The Mirror Crack'd:

Constraining the matter-antimatter asymmetry with T2K

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

+ Summer Update 2020

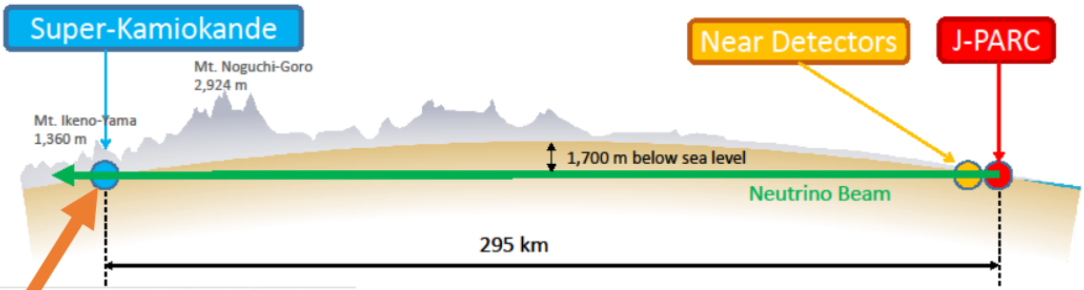
Outline

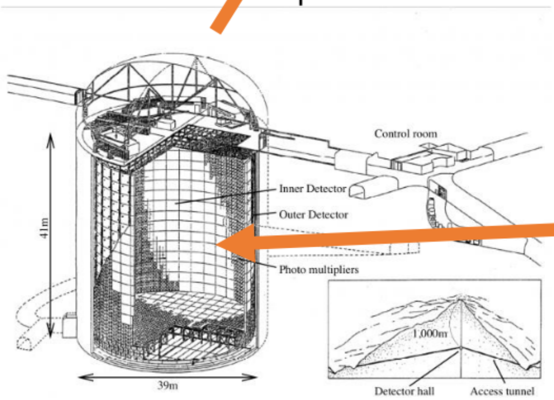
- Introduction to the T2K experiment
- Quick review of neutrino oscillations
- Excursion to matter-antimatter asymmetry
- The CP-violating phase measurement

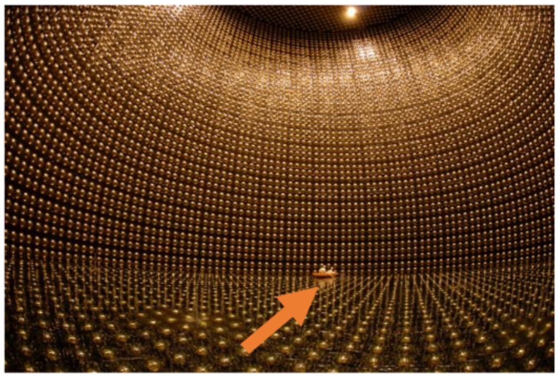
  - Will try to be light on the maths
  - Will borrow slides from Federico Sanchez' CERN seminar talk
  - T2K logo in top right corner

