NNN05 workshop,

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Neutrino oscillation studies with atmospheric neutrinos in Hyper-Kamiokande

- sub-dominant osc. in atm. neutrino exp's -

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Introduction

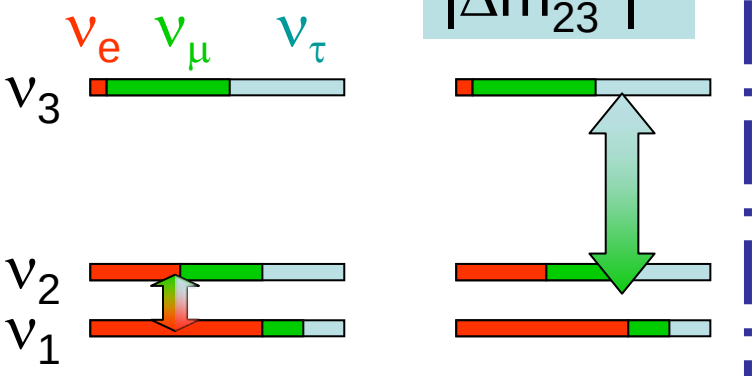
ν mass and mixing parameters:

θ_{12}, θ_{23}, θ_{13}, δ, Δm_{12}^2, $\Delta m_{13}^2 (= \Delta m_{23}^2)$

Known:

θ_{12}, Δm_{12}^2

θ_{23}, $|\Delta m_{23}^2|$

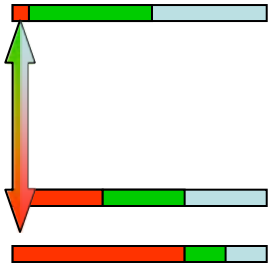


Solar, KamLAND

Atmospheric Long baseline

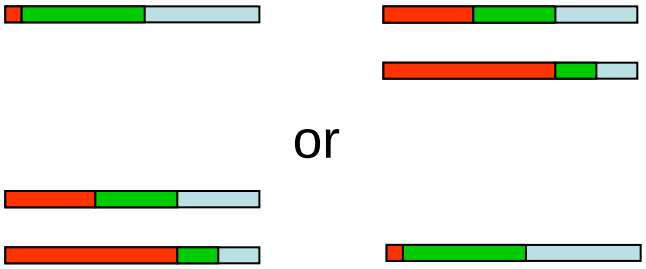
Unknown:

θ_{13}



If $\theta_{23} \neq \pi/4$, is it $>\pi/4$ or $<\pi/4$?

Sign of Δm_{23}^2



CP ?

How much can we learn from atmospheric neutrino experiments?

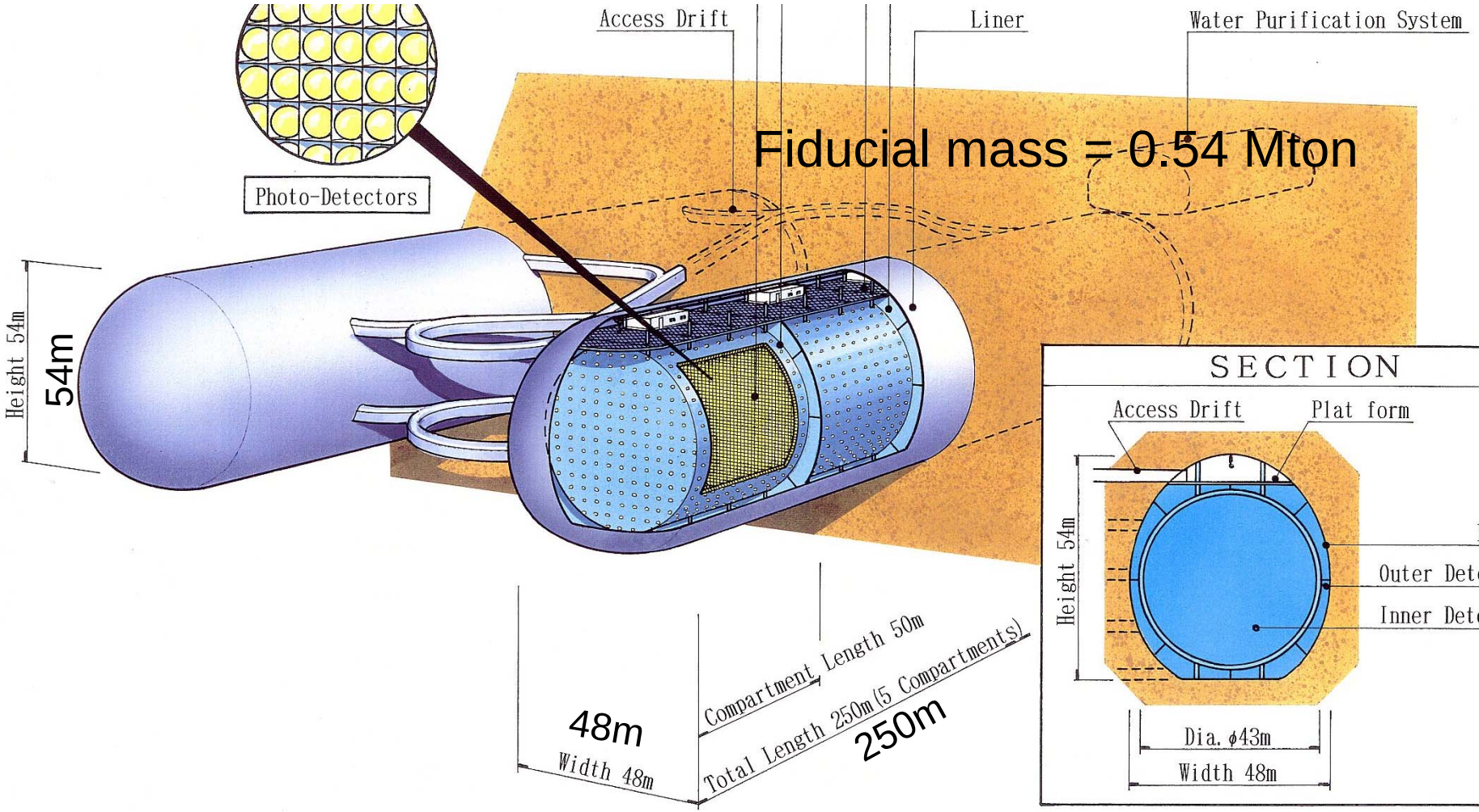
Outline

- Introduction
- $\sin^2\theta_{13}$?
- Sign of Δm_{23}^2 ?
- . $\theta_{23} > \pi/4$ or $< \pi/4$? (including solar oscillation terms)
- CP phase measurement ?
- Summary

Detector and assumption

Detector: Hyper-Kamiokande

The performance of the Hyper-K detector is assumed to be identical to Super-K.

