Solar neutrino results from Super-Kamiokande

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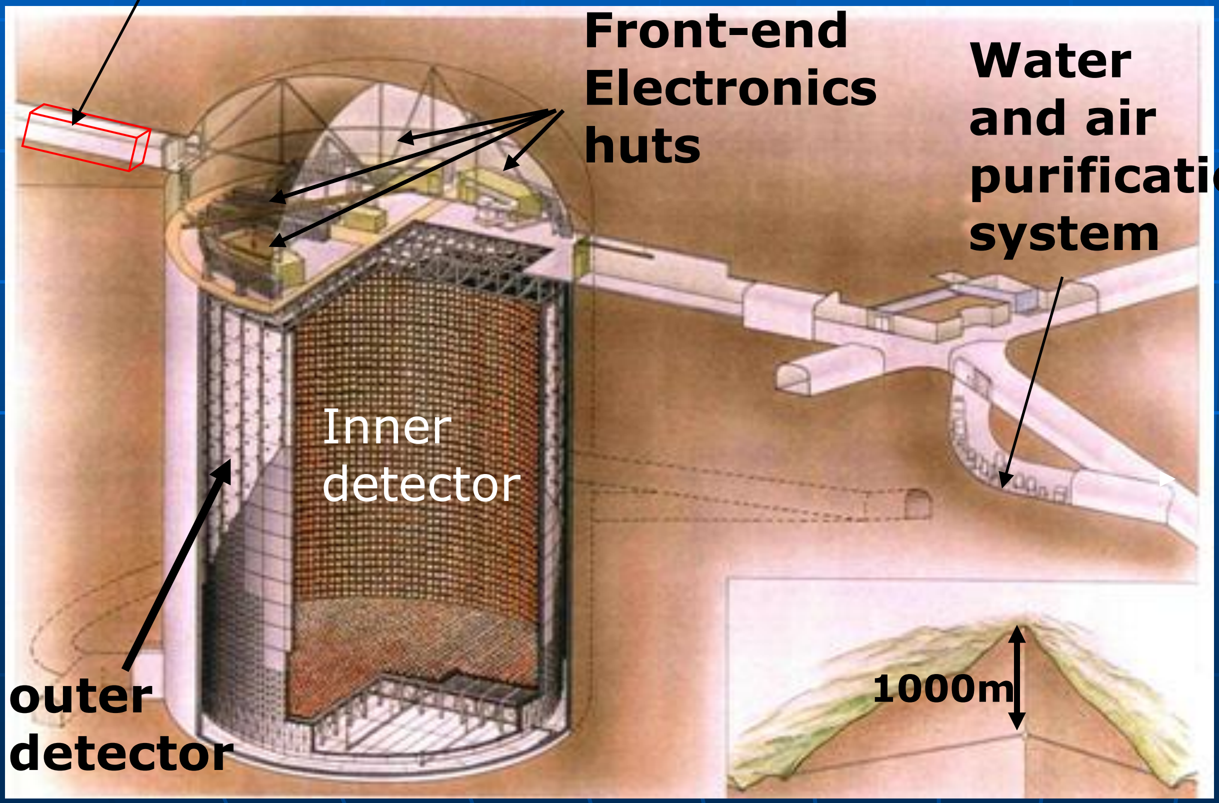
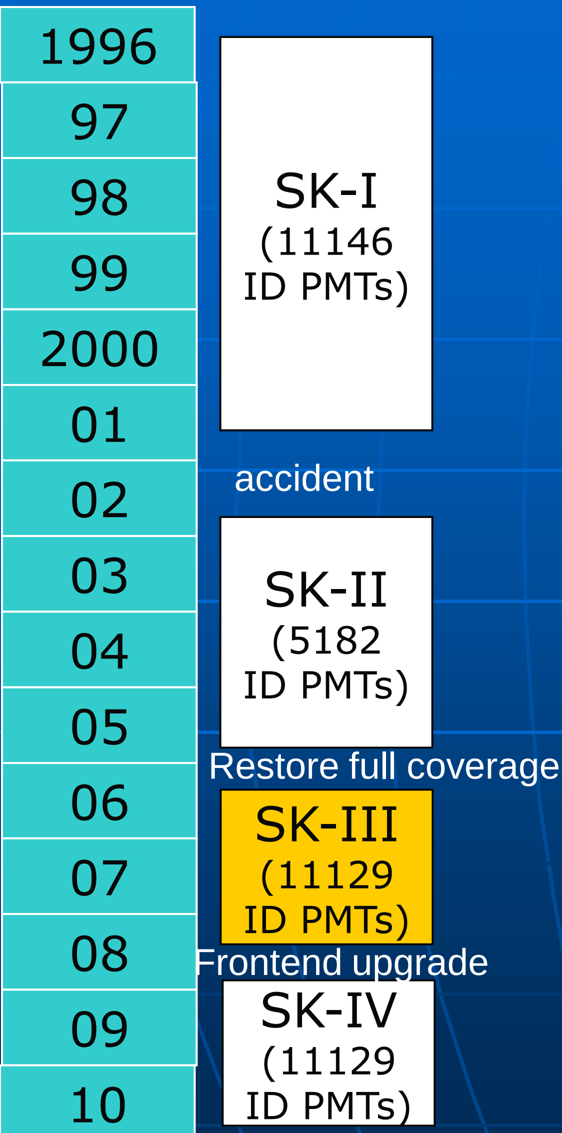
1, SK solar neutrino measurement

Super Kamiokande detector



- 50 kton water Cherenkov detector at 1000m underground (2700 w.e.)
- 32kton inner detector: 11129 PMTs (20inch)
- Fiducial volume : 22.5kton (2m from the wall)
- Outer detector : 1885 PMTs (8inch) for cosmic ray muon veto

Super Kamiokande experiment



1996 started on April
1998 Observed atmospheric neutrino oscillation
K2K experiment
2001 Solved solar neutrino problem together with the SNO CC result.
2008 Upgrade of front-end electronics and DAQ system
2009- T2K experiment

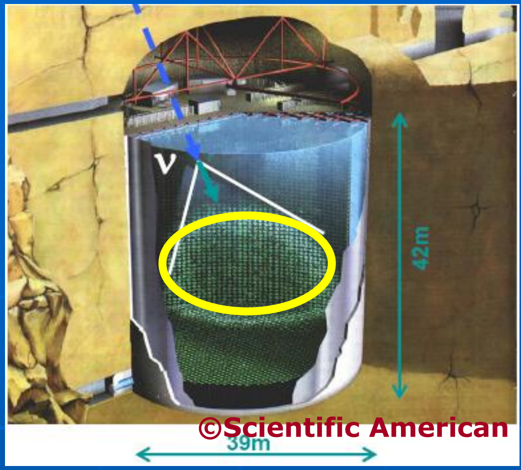
Physics

- **Solar neutrino measurement**
- Search for neutrino from supernova
- Atmospheric neutrino oscillation
- Neutrino from accelerator

- Proton decay search
- Indirect WIMP search

Solar Neutrino measurement at Super-K

ν + e⁻ -> ν + e⁻ (elastic scattering)

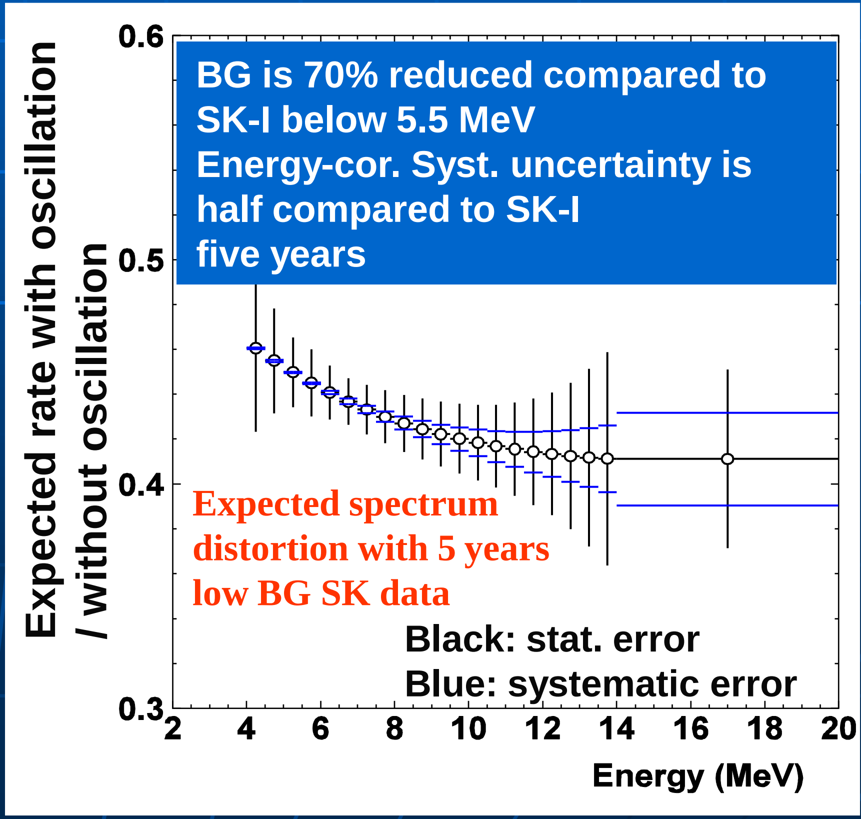


- Measure Cherenkov ring pattern from recoiled electron

- Timing information -> Vertex of interaction
- Hit pattern -> Direction
- # of hit PMTs -> Energy

- High statistics for ^{8}B neutrino (~15evnts/day for E_e > 5MeV)
- good angular resolution

Goal:
- Precise measurement of the solar neutrino parameters (flux, timing variation, oscillation parameters etc)
- Reduce the b.g. level and measure the upturn in the solar neutrino spectrum .



2, Recent SK solar neutrino analysis (SK-III phase)

http://arxiv.org/abs/1010.0118

Data set

SK-III period: 2006/8/5-2008/8/18
(live time : 548 days, E≥6.5 MeV,
289 days, E< 6.5MeV)
2006/8/5-2007/1/24 : 100%eff @6.5MeV
livetime 121.7 days
2007/1/24-2008/4/17 :100%eff @5.0MeV
livetime 331.5 days
(RR sample ❖ 210.7day)
2008/4/17-2008/8/18 : 100%eff @4.5MeV
livetime 94.8 days
(RR sample 87.5day)
❖RR sample : Radon Reduced sample for which high background rate periods are rejected from the normal run

