New Physics in the atmospheric sector: non-standard interactions and CPT violation

Michele Maltoni

Instituto de Física Teórica UAM/CSIC

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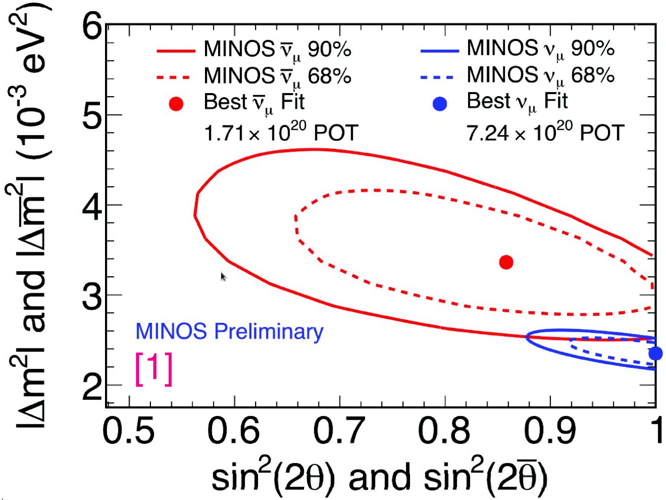
Minos disappearance: ν_μ vs $\bar{\nu}_\mu$

- in June 2010 Minos presented new data on ν_μ vs $\bar{\nu}_\mu$ disappearance [1];
- some tension appears between neutrino and anti-neutrino results;
- Tension (our fit): $\chi^2_{\text{CPT}} - \chi^2_{\not{\text{CPT}}} = 5.6\ (2.4\sigma) \Rightarrow$ small but not totally negligible;
- **more data needed before speculations!**
- Still, let's speculate: **IF** confirmed, it could be
  - evidence of CPT violation;
  - or just "conventional" New Physics...
- in either case, how does this relates to other neutrino experiments?

$$|\Delta\bar{m}^2_{\text{atm}}| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.86 \pm 0.11$$
[1]

$$|\Delta m^2_{\text{atm}}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2$$
$$\sin^2(2\theta_{23}) > 0.90\ \text{(90\% C.L.)}$$
[2]

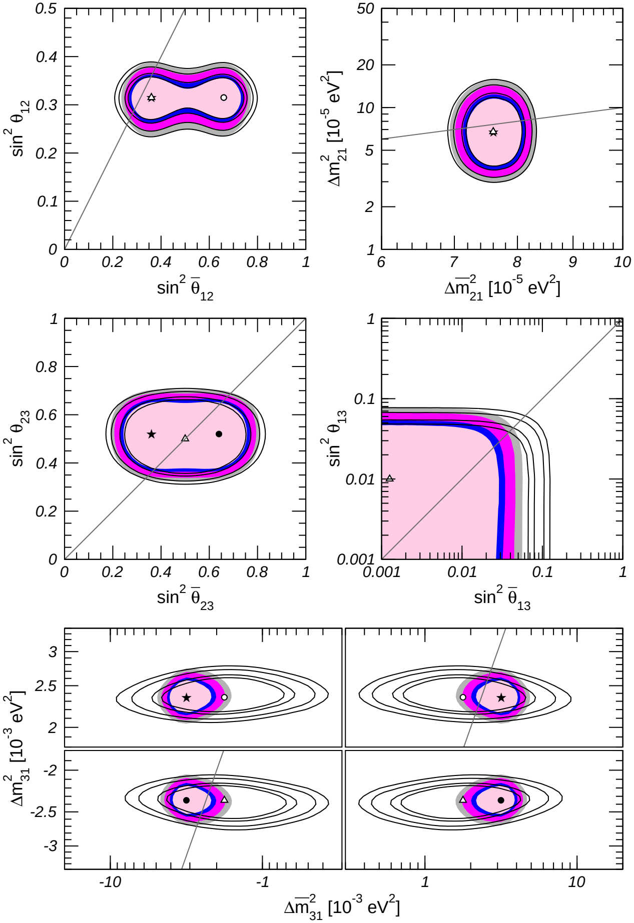


[1] A. Himmel, talk at Fermilab Joint Experimental-Theoretical Seminar, 14/06/2010.
[2] P. Adamson *et al.* [MINOS collaboration], `arXiv:1103.0340`.

