ATMOSPHERIC AND SOLAR NEUTRINO RESULTS FROM SUPER-KAMIOKANDE

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HQL2016, Virginia Tech

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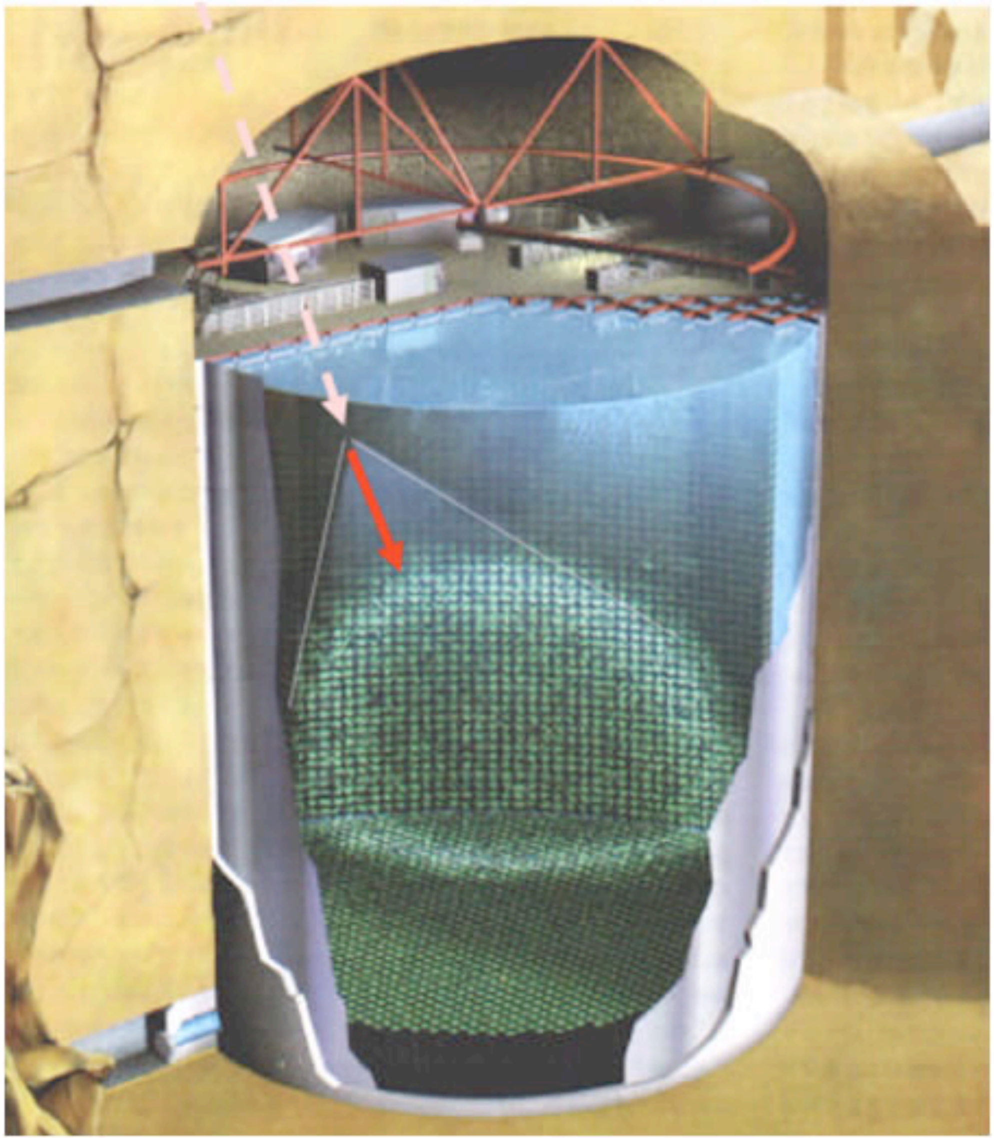
Super-Kamiokande Detector

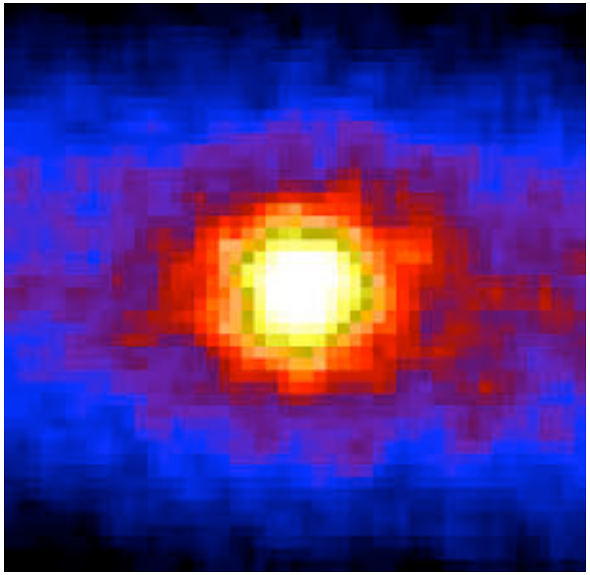


- Located near Kamioka, Japan
- 50 kton volume (22.5 kton fiducial volume)
- Optically separated into inner and outer volumes
- 11,146 20“ PMTs (ID) + 1885 8” PMTs (OD)

SK Physics Goals

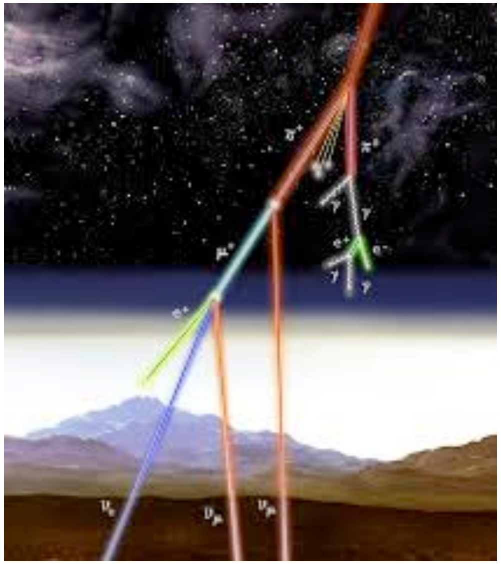
Neutrino detection:

Solar

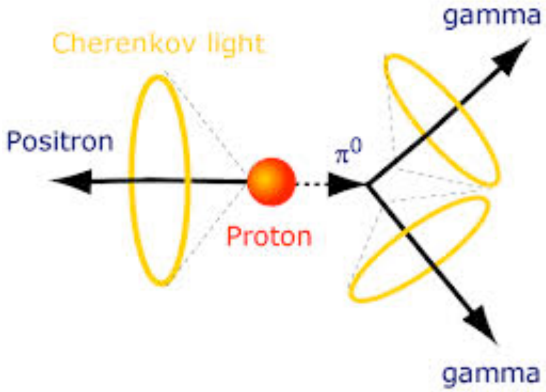


Supernova

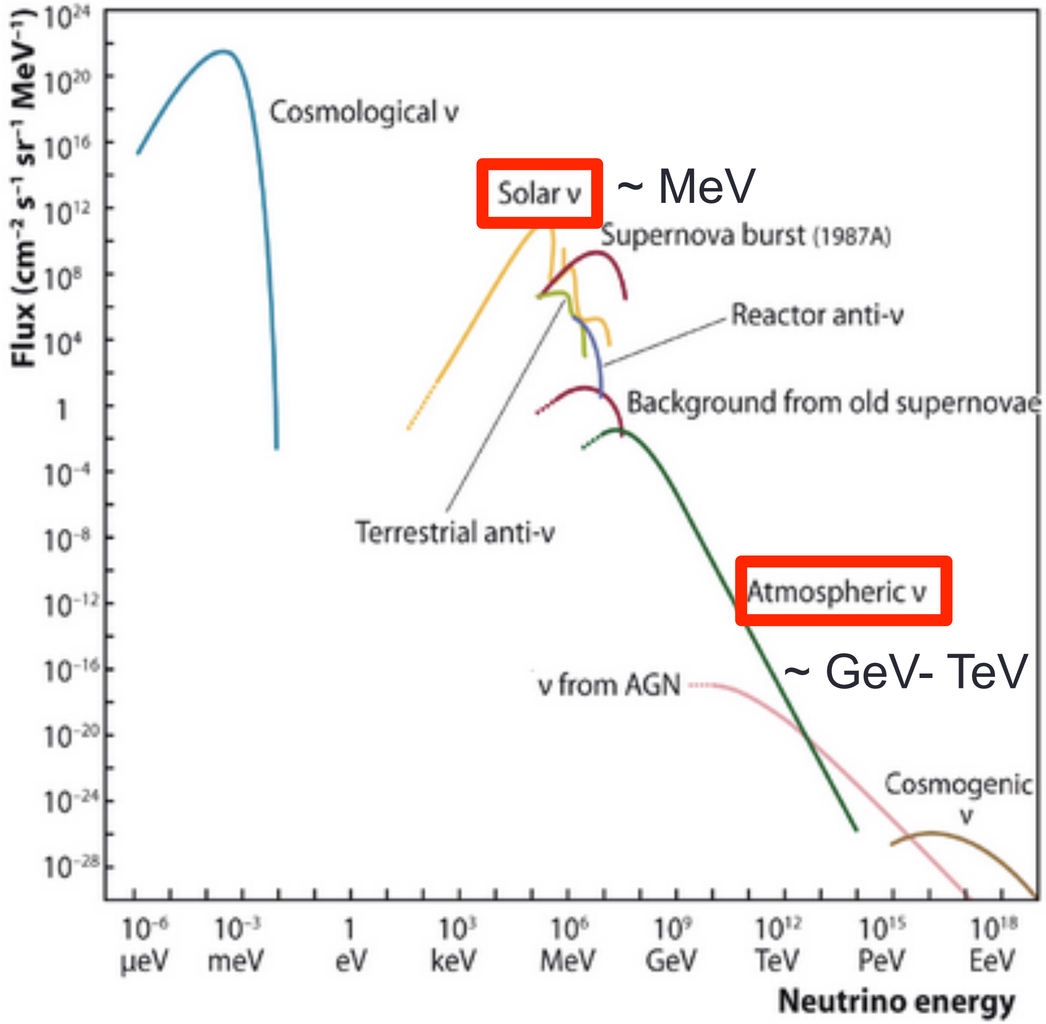
Atmospheric



Proton decay

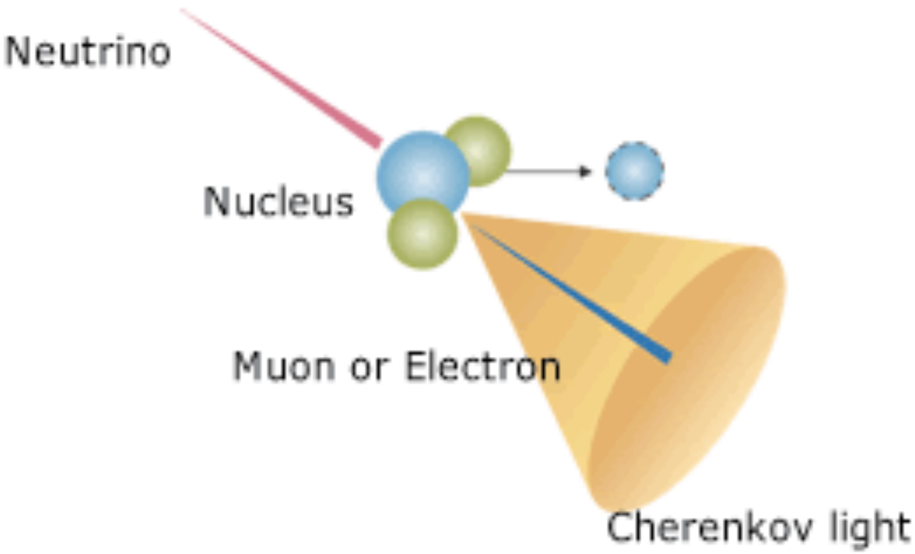


SK Physics Goals

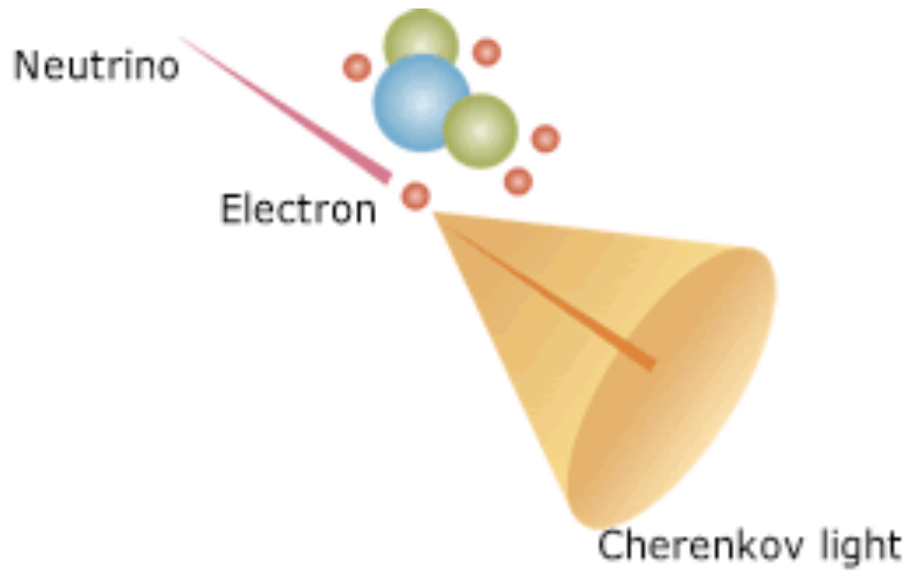


Detecting Neutrinos in SK

Atmospheric Neutrinos

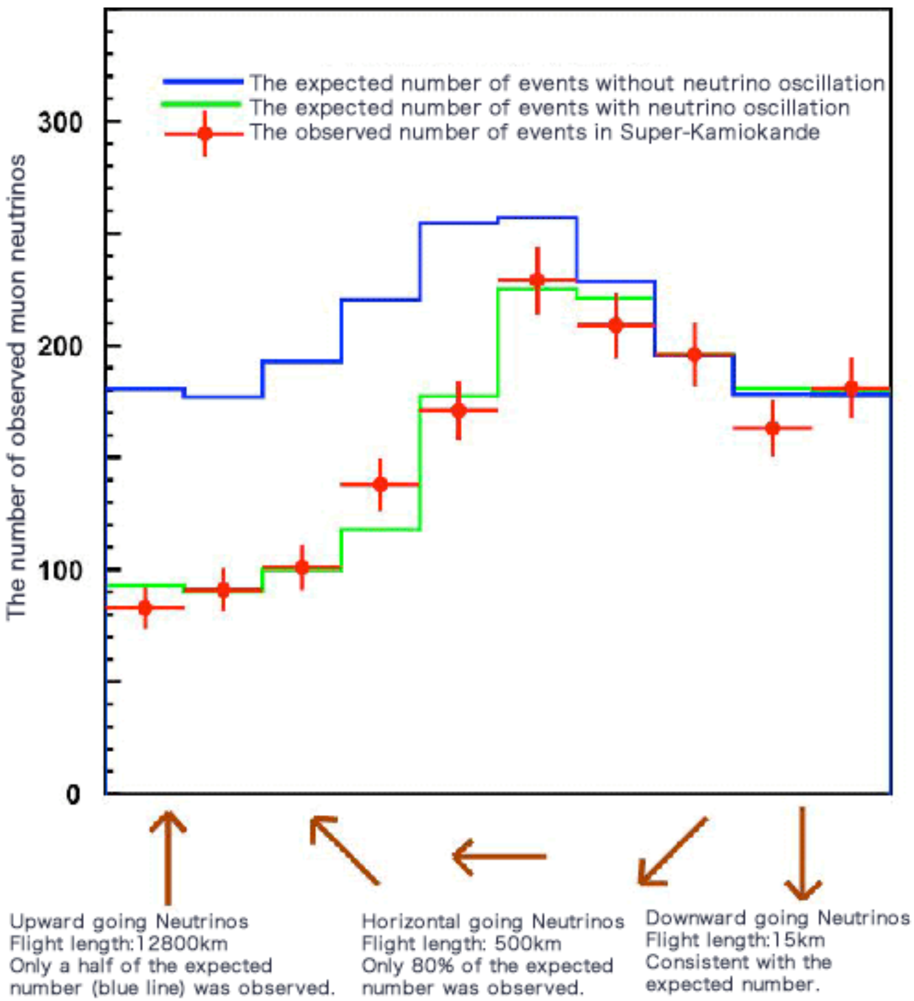


Solar Neutrinos



The generated charged particle emits the Cherenkov light.

Neutrino oscillations discovered in SK



1998: Super-Kamiokande publishes a paper (Phys. Rev. Lett. 81 (1998) 1562-1567) that showed:

- the atmospheric neutrino **ratio of ν_μ to ν_e is less than expected**
- the discrepancy was **dependent on neutrino path length** (neutrinos entering the bottom of the detector vs. the top of the detector)
- that the missing neutrinos were muon type neutrinos

The paper concluded that the behaviour fit all the hallmarks of neutrino oscillation and they calculated a best fit value for $\nu_\mu \rightarrow \nu_\tau$ mixing parameters

Measuring neutrino parameters using different neutrino sources

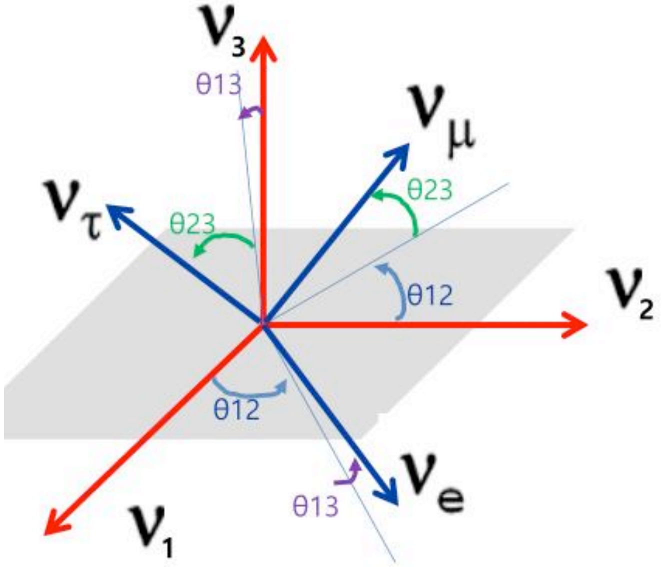
Δm^2_{21}: reactor, **solar**

Δm^2_{32}: accelerator, **atmospheric**

θ_{12}: **solar**, reactor

θ_{23}: accelerator, reactor, **atmospheric**

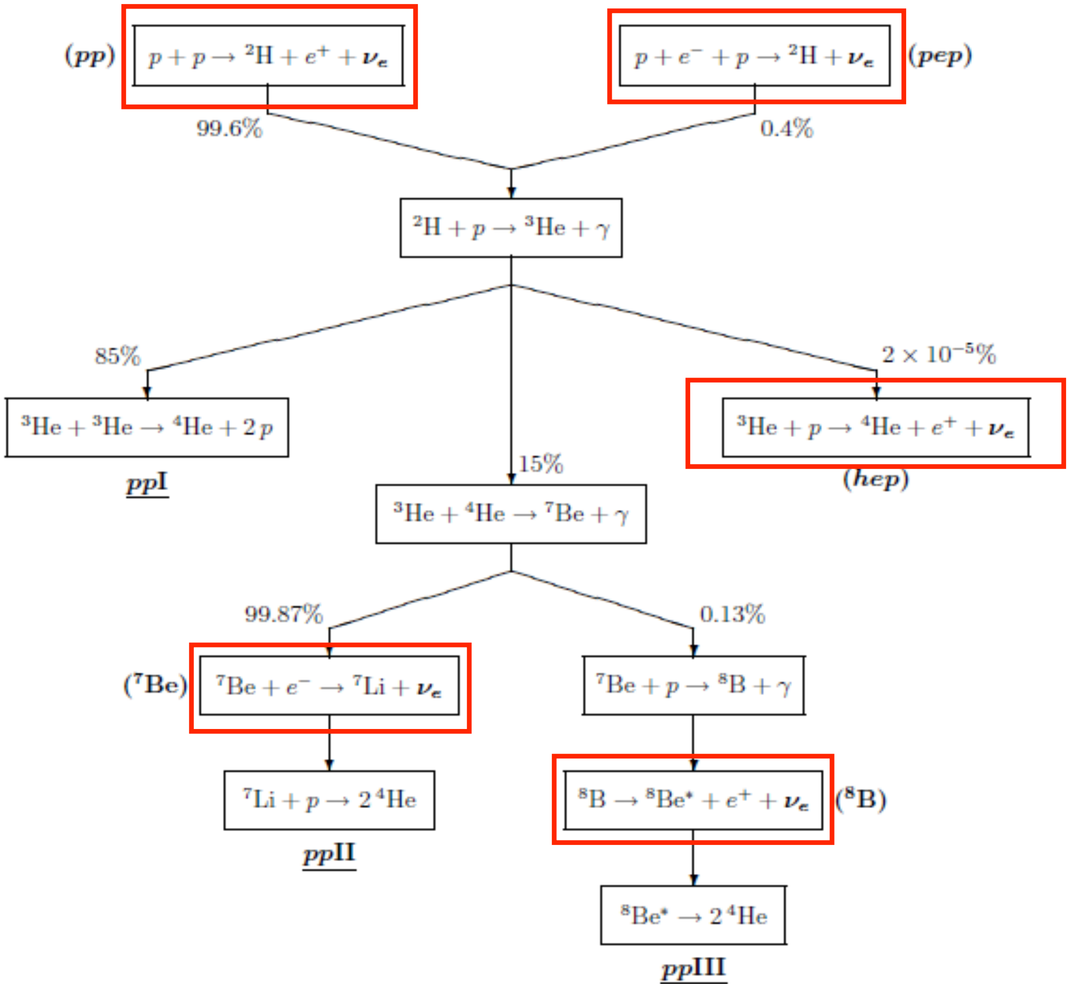
θ_{13}: reactor, accelerator, **(solar)**

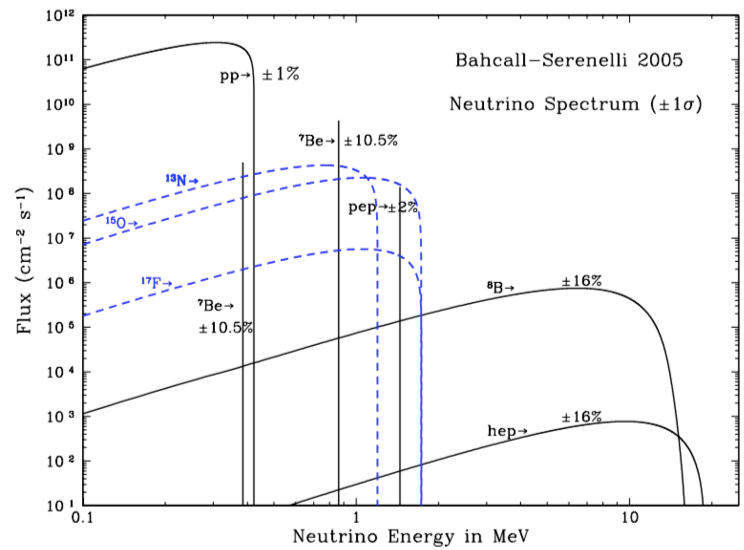


Solar and atmospheric neutrino measurements contribute (at least in some way) to many of the mixing parameters. Often they give complementary measurements.