Improvements in SK-III solar ν analysis

- Reduce Low energy BG ~70%
- Improved Systematics ~50%

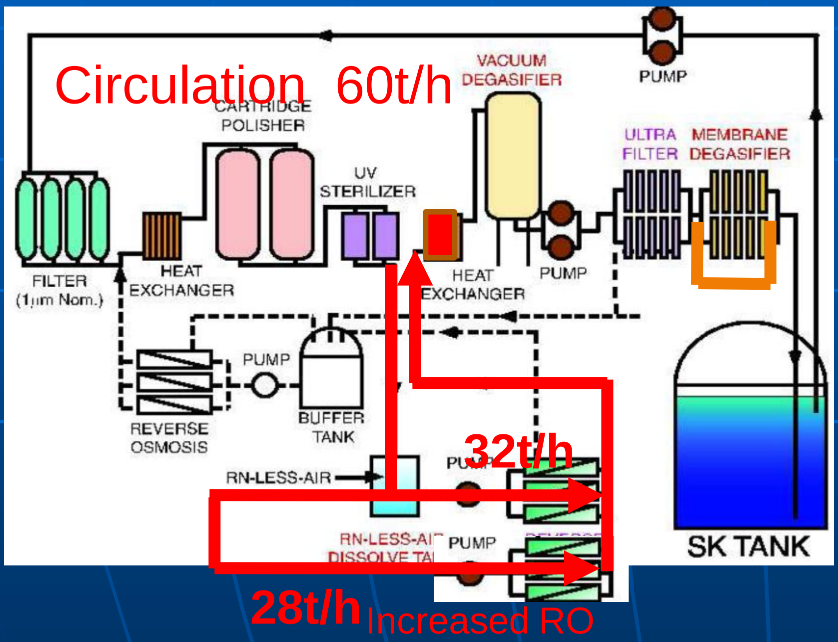
2-1, Reduction of background

Improvement of water circulation and purification system

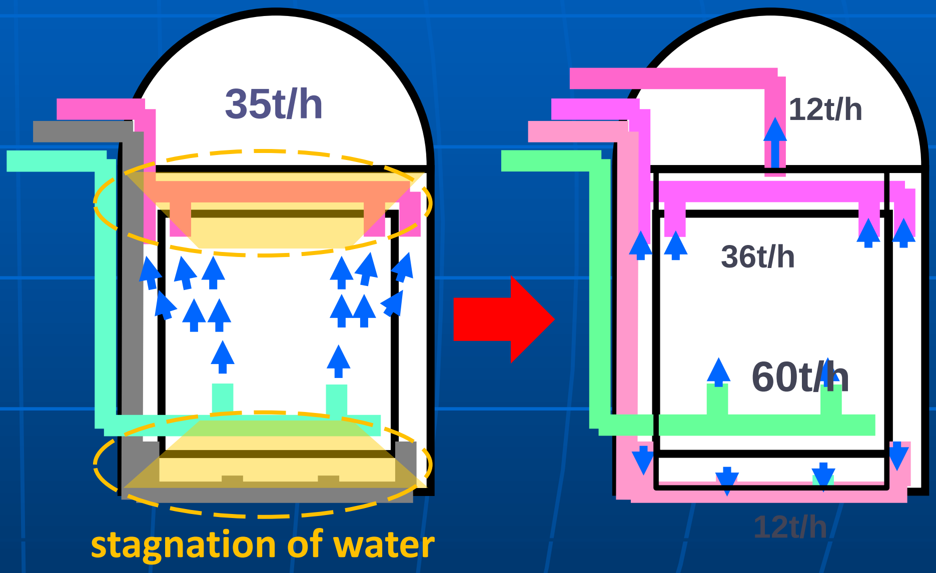
1, Improved water quality

Doubled circulation rate

Increased purification power

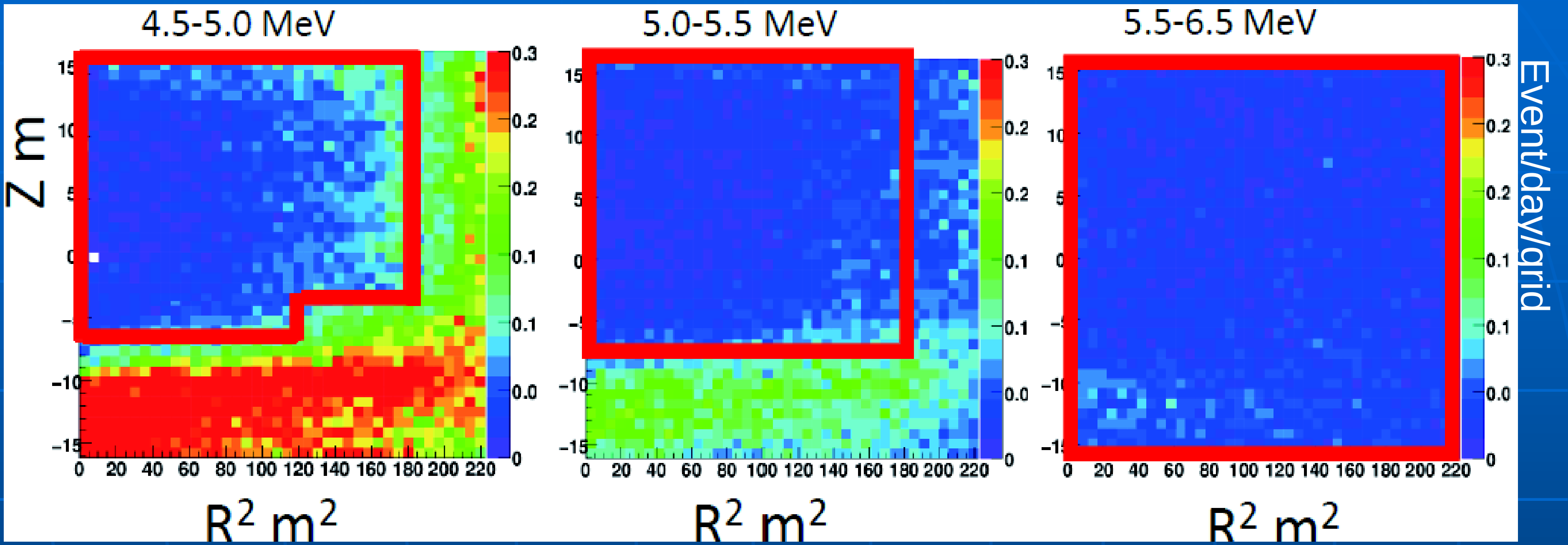


2, Optimized water flow in the tank



→ Lower Rn concentration in fiducial volume

Vertex distribution of final sample

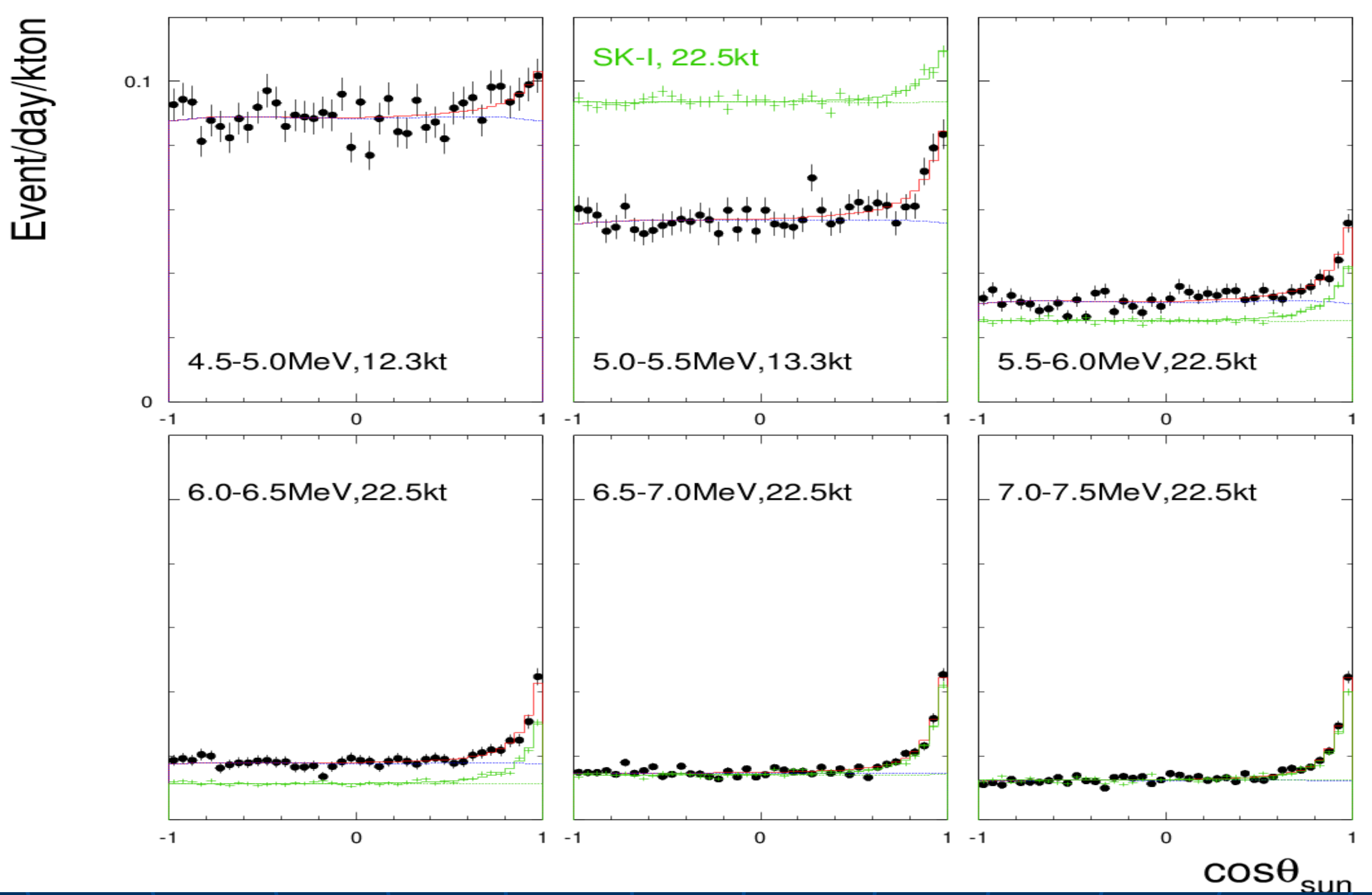


Fiducial volume of each energy region is shown as red box:
12.3kt (4.5-5MeV), 13.3kt(5-5.5MeV), and 22.5kt(5.5-20MeV)

With upgrade of water system, water with higher radioactivity stays near bottom region.
-> by applying tighter fiducial volume cut, low b.g. rate can be achieved for 4.5-5.5MeV region

Comparison of background rate between SK-I and III

Solar angular distribution for each energy range.

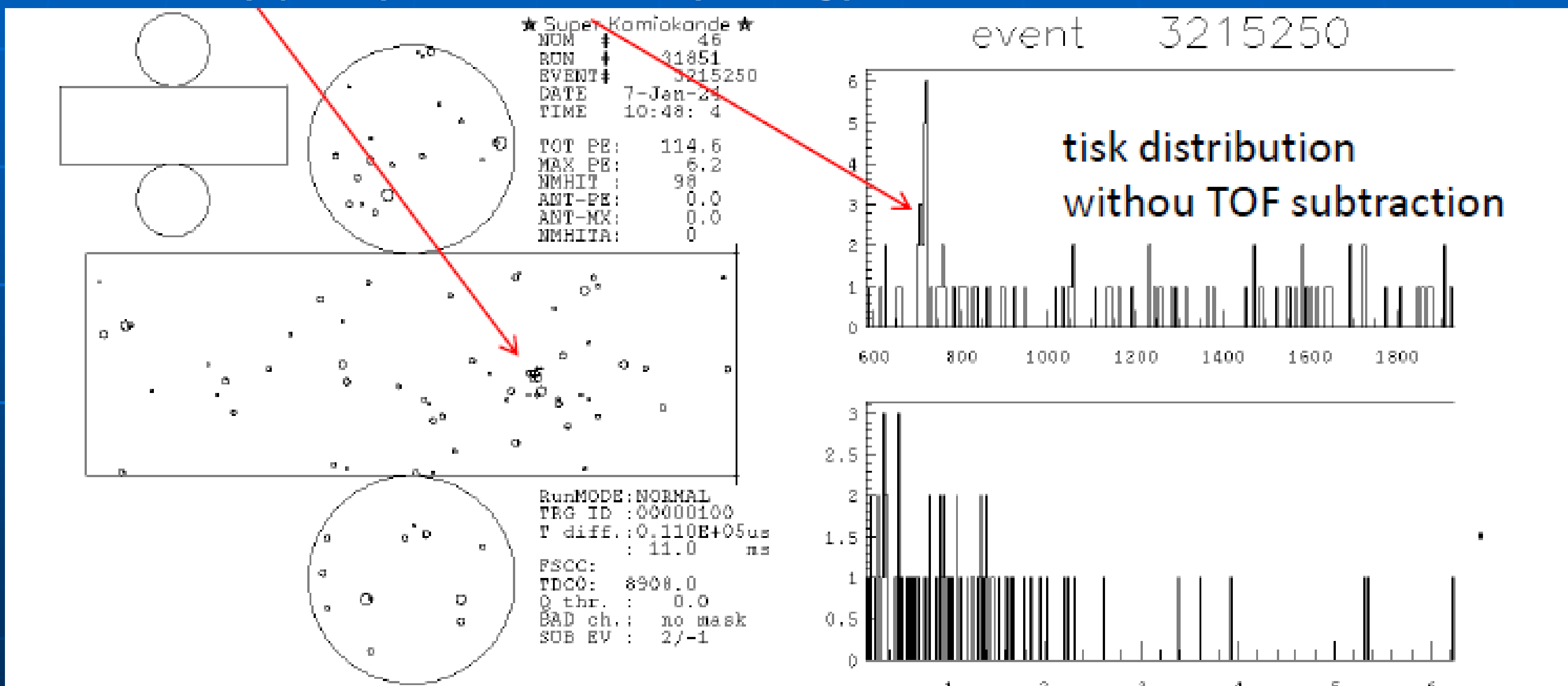


In lower energy region with tighter fiducial volume cut, SK-III has a lower b.g. rate due to lower radon concentration in water around the central region of the detector.

New cut for low energy events

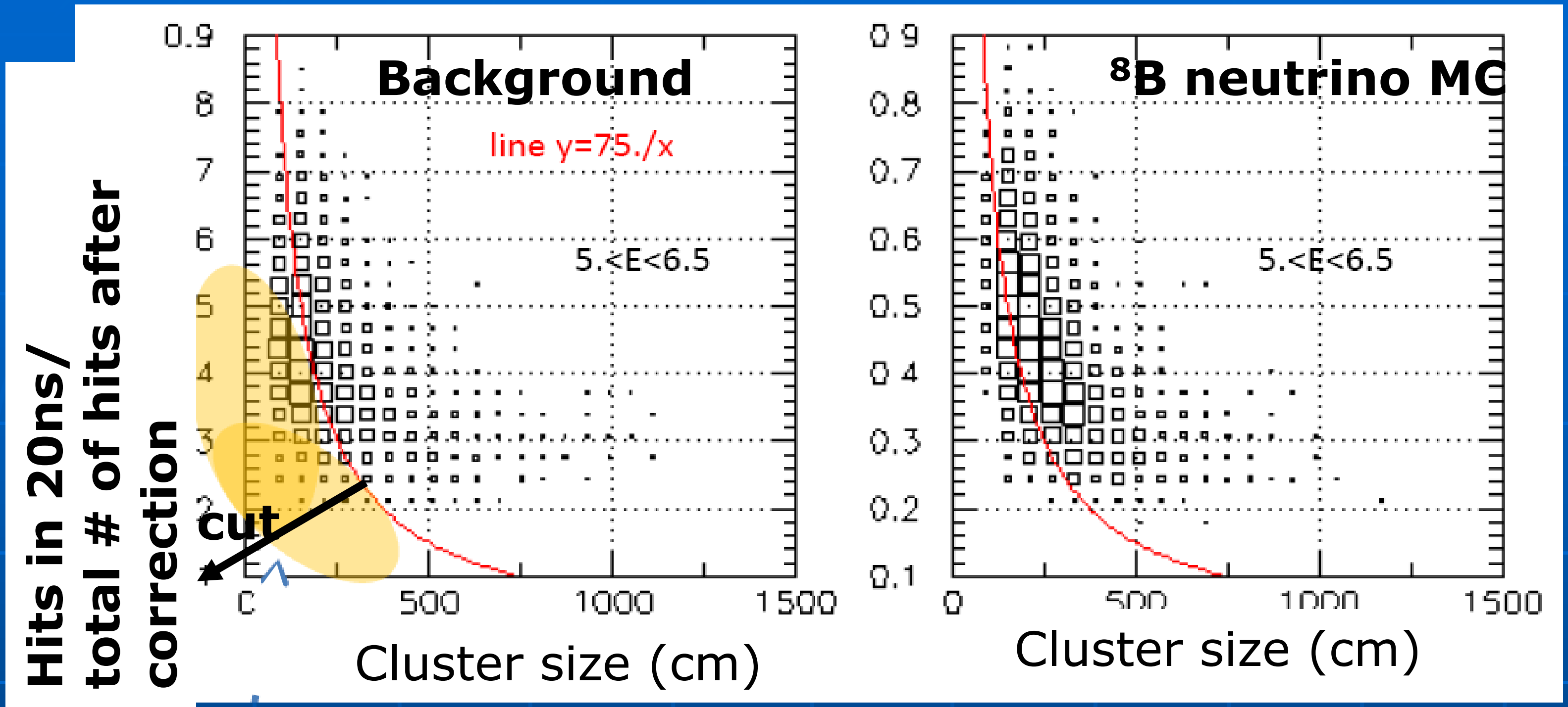
Background events coming from radioactive sources in FRP cover of PMTs or wall have small clusters in space and timing distribution, when compared with neutrino events near the wall.

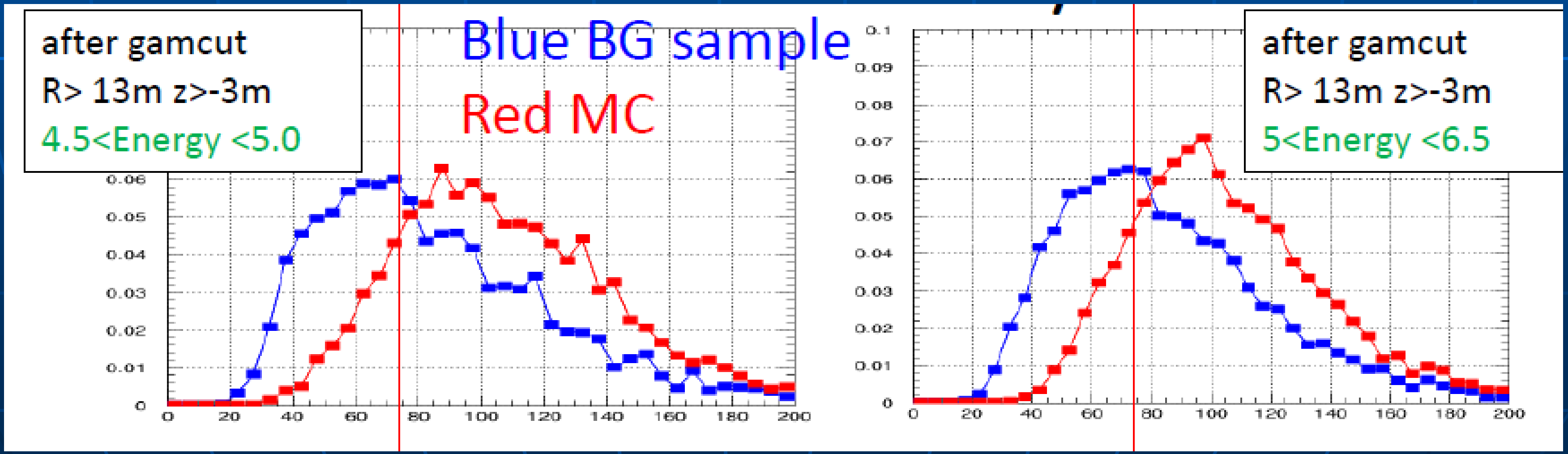
Cluster(space) Cluster(timing)



-> Use variables related with cluster size for b.g. reduction.

New cut for low energy events(cont'd)





Horizontal axis : Cluster size * concentration in timing distribution

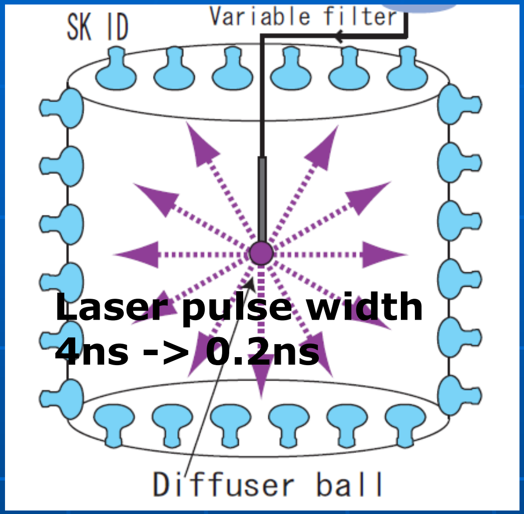
2-2, Improved systematics

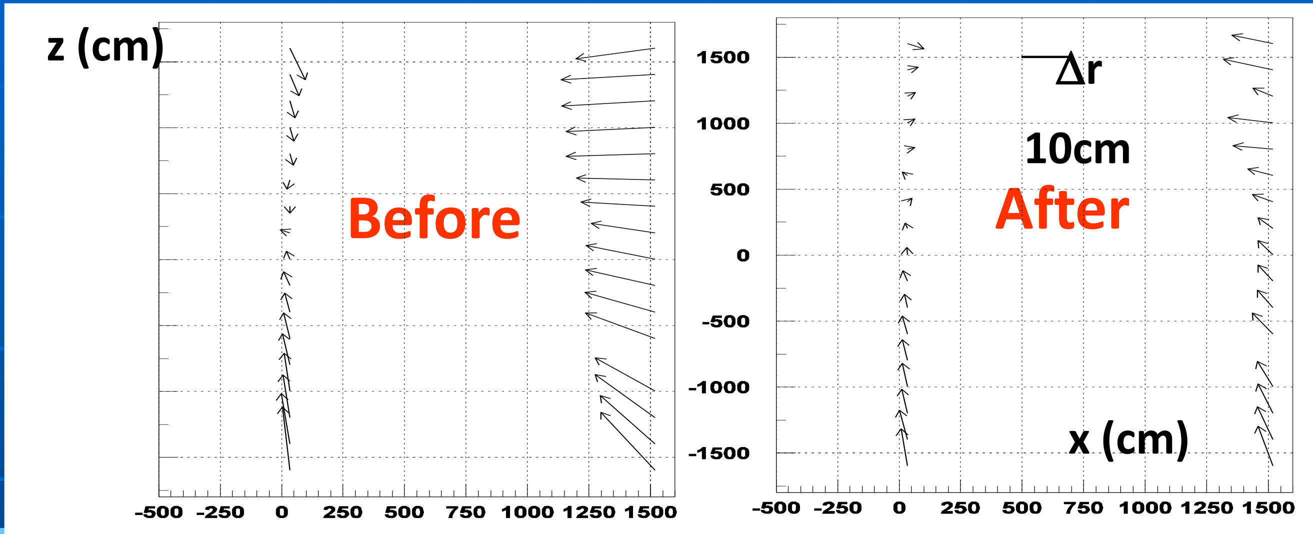
Timing Calibration improvement

New hit timing correction is installed.

