Physics goals of long baseline neutrino oscillation experiments

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Neutrino GDR
APC Paris

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Outline

1. **Present status of neutrino parameters**

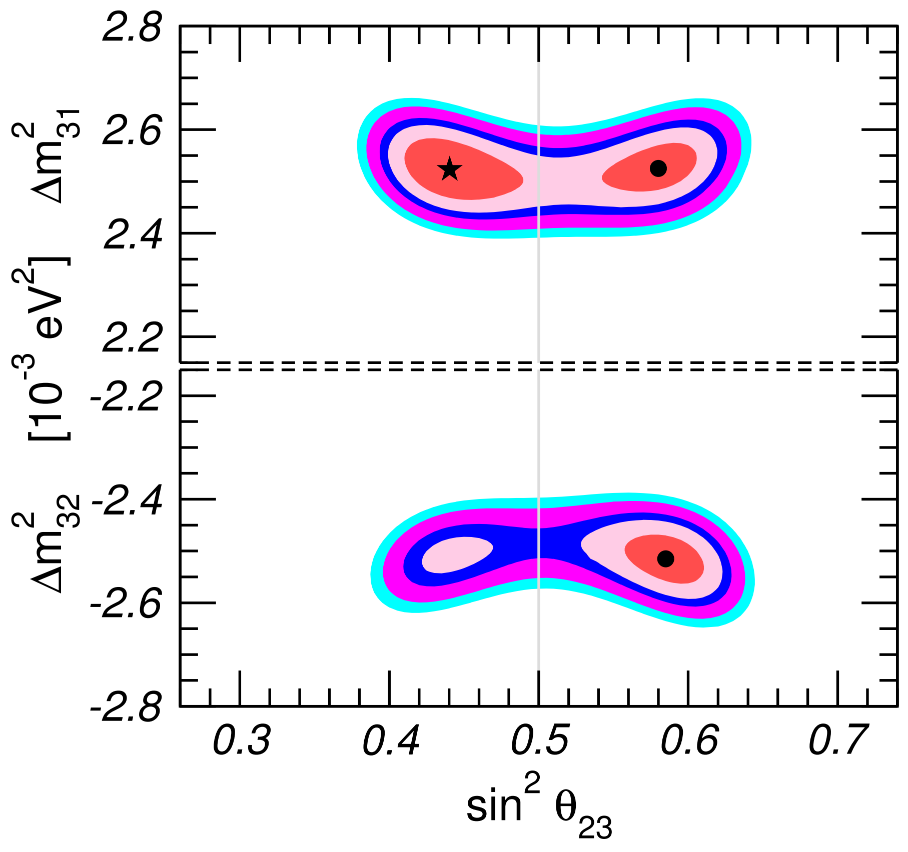
2. **LBL oscillation experiments physics goals. Bread and butter physics**
    - **Mass ordering**
    - **Leptonic CP-violation**
    - **Precision measurement of parameters**

3. **LBL oscillation experiments physics goals. Testing the 3-neutrino scenario**

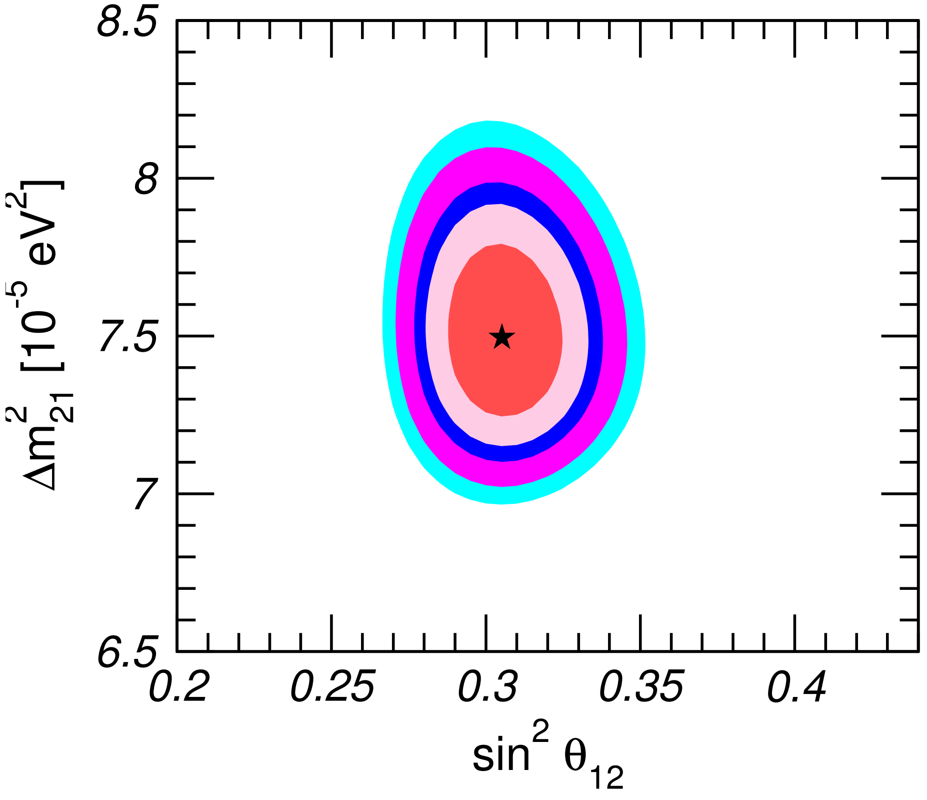
4. **LBL oscillation experiments physics goals. As a beam-dump experiment**

5. **Conclusions**

Current status of neutrino parameters



	Normal Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$
$\delta_{\mathrm{CP}}/^\circ$	234^{+43}_{-31}	$144 \to 374$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$



NuFit 3.0: M. C. Gonzalez-Garcia et al., 1611.01514, Pre-Neutrino 2018

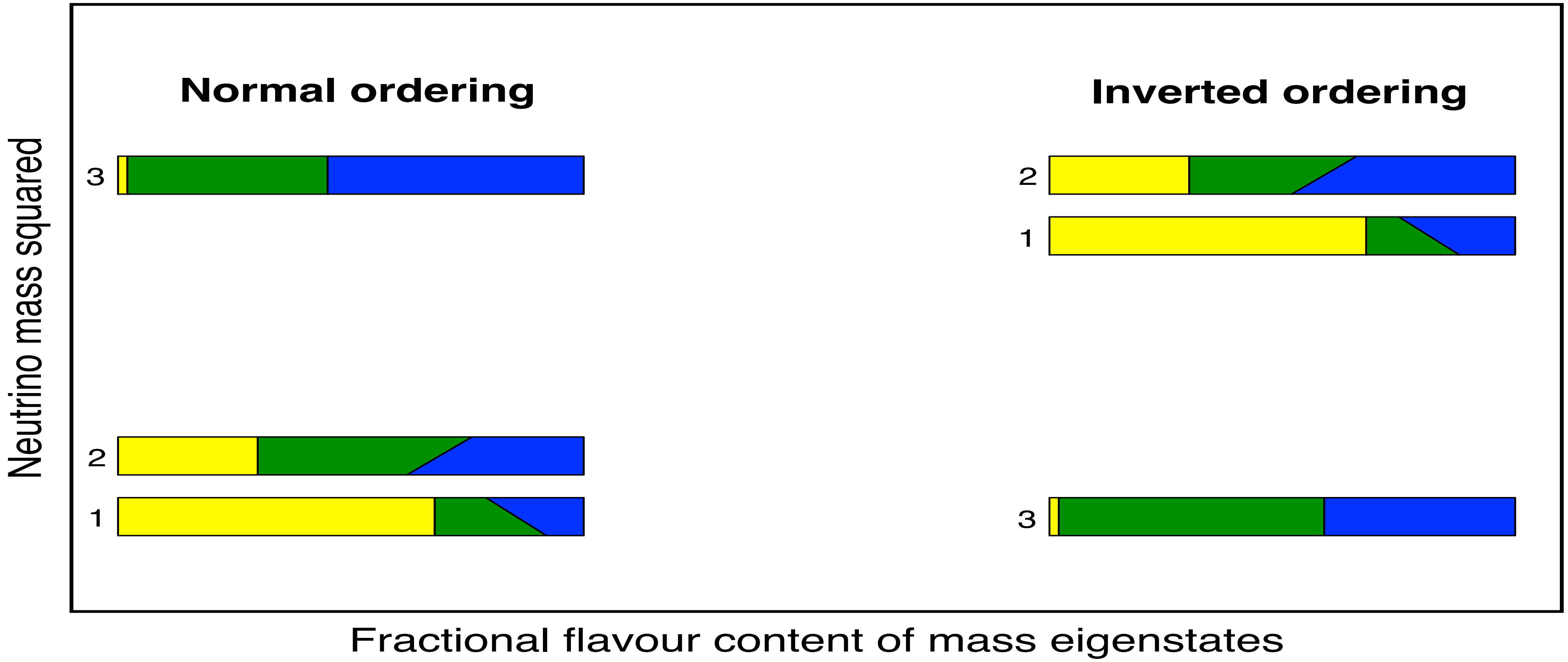
Global fit to neutrino oscillation data

See also F. Capozzi et al., 1703.04471

2 mass squared differences (one is positive, the sign of the other is unknown)

Neutrino masses

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



$$m_1 = m_\text{min} \qquad m_3 = m_\text{min}$$

$$m_2 = \sqrt{m_\text{min}^2 + \Delta m_\text{sol}^2} \qquad m_1 = \sqrt{m_\text{min}^2 + |\Delta m_\text{A}^2| - \Delta m_\text{sol}^2/2}$$

$$m_3 = \sqrt{m_\text{min}^2 + \Delta m_\text{A}^2 + \Delta m_\text{sol}^2/2} \qquad m_1 = \sqrt{m_\text{min}^2 + |\Delta m_\text{A}^2| + \Delta m_\text{sol}^2/2}$$

Measuring the masses requires:

- the mass scale: m_min
- the mass ordering. Currently there is a hint in favour of NO based mainly on atmospheric and LBL events.

NOvA

Prefers Normal Hierarchy at 1.8 σ

F. Capozzi et al., 1703.04471; See also SK, talks at ICHEP 2016 and NOW 2016, Neutrino 2018

Mixing and CP-violation

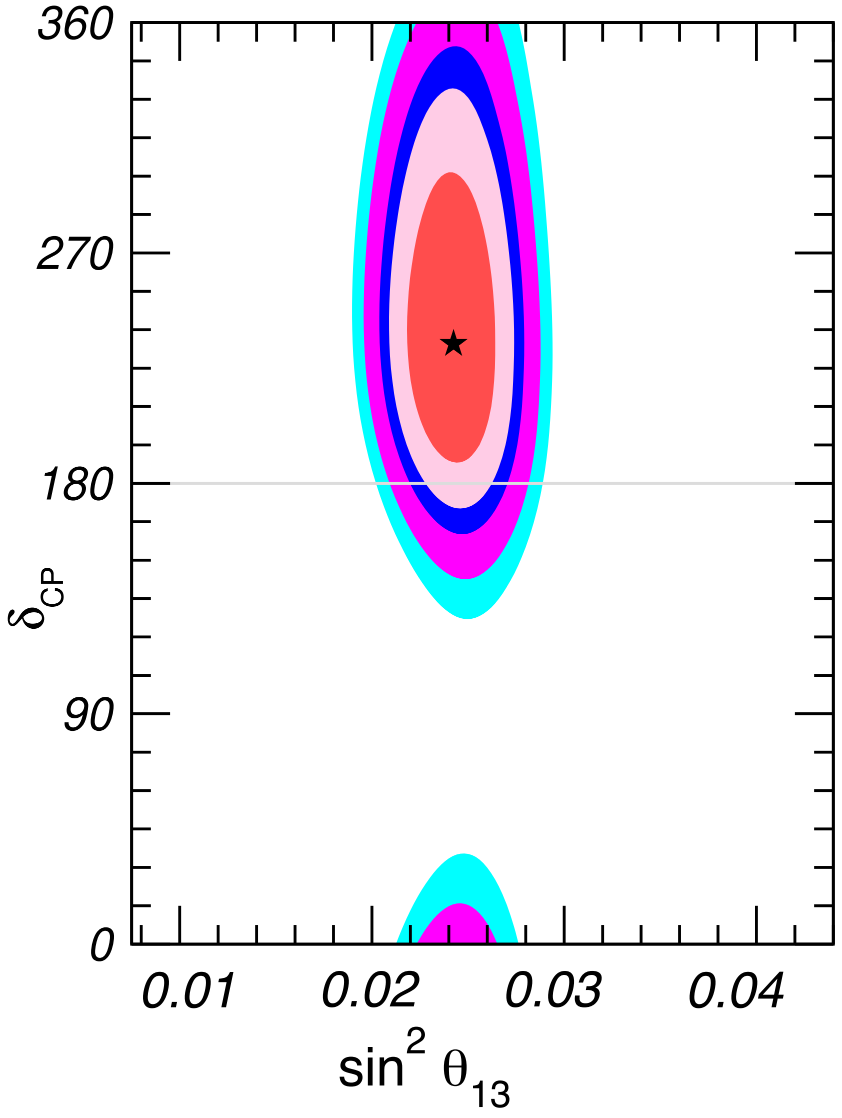
The Pontecorvo-Maki-Nakagawa-Sakata matrix

CPV?

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

- θ_{23} maximal or close to maximal
- θ_{12} significantly different from maximal
- θ_{13} quite large: challenge to flavour models
- Mixings very different from quark sector
- Possibly, large CPV. CPV is a fundamental question, possibly related to the origin of the baryon asymmetry and to the origin of the flavour structure

Hints for CP violation?



M. C. Gonzalez-Garcia et al., NuFit, 1611.01514
Pre-Neutrino 2018

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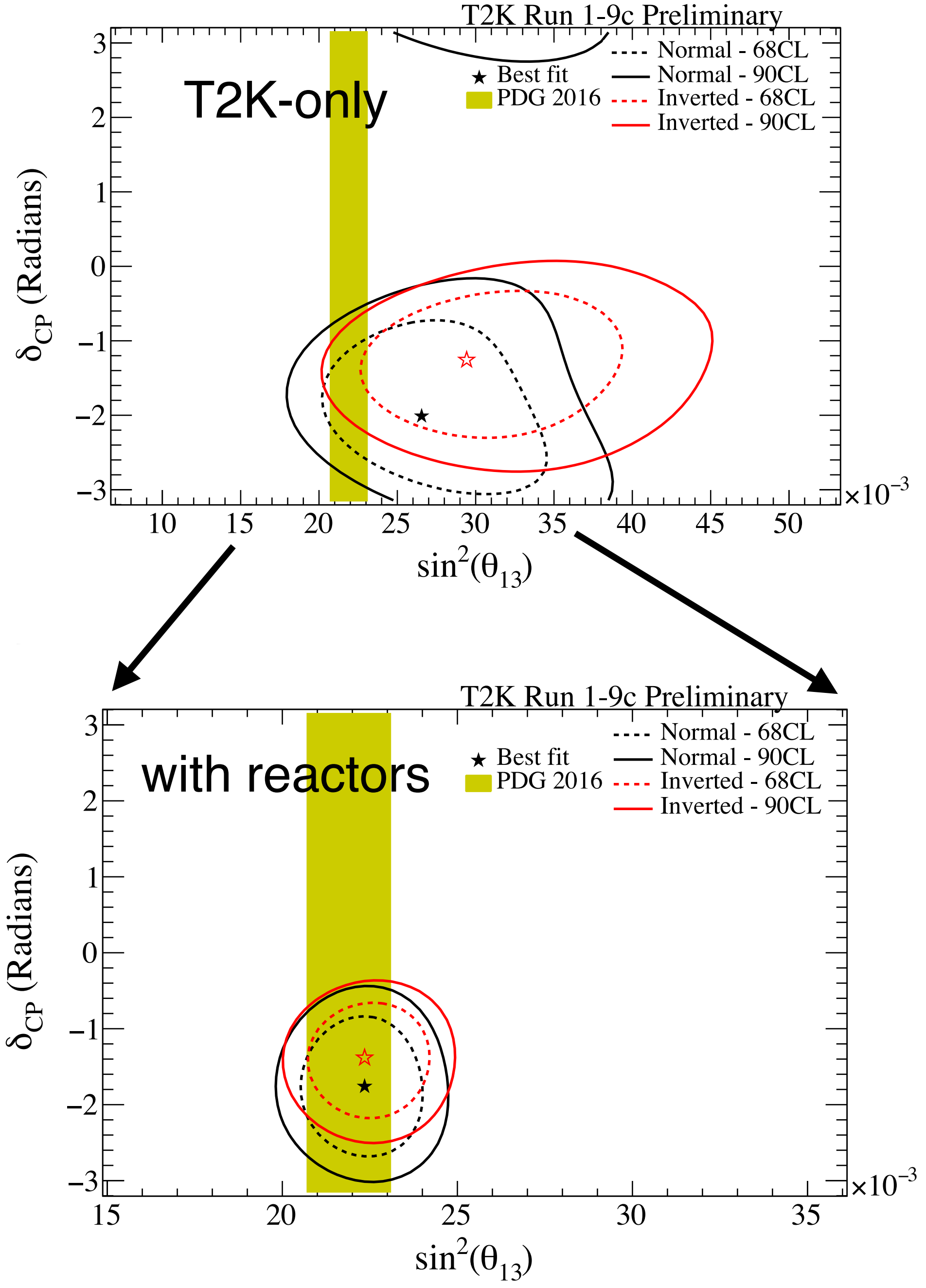
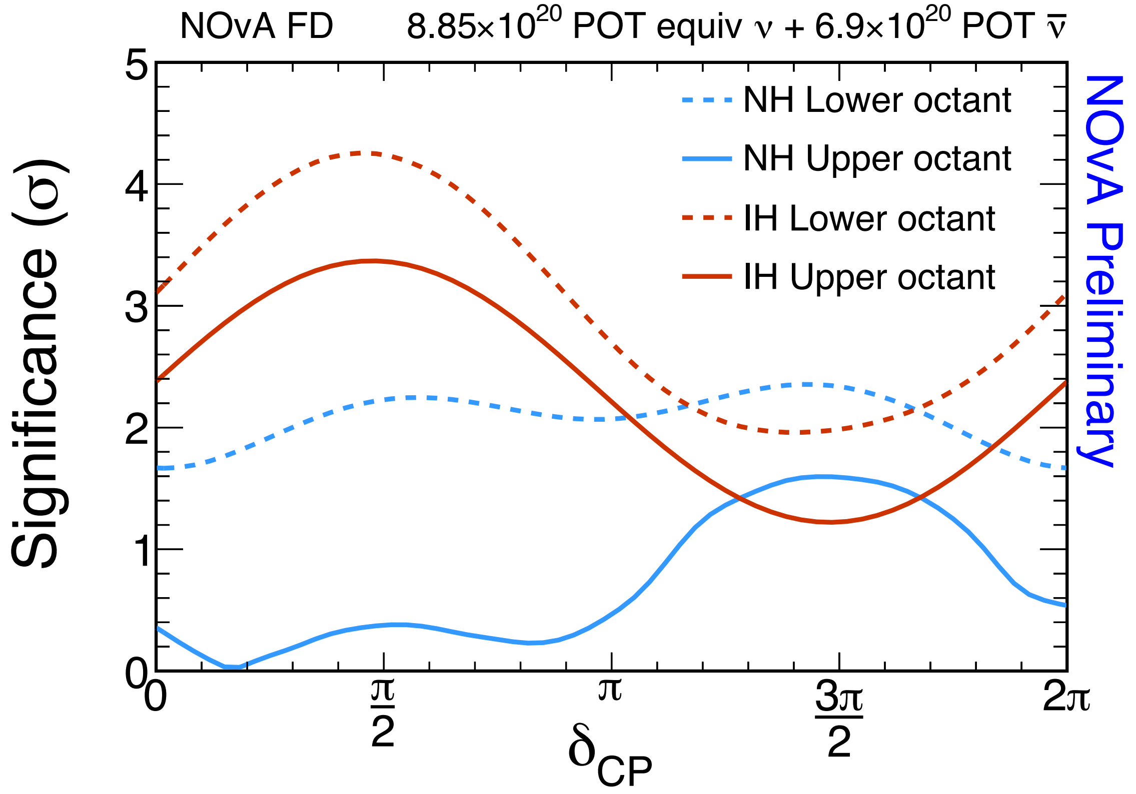


M. Wasko, for T2K, Neutrino 2018

M. Sanchez, for NOvA, Neutrino 2018



Some relevant preference for CP-violation, mainly due to combining T2K (NOvA) with reactor neutrino data.

