Low energy observation with Super-K; **Solar neutrino measurement in Super-Kamiokande III**

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29 Warsaw University, Poland
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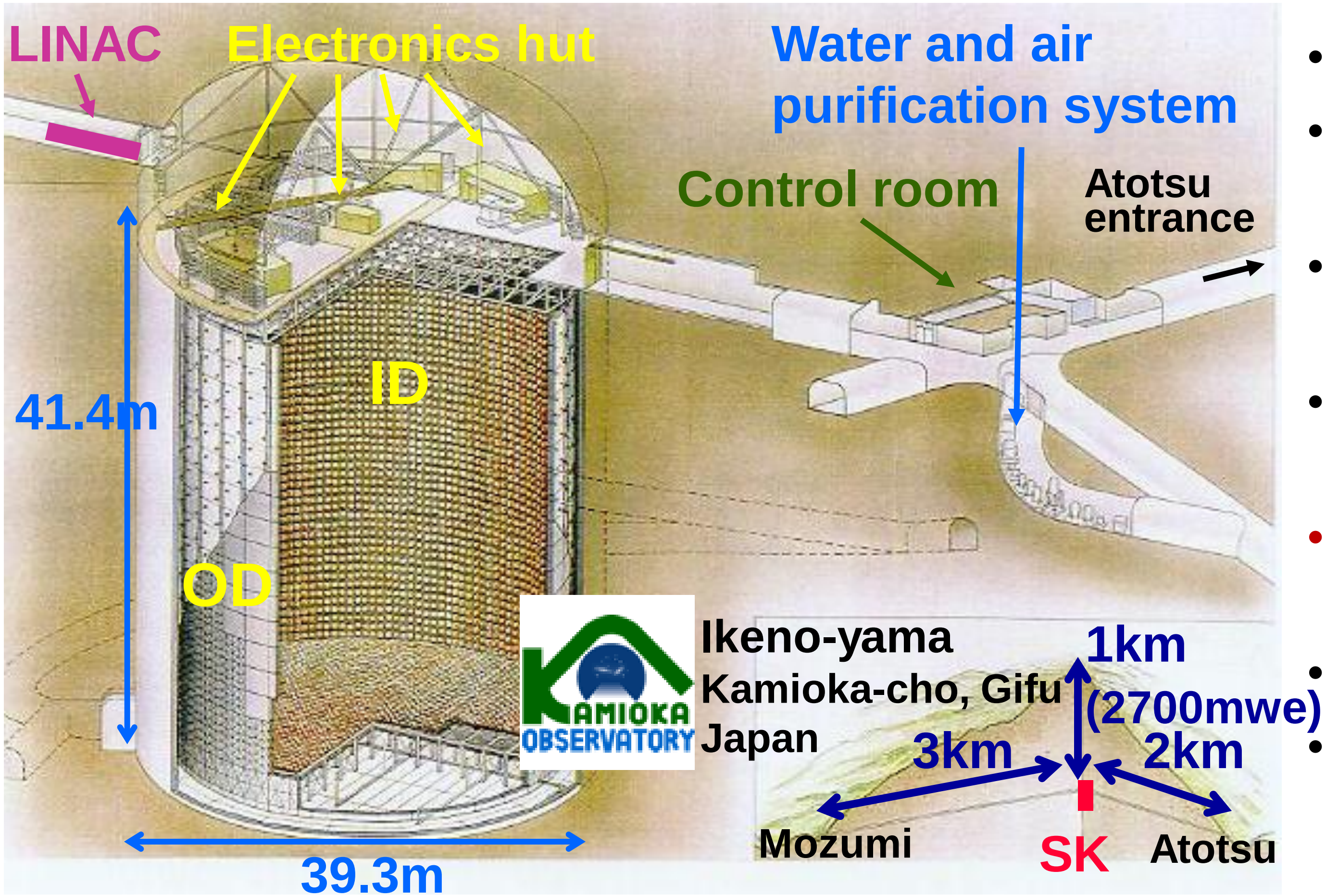
~120 collaborators

31 institutions, 6 countries

From PRD81, 092004 (2010)

Super-Kamiokande detector



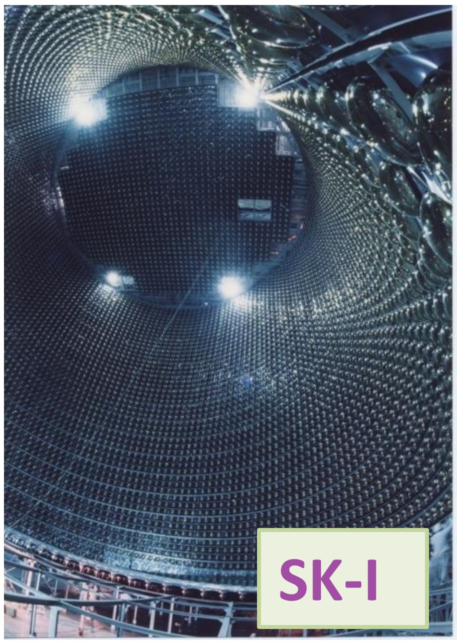
- 50kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- ~4.5MeV energy threshold
- SK-I: April 1996~
- SK-IV is running

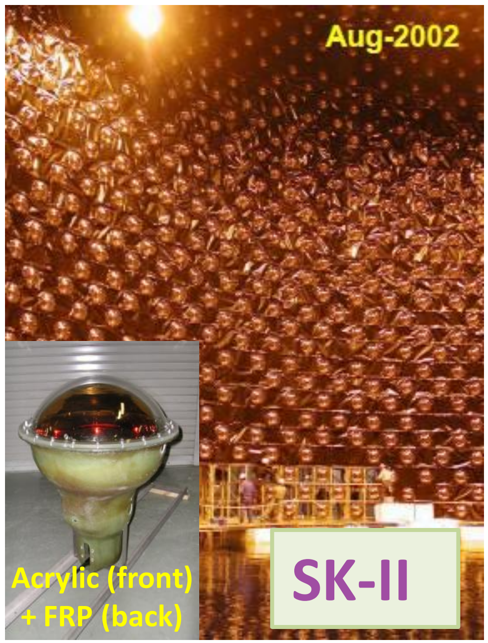
Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

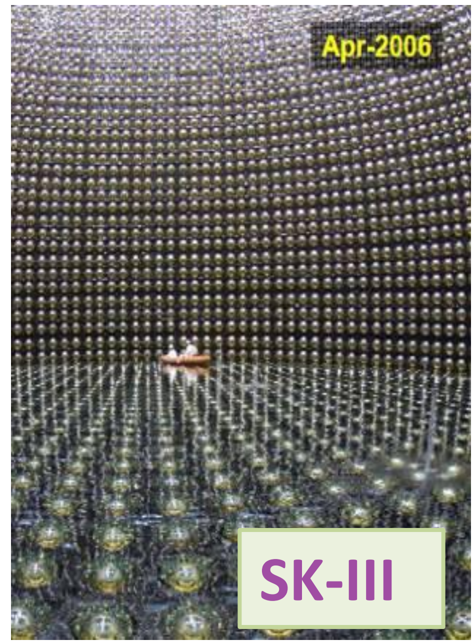
History of Super-Kamiokande

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

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





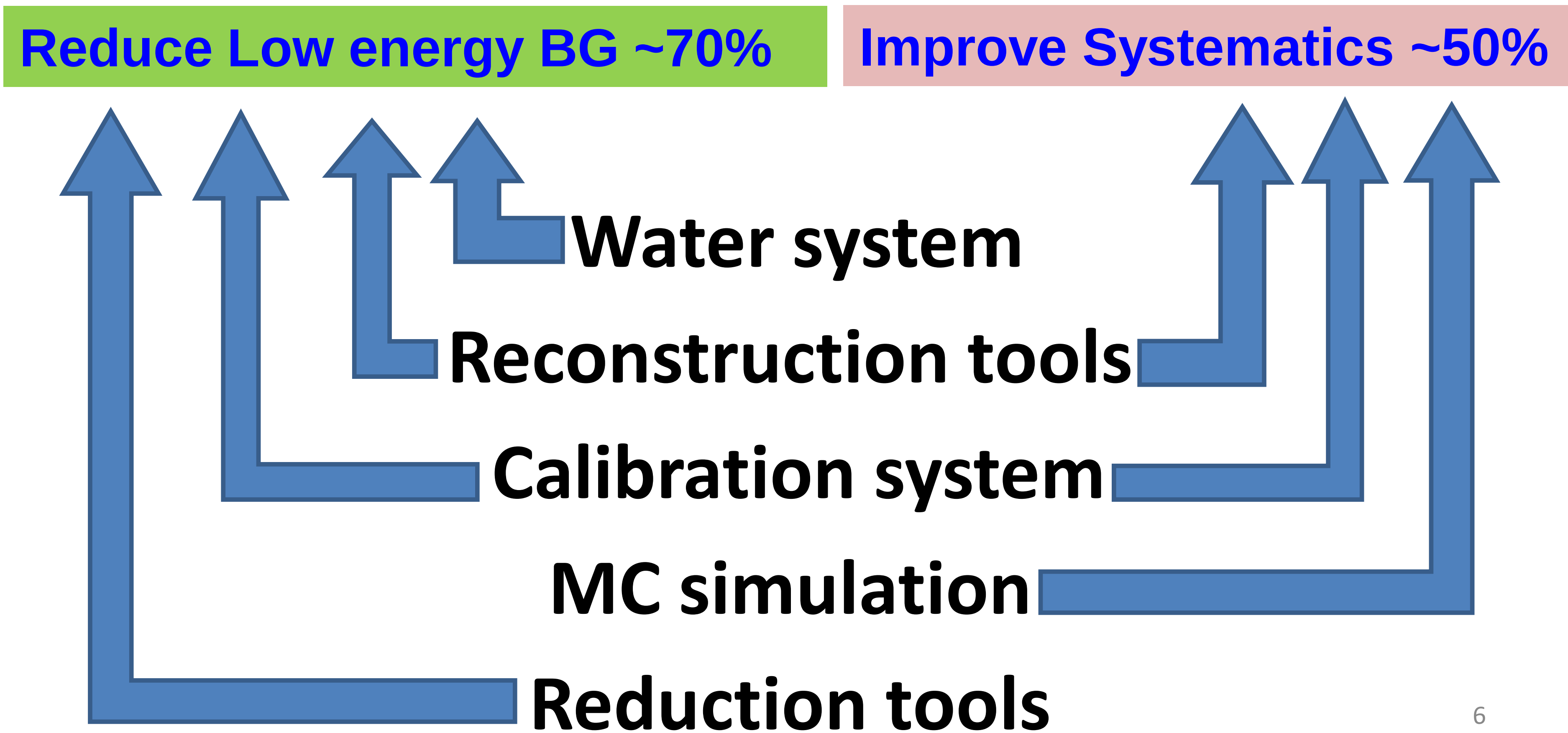


	SK-I	SK-II	SK-III	SK-IV	
	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	
Energy Threshold (Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV
				Current	Target

Target of SK-III Solar ν analysis

>Observation of upturn (MSW in Sun)

>Oscillation parameters (2f and 3f analysis)

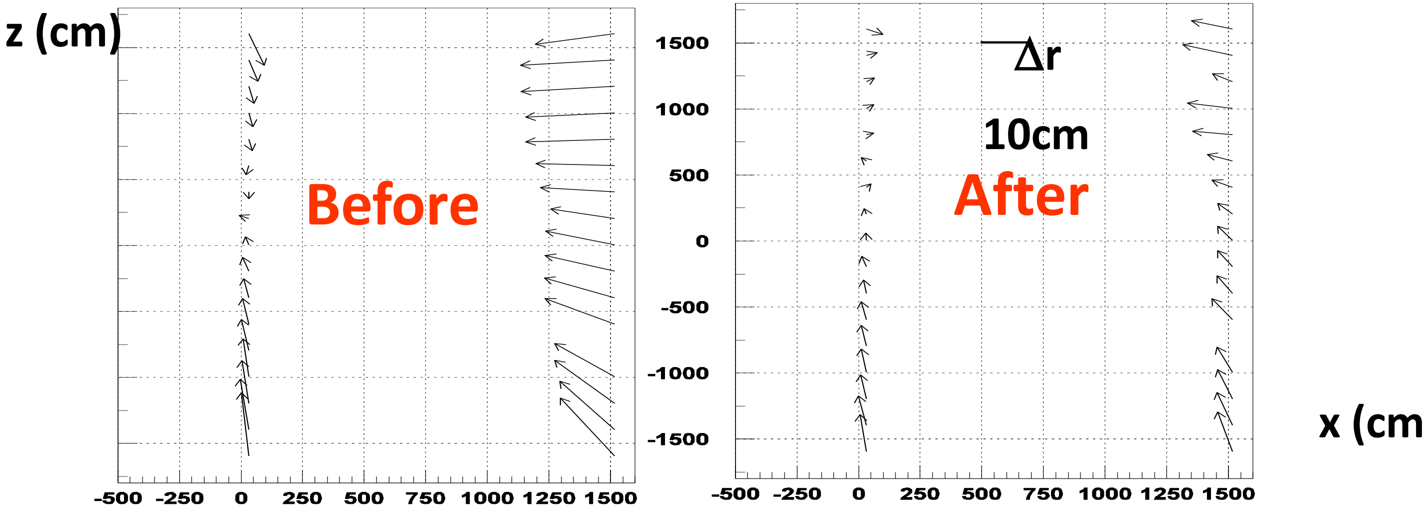


Timing Calibration improvement

New hit timing correction is installed.

