The physics goals and reach of ELBNF28

22 January 2015

ELBNF Proto-Collaboration Meeting

Fermilab

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IPPP – Durham University

Outline

1. Present status of neutrino parameters

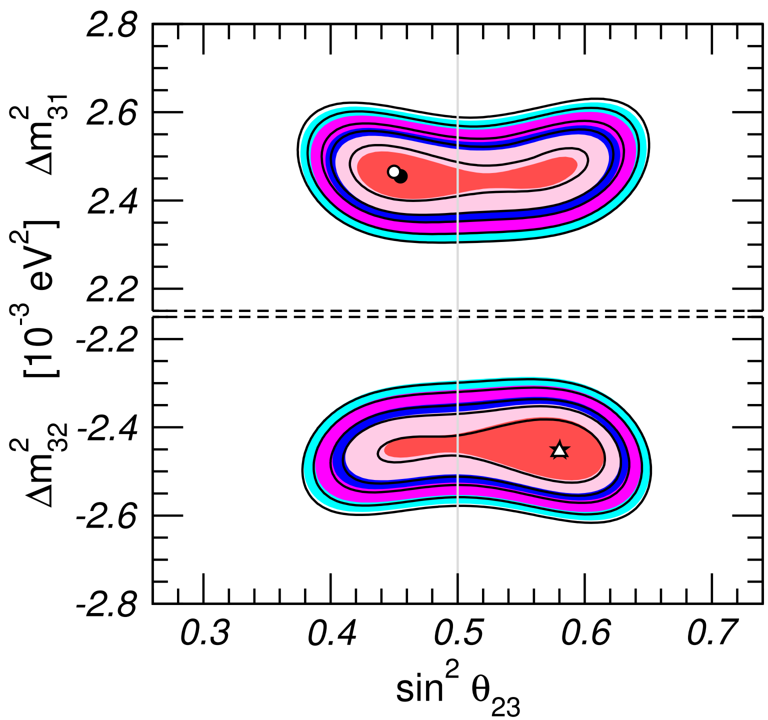
2. LBL oscillation experiments physics goals:
   - Mass ordering
   - Leptonic CP-violation
   - Precision measurement of parameters
   - Testing the 3-neutrino scenario

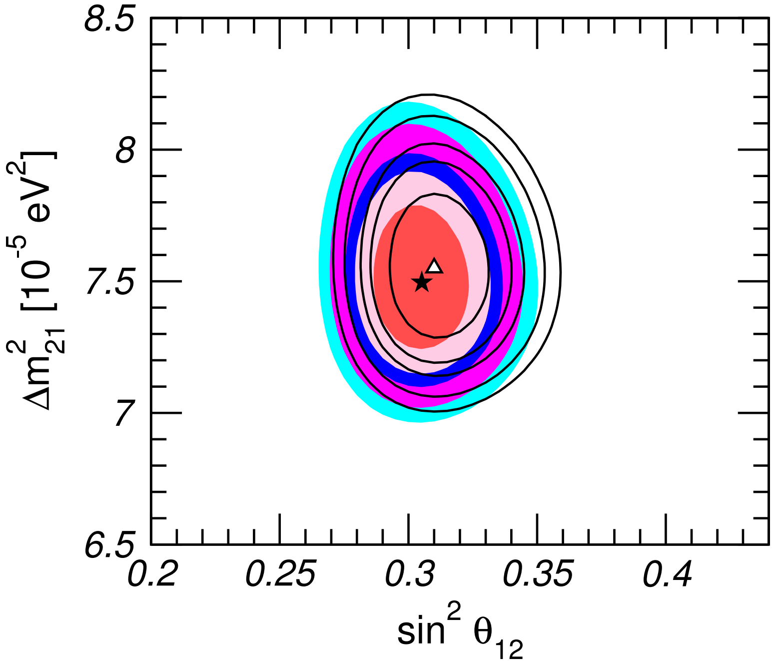
3. ELBNF28 physics reach

4. Synergies and complementarities with other experiments

4. Conclusions

Summary of current neutrino parameters





	Normal Ordering ($\Delta\chi^2 = 0.97$)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$
$\delta_{\mathrm{CP}}/^\circ$	306^{+39}_{-70}	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$

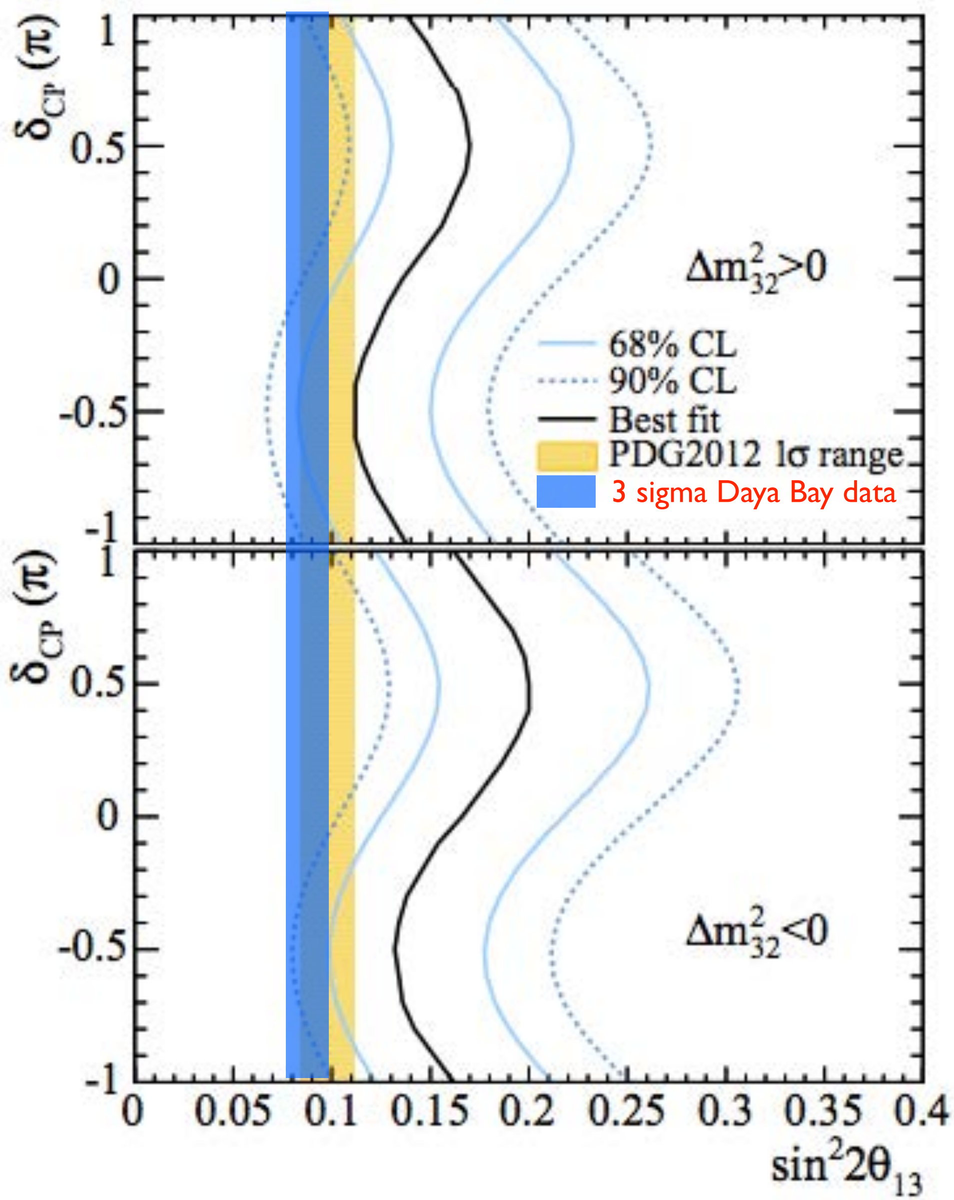
M. C. Gonzalez-Garcia et al., NuFit, 1409.5439

Global fit to neutrino oscillation data

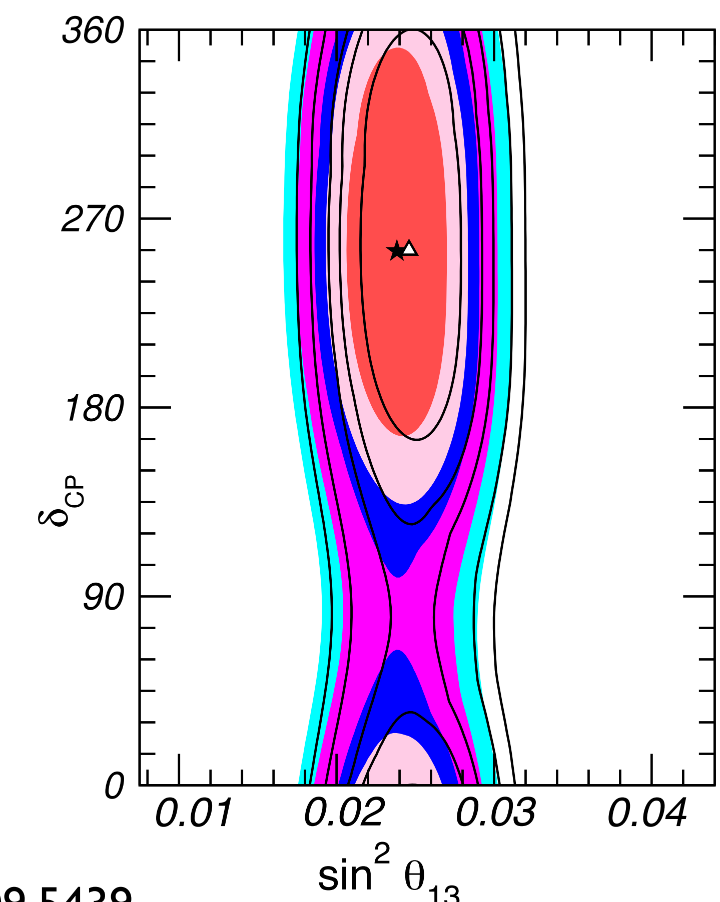
www.invisibles.eu

Hints for CP violation?