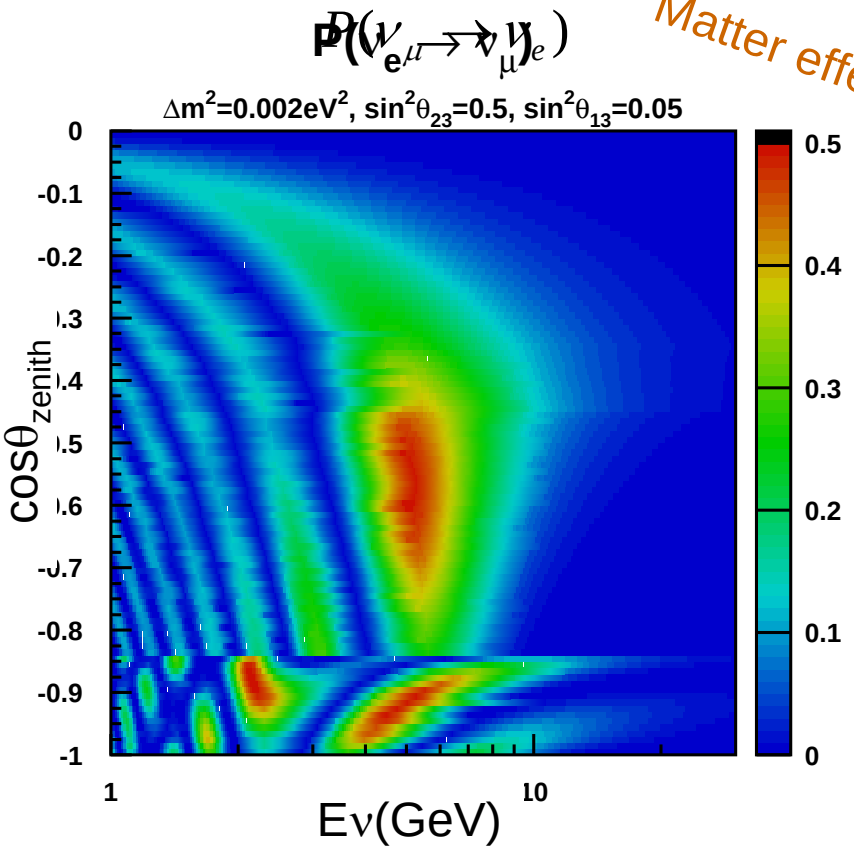


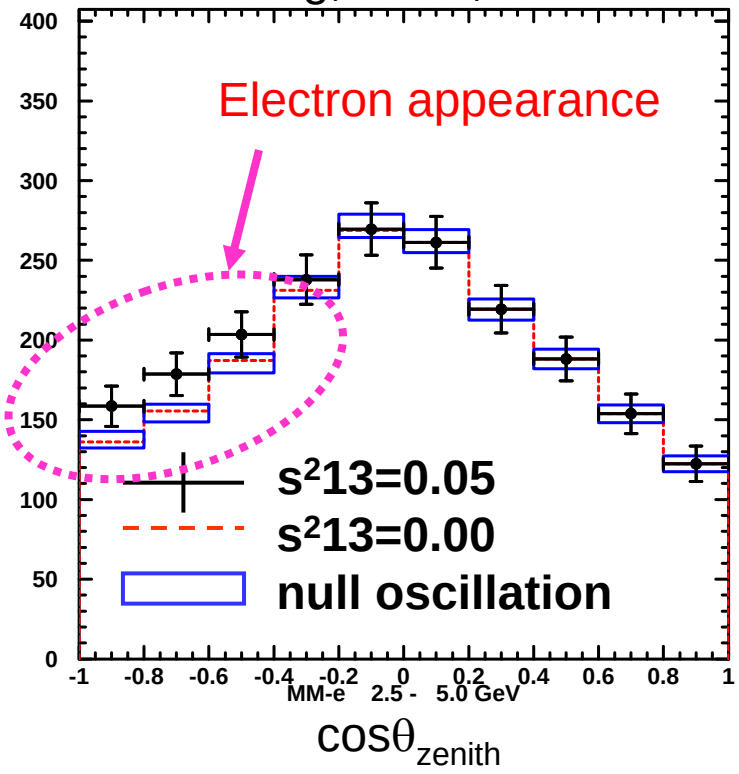
Search for non-zero θ_{13}

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \cdot \sin^2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

(Δm_{12}^2=0 assumed)

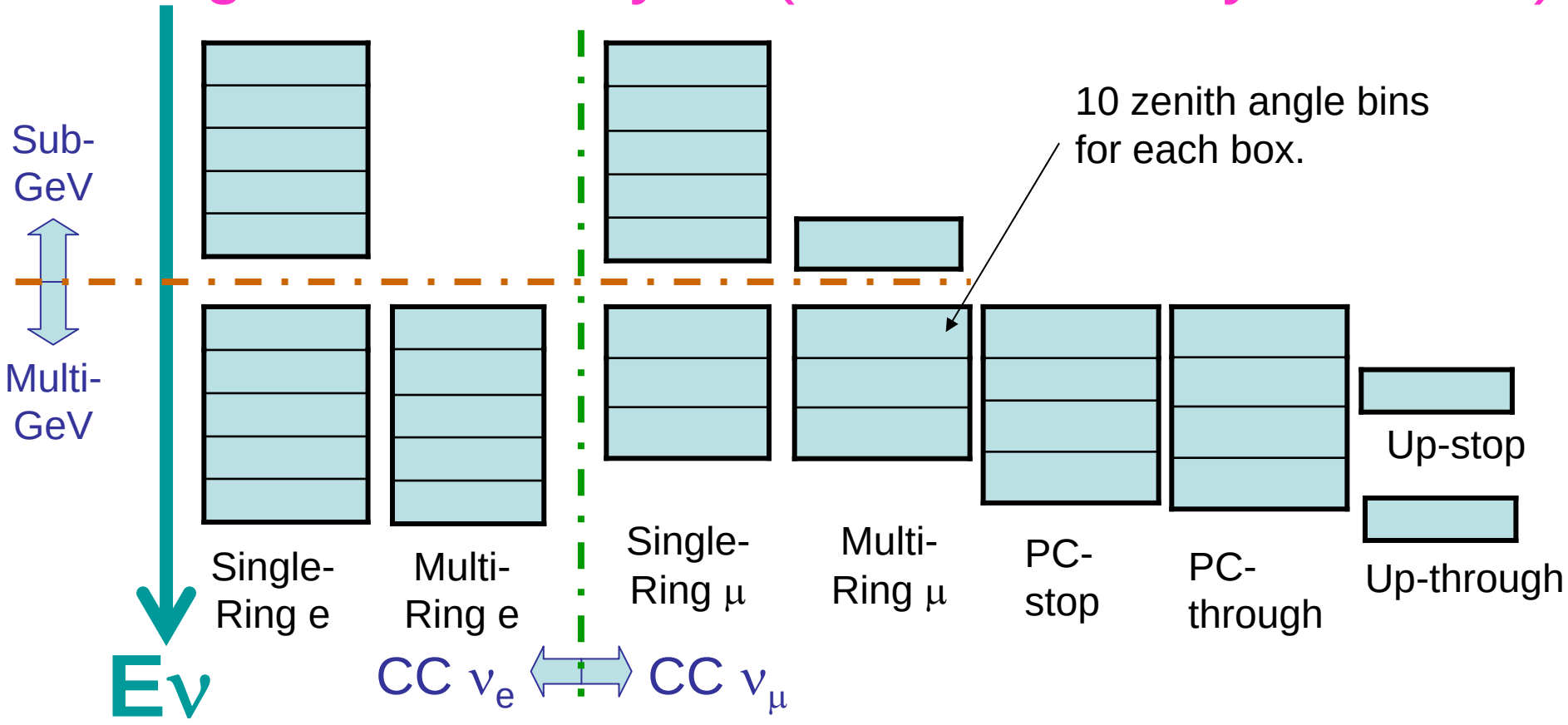
Matter effect





Electron appearance in the multi-GeV upward going events.

