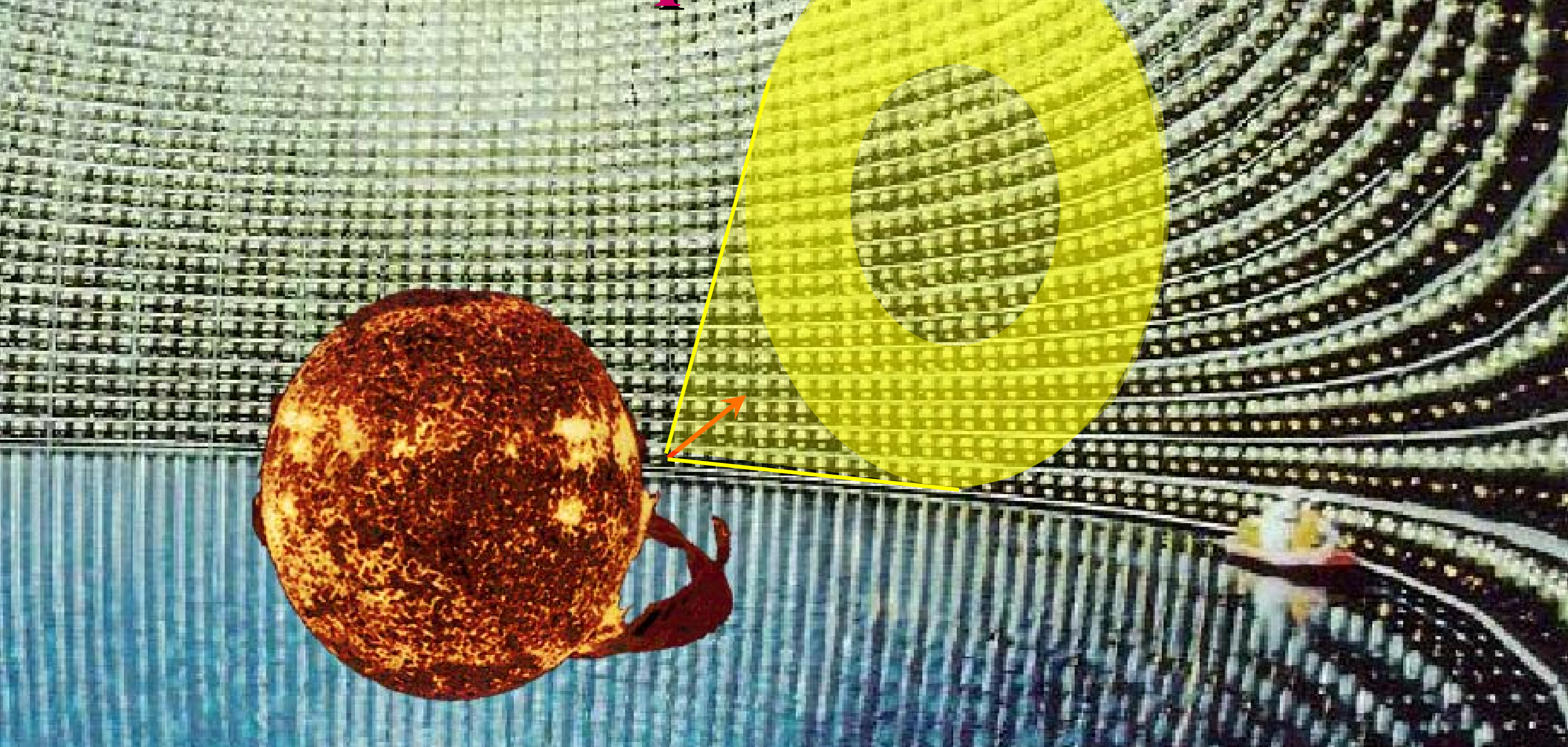
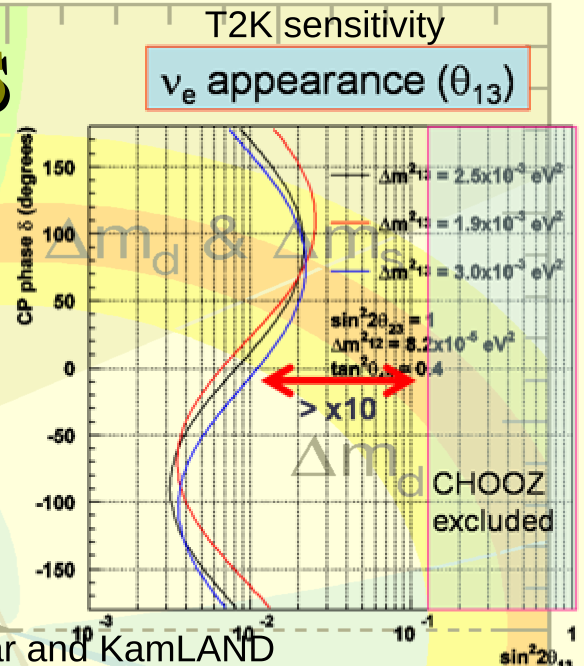
Latest Solar Neutrino Results from Super-Kamiokande

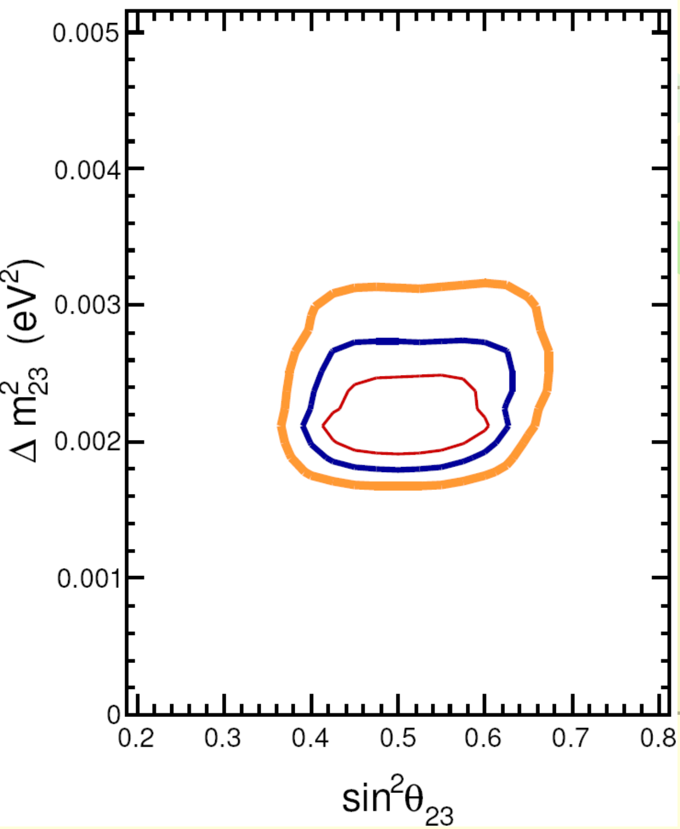


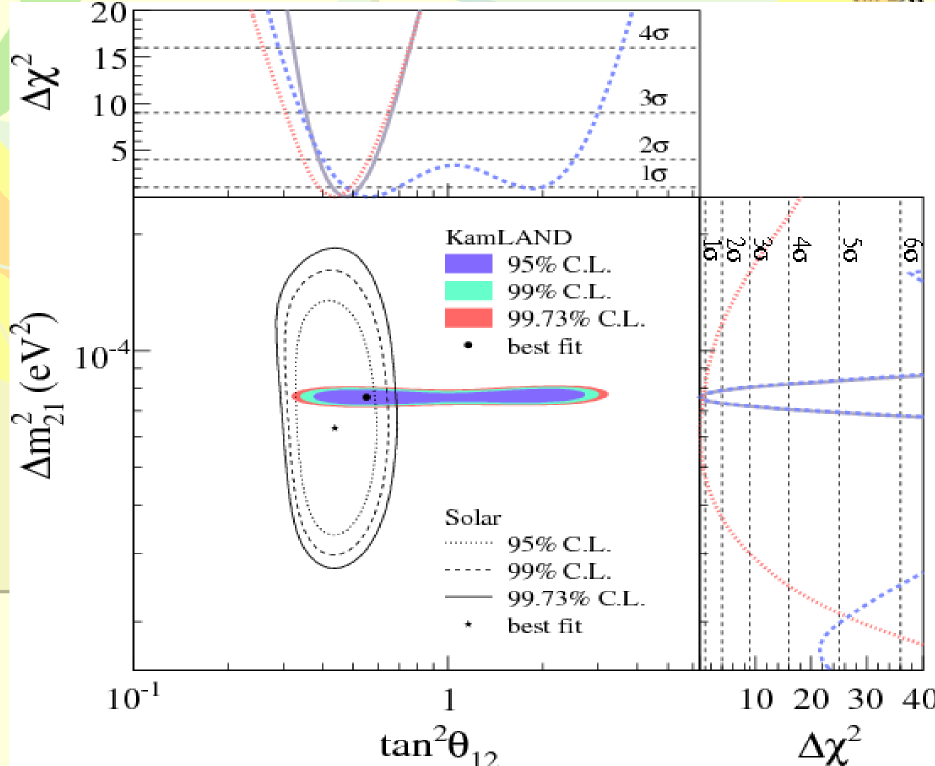
Physics Department Seminar
at Brookhaven National Laboratory
Thursday March 17th 2011
Michael Smy, UC Irvine

Neutrino Flavour Physics

- similar physics program as quark mixing, but…
- …large mixing and small cross sections
- best probed by oscillation experiments

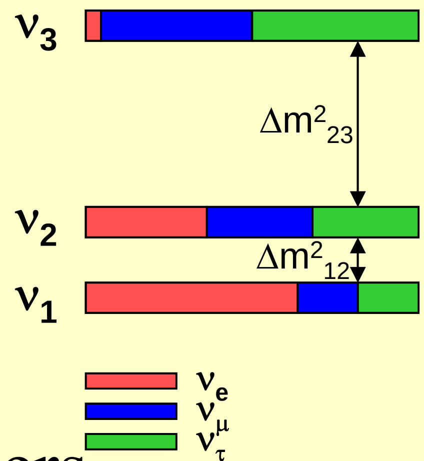






Neutrino Flavour Mixing: MNS Matrix

$$U = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -s_{12}c_{23} - e^{-i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ -e^{i\delta}c_{12}s_{13}c_{23} + s_{12}s_{23} & -e^{i\delta}s_{12}s_{13}c_{23} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix}$$



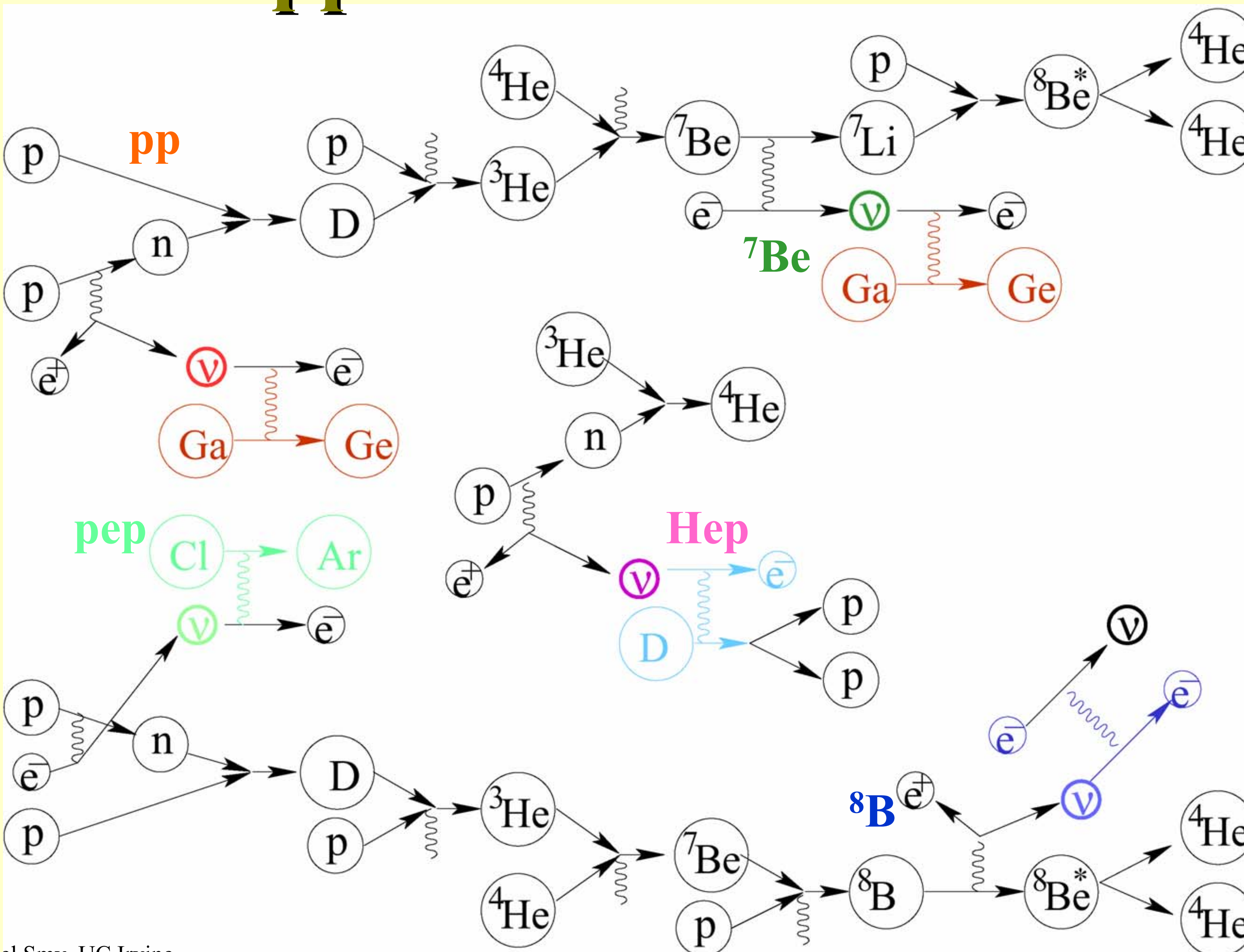
- Known Parameters
  - Two Mass² Diff. scales
    - atmospheric: Δm^2_{23}
    - solar /KamLAND: Δm^2_{12}
  - Two Mixing Angles
    - atmospheric : θ_{23}
    - solar/KamLAND: θ_{12}
  - Mass² ordering
    - solar: Δm^2_{12}
- Unknown Parameters
  - Third Mixing Angle θ_{13} (only limit)
  - CP-Violating Phases
    - accessible via ν oscillation: δ
    - accessible only via $0\nu\beta\beta$: α_1, α_2
  - Mass² ordering
    - atmospheric: Δm^2_{23}
  - Other
    - Mass?
    - Majorana or Dirac?

