Overview on the phenomenology of neutrino oscillations and mass hierarchy

ORCA Workshop

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Silvia Pascoli

IPPP - Durham University

Outline

1. Present status of neutrino oscillation parameters

2. CPV in neutrino oscillations

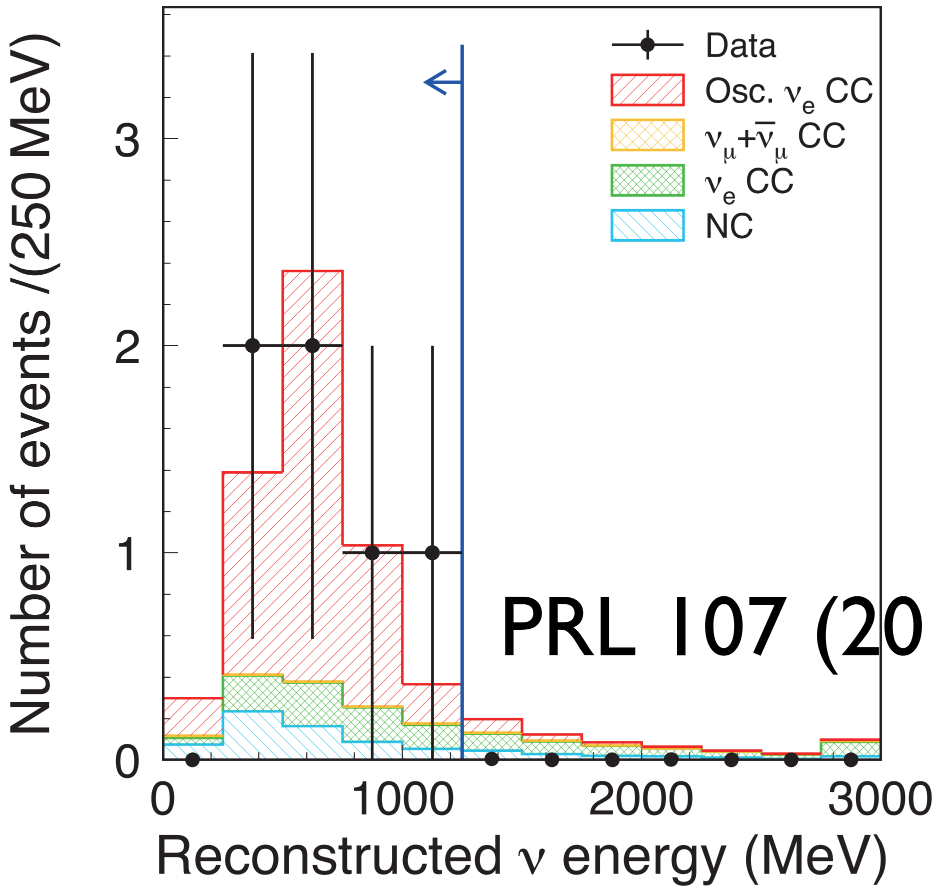
3. Matter effects

4. Impact of mass ordering on LBL and neutrinoless double beta decay

5. Conclusions

Present status of neutrino parameters

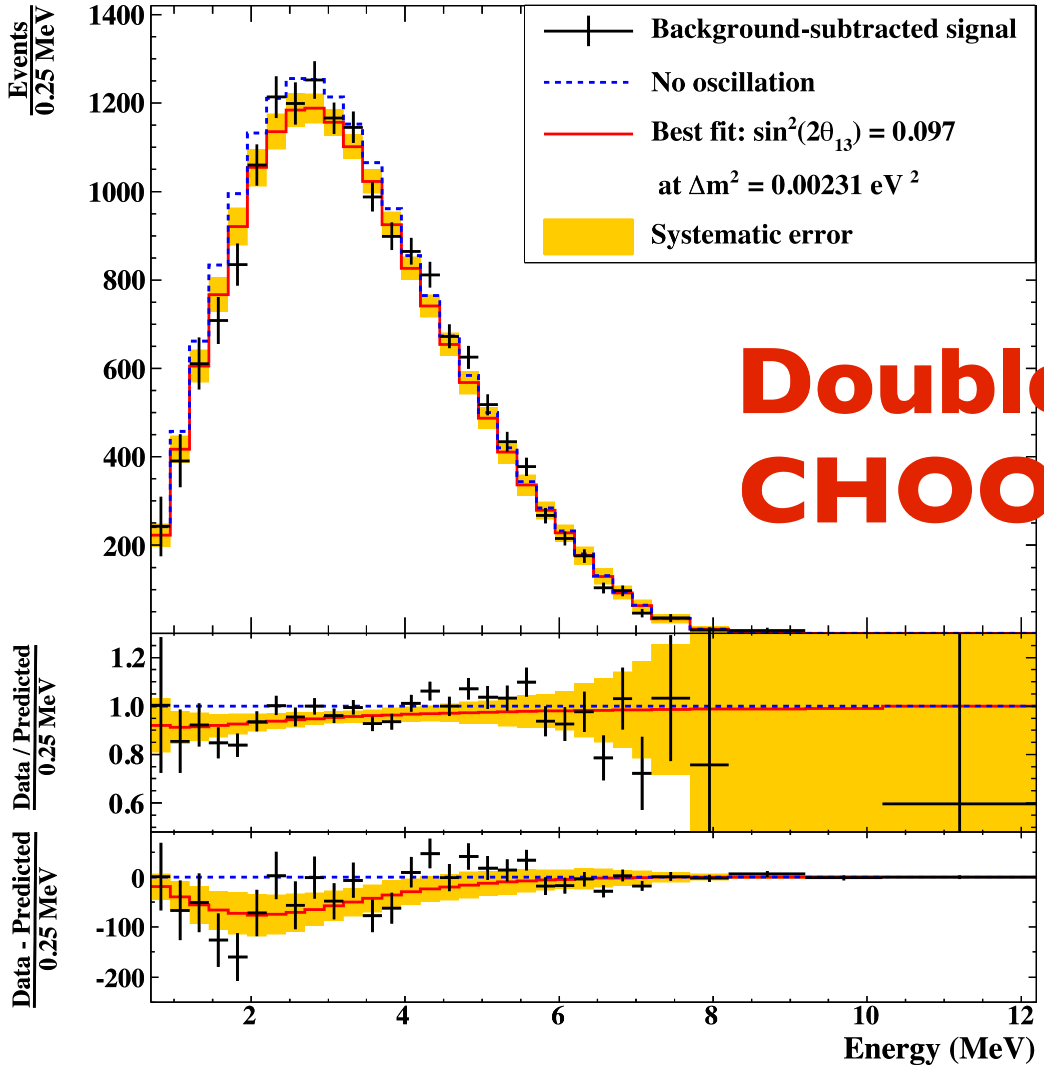
- T2K first data in May 2011. It observed **6 events** with a background of 1.5.



PRL 107 (2011)

- MINOS looked for appearance by distinguishing NC from e-like events. The 2011 results provided a 1.7 sigma hint of nonzero theta13.

MINOS Coll, 1108.0015

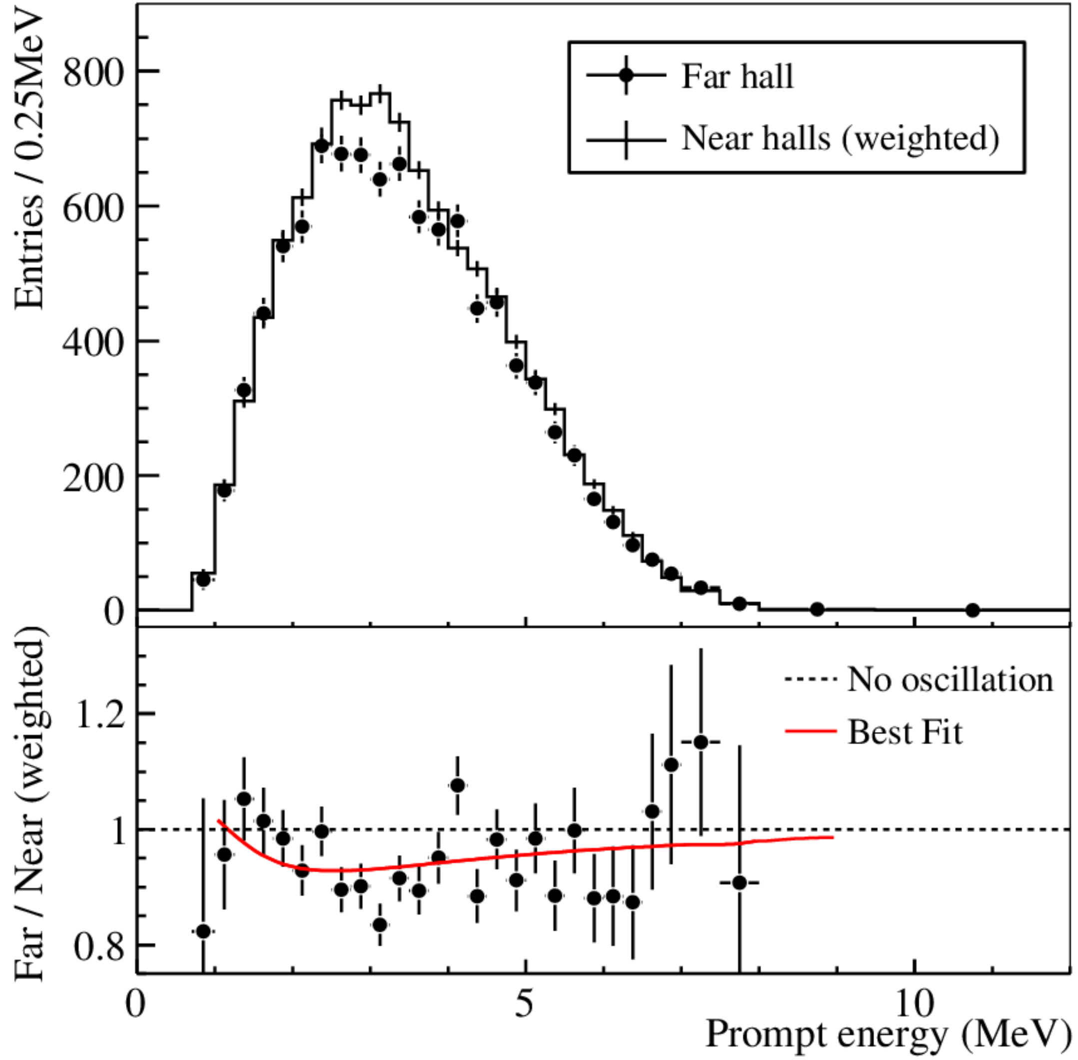


Double-CHOOZ

DCHOOZ Coll., 1301.2948

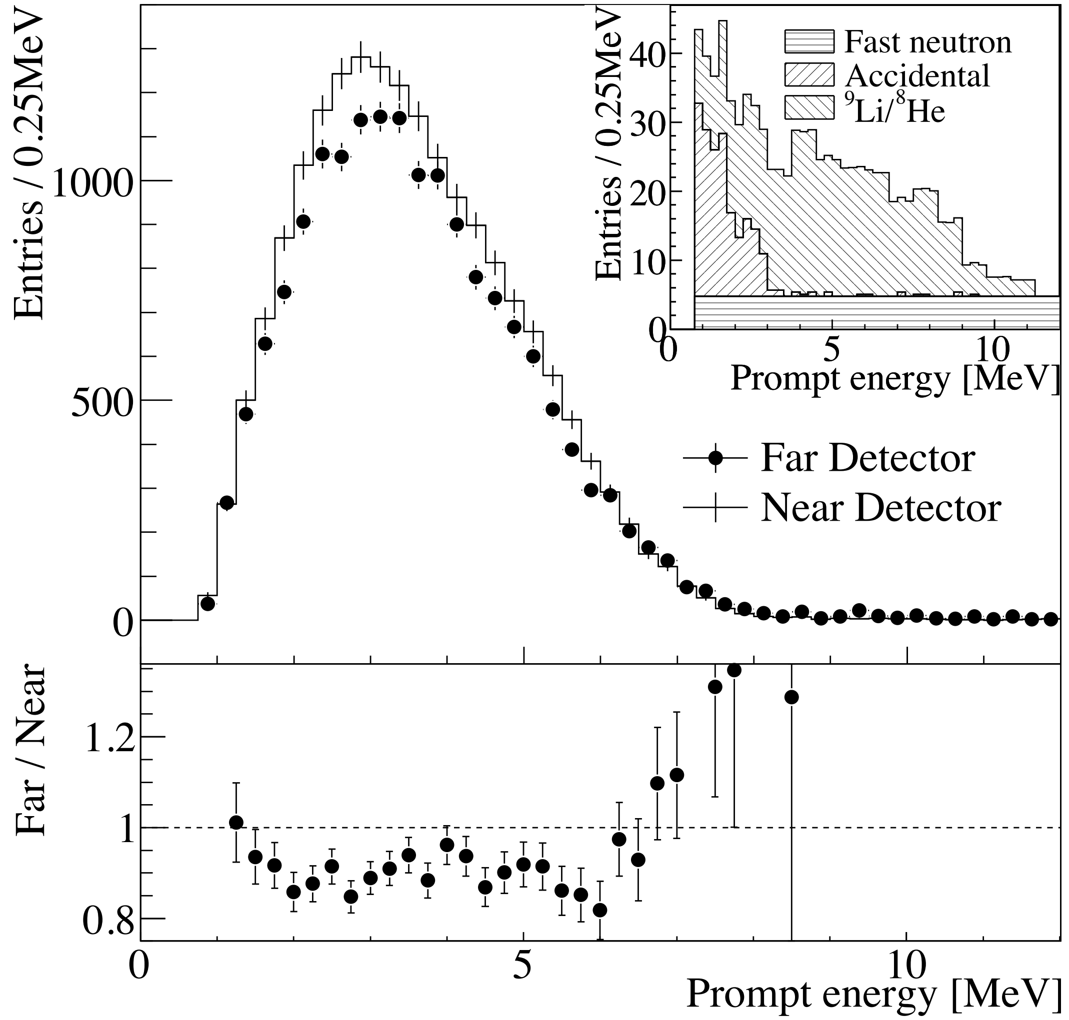
In 2012, previous hints for a nonzero third mixing angle were confirmed by Daya Bay and RENO: important discovery.

