Resent results of Super-Kamiokande

Yasuo Takeuchi
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- Super-Kamiokande detector
- Solar neutrino analysis in SK-IV
- Recent results

Inside of SK detector (April 2006)

The Super-Kamiokande Collaboration

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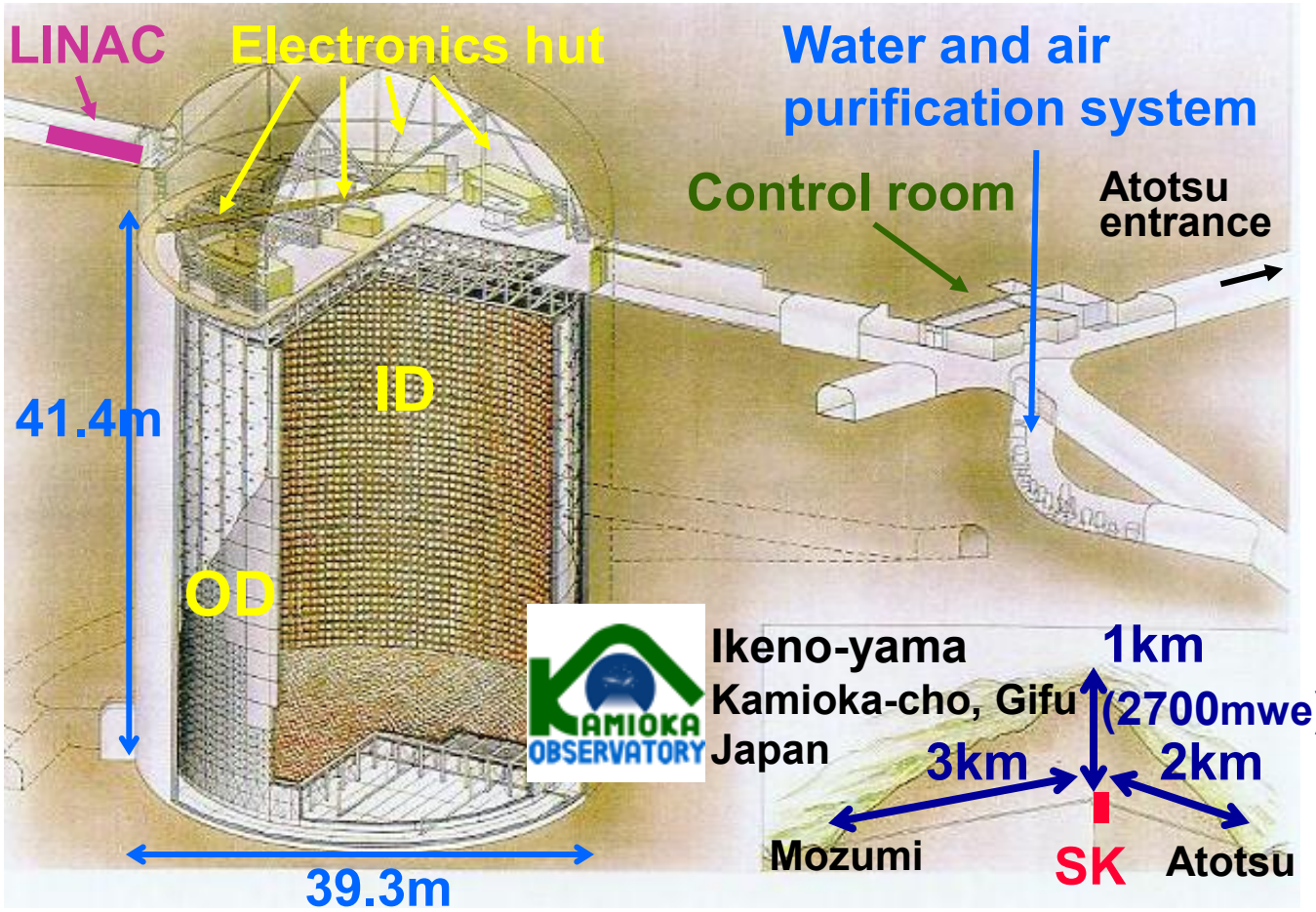
~110 collaborators
30 institutions, 6 countries

From PRD86, 012006 (2012)

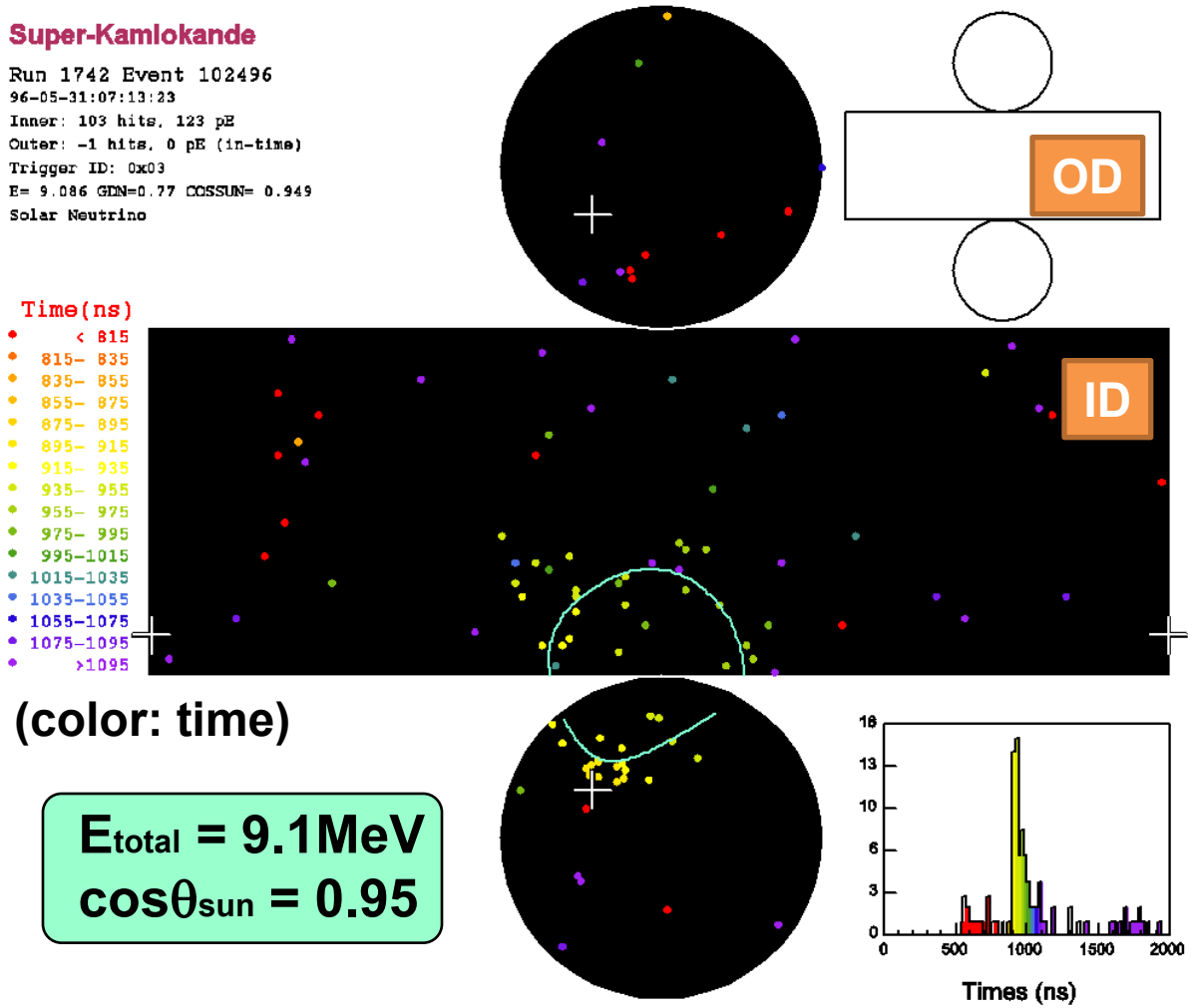
Super-Kamiokande detector



- 50kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-IV is running
- Trigger efficiency
  - >99%@4.0MeV$_{kin}$
  - ~86%@3.5MeV$_{kin}$

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

Typical low-energy event



E_{total} = 9.1MeV
$\cos\theta_{sun}$ = 0.95

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

Elastic scattering (ES) reaction is used for solar neutrinos

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

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

Resolutions (for E_{total}=10MeV electrons) (software improvement)

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

Solar neutrino analysis in SK-IV

Recent progresses

May 2012

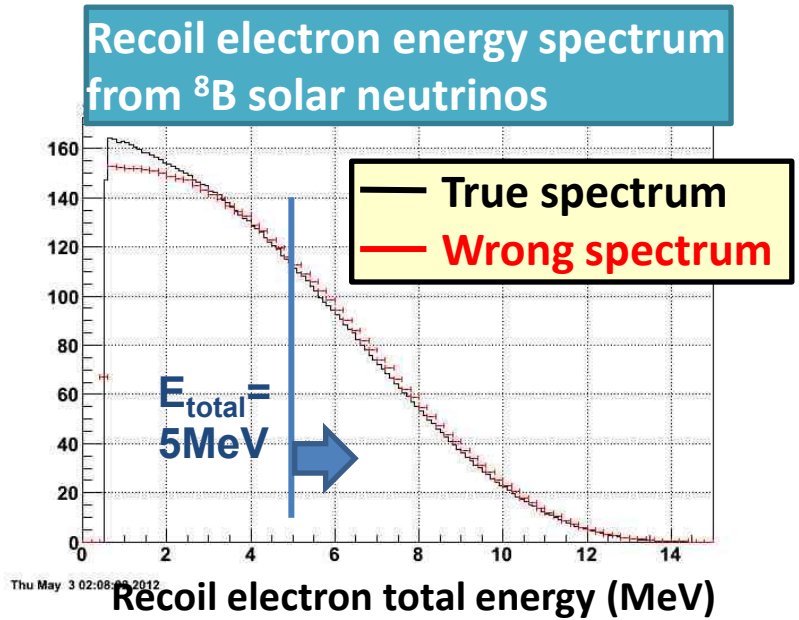
- Update live time:
  - 2008/10-2012/03 SK-IV 1069 days (cf. SK-I 1496 days)
- All the conventional event selection criteria are optimized in SK-IV
- Introduced a new event selection parameter
  - Multiple Scattering Goodness ⇦
- Systematic uncertainties are updated in SK-IV
- Obtained SK-IV initial preliminary results ⇦
- Carried out an oscillation analysis with SK-IV data ⇦
- Fixed a mistake in SK-III flux calculation ⇦
- Preparing a paper on SK-IV solar ν results

