Neutrino oscillation phenomenology at long-baseline experiments

Pilar Coloma

Fermilab

FNAL theory seminar

Feb 16th, 2014

Current status in neutrino oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Reactor/Interference Solar

$$\begin{aligned} \theta_{12} &\sim 33^\circ \\ \theta_{23} &\sim 45^\circ \\ \theta_{13} &\sim 8.5^\circ \\ \Delta m^2_{21} &\sim 7.5 \times 10^{-5}\text{eV}^2 \\ \Delta m^2_{31} &\sim \pm\, 2.45 \times 10^{-3}\text{eV}^2 \end{aligned}$$

Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439 [hep-ph]

(see also Capozzi et al 1312.2878 [hep-ph] and Forero et al, 1405.7540[hep-ph])

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Atmospheric — Reactor/Interference — Solar

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Unknowns:

δ ?

Octant of θ_{23} ?

Mass ordering ?

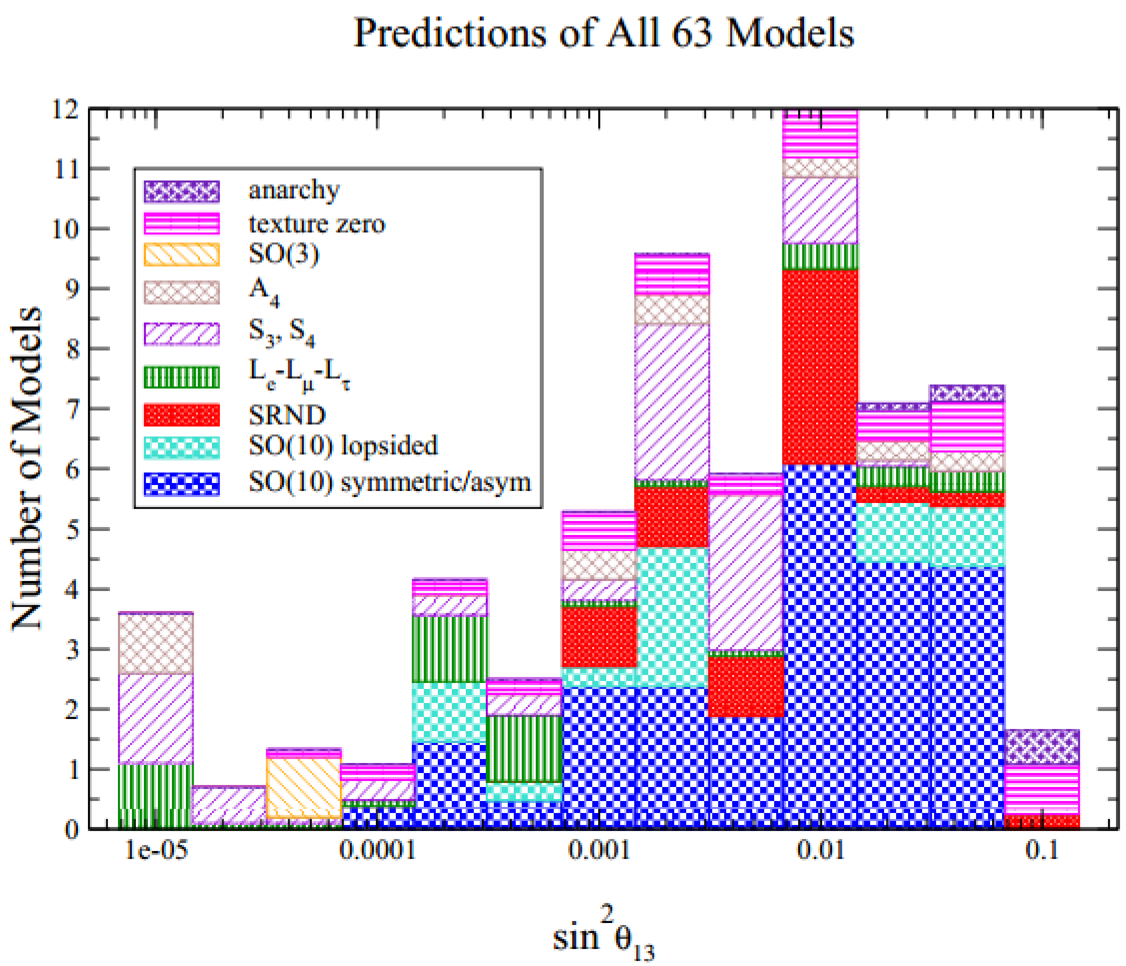
New Physics ?

Majorana/Dirac ?

Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439 [hep-ph]

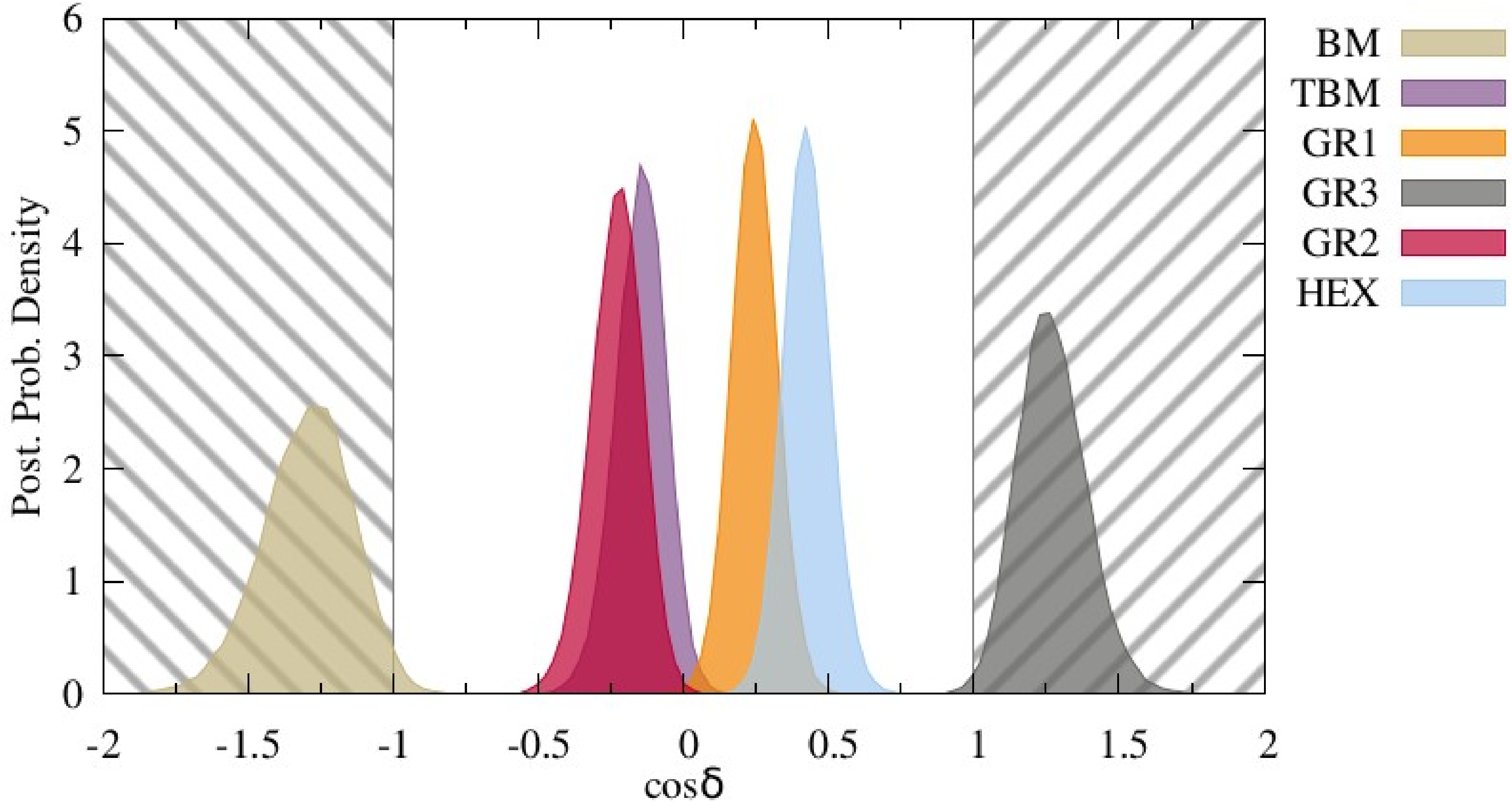
(see also Capozzi et al 1312.2878 [hep-ph] and Forero et al, 1405.7540[hep-ph])

Why precision?



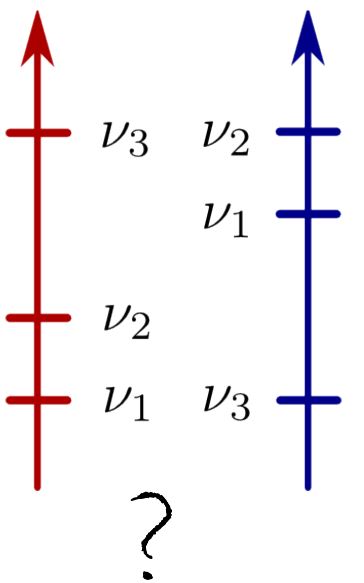
Albright and Chen, hep-ph/0608137, and Albright, 0911.2437
(see also, e.g., Albright, Dueck and Rodejohann, 1004.2798)

Why precision?



