Probing Non-standard Neutrino Interactions at Neutrino Factories

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Based on the work with
N. Cipriano Ribeiro, H. Minakata, S. Uchinami and R. Zukanovich Funchal,
to appear

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Outline

- Introduction
- A strategy to constrain or discover non-standard interactions (NSI) of neutrinos at neutrino factories (qualitative discussions) using bi-probability plots
- Results of our statistical analysis (quantitative discussions) on potential to probe NSI
- Summary

Current Status

- Standard 3 flavors of active massive and mixed neutrinos can perfectly explain all the neutrino data (except for LSND)
- Mass induced oscillation is the unique mechanism which can explain simultaneously all the neutrino data
- However, there is still some room to have some effect coming from new physics (non-standard neutrino properties) beyond the Standard Model as subdominant effect

Examples of possible sources of non-standard neutrino properties

- neutrino magnetic moment
- neutrino decay
- non-standard interactions (NSI) with matter
- decoherence
- violation of Lorentz invariance
- CPT violation
- Extra dimensions
- Mass Varying Neutrinos
- Long ragne force
- ....

We consider the following effective NSI

(Followng e.g., Davidson et al, hep-ph/0302093)

$$\mathcal{L}_{\mathrm{eff}} = -2\sqrt{2}G_F\varepsilon^{fP}_{\alpha\beta}(\overline{\nu}_\alpha\gamma_\rho L\nu_\beta)(\overline{f}\gamma^\rho Pf)$$

$\varepsilon_{\alpha\beta}$: paramter which charactrizes the strength of NSI

f: 1st generation SM fermions, e, u, d

$P = L$ or R (Projection Operator)

Such kinds of non-standard interactions (NSI) of neutrinos can contribute to "neutrino oscillation" signal

(i) via CC interactions in the soucer or detector,

or

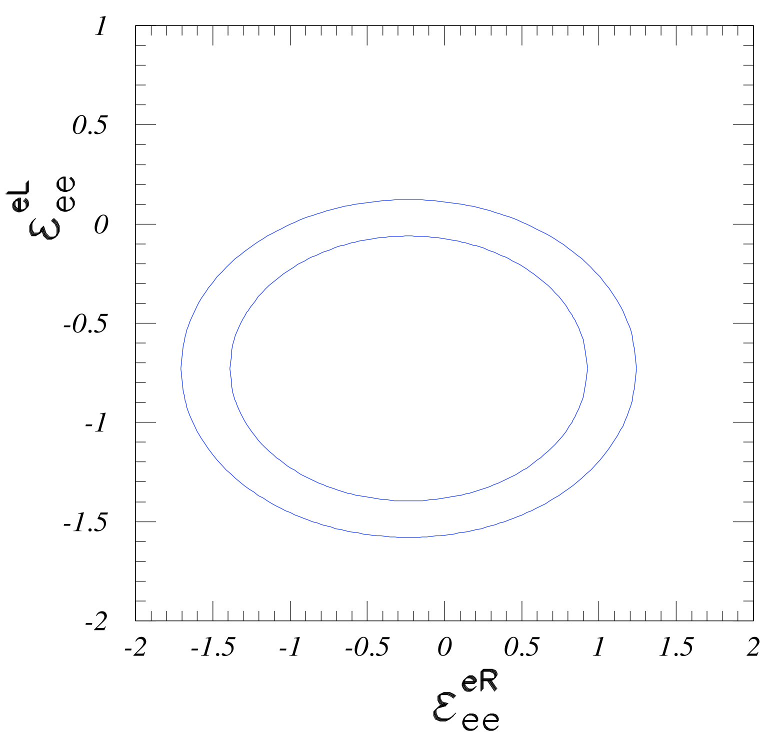
(ii) via NC interactions during the propagation from the source to detector

Bounds on NSI, an example

$\nu_e e \rightarrow \nu_e e$ scattering

$$\sigma(\nu_e e \to \nu e) = \frac{2G_F^2 m_e E_\nu}{\pi} \left[(1 + g_L^e + \varepsilon_{ee}^{eL})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{eL}|^2 + \frac{1}{3}(g_R^e + \varepsilon_{ee}^{eR})^2 + \frac{1}{3} \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{eR}|^2 \right]$$

vs $$\sigma(\nu_e e \to \nu e) = (1.17 \pm 0.17) \frac{G_F^2 m_e E_\nu}{\pi}\,, \quad \text{(LSND)}$$



(taken from Davidson et al, hep-ph/0302093)

Current and future bounds on NSI (Davidson et al, hep-ph/0302093)

vertex	current limits	future limit
$(\bar{e}\gamma^\rho P e)(\bar{\nu}_\tau \gamma_\rho L \nu_\tau)$	$\lvert\varepsilon^{eP}_{\tau\tau}\rvert < 0.5$ $(g^e_A$ @ LEP$)^{*)}$	$-0.2 < \varepsilon^{eL}_{\tau\tau} < 0.3$ $-0.9 < \varepsilon^{eR}_{\tau\tau} < 0.3$ KamLAND and SNO/SK
$(\bar{u}\gamma^\rho P u)(\bar{\nu}_\tau \gamma_\rho L \nu_\tau)$	$\lvert\varepsilon^{uL}_{\tau\tau}\rvert < 1.4$ $\lvert\varepsilon^{uR}_{\tau\tau}\rvert < 3$ $(\Gamma_{inv})^{*)}$	$-0.3 < \varepsilon^{uL}_{\tau\tau} < 0.25$ $-0.25 < \varepsilon^{uR}_{\tau\tau} < 0.3$ KamLAND and SNO/SK
$(\bar{d}\gamma^\rho L d)(\bar{\nu}_\tau \gamma_\rho L \nu_\tau)$	$\lvert\varepsilon^{dL}_{\tau\tau}\rvert < 1.1$ $\lvert\varepsilon^{dR}_{\tau\tau}\rvert < 6$ $(\Gamma_{inv})^{*)}$	$-0.25 < \varepsilon^{dL}_{\tau\tau} < 0.3$ $-0.3 < \varepsilon^{dR}_{\tau\tau} < 0.25$ KamLAND and SNO/SK
$(\bar{e}\gamma^\rho P e)(\bar{\nu}_\mu \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{eP}_{\mu\mu}\rvert < 0.03$ CHARM II	$\lvert\varepsilon^{eL}_{\mu\mu}\rvert < 0.003$ $\lvert\varepsilon^{eR}_{\mu\mu}\rvert < 0.001$ leptonic s^2_W at nufact
$(\bar{u}\gamma^\rho P u)(\bar{\nu}_\mu \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{uL}_{\mu\mu}\rvert < 0.003$ $-0.008 < \varepsilon^{uR}_{\mu\mu} < 0.003$ NuTeV	$\lvert\varepsilon^{uL}_{\mu\mu}\rvert < 0.001$ $\lvert\varepsilon^{uR}_{\mu\mu}\rvert < 0.002$ s^2_W in DIS at nufact
$(\bar{d}\gamma^\rho P d)(\bar{\nu}_\mu \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{dL}_{\mu\mu}\rvert < 0.003$ $-0.008 < \varepsilon^{dR}_{\mu\mu} < 0.015$ NuTeV	$\lvert\varepsilon^{dL}_{\mu\mu}\rvert < 0.0009$ $\lvert\varepsilon^{dR}_{\mu\mu}\rvert < 0.005$ s^2_W in DIS at nufact
$(\bar{e}\gamma^\rho P e)(\bar{\nu}_e \gamma_\rho L \nu_e)$	$-0.07 < \varepsilon^{eL}_{ee} < 0.1$ $-1 < \varepsilon^{eR}_{ee} < 0.5$ LSND	$\lvert\varepsilon^{eL}_{ee}\rvert < 0.0004$ $\lvert\varepsilon^{eR}_{ee}\rvert < 0.004$ leptonic s^2_W at nufact
$(\bar{u}\gamma^\rho P u)(\bar{\nu}_e \gamma_\rho L \nu_e)$	$-1 < \varepsilon^{uL}_{ee} < 0.3$ $-0.4 < \varepsilon^{uR}_{ee} < 0.7$ CHARM	$\lvert\varepsilon^{uL}_{ee}\rvert < 0.001$ $\lvert\varepsilon^{uR}_{ee}\rvert < 0.002$ s^2_W in DIS at nufact
$(\bar{d}\gamma^\rho P d)(\bar{\nu}_e \gamma_\rho L \nu_e)$	$-0.3 < \varepsilon^{dL}_{ee} < 0.3$ $-0.6 < \varepsilon^{dR}_{ee} < 0.5$ CHARM	$\lvert\varepsilon^{dL}_{ee}\rvert < 0.0009$ $\lvert\varepsilon^{dR}_{ee}\rvert < 0.005$ s^2_W in DIS at nufact

vertex	current limits	future limit
$(\bar{e}\gamma^\rho P e)(\bar{\nu}_\tau \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{eP}_{\tau\mu}\rvert < 1.2$ $(\tau \to \mu \bar{e} e)^{*)}$ $\lvert\varepsilon^{eP}_{\tau\mu}\rvert < 0.1$ CHARM II	$\lvert\varepsilon^{eL}_{\tau\mu}\rvert < 0.04, \lvert\varepsilon^{eR}_{\tau\mu}\rvert < 0.02$ leptonic s^2_W at nufact
$(\bar{u}\gamma^\rho P u)(\bar{\nu}_\tau \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{uP}_{\tau\mu}\rvert < 2.8$ $(\tau \to \mu\rho)^{*)}$ $\lvert\varepsilon^{uP}_{\tau\mu}\rvert < 0.05$ NuTeV	$\lvert\varepsilon^{uP}_{\tau\mu}\rvert < 0.03$ s^2_W in DIS at nufact
$(\bar{d}\gamma^\rho P d)(\bar{\nu}_\tau \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{dP}_{\tau\mu}\rvert < 2.8$ $(\tau \to \mu\rho)^{*)}$ $\lvert\varepsilon^{dP}_{\tau\mu}\rvert < 0.05$ NuTeV	$\lvert\varepsilon^{dP}_{\tau\mu}\rvert < 0.03$ s^2_W in DIS at nufact
$(\bar{e}\gamma^\rho P e)(\bar{\nu}_\mu \gamma_\rho L \nu_e)$	$\lvert\varepsilon^{eP}_{\mu e}\rvert < 5 \times 10^{-4}$ $(\mu \to 3e)^{*)}$	
$(\bar{u}\gamma^\rho P u)(\bar{\nu}_\mu \gamma_\rho L \nu_e)$	$\lvert\varepsilon^{uP}_{\mu e}\rvert < 7.7 \times 10^{-4}$ $(\mathrm{Ti}\mu \to \mathrm{Ti}e)^{*)}$	
$(\bar{d}\gamma^\rho P d)(\bar{\nu}_\mu \gamma_\rho L \nu_e)$	$\lvert\varepsilon^{dP}_{\mu e}\rvert < 7.7 \times 10^{-4}$ $(\mathrm{Ti}\mu \to \mathrm{Ti}e)^{*)}$	
$(\bar{e}\gamma^\rho P e)(\bar{\nu}_\tau \gamma_\rho L \nu_e)$	$\lvert\varepsilon^{eP}_{\tau e}\rvert < 2.9$ $(\tau \to e \bar{e} e)^{*)}$ $\lvert\varepsilon^{eL}_{\tau e}\rvert < 0.4, \lvert\varepsilon^{eR}_{\tau e}\rvert < 0.7$ LSND	$\lvert\varepsilon^{eL}_{\tau e}\rvert < 0.02, \lvert\varepsilon^{eR}_{\tau e}\rvert < 0.04$ leptonic s^2_W at nufact
$(\bar{u}\gamma^\rho P u)(\bar{\nu}_\tau \gamma_\rho L \nu_e)$	$\lvert\varepsilon^{uP}_{\tau e}\rvert < 1.6$ $(\tau \to e\rho)^{*)}$ $\lvert\varepsilon^{uP}_{\tau e}\rvert < 0.5$ CHARM	$\lvert\varepsilon^{uP}_{\tau e}\rvert < 0.03$ s^2_W in DIS at nufact
$(\bar{d}\gamma^\rho P d)(\bar{\nu}_\tau \gamma_\rho L \nu_e)$	$\lvert\varepsilon^{dP}_{\tau e}\rvert < 1.6$ $(\tau \to e\rho)^{*)}$ $\lvert\varepsilon^{dP}_{\tau e}\rvert < 0.5$ CHARM	$\lvert\varepsilon^{dP}_{\tau e}\rvert < 0.03$ s^2_W in DIS at nufact

Summary of Constraints on NSI parameters

$$\begin{pmatrix} -4 < \epsilon_{ee} < 2.6 & |\epsilon_{e\mu}| < 3.8 \times 10^{-4} & |\epsilon_{e\tau}| < 1.9 \\ & -0.05 < \epsilon_{\mu\mu} < 0.08 & |\epsilon_{\mu\tau}| < 0.25 \\ & & |\epsilon_{\tau\tau}| < 18.6 \end{pmatrix}$$

Davidson et al, hep-ph/0302093

We consider only (or mainly) the following most weakly constrained 3 paramters

ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$

Effect of NSI for neutrino propagation

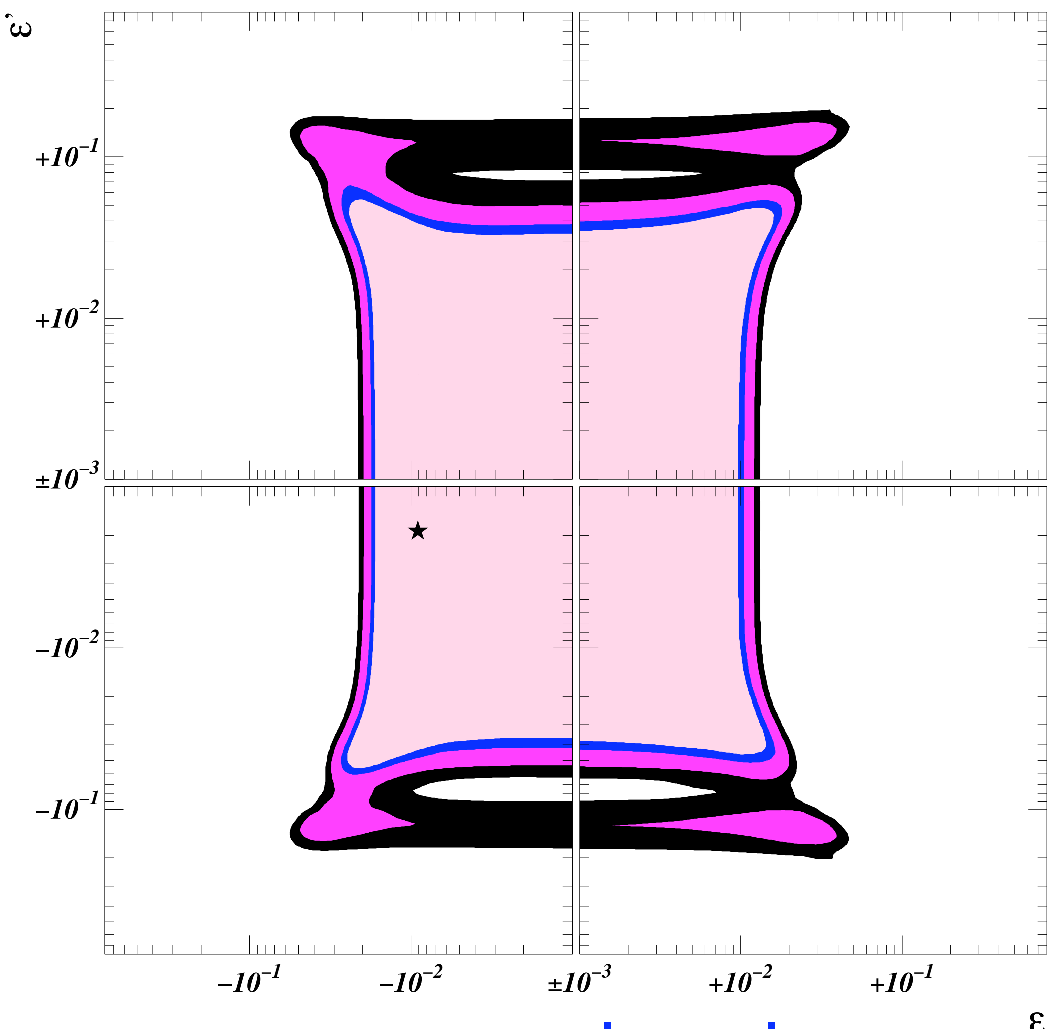
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \mathcal{H}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$\mathcal{H} = U\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m_{21}^2}{2E} & 0\\ 0 & 0 & \frac{\Delta m_{31}^2}{2E}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau}\end{pmatrix}$$

$$A \equiv \sqrt{2}G_F n_e$$

n_e : electron number density

Constraints on NSI parameters from Atmospheric neutrino data (Fornengo et al, hep-ph/0108043)



$$|\varepsilon_{\mu\tau}| = 3|\varepsilon| \lesssim 0.06 \qquad |\varepsilon_{\tau\tau}| = 3|\varepsilon'| \lesssim 0.6$$

How well Neutrino Factories can constrain NSI?

