SUPER-KAMIOKANDE

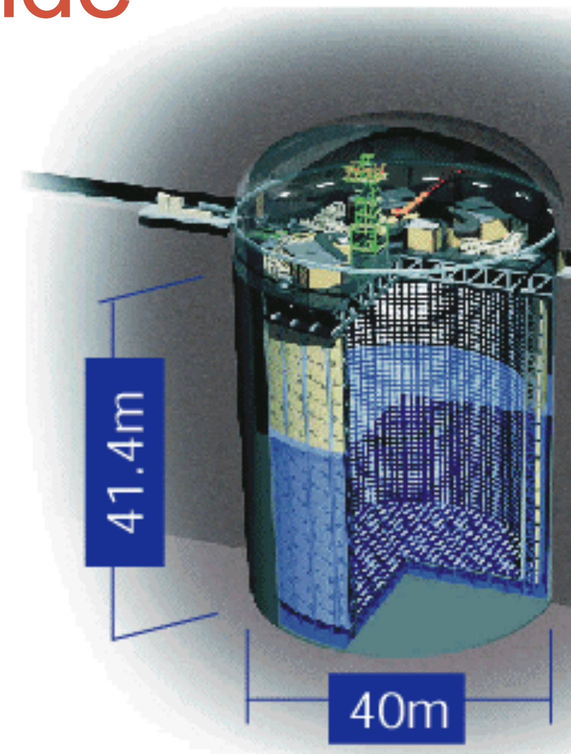
Jen Raaf, for the Super-K Collaboration

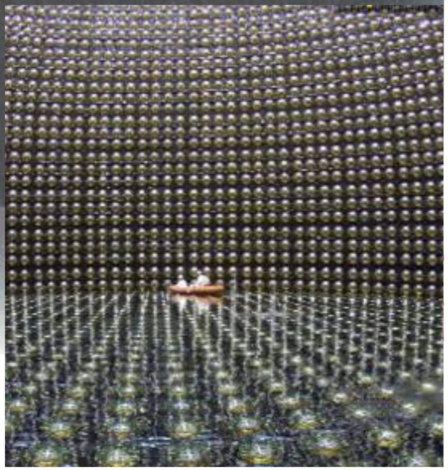
NNN '13

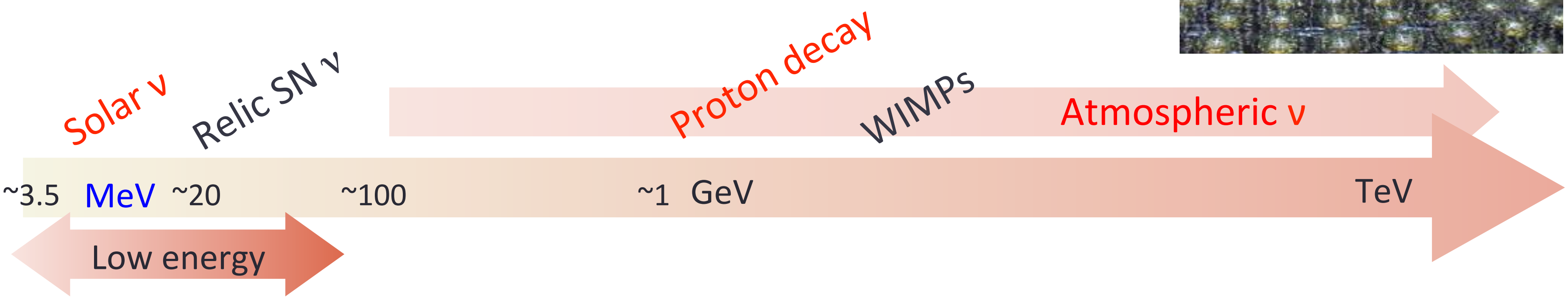
November 11, 2013

Super-Kamiokande

- 50 kilotons pure water
- 1 km (2700 m.w.e.) underground in Kamioka
- 11,129 20-inch Inner Detector (ID) PMTs
- 1,885 8-inch Outer Detector (OD) PMTs

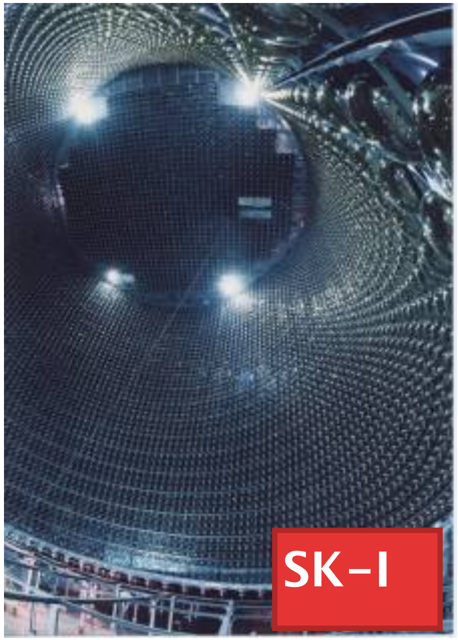




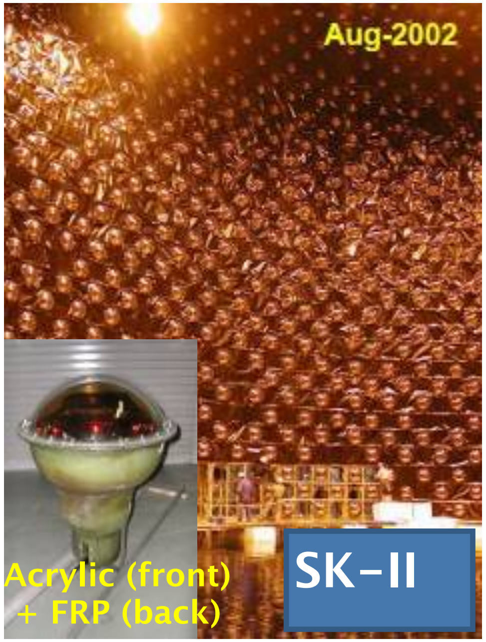


History of Super-K

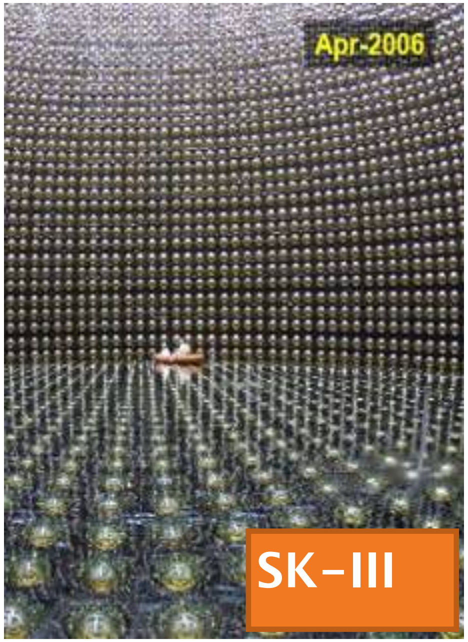
See poster #34 by A. Orii
"A New DAQ at SK for Nearby SN Bursts"



11146 ID PMTs
(40% coverage)



5182 ID PMTs
(19% coverage)



11129 ID PMTs
(40% coverage)

Electronics
Upgrade

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012

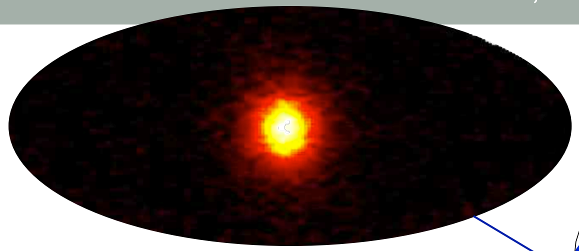
SK-I SK-II SK-III SK-IV

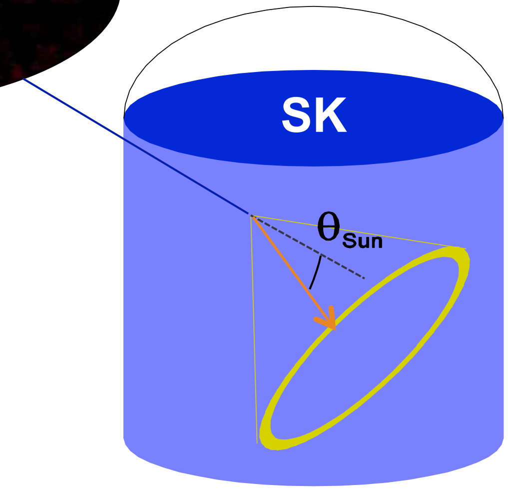
- Accident leading to lower coverage in SK-II has proven useful in sensitivity studies for future large detectors

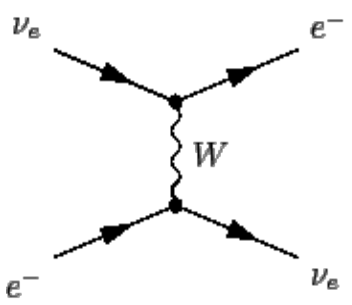
SK in the current era

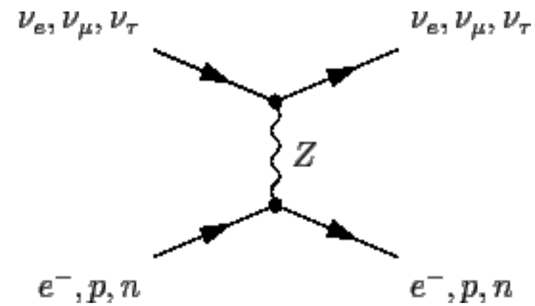
- Super-K has been operating for more than a decade!
- Focus is now on precision measurements, investigation of sub-dominant effects, searches for rare processes
  - ***Solar Neutrinos***: flux, upturn in energy spectrum, day/night effect
  - ***Atmospheric Neutrinos***: mass hierarchy, δ_{CP}, octant, sterile ν
  - ***Nucleon Decay***: search as many modes as possible, improve background rejection and signal selection efficiency
- Using more sophisticated analysis techniques, working hard to further reduce systematic errors and improve background rejection

