Search for Non-Standard Interactions by ν_{amt}

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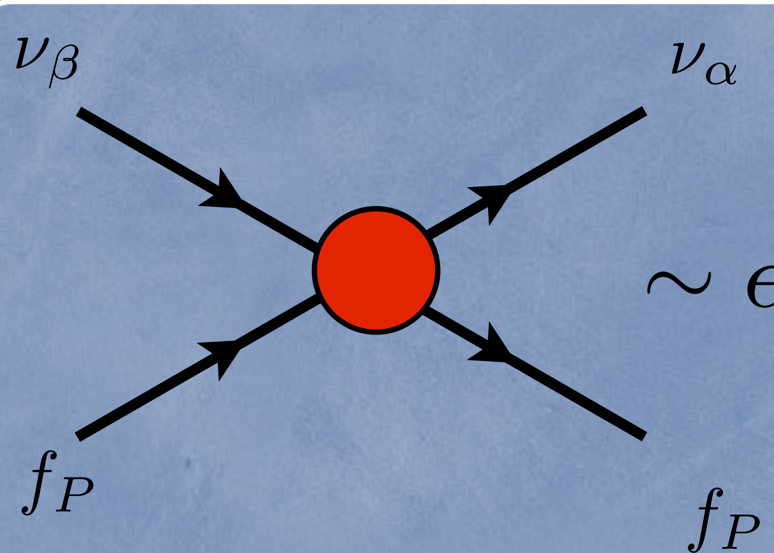
flavor-dependent exotic couplings of neutrinos with matter

Neutral current Non-Standard Interactions (NSI), which cause additional matter effects, are expressed by effective 4-fermi interactions:

$$\mathcal{L}_{NP} = -2\sqrt{2}G_F[\bar{\nu}_\alpha \gamma^\mu \nu_\beta][\epsilon^{f_L}_{\alpha\beta}\bar{f}_L\gamma_\mu f_L + \epsilon^{f_R}_{\alpha\beta}\bar{f}_R\gamma_\mu f_R].$$



$$\sim \epsilon^{f_P}_{\alpha\beta} G_F$$

Non-standard interactions

G_f : Fermi coupling constant

$\epsilon^{f_P}_{\alpha\beta}$: NSI coupling constant

$\alpha, \beta = e, \mu, \tau \qquad f = e, d, u$

NSI cause additional matter effects.

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = [U\mathcal{E}U^{-1} + \mathcal{A} + \mathcal{A}_{\mathcal{NP}}]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

U:PMNS matrix

Constraints on NSI①

$$\mathcal{L}_{NP} = -2\sqrt{2}G_F[\bar{\nu}_\alpha \gamma^\mu \nu_\beta][\epsilon_{\alpha\beta}^{f_L} \bar{f}_L \gamma_\mu f_L + \epsilon_{\alpha\beta}^{f_R} \bar{f}_R \gamma_\mu f_R]$$

$$\mathcal{A}_{NP} = A_{CC} \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \qquad \epsilon_{\alpha\beta} = \sum_{P=L,R} \sum_{f=e,u,d} \epsilon_{\alpha\beta}^{f_P} n_f / n_e$$

$$A_{CC} = \sqrt{2} G_F n_e$$

n_f : number density of fermions

Constraints from terrestrial experiments

$$\begin{pmatrix} |\epsilon_{ee}| < 4 \times 10^0 & |\epsilon_{e\mu}| < 3 \times 10^{-1} & |\epsilon_{e\tau}| < 3 \times 10^0 \\ & |\epsilon_{\mu\mu}| < 7 \times 10^{-2} & |\epsilon_{\mu\tau}| < 3 \times 10^{-1} \\ & & |\epsilon_{\tau\tau}| < 2 \times 10^1 \end{pmatrix}$$

$$|\epsilon_{e\mu}| \ll 1, \ |\epsilon_{\mu\mu}| \ll 1, \ |\epsilon_{\tau\mu}| \ll 1$$

are very weak

Carla Biggio et al. JHEP08(2009)090

There are rooms for improvement!!

