Some attempts to explain MINOS anomaly

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1. Introduction

Candidates for new physics to be tested at future LBL

Scenarios	Phenomenological bound on deviation from standard case
NSI at production / detection	O(1%)
NSI in propagation $\varepsilon_{\mu\alpha}$	O(1%)
NSI in propagation $\varepsilon_{[e\tau][e\tau]}$	O(100%)
Violation of unitarity due to heavy particles	O(0.1%)
Light sterile neutrinos	O(10%)

● NP in propagation (NP matter effect)

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\,\mathrm{diag}\,(E_1, E_2, E_3)\,U^{-1} + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$A \equiv \sqrt{2}G_F N_e$ $\quad N_e \equiv$ electron density

NP

● Constraints on $\varepsilon_{\alpha\beta}$

Davidson et al., JHEP 0303:011,2003; Berezhiani, Rossi, PLB535 ('02) 207; Barranco et al., PRD73 ('06) 113001; Barranco et al., arXiv:0711.0698

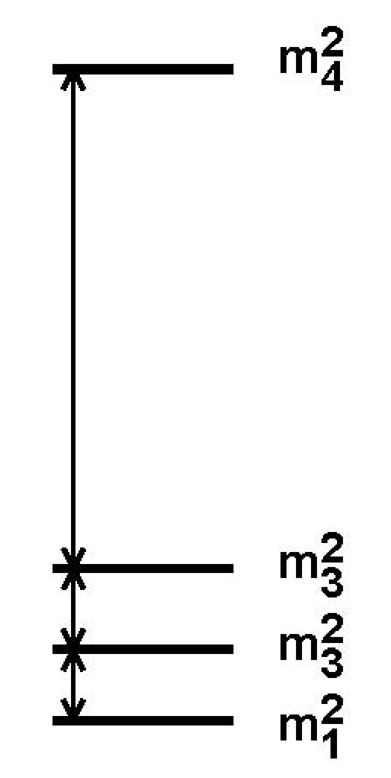
Biggio et al., JHEP 0908, 090 (2009) w/o 1-loop arguments

related to each other by ν_{atm}

can be improved by ν_{atm}

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

● Sterile neutrinos: (3+1)-schemes



(A) Take LSND/MB anti-ν seriously & assume tension with negative disappearance results is OK

(B) Forget about LSND/MB anti-ν & assume the mixing angles satisfy all the constraints of the negative results

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$U = R_{34}(\theta_{34},\, 0)\, R_{24}(\theta_{24},\, 0)\, R_{23}(\theta_{23},\, \delta_3)\, R_{14}(\theta_{14},\, 0)\, R_{13}(\theta_{13},\, \delta_2)\, R_{12}(\theta_{12},\, \delta_1)$$

θ_{34} : ratio of $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ in ν_{atm}

θ_{24} : ratio of $\sin^2(\frac{\Delta m^2_{\rm atm} L}{4E})$ and $\sin^2(\frac{\Delta m^2_{\rm SBL} L}{4E})$ in ν_{atm}

θ_{14} : mixing angle in $\nu_{reactor}$ at L=O(10m)

