Queen Mary
University of London

Experimental Overview of Neutrino Oscillations

Dr Linda Cremonesi

NNN 2023, Procida, Italy

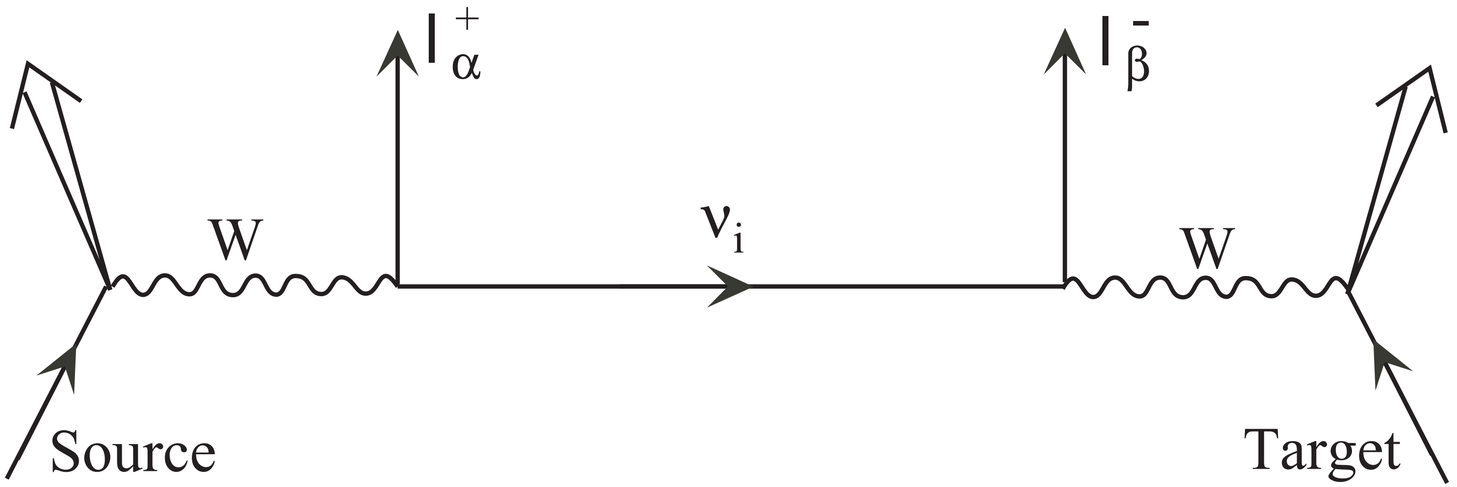
Neutrino flavour oscillations

Flavour eigenstates
ν_e, ν_μ, ν_τ

3x3 unitary matrix
PMNS matrix

Mass eigenstates
ν_1, ν_2, ν_3

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i$$



2015
Nobel Prize in Physics

PMNS Parametrisation - 3 flavours

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$

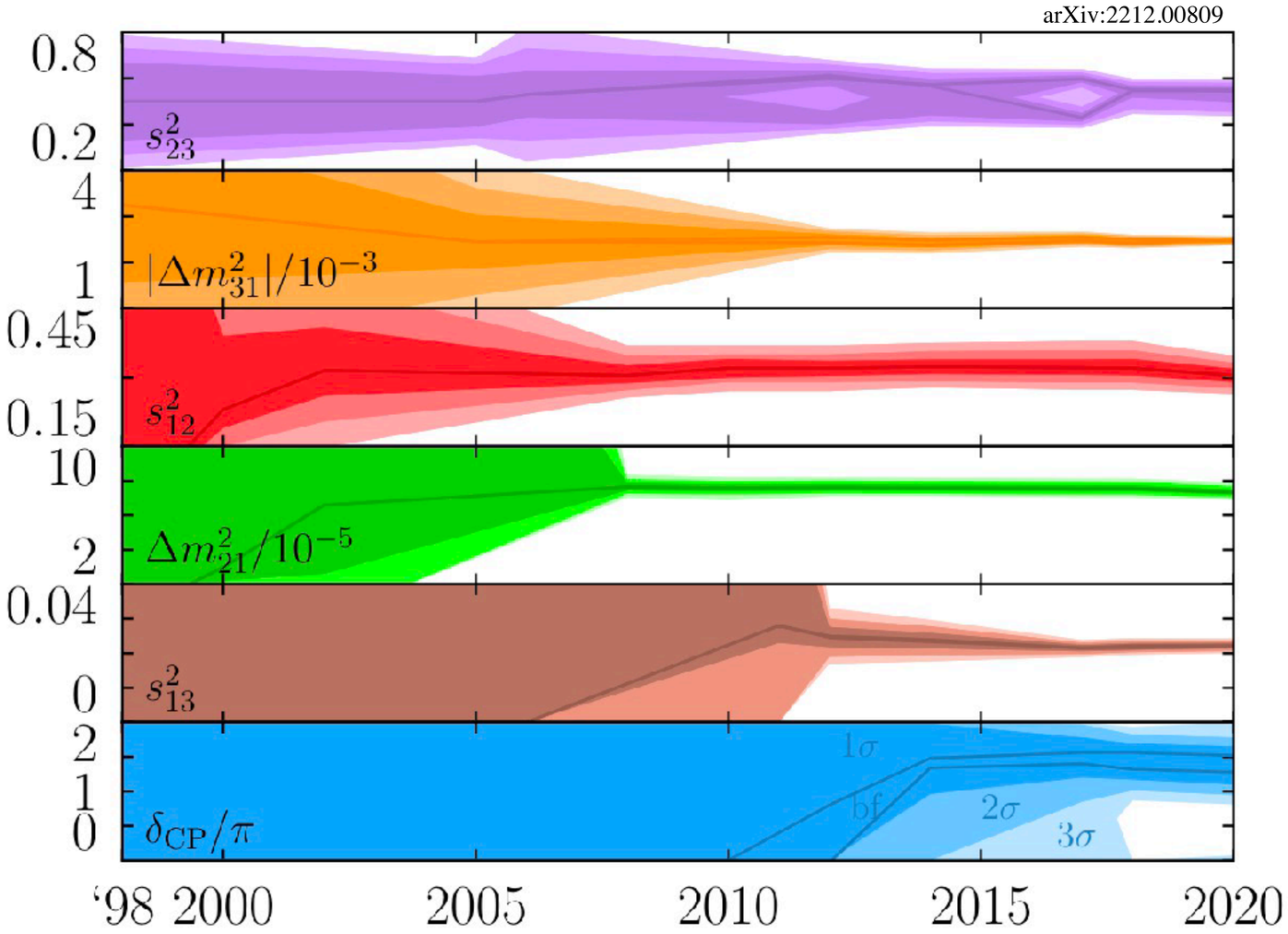
θ_{ij} : the mixing angles

δ : CP-violating phase

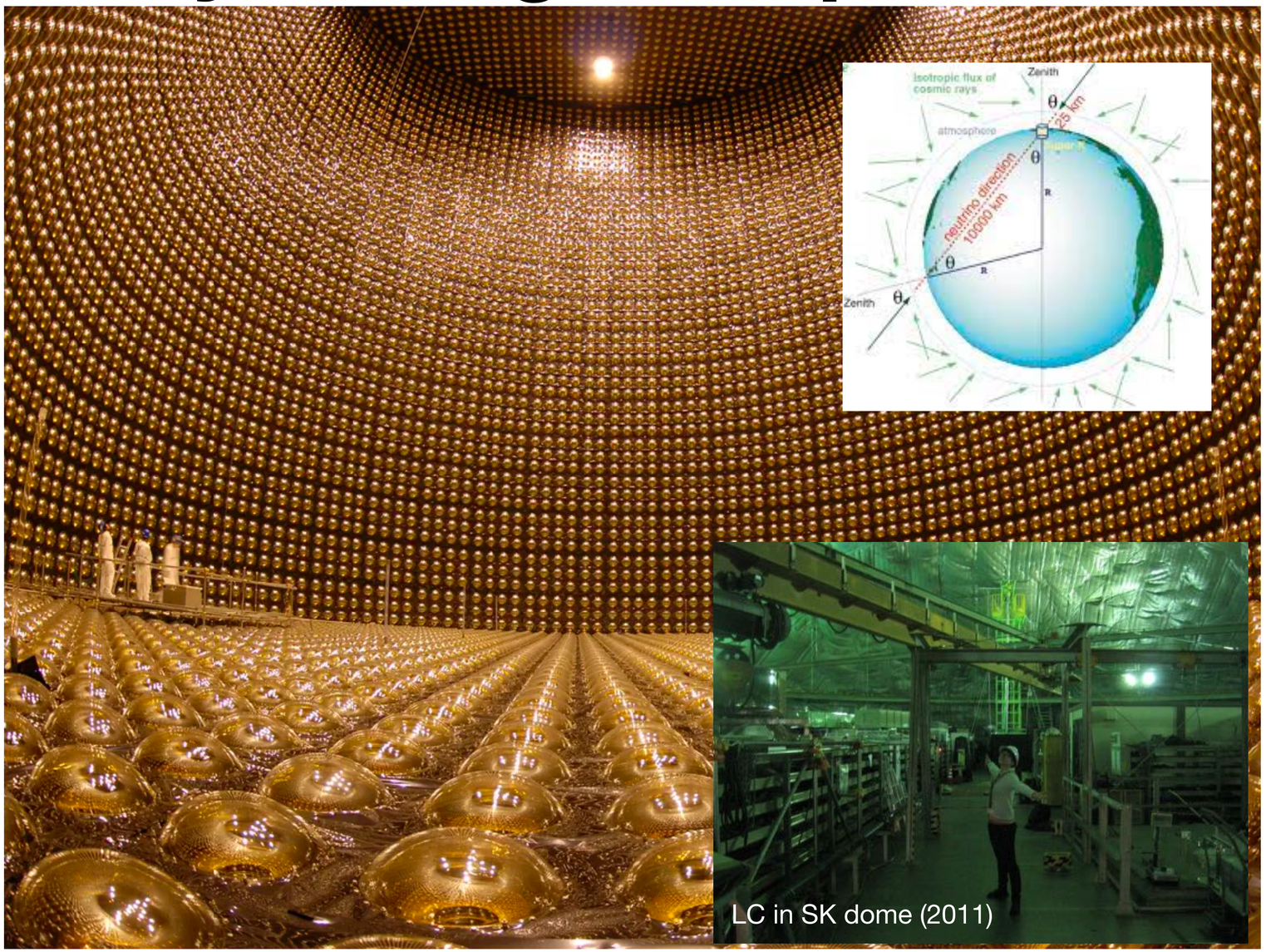
α, β : Majorana phases

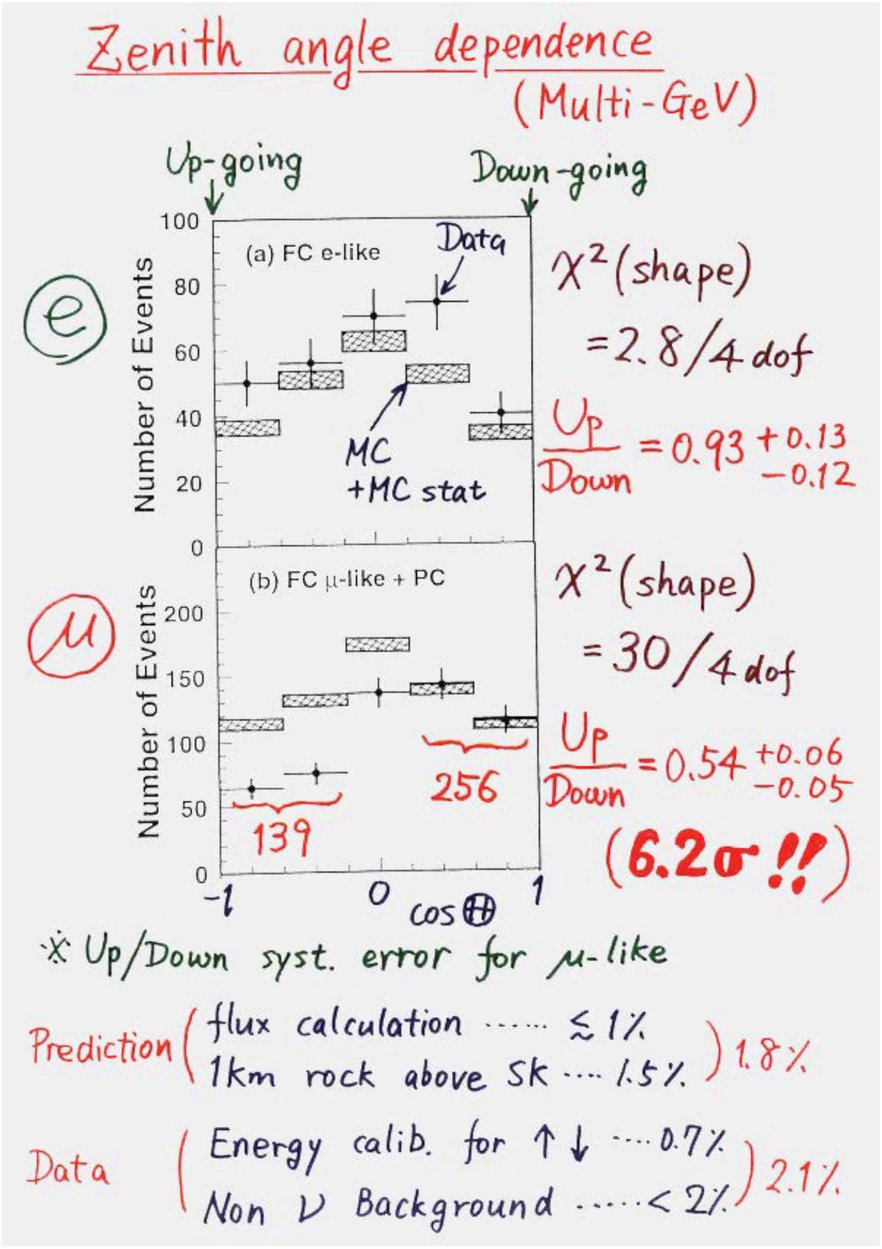
Atmospheric/LBL	Reactor/LBL	Reactor/Solar
$\theta_{23} \sim 45^o$	$\theta_{13} \sim 8.5^o$	$\theta_{12} \sim 33^o$
$\Delta m^2_{32} \sim \pm 2.5 \times 10^{-3} eV^2$	$\delta_{CP}???$	$\Delta m^2_{12} \sim 7.5 \times 10^{-5} eV^2$

What do we know now?

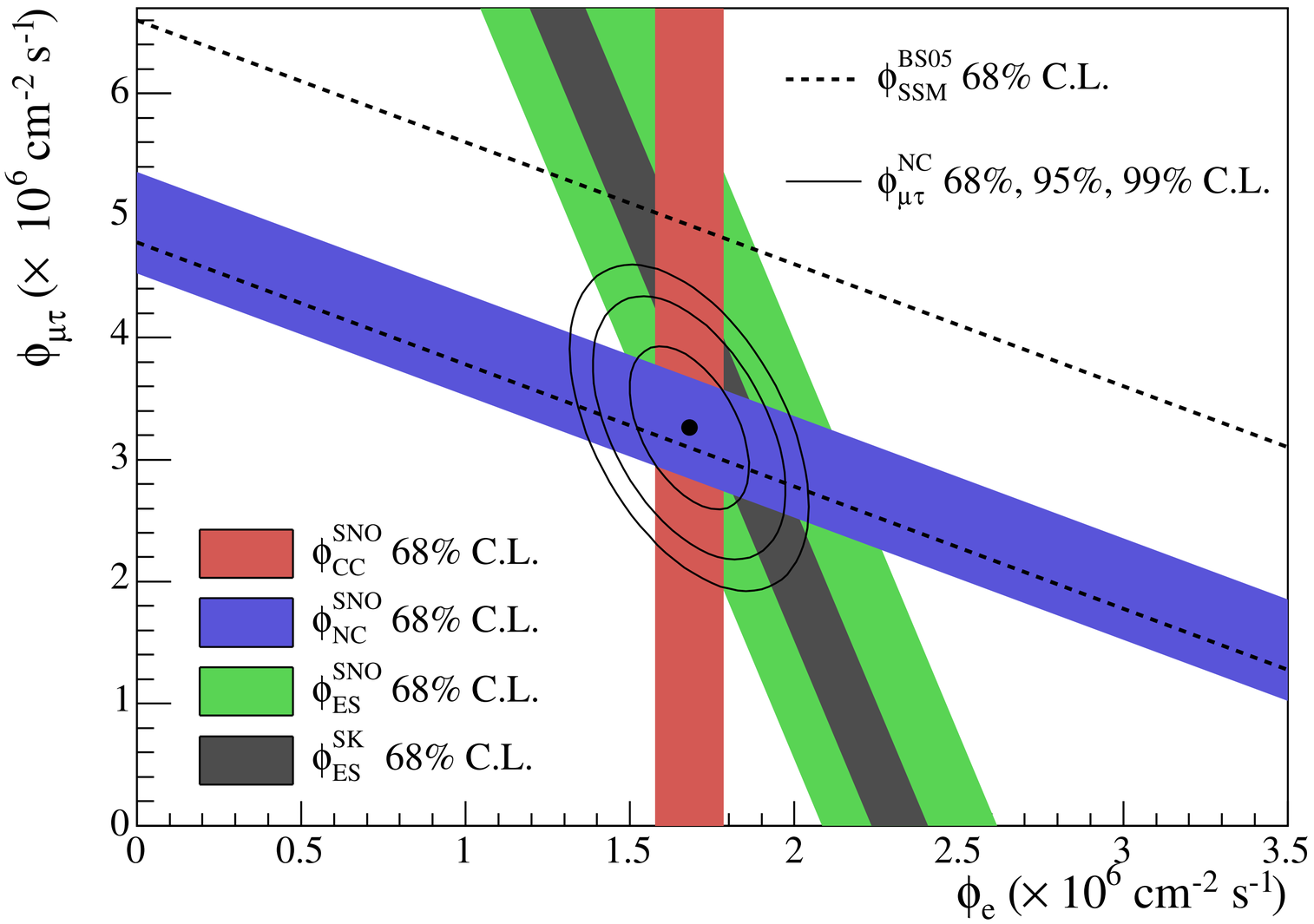


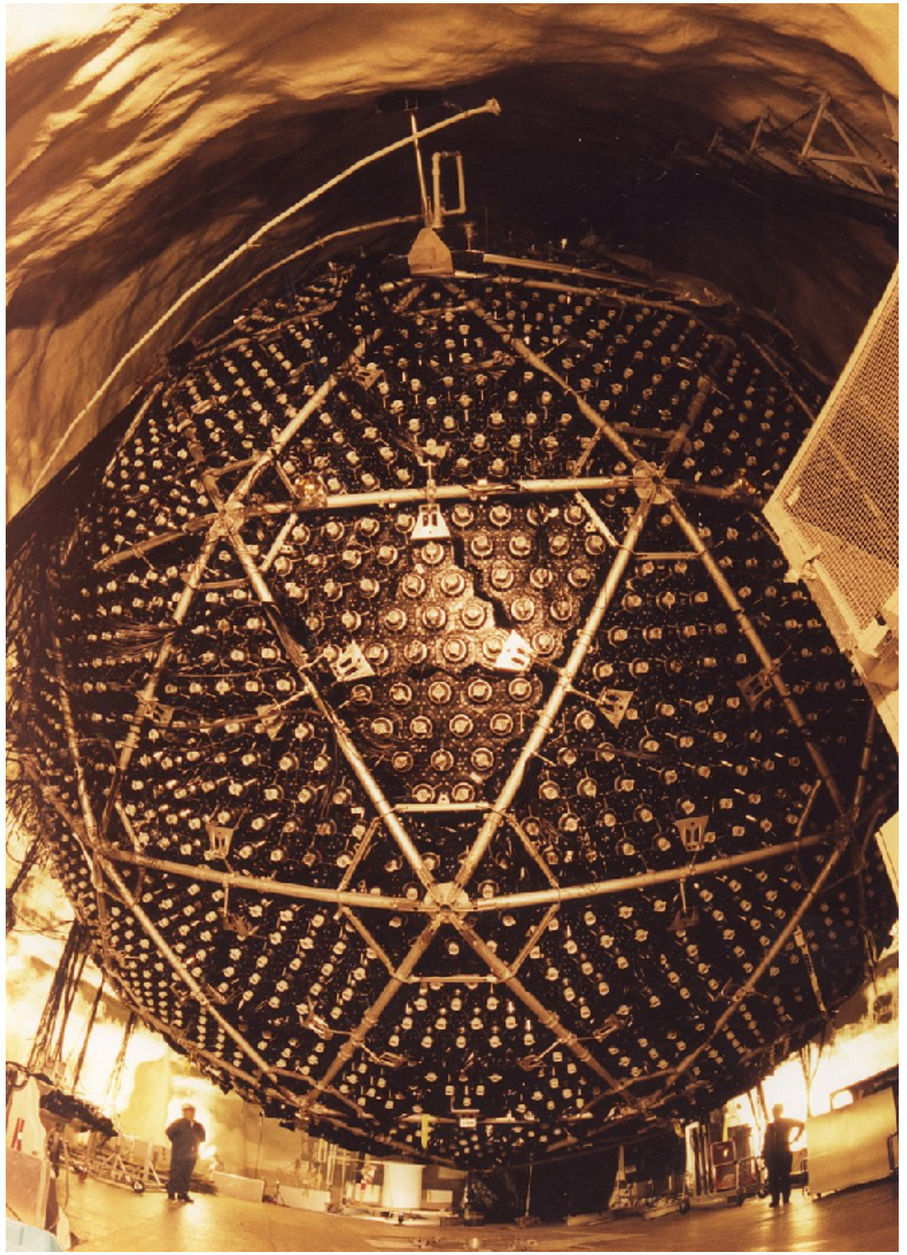
25 years ago - Super K!