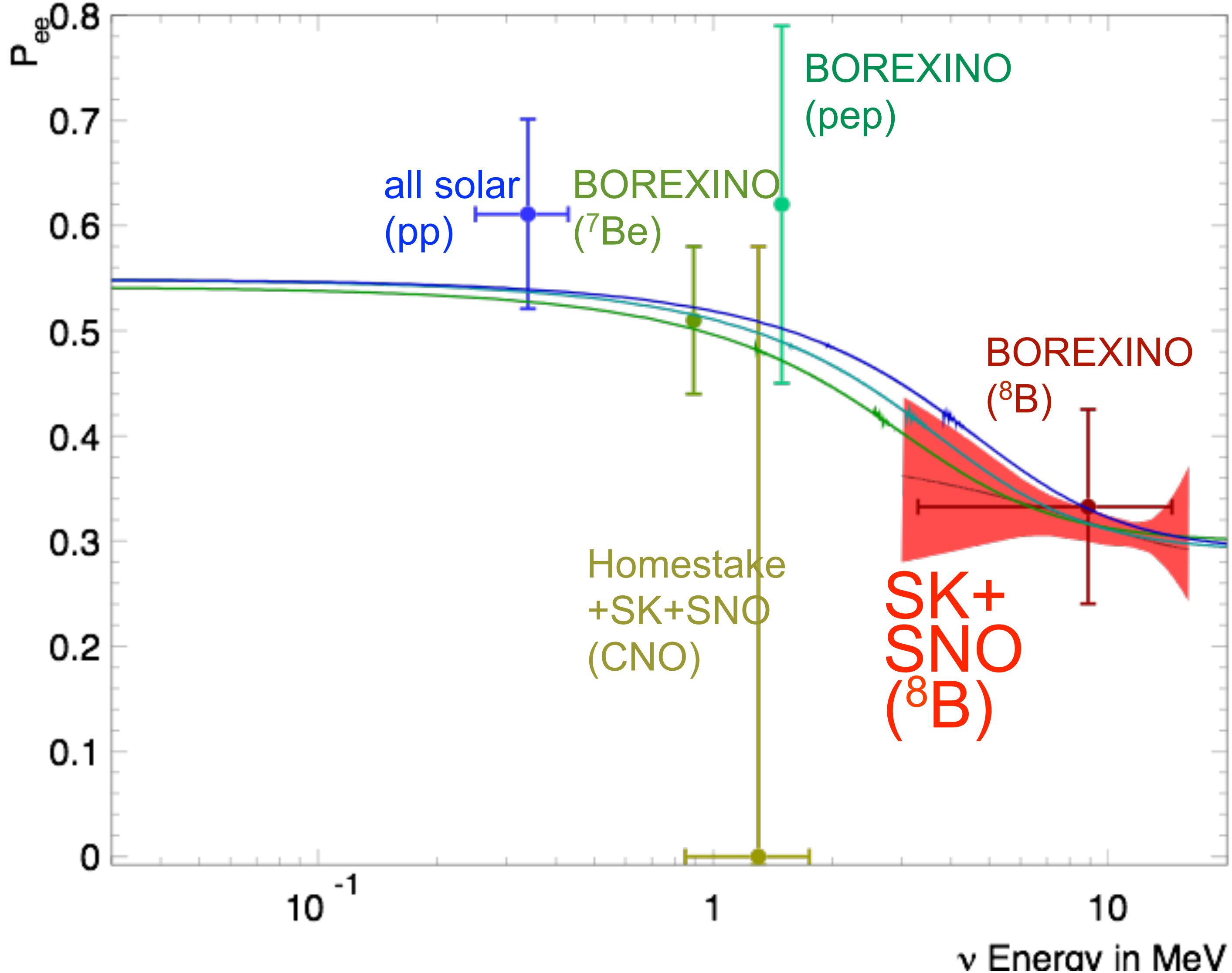
Solar Neutrinos

Mainly created in the pp chain (secondary process – the CNO cycle)

