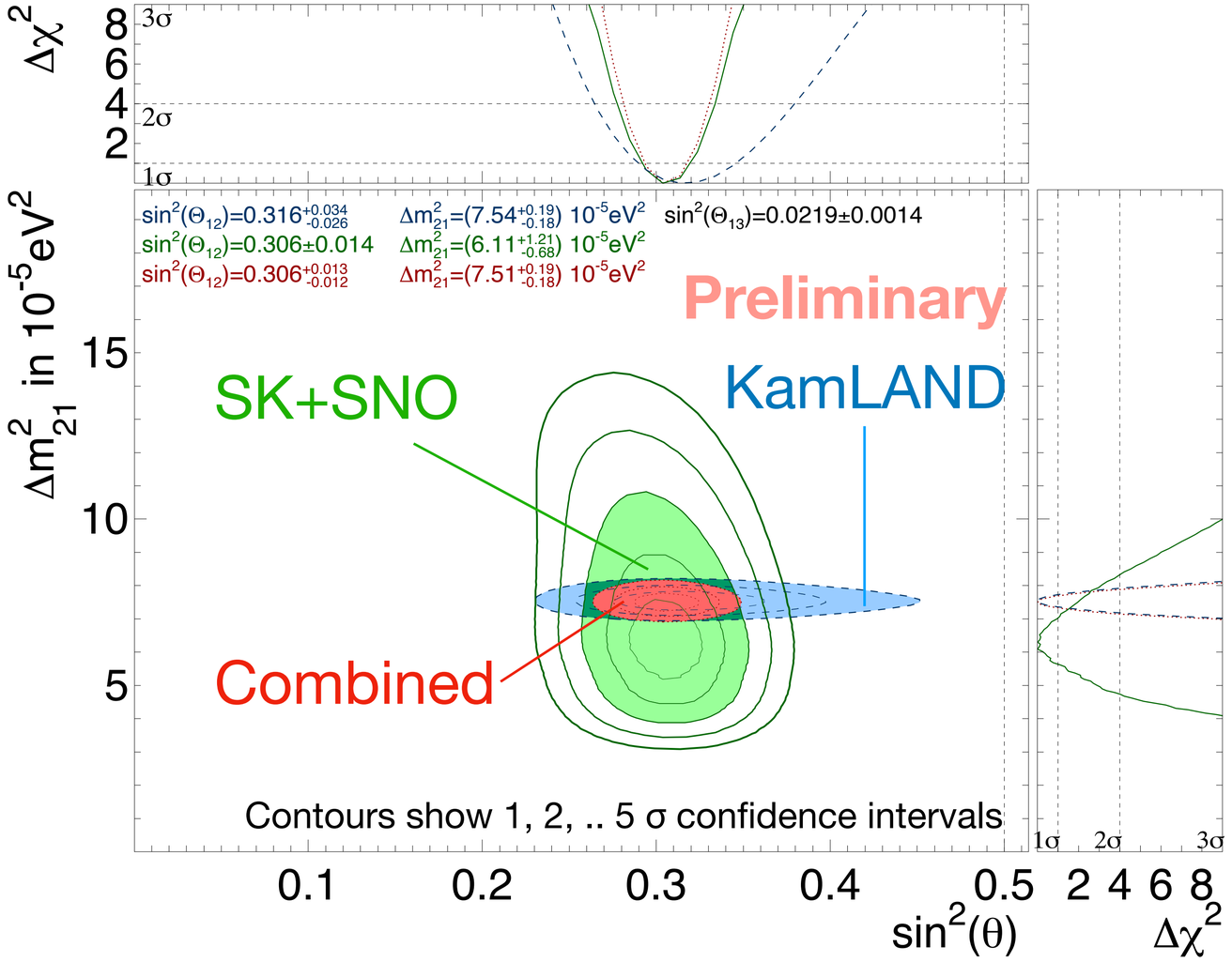
Oscillation Parameter Extraction

- Oscillation parameters extracted by combining all SK data, as well as SNO and KamLAND data

	$\sin^2(\theta_{12})$	Δm^2_{21} [10^{-5} eV^2]
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18}$
SK+SNO	0.306 ± 0.014	$6.11^{+1.21}_{-0.68}$
Combined	$0.306^{+0.013}_{-0.012}$	$7.51^{+0.19}_{-0.18}$

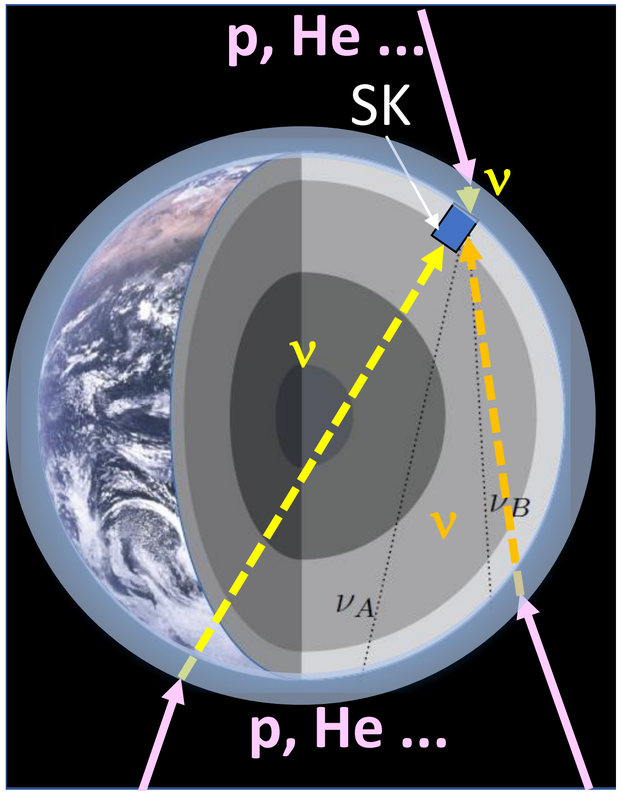
- Consistent θ_{12} values among experiments
- Solar best fit Δm^2_{21} lower than KamLAND, but difference is less than the previous analysis.

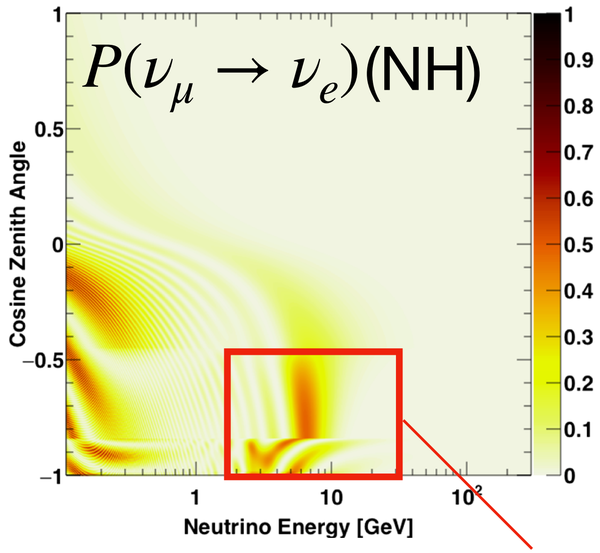
SK+SNO fit disfavors the KamLAND best fit value at ~1.4σ (was ~2σ)



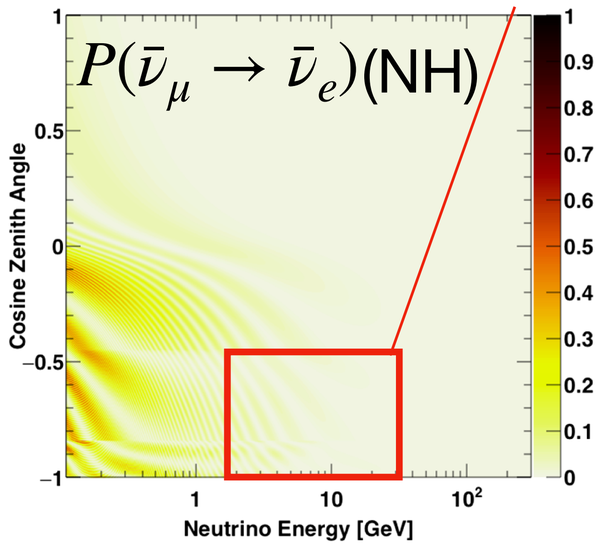
Atmospheric Neutrinos

Atmospheric Neutrinos





Matter effects



- Neutrinos produced by cosmic-ray interactions in earth's atmosphere
  - Baseline: O(10) km - O(10,000) km)
  - Energy: peaks at several hundreds of MeV, extends to ~TeV
- Goals:
  - Δm^2_{32} and θ_{23} measurements: primary through $\nu_\mu/\bar{\nu}_\mu$ disappearance
  - CP violation parameter δ and mass-ordering: $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

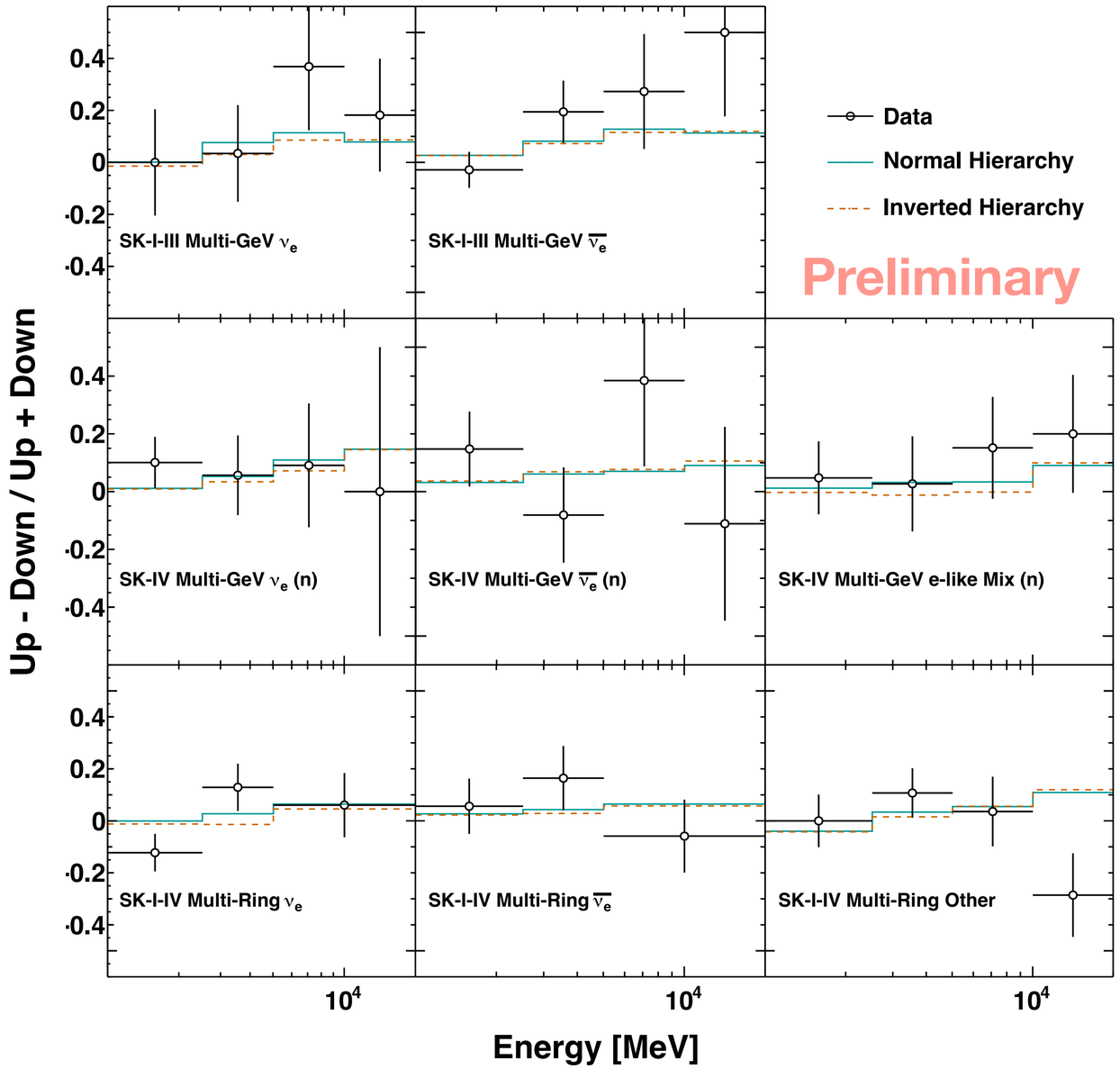
Atmospheric Neutrino Analysis at SK

- New results using the full data sets from SK-I to SK-IV
  - Exposure: 364.8 kton-years

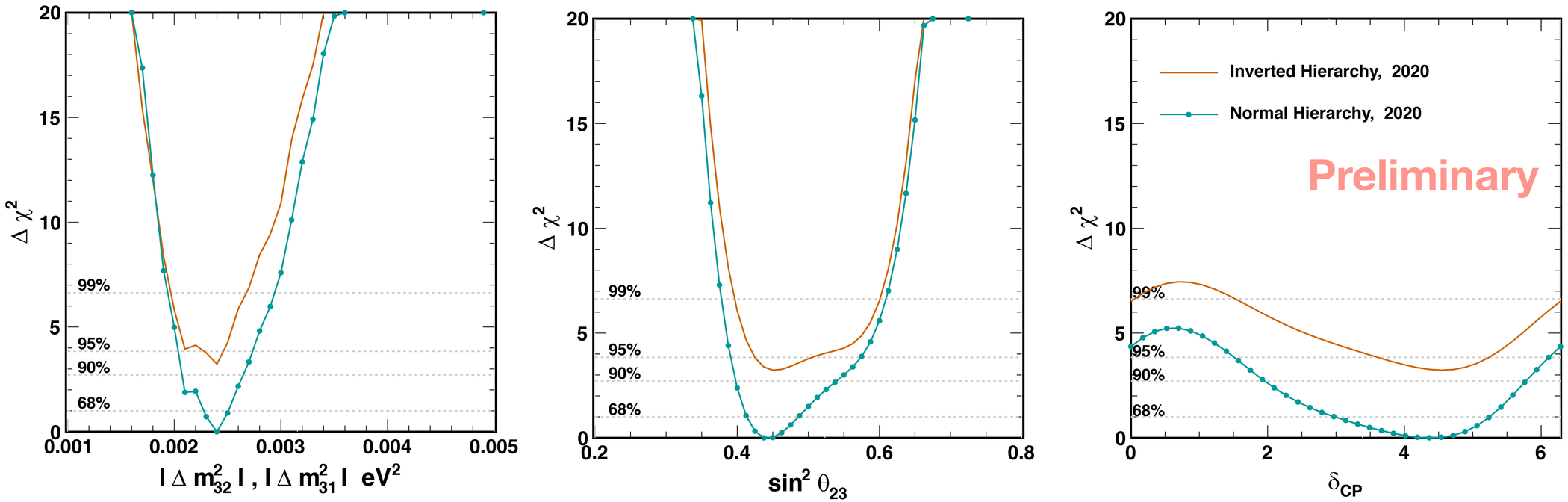
    (328 kton-years in Neutrino2018)

- Improvements in this analysis:
  - Neutron tagging (ε~25%) for $\nu/\bar{\nu}$ separation
  - New BDT-based event selection for multi-ring events
    - Increased signal efficiency and purity

Up: cosθ < -0.4, Down: cosθ > 0.4



Oscillation Parameter Measurement

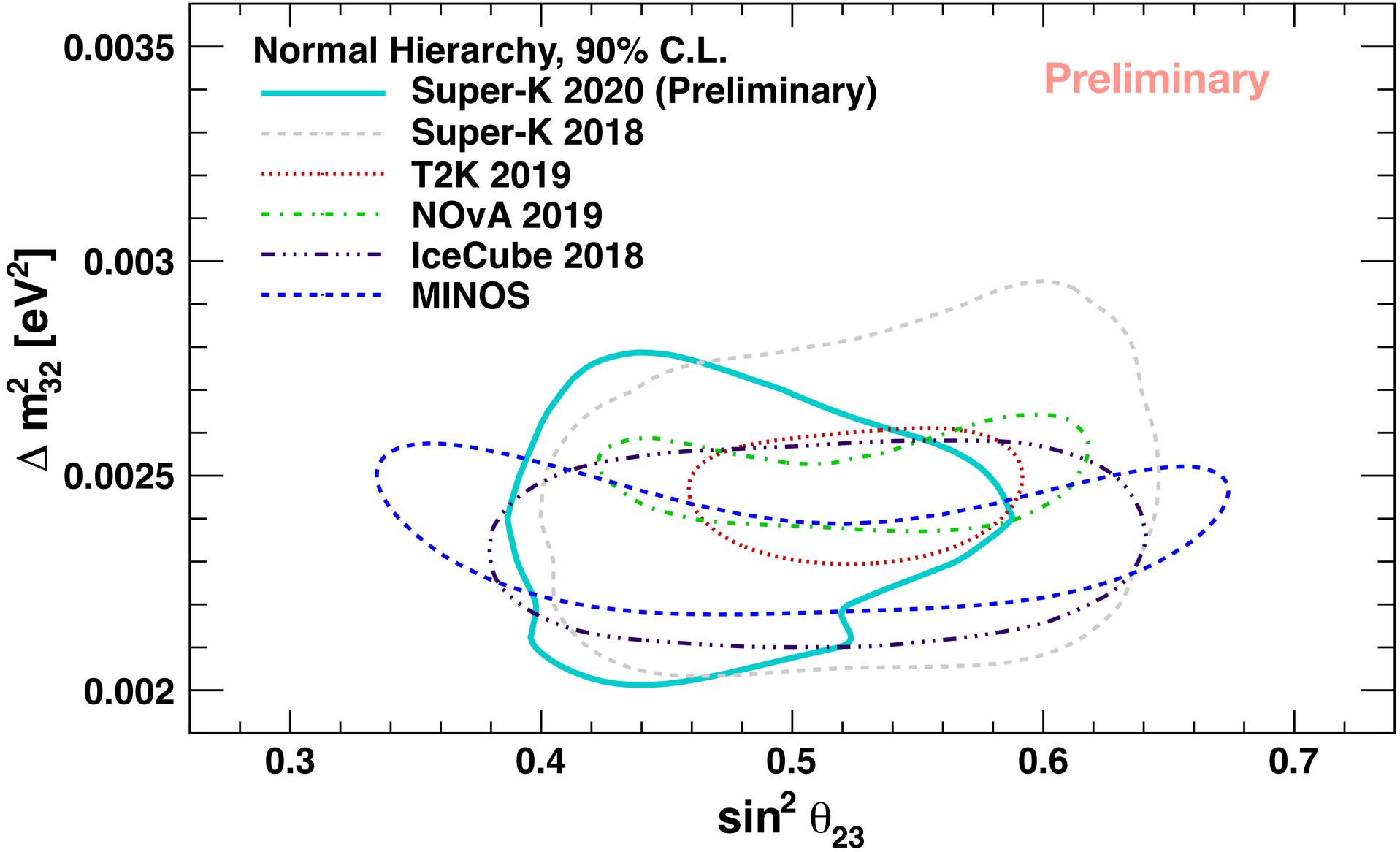


930 Bins	$\chi 2$	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} ($\times 10^{-3}$)
SK (NH)	**1037.5**	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
SK (IH)	**1040.7**	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

SK data disfavors Inverted Hierarchy at 71.4-90.3% CL_s (was 81.9-96.1% in 2018)

Also prefers: 1st θ_{23} octant and δ_{CP}~3/2π

Δm^2_{32} vs $\sin^2\theta_{23}$ constraints



Summary

- The new era of Super-Kamiokande, SK-Gd, is about to start
- New results from Super-Kamiokande:
  - Diffuse supernova background search: New limit within a several factors of many models
  - Solar neutrino measurements: New spectrum and Day/Night asymmetry measurements to test MSW
  - Atmospheric neutrino measurements: New constraints on Δm^2_{32}, θ_{23}, δ_{CP} and MO
- Please also enjoy more results from Super-Kamiokande at the poster sessions:

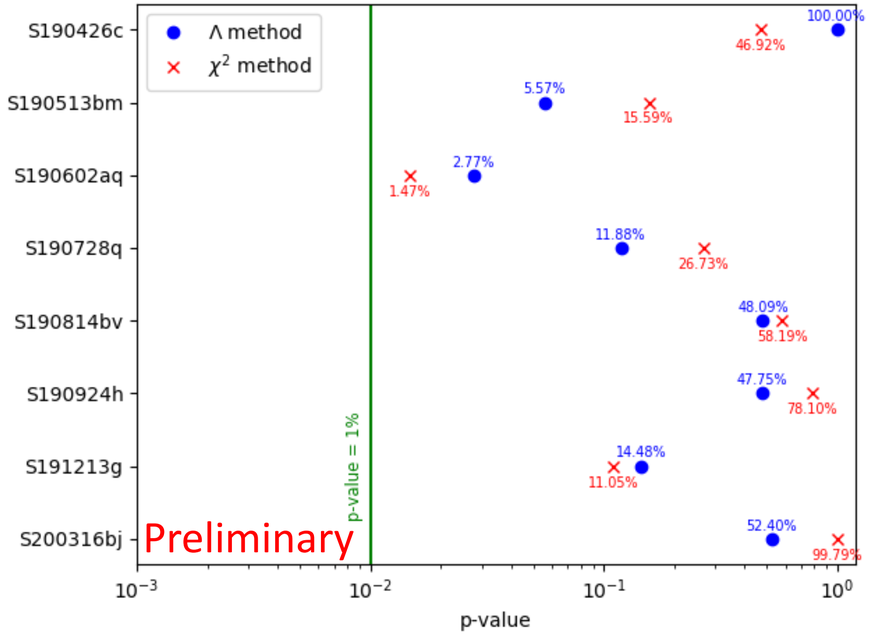
ID	Title	Presenter	Session
43	Neutron-antineutron oscillation search at Super-Kamiokande	Linyan Wan	3
85	Search for astronomical neutrino from the Gamma-ray burst with Super-Kamiokande	Masayuki Harada	2
136	Long time supernova simulation and supernova burst search at Super-Kamiokande	Masamitsu Mori	2
161	Follow-up of Gravitational Wave events with Super-Kamiokande	Mathieu Lamoureux	1
166	Spallation Studies in Super Kamiokande	Scott Locke	2
175	Study of the atmospheric neutrino background for Supernova Relic Neutrino search	Seiya Sakai	4
221	Reactor Neutrinos in Super-Kamiokande	Alexander Goldsack	1
231	The diffuse supernova neutrino background in Super-Kamiokande	Sonia El Hedri	3
350	Latest solar neutrino analysis results from Super-Kamiokande	Yuuki Nakano	4

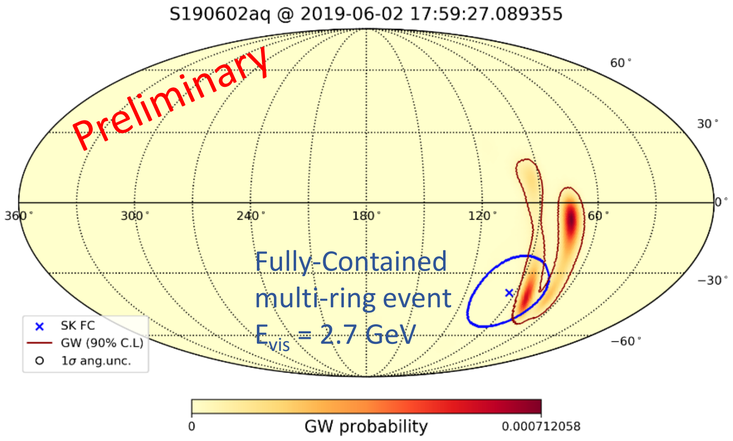
Backup

Gravitational Wave Follow-up

- Search for neutrinos in time coincidence with Gravitational Wave triggers detected by LIGO-Virgo during O3 (April 2019 – March 2020)
- A total of **46** follow-ups and **8** of them with neutrinos events within [-500s, 500 s] of a Gravitational Wave trigger.
- Direction of the neutrino is compared to GW sky localization to compute signal significance (p-value).

p-values for the 8 selected events





Most significant event (S190602aq)
p-value ≈ 1.5%

Poster #161 (session #1): **Follow-up of Gravitational Wave events with Super-Kamiokande** – Mathieu Lamoureux (link)