Constraints on NSI②

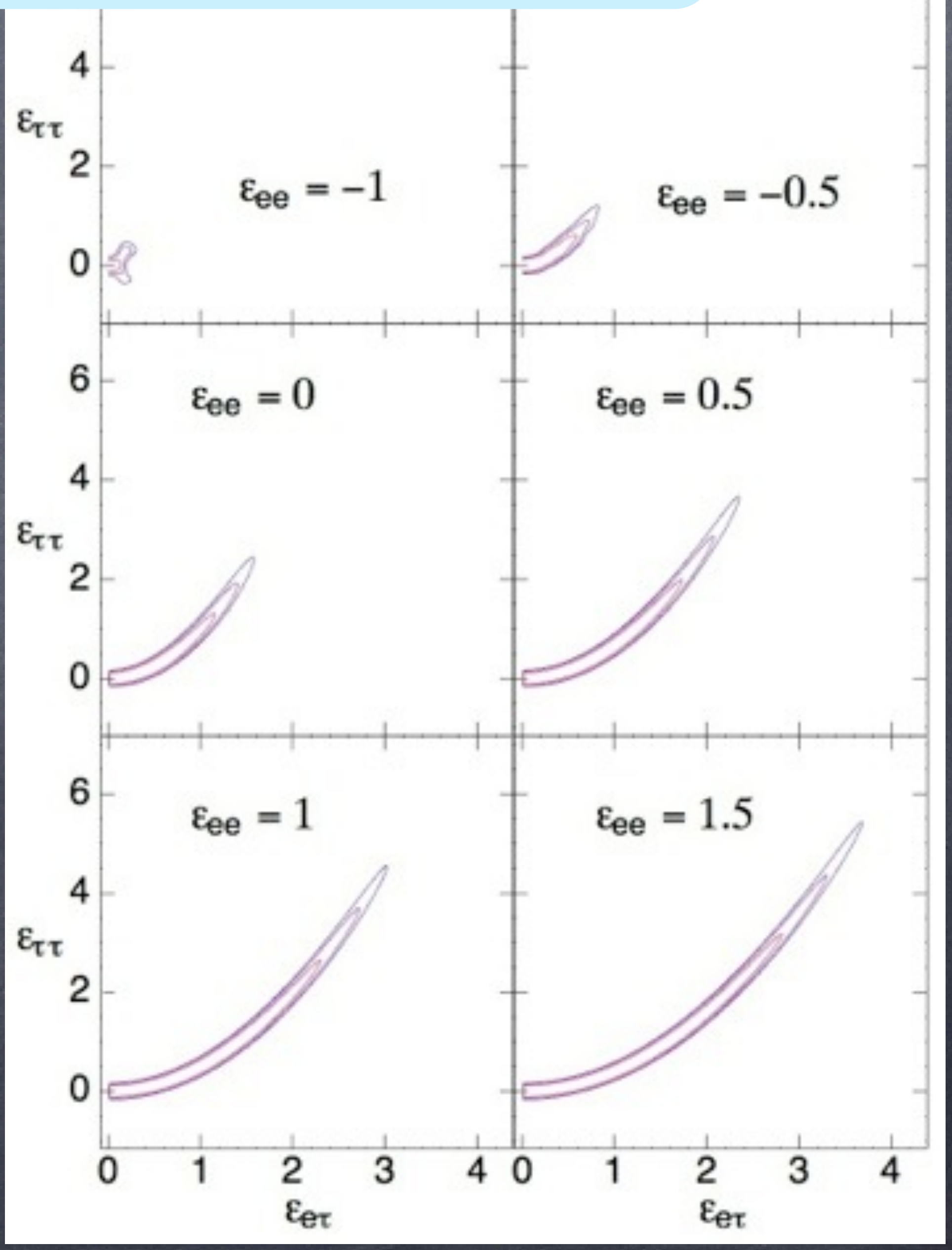
Constraints from high energy behavior of ν_{atm}

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m_{21}^2}{2E} & 0\\ 0 & 0 & \frac{\Delta m_{31}^2}{2E}\end{pmatrix}U^{-1} + \mathcal{A} + \mathcal{A}_{\mathcal{NP}}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

High energy ν_{atm} data are well described by vacuum oscillation between $\nu_\mu \Leftrightarrow \nu_\tau$.

$$\epsilon_{\tau\tau} \simeq \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}$$

Friedland-Lunardini
Phys. Rev. D 70, 111301(R) (2004)



Summary of the constraints on NSI

We analyze with the ansatz as follows :

$$\begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} = \begin{pmatrix} \epsilon_{ee} & 0 & |\epsilon_{e\tau}|e^{i\phi} \\ 0 & 0 & 0 \\ |\epsilon_{e\tau}|e^{-i\phi} & 0 & \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}} \end{pmatrix}$$

