Results from Super-Kamiokande

Yasuo Takeuchi
Kobe University

- Super-Kamiokande detector
- Atmospheric neutrino results
- Solar neutrino results

Inside of SK detector (April 2006)

The Super-Kamiokande Collaboration

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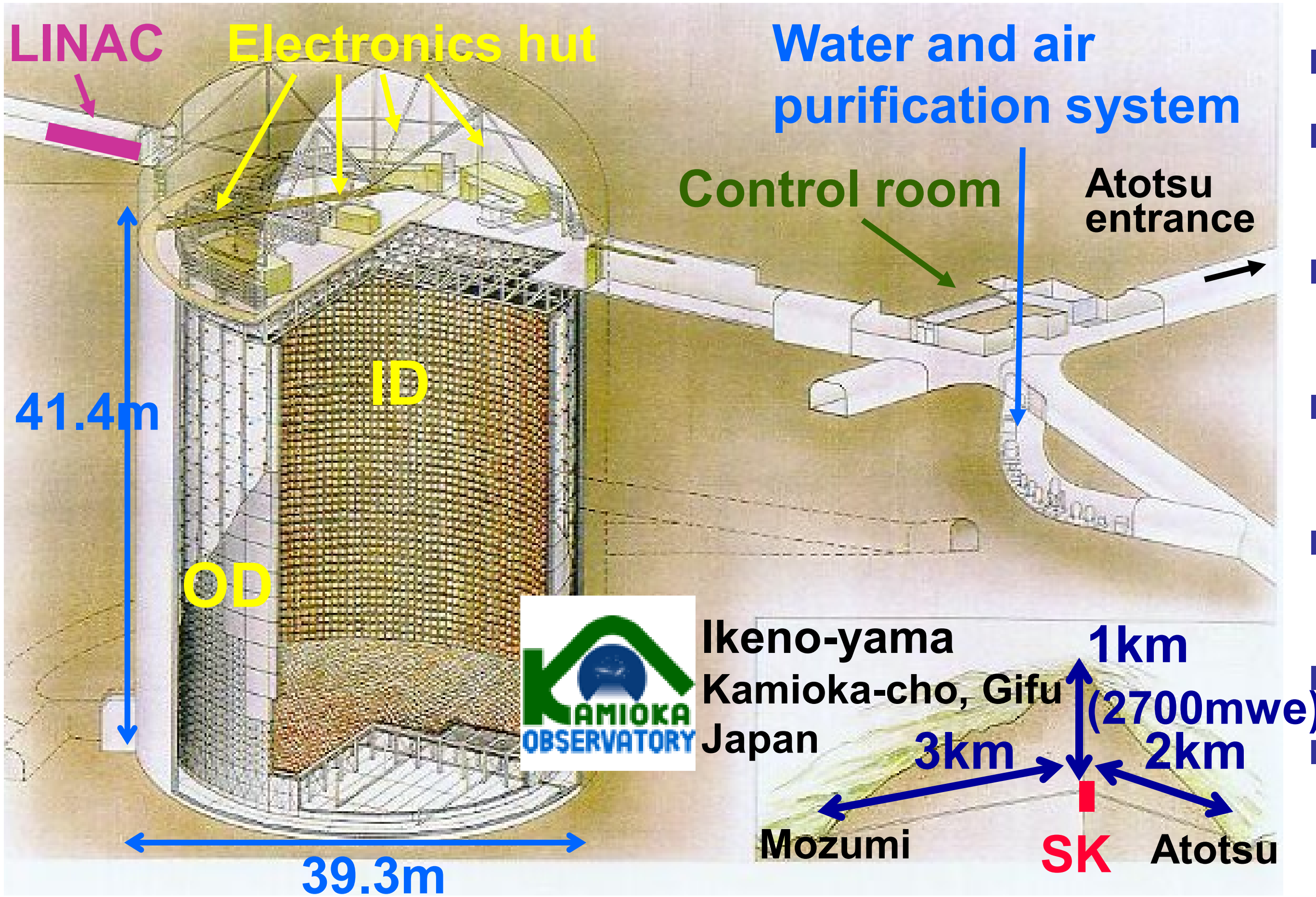
~120 collaborators
31 institutions, 6 countries

From PRD81, 092004 (2010)

Super-Kamiokande detector



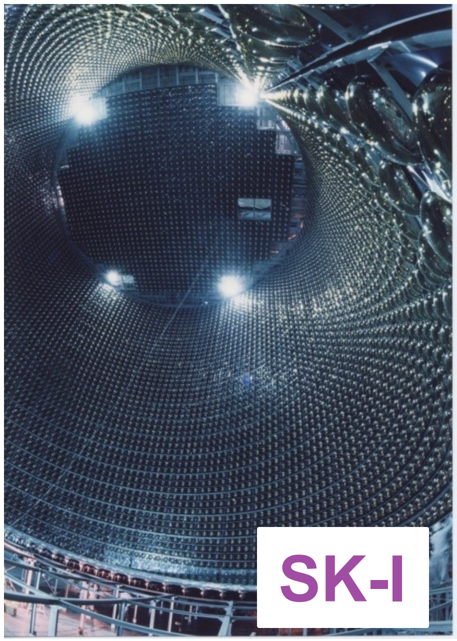
- 50kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- ~4.5MeV energy threshold
- SK-I: April 1996~
- SK-IV is running

Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

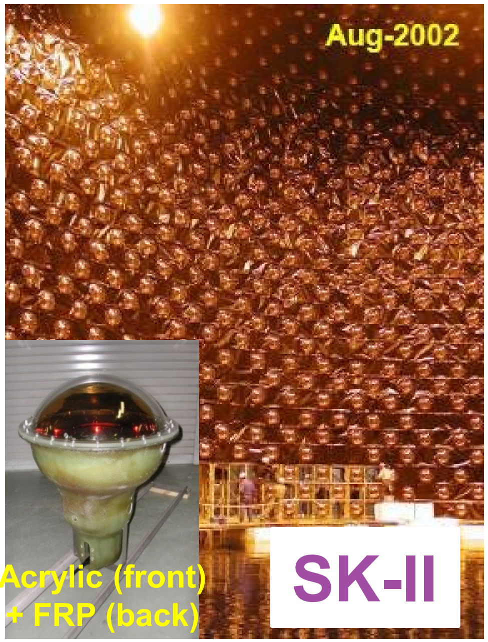
History of Super-Kamiokande

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

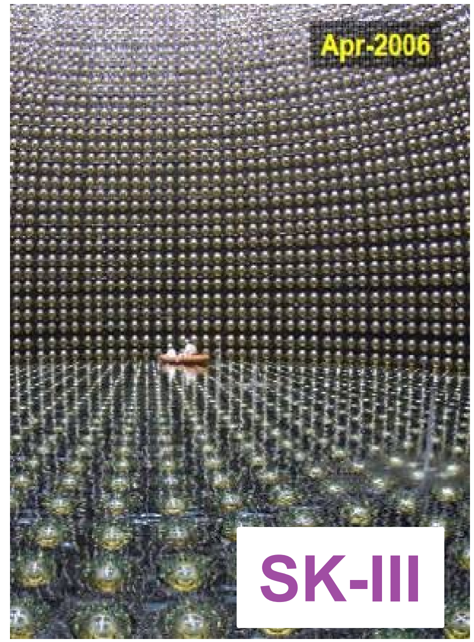
SK-I SK-II SK-III SK-IV



11146 ID PMTs
(40% coverage)



5182 ID PMTs
(19% coverage)



11129 ID PMTs
(40% coverage)

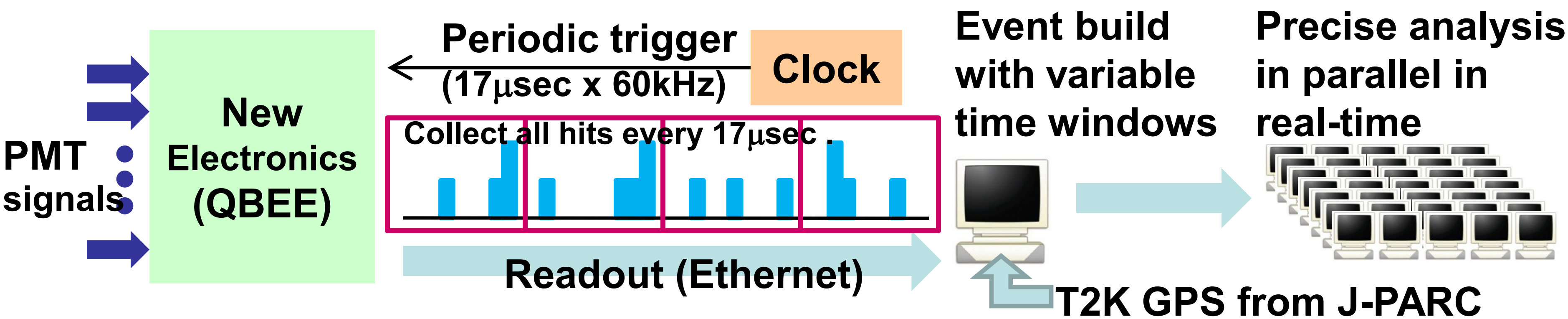
Electronics
Upgrade

Energy Threshold	SK-I	SK-II	SK-III	SK-IV Current	SK-IV Target
(Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV

Improvements of the DAQ system

IEEE Trans. Nucl. Sci. 57 (2010) 428

SK-I,II,III: partial data above threshold were read (1.3μsec window x3kHz)
SK-IV: All hits are read, then apply complex triggers by software.