Ballett, King, Luhn, Pascoli, Schmidt, 1410.7573 [hep-ph]
(see also, e.g., Girardi et al, 1410.8056, Meloni, 1308.4578)

Importance of mass ordering



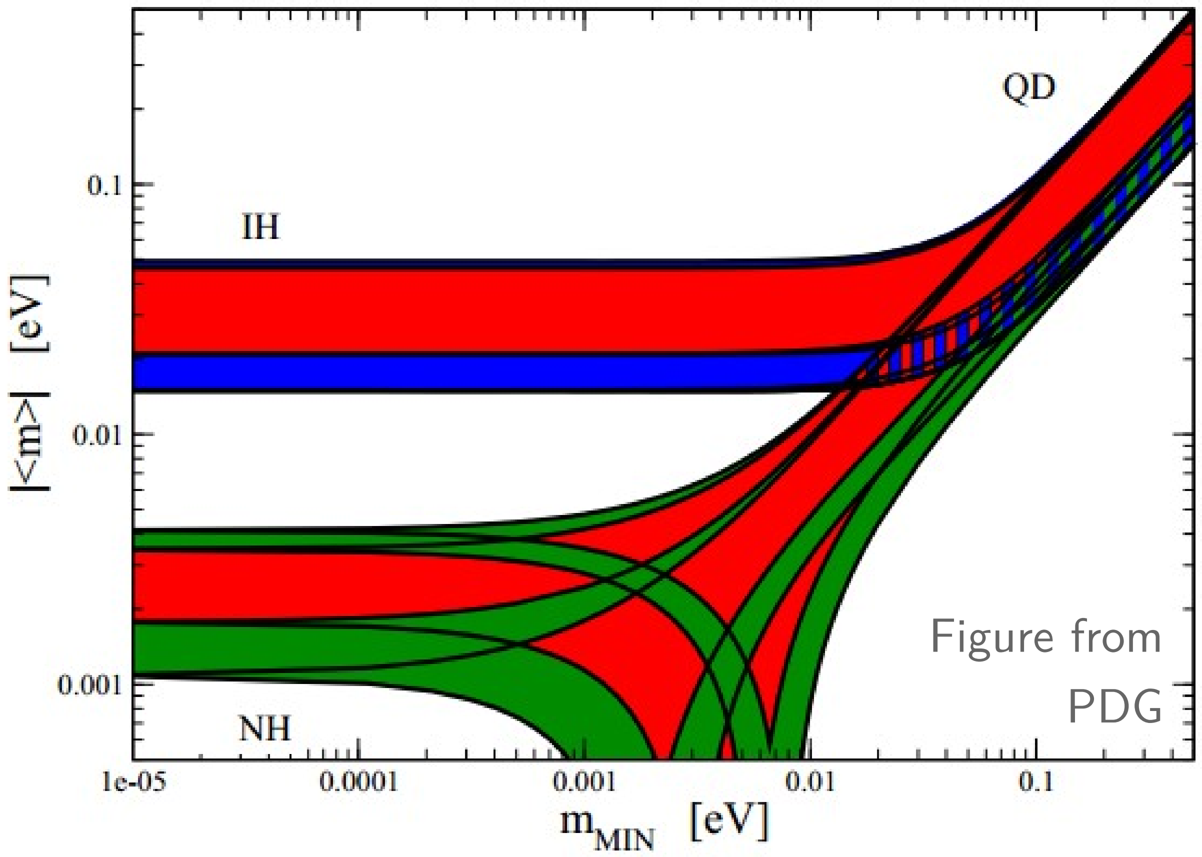
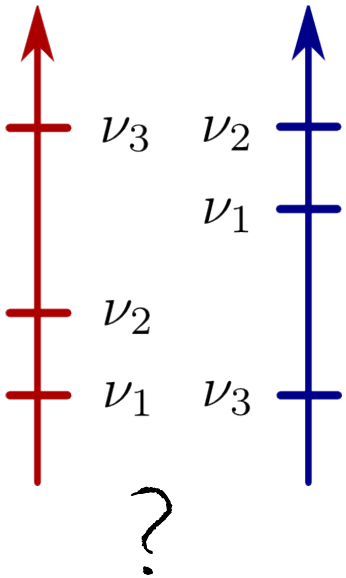


Figure from PDG

Importance of mass ordering



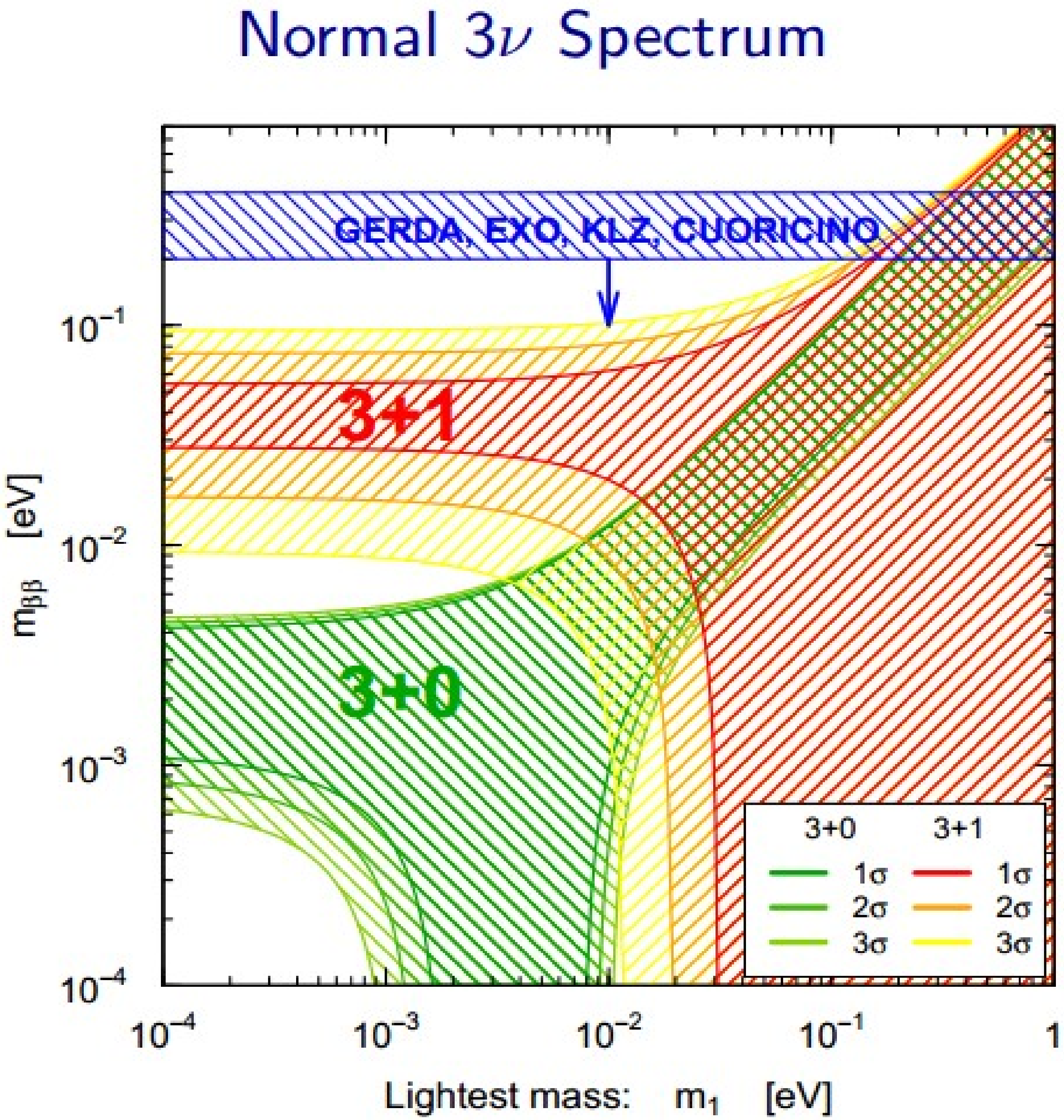
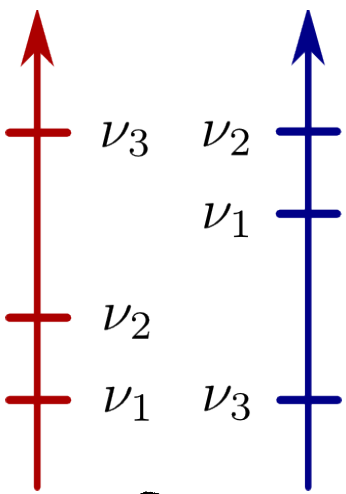


Figure taken from Giunti's talk at NuPhys 2014 (see also Bilenky et al, hep-ph/0104218, or Blennow et al, 1005.3240, among others)

Degeneracies



$$\theta_{23} \qquad \delta$$

? ? ?

$$P(\nu_\mu \to \nu_e)$$
$$P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

Outline

- Introduction to long-baseline experiments
- CP violation searches and delta
- Precise determination of theta23
- Determination of mass ordering
- Challenges for the future
- Summary

The very basics

$$\pi^+ \to \mu^+ \nu_\mu \qquad \begin{cases} \nu_\mu \longrightarrow \nu_e \\ \nu_\mu \longrightarrow \nu_\mu \end{cases}$$

Problems:

$$\pi^- \to \mu^- \bar{\nu}_\mu$$

$$K^+ \to e^+ \nu_e$$

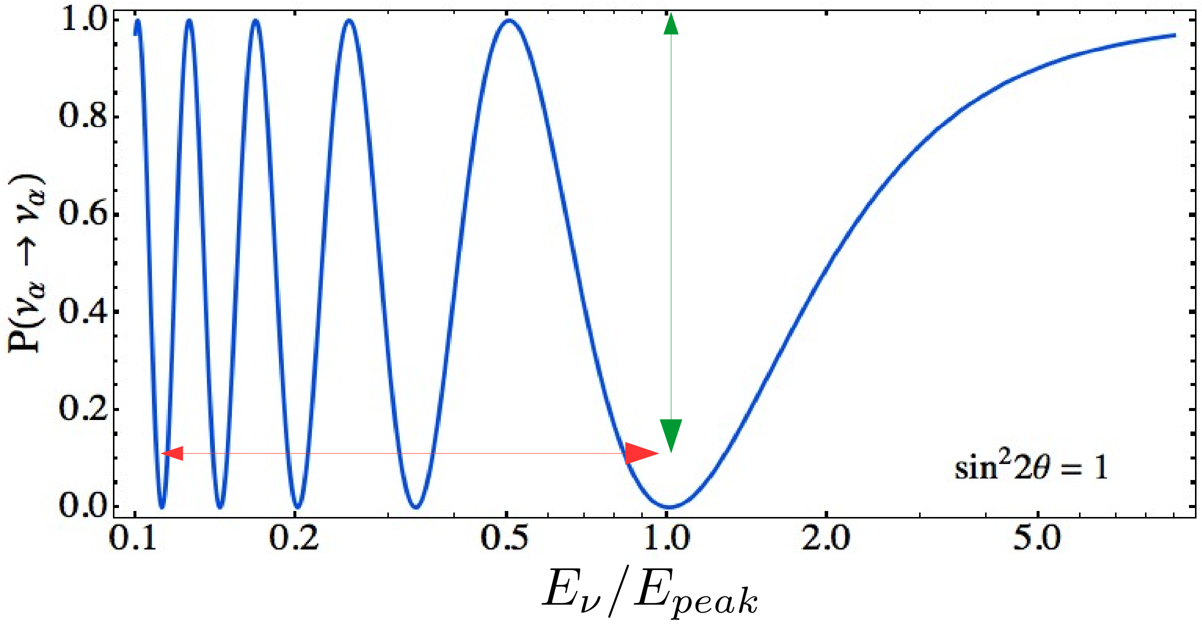
$$K^- \to e^- \bar{\nu}_e$$

NOTE: None of these fluxes can be computed analytically!

