Test of Non-Standard Interactions at Super-K

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Outline

- Introduction & Physics motivation
- Expected "NSI" phenomena at SK
- Data sets
- Analysis results
- Conclusions

What is NSI ?

- *Note: there are many non-standard interaction "NSI" in markets.*
- In this analysis, NSI is defined as either
  FCNC $\sigma(\nu_\alpha + f \to \nu_\beta + f) \neq 0$ $\varepsilon_{\alpha\beta}$
  and
  Non-universality(NU). $\sigma(\nu_\alpha + f) \neq \sigma(\nu_\beta + f)$ $\varepsilon_{\alpha\alpha}, \varepsilon_{\beta\beta}$

NSI driven transition probability

$$H^{NSI} = \sqrt{2} G_F N_f(\vec{r}) \begin{pmatrix} \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

$$\varepsilon \equiv \varepsilon_{\mu\tau}$$

$$\varepsilon' \equiv |\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}|$$

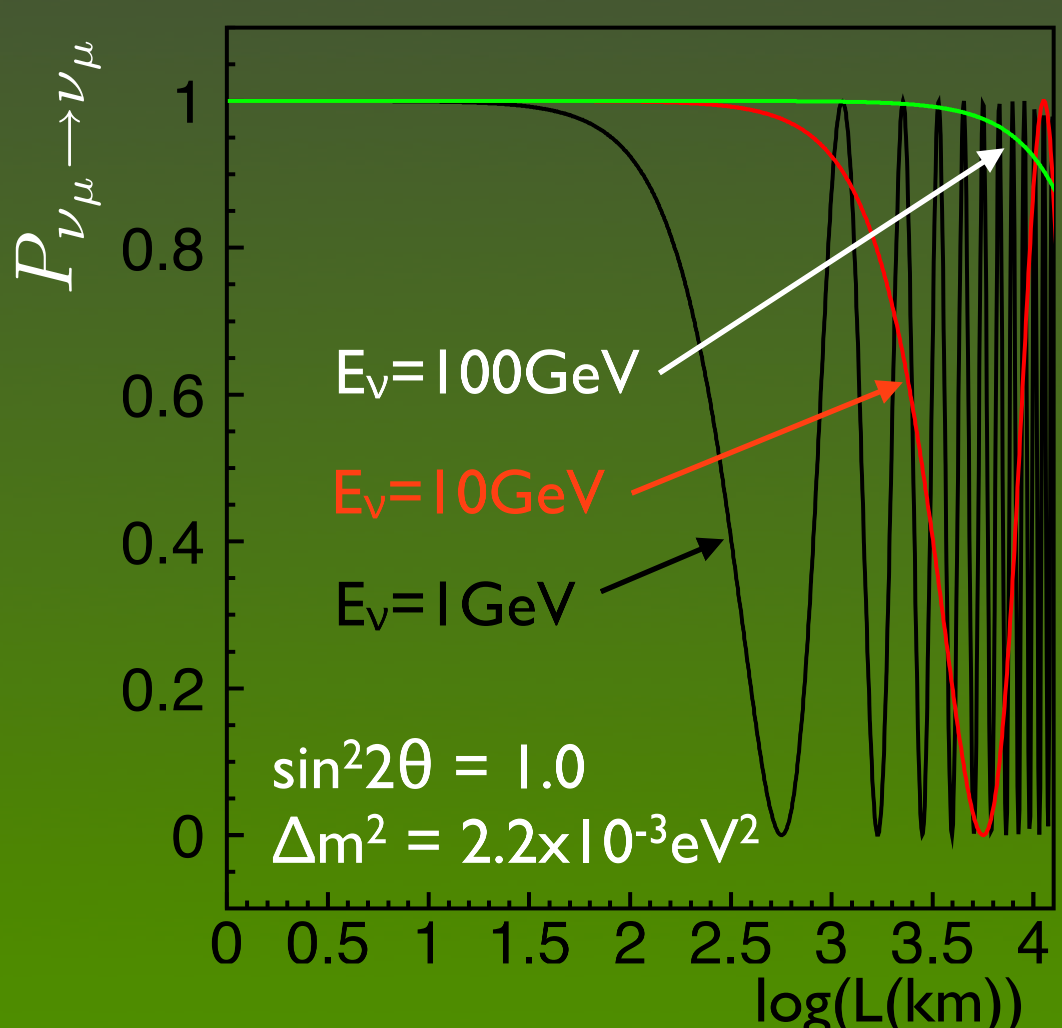
$$P_{\nu_\mu \to \nu_\mu} = 1 - \frac{4\epsilon^2}{4\epsilon^2 + \epsilon'^2} \sin^2(\sqrt{2} G_F < N_f > L \sqrt{\epsilon'^2/4 + \epsilon^2})$$

Probability changes as depending only on
the *number density "Nf"* and the *flight length "L"*.

Transition Probabilities

Standard Oscillation

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



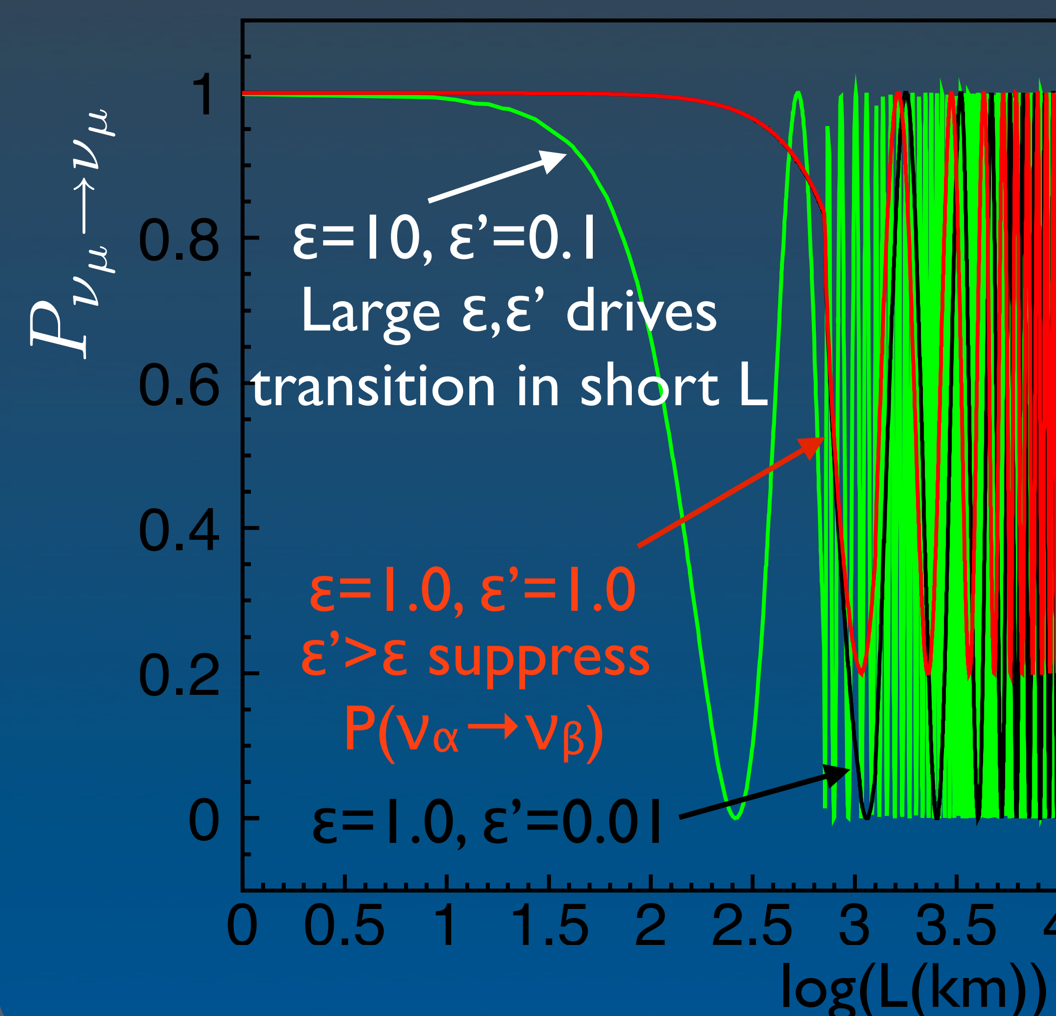
NSI

$$P_{\nu_\mu \to \nu_\mu} = 1 - f(\varepsilon,\varepsilon')\sin^2(\sqrt{2}G_F < N_f > L\varepsilon f(\varepsilon,\varepsilon'))$$

ε=FCNC

ε'=NU

$$f(\varepsilon,\varepsilon') \equiv \frac{4\varepsilon^2}{4\varepsilon^2 + \varepsilon'^2}$$



Sizable transition can occur in NSI even in high energy.