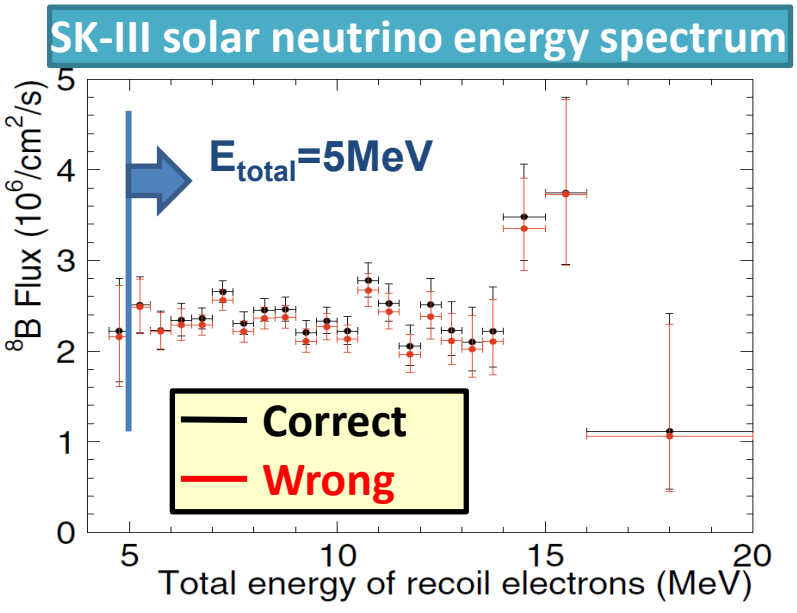
Mistake in SK-III flux calculation

May 2012

Preliminary

- The energy dependence in the ν-e differential cross section was accidentally eliminated only for the SK-III flux calculation in PRD83, 052010 (2011).
- The expected total flux was correct, but the ^{8}B energy spectrum shape was wrong.
- Fixing this problem changes SK-III ^{8}B flux value in ES reaction from (wrong) 2.32 to (correct) 2.40 [x10^6/cm^2/sec] in E_{total}=5.0-20MeV.
- This problem is fixed in this analysis. (We are preparing an errata.)





Multiple Scattering Goodness (MSG)

May 2012

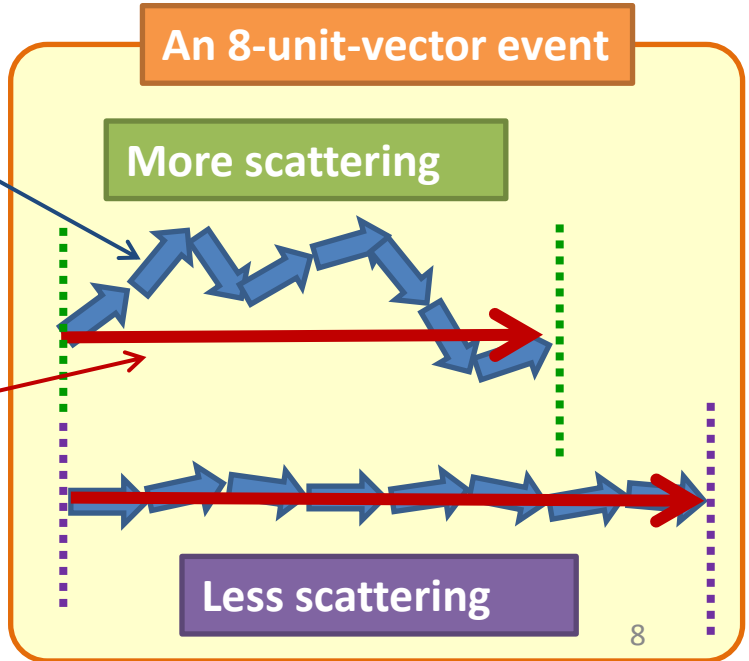
To reduce very low-energy background events (^{214}Bi, etc.)

- **Lower energy** electrons will incur **more multiple scattering** and will have more unit vectors pointing along different directions, giving a lower goodness
- **Higher energy** electrons will **scatter less** and will have unit vectors in better agreement, resulting in higher goodness
- Although the **^{214}Bi decay electrons** (majority of low-energy background) fluctuate up above 5.0 MeV in energy, they **truly have energy <3.27 MeV(total)** and should have more multiple scattering than true 5.0 MeV electrons, and therefore **a lower MSG**

"unit vectors" (reconstructed directions of an event, within 20ns hit PMTs, within 50° of this direction)

"best direction"
(longest vector sum of unit vectors)

$$\text{MSG} = \frac{\text{Length of best direction}}{\text{\# of unit vectors}}$$

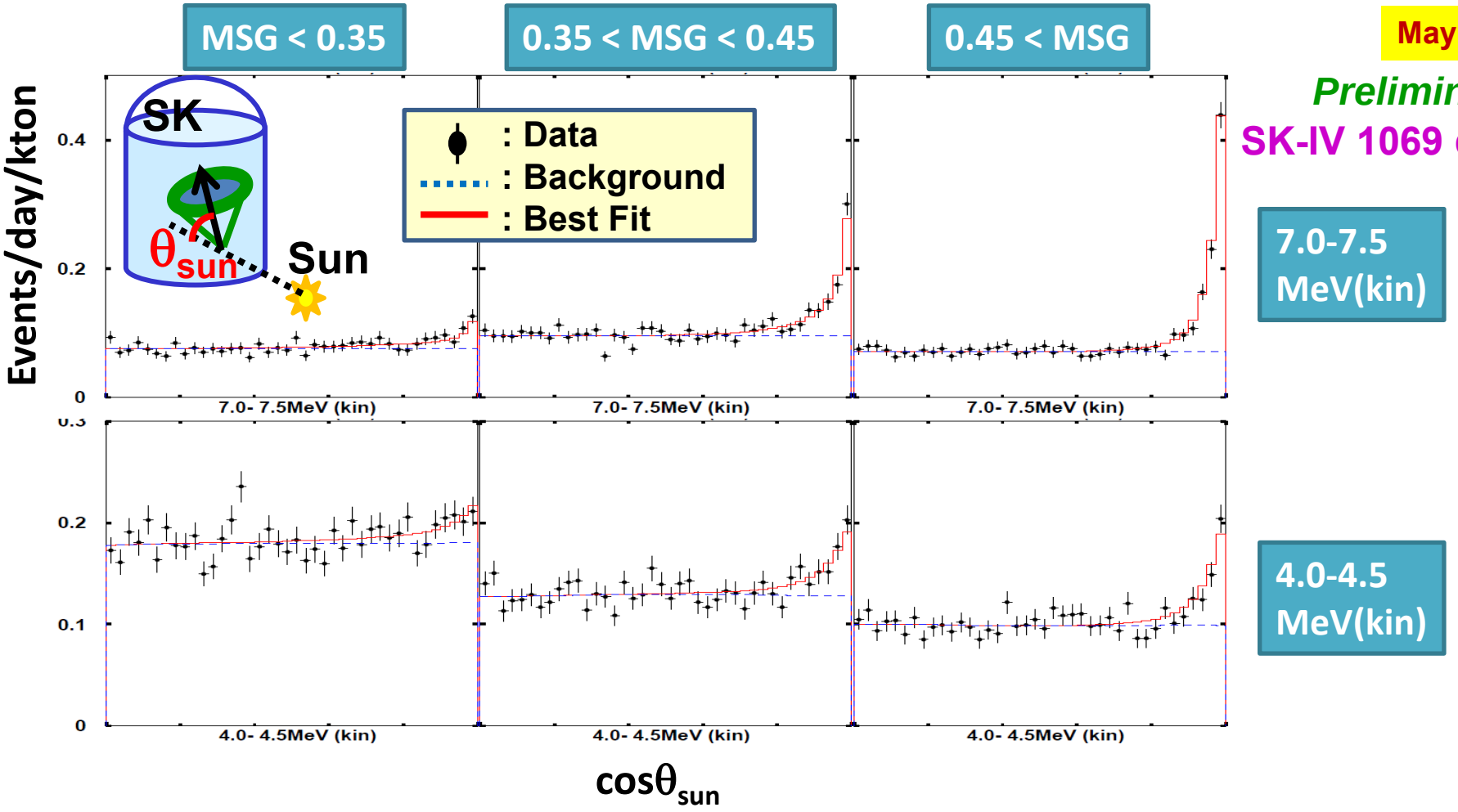


Solar angular distributions

May 2012

Preliminary

SK-IV 1069 days



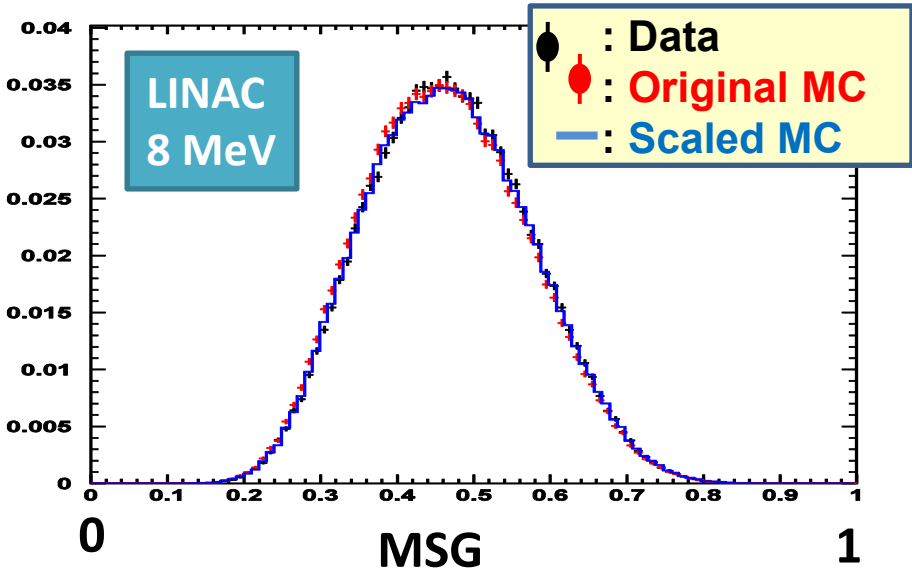
- Better signal-to-noise ratio in the higher MSG data set.
- Signal extraction with MSG is used below 7.5 MeV(kin) in SK-III and SK-IV in the energy spectrum analysis and the oscillation analysis.

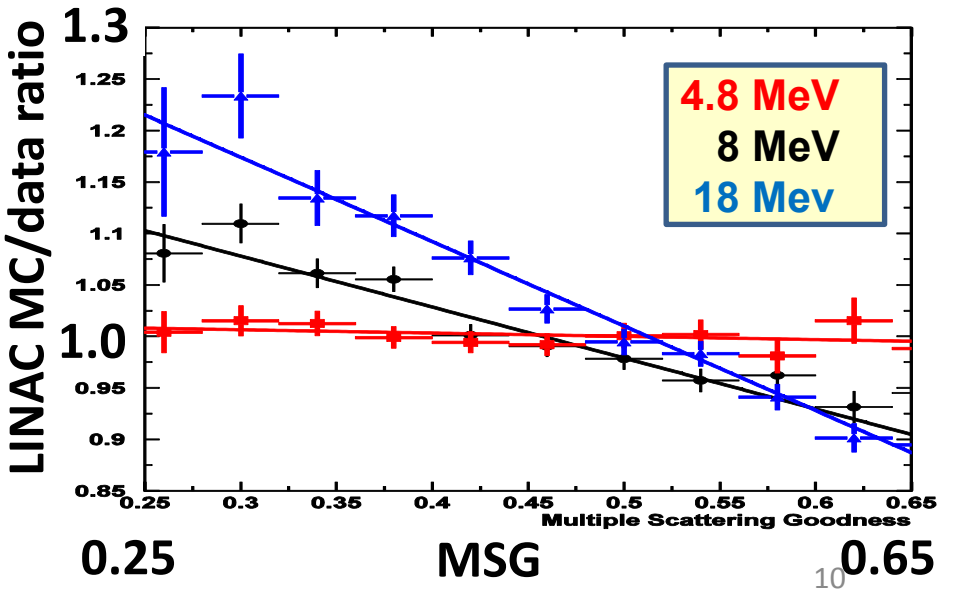
Systematic error from MSG

- The MSG distributions of data and MC simulation are compared using LINAC, then the difference is obtained as a scaling factor (LINAC MC/data ratio).
- The scaling factor is applied to solar neutrino MC in the solar signal extraction, then estimate possible flux value changes.