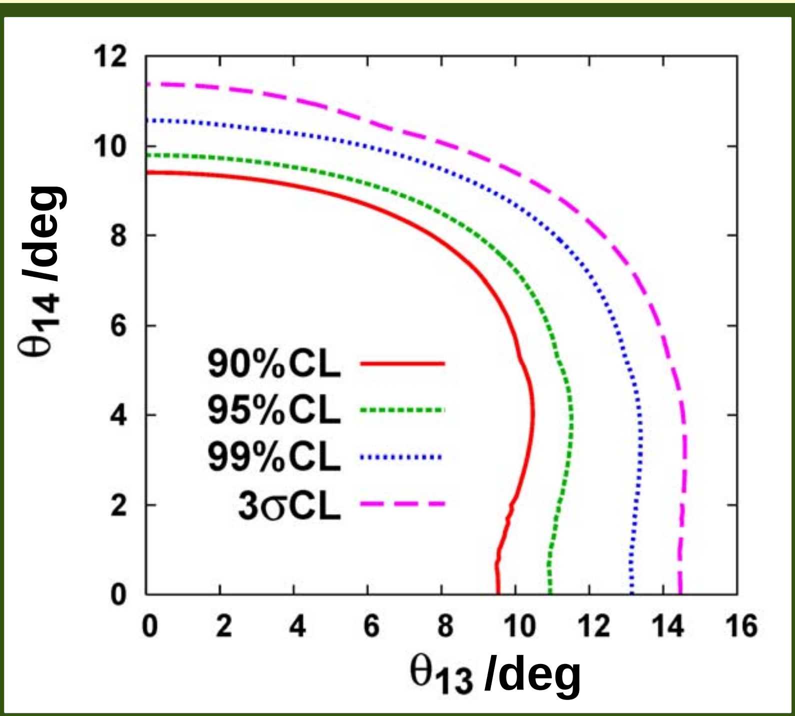
Constraints from ν_{atm} and SBL

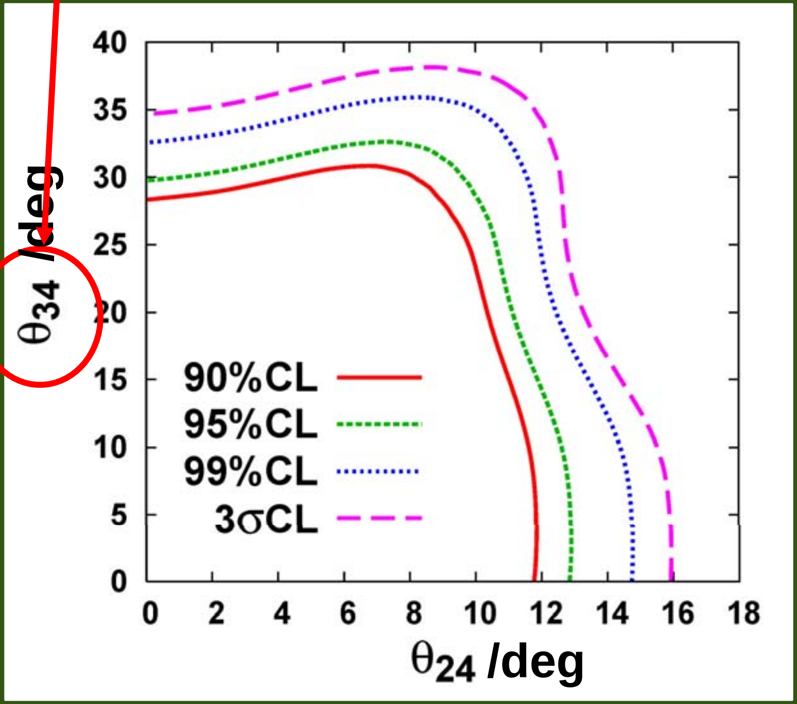
Donini-Maltoni-Meloni-Migliozzi-Terranova, JHEP 0712:013,'07

$$U = R_{34}(\theta_{34})\ R_{24}(\theta_{24})\ R_{23}(\theta_{23},\ \delta_3)\ R_{14}(\theta_{14})\ R_{13}(\theta_{13},\ \delta_2)\ R_{12}(\theta_{12},\ \delta_1)$$

Assumption on rapid oscillations in ν_{atm}: $\Delta m^2_{41} > 0.1\ eV^2$

θ_{34} : could be relatively large





2. High energy behavior of ν_{atm} data, NSI & ν_s

- **Standard case with $N_\nu=2$**

$$1 - P(\nu_\mu \to \nu_\mu) = \sin^2 2\theta_{\rm atm} \sin^2\left(\frac{\Delta m^2_{\rm atm} L}{4E}\right) \propto \frac{1}{E^2}$$

- **Standard case with $N_\nu=3$**

$$1 - P(\nu_\mu \to \nu_\mu) \sim \left(\frac{\Delta m^2_{31}}{2AE}\right)^2 \left[\sin^2 2\theta_{23}\left(\frac{c^2_{13} AL}{2}\right)^2 + s^2_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{AL}{2}\right)\right] \propto \frac{1}{E^2}$$

- **Deviation of 1-P($\nu_\mu \to \nu_\mu$) due to NP contradicts with data**

$$1 - P(\nu_\mu \to \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \frac{c_{20}L^2 + c_{21}\sin^2(c_{22}L)}{E^2}$$

→ High ν_{atm} data gives constraints on NP:

$|c_0| \ll 1, \ |c_1| \ll 1$

- with NSI

$$1 - P(\nu_\mu \to \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \frac{c_{20} L^2 + c_{21} \sin^2(c_{22} L)}{E^2}$$

$|c_0| \ll 1 \to$ $|\varepsilon_{e\mu}| << 1$, $|\varepsilon_{\mu\mu}| << 1$, $|\varepsilon_{\mu\tau}| << 1$

$|\varepsilon_{\mu\tau}| << 1$: Already shown for $N_\nu=2$ by Fornengo et al., PRD65, 013010, '02; Gonzalez-Garcia&Maltoni, PRD70, 033010, '04; Mitsuka@nufact08,NOW2010

→ From our argument this is valid also for $N_\nu=3$
Oki & OY, PRD82, 073009, '10

$|\varepsilon_{\mu\mu}| << 1$: Already shown by Davidson et al. JHEP 0303:011, '03 from data of other experiments

$|\varepsilon_{e\mu}| << 1$: New observation (analytical consideration only)
Oki & OY, PRD82, 073009, '10

$|c_1| \ll 1 \to$ $\left| \varepsilon_{\tau\tau} - |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee}) \right| << 1$

Already shown by Friedland-Lunardini, PRD72:053009,'05

Summary of the constraints on $\varepsilon_{\alpha\beta}$

To a good approximation, we are left with 3 independent variables ε_{ee}, $|\varepsilon_{e\tau}|$, $\arg(\varepsilon_{e\tau})$:

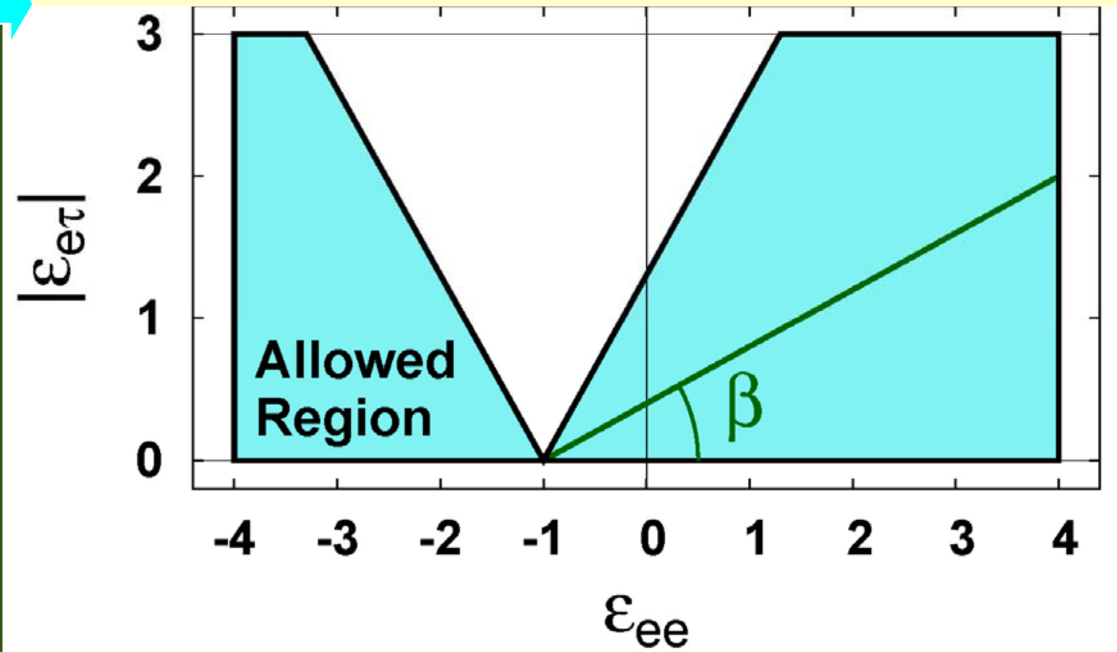
$$A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \Rightarrow A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^{*} & 0 & |\epsilon_{e\tau}|^2/(1+\epsilon_{ee}) \end{pmatrix}$$