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

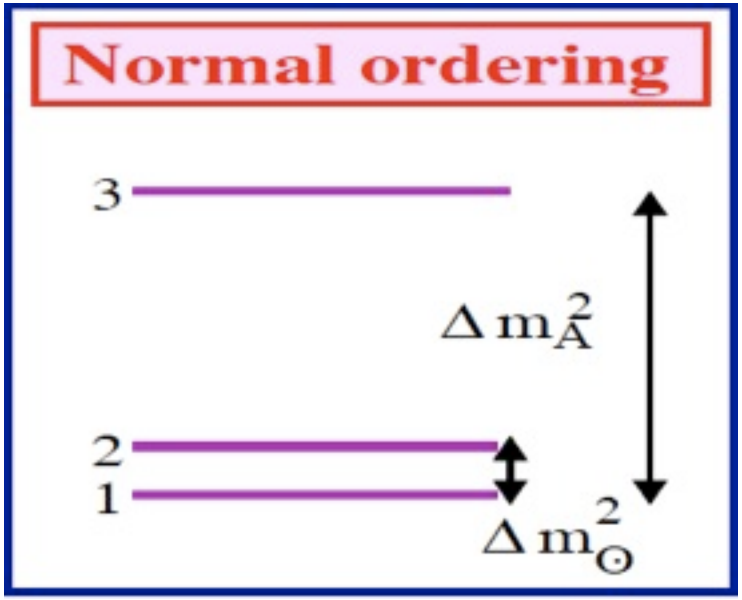


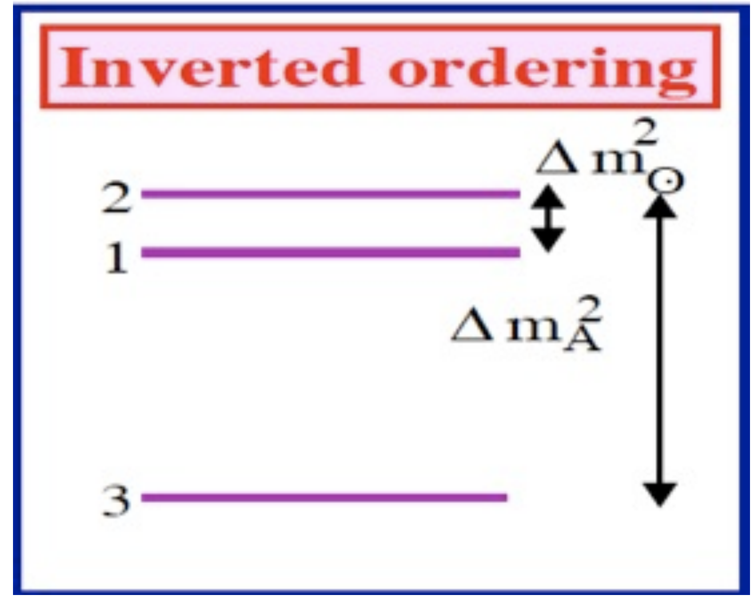
T2K Coll. PRL 112, 061802 (2014)



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

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





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

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

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the mass ordering.

The mixing matrix has 3 angles and 1(3) CPV phases.

Open Phenomenology questions

- **1. What is the nature of neutrinos?**
- **2. What are the values of the masses?** Absolute scale (KATRIN, ...?) and the mass ordering (MO).
- **3. Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **4. What are the precise values of mixing angles?** Do they suggest an underlying pattern?
- **5. Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

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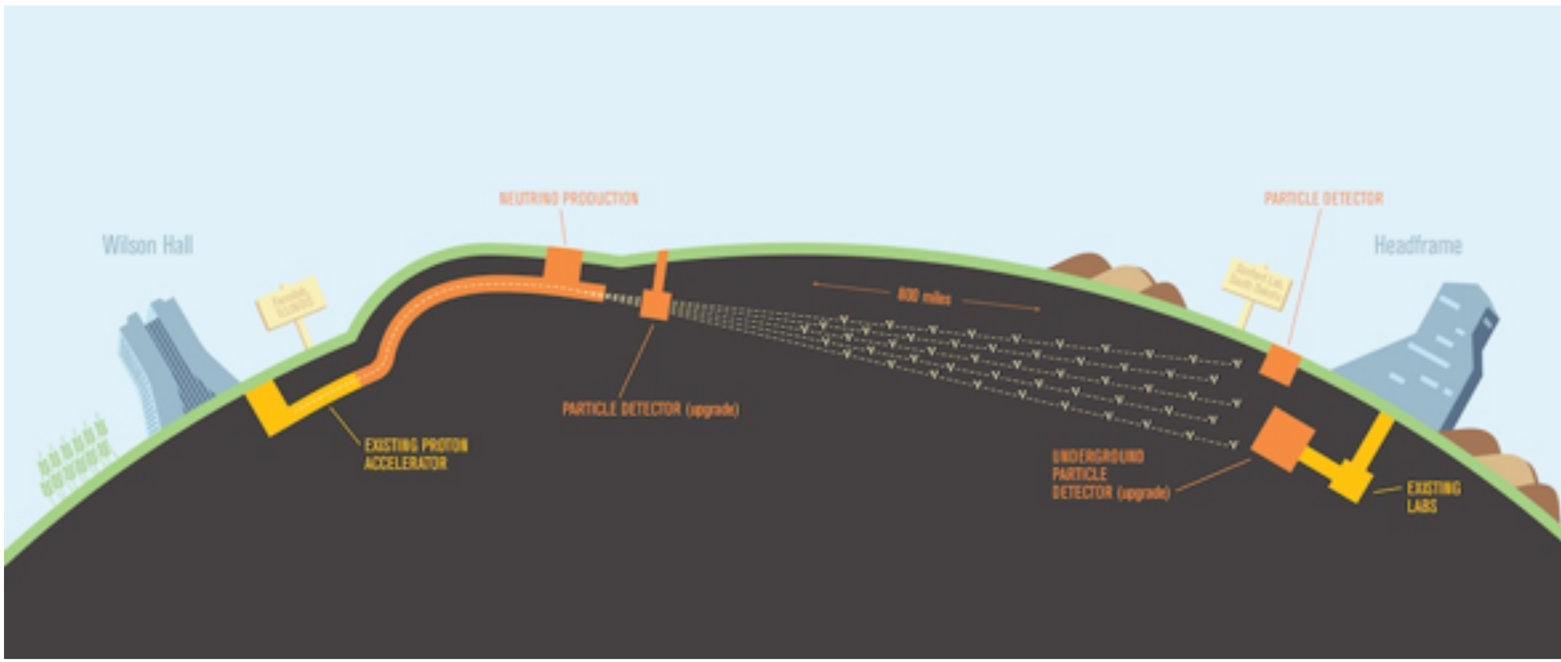
How can we search for the mass ordering and leptonic CP-violation in long baseline neutrino oscillation experiments?

Long-baseline neutrino oscillations and the ordering

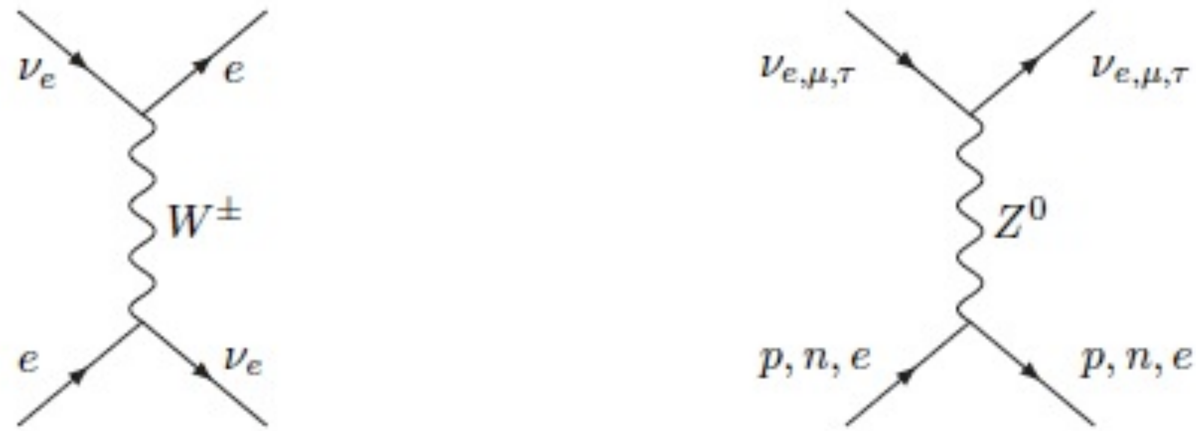
- When neutrinos travel through a medium, they interact with the background of e, p and n.



Credit: Symmetry magazine

- The background is CP and CPT violating, e.g. the Earth contains only particle and not antiparticles, and the resulting oscillations are CP and CPT violating.

