Highlights from Super-Kamiokande

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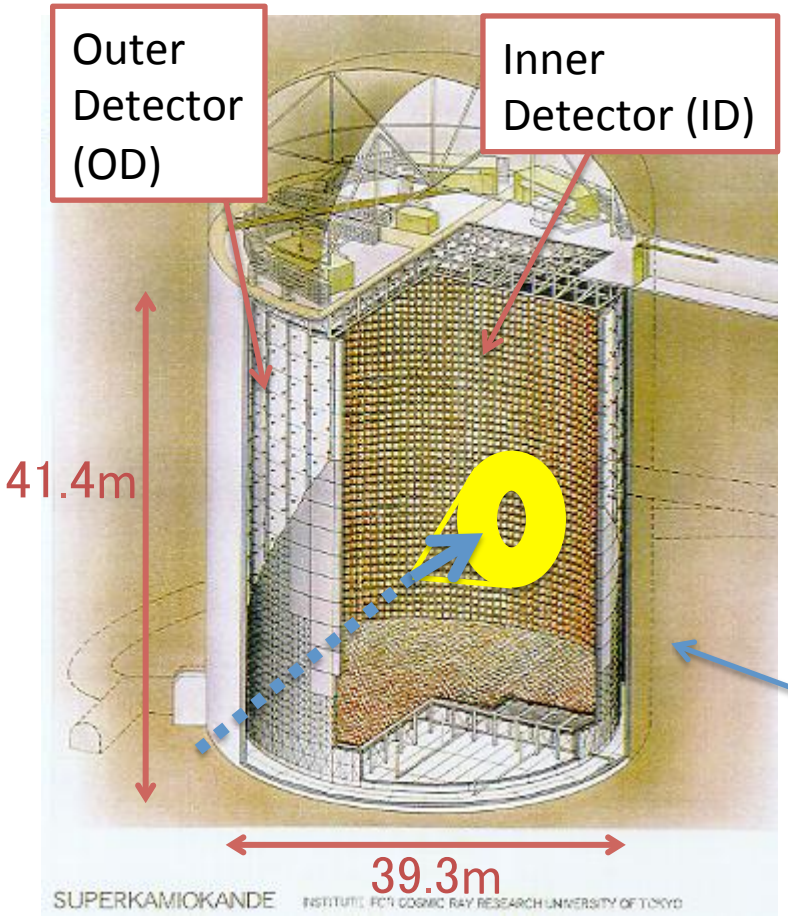
2014/8/2
ICNFP 2014 @ Crete, Greece

Super-Kamiokande detector

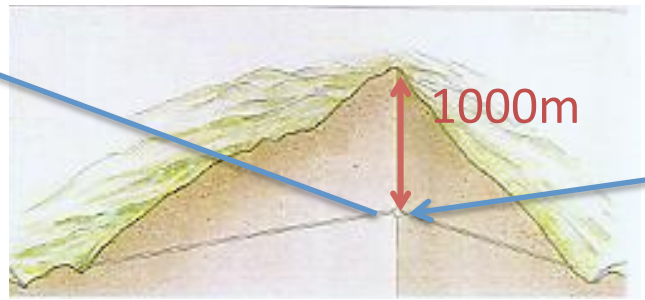


50,000ton water Cherenkov detector (22.5 kton fiducial mass)

11,129 20” PMTs for inner detector

1885 8” PMTs for outer detector

1000m underground (2700 m water equivalent)



’96	’97	’98	’99	’00	’01	’02	’03	’04	’05	’06	’07	’08	’09	’10	’11	’12	’13	‘14
SK-I							SK-II				SK-III		SK-IV					

Original configuration

half # of ID PMTs

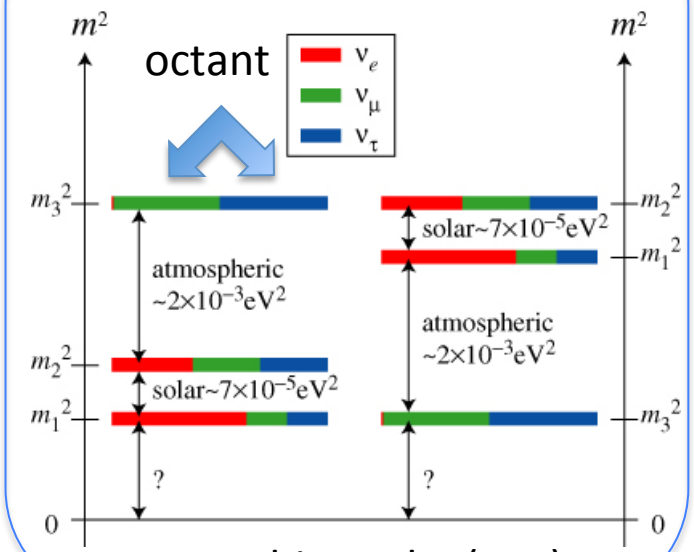
Full recovery of ID PMTs

Electronics/DAQ upgraded

Physics at Super-K

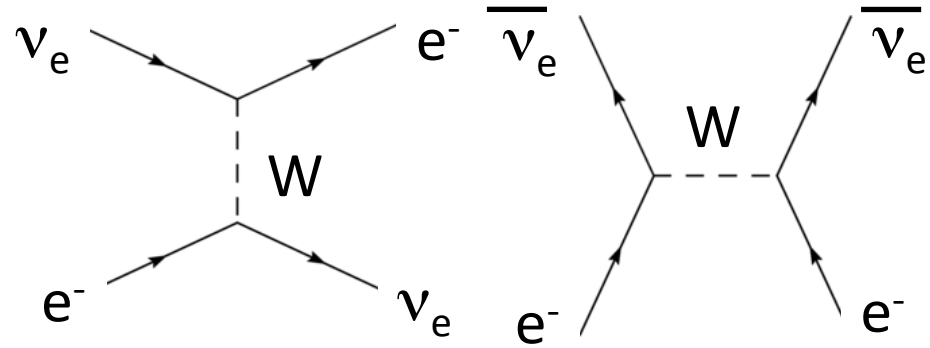
- Neutrino Physics
  - Massive neutrinos beyond the SM
  - Δm^2_{ij} & θ_{ij} measured/acc. improved
  - MH, θ_{23} oct. ($\gtrless\pi/2$), and $\not{CP}$ (atm. ν)
  - Matter effects (solar ν)
  - τ appearance
  - sterile, exotics…
- Search for proton decay
  - General prediction of GUT
- Astrophysical objects
  - Supernova physics
  - Dark matter annihilation

S. F. King and C. Luhn, Rep. Prog. Phys. 76 056201 (2013)



Mass hierarchy (MH)