Typical event time windows:

- Super-Low-Energy (SLE) events (<~6.5MeV): -0.5/+1.0μsec high rate (~3kHz)
- Normal events(>~6.5MeV): -5/+35μsec decay electrons
- Supernova Relic ν (SRN) candidates(>~10MeV, No OD): -5/+535μsec neutrons
- T2K events: -512/+512μsec at T2K beam spill timing

Wider dynamic range for charge measurement of each channel (>2000pC) x5
No dead time up to ~6MHz/10sec for Supernova burst neutrinos x100
Apply precise event reconstruction to remove more low-e BG events in real-time

Atmospheric neutrino results

Summary of the recent progress

- Oscillation analysis
  - 2-flavor (SK-I,II,III, zenith, L/E) Jun 2009
  - 3-flavor (SK-I,II,III, solar term, matter) Jun 2009 PRD81, 092004 (2010)
    - Chi2 map will be provided through our web site in near future
  - Full 3-flavor (SK-I,II,III, solar, θ13, δCP) May 2010
  - 3-flavor Non Standard Interaction (SK-I,II) Nov 2008
  - CPT violation (SK-I,II,III) Nov 2009 → Poster-79 Roger Wendell
  - (Tau appearance in SK-I: ~2σ observed) PRL97, 171801 (2006)
    - Under improving and updating with SK-I,II,III data.
- Nucleon decay Nov 2009 → Poster-148 Jennifer Raaf
  - p → e+ π0 : >1.0x10^34 year (SK-I,II,III, 172.8kt year)
- Astrophysics
  - WIMP search (SK-I,II,III, Sun, GC, diffuse source) May 2010

Poster-34 Takayuki Tanaka

Poster-61 Piotr Mijakowski

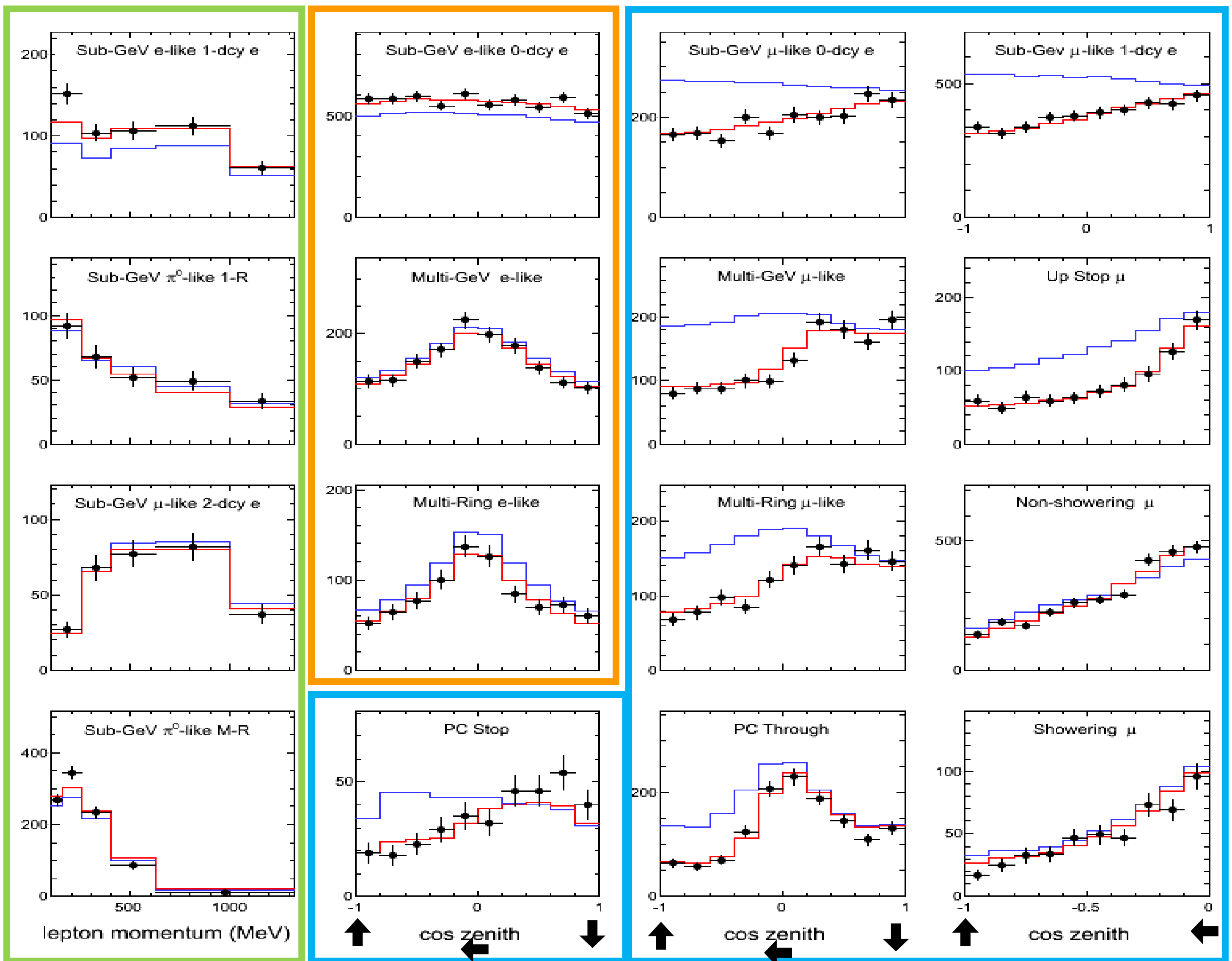
Zenith angle & lepton momentum distributions

SK-I+II+III

Preliminary

— $\nu_\mu - \nu_\tau$ oscillation (best fit)
— null oscillation

momentum | e-like | μ-like



Live time:

SK-I
- 1489d (FCPC)
- 1646d (Upmu)

SK-II
- 799d (FCPC)
- 827d (Upmu)

SK-III
- 518d (FCPC)
- 636d (Upmu)

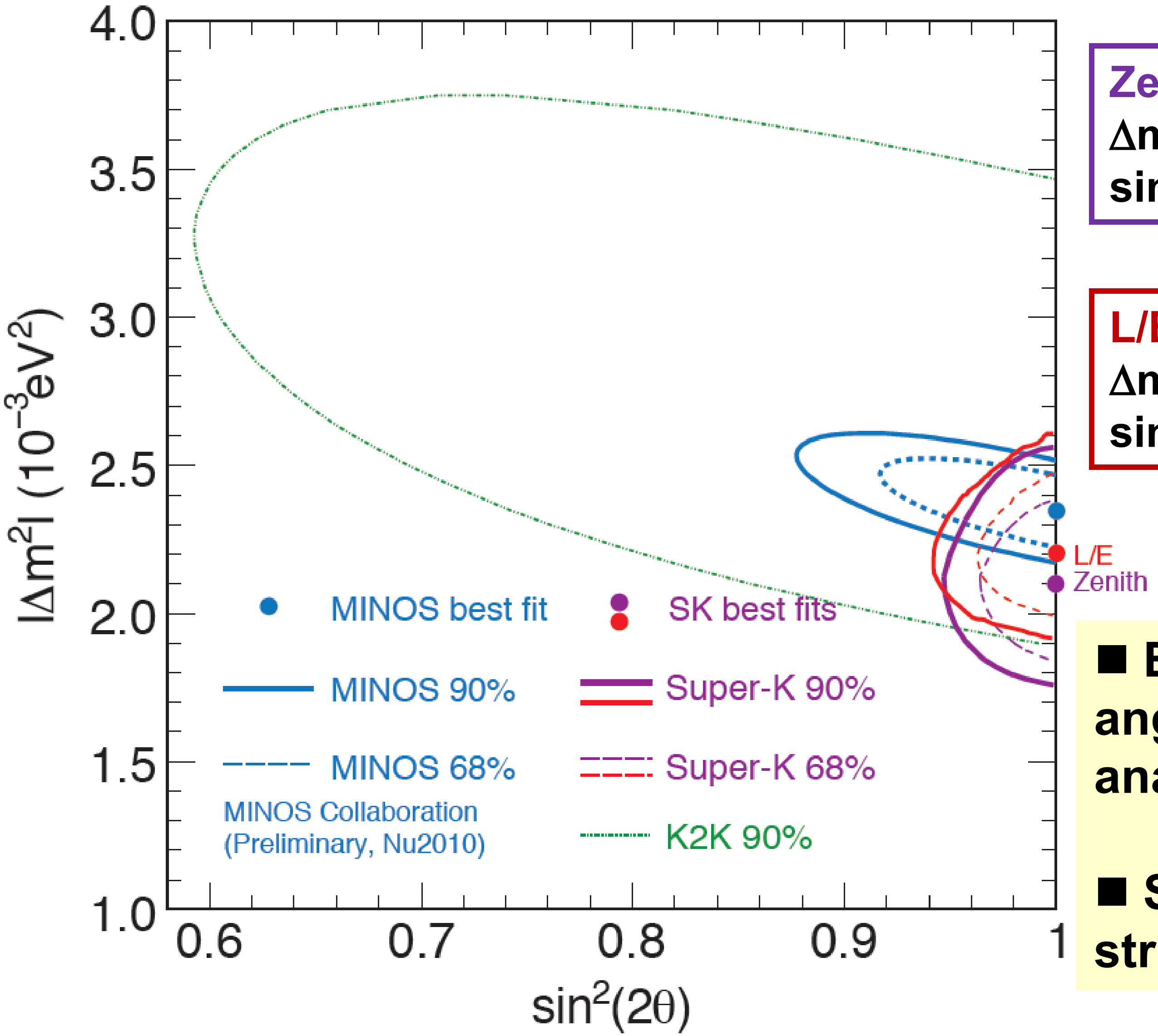
Sub-GeV samples are divided to improve sensitivity to low-energy oscillation effects

Jun 2009

2-flavor oscillation analysis results

SK-I+II+III *Preliminary*

Jun 2009



Zenith Physical Region (1σ)
Δm_{23}^2=2.11+0.11/-0.19 x10^{-3}
$\sin^2 2\theta_{23}$>0.96 (90%C.L.)

L/E Physical Region (1σ)
Δm_{23}^2=2.19+0.14/-0.13 x10^{-3}
$\sin^2 2\theta_{23}$>0.96 (90%C.L.)

- Both results of zenith angle analysis and L/E analysis are consistent.
- SK provides the most stringent limit for $\sin^2(2\theta_{23})$.

Full 3-flavor oscillation analysis

May 2010

- Consider both matter effect and solar term simultaneously.
- Matter effect: possible enhancement of ν_e is expected in several GeV energy region and in Earth core
  - ➡ θ_{13} and mass hierarchy could be studied.
- Solar term: possible enhancement of ν_e in sub-GeV region
  - ➡ θ_{23} octant degeneracy could be studied.
- Interference: CP phase could be studied. (when $\sin^2\theta_{13}$ >~0.05).

