Non-standard interactions in atmospheric neutrino experiments

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Standard high energy atm oscillation

✓ The standard oscillation of neutrinos disappear with the increase of energy

For ν_e (although the osc. length converges to the refraction length ~ Earth's radius):

$$\sin^2 2\theta_m \propto \frac{1}{(2\sqrt{2}G_F E_\nu n_e)^2} \to 0$$

For ν_μ and ν_τ the mixing angle is unsuppressed, but the osc. length increases with energy and becomes much larger than the Earth's diameter.

➡ For energies >~ 100 GeV, no standard oscillation

Non-standard neutrino interactions

Any oscillation at energies >~ 100 GeV
can testify NSI (generally new physics)

✓ Oscillation in the presence of NSI (for anti-nu: V -> -V and U -> U*)

$$\mathcal{H}_{3\nu} = \frac{1}{2E_\nu} U_{\rm PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger_{\rm PMNS} + \begin{pmatrix} \underbrace{\sqrt{2} G_F n_e}_{V_{\rm CC}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sum_f V_f \epsilon_f$$

where $V_f = \sqrt{2} G_F n_f$ and $\epsilon_f = \begin{pmatrix} \epsilon^f_{ee} & \epsilon^f_{e\mu} & \epsilon^f_{e\tau} \\ \epsilon^{f*}_{e\mu} & \epsilon^f_{\mu\mu} & \epsilon^f_{\mu\tau} \\ \epsilon^{f*}_{e\tau} & \epsilon^{f*}_{\mu\tau} & \epsilon^f_{\tau\tau} \end{pmatrix}$

$\epsilon^f_{\alpha\beta}$ quantifies $\nu_\alpha + f \to \nu_\beta + f$

Non-standard neutrino interactions

✓ Normalizing by the d-quark density

$$\epsilon = \sum_f \frac{n_f}{n_d} \epsilon^f$$

$$\Longrightarrow \quad \sum_f V_f \epsilon^f = 3\epsilon V_{\rm CC} \qquad \left(\frac{n_d}{n_e} \simeq 3 \right)$$

$$\mathcal{H}_{3\nu} = \frac{1}{2E_\nu} U_{\rm PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger_{\rm PMNS} + \begin{pmatrix} \sqrt{2} G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + 3V_{\rm CC}\, \epsilon$$

where $\epsilon = \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$ and we assume: $\epsilon_{\alpha\beta} = \epsilon^*_{\alpha\beta}$

Non-standard neutrino interactions

✓ Two-neutrino approximation:

for $\epsilon_{ee}, \epsilon_{e\mu}, \epsilon_{e\tau} \ll 1$ and $E_\nu > E_{res,13}$ (>~ 20 GeV)

$$\nu_{3m} \simeq \nu_e \qquad \text{and} \qquad \bar{\nu}_{1m} \simeq \bar{\nu}_e$$

→ The two-neutrino approximation can be used

$$\mathcal{H}_{2\nu} = \frac{\Delta m^2_{31}}{2E_\nu} U(\theta_{23}) \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} U(\theta_{23})^\dagger + V_d \begin{pmatrix} \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

Non-standard neutrino interactions

$$\mathcal{H}_{2\nu} = \frac{\Delta m_{31}^2}{2E_\nu} U(\theta_{23}) \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} U(\theta_{23})^\dagger + V_d \begin{pmatrix} \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

✓ At the very high energy $\frac{\Delta m_{31}^2}{2E_\nu} \ll V_d \epsilon_{\alpha\beta}$ → Oscillation is completely matter dominated

Diagonalizing:

$$\sin 2\xi = \frac{2\epsilon_{\mu\tau}}{\sqrt{4\epsilon_{\mu\tau}^2 + \epsilon'^2}}$$ mixing angle

$\epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu}$

$$\Delta\mathcal{H}_m = V_{\rm NSI} = V_d \sqrt{4\epsilon_{\mu\tau}^2 + \epsilon'^2}$$ level splitting

Osc. Prob.

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\xi \ \sin^2 \left(\underbrace{\frac{V_d L}{2} \sqrt{4\epsilon_{\mu\tau}^2 + \epsilon'^2}}_{\phi_{\rm matt}} \right)$$

Non-standard neutrino interactions

$$\phi_{\rm matt} = 35 \left(\frac{\bar\rho}{5.5\,{\rm g\ cm^{-3}}}\right)\left(\frac{L}{2R_\oplus}\right)\sqrt{4\epsilon_{\mu\tau}^2 + \epsilon'^2}$$

✓ With the decrease of ε the potential V_{NSI} and the matter phase decrease.

When $\varphi_{matt} \ll 1$

$$P(\nu_\mu \to \nu_\tau) \approx (\epsilon_{\mu\tau}\overline{V}_d L)^2$$

Akhmedov 2001

✓ No dependence on ε' : With the high energy neutrinos we can just constrain $\varepsilon_{\mu\tau}$

✓ No dependence on the sign of $\varepsilon_{\mu\tau}$. The same result for anti-neutrinos.

Estimating the sensitivity to $\varepsilon_{\mu\tau}$

$$\epsilon_{\mu\tau} = \frac{1}{\overline{V}_d L}\sqrt{P(\nu_\mu \to \nu_\mu)}$$

10% accuracy of P -> $\varepsilon_{\mu\tau} \sim 5\times10^{-3}$

1% accuracy of P -> $\varepsilon_{\mu\tau} \sim 2\times10^{-3}$

restricted sensitivity: quadratic dependence

Non-standard neutrino interactions

✓ In the general case:

$$\mathcal{H}_{2\nu} = \frac{\Delta m^2_{31}}{2E_\nu}\left[U(\theta_{23})\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}U(\theta_{23})^\dagger + R_0 U(\xi)\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}U(\xi)^\dagger\right]$$

where $R_0 \equiv \frac{2E_\nu V_{\rm NSI}}{\Delta m^2_{31}} = \sqrt{2}G_F n_d \sqrt{4\epsilon^2_{\mu\tau} + \epsilon'^2}\,\frac{2E_\nu}{\Delta m^2_{31}}$

relative strength of matter and vacuum contributions

the value $R_0 = 0.5\left(\frac{\bar{\rho}}{5.5\ {\rm g\ cm^{-3}}}\right)\left(\frac{E_\nu}{\rm GeV}\right)\sqrt{4\epsilon^2_{\mu\tau} + \epsilon'^2}$

Diagonalizing:

$$\Delta\mathcal{H}_m = \frac{\Delta m^2_{31}}{2E_\nu}R \quad \text{where} \quad R^2 = [R_0 + \cos 2(\theta_{23} - \xi)]^2 + \sin^2 2(\theta_{23} - \xi)$$

$$\sin^2 2\Theta_m = \frac{1}{R^2}\left(\sin 2\theta_{23} + R_0 \sin 2\xi\right)^2$$

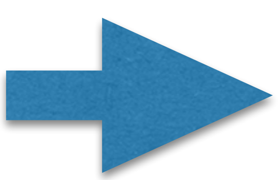
Non-standard neutrino interactions

✓ In the general case:

$$\mathcal{H}_{2\nu} = \frac{\Delta m^2_{31}}{2E_\nu}\left[U(\theta_{23})\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}U(\theta_{23})^\dagger + R_0 U(\xi)\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}U(\xi)^\dagger\right]$$

Oscillation half-phase

$$\Phi_m = \Delta\mathcal{H}_m \frac{L}{2} = \left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)\left[1 + R_0^2 + 2R_0 \cos 2(\theta_{23} - \xi)\right]^{1/2}$$



$$\Phi_m = (\phi_{\rm vac} + \phi_{\rm matt})\sqrt{1 - \frac{2R_0}{(1+R_0)^2}\left[1 - \cos 2(\theta_{23} - \xi)\right]}$$

Oscillation probability

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\Theta_m \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu} R\right)$$

Non-standard neutrino interactions

✓ In the general case:

Osc. prob. $$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\Theta_m \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu} R\right)$$

$$\sin^2 2\Theta_m = \frac{1}{R^2}\left(\sin 2\theta_{23} + R_0 \sin 2\xi\right)^2 \quad \& \quad R^2 = \left[R_0 + \cos 2(\theta_{23} - \xi)\right]^2 + \sin^2 2(\theta_{23} - \xi)$$

$\epsilon_{\mu\tau} \to -\epsilon_{\mu\tau}$ ➡ $\xi \to -\xi$

$\epsilon' \to -\epsilon'$ ➡ $\cos 2(\theta_{23} - \xi) \to -\cos 2(\theta_{23} + \xi)$

$\epsilon_{\mu\tau} \to -\epsilon_{\mu\tau}$ & $\epsilon' \to -\epsilon'$ ➡ $R_0 \to -R_0$

anti-neutrinos

Non-standard neutrino interactions

✓ In the general case:

Osc. prob.
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\Theta_m \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu} R\right)$$

$$\sin^2 2\Theta_m = \frac{1}{R^2}\left(\sin 2\theta_{23} + R_0 \sin 2\xi\right)^2$$ & $$R^2 = [R_0 + \cos 2(\theta_{23} - \xi)]^2 + \sin^2 2(\theta_{23} - \xi)$$

minimum value of resonance factor

Resonance condition → $R_0 = -\cos 2(\theta_{23} - \xi)$

$\xi = 0$ ↔ MSW resonance

Resonance energy
$$E_R = -\frac{\Delta m_{31}^2}{2V_d\sqrt{4\epsilon_{\mu\tau}^2 + \epsilon'^2}} \cos 2(\theta_{23} - \xi)$$

$\epsilon_{\alpha\beta} = 10^{-2}$ ↓ $E_R \simeq 100 \text{ GeV}$

Non-standard neutrino interactions

✓ In the general case:

Osc. prob. $$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\Theta_m \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu} R\right)$$

$$\sin^2 2\Theta_m = \frac{1}{R^2}(\sin 2\theta_{23} + R_0 \sin 2\xi)^2$$ & $$R^2 = [R_0 + \cos 2(\theta_{23} - \xi)]^2 + \sin^2 2(\theta_{23} - \xi)$$

What happens in the Resonance?

In the resonance: $R^2 = \sin^2 2(\theta_{23} - \xi) = 1 - R_0^2$ → $\sin^2 2\Theta_m = \cos^2 2\xi$

The two limits: $(\xi = \pi/4 \to \sin^2 2\Theta_m = 0)$ & $(\xi = 0 \to \sin^2 2\Theta_m = 1)$

matter dominated — MSW

Osc. phase in the Resonance $$\Phi_m = \frac{\Delta m^2_{31} L}{4E} \sin 2(\theta_{23} - \xi)$$

$\epsilon > 0$ → anti-neutrino

$\epsilon < 0$ → neutrino

Non-standard neutrino interactions

✓ In the general case:

Osc. prob. $$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\Theta_m \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu} R\right)$$

$$\sin^2 2\Theta_m = \frac{1}{R^2}\left(\sin 2\theta_{23} + R_0 \sin 2\xi\right)^2$$ & $$R^2 = [R_0 + \cos 2(\theta_{23} - \xi)]^2 + \sin^2 2(\theta_{23} - \xi)$$

What happens in the Resonance?

Maximal interplay between vacuum and NSI ⟷ $E \simeq E_R$ or $R_0 = -1$

In the range $E \simeq E_R$ → The probability depends linearly on ε

Non-standard neutrino interactions

✓ In the general case:

Osc. prob. $$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\Theta_m \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu} R\right)$$

$$\sin^2 2\Theta_m = \frac{1}{R^2}\left(\sin 2\theta_{23} + R_0 \sin 2\xi\right)^2 \quad \& \quad R^2 = [R_0 + \cos 2(\theta_{23} - \xi)]^2 + \sin^2 2(\theta_{23} - \xi)$$

R_0 quantifies the relative effect of NSI

$R_0 \to 0$ Low energies → $\xi \to 0$ and $R \to 1$

→ $\sin^2 2\Theta_m = \sin 2\theta_{23}, \quad \Delta\mathcal{H}_m \to \frac{\Delta m_{31}^2}{2E_\nu}, \quad \Phi_m \to \frac{\Delta m_{31}^2 L}{4E_\nu}$ vacuum osc. recovers

$R_0 \to \infty$ High energies → $R \to R_0$

→ $\sin 2\Theta_m \to \sin 2\xi, \quad \Delta\mathcal{H}_m \to V_{\rm NSI}$ matter dominated osc. recovers

Non-standard neutrino interactions

✓ In the general case:

Osc. prob. $$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\Theta_m \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu} R\right)$$

$$\sin^2 2\Theta_m = \frac{1}{R^2}\left(\sin 2\theta_{23} + R_0 \sin 2\xi\right)^2 \quad \& \quad R^2 = \left[R_0 + \cos 2(\theta_{23} - \xi)\right]^2 + \sin^2 2(\theta_{23} - \xi)$$

With the decrease of ε the energy where the NSI effect becomes dominating increases

Also: $l_m \propto 1/\Delta\mathcal{H}_m \sim 1/\epsilon$

At very small ε the oscillation length becomes much larger than the Earth's diameter

In this case: $$P(\nu_\mu \to \nu_\mu) = 1 - \left(\sin 2\theta_{23} + R_0 \sin 2\xi\right)^2 \cdot \left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)^2$$

For ξ = 0 the "vacuum mimicking" result can be obtained (Akhmedov 2001)

Non-standard neutrino interactions

✓ Flavor off-diagonal NSI (Universal NSI) $\epsilon_{\mu\tau} \neq 0 \;\;,\;\; \epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu} = 0$

In this case sin 2ξ = 1, and: $\sin^2 2\Theta_m = \dfrac{1}{1 + \cos^2 2\theta_{23} (R_0 + \sin 2\theta_{23})^{-2}}$ converges to maximal for large R_0

The resonance factor becomes $$R^2 = [R_0 + \sin 2\theta_{23}]^2 + \cos^2 2\theta_{23}$$

In the resonance ➡ $$\Phi_m = \frac{\Delta m^2_{31} L}{4E_\nu} \cos 2\theta_{23}$$

Far from the resonance ➡ $$\Phi_m \approx \phi_{\rm vac} + \phi_{\rm matt} = \frac{\Delta m^2_{32} L (1 + R_0)}{4E_\nu} = \frac{\Delta m^2_{32} L}{4E_\nu} + V_d L \epsilon_{\mu\tau}$$

modification of the phase is energy independent

In the high energy the vacuum term is negligible, while: $$\phi_{\rm matt} = 70 \left(\frac{\bar\rho}{5.5 \text{ g cm}^{-3}} \right) \left(\frac{L}{2R_\oplus} \right) \epsilon_{\mu\tau}$$

Non-standard neutrino interactions

✓ Flavor off-diagonal NSI (Universal NSI) $\epsilon_{\mu\tau} \neq 0 \;\; , \;\; \epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu} = 0$

For $\cos\theta_z = -1$ → $\phi_{\rm matt} = 62\epsilon_{\mu\tau}$

$\phi_{\rm matt} = \pi/2$ → minimum of muon survival prob. → $\epsilon_{\mu\tau} = 2.5 \times 10^{-2}$

$\cos\theta_z = -1$

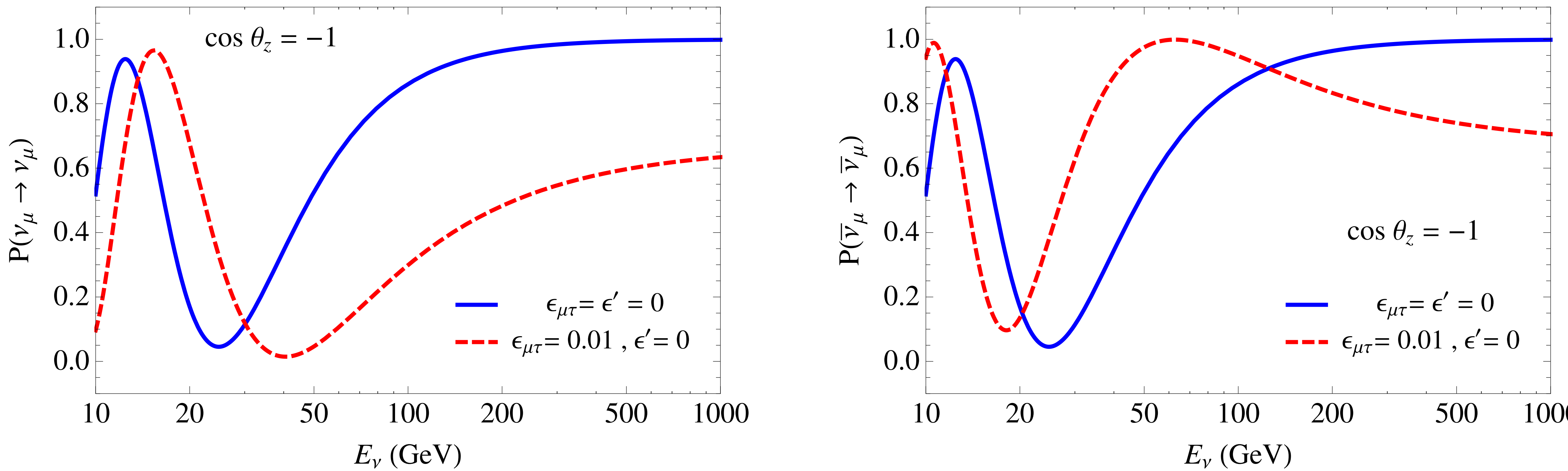
For $\epsilon_{\mu\tau} \gtrsim 2.5 \times 10^{-2}$ the minimum of probability occurs at $\cos\theta_z > -1$

✓ In asymptotic, i.e. high energies or very small $\varepsilon_{\mu\tau}$, we have: $P = \phi^2_{\rm matt}$.

