Phenomenology of neutrino oscillations

Colloquium Prague v13

Charles University - Prague
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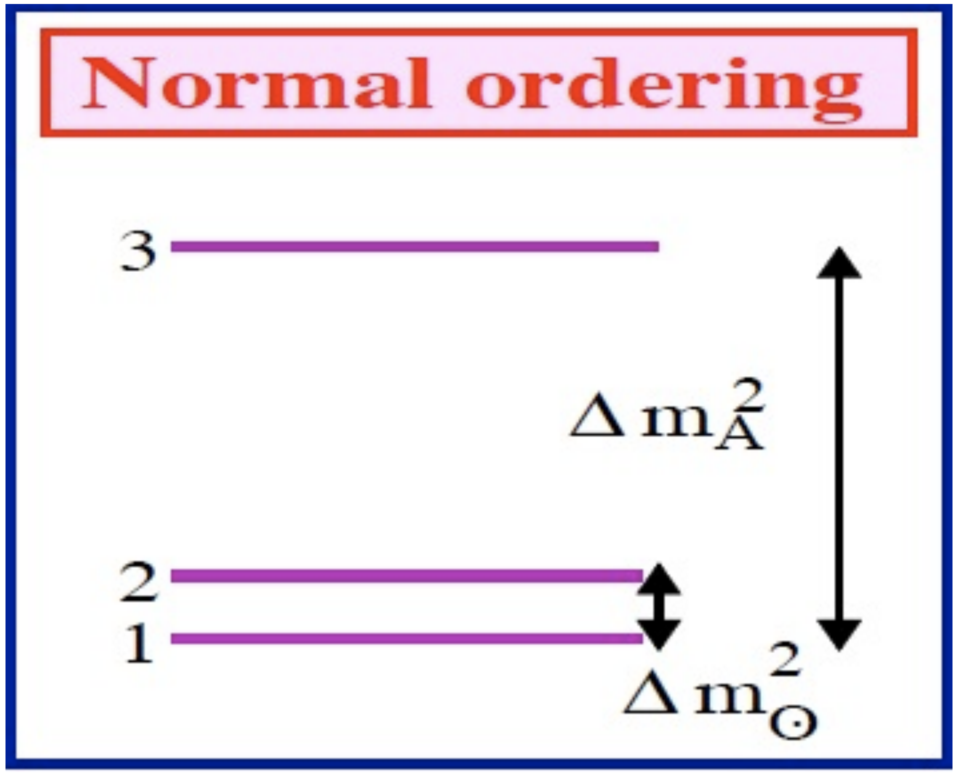
IPPP - Durham U. - ITN Invisibles

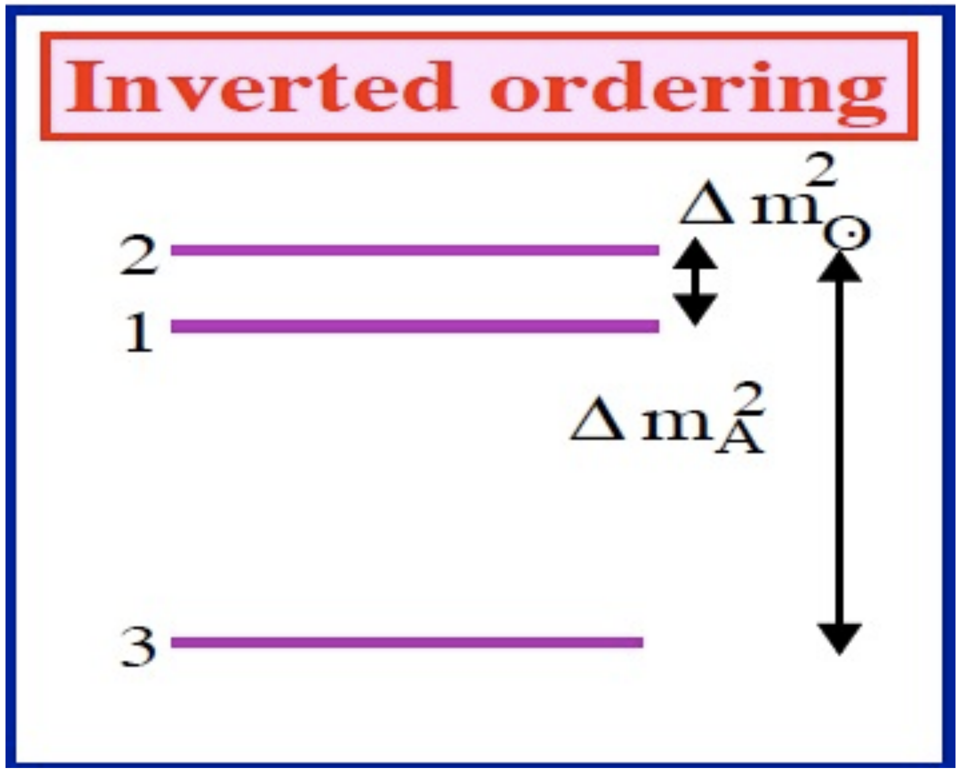
Outline

- Neutrino mixing
- Neutrino oscillations: the basic picture
- 2-neutrino mixing: in vacuum and matter effects
- 3-neutrino oscillations: CP-violation
- Long baseline neutrino oscillations: phenomenology and reach
- Sterile neutrinos (and NSI): anomalies and tests

Present status of (standard) neutrino physics

$\Delta m_{\mathrm{s}}^2 \ll \Delta m_{\mathrm{A}}^2$ implies at least 3 massive neutrinos.





$$m_1 = m_{\min}$$
$$m_2 = \sqrt{m_{\min}^2 + \Delta m_{\mathrm{sol}}^2}$$
$$m_3 = \sqrt{m_{\min}^2 + \Delta m_{\mathrm{A}}^2}$$

$$m_3 = m_{\min}$$
$$m_1 = \sqrt{m_{\min}^2 + \Delta m_{\mathrm{A}}^2 - \Delta m_{\mathrm{sol}}^2}$$
$$m_2 = \sqrt{m_{\min}^2 + \Delta m_{\mathrm{A}}^2}$$

Measuring the masses requires: $m_{\min}$ and the ordering .

Neutrino mixing

Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix, which enters in the CC interactions

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

Flavour states (α) — Mass states (i)

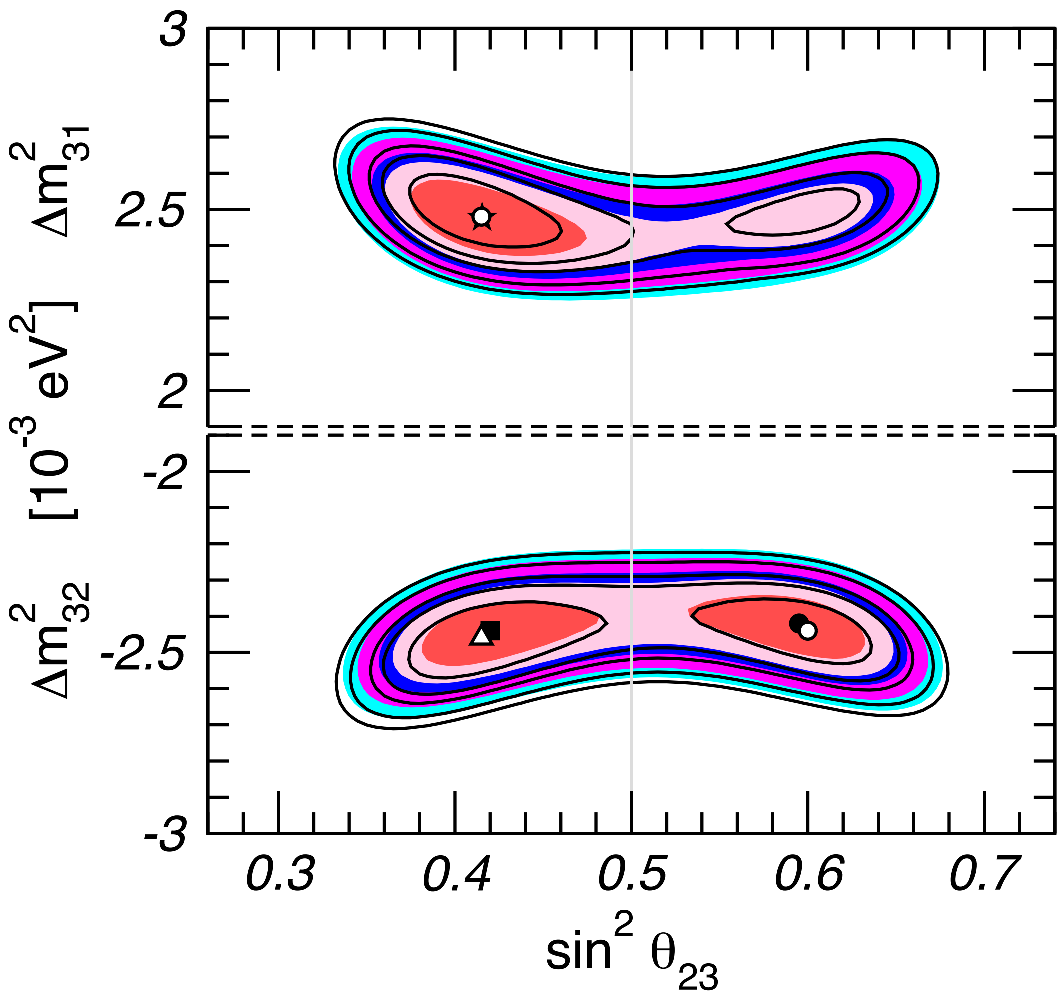
$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{k\alpha} (U^*_{\alpha k} \bar{\nu}_{kL} \gamma^\rho l_{\alpha L} W_\rho + \text{h.c.})$$

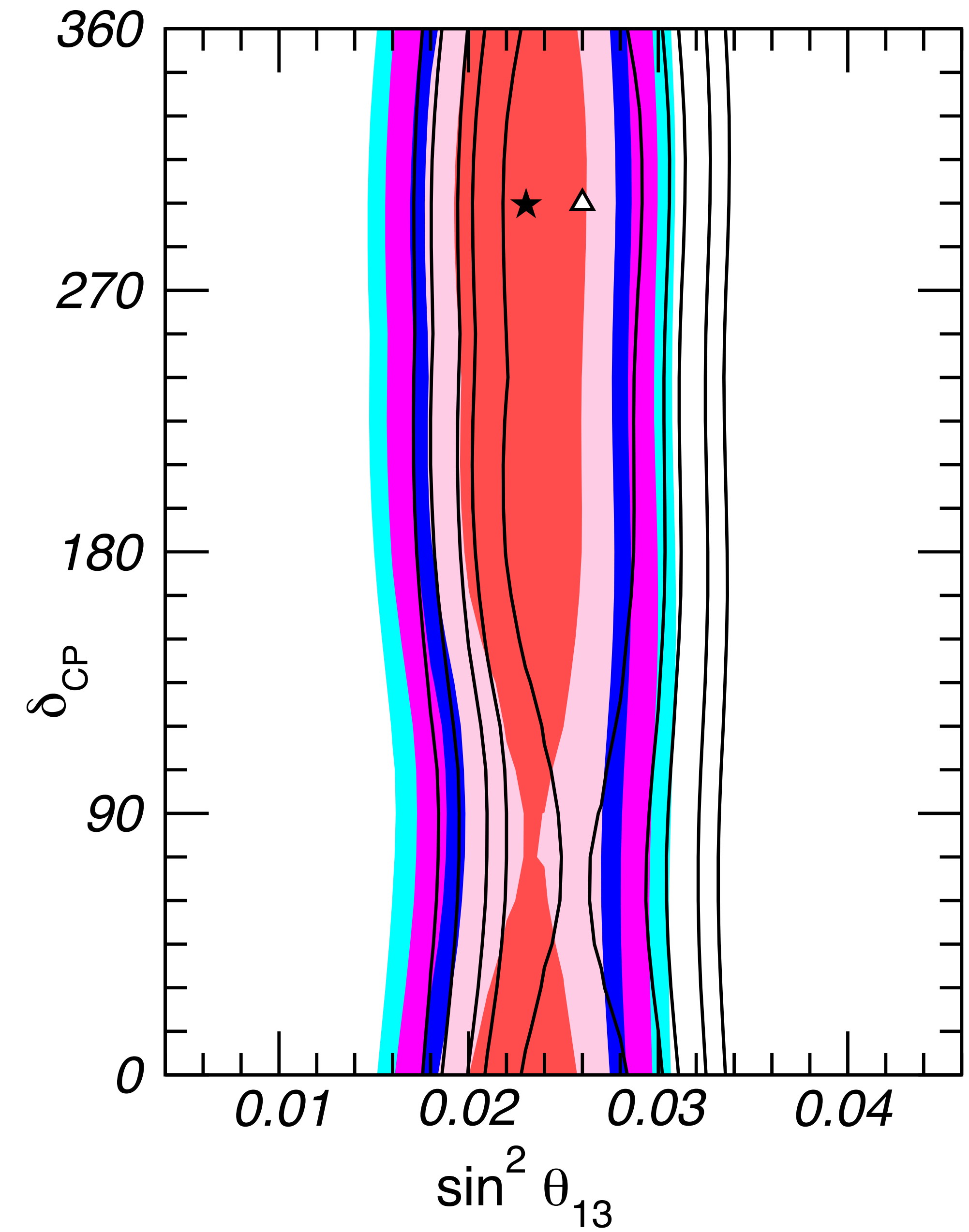
$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

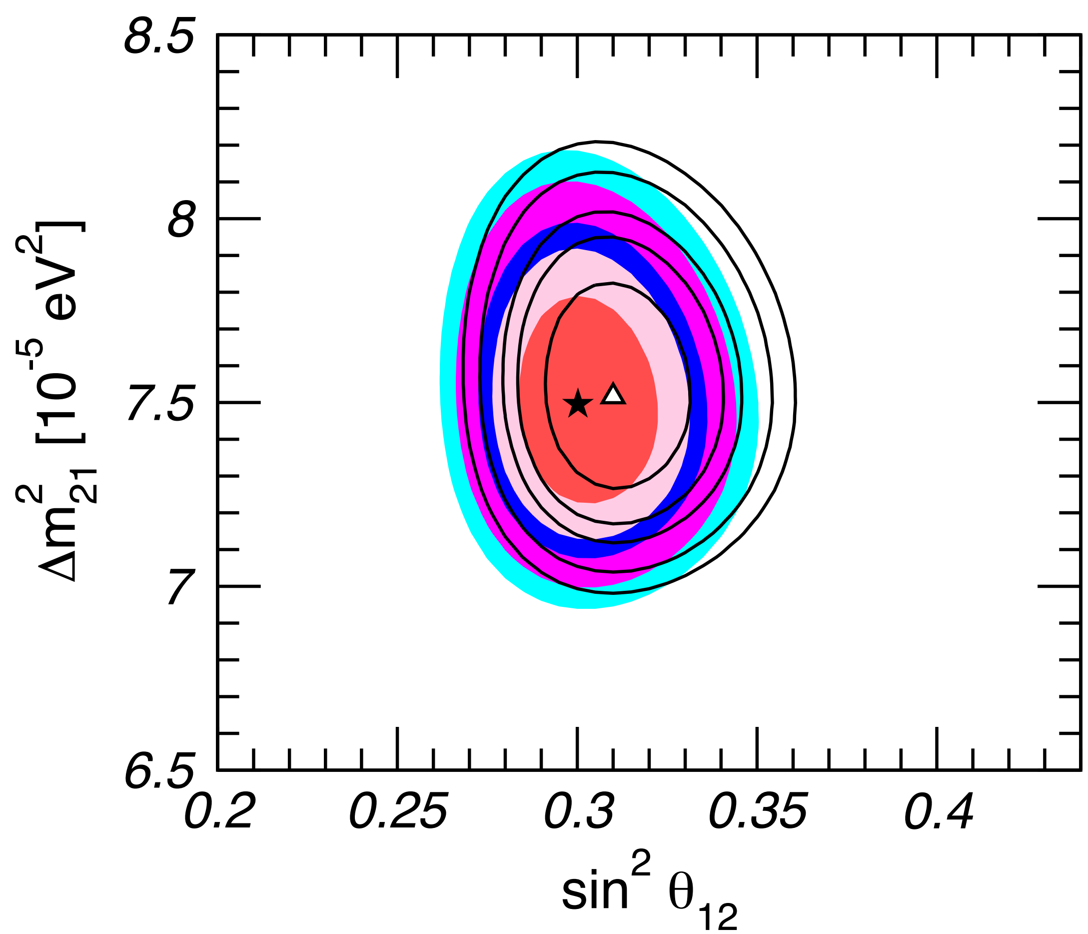
Solar, reactor $\theta_\odot \sim 30^o$ — Atm, Acc. $\theta_A \sim 45^o$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}$$

CPV phase — Reactor, Acc. $\theta_{13} \sim 9^o$ — CPV Majorana phases







M. C. Gonzalez-Garcia et al., 1209.3023

All oscillation parameters are measured with good precision, except for the mass hierarchy and the delta phase. One needs to check the 3-neutrino paradigm (sterile neutrino?).

Questions for the future

- What is the **nature** of neutrinos (Majorana vs Dirac)? Is Lepton number conserved?

  $(\beta\beta)_{0\nu}$ decay

  See S. Soldner-Rembold's talk

- Absolute values of **neutrino masses**?
  1. type of hierarchy; 2. lightest mass

  See S. Hannestad's and F. Glueck's talks

  $(\beta\beta)_{0\nu}$ decay, LBL oscillations, KATRIN, Cosmology

- **Leptonic CP-violation**? $\delta \neq 0$ and/or $\alpha_{ij} \neq 0, \pi$

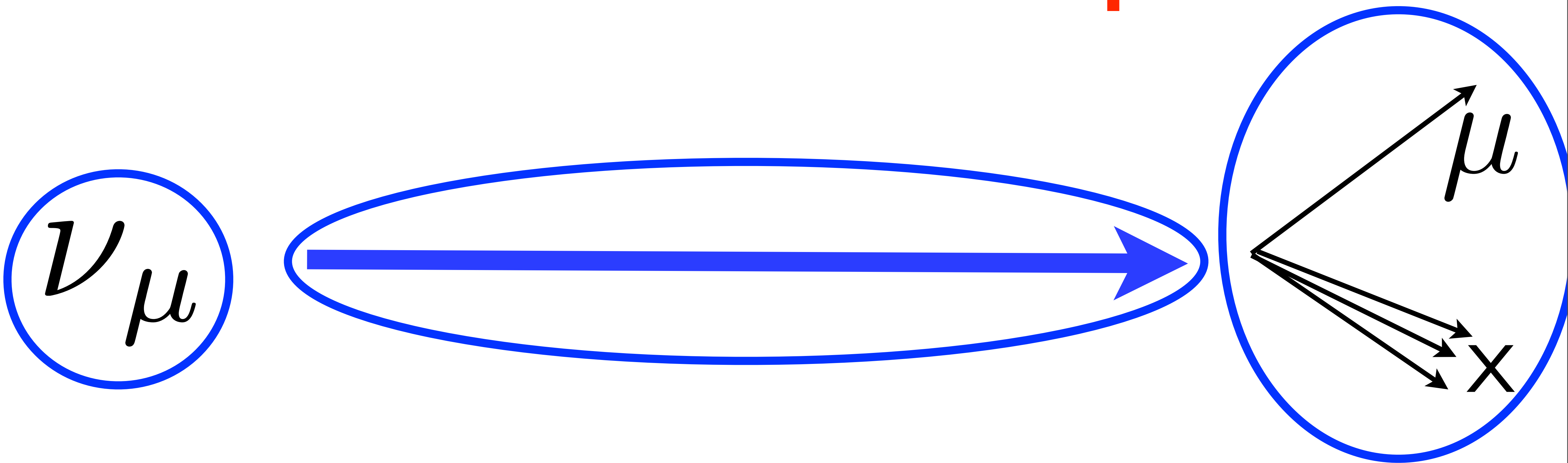
  $(\beta\beta)_{0\nu}$ decay, LBL oscillations

  See M. Malinsky's talk

- **Precision** measurements; tests of standard scenario
  1. $\theta_{23} \neq \pi/4?$ 2. NSI, sterile neutrinos.....

  Short baseline and LBL oscillations

Neutrino oscillations: the picture



Production	Propagation	Detection
Flavour states	Massive states (eigenstates of the Hamiltonian)	Flavour states

This is analogous to other QM systems (spin precession, NH3 etc.).

Neutrino oscillations in vacuum

Let's assume that at t=0 a muon neutrino is produced

$$|\nu_\mu\rangle = U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle + U_{\mu 3}|\nu_3\rangle$$

The time-evolution is given by

$$|\nu, t\rangle = \sum_i U_{\mu i} e^{-iE_i t}|\nu_i\rangle$$

$$P(\nu_\mu \to \nu_e) = \left| \sum_i U_{\mu i} U^*_{ei} e^{-i\frac{\Delta m^2_{i1} t}{2E}} \right|^2$$

- **neutrinos have mass** (different components of the initial state need to propagate with different phases)

- **neutrinos mix** (If no mixing the flavour eigenstates are also H eigenstates and they do not evolve).