Binning for this analysis (= 3flavor analysis in SK)



37 momentum bins x 10 zenith bins = 370 bins in total

(or slightly smaller number of bins for some analyses)

Small number of events per bin

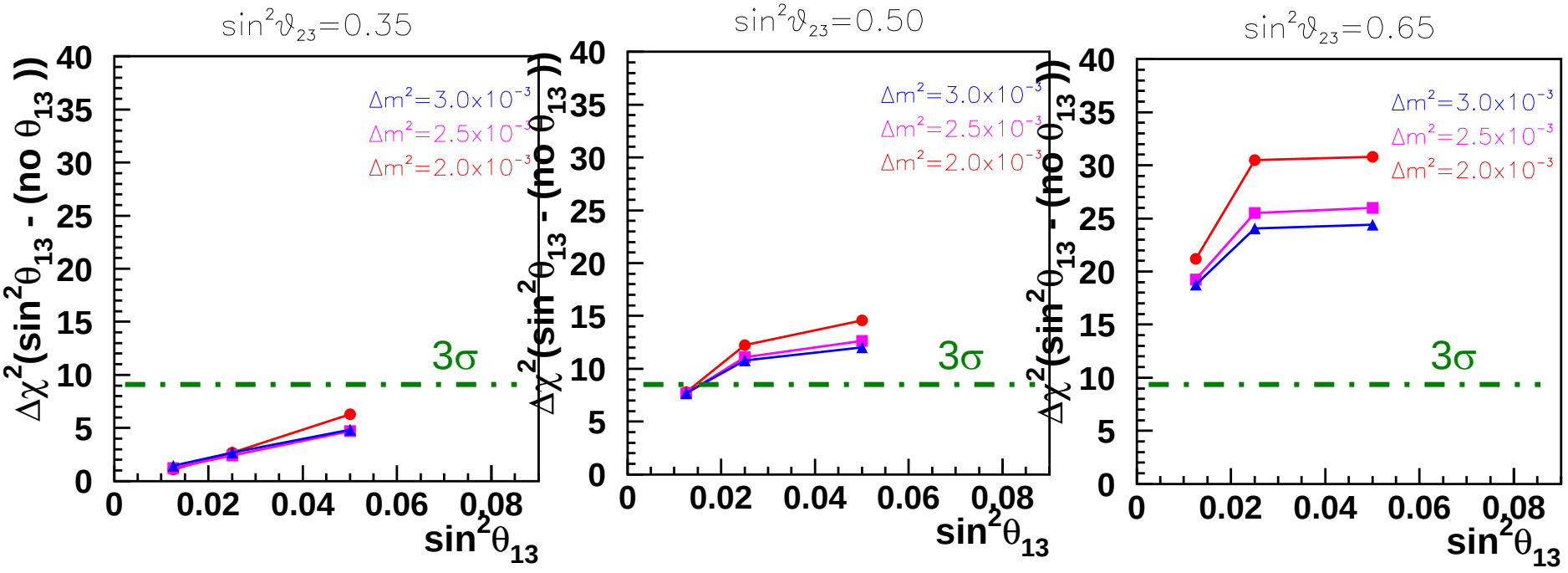
Poisson statistics to claculate χ^2 with 44 systematic error terms

Statistical significance for non-zero θ_{13}

Importance of $s^2\theta_{23}>0.5$; S.Pascoli et al., hep-ph/0305152

450 kton · yr = 0.8yr HK

Δm_{23}^2 ; positive assumed



($\Delta\chi^2$ is approximately proportional to the exposure)

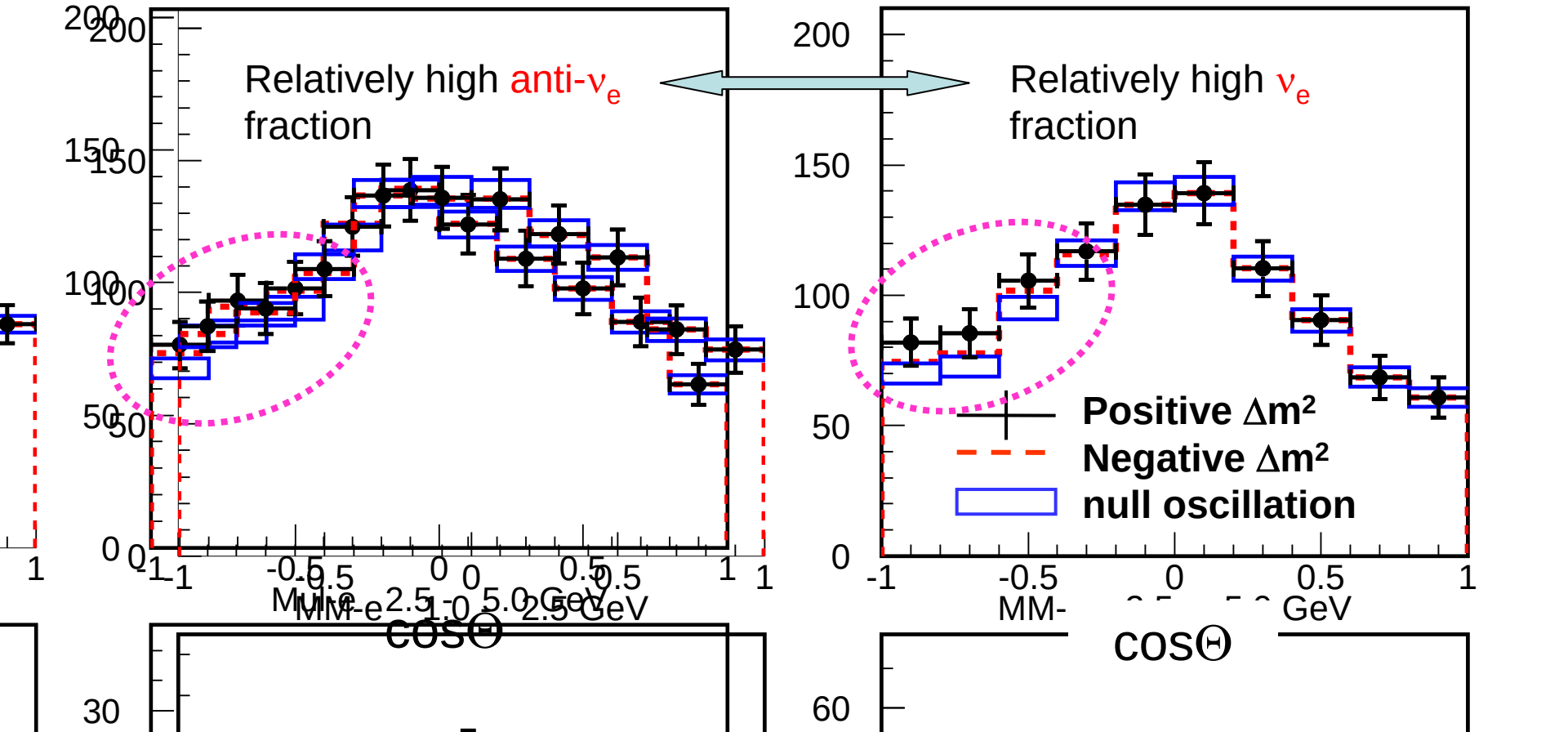
Sign of Δm^2 ?