(incomplete) list of some relevant works

- Gago et al, hep-ph/0105196
- Huber, Schwetz, Valle, hep-ph/011224, 0202048
- Sato, Ota, Yamashita, hep-ph/0112329
- Kopp, Lindner, Ota, hep-ph/0702269
- Yasuda, arXiv:0704.1531
- ....

Questions we want to answer

- How can we optimize in order to study non-standard interactions (NSI) at neutrino factories?
- To what extent we can probe/constrain non-standard neutrino interactions?
- What is the impact of these NSI on the determination of the usual mixing parameters?

assuming the case where θ_{13} is small and the standard high energy (> 20-30 GeV) and longer baseline (> 1000km) neutrino factory set up will be build somwhere

Our strategy to constrain/probe NSI at Neutrino Factories

We consider the so called

Golden Channel or

$\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$

For simplicity, we consider only (mainly) ε_{ee} , $\varepsilon_{e\tau}$ and $\varepsilon_{\tau\tau}$ for propagation and ignore possible impact of NSI at source and detection

Then which baseline is the best to constrain or to discover NSI?

Some Hint: hep-ph/0612002, by Minakata and Uchinami

Accurate (a few % level) determination of the Earth matter density can be done at the special baseline so called "Magic Baseline" (see next slides for definition)

Obs. $\rho \to \rho + \delta\rho$ is completely equivalent to add non-zero ε_{ee}

What is Magic baseline?

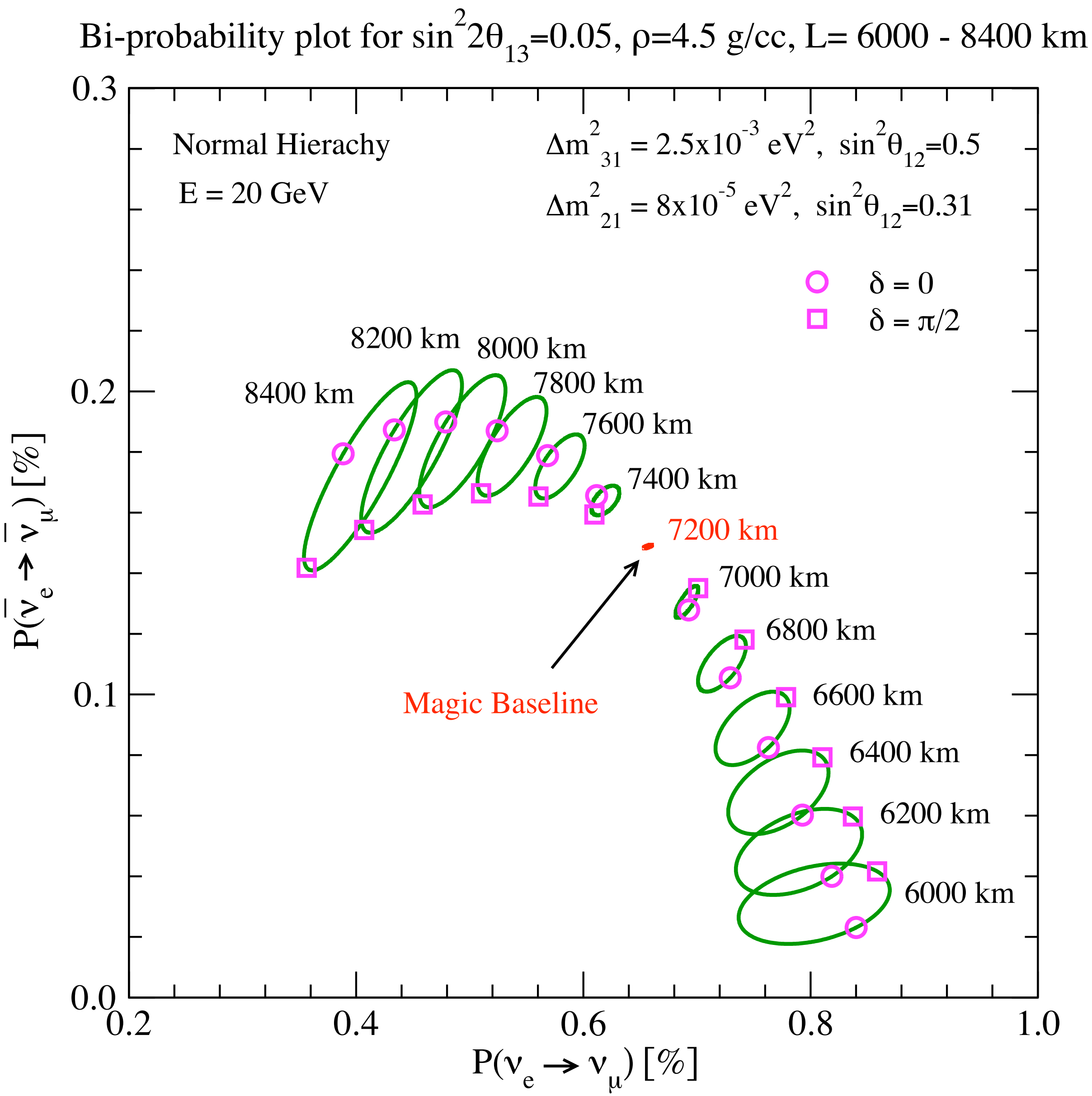
$$L_{magic} \equiv \sqrt{2}\pi/(G_F n_e)$$
$$\approx 7200\ [4.5\ \mathrm{gcm}^{-3}/\rho]\ \mathrm{km}$$

At L_{magic} dependence on solar mixing parameters and CP phase disappear

Huber, Walter, hep-ph/0301257

(see Smirnov, hep-ph/061098 for theoretical understanding)

Bi-probability ellipses srhink to a point at Magic baseline



θ_{13} : fixed

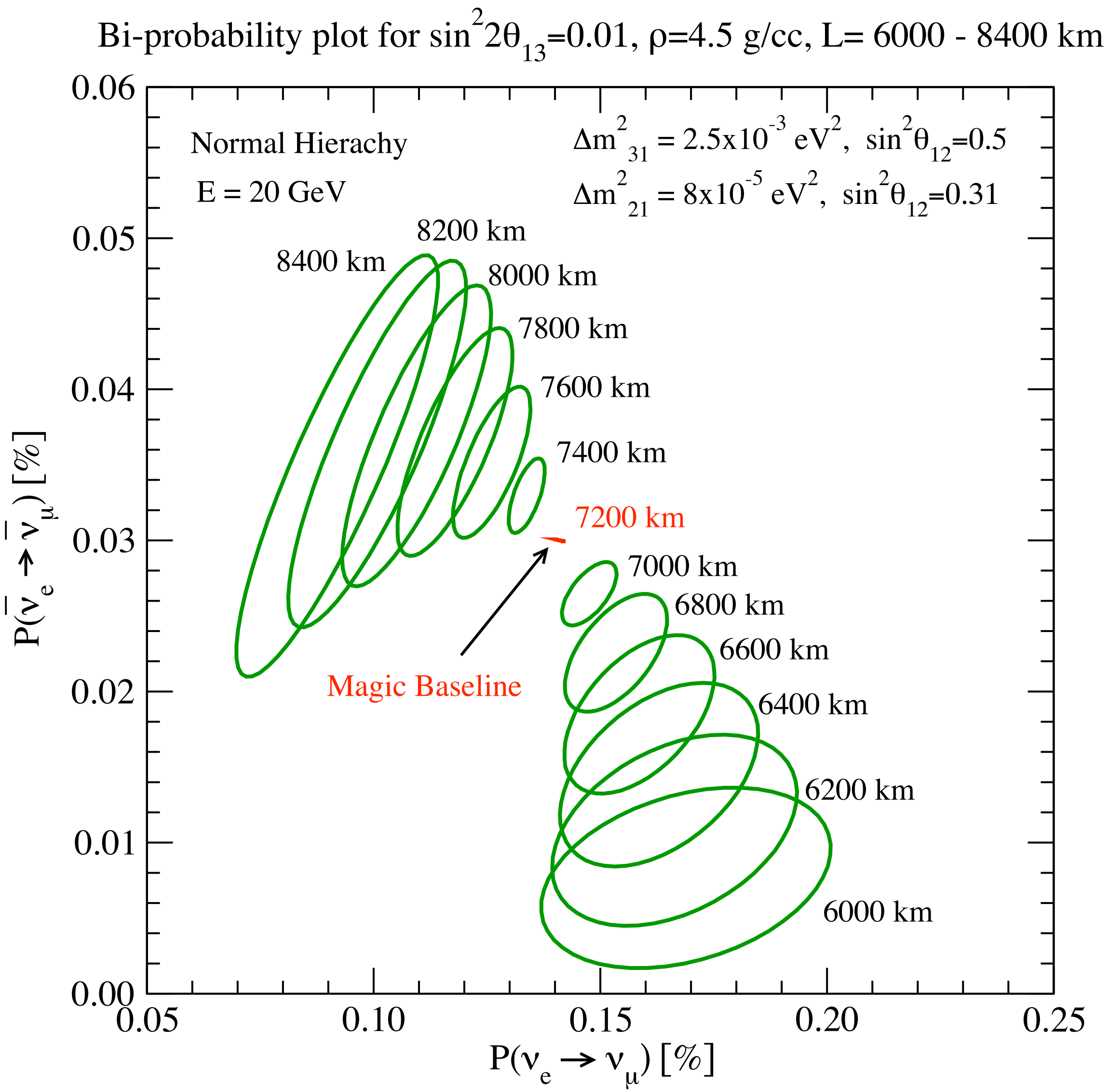
$\sin^2 2\theta_{13}$ =0.05

δ : varied from 0 to 2π

E = 20 GeV

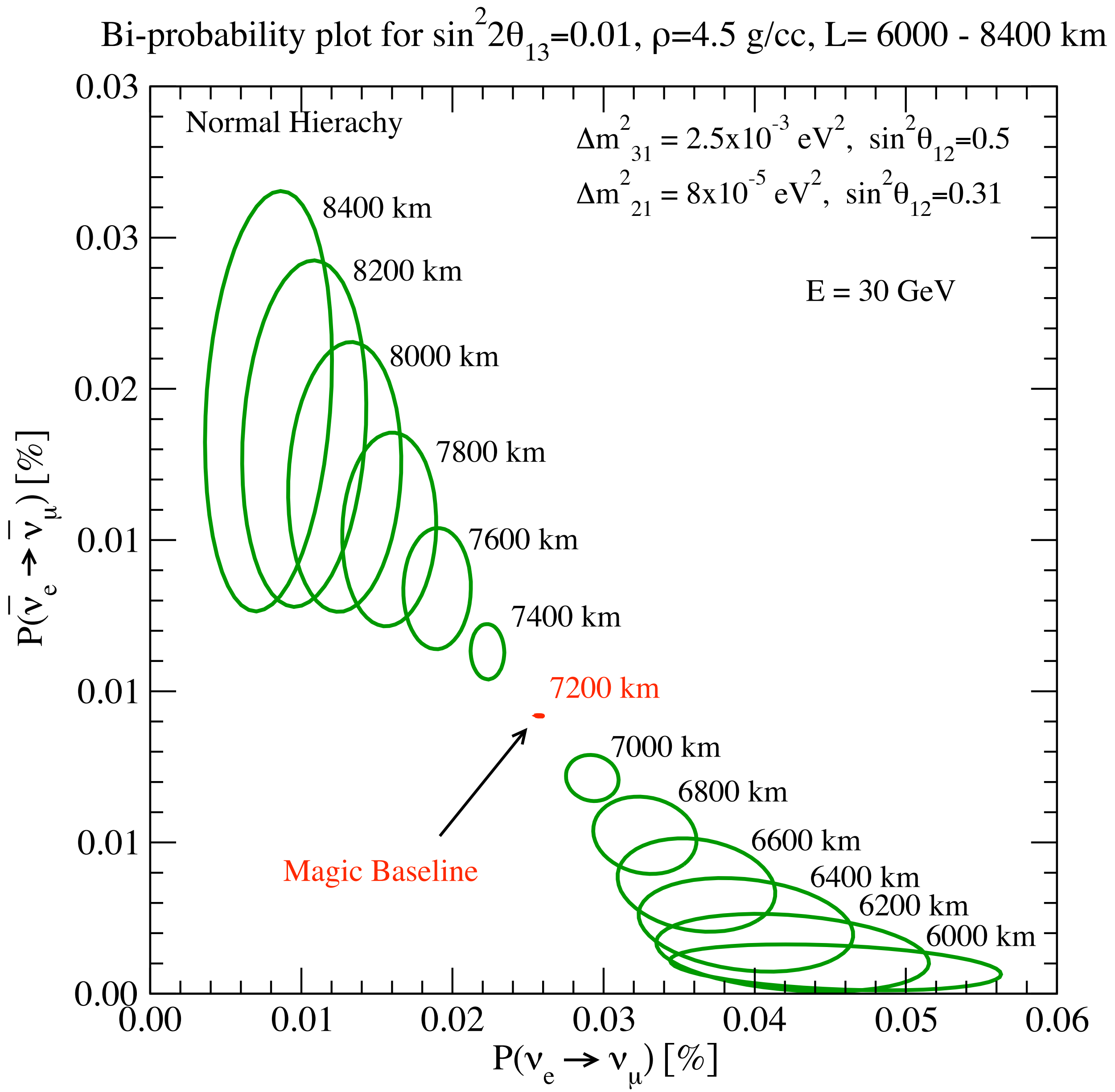
Standard 3 flavor neutrinos w/o NSI

For $\sin^2 2\theta_{13} = 0.01$, E = 20 GeV

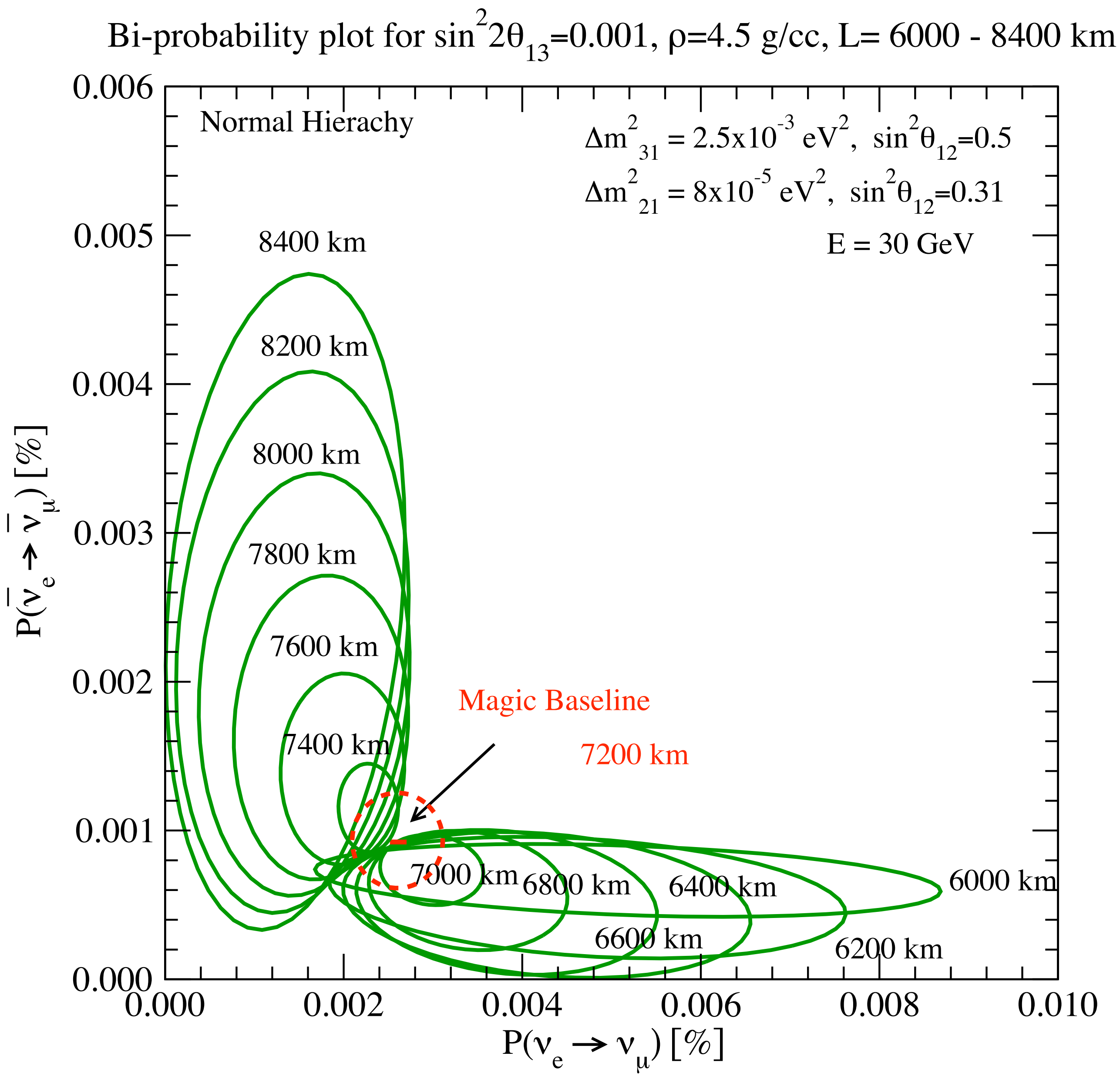


Standard 3 flavor neutrinos w/o NSI

For $\sin^2 2\theta_{13} = 0.01$, E = 30 GeV



For $\sin^2 2\theta_{13} = 0.001$, E = 30 GeV



Oscillation Probabilities (Approx.)

