Lecture 3: Neutrino oscillations

Aims

Consider neutrino oscillations in the future experimental programme and their role in answering the open questions in neutrino phenomenology.

Outline

Current knowledge of neutrino properties
Open phenomenological questions
Long baseline neutrino oscillations
Atmospheric and reactor neutrino oscillations
Sterile neutrinos
NSI and non-unitarity

Recap: Neutrinos oscillations in vacuum

- 2-neutrino appearance probability:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(\frac{\Delta m^2_{21}}{4E}L)$$

- 3-neutrino oscillations for $\frac{\Delta m^2_{21}}{4E}L \ll 1$

$$P(\nu_\alpha \to \nu_\beta) = 4|U_{\alpha 3}U_{\beta 3}|^2 \sin^2 \frac{\Delta m^2_{31}L}{4E}$$

- 3-neutrino oscillations for $\frac{\Delta m^2_{31}}{4E}L \gg 1$

$$P(\bar\nu_e \to \bar\nu_e; t) \quad \simeq \quad c^4_{13}\left(1 - \sin^2(2\theta_{12})\sin^2\frac{\Delta m^2_{21}L}{4E}\right) + s^4_{13}$$

- CP-asymmetry

$$P(\nu_\alpha \to \nu_\beta; t) - P(\bar\nu_\alpha \to \bar\nu_\beta; t) =$$

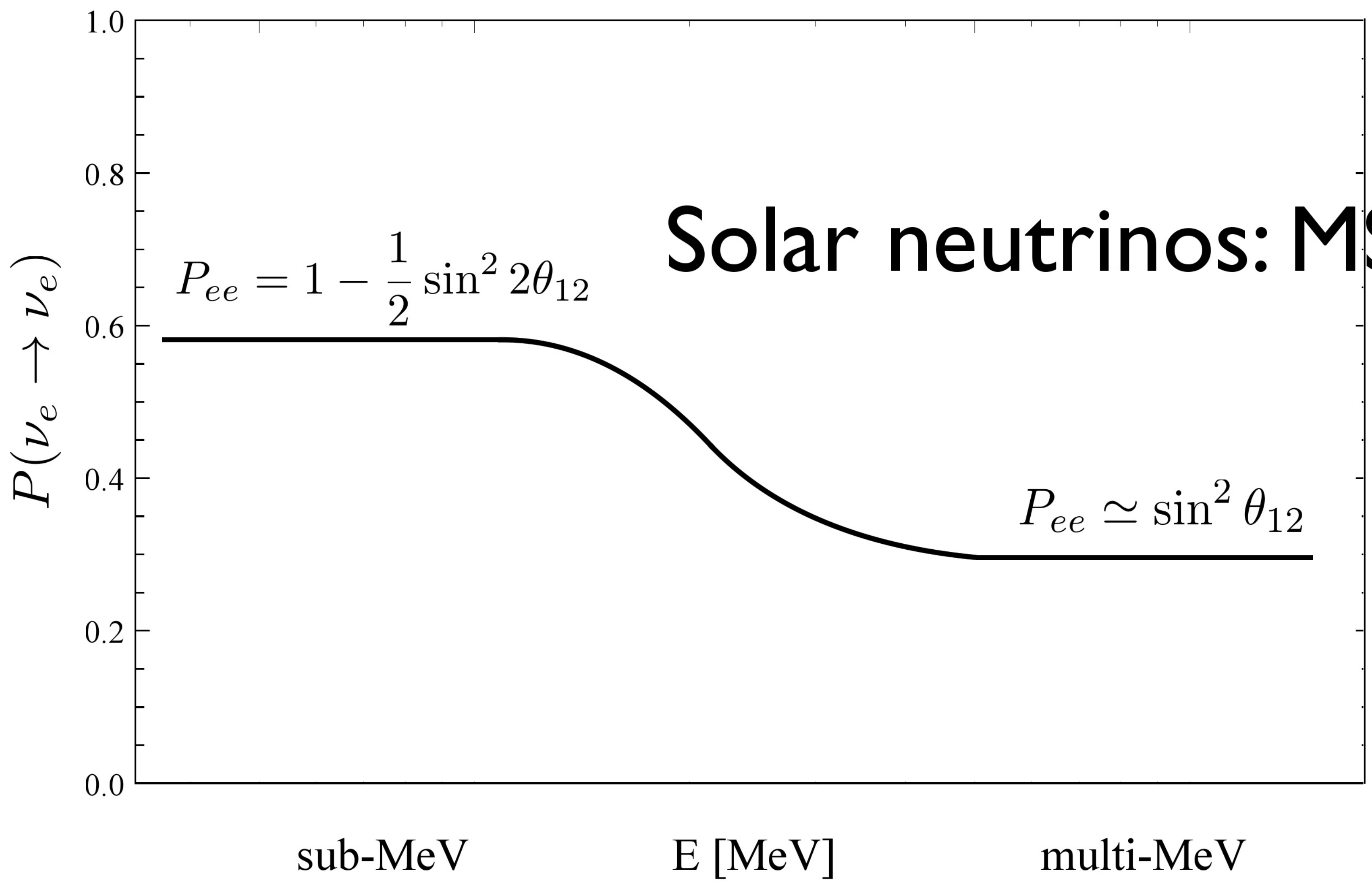
$$4 s_{12}c_{12}s_{13}c^2_{13}s_{23}c_{23}\sin\delta\Big[\sin\left(\frac{\Delta m^2_{12}L}{2E}\right) + \sin\left(\frac{\Delta m^2_{23}L}{2E}\right) + \sin\left(\frac{\Delta m^2_{31}L}{2E}\right)\Big]$$

Neutrinos oscillations in matter

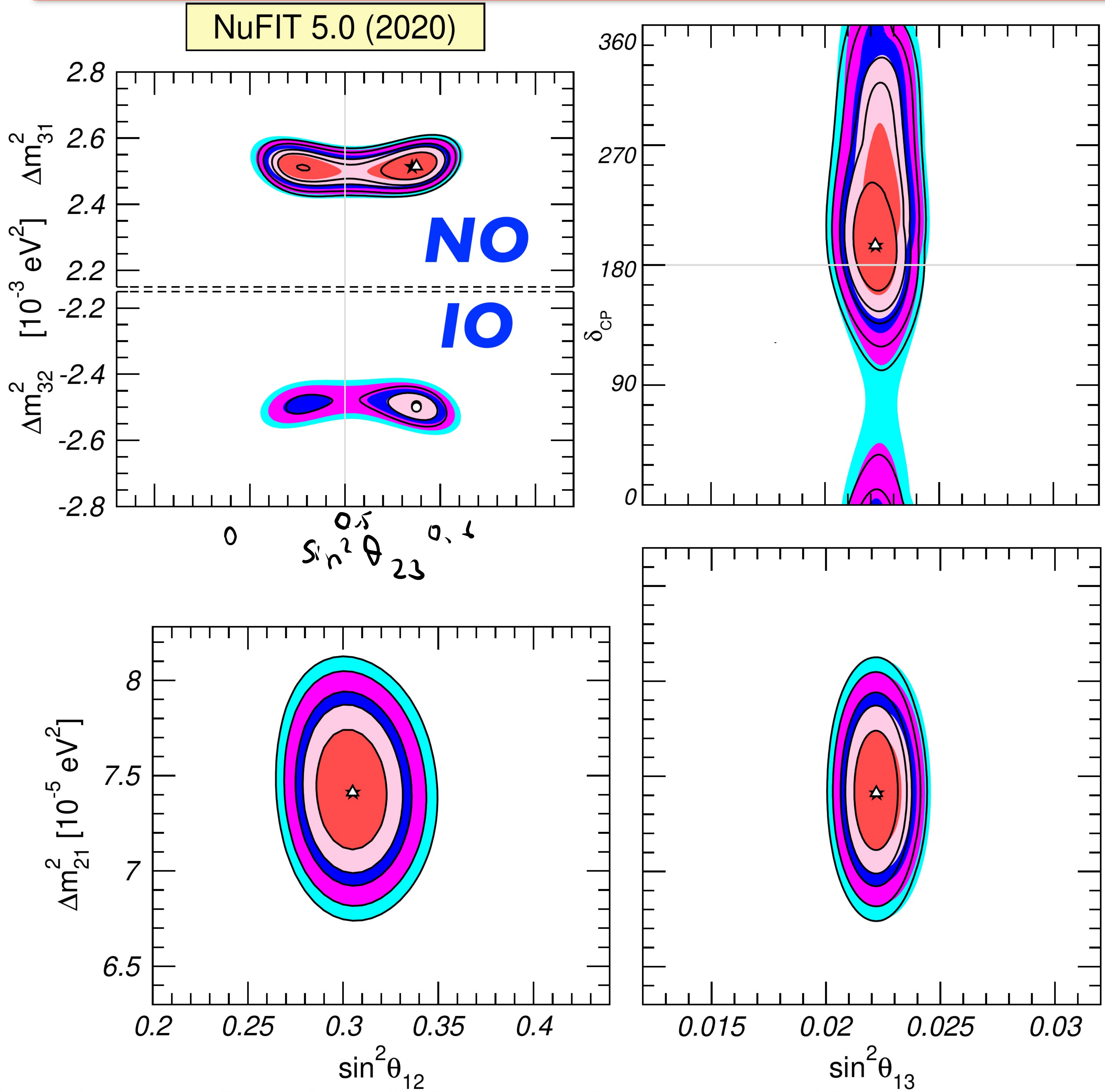
When neutrinos travel through a medium, they interact with the background, acquiring an effective mass. This modifies the oscillation probability w.r.t. vacuum.

$$\tan(2\theta_m) = \frac{\frac{\Delta m^2}{2E}\sin(2\theta)}{\frac{\Delta m^2}{2E}\cos(2\theta) - \sqrt{2}G_F N_e}$$

Solar neutrinos: MSW effect



Current status of neutrino parameters



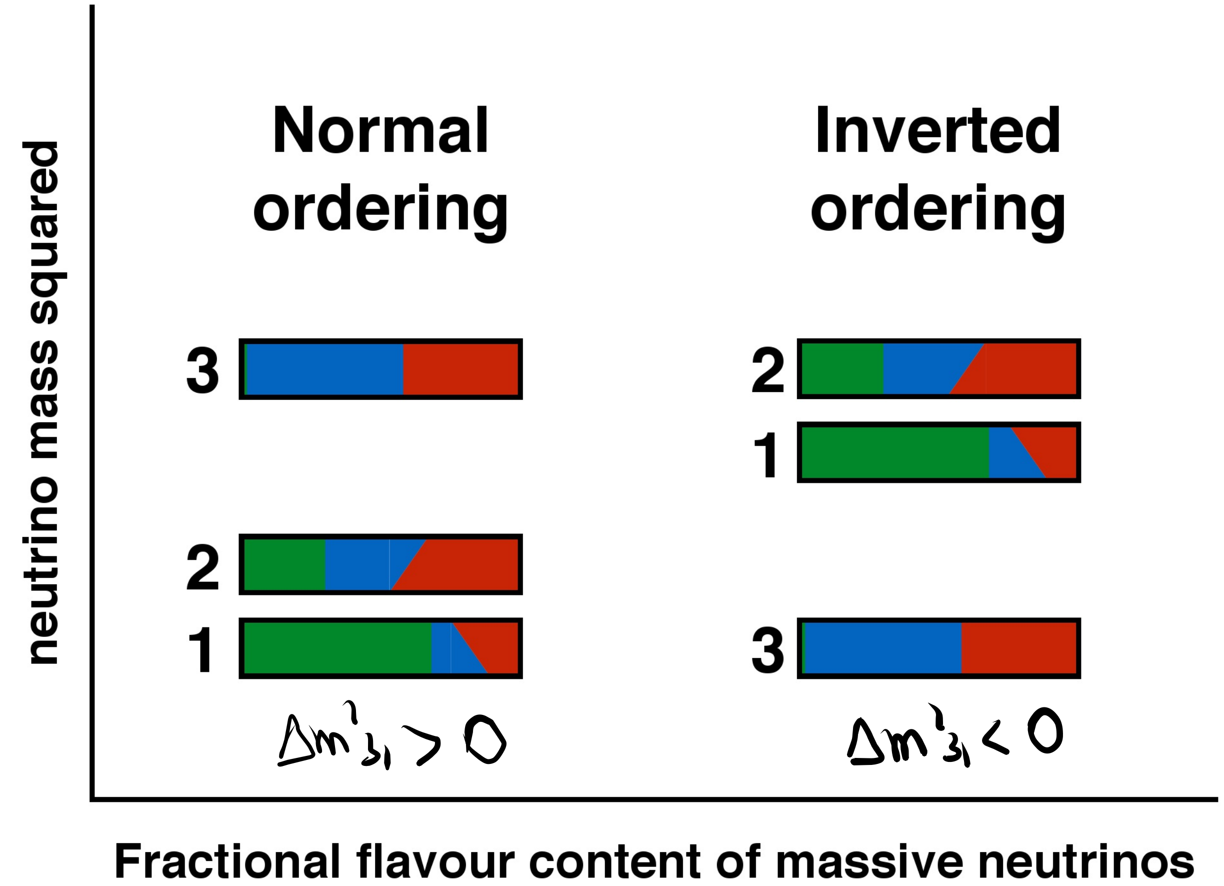
Current knowledge of neutrino properties:

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

http://www.nu-fit.org/ M. C. Gonzalez-Garcia et al., 2007.14792

Neutrino masses

$\Delta m_s^2 \ll \Delta m_A^2$ implies at least 3 massive neutrinos.



Using

$$m_2 = \sqrt{m_2^2 - m_1^2 + m_1^2} = \sqrt{\Delta m^2_{21} + m_1^2}$$

we can express the masses in terms of MO and m_{MIN}:

NO

$$m_3 = \sqrt{\Delta m^2_{31} + m_1^2}$$

$$m_2 = \sqrt{\Delta m^2_{21} + m_1^2}$$

m_1

IO

$$m_1 \simeq m_2 \simeq \sqrt{|\Delta m^2_{31}| + m_3^2}$$

m_3

There are three limiting cases:

- normal hierarchical spectrum (NH): requires NO and m_1~0.

$m_1 \sim 0$, $m_2 \sim \sqrt{\Delta m^2_{21}} \sim 0.01$ eV $m_3 \sim \sqrt{\Delta m^2_{31}} \sim 0.05$ eV

- inverted hierarchical spectrum (IH): requires IO and m_3~0.

$m_3 \sim 0$, $m_1 \sim m_2 \sim \sqrt{|\Delta m^2_{31}|} \sim 0.05$ eV

- quasi-degenerate spectrum (QD): for m1>0.1 eV.

$m_1 \sim m_2 \sim m_3$

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the mass ordering. Currently there is a hint in favour of NO based mainly on atmospheric and LBL events.

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

What do we still need to know?

- **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?

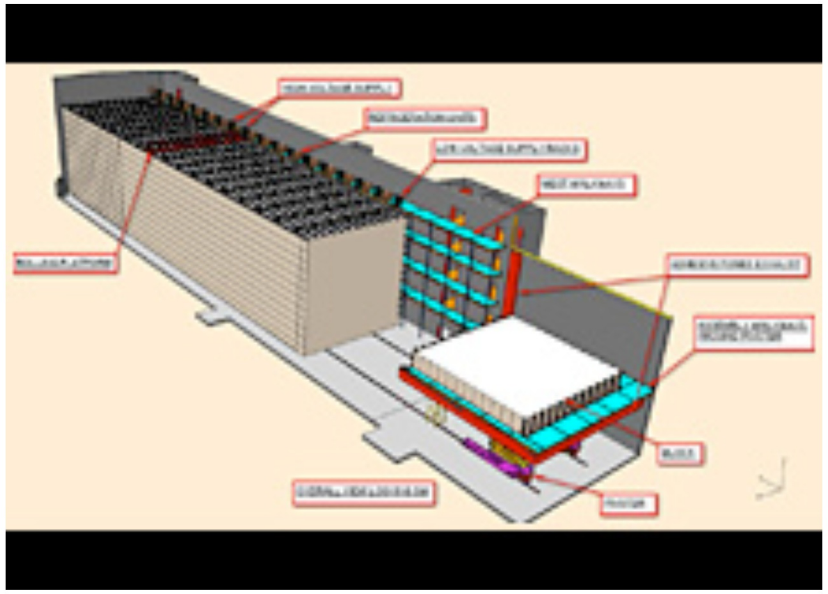
What do we still need to know?

- **What is the nature of neutrinos? Dirac vs Majorana?**
  Neutrinoless dbeta decay
- **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.

  LBL: T2K, NOvA, DUNE, T2HK, ESSnuSB, Daedalus, nuFACT..., PINGU, ORCA, INO, JUNO
- **What are the precise values of mixing angles?** Do they suggest an underlying pattern?

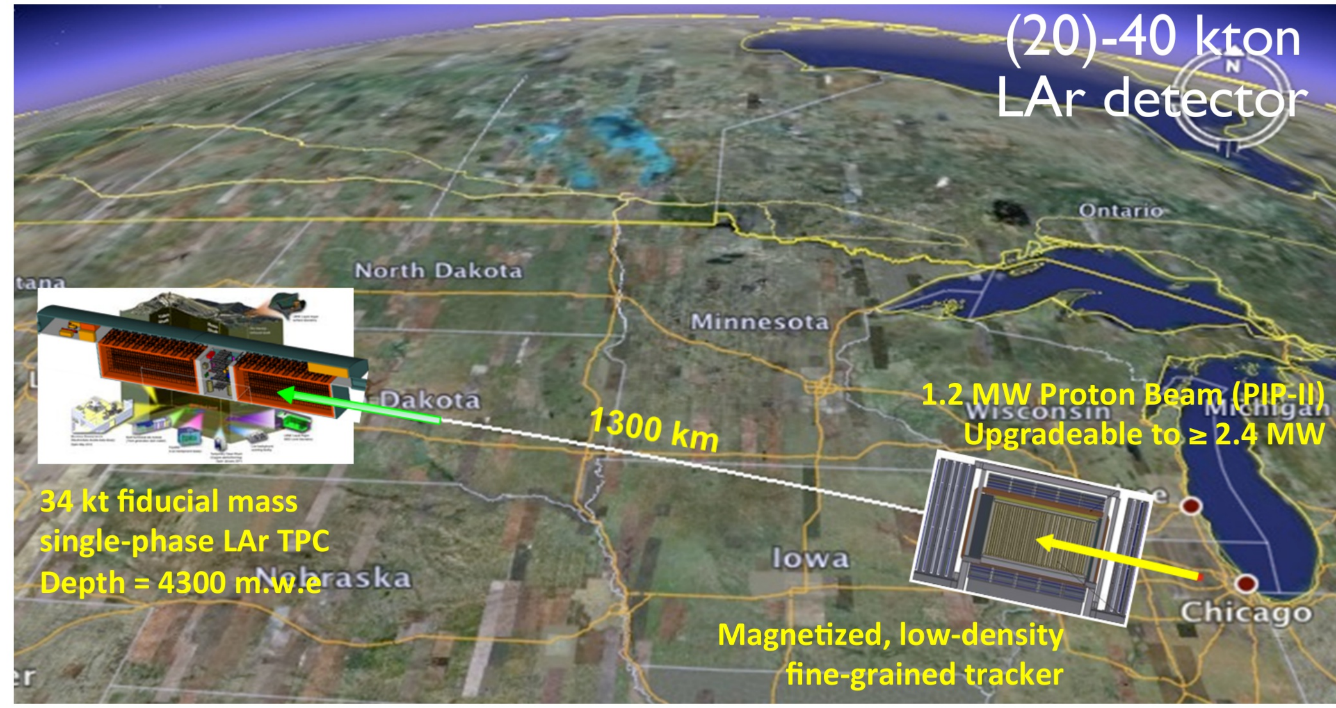
  reactor SBL and MBL, atm, LBL, ...
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects? MINOS+, MicroBooNE, SoLid, ...

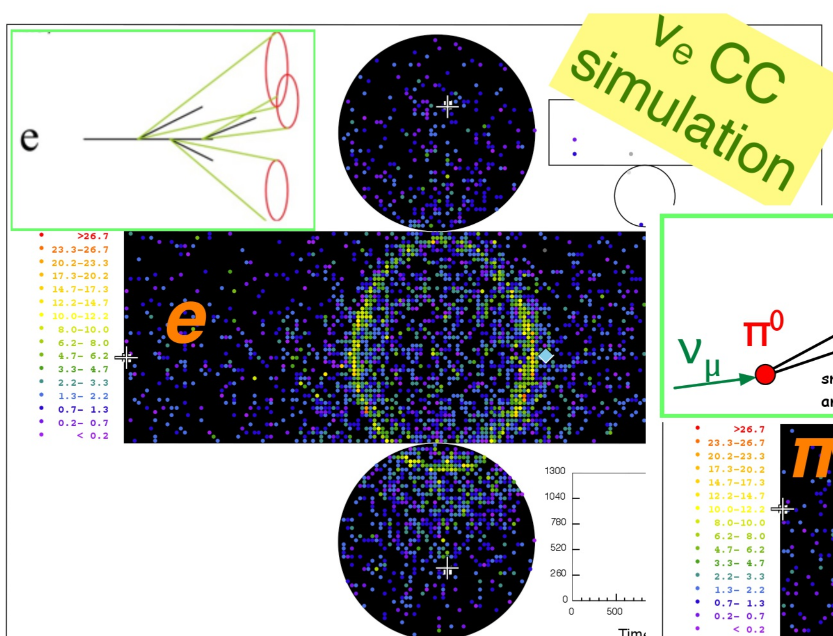
Long baseline neutrino oscillations



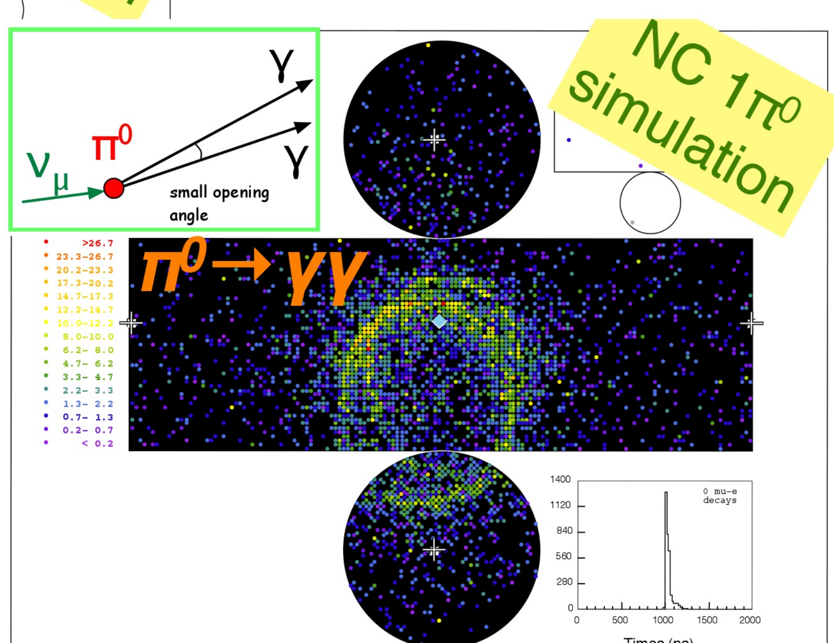
NOvA: 810 km off-axis
~14 kton plastic scintillator detector
T2K: 295 km off-axis
~22.5 kton WC detector

DUNE: 1300 km on-axis
(20)-40 kton LAr detector

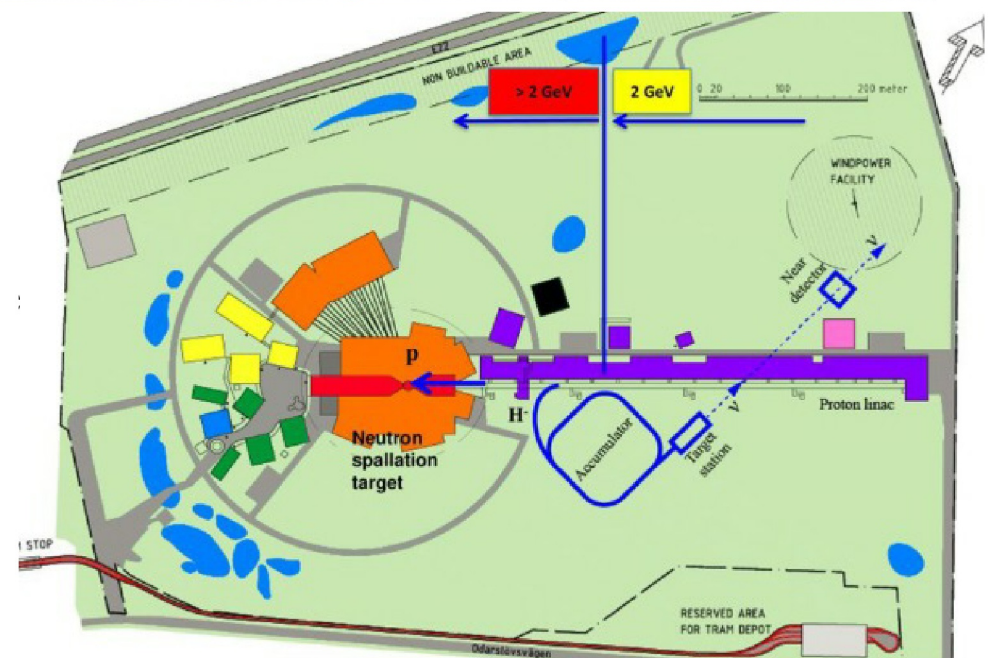




T2HK: 295 km off-axis
~1 Mton WC detector



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 oscillation maximum

Matter effects in long baseline experiments

We focus on the subdominant appearance oscillation channel muon to electron neutrinos:

$$P(\nu_\mu \to \nu_e)$$

At first approximation we neglect Δm^2_{21} but we include matter effects in the constant density approximation.

$$\tan(2\theta_m) = \frac{\frac{\Delta m^2}{2E}\sin(2\theta)}{\frac{\Delta m^2}{2E}\cos(2\theta) - \sqrt{2}G_F N_e}$$

Even if resonance is not achieved, there is an enhancement of the oscillation probability in neutrinos or antineutrinos.