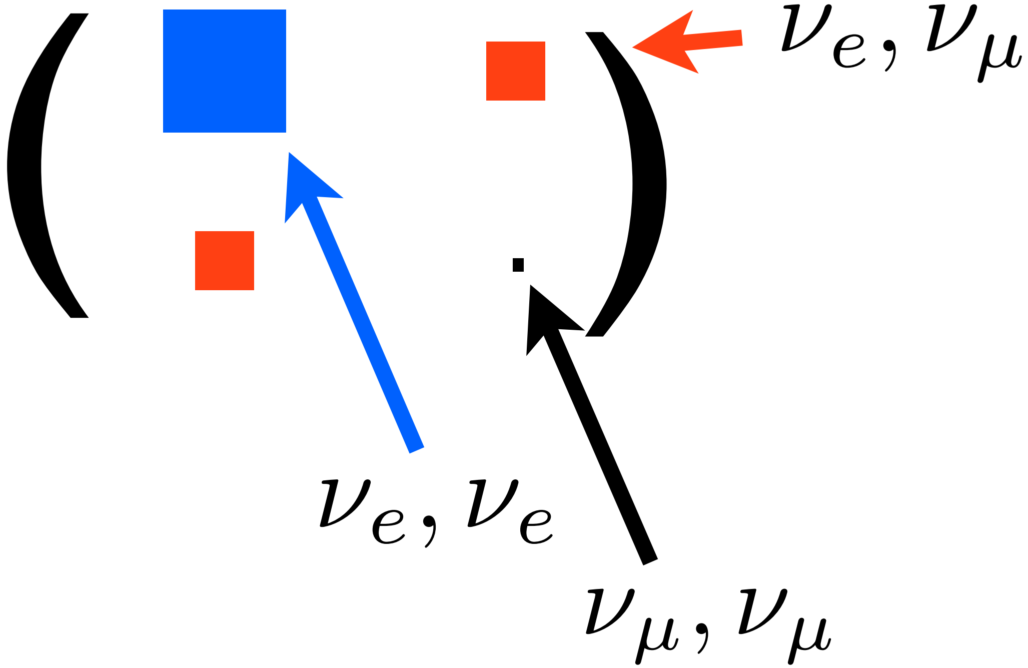
- Neutrinos undergo forward elastic scattering via CC and NC interactions.



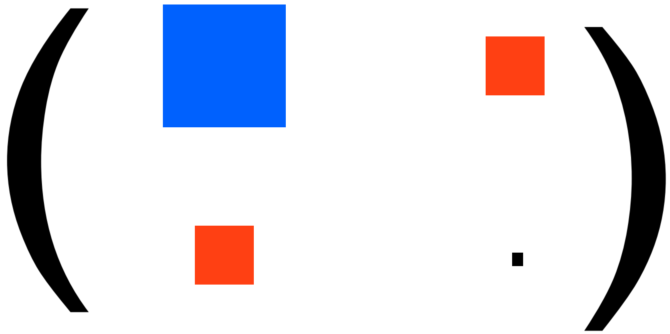
- Matter effects are described by a potential V in the effective Hamiltonian which determines the time evolution.

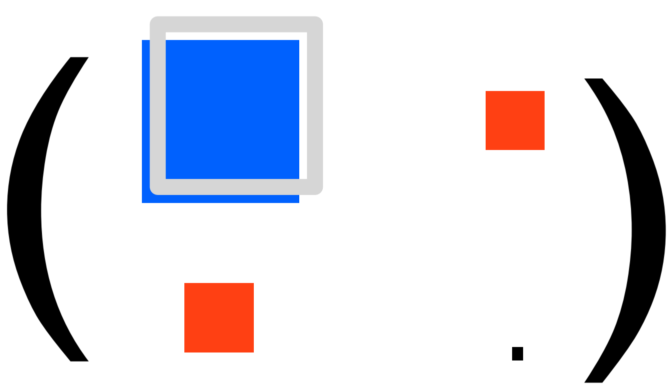
$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos(2\theta) + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin(2\theta) \\ \frac{\Delta m^2}{4E}\sin(2\theta) & \frac{\Delta m^2}{4E}\cos(2\theta)\end{pmatrix}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$

Effective Hamiltonian in the flavour basis



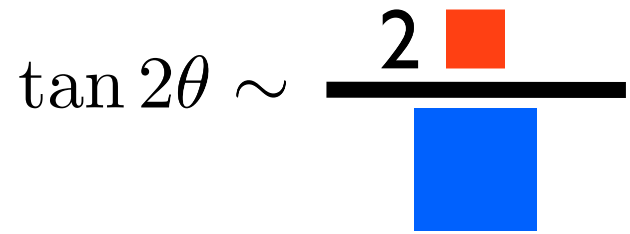
Effective Hamiltonian



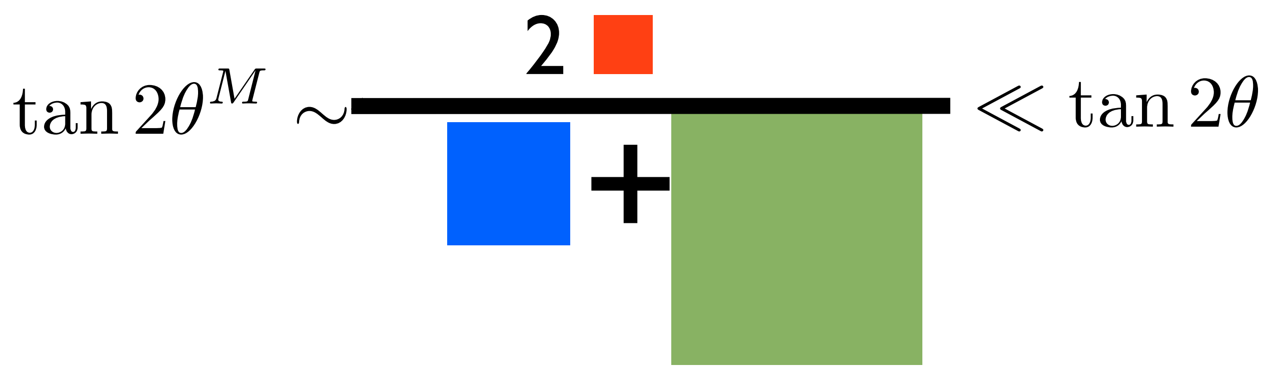


Mixing angle

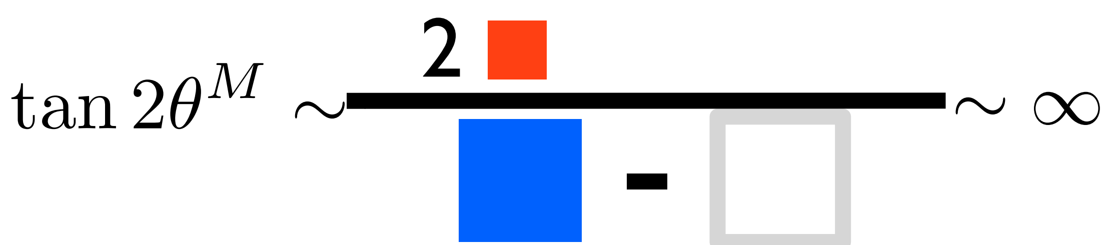
vacuum



matter suppression (Sun, SN)



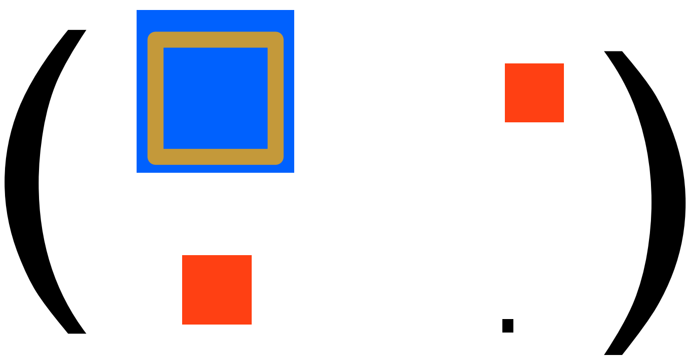
MSW resonance (Sun, SN)



In long baseline experiments

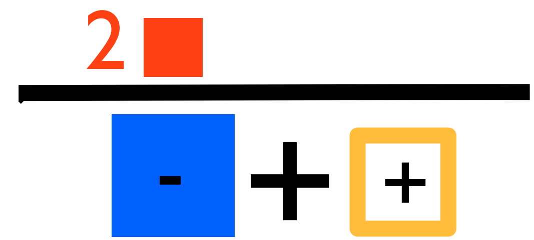
 $-\frac{\Delta m^2}{2E}\cos(2\theta)$ ν: $+\sqrt{2}G_F N_e$ $\bar{\nu}$: $-\sqrt{2}G_F N_e$

For neutrinos

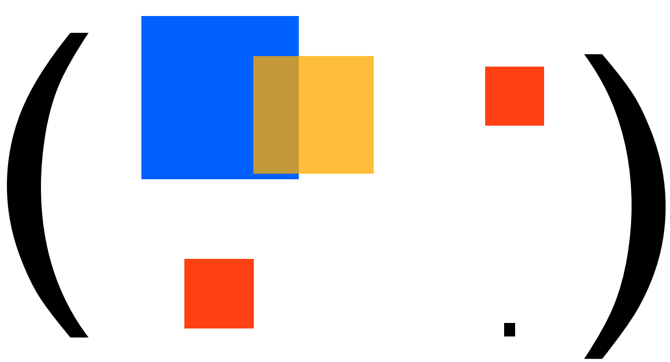


$\Delta m^2 > 0$ enhancement

$\tan 2\theta^M \sim$

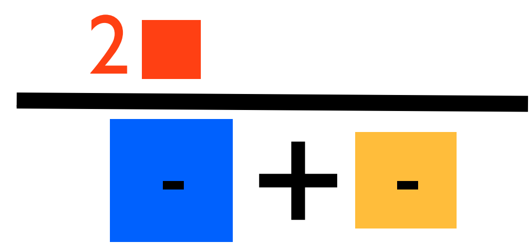


For antineutrinos



$\Delta m^2 > 0$ 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 $\Delta m^2 < 0$

