Long baseline neutrino oscillations

22 June 2023

Muon Collider Synergies Workshop
IJCLab Orsay

Silvia Pascoli

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos
Horizon2020
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INFN Istituto Nazionale di Fisica Nucleare

Current status of neutrino parameters: the era of very precise neutrino physics

NuFIT 5.1 (2021)

without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{\rm CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

Esteban et al., 2007.14792, See also Capozzi et al., de Salas et al.

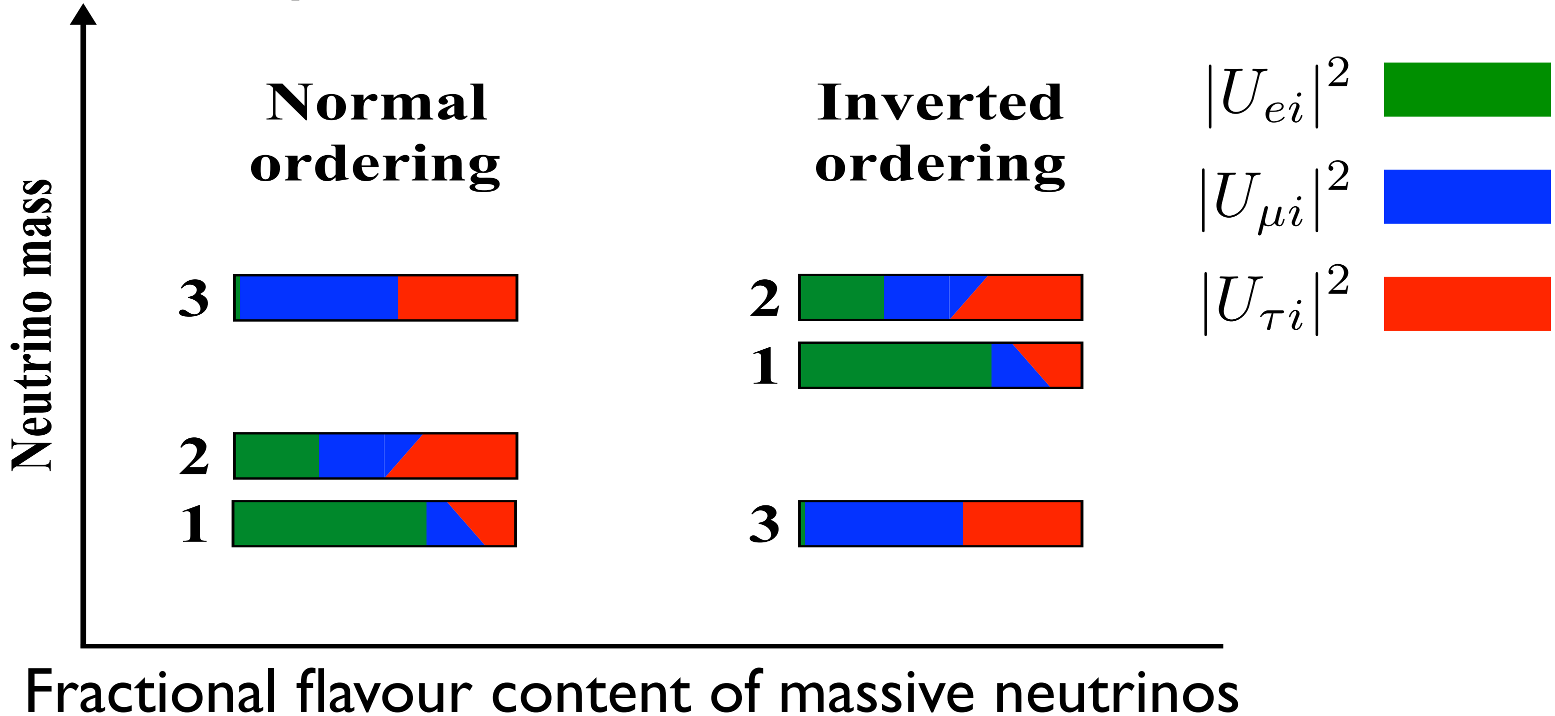
http://www.nu-fit.org/

- 2 mass squared differences
- 3 sizable mixing angles (one not too well known)
- mild hints of CPV (not robust)
- mild indications in favour of NO (?)

The past 20 years have seen a remarkable progress in determining neutrino properties! How about the next 20?

Neutrino masses

$\Delta m_{21}^2 \ll \Delta m_{31}^2$ implies at least 3 massive neutrinos.



$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min} + \Delta m_{21}^2}$$
$$m_3 = \sqrt{m_{\rm min} + \Delta m_{31}^2}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min} + |\Delta m_{32}^2| - \Delta m_{21}^2}$$
$$m_2 = \sqrt{m_{\rm min} + |\Delta m_{32}^2|}$$

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the MO: mild preference for NO ($\Delta\chi^2 \sim 2.7 (1.6\sigma)$).

Leptonic Mixing and CP-violation

The Pontecorvo-Maki-Nakagawa-Sakata matrix

$$\nu_i = U^\dagger \nu_\alpha \longrightarrow \mathcal{L}_{CC} = \frac{g}{\sqrt{2}} (\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L) \gamma^\mu U_{\rm osc} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} W_\mu$$

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

CPV?

- Mixings very different from quark sector.
- Possibly, large leptonic CPV.

  CPV is a fundamental question, possibly related to the origin of the baryon asymmetry and to the origin of the flavour structure.

What do we still need to know in 2022?

1. **What is the nature of neutrinos?**

2. **What are the values of the masses?** Absolute scale 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? Non-unitarity? Other effects?

Very exciting experimental programme.

Phenomenology questions for the future

1. What is the nature of neutrinos?

2. What are the values of the masses? Absolute scale and the ordering.

3. Is there leptonic CP-violation?

4. What are the precise values of mixing parameters?

Long baseline neutrino oscillation experiments

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

Very exciting experimental programme.

Neutrino oscillations

Let's assume that at t=0 a muon neutrino is produced

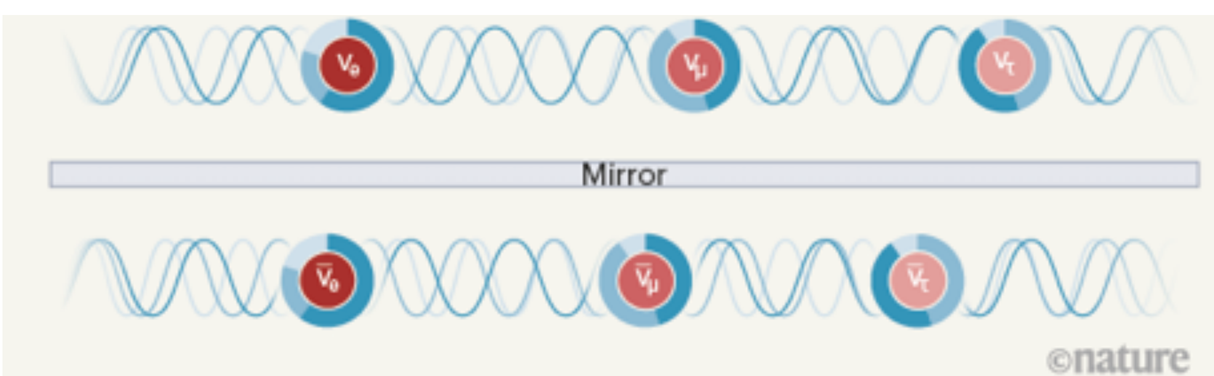
$$|\nu, t=0\rangle = |\nu_\mu\rangle = \sum_i U_{\mu i} |\nu_i\rangle$$

The time-evolution is given by the solution of the Schroedinger equation with free Hamiltonian:

$$|\nu, t\rangle = \sum_i U_{\mu i} e^{-iE_i t} |\nu_i\rangle$$

At detection, projecting over the flavour state :