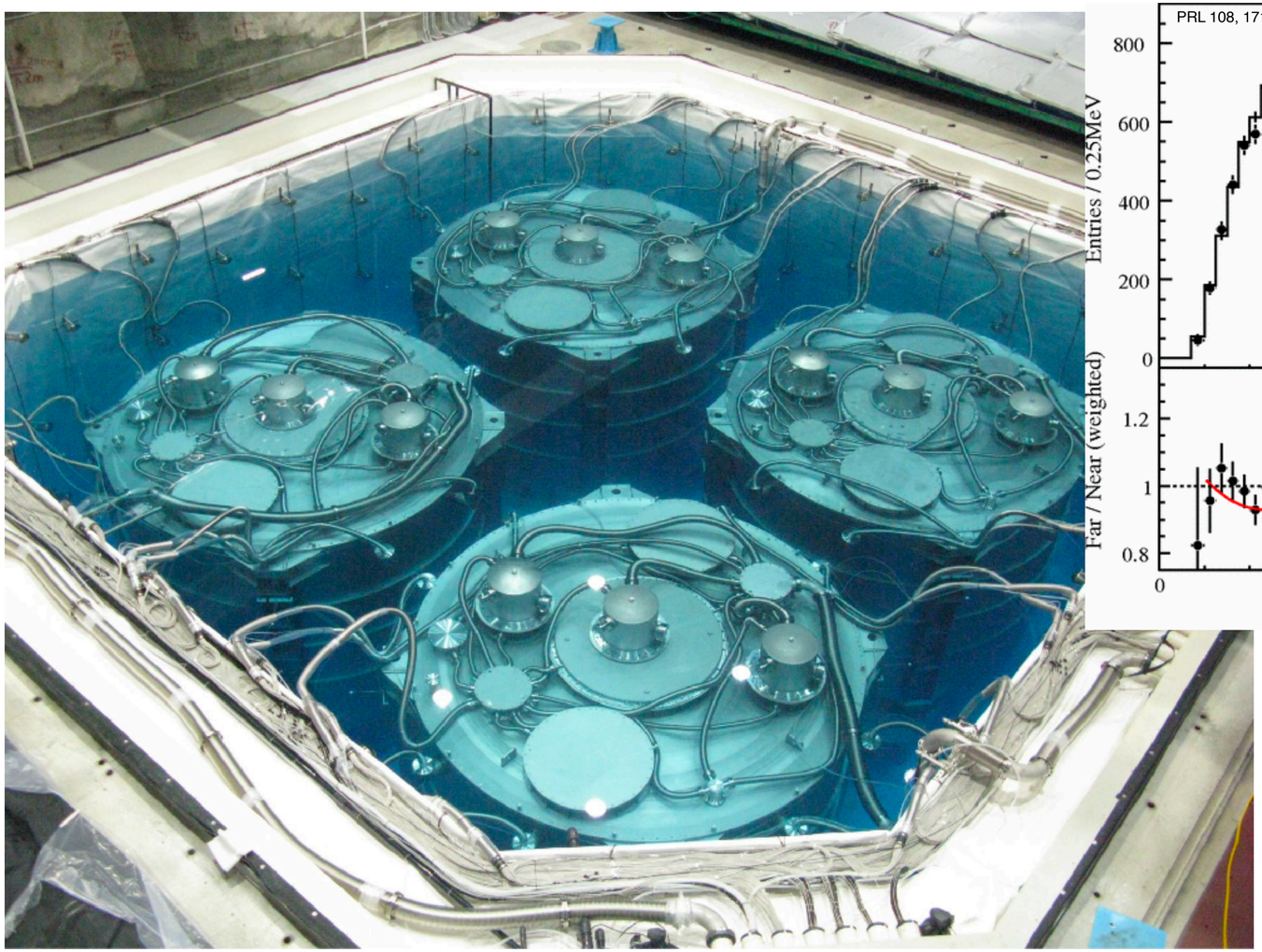


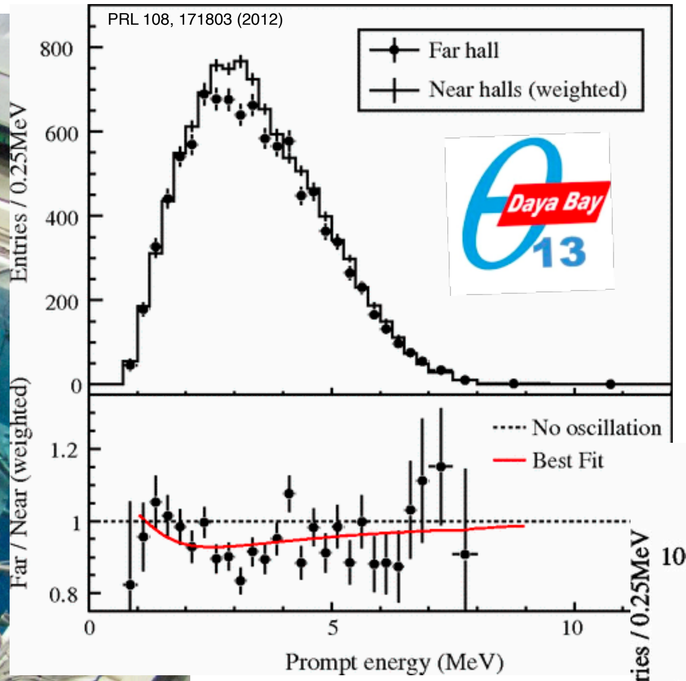
SNO and solar neutrinos



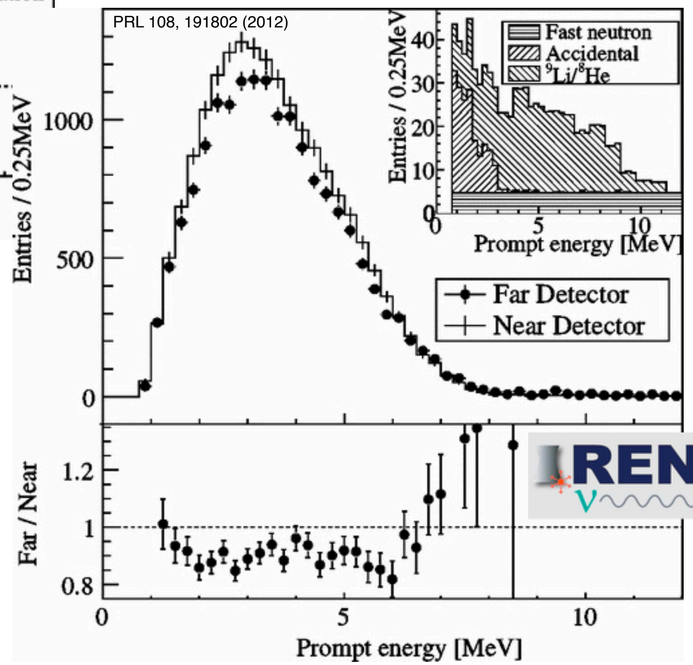


Daya Bay, RENO and θ_{13}





$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix}$$



See talk by Liangjian Wen on reactor neutrino experiments!

Big questions

How much do neutrinos mix?

Jargon alert: is θ_{23} maximal? Upper/Lower octant?

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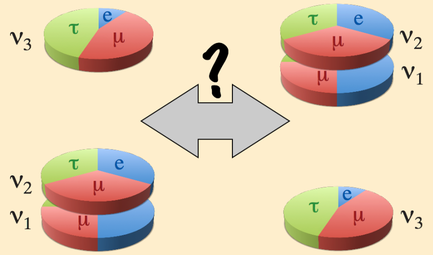
Which is the lightest neutrino?



Normal Ordering Inverted Ordering

Jargon alert: is $\Delta m^2_{32} \lessgtr 0$?

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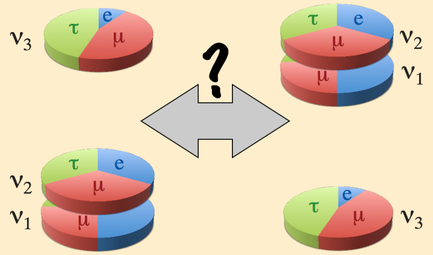

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Do neutrinos and antineutrinos oscillate in the same way?

?

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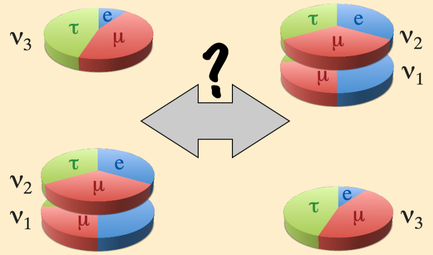

Normal Ordering Inverted Ordering

Jargon alert: is $\Delta m^2_{32} \lessgtr 0$?

Do neutrinos and antineutrinos oscillate in the same way?

?

Jargon alert: is $\delta_{CP} \neq 0$?

Is there a light sterile neutrino?

Jargon alert: ν_s ? ν_4 ?

All neutrino oscillation experiments are the same…

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Produce neutrinos

[possibly all in the same flavour]

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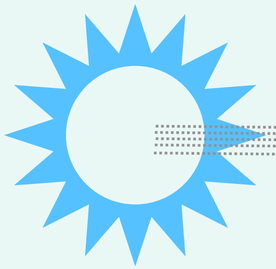


Propagate!

[a few km
to a few kpc]

Neutrino oscillations

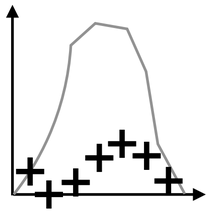
Matter Effects

All neutrino oscillation experiments are the same…

Produce neutrinos
[possibly all in the same flavour]

Propagate!
[a few km
to a few kpc]

Look for a deficit or excess!



Complications…

$$N \approx \Phi(E_\nu) \otimes \sigma(k, k') \otimes \epsilon \otimes P(\nu_\alpha \rightarrow \nu_\beta)$$

Oscillated Neutrinos

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Oscillated Neutrinos

Neutrino flux

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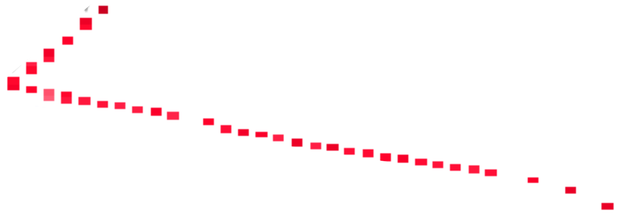
Oscillated Neutrinos

Neutrino flux

Neutrino interactions



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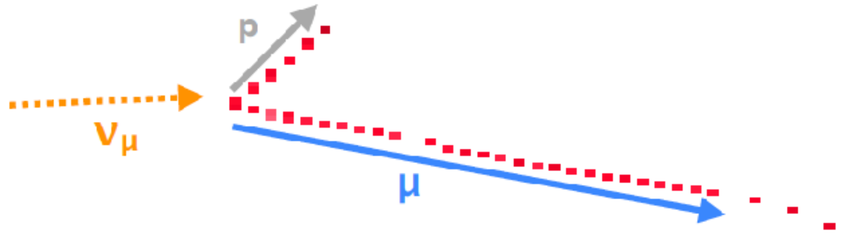
Oscillated Neutrinos

Neutrino flux

Neutrino interactions

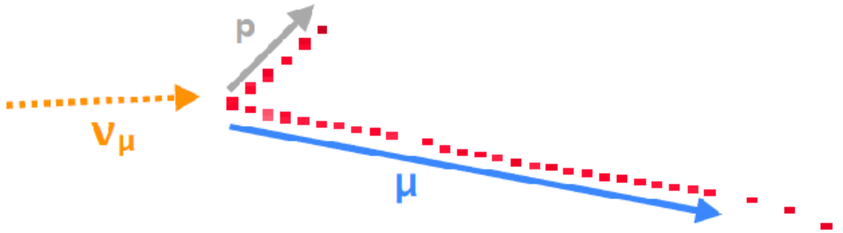
Detector response

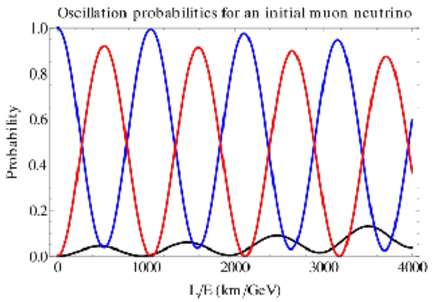


Complications…

$$N \approx \Phi(E_\nu) \otimes \sigma(k, k') \otimes \epsilon \otimes P(\nu_\alpha \to \nu_\beta)$$

Oscillated Neutrinos	Neutrino flux	Neutrino interactions	Detector response	Oscillation probability





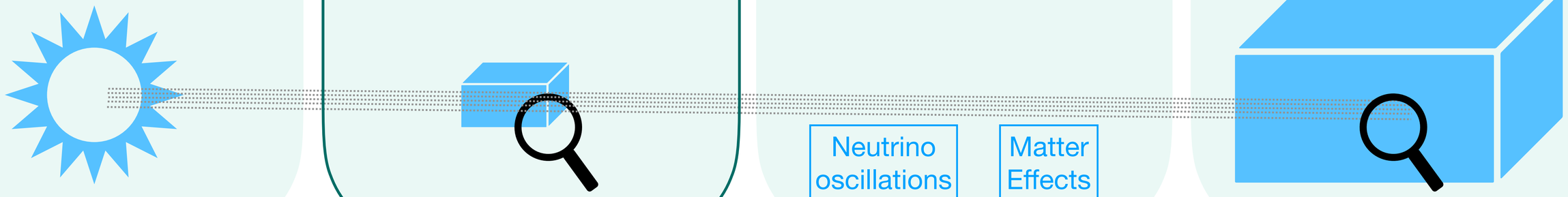
All neutrino oscillation experiments are the same…

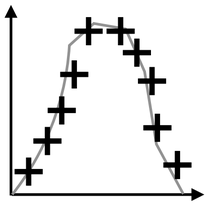
Produce neutrinos
[possibly all in the same flavour]

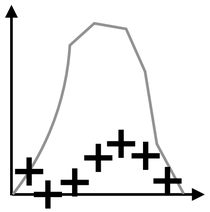
Check what you produced
[optional]

Propagate!
[a few km
to a few kpc]

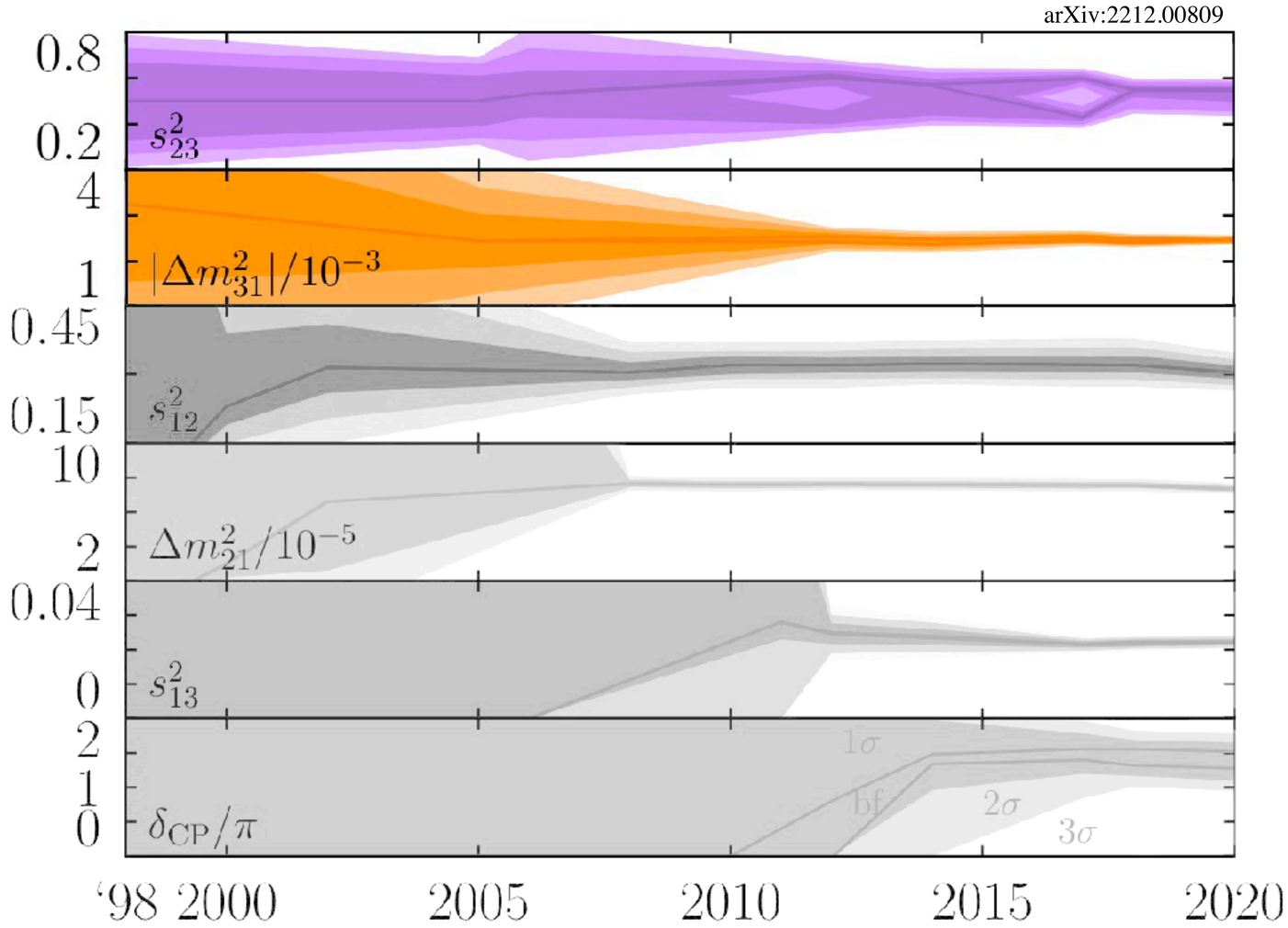
Look for a deficit or excess!





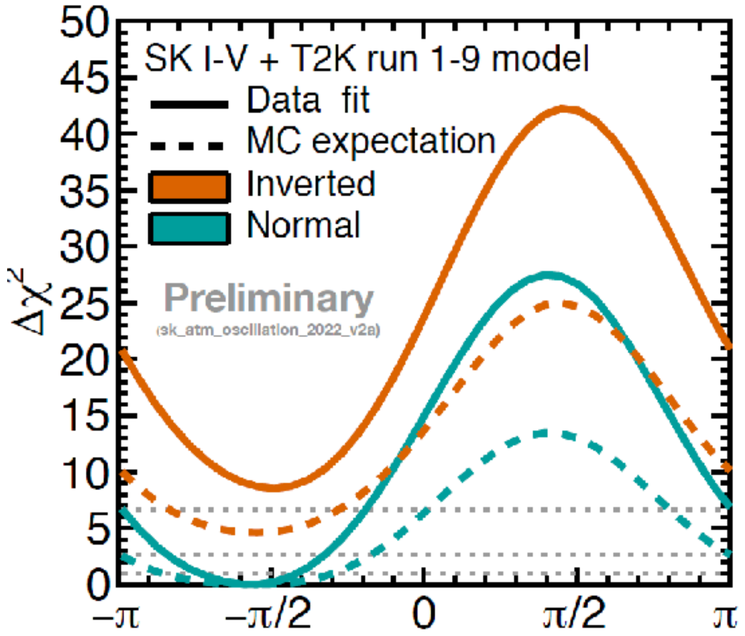


Atmospheric neutrino experiments



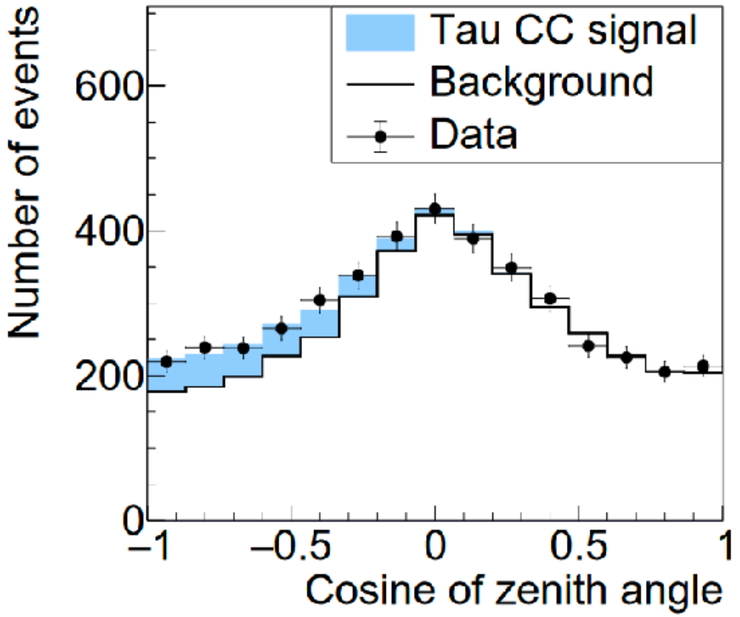
New results from SK

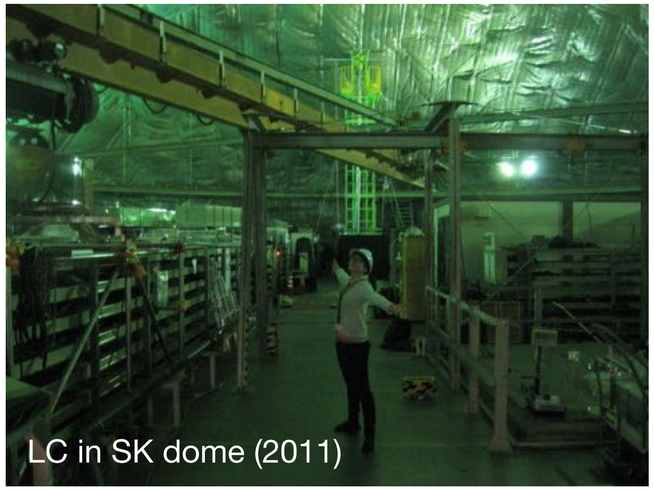
- Latest results:
  - expanded FV (22.5 → 27.2 kt) and more livetime (328 → 484 kt year in total)
  - neutron tagging (for SK IV-V) and new multi-ring event classification with BDT → enhanced $\nu/\bar{\nu}$ separation
  - atmospheric neutrino oscillation fit with external constraints:
    - θ_{13} from reactors and “T2K model”+T2K $\nu/\bar{\nu}$ data



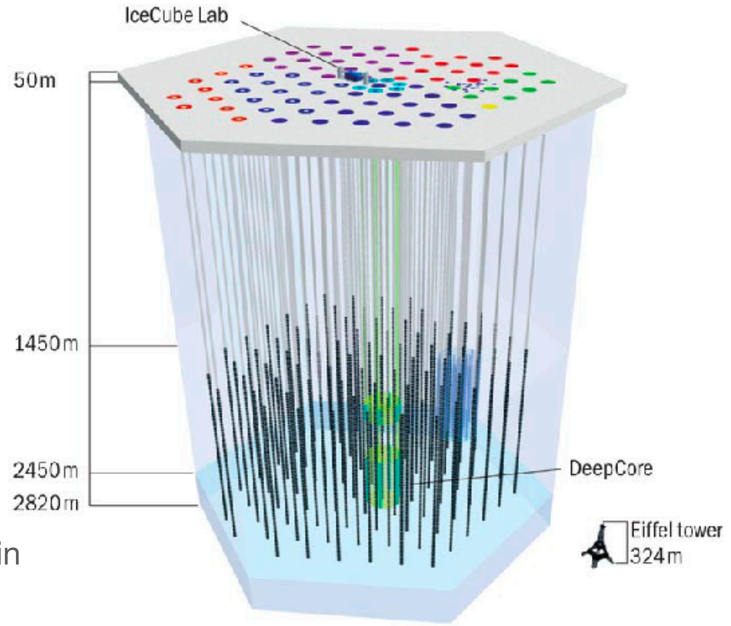
- Tau neutrino appearance
  - no ν_τ appearance hypothesis excluded at 4.8σ
  - tau events are background to mass ordering studies
- Doped with Gd salts since 2020

See talk by Aoi Eguchi on Super-K and T2K!