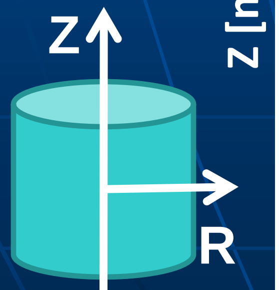
Electronics linearity is corrected by this correction

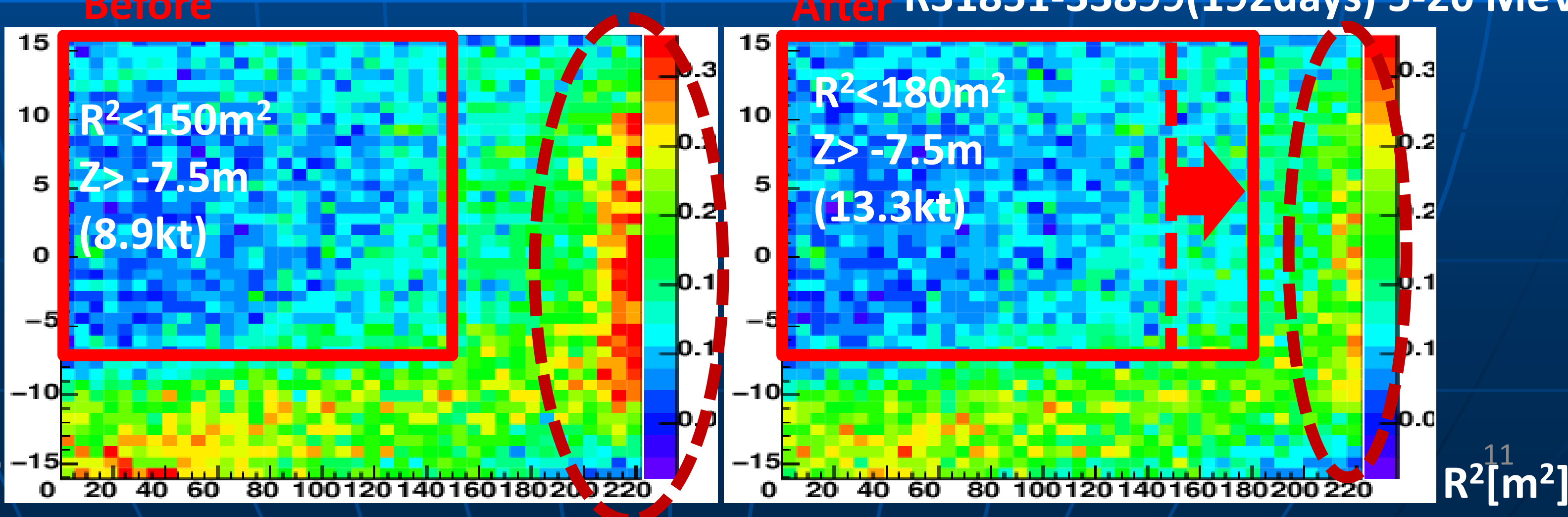
Improve systematics (vertex shift)





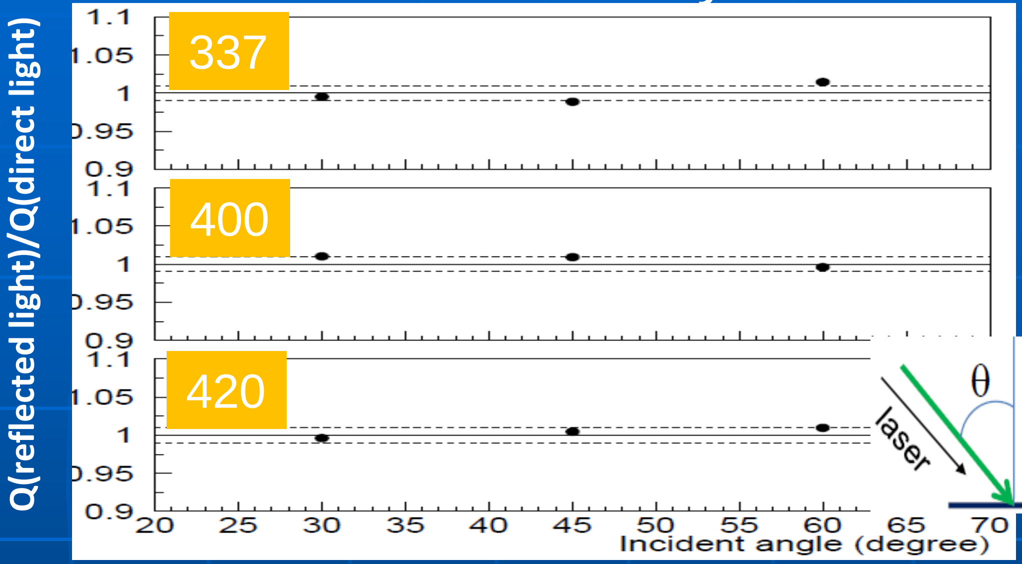
Reduce low energy BG





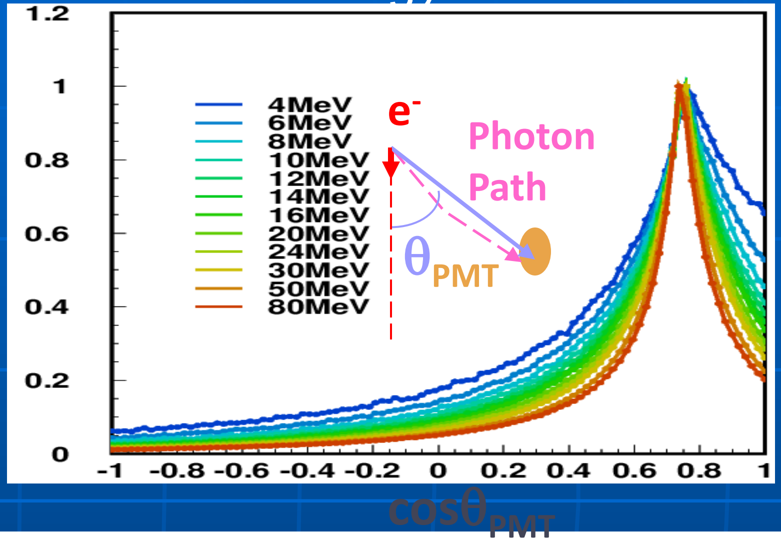
Angular reconstruction

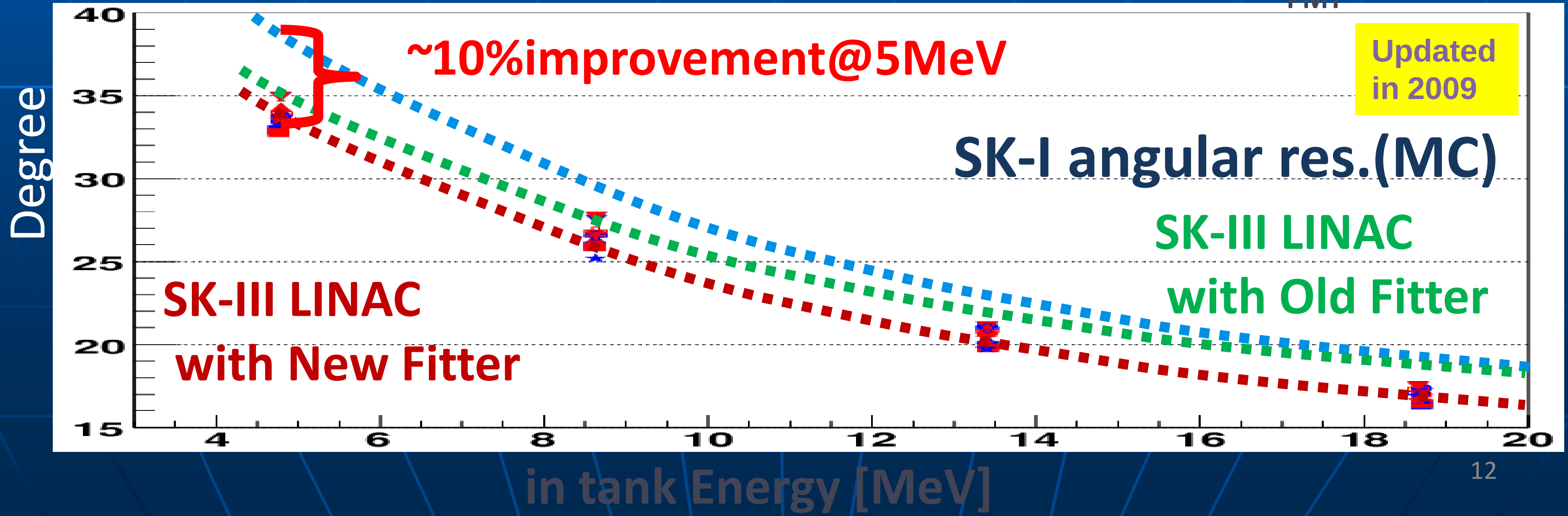
Calibration&MC tuning: black sheet reflectivity



Improving direction fitter

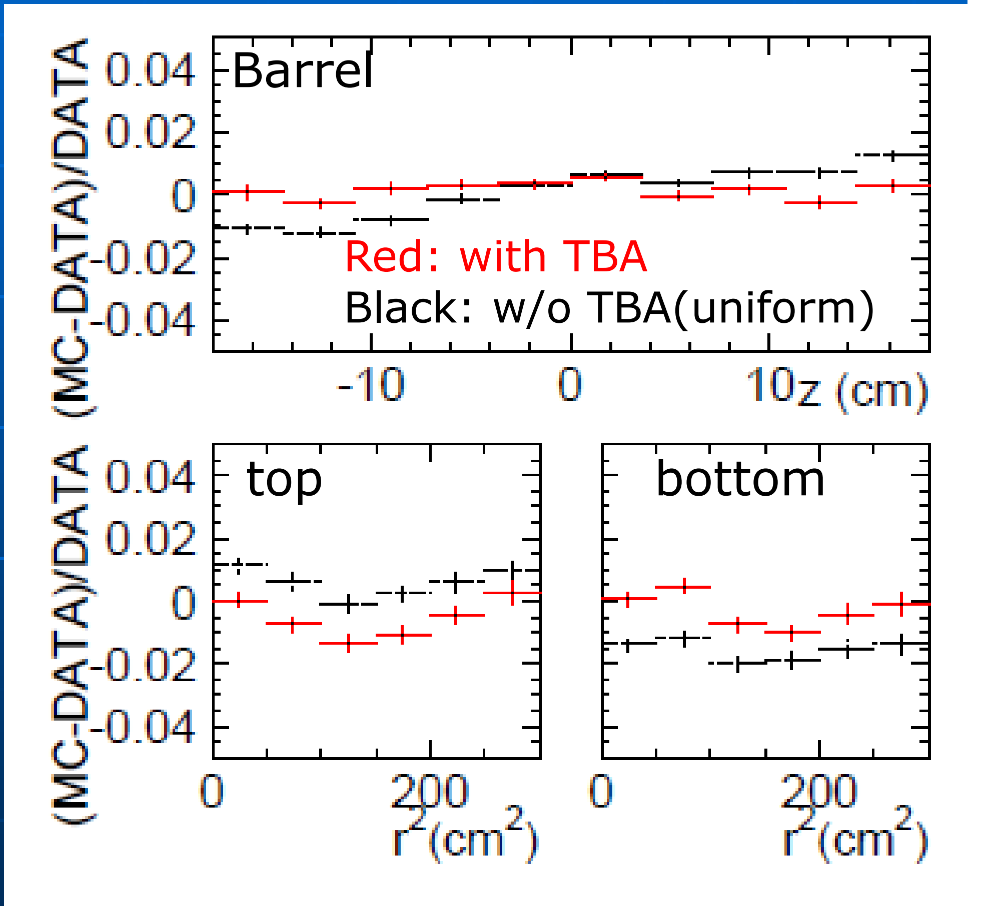
Made likelihood functions for different energy bins from MC



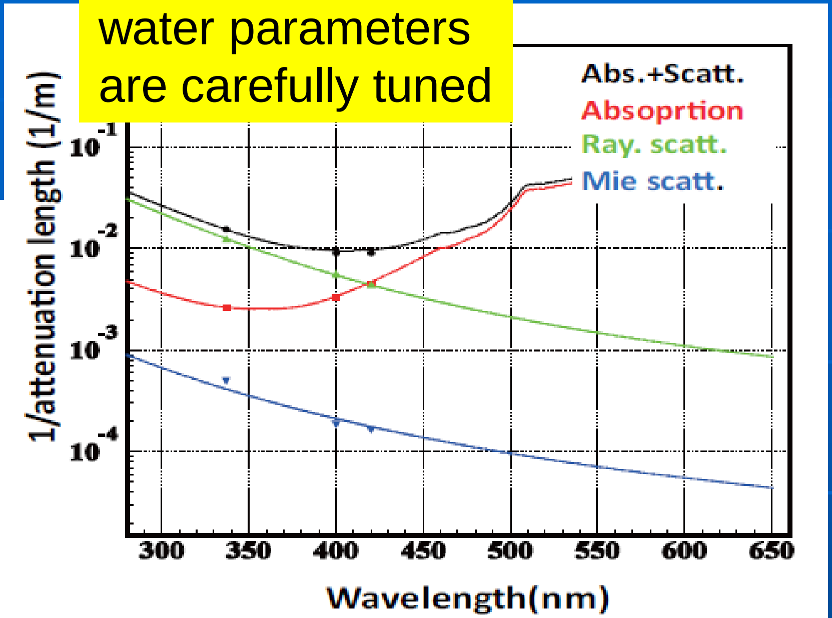


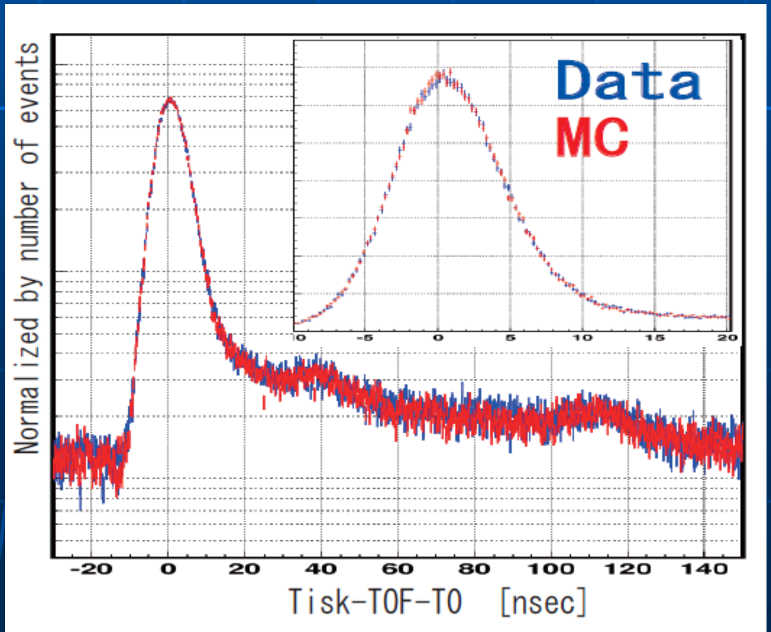
MC improvement

Top-bottom asym.(TBA) parameter is newly installed in SK-III MC's water transparency parameters