The very basics

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m^2_{\alpha\alpha} L}{4E} \right)$$

Tuned to be maximum



CP violation searches

Three-family ν_e appearance oscillation probability:

$$P_{\mu e} = (s_{23} \sin 2\theta_{13})^2 A_{atm}^2$$

$$+ \, \epsilon \sin 2\theta_{23} \sin 2\theta_{13} c_{13} A_{atm} A_{sol} \cos(\pm\delta + \Delta_{31})$$

$$+ \, O(\epsilon^2)$$

Nu/ Nubar

$$\Delta_{31} \equiv \frac{\Delta m_{31}^2 L}{4E}$$

Cervera et al, hep-ph/0002108

(see also Asano and Minakata, 1103.4387)

1^{st} vs 2^{nd} oscillation maxima

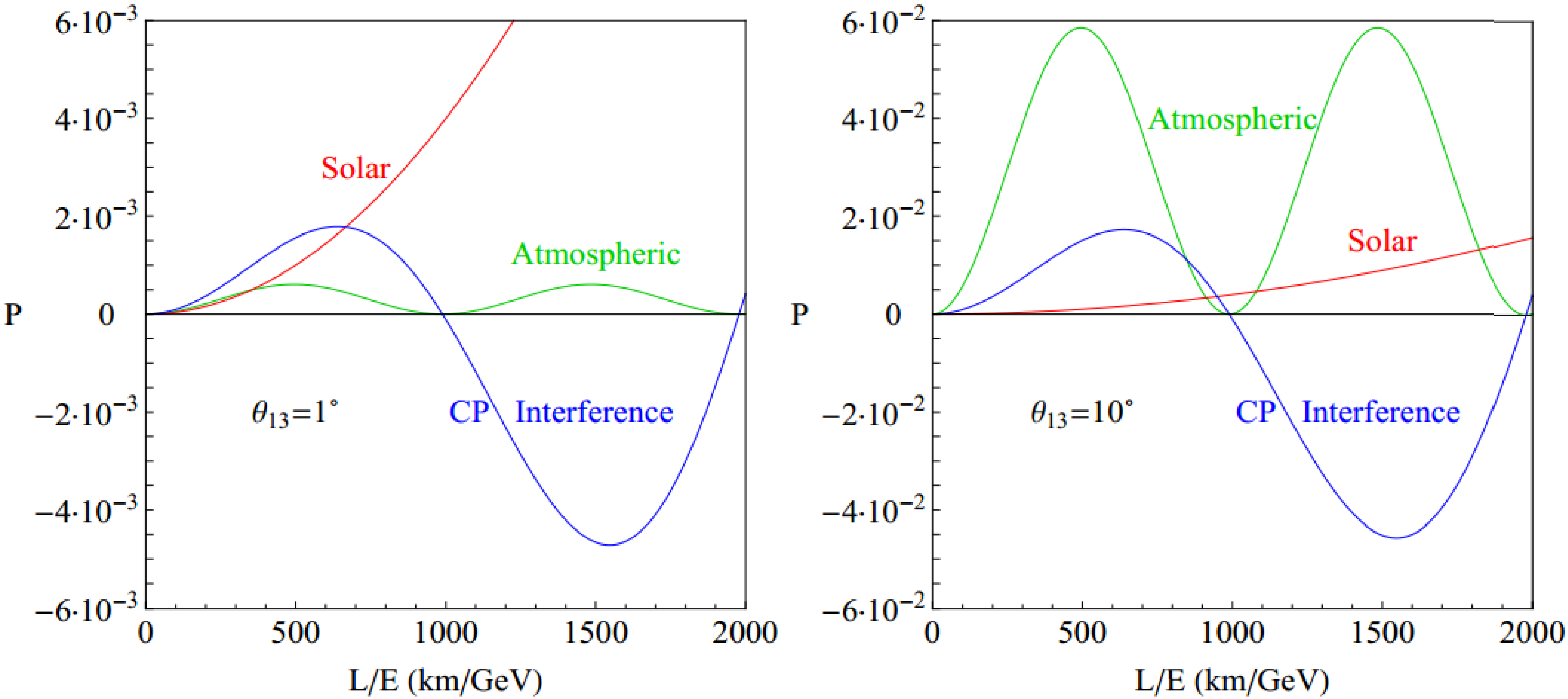
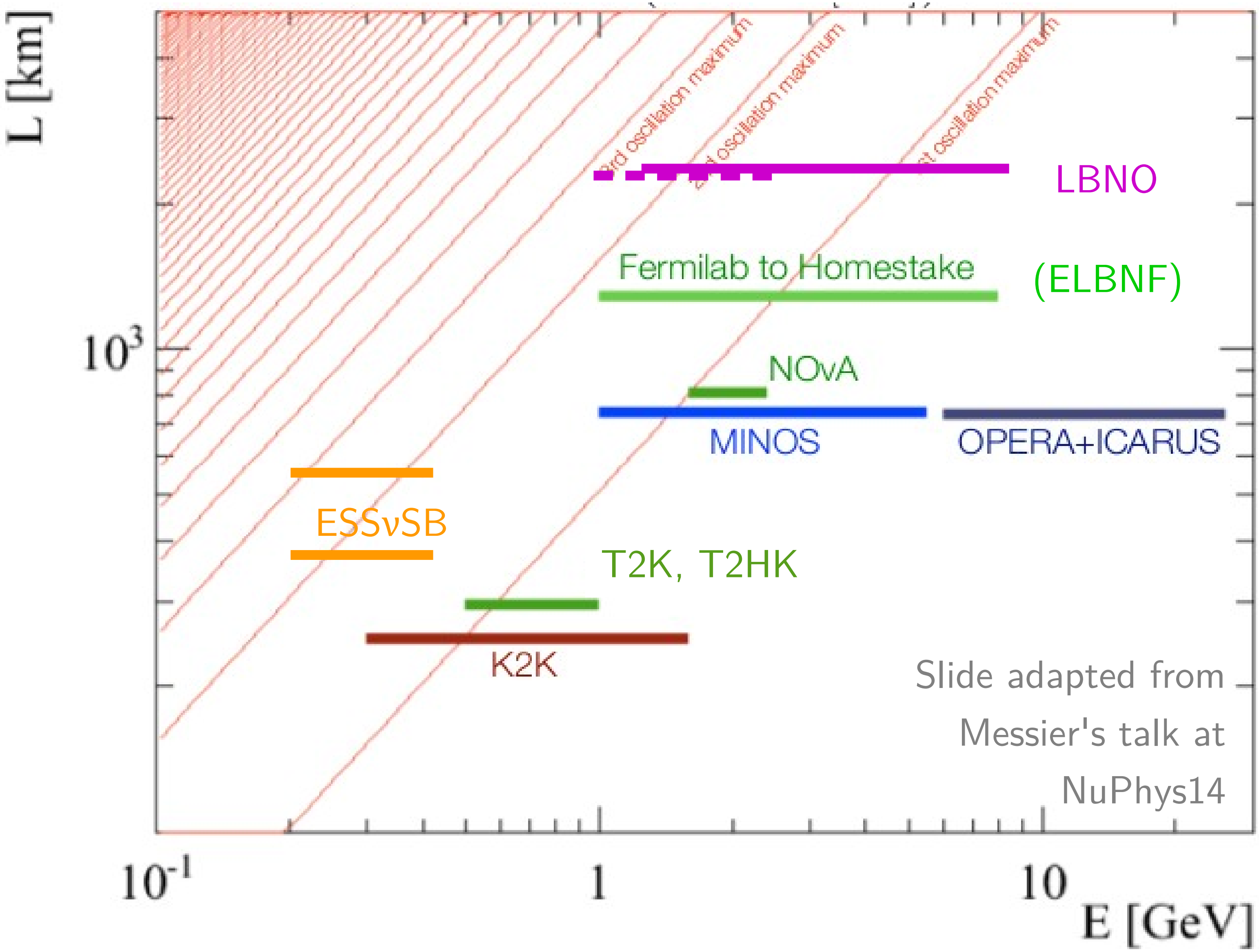


Figure from Coloma and Fernandez-Martinez, 1110.4583 [hep-ph].