The T2K Experiment

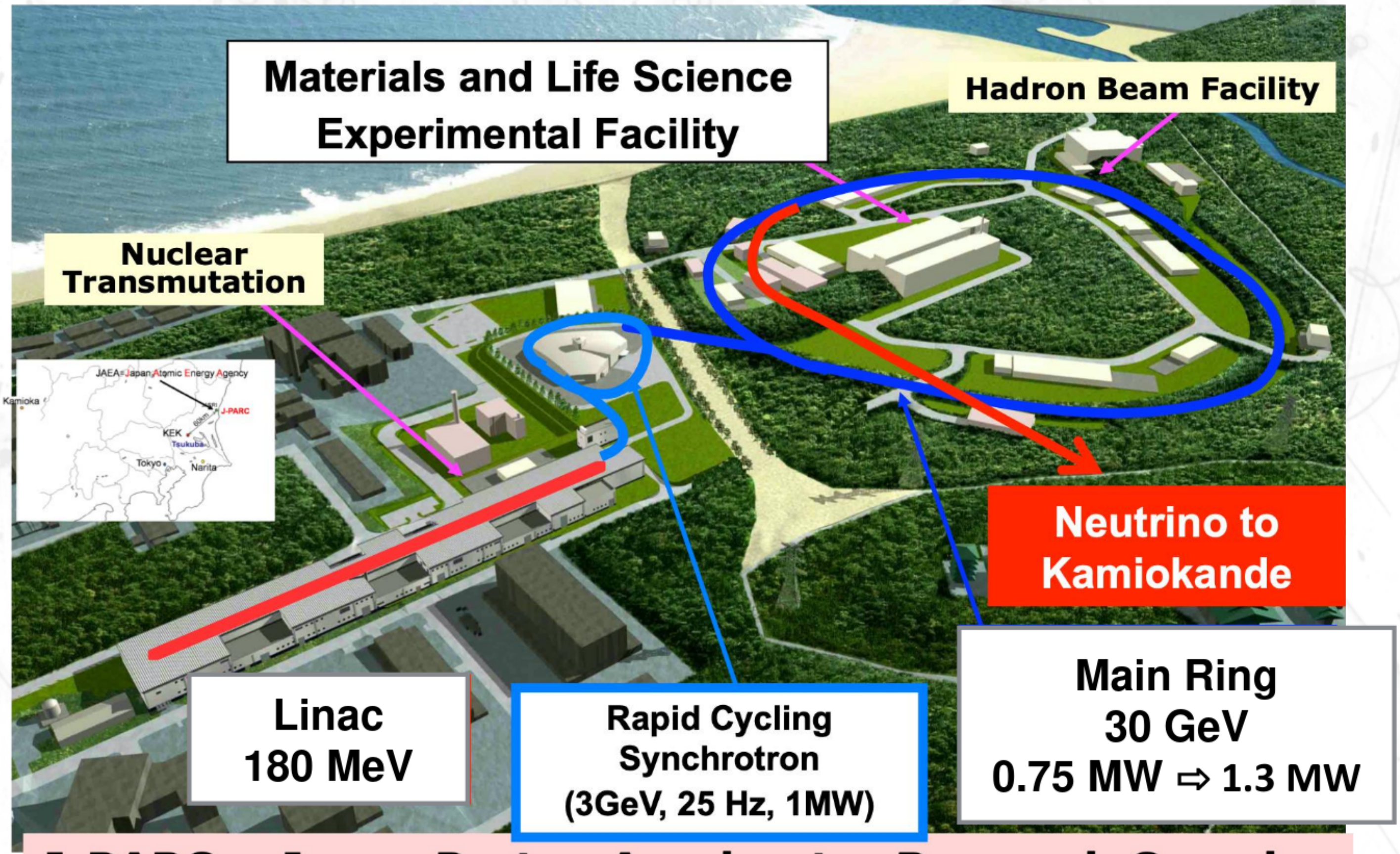
- T2K = Tokai To Kamioka
  - Neutrino beam experiment in Japan
- J-PARC (Tokai) → Super-Kamiokande (Kamioka)