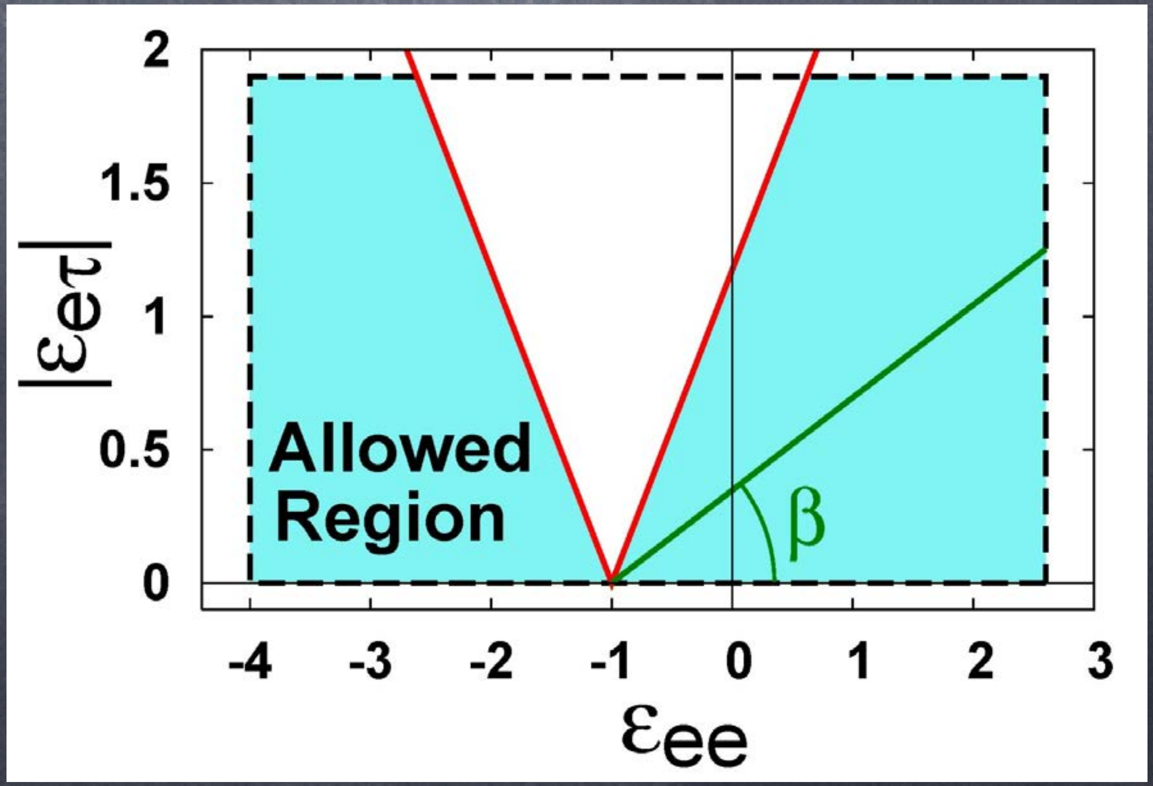
terrestrial experiments

high energy atmospheric neutrino

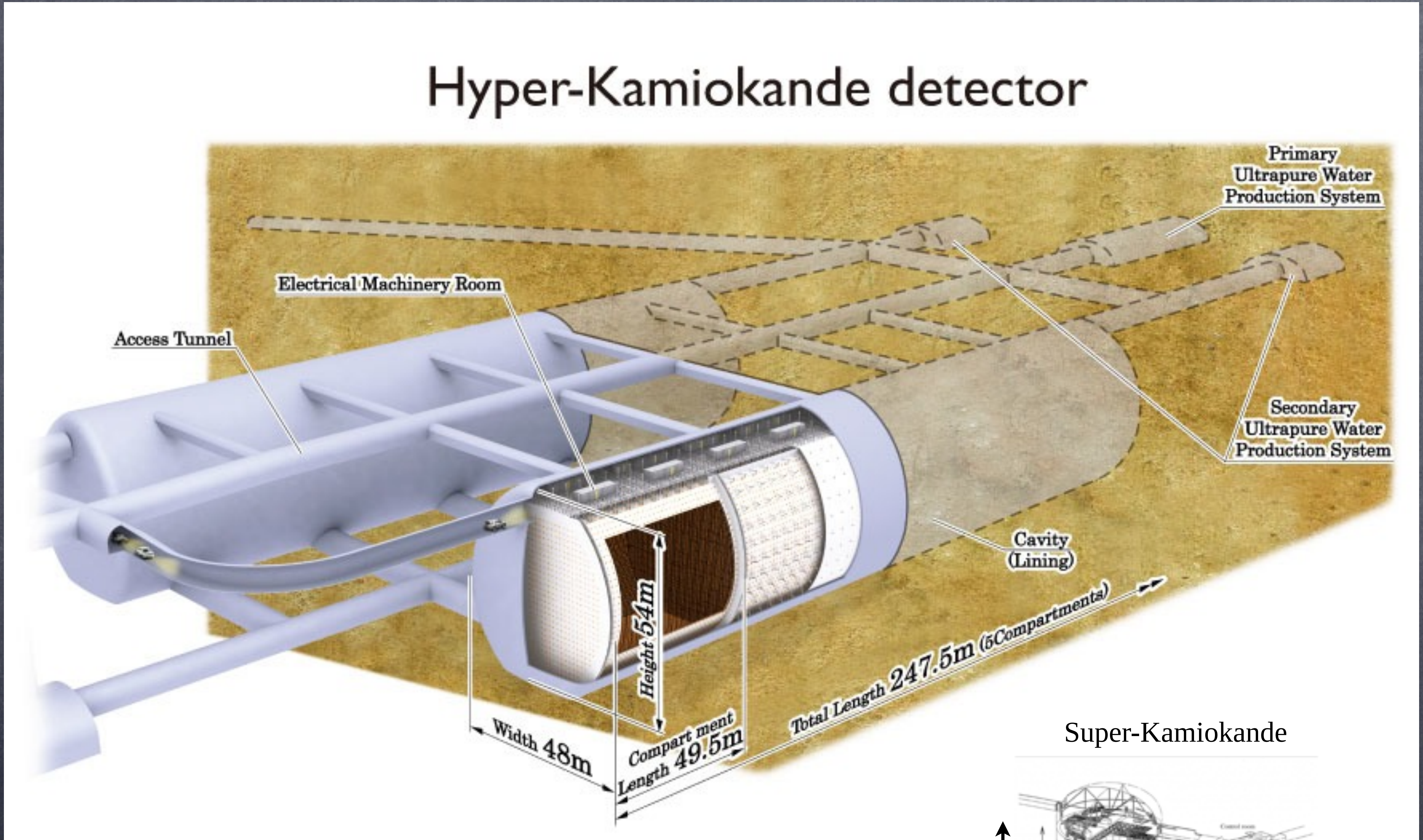
We consider the low energy atmospheric neutrino experiments data. It leads constrains on NSI as follows:

$$|\tan\beta| \equiv \frac{|\epsilon_{e\tau}|}{1+\epsilon_{ee}} < 1.5(@2.5\sigma).$$