$$P(\nu_e \rightarrow \nu_\mu) \approx \left|\sqrt{P_{atm}}\, e^{-i(\Delta_{32}-\delta)} - \sqrt{P_{sol}}\right|^2$$

$$= P_{atm} + 2\sqrt{P_{atm}}\sqrt{P_{sol}}\cos(\Delta_{32}-\delta) + P_{sol}$$

$$\sqrt{P_{atm}} \equiv \sin\theta_{23}\sin 2\theta_{13}\,\Delta_{31}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}$$

$$\sqrt{P_{sol}} \equiv \cos\theta_{23}\sin 2\theta_{12}\,\Delta_{21}\frac{\sin(aL)}{aL}$$

$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E$ $\qquad$ $a \equiv G_F N_e/\sqrt{2}$

Cervera et al, hep-ph/0002108

At Magic Basline, $L = \sqrt{2}\pi/(G_F N_e)$

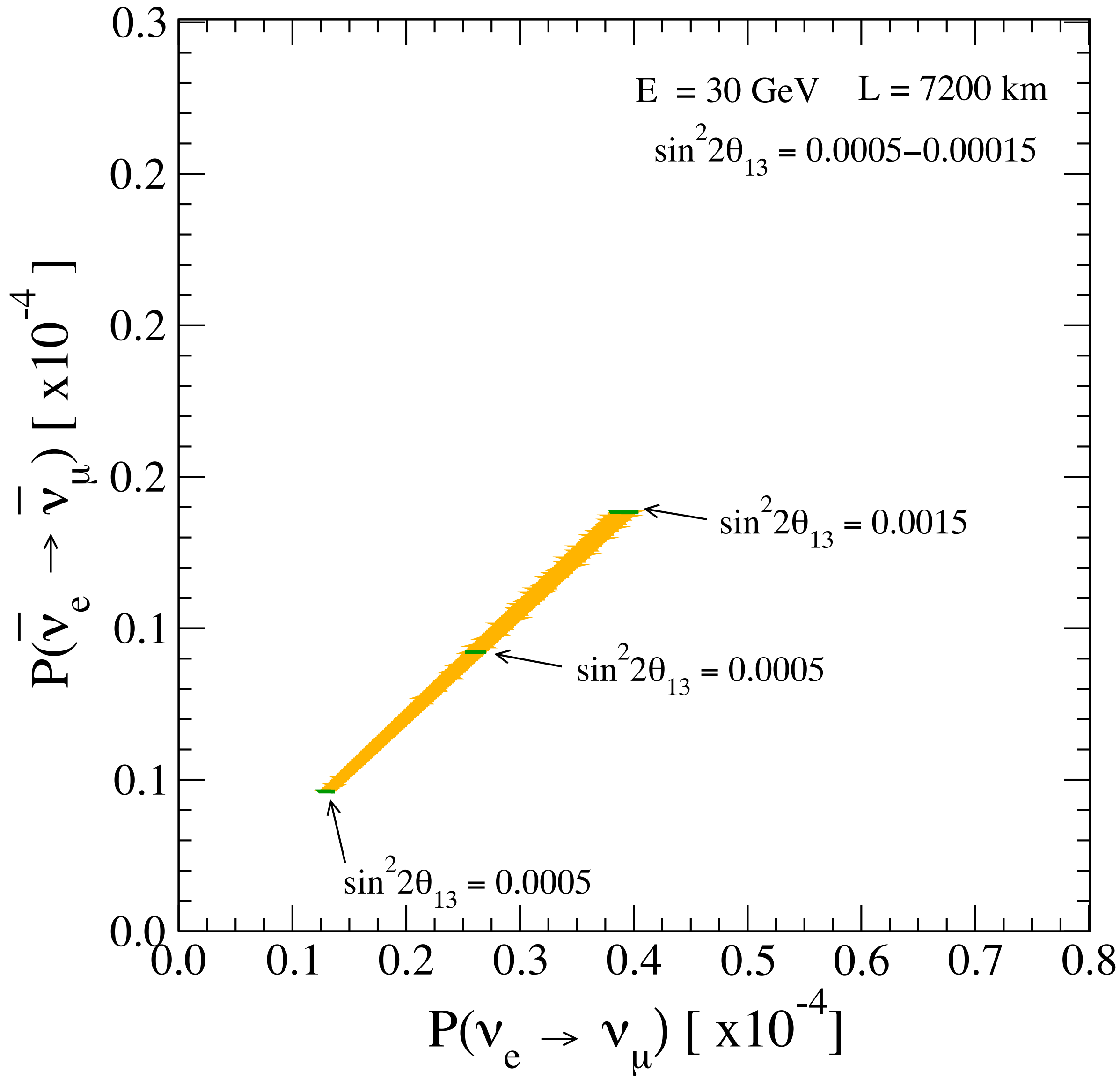
$\sqrt{P_{sol}}$ vanish

$$P(\nu_e \to \nu_\mu) \approx P_{atm}$$

$$= \sin^2\theta_{23} \sin^2 2\theta_{13}\, \Delta^2_{31} \frac{\sin^2\Delta_{31}}{(\Delta_{31} - \pi)^2}$$

No dependence on solar mixing paramters and CP phase

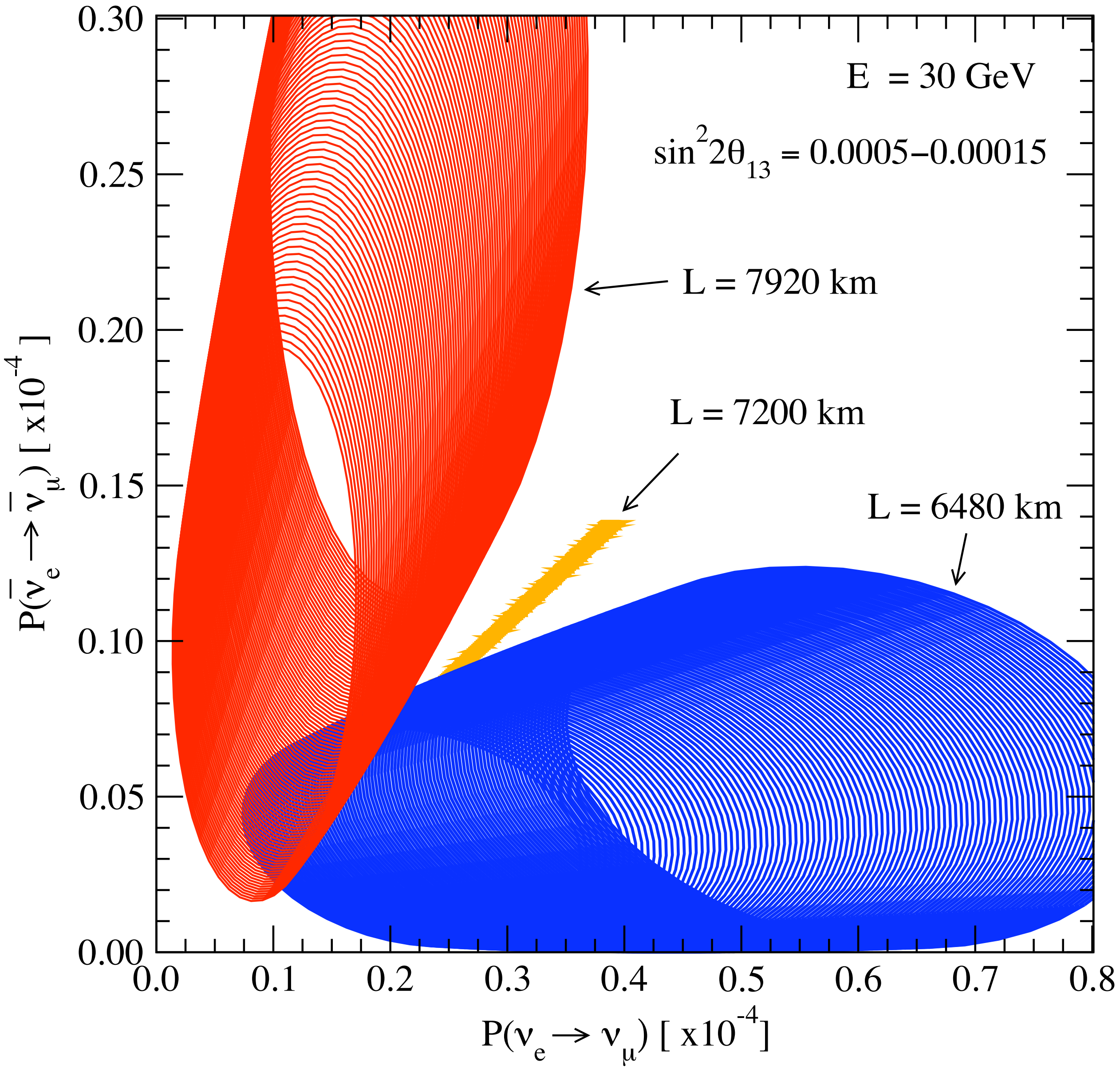
Allowed range of probabilities at Magic baseline



δ, θ_{13}:varied

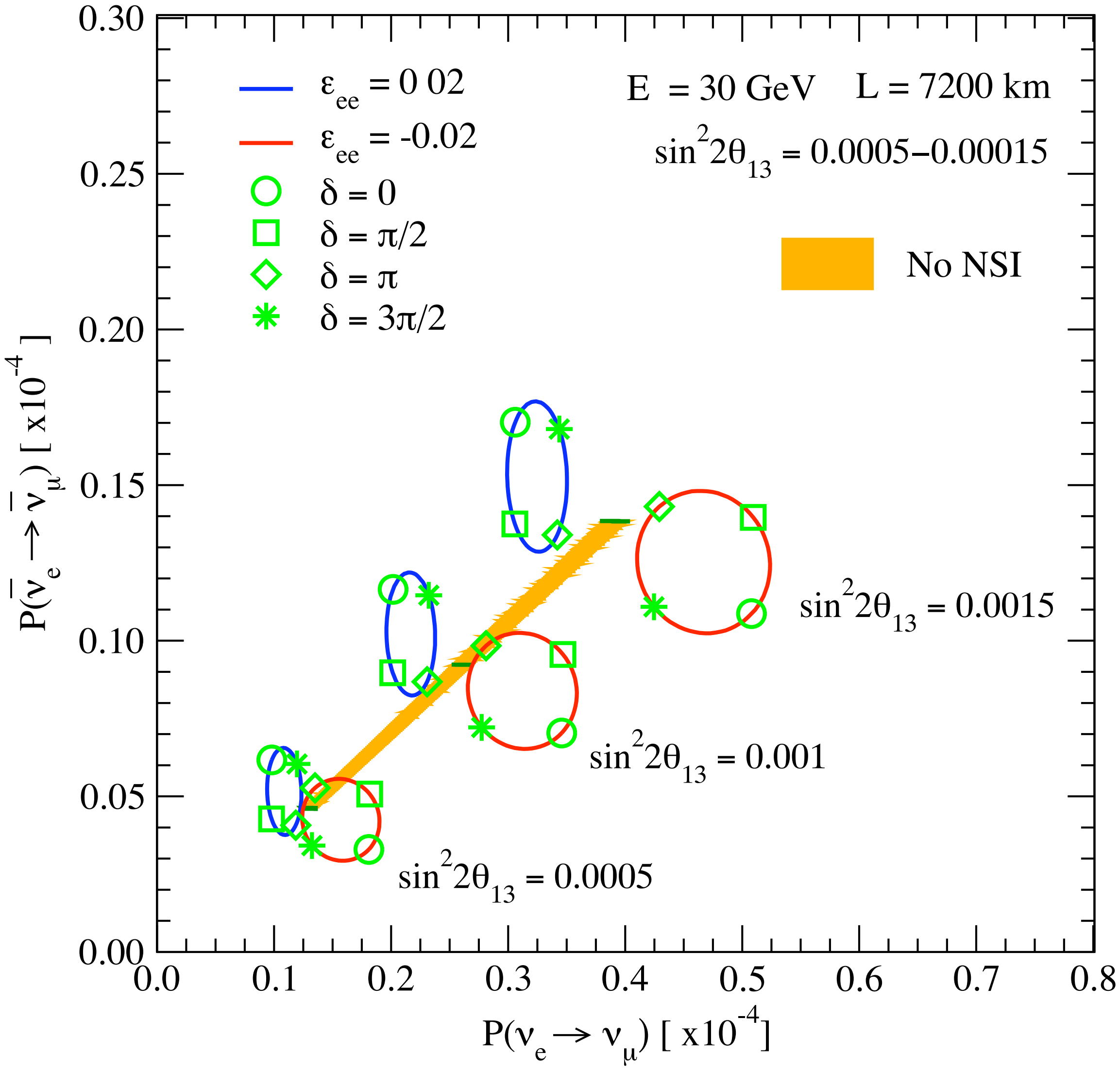
Allowed range of bi-probabilities is quite restricted !