Effect of electron in the Earth

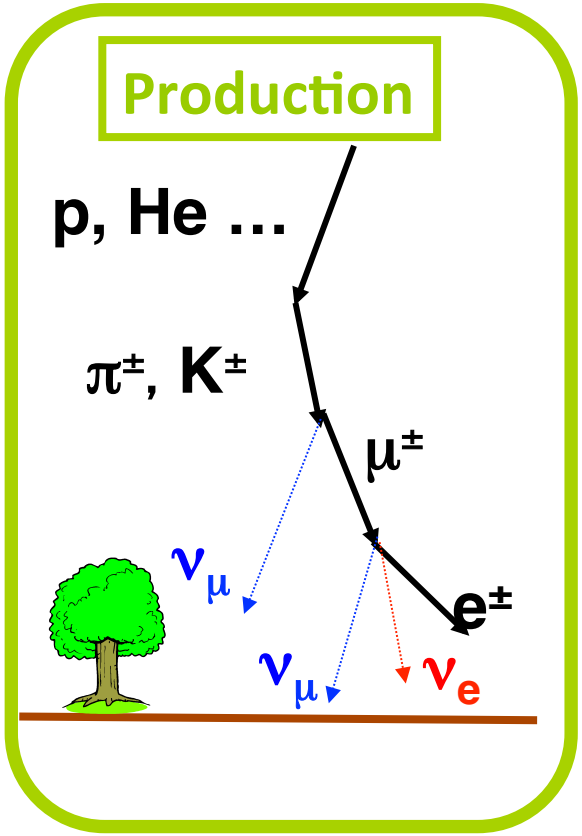


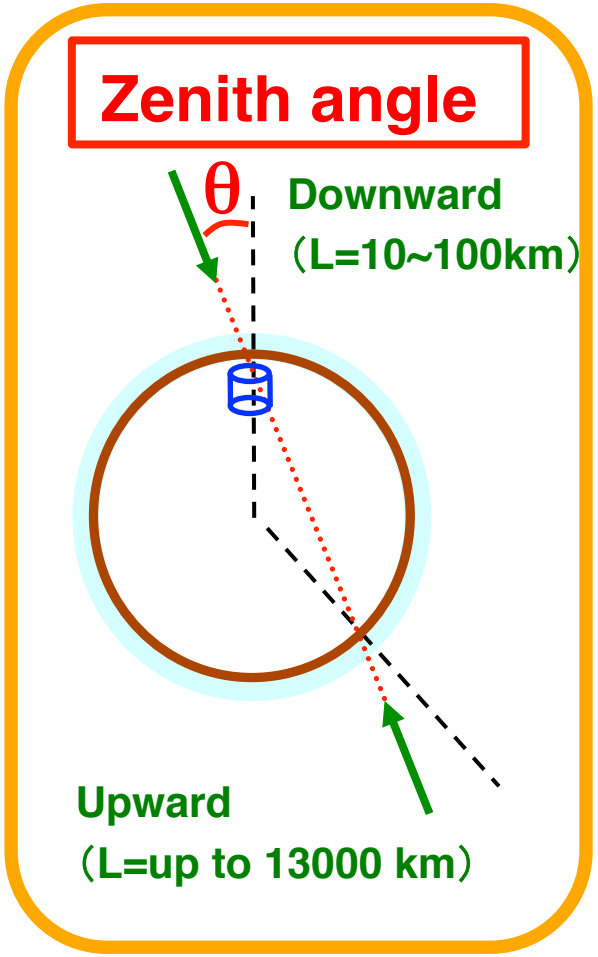
NC is common for all $\overset{(-)}{\nu}_e$ $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_\tau$

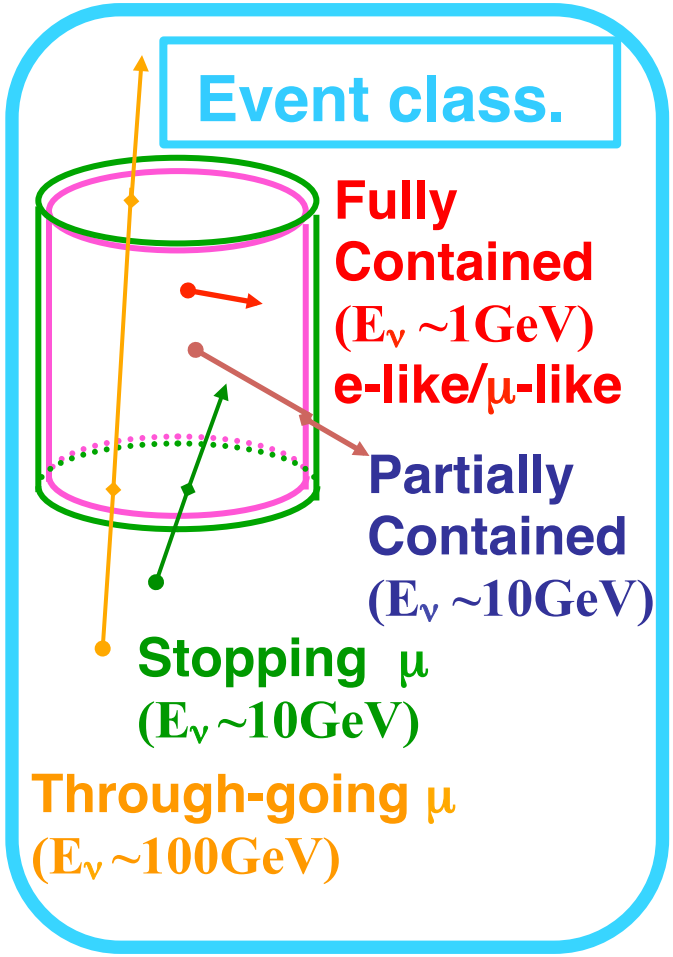
$P(\nu_a \rightarrow \nu_b) \mathrel{!=} P(\bar{\nu}_a \rightarrow \bar{\nu}_b)$

CP phase $\delta \mathrel{!=} 0, \pi$

Atmospheric neutrinos:
π, K decay → nuclear interactions







Wide range of L and E enables us to study neutrino oscillations.

Mass hierarchy, $\theta_{23} \gtrless \pi/2$, and ~~CP~~

- MH: utilize resonance effect in $\nu_\mu \Leftrightarrow \nu_e$ (driven by θ_{13})
  - presence of e^- (no e^+) in the Earth: $V = \pm\sqrt{2}G_F n_e$ +(-) for $\nu_e(\bar{\nu}_e)$

$$i\partial_x \Psi(x) = \frac{\Delta m^2}{4E}\begin{pmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{pmatrix}\Psi(x) + \begin{pmatrix} \frac{V}{2} & 0 \\ 0 & -\frac{V}{2} \end{pmatrix}\Psi(x) = \frac{\Delta M^2}{4E}\begin{pmatrix} \cos 2\theta_M & \sin 2\theta_M \\ -\sin 2\theta_M & \cos 2\theta_M \end{pmatrix}\Psi(x)$$

  - ν_e ($\bar{\nu}_e$) undergoes resonance only for normal (inverted) hierarchy @2-10GeV

- θ_{23} octant: Strength of the resonance

$$P(\nu_\mu \leftrightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}^M \sin^2\left(\frac{1.27\Delta m_M^2 L}{E}\right).$$

- CP violation: interference term btw Δm^2_{12} & Δm^2_{23}

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2\theta_{23} - 1) - r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$
$$+2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1)$$

