


The Mirror Crack'd:

Constraining the matter-
antimatter asymmetry with T2K

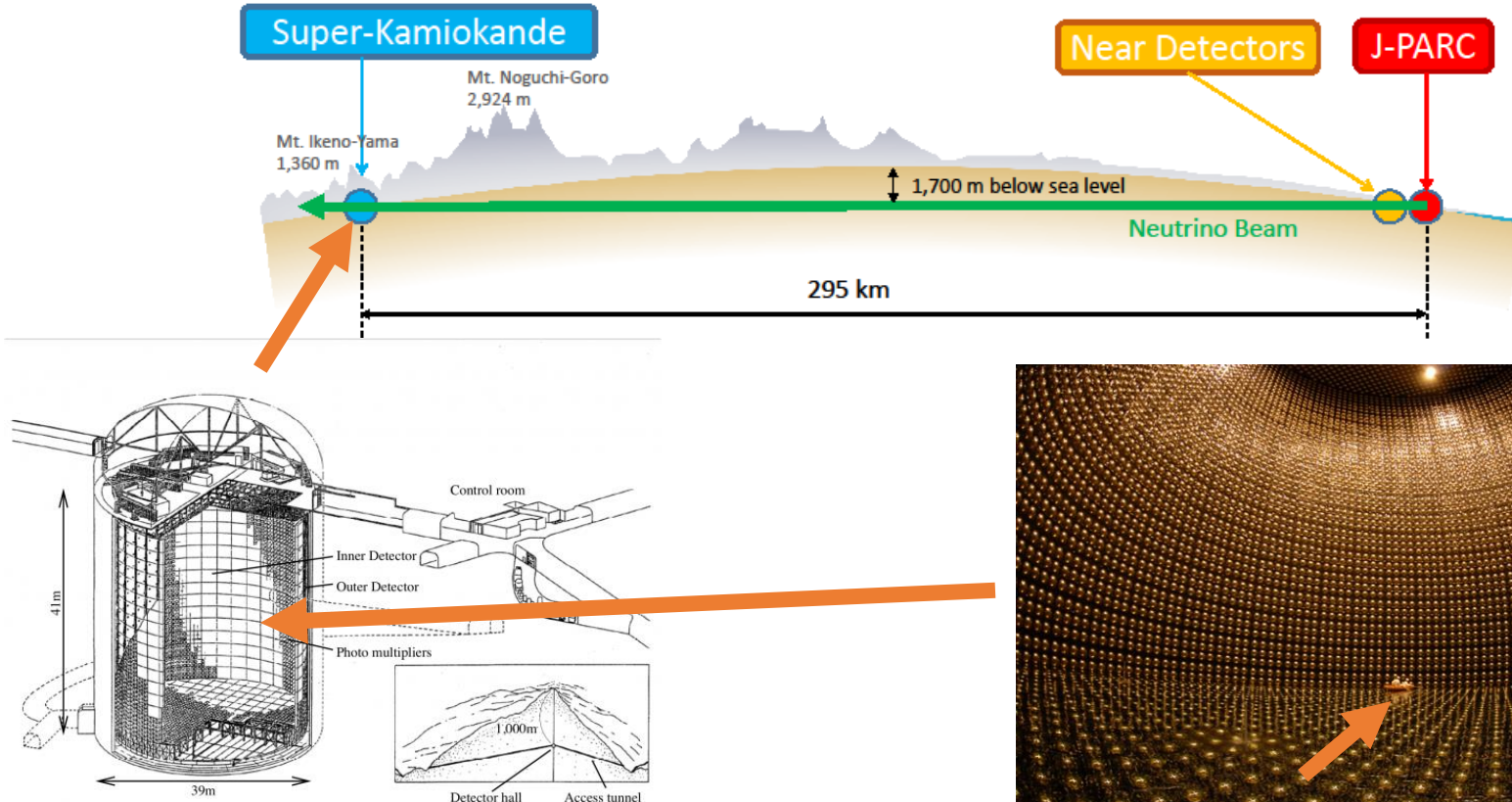
<https://doi.org/10.1038/s41586-020-2177-0>



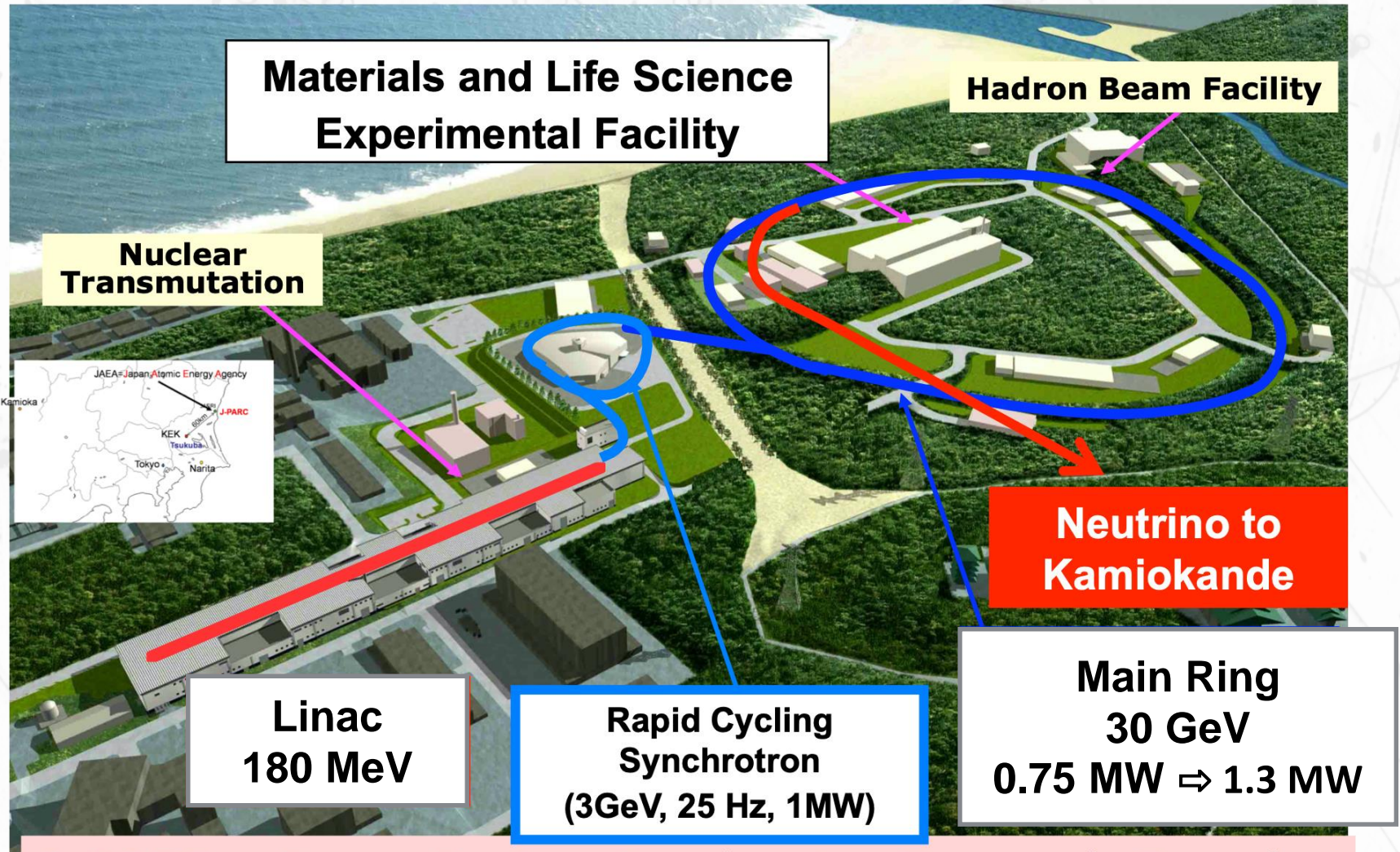
- Introduction to the T2K experiment
 - Quick review of neutrino oscillations
 - Excursion to matter-antimatter asymmetry
 - The CP-violating phase measurement
-
- Will try to be light on the maths
 - Will borrow slides from Federico Sanchez' CERN seminar talk
 -  logo in top right corner

The T2K Experiment

- T2K = Tokai To Kamioka
 - Neutrino beam experiment in Japan
- J-PARC (Tokai) → Super-Kamiokande (Kamioka)



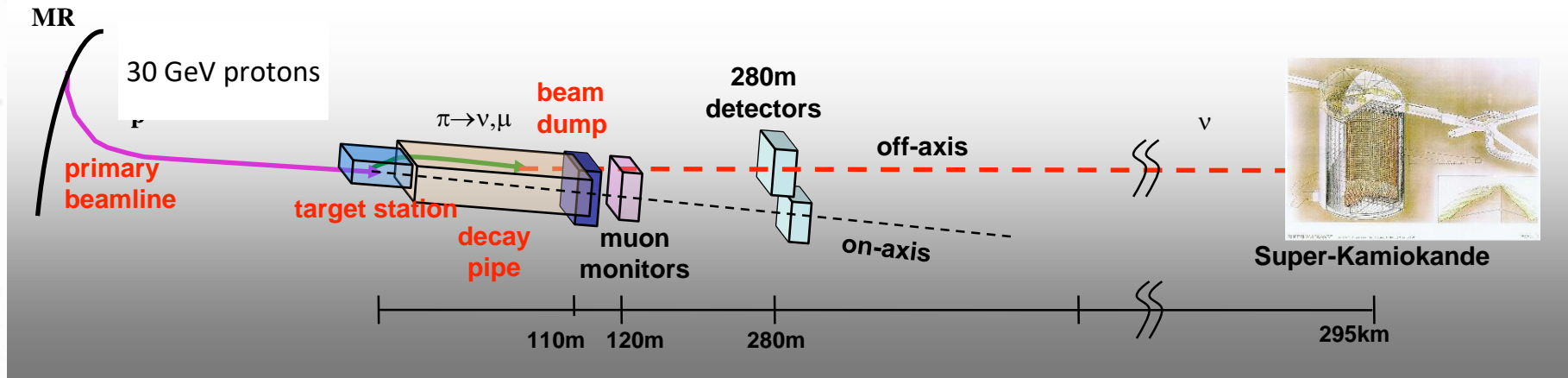
J-PARC



J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA

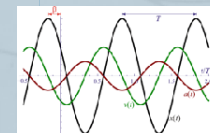
T2K experiment



Neutrinos produced in a particle accelerators or nuclear reactors.