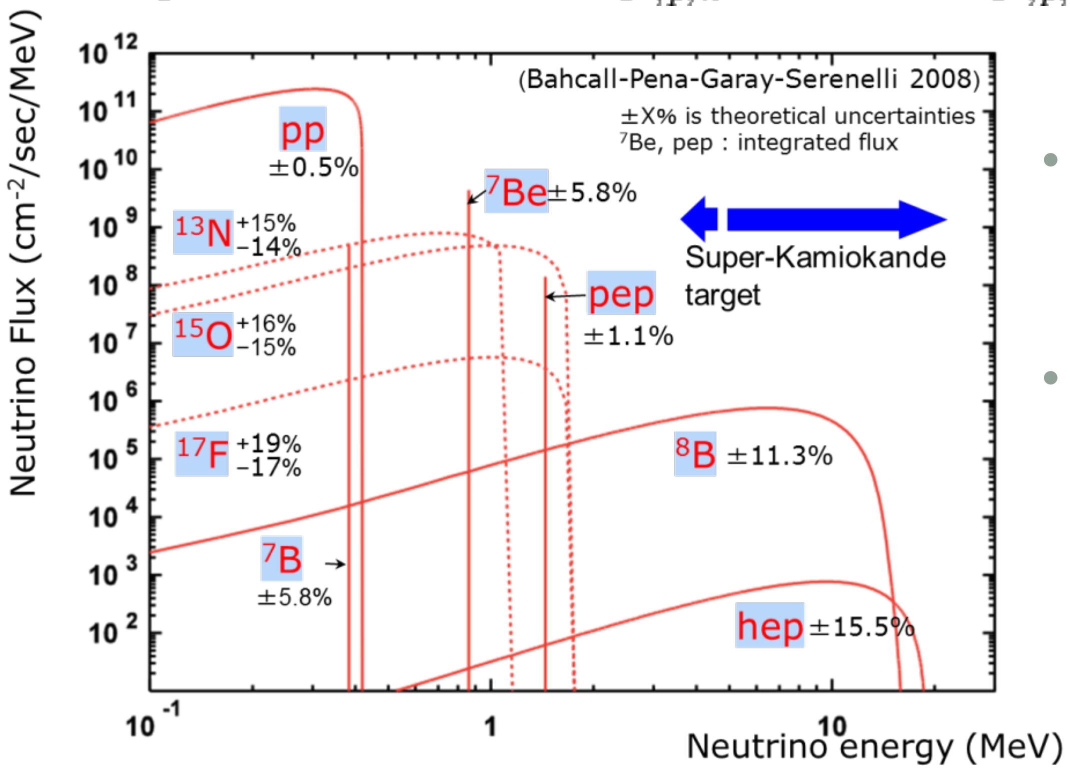
Solar Neutrinos







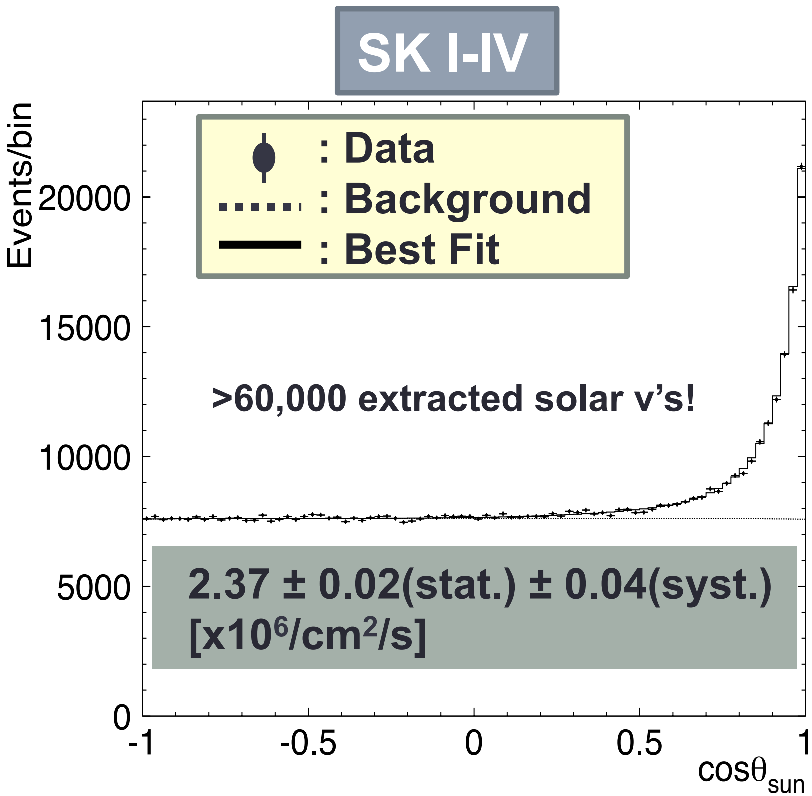


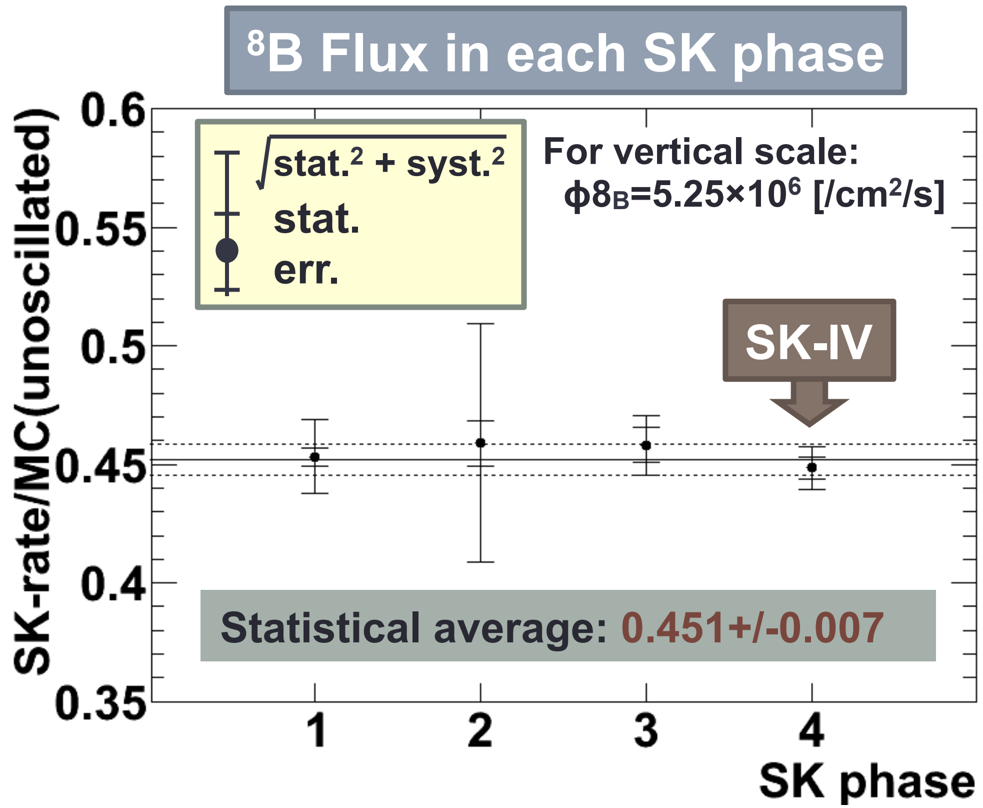


- ^{8}B neutrino measurement by elastic scattering (sensitive to all ν flavors)
- Reconstruct:
  - energy of recoil electron
  - direction relative to Sun

^{8}B Solar Neutrino Flux

- SK-IV improvements
  - Better water quality control (allows lower energy threshold)
  - New electronics (better timing determination)
  - New multiple scattering "goodness" parameter
  - Reduced systematic error (1.7% for flux, cf. SK-I: 3.2%, SK-III: 2.1%)





Matter Effects in Solar Neutrinos

Two testable signatures unique to neutrino oscillations:

Solar matter effect

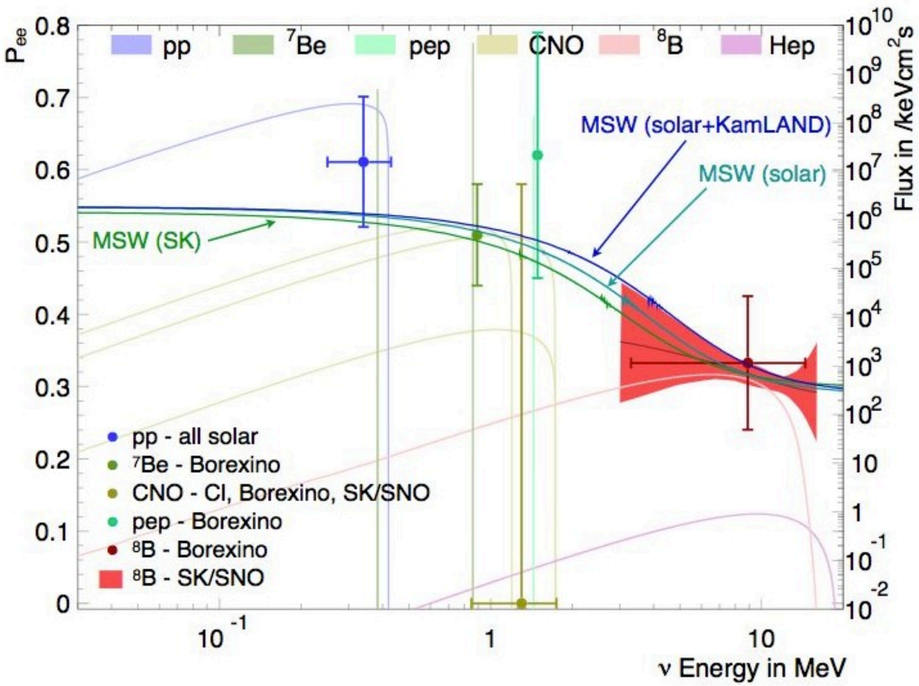
➔

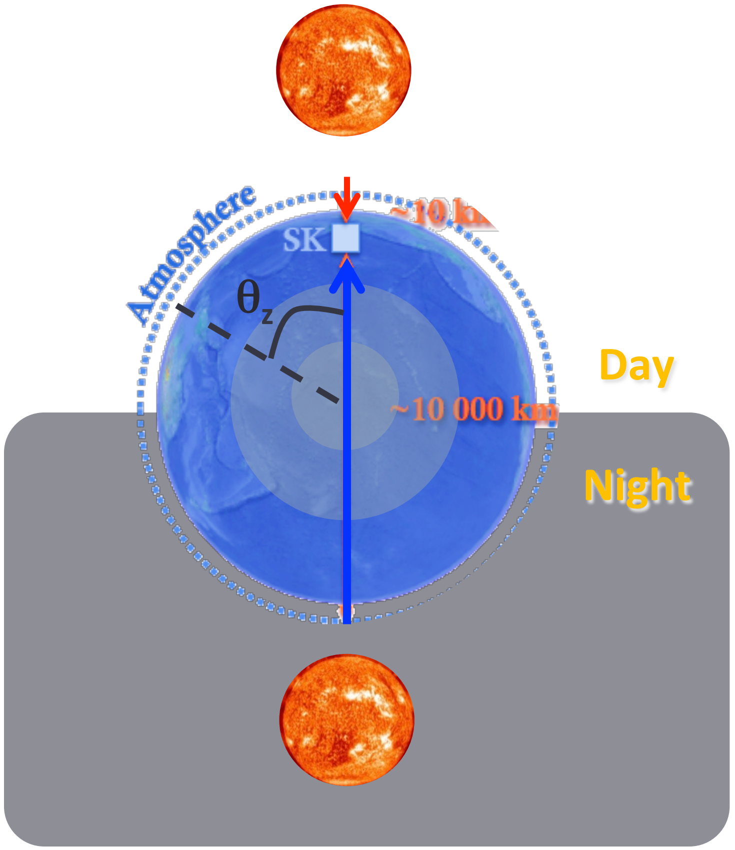
Upturn in energy spectrum

Earth matter effect

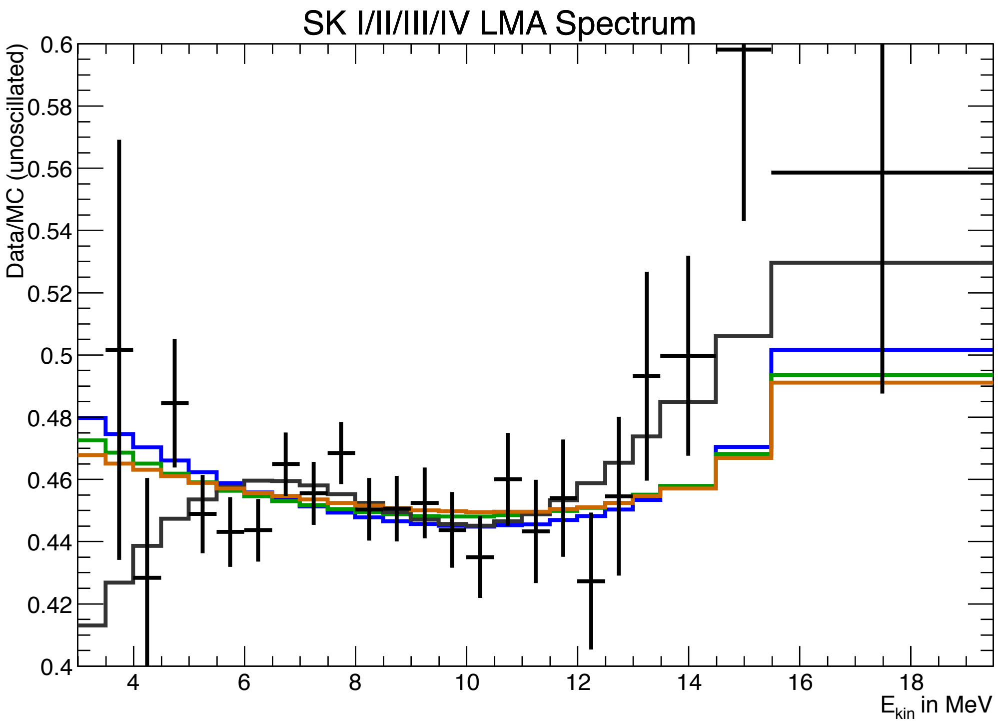
➔

Flux day/night asymmetry





MSW to Vacuum Oscillation Upturn?



- SK spectrum fit w/(solar global + KamLAND) best fit osc values ($\sin^2\theta_{12} = 0.304$, $\Delta m^2 = 7.41\text{x}10^{-5}\ \text{eV}^2$)
- SK spectrum fit with solar global best fit oscillation values ($\sin^2\theta_{12} = 0.314$, $\Delta m^2 = 4.9\text{x}10^{-5}\ \text{eV}^2$)
- SK spectrum fit to general exponential/quadratic function
- SK spectrum fit to cubic function

No strong evidence of upturn yet, but for the first time (SK-IV) a clear solar neutrino signal has been extracted in the 3.5-4 MeV energy bin!

