# PPEG Summary and plans

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University of Glasgow

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# Outline

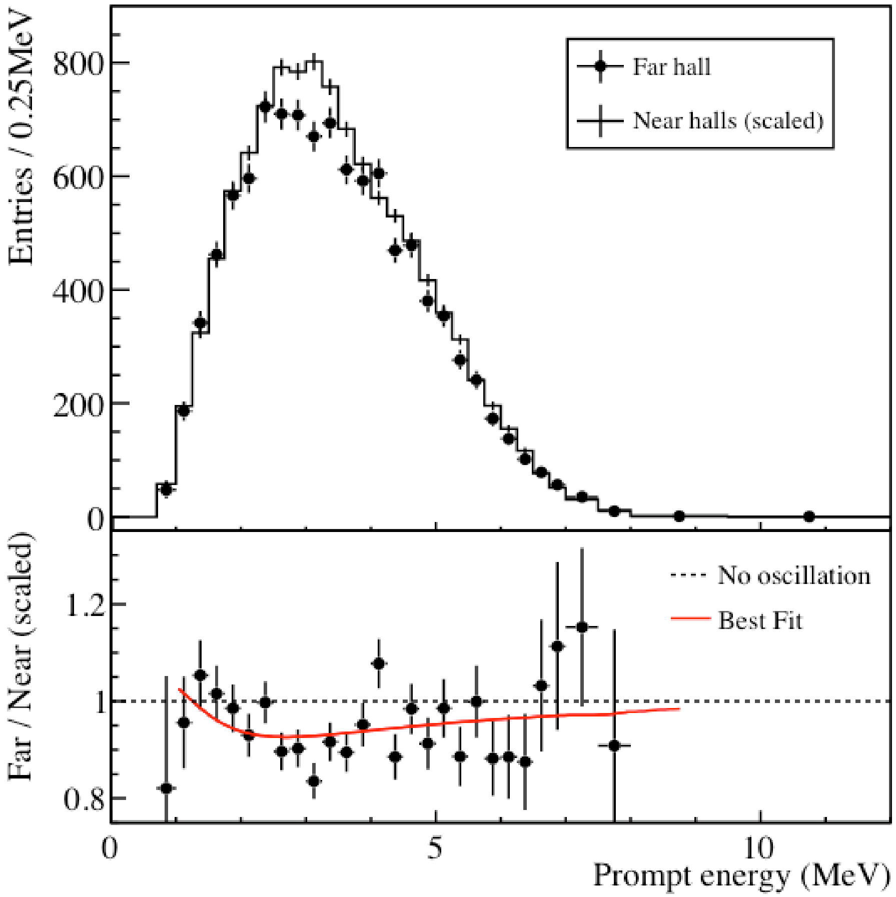
1. LENF baseline

2. Measuring the parameters in LBL

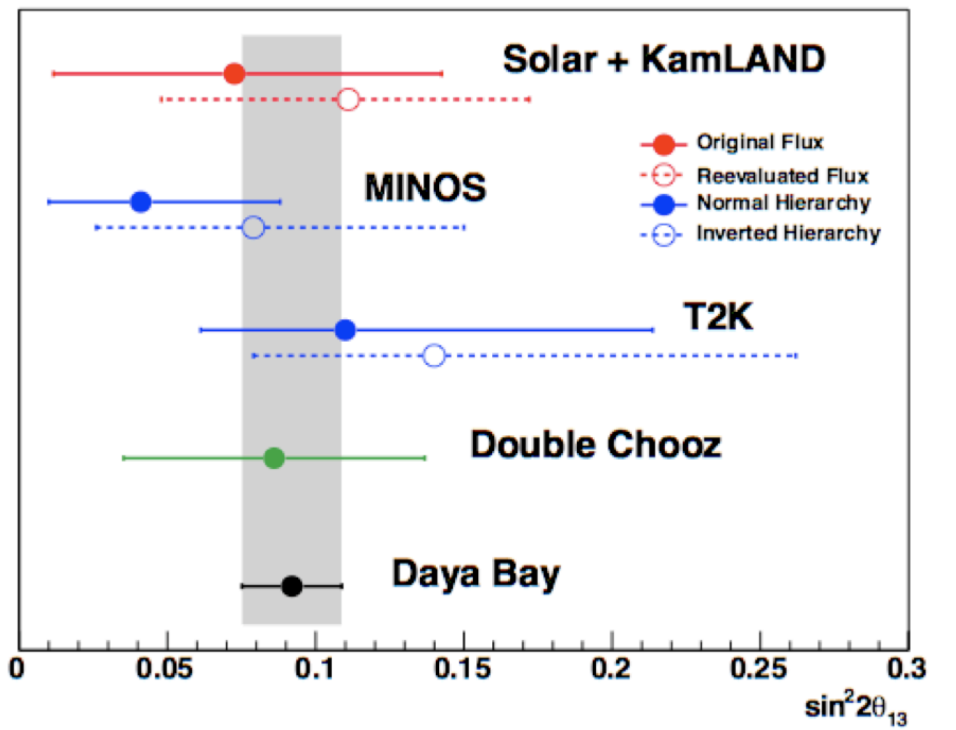
3. Systematic errors

4. Conclusions and outlook

In 2011, the first hints of large $\theta_{13}$ were found in T2K, MINOS and DoubleCHOOZ. Daya Bay (!) and RENO have confirmed these hints and discovered this angle.




Daya Bay




See K. McDonald's talk

**This has critical implications for NF.**

# From HENF to LENF

Due to large theta13, shorter baselines are preferred, correspondingly lower energies and the acceleration process can be streamlined

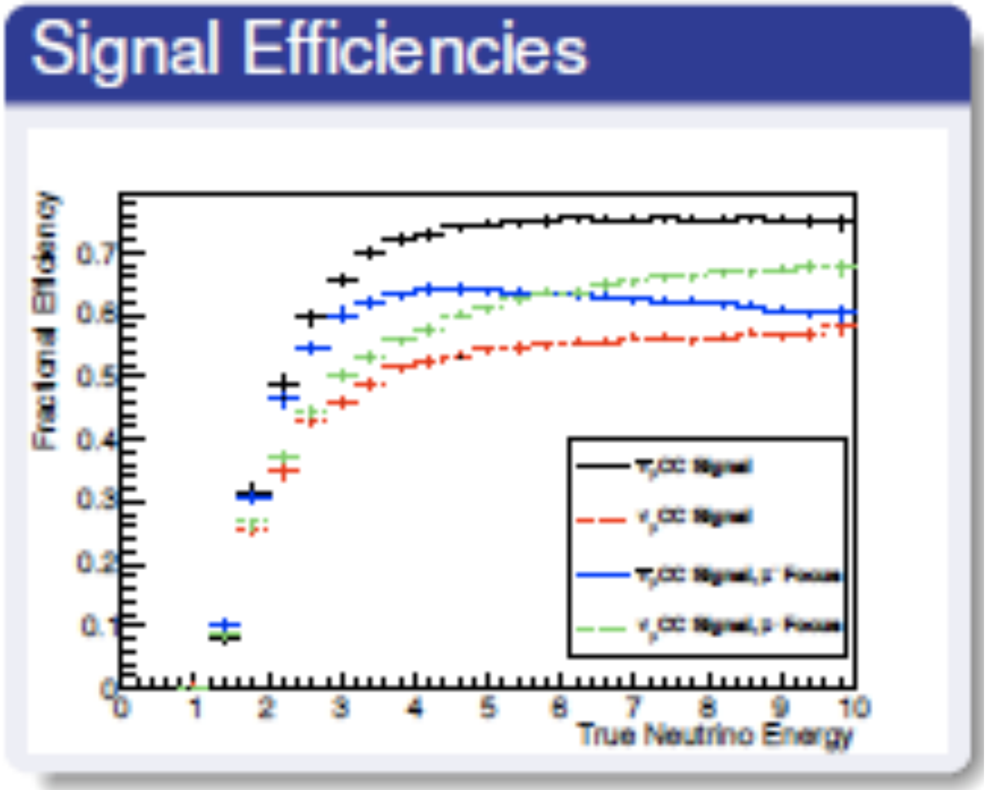
$\boxed{\text{low energy neutrino factory}}$

