Solar and Atmospheric Neutrinos in Super-Kamiokande

Jennifer Raaf
Boston University

on behalf of the Super-K collaboration

Neutrino 2008
Christchurch, NZ

Super-Kamiokande Collaboration

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~35 institutions

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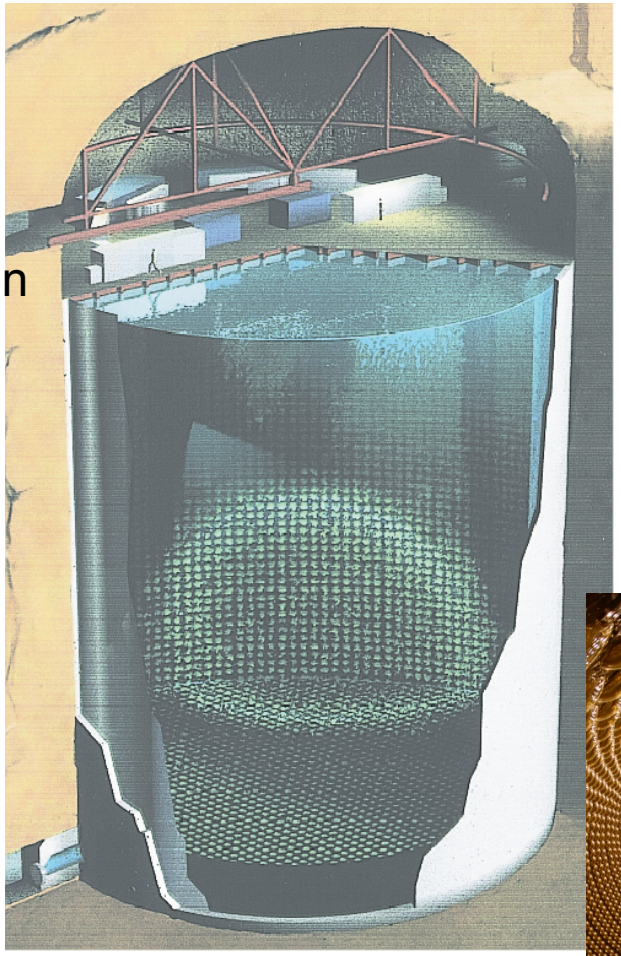
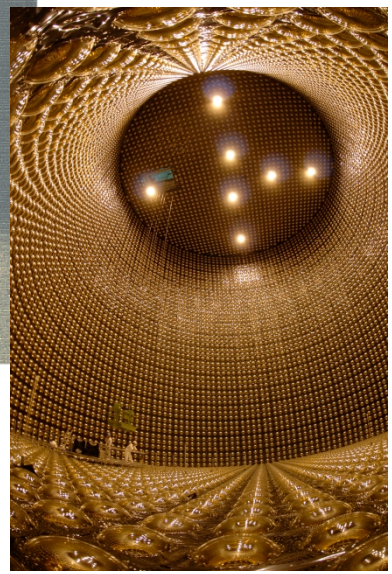
Super-Kamiokande

Kamioka-Mozumi zinc mine
1 km (2700 meters-water-equiv.) rock overburden

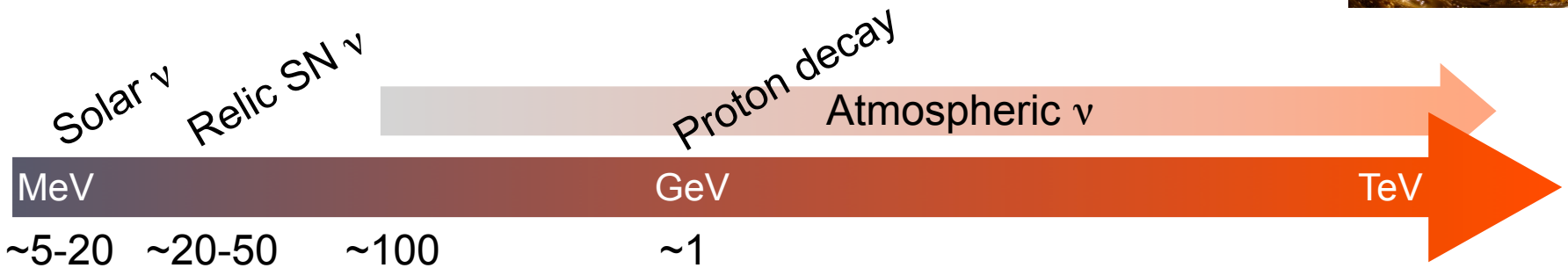
Water Čerenkov detector
50 ktons (22.5 ktons fiducial)

Instrumented with
50-cm PMTs in Inner Detector (ID)
20-cm PMTs in Outer Detector (OD)

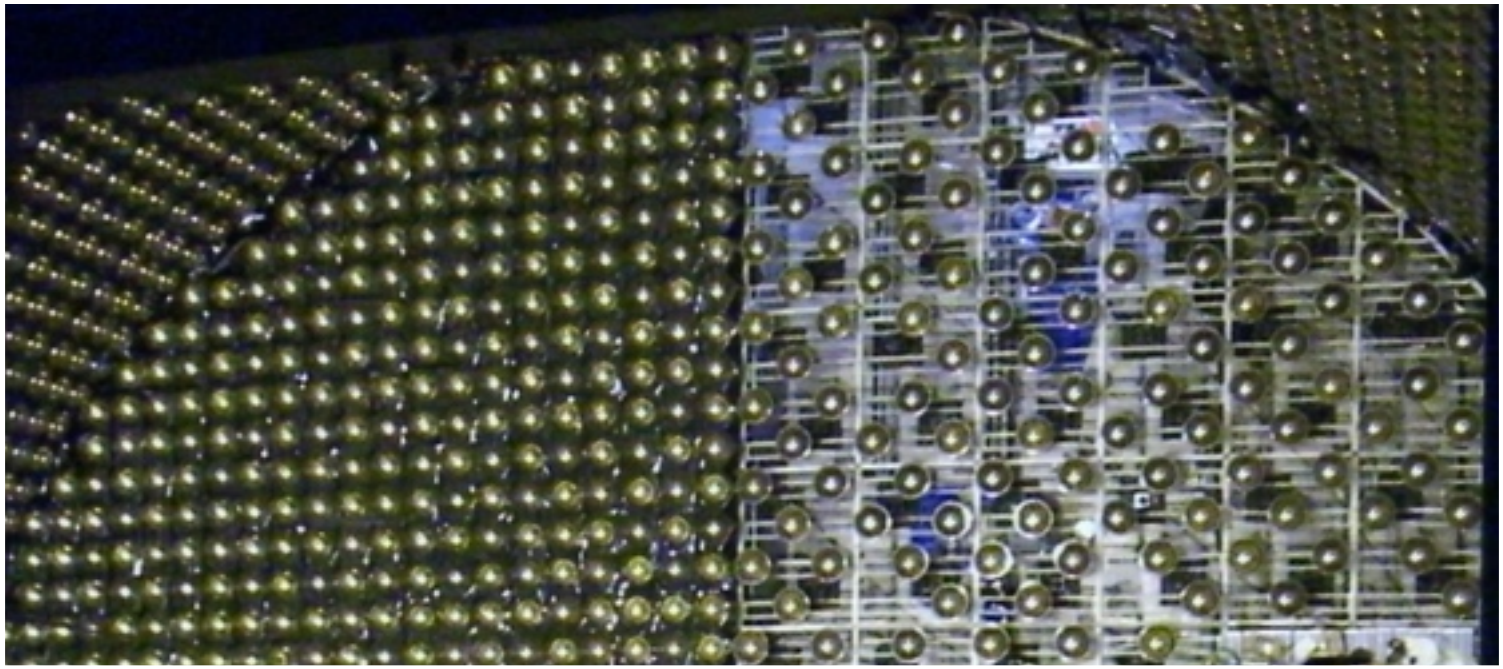




Goals of Super-K
Solar neutrinos
Supernova neutrinos (+ relic SN)
Atmospheric neutrinos
Proton decay



Timeline



During SK-III construction

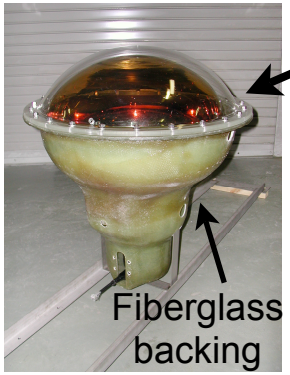
1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009

SK-I (1996-2001)
11,146 ID PMTs
(40% coverage)
1,885 OD PMTs

accident

SK-II (2003-2005)
5182 ID PMTs
(19% coverage)
Acrylic shields added

SK-III (2006-2008)
11,129 ID PMTs (40% cov.)
OD segmentation
(top/barrel/bottom)



Coming soon:
SK-IV (2008- ...)
Replace DAQ electronics

SK-IV: DAQ Upgrade

- Simplified detector operations
  unified readout scheme for ID and OD

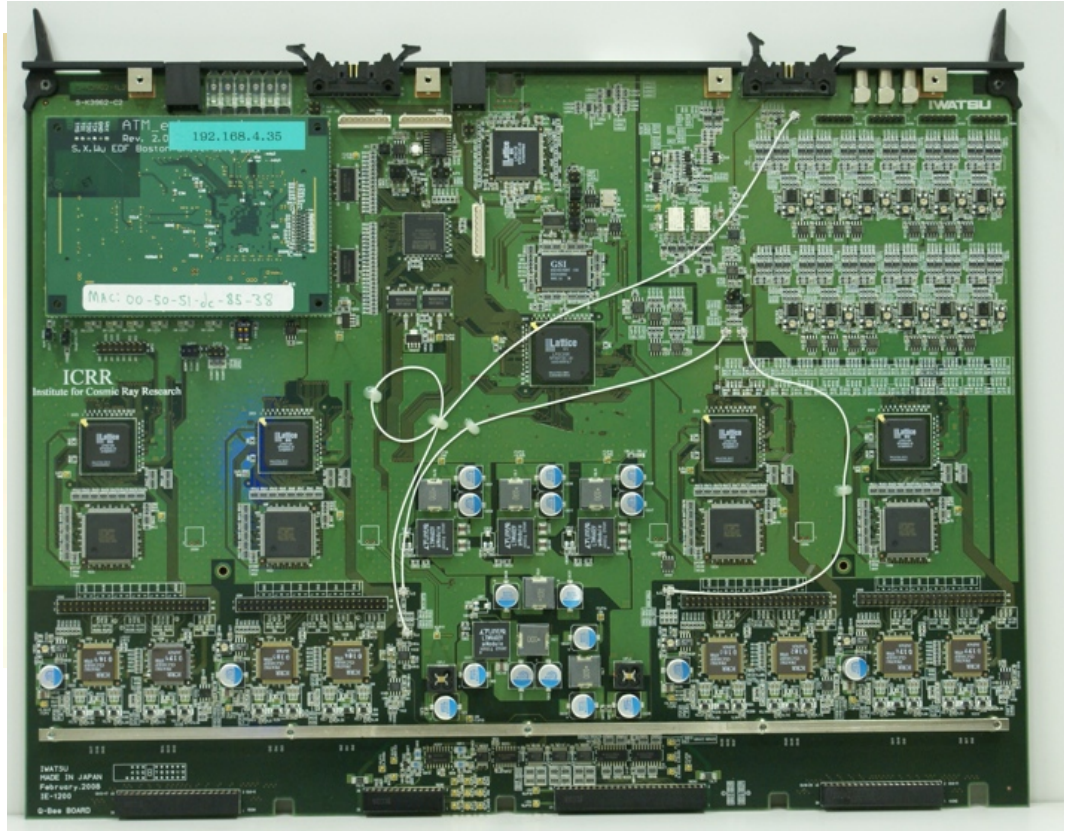
- Increased reliability/performance
  - fewer discrete components

  - improve energy resolution
    wider dynamic range

  - improve multiple-hit capability
    efficient ID of μ-decay electrons

  - reduce SPE hit threshold
    low E solar ν's
    γ-tagging for proton decay

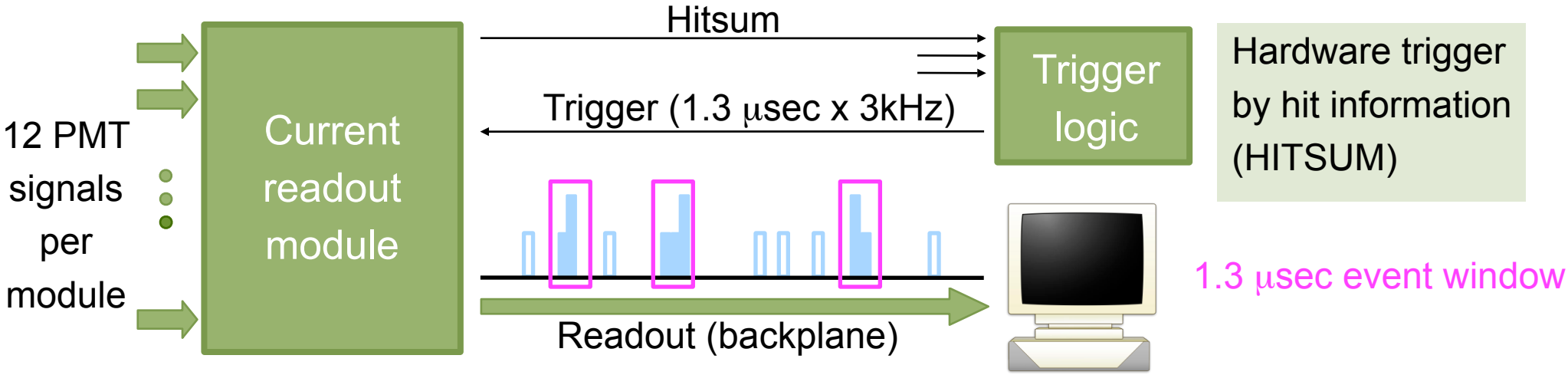
  - improve supernova burst capability



- Ethernet-based readout
  increased bandwidth and reduced dead time
  build DAQ system from commodity network devices!