Neutrino flux properties

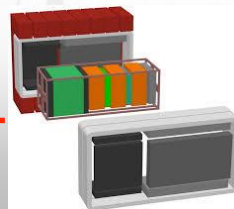
ν oscillations



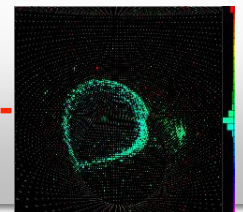
Neutrino flux & flavour



$\nu_\mu, \bar{\nu}_\mu$



$\nu_e \bar{\nu}_e$
 $\nu_\mu \bar{\nu}_\mu$



Off-axis beam

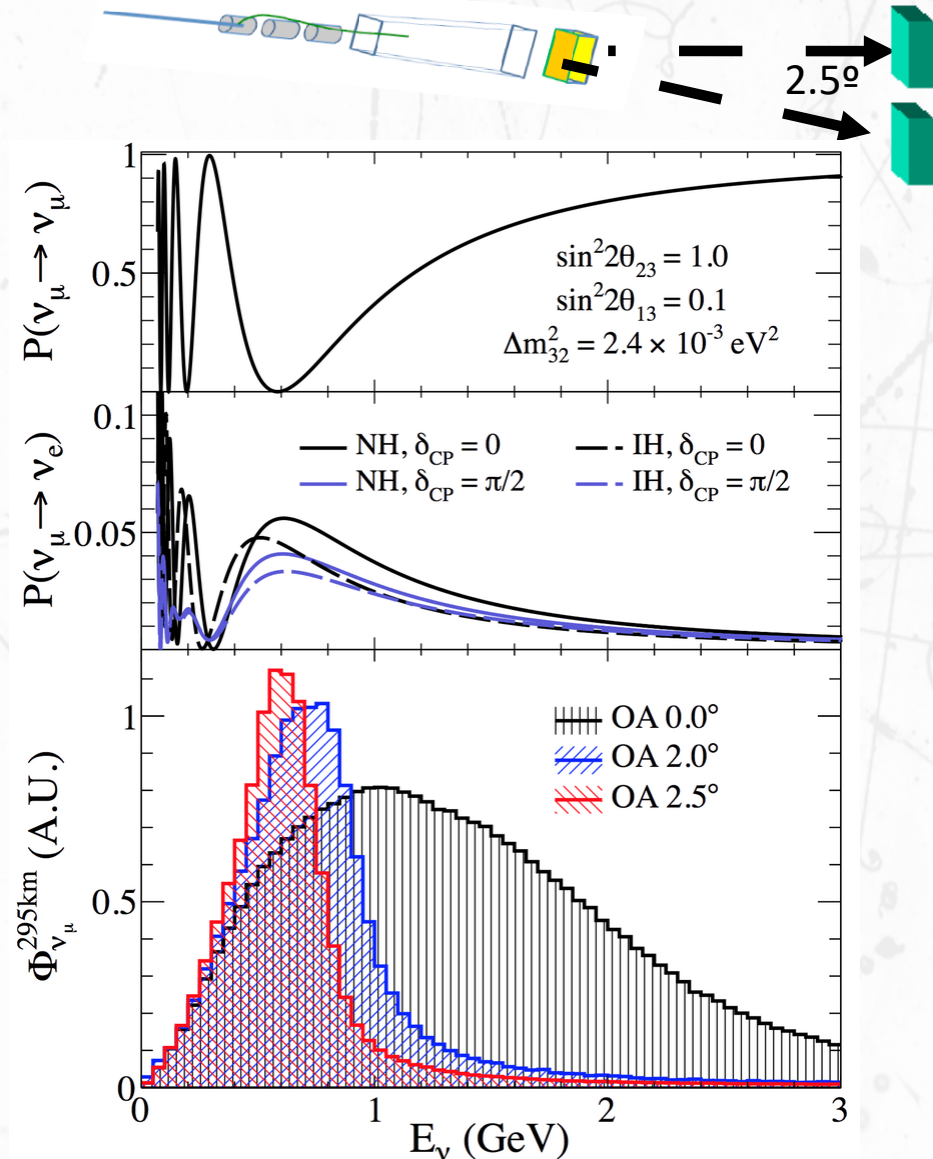


Off-axis

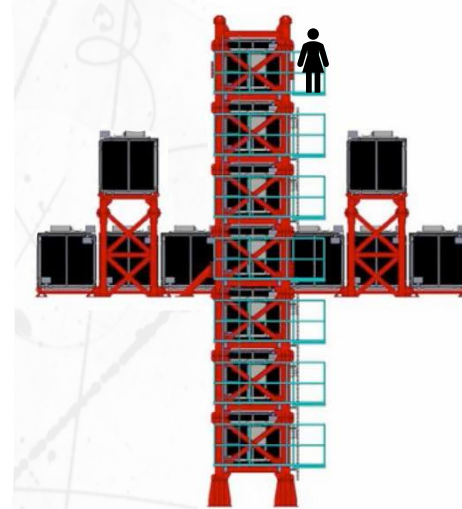
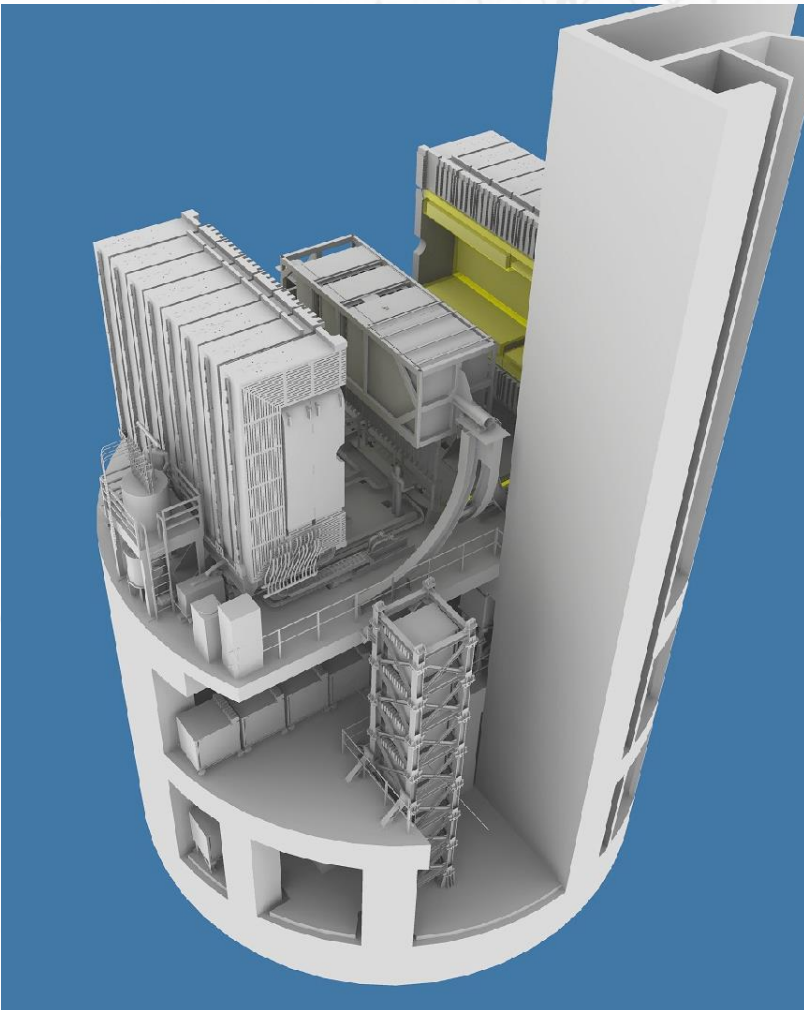
- off-axis optimises the flux at the maximum of the oscillation.
- Only one oscillation maximum can be measured at a fixed distance.
- Narrow beam less dependent on beam uncertainties but more on beam pointing.
- Lower energies achieved.

On-axis

- on-axis optimises the total integrated flux.
- Spectrum with higher neutrino energy (longer oscillation distances)
- If broad enough, more than one oscillation maximum can be measured at a fixed distance.

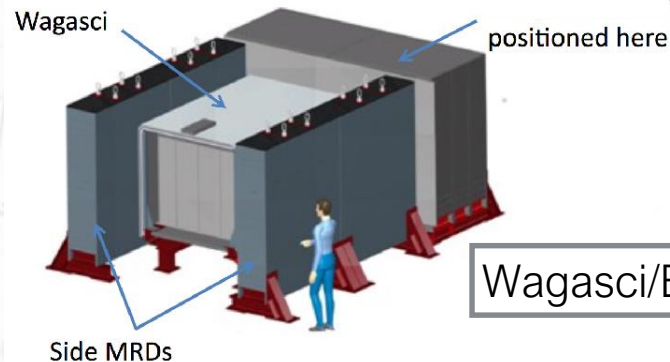
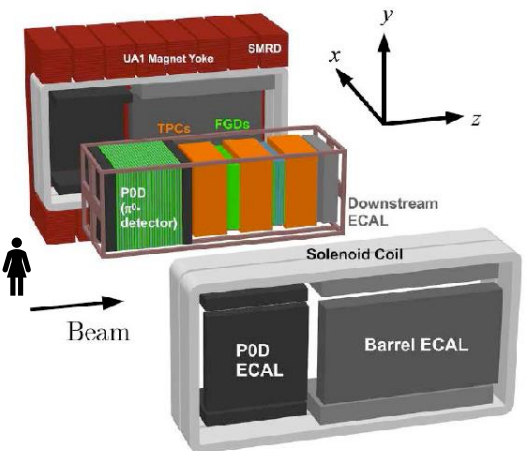


Near Detector Site



INGRID: On-axis

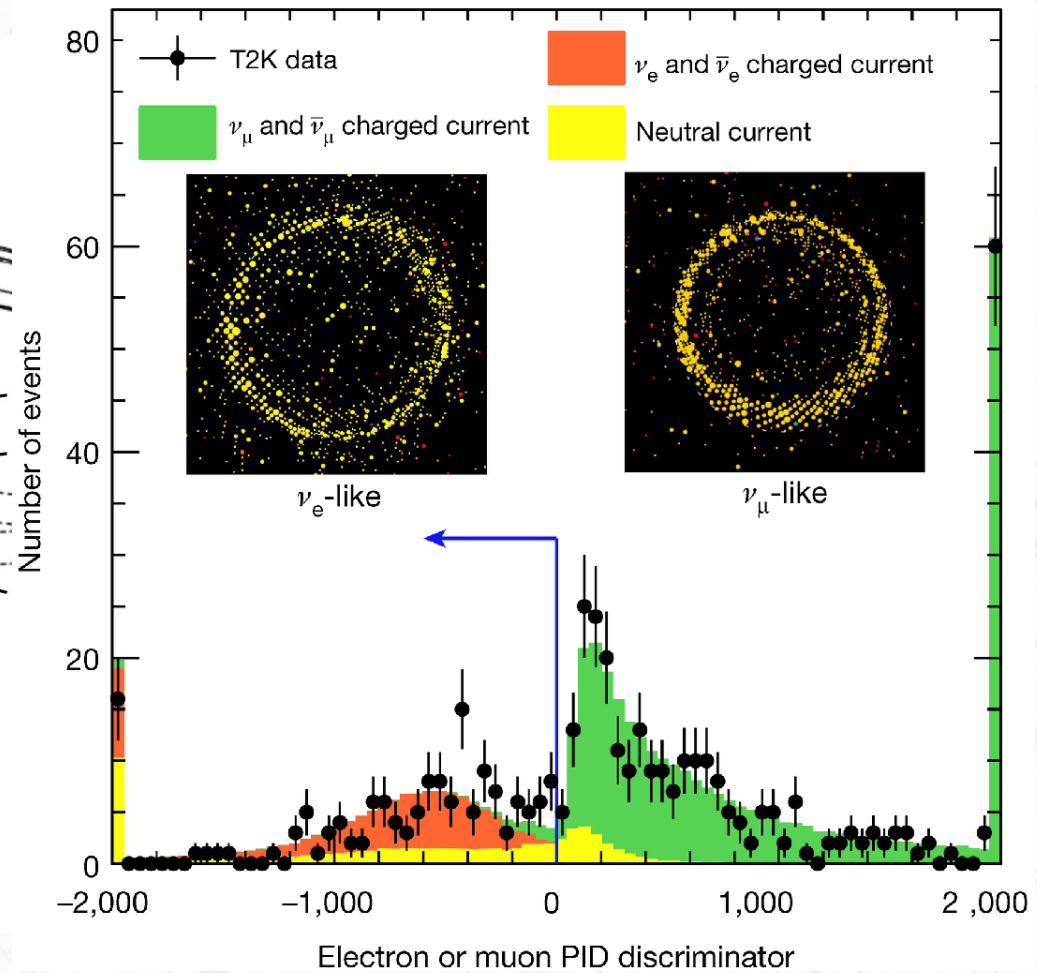
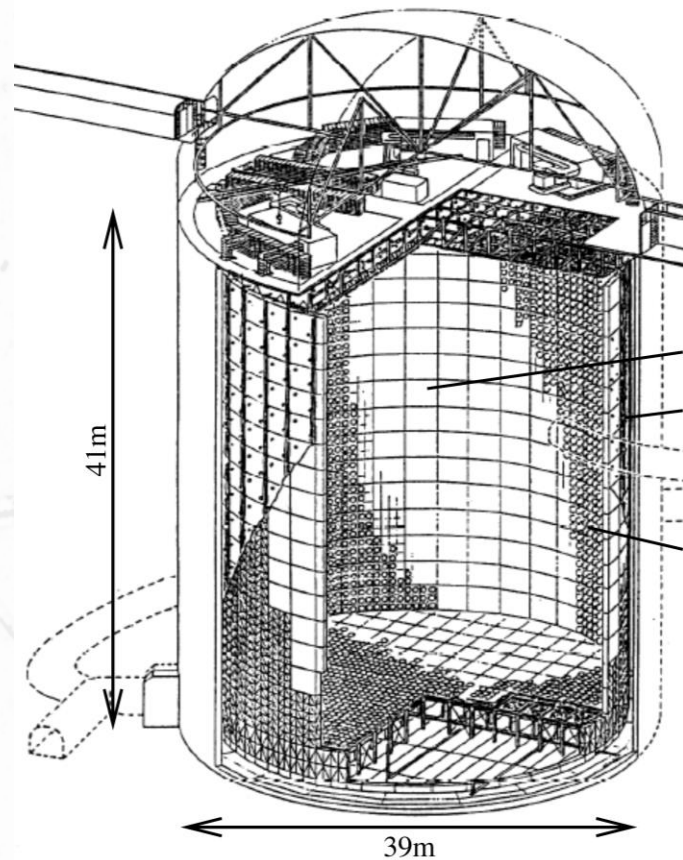
ND280: Off-axis



New!

Wagasci/BabyMind: Off-axis

Far detector



Particle identification

Interaction vertex reconstruction

Track Multiplicity

Particle range

Electromagnetic energy reconstruction

Hadronic interactions

Neutrino Oscillations

Neutrino oscillations



- Neutrino flavour eigenstates are not the same than the neutrino Lorentz eigenstates.
- Eigenstates are related through a rotation matrix.