Preliminary

May 2012





Systematic errors from MSG in oscillation analysis

	3.5-4.0 MeV_{kin}	4.0-5.5 MeV_{kin}	5.5-7.5 MeV_{kin}
SK-III		0.3%	1.7%
SK-IV	0.4%	0.3%	1.7%

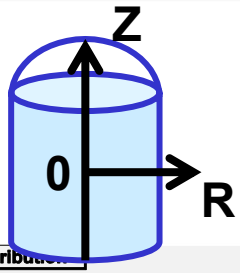
Tight fiducial volume cut in SK-IV

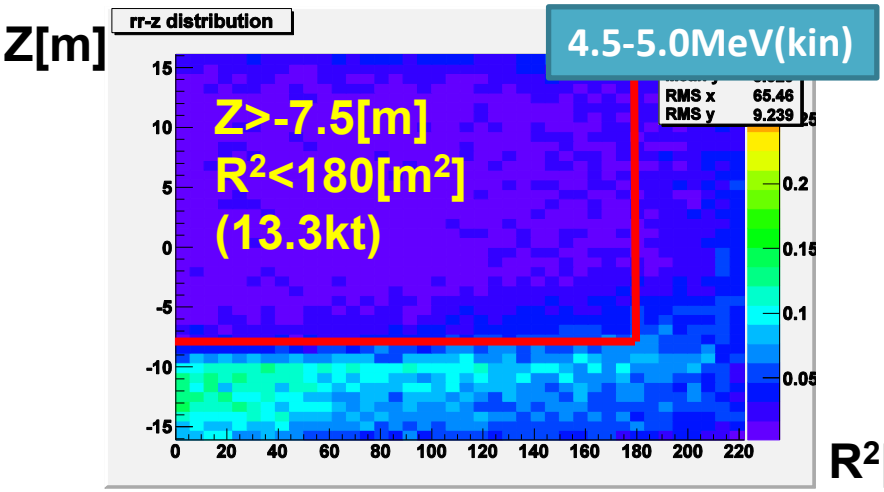
May 2012

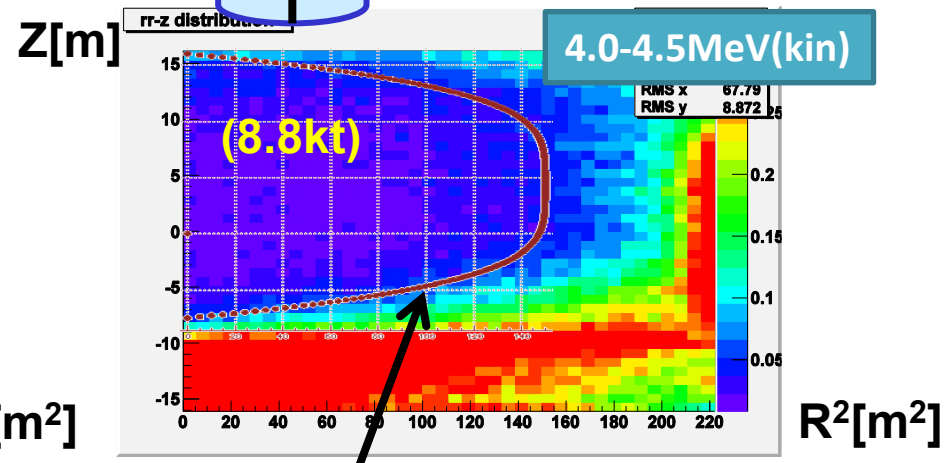
Preliminary

SK-IV 1069 days

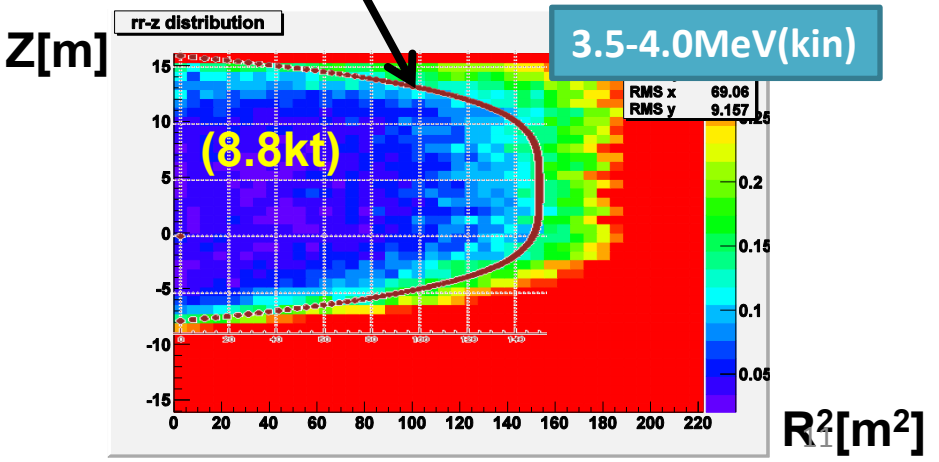
Color : Events/day/bin low→high







R+(150/11.75⁴)*|Z-4.25|⁴<150

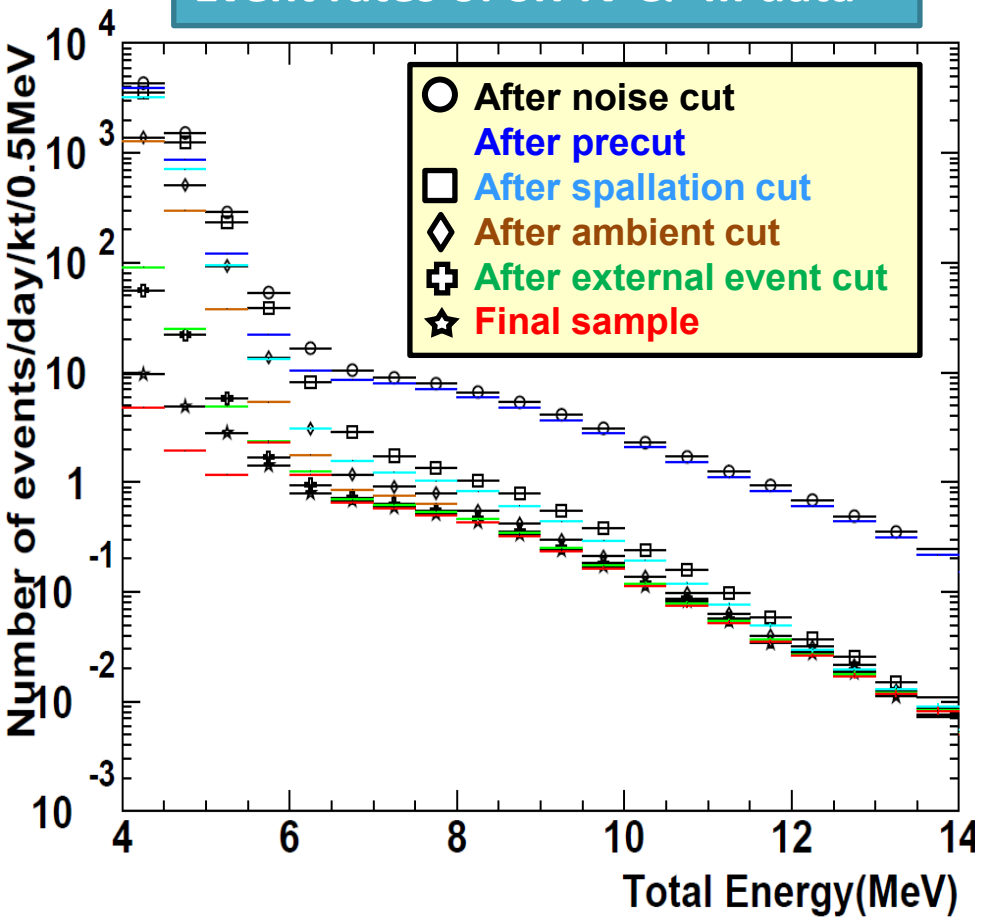


- Whole area in these plots corresponds to 22.5kton
- Above 5.0MeV(kin), fiducial volume is 22.5kton
- Below 5.0 MeV(kin), tight fid. vol. cut is applied to reduce events from detector wall.

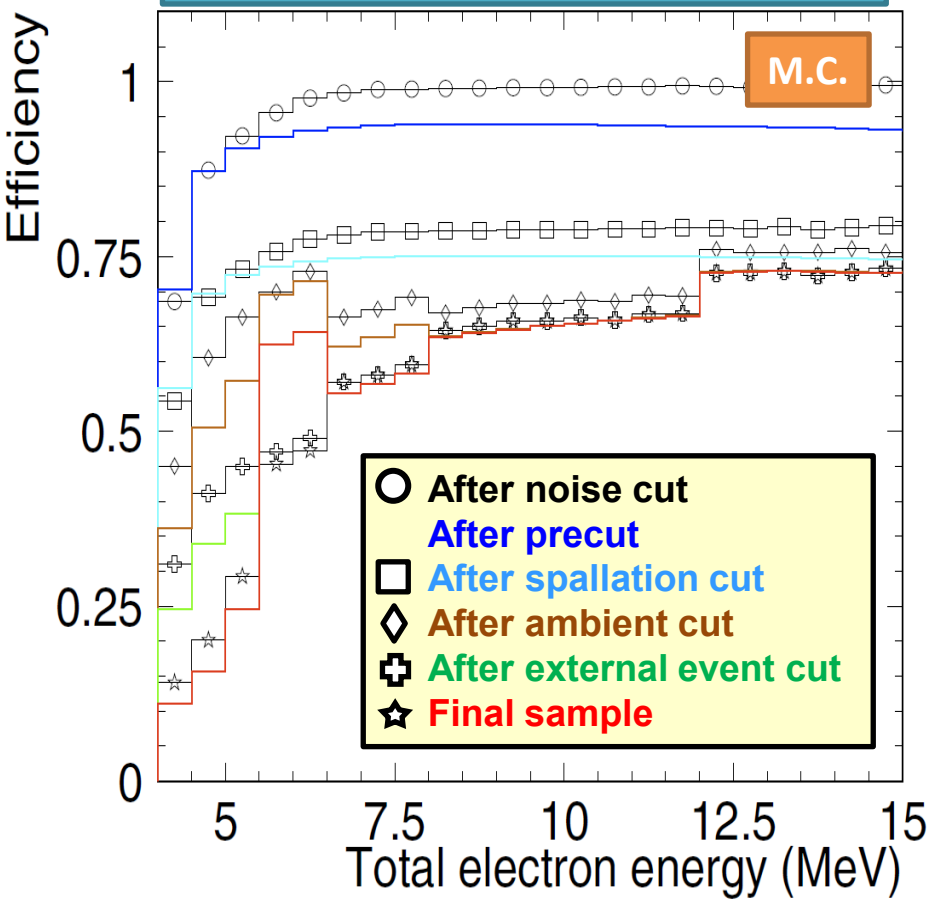
Data reduction in SK-IV & -III

SK-IV (color) SK-III (B&W) SK-IV 1069 days *Preliminary* May 2012

Event rates of SK-IV & -III data



Reduction efficiency in 22.5kt



Reduction steps are similar as SK-III, but selection criteria are optimized for SK-IV.