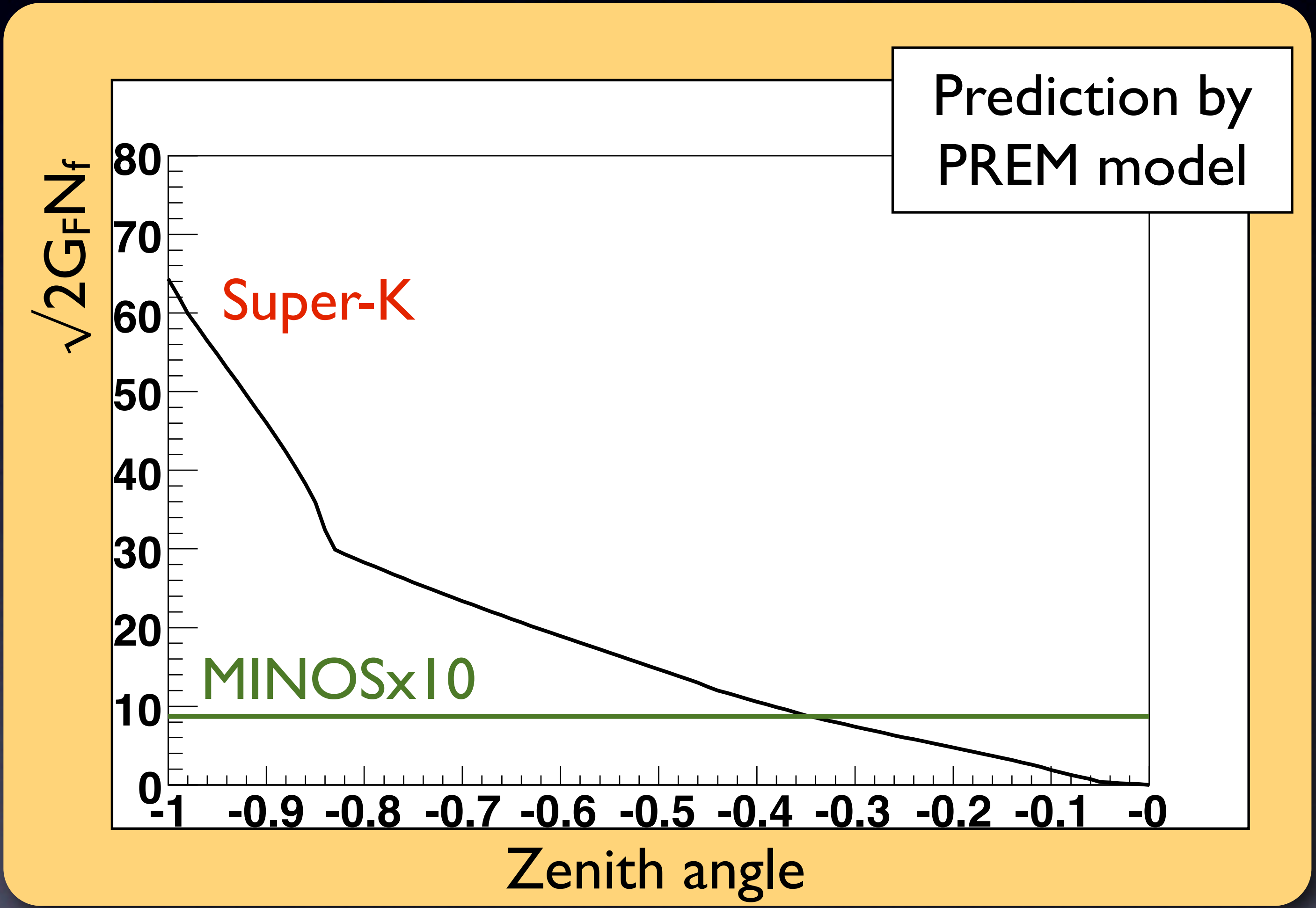
ν NSI hunting ?

- Precise measurement of ν-int. cross section
  CHARM, NuTeV, etc...
- Atmospheric neutrino
  Super-Kamiokande, MACRO
- Solar neutrino(matter→vacuum transition)
  Borexino
- Accelerator neutrino
  ν factory ?

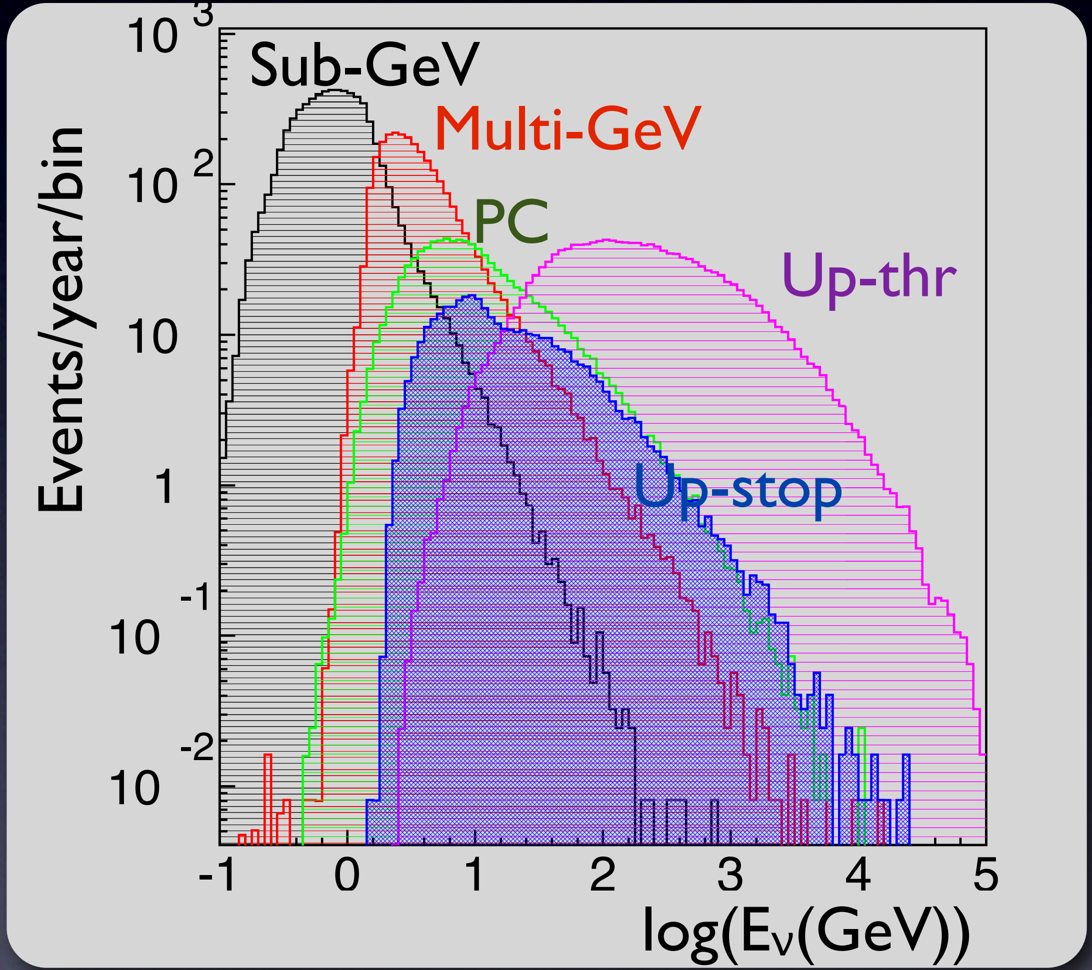
NOTE:MACRO data is phenomenologically analyzed