Friedland-Lunardini Phys. Rev. D 72, 053009 (2005)



SK vs. HK



HK ~ 20 × SK

Analysis

def. of χ²

Super-K $\chi^2(\epsilon_{ee}, |\epsilon_{e\tau}|) = \min[\sum_j \frac{\{N_j^0(\epsilon_{ee}, \epsilon_{e\tau}) - N_j(data)\}^2}{\sigma_j^2}]$

Hyper-K $\chi^2(\epsilon_{ee}, |\epsilon_{e\tau}|) = \min[\sum_j \frac{\{N_j^0(\epsilon_{ee}, \epsilon_{e\tau}) - N_j(standard)\}^2}{\sigma_j^2}]$

#events@HK = 20 x #events@SK (std. case is assumed)

parameters

fixed : $\theta_{12}, \theta_{13}, \Delta m^2_{21}$ ($\sin^2 2\theta_{12}$=0.86, $\sin^2 2\theta_{13}$=0.1, Δm^2_{21}=7.6×10^{-5}eV^2)

marginalized : θ_{23}, Δm^2_{31} , δ, arg($\varepsilon_{e\tau}$)

Based on O. Yasuda, Phys. Rev. D 58, 091301(R) (1998)

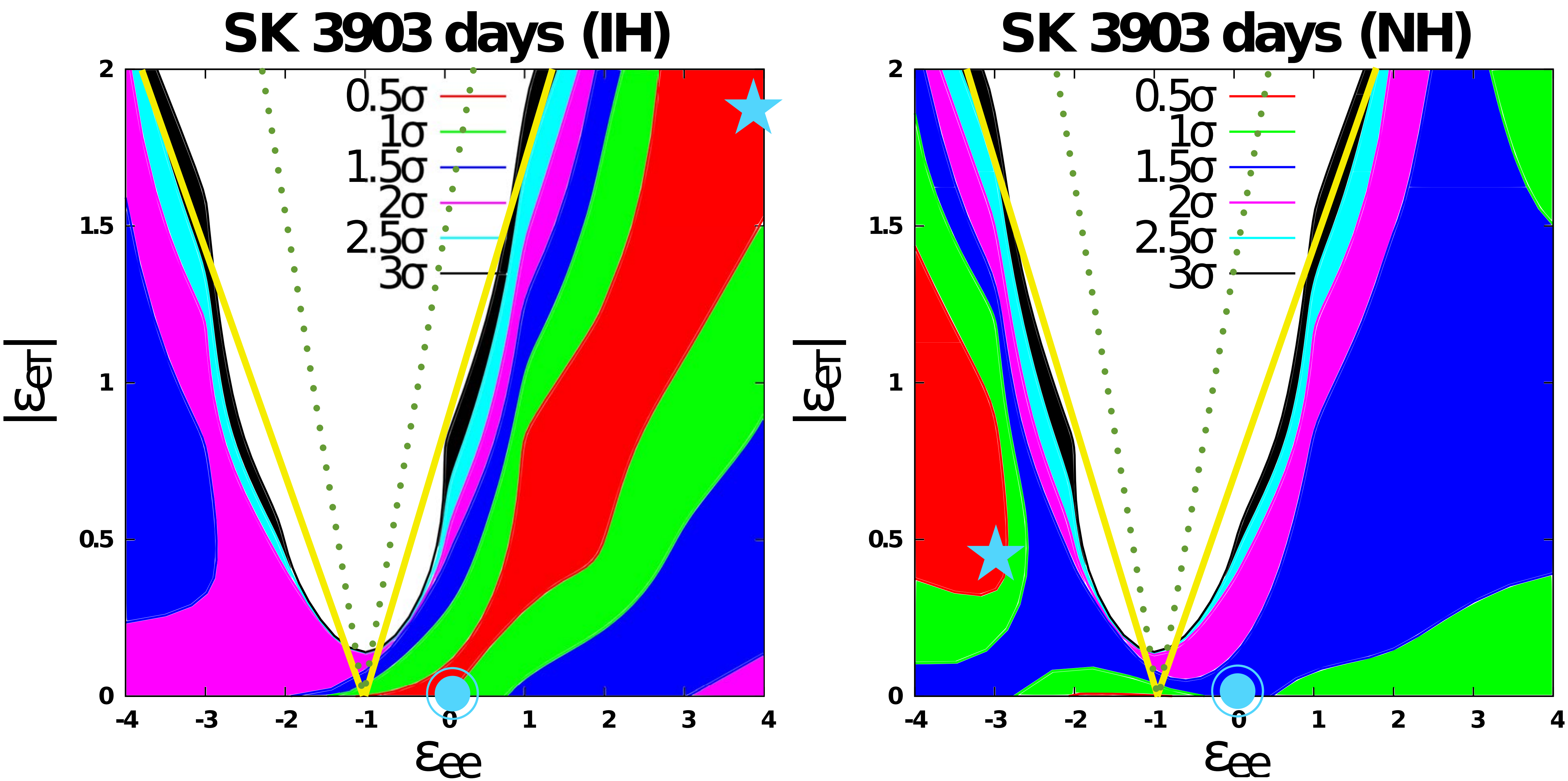
Results① - SK

NH: $\Delta m^2_{32} > 0$

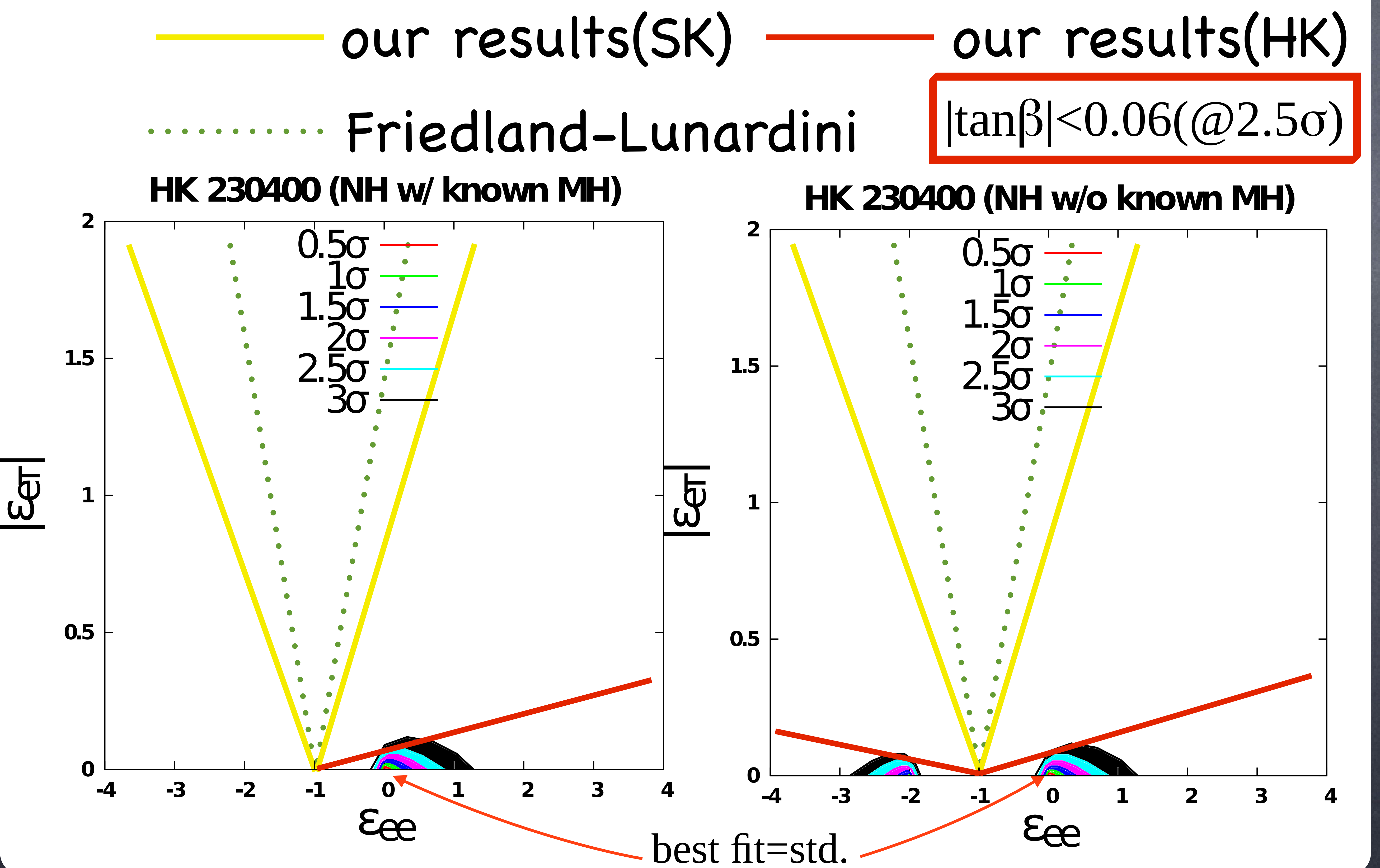
IH: $\Delta m^2_{32} < 0$

★ :best fit — our results $|\tan\beta| < 0.8$ (@2.5σ)