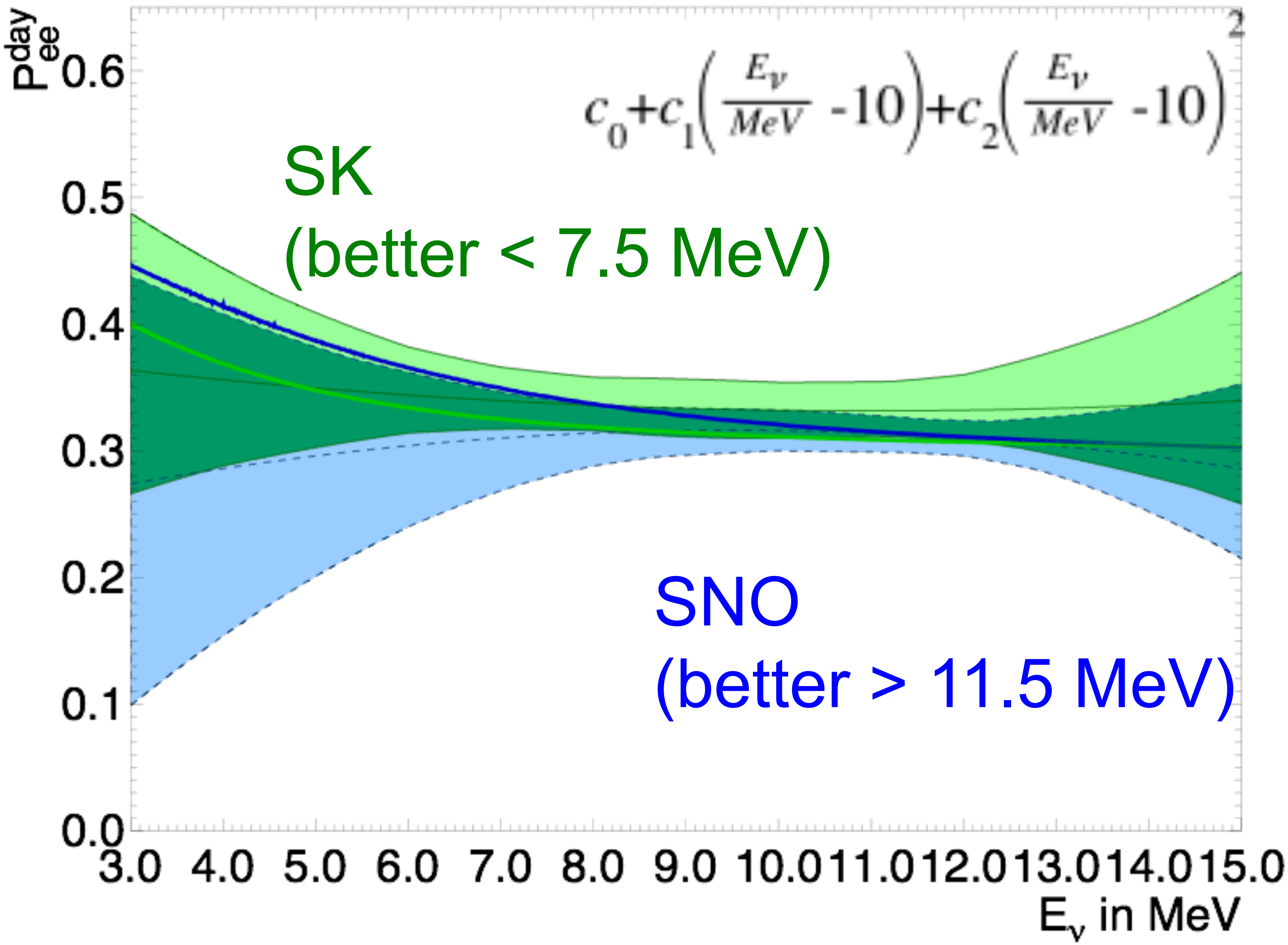




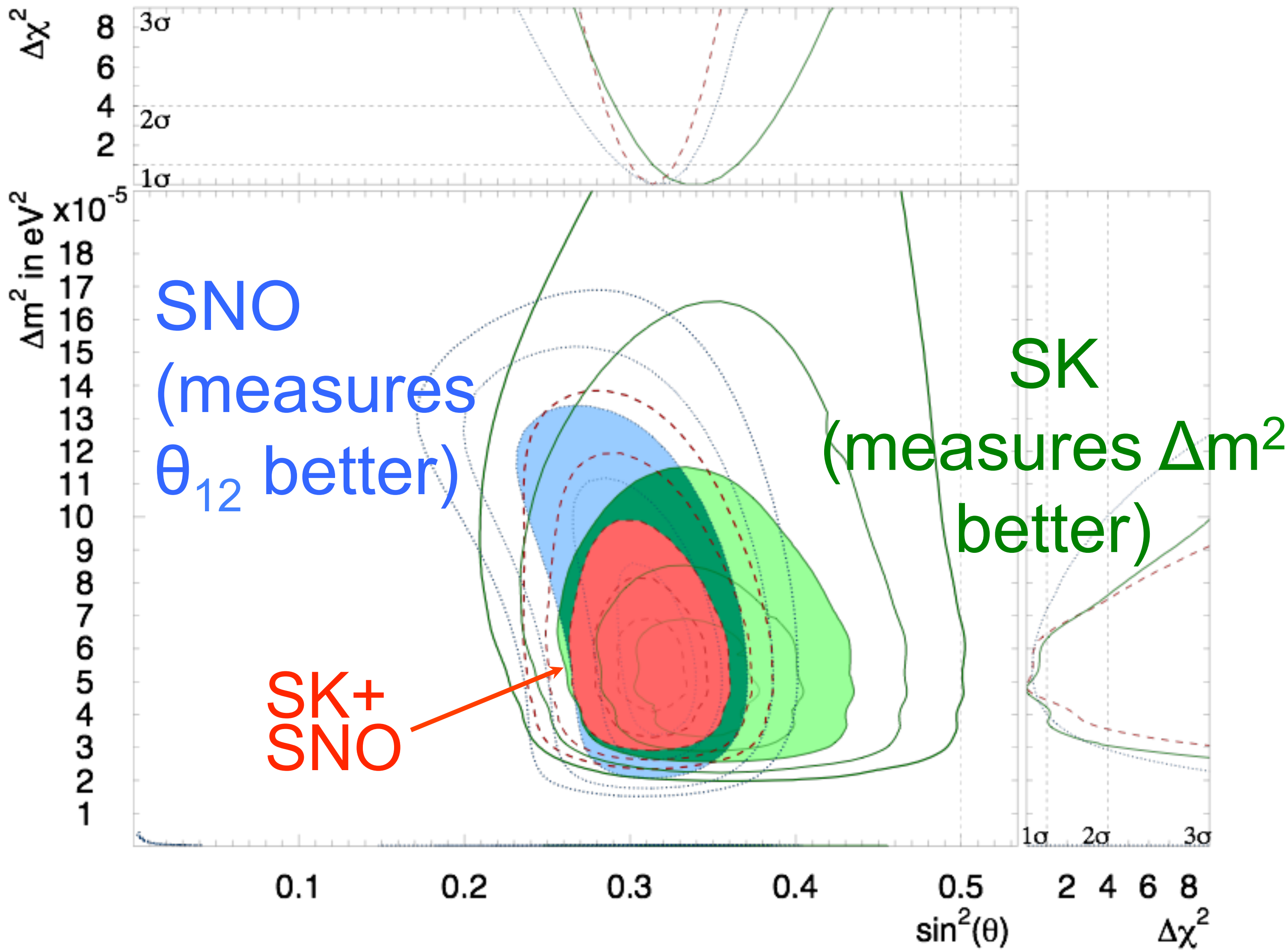
SK: Measuring ^{8}B neutrinos



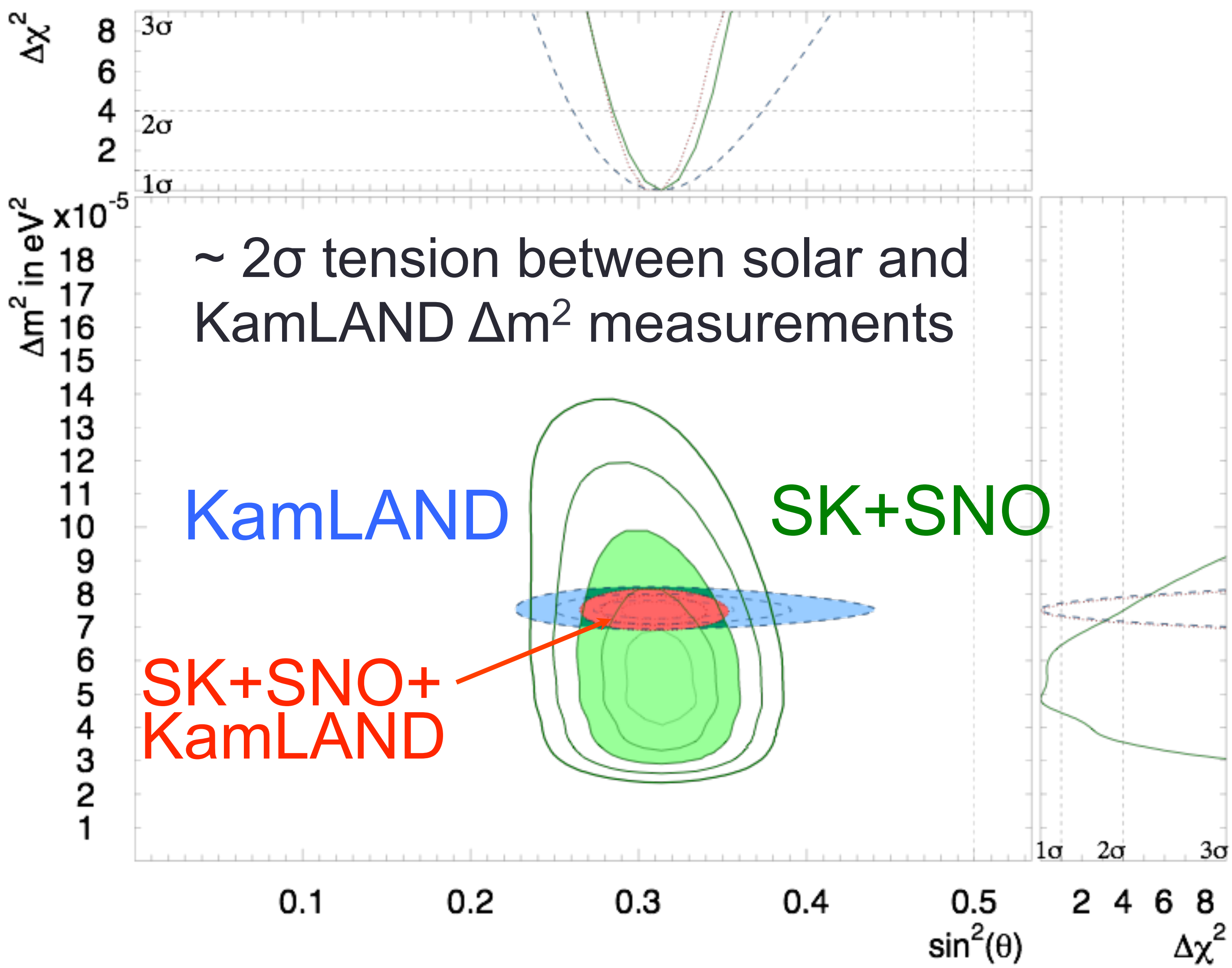
Solar Oscillation Measurements



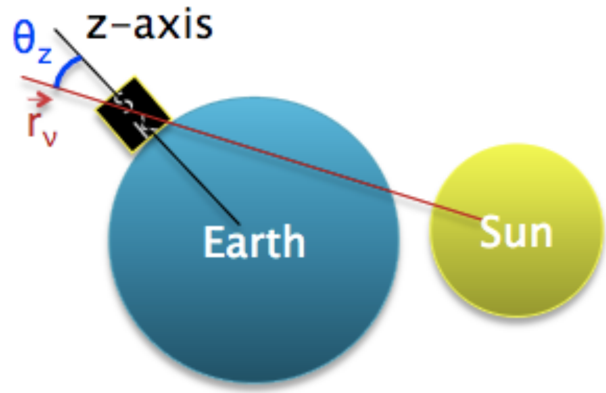
Solar Oscillation Measurements

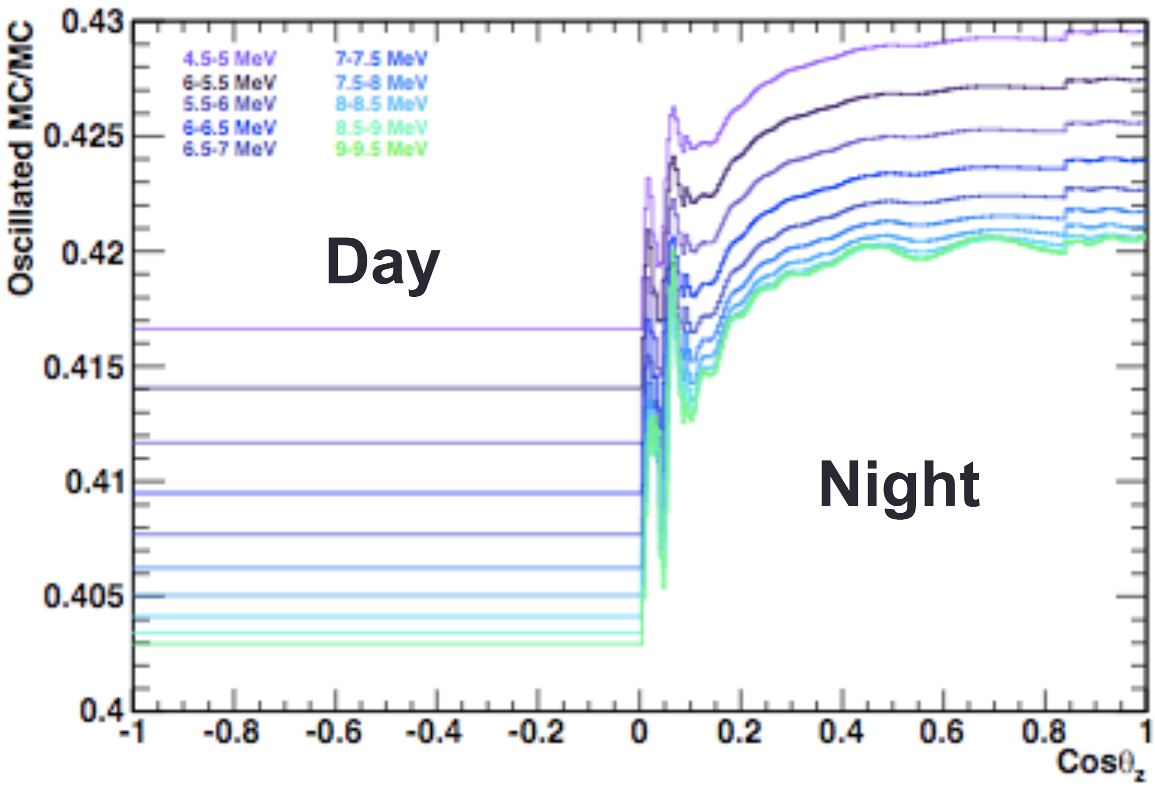


Solar Oscillation Measurements



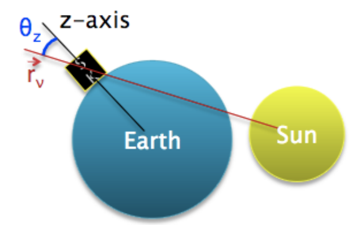
Day/Night Effect

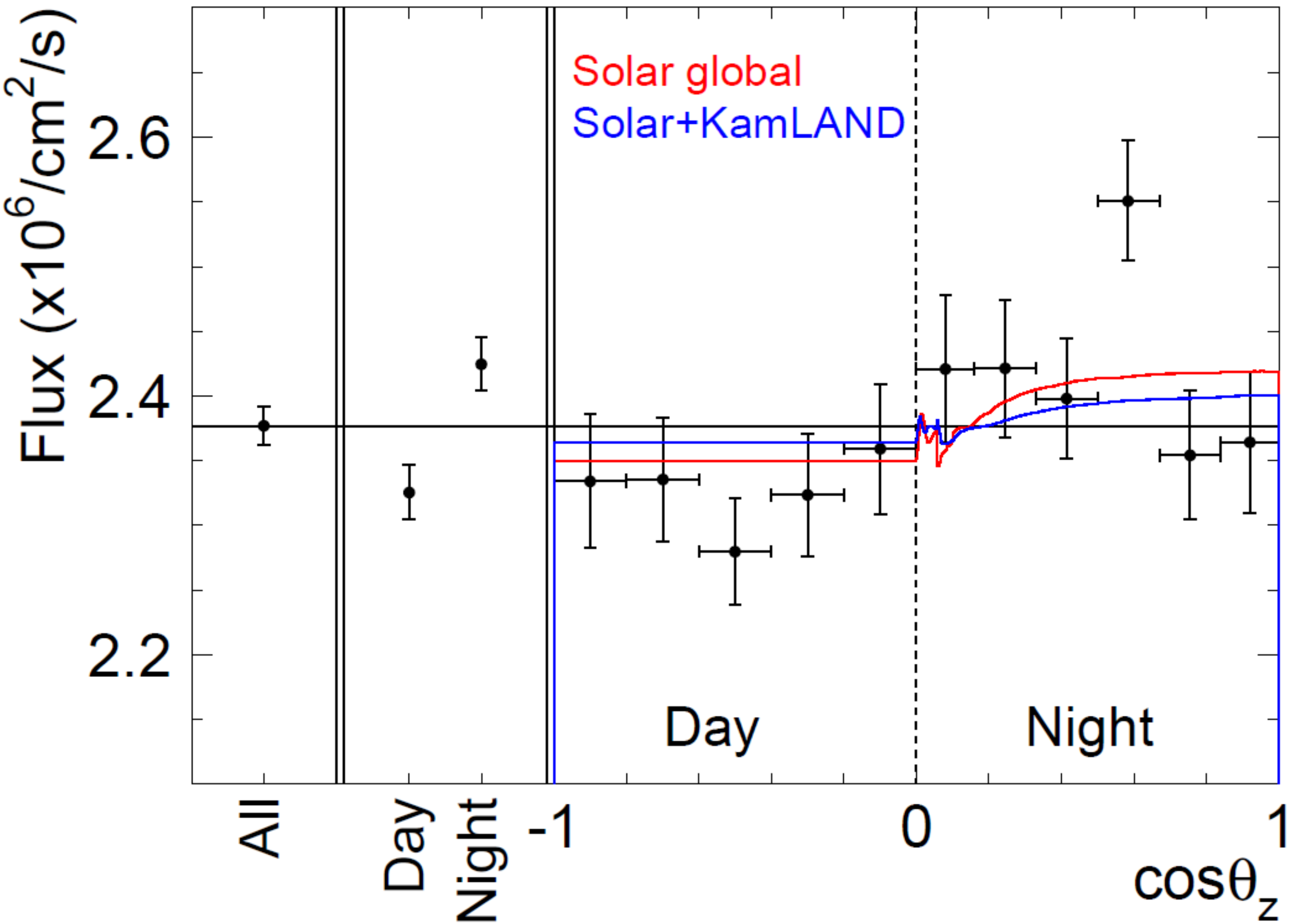




Electron neutrinos are regenerated as they pass through the Earth

