Neutrino oscillation physics

08 October 2020

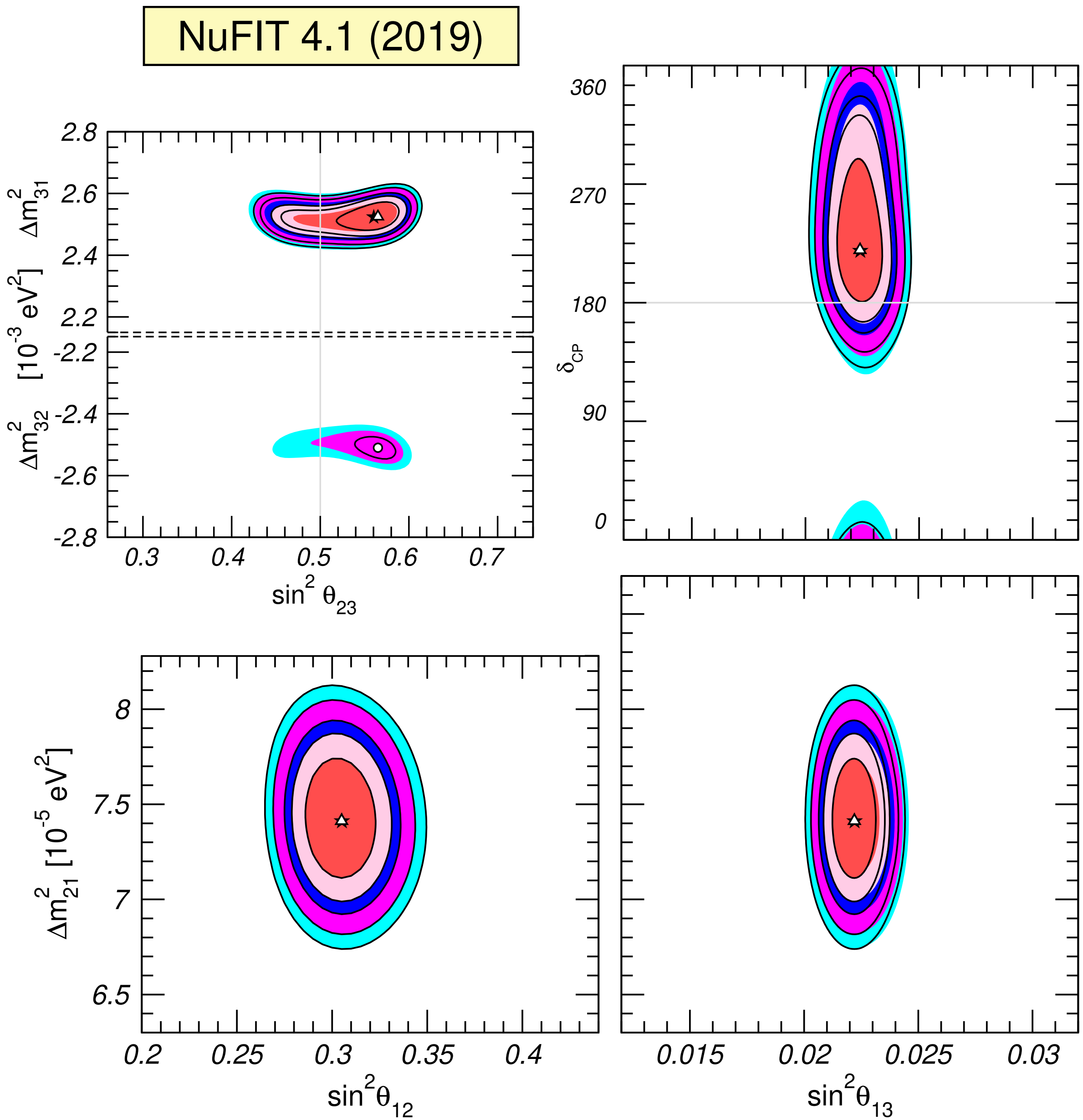
ESSnuSB Workshop
UHH - Barenfeld - DESY

Silvia Pascoli

IPPP – Durham University

T2K event

Neutrino properties after July 2019



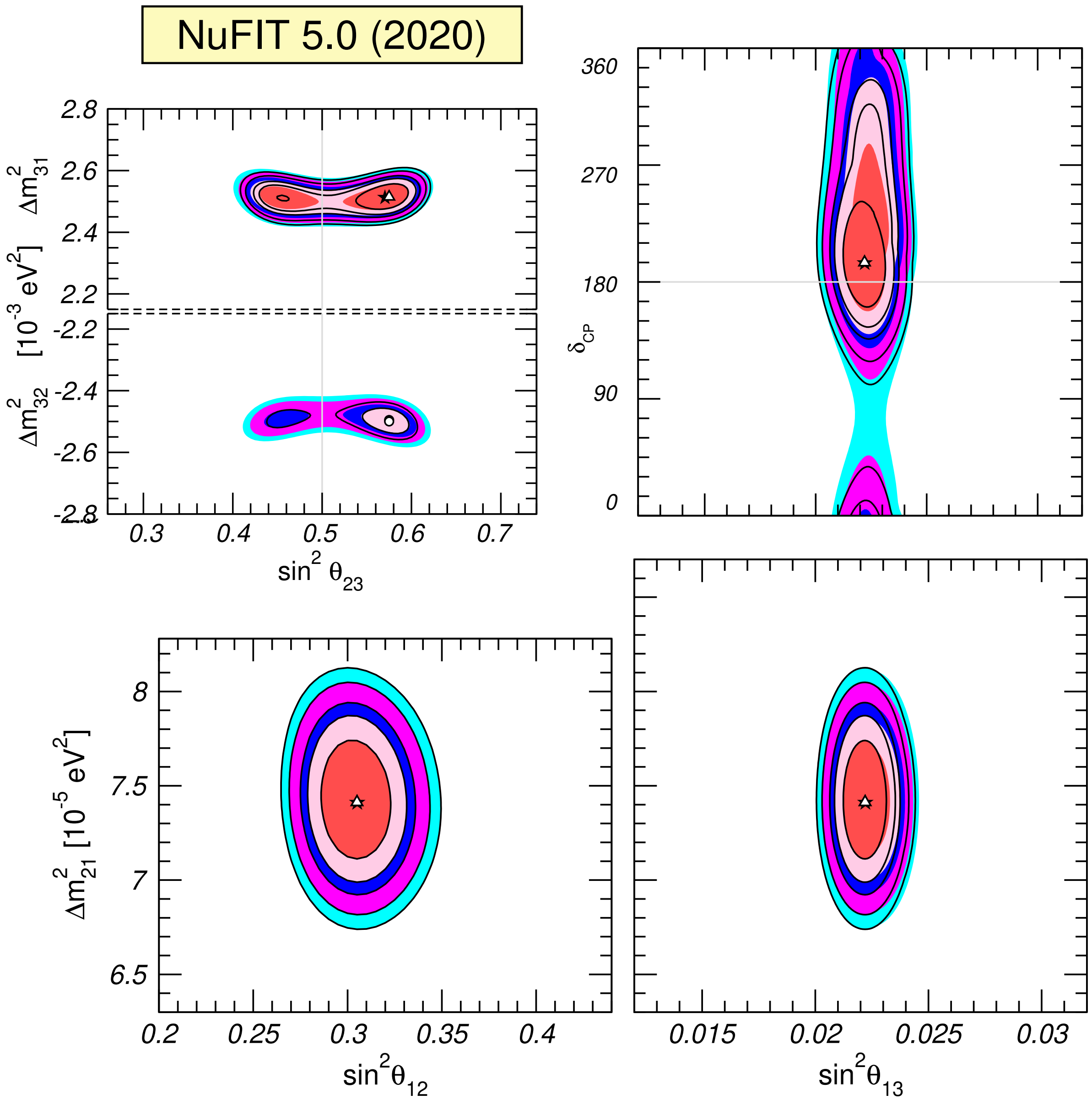
Neutrinos have masses and mix!

Current knowledge of neutrino properties:

- 2 mass squared differences
- 3 sizable mixing angles,
- hints of CPV
- indications in favour of NO

http://www.nu-fit.org/ M. C. Gonzalez-Garcia et al., 1811.05487

Neutrino properties after July 2020



Neutrinos have masses and mix!