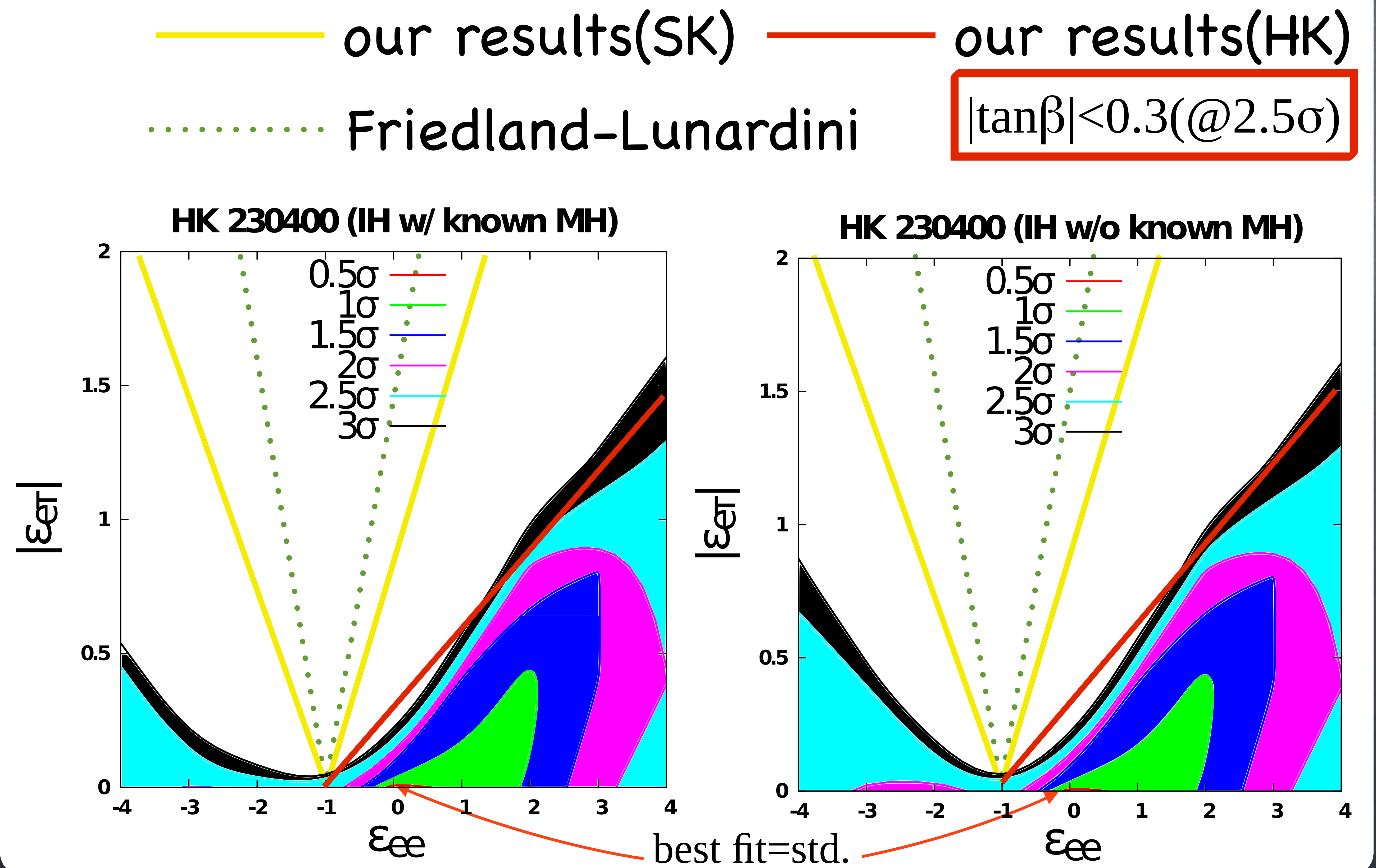
◉ :std. ······ Friedland-Lunardini $|\tan\beta| < 1.5$ (@2.5σ)



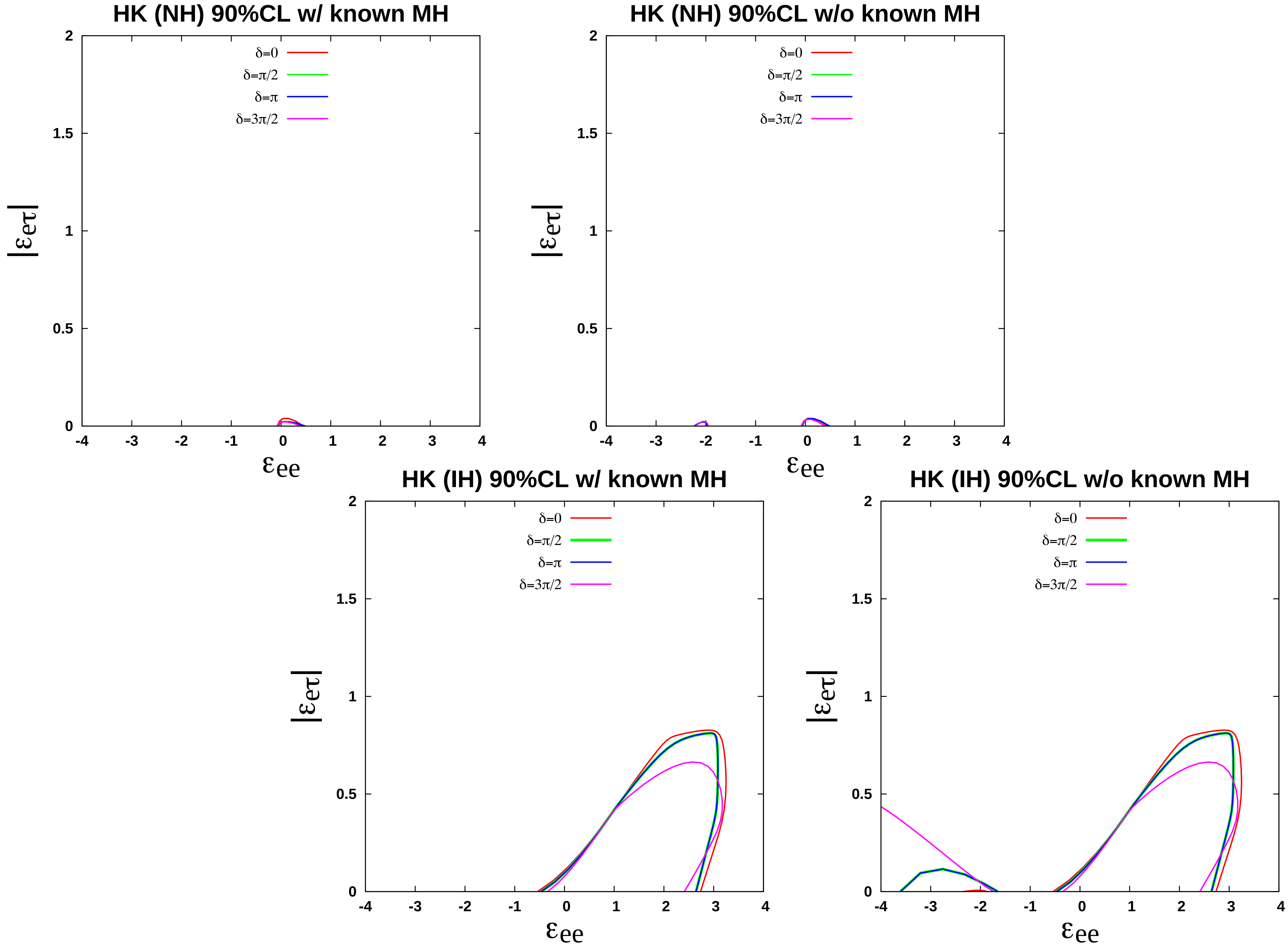
Results② - HK(Normal Hierarchy)