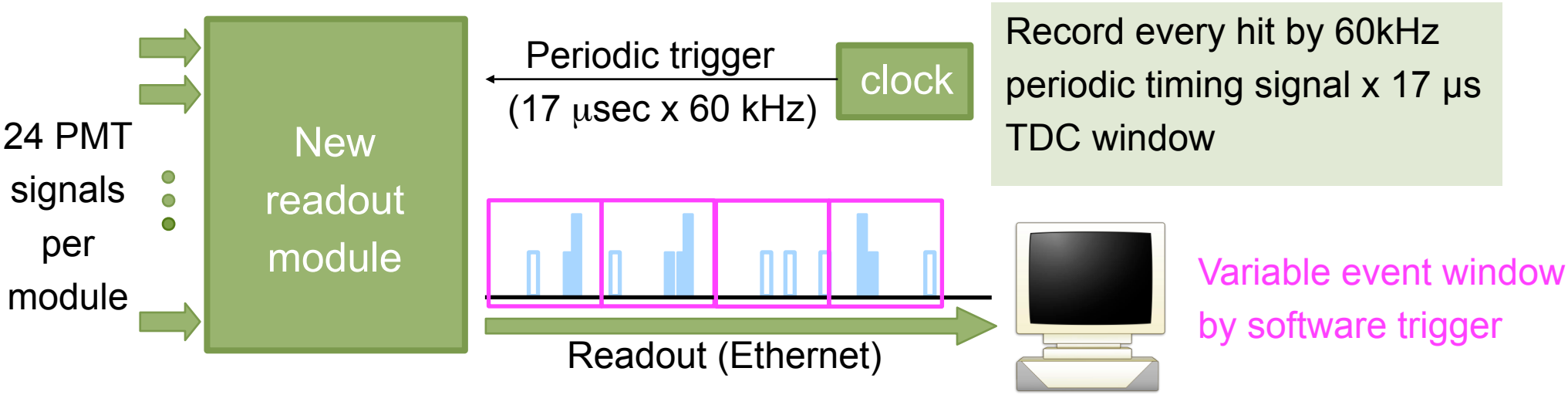
New DAQ readout scheme

SK-I,II,III DAQ scheme:



SK-IV DAQ scheme:

No hardware trigger. Instead record all hits and apply software triggers.



SK-IV Installation begins August 2008

to be completed by mid-September

~6-month commissioning period before T2K beam

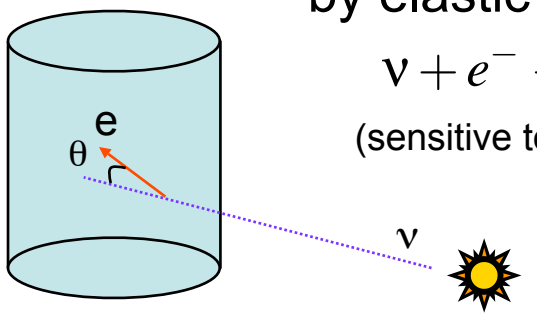
Super-Kamiokande Solar Neutrinos

Solar ν's at Super-K

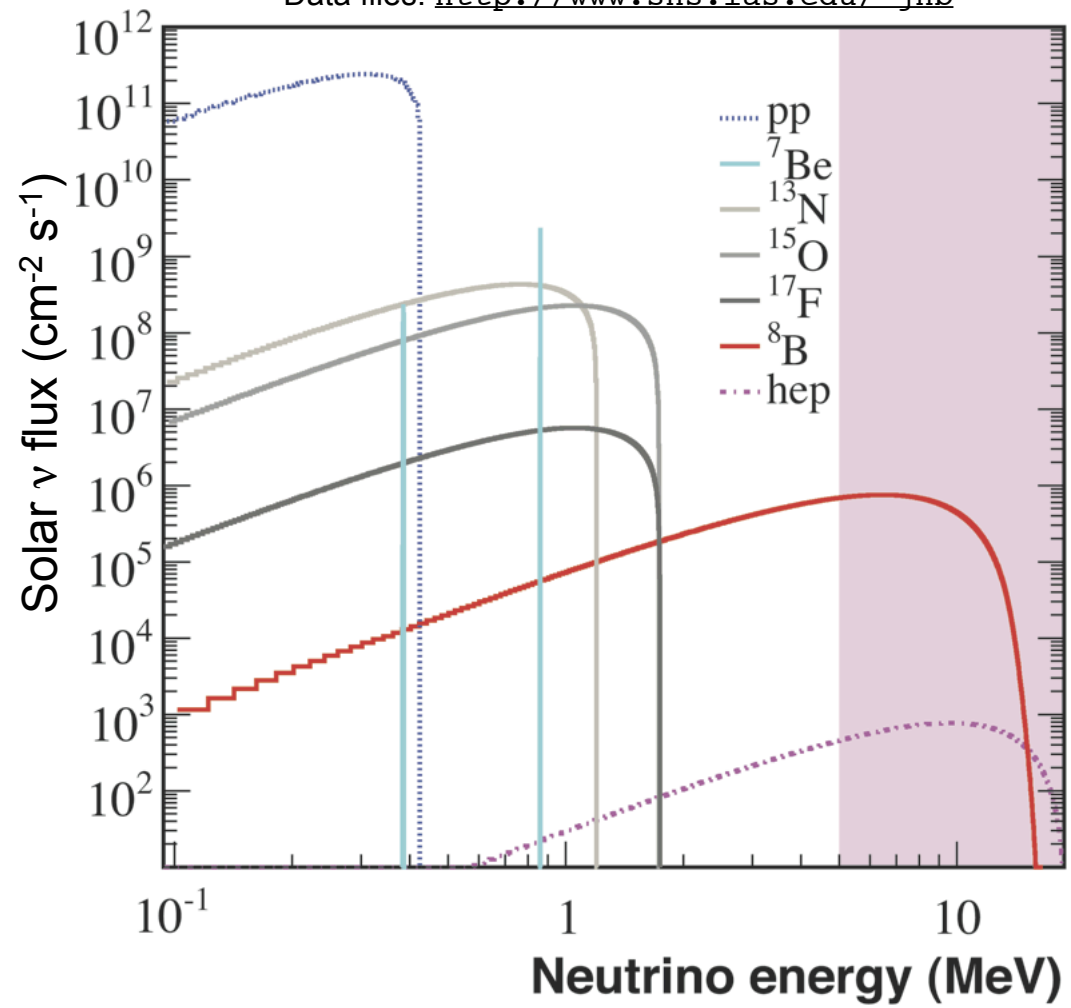
^{8}B neutrino measurement by elastic scattering:

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

(sensitive to all ν flavors)



SSM energy spectra (BP04)
Data files: http://www.sns.ias.edu/~jnb



Reconstruct:

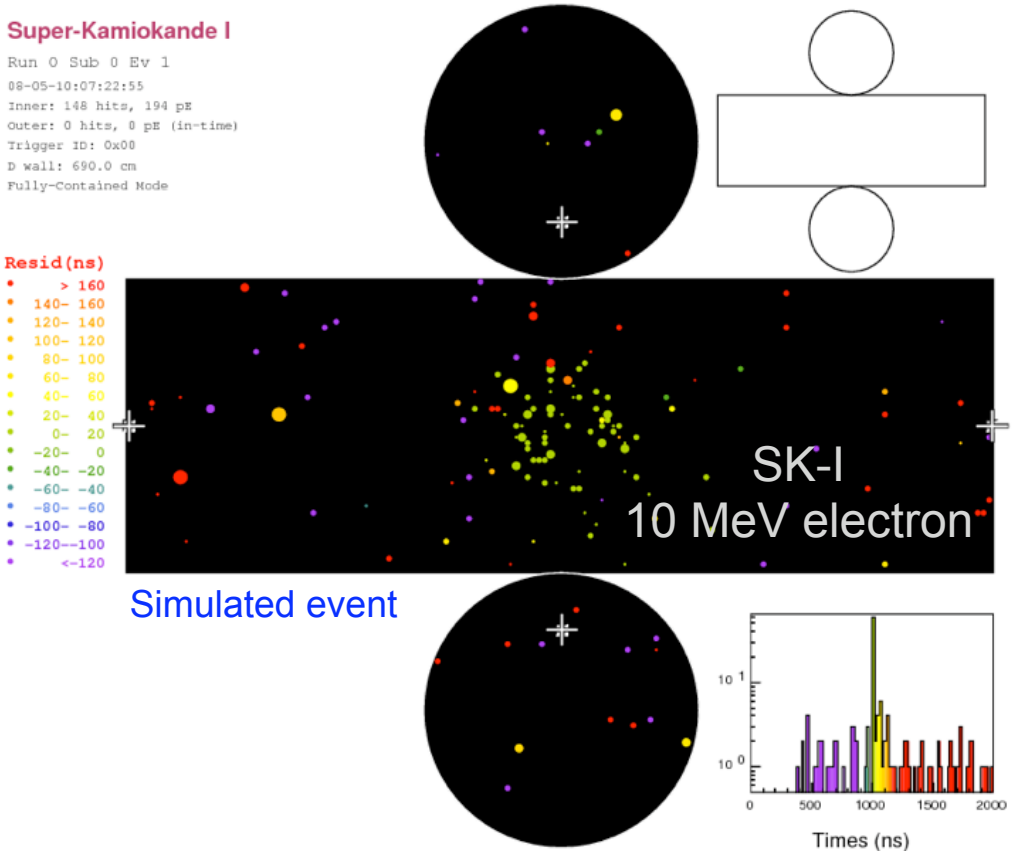
energy of recoil electron
direction relative to Sun

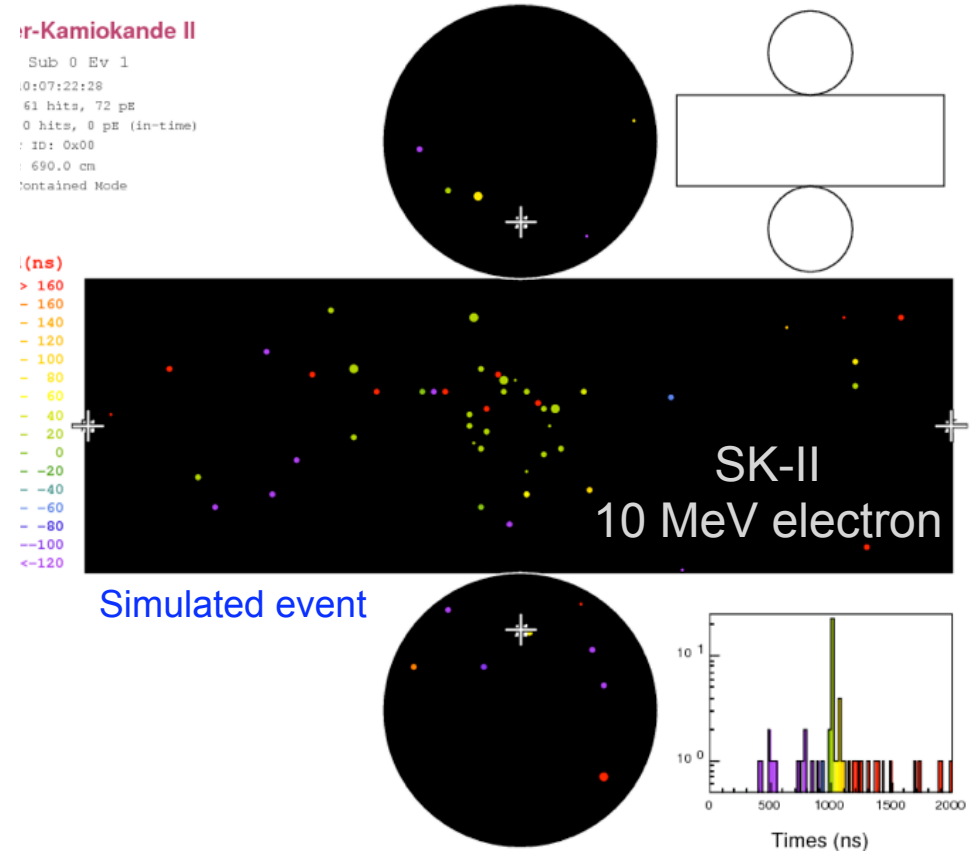
Measure/observe:

- ✦ Day/Night flux differences
- ✦ Seasonal flux variations
- ✦ Spectral distortion

Observed event rate in Super-K:
~15 evts/day with E_e > 5 MeV

Low energy events in Super-K





	Energy response	Vertex resolution for 10 MeV electron
SK-I	~6 p.e./MeV	~70 cm → 60 cm✝
SK-II	~3 p.e./MeV	~100 cm
SK-III	~6 p.e./MeV	in preparation