2-neutrino case

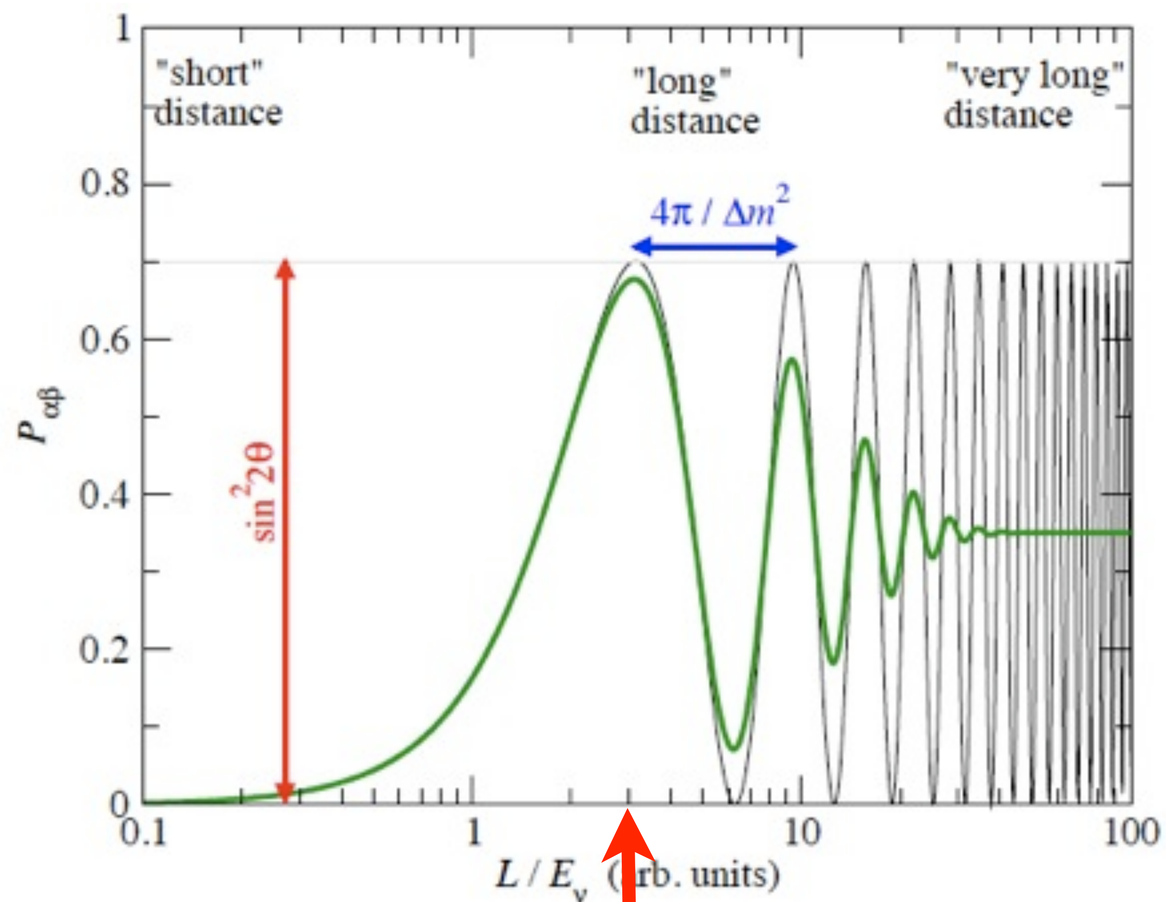
Let's recall that the mixing is

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

We compute the probability of oscillation

$$P(\nu_\alpha \to \nu_\beta)$$

$$= \boxed{\sin^2(2\theta)\sin^2(\frac{\Delta m^2_{21}}{4E}L)}$$



Thanks to T. Schwetz

First oscillation maximum

No CP-violation as there is no Dirac phase in the mixing matrix

$$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

3-neutrino oscillations

They depend on two mass squared-differences

$$\Delta m^2_{21} \ll \Delta m^2_{31}$$

3 angles and one CPV phase $\theta_{12}, \theta_{23}, \theta_{13}, \quad \delta$

Interesting 2-nu limits, which apply to current exps:

$$P(\nu_\mu \to \nu_e; t) = s^2_{23} \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

$$P(\nu_\mu \to \nu_\tau; t) = c^4_{13} \sin^2(2\theta_{23}) \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

$$P(\nu_\mu \to \nu_\mu; t) = 1 - 4 s^2_{23} c^2_{13} (1 - s^2_{23} c^2_{13}) \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

$$P(\nu_e \to \nu_e; t) = 1 - \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

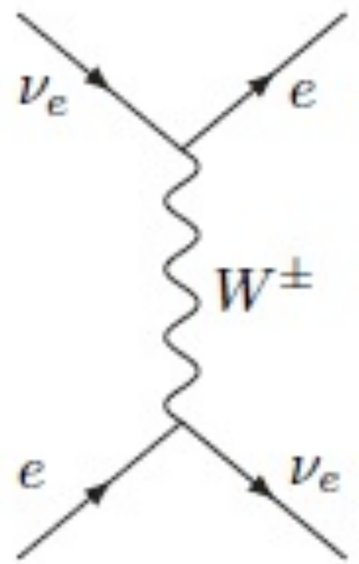
Neutrino oscillations in matter

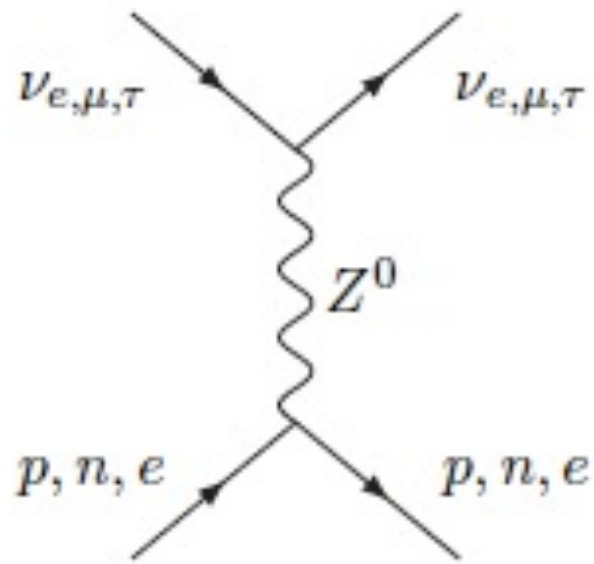
- When neutrinos travel through a medium, they interact with the background of electron, proton and neutrons and acquire an effective mass. [L. Wolfenstein, Phys. Rev. D 17, 2369 (1978); ibid. D 20, 2634 (1979), S. P. Mikheyev, A. Yu Smirnov, Sov. J. Nucl. Phys. 42 (1986) 913.]

- This modifies the mixing between flavour states and propagation states and the eigenvalues of the Hamiltonian, leading to a different oscillation probability w.r.t. vacuum.

- Typically the background is CP and CPT violating, e.g. the Earth and the Sun contain only electrons, protons and neutrons, and the resulting oscillations are CP and CPT violating.

Electron neutrinos have CC and NC interactions, while muon and tau neutrinos only the latter.





We treat the electrons as a background: $\langle \bar{e}\gamma_0 e \rangle = N_e$.

medium	A_{CC} for $\nu_e, \bar{\nu}_e$ only	A_{NC} for $\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}$
$e, \bar{e}$	$\pm\sqrt{2}G_F(N_e - N_{\bar{e}})$	$\mp\sqrt{2}G_F(N_e - N_{\bar{e}})(1 - 4s_W^2)/2$
$p, \bar{p}$	0	$\pm\sqrt{2}G_F(N_p - N_{\bar{p}})(1 - 4s_W^2)/2$
$n, \bar{n}$	0	$\mp\sqrt{2}G_F(N_n - N_{\bar{n}})/2$
ordinary matter	$\pm\sqrt{2}G_F N_e$	$\mp\sqrt{2}G_F N_n/2$

Table from Strumia and Vissani

2-neutrino case in constant density

$$i\frac{d}{dt}\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix}$$

- The diagonal basis and the flavour basis are related by a unitary matrix with angle in matter

$$\tan(2\theta_m) = \frac{\frac{\Delta m^2}{2E}\sin(2\theta)}{\frac{\Delta m^2}{2E}\cos(2\theta) - \sqrt{2}G_F N_e}$$

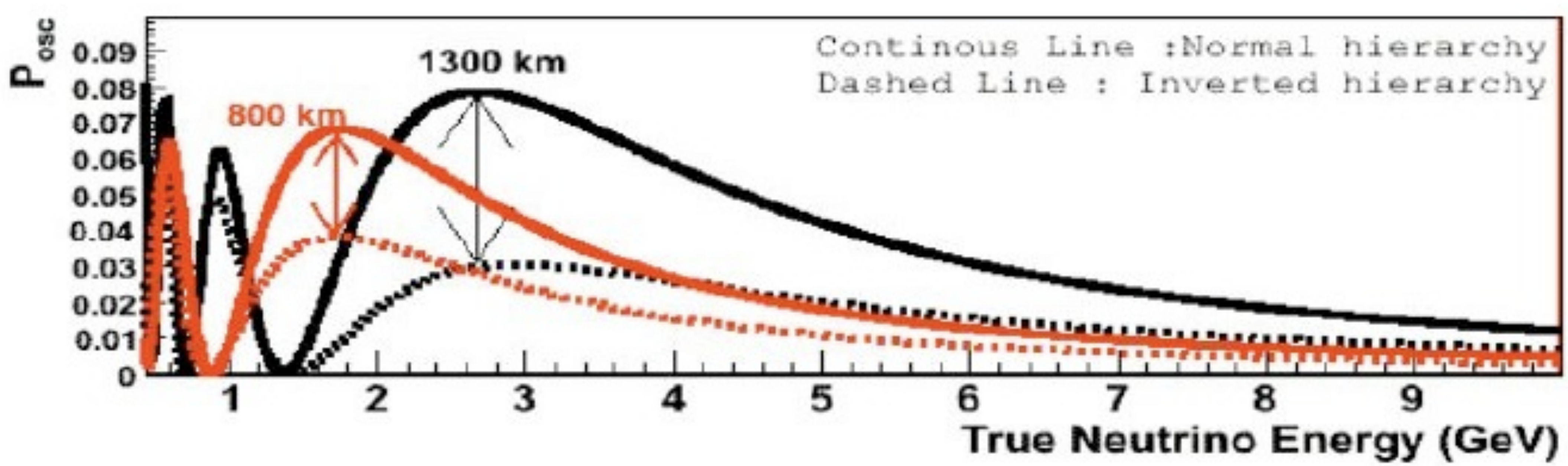
- The oscillation probability can be obtained as in the two neutrino mixing case but with

$$P(\nu_e \to \nu_\mu; t) = \sin^2(2\theta_m)\sin^2\frac{(E_A - E_B)L}{2}$$

- If $\sqrt{2}G_F N_e \gg \frac{\Delta m^2}{2E}\cos(2\theta)$, matter effects dominate and oscillations are suppressed.

- If $\sqrt{2}G_F N_e = \frac{\Delta m^2}{2E}\cos 2\theta$: resonance $\theta_m = \pi/4$

- The resonance condition can be satisfied for
  - neutrinos if $\Delta m^2 > 0$
  - antineutrinos if $\Delta m^2 < 0$



The mass hierarchy can be determined in long baseline neutrino experiments. In this case the constant matter density approximation holds.

See M. Messier's, T. Patzak's, M. Yokoyama's talks

- Superbeams: T2K, NOvA, LBNE, SPL, LAGUNA. Use very intense muon neutrino beams from pion decay and search for electron neutrino appearance. The ones which use intermediate baselines will be affected significantly if the ordering is not known.

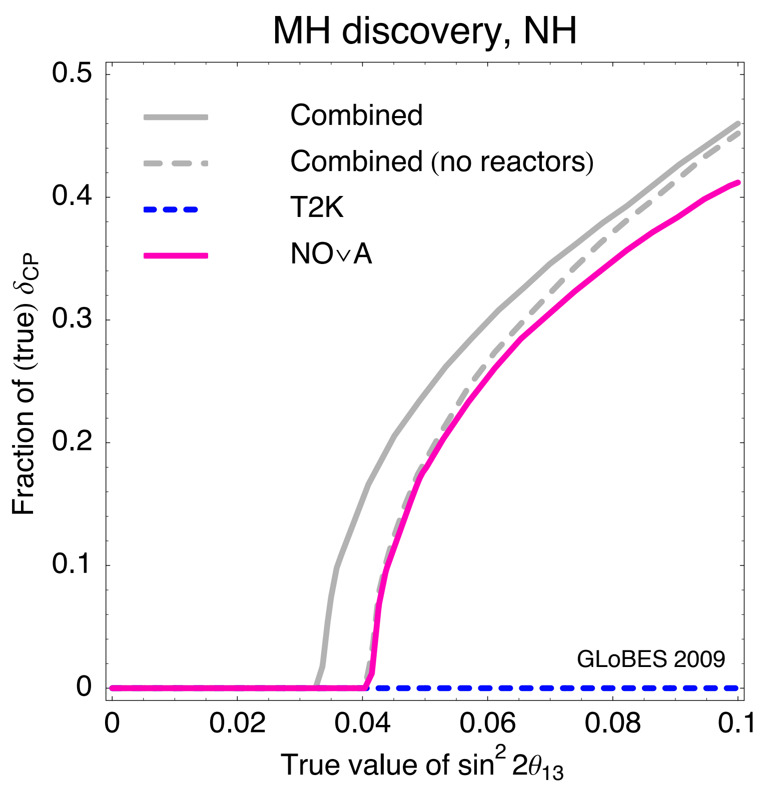
Medium term

- Neutrino factory: Use muon and electron neutrinos from high-gamma muon decays and needa magnetised detector. It would be able to determine the mass ordering very rapidly.

Long term

T2K and NOvA have poor sensitivity to MH and CPV.

T2K and NOvA



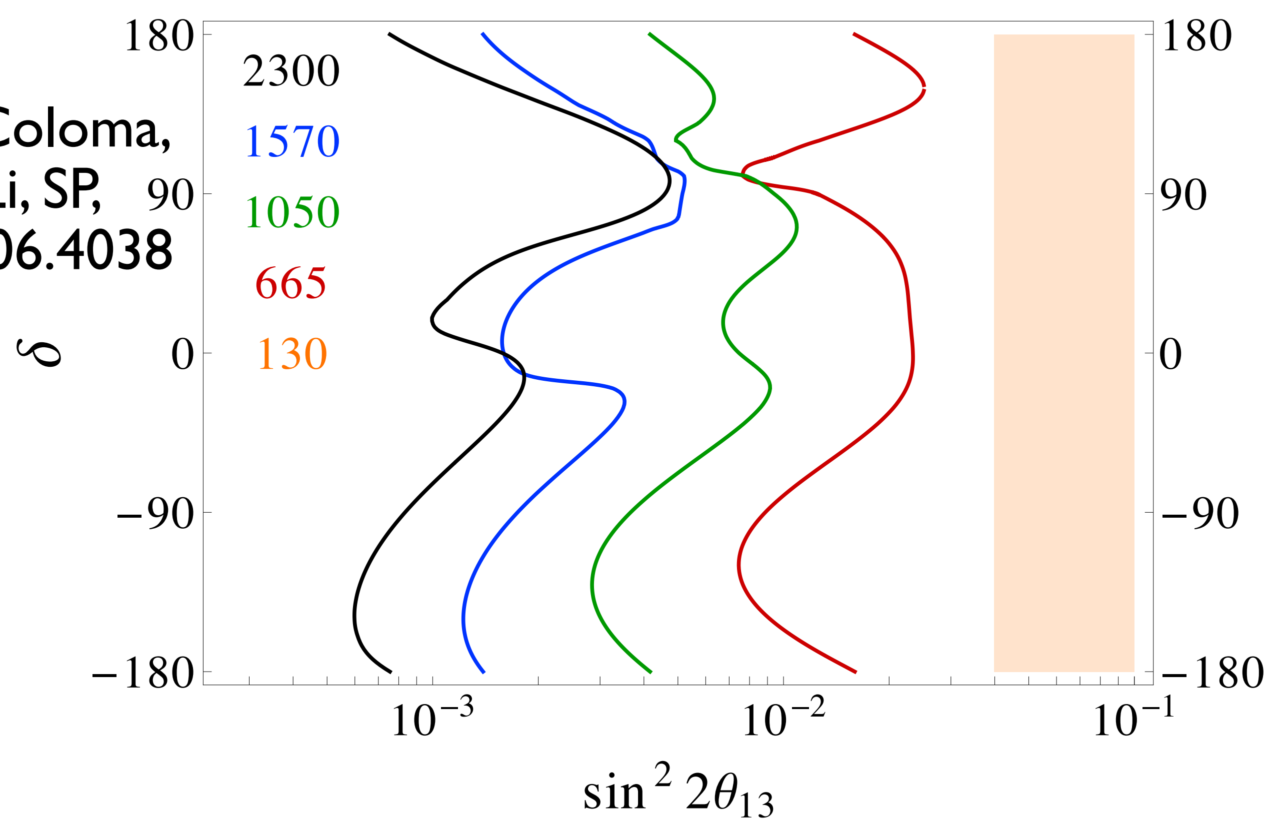
90% CL reach for T2K (0.75 MW 5 yrs), NOvA (0.7 MW, 3 yrs, nu+nubar, 15 kton detector)
Huber at al., 2009

Matter effects are used by LBL experiments to determine the mass ordering.

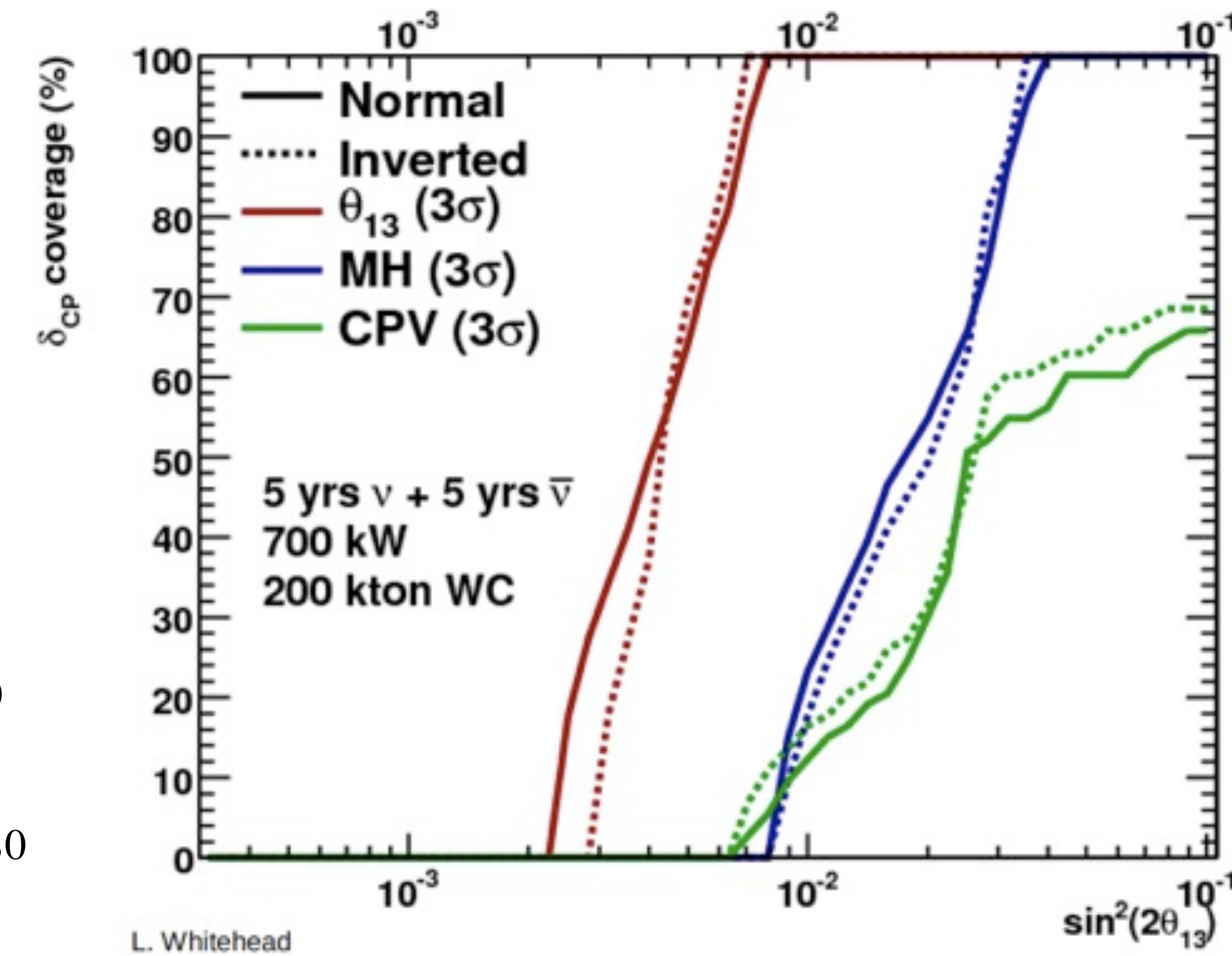
See M. Messier's, M. Yokoyama's, T. Patzak's talks