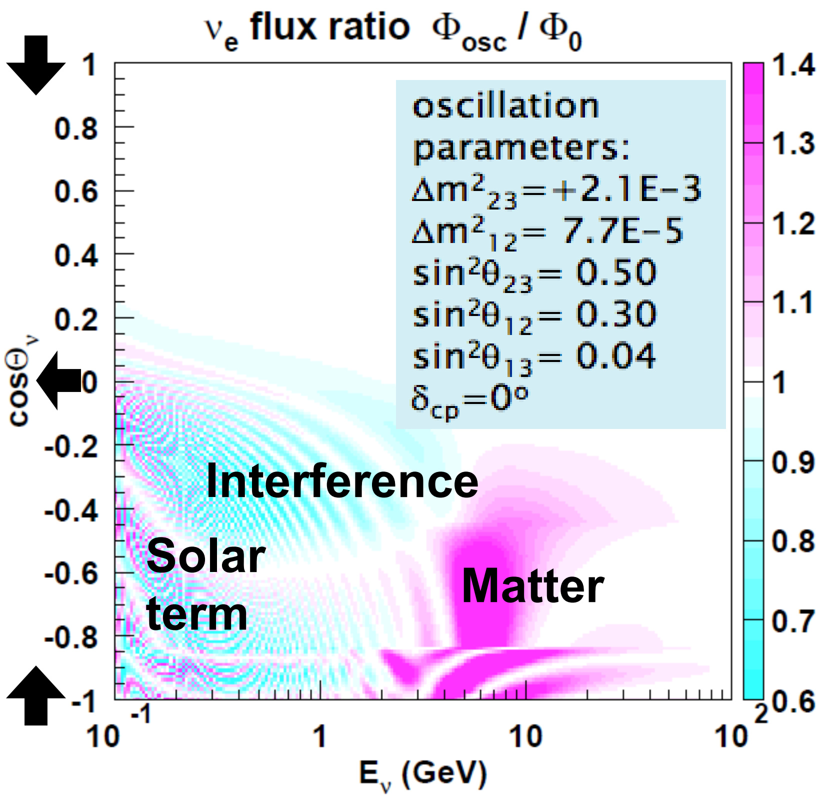
Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \quad \leftarrow \text{Matter effect}$$
$$+\Delta_2(\Delta m^2_{12}) \quad \leftarrow \text{Solar term}$$
$$+\Delta_3(\theta_{13}, \Delta m^2_{12}, \delta) \quad \leftarrow \text{Interference}$$

(The ν_μ flux difference is also expected.)

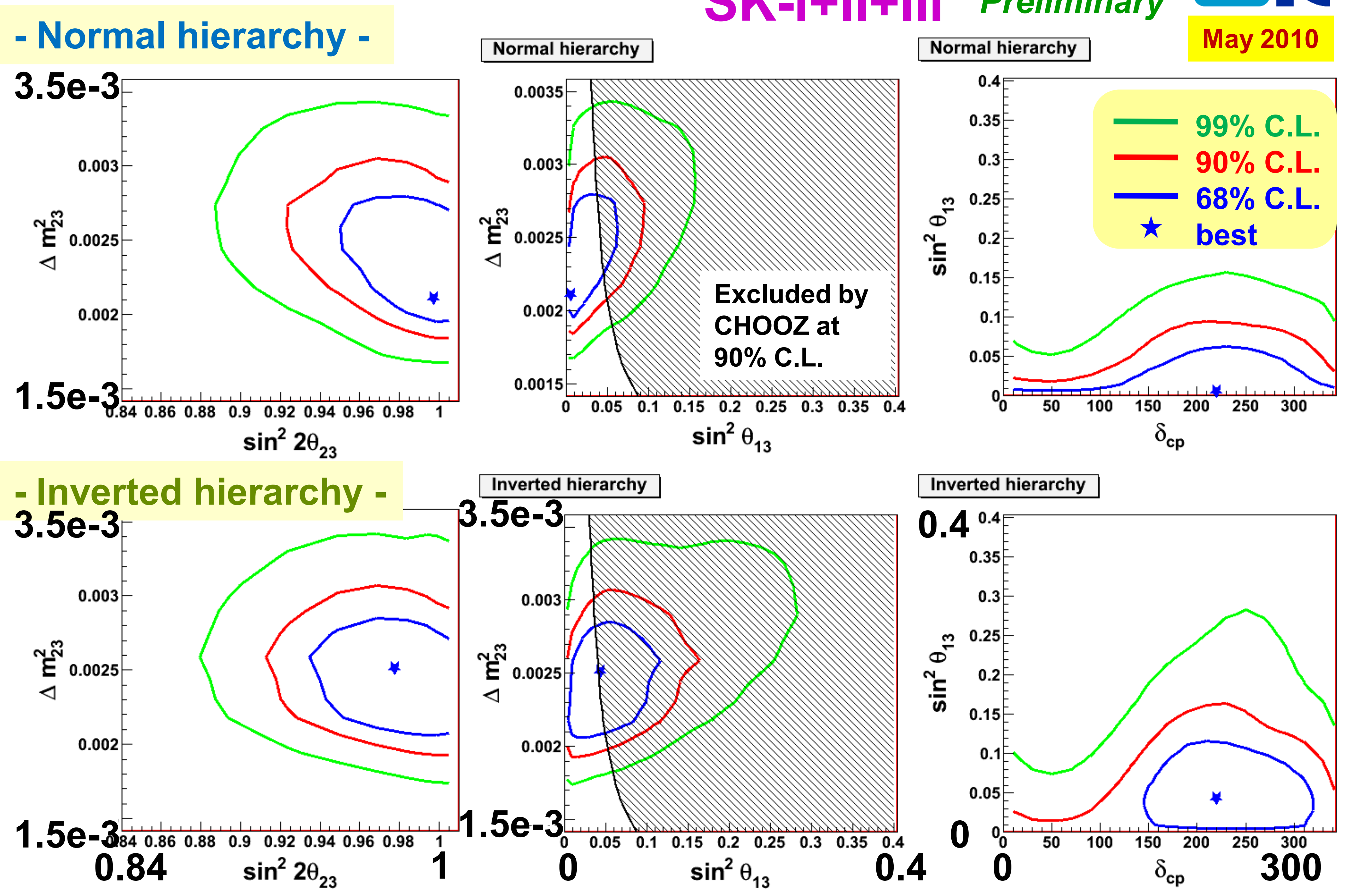
Full 3-f osc. analysis: all parameters are considered at a time.

PRD81, 092004: either matter effect or solar term is considered with some approximations (cannot test the interference part)



Full 3-flavor oscillation results

SK-I+II+III *Preliminary* **May 2010**



Full 3-flavor oscillation results

SK-I+II+III *Preliminary*

May 2010

- Normal hierarchy -

χ^2_{min} = 469.94 /416dof

Parameter	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10^3)	2.11 eV^2	1.88 - 2.75 eV^2	1.99 - 2.54 eV^2
$\sin^2\theta_{23}$	0.525	0.406 - 0.629	0.441 - 0.597
$\sin^2\theta_{13}$	0.006	< 0.066	< 0.036
CP-δ	220°	-	140.8 - 297.3°

- Inverted hierarchy -

χ^2_{min} = 468.34 /416dof

Parameter	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10^3)	2.51 eV^2	1.98 - 2.81 eV^2	2.09 - 2.64 eV^2
$\sin^2\theta_{23}$	0.575	0.426 - 0.644	0.501 - 0.623
$\sin^2\theta_{13}$	0.044	< 0.122	0.0122 - 0.0850
CP-δ	220°	121.4 - 319.1°	165.6 - 280.4°

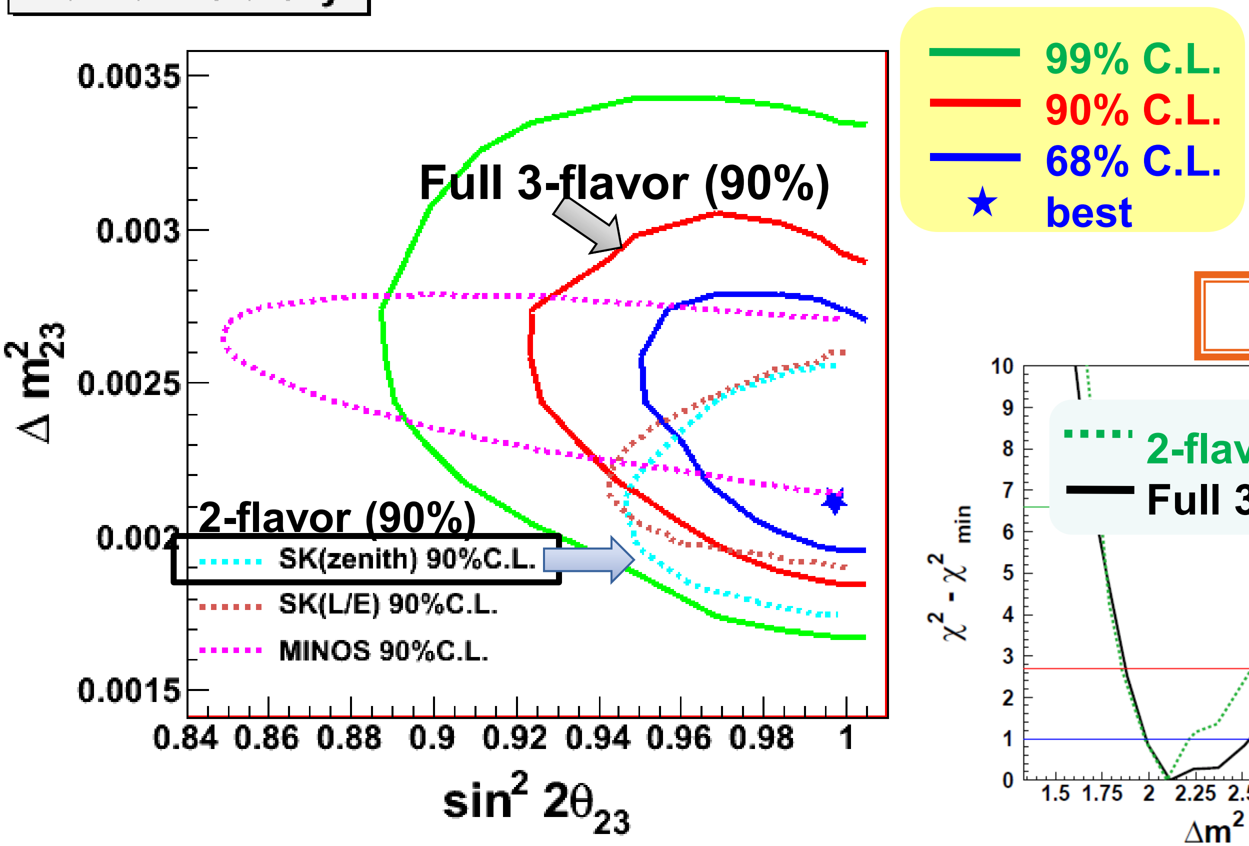
- No significant preference on hierarchy.
- No significant constraint on CP phase at 90% C.L.