See also: Marciano, hep-ph/0108181, Ishitsuka et al, hep-ph/0504026, Meregaglia and Rubbia, 0801.4035

Long-baseline experiments in the market



Possible ways to search for CP violation

- Rate comparison

Typically off-axis

Tests differences between ν and anti-ν

Dependent on systematics

Prone to degeneracies

- Spectral info

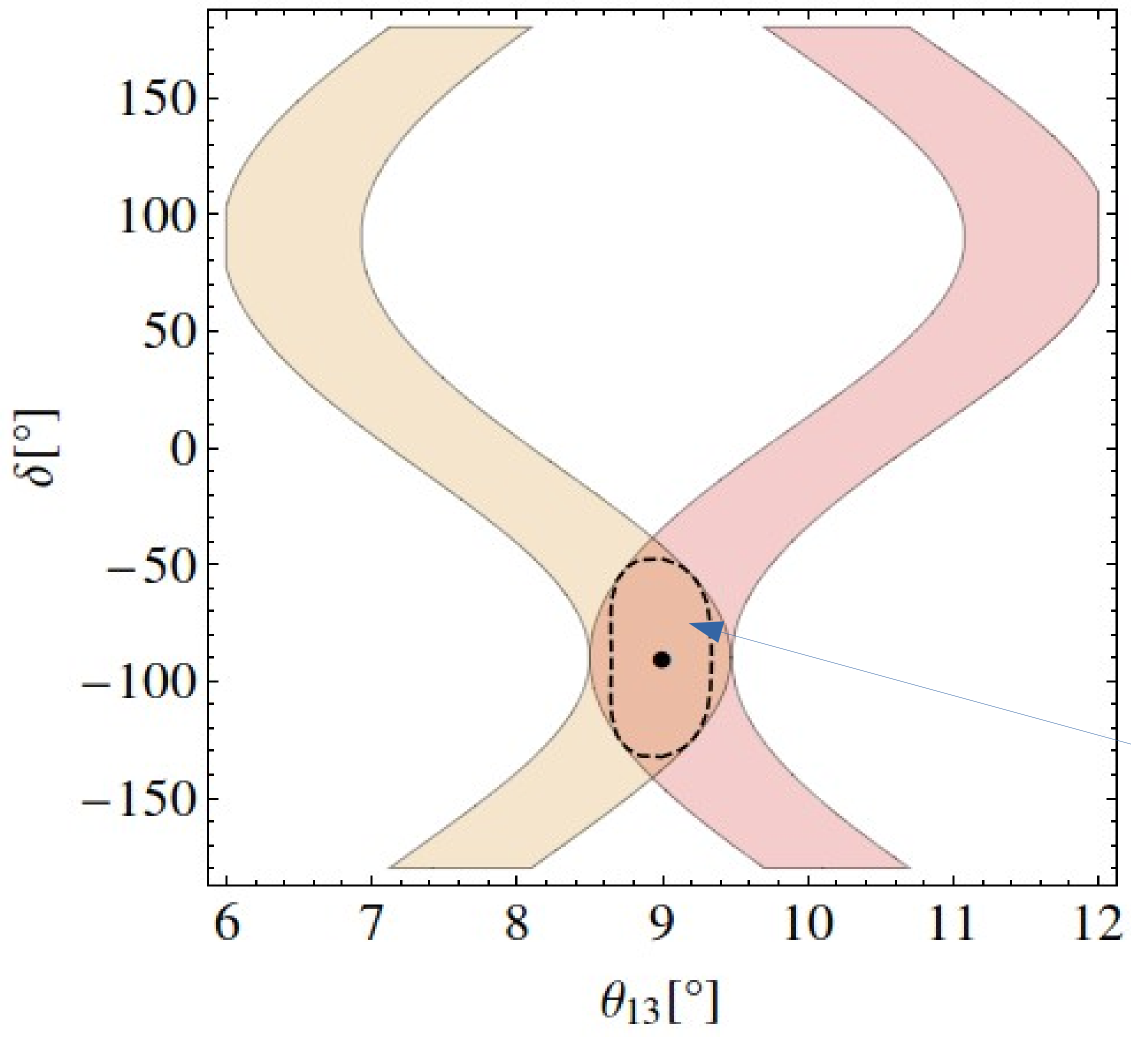
Typically wide-band beams

Tests the energy dependence of the oscillation probability

?

Degeneracies are easier to kill

Rate info vs energy info



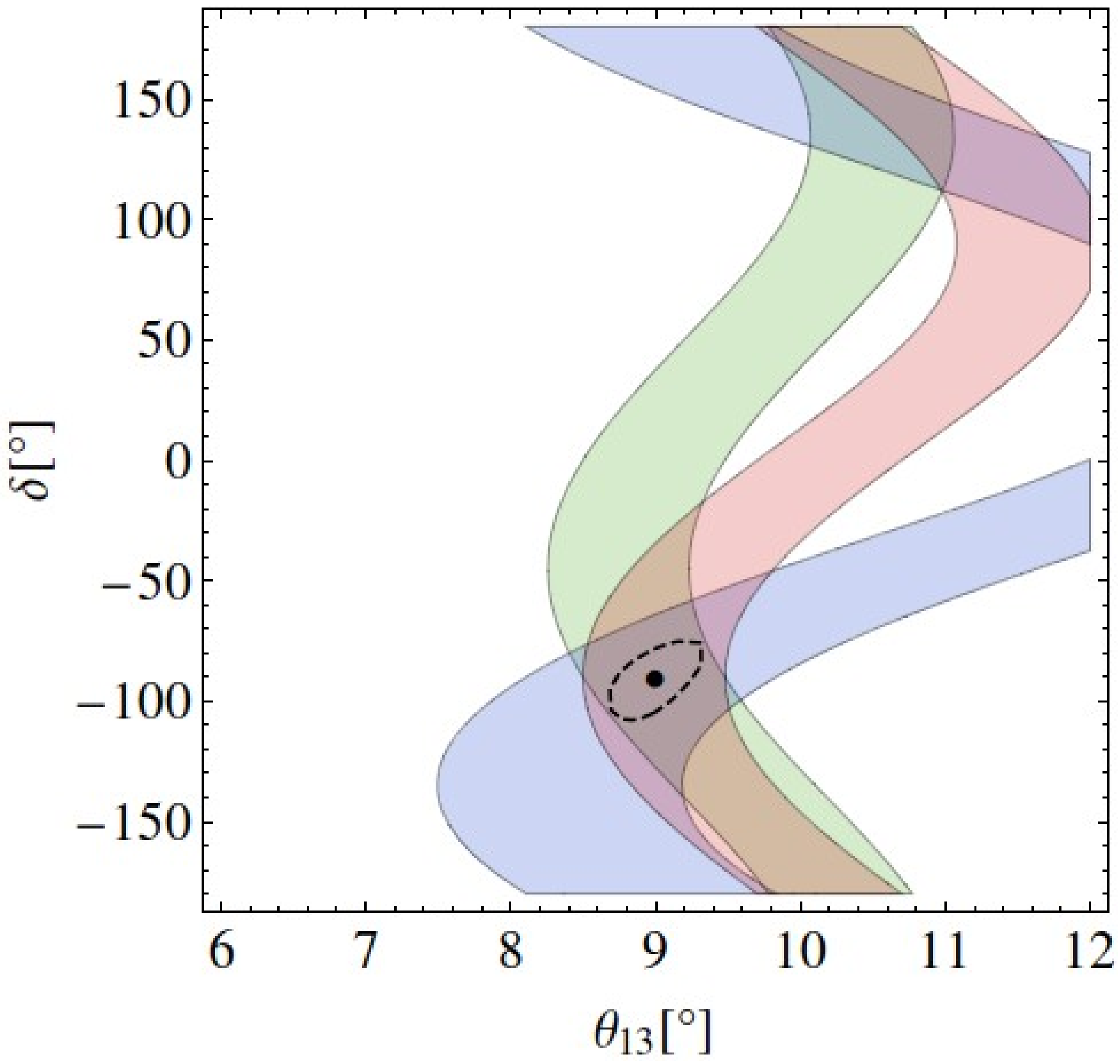
$$P_{\nu_\mu \to \nu_e}(\theta_{13}, \delta) = \overline{P_\nu}$$

$$E_\nu = E_{peak}$$

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e}(\theta_{13}, \delta) = \overline{P_{\bar{\nu}}}$$