Courtesy T. Maruyama, KEK

Solar Neutrinos

- conclusive proof that the sun shines because of nuclear reactions
- directly monitor the solar core
- MSW-resonant flavor conversion happens in the sun for high energy solar neutrinos (>~3 MeV)
- flavor conversion modified if neutrinos pass through the earth

Solar pp Chain and ν Detection



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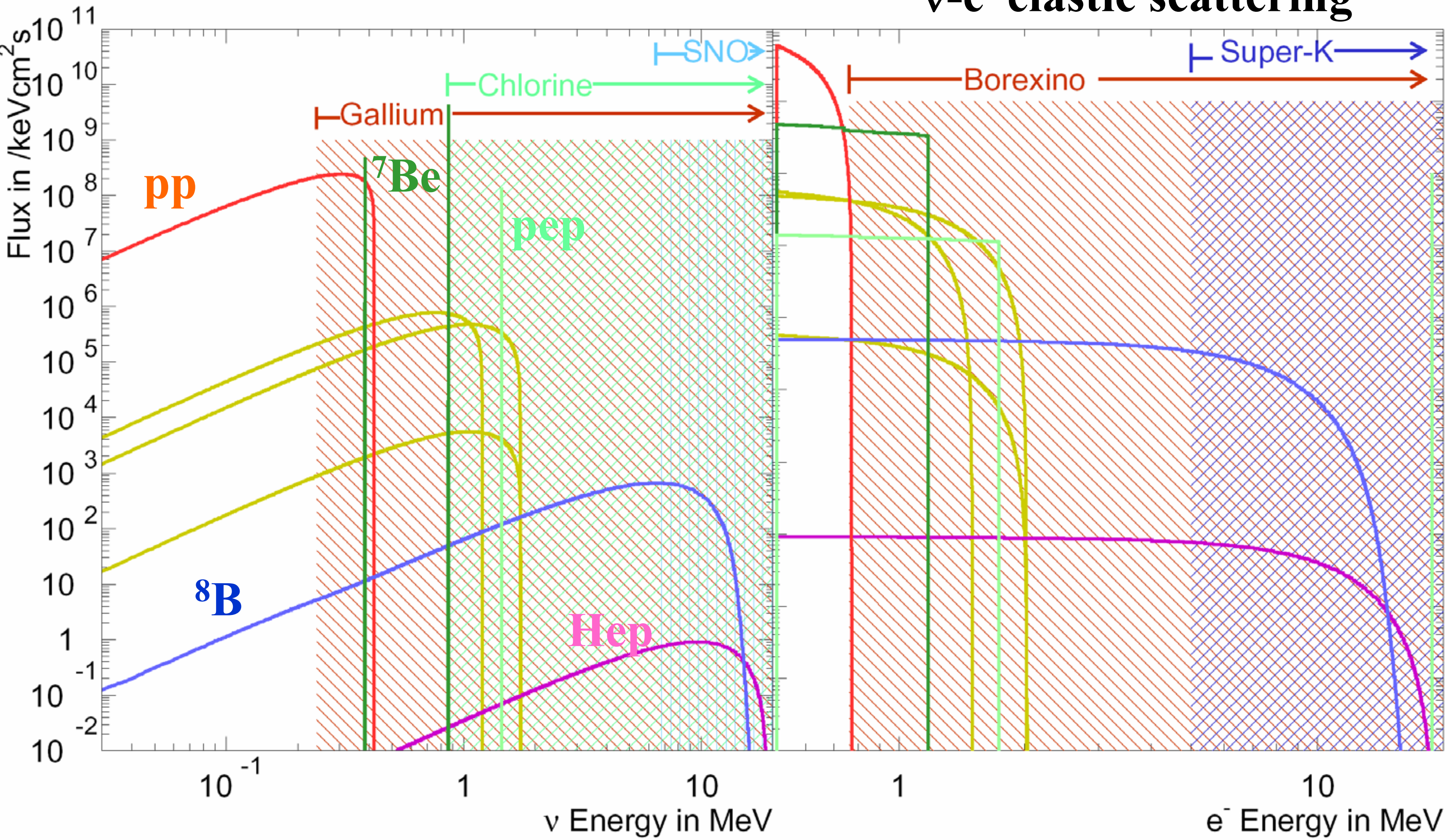
Solar ν Spectrum

Neutrino Flux | **rate seen from ν-e⁻ elastic scattering**



Solar ν Physics Began Here at BNL…

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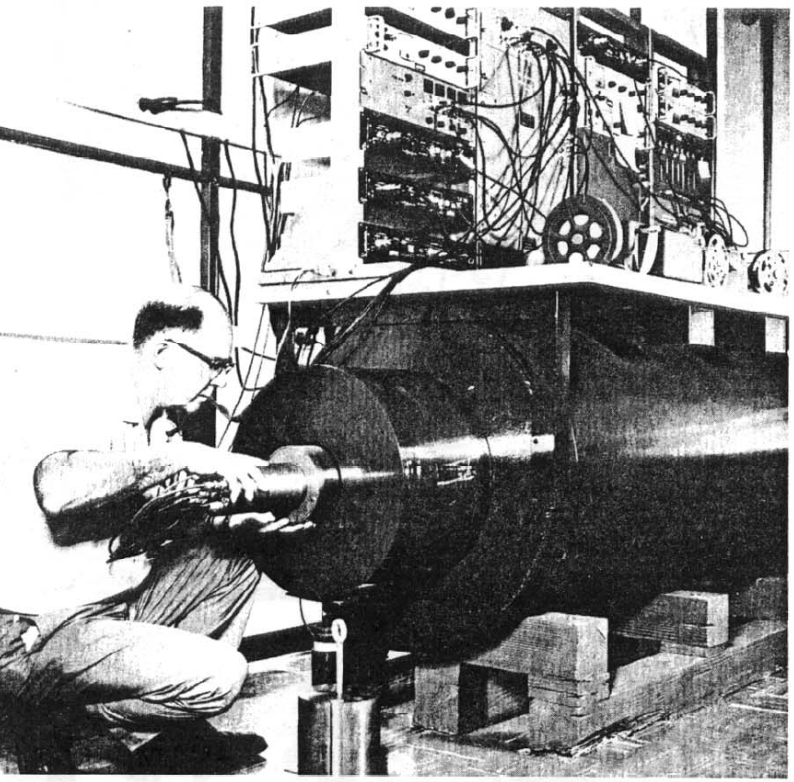
Volume 21, Number 36 — Published by the BNL Public Relations Office — September 14, 1967

9-1307-66

Solar Neutrinos Are Counted At Brookhaven



Dr. Ray Davis of Chemistry is shown placing a low level counter in a cut-down navy gun barrel which acts as a shield from stray cosmic radiation. This equipment is used in the Brookhaven Solar

underground tank was less than 2 neutrinos per day. Knowing this plus the efficiency of neutrino capture, allowed Dr. Davis and his group to calculate the flux from the Boron-8 decay to be ~~approximately 60~~ less than 12 million solar neutrinos per square inch per second at the earth's surface. Previous calculations had predicted the flux could be anywhere from 40 million to 150 million solar neutrinos per square inch per second at the earth's surface.

Dr. Davis stressed that this was only the first experimental run, and that additional measurements must be made extending over a period of several years.

(more)

equal to 2 million/cm²/sec.
updated info from R Davis on 2/2/68

SK-III result for ^{8}B Flux:

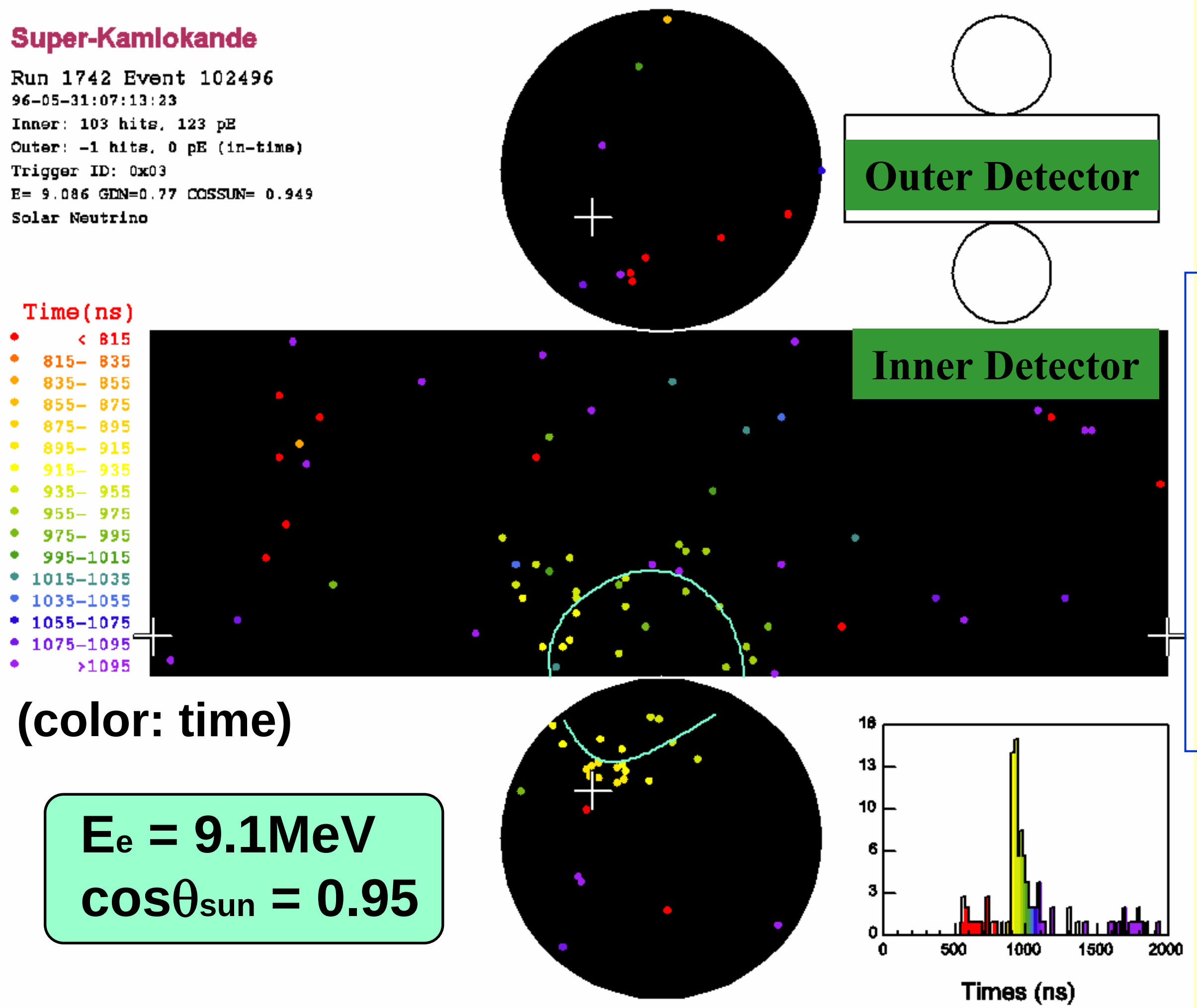
2.32+/-0.04(stat.)+/-0.05(syst.) (x10^6/cm^2/s)

(somewhat larger since oscillated solar neutrinos contribute)

Water-Cherenkov Technique

- electron-neutrino elastic scattering:
  - no threshold
  - strongly forward-peaked: recoil electrons point to the source
  - kinematic reconstruction required to measure neutrino energy
- preserve directional signature, but multiple Coulomb scattering prevents kinematic reconstruction
- low light yield implies high threshold (~3 MeV) and large energy resolution (~14% at 10 MeV)

Water Cherenkov Technique



(color: time)

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

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

- 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

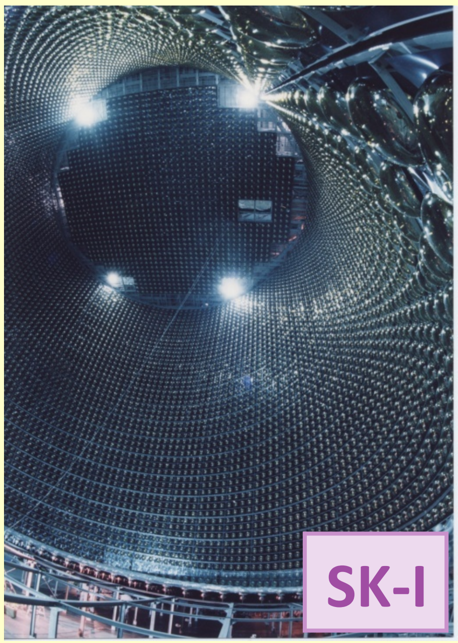
Courtesy Y. Takeuchi, ICRR

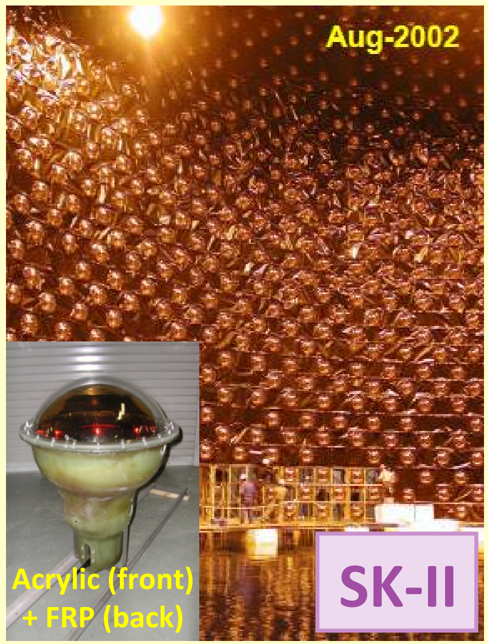
Super-Kamiokande History

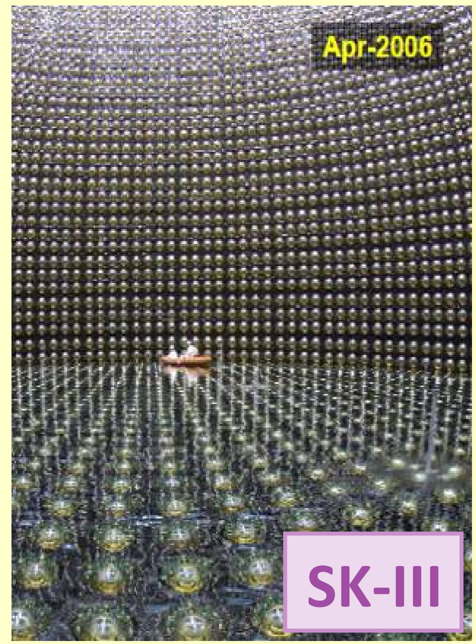
inner detector mass: 32kton   fiducial mass: 22.5kton

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

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 electron energy)	**5.0 MeV**	**7.0 MeV**	**4.5 MeV** work in progress	**< 4.0 MeV** target

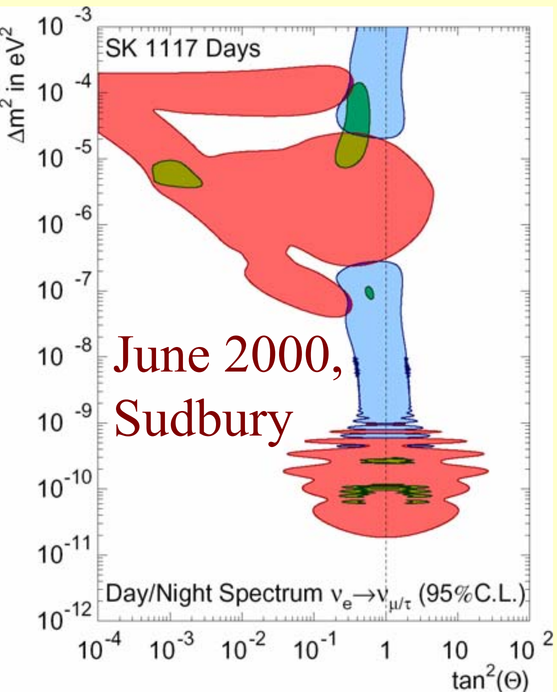
Impact of SK-I Solar Data on ν Oscillation