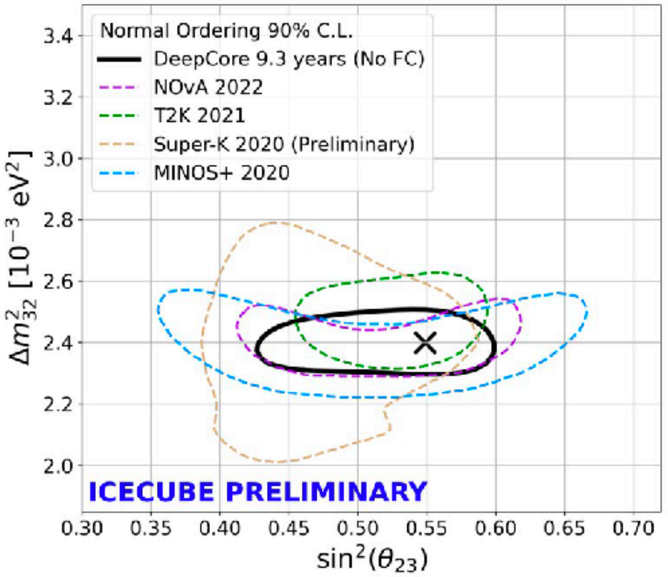



LC in SK dome (2011)

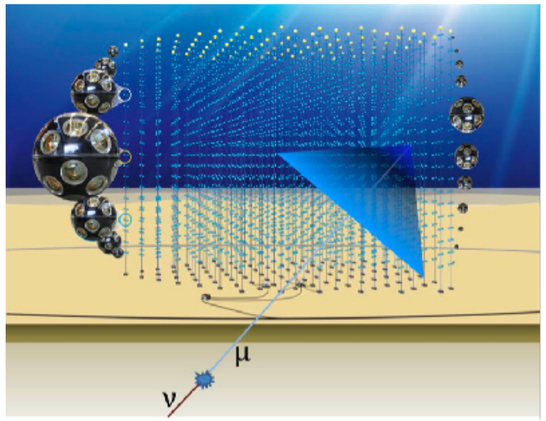
IceCube and KM3NeT/ORCA

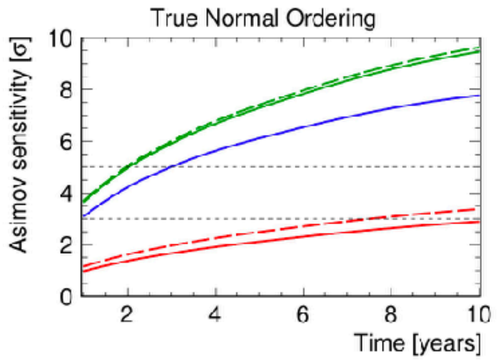


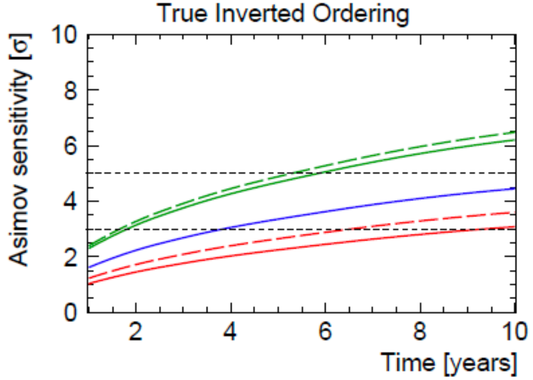
See talk by Alexandra Trettin



See talk by Maurizio Spurio

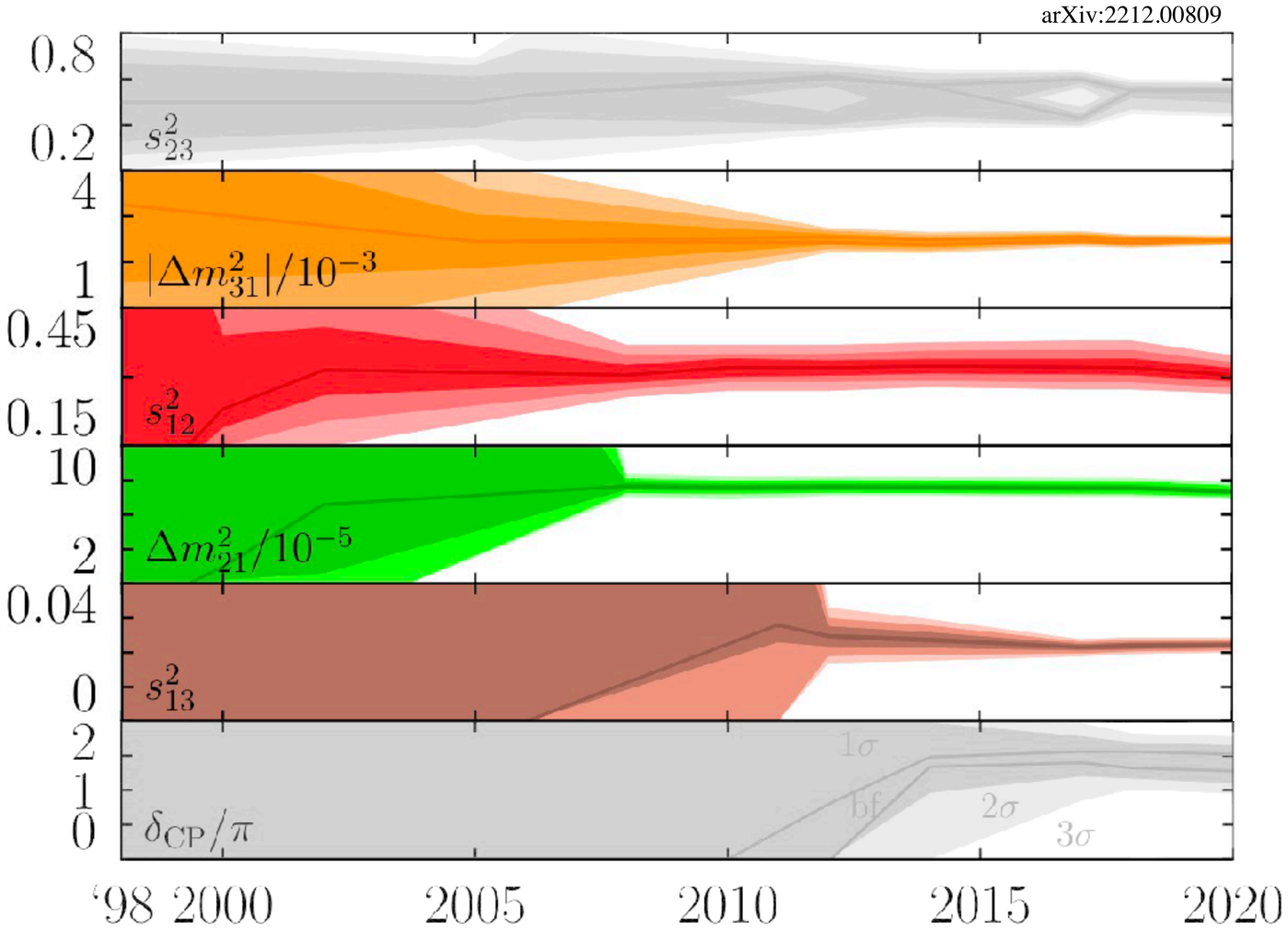




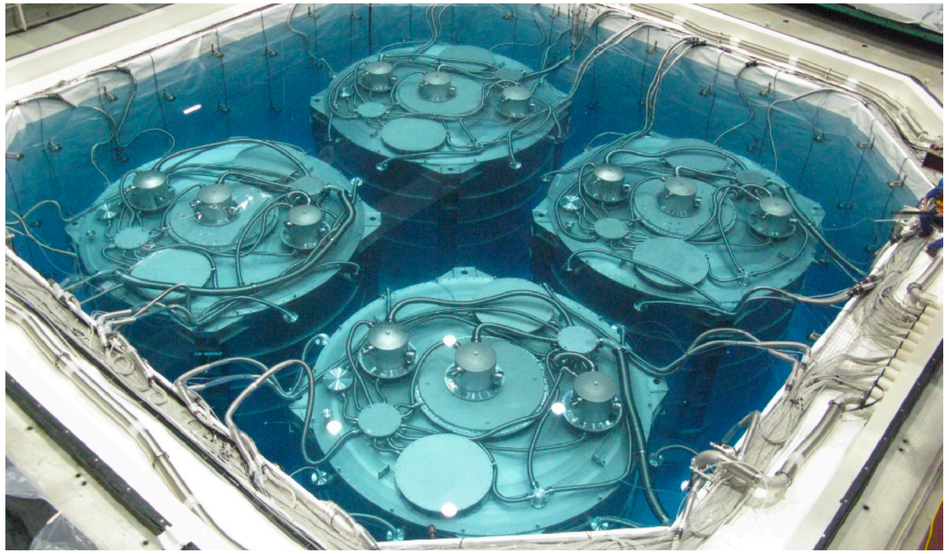


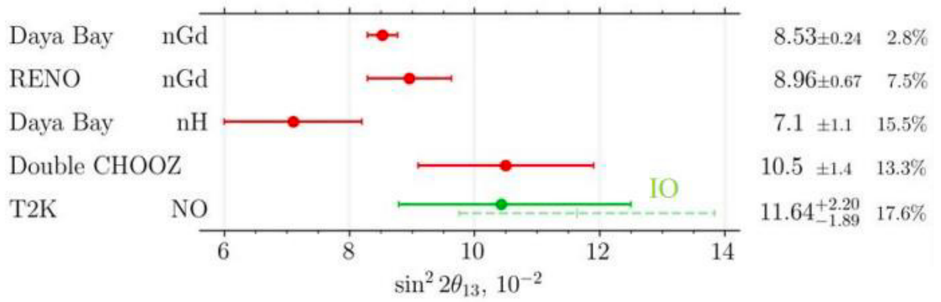
Joint
KM3NeT
JUNO

Reactor experiments



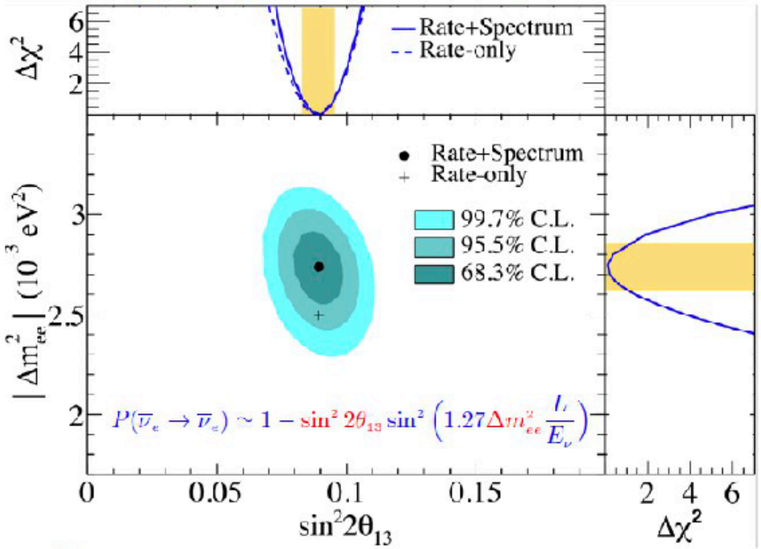
Latest measurements from Daya Bay and Reno





See talk by Runze Zhao on Daya Bay

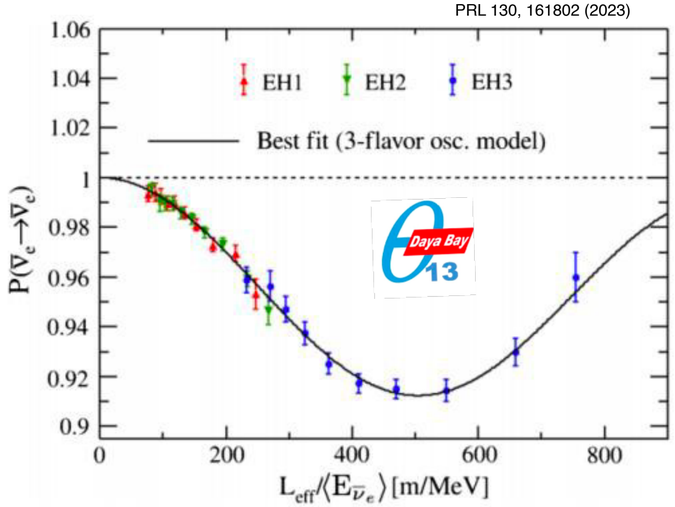
RENO 2900 days (Aug. 2011 — Feb. 2020)

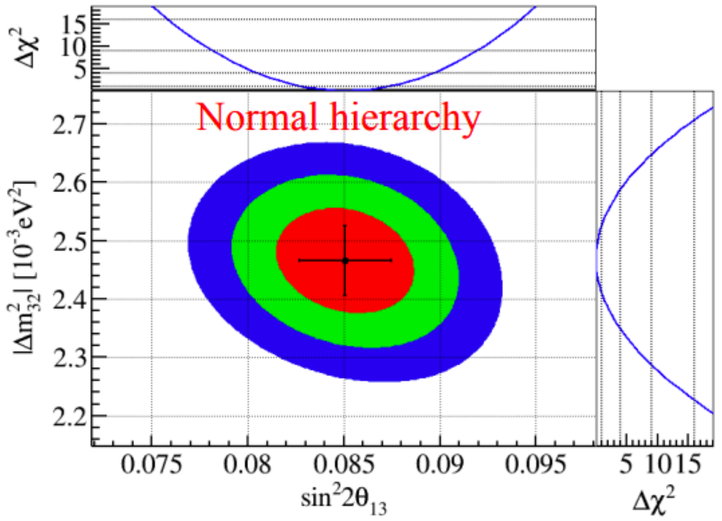


$\sin^2 2\theta_{13} - 0.0892 \pm 0.0044(stat.) \pm 0.0045(sys.)$ ± 7.0%

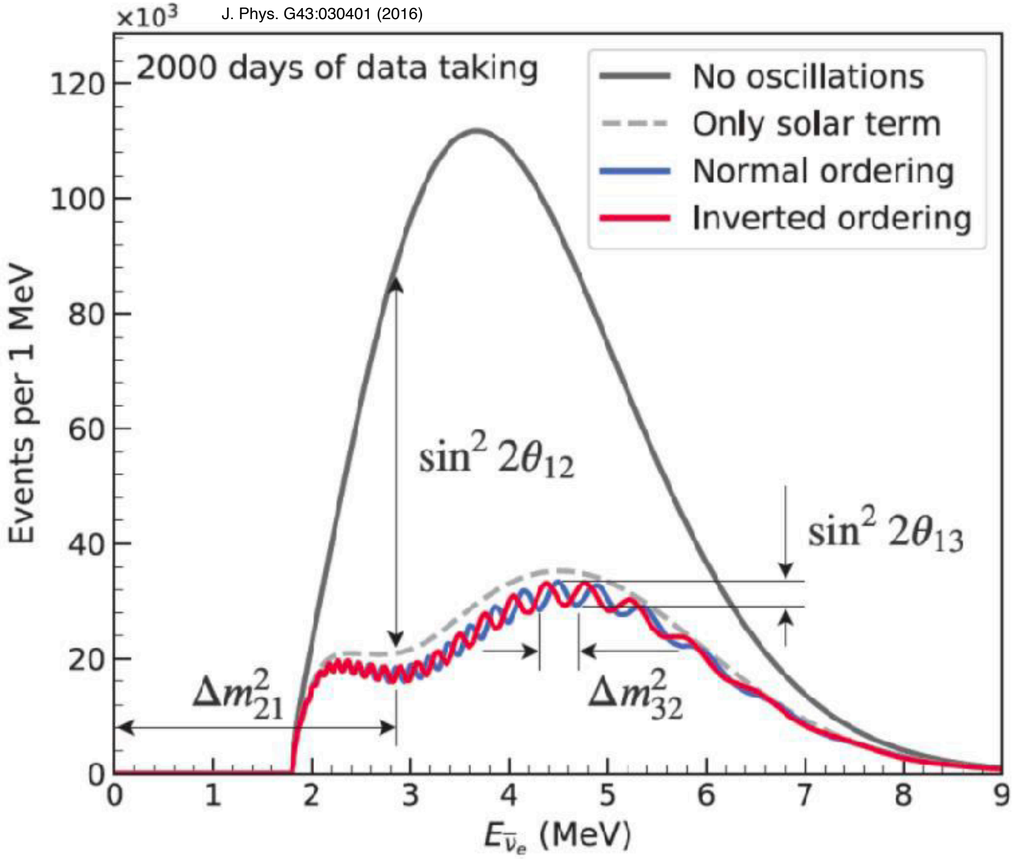
$|\Delta m^2_{ee}| - 2.74 \pm 0.10(stat.) \pm 0.06(sys.)(\times 10^{-3}\text{eV}^2)$ ± 4.4%

PRL 130, 161802 (2023)