Daya Bay



Daya Bay, PRL 108 (2012)

RENO



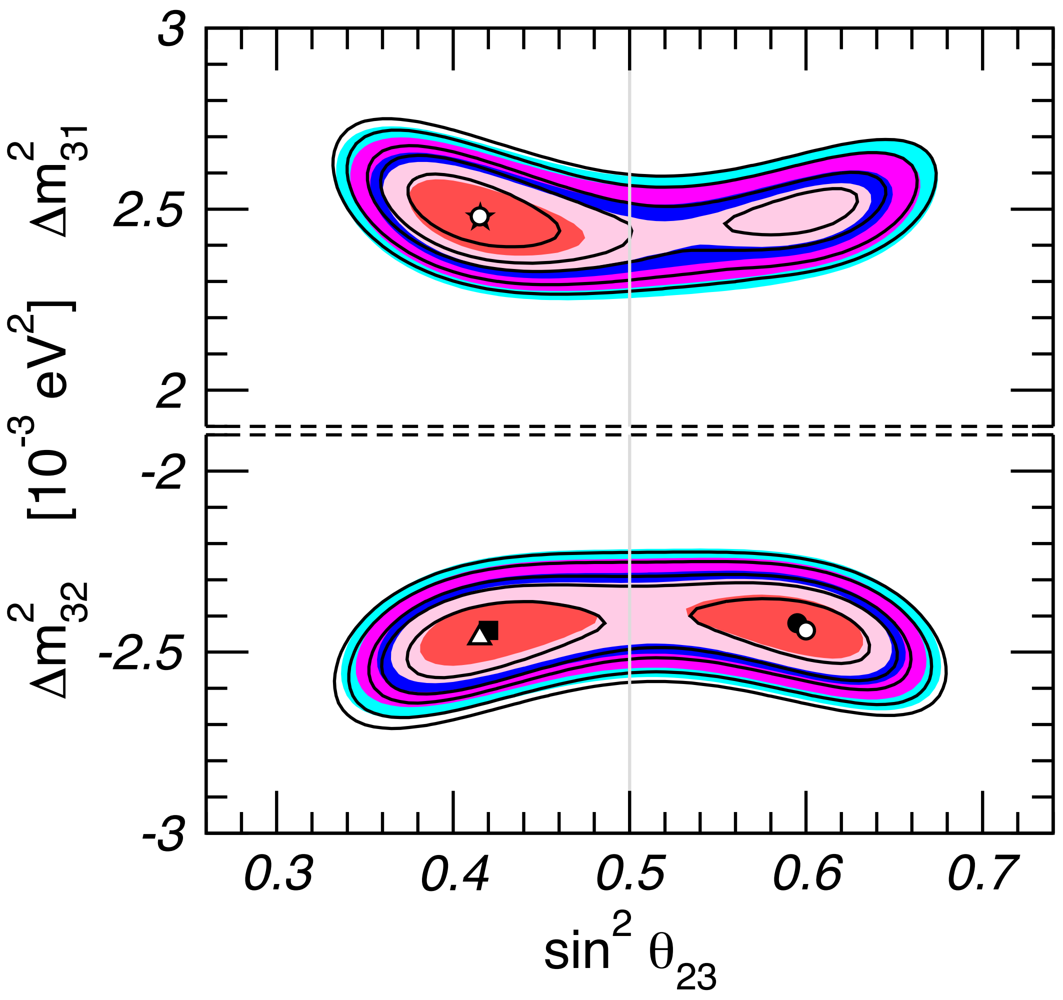
RENO, PRL 108 (2012)

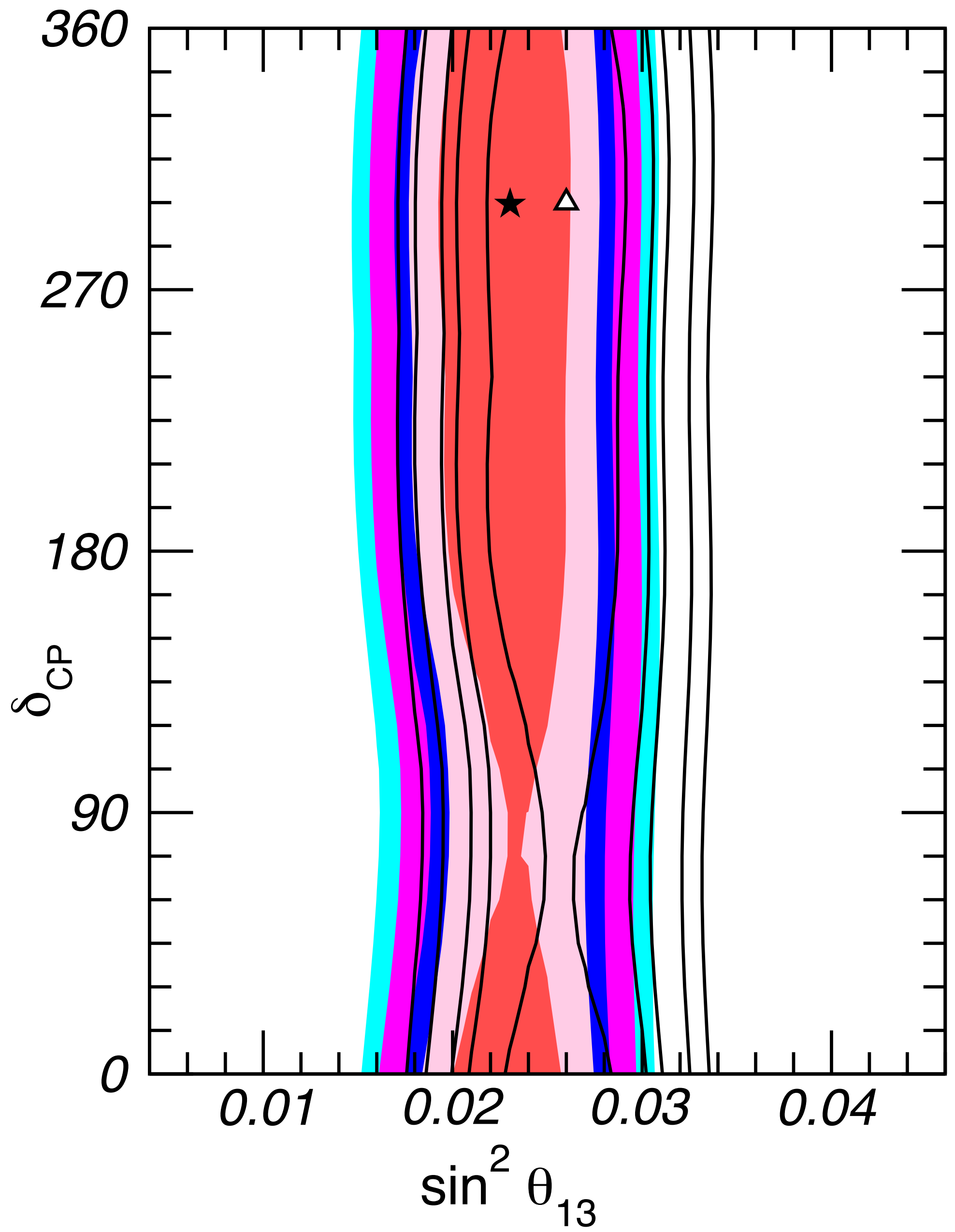
Observed: 9901 neutrinos at far site,
Prediction: 10530 neutrinos if no oscillation

R = 0.940 ±0.011 (stat) ±0.004 (syst)

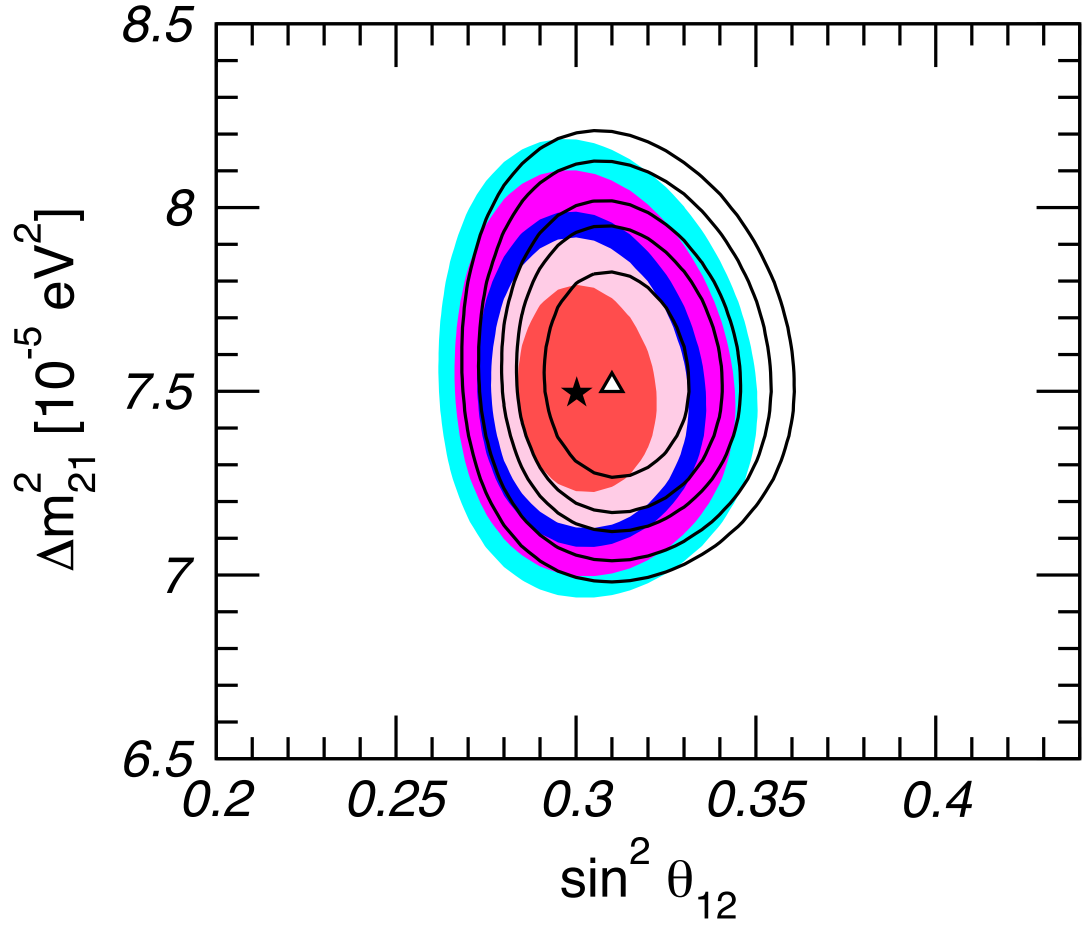
Y. Wang, March 2012

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$$





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.

Several “anomalies” are unexplained and might point towards new physics. Sterile neutrinos are advocated as a possible explanation (3+1 or 3+2 schemes).

- **LSND:** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

- **MiniBooNE:** observes an excess of events at low energy in the electron (anti-)neutrino spectra

- **Gallium anomaly:** a flux of solar neutrinos lower than expected at low energy

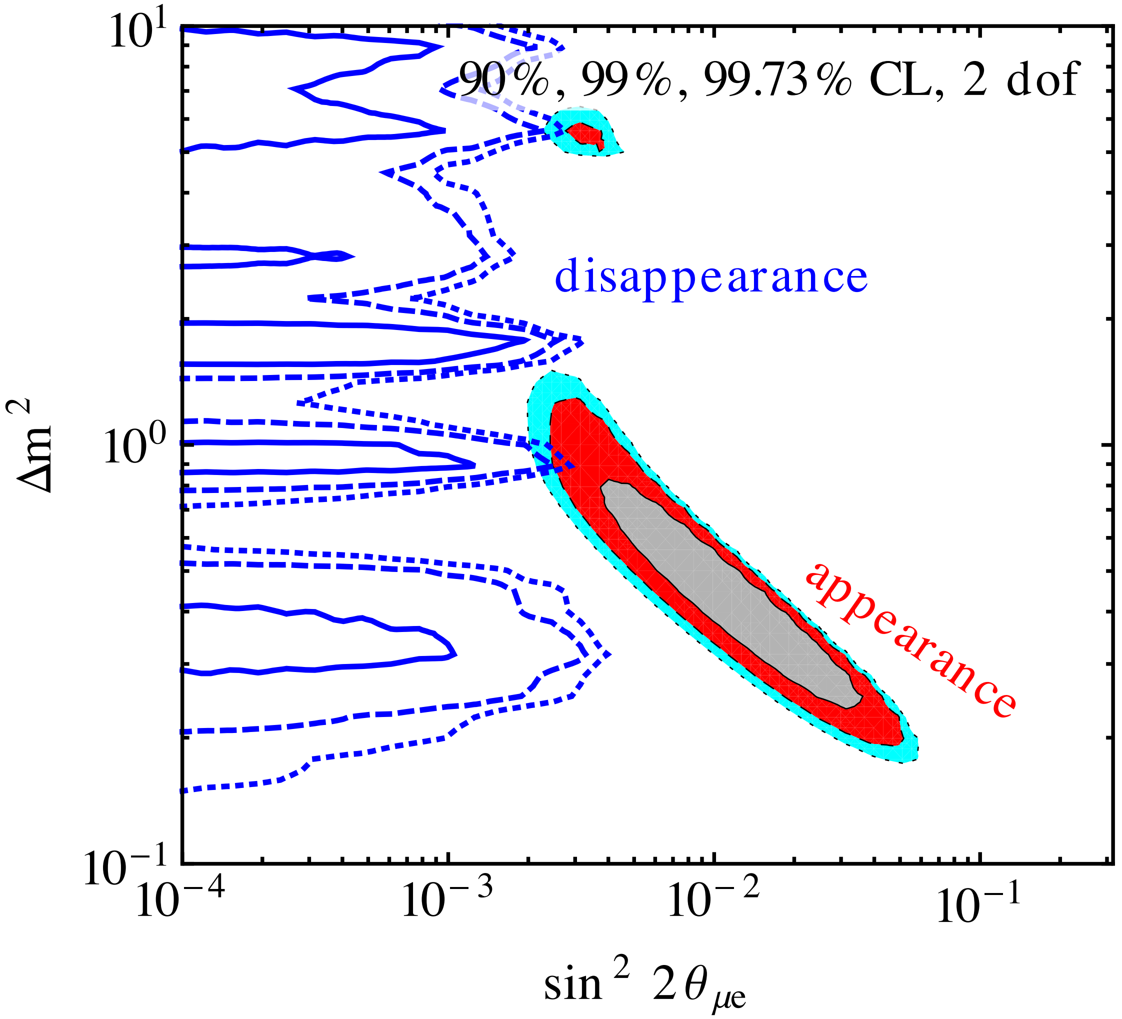
- **Reactor anomaly:** at short baseline (L<100 m) a reactor neutrino flux smaller than predicted.