Advantage of Super-K

Fermion number density sensitive to FCNC & NU



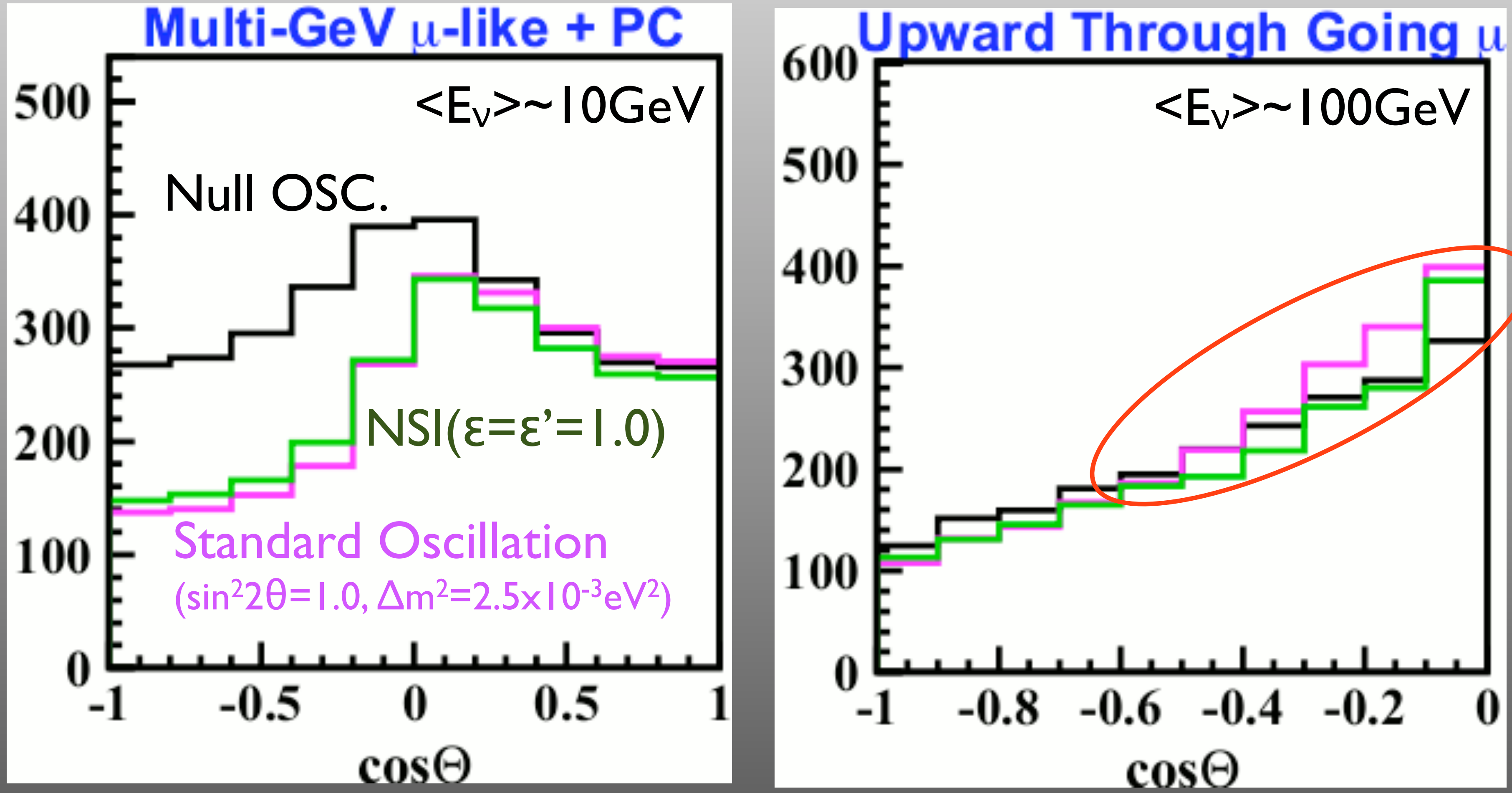
Surveying wide range energy 100MeV - 100TeV



Large number of events
2,900events/year @SK

Pure NSI ⇒ Hybrid NSI

SK-I & SK-II



No significant inconsistency is in fully or partially contained event, while clear difference in Upward going μ .

→Pure NSI scenario is ruled out.

Hybrid NSI Model

$$H_{\alpha\beta} = \frac{1}{2E} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} (U^\dagger)_{k\beta} + V_{\rm MSW} + \sqrt{2} G_F N_f(\vec{r}) \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu}^* & \varepsilon_{e\tau}^* \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}^* \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Standard Oscillation NSI

This talk presents the analyses based on the Hybrid model.

Analysis procedures

- Data&MC sets
  - FC, PC, and UPμ SK-I & II atm-ν data.
  - 2,280 livedays = 6.25years
  - MC statistics is 500years.
- Reconstruction tools and MC have been updated since the past oscillation analysis with SK-I and II.
- Agreement between data and MC is derived by checking "zenith angle" and "momentum" bins.
- Systematic errors related to neutrino flux, interaction, detector responses are taken into account(totally 90 terms).

2-Flavor Hybrid(μτ sector)

2-Flavor Hybrid model

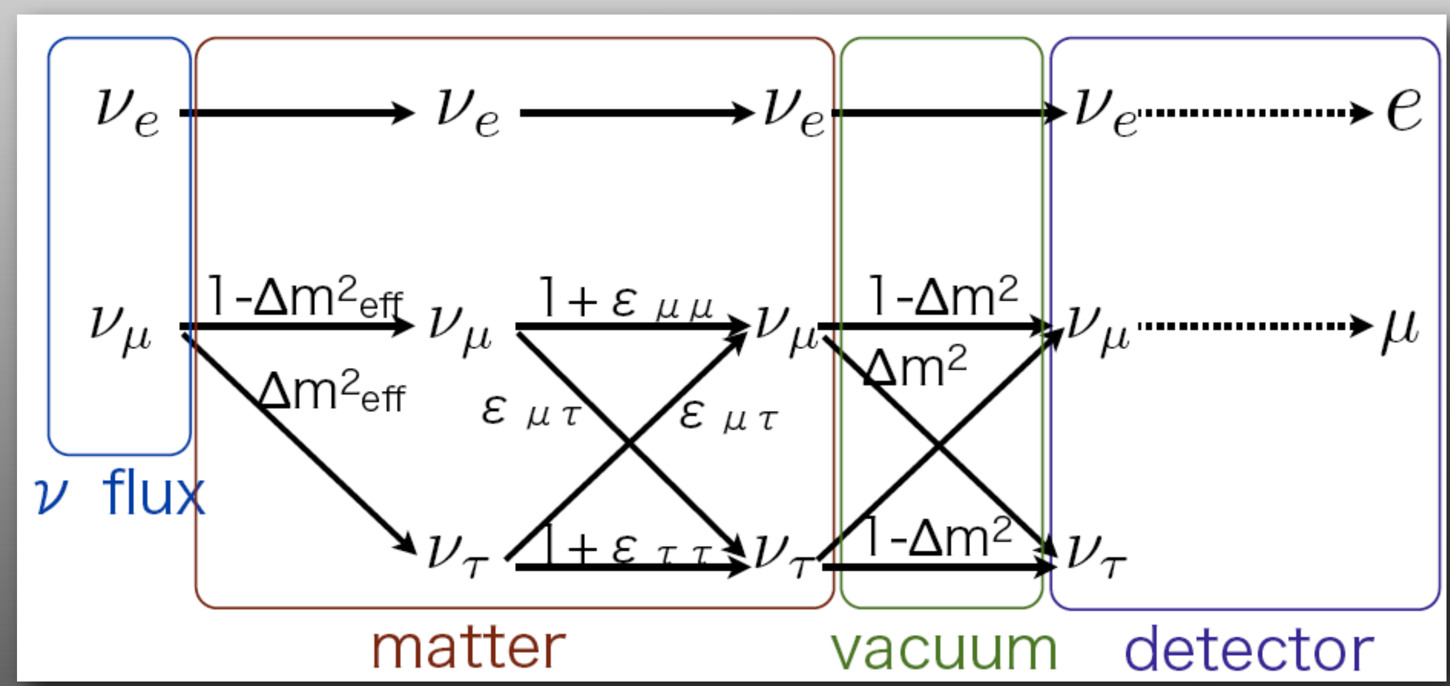
= 2-flavor OSC.(2⇔3) + 2-flavor NSI(μτ)

NSI Hamiltonian

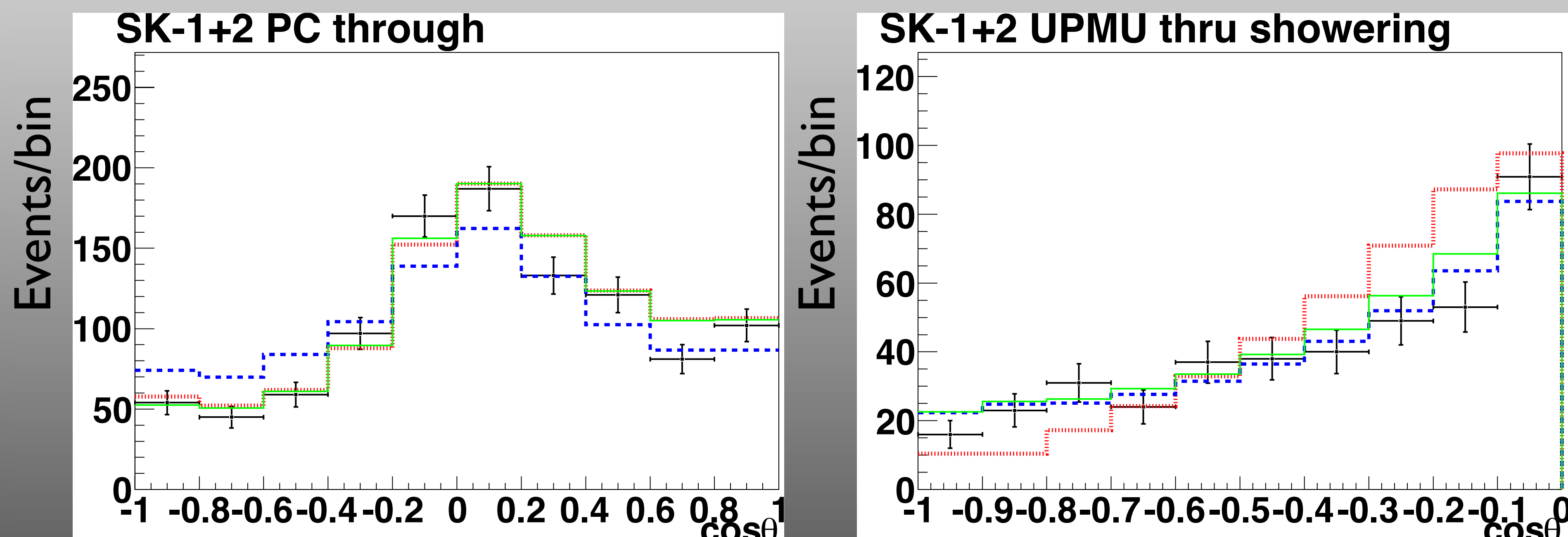
$$H_{\alpha\beta}^{NSI} = \sqrt{2}G_F N_f(\vec{r}) \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu}^{*} & \varepsilon_{e\tau}^{*} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}^{*} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Focusing only on μτ sector