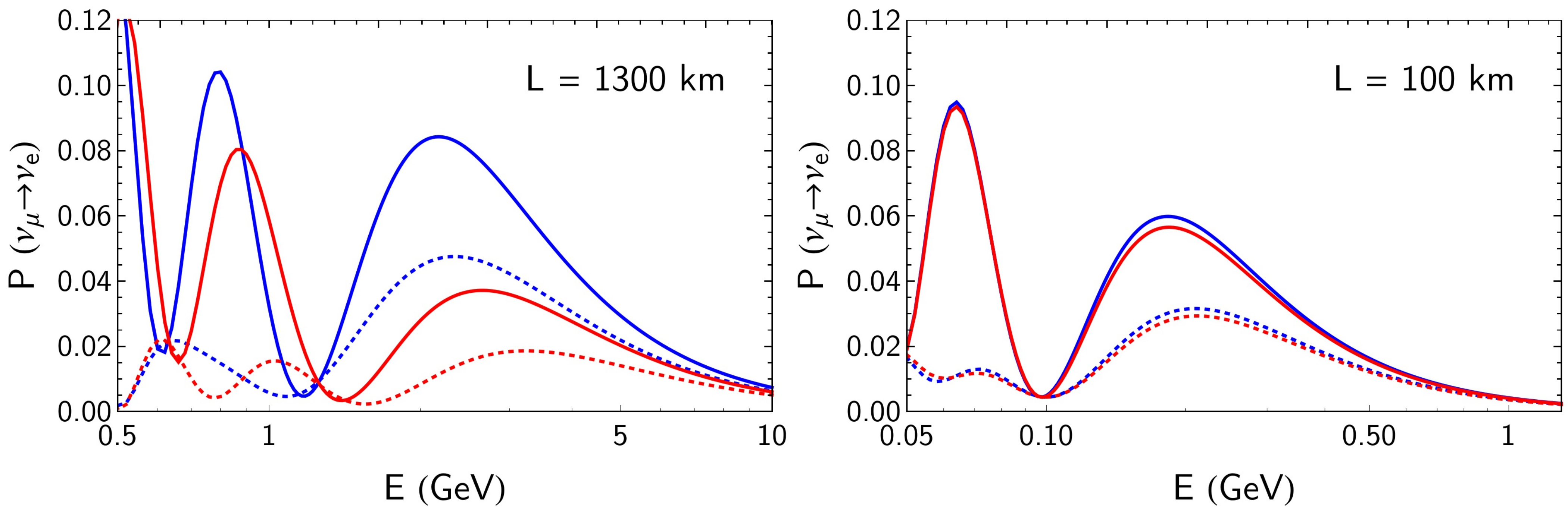
Matter effects modify the oscillation probability in LBL experiments.

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

The probability enhancement happens for

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

The impact is stronger at higher E and at longer L.



Now, let's consider the CPV effects. For simplicity, let's switch off matter effects.

$$P(\nu_\alpha \to \nu_\beta; t) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta; t) =$$

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

$$\sim \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\Delta m_{21}^2 L}{2E} \sin\delta \ldots$$

Considering all effects, one can approximate the probability:

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

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

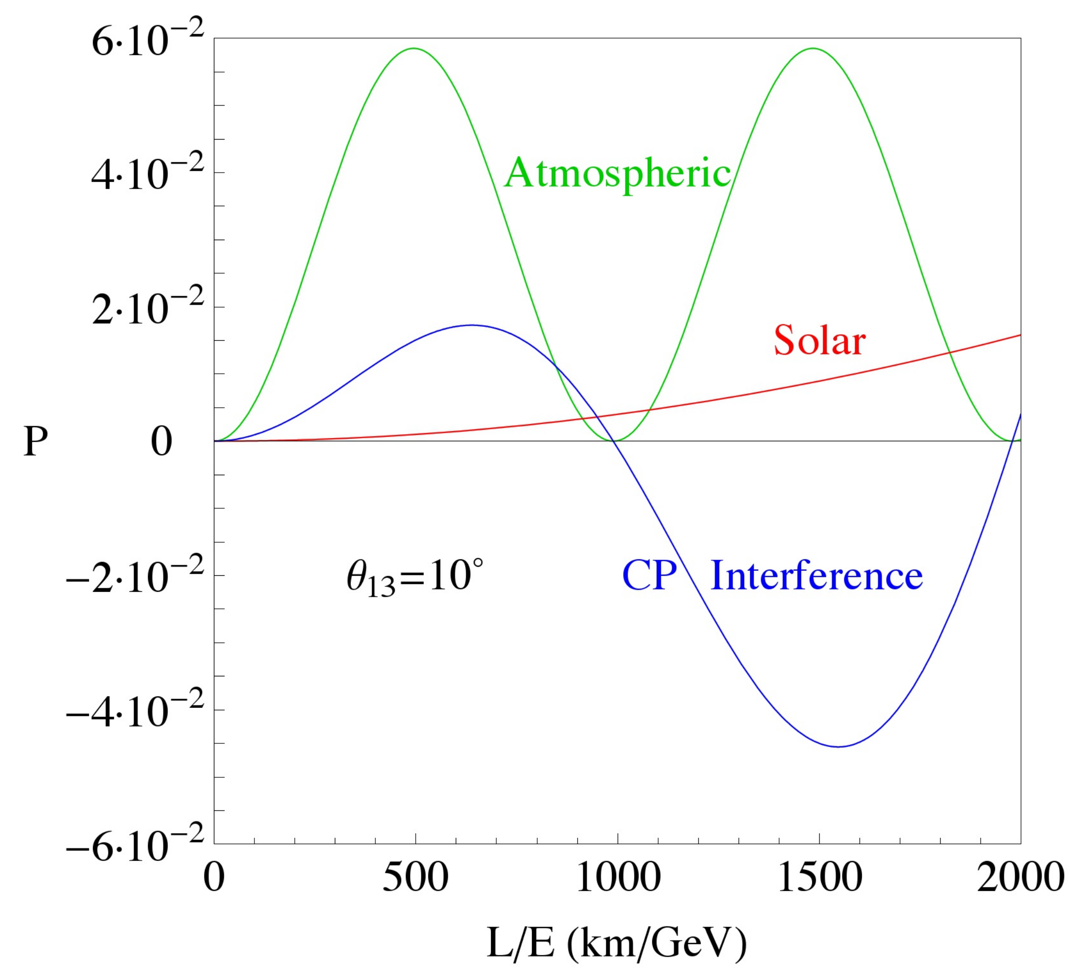
$r_A = \frac{2\sqrt{2} G_F N_e E}{\Delta_{31}}$

$\Delta_{31} = \Delta m^2_{31}$

$\Delta_{21} = \Delta m^2_{21}$

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

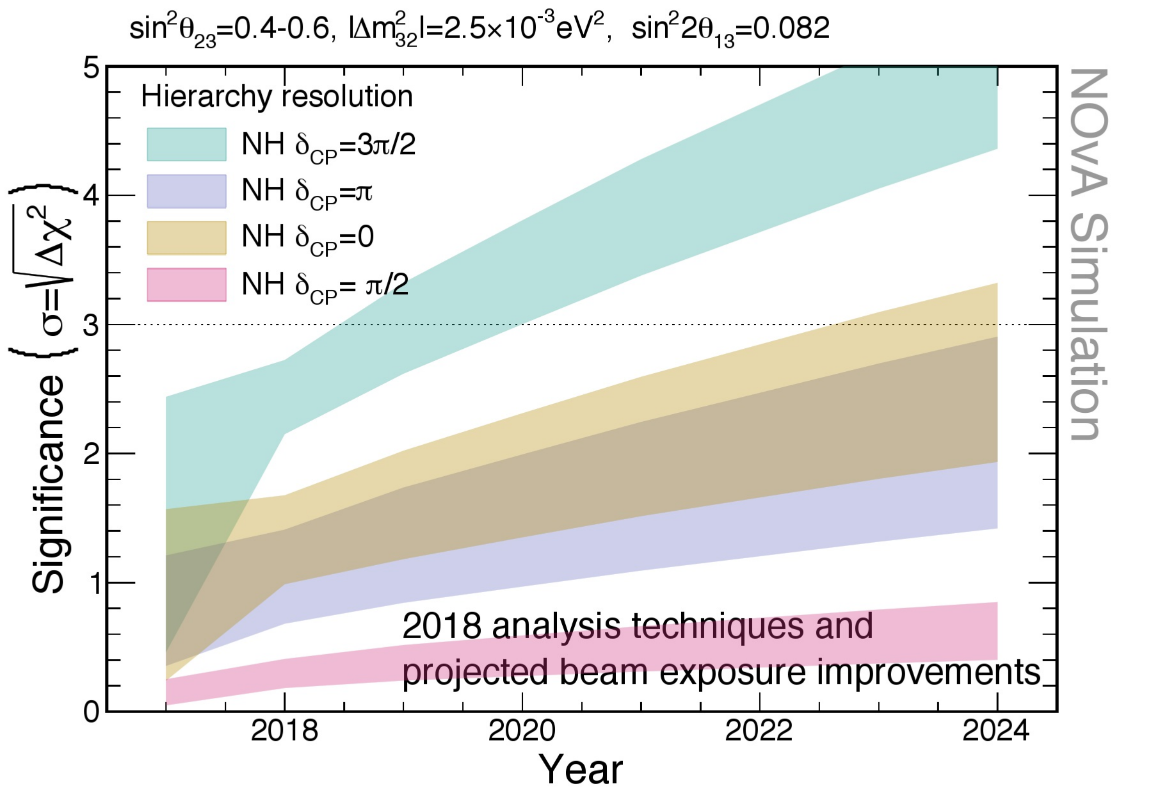
- The CP asymmetry peaks for sin^2 2 theta13 ~0.001. Large theta13 makes its searches possible but not ideal.
- Degeneracies with the mass hierarchy and theta23.
- CPV effects are more pronounced at low energy.



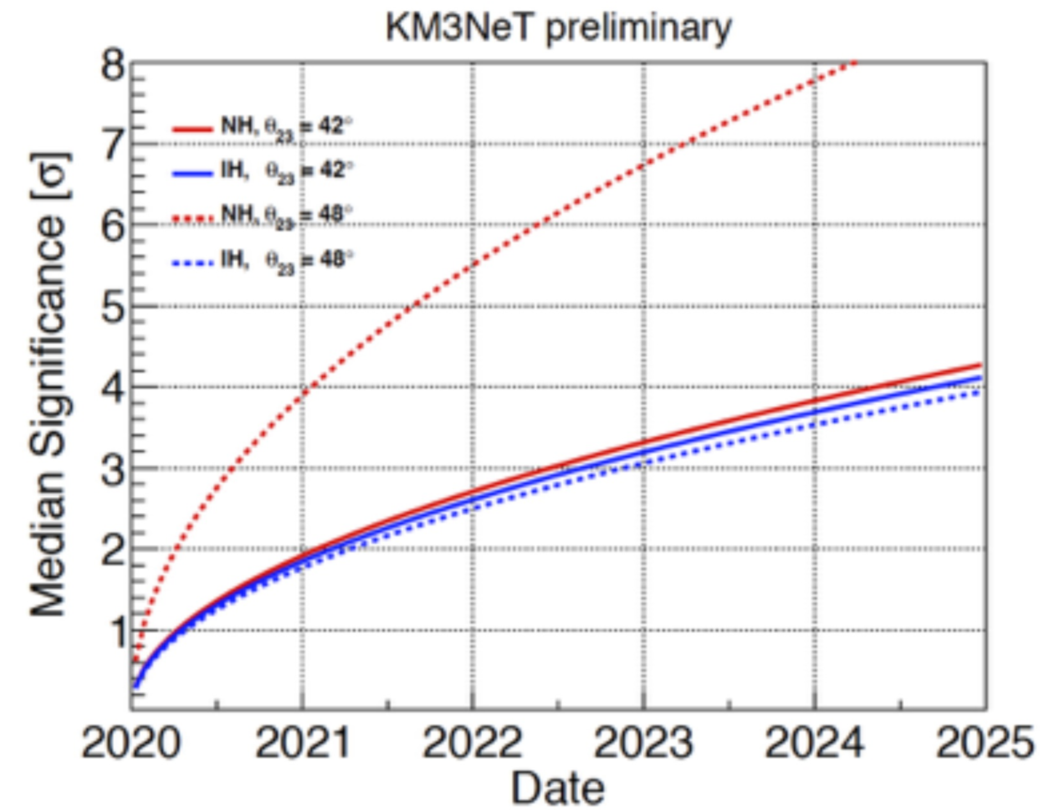
P. Coloma, E. Fernandez-Martinez, JHEP1204

Near future sensitivity

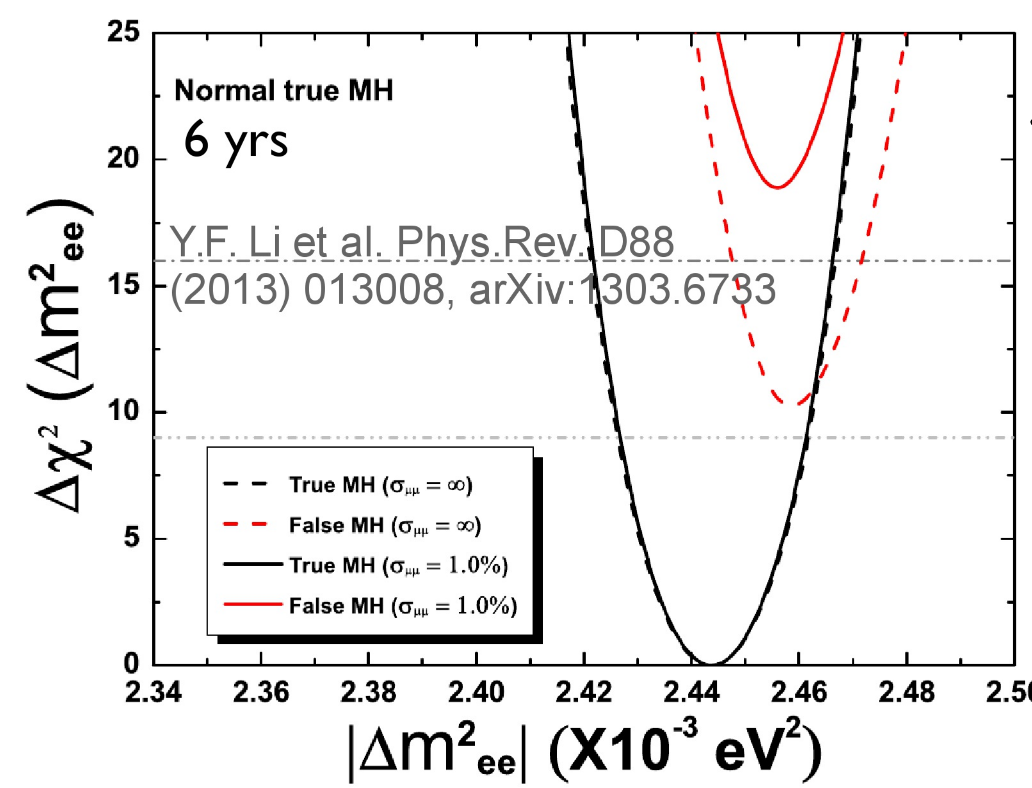
MO



M. Sanchez, Neutrino 2018



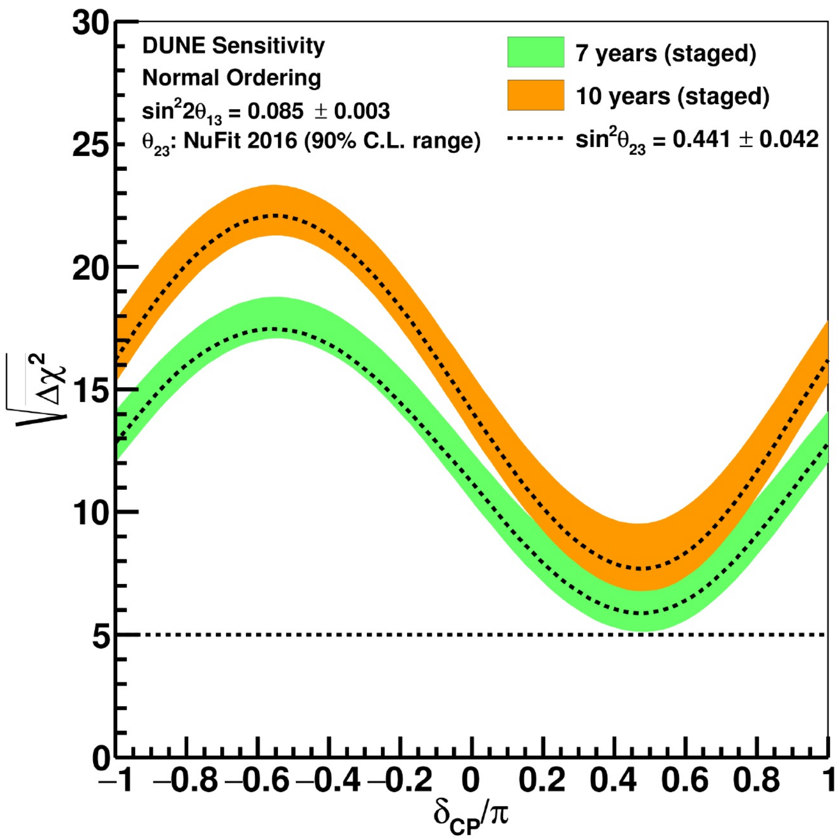
Adrian-Martinez et al., 1601.07459

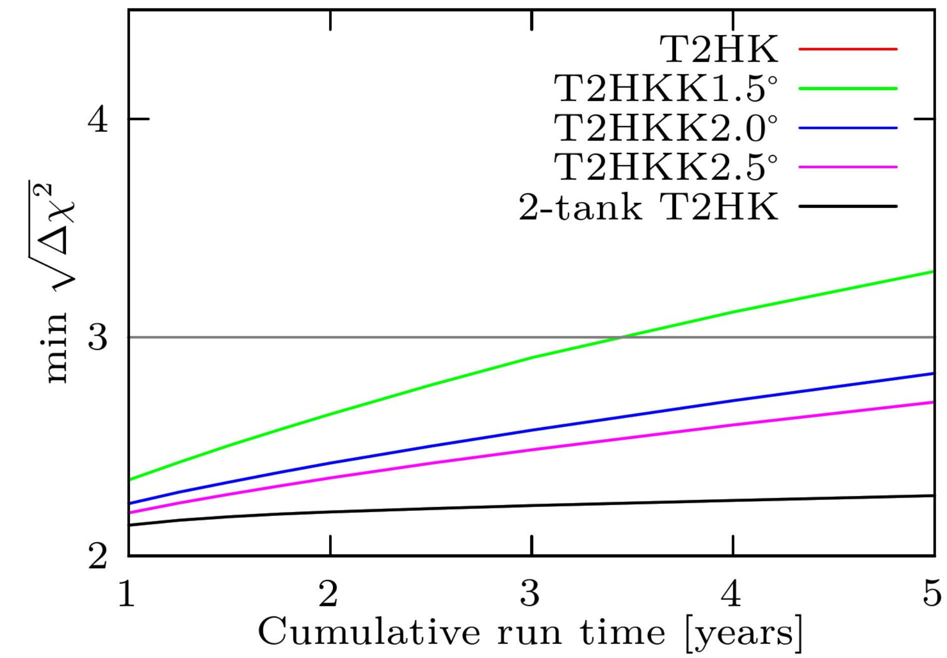


JUNO

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

DUNE, HK sensitivity

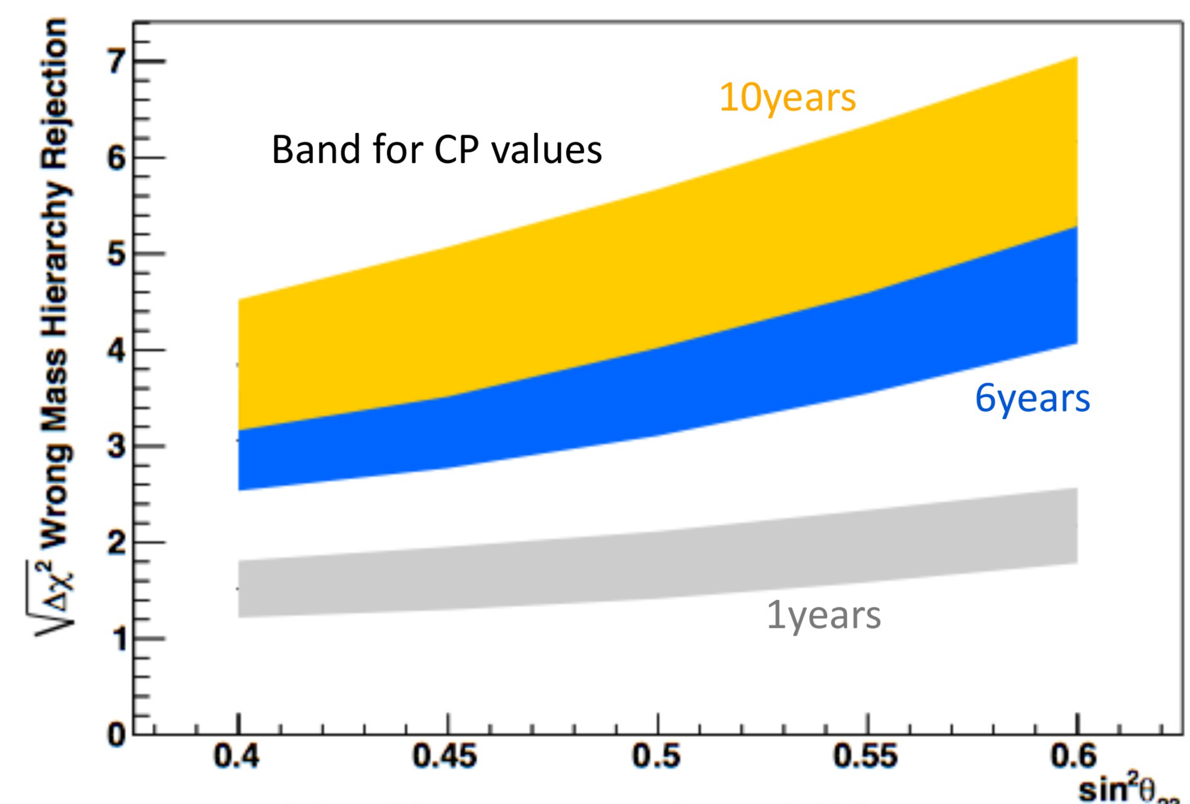




E. Worcester, for DUNE, Neutrino 2018

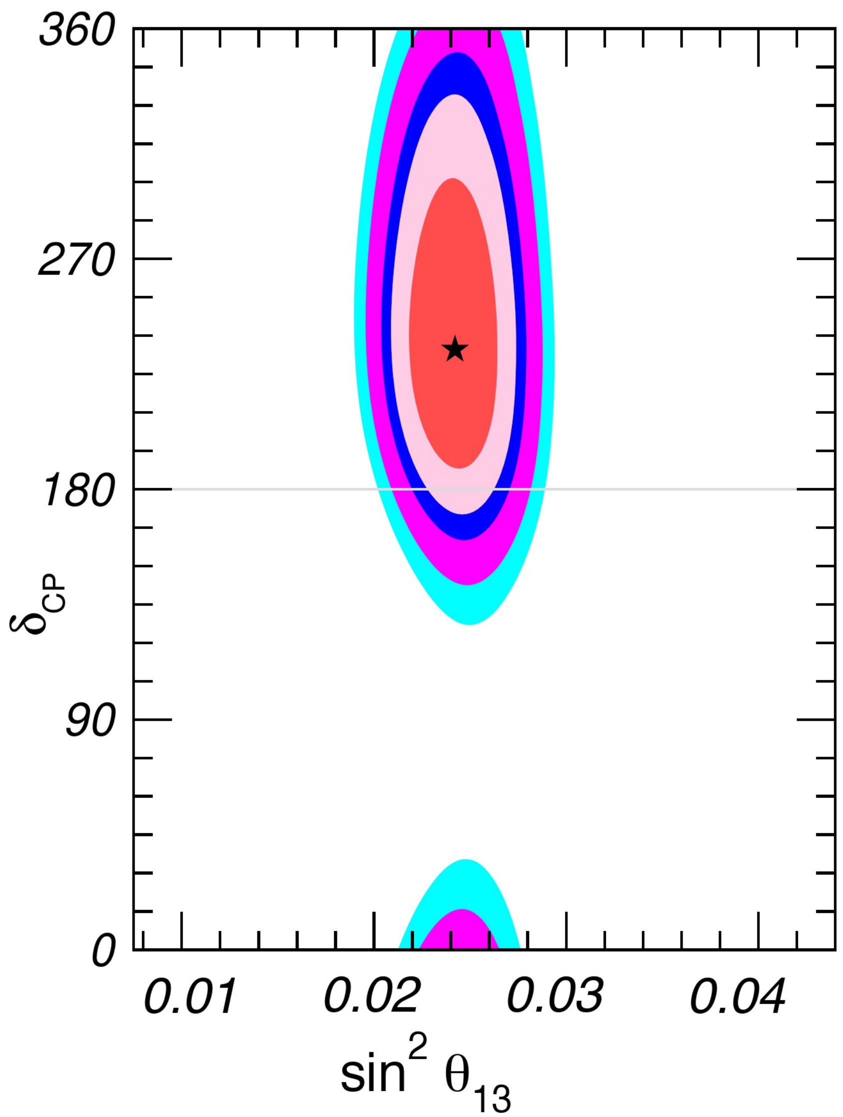
Ballett et al., 1612.07275

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.