Phenomenology questions for the future

- **What is the nature of neutrinos? Dirac vs Majorana?**
- **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 delta.
- **What are the precise values of mixing angles?** Do they suggest an underlying pattern?
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

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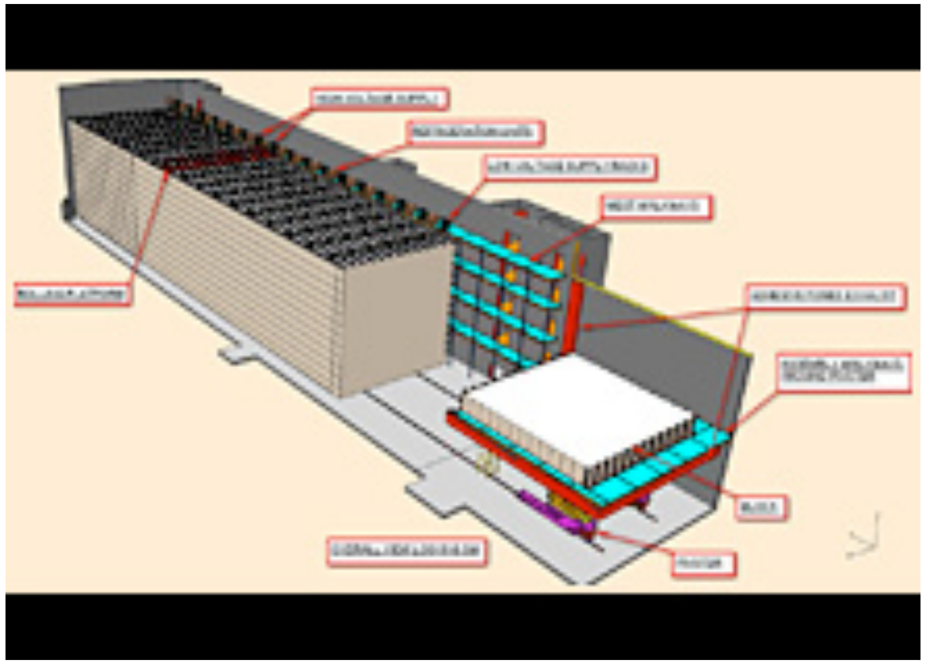
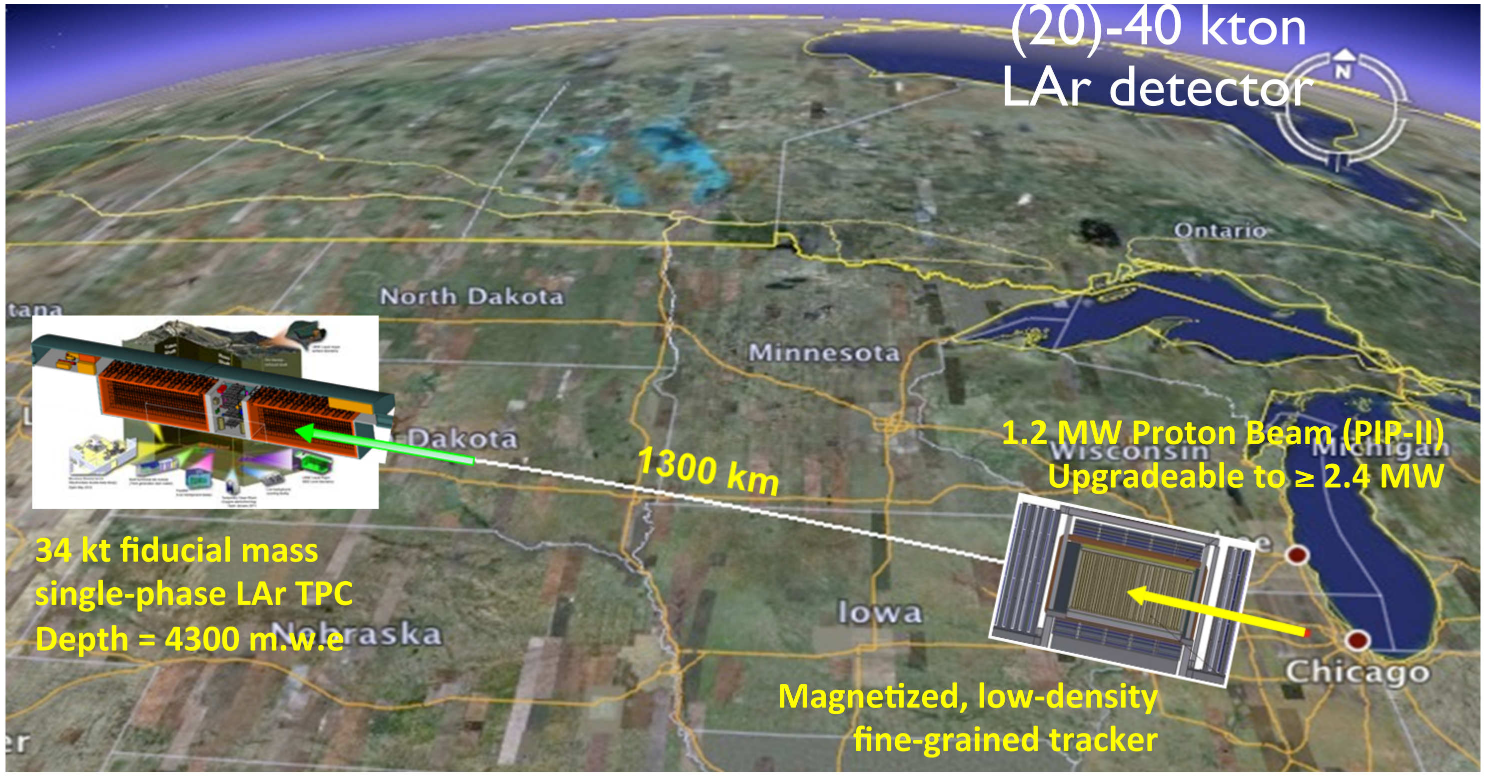
How can we search for the mass ordering and leptonic CP-violation in long baseline neutrino oscillation experiments?

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
(20)-40 kton LAr detector



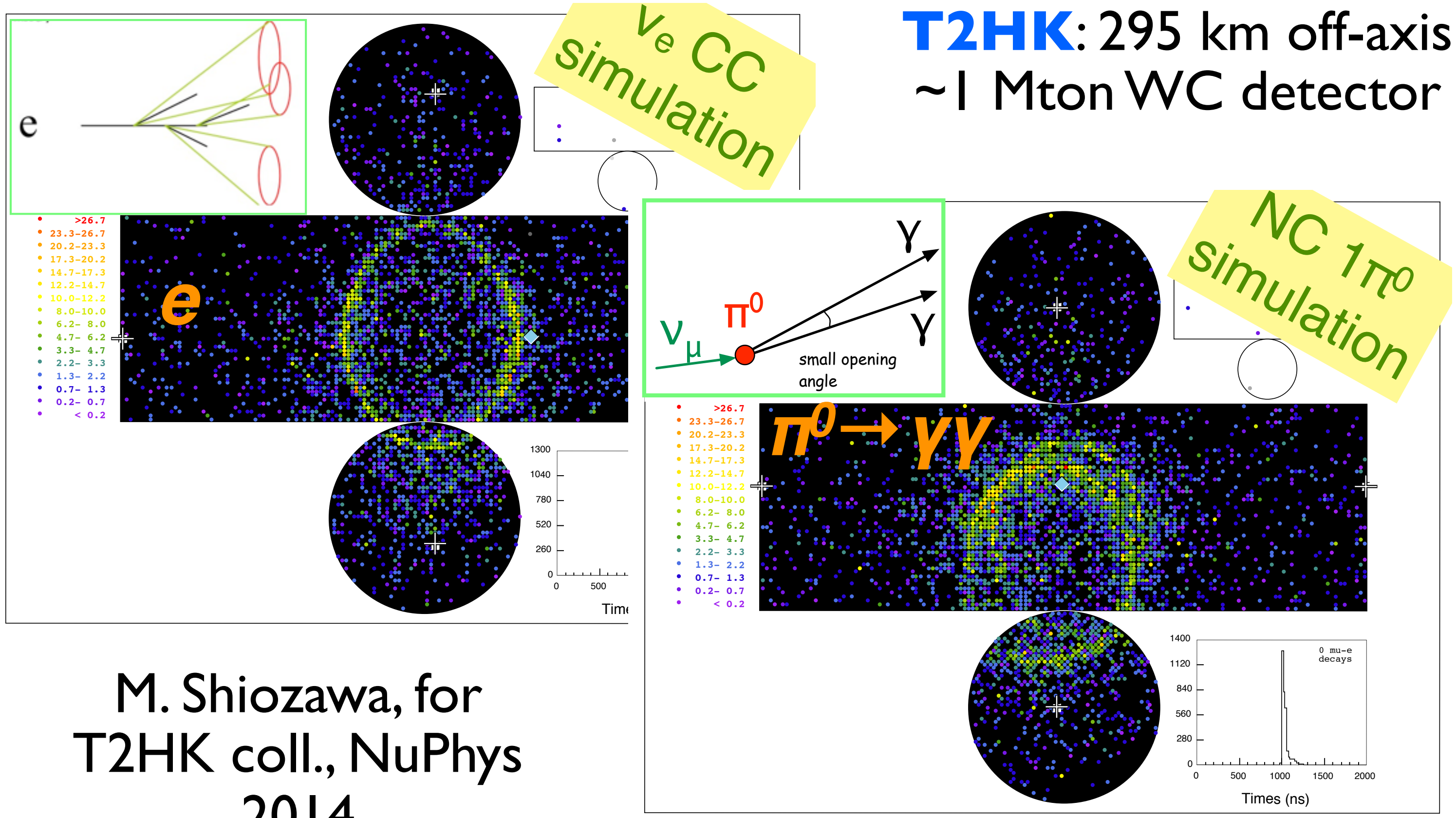
1300 km

34 kt fiducial mass
single-phase LAr TPC
Depth = 4300 m.w.e

1.2 MW Proton Beam (PIP-II)
Upgradeable to ≥ 2.4 MW

Magnetized, low-density
fine-grained tracker

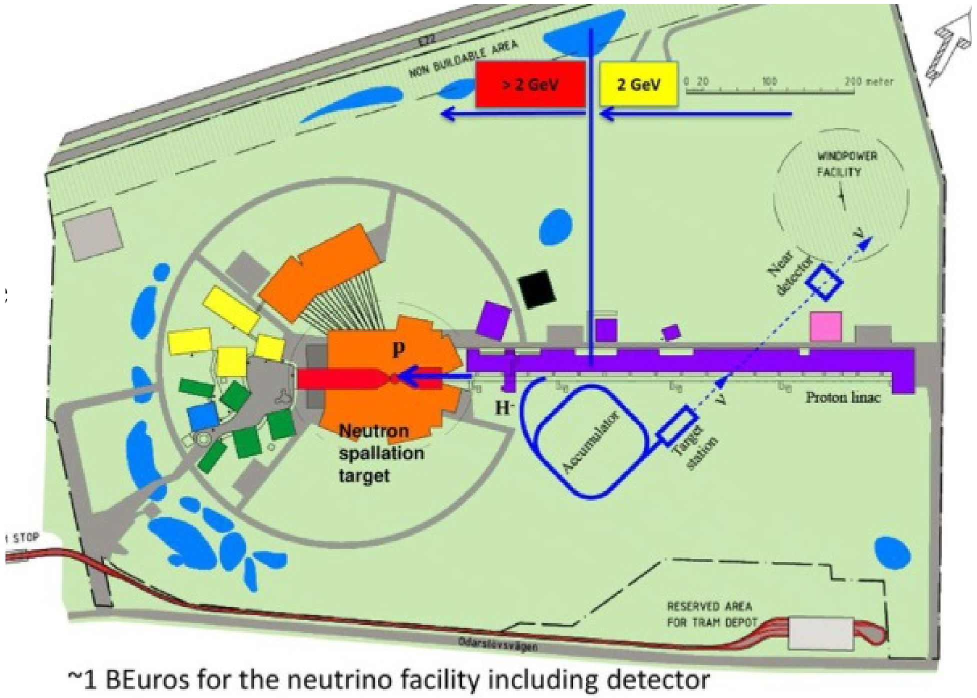
T2HK: 295 km off-axis
~1 Mton WC detector



ν_e CC simulation

NC $1\pi^0$ simulation

M. Shiozawa, for
T2HK coll., NuPhys
2014

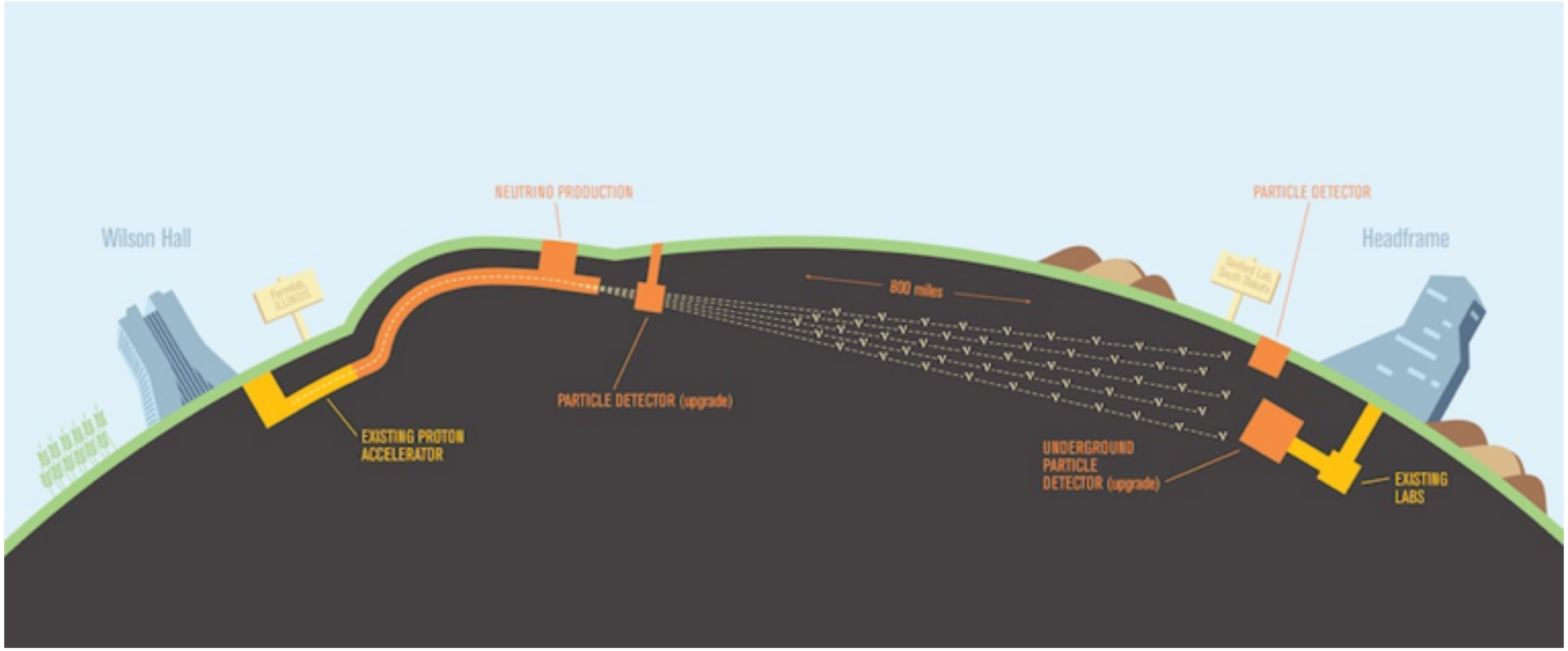


~1 BEuros for the neutrino facility including detector

ESSnuSB: 300-500 km
~0.5 Mton WC detector
second oscillation maximum

Long-baseline neutrino oscillations and the mass ordering

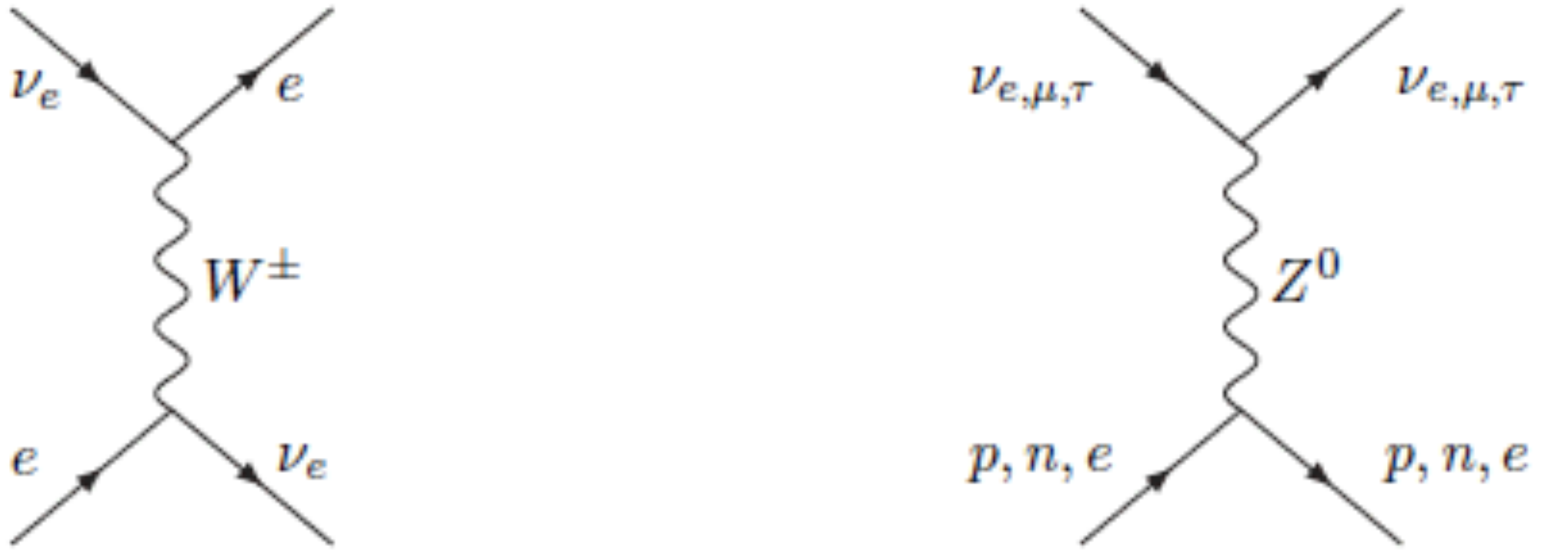
- When neutrinos travel through a medium, they interact with the background of e, p and n.



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.