Furthermore, ν_{atm} data implies

$\tan\beta = |\varepsilon_{e\tau}|/(1+\varepsilon_{ee}) < 1.3$

Friedland-Lunardini, PRD72:053009,'05

Allowed region in $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$

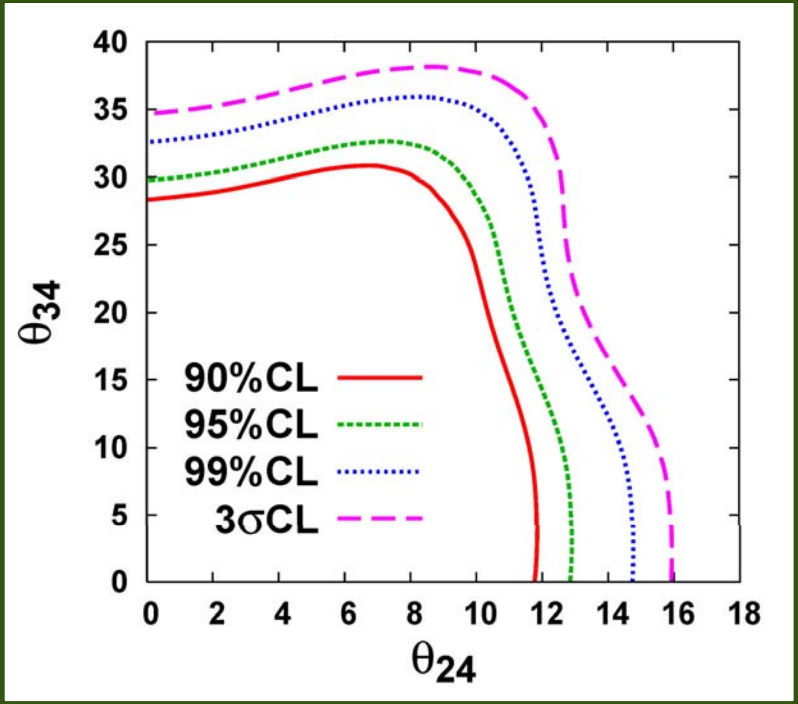


●with ν_s

$$1 - P(\nu_\mu \to \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \frac{c_{20} L^2 + c_{21} \sin^2(c_{22} L)}{E^2}$$

$|c_0| \propto s^2_{24} \ll 1 \to s^2_{24} \ll 1$

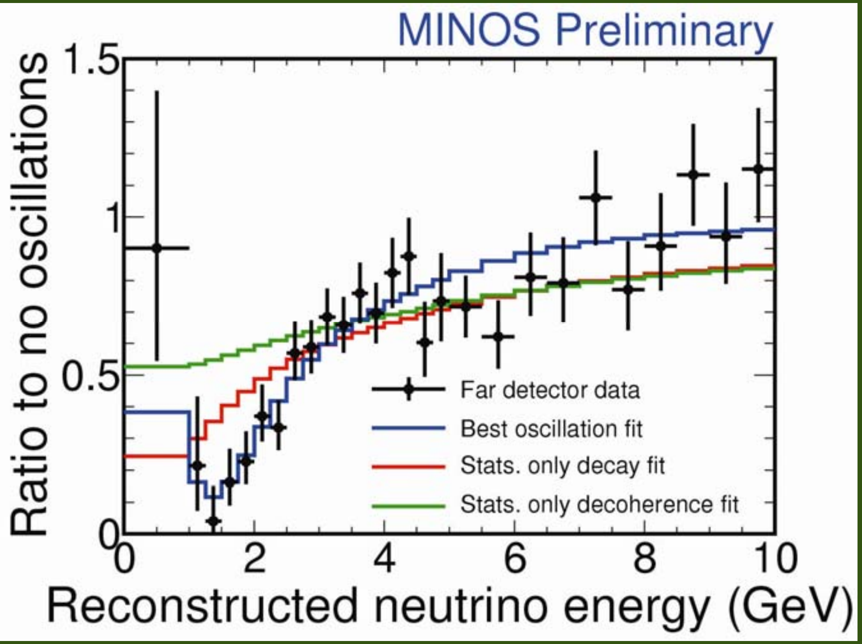
$|c_1| \propto s^2_{34} \ll 1 \to s^2_{34} \ll 1$