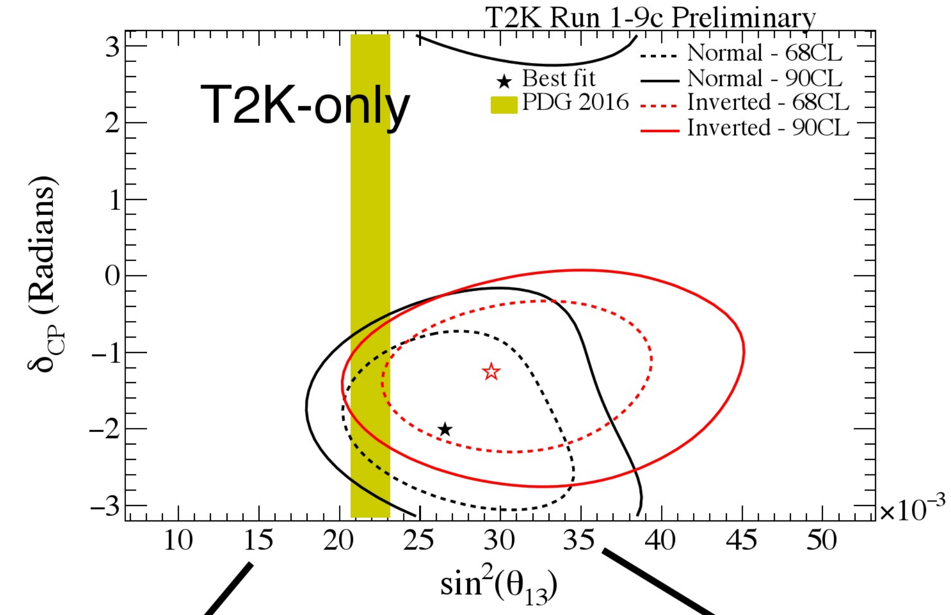
M. Shiozawa, for HK, Neutrino 2018

Hints for CP violation?

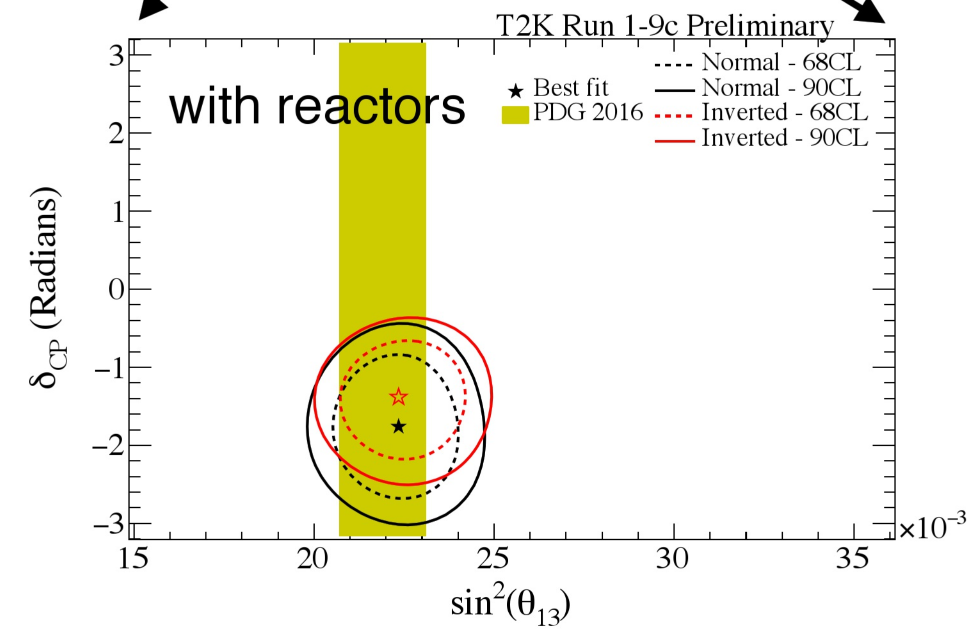


M. C. Gonzalez-Garcia et al., NuFit, 1611.01514 Pre-Neutrino 2018

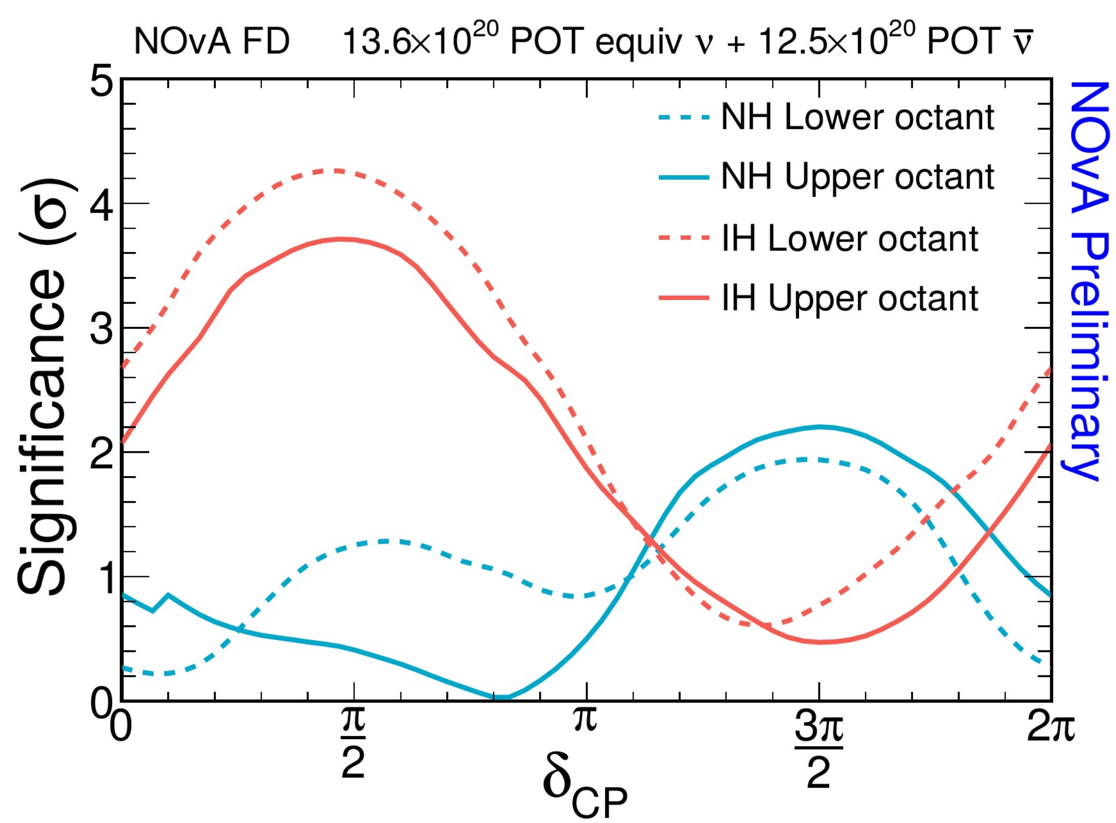
DATA FIT



M. Wasko, for T2K, Neutrino 2018

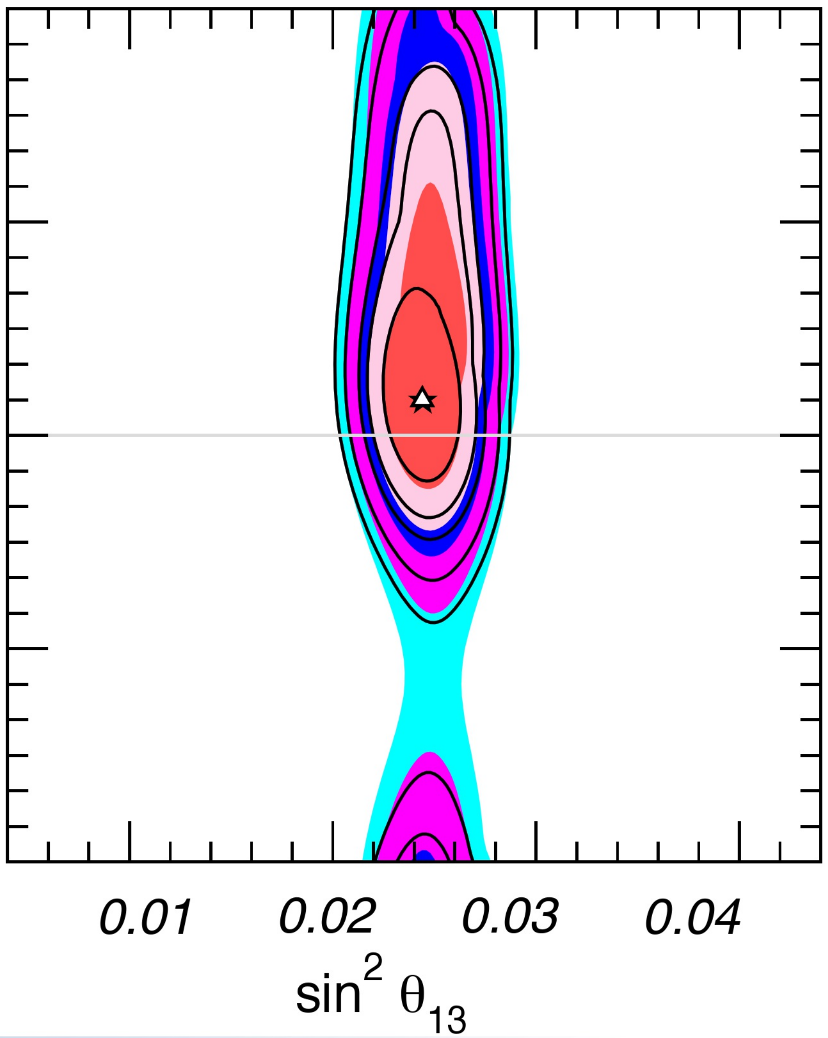


A. Himmel, for NOvA, Neutrino 2020



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

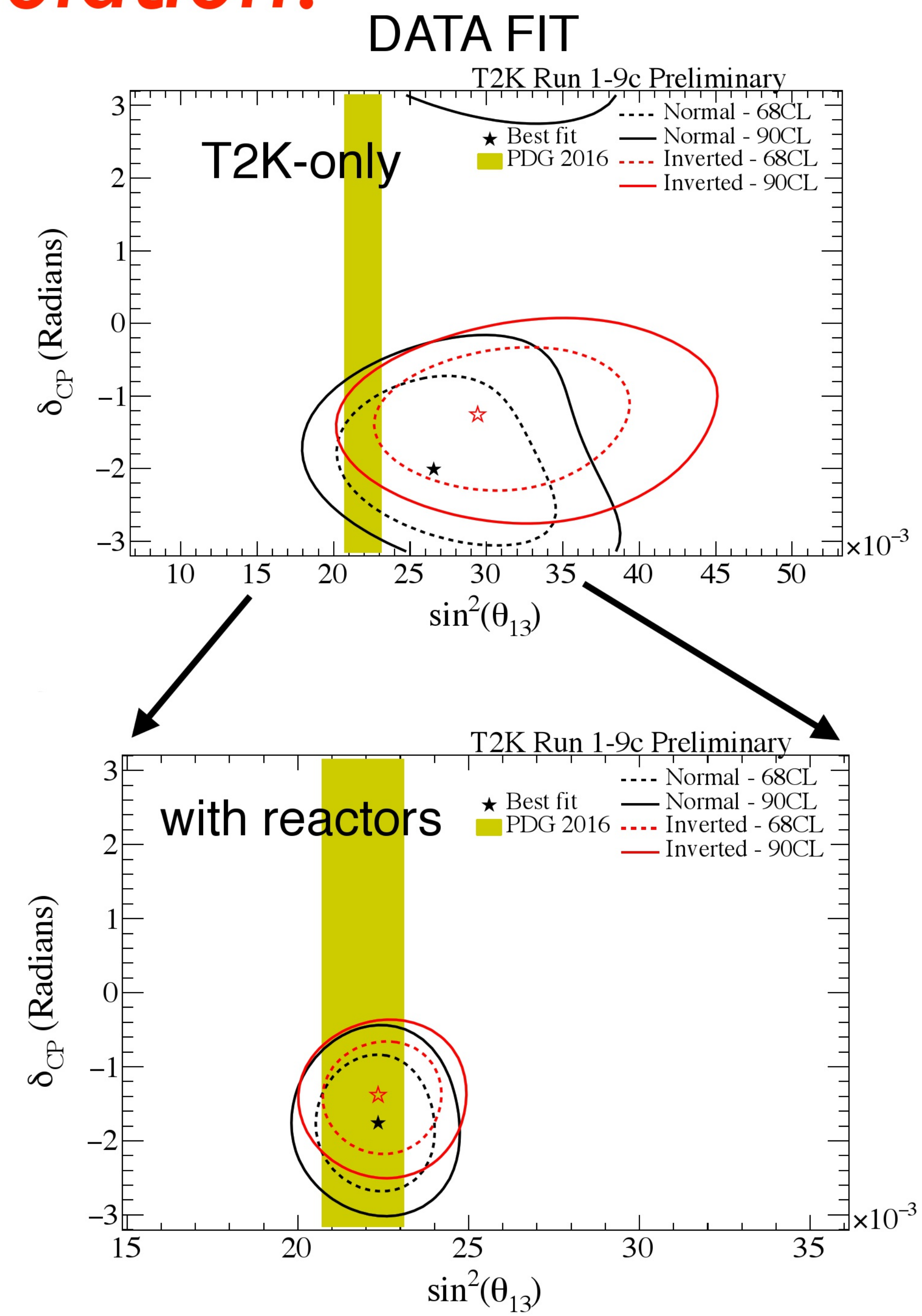
Hints for CP violation?



M. C. Gonzalez-Garcia et al., NuFit, 2007.14792

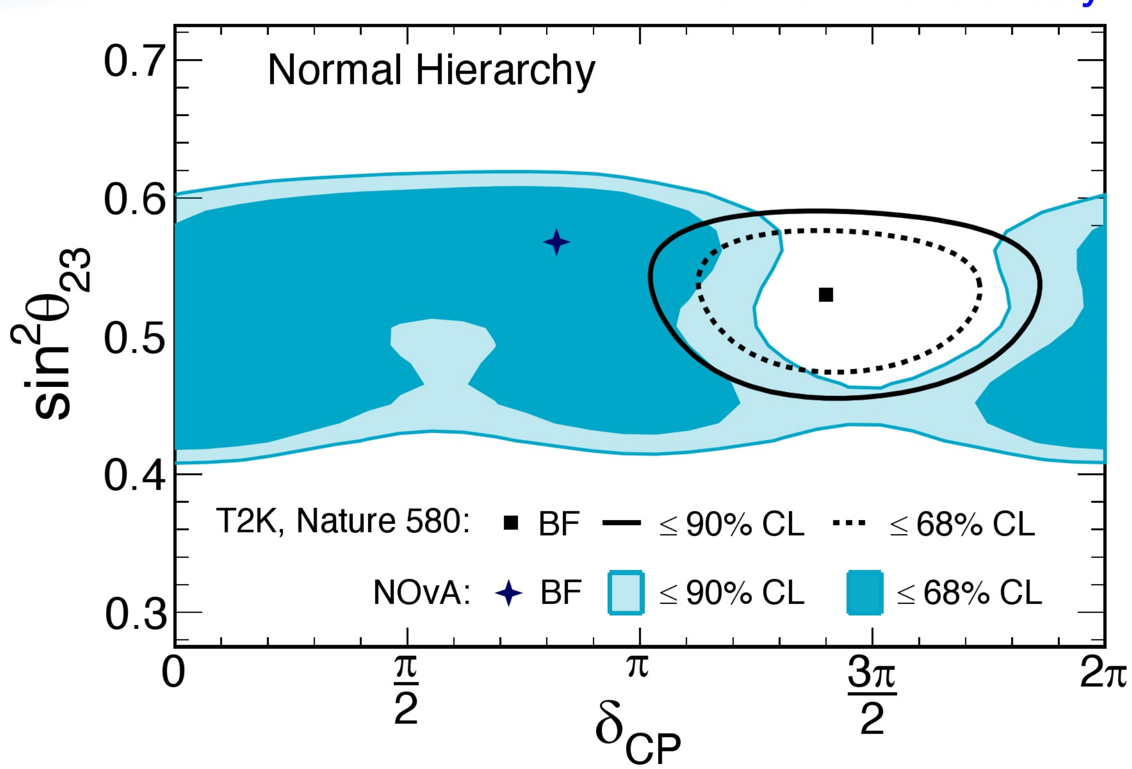
M. Wasko, for T2K, Neutrino 2018

A. Himmel, for NOvA, Neutrino 2020



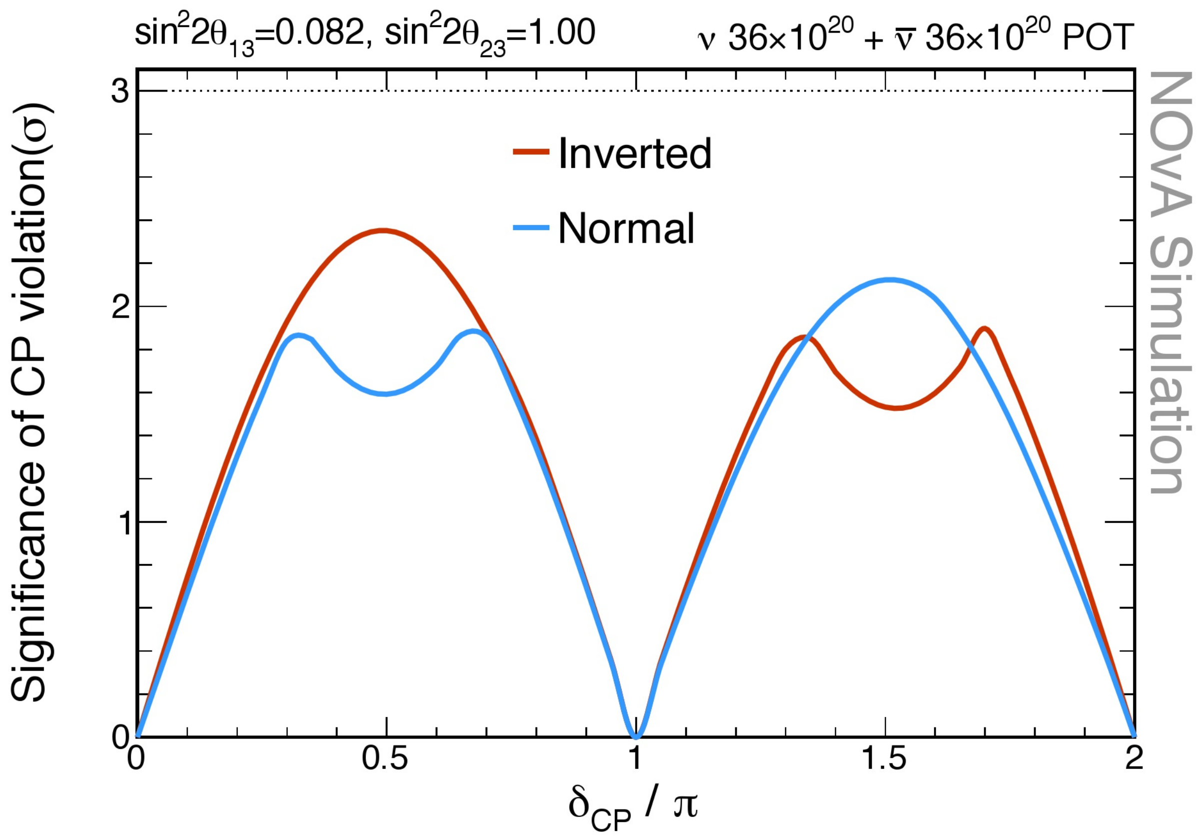
Comparison to T2K

NOvA Preliminary



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

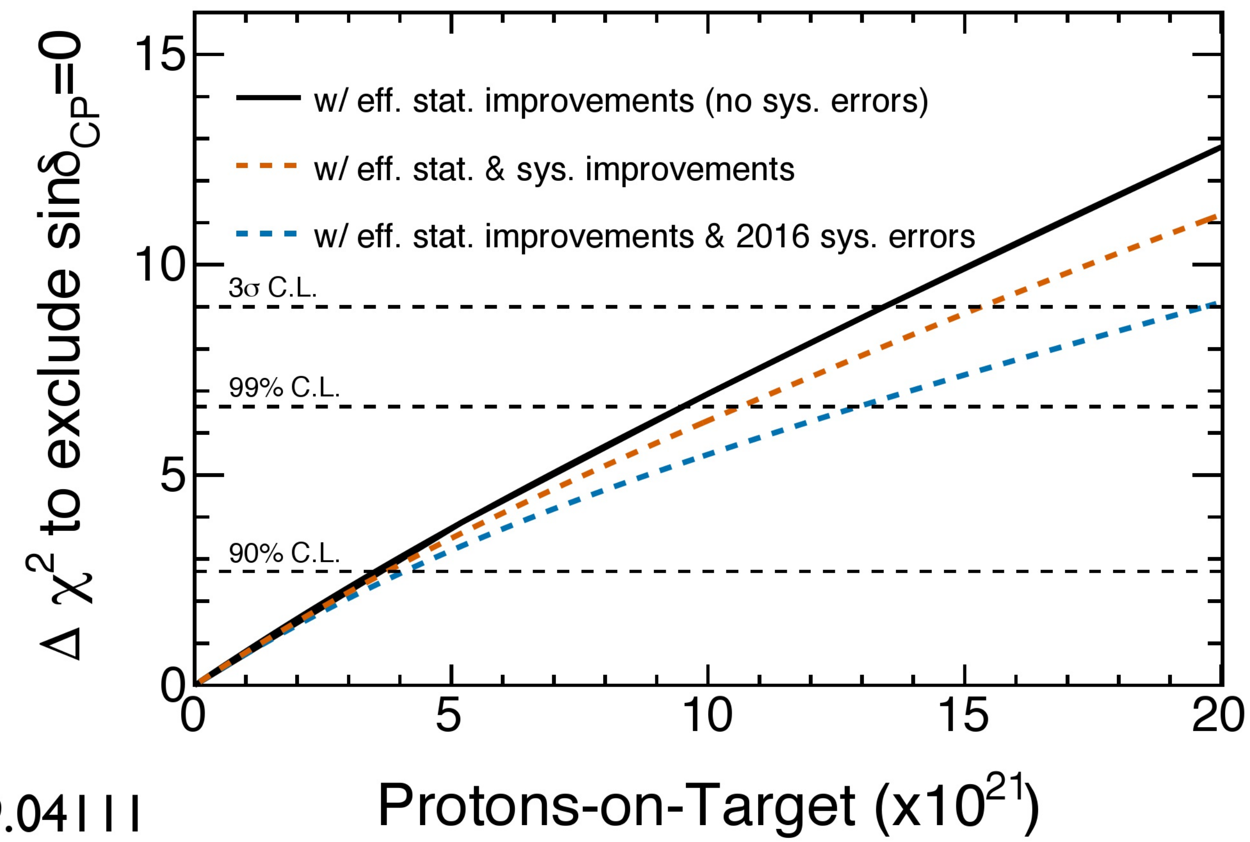
Near future sensitivity



M. Sanchez, Neutrino 2018

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

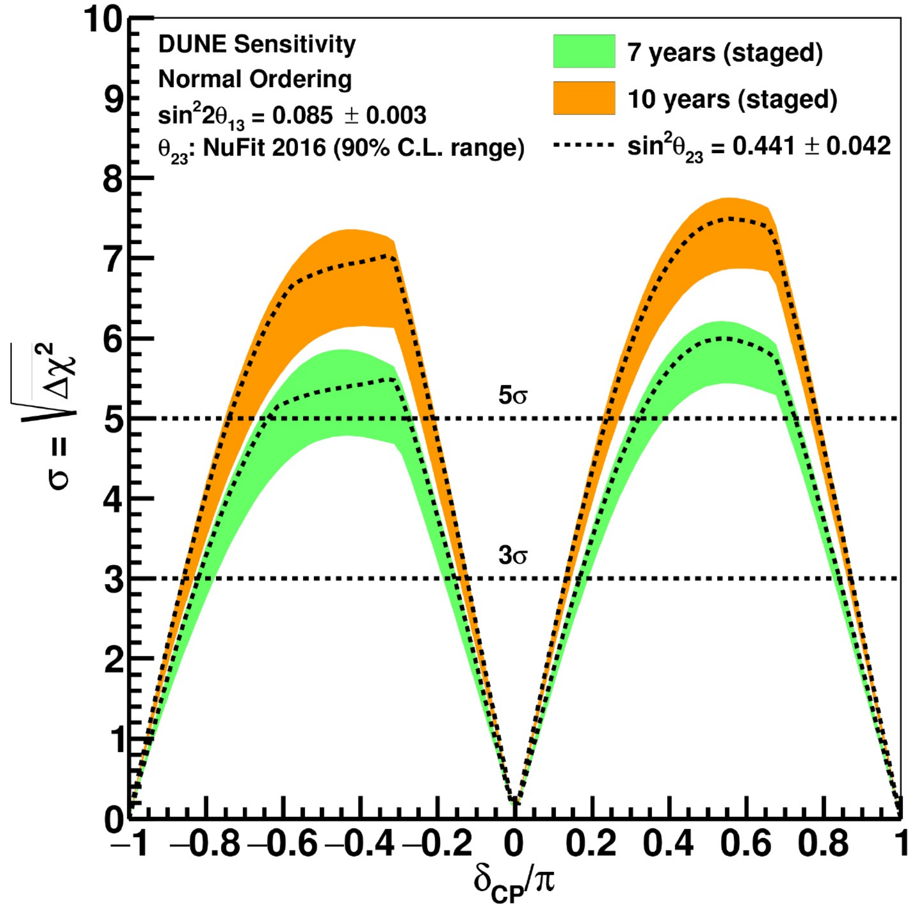
T2K phase 2 extension has received stage 1 approval by KEK/J-PARC in 2016.
It aims at reaching 1.3 MW by 2026 (20x10^21pot).