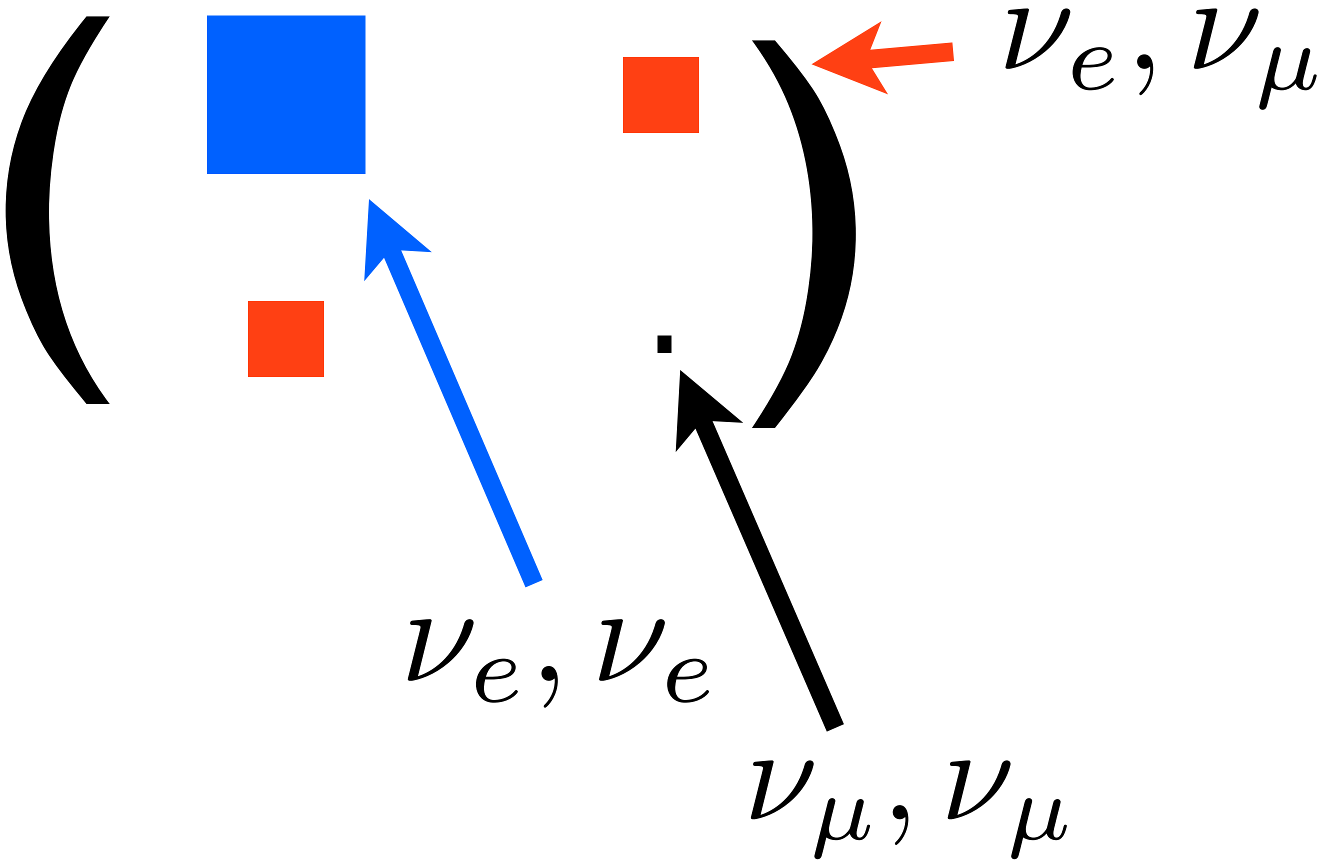
- Neutrinos undergo forward elastic scattering via CC and NC interactions.



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

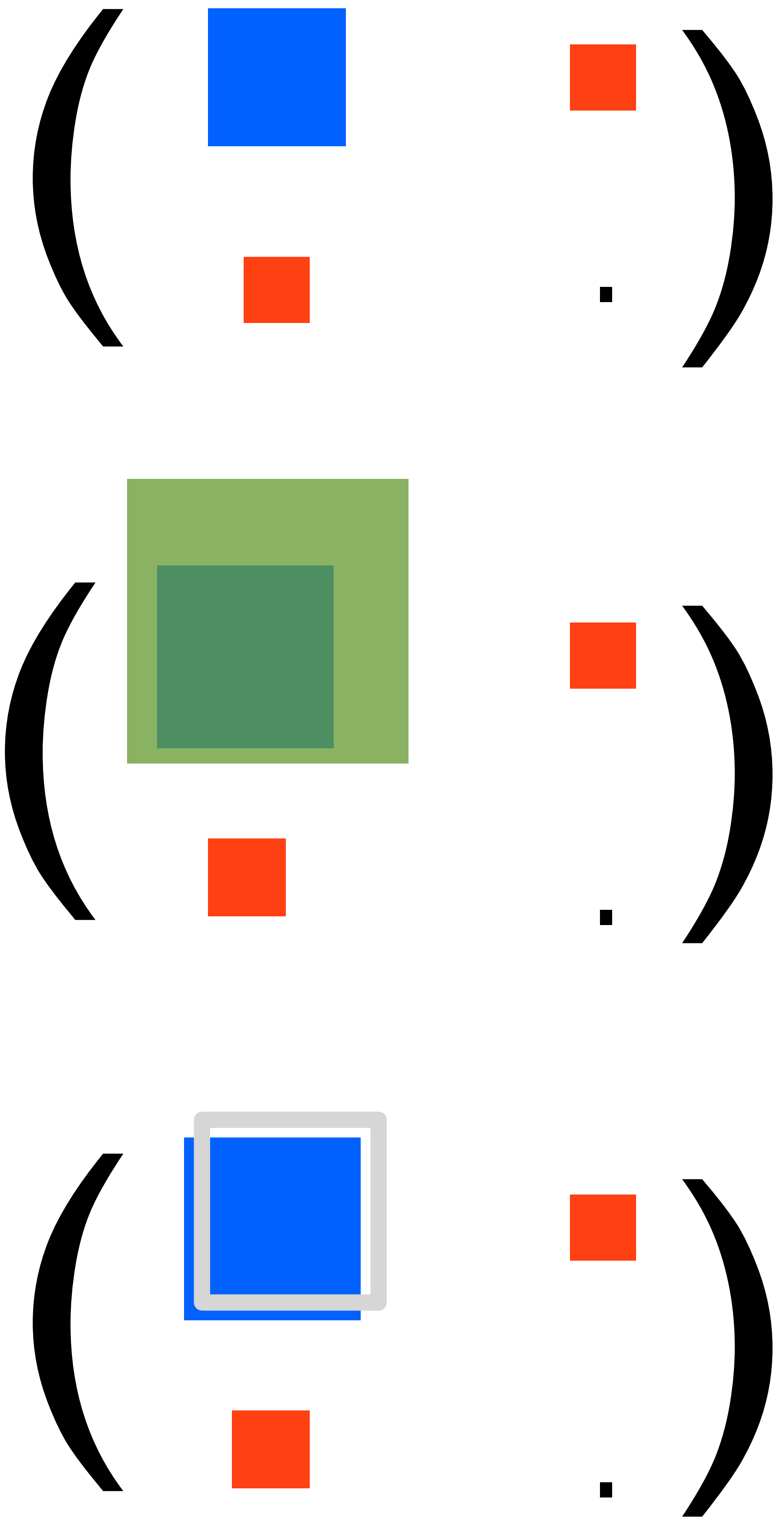
$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos(2\theta) + \boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2}{4E}\sin(2\theta) \\ \frac{\Delta m^2}{4E}\sin(2\theta) & \frac{\Delta m^2}{4E}\cos(2\theta)\end{pmatrix}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$

Effective Hamiltonian in the flavour basis



Effective Hamiltonian

Mixing angle



vacuum

$$\tan 2\theta \sim \frac{2\,\text{🟥}}{\text{🟦}}$$

matter suppression (Sun, SN)

$$\tan 2\theta^{M} \sim \frac{2\,\text{🟥}}{\text{🟦} + \text{🟩}} \ll \tan 2\theta$$

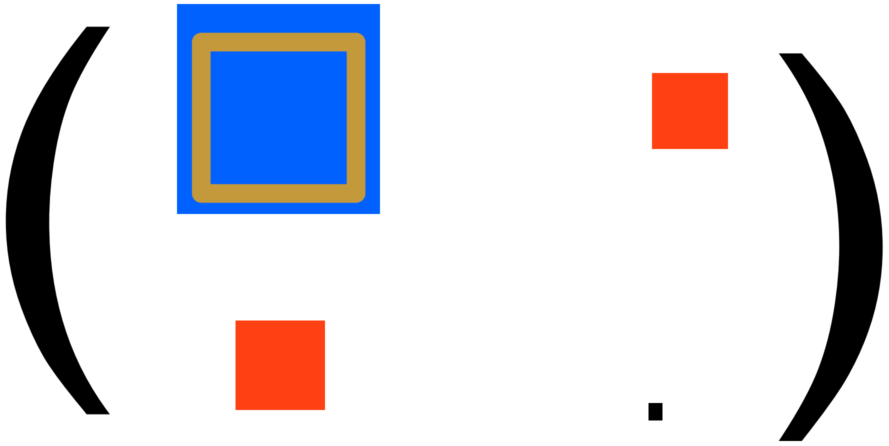
MSW resonance (Sun, SN)

$$\tan 2\theta^{M} \sim \frac{2\,\text{🟥}}{\text{🟦} - \text{☐}} \sim \infty$$

In long baseline experiments

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

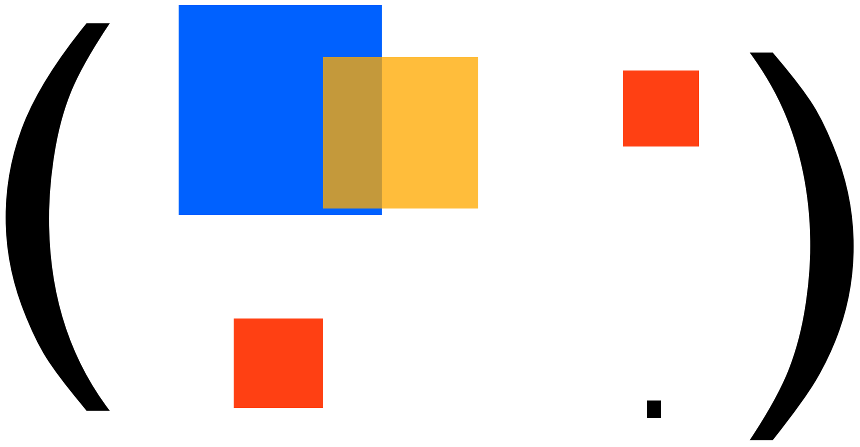
For neutrinos



$\Delta m^2 > 0$ enhancement

$\tan 2\theta^M \sim$ 2🟥 / (🟦 - + $\boxed{+}$)

For antineutrinos



$\Delta m^2 > 0$ suppression

$\tan 2\theta^M \sim$ 2🟥 / (🟦 - + 🟨 -)

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 $\Delta m^2 < 0$

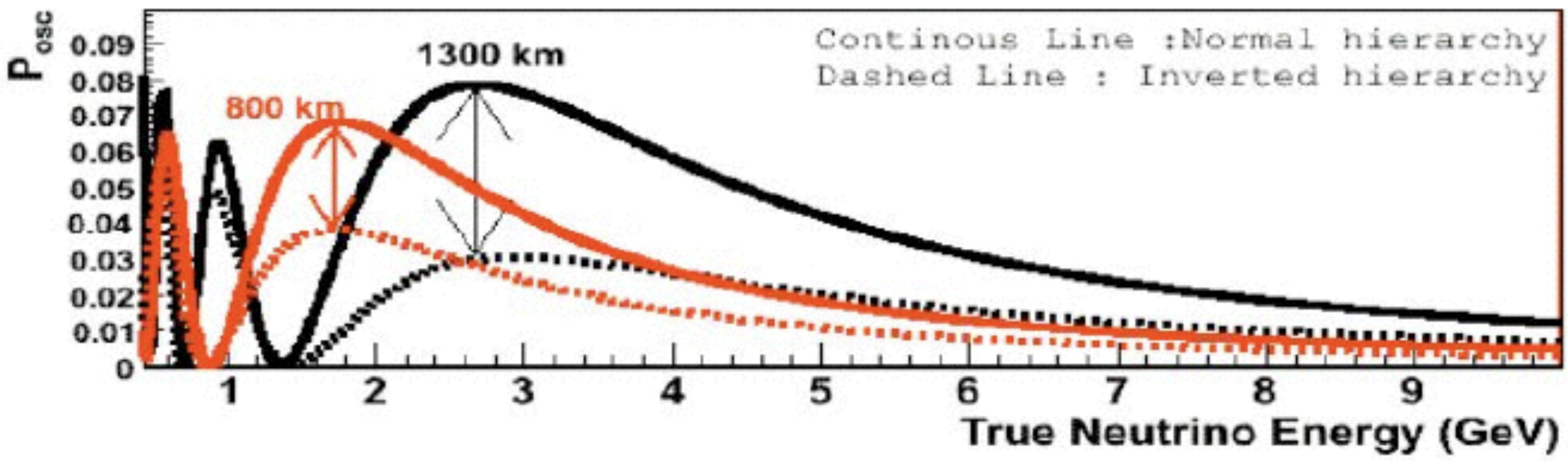
The impact of matter effects is stronger at higher energies and at longer baselines.

The 3 neutrino probability can be approximated as

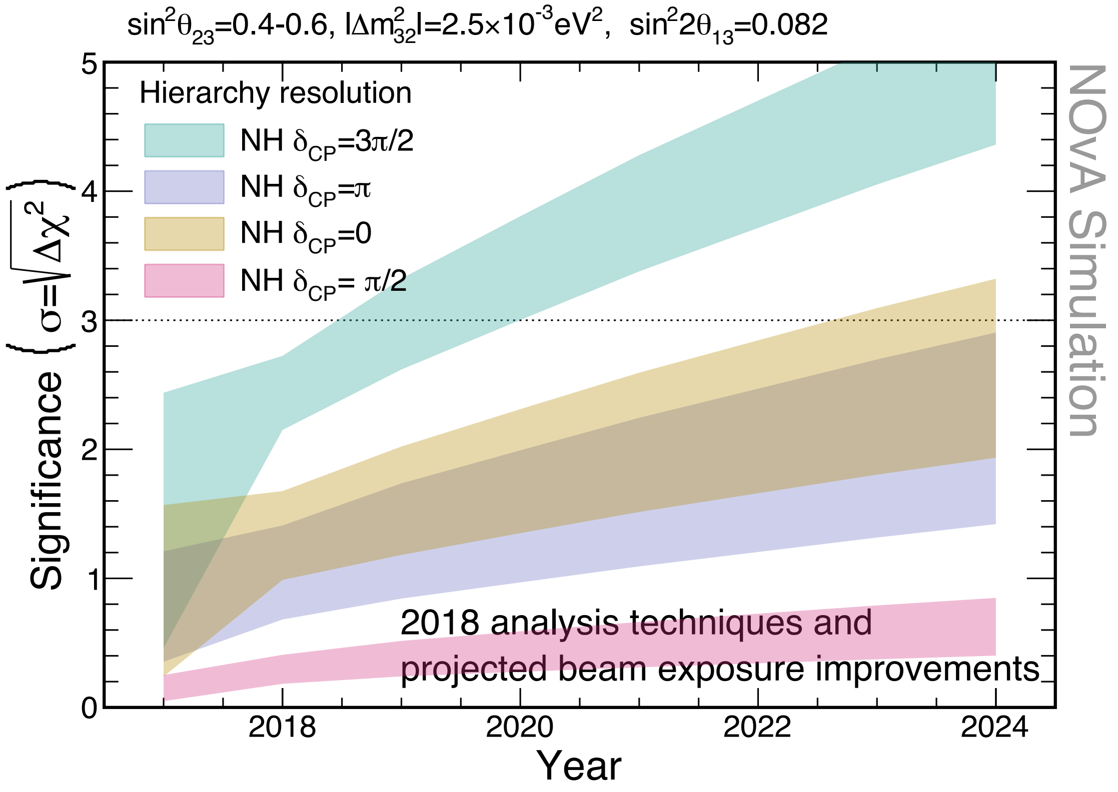
$$
\begin{aligned}
P_{\mu e} \simeq\, & 4c_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2}\sin^2\frac{(1-r_A)\Delta_{31}L}{4E} \\
& + \sin 2\theta_{12}\sin 2\theta_{23} s_{13}\frac{\Delta_{21}L}{2E}\sin\frac{(1-r_A)\Delta_{31}L}{4E}\cos\left(\delta-\frac{\Delta_{31}L}{4E}\right) \\
& + s_{23}^2\sin^2 2\theta_{12}\frac{\Delta_{21}^2L^2}{16E^2}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

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

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

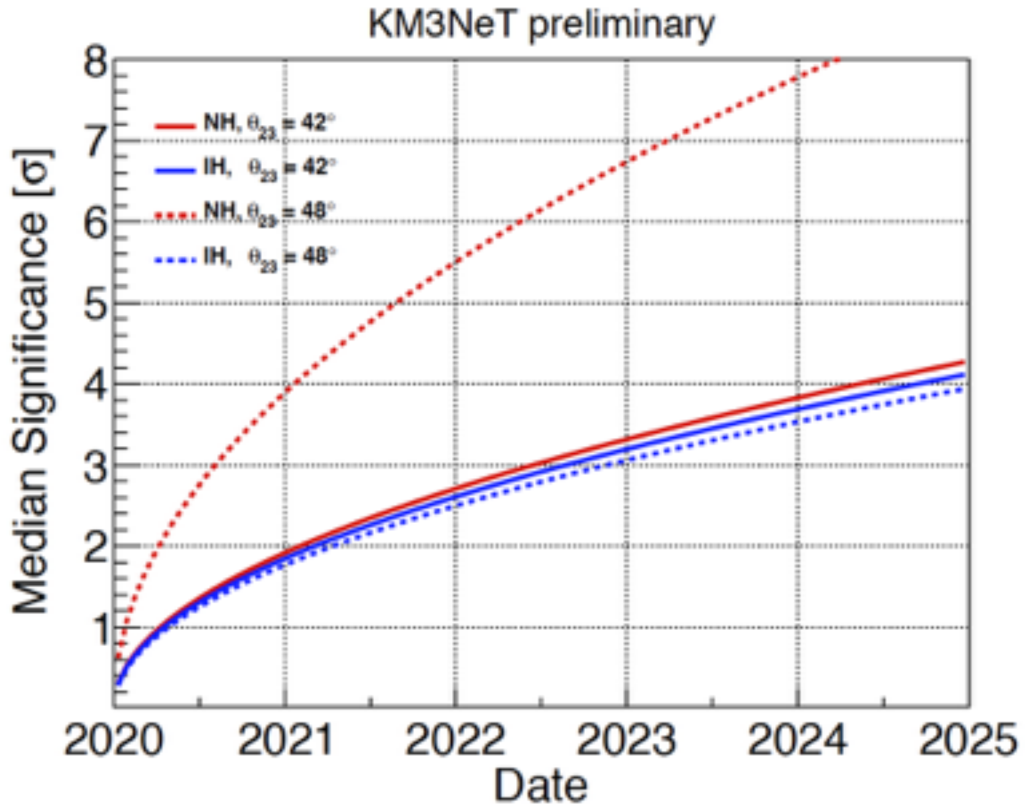


Near future sensitivity



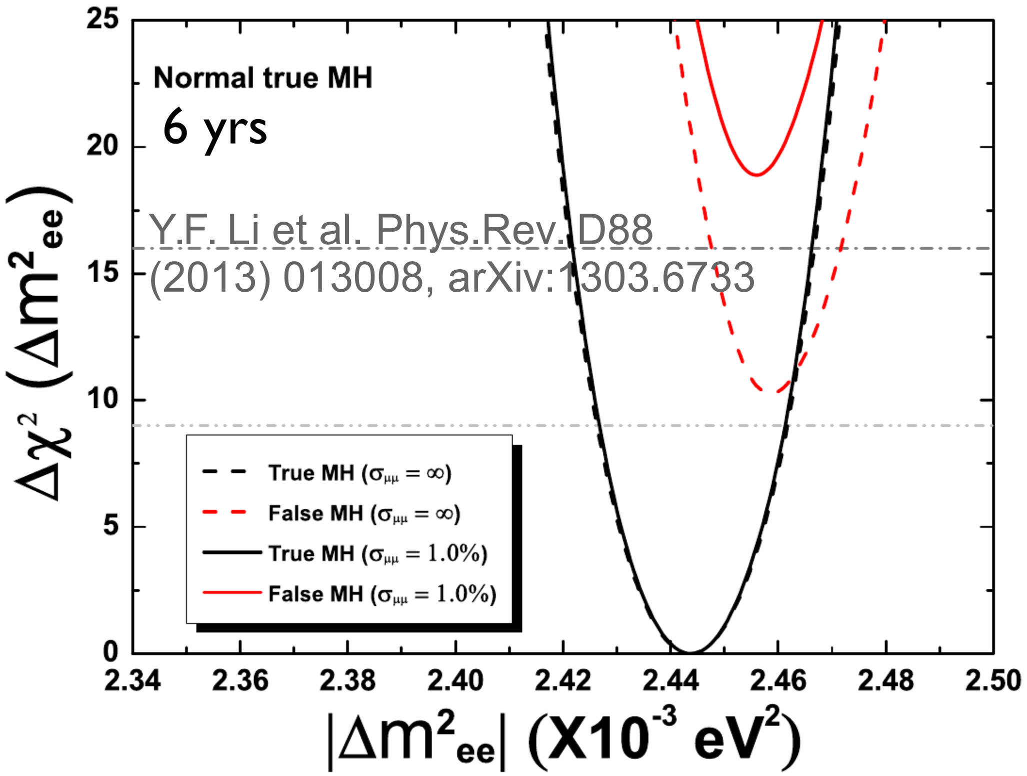
2018 analysis techniques and projected beam exposure improvements

M. Sanchez, Neutrino 2018



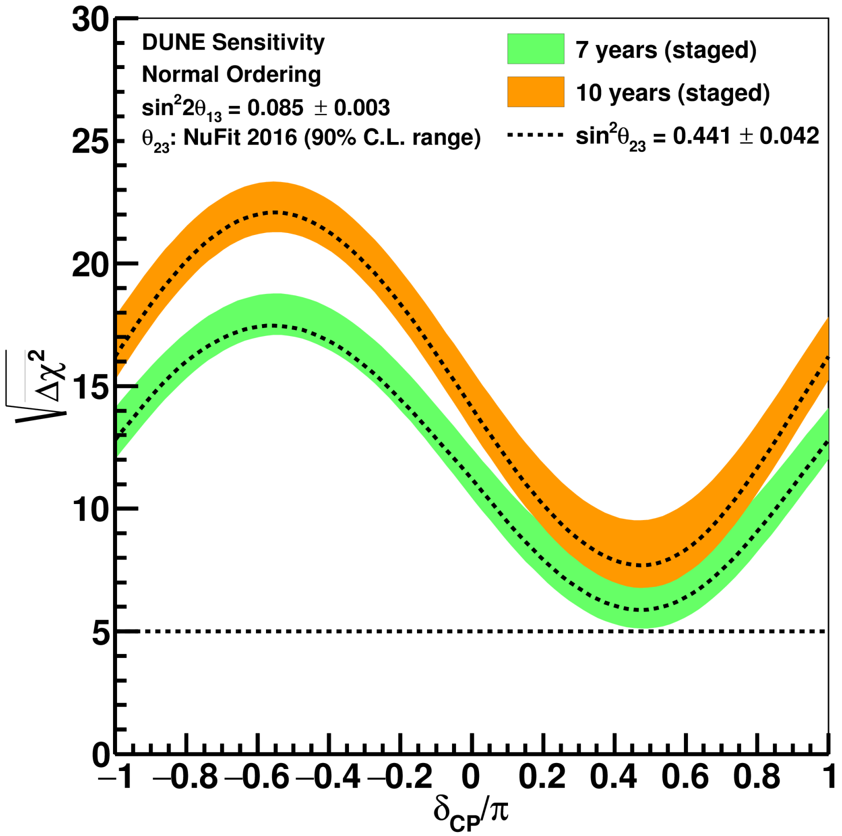
Adrian-Martinez et al., 1601.07459

Before 2025, further information will be provided by NOvA, ORCA/PINGU, JUNO. A joint T2K+NOvA analysis is also foreseen.