Flavour eigenstates

$$(\nu_e, \nu_\mu, \nu_\tau)$$

state of the neutrino interactions

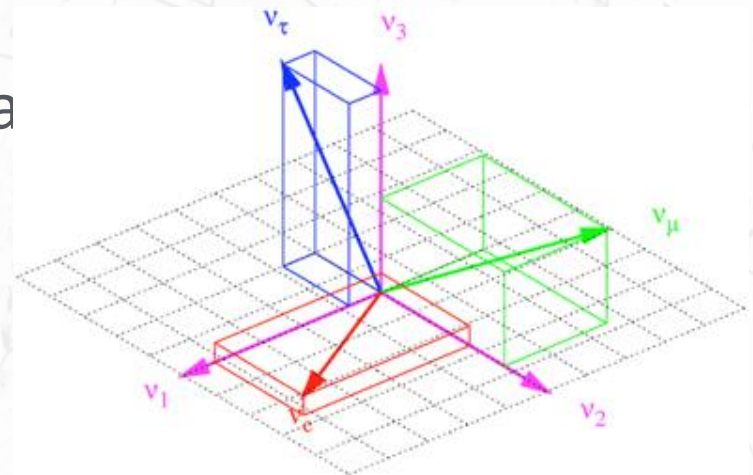
Lorentz eigenstates

$$(\nu_1, \nu_2, \nu_3)$$

states of the neutrino propagation in space

Pontecorvo–Maki–Nakagawa–Sakata
(PMNS) matrix

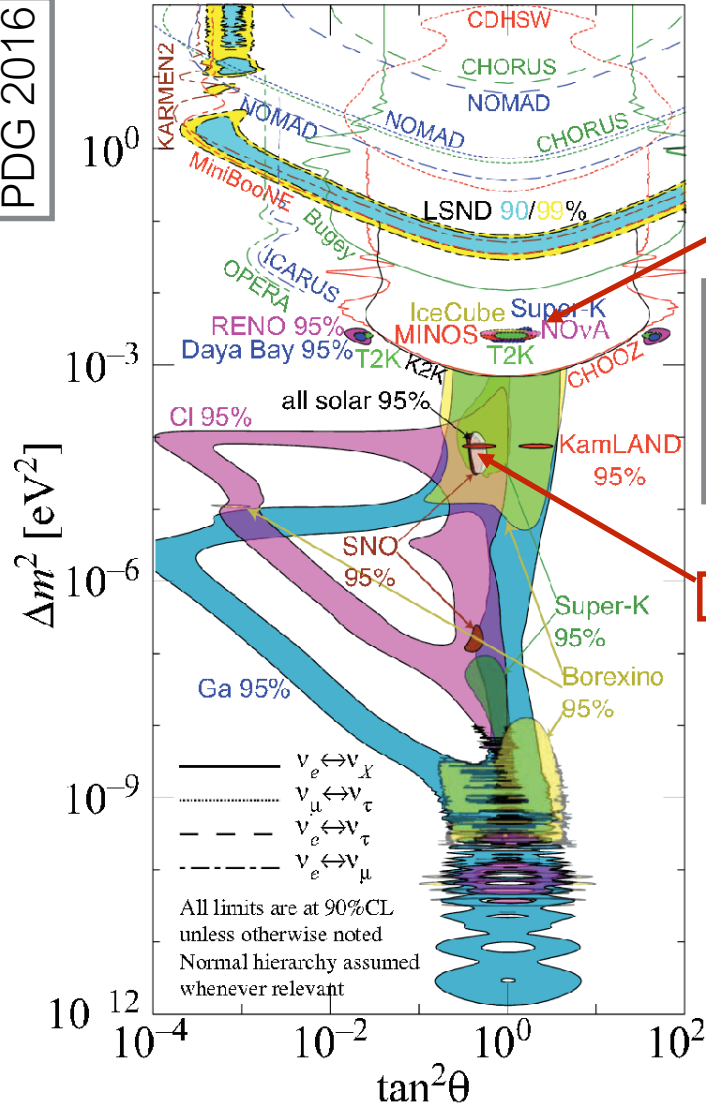
$$(\nu_e \quad \nu_\mu \quad \nu_\tau) = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Oscillation parameters



PDG 2016



PNMS Matrix

$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric

PDG 2018

Parameter	best-fit	3 σ
$\sim 4\%$ Δm_{21}^2 [10^{-5} eV ²]	7.37	6.93 – 7.96
$\sim 3\%$ $\Delta m_{31(23)}^2$ [10^{-3} eV ²]	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sim 11\%$ $\sin^2 \theta_{12}$	0.297	0.250 – 0.354
$\sin^2 \theta_{23}$, $\Delta m_{31(32)}^2 > 0$	0.425	0.381 – 0.615
$\sim 15\%$ $\sin^2 \theta_{23}$, $\Delta m_{32(31)}^2 < 0$	0.589	0.384 – 0.636
$\sin^2 \theta_{13}$, $\Delta m_{31(32)}^2 > 0$	0.0215	0.0190 – 0.0240
$\sim 7\%$ $\sin^2 \theta_{13}$, $\Delta m_{32(31)}^2 < 0$	0.0216	0.0190 – 0.0242
$\sim 31\%$ δ/π	1.38 (1.31)	2 σ : (1.0 - 1.9) (2 σ : (0.92-1.88))

solar

Most of the parameters measured with <10% precision

θ_{23} is known with 15% precision

Remaining parameters are δ_{CP} and the hierarchy

Mass hierarchy



- Oscillations is a quantum interference phenomenon that depends on the (quadratic) mass difference:

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

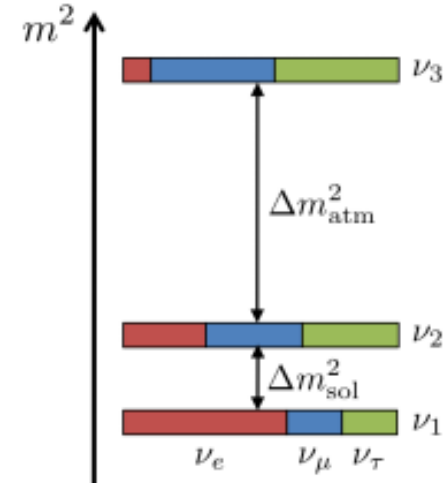
- Due to matter effects in solar neutrinos we know:

$$\Delta m^2_{12} > 0$$

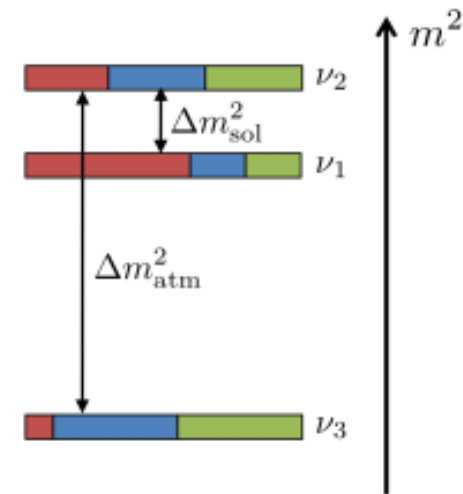
- Hierarchy determines the ordering of the masses. Traditionally:

- Normal: $m_1 < m_2 < m_3$
- Inverted: $m_3 < m_1 < m_2$

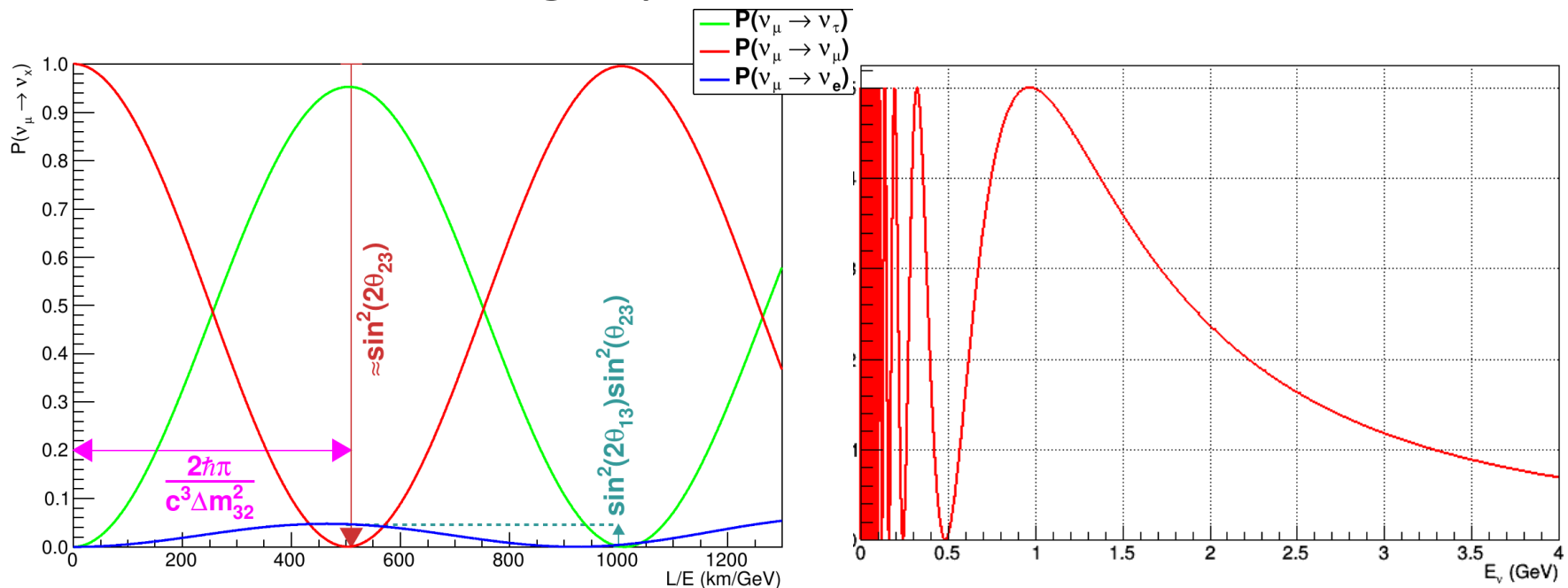
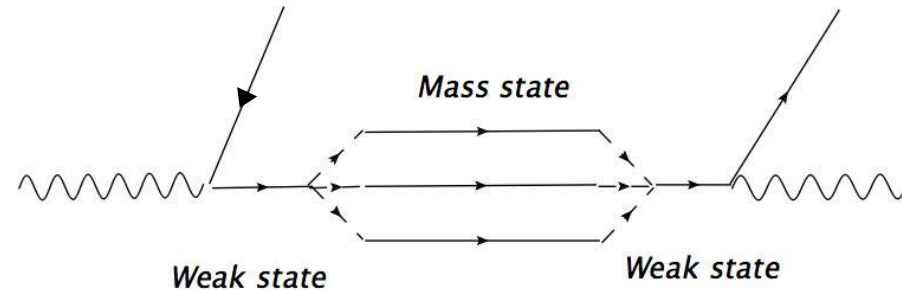
normal hierarchy (NH)



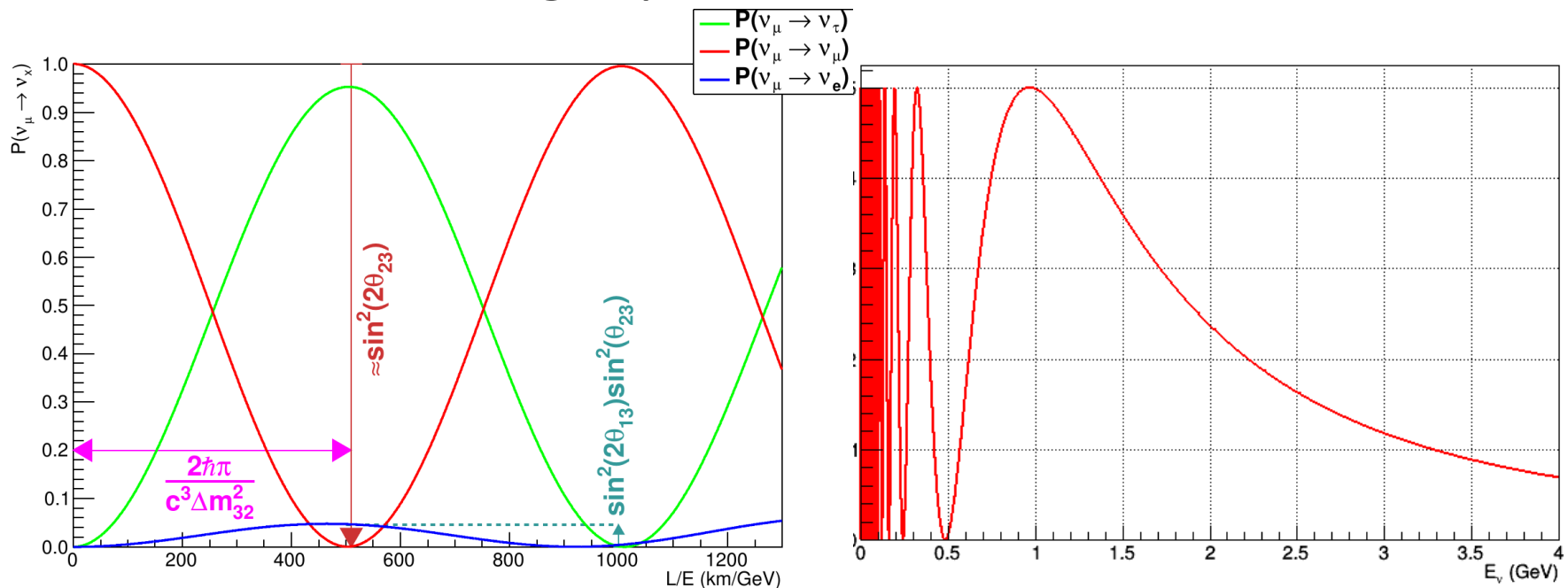
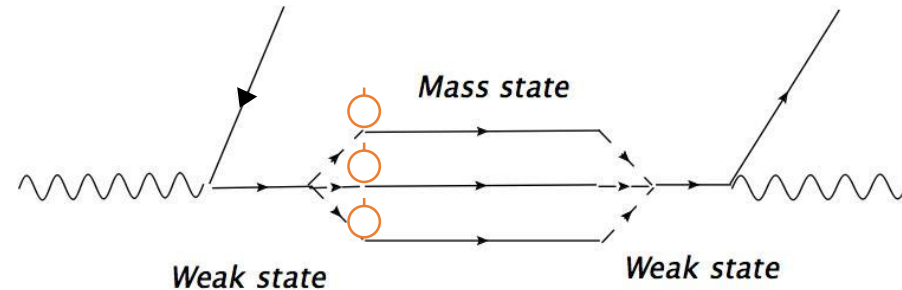
inverted hierarchy (IH)