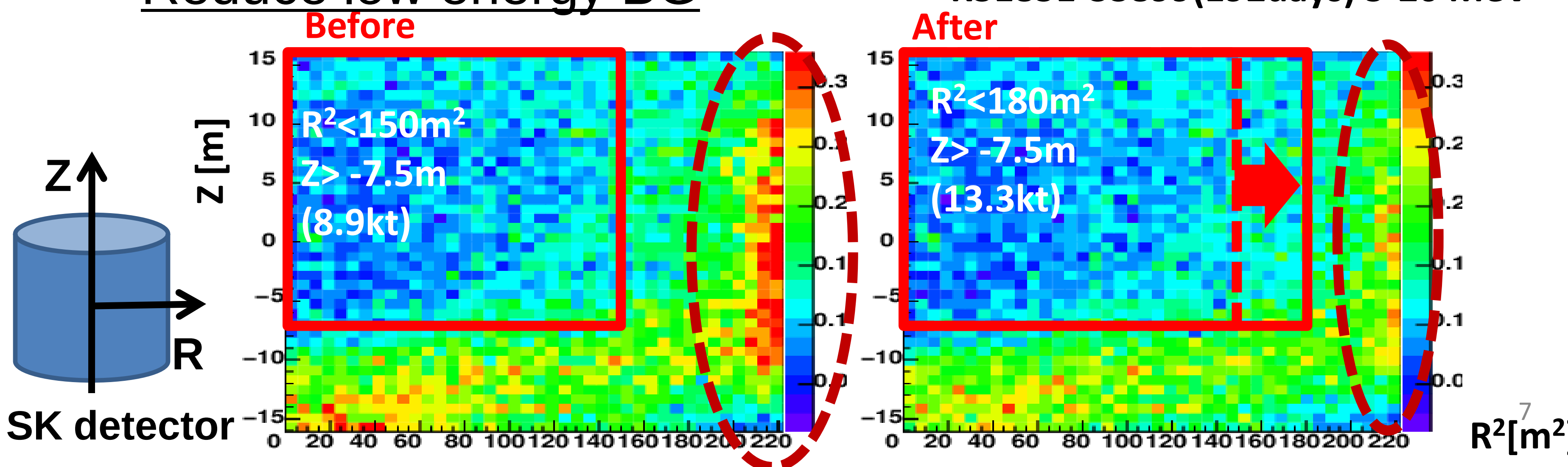
Electronics linearity is corrected by this correction

Improve systematics (vertex shift)



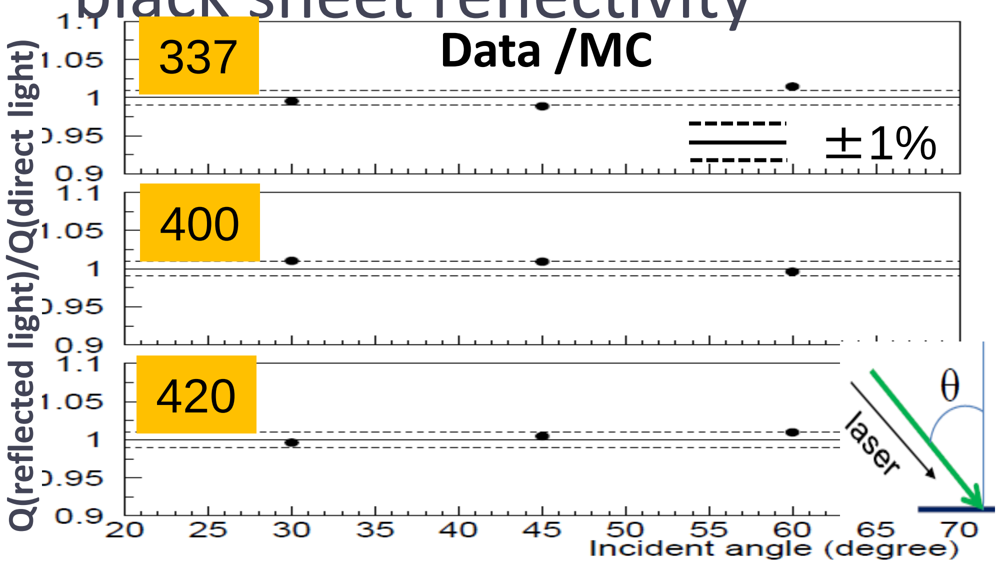
Reduce low energy BG

R31851-33899(192days) 5-20 MeV



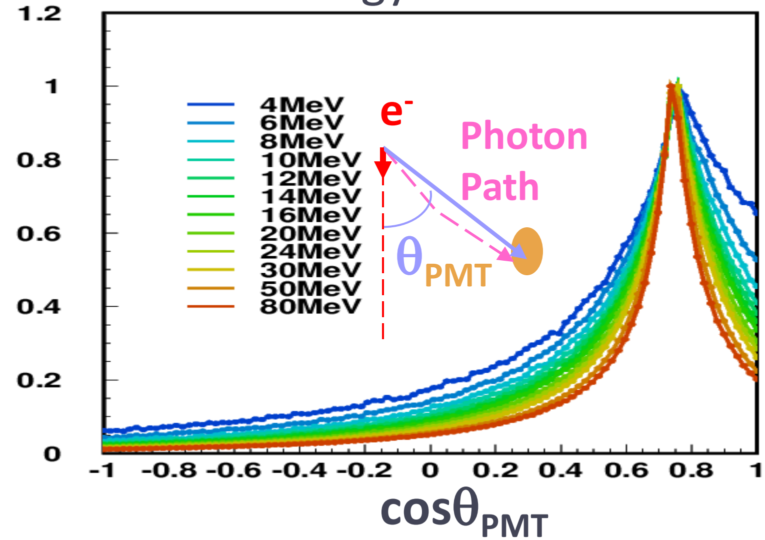
Angular reconstruction

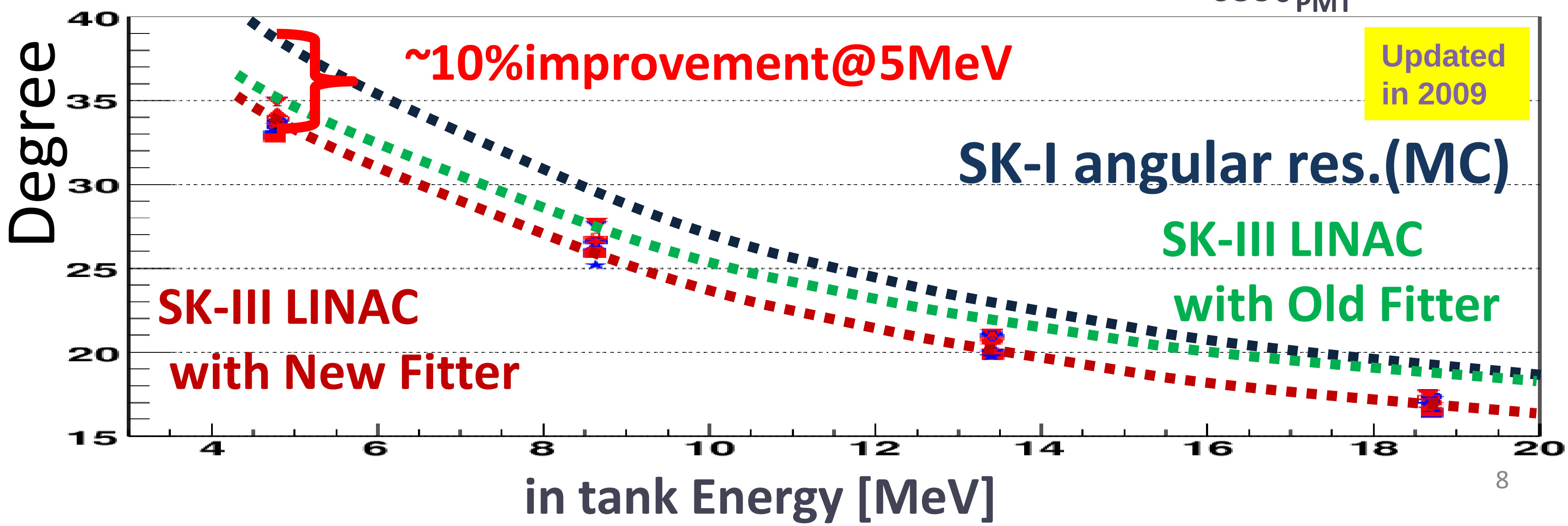
Calibration&MC tuning: black sheet reflectivity



Improving direction fitter

Made likelihood functions for different energy bins from MC





Systematic uncertainties on total flux

	SK-III	SK-I *
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%

Preliminary

Energy region:

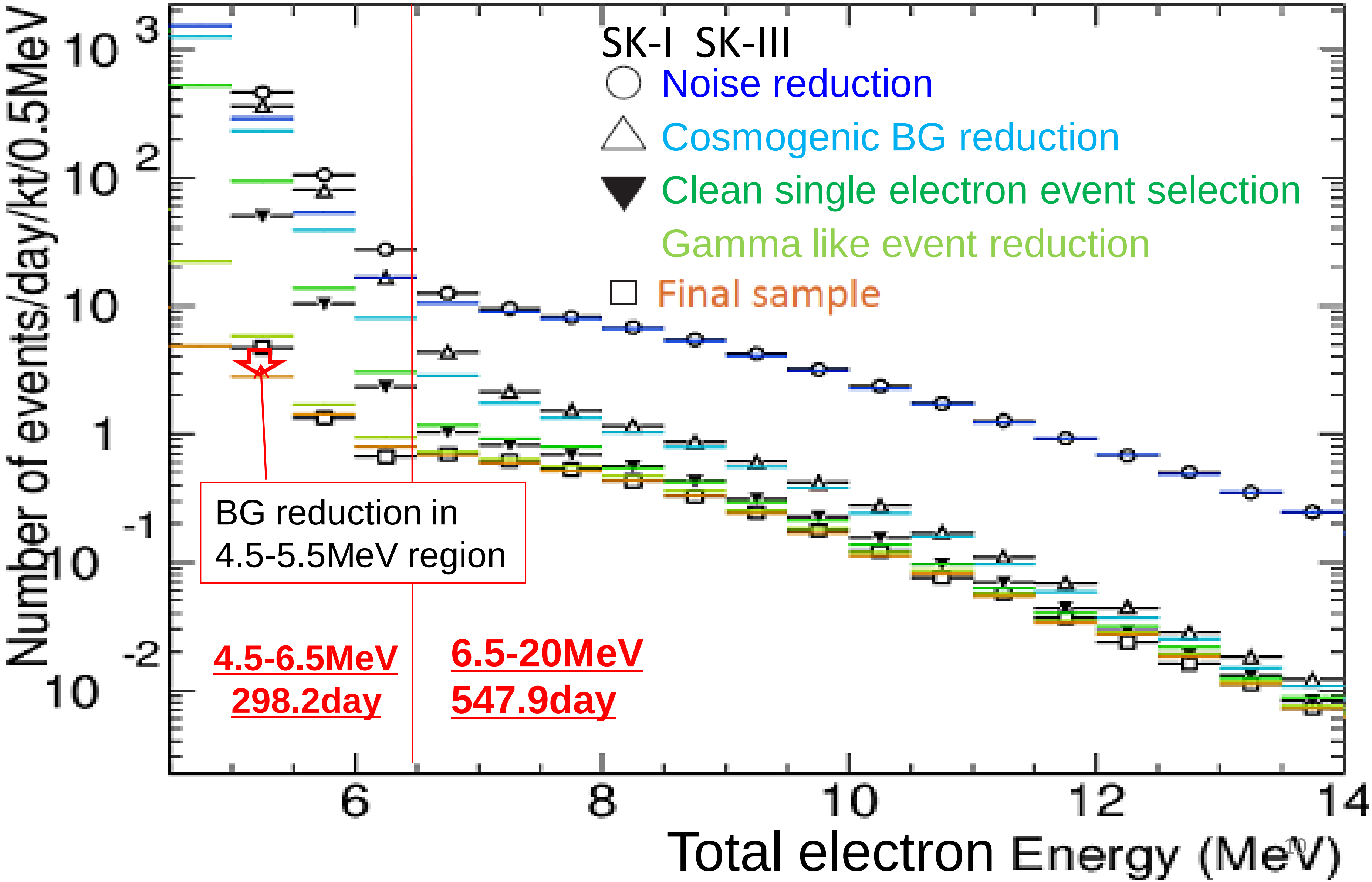
E_{total}=5.0-20.0MeV

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

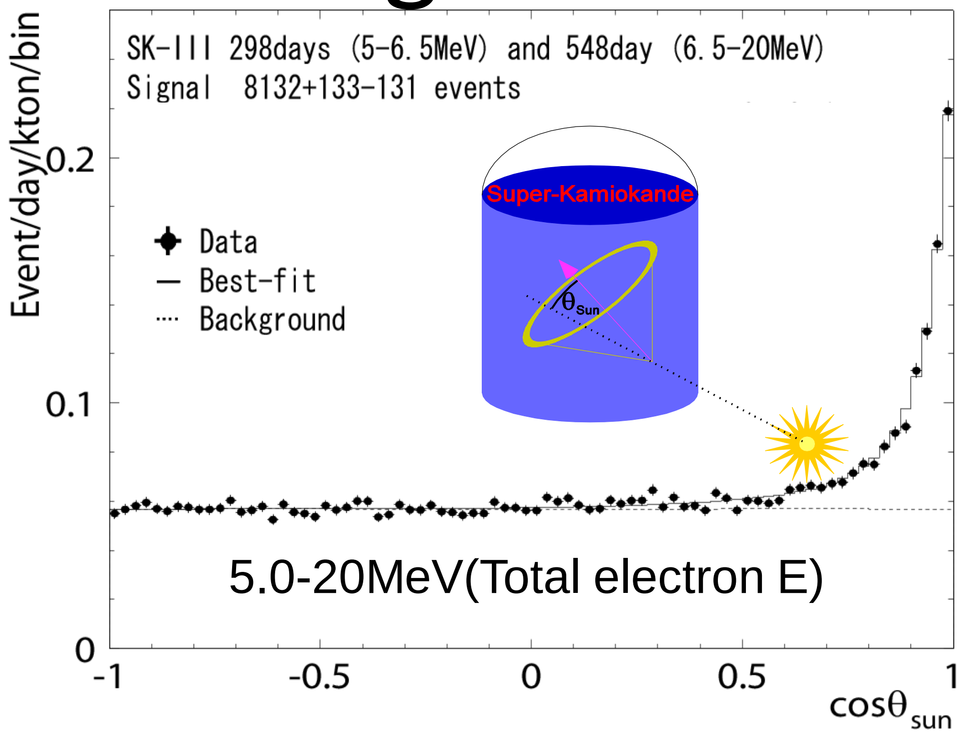
*(PRD73,112001)

Data set& analysis overview

Data taking period: From 2006 Aug to 2008Aug



Solar angle distribution



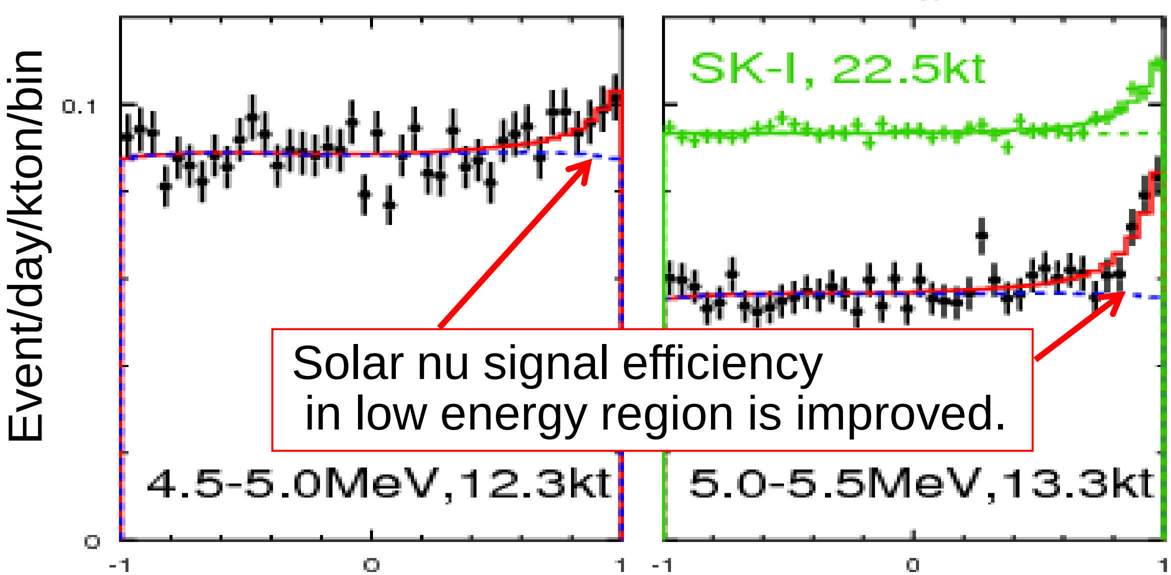
Flux 2.32±0.04(stat.)±0.05(sys.) $\times 10^6 cm^{-2}s^{-1}$
(with Winter06 B8 spectrum)

SK-I:2.38+/-0.02(sta.)+/-0.08(sys.) $\times 10^6 cm^{-2}s^{-1}$

SK-II:2.41+/-0.05(sta.)+/-0.16(sys.) $\times 10^6 cm^{-2}s^{-1}$

(re-fitted with Winter06 spectrum)

This flux value is the most precise result!