Systematic uncertainties on ^{8}B flux

May 2012

Source	SK-IV Flux (4.0-19.5MeV(kin)) *Preliminary*	SK-III Flux (4.5-19.5MeV(kin)) (PRD83, 052010)	SK-I Flux (4.5-19.5MeV(kin)) (PRD73,112001)
Energy Scale	±1.2%	±1.4%	±1.6%
Energy resolution	±0.15%	±0.2%	
8B spectrum	±0.33%	±0.2%	+1.1/-1.0%
Trigger efficiency	±0.1%	±0.5%	+0.4/-0.3%
Vertex shift	±0.17%	±0.54%	±1.3%
Reduction	±0.6%	±0.9%	+2.1/-1.6%
Spallation dead time	±0.1%	±0.2%	±0.2%
Background shape	±0.1%	±0.1%	±0.1%
Angular resolution	±0.36%	±0.67%	±1.2%
Signal extract method	±0.7%	±0.7%	
Cross section	±0.5%	±0.5%	±0.5%
Total	**±1.7%**	**±2.1%**	**+3.5/-3.2%**

The total systematic error on total flux in SK-IV is reduced by front-end electronics upgrade, precise calibrations, and software improvements

Recent solar neutrino results

- See also following reports:
  - M. Smy, “Results from Super-Kamiokande” @NEUTRINO2012
  - Y. Koshio, “Solar neutrino results from Super-Kamiokande” @ICHEP2012
  - H. Sekiya, “Super-Kamiokande low-energy results” @NOW2012

SK-IV solar neutrino flux

May 2012

Preliminary

- Total live time : 1069.3 days (2008/10-2012/03)
- Energy region for flux: $E_{kinetic}$ = 4.0 – 19.5 MeV
- Winter06 ^{8}B spectrum is used.
- ^{8}B Flux in ES reaction, without ν oscillation:
  - SK-IV: 2.34+/-0.03(stat.)+/-0.04(syst.) [x10^6/cm^2/s]
  - SK-I: 2.38+/-0.02(stat.)+/-0.08(syst.) 4.5 – 19.5 MeV(kin)
  - SK-II: 2.41+/-0.05(stat.)+0.16/-0.15(syst.) 6.5 – 19.5 MeV(kin)
  - SK-III: 2.40+/-0.04(stat.)+/-0.05(syst.) 4.5 – 19.5 MeV(kin)

    (SK-I,II are recalculated with the Winter06 ^{8}B spectrum.)

    (The problem in SK-III is fixed.)

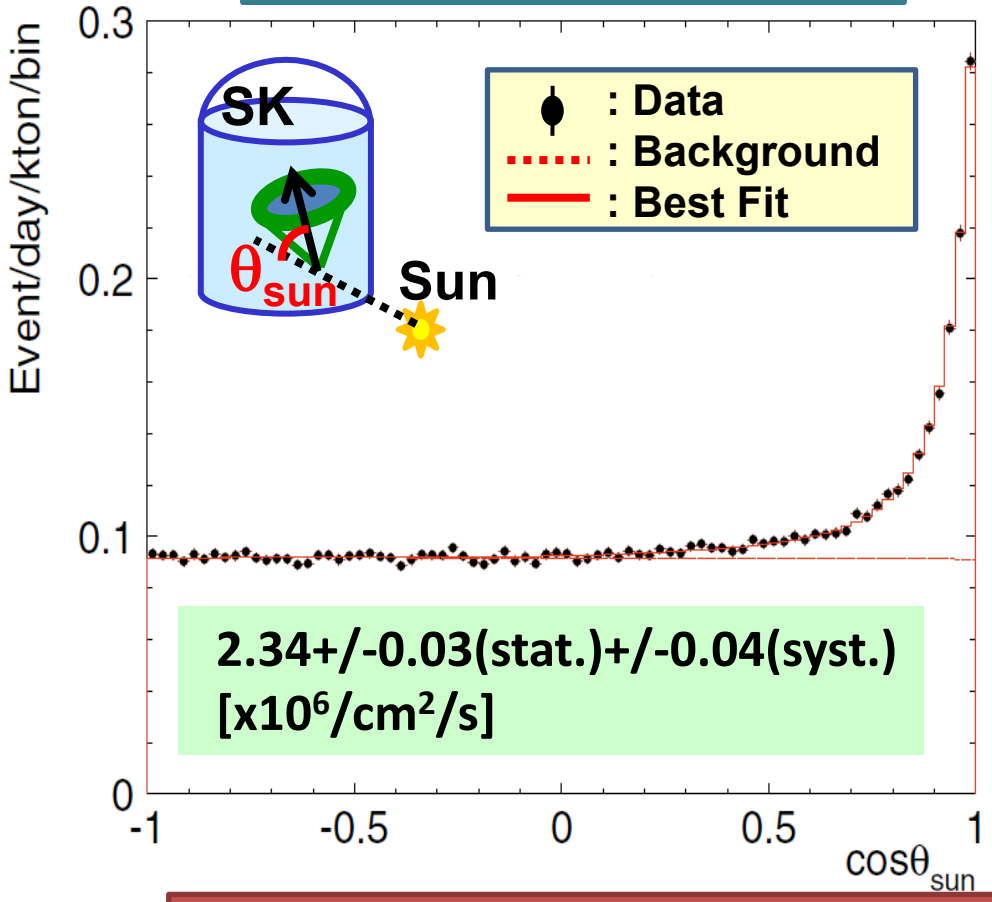
SK-I: PRD73, 112001
SK-II: PRD78, 032002
SK-III: PRD83, 052010

- 3.5-4.0MeV(kin) in SK-IV is used for oscillation analysis.
  - Energy threshold is lowest in SK-IV

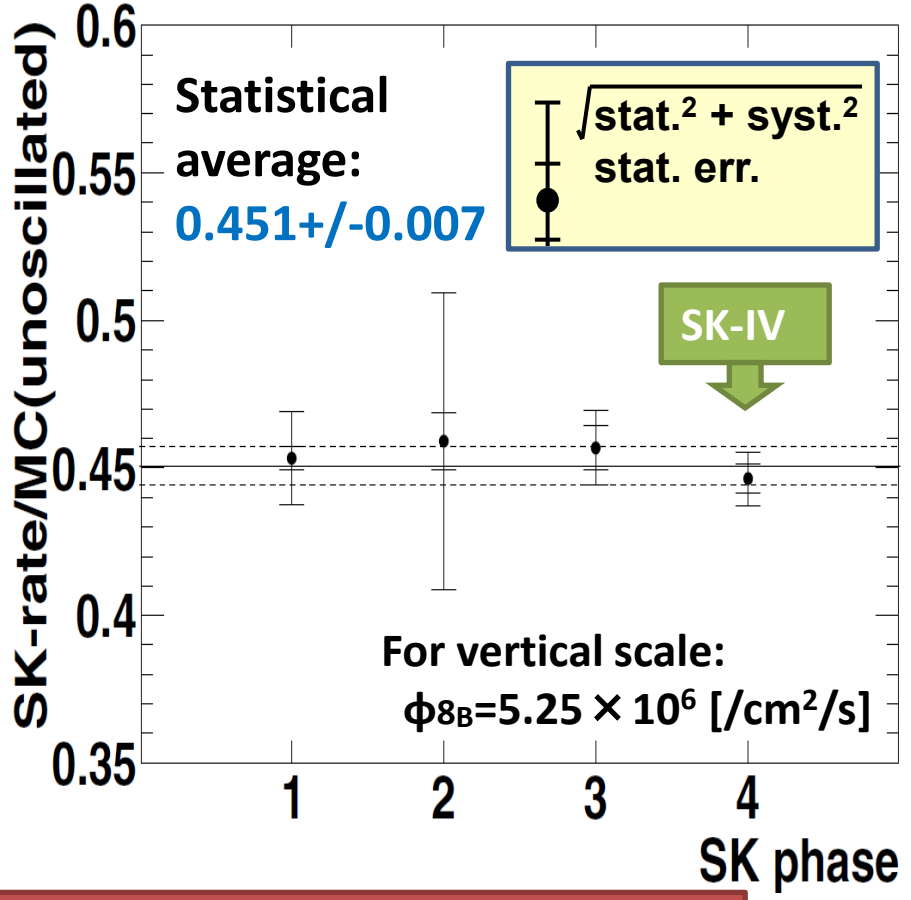
SK-IV solar neutrino flux

Preliminary May 2012

SK-IV 4.0-19.5MeV(kin)