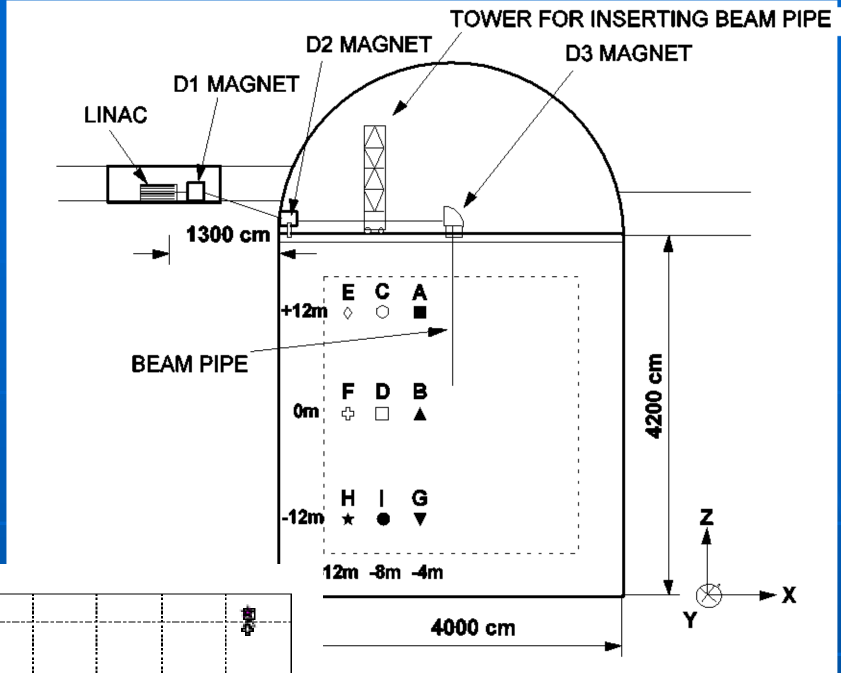
water parameters are carefully tuned

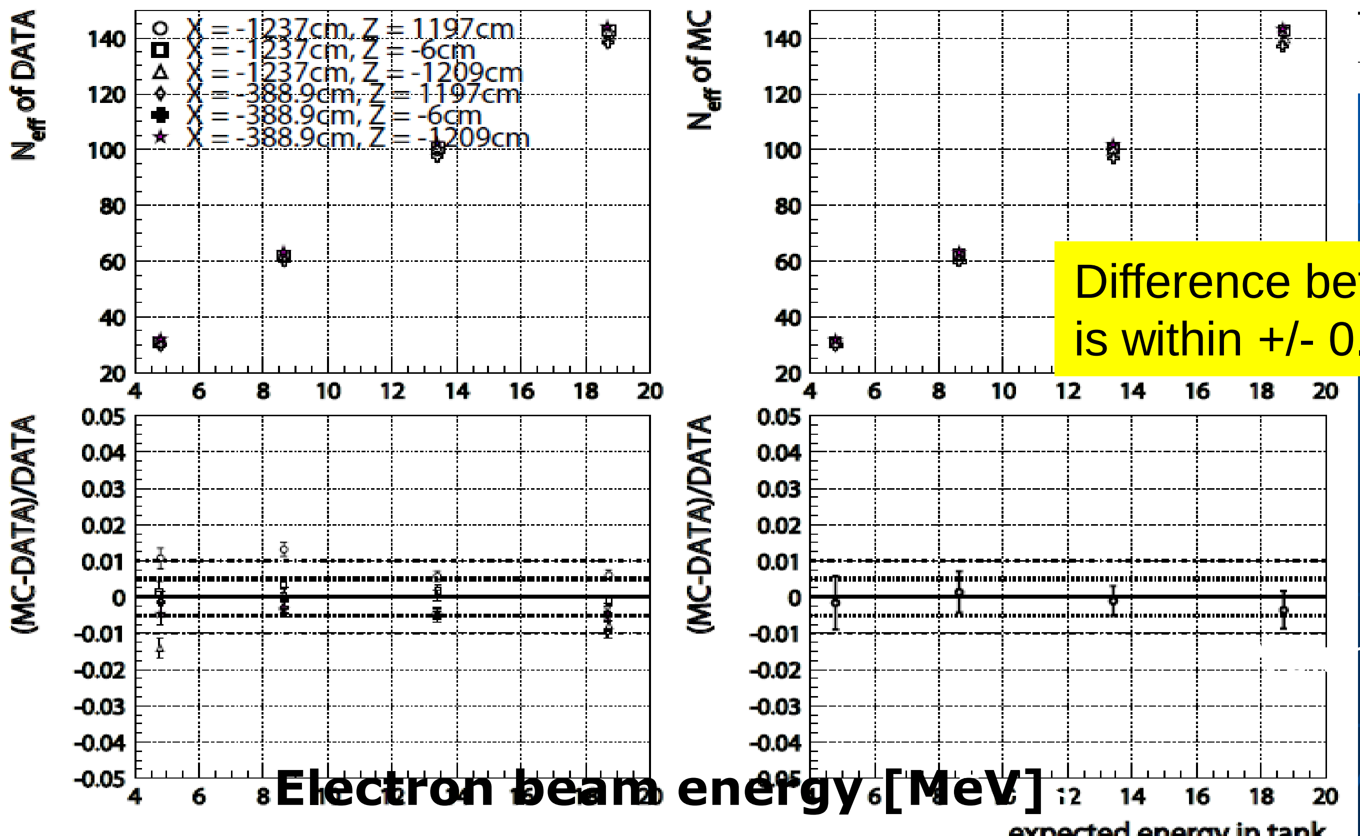




MC hit timing distribution of LINAC is perfectly matched to DATA

Energy scale





Difference between MC and DATA is within +/- 0.5%

me average

Electron beam energy [MeV]

Table of systematic uncertainties

	SK-III (Preliminary)	SK-I
Energy scale	+/-1.4	+/-1.6
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
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
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%

Timing calibration

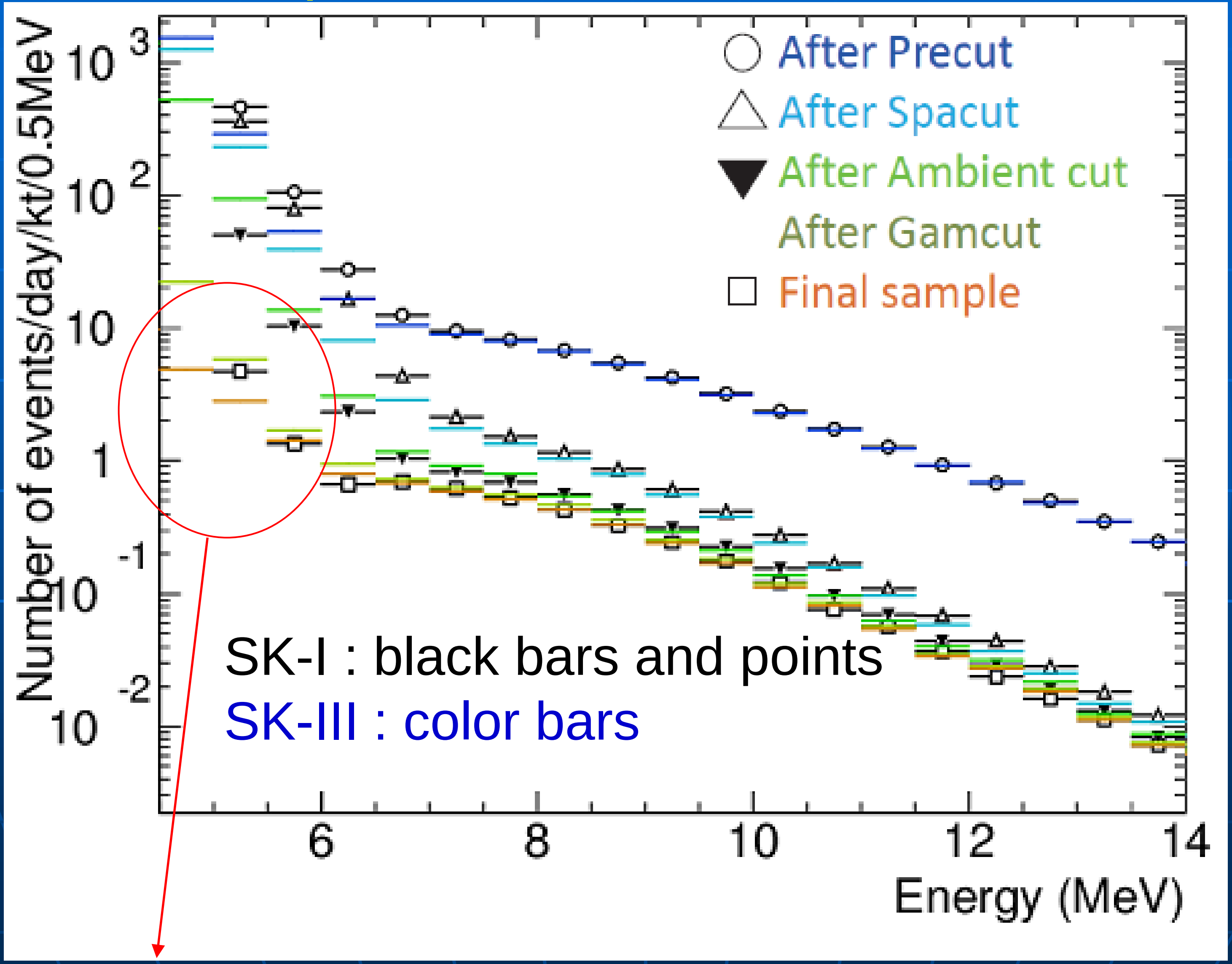
Improvement of reduction tools and MC

Improvement Direction fitter

Due to Improvement of detector MC, reconstruction tools and calibration, systematic errors were reduced from +3.5/-3.2%(SK-I) To +-2.1%(SK-III). -> ~60%

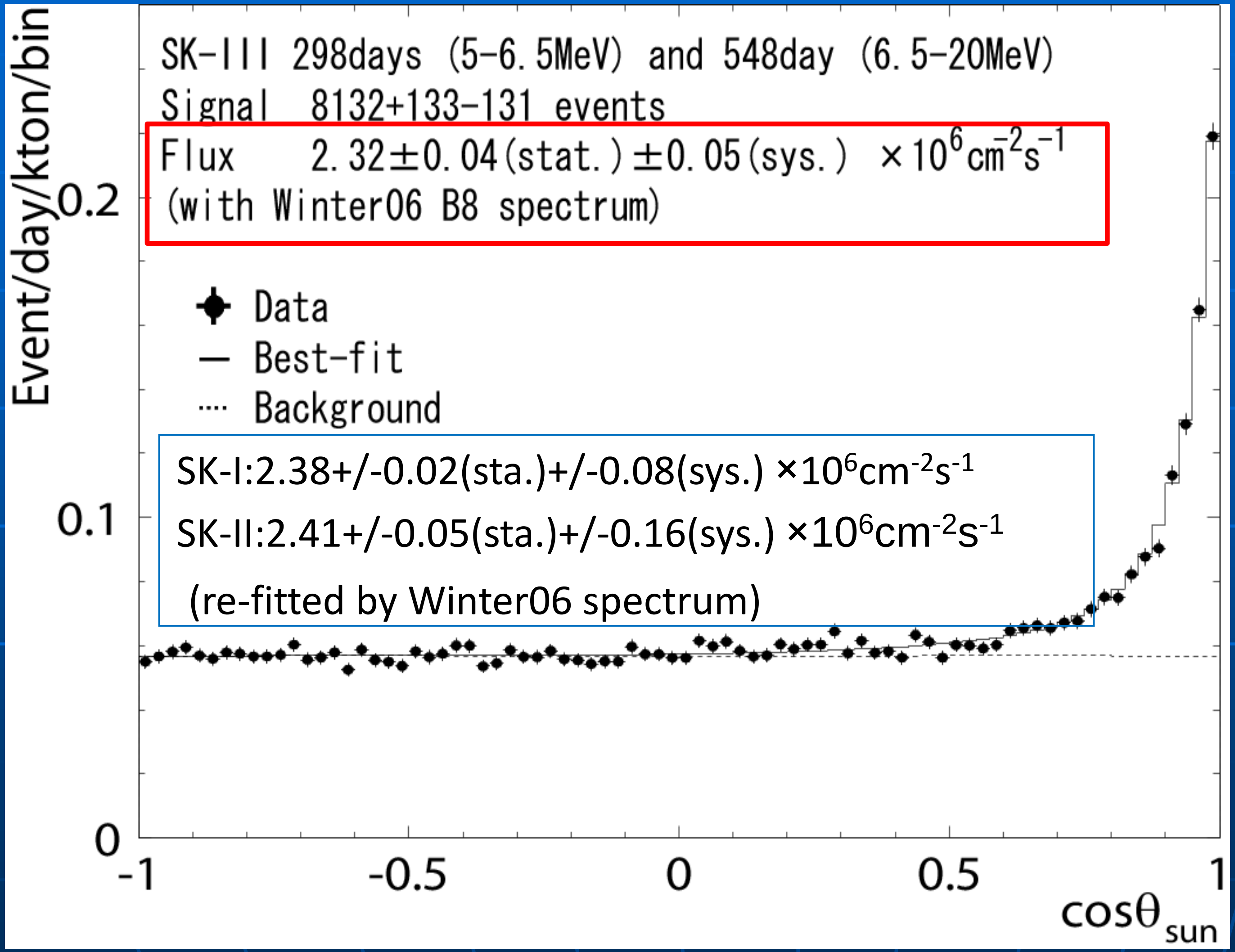
3, Solar neutrino results in SK-III

Reduction step



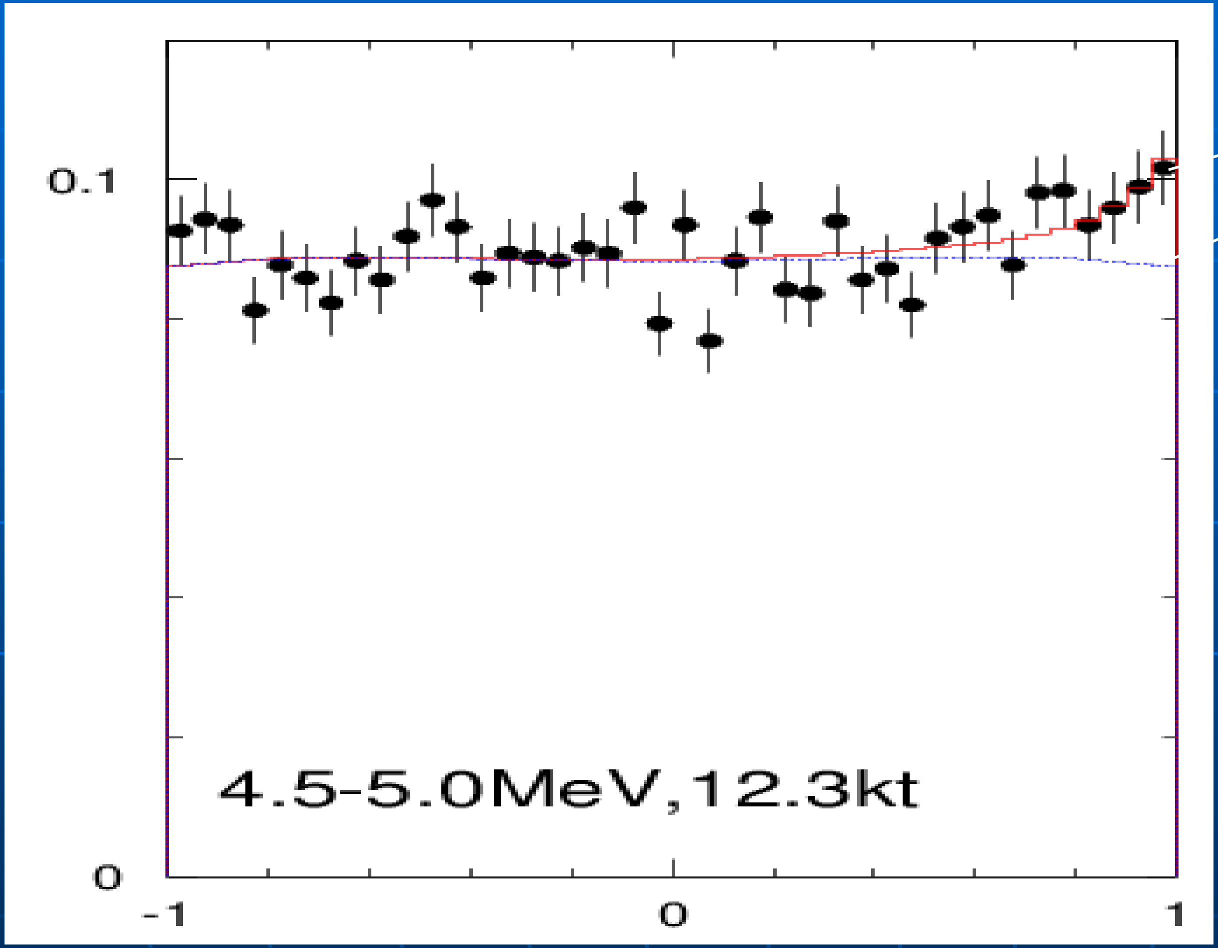
For lower energy region, SK-III has lower b.g. level than SK-I.

Solar neutrino flux for E=5-20MeV



- SK-III result is Consistent with SK-I and II.
- Systematic error is reduced.

Angular distribution for E=4.5-5.0MeV



RED: best fit curve

Blue: back ground

For 4.5-5.0MeV region,

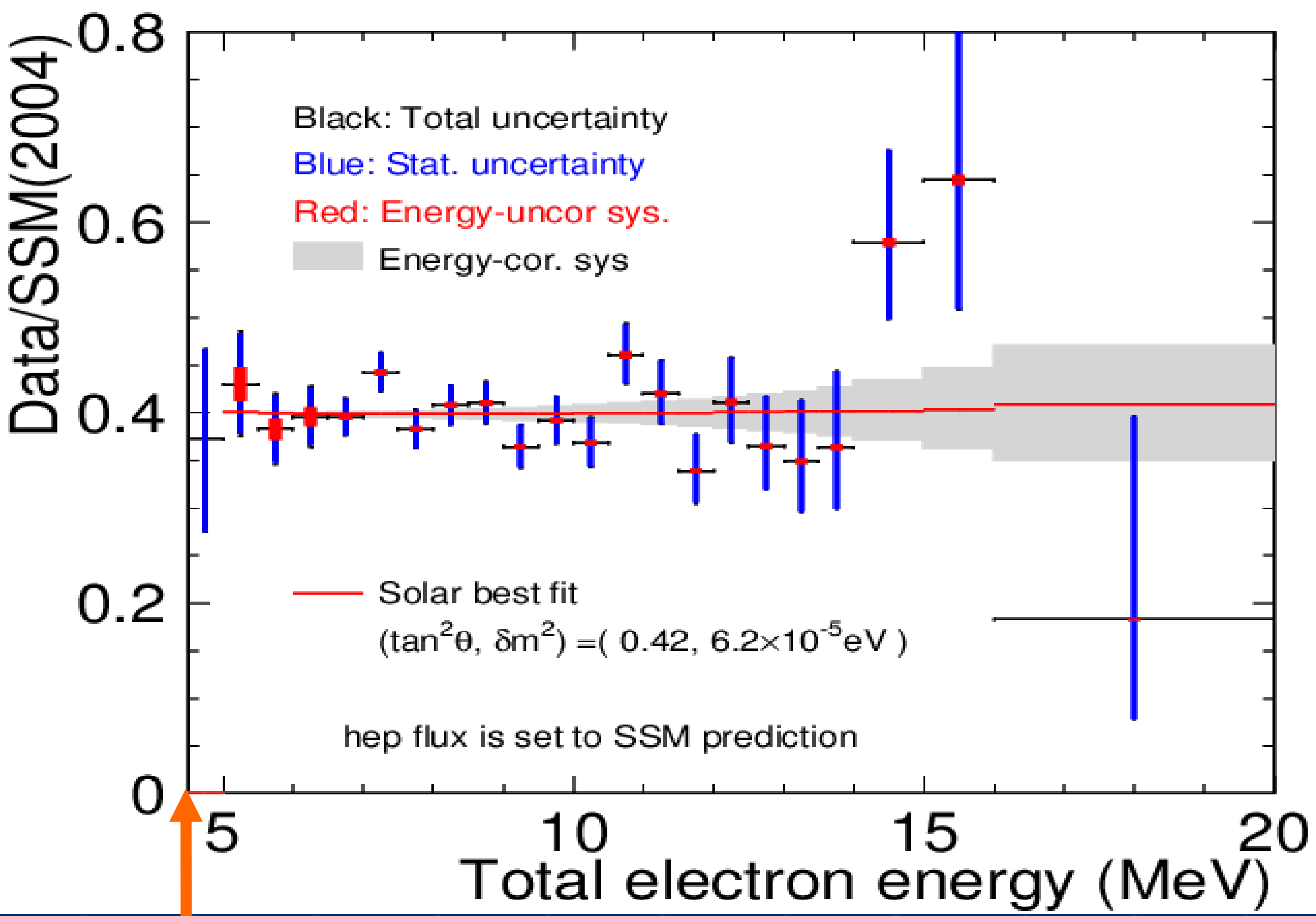
232. ±59. event

2.14 + 0.54-0.54(stat.)