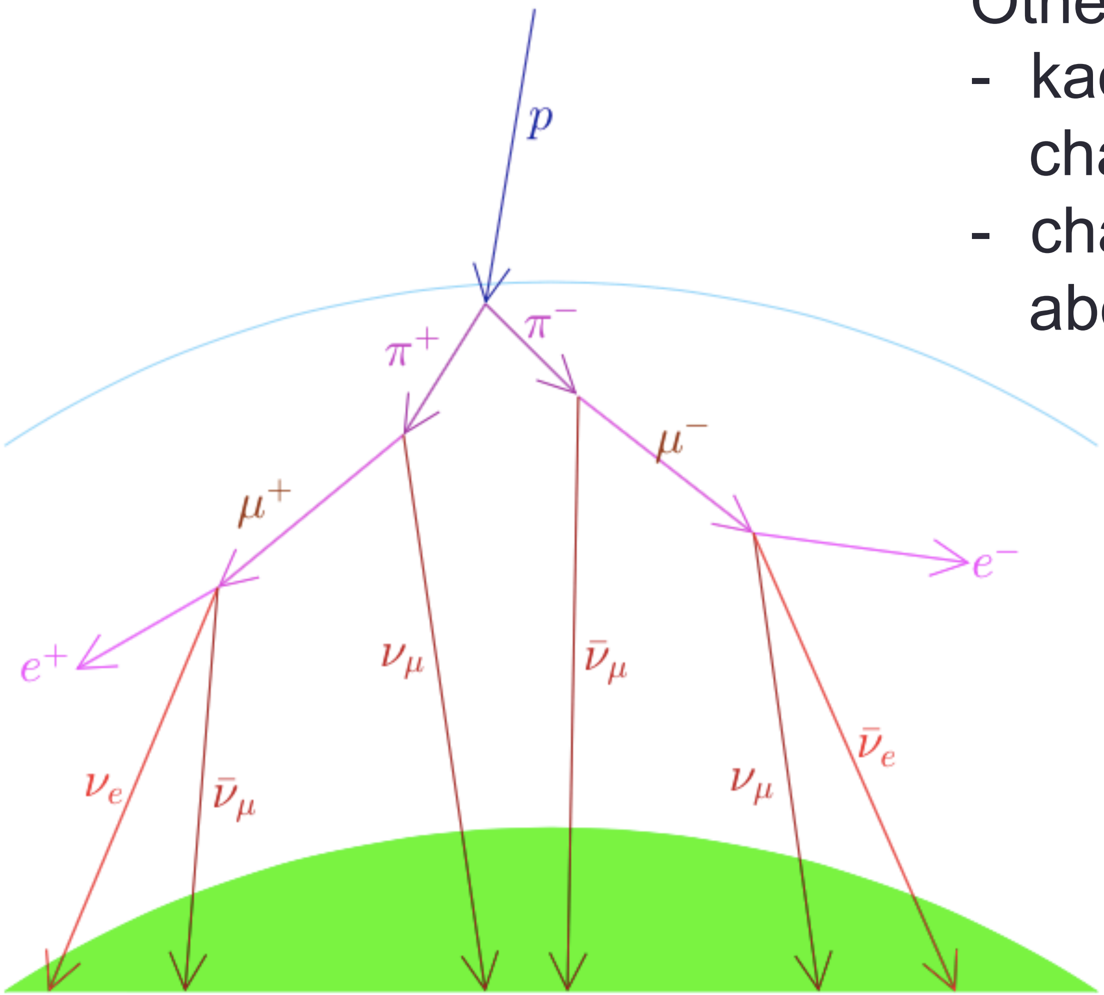
Day/Night Effect Results





Measured a 2.7-2.8 σ effect using all SK phases (PRL 112 (2014) 9, 091805, arXiv: 1312.5176)

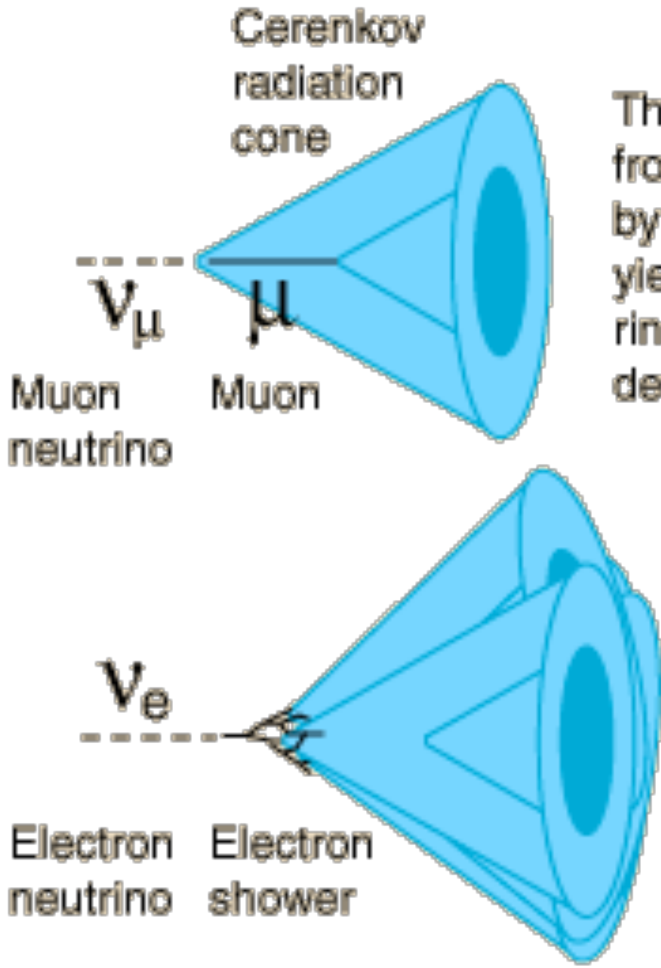
Atmospheric Neutrinos



Other channels possible:

- kaons (similar to pion channel)
- charm decay (significant above ~100 TeV)

Particle ID for Atmospheric Neutrinos

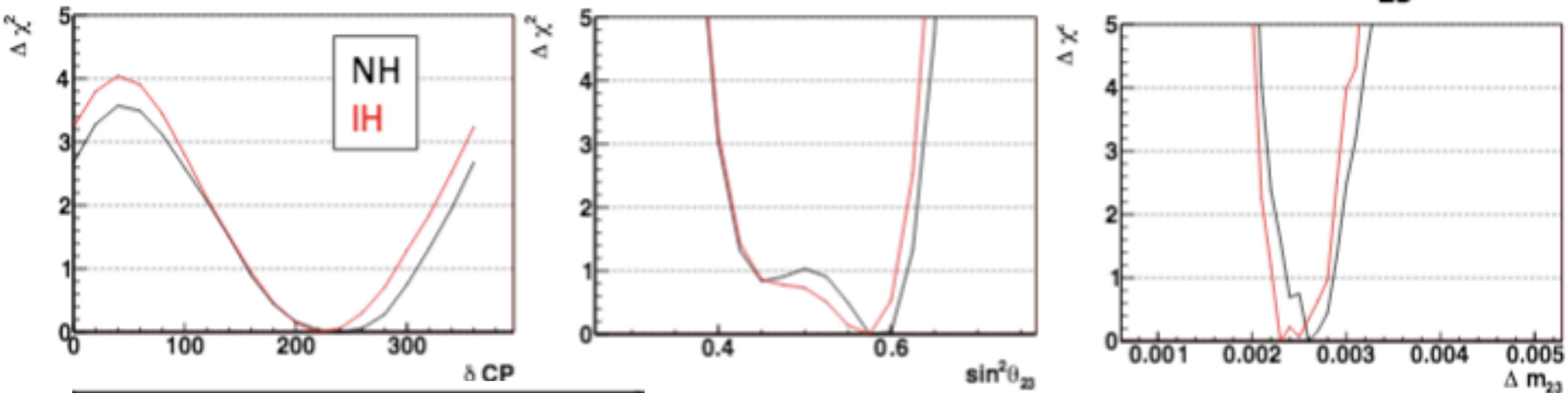


The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.