Allowed region

Rate info vs energy info



$$P_{\nu_\mu \to \nu_e}(\theta_{13}, \delta) = \overline{P_\nu}$$

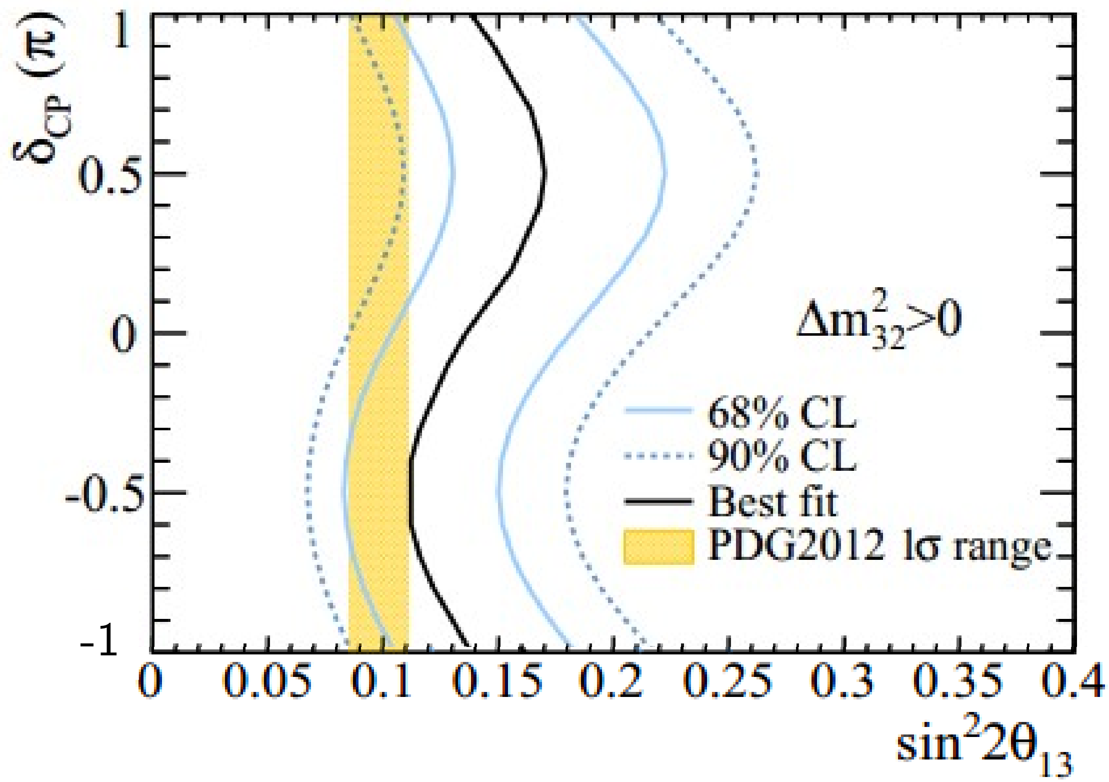
$E_\nu = E_{peak}$

$E_\nu = 2E_{peak}$

$E_\nu = 0.6E_{peak}$

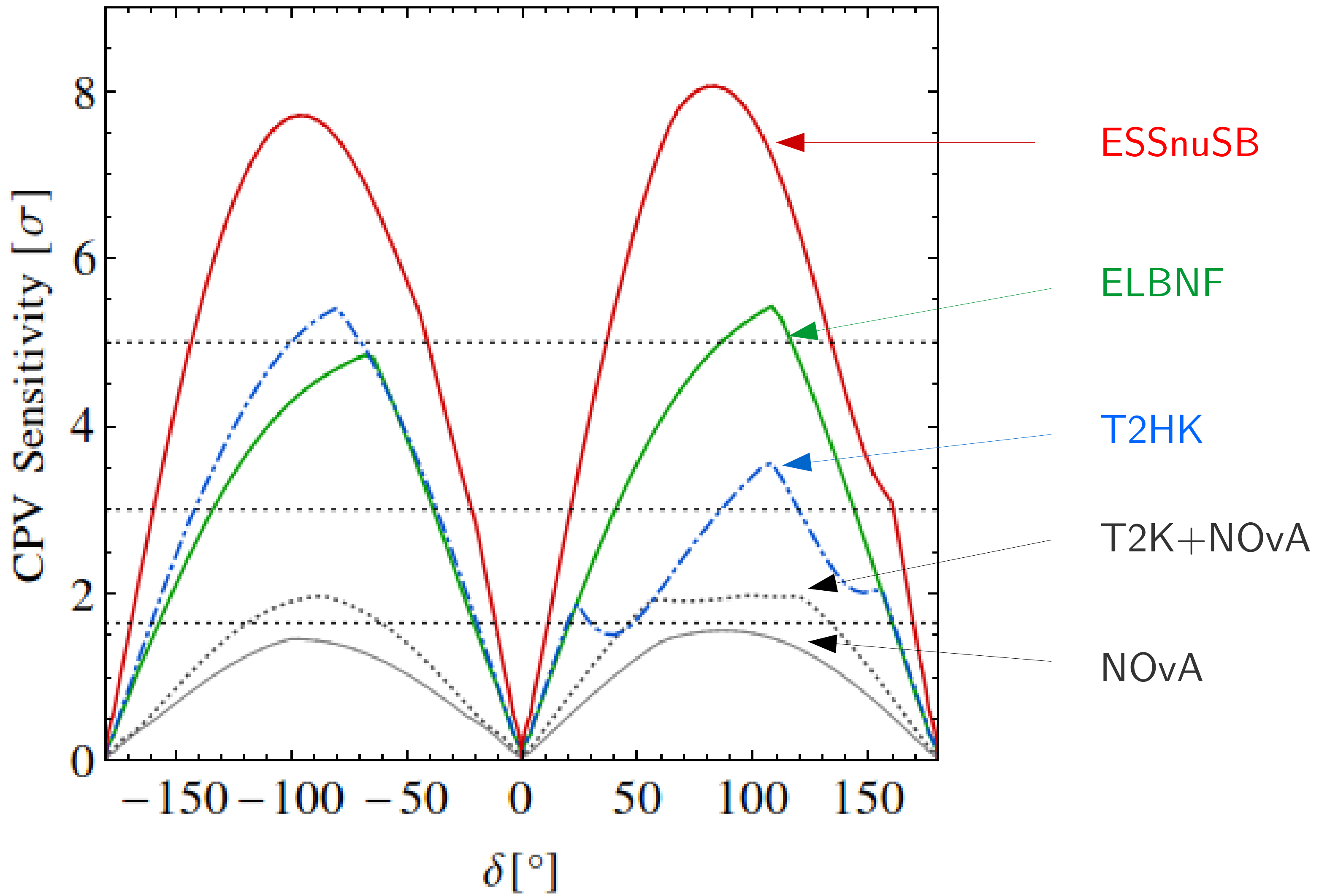
The current hint for CP violation

The combination of current T2K and Daya Bay (mainly) seems to indicate that delta is not CP conserving:



T2K coll., 1311.4750 (see also 1502.01550)