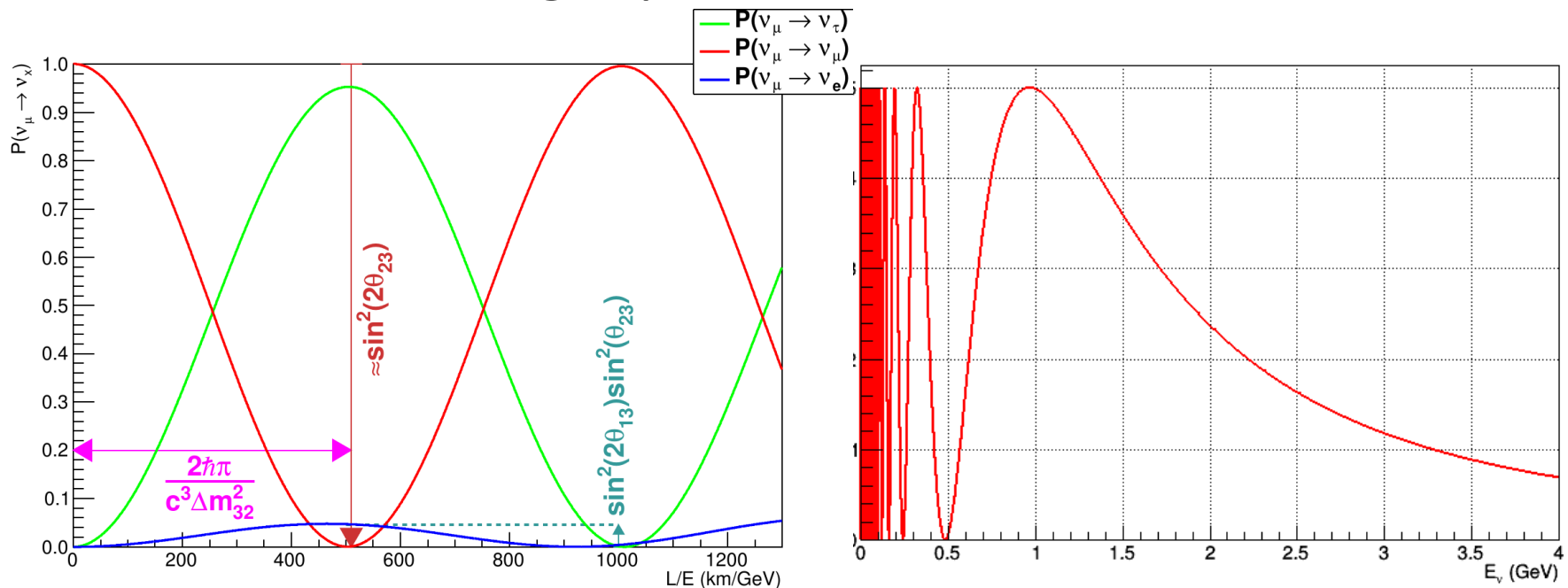
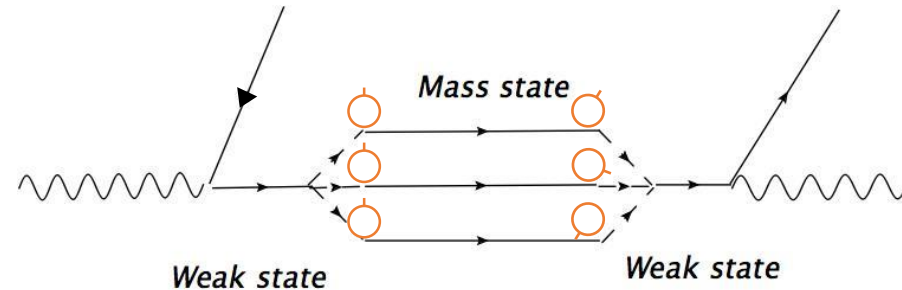
- Neutrino state vector of 3 complex (!) numbers
- Different mass eigenstates propagate with different phase velocities
- When expressing neutrino state as in flavour base after a while it is no longer pure!

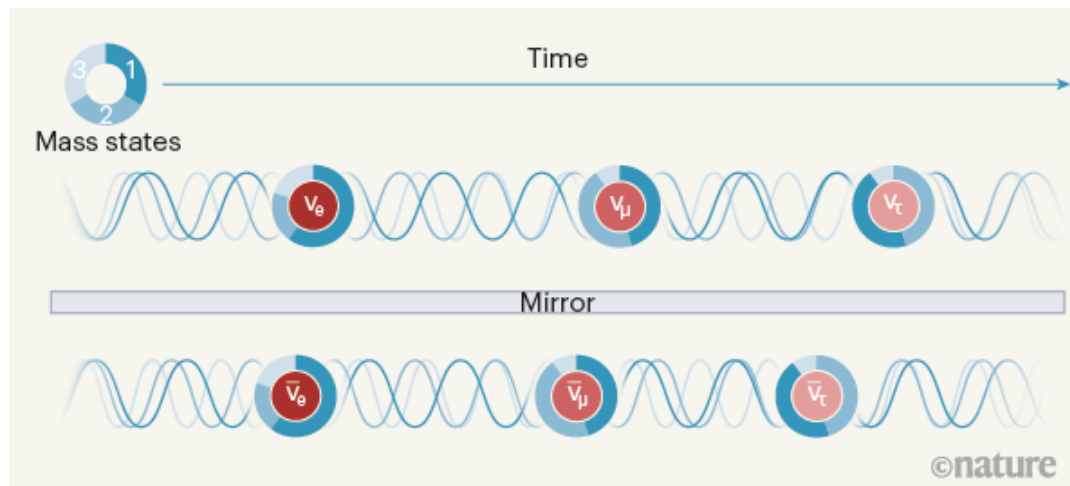


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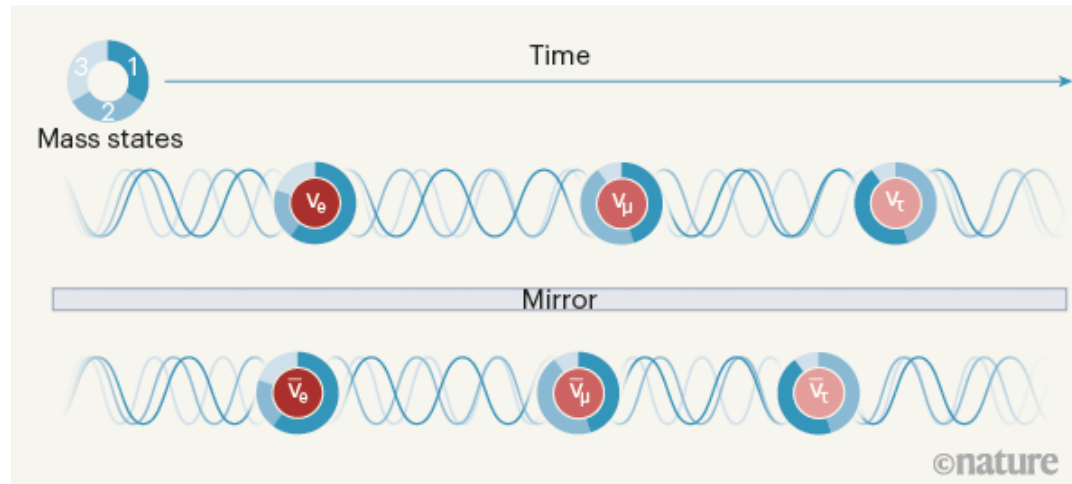




- Subdominant term changes electron appearance probability differently for (anti)neutrinos

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right) \pm \frac{1.27\Delta m_{21}^2 L}{E} 8J_{\text{CP}} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right) \quad (2)$$

- Up to 40% effect on # of expected events at SK
- Matter effects add another 10% → some sensitivity to mass ordering



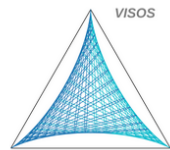
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$$\boxed{\mp} \frac{1.27\Delta m_{21}^2 L}{E} \delta J_{\text{CP}} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

- Up to 40% effect on # of expected events at SK
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- VISOS by Xianguo Lu, Rasched Haidari, Artur Sztuc
 - Web application to visualise changing flavour probabilities depending on oscillation parameters
- <http://www-pnp.physics.ox.ac.uk/~luxi/visos/>



VISOSim
— **VISualisation of OScillation**
interactive mode



$\sin^2 \vartheta_{12}$

0.297

$\sin^2 \vartheta_{23}$

0.425

$\sin^2 \vartheta_{13}$

0.0215

Default

([PDG 2018](#))

Bimaximal

([arXiv](#))

Δm^2_{21} (eV²)

7.37e-5

Δm^2_{32} (eV²)

2.49e-3

δ_{CP} (°)

248

Tribimaximal

([Wiki](#))

Trimaximal

([Wiki](#))

Flavor

μ

Energy (GeV)

0.6

Distance (km)

295

Matter Density

Earth Crust

Daya Bay

DUNE (1. OM*)

DUNE (2. OM)

HKK

JUNO

KamLAND

NOvA

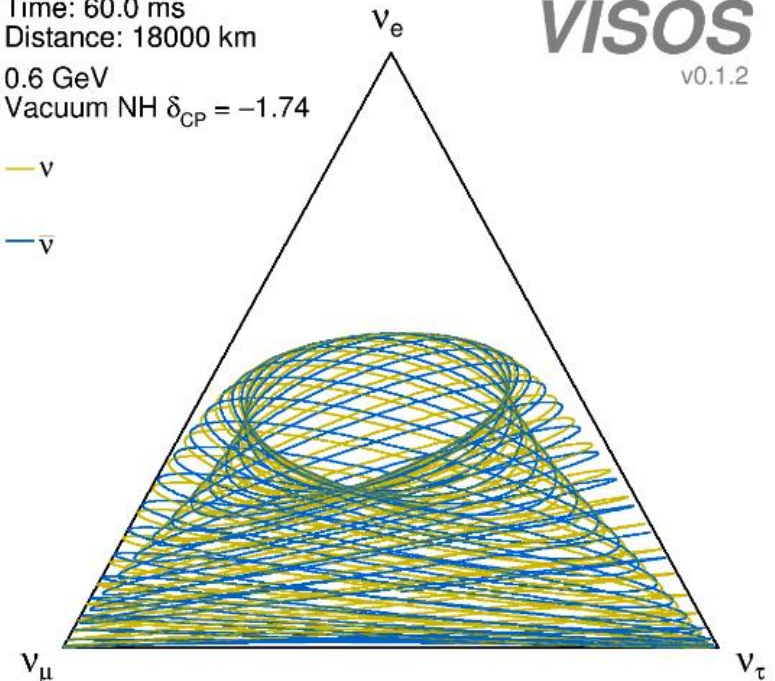
T2K/HK

Time: 60.0 ms
Distance: 18000 km
0.6 GeV
Vacuum NH $\delta_{CP} = -1.74$

ν

$\bar{\nu}$

VISOS
v0.1.2



CP Violation and the Matter-Antimatter Asymmetry

- Charge (C) and parity (P) symmetry are maximally broken in weak interactions
 - Things are different in a mirror universe, xor when switching all particles for antiparticles
 - See e.g. Wu experiment
- The combined CP symmetry is also broken, but less obviously so
 - Things are still different when in a mirror universe *and* switching all particles for antiparticles
 - Implies time symmetry (T) is also broken, assuming CPT is conserved
 - So far only observed in quark sector, see e.g. K^0 decay

- All standard model processes create/destroy matter and antimatter in equal amounts
- Need beyond standard model physics to explain the observed matter dominance in the universe
 - Baryogenesis
 - Leptogenesis
 - ...
- Sakharov conditions:
 - Baryon number violation
 - C and CP violation
 - Process out of thermal equilibrium
- CP violating effect in quark sector too weak to explain existence of matter excess via baryogenesis