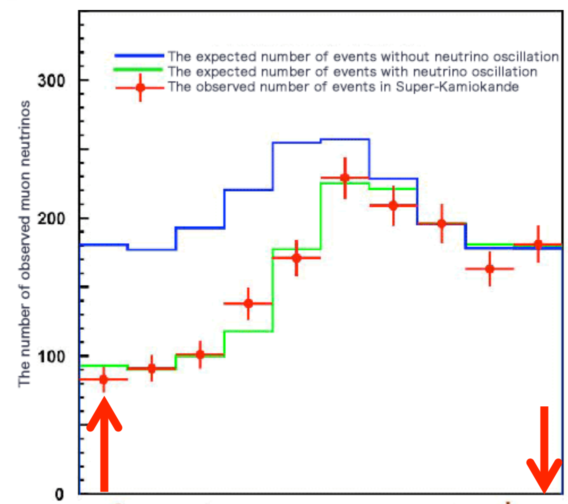
SK Atmospheric Oscillation Results

δCP | $\sin\theta_{23}$ | Δm^2_{23}

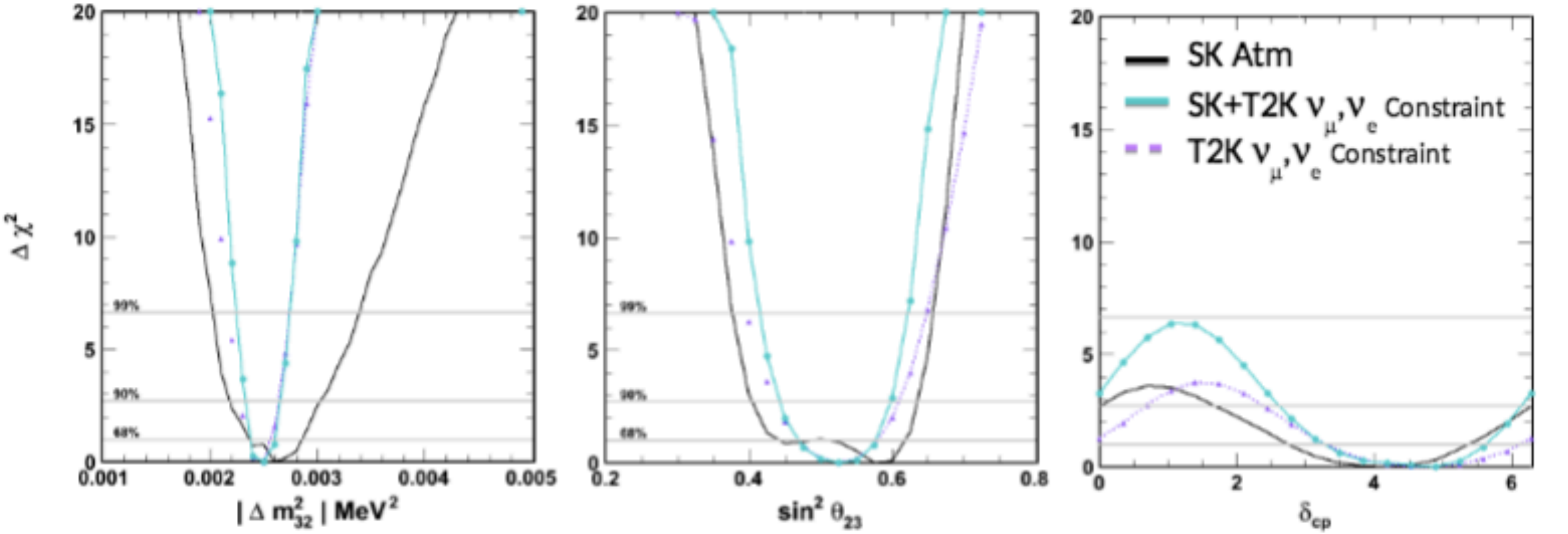


NH		
δCP	$\sin^2\theta_{23}$	Δm^2_{23}
240	0.575	0.0026

IH		
δCP	$\sin^2\theta_{23}$	Δm^2_{23}
220	0.575	0.0023



SK Atmospheric Oscillation Results



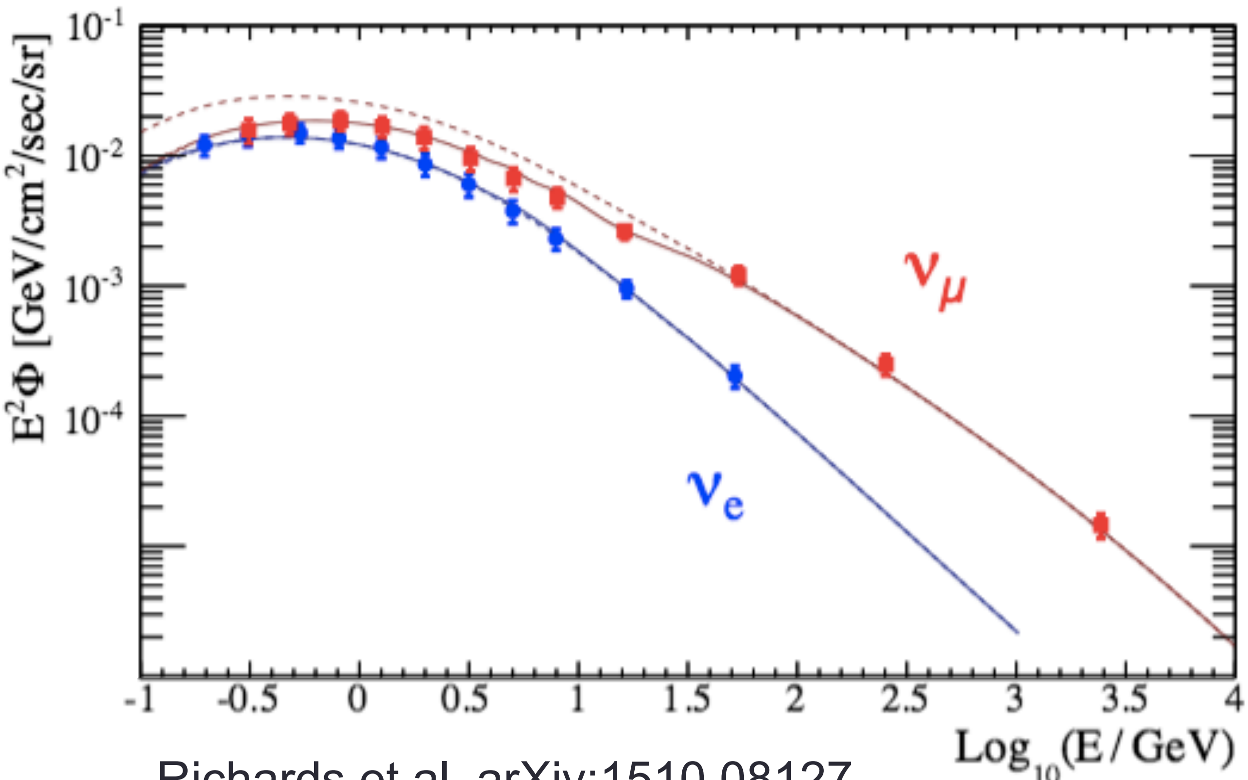
Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} ($\times10^{-3}$)
SK+T2K (NH)	651.53	0.0238	4.887	0.525	2.5
SK+T2K (IH)	654.73	0.0238	4.189	0.550	2.4

- $\chi^2_{NH} - \chi^2_{IH}$ = **-3.2** (**SK Only -3.0**)

Results slightly favour the NH

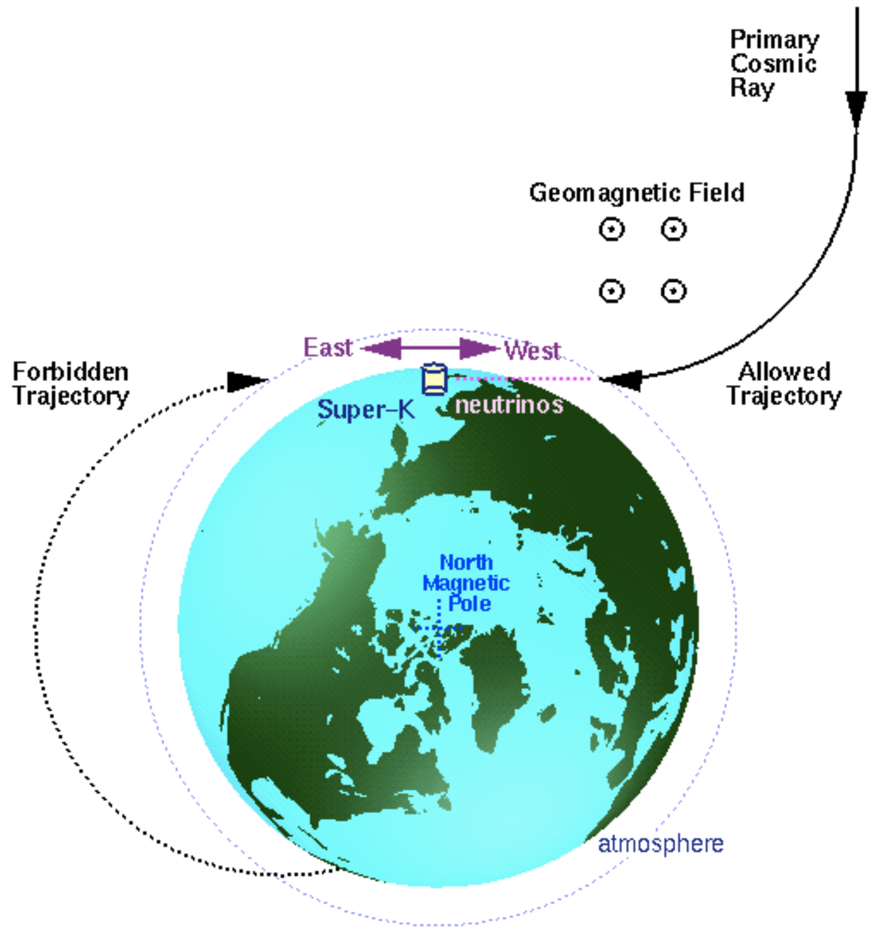
Updated Atmospheric Flux Measurements

New SK results: fluxes from 100 MeV to 10 TeV



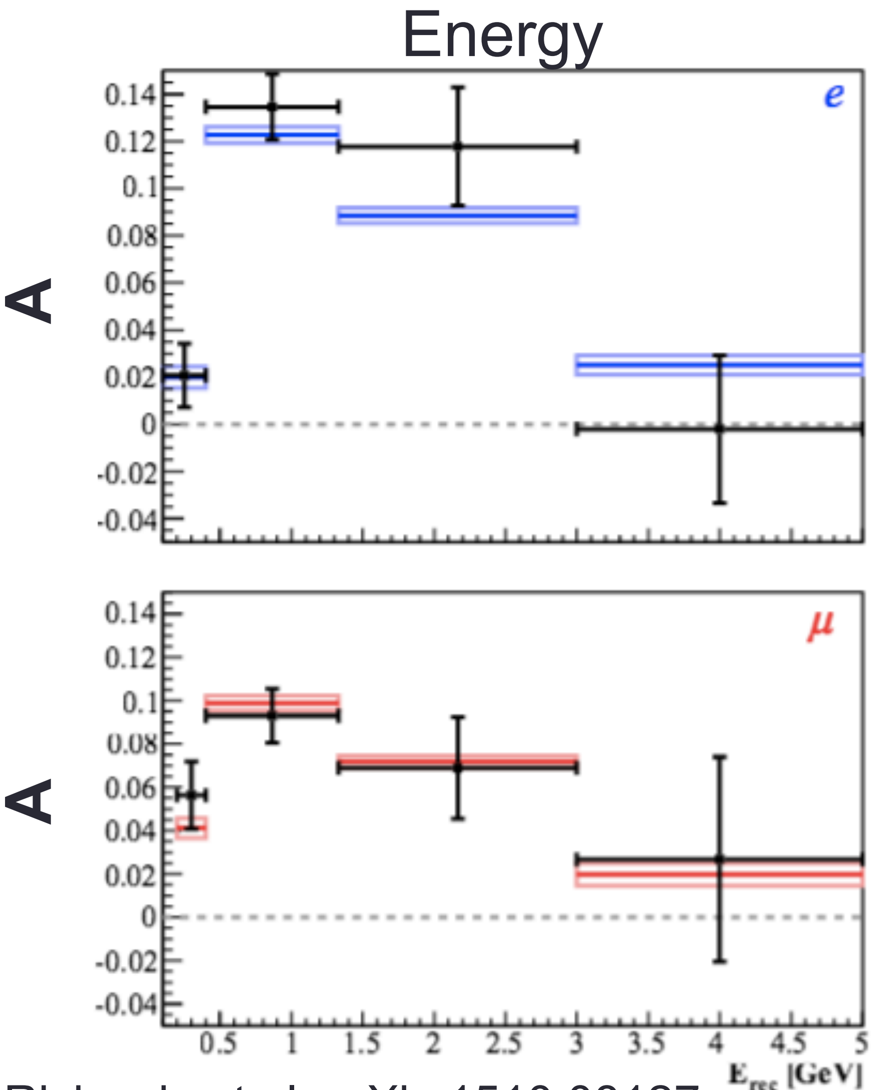
Richards et al. arXiv:1510.08127

East-West Effect



Due to asymmetric deflection of cosmic rays, more neutrinos coming from west than east