If Δm_{23}^2 is positive, resonance for neutrinos

If Δm_{23}^2 is negative, resonance for anti-neutrinos

$\Delta m^2 = 0.002 eV^2$
$s^2\theta_{23} = 0.5$
$s^2\theta_{13} = 0.05$
(0.45 Mtonyr)

ingle-ring | Single-ring e-like | / Multi-ring | Multi-ring e-like

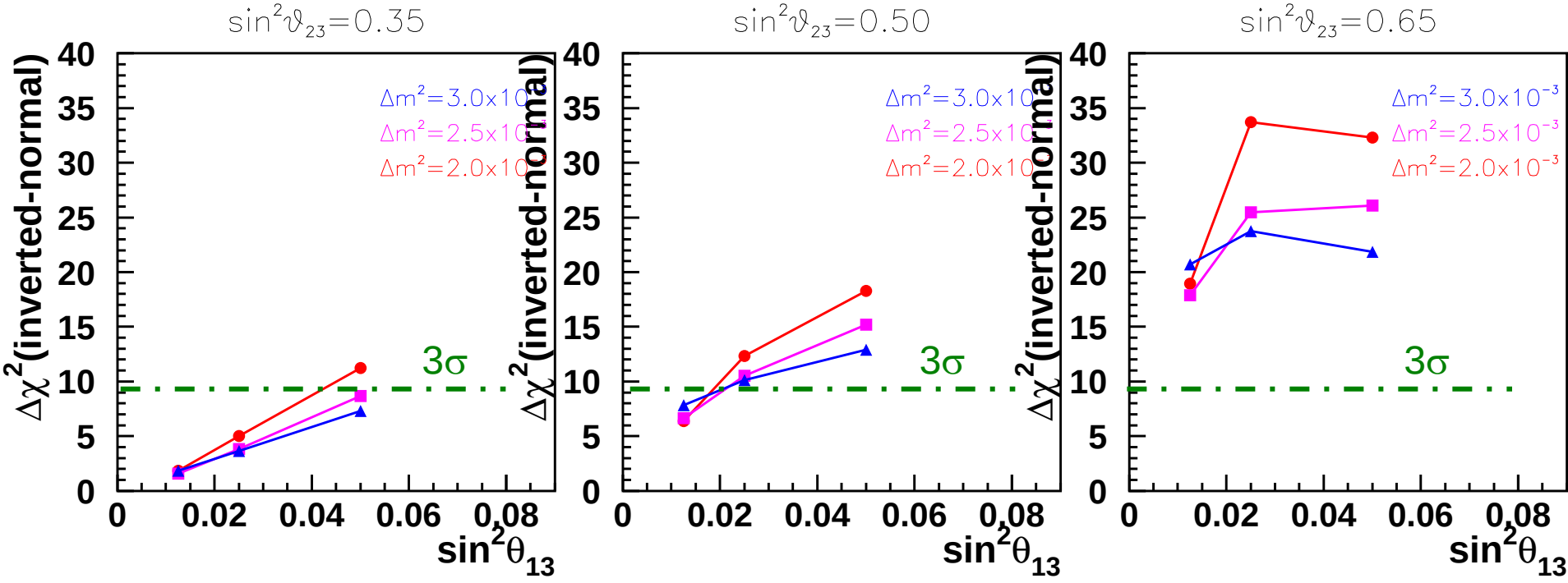


χ^2 difference (inverted-normal)

True= normal mass hierarchy assumed.

Δm^2: fixed, θ_{23}: free, θ_{13}: free

Exposure: 1.8Mtonyr
(HK = 3.3 yr)

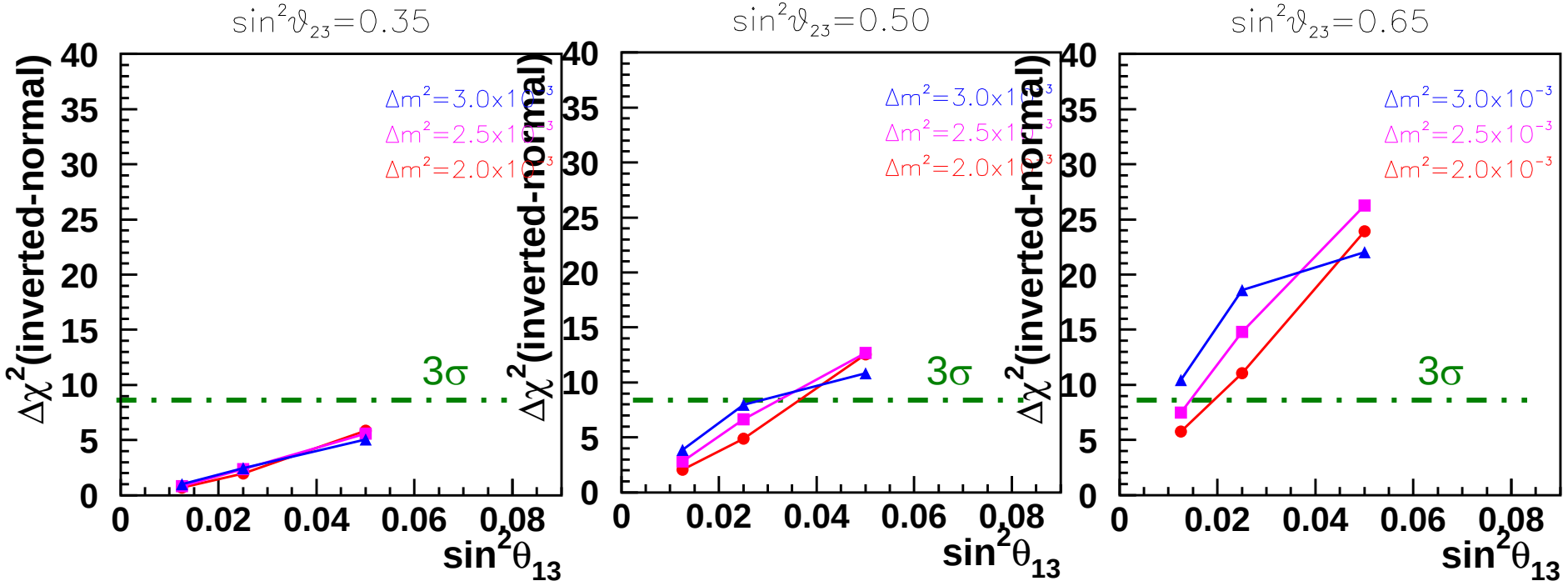


χ^2 difference (normal – inverted)

True= inverted mass hierarchy assumed.