$\times 10^{6} cm^{-2} sec^{-1}$

Solar neutrino in this energy region was measured with 4σ significance.

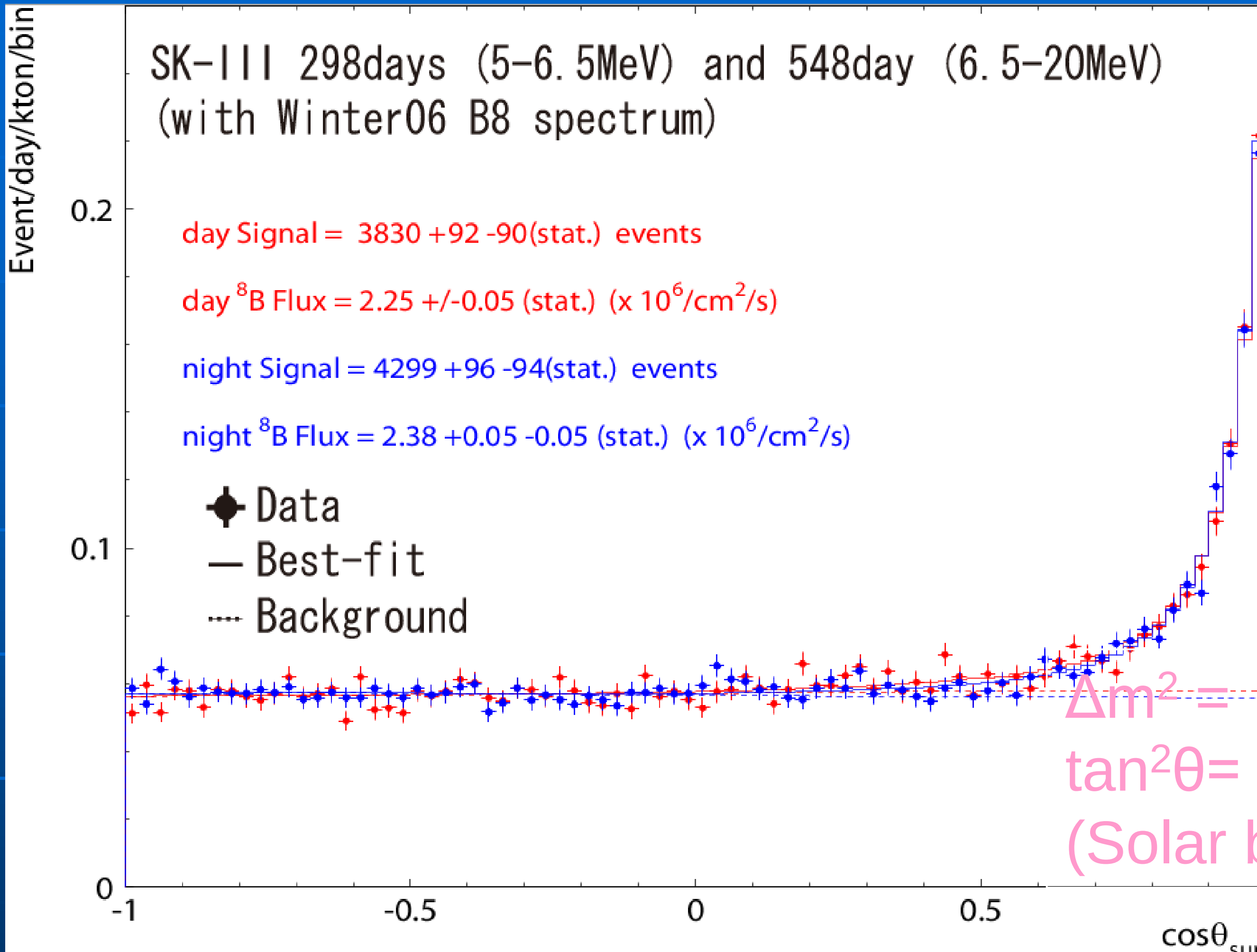
^{8}B Energy spectrum of SK-III data



4.5MeV (total energy)
4.0MeV(kinetic energy)

Consistent with
- SK-I result
- No distortion

Day/Night flux



$\Delta m^2 = 6.0\times10^{-5}eV^2$
$\tan^2\theta = 0.44$
(Solar best fit parameter)

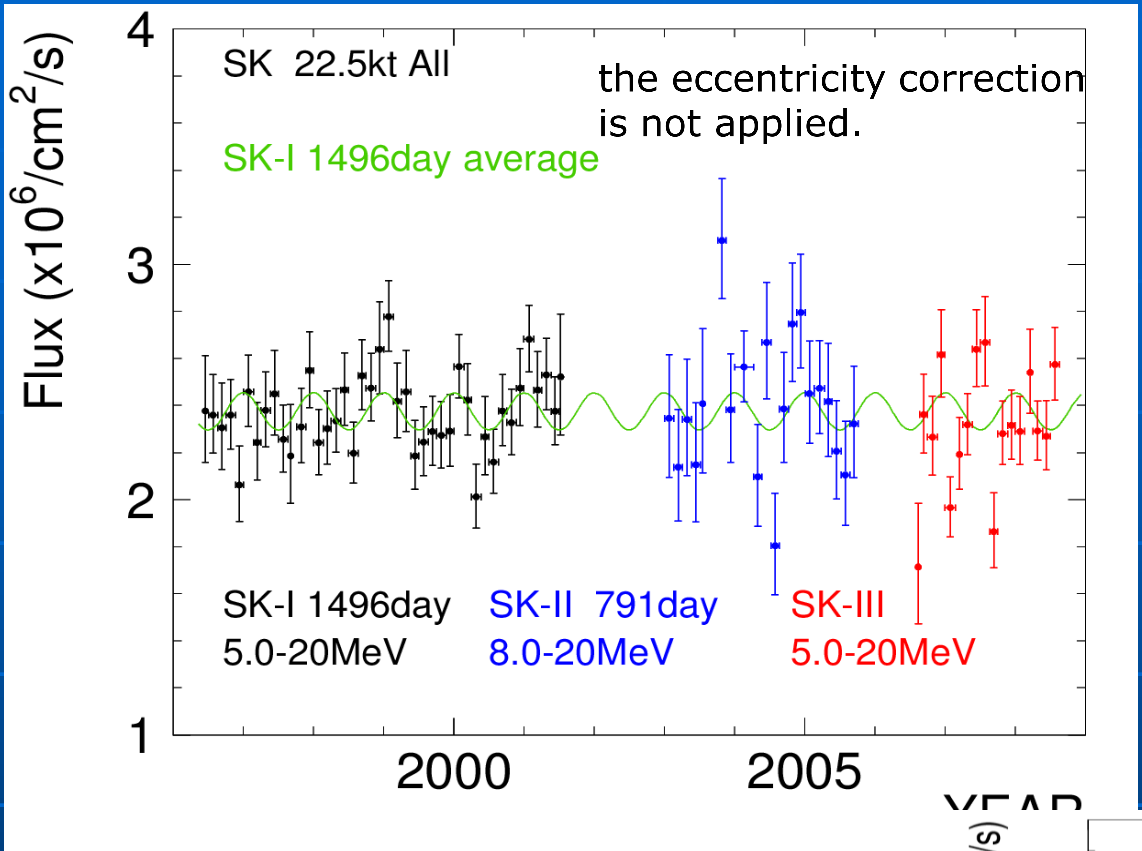
SK-I: $A_{DN} = -1.8 \pm 1.6 \; ^{+1.3}_{-1.2}\,\%$

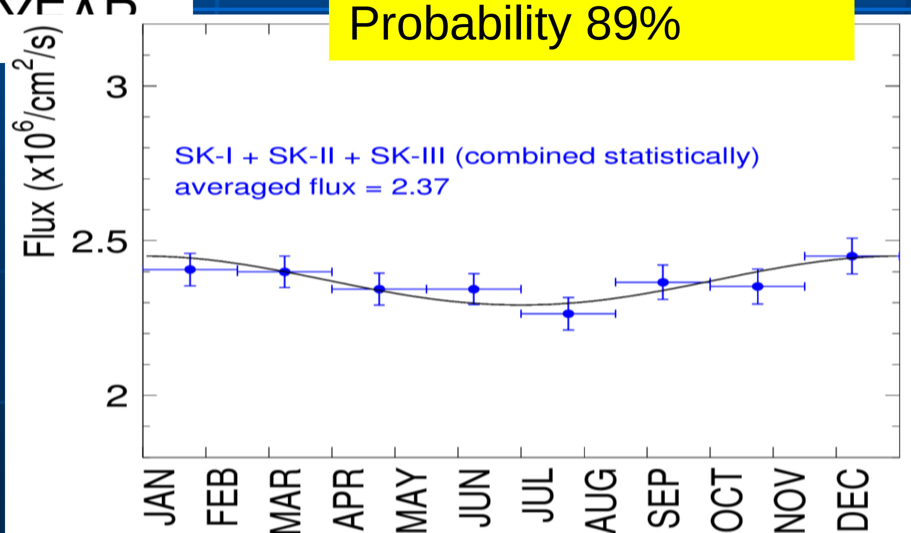
SK-II: $A_{DN} = -3.6 \pm 3.5 \pm 3.7\%$

SK-III: $A_{DN} = -4.1 \; ^{+2.5}_{-2.6} \pm 1.3\%$

combined: ADN=-2.3±1.3%(stat) sys : under study

Seasonal variation





SK-I,II,III
$\chi^2 = 3.6$
(only stat)
With dof = 7
Probability 89%

Consistent with the eccentricity of the orbit

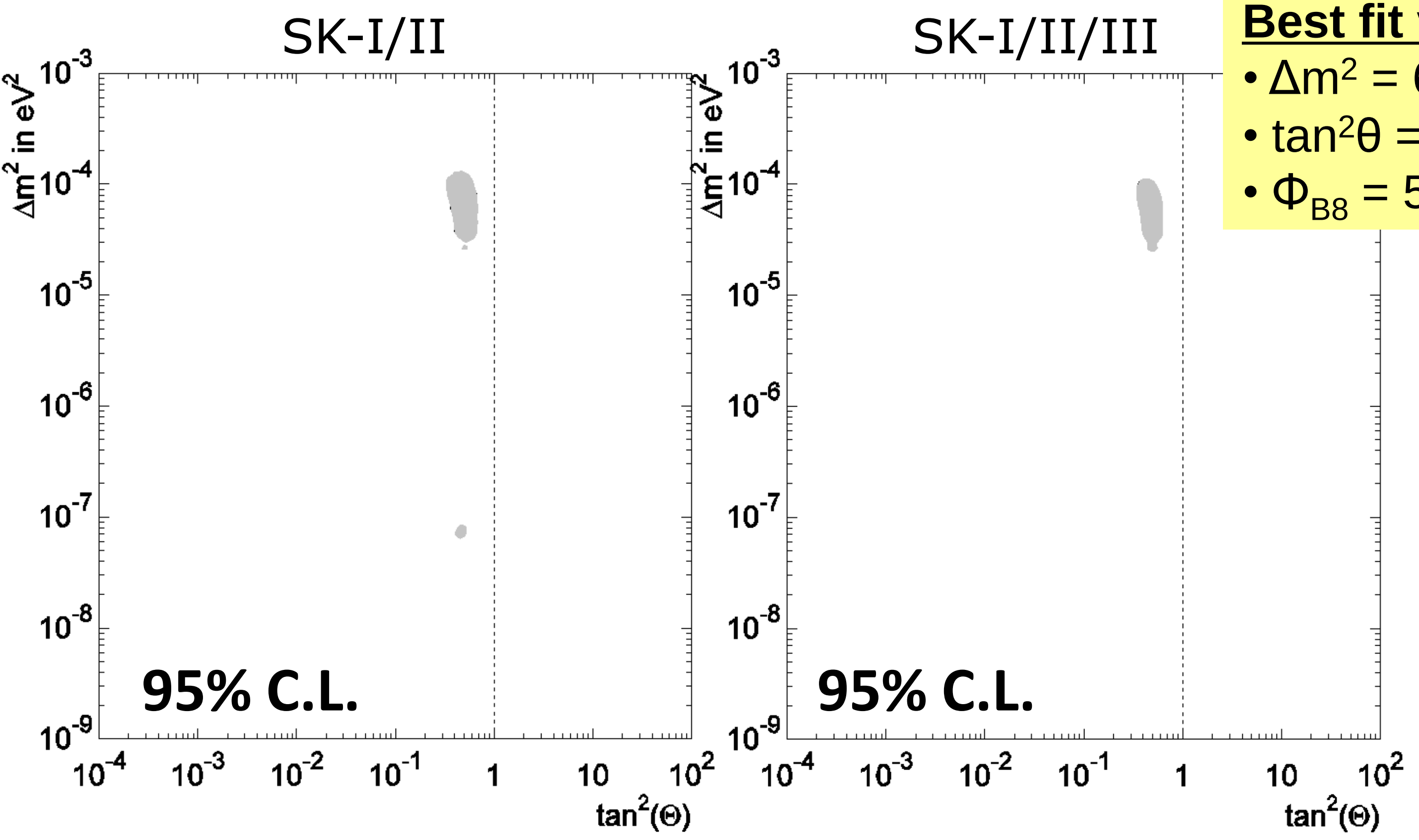
4, Oscillation results

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

- 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**

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

Hep is constrained by SSM flux with uncertainty(16%)



Best fit value (preliminary)

- Δm^2 = 6.1×10-5 eV^2
- $\tan^2\theta = 0.48$
- $\Phi_{B8} = 5.2\times10^6\ cm^{-2}s^{-1}$

Only LMA (i.e. LOW excluded)

Global oscillation analysis

Data set

- **SK-I/II/III**

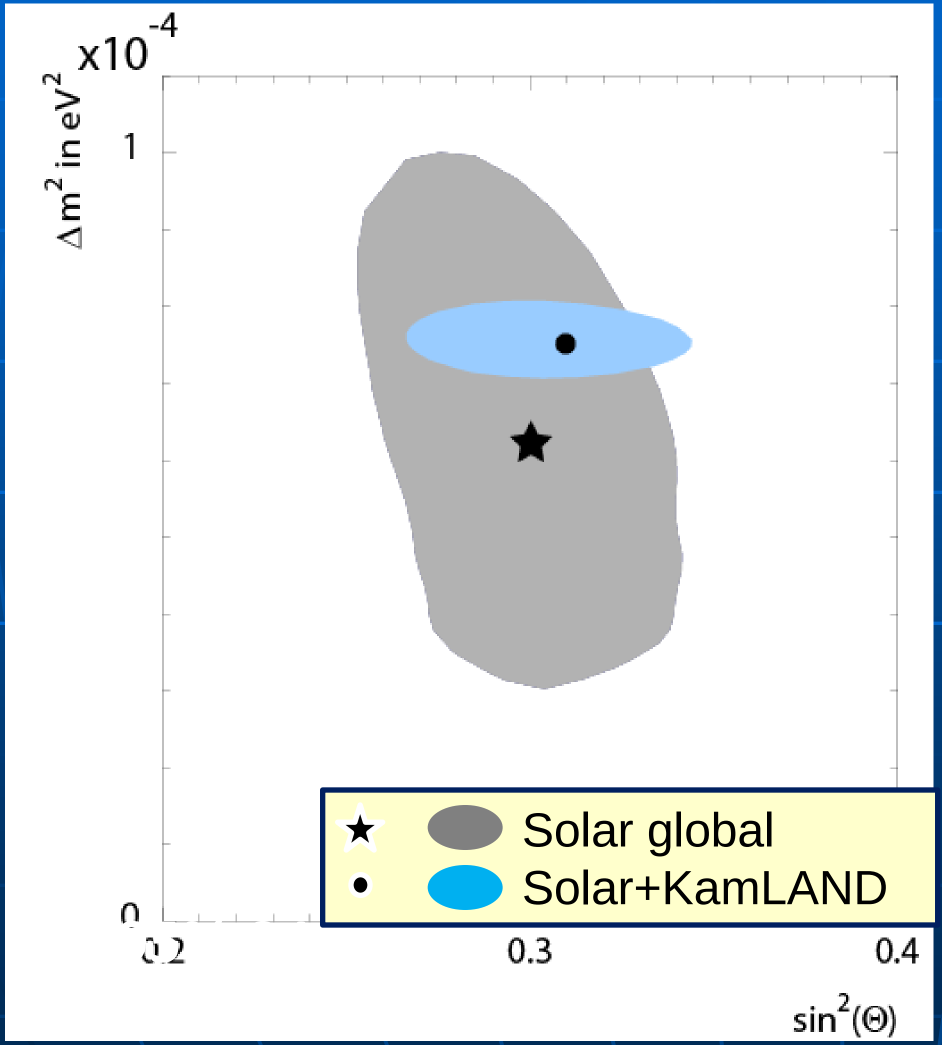
- **SNO** : CC flux(Phase-I & II & III)
  NC flux(Phase-III & LETA combined)
  (= (5.14+/-0.21) $10^6 cm^{-2} s^{-1}$)
  Day/Night asymmetry(Phase-I & II)