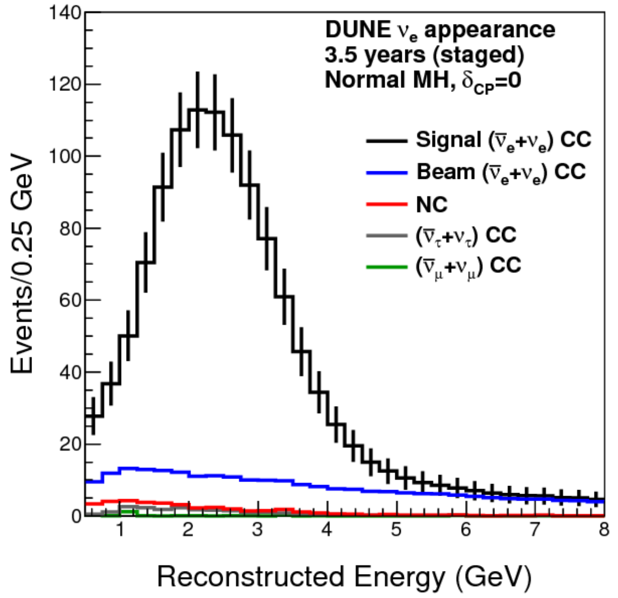


Y.F. Li et al. Phys.Rev. D88 (2013) 013008, arXiv:1303.6733

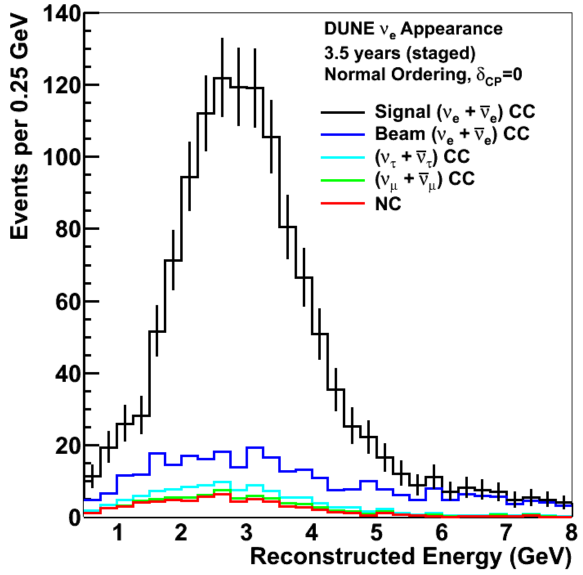
DUNE, HK sensitivity



CDR

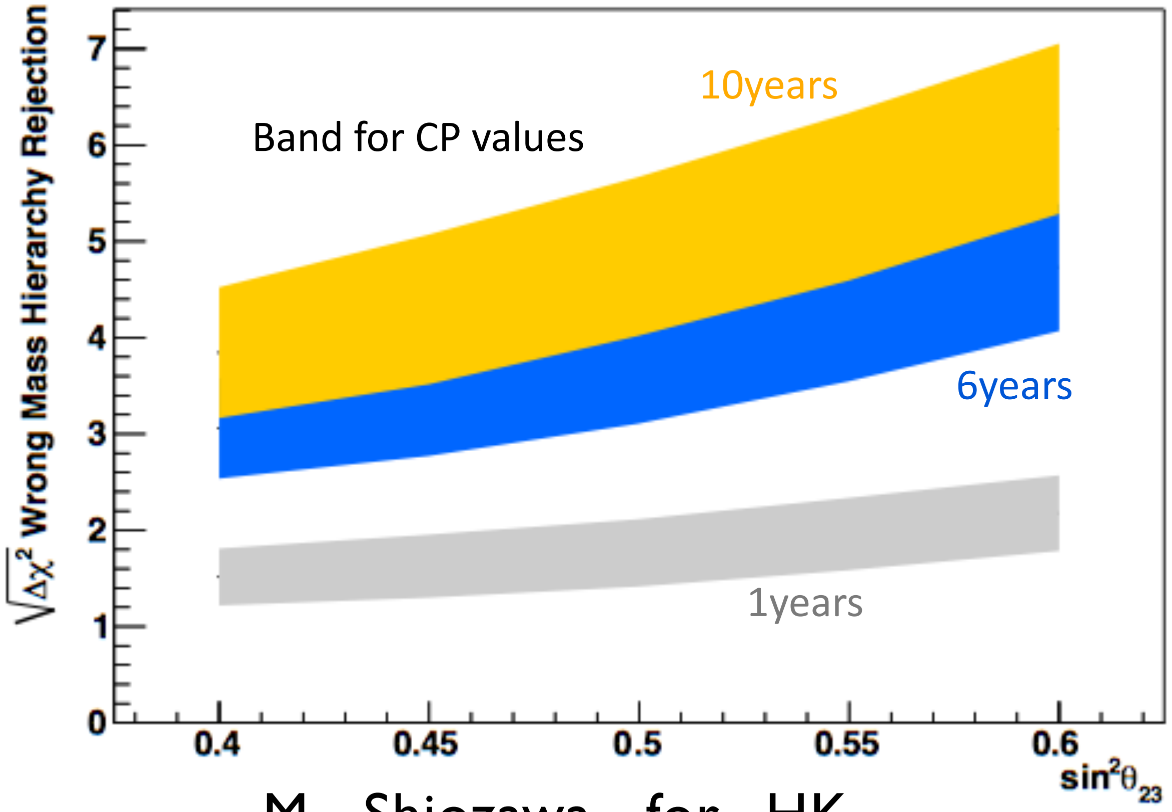


New!



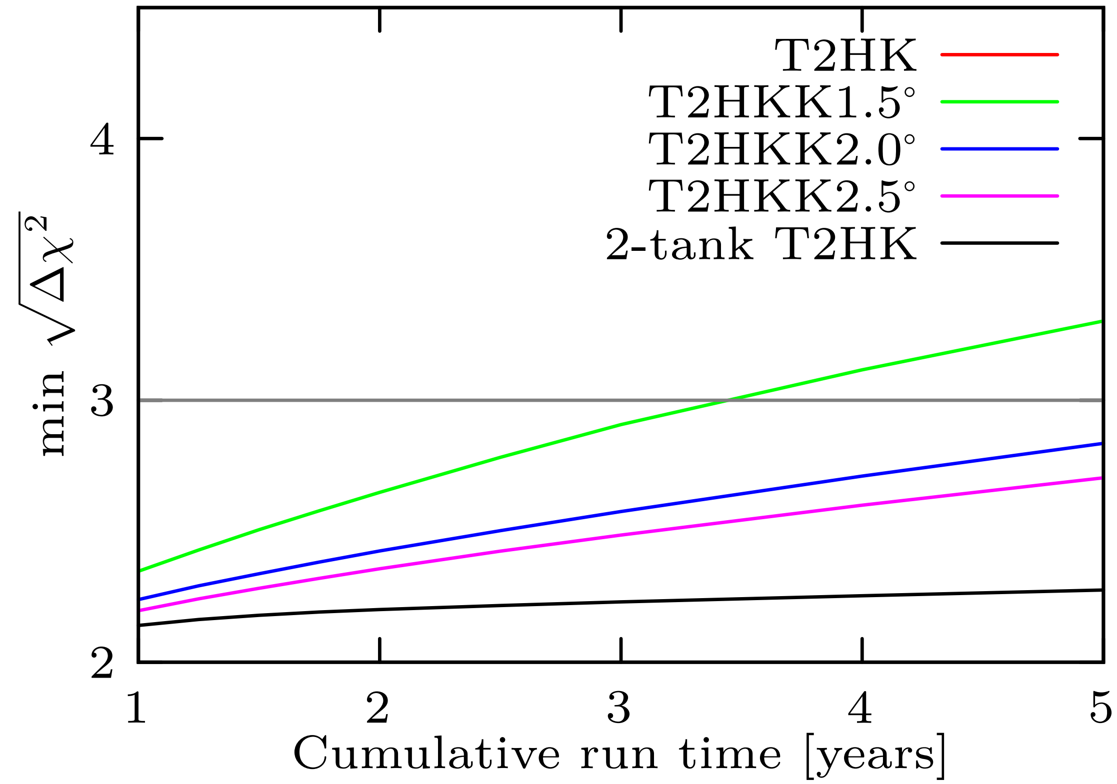
E. Worcester, for DUNE, Neutrino 2018

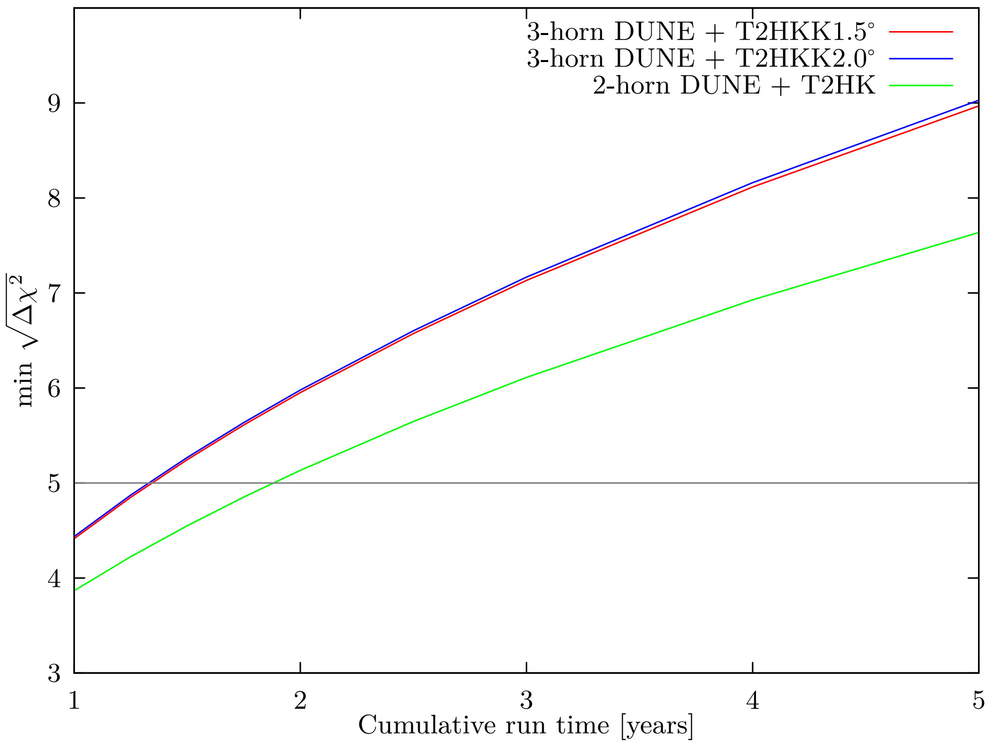
DUNE will have the ultimate sensitivity to the MO, reaching the discovery threshold independently of the values of the other oscillation parameters. HK can rely on atm neutrinos.



M. Shiozawa, for HK, Neutrino 2018

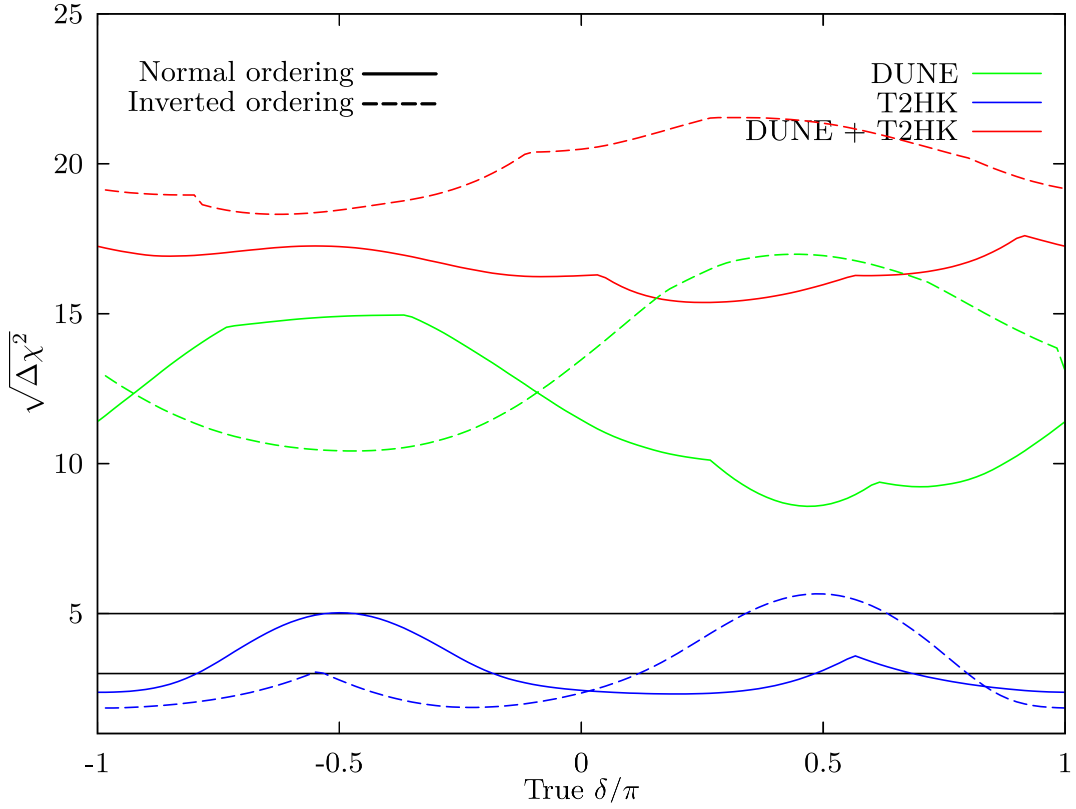
DUNE, T2HK sensitivity





T2HK can improve its sensitivity (without atm) by having a second detector in Korea.

The combination of DUNE and T2HK would provide the ultimate sensitivity.



Ballett et al., 1612.07275

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.

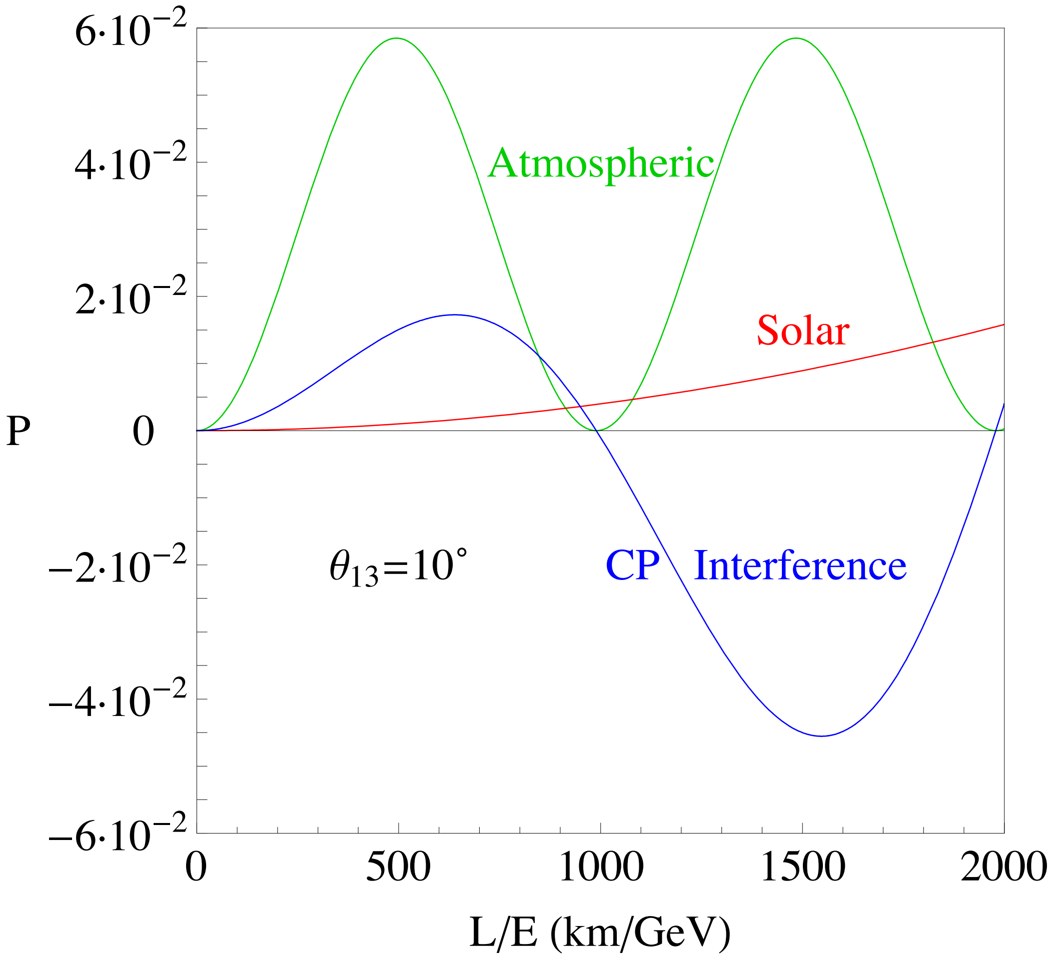
- It is proportional to the sine of the delta phase.

- Effective 2-neutrino probabilities are CP-symmetric. CPV needs to be searched for in LBL experiments which have access to 3-neutrino oscillations.