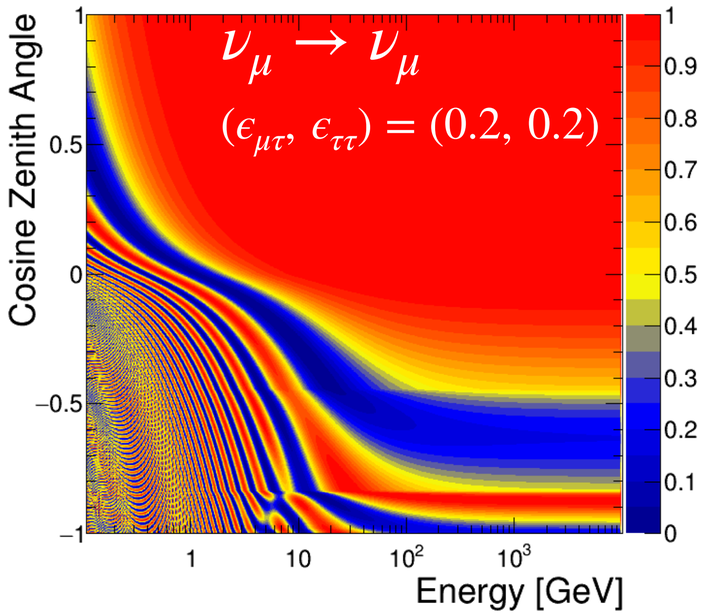
Test of Non-standard Interactions

- Non-standard interactions (NSI) can alter the neutrino propagation through the earth
- Tested with ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance signals
- No evidence for NSI found
- Set constraints on the effective parameters:

$$\mathscr{H}^{NSI} = \sqrt{(2)} G_F N_f(\vec{r}) \begin{pmatrix} \epsilon_{ee} & \epsilon^*_{e\mu} & \epsilon^*_{e\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon^*_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

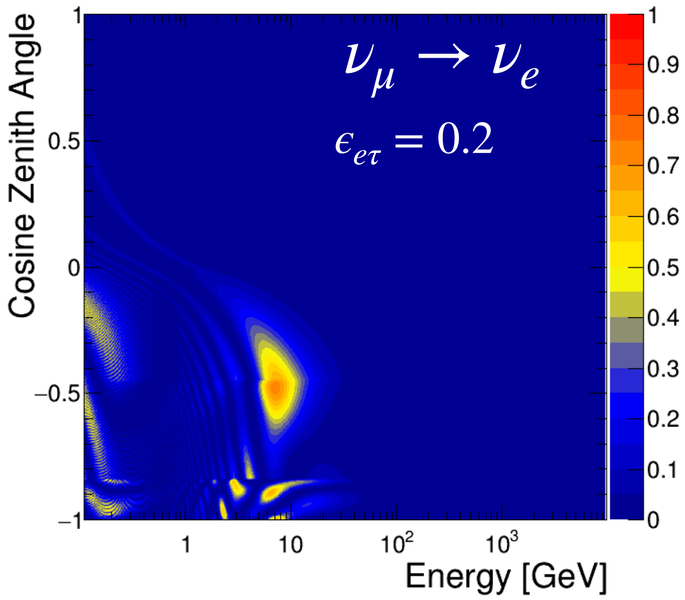
μ-τ sector

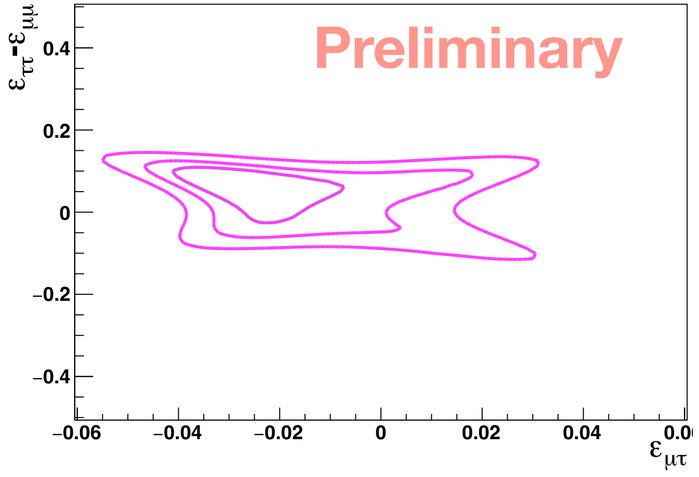
(ν_μ disappearance)



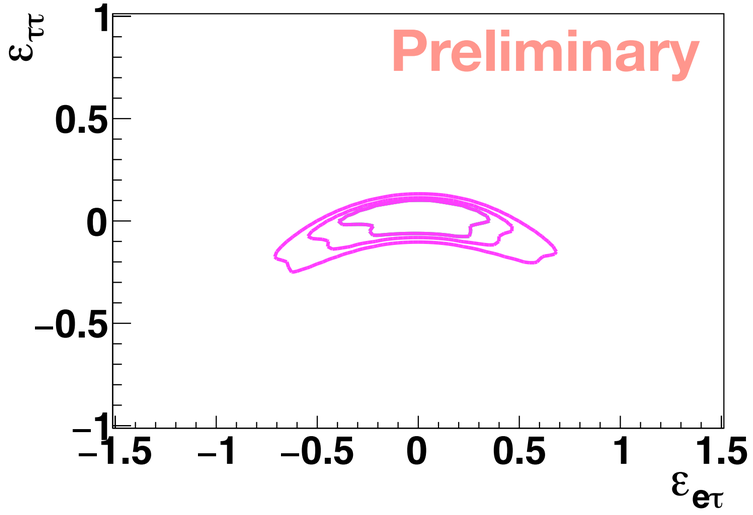
e-τ sector

(ν_μ disappearance and ν_e appearance)

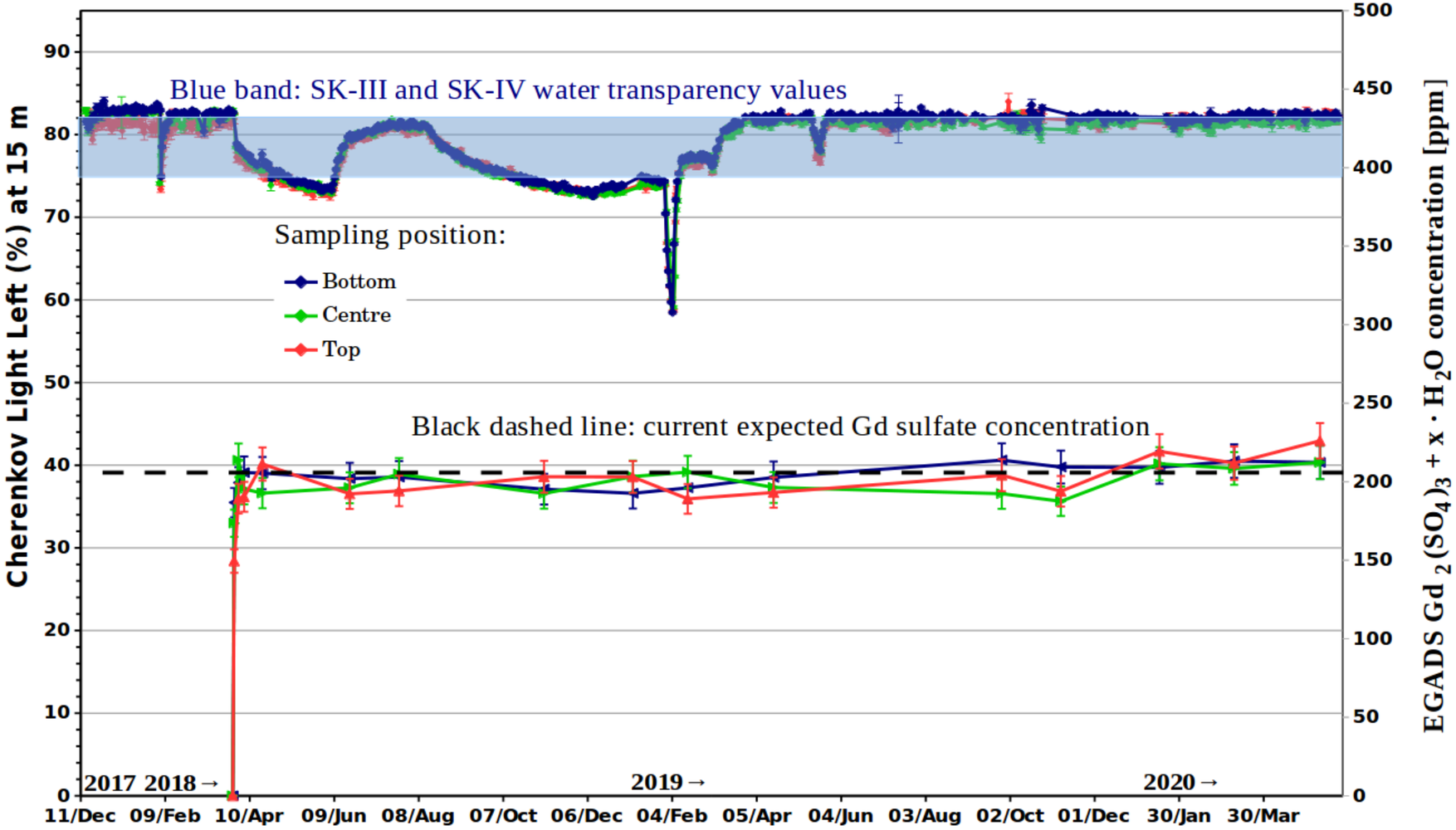




NH ε_{ee} = -3.0



EGADS water transparency (recent data)



Energy scale calibrations

Water model in SK

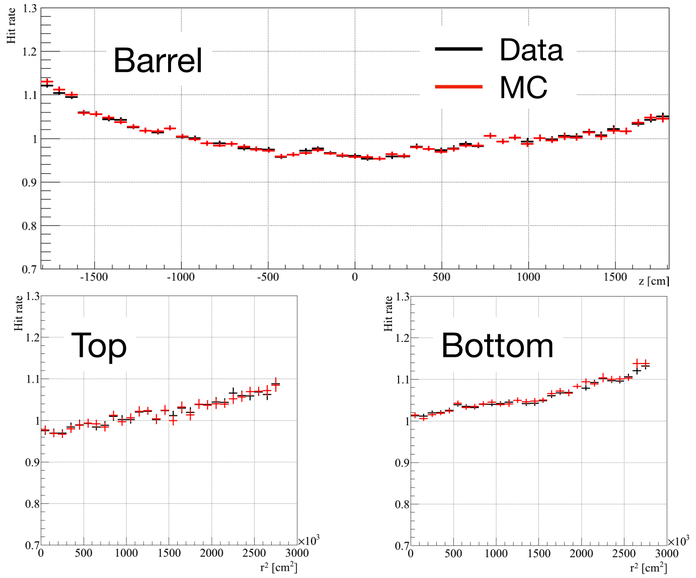
- It is known that water quality has the vertical position and time dependence.
- This dependence is introduced as the parameter β in MC as follows;

absorption factor $\alpha_{abs}(\lambda, z, t)$

$$= \begin{cases} \alpha(\lambda, t)(1 + \beta(t) \cdot z), & \text{for } z \geq -11 \text{ m} \\ \alpha(\lambda, t)(1 - \beta(t) \cdot 11), & \text{for } z \leq -11 \text{ m} \end{cases}$$

- To determine the parameter β, hit rate distribution from NiCf calibration is used.

- Data is in good agreement with MC after tuning β.
- The time dependence of β is corrected as a function of water transparency and its vertical asymmetry, which are measured with cosmic-ray muons and a calibration light source, respectively.



Energy scale reconstruction

- The energy is reconstructed from the effective number of hit PMTs (N_{eff}) for LOWE.

Correction for hits arrive later than 50 ns window

Correction for dead PMTs

PMT quantum efficiency

$$N_{\mathrm{eff}} = \sum_{i}^{N_{50}} \left[(X_i + \varepsilon_{\mathrm{tail}} - \varepsilon_{\mathrm{dark}}) \times \frac{N_{\mathrm{all}}}{N_{\mathrm{alive}}} \times \frac{S(0,0)}{S(\theta_i, \phi_i)} \times \exp\left(\frac{r_i}{WT}\right) \times \frac{1}{\mathrm{QE}_i(t)} \right]$$

Occupancy correction for multiple hits

PMT dark rate

Photo-coverage correction

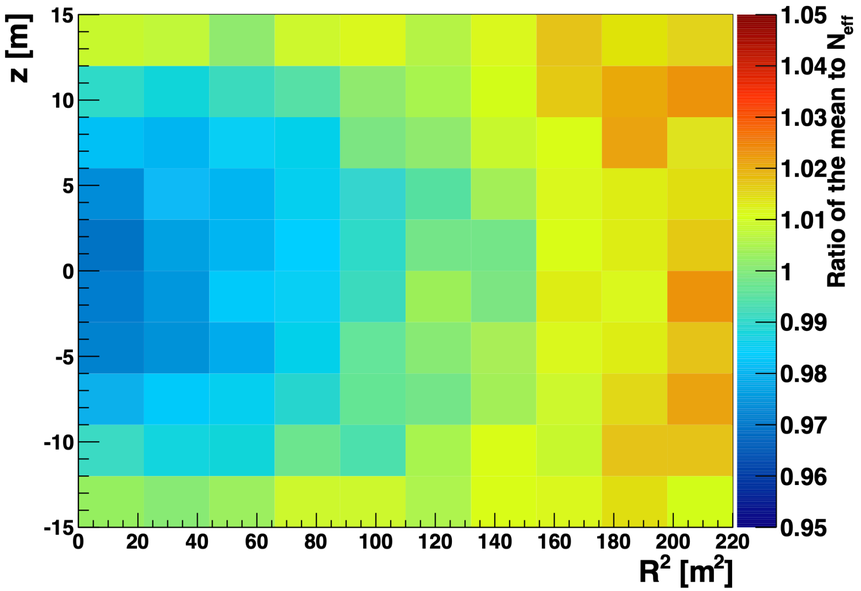
Water transparency correction

- In solar neutrino analysis, position dependence is the largest systematic uncertainty of energy scale.
- N_{eff} calculation is updated to suppress position dependence.
  - Photo-coverage correction:
    PMT response is take into account additionally.
  - Water transparency correction:
    Vertical asymmetry of water transparency is considered newly.

New photo-coverage correction

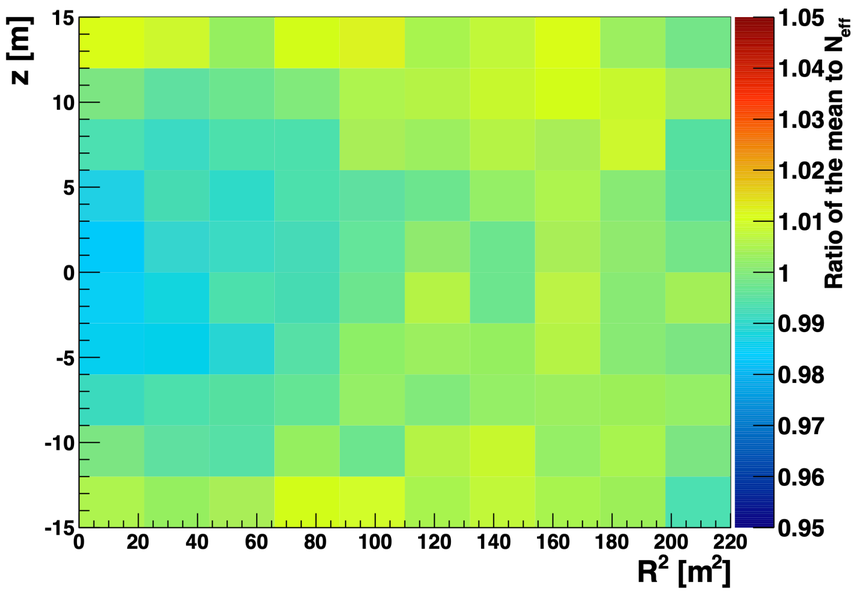
- Previous method used a toy simulation with PMT array on flat space.
- New method uses Geant4-based simulation assuming full-cylindrical SK detector, including optical response on the PMT surface.
- New photo-coverage correction is applied for MC events with infinite water transparency.

w/ previous method



Position dependence: 1.40 %

w/ new method

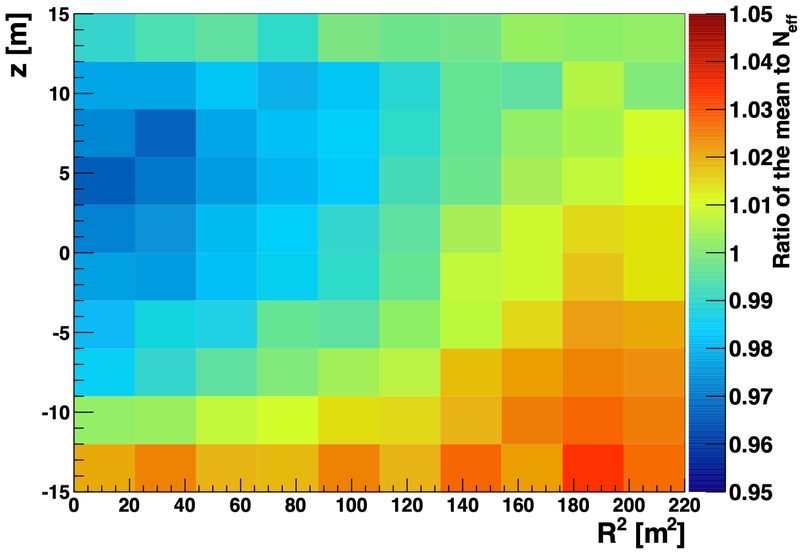


Position dependence: 0.66 %

Water transparency correction

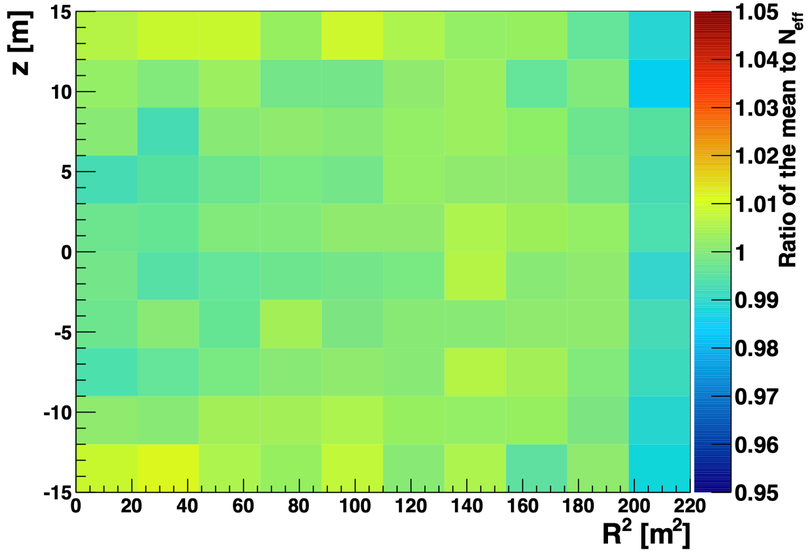
- Previous method used single water transparency for all hits.
- New method uses water transparency calculated effectively for each hit, including vertical asymmetry of water quality. Effective water transparency is determined as a function of hit PMT and vertex positions.
- New photo-coverage and water transparency corrections are applied for MC events which are generated monoenergetic electrons uniformly.
- Position dependence is suppressed to less than 0.5%.

w/ previous method



Position dependence: 1.66%

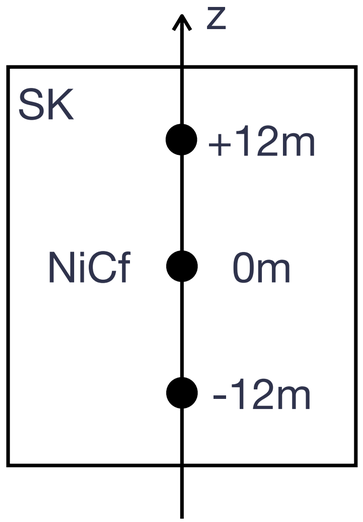
w/ new method



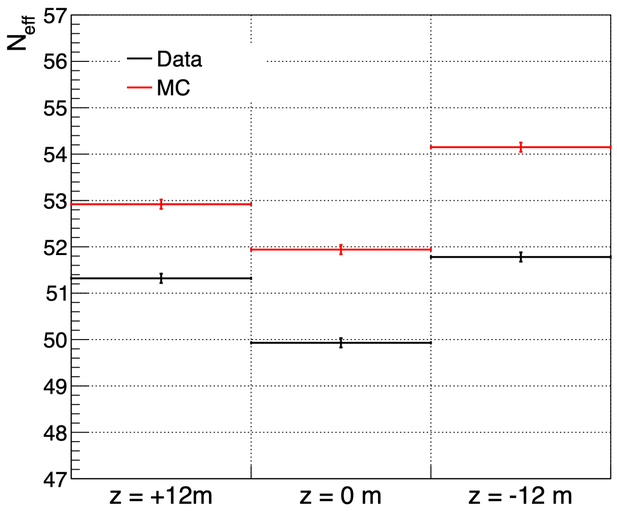
Position dependence: 0.47%

New N_{eff} calculation for NiCf

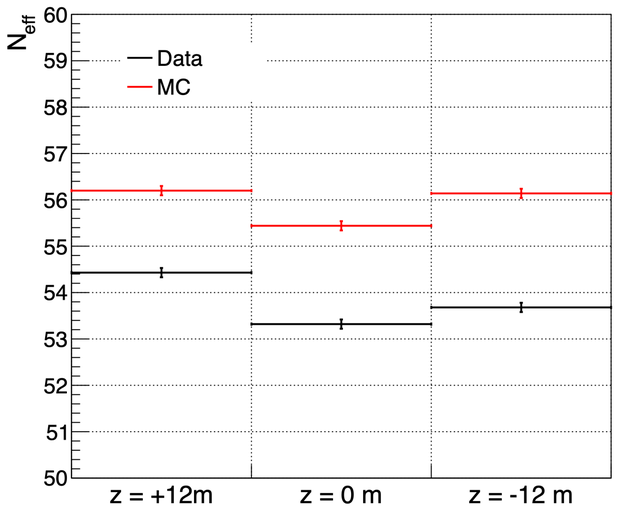
- New N_{eff} calculation method is applied for NiCf data and MC.
- NiCf runs: #77531, #77533 and #77535 which are taken in Feb. 01, 2018.