Non-standard neutrino interactions

- Flavor off-diagonal NSI (Universal NSI) $\epsilon_{\mu\tau} \neq 0 \;\; , \;\; \epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu} = 0$

Equivalent to negative $\varepsilon_{\mu\tau}$

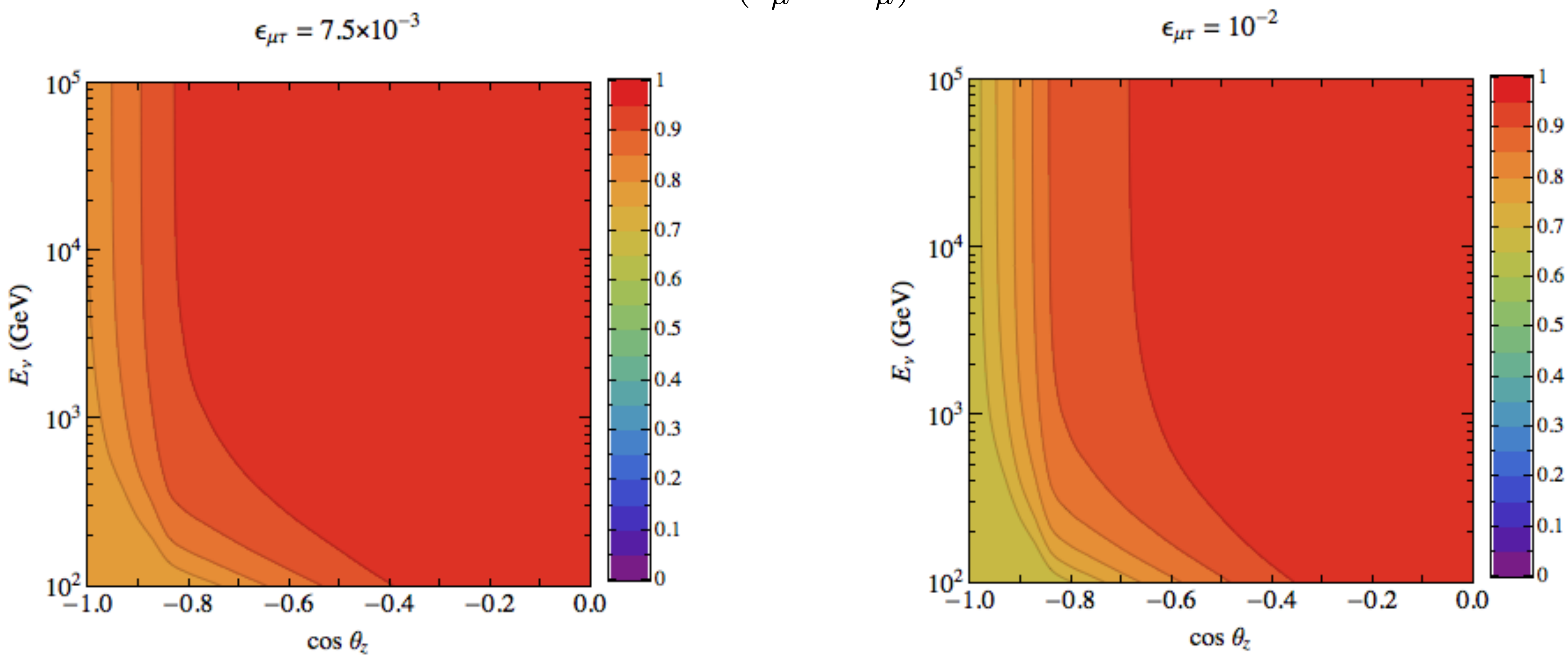


- For E_ν < 100 GeV, the NSI leads to shift of the oscillatory pattern to lower (neutrino) and higher (anti-neutrino) energies for $\varepsilon_{\mu\tau} > 0$.
- A small change in the depth of minimum, due to the change in mixing angle.
- In the resonance, $E_R \sim 60$ GeV, the mixing is zero, $\sin\Theta_m = 0$ —> no osc. for anti-neutrino.
- With the increase of energy, both nu and anti-nu oscillation probabilities converge to the same asymptotic value, $P = \phi^2_{matt.}$

Non-standard neutrino interactions

✓ Flavor off-diagonal NSI (Universal NSI) $\epsilon_{\mu\tau} \neq 0 \ , \ \epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu} = 0$

$$P(\nu_\mu \to \nu_\mu)$$



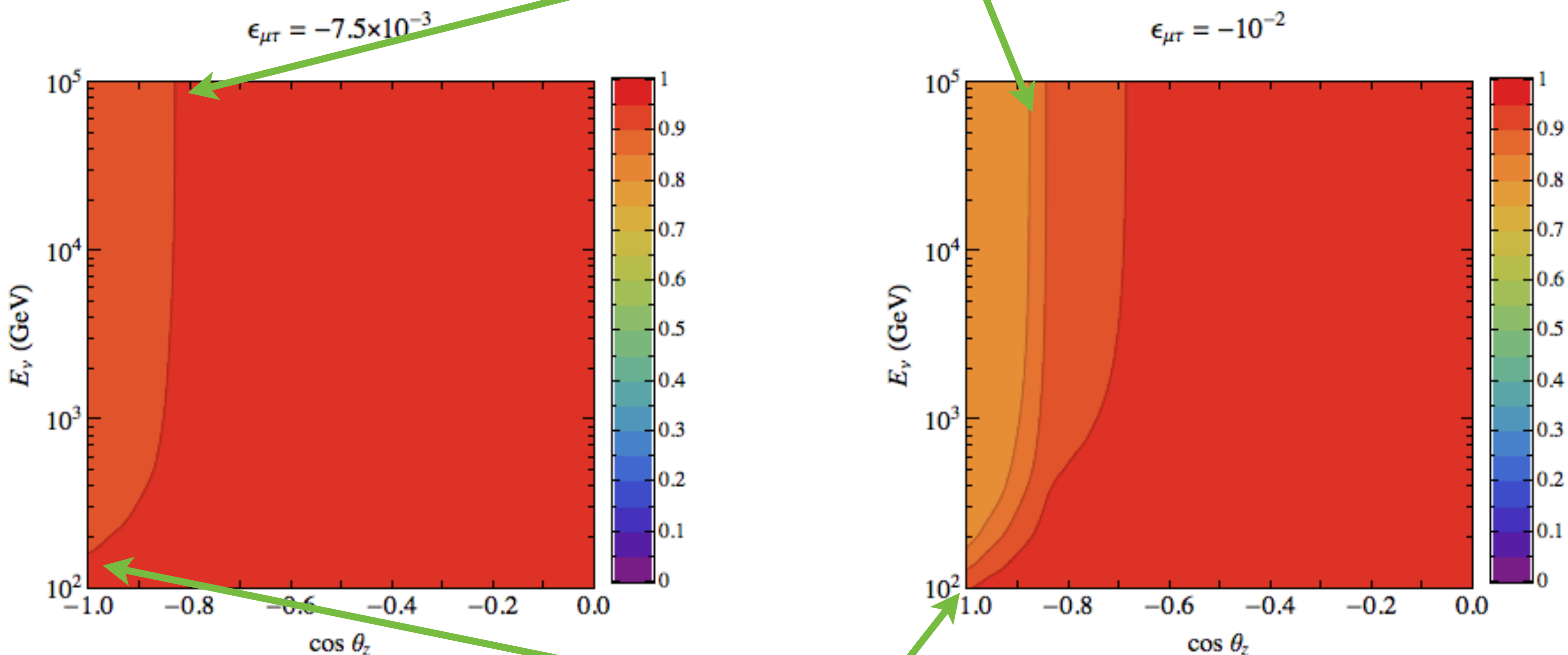
Non-standard neutrino interactions

✓ Flavor off-diagonal NSI (Universal NSI) $\epsilon \neq 0 \quad , \quad \epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu} = 0$

$P(\nu_\mu \to \nu_\mu)$

Equivalent to anti-nu

matter dominated oscillation

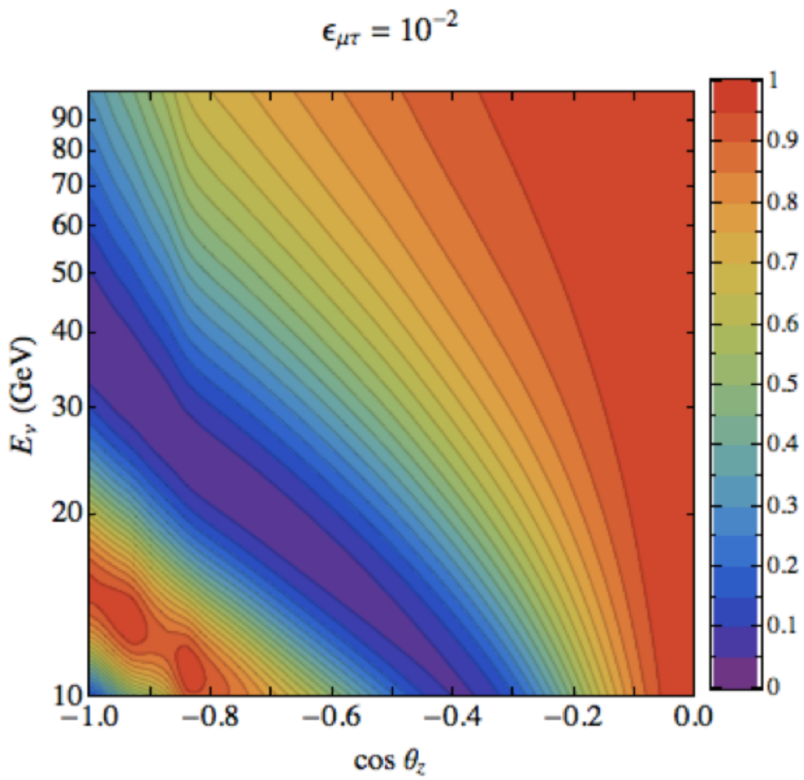


resonance $(\sin^2 2\Theta_m = 0)$

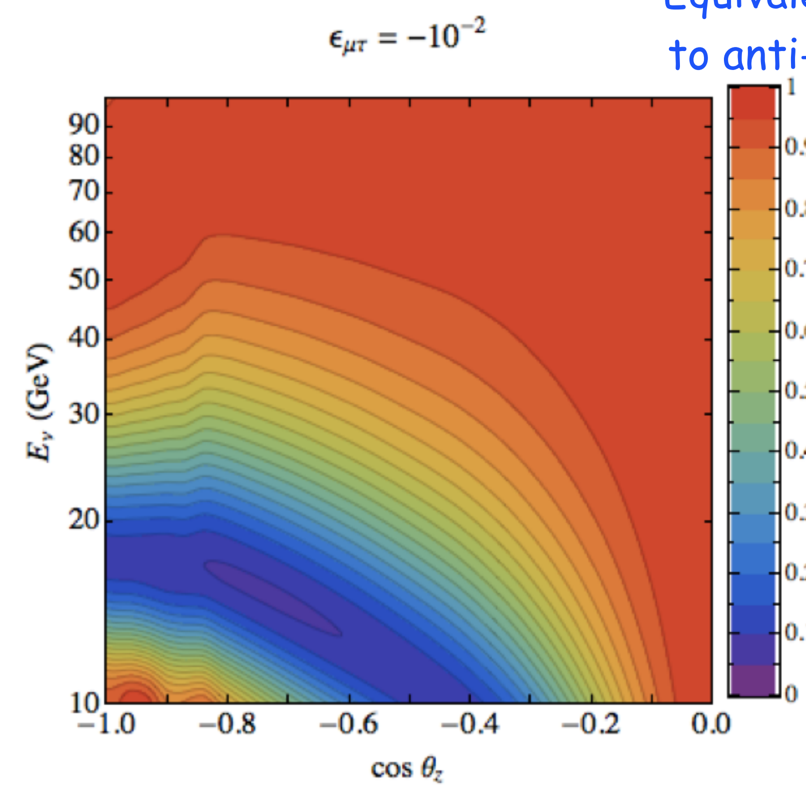
Non-standard neutrino interactions

✓ Flavor off-diagonal NSI (Universal NSI) $\epsilon_{\mu\tau} \neq 0 \; , \; \epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu} = 0$