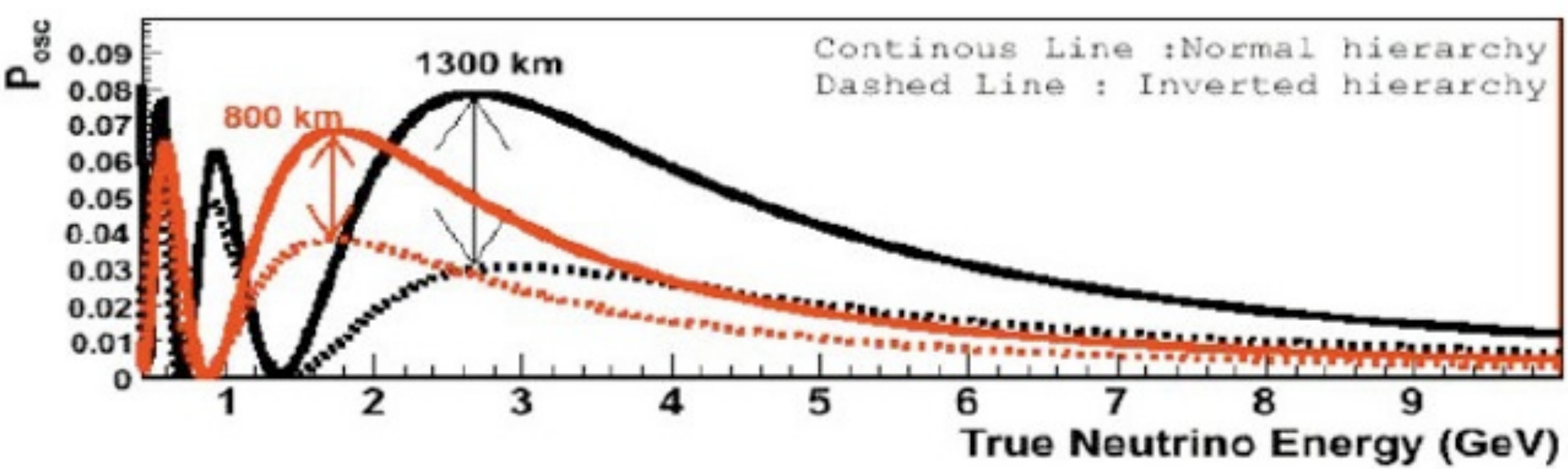
The impact of matter effects is stronger at higher energies and at longer baselines.

The 3 neutrino probability can be approximated as

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

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

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



CP-violation in LBL experiments

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

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

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

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

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

$$P_{\mu e} \simeq 4 c_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$
$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21} L}{2E} \sin \frac{(1-r_A)\Delta_{31} L}{4E} \cos\left(\delta - \frac{\Delta_{31} L}{4E}\right)$$
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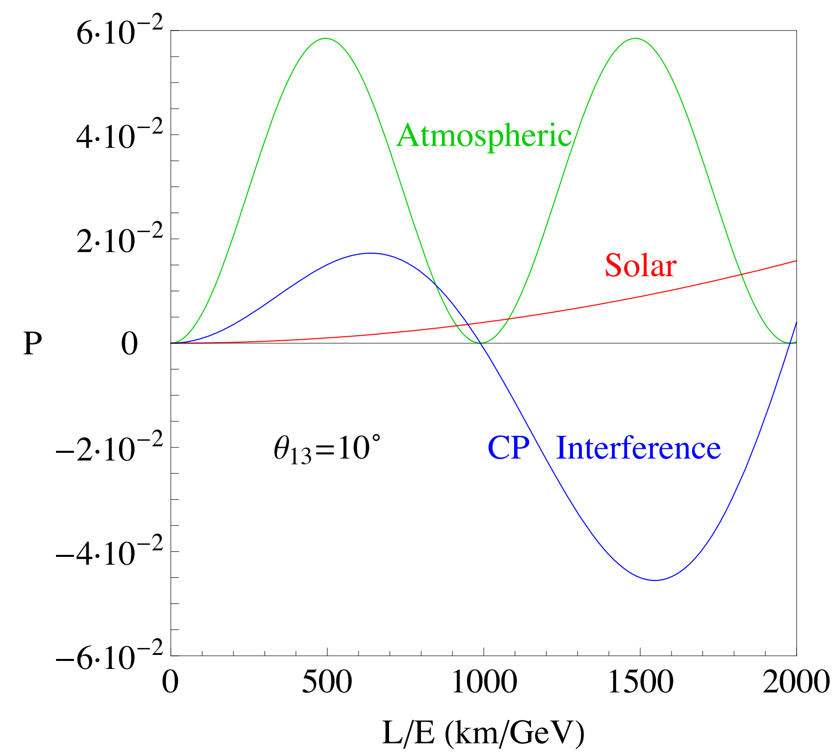
A. Cervera et al., hep-ph/0002108; K. Asano, H. Minakata, 1103.4387; S. K. Agarwalla et al., 1302.6773...

- 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

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: $\theta_{23} \sim 45^o, \quad \theta_{13}$ 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.

Tests of the standard 3-neutrino paradigm

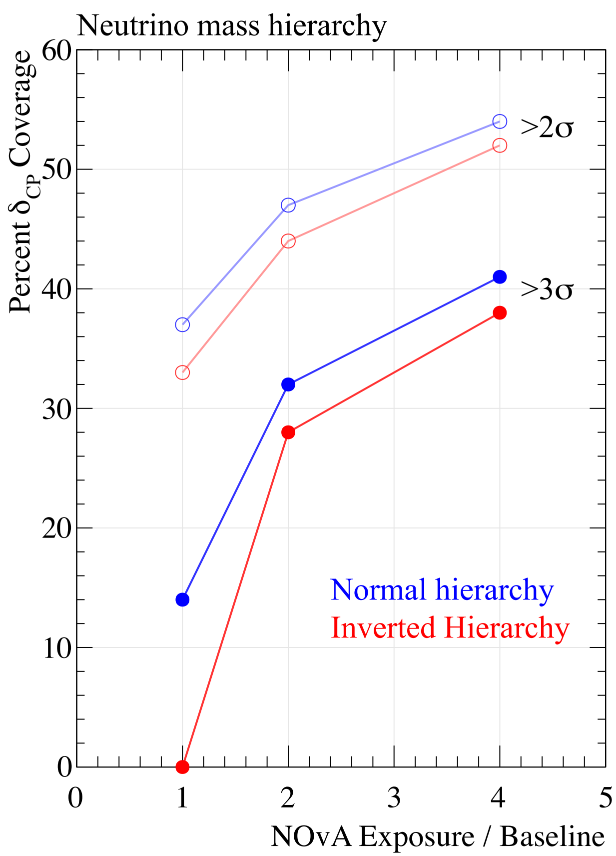
- Sterile neutrinos (as suggested or not by current hints). Synergy with SBN.
- New interactions: NSI, light mediators...
- Decoherence, Lorentz violation...

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

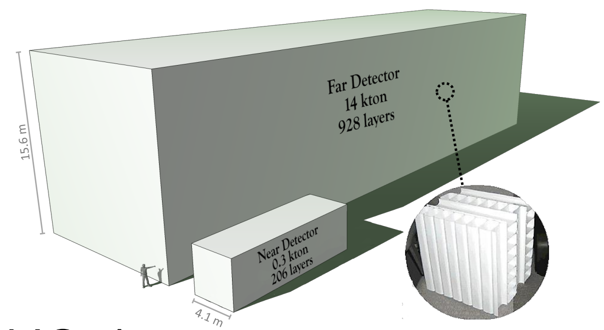
What we will now by early 2020s?

T2K, NOvA will have collected several years of data, INO is expected to be online as PINGU and JUNO (RENO50) will.

“NOvAplus”