East-West Effect



Significance: 6.0 σ for ν_μ and 8.0 σ for ν_e

$$A = \frac{n_{\text{east}} - n_{\text{west}}}{n_{\text{east}} + n_{\text{west}}}$$

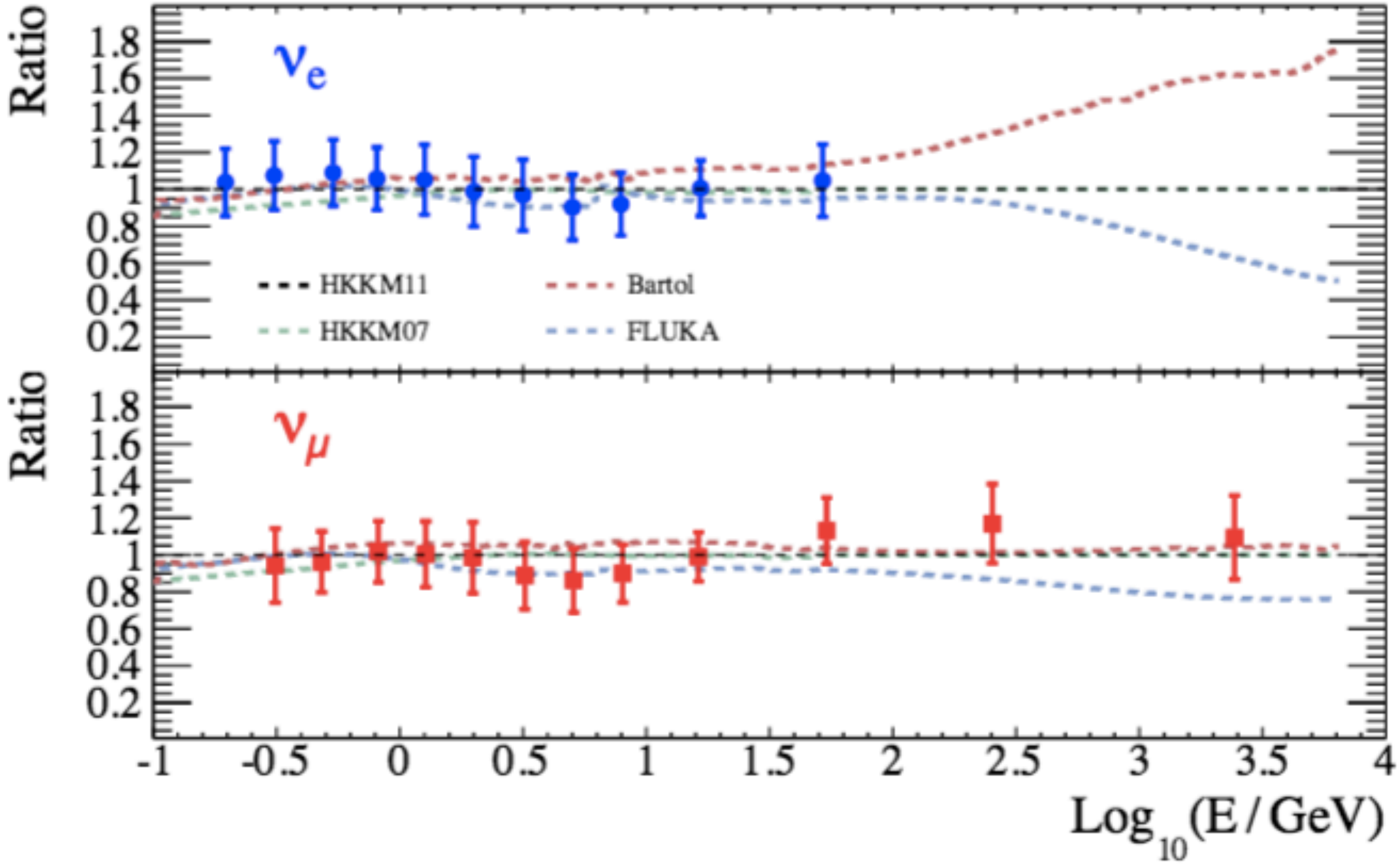
Richards et al. arXiv:1510.08127

Conclusions

- Super-Kamiokande has been measuring solar and atmospheric neutrinos for over 20 years
- Solar and atmospheric neutrino measurements have contributed to our understanding of neutrinos oscillation parameters
- Neutrino measurements can also be used to probe for interesting effects, such as the day-night effect (solar) or the east-west effect (atmospheric)

Comparison of model predictions to new flux data

Richards et al. arXiv:1510.08127



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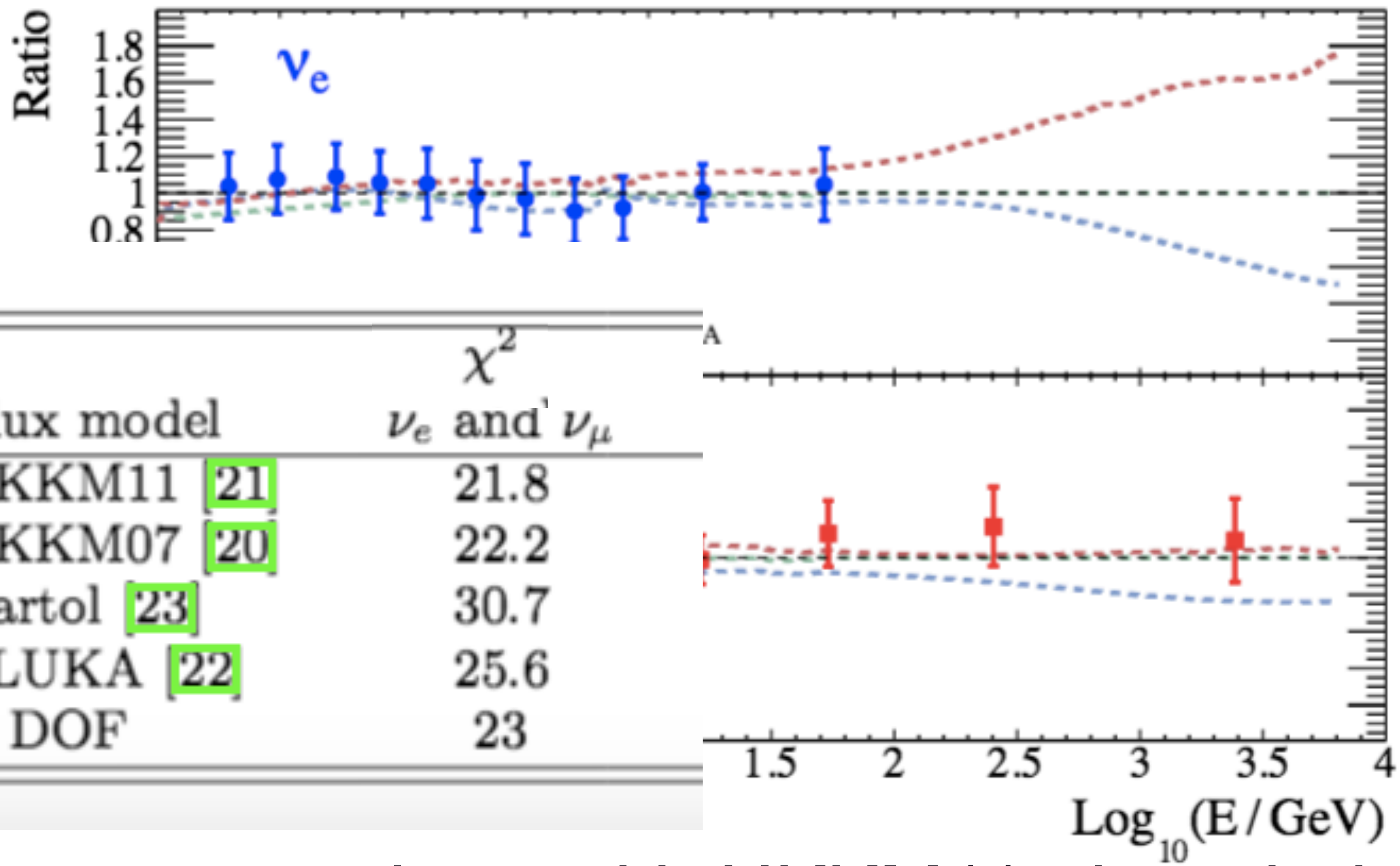
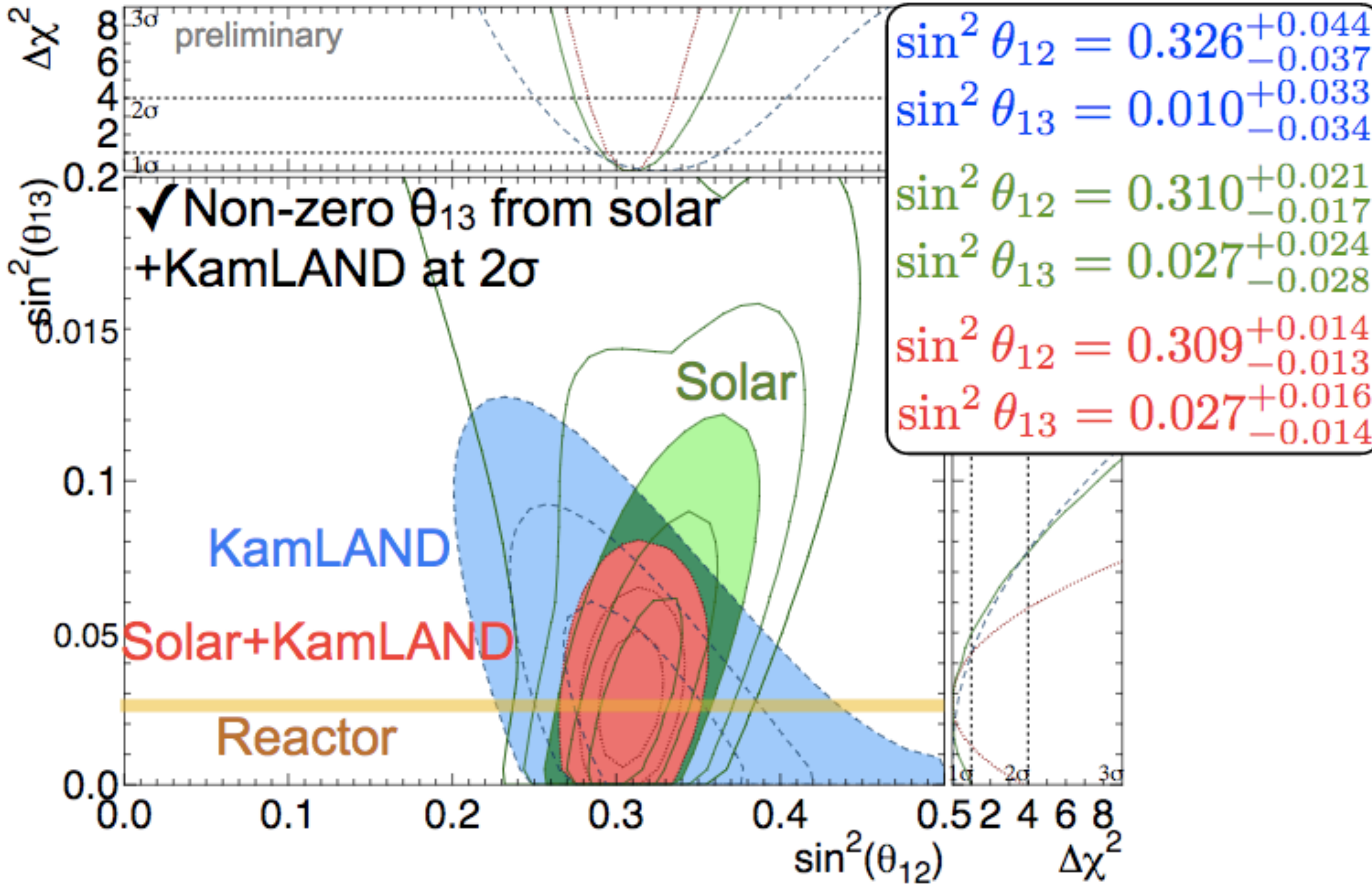