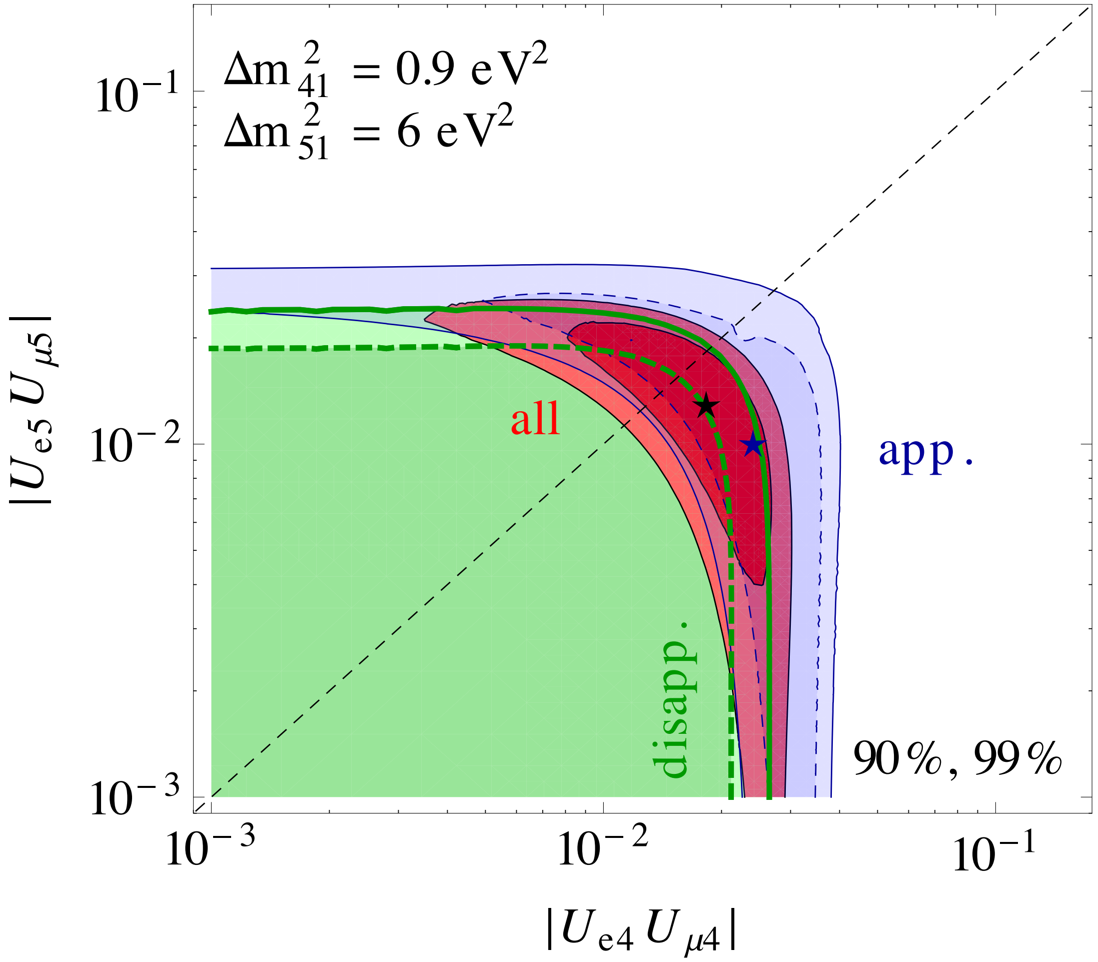
Some tension is present between appearance and disappearance data.

$$P_{ee}^{\mathrm{SBL},3+1} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E}$$

$$P_{\mu\mu}^{\mathrm{SBL},3+1} = 1 - 4|U_{\mu4}|^2(1 - |U_{\mu4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E}$$

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e}^{\mathrm{SBL},3+1} = 4|U_{\mu4}U_{e4}|^2\sin^2\frac{\Delta m_{41}^2 L}{4E}$$

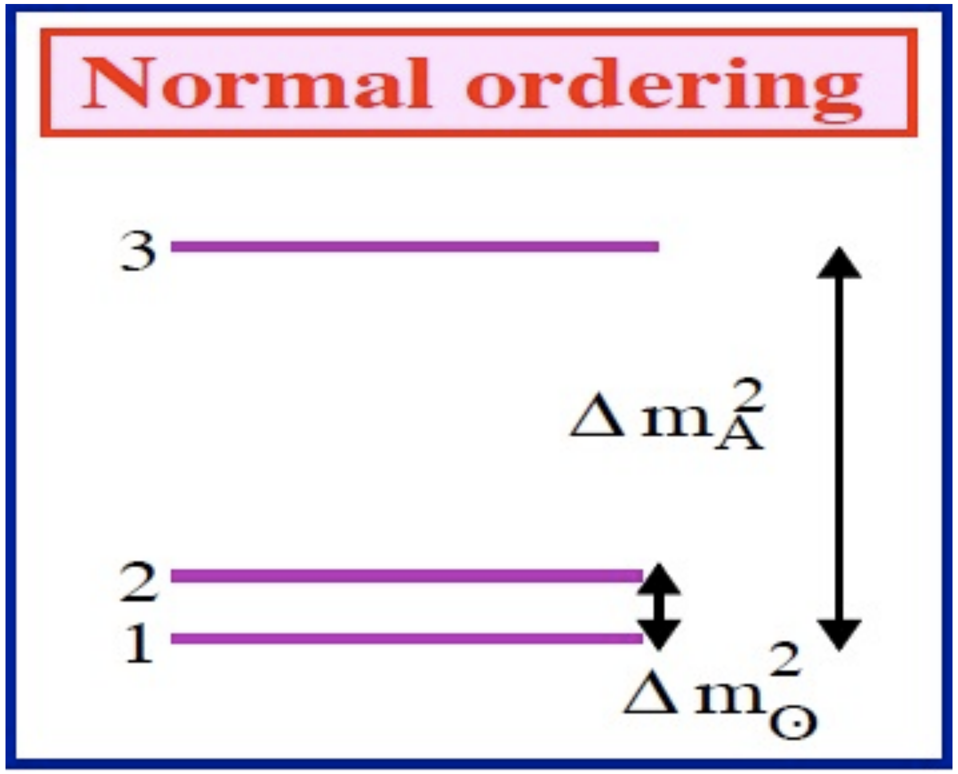


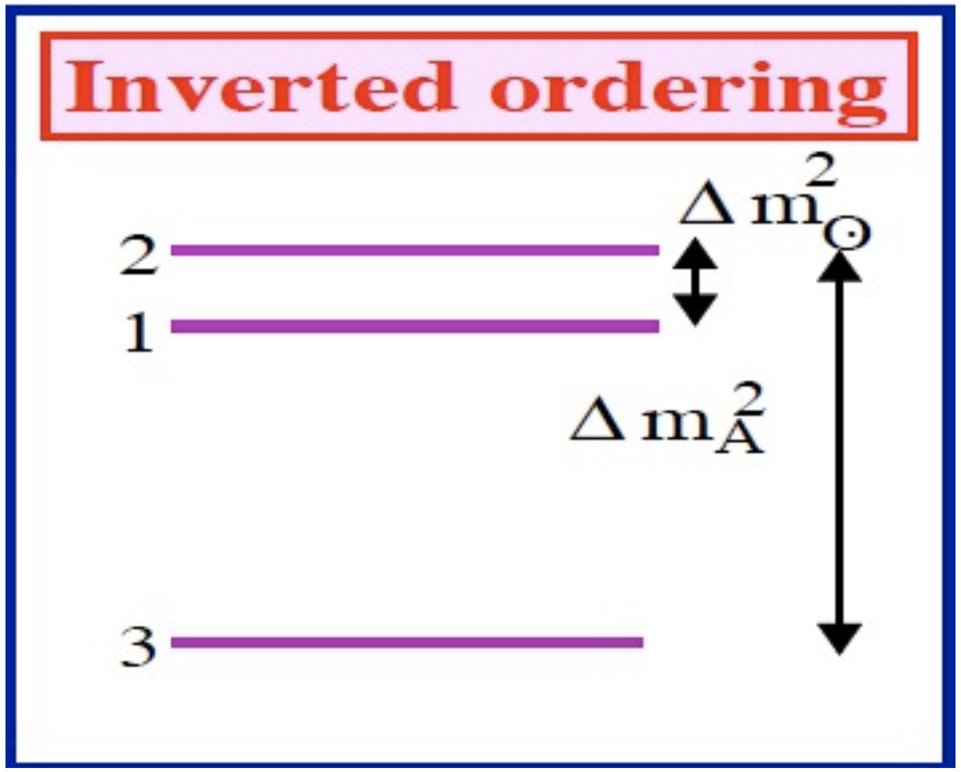


Kopp et al., 1303.3011

Present status of (standard) neutrino physics

$\Delta m_s^2 \ll \Delta m_A^2$ implies at least 3 massive neutrinos.





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

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

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

Neutrino mixing

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

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

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

$$U = \underset{\text{Solar, reactor } \theta_\odot \sim 30^o}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \underset{\text{Atm, Acc. } \theta_A \sim 45^o}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}$$

$$\underset{\text{CPV phase}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}} \underset{\text{Reactor, Acc. } \theta_{13} \sim 9^o}{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}} \underset{\text{CPV Majorana phases}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}}$$

CP-conservation requires U is real $\Rightarrow \delta = 0, \pi$

CPV effects in neutrino oscillations

In many experimental situations the probabilities can be approximated for 2 neutrinos. In this case there are no CPV effects.

- $\boxed{\frac{\Delta m^2_{21}}{4E} L \ll 1}$, applies to atmospheric, reactor (CHOOZ...), current accelerator neutrino experiments

$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) &= 4\,|U_{\alpha 3} U_{\beta 3}|^2 \sin^2(\frac{\Delta m^2_{31}}{4E} L) \\
P(\nu_\mu \to \nu_e; t) &= s^2_{23} \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
P(\nu_e \to \nu_e; t) &= 1 - \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m^2_{31} L}{4E}
\end{aligned}
$$

- $\boxed{\frac{\Delta m^2_{31}}{4E} L \gg 1}$: for reactor neutrinos (KamLAND).

The oscillations due to the atmospheric mass squared differences get averaged out.

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

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

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

- 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 effective 2-neutrino probabilities are CP-symmetric.

Neutrino oscillations in matter

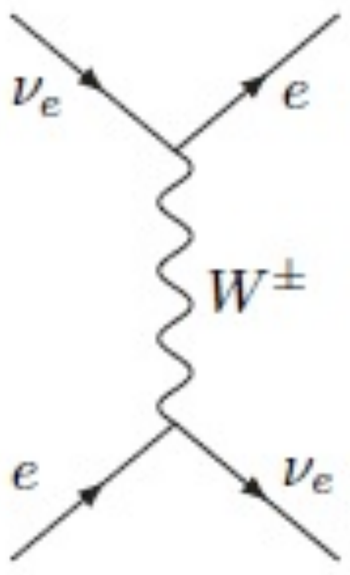
- When neutrinos travel through a medium, they interact with the background of electron, proton and neutrons and acquire an effective mass and oscillations are modified.
- Typically the background is CP and CPT violating and the resulting oscillations are CP and CPT violating.

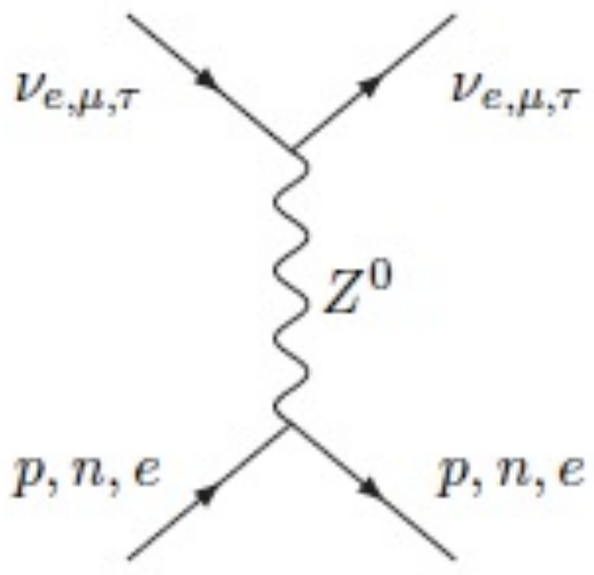
Neutrinos undergo forward elastic scattering. [L.Wolfenstein, Phys. Rev. D 17, 2369 (1978); ibid. D 20, 2634 (1979), S. P. Mikheyev, A. Yu Smirnov, Sov. J. Nucl. Phys. 42 (1986) 913.]

$$\mathcal{L}_{4-f} = -2\sqrt{2}G_F(\bar{\nu}_{eL}\gamma^\rho \nu_{eL})(\bar{e}_L\gamma_\rho e_L) + \cdots$$

If additional interactions were present, these would modify the matter effects we observe.

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





For a useful discussion, see E. Akhmedov, hep-ph/0001264; A. de Gouvea, hep-ph/0411274.

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

medium	$A_{\rm CC}$ for $\nu_e, \bar\nu_e$ only	$A_{\rm NC}$ for $\nu_{e,\mu,\tau}, \bar\nu_{e,\mu,\tau}$
$e, \bar e$	$\pm\sqrt{2}G_{\rm F}(N_e - N_{\bar e})$	$\mp\sqrt{2}G_{\rm F}(N_e - N_{\bar e})(1-4s_{\rm W}^2)/2$
$p, \bar p$	0	$\pm\sqrt{2}G_{\rm F}(N_p - N_{\bar p})(1-4s_{\rm W}^2)/2$
$n, \bar n$	0	$\mp\sqrt{2}G_{\rm F}(N_n - N_{\bar n})/2$
ordinary matter	$\pm\sqrt{2}G_{\rm F}N_e$	$\mp\sqrt{2}G_{\rm F}N_n/2$

Strumia and Vissani

The full Hamiltonian in matter can then be obtained by adding the potential terms, diagonal in the flavour basis. For electron and muon neutrinos

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

For antineutrinos the potential has the opposite sign.