Allowed range of probabilities at Off-Magic baseline



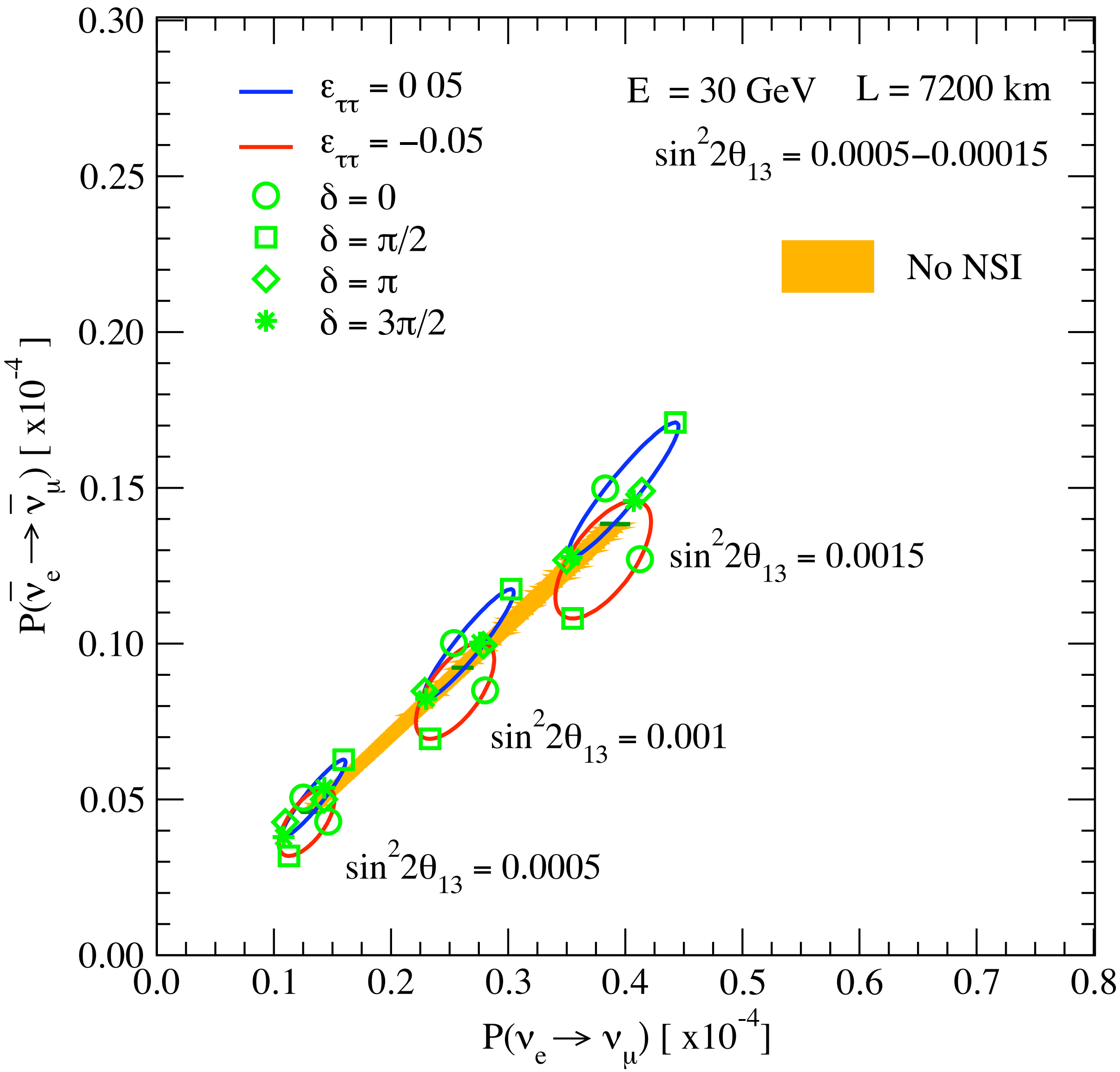
10% away from the Magic baseline

Effects of ε_{ee} on bi-probabilities at Magic baseline

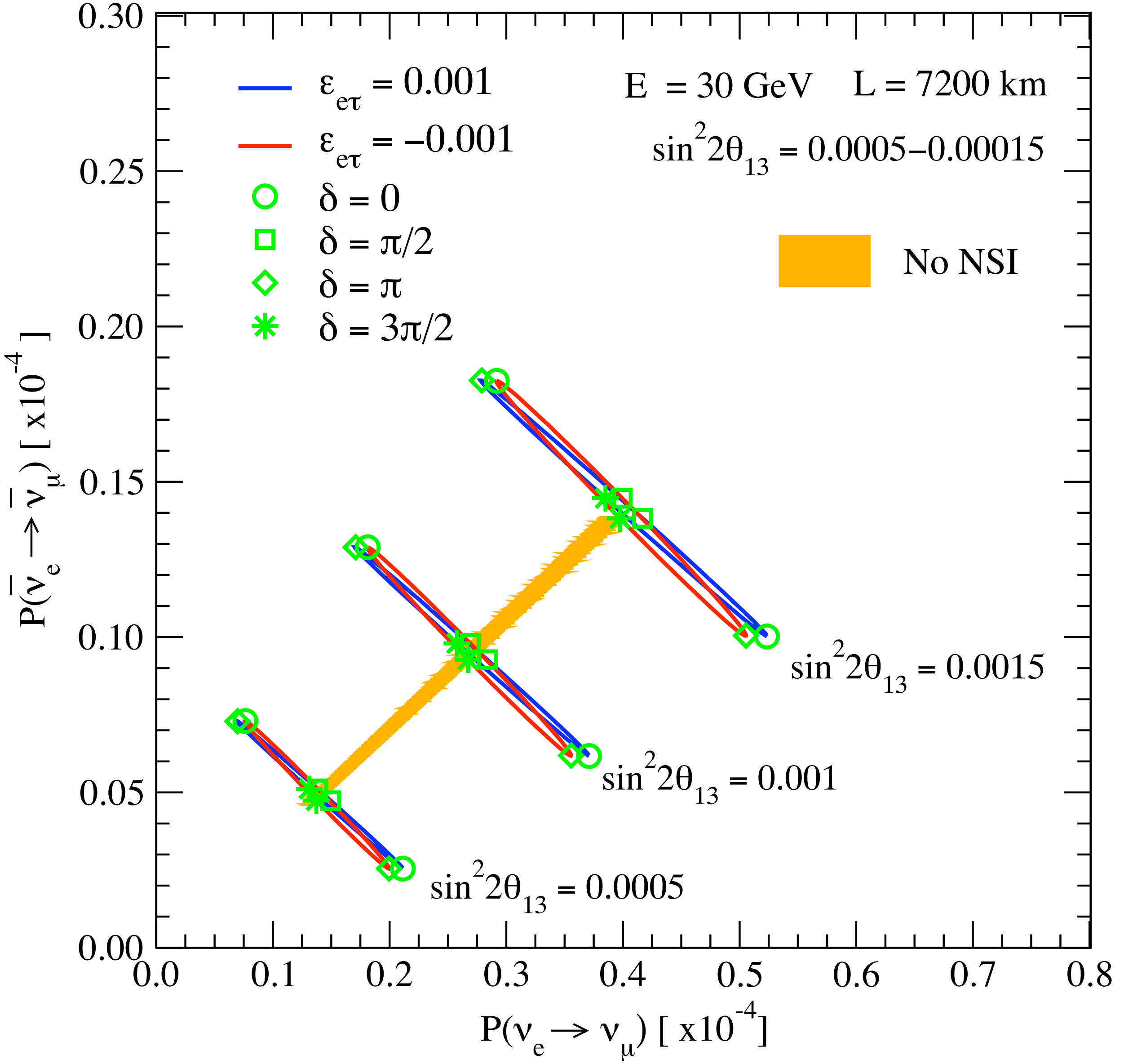


It is equivalent to shift the matter density by 2%

Impact of $\varepsilon_{\tau\tau}$ on bi-probabilities at Magic baseline



Impact of $\varepsilon_{e\tau}$ on bi-probabilities at Magic baseline



Large effect is expected even for small NSI !

At Magic Baseline, for non-zero $\varepsilon_{e\tau}$

$$P(\nu_e \to \nu_\mu) \approx \sin^2\theta_{23} \sin^2 2\theta_{13}\, \Delta^2_{31} \frac{\sin^2\Delta_{31}}{(\Delta_{31}-\pi)^2}$$

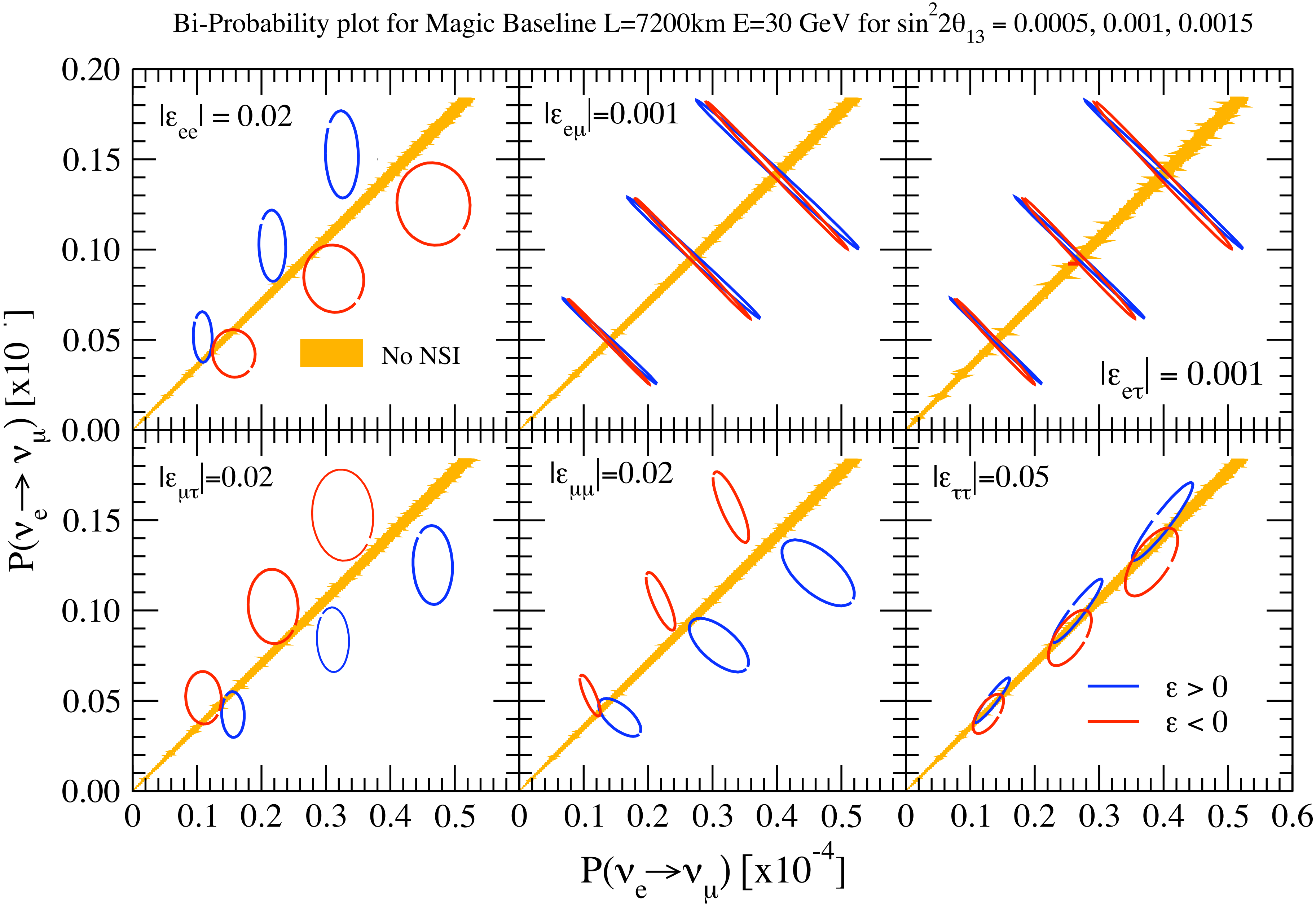
standard term

$$+ \frac{4\pi^2}{(\Delta_{31}-\pi)^2} \cos\theta_{23} \sin^2\theta_{23} \sin^2\Delta_{31}$$

$$\times\left\{2(\Delta_{31}/\pi)\sin\theta_{13}\mathrm{Re}[\varepsilon_{e\tau}e^{i\delta}]+\cos\theta_{23}|\varepsilon_{e\tau}|^2\right\}$$