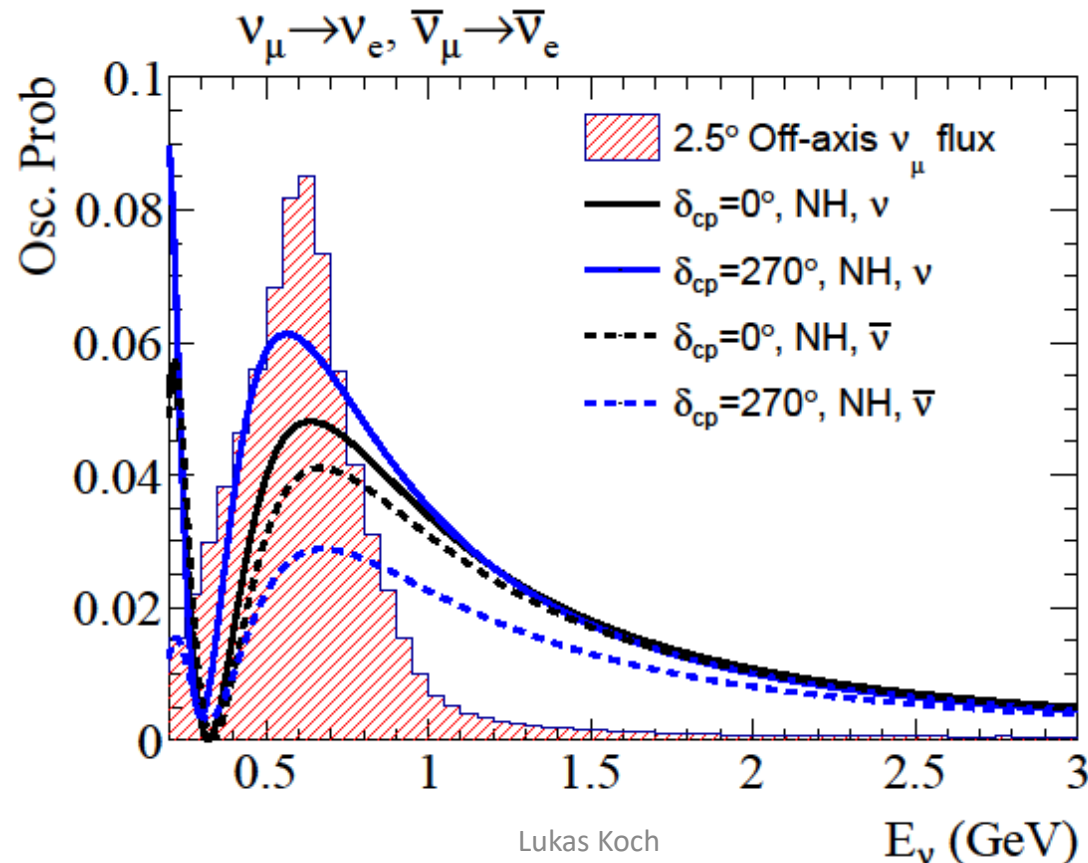
- CP violation in lepton sector not observed yet
- Could be large enough to “explain” existence of matter excess via leptogenesis
 - Jarlskog invariant in lepton sector (PMNS matrix):

$$J_{\text{CP},l} = \frac{1}{8} \cos\theta_{13} \sin(2\theta_{12}) \sin(2\theta_{23}) \sin(2\theta_{13}) \sin\delta_{\text{CP}} \quad (1)$$
$$\approx 0.033 \sin\delta_{\text{CP}}$$

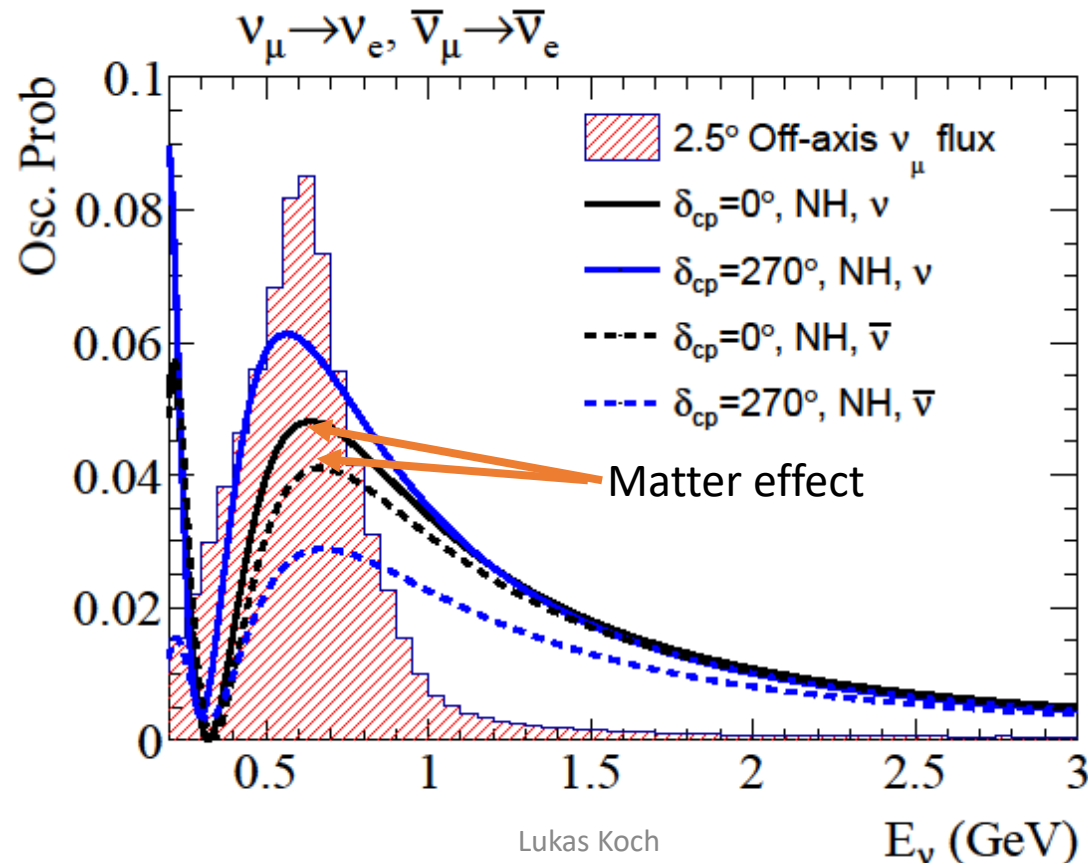
- In quark sector (CKM matrix): ($J_{\text{CP},q} = 3 \times 10^{-5}$)
- CP violation is a necessary condition, not sufficient
 - Still need beyond standard model processes for other Sakharov conditions

T2K's δ_{CP} Measurement

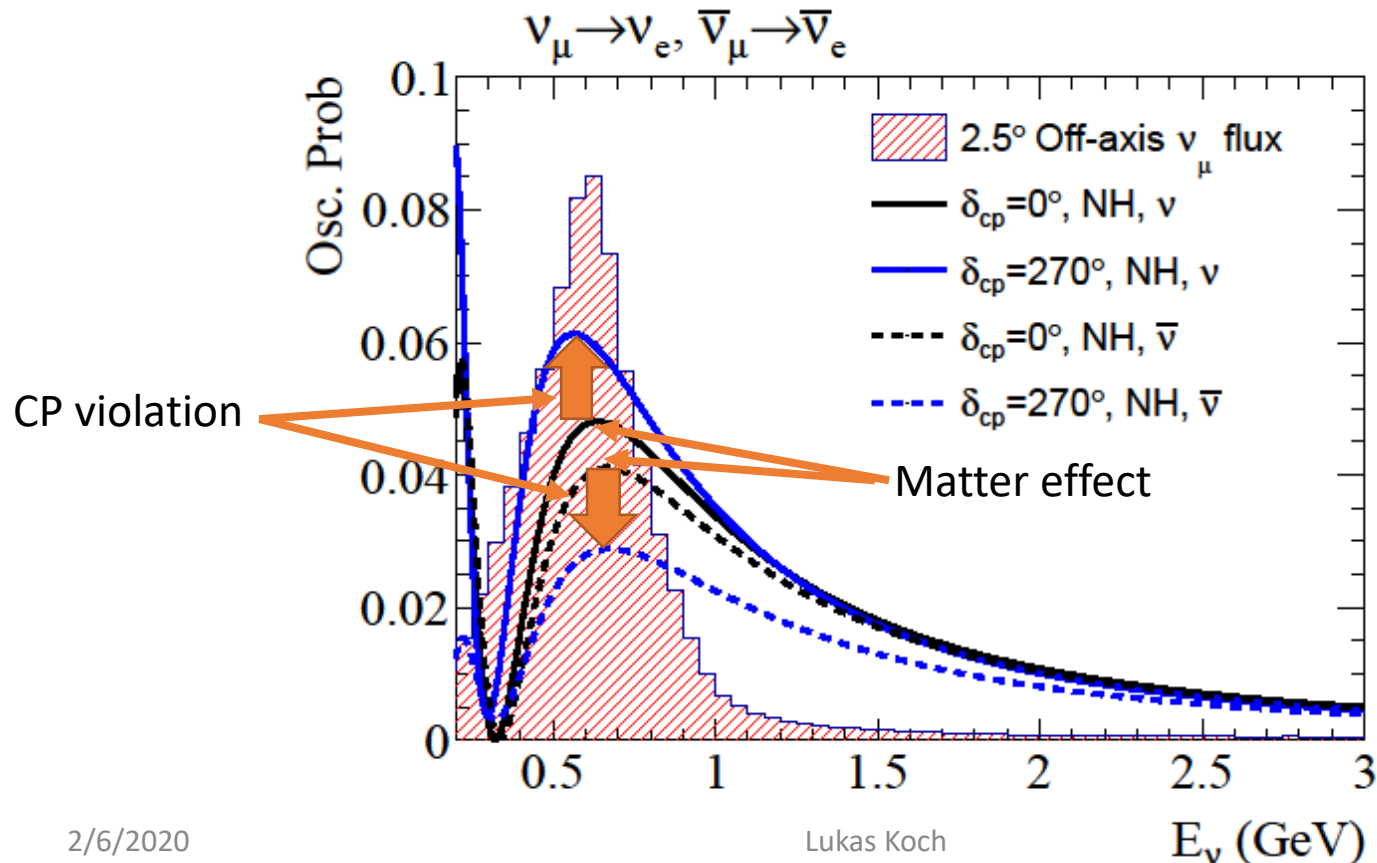
- Count electron-neutrino events in SuperK
 - Both in neutrino and antineutrino beam mode
 - Data analysed here taken between 2009 and 2018
- Compare with model expectations
 - Exclude parameter space that is incompatible with data