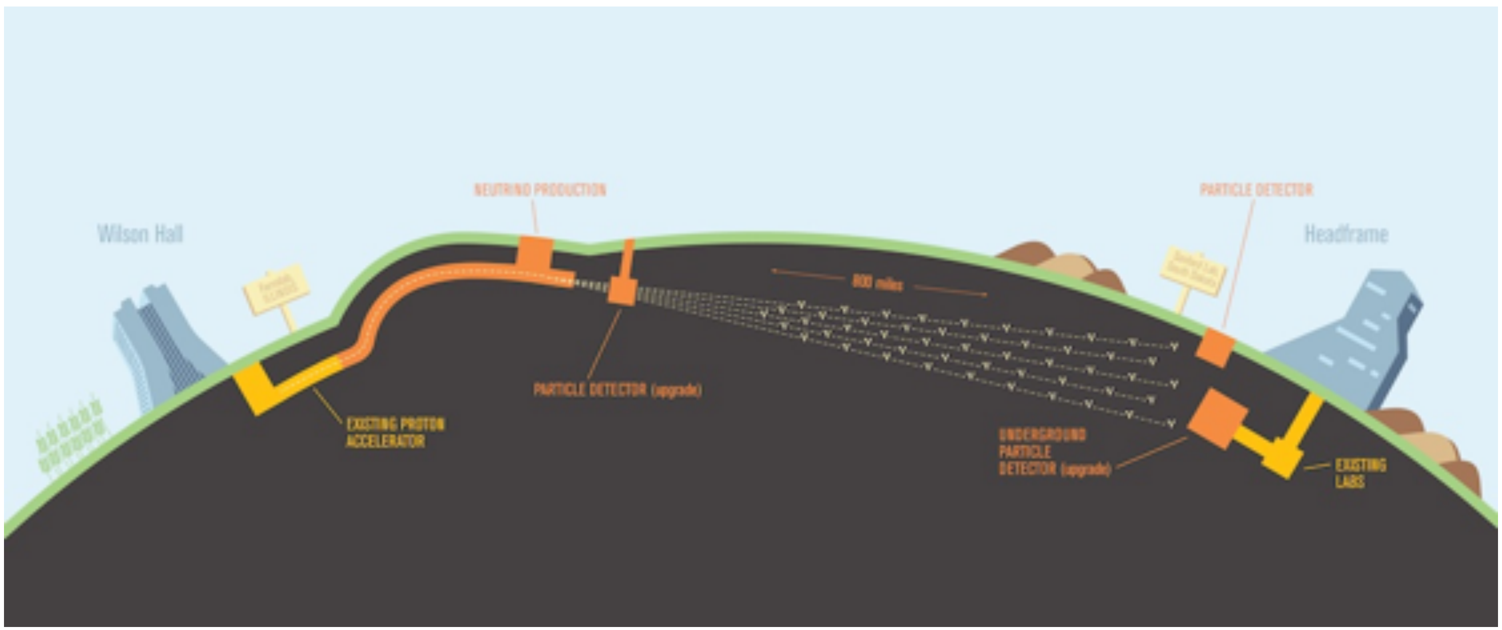
$$P(\nu_\alpha \to \nu_\beta) \quad = \quad \left| \sum_i U_{\alpha 1} U^*_{\beta 1} e^{-i \frac{\Delta m^2_{i1}}{2E} L} \right|^2 \overset{2\nu}{=} \sin^2 2\theta \ \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$



Nature, SP and J. Turner, News and views, 15 April 2020

Long-baseline neutrino oscillations

- LBL experiments search for neutrino oscillations, for neutrinos that are produced at an accelerator complex and travel 100s Km before scattering in large detectors.

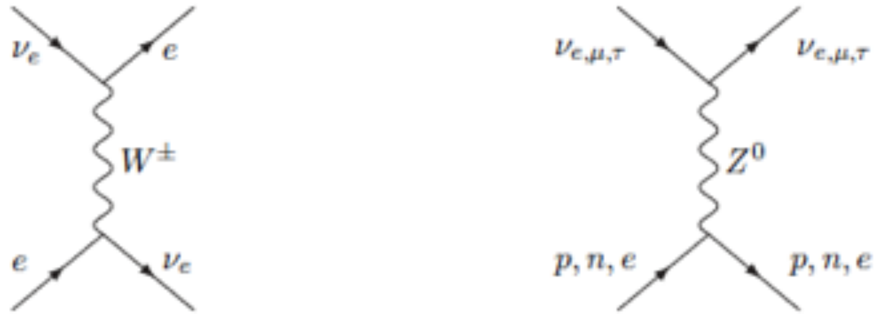


Credit: Symmetry magazine

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

The background is CP and CPT violating, and the resulting oscillations are as well.

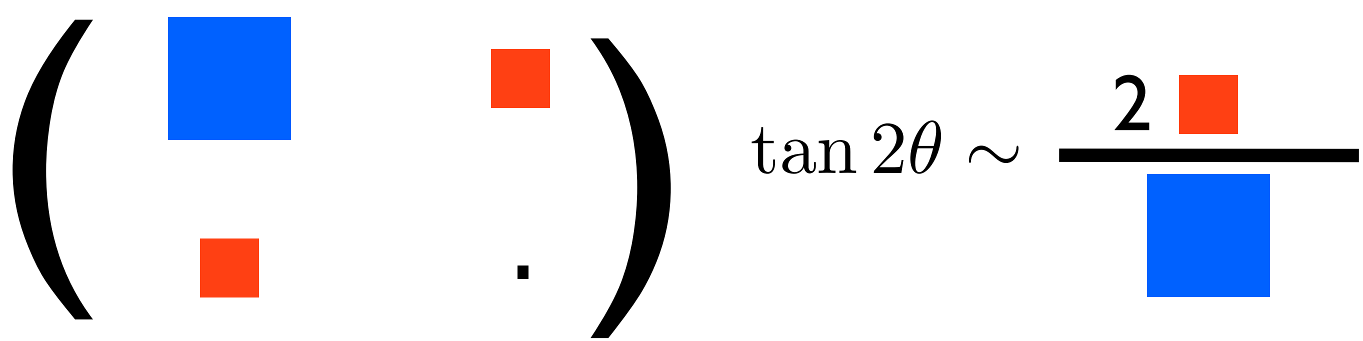
- Neutrinos undergo forward elastic scattering via CC and NC interactions.



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

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

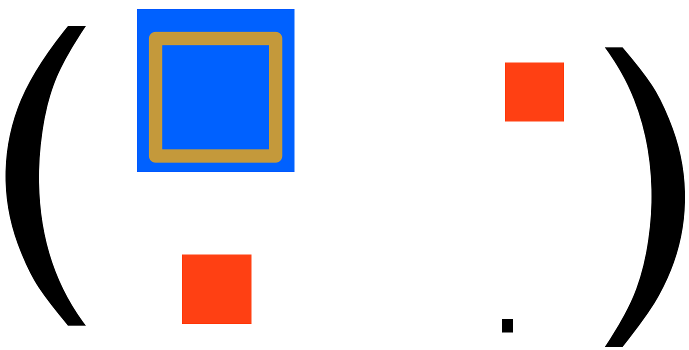
Effective Hamiltonian



In long baseline experiments

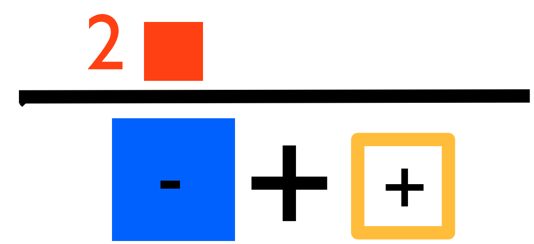
$-\frac{\Delta m^2}{2E}\cos(2\theta)$ $\quad \nu$ $+\sqrt{2}G_F N_e$ $\quad \bar{\nu}$ $-\sqrt{2}G_F N_e$