Lowering SK energy threshold:
See poster #28 by G. Carminati
“New wideband trigger for SK Solar”

Terrestrial Matter Effects (Day-Night Asymmetry)

- Test directly by comparing solar ν's that pass through Earth (night) to those which do not (day).

$$A_{DN} = \frac{r_D - r_N}{\frac{1}{2}(r_D + r_N)}$$

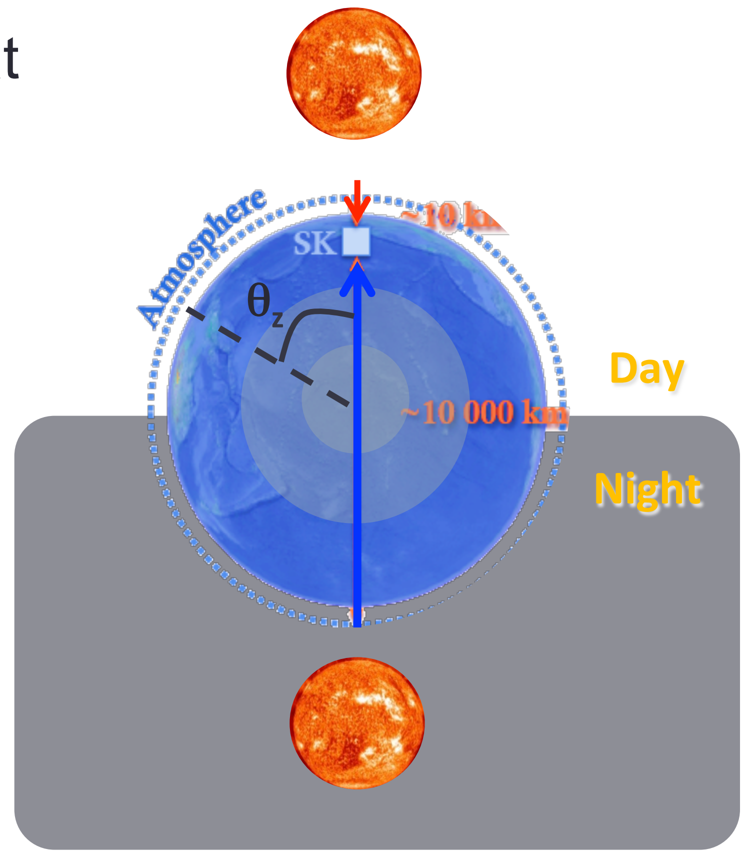
- A_{DN} = 0 implies no matter effects in the Earth
- Two methods:

① Straight calculation

No oscillation parameter dependence

② "Amplitude fit" $(A_{DN}^{fit} = A_{DN}^{calc} \times \alpha)$

Less vulnerable to some systematic effects (e.g., directional variation of energy scale)

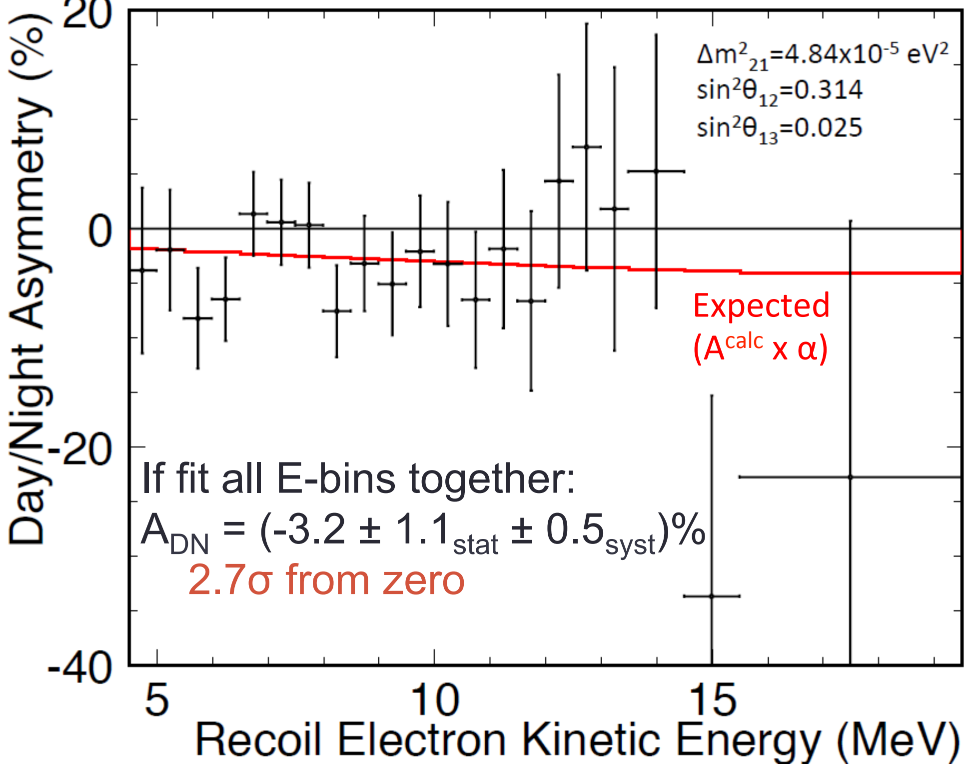


Day/Night Asymmetry

Straight Calculation

	Asymmetry
SK-I	-2.1 ± 2.0 ± 1.3%
SK-II	-5.5 ± 4.2 ± 3.7%
SK-III	-5.9 ± 3.2 ± 1.3%
SK-IV	-5.3 ± 2.0 ± 1.4%
Combined	-4.2 ± 1.2 ± 0.8% (2.8σ from zero)

Amplitude Fit



First direct indication that neutrino oscillation probabilities are modified by the presence of matter

Solar Neutrino Mini-Summary

- Flux measurements agree across all phases of SK
- Upturn not yet seen in SK recoil electron energy spectrum
- SK measures solar neutrino day/night asymmetry
  - -4.2 ± 1.5% (straight calculation), 2.8σ from zero
  - -3.2 ± 1.2% (amplitude fit), 2.7σ from zero
  - **Direct indication of matter-enhanced neutrino oscillation**
- Oscillation analysis (solar global + KamLAND) best fit:

$\sin^2\theta_{12} = 0.304 \pm 0.013$

$\sin^2\theta_{13} = 0.031 +0.017 -0.015$

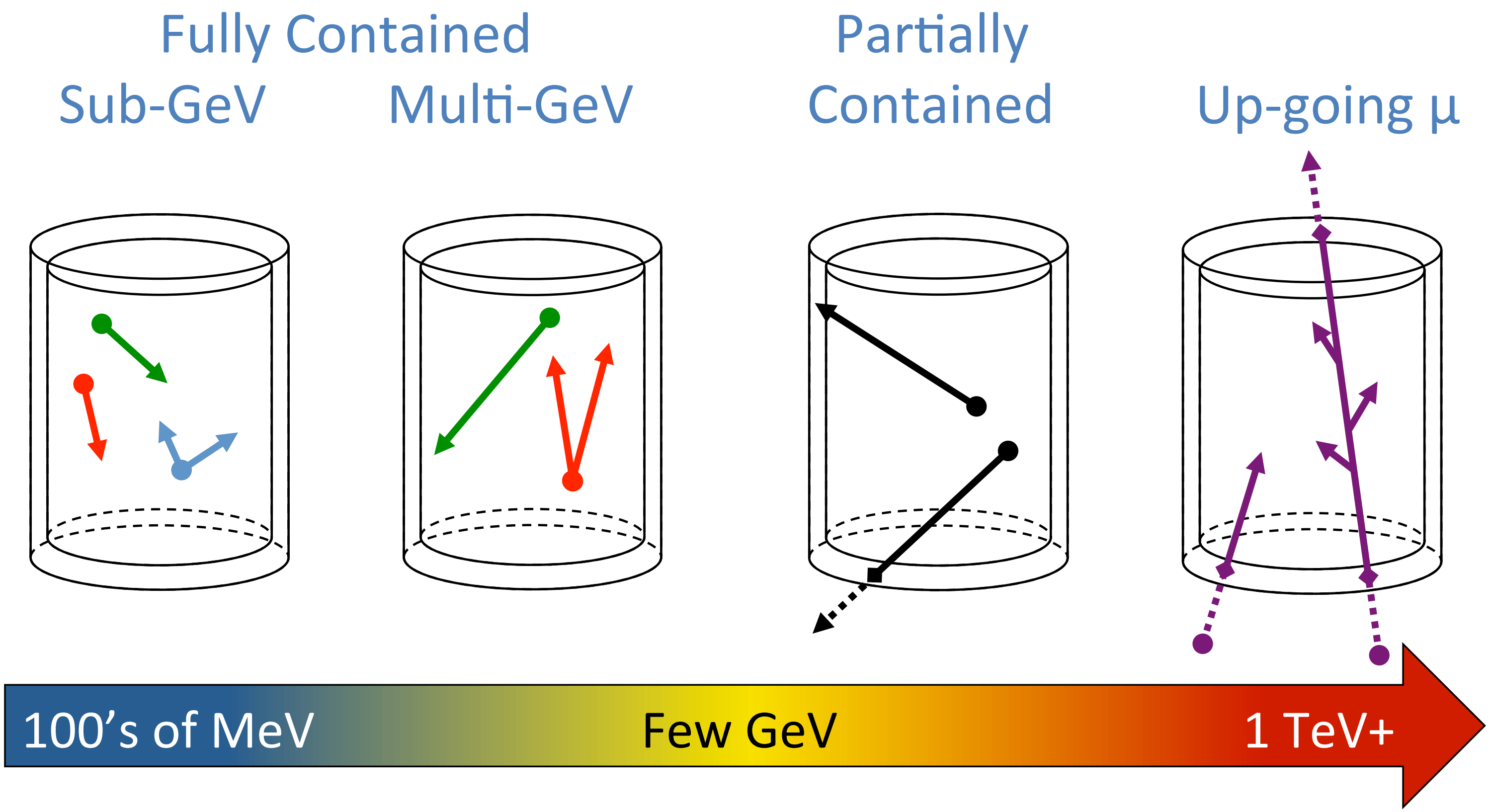
$\Delta m^2_{21} = 7.45 \pm 0.2 \times 10^{-5}\ \mathrm{eV}^2$

Improved signal extraction at low energy have allowed us to push analysis threshold to 3.5 MeV for the first time

See poster #25 by Y. Nakano "Solar neutrino results in SK-IV"

Atmospheric Neutrinos

>38,000 atmospheric ν's collected in SK-I+II+III+IV

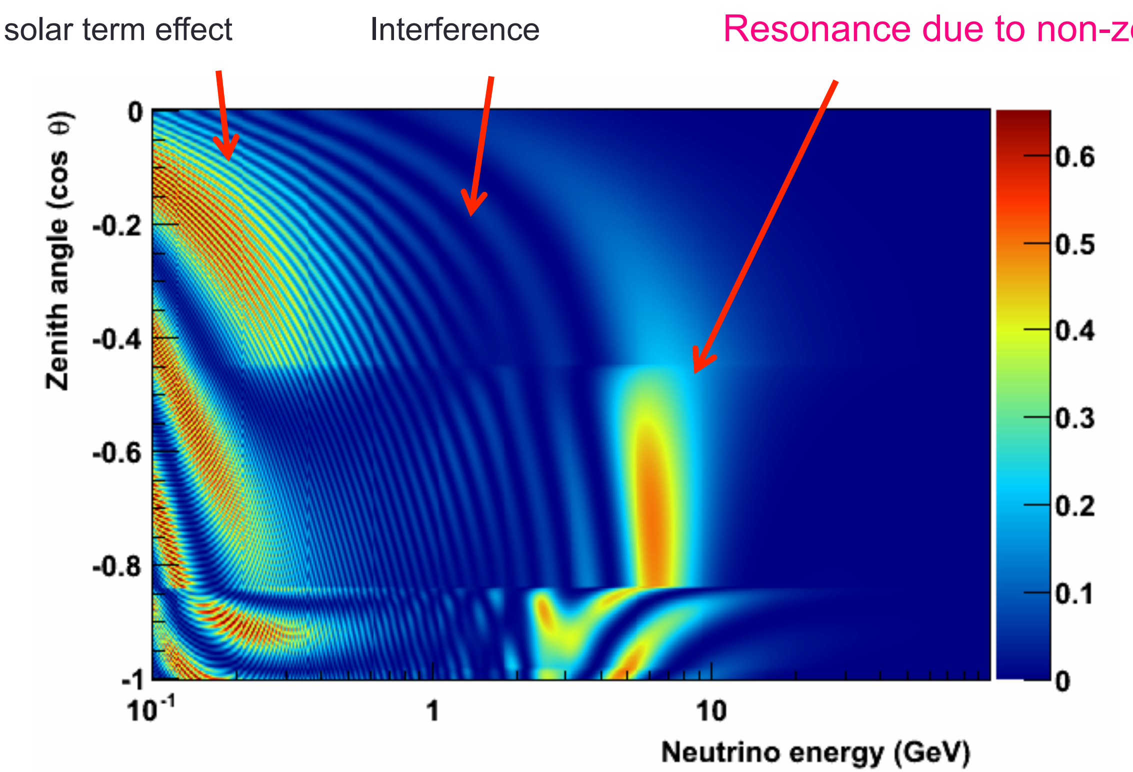


μ-like, e-like ($\nu_e/\bar{\nu}_e$), NCπ^0-like

Long tracks – all μ-like

Mass Hierarchy, θ_{23} octant, and δ_{CP}

- Study more sub-leading oscillation effects with sample of atmospheric neutrinos spanning large range of energies and angles:
  - Non-zero θ_{13} allows the possibility to investigate mass hierarchy
  - Also sensitive to θ_{23} octant and δ_{CP}