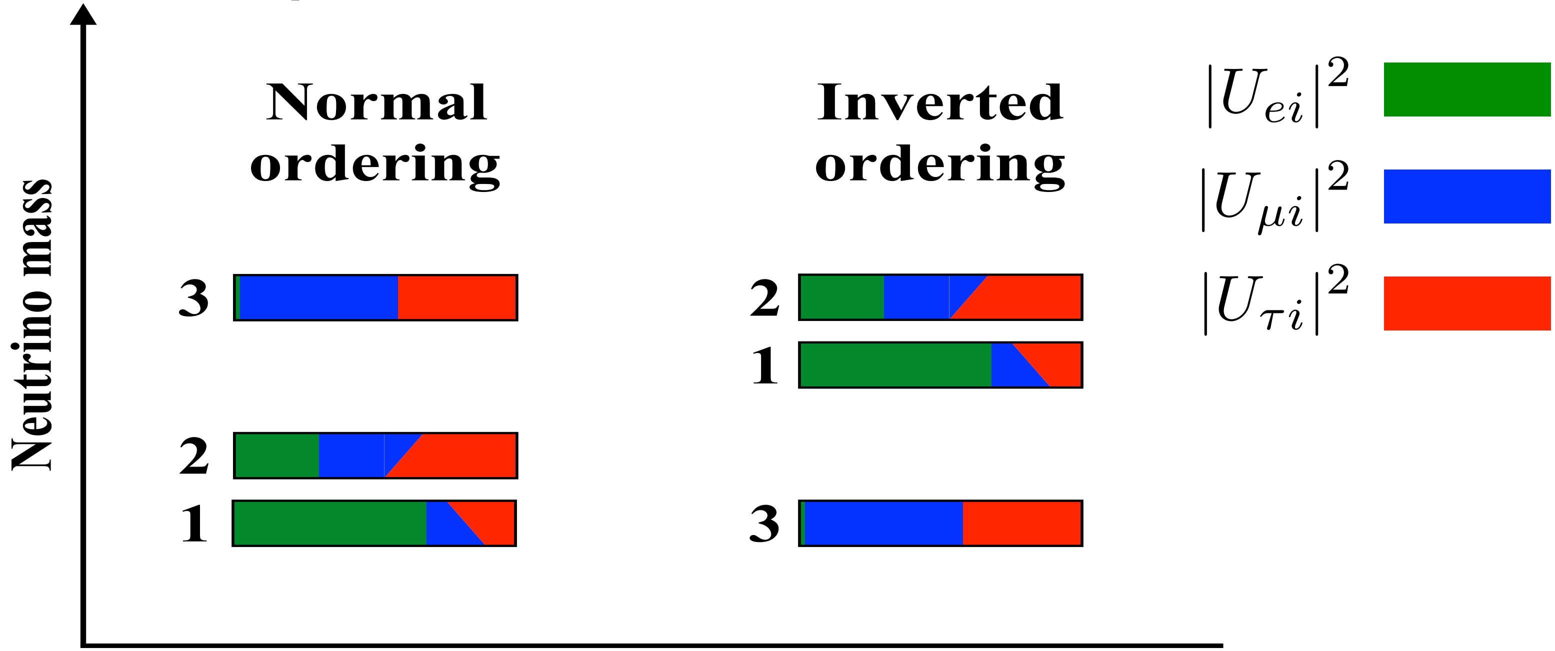
Current knowledge of neutrino properties:

- 2 mass squared differences
- 3 sizable mixing angles,
- some hints of CPV
- preference for NO

http://www.nu-fit.org/ I. Esteban et al., 2007.14792

Neutrino masses

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



Fractional flavour content of massive neutrinos

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

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

Measuring the masses requires:

- the mass scale: $m_{\min}$
- 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

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

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

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.

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?

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

Very exciting experimental programme now and for the future.

Phenomenology questions for the future

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Long baseline neutrino oscillation experiments

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

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Neutrino oscillations

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

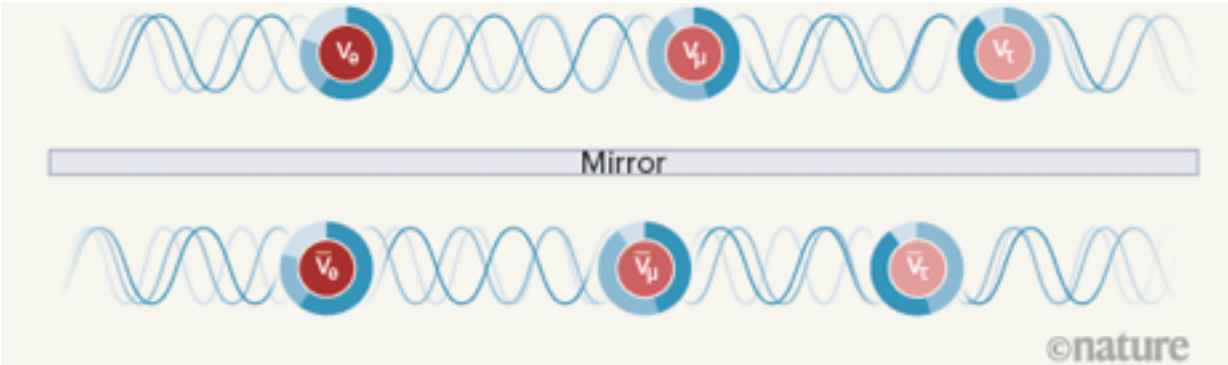
$$|\nu, t=0\rangle = |\nu_\mu\rangle = \sum_i U_{\mu i} |\nu_i\rangle$$

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 :

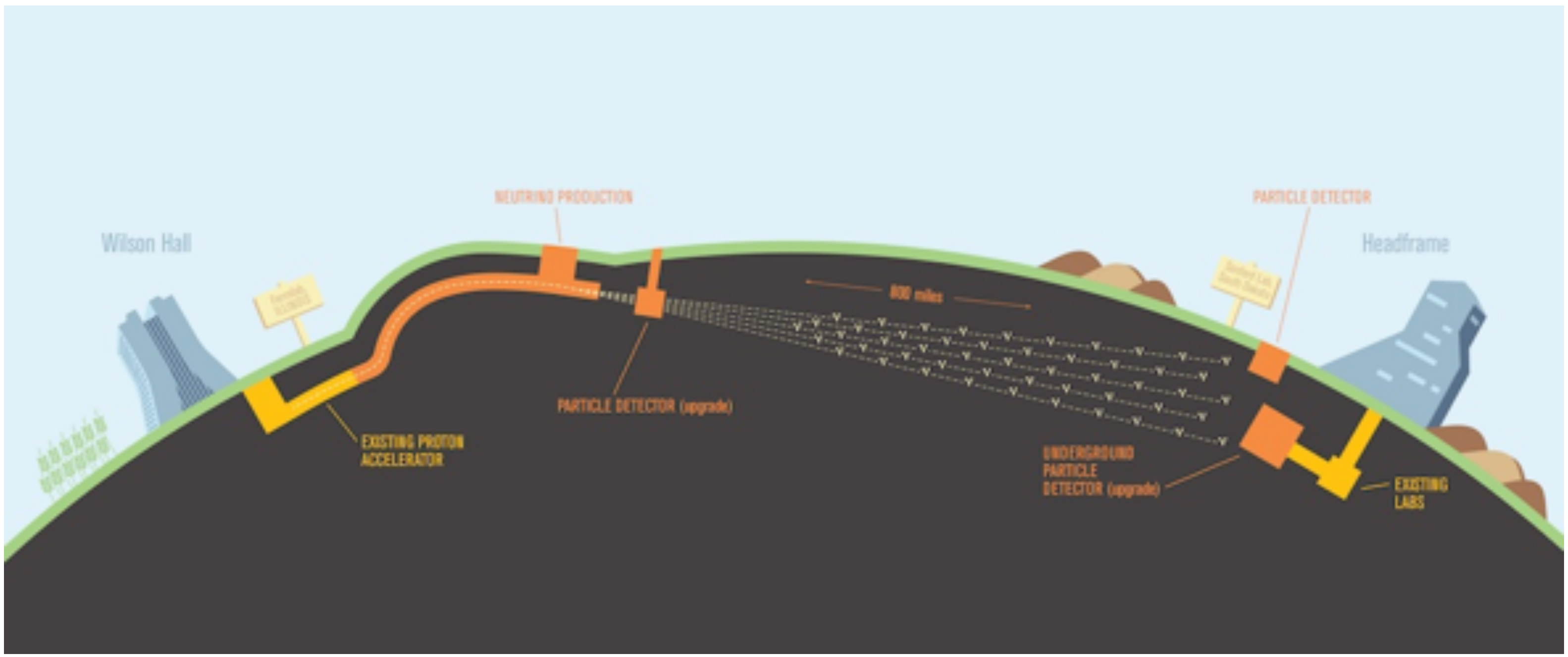
$$P(\nu_\alpha \to \nu_\beta) \quad = \quad \left| \sum_i U_{\alpha 1} U^*_{\beta 1} e^{-i \frac{\Delta m^2_{i1}}{2E} L} \right|^2 \overset{2\nu}{=} \sin^2 2\theta \ \sin^2 \frac{\Delta m^2 L}{4 E_\nu}$$



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

Long-baseline neutrino oscillations and the mass ordering

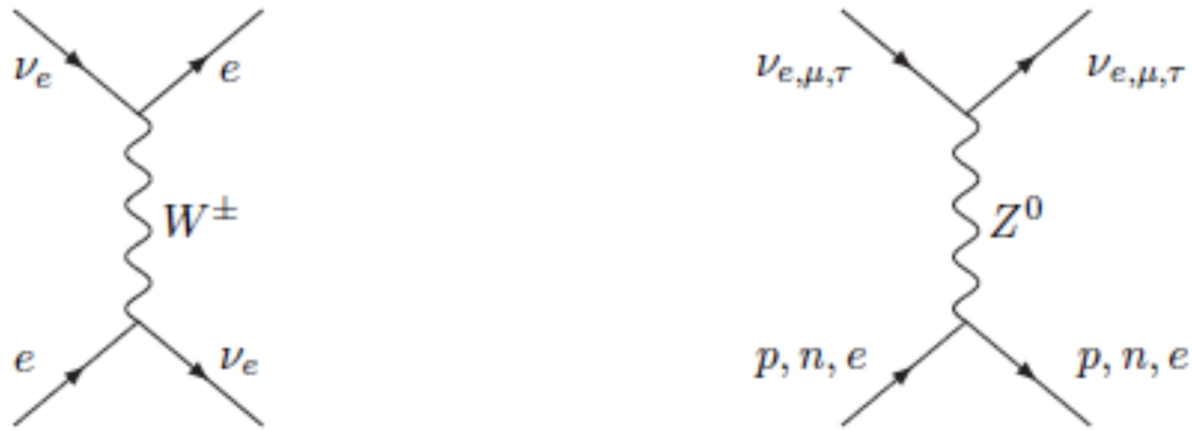
- When neutrinos travel through a medium, they interact with the background of e, p and n.