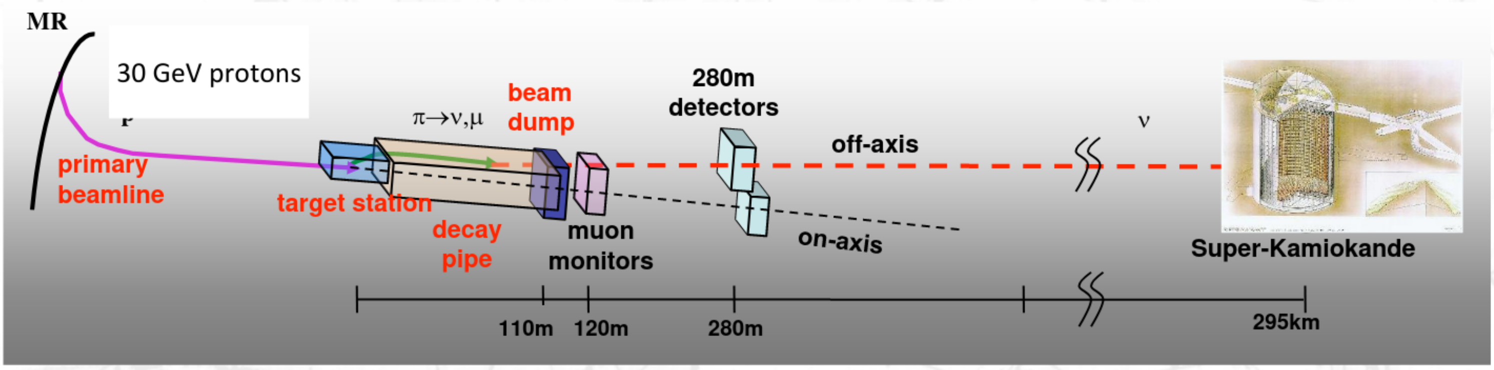
J-PARC



J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA

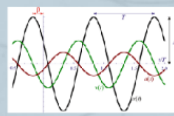
T2K experiment



Neutrinos produced in a particle accelerators or nuclear reactors.