T2K, 1609.04111

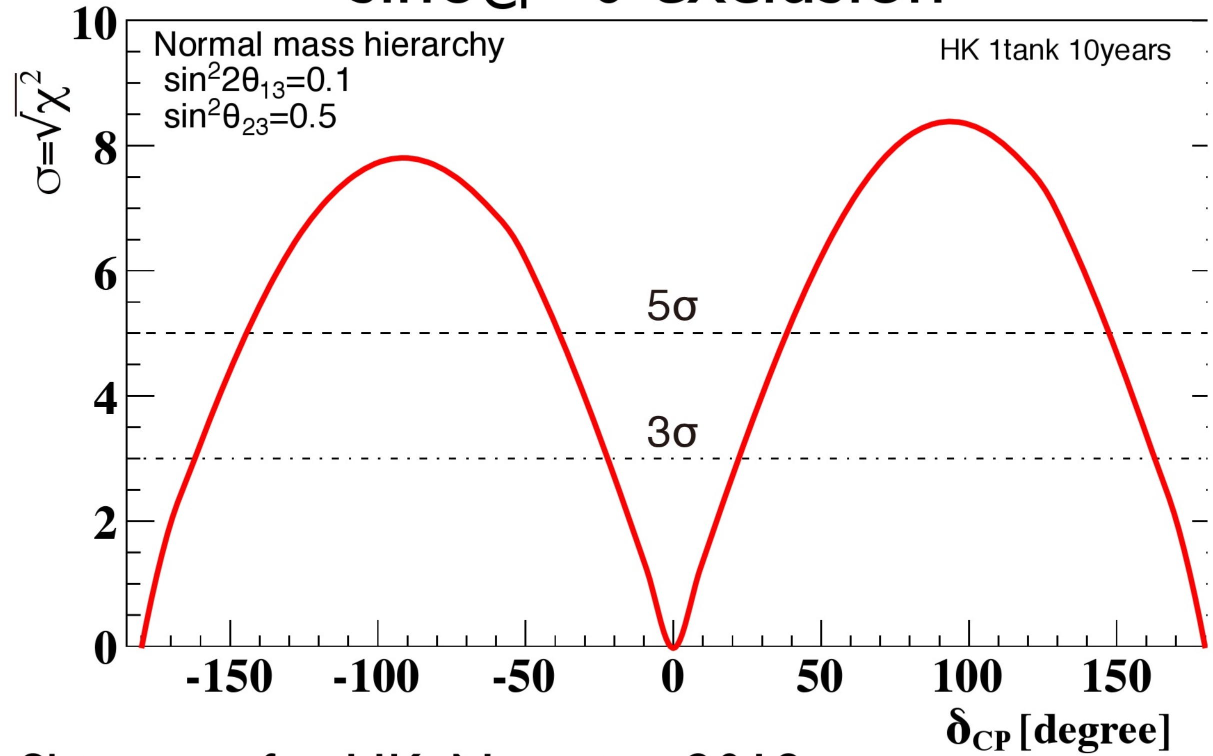
DUNE, T2HK sensitivity

CP Violation



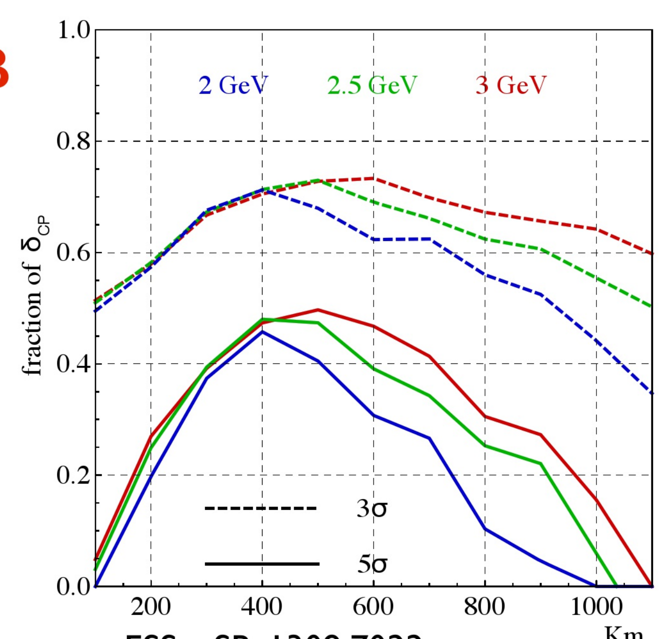
E.Worcester, for DUNE, Neutrino 2018

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

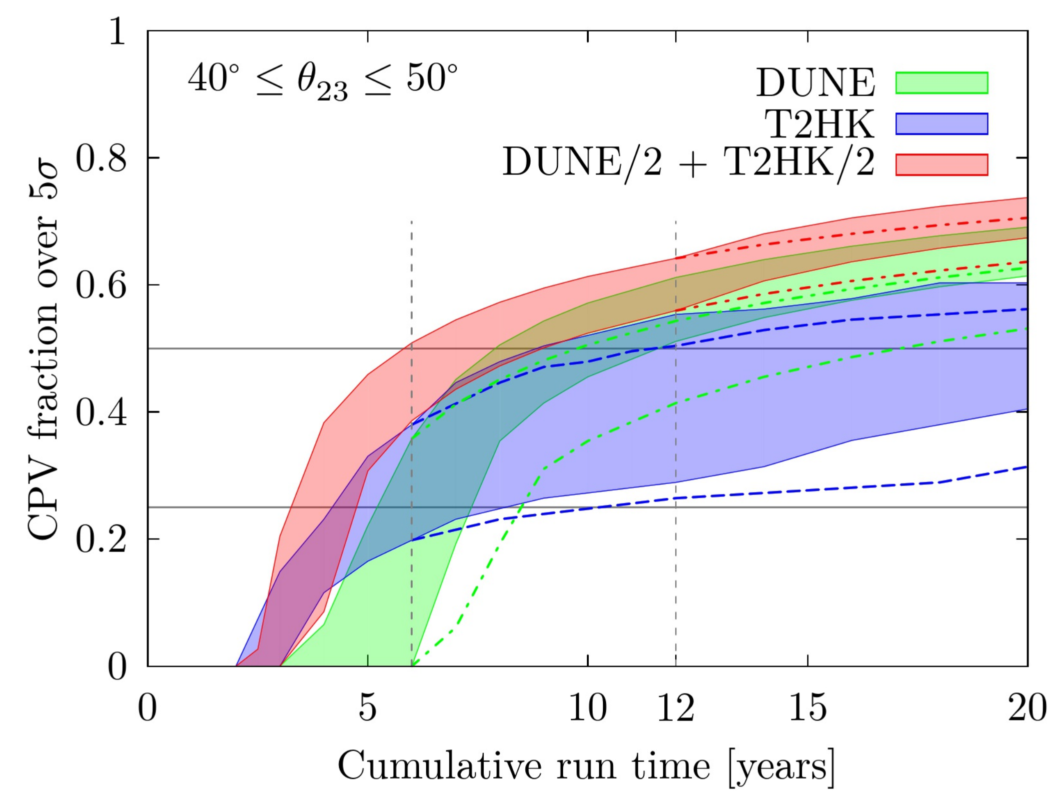


M. Shiozawa, for HK, Neutrino 2018

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 of future LBL and reactor exp.

- 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:

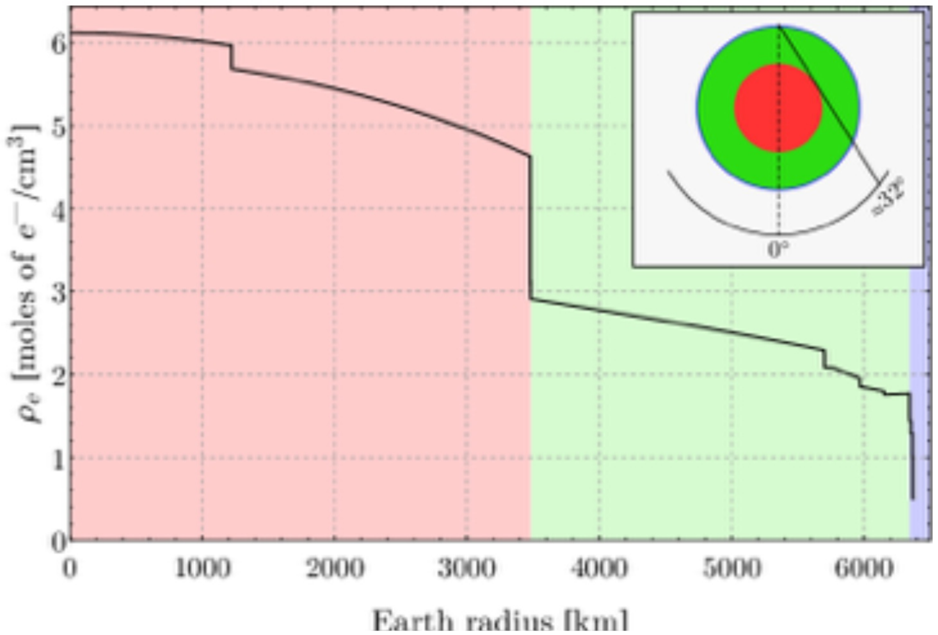
$$a = \sigma r \cos\delta \qquad \sigma = 1, -1/2$$

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.

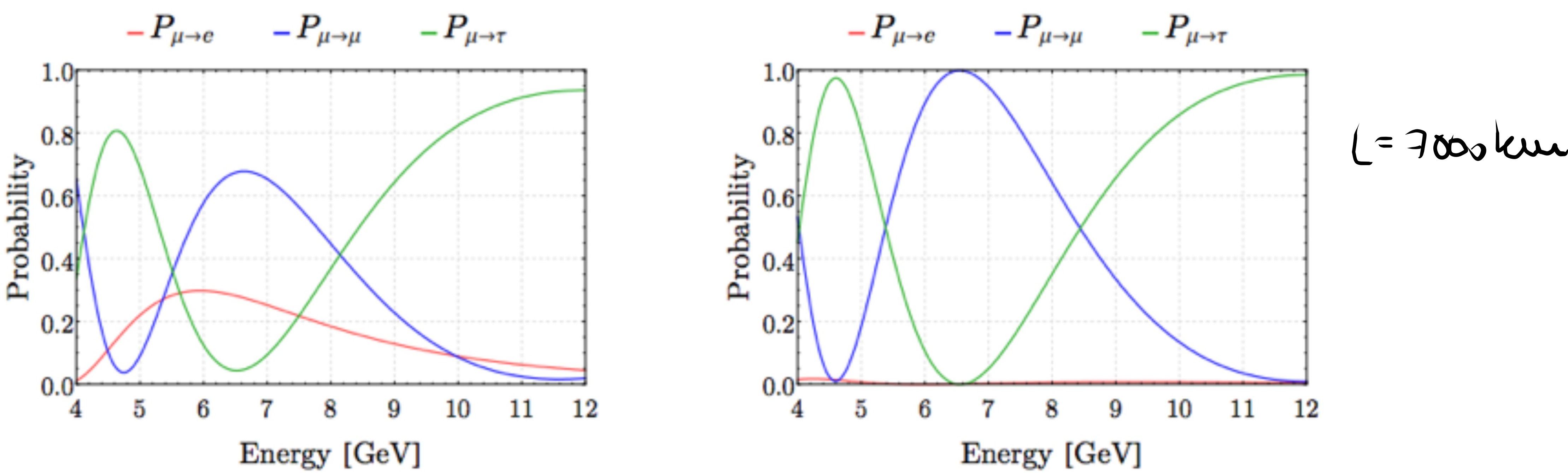
Atmospheric neutrino oscillations

The Earth has a profile with smooth density changes and abrupt drops: PREM model.



Dziewonski and D. L. Anderson, 1981

This induces complex matter effects.

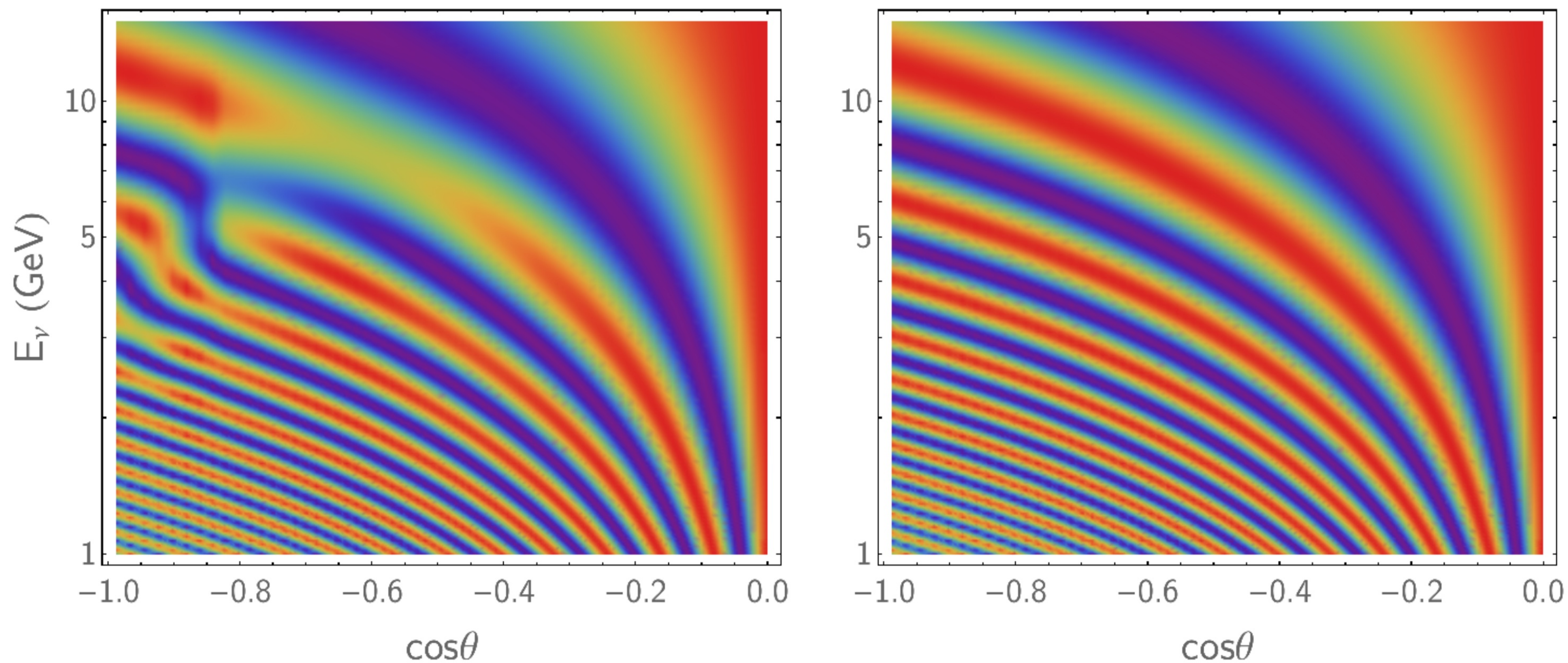


(a) Normal hierarchy. (b) Inverted hierarchy.

Fantini et al., 1802.05781

Atmospheric neutrino oscillations are sensitive to the mass ordering. This requires large number of events, good energy and angular resolution and, possibly, charge discrimination.

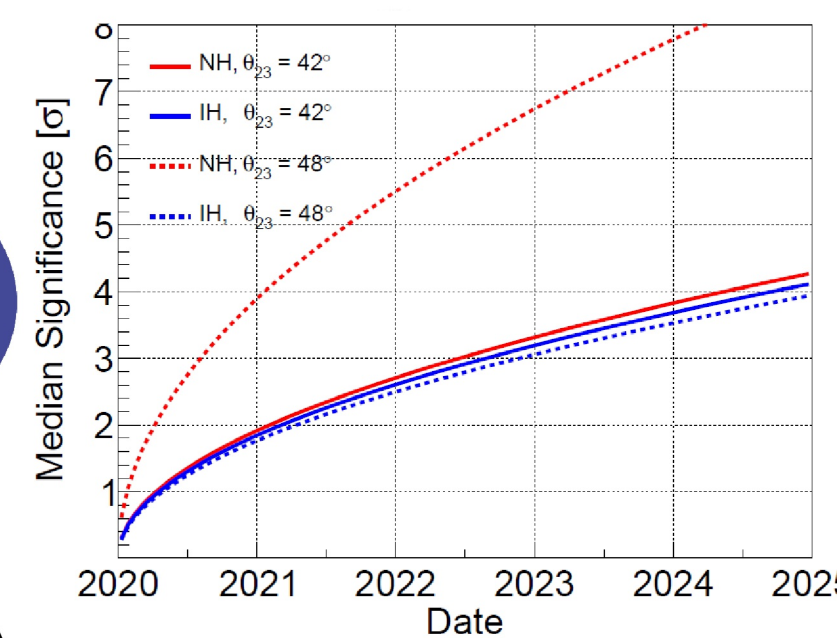
Petcov et al.; Akhmedov, Smirnov et al.; Gandhi et al.; Mena et al.; Schwetz et al.; Koskinen; Gonzalez-Garcia et al.; Barger et al.; ....



P. Coloma and SP, World Scientific

PINGU

PINGU in IceCube,
ORCA in KM3Net,
ICAL at INO

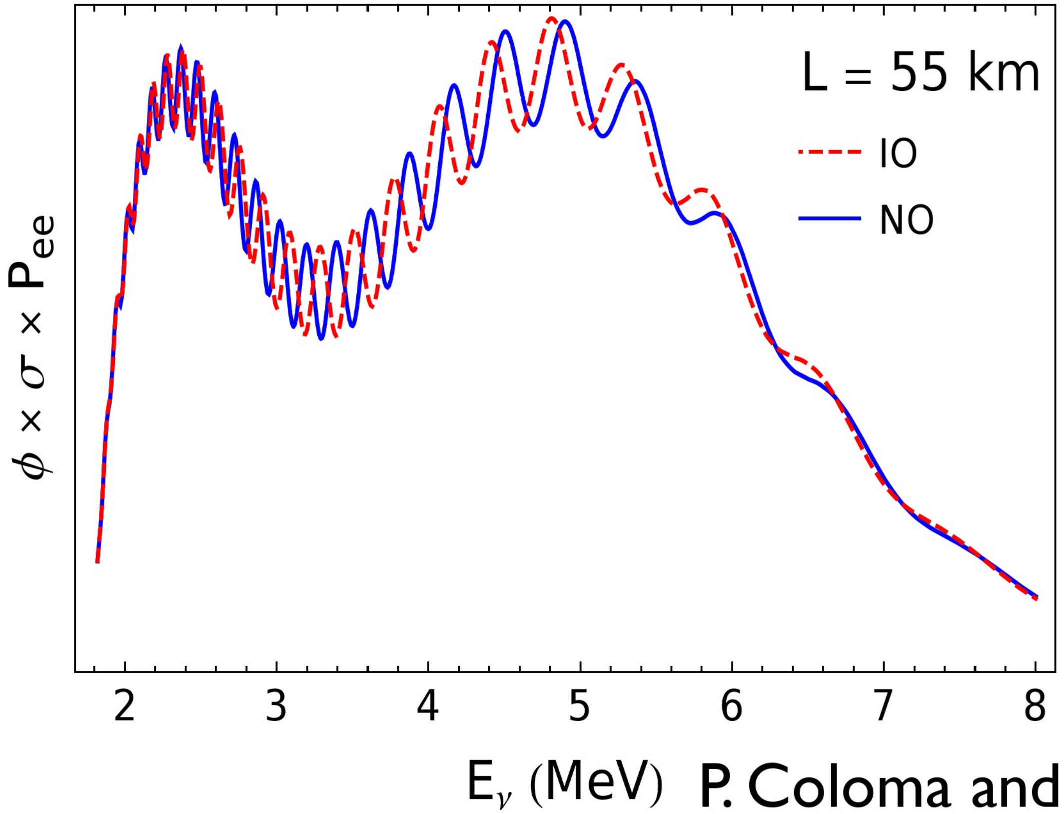


ORCA

Reactor neutrino oscillations

The interference between atmospheric and solar mass squared differences in medium baseline reactor neutrino oscillation allows sensitivity to the mass ordering.

$$
\begin{aligned}
P_{\nu_e \to \nu_e} &= 1 - \cos^4\theta_{13}\,\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \\
&- \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\,\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12}\,\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]
\end{aligned}
$$

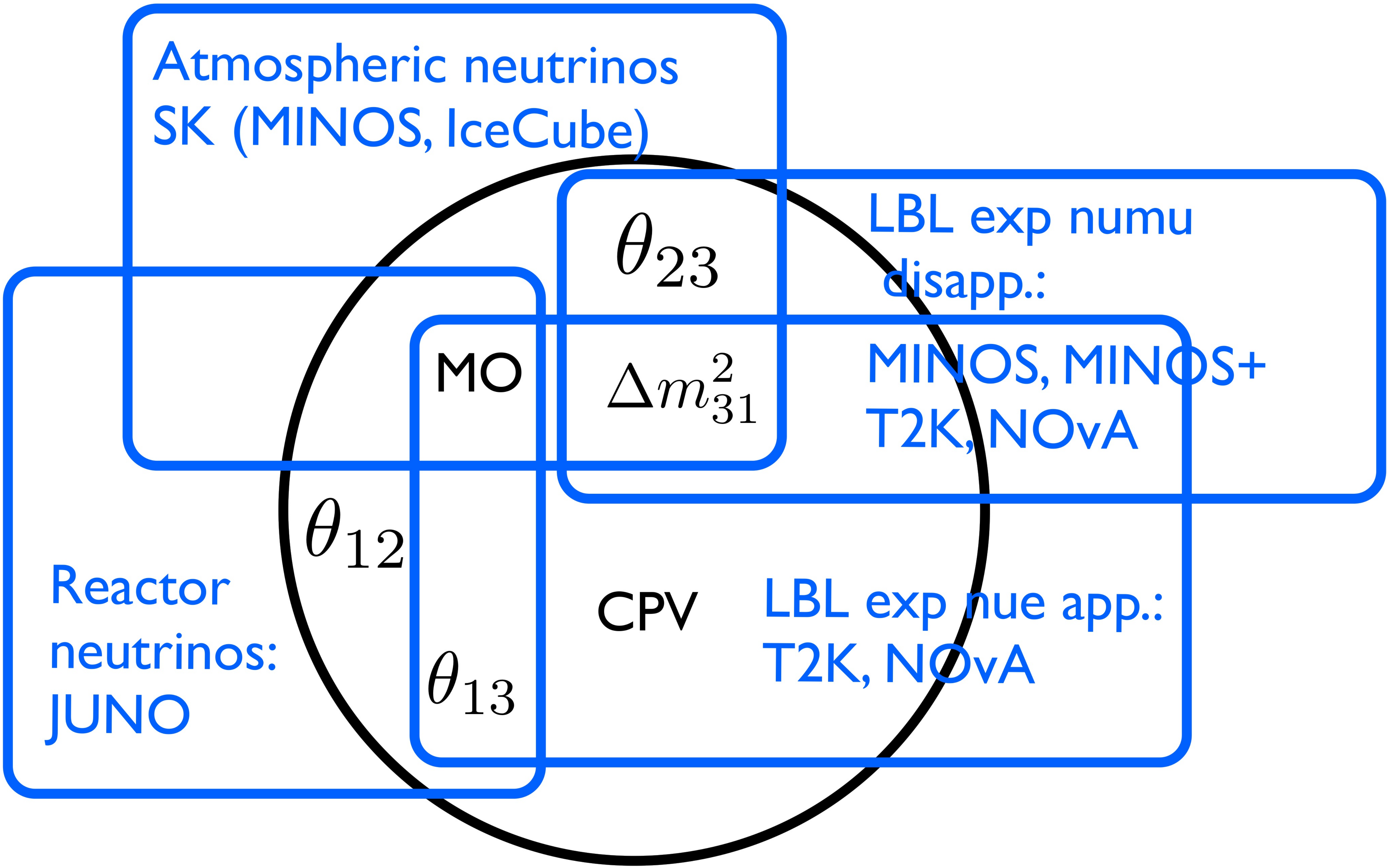


P. Coloma and SP, World Scientific

Petcov, Piai, hep-ph/0112074, Choubey, Petcov, Piai, hep-ph/0306017, Goshal, Petcov, 1208.6473; see also Ciuffoli et al.; Qian et al.