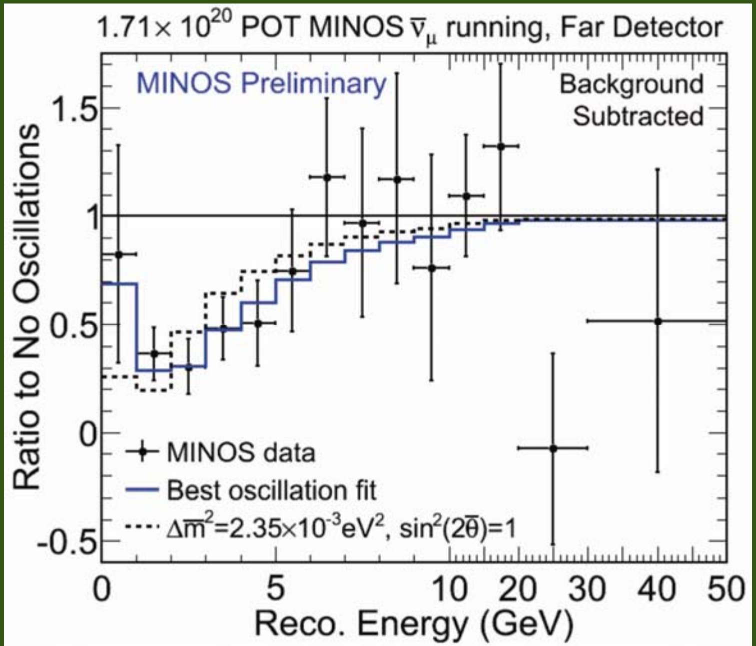


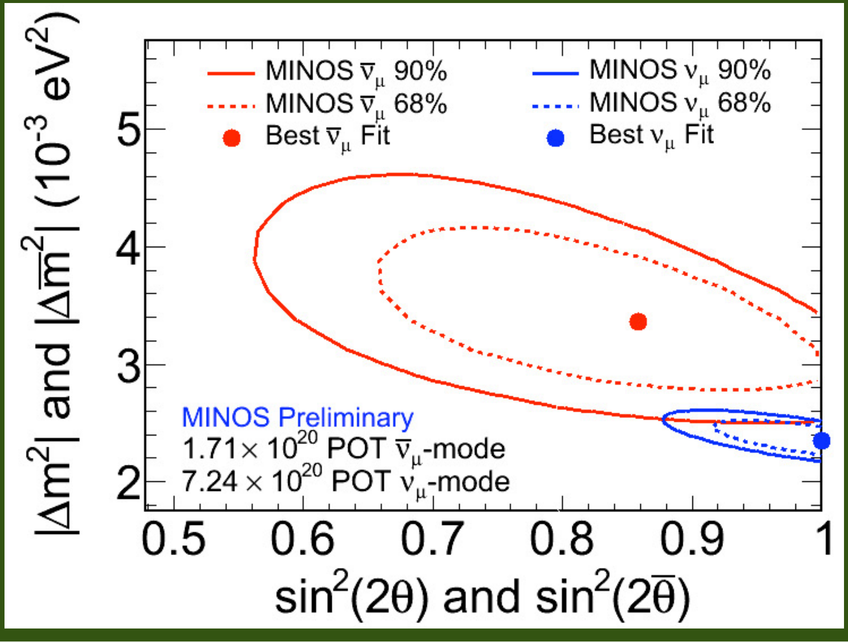
Donini-Maltoni-Meloni-Migliozzi-Terranova, JHEP 0712:013,'07

3. MINOS anomaly

Vahle@nu2010



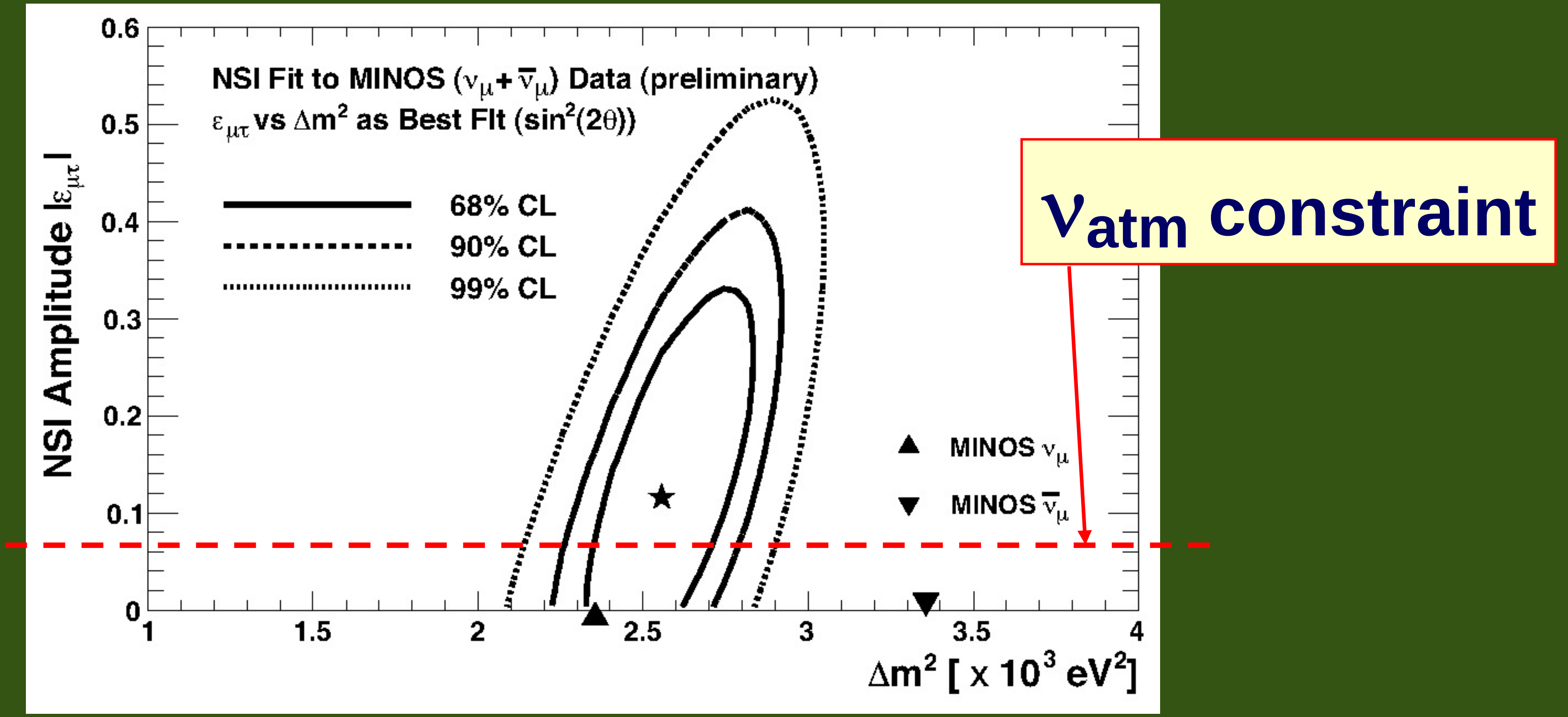




An effort to explain with $\varepsilon_{\mu\tau}$

Mann-Cherdack-Musial-Kafka, arXiv:1006.5720 [hep-ph]

$$A\begin{pmatrix} 1 & 0 & 0 \\ 0 & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ 0 & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}$$



