Neutrino oscillations: status and prospects

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Fermilab

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Outline

1. Present status of neutrino parameters

2. Theoretical implications

3. Oscillation experiments physics goals:

   - Mass ordering
   - Leptonic CP-violation
   - Precision measurement of parameters
   - Testing the 3-neutrino scenario

4. Conclusions

Current neutrino parameters

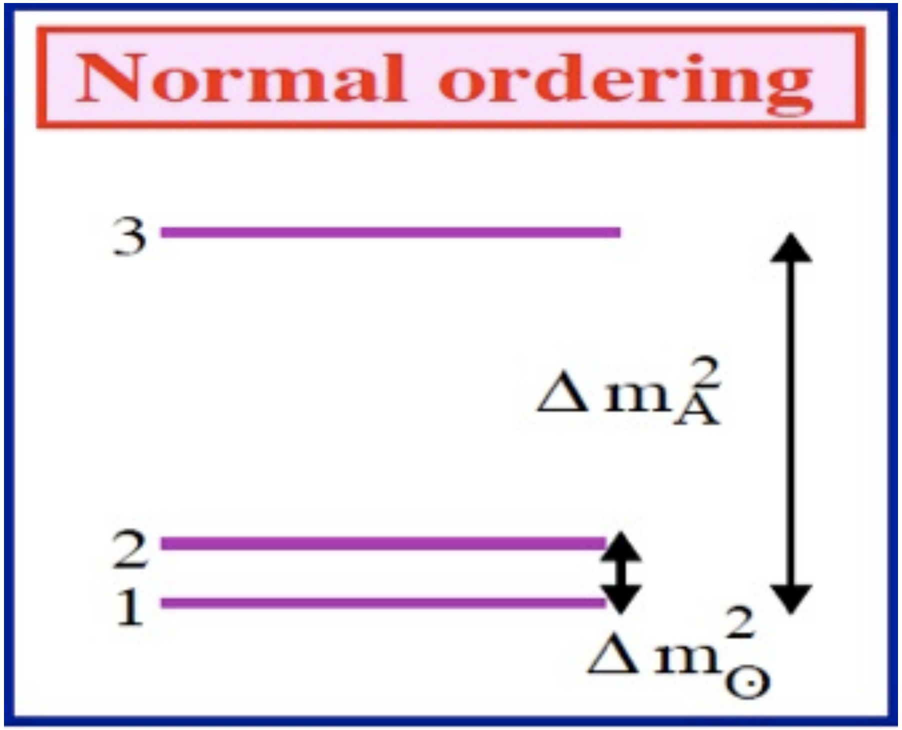
	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

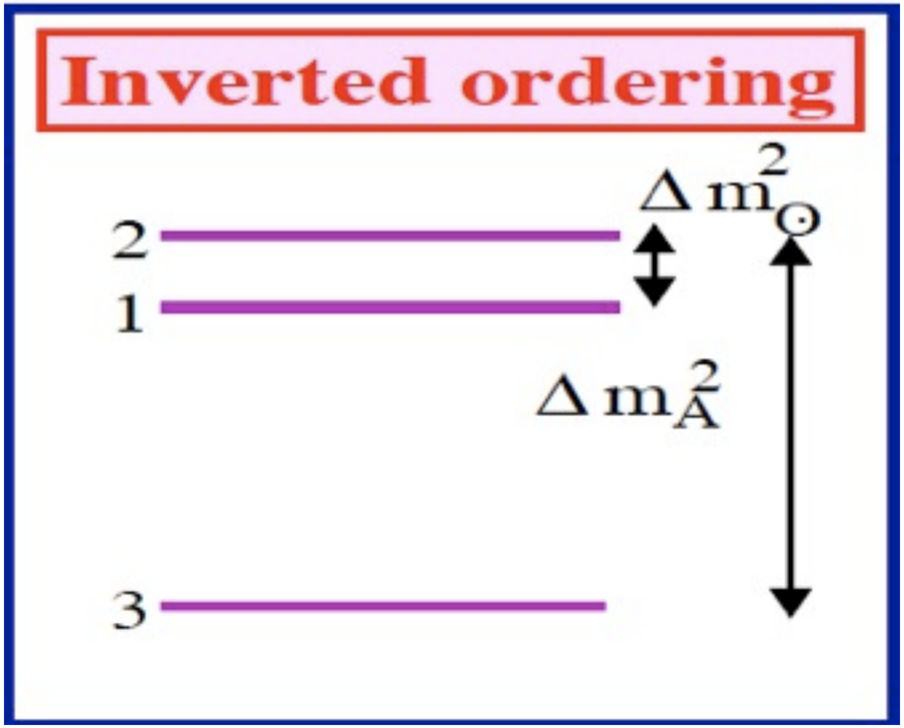
2 mass squared differences

M. C. Gonzalez-Garcia et al., NuFit, 1409.5439

Masses are much smaller than the other fermions.

$\Delta m_s^2 \ll \Delta m_A^2$ 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 .

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3 sizable mixing angles

M. C. Gonzalez-Garcia et al., NuFit, 1409.5439

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

Mixing angles are much larger than in the quark sector.

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CP-violation?

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

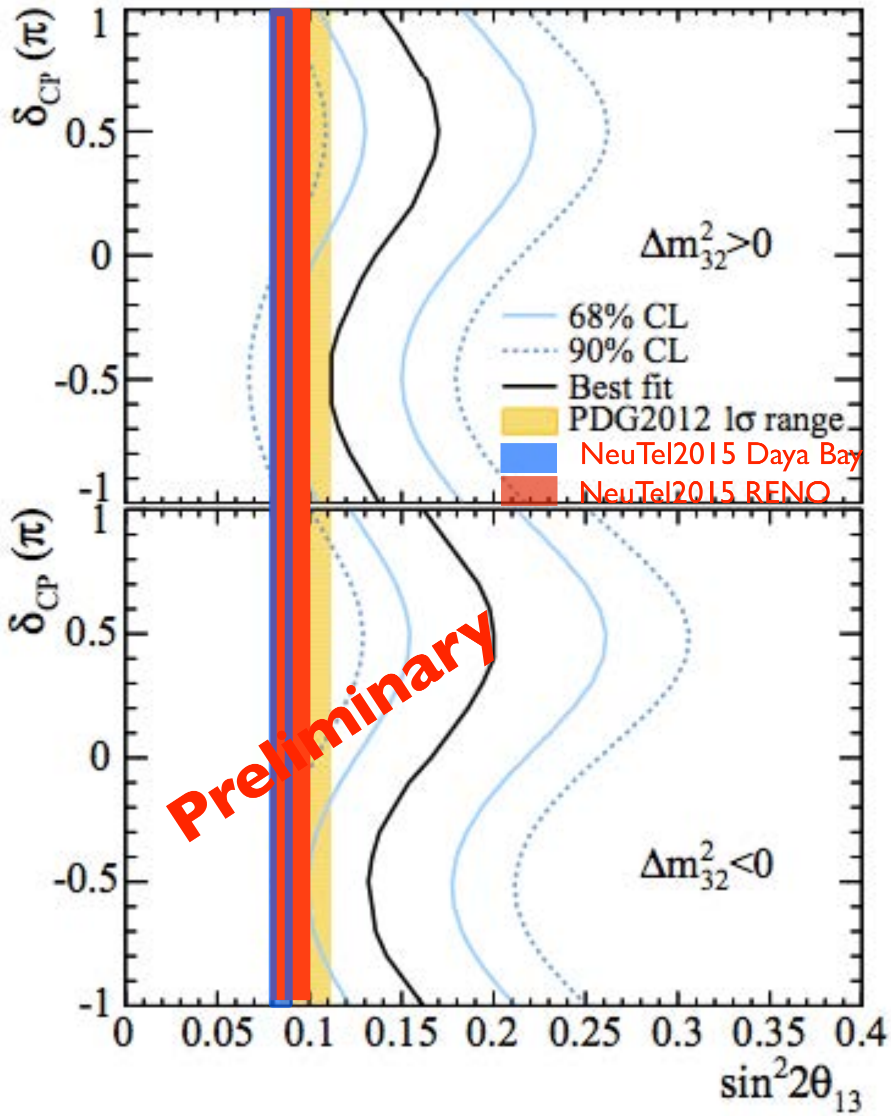
For antineutrinos,

$$U \to U^*$$

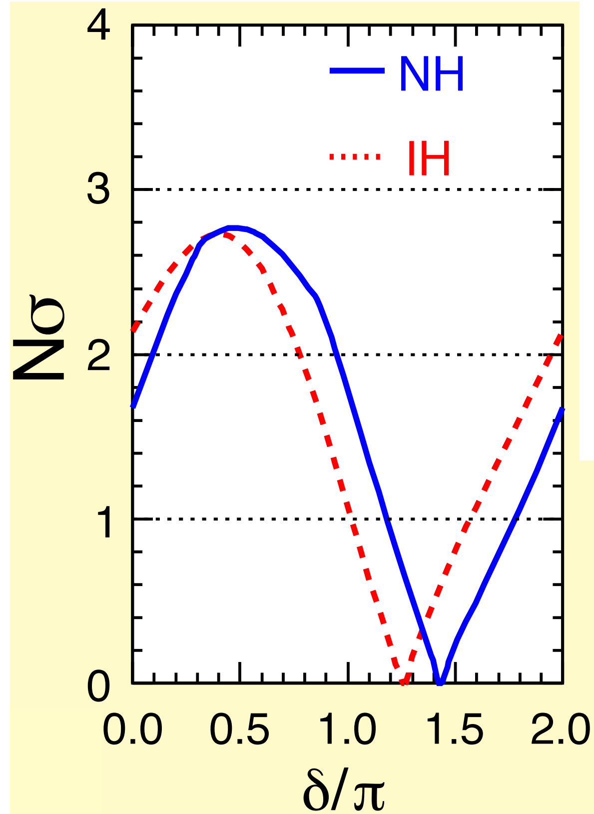
CP-conservation:

U is real $\Rightarrow \delta = 0, \pi$

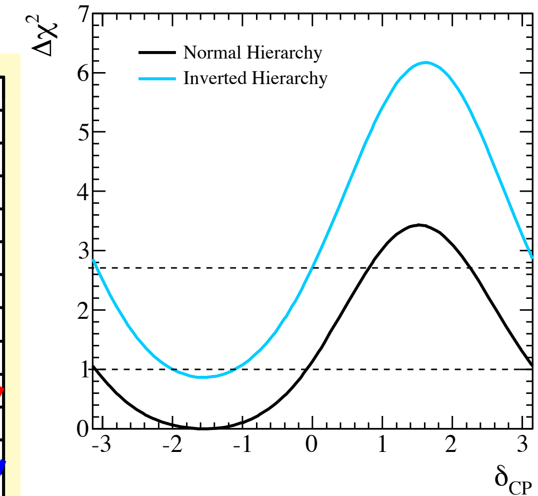
Hints of leptonic CP-violation?



T2K Coll. PRL 112, 061802 (2014)



G. Fogli, NeuTel2015



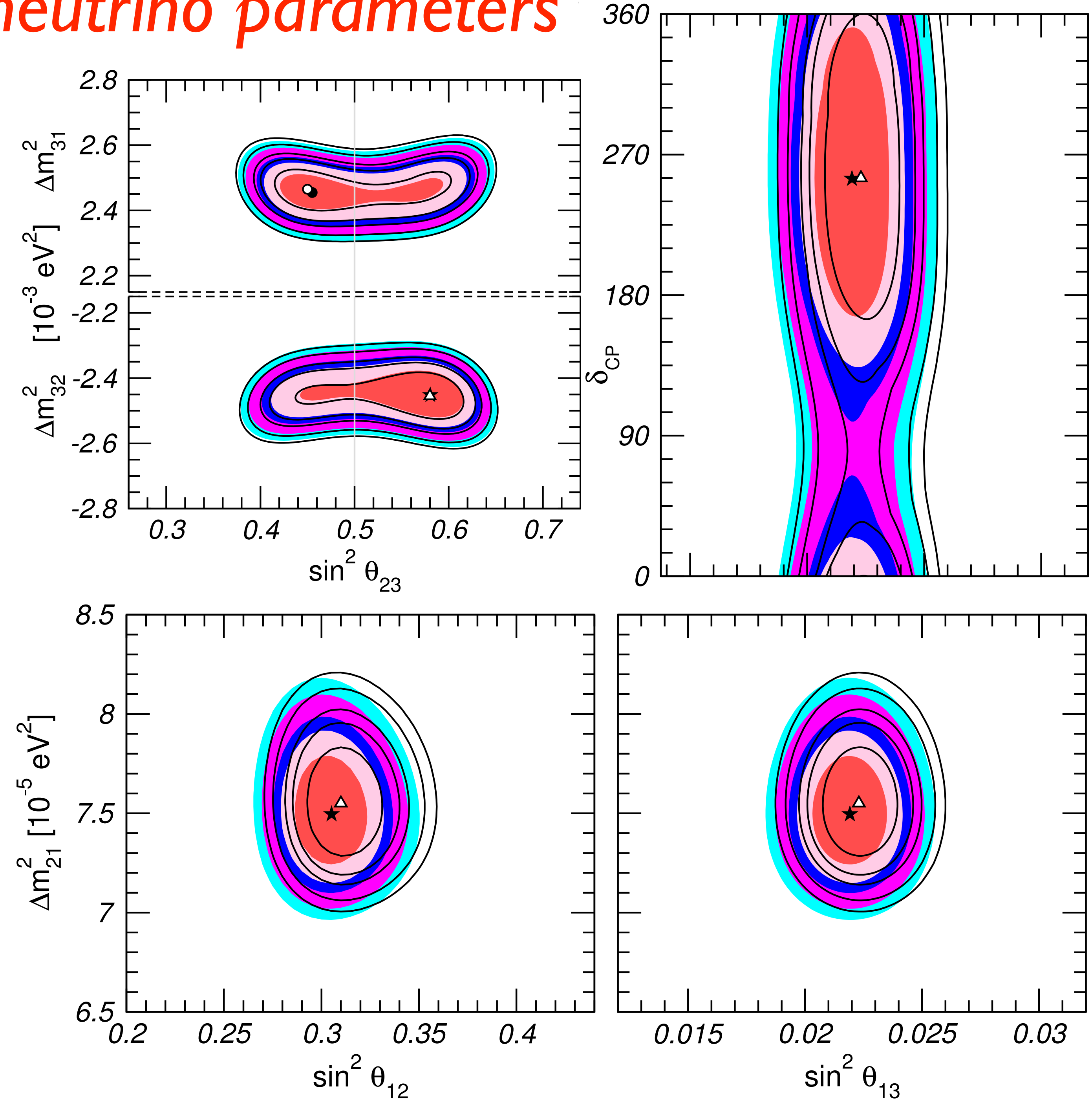
T2K Coll. 1502.01550

There is a slight preference for CP-violation, which is mainly due to the combination of T2K and reactor neutrino data.