LBNO

P. Coloma, T. Li, SP, 1206.4038

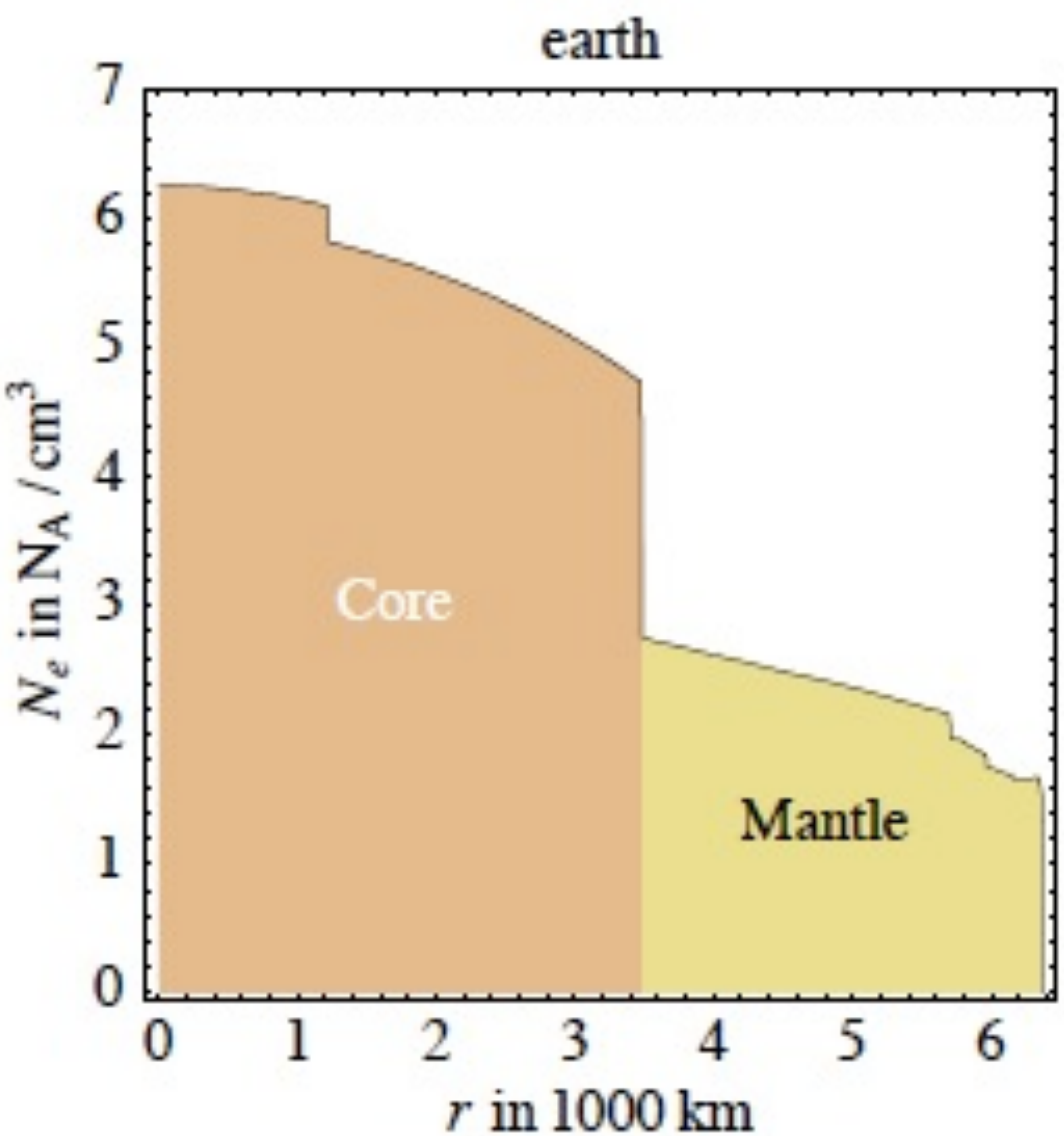


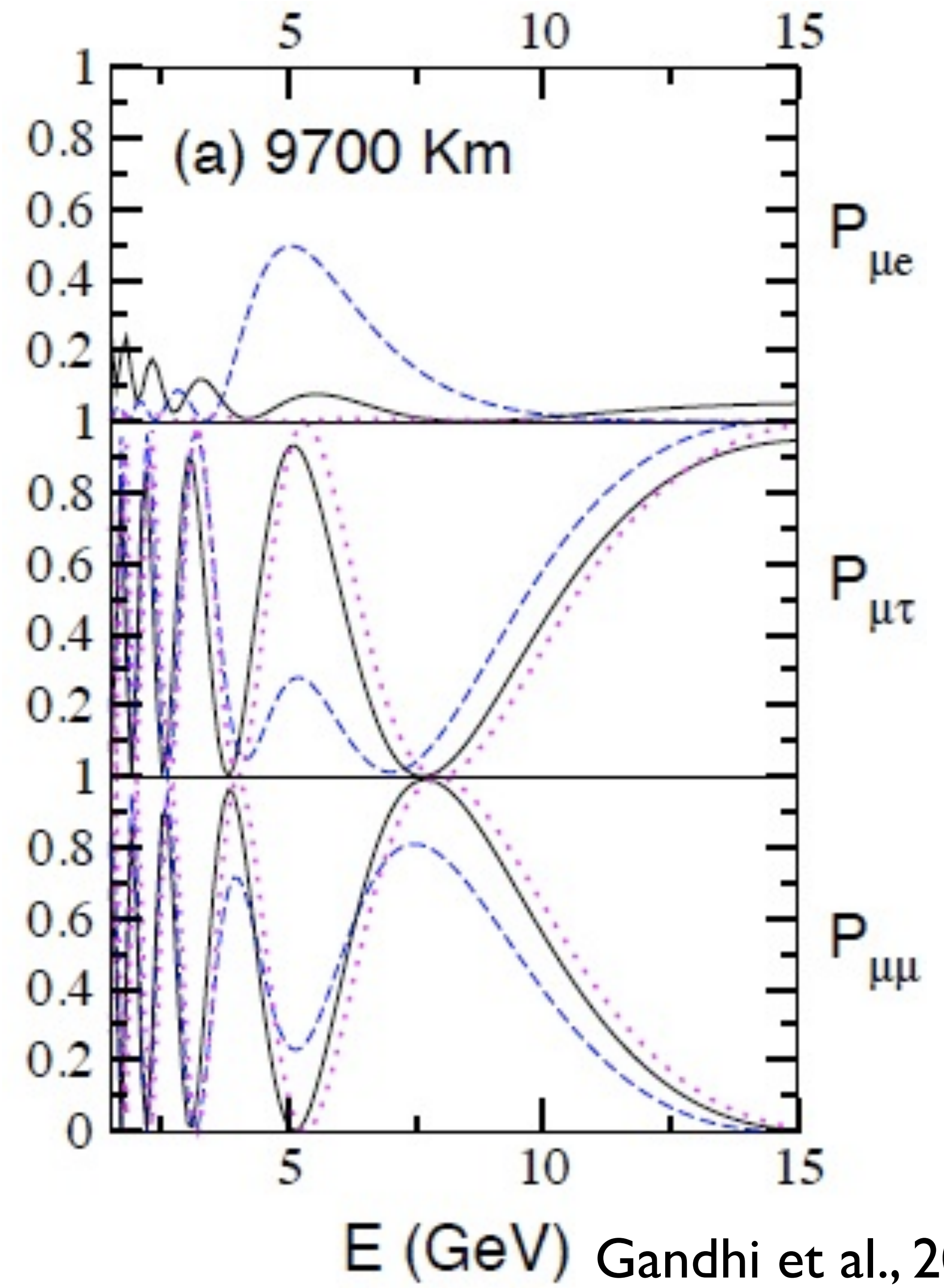
LBNE



2-neutrino oscillations with varying density

Let's consider the case in which the density profile is more complex. This happens, e.g., for atmospheric nus.



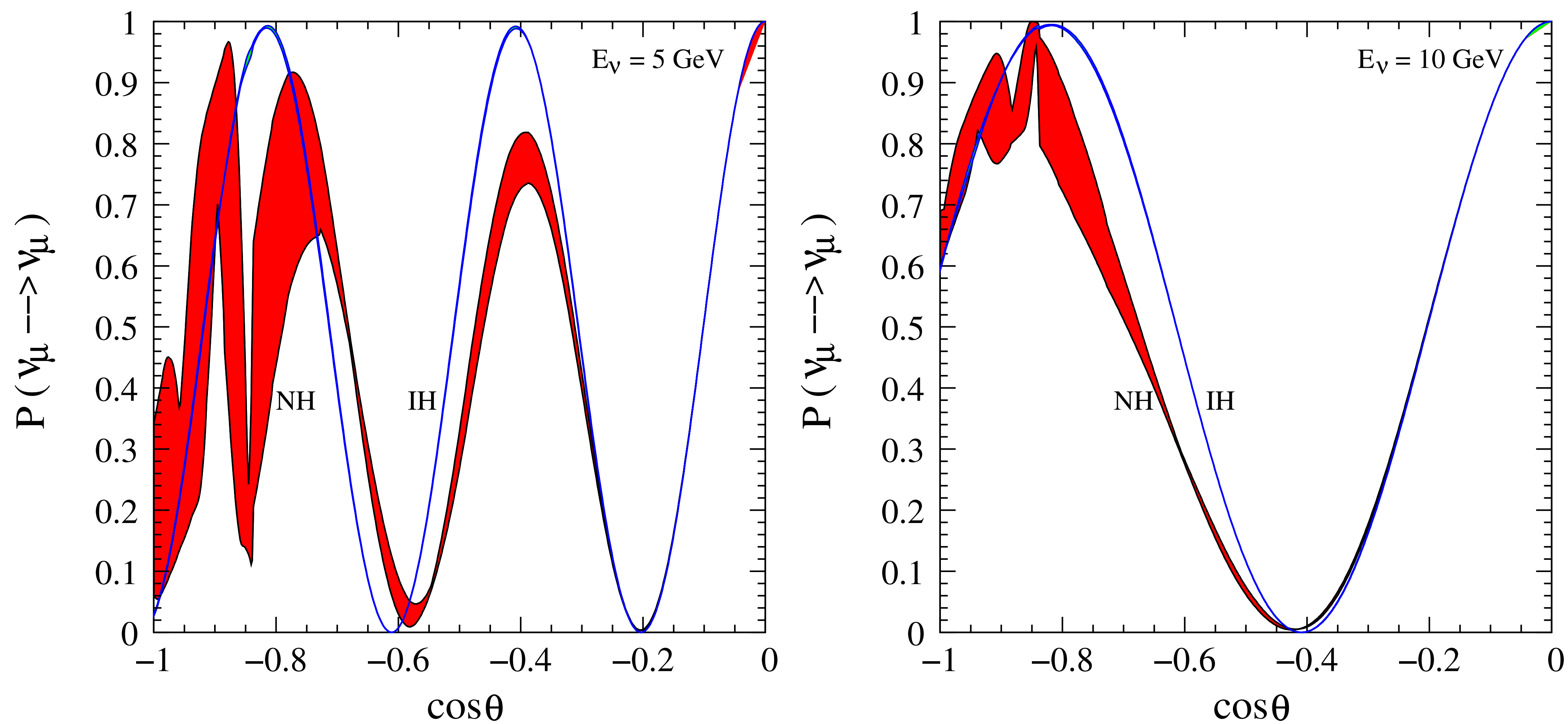


Gandhi et al., 2004

For large theta13 and subdominant 1-2 oscillations

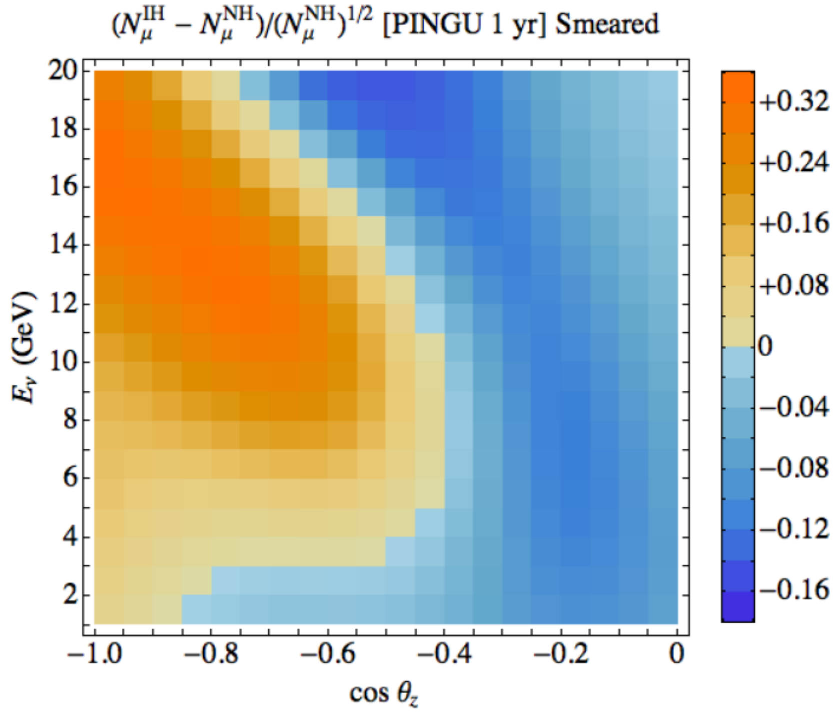
$$
\begin{aligned}
P_{3\nu}(\nu_e \to \nu_e) &\simeq 1 - P_{2\nu}\,, \\
P_{3\nu}(\nu_e \to \nu_\mu) &\simeq P_{3\nu}(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\,P_{2\nu}\,, \\
P_{3\nu}(\nu_e \to \nu_\tau) &\simeq \cos^2\theta_{23}\,P_{2\nu}\,, \\
P_{3\nu}(\nu_\mu \to \nu_\mu) &\simeq 1 - \frac{1}{2}\sin^2 2\theta_{23} - \sin^4\theta_{23}\,P_{2\nu} + \frac{1}{2}\sin^2 2\theta_{23}\,Re\,\left(e^{-i\kappa}A_{2\nu}(\nu_\tau \to \nu_\tau)\right) \\
P_{3\nu}(\nu_\mu \to \nu_\tau) &= 1 - P_{3\nu}(\nu_\mu \to \nu_\mu) - P_{3\nu}(\nu_\mu \to \nu_e)
\end{aligned}
$$

Agarwalla et al., 1212.2238. See Petcov, 98; Akhmedov, 98; Chizhov et al., 98, 98 and 99;

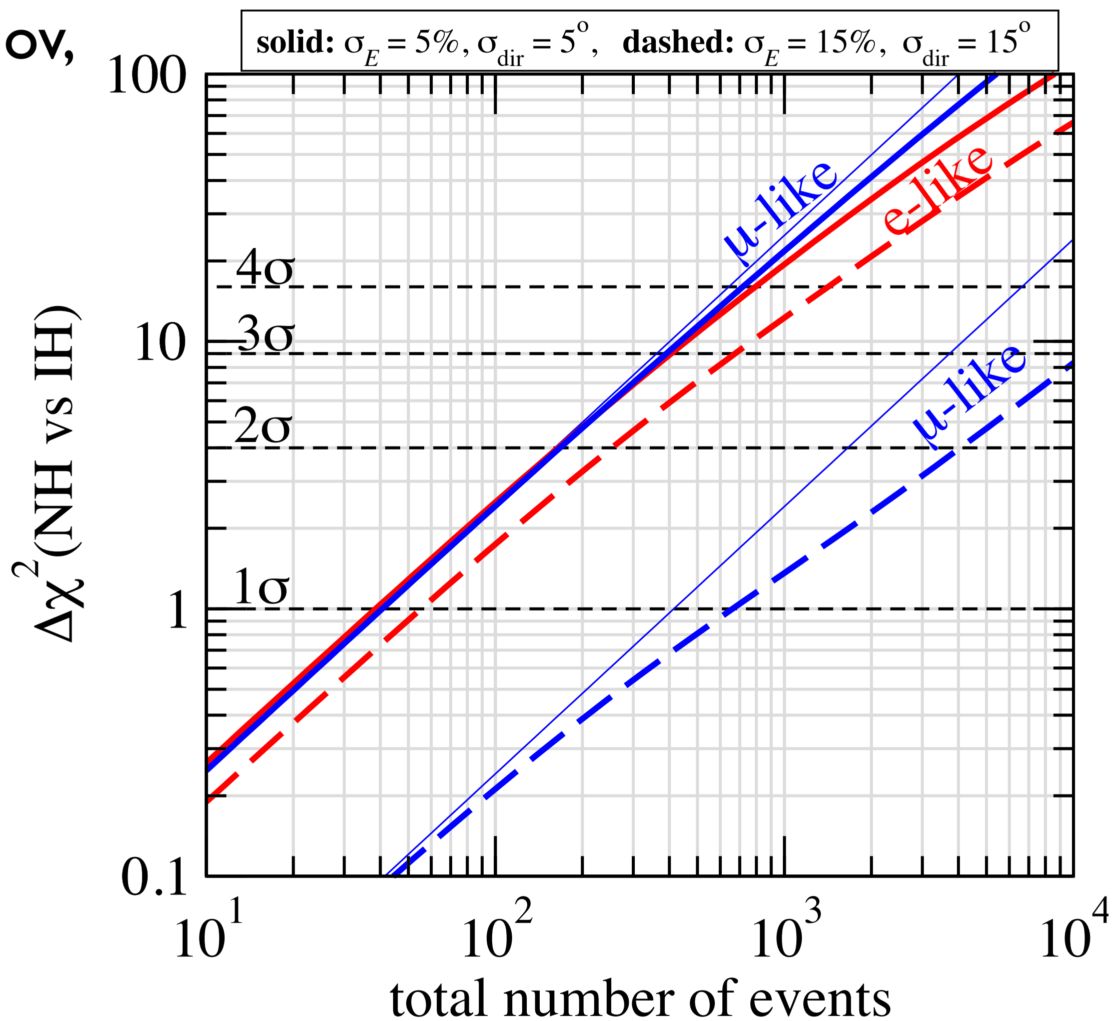


Atmospheric neutrino oscillations can determine the mass ordering, with large number of events, good energy and angular resolution.

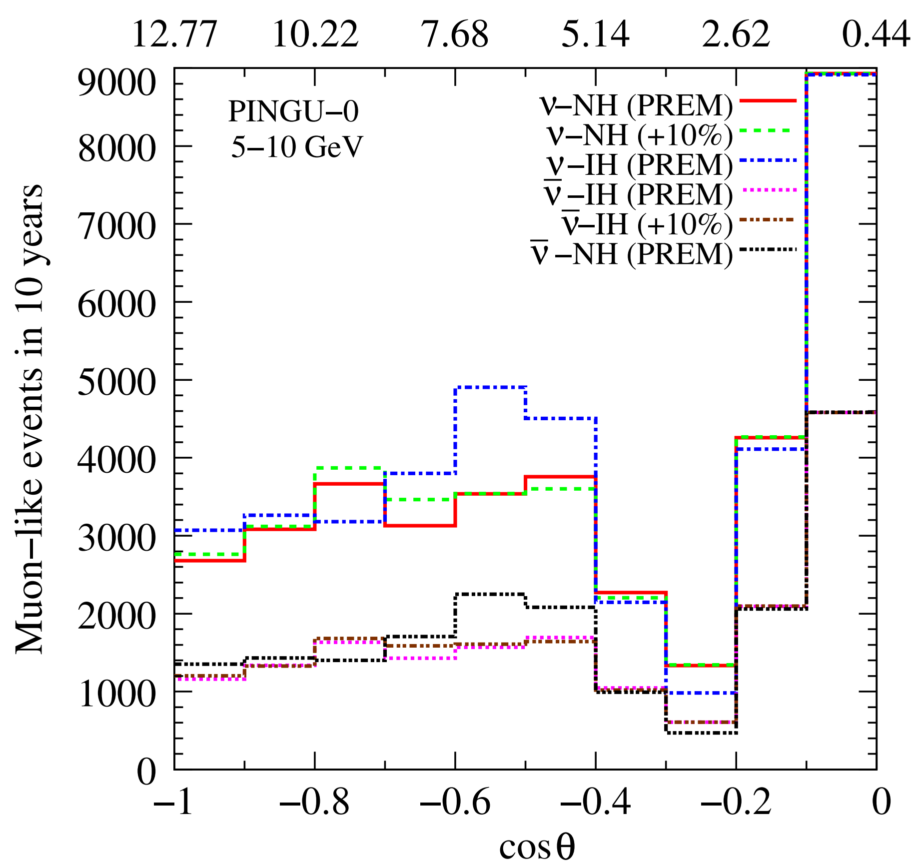
Petcov et al.; Chizov et al.; Akhmedov, Smirnov et al.; Gandhi et al.; Mena et al.; Schwetz et al.; Koskinen; Gonzalez-Garcia et al.; Barger et al



Akhmedov, Razzaque, Smirnov, 1205.8071



Petcov, Schwetz, hep-ph/0511277



Agarwalla et al., 1212.2238

PINGU in IceCube, ORCA in KM3Net

See M. Yokoyama's and C. Spiering's talk. Also for MH: C. Yang's talk.

CPV effects

CP-violation will manifest itself in neutrino oscillations, due to the delta phase. The CP-asymmetry:

$$P(\nu_\mu \to \nu_e; t) - P(\bar{\nu}_\mu \to \bar{\nu}_e; t) =$$

$$= 4 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \left[\sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{23}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \right]$$

- CP-violation requires all angles to be nonzero.
- It is proportional to the sine of the delta phase.
- If one can neglect Δm_{21}^2, the asymmetry goes to zero as we have seen that effective 2-neutrino probabilities are CP-symmetric.

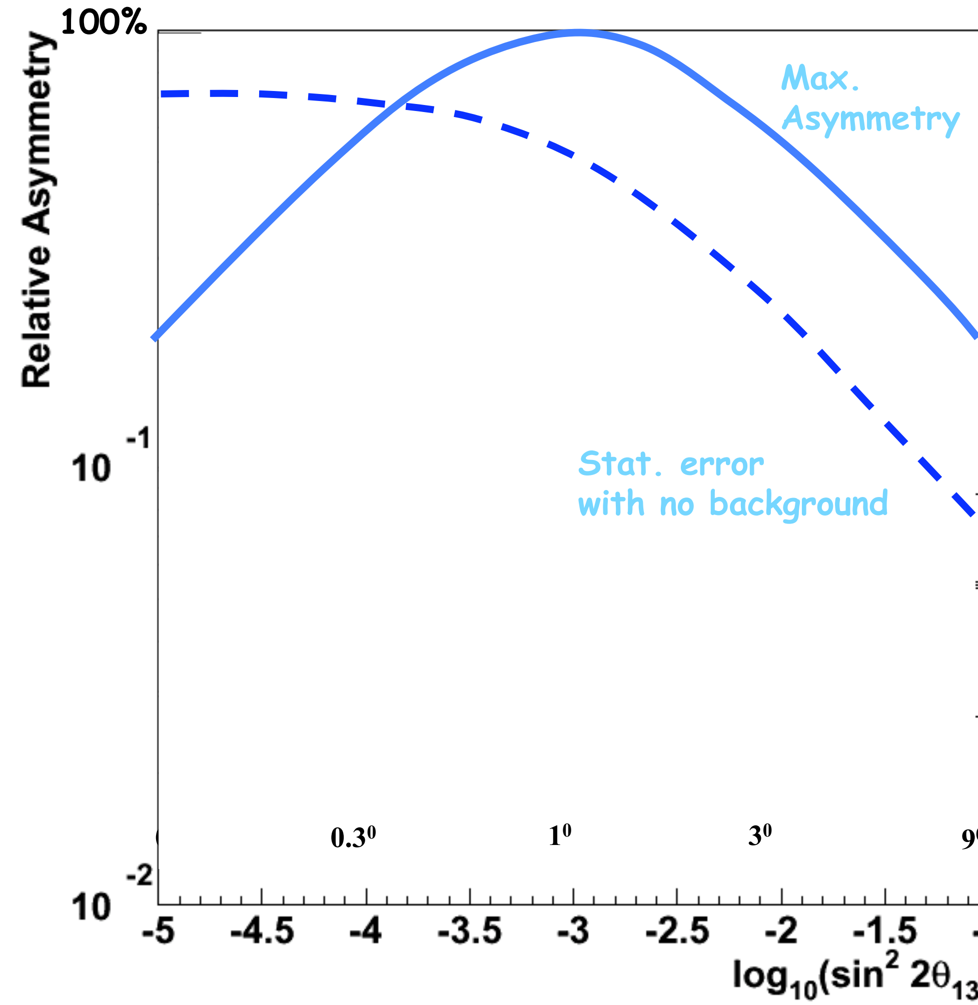
CPV needs to be searched for in long baseline neutrino experiments which have access to 3-neutrino oscillations.

$$P(\bar{P}) \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A\mp\Delta_{13}}\right)^2 \sin^2 \frac{(A\mp\Delta_{13})L}{2} + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{A\mp\Delta_{13}} \sin\frac{AL}{2} \sin\frac{(A\mp\Delta_{13})L}{2} \cos\left(\mp\delta + \frac{\Delta_{13}L}{2}\right) + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

CP-violation

Matter effects

The CP asymmetry peaks for sin^2 2 theta13 ~0.001. Large theta13 makes its searches possible but not ideal.