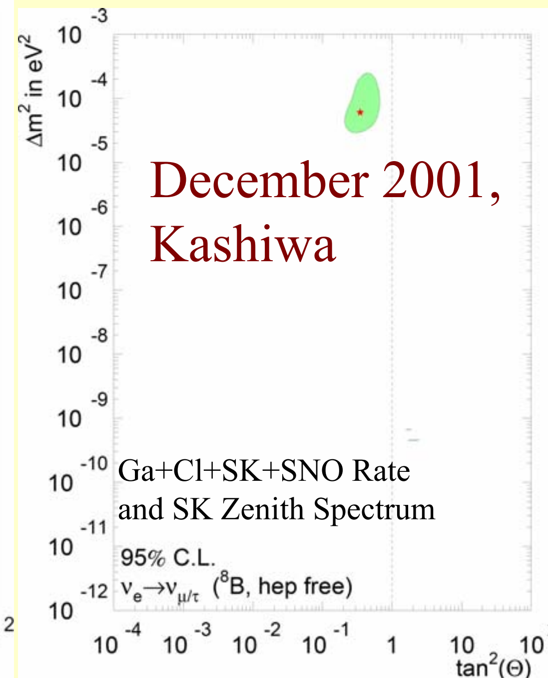
Before Super-Kamiokande-I:

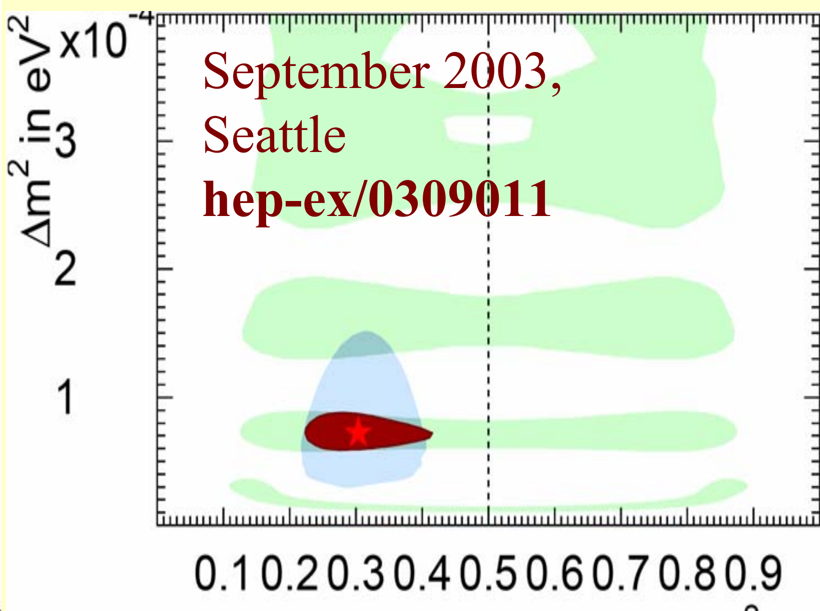
- Really Oscillations?
- Active or Sterile Oscillations?
- SMA, VAC, LMA, LOW?

After Super-Kamiokande-I:

- ✓ Active Oscillation! (June 2000)
- ✓ Large Angle! (June 2000)
- ➢ Not VAC, SMA! (June 2000)
- ➢ Not LOW! (December 2001)
- ➢ LMA-I (September 2003)
- ✓ Really Osc.! (with SNO: 2001)







Michael Smy, UC Irvine

… but now what?

- after completion of Super-Kamiokande-I and SNO, solar neutrino flavor conversion is well established, parameters are measured and in agreement with reactor neutrino measurements
- however, transition from solar resonance to averaged vacuum oscillation has not been probed; resulting distortion to the observed spectrum so far not confirmed
- modification of conversion by Earth matter effect is unobserved
- better measurement of solar mass splitting Δm^2_{12} desirable to compare to reactor neutrino measurements

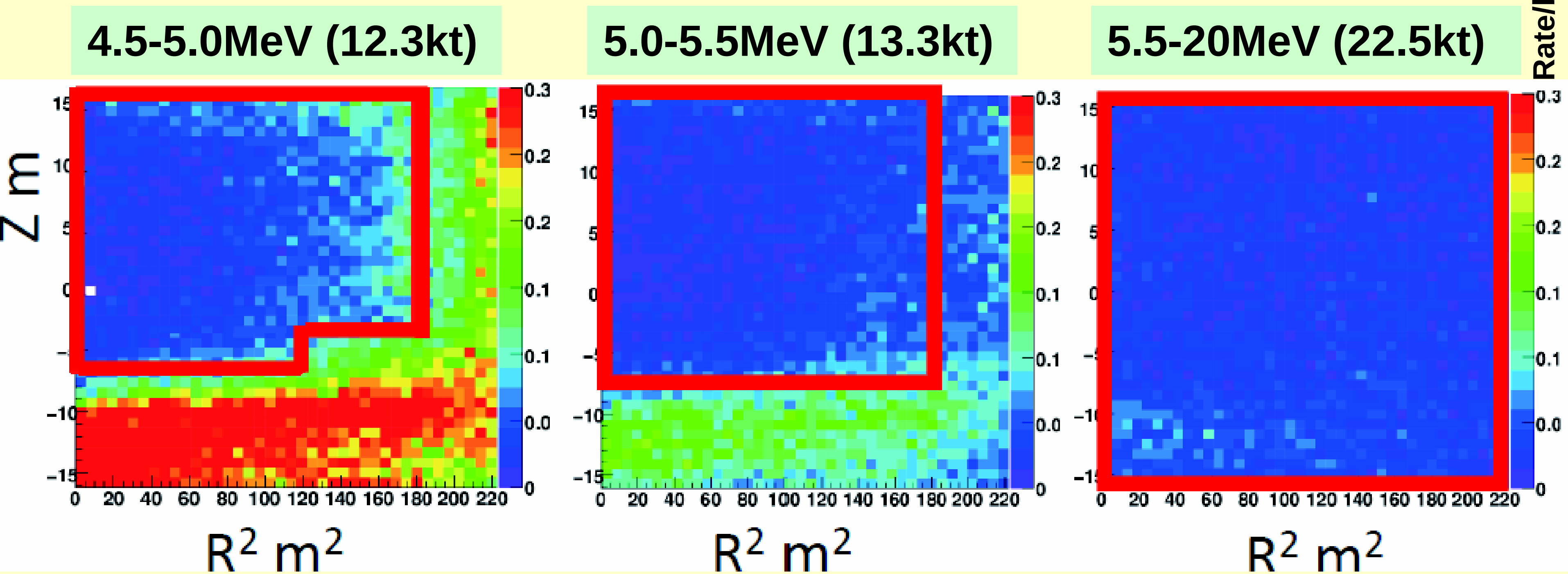
Super-Kamiokande III

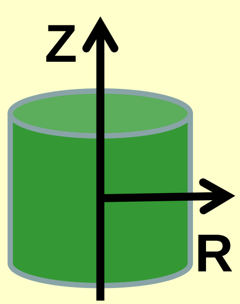
- added PMT enclosures (acrylic front, fiberglass back) lead to higher radioactivity level
- reduce this by software (better event reconstruction)
- reduce background due to dissolved Radon gas by better control of water flow in detector (via injection water temperature; very fickle: need about 0.01 degrees measurements)
- still have a convection cell at the bottom of the detector transporting Radon deep inside

Vertex distributions in SK-III

Fiducial volume in SK-III

Final data sample before tight fiducial volume cut





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).

Courtesy Y. Takeuchi, ICRR

Systematic Uncertainties on Total Flux

	SK-III	SK-I (PRD73,112001)
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%

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

Courtesy Y. Takeuchi, ICRR

SK-III solar neutrino results

- 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)

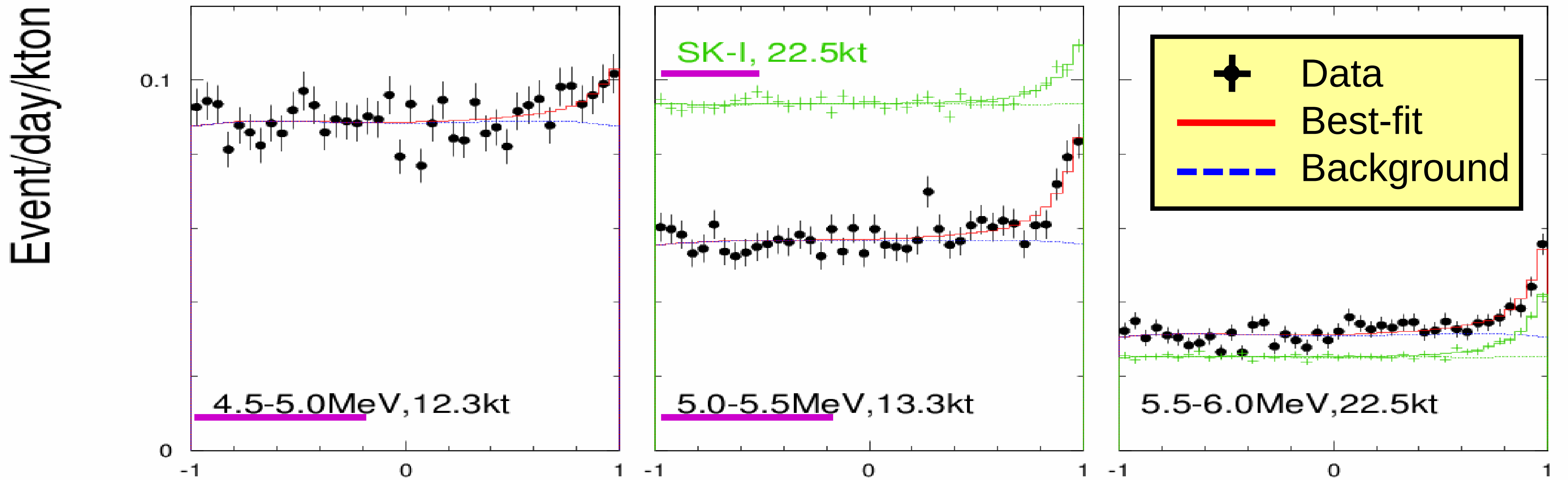
- Day / Night ratio:

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

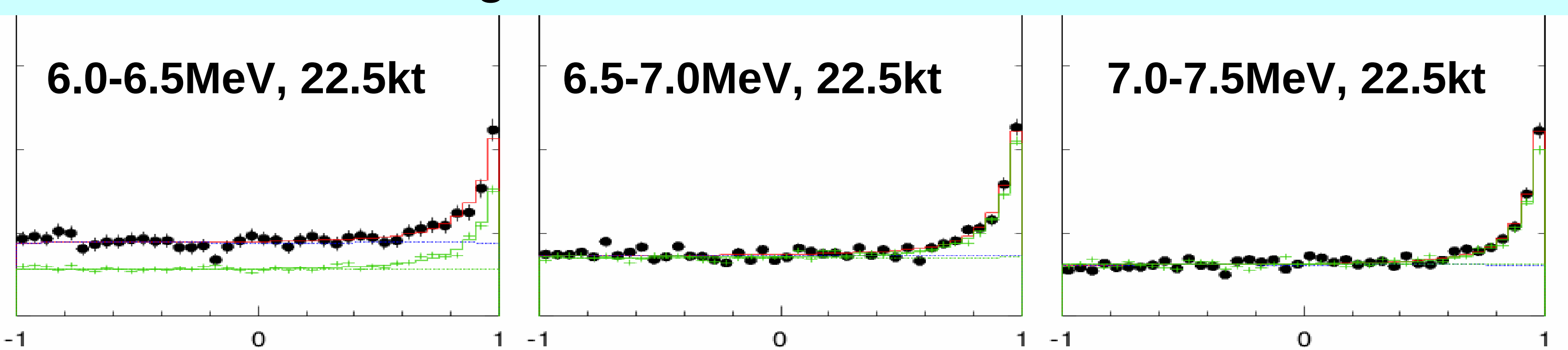
  - SK-I: -0.021±0.020(stat) ±0.013(syst.)
  - SK-II: -0.063±0.042(stat) ±0.037(syst.)

Courtesy Y. Takeuchi, ICRR

Angular distributions in SK-III



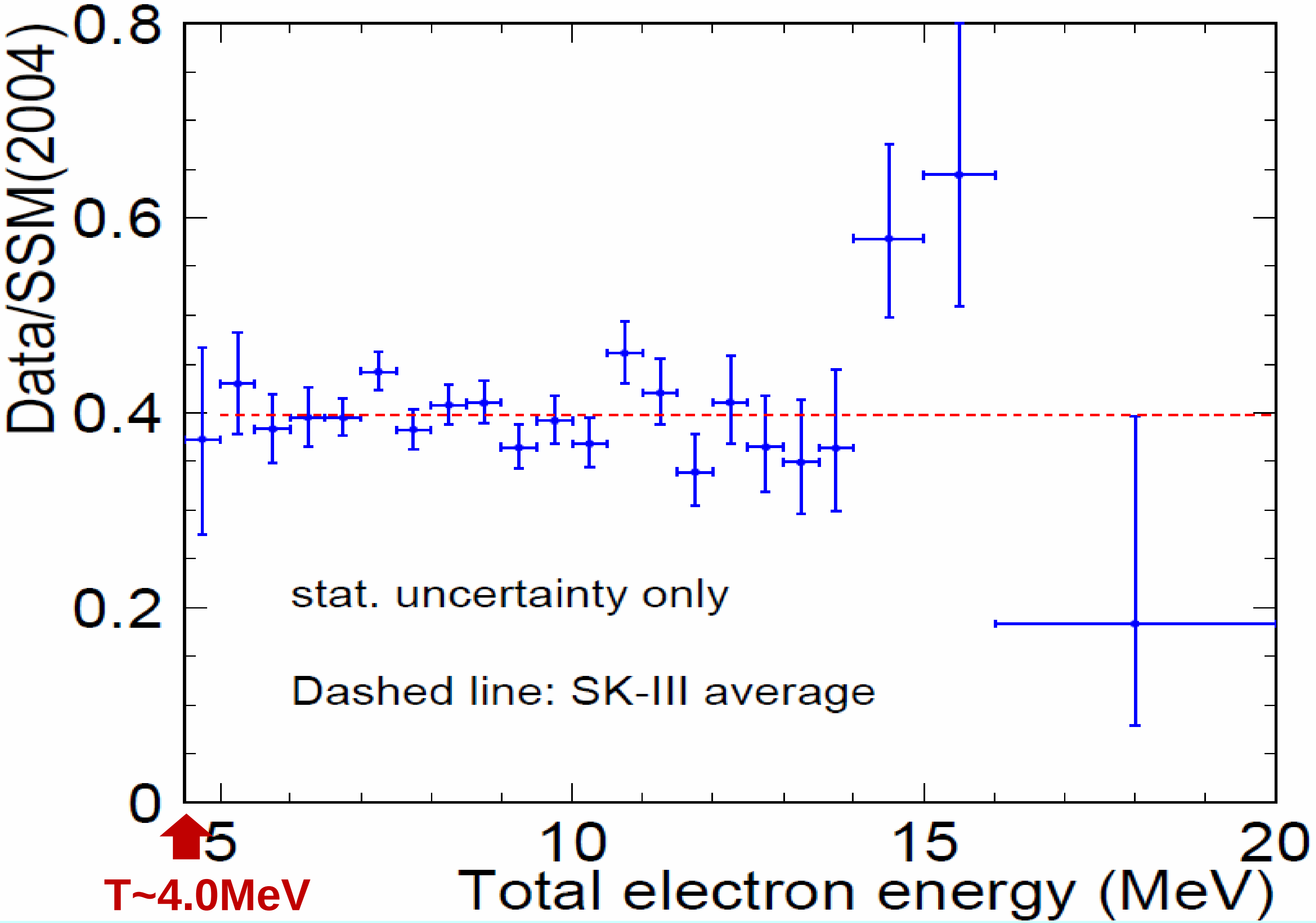
- ■Angular resolution in SK-III is better
- ■In E_{total}=5.0-5.5MeV, SK-III has better Signal to Noise ratio.
- ■BG level in 4.5-5.0MeV region is similar as that in 5.0-5.5MeV of SK-I



