Experimental determination of neutrino oscillation in atmospheric neutrinos / solar neutrinos

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for
Super-Kamiokande collaboration

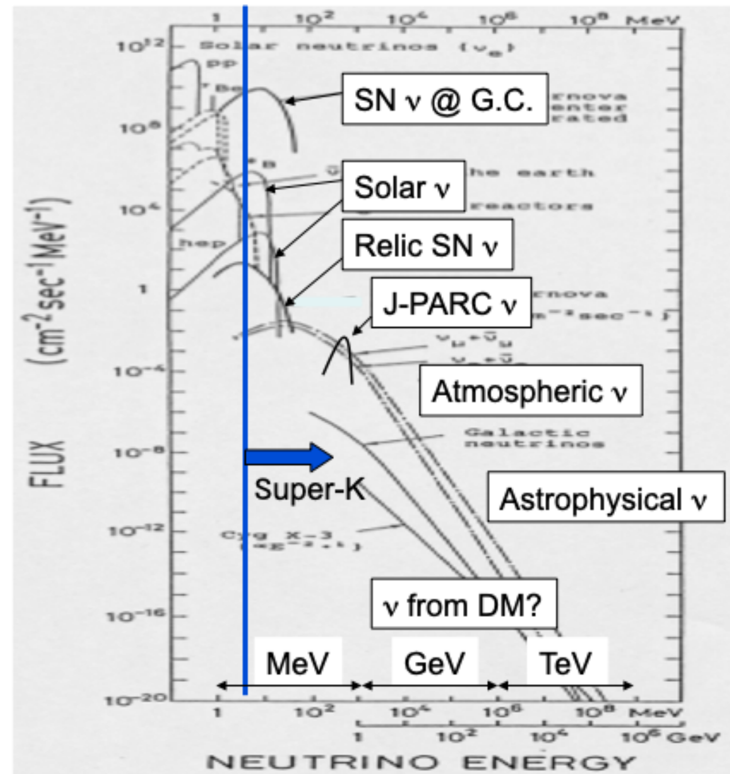
Three neutrinos and beyond
Aug.5th, 2019
Qui Nhon, Vietnam

Neutrinos from natural sources

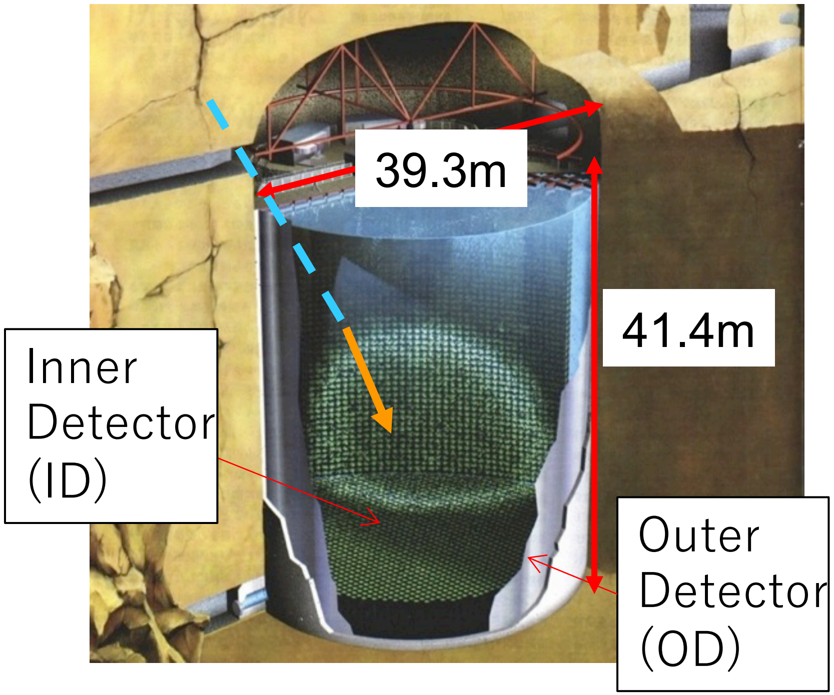
- Neutrino sources in nature
  - Astrophysical objects (Solar, Super-Nova, DM..)
  - Radioactivities in the earth
  - High energy CR interactions in atmosphere (atmospheric neutrino) …

- Big roles to discover neutrino oscillations and parameter determination in last two decades.
- Also unique channels to probe the objects.

- Many experiments.
- My talk focused on a experiment, Super-Kamiokande



Super-Kamiokande



- Ring-imaging Water Cherenkov Detector, @1000m underground, Kamioka, Japan
- Multi-Purpose experiment

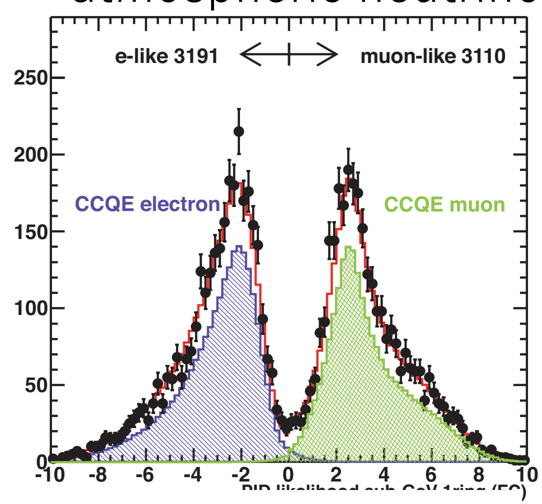
  (Atm.ν, WIMP, Proton decay, solar-ν, beam ν)
- Wide dynamic range

  A few MeV ~ over TeV

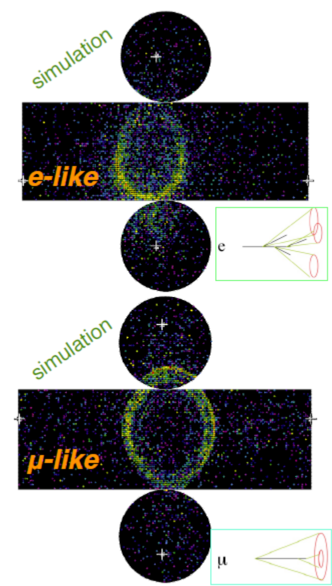
- 4π acceptance, very efficient π^0/e separation.
- High Particle ID (μ/e) power (~99% at 600MeV/c)

Four periods in above 20yrs
→ total ~5300 livetime-days data
5th period started from Feb.2019.

atmospheric neutrinos

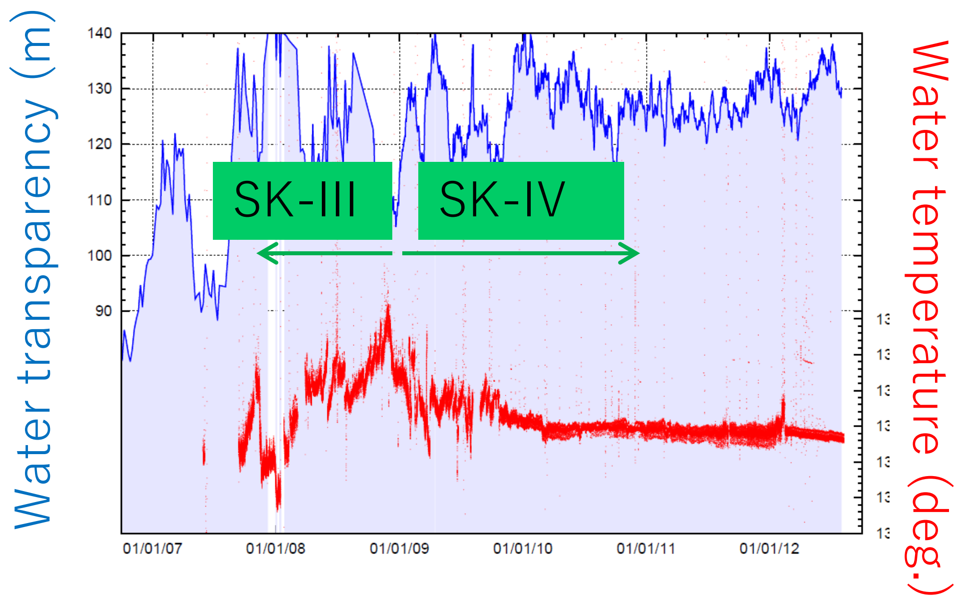


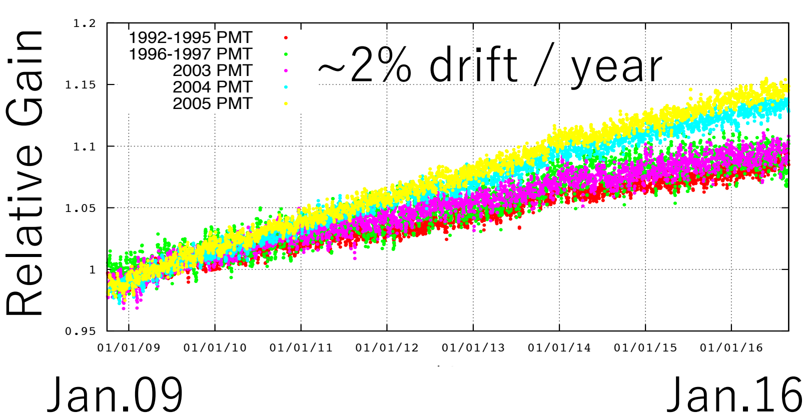
Particle Identifier

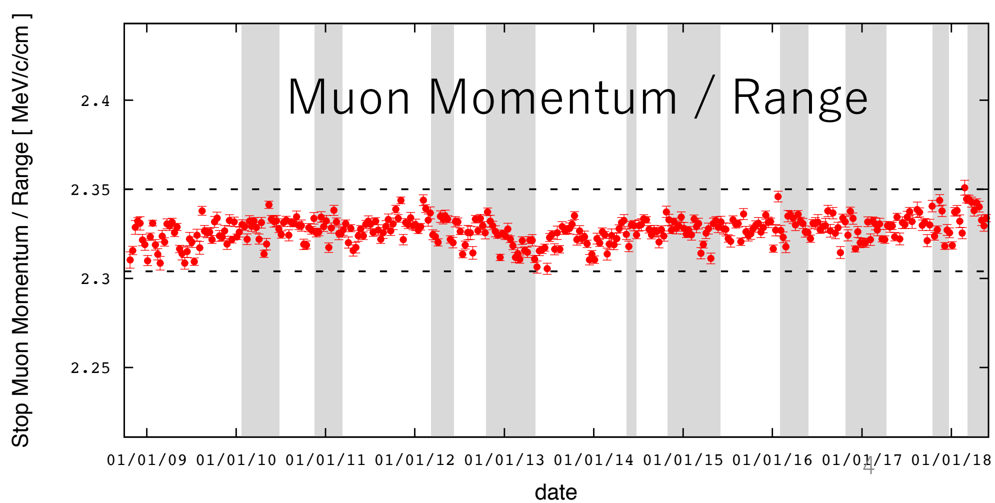


A key : stability of the detector

- Detailed calibrations with various sources.
  - *in-situ* laser for water transparency.
  - Neutron sources (DT generator)
  - Monochromatic electron (LINAC)
  - Gamma ray sources (Ni+Cf)
  - CR muons, …
- Water transparency is a key of Water Cherenkov detector.
- Measurement & modeling in full MC simulation.
- Also, gain drift of PMTs are considered.





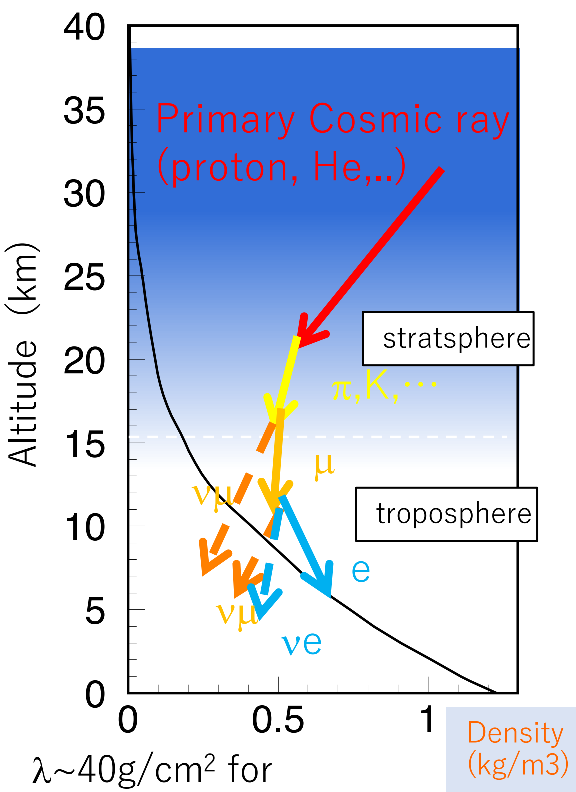


Atmospheric neutrinos

= Secondary products of primary cosmic rays in the atmosphere

p + A → π's, ….