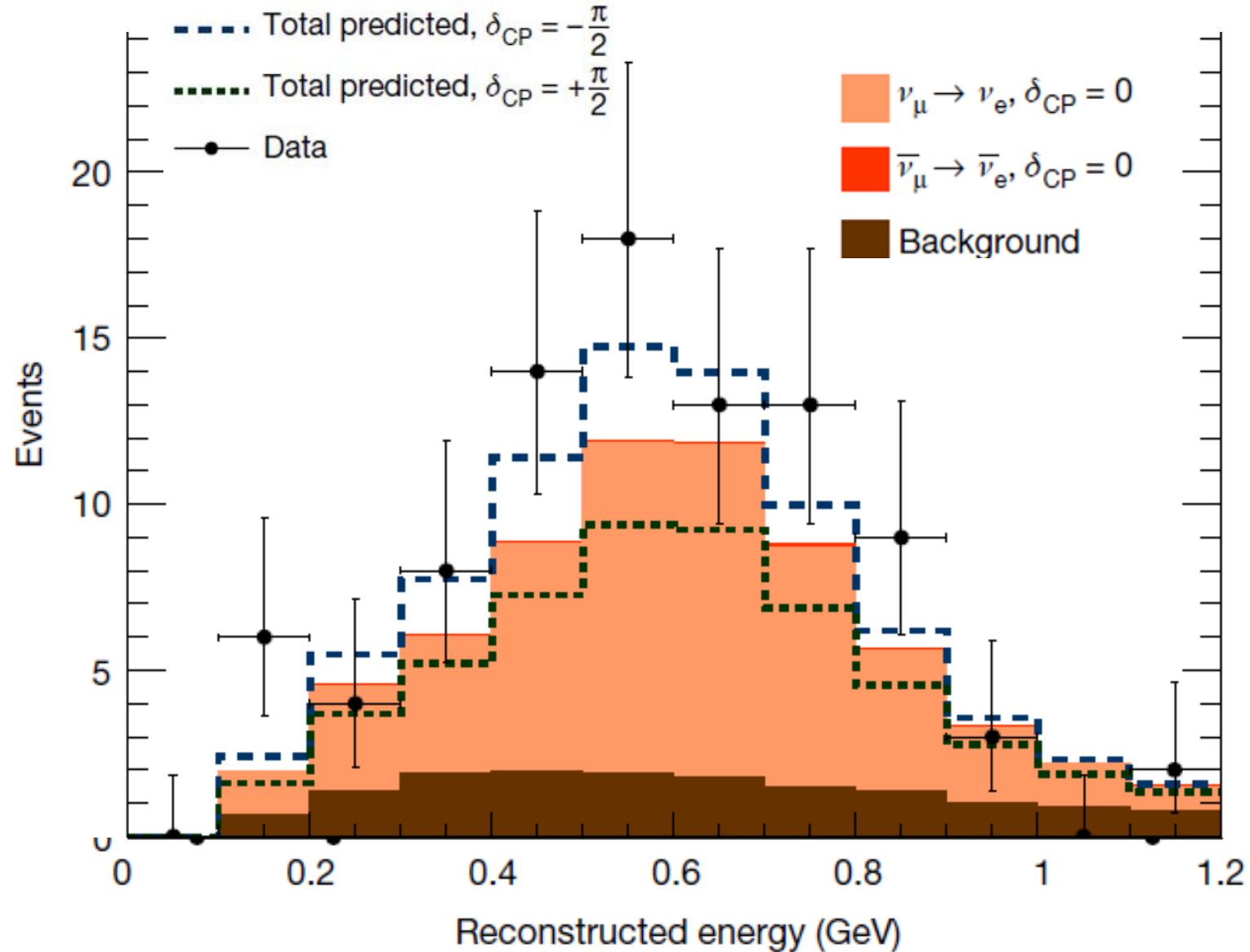


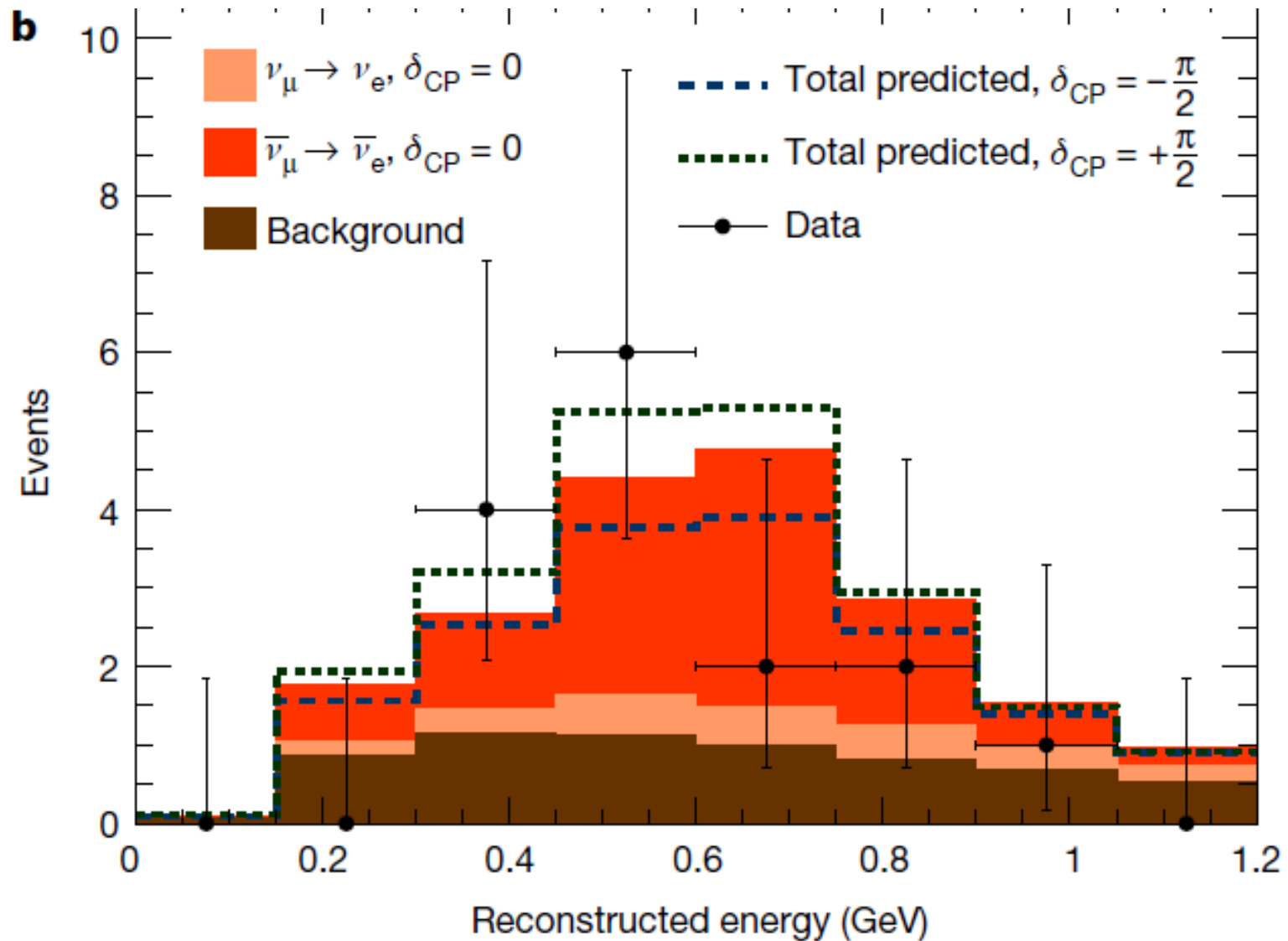
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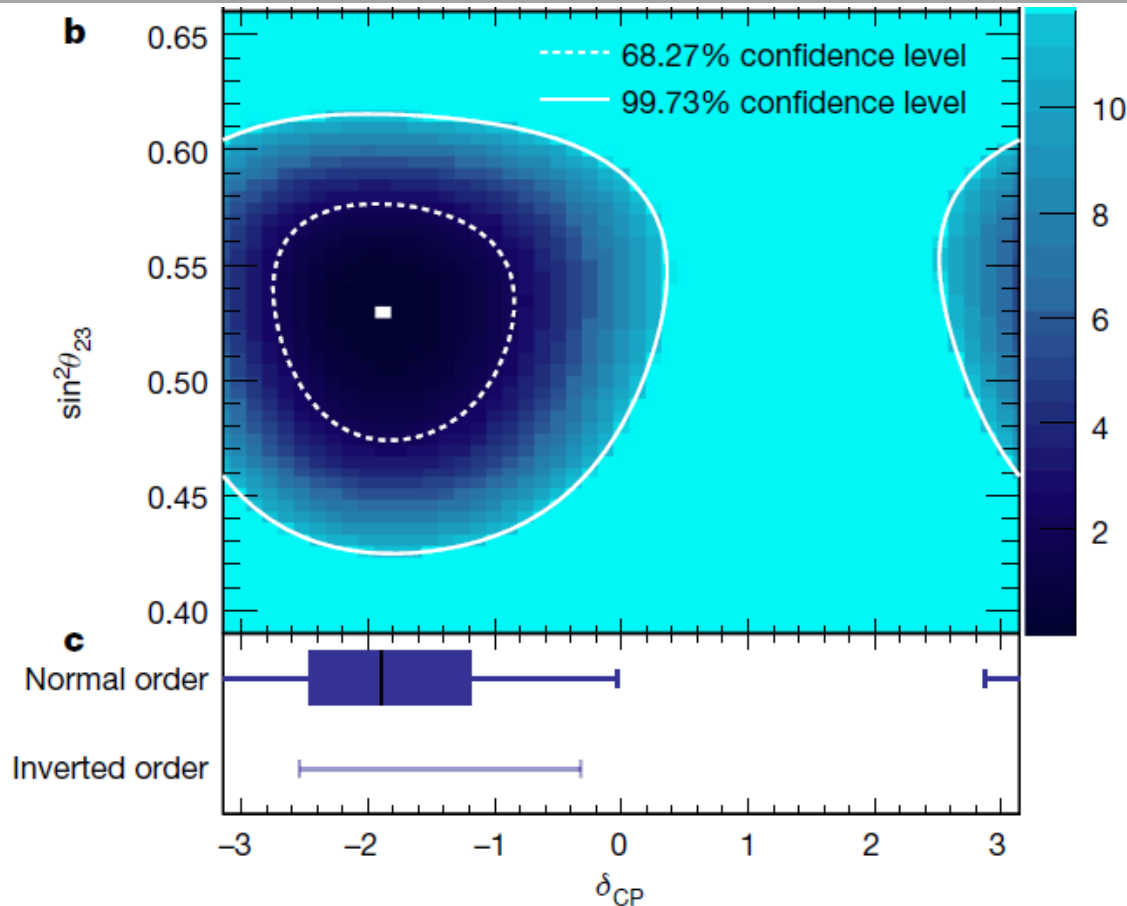


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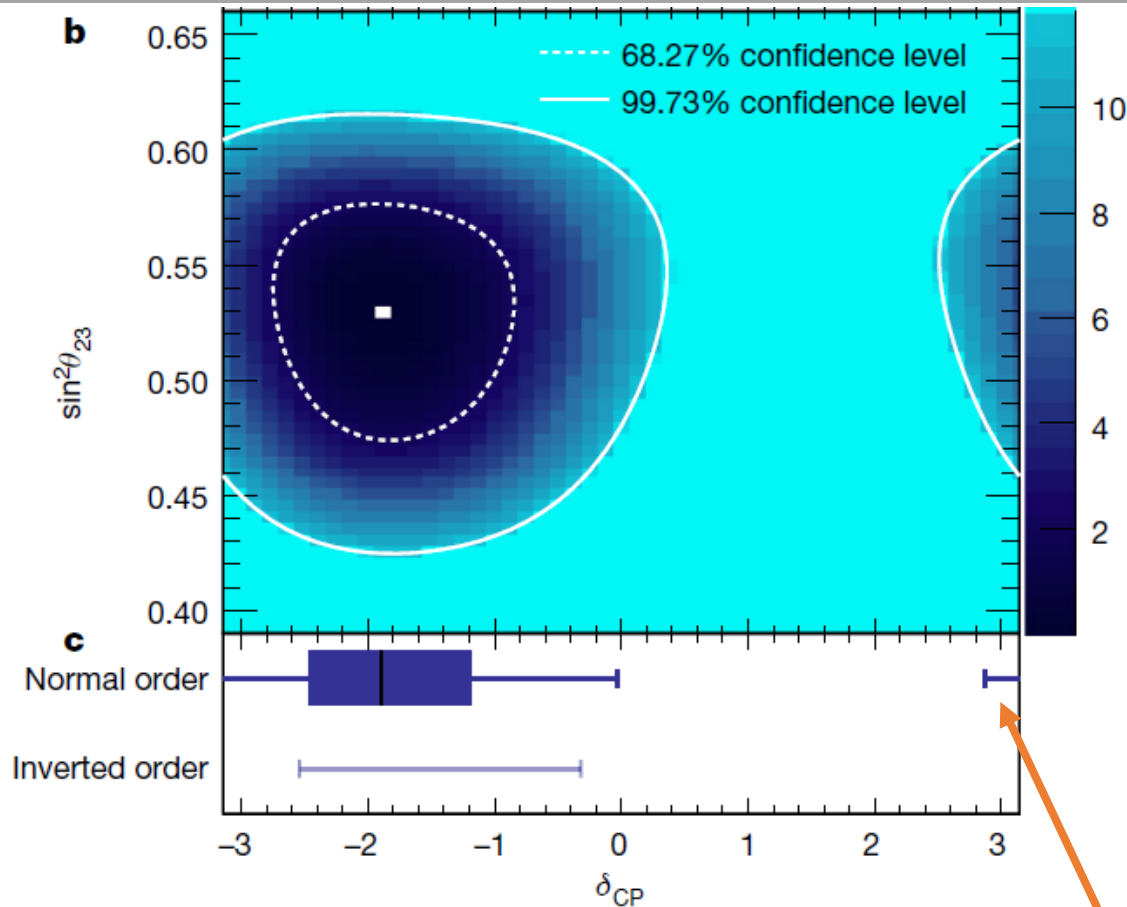






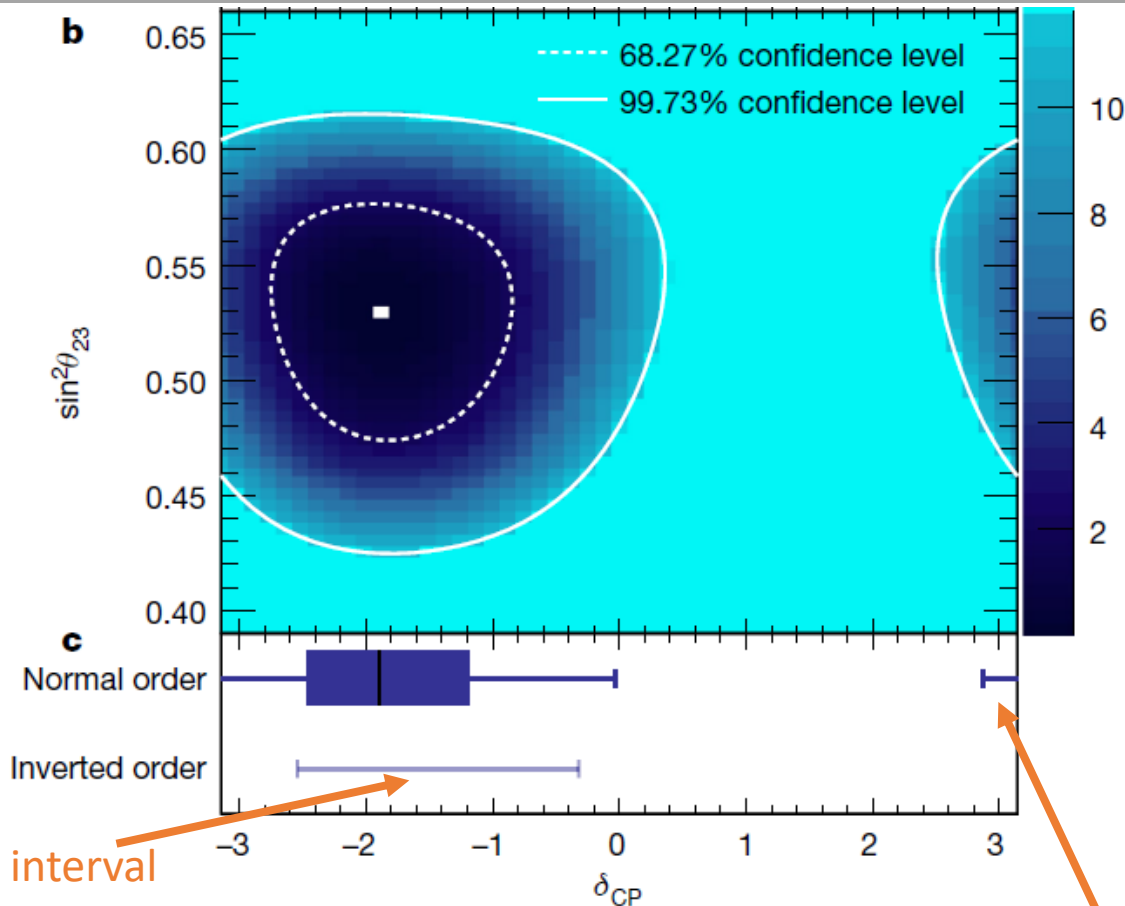


- First 3-sigma confidence interval of δ_{CP} :
 - In normal mass ordering ($m_3 > m_{1,2}$): $[-3.41, -0.03]$
 - In inverted mass ordering ($m_3 < m_{1,2}$): $[-2.54, -0.32]$
 - Favouring maximal CP violation



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$< -\pi$!