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.

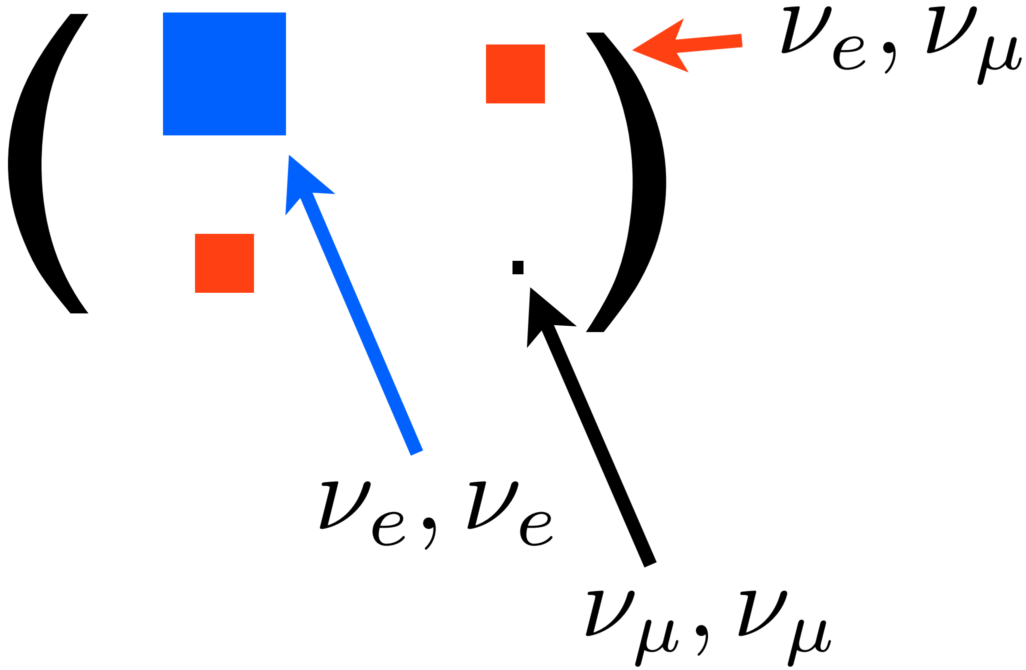
- Neutrinos undergo forward elastic scattering via CC and NC interactions.



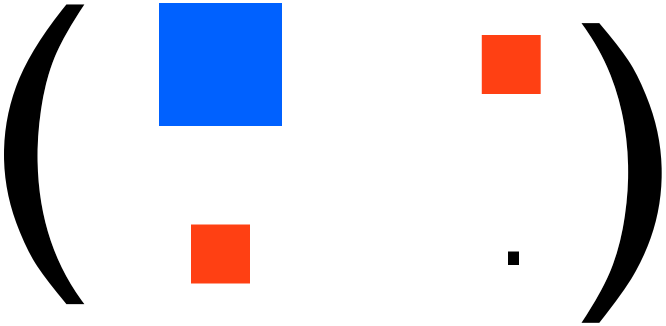
- Matter effects are described by a potential V in the effective Hamiltonian which determines the time evolution.

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

Effective Hamiltonian in the flavour basis

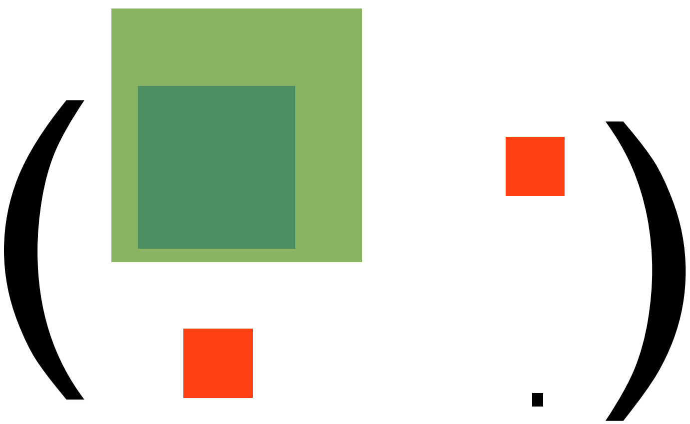


Effective Hamiltonian	Mixing angle



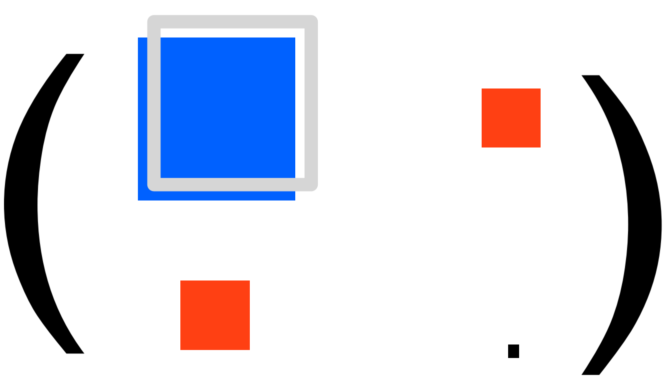
vacuum

$$\tan 2\theta \sim \frac{2\,\square}{\square}$$



matter suppression (Sun, SN)

$$\tan 2\theta^M \sim \frac{2\,\square}{\square + \square} \ll \tan 2\theta$$



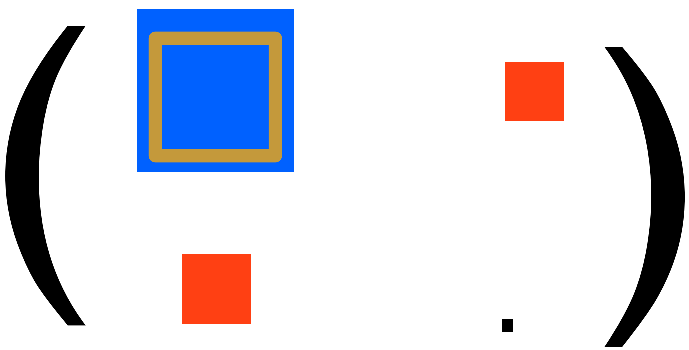
MSW resonance (Sun, SN)

$$\tan 2\theta^M \sim \frac{2\,\square}{\square - \square} \sim \infty$$

In long baseline experiments

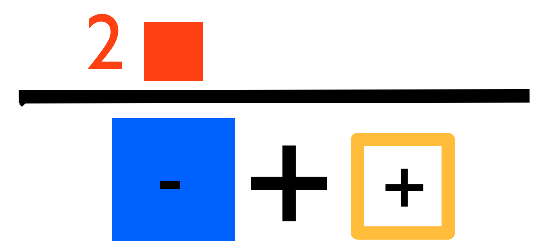
 $-\frac{\Delta m^2}{2E}\cos(2\theta)$ ν $+\sqrt{2}G_F N_e$ $\bar{\nu}$ $-\sqrt{2}G_F N_e$