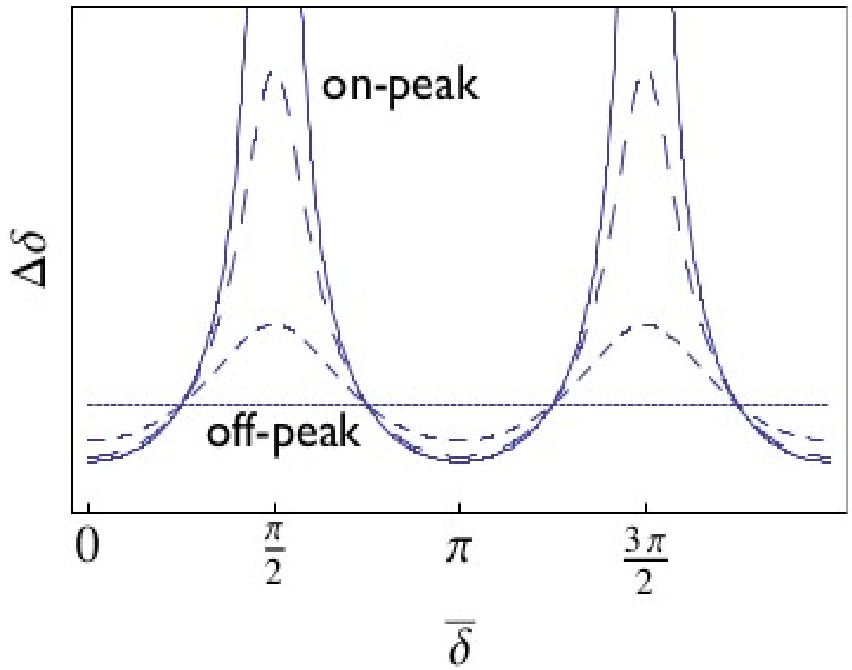
CP violation prospects



Precision on δ

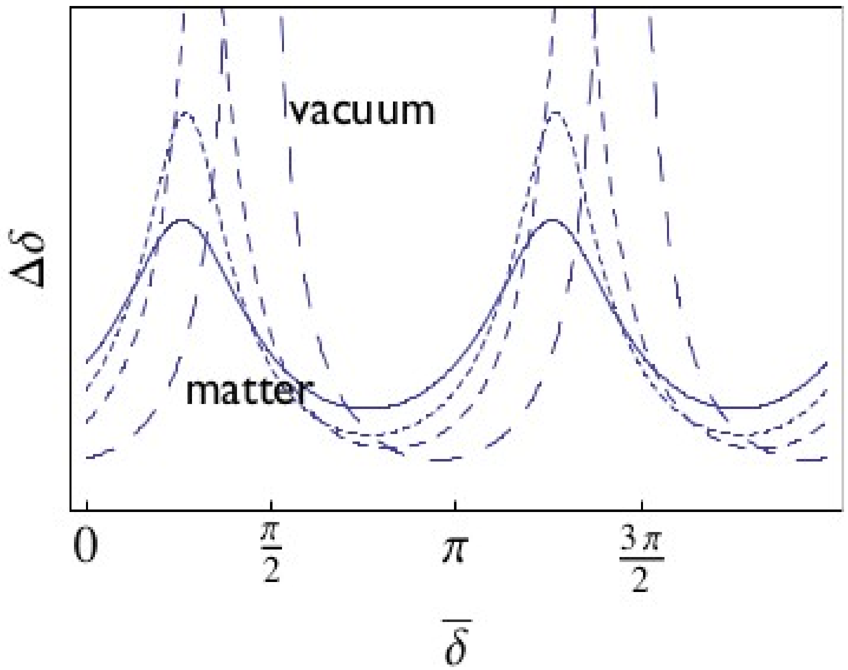
VACUUM

$$(\Delta\delta)_\pm \propto [\sin(\Delta \mp \delta)]^{-1}$$



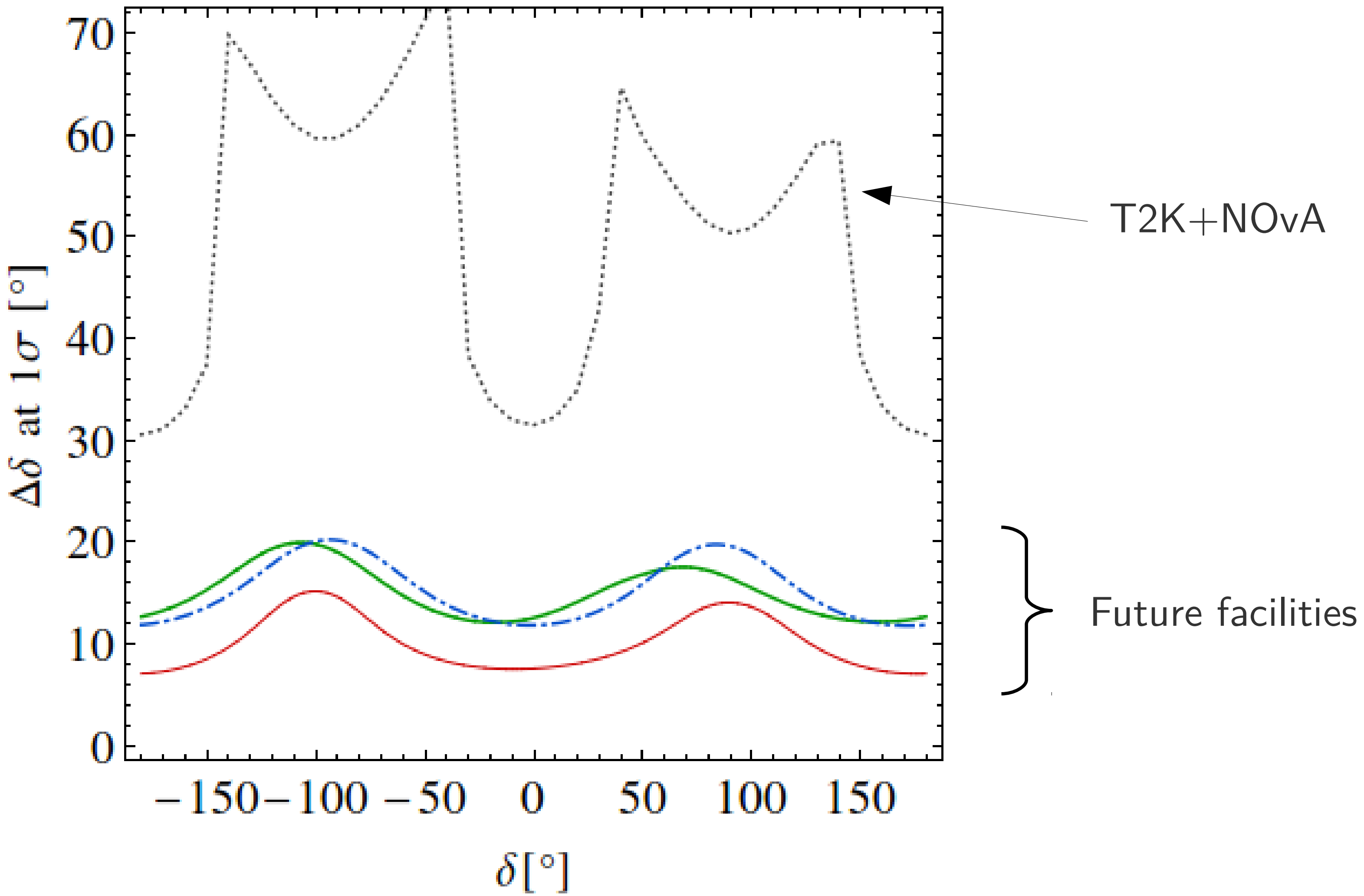
MATTER

$$(\Delta\delta)_\pm \propto \left[\sin\left(\Delta \frac{\hat{A}}{1 \mp \hat{A}} \mp \delta\right)\right]^{-1}$$



Coloma, Donini, Fernandez-Martinez, Hernandez, 1203.5651 [hep-ph]

Precision on δ



theta23

Recent literature:

Agarwalla, Prakash, Sankar, 1304.3251 and 1301.2574

Ghosh, Ghoshal, Goswami, Raut, 1306.2500 and 1308.5979

Machado, Minakata, Nunokawa, Zukanovich Funchal, 1307.3248

Barger, Bhattacharya, Chatterjee, Gandhi, Marfatia, Masud, 1405.1054, 1307.2519

Barger et al, 1203.6012

Precision on θ_{23}

In disappearance:

$$\mathrm{P}_{\mu\mu}^{vac} \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31}$$

$$+ \, 4\sin^2\theta_{13} \sin^2\theta_{23} \cos 2\theta_{23} \sin^2\Delta_{31}$$

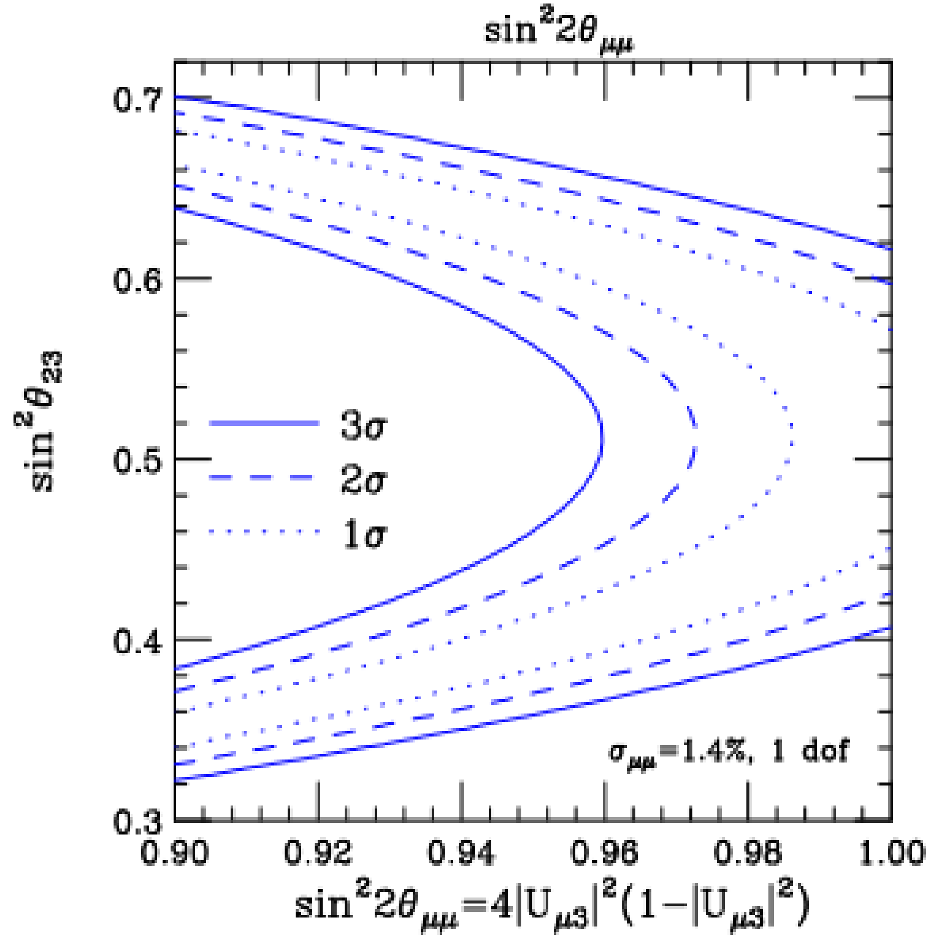
$$+ \, \mathrm{O}(\mathrm{s}_{13}\epsilon) + \mathcal{O}(\epsilon^2)$$

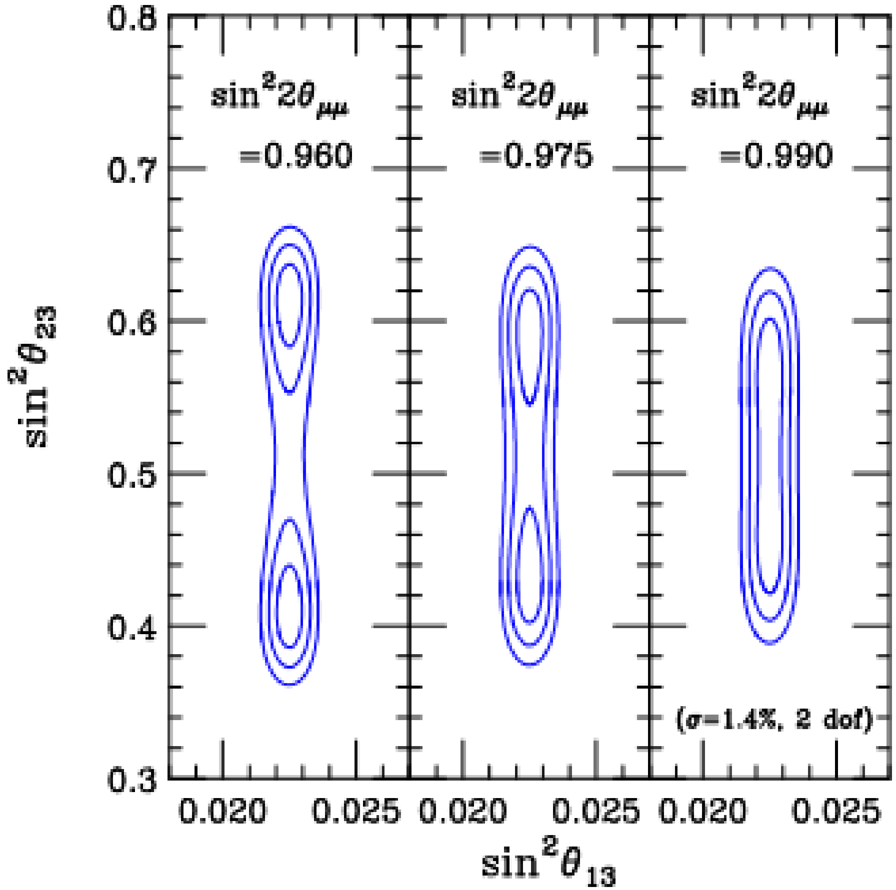
$$P_{\mu\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \Delta_{\mu\mu}$$

$$\Delta_{31} \equiv \frac{\Delta m_{31}^2 L}{4E} \qquad \epsilon \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$$

$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

Precision on θ_{23}





S. Raut, 1209.5658 [hep-ph]

Coloma, Minakata, Parke, 1406.2551 [hep-ph]