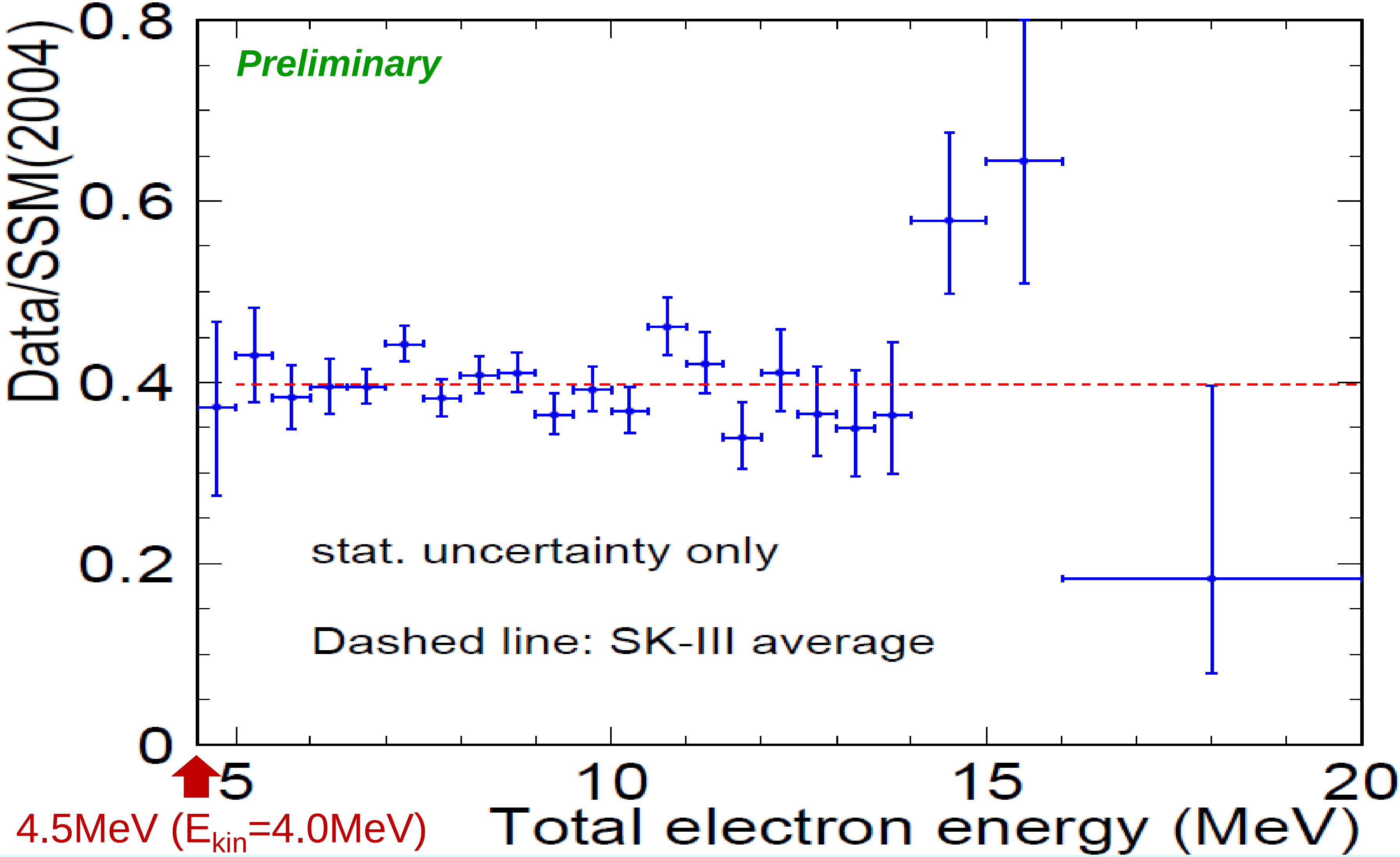


Due to the reduction of low energy BG, the signal to BG ratio improved. Signals in 4.5-5.0MeV can be seen 4σ level.

$4.5-5MeV$: $232.\pm 59.event$

$2.14^{+0.56}_{-0.54}(stat.)\ \times 10^6 cm^{-2} sec^{-1}$

SK-III ^8B energy spectrum



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

Oscillation analysis

Data set for oscillation analysis

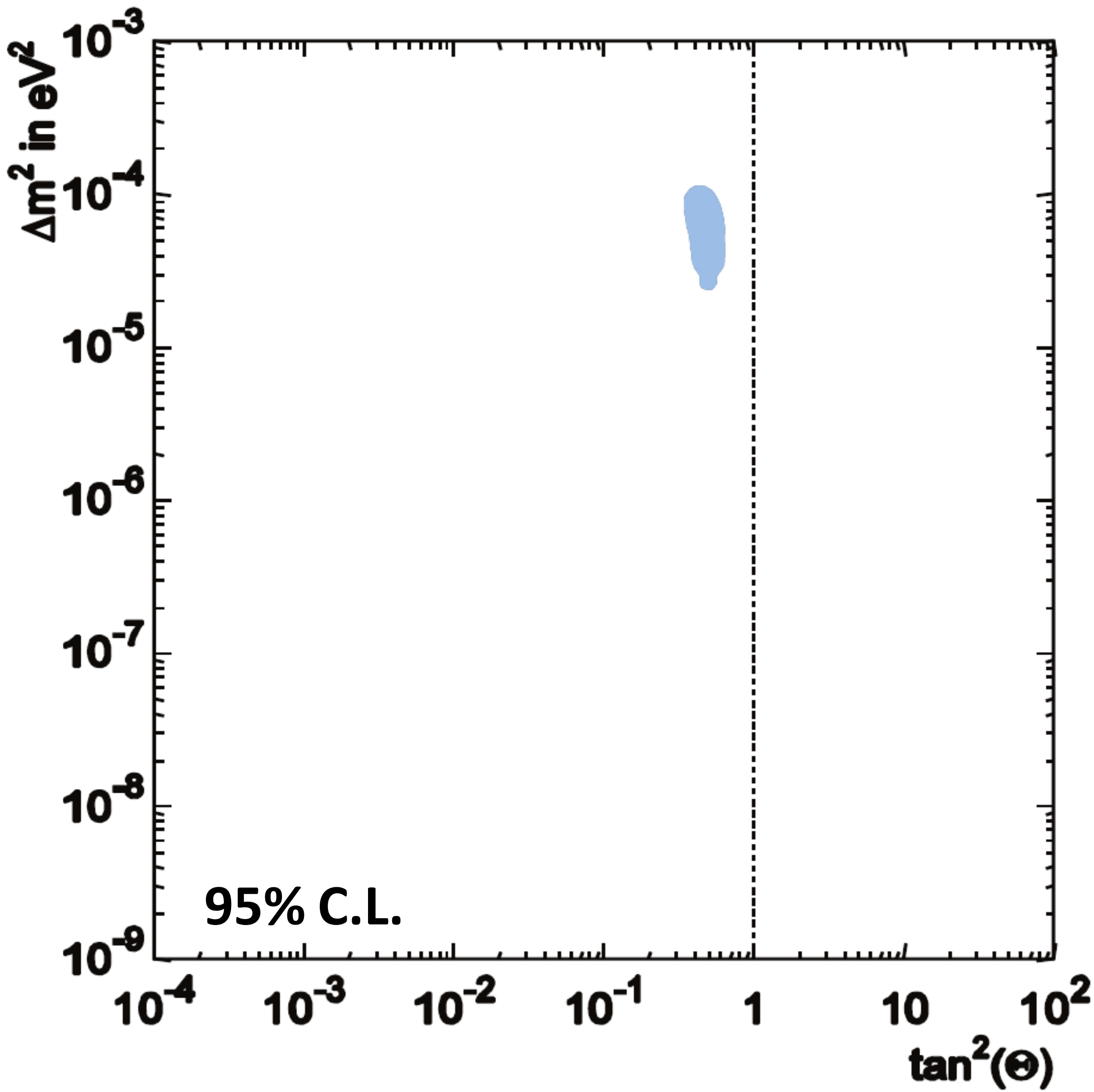
- **SK**
  - SK-I 1496 days, spectrum 5.0-20MeV + D/N : E ≥ 5.0MeV
  - SK-II 791 days, spectrum 7.0-20MeV + D/N : E ≥ 7.5MeV
  - SK-III 548 days, spectrum 5.0-20.0MeV + D/N : E ≥ 5.0MeV
- **SNO**
  - **CC flux (Phase-I & II & III)**
  - **NC flux (Phase-III & LETA combined) (= (5.14+/-0.21) $10^6 cm^{-2}s^{-1}$)**
  - **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)
- SSM BP2004

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



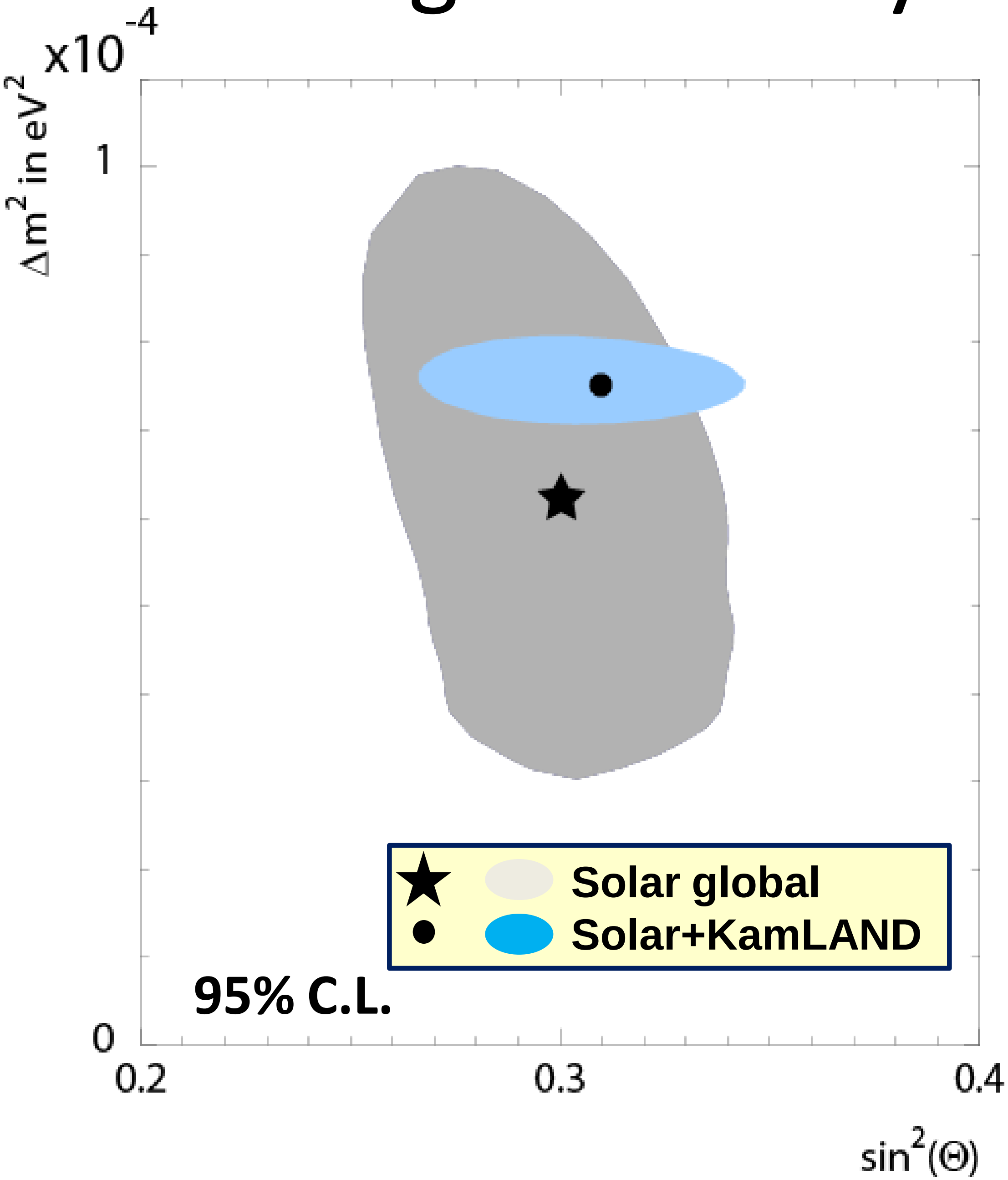
$\Delta m^2 = 6.1 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.48$
$\Phi_{B8} = 5.2 \times 10^6 \text{cm}^{-2}\text{s}^{-1}$