Summary of current neutrino parameters

NuFIT 2.0 (2014)

Global fit to neutrino oscillation data



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www.invisibles.eu

Neutrino oscillations imply that neutrinos have mass and mix.

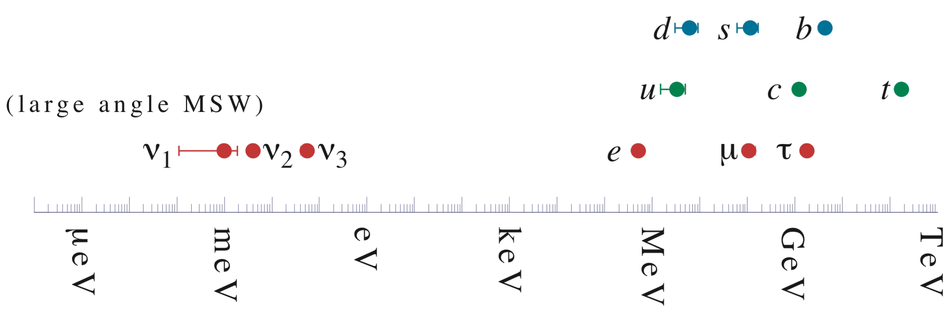
First evidence of physics beyond the SM.

The ultimate goal is to understand
- where do neutrino masses come from?
- what is the origin of leptonic mixing?

Open window on Physics beyond the SM

Neutrinos give a different perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass?
and why are they so light?
and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

sub-eV eV keV MeV GeV TeV GUT scale

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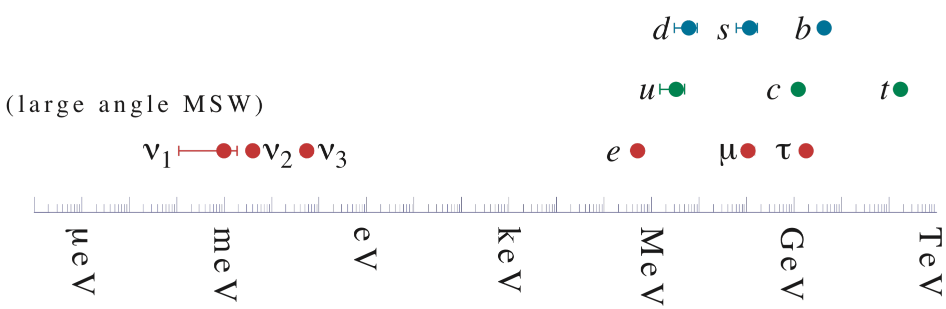

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Why leptonic mixing is so different from quark mixing?

This points towards a different origin of neutrino masses, possibly related to lepton number violation, e.g. see-saw mechanism: knowing the masses is important.

Open window on Physics beyond the SM

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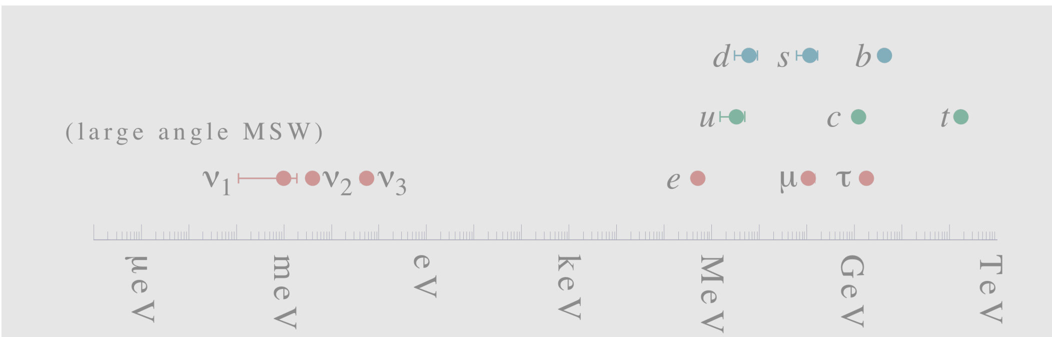

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Why leptonic mixing is so different from quark mixing?

We want to understand the origin of mixing. CP is a key symmetry: is it violated also in the lepton sector? Could it be at the origin of the matter-antimatter asymmetry?

Various strategies and ideas can be employed to understand the observed pattern (many many models!).

- Texture zero models with

$$\theta_{12,23,13} = \text{function}(\frac{m_e}{m_\mu}, \ldots, \frac{m_1}{m_2})$$

- Flavour symmetries: A4, A5, S4, ...

- Complementarity between quarks and leptons

$$\theta_{12} + \theta_C \simeq 45^o$$

- Anarchy (all elements of the matrix of same order).

The models predict specific values for the mixing angles and specific relations between the deviations from special values $\theta_{23} \sim 45^o, \theta_{13} \sim 0^o$.

Two necessary ingredients for testing flavour models:

- Precision measurements of the oscillation parameters at future experiments (including the delta phase).

- The determination of the mass ordering and of the neutrino mass spectrum.

Reference	Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2 \theta_{12}$	$\sin^2 \theta_{13}$
Anarchy Model:				
dGM [18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:				
BM [35]	Inverted			0.00029
BCM [36]	Inverted			0.00063
GMN1 [37]	Inverted		≥ 0.52	≤ 0.01
GL [38]	Inverted			0
PR [39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:				
CFM [40]	Normal			0.00006 - 0.001
HLM [41]	Normal	1.0	0.43	0.0044
	Normal	1.0	0.44	0.0034
KMM [42]	Inverted	1.0		0.000012
MN [43]	Normal			0.0024
MNY [44]	Normal			0.000004 - 0.000036
MPR [45]	Normal			0.006 - 0.01
RS [46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
	Normal	$\theta_{23} \leq 45°$		0
TY [47]	Inverted	0.93	0.43	0.0025
T [48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:				
ABGMP [49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL [50]	Normal			0.006 - 0.04
Ma [51]	Normal	1.0	0.45	0
SO(3) Models:				
M [52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:				
CPP [53]	Normal			0.007 - 0.008
	Inverted			≥ 0.00005
	Inverted			≥ 0.032
WY [54]	Either			0.0006 - 0.003
	Either			0.002 - 0.02
	Either			0.02 - 0.15

Albright, Chen, PRD 74

Phenomenology questions for the future

- **1. What is the nature of neutrinos?**
- **2. What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **3. Is there CP-violation?**
- **4. What are the precise values of mixing angles?**
- **5. Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

Phenomenology questions for the future

- **1. What is the nature of neutrinos?** Neutrinoless dbeta decay
- **2. What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering. LBL: T2K, NOvA, DUNE, T2HK, ESSnuSB, Daedalus, nuFACT..., PINGU
- **3. Is there CP-violation?**
- **4. What are the precise values of mixing angles?** reactor SBL and MBL, atm, LBL, ...
- **5. Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects? MINOS+, MicroBooNE, SBND...

Very exciting experimental programme now and for the future.

Phenomenology questions for the future

- **1. What is the nature of neutrinos?**
- **2. What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
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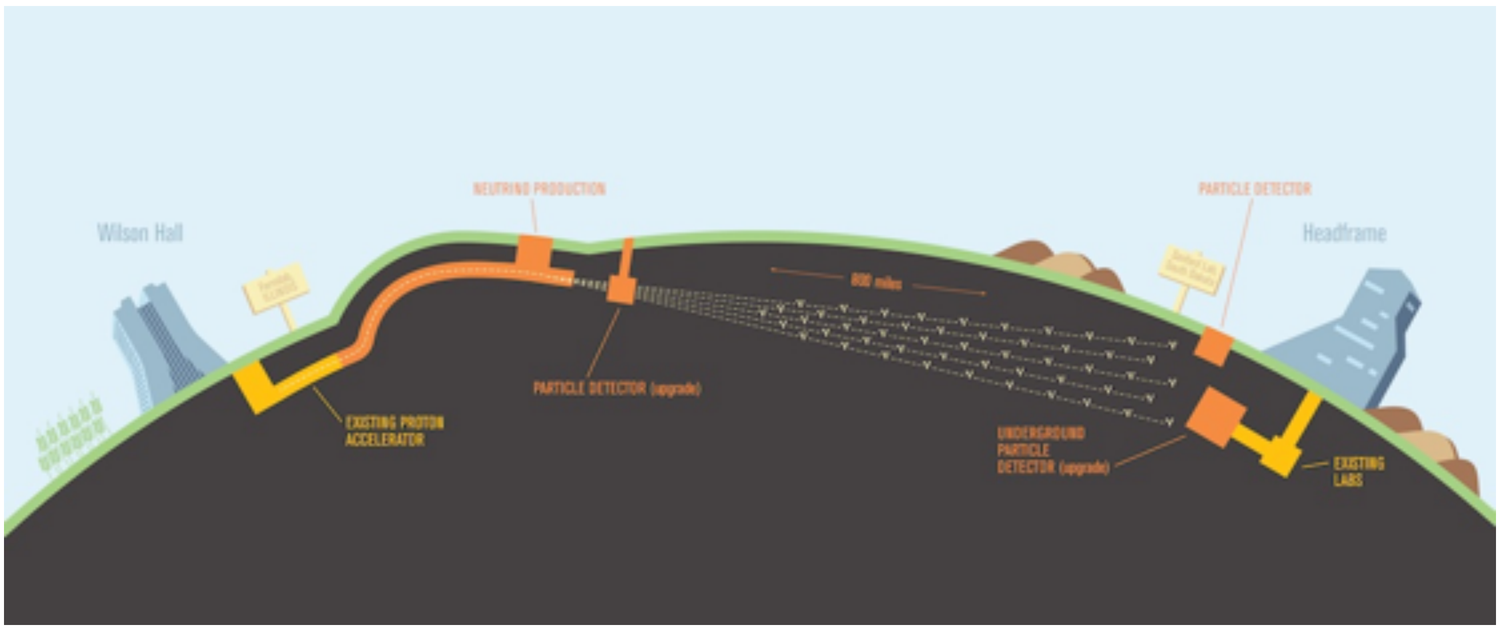
How can we search for the mass ordering and leptonic CP-violation?

Long-baseline oscillations and MO

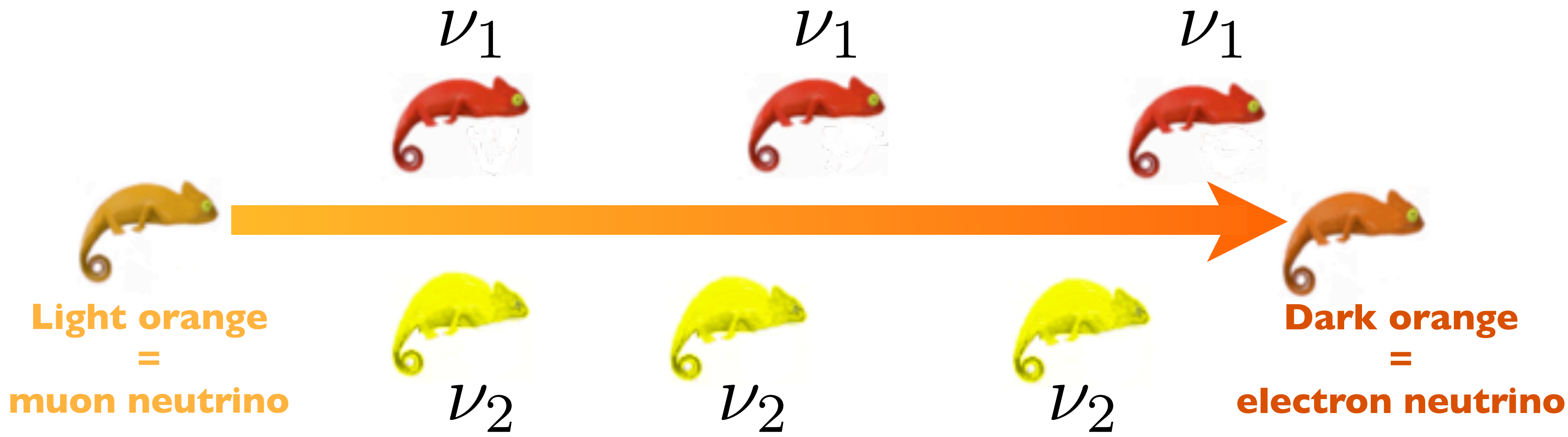
- When neutrinos travel in a medium, they interact with the background of e, p, n and get an effective mass.



Credit: Symmetry magazine

- 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 (different for neutrinos and antineutrinos).