Precision on θ_{23}

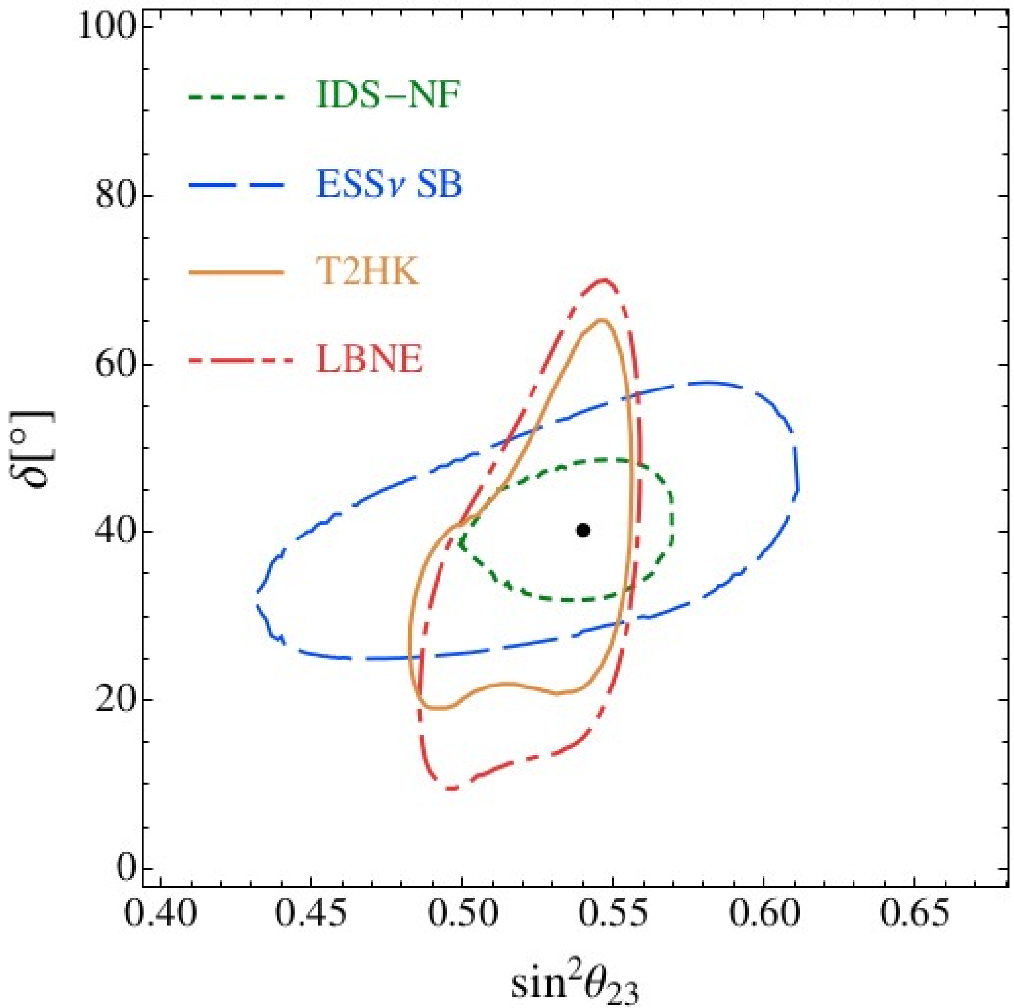
In appearance:

$$P_{\mu e} = \boxed{(s_{23}\sin 2\theta_{13})^2 A_{atm}^2}$$

$$+ \epsilon \sin 2\theta_{23} \sin 2\theta_{13} c_{13} A_{atm} A_{sol} \cos(\delta + \Delta_{31})$$

$$+ \mathrm{O}(\epsilon^2)$$

Precision on θ_{23}



Coloma, Minakata, Parke, 1406.2551 [hep-ph]

Ordering of neutrino masses

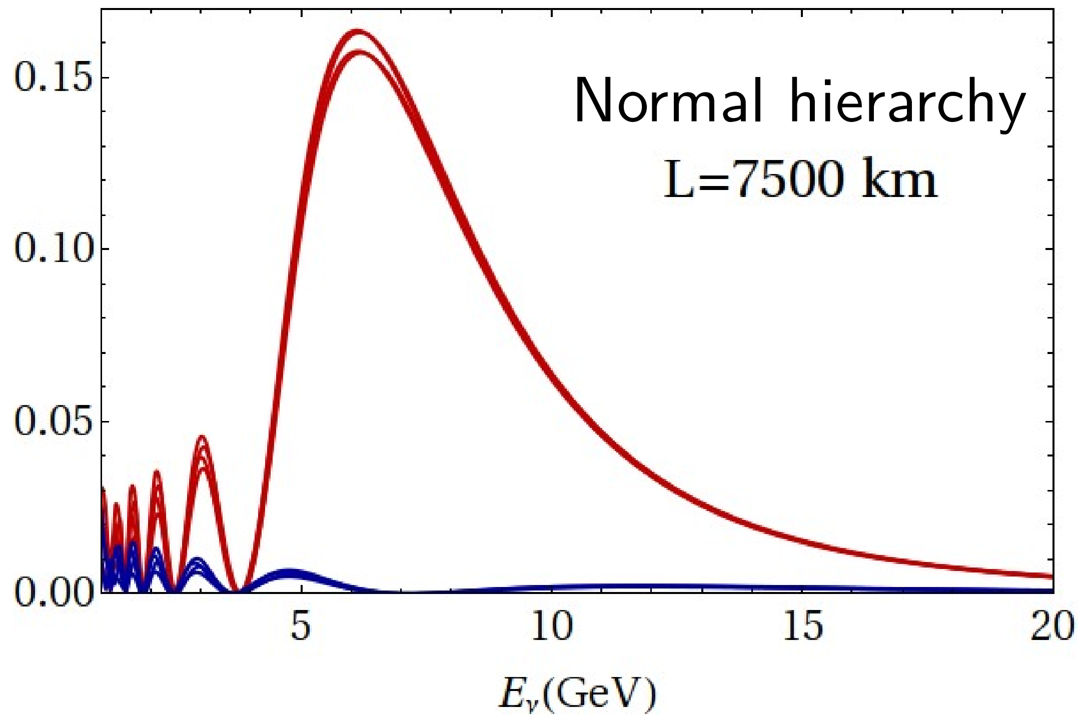
Matter effects in appearance (beams)

In two-families:

$$P = \sin^2 2\theta_M \sin^2\left(\frac{\Delta m_M^2 L}{4E}\right)$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos\theta - A)^2}\,; \quad A = \frac{2EV}{\Delta m^2}$$

Wolfenstein ('78), Barger et al ('80), Mikheev and Smirnov ('85)



Other ways to measure the MO

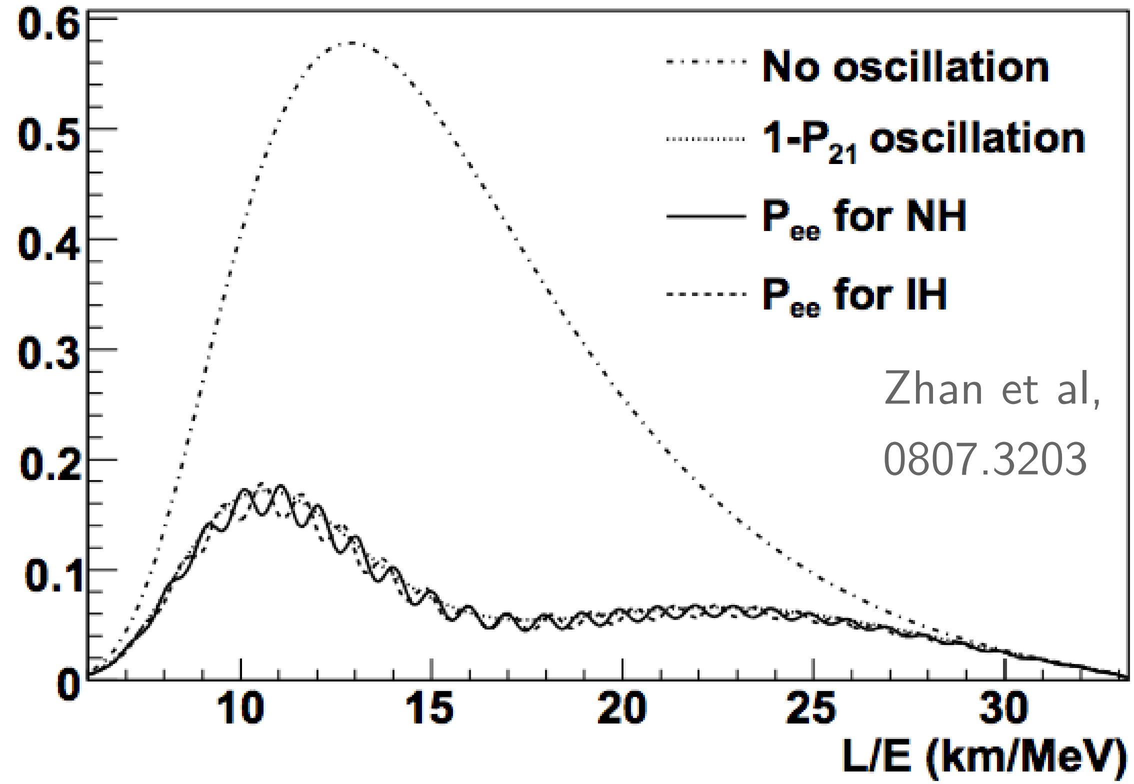
1) Reactor experiments at medium baselines (JUNO, RENO50)

2) Matter effects in atmospheric neutrino experiments (PINGU, ORCA, INO, HK)