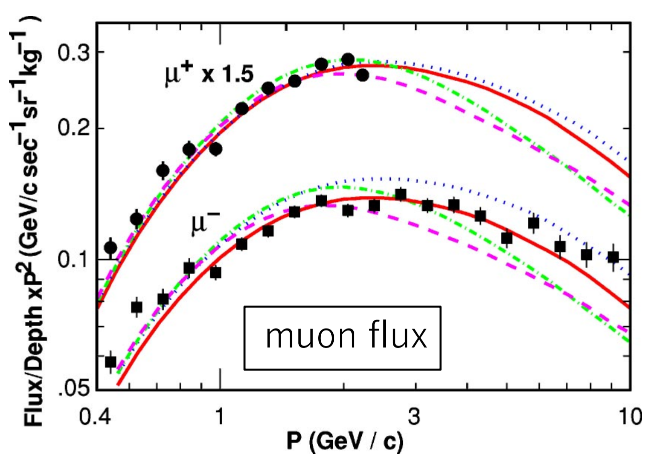
$$\pi^{\pm} \rightarrow \mu^{\pm} + \boxed{\nu_{\mu}(\bar{\nu}_{\mu})}$$
$$\rightarrow e^{\pm} + \boxed{\nu_{e}(\bar{\nu}_{e})} + \boxed{\bar{\nu}_{\mu}(\nu_{\mu})}$$

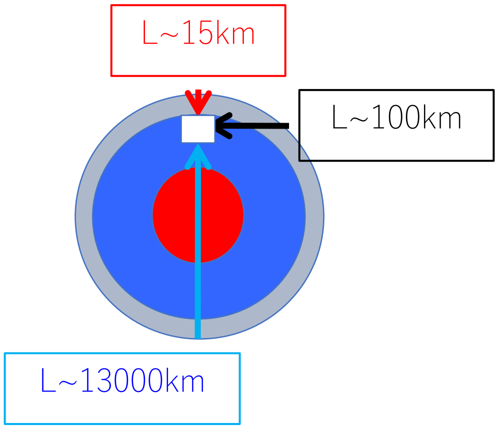


λ~40g/cm² for proton →L~15km

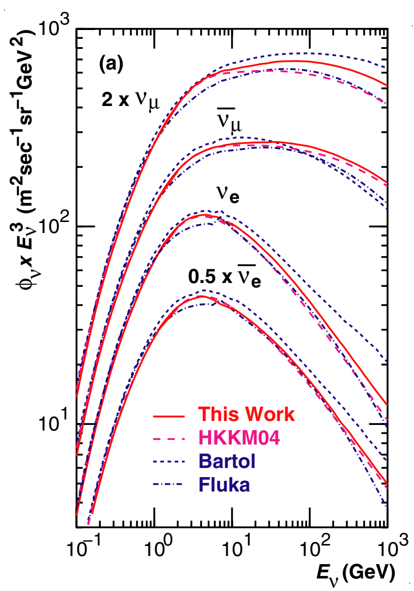
- First observation in 1965 in two deep underground experiments.
- Several Flux calculations on the market:
  - Primary CR fluxes, p+A cross sections,
  - π's production, Geo-magnetic field, ..

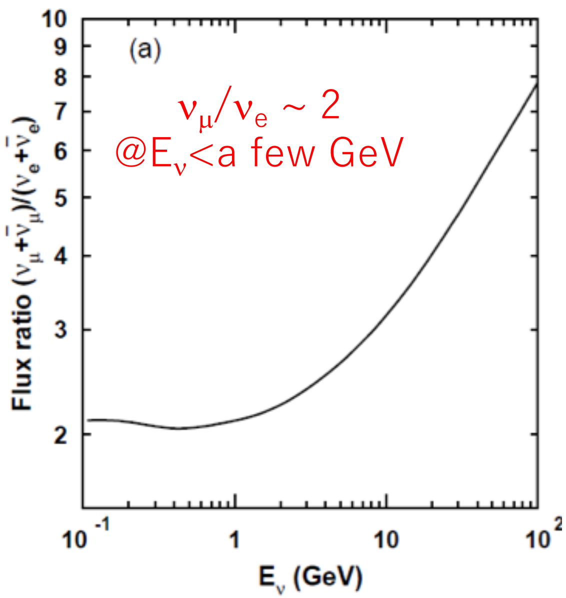
- Calculated fluxes are well tested (calibrated) by Cosmic Ray muons.



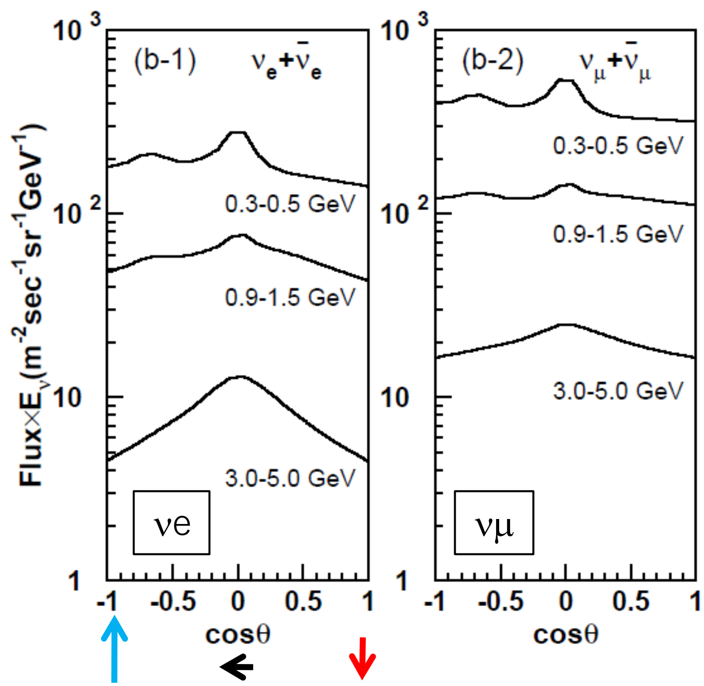


- Wide energy range, wide range of flight length.
- Passing through dense matter inside the Earth (matter effect is expected).
- Mixture of ν_μ, ν_e, and their anti-neutrinos.
- Up/Down symmetric (> a few GeV)
- DC-like continuous beam, FREE!



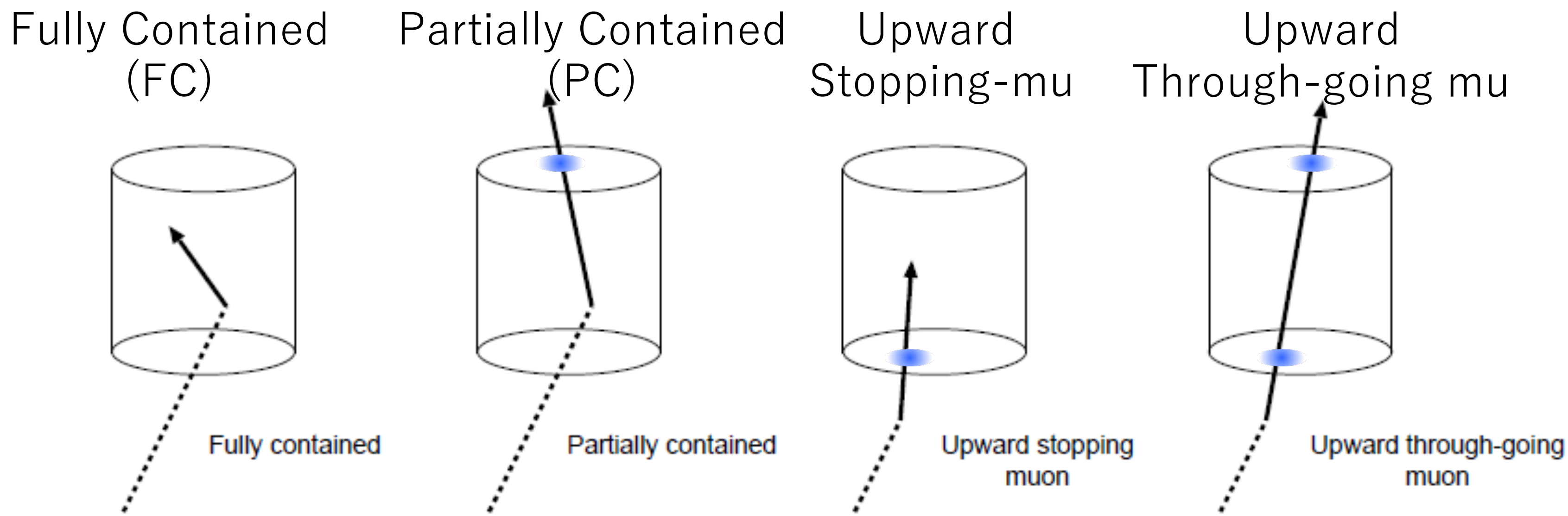


Flux ~ $E^{-2.71}$ at high energy region
<10% uncertainty @1GeV region

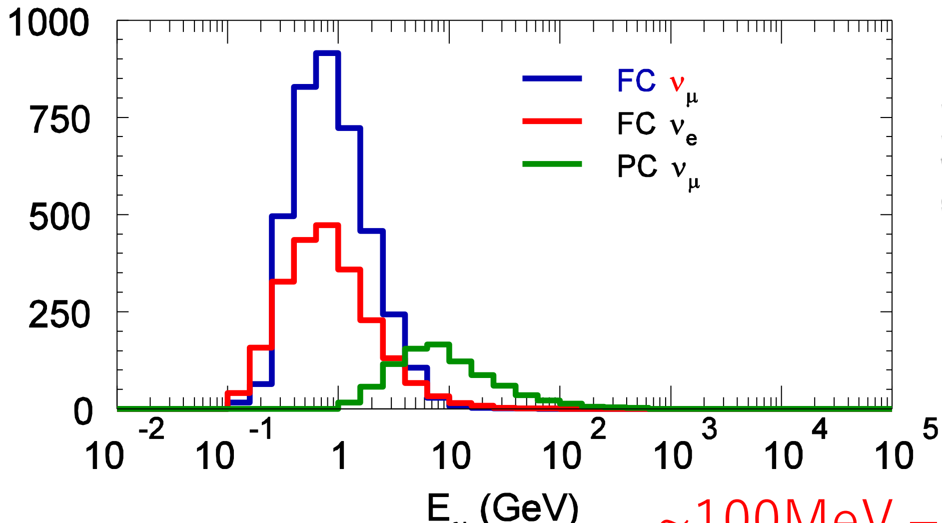


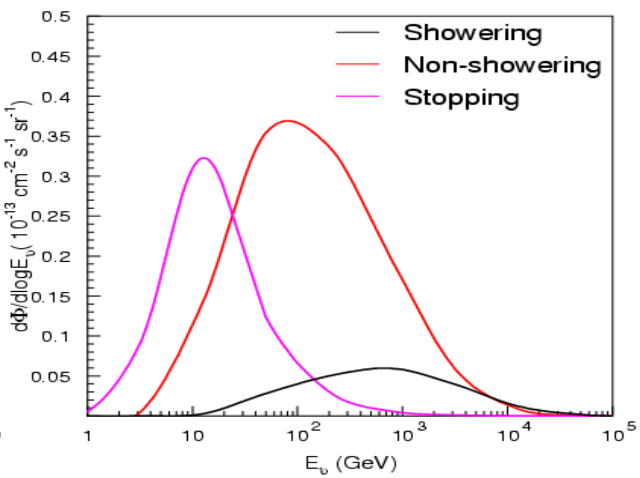
Symmetric for E_ν > a few GeV

Event topologies of Super-K events



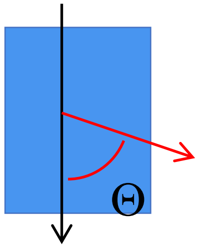
Energy spectrum of neutrinos





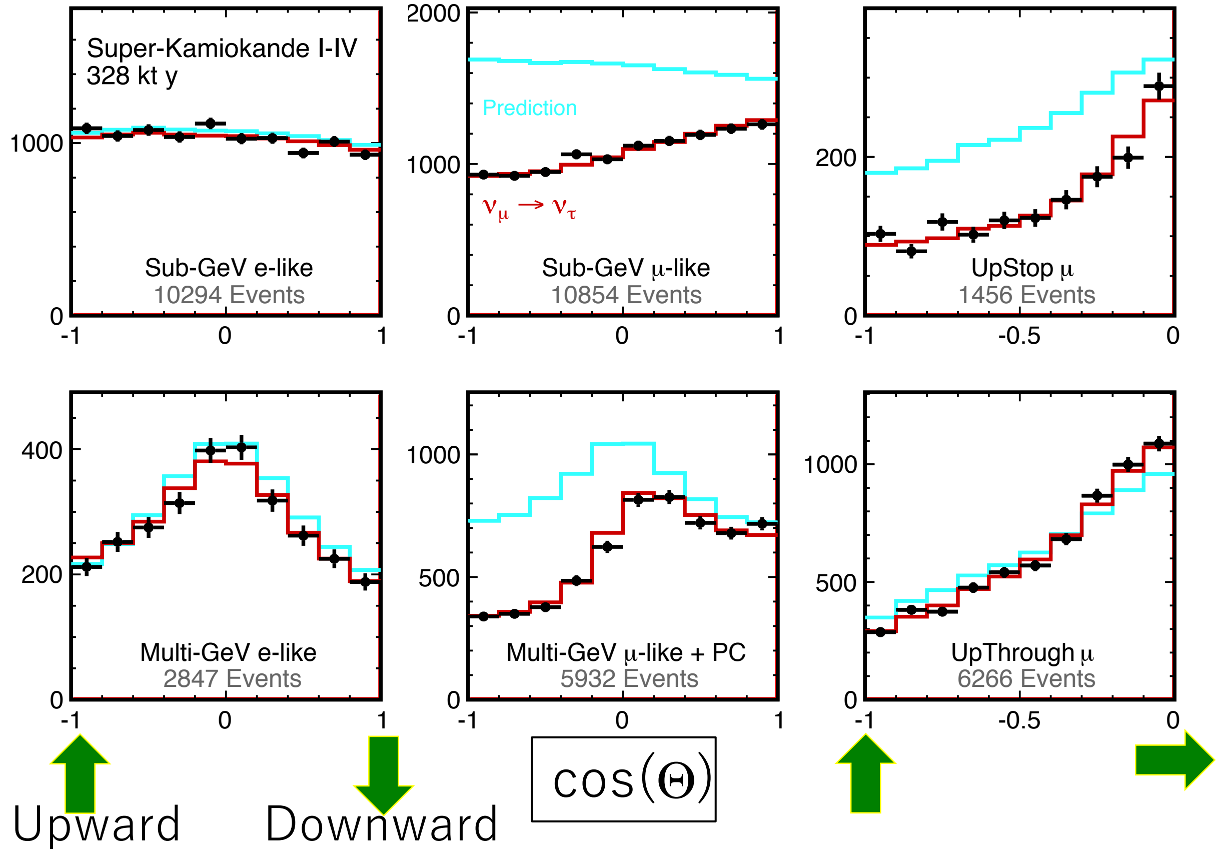
~100MeV – over TeV neutrinos

Super-K I+II+III+IV data (5300 days)