Courtesy Y. Takeuchi, ICRR

$\cos\theta_{sun}$

SK-III ^{8}B energy spectrum



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

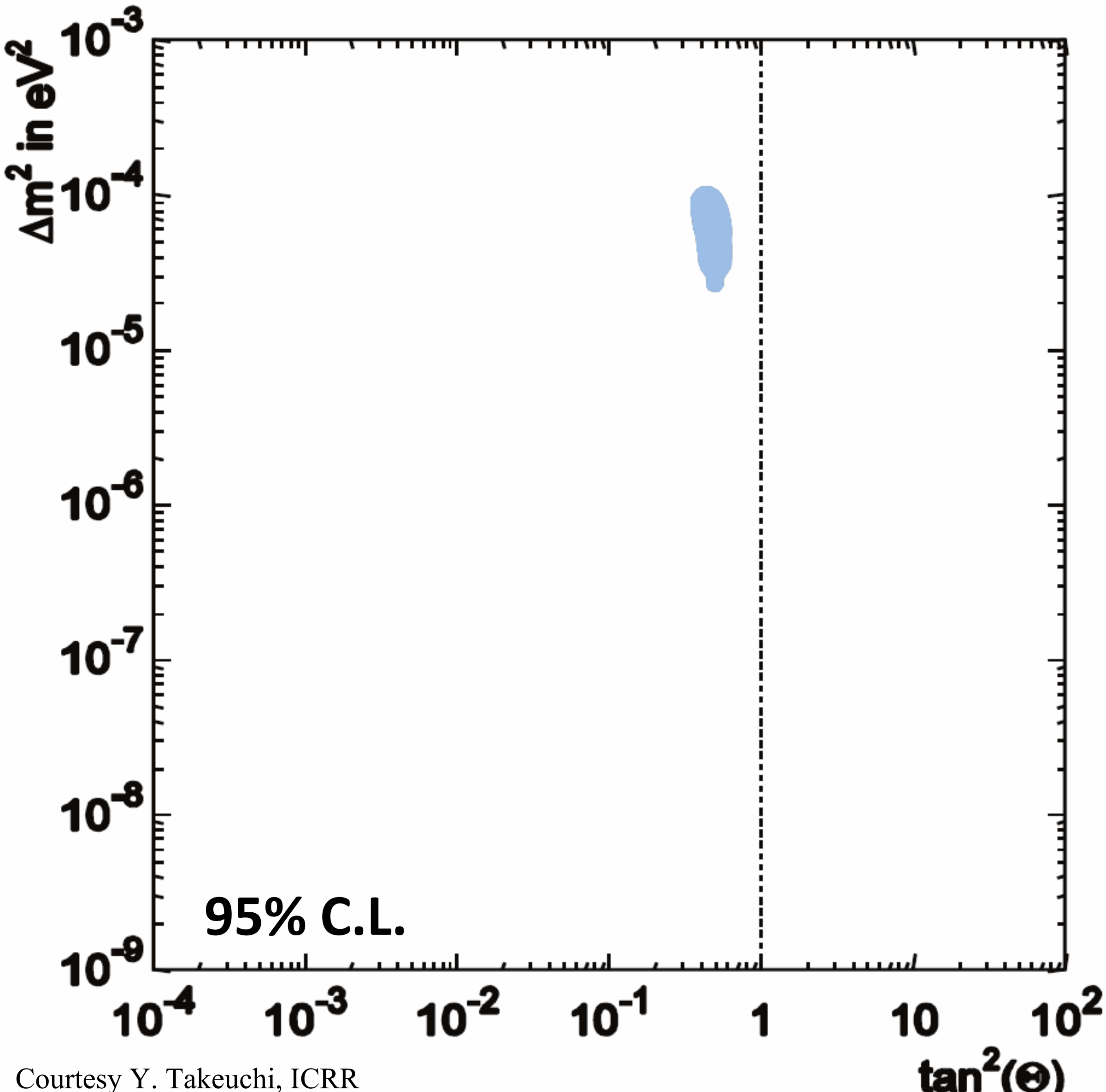
Data set for oscillation analysis

- 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)

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

Courtesy Y. Takeuchi, ICRR

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



Courtesy Y. Takeuchi, ICRR

Min χ^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) 10^6cm^{-2}s^{-1}

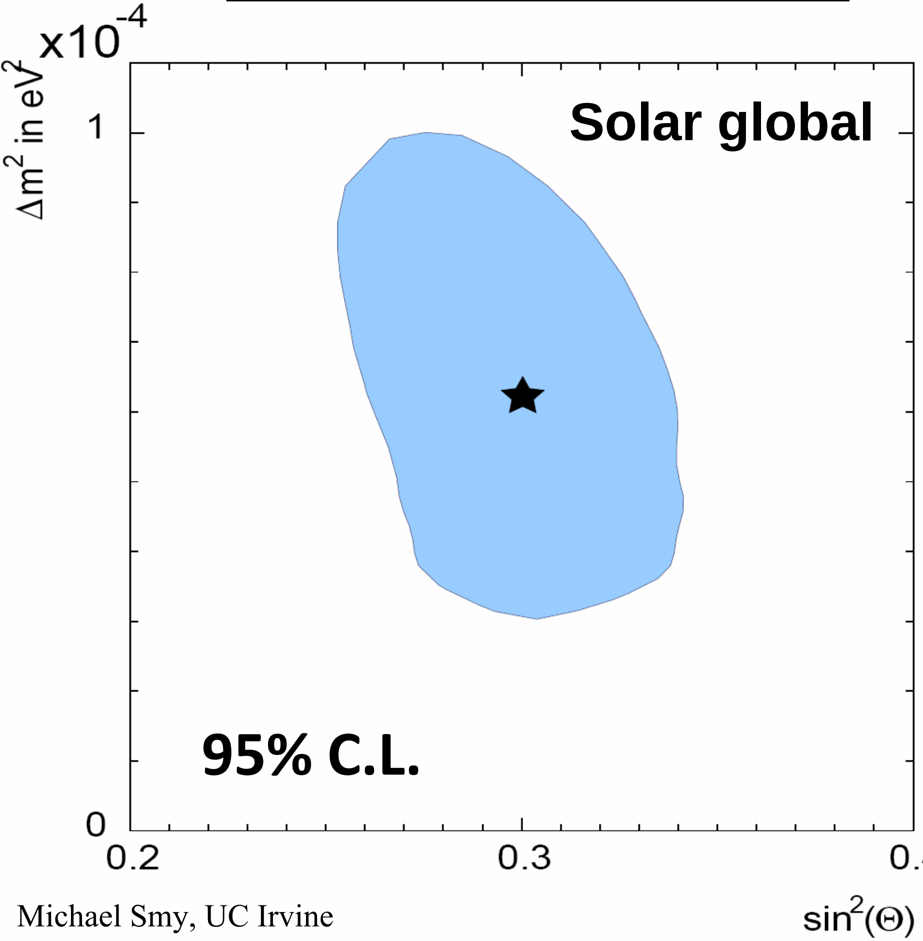
***hep* rate is constrained by SSM flux and uncertainty(16%).**

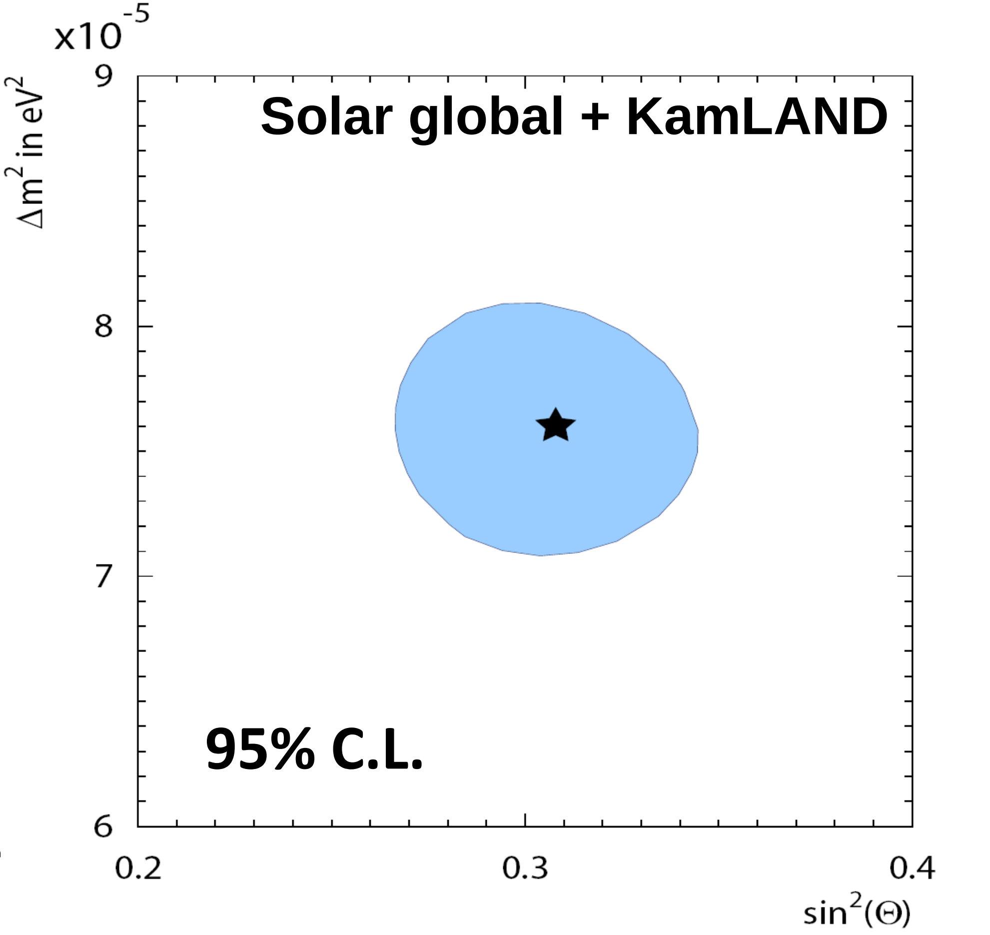
Only LMA solution

Two-Flavor Global Analysis

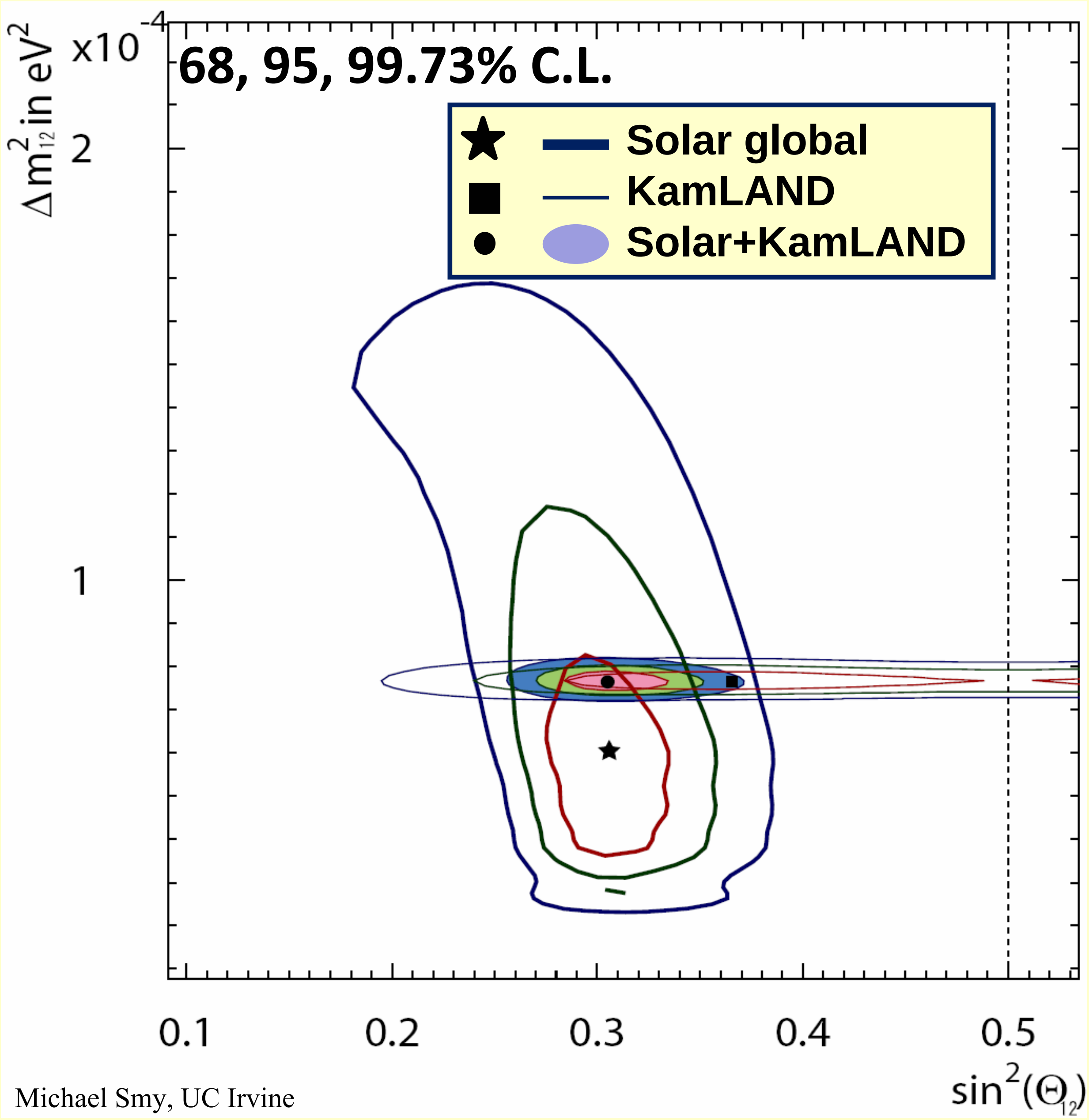
Min $\chi^2 = 53.7$
$\Delta m^2 = 6.0 \times 10^{-5}\ eV^2$
$\sin^2\theta_{12} = 0.31$
$\Phi_{B8} = 0.92 \times \Phi_{B8,SSM}$