For neutrinos

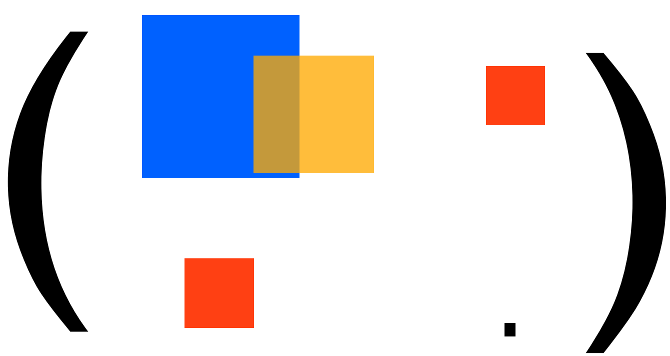


$\Delta m^2 > 0$ enhancement

$\tan 2\theta^M \sim$

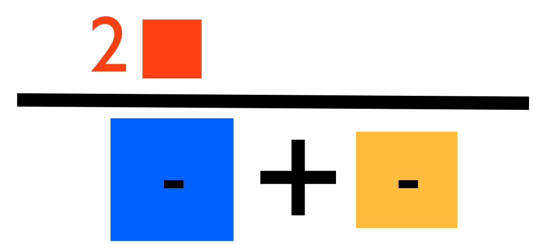


For antineutrinos



$\Delta m^2 > 0$ suppression

$\tan 2\theta^M \sim$



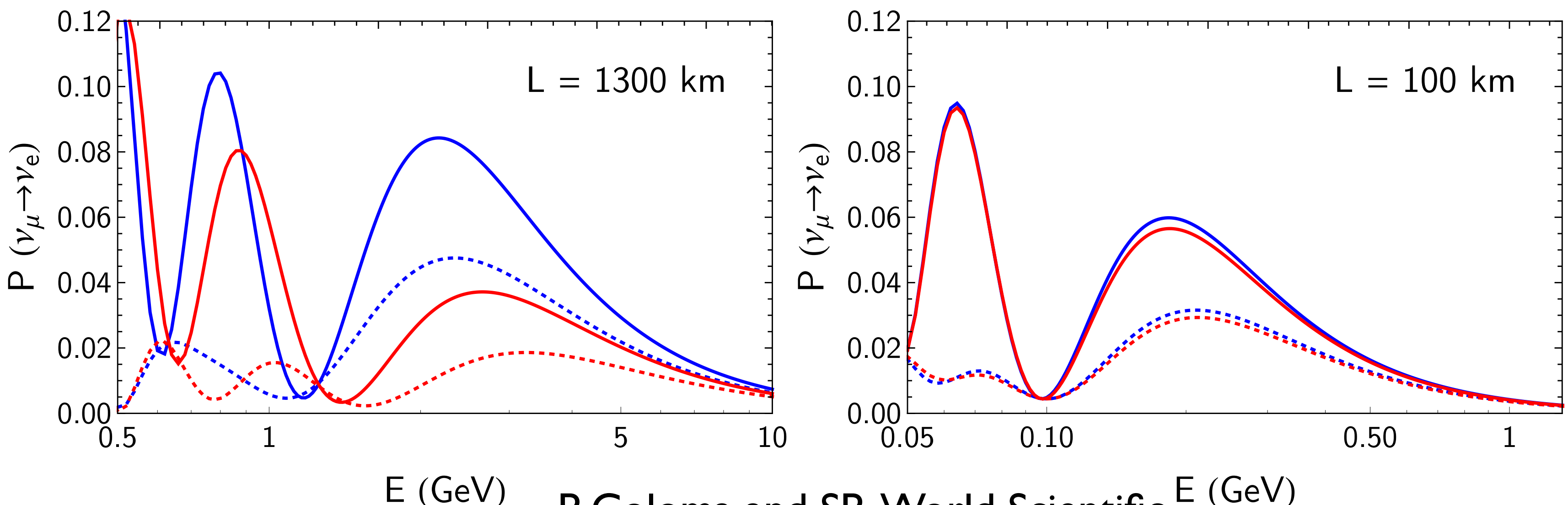
The 3-neutrino probability can be approximated as

A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773;
P. Denton, S. Parke and X. Zhang, 1907.02534…

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

with

$$\Delta_{31} \equiv \Delta m_{31}^2/(2E_\nu)$$
$$r_A \simeq \frac{\sqrt{2} G_F N_e}{\Delta m_{31}^2/(2E_\nu)}$$



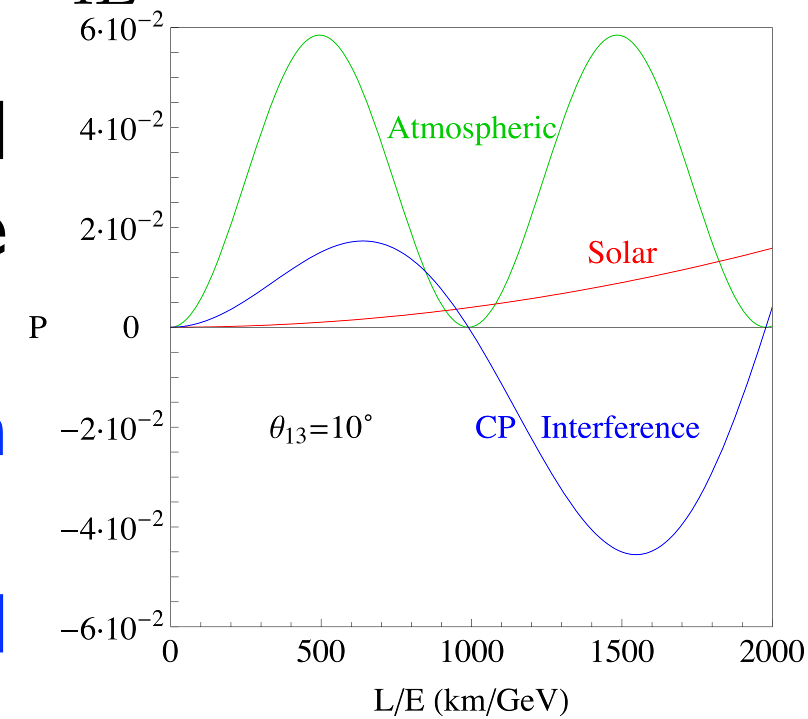
P. Coloma and SP, World Scientific

Long-baseline neutrino oscillations and leptonic CP violation

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

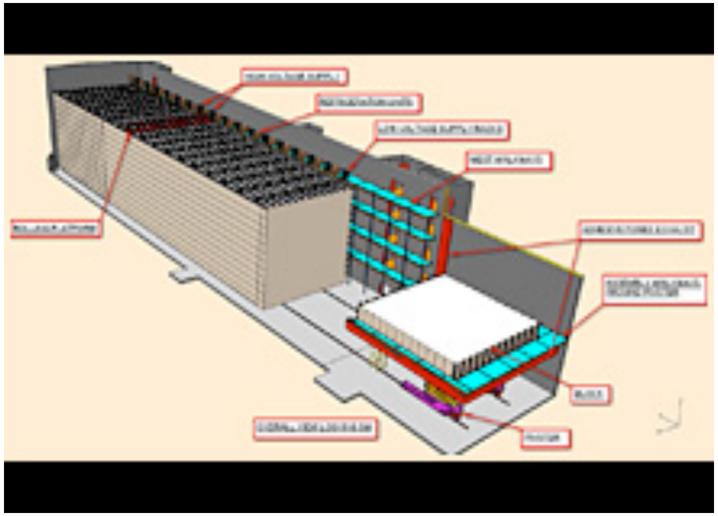
A. Cervera et al., hep-ph/0002108; K. Asano, H. Minakata, 1103.4387; S. K. Agarwalla et al., 1302.6773...

- The determination of CPV and of the mass ordering are entangled.
- Matter effects increase with energy and distance.
- CPV effects more pronounced at low energy.