For neutrinos

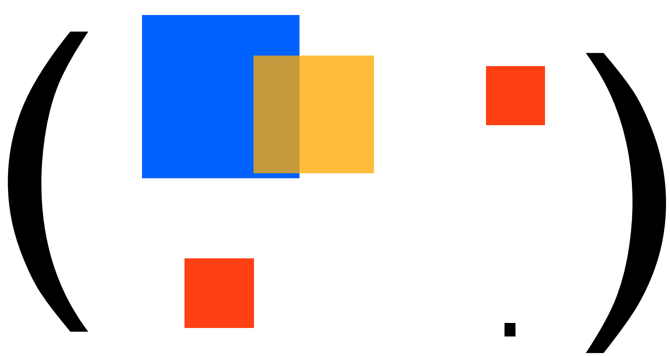


$\Delta m^2 > 0$ enhancement

$\tan 2\theta^M \sim$

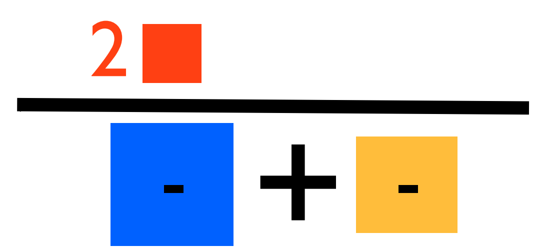


For antineutrinos



$\Delta m^2 > 0$ suppression

$\tan 2\theta^M \sim$



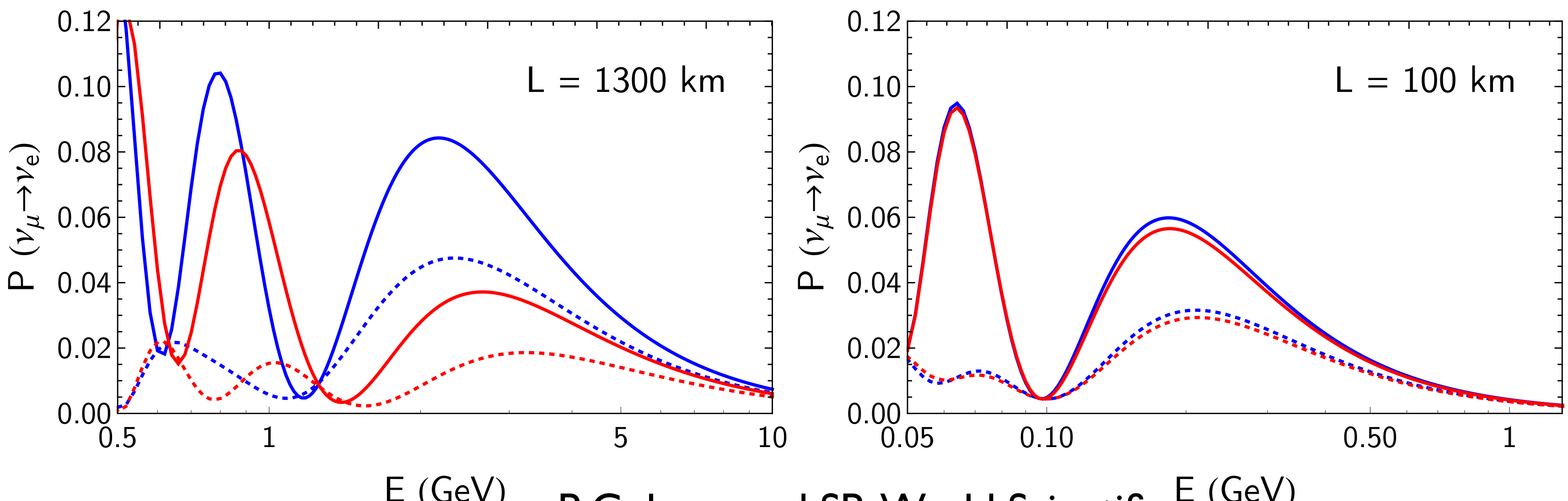
The 3 neutrino probability can be approximated as

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…

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

with

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



P. Coloma and SP, World Scientific

Long-baseline neutrino oscillations and leptonic CP violation

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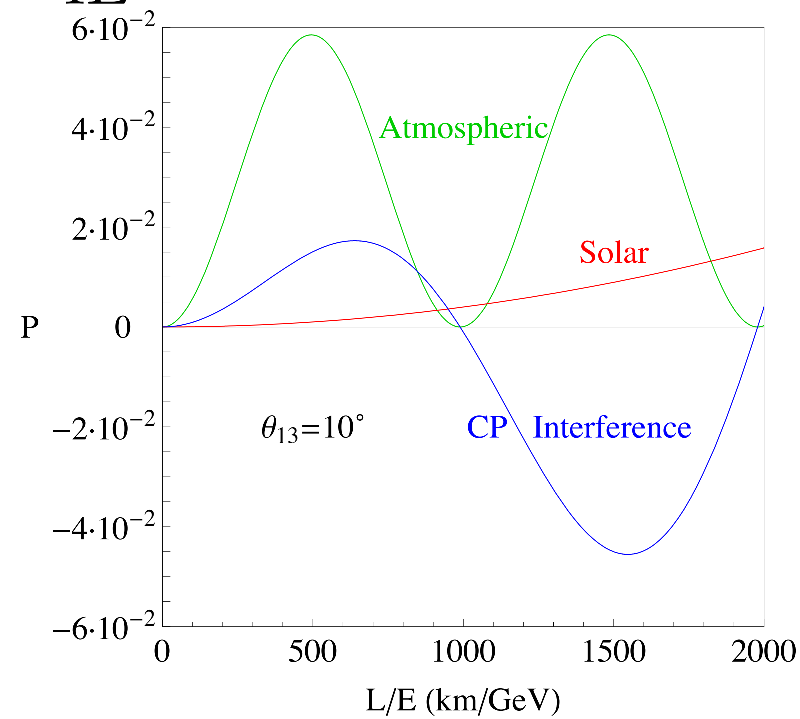
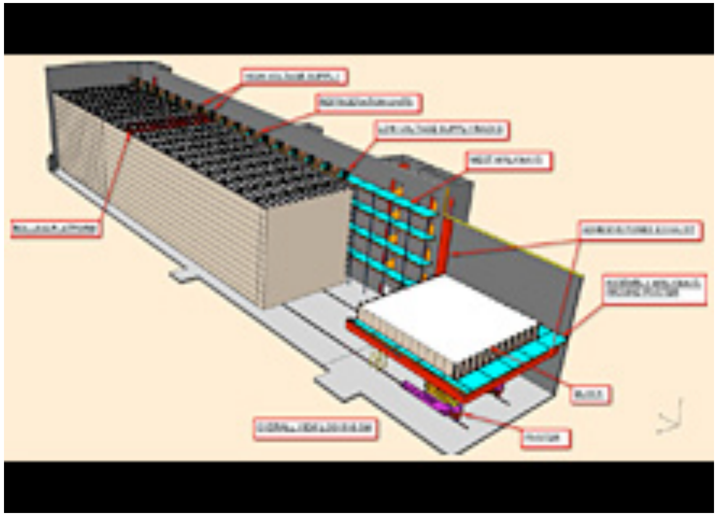
A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773...

- The 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

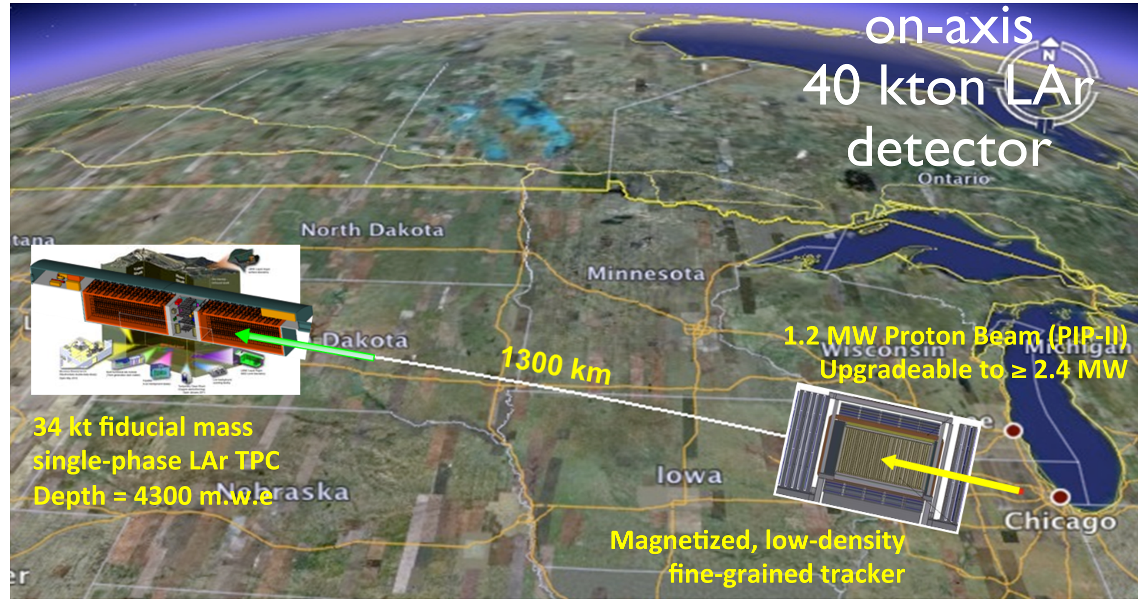
Present/Future LBL exp

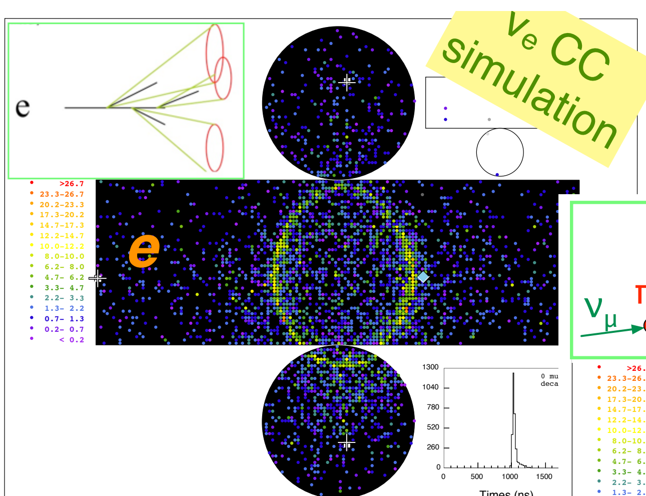


NOvA: 810 km off-axis
~14 kton plastic scintillator detector

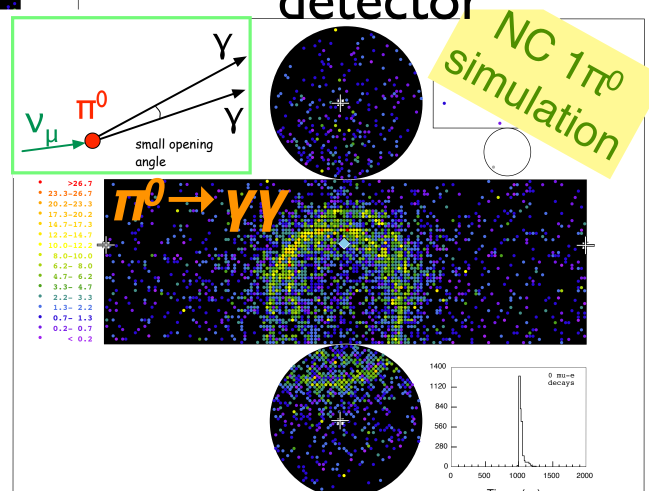
T2K: 295 km off-axis
~22.5 kton WC detector