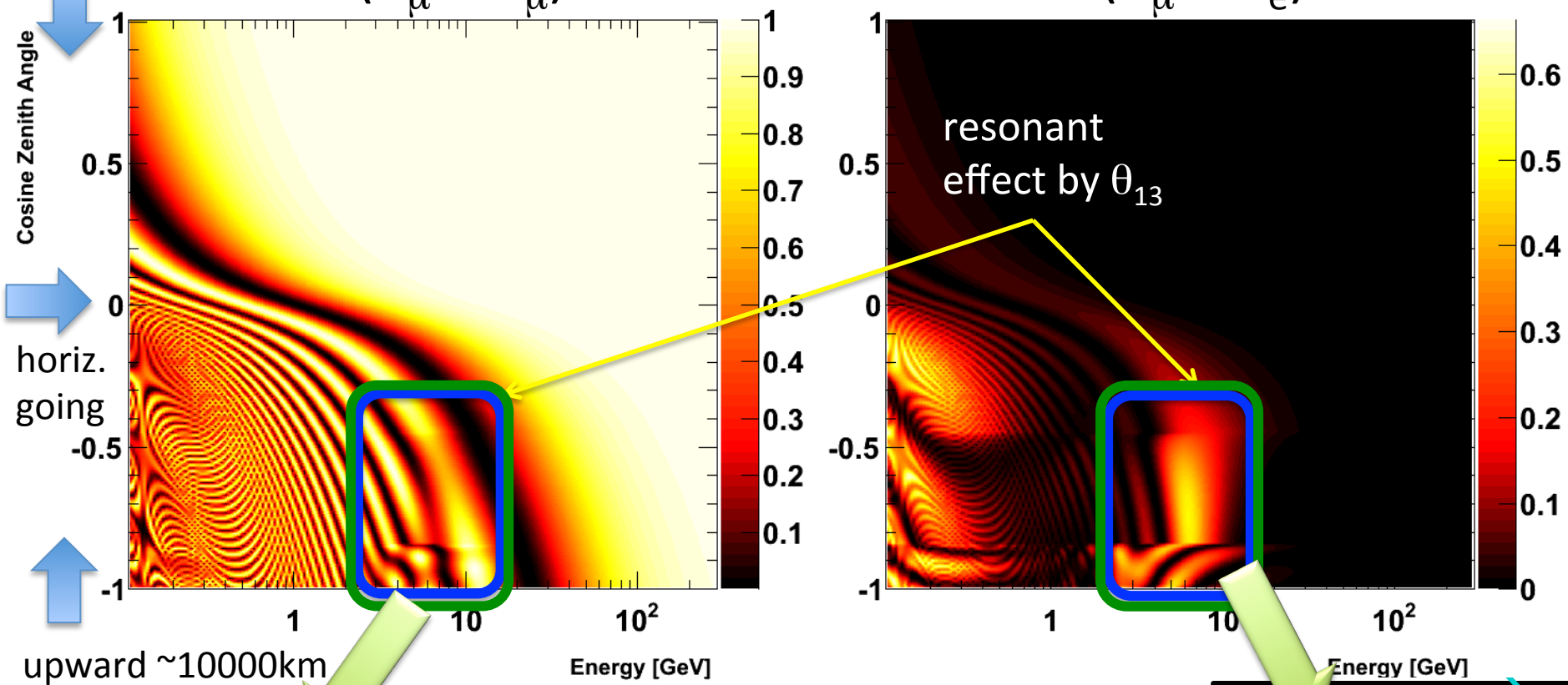
Signatures in the three flavor oscillation

downward~1000km

$P(\nu_\mu \rightarrow \nu_\mu)$

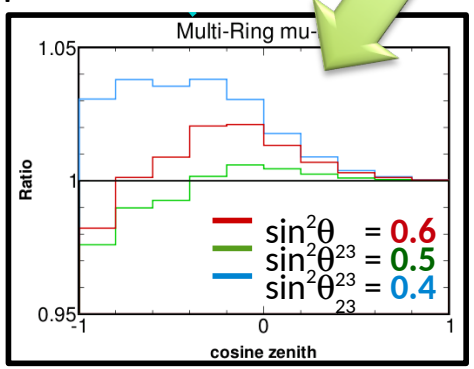
assuming normal MH

$P(\nu_\mu \rightarrow \nu_e)$



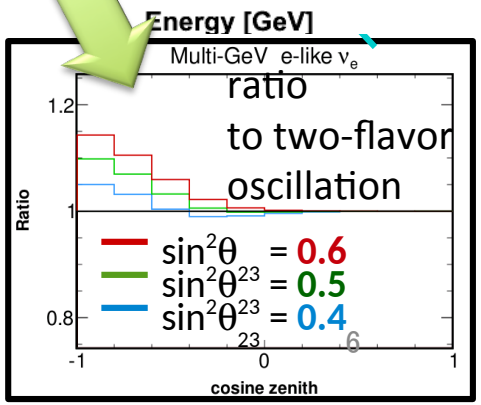
horiz. going

upward ~10000km



The size of the resonance effect is sensitive to $\sin^2\theta_{23}$ and MH.
Broad range of data useful for MH.

1d figures are the ratio to 2 flavor oscillation.



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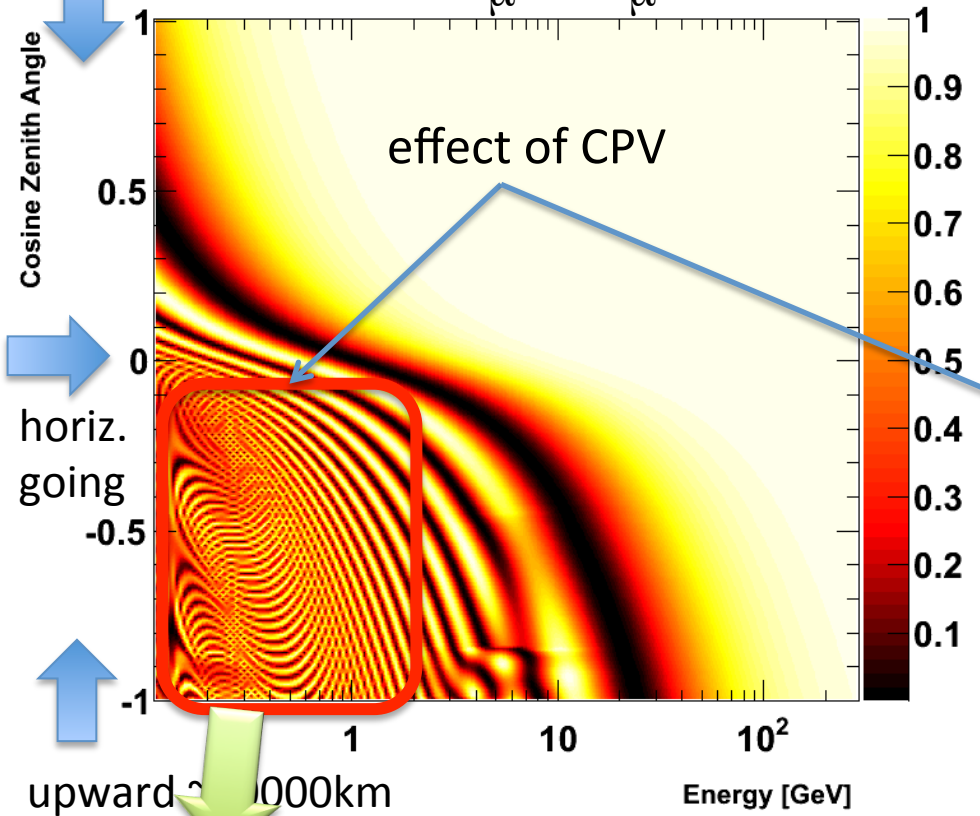
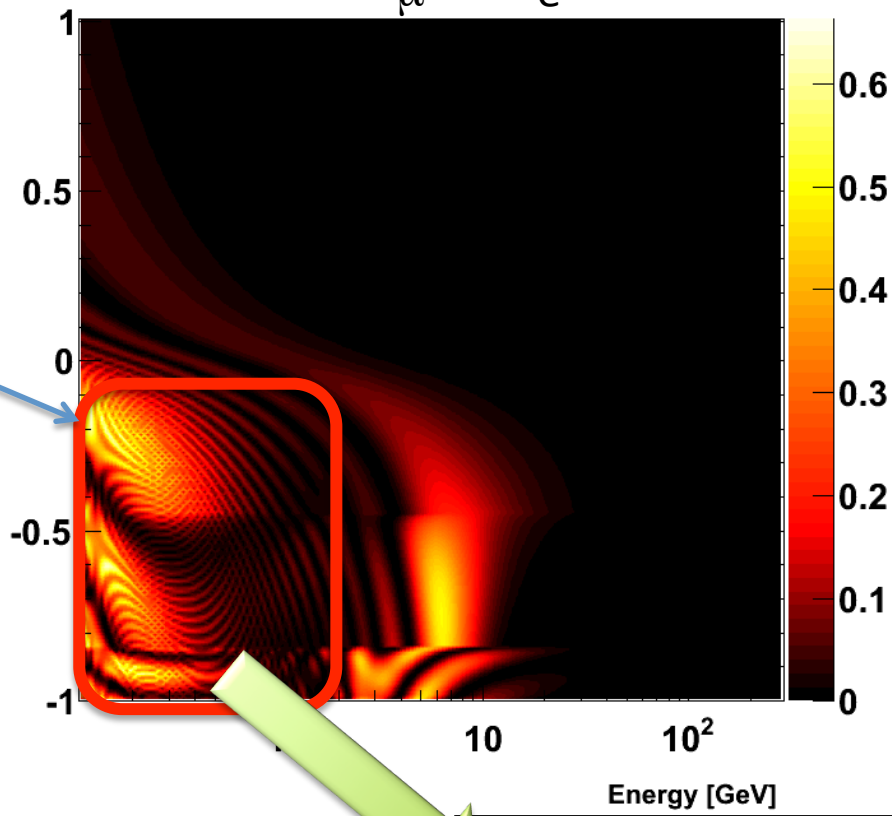
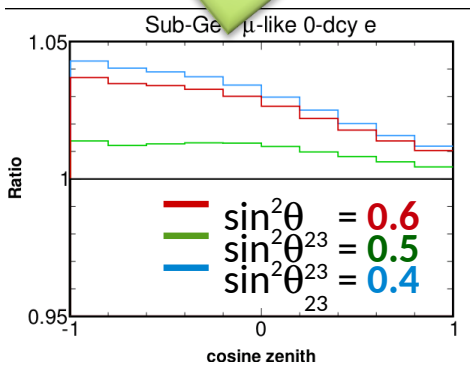