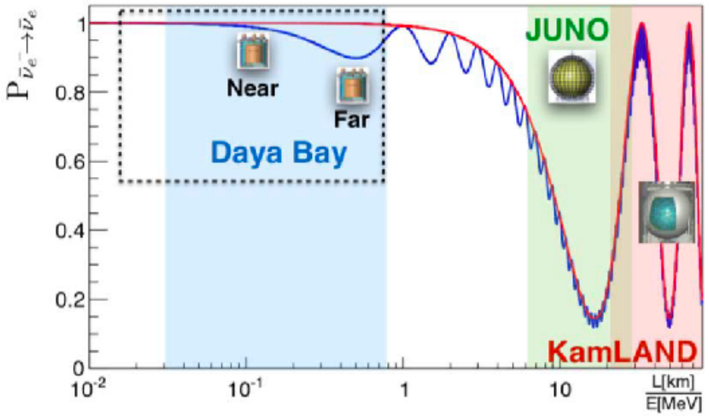


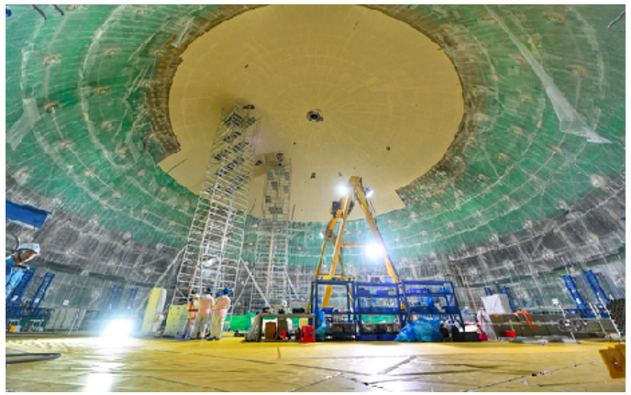


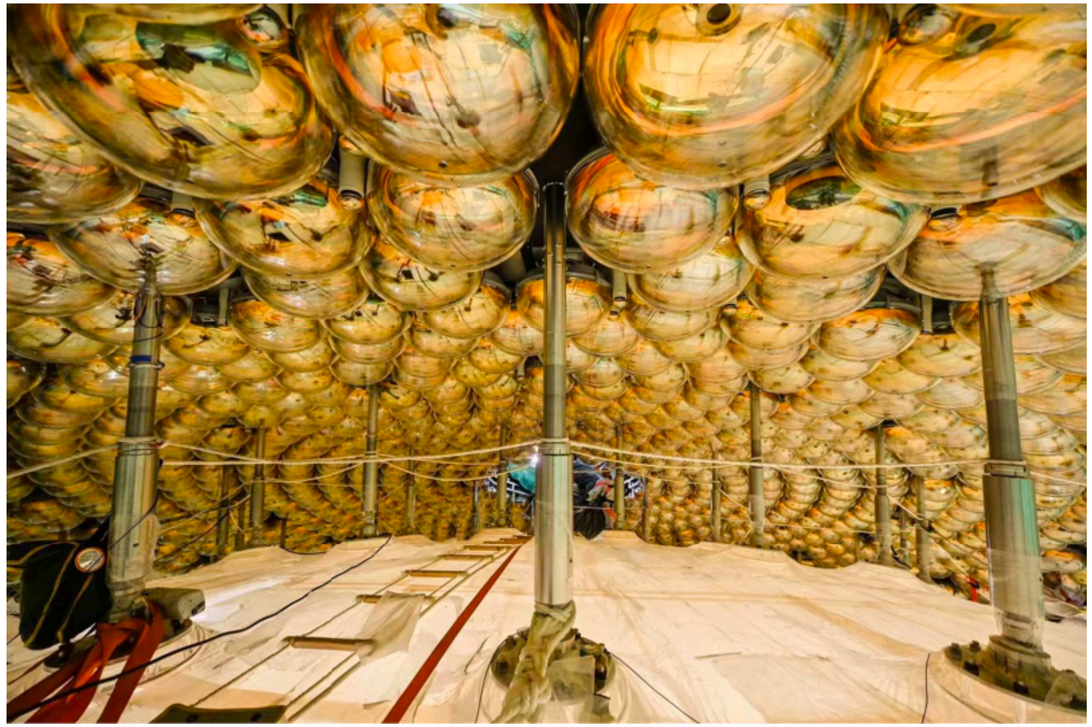
JUNO experiment



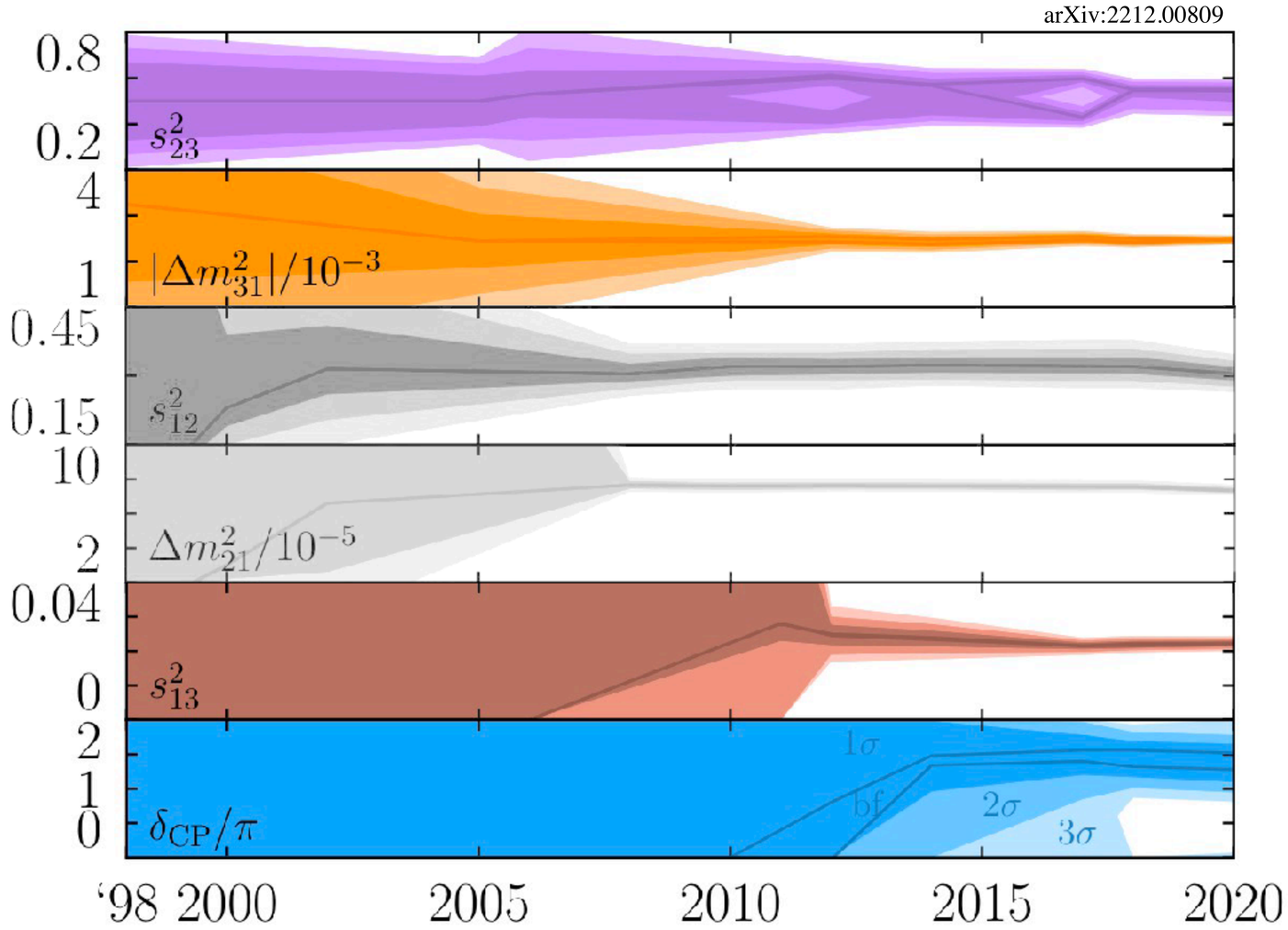
See talk by Marco Grassi on JUNO



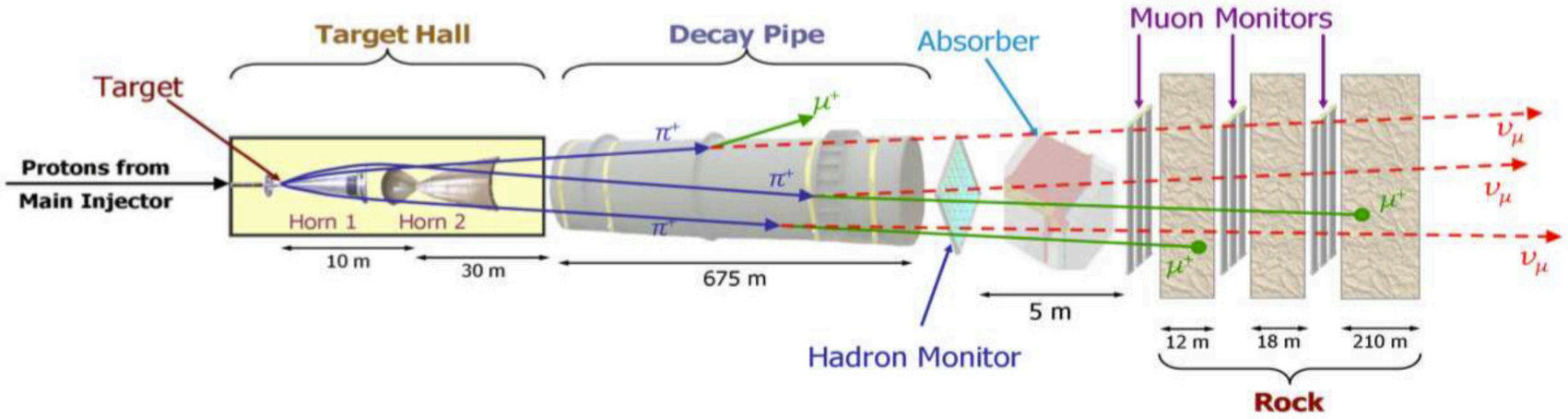




Accelerator experiments

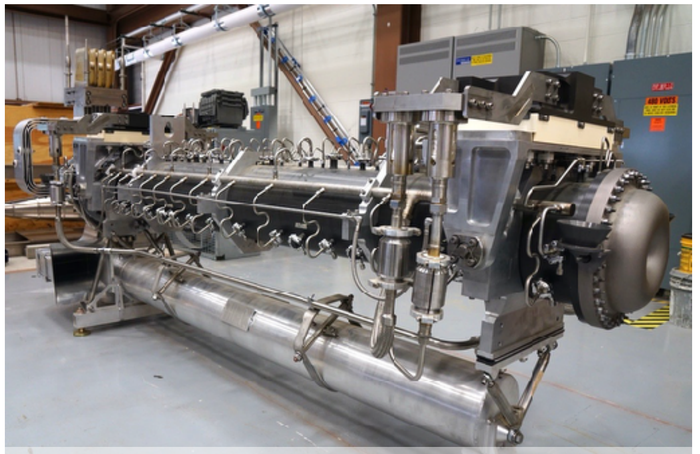


Accelerator neutrinos

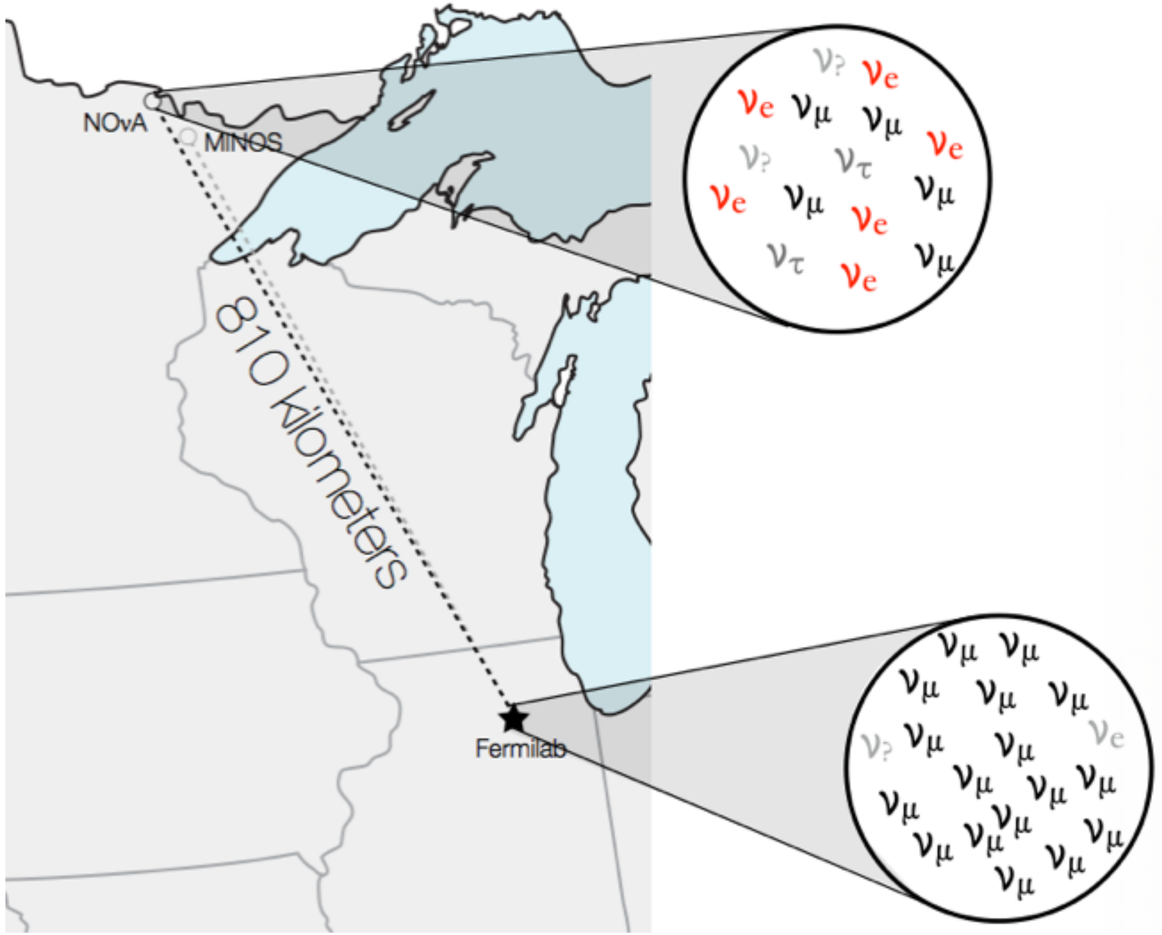



MW-capable target

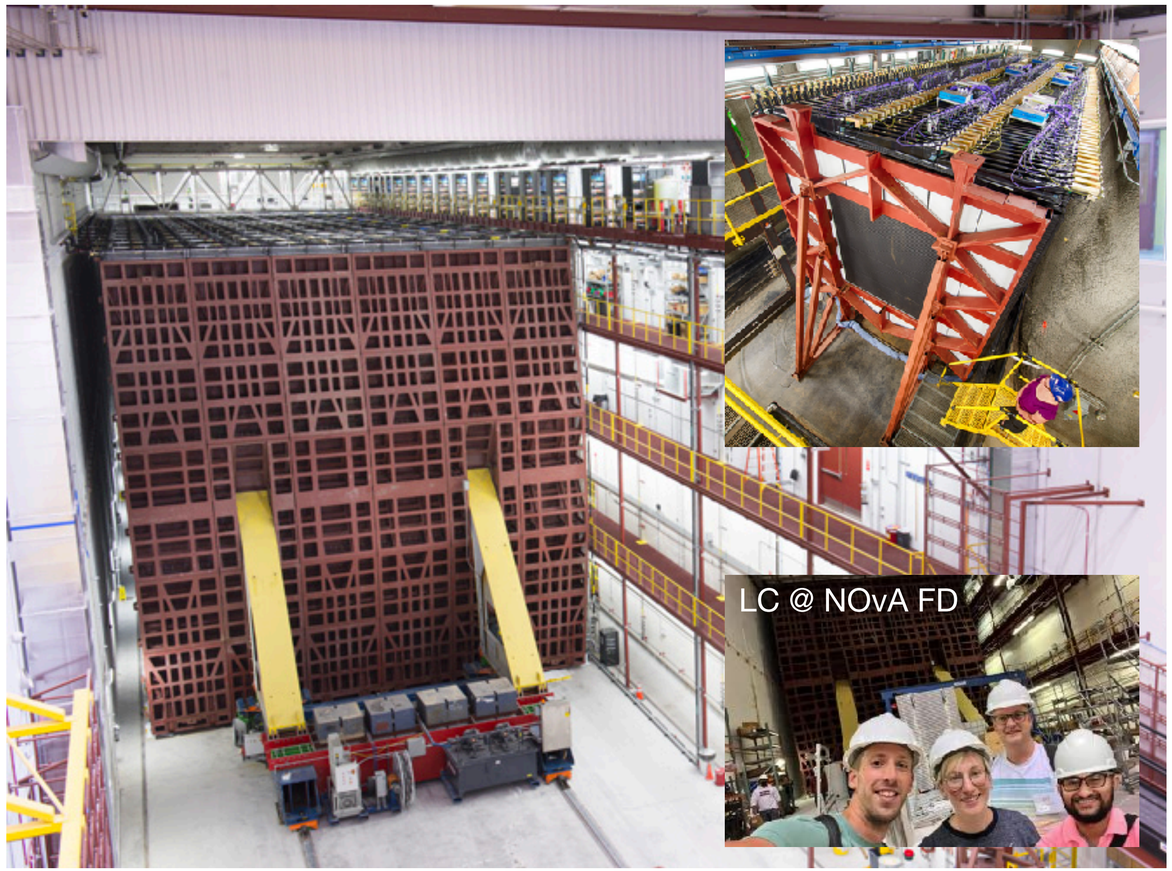
- Muon (anti)neutrinos from pion decay in flight
- Narrow band beam with off-axis technique
- Sensitive to θ_{23} octant, size of δ_{CP} and mass ordering