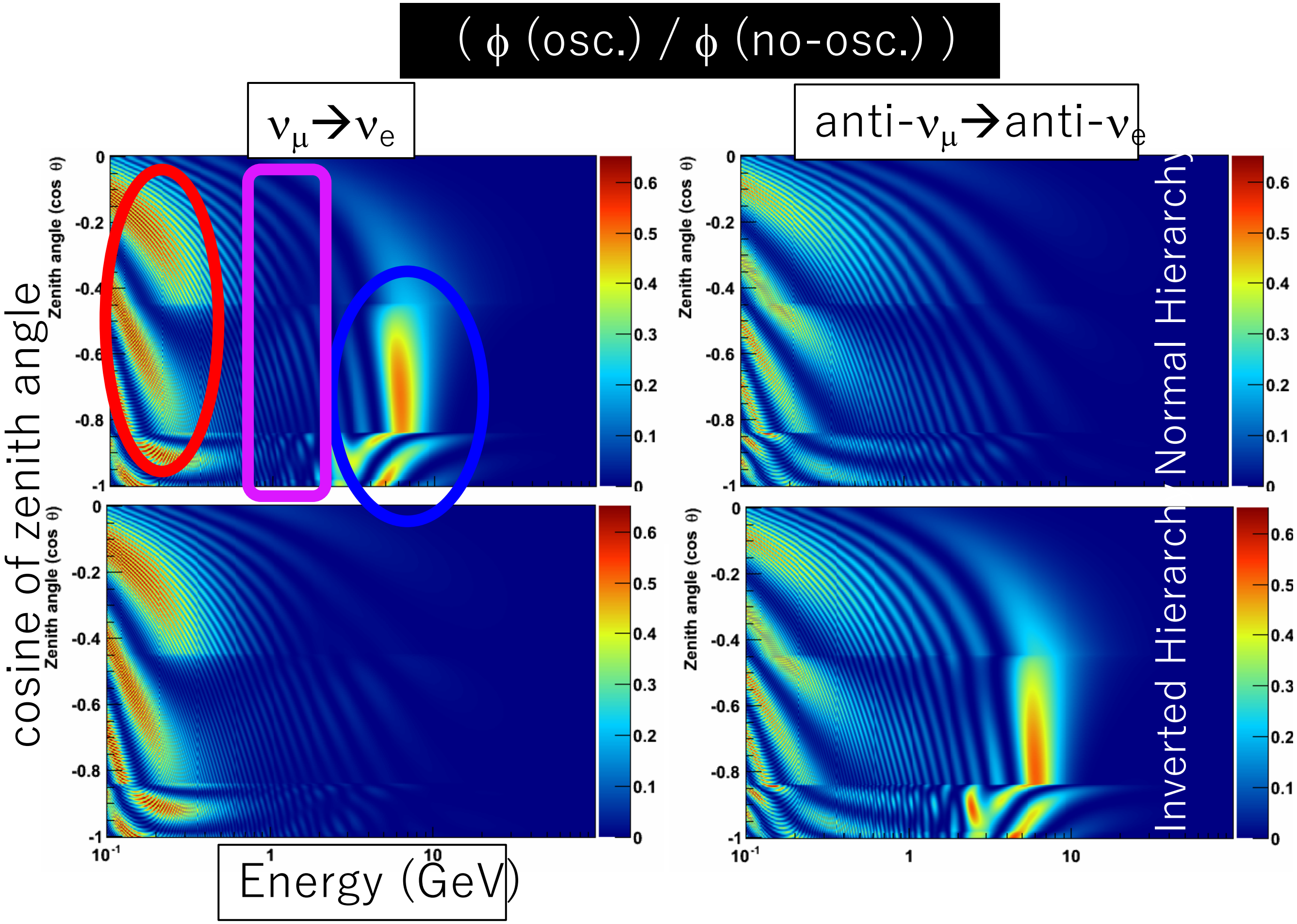
Totally 19 Sub-divided samples.
They further binned by
- zenith angle
- energy (momentum)
- SK period

FC e-like	FC μ-like + PC	upward-going μ
(CC ν_e enhanced)	(CC ν_μ enhanced)	(CC ν_μ)



- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillation, ν_e oscillation is sub-dominant effect.
- Fit MC expectation by modifying within the estimated systematic errors (~150 systematic errors from SK detector, flux, σ int.).

Neutrino oscillation in atmospheric ν



- "Solar term" → $\sin^2\theta_{23}$ octant
- Interference term → CP violation phase
- Resonance term → mass hierarchy

Resonance on ν or anti-ν depending on mass hierarchy.

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \cong P_2(r \cdot \cos^2\theta_{23} - 1)$$

"Solar Term"

$$- r \cdot \sin^2\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} (\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2)$$

Interference

$$+ 2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1)$$

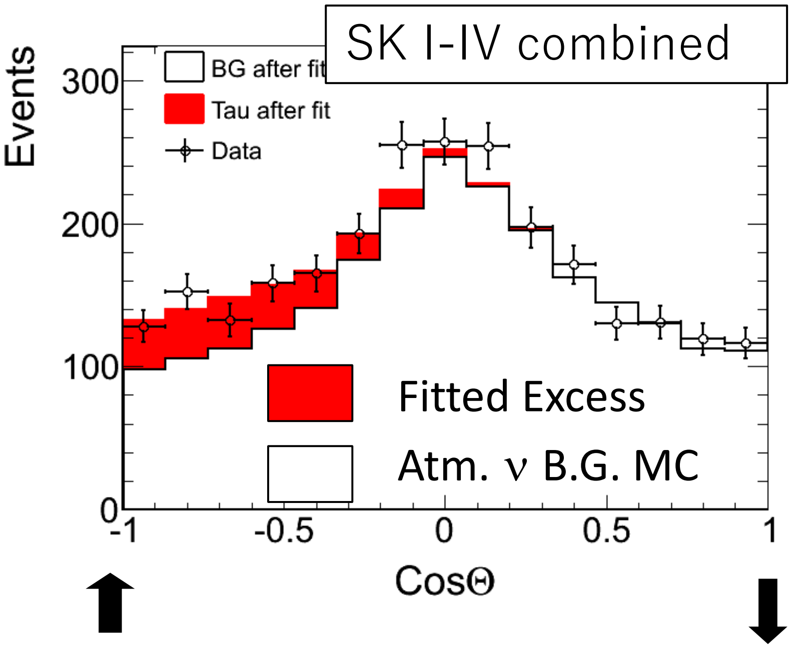
Resonance

P2: Osc. prob. driven by 12 sector
r: ν_μ/ν_e flux ratio
R2, I2: osc. prob driven by 12sector

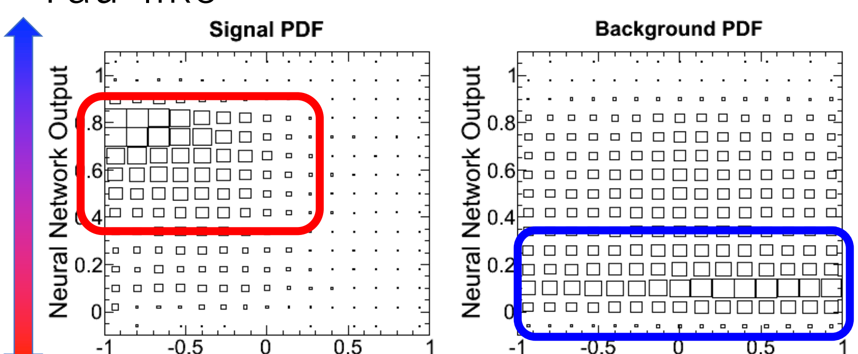
Results of analysis of ν oscillation

Evidence for ν_τ appearance at Super-K

[Phys. Rev. D 98, 052006](https://) (2018)

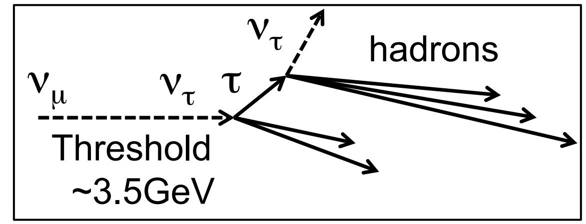


Tau-like



cosine of zenith angle

- Search for events consistent with hadronic decay of τ leptons.



- Neural networks to discriminate from B.G. mainly multi-hadronic production.
- Prompt ν_τ is negligible.
- 2D Un-binned maximum likelihood method is employed using a PDF:

PDF
$= \mathrm{PDF(b.g)} + \alpha \times \mathrm{PDF}(\tau) + \Sigma\ \varepsilon_i \times \Delta \mathrm{PDF}_i$

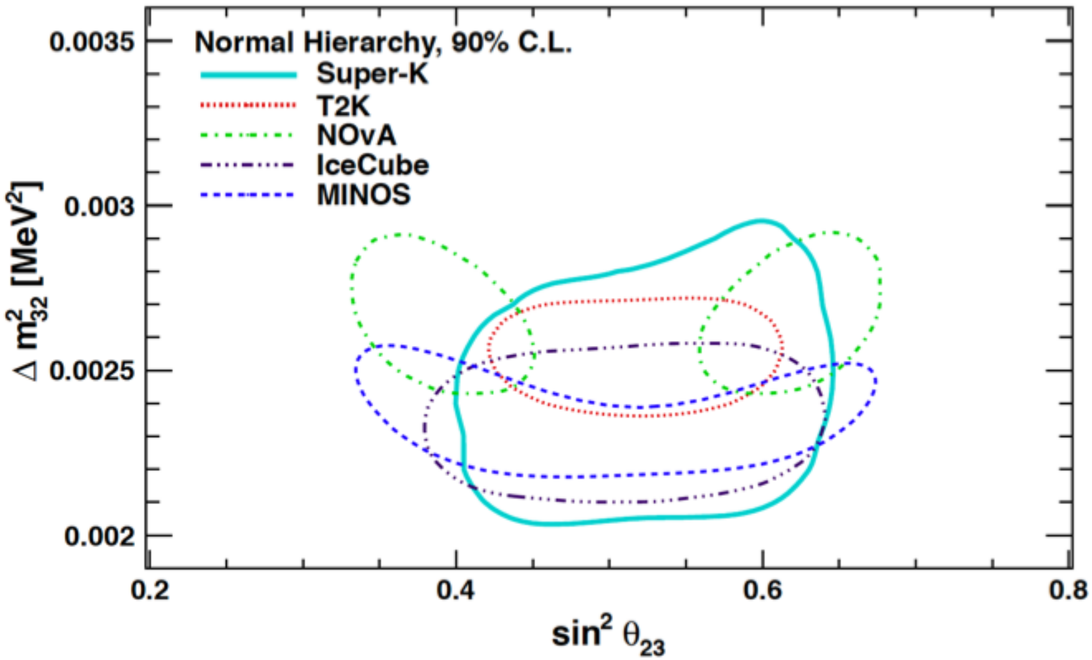
$\alpha = 1.47 \pm 0.32$

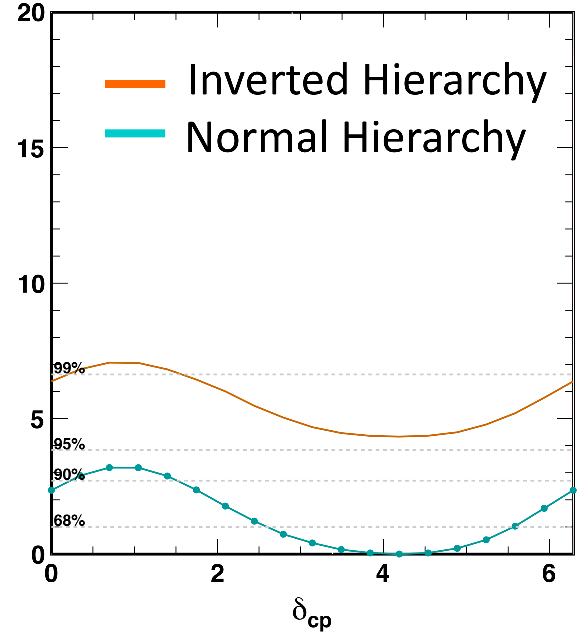
4.6 σ excess from no-τ

(Expected 3.3 σ significance)

Allowed regions on $(\sin^2\theta_{23}, \Delta m^2_{32})$

PRD97 072001(2018)





Consistent with other experiments, weak preference for second octant ($< 1\sigma$)

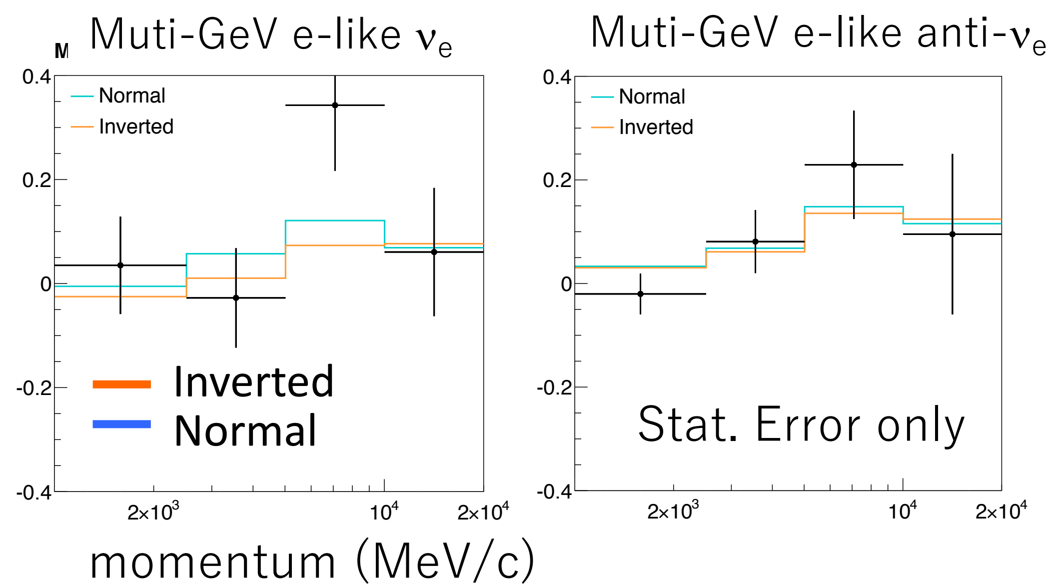
Super-K results:

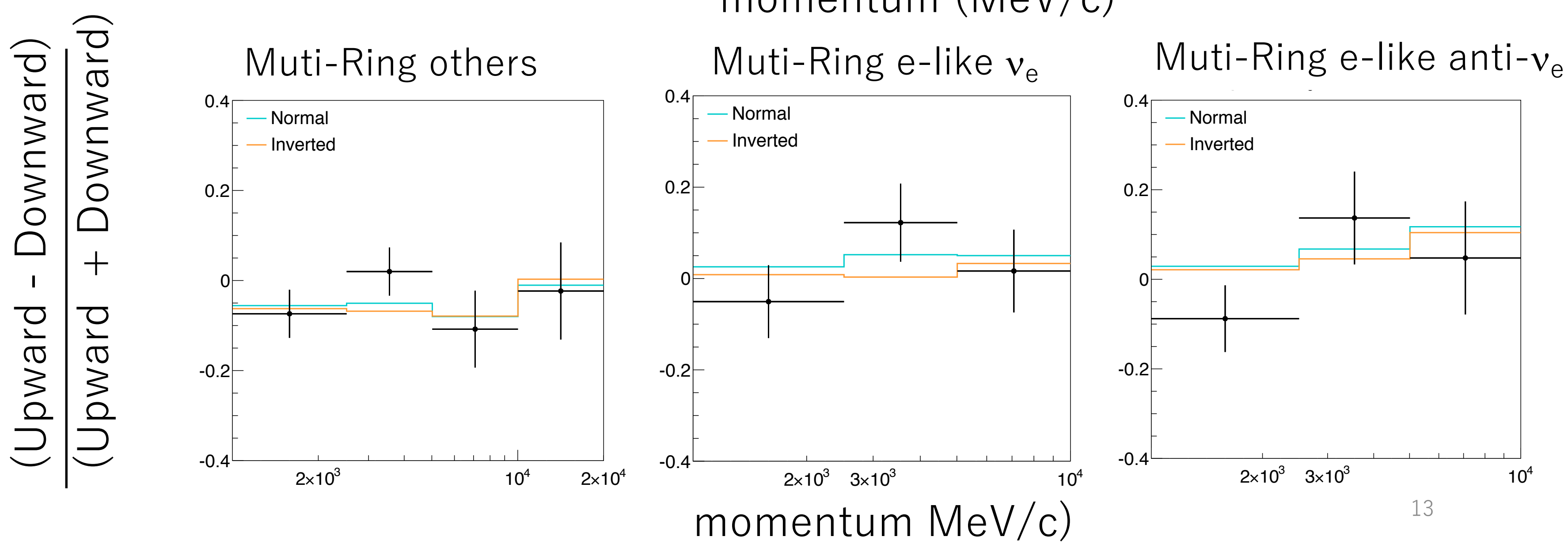
$$\Delta m^2_{32} = 2.5^{+0.13}_{-0.20} \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.588^{+0.031}_{-0.064}$$

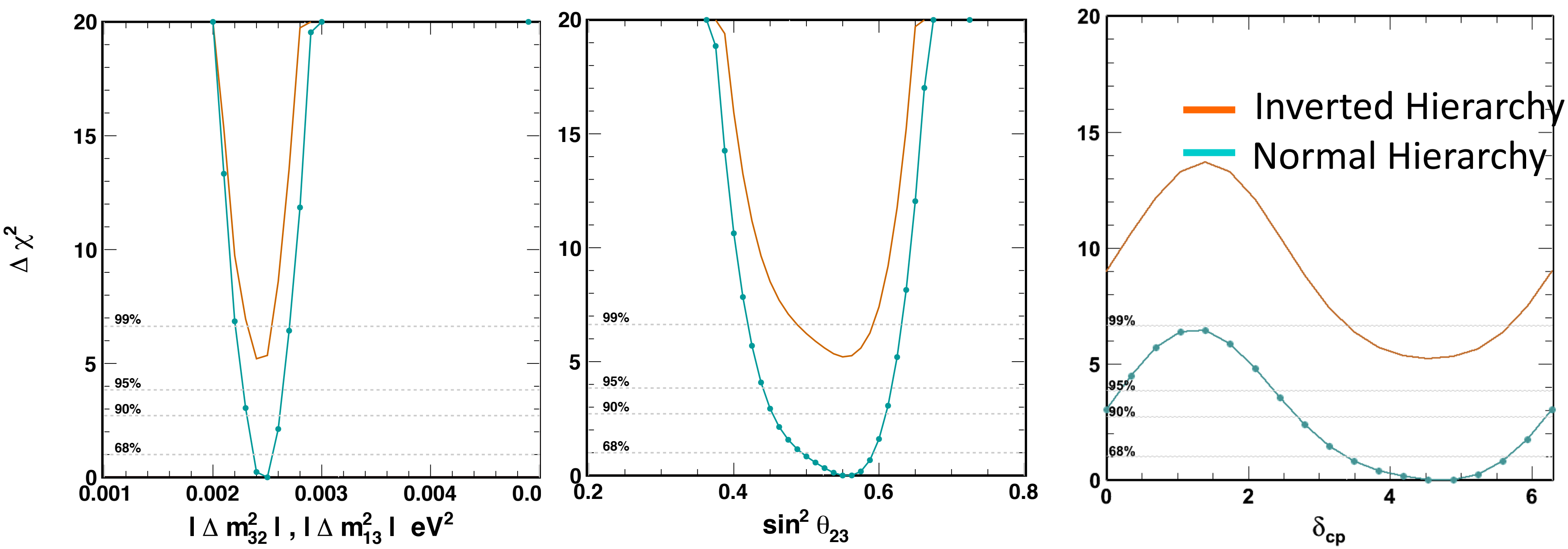
- Driven by excess of upward-going e-like events:
  - Primarily in SK-IV data
  - consistent with the effects of θ_{13} driven ν oscillation.

Upward/Downward asymmetry in energetic electron samples (νe/anti-νe enriched)





SK atm.ν + constraint from T2K ν_μ, ν_e published results



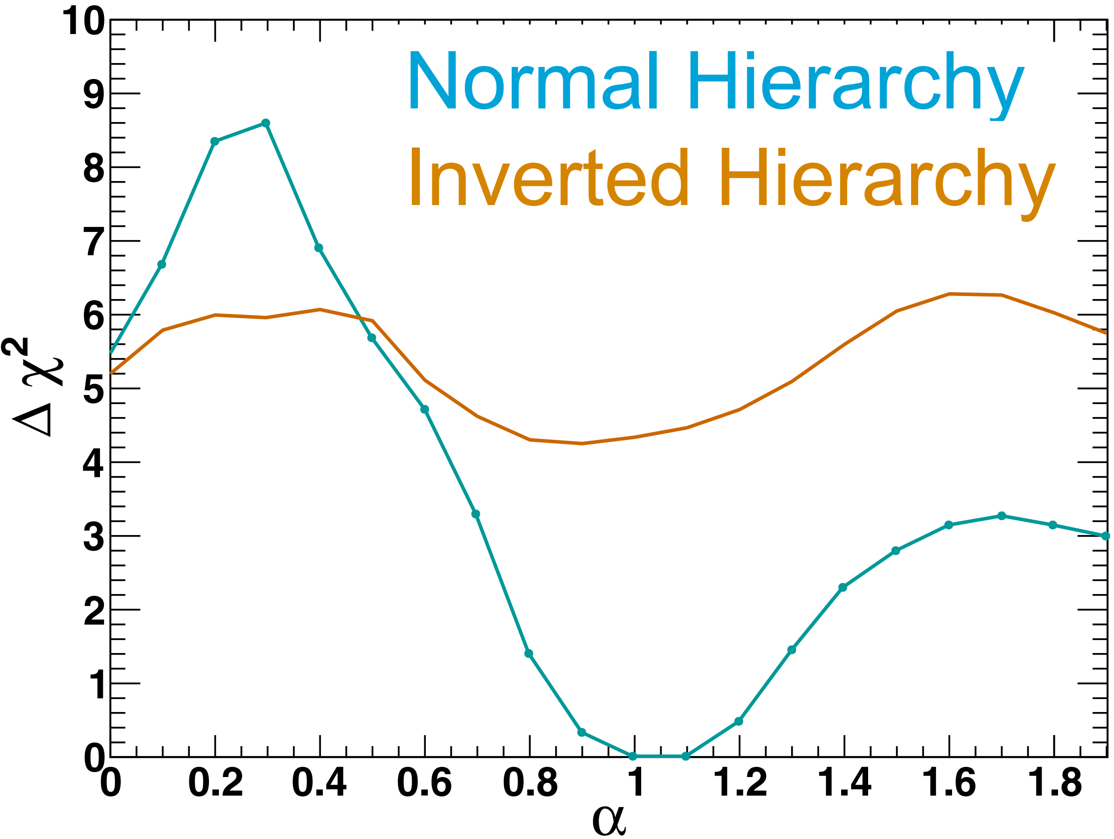
Fit (517 dof)	$\chi2$	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK + T2K (NH)	639.61	4.887	0.550	2.4
SK + T2K (IH)	644.82	4.538	0.550	2.5

- Add constraint from T2K by mimic data reproducing published results.
- $\chi^2_{NH} - \chi^2_{IH}$ = **-5.2** (-4.3 SK only)
- Significance of IH is disfavored by 91.9% ~ 94.5% (81.9% ~96.7% SK only) at allowed 90% CL region, based on psudo-experiments.

Test of Matter effect

- Atmospheric neutrino data in SK prefer the matter effect hypothesis or not?
- Introduce a phenomenological scaling factor α to electron potential:

$$H = UMU^{\dagger} + \alpha \cdot V_e \quad (\alpha = 1 \text{ is nominal matter})$$

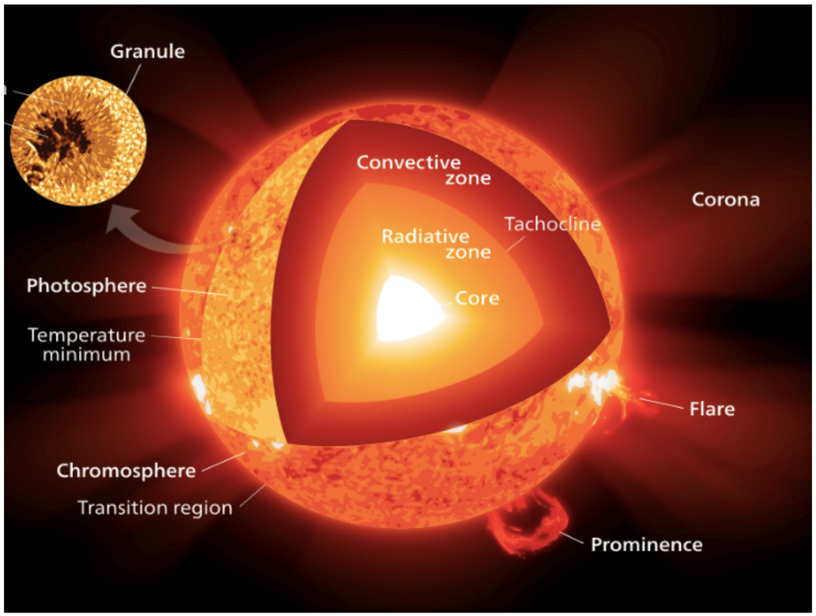


- Best fit is at $\alpha = 1$.
- Significance to reject $\alpha=0$ (no matter effect) is 1.6σ level, based on toy MC estimation.