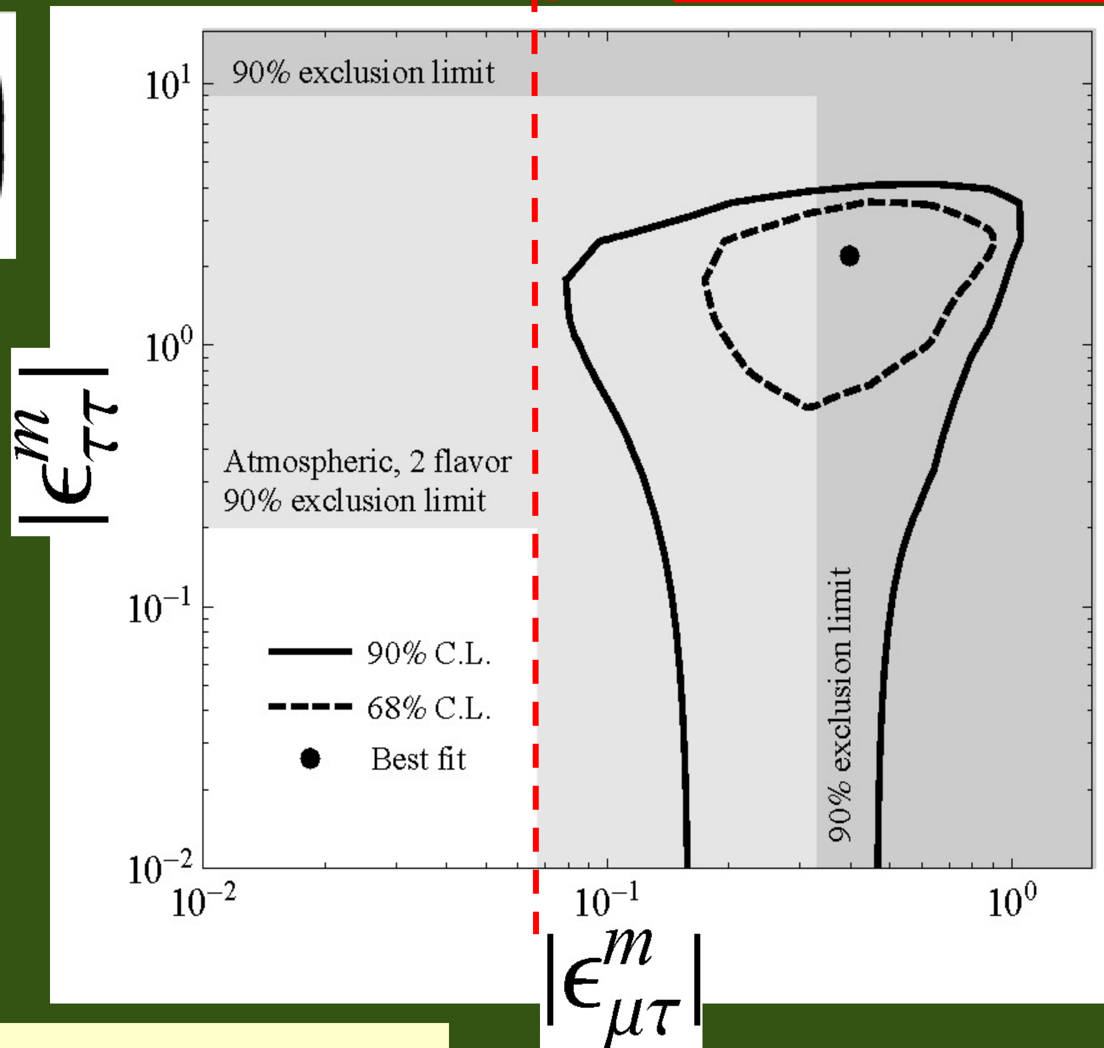
Contradicts with ν_{atm} constraint

An effort to explain with $\varepsilon_{\mu\tau}$

Kopp-Machado-Parke, arXiv:1009.0014 [hep-ph]

$$A\begin{pmatrix} 1 & 0 & 0 \\ 0 & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ 0 & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}$$

ν_{atm} constraint



Contradicts with ν_{atm} constraint

An effort to explain with gauging L_α-L_β

Heeck-Rodejohann,arXiv:1007.2655 [hep-ph]

$$A\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix} + \begin{pmatrix}V&0&0\\0&-V&0\\0&0&0\end{pmatrix},\quad \begin{pmatrix}V&0&0\\0&0&0\\0&0&-V\end{pmatrix},\quad \begin{pmatrix}0&0&0\\0&V&0\\0&0&-V\end{pmatrix}$$

L_e-L_μ $\quad$ L_e-L_τ $\quad$ L_μ-L_τ

ν_{sol} constraint

$$\left.\frac{\Delta m^2_{31}}{E}\right|_{\text{MINOS}} \sim A \sim V_{\text{MINOS}} = \frac{const}{d_{Sun-Earth}}$$

$$100 \times V_{\text{MINOS}} \sim 100 \times \left.\frac{\Delta m^2_{31}}{E}\right|_{\text{MINOS}}$$

$$\sim \left.\frac{\Delta m^2_{21}}{E}\right|_{\text{solar}} << V|_{\text{solar}} = \frac{const}{R_{Sun}}$$