Neutrino oscillations: the formalism



Production

$$|\nu_\mu\rangle = \sum_i U_{\mu i}|\nu_i\rangle$$
$$= \sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

Flavour states coherent superposition of massive states

Propagation

$$\nu_1 : \quad e^{-iE_1 t}$$
$$\nu_2 : \quad e^{-iE_2 t}$$
$$\nu_3 : \quad e^{-iE_3 t}$$

Massive states (eigenstates of the Hamiltonian)

Detection: projection over

$$\langle\nu_e|$$

Flavour states

Lets's consider for simplicity the case of 2-neutrino mixing. The time evolution is given by

$$|\nu, t\rangle = e^{-i\mathcal{H}t}|\nu, 0\rangle = -\sin\theta e^{-iE_1 t}|\nu_1\rangle + \cos\theta e^{-iE_2 t}|\nu_2\rangle$$

As neutrinos are highly relativistic,

$$E_2 - E_1 \simeq (p + \frac{m_2^2}{2E}) - (p + \frac{m_1^2}{2E}) \simeq \frac{\Delta m^2}{2E}$$

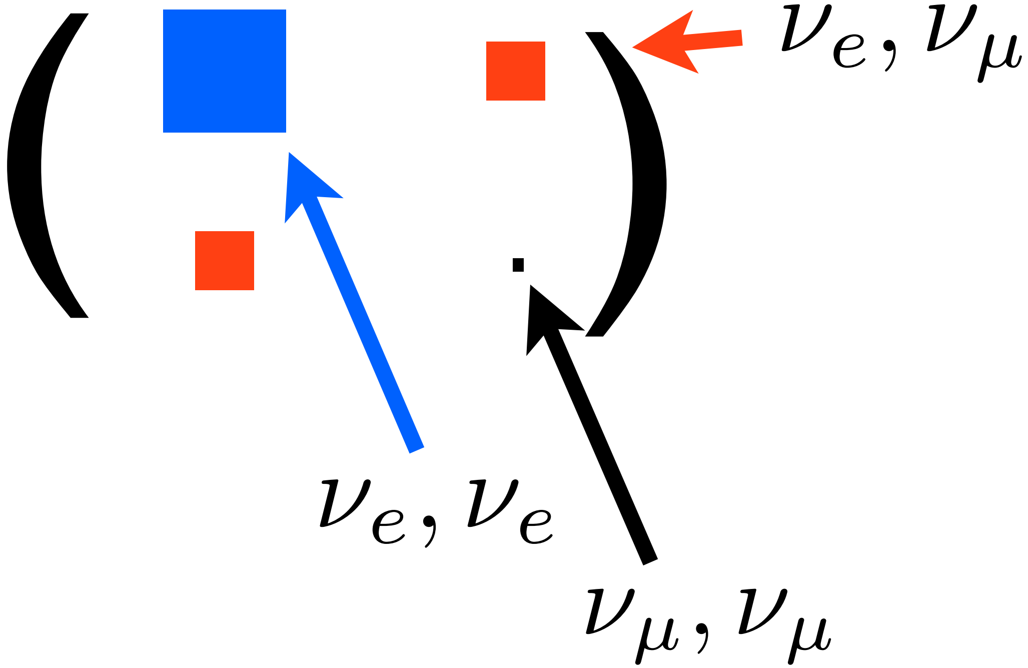
The **probability** for ν_μ to transform into ν_e is:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\frac{(m_2^2 - m_1^2)L}{4E}$$

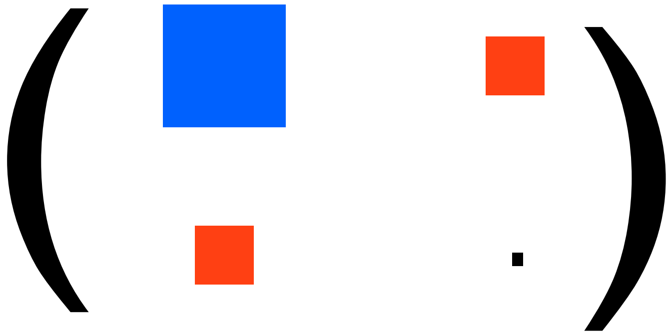
Mixing angle: disalignment between flavour and mass states

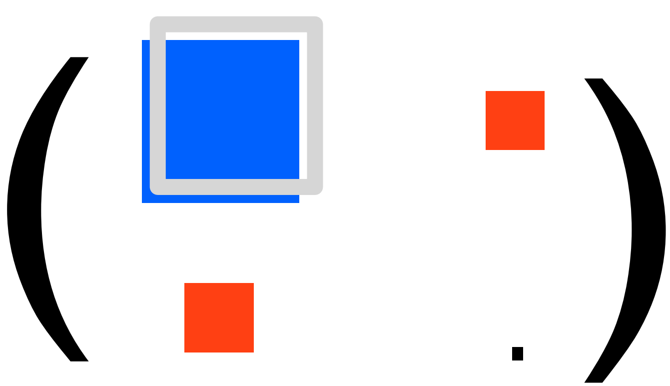
Neutrino masses

Effective Hamiltonian in the flavour basis



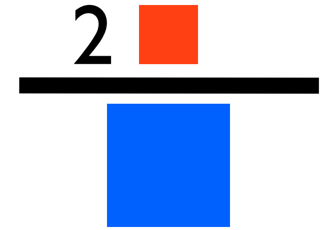
Effective Hamiltonian



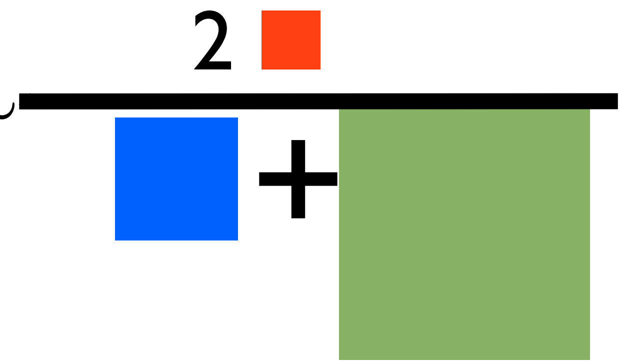


Mixing angle

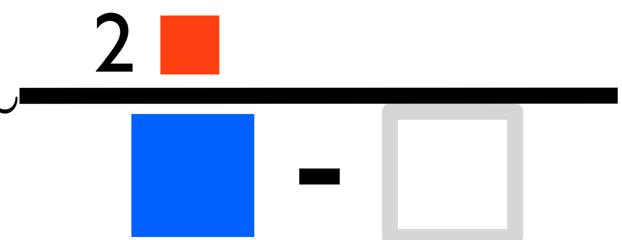
vacuum

$\tan 2\theta \sim$ 

matter suppression (Sun, SN)

$\tan 2\theta^M \sim$  $\ll \tan 2\theta$

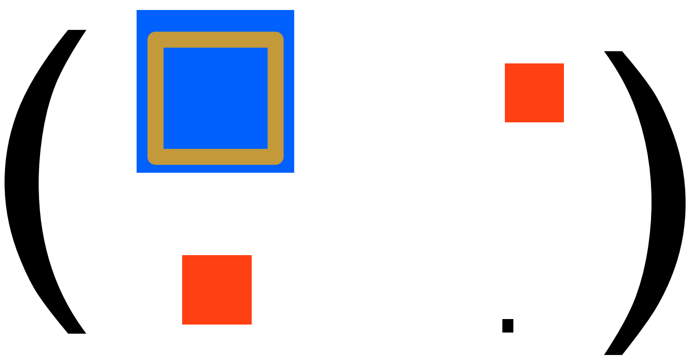
MSW resonance (Sun, SN)

$\tan 2\theta^M \sim$  $\sim \infty$

In long baseline experiments

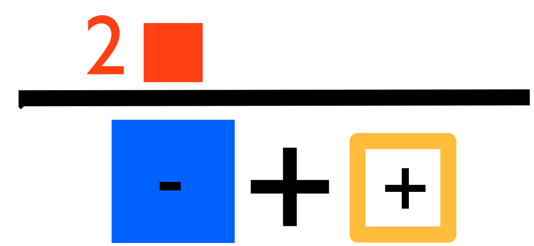
$-\frac{\Delta m^2}{2E}\cos(2\theta)$ $\quad \nu \quad +\sqrt{2}G_F N_e \quad \bar{\nu} \quad -\sqrt{2}G_F N_e$

For neutrinos

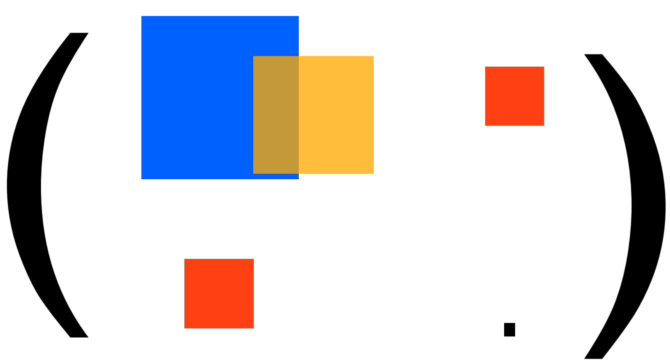


$\Delta m^2 > 0$ enhancement

$\tan 2\theta^M \sim$

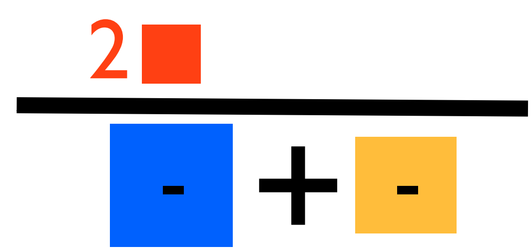


For antineutrinos



$\Delta m^2 > 0$ suppression

$\tan 2\theta^M \sim$



Matter effects modify the oscillation probability in LBL experiments.

$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23} \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta_{13}^m L}{2}$$

The probability enhancement happens for

- neutrinos if $\Delta m^2 > 0$
- antineutrinos if $\Delta m^2 < 0$

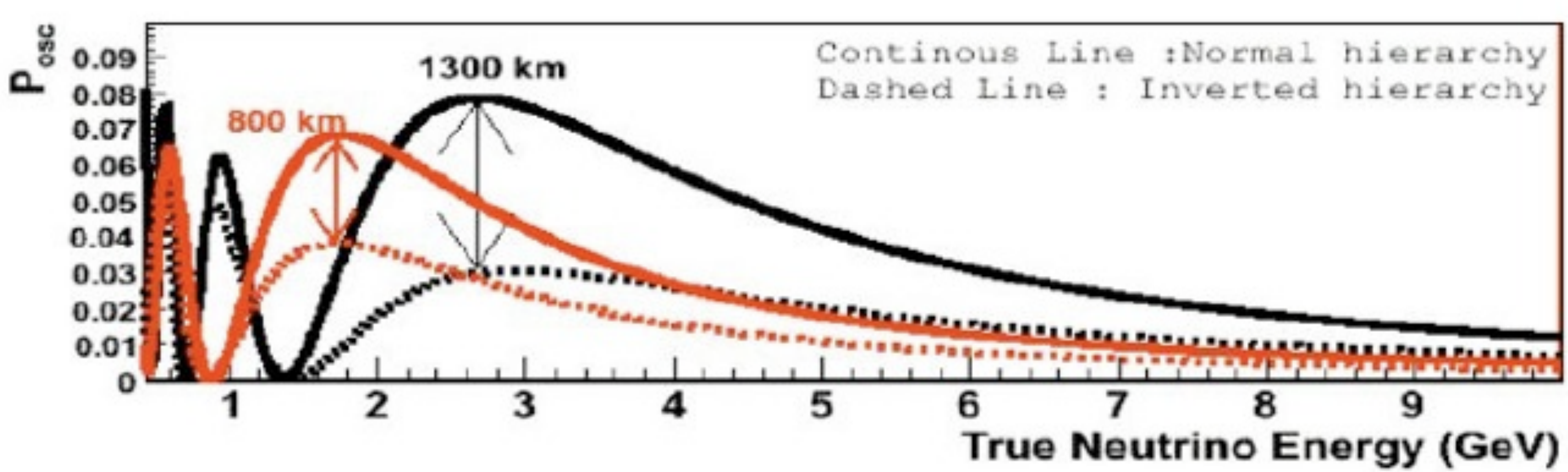
The impact of matter effects is stronger at higher energies and at longer baselines.

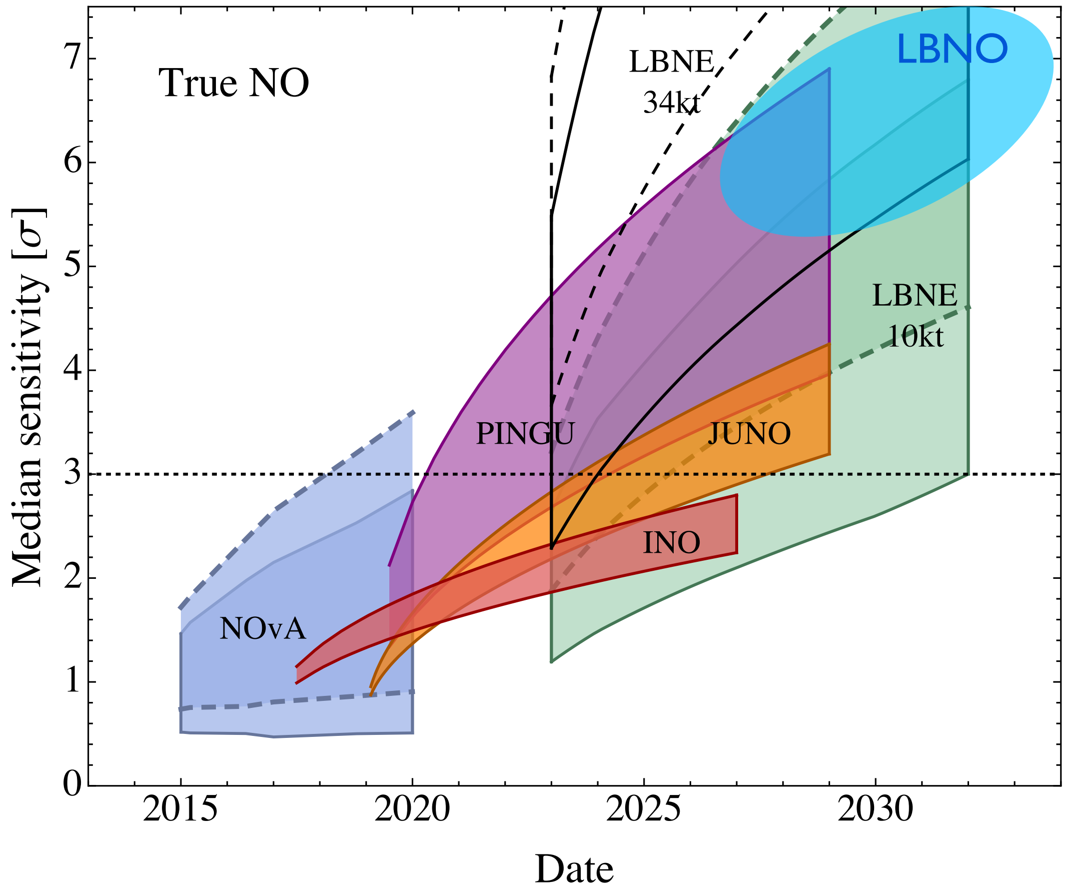
The 3 neutrino probability can be approximated as