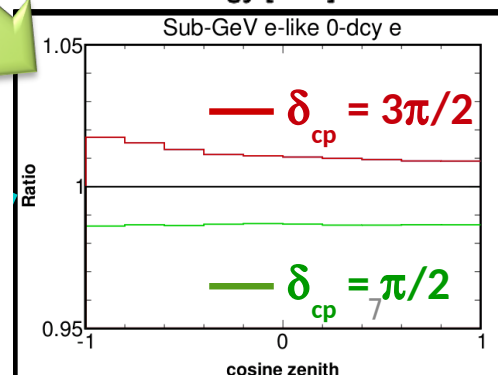


upward ~1000km



The low energy electron events (between Δm^2_{12} & Δm^2_{23}) are affected by CP violation phase.

1d figures are the ratio to 2 flavor oscillation.

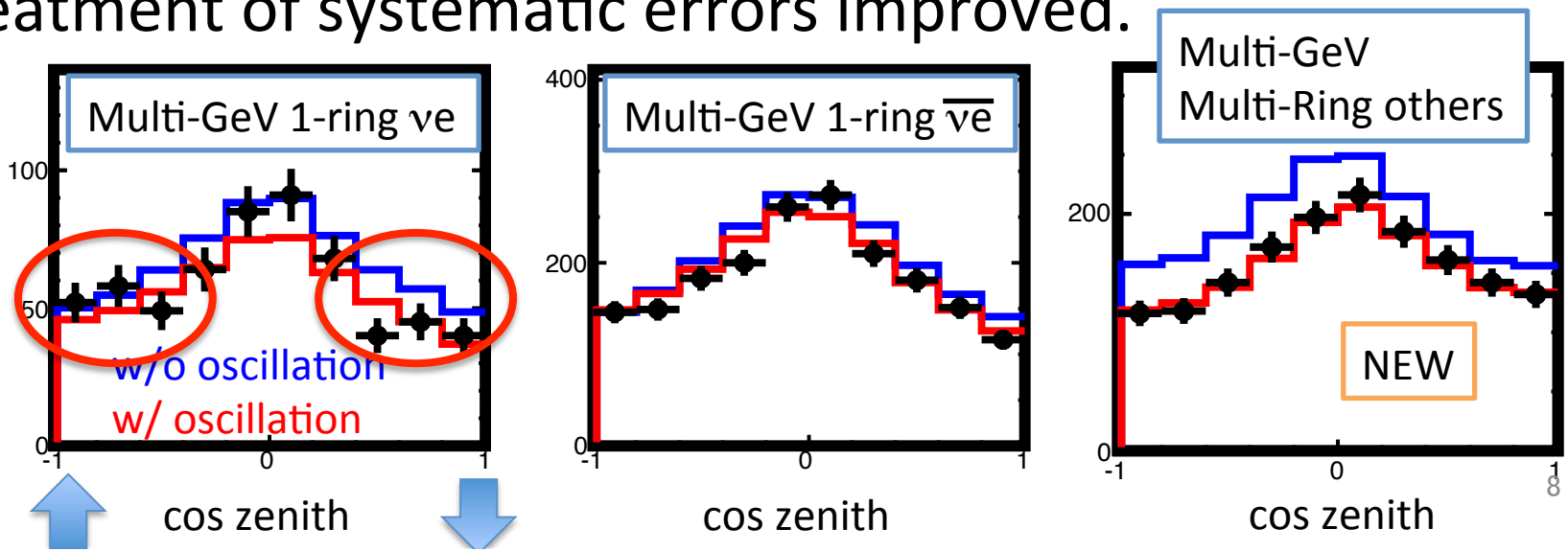


Data set and recent improvements

- 1775 days of SK-IV, in total, 4581.4 days, ~40,000 ev
- $\nu e/\overline{\nu e}$ enriched samples to enhance MH sensitivity.
  - νe CC produces more π^+ → more μ decays, etc.