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

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

Only LMA solution

2-flavor global analysis



Preliminary

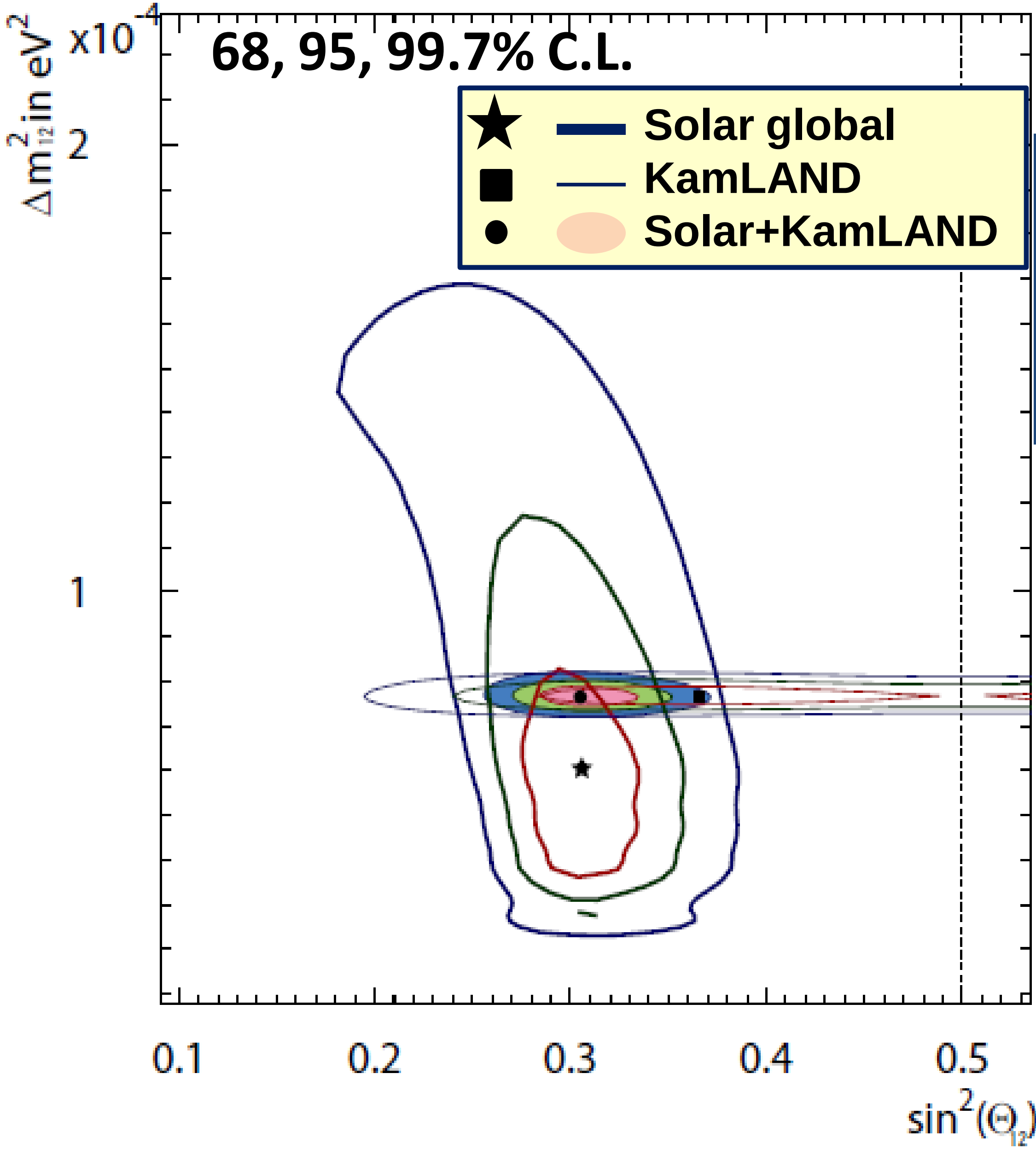
Solar global:

$\Delta m^2 = 6.2 \times 10^{-5}\ eV^2$
$\sin^2\theta = 0.30$
$\Phi_{B8} = 5.3 \pm 0.2 \times 10^6 cm^{-2}s^{-1}$

Solar global + KamLAND:

$\Delta m^2 = 7.6 \times 10^{-5}\ eV^2$
$\sin^2\theta = 0.31$
$\Phi_{B8} = 5.1 \pm 0.1 \times 10^6 cm^{-2}s^{-1}$

3-flavor analysis: θ_{12} - Δm_{12}^2



Preliminary

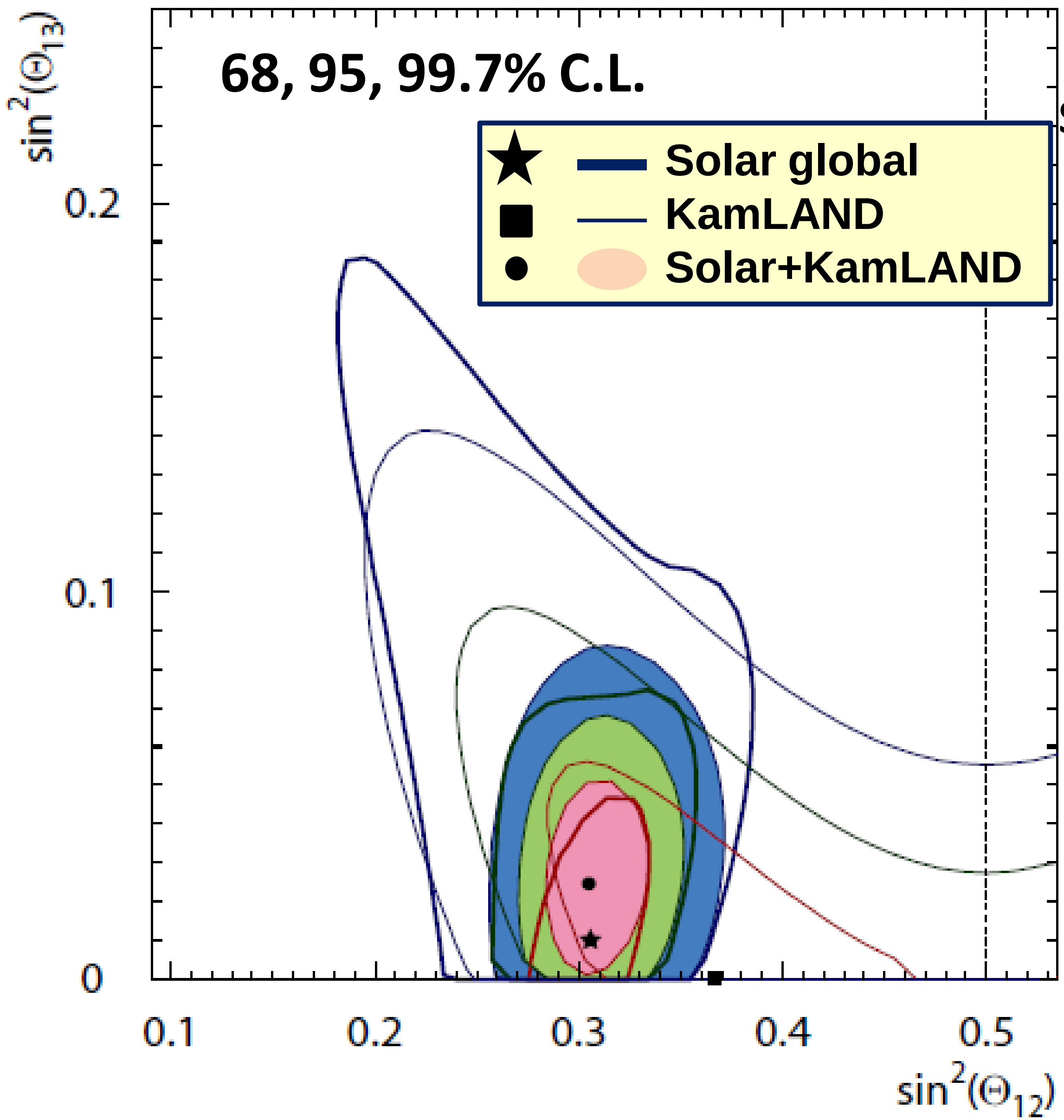
Solar global:

$\Delta m^2 = 6.0 \times 10^{-5}$ eV^2
$\sin^2\theta_{12} = 0.31$
$\sin^2\theta_{13} = 0.010$
$\Phi_{B8} = 5.3 \pm 0.2 \times 10^6 cm^{-2}s^{-1}$

Solar global + KamLAND:

$\Delta m^2 = 7.7 \times 10^{-5}$ eV^2
$\sin^2\theta_{12} = 0.31$
$\sin^2\theta_{13} = 0.025$
$\Phi_{B8} = 5.3^{+0.1}_{-0.2} \times 10^6 cm^{-2}s^{-1}$

3-flavor analysis: θ_{12} - θ_{13}



Preliminary

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.)

Summary

- The result of solar neutrino measurement in SK-III is summarized.
- With improved calibrations, simulation, and analysis methods, the systematic uncertainty on the total neutrino flux is estimated to be 2*.1%.*
- Total flux (5.0-20MeV):2.32 ±0.04 (stat.) ±0.05 (sys.) 106 cm^2sec^{-1}
- Reduce low energy BG successfully.
- Oscillation analysis:
  - Two Flavor

  $\sin^2\theta_{12} = 0.31 \pm 0.01 \times 0.01$, $\Delta m^2_{21} = 7.6 \pm 0.2 \times 10^5 eV^2$

  - Three Flavor

  $\sin^2\theta_{12} = 0.31 \pm 0.02 \times 0.01$, $\Delta m^2_{21} = 7.7 \pm 0.2 \times 10^5 eV^2$

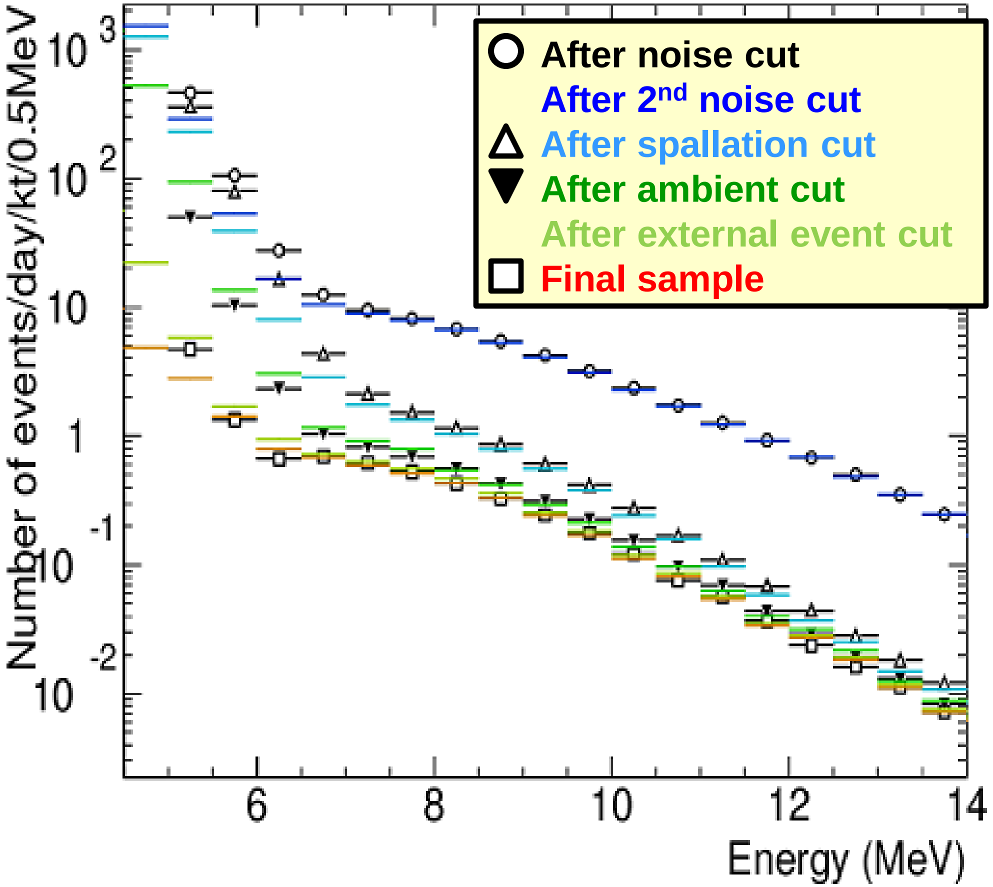
  $\sin^2\theta_{13} = 0.025^{+0.018}_{-0.016}$, < 0.059 @95% C.L.