Min $\chi^2 = 57.7$
$\Delta m^2 = 7.7 \times 10^{-5}\ eV^2$
$\sin^2\theta_{12} = 0.31$
$\Phi_{B8} = 0.89 \times \Phi_{B8,SSM}$





Three-Flavor analysis: θ_{12} - Δm_{12}^2



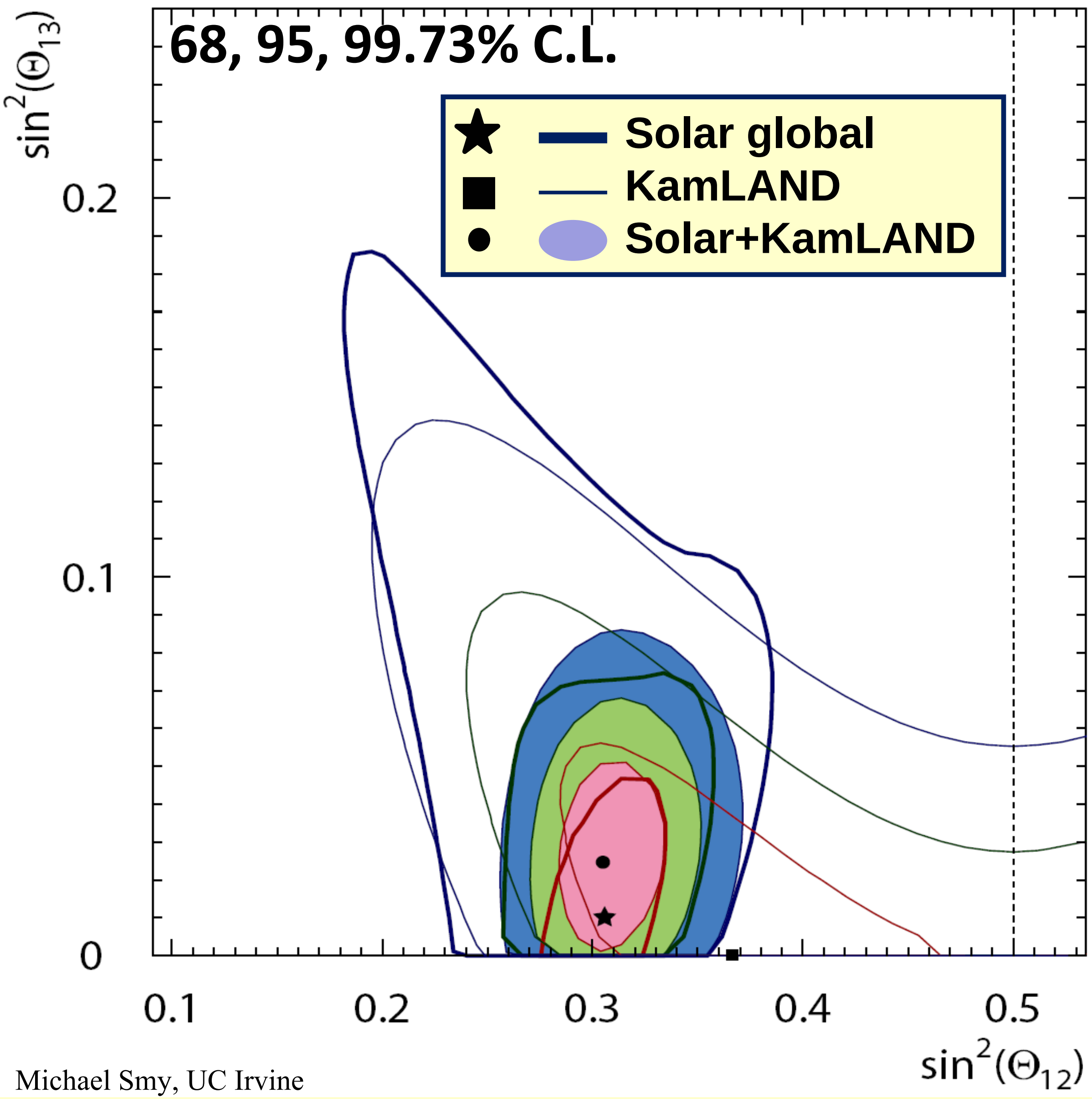
Solar global:

Min χ^2 = 52.8
$\Delta m^2 = 6.0 \times 10^{-5}$ eV^2
$\sin^2\theta_{12} = 0.31$
$\sin^2\theta_{13} = 0.010$
$\Phi_{B8} = 0.92 \times \Phi_{B8,SSM}$

Solar global + KamLAND:

Min χ^2 = 71.2
$\Delta m^2 = 7.7 \times 10^{-5}$ eV^2
$\sin^2\theta_{12} = 0.31$
$\sin^2\theta_{13} = 0.025$
$\Phi_{B8} = 0.91 \times \Phi_{B8,SSM}$

Three-Flavor Analysis: θ_{12} - θ_{13}



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.)

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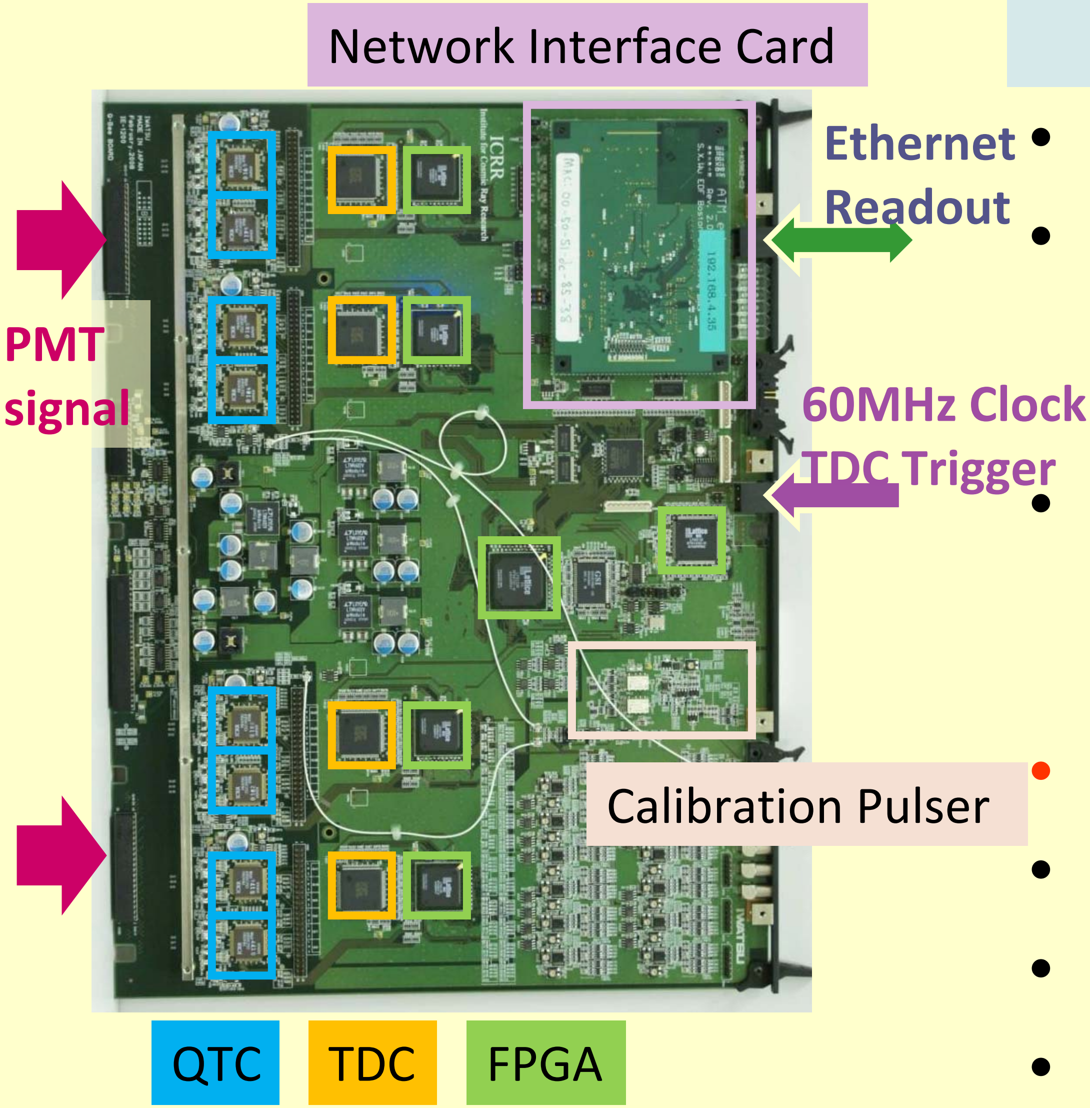
SK-IV's new DAQ: QBEE replaces ATM

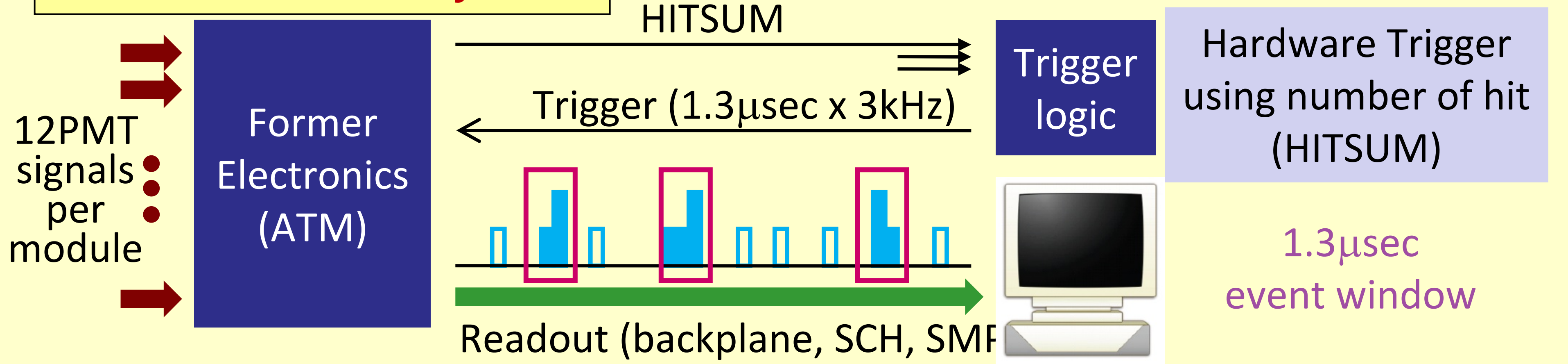


QTC-Based Electronics with Ethernet (QBEE)

- 24 channel input
- QTC (custom ASIC)
  - three gain stages
  - wider (5x!) dynamic range
- Pipe line processing
  - multi-hit TDC (AMT3)
  - FPGA
- Ethernet Readout
- 60MHz common clock
- Internal calibration pulser
- Low (<1W/ch!) power

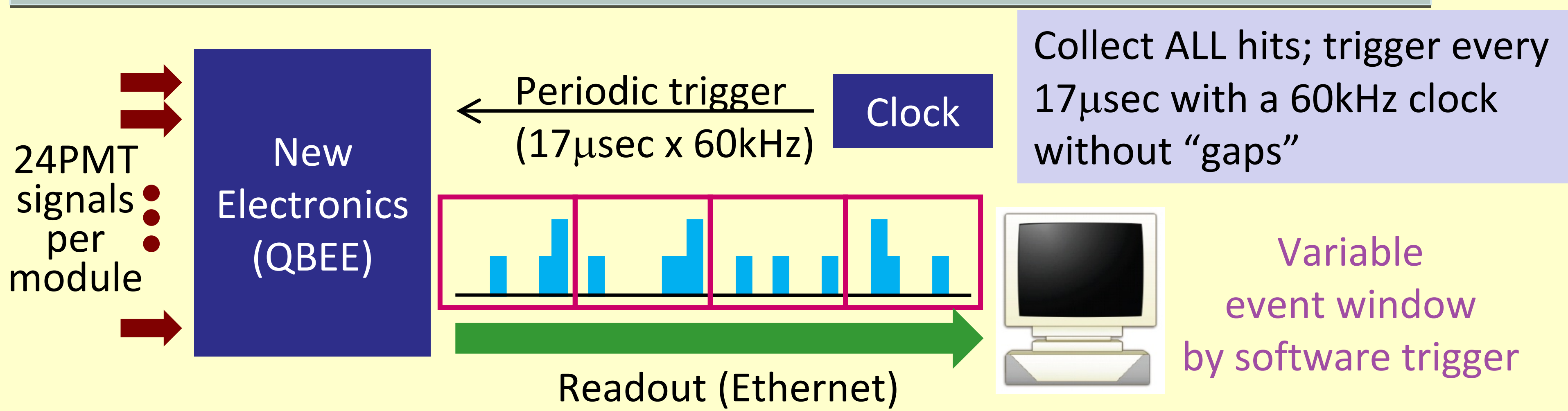
Difference in Readout System

Former readout system



New readout system

No hardware trigger. All hits are read out. Apply software trigger.