✝Using SK-II improved algorithm

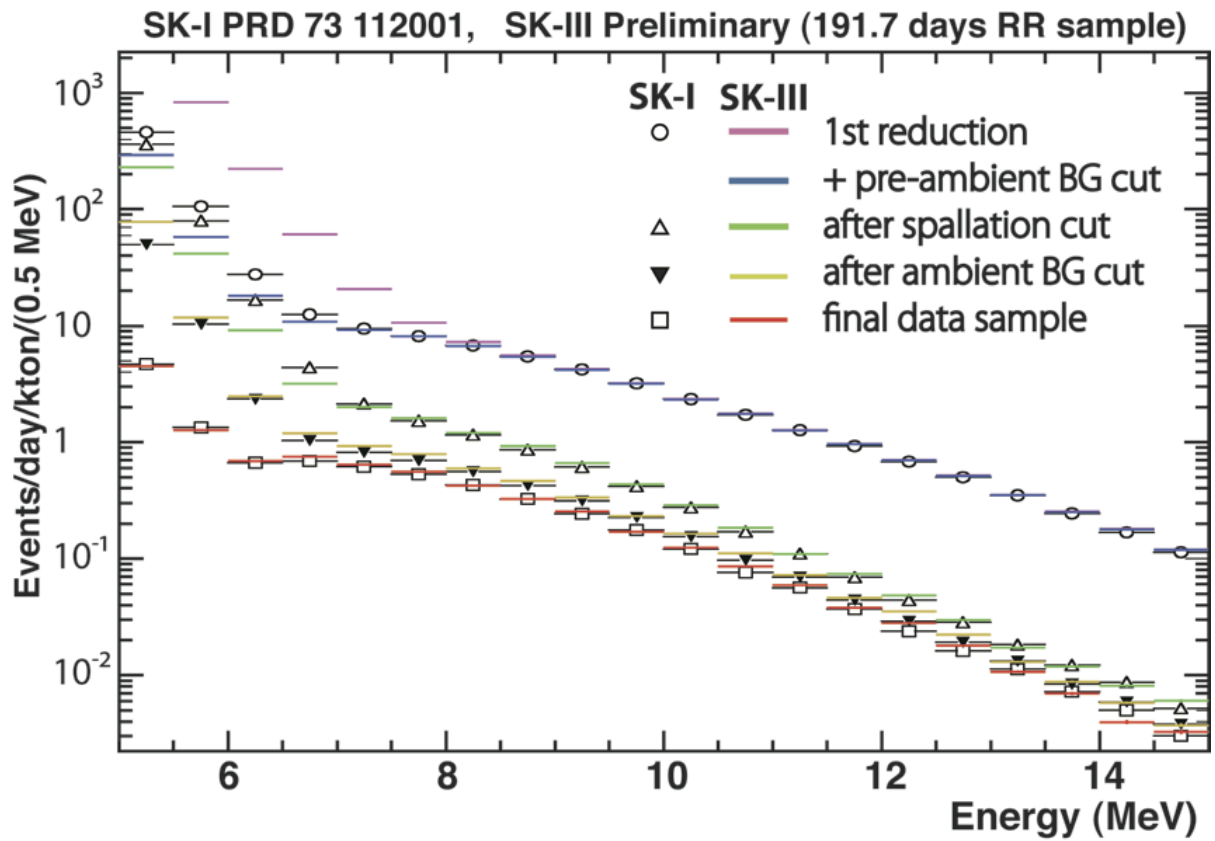
Solar neutrino data reduction: SK-III

Run period shown: Jan. 24, 2007 - Mar. 2, 2008

Datasets:

✤ Full Final (FF) sample
Livetime: 288.9 days
Energy > 6.5 MeV

✤ Radon Reduced (RR) sample (shown)
→ periods of high radon activity removed
Livetime: 191.7 days
Energy > 5 MeV

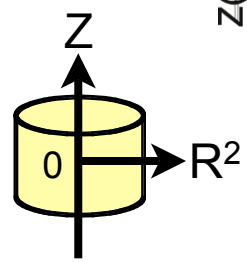


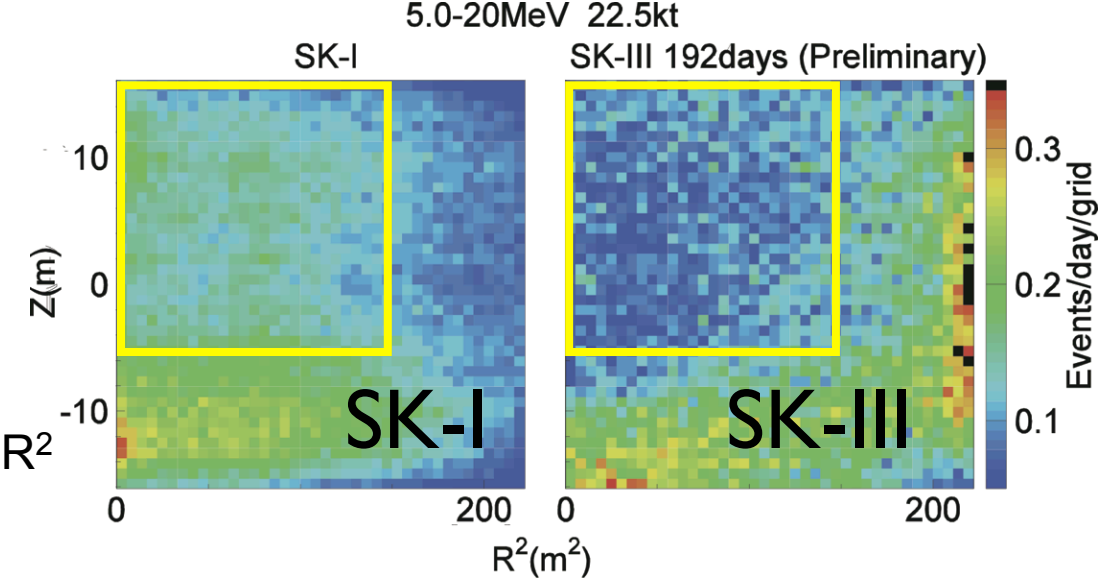
100% trigger efficiency at 5 MeV
Preliminary SK-III reduction tools

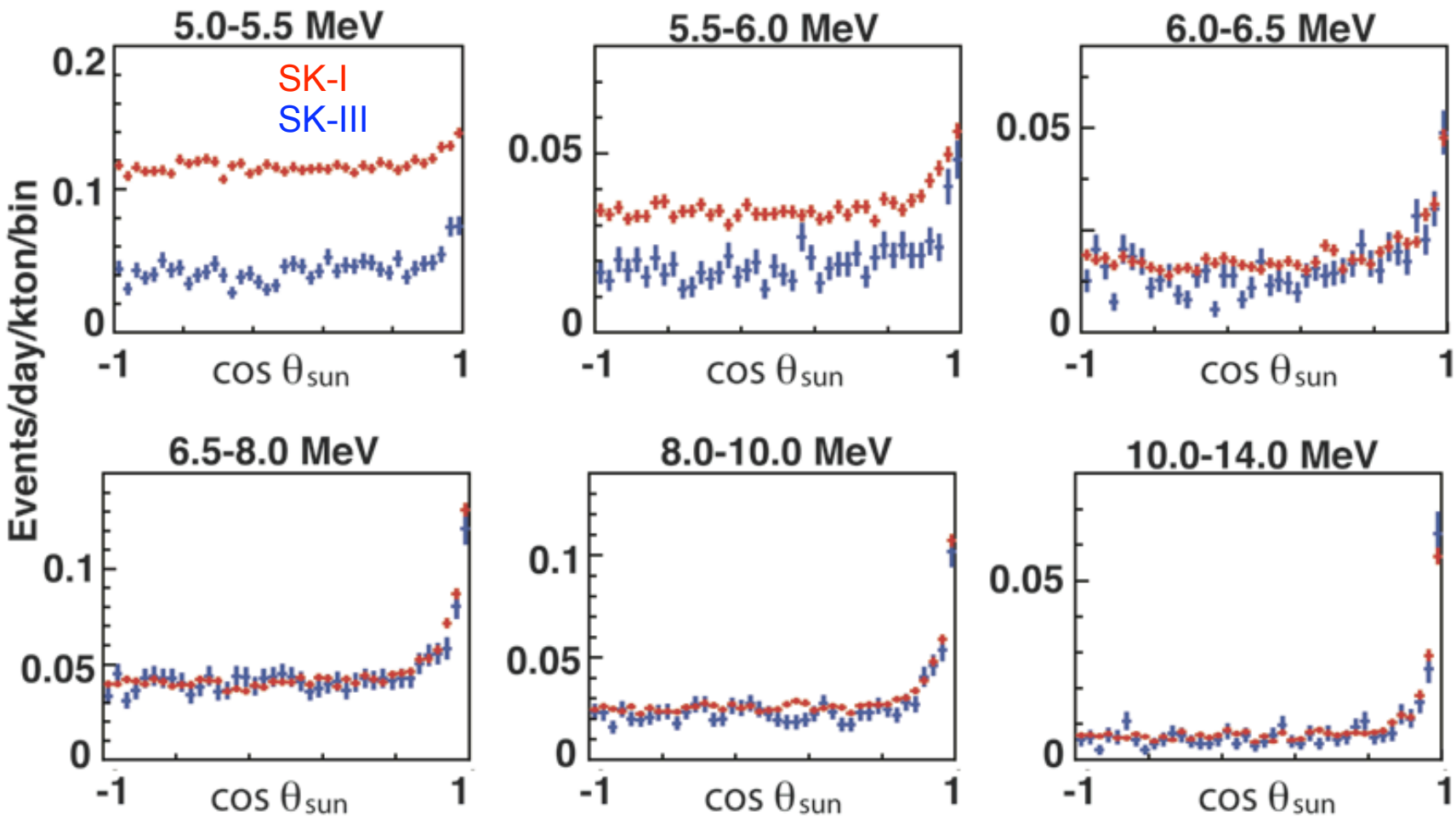
Good agreement of SK-III with SK-I final data sample

SK-III: Background in the central region (RR sample)

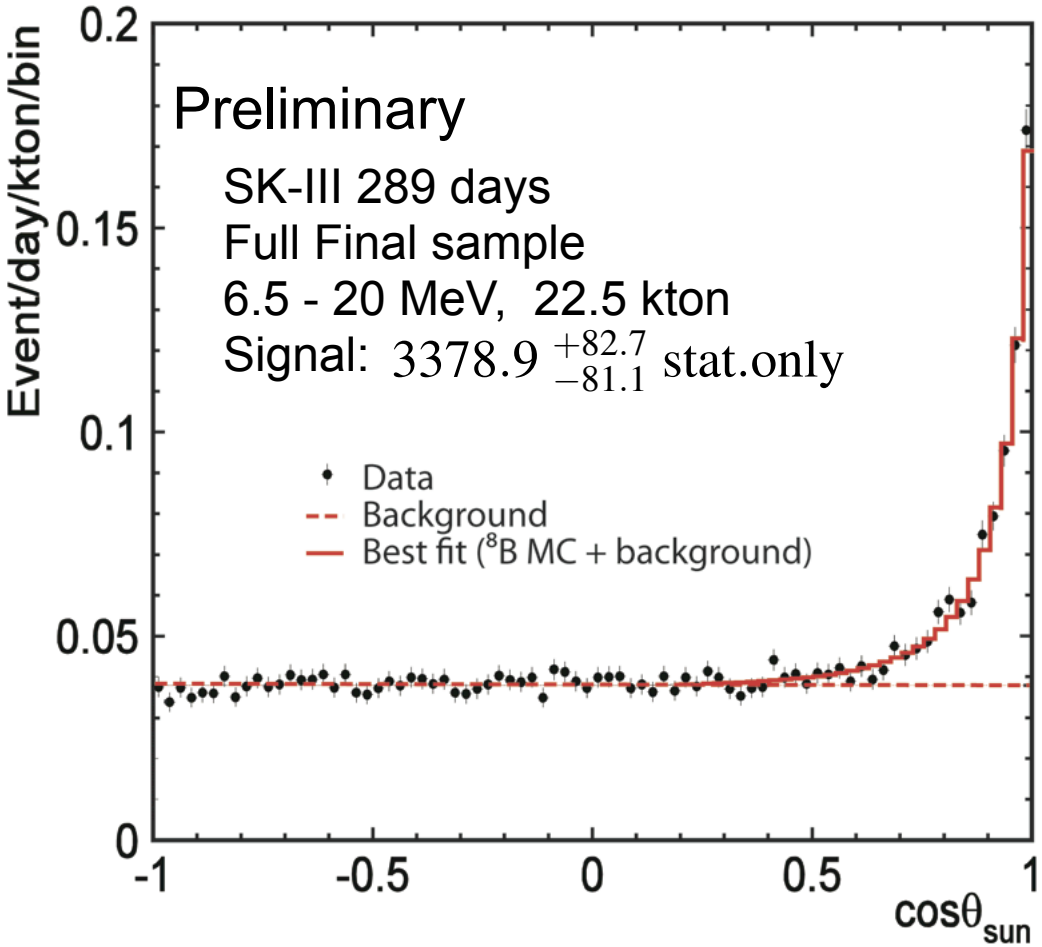
SK-III background rate lower than SK-I in central region







SK-III Solar ν Measurements



Poster by M. Ikeda:
"Solar Neutrino Measurements at Super-Kamiokande-III"

Extract number of signal events by fit to signal + background shapes

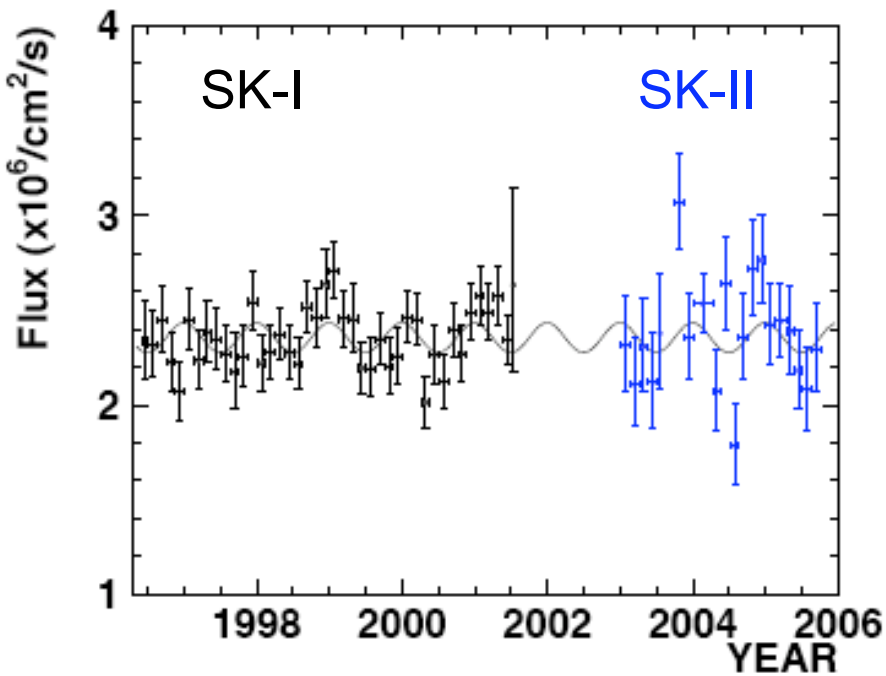
	Livetime (days)	Energy range (MeV)	Number of signal events	Flux ($\times 10^6$ cm^{-2} sec^{-1})
SK-III	289	6.5-20.0	$3378.9\ ^{+82.7}_{-81.1}$(stat only)	In preparation