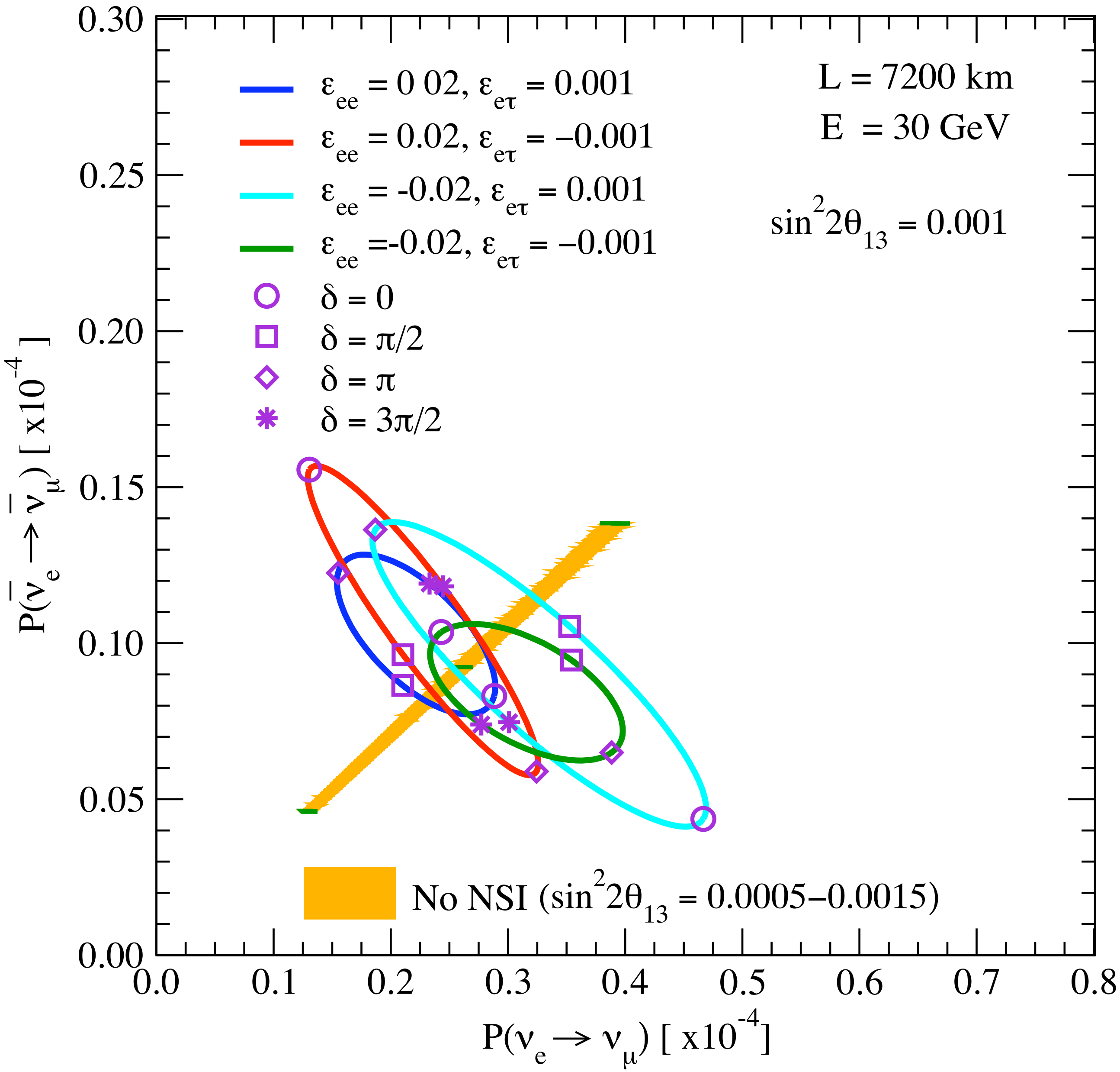
correction due to $\varepsilon_{e\tau}$

Impact of individual ε at Magic baseline

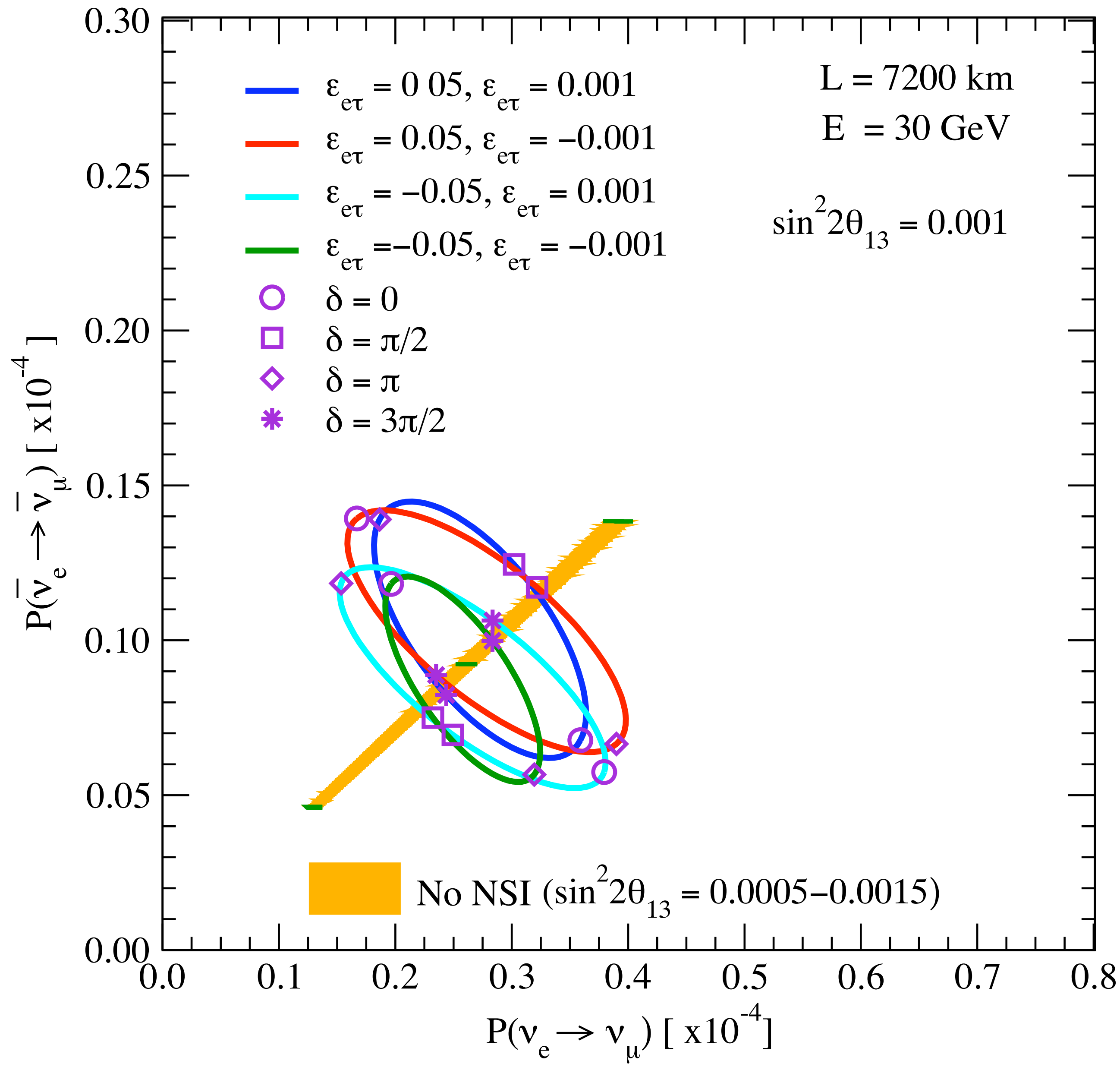


Even a few (or less) % level of ε can cause large impact

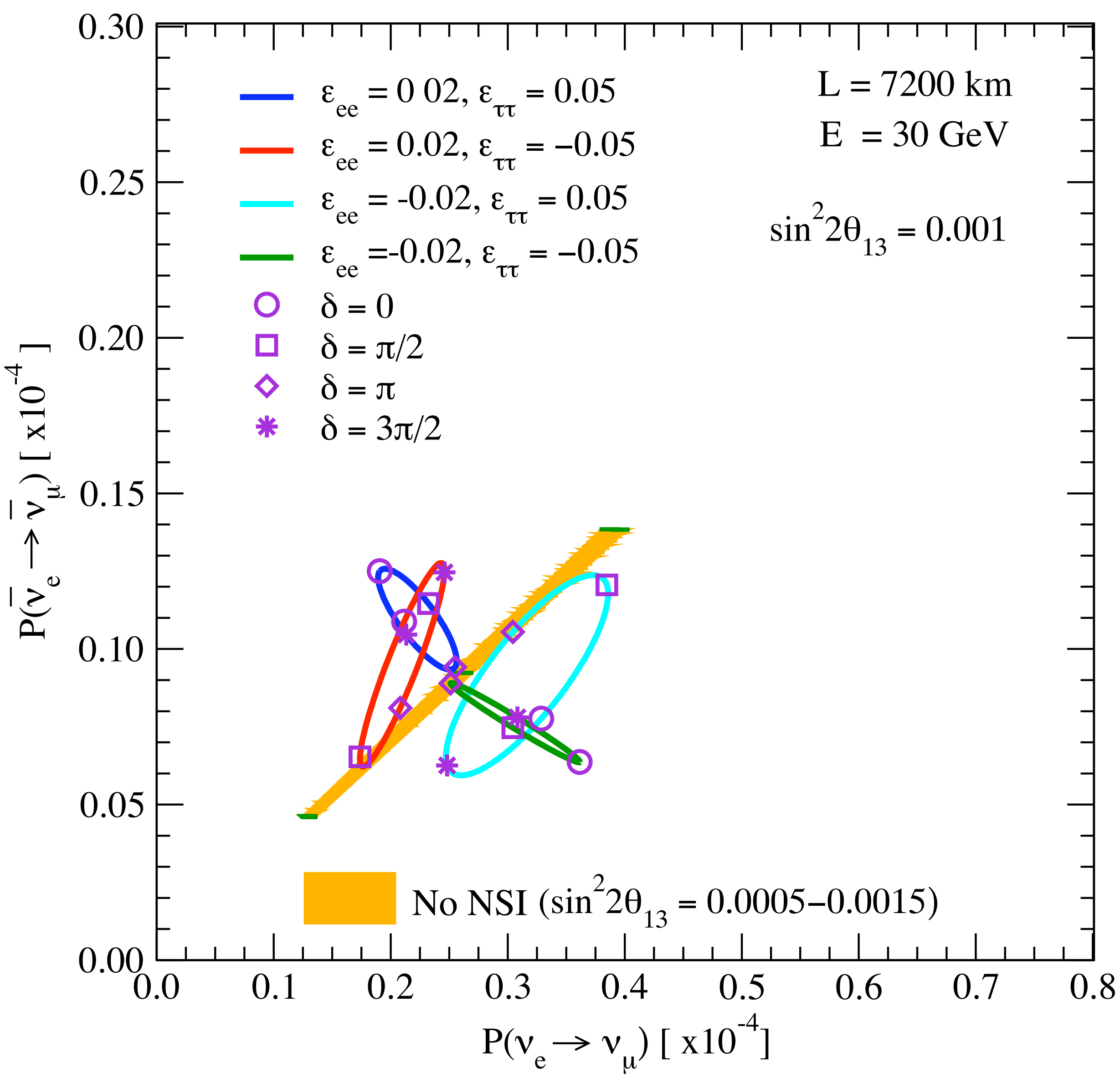
Impact of ε_{ee}+ $\varepsilon_{e\tau}$ on bi-probabilities at Magic baseline



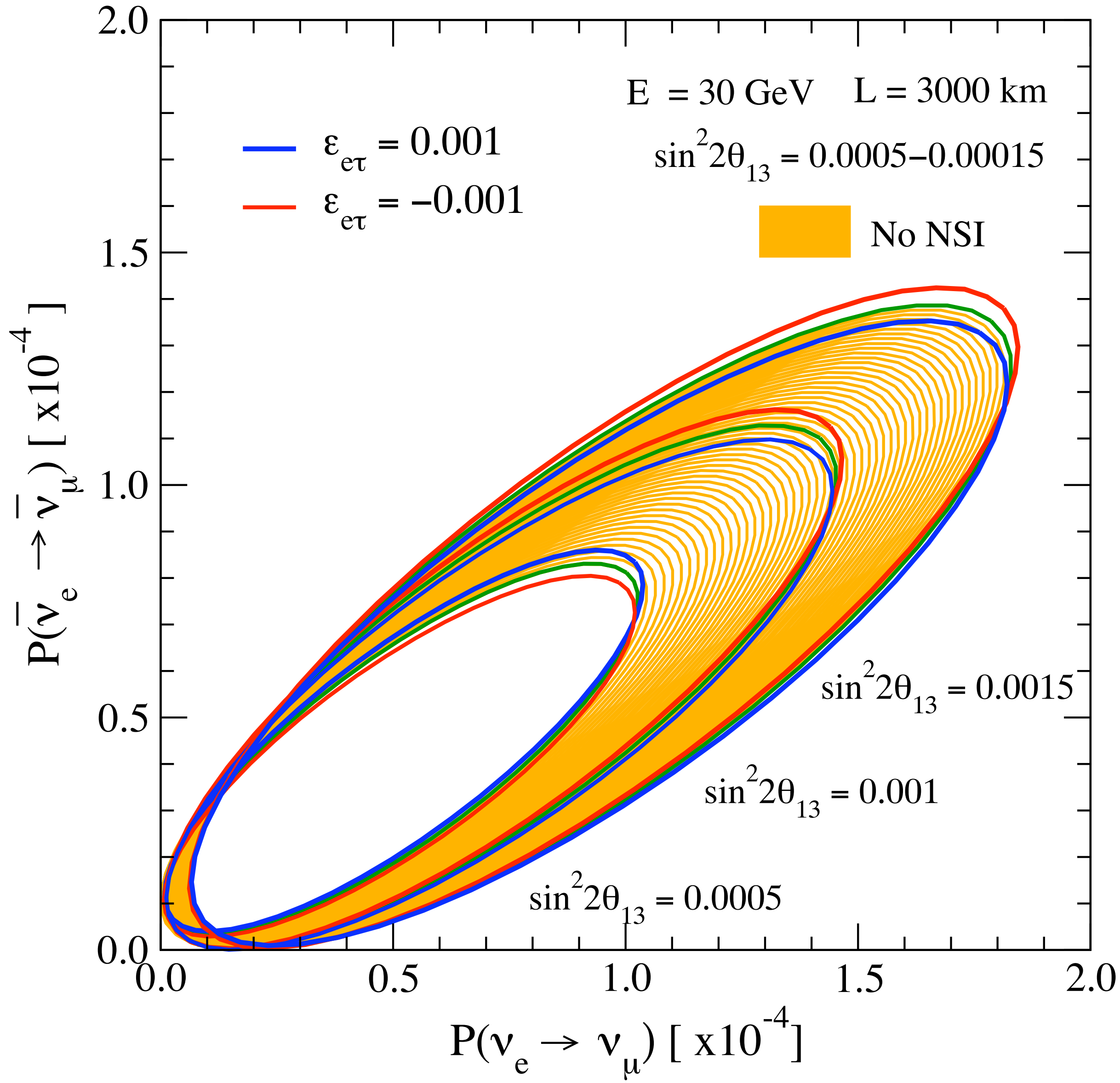
Impact of $\varepsilon_{\tau\tau}$+ $\varepsilon_{e\tau}$ on bi-probabilities at Magic baseline



Impact of ε_{ee}+ $\varepsilon_{\tau\tau}$ on bi-probabilities at Magic baseline

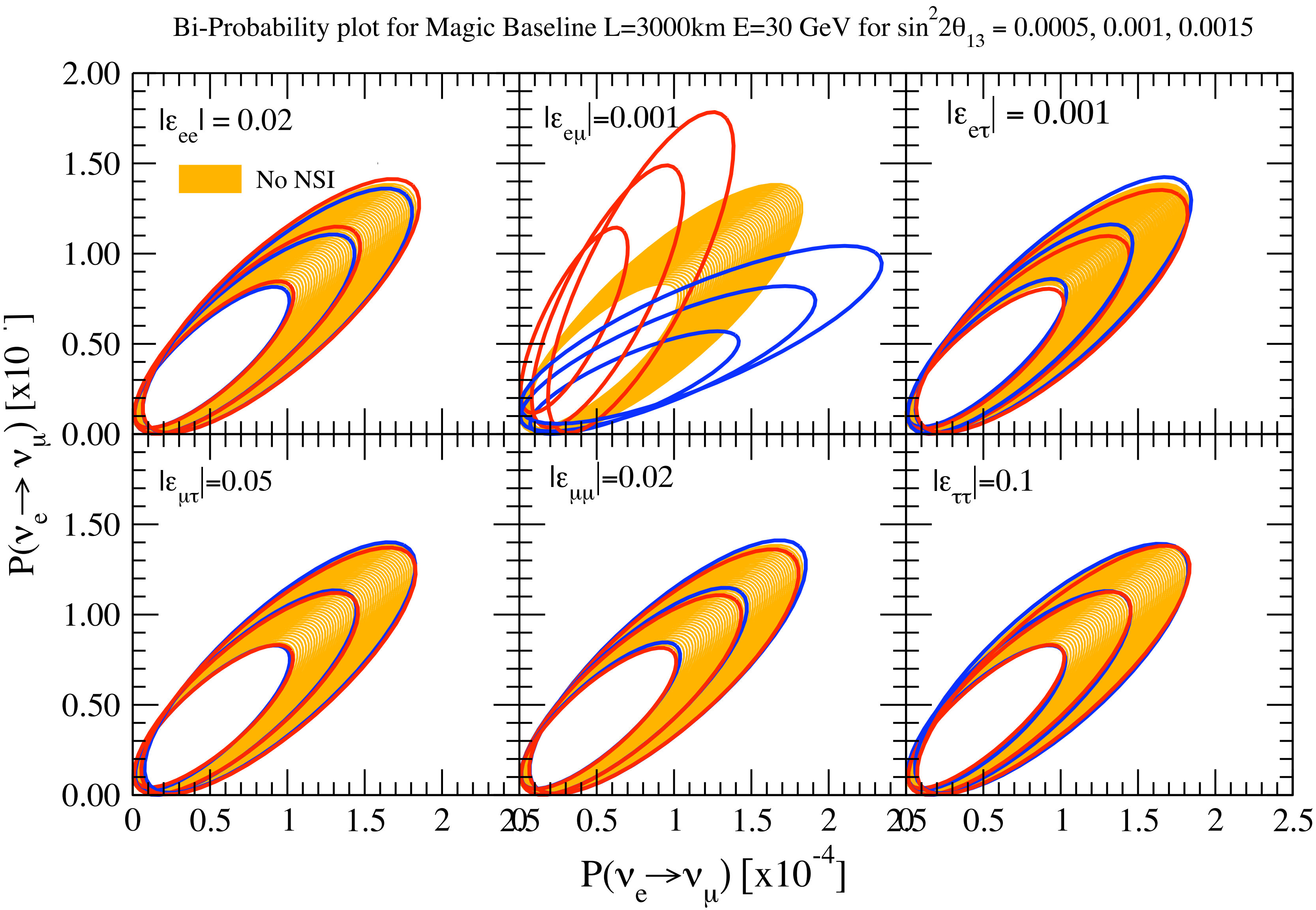


Impact of $\varepsilon_{e\tau}$ is much smaller at L = 3000 km



One can measure δ and θ_{13} rather well w/o worryng much about NSI (if small) at L = 3000 km

Impact of individual ε at the baseline L = 3000 km



Impact of $\varepsilon_{e\mu}$ at 3000 km, see Kopp et al, hep-ph/0702269

Combination of the 2 baseline ~3000-4000km +
Magic baseline (~7000km) seem to work well !

Large "synergy" effect is expected

Experimental setup to optimize the determination (by lifting parameter degeneracy) of standard mixing paramters (w/o NSI) could work well
also to probe NSI w/o spoiling the determination of the standard parameters

Procedure of our statistical analysis (1)

$$\chi^2 \equiv \min_{\theta_{13},\delta,\varepsilon} \sum_{i=1}^{3}\sum_{j=1}^{2}\sum_{k=1}^{2} \frac{\left[N_{i,j,k}^{\rm obs} - N_{i,j,k}^{\rm theo}(\theta_{13},\delta,\varepsilon)\right]^2}{N_{i,j,k}^{\rm theo}(\theta_{13},\delta,\varepsilon)},$$

i: # of bins = 3, j: 3000, 7000km, k: ν, $\bar{\nu}$

$$N^{\rm theo}(\theta_{13},\delta,\varepsilon) = n_\mu T M \frac{10^9 N_{\rm A}}{m_\mu^2 \pi} \frac{E_\mu^3}{L^2} \int_{E_{\rm min}}^{E_{\rm max}} g(E) P_{\nu_e\to\nu_\mu(\bar{\nu}_e\to\bar{\nu}_\mu)}(E;\theta_{13},\delta,\varepsilon) dE,$$

$$g(E) \equiv 12 \frac{E^2}{E_\mu^2}\left(1 - \frac{E}{E_\mu}\right)\frac{\sigma_{\nu_\mu(\bar{\nu}_\mu)}(E)}{E_\mu^2},$$

n_μ: # of useful muon decay per year = 10^{21}

T: running period, 4+4 years for ν and $\bar{\nu}$

M: detector mass = 50 kton

Procedure of our statistical analysis (2)

Assuming that NSI paramters are very small, we try to get sensitivity as follows

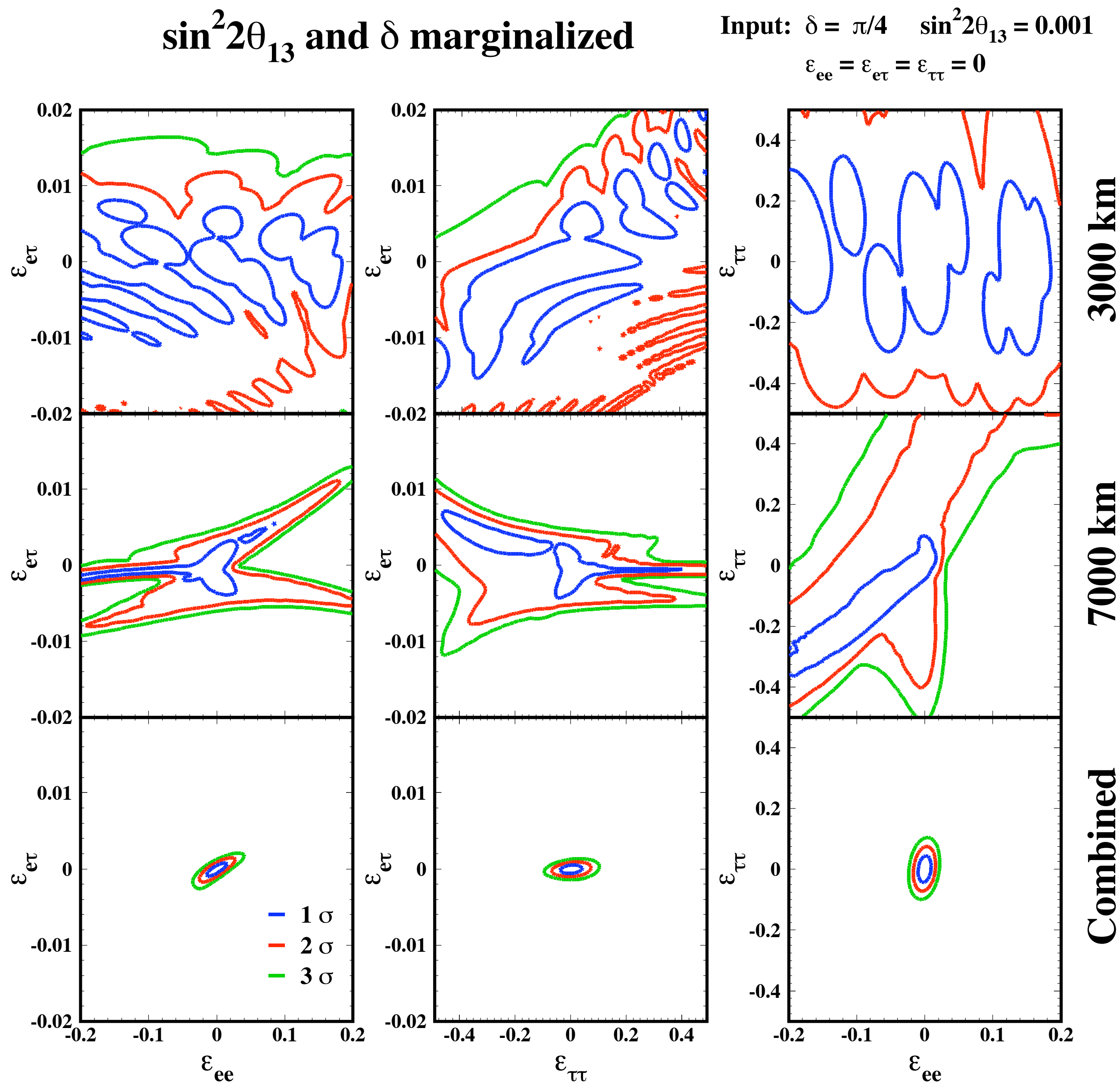
Input: δ, θ_{13}, all ε's = 0 (true values)