Δm^2: fixed, θ_{23}: free, θ_{13}: free

Exposure: 1.8Mtonyr
(HK =3.3 yr)



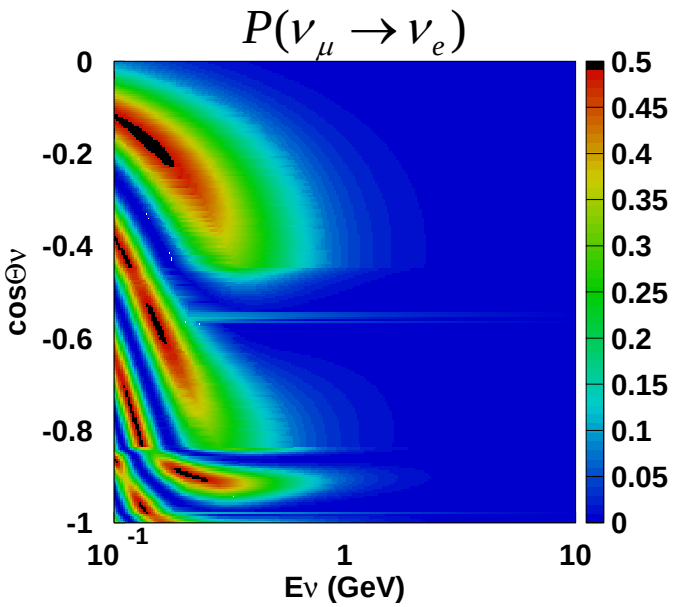
$\theta_{23} > \pi/4$ or $< \pi/4$?

CP phase measurement ?

Expected oscillation with solar terms (1)

Peres & Smirnov
NPB 680 (2004)
479

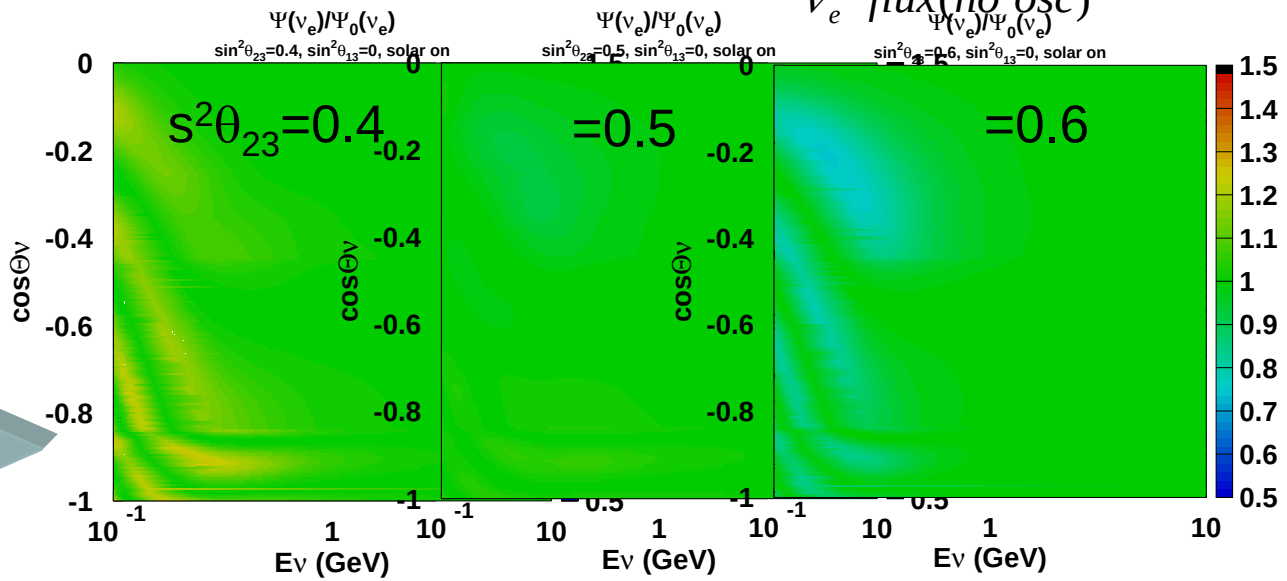
Because of the LMA solution, atmospheric neutrinos should also oscillate by (θ_{12}, Δm_{12}^2).



$s^2 2\theta_{12}=0.825$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$
$\sin^2\theta_{13}=0$

However, due to the cancellation between $\nu_\mu \to \nu_e$ and $\nu_e \to \nu_\mu$, the change in the ν_e flux is small.

$$\frac{\nu_e \ \ flux(osc)}{\nu_e \ \ flux(no\ osc)}$$



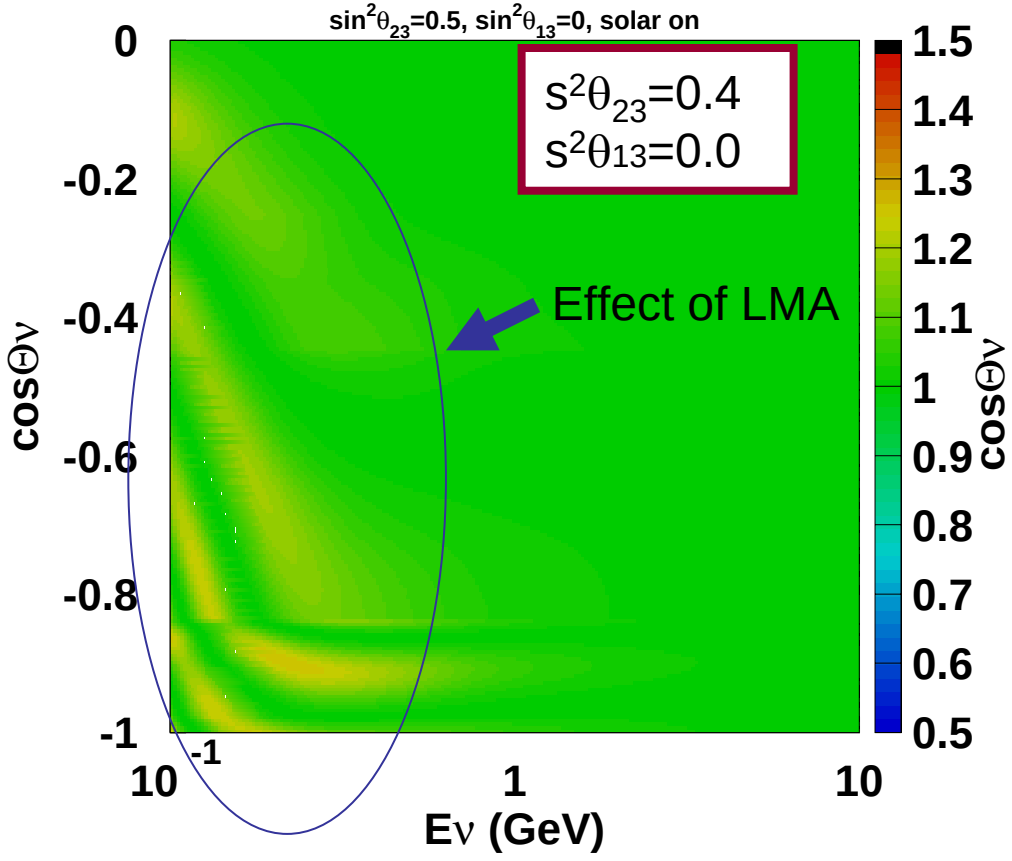
Oscillation probability is different between $s^2\theta_{23}$=0.4 and 0.6
➔ discrimination between θ_{23} >π/4 and <π/4 might be possible.