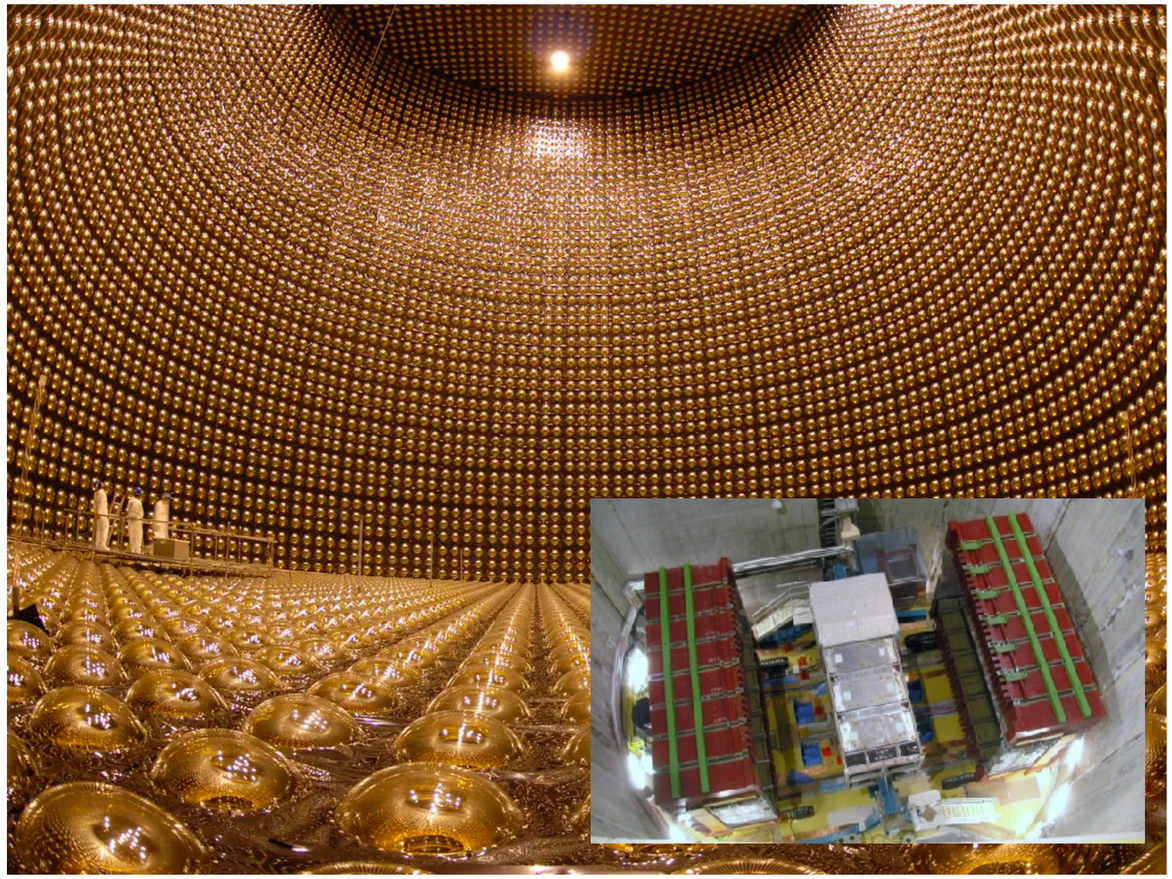

MW-capable horn

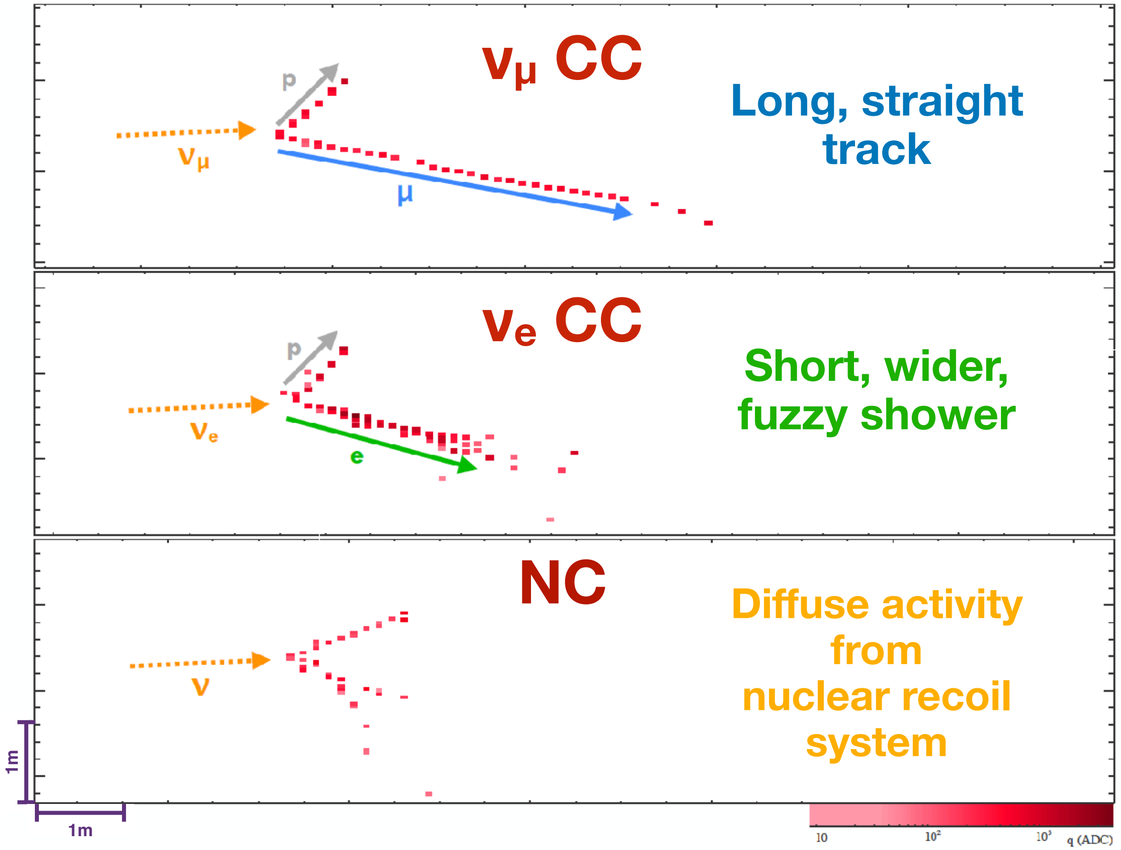
See talk by Erika Catano-Mur on NOvA

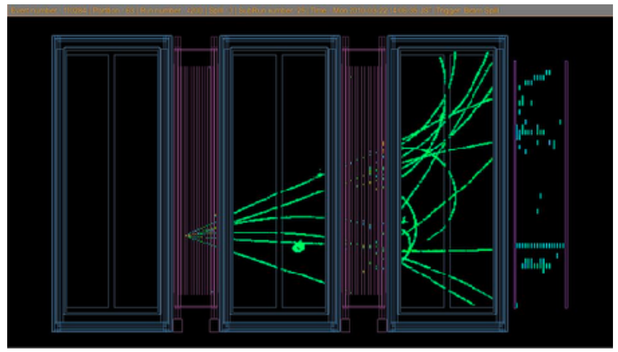


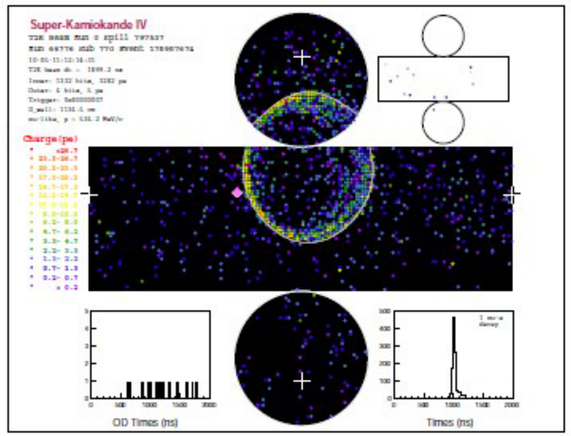
See talk by Lorenzo Magaletti on T2K

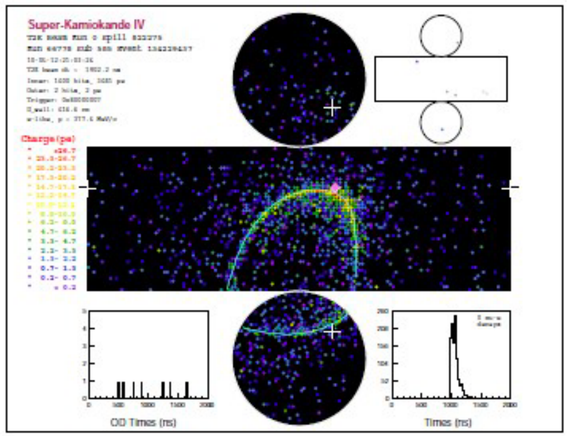

LC @ NOvA FD



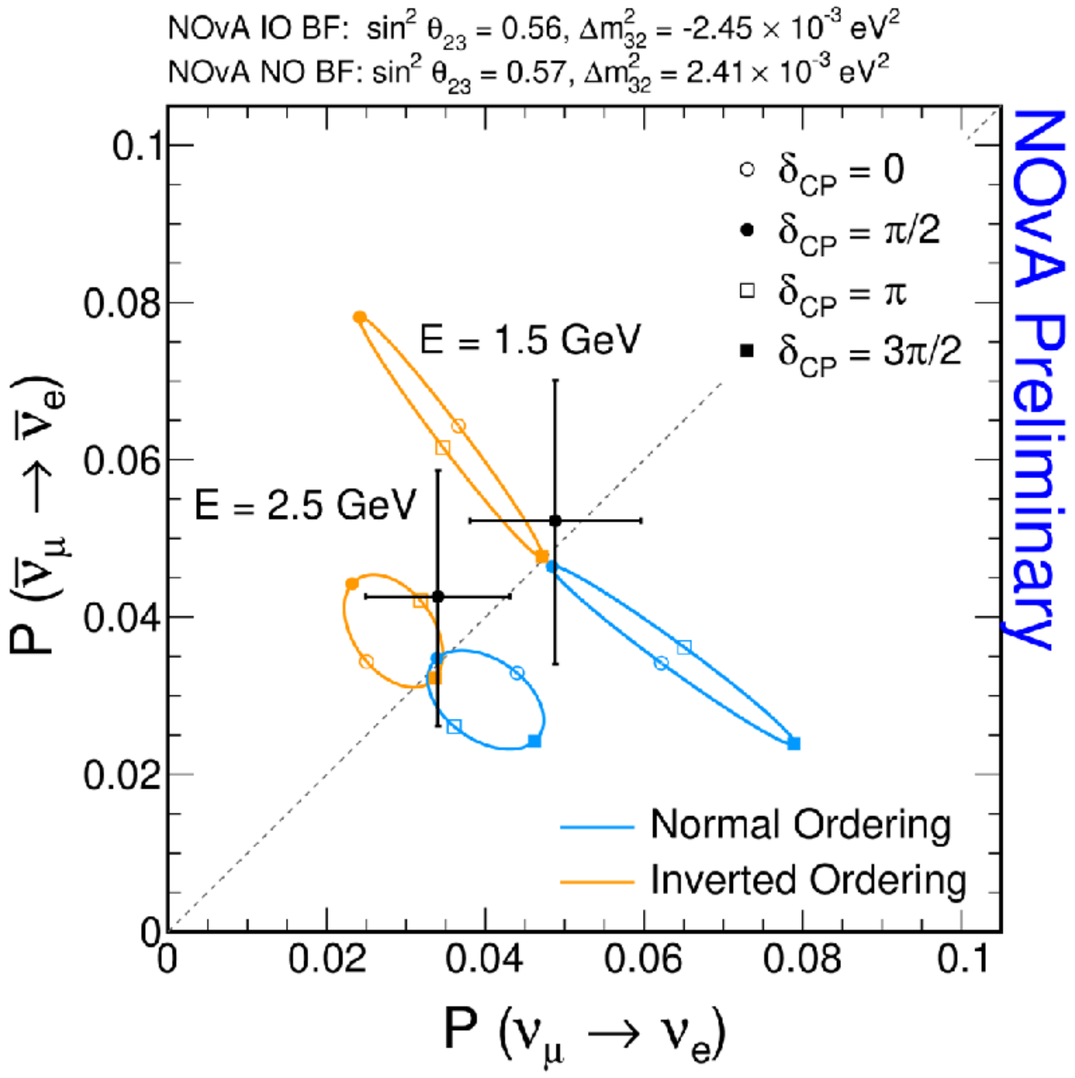

νμ CC
Long, straight track
p
νμ
μ
νe CC
Short, wider, fuzzy shower
p
νe
e
NC
Diffuse activity from nuclear recoil system
ν
1m
1m
10
10²
10³
q (ADC)



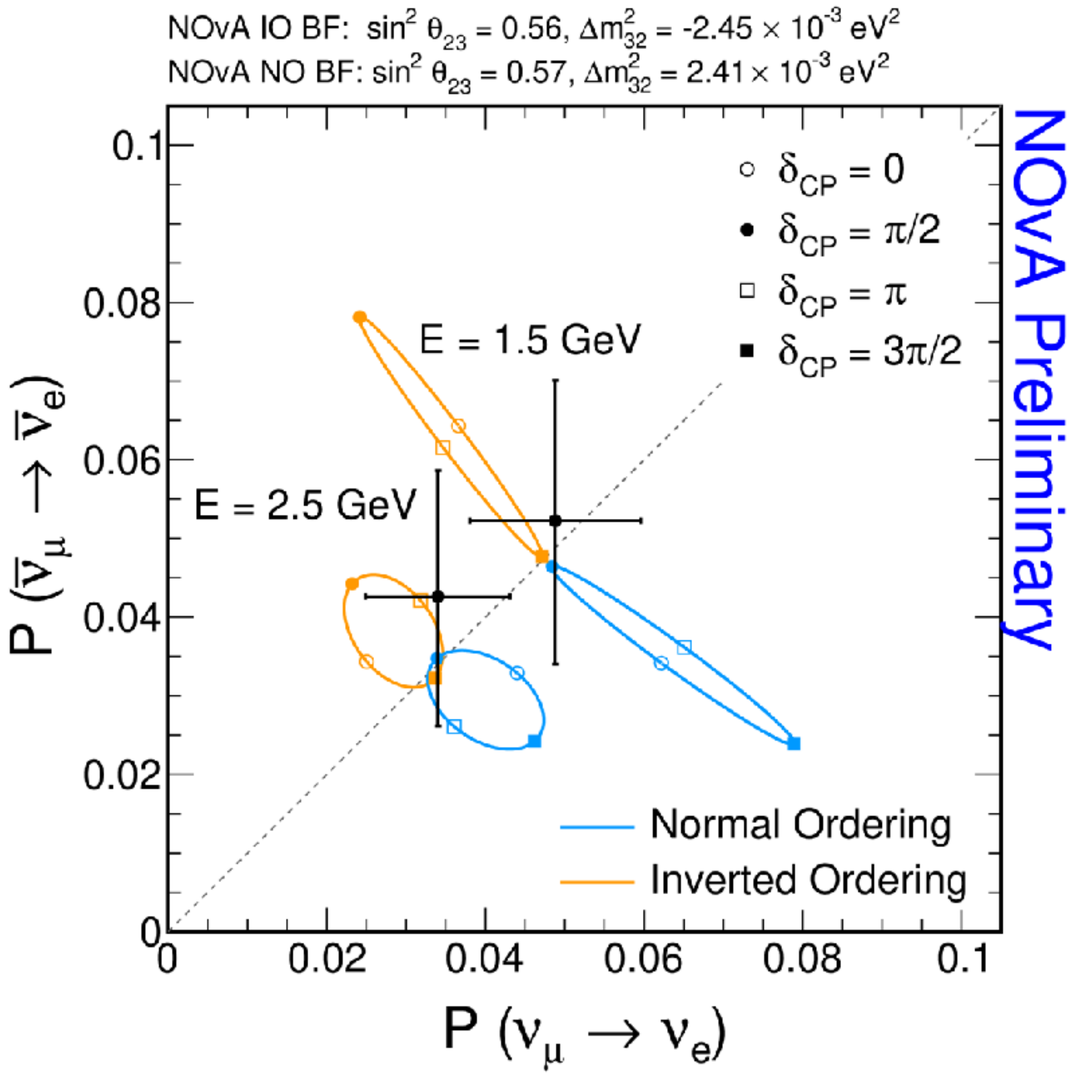

Super-Kamiokande IV
OD Times (ns)
Times (ns)

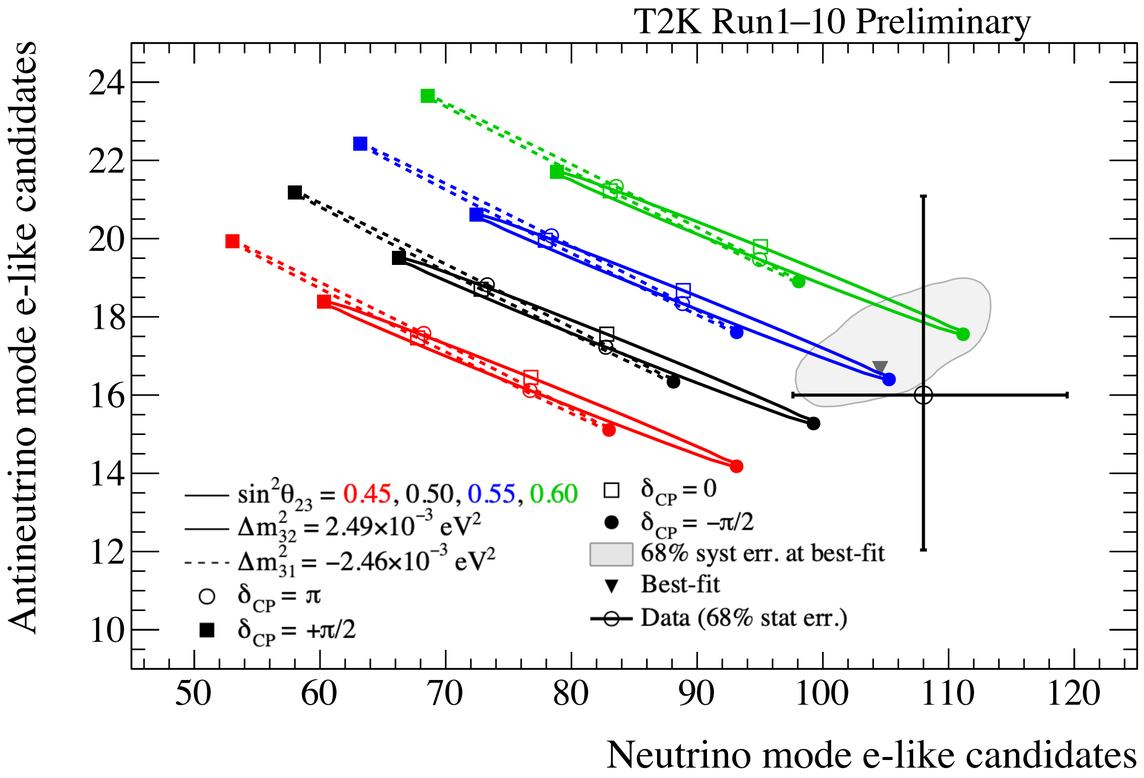

Super-Kamiokande IV
OD Times (ns)
Times (ns)