fix all the other mixing paramters

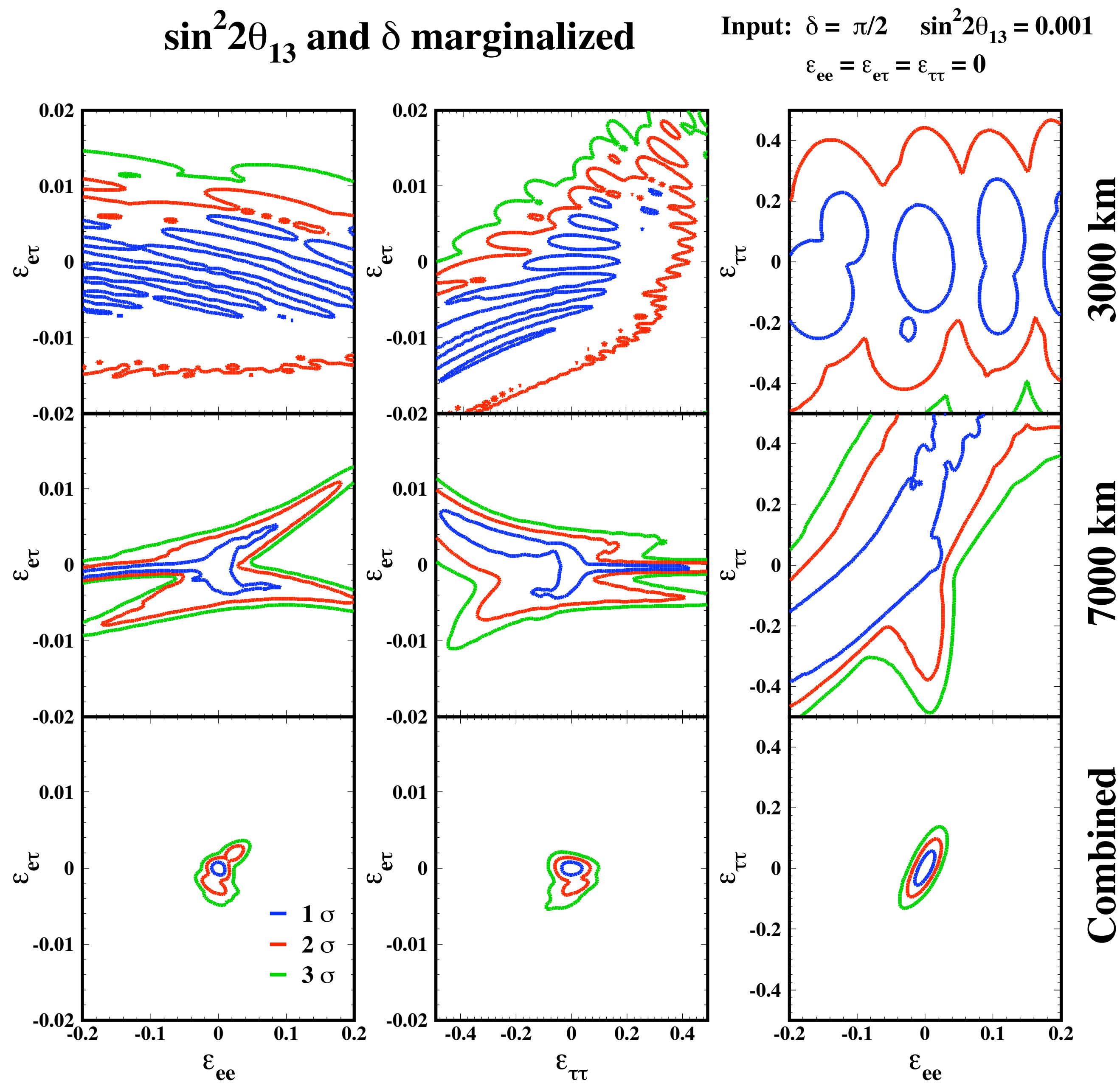
Fit: We vary δ, θ_{13}, and 2 of ε's

3 combinations $(\varepsilon_{ee}, \varepsilon_{e\tau}), (\varepsilon_{\tau\tau}, \varepsilon_{e\tau}), (\varepsilon_{ee}, \varepsilon_{\tau\tau})$

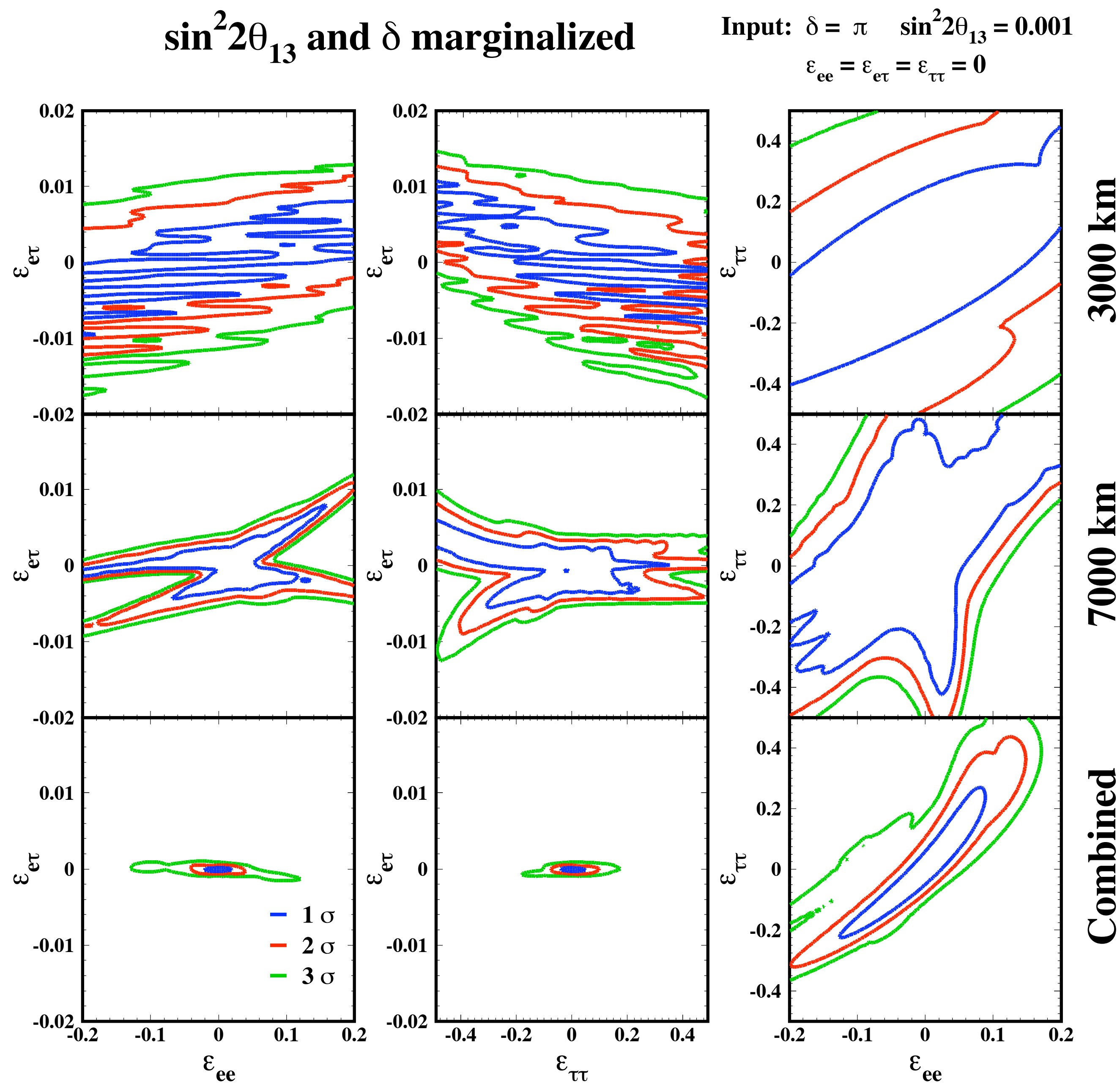
Results of our statistical analysis (1)



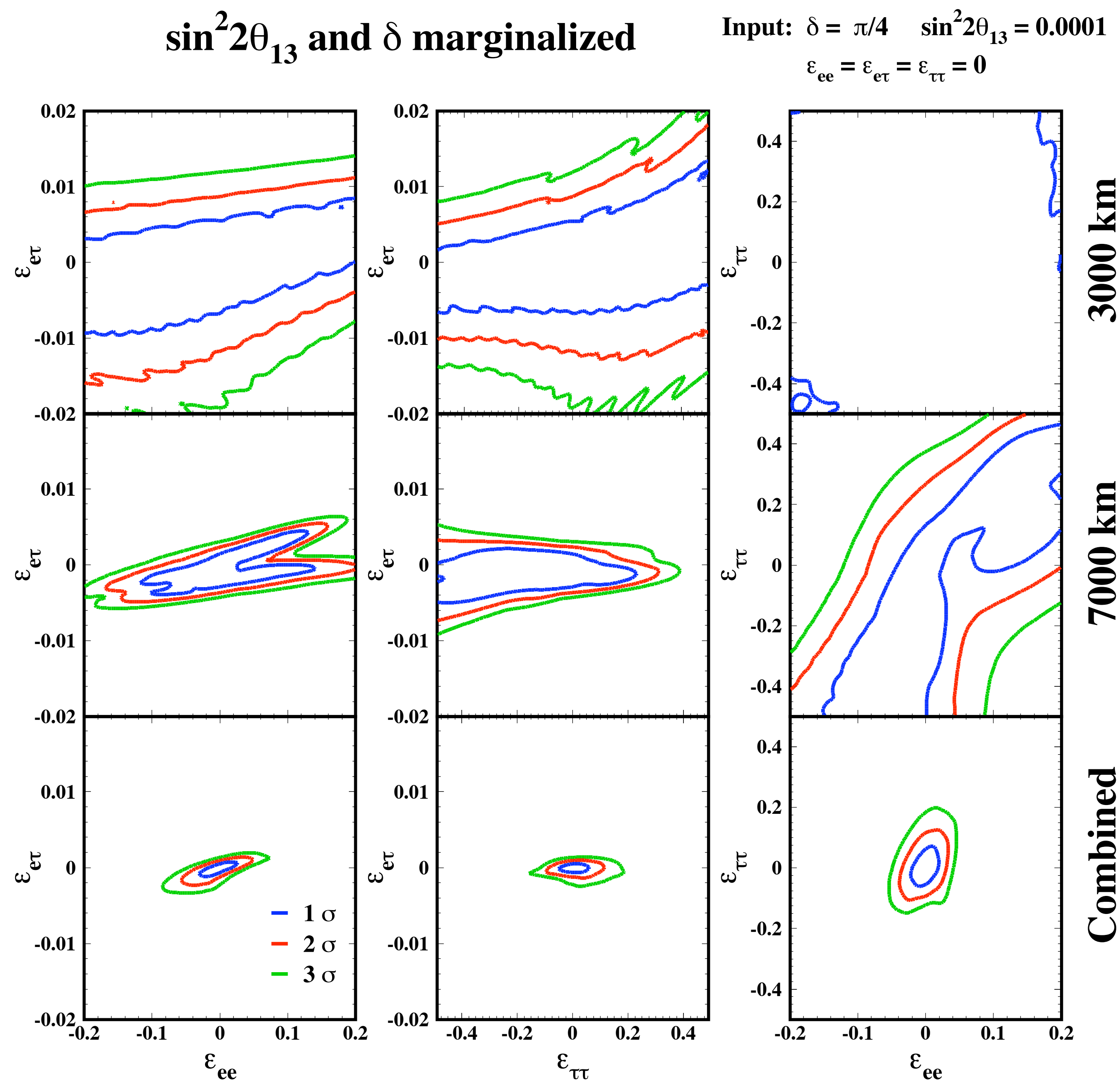
Results of our statistical analysis (2)



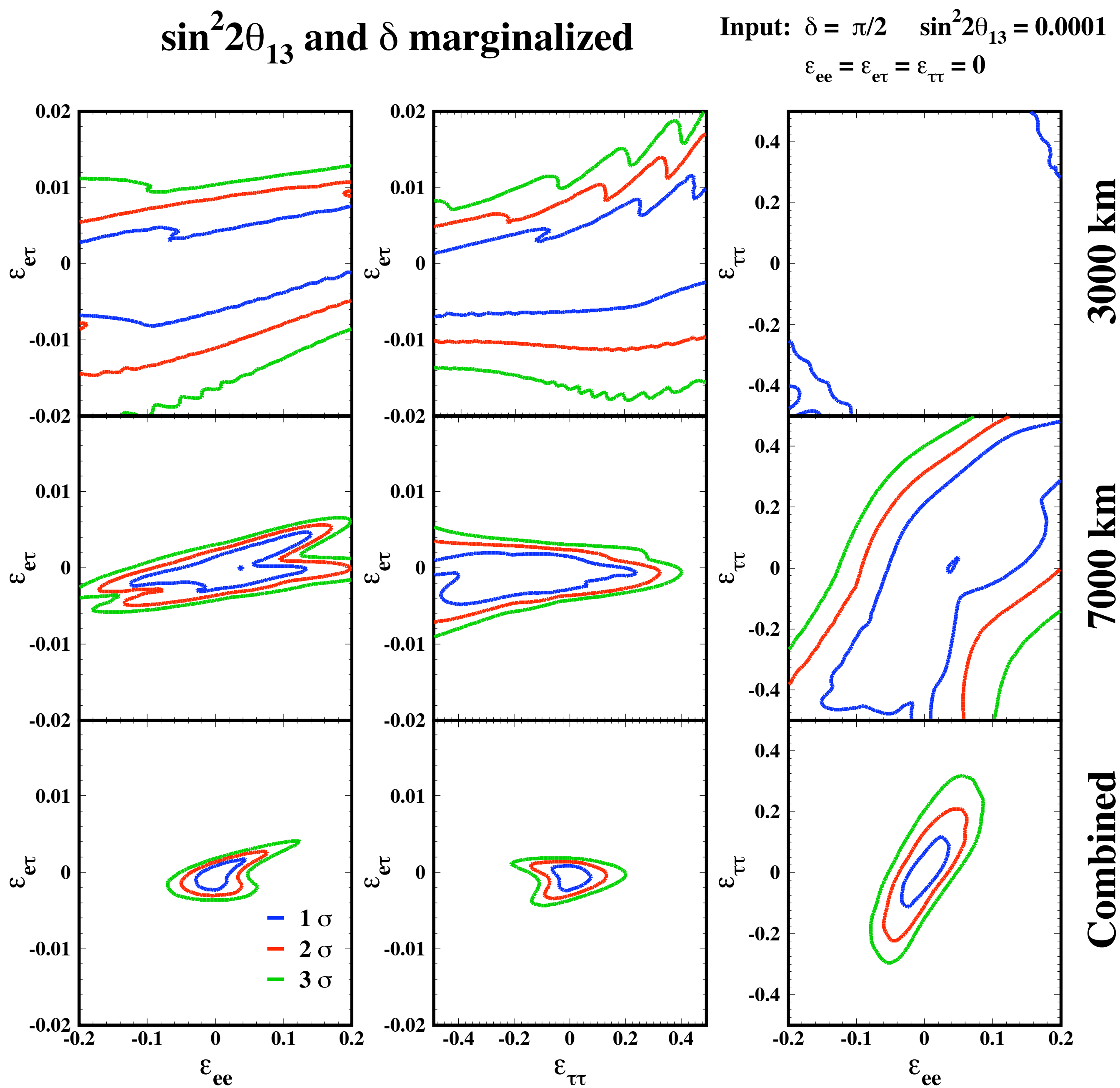
Results of our statistical analysis (3)