SK-I + SK-II Solar ν Flux

	Livetime (days)	Energy range (MeV)	Number of signal events	Flux ($\times 10^6$ cm^{-2} sec^{-1})
SK-I	1496	5.0-20.0	22404 ± 226 (stat) $^{+784}_{-717}$ (sys)	2.35 ± 0.02 (stat) ± 0.08 (sys)
SK-II	791	7.0-20.0	$7212.8\,^{+152.9}_{-150.9}$ (stat) $^{+483.3}_{-461.6}$ (sys)	2.38 ± 0.05 (stat) $^{+0.16}_{-0.15}$ (sys)

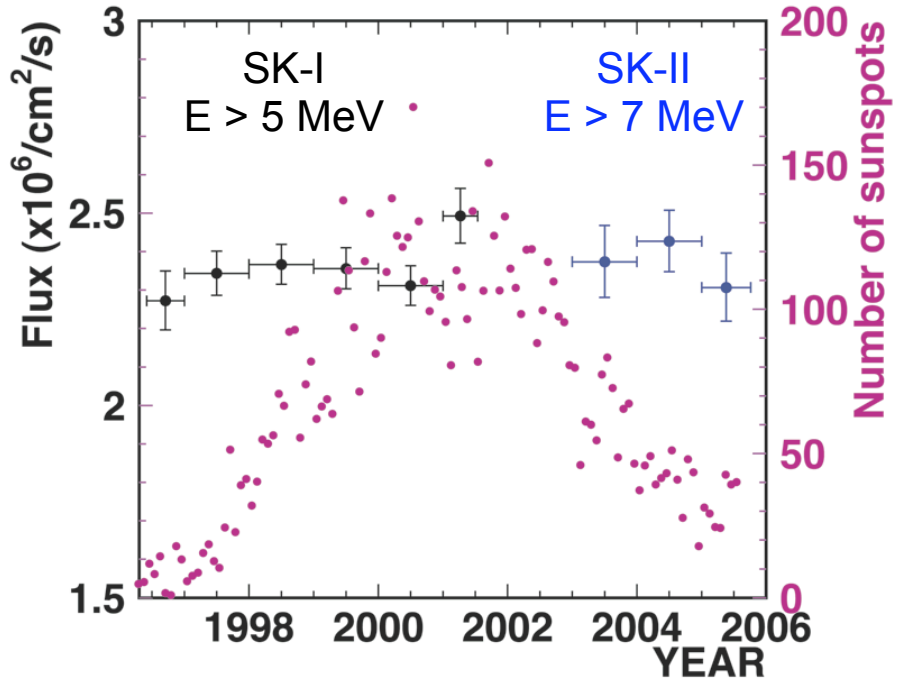
Time Variations of Flux

Seasonal Variation



Consistent with expected variations due to eccentricity of Earth's orbit

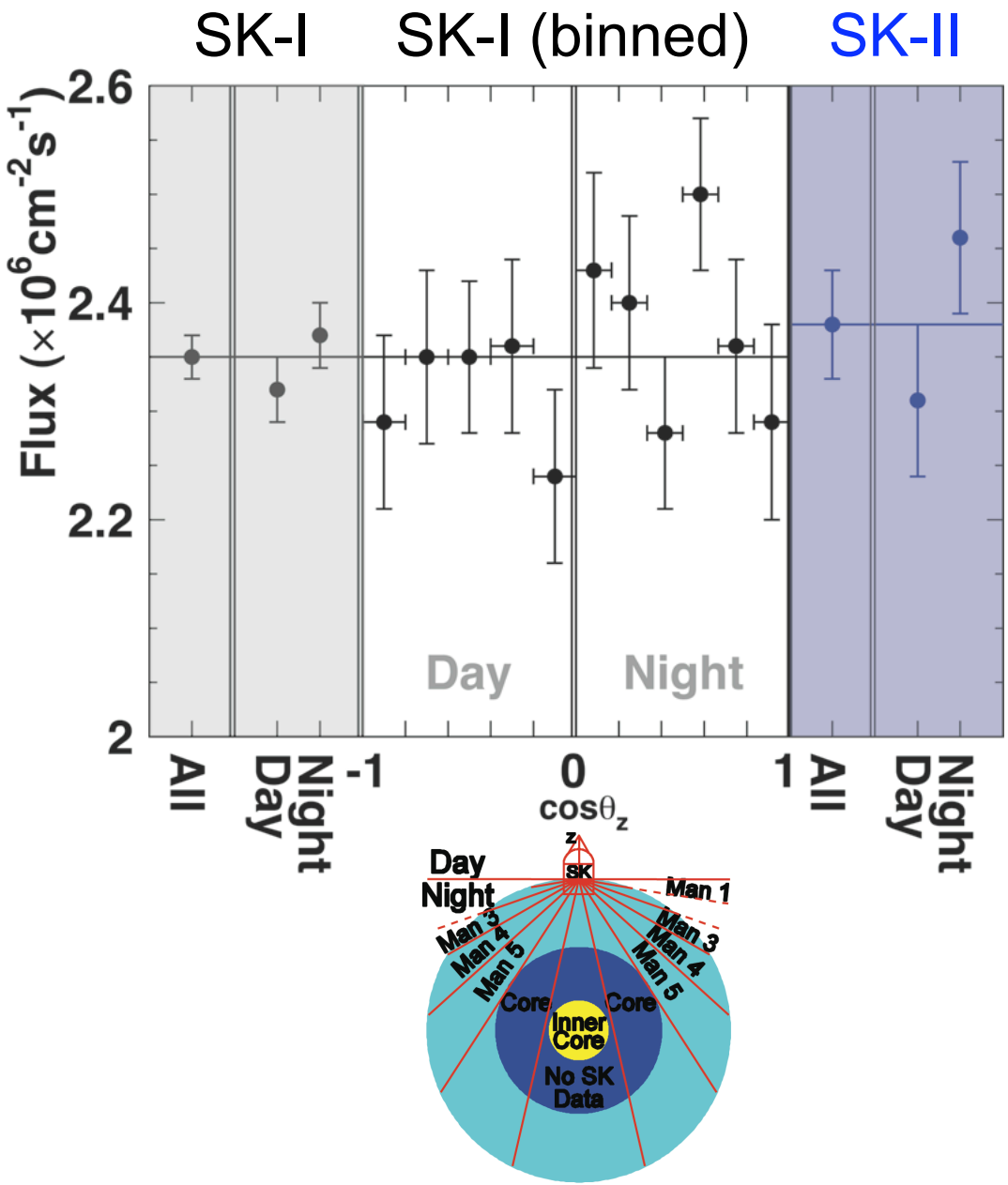
Correlation with Solar Activity



No correlation with solar cycle minima or maximum seen

SK-I + SK-II Solar ν Flux

Day-Night Asymmetry



$$\mathcal{A} = \frac{\Phi_{day} - \Phi_{night}}{\frac{1}{2}(\Phi_{day} + \Phi_{night})}$$

SK-I day-night asymmetry:

$$-0.021 \pm 0.020\ (\text{stat})^{+0.013}_{-0.012}\ (\text{sys})$$

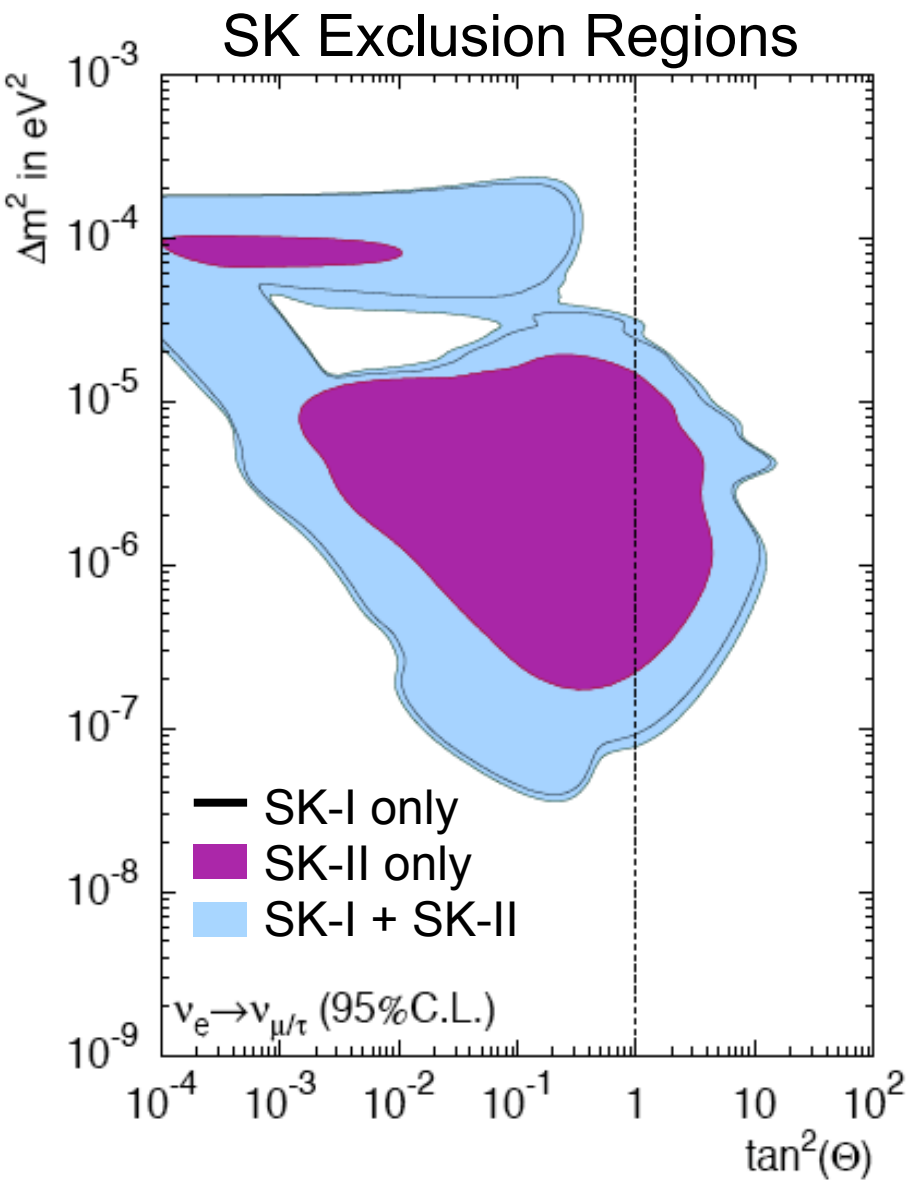
SK-II day-night asymmetry:

$$-0.063 \pm 0.042\ (\text{stat}) \pm 0.037\ (\text{sys})$$

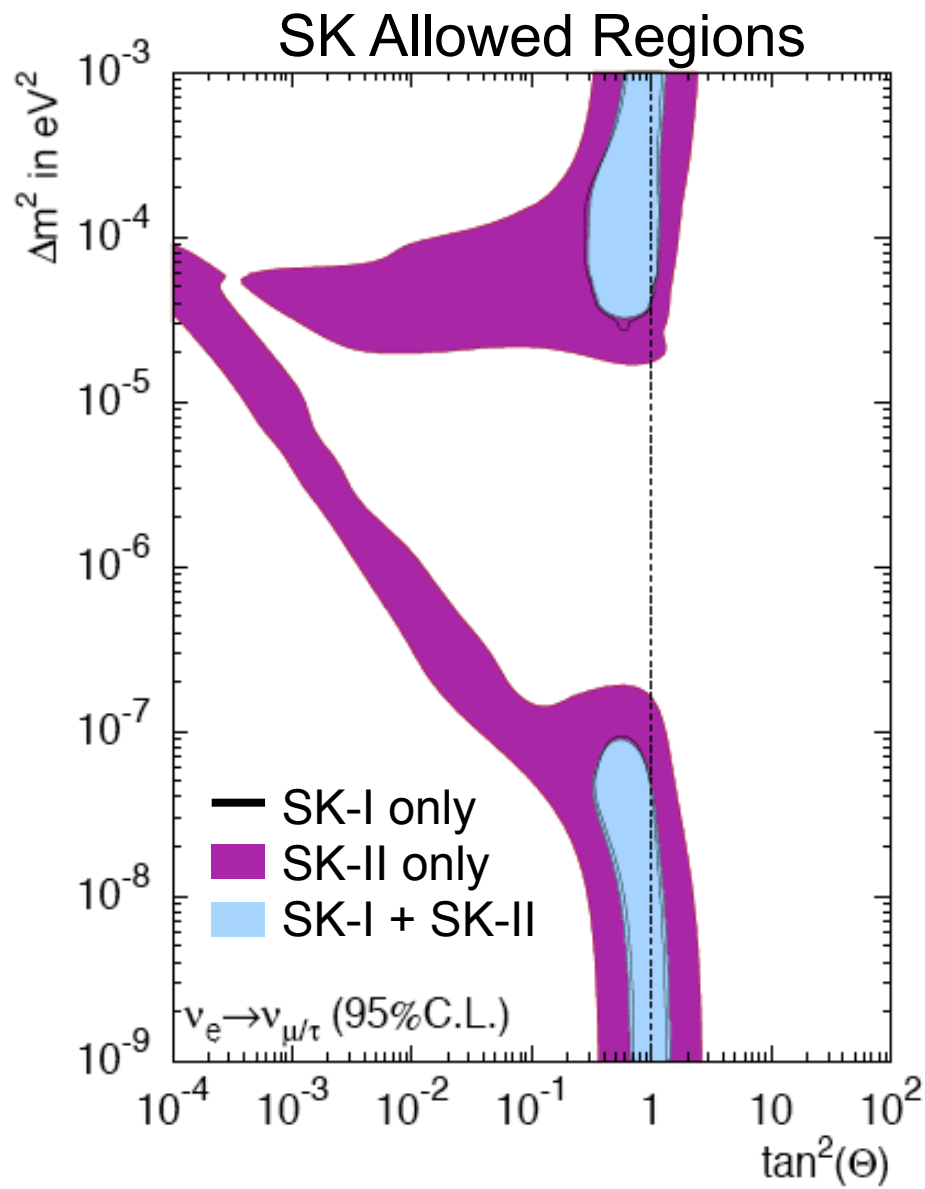
Consistent with zero

Solar ν Oscillation Analysis (SK only)