Flavor transition from source to detector



Zenith angle distributions with typical parameters



ε=FCNC
ε'=NU

(ε,ε')=

Green:(1.0×10^{-3}, -2.4×10^{-2})

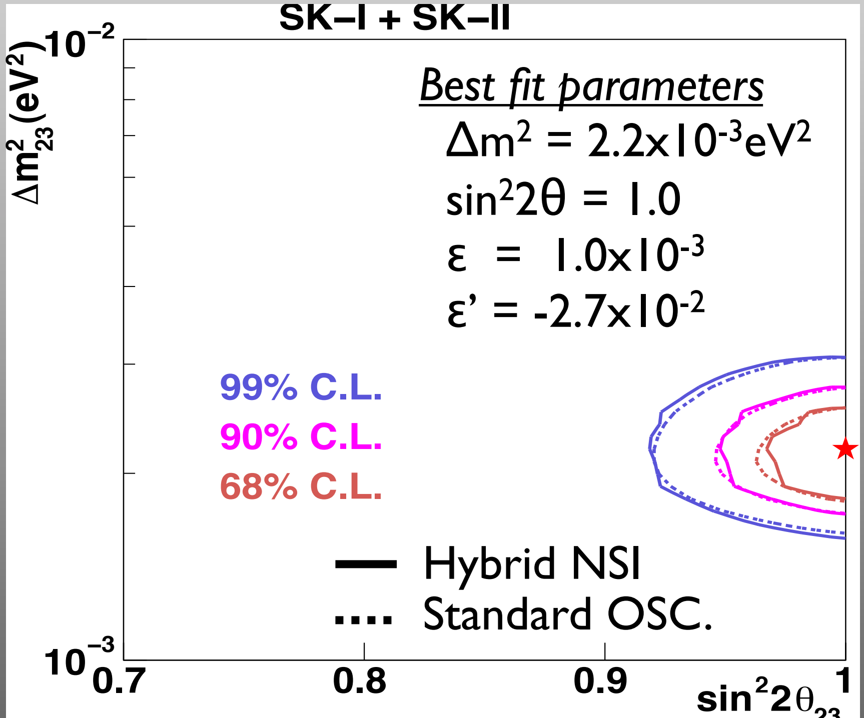
Blue: (1.0×10^{-3}, -0.38)

Red: (3.2×10^{-3}, -2.4×10^{-2})

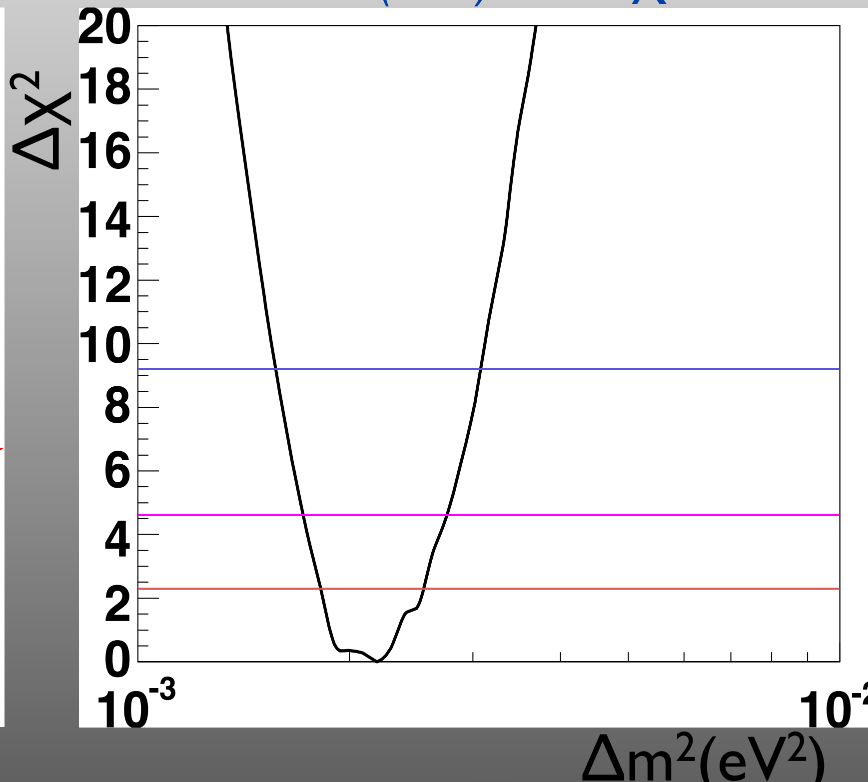
Note : All lines after χ^2 fitting with systematics.

2-Flavor Hybrid(μτ sector)

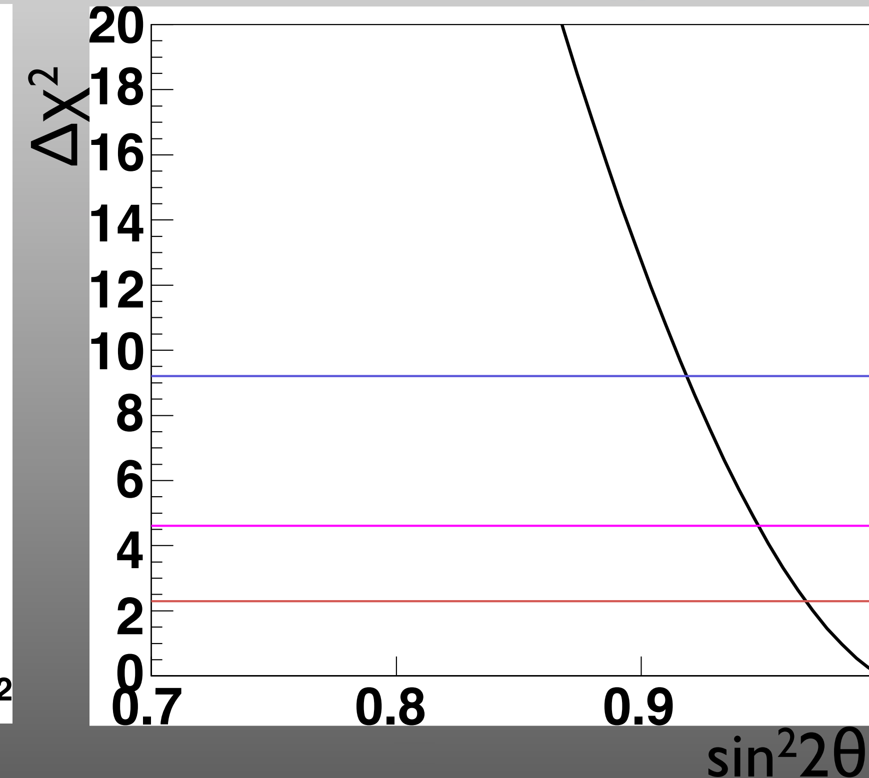
2D contour(OSC pars.)



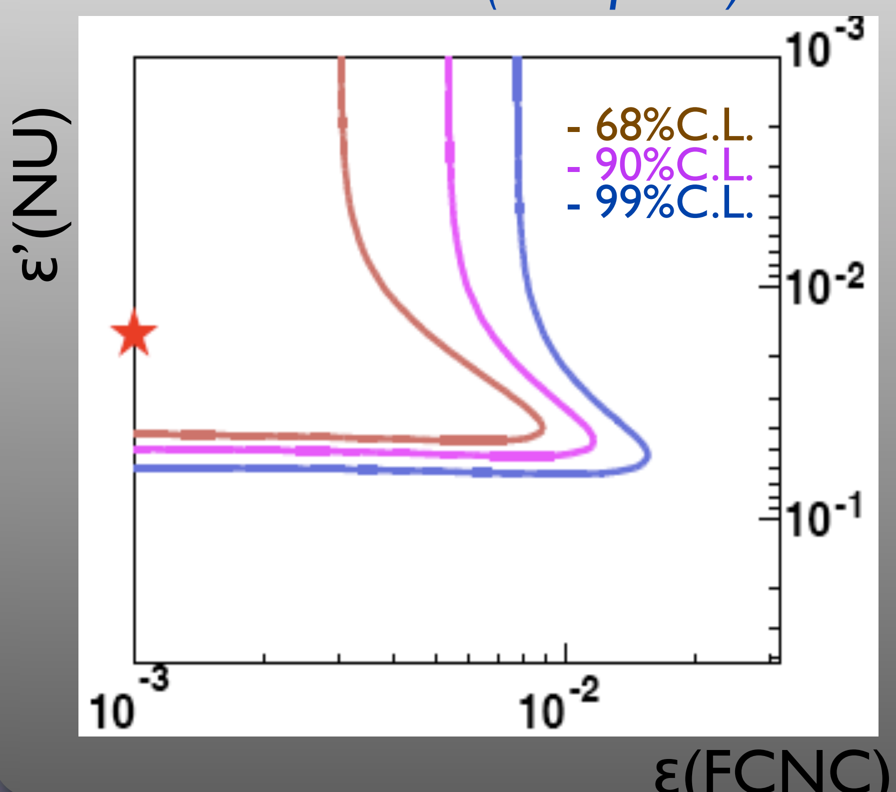
Δm^2(eV^2) vs. $\Delta\chi^2$



$\sin^2 2\theta$ vs. $\Delta\chi^2$



2D contour(NSI pars.)