I. CPT violation in three-neutrino models

Status of CPT violation with 3ν

- Global fit of solar, atmospheric, reactor and accelerator data;
- only 3ν models considered here [3];
- Tension: $\chi^2_{\text{CPT}} - \chi^2_{\not{\text{CPT}}} = 4.5\ (2.1\sigma)$ slightly reduced with respect to MINOS-only;
- MINOS ($\bar{\nu}_\mu$) data removed $\Rightarrow$ hint of CPT violation completely disappear;
- weak but robust $\Delta\bar{m}^2_{31}$ bound from ATM data $\Rightarrow$ no room for LSND in 3ν ~~CPT~~ models;
- chain effect: MINOS ($\bar{\nu}_\mu$) $\Rightarrow$ $\Delta\bar{m}^2_{31}$ strongly improved $\Rightarrow$ CHOOZ bound on $\bar{\theta}_{13}$ enhanced $\Rightarrow$ KamLAND bound on $\bar{\theta}_{13}$ slightly better.



[3] see Giunti's talk for ~~CPT~~ + sterile ν.

Non-standard neutrino interactions: formalism

- Effective low-energy Lagrangian for **standard** neutrino interactions with matter:

$$\mathcal{L}_{\text{SM}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{\beta} \left([\bar{\nu}_\beta \gamma_\mu L \ell_\beta][\bar{f}\gamma^\mu L f'] + \text{h.c.} \right) - 2\sqrt{2}G_F \sum_{P,\beta} g_P^f [\bar{\nu}_\beta \gamma_\mu L \nu_\beta][\bar{f}\gamma^\mu P f]$$

where $P \in \{L, R\}$, (f, f') form an SU(2) doublet, and g_P^f is the Z coupling to fermion f:

$$g_L^\nu = \frac{1}{2}, \quad g_L^\ell = \sin^2\theta_W - \frac{1}{2}, \quad g_L^u = -\frac{2}{3}\sin^2\theta_W + \frac{1}{2}, \quad g_L^d = \frac{1}{3}\sin^2\theta_W - \frac{1}{2},$$

$$g_R^\nu = 0, \quad g_R^\ell = \sin^2\theta_W, \quad g_R^u = -\frac{2}{3}\sin^2\theta_W, \quad g_R^d = \frac{1}{3}\sin^2\theta_W;$$

- here we consider NC-like **non-standard** neutrino-matter described by:

$$\mathcal{L}_{\text{NSI}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{P,\alpha,\beta} \varepsilon_{\alpha\beta}^{fP} [\bar{\nu}_\alpha \gamma_\mu L \nu_\beta][\bar{f}\gamma^\mu P f];$$

note that $\varepsilon_{\alpha\beta}^{fP}$ is Hermitian;

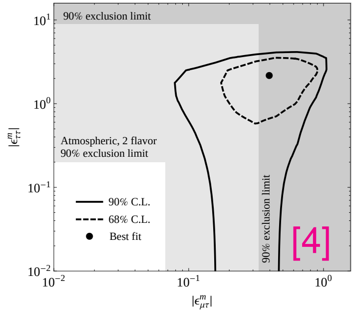
- neutrino **propagation** is only sensitive to the vector couplings $\varepsilon_{\alpha\beta}^{f} = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$;
- note that NC-like NSI's do **not** affect CC processes such as lepton appearance.

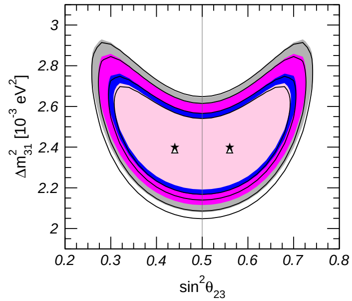
NSI in the $\mu - \tau$ sector: impact on MINOS data