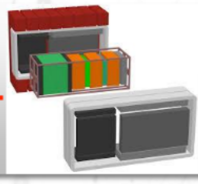
Neutrino flux properties

ν oscillations



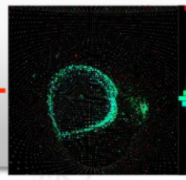
Neutrino flux & flavour

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

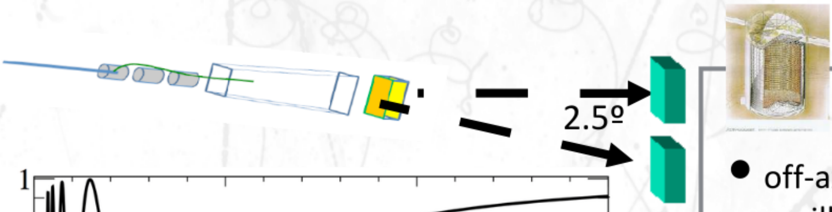


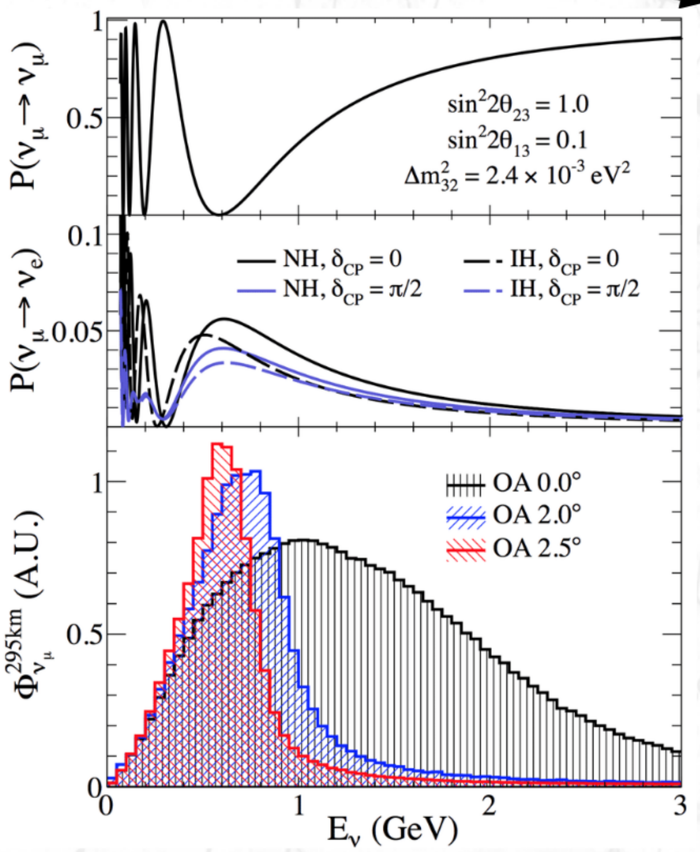
$\nu_e \bar{\nu}_e$

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



Off-axis beam





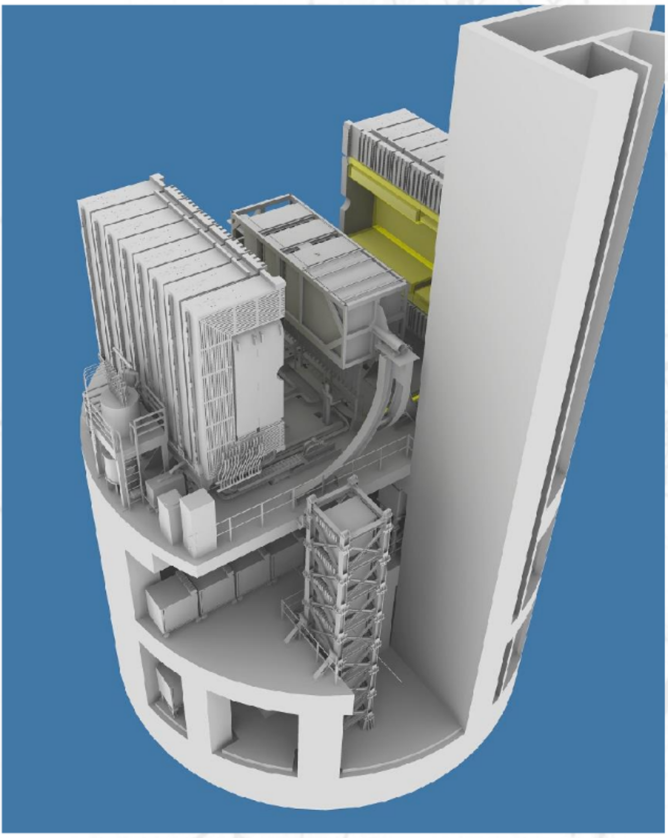
Off-axis

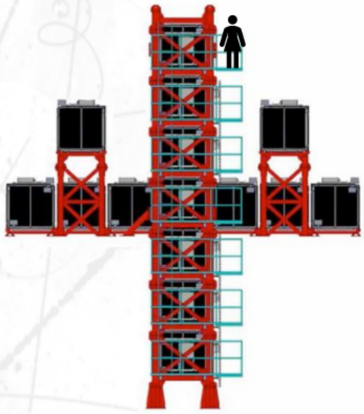
- off-axis optimises the flux at the maximum of the oscillation.
- Only one oscillation maximum can be measured at a fixed distance.
- Narrow beam less dependent on beam uncertainties but more on beam pointing.
- Lower energies achieved.

On-axis

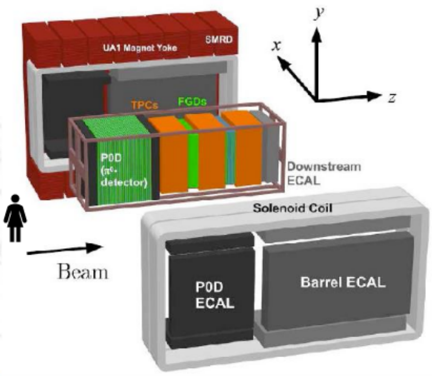
- on-axis optimises the total integrated flux.
- Spectrum with higher neutrino energy (longer oscillation distances)
- If broad enough, more than one oscillation maximum can be measured at a fixed distance.