A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773;
Minakata, Parke, 1505.01826 ...

$$P_{\mu e} \simeq 4c_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta_{31}L}{4E}$$
$$+\sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21}L}{2E} \sin \frac{(1-r_A)\Delta_{31}L}{4E} \cos\left(\delta - \frac{\Delta_{31}L}{4E}\right)$$
$$+s_{23}^2 \sin^2 2\theta_{12} \frac{\Delta_{21}^2 L^2}{16E^2} - 4c_{23}^2 s_{13}^4 \sin^2 \frac{(1-r_A)\Delta_{31}L}{4E}$$

with $r_A \equiv \frac{2E}{\Delta m_{31}^2}\sqrt{2}G_F N_e$





Blennow, Coloma, Huber, Schwetz, 1311.1822

Experiment	Physics effect	Challenges
DUNE, nuFactory	Matter effects in crust	delta, theta23
Atm nus (INO, PINGU, ORCA)	Matter effects (mantle, mantle+core)	theta23, energy and angular resolution
Reactor exp (JUNO, RENO50)	Vacuum oscillations	energy resolution and reconstruction

See also W.Winter's talk at Neutrino 2014

CP-violation in LBL experiments

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

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

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

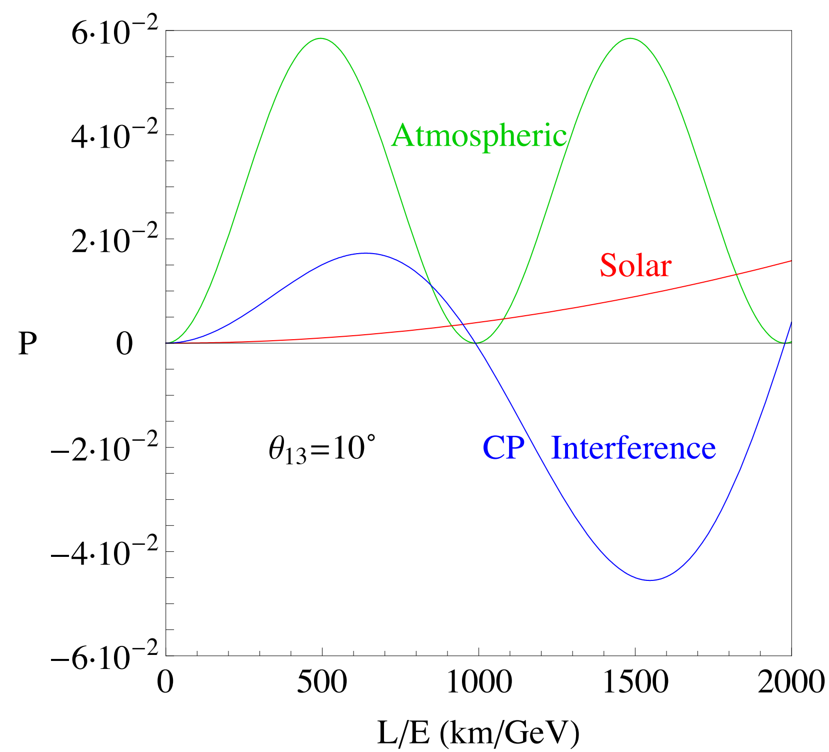
- CP-violation requires all angles to be nonzero.
- It is proportional to the sine of the delta phase.
- Effective 2-neutrino probabilities are CP-symmetric.

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

$$P_{\mu e} \simeq 4 c_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$
$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21} L}{2E} \sin \frac{(1-r_A)\Delta_{31} L}{4E} \cos\left(\delta - \frac{\Delta_{31} L}{4E}\right)$$
$$+ s_{23}^2 \sin^2 2\theta_{12} \frac{\Delta_{21}^2 L^2}{16 E^2} - 4 c_{23}^2 s_{13}^4 \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$

A. Cervera et al., hep-ph/0002108; K. Asano, H. Minakata, 1103.4387; S. K. Agarwalla et al., 1302.6773...

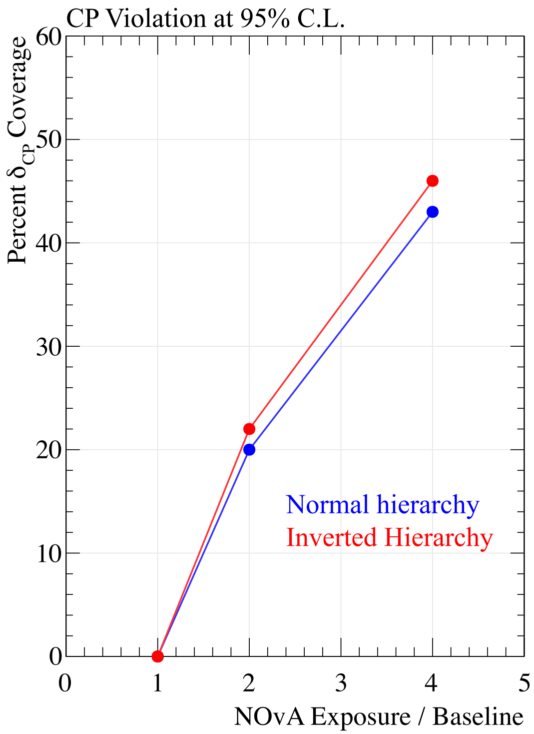
- The CP asymmetry peaks for sin^2 2 theta13 ~0.001. Large theta13 makes its searches possible but not ideal.
- Degeneracies with the mass hierarchy and theta23.
- CPV effects are more pronounced at low energy.



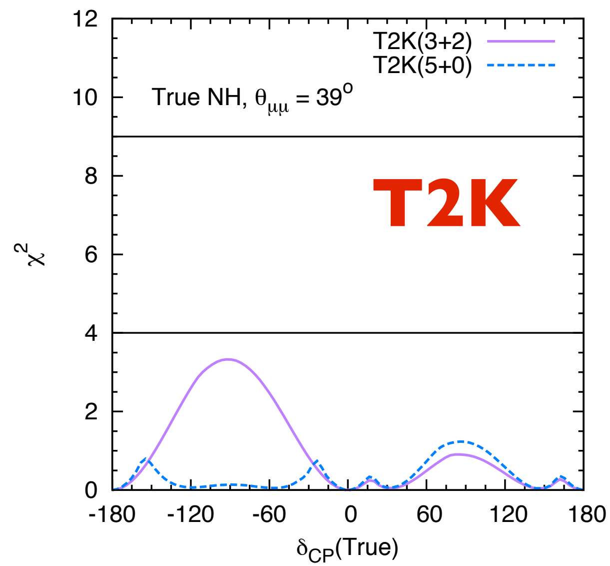
P. Coloma, E. Fernandez-Martinez, JHEP1204

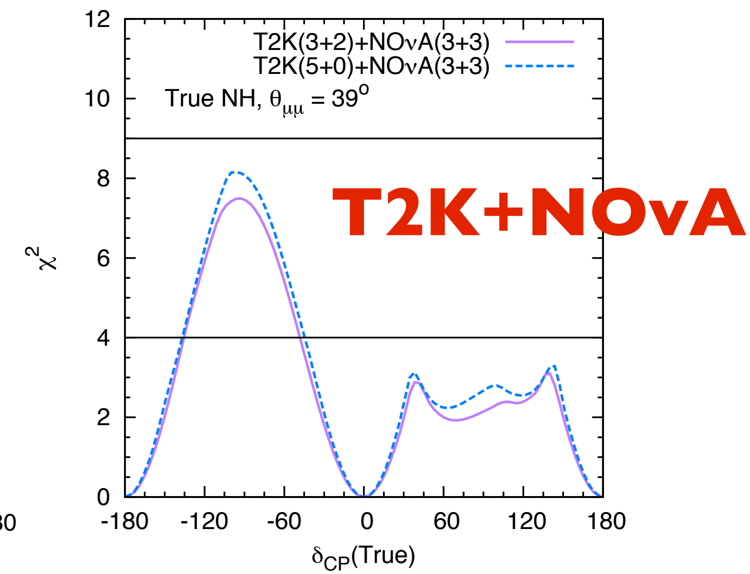
CPV Searches   *Near future: T2K and NOvA*

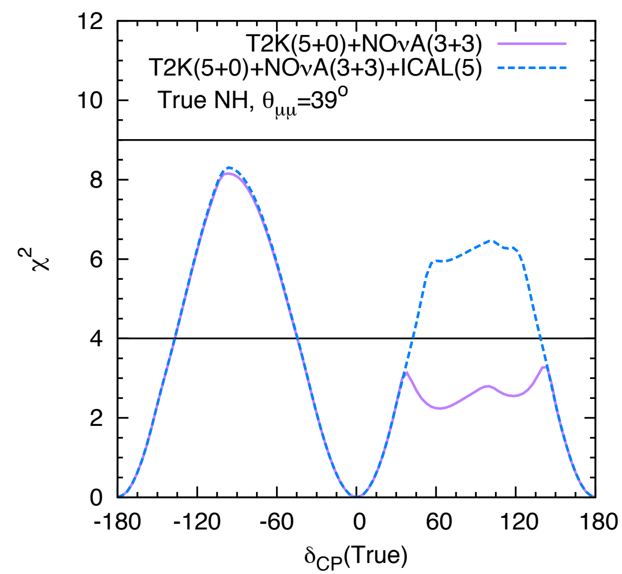
“NOvAplus”



NOvA Coll., 1308.0106



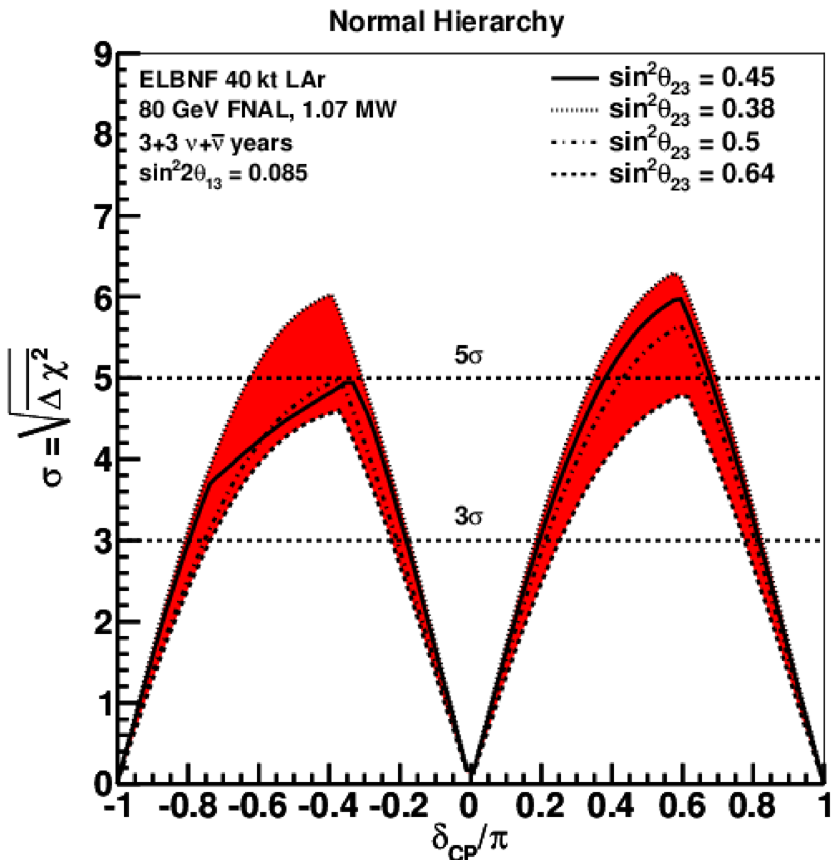




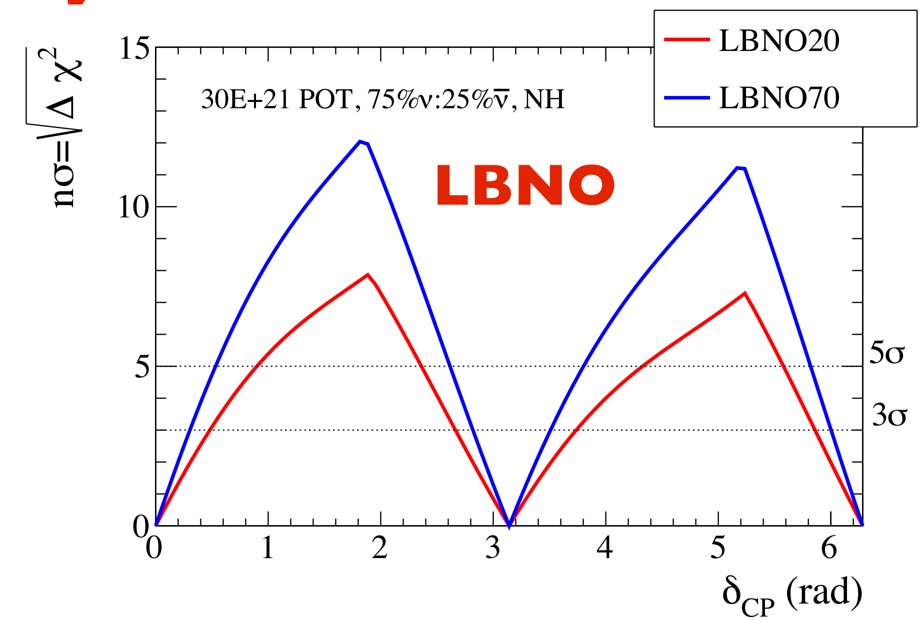
M. Gosh et al., 1401.7243; see also Machado et al.; Huber et al.; For first studies of synergy between T2K and NOvA, see Mena, Nunokawa, Parke, hep-ph/0609011

If delta is in the right region with the right hierarchy, a sensitivity >2 sigma could be achieved.