The JUNO reactor experiment is using detectors at ~60 km to perform this measurement.
Excellent energy resolution is needed.

Interplay between different experiments



Also: Tests of standard neutrino paradigm

Determination of neutrino masses

As we know only mass squared differences, we need to establish the mass ordering and the mass scale.

- Mass ordering:

  - Neutrinoless double beta decay (with some caveats).

  - Neutrino oscillations relying on matter effects (atmospheric neutrinos: PINGU in IceCube, ORCA in KM3Net, ICAL at INO; long baseline neutrino oscillations: DUNE)

  - Neutrino oscillations in vacuum with reactor neutrinos at ~60 km (JUNO)

- Value of masses:

  - beta decay

  - neutrino cosmology

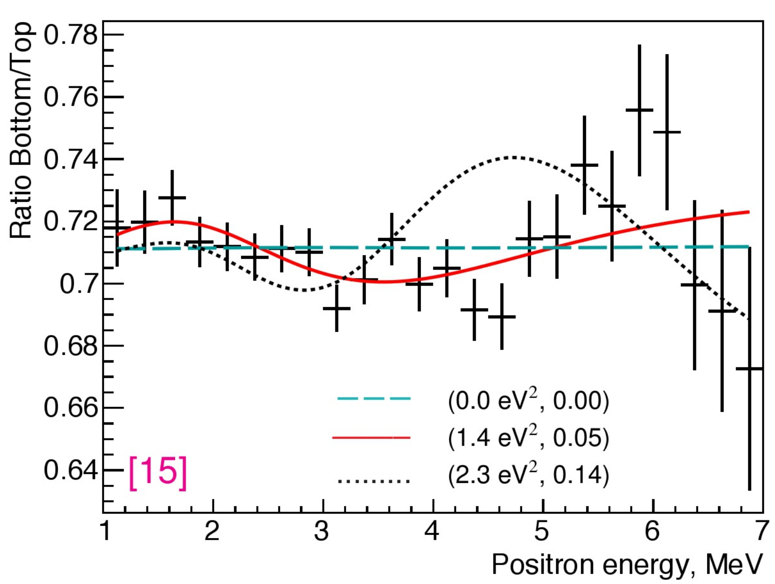
What do we still need to know?

- 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?

Is the standard 3-neutrino mixing paradigm correct?

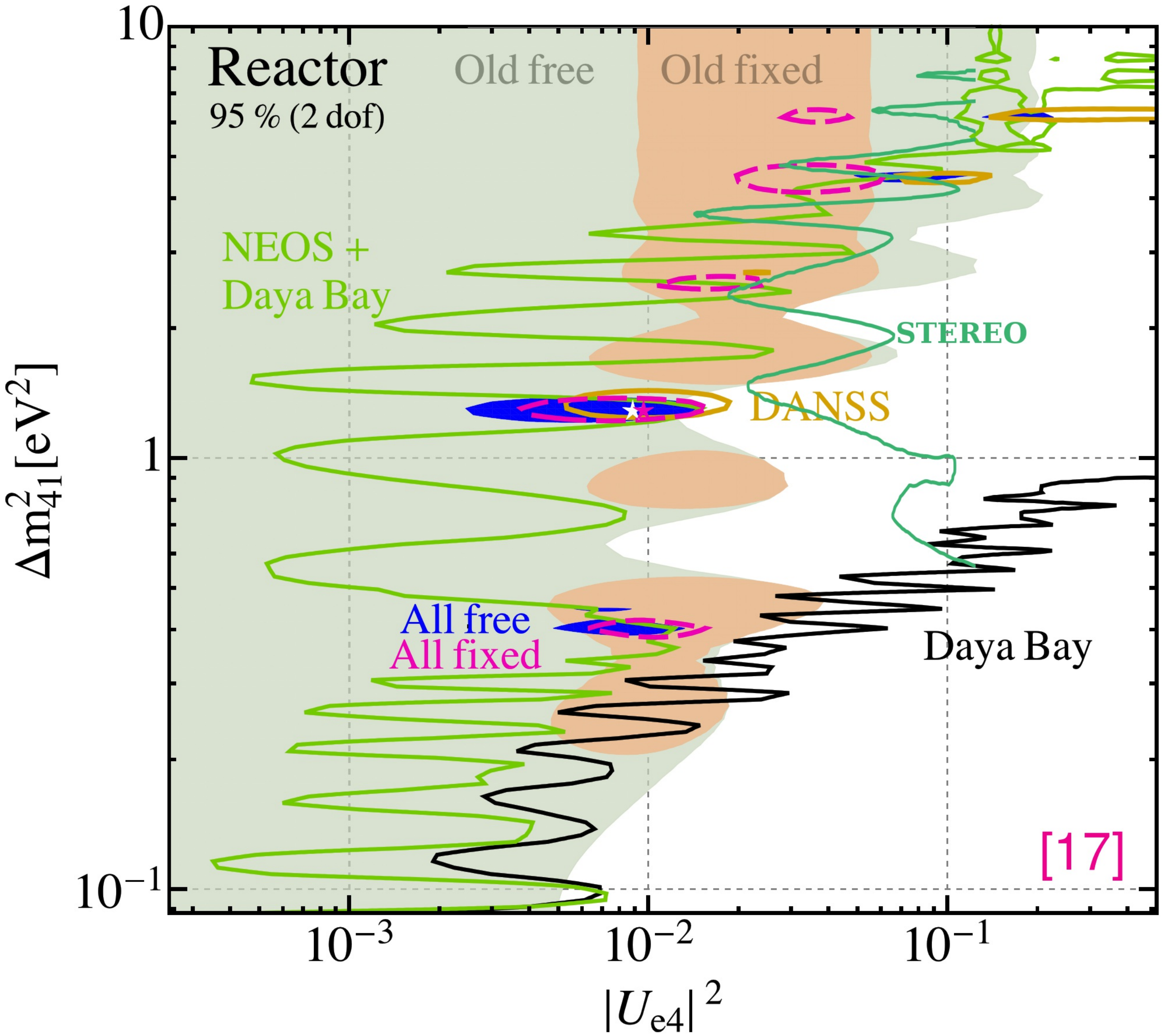
Tests of the standard 3-neutrino paradigm

- 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

Sterile neutrino oscillations

Sterile neutrinos: hypothetical neutral fermionic singlets of the Standard Model.

Generically they mix with the light neutrinos:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U_{4\times 4} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Flavour state

Massive state

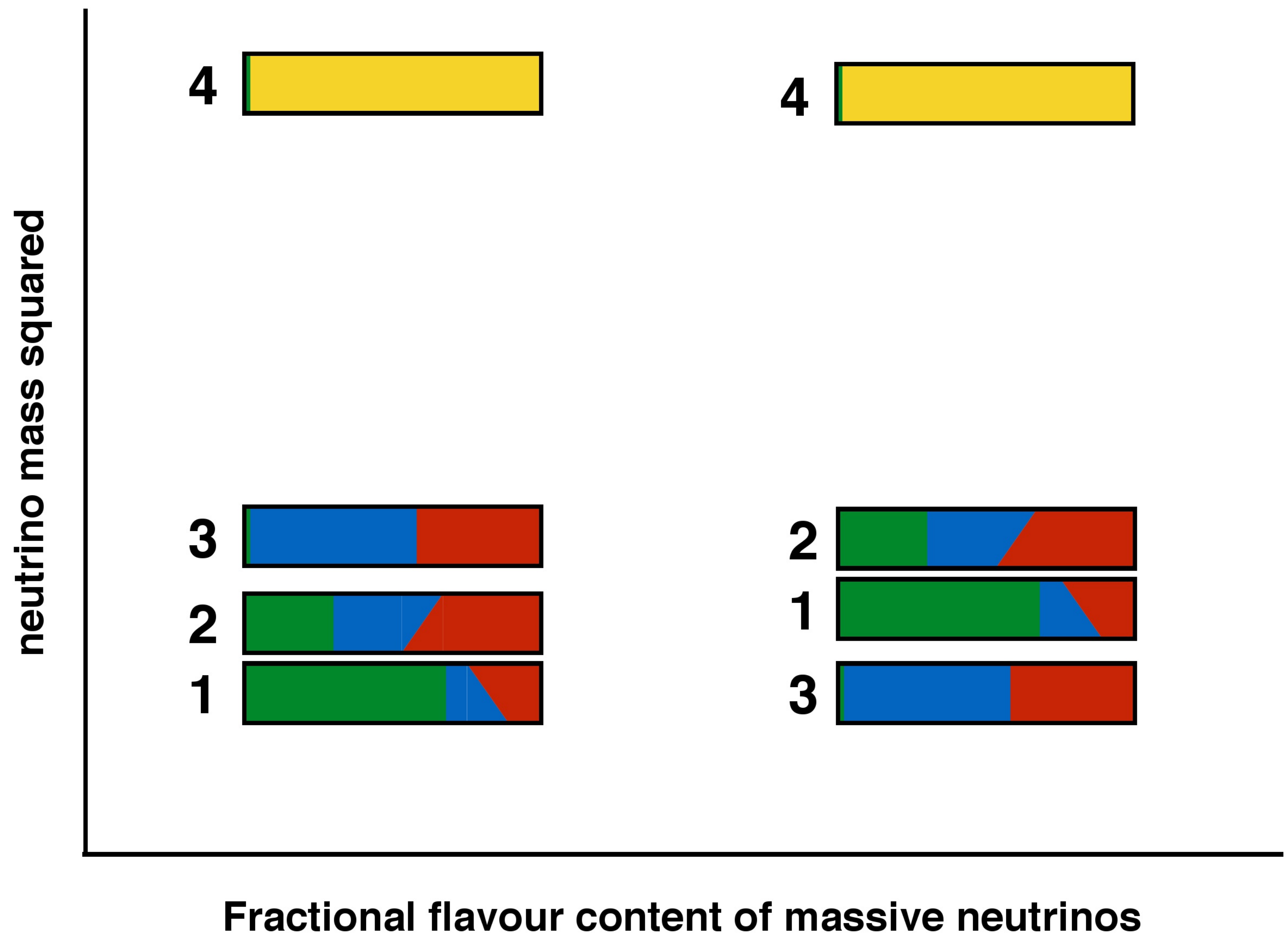
Nearly-sterile neutrino, commonly called sterile neutrino

$$\mathcal{L} = \cdots + \bar{\ell}_L U_{\ell 4} \gamma_\mu \nu_{4,L} W^\mu + \text{NC} + \text{h.c.}$$

Neutrino masses

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

$\Delta m^2_s \ll \Delta m^2_A \ll \Delta m^2_{41}$ implies at least 4 massive nus.



Appearance oscillation probability at short baselines.:

$$\frac{\Delta m^2_{21} L}{2E}, \quad \frac{\Delta m^2_{31} L}{2E} \ll 1$$

$$P(\nu_\alpha \to \nu_\beta) \simeq \left| \underbrace{U^*_{\alpha 1} U_{\beta 1} + U^*_{\alpha 2} U_{\beta 2} + U^*_{\alpha 3} U_{\beta 3}}_{-U^*_{\alpha 4} U_{\beta 4}} + U^*_{\alpha 4} U_{\beta 4} e^{-i \frac{\Delta m^2_{41} L}{2E}} \right|^2$$

$$\simeq \ldots$$

$$P(\nu_\alpha \to \nu_\beta) = 4 |U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

Oscillation disappearance probability:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4 |U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

Adding sterile neutrinos to the Standard Model is the simplest possible extension BSM.

- Theory remains anomaly free.

- Can give origin to neutrino masses and explain their smallness (at least in some cases).

- GUT theories embedding L-R symmetries, e.g. SU(4), SO(10),... predict their existence.

- A part from GUT theories, there is no strong motivation for choosing one mass scale instead of another (except for a naturalness principle: setting their mass to zero restores the lepton number symmetry).
Here we consider only eV scale sterile neutrinos, relevant for oscillations.

Neutrino oscillation appearance channel

There are hints beyond the standard 3 neutrino mixing.

LSND, nucl-ex/9605002

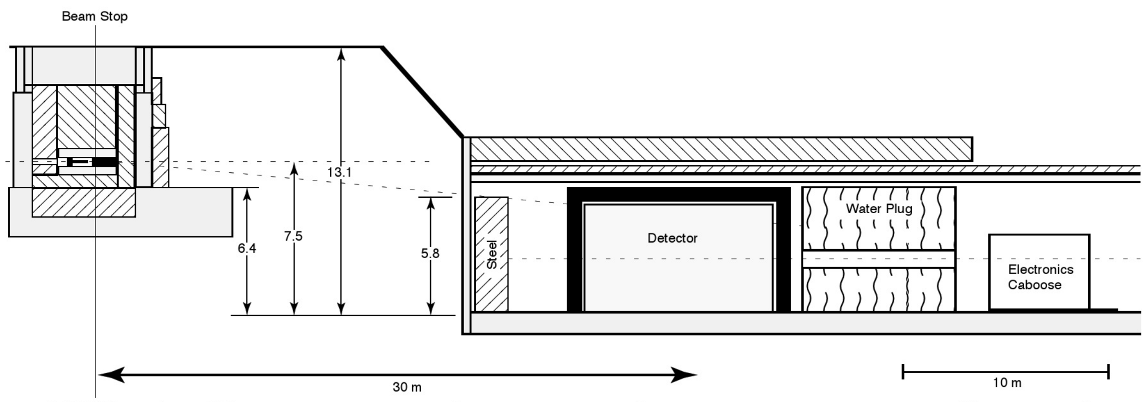
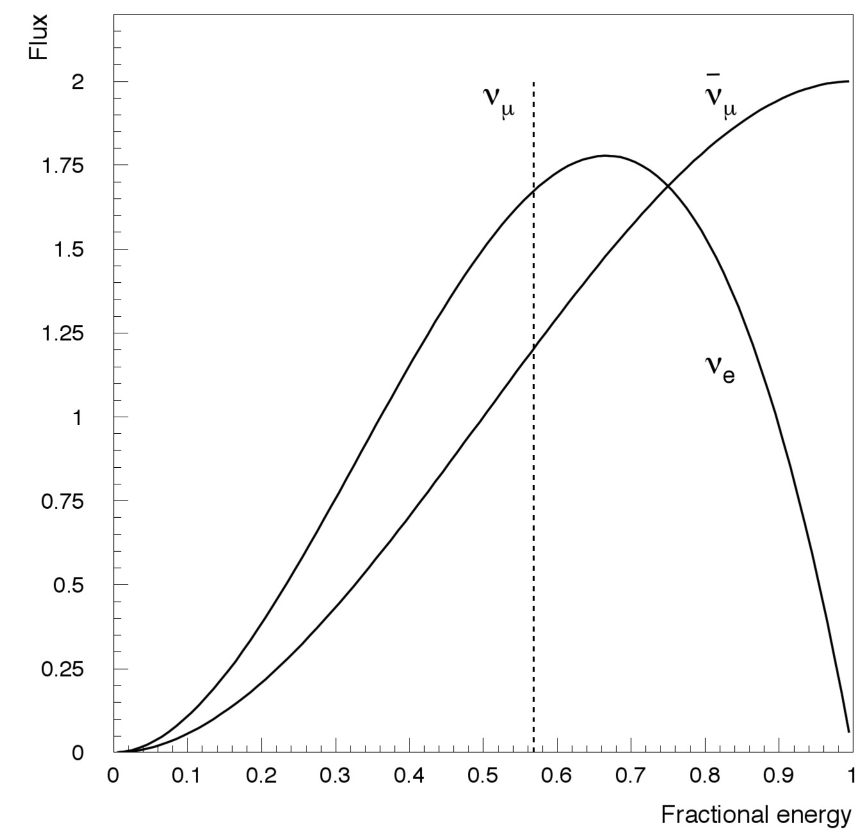


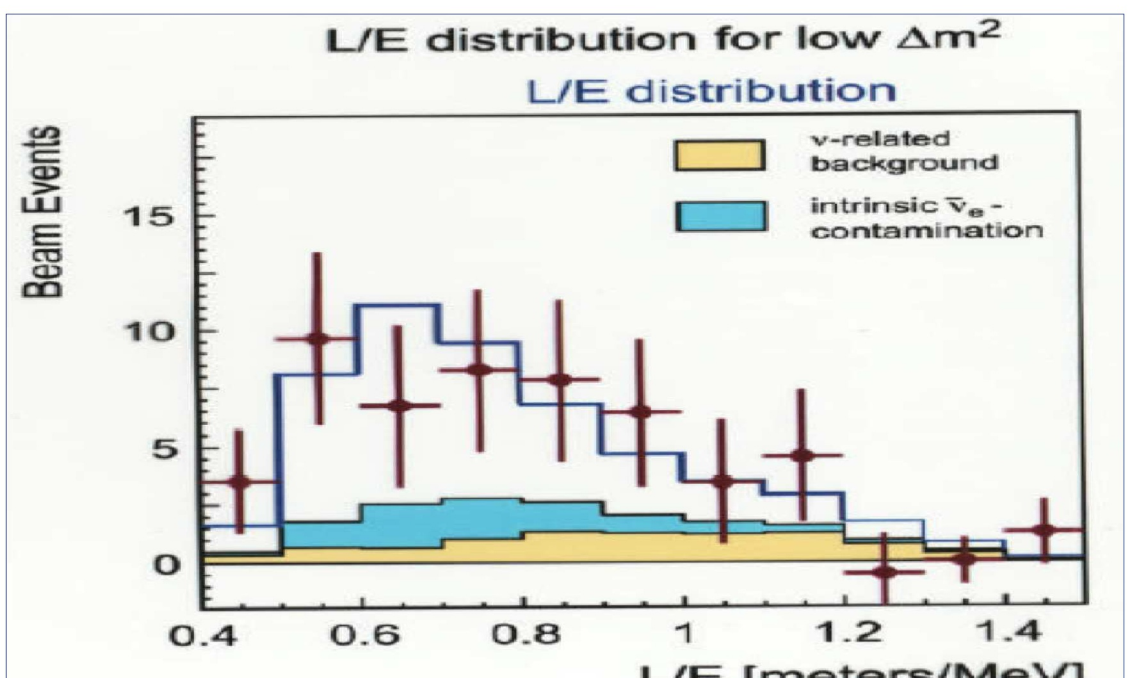
FIG. 1. Detector enclosure and target area configuration, elevation view

$$\pi^+ \to \mu^+ + \nu_\mu \quad ,$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