Best fit parameters

$\varepsilon = 1.0\times10^{-3}$

$\varepsilon' = -2.7\times10^{-2}$

Limit from SK-I & SK-II (90%C.L.)

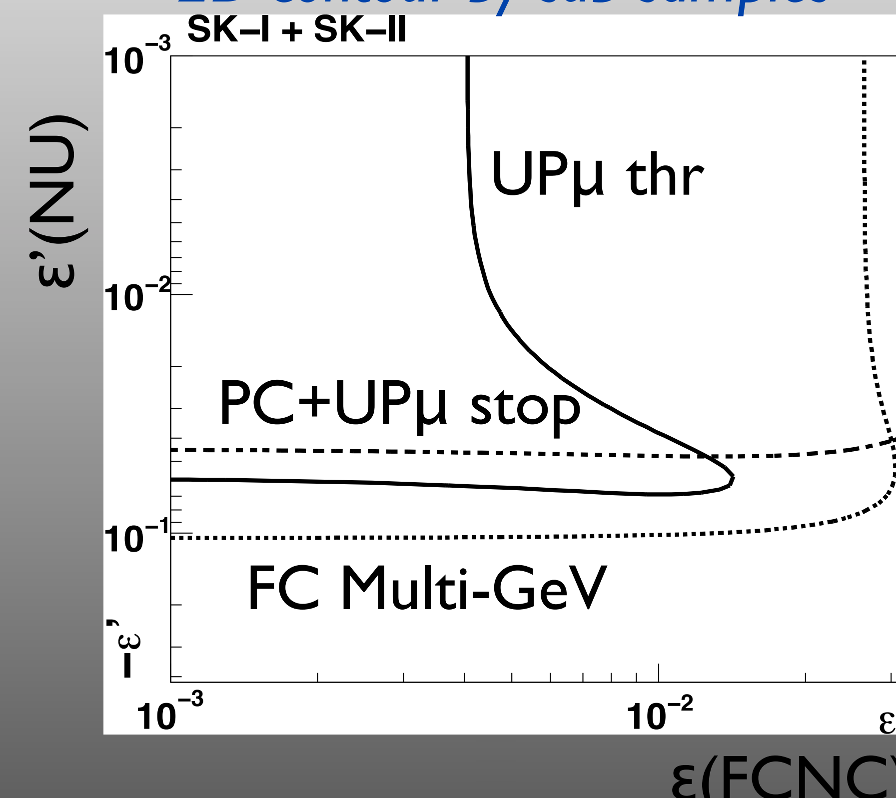
$|\varepsilon| < 1.1\times10^{-2}$

$|\varepsilon'| < 4.9\times10^{-2}$

ε=FCNC

ε'=NU

2D contour by sub-samples



3-Flavor Hybrid(eτ sector)

3-Flavor Hybrid model

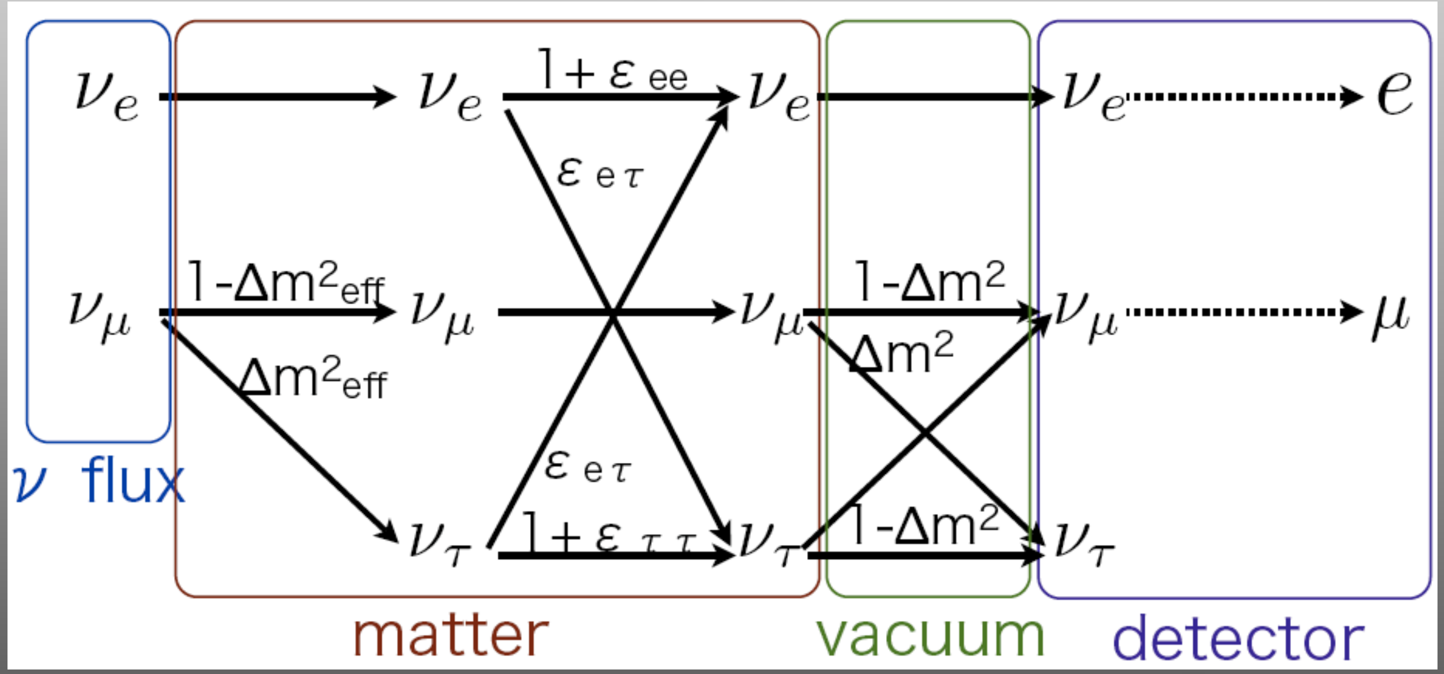
= 2-flavor OSC.(2⇔3) + 2-flavor NSI(eτ)

NSI Hamiltonian

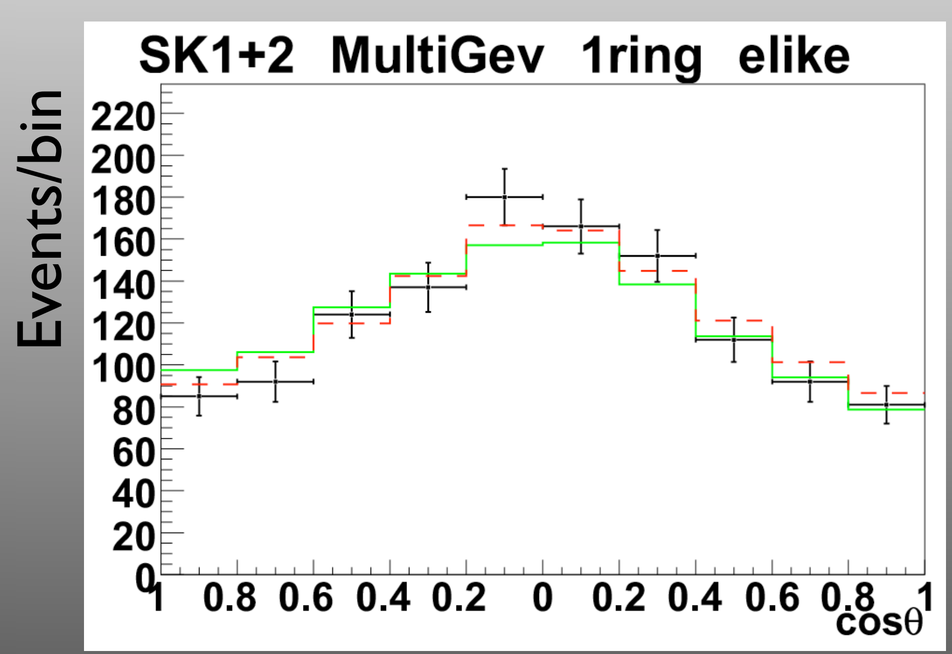
$$H^{NSI}_{\alpha\beta} = \sqrt{2}G_F N_f(\vec{r}) \begin{pmatrix} \boxed{\varepsilon_{ee}} & \varepsilon^*_{e\mu} & \boxed{\varepsilon^*_{e\tau}} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon^*_{\mu\tau} \\ \boxed{\varepsilon_{e\tau}} & \varepsilon_{\mu\tau} & \boxed{\varepsilon_{\tau\tau}} \end{pmatrix}$$