P. Coloma, E. Fernandez-Martinez, JHEP1204

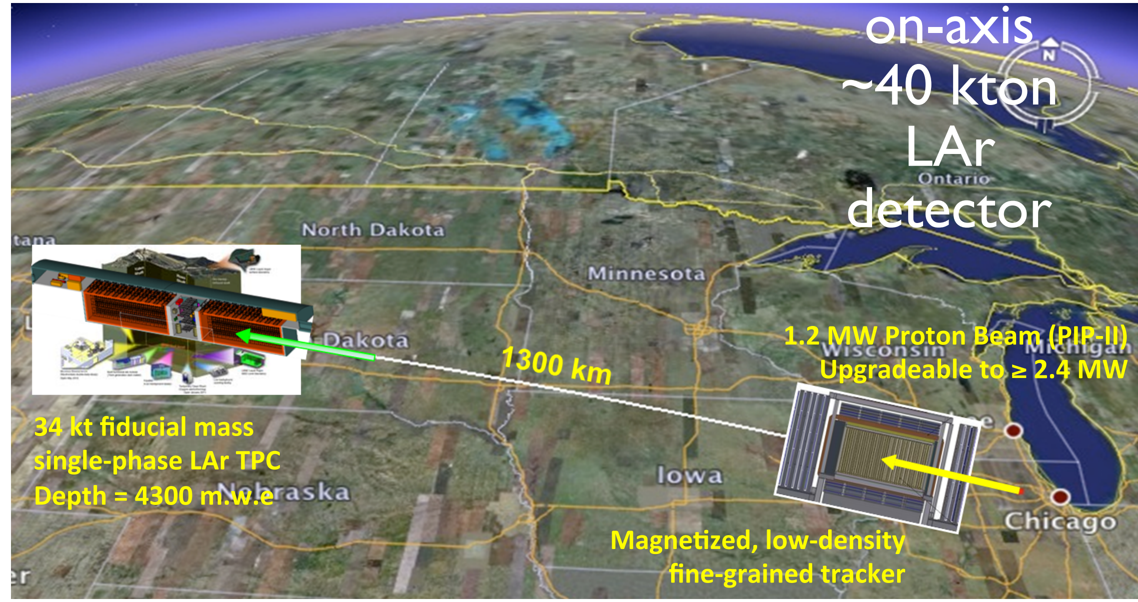
Present/Future LBL exp

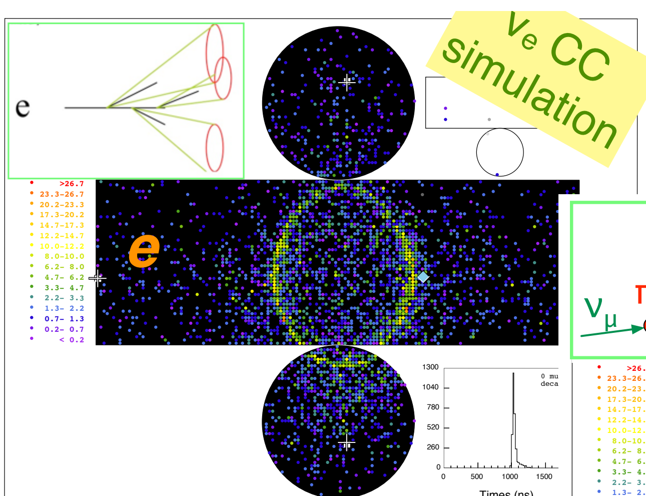


NOvA: 810 km off-axis
~14 kton plastic scintillator detector

T2K: 295 km off-axis
~22.5 kton WC detector

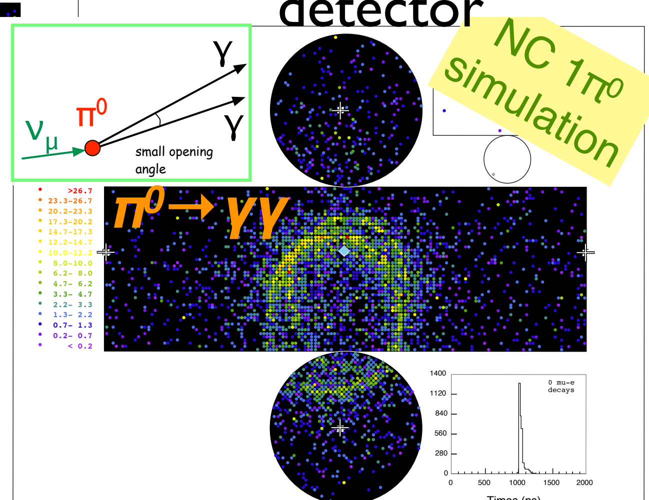
DUNE:
1300 km
on-axis
~40 kton
LAr
detector

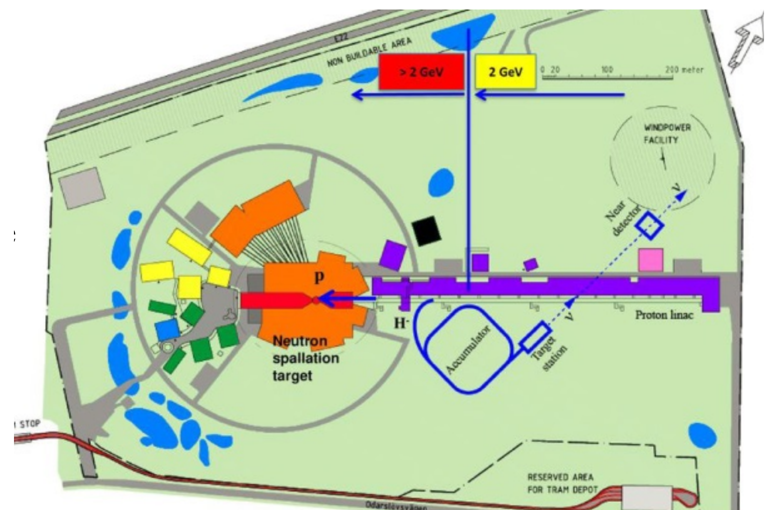




M. Shiozawa, for T2HK coll., NuPhys 2014

T2HK: 295 km
off-axis
~1 Mton WC
detector



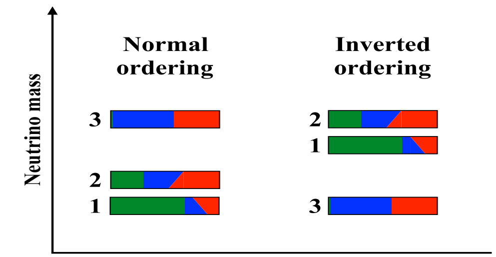


~1 BEuros for the neutrino facility including detector

***ESSnuSB**: 300-500 km*
~0.5 Mton WC detector
second osc. maximum

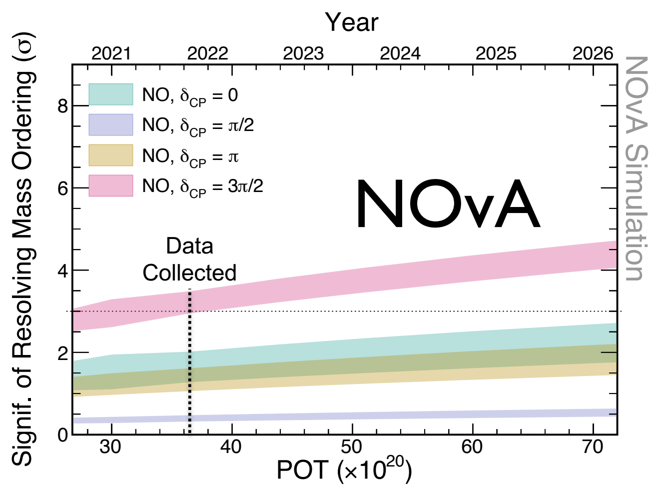
Question:
Neutrino mass ordering

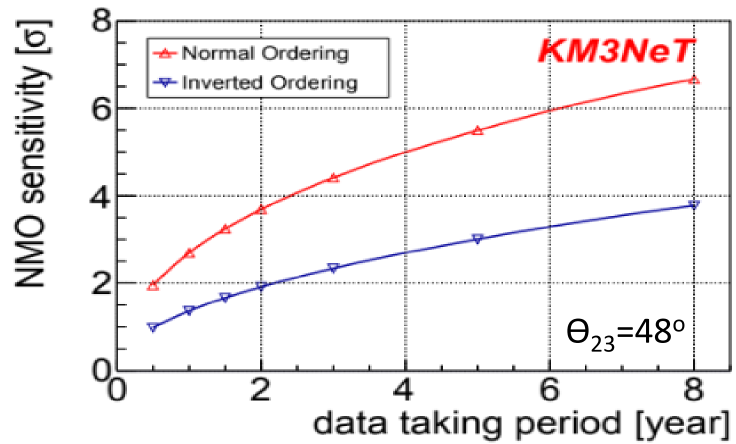
Mass ordering sensitivity



The current situation is still rather uncertain.

We know we will know the ordering by 2035ish.