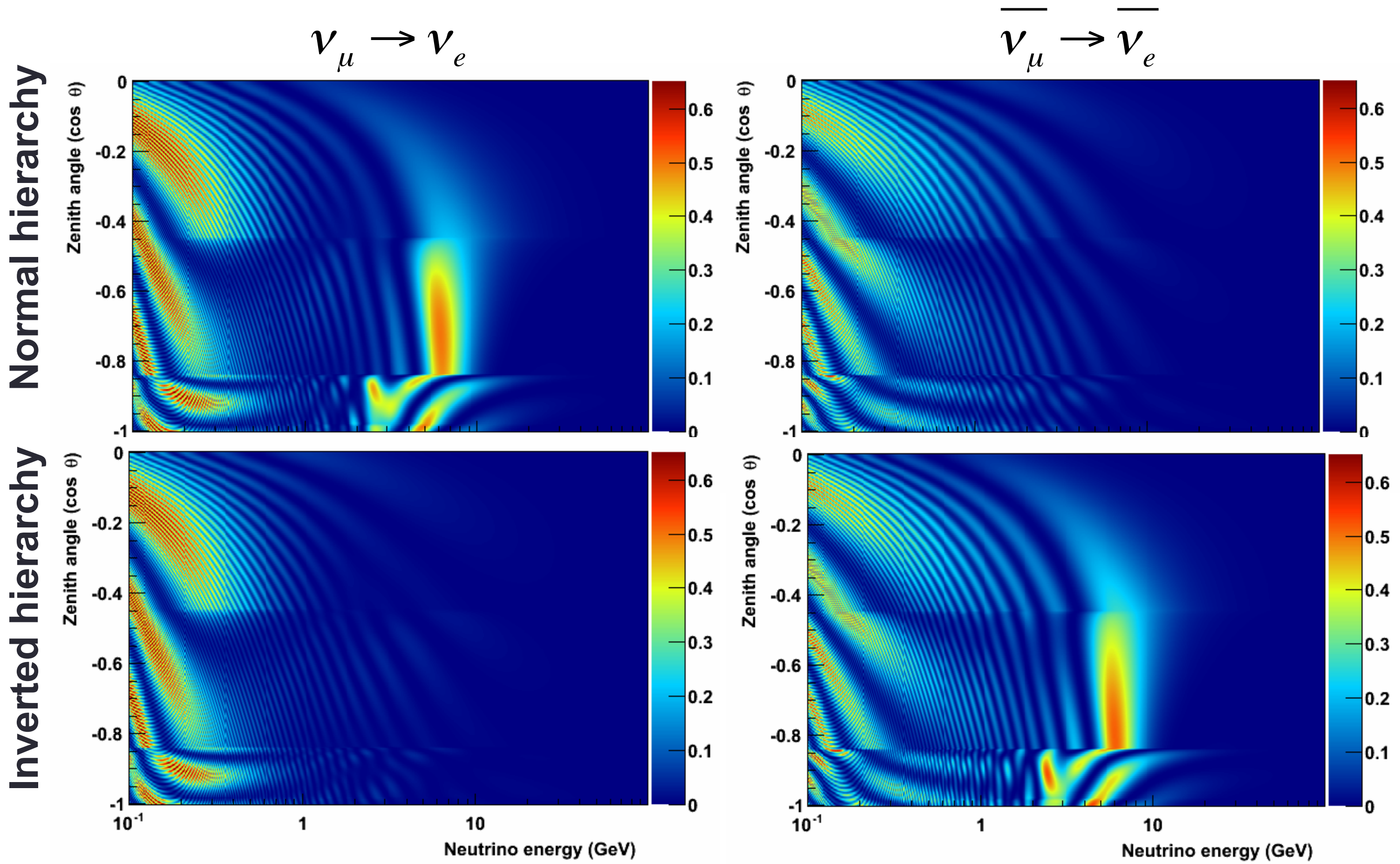
Solar term effect
sensitive to θ_{23} octant

Interference region
sensitive to δ_{CP}

θ_{13} resonance region
sensitive to θ_{23}, θ_{13}, MH

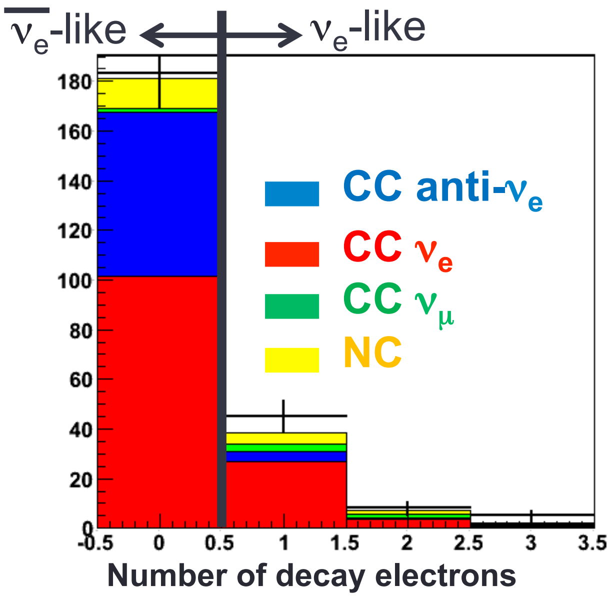
Mass Hierarchy

- Resonance feature depends on neutrino type and mass hierarchy
- Possible to determine MH if we can separate ν_e from anti-ν_e

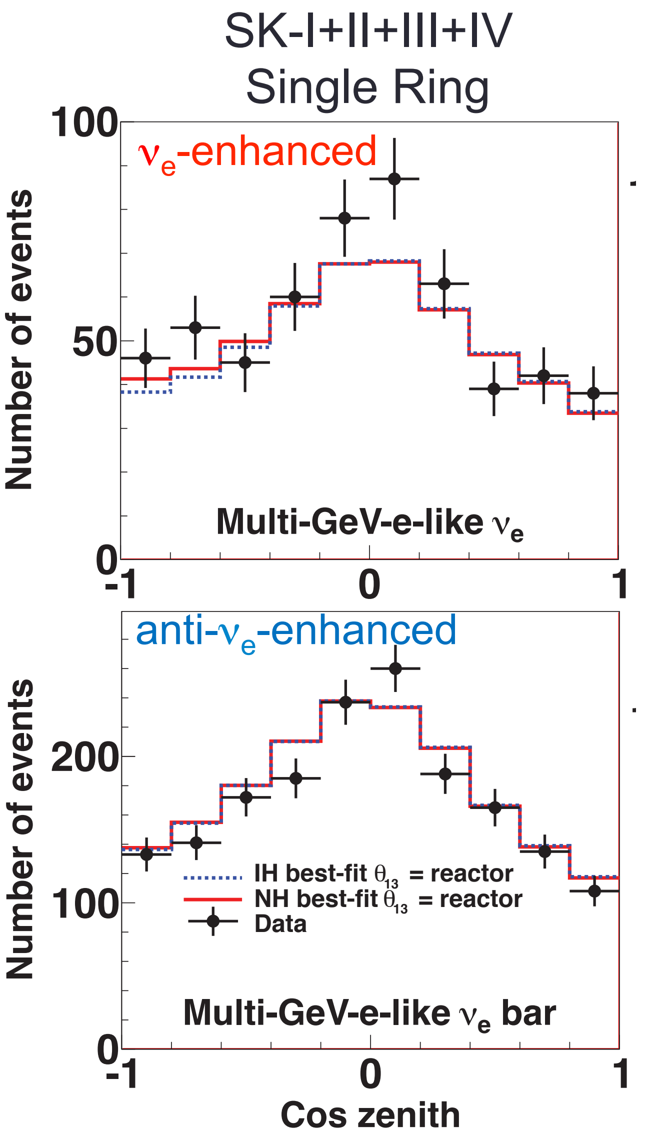


Increasing MH Sensitivity

- Separating ν from anti-ν is difficult in SK
- Can't determine lepton charge, but some statistical separation is possible
  - Separate ν from anti-ν in single ring sample using number of decay electrons

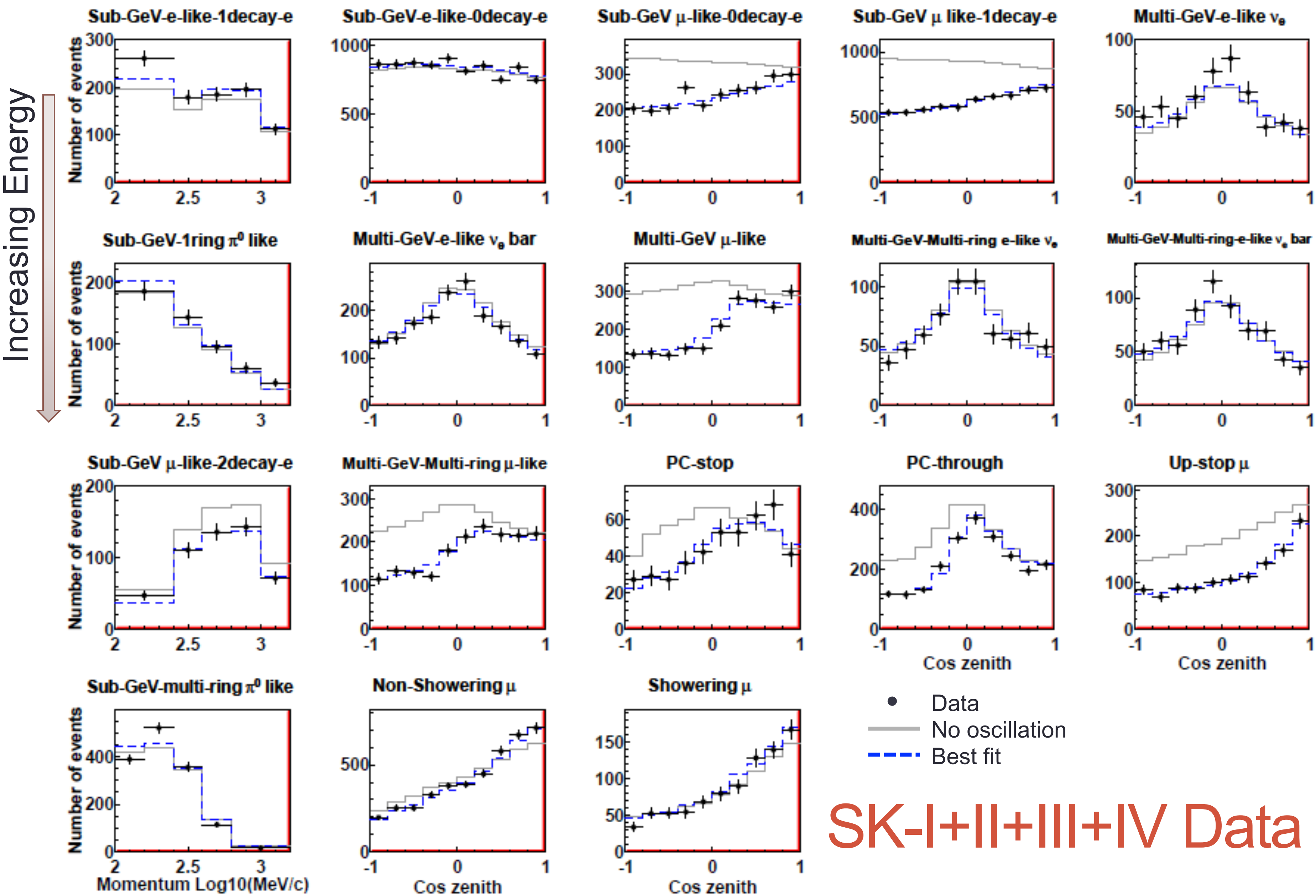


Absorption of π^- from CC 1π anti-ν interaction
$\Rightarrow$ no μ from π decay
$\Rightarrow$ no e from μ decay



Multi-ring events are more complicated. Separation uses likelihood function with kinematic variables (e.g., p_T, energy fraction of outgoing lepton, # rings)

See poster #15 by T. Irvine "Neutron detection and distinguishing high energy anti-neutrinos in SK"



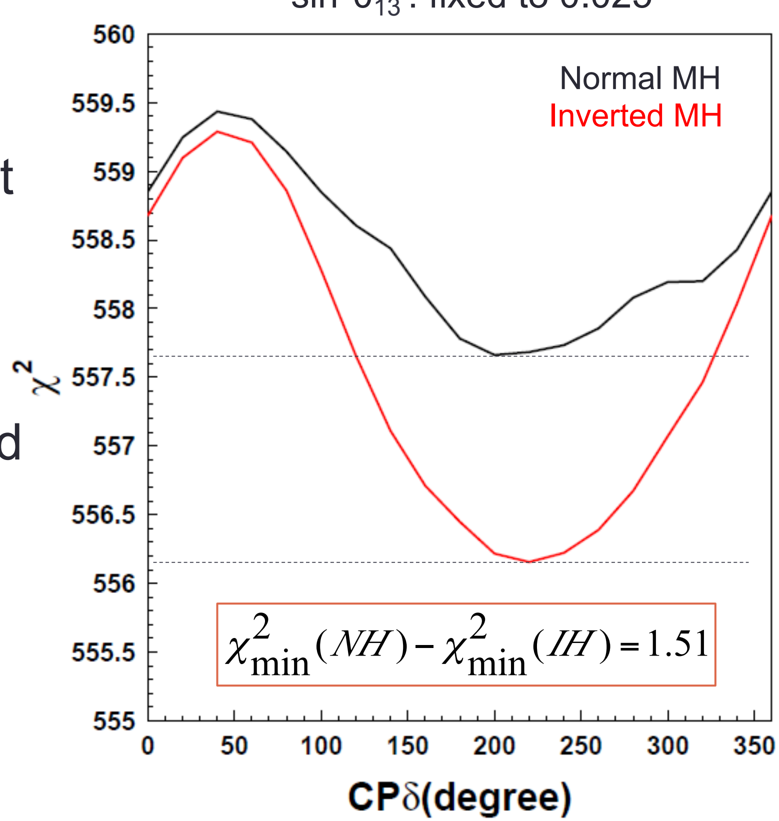
SK-I+II+III+IV Data

MH, θ_{23} octant, δ_{CP}

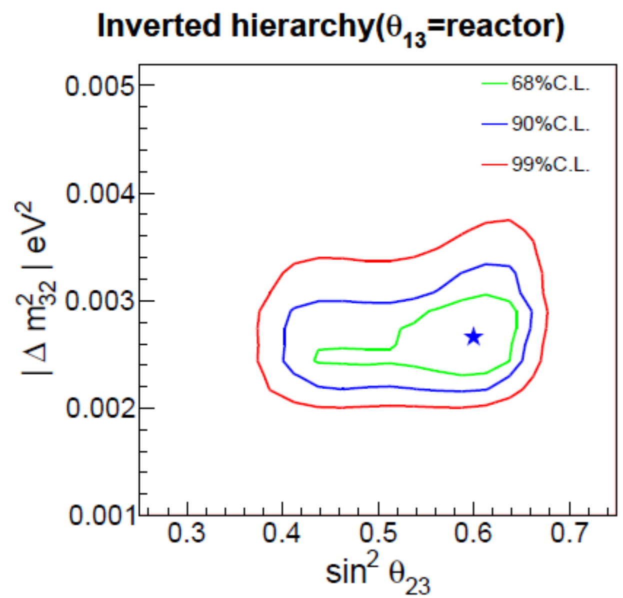
SK data show slight preference for inverted hierarchy, not significant