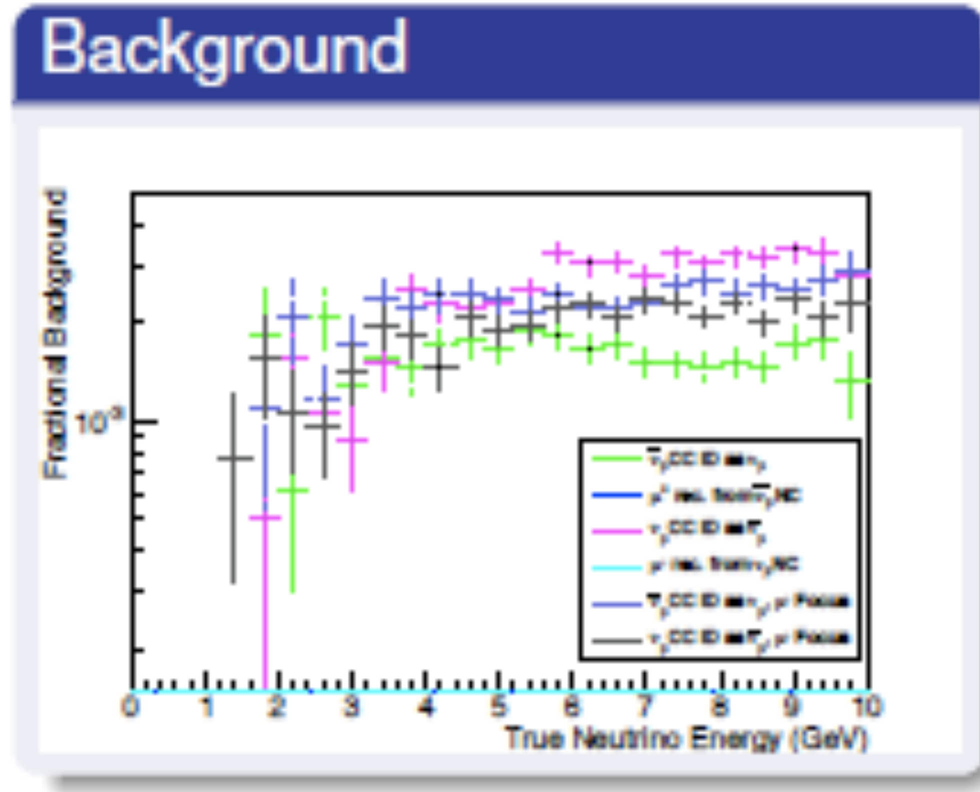
- Only one baseline Distance: L~1000-2500 km.
- Muon energy: 4-10 GeV
- MIND provides excellent physics reach if E is sufficiently high (E>8-10 GeV). Ideally Magnetised TASD or LiAr detector (probably too difficult).

Geer, Mena, Pascoli, Phys.Rev. D75 (2007) 093001; Bross et al., Phys.Rev. D77 (2008) 093012;
Agarwalla, Huber, Tang, Winter, 1012.1872.

# The performance of MIND at low energy

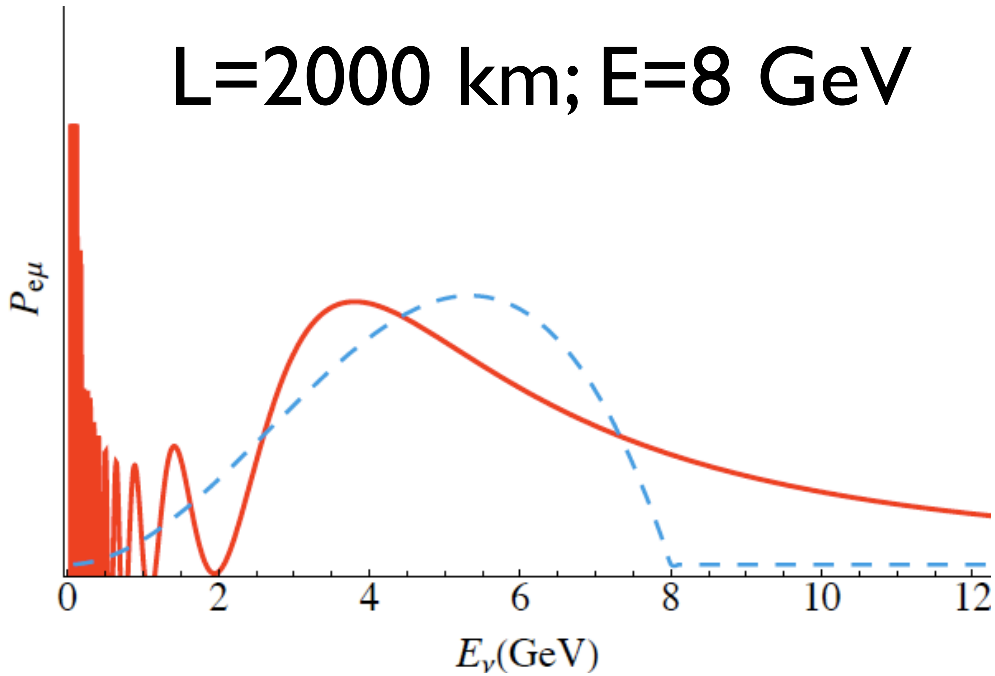
For the given baseline, L<2500 km, the low energy efficiency is crucial to fully exploit the oscillatory pattern of the signal.

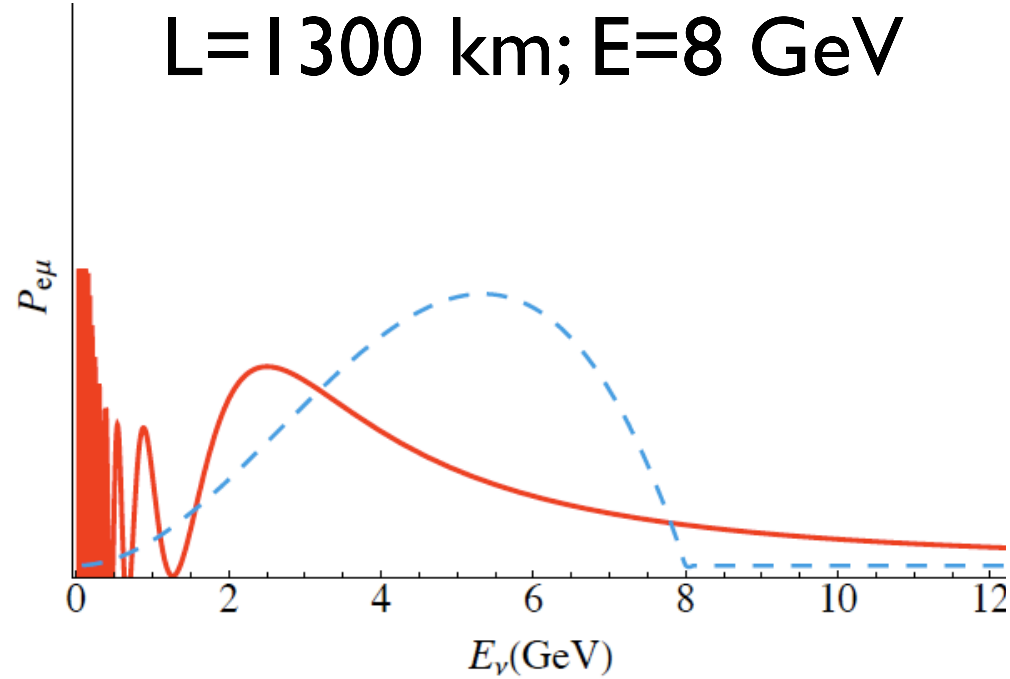


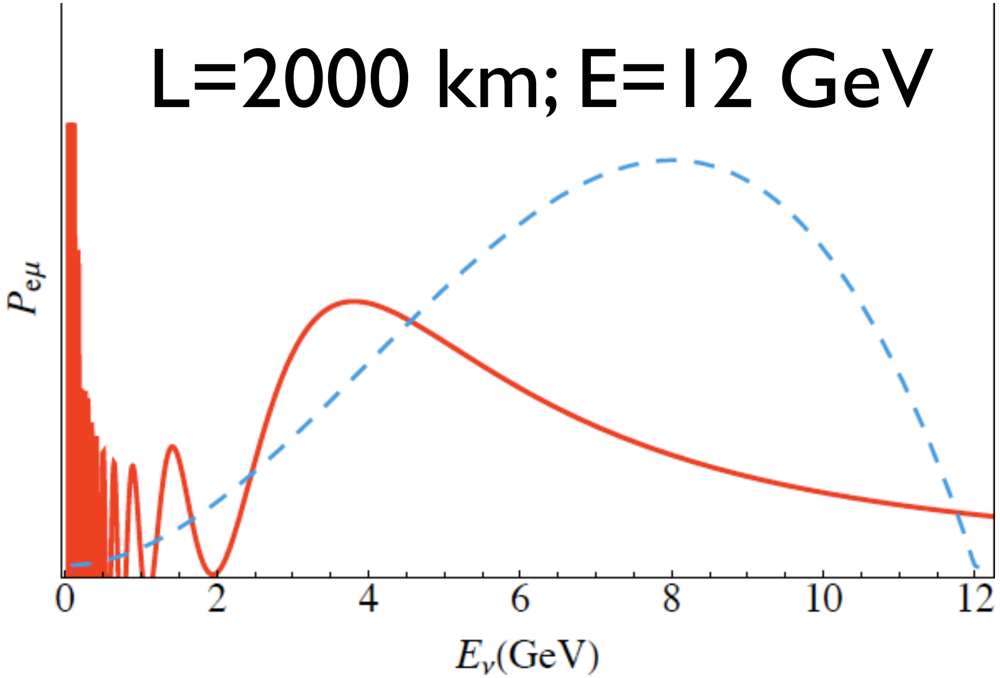




Bayes's talk

Maybe some space for optimisation, allowing larger background at low energy in order to have higher efficiency.