- **Radiochemical** : Cl, Ga
  - New Ga rate: 66.1 +- 3.1 SNU (All Ga global) (Phys.Rev.C80:015807,2009.)
  - Cl rate: 2.56+/-0.23 (Astrophys. J. 496 (1998) 505)

- **Borexino**
  - ^{7}Be rate: 48 +/- 4 cpd/100tons (PRL 101: 091302, 2008)

- **KamLAND** : 2008

2-flavor global analysis

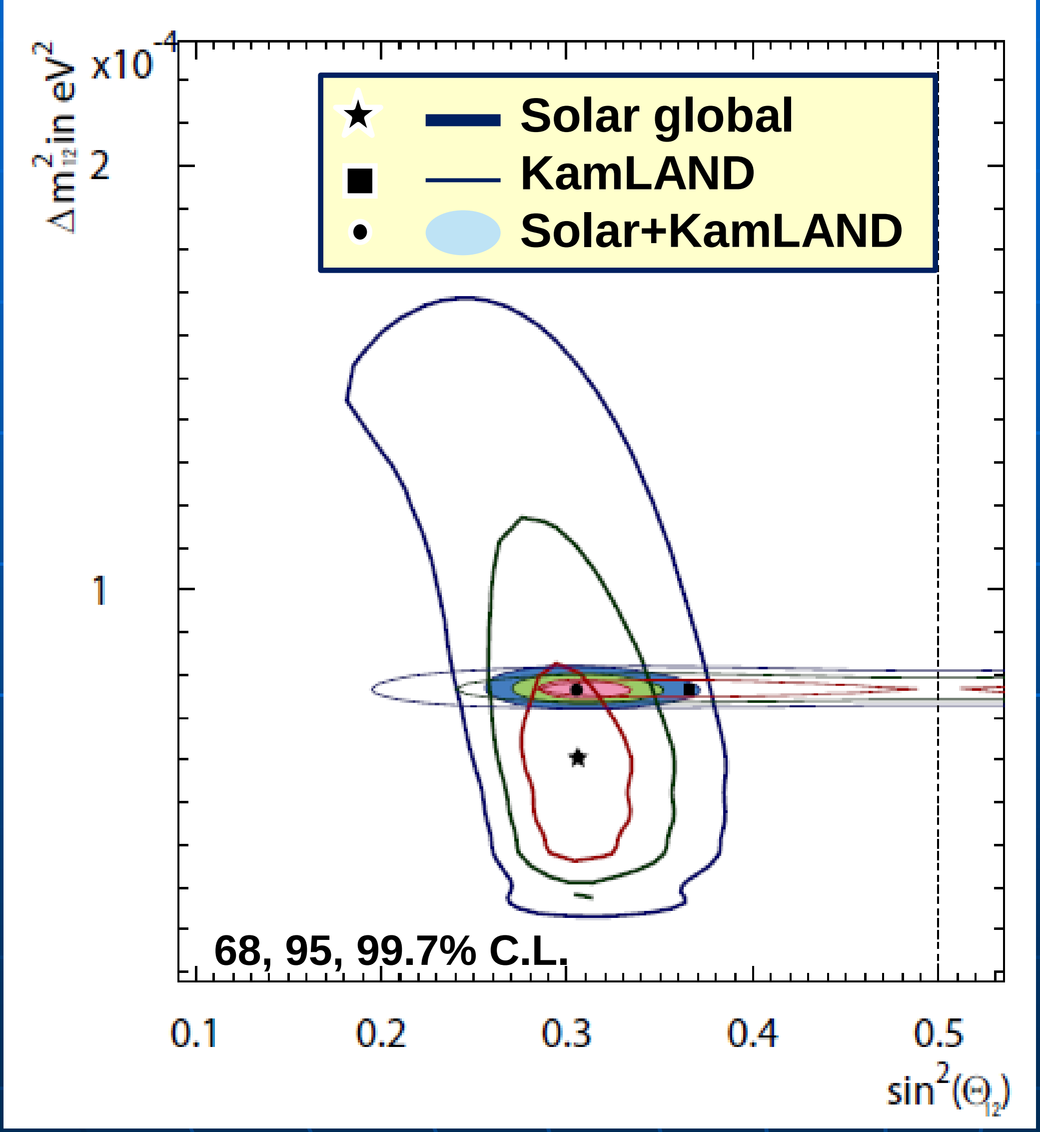


Best fit value (preliminary)

Solar global
- $\Delta m^2 = 6.2\times10^{-5}\ eV^2$
- $\tan^2\theta = 0.48$
- $\Phi_{B8} = 5.3\pm0.2\times10^6\ cm^{-2}s^{-1}$

Solar global + KamLAND
- $\Delta m^2 = 7.6\times10^{-5}\ eV^2$
- $\tan^2\theta = 0.3$
- $\Phi_{B8} = 5.1\pm0.1\times10^6\ cm^{-2}s^{-1}$

3-flavor global analysis: θ_{12} - Δm_{12}^2



Free parameters : $\theta_{12}, \theta_{13}, \Delta m_{12}$

Best fit value (preliminary)

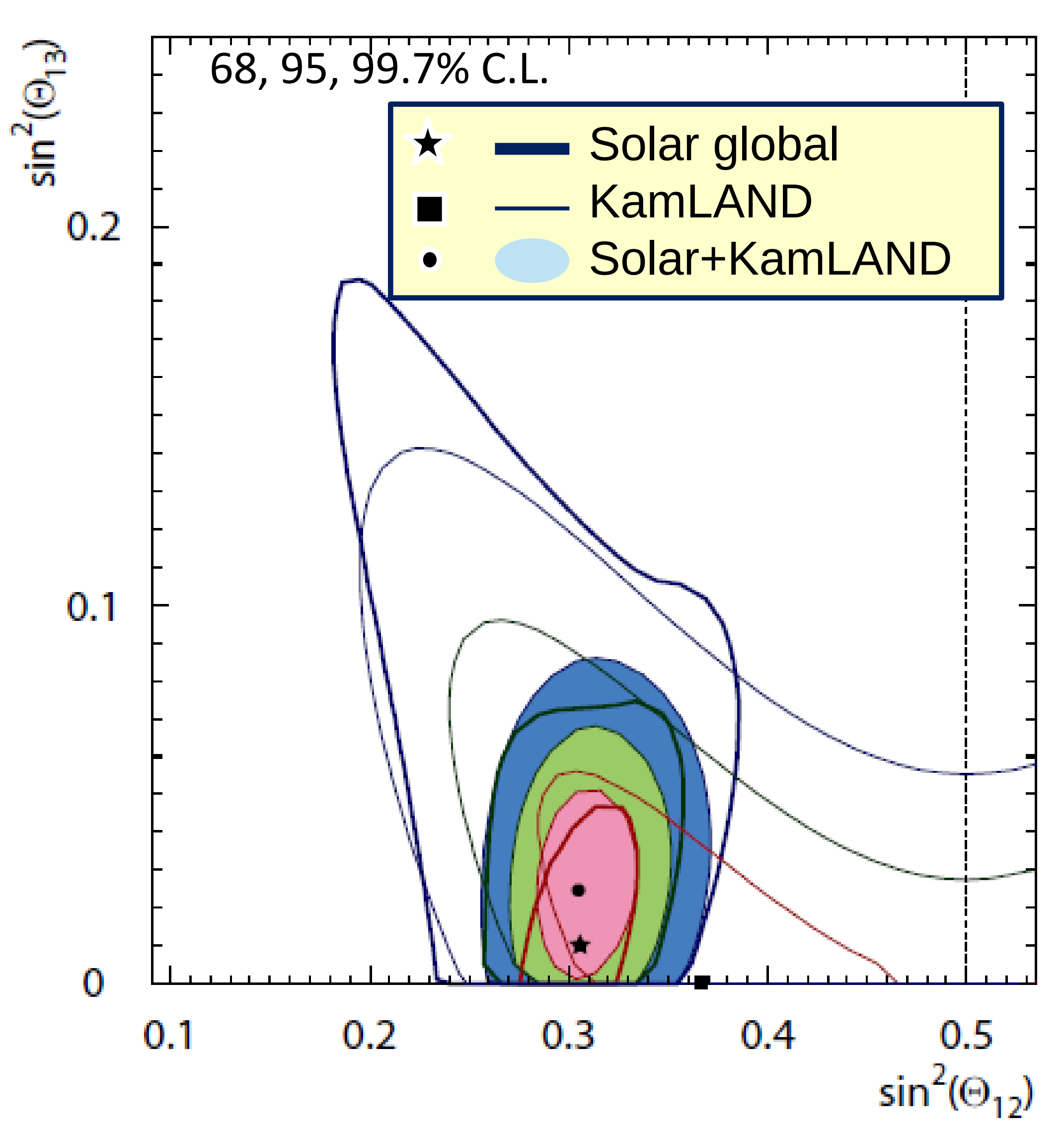
Solar global

- $\Delta m^2 = 6.2\times10^{-5}\ eV^2$
- $\sin^2\theta_{12} = 0.31$
- $\sin^2\theta_{13} = 0.010$
- $\Phi_{B8} = 5.3\pm0.2\times10^{6}\ cm^{-2}s^{-1}$

Solar global+KamLAND

- $\Delta m^2 = 7.7\times10^{-5}\ eV^2$
- $\sin^2\theta_{12} = 0.31$
- $\sin^2\theta_{13} = 0.025^{+0.018}_{-0.016}$
- $\Phi_{B8} = 5.3+0.1-0.2\times10^{6}\ cm^{-2}s^{-1}$

3-flavor global analysis: θ_{12} - θ_{13}



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

Solar global + KamLAND
$\sin^2\theta_{13} < 0.059$
@95% C.L.

5, SK-IV status

1, SK-IV Electronics and DAQ system were updated at the beginning of SK-IV phase)

Improvements of front-end electronics

- 5 times wider dynamic range for charge measurement (>2000pC)
- **Larger amount of data can be sent to Online system via 100Base/T Ethernet**
- Low power consumption (< 1W/ch)

Improvements of online-DAQ system

- SK-I/II/III DAQ system

  Hardware trigger was used. Only Triggered hit data was sent to online system.
- SK-IV system

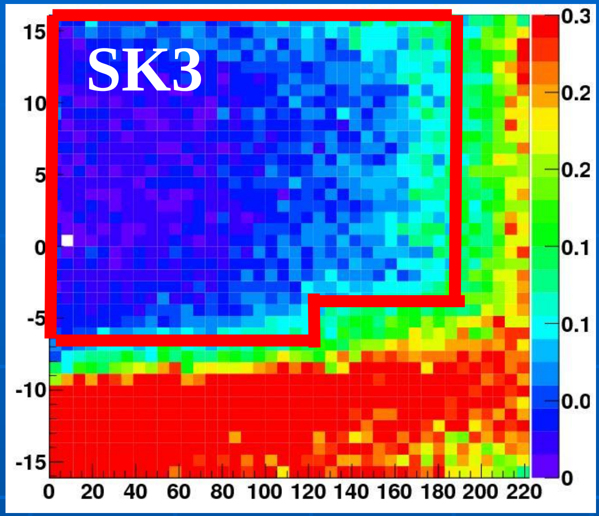
  All the hit data is sent to the online system and event building is done by software

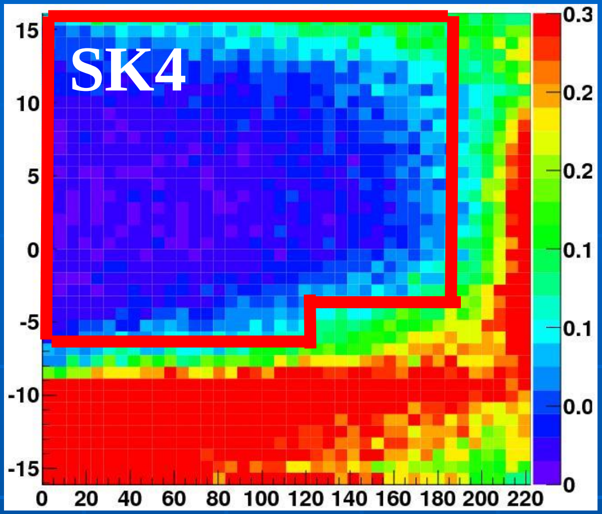
  -> capable of lower energy threshold

2,Fine water temperature control for inlet water -> Lower radon concentration in fiducial volume

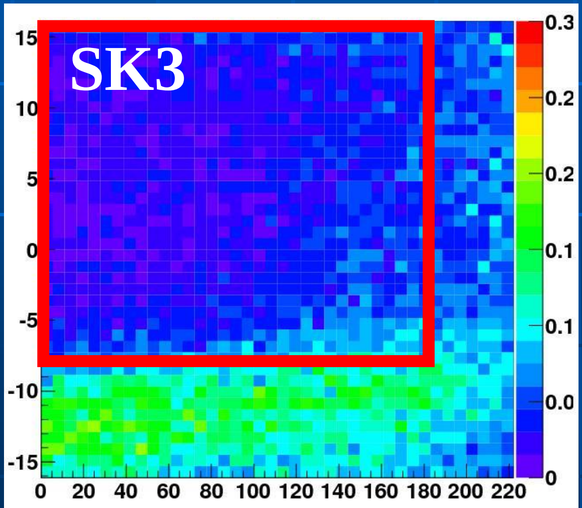
Background level in SK-IV

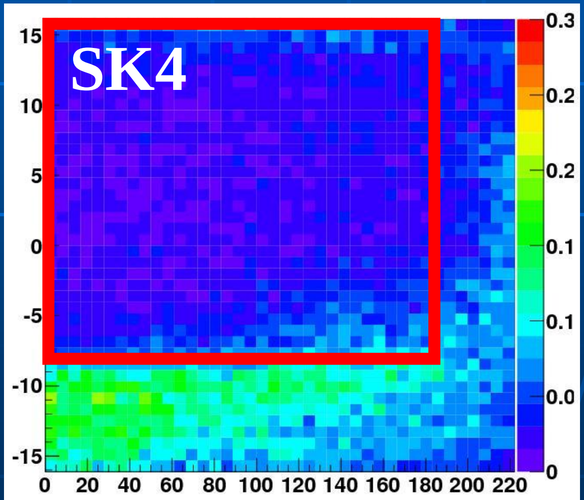
4.5-5.0 MeV





5.0-5.5 MeV





Same level of b.g. level as SK-III have been achieved in SK-IV phase.

6, Summary

- Results of solar measurement in SK-III phase have been reported.

- There are improvements for b.g. level and systematic uncertainty in SK-III data analysis due to
  - -- Water system modification
  - -- Improvement of reconstruction tools
  - -- Precise calibration and upgrade of detector simulation

- Solar flux, energy spectrum and oscillation results are upgraded including SK-III data

- Measurement in SK-IV phase is on-going, after upgrading front-end electronics and DAQ system.

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

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

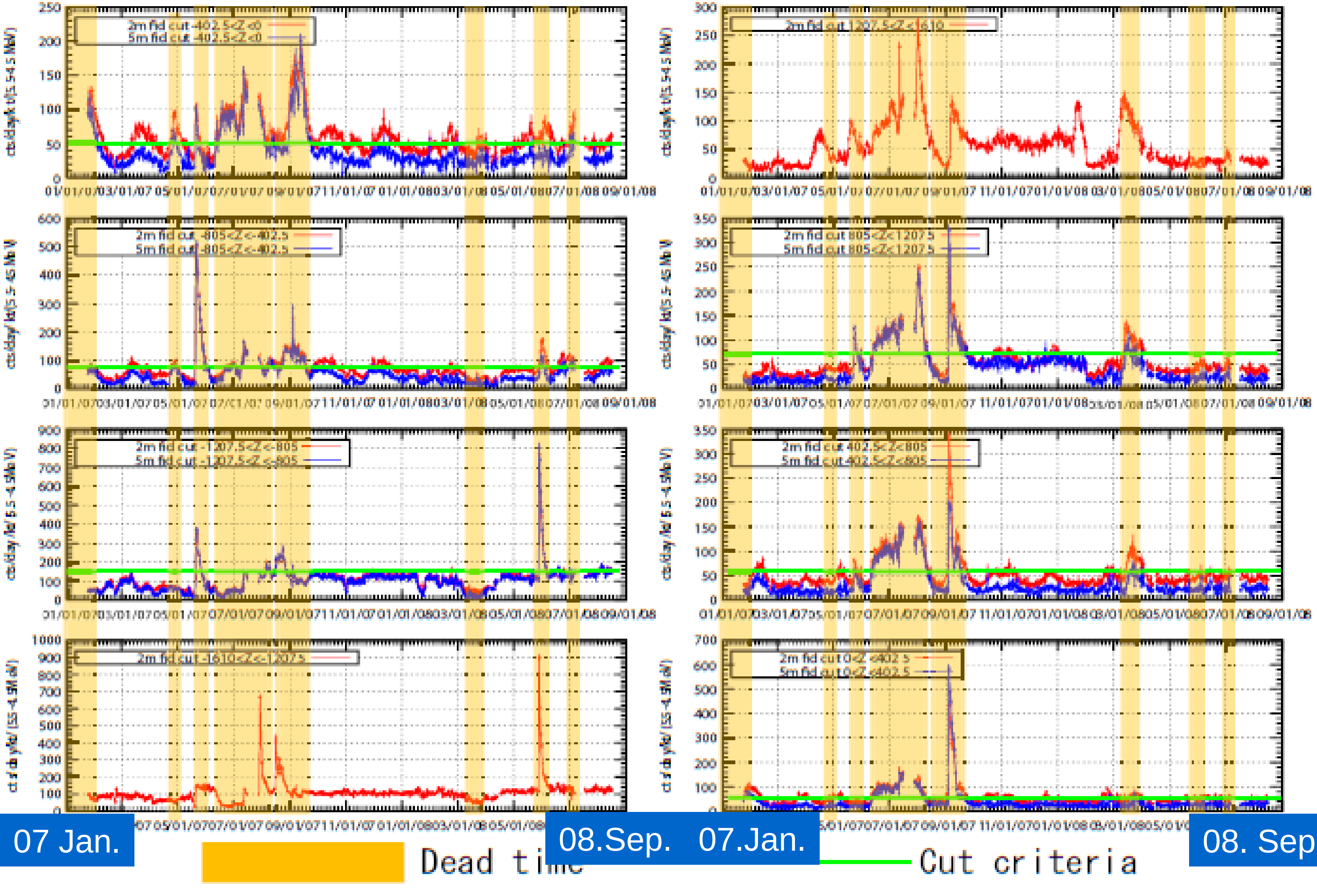
$$b_i = \frac{^8\mathrm{B}_i^{\mathrm{osc}}(\Delta m^2, \tan^2\theta)}{^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}, \quad h_i = \frac{hep_i^{\mathrm{osc}}(\Delta m^2, \tan^2\theta)}{^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}$$

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 andδs are chosen to minimize the spectrum fit χ^2.