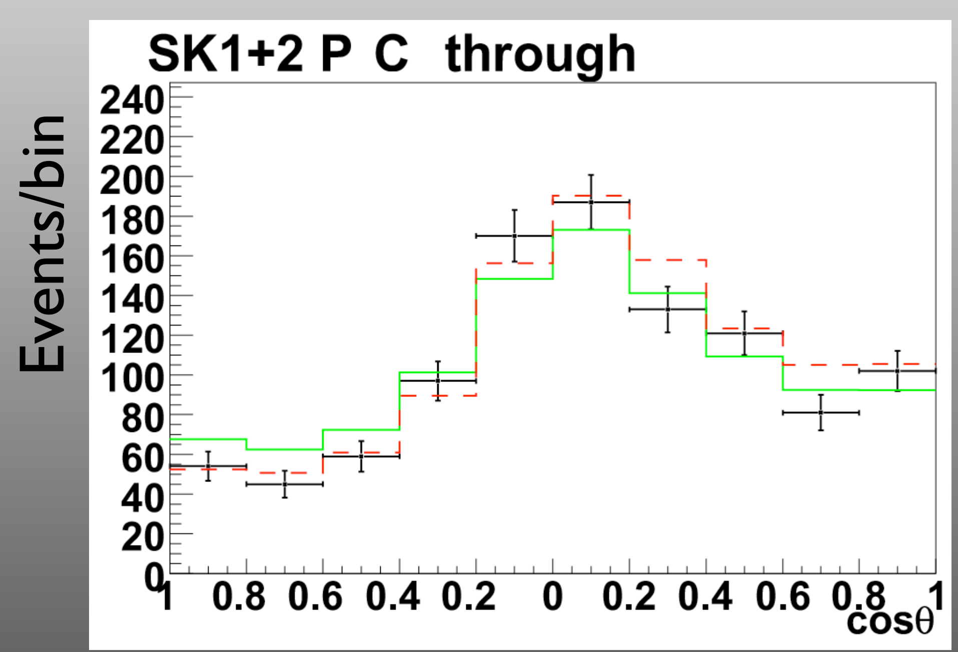
Focusing only on eτ sector

Flavor transition from source to detector



Zenith angle distributions with typical parameters





Red : Standard oscillation

Green : NSI

$\varepsilon_{ee} = 0.0$

$\varepsilon_{e\tau} = 0.2$

$\varepsilon_{\tau\tau} = 0.2$

Note : All lines after χ^2 fitting with systematics.

3-Flavor Hybrid(eτ sector)

Note : No constraint to ε_{ee} can be given by atm-ν. External constraint by CHARM is added($-0.6<\varepsilon_{ee}<0.5$).

Best fit parameters

$\Delta m^2 = 2.1\times10^{-3}eV^2$

$\sin^2 2\theta = 1.0$

$\varepsilon_{ee} = -0.25$

$\varepsilon_{e\tau} = 0.016$

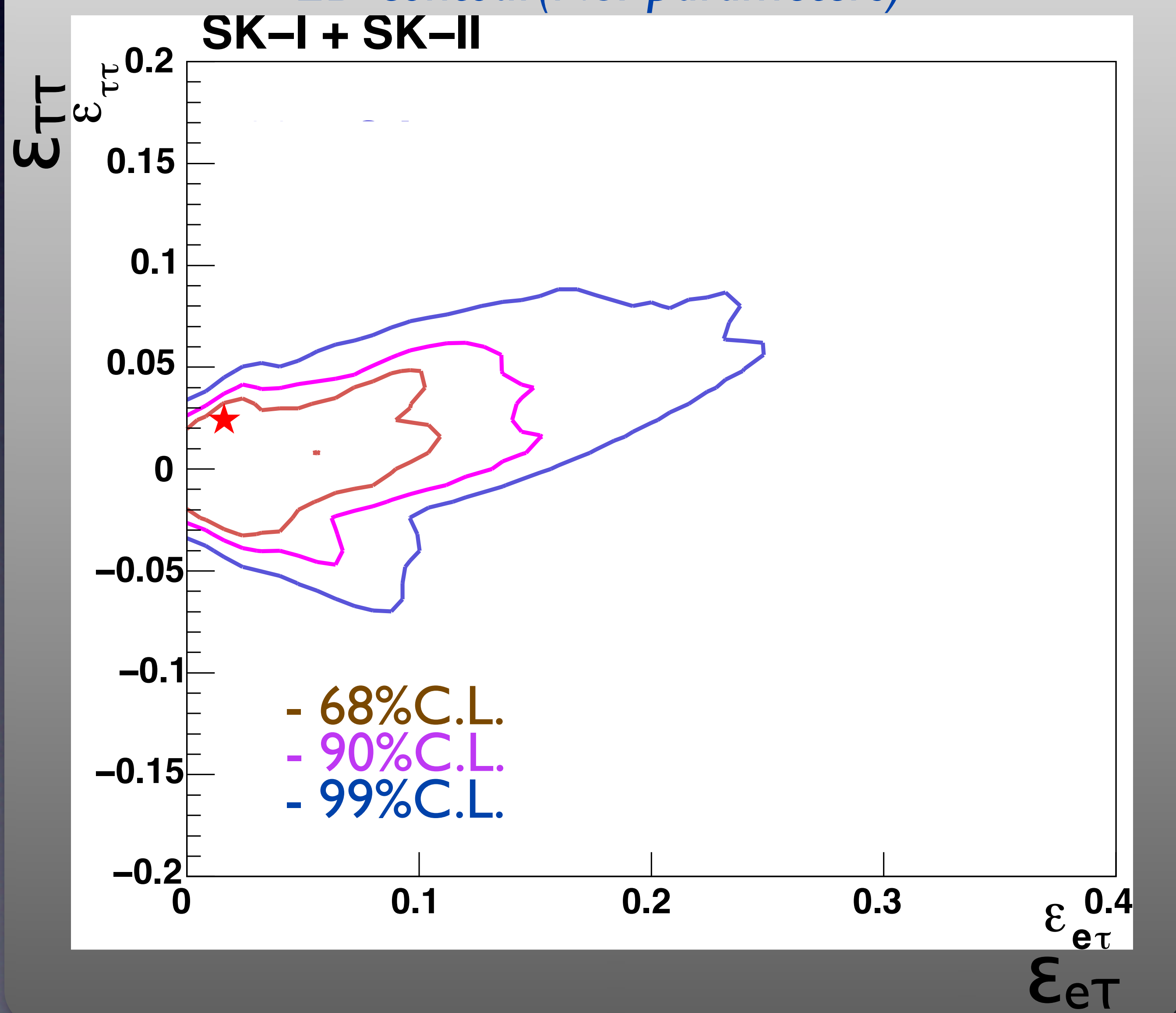
$\varepsilon_{\tau\tau} = 0.024$

Limit from SK-I & SK-II (90%C.L.)

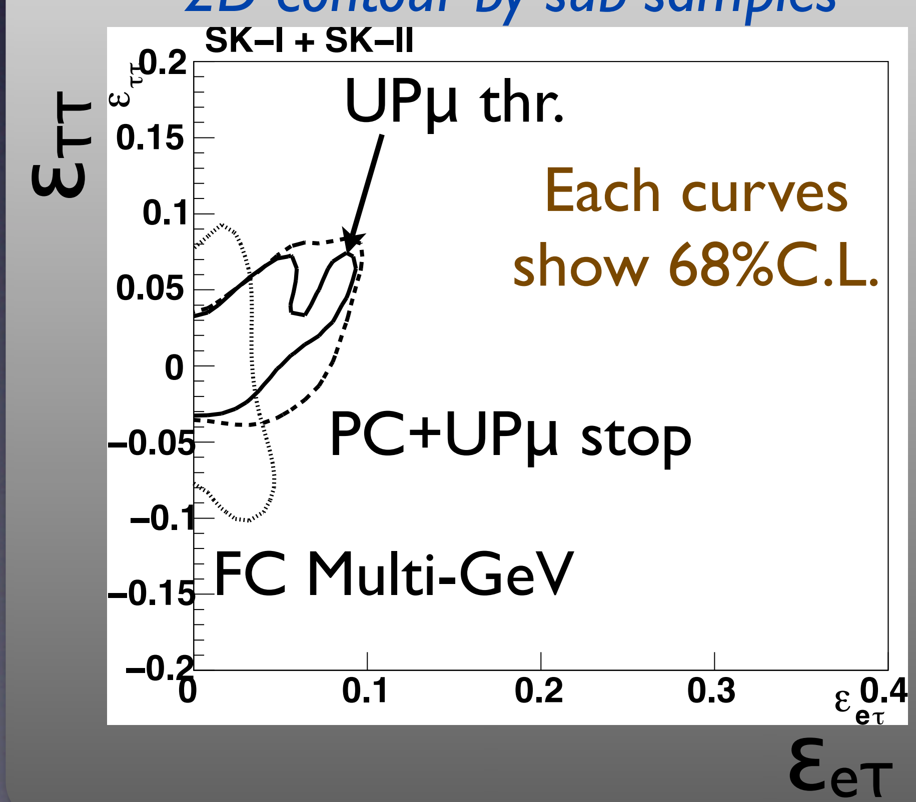
$|\varepsilon_{e\tau}|<0.16$

$-0.05<\varepsilon_{\tau\tau}<0.06$

2D contour(NSI parameters)