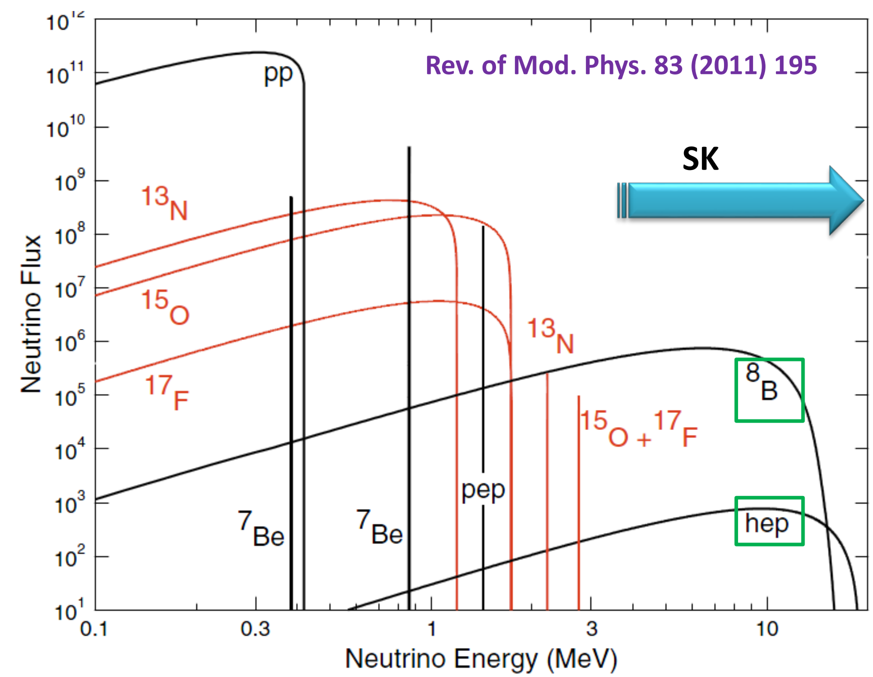
Solar neutrinos

Nuclear fusion yields energy and neutrinos:

$$4p \rightarrow {}^4He + 2e^- + 2\nu_e + 25MeV$$



https://en.wikipedia.org/wiki/Sun#/media/File:Sun_pos

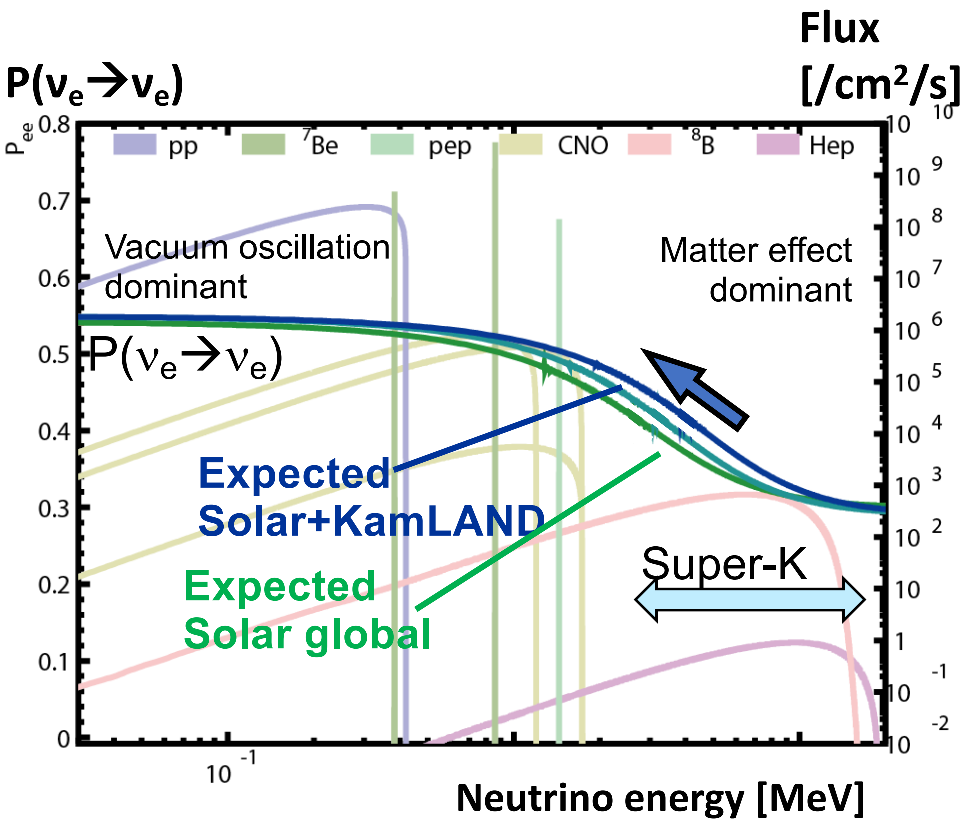


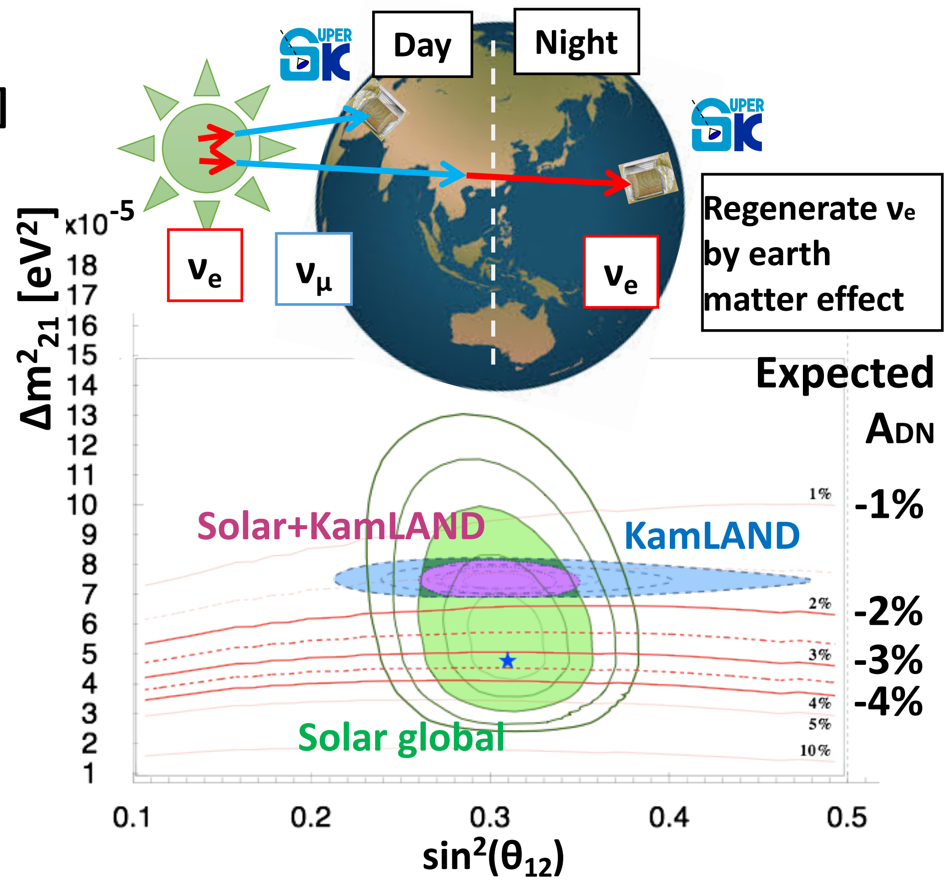
- Most intensive source of neutrino on the earth.
- Well described by a standard solar model (SSM) and fluxes prediction available.
- A chain reaction starting from p+p fusion is the main source of the power (called ”pp chain”). Alternative reaction cycle (“CNO” cycle) is predicted but not observed yet.
- Metalicity problem: Composition of relative heavy materials

Determination of neutrino parameters of 12 sector and the mechanism of the neutrino oscillation

Spectrum distortion due to neutrino oscillation effect. (test non-standard scenario).

Day /night difference due to matter effect in the earth

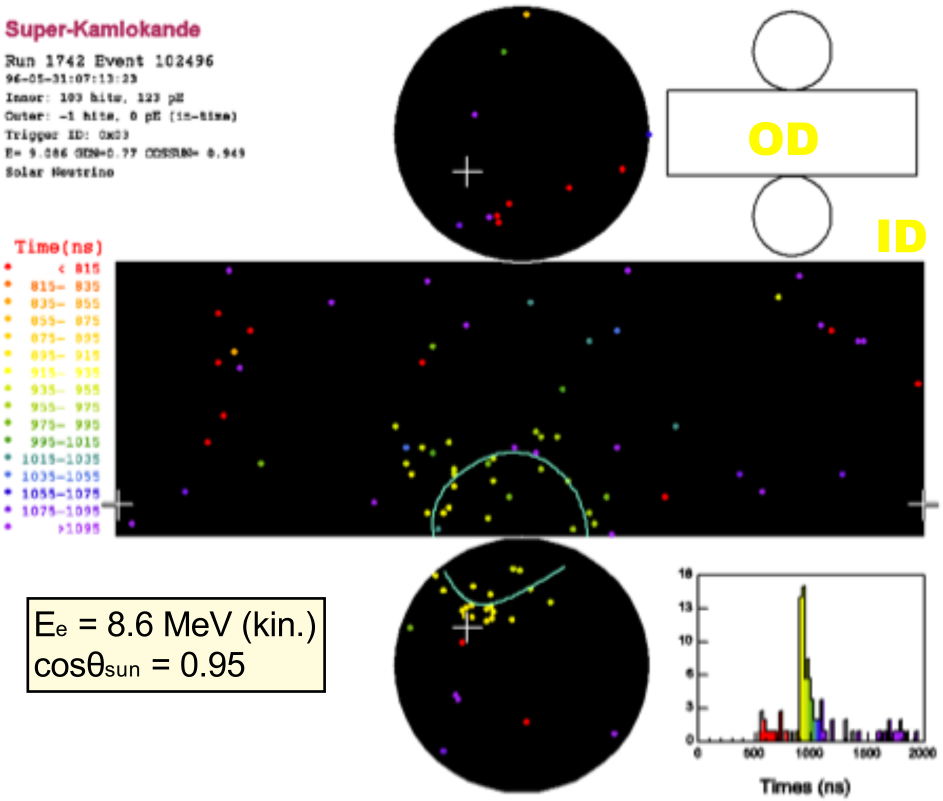




Solar neutrino signals in Super-Kamiokande

$\boxed{\nu + e^- \rightarrow \nu + e^-}$

Event display of solar ν candidate



E_e = 8.6 MeV (kin.)
$\cos\theta_{sun}$ = 0.95

- Realtime measurements yields solar direction and path in the earth.
- Energy determination is crucial for spectrum study. Detailed calibration yields 0.5% level energy scale calibration.

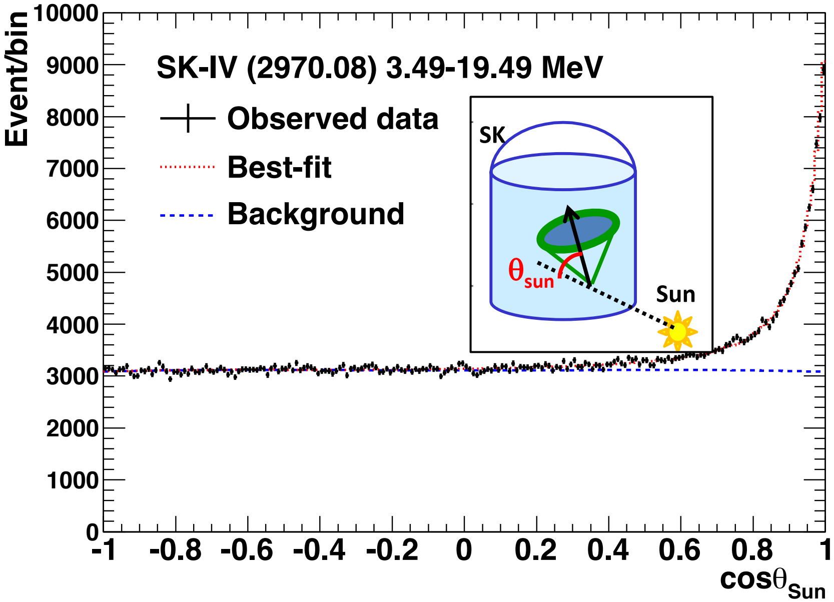
Detector performance

	resolution (10 MeV)	information
vertex	55cm	hit timing
direction	23deg.	hit pattern
energy	14%	# of hits.

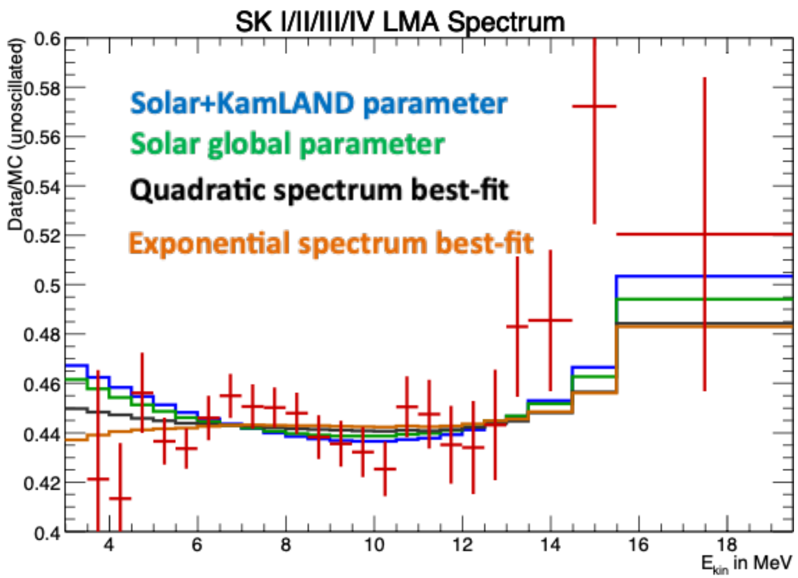
~ 6 hits/MeV
well calibrated by LINAC and DT within 0.5% precision

Recoil electron direction / spectrum

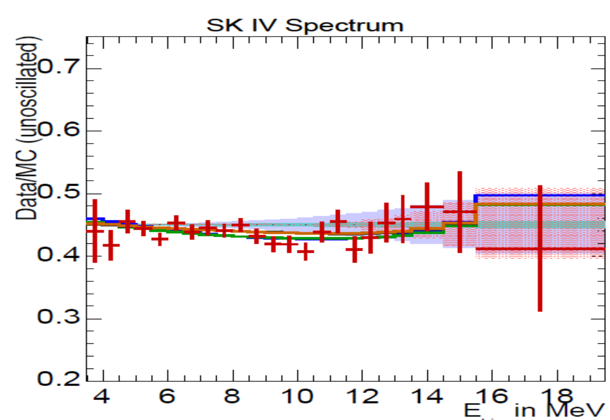
preliminary



Clear sun directions. It provides a good signal estimation by fitting background and signal models.