($\sin^2\theta_{12}$, Δm^2_{12}) are fixed at (0.304, 7.66x10^{-5} eV^2)

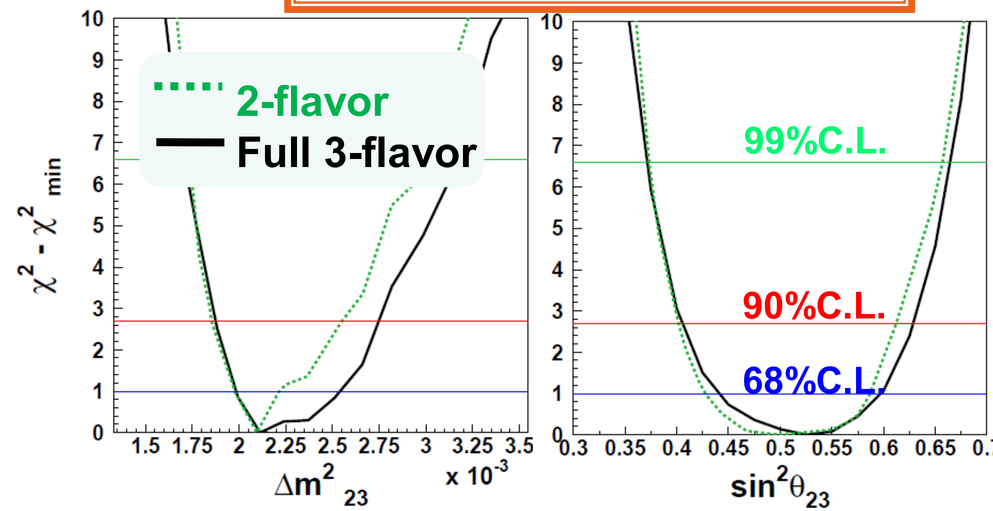
Comparison with 2-flavor analysis

May 2010

Normal hierarchy



$\chi^2 - \chi^2_{min}$ distributions



Consistent results are obtained.
No deviation of $\sin^2\theta_{23}$ from 0.5.
Allowed region of Δm^2_{23} is a bit larger than that of the 2-flavor analysis as the effect of CP phase is also taken into account.

90%C.L. allowed region (1dof, $\chi^2=\chi^2_{min}+2.71$)

Full 3-flavor (NH)	*Global-best*
$(1.88 < \Delta m^2_{23} < 2.75)$ e-3	$(2.22 < \Delta m^2_{23} < 2.60)$ e-3
$0.406 < \sin^2\theta_{23} < 0.629$	$0.401 < \sin^2\theta_{23} < 0.615$
$(0.93 < \sin^2 2\theta_{23})$	$(0.95 < \sin^2 2\theta_{23})$

Comparison of hierarchies

May 2010

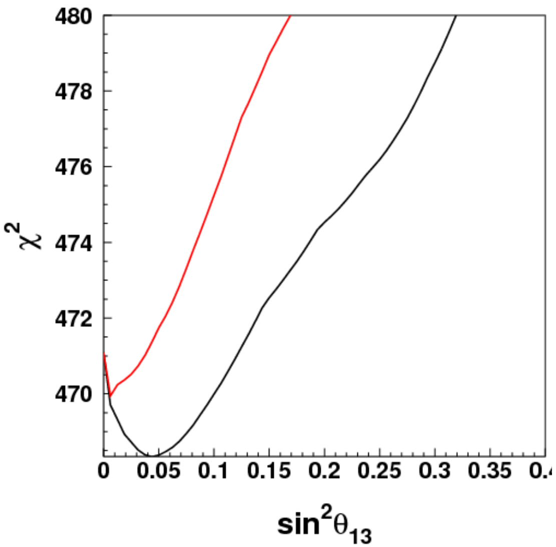
Best fit is in the inverted hierarchy case

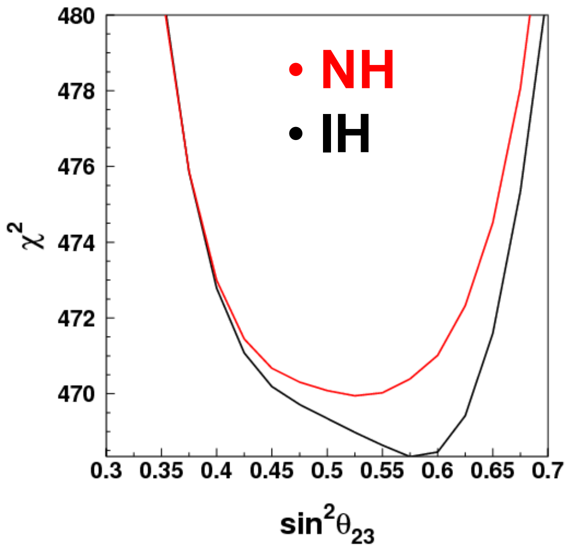
Normal hierarchy (NH): χ^2_{min} = 469.94/416dof

Inverted hierarchy (IH): χ^2_{min} = 468.34/416dof

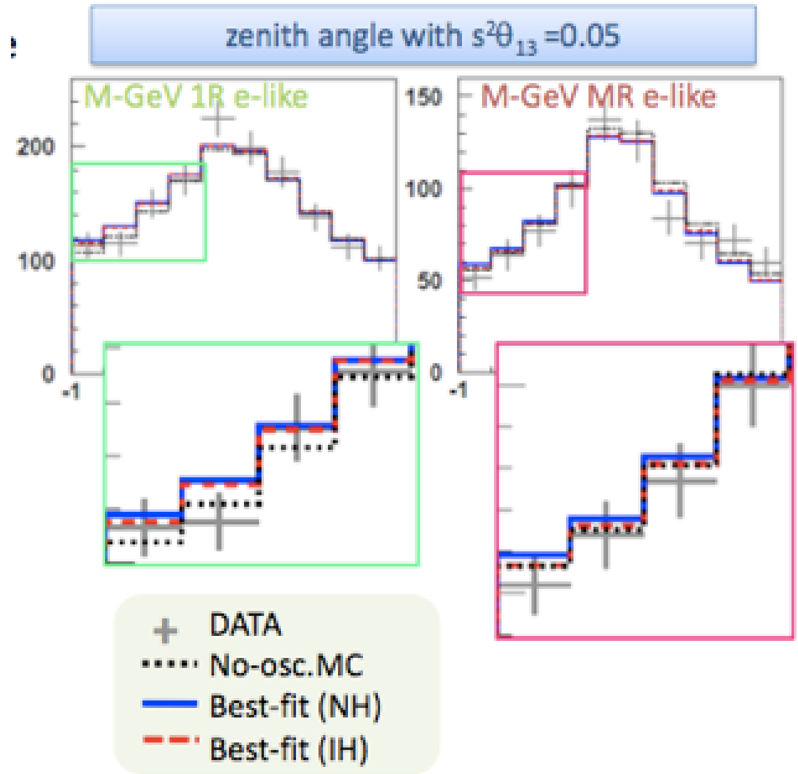
→ $\Delta\chi^2 = 1.6$

No significant difference





Multi-GeV samples tend to favor inverted hierarchy.



There are also some contributions from Multi-GeV μ-like samples favoring IH to NH.