Wideband **I**ntelligent **T**rigger

I. online conversion of ADC/ TDC to times/charges

II. sort hits by time

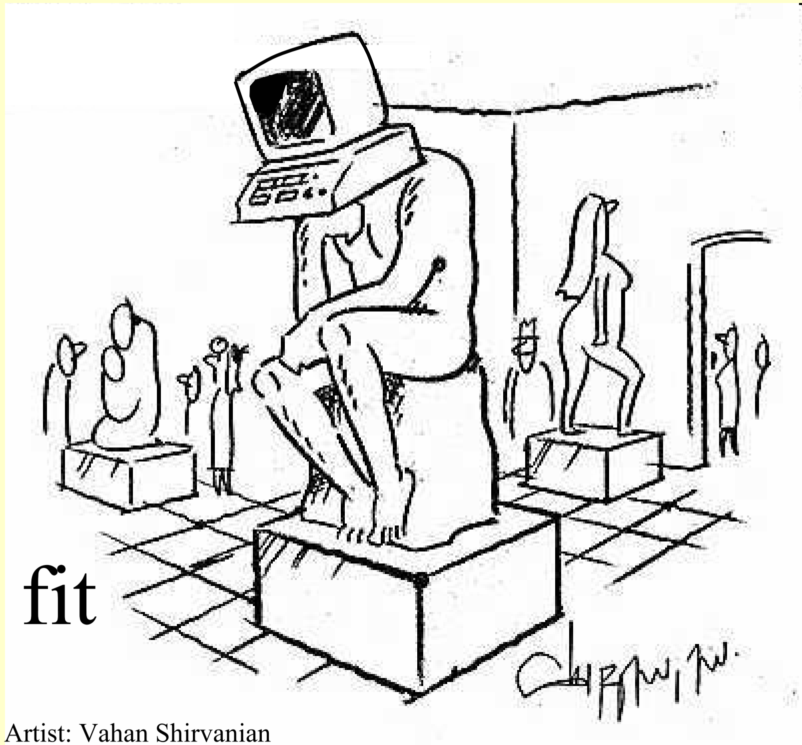
III. pre-filter based on N_{230} (# of hits within 230ns)

IV. **S**oftware **T**riggered **O**nline **R**econstruction of **E**vents: coincidence after time-of-flight subtraction using vertices from selected four-hit combinations

V. fast vertex fit

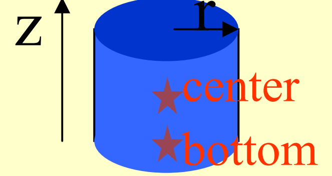
VI. if fiducial, precision vertex fit

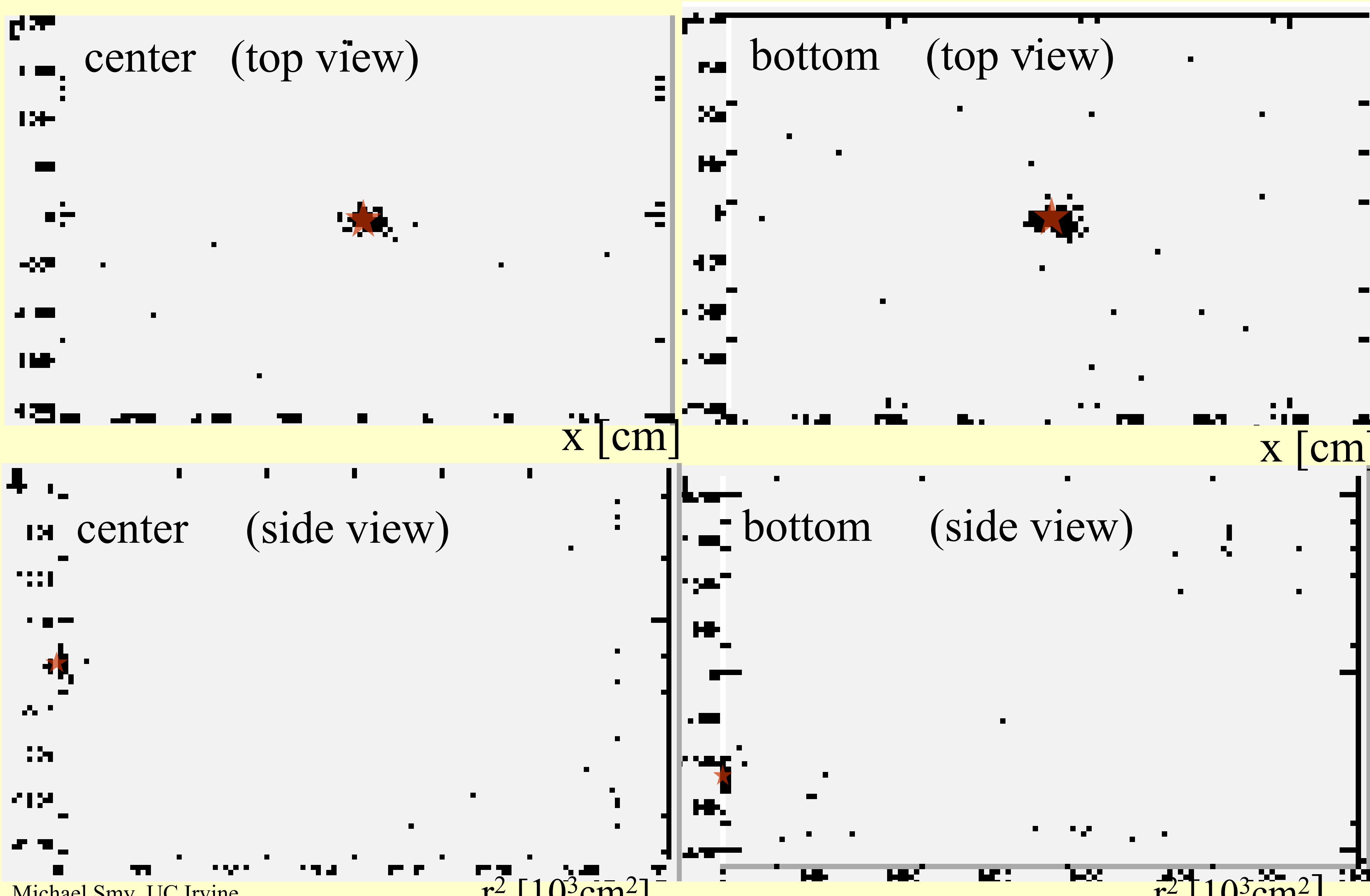
VII. if fiducial, save event



Artist: Vahan Shirvanian

Test with Ni-Cf γ Source





SK IV Low Energy Trigger

- so far, WIT is not running yet
- just emulate previous hardware trigger with larger trigger rate
- use same CPUs as the high energy trigger
- ~100% efficient at 4.5 MeV total energy

New Ideas for Analysis

- from now on, I'm showing work I did with my student Andrew Renshaw
- not official results approved by SK collaboration unless specifically indicated

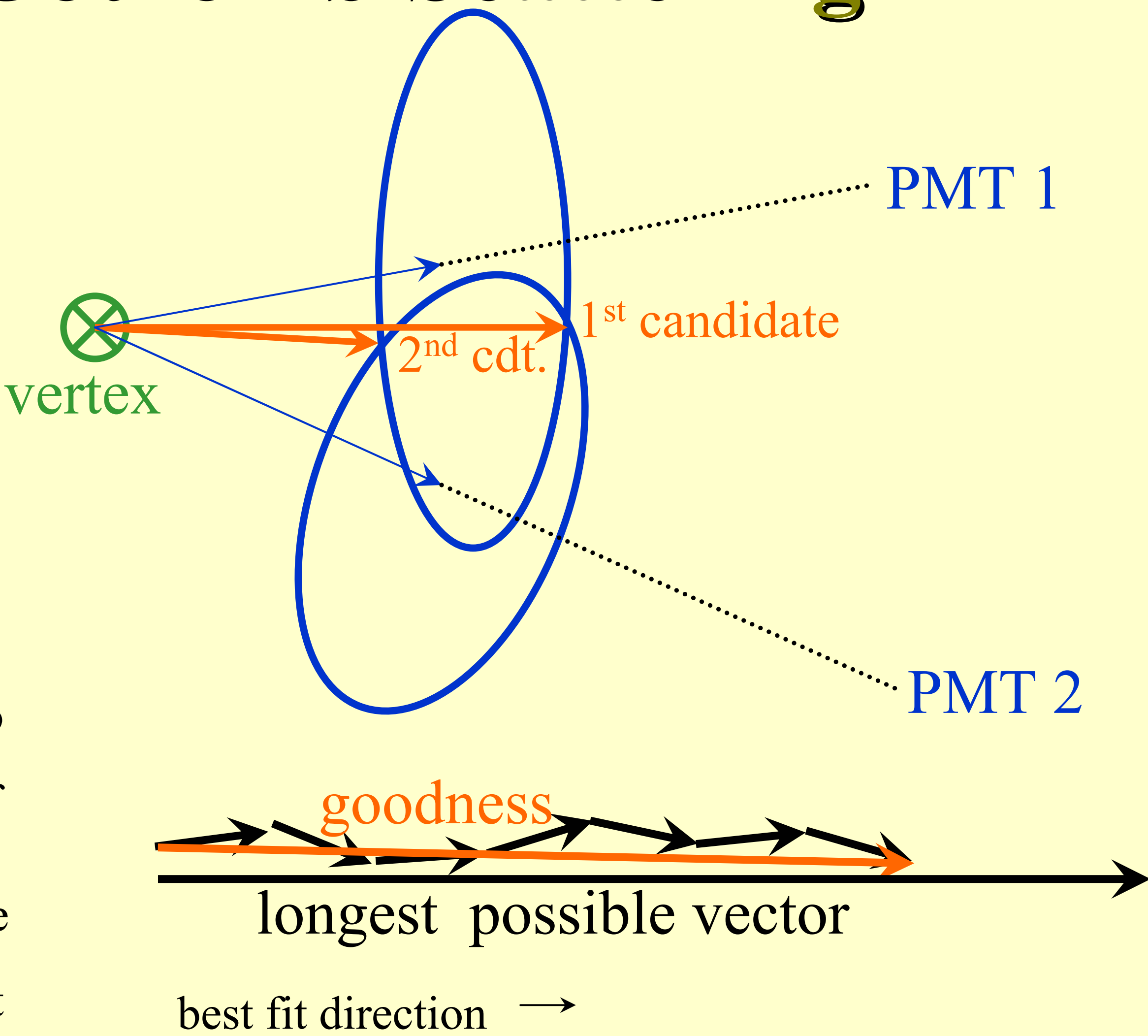
How to Reduce Radon Background?

- Radon decays to ^{214}Bi which β decays
- real electrons <3.1MeV fluctuating in light yield up to 6.5 MeV equivalent
- however, multiple Coulomb scattering is still that of ~2 to 3 MeV electrons, so events should be somewhat more isotropic than 5 MeV solar neutrinos

Reconstructing Amount of Multiple Coulomb Scattering

Hough transformation for PMT pairs:

1. assign a unit direction vector to each PMT hit
2. Draw cone around each vector with the Cherenkov angle as the opening angle
3. the cone intersections are candidates for particle direction: each pair typically contributes two
4. define "goodness" as the length of the vector sum of all candidates within a maximum deviation angle
5. normalize goodness by the longest possible vector sum



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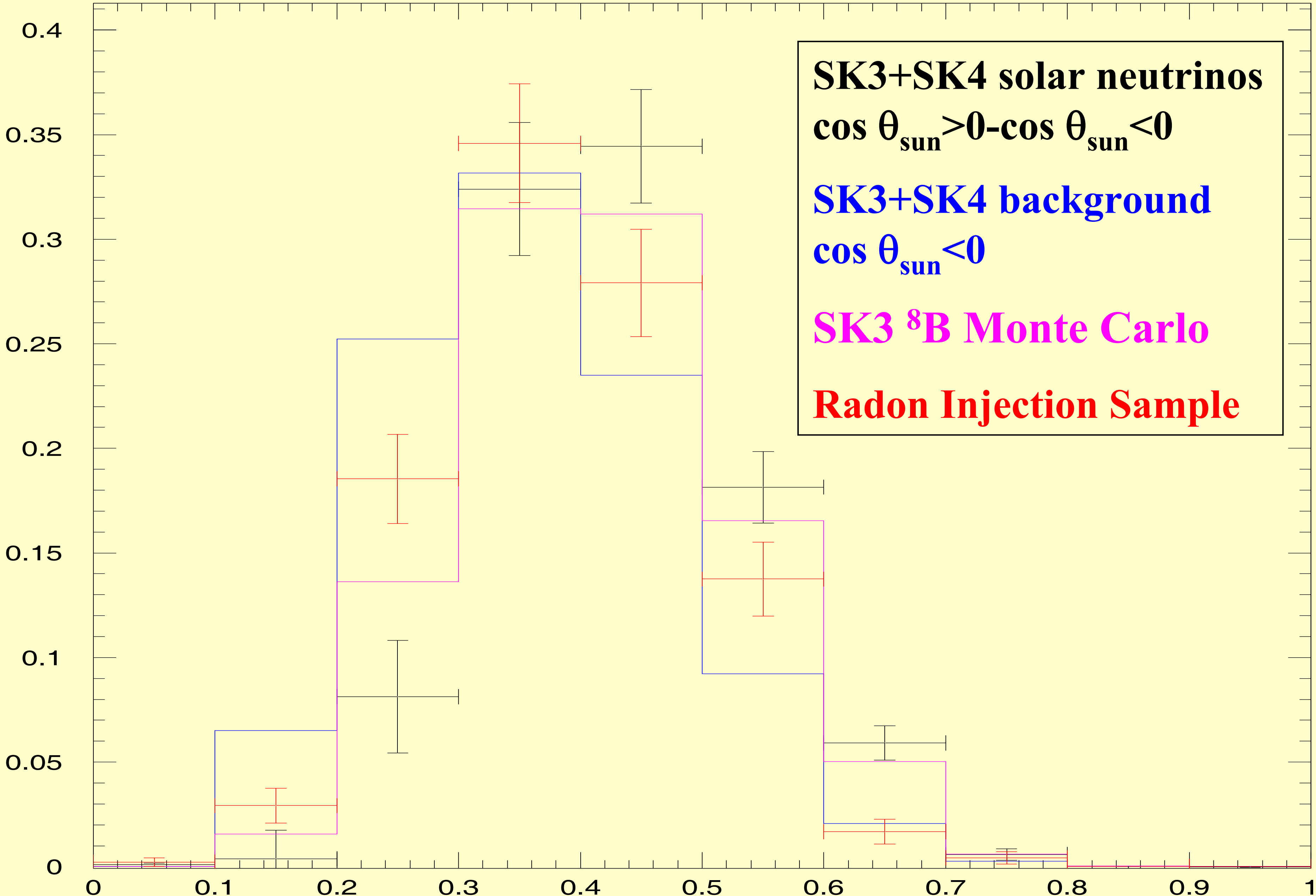
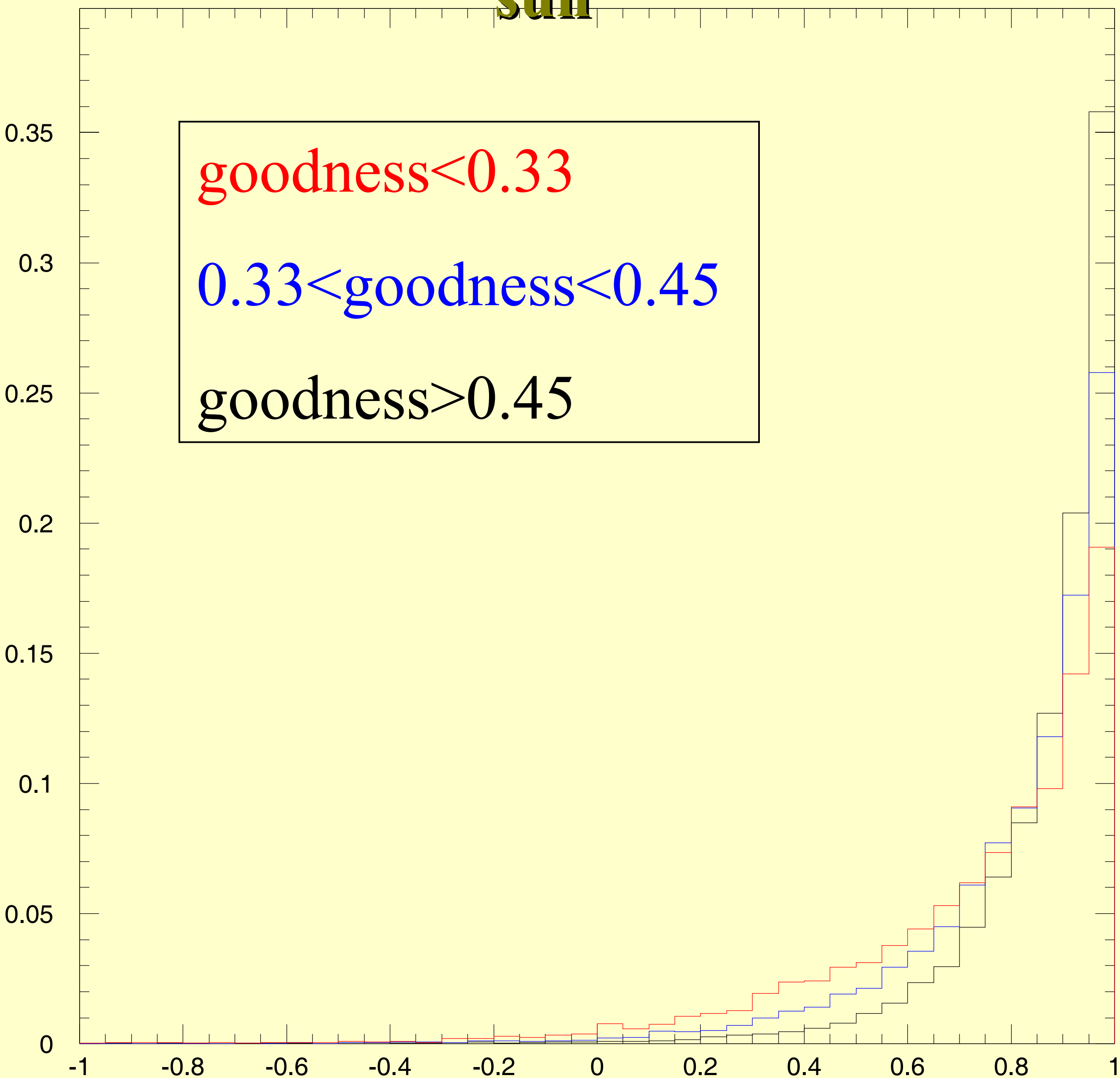
Goodness Distribution 4MeV<E<6.5MeV