In general the evolution is a complex problem (e.g. for atmospheric neutrinos, see talks later) but there are few cases in which analytical or semi-analytical results can be obtained (atmospheric neutrino in some cases, long baseline neutrino, solar neutrino oscillations) .

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

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

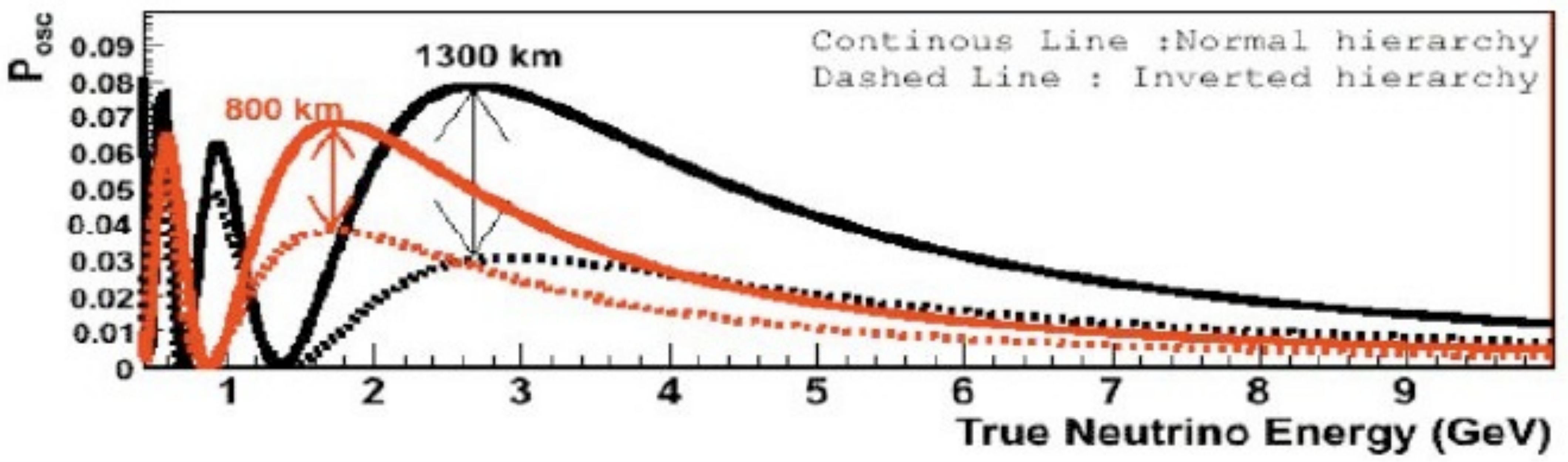
- The oscillation probability can be obtained as in the two neutrino mixing case but with

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

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

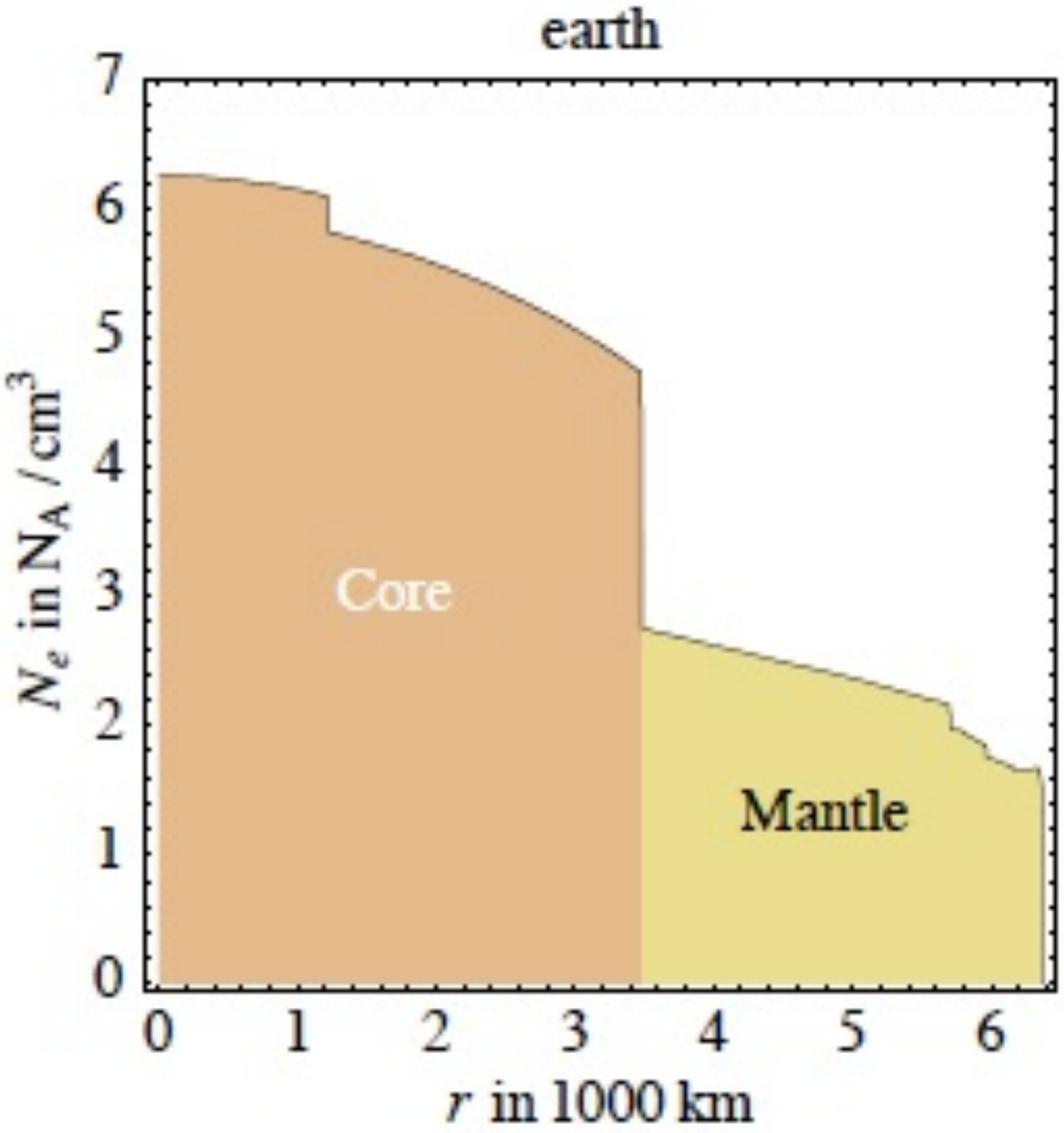
- If $\boxed{\sqrt{2}G_F N_e = \frac{\Delta m^2}{2E}\cos 2\theta}$: resonance $\boxed{\theta_m = \pi/4}$

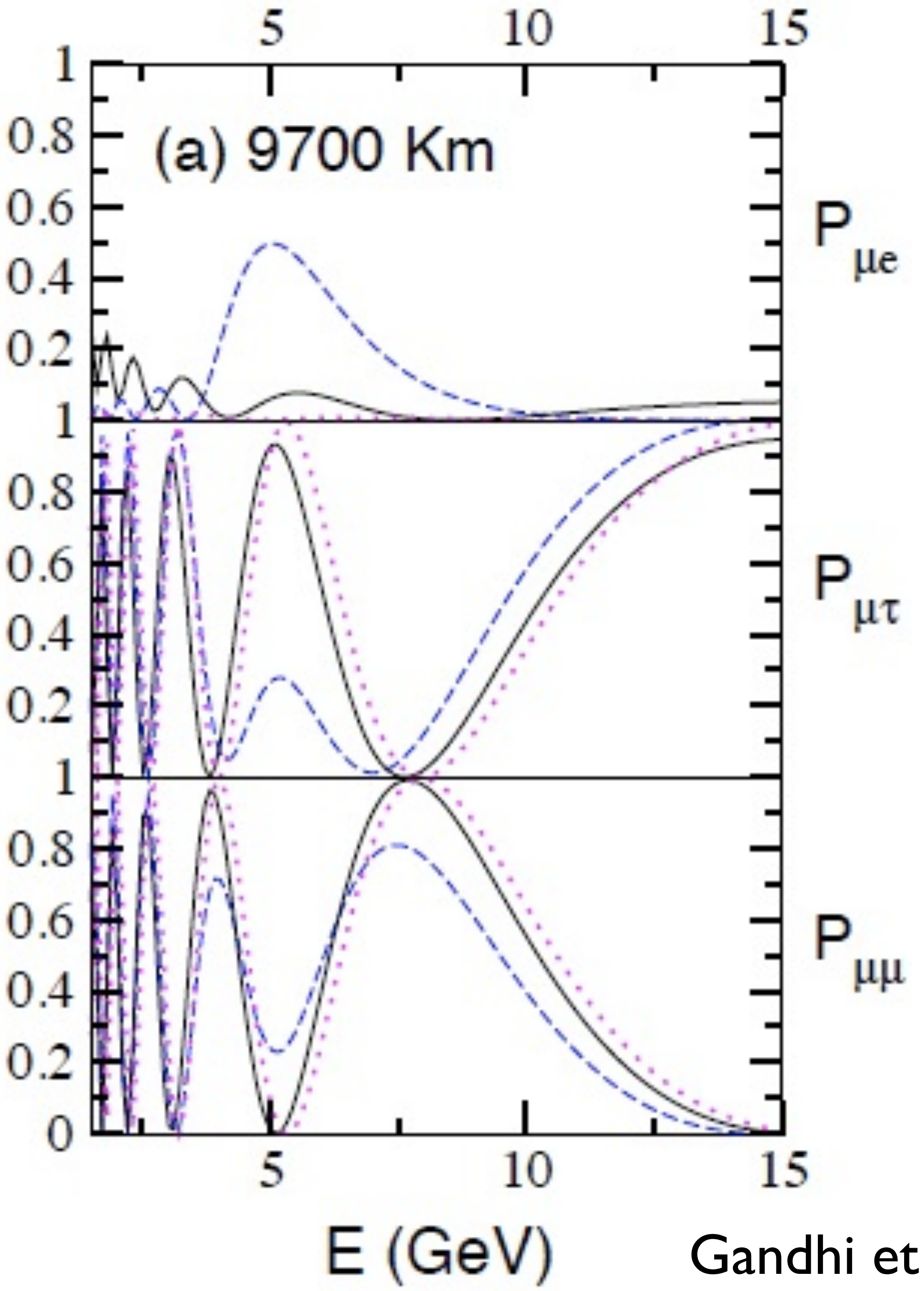
- The resonance condition can be satisfied for
  - neutrinos if $\Delta m^2 > 0$
  - antineutrinos if $\Delta m^2 < 0$



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 neutrinos.





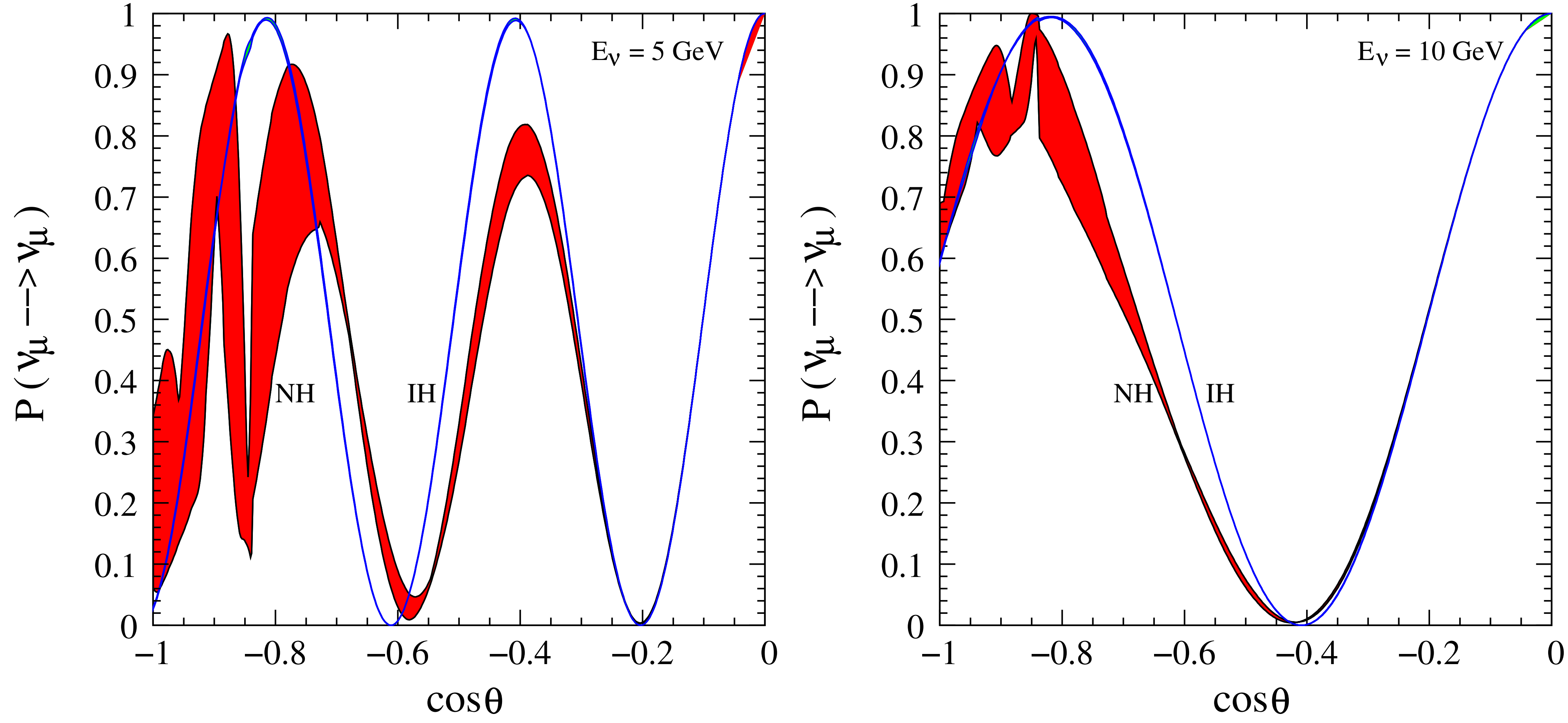
Gandhi et al., 2004

For large theta13 and subdominant 1-2 oscillations

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

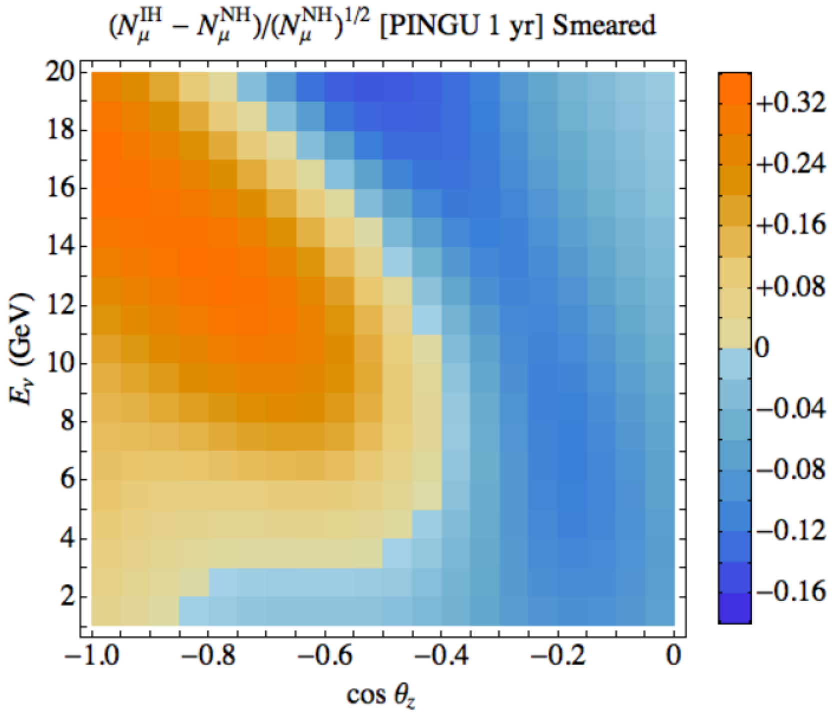
See Palomares-Ruiz's talk.