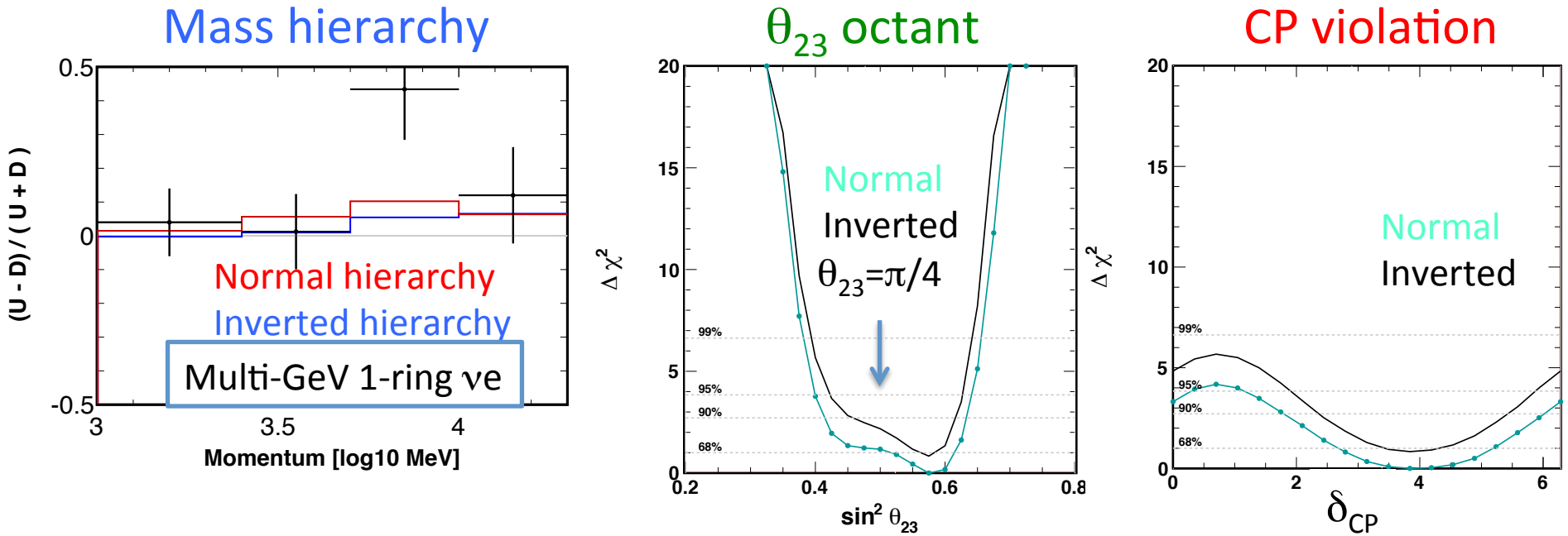
	νe CC	anti-νe CC	others	Total
Multi-GeV 1 ring νe like	60%	10%	30%	100%
Multi-GeV 1 ring anti-νe like	57%	34%	9%	100%

- "Multi-ring others" which fails both μ/e selection added.
- Treatment of systematic errors improved.



Fixed θ_{13}, results with SK only

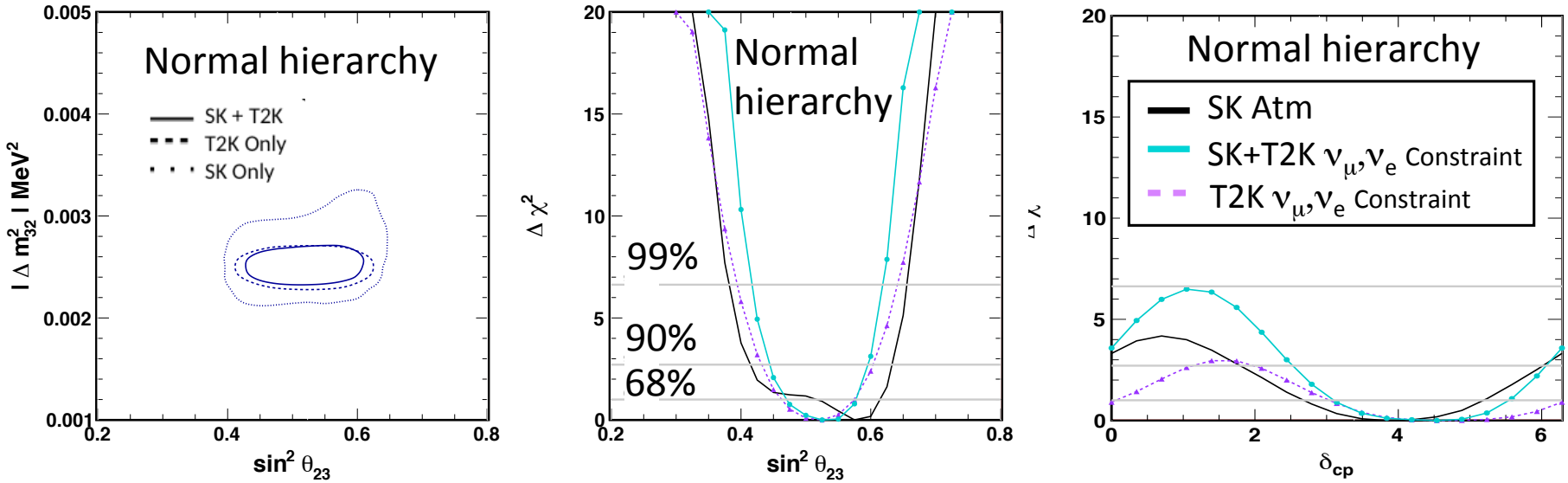
preliminary



- Normal hierarchy slightly favored at $\chi^2_{IH}-\chi^2_{NH} = 0.9$
- $\theta_{23} > \pi/2$ slightly (~1σ level) preferred.
- Driven by excess of up-going e-like events consistent with the effects of θ_{13}.
- δ_{CP}~$3\pi/2$ is slightly preferred by excess in Multi-Ring e-like $\overline{\nu}_e$ and deficit in Multi-GeV 1R μ-like. Consistent with sensitivity.

Including the external T2K result

- T2K's published constraints on $\Delta m^2_{23}/\theta_{23}$ could enhance mass hierarchy determination power. preliminary
  - Matter effect for T2K is small since baseline ~295km.

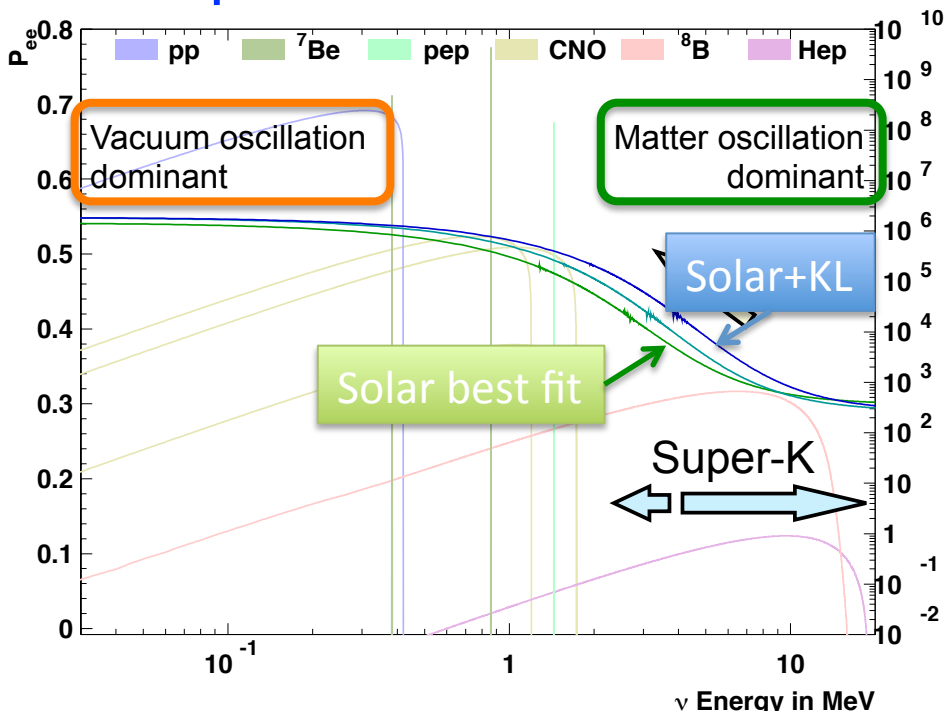


- Preference of NH is strengthened: $\chi^2_{IH}-\chi^2_{NH} = 1.2$
- T2K favors $\theta_{23}=\pi/2+\varepsilon$ because of max. red. of μ obs.
- Preference of $\delta_{CP}\sim 3\pi/2$ strengthened, but CP conservation ($\delta_{CP}=0$ and π) is still allowed at 90% C.L.