Data reduction in SK-III & -I

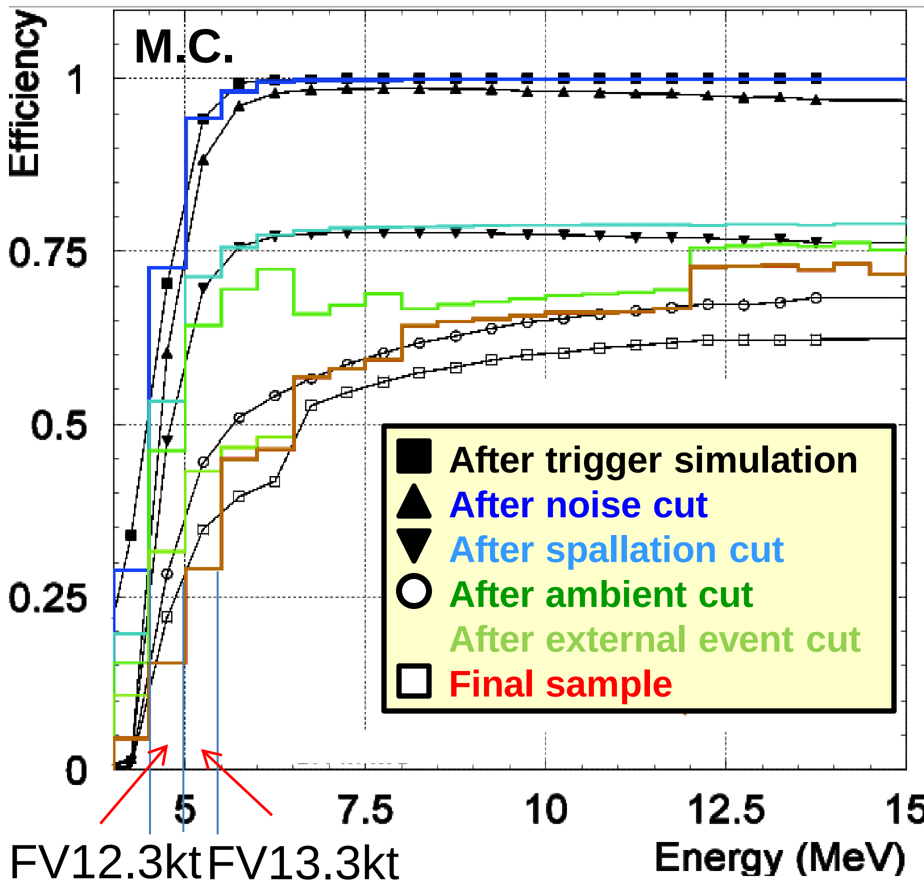
SK-III(color) SK-I(B&W)

May 2010

Event rates of SK-III & -I data

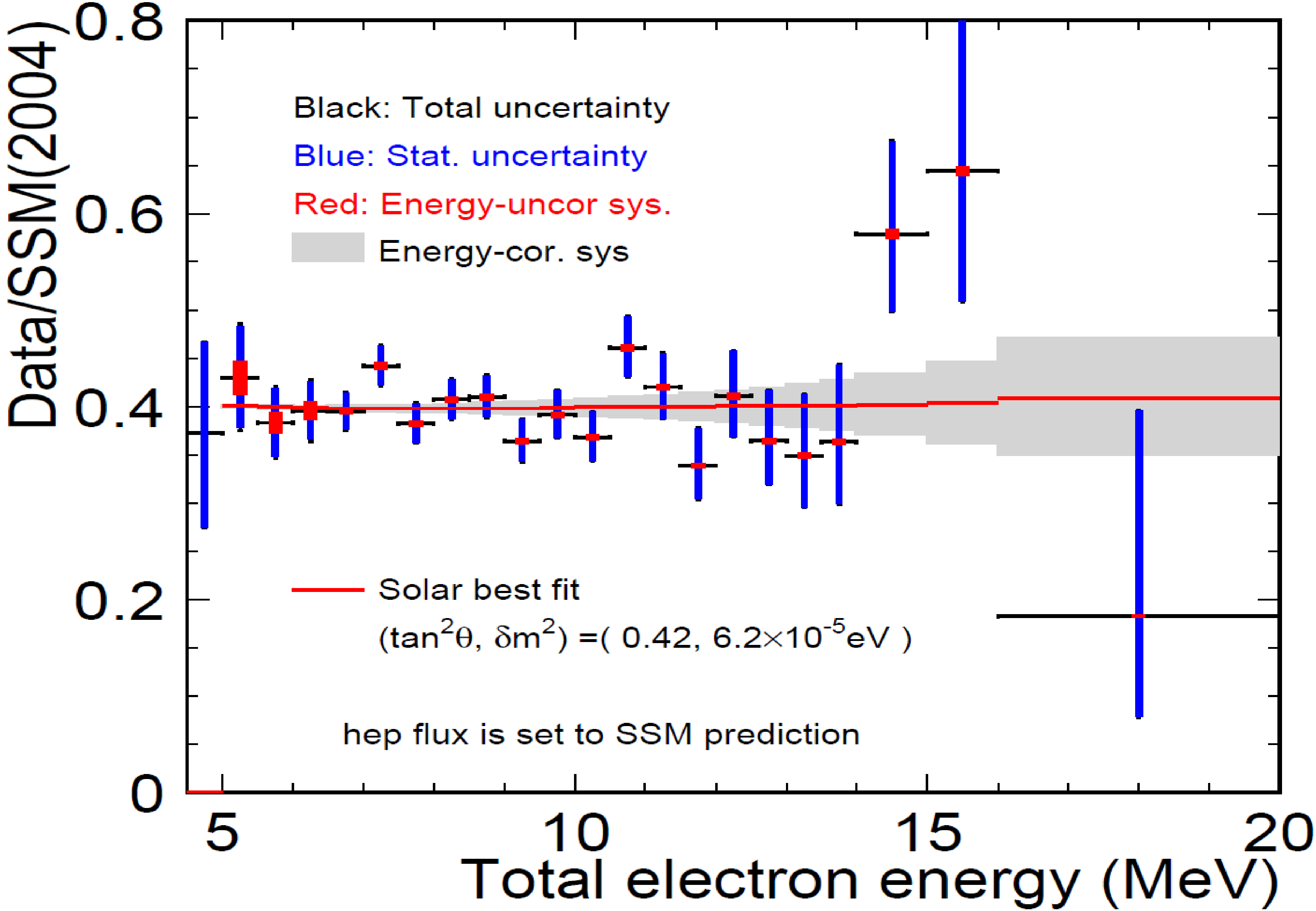


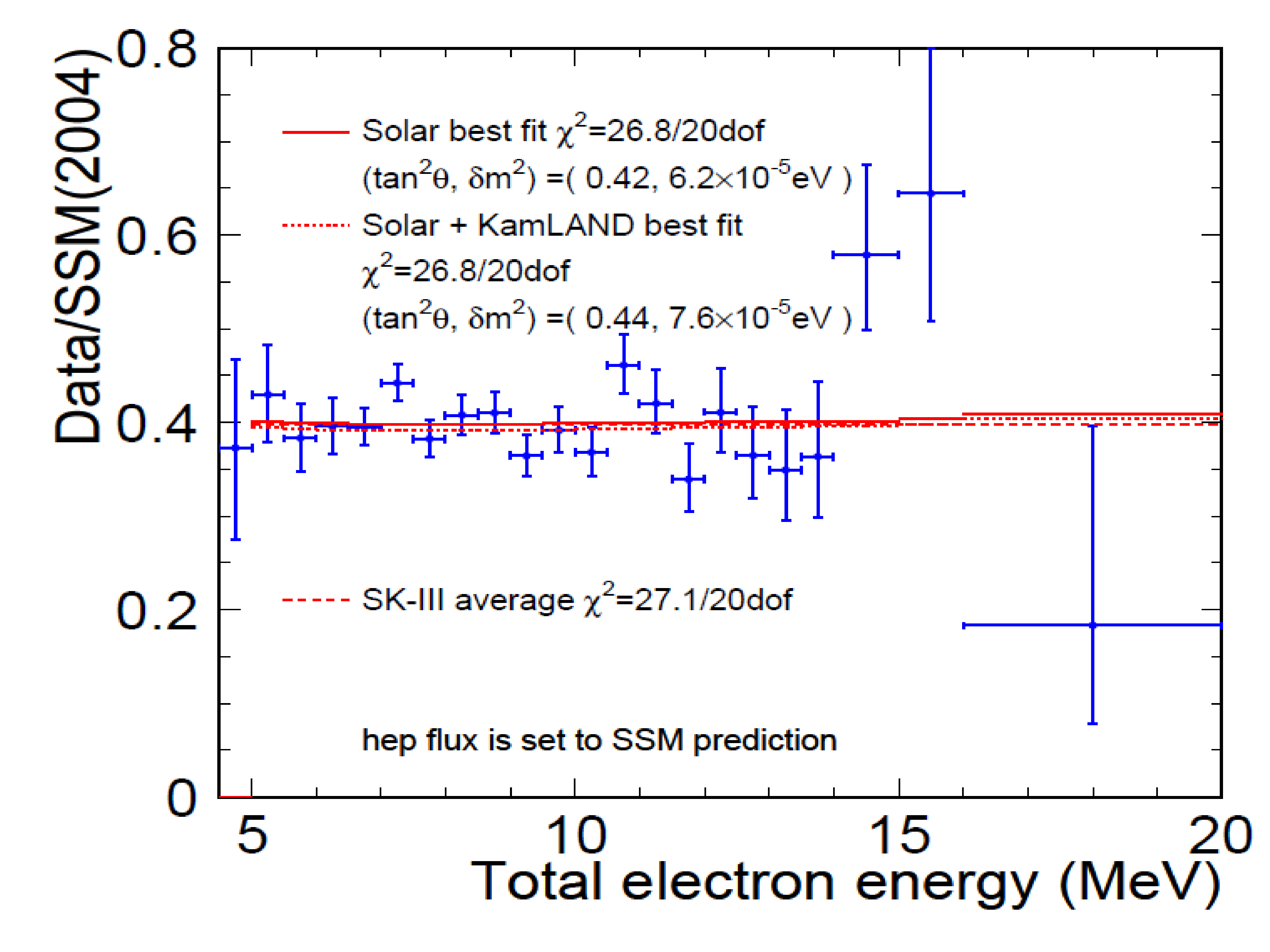
Reduction efficiency in 22.5kt



- E_{total}>5.5MeV, SK-III has higher efficiency.
- E_{total}<5.5MeV, event rate in SK-III is lower than SK-I.

DATA/SSM


Data/SSM(2004)
0.8
0.6
0.4
0.2
0
5
10
15
20
Total electron energy (MeV)
Black: Total uncertainty
Blue: Stat. uncertainty
Red: Energy-uncor sys.
Energy-cor. sys
Solar best fit
$(\tan^2\theta, \delta m^2) = (0.42, 6.2\times10^{-5}eV)$
hep flux is set to SSM prediction


Solar best fit χ^2=26.8/20dof
($\tan^2\theta$, δm^2) =(0.42, 6.2×10^{-5}eV)
Solar + KamLAND best fit
χ^2=26.8/20dof
($\tan^2\theta$, δm^2) =(0.44, 7.6×10^{-5}eV)
SK-III average χ^2=27.1/20dof
hep flux is set to SSM prediction
Data/SSM(2004)
Total electron energy (MeV)
0
0.2
0.4
0.6
0.8
5
10
15
20

SK-III low-energy data set

- SK-III period: 2006/8/5-2008/8/18
- Total live time : 548 days, $E_{total} \geq 6.5$ MeV
  289 days, $E_{total} < 6.5$ MeV
  - LE only: 2006/8/5-2007/1/24, 100% trig. eff. @6.5MeV
    - Live time = 122 days
  - SLE1: 2007/1/24-2008/4/17, 100% @5.0MeV
    - Live time = 332 days (E<6.5MeV: 211days)
  - SLE2: 2008/4/17-2008/8/18, ~100% @4.5MeV
    - Live time = 95 days (E<6.5MeV: 88days)
  - For E<6.5MeV data sample, high background rate periods due to bad water condition are rejected.
- Energy region for solar ν osc. analysis: E_{total}=5.0-20.0MeV

May 2010

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

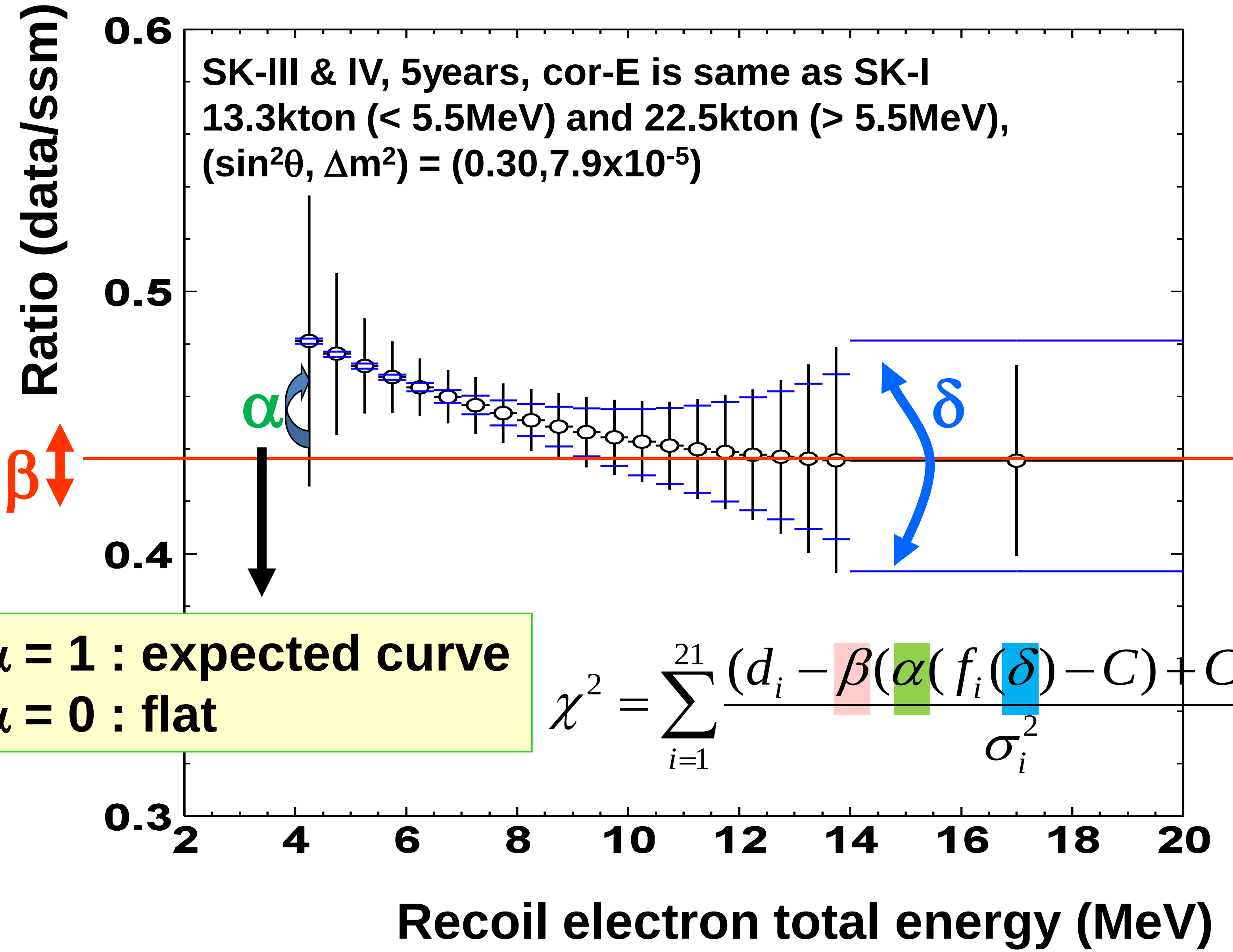
- ^{8}B Flux: 2.32+/-0.04(stat.)+/-0.05(syst.) (x10^{6}/cm^{2}/s)
  - SK-I: 2.38+/-0.02(stat.)+/-0.08(syst.)
  - SK-II: 2.41+/-0.05(stat.)+0.16/-0.15(syst.)