arXiv:0803.4312



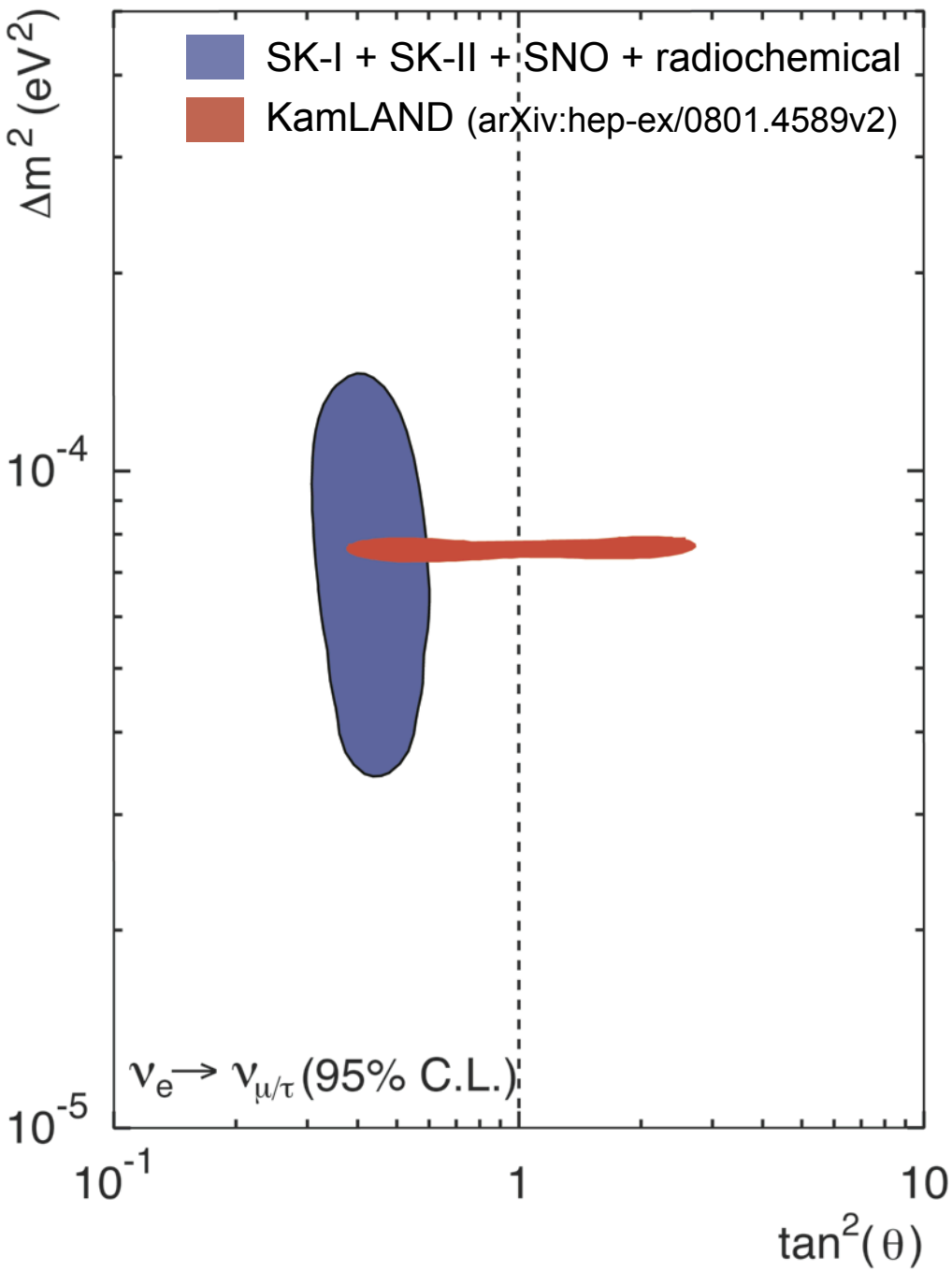
Based on SK energy spectrum shape, and time variations



^{8}B flux constrained to SNO Salt Phase NC flux

S.N. Ahmed et al., PRL92 (2004) 181301

Solar ν Oscillation (SK + other solar expts.)



SNO data:

371-day salt phase (CC & NC fluxes)

306-day pure D_2O phase (A_{D-N})

Radiochemical data:

Homestake

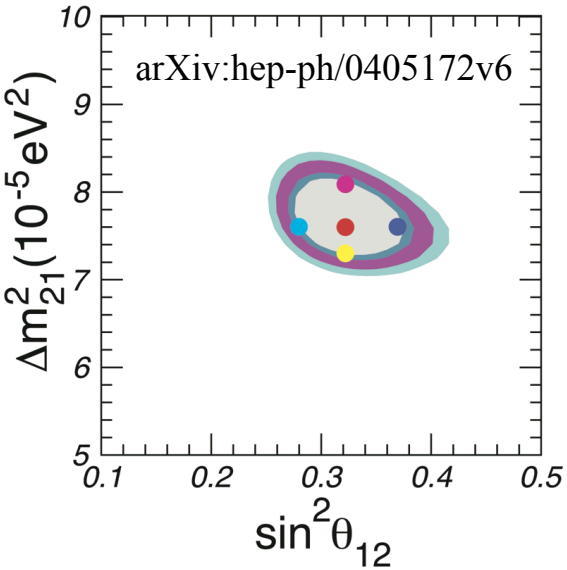
SAGE

GALLEX

Combined experimental data allow us to measure the oscillation parameters in this framework...

...but we would still like to observe predicted upturn at low energy

Future Prospects for SK Solar

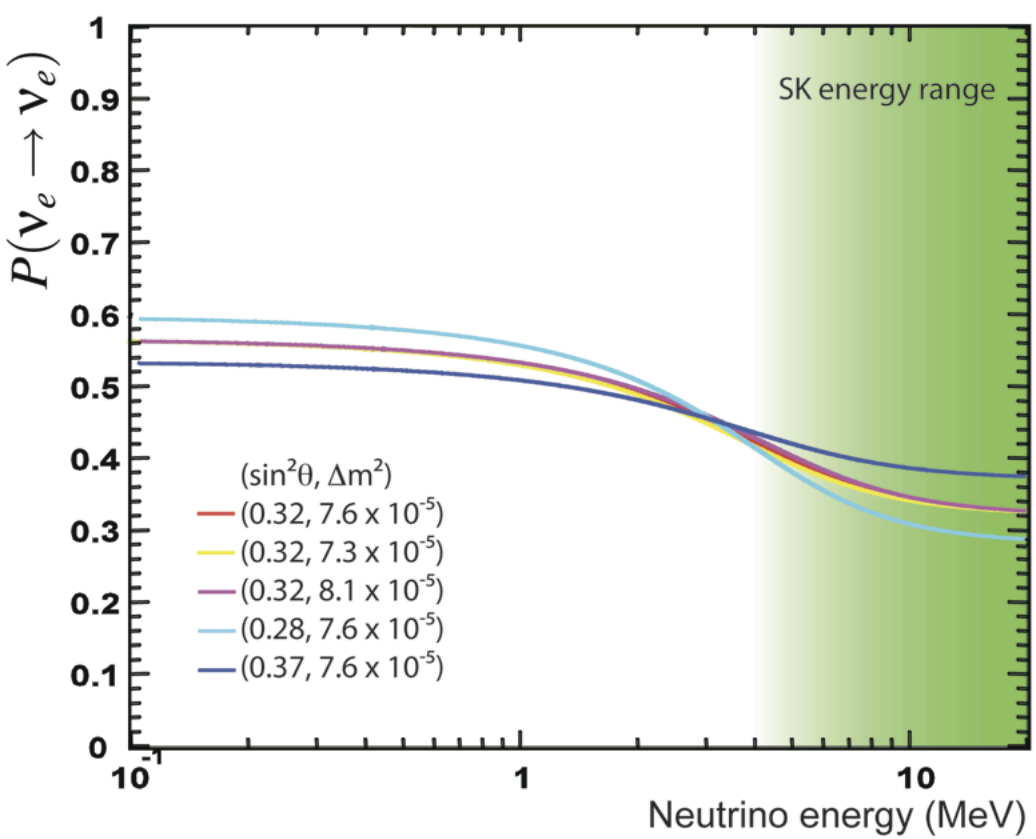


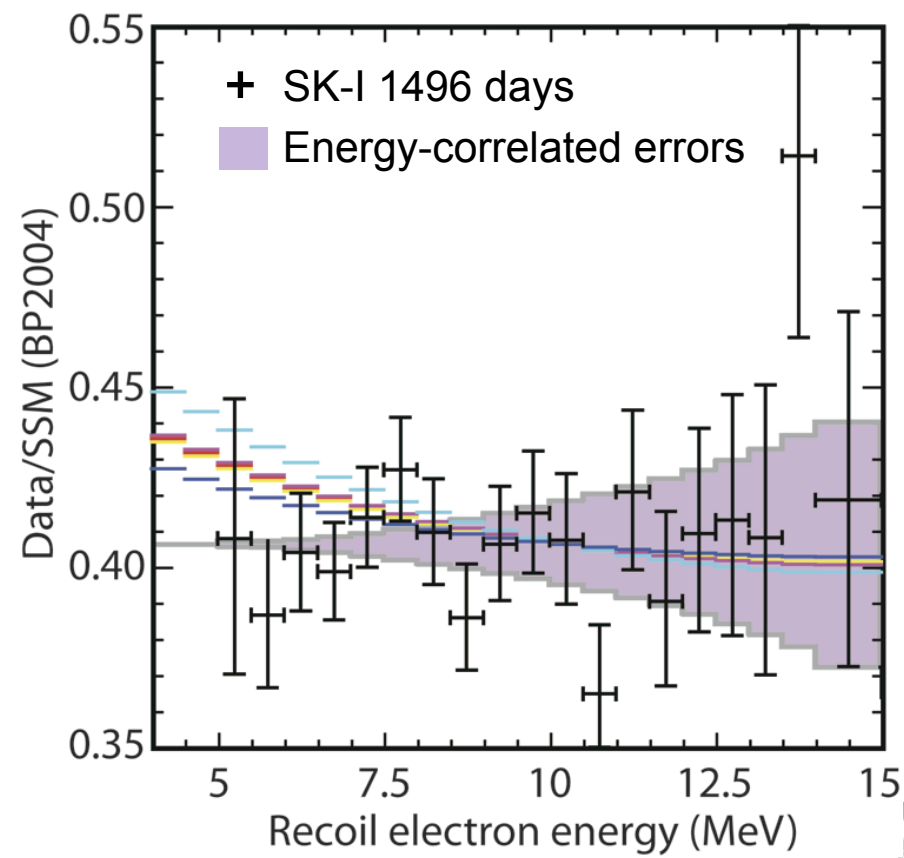
Low energy upturn ~10% effect in Super-K

In order to see it, we must:

- reduce statistical errors
- reduce energy-correlated sys errors (0.5 x SK-I)
- lower energy threshold

Work in progress...

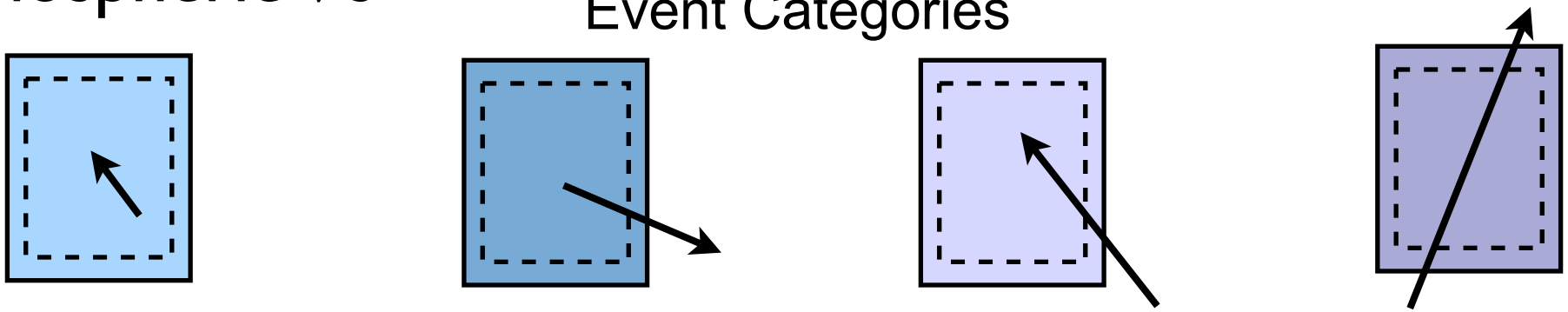




Super-Kamiokande Atmospheric Neutrinos

Atmospheric ν's

Event Categories



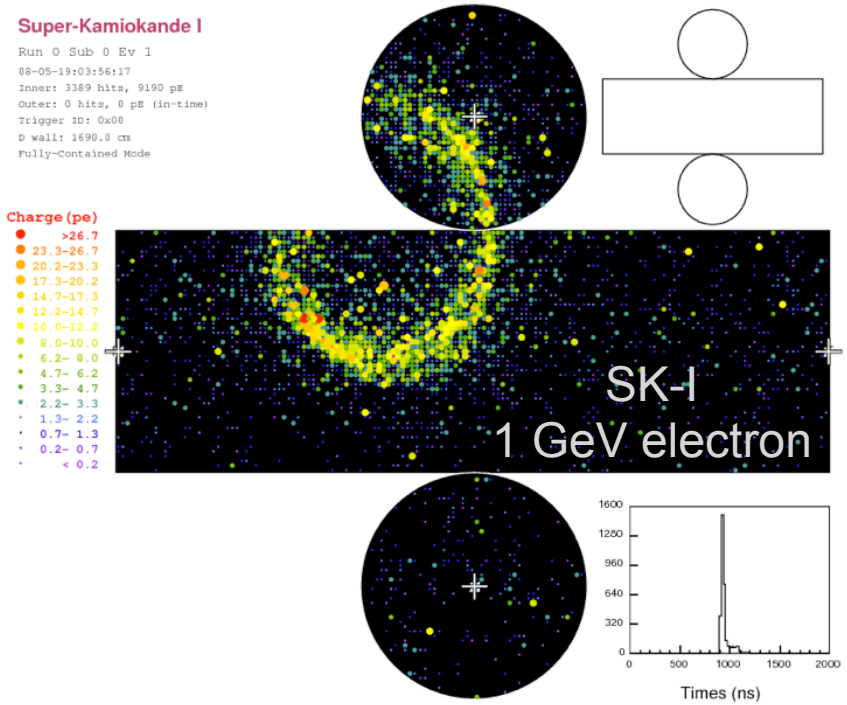
Fully-Contained | Partially-Contained | Upward Stopping Muon | Upward Through-going Muon