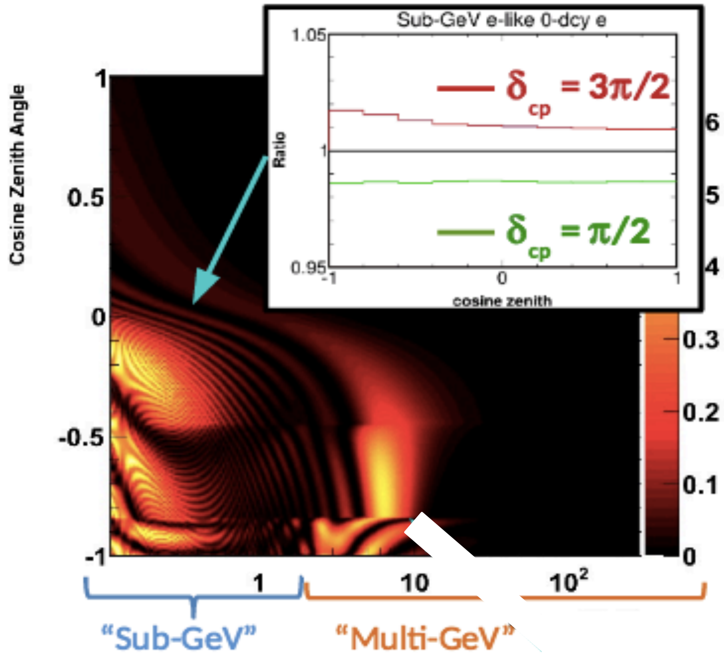
Flux model	χ^2 ν_e and ν_μ
HKKM11 [21]	21.8
HKKM07 [20]	22.2
Bartol [23]	30.7
FLUKA [22]	25.6
(DOF	23

Data agrees best with HKKM11, though the agreement is generally good for all models.

Without reactor θ_{13} constraint



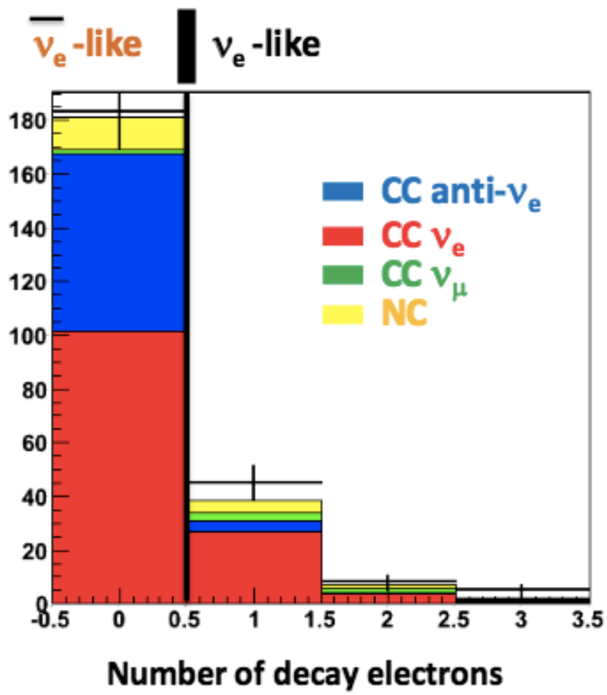
Determining CPV in SK with atmospheric neutrinos



CP violation in atmospheric neutrinos appears as a modulation of low energy electron-like events (mostly for low energy ~400MeV).

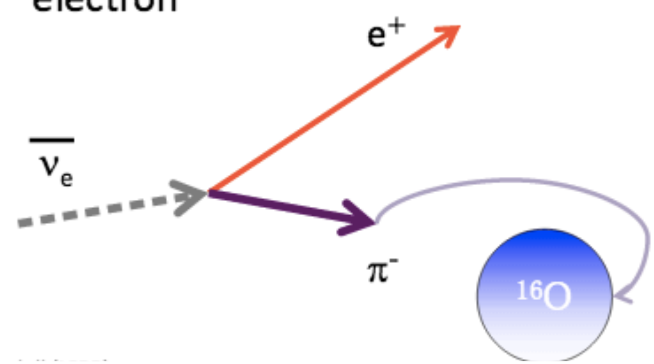
Neutrinos and antineutrinos in SK

Sample Selection : Multi-GeV Single-Ring anti-ν_e and ν_e -like



(Multi-ring events are in general more complicated separation is done using a likelihood)

- Separate neutrinos from anti-neutrinos in the single-ring sample using the number of observed decay electrons
- The outgoing π^- from an anti-neutrino CC-1 π event can be absorbed on a ^{16}O nuclei before it decays. The lack of an outgoing muon means there is no possibility of a subsequent Michel (decay) electron



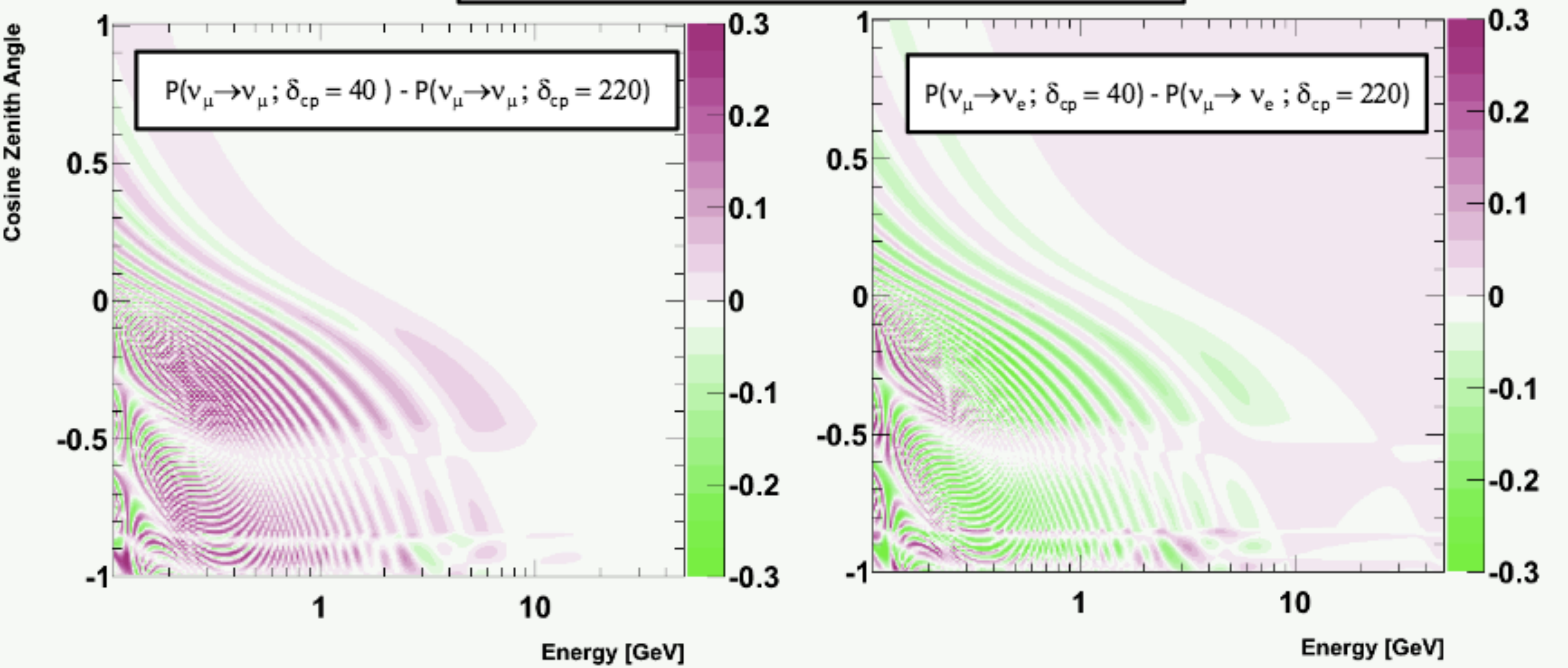
Roger Wendell NNN 2012

Determining mass hierarchy in SK with atmospheric neutrinos

Upward-going neutrinos with about 2-10 GeV of energy experience and enhanced numu->nue oscillation probability. The enhancement exists only for neutrinos if the hierarchy is normal, and only for antineutrinos if the hierarchy is inverted. We probe the hierarchy by looking for an increase in the upward-going event rate of high energy e-like samples.

δ_{cp} Preference : Oscillograms

P(40 degrees) - P(220 degrees)



δ_{cp} = 40 vs 220	$P(\nu_\mu \to \nu_\mu)$	$P(\nu_\mu \to \nu_e)$
E ~ Sub-GeV	Less disappearance	Less appearance
E ~ **Multi**-GeV	Less disappearance	Less appearance