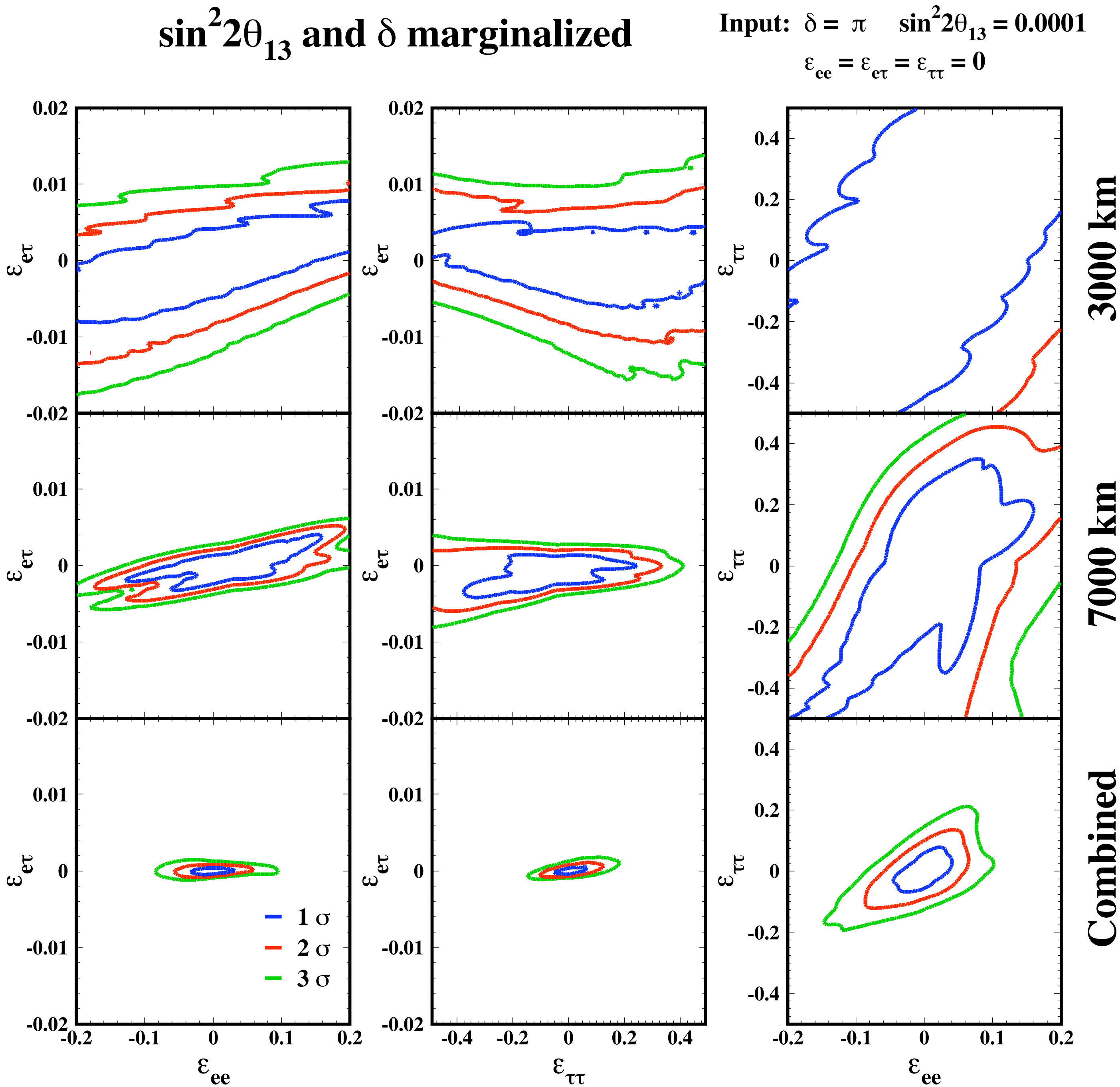
Results of our statistical analysis (1b)



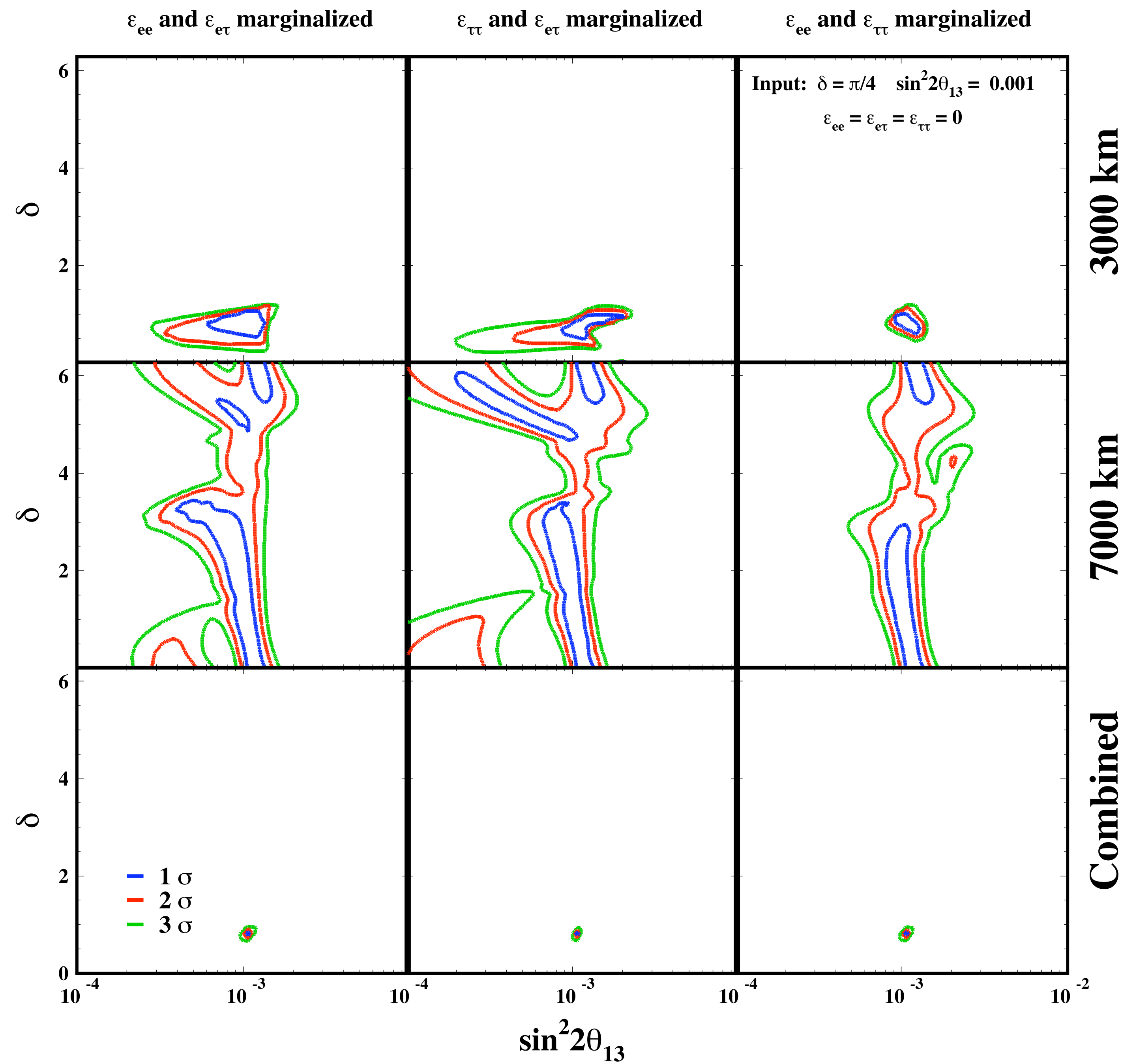
Results of our statistical analysis (2b)



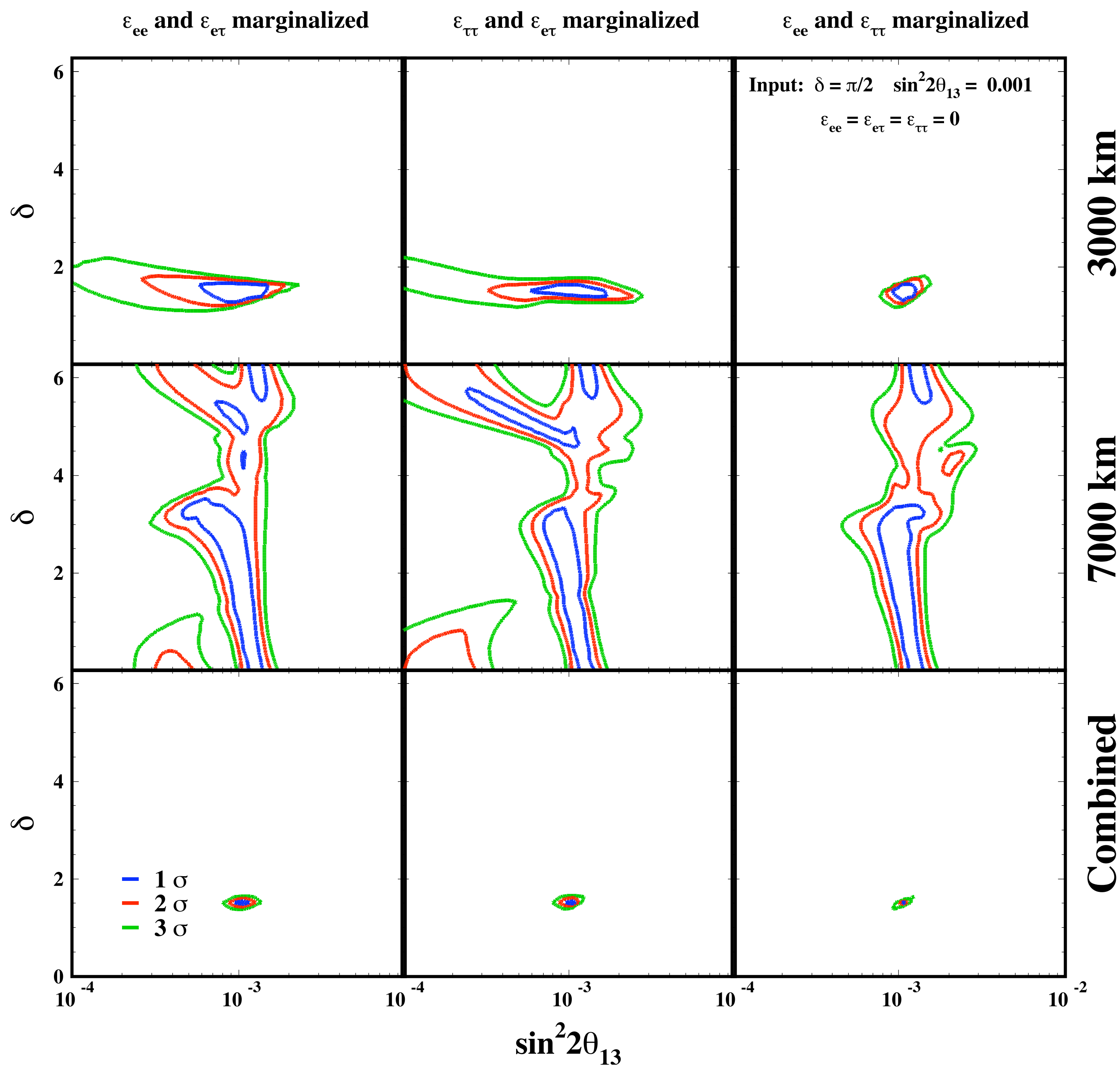
Results of our statistical analysis (3b)



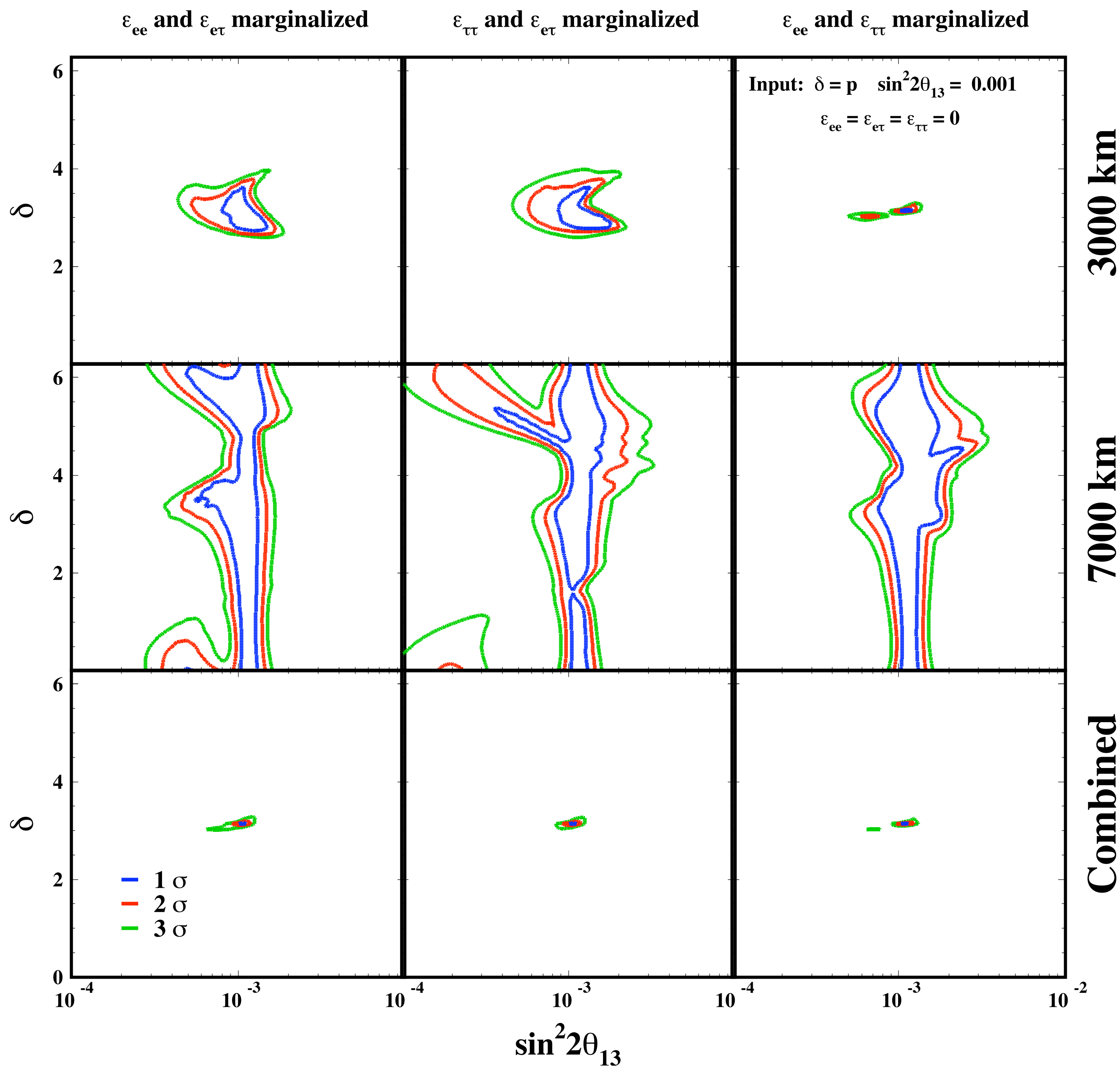
Results of our statistical analysis (1c)



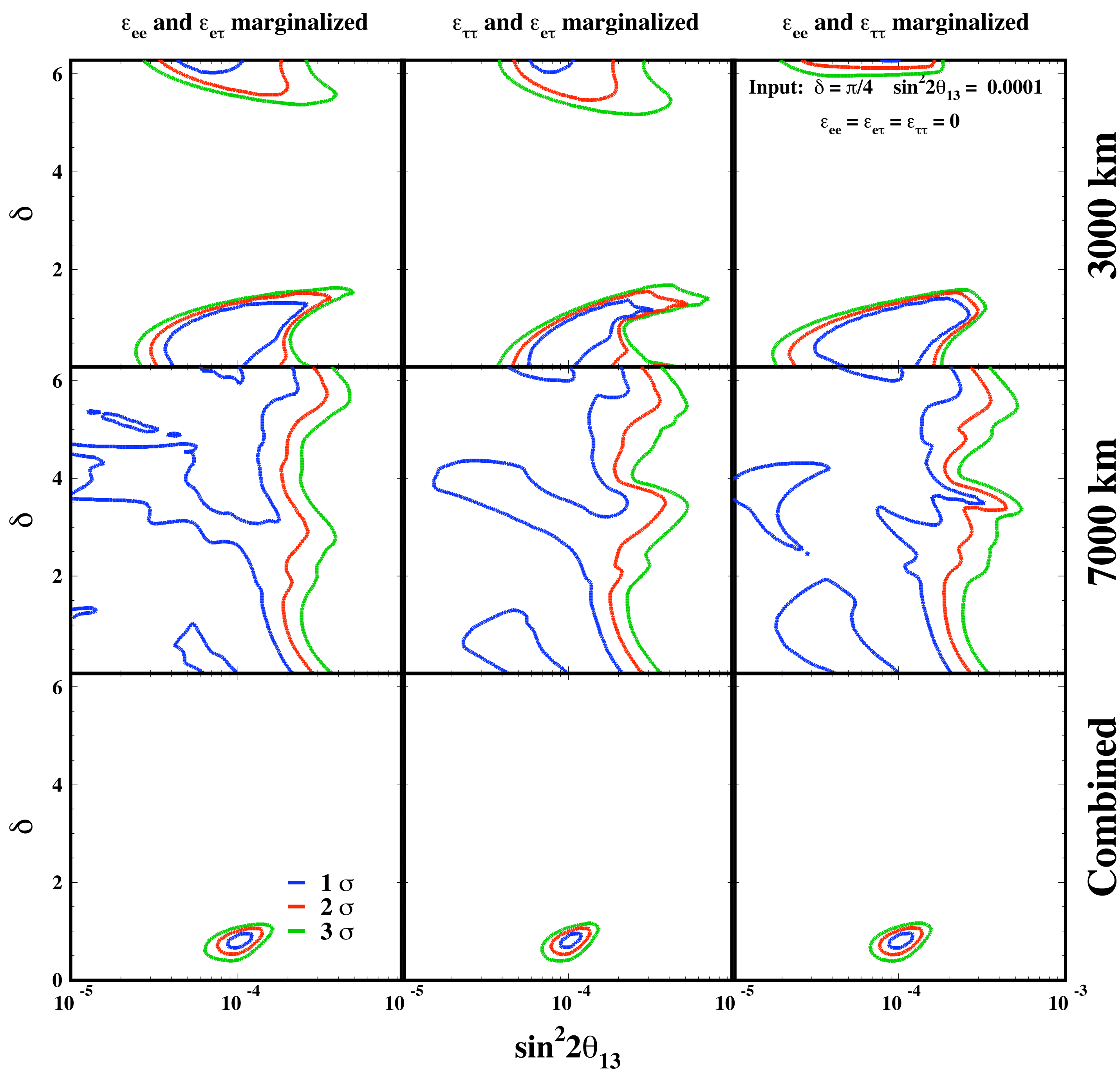
Results of our statistical analysis (2c)