2D contour by sub-samples



Constraints by SK

Note : Atm-ν cannot distinguish "L" and "R".

$$\varepsilon_{\alpha\beta} = \varepsilon^{dL}_{\alpha\beta} + \varepsilon^{dR}_{\alpha\beta}$$

Existing limits

CHARM(90%C.L.)

$$|\varepsilon^{dL}_{e\tau}| < 0.5$$

$$|\varepsilon^{dR}_{e\tau}| < 0.5$$

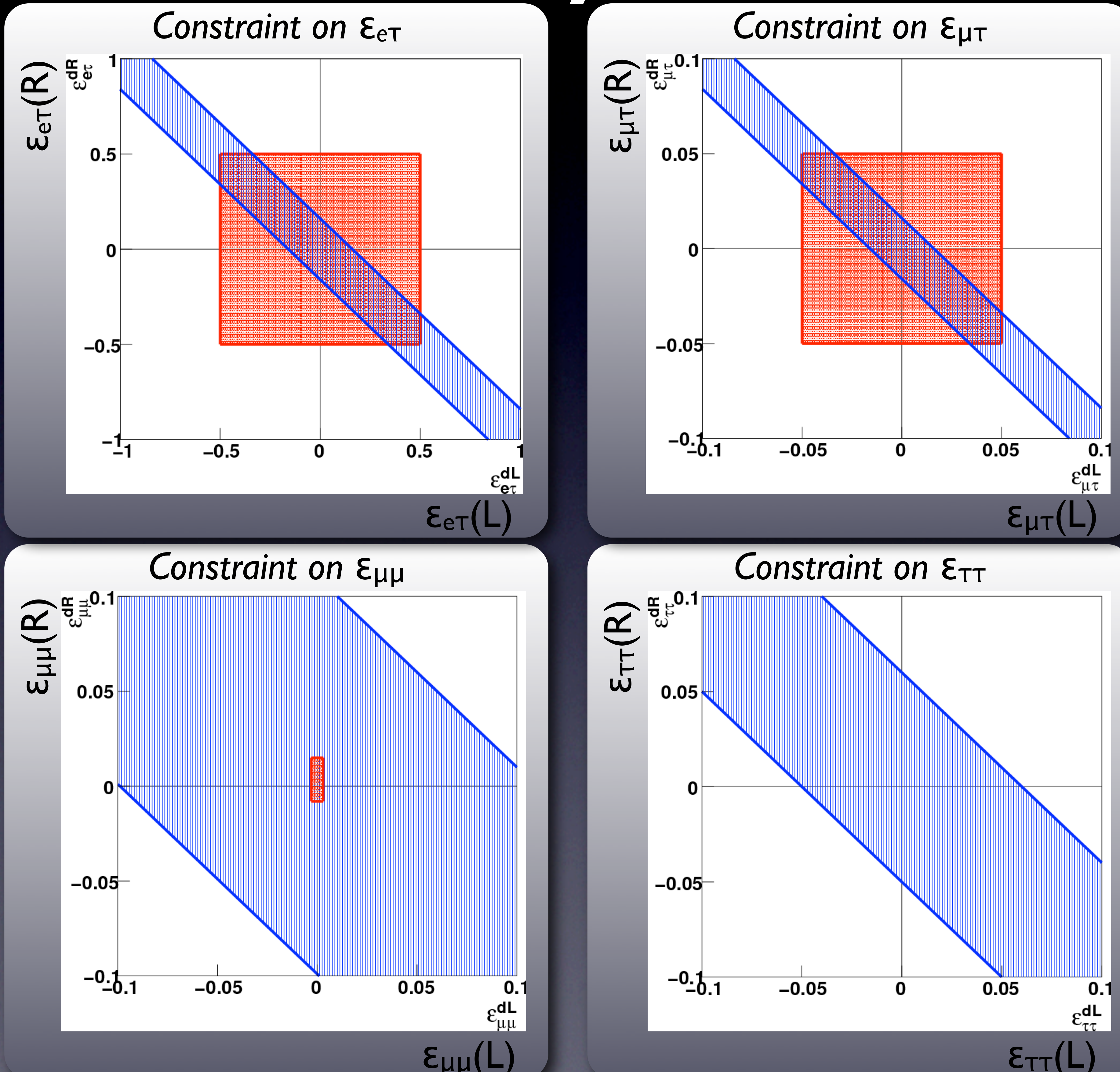
NuTeV(90%C.L.)

$$|\varepsilon^{dL}_{\mu\mu}| < 0.003$$

$$-0.008 < \varepsilon^{dR}_{\mu\mu} < 0.015$$

$$|\varepsilon^{dL}_{\mu\tau}| < 0.05$$

$$|\varepsilon^{dR}_{\mu\tau}| < 0.05$$



Conclusion

- ν oscillation is stable even with additional NSI term.
- NSI is consistent with 0.
- Limit on FCNC is tighter by an order of magnitude.
- Limit on NU($\tau\tau$) is significantly improved.

Backup

What is NSI ?

- NSI : Interaction between a given particle and another one beyond standard model
- NSI is studied in neutrino as well as top-pair and decay etc...

Theorists' opinions

- Hybrid mode with oscillation and NSI can be expected, where NSI is contained as sub-dominant channel[1,2]
- Large value is theoretically allowed in $e\tau$ channel[3]
- Loose limit on $e\tau$ channel can spoils the sensitivity ofθ_{13}[3,4]

[1] N. Fornengo et al., Phys. Rev. D65 (2002) 013010 [hep-ph/0108043]
[2] M. C. Gonzalez-Garcia and M. Maltoni,

Hybrid model
with oscillation and NSI

We follow the formalism by M. C. Gonzalez-Garcia
and Michele Maltoni in PRD 70, 033010 (2004)

$$H = \frac{\Delta m^2_{23}}{4E} R_\theta \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \pm \sqrt{2} G_F N_r(r) R_\phi \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} R_\phi$$

oscillation NSI

where $R_\theta = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$ $R_\phi = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix}$ $\phi = \frac{1}{2}\arctan\left(\frac{\varepsilon}{\varepsilon'/2}\right)$

Survival probability

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\Theta \sin^2\left(\frac{\Delta m^2 L}{4E} R\right)$$

Scanning parameters
sin22θ,Δm2(for osc.)
ε,ε',cosη(for NSI)

relative phase:
η=arg(ε)

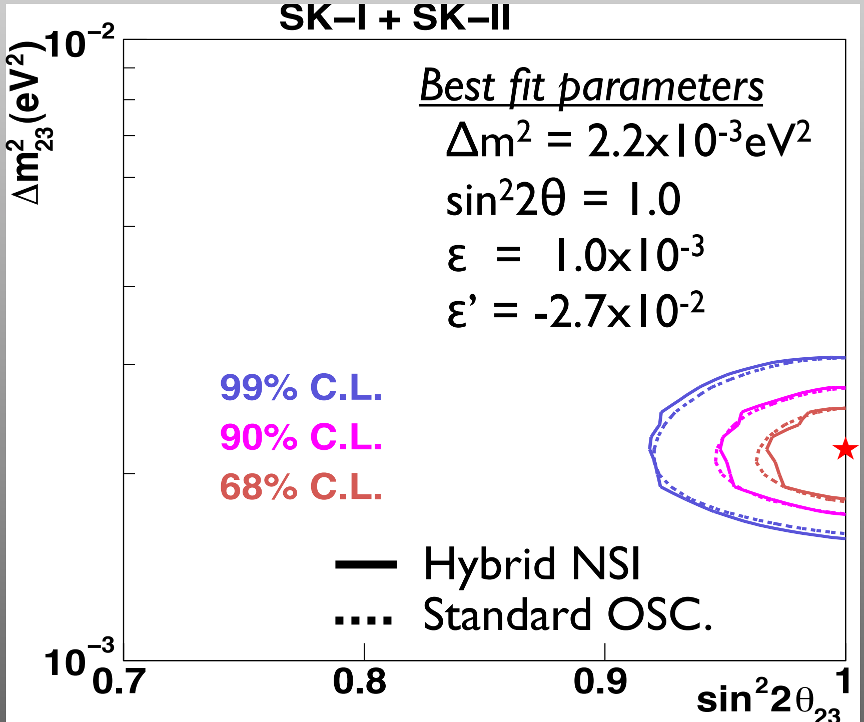
where

$$\sin^2 2\Theta = \frac{1}{R^2}\left(\sin^2 2\theta + R^2 \sin^2 2\phi + 2R \sin 2\theta \sin 2\phi \cos\eta\right)$$