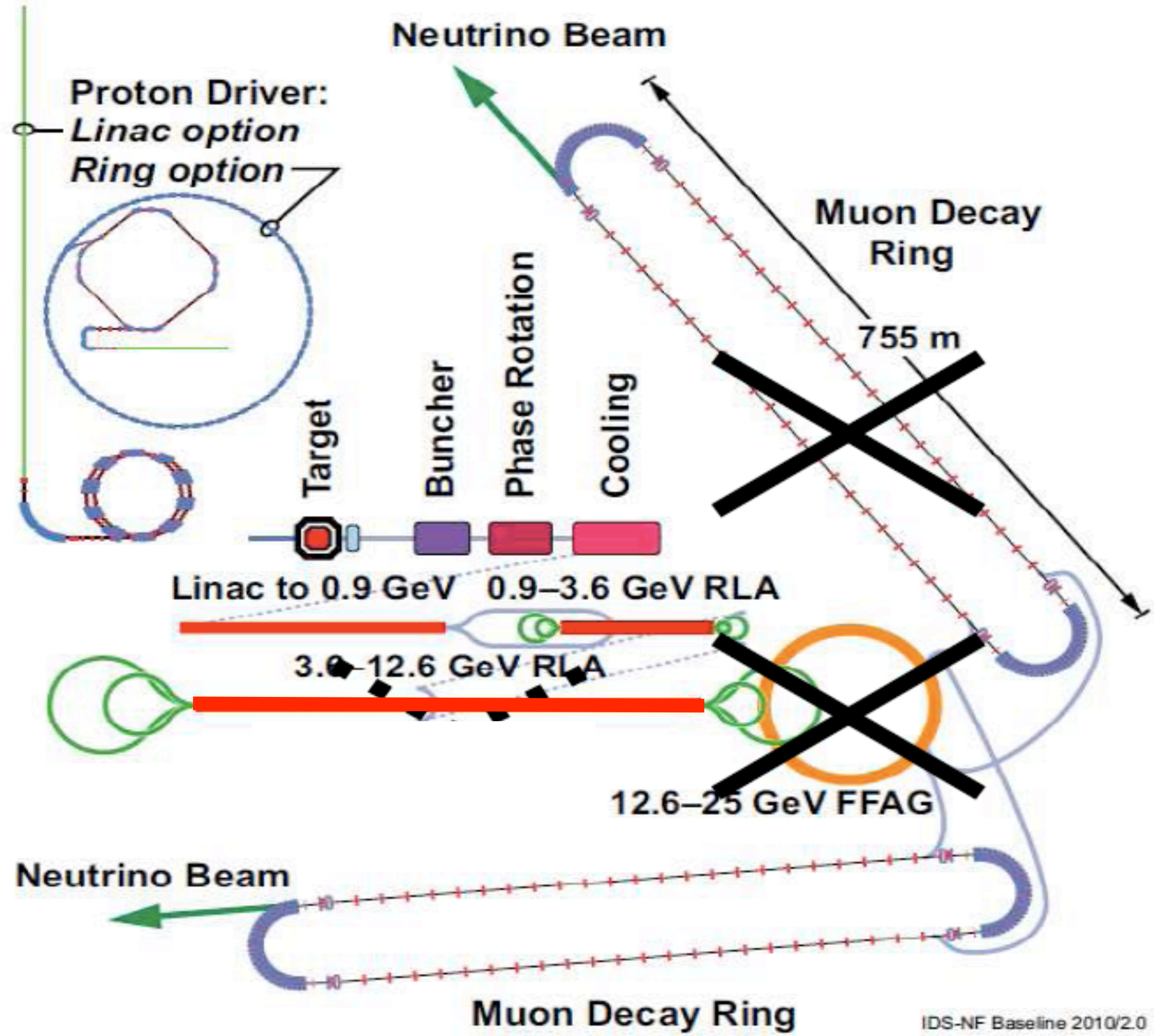



Thanks to Coloma

For a given MIND threshold, the physics reach is determined by L. Going to high energies might not help or be counterproductive.




# LENF: E=10 GeV and L=2000 km

# Phenomenology questions and LBL

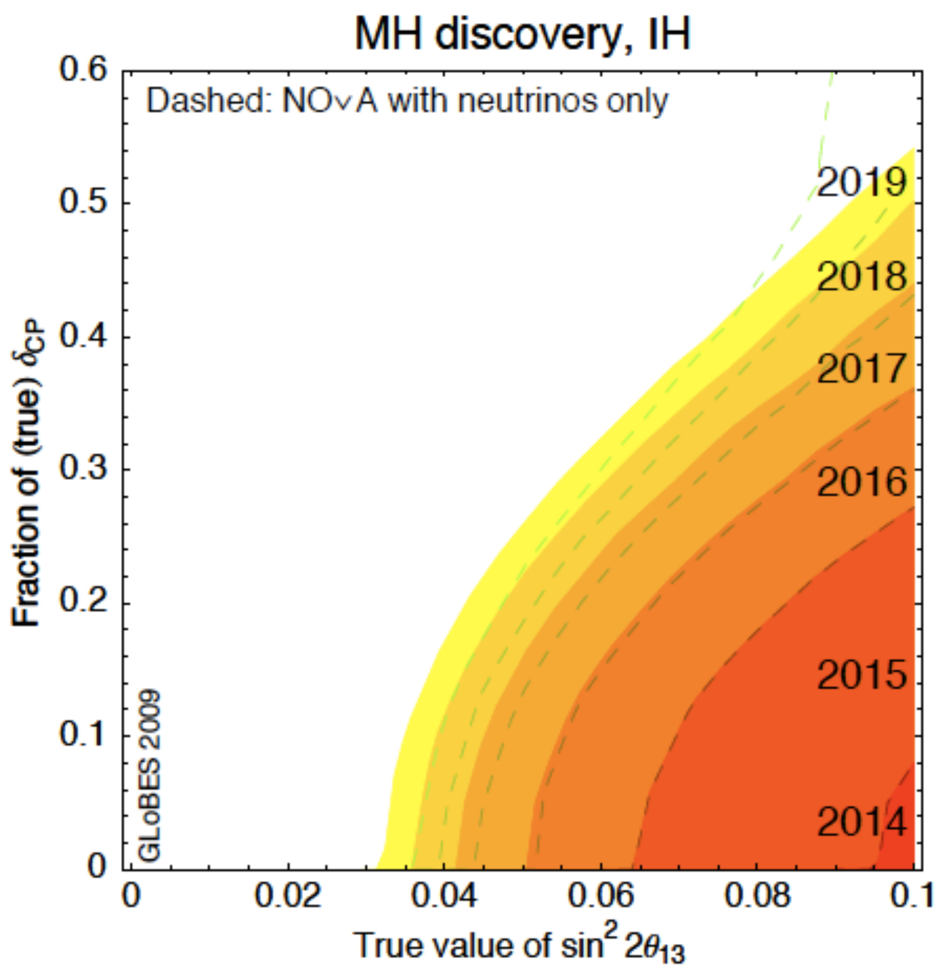
- What are the values of the masses? Absolute scale (KATRIN, ...?) and the ordering.

- Is there CP-violation? Its discovery in the next generation of LBL depends on the value of theta13.

- What are the precise values of mixing angles (tribimaximal mixing?)?

- Is the standard picture correct? Are there NSI? Sterile neutrinos? Other effects?

# Neutrino mass ordering




Combining T2K, NOvA, reactor.

P. Huber, M. Lindner, T. Schwetz, W. Winter, 2009. See also Patrick's talk.

It is likely that the next generation of LBL experiments (LBNE, LBNO, T2KO) and/or atmospheric or reactor neutrino experiment will determine the hierarchy.