To keep the success of ν_{sol}, we have to avoid L_e-L_μ , L_e-L_τ

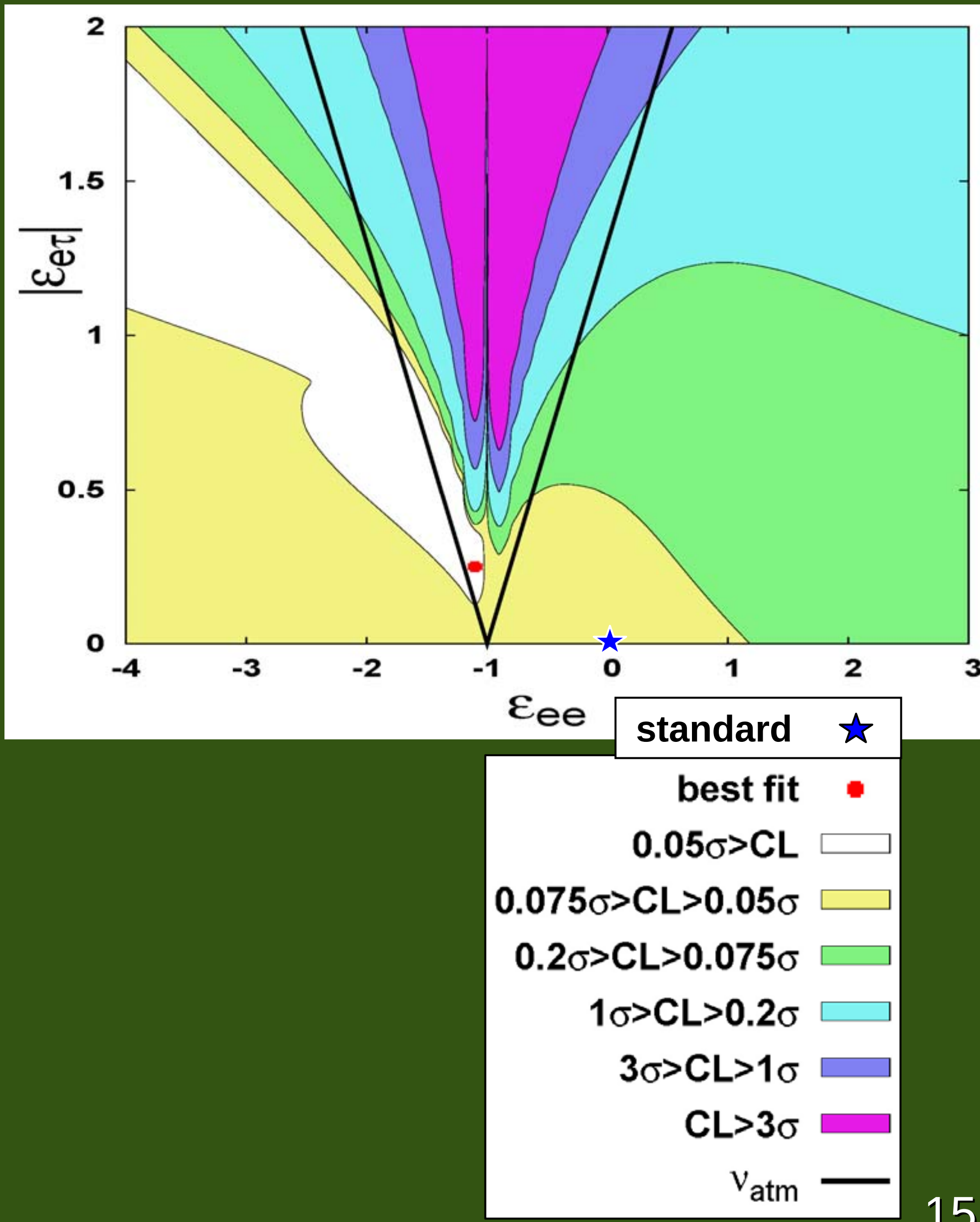
ν_{atm} constraint

L_μ-L_τ contradicts with $|\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}| << 1$

An effort to explain with $\varepsilon_{e\tau}$

Unpublished work by OY (2010)

$$A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^{*} & 0 & |\epsilon_{e\tau}|^2/(1+\epsilon_{ee}) \end{pmatrix}$$



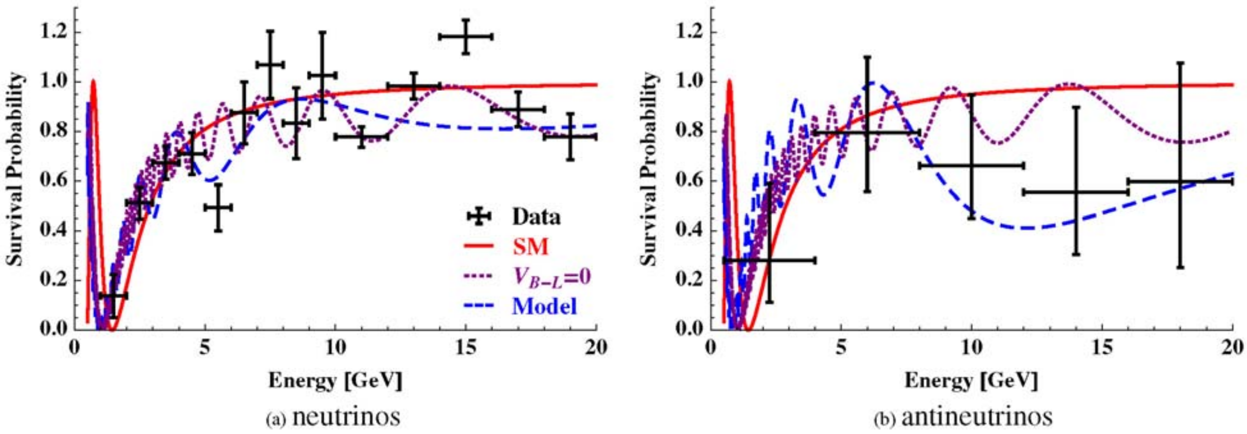
- Best fit point lies in the excluded region of ν_{atm}
- χ^2(SM)-χ^2(min)=0.1 (2dof): 0.07σ (not significant at all)