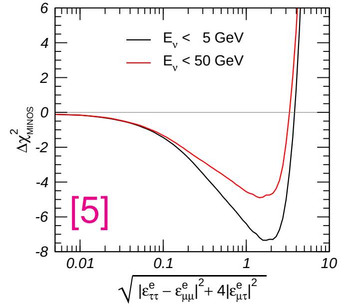
- Matter effects change sign between ν and $\bar{\nu}$ $\Rightarrow$ could be responsible for MINOS anomaly: $\vec{\nu} = (\nu_\mu, \nu_\tau)^T$

$$i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2_{31}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23}\end{pmatrix} \pm \sqrt{2}\, G_F N_e(r) \begin{pmatrix} \varepsilon^e_{\mu\mu} & \varepsilon^e_{\mu\tau} \\ \varepsilon^{e\star}_{\mu\tau} & \varepsilon^e_{\tau\tau}\end{pmatrix}\right] \vec{\nu};$$

- indeed NSI's considerably improve the fit: $\Delta\chi^2 = 7.5$ in [4];
- however, the strength of the improvement is reduced if the entire spectrum is used: $\Delta\chi^2 = 7.3$ $(0-5$ GeV$) \to 4.9$ $(0-50$ GeV$)$ [5];
- conversely, the **pure** oscillation solution is quite insensitive to the energy range used for the fit;
- problem: matter effects in MINOS are weak $\Rightarrow$ very large $\varepsilon_{\alpha\beta}$ are needed $\Rightarrow$ incompatible with ATM data?







[4] J. Kopp *et al.*, Phys. Rev. **D82** (2010) 113002 [arXiv:1009.0014].
[5] M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, in preparation.

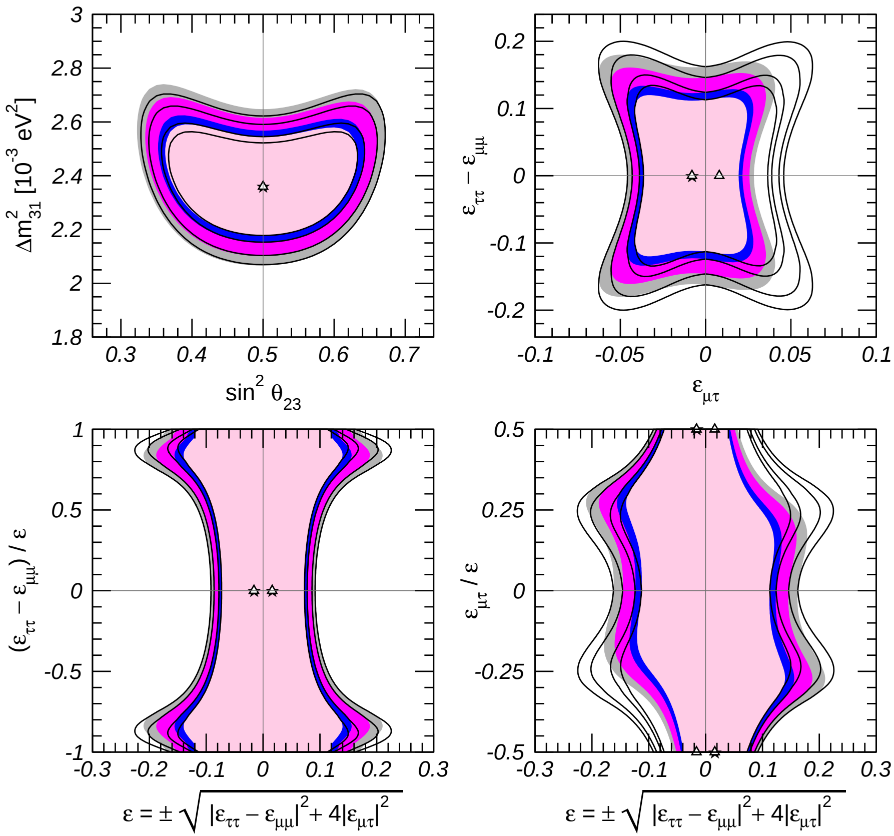
NSI in the $\mu - \tau$ sector: global analysis

- As expected, inclusion of ATM data rules out the NSI solution to the MINOS anomaly;
- determination of the oscillation parameters is very stable;
- 90% (3σ) bounds on NSI:

$$|\varepsilon^e_{\mu\tau}| \leq 0.035\ (0.055),$$
$$|\varepsilon^e_{\tau\tau} - \varepsilon^e_{\mu\mu}| \leq 0.11\ (0.18);$$

- bounds on $|\varepsilon^e_{\tau\tau} - \varepsilon^e_{\mu\mu}|$ considerably stronger than LAB ones;

¿? do these bounds still hold in the general 3ν oscillation+NSI scenario?