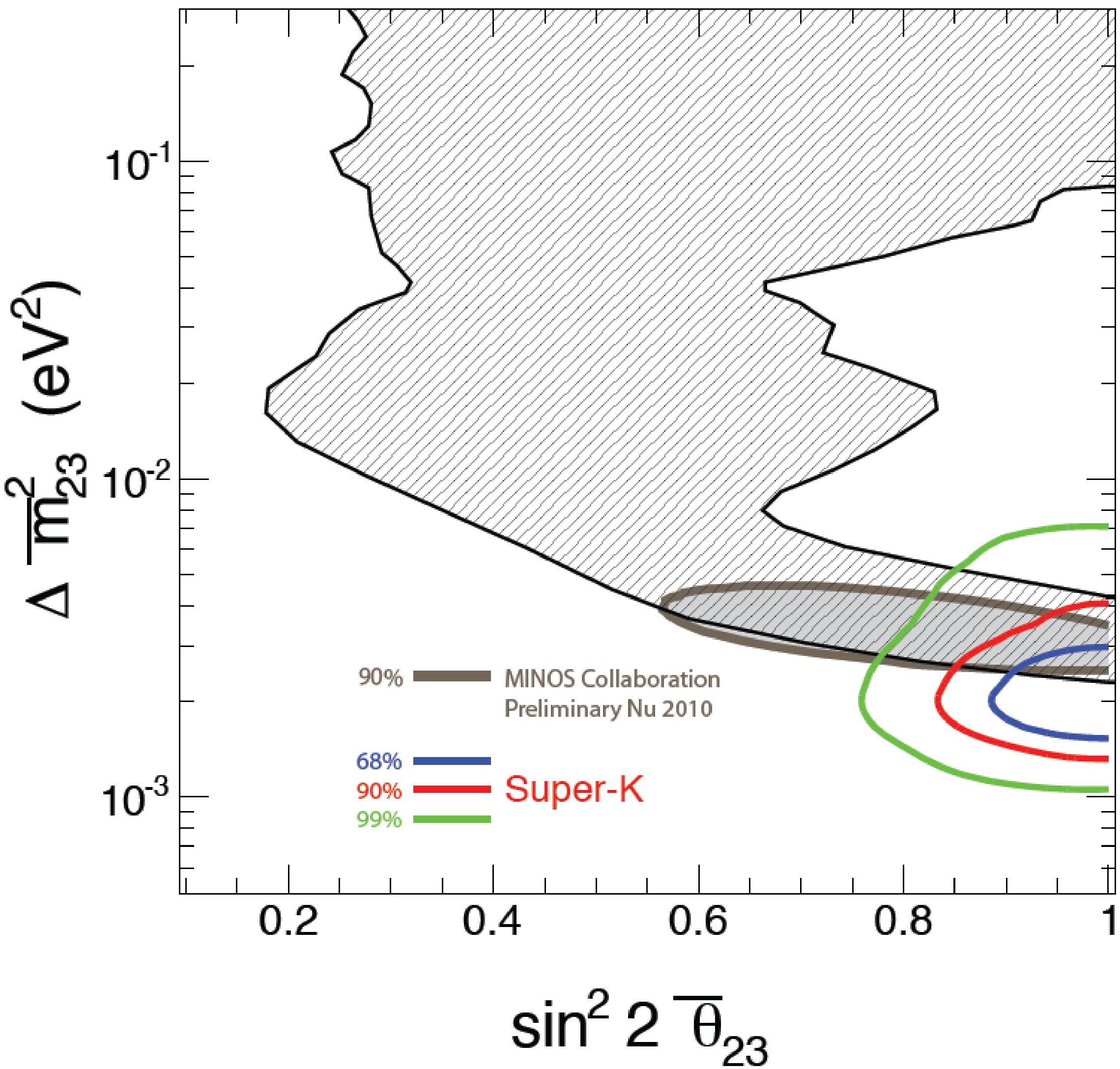
Search for CPT violation in atm. ν

Jun 2009

- Under the CPT theorem, $P(\nu \rightarrow \nu)$ and $P(\bar{\nu} \rightarrow \bar{\nu})$ should be same.
- Test ν oscillation or $\bar{\nu}$ oscillation separately.

SK-I+II+III

Preliminary



Neutrino:

$\Delta m_{23}^2 = 2.2\times10^{-3}\,eV^2$

$\sin^2 2\theta_{23} = 1.0$

Anti-neutrino:

$\Delta \overline{m}_{23}^2 = 2.0\times10^{-3}\,eV^2$

$\sin^2 2\overline{\theta}_{23} = 1.0$

No evidence for CPT violating oscillations is found

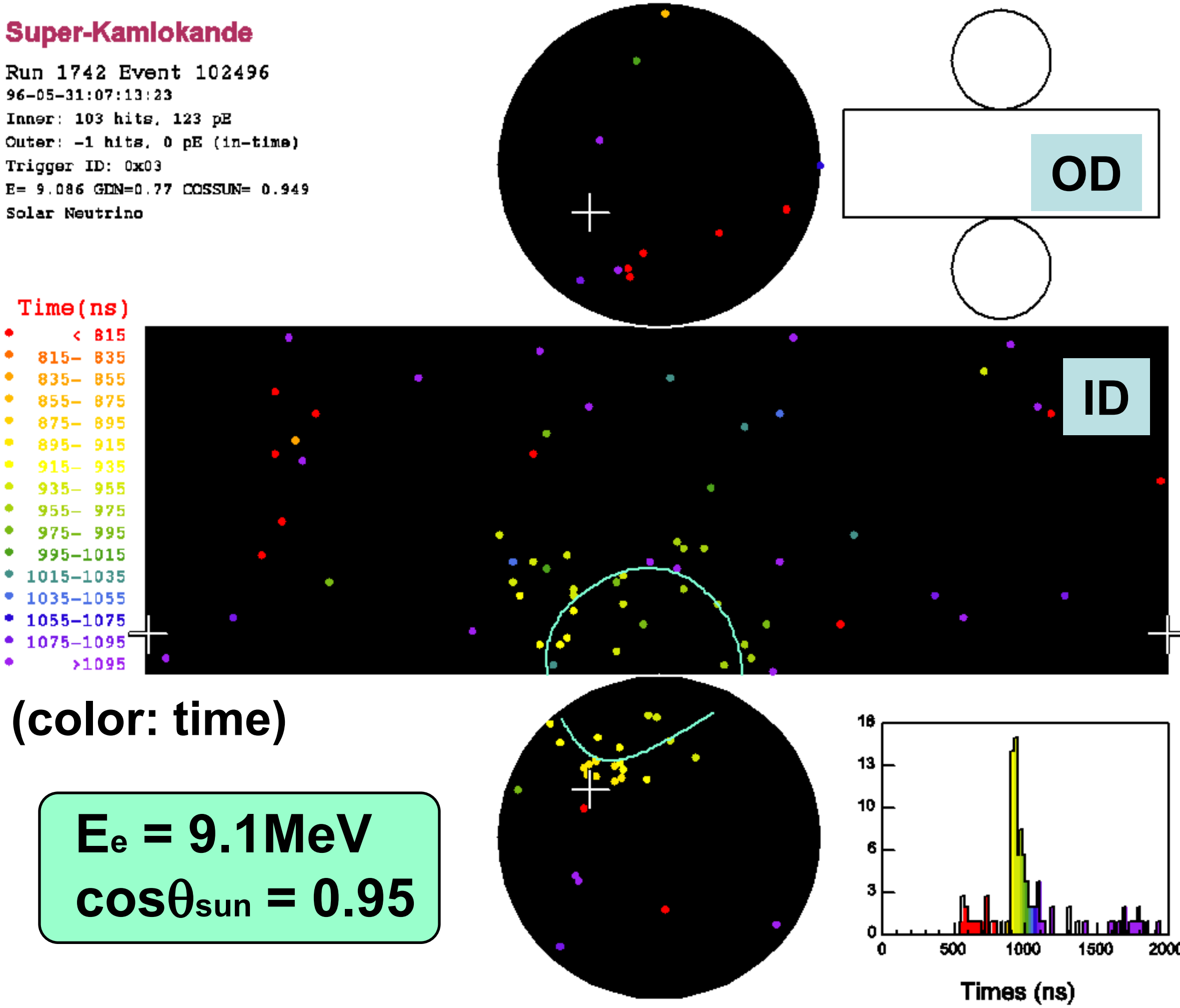
Poster-79 by Roger Wendell

Solar neutrino results

Summary of the recent progress

- Solar neutrino analysis
  - **SK-III results are summarized.**
    - A 3-flavor analysis with SK-III data was done. May 2010
      - Poster-54 Byeongsu Yang
- Supernova Relic Neutrino
  - Analysis improvement is on going. (almost done)
    - Poster-35 Kirk Bays
  - A R&D for GADZOOKS! (EGADS) was funded. Apr 2009
    - Poster-64 Andrew Renshaw (will be covered by Mark Vagins's talk)
- Other astrophysics
  - Monopole search results (SK-I,II,III, Sun) May 2010
    - Poster-37 Koh Ueno
- SK-IV: Running 100% trigger efficiency at E_{total}~4.5MeV.
  - Target in near future: E_{total}<=4.0MeV ($E_{kinetic}$<=3.5MeV)

Typical low-energy event



(color: time)

E_e = 9.1MeV
$\cos\theta_{sun}$ = 0.95

$\nu + e^- \rightarrow \nu + e^-$

(for solar neutrinos)

- Timing information
  ➡ vertex position
- Ring pattern
  ➡ direction
- Number of hit PMTs
  ➡ energy

~6hit / MeV
(SK-I, III, IV)

Resolutions (for 10MeV electrons) (software improvement)

Energy: 14%	Vertex: 87cm	Direction: 26°	SK-I
Energy: 14%	Vertex: 55cm	Direction: 23°	SK-III

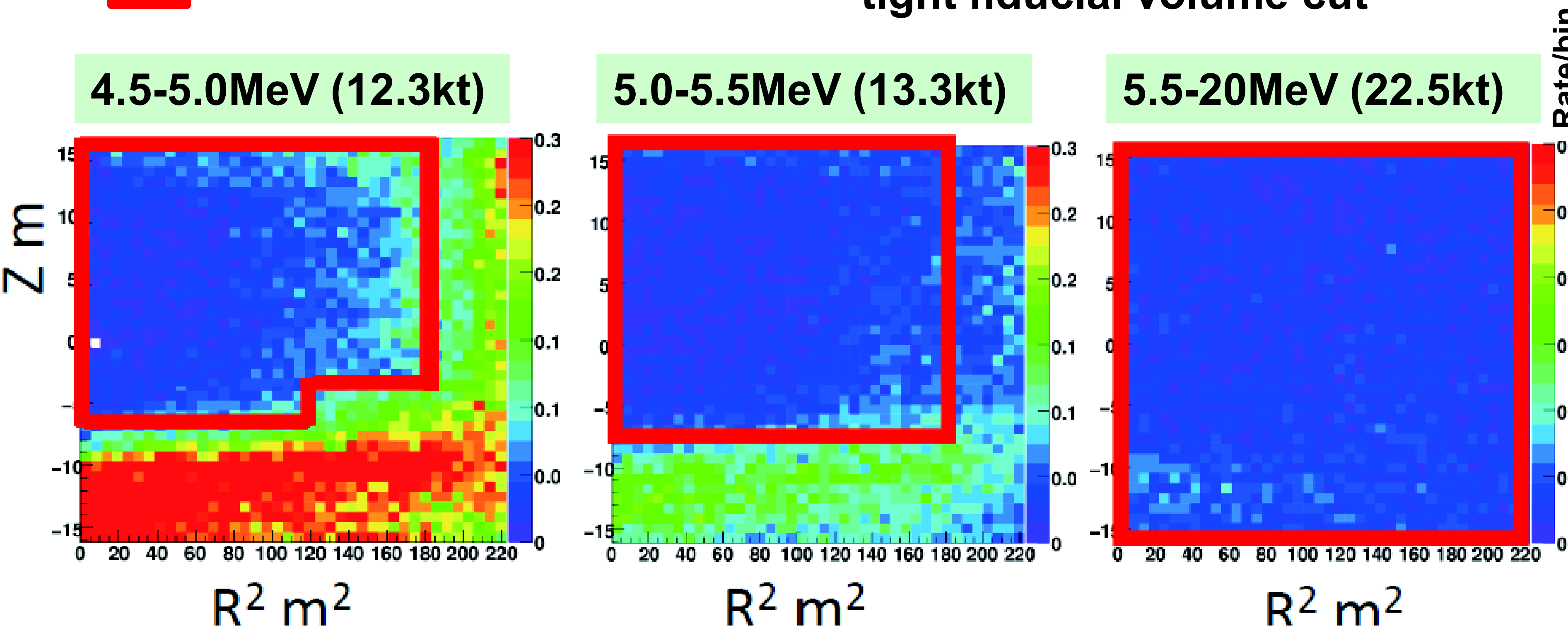
Vertex distributions in SK-III

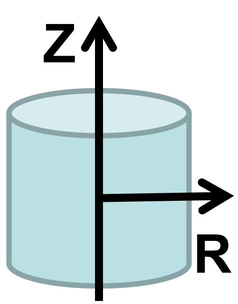
Fiducial volume in SK-III

Final data sample before tight fiducial volume cut

May 2010

4.5-5.0MeV (12.3kt) | 5.0-5.5MeV (13.3kt) | 5.5-20MeV (22.5kt)