DUNE: 1300 km on-axis
40 kton LAr detector

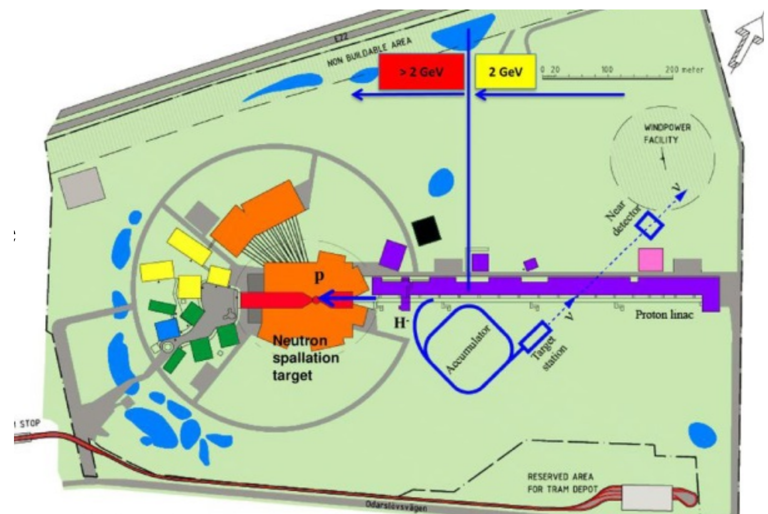




T2HK: 295 km off-axis
~1 Mton WC detector



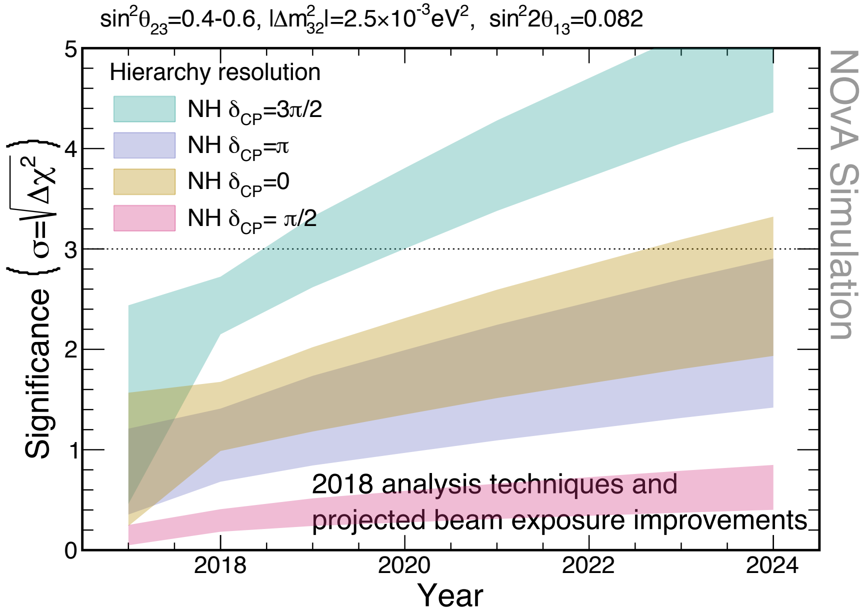
M. Shiozawa, for T2HK coll., NuPhys 2014



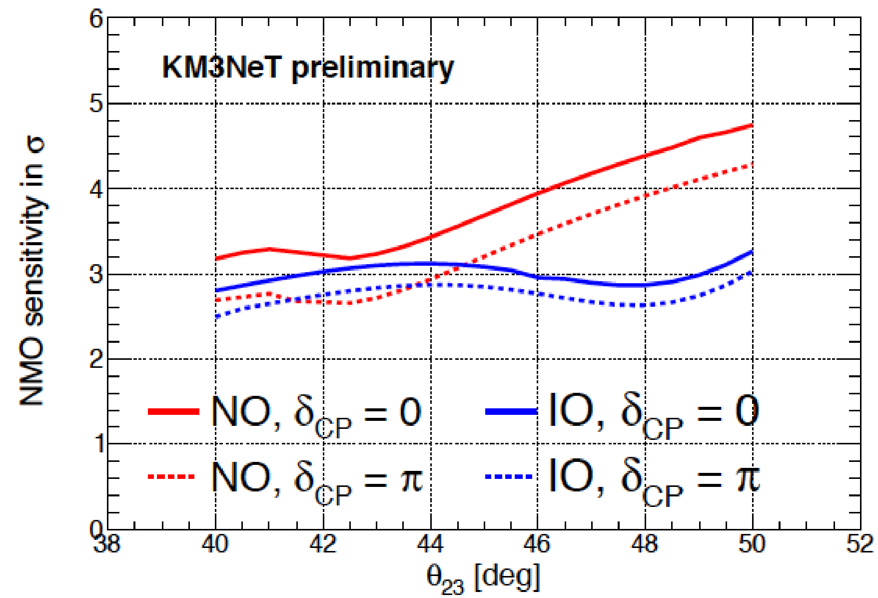
~1 BEuros for the neutrino facility including detector

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

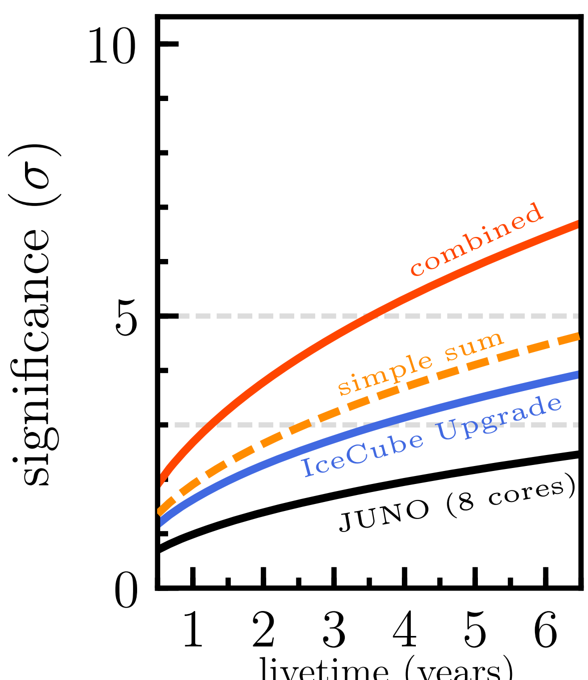
Mass ordering sensitivity



M. Sanchez, Neutrino 2018

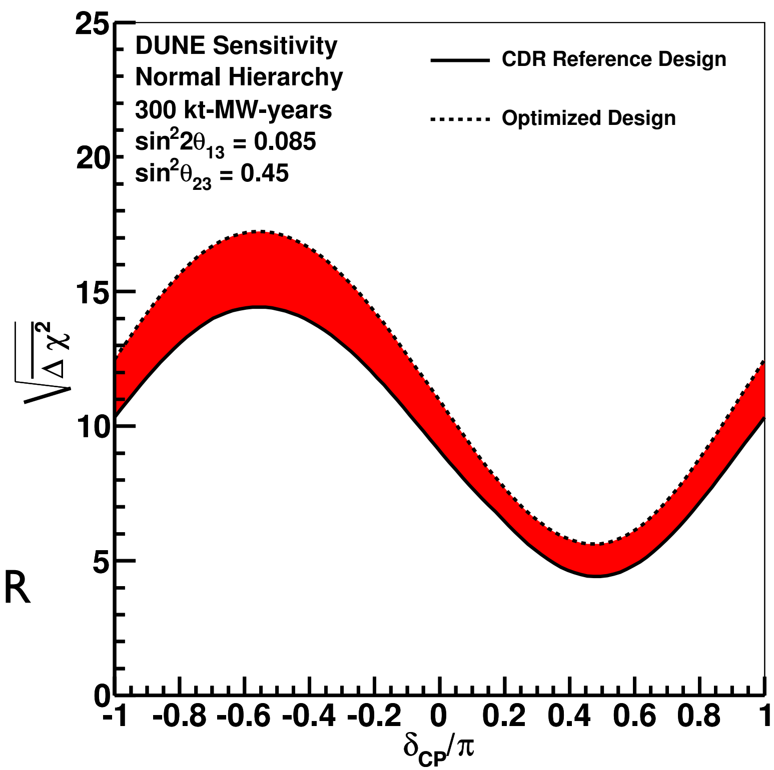


KM3Net, ORCA Coll., 2004.05004

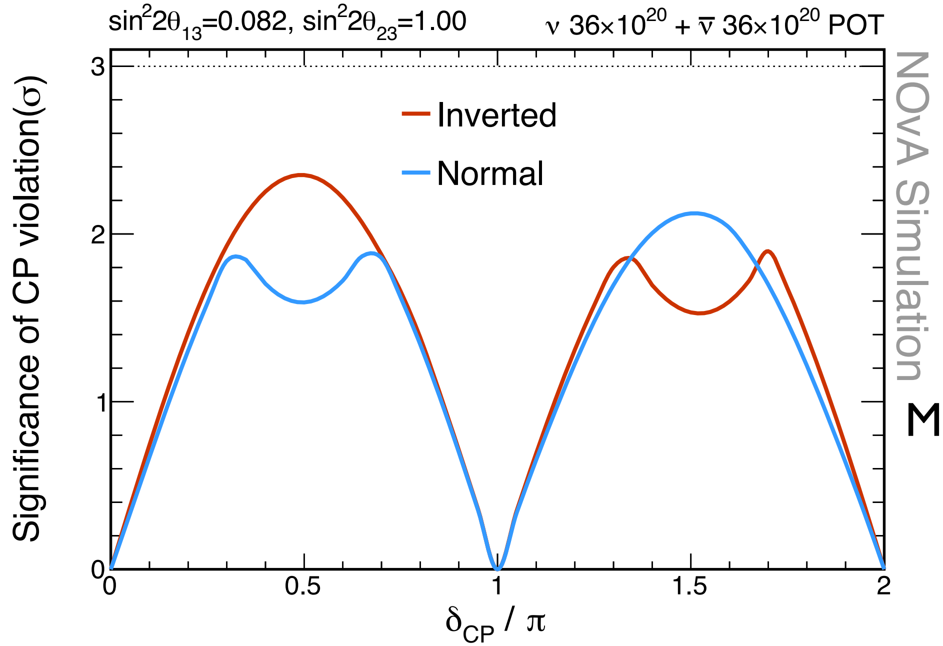


JUNO+PINGU, PRD101 (2020)