Appearance asymmetry

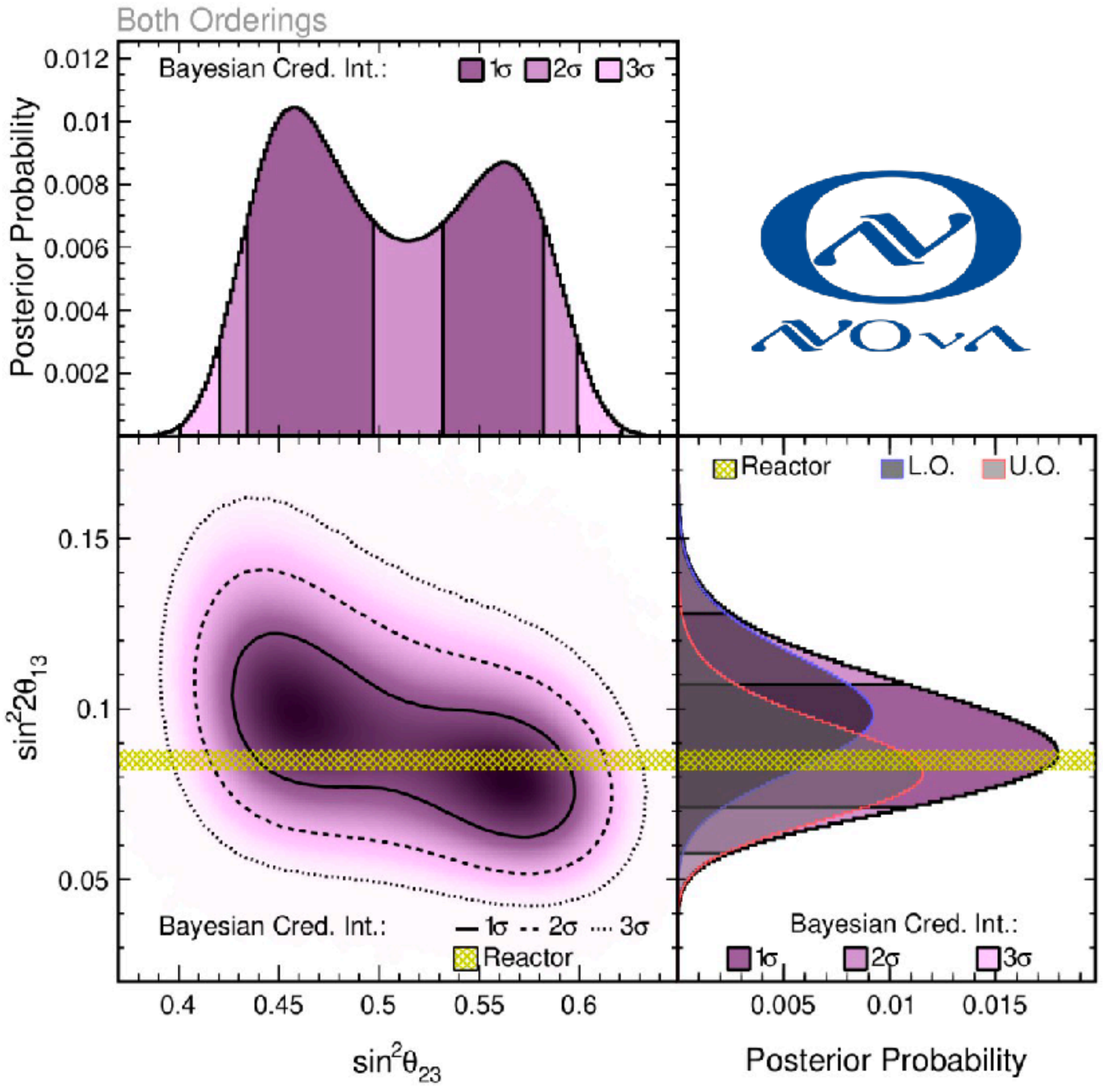


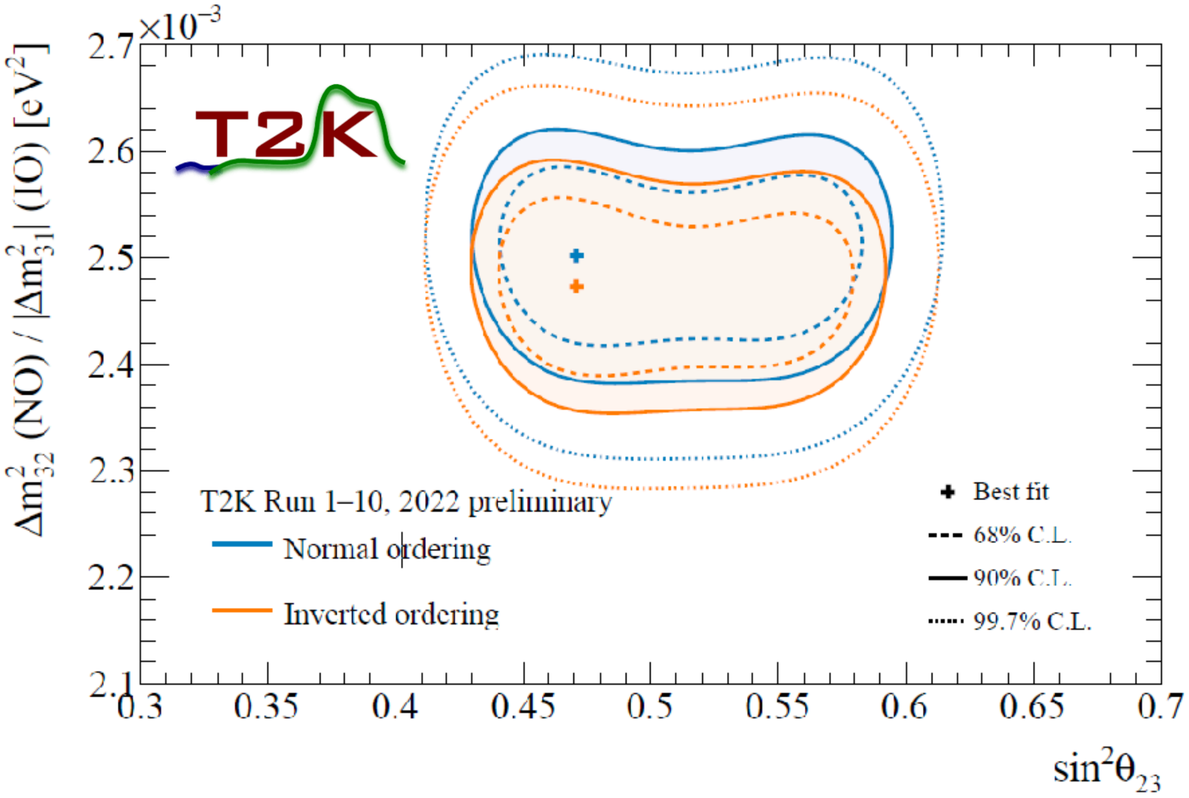
Appearance asymmetry



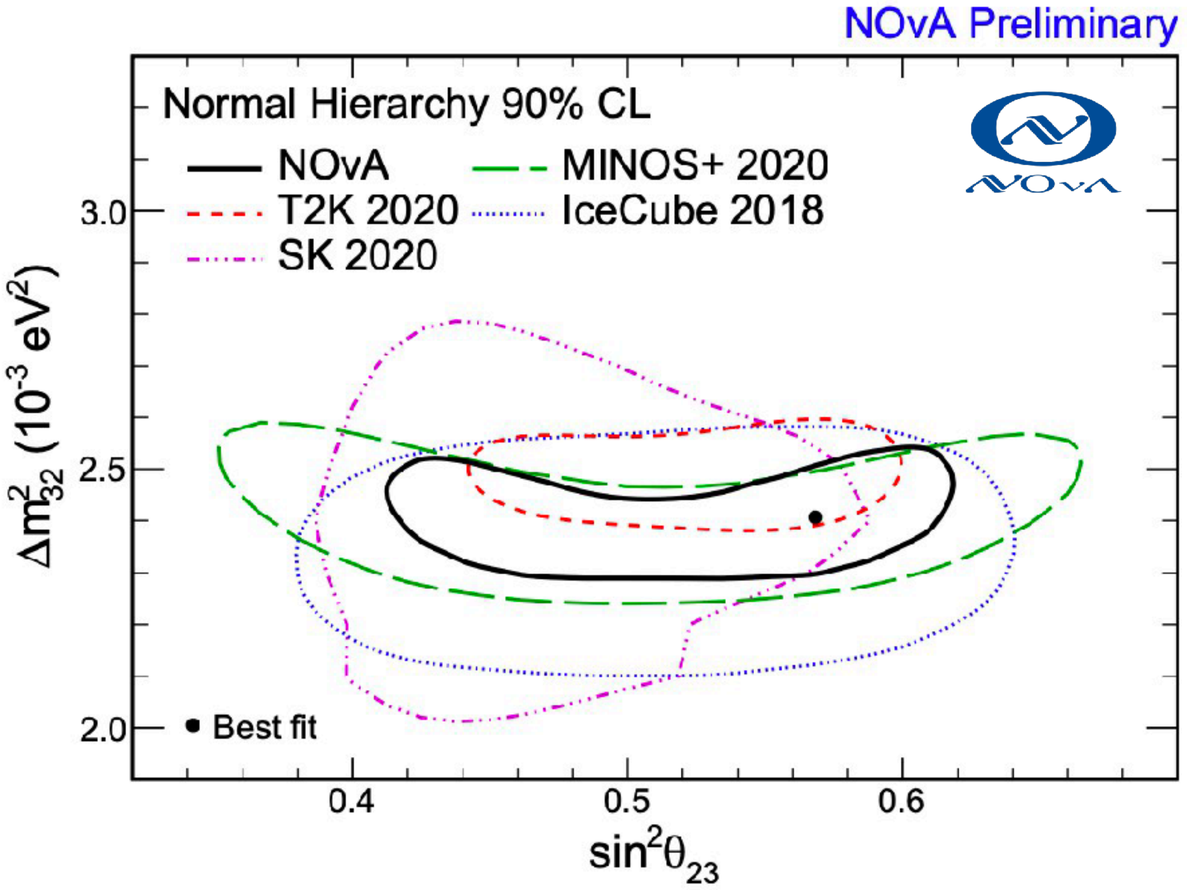


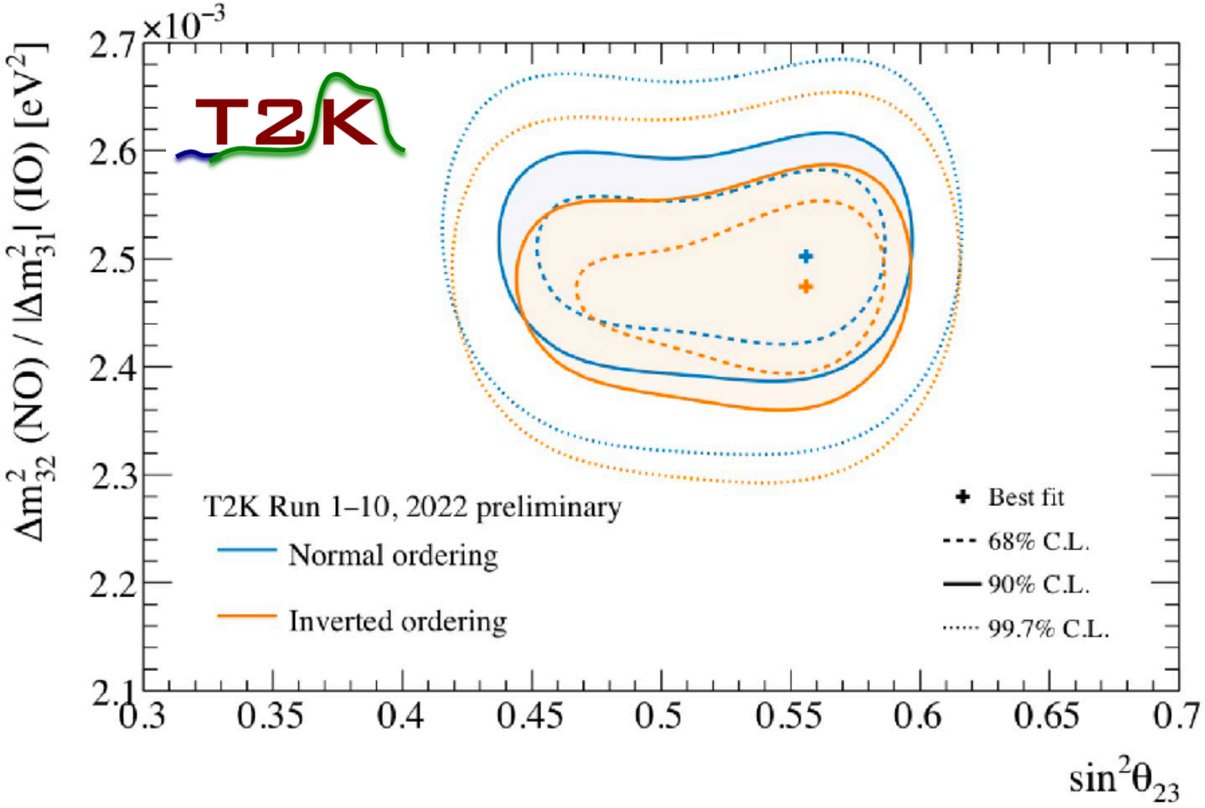
Δm^2_{32} and θ_{23} without reactor constraints



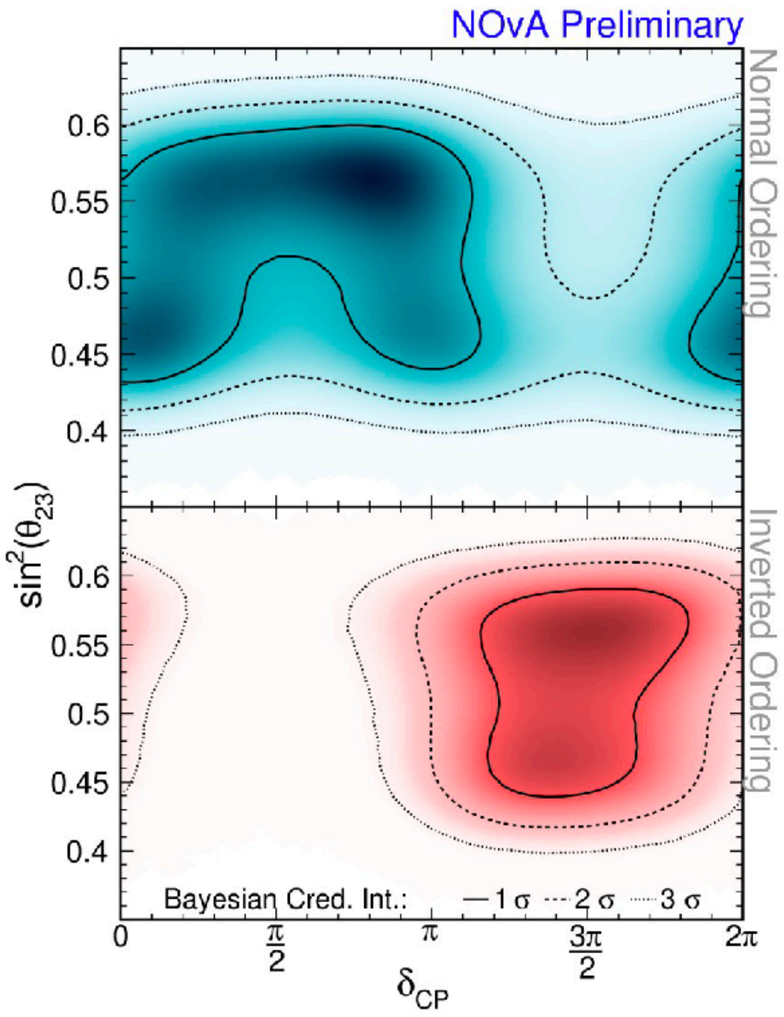


Δm^2_{32} and θ_{23} with reactor constraints





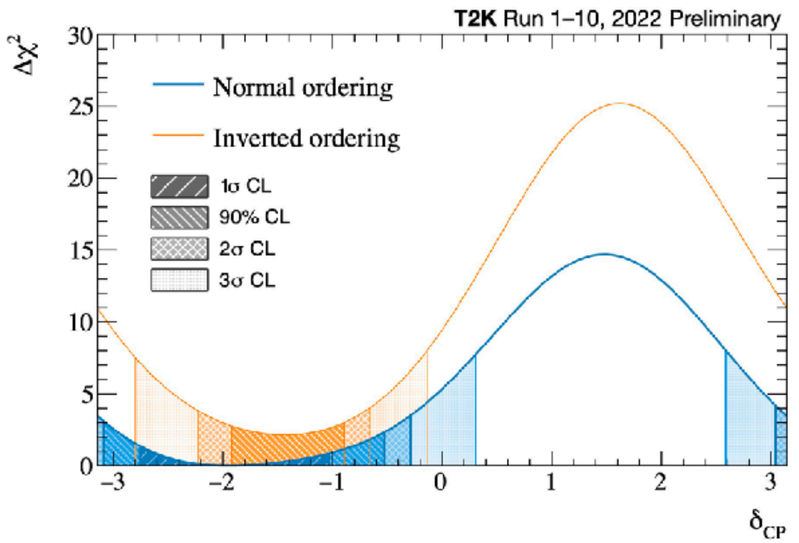
δ_{CP}

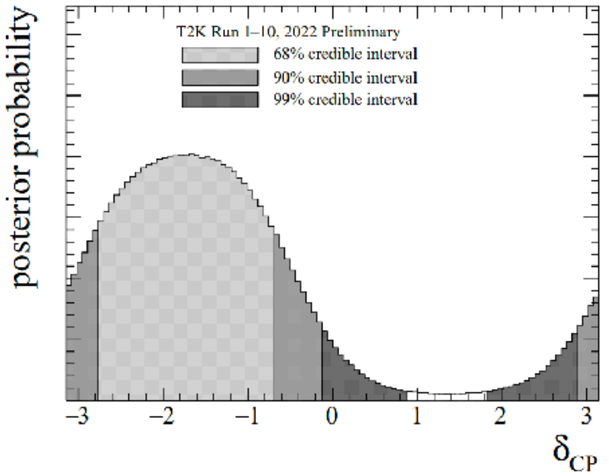


$\nu_e/\bar{\nu}_e$ appearance disfavours MO/δ_{CP} combinations with large asymmetry

Disfavor NH, $\delta_{CP} = 3\pi/2$ at ~2σ

Disfavor IH, $\delta_{CP} = \pi/2$ at >3σ

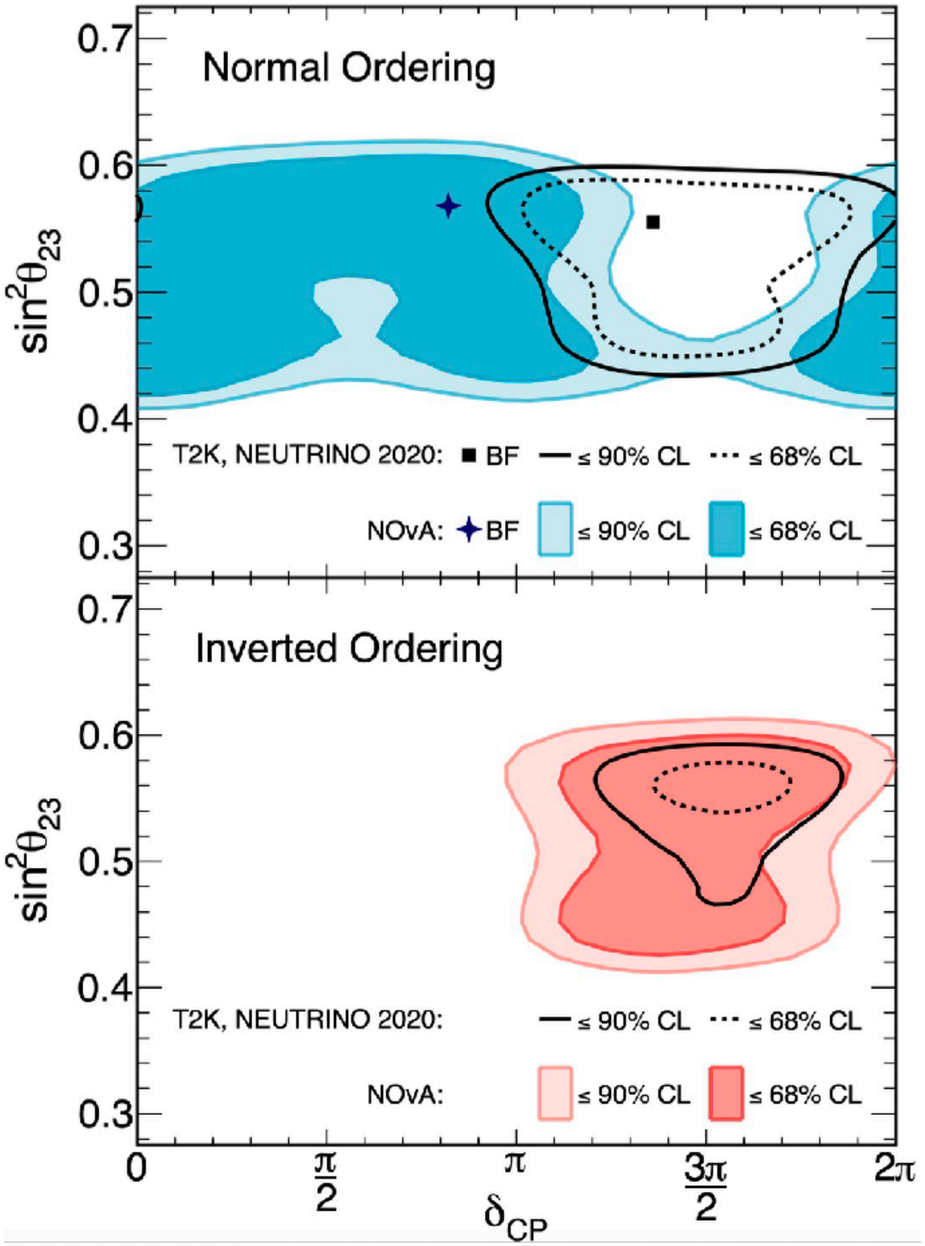




CP conservation ($\delta_{CP} = 0,\pi$) excluded at 90%
Weak preference for normal ordering

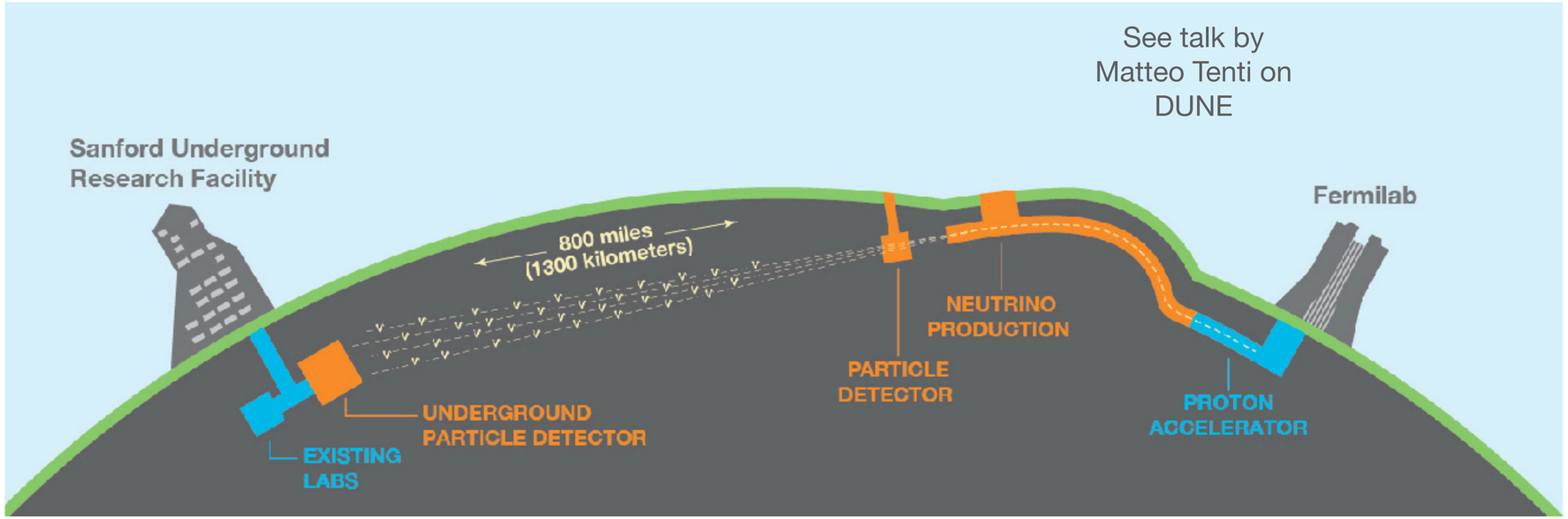
NOvA-T2K

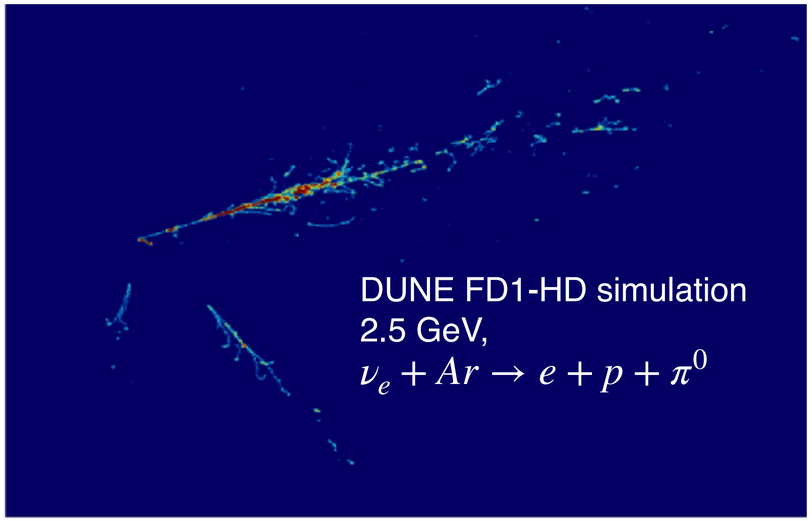
- Both show a weak preference for NO
  - some tension in δ_{CP} but remember: current results are **statistically limited**!
- if IO: consistent preference for the 3π/2 region, small preference for upper octant
- **more data needed** in both experiments!
- joint analysis NOvA-T2K in progress, results expected soon
- Both undergoing upgrade, and new analyses from both expected 2024