# Sensitivity to CP-violation

BB100,BB350:
hep-ph/0406132
hep-ph/0503021

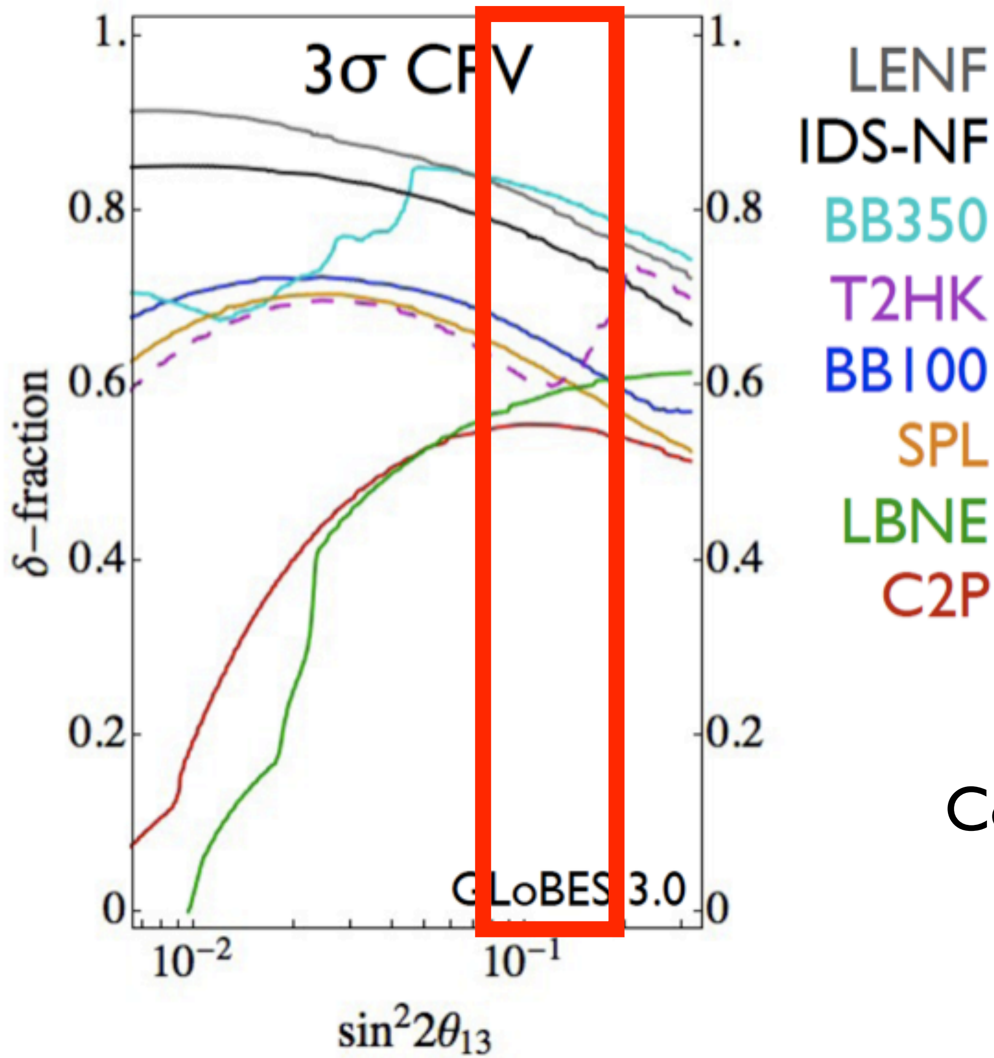
T2HK: hep-ex/0106019

C2P, SPL:
1001.0077 [physics.ins-det]
hep-ex/0411062
1106.1096 [physics.acc-ph]

LENF: 1012.1872 [hep-ph]

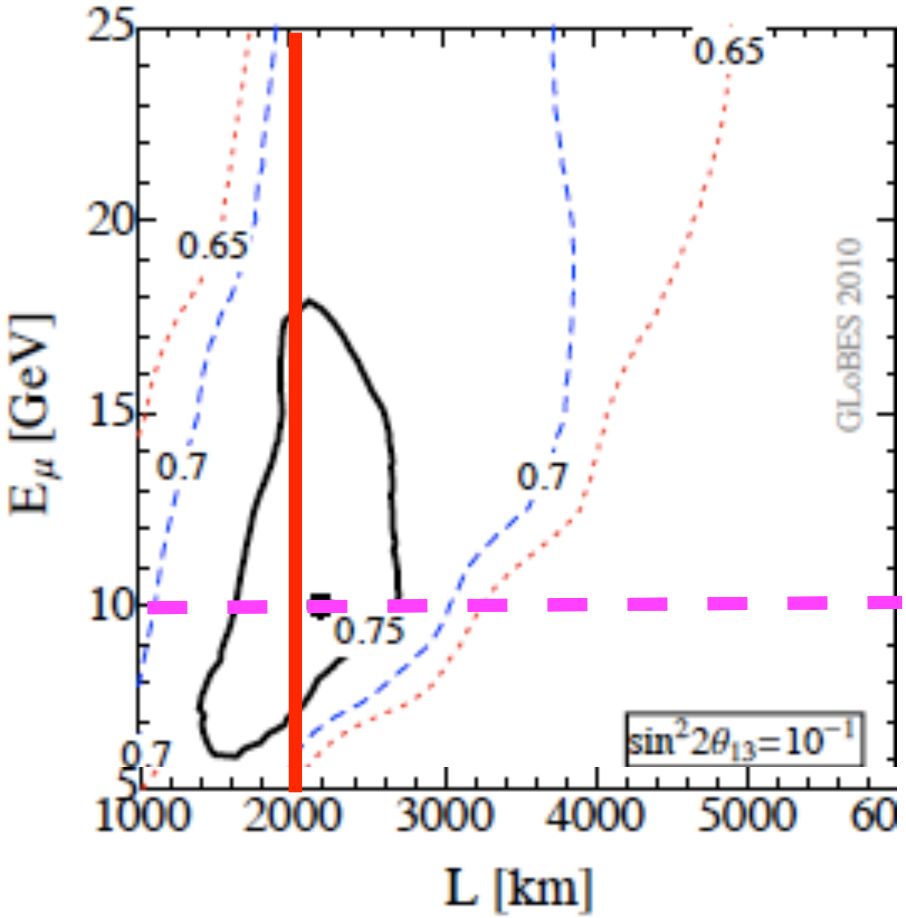
LBNE: 1110.6249 [hep-ex]

IDS: 1112.2853 [hep-ex]

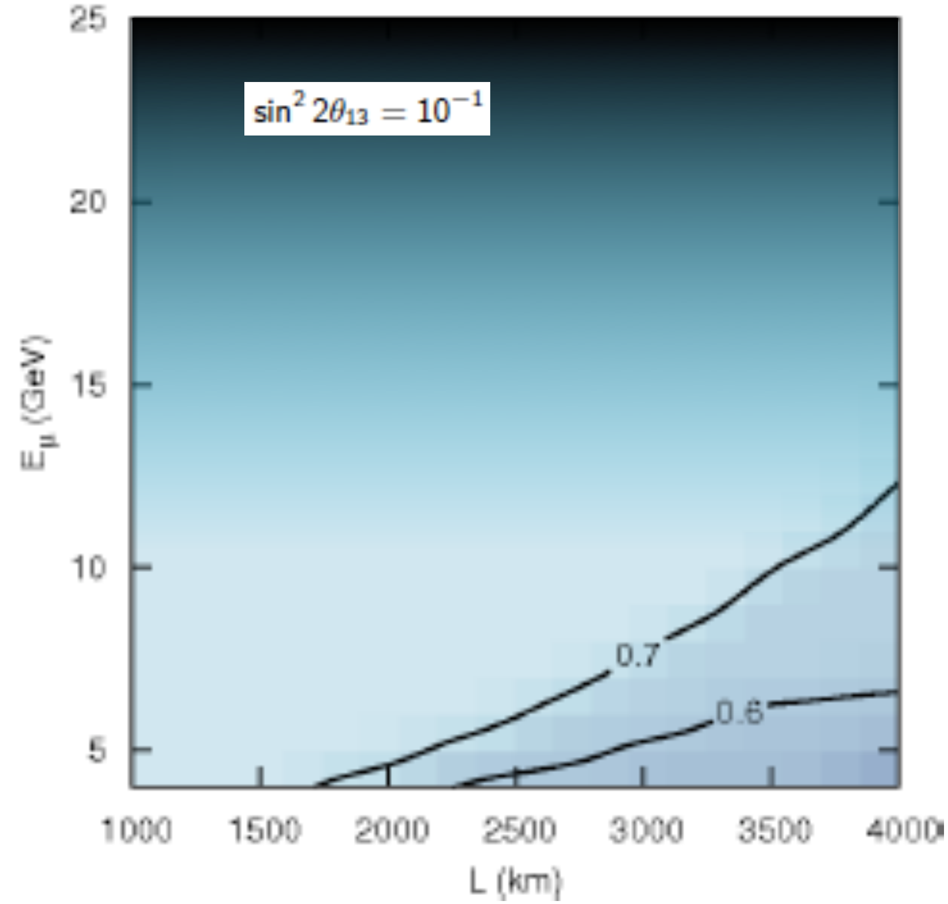



Coloma's talk

CPV might be discovered by the next generation of LBL.
LENF (E=10 GeV, L=2000 km) gives the best coverage.