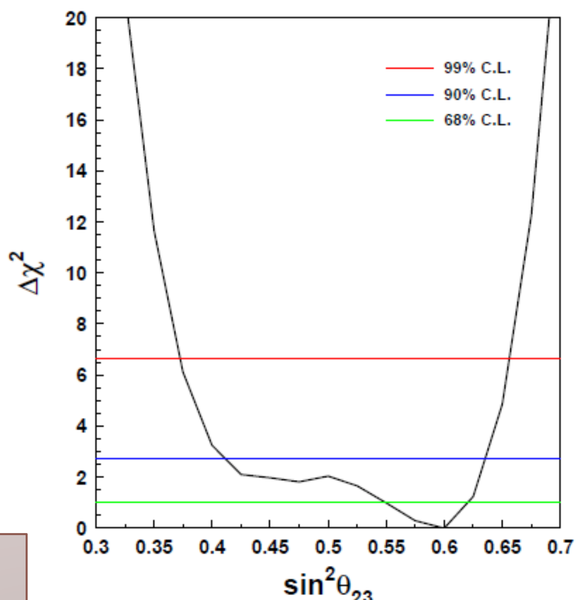
δ_{CP} ~ 220° preferred

Favor 2nd octant of θ_{23}, regardless of hierarchy



Δχ²=2.3 expected by sensitivity study





See poster #27 by K. Iyogi
"Three-flavor oscillation analysis with atmospheric neutrinos in SK"

Sterile Neutrinos

- Searches using SK atmospheric data are independent of sterile Δm^2 and number of sterile neutrinos
  - 3+1 models and 3+N models have same signature in Super-K

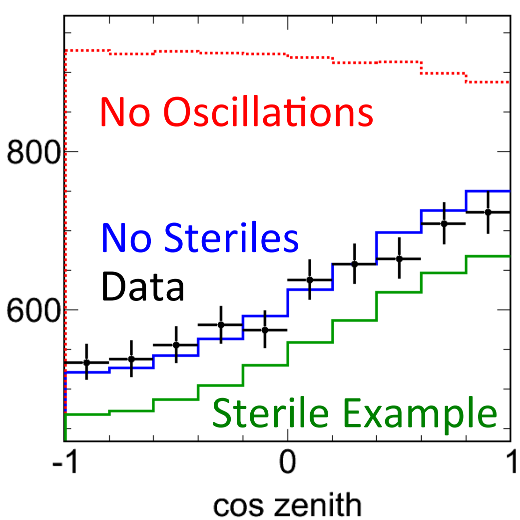
$$\begin{array}{c} \text{PMNS} \\ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \end{array}$$

- Atmospheric neutrinos can say something about:

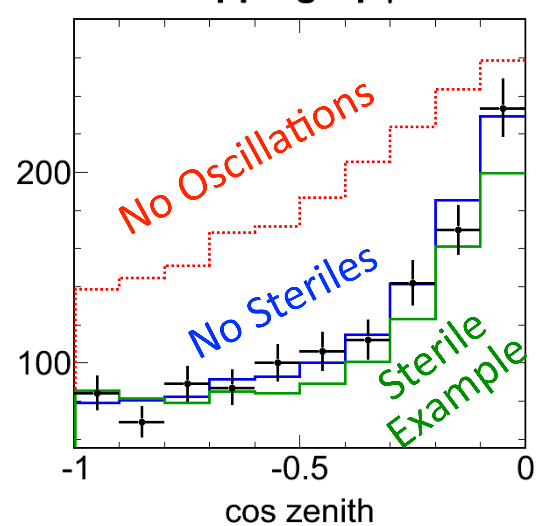
$|U_{\mu 4}|^2$: Signature is extra ν_μ disappearance in all μ–like data samples, at all energies and angles

$|U_{\tau 4}|^2$: Signature is shape distortion in angular distribution of higher energy subsamples

Sub-GeV μ-like 1-dcy e



Stopping Up μ



Sterile Neutrinos

Reactors/Ga ~ $|U_{e4}|^2$

SBL $\nu_\mu \rightarrow \nu_e$ ~ $|U_{e4}|^2|U_{\mu 4}|^2$

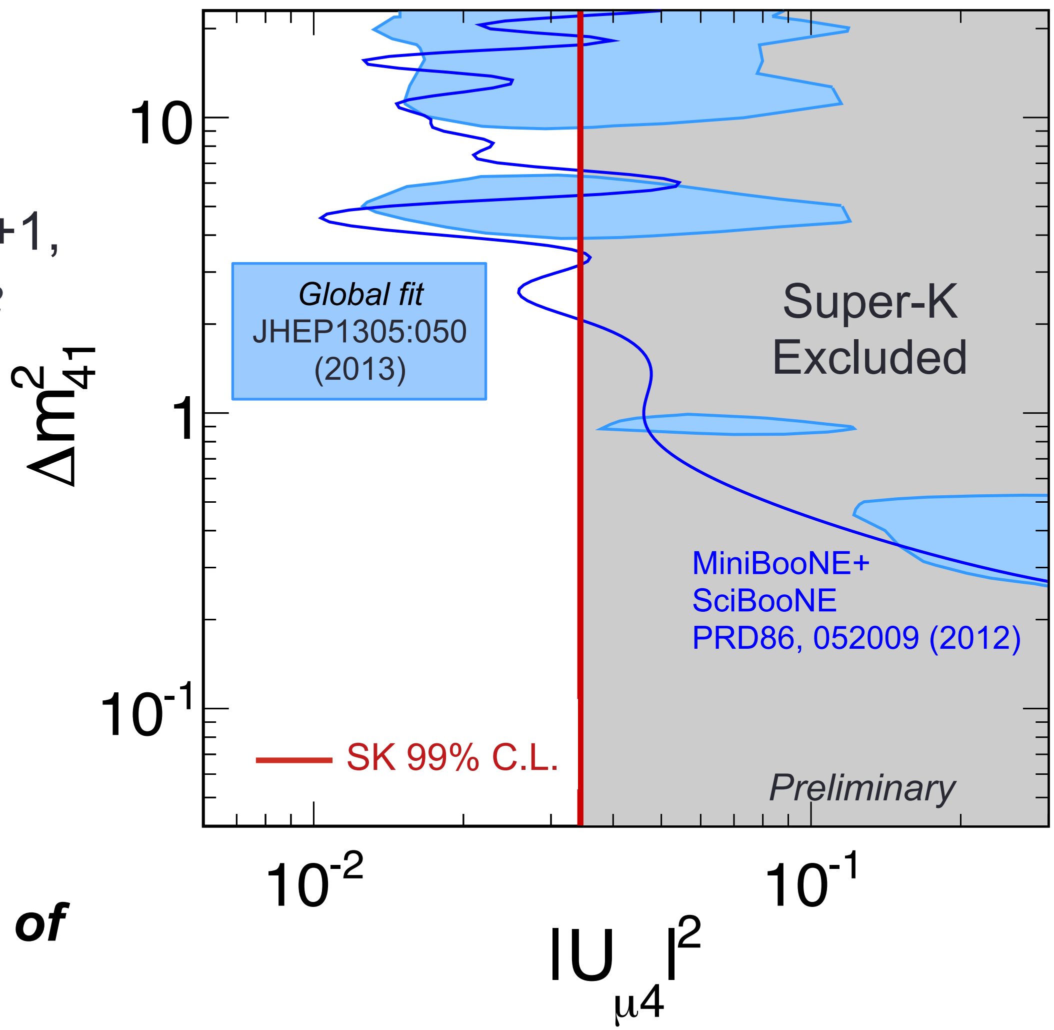
Global fit to both, assuming 3+1, gives allowed regions in $|U_{\mu 4}|^2$

Fit for $|U_{\mu 4}|^2$ in SK-I+II+III+IV data (1631 days):

$|U_{\mu 4}|^2 < 0.021$ at 90% C.L.

$|U_{\mu 4}|^2 < 0.031$ at 99% C.L.

SK excludes a large portion of the global allowed regions.



Sterile Neutrinos

Fit for $|U_{\tau 4}|^2$ in SK-I+II+III+IV data (1631 days):

- $|U_{\tau 4}|^2 < 0.22$ at 90% C.L.
- $|U_{\tau 4}|^2 < 0.27$ at 99% C.L.

$$|U_{\tau 4}|^2 \approx \frac{P(\mu \to s)}{P(\mu \to *)}$$

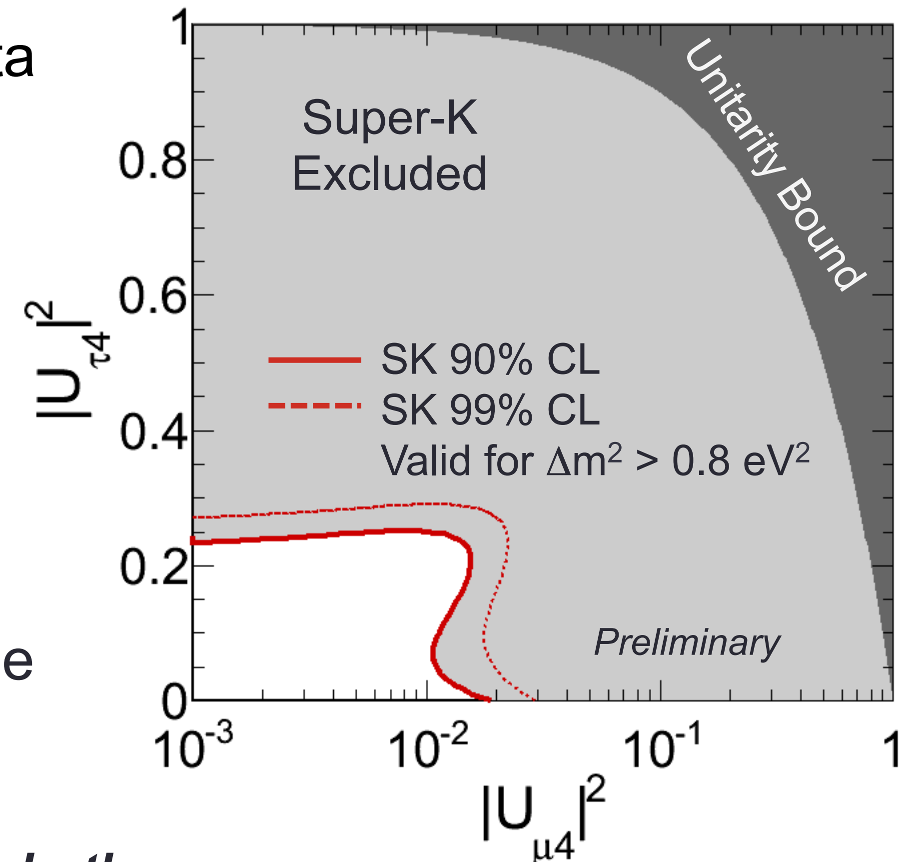
as $|U_{\mu 4}|^2 \to 0$

Constraint from *not* seeing sterile matter effect

Conclusion from both fits:

Limits from SK are applicable to both 3+1 and 3+N models.