w/ previous method

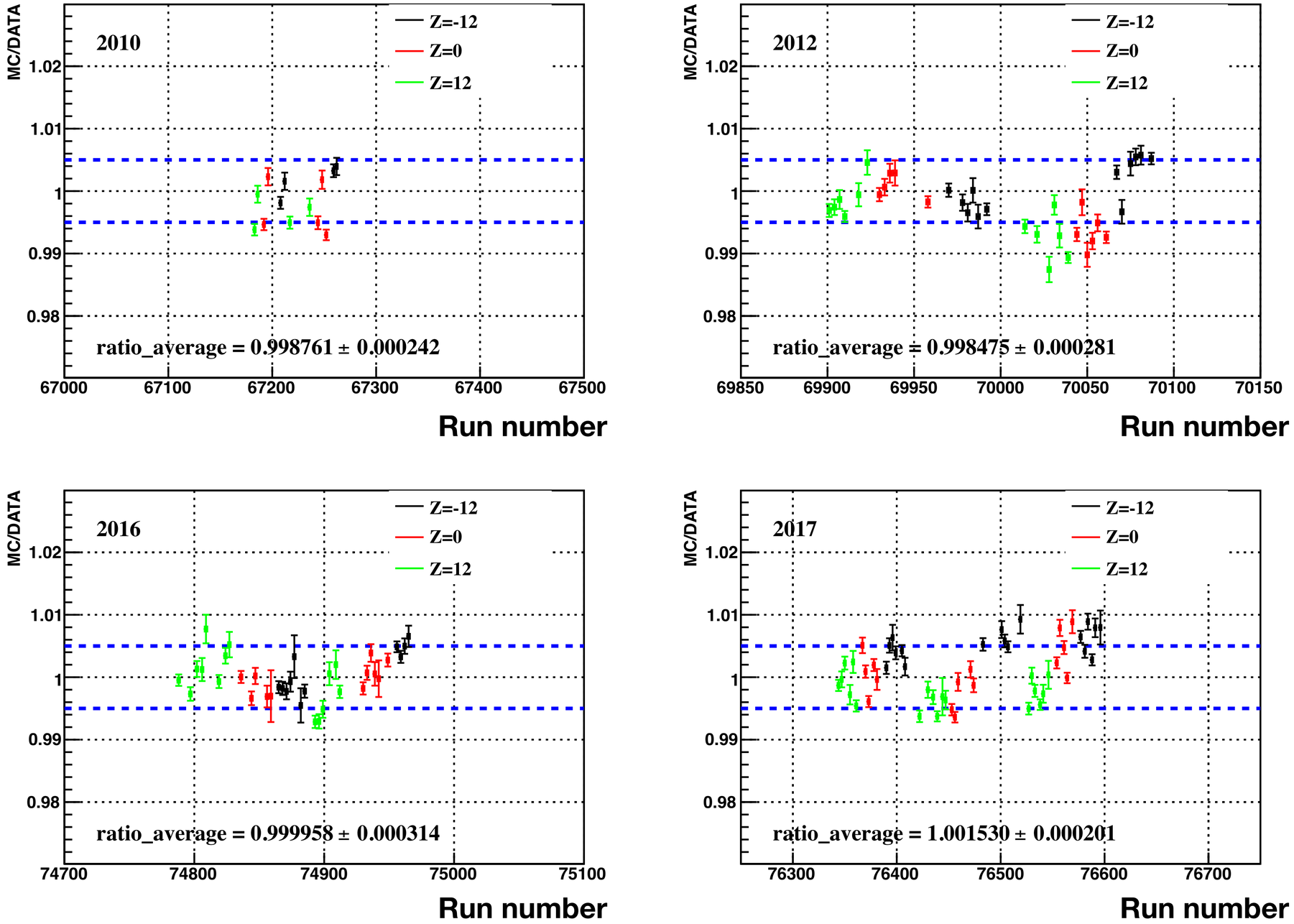


w/ new method



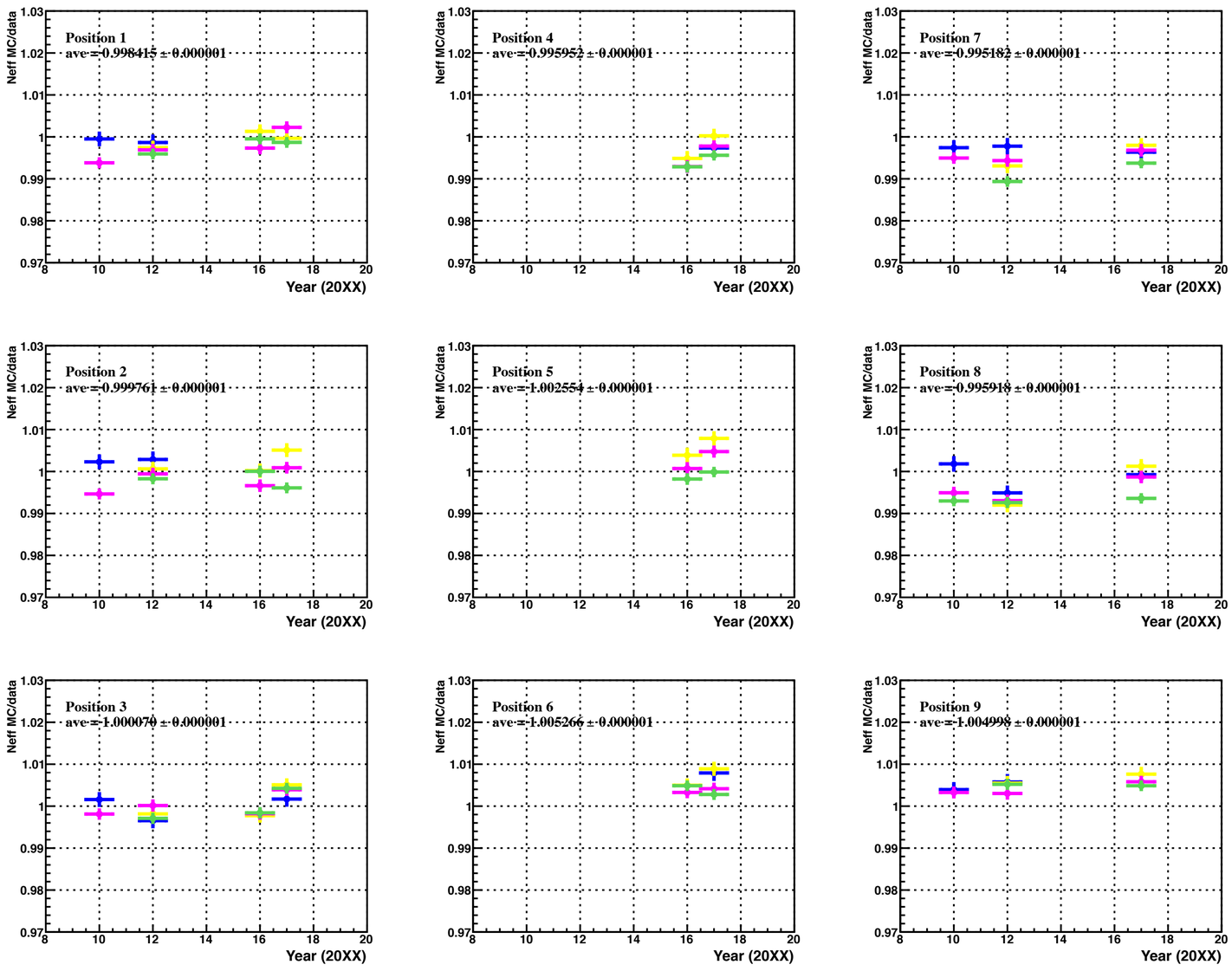
- Position dependence of N_{eff} is suppressed with new method.
- N_{eff} vertical asymmetry (the difference between +12m & -12m) corrected for MC with new method.
- For data, N_{eff} vertical asymmetry is overcorrected with new method.

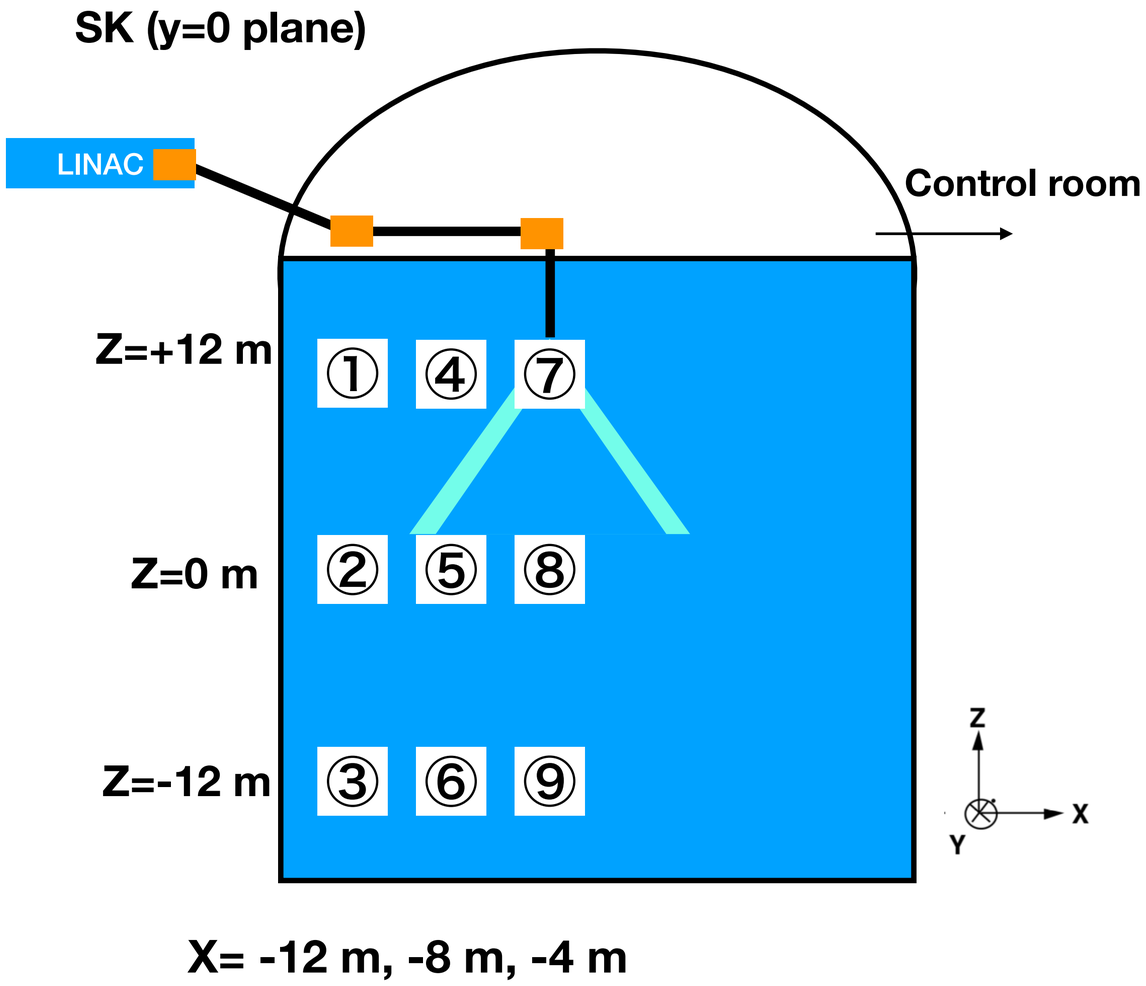
Effective hit ratio for each LINAC run (MC/DATA)



- Energy scale was checked LINAC data and MC.

Position dependence of Neff ratio MC/data

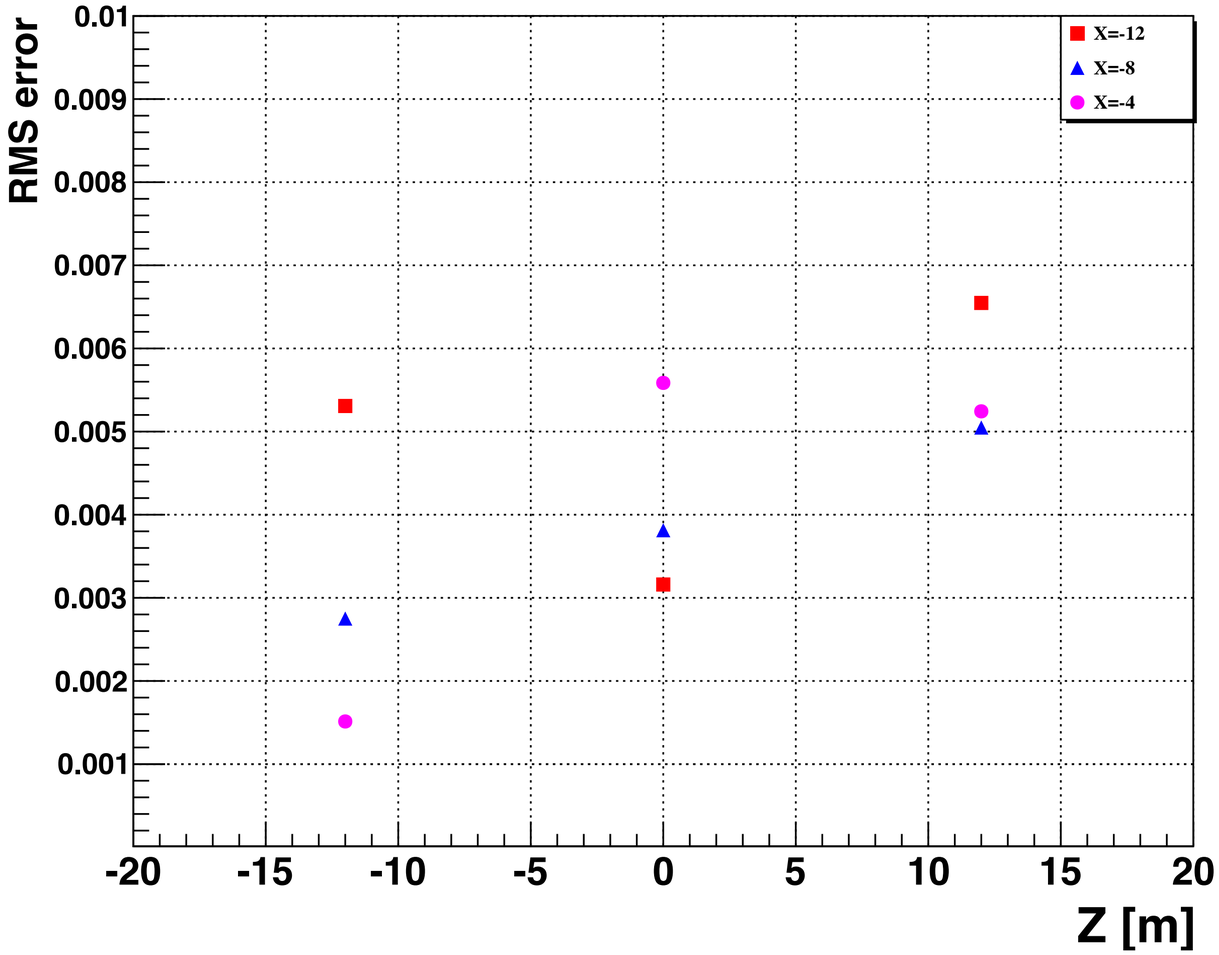




Schematic view for the LINAC calibration
Numbers are position index definitions.

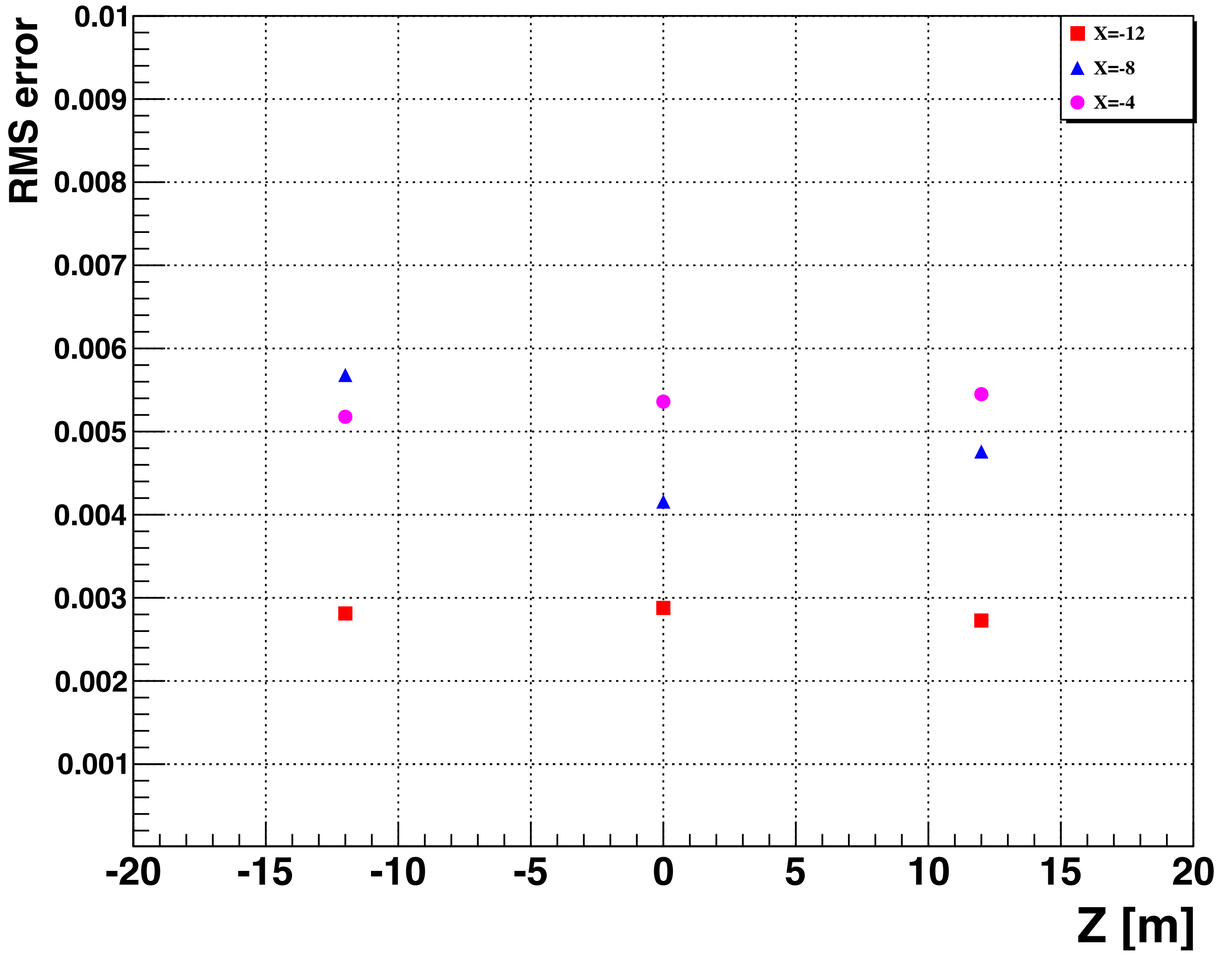
6 MeV 8 MeV 12 MeV 18 MeV

Comparison between before and after improvement (Z dependence)



Result which is produced samples before improvement

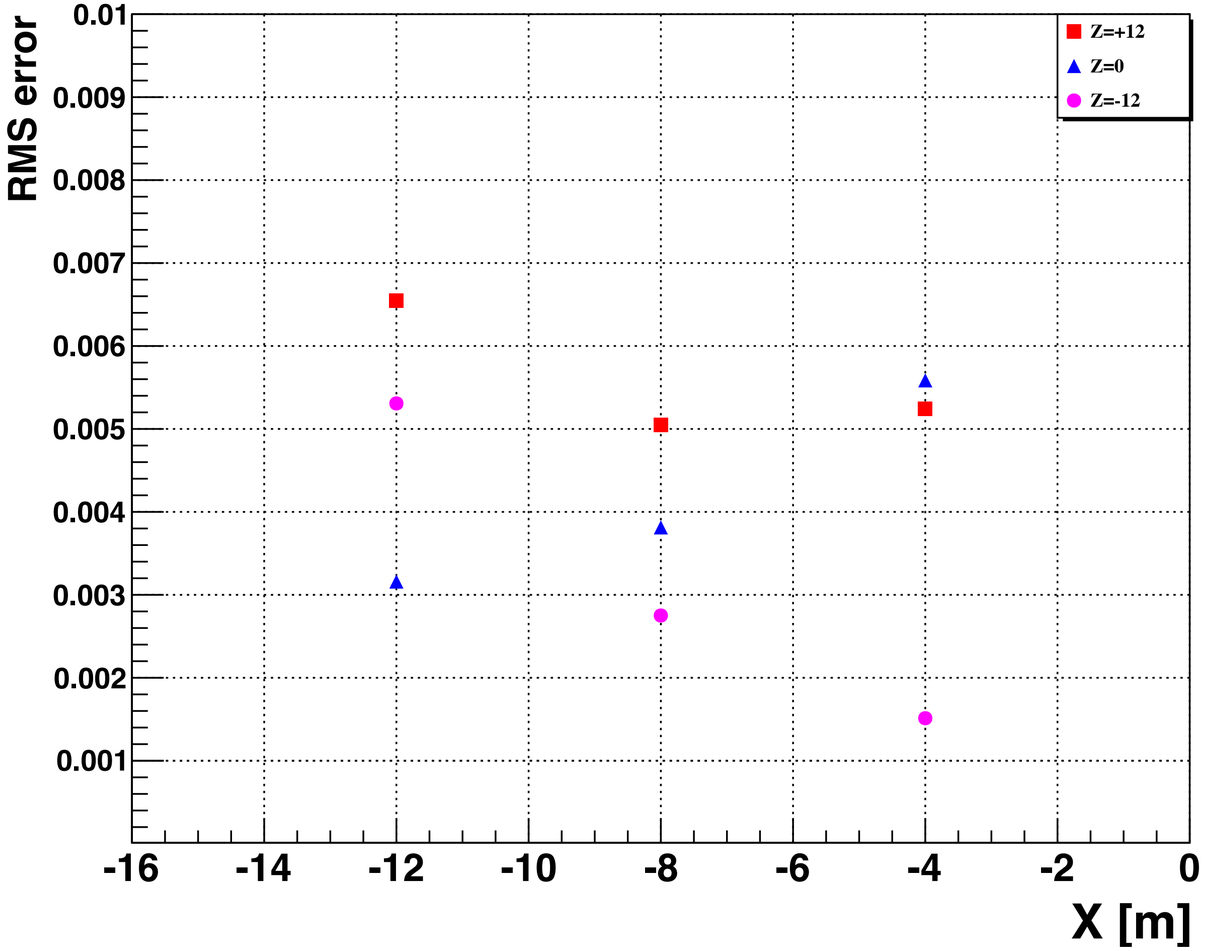
Systematic uncertainty on energy scale (position part) : 0.47%



Result which is produced samples after improvement

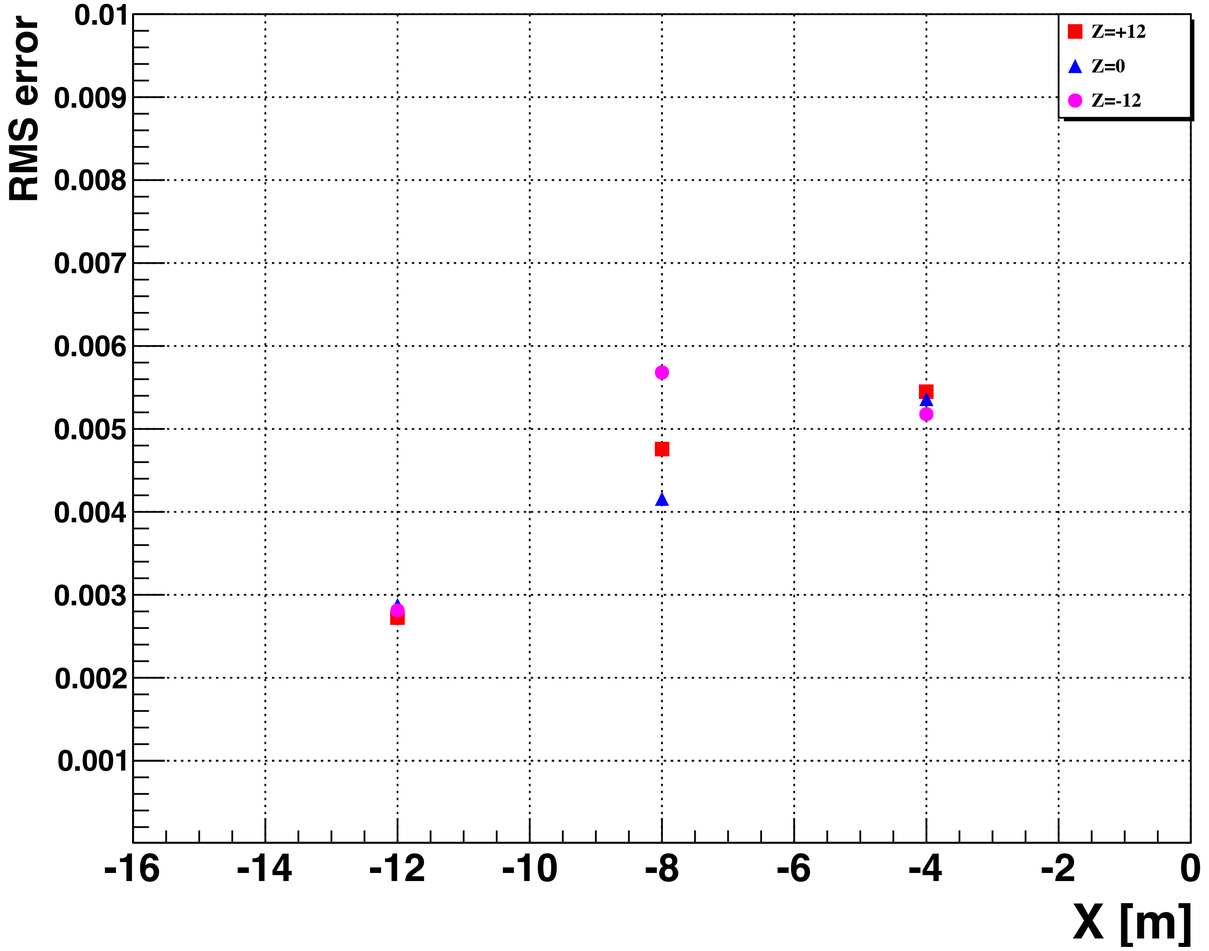
Systematic uncertainty on energy scale (position part) : 0.40%

Comparison between before and after improvement (X dependence)



Result which is produced samples before improvement

Systematic uncertainty on energy scale (position part) : 0.47%



Result which is produced samples after improvement

Systematic uncertainty on energy scale (position part) : 0.40%

Total systematic E scale uncertainty

- Combined the other systematic source on energy scale.
- Systematic uncertainty on energy scale become 0.48 % from 0.53 %.