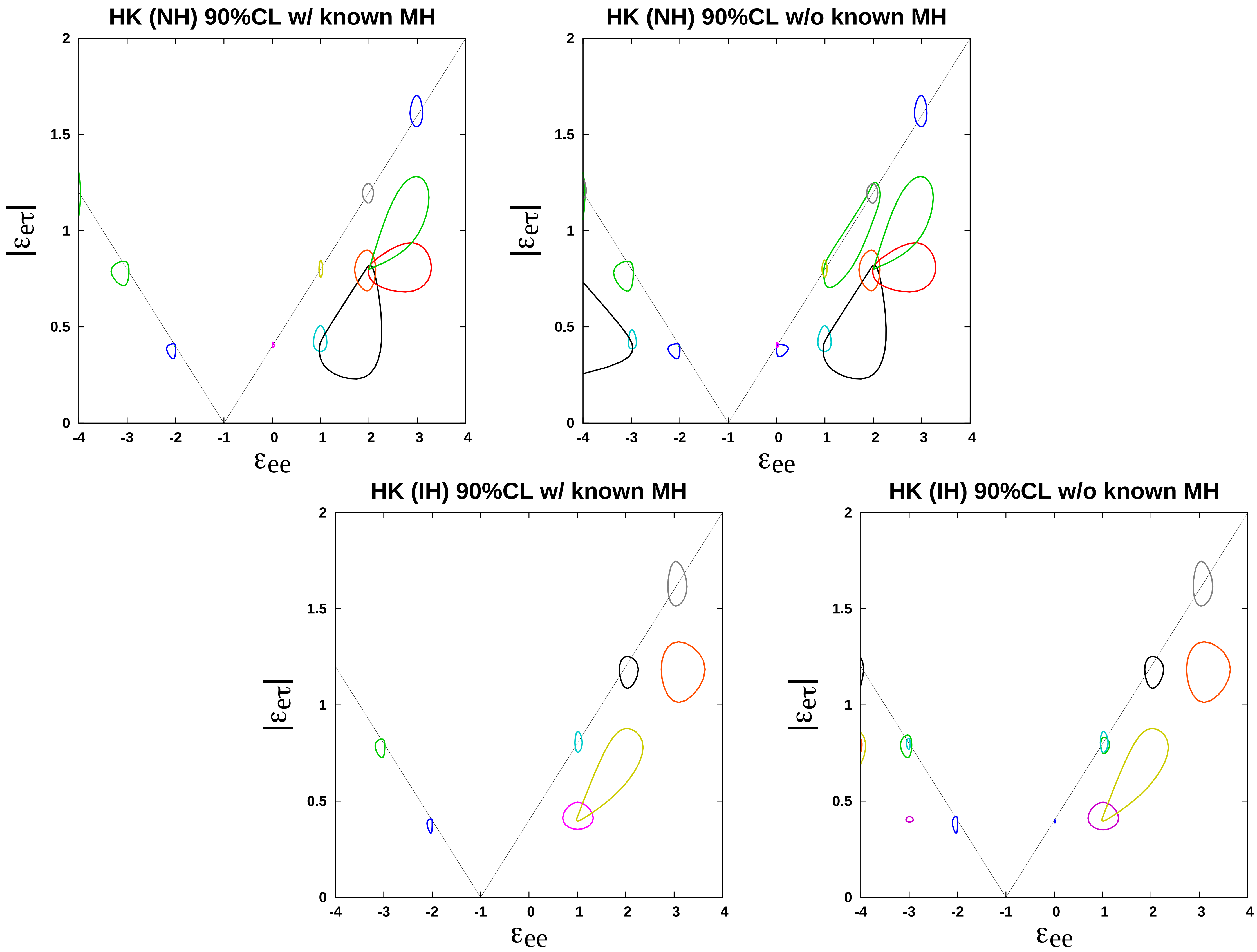
Results③ - HK(Inverted Hierarchy)