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$< -\pi$!

c	1e0de ν -mode	1e0de $\bar{\nu}$ -mode	1e1de ν -mode
$\delta_{\text{CP}} = -\frac{\pi}{2}$ $\nu_\mu \rightarrow \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15

- Systematic uncertainties constrained by near detector fits
 - $\sim 17\% \rightarrow \sim 9\%$ in single lepton samples
 - $\sim 22\% \rightarrow \sim 19\%$ in pion sample
- Largest uncertainties from neutrino interaction models
 - “Largest individual contribution” 7.1% of total 8.8%

Delayed electron = pion
↓


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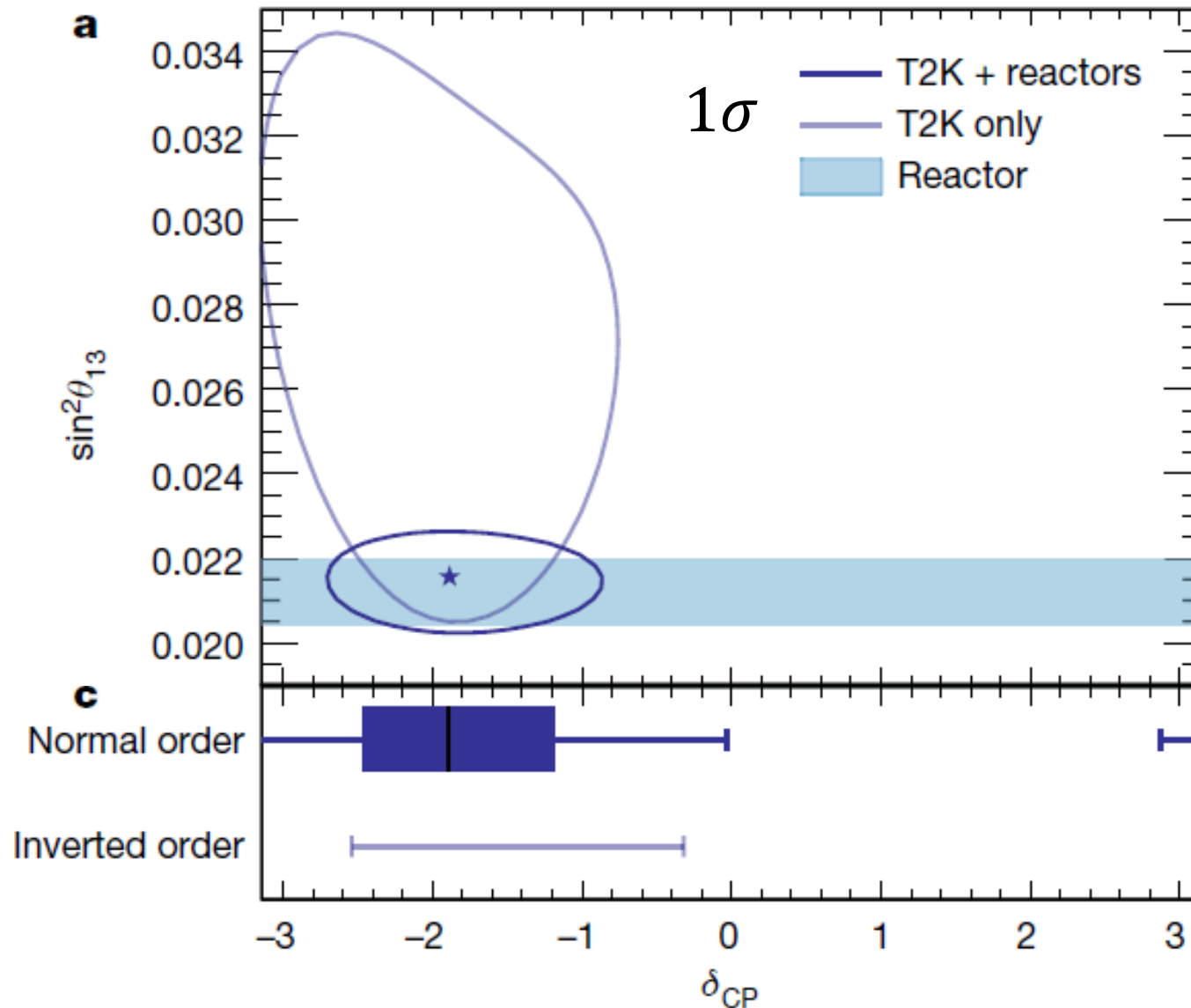
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“The probability of observing an excess over prediction in one of our five samples at least as large as that seen in the electron-like charged pion sample is 6.9%, [...]”



- Result also uses reactor neutrino results as constraint

- The (anti)electron-neutrino appearance probability in a (anti)muon-neutrino beam depends on a CP-violating phase in the PNMS matrix
 - It affects neutrinos and antineutrinos in opposite ways
- T2K was able to exclude a large region of the phase space at the 3-sigma level
 - Result point towards maximal CP violation
 - Slight preference for normal mass ordering
- CP violation in the lepton sector is a necessary building block for explaining the matter dominance via leptogenesis
 - Not a finished explanation, but important input for models

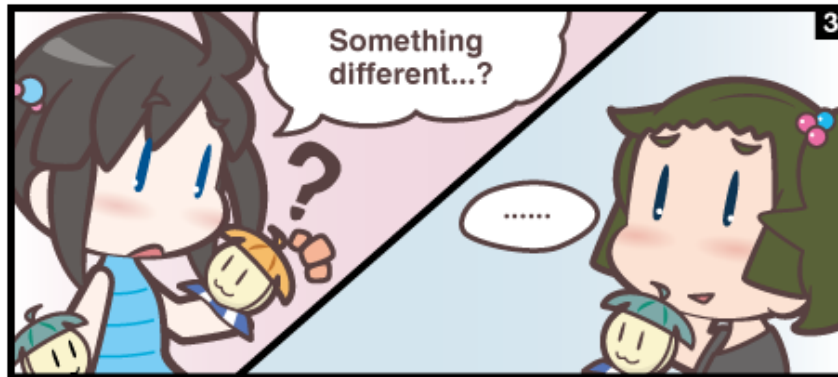
Thank you!



UNIVERSITY OF
OXFORD



T2K



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J-PARC-chan

lives in Tokai-mura, Naka-gun, Ibaraki, Japan.



Super-Kamiokande-chan

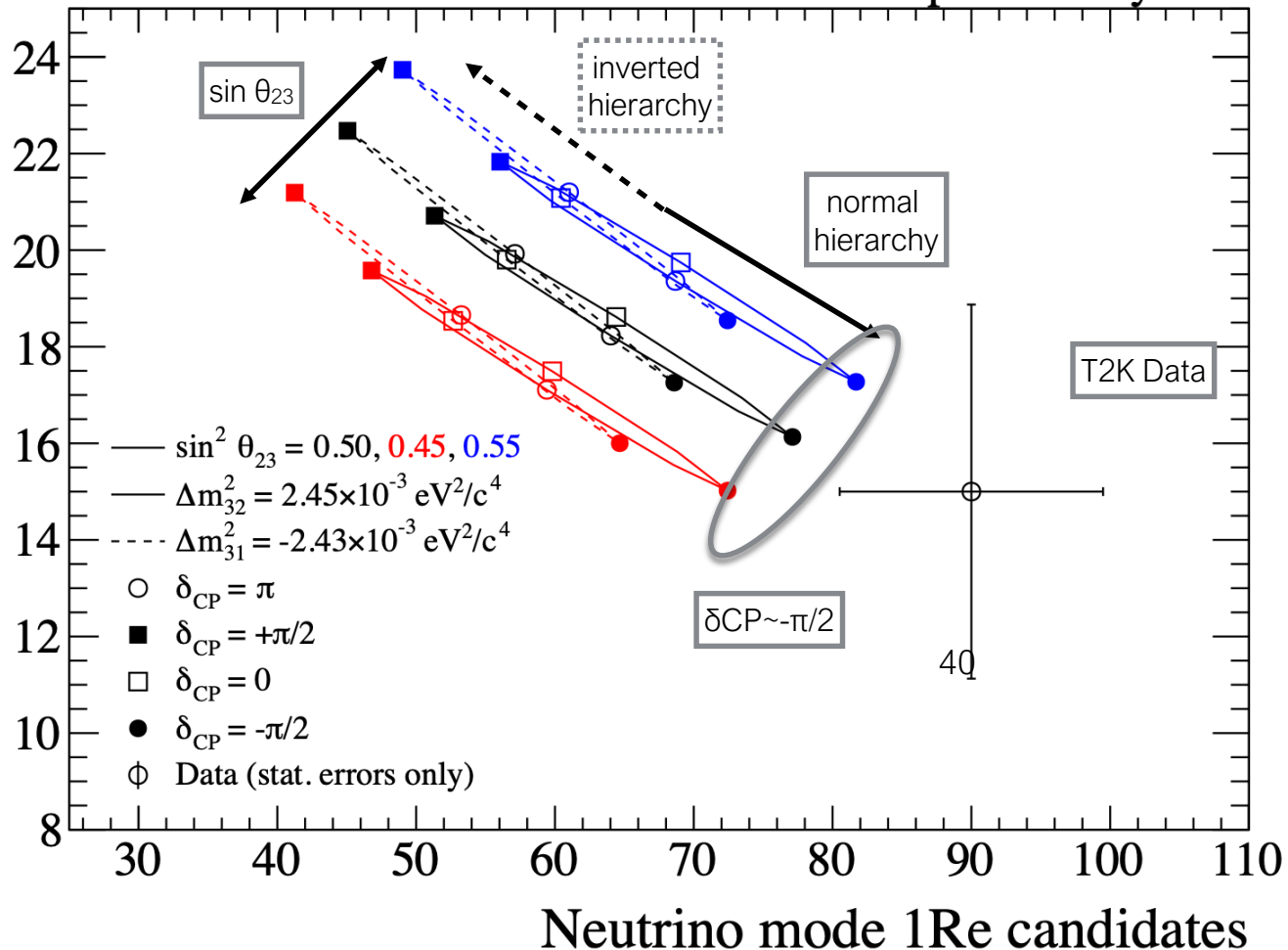
lives in Kamioka-cho, Hida-city, Gifu, Japan.