SK, HK, IceCube

A. Heijboer's talk at Neutrino 2022

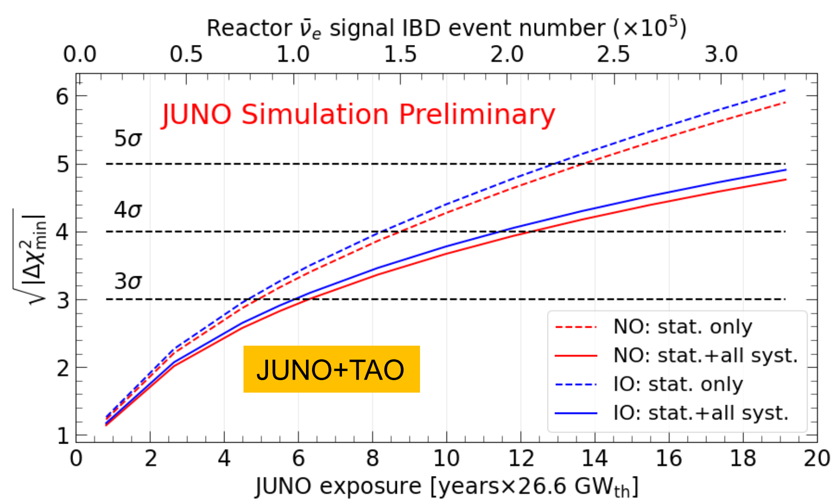
J. Hartnell's talk at Neutrino 2022

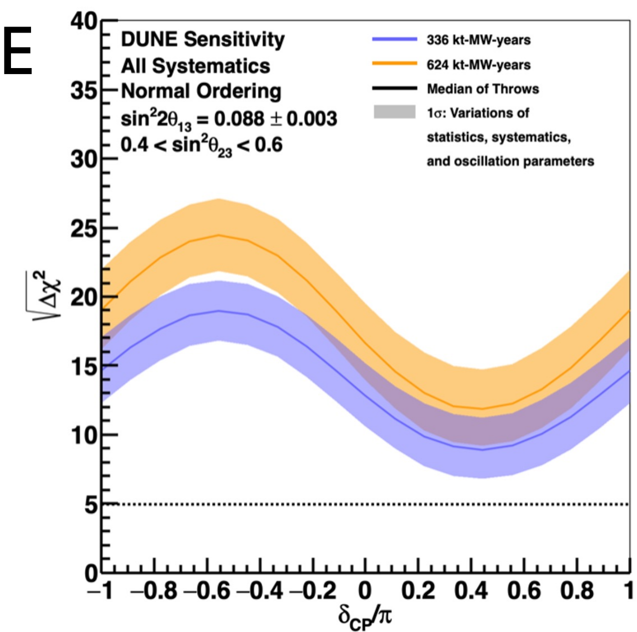
DUNE Coll., 2006.16043

DUNE

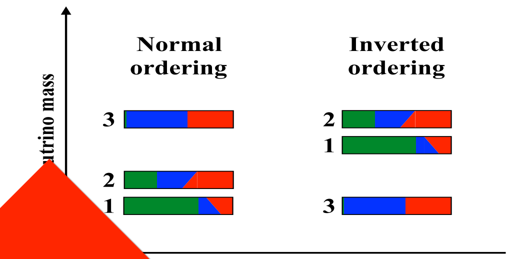
JUNO

J. Zhao's talk at Neutrino 2022





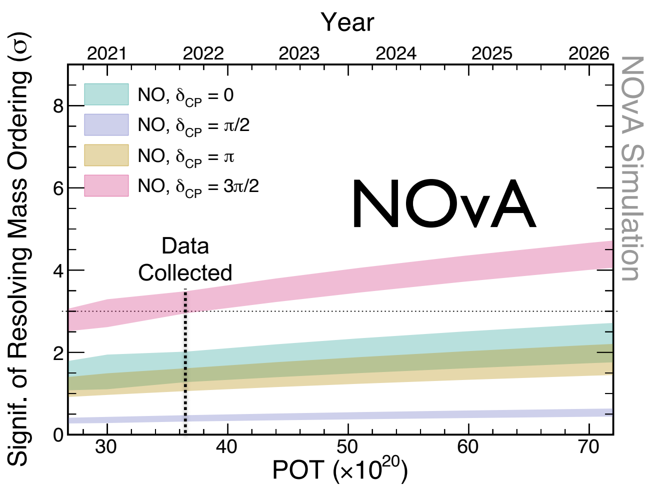
Mass ordering sensitivity



The current situation is still rather uncertain.

We know we will know the ordering by ... sh.

Answered by ~2035



J. Hartnell's talk at Neutrino 20...

SK, HK, IceCube

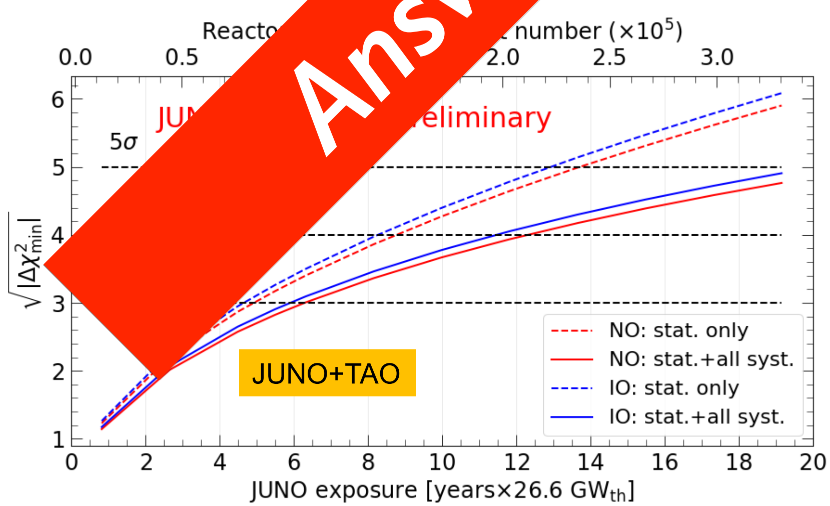
A. Heijboer's talk at Neutrino 2022

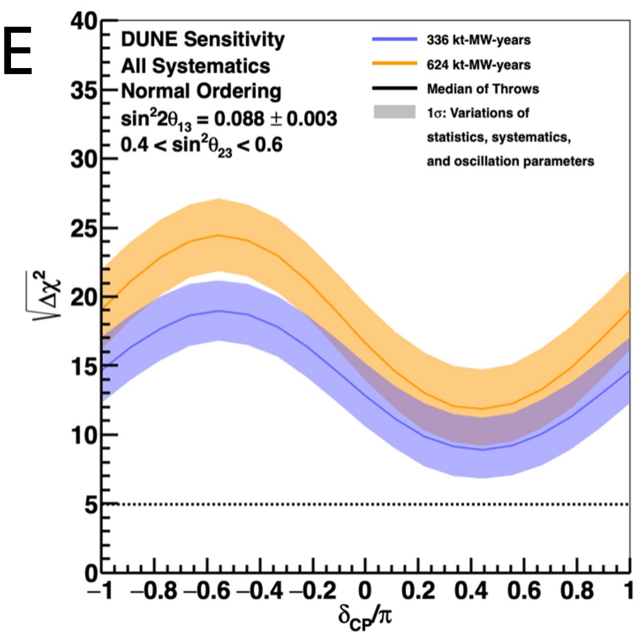
DUNE Coll., 2006.16043

DUNE

JUNO

J. Zhao's talk at Neutrino 2022





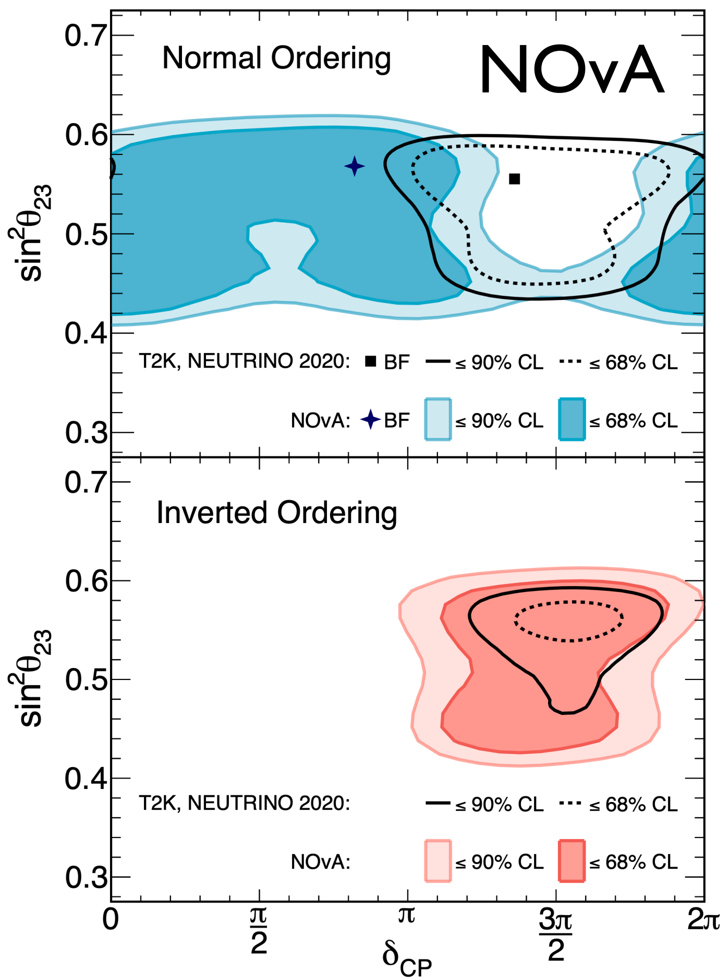
Question: Leptonic CP violation

CPV sensitivity

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

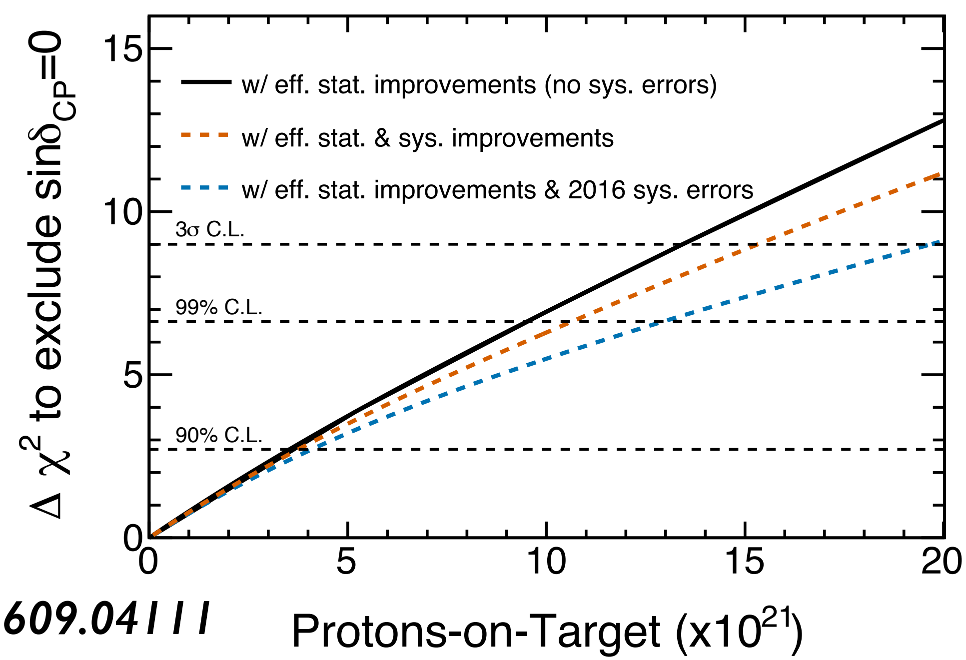
Hints of leptonic CPV?
Situation remains unclear.
Expect soon T2K-NOvA joint analysis.