→ Probably not worth introducing $\varepsilon_{e\tau}$

An effort to explain with ν_s or ν_s+gauged B-L

Engelhardt-Nelson-Walsh, Phys.Rev.D81:113001,2010

- old data is used
- $\theta_{24}=0 \rightarrow$ no conflict with CDHSW
- $\theta_{34} \neq 0 \rightarrow 0 \leq \theta_{34} < 30°$
- $\theta_{23}=\pi/4$



(a) neutrinos (b) antineutrinos

$$\begin{pmatrix} \pm(V_{CC}-V_{NC}-V_{B-L}) & 0 & 0 & 0 \\ 0 & \pm(V_{NC}-V_{B-L}) & 0 & 0 \\ 0 & 0 & \pm(V_{NC}-V_{B-L}) & 0 \\ 0 & 0 & 0 & \pm V_{B-L} \end{pmatrix}$$

Best fit

- with B-L $\Delta m^2_{32}=2.5\times10^{-3}$eV^2, $\Delta m^2_{42}=2.5\times10^{-2}$eV^2, $V_{NC}/2+V_{B-L}=5\times10^{-14}$eV, $\chi^2=24.8$ (20 dof)
- w/o B-L $\Delta m^2_{32}=1.8\times10^{-3}$eV^2, $\Delta m^2_{42}=9.5\times10^{-2}$eV^2, $\chi^2=28.1$ (21 dof)

An effort to explain with ν_S

Unpublished work by OY (2010)

- new data is used
- Δm^2_{42} is fixed as 1eV^2
- $\theta_{24}=0 \rightarrow$ no conflict with CDHSW
- potential enhancement for $\bar{\nu}$ / suppression for ν occurs if $\theta_{34}<\pi/4$&NH or $\theta_{34}>\pi/4$&IH

$$\tan 2\tilde{\theta}_{23} = \frac{\Delta E_{32} \sin 2\theta_{23}}{\Delta E_{32} \cos 2\theta_{23} \pm V s_{34}^2}$$

$$\sin^2 2\tilde{\theta}_{23} = \frac{\left(\Delta E_{32} \sin 2\theta_{23}\right)^2}{\left(\Delta E_{32} \cos 2\theta_{23} \pm V s_{34}^2\right)^2 + \left(\Delta E_{32} \sin 2\theta_{23}\right)^2}$$

$$1 - P(\nu_\mu \rightarrow \nu_\mu) = \sin^2 2\tilde{\theta}_{23} \sin^2\left(\frac{\Delta\tilde{E}_{32} L}{2}\right)$$

$$\Delta\tilde{E}_{32} \equiv \sqrt{\left(\Delta E_{32} \cos 2\theta_{23} \pm V s_{34}^2\right)^2 + \left(\Delta E_{32} \sin 2\theta_{23}\right)^2}$$

$\sin^2 2\tilde{\theta}_{23}$ is almost 1 anyway $\rightarrow$ difficult to distinguish ν & $\bar{\nu}$

(Best fit point with ν_S) = (Best fit point for N_ν=3 case)

$\rightarrow$ Probably not worth introducing

4. Conclusions

- People made efforts to account for MINOS anomaly, but they all seem either to give little contribution to distinguish ν & $\bar{\nu}$ or to have conflict with atmospheric neutrinos and/or solar neutrinos.
- After all, MINOS anomaly is only a 2σ effect, so we should wait until we have more statistics.