$P(\nu_\mu \to \nu_\mu)$



Equivalent to anti-nu



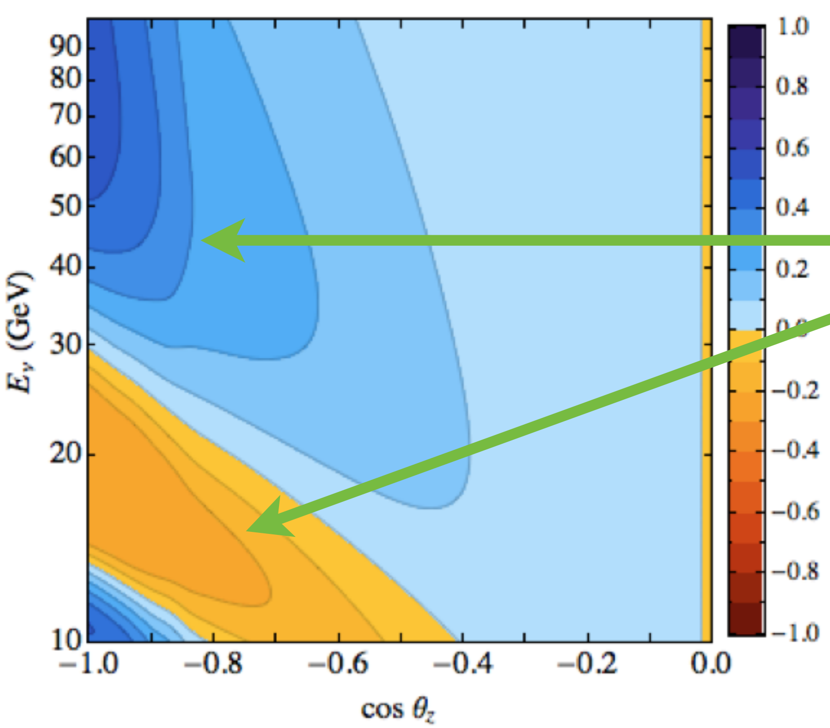
$E_{\nu,min}$ = 18 GeV

depth decreases

$E_{\nu,min}$ = 38 GeV

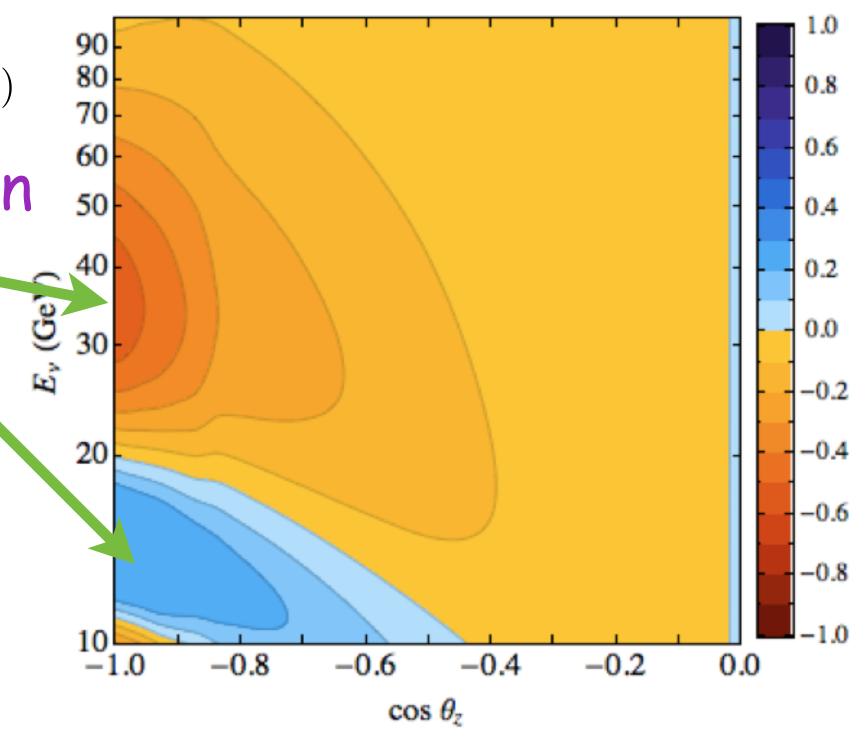
$P^{\rm STD}(\nu_\mu \to \nu_\mu) - P(\nu_\mu \to \nu_\mu; \{\epsilon_{\mu\tau}, \epsilon' = 0\})$

the difference change sign



(nu+anti-nu) decreases the sensitivity

Energy integration decreases the sensitivity



Non-standard neutrino interactions

✓ Flavor conserving NSI (non-Universal NSI) $\epsilon_{\mu\tau} = 0 \;,\; \epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu} \neq 0$

In this case sin 2ξ = 0, and the mixing and mass-splitting formulas can be obtained from the usual MSW formulas with the potential $V_{NSI} = V_d\, \varepsilon'$.

$$\sin^2 2\Theta_m = \frac{\sin^2 2\theta_{23}}{(R_0 + \cos 2\theta_{23})^2 + \sin^2 2\theta_{23}}$$

and

$$\Delta\mathcal{H}_m = \frac{\Delta m^2_{31}}{2E}\left[(R_0 + \cos 2\theta_{23})^2 + \sin^2 2\theta_{23}\right]^{1/2}$$

Where

$$R_0 = 0.5\left(\frac{\bar\rho(\theta_z)}{5.5\ \mathrm{g\ cm^{-3}}}\right)\left(\frac{E_\nu}{\mathrm{GeV}}\right)\epsilon'$$

resonance condition
$R_0 = -\cos 2\theta_{23}$ ➡

$$E_R = 2\ \mathrm{GeV}\left(\frac{5.5\ \mathrm{g\ cm^{-3}}}{\bar\rho(\theta_z)}\right)\left(\frac{\cos 2\theta_{23}}{\epsilon'}\right)$$

For small $\varepsilon' = 5\times10^{-2}$, E_R ~ 10 GeV for mantle crossing trajectories. However, the resonance enhancement of oscillation is very weak because the mixing angle is already large. The main effect of NSI is the suppression of oscillation at $E_\nu > E_R$.

Non-standard neutrino interactions

✓ Flavor conserving NSI (non-Universal NSI) $\epsilon_{\mu\tau} = 0 \;\; , \;\; \epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu} \neq 0$

For the core-crossing neutrinos ($\cos\theta_z = -1$), approximately:

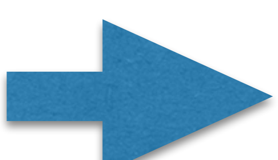
$$\Phi_m = 38 \left(\frac{\mathrm{GeV}}{E_\nu}\right) \sqrt{1 + \cos 2\theta_{23} \left(\frac{E_\nu}{\mathrm{GeV}}\right) \epsilon' + 0.25 \left(\frac{E_\nu}{\mathrm{GeV}}\right)^2 \epsilon'^2}$$

small in high energies

$$\sin^2 2\Theta_m = \frac{\sin^2 2\theta_{23}}{1 + \cos 2\theta_{23} \left(\frac{E_\nu}{\mathrm{GeV}}\right) \epsilon' + 0.25 \left(\frac{E_\nu}{\mathrm{GeV}}\right)^2 \epsilon'^2}$$

approximating the sensitivity to ε' : the effect is linear in ε' with a coefficient given by:

$$\delta \equiv 2\cos 2\theta_{23} R_0 = \frac{2\epsilon' \cos 2\theta_{23} 2 E_\nu V_d}{\Delta m^2_{31}}$$



For maximal 2-3 mixing the linear term is zero and the effect is very small (ε'^2)

Non-standard neutrino interactions

✓ Flavor conserving NSI (non-Universal NSI) $\epsilon_{\mu\tau} = 0 \ , \ \epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu} \neq 0$

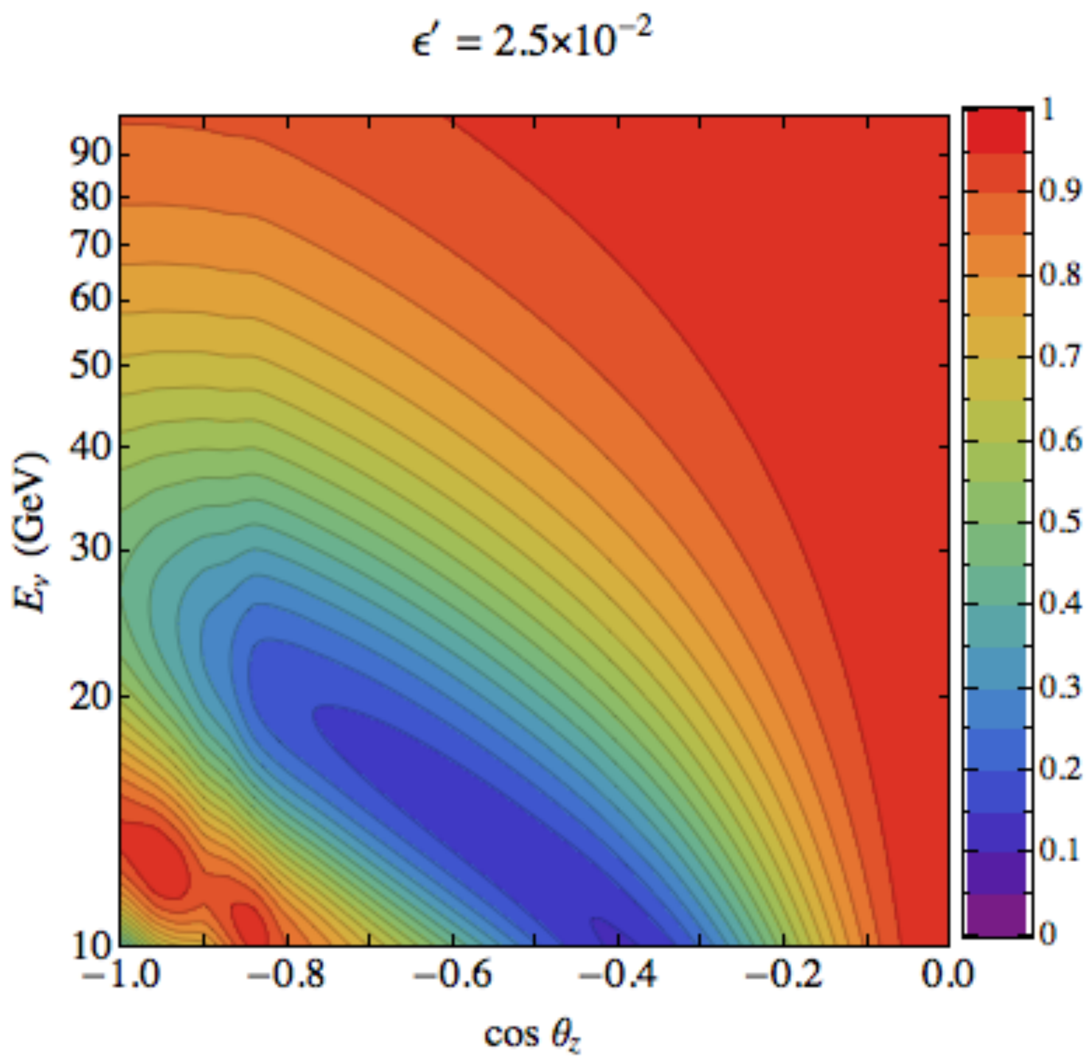
In the linear approximation of δ, $\Delta P \approx \delta \left(-\sin^2\phi_{\rm vac} + \phi_{\rm vac} \sin\phi_{\rm vac} \cos\phi_{\rm vac} \right)$

$$\epsilon' \sim \Delta P \frac{\Delta m^2_{31}}{2E_\nu V_d} \left(-\sin^2\phi_{\rm vac} + \phi_{\rm vac} \sin\phi_{\rm vac} \cos\phi_{\rm vac} \right)^{-1}$$ sensitivity

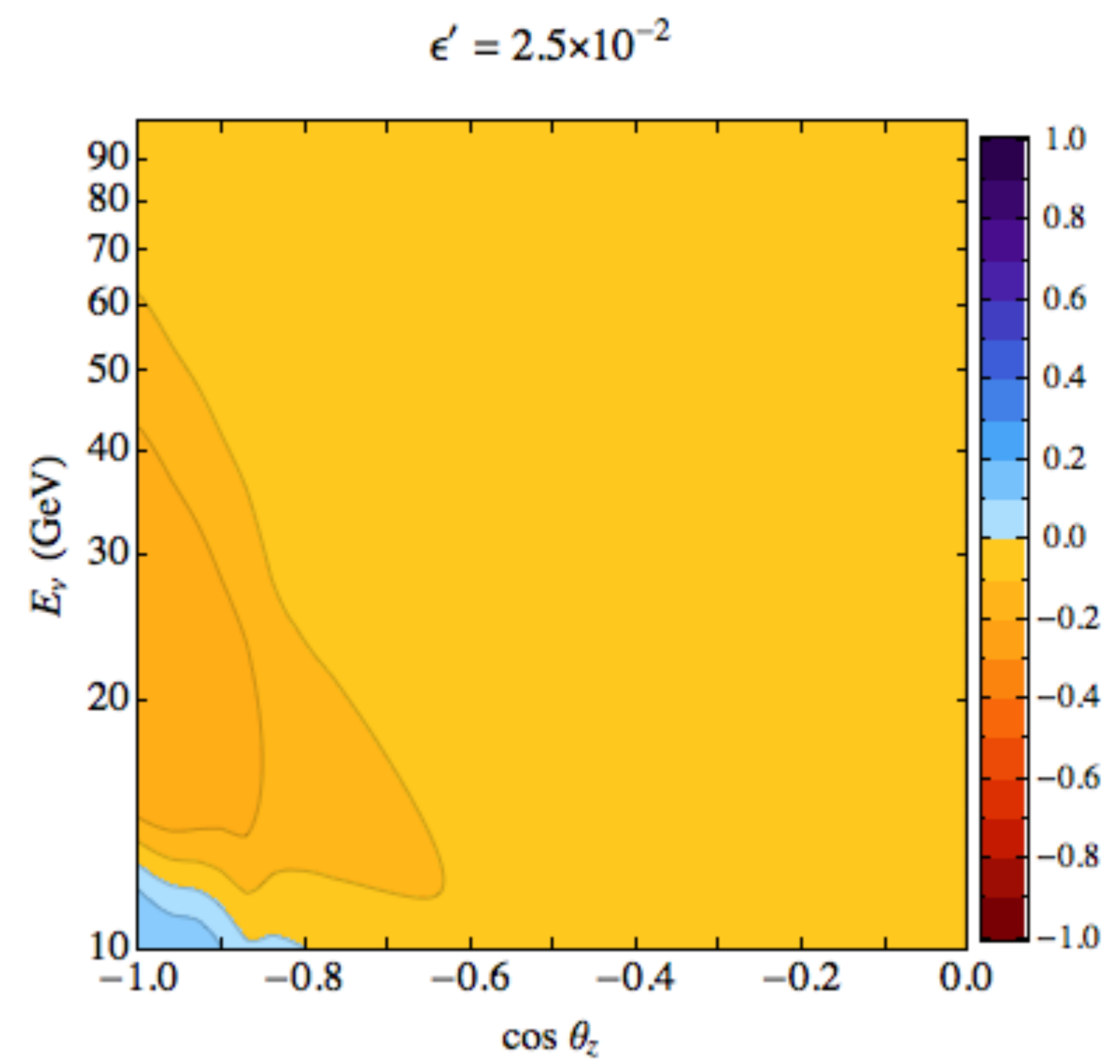
10% accuracy of P and E_ν = 30 GeV -> $\varepsilon' \sim 2\times10^{-2}$

Non-standard neutrino interactions

✓ Flavor conserving NSI (non-Universal NSI) $\epsilon_{\mu\tau} = 0 \;\; , \;\; \epsilon' = \epsilon_{\tau\tau} - \epsilon_{\mu\mu} \neq 0$



$P(\nu_\mu \to \nu_\mu)$

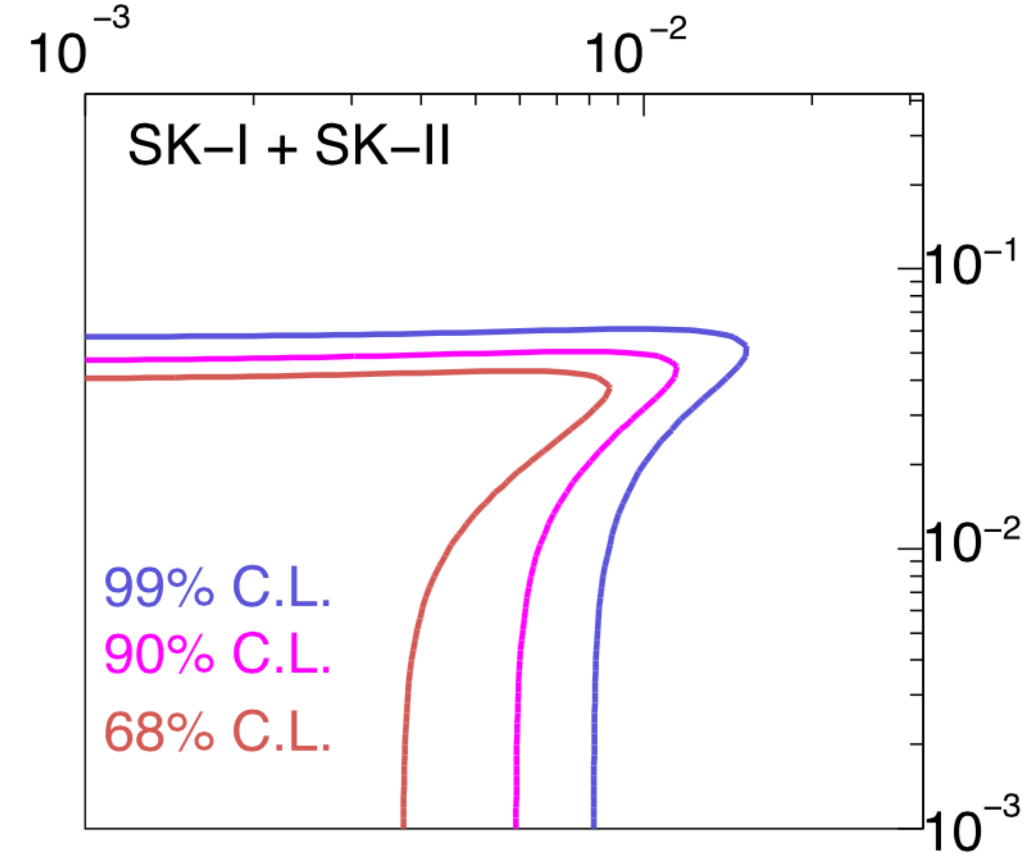


$P^{\rm STD}(\nu_\mu \to \nu_\mu) - P(\nu_\mu \to \nu_\mu; \{\epsilon_{\mu\tau}, \epsilon' = 0\})$