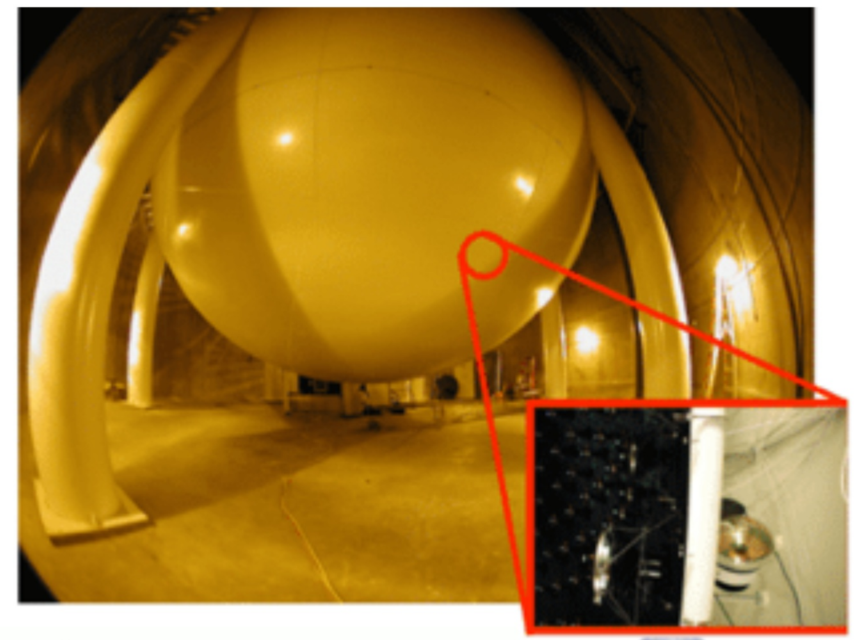


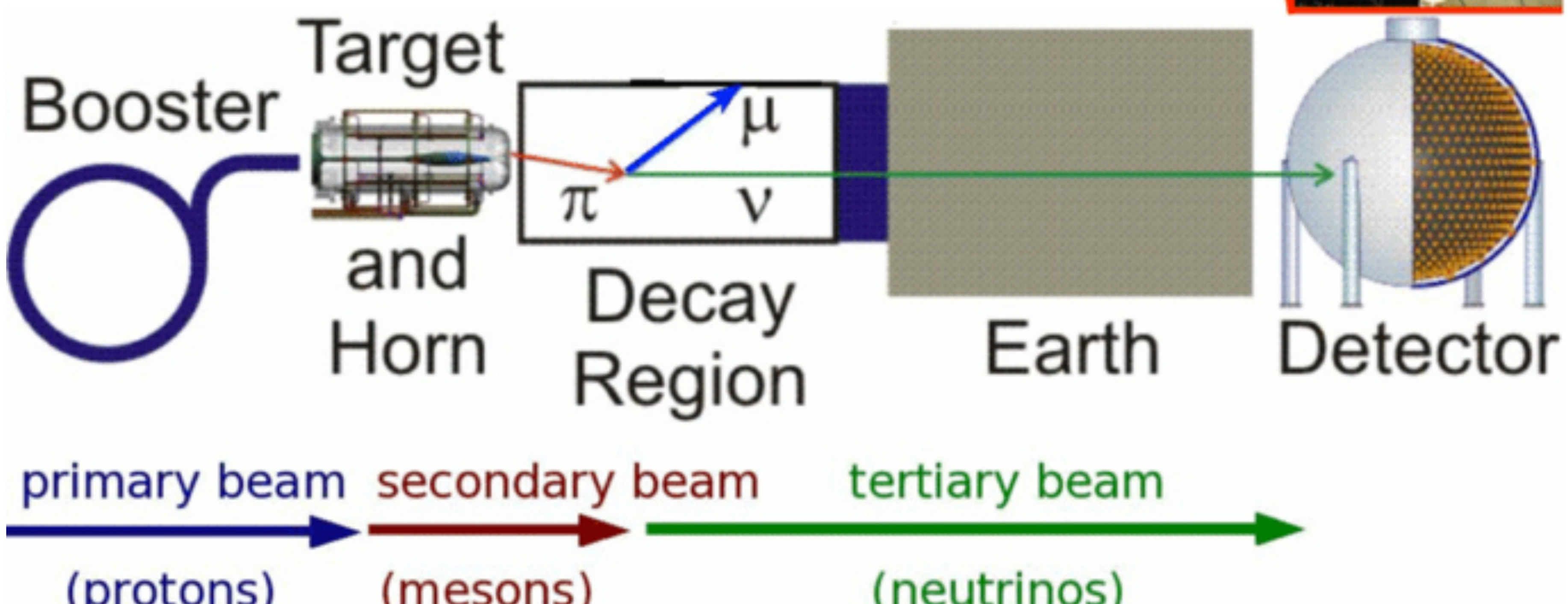
LSND, PRL81 (1998) 1774



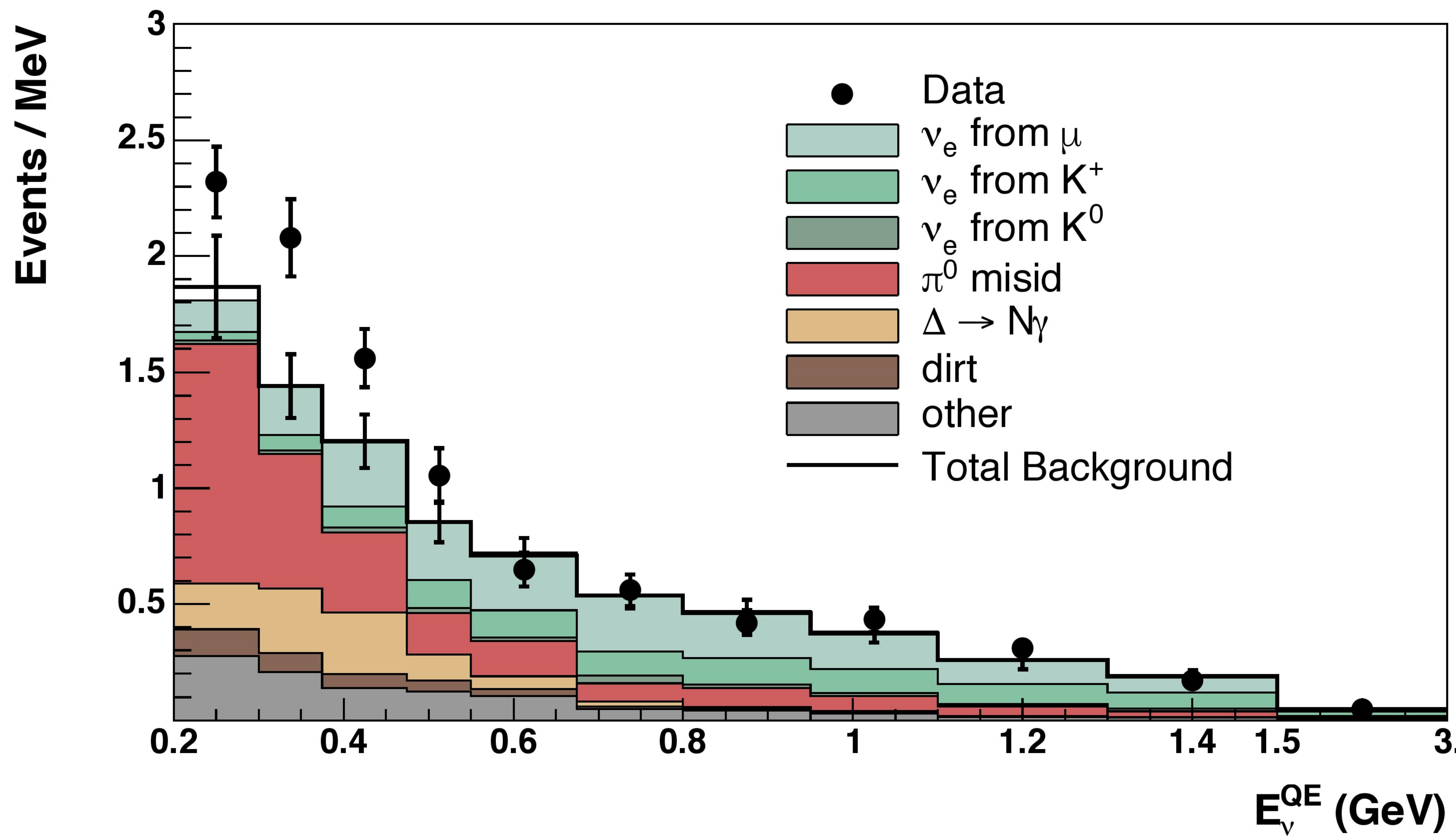
LSND reported the appearance of electron anti-neutrinos (inverse beta decay) at short distance (~30 m) from muon decays (DAR). A 3.8 sigma effect, not confirmed by KARMEN.

MiniBooNE was designed to test the LSND results. <E>~700 MeV and L~500 m. It found an excess of events at low energy.



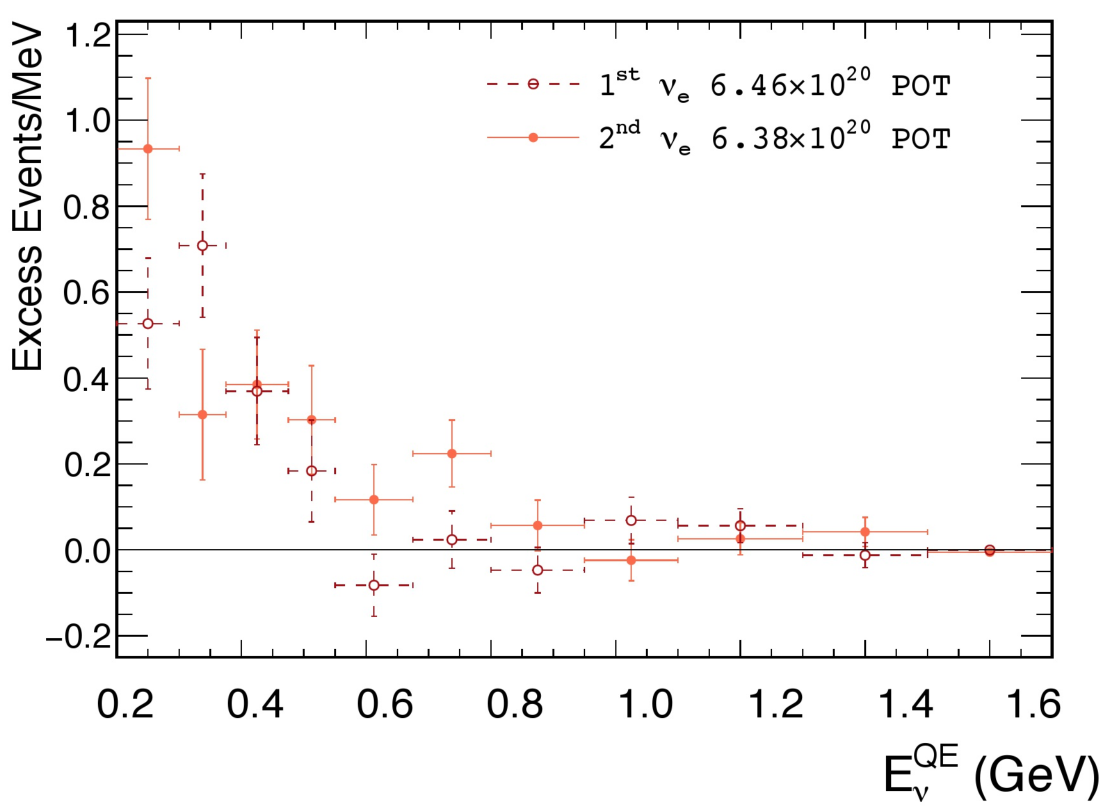


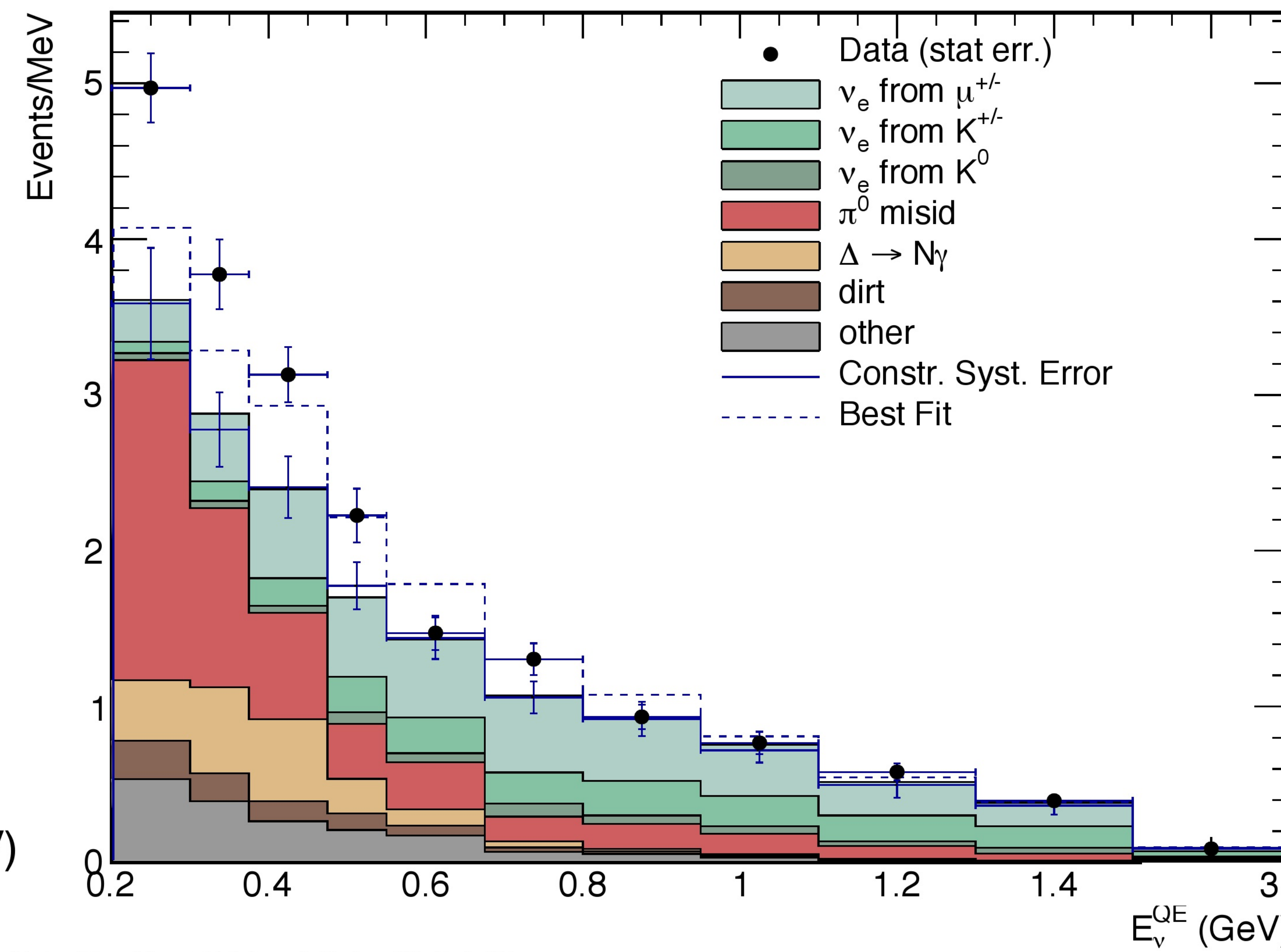
MiniBooNE reports a low-E excess which has increased in significance in the past couple of years (3.6σ -> 4.7σ -> 4.8σ).



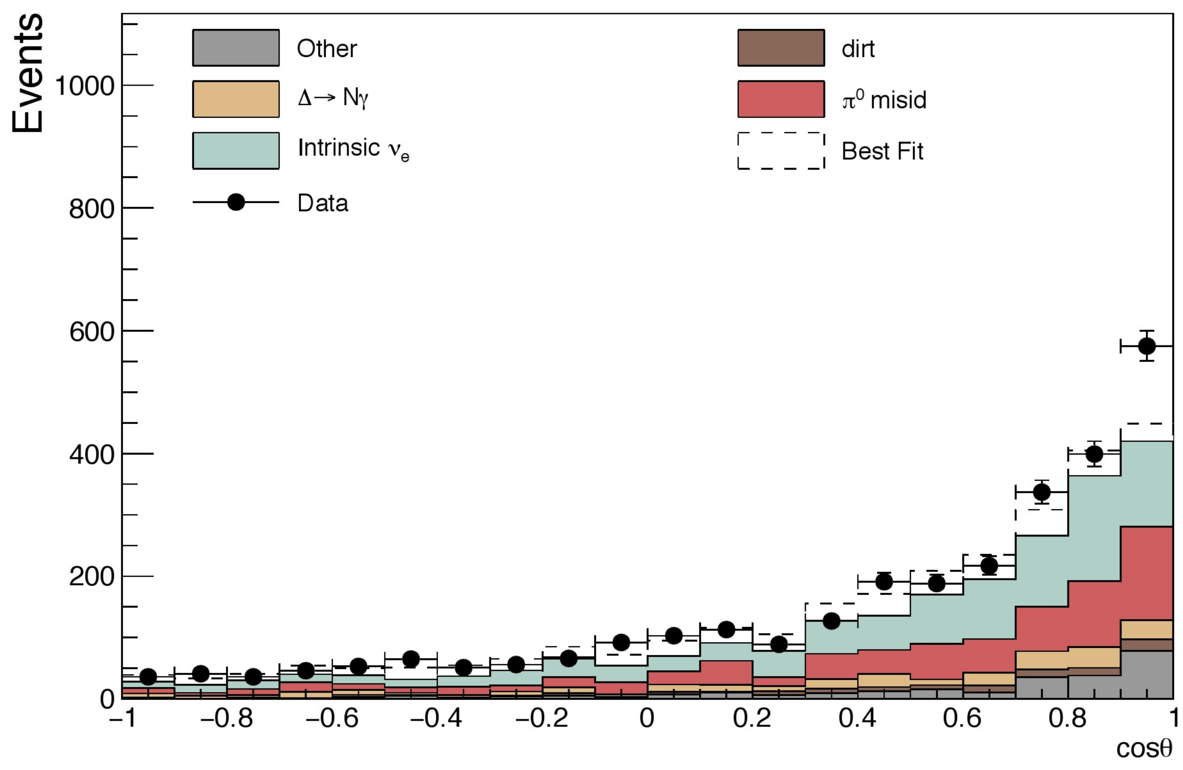
MiniBooNE Coll., PRL 102 (2008)

MiniBooNE released the latest analysis: 638.0±132.8 electron-like events (4.8σ) with a 46% increase in neutrino data.





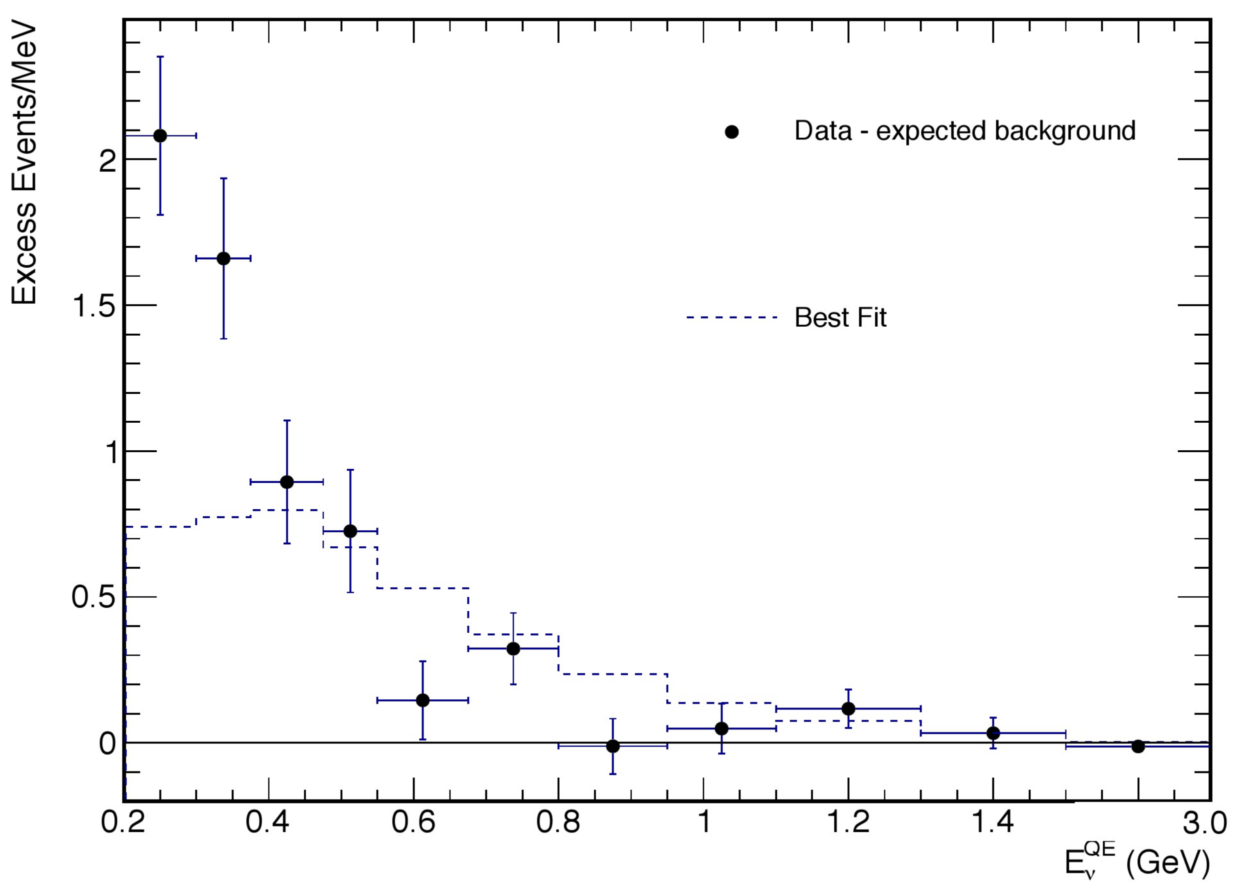
MiniBooNE Coll., PRL 121 (2018)



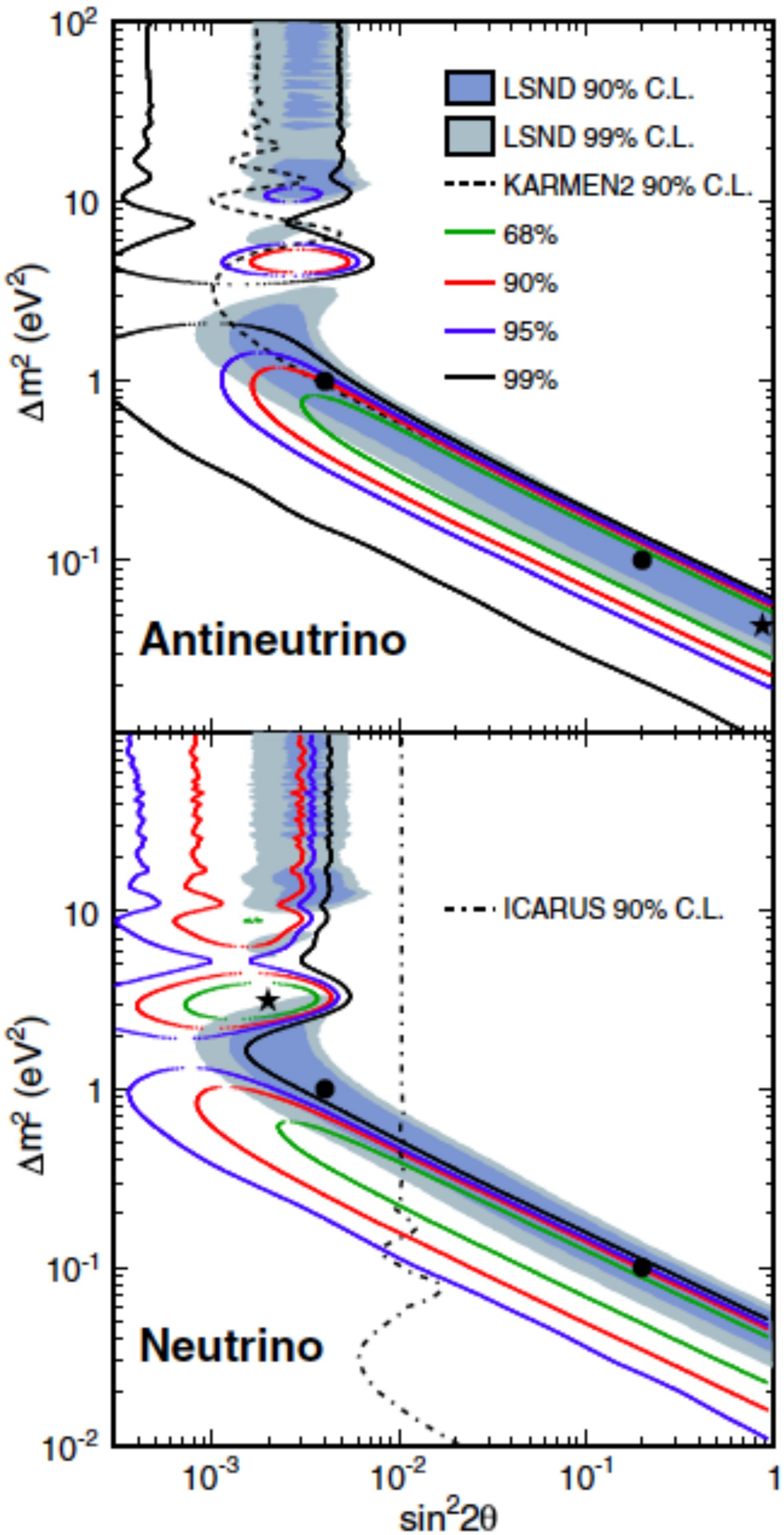
MiniBooNE Coll., 2006.16883

The angular distribution is quite flat resembling SM neutrino interactions.

The explanation with light sterile neutrino oscillations has been put forward and it is compatible with LSND.



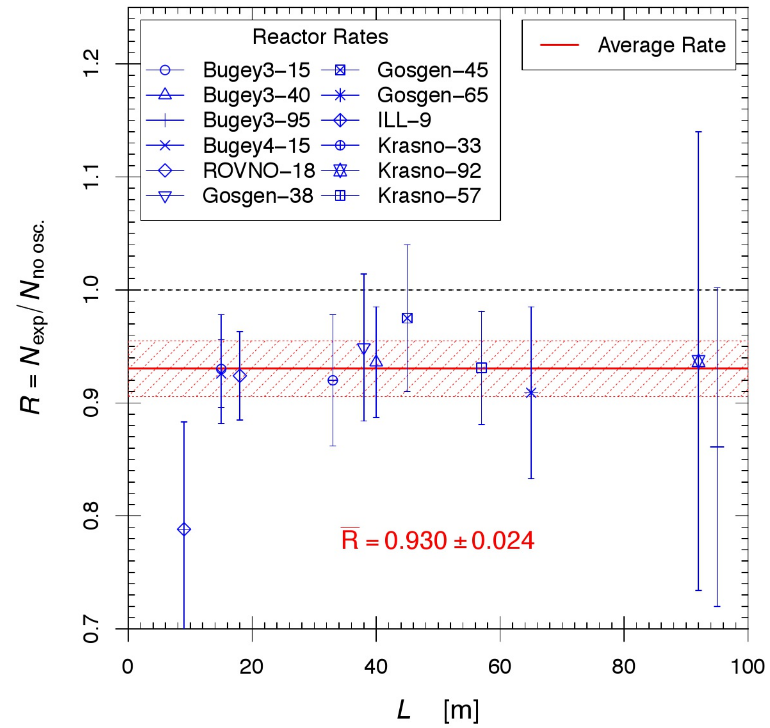
MiniBooNE Coll., 2006.16883



The LSND and MiniBooNE signals can be explained in terms of neutrino oscillations.

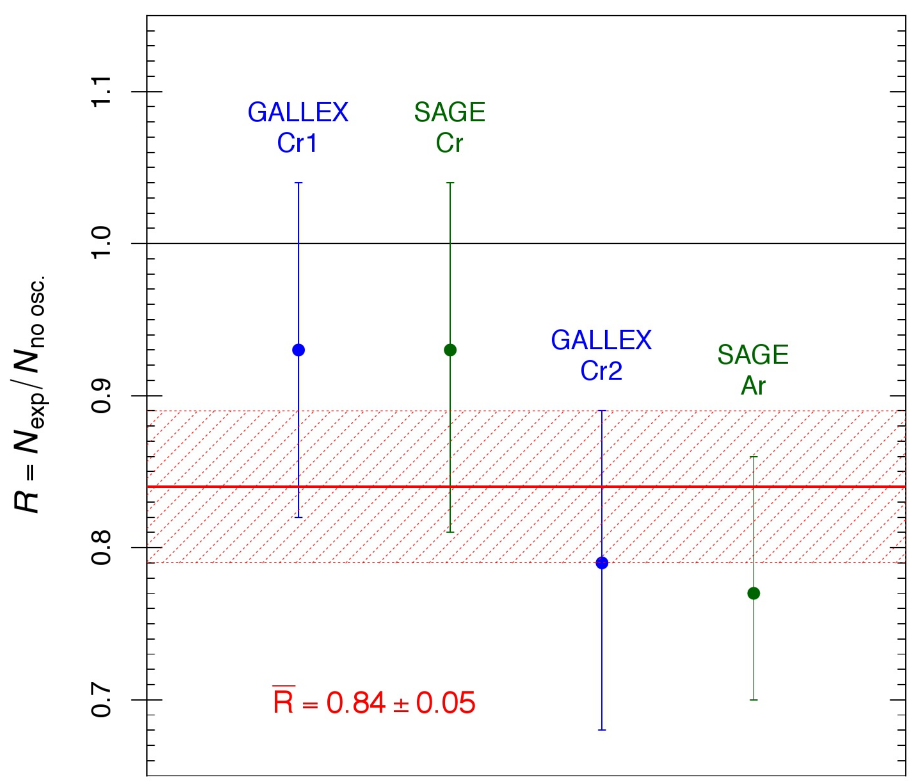
$$P(\nu_\mu \to \nu_e) = \underbrace{4|U_{e4}|^2|U_{\mu 4}|^2}_{\sin^2 2\theta} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

Electron neutrino disappearance



Mention et al., 2011. See also Muller et al., PRC 832011; Huber et al, PRC84 2011. And Sinev, 1103.2452; Ciuffoli et al., JHEP 12 2012; Zhang et al., PRD87 2013; Ivanov et al., 1306.1995.