Expected oscillation with solar terms (2)

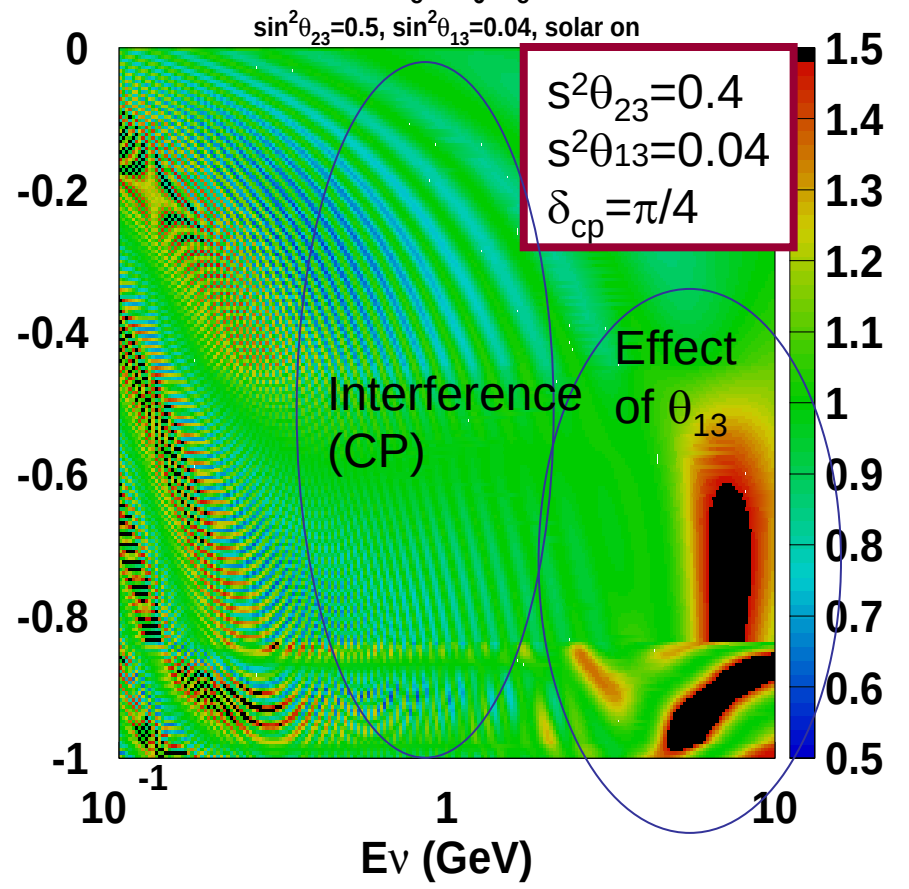
$s^2 2\theta_{12}=0.825$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$
(always assumed later in this talk)

In addition, we may have non-zero θ_{13}.

$$\frac{\nu_e \ \ flux(osc)}{\nu_e \ \ flux(no\ osc)}$$



$\Psi(\nu_e)/\Psi_0(\nu_e)$



Effect of the solar term to sub-GeV e-like zenith angle

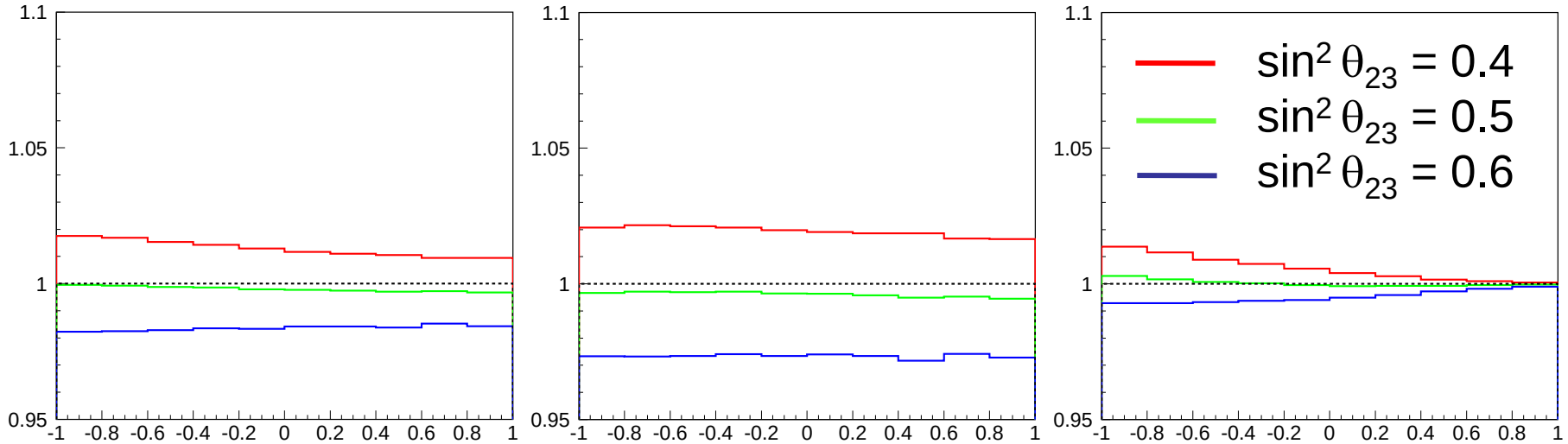
Δm^2_{12} = 8.3 x 10^{-5} eV^2
Δm^2_{23} = 2.5 x 10^{-3} eV^2
$\sin^2 2\theta_{12}$ = 0.82
$\sin^2\theta_{13}$=0

sub-GeV e-like

(P_e :100 ~ 1330 MeV)

(P_e :100 ~ 400 MeV)

(P_e :400 ~ 1330 MeV)