DUNE CDR



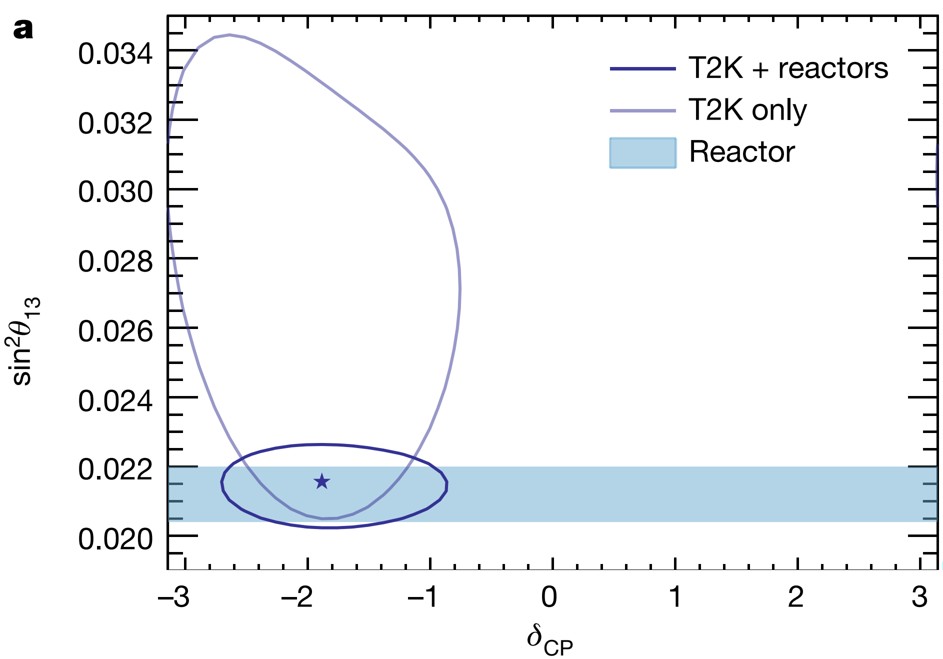
CPV sensitivity



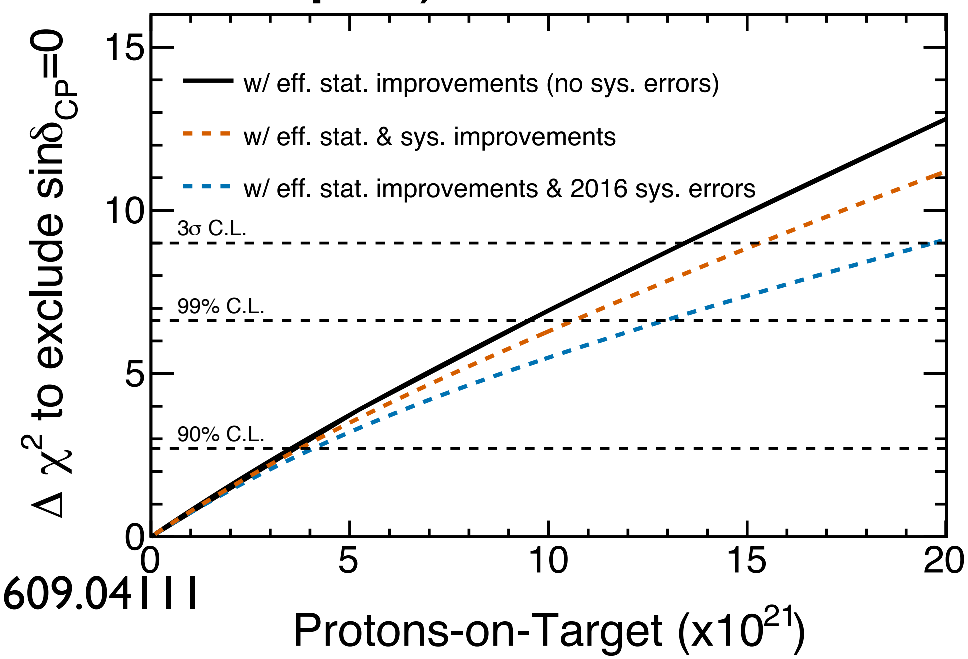
NOvA plans an extended run till 2024 (50% nu, 50% antinu) with further accelerator improvements.

M. Sanchez, Neutrino 2018

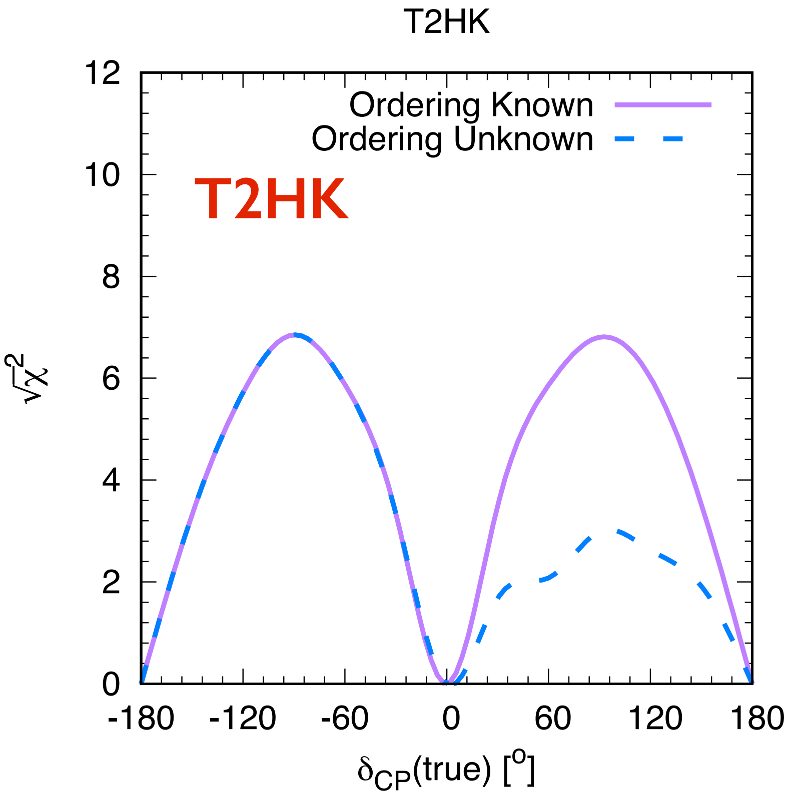
T2K phase 2 extension aims at reaching 1.3 MW by 2026 (20x10^21pot).

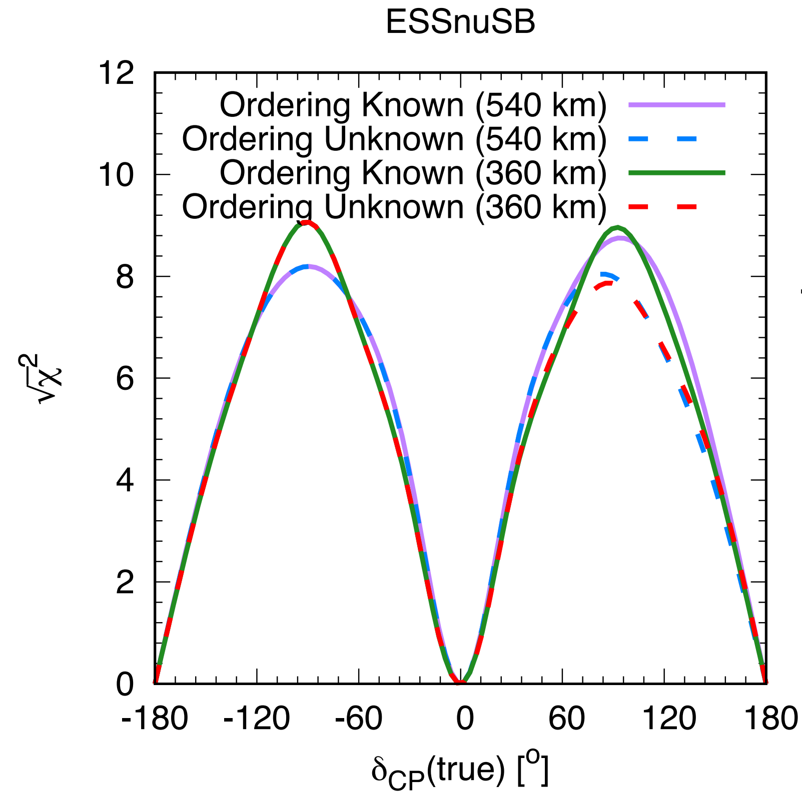


T2K Coll., Nature 580 (2020)