Before improvement

Table 4.1: Summary of the uncertainty of the energy scale in SK-IV

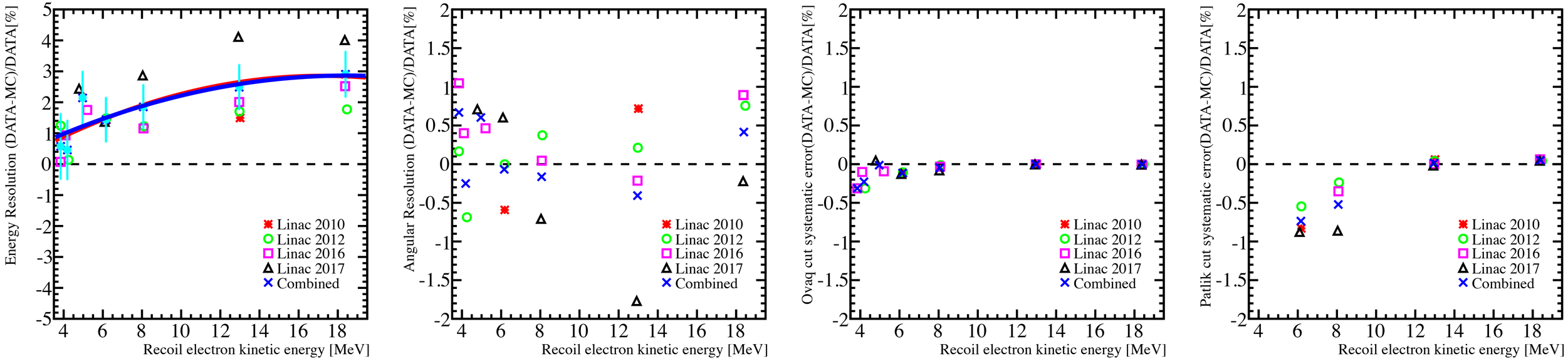
Position Dependence	0.46%
Direction Dependence	0.10%
Water Transparency	0.11%
LINAC Energy	0.21%
Total	0.53%

After improvement

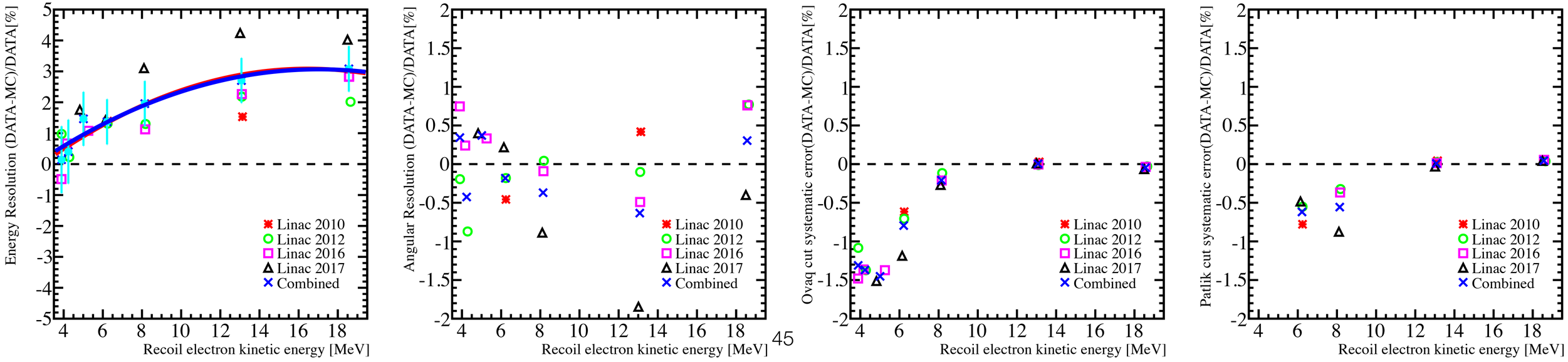
Source	Value
Position dependence	0.40%
Direction dependence	0.10%
Water Transparency	0.11%
LINAC Energy	0.21%
Total	0.48%

Systematic uncertainty comparison between before and after

Result after improvement



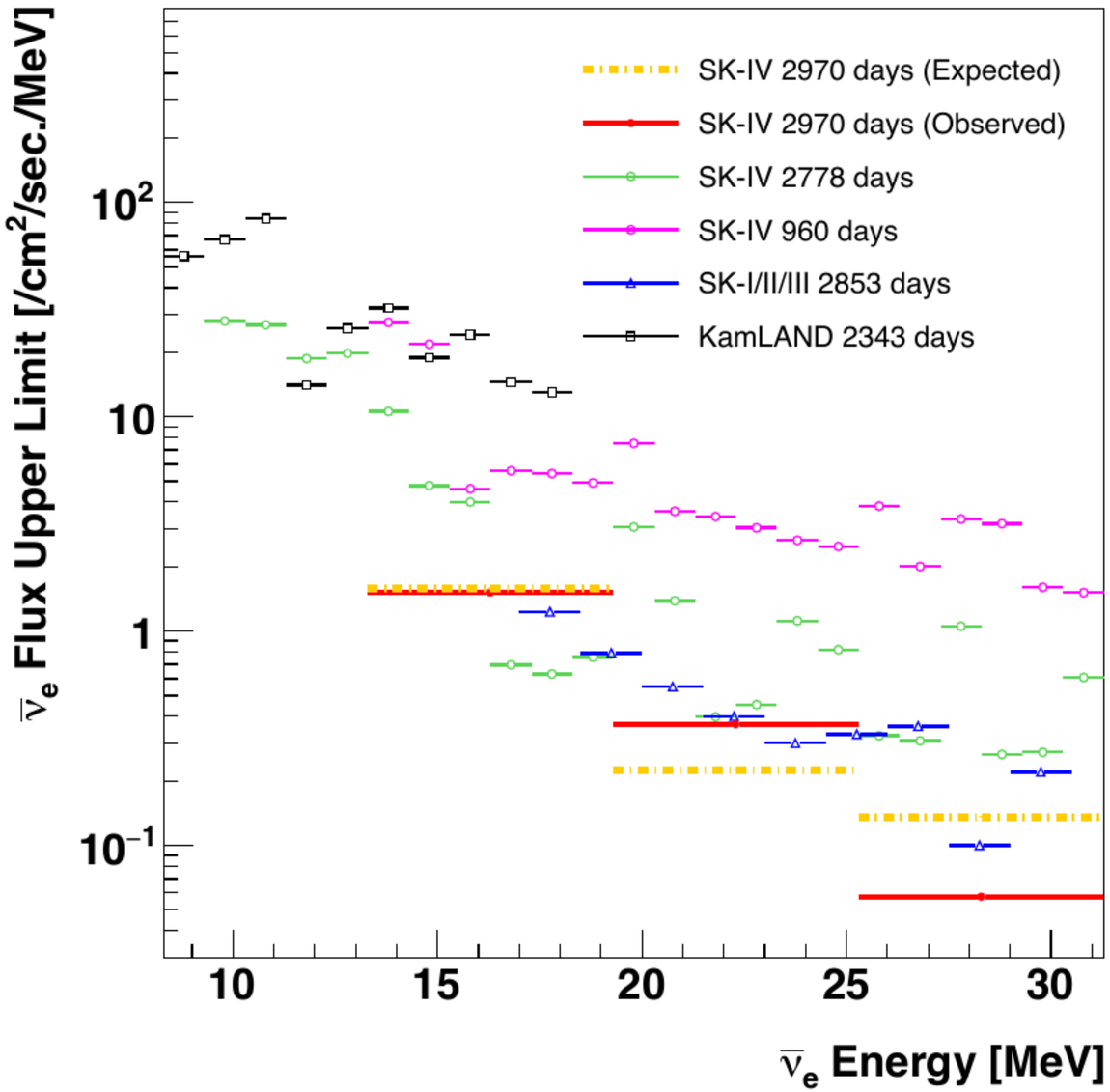
Result which is reproduced with before improvement



DSNB search

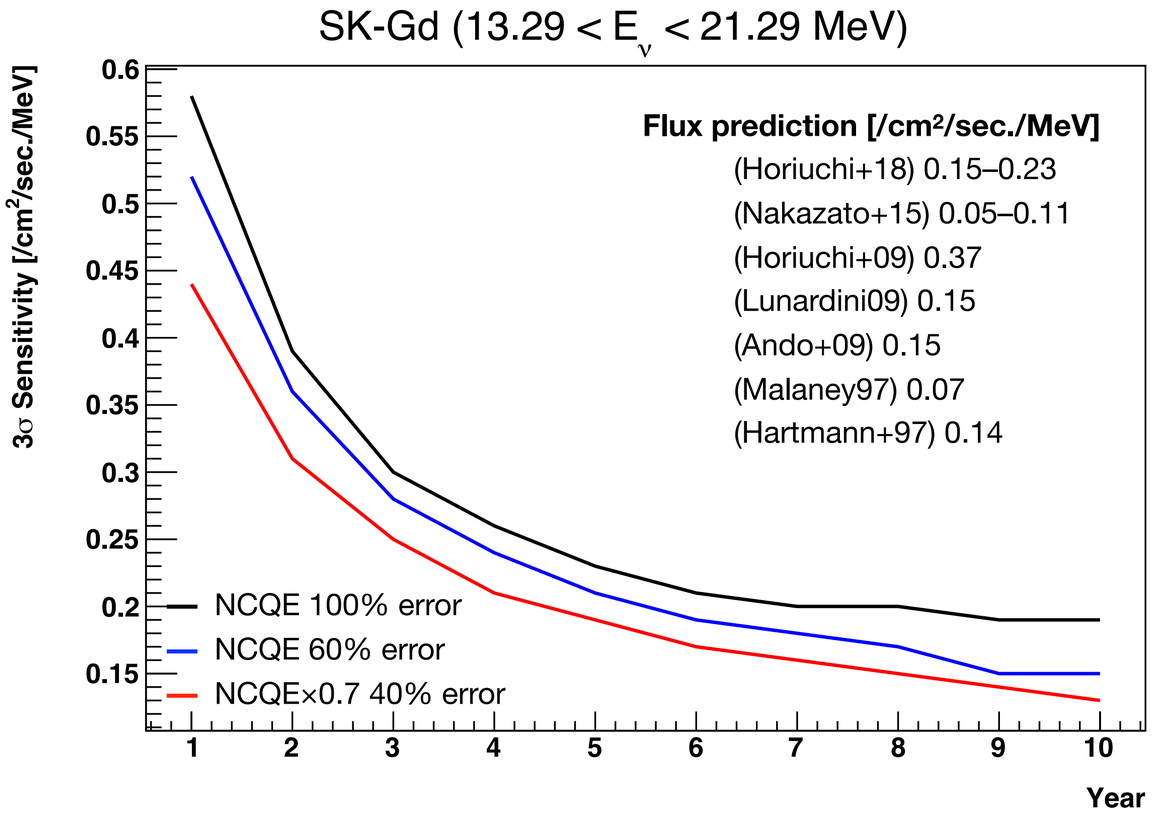
DSNB-model independent flux limit

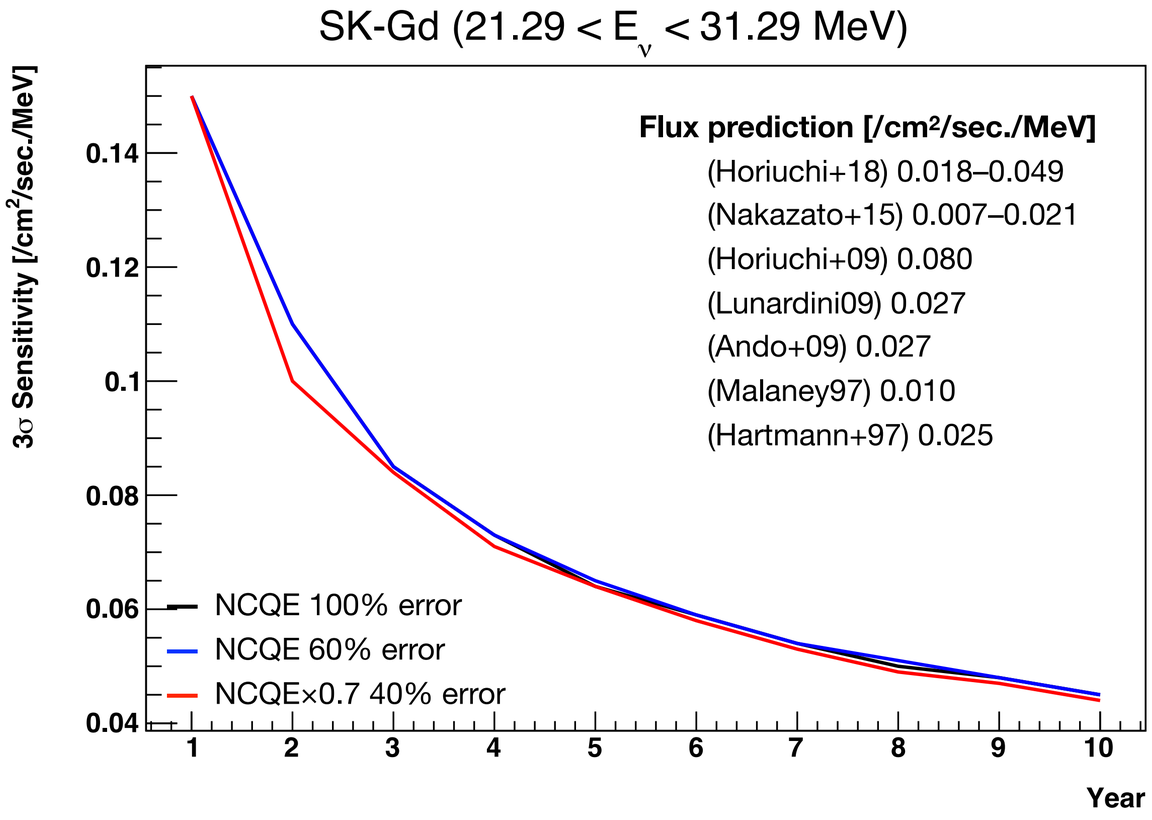
- One of the most stringent limit at $E_\nu > 13$ MeV



DSNB sensitivity at SK-Gd

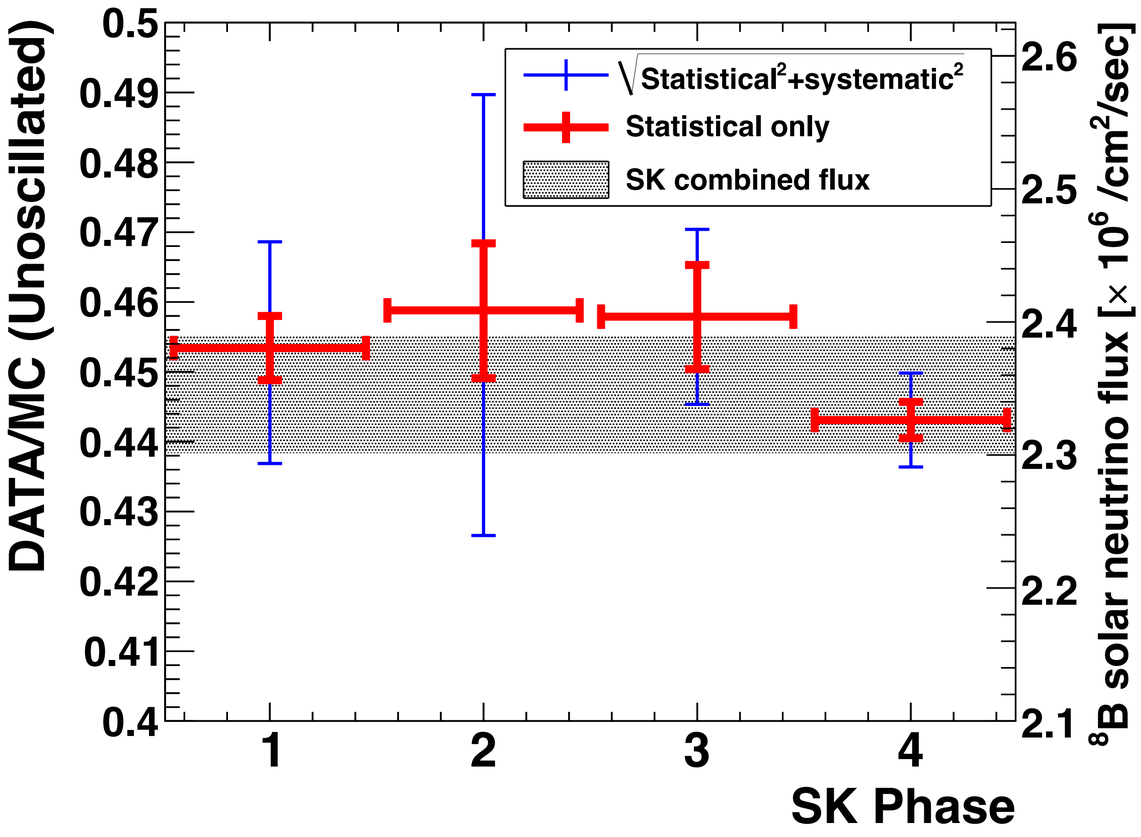
Y. Ashida, Ph.D thesis (2020)