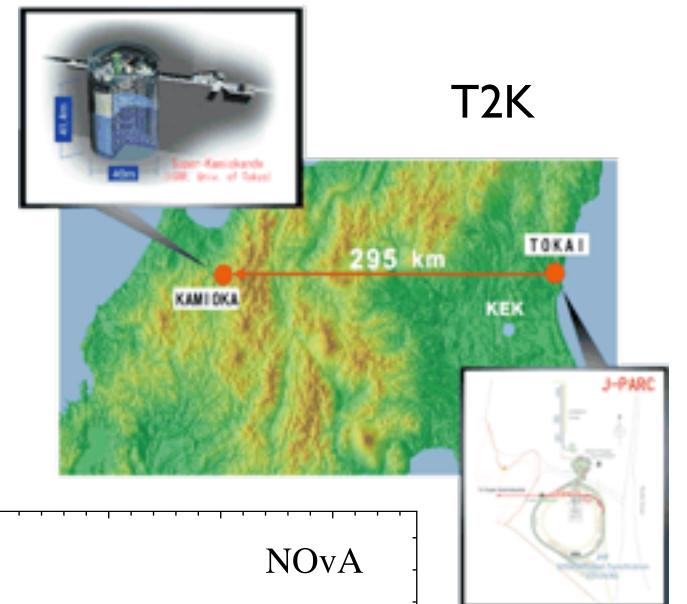


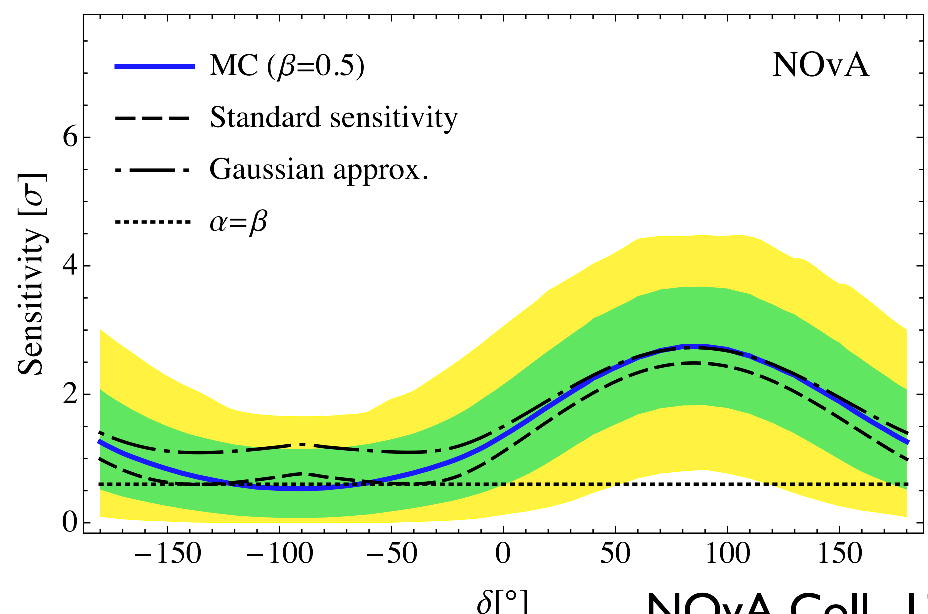
NOvA Coll., 1308.0106



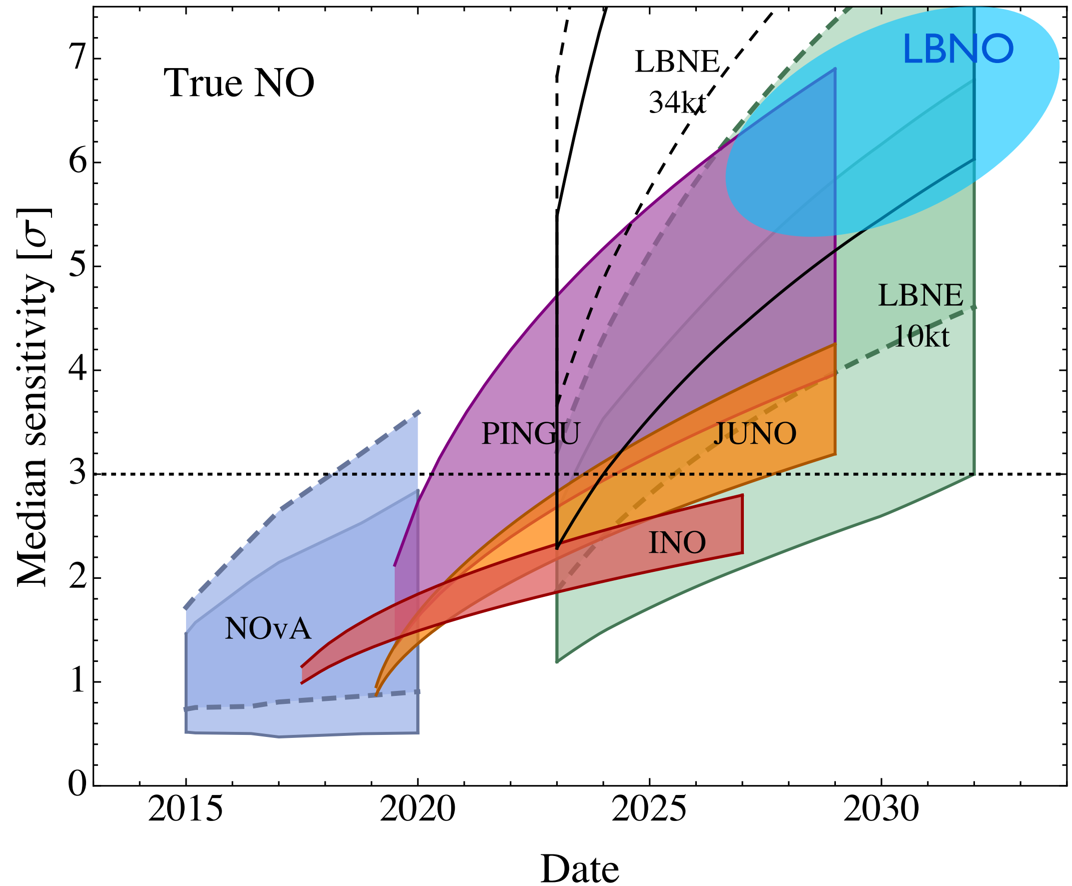
NOvA

T2K





NOvA Coll., 1308.0106



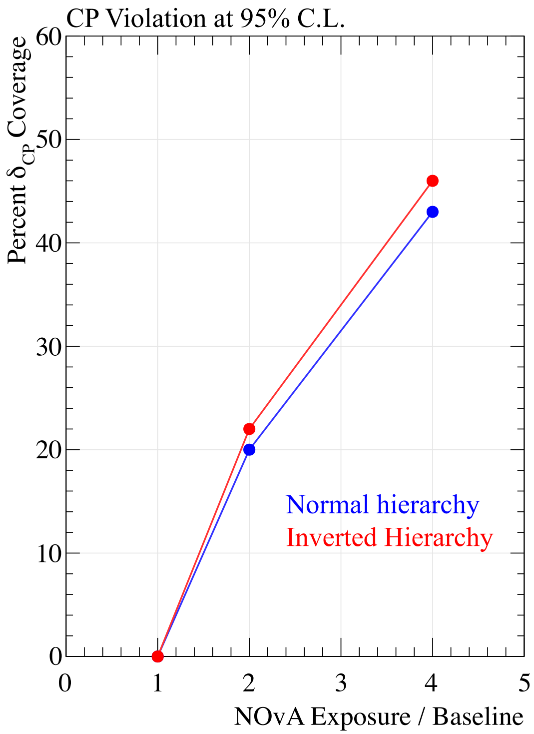
Blennow, Coloma, Huber, Schwetz, 1311.1822

Experiment	Physics effect	Challenges
ELBNF	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

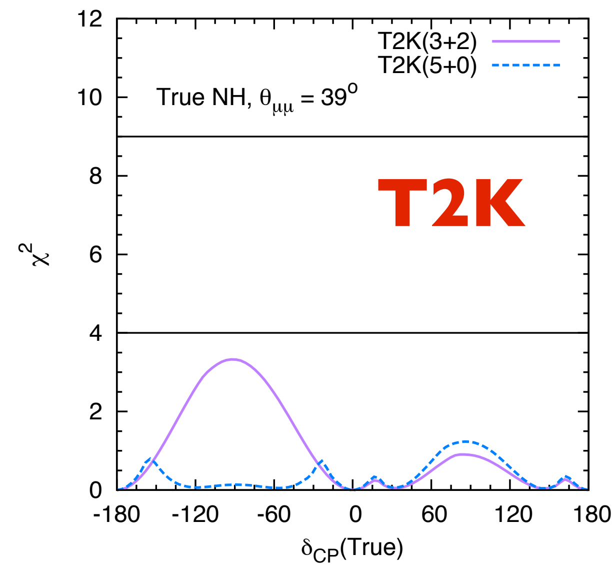
See also W.Winter's talk at Neutrino 2014

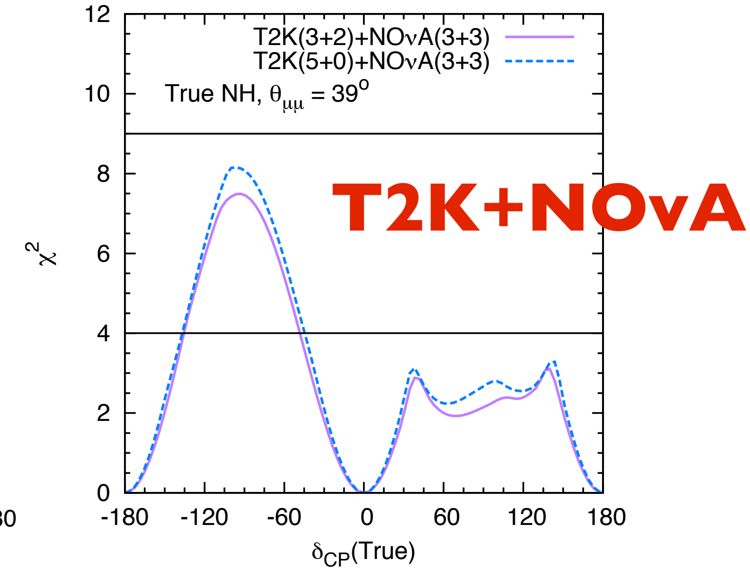
Sensitivity to CPV

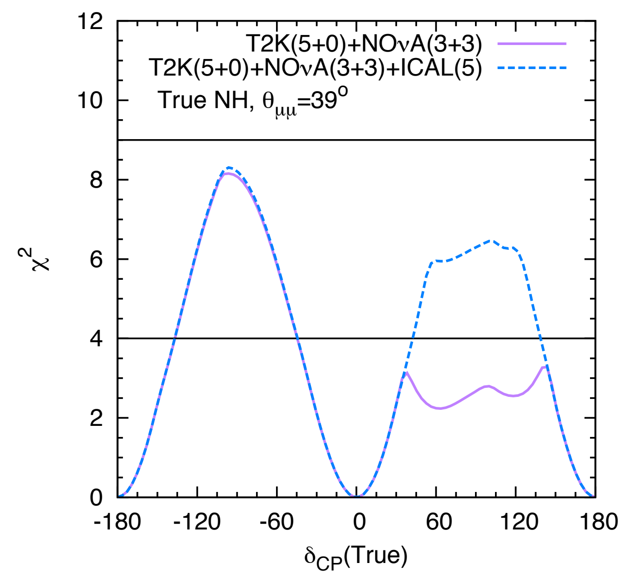
“NOvAplus”



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.