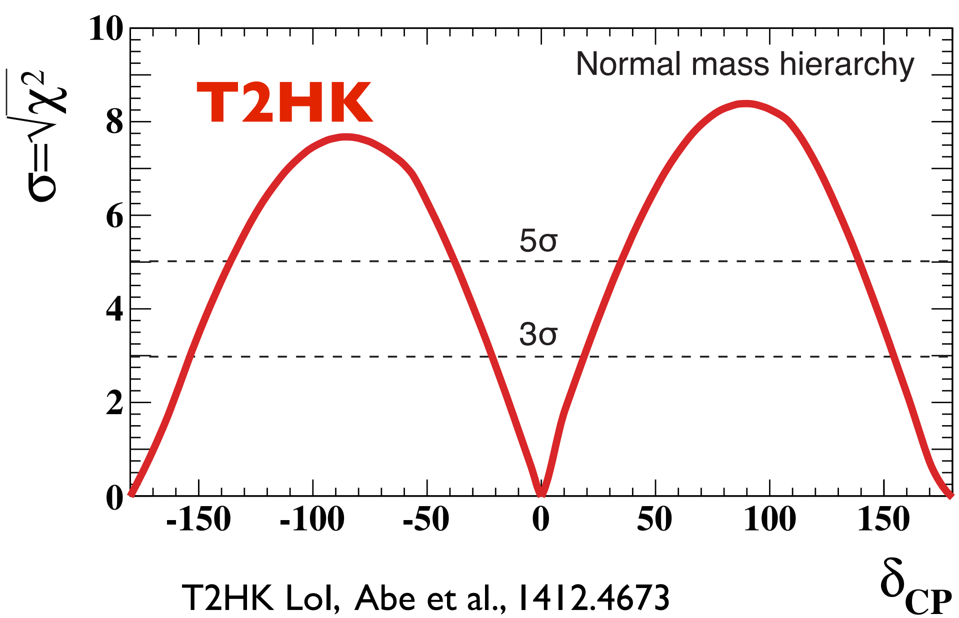
ELBNF (now DUNE), as of Jan 2015



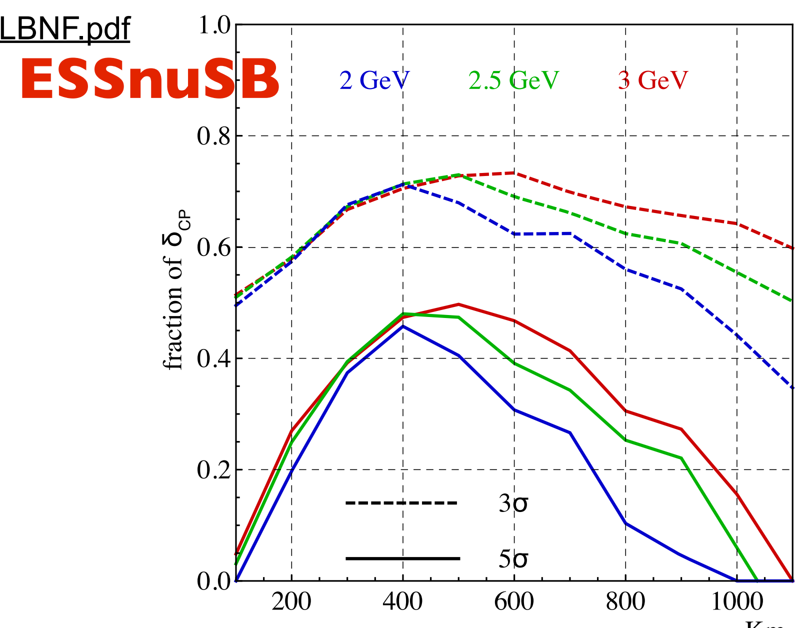
http://www.fnal.gov/directorate/program_planning/Jan2015Public/LOI-LBNF.pdf



LAGUNA-LBNO, 1412.0593. See also 1312.6520



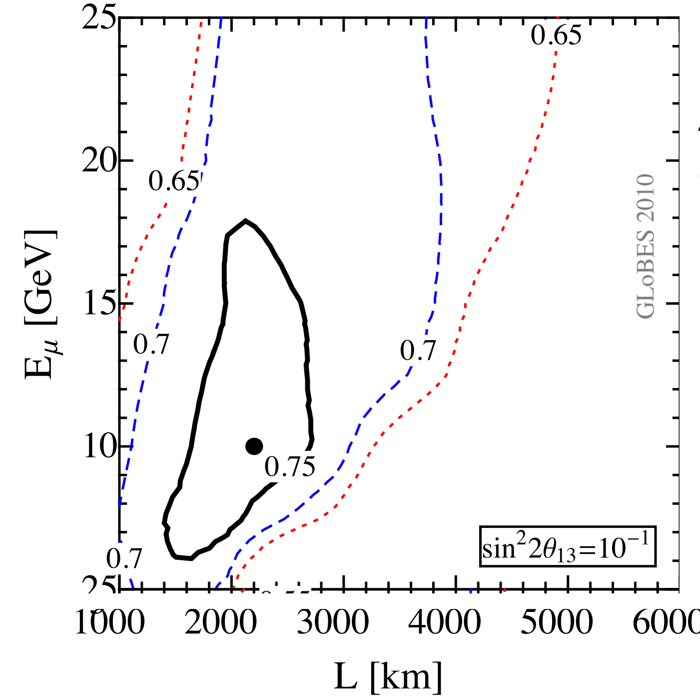
T2HK LoI, Abe et al., 1412.4673



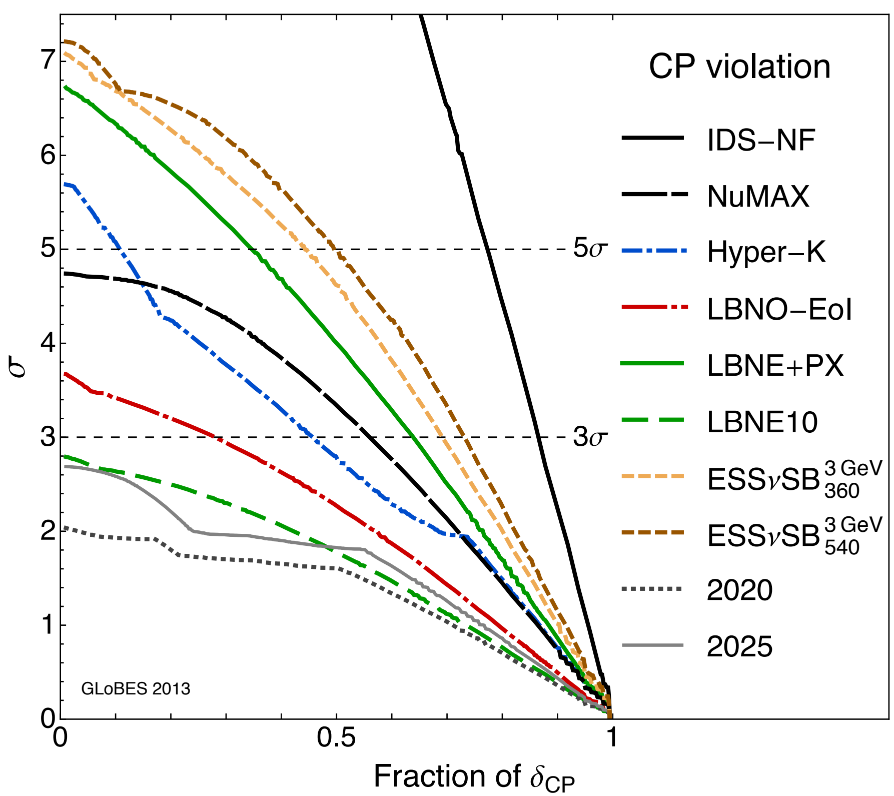
ESSnuSB, 1309.7022

Neutrino factory

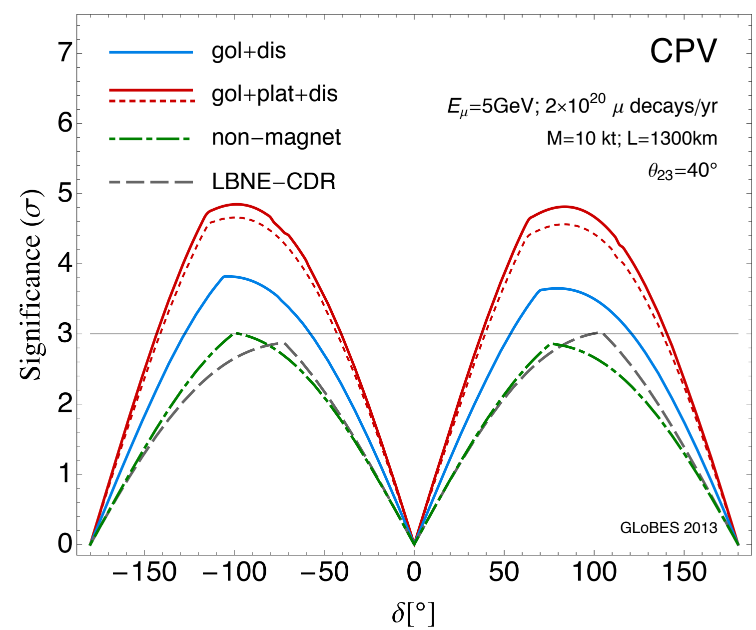
The neutrino factory has the best sensitivity to CPV. Due to large theta13, low energy muons and not-too-long baselines are needed.



Agarwalla et al., JHEP 1101



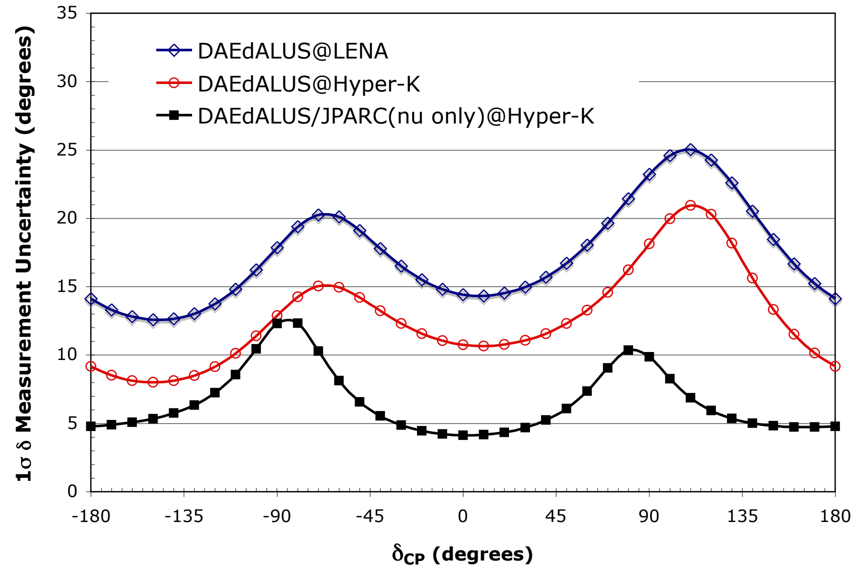
ESSnuSB, 1309.7022



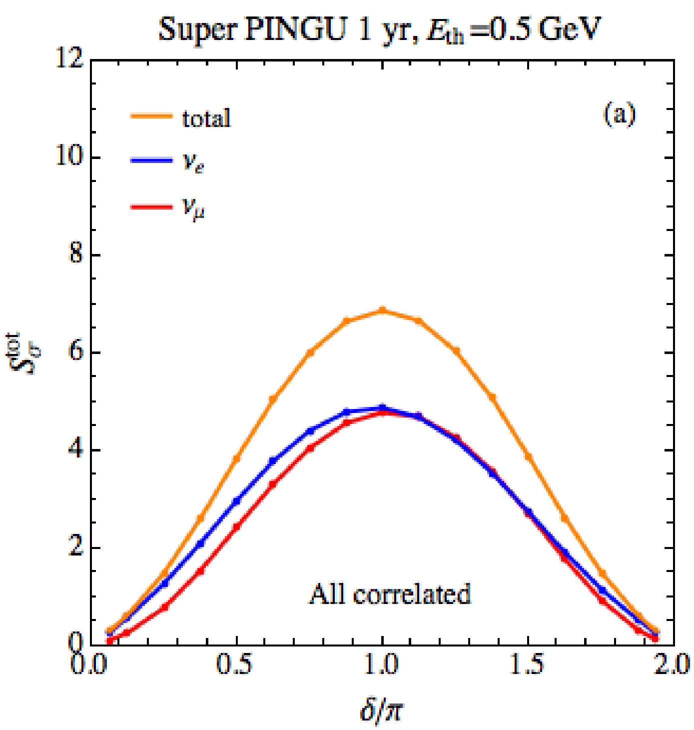
Christensen et al., PRL 111. See also Geer, Mena SP, PRD 75, Bross et al, PRD77; Fernandez-Martinez, Li, Mena, SP, PRD 81; and Rubbia et al., 2001; IDS-NF...

DAEdALUS

Uses the probability of oscillation of low energy muon antineutrino into electron antineutrinos at short baselines (1.5-20 Km).



DAEdALUS Coll., 1307.2949



Razzaque, Smirnov, 1406.1407

Atmospheric neutrinos

These experiments have access to a broad range of baselines and energies. Limited energy and angular resolution and nu-anti nu discrimination affect their reach.