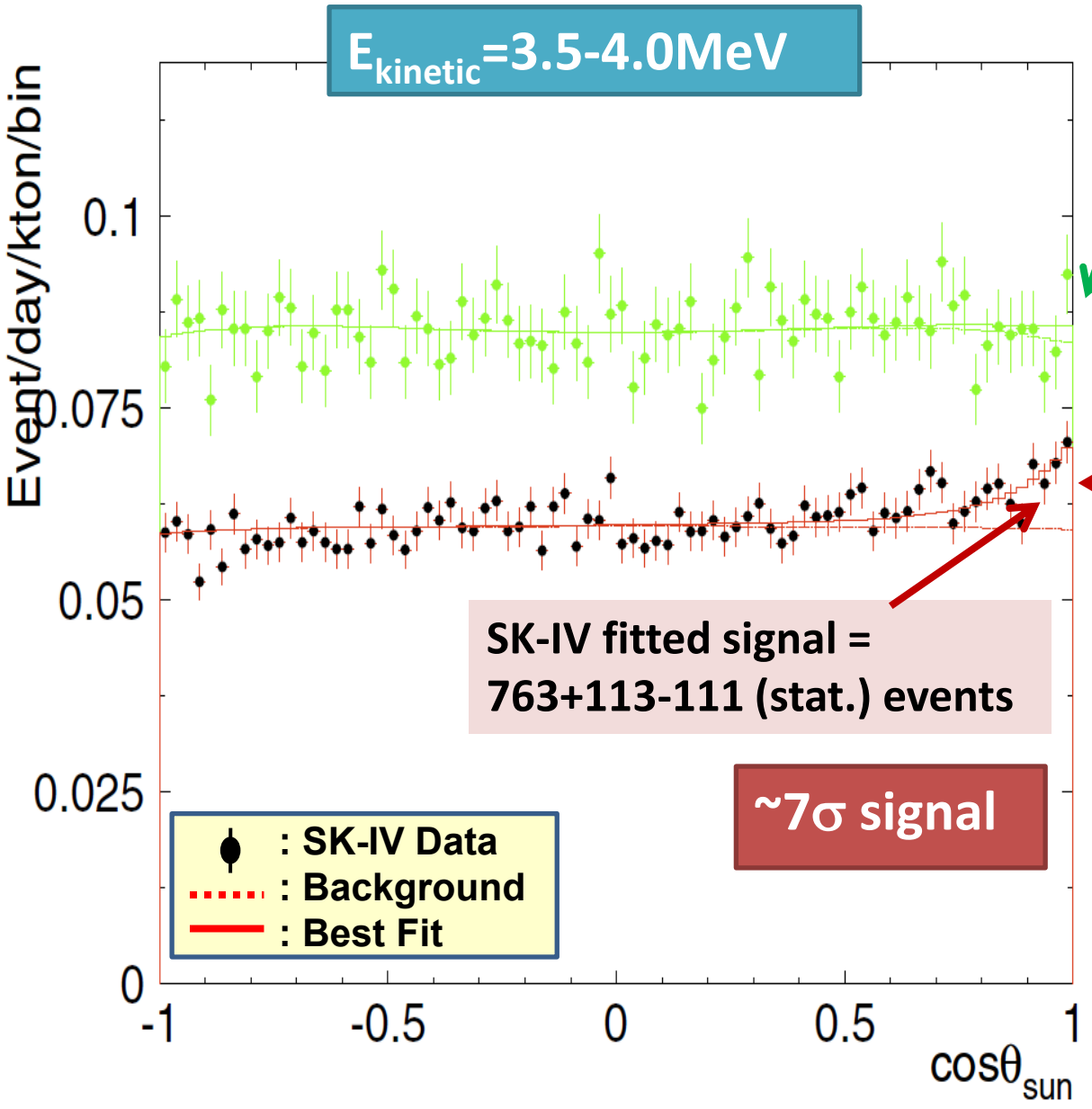
^{8}B Flux in each SK phase



- Consistent flux values within statistical error are observed among SK phases

SK-IV: low-energy solar signal

Preliminary May 2012



SK-III SLE1+2 298days

Trigger efficiency
SLE1 (212 days)
>99%@4.5MeV$_{kin}$
SLE2 (87 days)
>98%@4.0MeV$_{kin}$

SK-IV 1069days

Trigger efficiency
>99%@4.0MeV$_{kin}$
~86%@3.5MeV$_{kin}$

We are planning to lower the energy threshold more by a new intelligent trigger system (hardware is ready in Dec. 2012)

Data set for oscillation analysis

May 2012

- SK
  - SK-I 1496 days, spectrum 4.5-19.5MeV(kin) + D/N : E ≥ 4.5MeV(kin)
  - SK-II 791 days, spectrum 6.5-19.5MeV(kin) + D/N : E ≥ 7.0MeV(kin)
  - SK-III 548 days, spectrum 4.0-19.5MeV(kin) + D/N : E ≥ 4.5MeV(kin)
  - SK-IV 1069 days, spectrum 3.5-19.5MeV(kin) + D/N : E ≥ 4.5MeV(kin)
- SNO : SNO combined (arXiv:1109.0763) (NC flux = (5.25+/-0.20) $10^6 cm^{-2} s^{-1}$)
- Radiochemical : Cl, Ga
  - Ga rate: 66.1+/-3.1 SNU (All Ga global) (PRC80, 015807(2009))
  - Cl rate: 2.56+/-0.23 SNU (Astrophys. J. 496 (1998) 505)
- Borexino : PRL107, 141302 (2011)
- KamLAND : PRL 100, 221803 (2008)
- ^{8}B spectrum : Winter (2006)

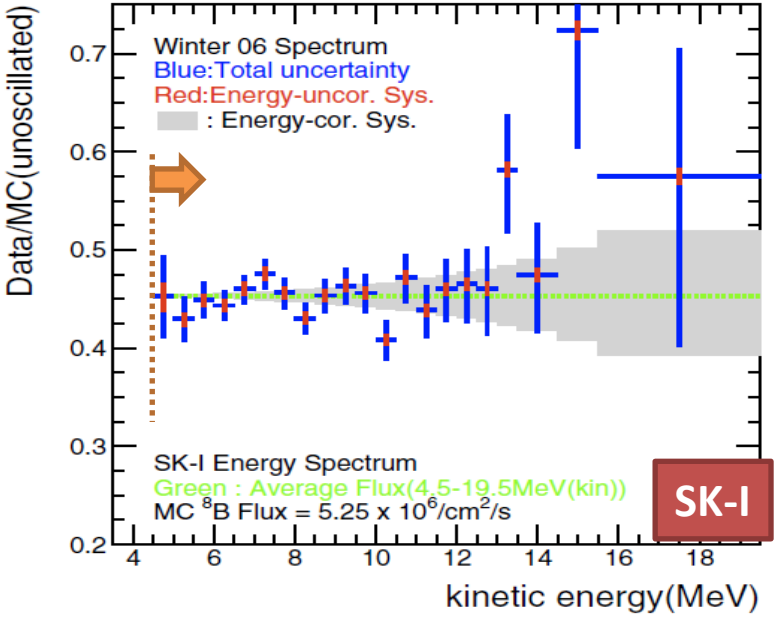
- ^{8}B and *hep* flux free, if not mentioned.

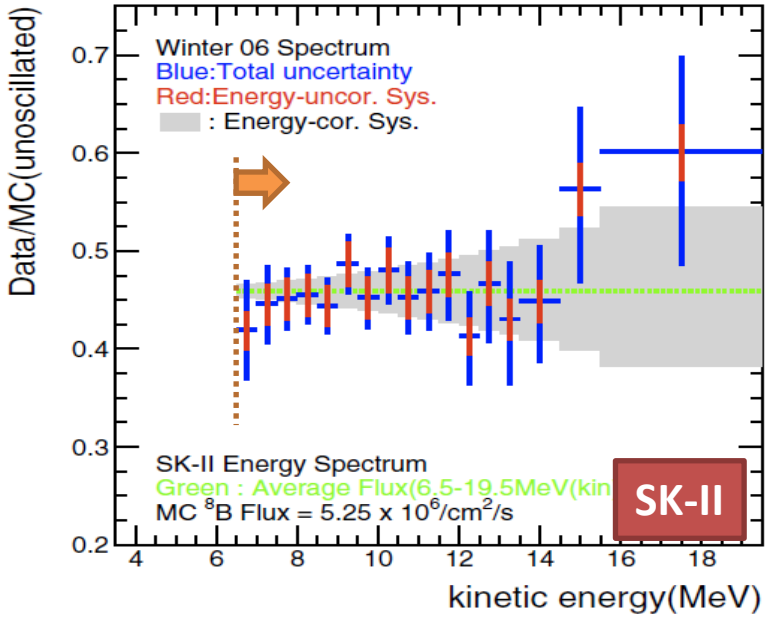
updates since our previous oscillation analysis (PRD83, 052010 (2011))

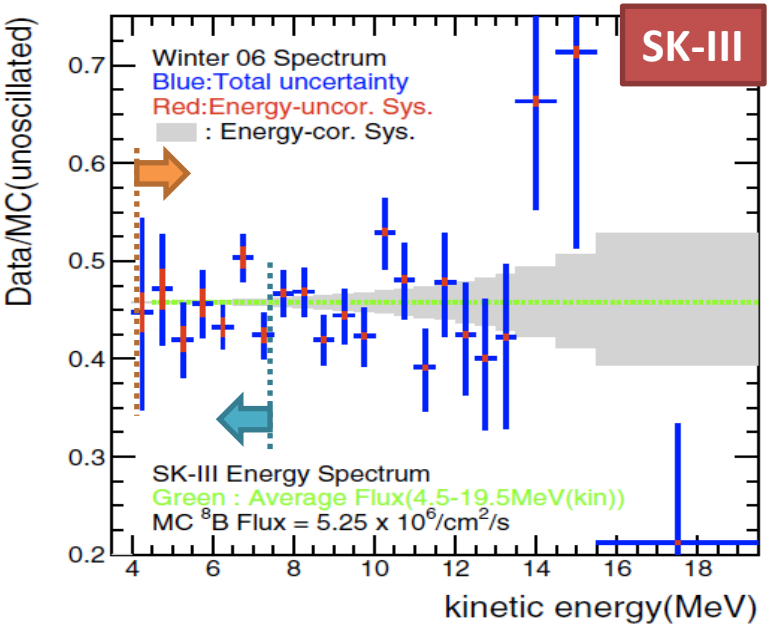
^{8}B energy spectrum

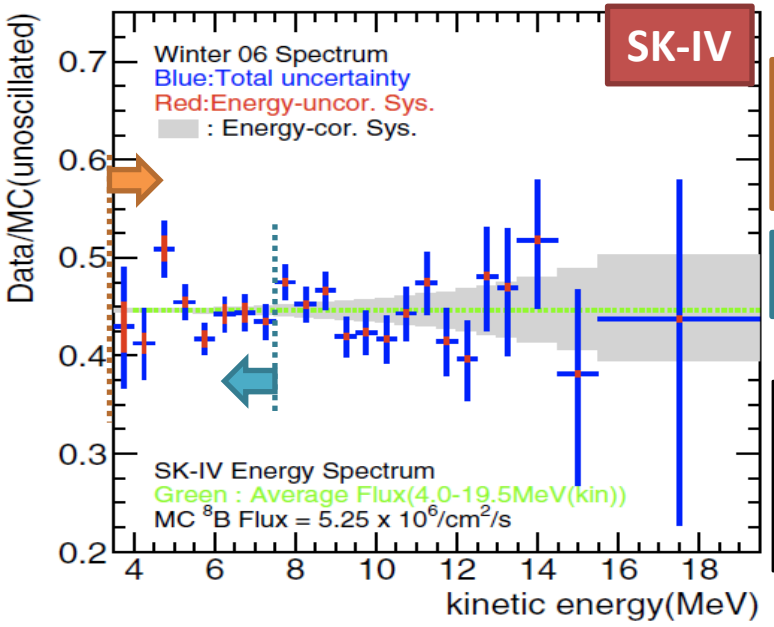
May 2012

Preliminary









Used in osc. analysis

MSG applied

For vertical scale:
$\phi_{^8B}$=5.25 × 10^6 [/cm^2/s]