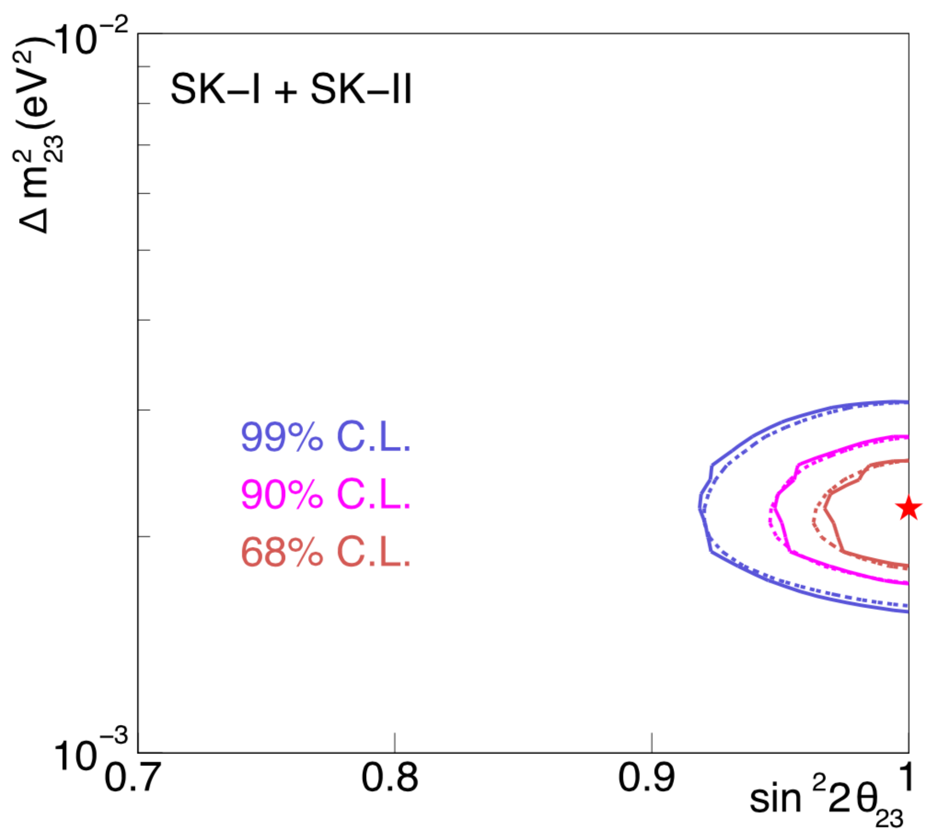
The important energy range (20 — 40) GeV

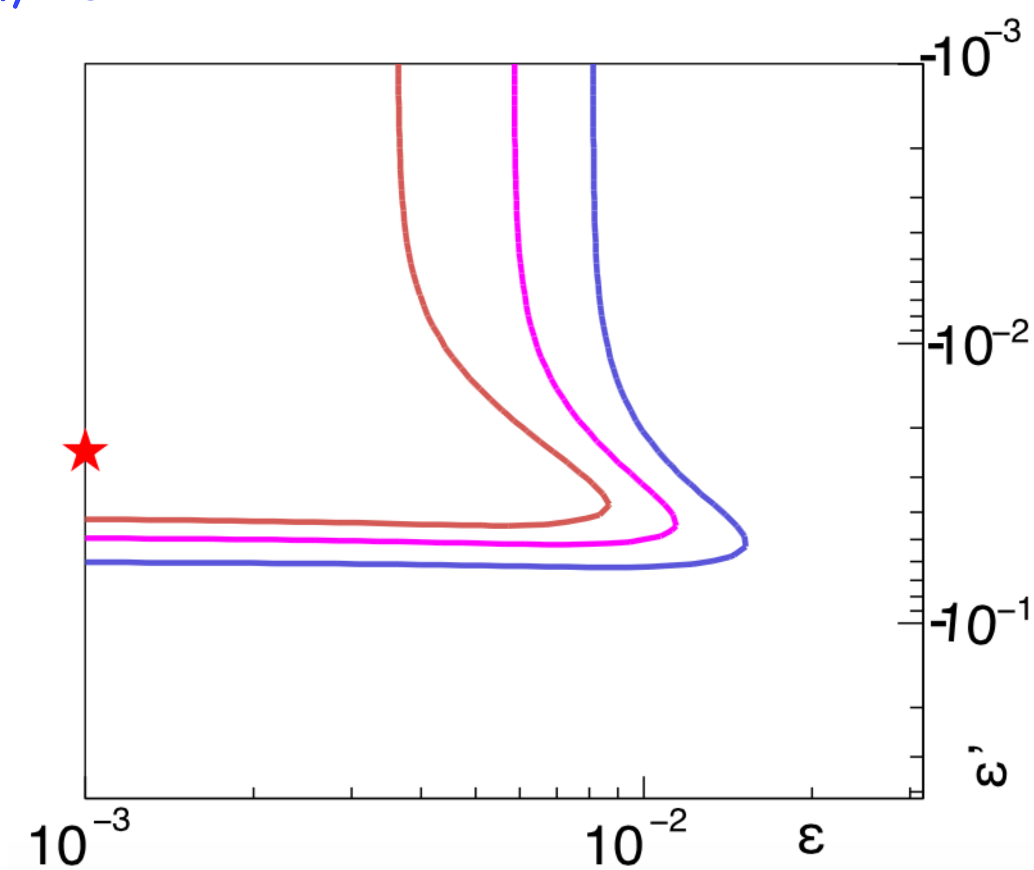
Stronger effect for positive ε′

- ✓ SuperKamiokande, μ-τ sector
- ✓ 1 GeV < E_ν < 30 GeV (lower and higher also included)



SK collaboration, 2011





✓ IC-79 dataset + DeepCore data, μ-τ sector

✓ (100 GeV - 10 TeV) + (20 GeV - 100 GeV)

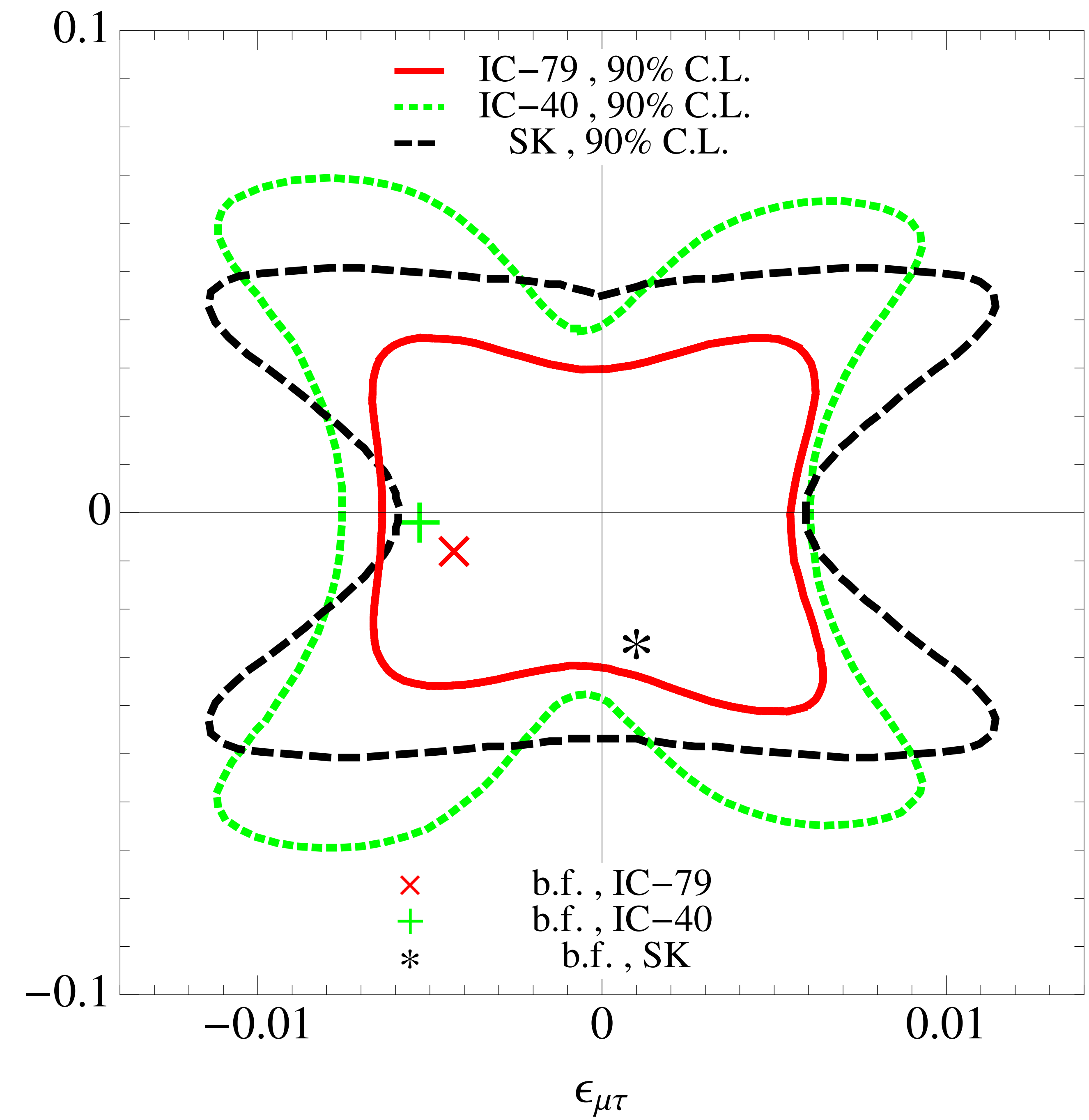
✓ Considering both $\nu_e \to \nu_\mu$ and $\nu_\mu \to \nu_\mu$

A.E., Alexei Smirnov, 2013

Marginalized 1-D limits (90% C.L.):

$$-6.1 \times 10^{-3} < \epsilon_{\mu\tau} < 5.6 \times 10^{-3}$$

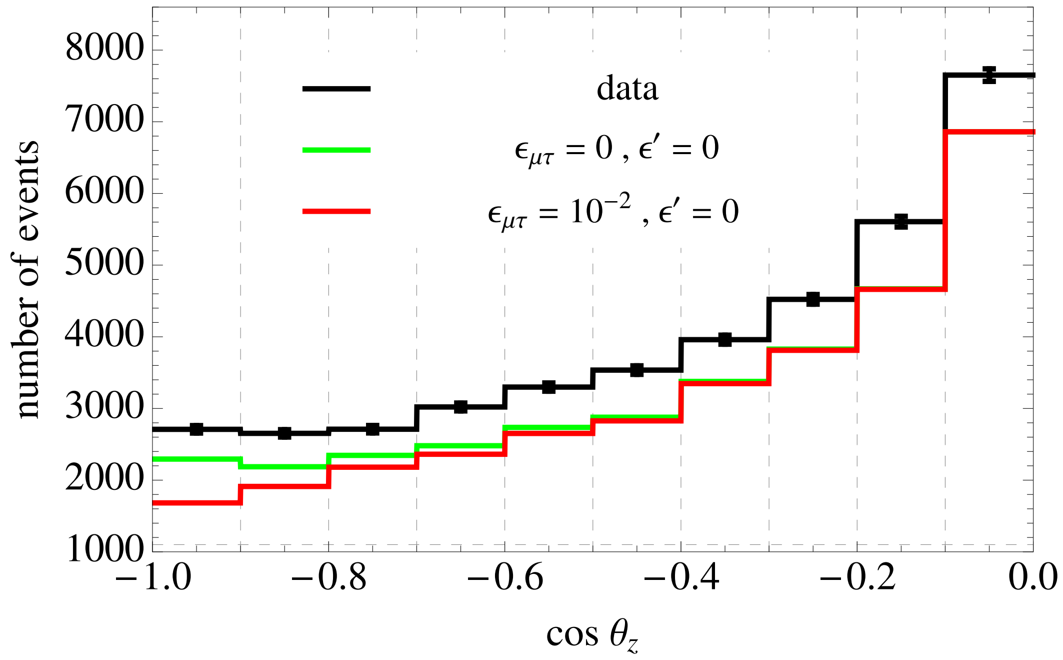
$$-3.6 \times 10^{-2} < \epsilon' < 3.1 \times 10^{-2}$$



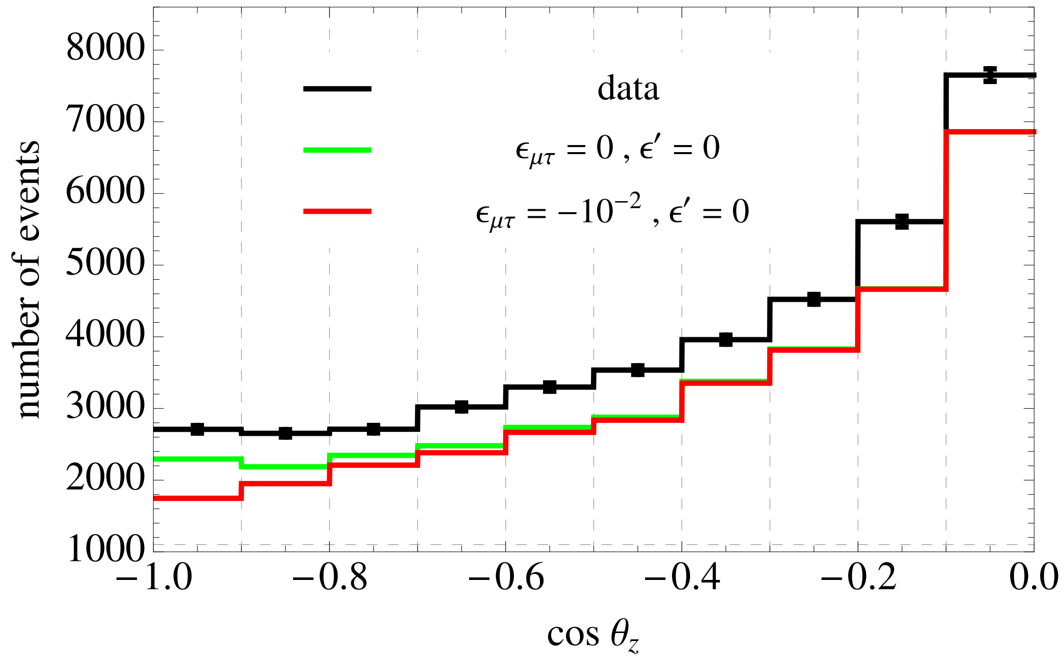
see also Salvado et al., 2016

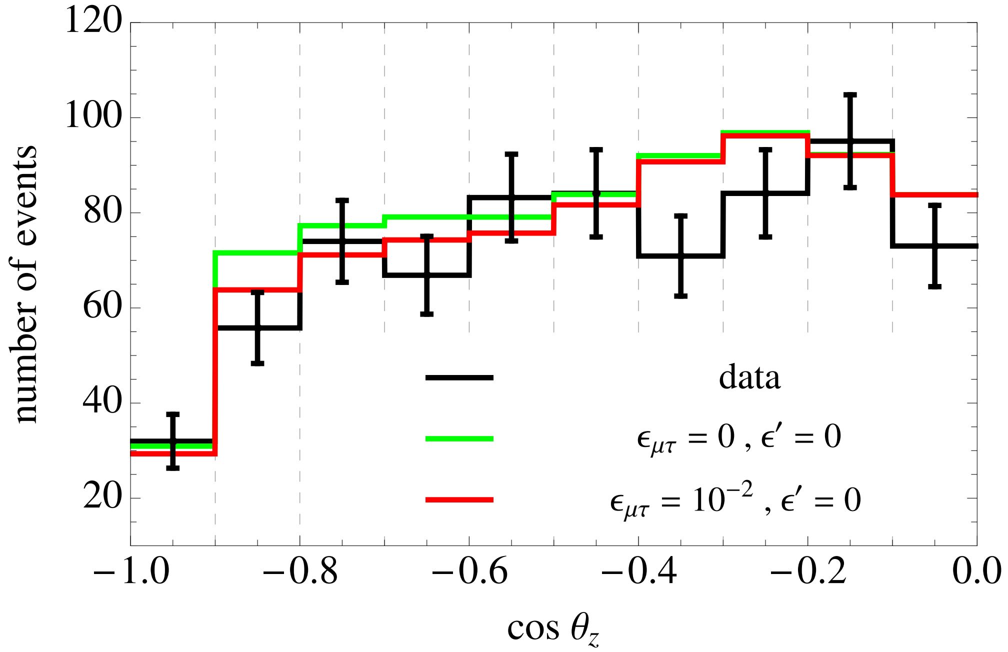
IC-79 dataset + DeepCore data, μ-τ sector