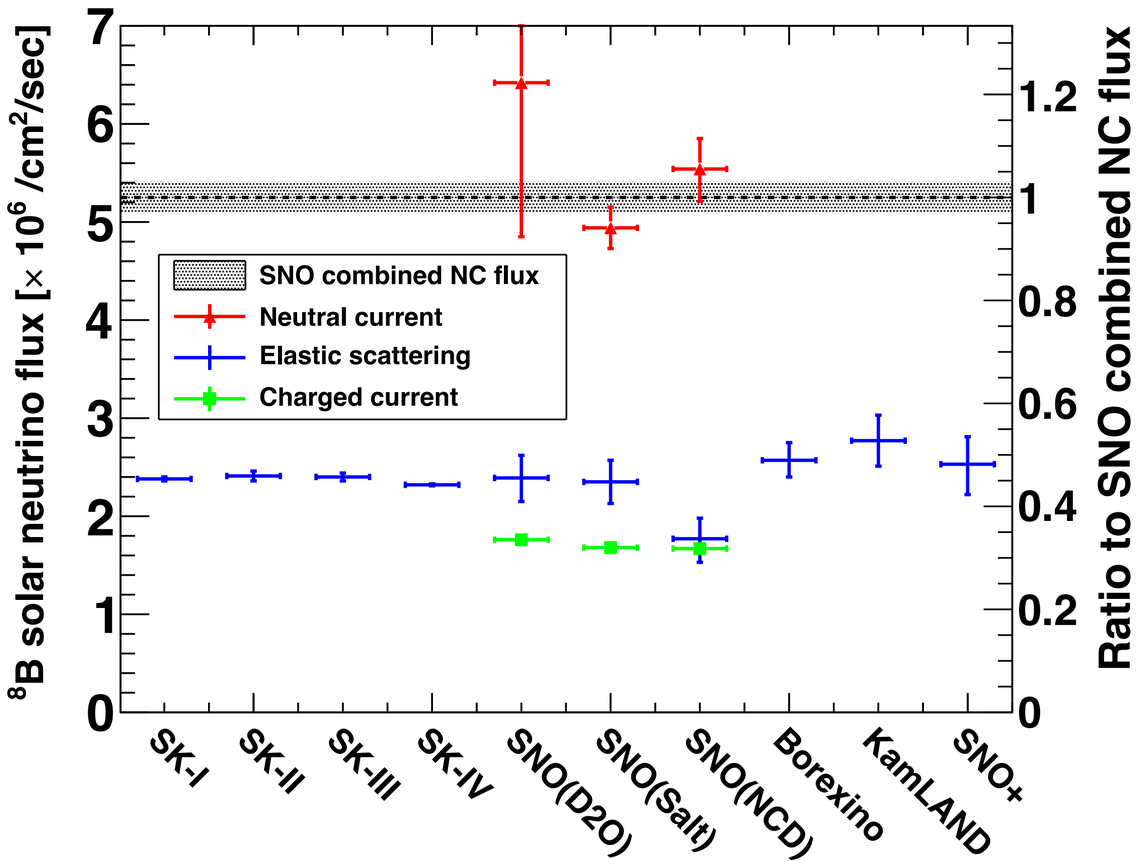




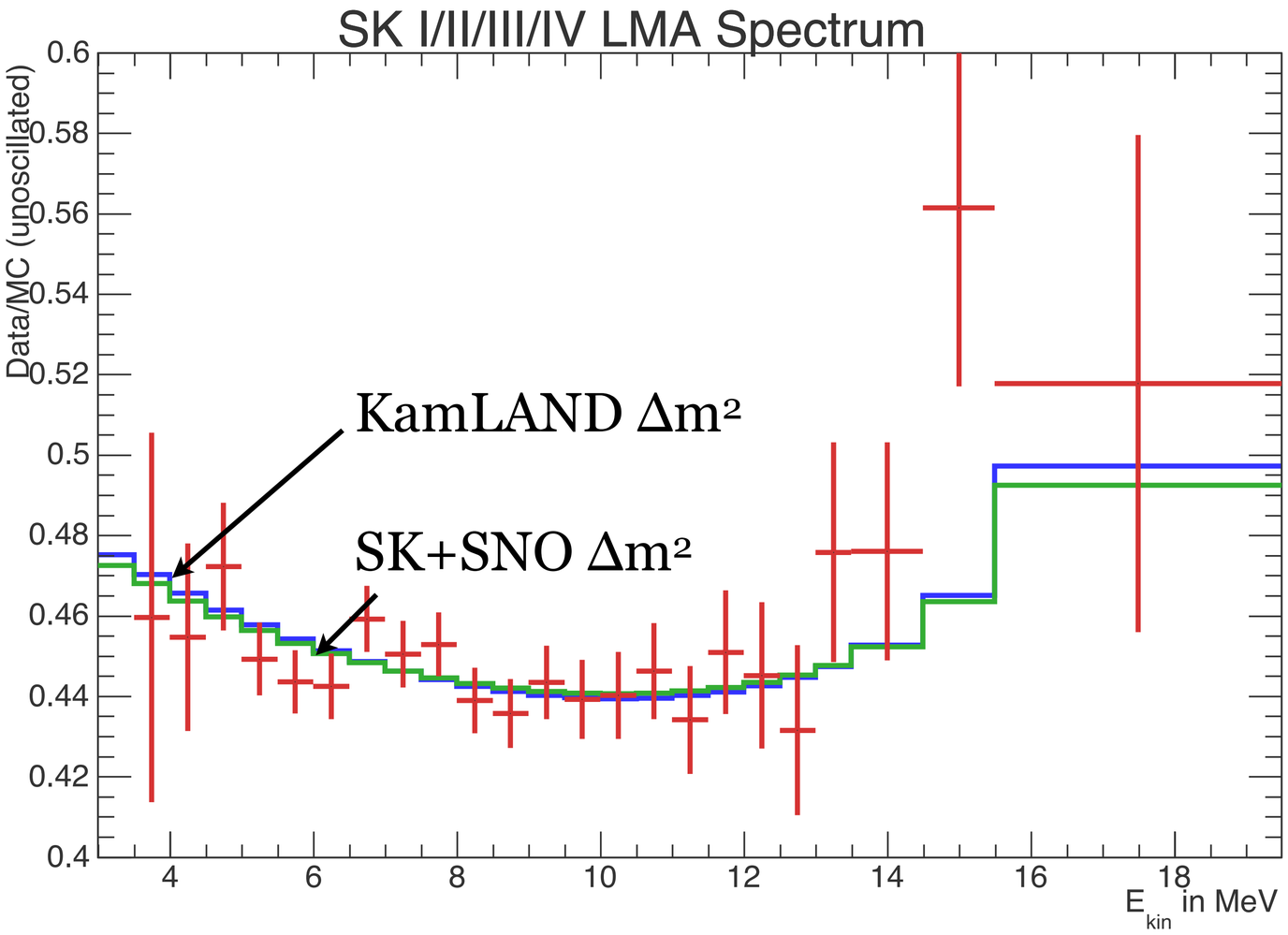
Solar

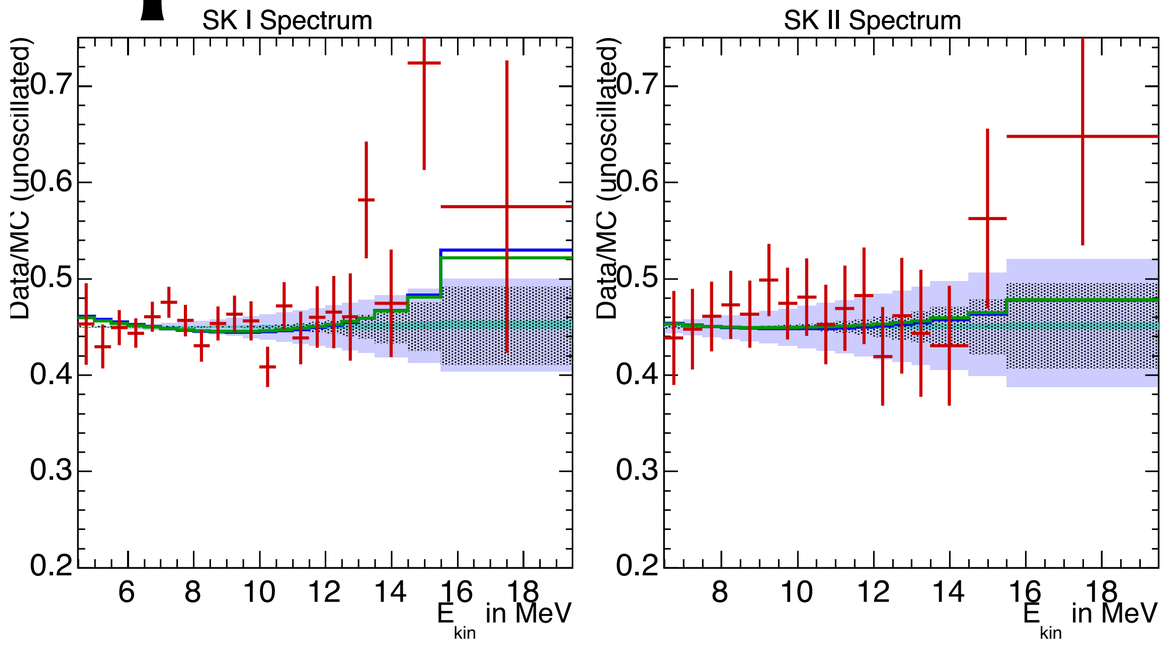
B8 flux comparisons

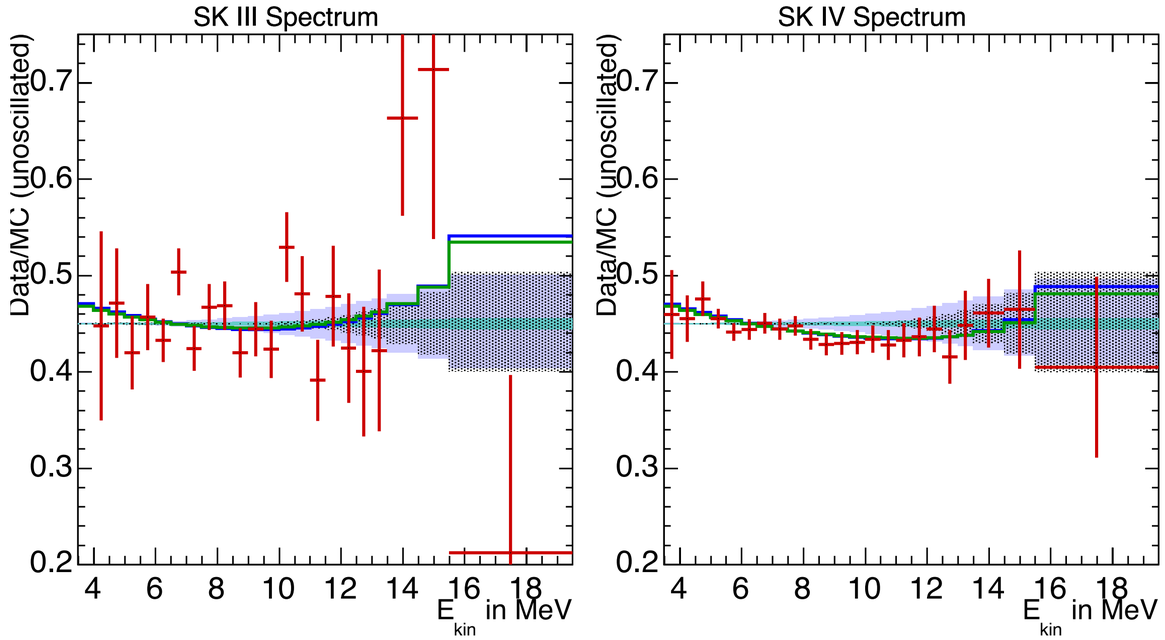




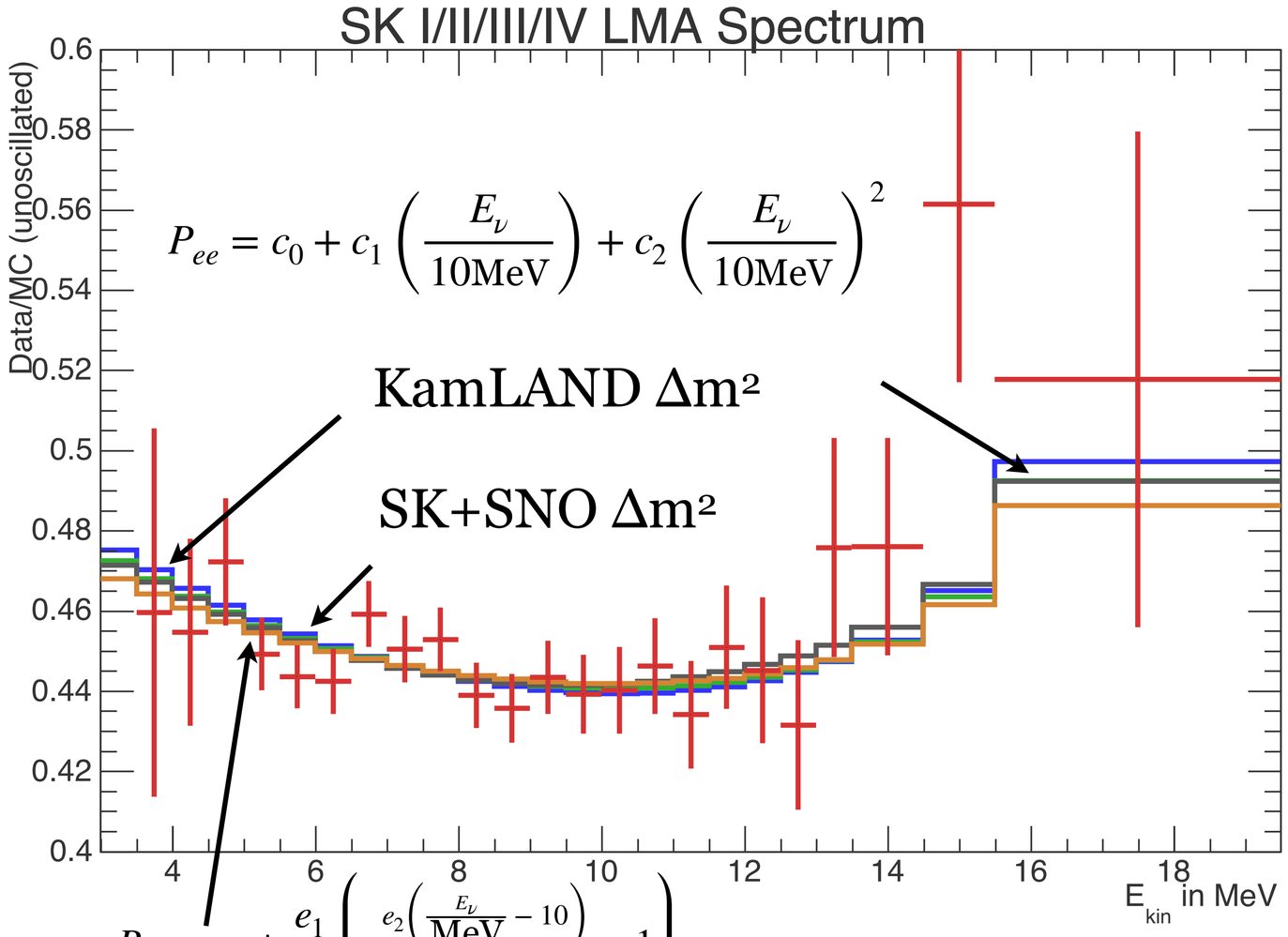
^{8}B Solar Neutrino Spectrum





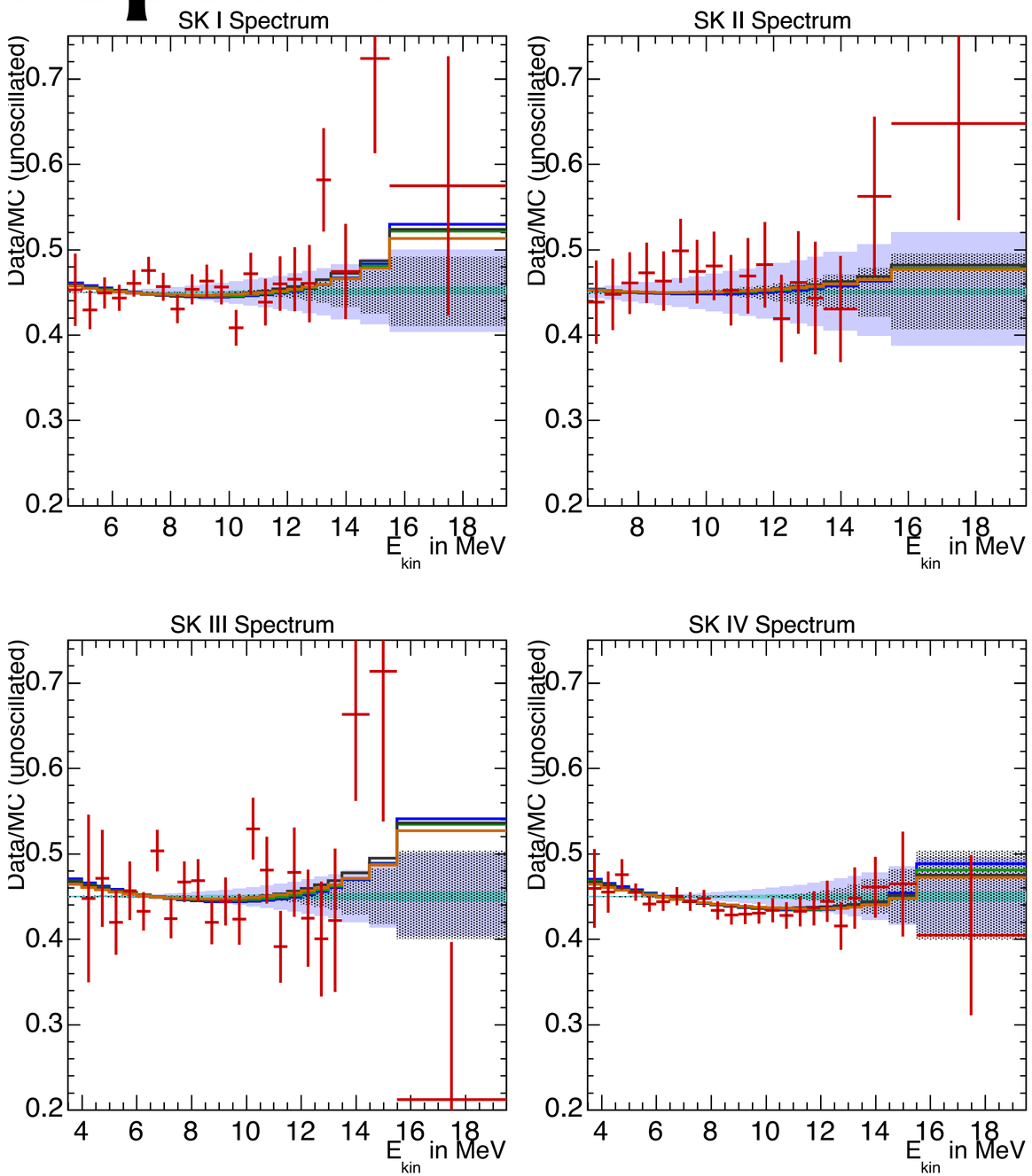


^{8}B Solar Neutrino Spectrum

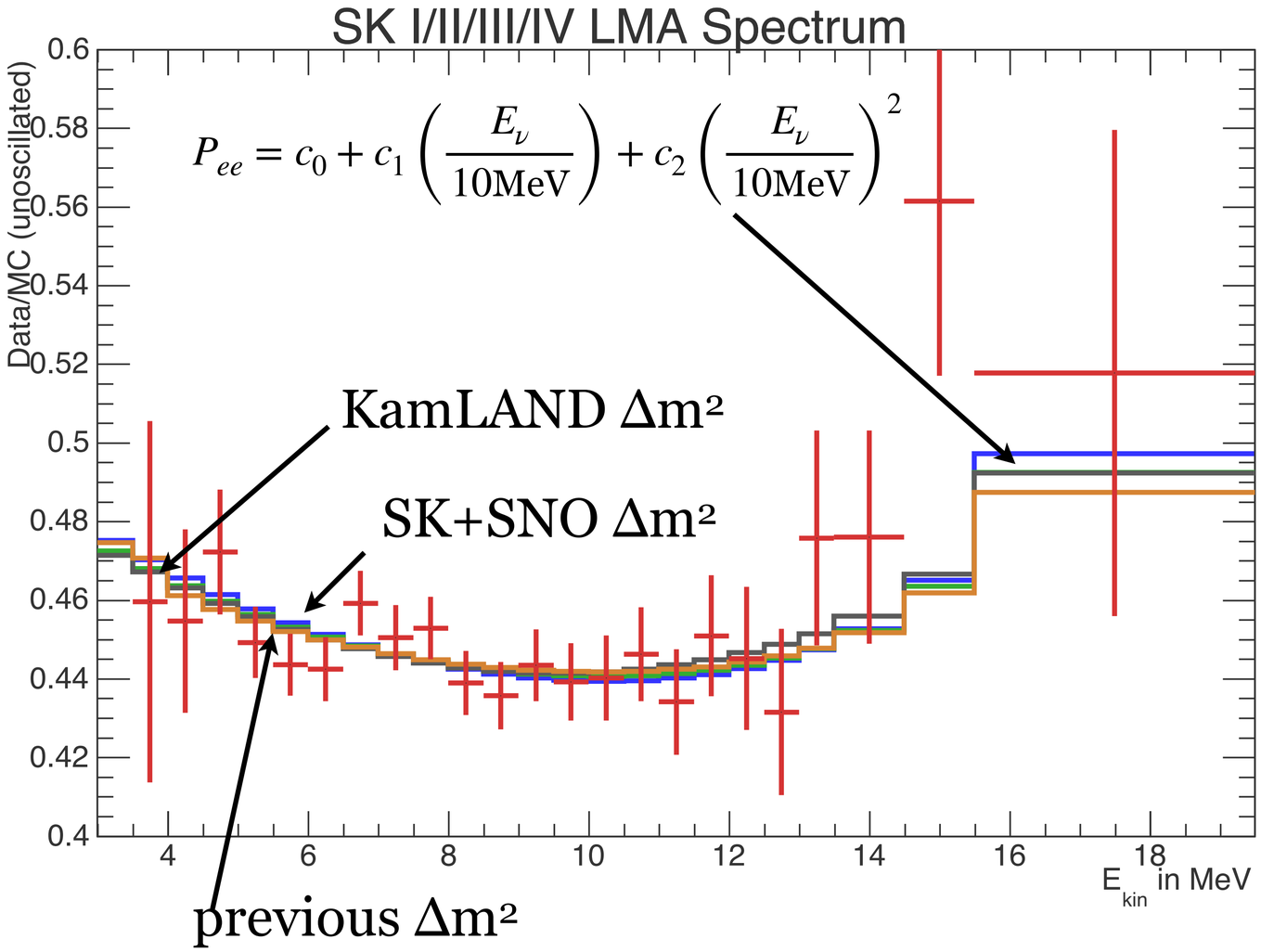


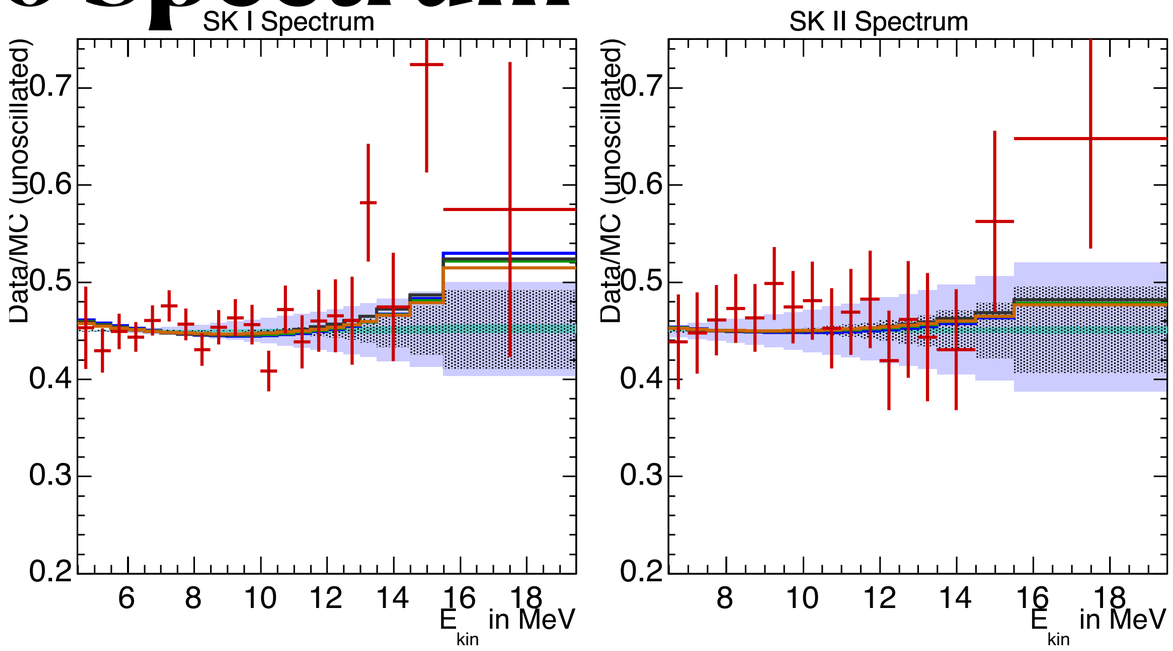
$$P_{ee} = c_0 + c_1\left(\frac{E_\nu}{10\text{MeV}}\right) + c_2\left(\frac{E_\nu}{10\text{MeV}}\right)^2$$

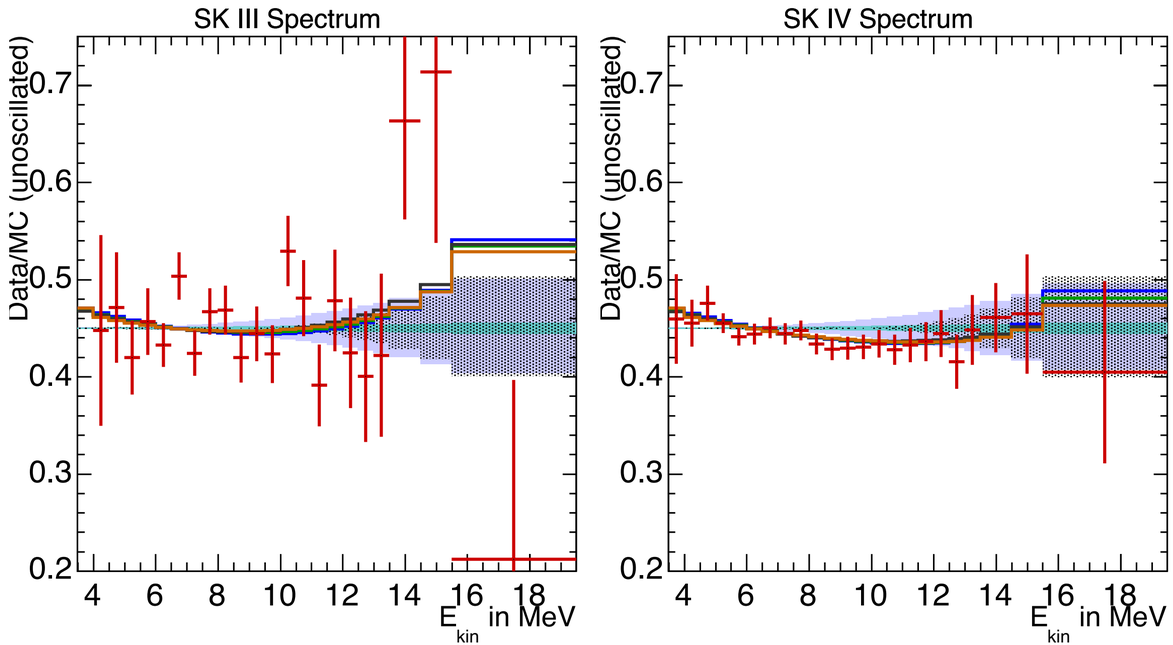
$$P_{ee} = e_0 + \frac{e_1}{e_2}\left(e^{e_2\left(\frac{E_\nu}{\text{MeV}} - 10\right)} - 1\right)$$