ELBNF28

2021 Milestone: 10 kton LArTPC at SURF

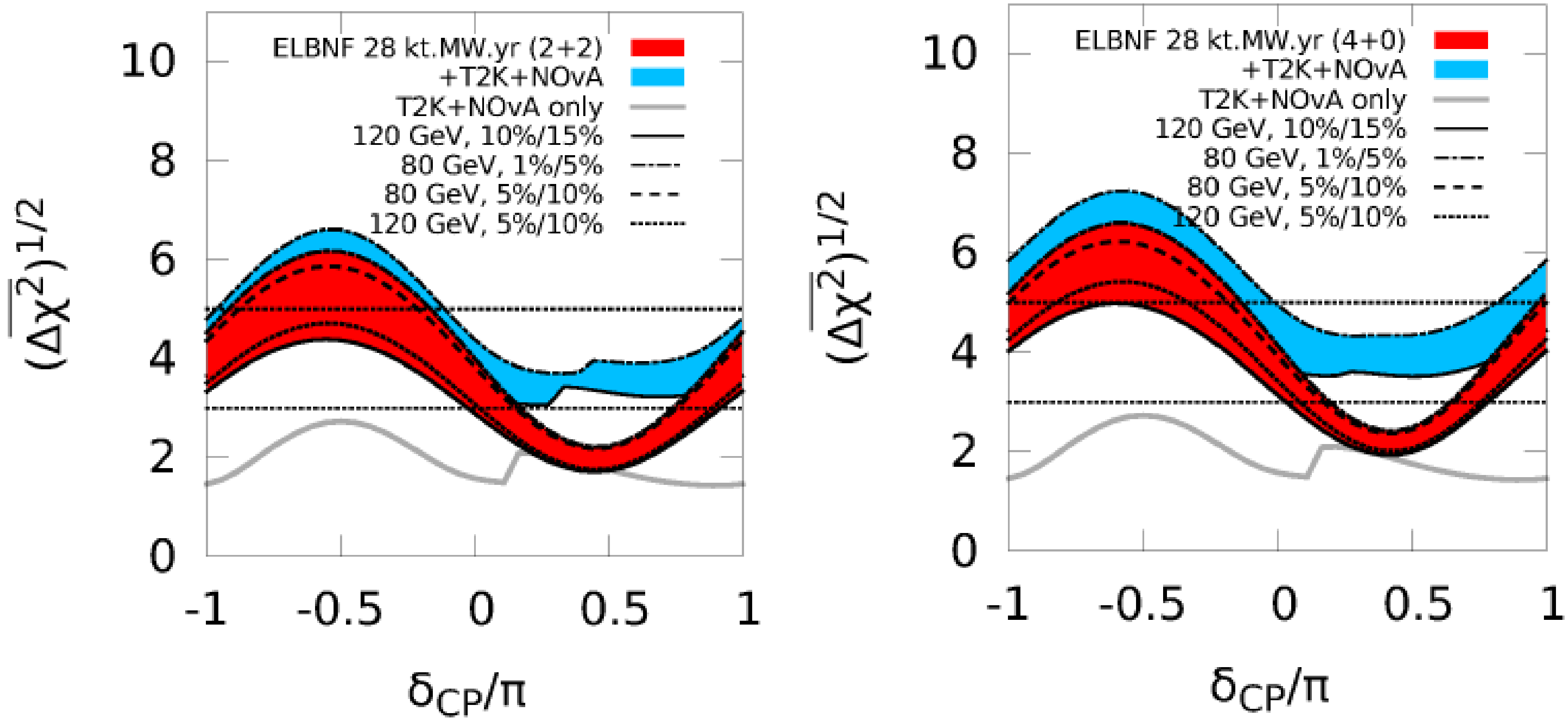
Beam assumptions for oscillation physics sensitivities: 4 years (neutrino+antineutrino, or neutrinos only), 700 kW with 80 GeV protons (28 MW-kton-yrs).

Number of events

Run Mode	Signal Events δ			Background Events			
	$-\pi/2$	0	$\pi/2$	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC
Neutrino	117	94	71	8	9	20	6
Antineutrino	18	23	25	4	5	12	4

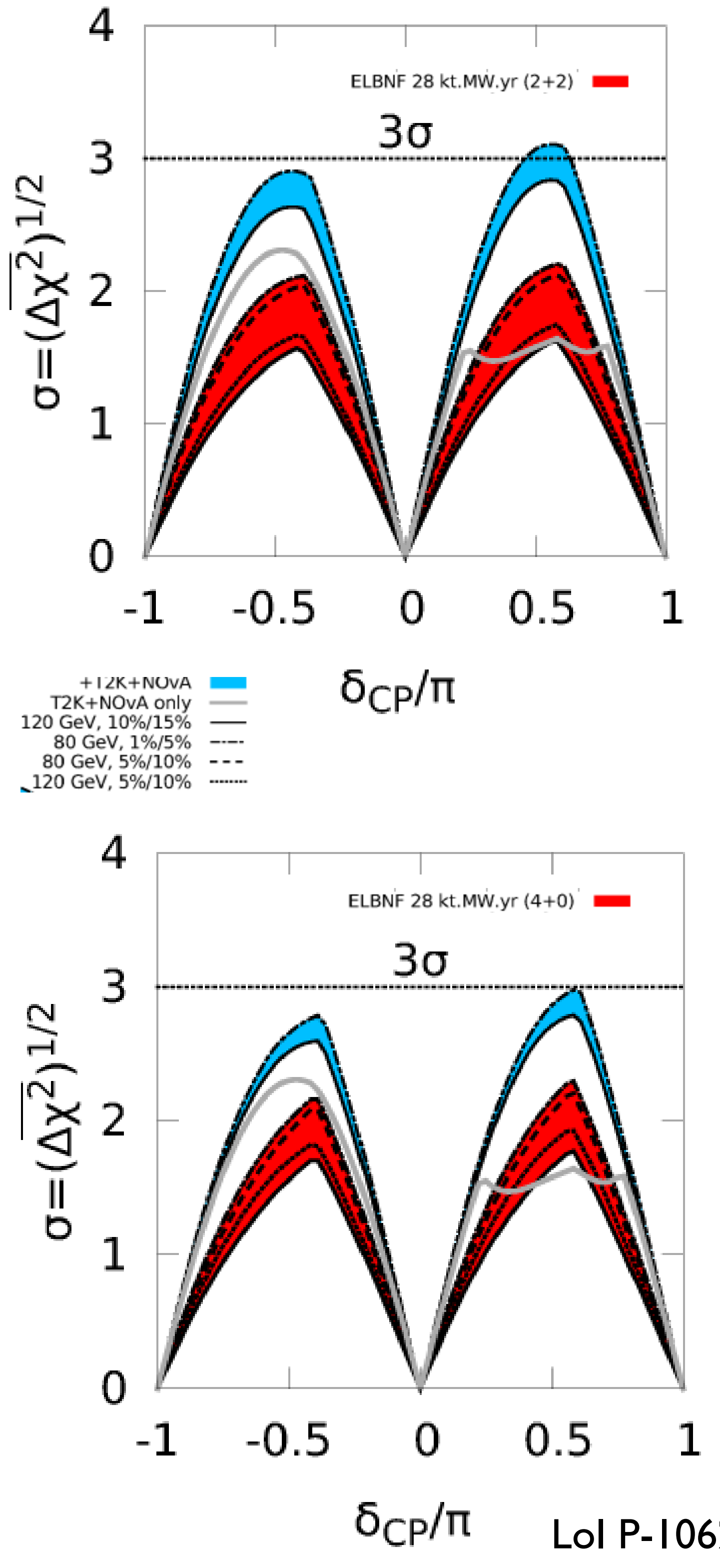
Strongly statistically limited!

ELBNF28



LoI P-1062, submitted to PAC Jan 15

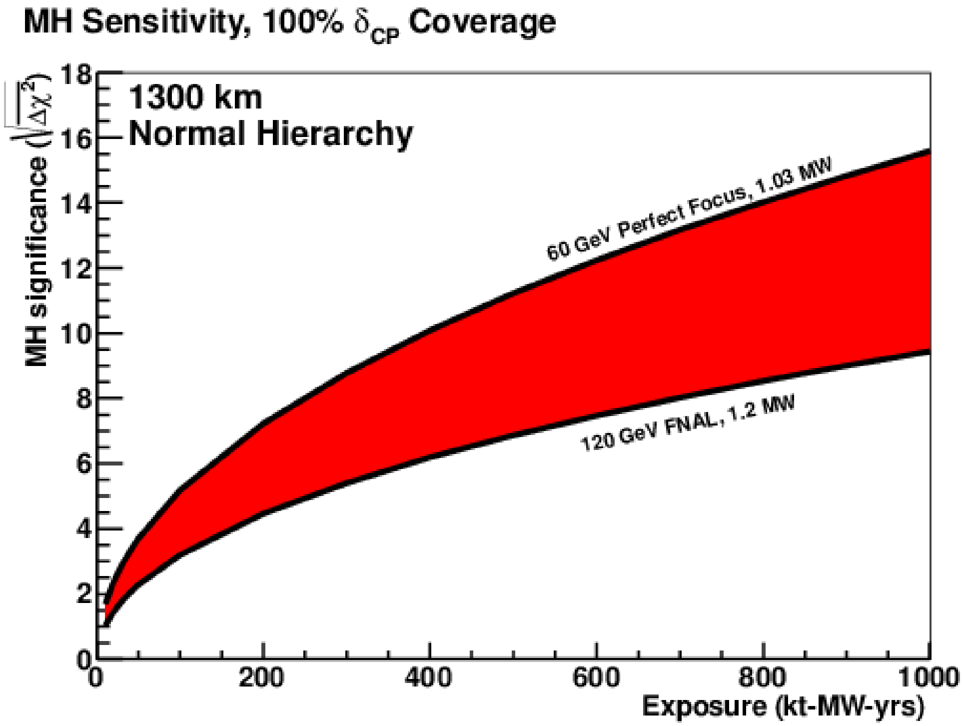
Thanks to the strong matter effects, a sensitivity to MO of 2-6 sigma could be achieved, depending on the delta phase. For the favoured region (to be confirmed), better than 3 sigma determination of MO.