Agarwalla's talk and 1012.1872




Ballett's talk and 1201.6299

Sensitivity to CP-violation: Lines show the fraction of delta for which CPV can be determined.

Excellent sensitivity for large $\theta_{13}$ rather independent from L and E → **E=10 GeV and L=2000 km**

# Standard scenario: precision measurements

- What are the precise values of mixing angles?

The precise values of the mixing angles have a strong theoretical impact for understanding the flavour problem. Symmetry motivated patterns:

- Bimaximal

$$U_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} P \qquad \theta_{12} = 45^o$$

- Tri-bimaximal

  Harrison, Perkins, Scott

$$U_{TB} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} P \qquad \theta_{12} = 35.26^o$$

- Golden ratio

  Kajirama, Raidal, Strumia; Everett, Stuart

$$U_{BM} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -\frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} P$$

$$\phi = \frac{1+\sqrt{5}}{2} \qquad \tan\theta_{12} = \frac{1}{\phi} \qquad \theta_{12} = 31.7^o$$

King's talk

Anarchy

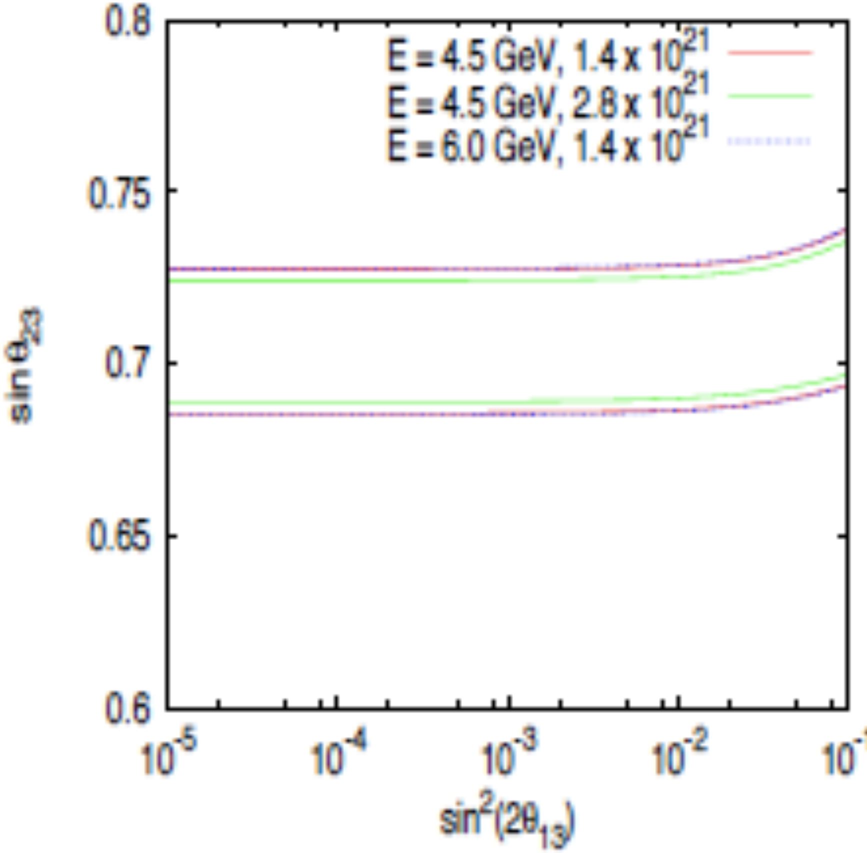
Deviation from these patterns is expected theoretically, e.g. GUTs, and is required by experimental data. Theoretical models typically lead to correlations between parameters (sum rules).

- Bimaximal $\theta_{12} = 45^o + \theta_{13} \cos\delta$ c.f. QLC $\theta_{12} + \theta_C = 45^o$
- Tri-bimaximal $\theta_{12} = 35^o + \theta_{13} \cos\delta$
- Golden ratio $\theta_{12} = 32^o + \theta_{13} \cos\delta$

- Tri-bimaximal (s=a=r=0)
- Tri-bimaximal-reactor (s=a=0)
- Tri-maximal 1 (s=0, a=r.cosδ)

After CPV, the main goal for LBL might shift to precision measurements. This needs to be included in the LENF physics motivation.

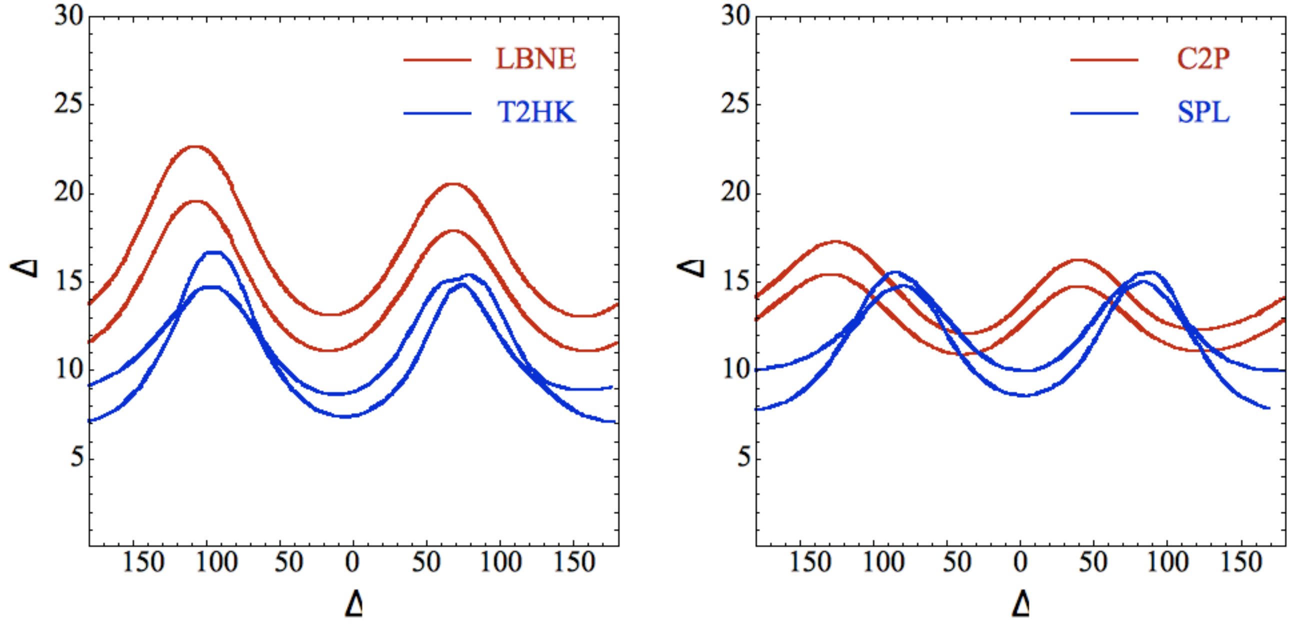
We have just started to address the problem of precision measurement of the parameters in a detailed and comprehensive way.



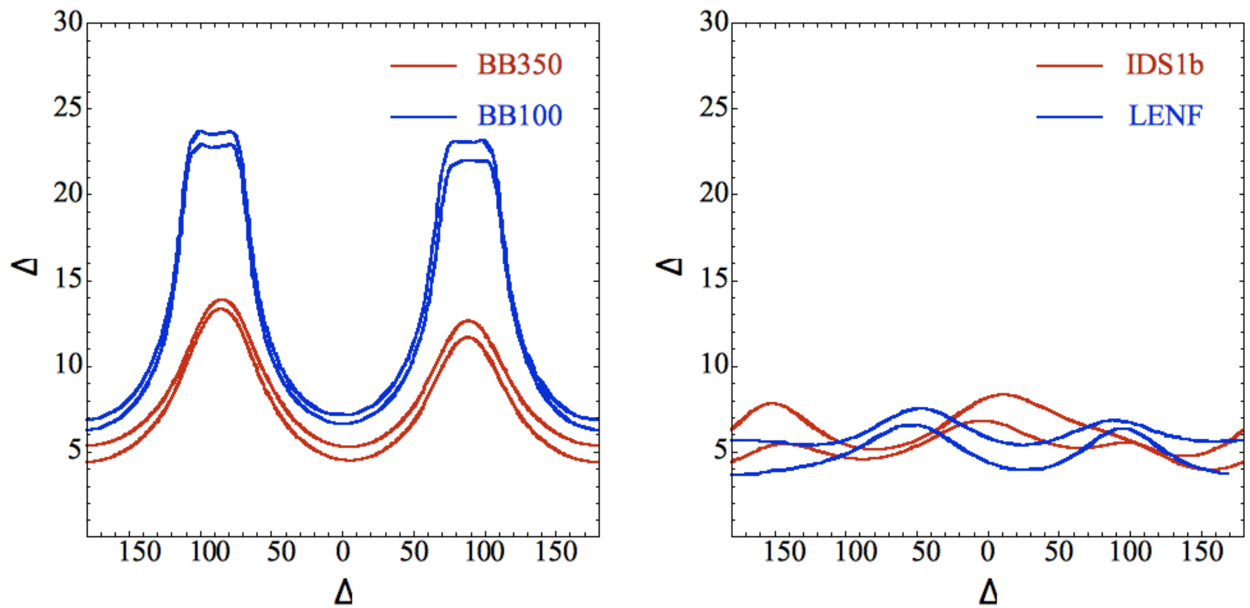

Fernandez-Martinez et al., 0911.3776

The parameters which are theoretically interesting are:
deviations from 45 of $\theta_{23}$
the value of $\theta_{13}$
the value of $\theta_{12}$
and the value of delta.