A. Blondel

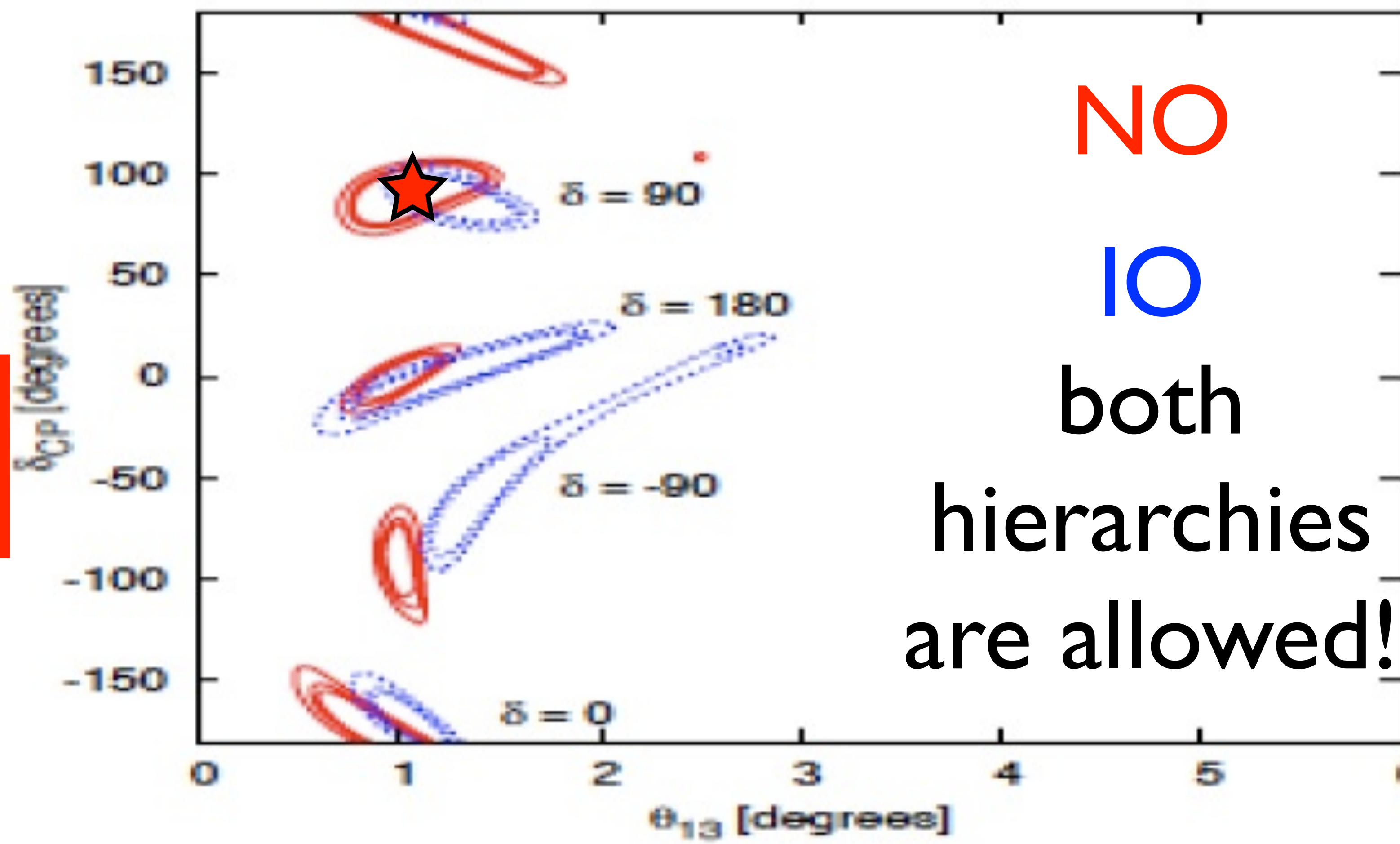
Degeneracies

The determination of CPV and the mass ordering is complicated by the issue of **degeneracies**: different sets of parameters which provide an equally good fit to the data (eight-fold degeneracies).

$$\theta_{13}, \delta, \mathrm{sgn}(\Delta m^2_{31}), \theta_{23}$$

$$P(L/E) \quad \text{and} \quad \bar{P}(L/E)$$

$$\theta'_{13}, \delta', \mathrm{sgn}'(\Delta m^2_{31}), \theta'_{23}$$



both hierarchies are allowed!

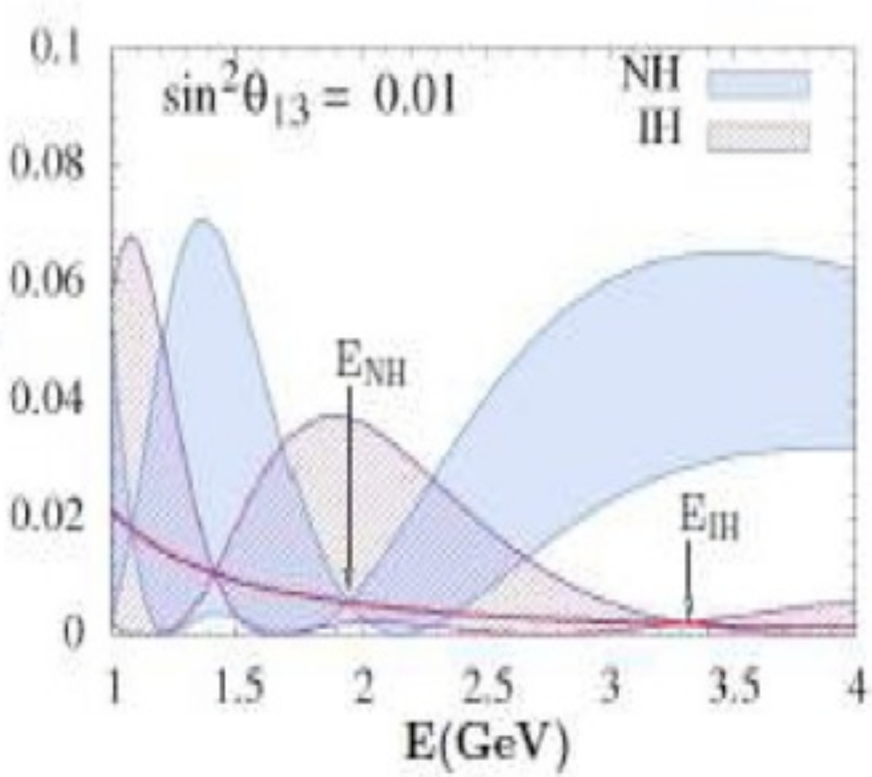
- (θ_{13}, δ) degeneracy (Koike, Ota, Sato; Burguet-Castell et al.)

$$\begin{aligned} \delta' &= \pi - \delta \\ \theta'_{13} &= \theta_{13} + \cos\delta \sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E} \cot\theta_{23} \cot \frac{\Delta m^2_{13} L}{4E} \end{aligned}$$

Having information at different L/E can resolve this.

- sign(Δm^2_{31}) vs CPV (matter effects). In vacuum:

$$\delta' \to \pi - \delta \qquad \text{sign}'(\Delta m^2_{13}) \to -\text{sign}(\Delta m^2_{13})$$

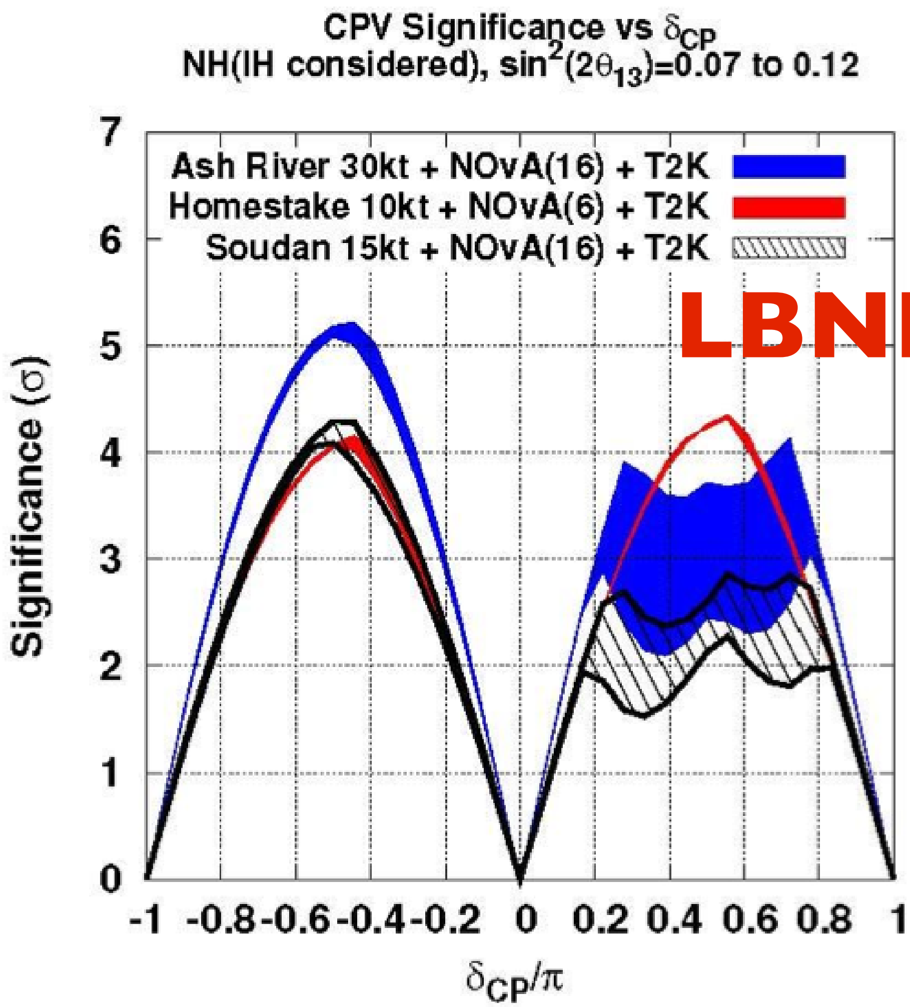


This degeneracy is broken by matter effects.

For ex. Bimagic baseline at L=2540 km
Excellent sensitivity to the hierarchy
A. Dighe et al., 1009.1093; Raut et al. 0908.3741; Joglekar et al. 1011.1146

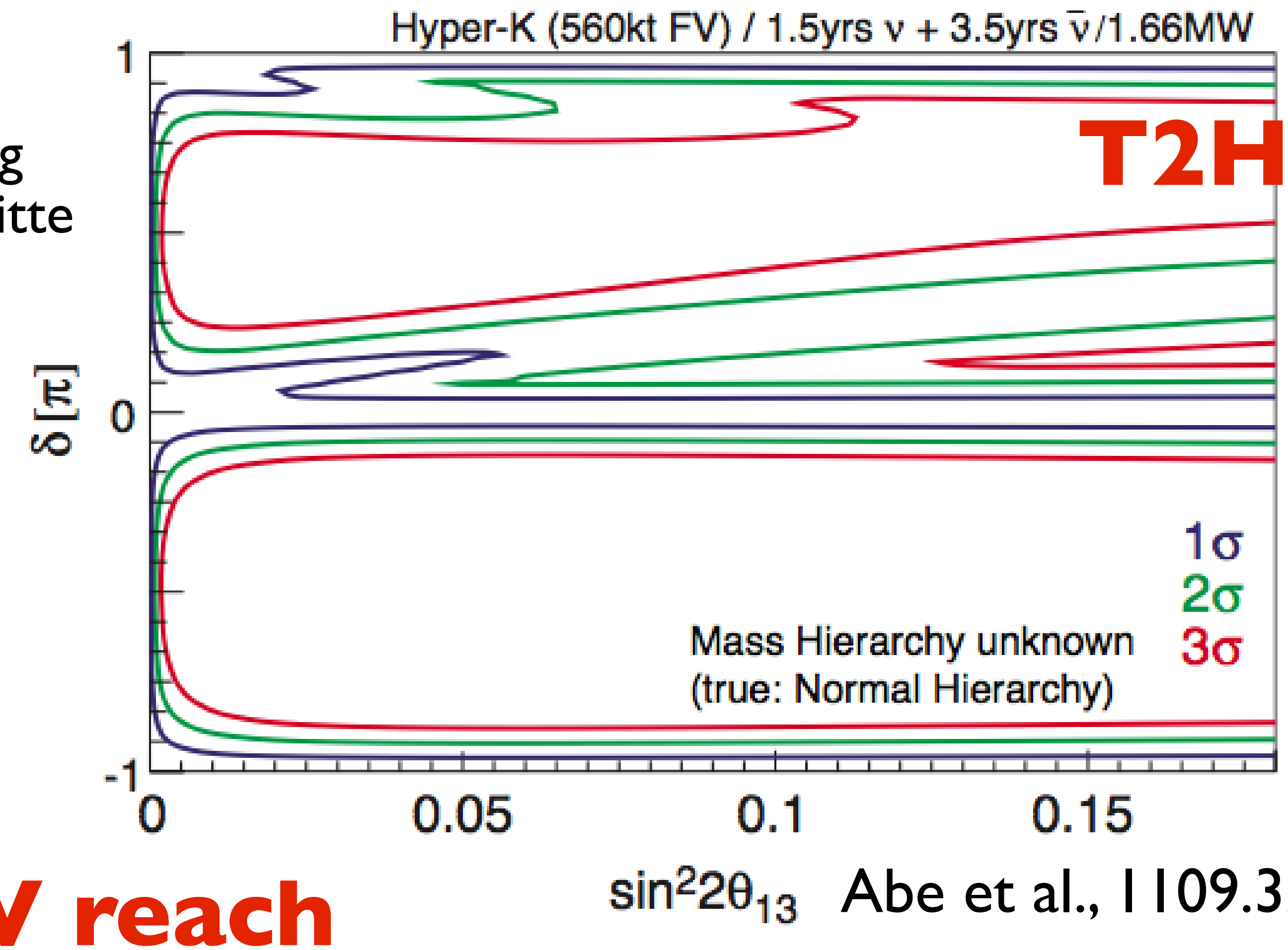
- the octant of θ_{23} (low E data) (Fogli, Lisi)

CPV reach



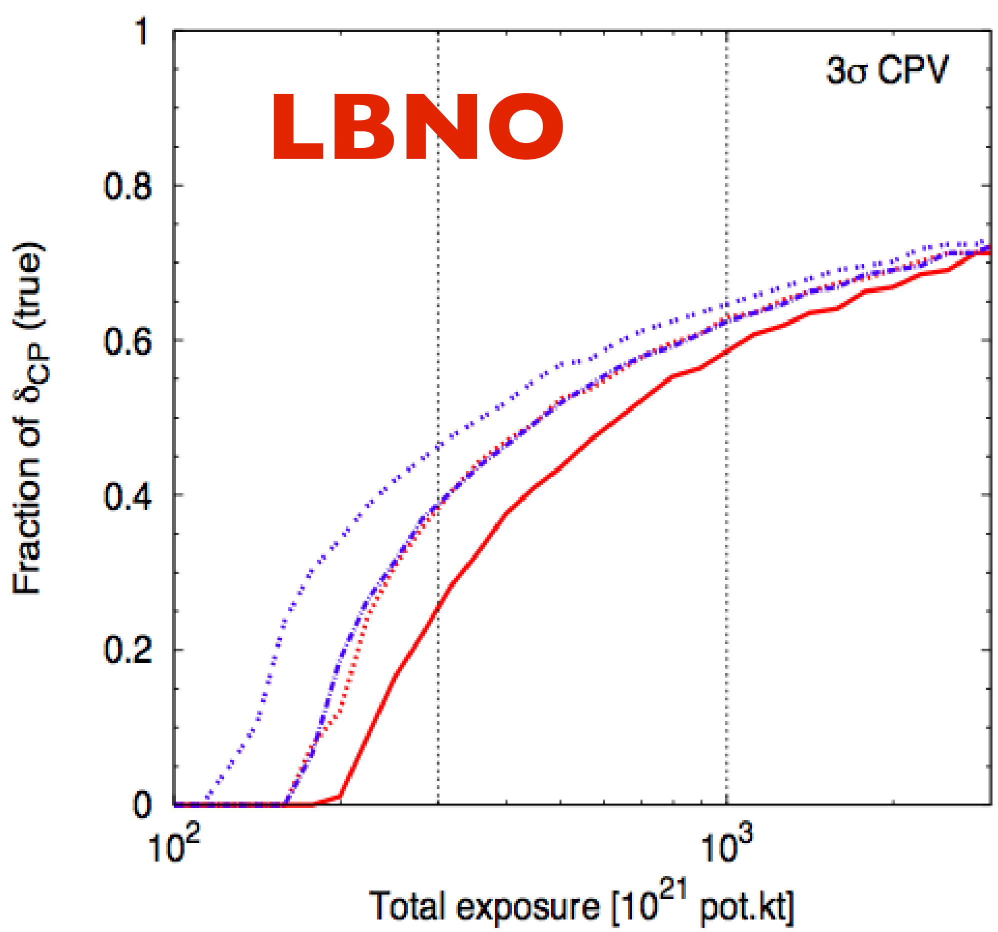
LBNE Steering Committe

T2HK

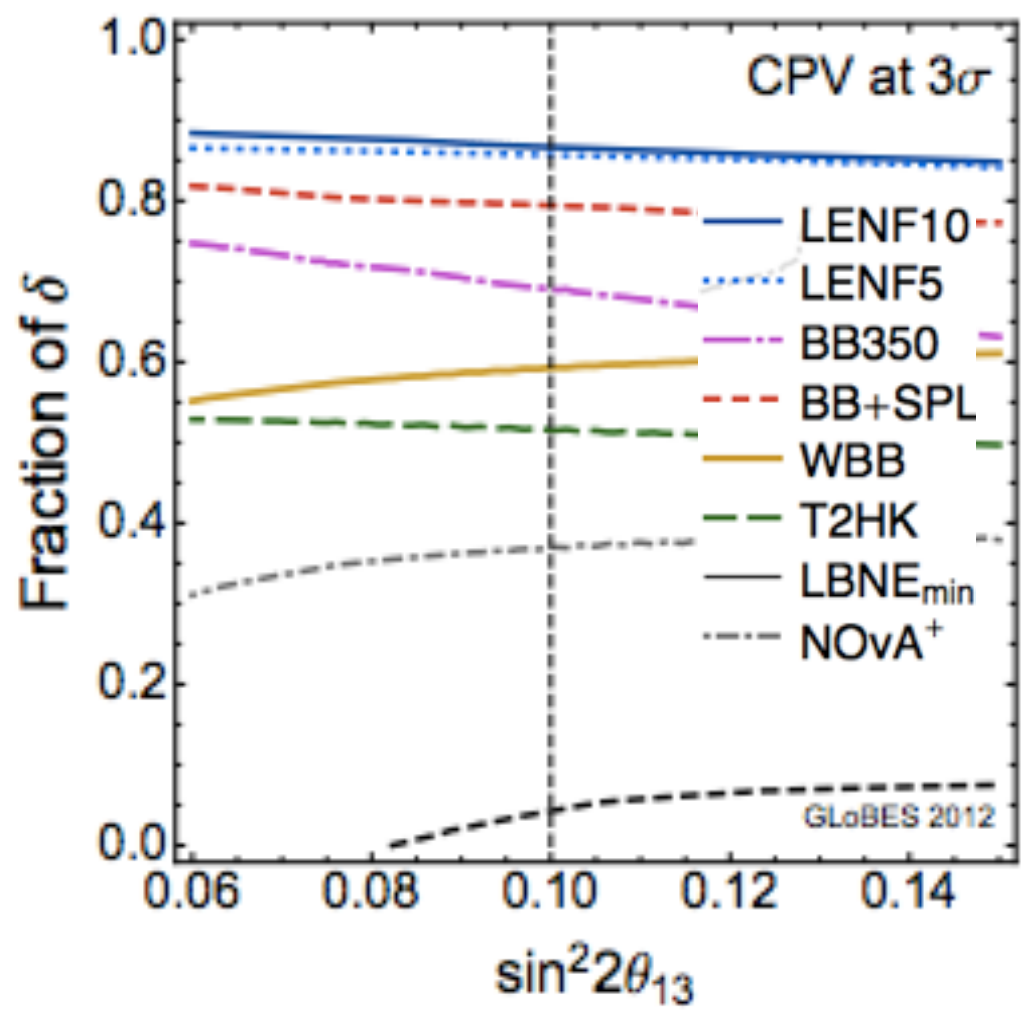


Abe et al., 1109.3262.