Atmospheric ν: the $\nu_e - \nu_\tau$ channel

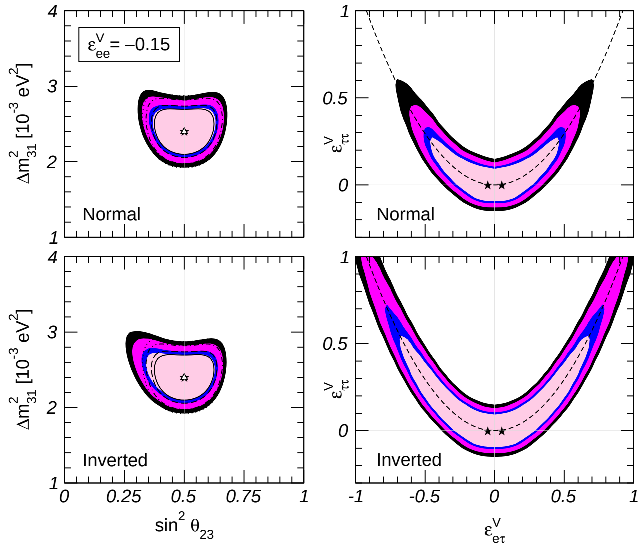
- Let us now turn to the $e-\tau$ sector [6, 7, 8]:

$$V_{\text{NSI}} \propto \begin{pmatrix} \varepsilon_{ee} & 0 & \varepsilon_{e\tau} \\ 0 & \varepsilon_{\mu\mu} & 0 \\ \varepsilon_{e\tau}^\star & 0 & \varepsilon_{\tau\tau} \end{pmatrix} \quad \varepsilon_{\alpha\beta} \equiv \sum_f \frac{N_f}{N_e} \varepsilon_{\alpha\beta}^f \approx \varepsilon_{\alpha\beta}^e + \mathbf{3}\, \varepsilon_{\alpha\beta}^u + \mathbf{3}\, \varepsilon_{\alpha\beta}^d$$

$$\oplus \begin{cases} N_u/N_e = 3.137 \text{ (core)}, 3.012 \text{ (mantle)} \\ N_d/N_e = 3.274 \text{ (core)}, 3.024 \text{ (mantle)} \end{cases}$$

- a dramatic cancellation [6] occurs along the parabola $(1+\varepsilon_{ee}-\varepsilon_{\mu\mu})(\varepsilon_{\tau\tau}-\varepsilon_{\mu\mu}) = |\varepsilon_{e\tau}|^2$;
- determination of osc. parameters **still stable**;
- **but** bound on $|\varepsilon_{\tau\tau}-\varepsilon_{\mu\mu}|$ no longer applies;
- however, the $\perp$ bound is still strong;

$\Rightarrow$ **Correlations among different $\varepsilon_{\alpha\beta}$ can have very important consequences!**



[6] A. Friedland, C. Lunardini, and M. Maltoni, Phys. Rev. **D70** (2004) 111301 [hep-ph/0408264].

[7] A. Friedland and C. Lunardini, Phys. Rev. **D72** (2005) 053009 [hep-ph/0506143].

[8] A. Friedland and C. Lunardini, Phys. Rev. **D74** (2006) 033012 [hep-ph/0606101].

Bounds from non-oscillation experiments

- Present bounds on $\varepsilon_{\alpha\beta} = \varepsilon^{e}_{\alpha\beta} + 3\,\varepsilon^{u}_{\alpha\beta} + 3\,\varepsilon^{d}_{\alpha\beta}$ [14]:

$\lvert\varepsilon_{ee}\rvert \lesssim \mathcal{O}(1)$	poor	LSND, Reactors, CHARM	[9, 10, 11]
$\lvert\varepsilon_{\mu\mu}\rvert \lesssim \mathcal{O}(0.01)$	good	CHARM II, NuTeV	[9, 11]
$\lvert\varepsilon_{\tau\tau}\rvert \lesssim \mathcal{O}(10)$	poor	LEP, τ decay	[9, 11, 12]
$\lvert\varepsilon_{e\mu}\rvert \lesssim$ ~~$\mathcal{O}(0.001)$~~	~~strong~~	~~radiative corrections~~	~~[11]~~
$\mathcal{O}(0.1)$	mild	CHARM II, NuTeV	[13, 14]
$\lvert\varepsilon_{e\tau}\rvert \lesssim \mathcal{O}(1)$	poor	LEP+LSND+Reactors, CHARM	[9, 11, 12]
$\lvert\varepsilon_{\mu\tau}\rvert \lesssim \mathcal{O}(0.1)$	mild	CHARM II, NuTeV	[9, 11]

- no strong bound (other than $\varepsilon_{\mu\mu}$) appear;
- in particular, the common assumption $\varepsilon_{e\mu} = 0$ is not justified.

[9] J. Barranco *et al.*, arXiv:0711.0698.
[10] J. Barranco *et al.*, Phys. Rev. **D73** (2006) 113001 [hep-ph/0512195].
[11] S. Davidson *et al.*, JHEP **03** (2003) 011 [hep-ph/0302093].
[12] Z. Berezhiani and A. Rossi, Phys. Lett. **B535** (2002) 207 [hep-ph/0111137].
[13] C. Biggio, M. Blennow, E. Fernandez-Martinez, JHEP **0903** (2009) 139 [arXiv:0902.0607].
[14] C. Biggio, M. Blennow, E. Fernandez-Martinez, JHEP **0908** (2009) 090 [arXiv:0907.0097].

Non-standard interactions and 3ν oscillations

- Equation of motion: **6** (vac) + **8** (NSI) = **14** parameters:

$$i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}; \qquad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^\dagger \pm V_{\text{mat}}; \qquad D_{\text{vac}} = \frac{1}{2E_\nu}\,\text{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31}\right);$$

$$U_{\text{vac}} = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\text{CP}}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\text{CP}}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\text{CP}}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\text{CP}}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\text{CP}}} & c_{13}\,c_{23} \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix},$$

$$\varepsilon_{\alpha\beta} \equiv \sum_f \frac{N_f}{N_e}\varepsilon^f_{\alpha\beta}, \qquad V_{\text{mat}} \equiv V_{\text{SM}} + V_{\text{NSI}} = \sqrt{2}G_F N_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^\star_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^\star_{e\tau} & \varepsilon^\star_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix};$$

- too much parameters $\Rightarrow$ only partial analyses technically possible;
- so far, most numerical studies assumed some specific $\varepsilon_{\alpha\beta}$ to be zero;
- in what follows we will try to simplify the problem while being as conservative as possible, based on the results of partial analyses presented in the previous slides.

The degenerate matter-eigenvalues approximation

- So far we have learned that:
  - from $\mu-\tau$: NSI spoil the vacuum oscillation patterns favored by data $\Rightarrow$ strong bounds;
  - from $e-\tau$: bounds become very weak when two eigenvalues of V_{mat} coincide;
- hence, the limit of two coinciding V_{mat} eigenvalues is the most conservative one.
- general parametrization:

$$V_{\text{mat}} = P_{\text{rel}} U_{\text{mat}} D_{\text{mat}} U_{\text{mat}}^\dagger P_{\text{rel}}^\dagger ,$$