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

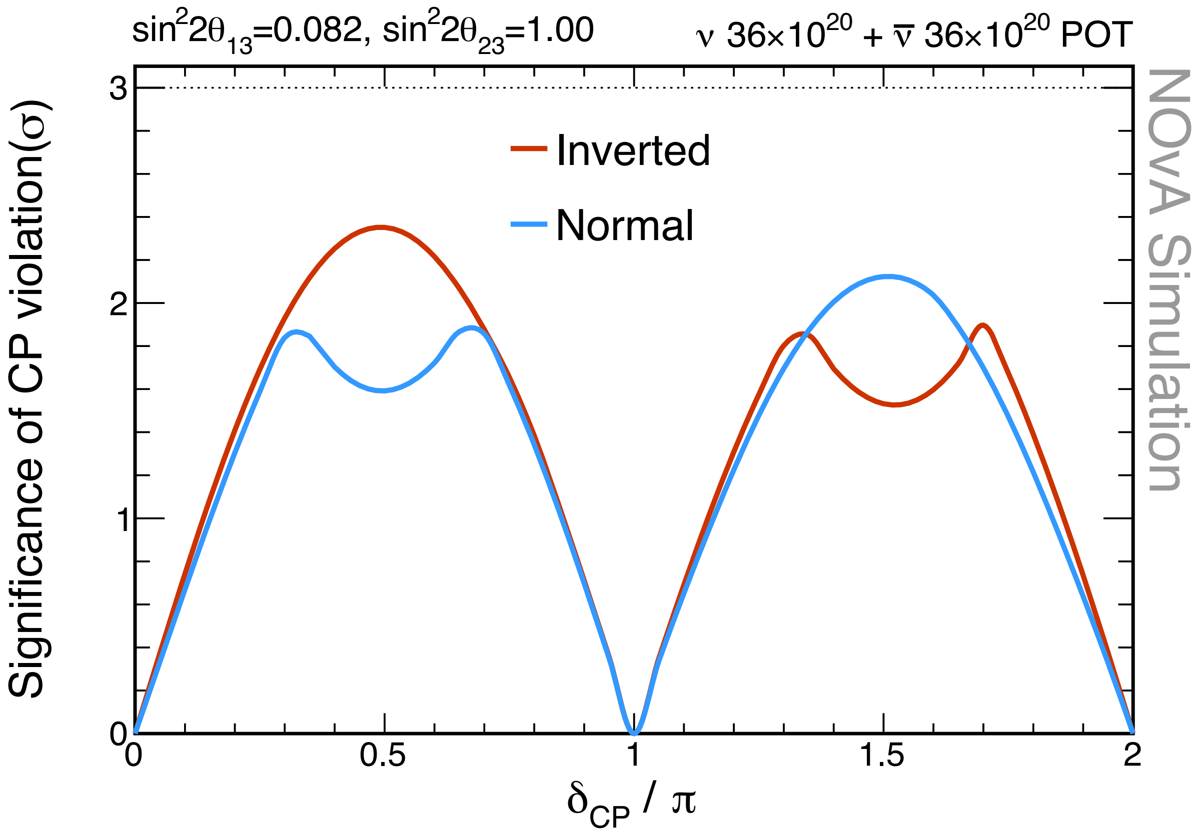
A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773...

- 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

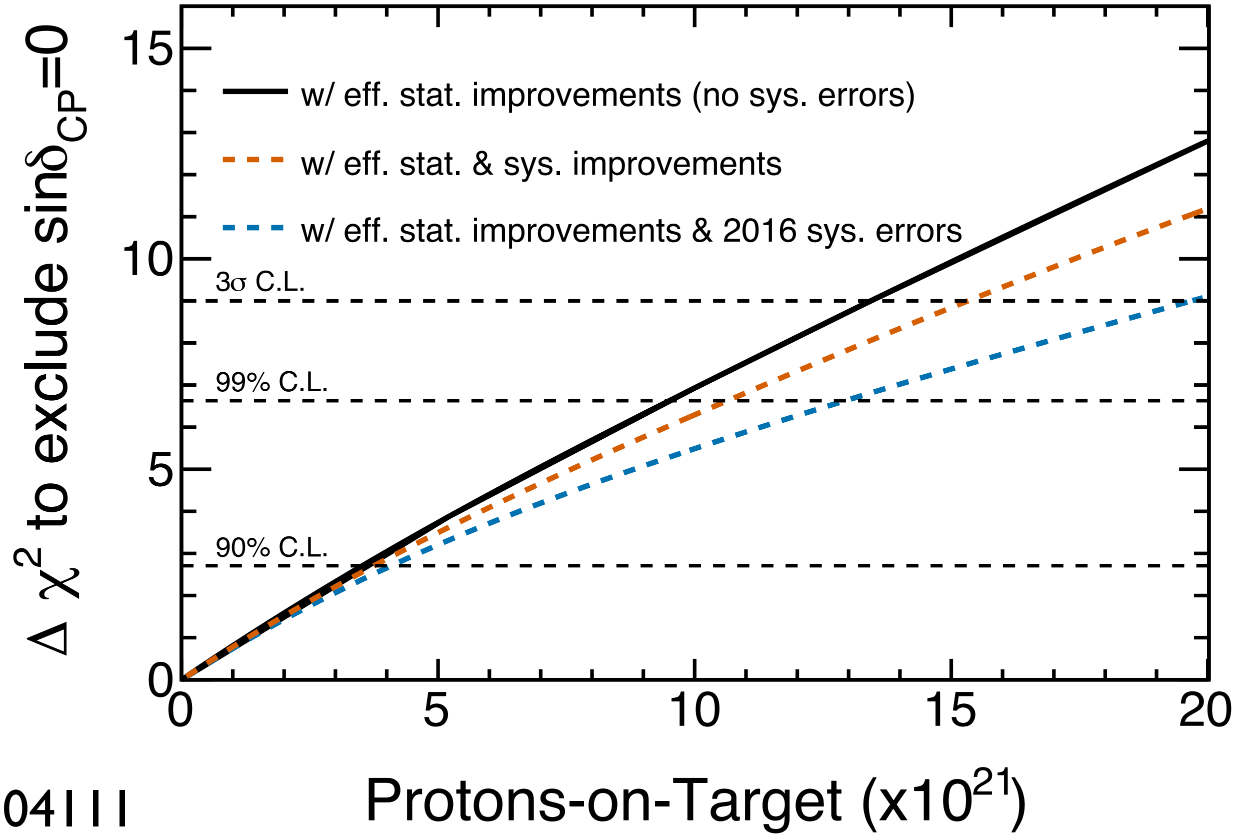
Near future sensitivity



M. Sanchez, Neutrino 2018

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

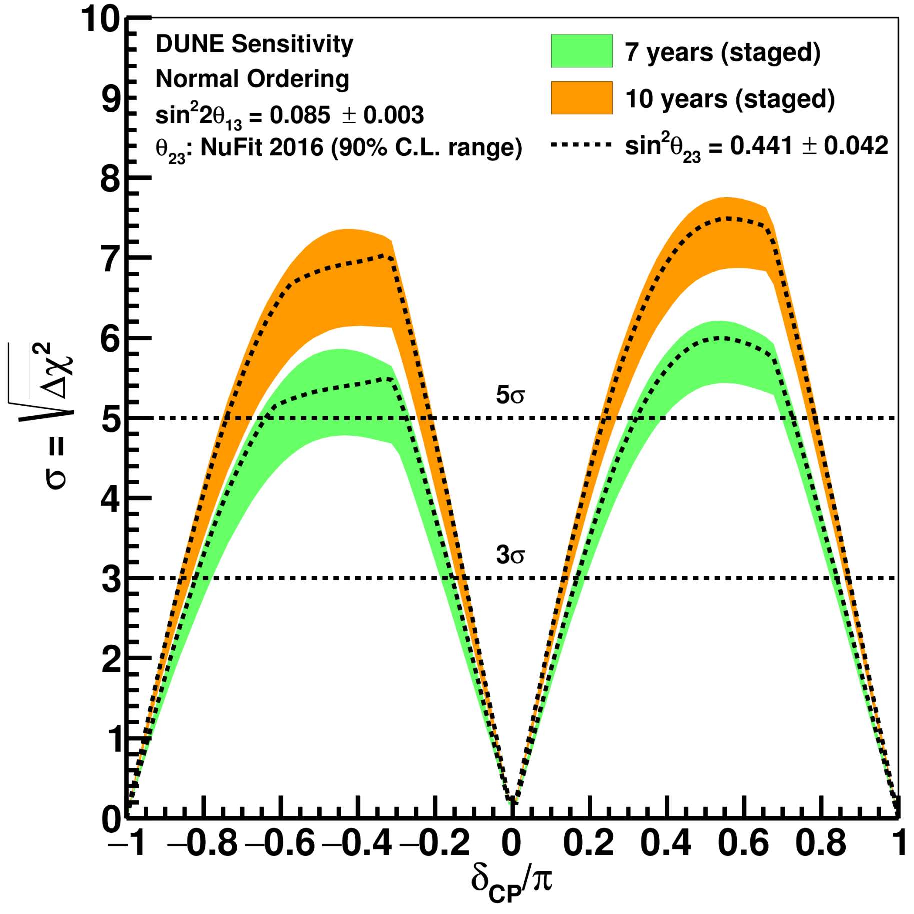
T2K phase 2 extension has received stage 1 approval by KEK/J-PARC in 2016.
It aims at reaching 1.3 MW by 2026 (20x10^21pot).



T2K, 1609.04111

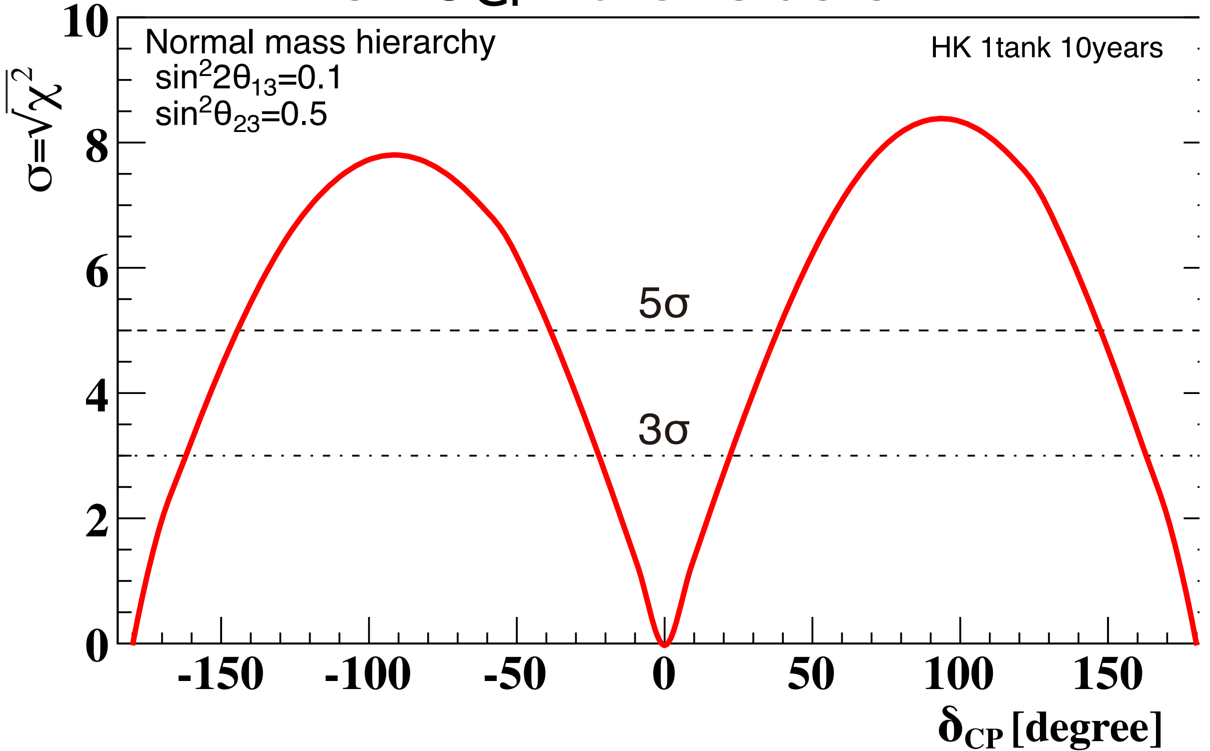
DUNE, T2HK sensitivity

CP Violation



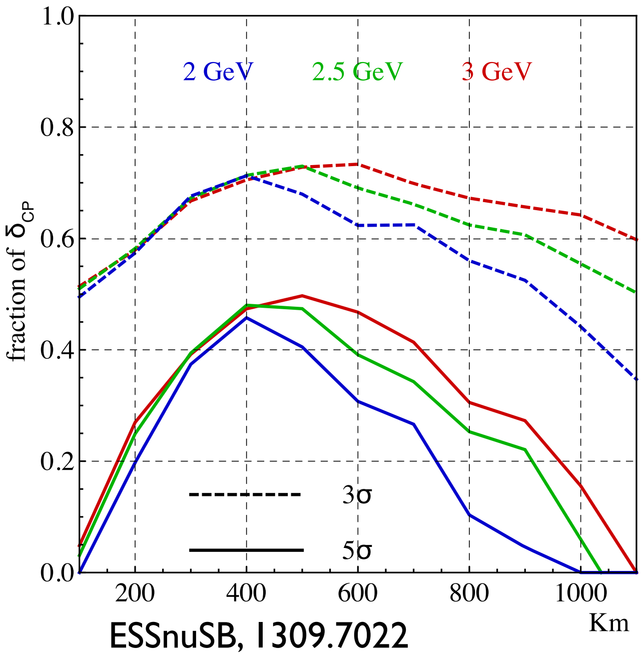
E. Worcester, for DUNE, Neutrino 2018

$\sin\delta_{CP}$=0 exclusion

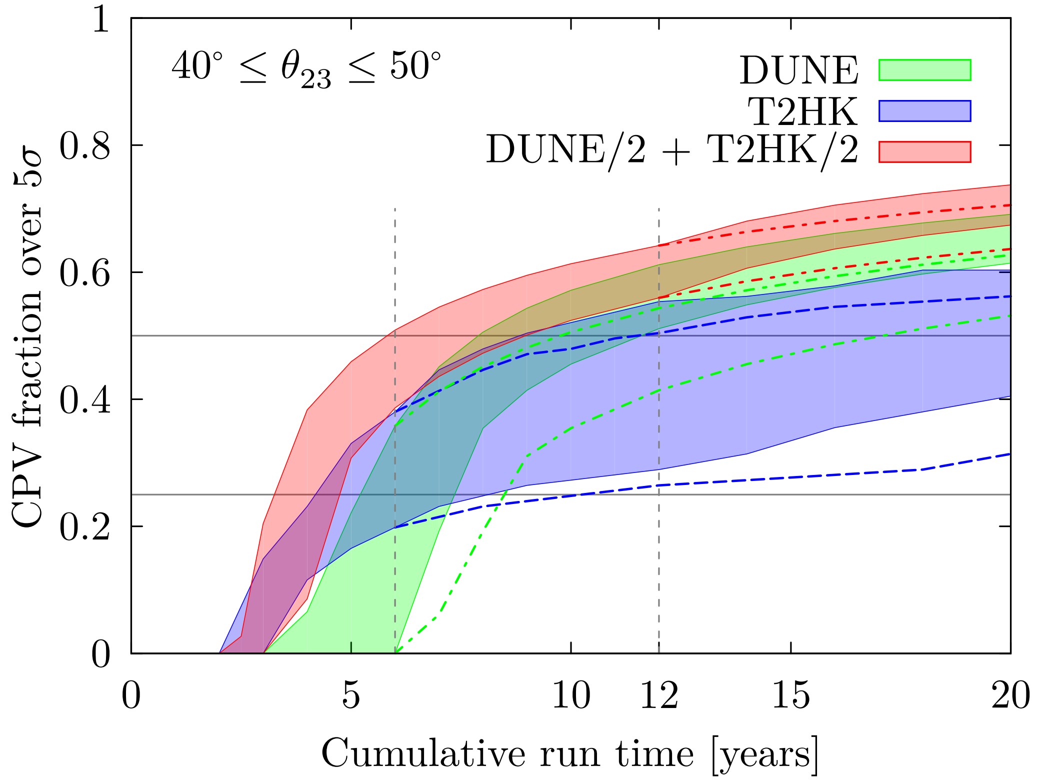


M. Shiozawa, for HK, Neutrino 2018

ESSnuSB



ESSnuSB, 1309.7022



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.

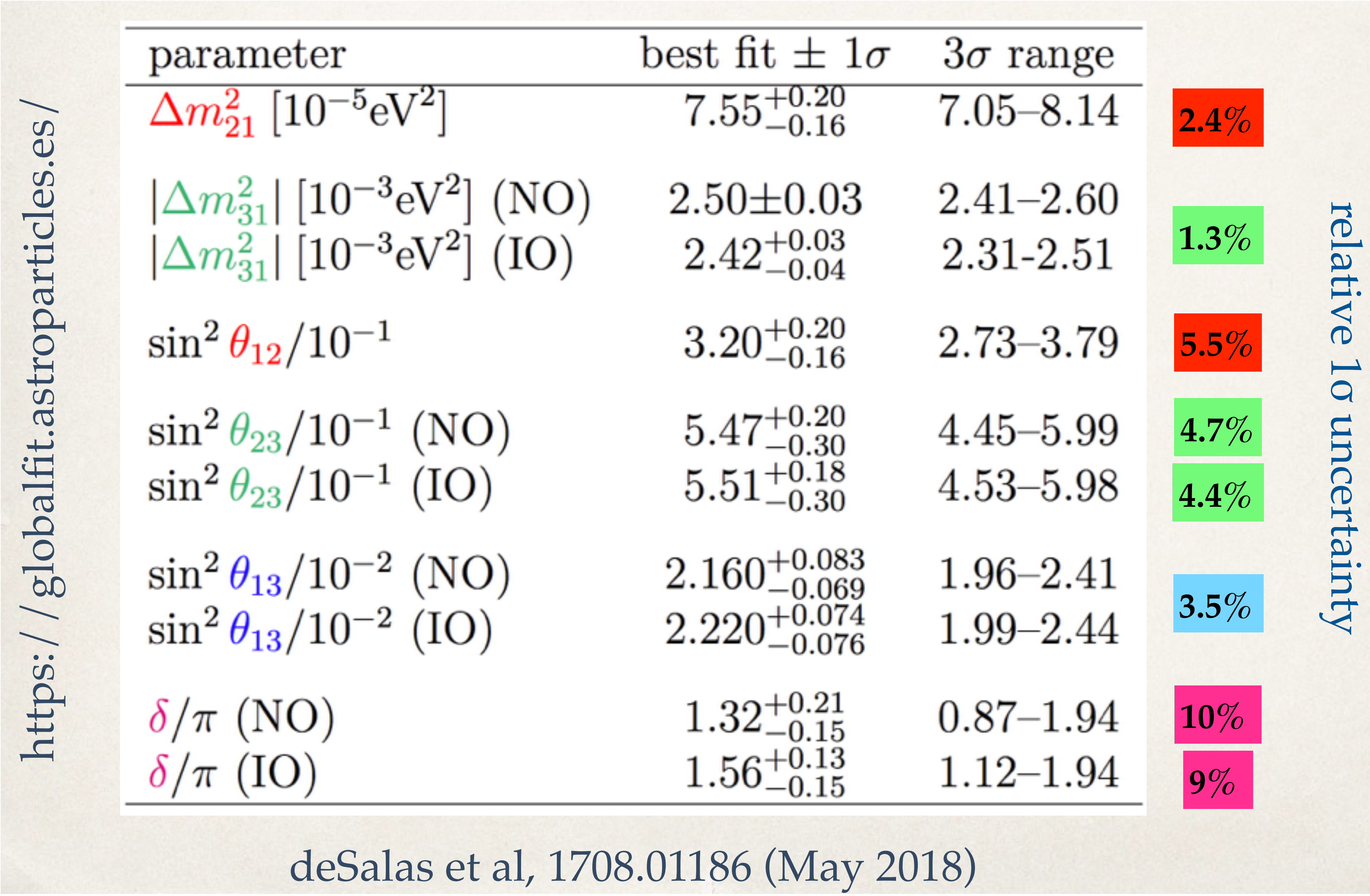
- The values of the mixing angles seem to indicate an underlying symmetry: $\theta_{23} \sim 45^o, \quad \theta_{13}$ not too far from 0.