Solar ν observation by ν+e scattering: Motivation of the measurement

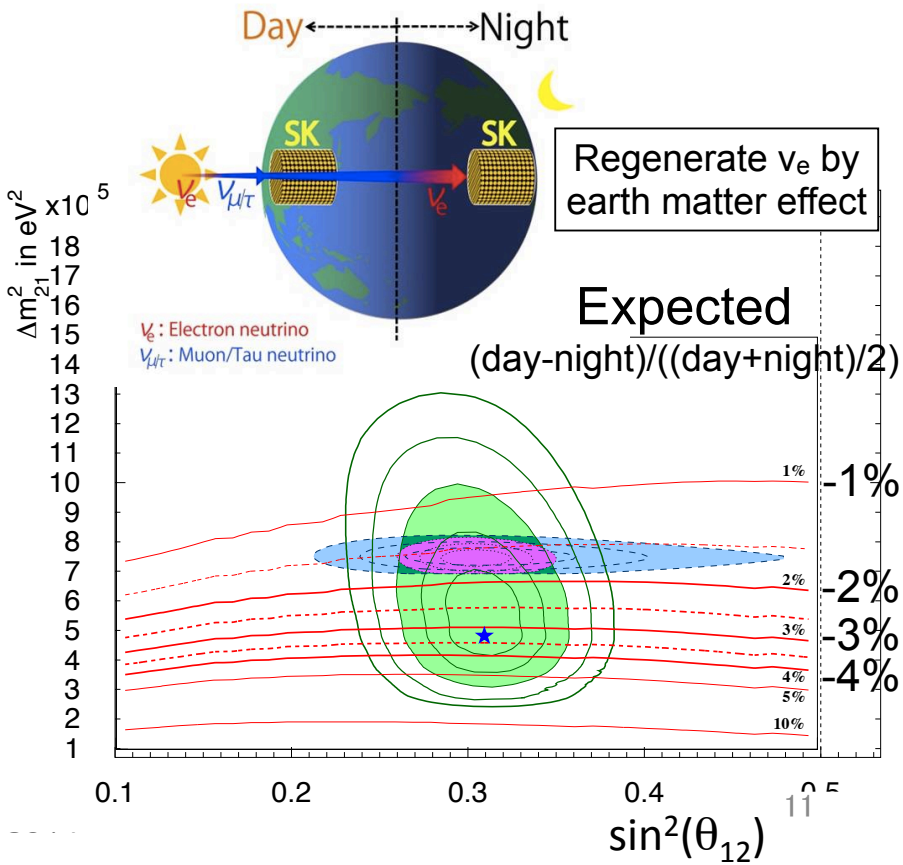
See the clear evidence that the neutrino flavor conversion is indeed due to neutrino oscillations.

Spectrum distortion

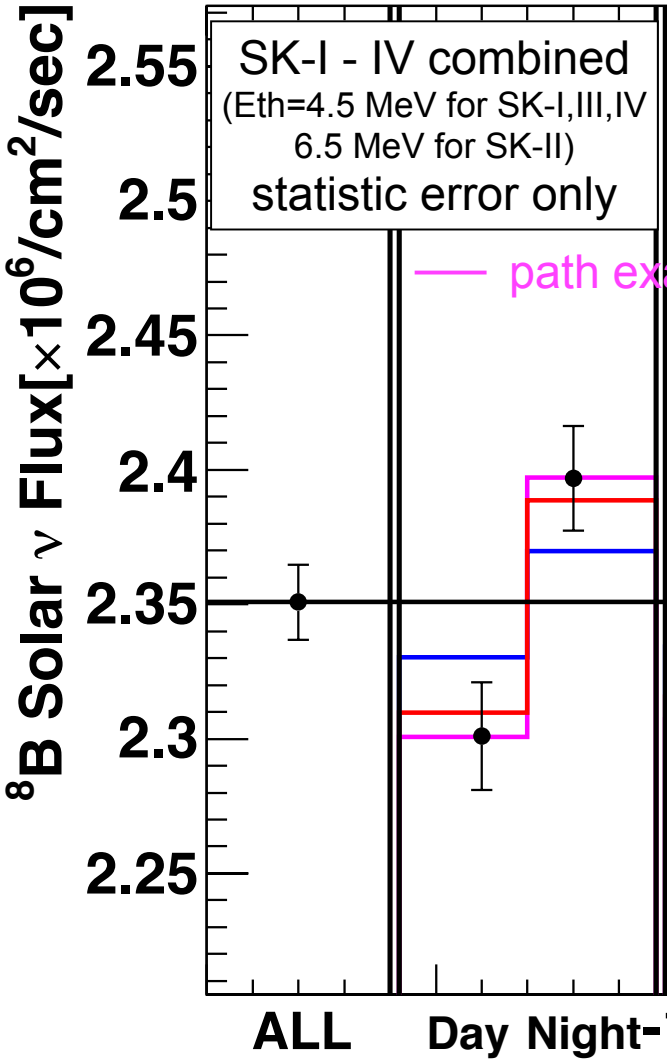


Super-K can search for the spectrum "upturn" expected by neutrino oscillation MSW effect

Day-Night flux asymmetry



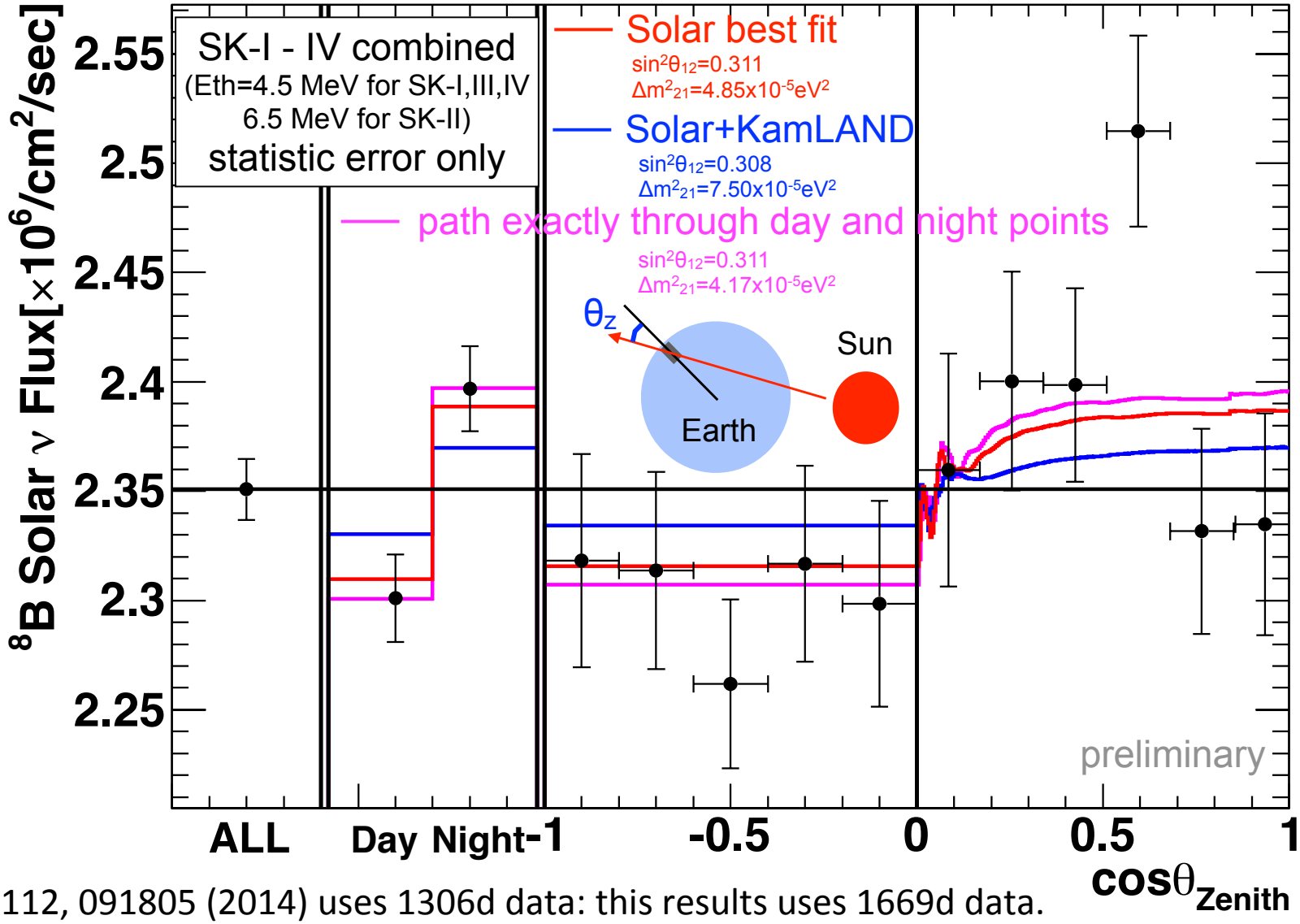
D/N effect as a direct confirmation of matter effect on neutrino oscillations