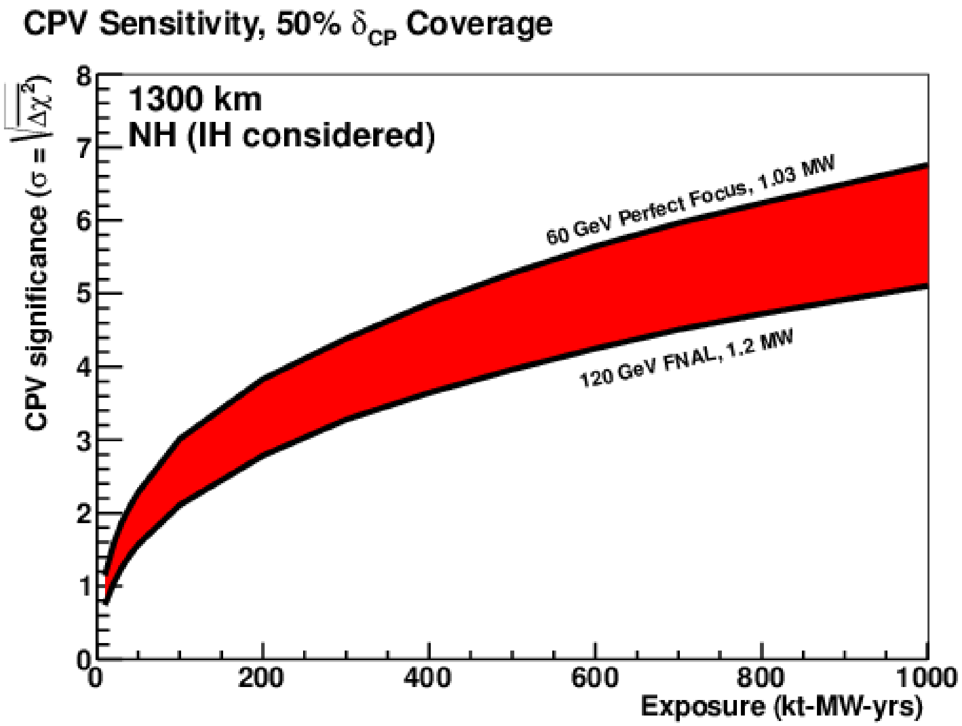


LoI P-1062

- This measurement is strongly limited by statistics.
- The addition of NOvA and T2K data makes a significant improvement in the reach.
- Running in neutrino and antineutrino mode is preferable.
- A 3 sigma CPV sensitivity could be within reach for maximal CPV.

Effect of exposure





LOI P-1062

Predicted sensitivities should be read with some caution as they critically depend on:

- setup assumed: detector and its performance, beam...
- values of oscillation parameters and their errors;
- treatment of backgrounds and systematic errors.

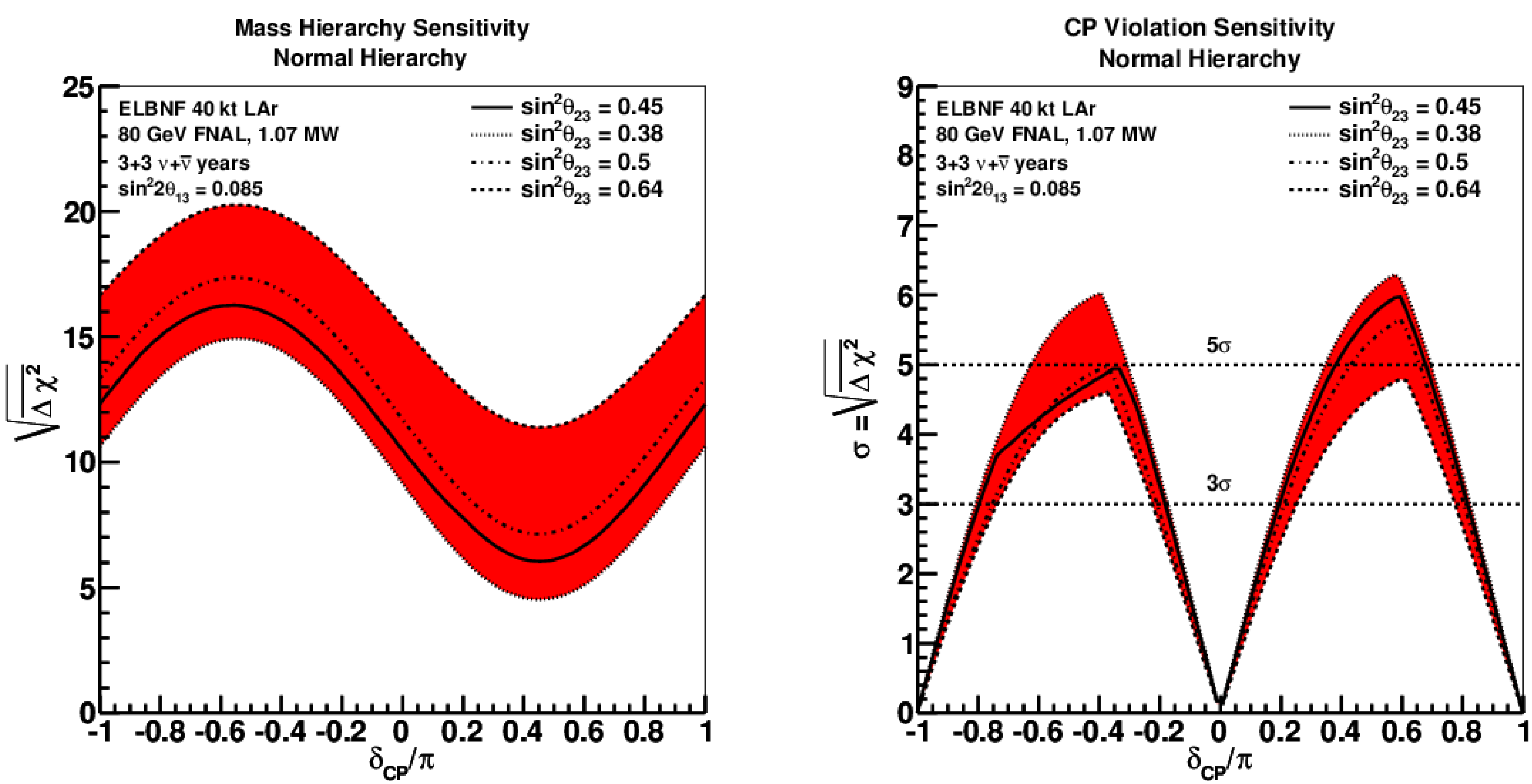
Space for further optimizations.