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

- Day / Night ratio:

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

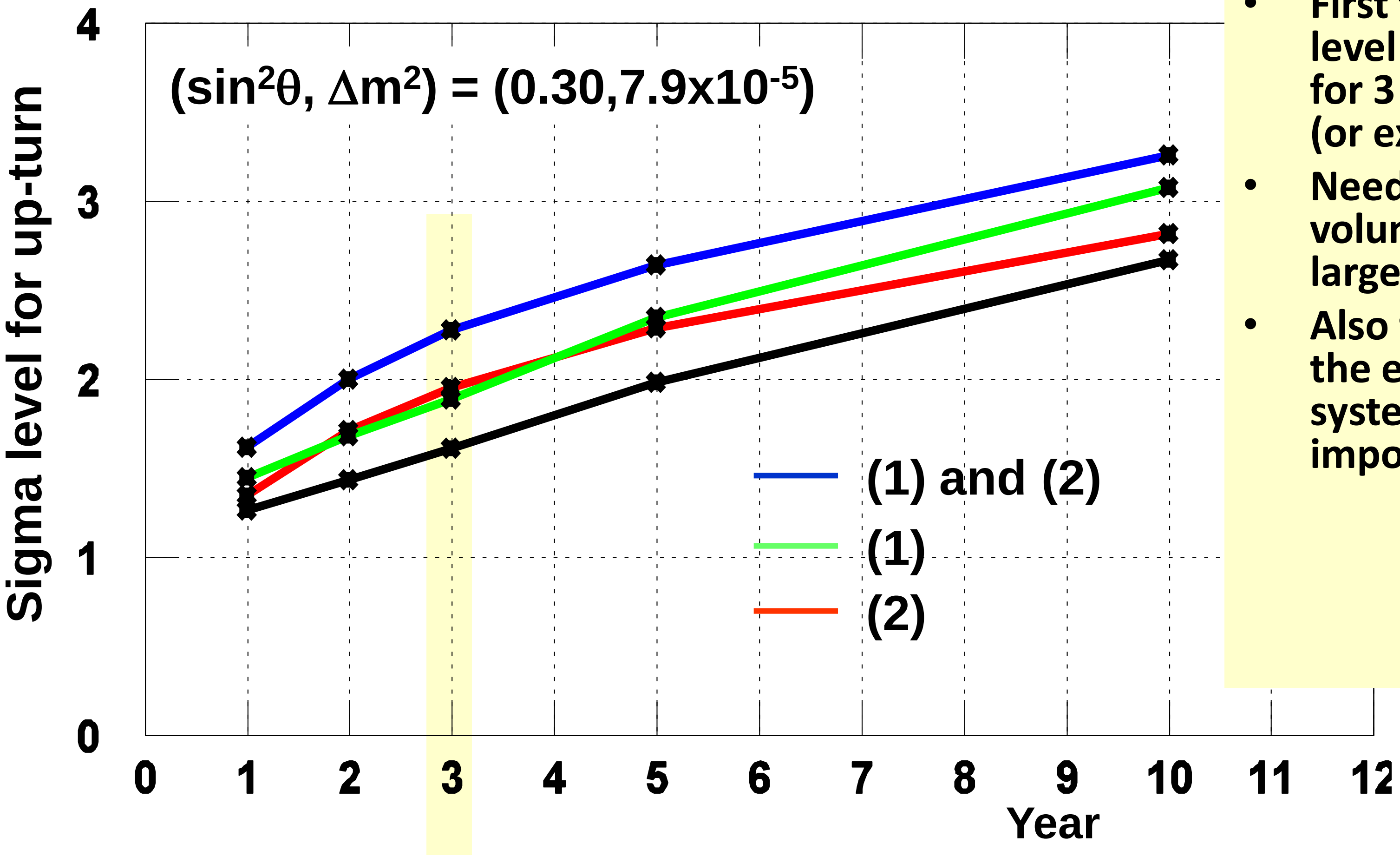
Upturn sensitivity calculation



α = 1 : expected curve
α = 0 : flat

$$\chi^2 = \sum_{i=1}^{21} \frac{(d_i - \beta(\alpha(f_i(\delta) - C) + C))^2}{\sigma_i^2} + \frac{\delta^2}{\sigma_{cor}^2}$$

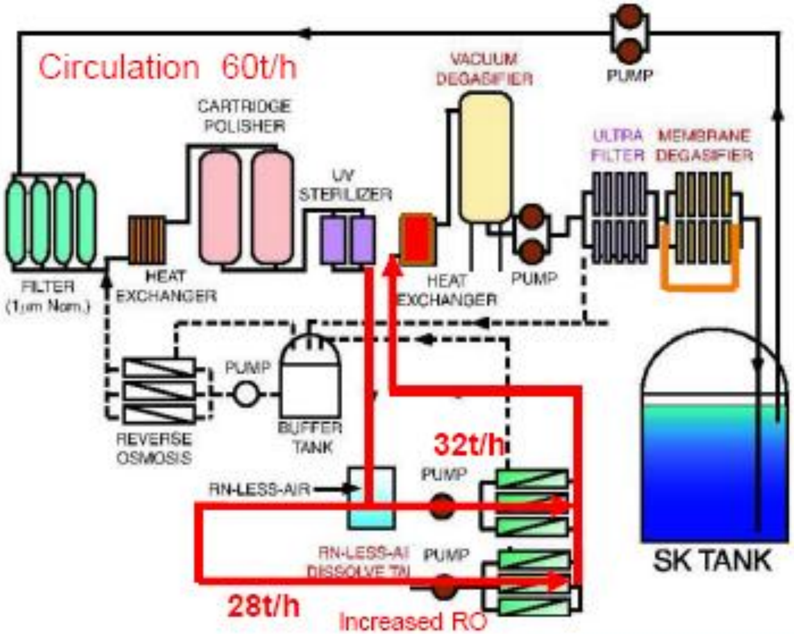
Sensitivity of the upturn measurement



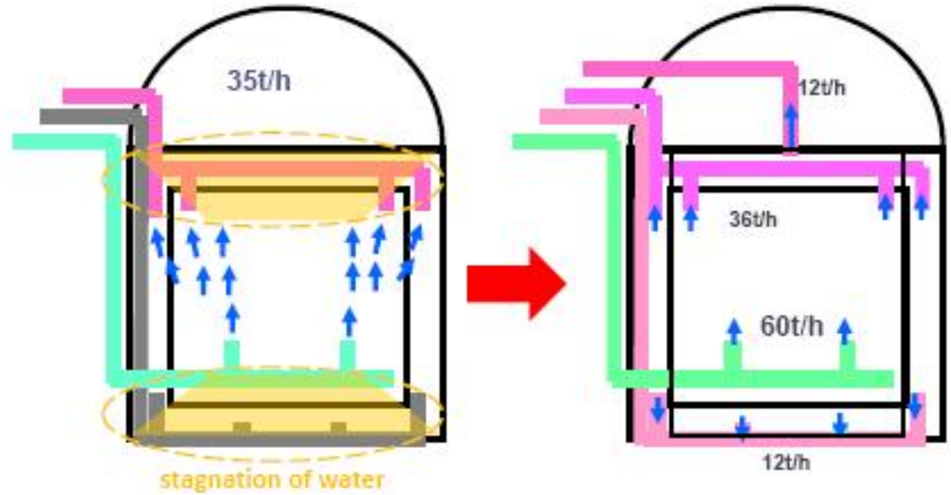
- **First target : 2 sigma level up-tern discovery for 3 years observation. (or exclude the up-tern)**
- **Need to enlarge fiducial volume with low BG as large as possible**
- **Also the reduction of the energy correlated systematic error is important.**

(1) Enlarge fiducial volume to 22.5kton with low B.G.
(2) Half energy correlated systematic error as SK-1.
The black line shows the 13.3kton (<5.5MeV), 22.5kton (>5.5MeV) fiducial volume with the same energy correlated error as SK-1

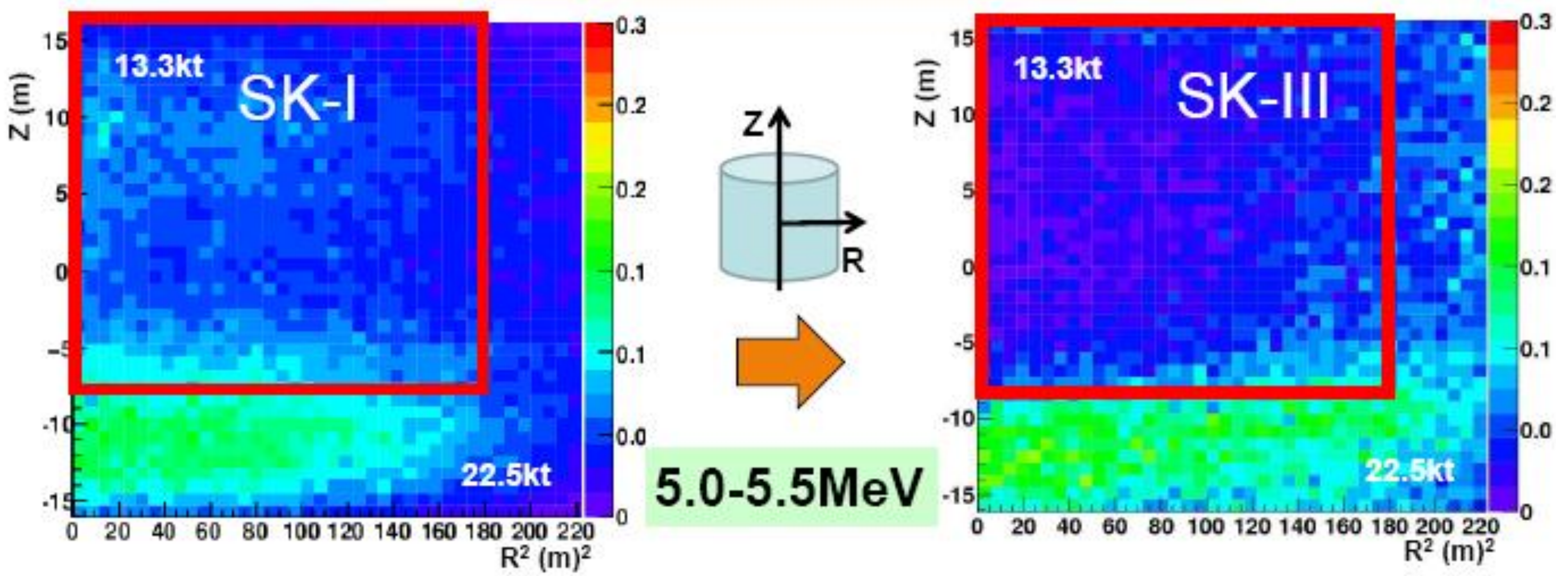
Twice increased circulation rate



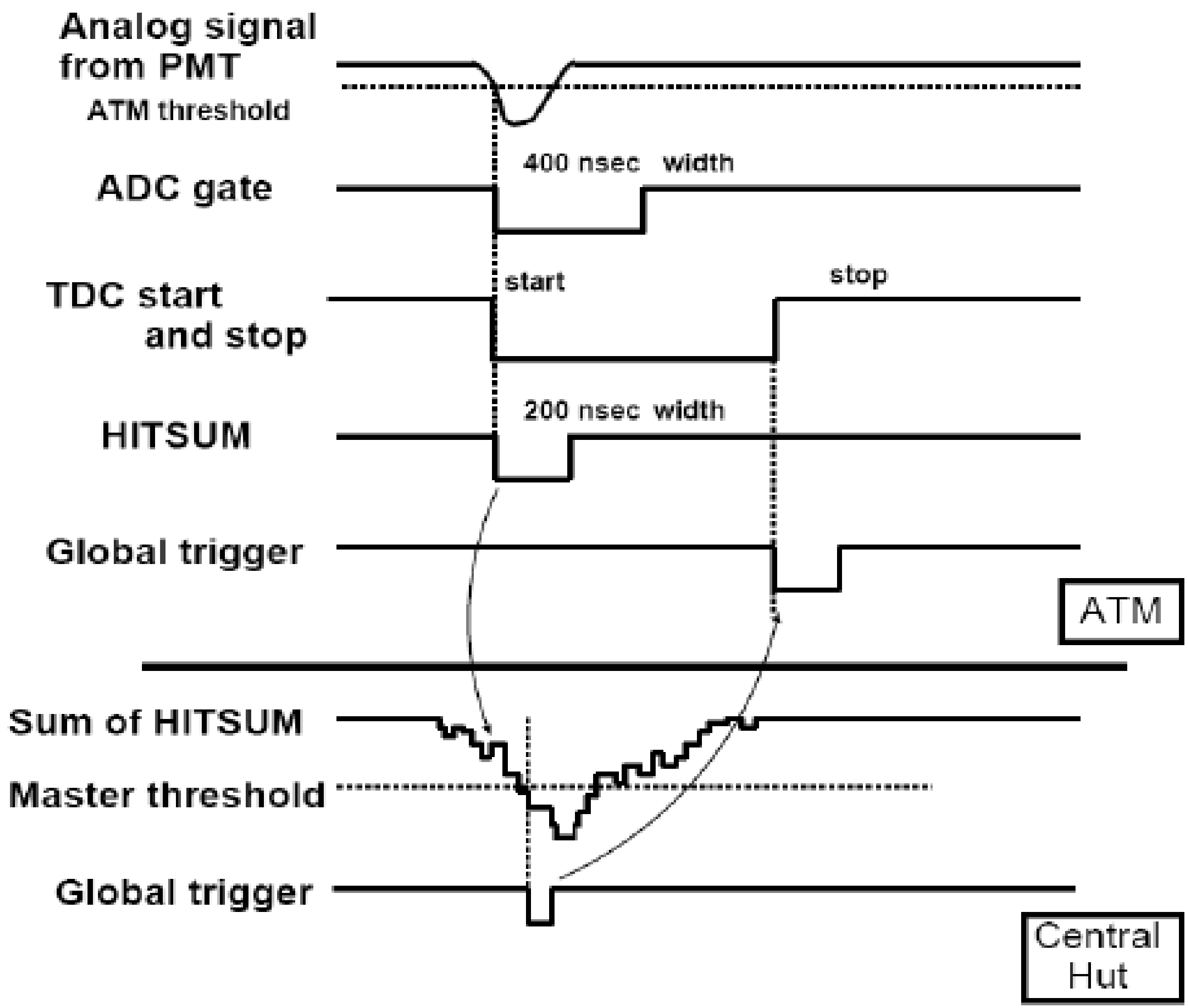
Optimized water flow in the tank



Vertex distribution (mainly BG)



Definition of hit timing



Definition of SK χ^2

Stat.+Energy-uncorrelated sys **Energy correlated sys.** **Spectrum fit**

$$\chi^2 = \sum_{p}^{N_{phase}} \left(\sum_{i}^{N_{bin,p}} \frac{(d_{i,p} - \rho_{i,p})^2}{\sigma_{i,p}^2} + \delta_{S,p}^2 + \delta_{R,p}^2 \right) + \delta_B^2 + \frac{(\beta - \beta_{NC})^2}{\sigma_{NC}^2} + \frac{(\eta - 1)^2}{\sigma_{hep}^2}$$

$$+ \sum_{p}^{N_{phase}} \Delta\chi^2_{t.v.,p}(\beta, \eta, \delta_B, \delta_{S,p}, \delta_{R,p})$$

Time variation

B^8 rate is constrained by SNO NC flux

hep rate is constrained by SSM flux and uncertainty.

oscillated/unoscillated of ^{8}B (*hep*) flux

$$d_i = \frac{\mathrm{Data}_i}{^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}, \quad \rho_i = \frac{\beta b_i + \eta h_i}{f_i}$$

$$b_i = \frac{^8\mathrm{B}_i^{\mathrm{osc}}(\Delta m^2, \tan^2\theta)}{^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}, \quad h_i = \frac{hep_i^{\mathrm{osc}}(\Delta m^2, \tan^2\theta)}{^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}$$

correlation function *8B spectrum shape* *energy scale* *energy resolution*

$$f_i(\delta_B, \delta_S, \delta_R) = f_i^B(\delta_B) \times f_i^S(\delta_S) \times f_i^R(\delta_R)$$

β, η and δs are chosen to minimize the spectrum fit χ^2.