^{8}B Solar Neutrino Spectrum



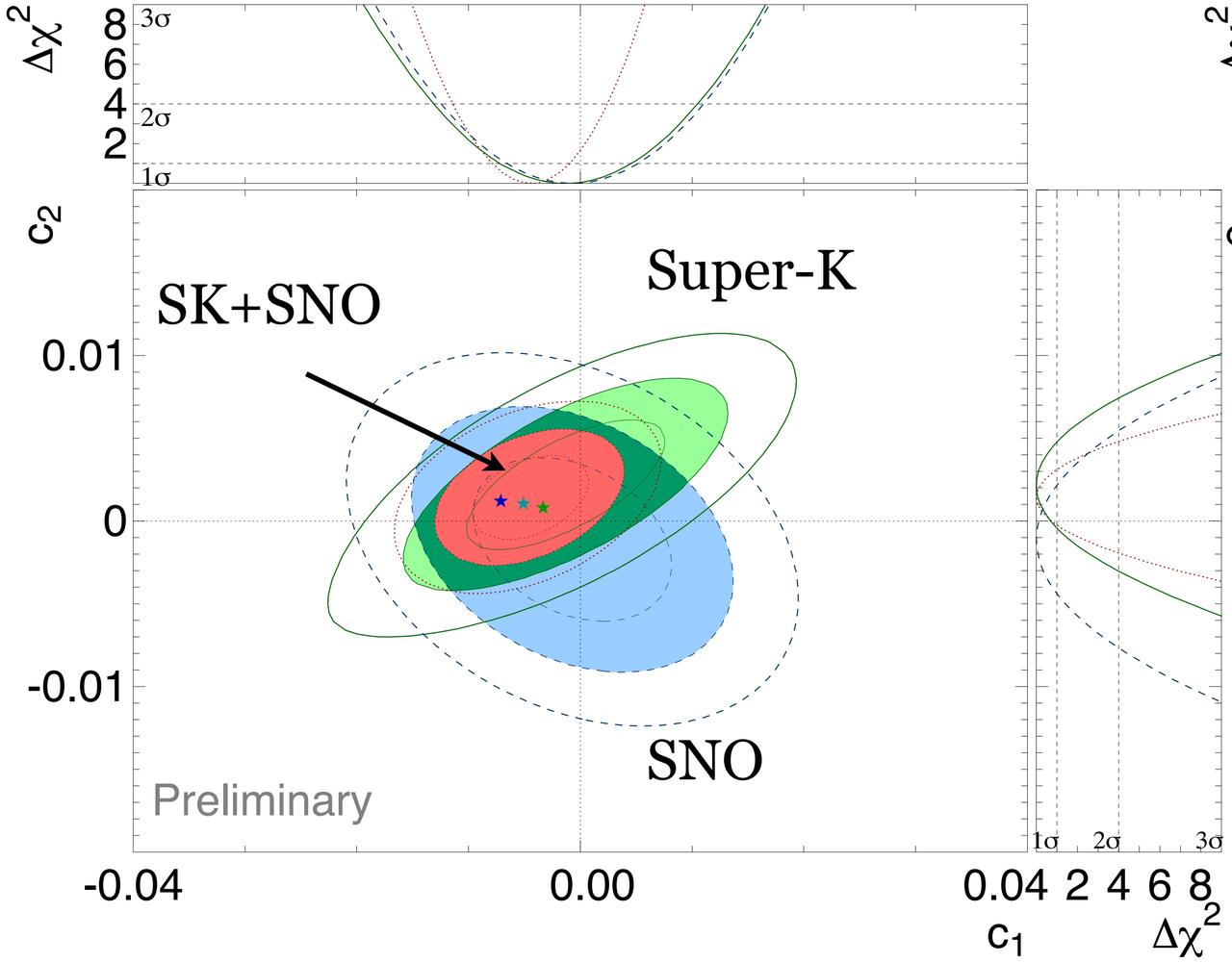


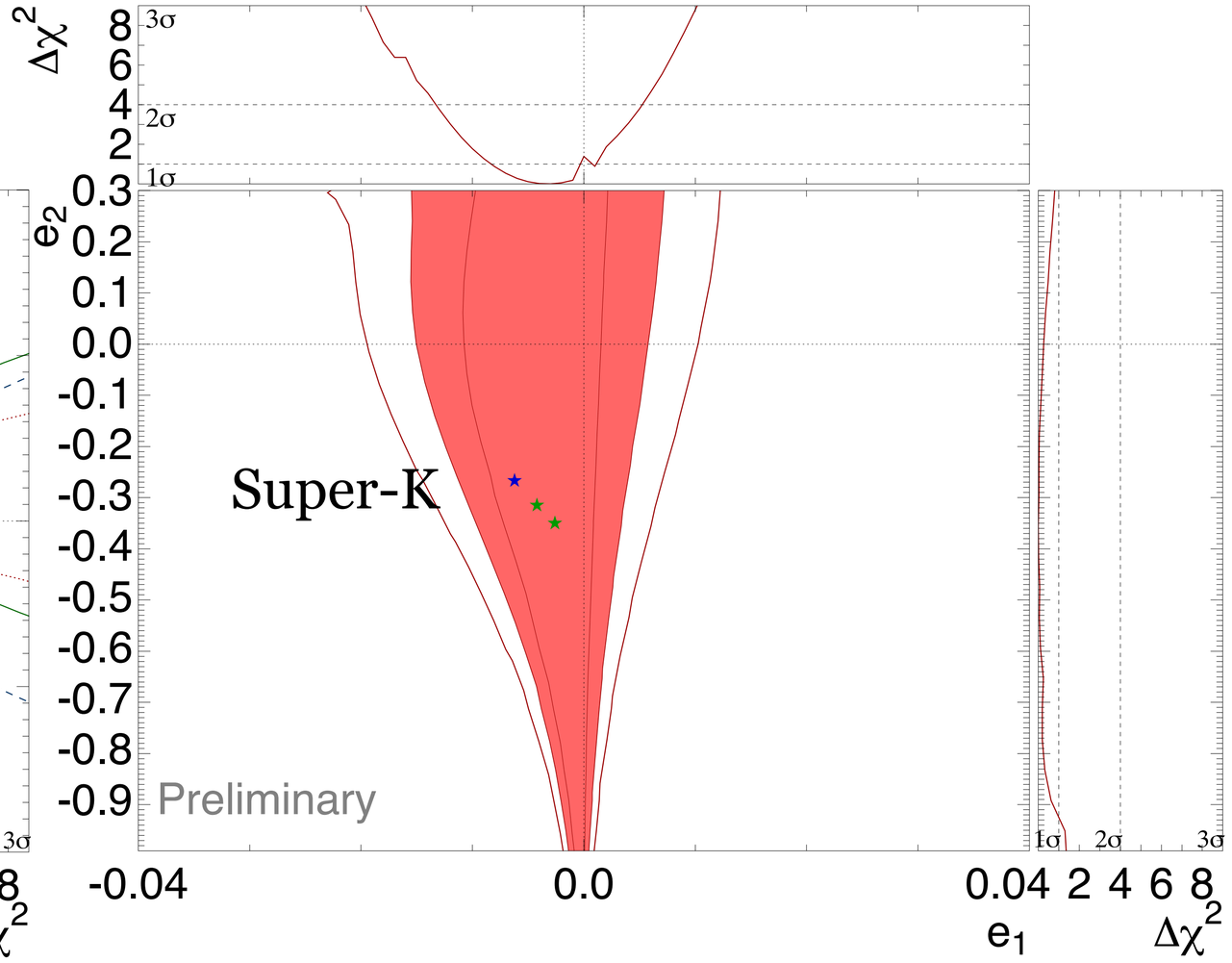


Generic Function Fits

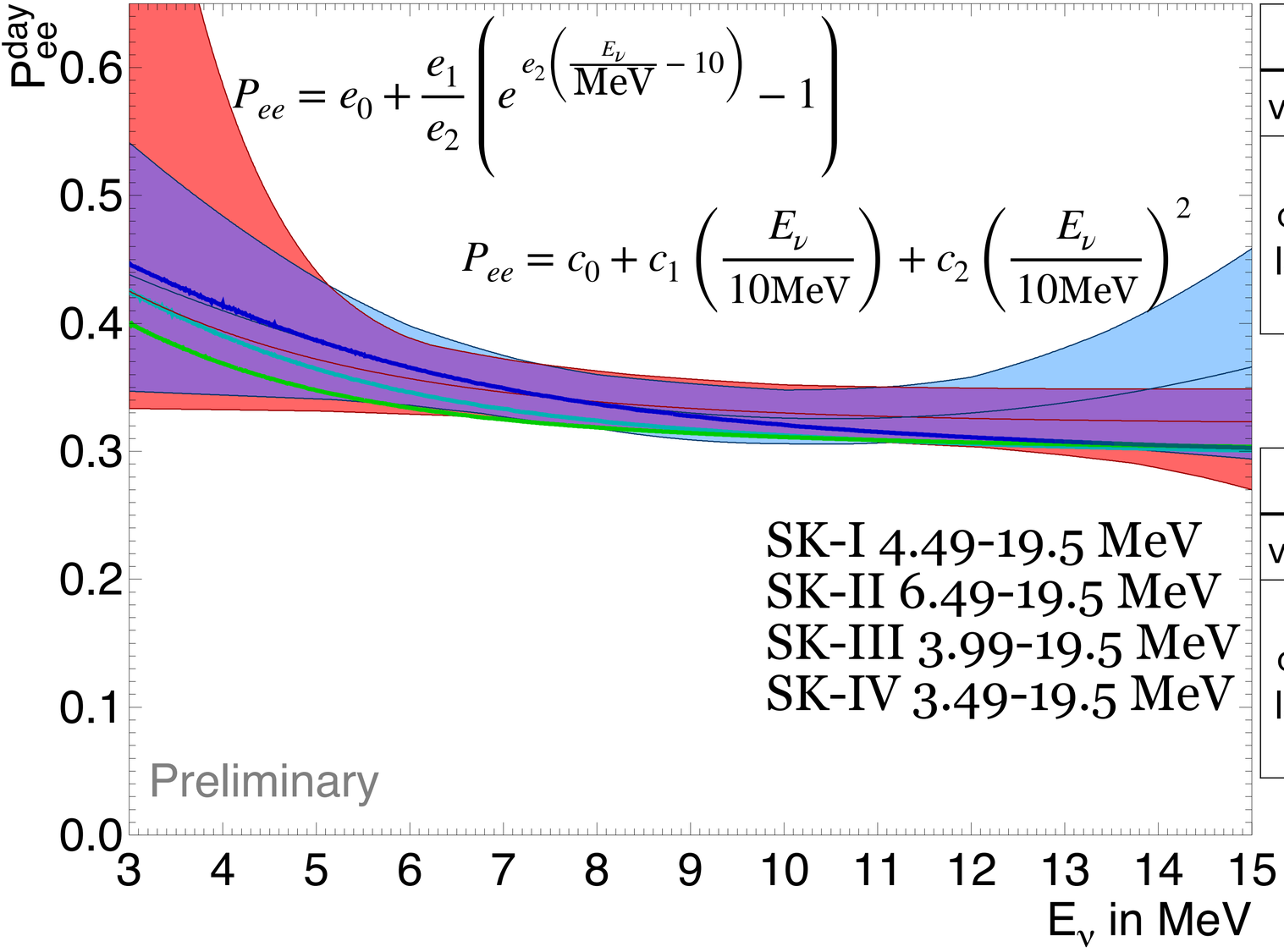
$$P_{ee} = c_0 + c_1\left(\frac{E_\nu}{10\text{MeV}}\right) + c_2\left(\frac{E_\nu}{10\text{MeV}}\right)^2$$

$$P_{ee} = e_0 + \frac{e_1}{e_2}\left(e^{e_2\left(\frac{E_\nu}{\text{MeV}} - 10\right)} - 1\right)$$





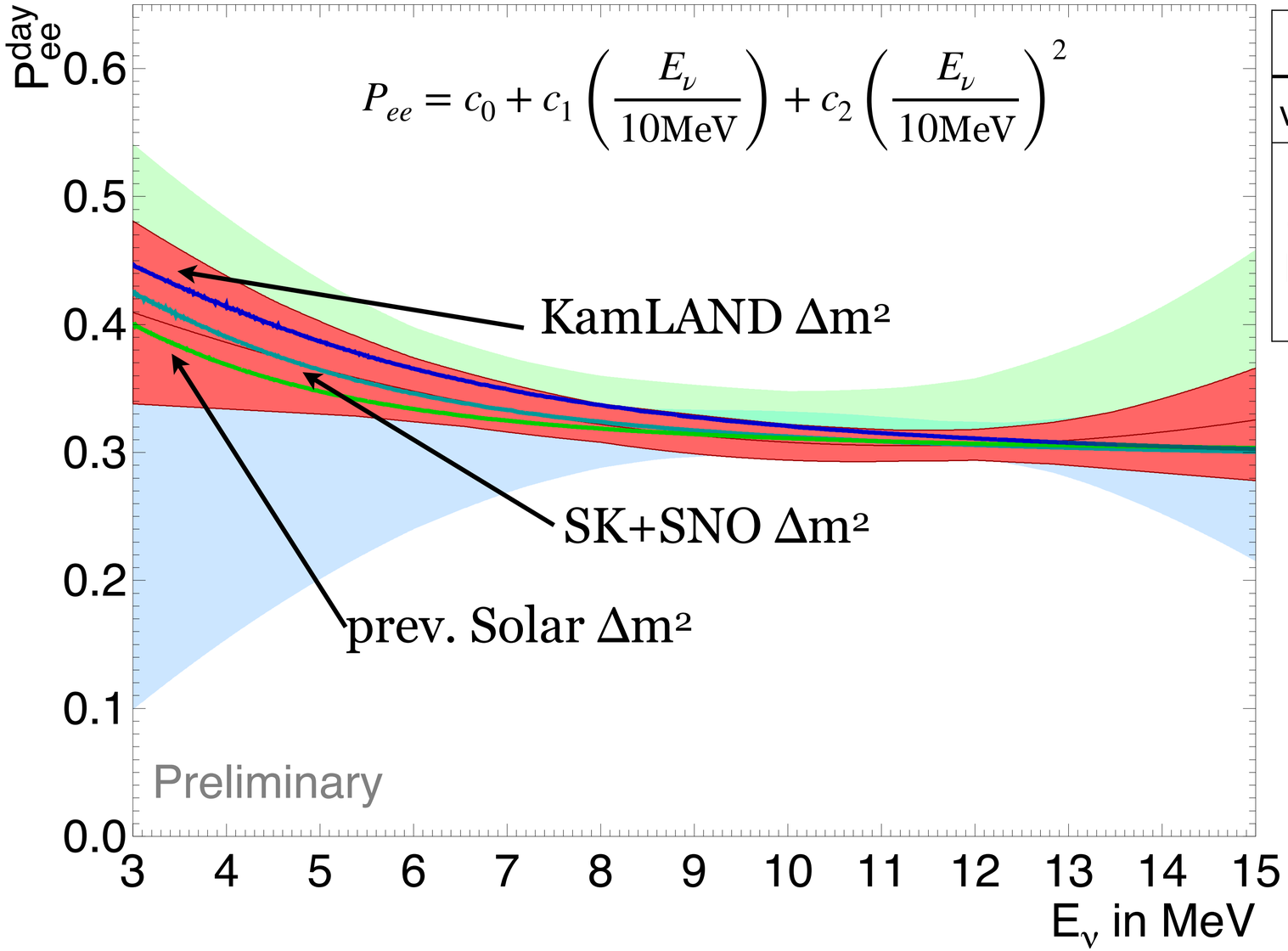
Super-K Generic Function Fits



	c_0	c_1	c_2
values	0.329±0.022	-0.0013±0.0059	0.0022±0.0026
correlation	1	-0.126	-0.281
	-0.126	1	0.672
	-0.281	0.672	1

	e_0	e_1	e_2
values	0.333±0.023	-0.0042±0.0048	-0.7±2.7
correlation	1	0.076	0.169
	0.076	1	0.082
	0.169	0.082	1

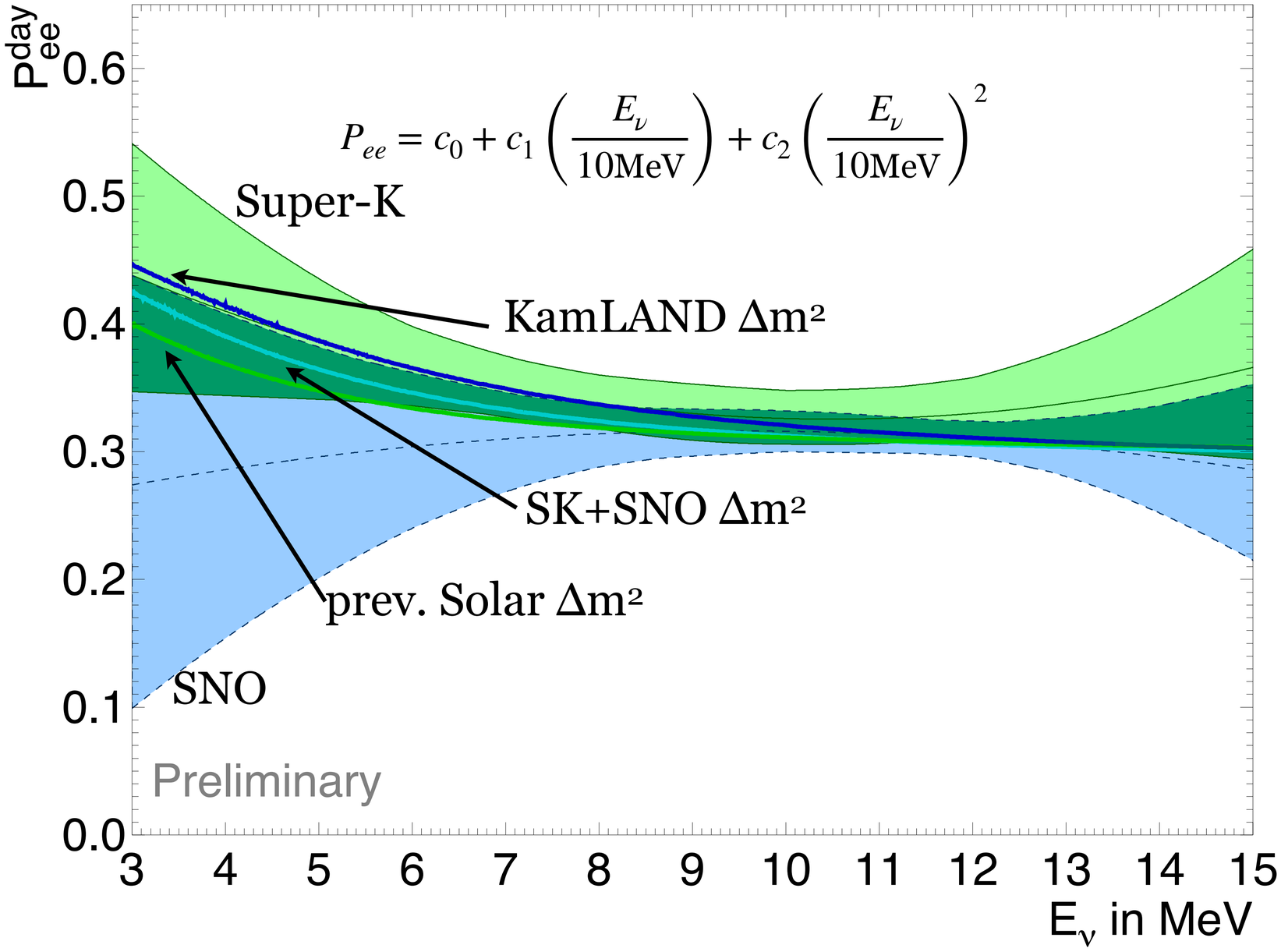
SK+SNO Quadratic Function Fit



	c_0	c_1	c_2
values	0.309±0.015	-0.0045±0.0035	0.0014±0.0017
correlation	1	-0.472	-0.390
	-0.472	1	0.371
	-0.390	0.371	1

SK-I 4.49-19.5 MeV
SK-II 6.49-19.5 MeV
SK-III 3.99-19.5 MeV
SK-IV 3.49-19.5 MeV
SNO-I/II/III

SK vs. SNO Quadratic Function Fit



SK-I 4.49-19.5 MeV
SK-II 6.49-19.5 MeV
SK-III 3.99-19.5 MeV
SK-IV 3.49-19.5 MeV
SNO-I/II/III

Best Fit χ^2 values

SK+SNO MSW

$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	Δm^2_{21}	^8B	hep	χ^2	$\Delta\chi^2$	
0.304	0.02	6.1×10^{-5} eV^2	5.35×10^6 /cm^{2}s	8×10^3 /cm^{2}s	57.39		
0.304	0.02	7.5×10^{-5} eV^2	5.24×10^6 /cm^{2}s	8×10^3 /cm^{2}s	59.34	1.95	1.4σ

Super-K spectrum quadratic fit

c_0	c_1	c_2	^8B	hep	χ^2	$\Delta\chi^2$	
0.326	-0.002	0.002	5.25×10^6 /cm^{2}s	12×10^3 /cm^{2}s	60.87		
0.336	0	0	5.26×10^6 /cm^{2}s	13×10^3 /cm^{2}s	62.69	1.82	1.3σ

Super-K spectrum MSW

$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	Δm^2_{21}	^8B	hep	χ^2	$\Delta\chi^2$	
0.304	0.02	6.1×10^{-5} eV^2	5.42×10^6 /cm^{2}s	14×10^3 /cm^{2}s	61.57		
0.304	0.02	7.5×10^{-5} eV^2	5.29×10^6 /cm^{2}s	14×10^3 /cm^{2}s	62.30	0.73	0.8σ

Super-K spectrum exponential fit

e_0	e_1	e_2	^8B	hep	χ^2	$\Delta\chi^2$	
0.330	-0.003	-0.36	5.26×10^6 /cm^{2}s	14×10^3 /cm^{2}s	61.30		
0.336	0	0	5.26×10^6 /cm^{2}s	13×10^3 /cm^{2}s	62.69	1.39	1.2σ

χ^2 values for "flat P_{ee} shape"

	baseline	^8B	hep	χ^2	$\Delta\chi^2$	
w/o D/N	0.306	5.54×10^6 / cm^2s	15×10^3 / cm^2s	62.17		
with D/N	0.336	5.26×10^6 / cm^2s	13×10^3 / cm^2s	62.69	0.52	0.7σ
flat data/ SSM	0.317	5.53×10^6 / cm^2s	13×10^3 / cm^2s	64.13	1.96	1.4σ

χ^2 values "MSW Emulation"

	$\sin^2\theta_{12}$ c_0/e_0	$\sin^2\theta_{13}$ c_1/e_1	Δm^2_{21} c_2/e_2	^8B	hep	χ^2	$\Delta\chi^2$
MSW	0.304	0.02	6.1×10^{-5} eV^2	5.42×10^6 $/cm^2s$	14×10^3 / cm^2s	61.57	
quad.	0.30791	-0.00509	0.00105	5.46×10^6 $/cm^2s$	14×10^3 / cm^2s	61.41	0.16
expon.	0.30916	-0.00421	-0.31897	5.46×10^6 $/cm^2s$	14×10^3 / cm^2s	61.49	0.08
MSW	0.304	0.02	7.5×10^{-5} eV^2	5.29×10^6 $/cm^2s$	14×10^3 / cm^2s	62.30	
quad.	0.31939	-0.00711	0.00119	5.31×10^6 $/cm^2s$	14×10^3 / cm^2s	62.08	0.22
expon.	0.32053	-0.00622	-0.27074	5.31×10^6 $/cm^2s$	14×10^3 / cm^2s	62.06	0.24

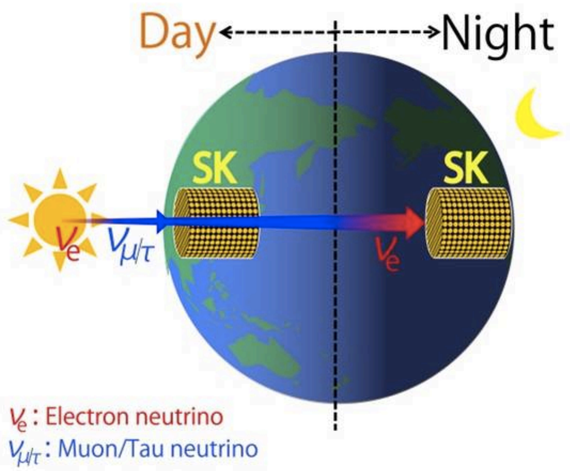
Solar oscillation analysis results

Day/Night Asymmetry

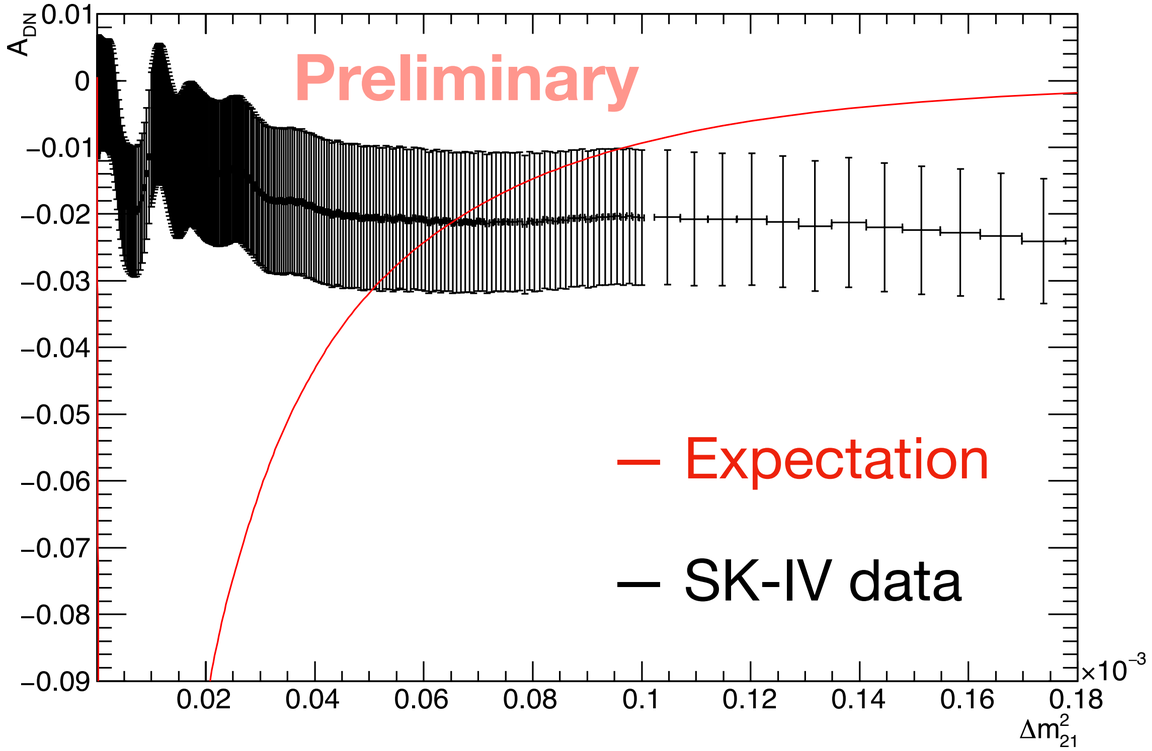
- Updated Day/Night asymmetry analysis with the full data set