LBNO

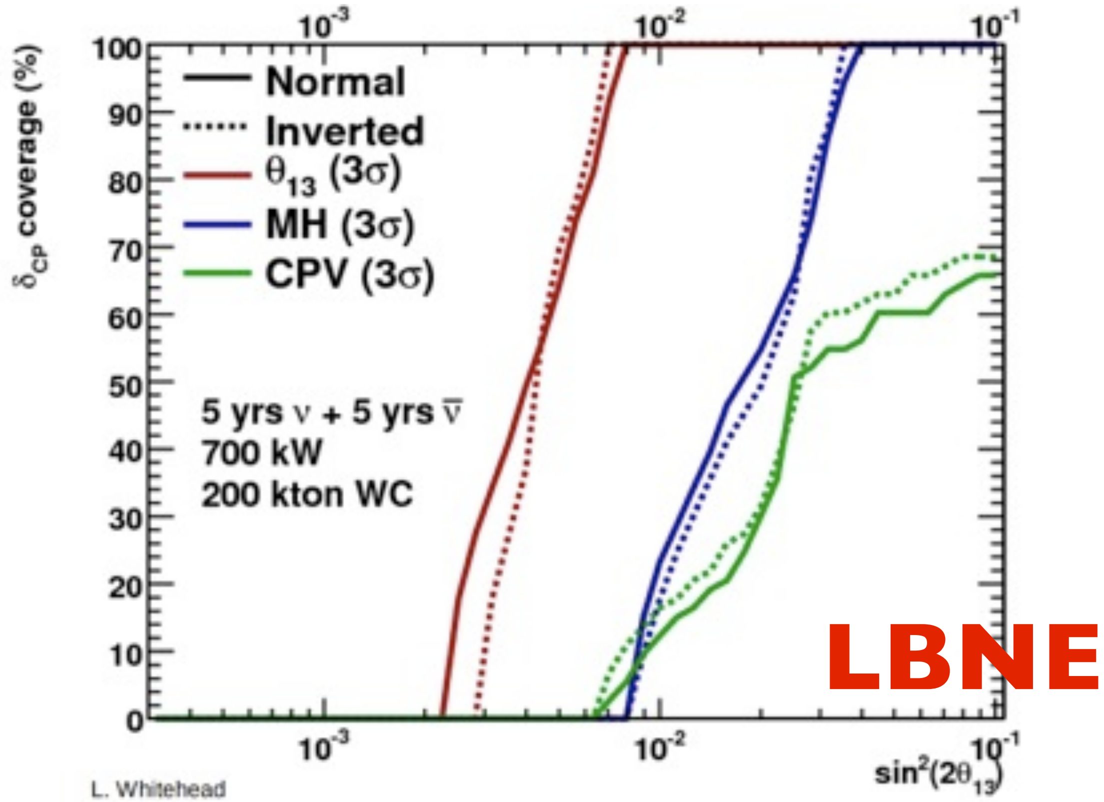


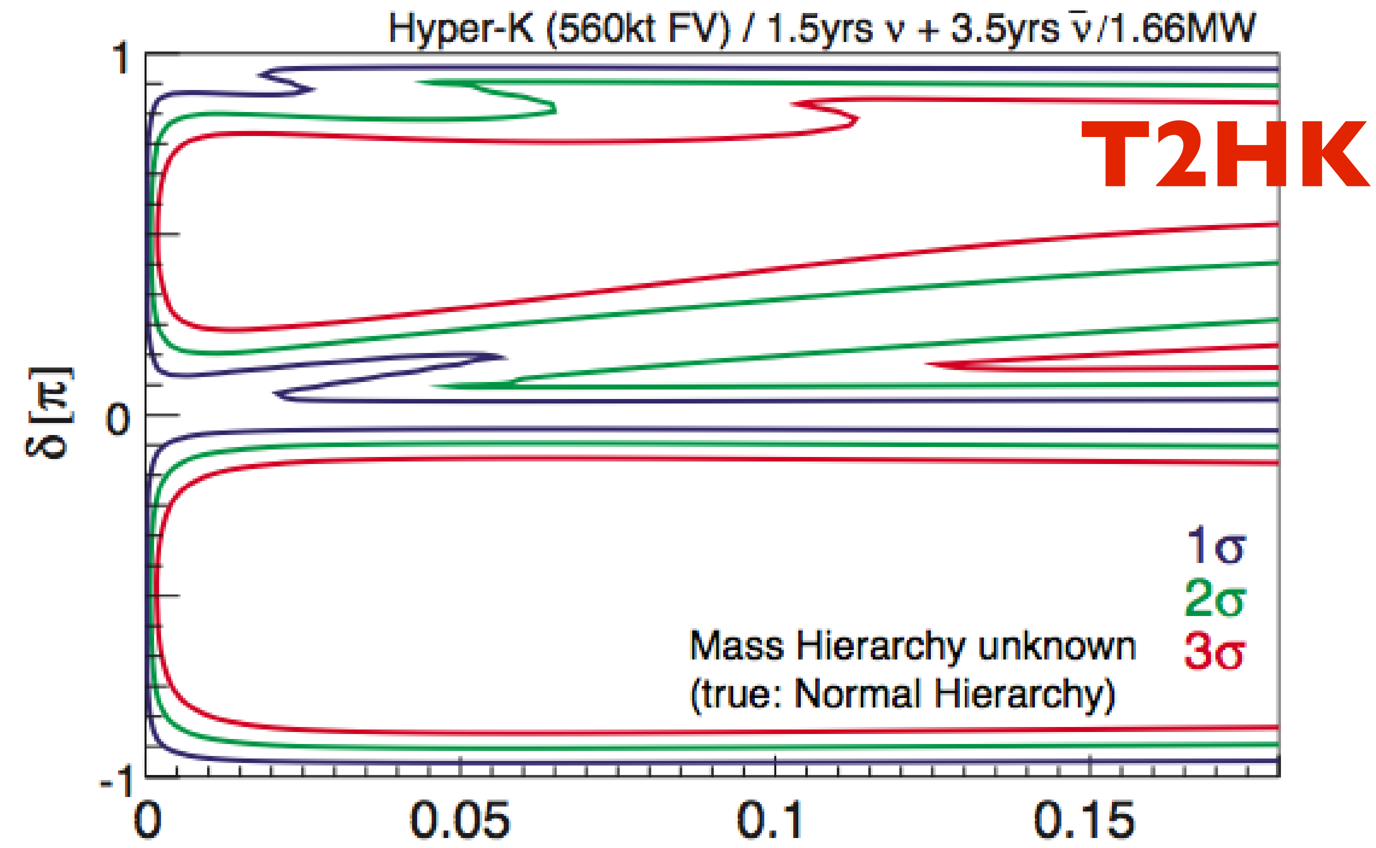
Agarwalla, Li, Rubbia, 1109.6526



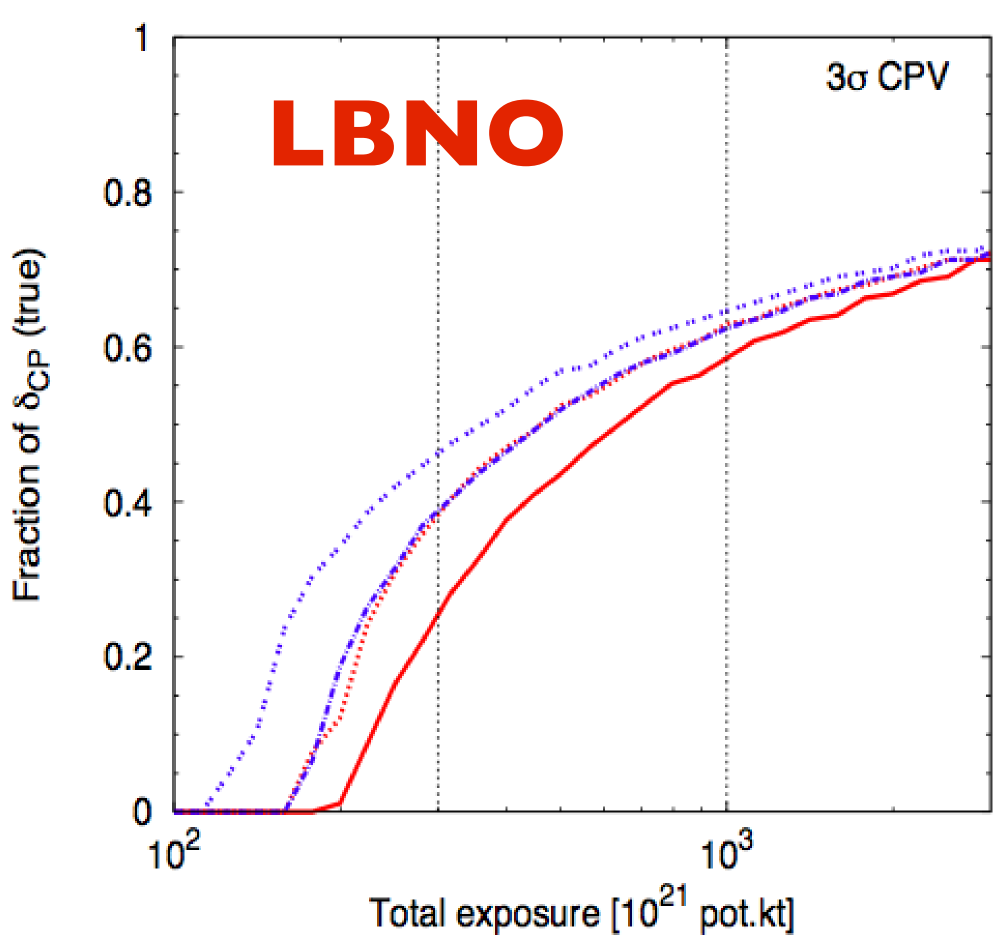
Coloma, Huber, Kopp, Winter, 1209.5973

CPV reach





Abe et al., 1109.3262.



Agarwalla, Li, Rubbia, 1109.6526

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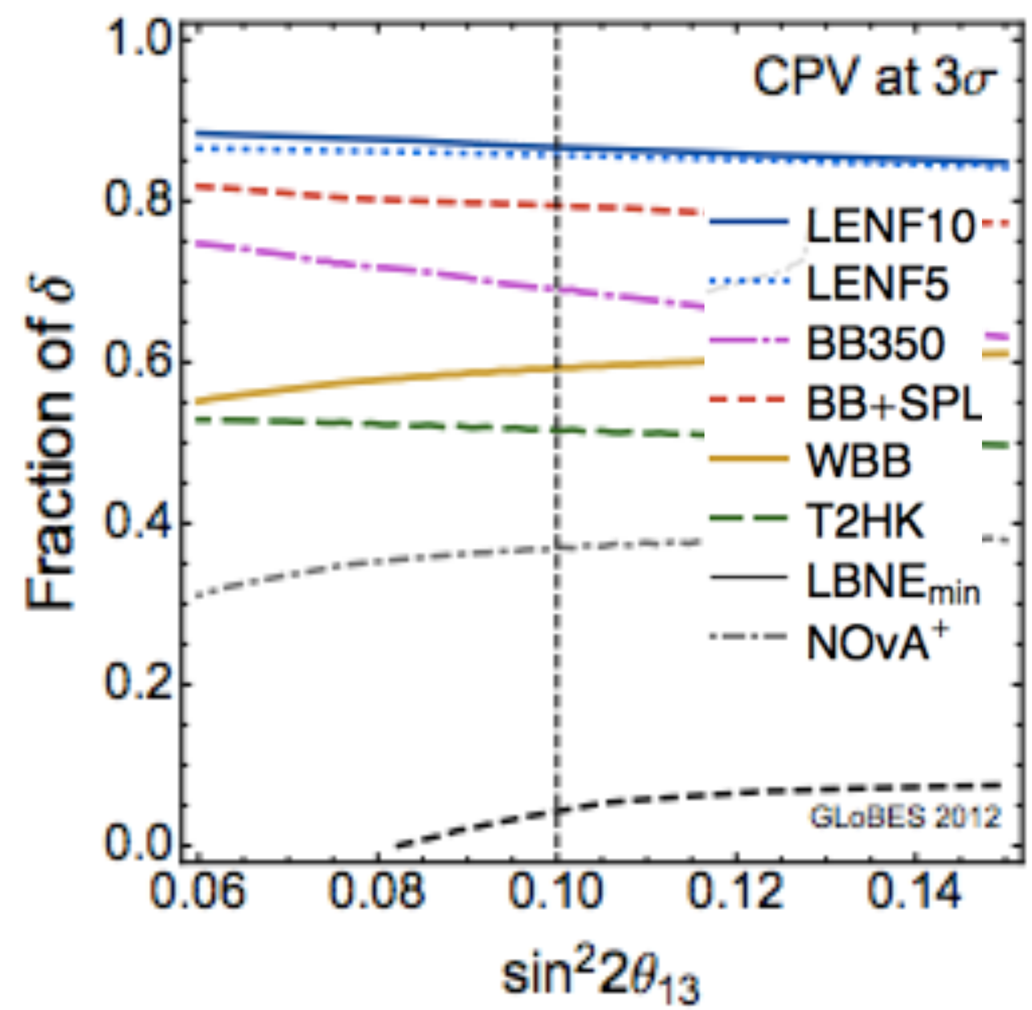
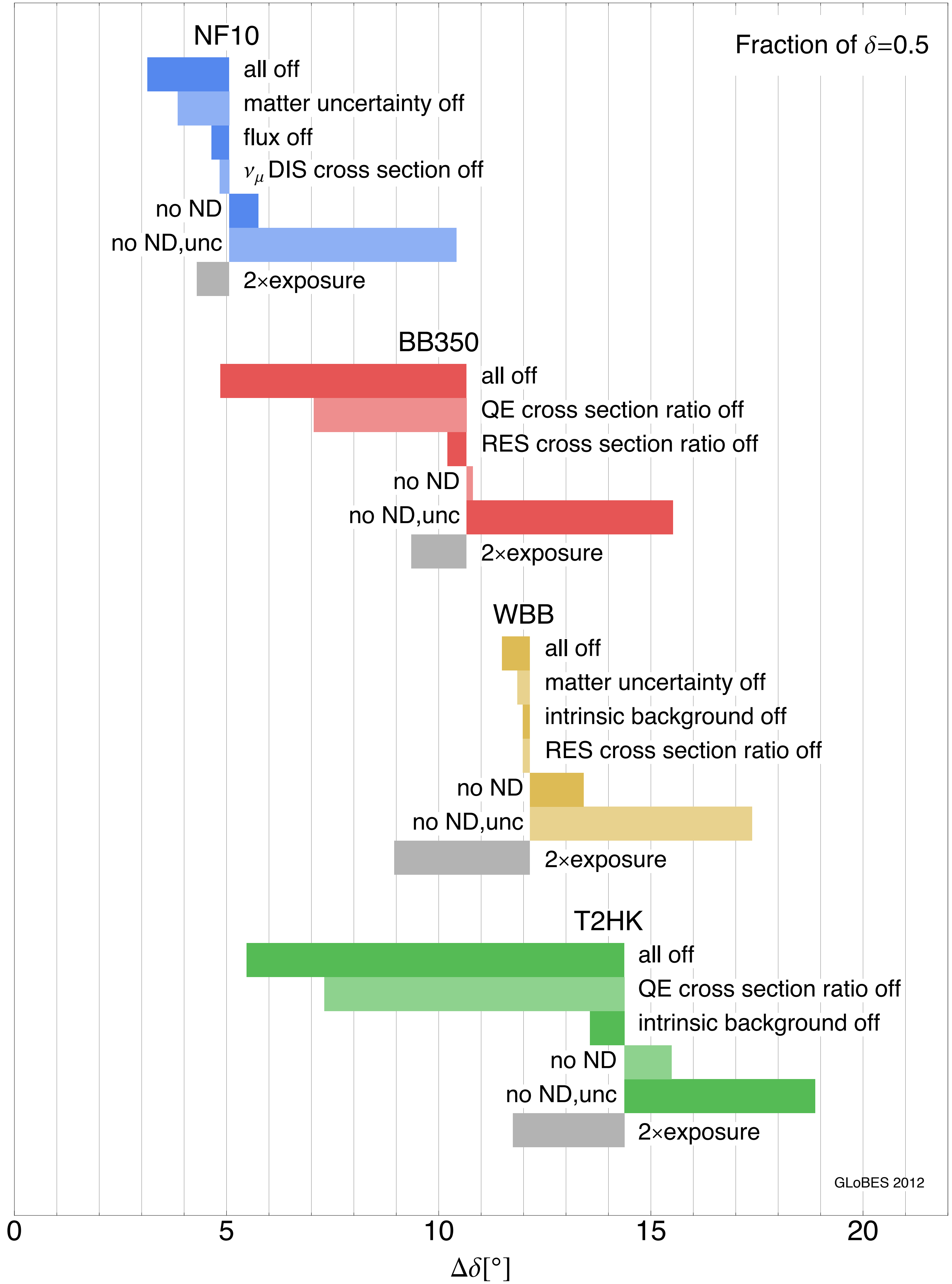




Good energy resolution, wide band beam, additional input will help in reducing the impact of systematic errors. The near detector(s) will play an important role.

Comparison between facilities needs to be done with care.

Coloma, Huber, Kopp, Winter, 1209.5973

Precision measurements of oscillation parameters

The precision measurement of the oscillation parameters will become very important once the mass hierarchy and CPV are established. LBL experiments can give information on $\theta_{23},\ \theta_{13},\ \delta$.

The expected precision on theta13 can be related to

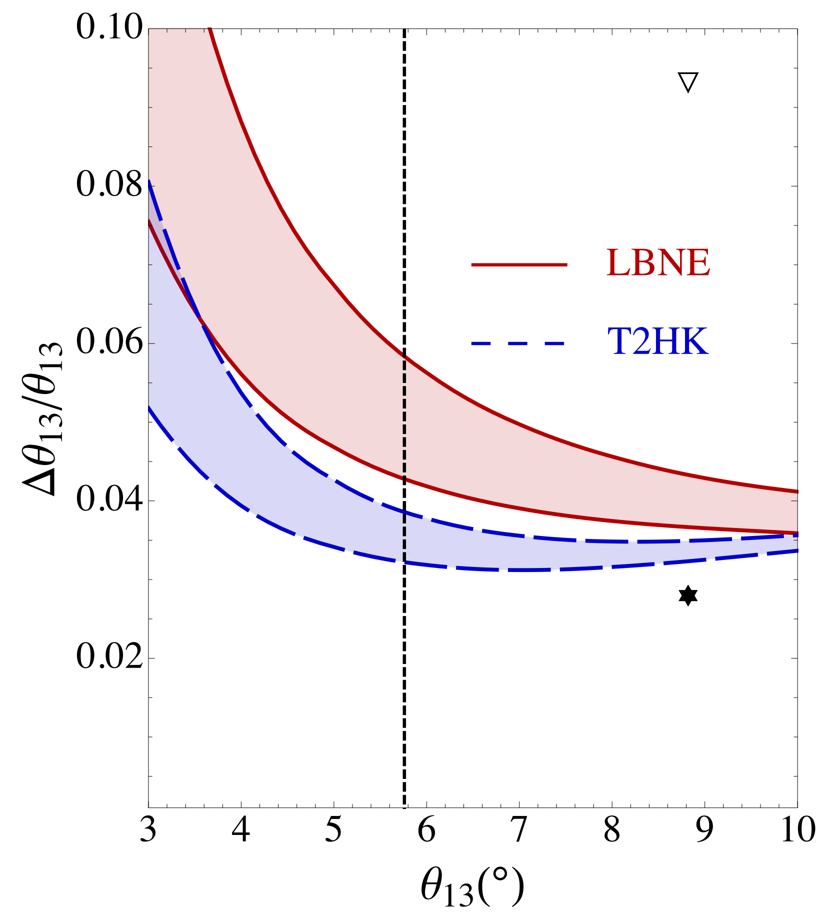
$$N_{\text{events}} \sim P_{\mu e} \sim \sin^2 2\theta_{13} \sim (\theta_{13})^2 \Rightarrow \Delta N \sim \theta_{13}\Delta\theta_{13}$$

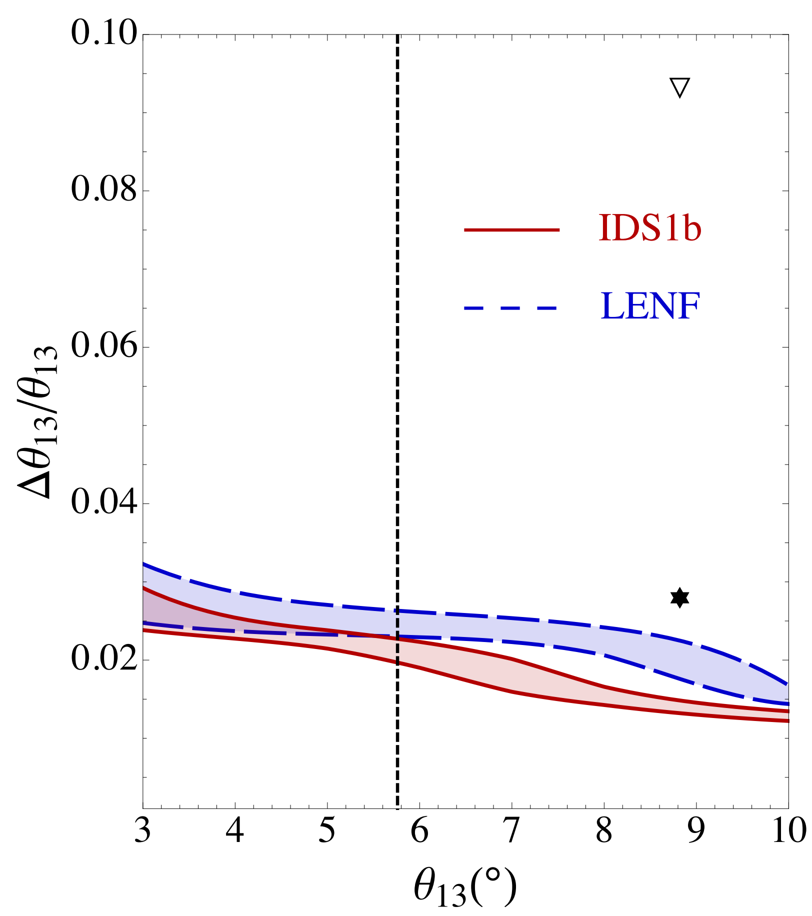
If the statistical error dominates: $\frac{\Delta\theta_{13}}{\theta_{13}} \sim \frac{1}{\theta_{13}}$

If the systematic error on the signal does: $\frac{\Delta\theta_{13}}{\theta_{13}} \sim \text{constant}$

If that on the background: $\frac{\Delta\theta_{13}}{\theta_{13}} \sim \frac{1}{\theta_{13}^2}$

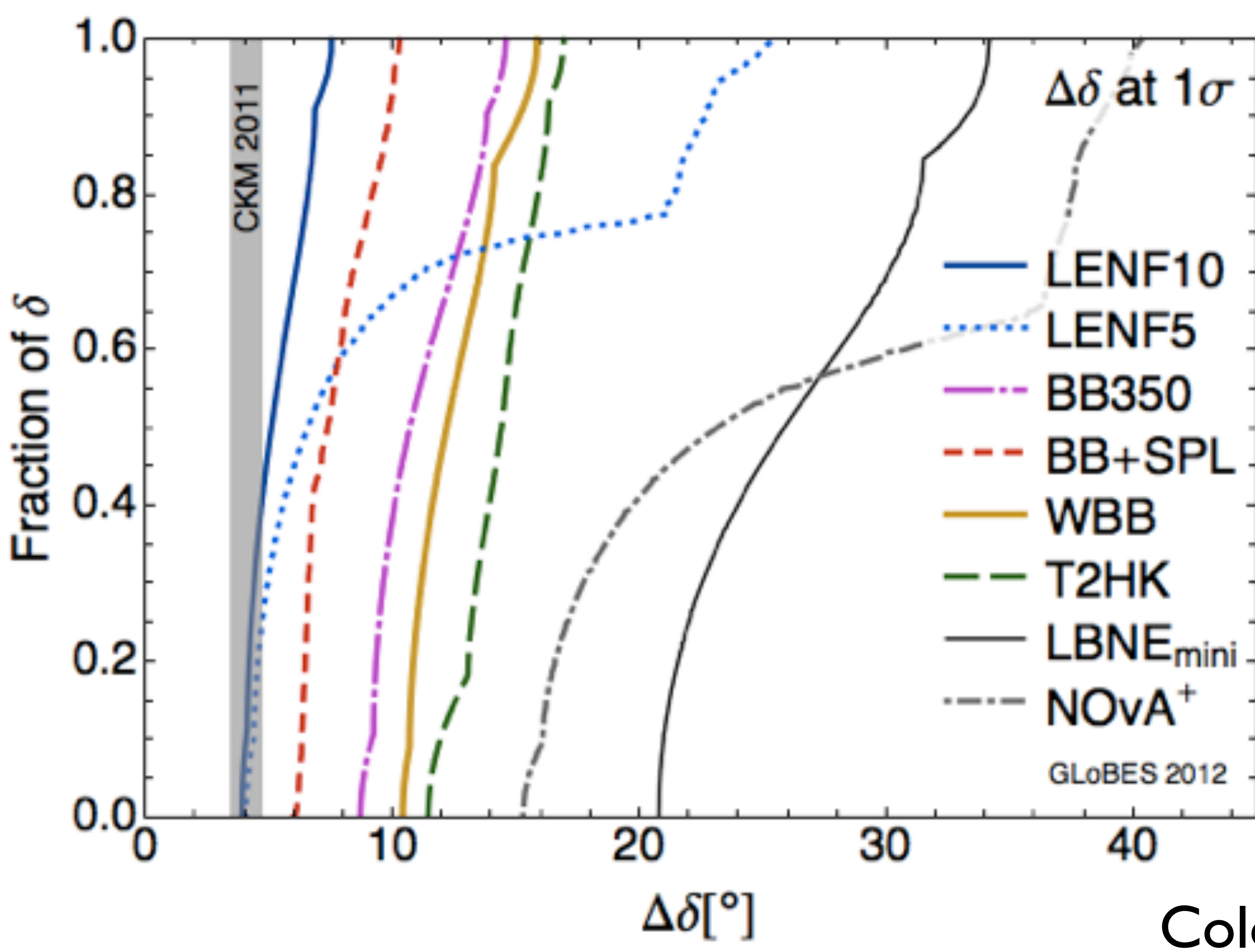
Coloma, Donini, Fernandez Martinez, Hernandez, 1203.5651





Coloma, Donini, Fernandez Martinez, Hernandez, 1203.5651

The best measurement of theta13 will be provided by Daya Bay, unaffected by degeneracies, and it could be marginally improved by LENF.