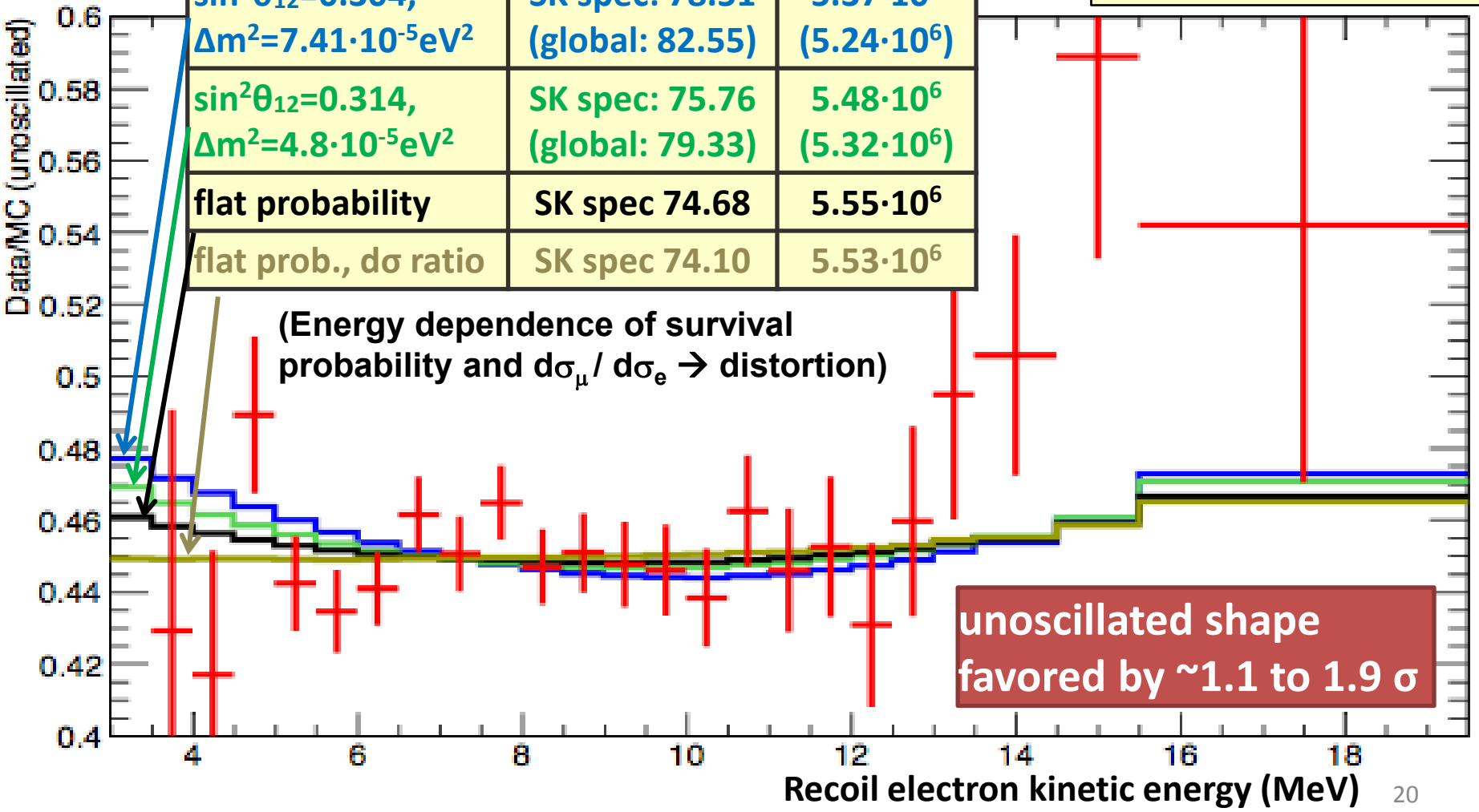
^{8}B energy spectrum (SK combined)

- $\sin^2\theta_{13}$ is fixed at 0.025
- *hep* flux is constrained to 7.88 (1+/-0.16) [$\times 10^3$ /cm^2/s]

Preliminary May 2012

For vertical scale:
$\phi_{8B}=5.25 \times 10^6$
$\phi_{hep}=7.88 \times 10^3$ [/cm^2/s]

	χ^2	ϕ^8_B [/cm^2/s]
$\sin^2\theta_{12}=0.304$, $\Delta m^2=7.41\cdot10^{-5}$eV^2	SK spec: 78.51 (global: 82.55)	$5.37\cdot10^6$ ($5.24\cdot10^6$)
$\sin^2\theta_{12}=0.314$, $\Delta m^2=4.8\cdot10^{-5}$eV^2	SK spec: 75.76 (global: 79.33)	$5.48\cdot10^6$ ($5.32\cdot10^6$)
flat probability	SK spec 74.68	$5.55\cdot10^6$
flat prob., dσ ratio	SK spec 74.10	$5.53\cdot10^6$

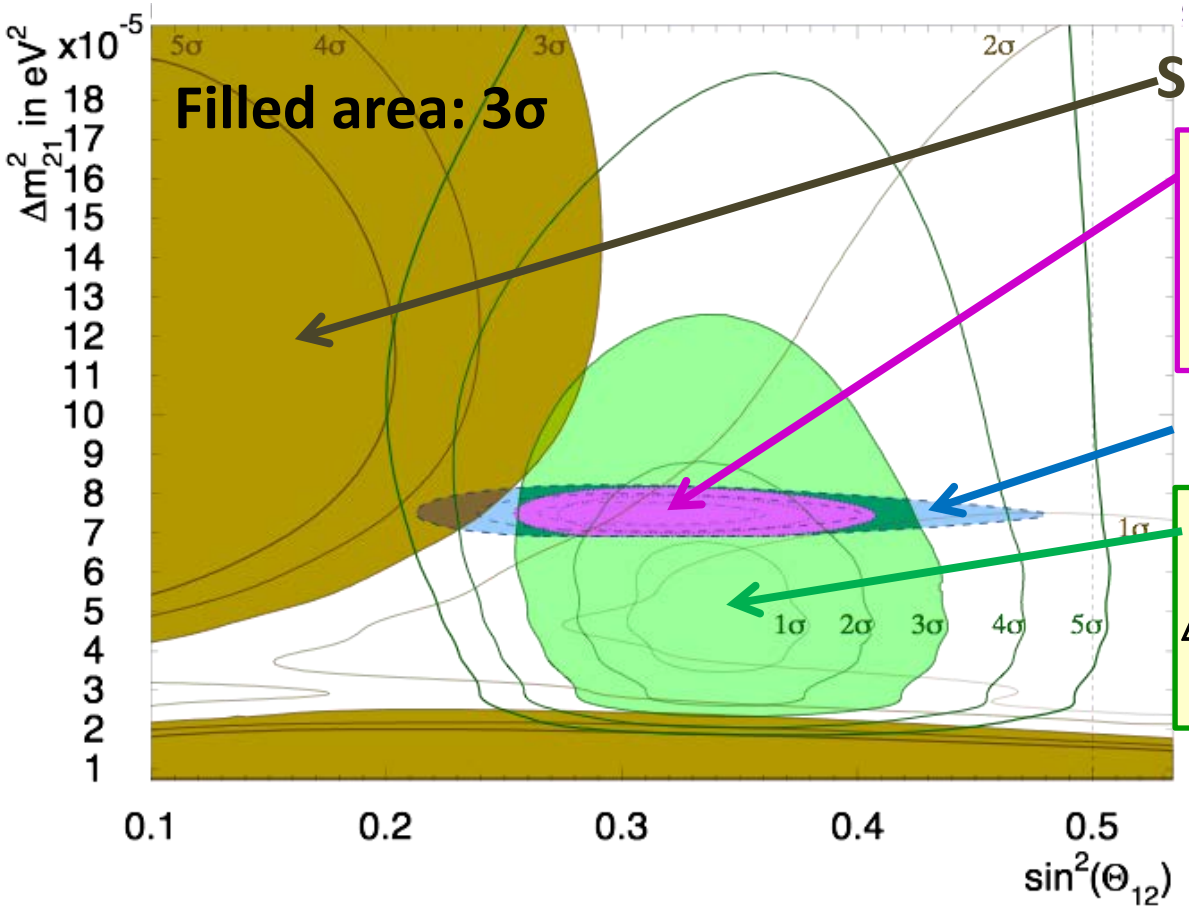


SK combined : θ_{12} - Δm_{21}^2

May 2012

Preliminary

- $\sin^2\theta_{13}$ is fixed at 0.025
- ^{8}B flux is constrained to 5.25+/-0.20 [$\times 10^6$ /cm^2/s] in the flux constrained analysis.



SK only, flux unconstrained

SK + KamLAND:

$\Delta m^2 = (7.5+/-0.2)\ [\times 10^{-5}\text{eV}^2]$

$\sin^2\theta_{12} = 0.322^{+0.024}_{-0.020}$

KamLAND only:

SK only, flux constrained:

$\Delta m^2 = (4.7^{+1.8}_{-0.8})\ [\times 10^{-5}\text{eV}^2]$

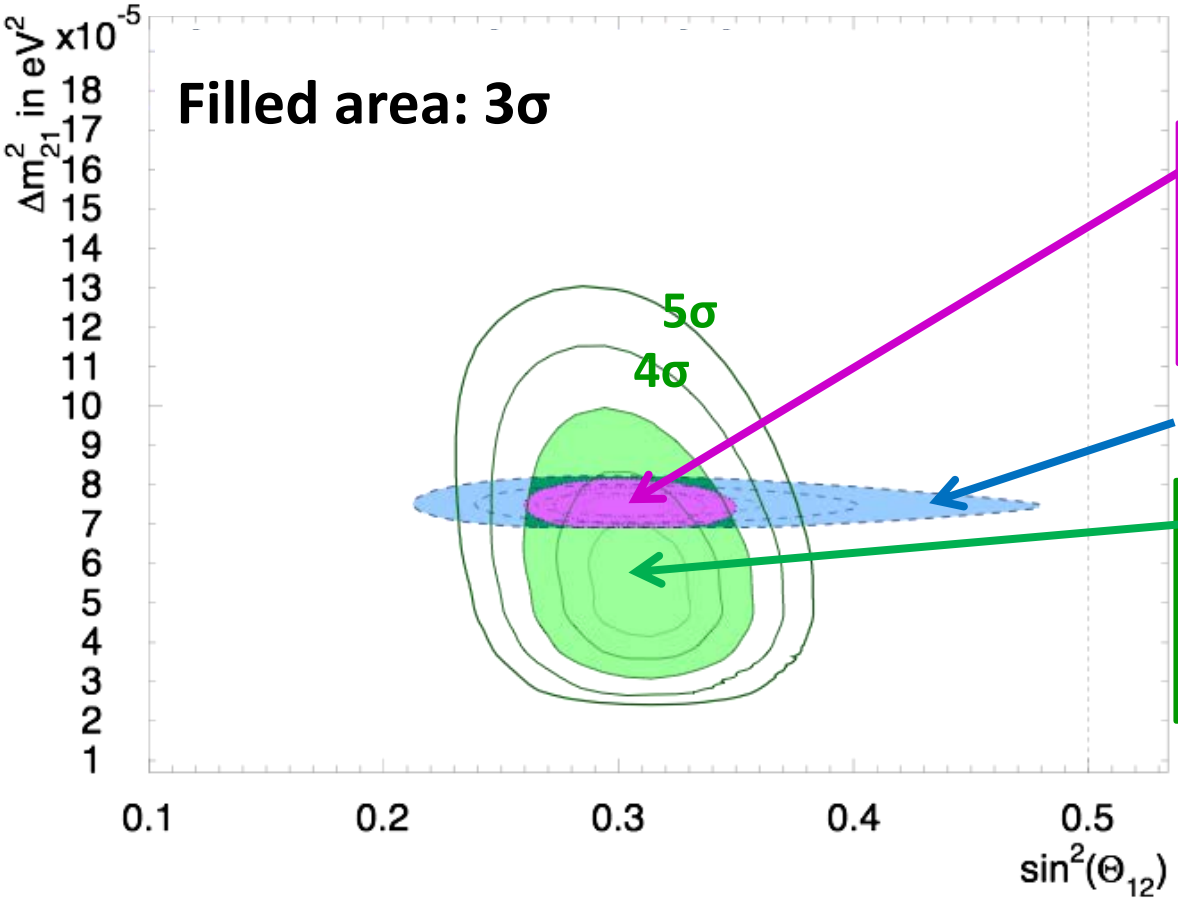
$\sin^2\theta_{12} = 0.339^{+0.028}_{-0.024}$