Peres, Smirnov; Kimura et al., Gonzalez-Garcia, Maltoni; Akhmedov et al.; Mena et al.; Hay, Latimer; Agarwalla et al.; Ohlsson et al.; Ge et al.; Abe et al.; Kearns et al.; Adams et al; ...

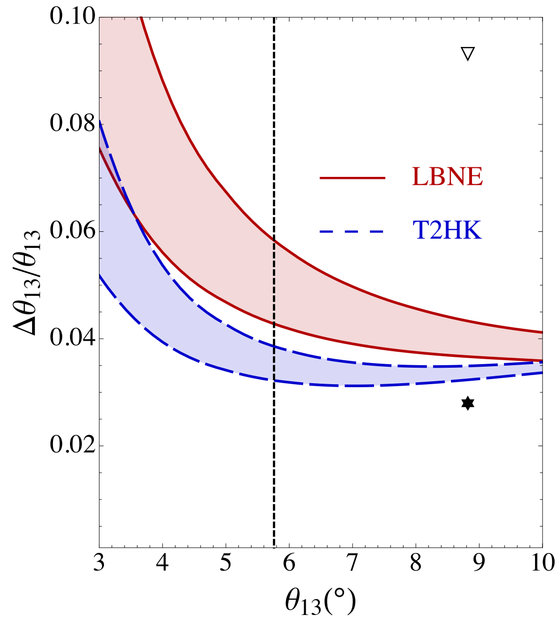
Precision measurements of oscillation parameters

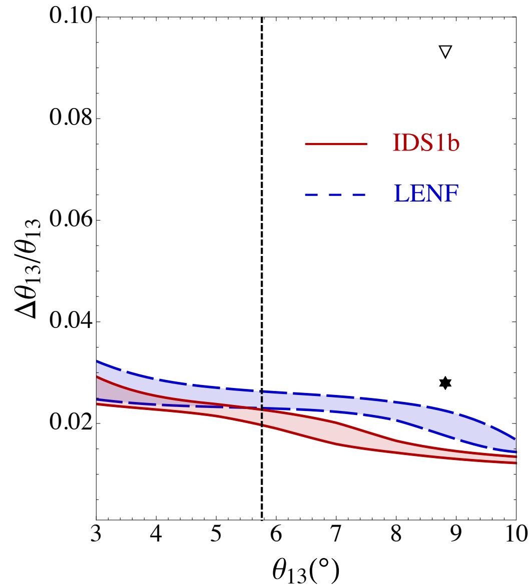
The precision measurement of the oscillation parameters will become very important in the future.

- The values of the mixing angles seem to indicate an underlying symmetry: $\theta_{23} \sim 45^o$, θ_{13} not too far from 0.
- Predictions for the CPV phase delta and relations among parameters in flavour models (e.g. sum rules).

Crucial information in order to discriminate between different flavour models.

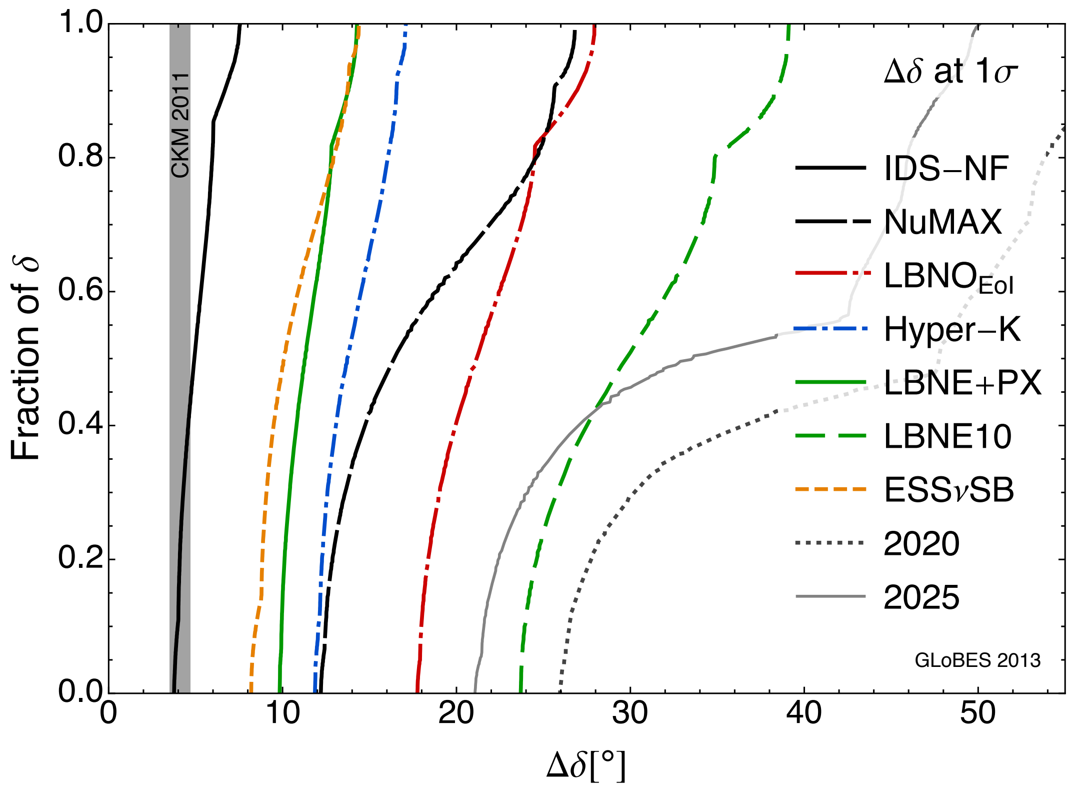
LBL experiments can give information on θ_{23}, θ_{13}, δ .





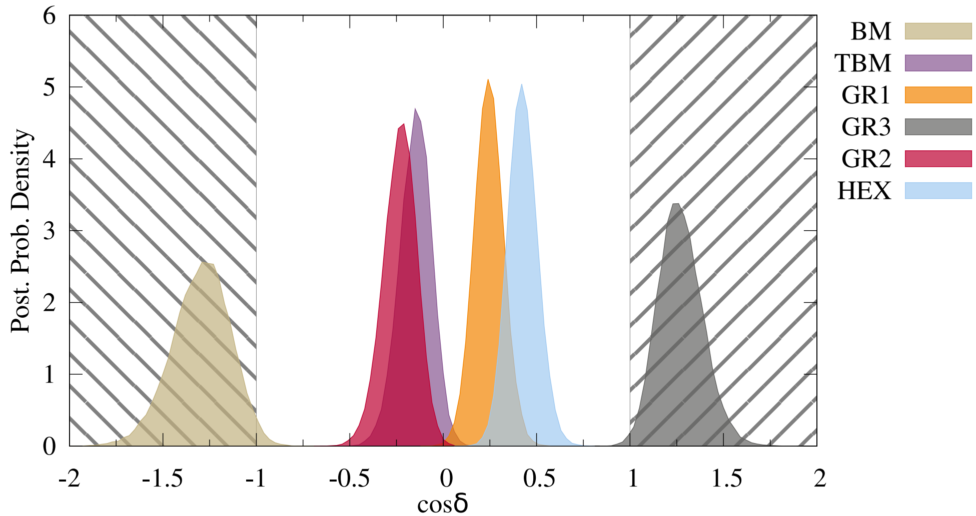
Coloma, Donini, Fernandez Martinez, Hernandez, 1203.5651

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

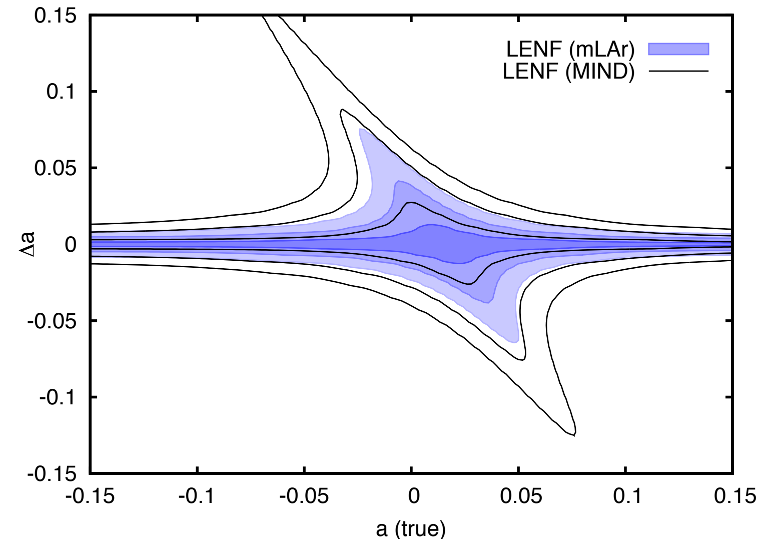


WG Report: Neutrinos, de Gouvea (Convener) et al., 1310.4340; see also, Coloma et al., JHEP 1206; Minakata, Parke, PRD87; D. Meloni, PLB728

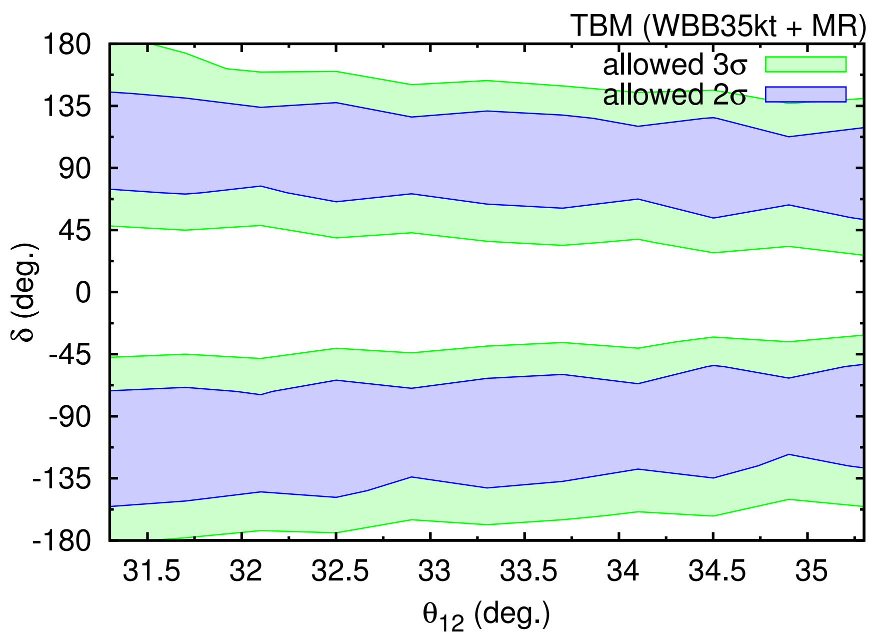
In addition to delta, the study of sum rules and possible mixing patterns requires a precise measurement of the atmospheric and solar mixing angles.

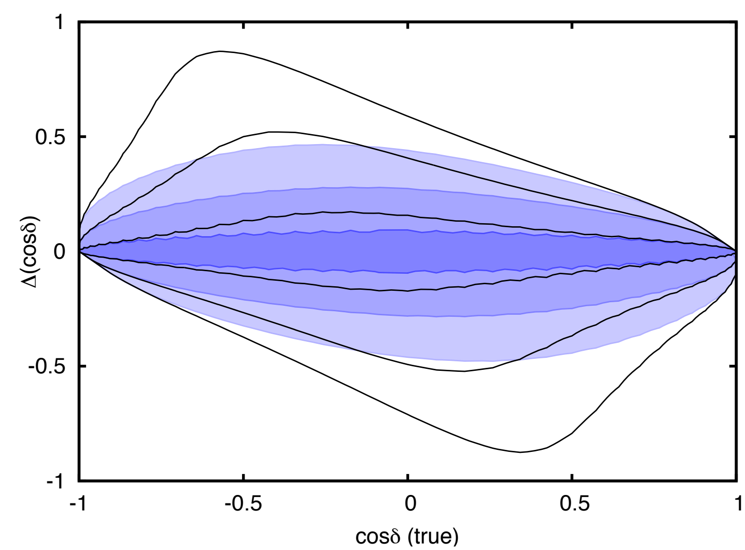


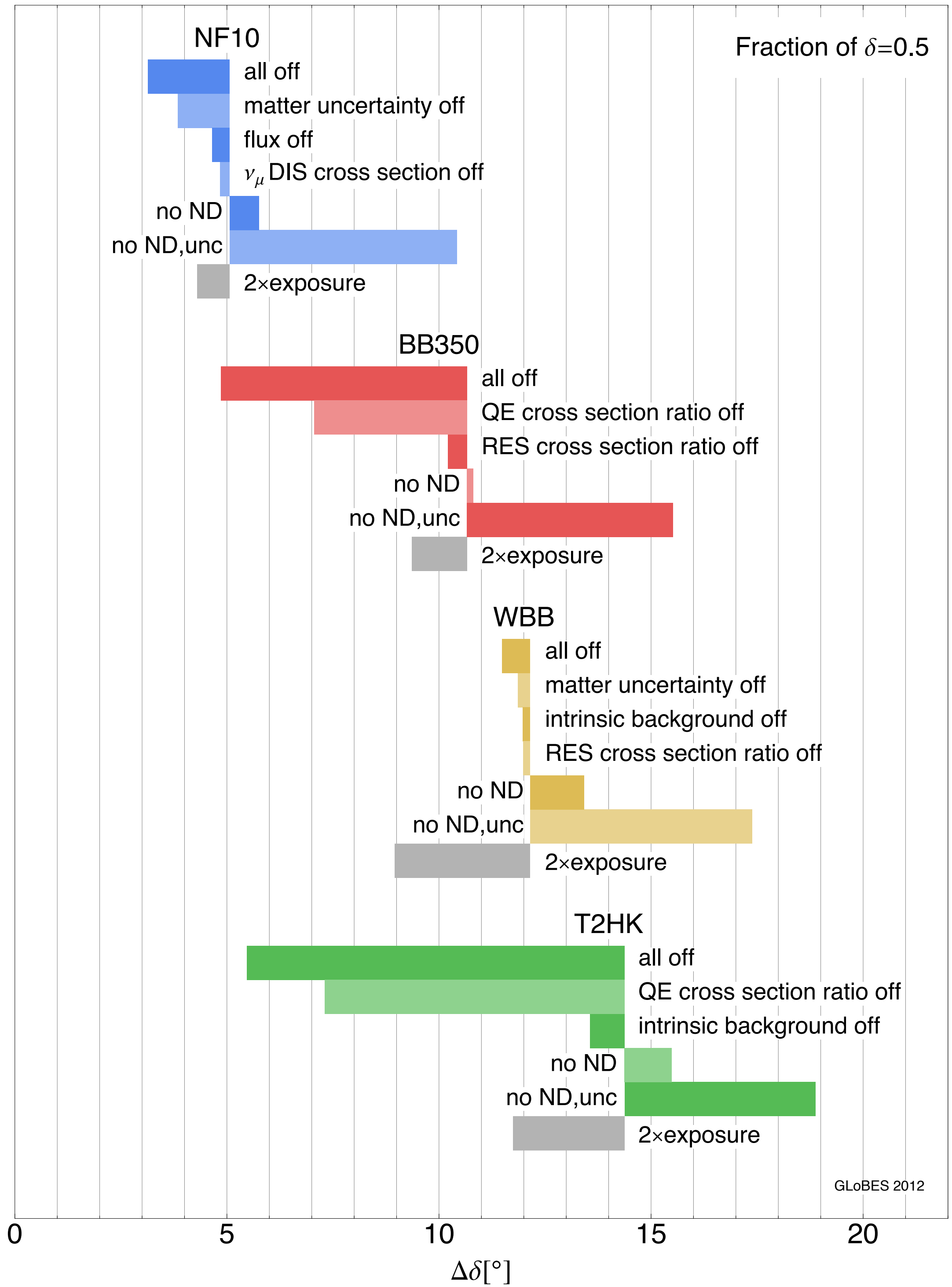
Ballett, King, Luhn, SP, Schmidt, 1410.7573