A.E., Alexei Smirnov, 2013

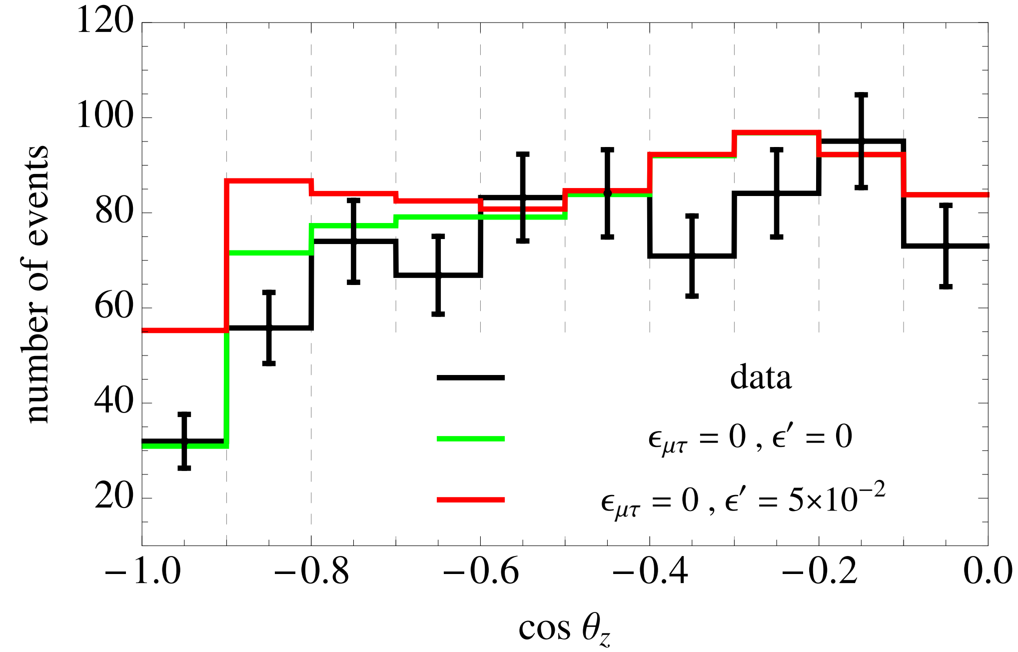


High energy data
100 GeV - 100 TeV





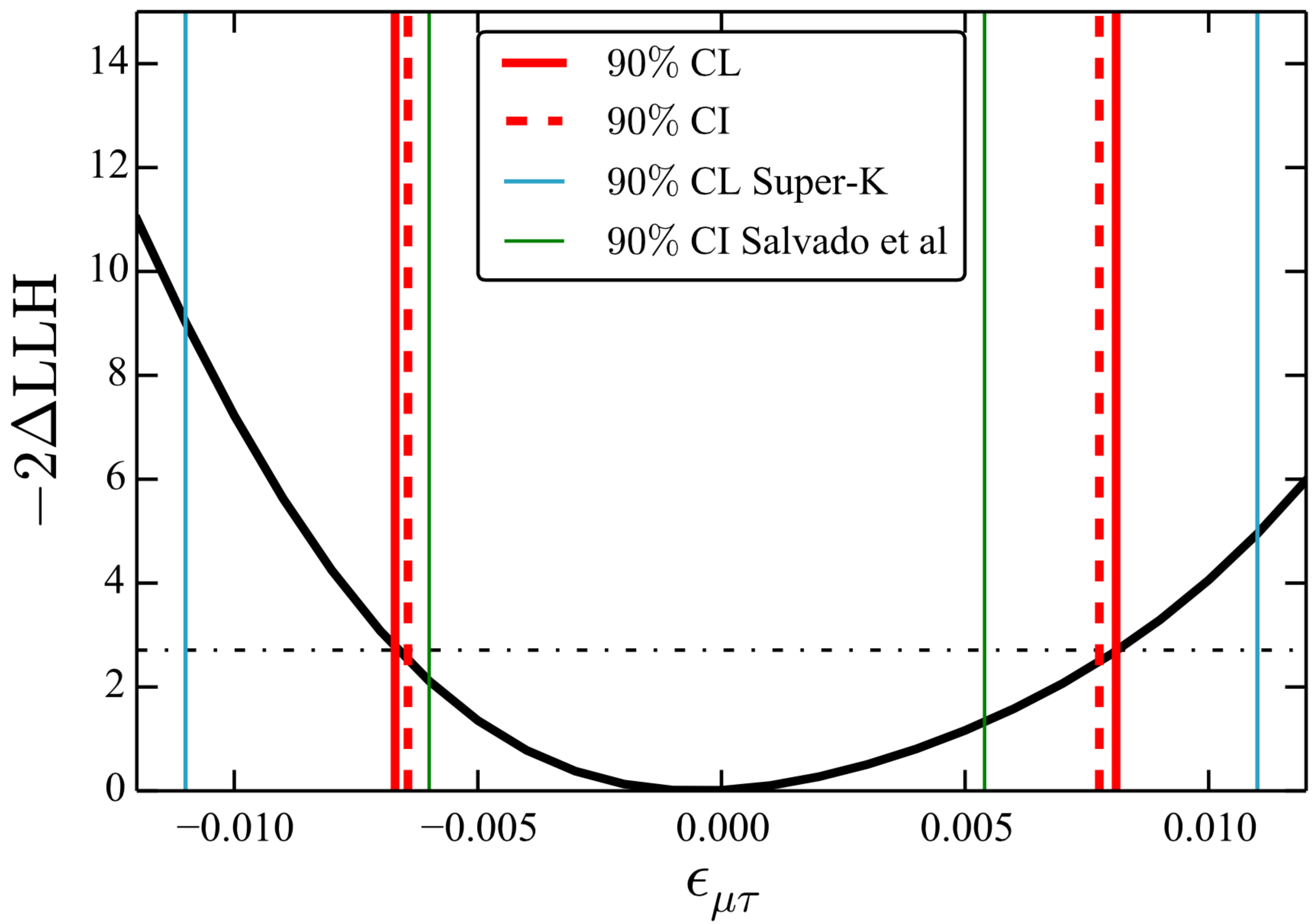
Low energy data
20 GeV - 100 GeV



✓ IceCube collaboration results (1 NSI parameter analysis, $\varepsilon_{\mu\tau}$):

Three years DeepCore data

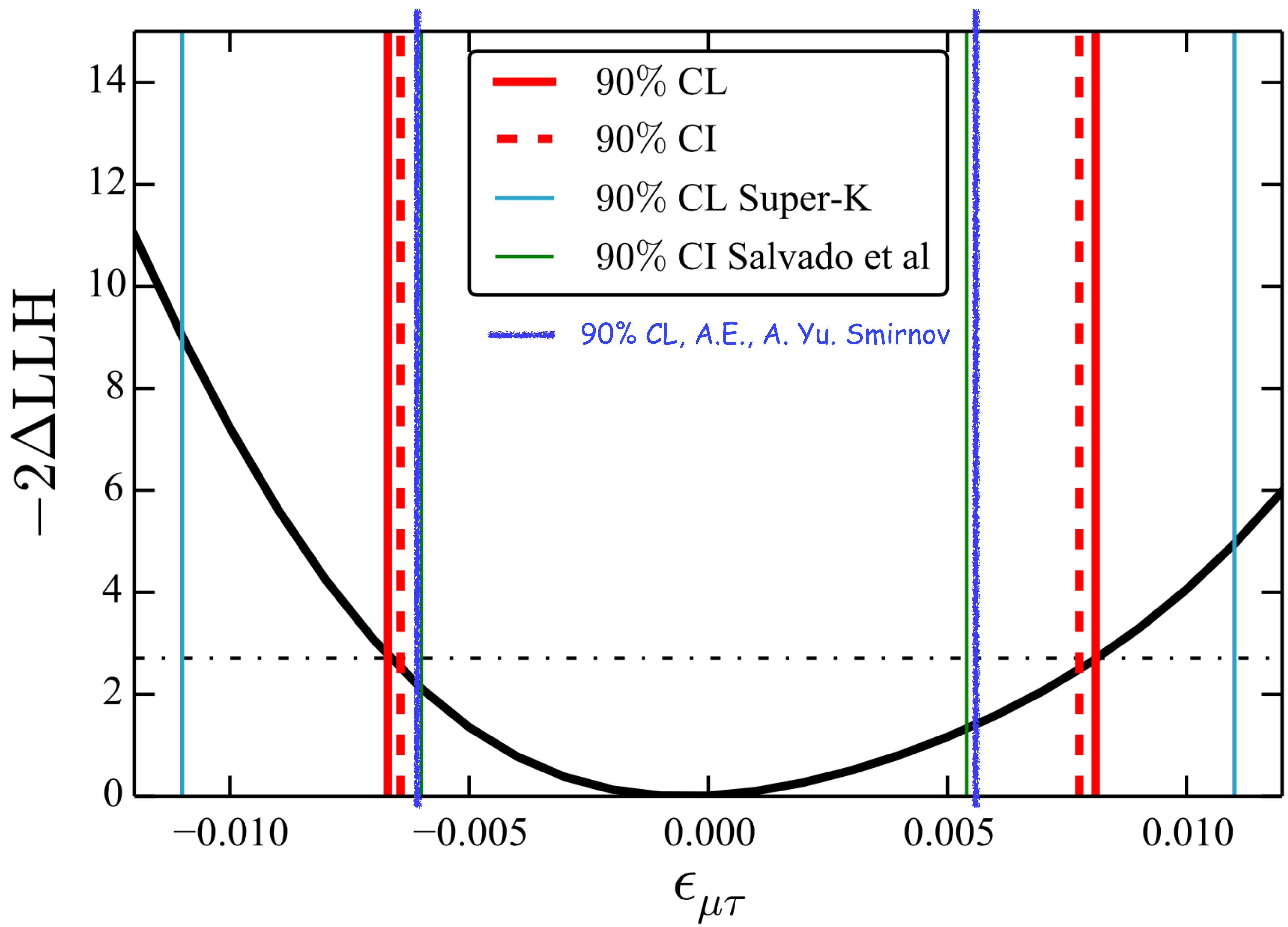
IceCube collaboration, 2017



✓ IceCube collaboration results (1 NSI parameter analysis, $\varepsilon_{\mu\tau}$):

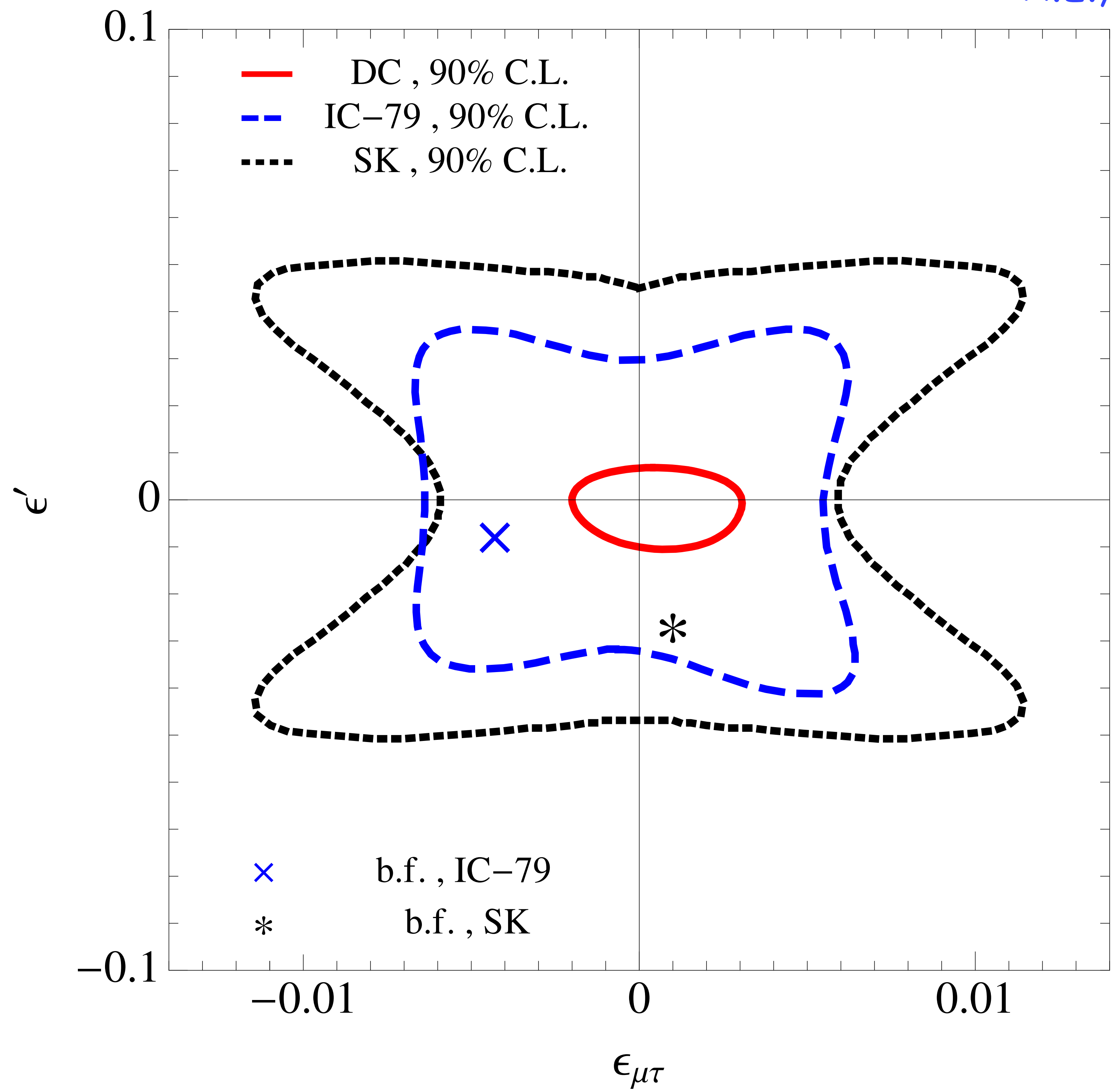
Three years DeepCore data

IceCube collaboration, 2017



✓ 3 years of DeepCore data (future reach)