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

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

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.



https://globalfit.astroparticles.es/

parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

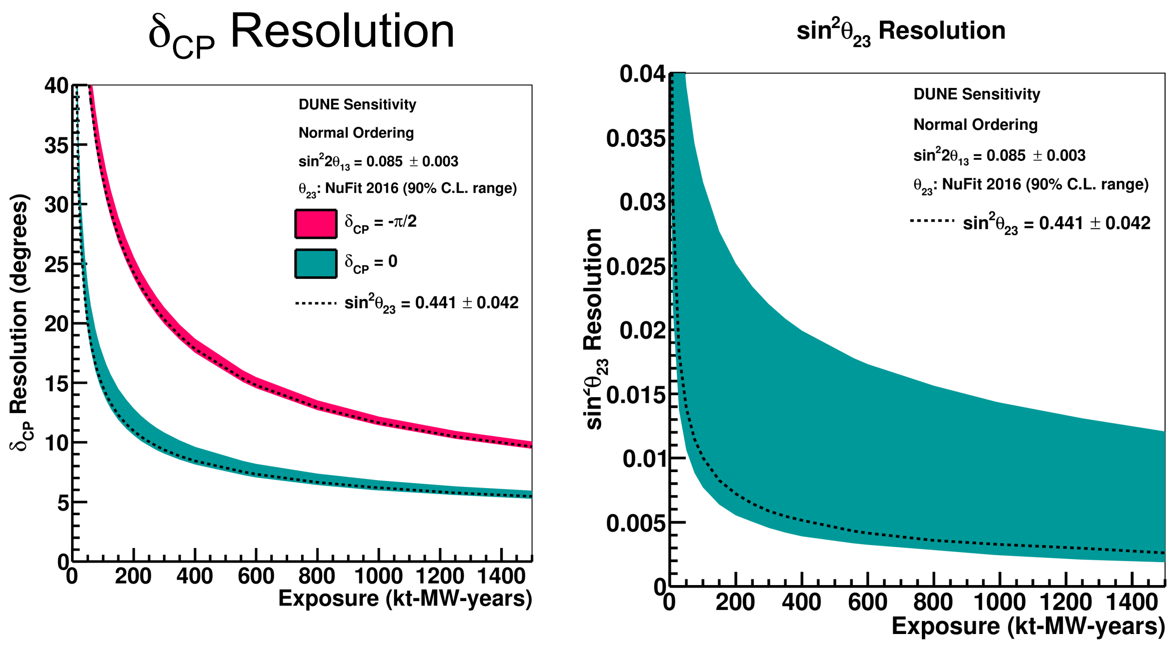
deSalas et al, 1708.01186 (May 2018)

M. Tortola, Neutrino 2018

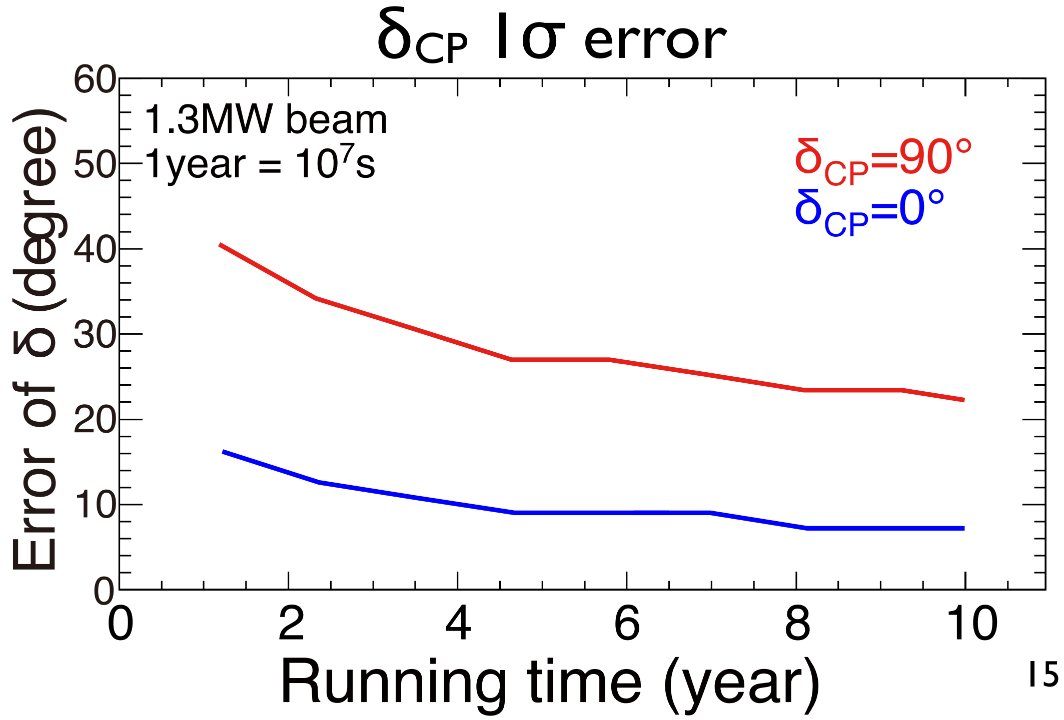
	Δm^2_{21}	$\sin^2\theta_{12}$	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant experiment	KamLAND	SNO	T2K & NOvA /Daya Bay	Daya Bay	T2K
Individual 1σ	2.4%	6.7%	3.2%/3.5%	4.0%	9.8%
Global 1σ *	2.2%	3.9%	1.2%	3.4%	5%
JUNO expected 1σ	0.6%	0.7%	0.4%	~15%	-

B. Wonsak, JUNO, Neutrino 2018

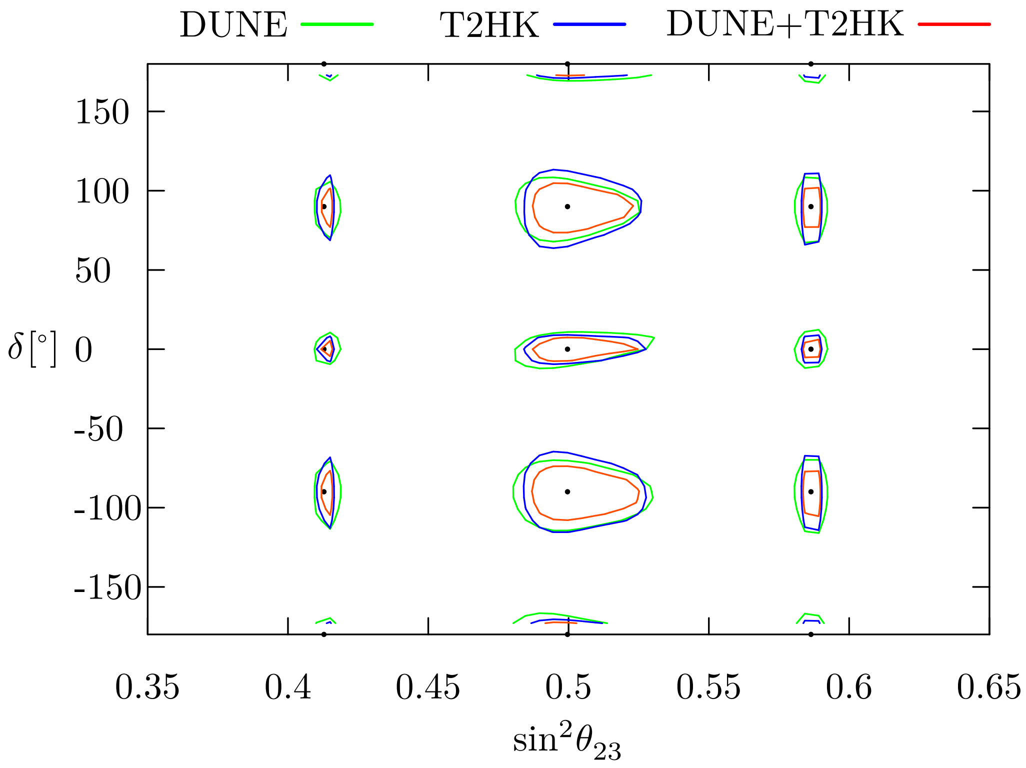
DUNE CDR:



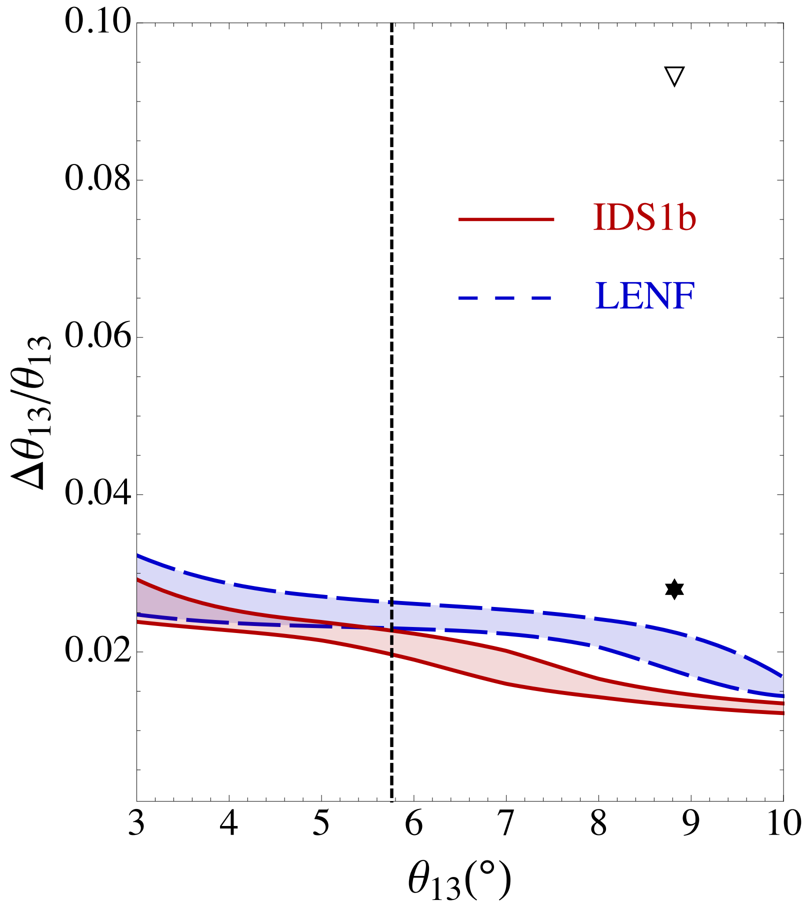
E.Worcester, for DUNE, Neutrino 2018



M. Shiozawa, for HK, Neutrino 2018

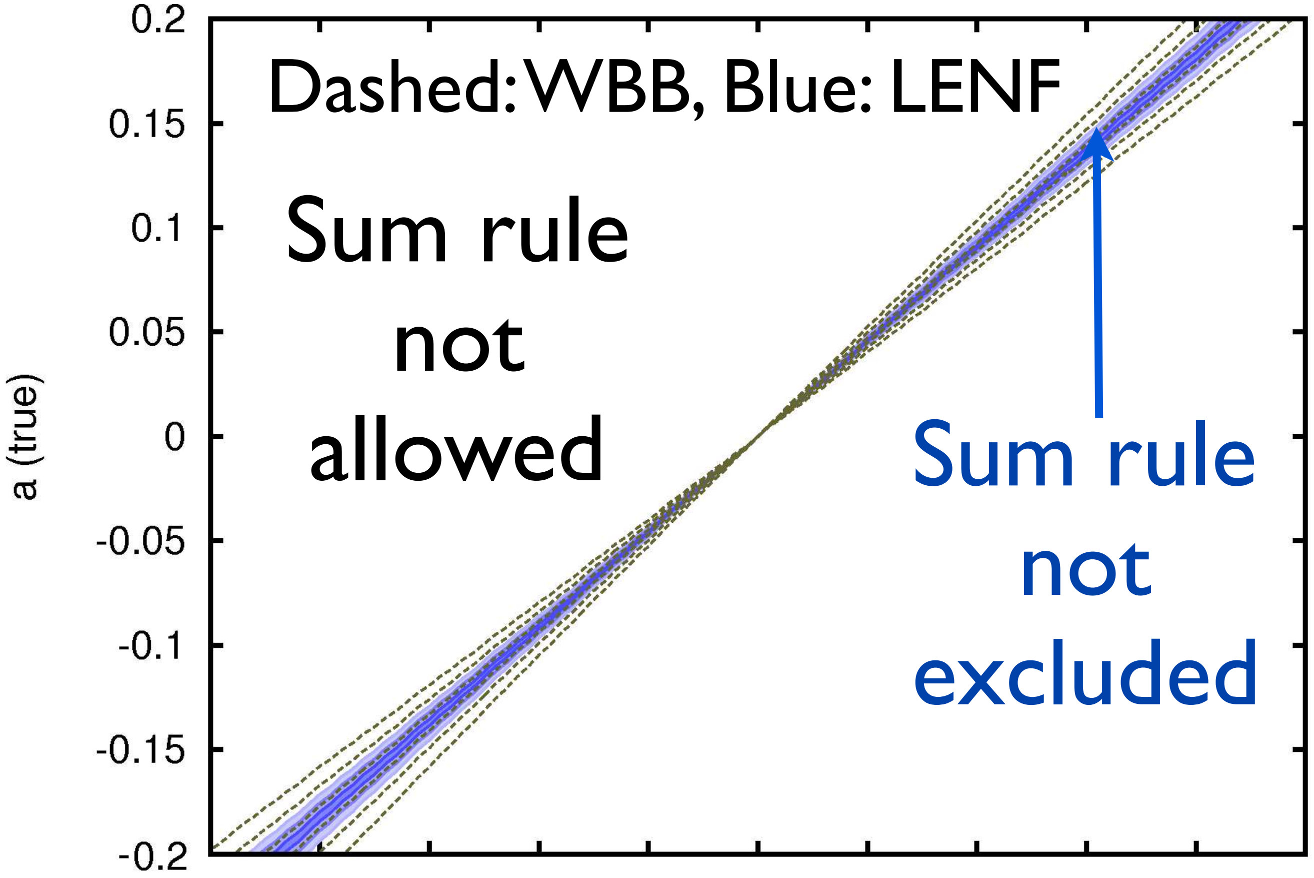


Ballett et al., 1612.07275



Coloma, Donini, Fernandez Martinez, Hernandez, 1203.5651

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



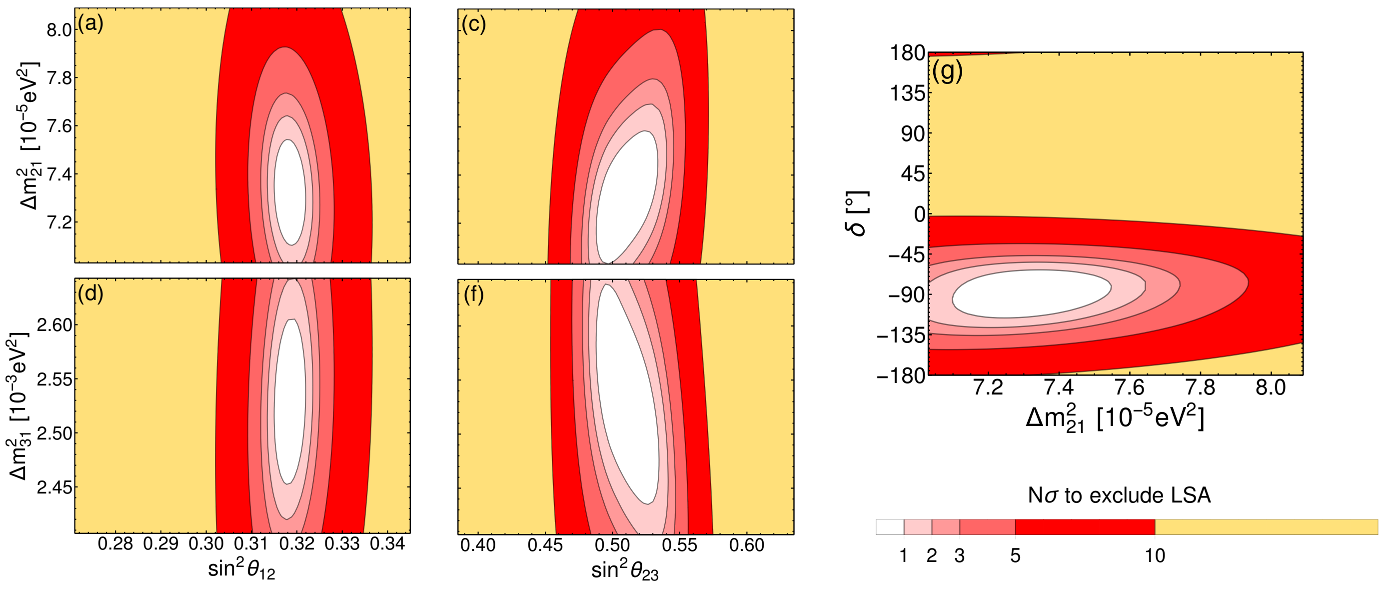
Dashed: WBB, Blue: LENF

Sum rule not allowed

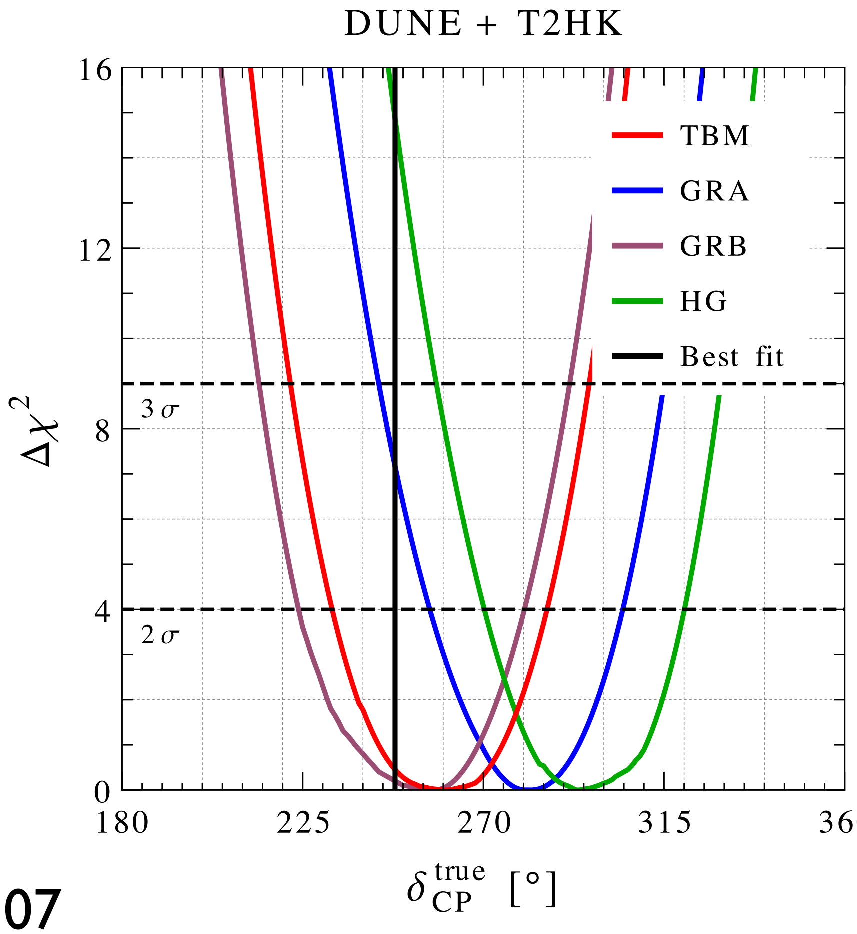
Sum rule not excluded

Ballett, King, Luhn, SP, Schmidt, 1308.4314

P. Ballett et al., 1612.01999



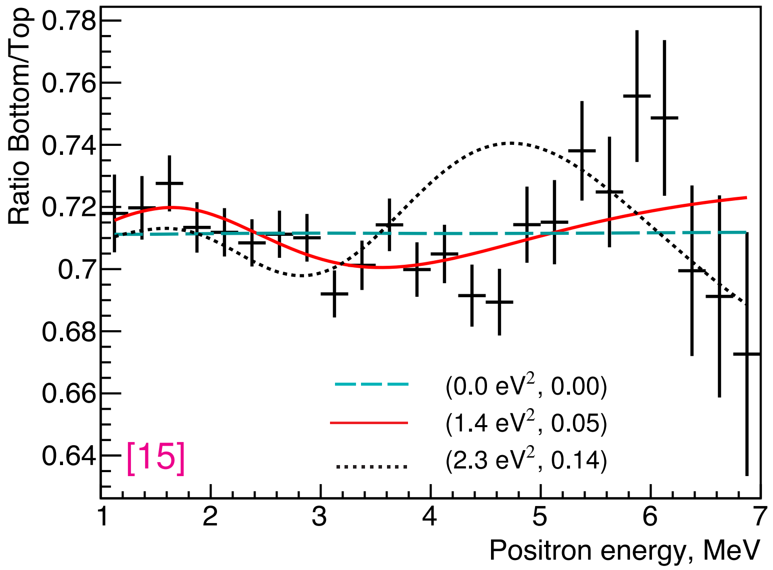
Symmetry form	θ_{12}^{ν} [°]	$\cos\delta_{\rm CP}$	$\delta_{\rm CP}$ [°]
BM	45	unphysical	unphysical
TBM	$\arcsin(1/\sqrt{3}) \approx 35$	-0.16	$99 \vee 261$
GRA	$\arctan(1/\phi) \approx 32$	0.21	$78 \vee 282$
GRB	$\arccos(\phi/2) = 36$	-0.24	$104 \vee 256$
HG	30	0.39	$67 \vee 293$