Delta and $\theta_{13}$ might also be related to leptogenesis.




Donini's talk and 1203.5651




The NF is the precision LBL experiment. More work is needed to fully understand the precision reachable.

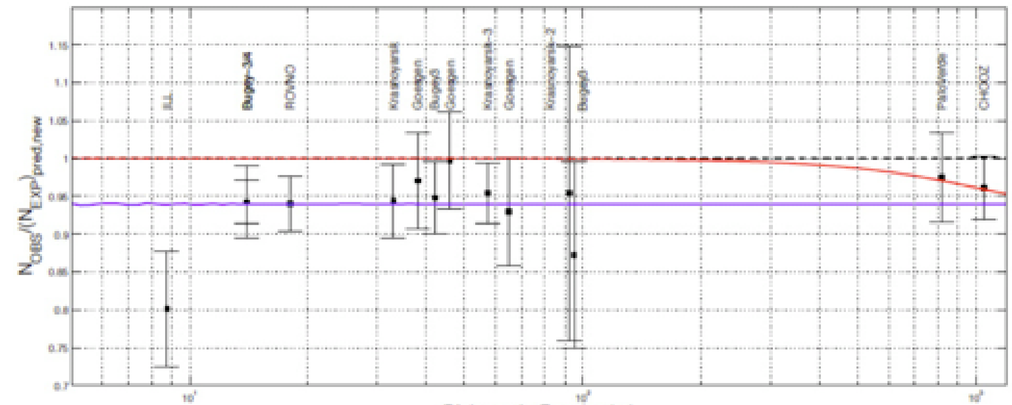
# Is the standard picture correct?

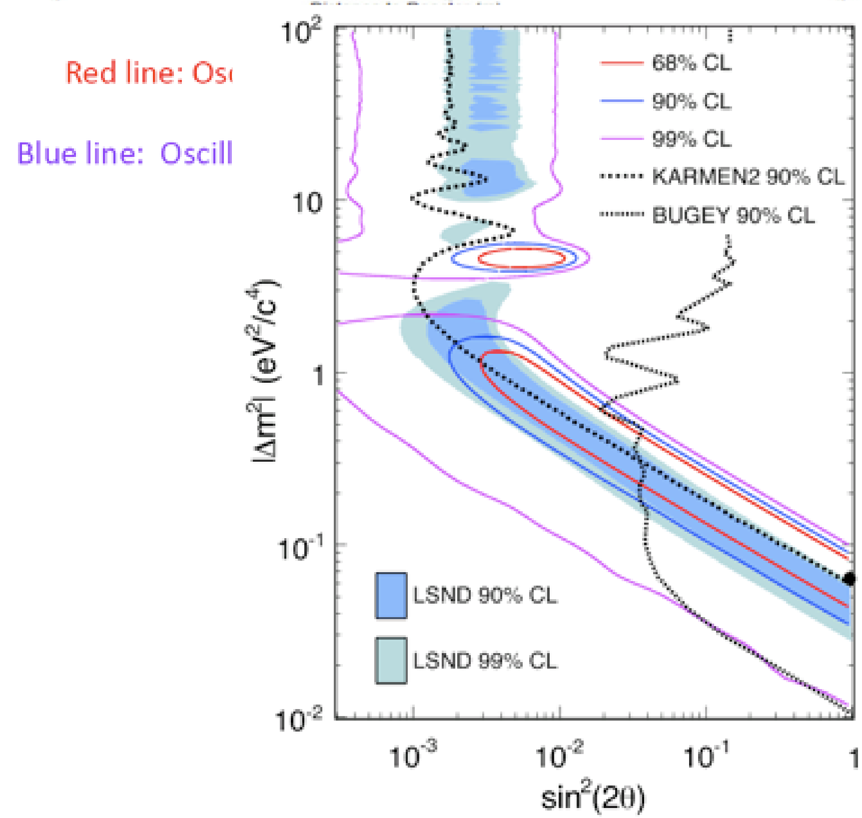
A plethora of hints of physics beyond 3 neutrino mixing and SM interactions is present.