3) Precise determination of mass splittings

Reactor experiments at medium baselines

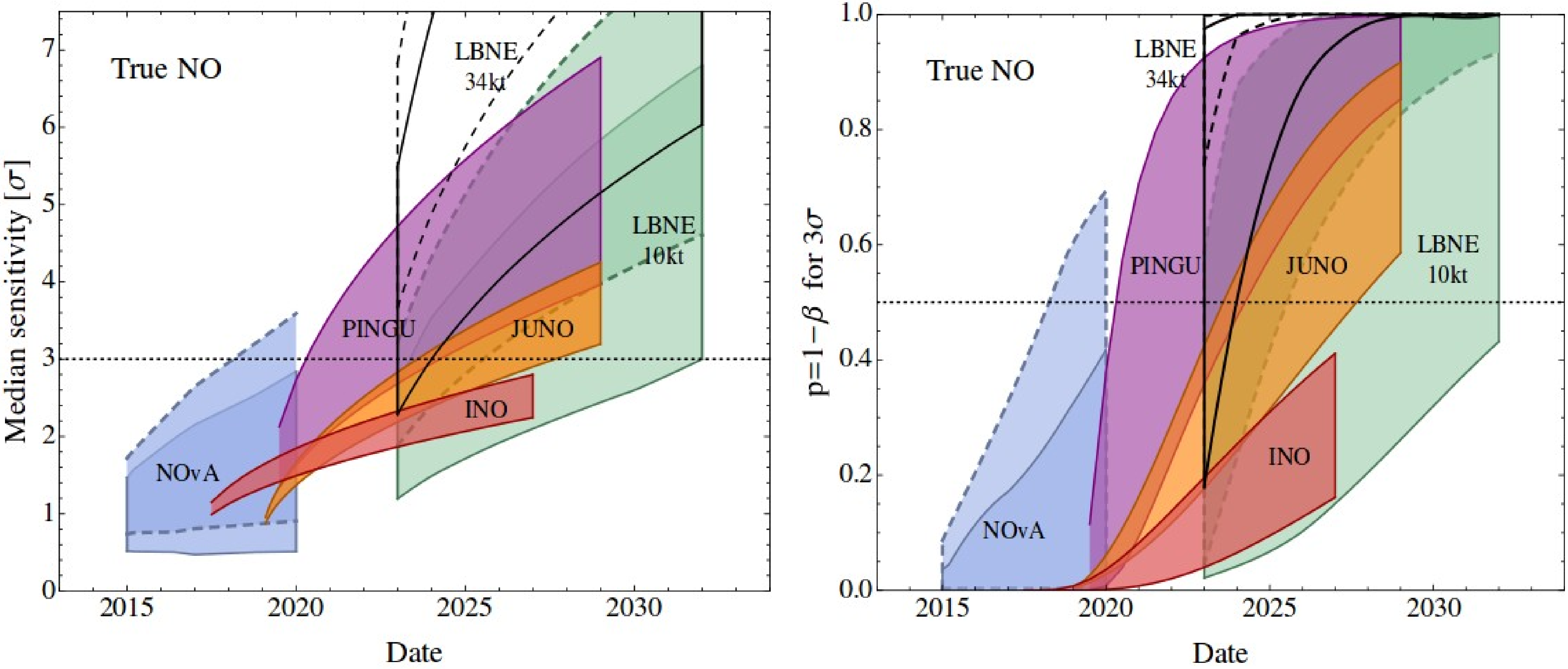
Petcov, Piai, hep-ph/01102074
Choubey, Petcov, Piai, hep-ph/0306017



Zhan et al, 0807.3203

$$P_{ee} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)\right]$$

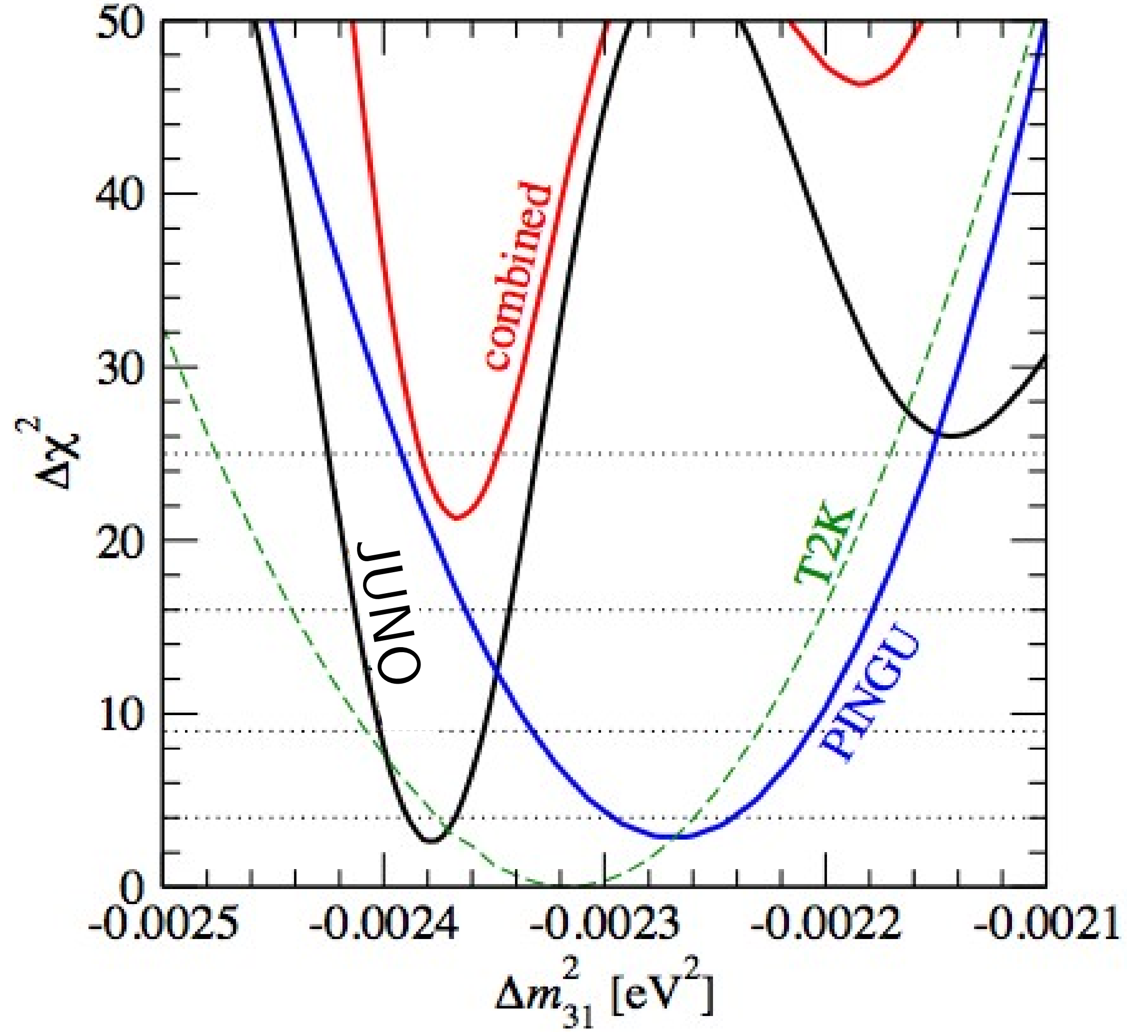
Prospects for mass ordering



Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

Precise measurement of mass splittings

The ordering of neutrino masses may as well come from a global fit to different data



Blennow, Schwetz, 1306.3988 [hep-ph]

(see also Li *et al*, 1303.6733 [hep-ph], for instance)

Systematics and nuclear effects

Near detectors and systematics

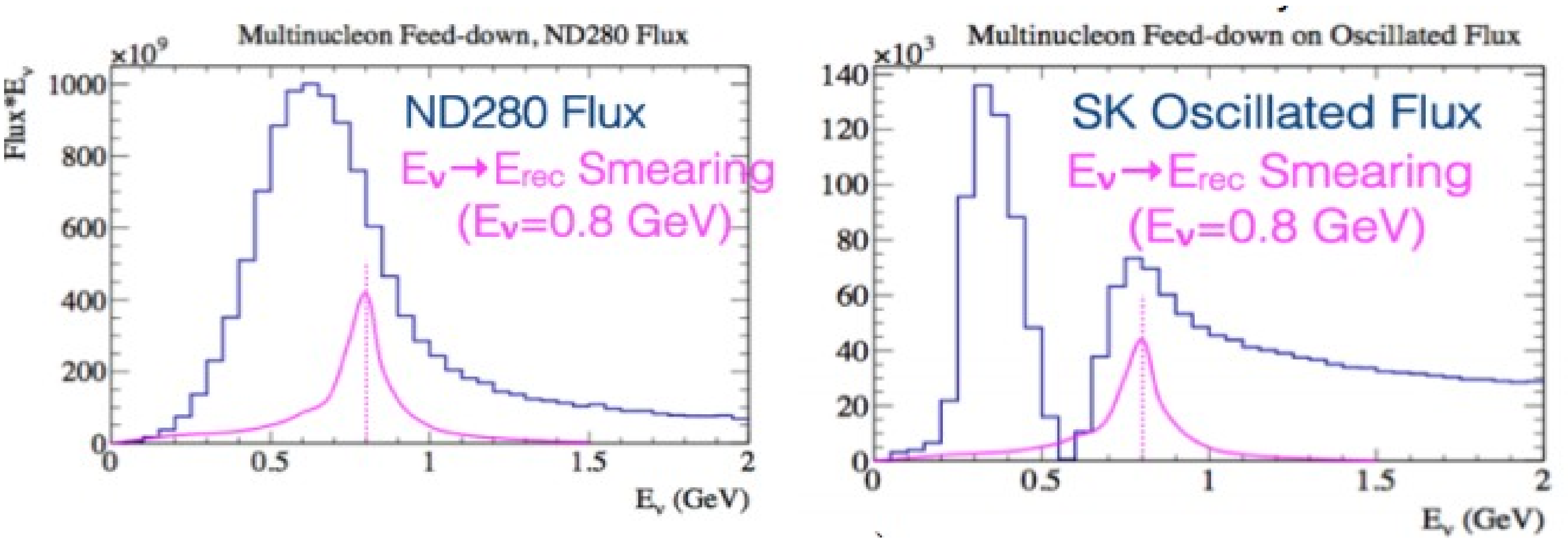
$$n_{\alpha\to\beta}(L,E) \sim \frac{1}{L^2}\epsilon_\beta(E)\times\sigma_\beta(E)\times\phi_\alpha(E)\times P_{\alpha\beta}(L,E)$$

At reactor experiments, the cancellation of systematics between near/far detectors is very effective:

$$\frac{n_{ee}^{FD}}{n_{ee}^{ND}} \sim \frac{L_{ND}^2}{L_{FD}^2}\frac{\epsilon_e\sigma_e\phi_e}{\epsilon_e\sigma_e\phi_e}P_{ee}$$

Nuclear effects

The **big** problem with nuclear effects in neutrino oscillation experiments is the determination of the neutrino energy



(Figures by K. Mahn, nuSTEC school 2014)

Conclusions

- The neutrino picture is still far from being complete
- Next milestone seems to be the ordering of neutrino masses
- Current generation of experiments is already producing exciting new results
- A next generation of long-baseline experiments is well-motivated:
  - Provide a clear signal for CP violation
  - Provide a clear determination of the mass ordering
  - Enter the era of precision in neutrino oscillations (searches for New Physics, model discrimination, etc)

Thank you!