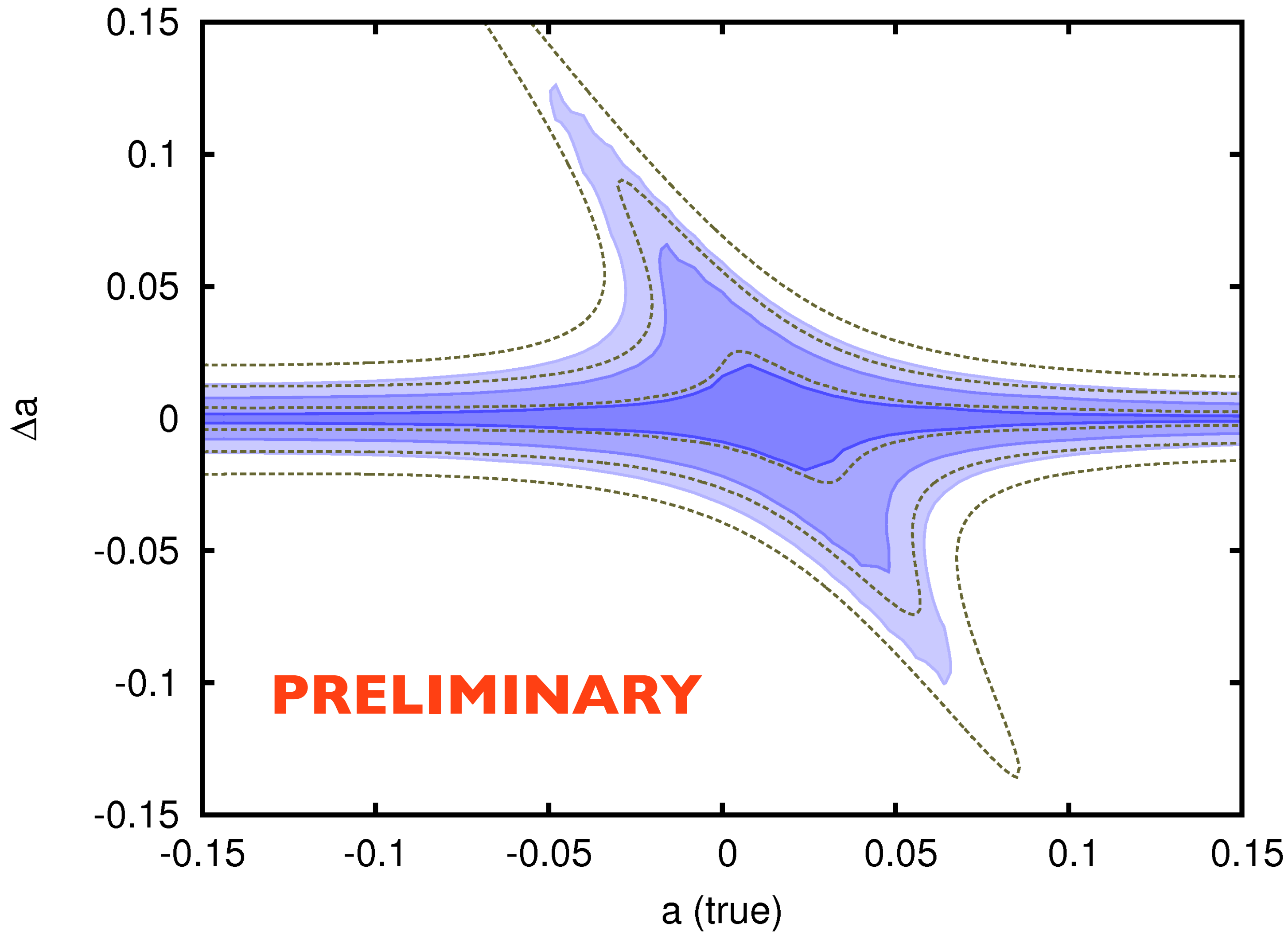
Coloma, Huber, Kopp, Winter, 1209.5973

In addition to delta, the study of sum rules and possible mixing patterns requires a precise measurement of the atmospheric and solar mixing angles.

Useful parameterisation:

King, 0710.0530

$$\sin\theta_{12} = \frac{1+s}{\sqrt{3}}, \quad \sin\theta_{13} = \frac{r}{\sqrt{2}}, \quad \sin\theta_{23} = \frac{1+a}{\sqrt{2}}$$



Current data:

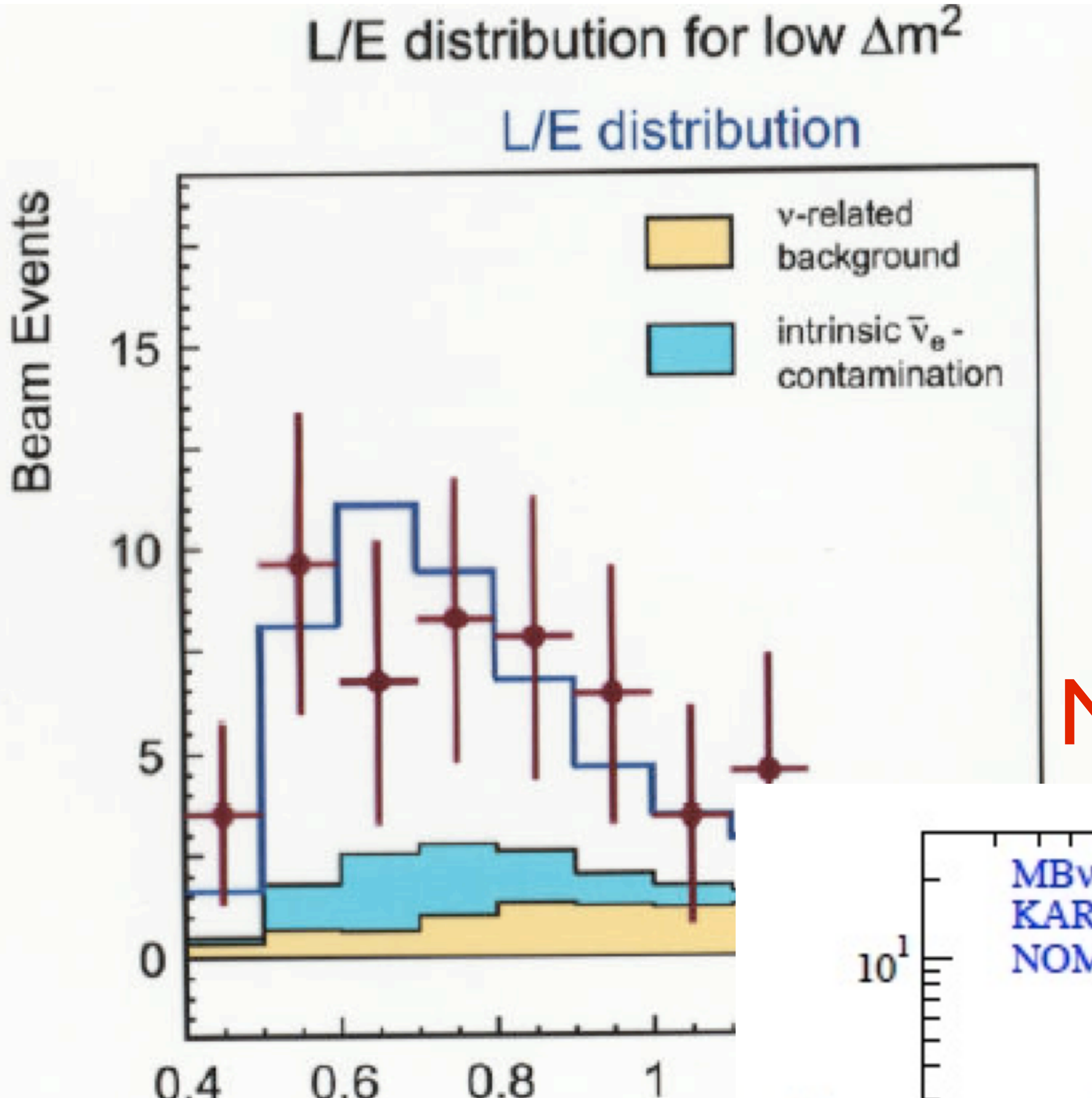
$$-0.07 \leq s \leq -0.01$$
$$0.21 \leq r \leq 0.23,$$
$$-0.15 \leq a \leq -0.07$$

Dashed: WBB

Blue: LENF

Ballett, King, Luhn, Pascoli, Schmidt, in prep

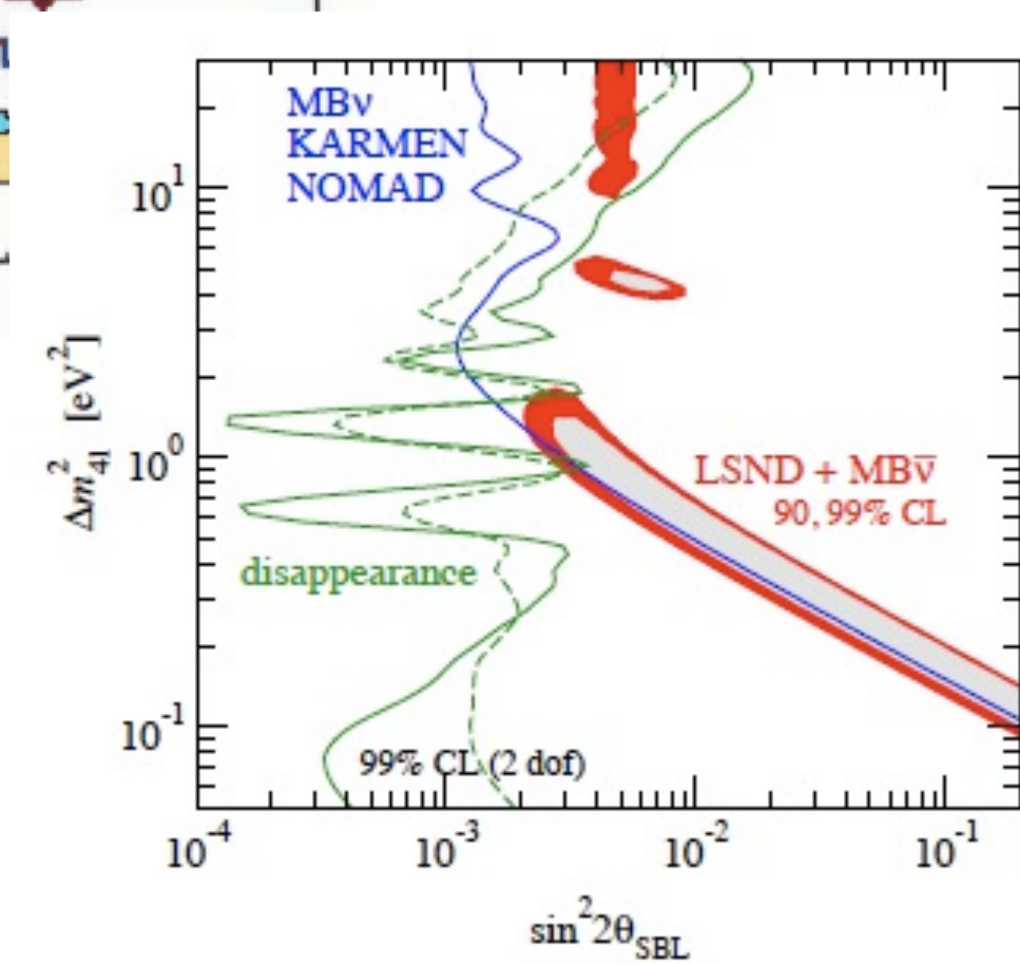
4- or 5- neutrino oscillations: sterile neutrinos



LSND

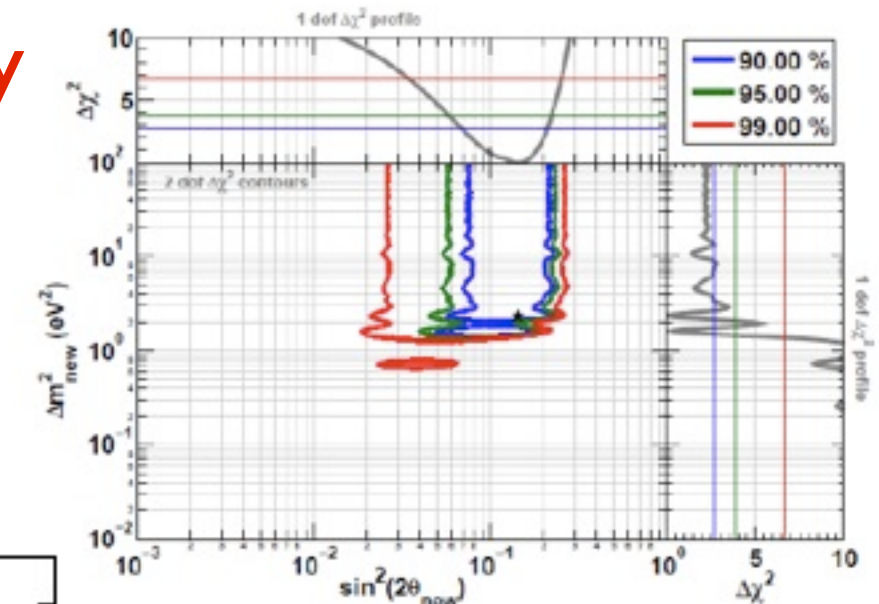
Kopp et al., 1103.4570

MiniBooNE



Reactor anomaly

Combining reactor rates + shape + Gallium Anomaly



no-oscillation disfavored at 99.8% CL

G. Mention et al., 1101.2755

Various hints of oscillations with

$$\Delta m^2 \sim 1 \text{ eV}^2$$

As the Δm^2 required to explain these experiments is different from $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm A}$, this means that there are at least 4 neutrinos. The fourth one needs to be sterile, i.e. it does not have SM interactions.

Clarification: 4 flavour states $\nu_e, \nu_\mu, \nu_\tau, \nu_s$

4 mass states $\nu_1, \nu_2, \nu_3, \nu_4$

Sterile neutrinos could be present in extensions of the SM with masses from sub-eV to GUT scale.

Their existence would have signatures in other experiments (e.g. neutrinoless double beta decay) and in cosmology. See S. Hannestad's talk.

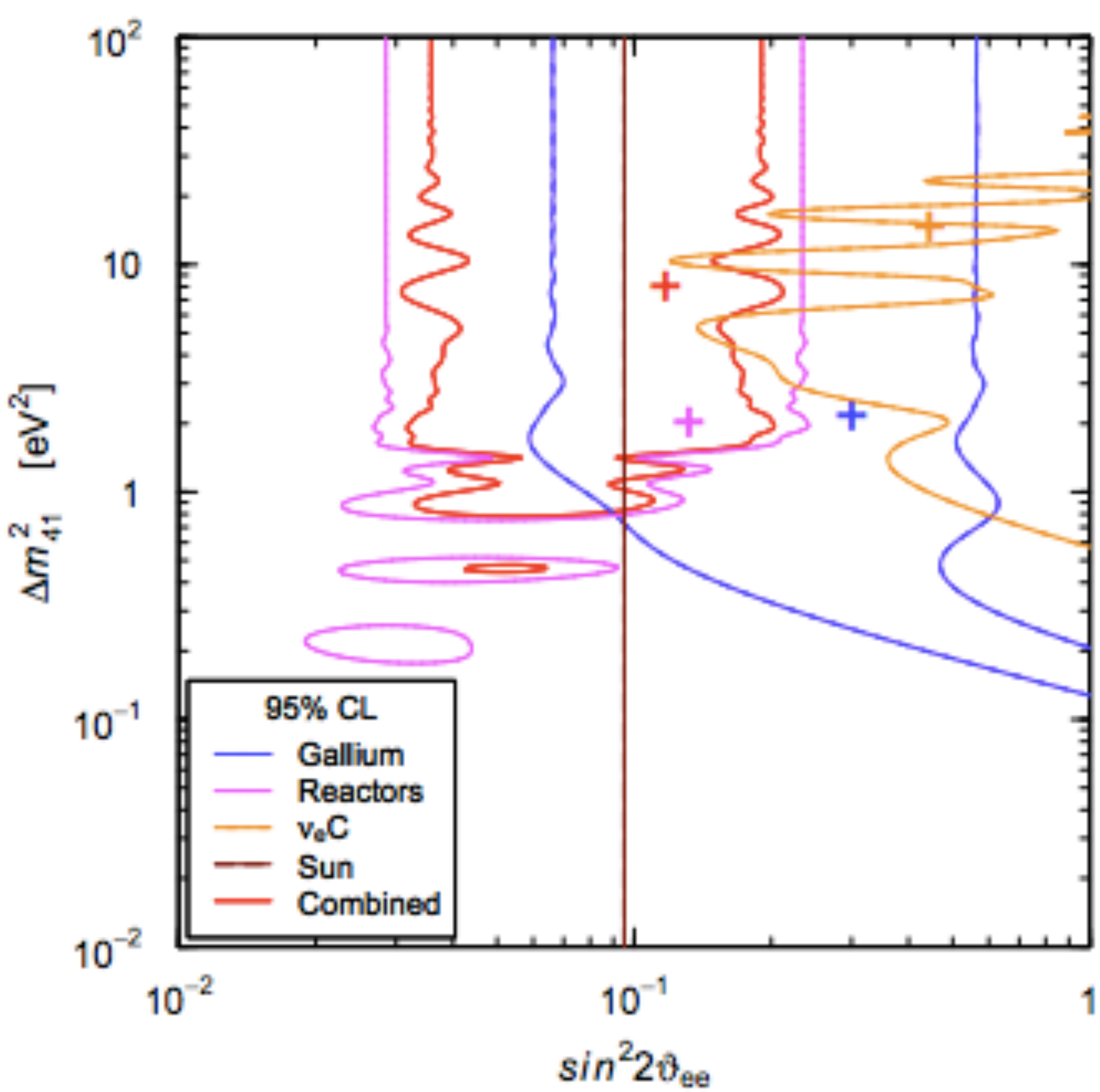
Disappearance experiments

$$P(\nu_e \to \nu_e) = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\sin^2(\Delta m^2 L/4E)$$

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

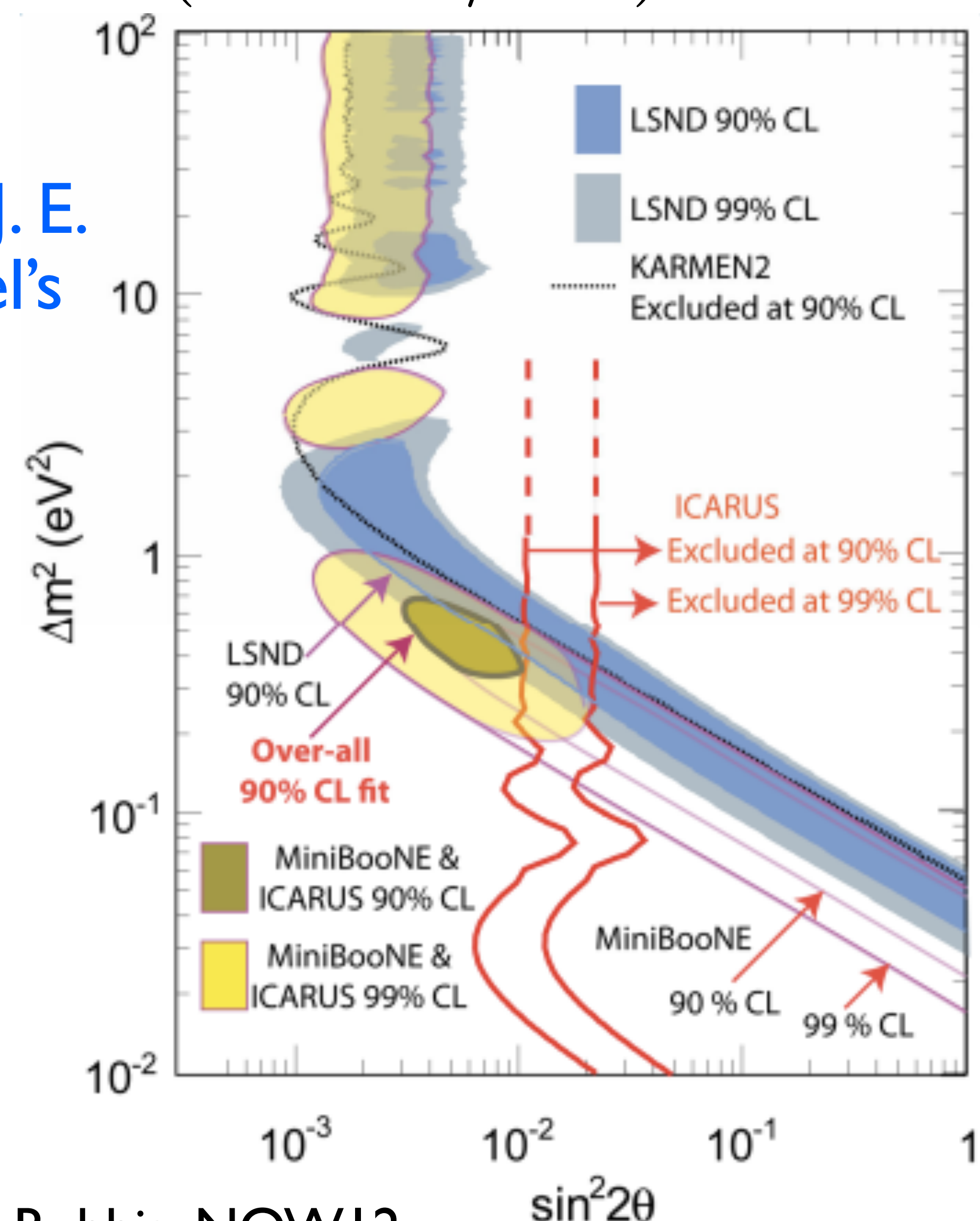
Appearance experiments

$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2|U_{\mu 4}|^2\sin^2(\Delta m^2 L/4E)$$