LSND appearance experiment

MiniBooNE neutrino and antineutrino results

Reactor anomaly

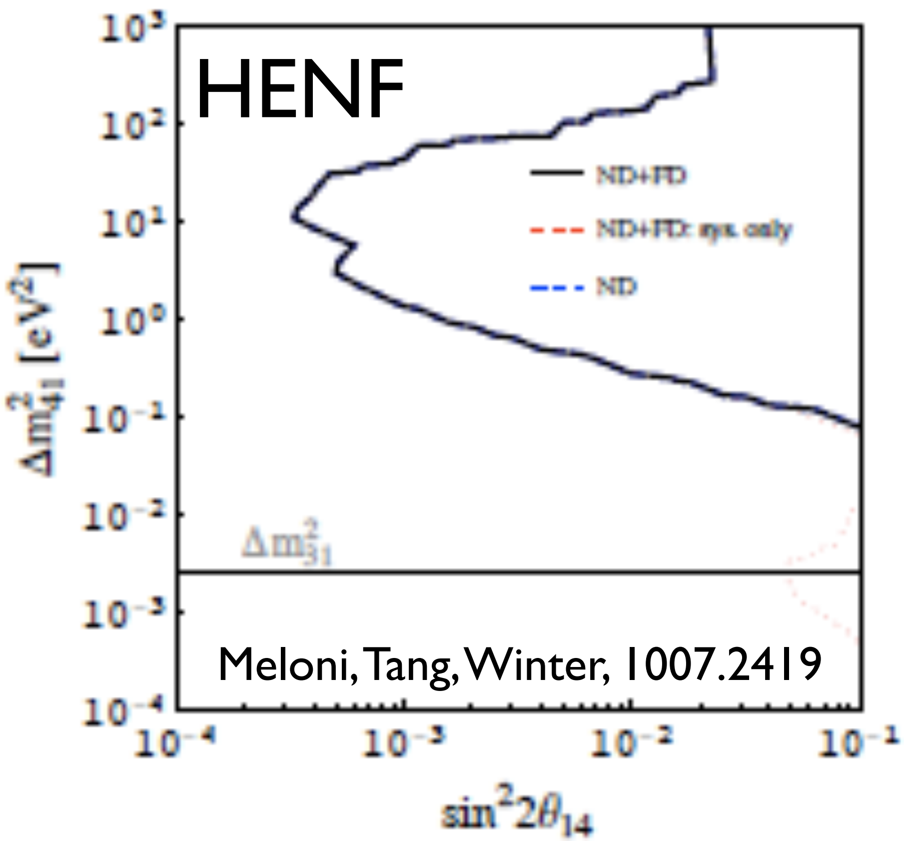


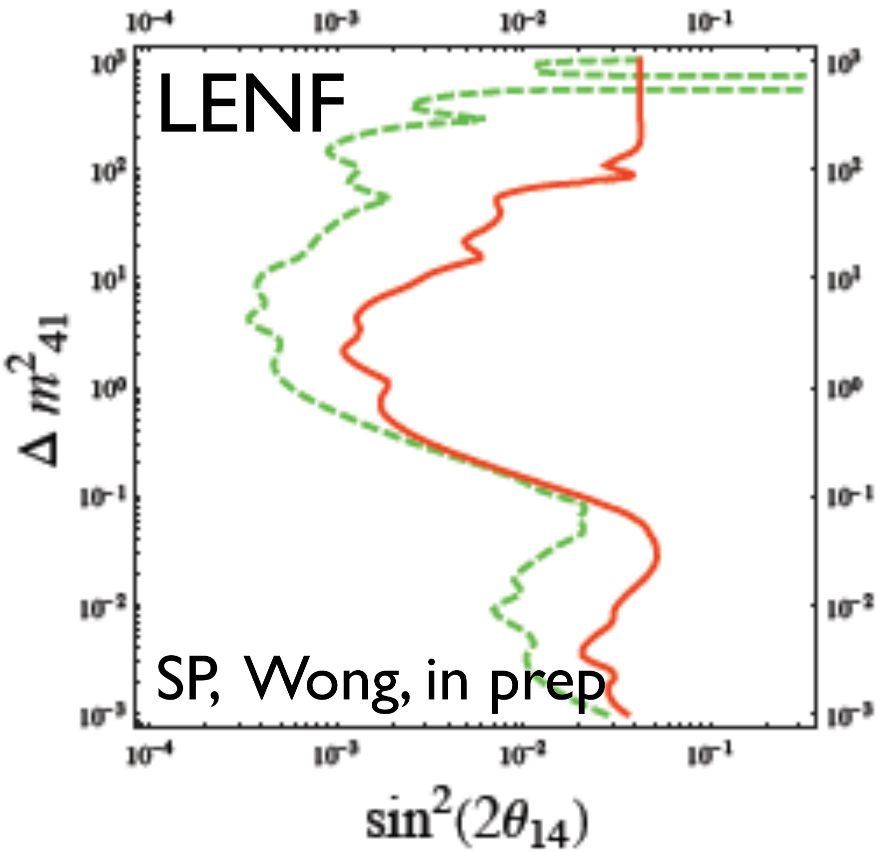



If confirmed, it would lead to a radical shift in our understanding of neutrino and physics BSM and would require a reanalysis of the reach of future neutrino oscillation experiments.

# Sterile neutrinos

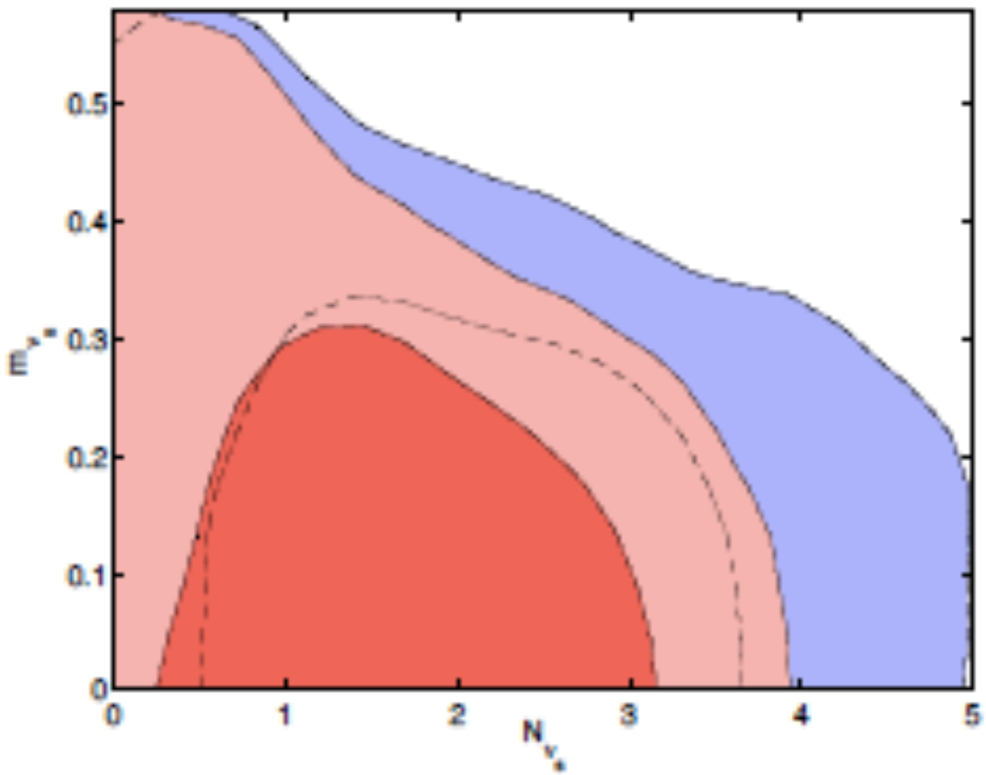
Of phenomenological interest for oscillations are those with sub-eV to multi-eV masses (LSND, MiniBooNE). New angles and CPV phases appear.



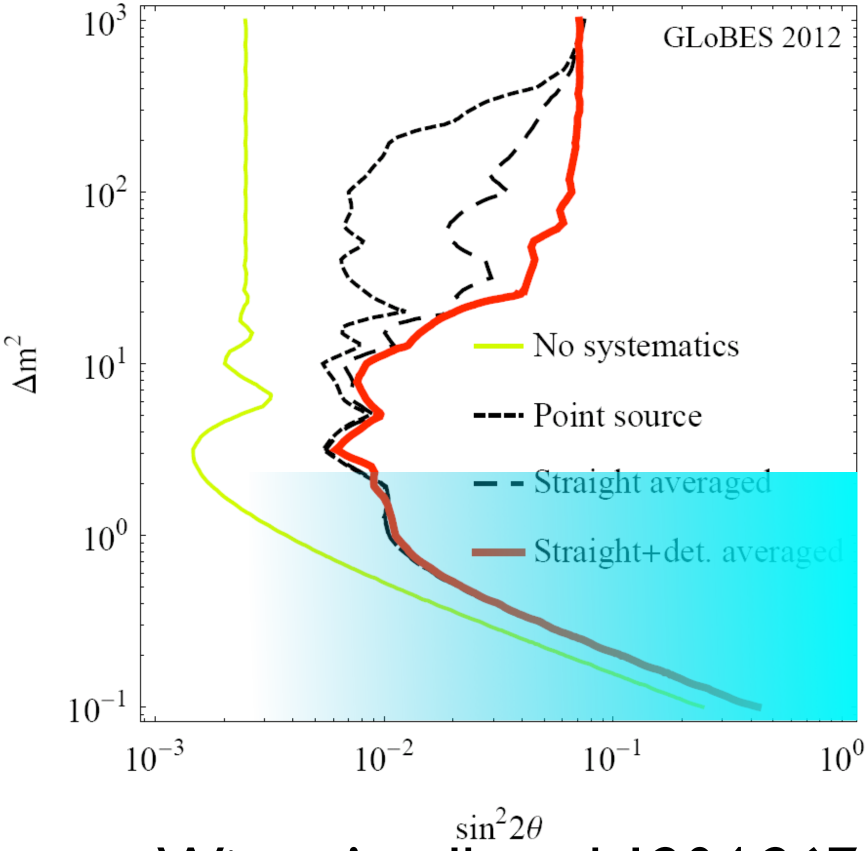




See also, Donini et al., Antusch et al., Tang and Winter...

Sterile neutrinos could be present in extensions of the SM with masses from sub-eV to GUT scale. They have implications in cosmology: WMD or HDM, BBN and CMB.




Giusarma et al., 1102.4774




Winter's talk and 1204.2671

Cosmological data seem to prefer extra degrees of freedom, possibly a sterile neutrino. They can be produced in the Early Universe via oscillations.

# NSI

NSI appear as additional effects in the H:

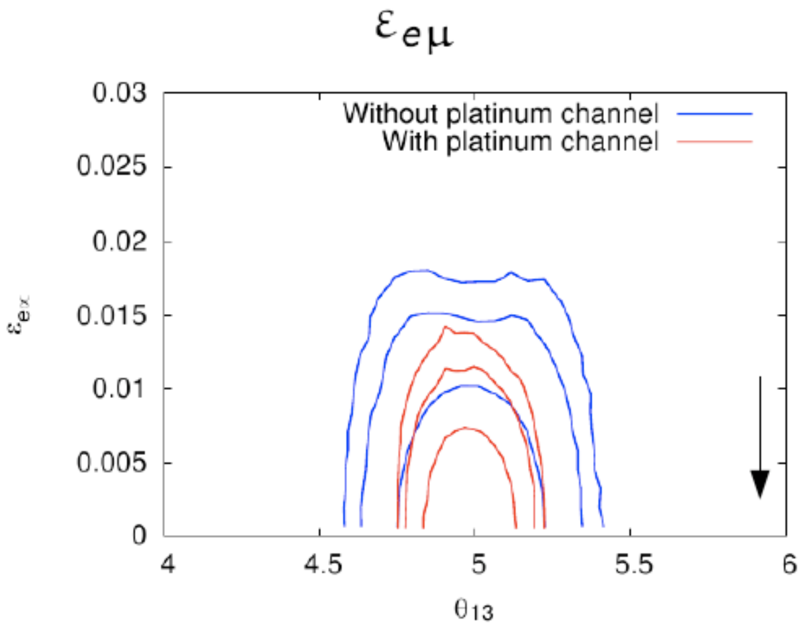
$$\hat{H}^{fl} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^\dagger \pm A \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^*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