$$A_{D/N} = \frac{\Phi_{day} - \Phi_{night}}{0.5(\Phi_{day} + \Phi_{night})}$$

- Extracted Day/Night asymmetry w/ spectrum fit as a function of Δm^2_{21}



Day/Night Variation Amplitude

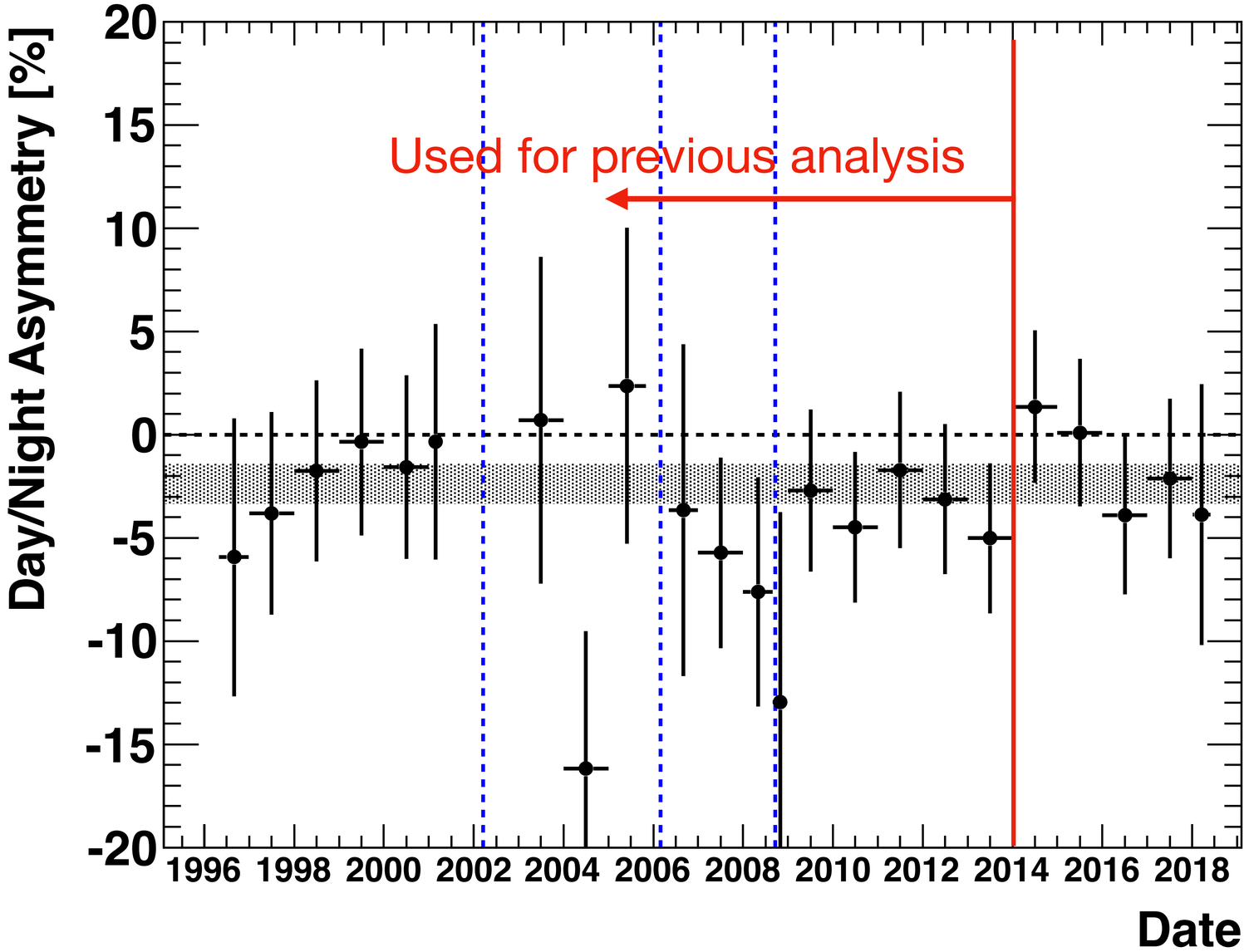


Results from SK I-IV data

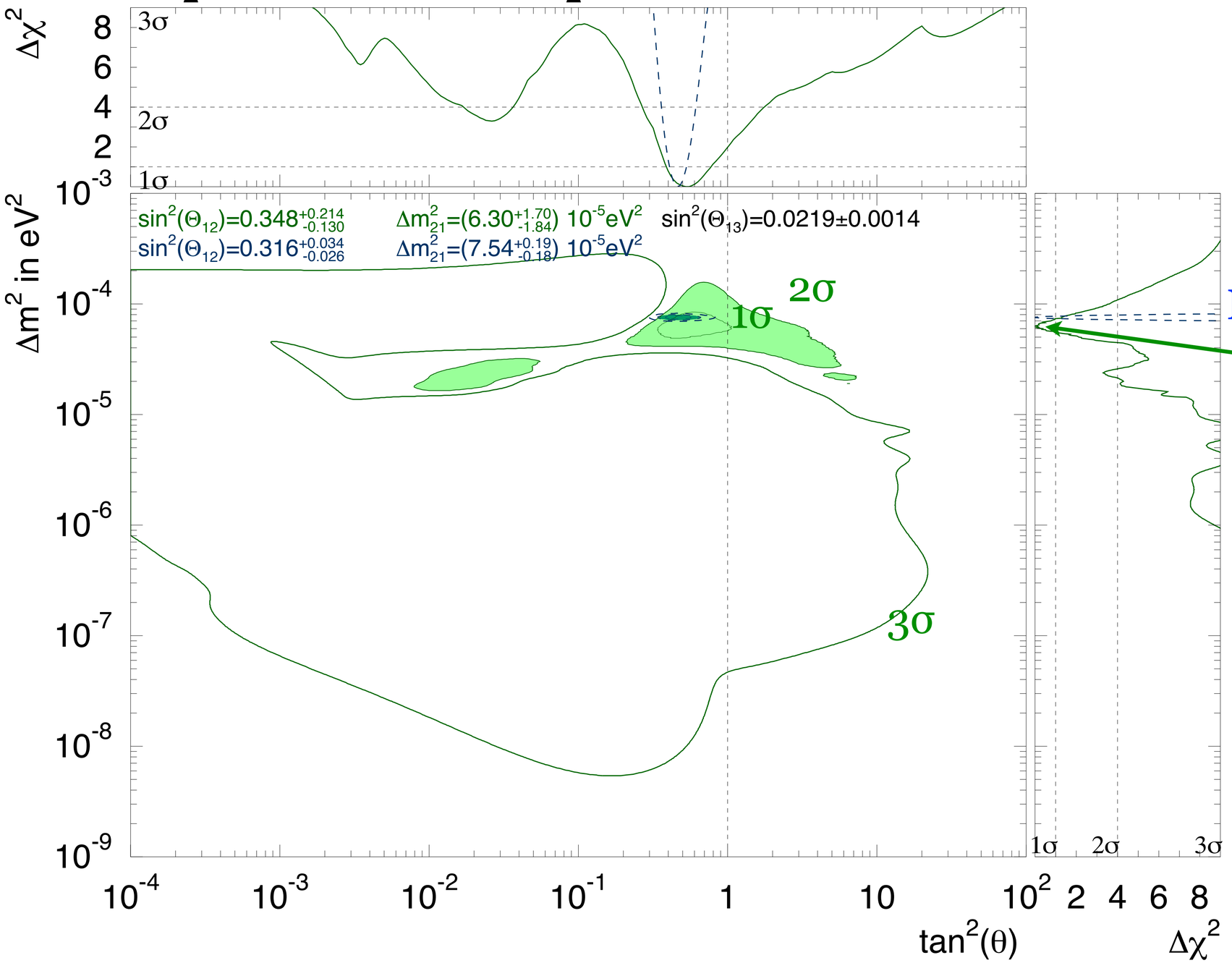
Energy range	3.5 - 19.5 MeV	4.5 - 19.5 MeV
Raw count	- 1.9% ± 1.2%	- 1.8% ± 1.2%
Fit result	- 2.1% ± 1.1%	- 2.0% ± 1.1%

Prefers non-zero Day/Night asymmetry at ~2σ significance

History of Day/Night asymmetry



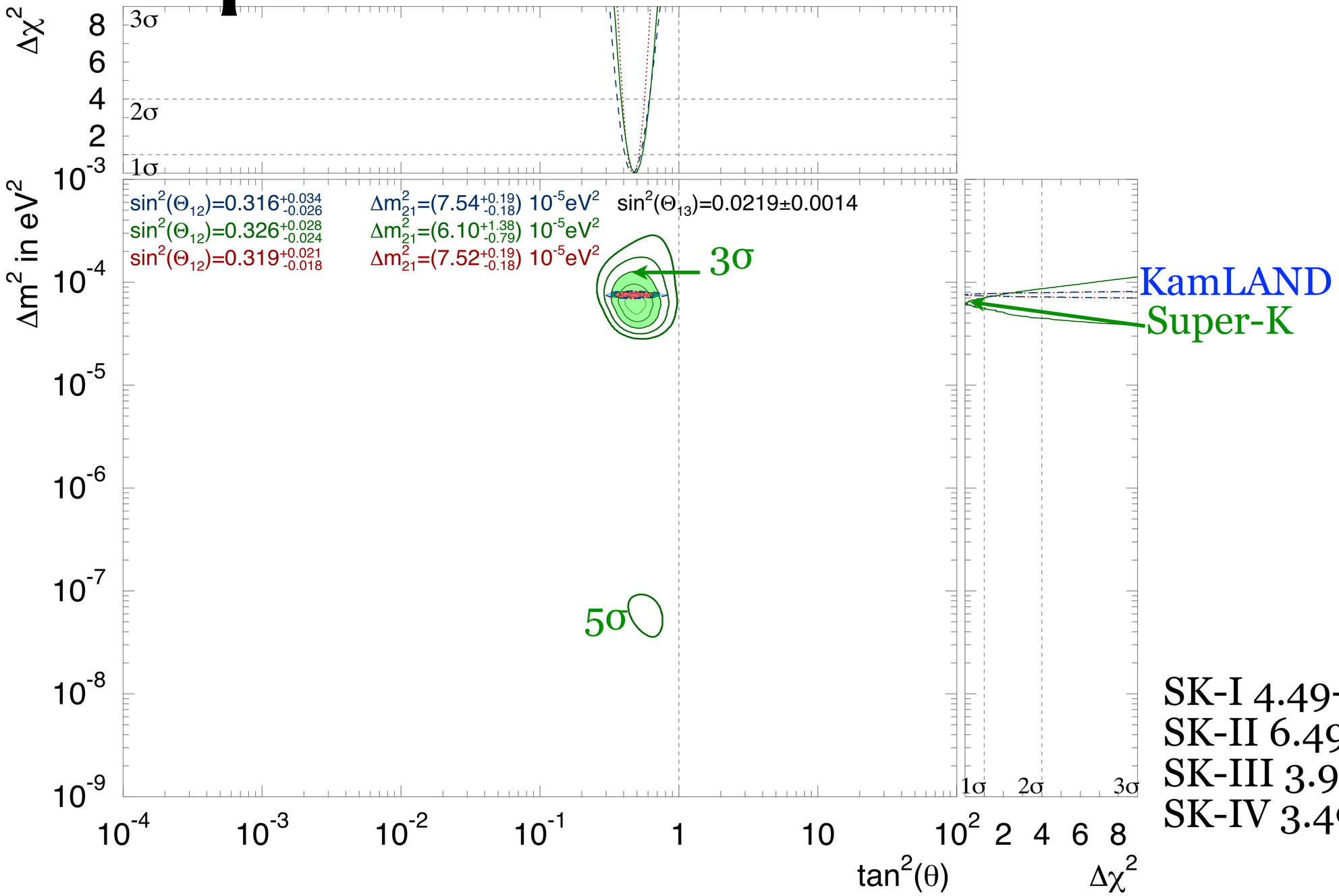
^{8}B and hep ν Flux Independent Oscillation Constraints



KamLAND
Super-K

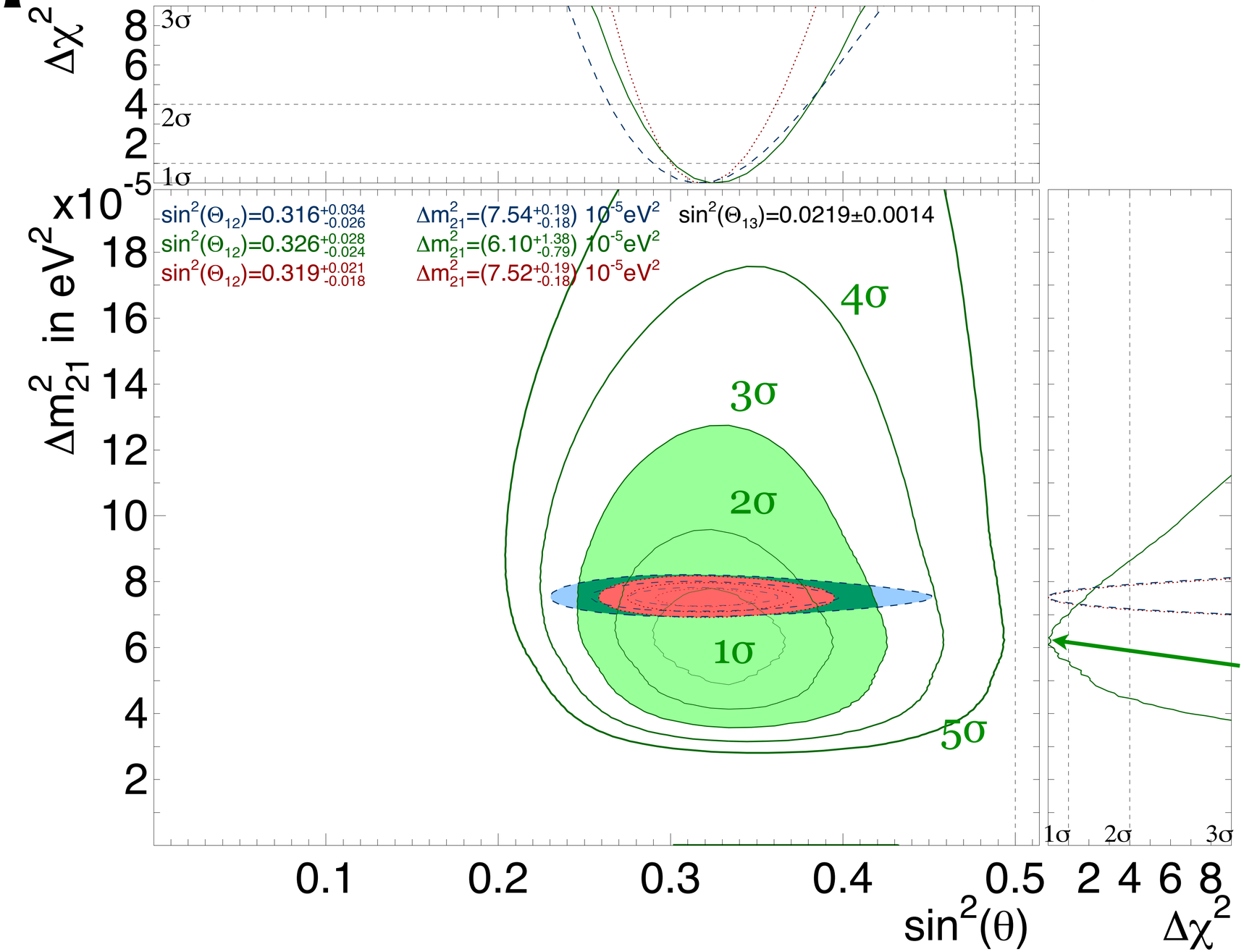
SK-I 4.49-19.5 MeV
SK-II 6.49-19.5 MeV
SK-III 3.99-19.5 MeV
SK-IV 3.49-19.5 MeV

Super-K Oscillation Constraints



SK-I 4.49-19.5 MeV
SK-II 6.49-19.5 MeV
SK-III 3.99-19.5 MeV
SK-IV 3.49-19.5 MeV

Super-K Oscillation Constraints (Linear Scale)