CP violation phase



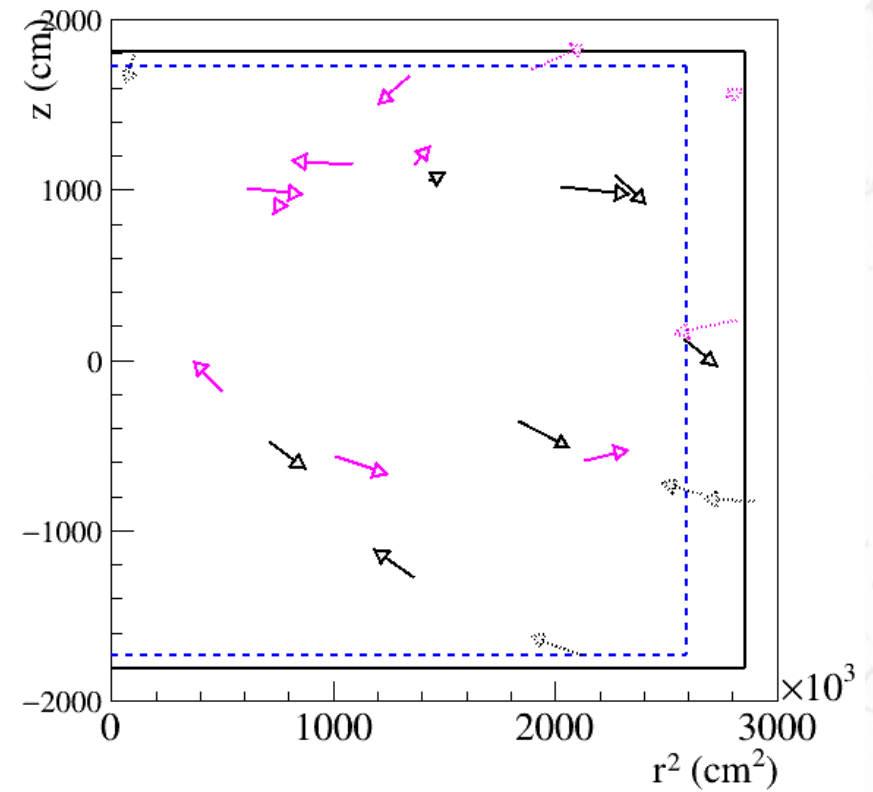
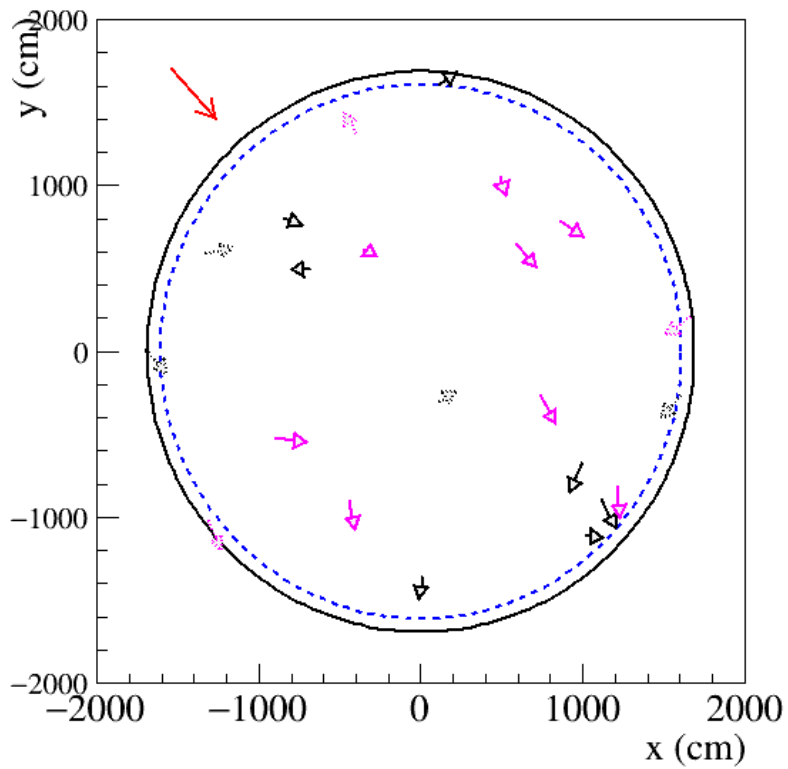
Antineutrino mode 1Re candidates

T2K Run 1-9 preliminary



ν energy dependency is not reflected in this plot

$\bar{\nu}_e$ vertex distribution

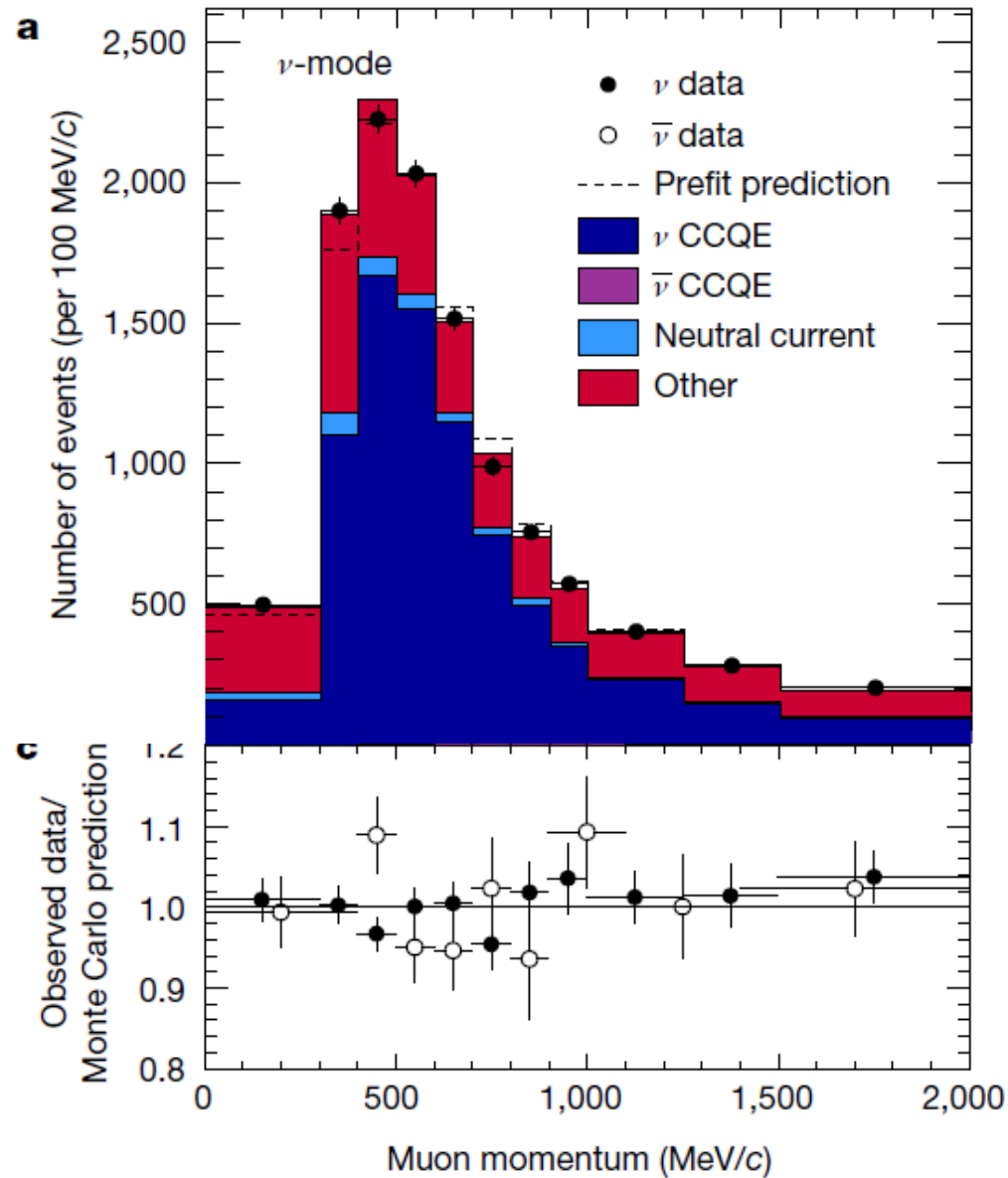


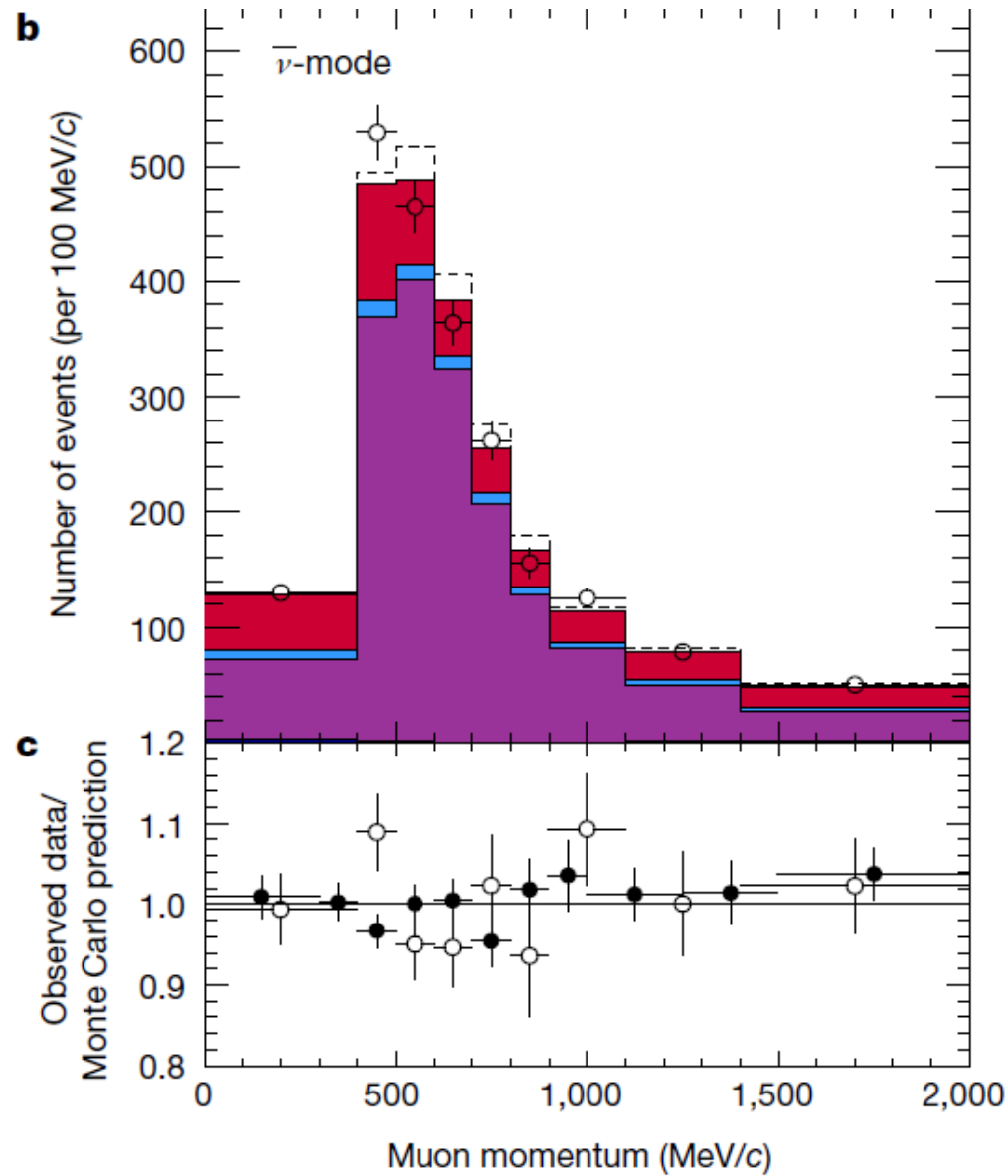
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Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

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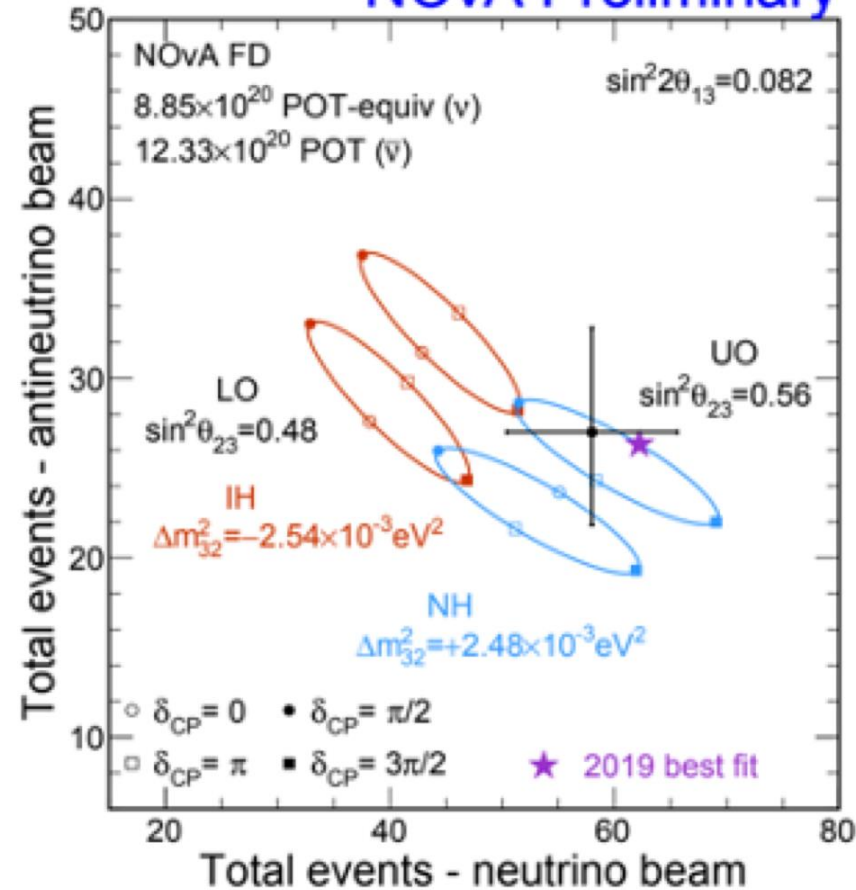




Nova results



NOvA Preliminary



T2K Run 1-9 preliminary

Antineutrino mode 1Re candidates