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

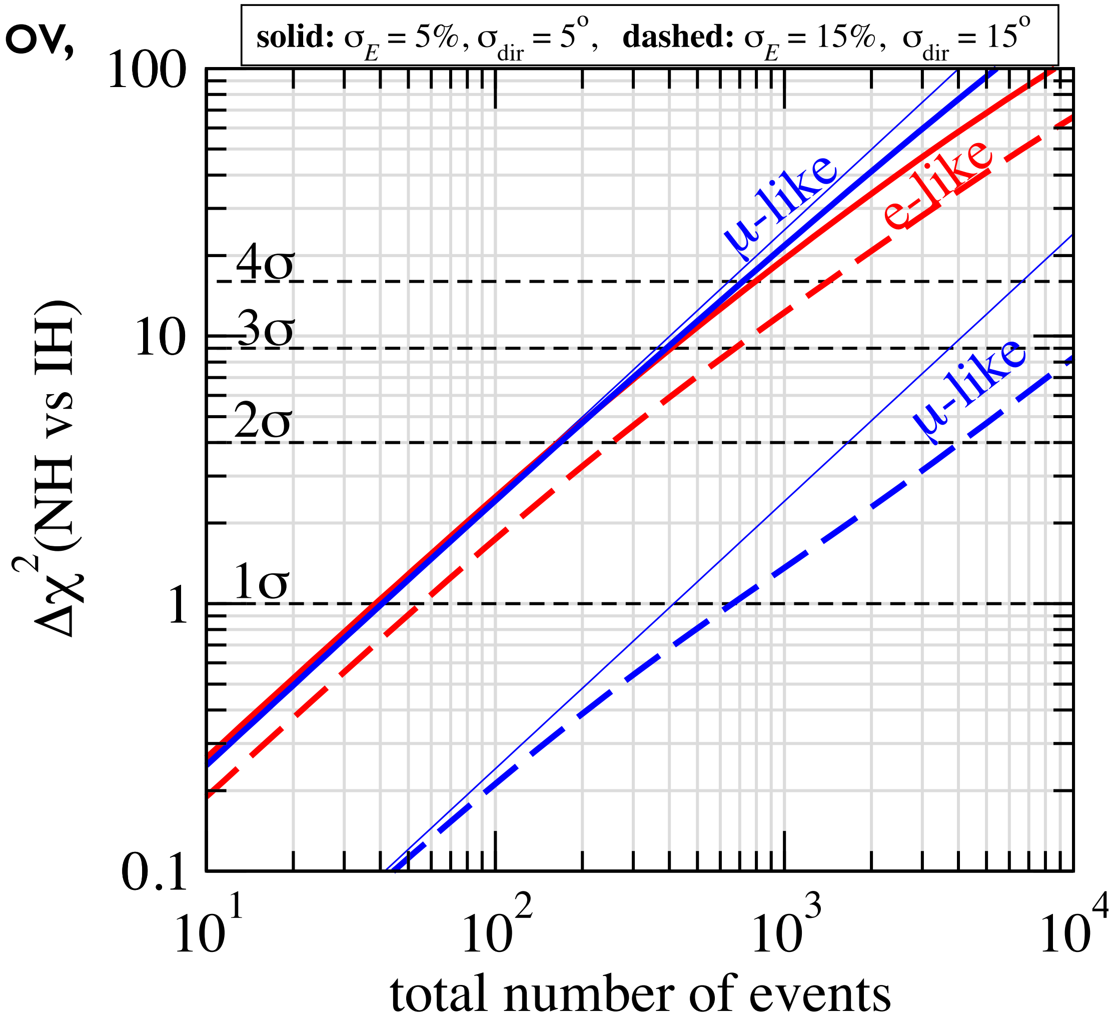


Atmospheric neutrino oscillations can determine the mass ordering, with large number of events, good energy and angular resolution.

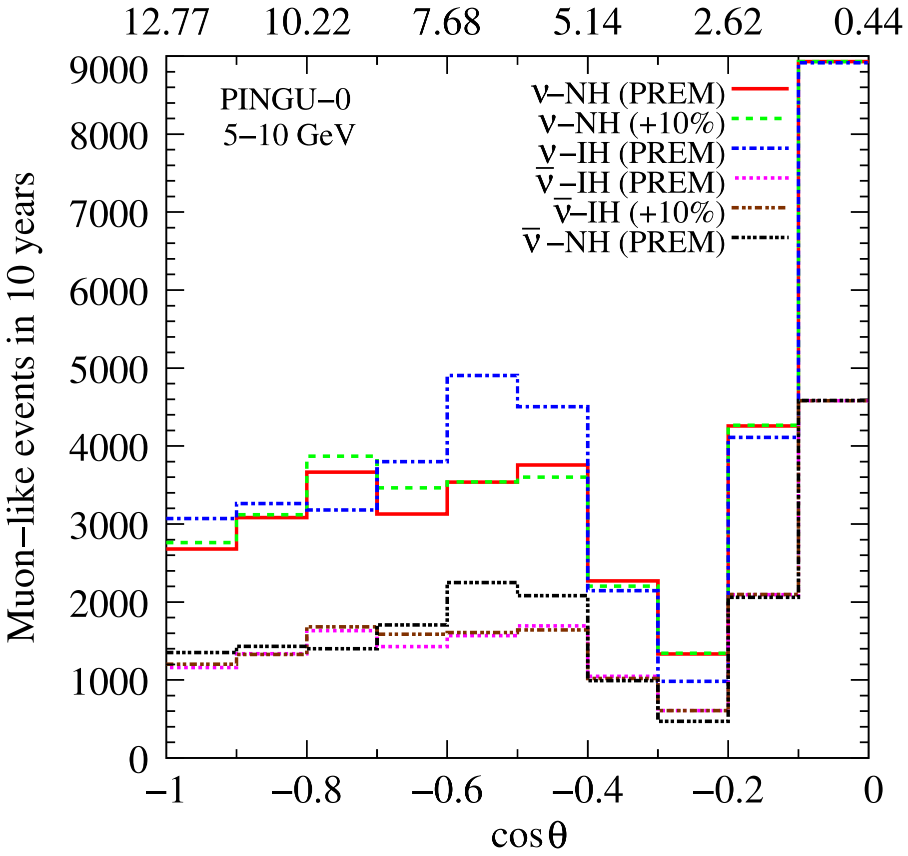
Petcov et al.; Chizov et al.; Akhmedov, Smirnov et al.; Gandhi et al.; Mena et al.; Schwetz et al.; Koskinen; Gonzalez-Garcia et al.; Barger et al



Akhmedov, Razzaque, Smirnov, 1205.8071



Petcov, Schwetz, hep-ph/0511277



Agarwalla et al., 1212.2238

PINGU in IceCube, ORCA in KM3Net

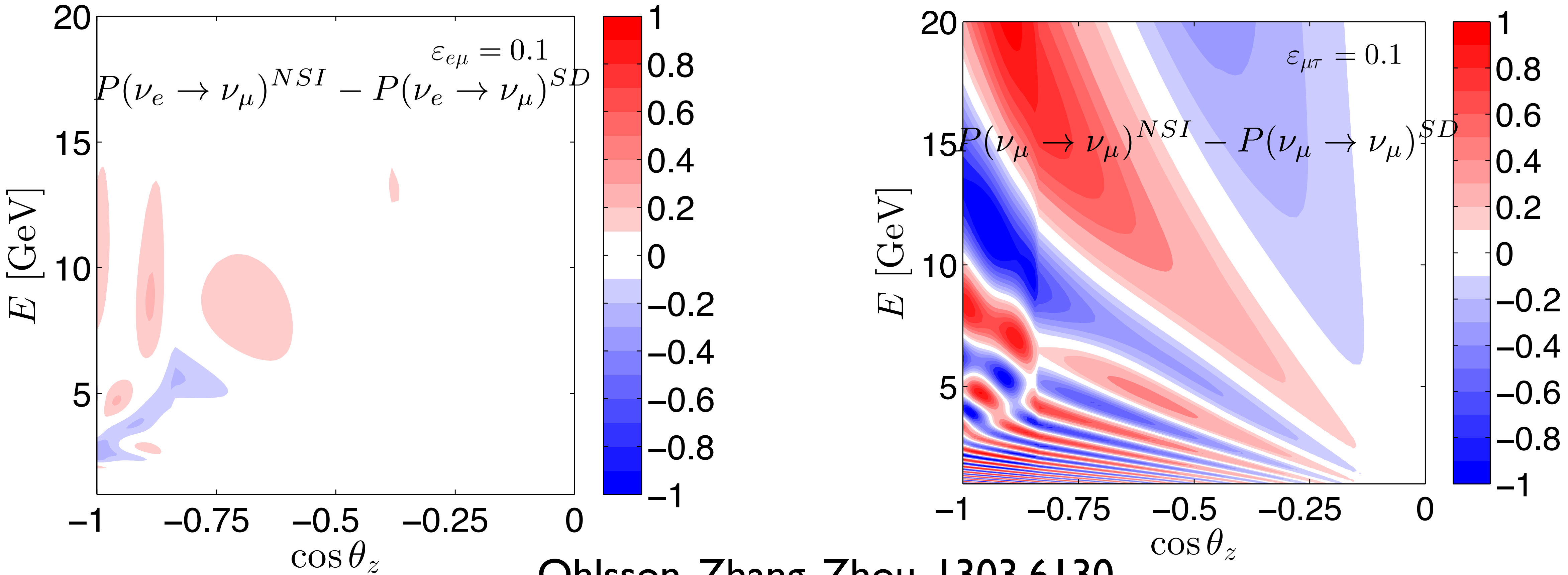
See Palomares-Ruiz's, Ribordy's, Shanidze's and Meregaglia's talks.

In presence of “new” neutrino interactions, matter effects can be modified significantly (NSI).

$$\mathcal{H}_{\rm m}(x) = V_{\rm CC}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix} \qquad \mathcal{H}_{\rm NSI}(x) = V_{\rm CC}\begin{pmatrix}\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}$$

$$\begin{pmatrix}|\varepsilon_{ee}| < 4.2 & |\varepsilon_{e\mu}| < 0.33 & |\varepsilon_{e\tau}| < 3.0\\ & |\varepsilon_{\mu\mu}| < 0.068 & |\varepsilon_{\mu\tau}| < 0.33\\ & & |\varepsilon_{\tau\tau}| < 21\end{pmatrix}$$

Biggio et al., JHEP 2009



Ohlsson, Zhang, Zhou, 1303.6130

Is it important to determine the mass ordering?

- This is the key information to establish neutrino masses -> critical to study the origin of neutrino masses and of flavour.