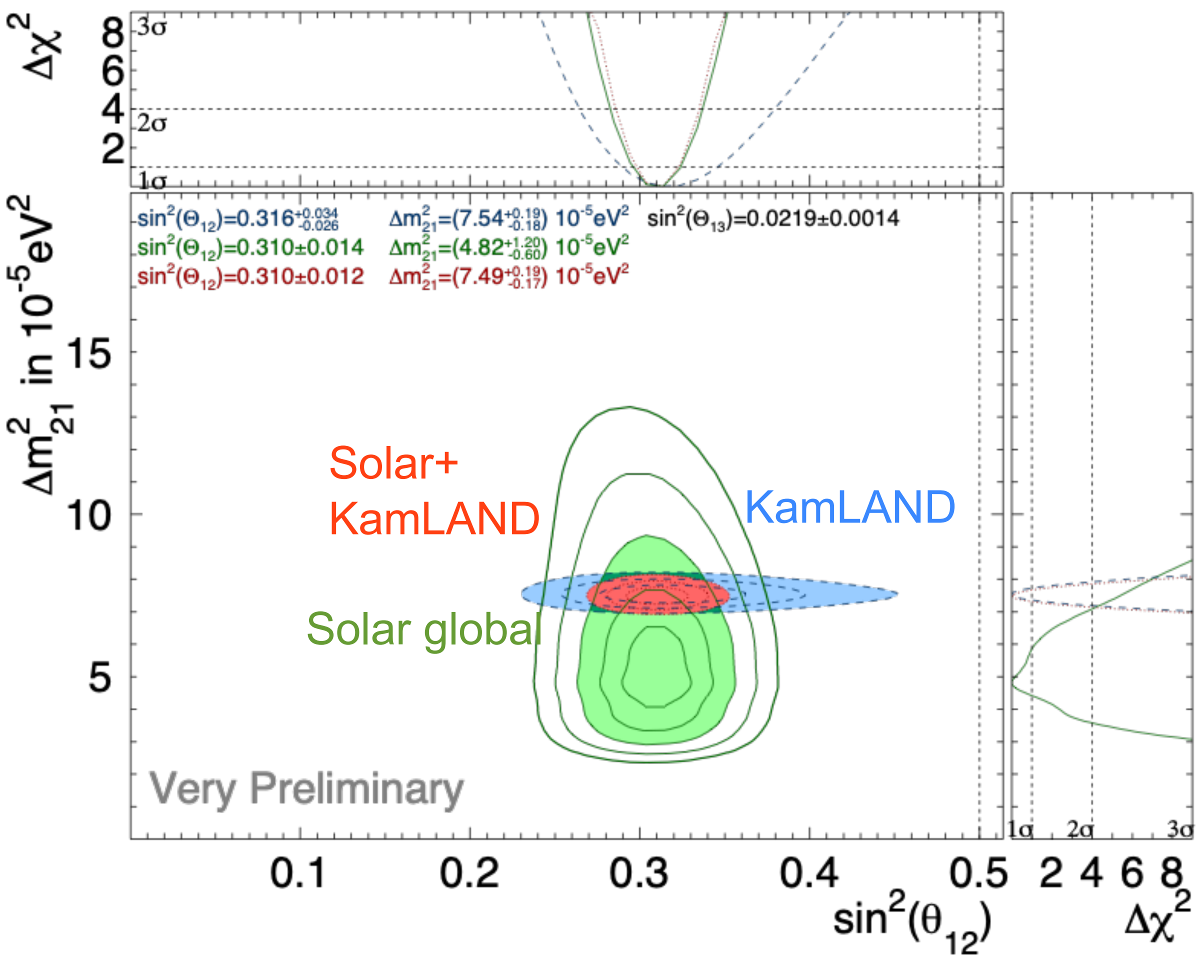


SK spectrum data is consistent within 1 σ for the Solar best fit parameters, while marginally consistent within 2 σ for the Solar+KamLAND best fit parameters.



Neutrino oscillation analysis

preliminary



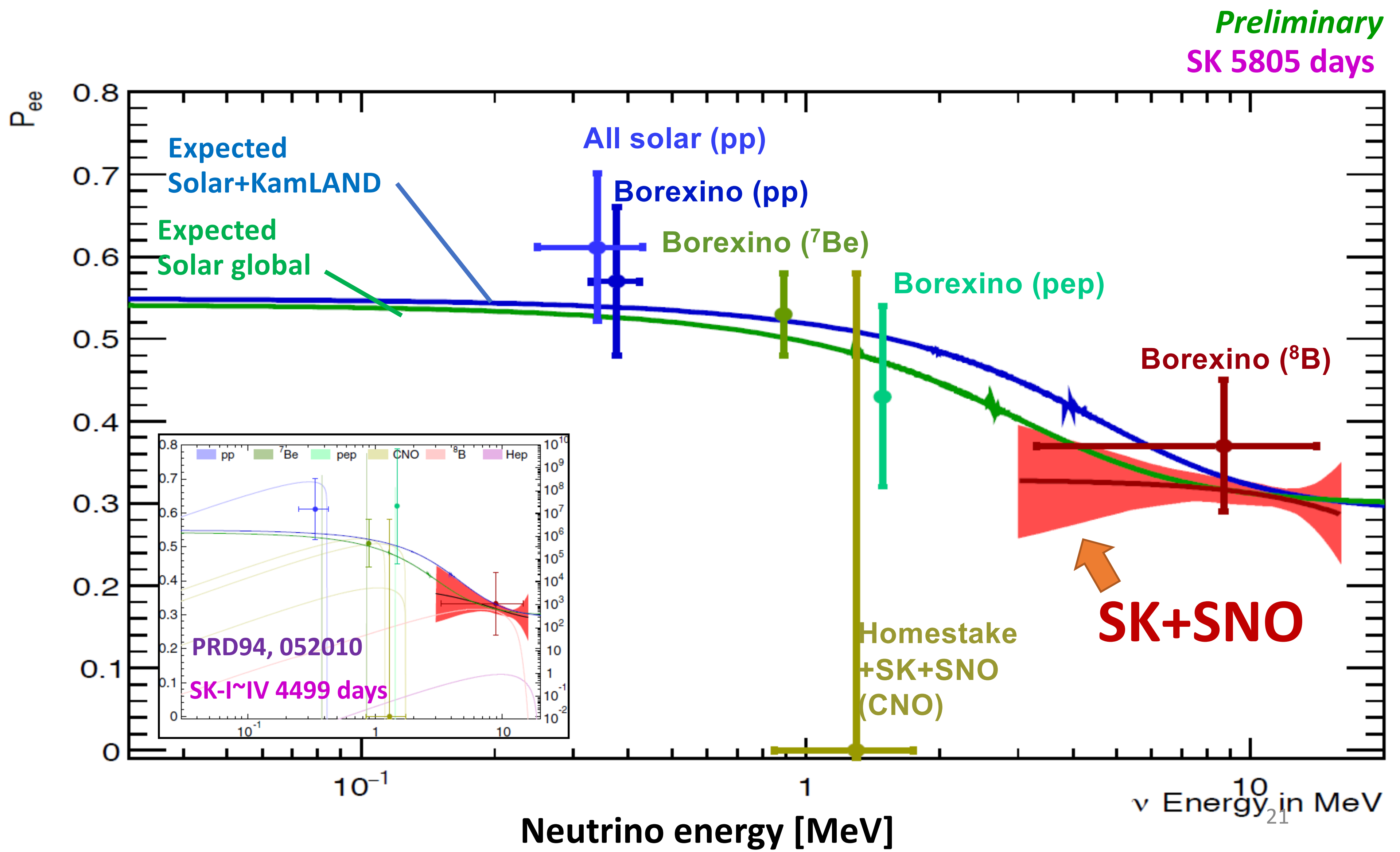
$$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.310 \pm 0.014$$
$$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60}$$
$$\sin^2\theta_{12} = 0.310 \pm 0.012$$
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

$\sin^2\theta_{13}=0.0219\pm0.0014$

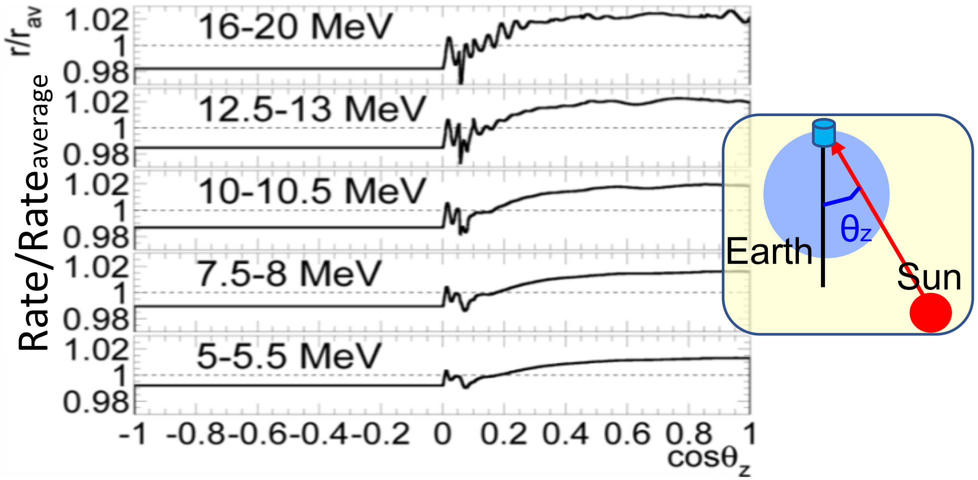
About 2σ tension between Solar global and KamLAND in Δm^2_{21}.

Probability of $\nu_e \rightarrow \nu_e$



Day/Night asymmetry (A_{DN}^{fit})

Rate dependence of the path in the earth

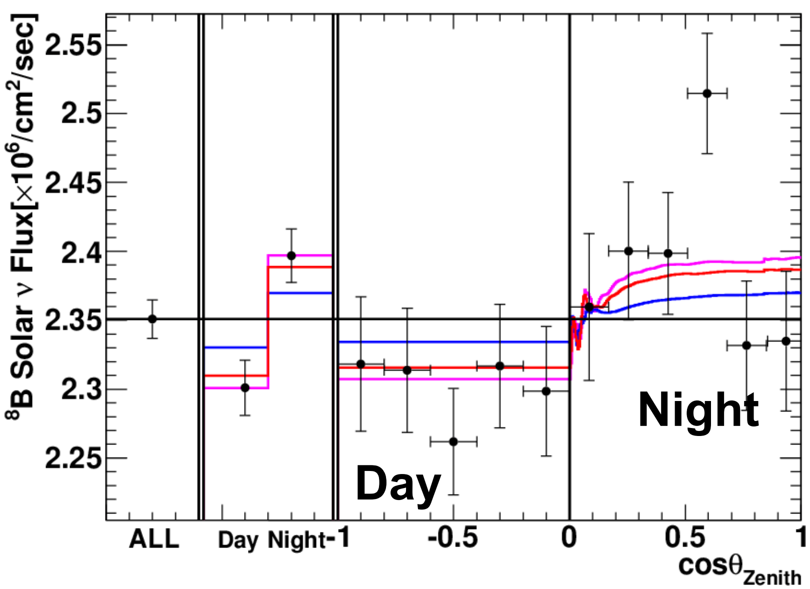


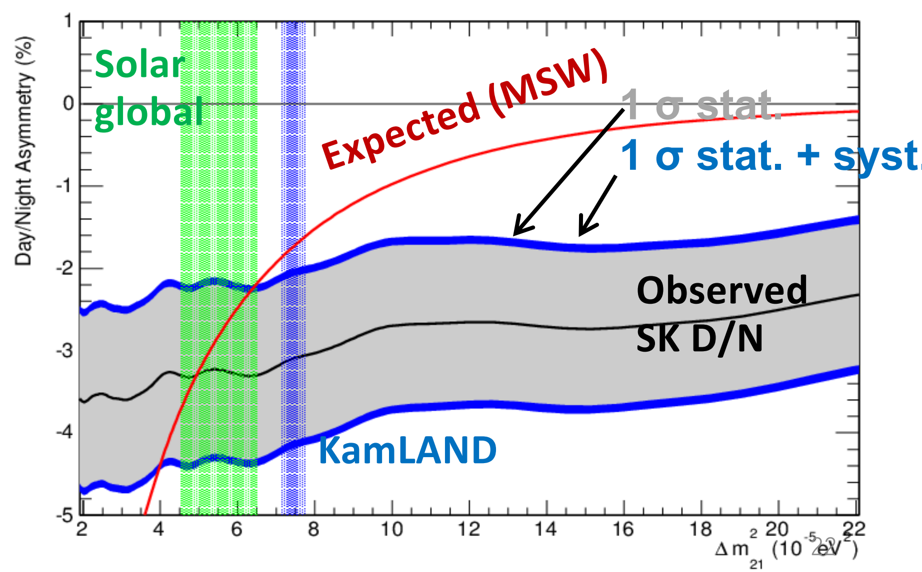
For solar global parameter:
Δm^2_{21}=4.84x10^{-5} eV^2
$\sin^2\theta_{12}$=0.311