SK detector

- **Tight fiducial volume cut is applied in E_{total}<5.5MeV to remove the background events. (probably Rn, γ-rays from detector wall).**

Systematic uncertainties on total flux

May 2010

Preliminary

	SK-III	SK-I (PRD73,112001)
Energy scale	+/-1.4	+/-1.6 (Energy scale + Energy resolution)
Energy resolution	+/-0.2	
8B spectrum shape	+/-0.2	+1.1/-1.0
Trigger efficiency	+/-0.5	+0.4/-0.3
Vertex shift	+/-0.54	+/-1.3
Reduction	+/-0.65	+2.1/-1.6 (Reduction + Small cluster hits cut)
Small cluster hits cut	+/-0.5	
Spallation cut	+/-0.2	+/-0.2
External event cut	+/-0.25	+/-0.5
Background shape	+/-0.1	+/-0.1
Angular resolution	+/-0.67	+/-1.2 (Angular resolution + Signal extraction method)
Signal extraction method	+/-0.7	
Cross section	+/-0.5	+/-0.5
Live time calculation	+/-0.1	+/-0.1
Total	+/-2.1	+3.5/-3.2%

Energy region:

E_{total}=5.0-20.0MeV

The systematic error on total flux of SK-III is reduced by precise calibrations and software improvements

SK-III solar neutrino results

May 2010

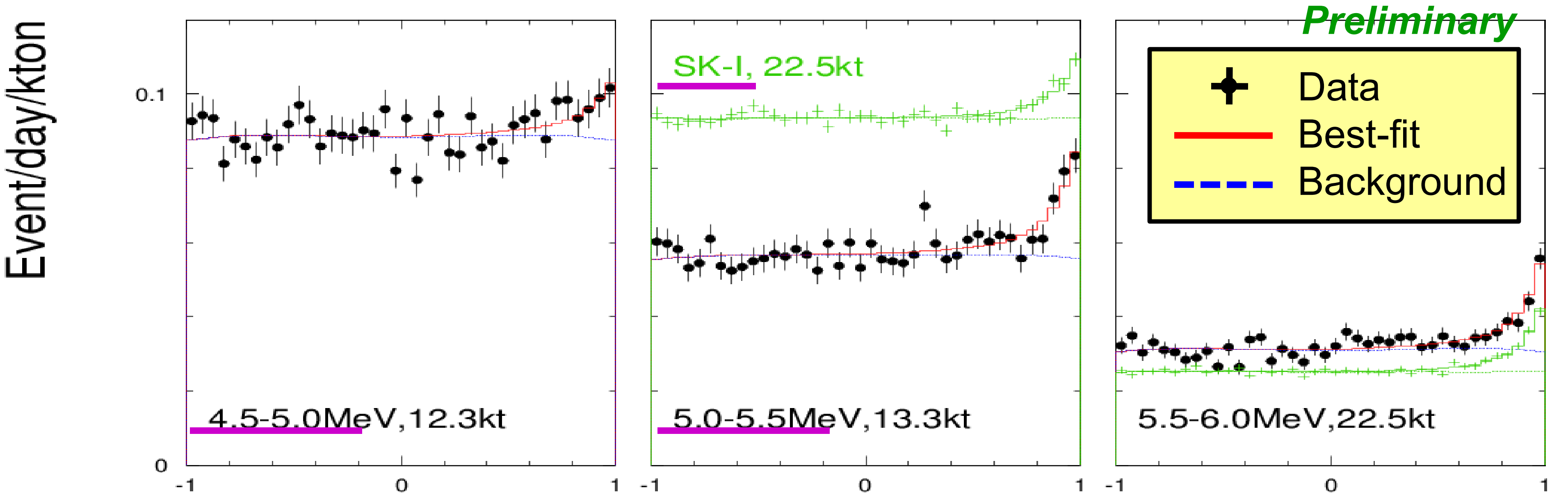
Preliminary

- Total live time : 548 days, $E_{total} \geq 6.5$ MeV
  289 days, $E_{total} < 6.5$ MeV
- Energy region: E_{total}=5.0-20.0MeV
- ^{8}B Flux: 2.32+/-0.04(stat.)+/-0.05(syst.) ($\times 10^{6}/cm^{2}/s$)
  - SK-I: 2.38+/-0.02(stat.)+/-0.08(syst.)
  - SK-II: 2.41+/-0.05(stat.)+0.16/-0.15(syst.)

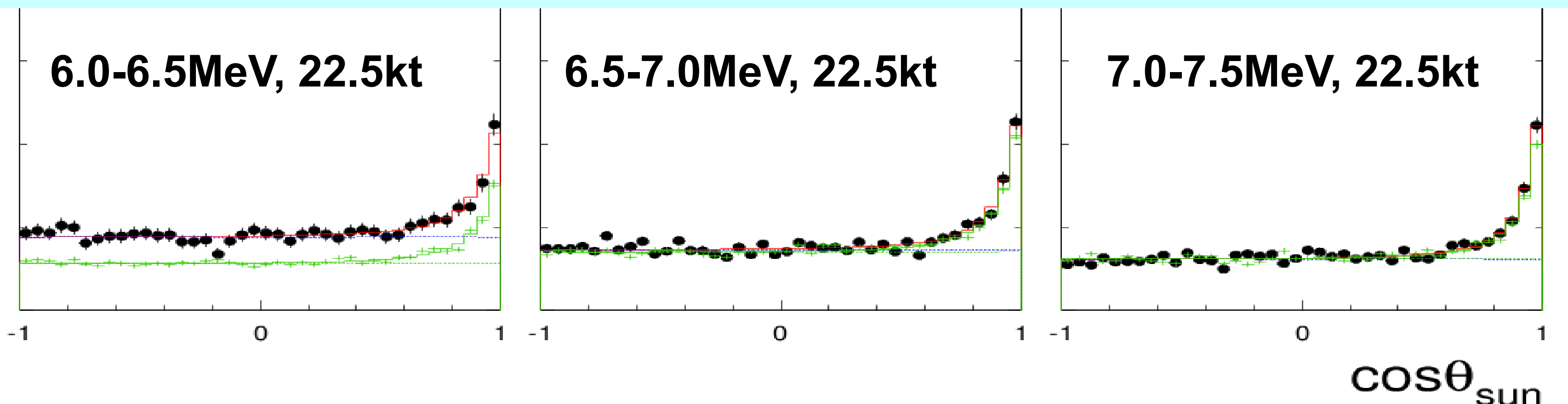
  (SK-I,II are recalculated with the Winter06 ^{8}B spectrum)
- Day / Night ratio:

$$A_{DN} = \frac{(\Phi_{Day} - \Phi_{Night})}{(\Phi_{Day} + \Phi_{Night})/2} = -0.056 \pm 0.031(\text{stat.}) \pm 0.013(\text{syst.})$$

Angular distributions in SK-III



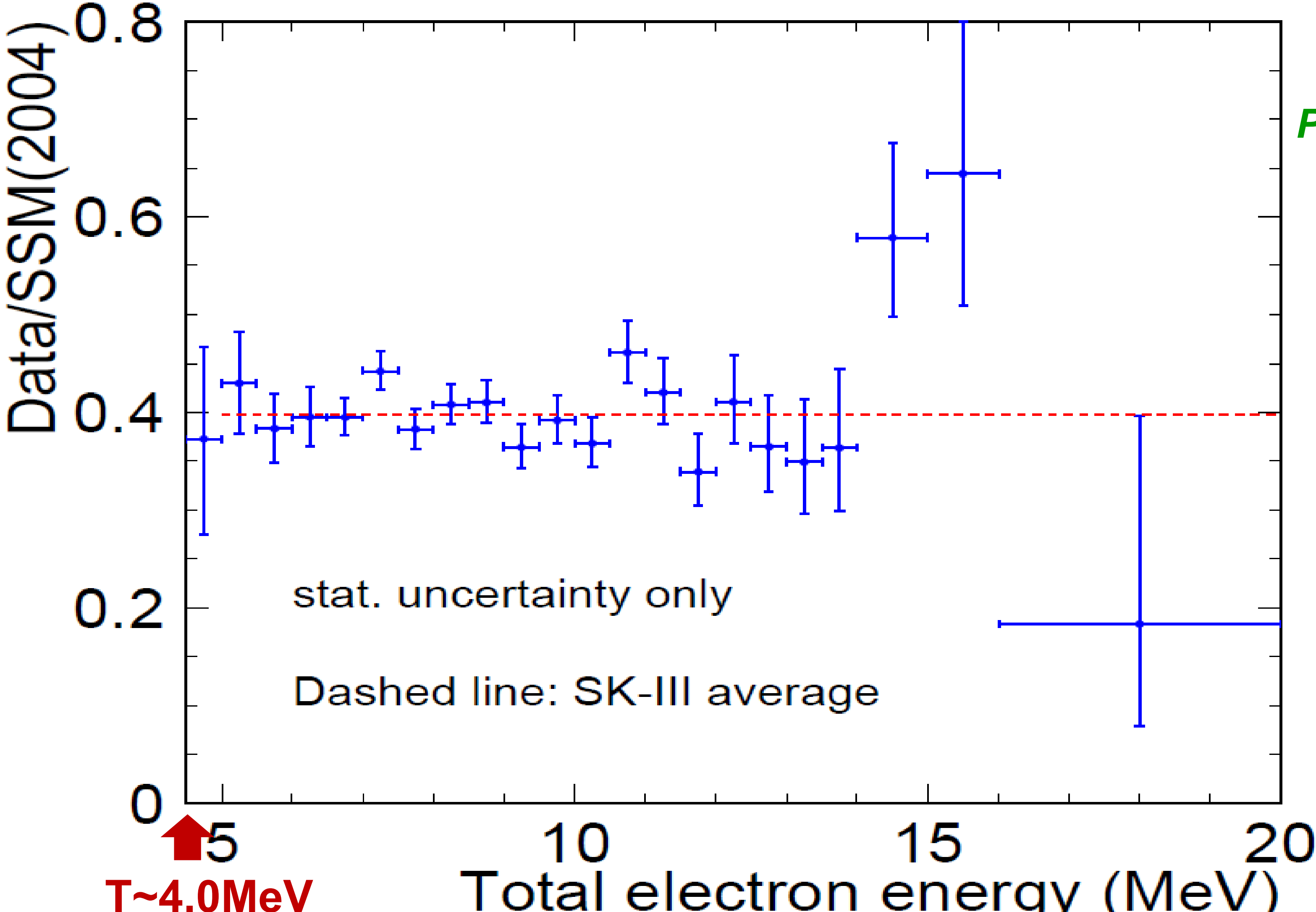
- Angular resolution in SK-III is better
- In E_{total}=5.0-5.5MeV, SK-III has better Signal to Noise ratio.
- BG level in 4.5-5.0MeV region is similar as that in 5.0-5.5MeV of SK-I