- It has also important phenomenological consequences, allowing to extract further information from other experiments:
  - long baseline neutrino experiments
  - neutrinoless double beta decay

Long baseline neutrino oscillations

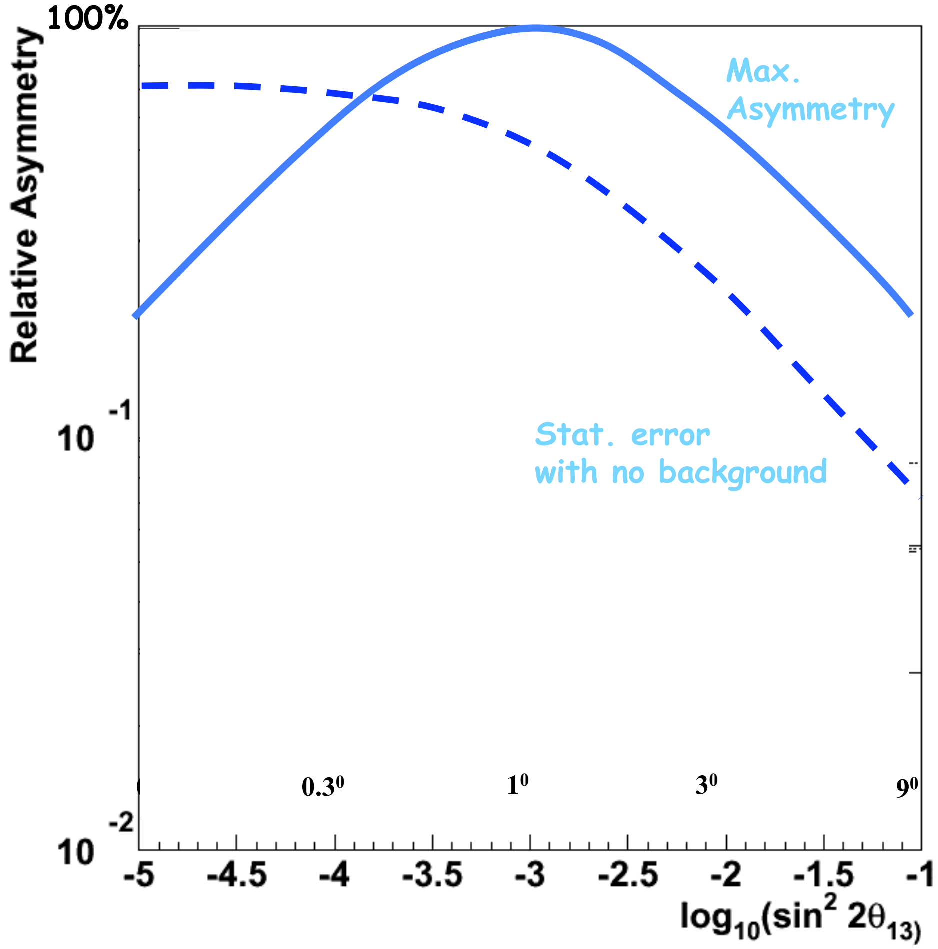
Long baseline neutrino oscillation experiments will aim at studying the subdominant channels

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

CP-violation

Matter effects

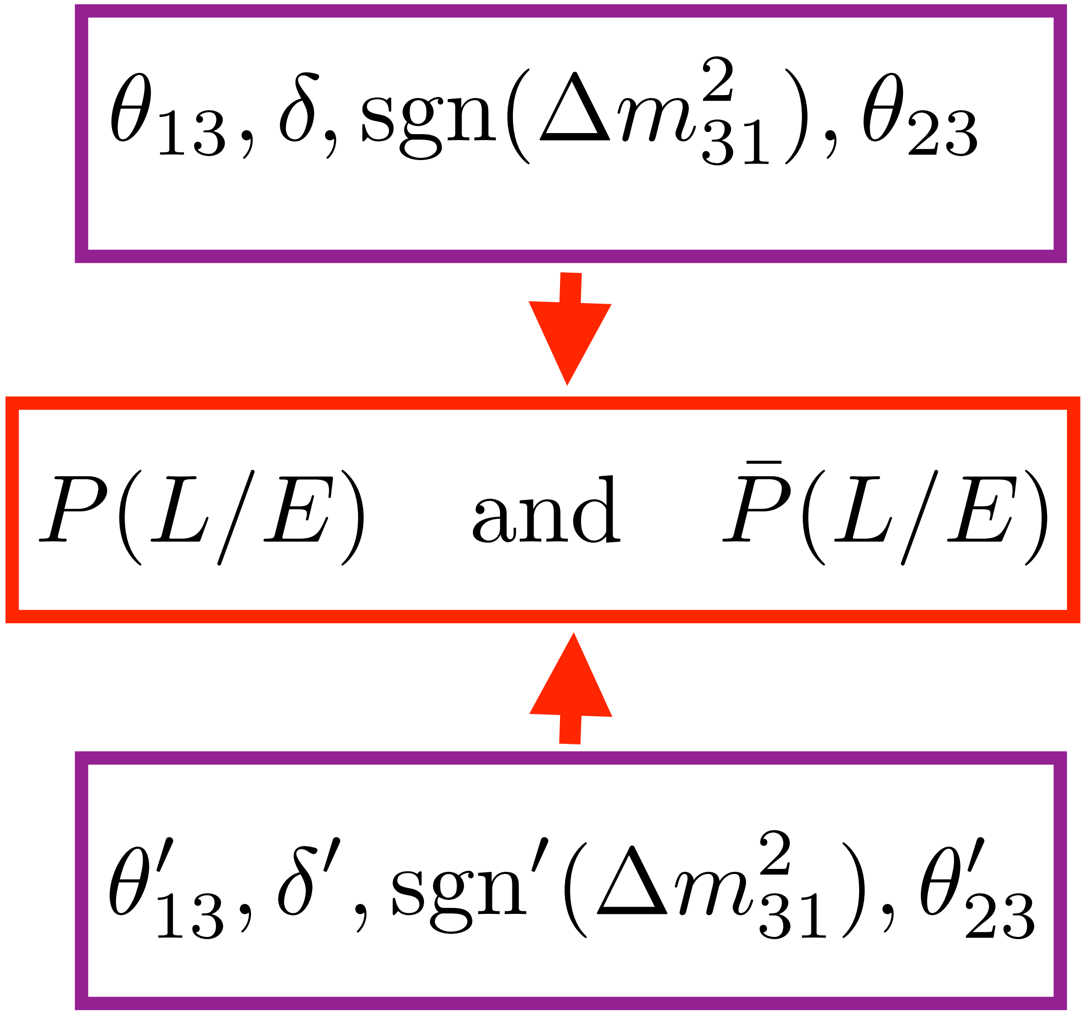
The CP asymmetry peaks for sin^2 2 theta13 ~0.001. Large theta13 makes its searches possible but not ideal.



A. Blondel

Degeneracies

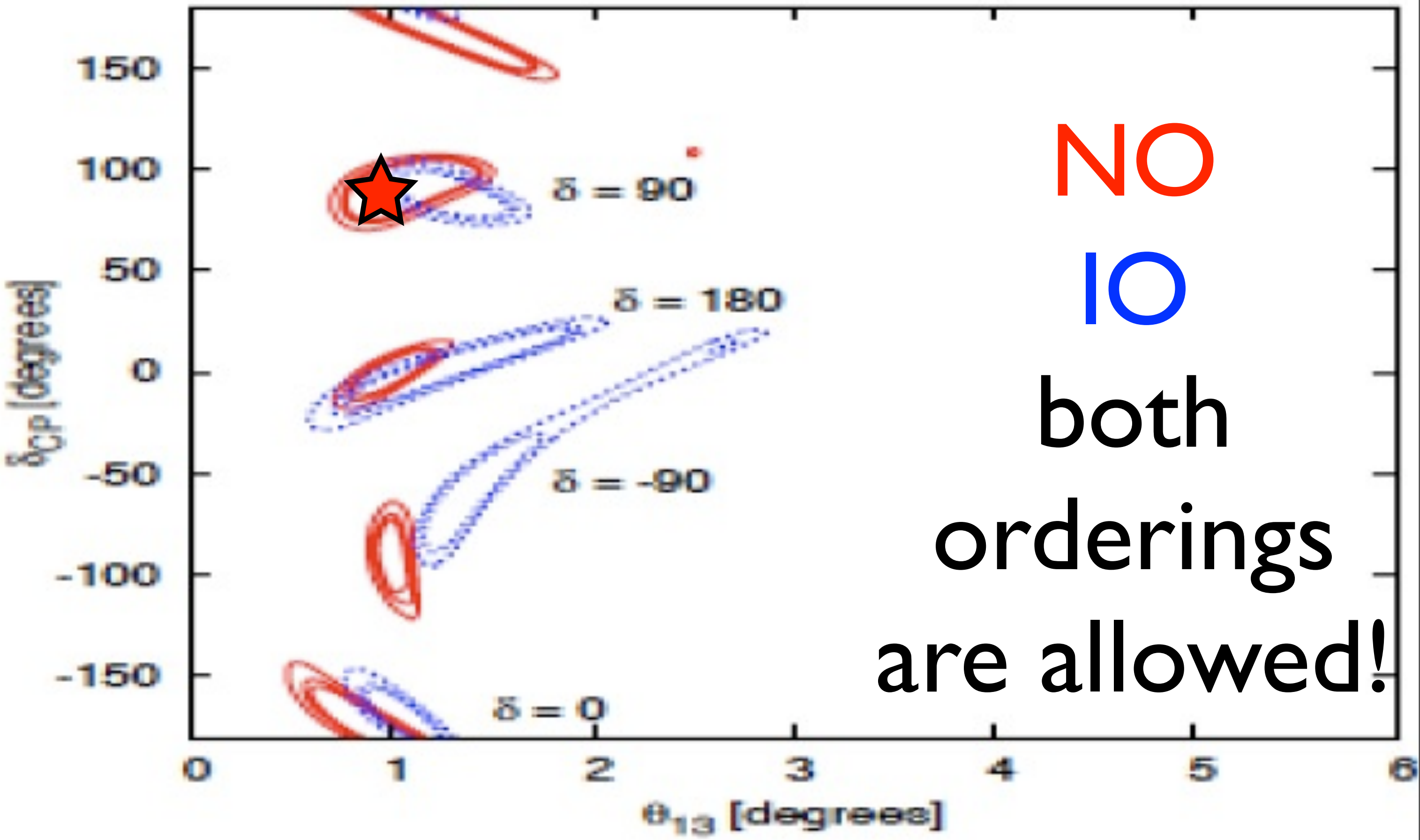
The determination of CPV and the mass ordering is complicated by the issue of **degeneracies**: different sets of parameters which provide an equally good fit to the data (eight-fold degeneracies).



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

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

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



NO

IO

both orderings are allowed!

Knowing the ordering allows to get better sensitivity to CP-violation.

Future long baseline experiments

- 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

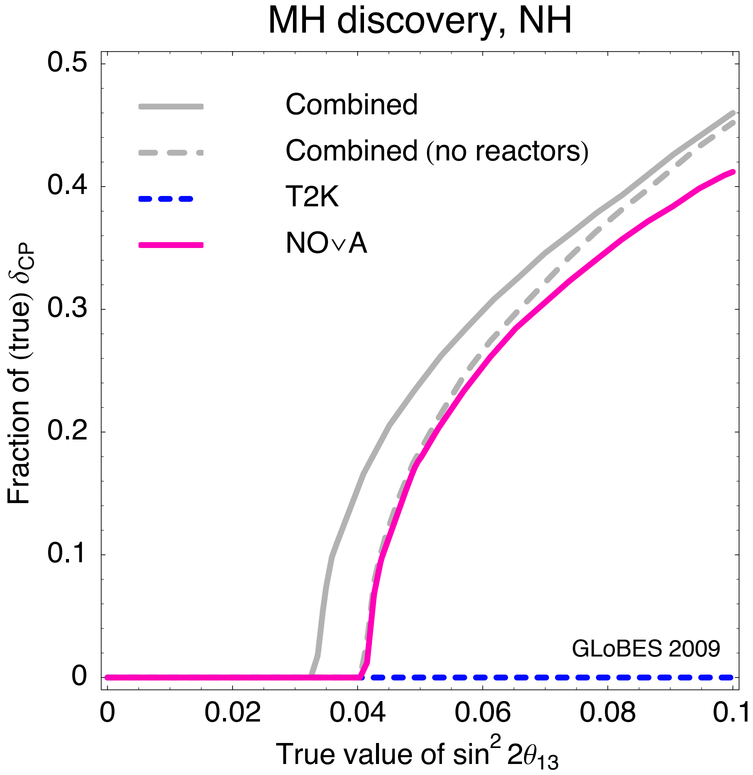
- Neutrino factory: Use muon and electron neutrinos from high-gamma muon decays and need a magnetised detector. It would be able to determine the mass ordering very rapidly.

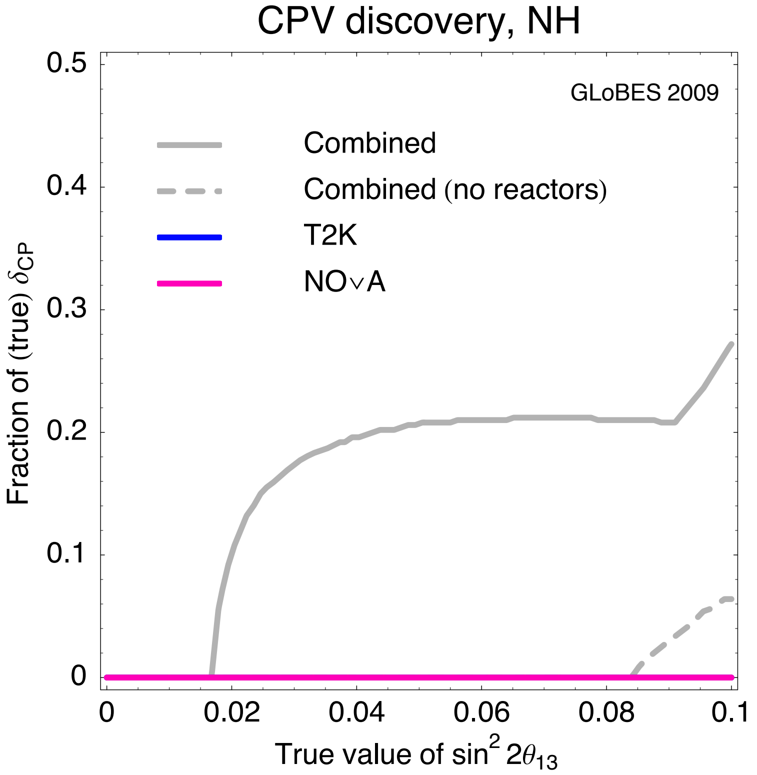
Long term

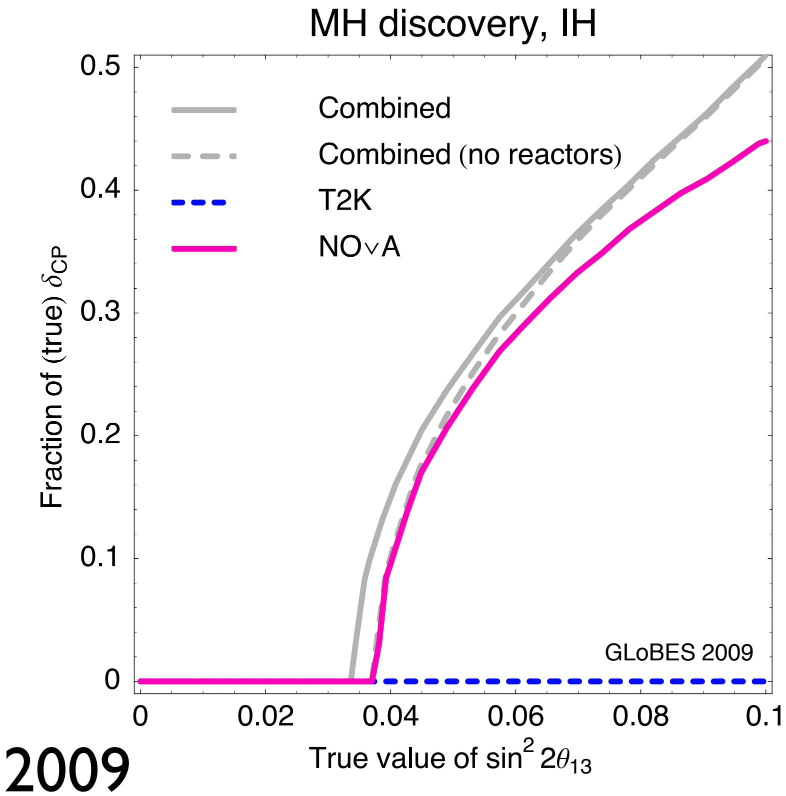
T2K is currently running and NOvA will start data taking this year. They will have little sensitivity to mass ordering and CPV.