S. K. Agarwalla et al., 1711.02107

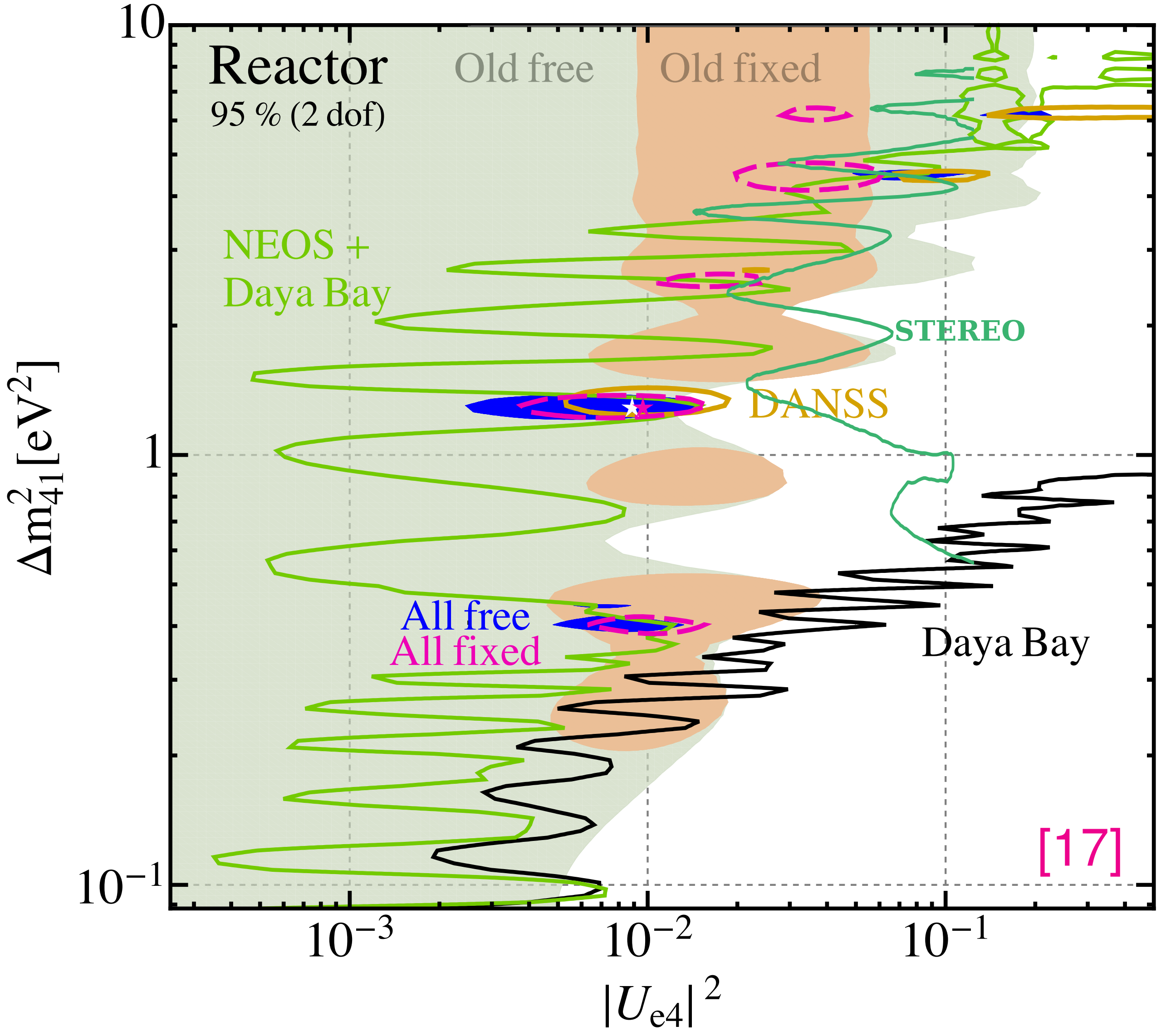
Tests of the standard 3-neutrino paradigm

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

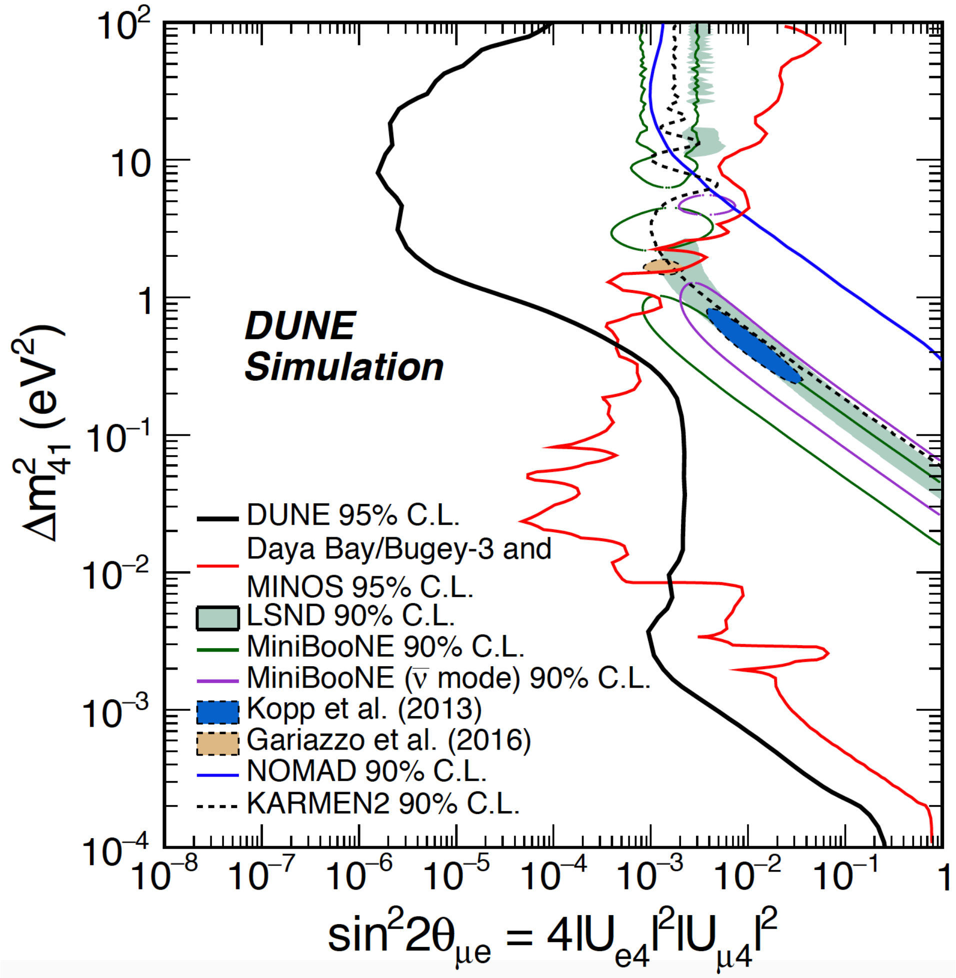


DANSS, 1804.04046

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

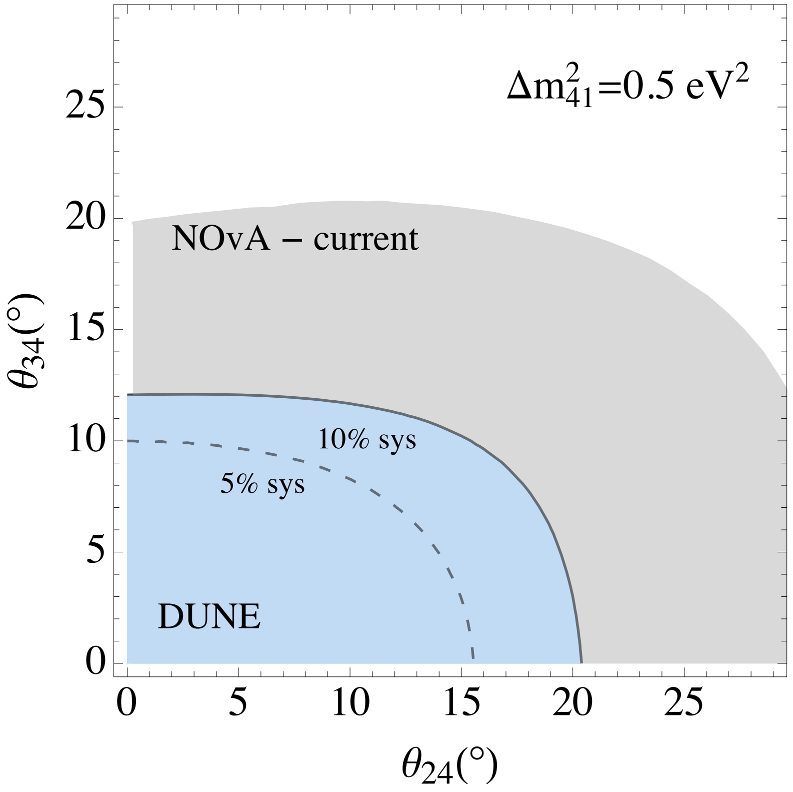


M. Dentler et al., 1803.10661

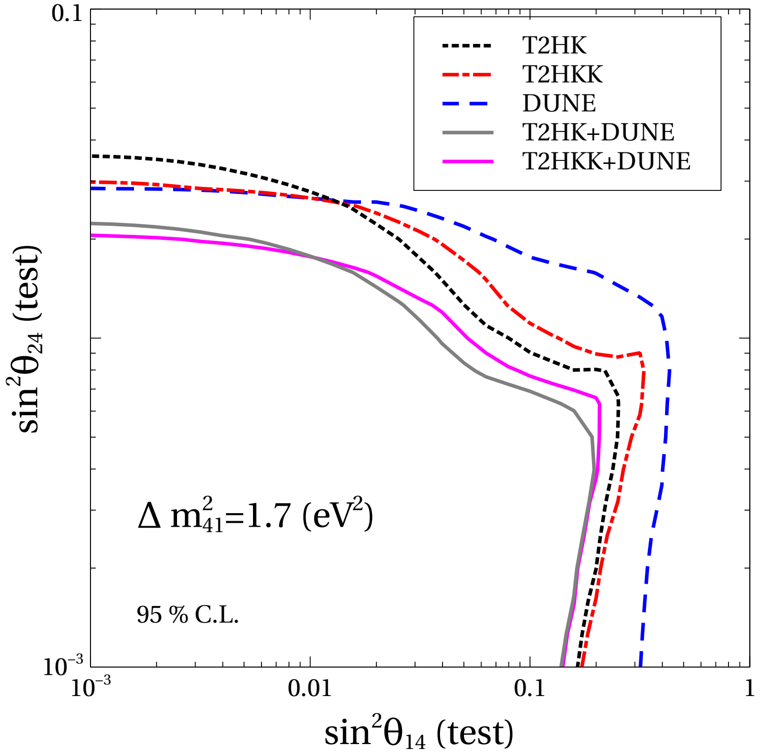


- DUNE sensitive to many BSM particles and processes
  - Light dark matter
  - Boosted dark matter
  - Sterile neutrinos
  - Non-standard interactions, non-unitary mixing, CPT violation
  - Neutrino trident searches
  - Large extra dimensions
  - Neutrinos from dark matter annihilation in sun

E. Worcester, for DUNE, Neutrino 2018



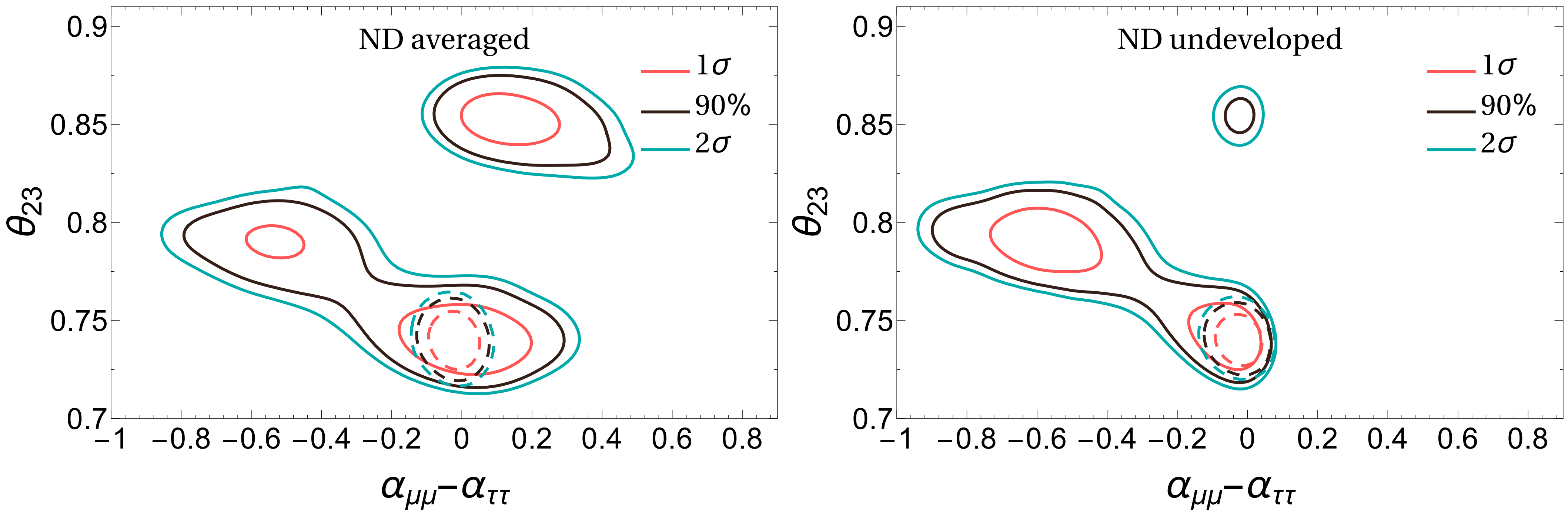
P. Coloma et al., 1707.05348



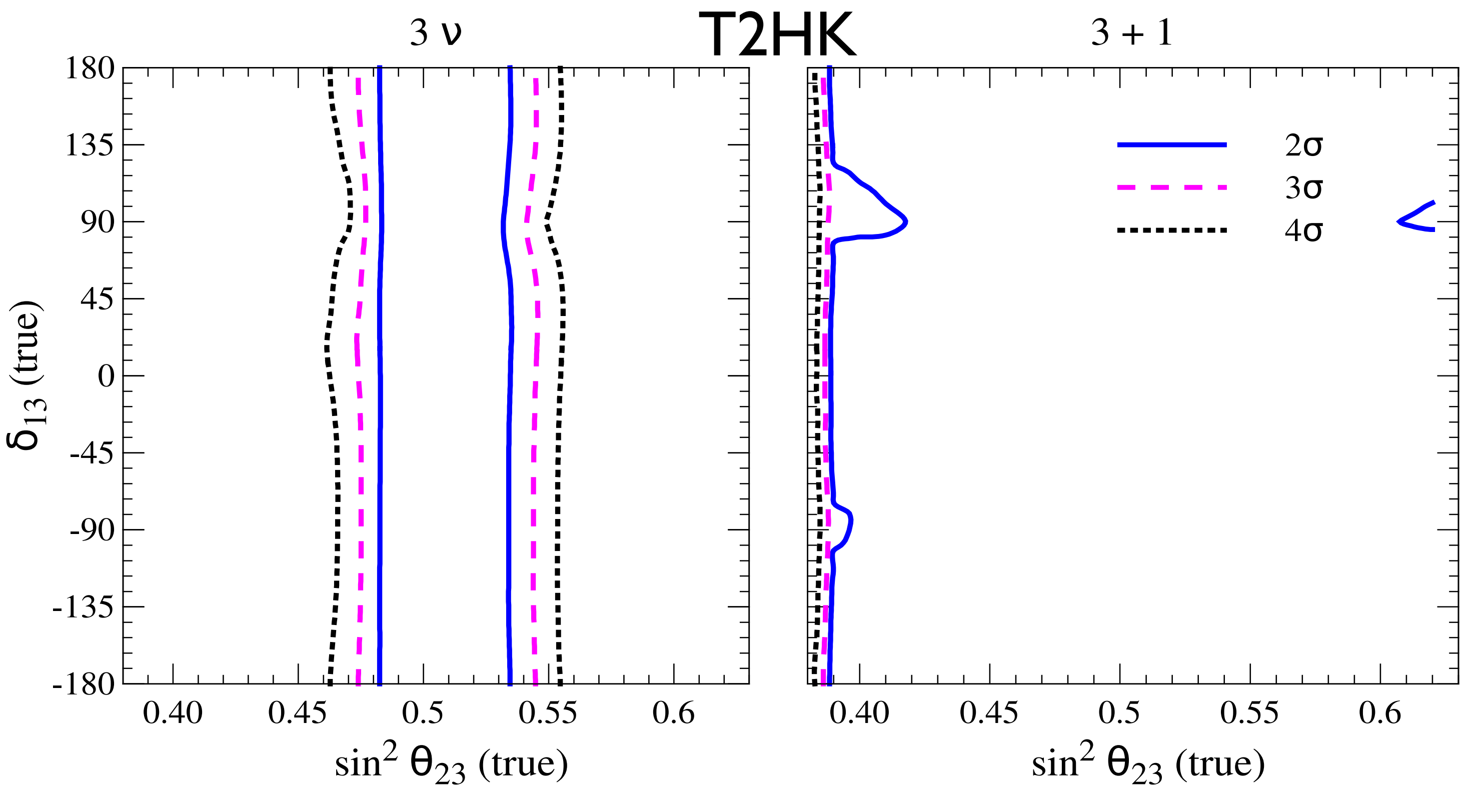
S. Choubey et al., 1711.07464

Thanks to the ND/FD, sensitivity to sterile neutrinos at different masses could be achieved.

DUNE



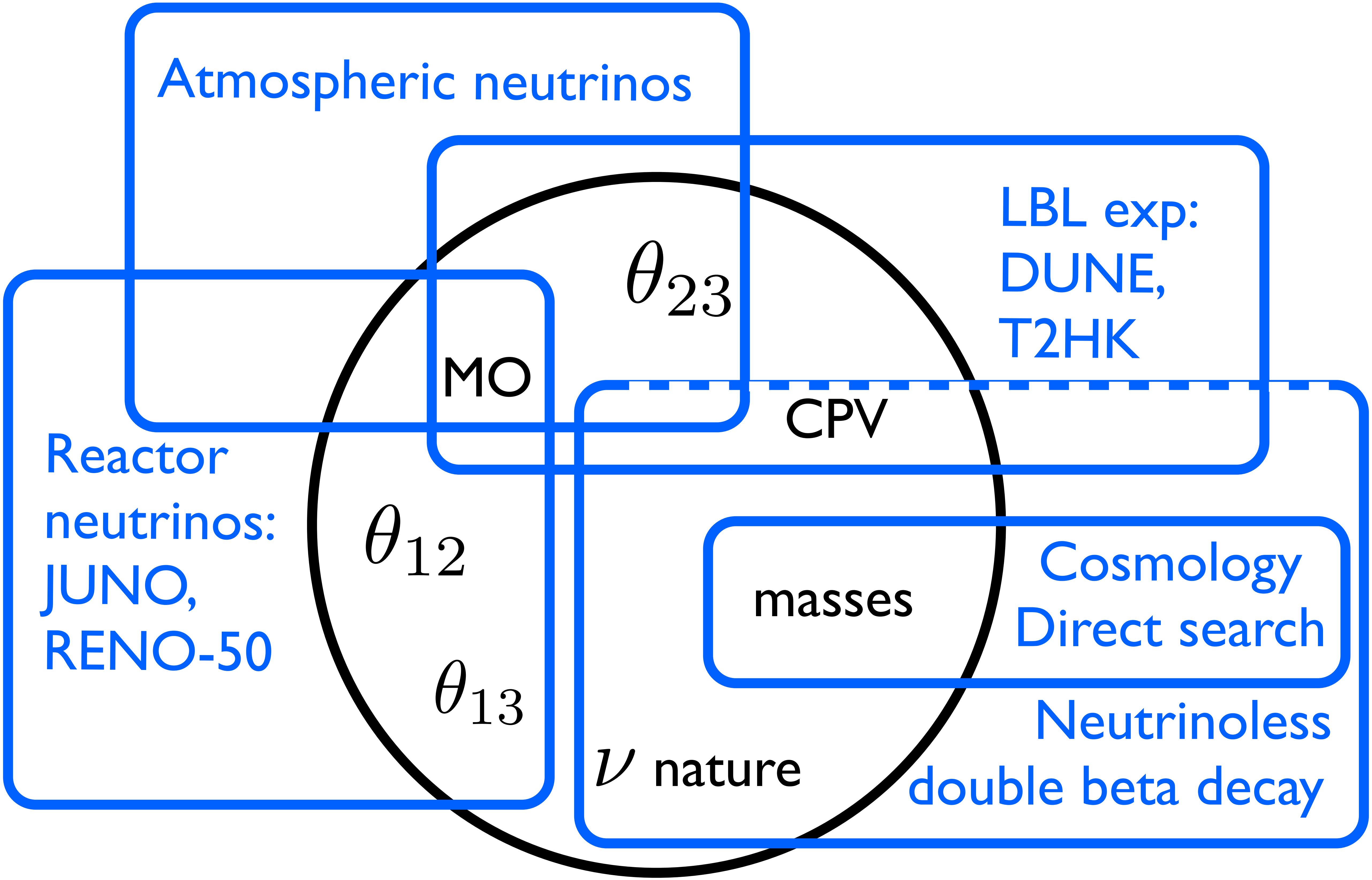
Blennow et al., 1609.08637; See also e.g. Gosh, Yasuda



While the MO and standard CPV remain broadly unaffected, theta23 determination can dramatically worsen.