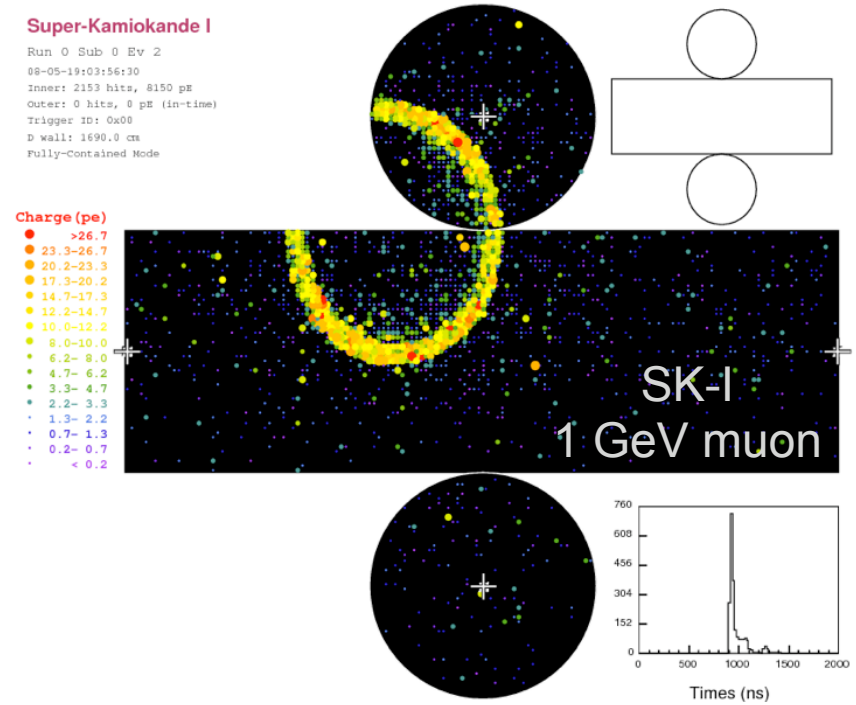
SK-III run period: July 29, 2006 - present

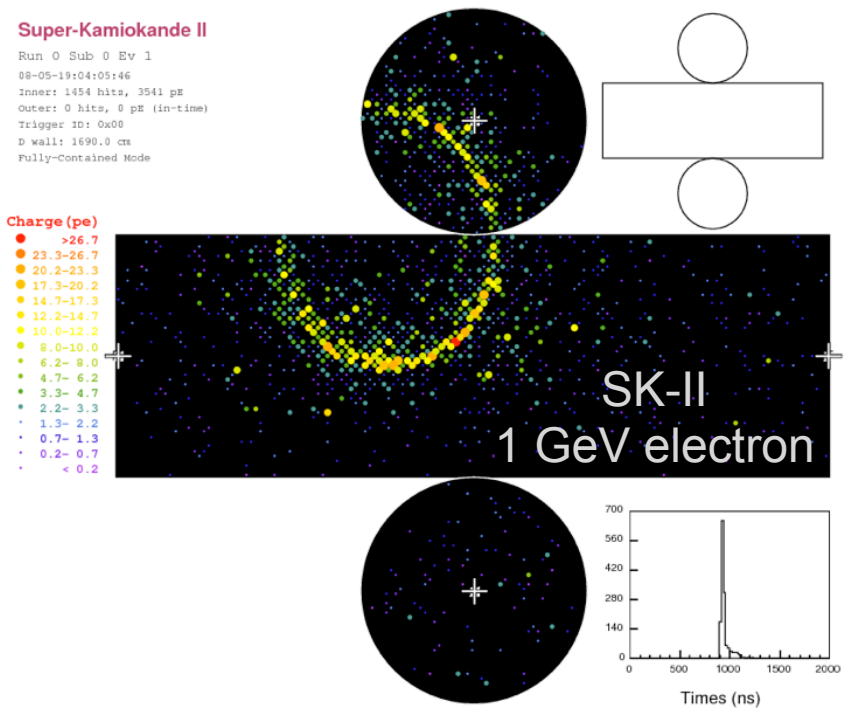
Event Category	Event Rate (events/day)		
	SK-I	SK-II	SK-III (Preliminary)
Fully Contained (FC)	8.18 ± 0.07	8.22 ± 0.10	8.31 ± 0.22
Partially Contained (PC)	0.61 ± 0.02	0.54 ± 0.03	0.57 ± 0.06
Upward-stopping μ (Upstop)	0.25 ± 0.01	0.28 ± 0.02	0.24 ± 0.03
Upward-thrugoing μ (Upthru)	1.12 ± 0.03	1.07 ± 0.04	1.11 ± 0.06

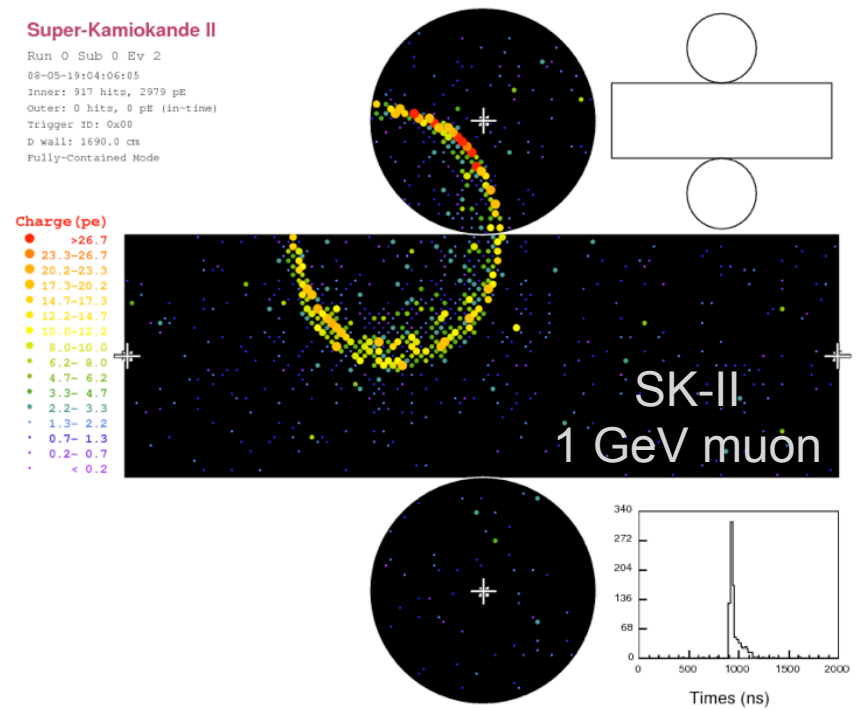
Event rates consistent across all phases of SK

Atmospheric ν's at Super-K (simulated events)

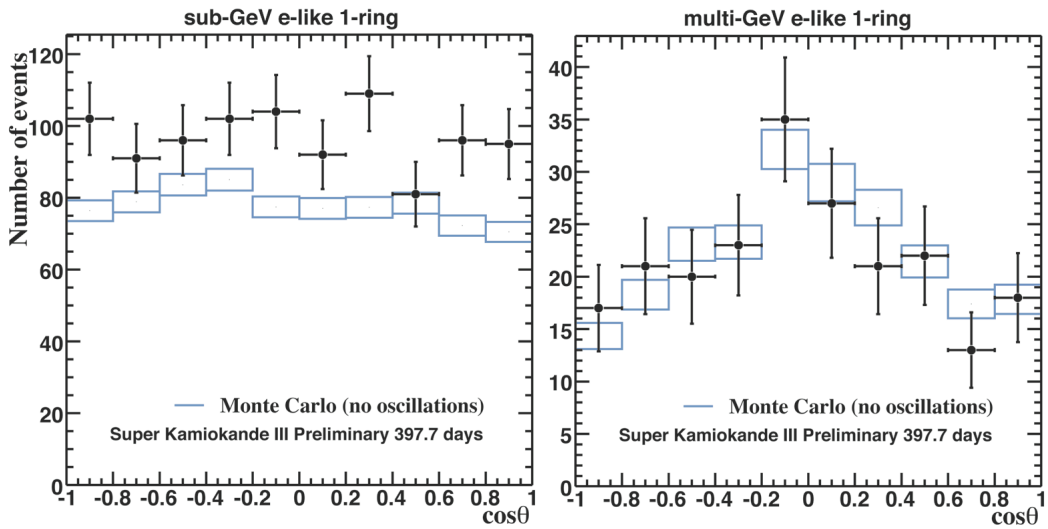






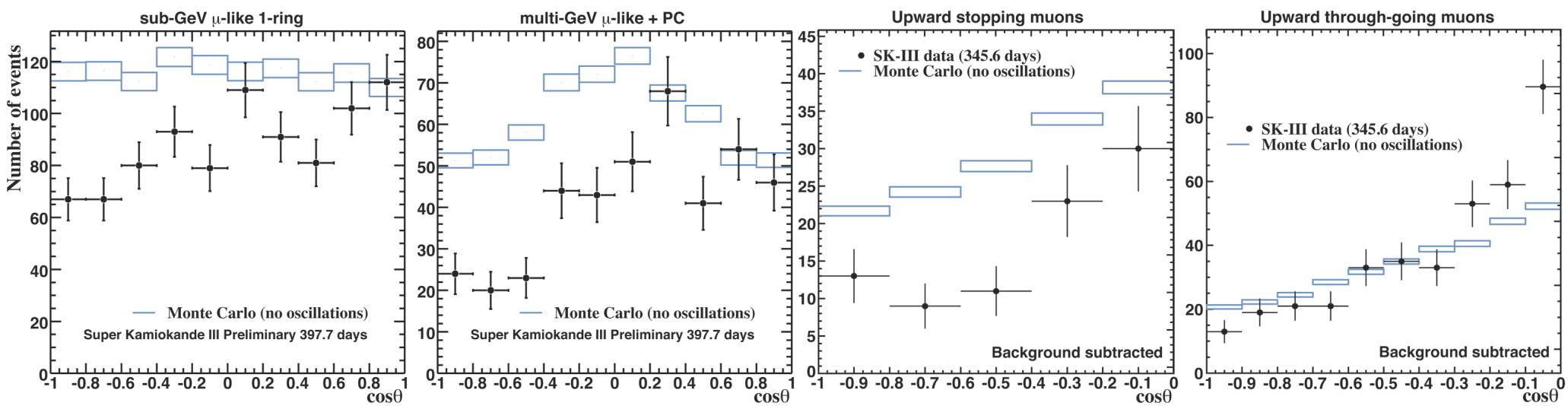


SK-III Atmospheric ν Zenith Distributions



>25,000 atmospheric ν events in SK-I + II + III

- SK-III data
- Monte Carlo (no oscillations)



No oscillation analysis yet, but zenith angle distortion clearly visible

Atmospheric ν Analyses

Oscillation:

Zenith angle (2-flavor)

L/E

Non-standard interactions

Poster by G. Mitsuka:
"Limit on Non-Standard Interactions from the Atmospheric Neutrino Data in Super-Kamiokande"

Zenith angle (3-flavor) (Phys. Rev. D 74, 032002 (2006))

ν_τ appearance (Phys. Rev. Lett. 97, 171801 (2006))

MaVaNs (Phys. Rev. D 77, 052001 (2008))

Exotic scenarios: LIV, CPT, Sterile

3-flavor with solar term

} Not presented today

Non-oscillation:

Nucleon decay searches

Poster by H. Nishino:
"Search for proton decays via $p \rightarrow e^+ \pi^0$ and $p \rightarrow \mu^+ \pi^0$ in Super-Kamiokande"

WIMP search

Poster by T. Tanaka
"Search for Indirect Signal of WIMPs in Super-Kamiokande"

Atmospheric ν Analyses

Exotic Scenarios

Model	Exclusion level or limit
$\nu_\mu \rightarrow \nu_s$ oscillation	SK-I+II: 7.3σ
Admixture (2+2 hierarchy)	SK-I+II: 23% allowed
Decay I ($\sin^4\theta + \cos^4\theta\, e^{-\alpha L/E}$)	SK-I+II: 17σ
Decay II ($\sin^2\theta + \cos^2\theta\, e^{-\alpha L/2E})^2$	SK-I+II: 3.9σ
Decay Limit (GeV^2)	SK-I+II: 6.5×10^{-23}
Decoherence ($(1+e^{-\beta L/E})/2$)	SK-I+II: 4.2σ
Decoherence Limit (GeV)	SK-I+II: 6.0×10^{-24}
LIV Limit	SK-I+II: 1.2×10^{-24}
CPTV Limit (GeV)	SK-I+II: 0.9×10^{-23}
MaVaNs (various models)	SK-I: $3.5\text{-}3.8\sigma$
Non-Standard Interactions	See poster by G. Mitsuka

Neutrinos frequently set stringent limits, although not usually testing exactly the same parameters.

e.g., cosmic ray spectrum LIV $< 10^{-15}$, NMR LIV $< 10^{-22}$

K^0K^0bar CPTV $< 10^{-18}$

Super-K Simulation/Reconstruction Updates

Re-analysis of SK-I and SK-II data due to many changes/improvements:

Simulation

atmospheric neutrino flux model: Honda06

neutrino interaction model (`neut`)

QE: M_A = 1.2 GeV

1π (resonant): M_A = 1.2 GeV

Add $\Delta \rightarrow N\gamma$

Add lepton mass effects in CC1π

1π (coherent): Rein & Sehgal with lepton mass correction

DIS: GRV98 PDF with Bodek-Yang correction

detector simulation

more detailed model of light reflections and scattering

better OD tuning

Reconstruction

improved ring counting

Other

higher MC statistics

re-evaluate and add systematic uncertainties

Changed to agree with K2K measurement.
Effect: Increase number of events

Effect: Small change in lepton momentum distributions

Effect: Suppression in forward direction of lepton scattering angle

Effect: Reduction in number of multiple-π events

Effect: Better data/MC agreement for various quantities

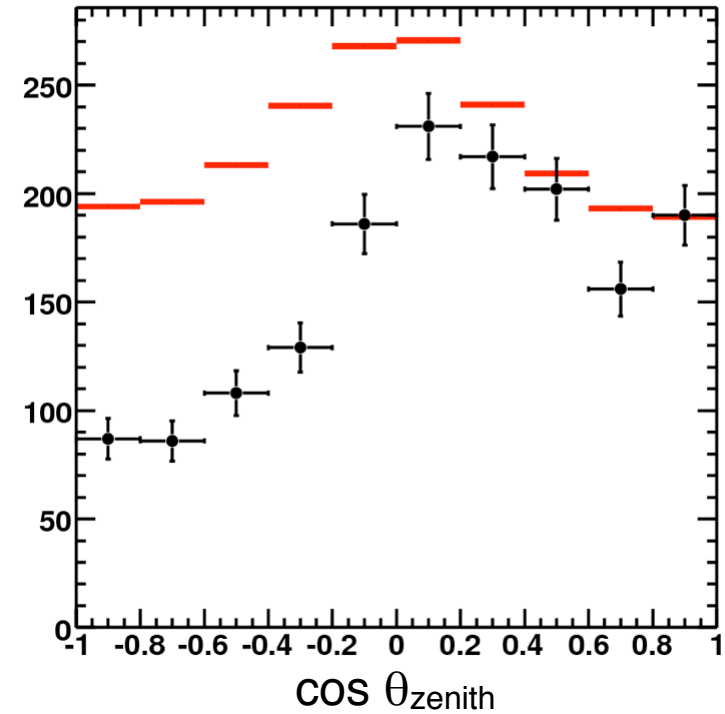
Effect: Reduced systematic errors

Increase from 100 yrs to 500 yrs

Oscillation Analyses

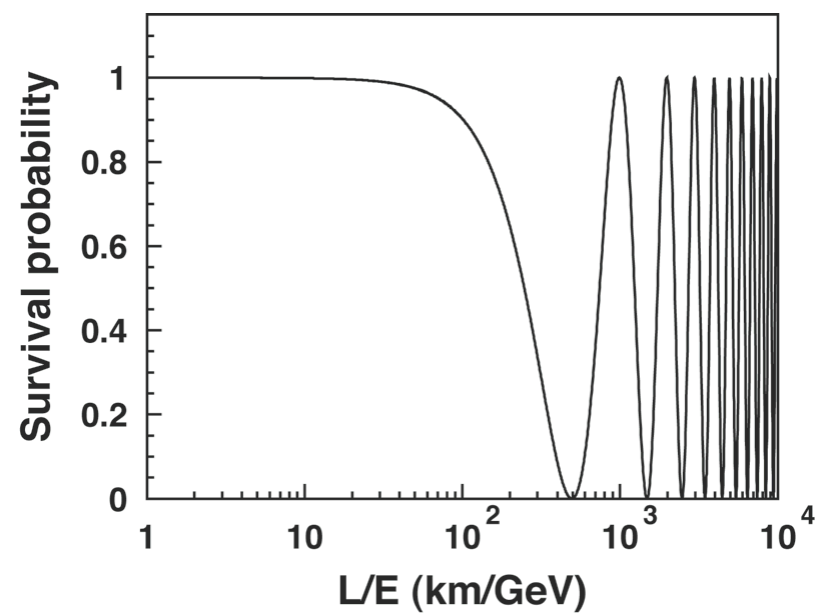
Zenith angle 2-flavor analysis (fine-binned)

Use many subsamples of data
Look for zenith angle distortion



L/E analysis

Use much more selective subsample of data
Require good L/E resolution
Look for first oscillation dip



Zenith Angle Analysis (2-flavor)

Datasets
- SK-I FC/PC: 1489 days
- SK-I Upmu: 1646 days
- SK-II FC/PC: 799 days
- SK-II Upmu: 828 days

Data binned according to:

event type + momentum + zenith angle } 400 bins for SK-I, 350 bins for SK-II

χ^2 fit in bins of zenith angle with systematic error pull terms:

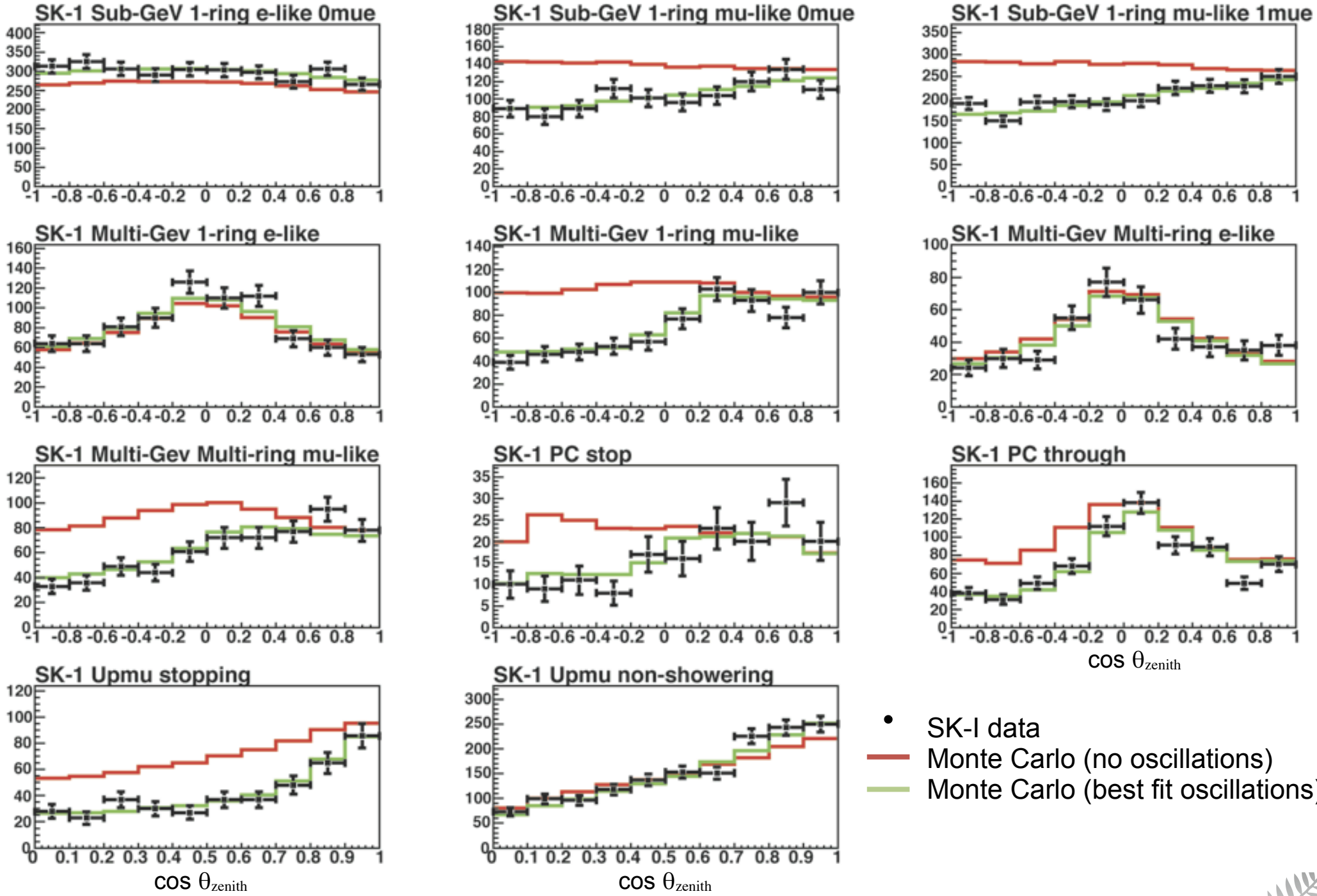
$$\chi^2 = \sum_{i=1}^{N_{bins}} 2\left(N_i^{exp} - N_i^{obs} + N_i^{obs}\ln\frac{N_i^{obs}}{N_i^{exp}}\right) + \sum_{j=1}^{N_{sys}}\left(\frac{\varepsilon_j}{\sigma_j^{sys}}\right)^2$$

where $$N_i^{exp} = N_i^0 \cdot P(\nu_\alpha \rightarrow \nu_\beta)\left(1 + \sum_{j=1}^{N_{sys}} f_j^i \varepsilon_j\right)$$

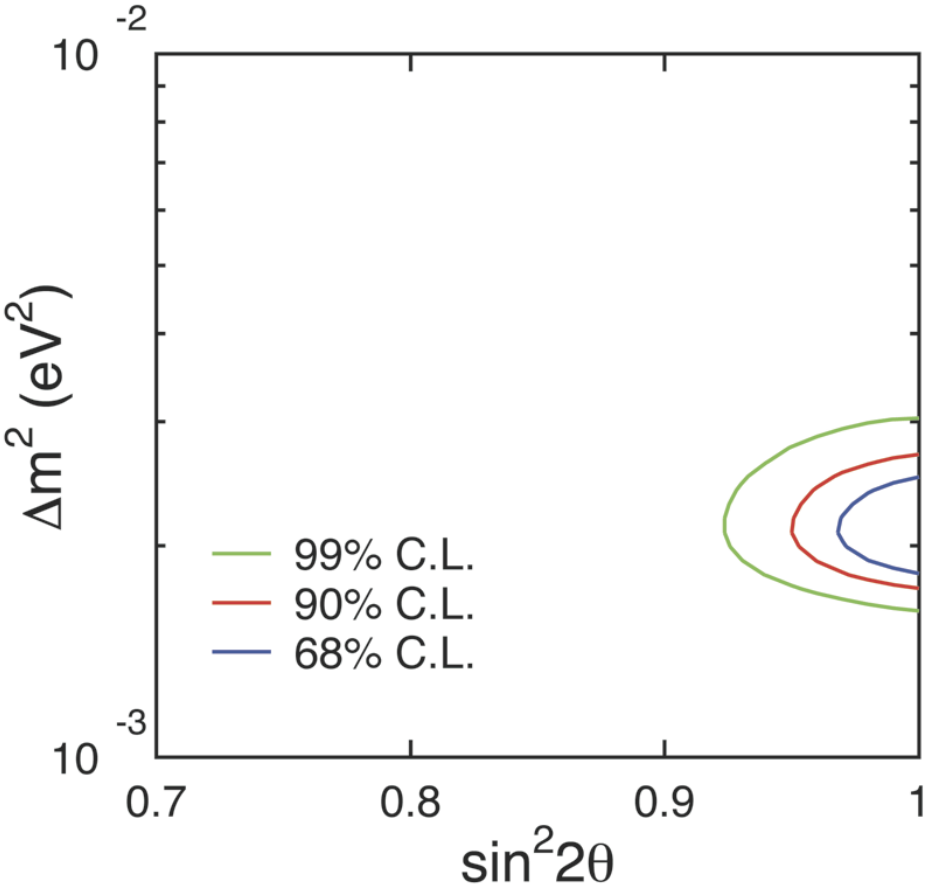
90 systematic error terms to account for uncertainties in:

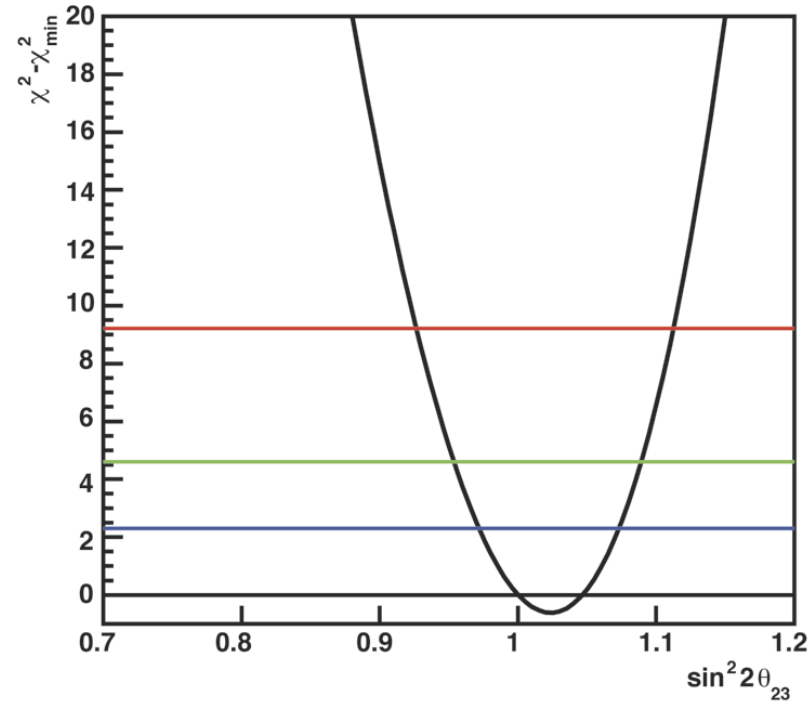
Neutrino flux	Cross sections
Event reconstruction	Data reduction

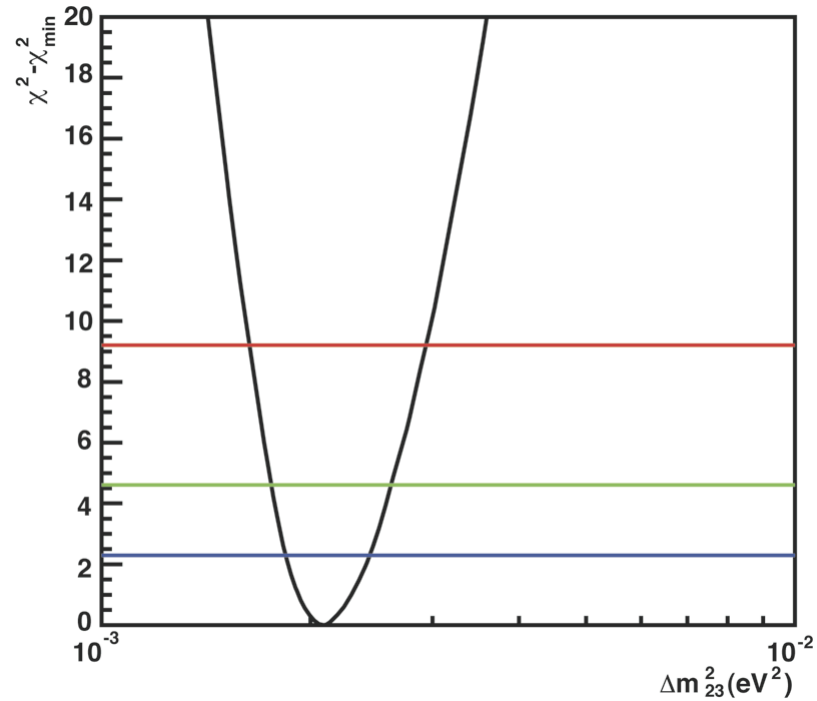
Zenith Angle Analysis: SK-I + SK-II



Zenith Angle Analysis: SK-I + SK-II







Best fit:

$\Delta m^2 = 2.1 \times 10^{-3}$ eV^2

$\sin^2 2\theta = 1.02$

$\chi^2 = 830.1 / 745$ d.o.f.