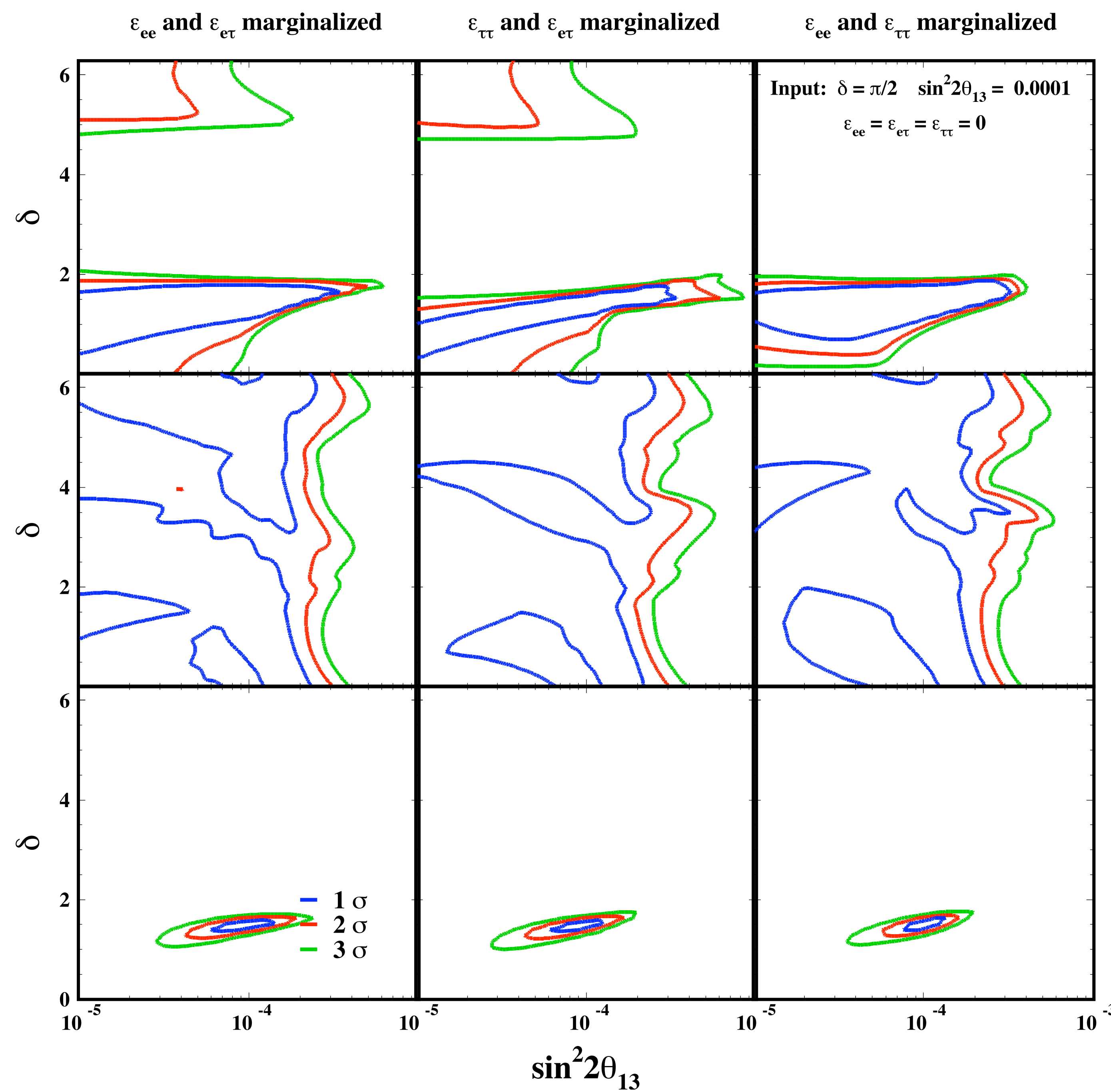
Results of our statistical analysis (3c)



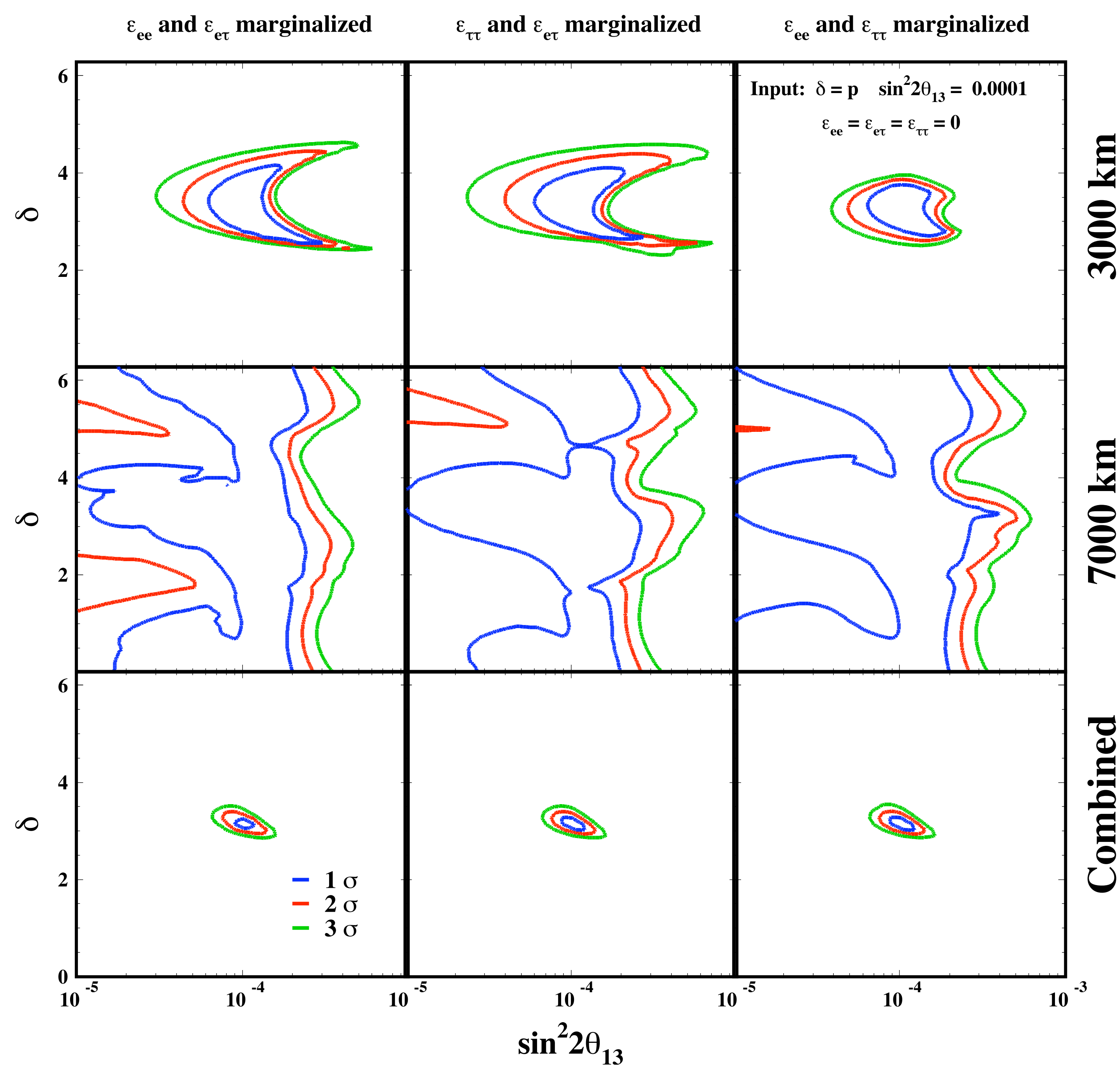
Results of our statistical analysis (1d)



Results of our statistical analysis (2d)



Results of our statistical analysis (3d)

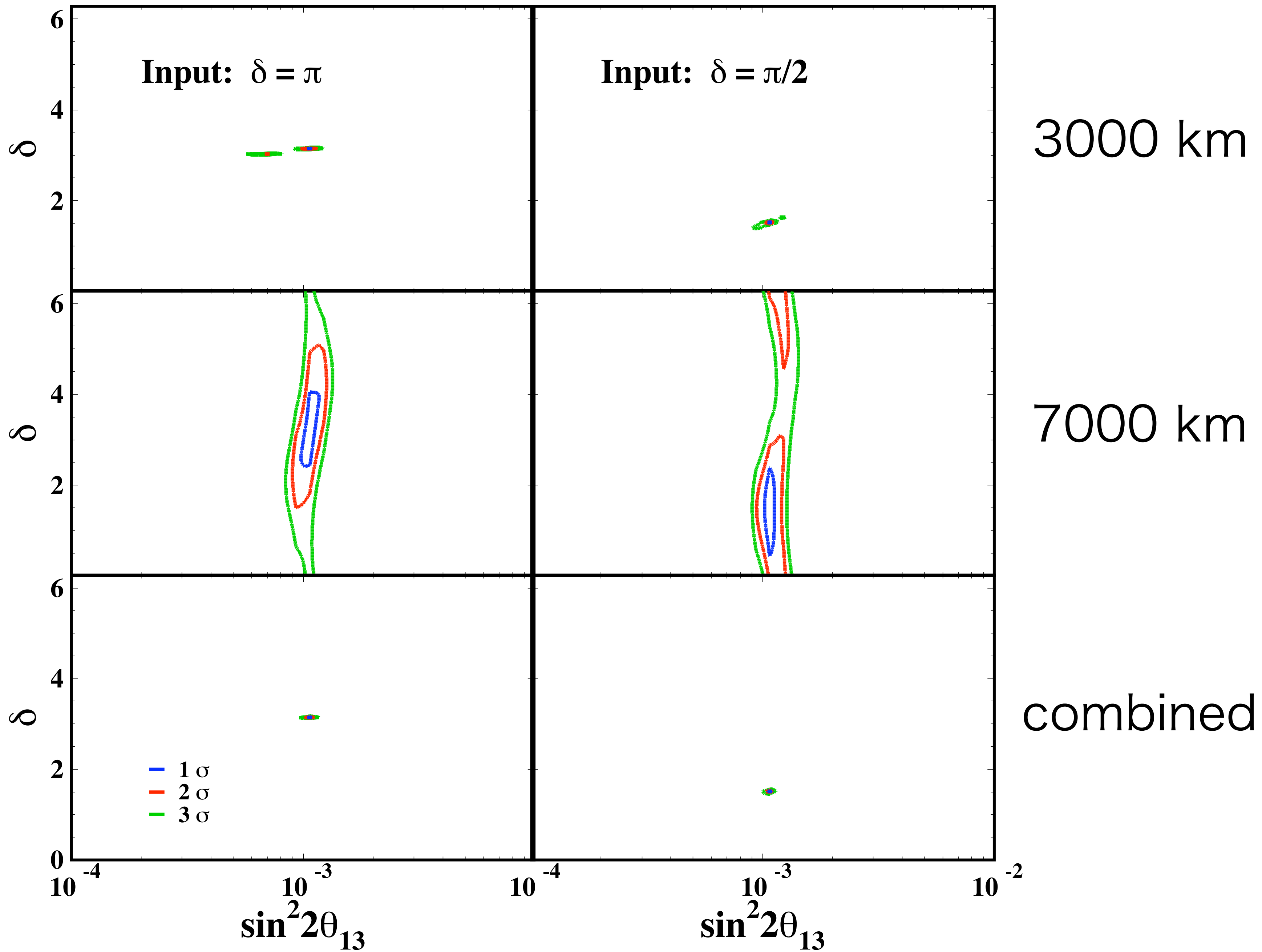


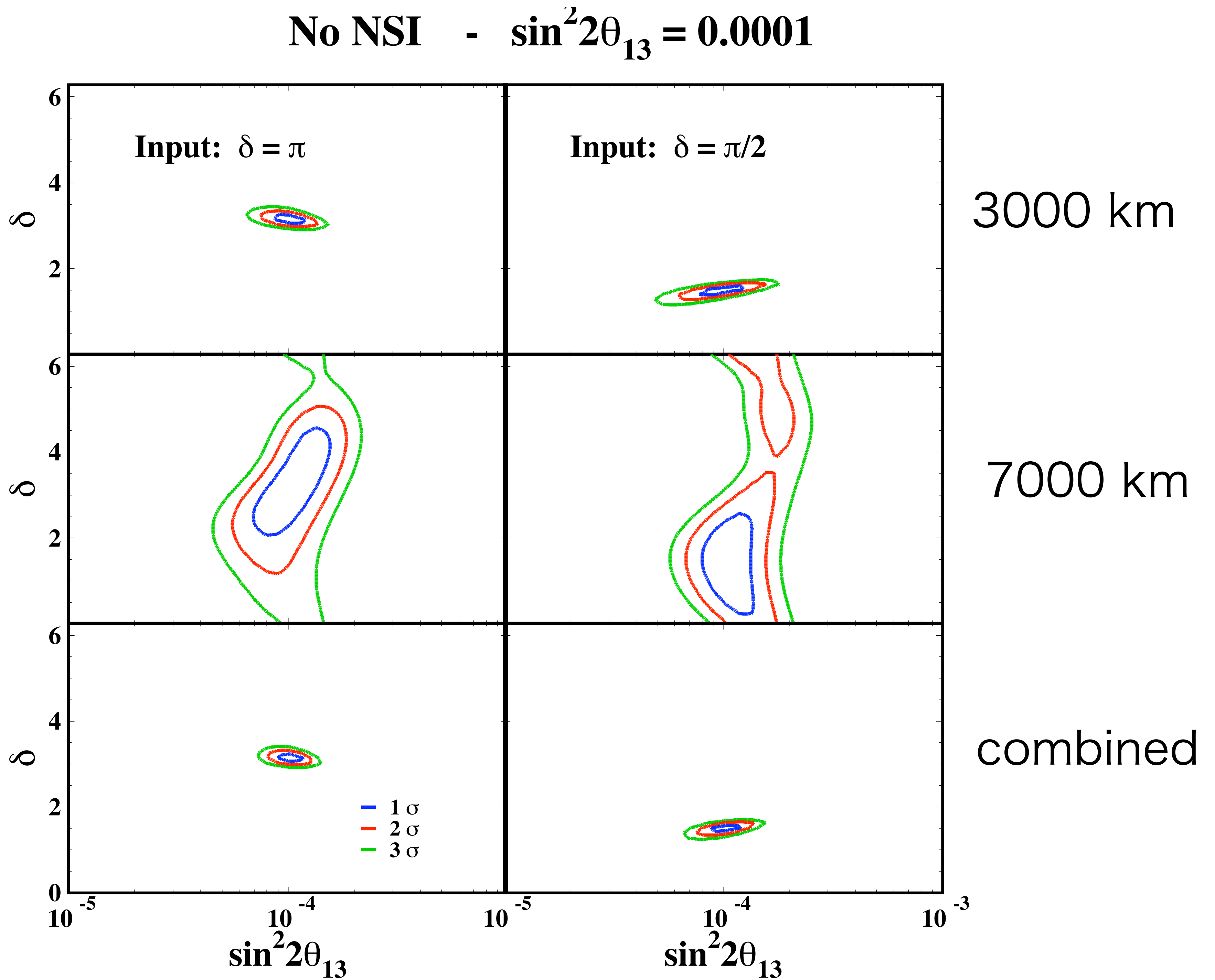
Summary

- Impact of NSI can be significantly large at the Magic basline (~7200 km), a few % NSI could incude a factor of ~O(10) or larger effect in terms of probabilities
- Ambiguity (uncertainty) on δ could reduce significantly sensitivities to NSI
- Combination of L ~ 3000 km and the magic basline seems to be powerful in probing NSI w/o spoiling the original purpuose (pinning down the standard mixing parameters)

Backup Slides

No NSI - $\sin^2 2\theta_{13} = 0.001$





No NSI - sin²2θ13 = 0.0001
Input: δ = π
Input: δ = π/2
3000 km
7000 km
combined
δ
6
4
2
0
10^-5
10^-4
10^-3
sin²2θ13
1 σ
2 σ
3 σ