$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$

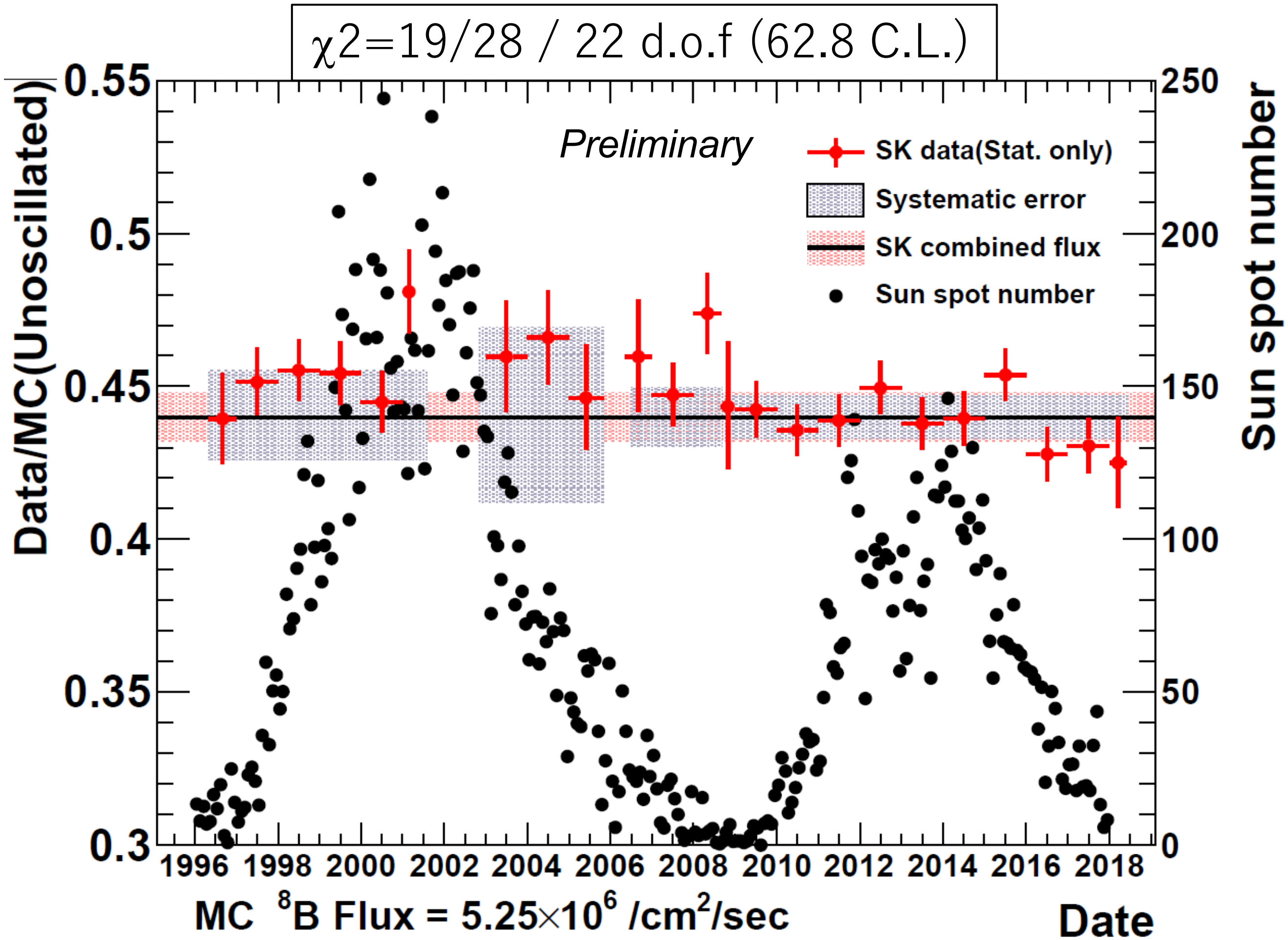
A_{DN}=-3.3+-1.0+-0.5%

Non-zero significance is
3 σ
in SK-I to IV (4499 days)





Time variation of the ^{8}B neutrino flux



Averaged ^{8}B flux with no oscillation $= (2.33 +/- 0.04) \times 10^6/\mathrm{cm}^2/\mathrm{s}$

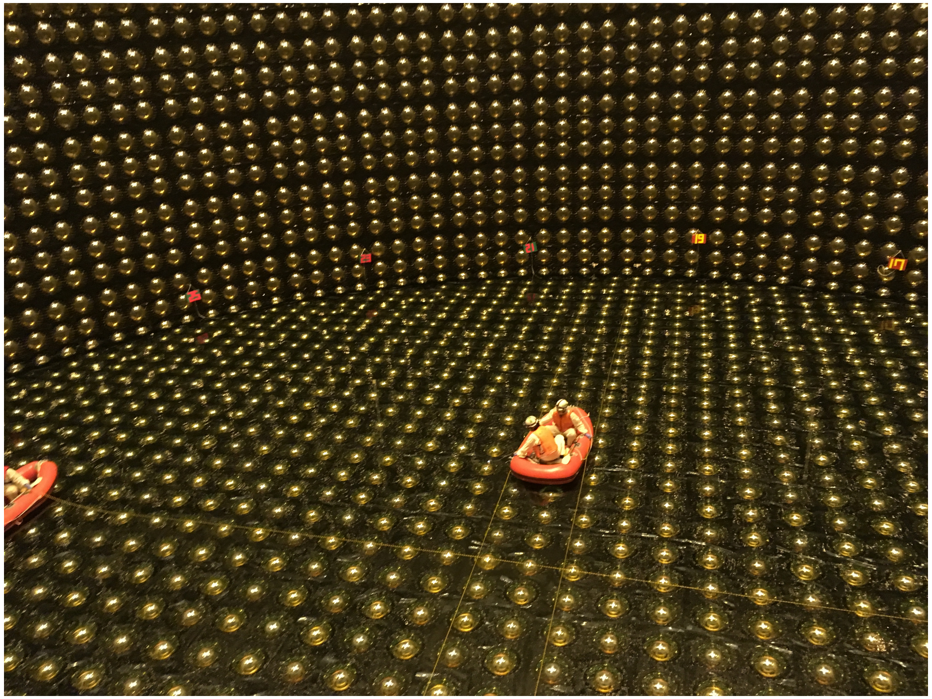
Sun spot number: WDC-SILSO, Royal Observatory of Belgium, Brussels

Super-K covers two interval of solar cycle.

^{8}B neutrino rate are consistent with a constant flux.

Status and future of Super-Kamiokande

- Super-Kamiokande was stopped for refurbishment toward new phase with Gd-loaded water from June 2018 to Feb. 2019.



- Replacing materials with Gd water compatible materials.
- Water leakage repair.
- Water system upgrades for Gd loading.
- Detailed magnetic field measurements / dynode direction recording for understanding of systematic errors.
- About 100 dead PMTS are replaced for a newly developed 20 inch PMTs for Hyper-Kamiokande. (x2 QE/CE, better time resolution)

- Refurbishment is done successfully. No water leak.
- Restarted data taking from Feb. 2019. Plan to start Gd loading in this FY.

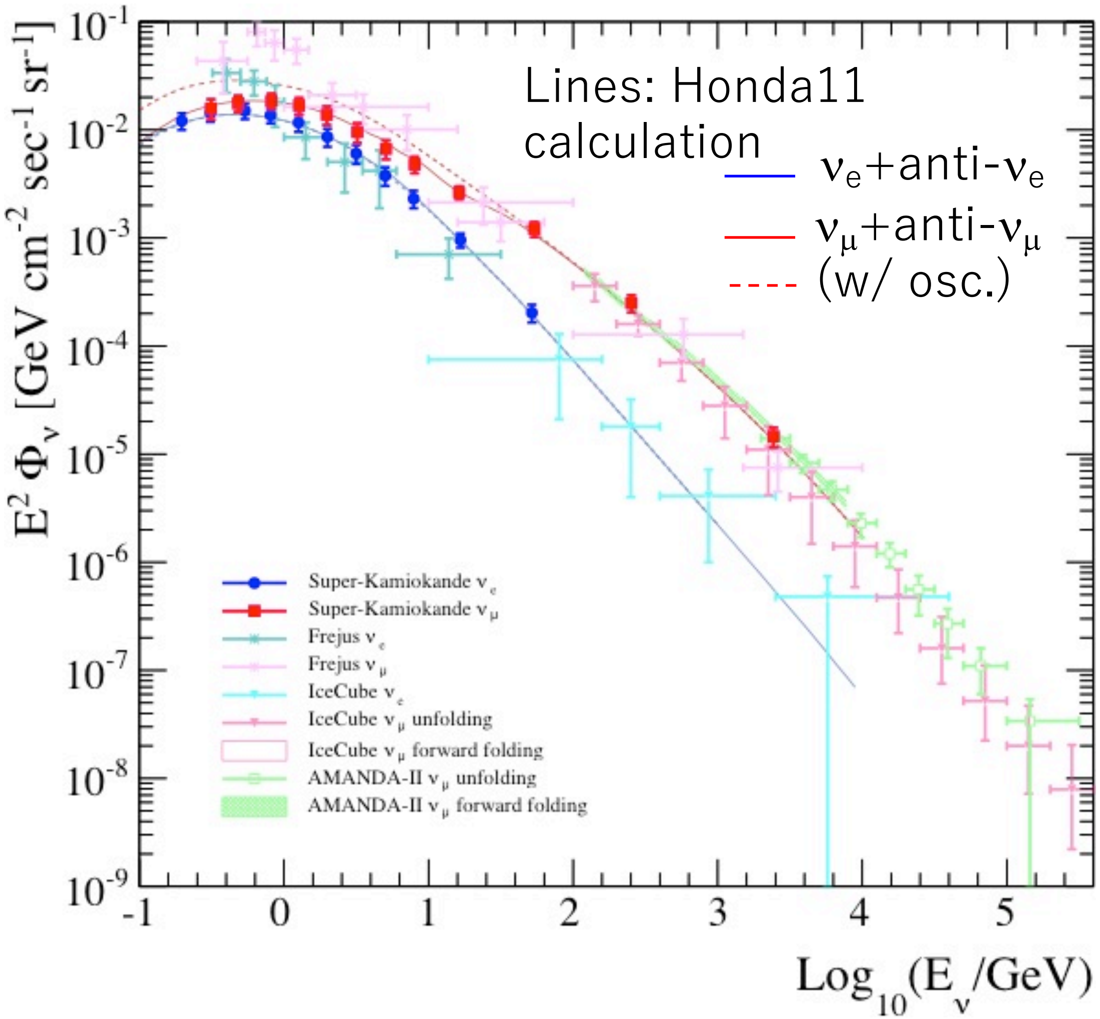
Status and future of Super-Kamiokande (2)

- Atmospheric neutrino (and nucleon decay)
  - New algorithm of event reconstruction
  - Expanding the fiducial volume (22.5kton to 29.7kton)
  - Neutron tagging is expected to improve separation of n / anti-n, and energy reconstruction. Gd loading is in preparation.
- Solar neutrino
  - Lowering threshold : WIT system, which applies reconstruction and reduction just after front-end.
  - Reduction of spallation event will be improved.
  - Keep continuing solar neutrino analysis in Super-K Gd era.
  - Non standard interaction (NSI) study is on-going.

Summary

- Neutrino oscillation studies in Super-Kamiokande, based on atmospheric neutrinos and solar neutrinos are presented.
- Refurbishment is done last year.
- New phase of the Super-Kamiokande started from Feb.2019, and calibration works are on-going

Atmospheric neutrino flux measurement in Super-K



- Neutrino fluxes (ν_μ+anti-ν_μ, ν_e+anti-ν_e) by an unfolding method with Bayesian theory: No bias, mathematically robust.
- Systematic errors from SK, neutrino interactions are considered.
- Super-K gives good measurement especially in low energy region.

Super-Kamiokande collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
University of British Columbia, 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
NFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
KEK, Japan
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
Osaka University, Japan
University of Oxford, UK
Queen Mary University of London, 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
The University of Winnipeg, Canada
Yokohama National University, Japan

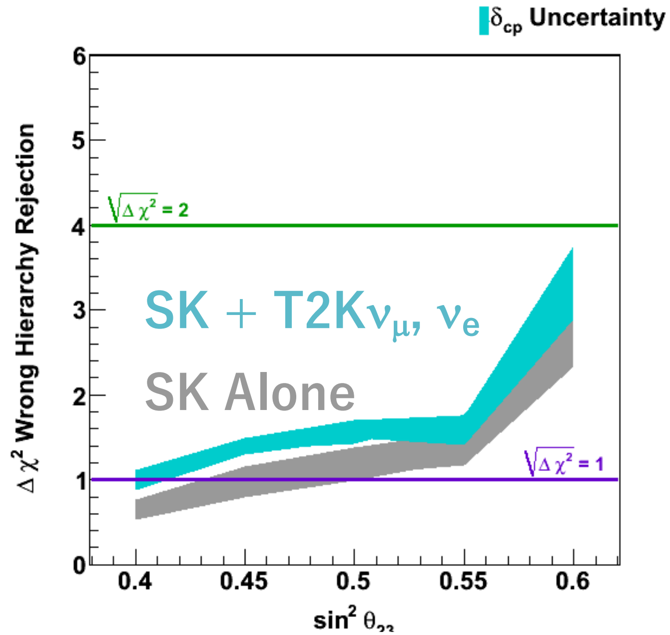
178 collaborators
from 45 institutes
10 countries

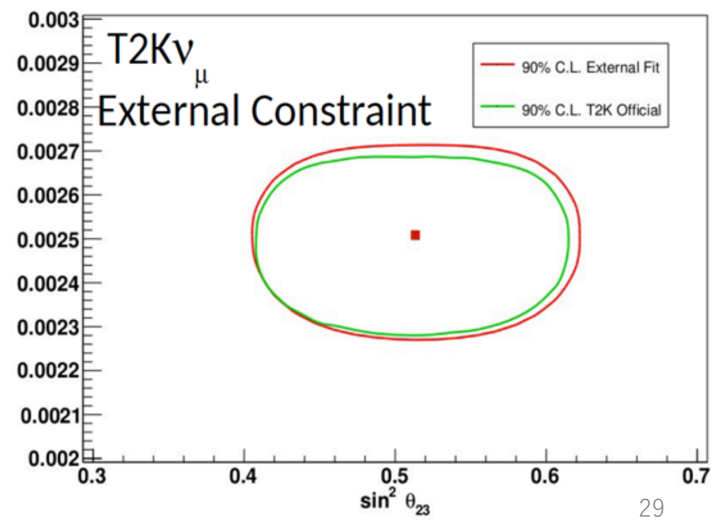
External Constraint from other Experiments

- Adding external data set to atmospheric neutrinos improve the sensitivity to the mass hierarchy: Sensitivity depends on values of Δm^2 and $\sin^2\theta_{23}$.
- Fit the T2K ν_μ and ν_e , and anti-neutrino data sets simultaniously.
- Fit is based on **publicly available** T2K information and results
  - Make a mimic T2K data, and analyzed with SK atm. ν data.
  - (not a joint result of the T2K and SK collaborations)