Select period with stable event rate



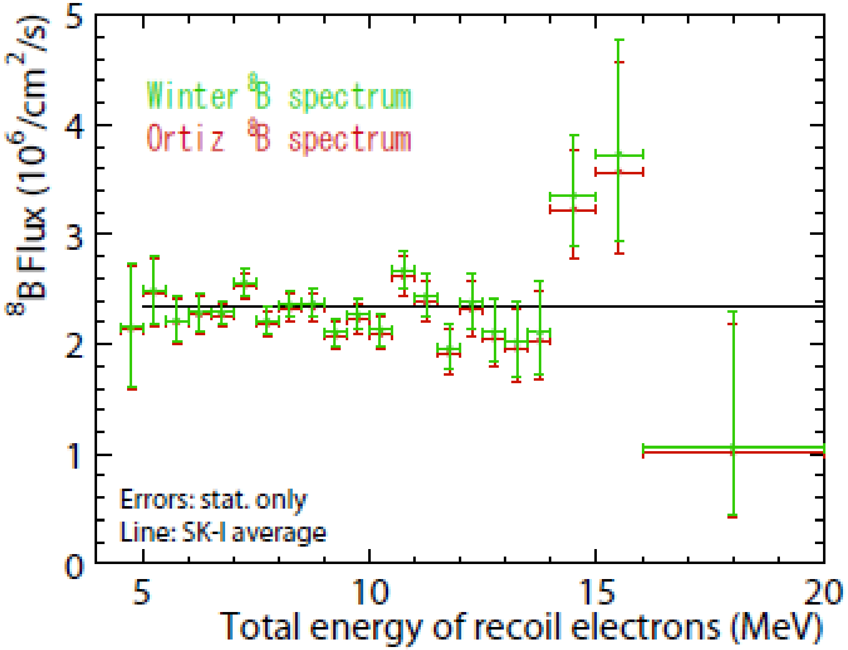


Figure 12.3: SK-III data /SSM (BP2004) with Winter and Ortiz ^{8}B spectrum. Green shows SSM with Winter ^{8}B spectrum, and red shows SSM with Ortiz ^{8}B spectrum.

^{8}B flux comparison

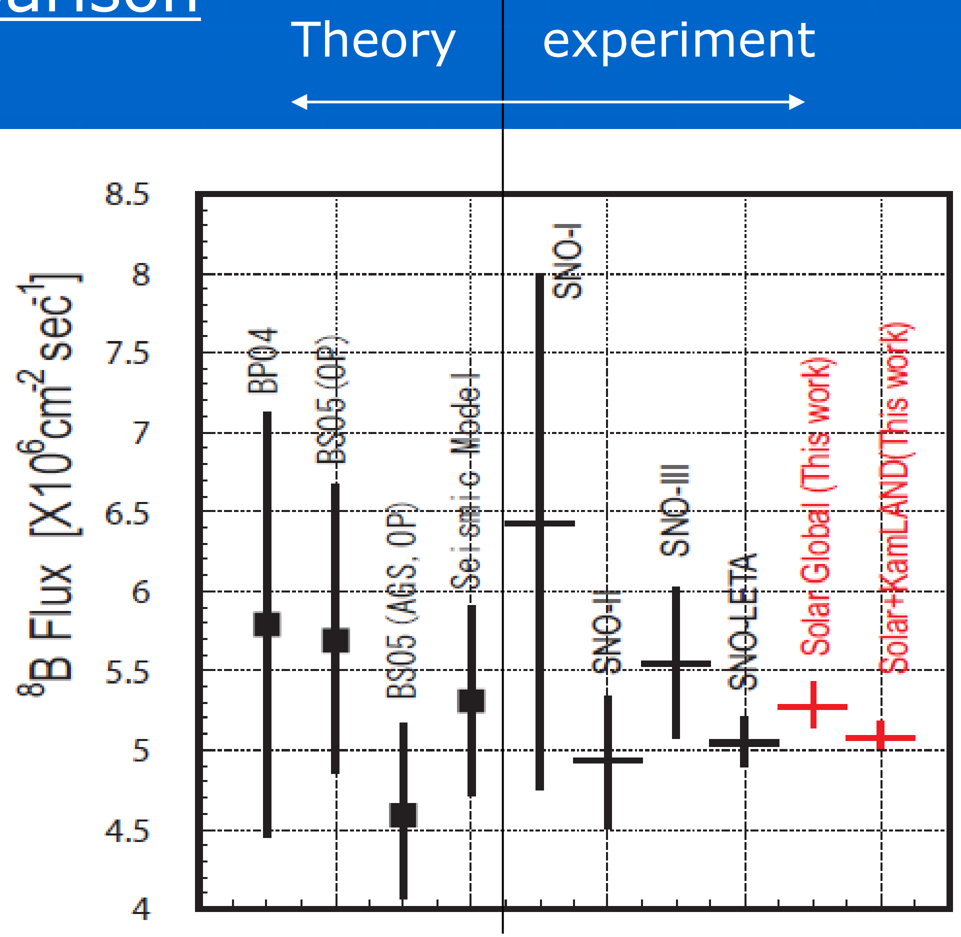
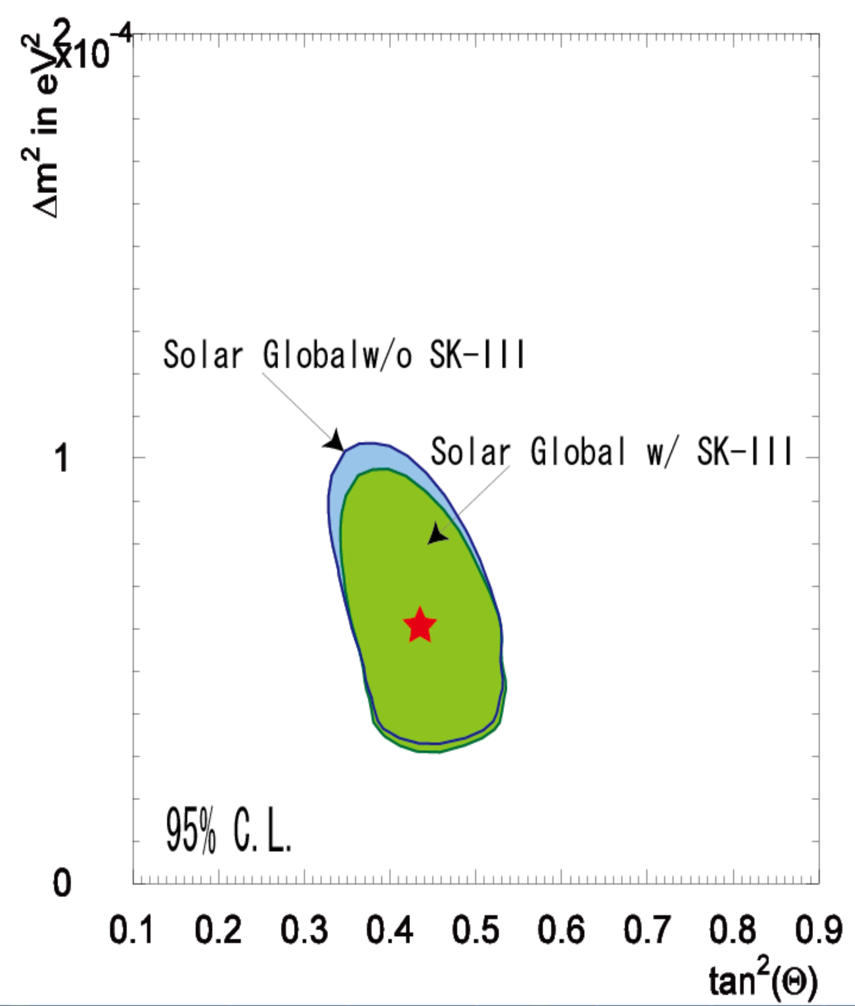
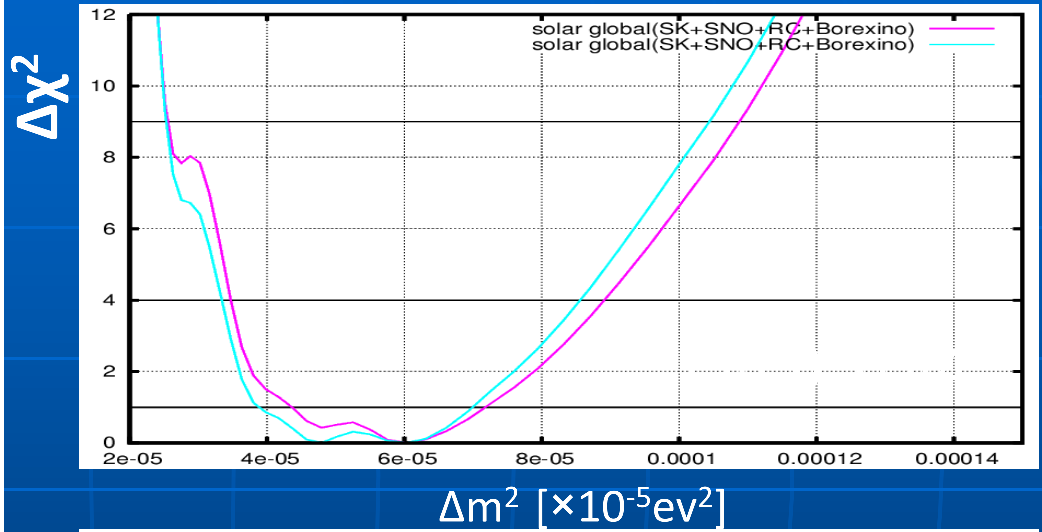


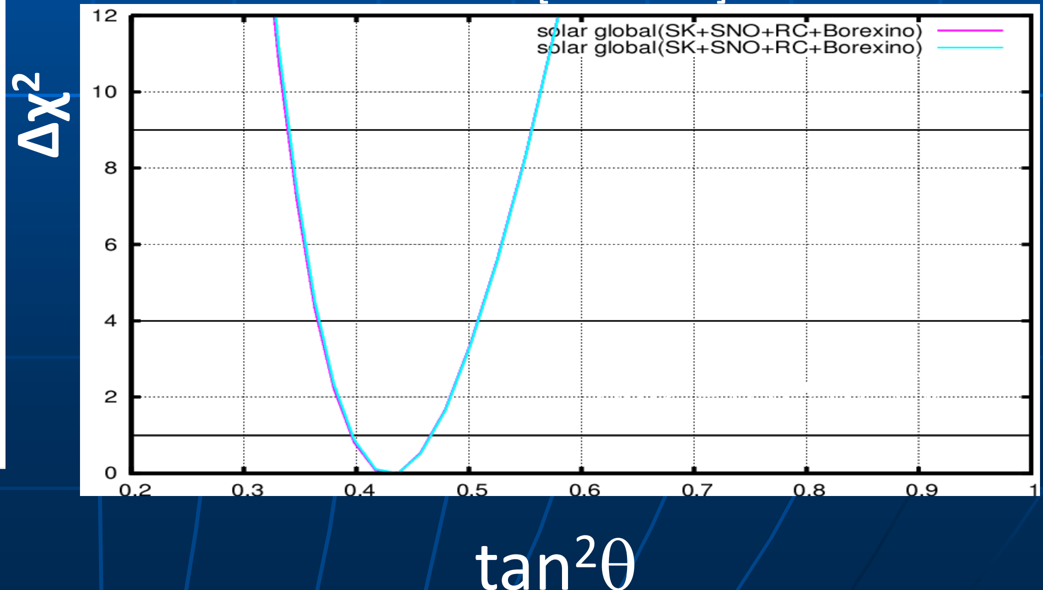
Figure 12.6: Comparison of the ^{8}B flux between SNO results and the results obtained by this thesis. the error size corresponds to 1 σ uncertainty of (stat.+sys.). Square mark shows theoretical predictions and cross marks shows experimental results.

M. Ikeda, phD thesis

Contribution of SK-III result







Definition of χ^2s for global analysis

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 andδs are chosen to minimize (SK spectrum+SNO flux fit) χ^2.

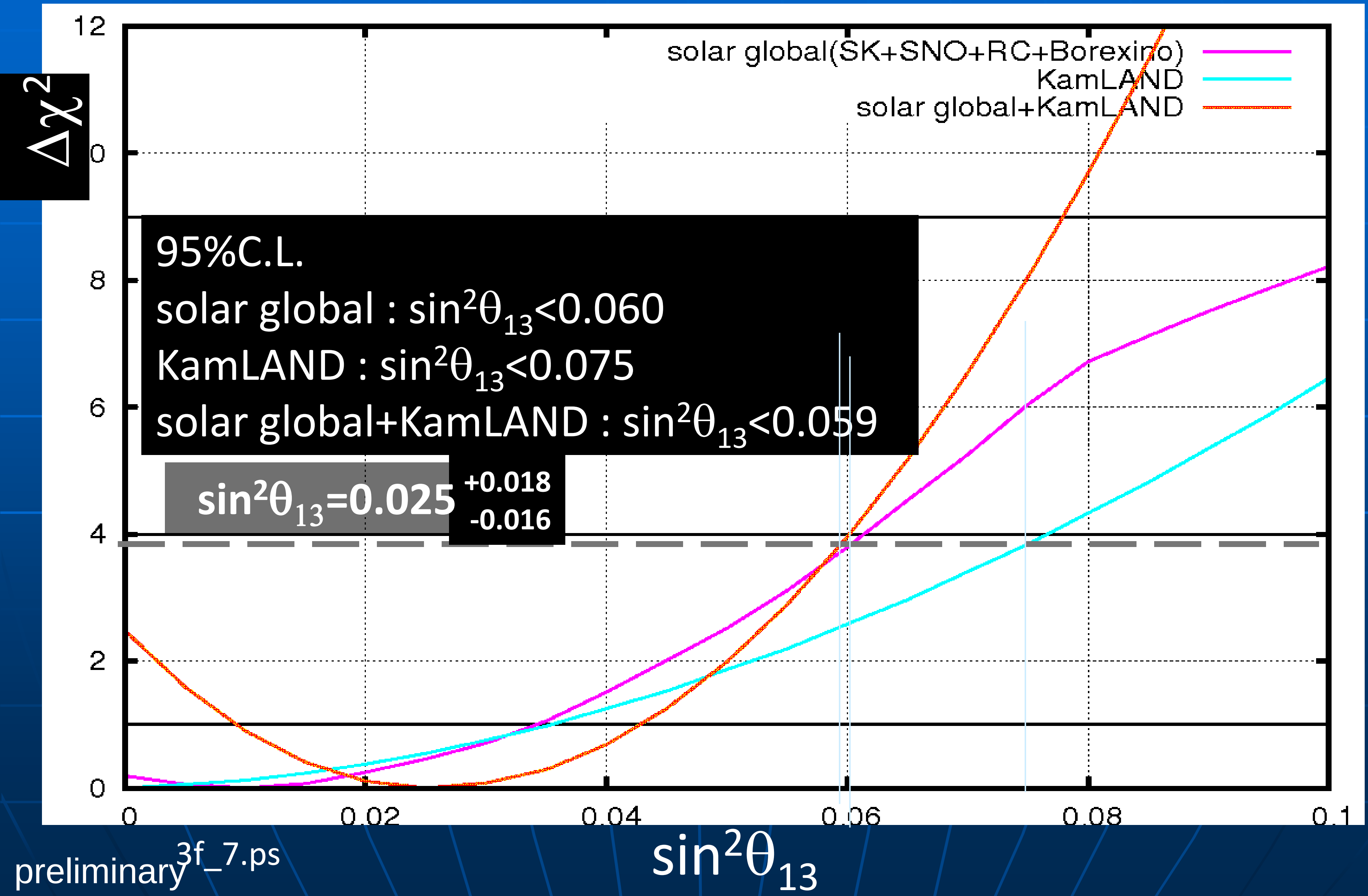
$$\chi^2_{GaCl} = \sum_{n,m=1}^{N(=2)} (R^{\exp t}_n - R^{theor}_n)[\sigma^2_{nm}]^{-1}(R^{\exp t}_m - R^{theor}_m)$$