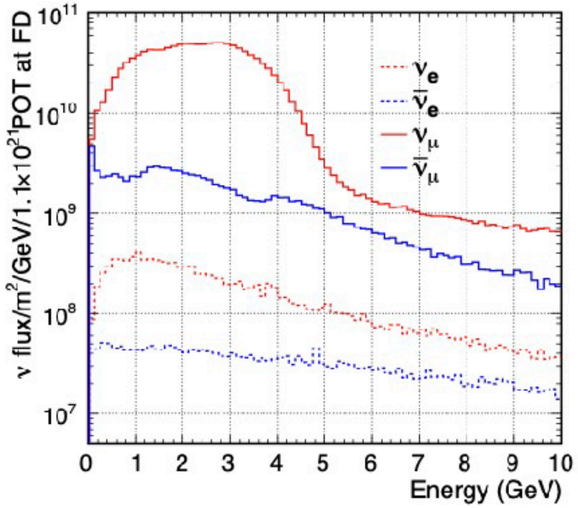


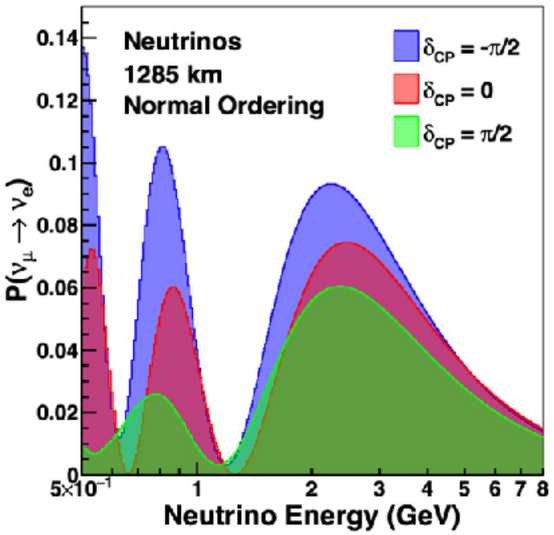
DUNE

See talk by Matteo Tenti on DUNE

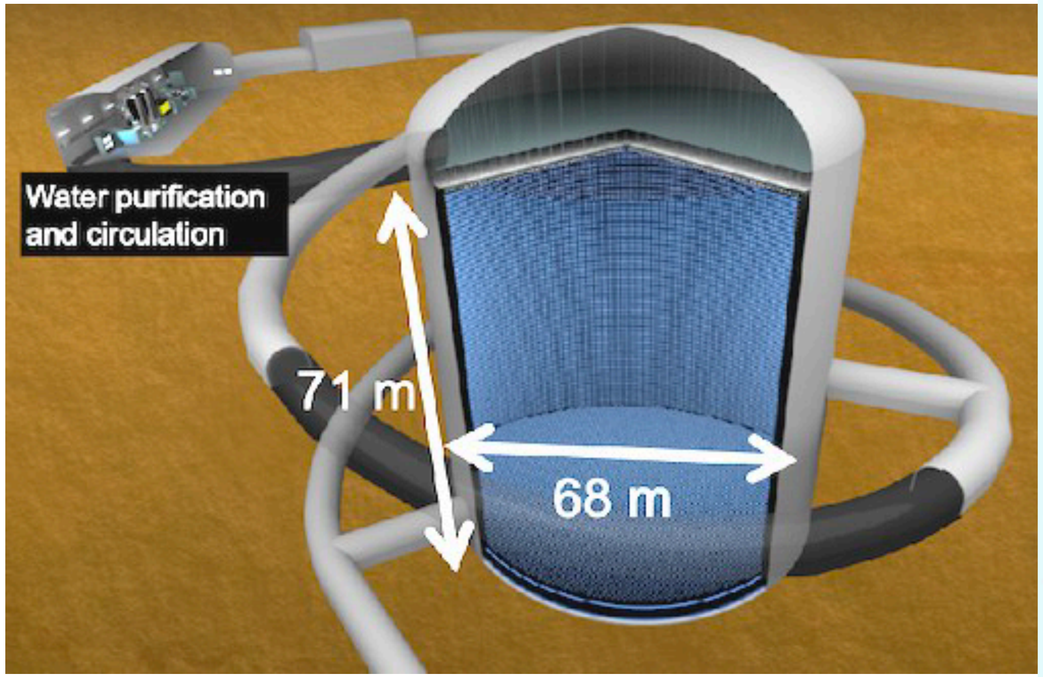




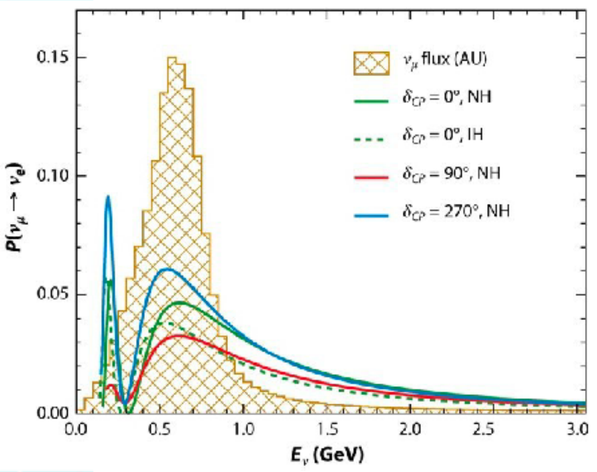




Hyper-Kamiokande

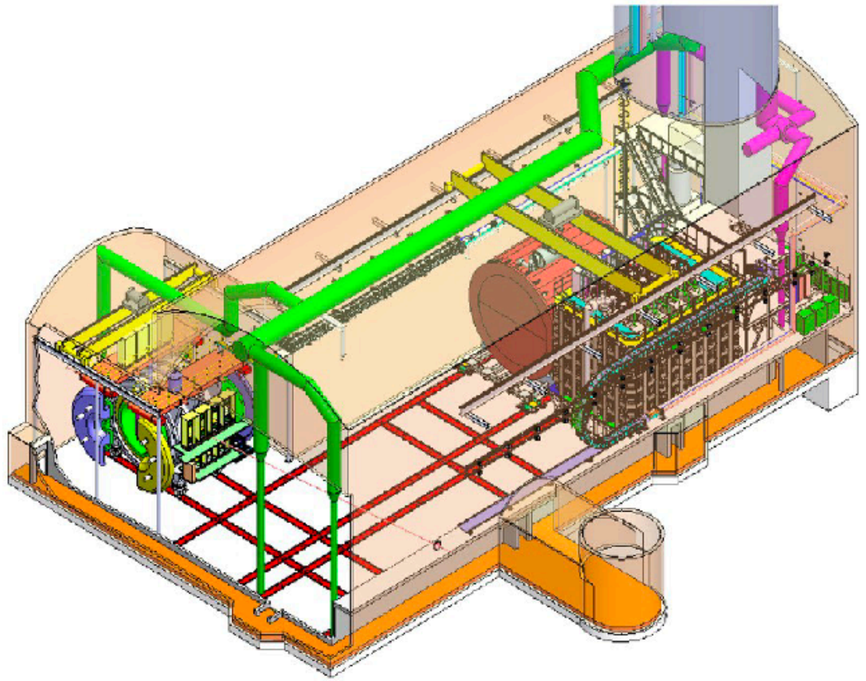


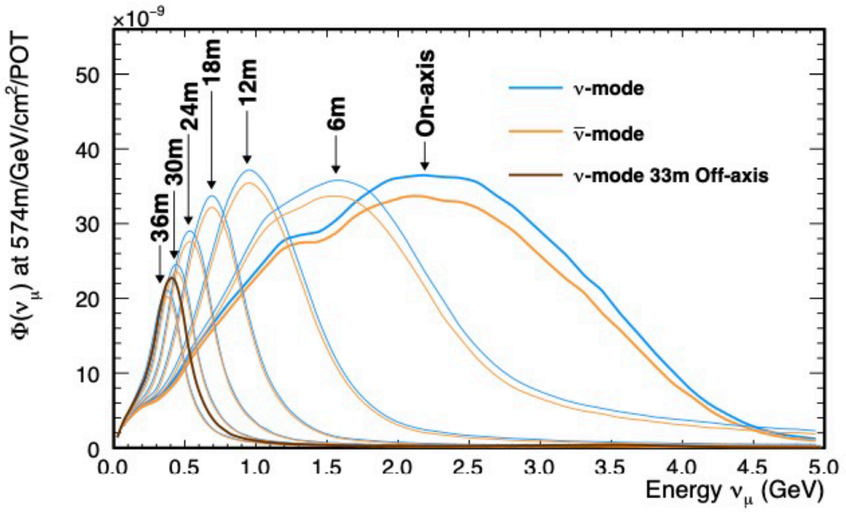
See talk by Katsuki Hiraide on Hyper-K

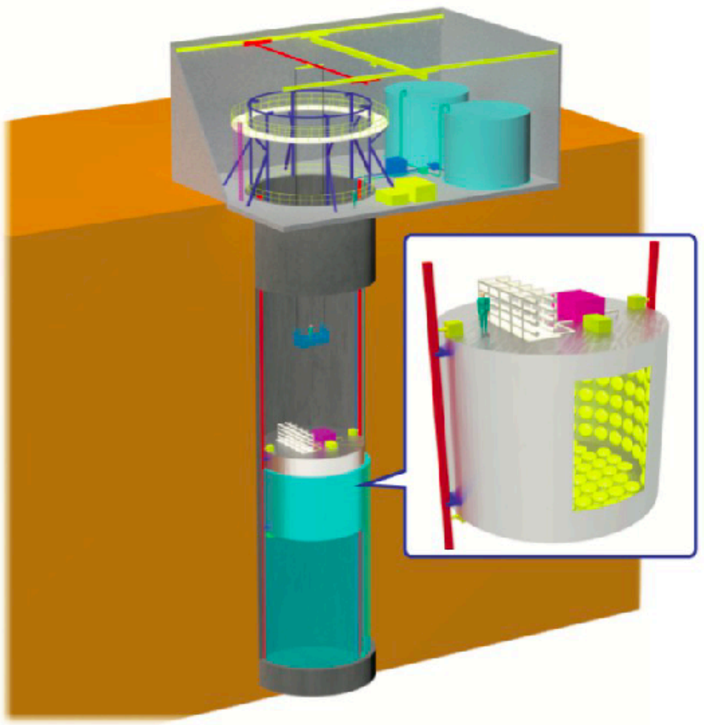


PRISM

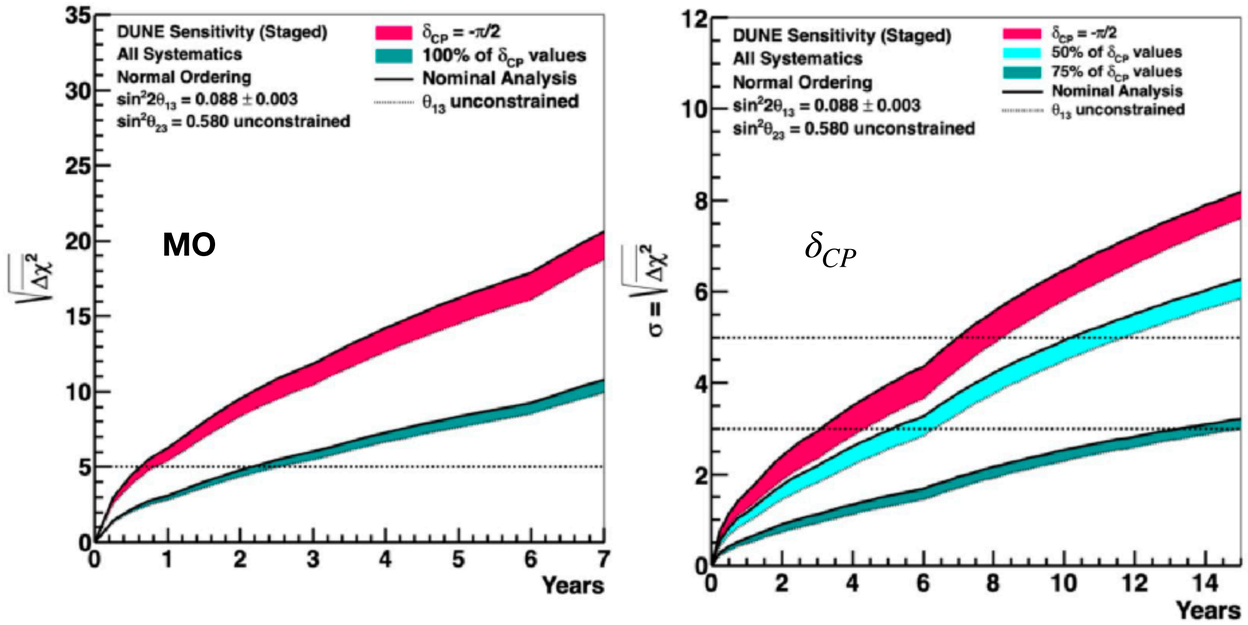
- Both DUNE and Hyper-K will have a moveable near detector to enhance flux at lower energies.
- These samples allow one to build a linear combination to match FD oscillated spectra and build analysis with minimal interaction modelling.



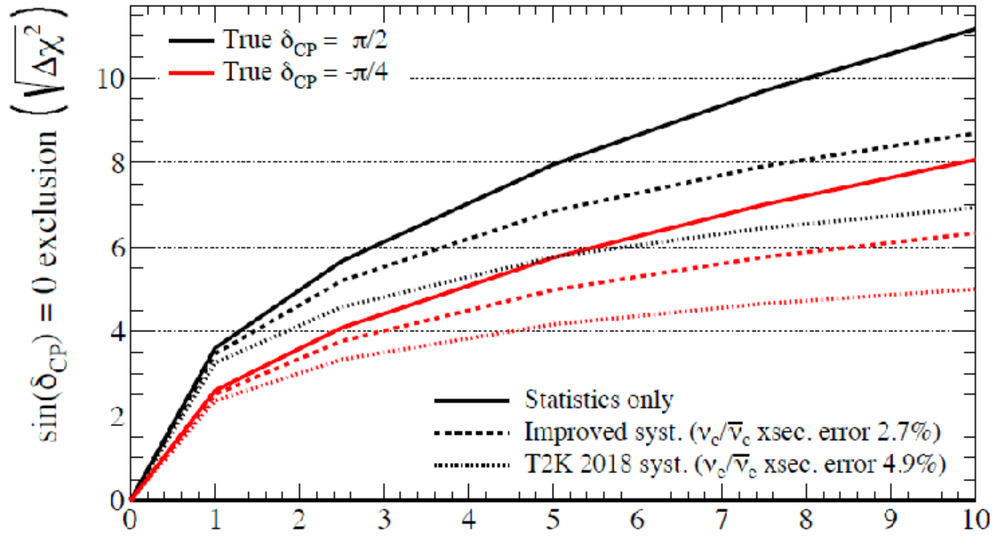


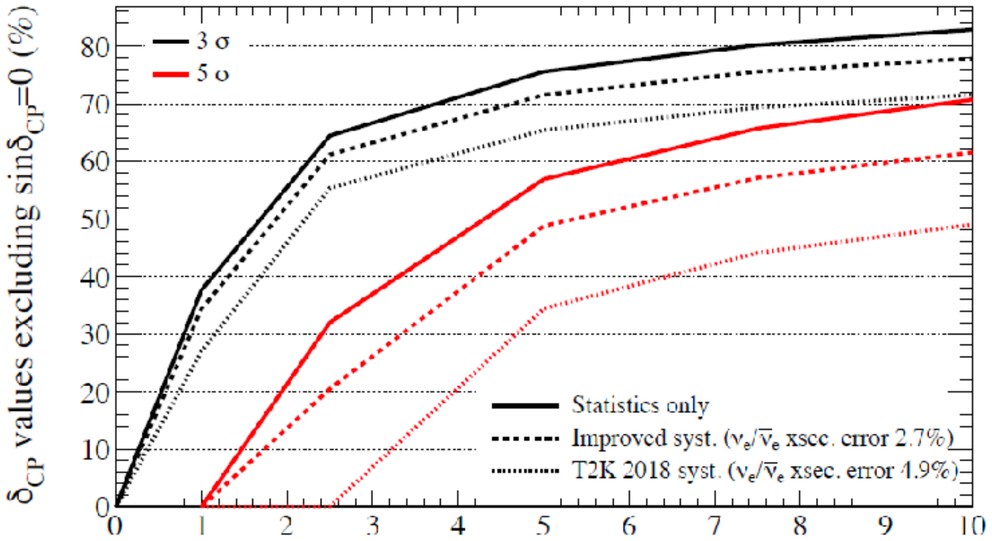


Sensitivities

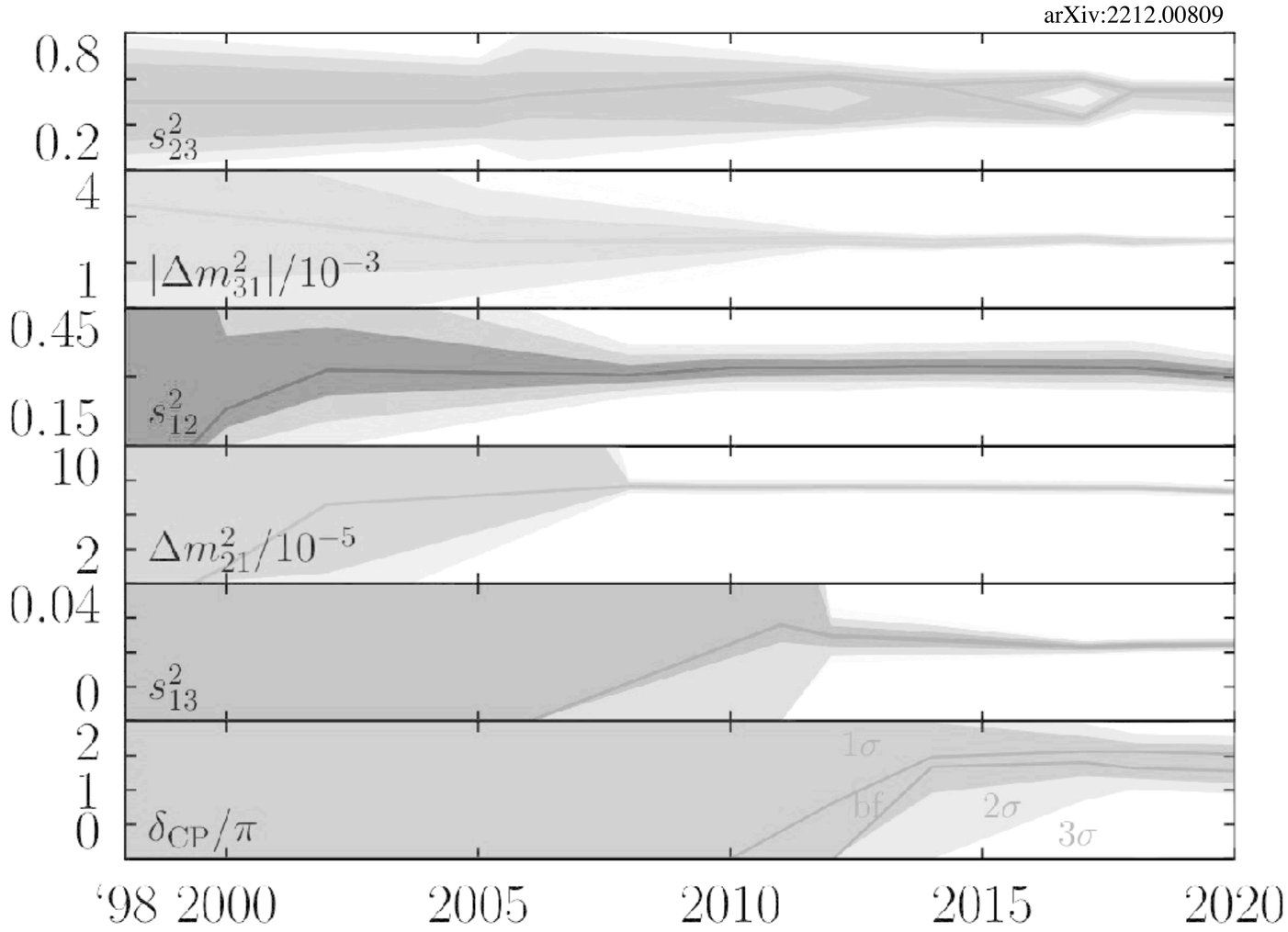


- DUNE: Mass ordering determination in phase I
- Hyper-K: if MO known, 2-3 years to exclude CP conservation at 5 sigmas
- After 10 years, 5sigma sensitivity for 50% of δ_{CP} values in DUNE and 60% in HyperK



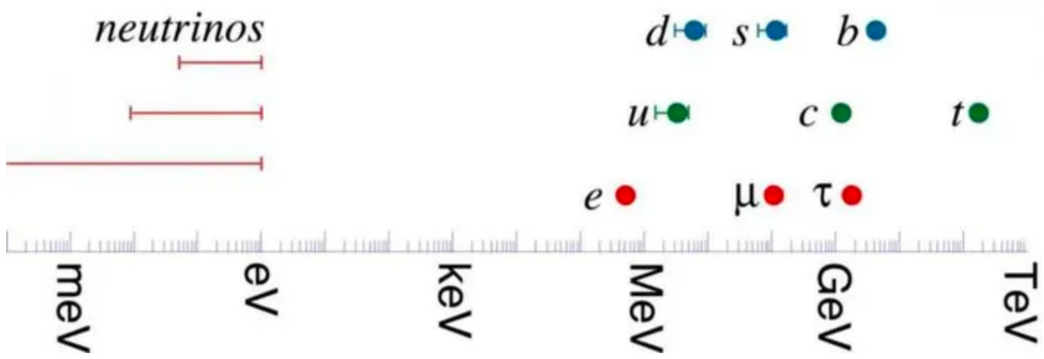


Sterile neutrinos

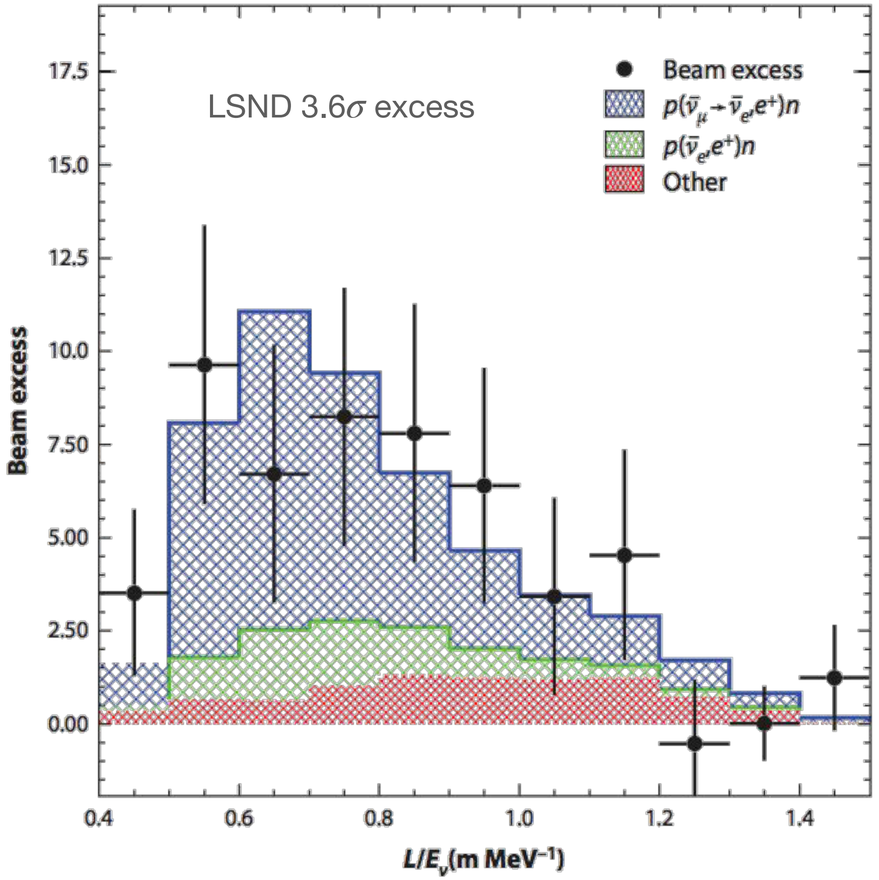


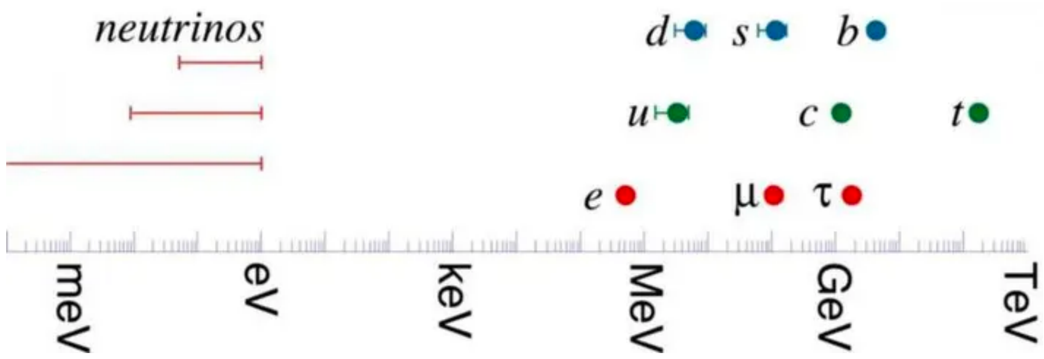
θ_{14}? θ_{24}? θ_{34}?