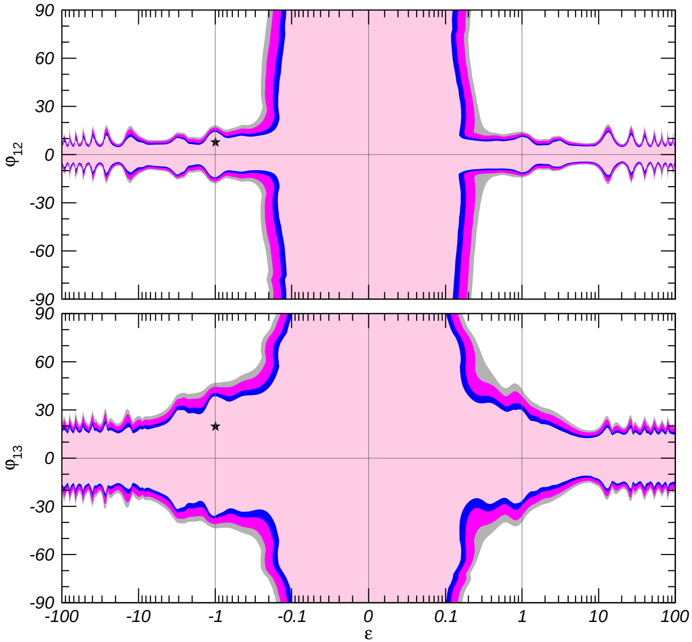
$$\begin{cases} P_{\text{rel}} = \operatorname{diag}\left(e^{i\alpha_1}, e^{i\alpha_2}, e^{-i\alpha_1 - i\alpha_2}\right), \\ U_{\text{mat}} = R_{12}(\varphi_{12}) R_{13}(\varphi_{13}) , \\ D_{\text{mat}} = \sqrt{2} G_F N_e(r) \operatorname{diag}(\varepsilon, 0, 0) ; \end{cases}$$

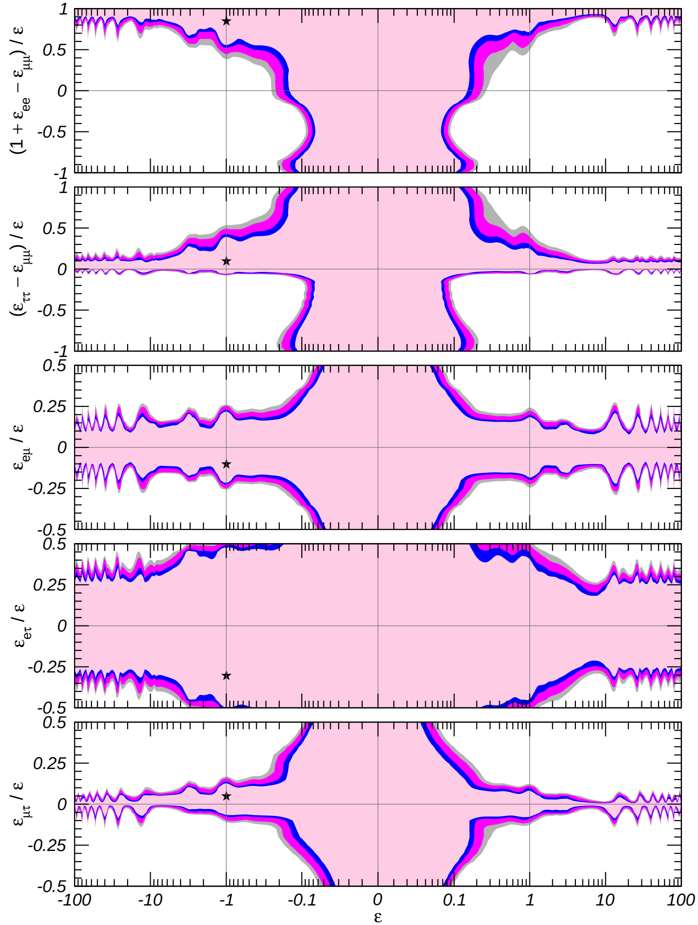
$$\begin{aligned} 1 + \varepsilon_{ee} - \varepsilon_{\mu\mu} &= \varepsilon (\cos^2\varphi_{12} - \sin^2\varphi_{12}) \cos^2\varphi_{13} , \\ \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} &= \varepsilon (\sin^2\varphi_{13} - \sin^2\varphi_{12} \cos^2\varphi_{13}) , \\ \varepsilon_{e\mu} &= -\varepsilon \cos\varphi_{12} \sin\varphi_{12} \cos^2\varphi_{13} \, e^{i(\alpha_1 - \alpha_2)} , \\ \varepsilon_{e\tau} &= -\varepsilon \cos\varphi_{12} \cos\varphi_{13} \sin\varphi_{13} \, e^{i(2\alpha_1 + \alpha_2)} , \\ \varepsilon_{\mu\tau} &= \varepsilon \sin\varphi_{12} \cos\varphi_{13} \sin\varphi_{13} \, e^{i(\alpha_1 + 2\alpha_2)} . \end{aligned}$$

- set $\Delta m^2_{21} = 0 \Rightarrow \theta_{12}$ and δ_{CP} disappear $\Rightarrow$ **3** (vac) + **2** (rel) + **3** (mat) = **8** parameters;
- SM is recovered for $\varphi_{12} = \varphi_{13} = 0$ and $\varepsilon = \pm 1$, with $\operatorname{sgn}(\varepsilon) \cdot \operatorname{sgn}(\Delta m^2_{31}) \Leftrightarrow$ mass hierarchy;
- it can be shown that neutrino evolution reduces to an effective $(1\nu + 2\nu)$ scenario.