Solar global : θ_{12} - Δm_{21}^2

May 2012

Preliminary

- $\sin^2\theta_{13}$ is fixed at 0.025



Solar global + KamLAND:

$\Delta m^2 = (7.4+/-0.2)\ [\times 10^{-5}eV^2]$

$\sin^2\theta_{12} = 0.304+/-0.013$

KamLAND only:

Solar global:

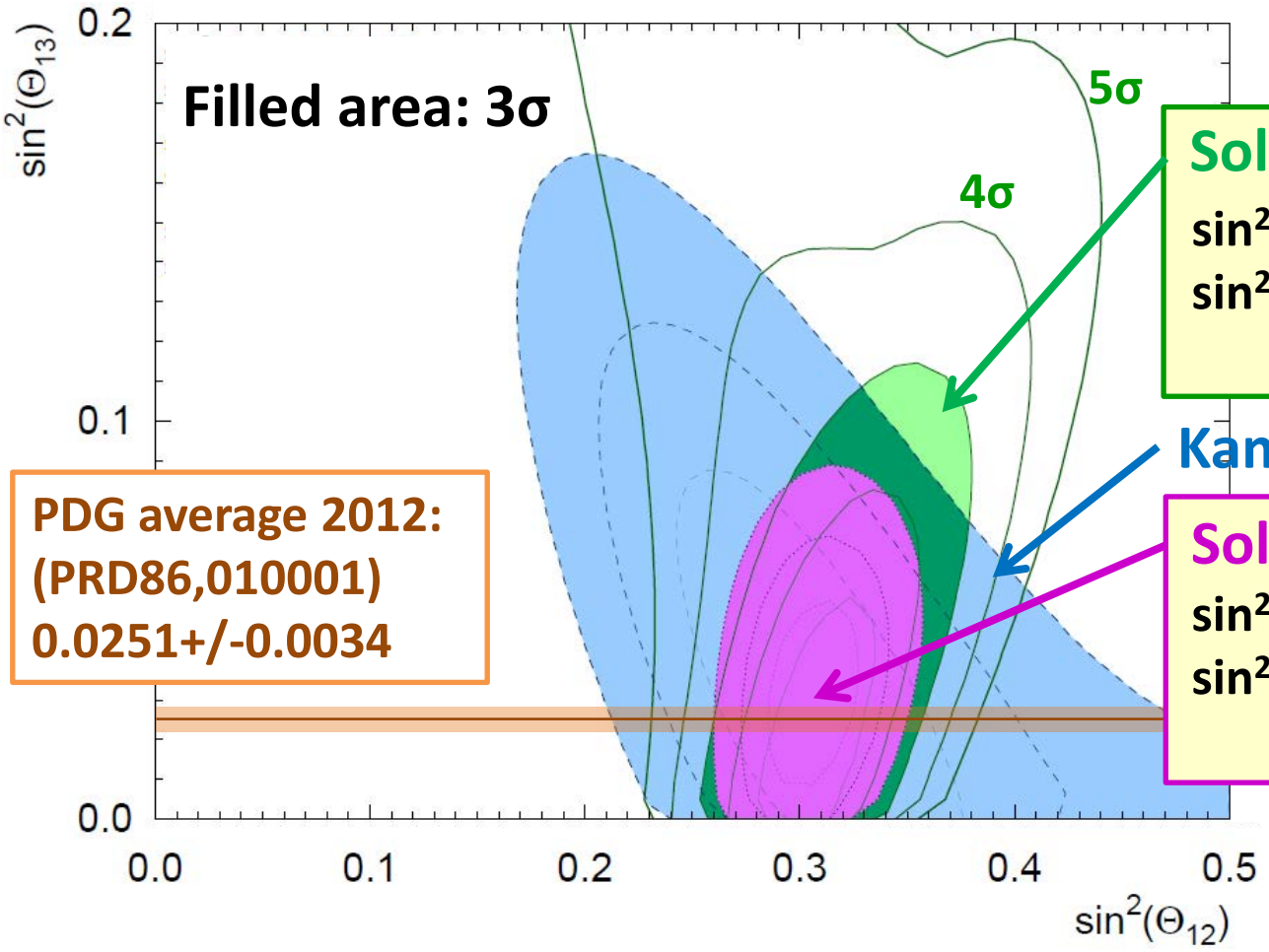
$\Delta m^2 = (4.9+1.4/-0.5)\ [\times 10^{-5}eV^2]$

$\sin^2\theta_{12} = 0.310+0.014-0.015$

Solar & KamLAND : θ_{12} - θ_{13}

May 2012

Preliminary



Solar global:

$\sin^2\theta_{12}$ = 0.305+0.021-0.016

$\sin^2\theta_{13}$ = 0.014+0.027-0.021

< 0.059 (95% C.L.)

KamLAND only:

Solar global + KamLAND:

$\sin^2\theta_{12}$ = 0.305+0.015-0.014

$\sin^2\theta_{13}$ = 0.030+0.017-0.015

< 0.058 (95% C.L.)

PDG average 2012:
(PRD86,010001)
0.0251+/-0.0034

■ **Consistent with PDG average (=reactor experiments)**

Day-Night variation

Preliminary May 2012

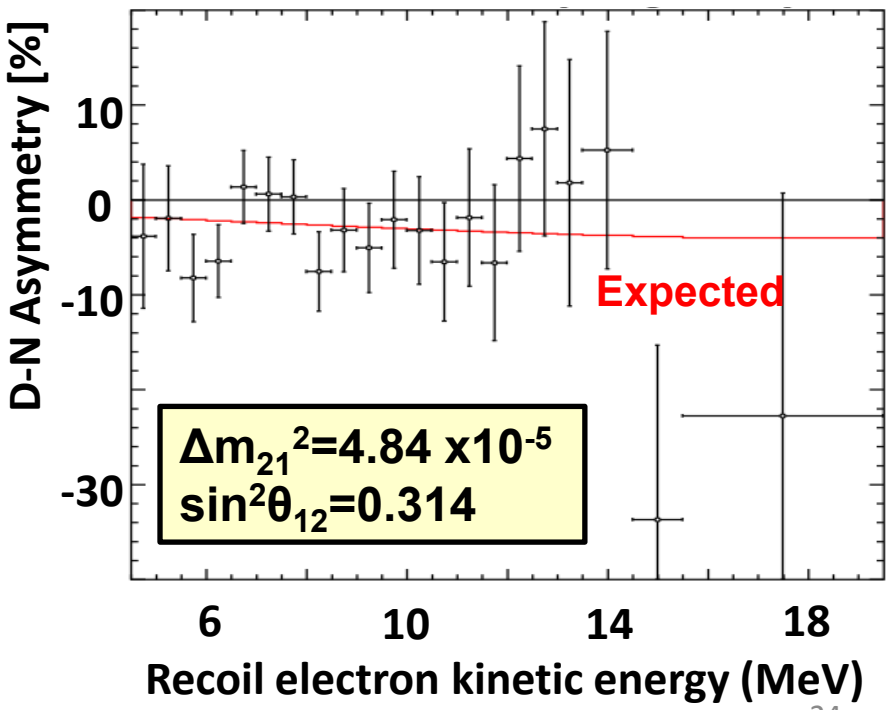
- Un-binned Day-Night analysis (PRD69, 011104) is applied in each SK phase, then obtained Day-Night asymmetry values (=A_{DN}) from fitted Day-Night amplitude parameter.
  - Consider energy and zenith angle dependence of event rate variation.

$$A_{DN} = \frac{\text{Day flux} - \text{Night flux}}{0.5\,(\text{Day flux} + \text{Night flux})}$$

	A_{DN} (±stat.±sys.)
SK-I	-2.0±1.7±1.0 %
SK-II	-4.3±3.8±1.0 %
SK-III	-4.3±2.7±0.7 %
SK-IV	-2.8±1.9±0.7 %
SK combined	-2.8±1.1±0.5 %