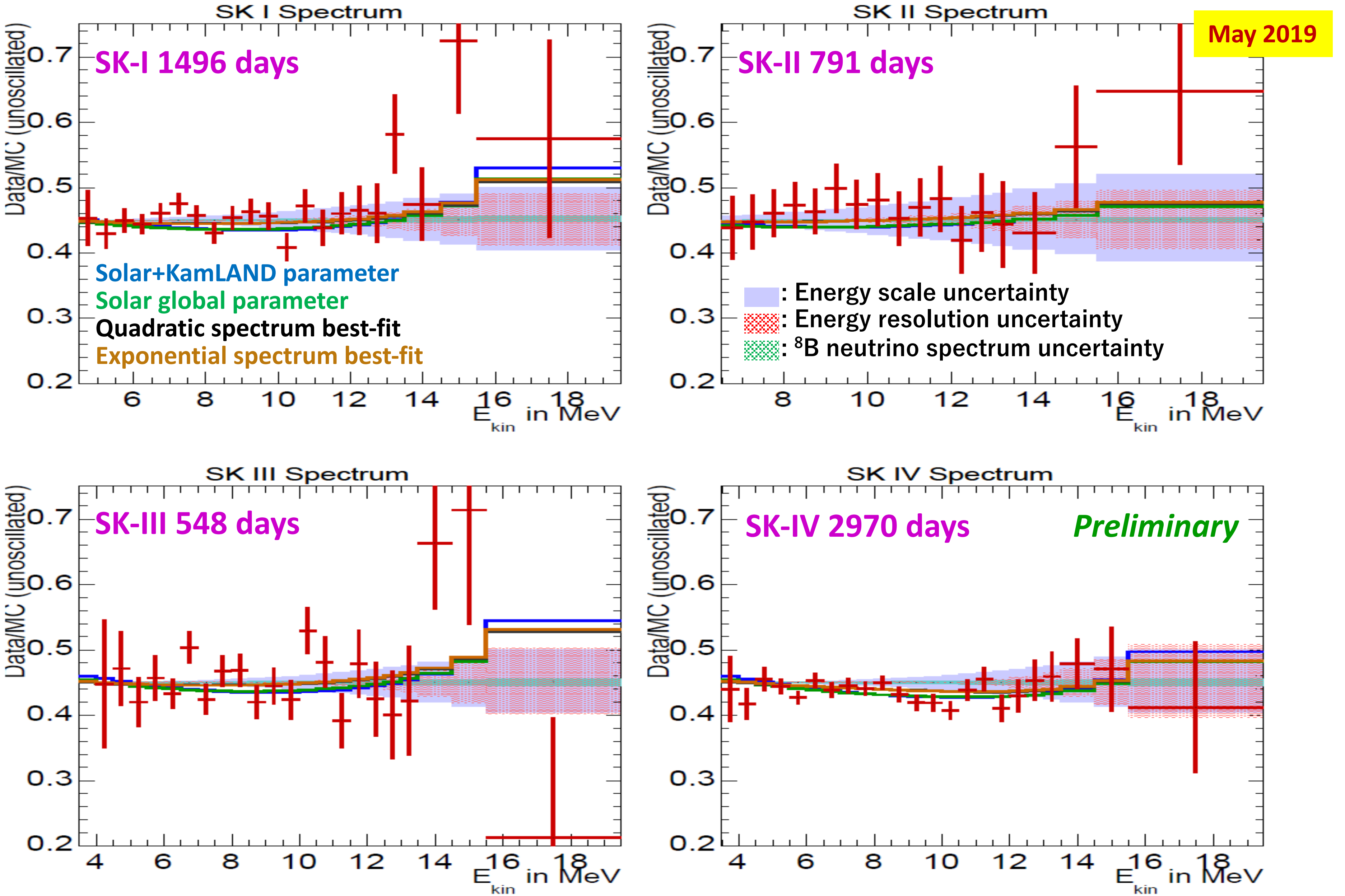
MINOS constraint is similarly important but harder to model accurately (so far...)

Hierarchy Sensitivity NH True





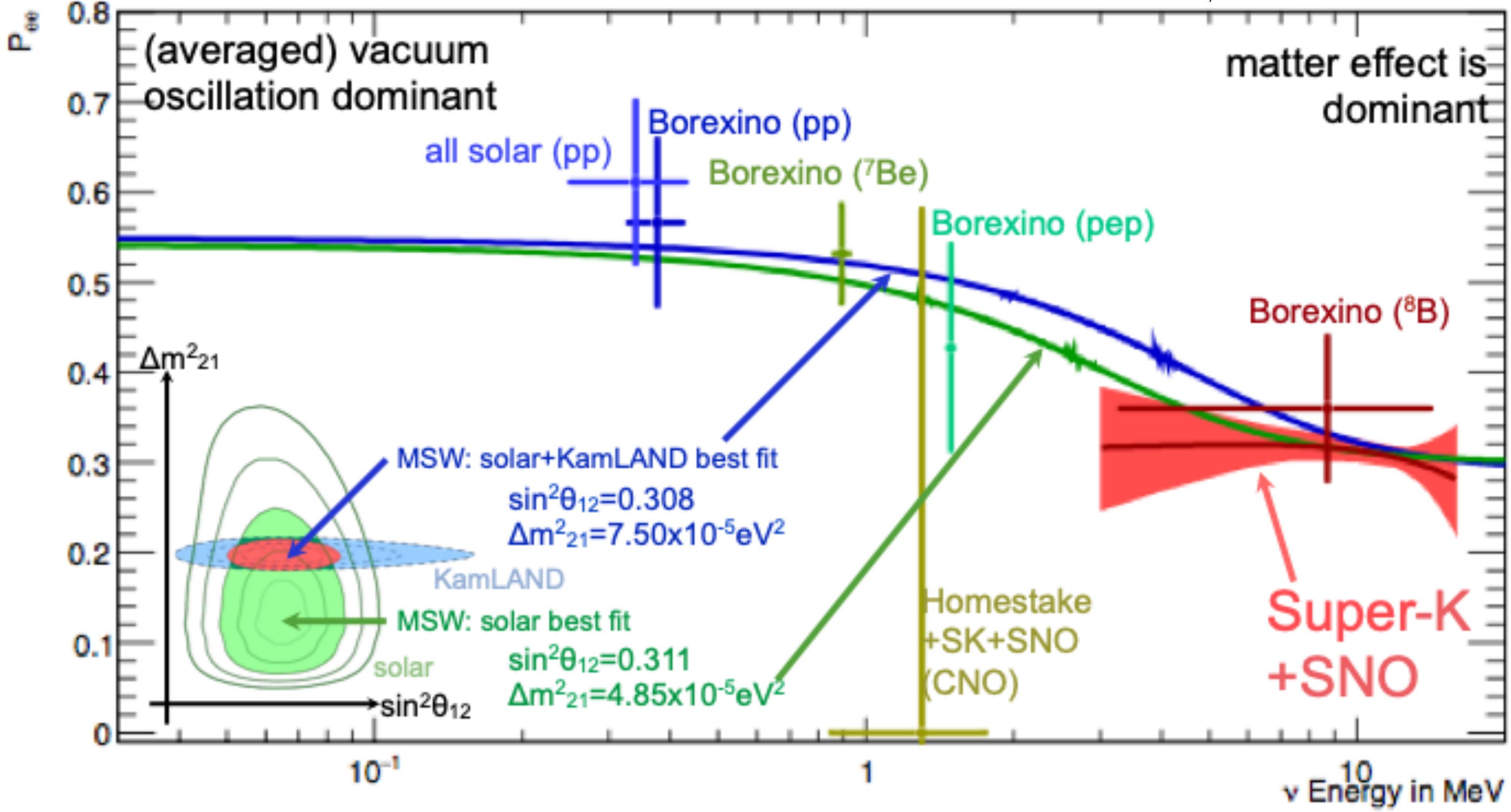
Energy spectrum

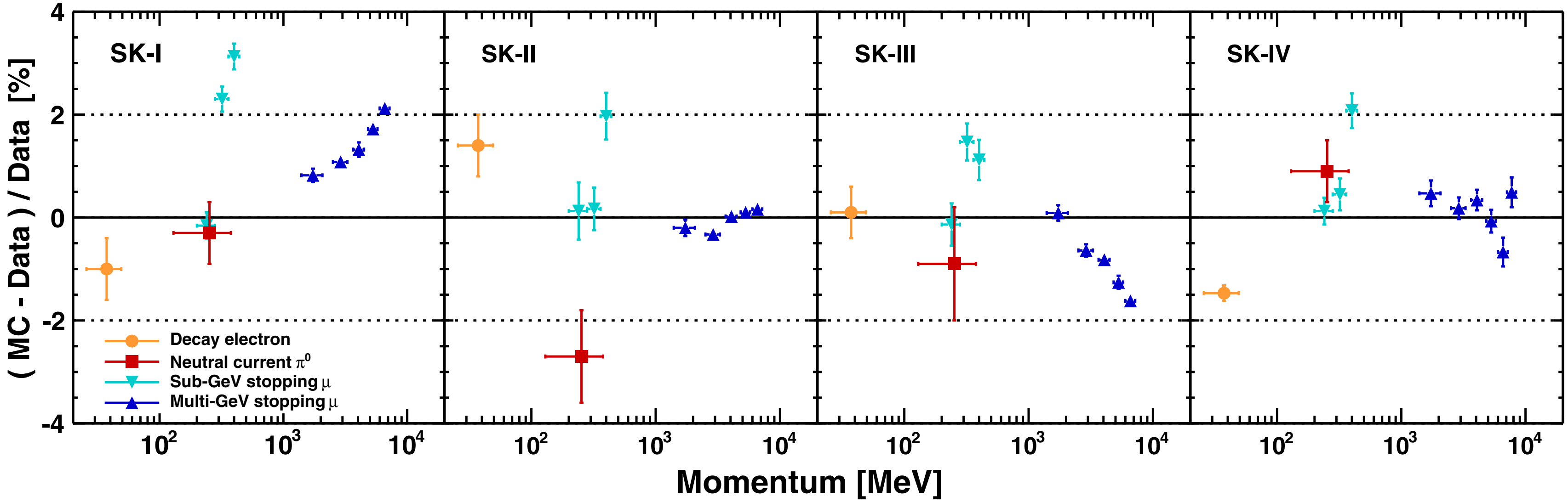


Preliminary

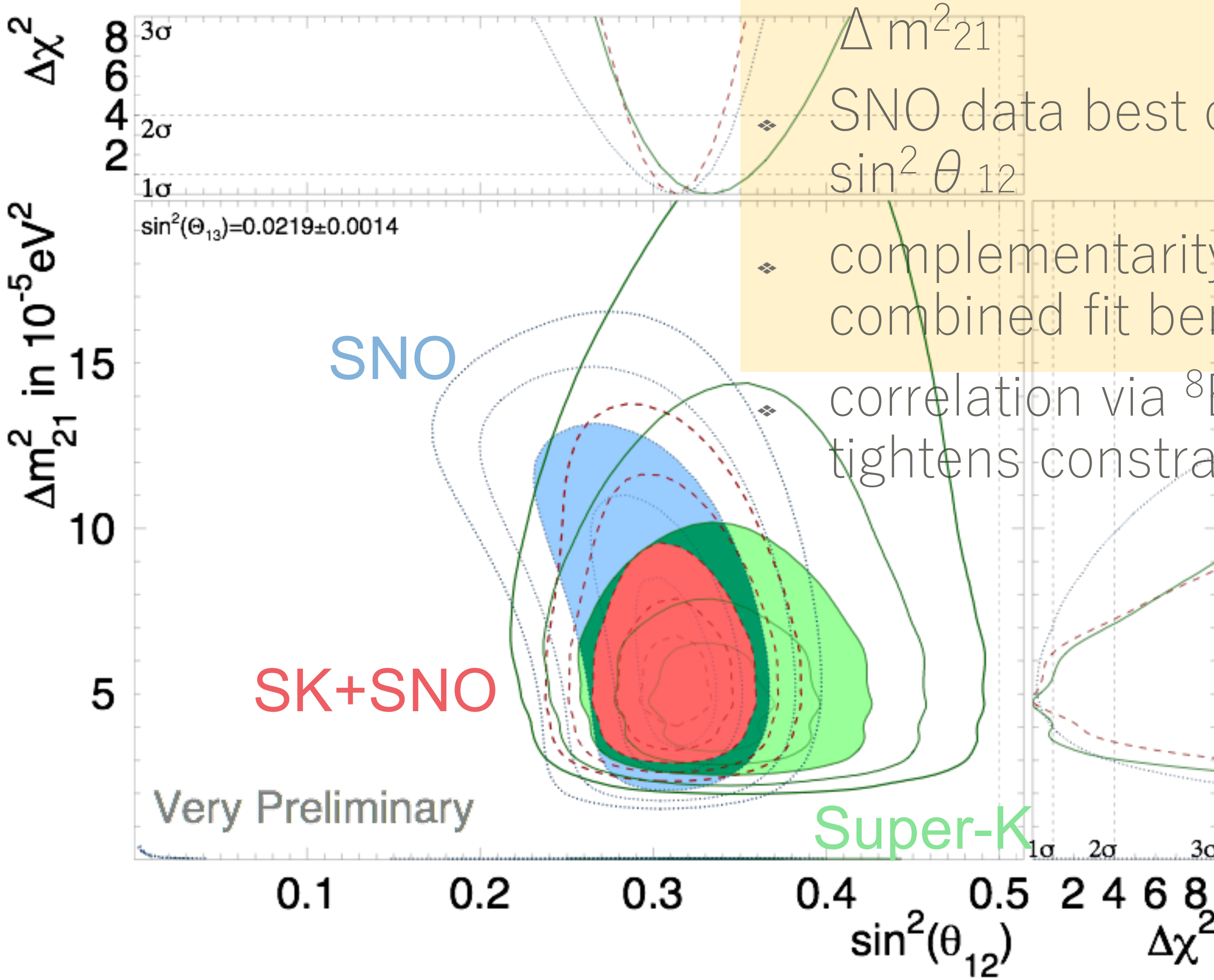
Survival probabilities

M. Ikeda, Neutrino 2018
DOI: 10.5281/zenodo.1286857




SK-I
SK-II
SK-III
SK-IV
Decay electron
Neutral current π^0
Sub-GeV stopping μ
Multi-GeV stopping μ
(MC - Data) / Data [%]
Momentum [MeV]
4
2
0
-2
-4
10^2
10^3
10^4

Solar ν Angle θ_{12} & Mass^2 Difference



- Super-K data best constrains Δm^2_{21}
- SNO data best constrains $\sin^2\theta_{12}$
- complementarity makes combined fit beneficial
- correlation via ^8B flux further tightens constraints