Results④ – allowed regions at HK with various CP phases



Results⑤ – Sensitivity to non-zero ε at HK



Conclusion

- Considering constraints from terrestrial experiments and high energy behavior of ν_{atm}, we set the ansatz :

$$\varepsilon_{e\mu} = \varepsilon_{\mu\mu} = \varepsilon_{\mu\tau} = 0 \ \& \ \varepsilon_{\tau\tau}=|\ \varepsilon_{e\tau}\ |^2/(1+\varepsilon_{ee}).$$

Under the ansats we studied sensitivity to NIS of ν_e-ν_τ sector in propagation at SK and HK.

- The excluded region at SK is improved compared with old one given by Friedland-Lunardini in 2005, because we used updated SK data.

- The excluded region at HK are obtained and HK are expected to improve constraints.

- We studied sensitivity to non-zero NSI at HK. If NSI are sufficiently large, HK can determine ε_{ee} and $|\varepsilon_{e\tau}|$ precisely.

back up

chi^2

$$\chi^2(\epsilon_{ee},|\epsilon_{e\tau}|,\theta_{23},\Delta m^2_{32},\delta_{cp},\phi) = \min_{\substack{\alpha,\beta_s,\\ \beta_m,\eta_s,\eta_m}} \Big\{\sum_j \sum_{A=s,m} \Big[\frac{1}{N^{ex,j}_{A,e}}\{N^{ex,j}_{A,e} - (1+\alpha+\beta_A+\eta_A)N^j_{A,ee}$$
$$-(1+\alpha-\beta_A+\eta_A)N^j_{A,\mu e} - (1+\alpha+\beta_A-\eta_A)\overline{N}^j_{A,ee} - (1+\alpha-\beta_A-\eta_A)\overline{N}^j_{A,\mu e}\}^2$$
$$+\frac{1}{N^{ex,j}_{A,\mu}}\{N^{ex,j}_{A,\mu} - (1+\alpha+\beta_A+\eta_A)N^j_{A,e\mu} - (1+\alpha-\beta_A+\eta_A)N^j_{A,\mu\mu}$$
$$-(1+\alpha+\beta_A-\eta_A)\overline{N}^j_{A,e\mu} - (1+\alpha-\beta_A-\eta_A)\overline{N}^j_{s,\mu\mu}\}^2\Big]$$
$$+\left(\frac{\alpha}{\sigma_\alpha}\right)^2+\left(\frac{\beta_s}{\sigma_{\beta_s}}\right)^2+\left(\frac{\beta_m}{\sigma_{\beta_m}}\right)^2+\left(\frac{\eta_s}{\sigma_{\eta_s}}\right)^2+\left(\frac{\eta_m}{\sigma_{\eta_m}}\right)^2\Big\}$$

j:zenith angels

σ_α:flux
$\sigma_{\beta s}$:ν_e/ν_μ(sub-Gev)
$\sigma_{\beta m}$:ν_e/ν_μ(multi-Gev)
$\sigma_{\eta s}$:$\overline{\nu}/\nu$(sub-Gev)
$\sigma_{\eta m}$:$\overline{\nu}/\nu$(multi-Gev)

derivation of $\epsilon_{\tau\tau} \simeq \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E} & 0\\ 0 & 0 & \frac{\Delta m^2_{31}}{2E}\end{pmatrix}U^\dagger + A_{\rm CC}\begin{pmatrix}1+\epsilon_{ee} & 0 & \epsilon_{e\tau}\\ 0 & 0 & 0\\ \epsilon^*_{e\tau} & 0 & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

diagonalize

$$i\frac{d}{dt}\begin{pmatrix}\nu'_e\\ \nu_\mu\\ \nu'_\tau\end{pmatrix} = \left[U'\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E} & 0\\ 0 & 0 & \frac{\Delta m^2_{31}}{2E}\end{pmatrix}U'^\dagger + \begin{pmatrix}\lambda'_e & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & \lambda'_\tau\end{pmatrix}\right]\begin{pmatrix}\nu'_e\\ \nu_\mu\\ \nu'_\tau\end{pmatrix}$$

$$\lambda'_e = A_{cc}(1+\epsilon_{ee}+\epsilon_{\tau\tau}+\sqrt{(1+\epsilon_{ee}-\epsilon_{\tau\tau})+4|\epsilon_{e\tau}|^2})$$
$$\lambda'_\tau = A_{cc}(1+\epsilon_{ee}+\epsilon_{\tau\tau}-\sqrt{(1+\epsilon_{ee}-\epsilon_{\tau\tau})+4|\epsilon_{e\tau}|^2})$$

vacuum oscillation between $\nu'_\mu \Leftrightarrow \nu_\tau$ ⇒ $\lambda'_e=0$

$$\lambda'_e = 0 \leftrightarrow \epsilon_{\tau\tau} = \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}$$