2020 data set: https://arxiv.org/abs/2108.08219



J. Hartnell's talk at Neutrino 2022

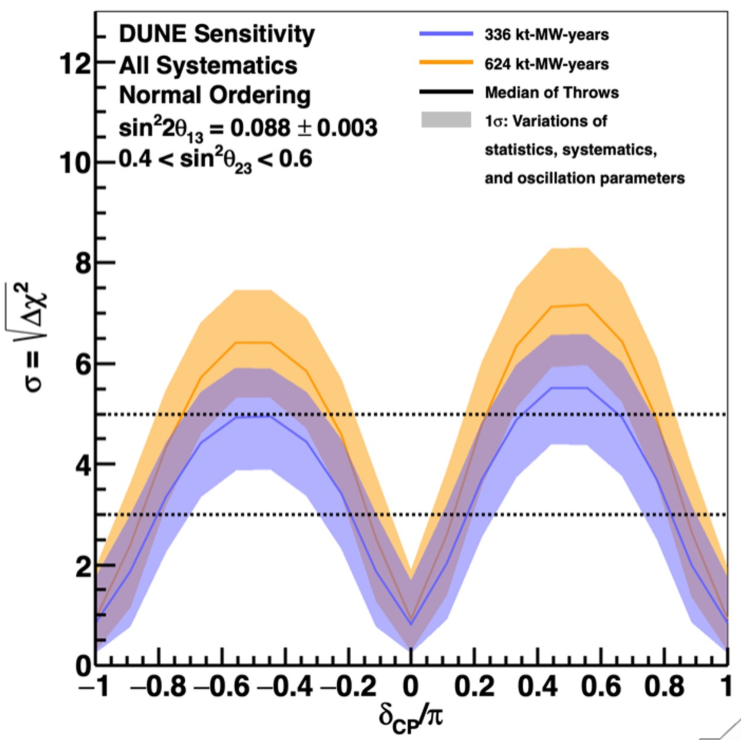
T2K phase 2 extension aims at reaching 1.3 MW by 2026 (20x10^21pot).



T2K, 1609.04111

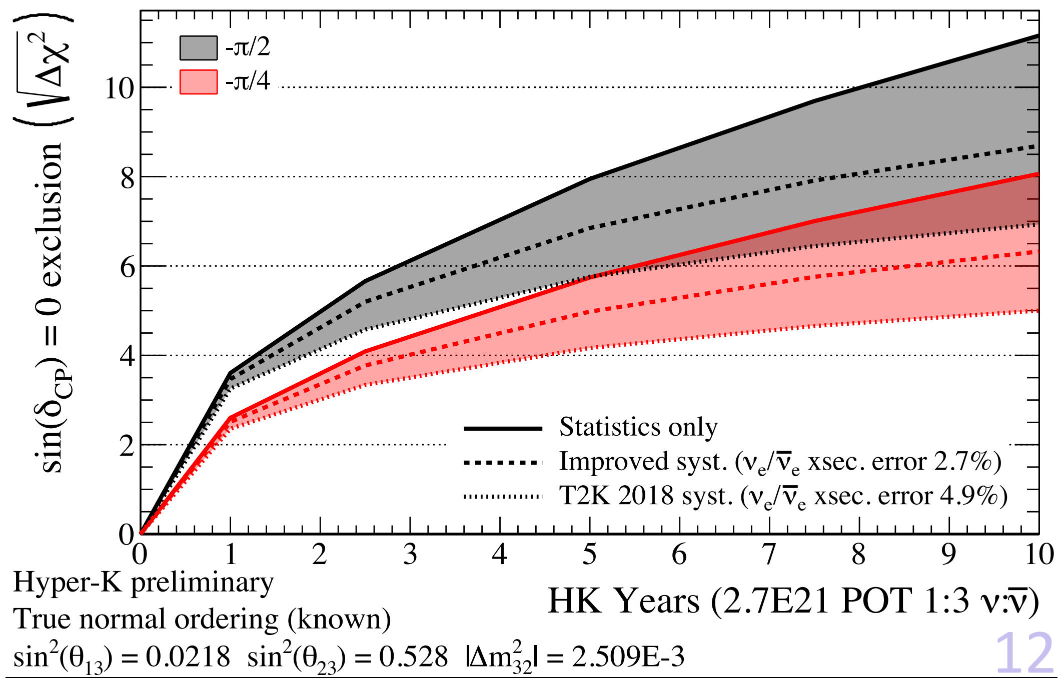
DUNE and T2HK will get to 5 sigma for a large range of values of delta by 2040 (possibly 2035??). Whether we discover it or not depends on the true delta.

DUNE



DUNE Coll., 2006.16043

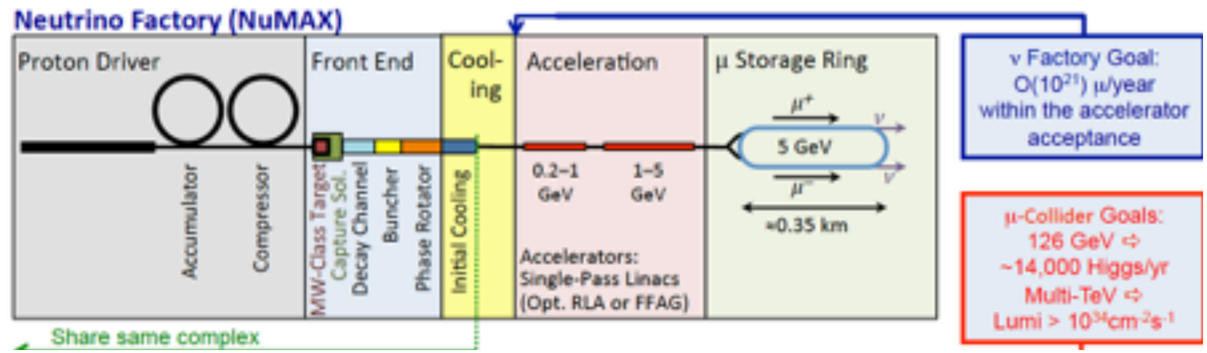
T2HK



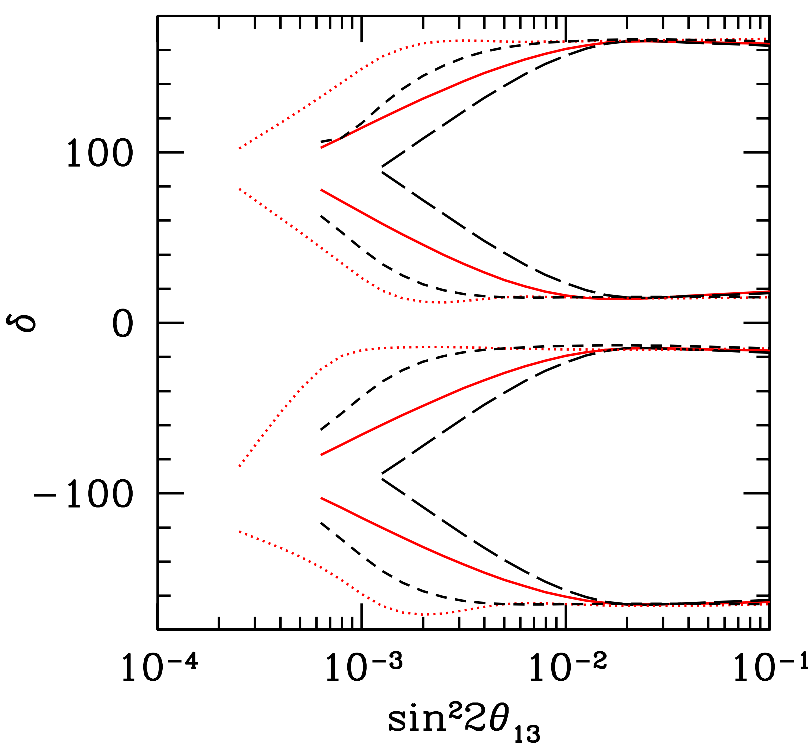
J. Wilson's talk at Neutrino 2022

Scenario 1: no leptonic CPV discovery

If the delta phase is too close to 0, pi, DUNE and T2HK will not be able to discover leptonic CPV.



J.-P. Delahaye et al., 1803.07431



It is essential to pursue this measurement with a more sensitive experiment: neutrino factory.