See Vissani's, Brunner's, Buizza-Avanzini's talks.

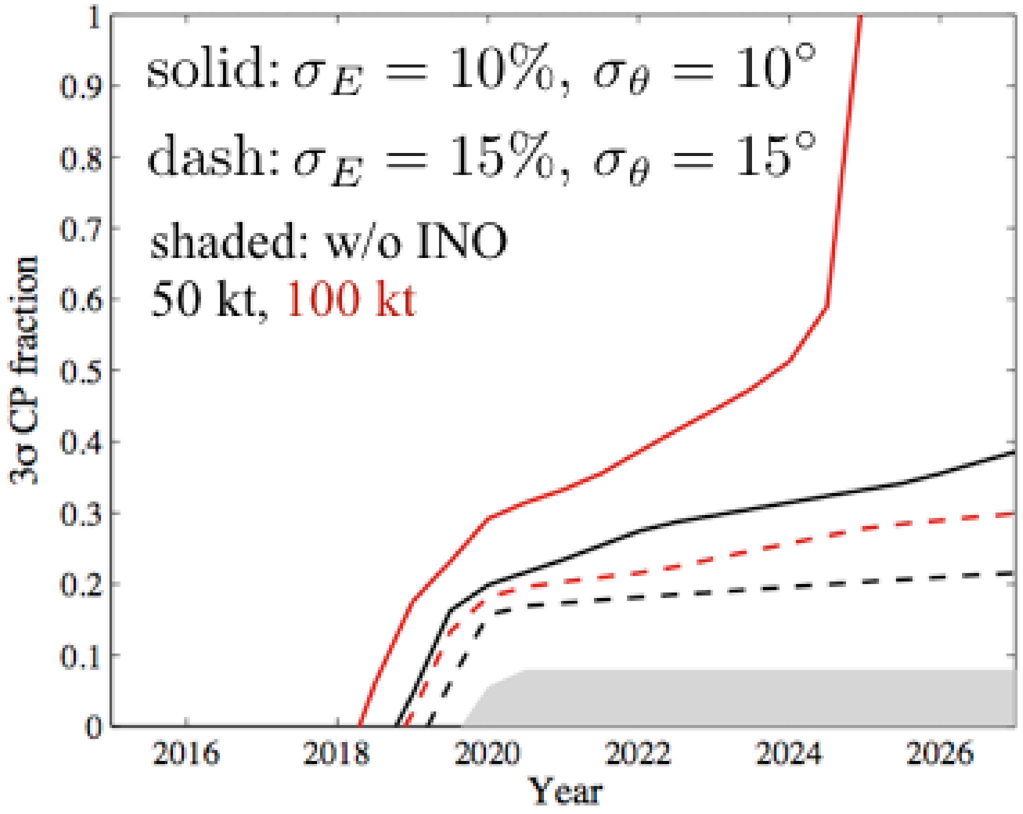
90% CL reach for T2K (0.75 MW 5 yrs), NOvA (0.7 MW, 3 yrs, nu+nubar, 15 kton detector)


MH discovery, NH


CPV discovery, NH


MH discovery, IH

Huber at al., 2009

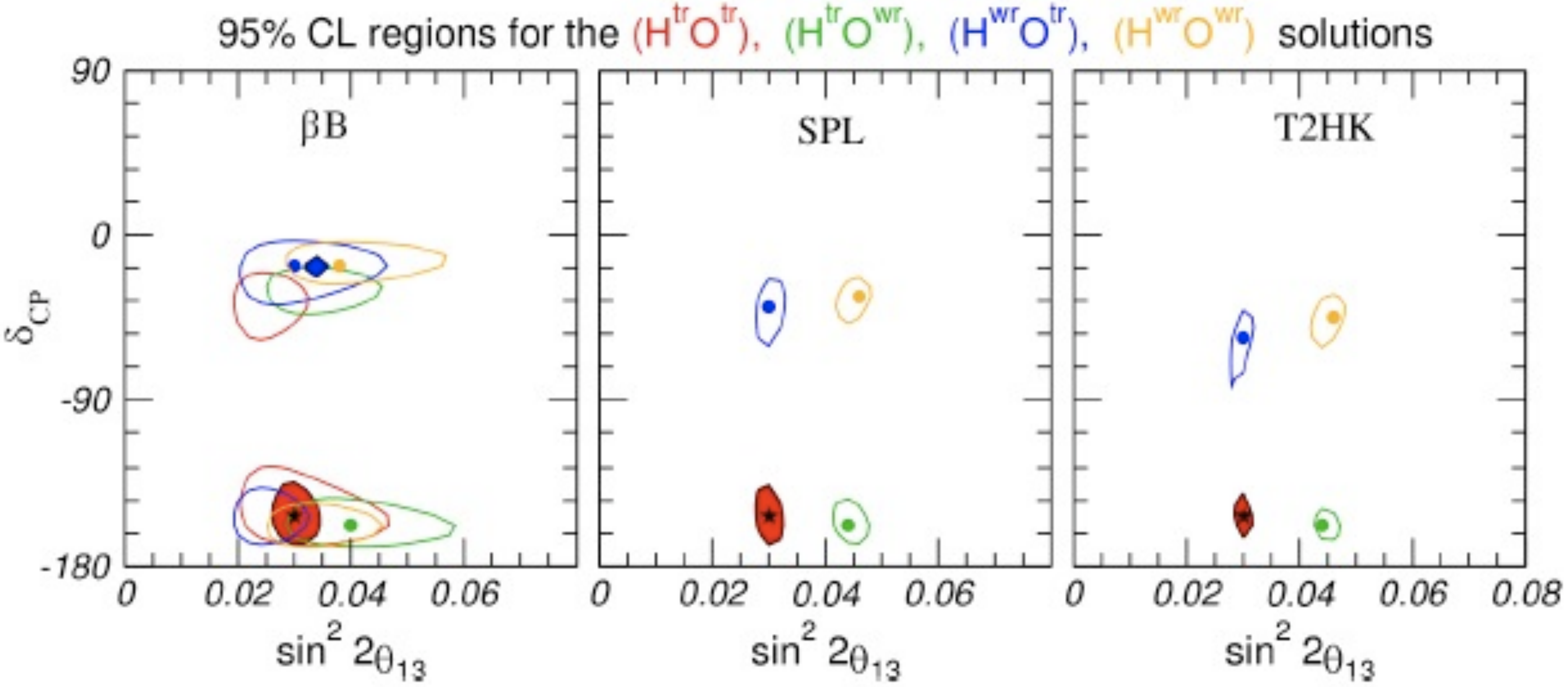


INO +T2K, NOvA

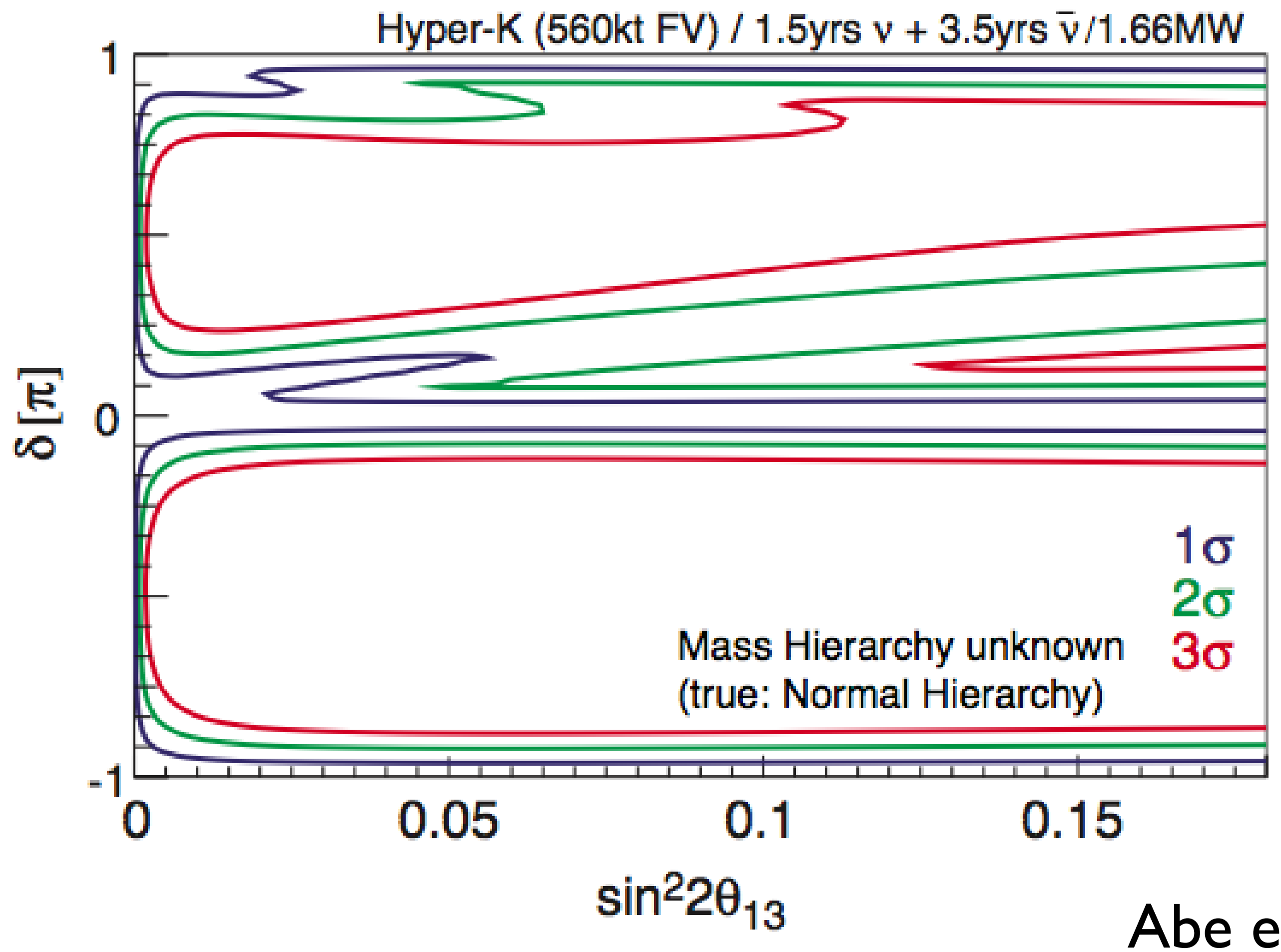
Blennow, Schwetz, 1203.3388

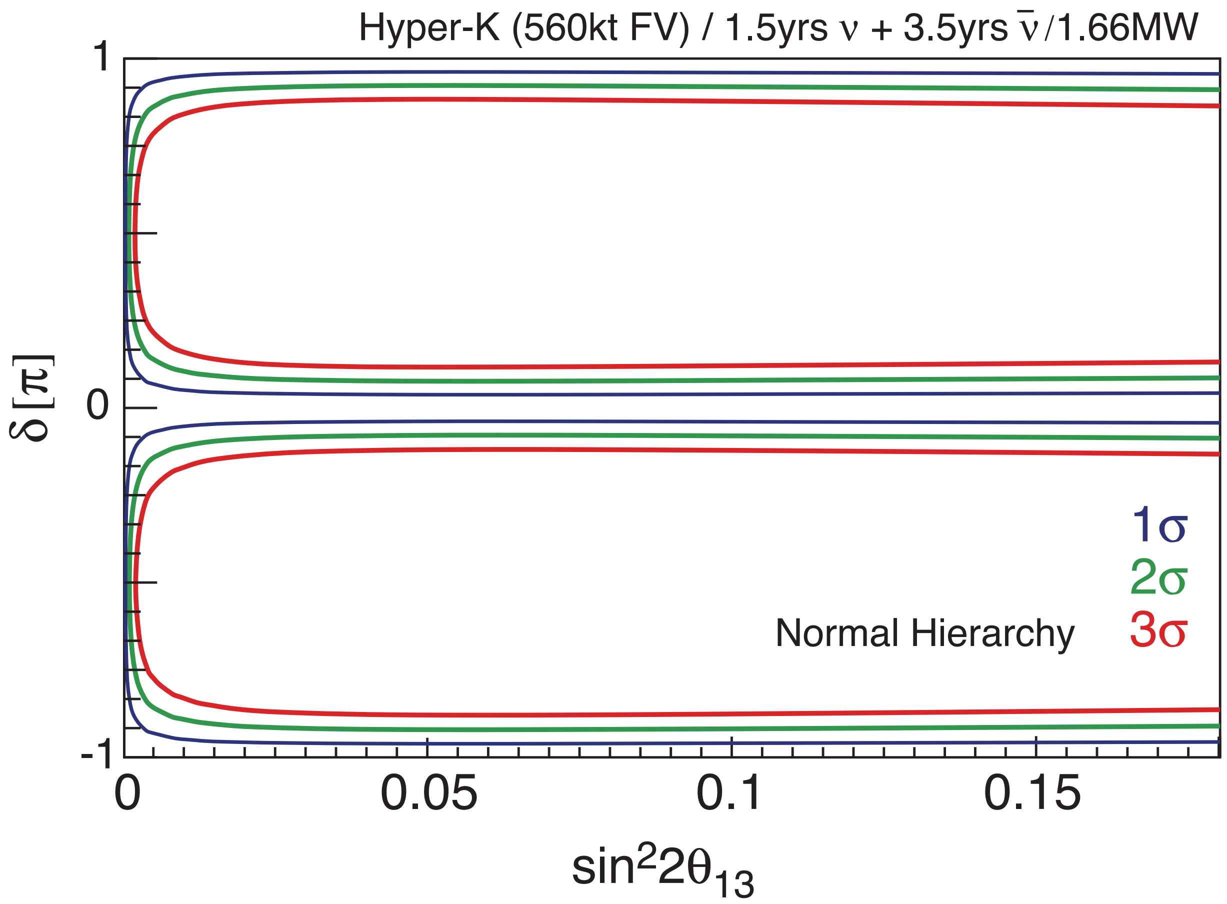
Medium baseline experiments

Experiments with distances of 100-400 km have subdominant matter effects and they cannot determine the mass ordering for all CPV values. This consequently affects their ability to discover CPV.