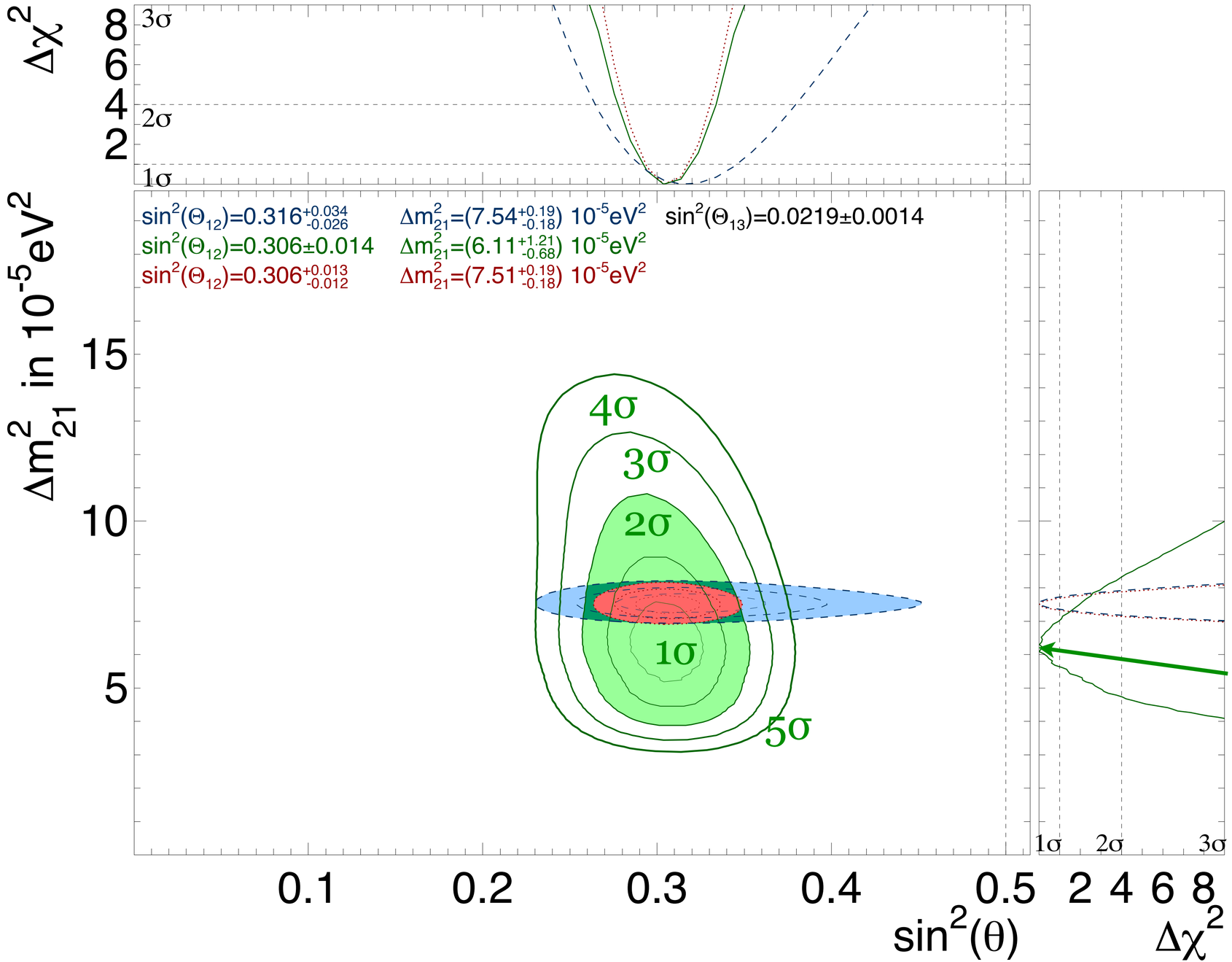


KamLAND

Super-K

SK-I 4.49-19.5 MeV
SK-II 6.49-19.5 MeV
SK-III 3.99-19.5 MeV
SK-IV 3.49-19.5 MeV

SK+SNO Oscillation Constraints

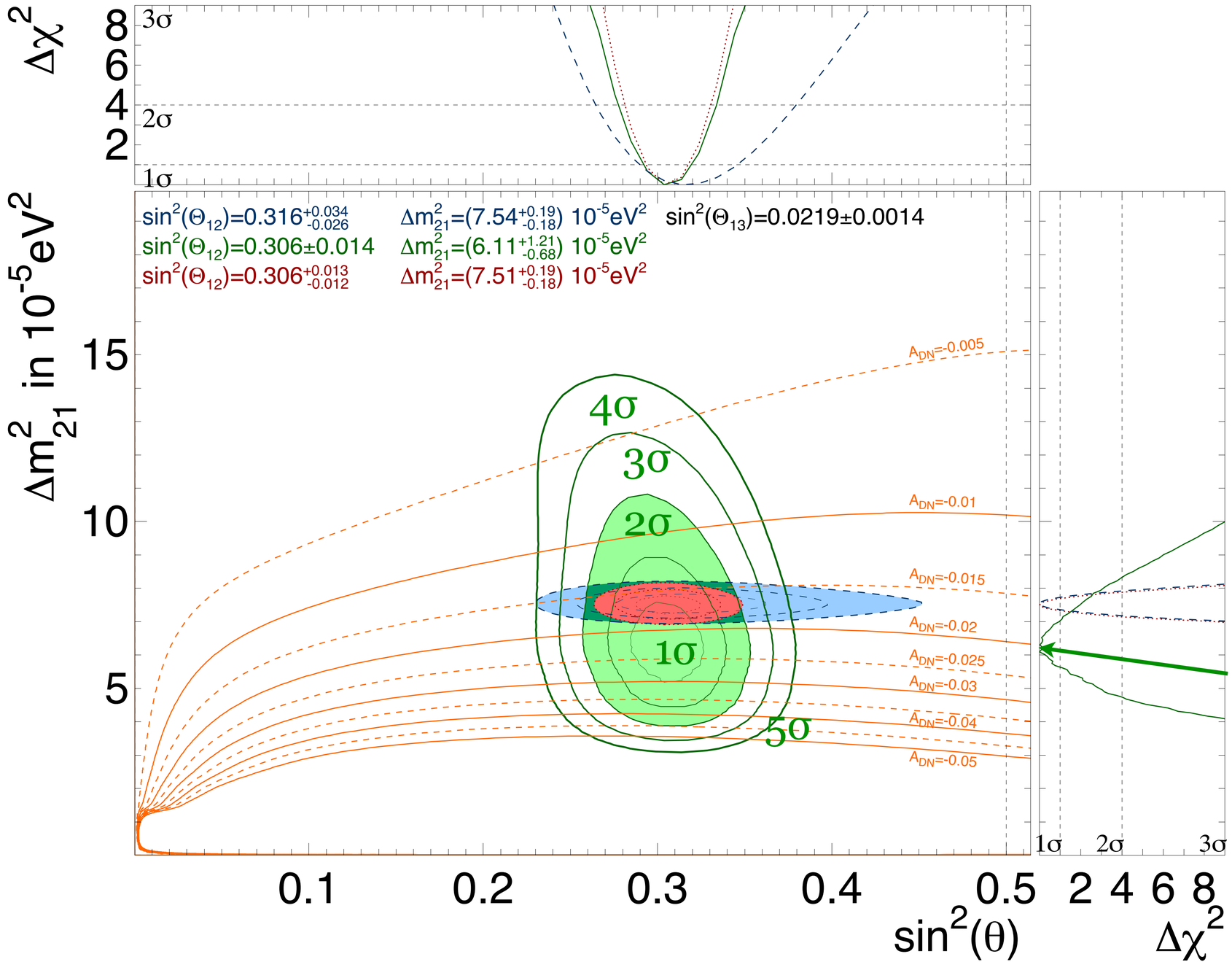


SK-I 4.49-19.5 MeV
SK-II 6.49-19.5 MeV
SK-III 3.99-19.5 MeV
SK-IV 3.49-19.5 MeV
SNO-I/II/III

KamLAND

Super-K+SNO

SK+SNO Oscillation Constraints and SK-IV D/N

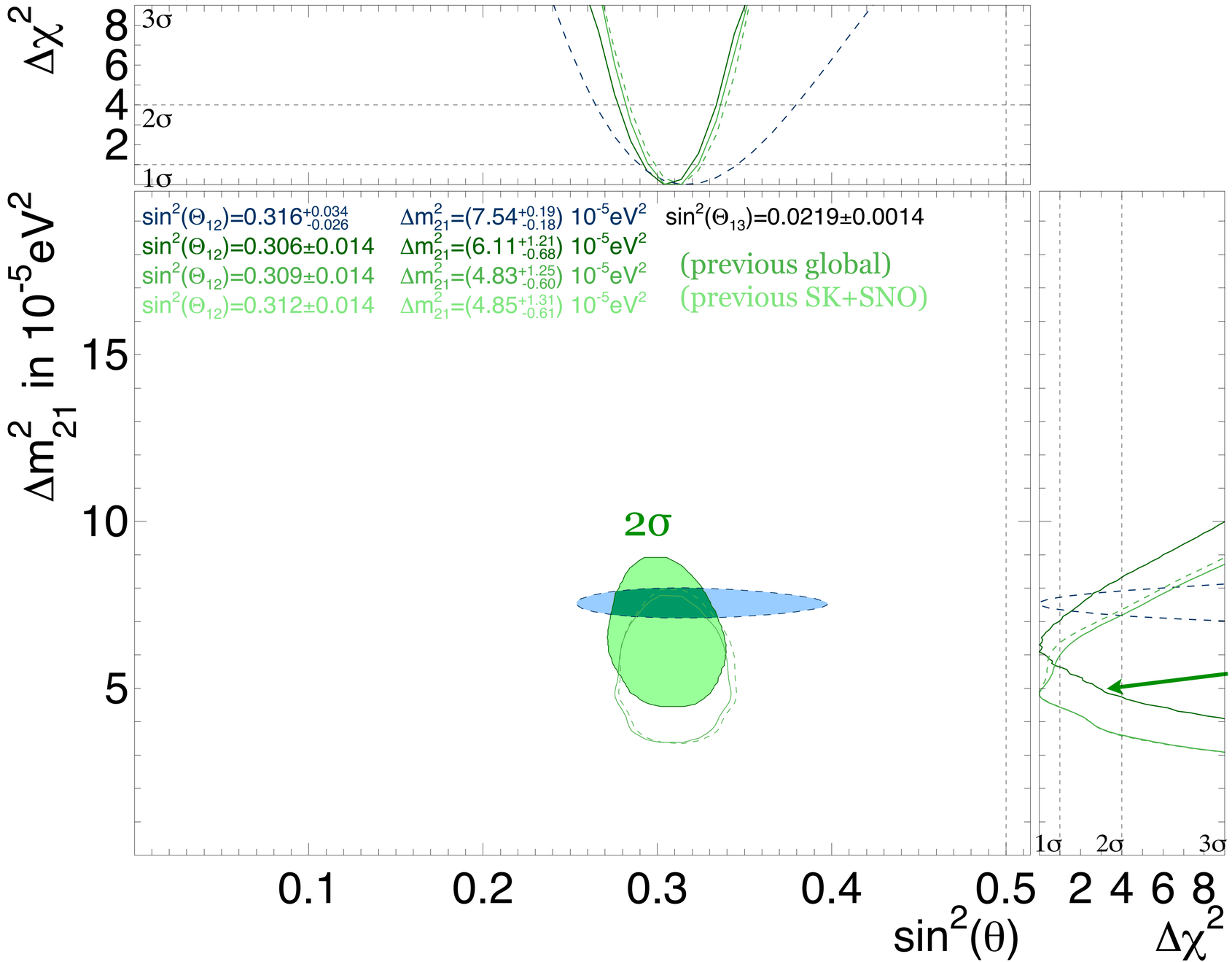


SK-I 4.49-19.5 MeV
SK-II 6.49-19.5 MeV
SK-III 3.99-19.5 MeV
SK-IV 3.49-19.5 MeV
SNO-I/II/III

KamLAND

Super-K+SNO

SK+SNO Oscillation Constraints and Previous

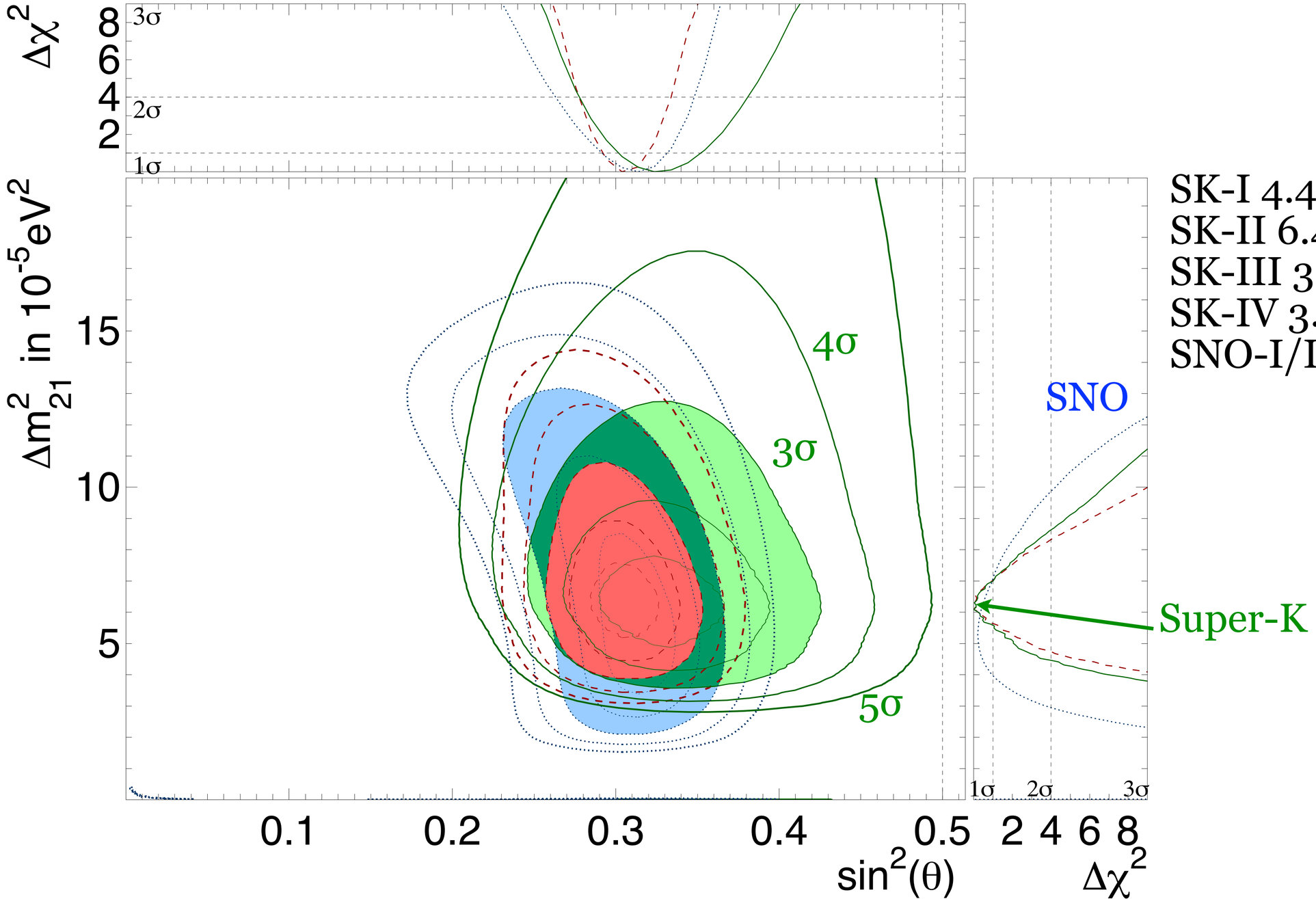


SK-I 4.49-19.5 MeV
SK-II 6.49-19.5 MeV
SK-III 3.99-19.5 MeV
SK-IV 3.49-19.5 MeV
SNO-I/II/III

KamLAND

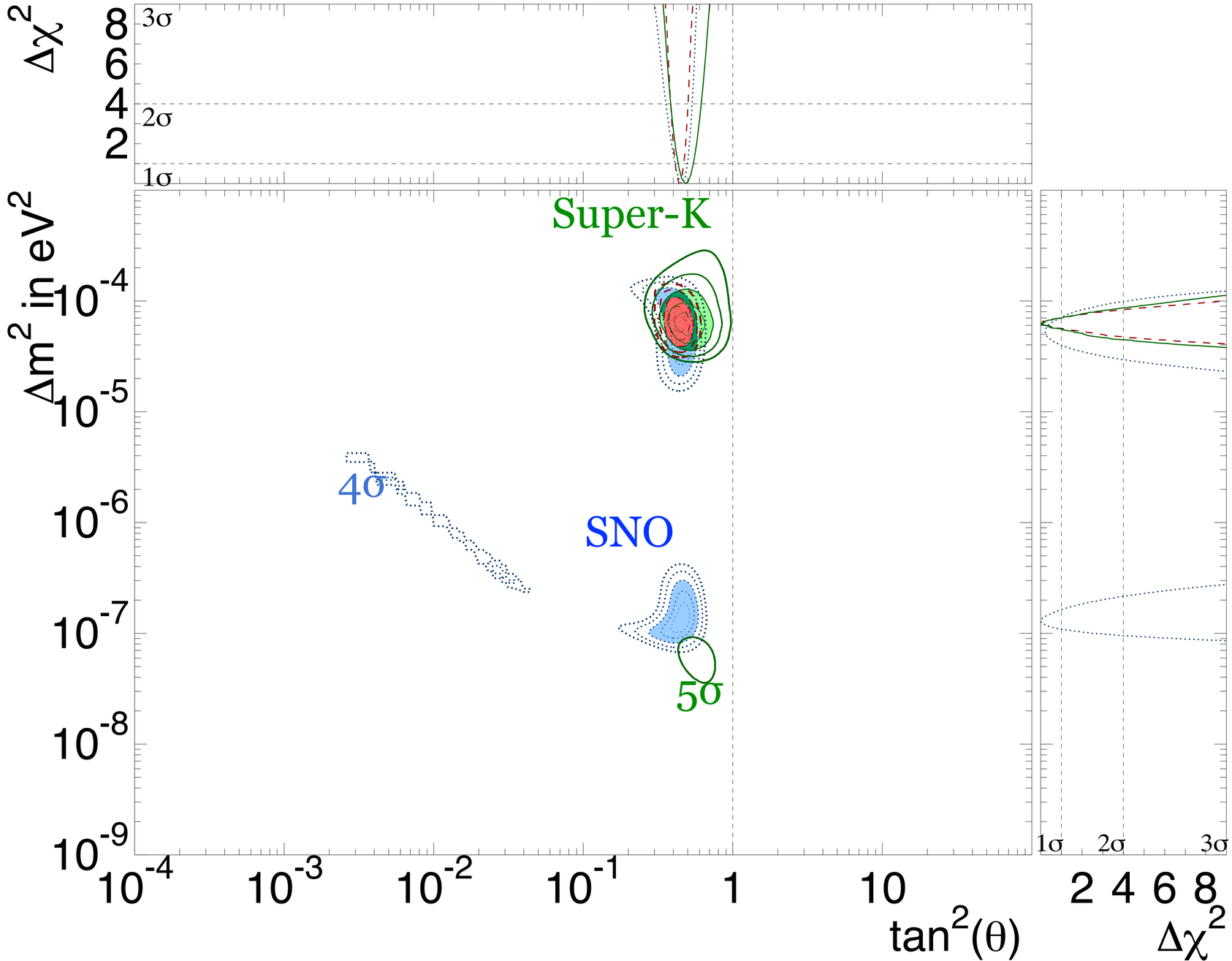
Super-K+SNO

SK vs SNO Oscillation Constraints



SK-I 4.49-19.5 MeV
SK-II 6.49-19.5 MeV
SK-III 3.99-19.5 MeV
SK-IV 3.49-19.5 MeV
SNO-I/II/III

SK vs SNO Oscillation Constraints (log scale)



SK-I 4.49-19.5 MeV
SK-II 6.49-19.5 MeV
SK-III 3.99-19.5 MeV
SK-IV 3.49-19.5 MeV
SNO-I/II/III

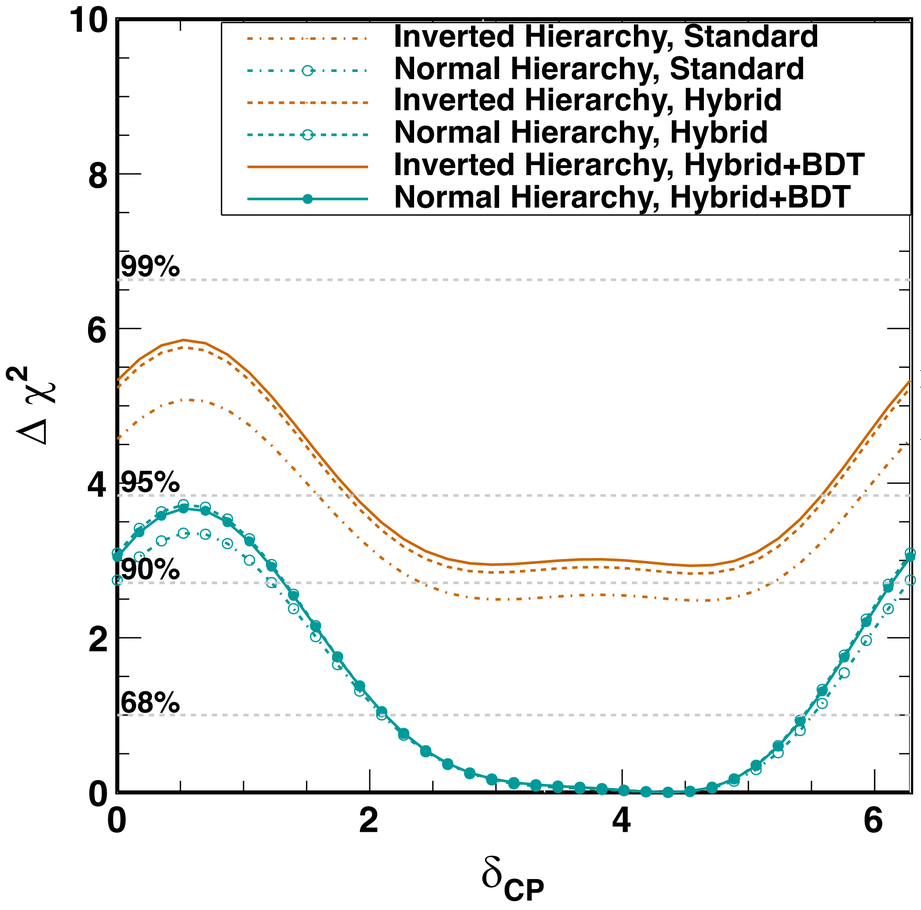
Best Fit χ^2 values

SK+SNO MSW

$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	Δm^2_{21}	^8B	hep	χ^2	$\Delta\chi^2$		
0.304	0.02	6.1×10^{-5} eV^2	5.35×10^6 /cm^{2}s	8×10^3 /cm^{2}s	57.39			"SK+SNO" Δm^2_{21}
0.304	0.02	7.5×10^{-5} eV^2	5.24×10^6 /cm^{2}s	8×10^3 /cm^{2}s	59.34	1.95	1.4σ	"KamLAND" Δm^2_{21}

Atmospheric Neutrino Analysis

Impact of Changes to Event Selection



All plots use NEUT 5.4.0 19b libraries
And full SK-I~IV livetime

Add BDT for Multi-Ring selection

Add Neutron Tagging (single-ring)

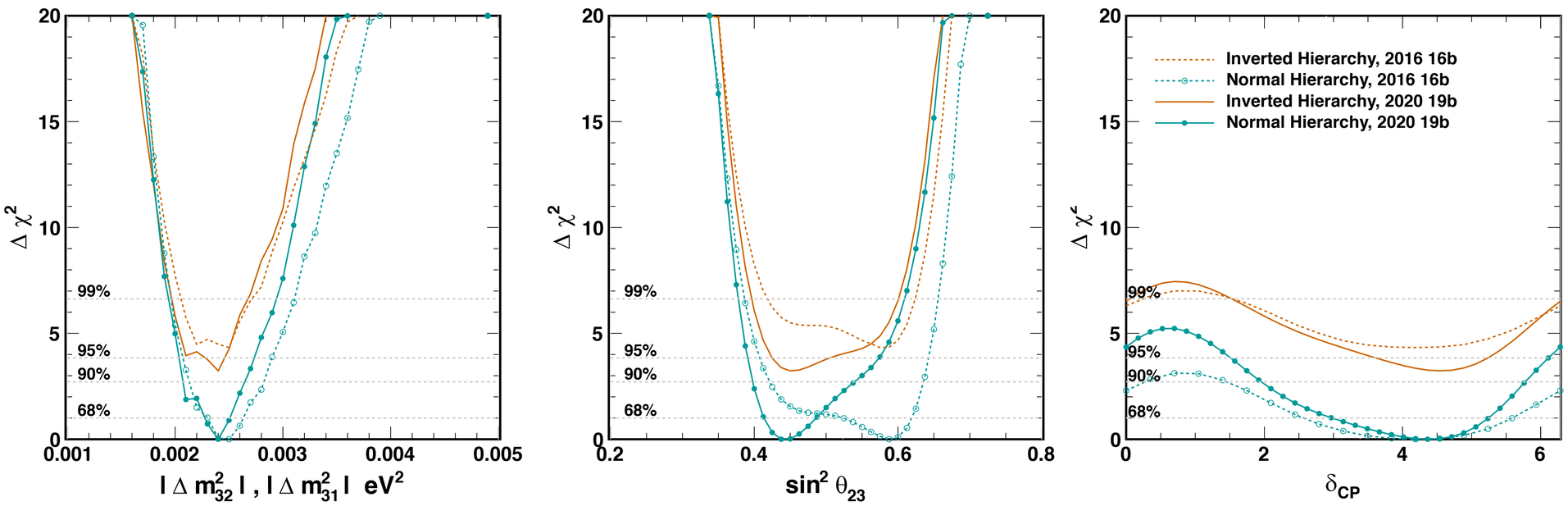
Standard Event Selection

- Vertical distance between cyan and orange lines shows the hierarchy sensitivity

- Solid lines are the final sensitivity projection for the current analysis
  - Assumes $\sin^2\theta_{23} = 0.525$, $\Delta m^2 = 2.5\text{x}10^{-3}$ eV^2, $\delta_{CP} = 4.188$
- Systematic errors are included in all lines

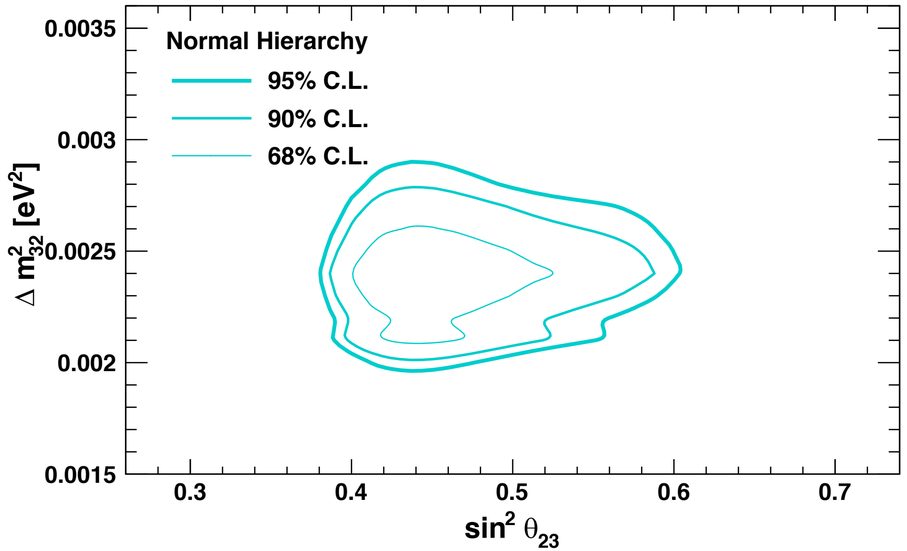
SKI-IV Fit Results (19b) : Comparison with 2018 Paper

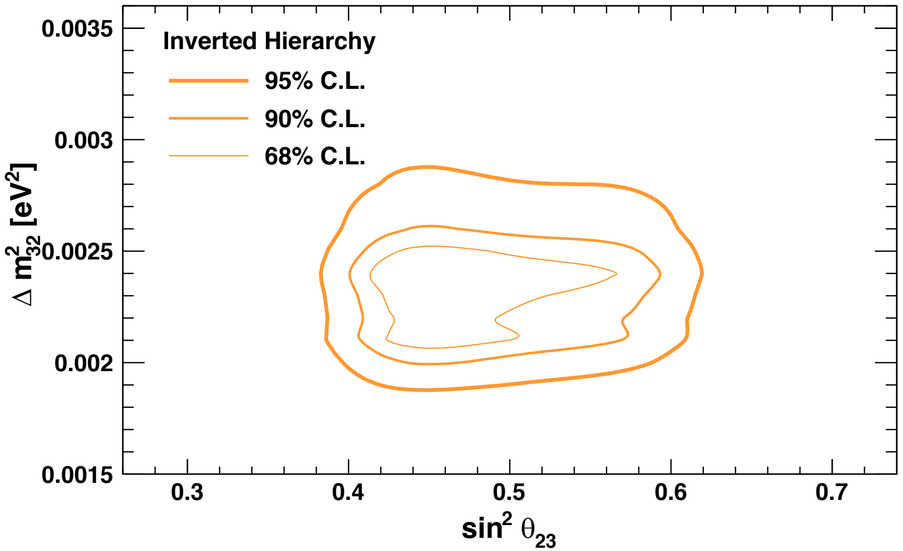
contours/19b-16b.data.nh-ih/

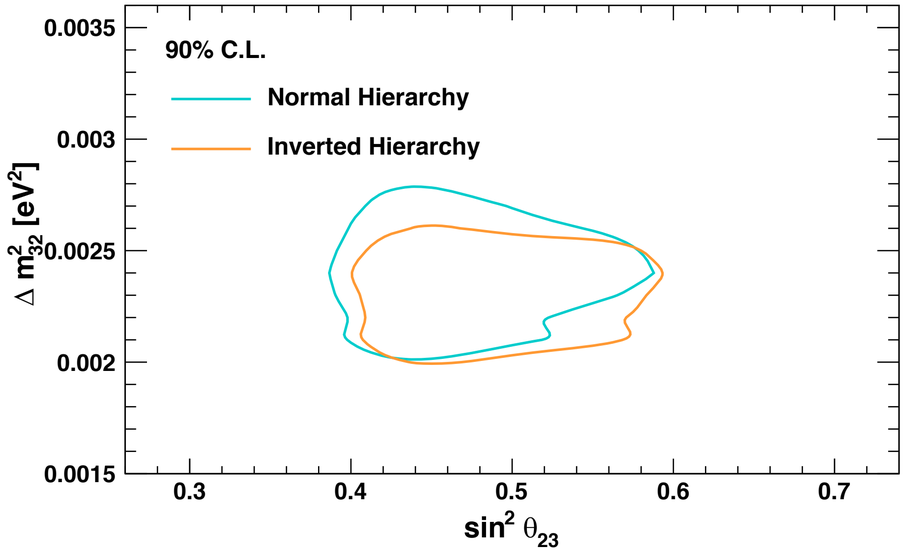


- Takeaways relative to 2018 Paper
  - Preference for Normal Hierarchy is weaker
    - CLs ~ 0.14 (86% pref. NH), similar to 2018 CLs ~ 0.18
  - Preference changed to **1st** octant
  - Stronger rejection of sin(δ) ~ 0 , p-value > 0.40

Atmospheric Mixing Overlay



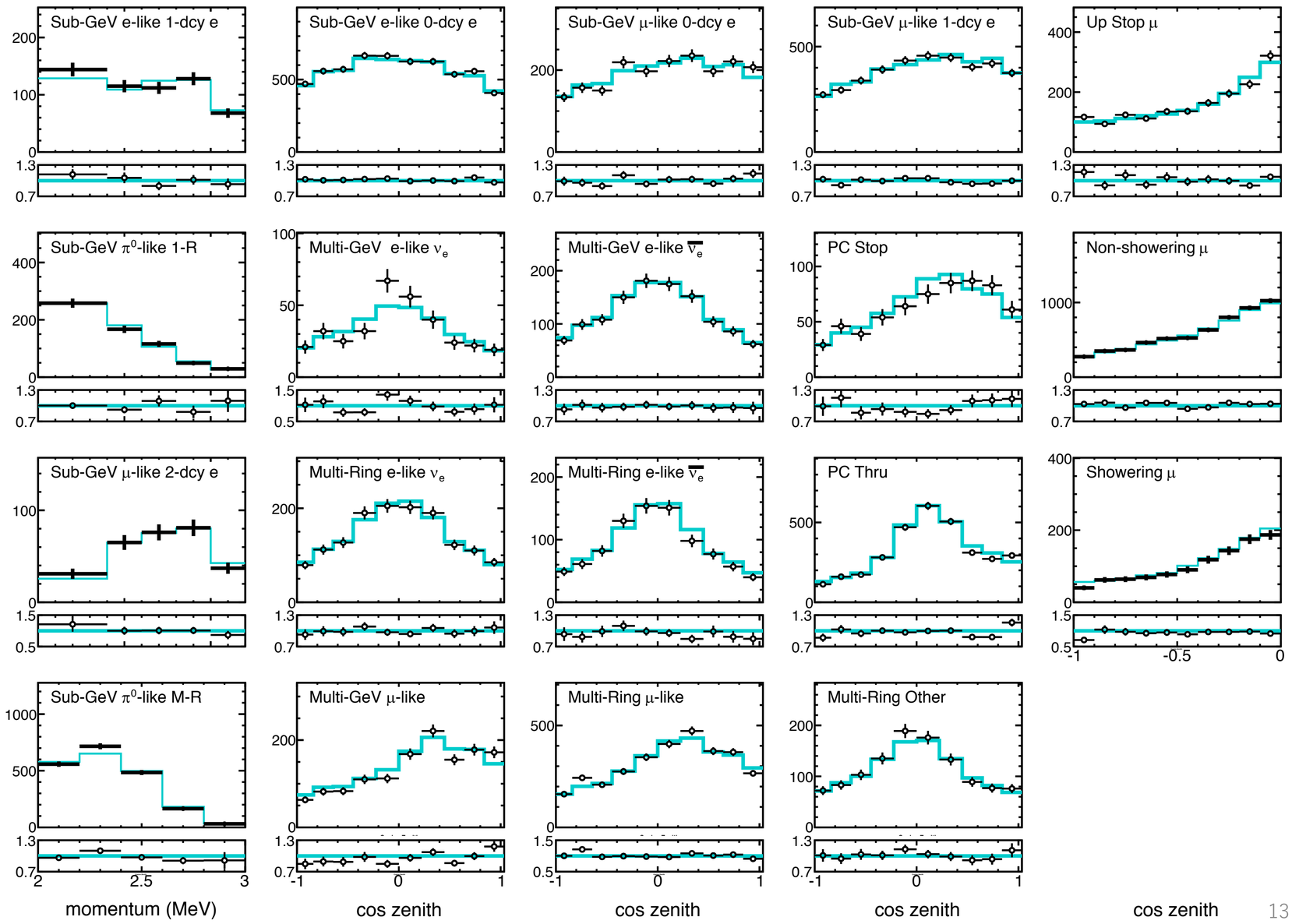




- IH curves have been calculated relative to the best fit (NH) χ^2

Zenith Distributions (no neutrons)

zenith/



Zenith Distributions (using neutrons)

zenith/