Reactor anomaly: A recomputation of the reactor fluxes seems to indicate neutrino disappearance, compatible with oscillations into sterile neutrinos with large masses.



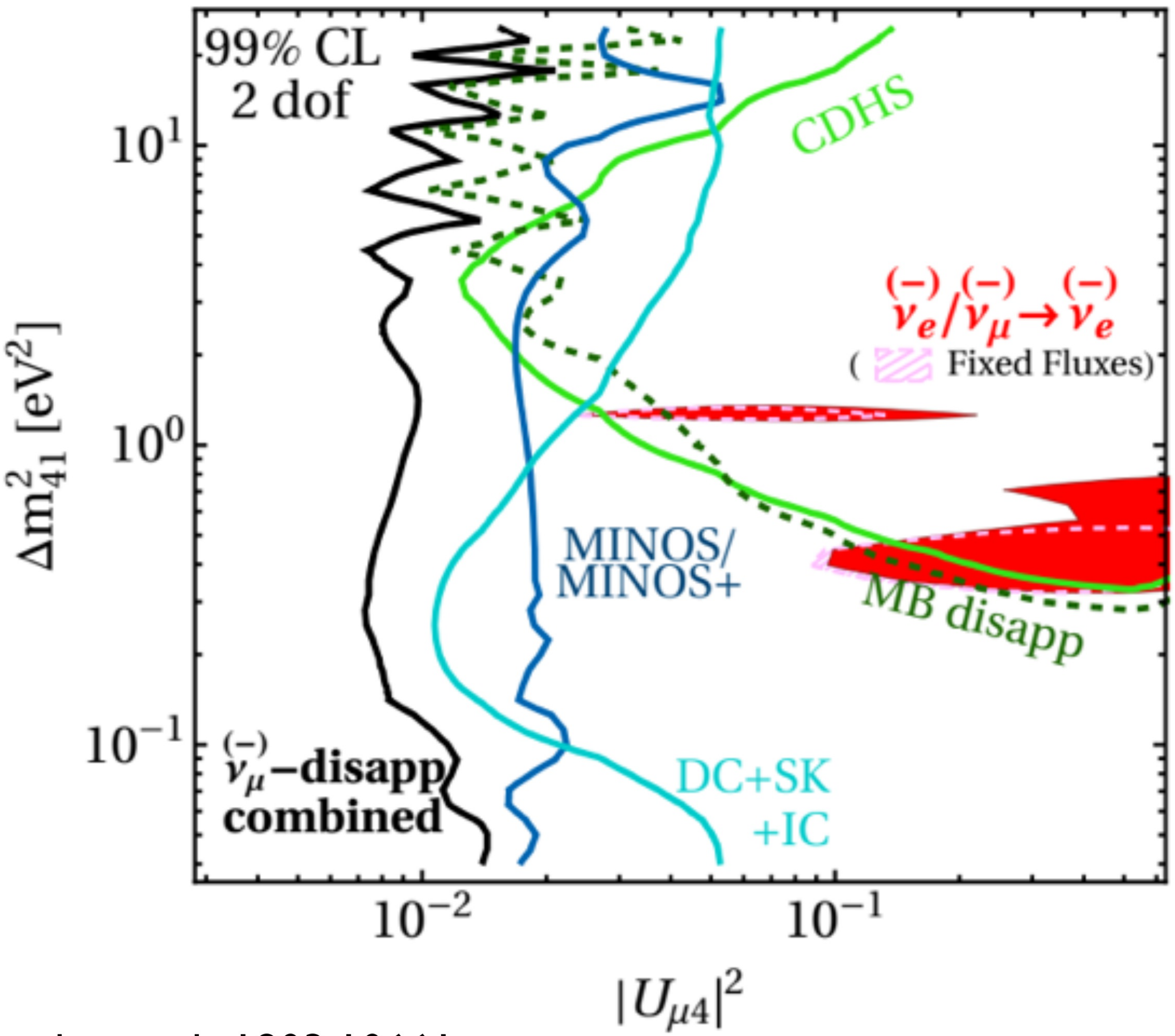
Frekers et al., PLB 706 2011. See also SAGE 2006, 2009; Laveder et al., NPPS 2007, MPLA 2007, PRD 2008, PRC 2011, PRD 2012.

Gallium anomaly: The measurement of the fluxes of electron neutrinos in Gallium Radioactive sources reports a value 2.9 sigma away from what expected.

Muon neutrino disappearance channel

Muon neutrino disappearance studies have reported no hints but only strong bounds.

IceCube
CDHS
MiniBooNE
SK
DeepCore
NOvA
MINOS/MINOS+



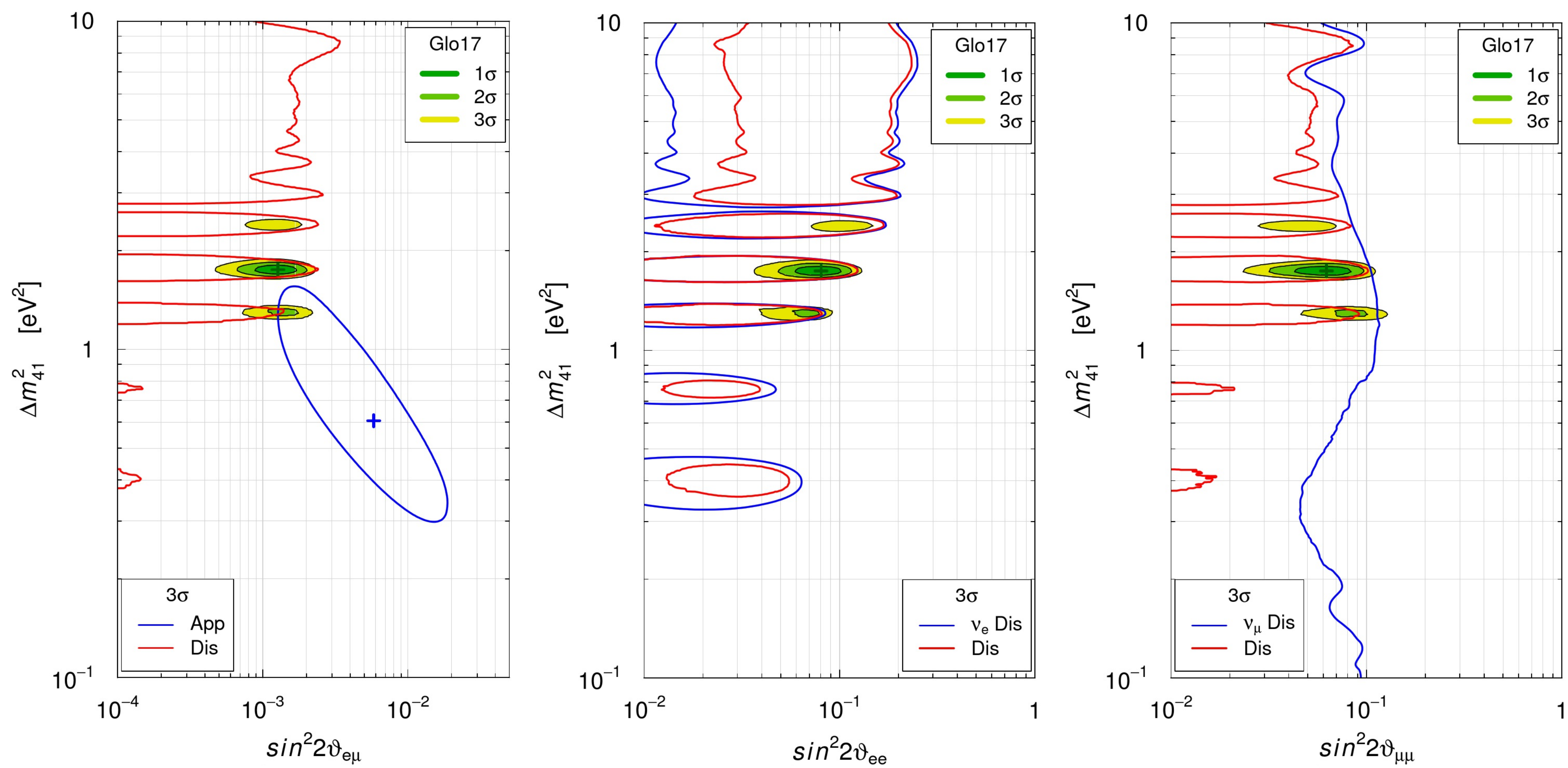
A. Dentler et al., 1803.10661

Oscillation disappearance:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\frac{\Delta m^2_{41} L}{4E}$$

Appearance experiments require mixing both with electron neutrinos and muon neutrinos: Tension.

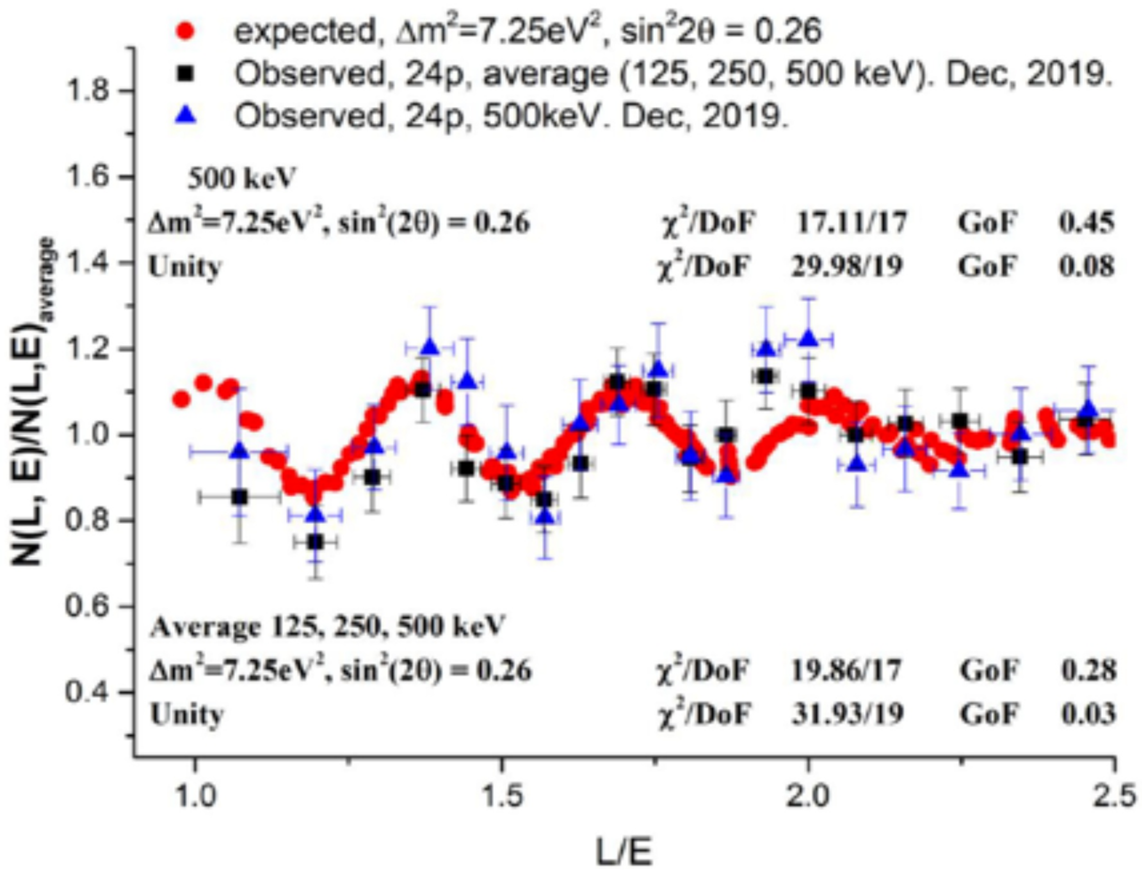
$$P(\nu_\alpha \to \nu_\beta) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\sin^2\frac{\Delta m^2_{41} L}{4E}$$

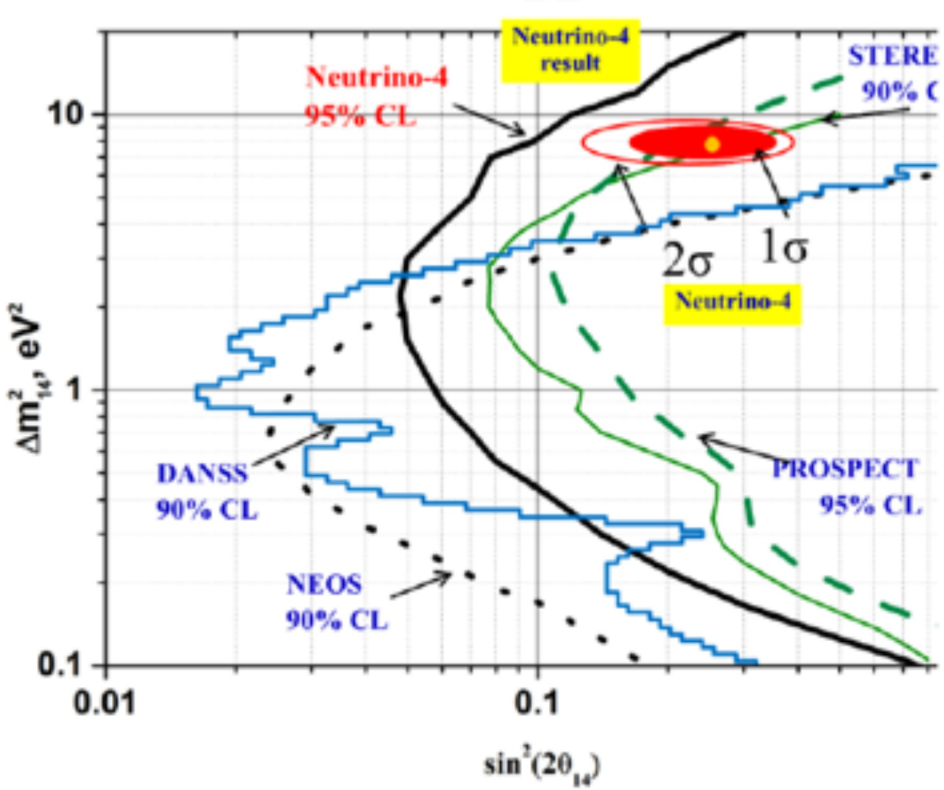


Gariazzo et al., JHEP 1706 (2017)

Very short baseline experiments

Experiments with very short baselines have been designed to test these anomalies in controlled conditions.



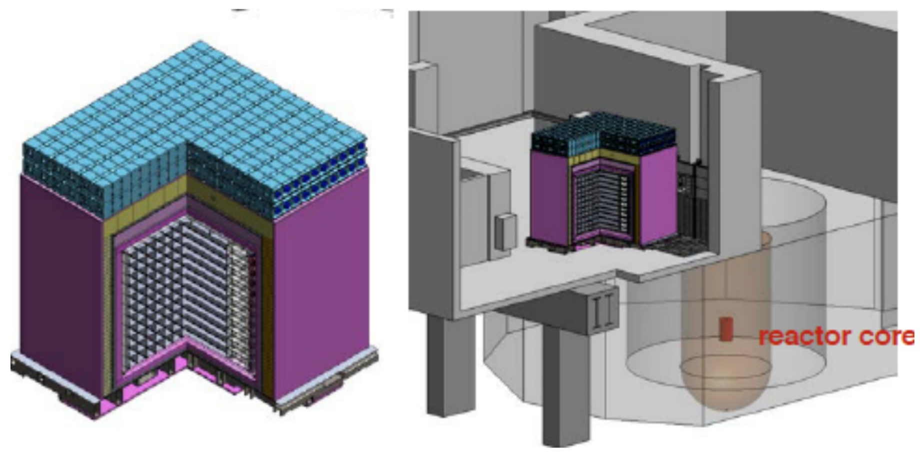


Short baseline reactor antineutrino experiments: Neutrino4 (anomaly?),

Neutrino4 Coll., 2005.05301

Very short baseline experiments

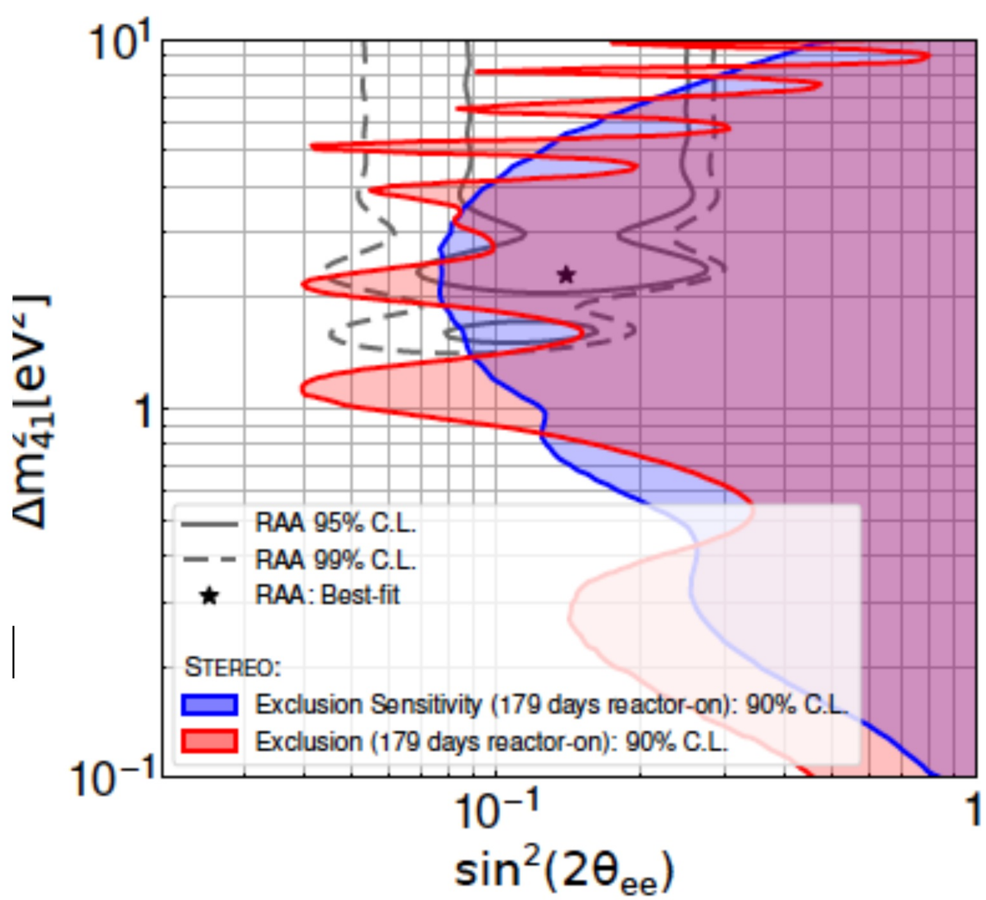
Experiments with very short baselines have been designed to test these anomalies in controlled conditions.



^{6}Li Liquid Scint. Detector @ 7.9m from HFIR, ORNL,
85MW, Highly-Enriched Uranium (HEU, 93%)
>99% of ν flux from ^{235}U

Short baseline reactor antineutrino experiments: Neutrino4 (anomaly?), PROSPECT, STEREO,

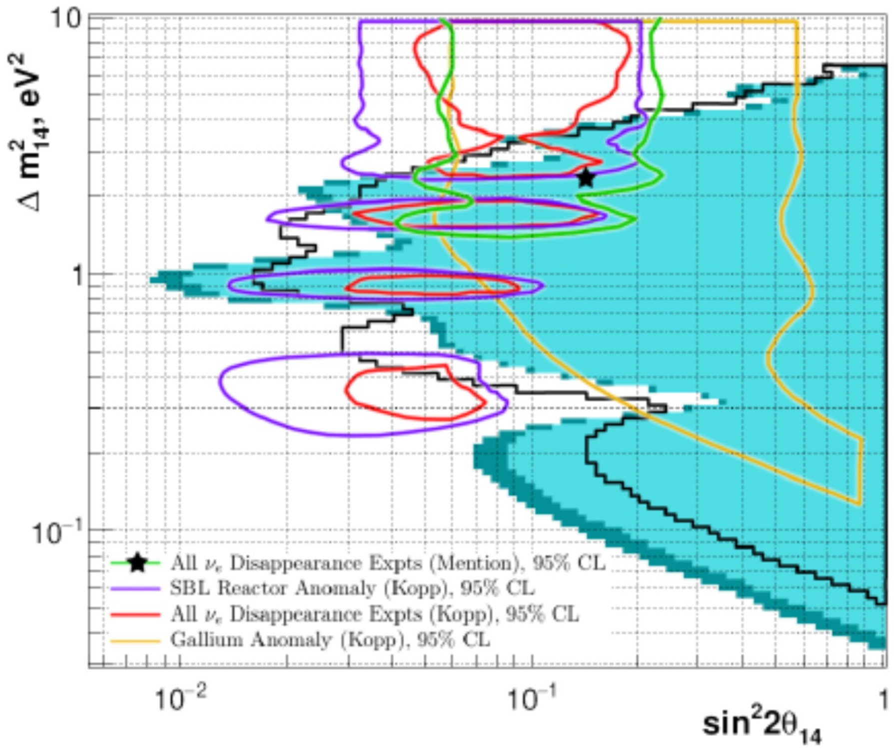
For review, see Fallot's talk, Neutrino 2020



STEREO Coll., 2004.04075

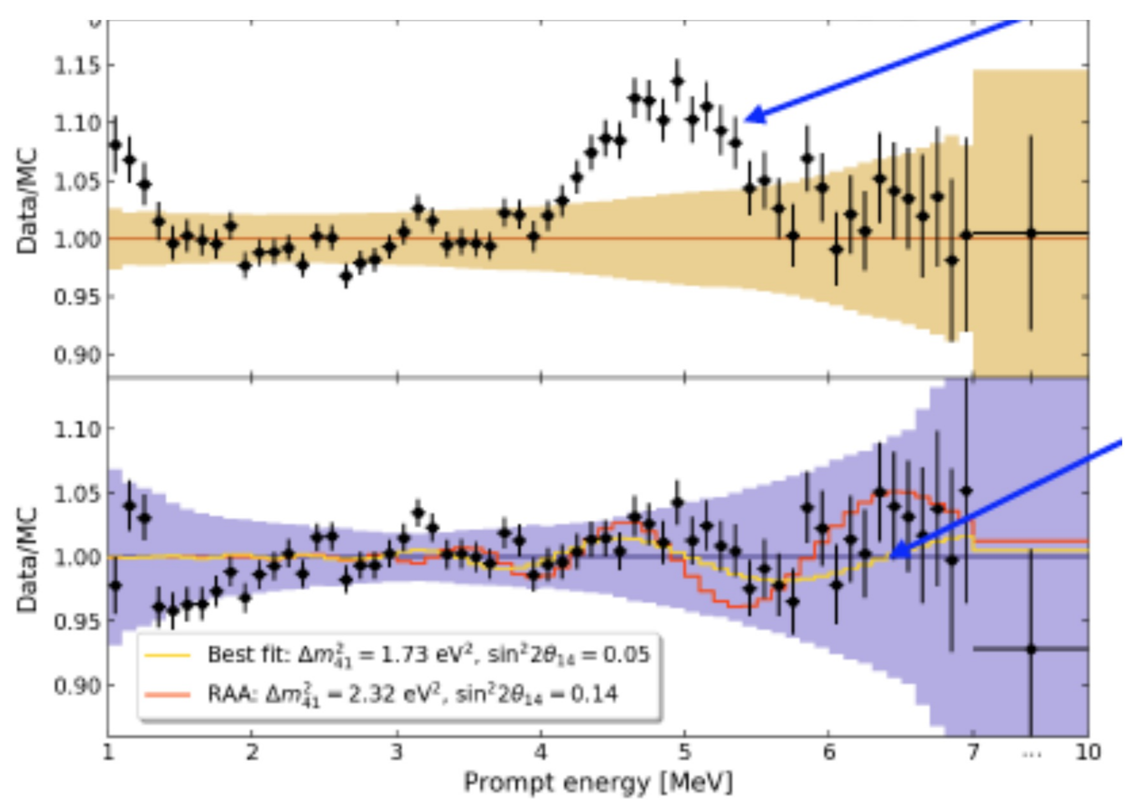
Very short baseline experiments

Experiments with very short baselines have been designed to test these anomalies in controlled conditions.