General bounds on NSI

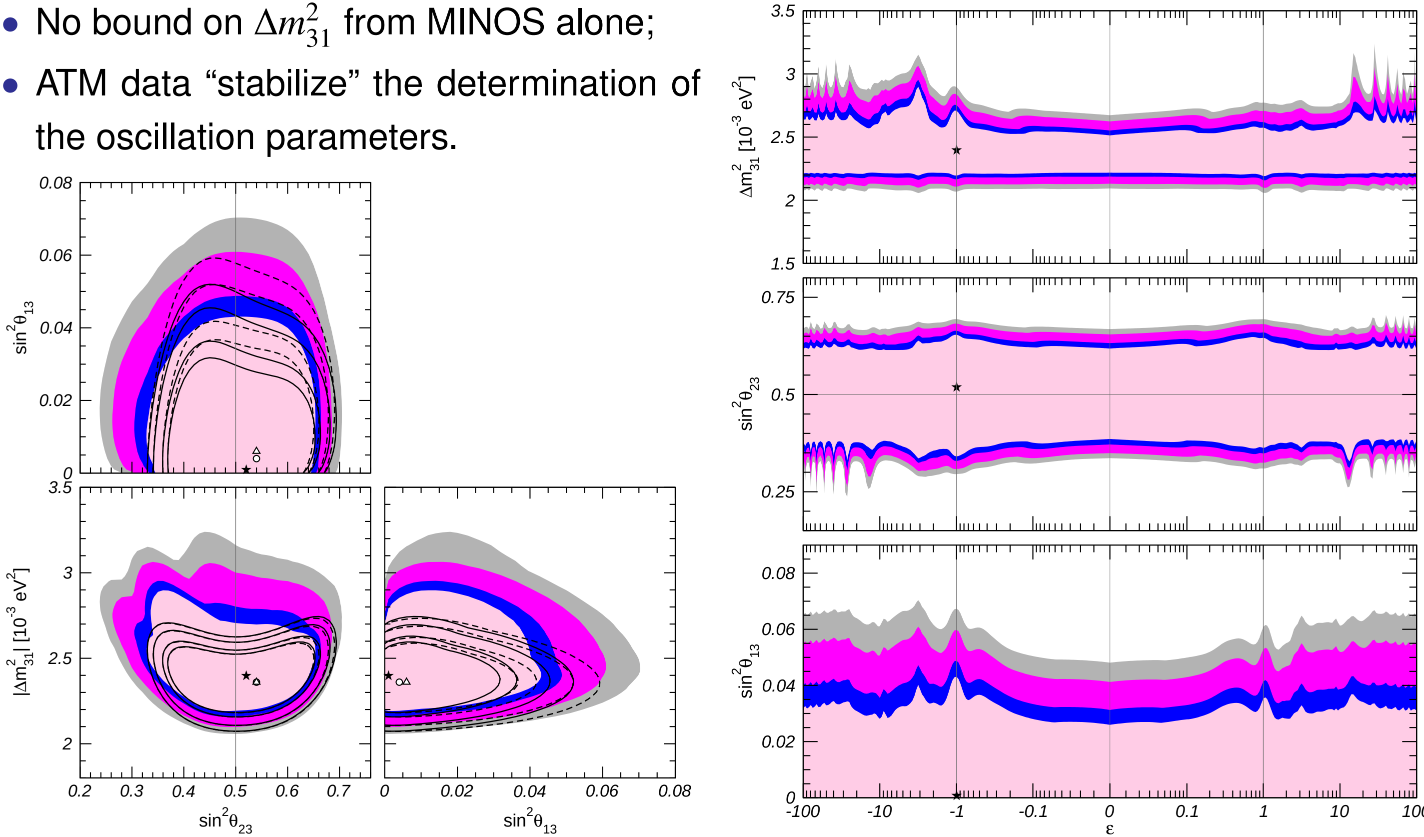
- No bound on $|\varepsilon|$ available from osc. data;
- however, $|\varepsilon| \gtrsim 1$ requires $|\varphi_{12}| \lesssim 10°$ and $|\varphi_{13}| \lesssim 30°$.