A. Bross et al., 0709.3889

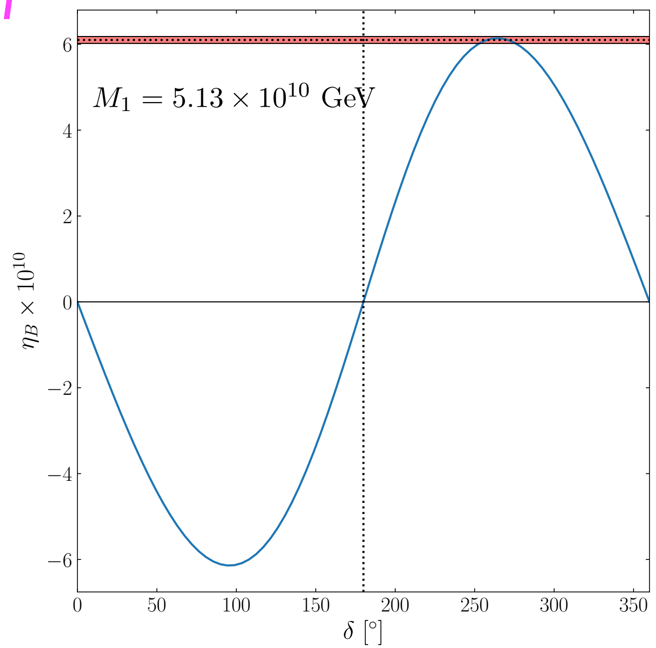
- CP violation is a key aspect of the SM and it is important to establish if it concerns also the leptonic sector.
- CPV is related to the origin of the leptonic mixing structure.
- The delta phase can explain the baryon asymmetry of the Universe but only if it is sufficiently CP-violating.

For high E see-saw type I

$$|\sin\theta_{13}\,\sin\delta| \gtrsim 0.09$$

SP, Petcov, Riotto, hep-ph/0609125

Generically, if $\delta < 25^o - 35^o$ and similarly around 180^o, delta cannot be responsible for the baryon asymmetry in high E see-saw type I.



K. Moffat et al., 1809.08251

Question:
Precision measurement of oscillation parameters

Scenario 2: leptonic CPV discovered

If discovered, the key physics goal will be the precise measurement of the oscillation parameters.

- 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.

	2012 NuFIT 1.0	2014 NuFIT 2.0	2016 NuFIT 3.0	2018 NuFIT 4.0	2021 NuFIT 5.1
θ_{12}	15%	14%	14%	14%	14%
θ_{13}	30%	15%	11%	8.9%	9.0%
θ_{23}	43%	32%	32%	27%	27%
Δm^2_{21}	14%	14%	14%	16%	16%
$\lvert\Delta m^2_{3\ell}\rvert$	17%	11%	9%	7.8%	6.7% [6.5%]
δ_{CP}	100%	100%	100%	100% [92%]	100% [83%]
$\Delta\chi^2_{\text{IO-NO}}$	± 0.5	-0.97	$+0.83$	$+4.7$ [$+9.3$]	$+2.6$ [$+7.0$]

w/o [w] SK atm data

Gonzalez-Garcia et al., 2111.03086

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	$\pm$0.034 (1.3%)	$\pm$0.021 (0.8%)	$\pm$0.0047 (0.2%)	$\pm$0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	$\pm$0.18 (2.4%)	$\pm$0.074 (1.0%)	$\pm$0.024 (0.3%)	$\pm$0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	$\pm$0.013 (4.2%)	$\pm$0.0058 (1.9%)	$\pm$0.0016 (0.5%)	$\pm$0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	$\pm$0.0007 (3.2%)	$\pm$0.010 (47.9%)	$\pm$0.0026 (12.1%)	$\pm$0.0016 (7.3%)

JUNO Coll., 2204.13249

- Predictions for the CPV phase delta and relations among parameters in flavour models (e.g. sum rules), e.g.:

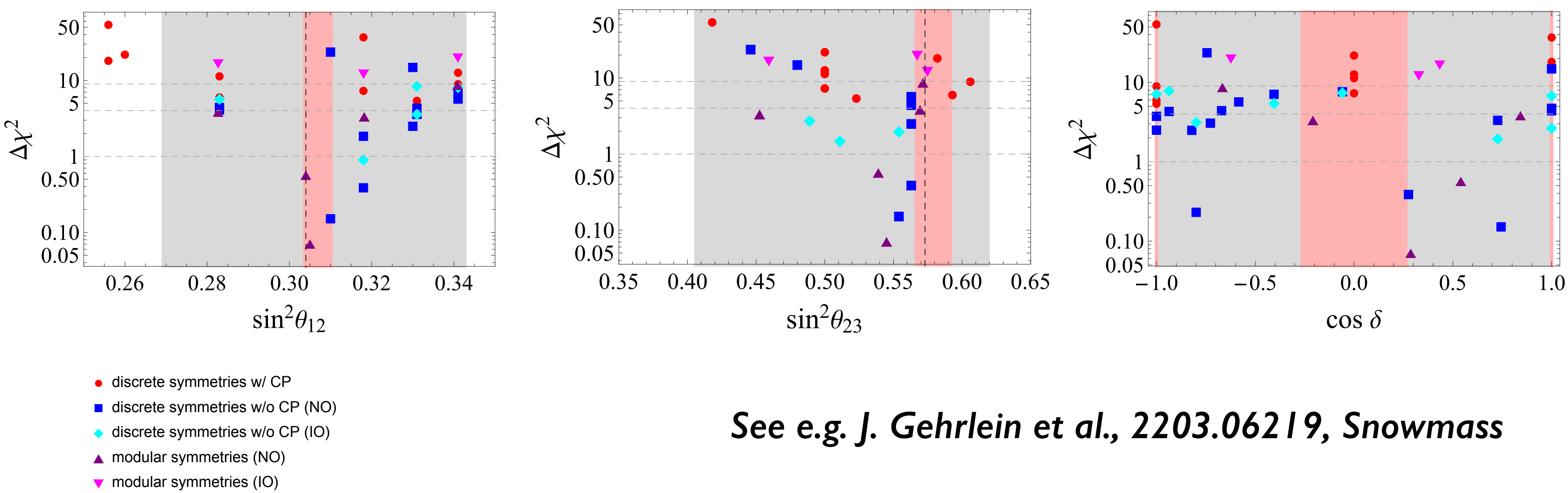
$$a = \sigma r \cos\delta \qquad \sigma = 1, -1/2$$

with

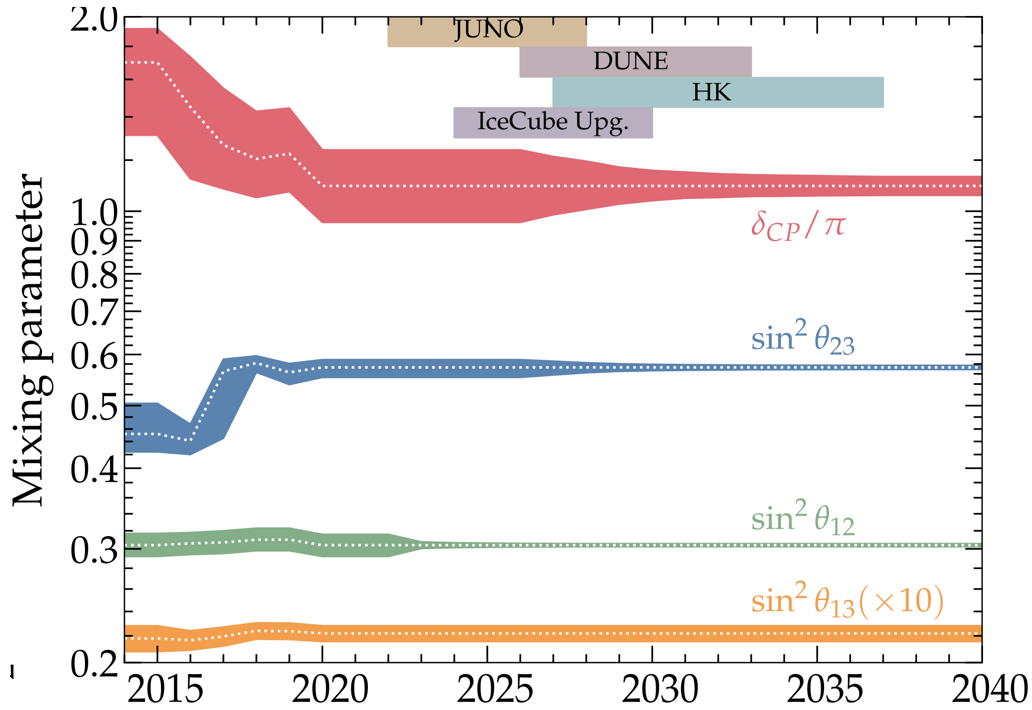
$$\sin\theta_{12} = \frac{1+s}{\sqrt{3}}, \quad \sin\theta_{13} = \frac{r}{\sqrt{2}}, \quad \sin\theta_{23} = \frac{1+a}{\sqrt{2}}$$