SK-III ^{8}B energy spectrum

May 2010

Preliminary



- **Consistent with no distortion**
- **E_{total}=4.5-5.0MeV data isn't used in the oscillation analysis.**

Data set for oscillation analysis

May 2010

- SK
  - SK-I 1496 days, spectrum 5.0-20MeV + D/N : E ≥ 5.0MeV
  - SK-II 791 days, spectrum 7.0-20MeV + D/N : E ≥ 7.5MeV
  - SK-III 548 days, spectrum 5.0-20.0MeV + D/N : E ≥ 5.0MeV
- SNO
  - CC flux (Phase-I & II & III)
  - NC flux (Phase-III & LETA combined) (= (5.14+/-0.21) $10^6 cm^{-2} s^{-1}$)
  - Day/Night asymmetry (Phase-I & II)
- Radiochemical : Cl, Ga
  - Ga rate: 66.1+/-3.1 SNU (All Ga global) (PRC80, 015807(2009))
  - Cl rate: 2.56+/-0.23 (Astrophys. J. 496 (1998) 505)
- Borexino
  - ^{7}Be rate: 48 +/- 4 cpd/100tons (PRL101, 091302(2008))
- KamLAND : 2008
- ^{8}B spectrum : Winter(2006)

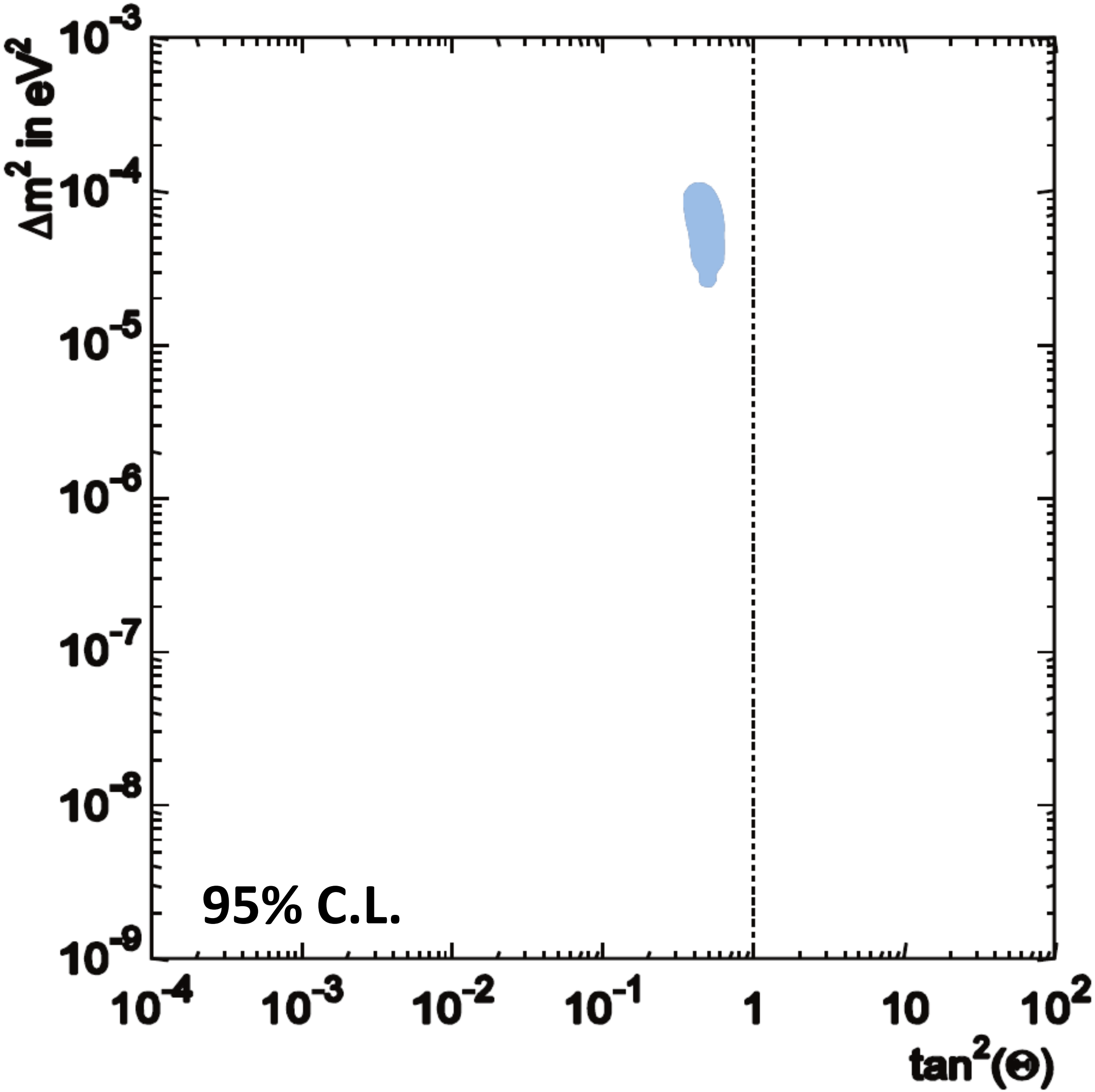
updates since our previous oscillation analysis (PRD78,032002(2008))

(Need to add SNO spectrum information.)

2-flavor SK-I/II/III with flux constraint

Preliminary

May 2010



Min $\chi^2 = 48.8$
$\Delta m^2 = 6.1 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.48$
$\Phi_{B8} = 0.89 \times \Phi_{B8,SSM}$

B8 rate is constrained by SNO(NCD+LETA) NC flux = (5.14+/-0.21) $10^6 cm^{-2}s^{-1}$

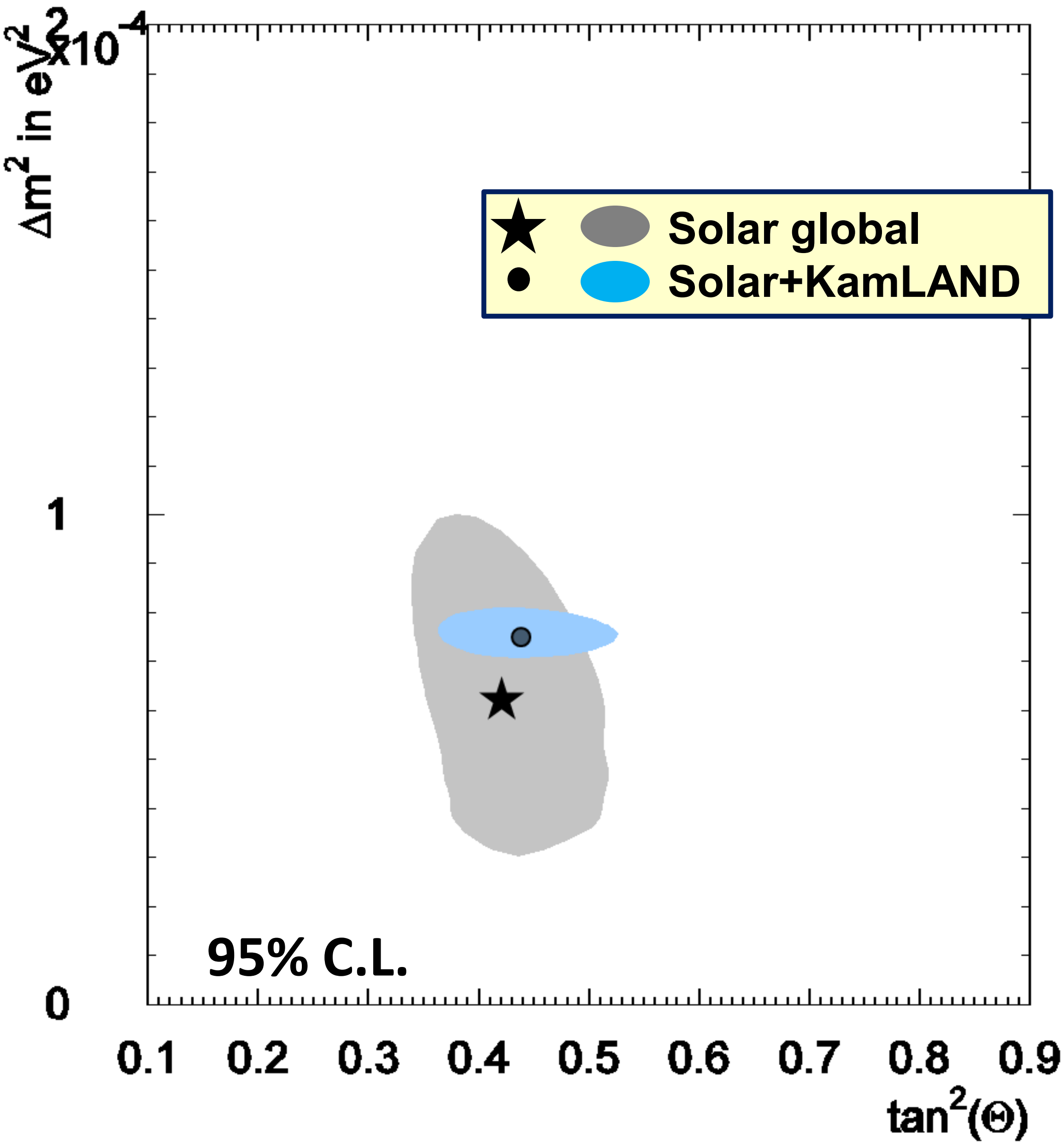
hep rate is constrained by SSM flux and uncertainty(16%).