Ga/Cl

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

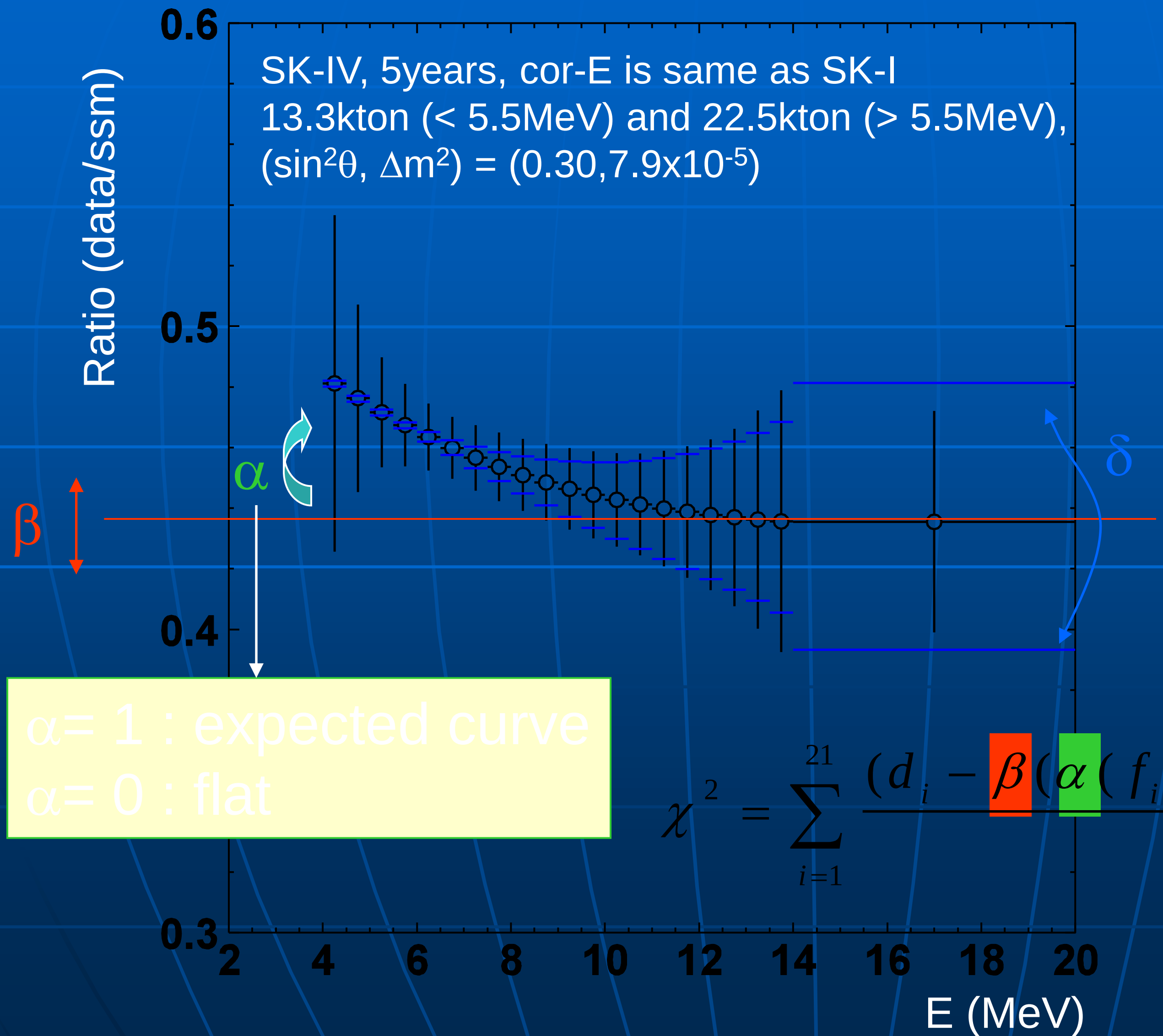
Ga/Cl/Borexino

1D plot – this time analysis



preliminary

Sensitivity calculation

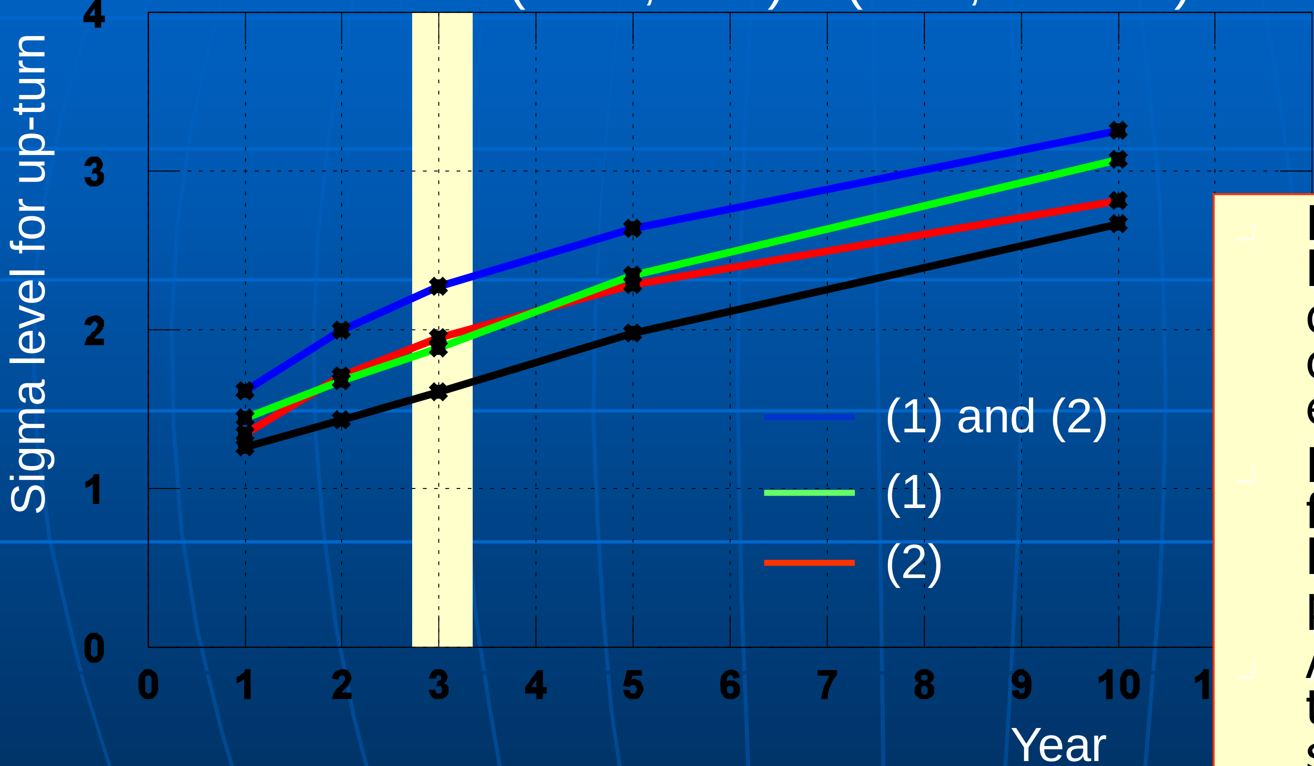


α= 1 : expected curve
α= 0 : flat

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

Sensitivity of the upturn measurement

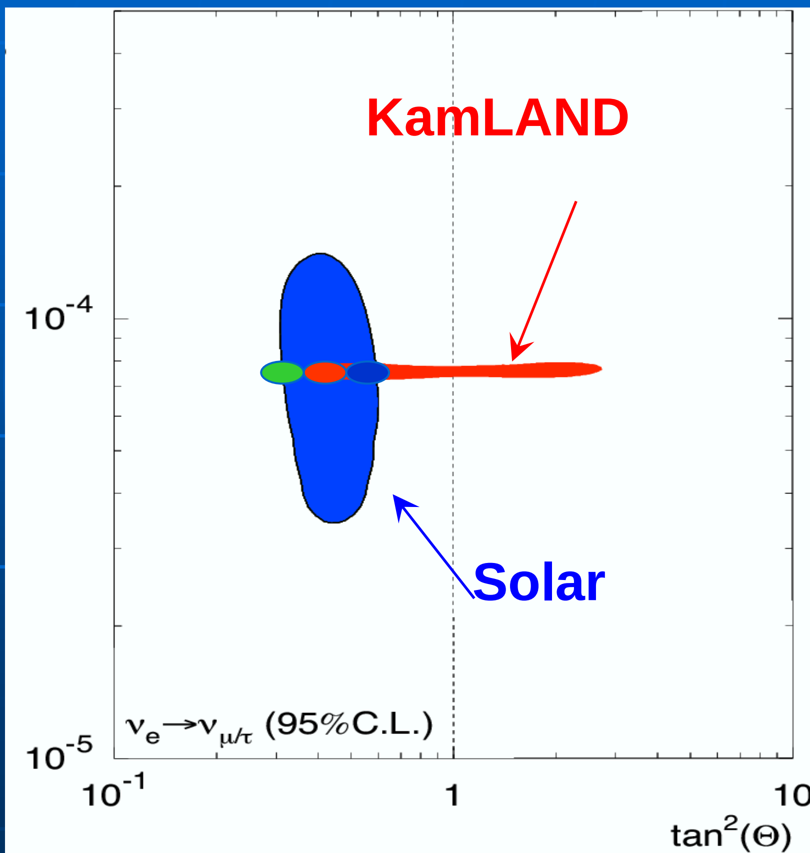
In the case of $(\sin^2\theta, \Delta m^2) = (0.30, 7.9\times10^{-5})$



- 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.

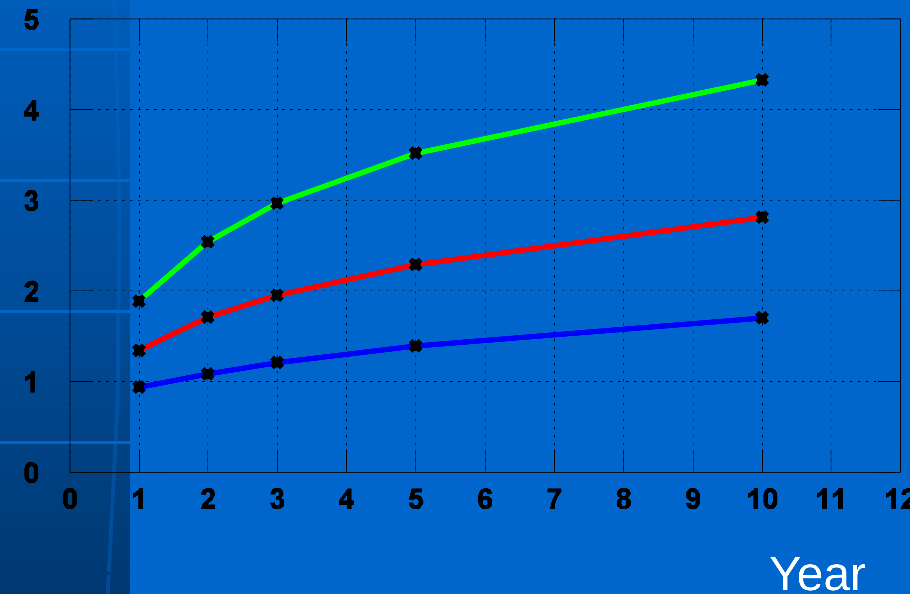
(1) Enlarge fiducial volume to 22.5kton with low B.G.
(2) Half energy correlated systematic error as SK-1.
The black line shows the 13.3kton (<5.5MeV), 22.5kton (>5.5MeV) fiducial volume with the same energy correlated error as SK-1

Oscillation parameter dependence

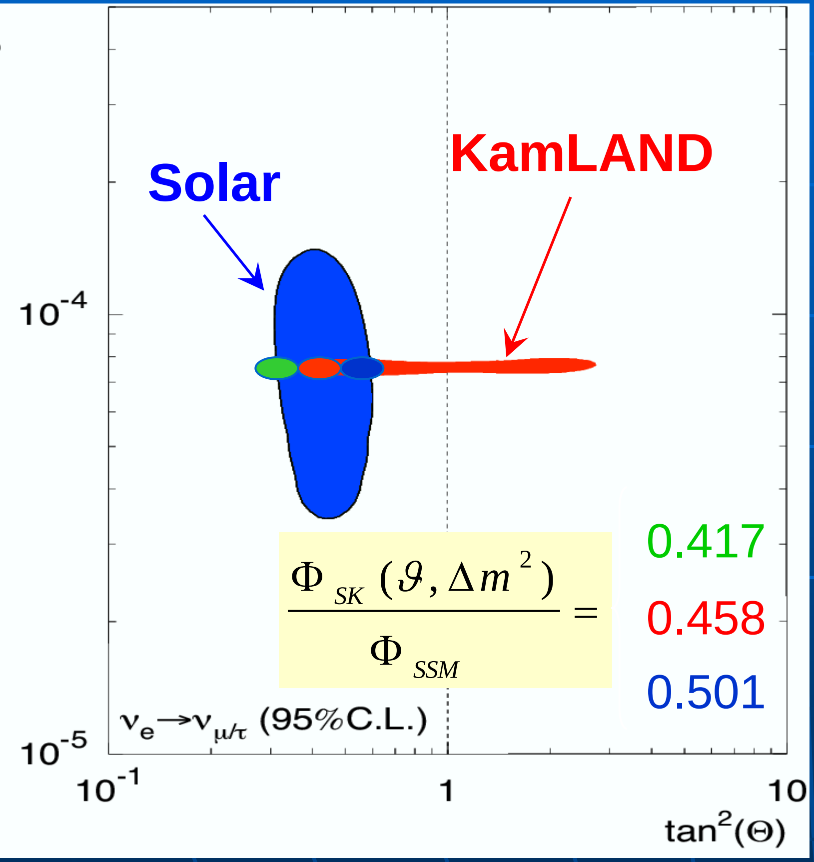


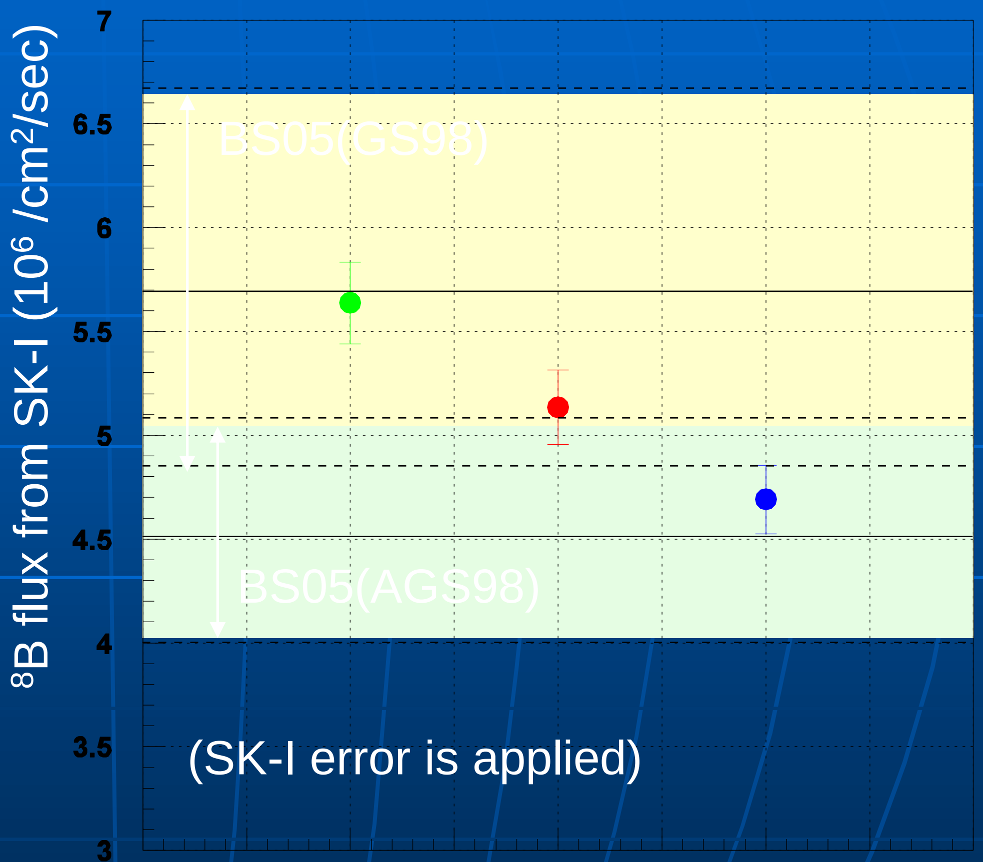
The correlated error is half as SK-1

13.3kton (< 5.5MeV) and 22.5kton (> 5.5MeV)



Flux measurement in SK





If theta12 is determined, the precise ^{8}B flux measurement in SK may be possible to contribute the improvement of the Solar Model.