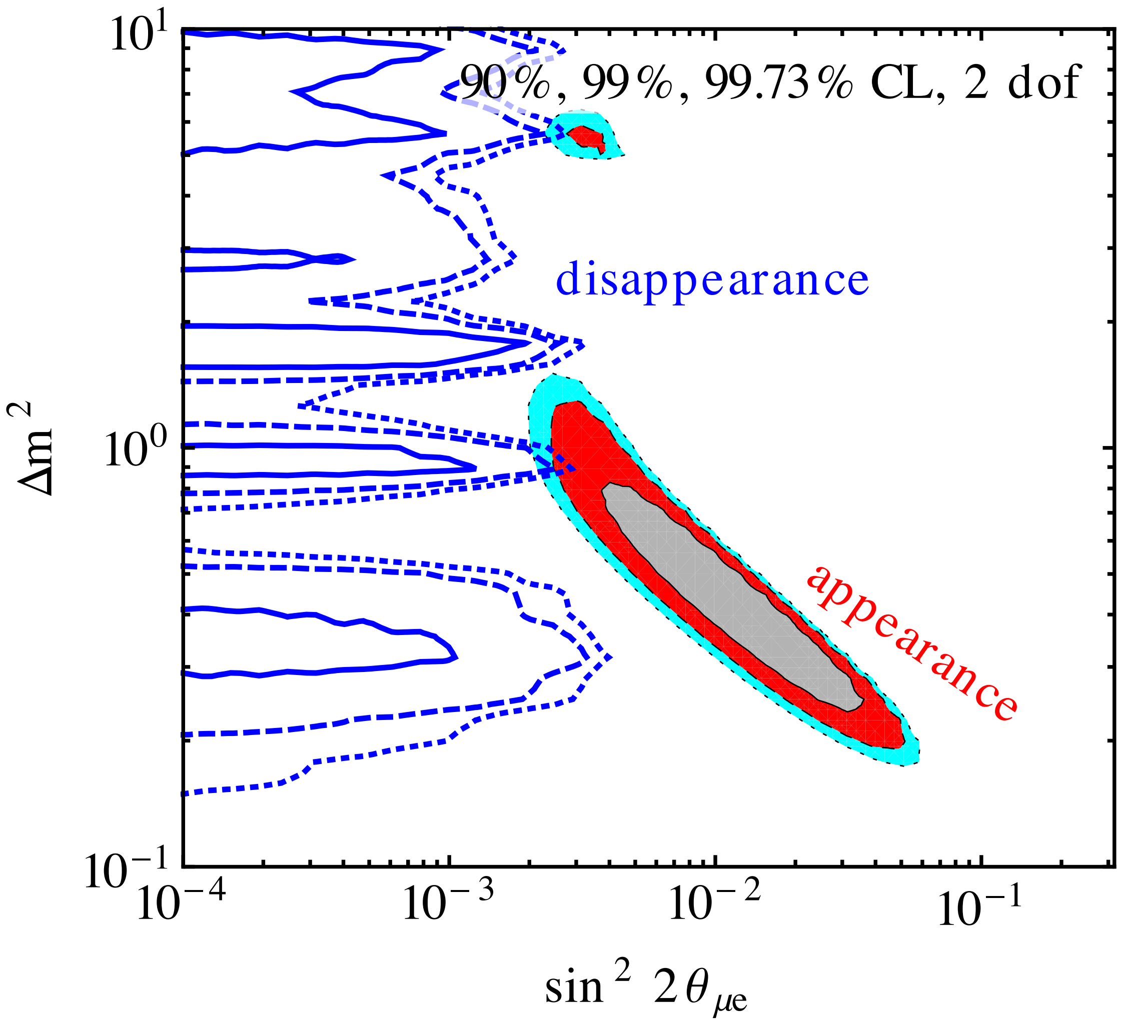
Giunti et al., 1210.5715

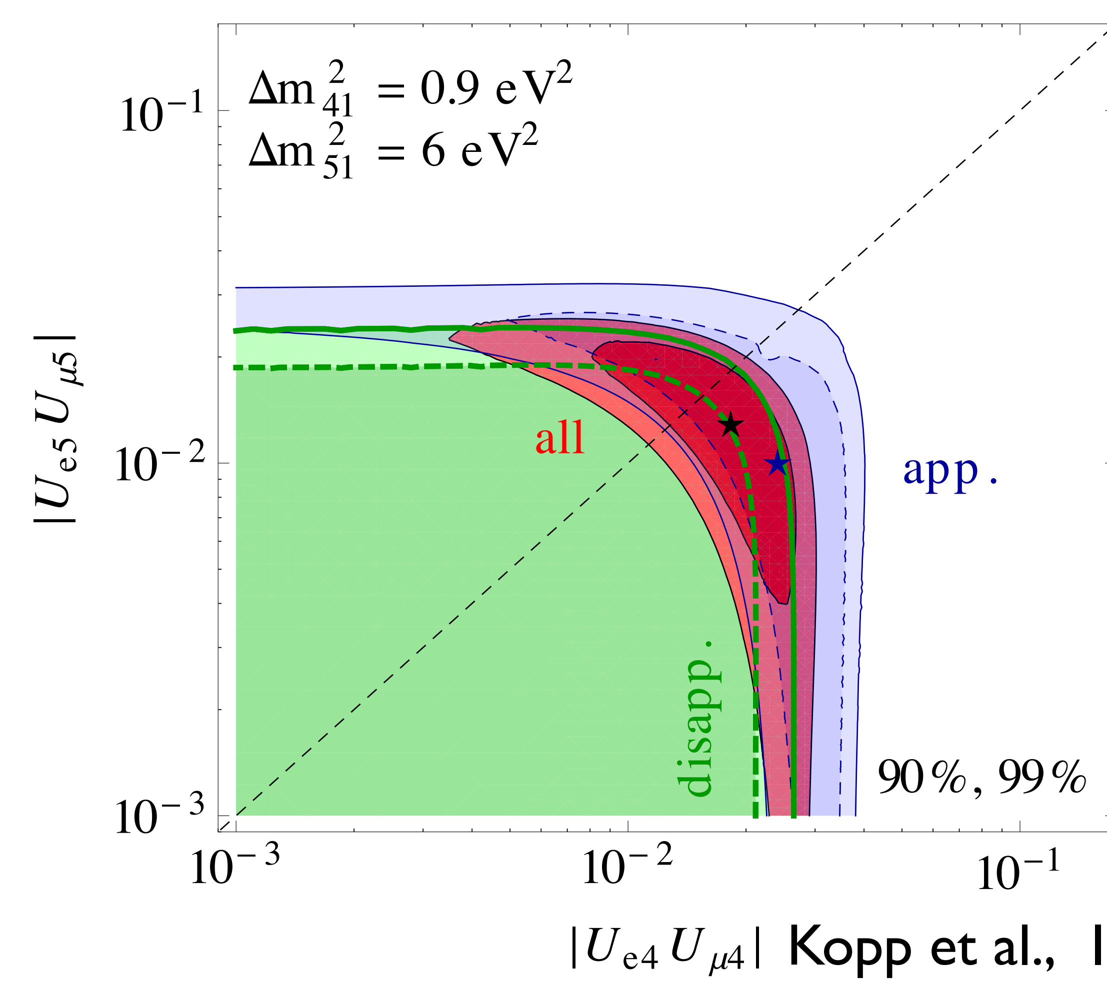
See J. E. Kisiel's talk



C. Rubbia, NOW12

Disappearance exps put strong bounds on masses and mixing angles (CDHS, Atm, MiniBooNE, MINOS).



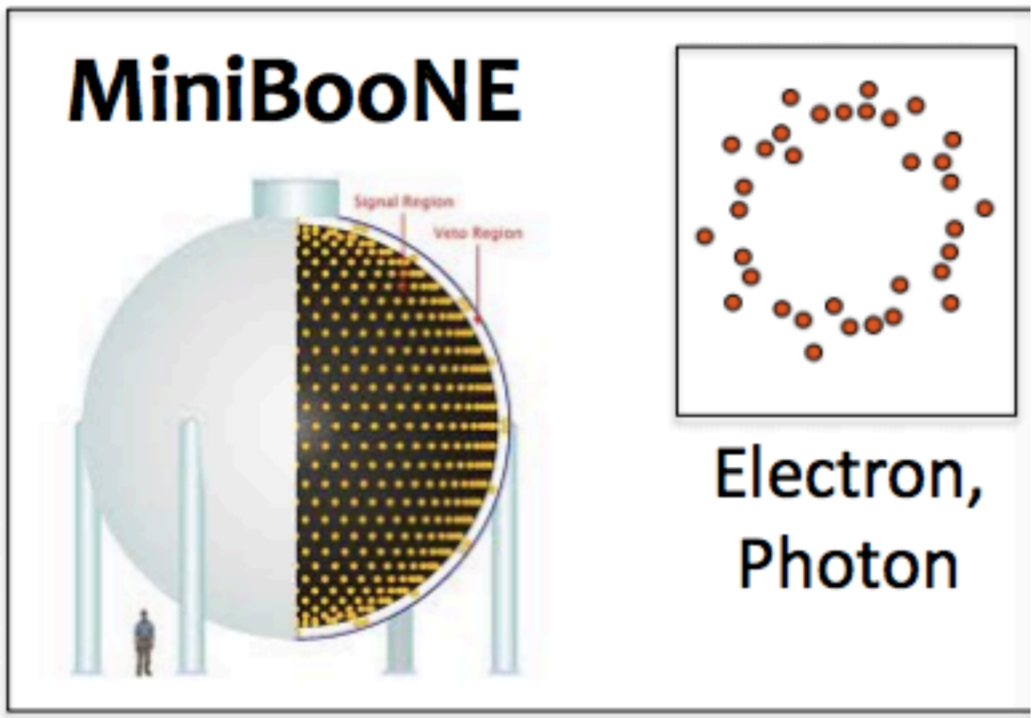


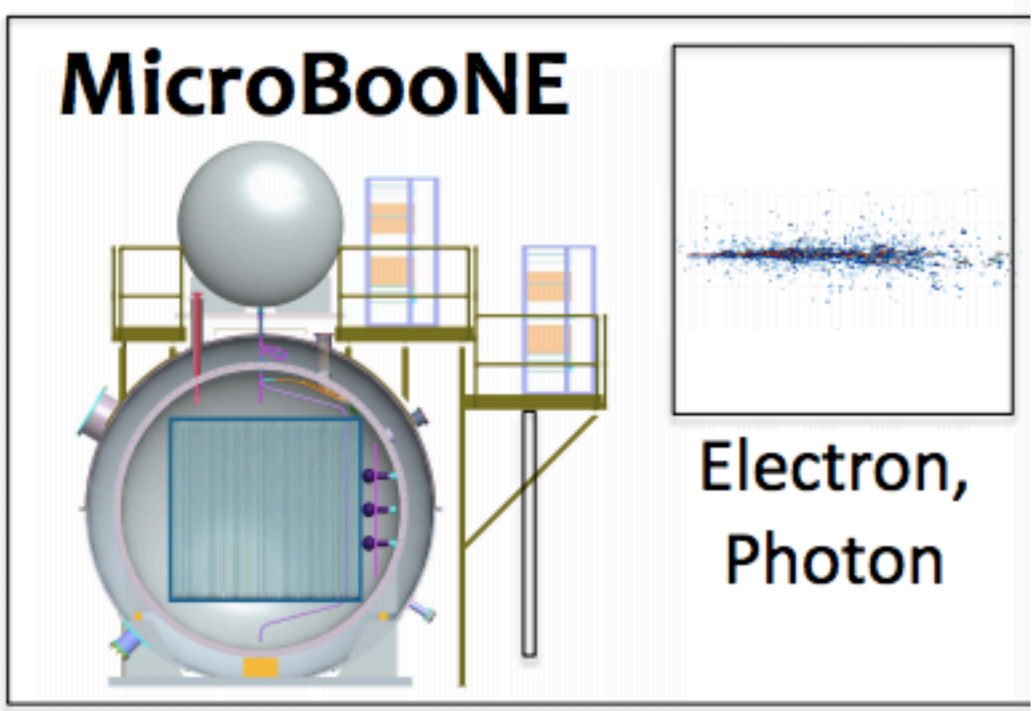
Kopp et al., 1303.3011

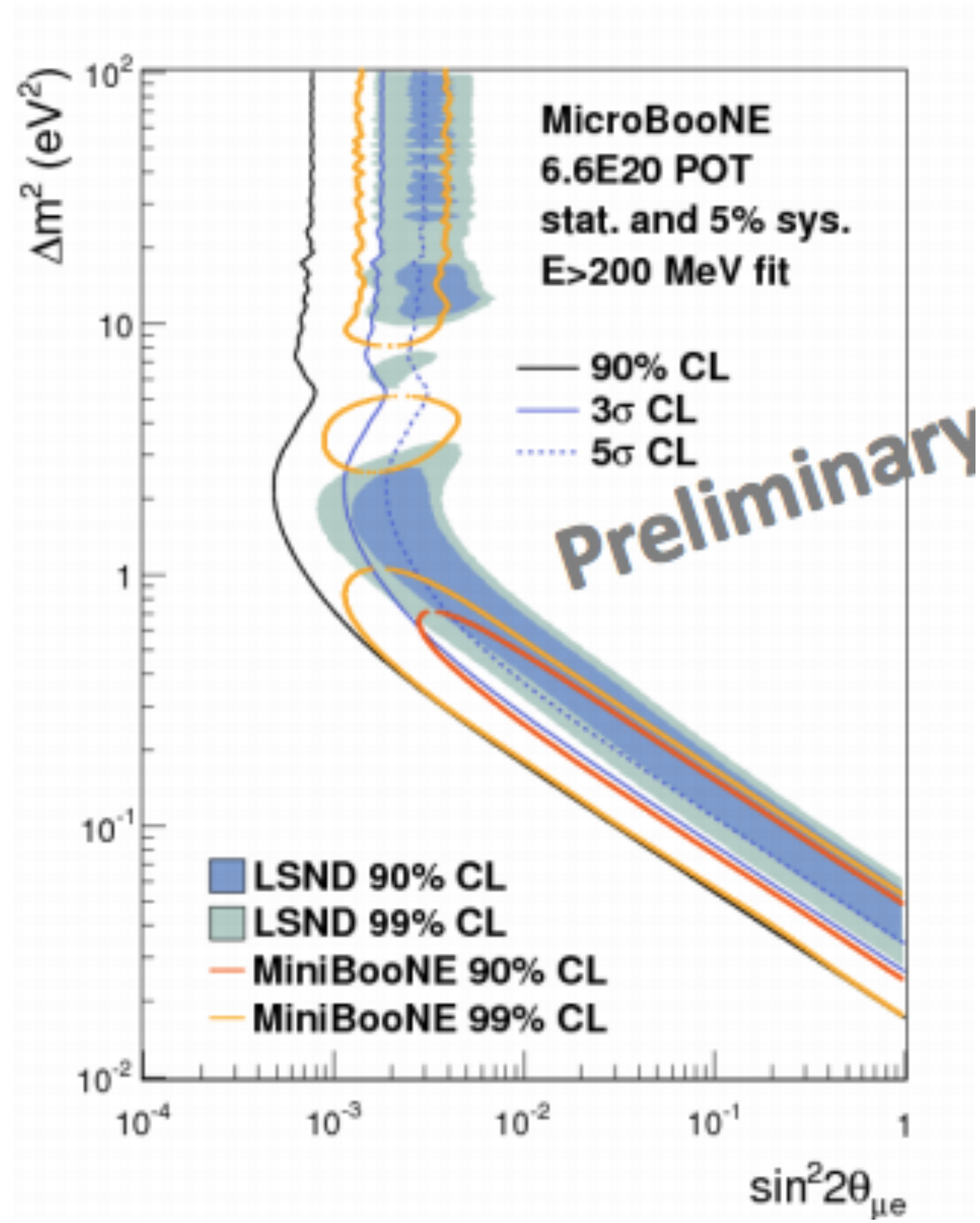
Some tension is present between appearance and disappearance data. Adding 2 extra sterile neutrinos gives more freedom but moderately improves the fit to the data. Present and future searches will test these effects. See J. E. Kisiel's, K. Long's, A.Olshevskiy's, J.Thomas' talks

MicroBooNE: a 86 ton LAr TPC searching for nue appearance in the Booster beam. Cryostat deployed in March, data taking in 2014.

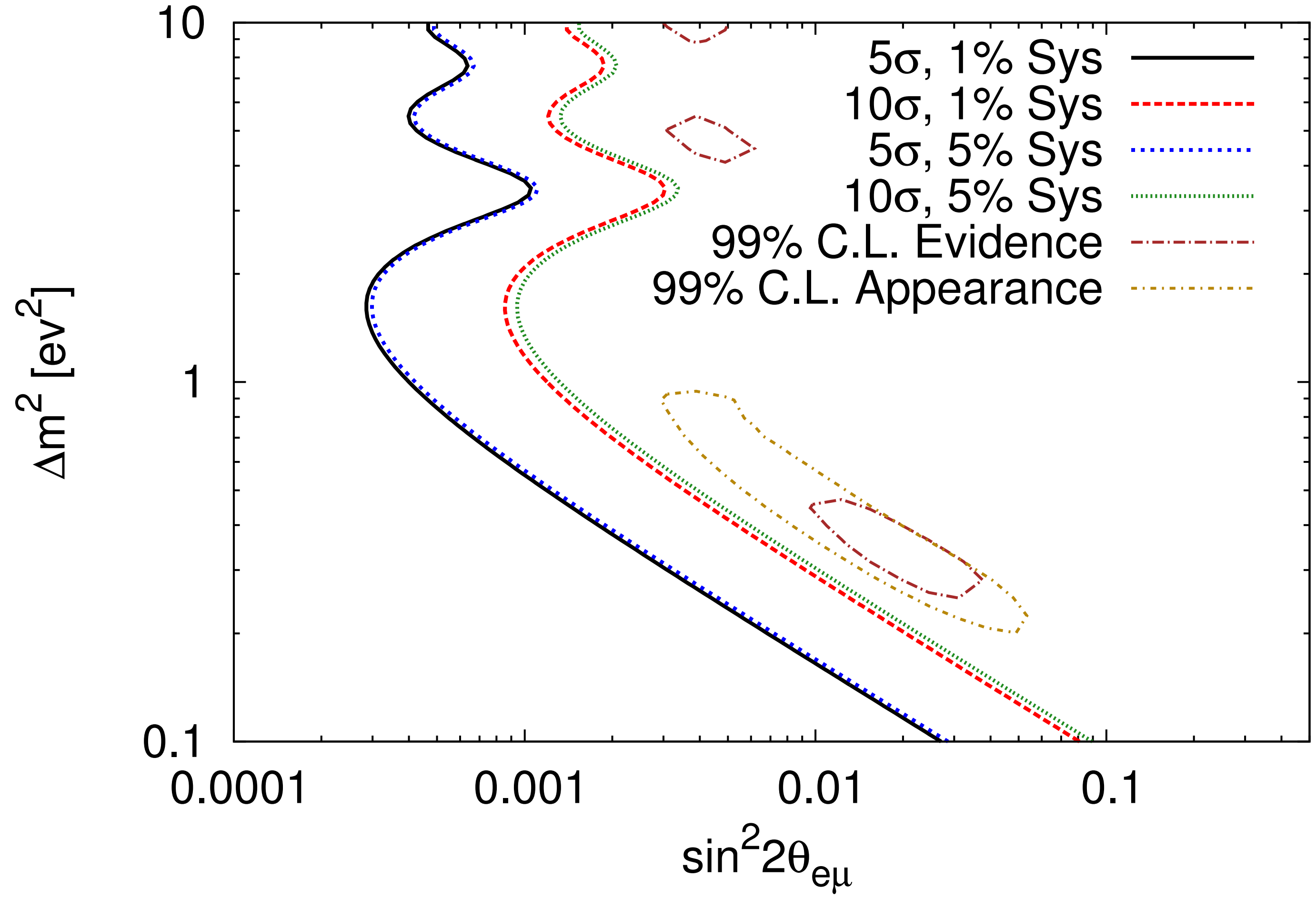
Jennet Dickinson, for MicroBooNE collaboration at APS 2013.