Definition of χ^2s

SK spectrum+SNO flux fit

$$\chi^2_{SK+SNO} = \sum_p^{N_{phase}} \left(\sum_i^{N_{bin,p}} \frac{(d_{i,p} - \rho_{i,p})^2}{\sigma^2_{i,p}} + \delta^2_{S,p} + \delta^2_{R,p} \right) + \delta^2_B + \frac{(\eta - 1)^2}{\sigma^2_{hep}} + \chi^2_{SNO,\,flux}(\beta,\eta)$$

$$+ \sum_p^{N_{phase}} \Delta\chi^2_{t.v.,p}(\beta,\eta,\delta_B,\delta_{S,p},\delta_{R,p}) + \sum_{p=1}^{2} \frac{(ADN^p_{CC} - ADN^p_{prde}(\beta,\eta))^2}{(\sigma^p_{ADN})^2}$$

SK Time variation

SNO CC flux Day/Night asymmetry

$$\chi^2_{SNO,\,flux}(\beta,\eta) = \sum_{p=1}^{3} \frac{(D^p_{CC} - (\beta B^p_{CC} + \eta H^i_{CC}))^2}{(\sigma^p_{cc})^2} + \frac{(D_{NC} - (\beta B_{SSM} + \eta H_{SSM}))^2}{(\sigma_{NC})^2}$$

β, η and δs are chosen to minimize (SK spectrum+SNO flux fit) χ^2.

$$\chi^2_{GaCl} = \sum_{n,m=1}^{N(=2)} (R^{\text{expt}}_n - R^{theor}_n)[\sigma^2_{nm}]^{-1}(R^{\text{expt}}_m - R^{theor}_m)$$

Ga/Cl

$$\chi^2_{GaClBore} = \sum_{n,m=1}^{N(=3)} (R^{\text{expt}}_n - R^{theor}_n)[\sigma^2_{nm}]^{-1}(R^{\text{expt}}_m - R^{theor}_m)$$

Ga/Cl/Borexino

Contribution of SK-III

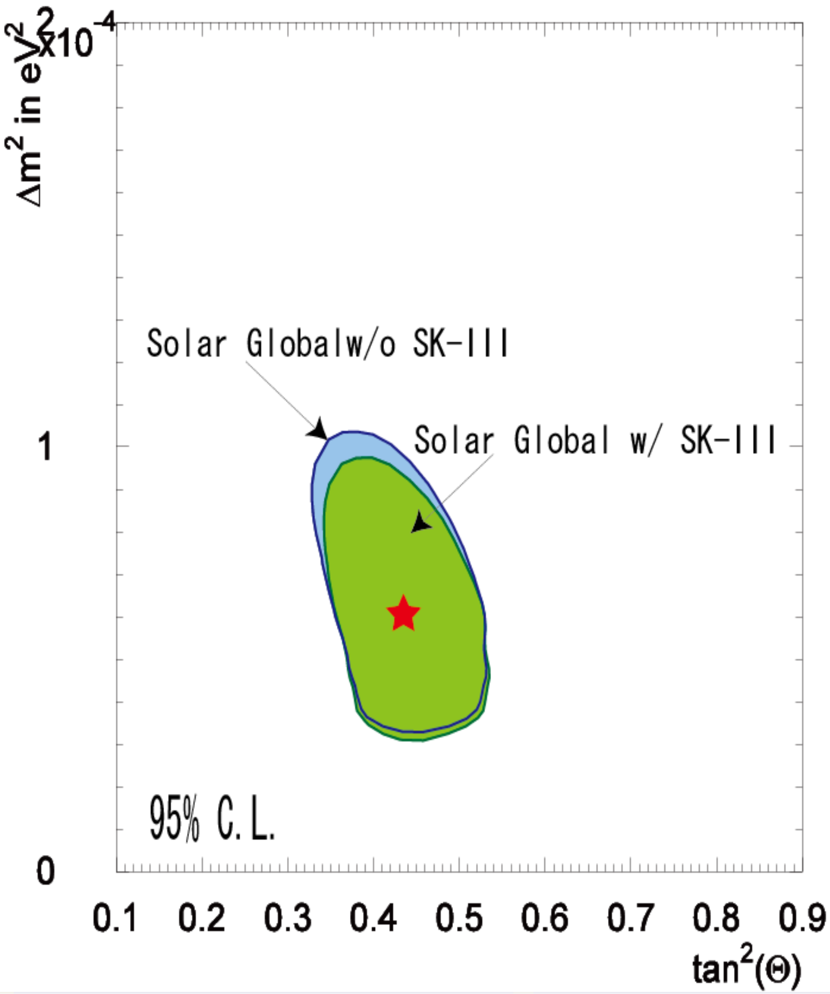
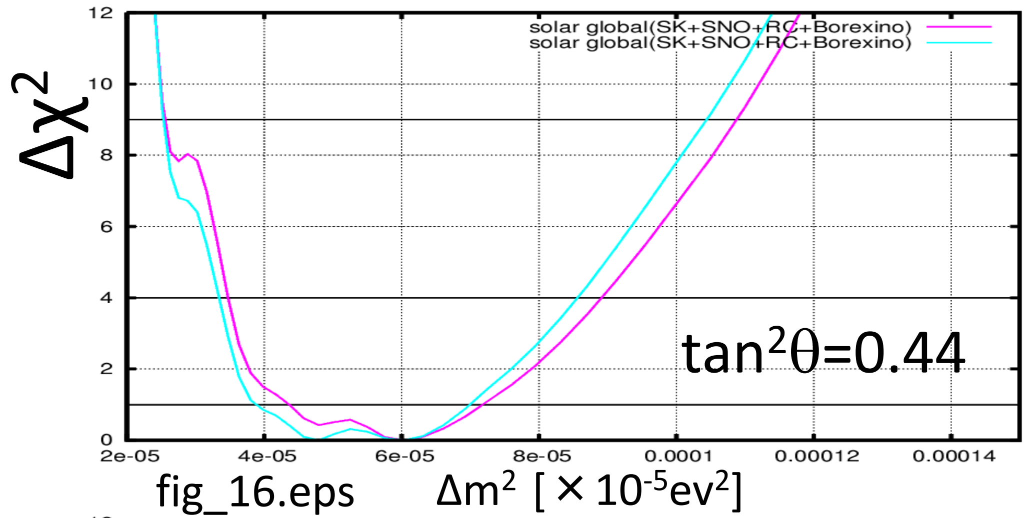


fig_15.eps



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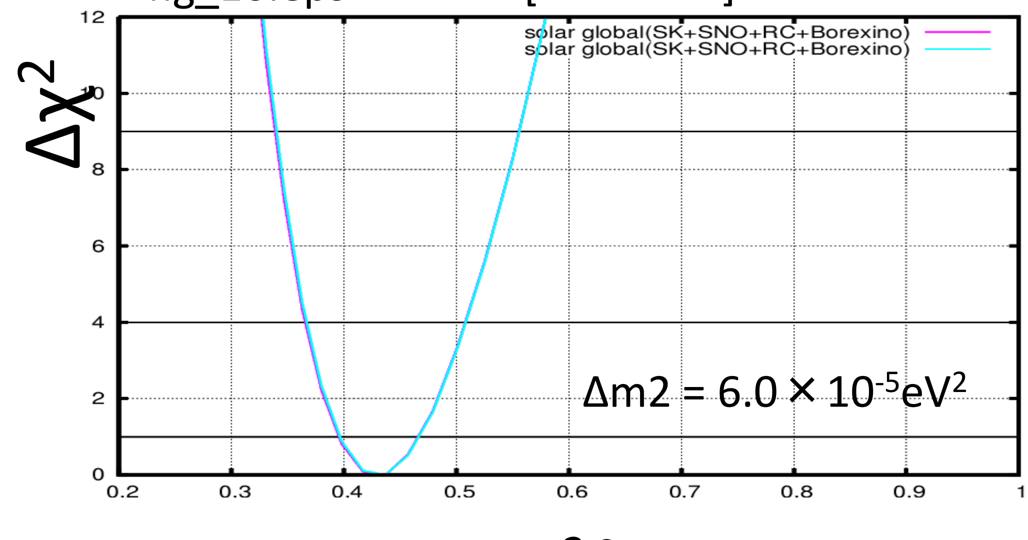
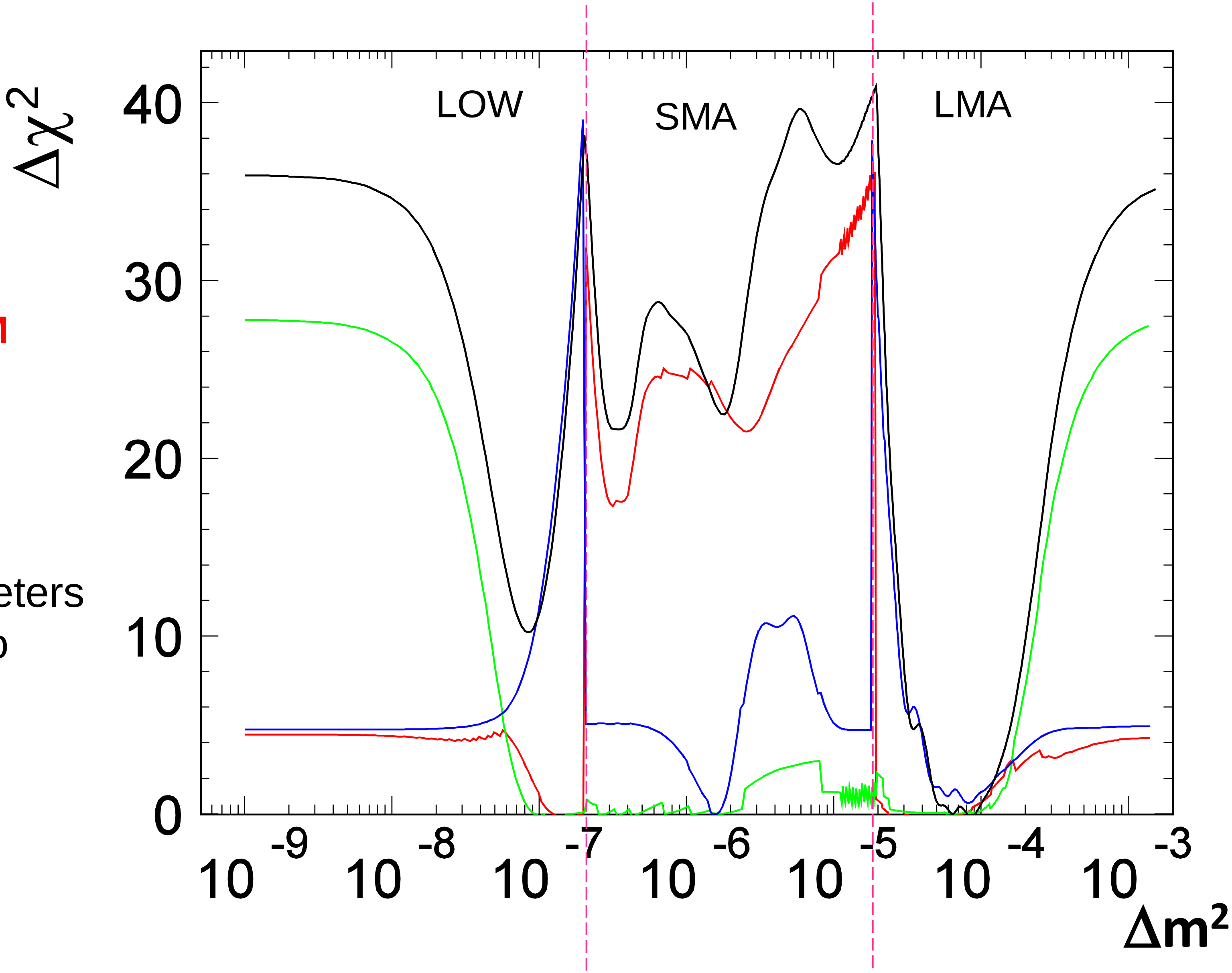