Campagne, Maltoni,
Mezzetto, Schwetz





Abe et al., 1109.3262.

- Knowing the mass ordering will also impact on the planning of future experiments and in particular on the choice of neutrino vs antineutrino running lengths. If NO, the neutrino signal is enhanced, if IO the antineutrinos gain impact on CPV searches.

Impact on neutrinoless betabeta-decay

The predictions for |<m>| depend on the neutrino mass spectrum (and therefore on the ordering)

- NH (m1<<m2<<m3): |<m>| ~ 2.5-3.9 meV

$$|<m>| \simeq \left| \sqrt{\Delta m^2_\odot} \cos^2\theta_{13} \sin^2\theta_\odot + \sqrt{\Delta m^2_{\mathrm{atm}}} \boxed{\sin^2\theta_{13}} e^{i\alpha_{32}} \right|$$

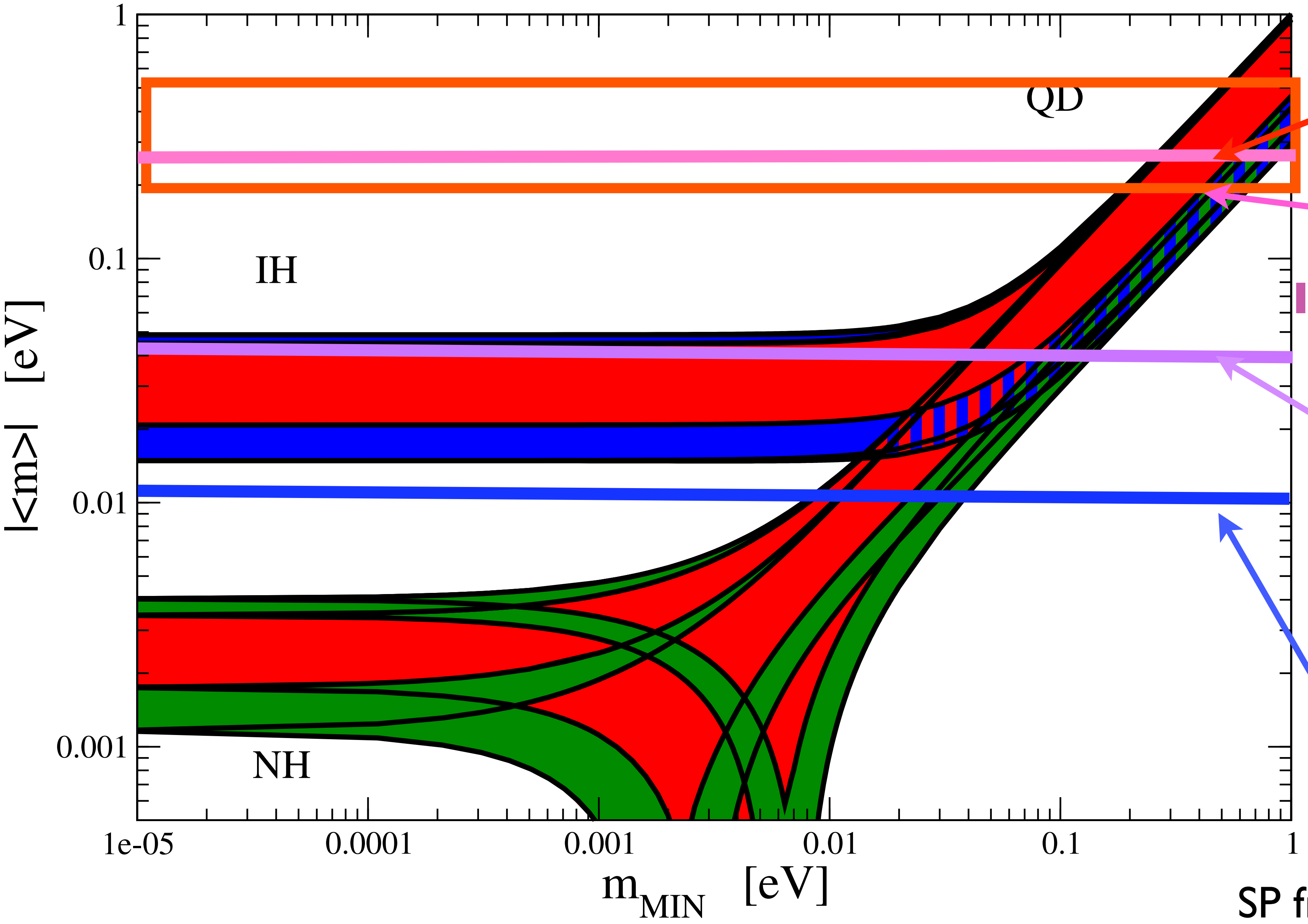
- IH (m3<<m1~m2): 10 meV < |<m>| < 50 meV

$$\sqrt{\Delta m^2_{\mathrm{atm}}} \boxed{\cos 2\theta_\odot} \le |<m>| \simeq \sqrt{\left(1 - \sin^2 2\theta_\odot \sin^2 \frac{\alpha_{21}}{2}\right)\Delta m^2_{\mathrm{atm}}} \le \sqrt{\Delta m^2_{\mathrm{atm}}}$$

- QD (m1~m2~m3): 44 meV < |<m>| < m1

$$|<m>| \simeq m_{\bar{\nu}_e} \left| \left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}}\right) \cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}} \right|$$

$$|\langle m\rangle| \sim \left|\boxed{m_1}\cos^2\theta_{12} + \boxed{m_2}\sin^2\theta_{12}e^{i\alpha_{21}} + \boxed{m_3}\sin^2\theta_{13}e^{i\alpha_{31}}\right|$$



Klapdor-Kleingrothaus claim 2002 and 2006

Present bounds: Heidelberg-Moscow, IGEX, Cuoricino and NEMO3

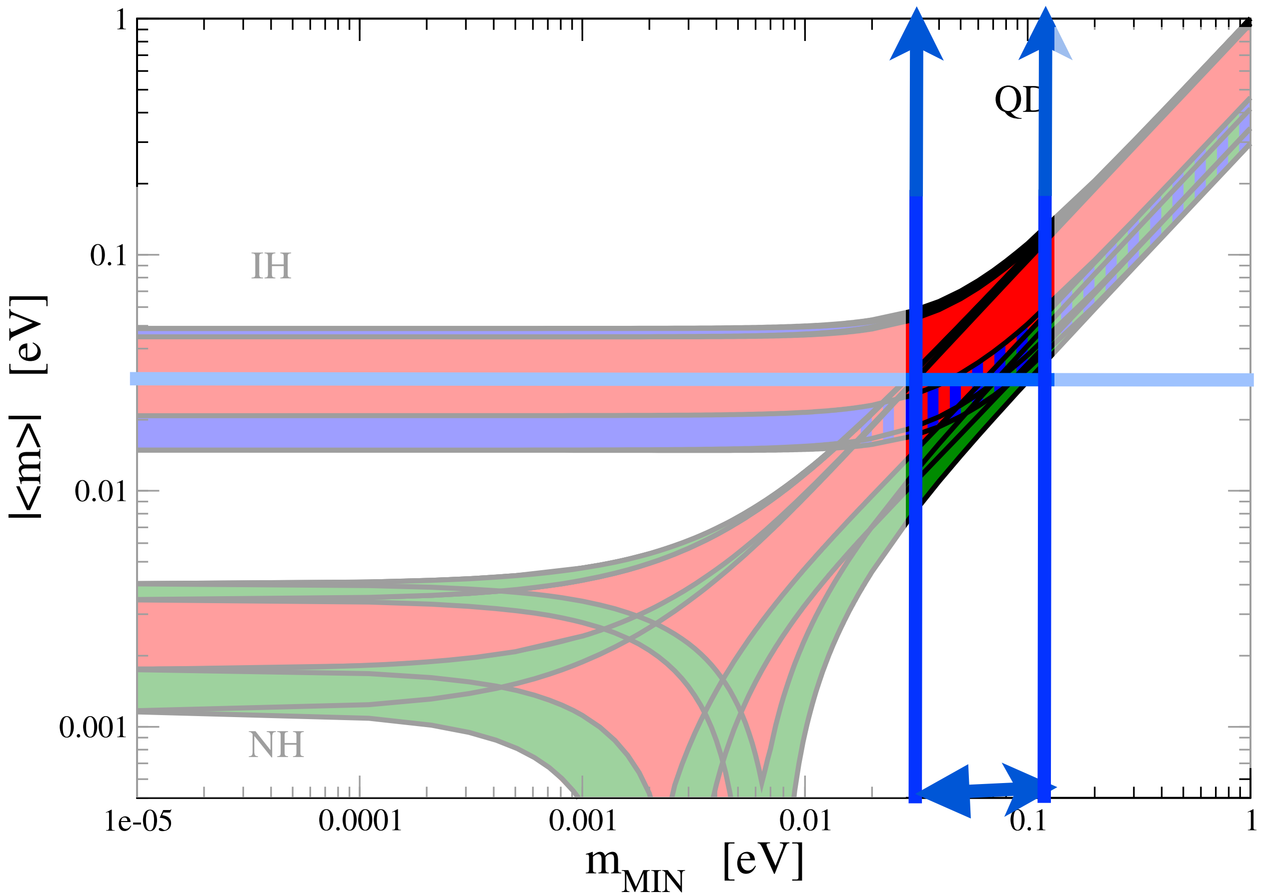
Next generation: GERDA, KamLAND-ZEN, EXO, CUORE, SuperNEMO, SNO+, Majorana, COBRA...

Future experiments: ~1 ton

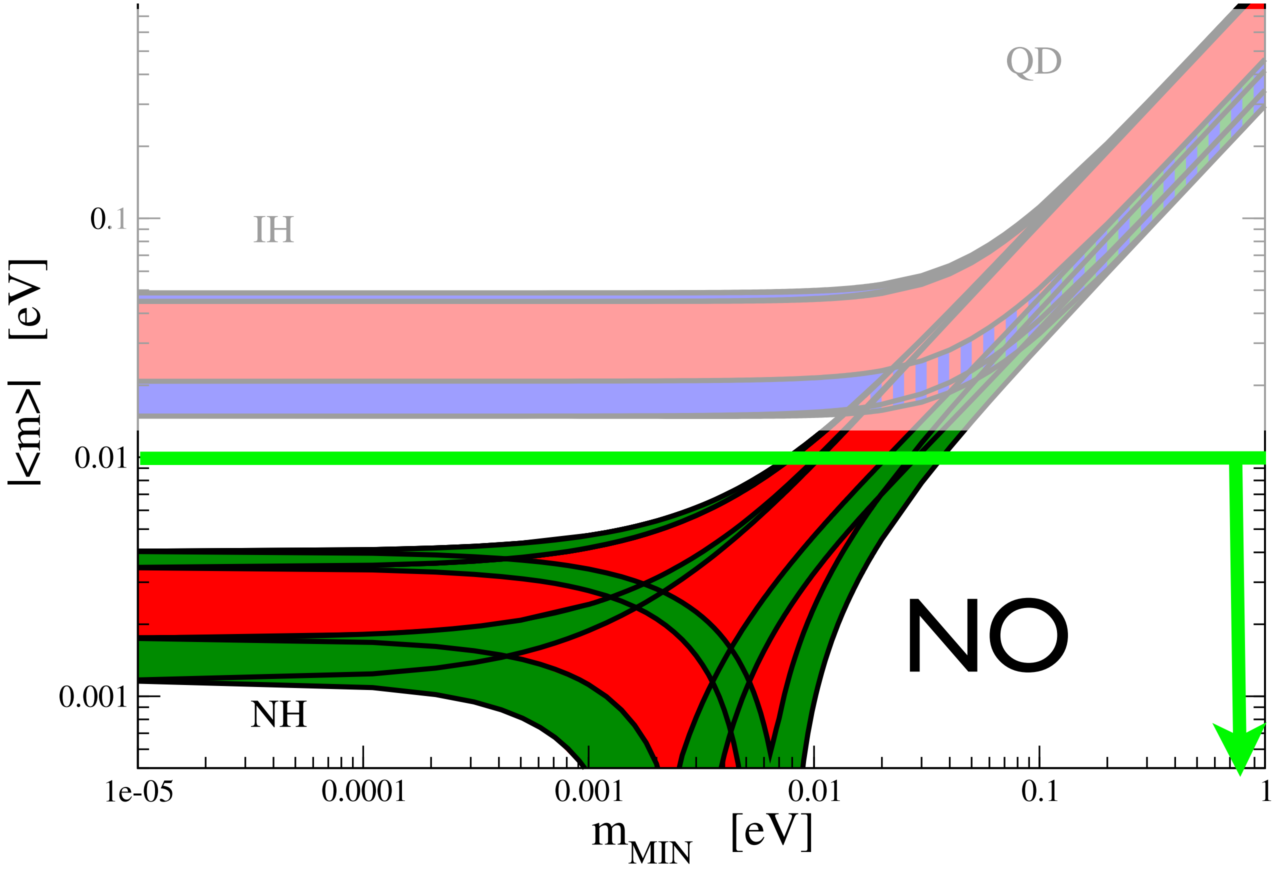
SP from Nakamura, Petcov review in PDG

Wide experimental program for the future: **a positive signal would indicate that L is violated!**

Knowing the mass ordering in neutrinoless dbeta decay



- If experiments find NO and |<m>| > 10 meV:
  - either m1 in in the 20-100 meV region;
  - or m1 smaller but a new mechanism is responsible for the signal.



- • If no signal for |<m>| ~10 meV, then only NO is allowed.
  • If experiments find IO, neutrino are Dirac particles (without fine-tuned cancellations).

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 oscillation experiments.
- Matter effects can determine the mass ordering in atmospheric and LBL experiments. Other strategies include SN neutrino (See Volpe's talk) and reactor neutrino exps (See Novella Garijo's talk).
- Determining the mass ordering is crucial for theoretical reasons (origin of neutrino masses and of flavour structure) and phenomenologically (impact on medium baseline LBL and on neutrinoless double beta decay, and cosmology (See Rich's talk)).