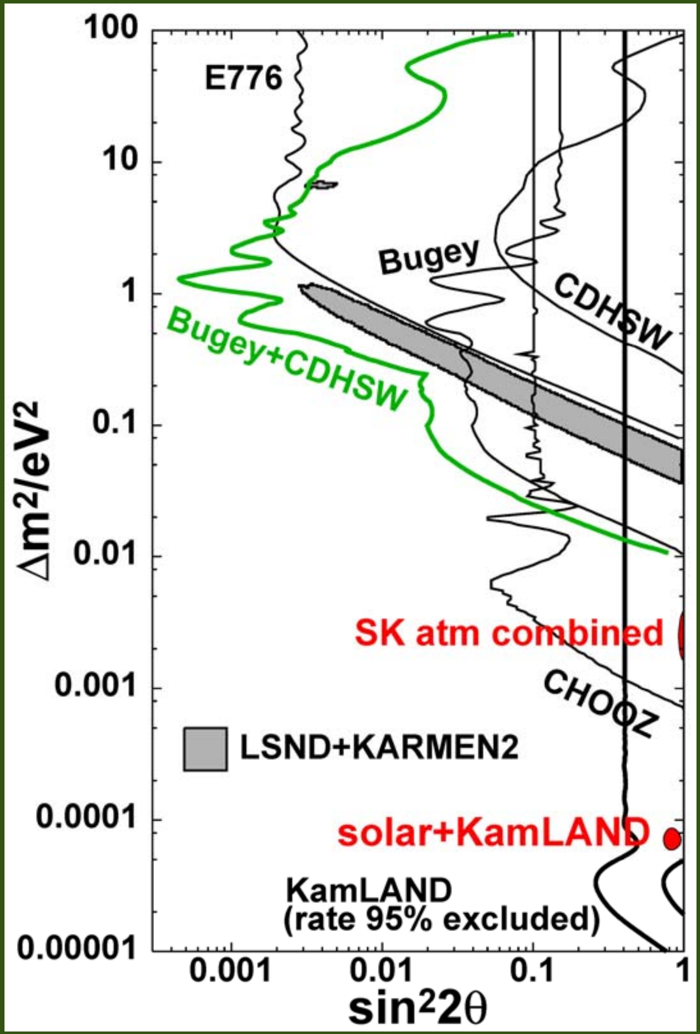
Backup slides

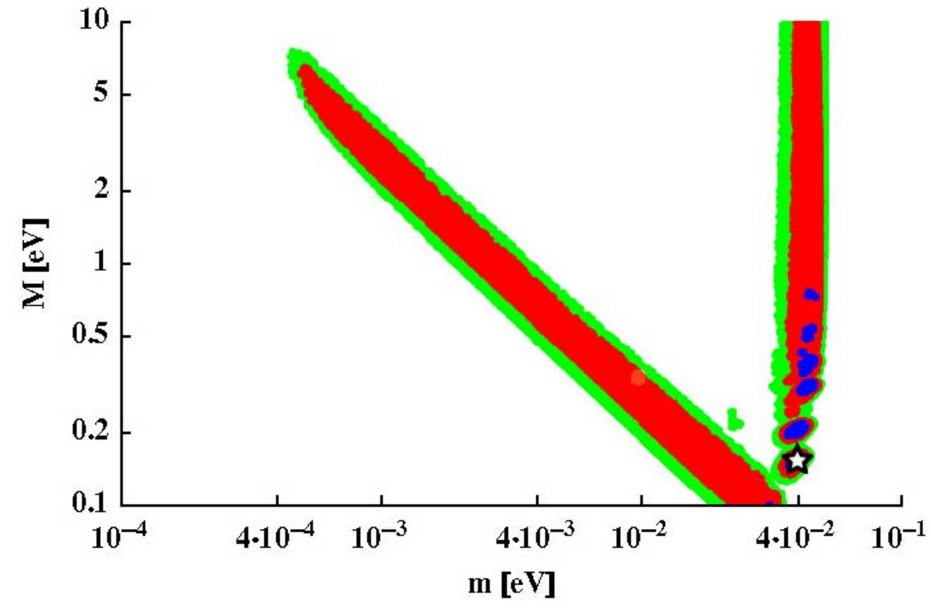
(3+1)-scheme

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2(\Delta m^2_{41}L/4E)$$
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2(\Delta m^2_{41}L/4E)$$

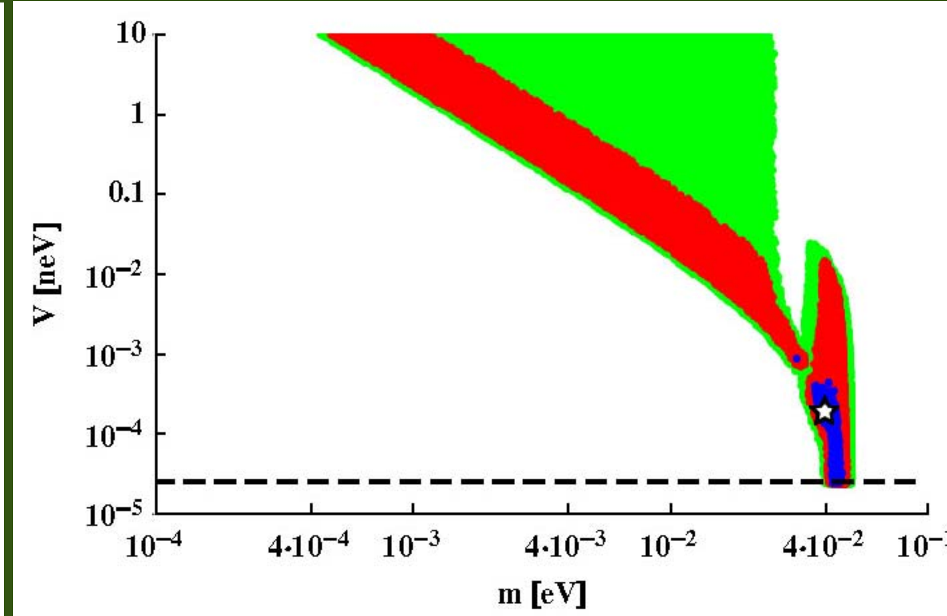
$$\sin^2 2\theta_{Bugey} > 4|U_{e4}|^2(1-|U_{e4}|^2) = \sin^2 2\theta_{14}$$

$$\sin^2 2\theta_{CDHSW} > 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2) \cong \sin^2 2\theta_{24}$$

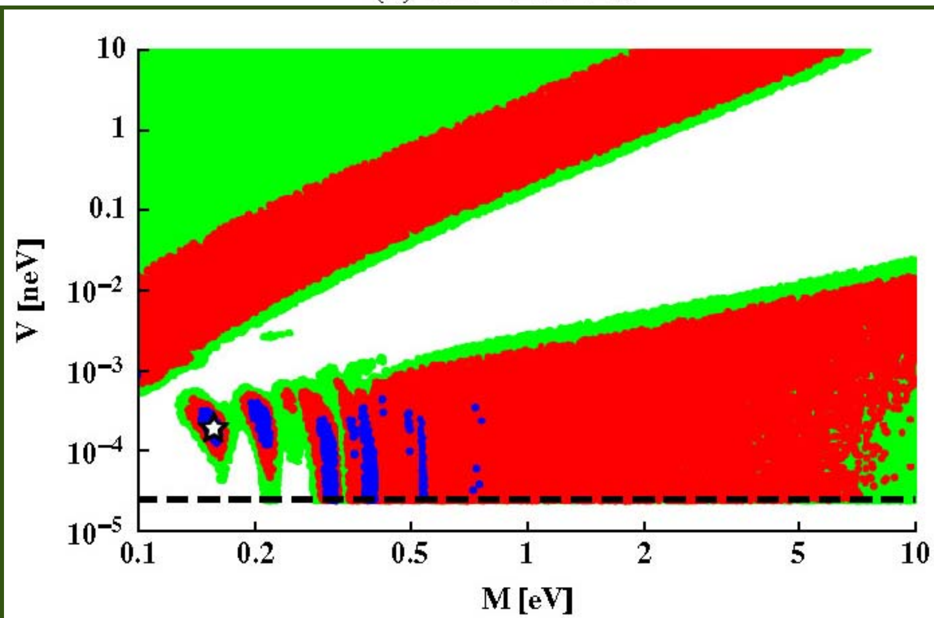




(a) M vs. m



(b) V vs. m



(c) V vs. M

$M=(\Delta m^2_{42})^{1/2}$

$m=(\Delta m^2_{32})^{1/2}$

$V=V_{NC}/2+V_{B\text{-}L}$

Engelhardt-Nelson-Walsh, Phys.Rev.D81:113001,2010