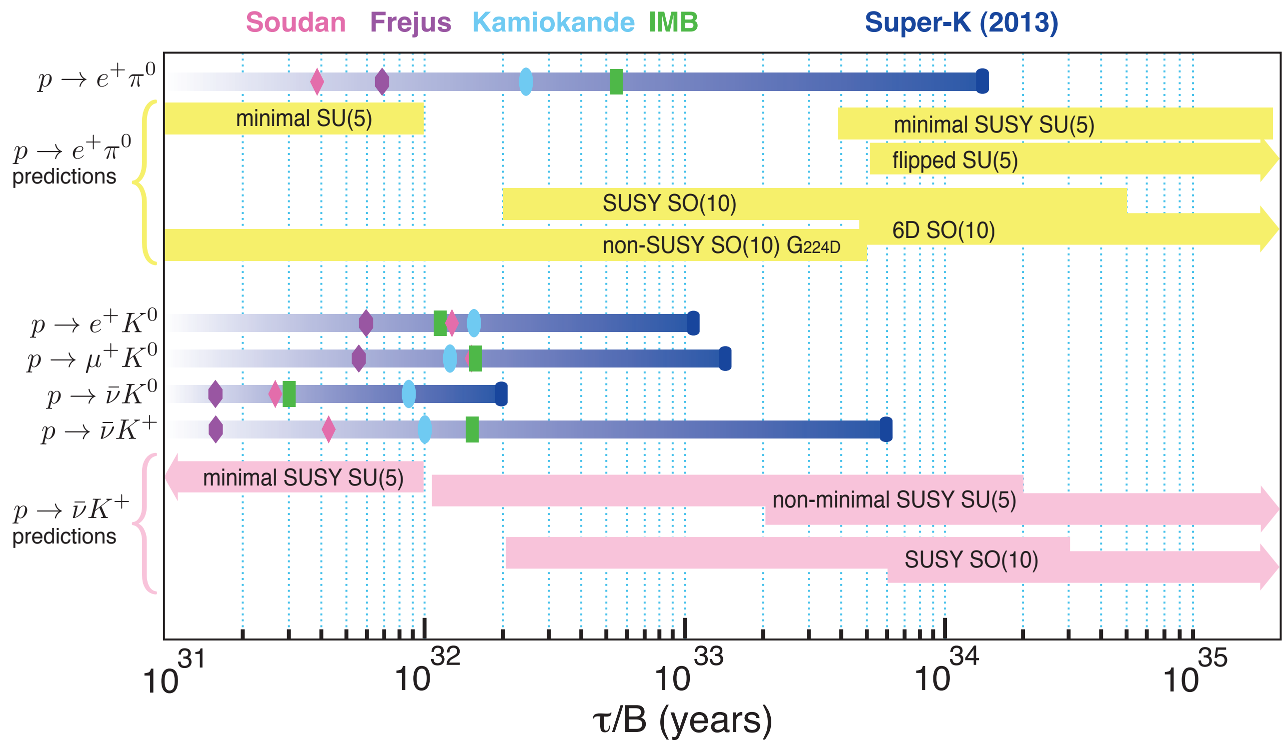
SK sees no evidence of oscillations with sterile neutrinos.



Related analysis:
See poster #30 by E. Richard,
"Sterile Neutrino Decay in SK"

Nucleon Decay

The fully-contained atmospheric neutrino sample is the haystack in which we can search for rare processes.



Directly test the idea of Grand Unification

- GUTs generally allow lepton and baryon number violation, and predict instability of nucleons
- Many theories, many decay modes…

Observation of a *single* event could mark discovery!

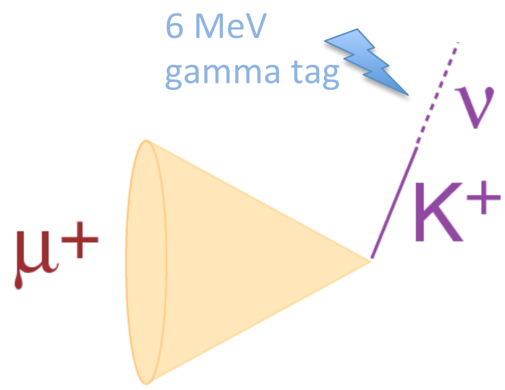
No observation so far ⇒ constraints on GUT models

Experimental Challenges

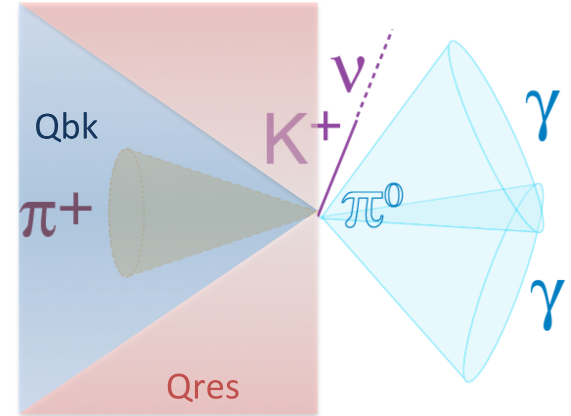
$$\frac{\tau}{B} = \frac{N_0 \, \Delta t \, \epsilon}{n_{obs} - n_{bg}}$$

Sensitivity to partial decay lifetime is affected by:

- **Signal detection efficiency**
  - Keep this as high as possible
- **Background rate**
  - Keep this as low as possible
  - Improved knowledge of BG needed to extract convincing signal
- **Exposure**
  - SK-I+II+III+IV = (91.7 + 49.2 + 31.9 + 87.3) = 260.1 kton-yrs
  - Gains with more SK running are marginal. Get bigger detector!
- **Systematic uncertainties**
  - Keep these as low as possible



Improvements in $p \rightarrow \bar{\nu} K^+$



- Better momentum reconstruction & γ-tagging efficiency
  Reduces atmospheric ν BG
- Better decay-electron tagging efficiency
  SK-I,II,III ~80% *cf.* SK-IV ~96%
- Refined particle ID and new π^0 reconstruction algorithm

$$\frac{\tau}{B_{p\rightarrow\nu K^+}} > 5.9\times10^{33} \text{ years (90\% CL)}$$

SK-I+II+III+IV Preliminary

γ-tag and $\pi^+\pi^0$	SK-I	SK-II (20% coverage)	SK-III	SK-IV (new electronics)
Efficiency	15.7%	13.0%	15.6%	19.1%
Background rate (evts/Mton/yr)	2.8 ± 0.4	6.2 ± 0.8	3.1 ± 0.5	3.5 ± 0.4

SK-I (PRD72, 052007 (2005)) 14.6% efficiency, ~14 evts/Mton/yr

Non-Traditional Searches (I)

- Dinucleon decay ($\Delta B = 2$)
  - Quarks of two bound nucleons interact to produce decay
    - Could be mediated by exchange of non-Standard Model particle
  - Violates only baryon number (single nucleon decay violates both B and L)
- Several modes searched for in Super-K so far, no dinucleon decay observed

$$pp \rightarrow K^+K^+ \qquad \frac{\tau}{B} > 1.7 \times 10^{32} \text{ years (SK-I 90\% CL)}$$

$$pp \rightarrow e^+e^+ \qquad \frac{\tau}{B} > 1.0 \times 10^{33} \text{ years (SK-I 90\% CL)}$$

$$\boxed{pp \rightarrow \pi^+\pi^+ \qquad \frac{\tau}{B} > 3.07 \times 10^{31} \text{ years (SK-IV 90\% CL)}}$$

Super-K limits
Preliminary

See poster #17 by J. Gustafson,
"Searches for Processes Violating Baryon Number by Two Units at SK"

Non-Traditional Searches (II)

- Some GUTs predict interesting modes such as B-L violating tri-lepton decay: p → eνν

  Historically, proposed to explain the "neutrino anomaly"

Physics Letters B 291 (1992) 200–205
North-Holland

PHYSICS LETTERS B

The atmospheric flux ν_μ/ν_e anomaly as manifestation of proton decay $p \to e^+\nu\nu$

W.A. Mann, T. Kafka and W. Leeson
Department of Physics, Tufts University, Medford, MA 02155, USA

Received 22 June 1992

- First SK search for 3-body modes

$$\frac{\tau}{B(p \to e\nu\nu)} > 1.7 \times 10^{32}\ \text{yrs}$$

$$\frac{\tau}{B(p \to \mu\nu\nu)} > 1.9 \times 10^{32}\ \text{yrs}$$

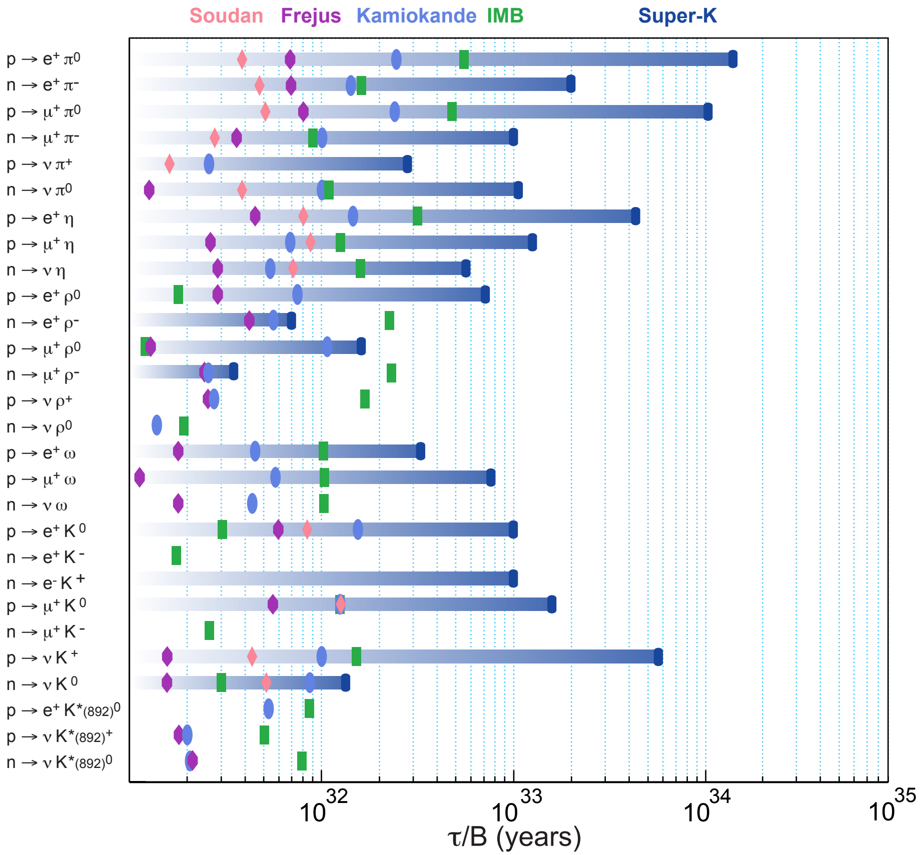
90% CL
SK-I+II+III+IV
Preliminary

See poster #21 by V. Takhistov, "Proton Decay into Purely Leptonic Three-Body Final States"

Order of magnitude improvement over existing published limits

Where We Are…

Antilepton + meson two-body modes



PDG particle data group

***p* DECAY MODES**	Partial mean life (10^{30} years)	
Three (or more) leptons		
$p \to e^+ e^+ e^-$	> 793	
$p \to e^+ \mu^+ \mu^-$	> 359	
$p \to e^+ \nu \nu$	$> \cancel{17}$	>170 (SK-I-IV)
$n \to e^+ e^- \nu$	> 257	
$n \to \mu^+ e^- \nu$	> 83	
$n \to \mu^+ \mu^- \nu$	> 79	
$p \to \mu^+ e^+ e^-$	> 529	
$p \to \mu^+ \mu^+ \mu^-$	> 675	
$p \to \mu^+ \nu \nu$	$> \cancel{21}$	>190 (SK-I-IV)
$p \to e^- \mu^+ \mu^+$	> 6	
$n \to 3\nu$	> 0.0005	

x10^{30} yrs

$\Delta B = 2$ dinucleon modes

The following are lifetime limits per iron nucleus.

$pp \to \pi^+ \pi^+$	$> \cancel{0.7}$	>30.7 (SK-IV only) per oxygen nucleus
$pn \to \pi^+ \pi^0$	> 2	
$nn \to \pi^+ \pi^-$	> 0.7	
$nn \to \pi^0 \pi^0$	> 3.4	
$pp \to e^+ e^+$	$> \cancel{5.8}$	>1000 (SK-I only) per oxygen nucleus
$pp \to e^+ \mu^+$	> 3.6	
$pp \to \mu^+ \mu^+$	> 1.7	
$pn \to e^+ \overline{\nu}$	> 2.8	
$pn \to \mu^+ \overline{\nu}$	> 1.6	
$nn \to \nu_e \overline{\nu}_e$	> 1.4	
$nn \to \nu_\mu \overline{\nu}_\mu$	> 1.4	
. . .. .		
$pp \to K^+ K^+$		> 170 (SK-I only) per oxygen nucleus