King, 0710.0530

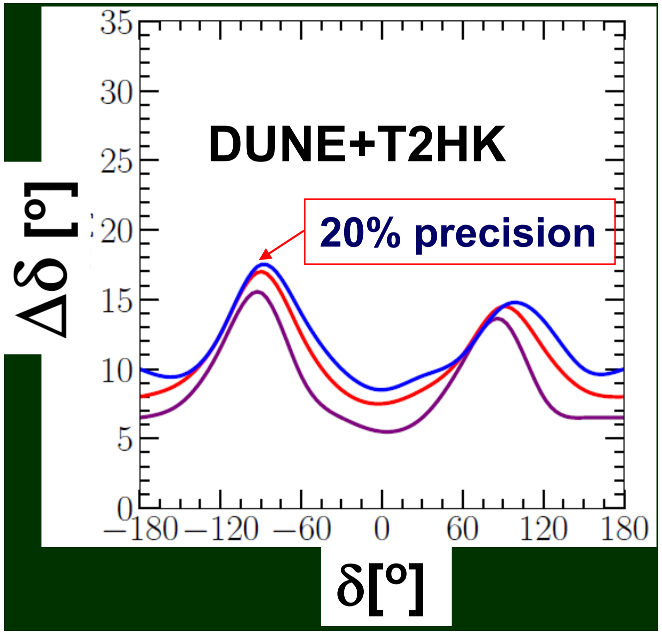
Crucial information in order to discriminate between different flavour models.



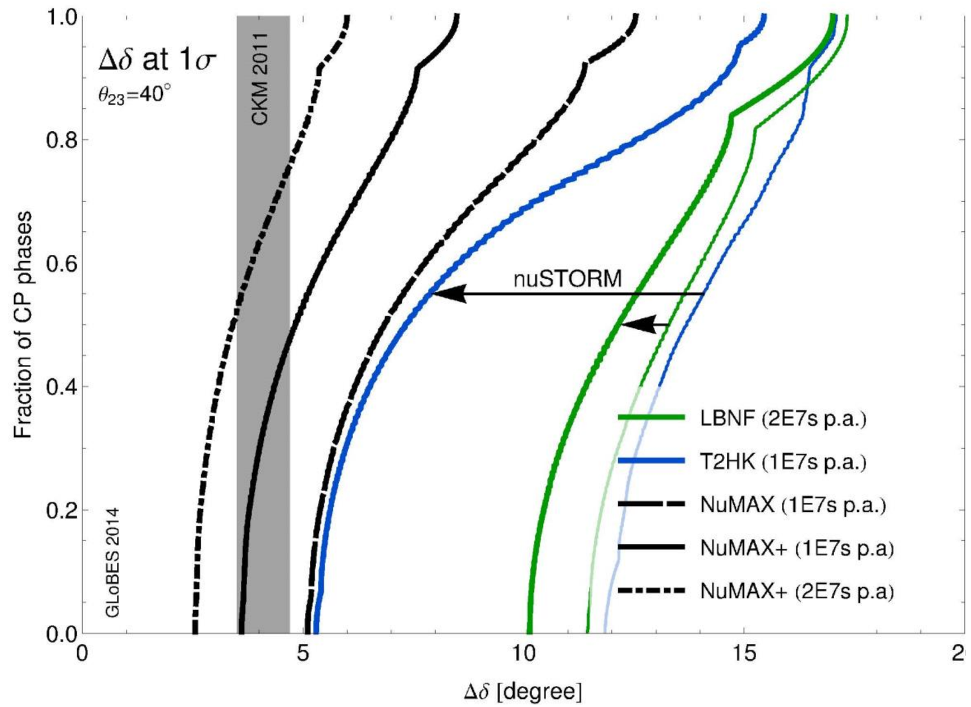
See e.g. J. Gehrlein et al., 2203.06219, Snowmass



N. Song et al., 2012.12893



See O. Yasuda's talk at Neutrino 2022



A neutrino factory would be able to increase the precision on delta very significantly.

J.-P. Delahaye et al., 1803.07431

Question:
Beyond 3-neutrino mixing

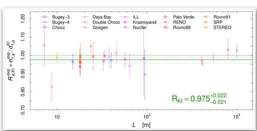
Is the standard 3-neutrino picture correct?

Neutrinos are the least known of the SM fermions and could provide a privileged window on new physics BSM.

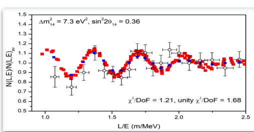
With great precision of neutrino properties, the search for beyond 3-nu mixing becomes very compelling:
Neutrino 2002: 5 talks mainly on sterile neutrinos
Neutrino 2012: 4 talks mainly on sterile neutrinos
Neutrino 2022: 10 talks with many new results and theory developments
Neutrino 2032: ?????

- Non standard interactions, non-unitarity.
- Dark sector connection (with dark photons, FIPs, DM)
- Exotic properties: decays, decoherence, CPT and Lorentz violation…

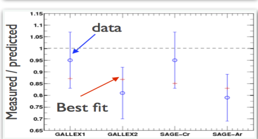
- Sterile neutrinos: Current hints for eV sterile neutrinos (LSND, MiniBooNE, BEST?) have not yet been confirmed or disproven. SBL oscillation experiments (SBN, reactor neutrino exp, BEST…) are testing them and will provide a definitive (???) answer by the end of this decade.



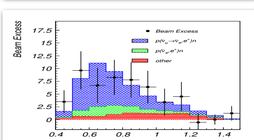
reactor flux anomaly
resolved with new input data to flux calculation ✓



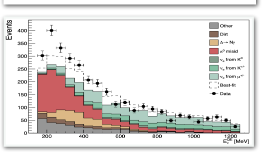
reactor spectra
is there really an anomaly? ?



gallium anomaly
unresolved, recently reinforced ?

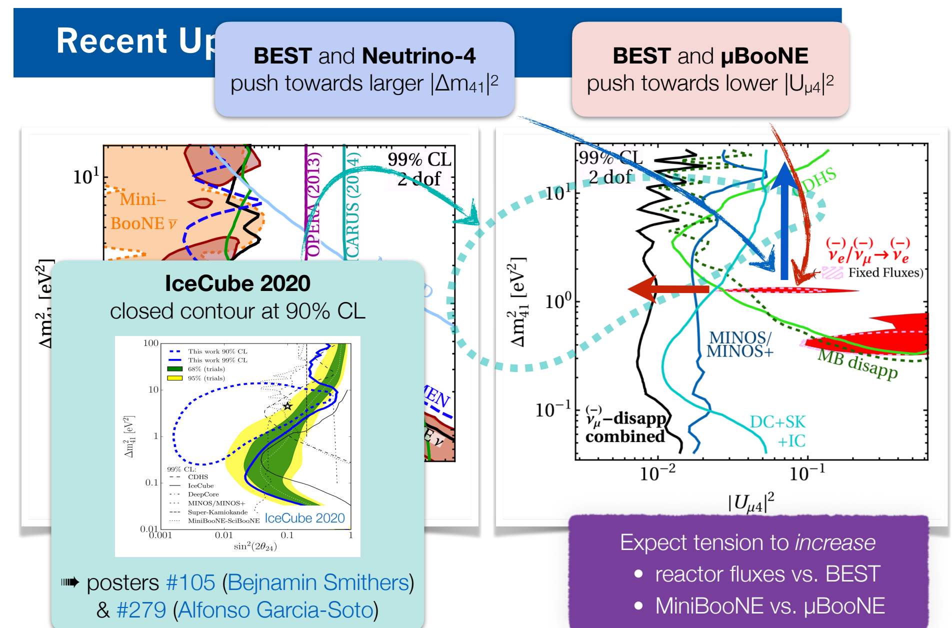


LSND
unresolved ?



MiniBooNE
unresolved ?

See J. Kopp's talk at Neutrino 2022



The discovery of any signature beyond 3-neutrinos, would be game-changing for experiments and theory. Need to continue the search even for negative results.

Conclusions

- **Neutrino oscillations imply that neutrinos have mass and mix: First particle physics evidence of physics beyond the SM.** They provide a complementary window w.r.t. collider and flavour physics searches.

- The ultimate goal is to understand the origin of neutrino masses and leptonic mixing.

- By the end of the planned LBL programme, it is likely that some questions will remain open.

Question	By ~2040	Caveats
Neutrino mass ordering	Yes	Increasing significance and discovery
Delta CPV	Likely?	Depends on value of delta
Precision in oscillation parameters	Some	t23 and delta with still some uncertainty
Sterile nus, NSIs, and other B3nu	Maybe	Surprises in store?
DSs: dark photons, HNLs,…	Maybe	Surprises in store?
Baryon asymmetry	Not really	Some hints if LNV and CPV