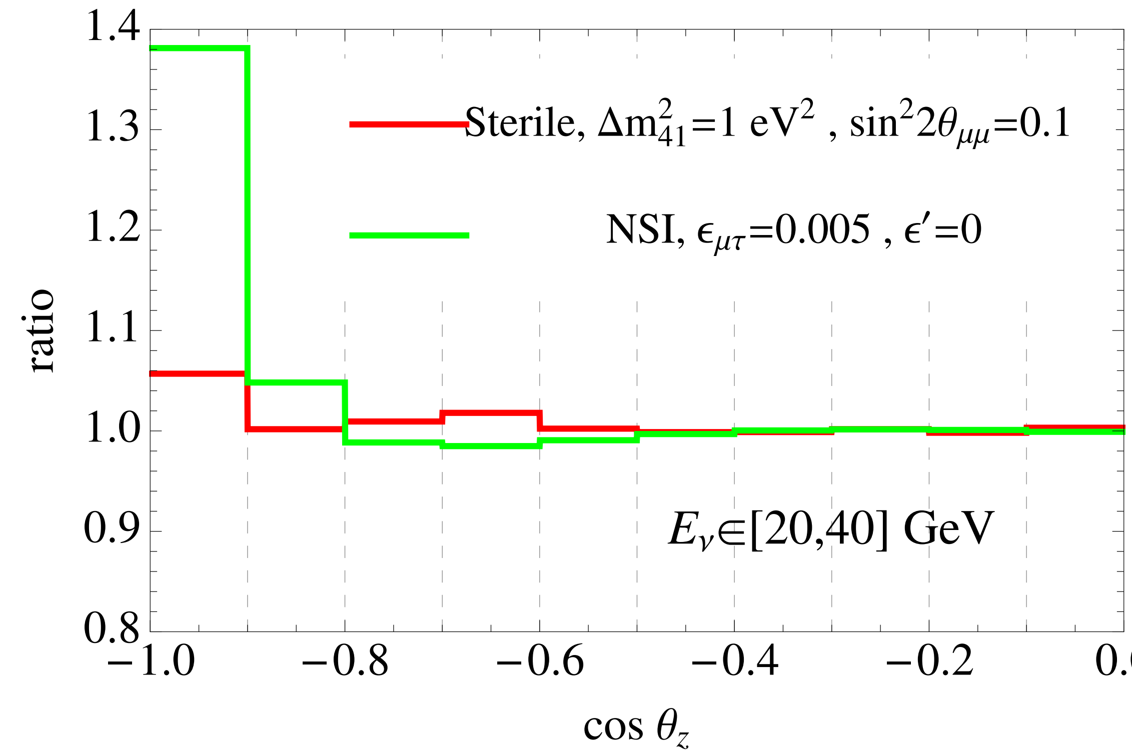
A.E., Alexei Smirnov, 2013



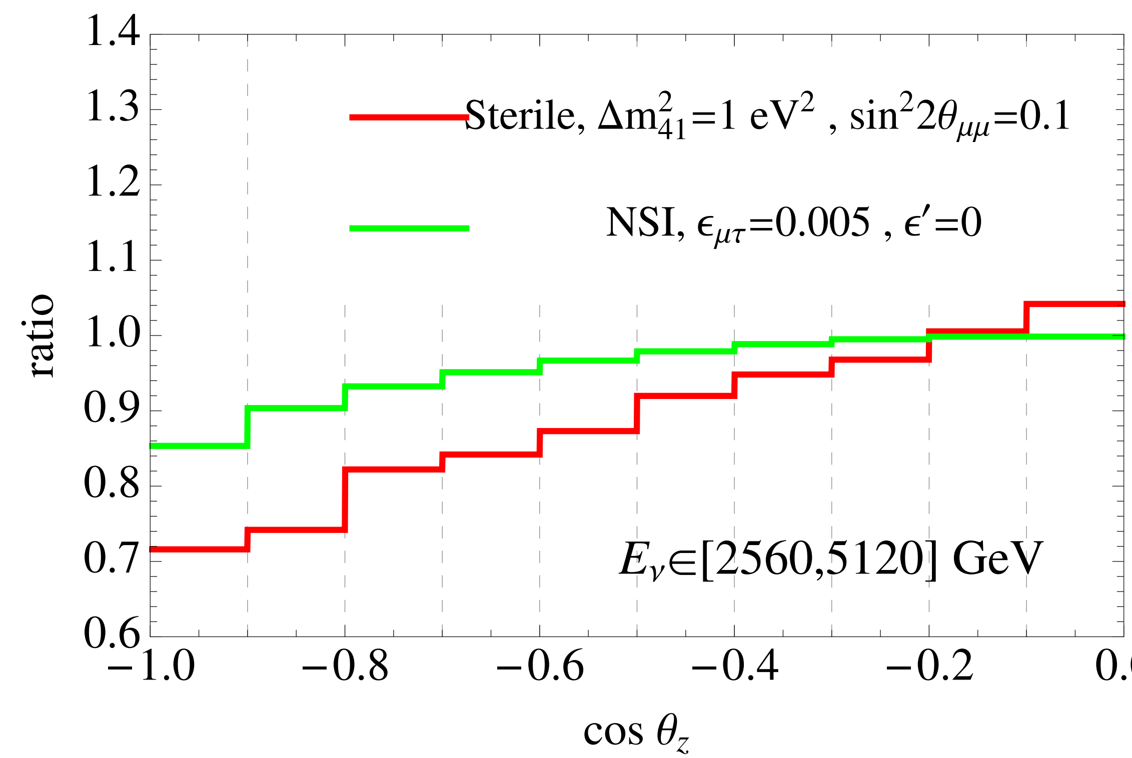
✓ Disentangling between NSI and eV-scale sterile neutrino

A.E., Alexei Smirnov, 2013

In the energy bin containing the minimum of ν_μ survival probability, the NSI shifts the minimum.

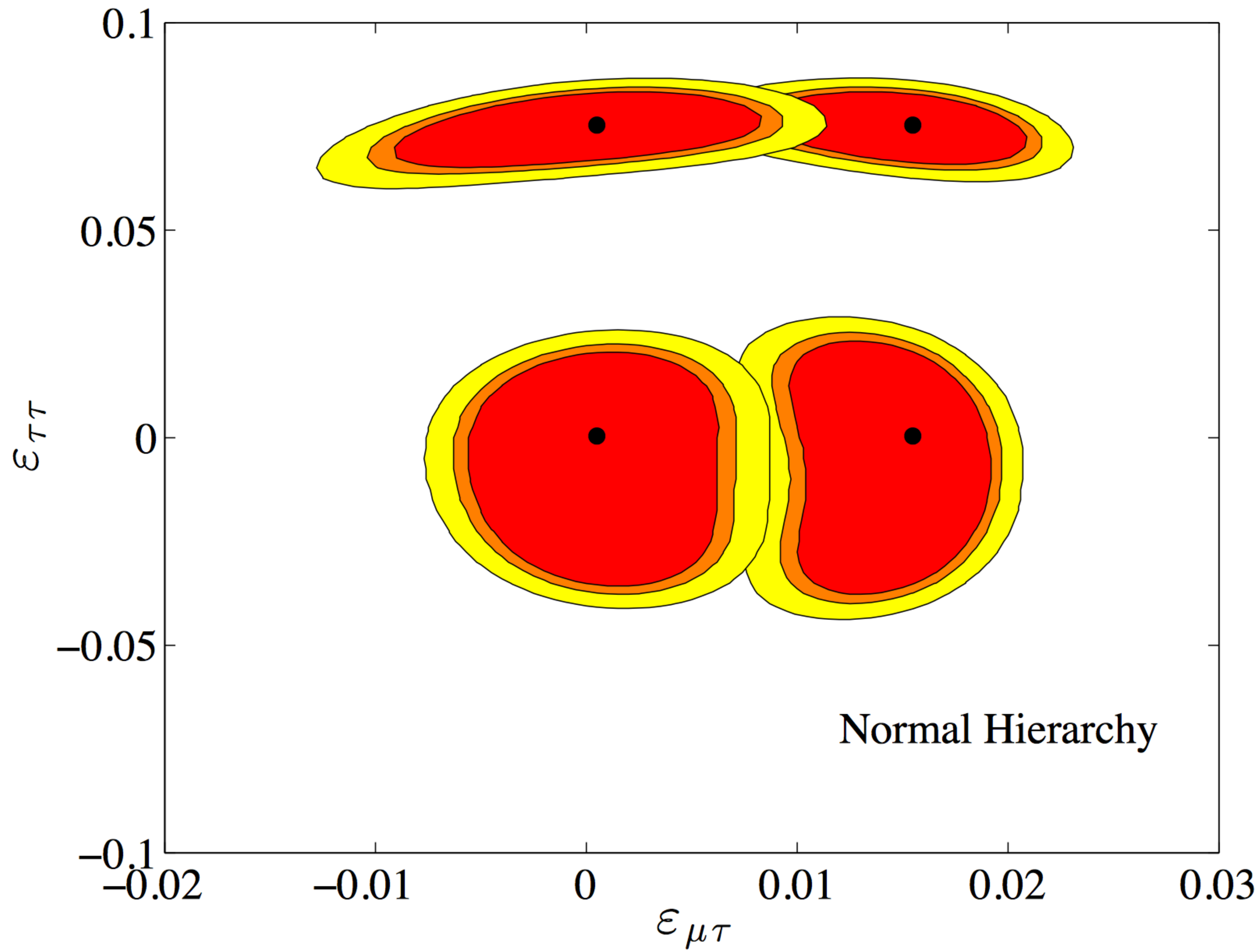


In the energy bin containing the MSW resonance ν_μ -> ν_s, there is a strong suppression of signal compared to the NSI effect.



✓ Future sensitivity (PINGU, 3 years)

S. Choubey, T. Ohlsson, 2014

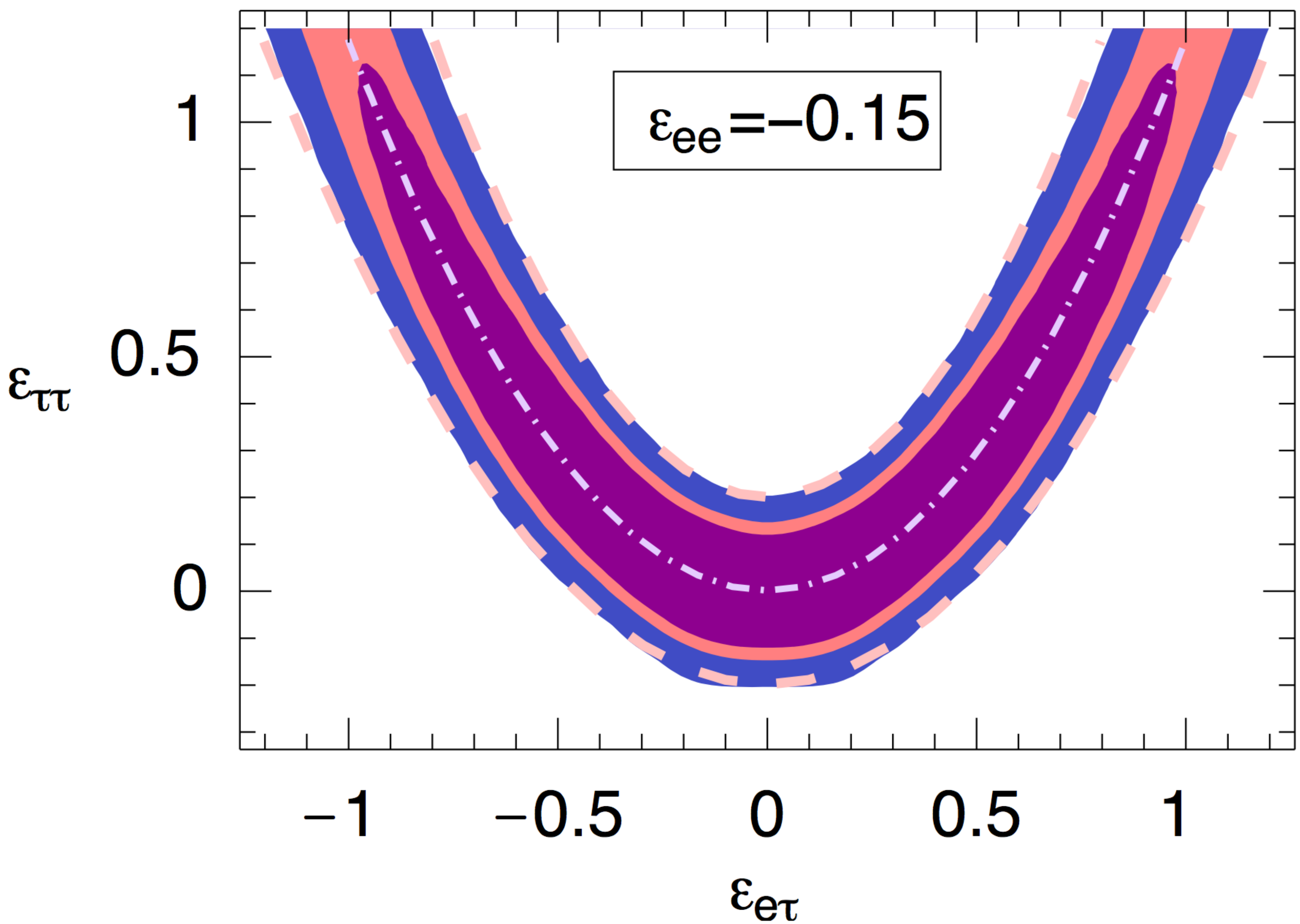


✓ Opening up the e-tau sector:

A. Friedland, C. Lunardini, 2004

A. Friedland, C. Lunardini, M. Maltoni, 2005

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



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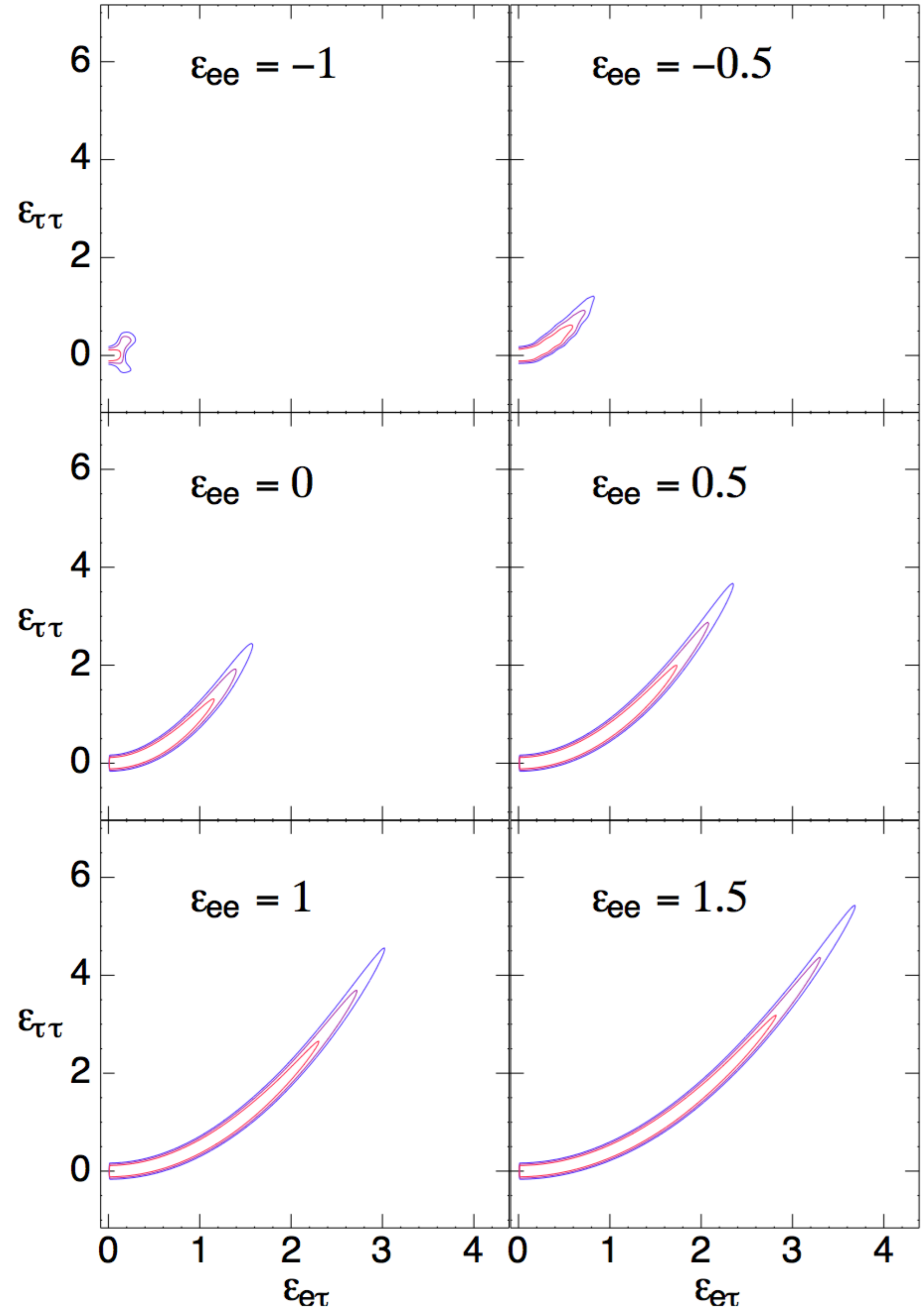
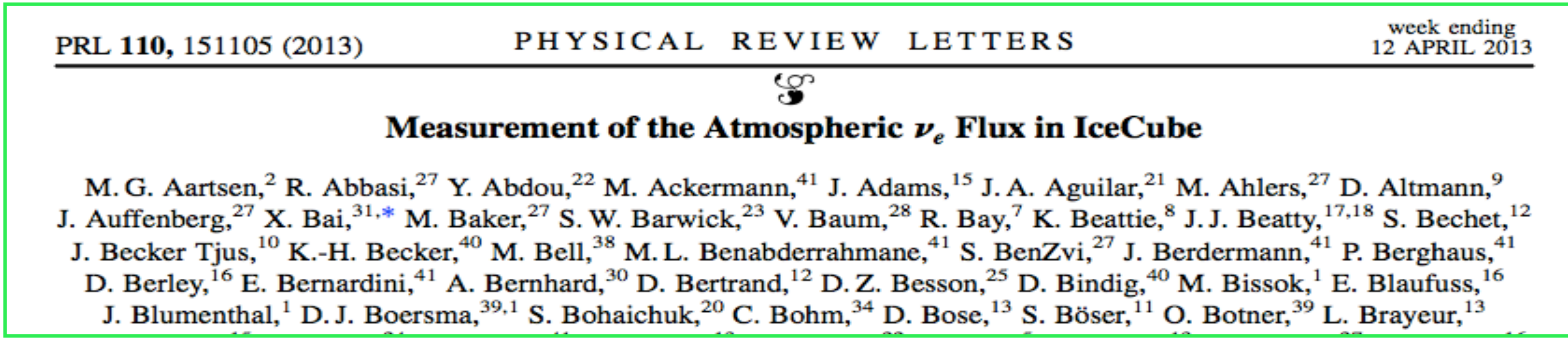
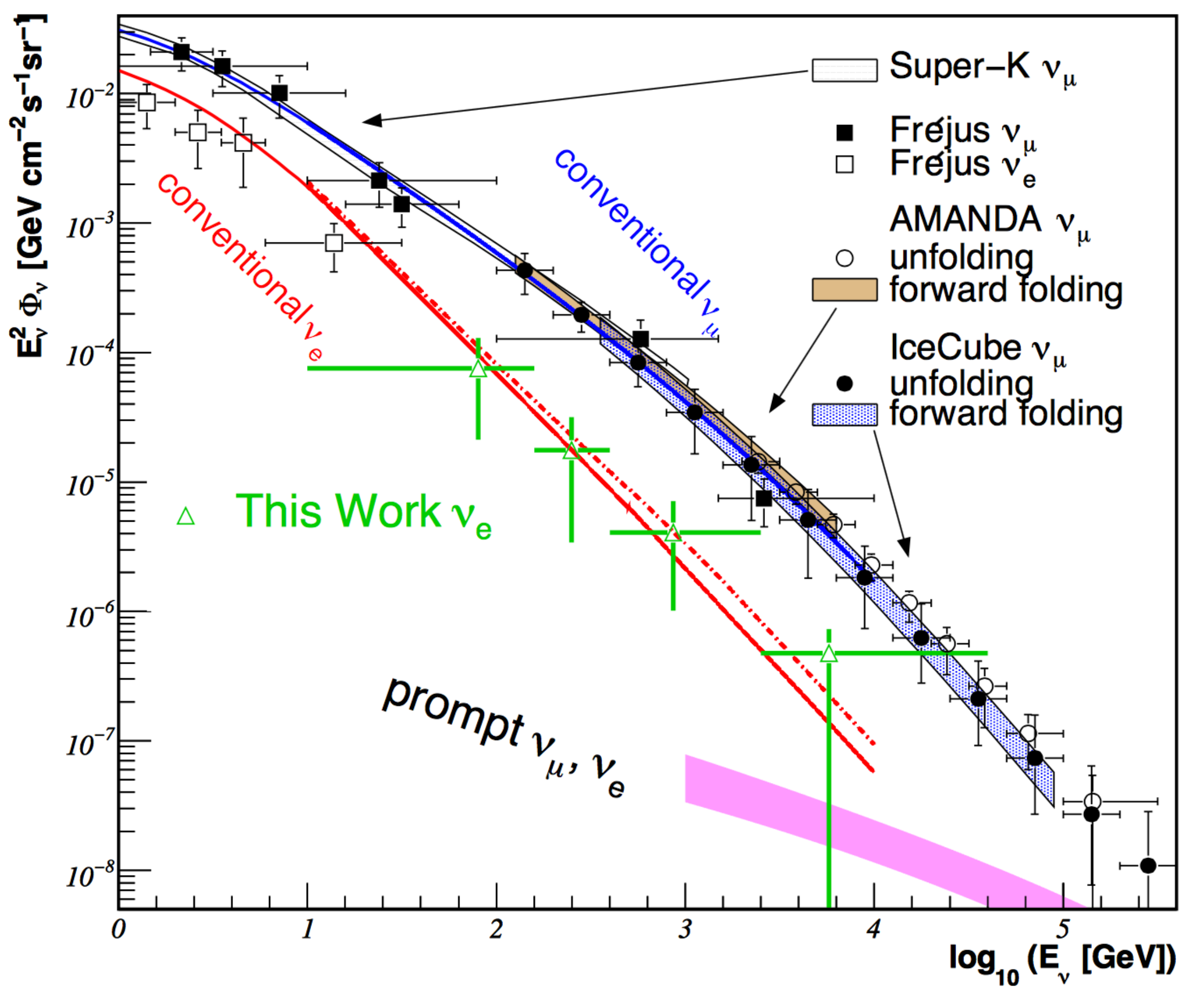


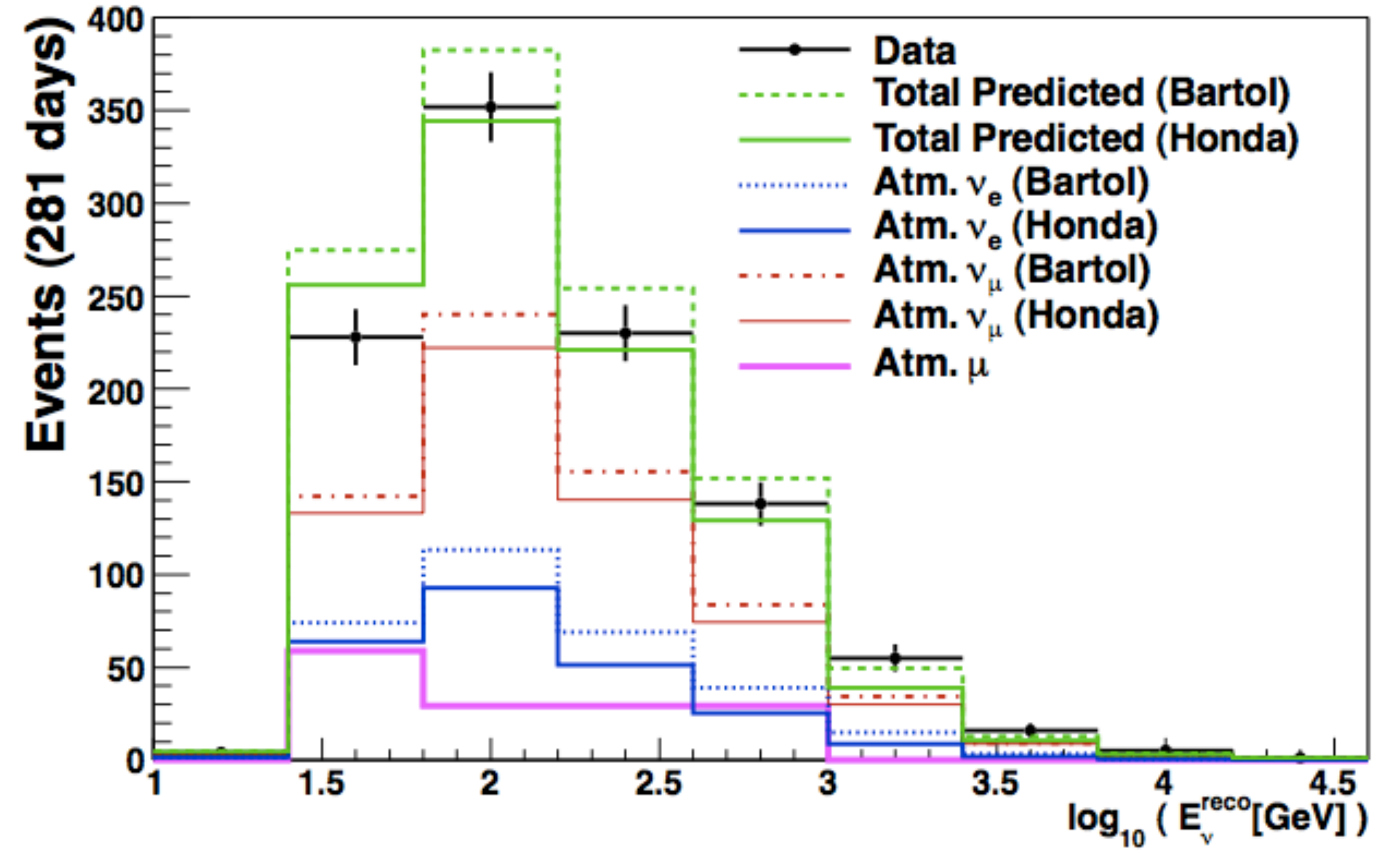
✓ Opening up the e-tau sector:


PRL **110,** 151105 (2013) PHYSICAL REVIEW LETTERS week ending 12 APRIL 2013

Measurement of the Atmospheric ν_e Flux in IceCube

M. G. Aartsen,[2] R. Abbasi,[27] Y. Abdou,[22] M. Ackermann,[41] J. Adams,[15] J. A. Aguilar,[21] M. Ahlers,[27] D. Altmann,[9] J. Auffenberg,[27] X. Bai,[31,*] M. Baker,[27] S. W. Barwick,[23] V. Baum,[28] R. Bay,[7] K. Beattie,[8] J. J. Beatty,[17,18] S. Bechet,[12] J. Becker Tjus,[10] K.-H. Becker,[40] M. Bell,[38] M. L. Benabderrahmane,[41] S. BenZvi,[27] J. Berdermann,[41] P. Berghaus,[41] D. Berley,[16] E. Bernardini,[41] A. Bernhard,[30] D. Bertrand,[12] D. Z. Besson,[25] D. Bindig,[40] M. Bissok,[1] E. Blaufuss,[16] J. Blumenthal,[1] D. J. Boersma,[39,1] S. Bohaichuk,[20] C. Bohm,[34] D. Bose,[13] S. Böser,[11] O. Botner,[39] L. Brayeur,[13]

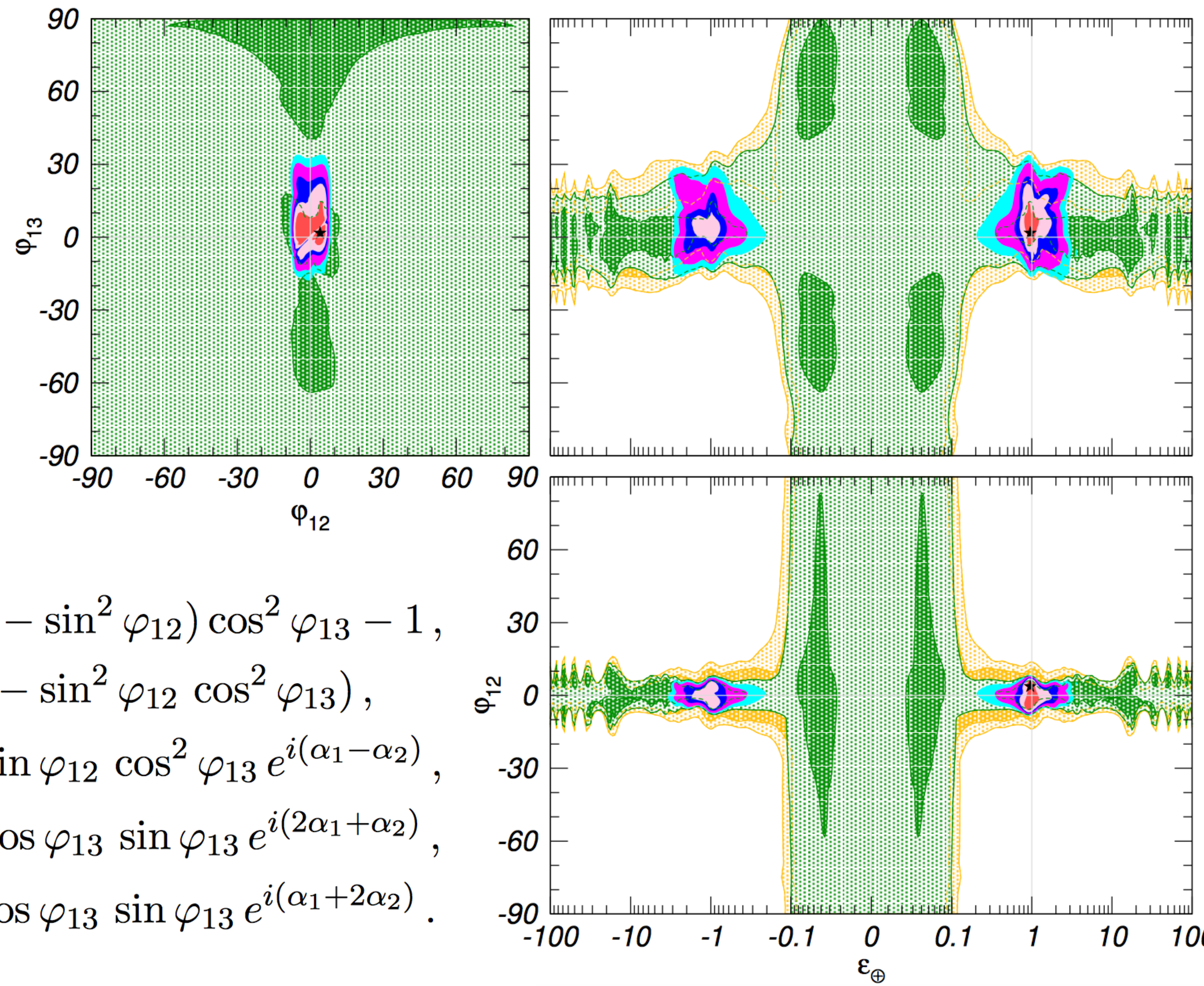




6 GeV - 80 TeV

✓ More general analysis:

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. Salvado; arXiv:1805.04530



$$\varepsilon^{\oplus}_{ee} - \varepsilon^{\oplus}_{\mu\mu} = \varepsilon_{\oplus}\,(\cos^2\varphi_{12} - \sin^2\varphi_{12})\cos^2\varphi_{13} - 1\,,$$

$$\varepsilon^{\oplus}_{\tau\tau} - \varepsilon^{\oplus}_{\mu\mu} = \varepsilon_{\oplus}\,(\sin^2\varphi_{13} - \sin^2\varphi_{12}\,\cos^2\varphi_{13})\,,$$

$$\varepsilon^{\oplus}_{e\mu} = -\varepsilon_{\oplus}\,\cos\varphi_{12}\,\sin\varphi_{12}\,\cos^2\varphi_{13}\,e^{i(\alpha_1-\alpha_2)}\,,$$

$$\varepsilon^{\oplus}_{e\tau} = -\varepsilon_{\oplus}\,\cos\varphi_{12}\,\cos\varphi_{13}\,\sin\varphi_{13}\,e^{i(2\alpha_1+\alpha_2)}\,,$$

$$\varepsilon^{\oplus}_{\mu\tau} = \varepsilon_{\oplus}\,\sin\varphi_{12}\,\cos\varphi_{13}\,\sin\varphi_{13}\,e^{i(\alpha_1+2\alpha_2)}\,.$$

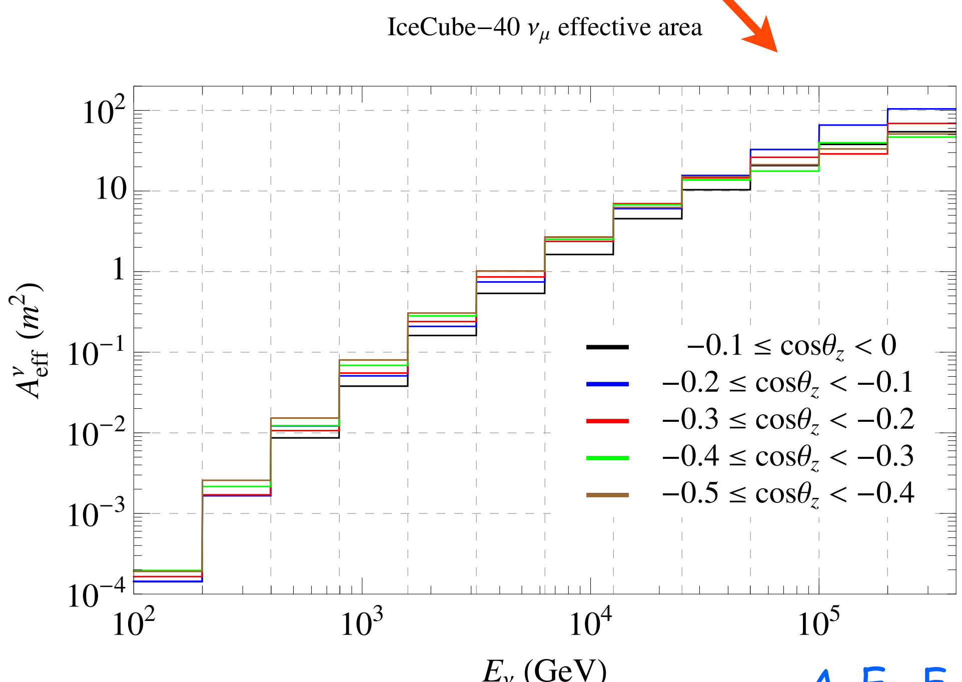
$$\varepsilon^{\oplus}_{\alpha\beta} = \varepsilon^{\eta}_{\alpha\beta}\big(\xi^p + Y^{\oplus}_n\xi^n\big) = \sqrt{5}\,\big(\cos\eta + Y^{\oplus}_n\sin\eta\big)\,\varepsilon^{\eta}_{\alpha\beta}\,.$$

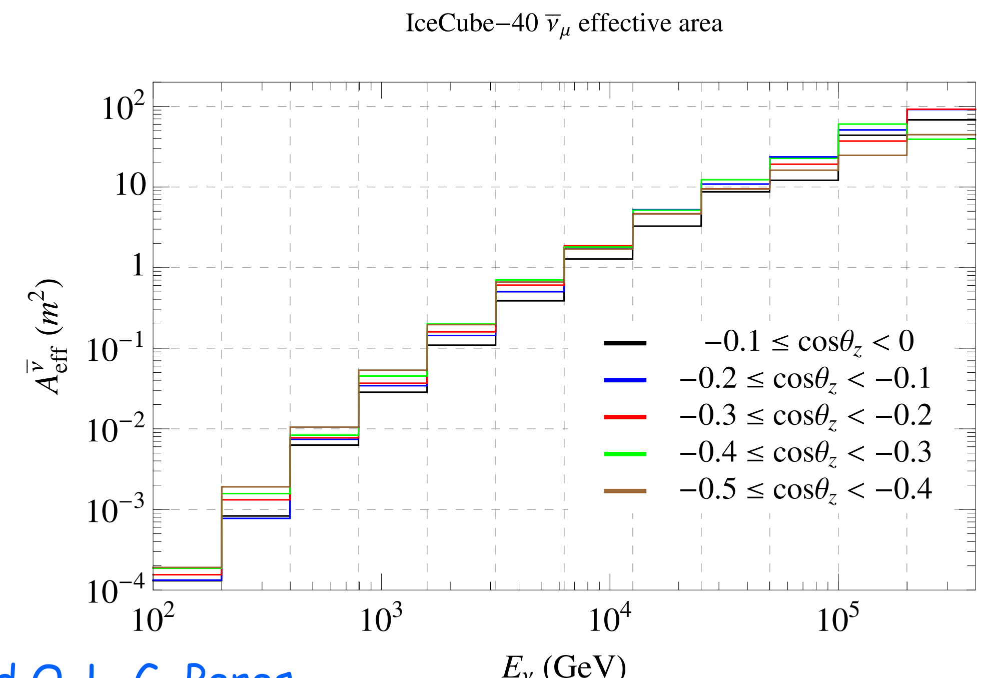
Thank you !

Constraining sterile neutrino with IC-40 data

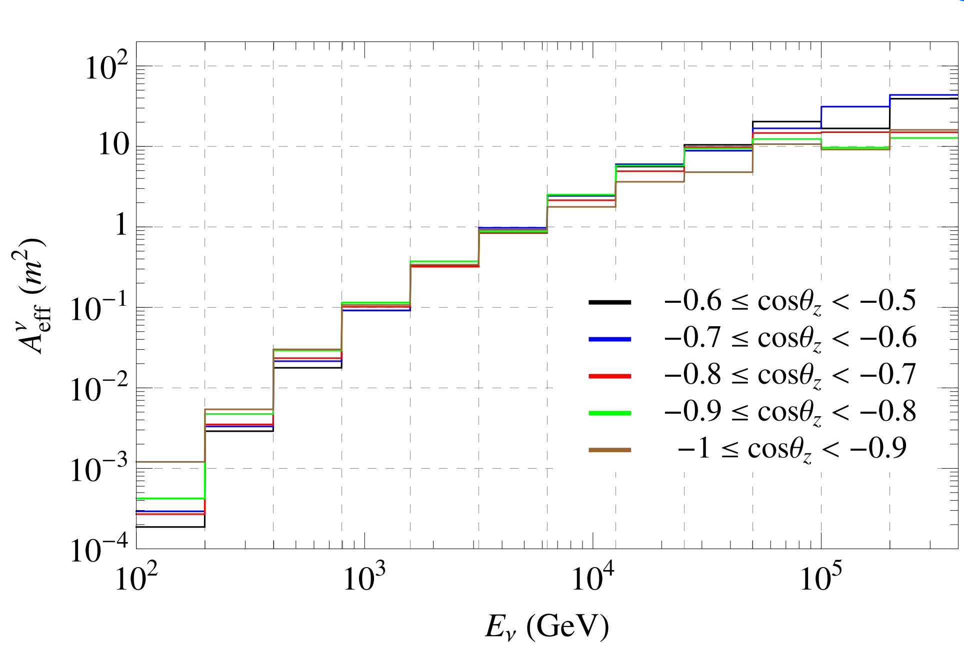
(atm flux (Honda+Volkova

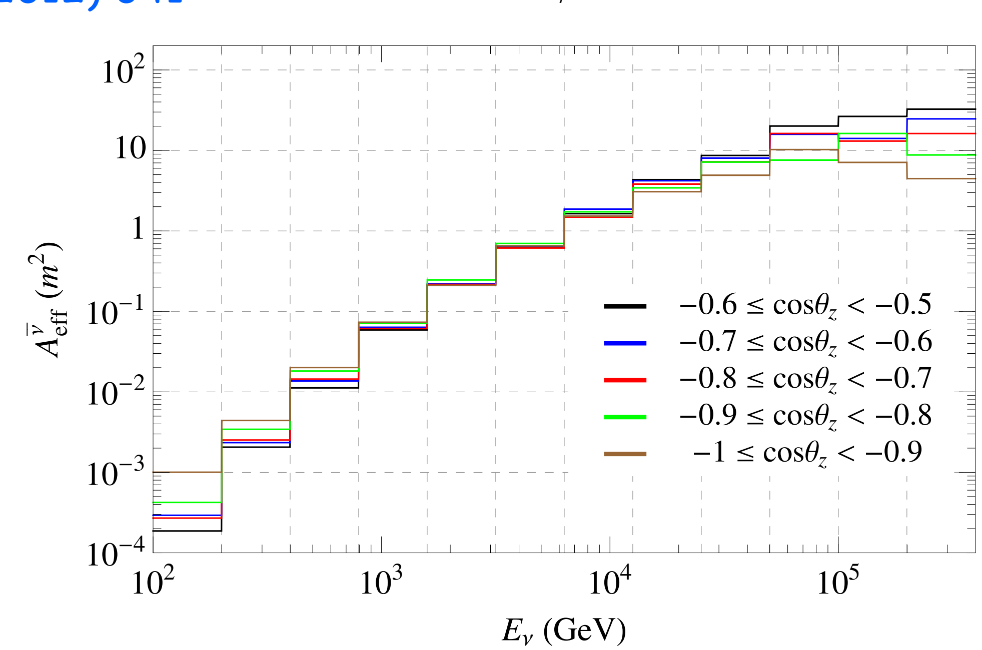
$$N = T(2\pi)\left[\int A^{\nu}_{\rm eff}(E_\nu,\cos\theta_z)\,\Phi_\nu(E_\nu,\cos\theta_z)\,{\rm d}E_\nu\,{\rm d}\cos\theta_z + (\nu \to \bar{\nu})\right]$$





A. E., F. Halzen and O. L. G. Peres,
JCAP 1211 (2012) 041

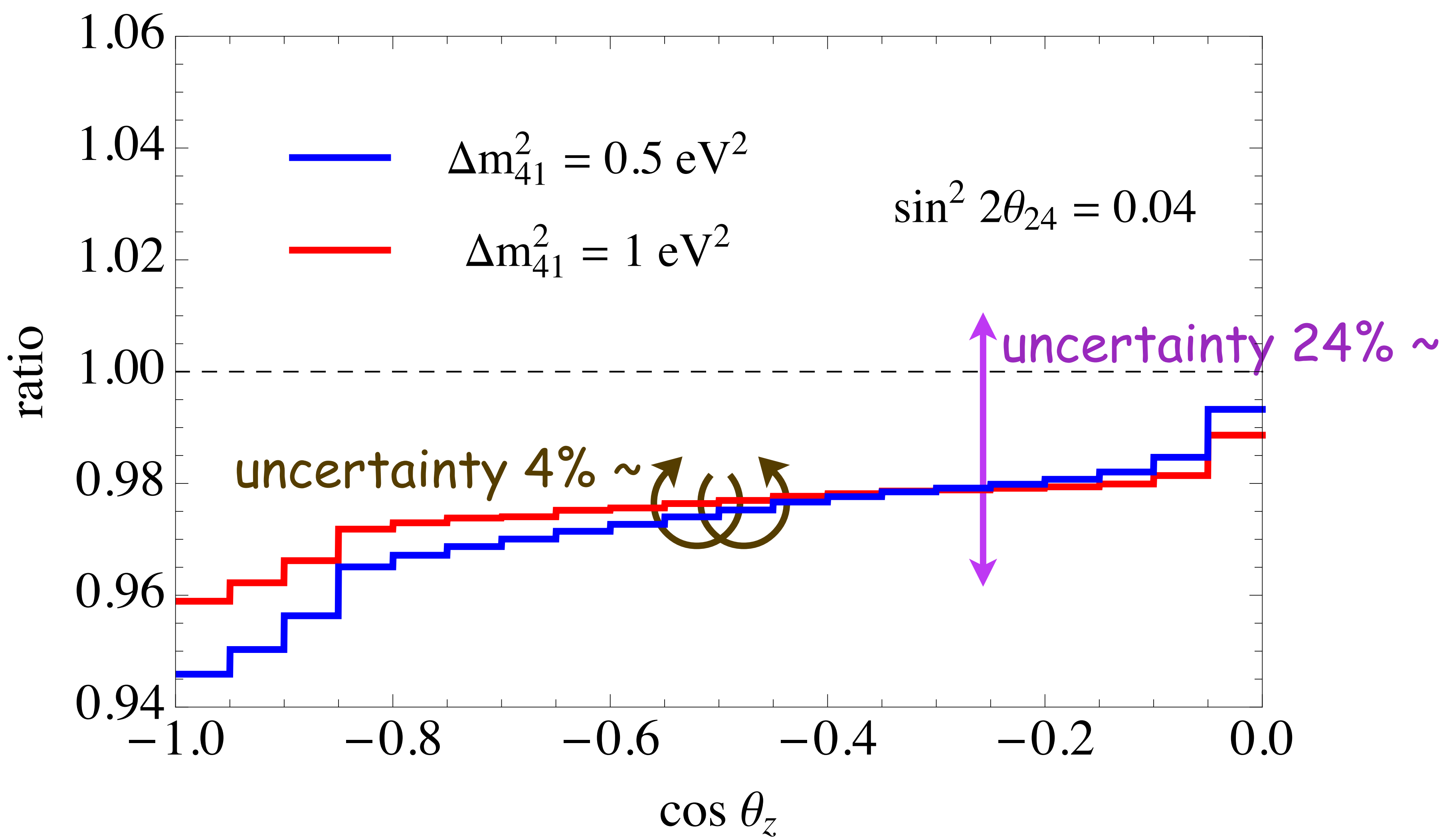




IceCube sensitivity to sterile neutrinos (muon-track events)

✓ We analyzed the zenith distribution of muon-track events

$$\frac{N_\mu(\theta_{24})}{N_\mu(\theta_{24}=0)}$$



$$\chi^2(\Delta m^2_{41},\theta_{24};\alpha,\beta)=\sum_i \frac{\{N_i(\theta_{24}=0)-\alpha[1+\beta(0.5+(\cos\theta_z)_i)]N_i(\theta_{24})\}^2}{\sigma^2_{i,\mathrm{stat}}+\sigma^2_{i,\mathrm{sys}}}+\frac{(1-\alpha)^2}{\sigma^2_\alpha}+\frac{\beta^2}{\sigma^2_\beta}$$