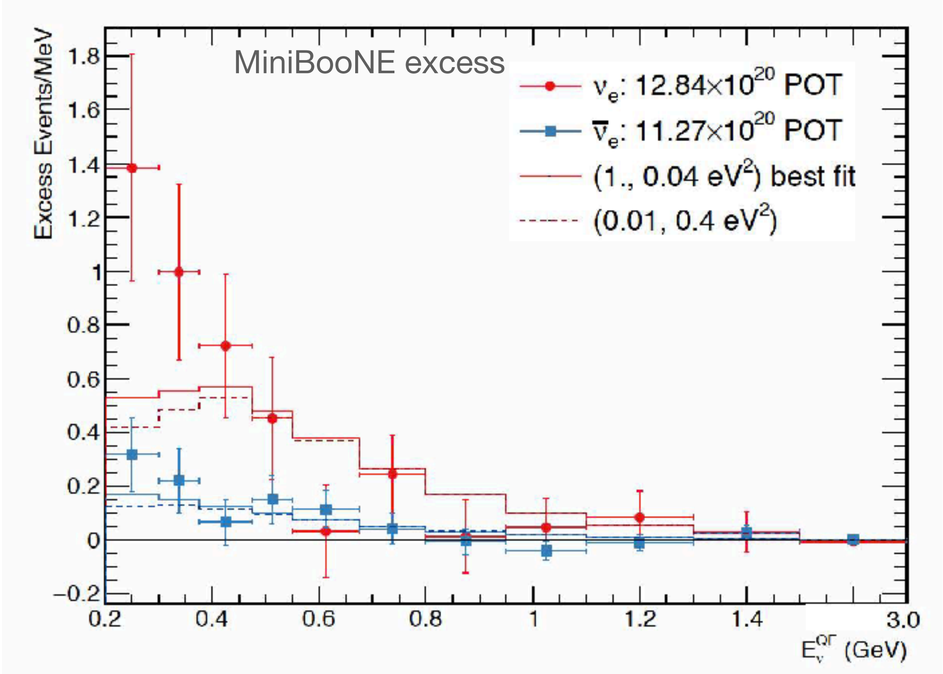
Sterile neutrino searches



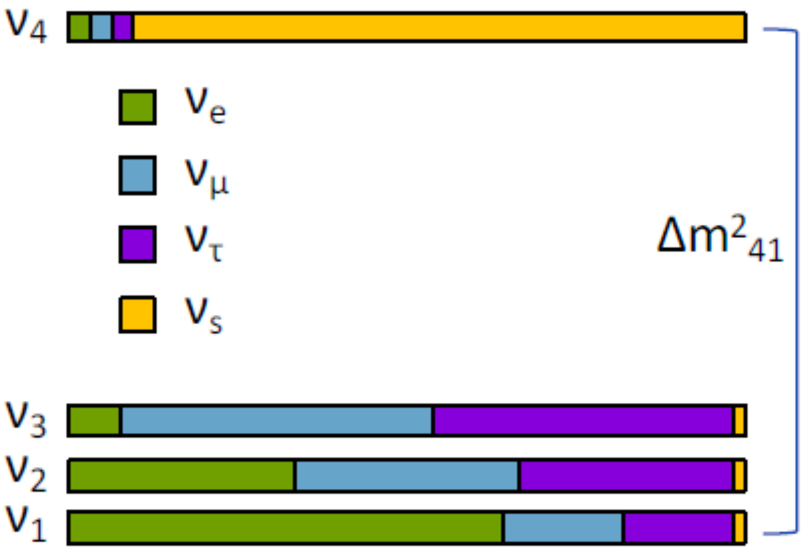
Sterile neutrino searches





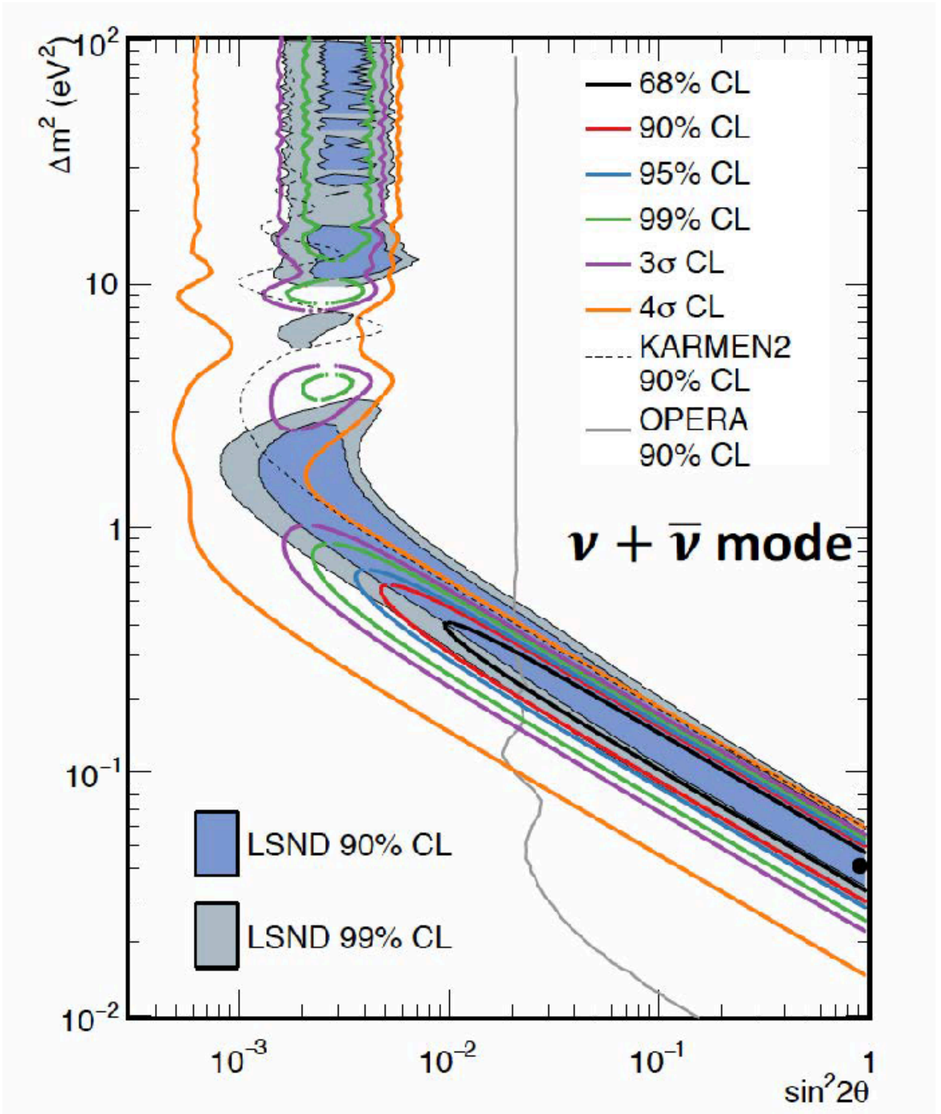


Interpretation of LSND and MiniBooNE in 3+1



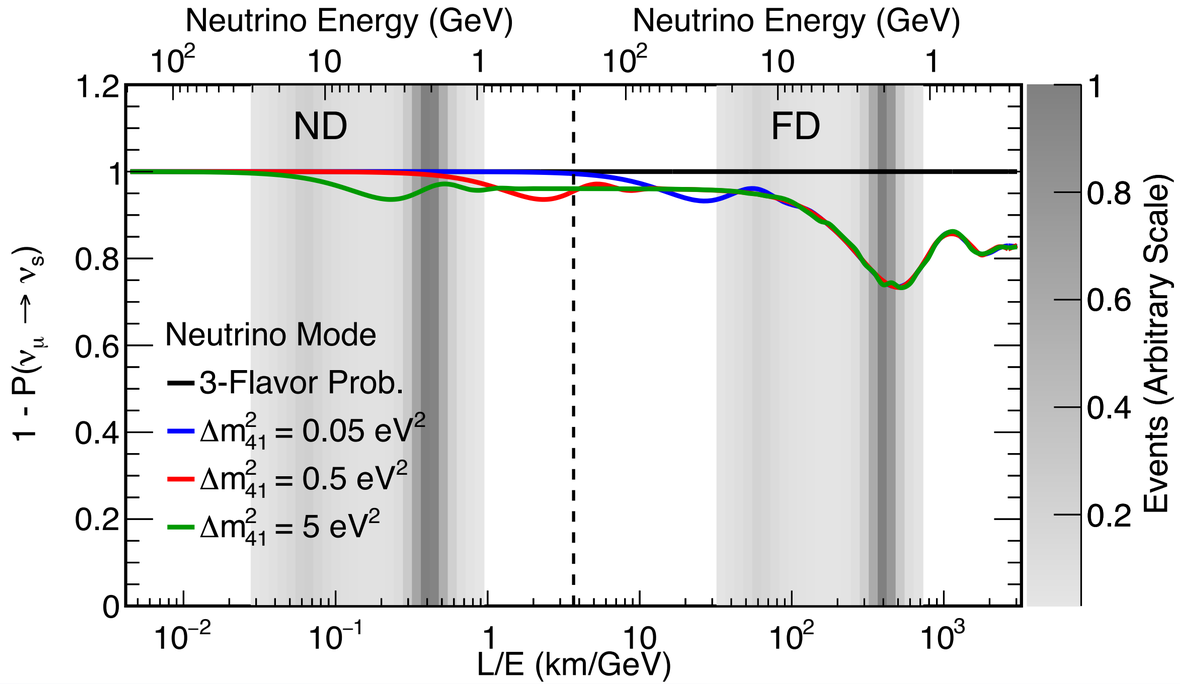
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

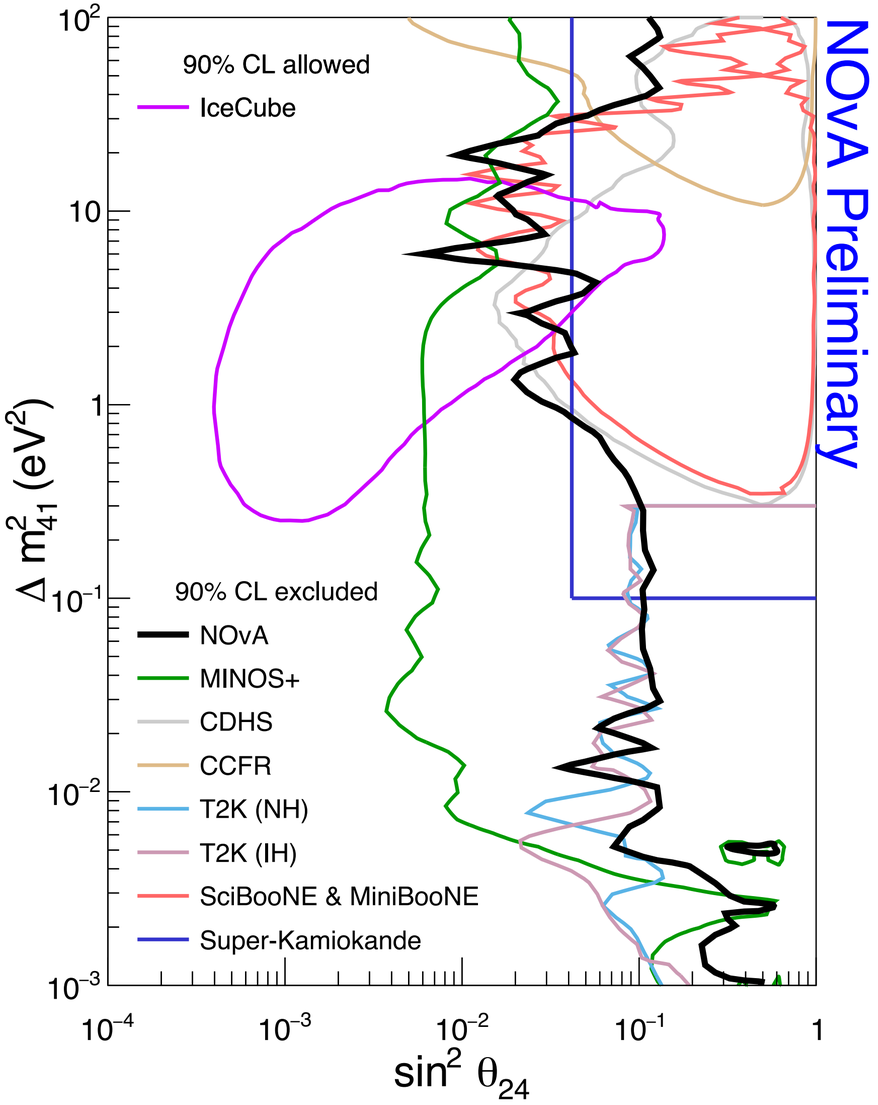
SBL



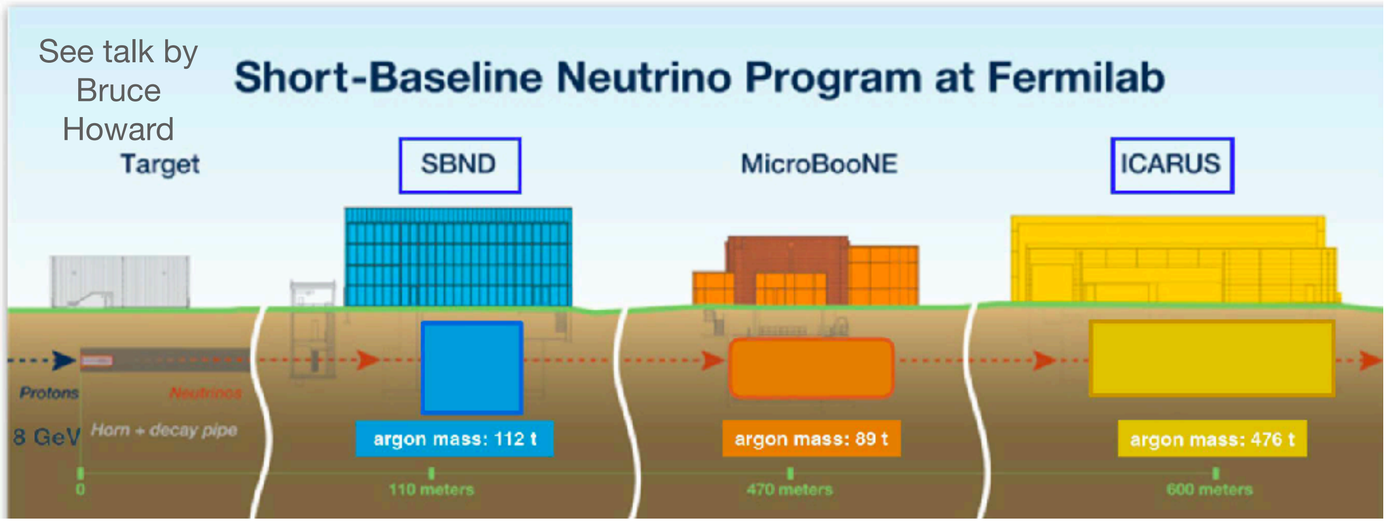
Sterile neutrinos in disappearance channel

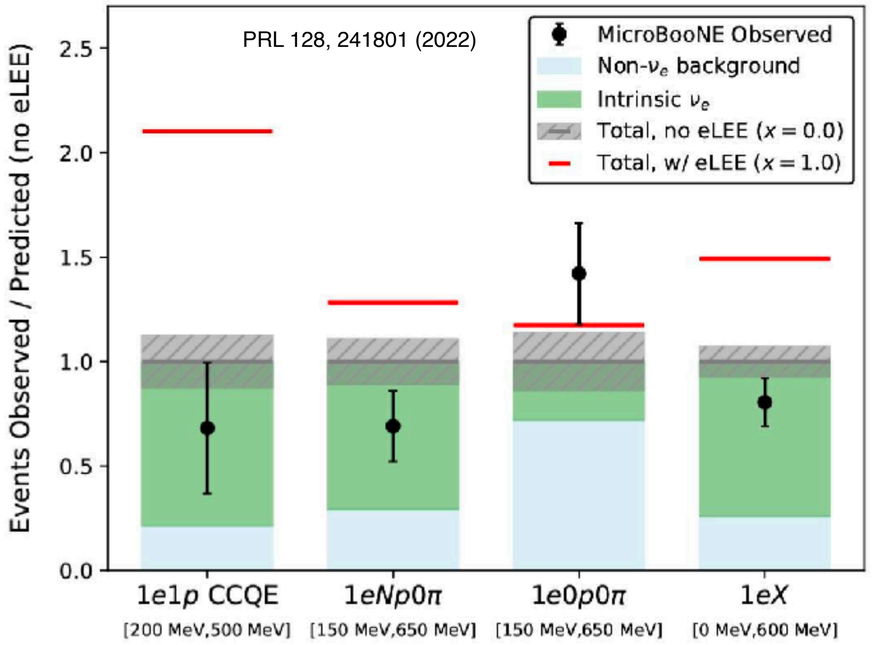
- Electron neutrino appearance through $\nu_\mu \rightarrow \nu_e$ with eV scale sterile neutrinos implies additional disappearance in $\nu_\mu \rightarrow \nu_\mu$
- This is not seen by a number of experiments (MINOS, NOvA, IceCube)
- This creates a tension: there is no model involving sterile neutrinos which can simultaneously fit the appearance claims and the disappearance measurements.



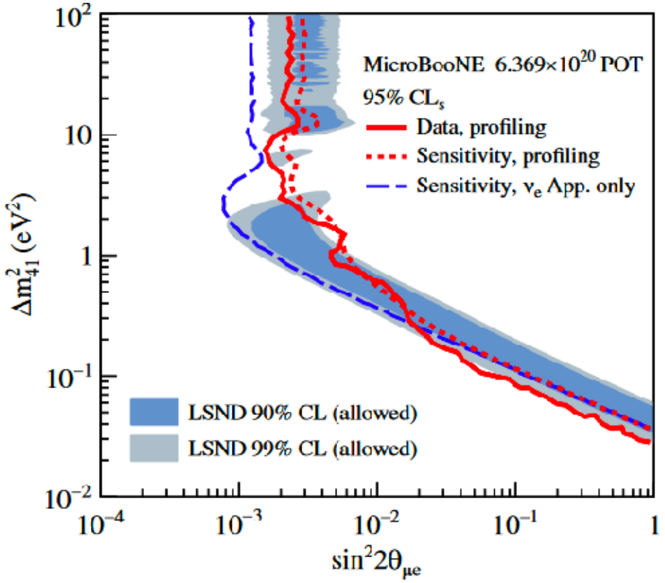


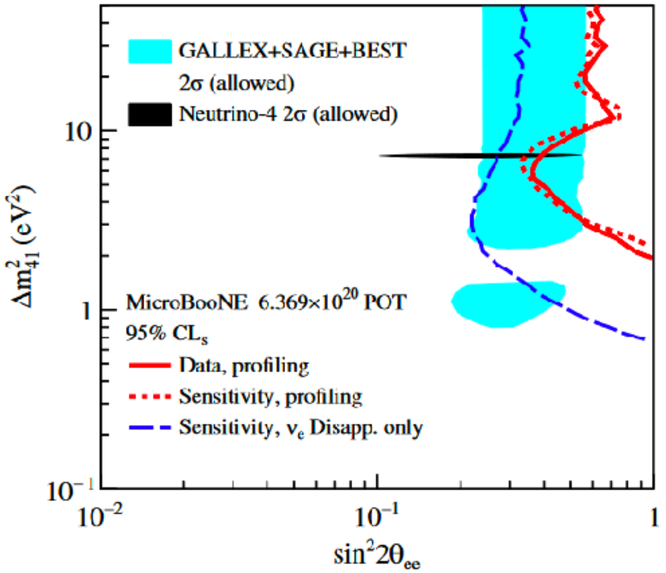
MicroBooNE and SBN





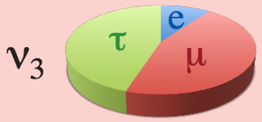
- MicroBooNE:
  - electron searches, covering 4 final states reject electrons as the sole LEE explanation at > 97% CL
  - photon search disfavours NC Δ→Nγ decay as a sole source of LEE at 94.8% C.L
  - data from inclusive electron search used to test the (3+1) sterile neutrino hypothesis → no evidence of sterile neutrino oscillation
- SBN status: ICARUS taking data, SBND starts next year, multi-detector oscillation analyses



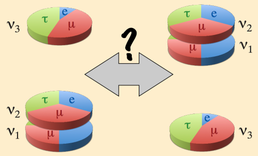


What I am excited to see now?

How much do neutrinos mix?



Which is the lightest neutrino?



Normal Ordering Inverted Ordering

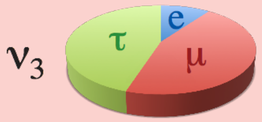
Do neutrinos and antineutrinos oscillate in the same way?


?

Is there a light sterile neutrino?

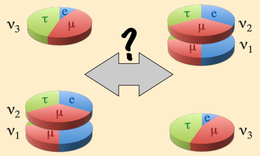
What I am excited to see now?

How much do neutrinos mix?



IceCube
Super-K
T2K
NOvA

Which is the lightest neutrino?



Normal Ordering Inverted Ordering

JUNO
IceCube
NOvA
DUNE

Do neutrinos and antineutrinos oscillate in the same way?


?

NOvA
T2K
DUNE
Hyper-K

Is there a light sterile neutrino?

SBN
LBL


Thank you!