Ballett, King, Luhn, SP, Schmidt, 1308.4314

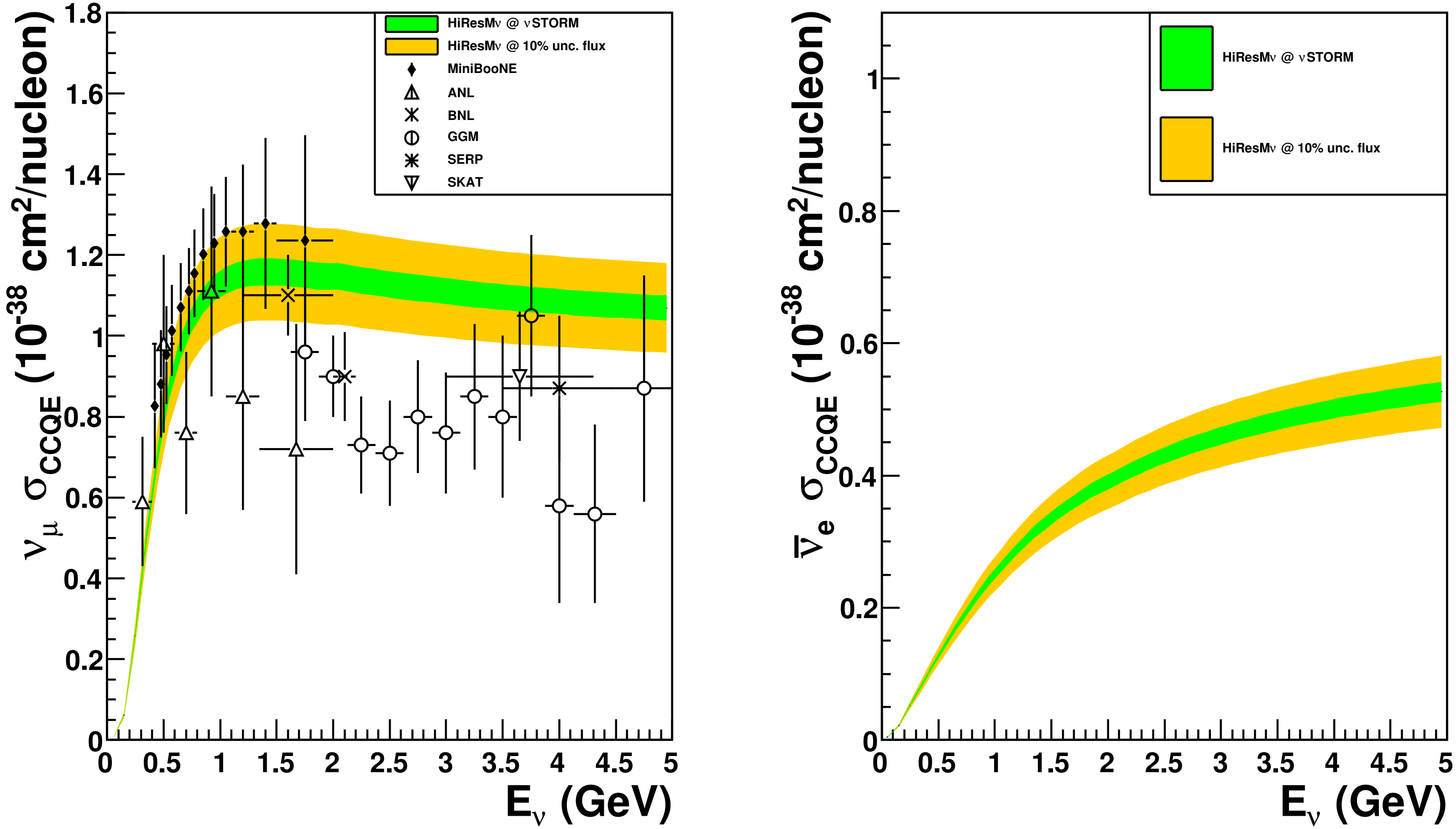






Systematic errors significantly affect the sensitivity.
Good energy resolution, wide band beam, additional input will help in reducing their impact.
Excellent knowledge of cross sections will be crucial. The near detector(s) will also play an important role.

Coloma, Huber, Kopp, Winter, 1209.5973



nuSTORM, 1308.6822

NuSTORM can provide a very precise measurement of the cross sections both for muon and electron (!) neutrinos in the relevant range of energies.

Phenomenology questions for the future

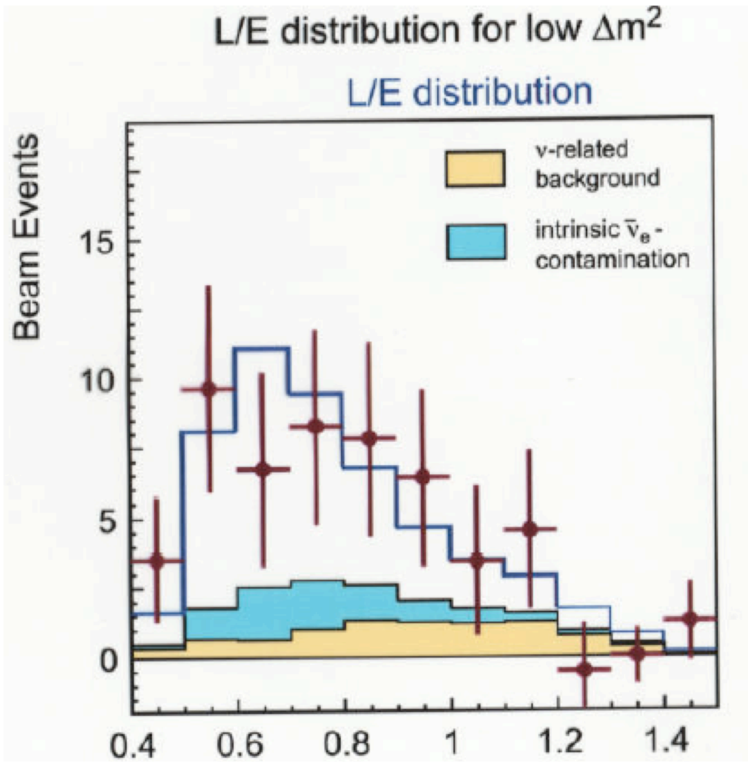
- **5. Is the standard picture correct?**

Tests of the standard 3-neutrino paradigm

- Sterile neutrinos (as suggested or not by current hints).
- New interactions: NSI, light mediators...
- Decoherence, Lorentz violation...

A deviation from the standard picture would have a groundbreaking impact.

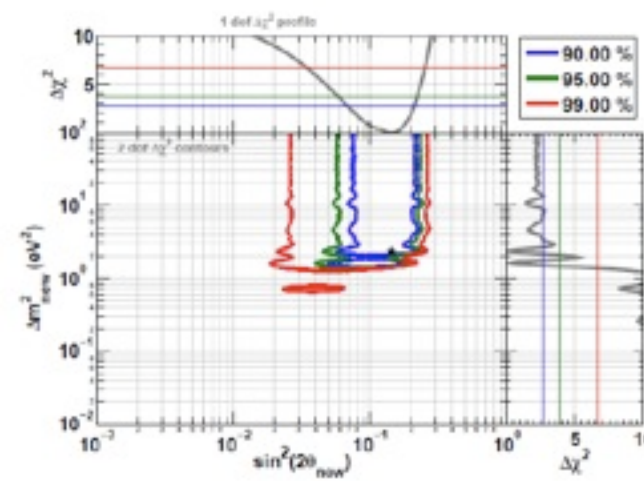
4- or 5- neutrino oscillations: sterile neutrinos



LSND

Reactor anomaly

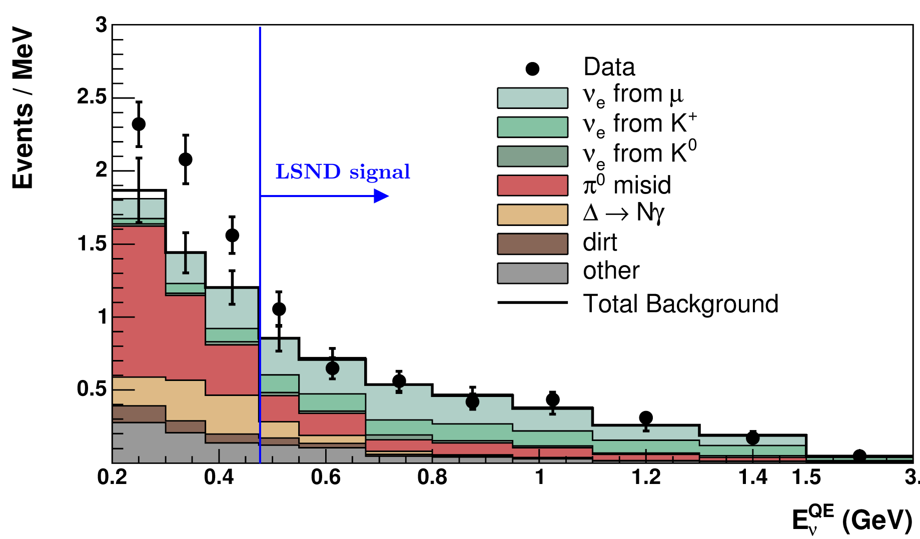
Combining reactor rates + shape + Gallium Anomaly



no-oscillation disfavored at 99.8% CL

G. Mention et al., 1101.2755; Mueller et al., PRC 83; Huber PRC 84.

MiniBooNE



MiniBooNE, PRL102

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 $\Delta m^2_{\mathrm{sol}}$ and Δm^2_{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 (possible tension with data).

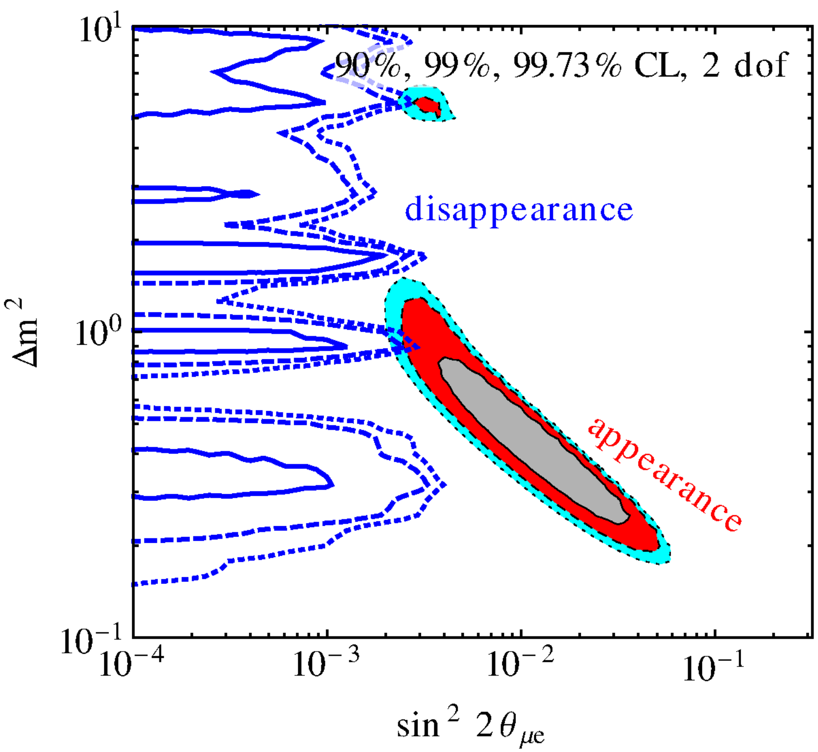
Disappearance experiments

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

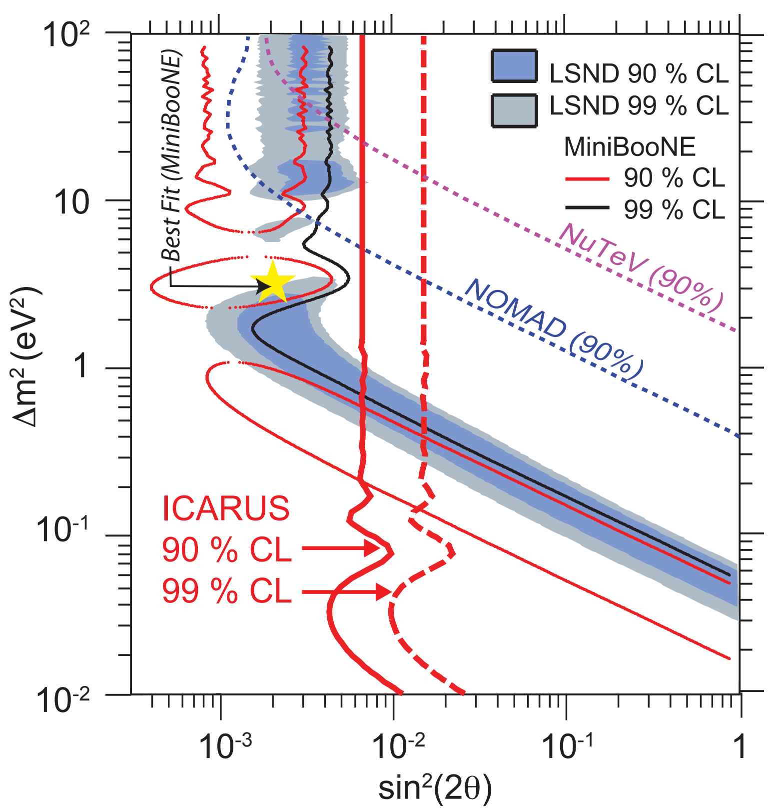
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu4}|^2(1 - |U_{\mu4}|^2)\sin^2(\Delta m^2 L/4E)$$