Stability of the oscillation solution

- No bound on Δm^2_{31} from MINOS alone;
- ATM data "stabilize" the determination of the oscillation parameters.



Perspective: combining solar and atmospheric neutrinos

- As in the SM case, solar neutrinos can be reduced to an effective 2ν problem:

$$i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} \pm \sqrt{2}\, G_F N_e(r) \begin{pmatrix} c^2_{13} & 0 \\ 0 & 0 \end{pmatrix} \pm \sqrt{2}\, G_F N_f(r) \begin{pmatrix} 0 & \varepsilon_f \\ \varepsilon_f & \varepsilon'_f \end{pmatrix}\right] \vec{\nu},$$

$$\vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix}, \qquad \begin{cases} \varepsilon_f = c_{13}(\varepsilon^f_{e\mu} c_{23} - \varepsilon^f_{e\tau} s_{23}) - s_{13}[\varepsilon^f_{\mu\tau}(c^2_{23} - s^2_{23}) + (\varepsilon^f_{\mu\mu} - \varepsilon^f_{\tau\tau}) c_{23} s_{23}]\,, \\ \varepsilon'_f = \varepsilon^f_{\mu\mu} c^2_{23} + \varepsilon^f_{\tau\tau} s^2_{23} - \varepsilon^f_{ee} - 2\varepsilon^f_{\mu\tau} c_{23} s_{23} + 2 s_{13} c_{13} (\varepsilon^f_{e\tau} c_{23} + \varepsilon^f_{e\mu} s_{23}) \\ \qquad - s^2_{13}(\varepsilon^f_{\tau\tau} c^2_{23} + \varepsilon^f_{\mu\mu} s^2_{23} - \varepsilon^f_{ee} + 2\varepsilon^f_{\mu\tau} s_{23} c_{23})\,; \end{cases}$$

- pre-Borexino solar data *can be perfectly fitted* by NSI only $\Rightarrow$ solar LMA solution **is unstable** with respect to the introduction of NSI [15, 16, 17];
- KamLAND **requires** Δm^2_{21} but is insensitive to NSI $\Rightarrow$ it **determines** Δm^2_{21};
- Solar+KamLAND bounds on NSI very weak [15], but **not** be affected by the ATM cancellation $\Rightarrow$ potential for **synergy**! Example: $1 + \varepsilon_{ee} = 0 \Rightarrow$ no MSW $\Rightarrow$ excluded.

[15] O. G. Miranda, M. A. Tortola, and J. W. F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280].
[16] M. M. Guzzo, P. C. de Holanda, and O. L. G. Peres, Phys. Lett. **B591** (2004) 1 [hep-ph/0403134].
[17] A. Friedland, C. Lunardini, and C. Pena-Garay, Phys. Lett. **B594** (2004) 347 [hep-ph/0402266].

- MINOS observes a 2.4σ discrepancy between neutrino and antineutrino parameters;
- this "hint" of CPT violation is presently an isolated feature: a global fit of all neutrino data except MINOS($\bar{\nu}_\mu$) is perfectly consistent with CPT conservation;
- NSI in the $\mu - \tau$ sector could perfectly explain this asymmetry, however they are incompatible with atmospheric data;
- indeed a combined analysis of ATM and MINOS data allow to put a strong bound on NSI in the $\mu - \tau$, but this bound is lost in the general 3ν framework.
- We have studied the case of 3ν NSI with two degenerate matter eigenvalues. This is equivalent to generalizing the SM matter potential by rescaling its strength, rotating it away from the ee sector, and rephasing. We have found that:
  - the strength of the matter potential cannot be constrained by ATM+LBL data only;
  - the determination of the oscillation parameters is stable.
- Combining these results with a similar analysis of solar neutrinos (in progress) will provide complementary information.