Only LMA solution

2-flavor global analysis

Preliminary

May 2010



Solar global:

Min $\chi^2 = 53.7$
$\Delta m^2 = 6.2 \times 10^{-5}\ eV^2$
$\tan^2\theta = 0.42$
$\Phi_{B8} = 0.92 \times \Phi_{B8,SSM}$

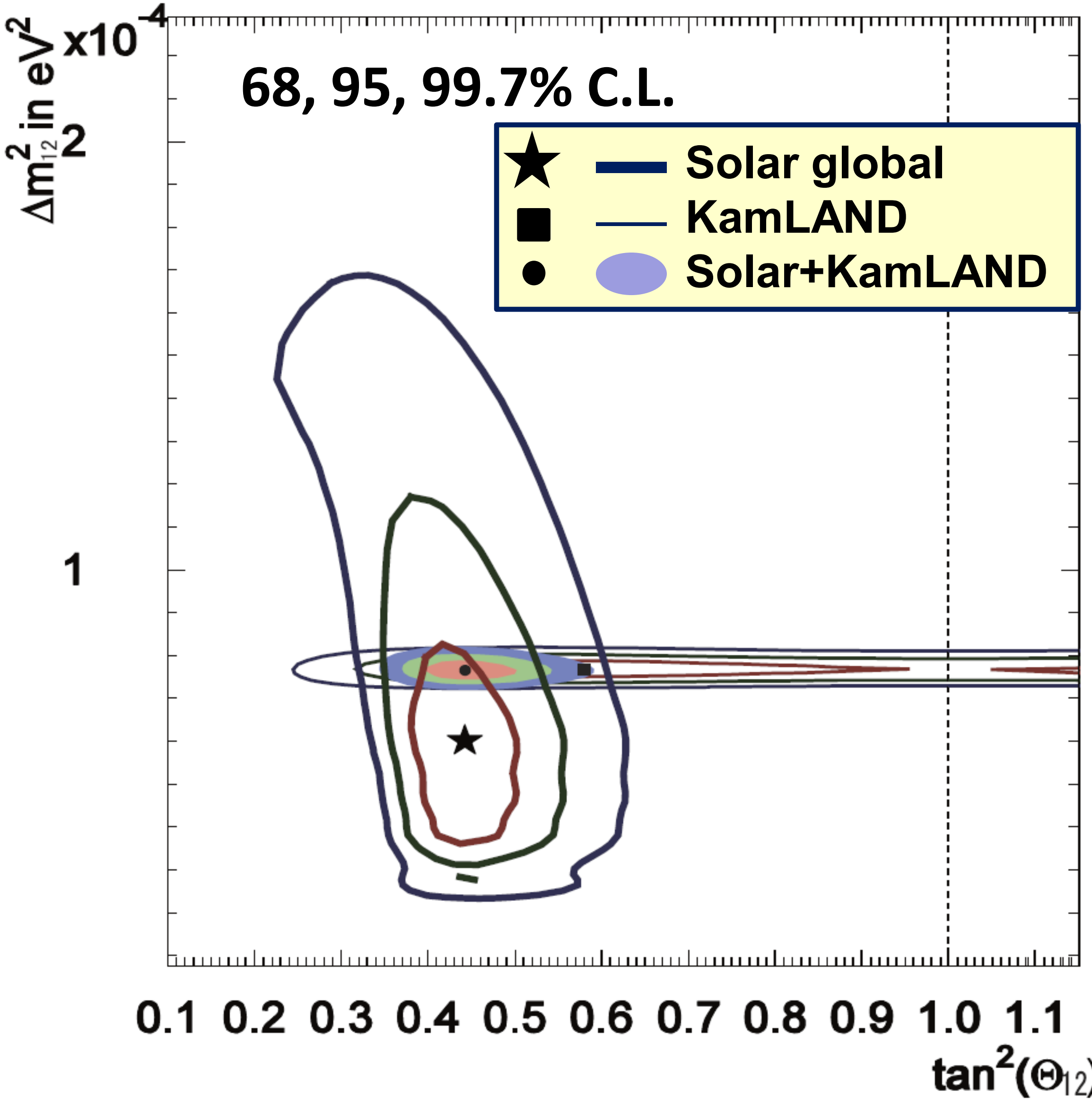
Solar global + KamLAND:

Min $\chi^2 = 57.7$
$\Delta m^2 = 7.6 \times 10^{-5}\ eV^2$
$\tan^2\theta = 0.44$
$\Phi_{B8} = 0.89 \times \Phi_{B8,SSM}$

3-flavor analysis: θ_{12} - Δm_{12}^2

Preliminary

May 2010



Solar global:

Min $\chi^2 = 52.8$
$\Delta m^2 = 6.0 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.44$
$\sin^2\theta_{13} = 0.010$
$\Phi_{B8} = 0.92 \times \Phi_{B8,SSM}$

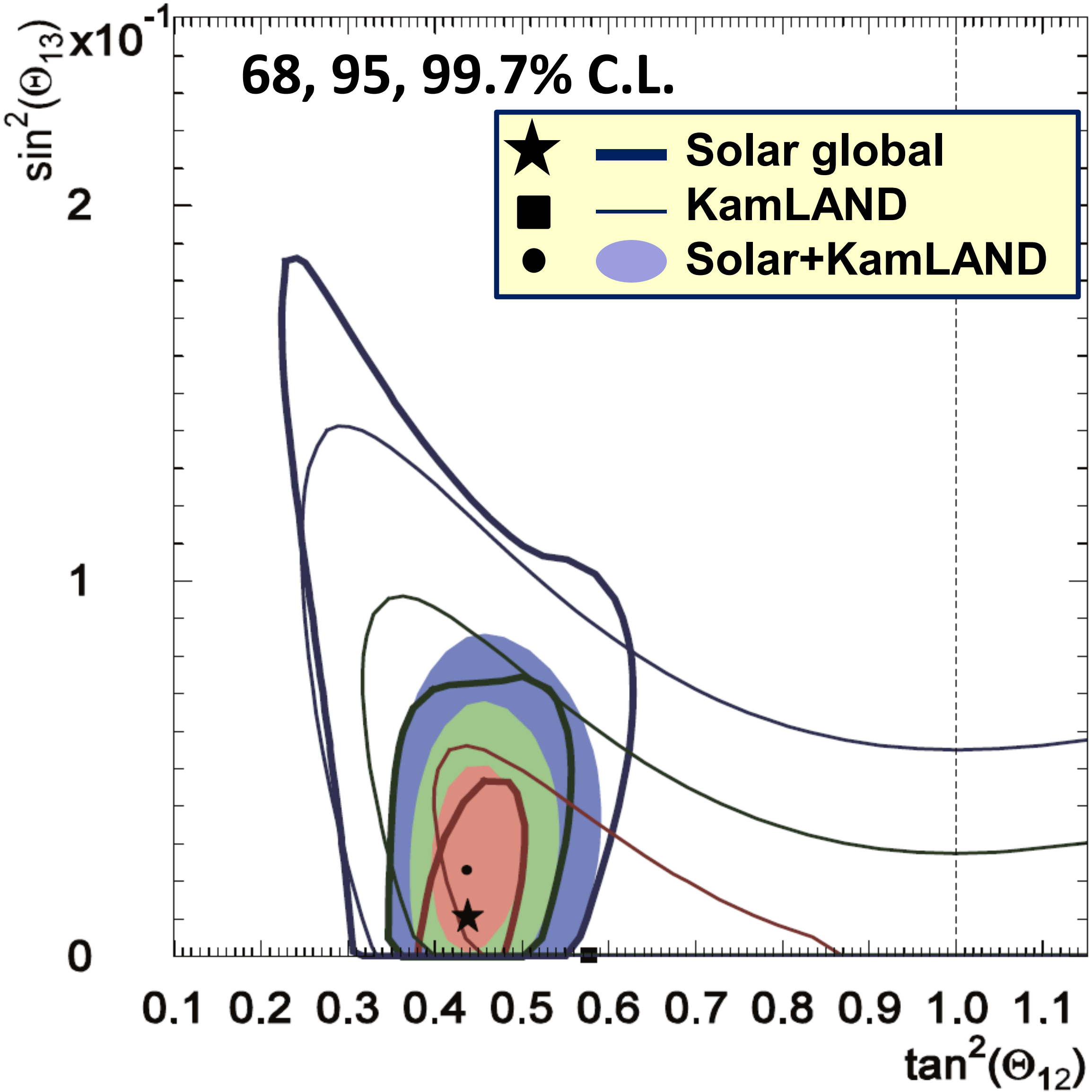
Solar global + KamLAND:

Min $\chi^2 = 71.2$
$\Delta m^2 = 7.7 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.44$
$\sin^2\theta_{13} = 0.025$
$\Phi_{B8} = 0.91 \times \Phi_{B8,SSM}$

3-flavor analysis: θ_{12} - θ_{13}

Preliminary

May 2010



Solar global:

$\sin^2\theta_{13} < 0.060$ @95%C.L.

Solar global + KamLAND:

$\sin^2\theta_{13} = 0.025^{+0.018}_{-0.016}$

(<0.059 @95%C.L.)

Cf. PRC81, 055504 (2010)

$\sin^2\theta_{13}$=0.020+0.021-0.016

(<0.057 @95%C.L.)

Poster-54 Byeongsu Yang

Summary

- SK-IV is running with the lowest energy threshold in SK.
  - 100% efficiency is at E_{total}~4.5MeV
- Full 3-flavor atmospheric ν oscillation results from SK-I,II,III data are released.
- A 3-flavor solar ν oscillation results from SK-I,II,III data are released.
- Some other new results are also available.
  - CPTv, NSI, p-decay, WIMP search, monopole search
- Some new results will be released in near future.
  - SRN analysis with SK-I,II,III, Tau analysis with SK-I,II,III
- R&D of GADZOOKS! is on going.
  - Budget for EGADS was approved.