x10^{30} yrs

Summary & Conclusions

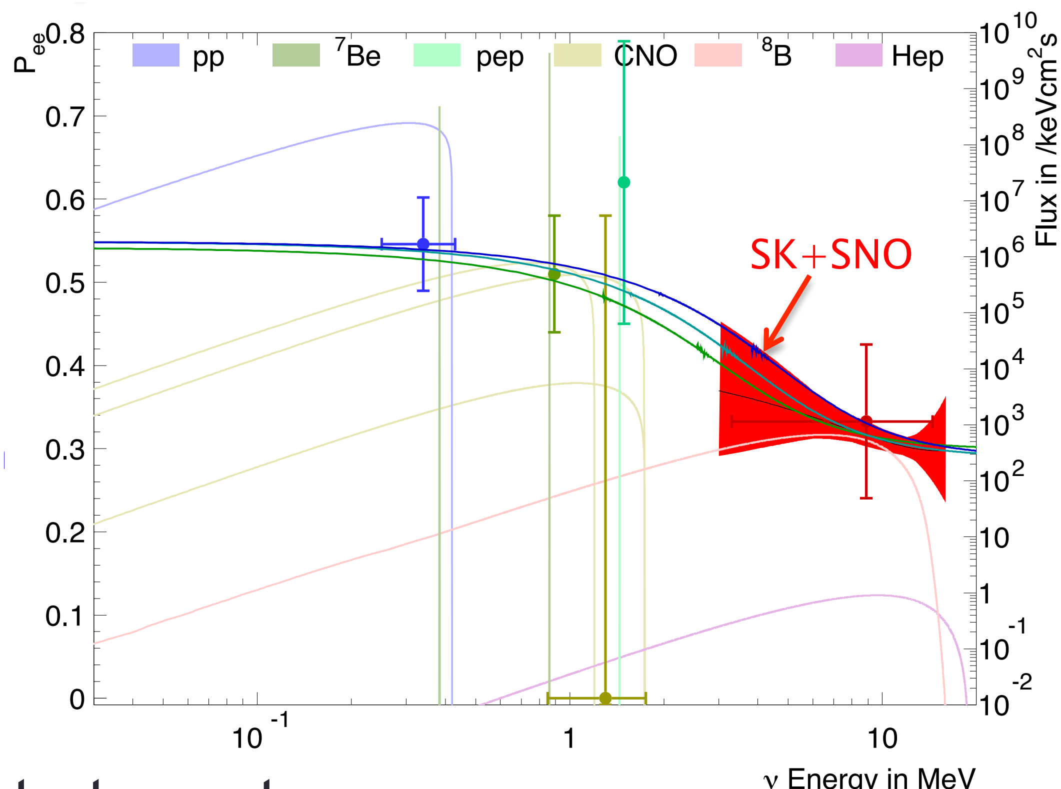
- **Solar neutrinos:**
  - D/N asymmetry gives first evidence of matter-enhanced neutrino oscillation, but no evidence of solar upturn yet
  - Working to push energy threshold even lower
- **Atmospheric neutrinos:**
  - Data are well described by 3-flavor oscillations with weak preference for inverted hierarchy, favor 2^{nd} octant and δ_{CP}~220°.
  - No evidence of sterile neutrinos
- **Nucleon decay:**
  - No observation yet, but important to test as many modes as possible and continue working to reduce BG & increase signal efficiency

Neutrino physics is in the era of precision measurements and investigation of sub-leading effects (& continued searches for rare processes).

While planning and building the next generation of experiments, we continue to make small gains in every way that we can.

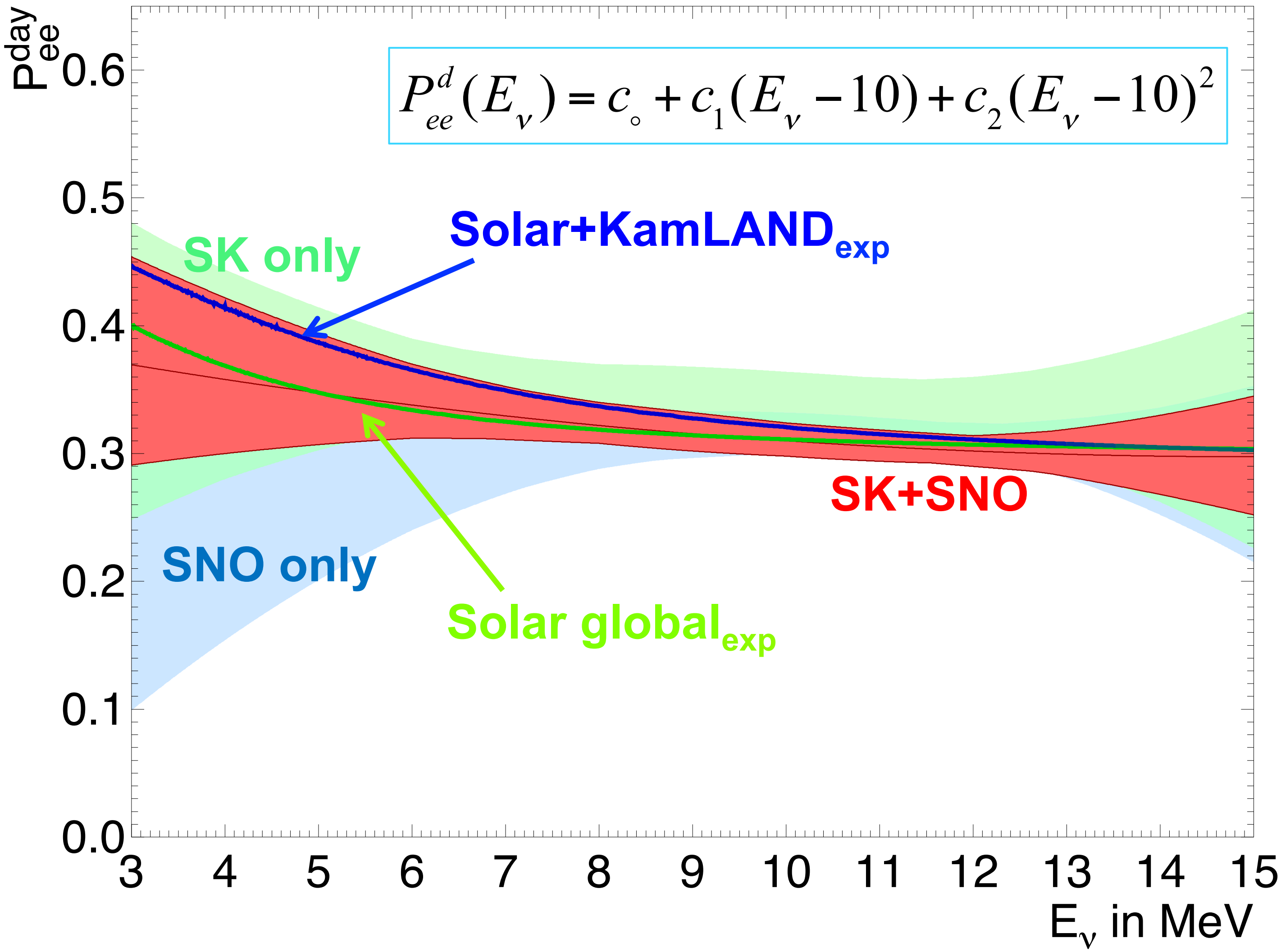
Spectrum Upturn

- MSW resonance leads to energy dependence of ν_e survival probability
- Search for signature "upturn" in recoil electron energy spectrum



- Other factors can also distort spectrum:
  - Solar *hep* ν's observed in high energy end
  - E-dependence of time varying oscillation effects
  - E-dependence of differential cross sections

Allowed Survival Probability $P_{ee}(E_\nu)$



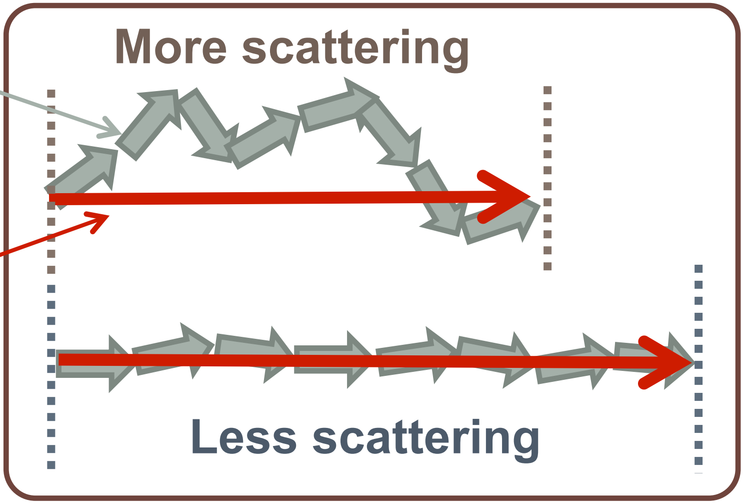
Multiple Scattering Goodness

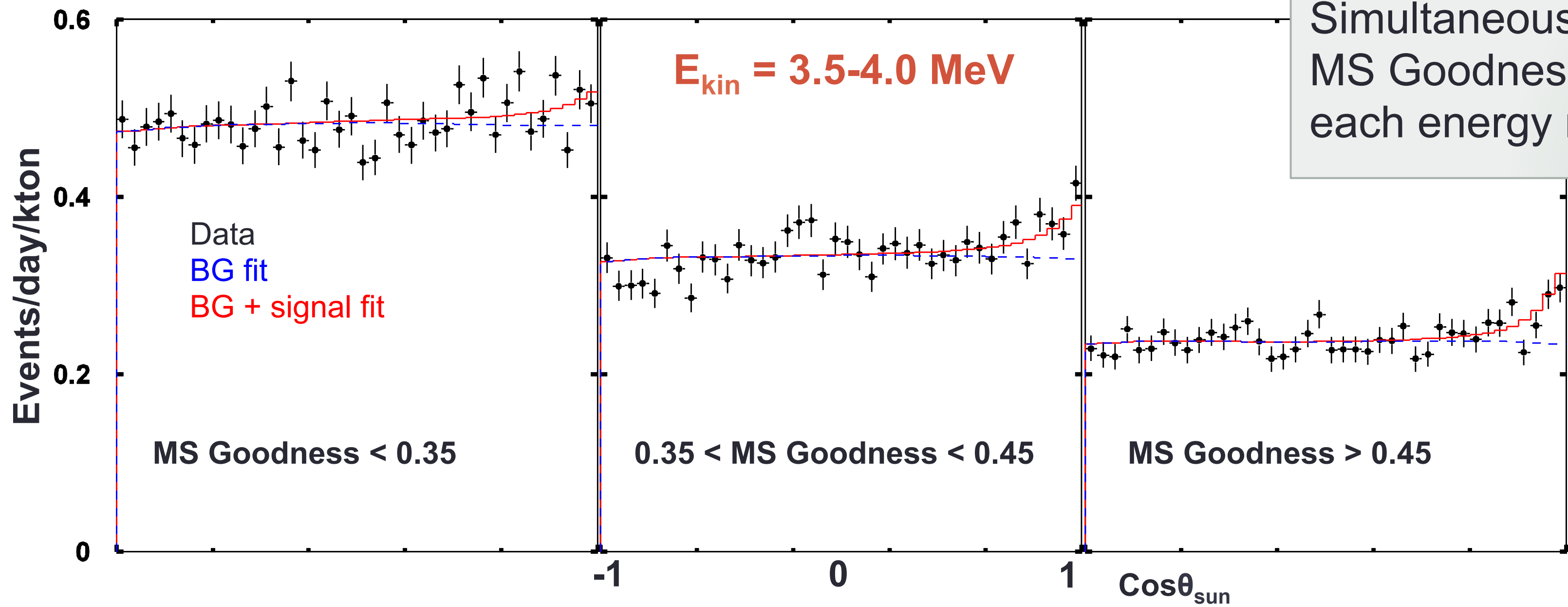
"unit vectors"
(test directions from Hough transform of PMT pairs, within 20ns hit PMTs, within 50°)

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

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

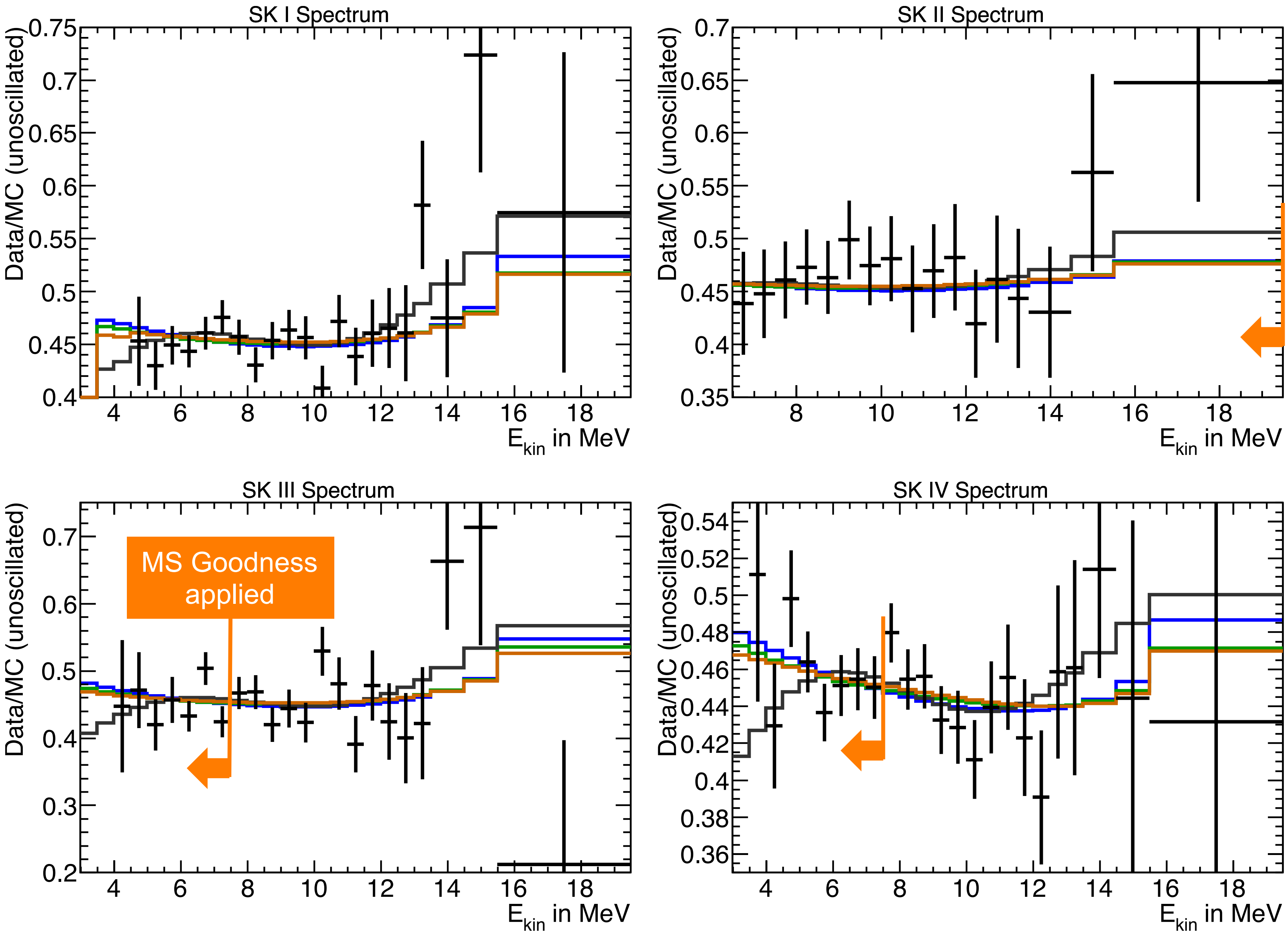
An 8-unit-vector event





Simultaneous fit to 3 MS Goodness bins for each energy range.