Day-Night asymmetry consistent with zero @ 2.3 σ

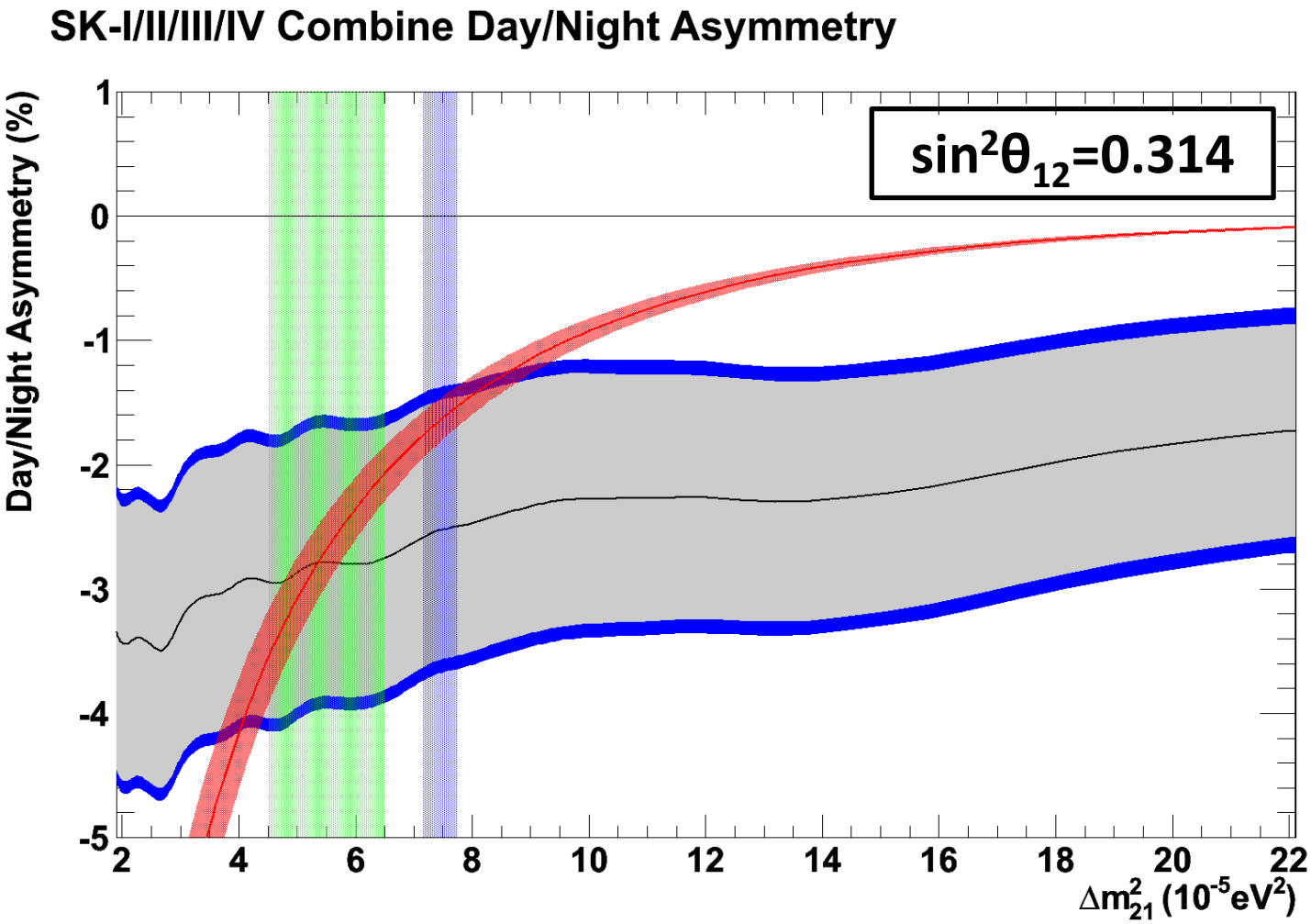
SK combined D-N asymmetry values



Day/Night amplitude fits as a function of Δm^2

May 2012

Preliminary



Best Fit

1σ Stat.

1σ Stat. + Sys.

Expected

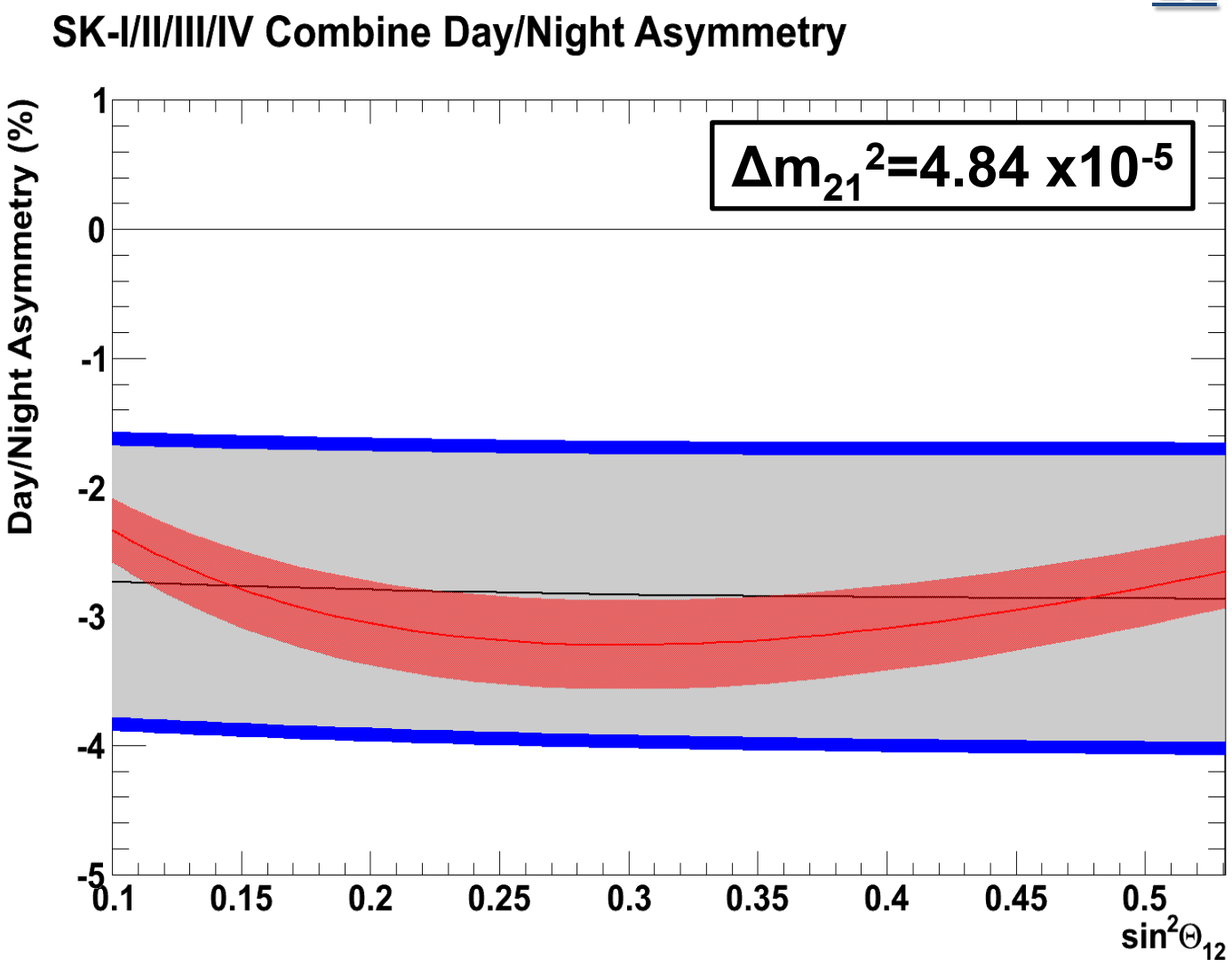
1σ Kamland

1σ Solar

Day/Night amplitude fits as a function of $\sin^2\theta_{12}$

May 2012

Preliminary



Best Fit

1σ Stat.

1σ Stat. + Sys.

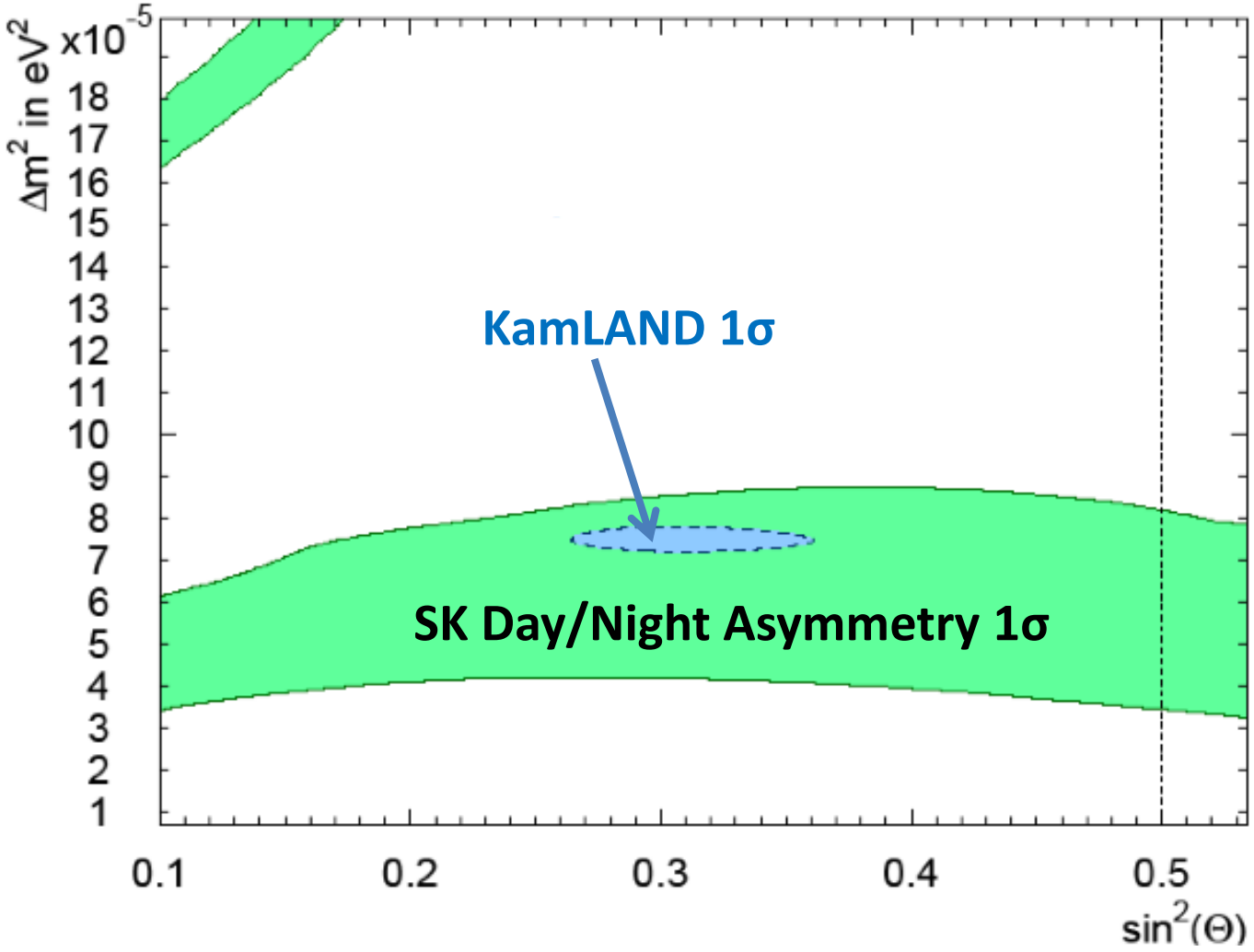
Expected

Only SK Day/Night : θ_{12} - Δm_{21}^2

May 2012

Preliminary

- $\sin^2\theta_{13}$ is fixed at 0.025



Summary

- SK-IV is running with the lowest energy threshold in SK
  - Trigger efficiency: >99%@4.0MeV(kin), ~86%@3.5MeV(kin)
  - The energy threshold will be lowered in near future.
- The initial results from SK-IV are obtained in May 2012.
  - Observed ^{8}B fluxes are consistent among SK phases
  - ~7 sigma signal in 3.5-4.0MeV(kin) region
  - Performed an oscillation analysis with SK-IV data *Preliminary*

Solar global:
$\Delta m^2 = (4.9+1.4/-0.5)\ [\times 10^{-5} eV^2]$
$\sin^2\theta_{12} = 0.310+0.014-0.015$

Solar global + KamLAND:
$\Delta m^2 = (7.4+/-0.2)\ [\times 10^{-5} eV^2]$
$\sin^2\theta_{12} = 0.304+/-0.013$

  - Possible spectrum distortion: 1.1 sigma to 1.9 sigma
  - Day-Night asymmetry: consistent with zero at 2.3 sigma
  - Δm_{21}^2 : some tension between solar global and KamLAND