“cos θ_{sun}” for LINAC Data

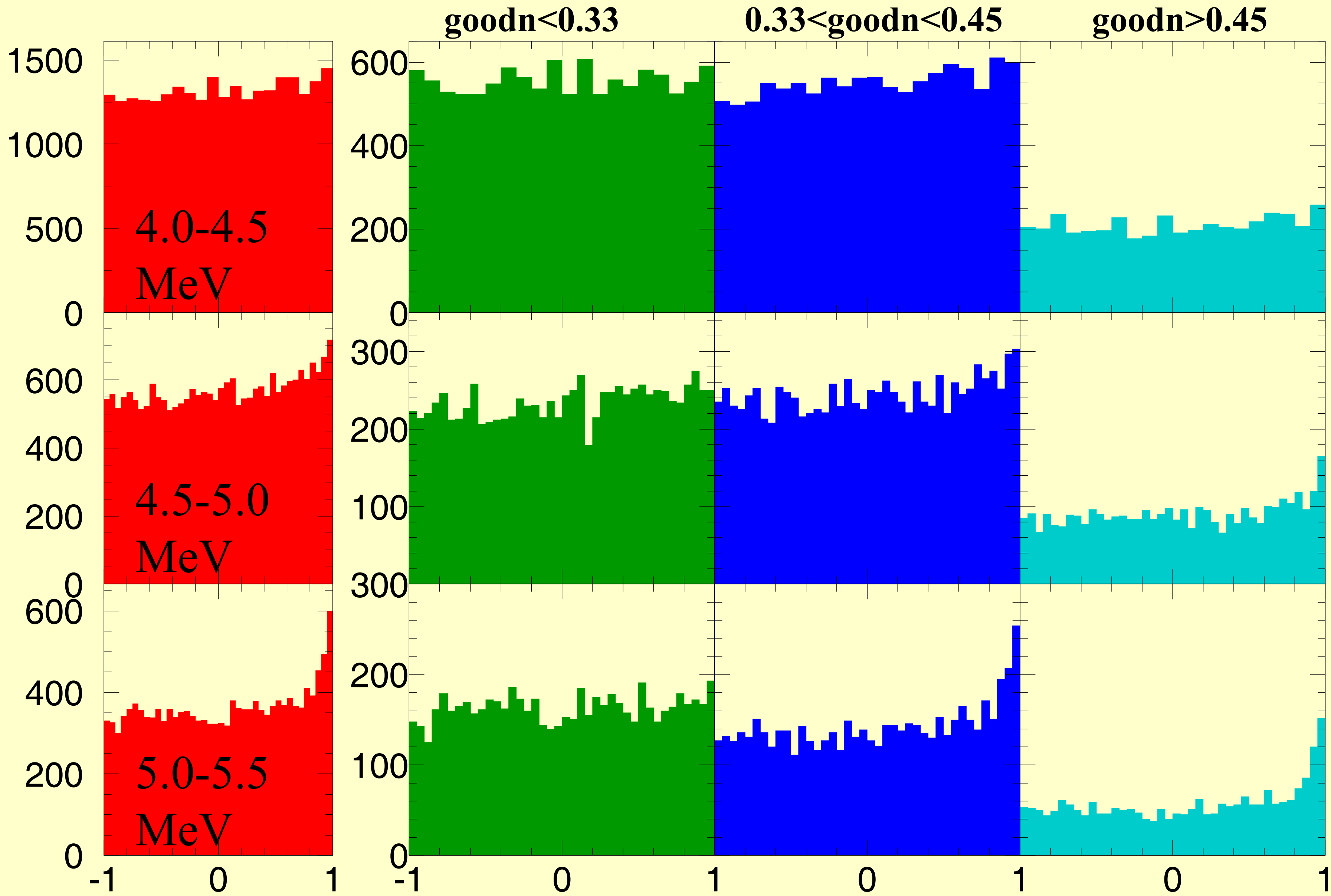


defined as the angle between –z (beam direction) and reconstructed direction

4.8 MeV Linac Data taken at (-3.9,-0.1,0)m

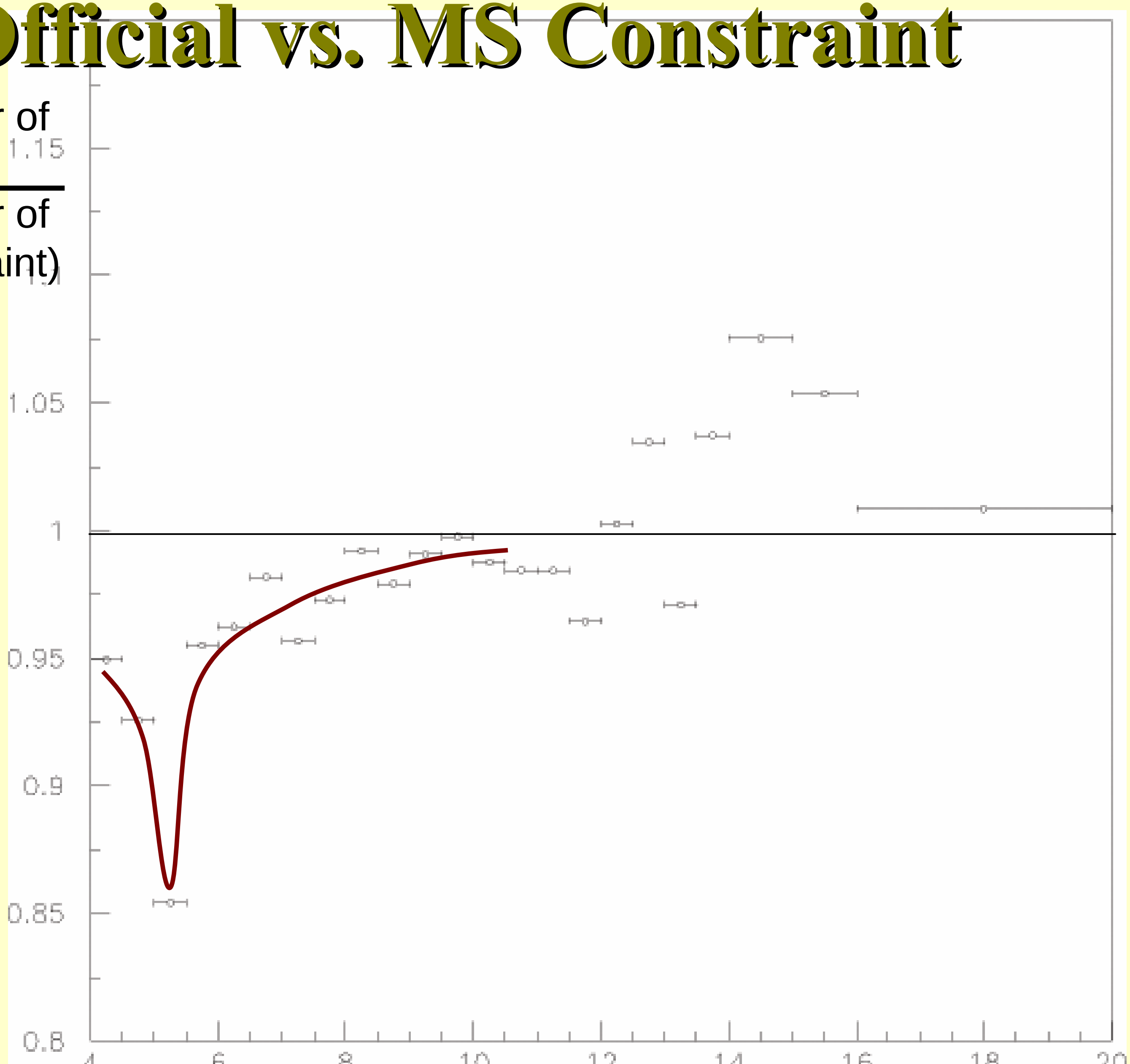
The “ES peak” sharpens in regions of higher goodness (true for all LINAC momenta at all positions)

SK IV cos θ_{sun} Distributions

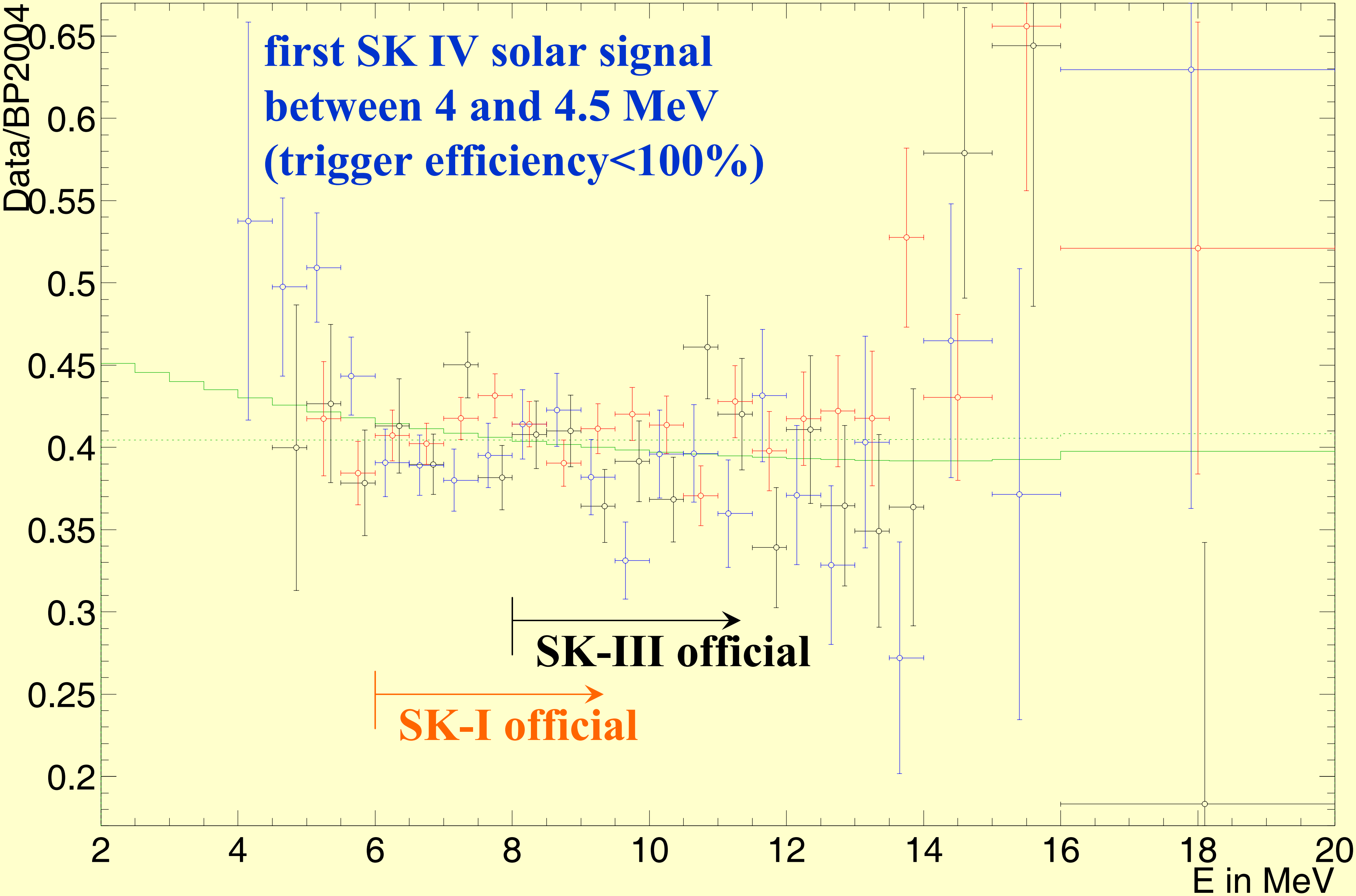


SK-IV Stat. Error : Official vs. MS Constraint

(Percentage error of official result)
(Percentage error of multi-scat constraint)