T2K, 1609.04111

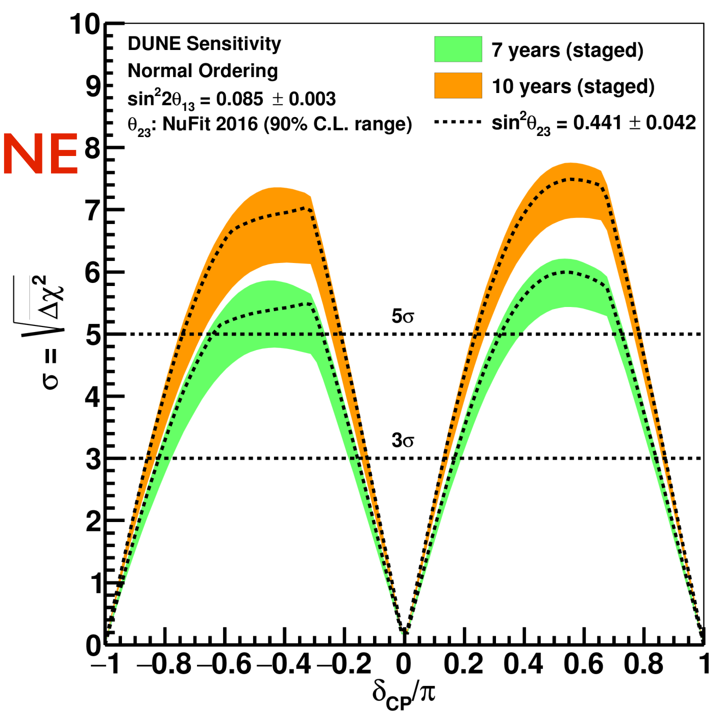


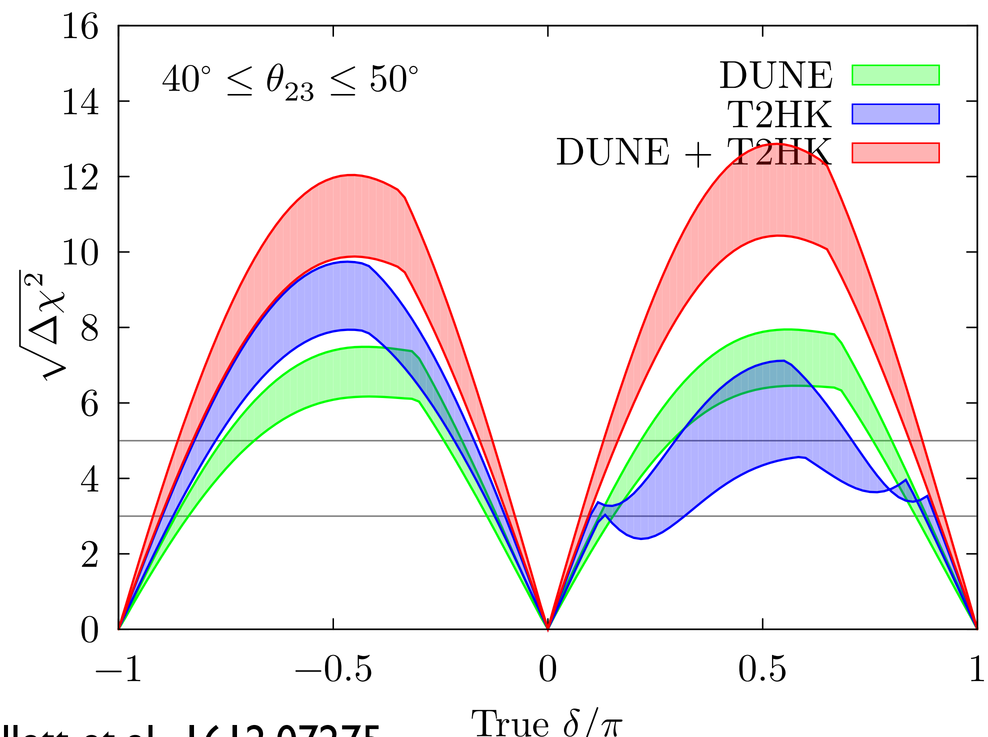


ESSnuSB

M. Ghosh and T. Ohlsson, 1906.05779

DUNE





E. Worcester, for DUNE, Neutrino 2018

Ballett et al., 1612.07275

Precision measurements of the oscillation parameters in LBL experiments

The precision measurement of the oscillation parameters is a primary physics goal for LBL experiments.

- 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.

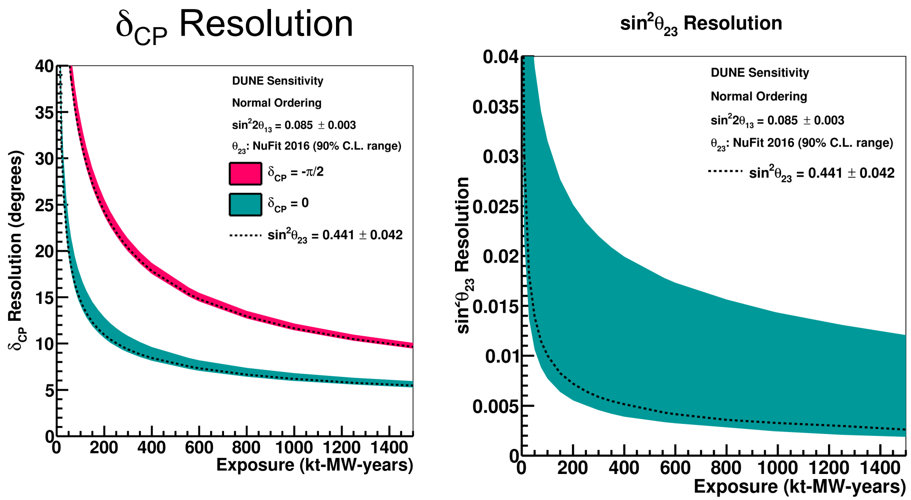
- Predictions for the CPV phase delta and relations among parameters in flavour models (e.g. sum rules), e.g.:

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

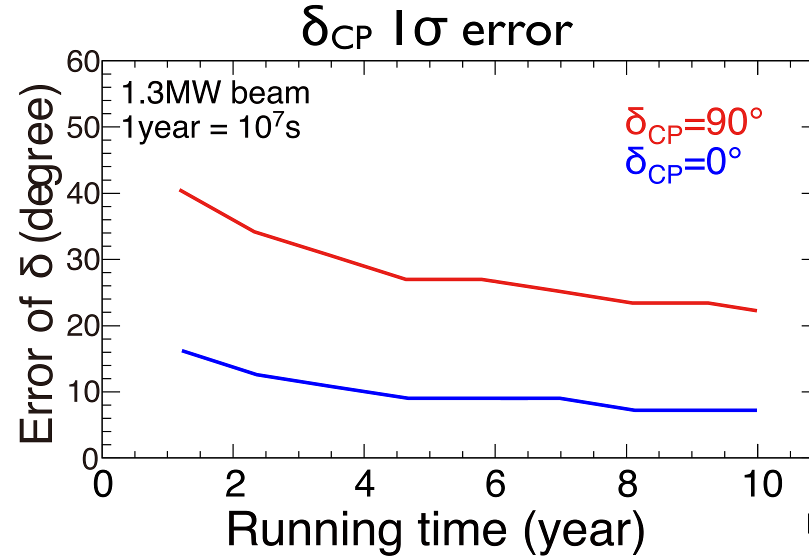
with $\sin\theta_{12} = \frac{1+s}{\sqrt{3}}, \quad \sin\theta_{13} = \frac{r}{\sqrt{2}}, \quad \sin\theta_{23} = \frac{1+a}{\sqrt{2}}$ King, 0710.0530

Crucial information in order to discriminate between different flavour models.

DUNE CDR:



E. Worcester, for DUNE, Neutrino 2018



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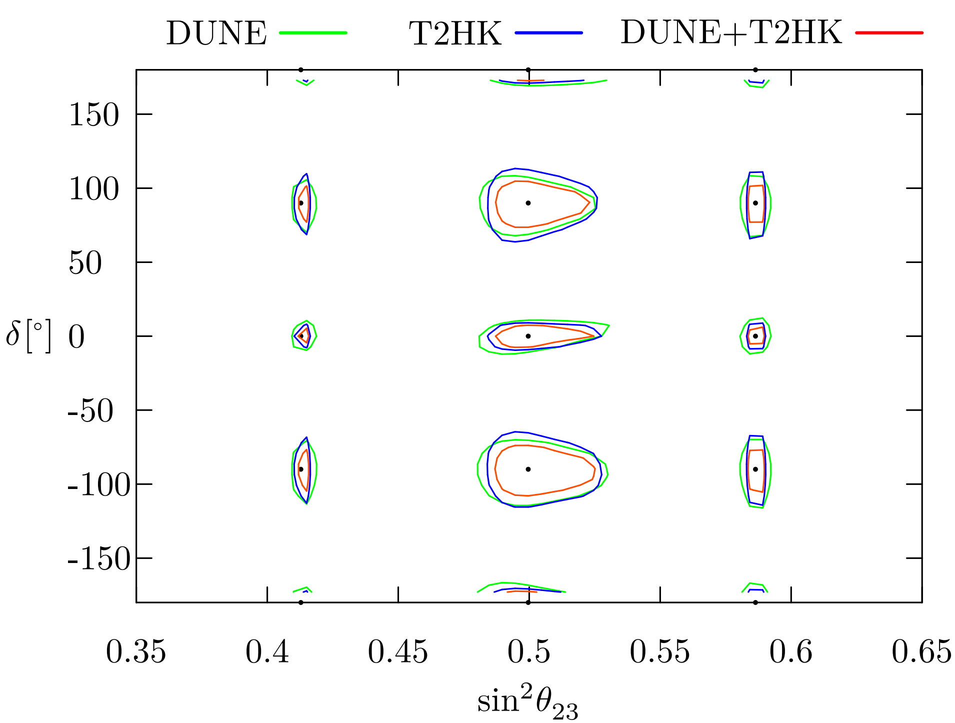
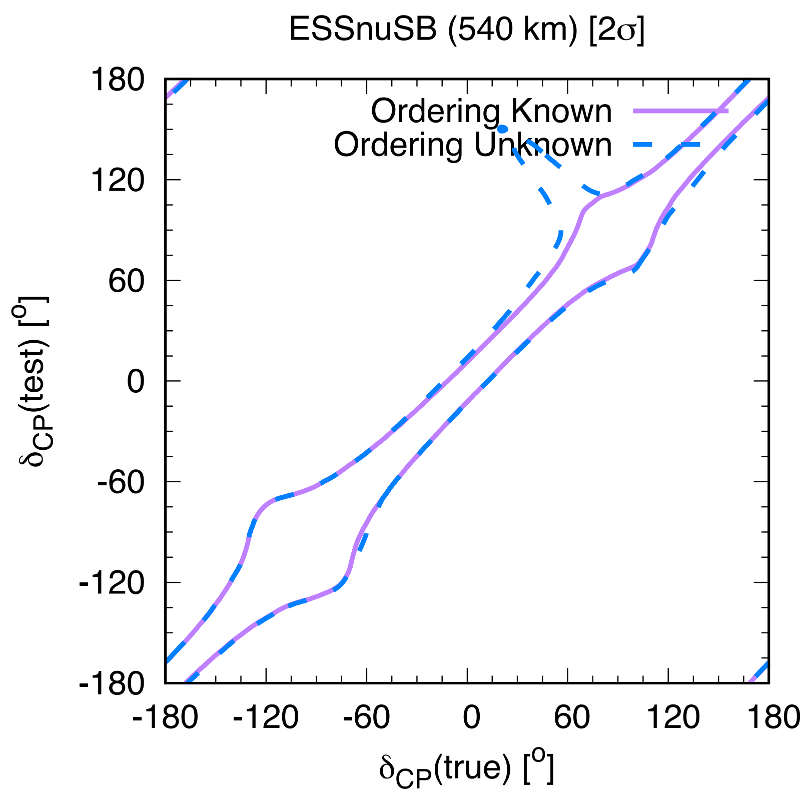
M. Shiozawa, for HK, Neutrino 2018



Ballett et al., 1612.07275



M. Ghosh and T. Ohlsson, 1906.05779

Complementarity with other experiments

2020 — 2025 — 2030 — 2035

LBL osc.
- T2K
- NOvA
- LBNF-DUNE
- T2HK (T2HKK)
- ESSnuSB,
- nufactory?

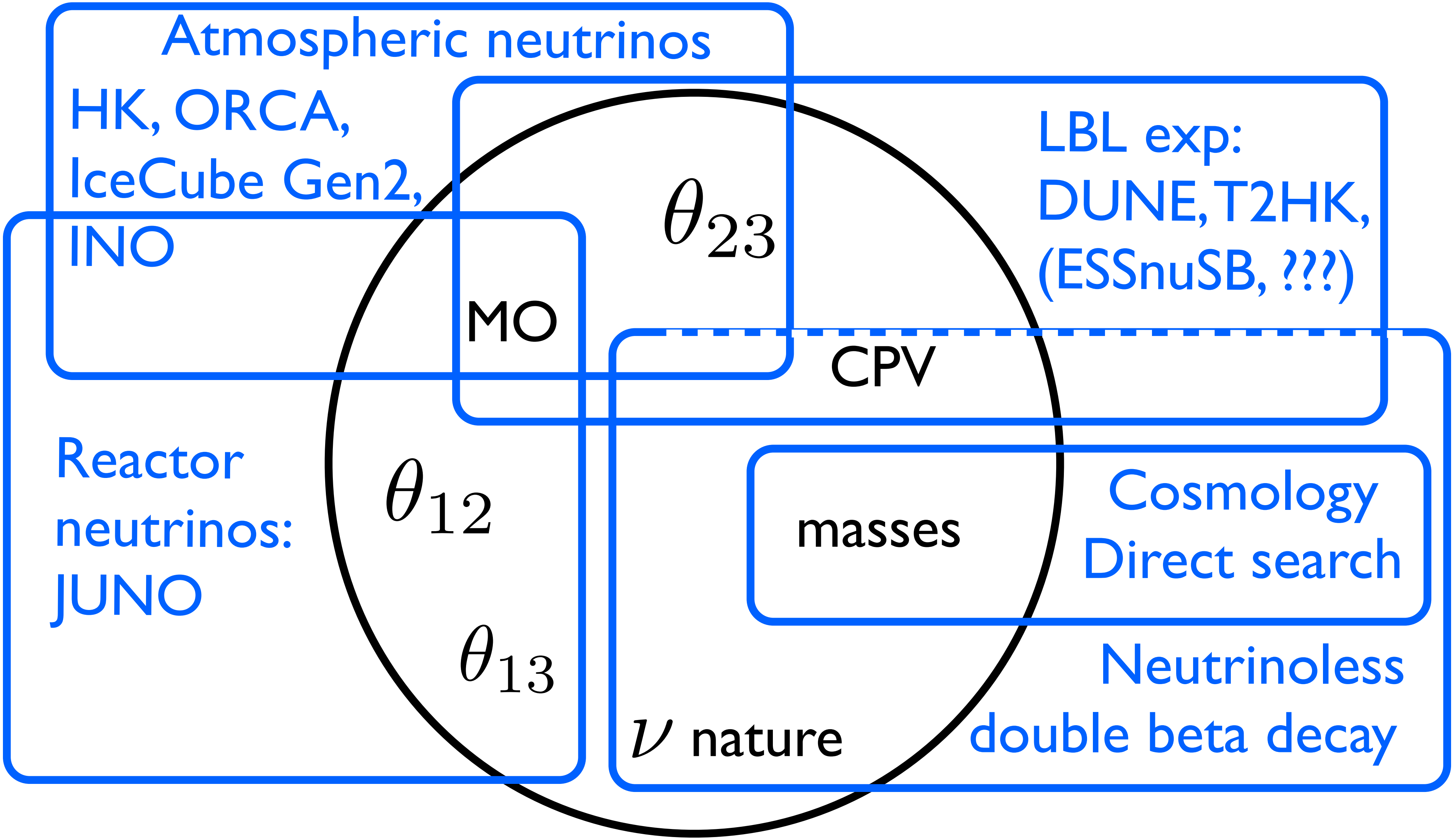
SBL osc.
- SBL reactor,...
- MicroBooNE
- SBN
- LBNF-DUNE ND
- T2HK ND
- ???

Other osc.
- SK, Borexino,
- LBL detectors
- JUNO
- DUNE
- HK
- Theia???

Direct mass
- KATRIN
- Project 8

DBD0 nu
- KamLAND-Zen
- GERDA, CUORE
- LEGEND-200
- NEXT-100, nEXO...
- LEGEND-1000
- CUPID, NEXT-HD,
- PANDAX...
- Next-next gen?

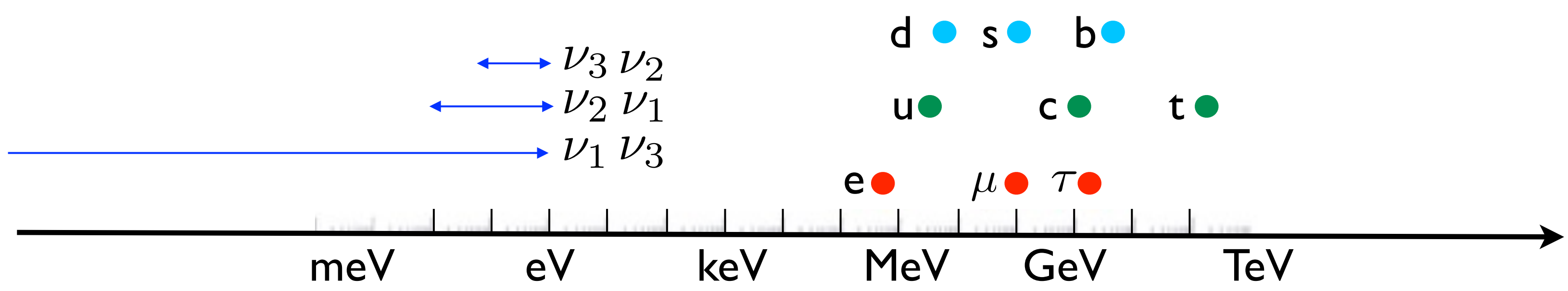
UHE
- IceCube
- IceCubeGen2
- ORCA, KM3Net



Tests of standard neutrino paradigm: SBL oscillations (SBN, reactor exp), LBL/atm oscillations, neutrino less DBD, beta decays, cosmology (BBN, CMB, LSS), dedicated searches.

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.

- It is necessary to known the values of the masses and of the mixing angles and CPV phase (with precision!). An exciting experimental programme is under way.