L/E Analysis: SK-I + SK-II

Datasets	
SK-I FC/PC μ-like:	1489 days
SK-II FC/PC μ-like:	799 days

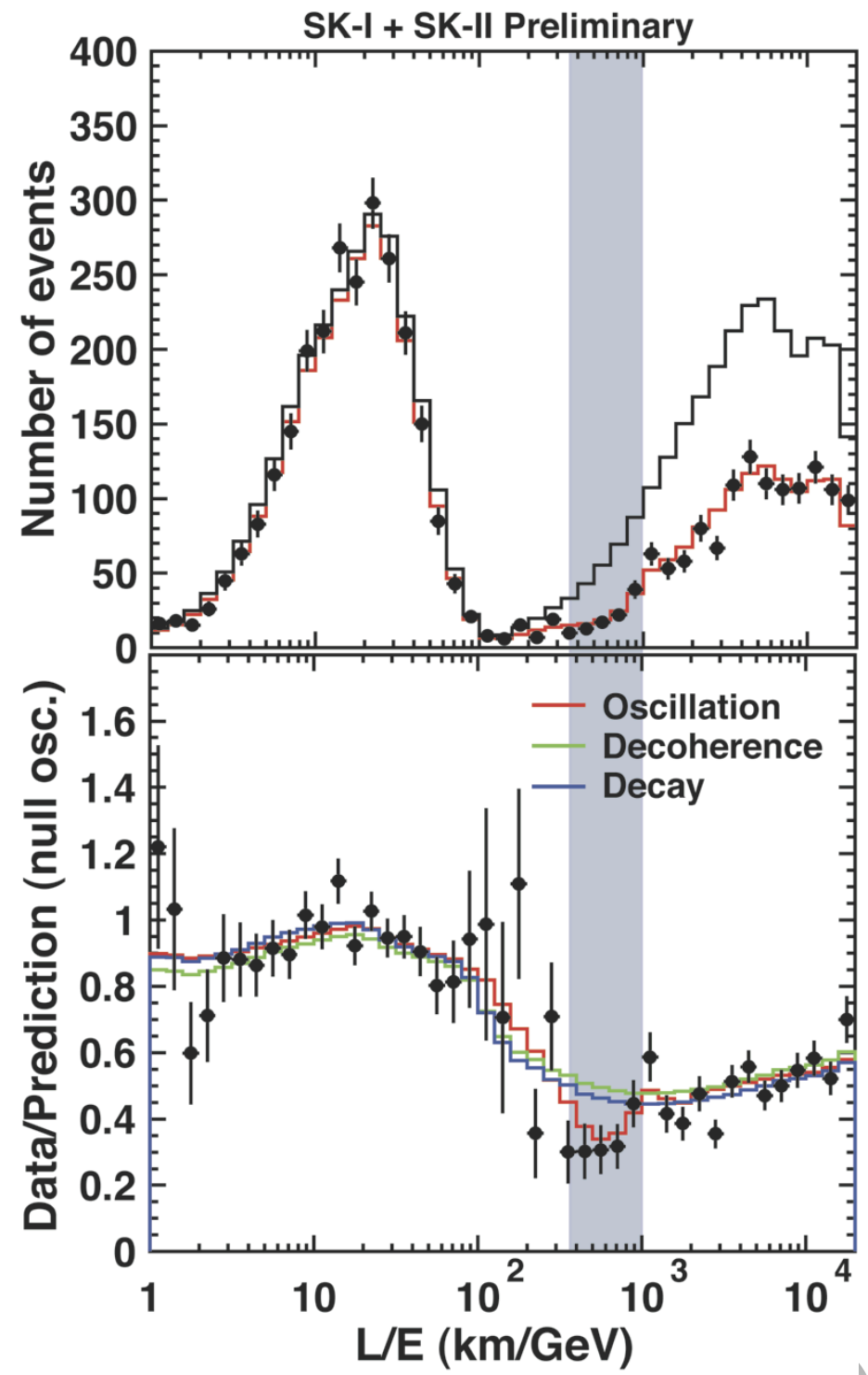
Use only event categories with good L/E resolution:

Partially-contained muons
Fully-contained muons

χ^2 fit to 43 bins of $\log_{10}(L/E)$ with 29 systematic error terms

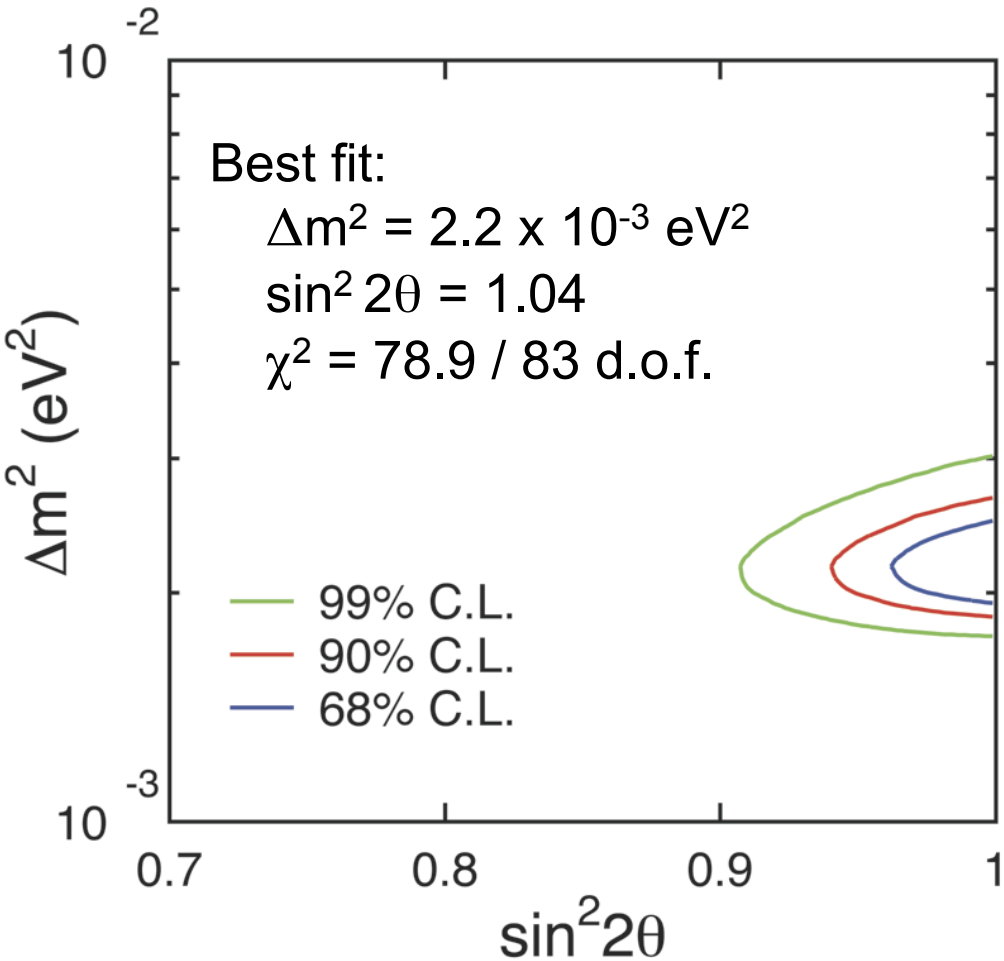
Compare against:

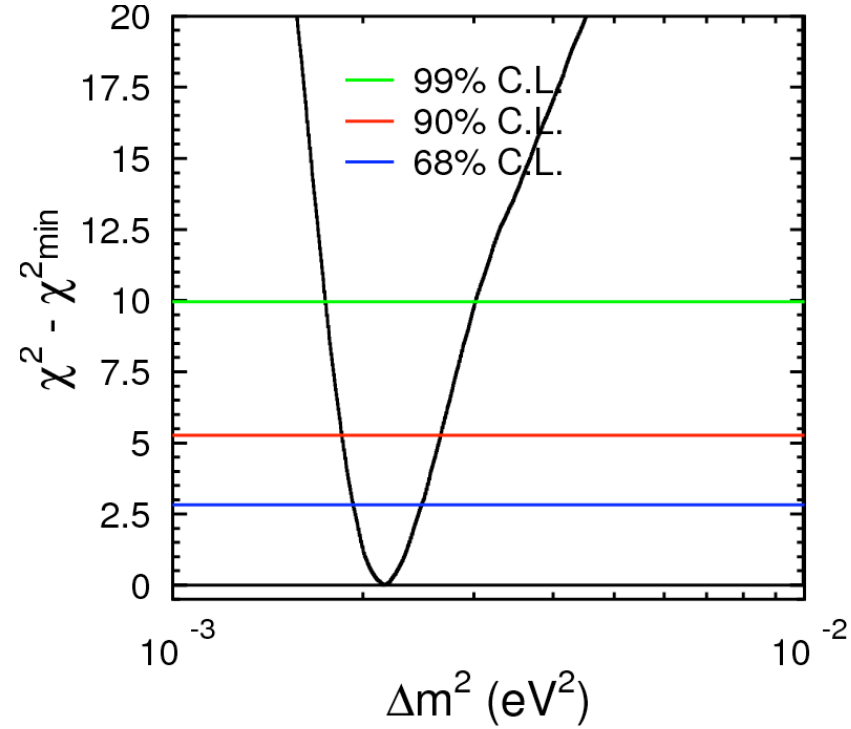
Neutrino decoherence (5.0σ)
Neutrino decay (4.1σ)

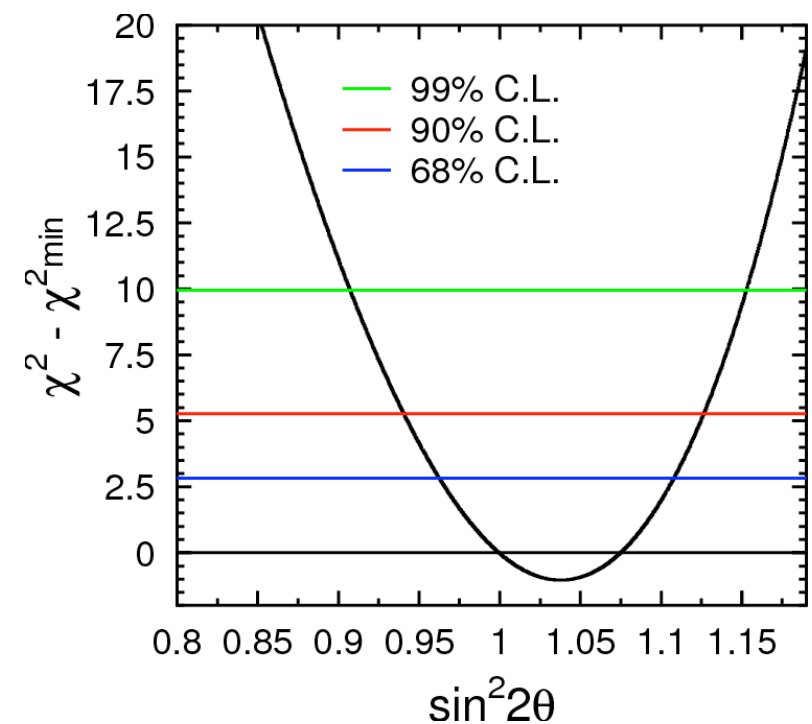


Grossman and Worah: hep-ph/9807511
Lisi *et al*.: PRL85 (2000) 1166
Barger *et al*.: PRD54 (1996) 1, PLB462 (1999) 462

L/E Analysis: SK-I + SK-II







90% C.L. allowed region

$\sin^2 2\theta > 0.94$

$1.85 \times 10^{-3} < \Delta m^2 < 2.65 \times 10^{-3}$ eV^2

Summary

SK-I + II + III
12 years dataset for atmospheric & solar neutrinos

SK-IV
detector improvements by upgraded electronics

By Neutrino2010...
~40,000 solar ν
~30,000 atmospheric ν

Search for sub-dominant, exotic, and non-oscillation physics

Study "Standard Model" oscillation physics
- help constrain solar parameters
- precisely measure atmospheric parameters
  best constraint on mixing angle
- try to observe every predicted effect

Thank you.