ELBNF-34kton

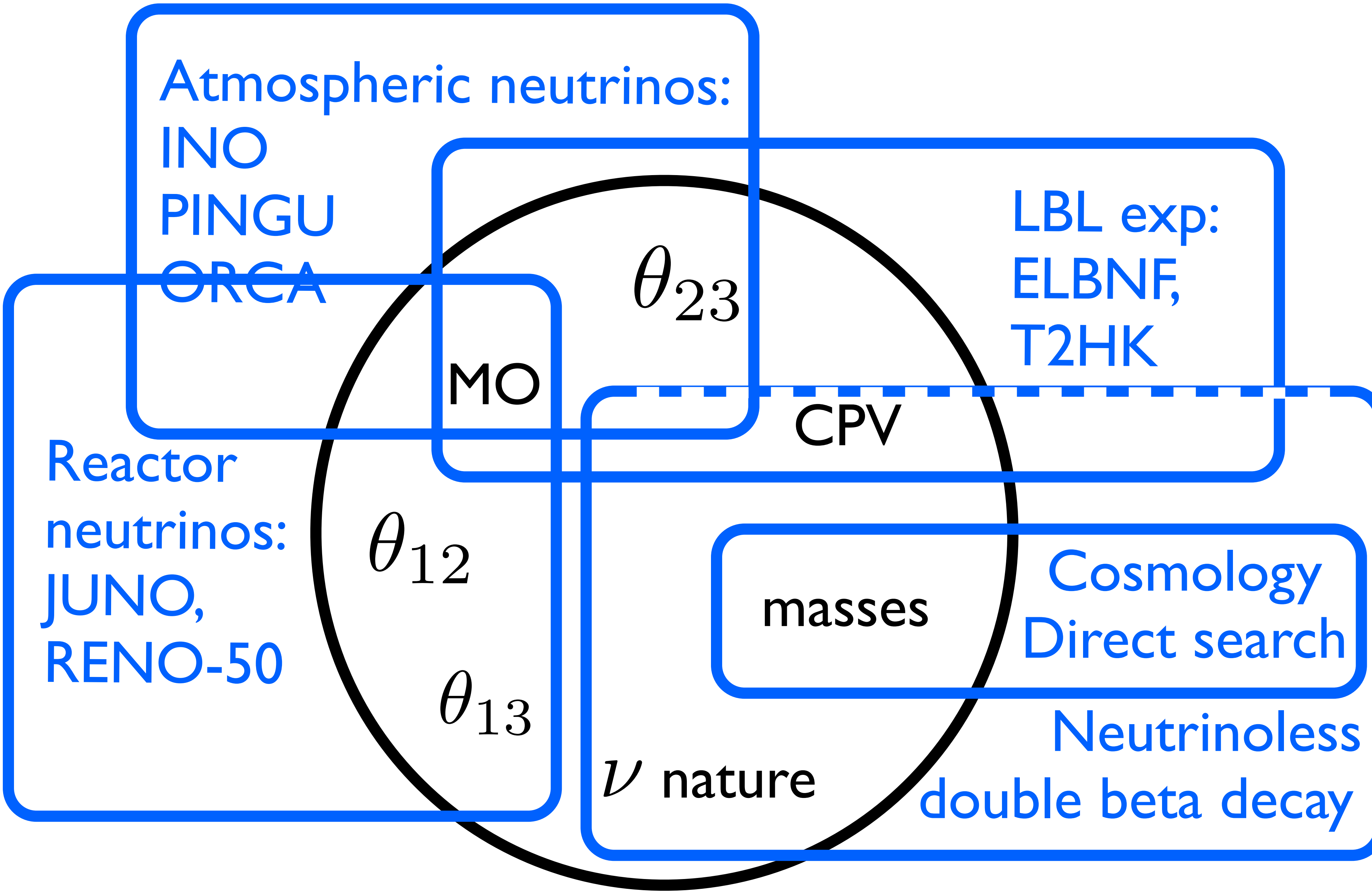
40 kton LArTPC, 80 GeV 1.07 MW beam, 3 yrs neutrinos + 3 yrs antineutrinos

LoI P-1062, submitted to PAC Jan 15

Run Mode	Signal Events			Background Events			
	δ_{CP}						
	$-\pi/2$	0	$\pi/2$	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC
Neutrino	1068	864	649	72	83	182	55
Antineutrino	166	213	231	41	42	107	33



Complementarity with other searches

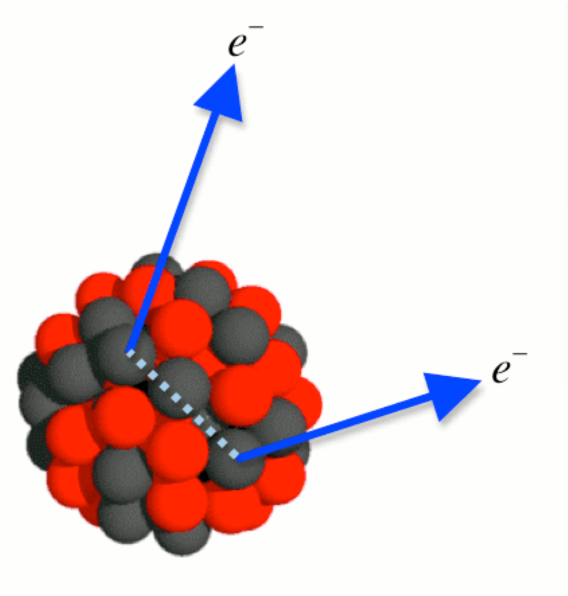


Also: Tests of standard neutrino paradigm

Synergy

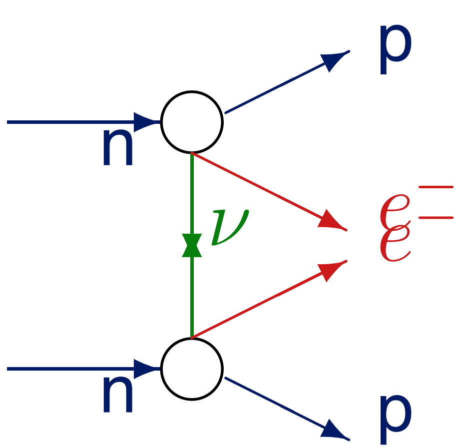
LBL with Neutrinoless double beta decay

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2 e, will test the nature of neutrinos.



Thanks to R. Saakyan, talk at NuPhys 2014

At the fundamental level, exchange of light Majorana neutrino (or other exotic mechanism).



The half-life time depends on neutrino properties

$$\left[T^{1/2}_{0\nu}(0^+ \to 0^+)\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 \, |{<}m{>}|^2$$

- $|\langle m \rangle| = m_{ee}$: the effective Majorana mass parameter

$$| < m > | \simeq |m_1 \sin^2\theta_{12} + m_2 \cos^2\theta_{12} e^{i\alpha_{21}} + m_3 \sin^2\theta_{13} e^{i\alpha_{31}}$$

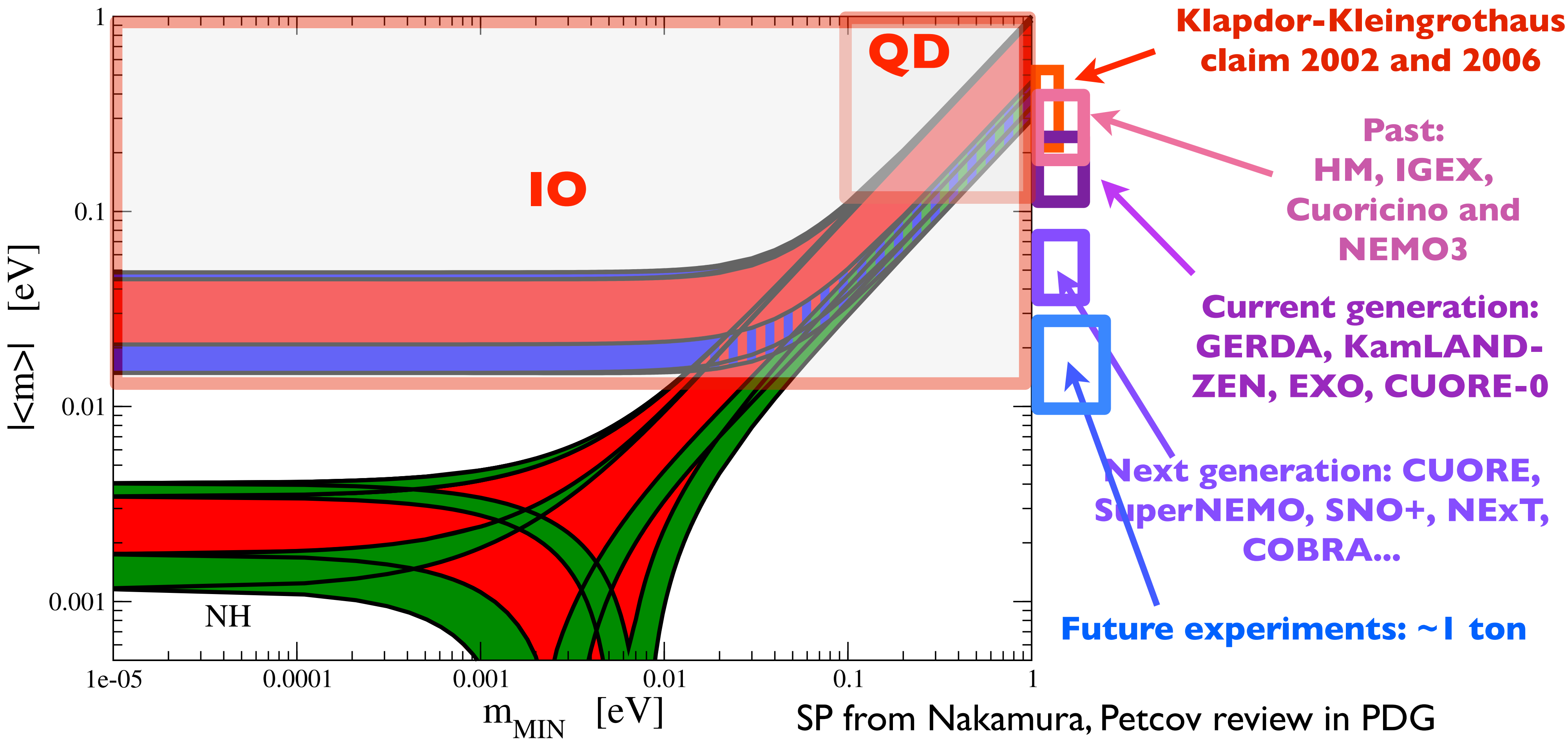
Mixing angles (known)

CPV phases (unknown)

Masses (partially known)

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

$$| < m > | \simeq \sqrt{\Delta m^2_{31}}\, |\cos^2\theta_{12} + \sin^2\theta_{12} e^{i\alpha_{21}}|$$



SP from Nakamura, Petcov review in PDG

If:

LBL, atm...
finds IO

Nuless dbeta decay
No signal down to mee ~ 10 meV

Nus are Dirac particles or cancellations in double beta decay (e.g. low energy see-saw)

Conclusions

- LBL experiments can search for the
  mass ordering,
  CPV,
  precise values of the oscillation parameters,
  tests of the 3-neutrino scenario.

- There is a strong complementarity and synergy with other searches (e.g. neutrinoless double beta decay, atmospheric, reactor and supernova neutrinos, cosmology,...).

- ELBNF28 is a milestone towards ELBNF with an improved physics reach compared to T2K and NOvA: sensitivity to MO and CPV (depending on delta).