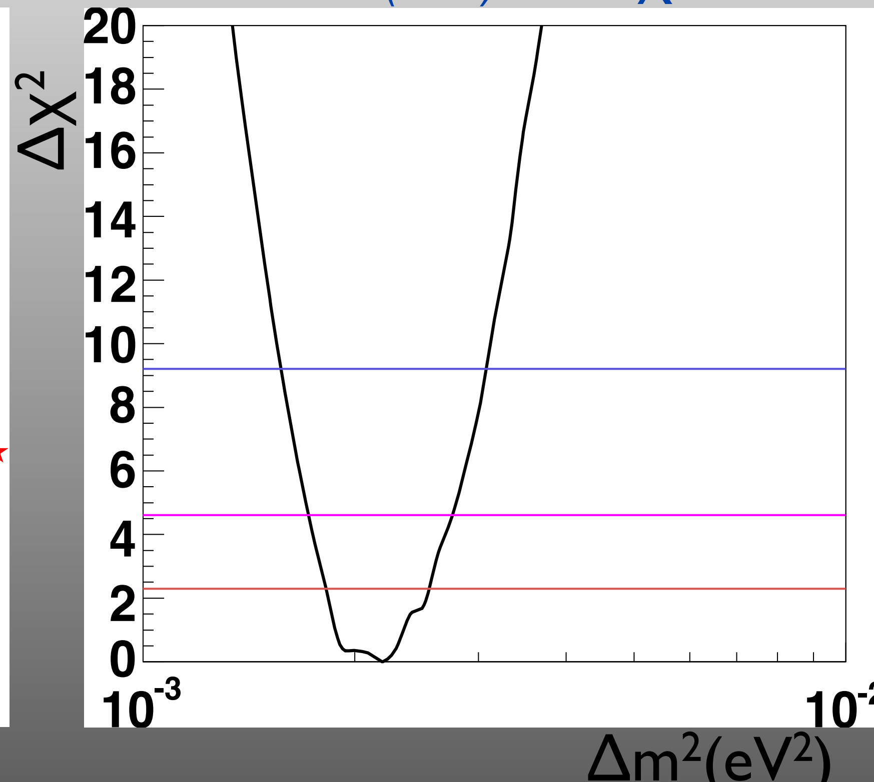
$$R = \sqrt{1 + R^2 + 2R(\cos 2\theta \cos 2\phi + \sin 2\theta \sin 2\phi \cos\eta)}$$

2-Flavor Hybrid(μτ sector)

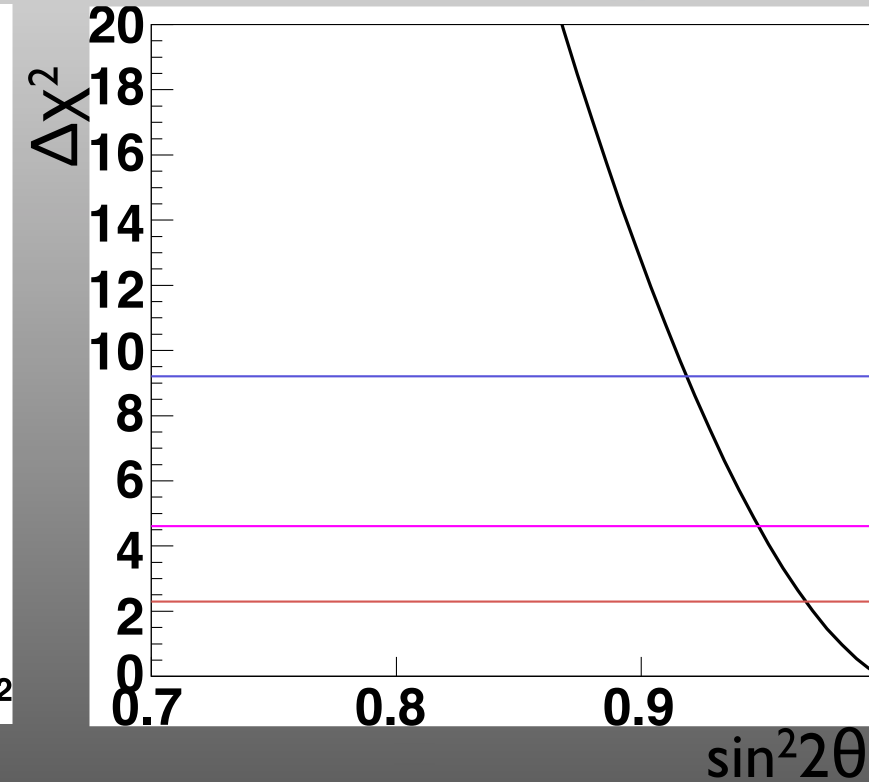
2D contour(OSC pars.)



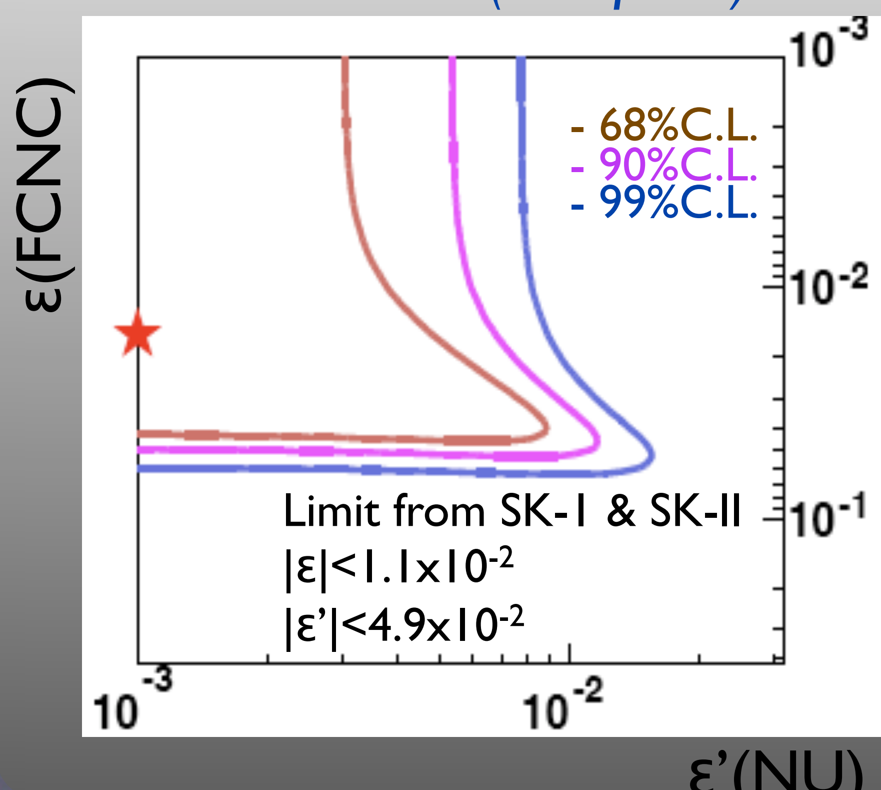
Δm²(eV²) vs. Δχ²



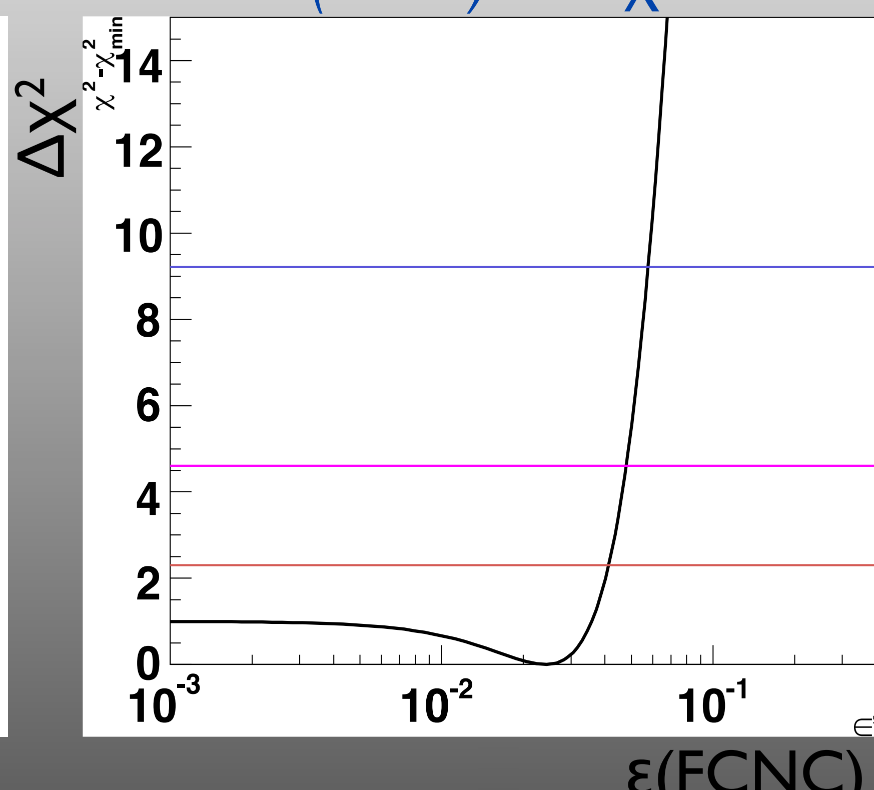
sin²2θ vs. Δχ²



2D contour(NSI pars.)



ε(FCNC) vs. Δχ²



ε'(NU) vs. Δχ²