Appearance experiments

$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2|U_{\mu4}|^2\sin^2(\Delta m^2 L/4E)$$

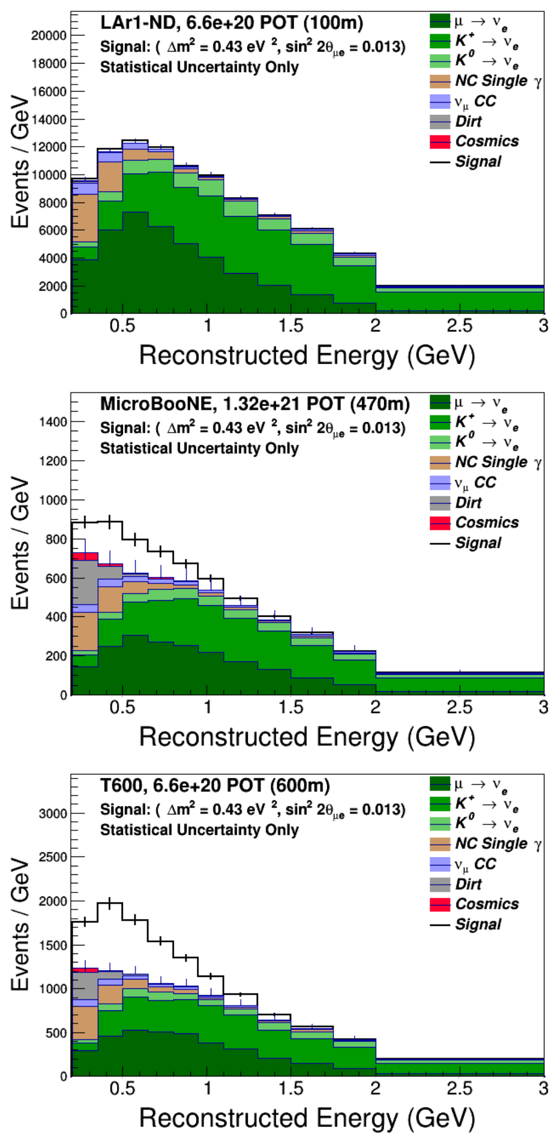


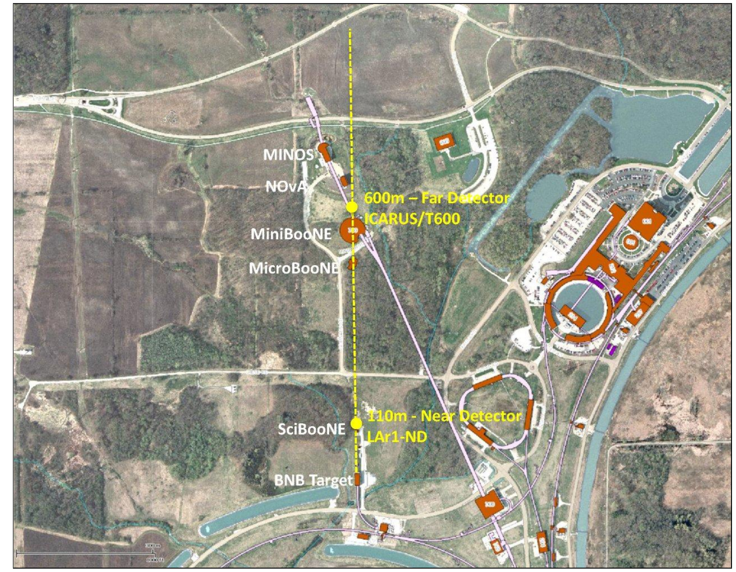
Kopp, Machado, Maltoni, Schwetz, JHEP 1305

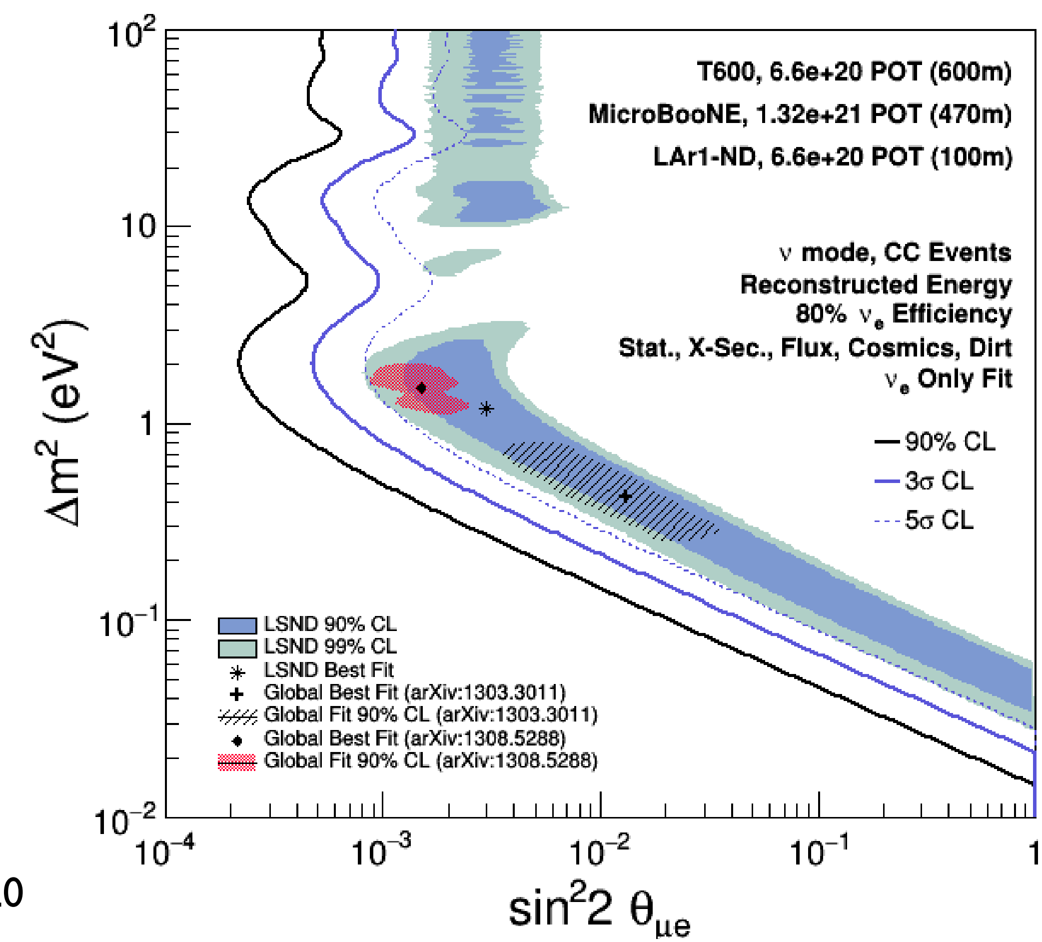


ICARUS+LAr1-ND+MicroBooNE+..., 1503.01520

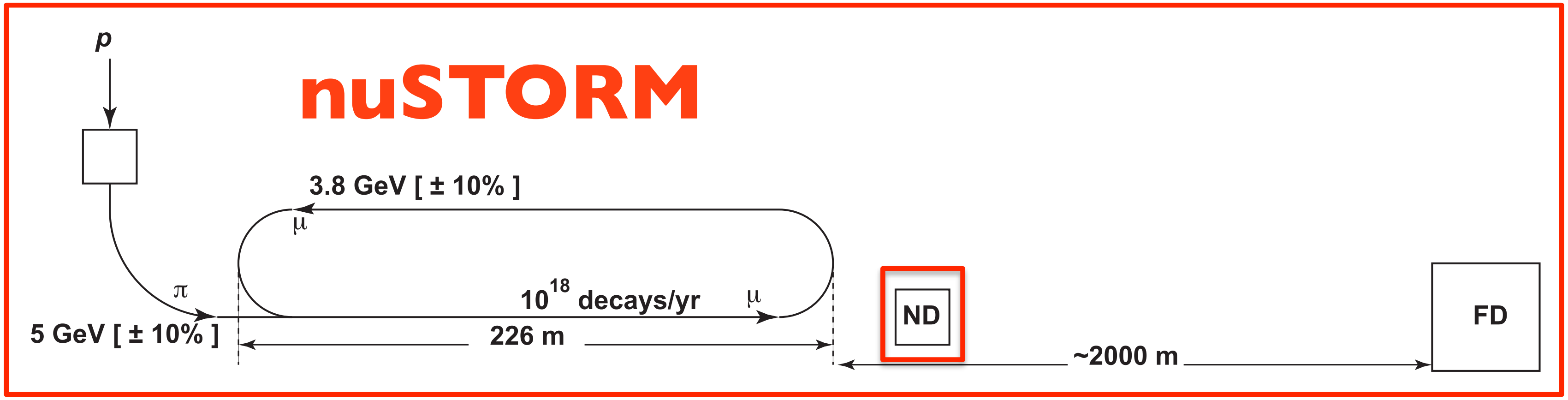
SBN programme at FNAL: MicroBooNE + LAr1-ND+ICARUS (T600).



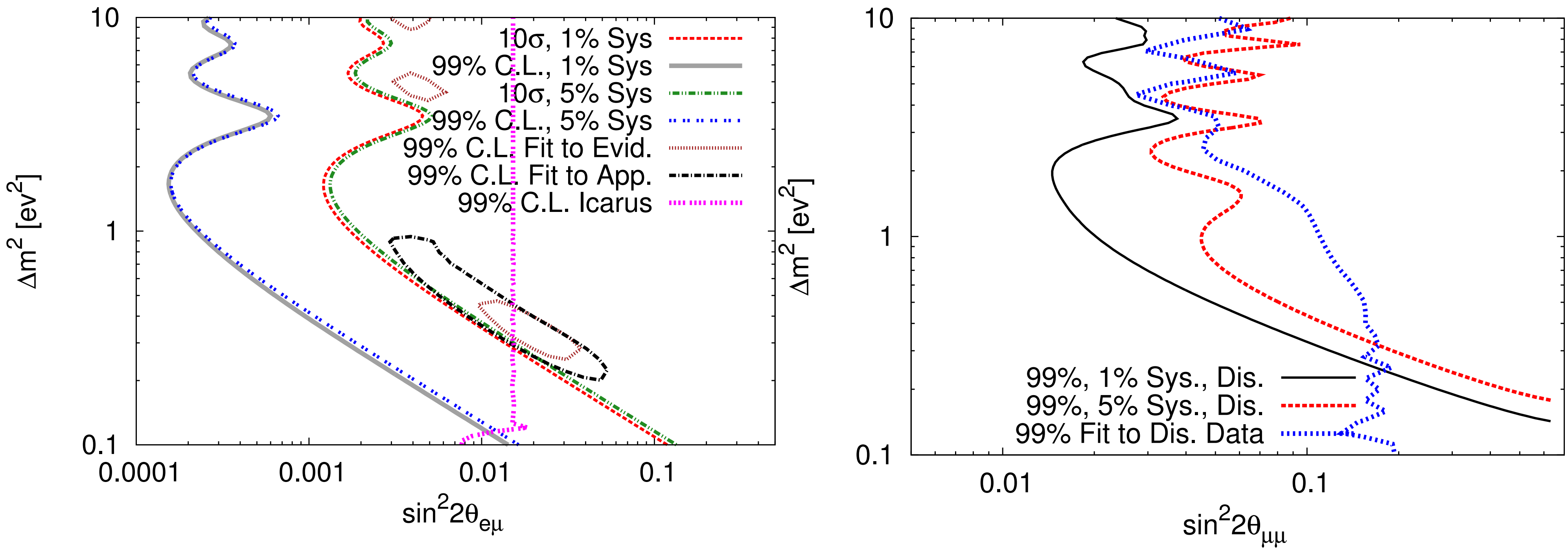




ICARUS+LAr1-ND+MicroBooNE+..., 1503.01520



K. Long at NeuTel 2015



nuSTORM 1402.5250

It would easily confirm/disprove the oscillation hypothesis.

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 ordering, CPV searches and precision measurements of the oscillation parameters. The physics reach of a facility depends on beams, detector performance, systematic errors and backgrounds.
- Anomalies have been found (LSND, MiniBooNE, reactors). In the next few years, dedicated experiments will test them and provide additional information.