PRL 112, 091805 (2014) uses 1306d data: this results uses 1669d data.

$\cos\theta_{Zenith}$

D/N effect as a direct confirmation of matter effect on neutrino oscillations



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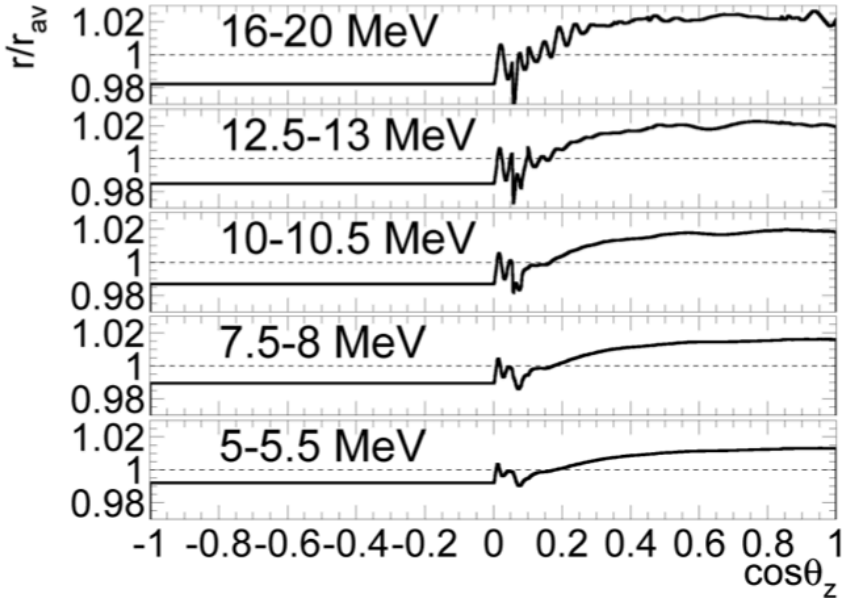
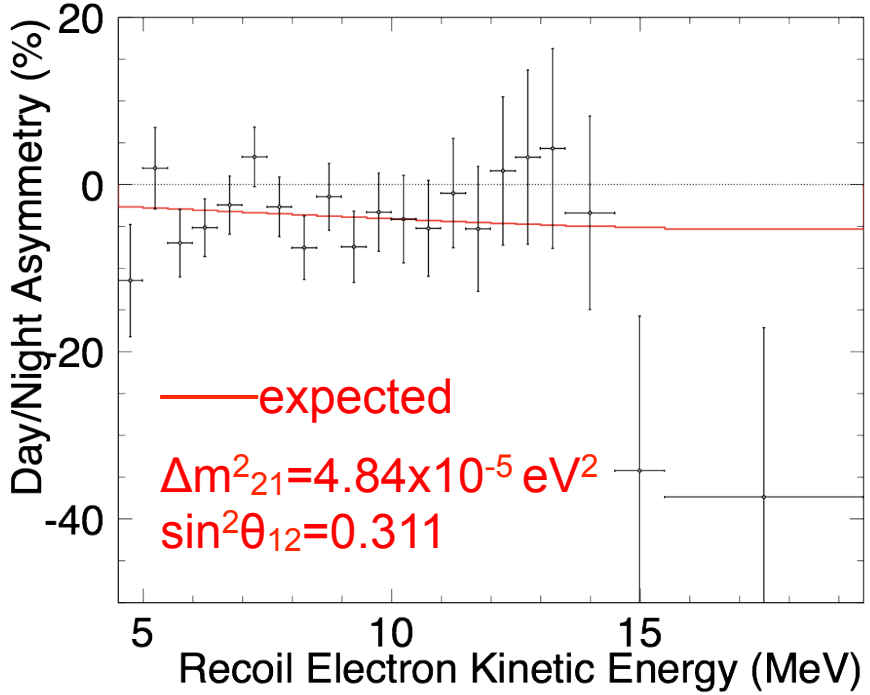
Day/night differences

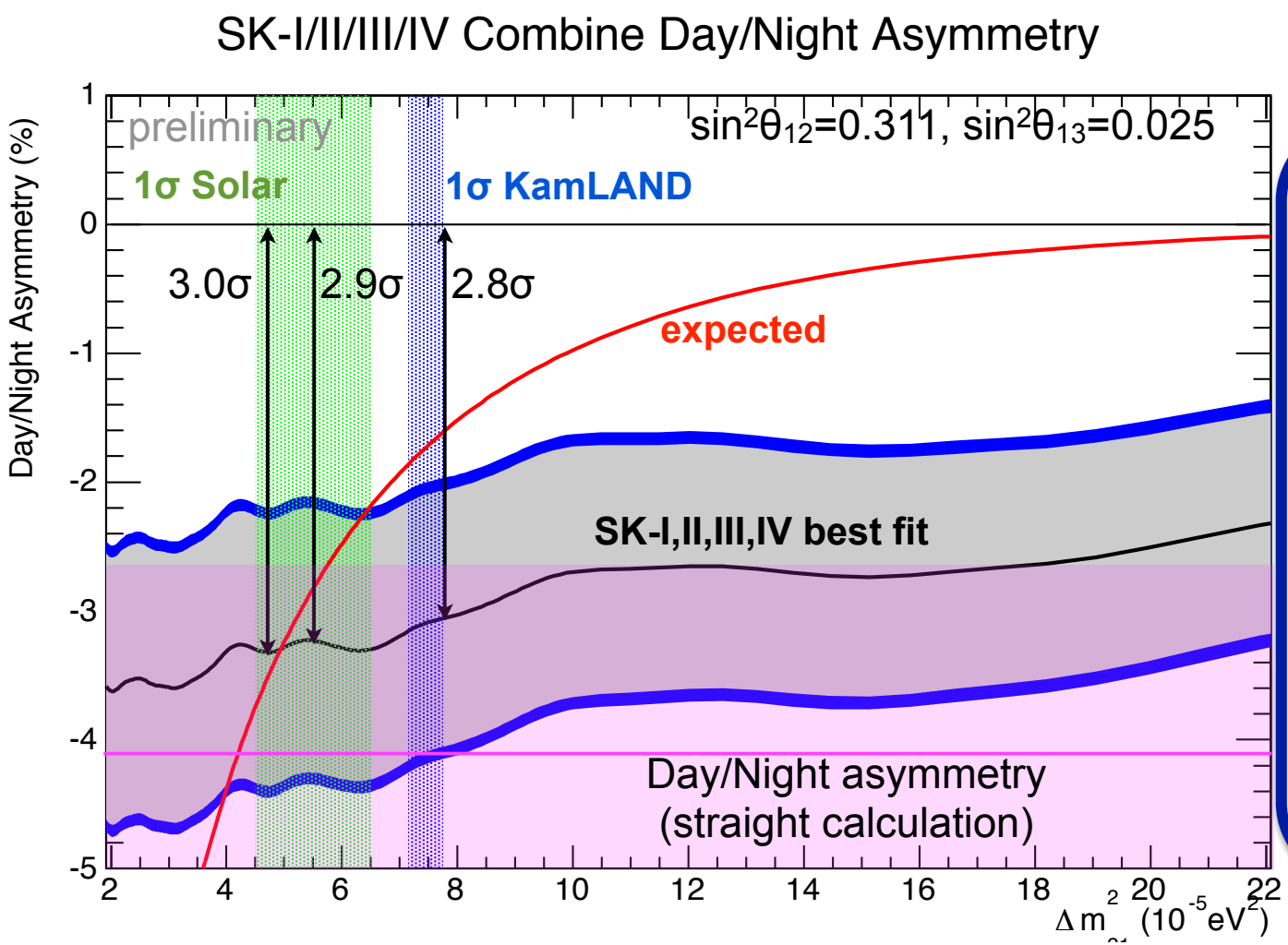
Expected time variation as a func. of $\cos\theta_z$