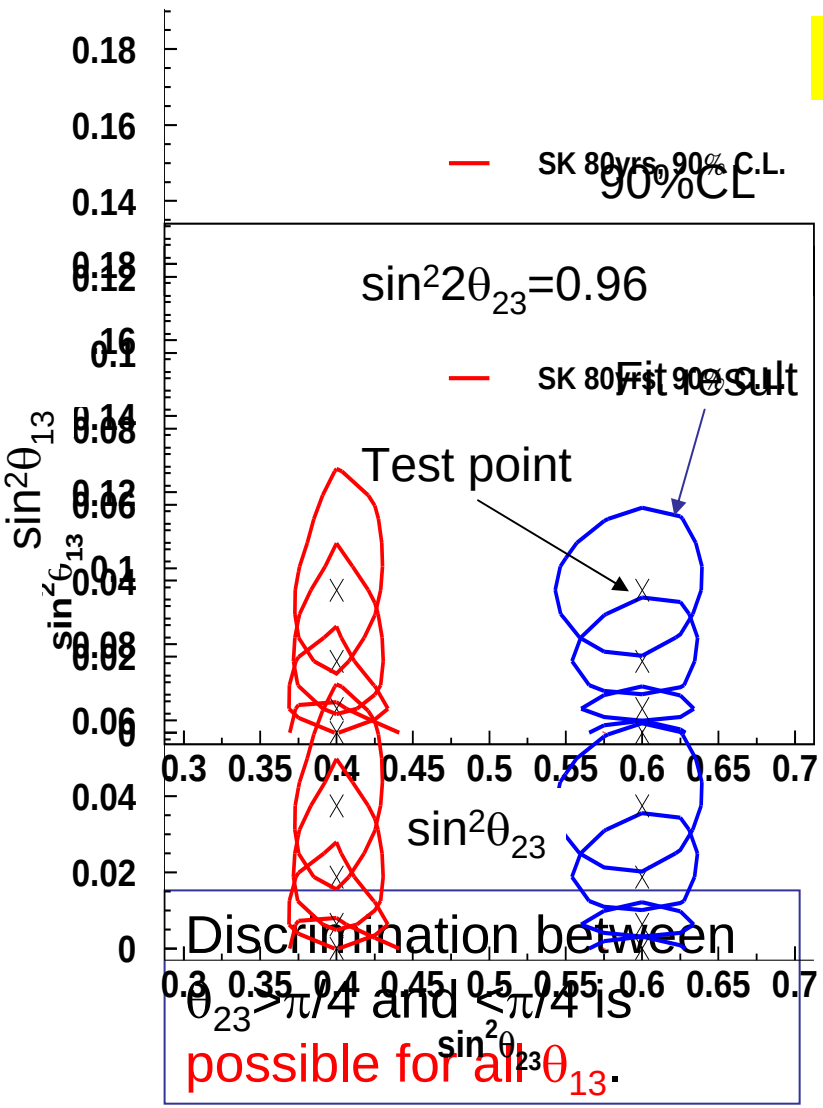
(Much smaller and opposite effect for μ-like events.)

μ/e ratio @low energy is useful to discriminate $\theta_{23}>\pi/4$ and $<\pi/4$.

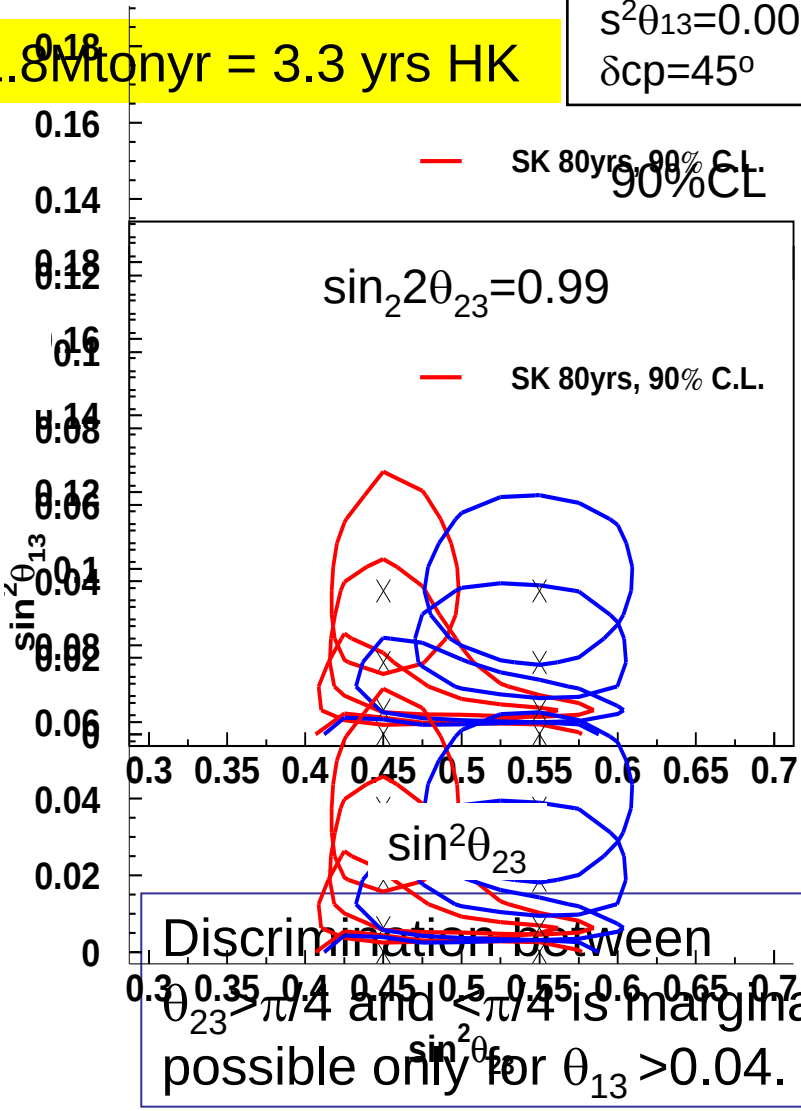
Discrimination between $\theta_{23} > \pi/4$ and $< \pi/4$ with the (12) and (13) terms

$s^2\theta_{23}$=0.40 ~ 0.60
$s^2\theta_{13}$=0.00~0.04
δcp=45°

1.8Mtonyr = 3.3 yrs HK

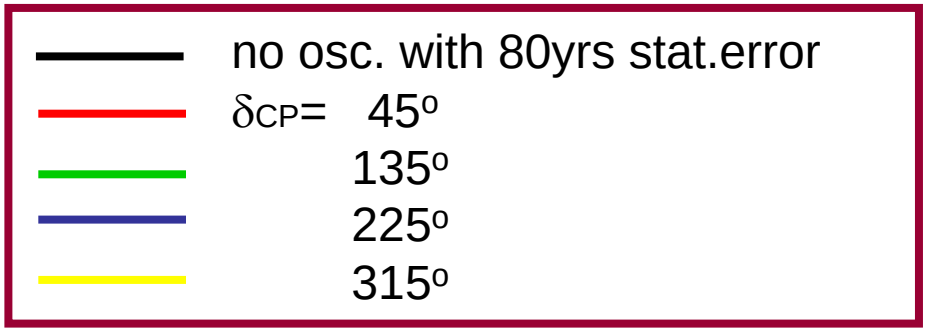


Discrimination between $\theta_{23} > \pi/4$ and $< \pi/4$ is possible for all θ_{13}.