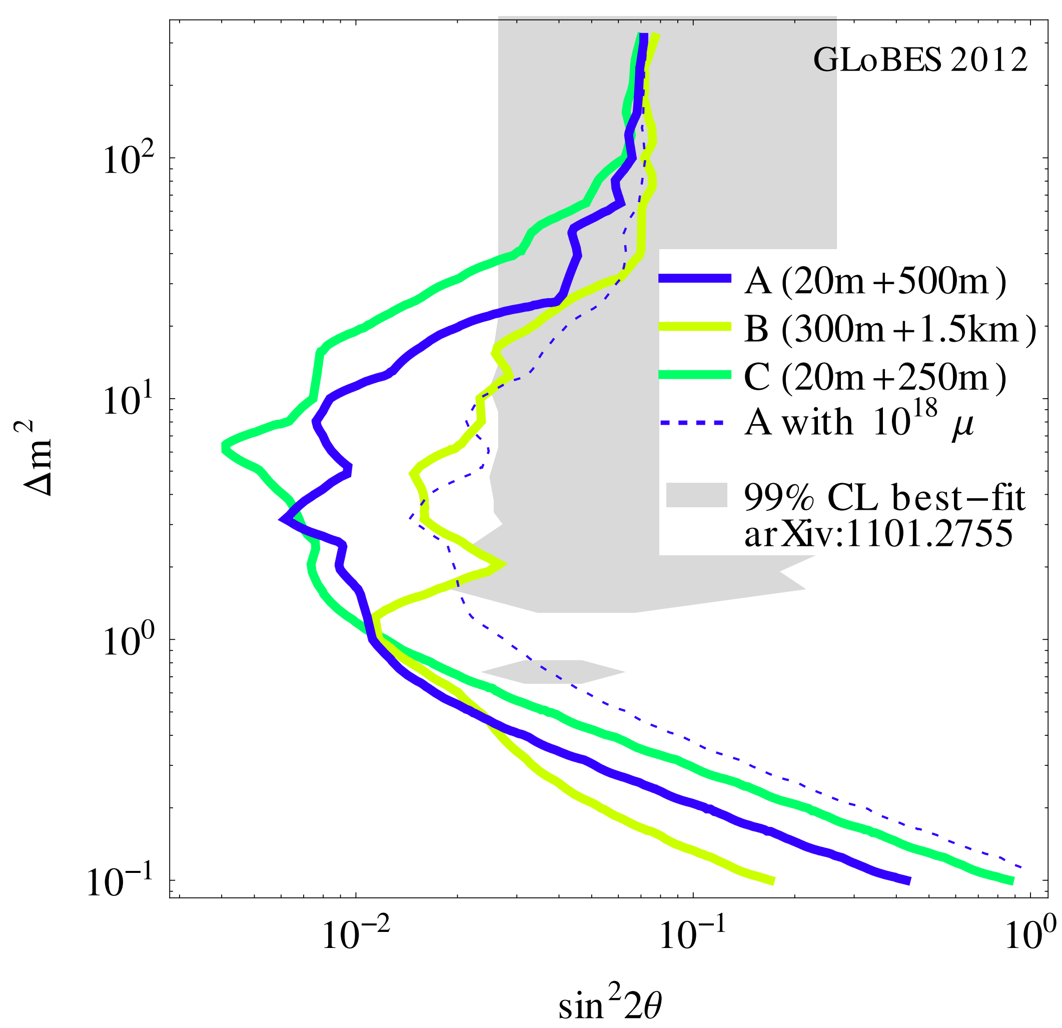


nuSTORM: uses a muon beam, E=2 GeV and 10^19 muons, and two detectors (200 t ND and1 kton FD).



nuSTORM LoI

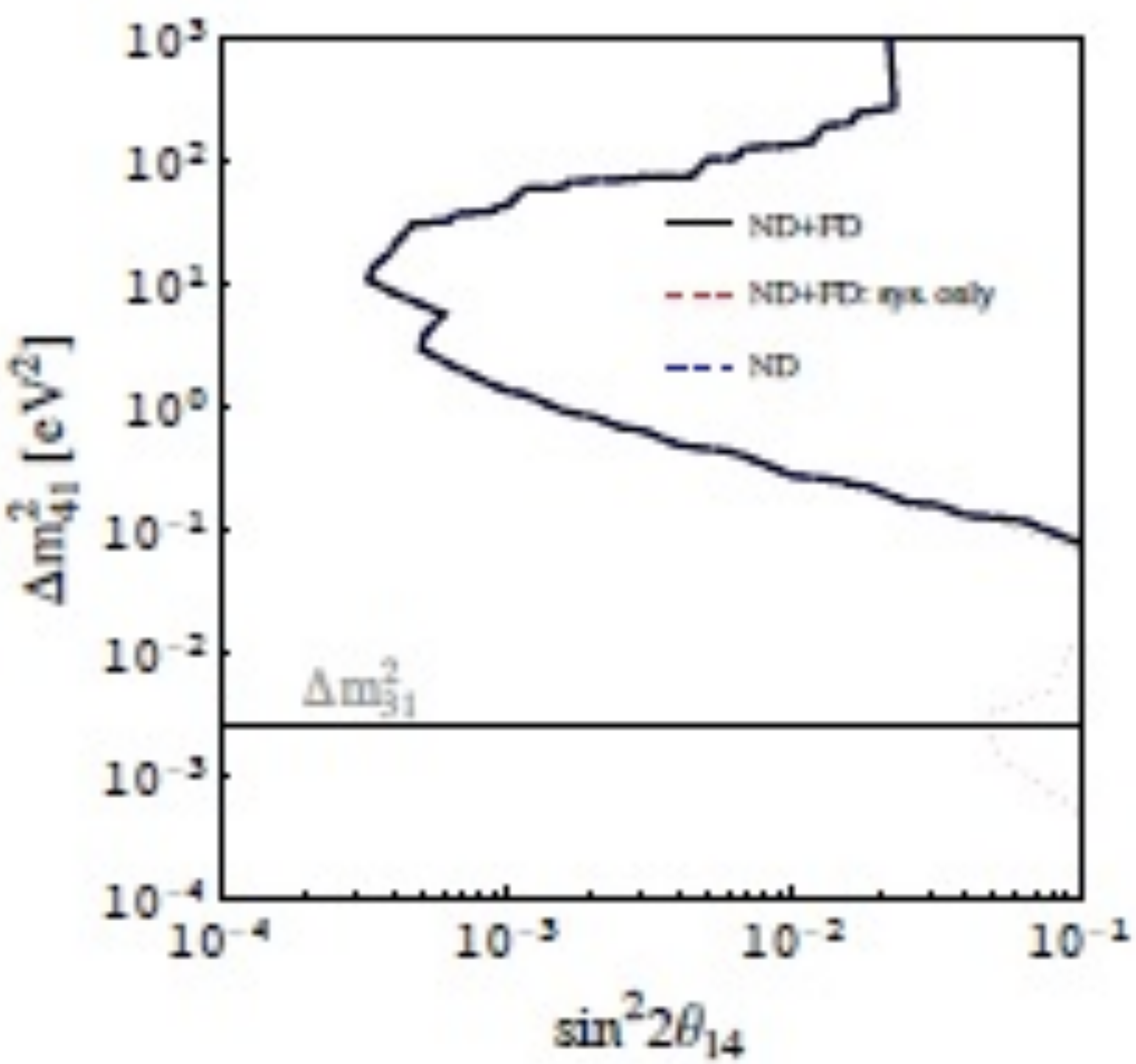
Winter, PRD85

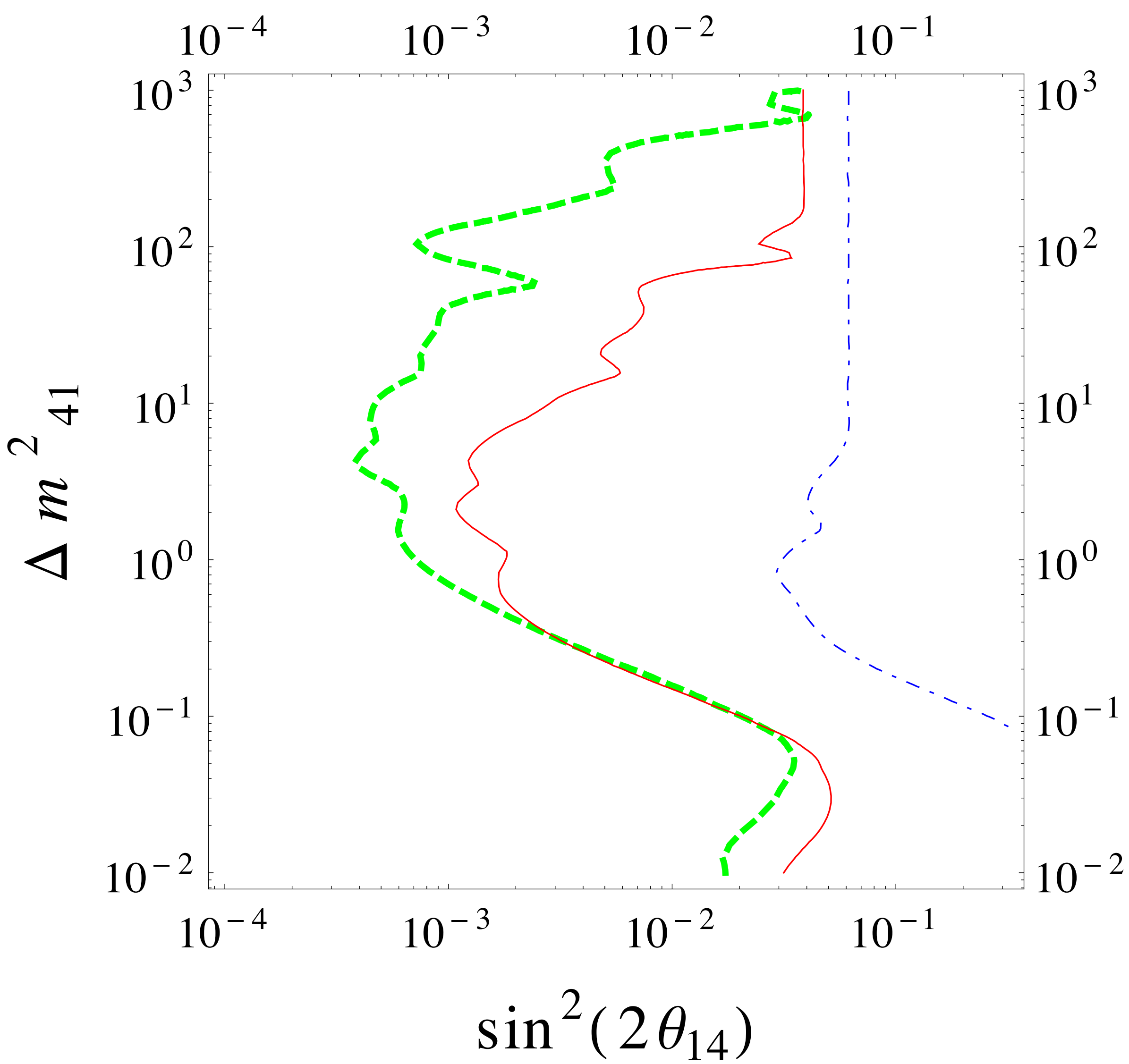


It would easily confirm/disprove the oscillation hypothesis. See K. Long's talk.

Neutrino Factory: Sensitivities to the sterile neutrino parameters using a near detector at 2.3 km.

See e.g. Meloni, Tang, Winter, 1007.2419. Also, Donini et al., Antusch et al., Tang and Winter...





Pascoli, Wong, in preparation

The NF would provide the ultimate sensitivity and, in case they exist, the best parameter measurement.

Non Standard Interactions (NSI)

NSI appear as additional effects in the H:

$$\hat{H}^{fl} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^\dagger \pm A \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

NSI can arise in extensions of the SM. For instance D=6 operators typically lead to

$$\mathcal{O}^6 = \frac{1}{\Lambda^2} \left(L_\sigma \gamma^\lambda L_\rho\right) \left(L_\psi \gamma_\lambda L_\zeta\right) \longleftrightarrow \epsilon \sim g^2 M_W^2/(g_{NSI}^2 M_{NSI}^2)$$

Strong bounds arise from oscillations, pion decay, CKM unitarity..., typically <0.001, 0.1, and at the loop-level, if charged current processes cannot be avoided.

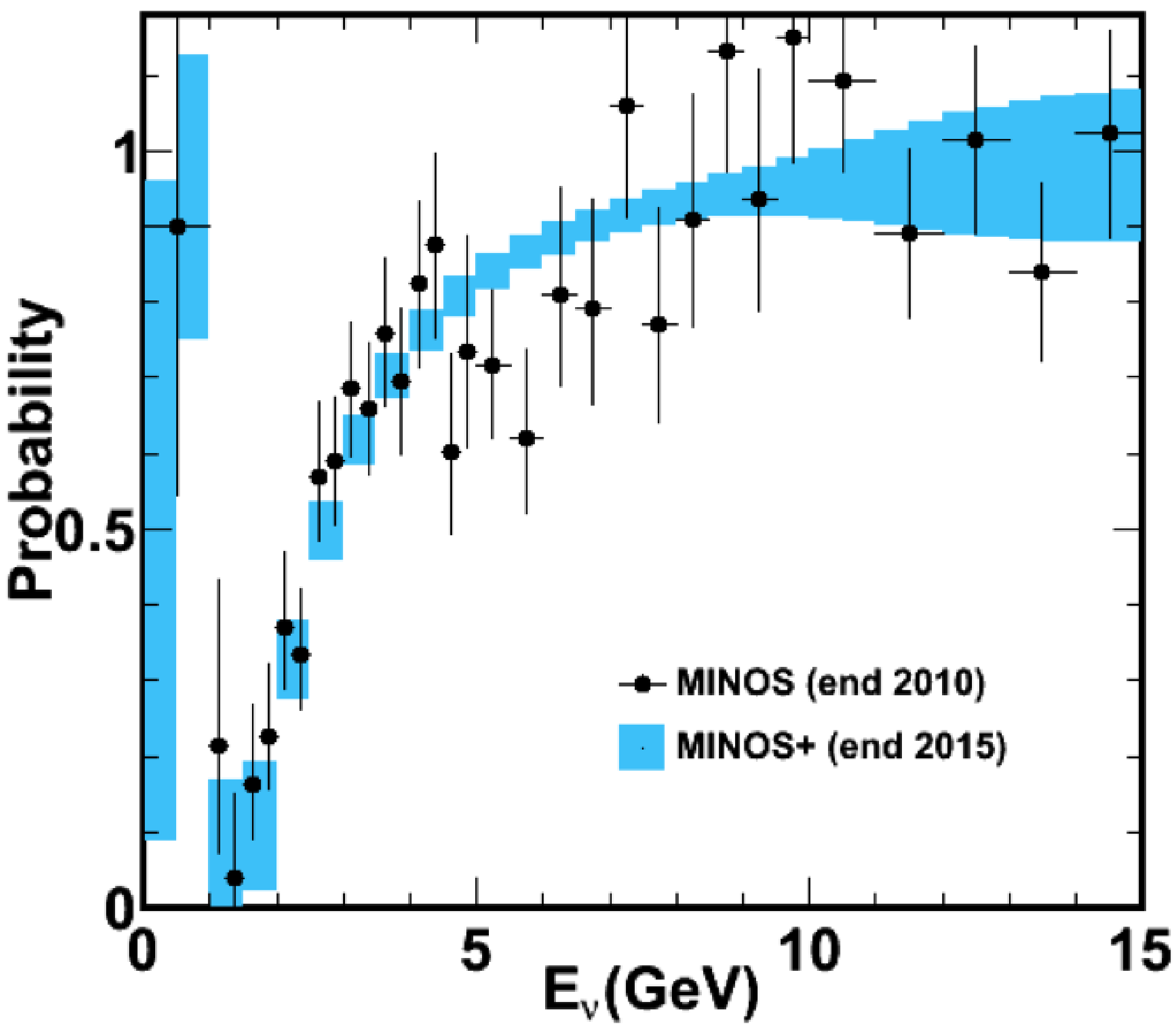
LBL experiments are also sensitive to NSI at source, propagation and detection (Grossman, 95):

matter effects

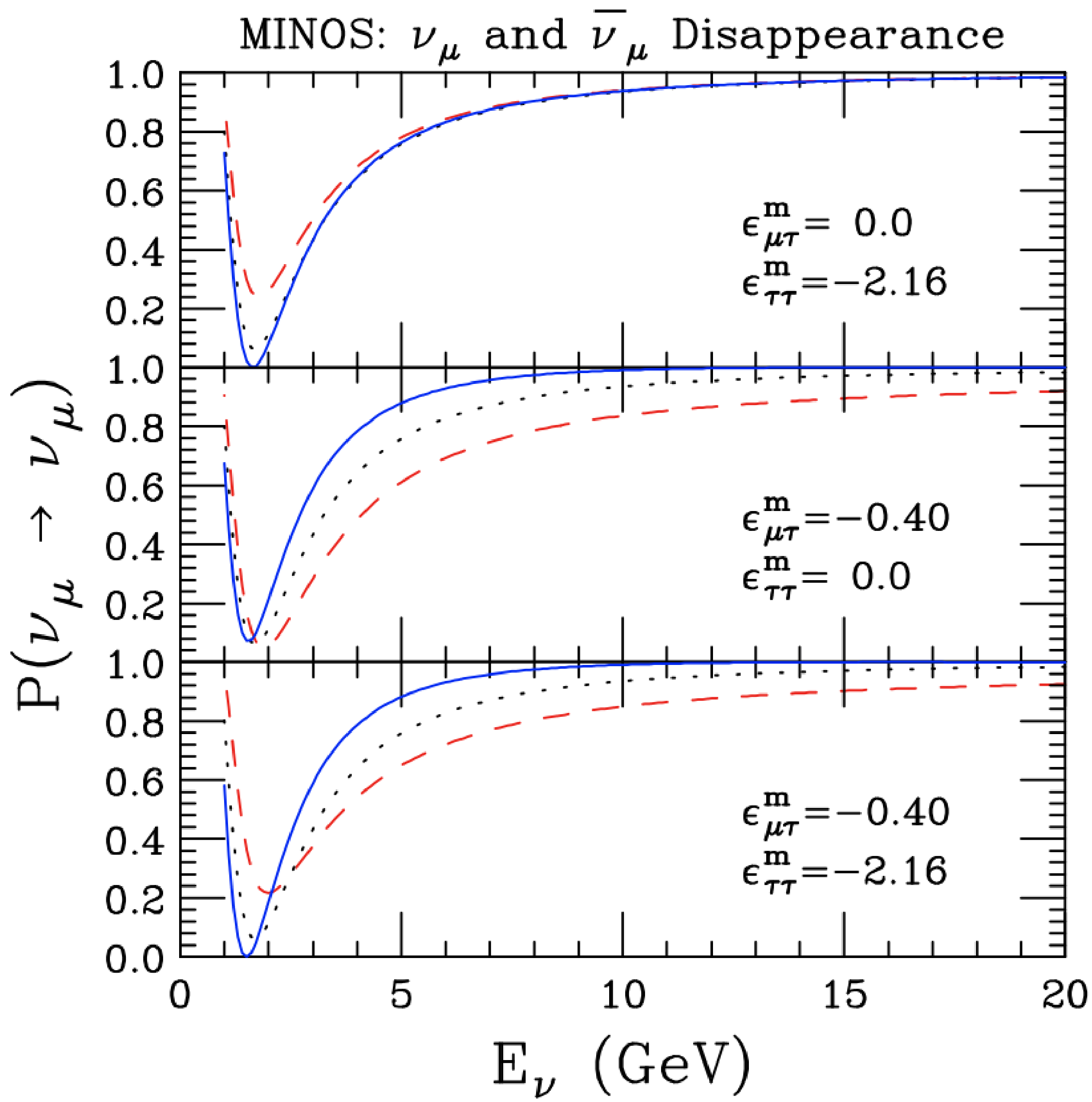
$$P_{\nu_e \to \nu_\mu} \simeq \frac{s^2_{213} s^2_{23}}{\left(1 - \frac{A}{\Delta_{31}}\right)^2}$$
$$+ \frac{s_{213} c_{13} s_{212} s_{223}}{1 - \frac{A}{\Delta_{31}}} \frac{\Delta_{21}}{A} \sin\left(\frac{AL}{2}\right) \cos\left(\frac{\pi + AL}{2} - \delta\right)$$
$$- 4\varepsilon_{e\mu} \frac{s_{213} c_{23} s^2_{23}}{1 - \frac{A}{\Delta_{31}}} \sin\left(\frac{AL}{2}\right) \cos\left(\frac{\pi + AL}{2} - \delta + \phi_{e\mu}\right)$$
$$- 4\varepsilon_{e\tau} \frac{s_{213} c_{23} s^2_{23}}{1 - \frac{A}{\Delta_{31}}} \sin\left(\frac{AL}{2}\right) \cos\left(\frac{\pi + AL}{2} - \delta + \phi_{e\tau}\right)$$

The longer baseline (higher energy), the better the physics reach as NSI effects become more important.

The effects are enhanced at high energies. **MINOS+** will have very good sensitivity to these effects.



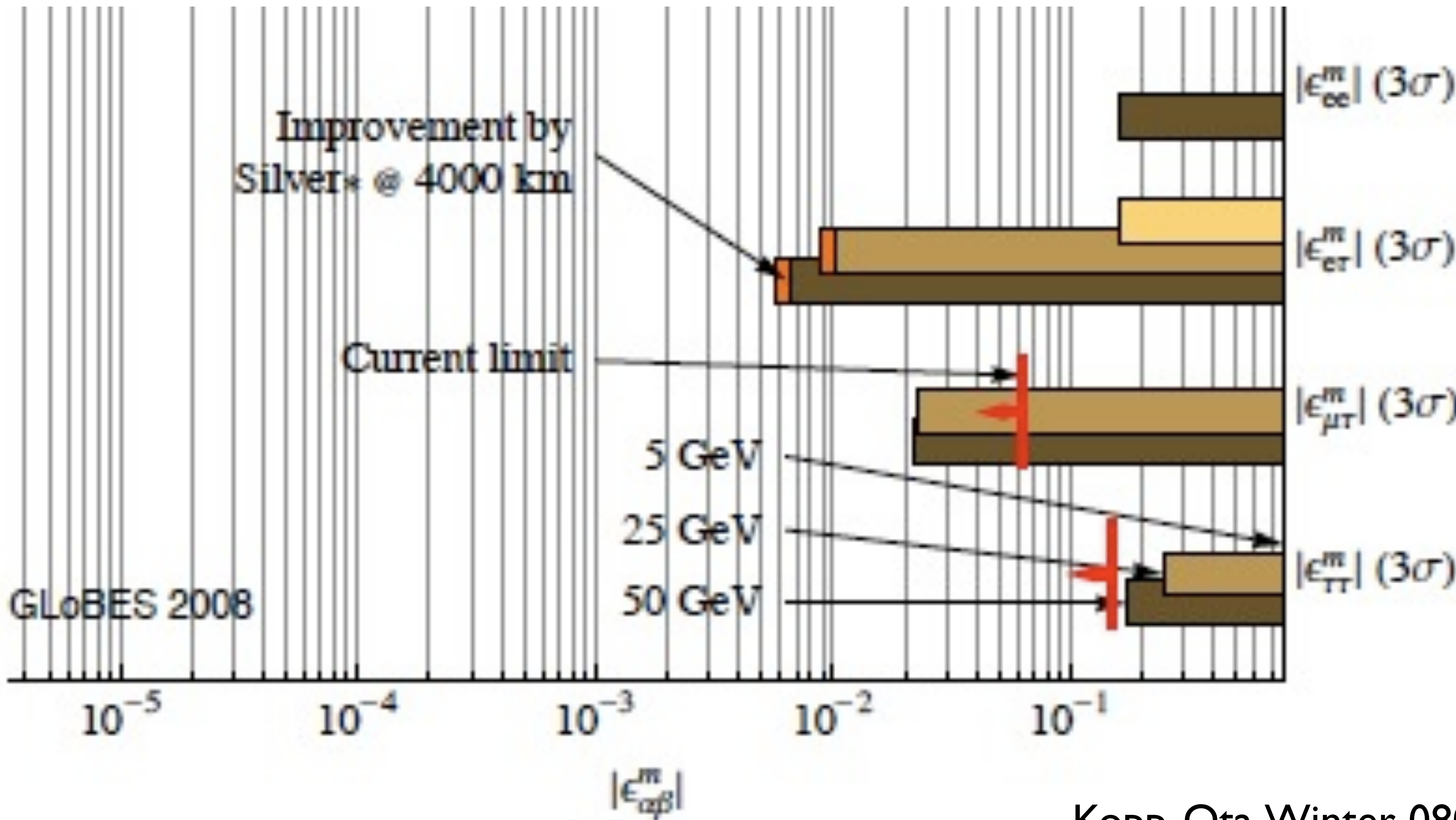
MINOS+ Proposal



See J. Thomas' talk

Kopp, Machado, Parke, PRD82

The HENF provides the best sensitivity to NSI



Kopp, Ota, Winter, 0804.2261

The LENF has also good sensitivity. The inclusion of the platinum channel helps in resolving degeneracies and to improve the sensitivity.

Conclusions

- In the past few years, the neutrino oscillation parameters have been measured with good precision. The recent discovery of non-zero θ_{13} has important implications for neutrino oscillation experiments.

- Next generation oscillation experiments will address the mass hierarchy, CPV searches and precision measurements of the oscillation parameters. The physics reach of a facility depends on beams, detector performance, systematic errors and backgrounds. Comparisons should be done with great care.

- Anomalies have been found (LSND, MiniBooNE, reactors) but tension between appearance and disappearance data is present for sterile neutrinos.