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

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

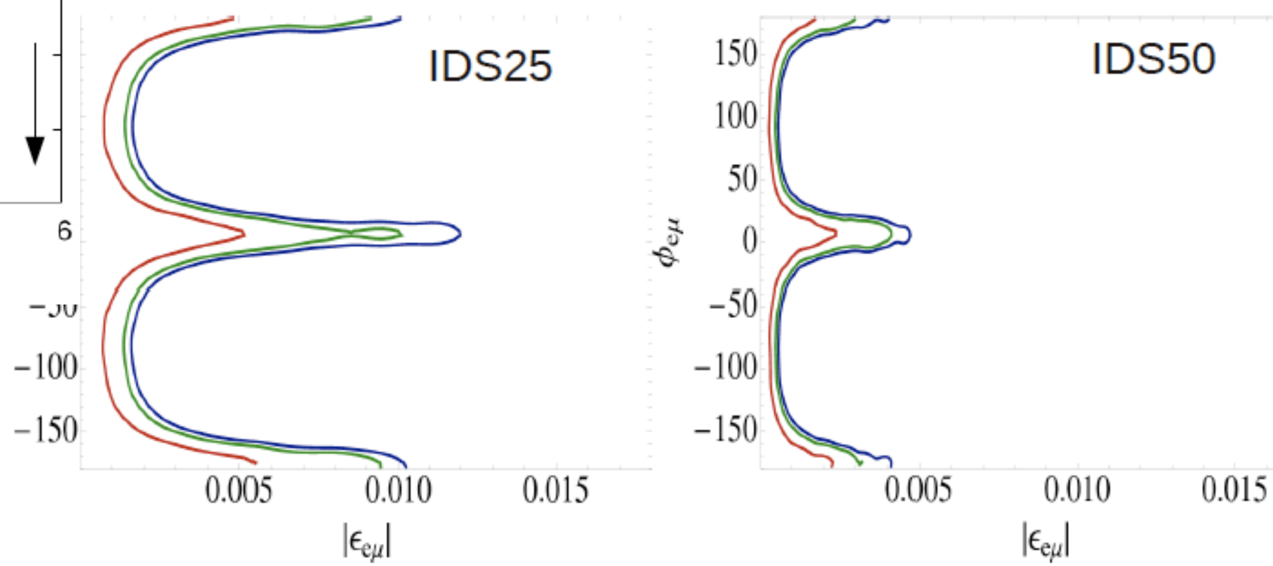
Strong bounds arise from oscillations, pion decay, CKM unitarity..., typically <0.001, 0.1, and at the loop-level, if charged current processes cannot be avoided.

# LBL experiments are also sensitive to NSI at source, propagation and detection:




Lopez-Pavon's talk and 1105.5936

Li et al., in preparation




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

# Systematic errors

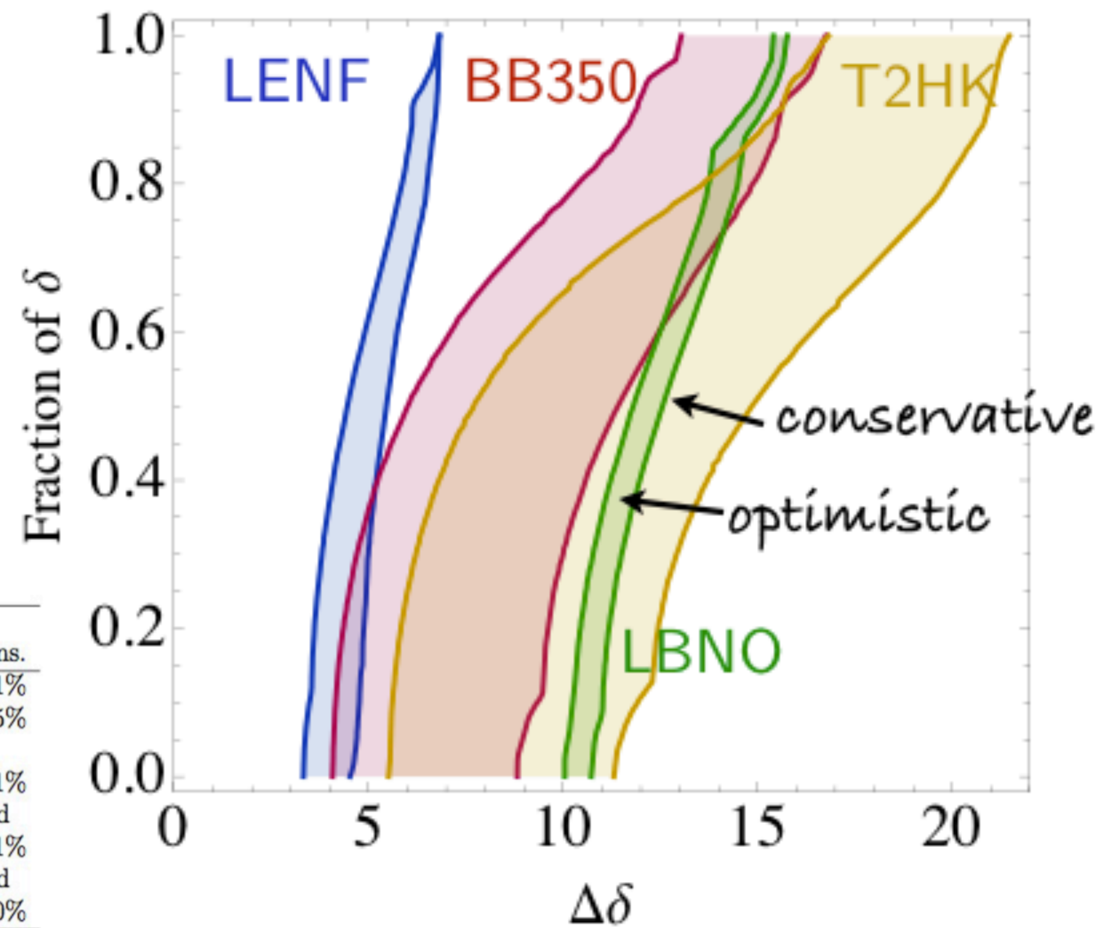
For large theta13, systematic errors become critical.

Difference between optimistic and pessimistic assumptions (two-det case):

$$L_{ND} \sim 1 - 2 \text{ km}$$

$$M_{ND} \sim 25 - 100 \text{ tons}$$

| Systematics | SB Opt. | SB Cons. | BB Opt. | BB Cons. | NF Opt. | NF Cons. |
|---|---|---|---|---|---|---|
| Fiducial volume ND | 0.2% | 1% | 0.2% | 1% | 0.2% | 1% |
| Fiducial volume FD (incl. near-far extrapolation) | 2.5% | 5% | 2.5% | 5% | 2.5% | 5% |
| Flux error signal $\nu$ | 5% | 10% | 1% | 2.5% | 0.1% | 1% |
| Flux error background $\nu$ | 10% | 20% | correlated | | correlated | |
| Flux error signal $\bar{\nu}$ | 10% | 20% | 1% | 2.5% | 0.1% | 1% |
| Flux error background $\bar{\nu}$ | 20% | 40% | correlated | | correlated | |
| Background uncertainty | 5% | 10% | 5% | 10% | 10% | 20% |
| Cross sections $\times$ efficiencies QE | 10% | 20% | 10% | 20% | 10% | 20% |
| Cross sections $\times$ efficiencies RES | 10% | 20% | 10% | 20% | 10% | 20% |
| Cross sections $\times$ efficiencies DIS | 5% | 10% | 5% | 10% | 5% | 10% |
| Cross sec. $\times$ efficiency ratio $\nu_e/\nu_\mu$ QE | Energy-dependent | | | | | |
| Cross sec. $\times$ efficiency ratio $\nu_e/\nu_\mu$ RES | 2.7% | 11% | 2.7% | 11% | 2.7% | 11% |
| Cross sec. $\times$ efficiency ratio $\nu_e/\nu_\mu$ DIS | 2.5% | 10% | 2.5% | 10% | 2.5% | 10% |




Coloma's talk

# Conclusions

- The sensitivity of LENF (one baseline, E<15 GeV, MIND detector) to CPV is rather flat in muon energy and L. We will study the LAr/MIND ratio and the impact of the platinum channel. (ACTION)
We recommend **L=2000 km and E=10 GeV** as baseline.

- Detailed studies of the precision reachable on theta13, theta23, delta are required and underway. (ACTION)
On top of the best CPV reach, LENF is the **precision LBL experiment**.

- As theta13 large, systematic errors are crucial and great care needs to be put in understanding their impact. (ACTION)

- LENF has also excellent sensitivity to sterile neutrinos, NSI (production, detection, propagation) and can test the standard 3-neutrino mixing scenario. (ACTION)