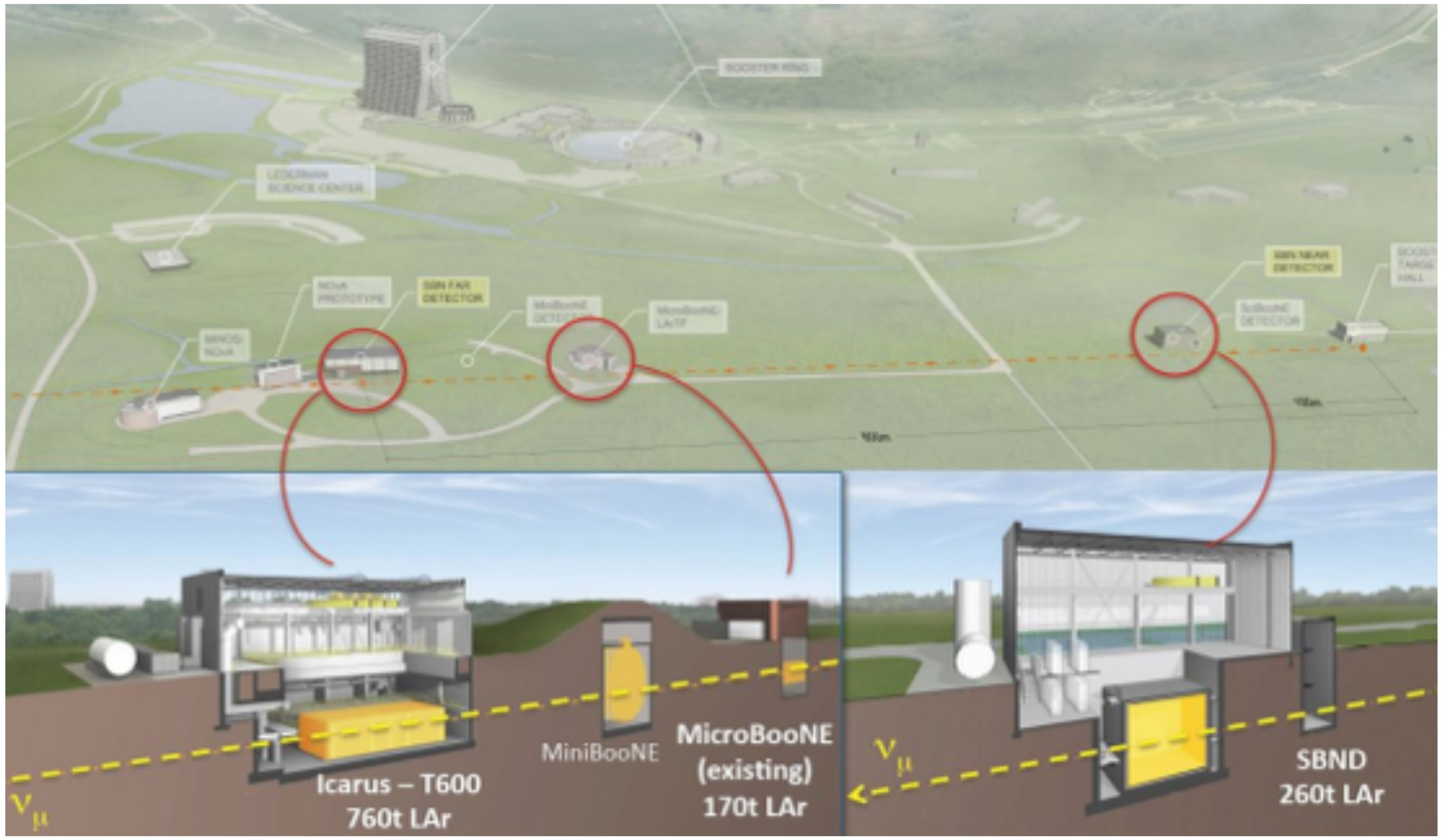
DANSS Coll., 1911.10140

Short baseline reactor antineutrino experiments: Neutrino4 (anomaly??), PROSPECT, STEREO, DANSS, NEOS (anomaly?), SoLid@BR2.



NEOS, PRL 118 (2017)

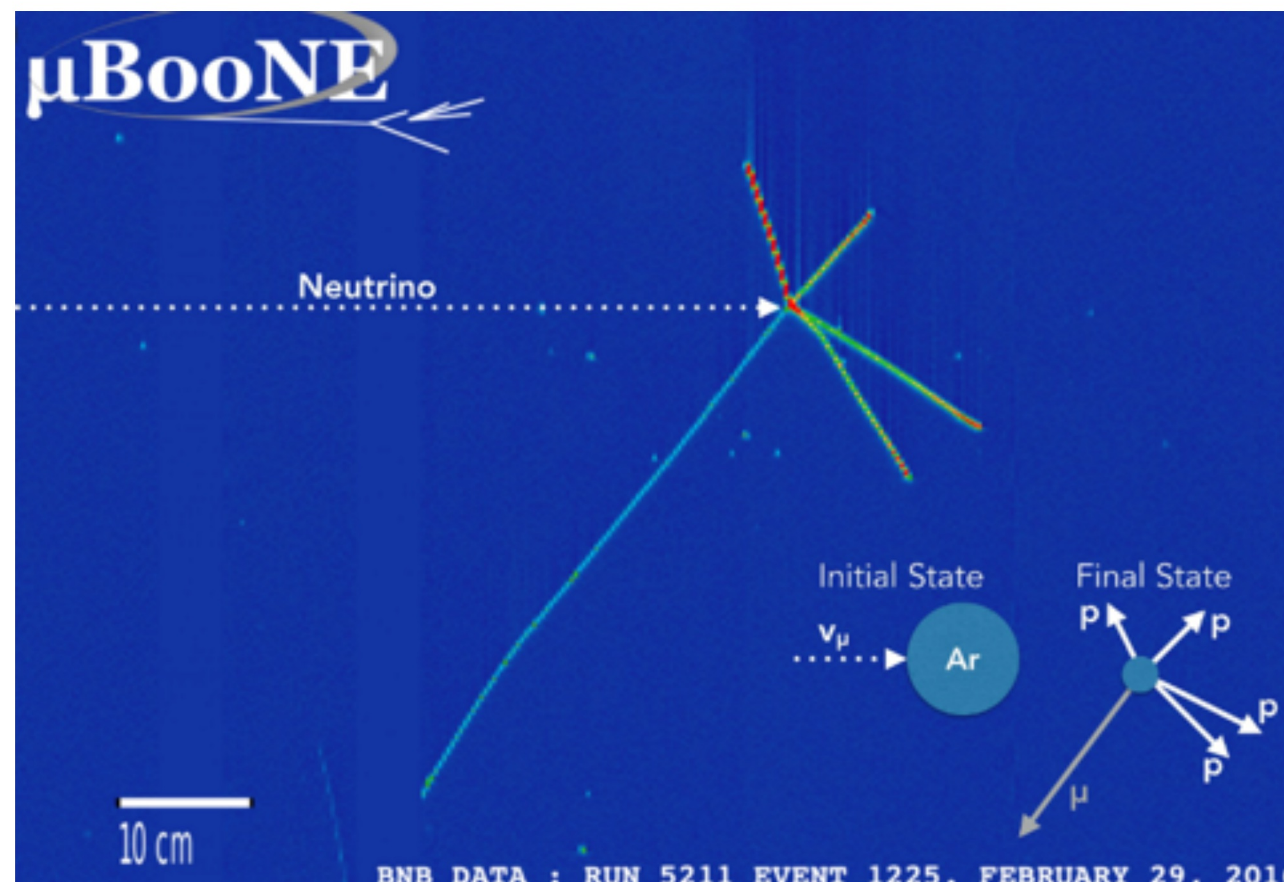
MicroBooNE and SBN at Fermilab



They use accelerator neutrino experiments with L~100-600m and E~700-800 MeV.

https://www.bo.infn.it/gruppo2/sbn-it/

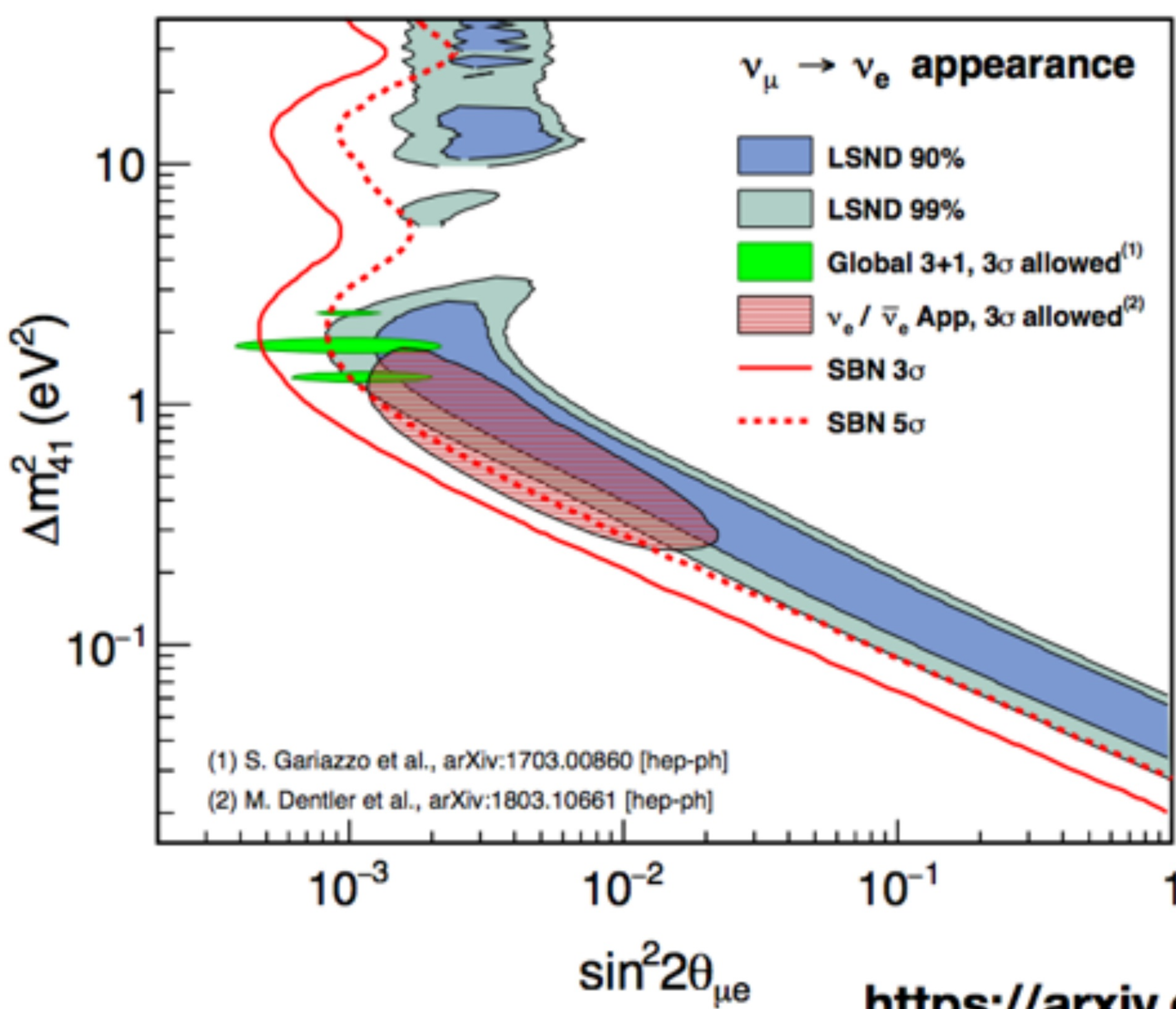
MicroBooNE detector



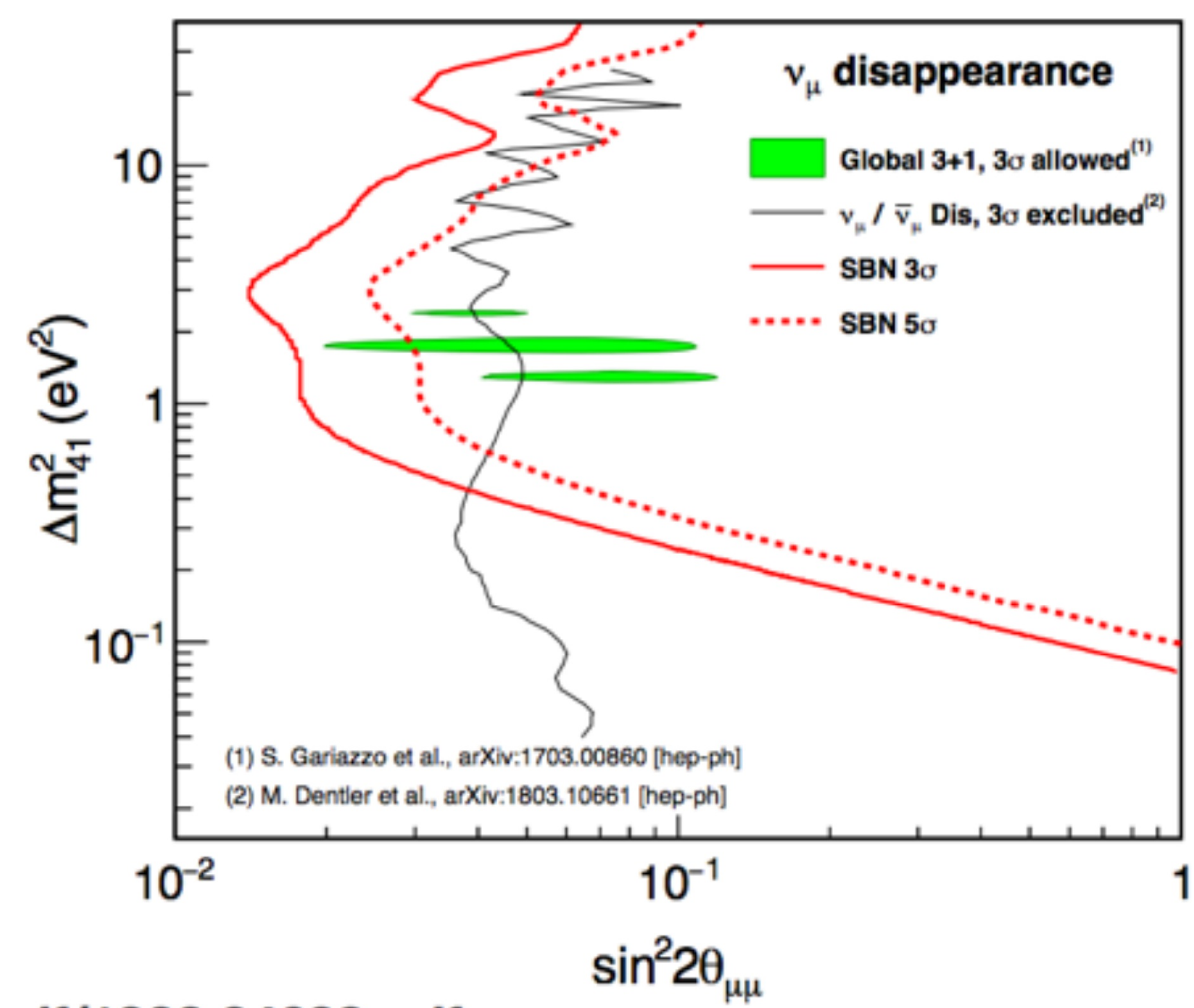
MicroBooNE event: muon neutrino scattering in LAr

Accelerator neutrino experiments should provide the definitive answer and can check both the appearance and disappearance channels.

ν_e appearance



ν_μ disappearance



https://arxiv.org/pdf/1903.04608.pdf

M. Betancourt, Neutrino 2020

Non-unitarity

If some of the heavy states are not kinematically accessible (e.g. very heavy HNLs), it will result in non-unitarity effects. At leading order these are equivalent to averaged sterile neutrino oscillations.

Active-nearly sterile mixing

$$V_{n\times n} = \begin{pmatrix} U_{3\times 3} & T \\ S & Z \end{pmatrix}$$

U is non-unitary.

Schechter, Valle 1980
Langacker, London 1988
Antusch, et al. 2006

Blennow et al., 1609.08637

	"Non-Unitarity" ($m >$ EW)
α_{ee}	$1.3 \cdot 10^{-3}$ [46]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$ [46]
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$ [46]
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ ($2.4 \cdot 10^{-5}$) [46]
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$ [46]
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$ [46]

NSI

If neutrinos have additional interactions, matter effects can be modified:

$$\mathcal{L}_{\rm NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta)(\bar{f}\gamma_\mu P f')$$

Dev et al., 1907.00991

From a theoretical point of view, typically NSI are strongly constrained by the fact that neutrinos belong to the SU(2) leptonic doublet:
charged lepton constraints -> NSI constraints

$$\epsilon \propto g_X^2 / M_X^2 G_F^{-1}$$

It is possible to evade these bounds invoking light BSM.

See e.g., Farzan, Tortola, Front. Phys. 27

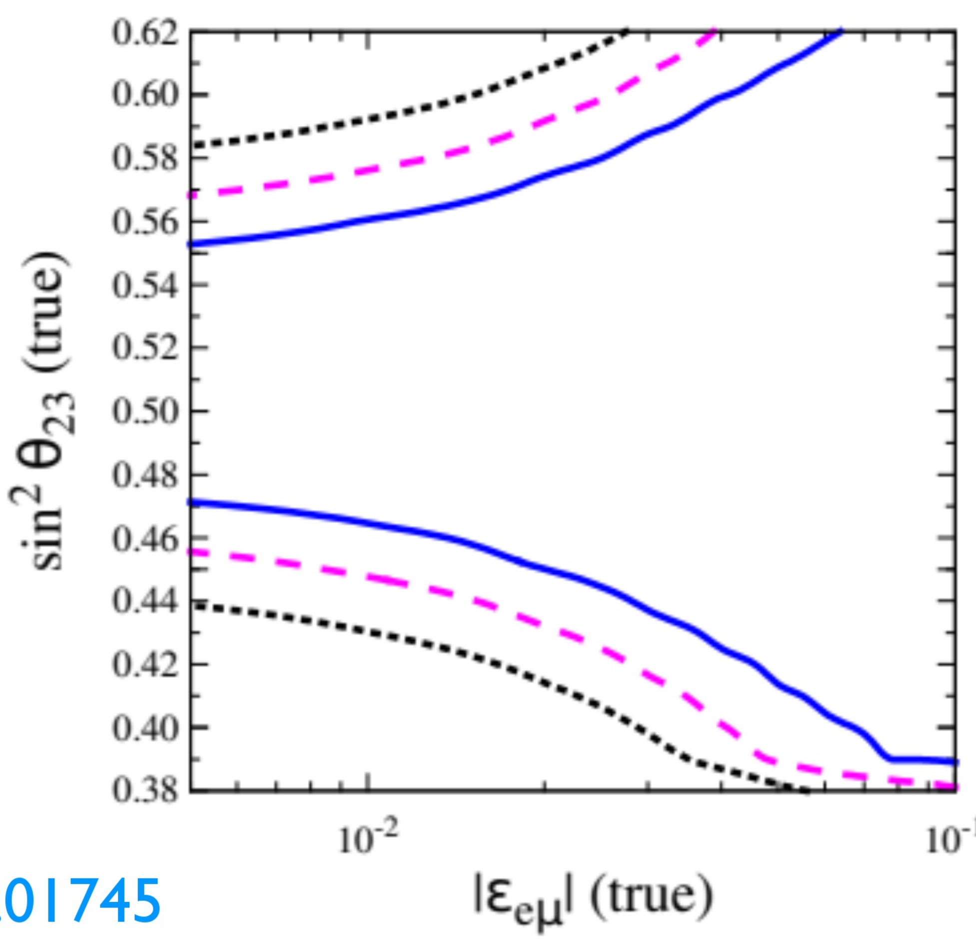
CC NSI can lead to 0-distance effects in production and detection.
NC NSI manifest themselves in matter effects

$$H = \frac{1}{2E}\left[U_{\rm PMNS}\begin{pmatrix}0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger_{\rm PMNS} + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

$$a = 2\sqrt{2}G_F N_e E$$

Dev et al., 1907.00991

and can affect the determination of the standard parameters.



Agarwalla, Chatterjee, Palazzo, 1607.01745

Considering neutrino oscillations experiments:

	90% C.L. range	Origin
NSI WITH QUARKS		
ϵ_{ee}^{dL}	[−0.3, 0.3]	CHARM
ϵ_{ee}^{dR}	[−0.6, 0.5]	CHARM
ϵ_{ee}^{dV}	[0.030, 0.55]	Oscillation data + COHERENT
ϵ_{ee}^{uV}	[0.028, 0.60]	Oscillation data + COHERENT
$\epsilon_{\mu\mu}^{dV}$	[−0.042, 0.042]	Atmospheric + accelerator
$\epsilon_{\mu\mu}^{uV}$	[−0.044, 0.044]	Atmospheric + accelerator
$\epsilon_{\mu\mu}^{dA}$	[−0.072, 0.057]	Atmospheric + accelerator
$\epsilon_{\mu\mu}^{uA}$	[−0.094, 0.14]	Atmospheric + accelerator
$\epsilon_{\tau\tau}^{dV}$	[−0.075, 0.33]	Oscillation data + COHERENT
$\epsilon_{\tau\tau}^{uV}$	[−0.09, 0.38]	Oscillation data + COHERENT
$\epsilon_{\tau\tau}^{qV}$	[−0.037, 0.037]	Atmospheric
NSI WITH ELECTRONS		
ϵ_{ee}^{eL}	[−0.021, 0.052]	Solar + KamLAND
ϵ_{ee}^{eR}	[−0.07, 0.08]	TEXONO
$\epsilon_{\mu\mu}^{eL}, \epsilon_{\mu\mu}^{eR}$	[−0.03, 0.03]	Reactor + accelerator
$\epsilon_{\tau\tau}^{eL}$	[−0.12, 0.06]	Solar + KamLAND
$\epsilon_{\tau\tau}^{eR}$	[−0.98, 0.23]	Solar + KamLAND and Borexino
	[−0.25, 0.43]	Reactor + accelerator
$\epsilon_{\tau\tau}^{eV}$	[−0.11, 0.11]	Atmospheric

[a]Bound adapted from $\epsilon_{\tau\tau}^{eV}$.

	90% C.L. range	Origin
NSI WITH QUARKS		
$\epsilon_{e\mu}^{qL}$	[−0.023, 0.023]	Accelerator
$\epsilon_{e\mu}^{qR}$	[−0.036, 0.036]	Accelerator
$\epsilon_{e\mu}^{uV}$	[−0.073, 0.044]	Oscillation data + COHERENT
$\epsilon_{e\mu}^{dV}$	[−0.07, 0.04]	Oscillation data + COHERENT
$\epsilon_{e\tau}^{qL}, \epsilon_{e\tau}^{qR}$	[−0.5, 0.5]	CHARM
$\epsilon_{e\tau}^{uV}$	[−0.15, 0.13]	Oscillation data + COHERENT
$\epsilon_{e\tau}^{dV}$	[−0.13, 0.12]	Oscillation data + COHERENT
$\epsilon_{\mu\tau}^{qL}$	[−0.023, 0.023]	Accelerator
$\epsilon_{\mu\tau}^{qR}$	[−0.036, 0.036]	Accelerator
$\epsilon_{\mu\tau}^{qV}$	[−0.006, 0.0054]	IceCube
$\epsilon_{\mu\tau}^{qA}$	[−0.039, 0.039]	Atmospheric + accelerator
NSI WITH ELECTRONS		
$\epsilon_{e\mu}^{eL}, \epsilon_{e\mu}^{eR}$	[−0.13, 0.13]	Reactor + accelerator
$\epsilon_{e\tau}^{eL}$	[−0.33, 0.33]	Reactor + accelerator
$\epsilon_{e\tau}^{eR}$	[−0.28, −0.05] & [0.05, 0.28]	Reactor + accelerator
	[−0.19, 0.19]	TEXONO
$\epsilon_{\mu\tau}^{eL}, \epsilon_{\mu\tau}^{eR}$	[−0.10, 0.10]	Reactor + accelerator
$\epsilon_{\mu\tau}^{eV}$	[−0.018, 0.016]	IceCube

[a]Bound adapted from $\epsilon_{\mu\tau}^{qV}$.

See e.g., Farzan, Tortola, Front. Phys. 27

Summary and Conclusions

Neutrino oscillations imply that neutrinos have mass and mix.

Since their discovery, neutrino oscillations have provided us with a precise picture of neutrino properties.

Key open questions remain open and a wide experimental programme is ongoing/planned to answer them:

- neutrino nature
- leptonic CPV
- neutrino masses
- precise measurement of mixing parameters
- tests of standard 3-neutrino mixing paradigm.