For vertical scale: $\phi_{8B}=5.25\times10^{6}\ /cm^2/s$



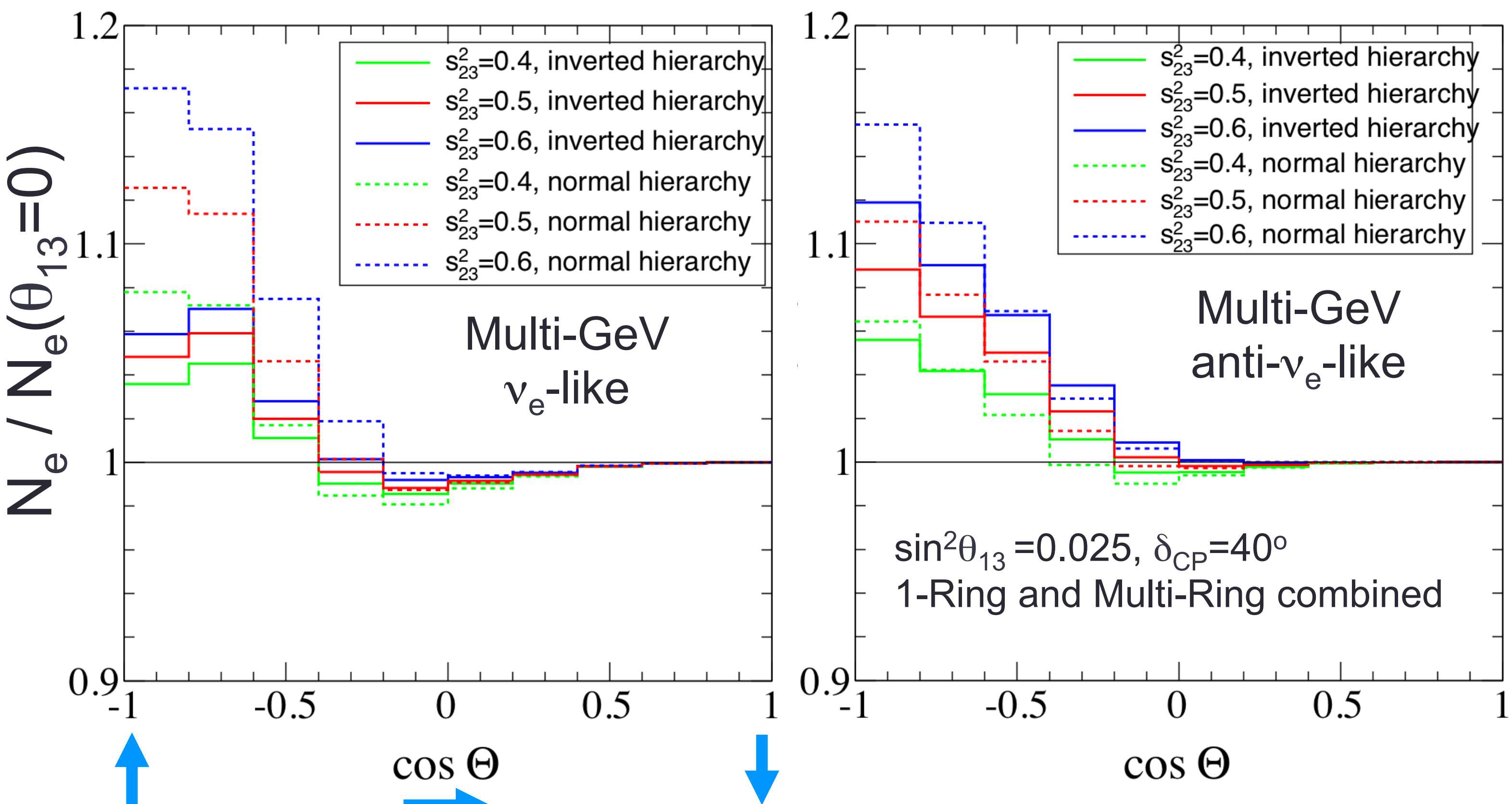
ν_e / anti-ν_e enriched samples

- ν/anti-ν separation by statistical method is not perfect, but does make reasonably enriched samples
- NC and CC ν_μ backgrounds, which cause hadronic shower events, amount to ~20%

Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_e like	1R	60.2	10.6	13.5	14.8
	MR	57.5	17.4	10.7	13.7
Anti-ν_e like	1R	55.7	36.6	1.1	6.4
	MR	51.9	20.7	8.2	19.7

Expected Multi-GeV Electron Enhancement

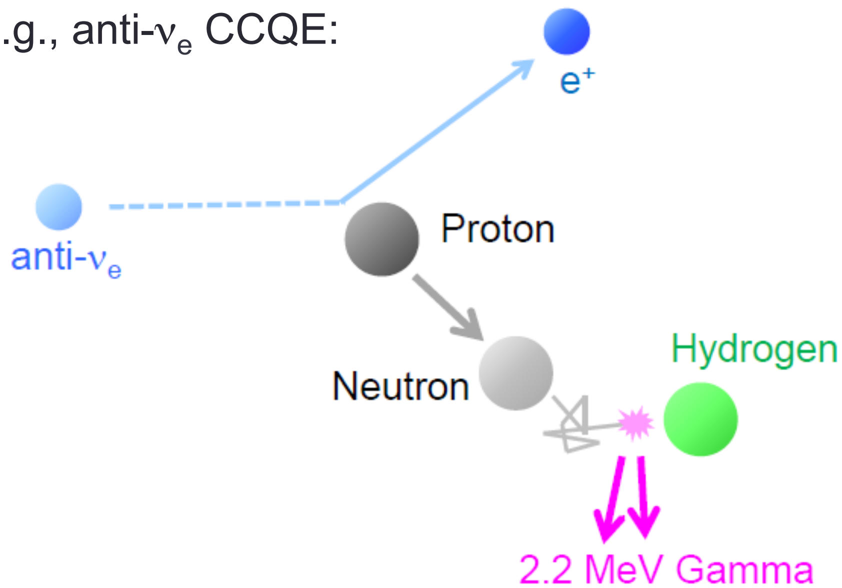
- Both samples have enhancement in upward-going events, compared to θ_{13} = 0, but amount differs depending on MH
  - Larger excess in ν_e-like (anti-ν_e-like) for normal (inverted) hierarchy



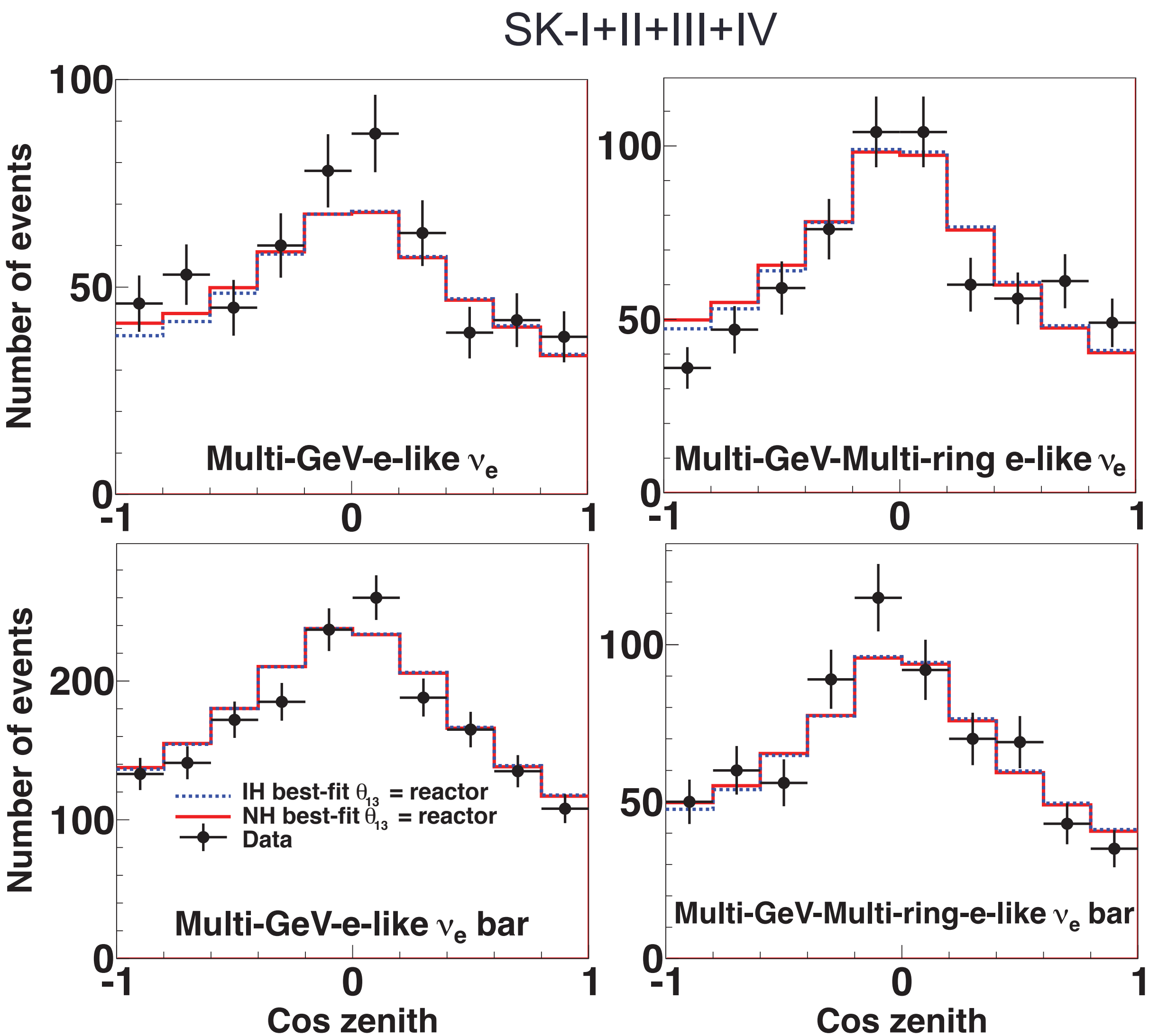
Future Improvement: Neutron Tagging

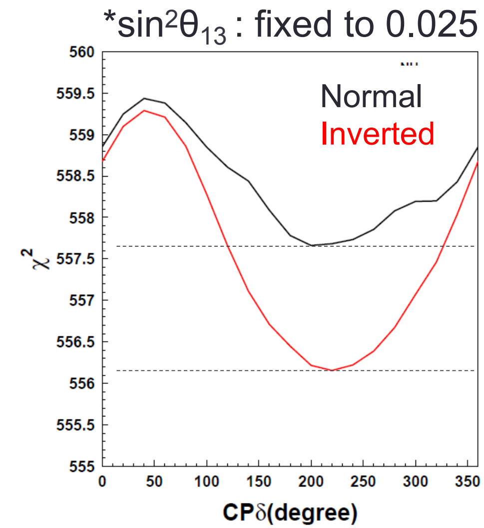
- Identify anti-ν events by neutron tagging
- Promising work currently underway. Hope to incorporate into oscillation analyses soon

e.g., anti-ν_e CCQE:



SK Hierarchy Preference?





$\Delta\chi^2$=2.3 expected by sensitivity study

$$\chi^2_{min}(NH) - \chi^2_{min}(IH) = 1.51$$

Inverted hierarchy slightly favored

δ_{CP}

- SK data favor δ_{CP} = 220° over 40°, regardless of assumed hierarchy
  - Preference is stronger for inverted hierarchy
  - Slightly more electron appearance and slightly more muon disappearance preferred by a few low energy data subsamples