S. K. Agarwalla et al., 1801.04855; see also, S. K. Agarwalla et al., PRL 118 (2017), Escrihuela et al., Kayser et al., De Gouvea et al., Dutta et al.

Complementarity



Atmospheric neutrinos

LBL exp:
DUNE,
T2HK

θ_{23}

MO

CPV

Reactor
neutrinos:
JUNO,
RENO-50

θ_{12}

θ_{13}

masses

Cosmology
Direct search

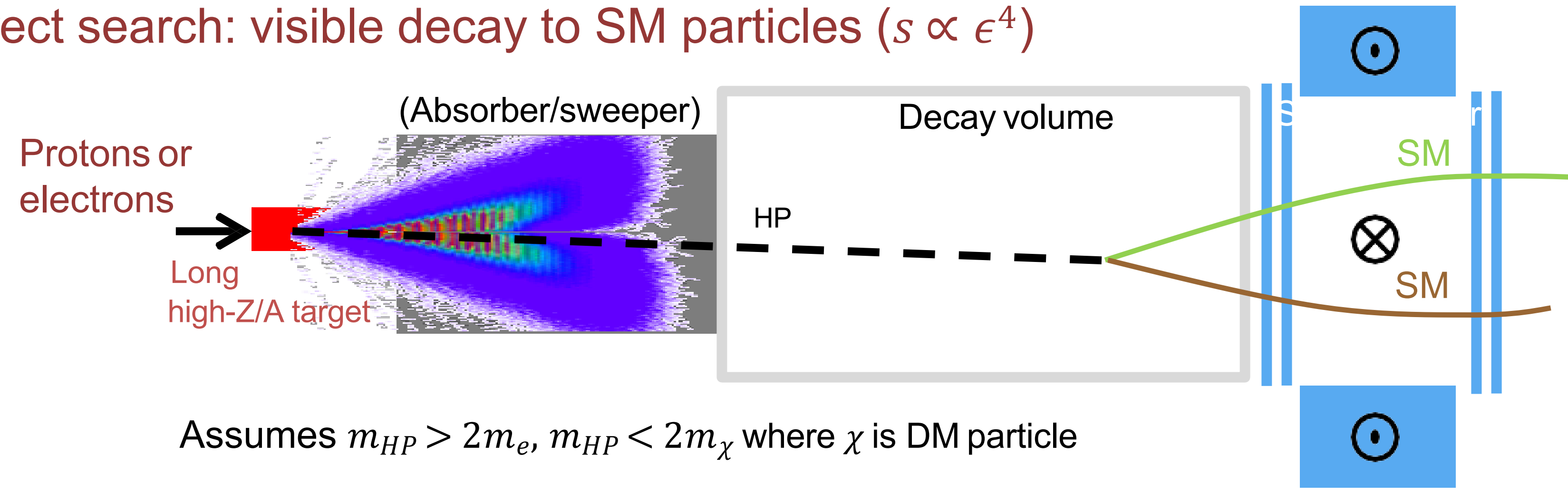
Neutrinoless
double beta decay

ν nature

Also: Tests of standard neutrino paradigm

DUNE ND as a beam-dump experiment

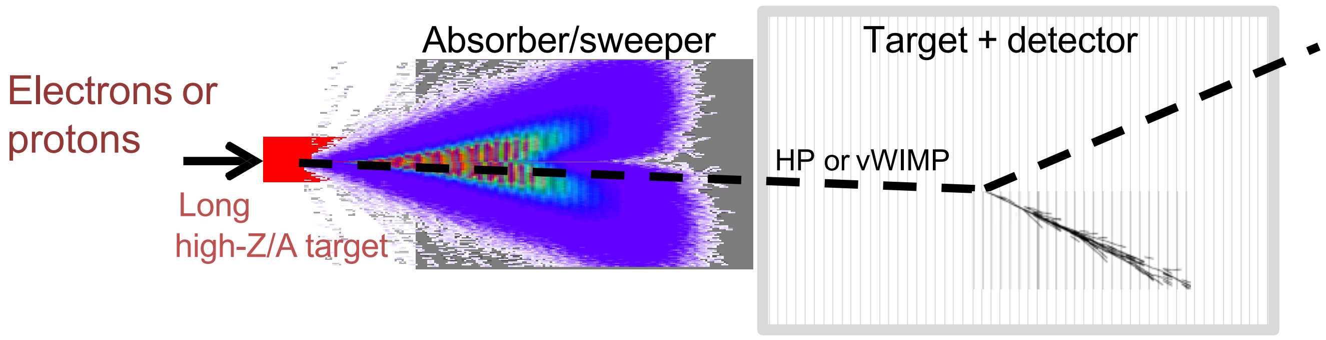
- Direct search: visible decay to SM particles ($s \propto \epsilon^4$)



Assumes $m_{HP} > 2m_e$, $m_{HP} < 2m_\chi$ where χ is DM particle

NA62++@CERN (p@400, 10^{18})
HPS, APEX, DarkLight@JLAB (e@1-10)
SHiP@CERN (p@400, 2×10^{20}),
SeaQuest@FNAL (p@120, 10^{18}–10^{20})
(LBNF@FNAL)

- Direct search: Scattering off atomic electrons and nuclei ($s \propto \epsilon^4$)



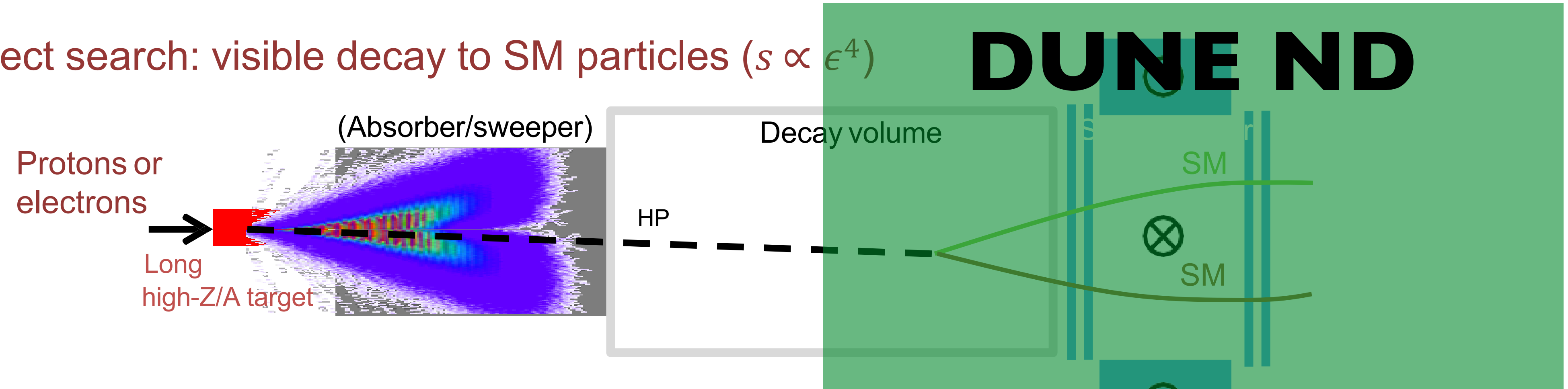
BDX@JLAB (e@11, 10^{22}),
MiniBooNE@FNAL (p@8.9, 10^{20}),
SHiP@CERN (p@400, 2×10^{20})
PADME (LNF)
(interest for BDX-like experiments at Mainz (MESA), SLAC, Cornell…)

M. Mezzetto, Neutrino 2018; Courtesy of R. Jacobsson

In recent years, interest has grown in BSM searches with neutrino detectors or in neutrino-related experiments: NA62, SHiP, MiniBooNE…

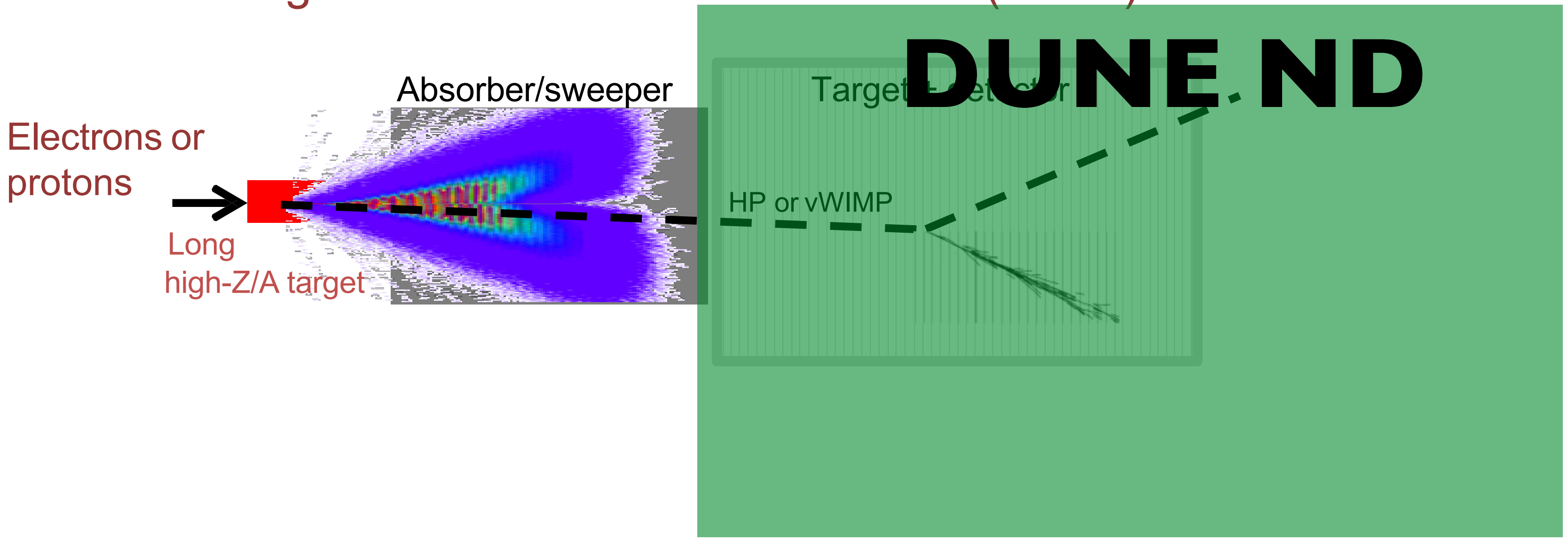
DUNE ND as a beam-dump experiment

- Direct search: visible decay to SM particles ($s \propto \epsilon^4$)



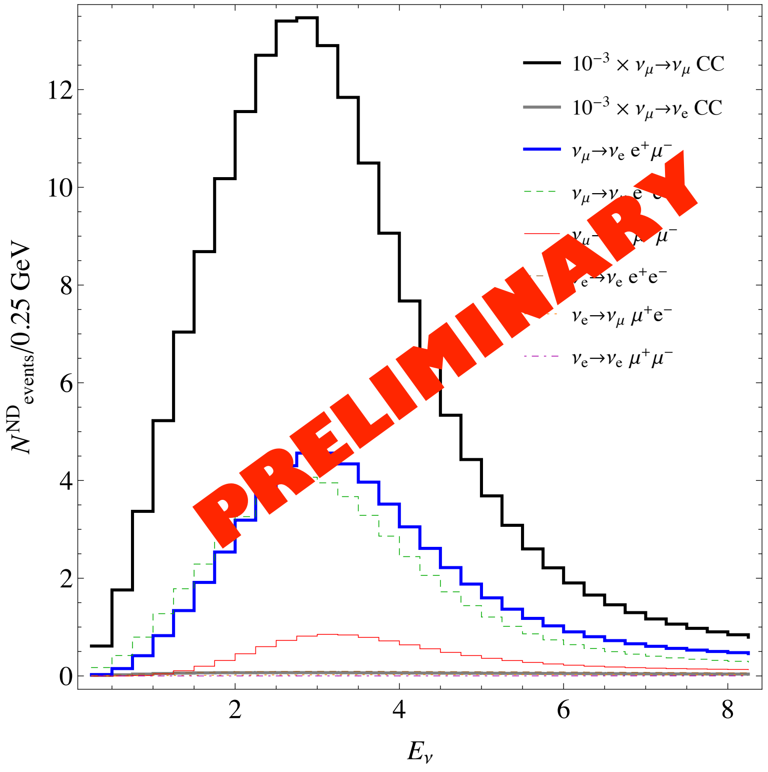
Assumes $m_{HP} > 2m_e$, $m_{HP} < 2m_\chi$ where χ is DM particle

- Direct search: Scattering off atomic electrons and nuclei ($s \propto \epsilon^4$)

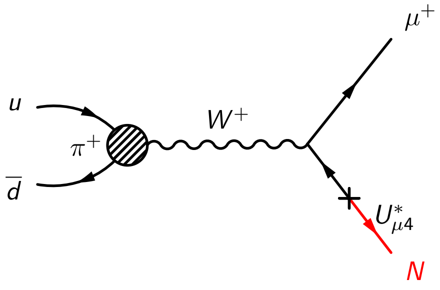


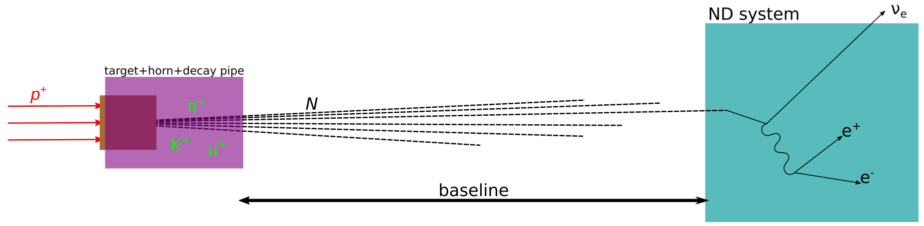
Any LBL experiment has the ingredients necessary for beam-dump-type of searches: a proton beam, target, an absorber (Earth), a near detector.

Trident searches at the DUNE ND, thanks to the very large flux.



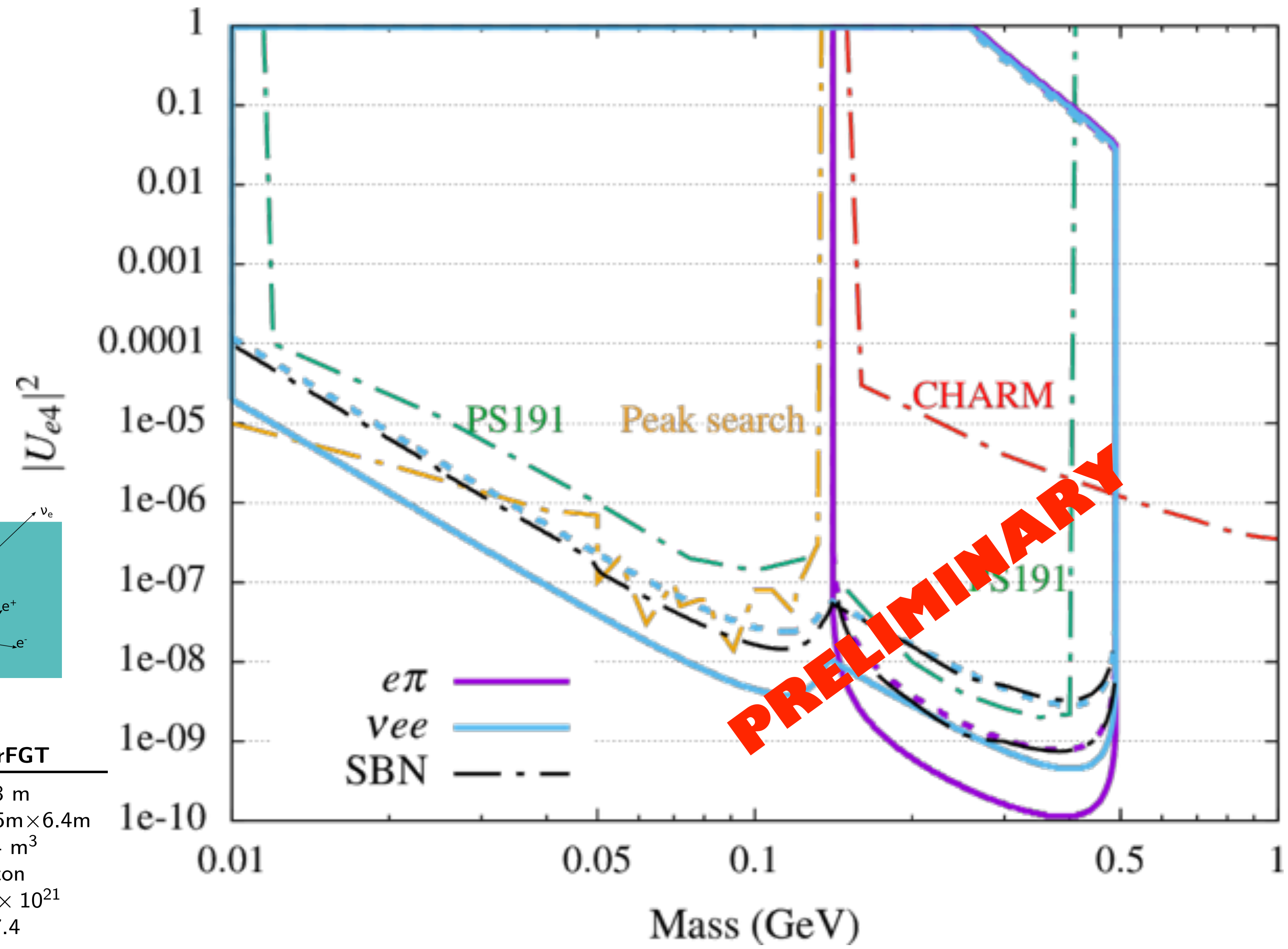
Ballett et al., in preparation





	PS191	SBND*	LArTPC	HPArFGT
Baseline	128 m	110 m	574 m	578 m
Size	–	4m×4m×5m	3m×3m×4m	3.5m×3.5m×6.4m
Volume	216 m^3	80 m^3	36 m^3	78.4 m^3
Weight	–	112 ton	50 ton	8 ton
POT	0.86×10^{19}	6.6×10^{20}	13.23×10^{21}	13.23×10^{21}
Exposure	1.0	39.5	12.7	27.4

Ballett et al., in preparation



Conclusions

- In the past few years, the neutrino oscillation parameters have been measured with good precision. First hints for CPV and MO are present,
- The main goals of future LBL experiments are the mass ordering, CPV searches and precision measurements of the oscillation parameters.
- They allow also searches for non-standard neutrino physics (sterile neutrinos, NSI, non-unitarity…) and can act as beam-dump experiments (heavy sterile neutrino, DM, Z'…)