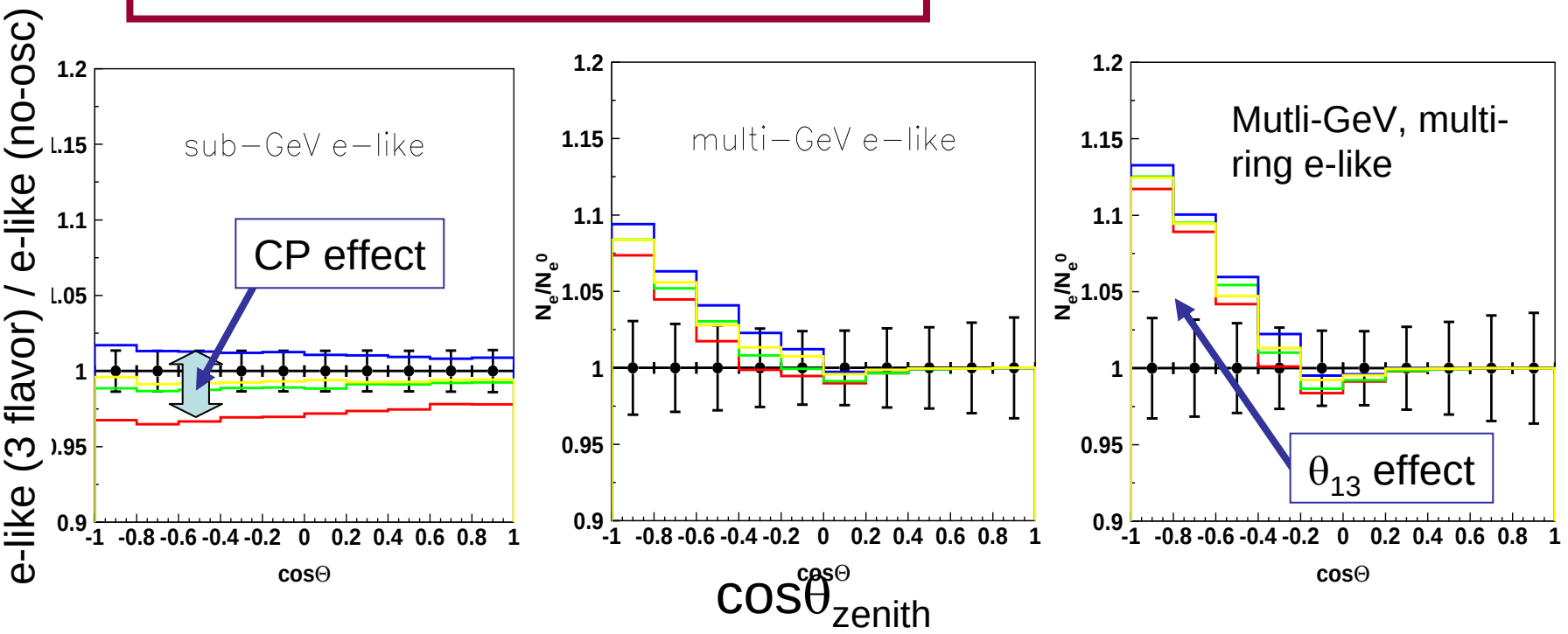


Discrimination between $\theta_{23} > \pi/4$ and $< \pi/4$ is marginally possible only for $\theta_{13} > 0.04$.

Effect of δ_{CP} in atmospheric neutrino data



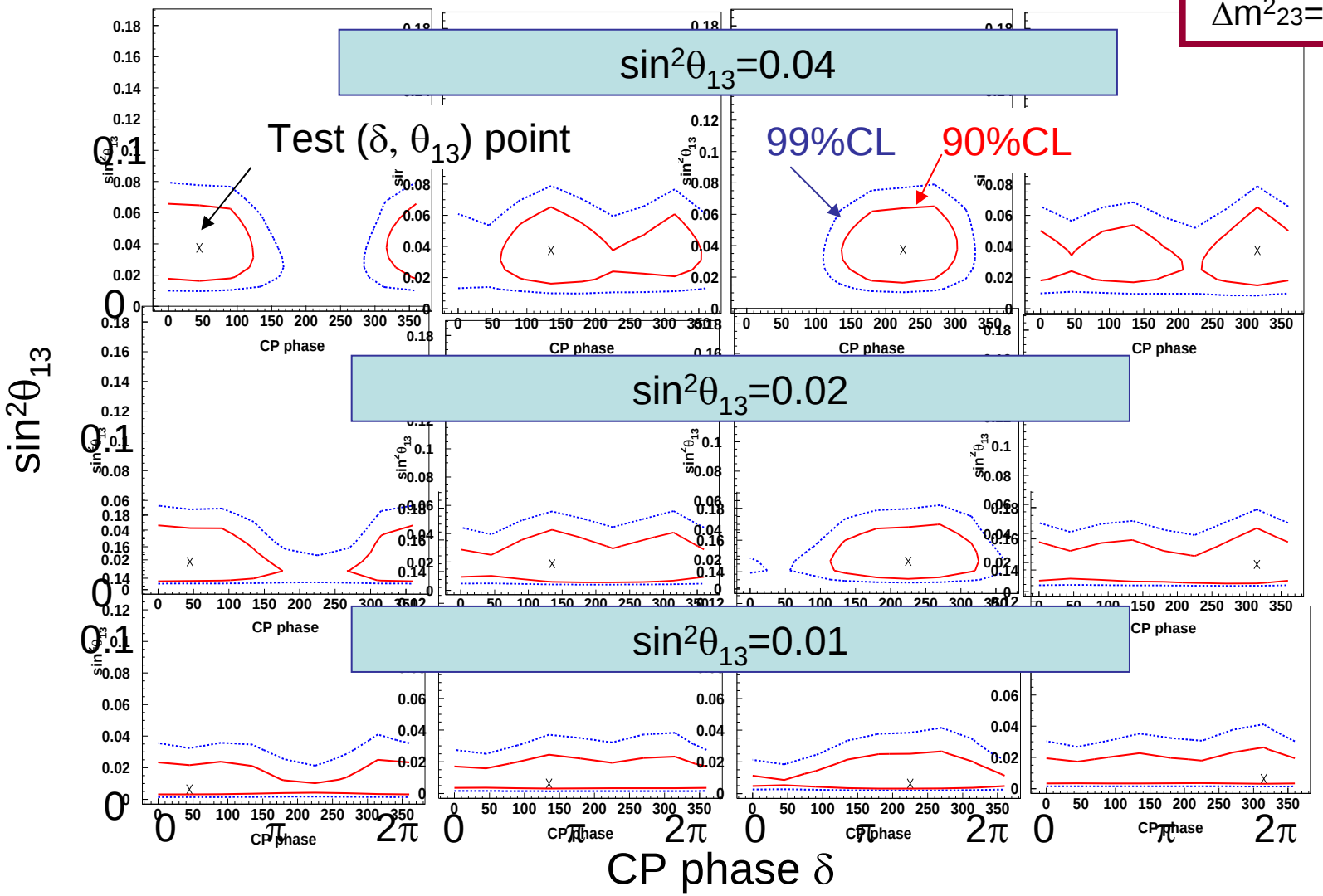
$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.04$
$\Delta m^2_{12}=+8.3e\text{-}5$
$\Delta m^2_{23}=+2.5e\text{-}3$



Sensitivity to δ_{cp}

1.8 Mtonyr ~ 3.3yrs HK

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.01\sim0.04$
$\Delta m^2_{12}=+8.3e\text{-}5$
$\Delta m^2_{23}=+2.5e\text{-}3$



CP phase could be seen if θ_{13} is close to the CHOOZ limit.

Summary

- The present Monte Carlo study suggests that the future atmospheric neutrino experiments with very high statistics will be very interesting, if θ_{13} is large enough.
- For large θ_{13}, atmospheric neutrino experiments with > 2 Mtonyr exposure will;
  - ➔discriminate the mass hierarchy
  - ➔discriminate between $\theta_{23} > \pi/4$ and $< \pi/4$
    (if $\sin^2 2\theta_{23}$ is smaller than 0.99)
    (if $\sin^2 2\theta_{23}$ is about 0.96 or smaller,
    the discrimination is possible even if $\theta_{13}=0$)
  - ➔give some information on the CP phase

End