	Amplitude fit		Straight calc. (D-N)/((D+N)/2)
	$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2	$\Delta m^2_{21}=7.50\times10^{-5}$ eV^2	
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%	-5.5±4.2±3.7%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%	-5.9±3.2±1.3%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%	-4.9±1.8±1.4%
combined	**-3.3±1.0±0.5%**	**-3.1±1.0±0.5%**	**-4.1±1.2±0.8%**
non-zero significance	3.0 σ	2.8 σ	2.8 σ

Δm^2_{21} dependence



Solar region

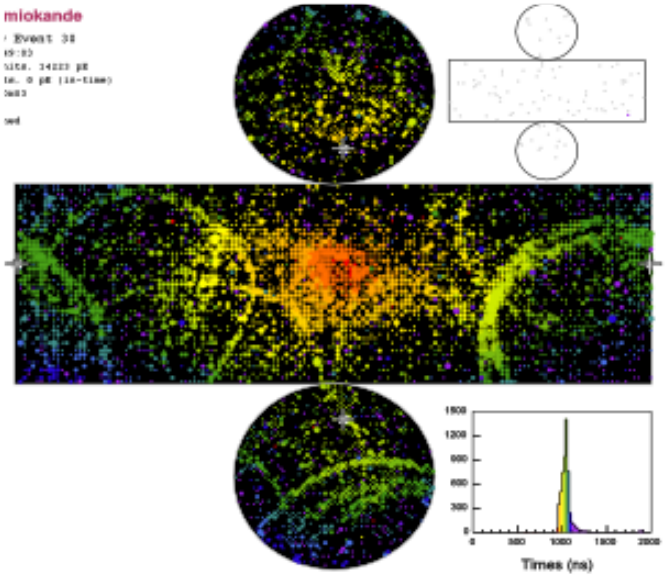
- ✓ differ from zero by 2.9~3.0σ
- ✓ agree with expect by 1.0σ

KamLAND region

- ✓ differ from zero by more than 2.8σ
- ✓ agree with expect by 1.3σ

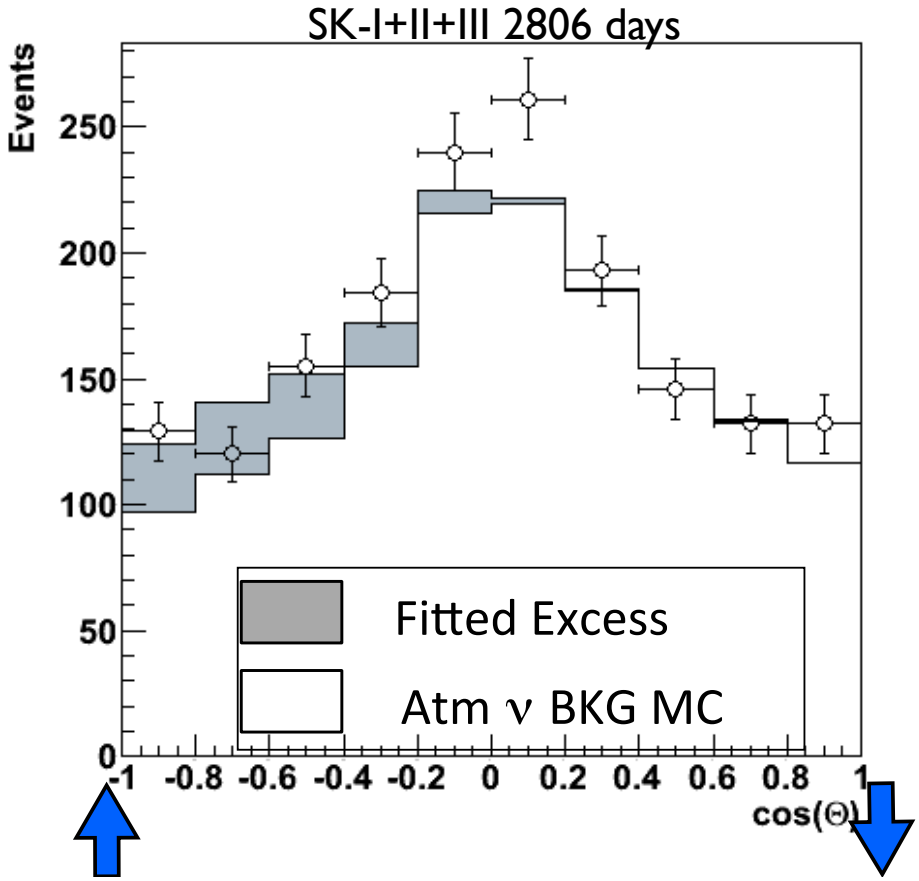
The first indication at 2.8-3.0σ of terrestrial matter effect.

Evidence for τ neutrino appearance



Published in PRL 110, 181802 (2013)

Zenith Distribution of τ-like events



Neural network to enhance events consistent with hadronic decays of τ

$N_\tau^{DATA}/N_\tau^{exp}$
$=1.42\pm0.35(stat)+^{0.14}_{-0.12}(syst)$

3.8σ significance for null τ

$\nu_\mu \rightarrow \nu_\tau$ channel has been confirmed by τ identification

Summary

- Using atmospheric neutrino data and solar neutrino data we are searching for ***the matter effect*** in order to find the mass hierarchy, octant of θ_{23}, CP violation, and a direct evidence of ν oscillation of solar ν.
- For the mass hierarchy, using 4538days data there is a ***~1σ preference for*** the NH and the second octant.
- ***The first indication at 2.8-3.0σ*** of terrestrial matter effect in 4504 days data of ^{8}B solar ν.
- $\nu_\mu \rightarrow \nu_\tau$ channel as a solution of "atmospheric neutrino anomaly" has been confirmed by ***the evidence of τ appearance at 3.8σ.***