SK I/III/IV Spectrum Comparison



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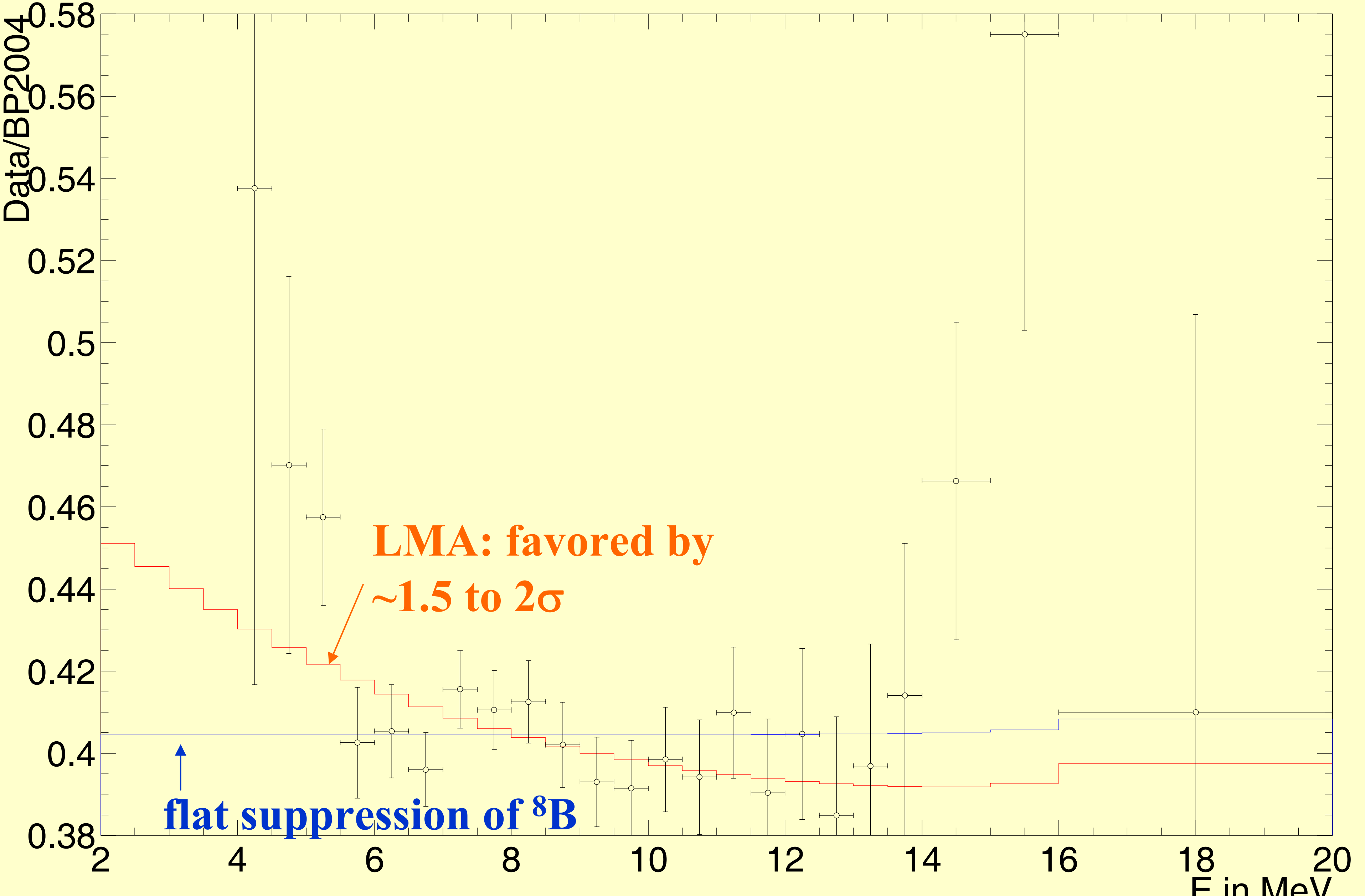
SK I/III/IV Spectrum with MS Constr



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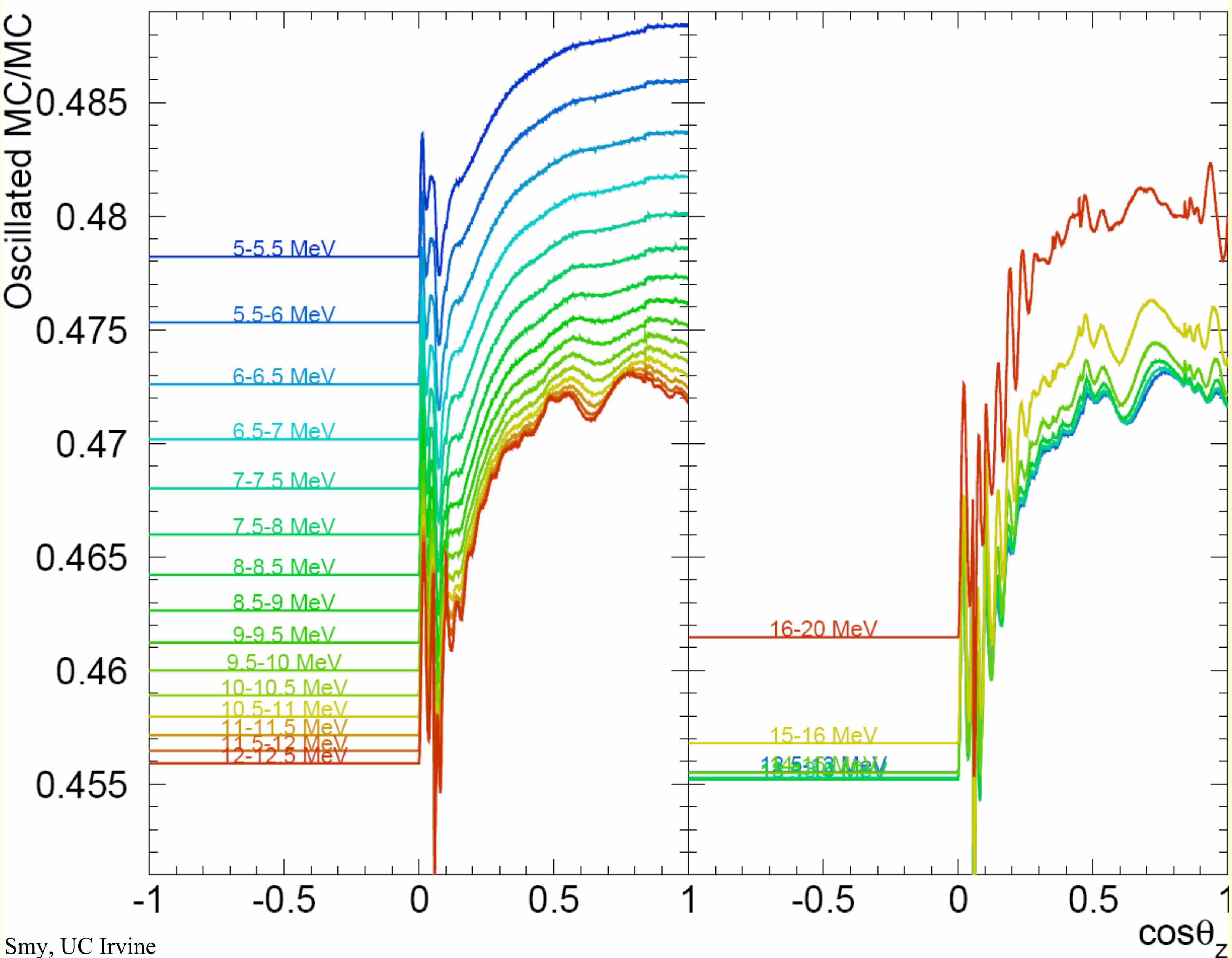
Day/Night Effect at KamLAND Δm_{12}^2



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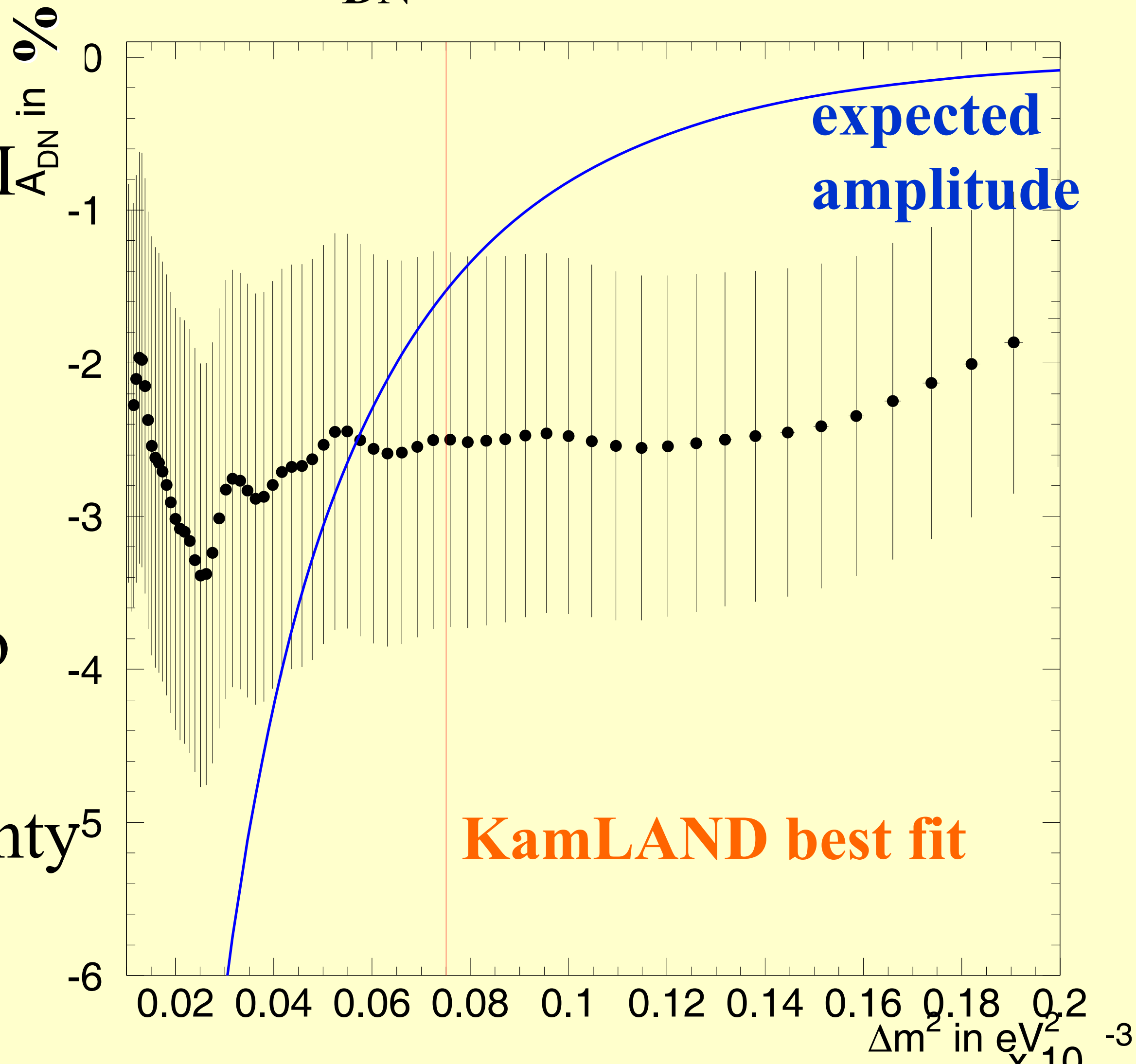
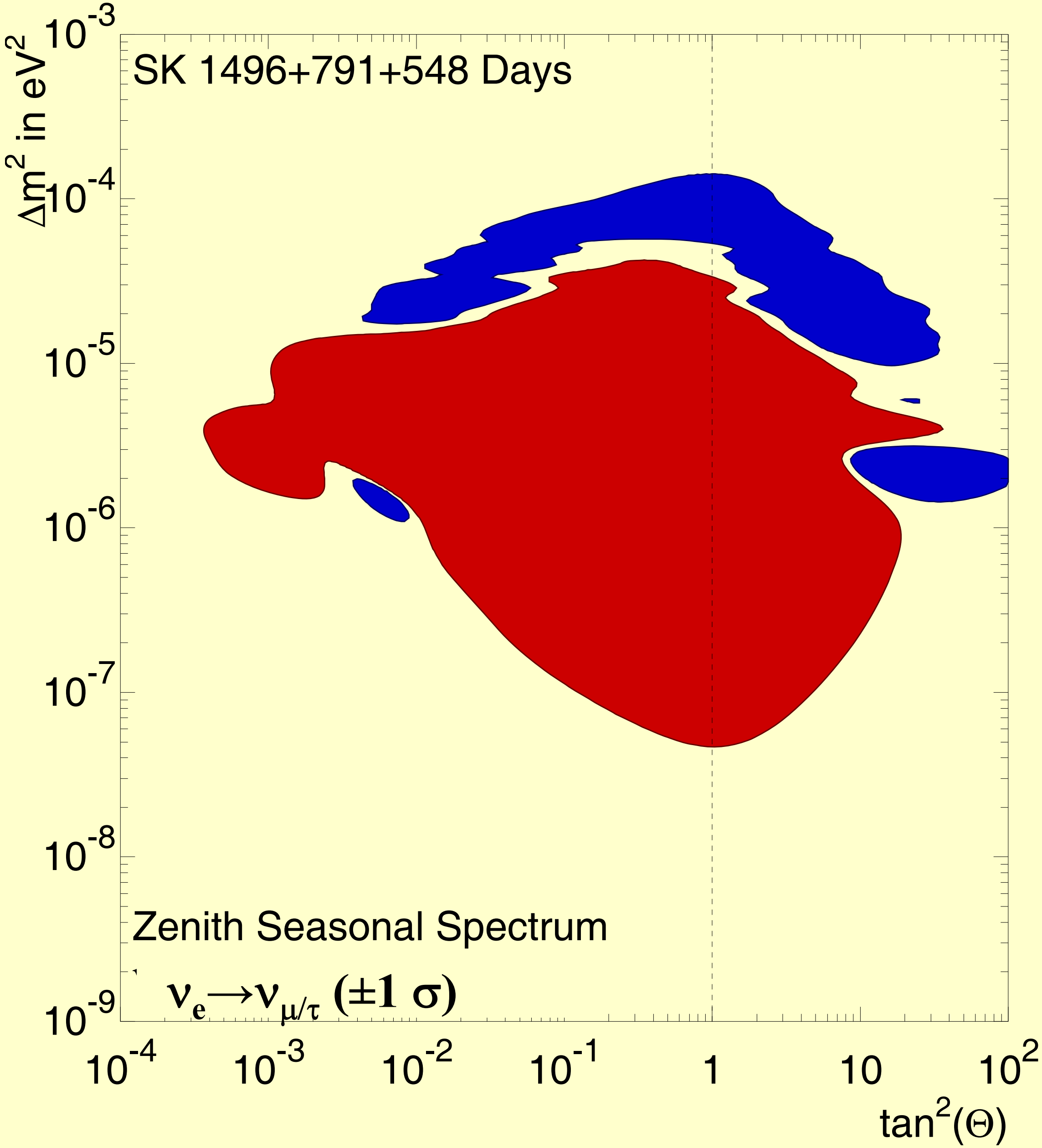
Fit Day/Night Amplitude to SK Data

- used for SK-I: A_{DN}(I)=-0.018±0.016(stat) ±0.013(syst)
- A_{DN}(II)=-0.036±0.035(stat), A_{DN}(III)=-0.040±0.025(stat)
- depends on Δm^2
- Combine SK-I/II/III: **-0.026±0.013(stat)** at KamLAND Δm^2
- consistent with expected amplitude
- consistent with zero within 2σ
- systematic uncertainty under study



Favored and Disvfavored Oscillation Parameters

- in this case, amplitude is not fit; just compared D/N effect to no D/N effect!!!
- blue area has D/N effect favored by at least one σ
- red area has D/N disfavored by at least one σ



Conclusions

- SK-III data has already impacted solar neutrino global fits:
  - lower background
  - solar neutrino flux estimate below 5 MeV
  - three flavor analysis
- SK-IV can go lower in threshold: the goal is 4 MeV total recoil electron energy and it seems within reach
- SK solar analysis begins to see oscillation signatures