fig_17.eps

$\Delta\chi^2$ of Δm^2



ALL
SPECTRUM
FLUX
DAY/NIGHT

Other parameters are chosen to minimize $\Delta\chi^2$

1D plot - 2-flavor analysis

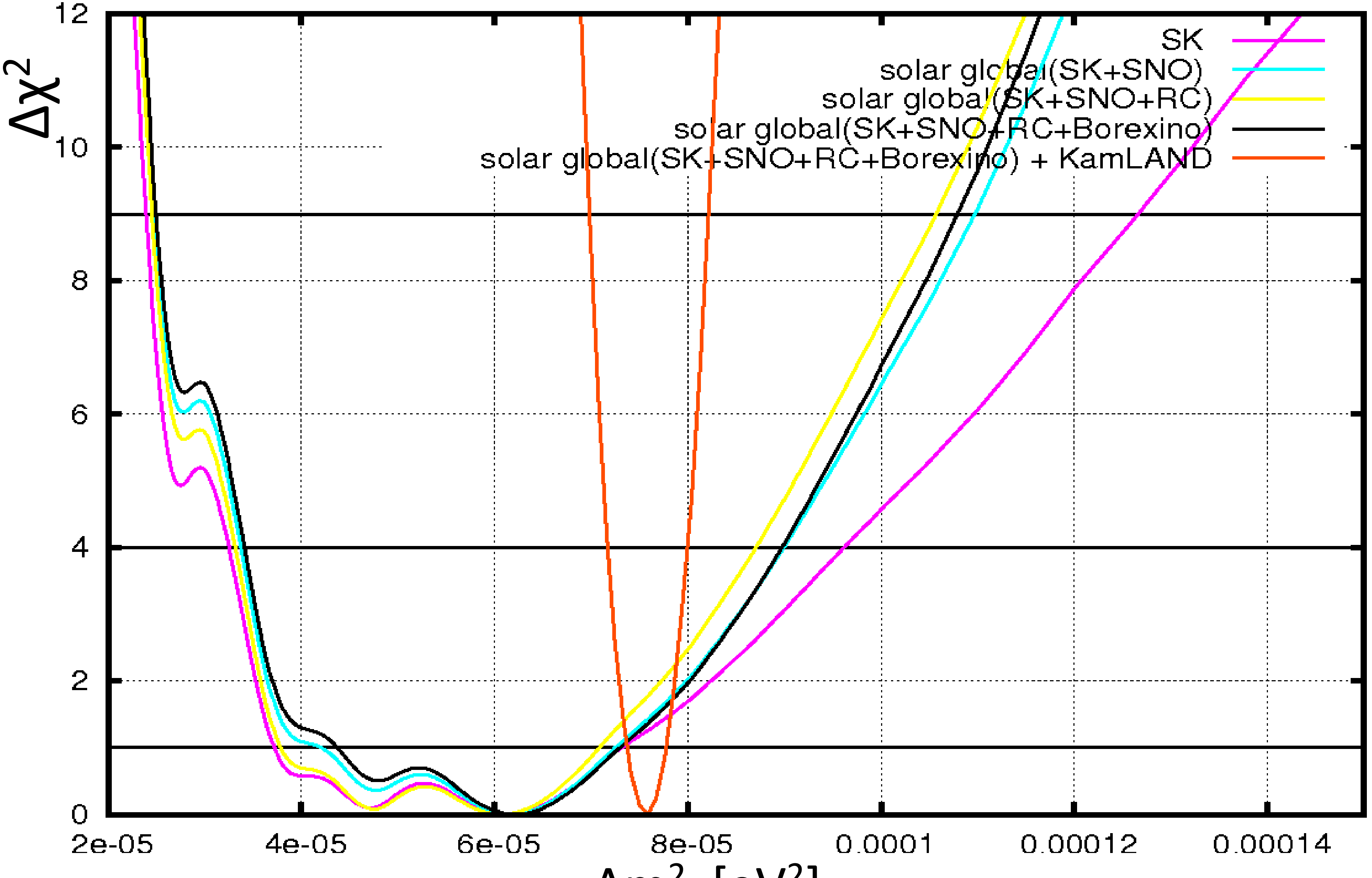
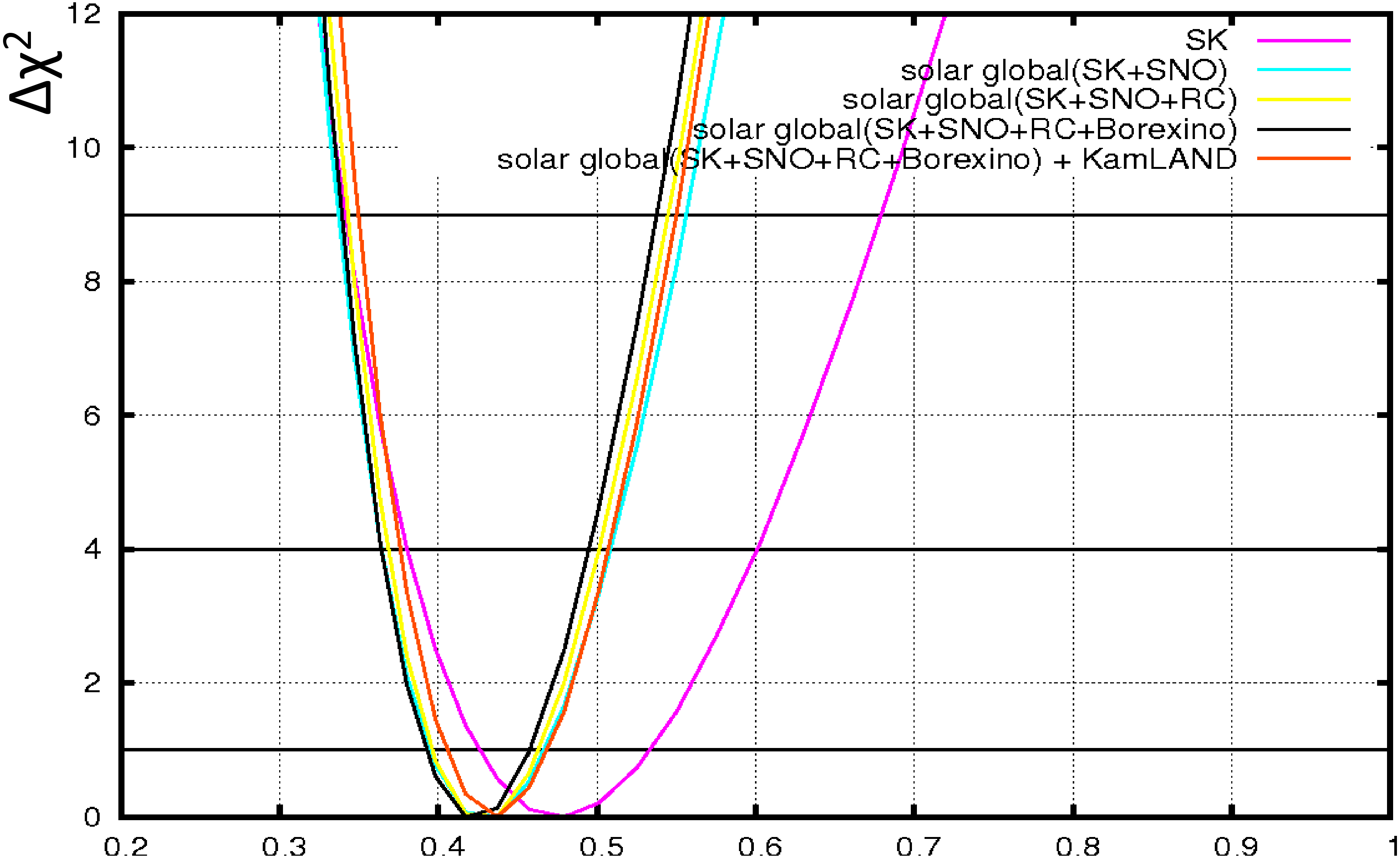


fig_13.ps

preliminary

1D plot - 2-flavor analysis

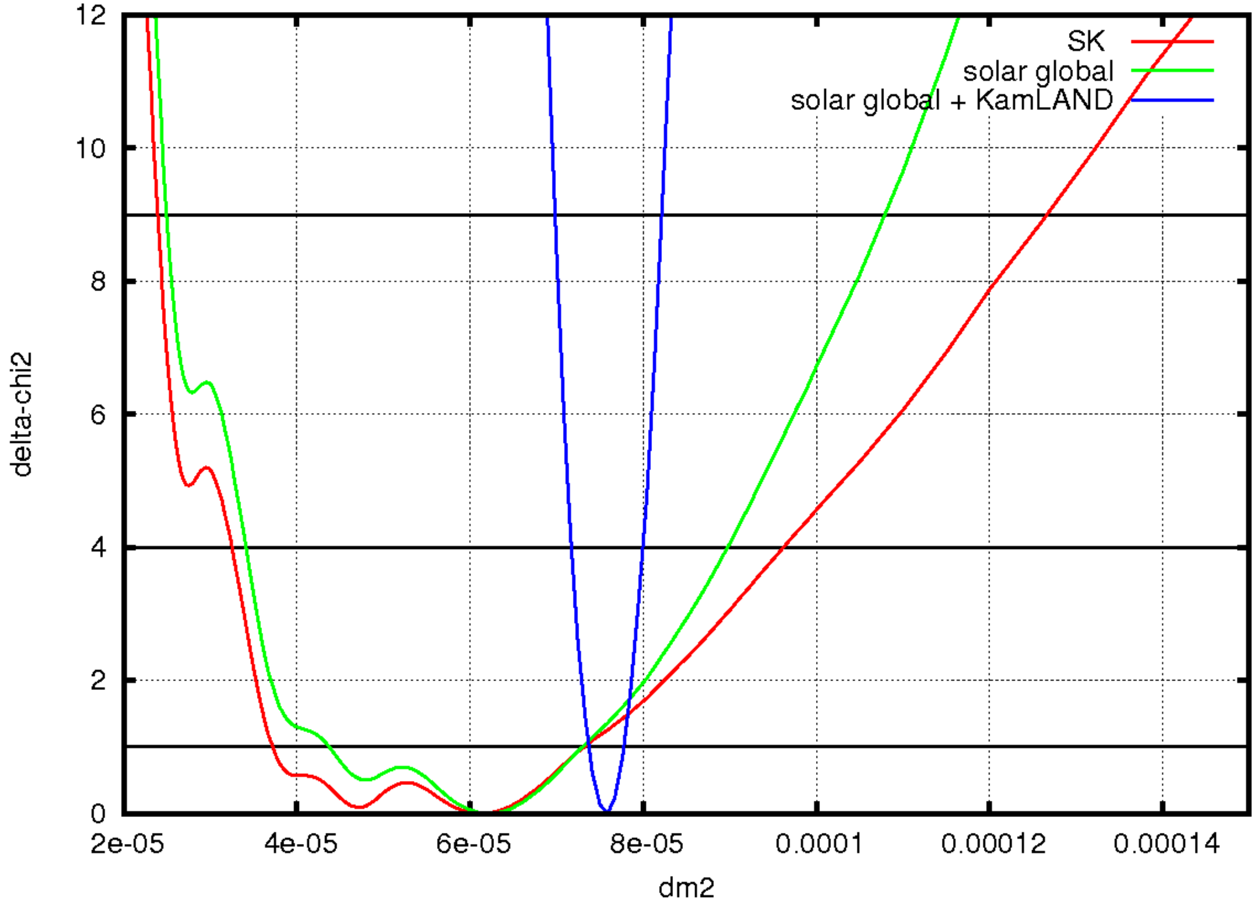


$\tan^2\theta$

preliminary fig_14.ps

1D plot 3-flavor analysis

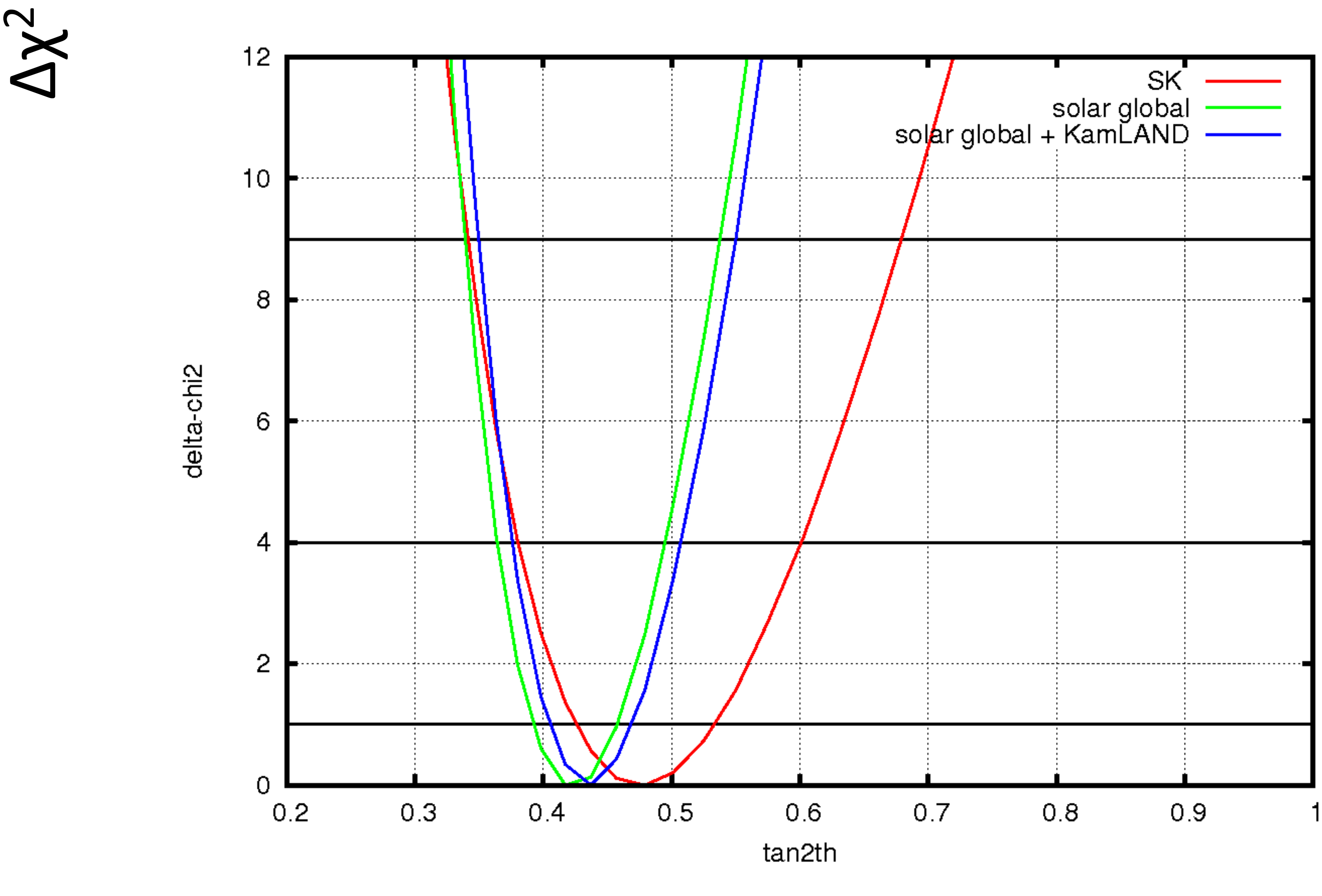
$\Delta\chi^2$



Δm^2 [eV^2]

preliminary

1D plot 3-favor analysis



preliminary

3f analysis parameters

Oscillation parameter in 3f analysis

– **θ_{12}、θ_{13}、Δm_{12} (θ_{12} Δm_{12}:LMA, $\sin^2\theta_{13}$ =0-0.1)**

- $\Delta m_{23}=2.4\times 10^{-3}eV^2$
- θ23=2/Pi, CP=0, Normal Hierarchy

1D plot – 3-flavor analysis