Near Detector Site

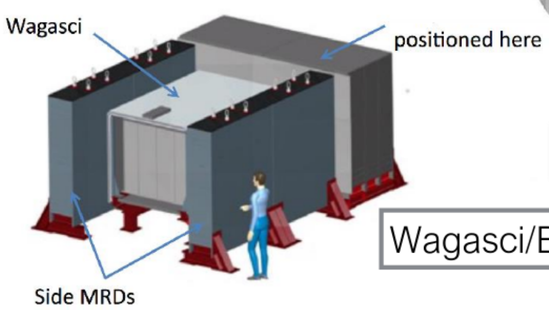




INGRID: On-axis



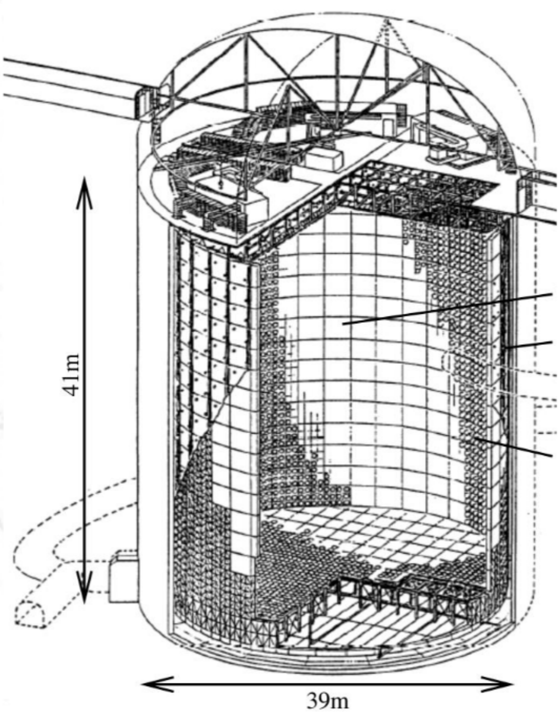
ND280: Off-axis

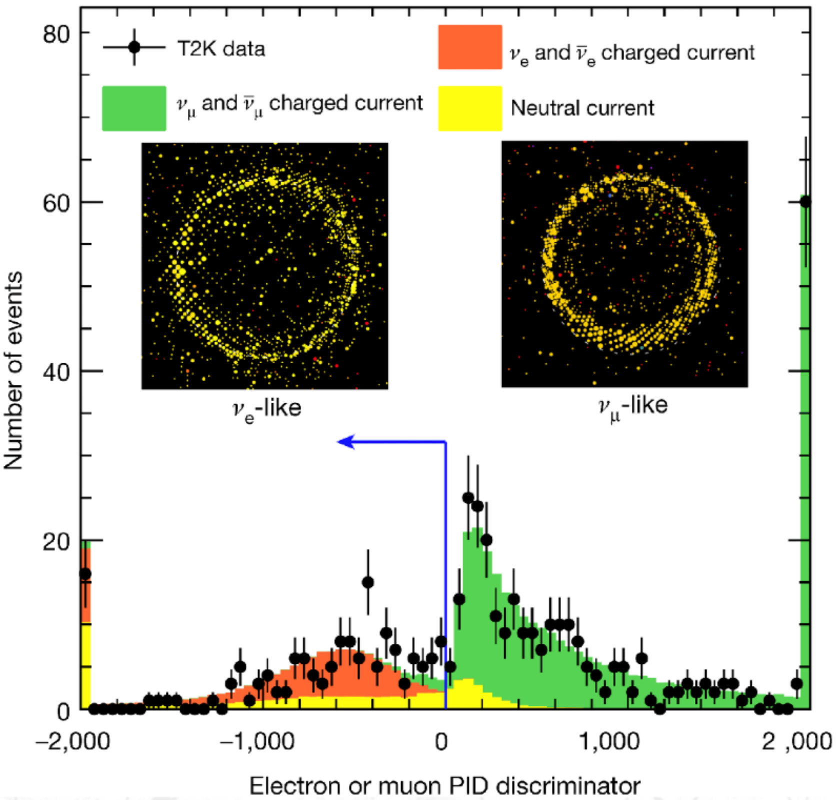


New!

Wagasci/BabyMind: Off-axis

Far detector





Particle identification

Interaction vertex reconstruction

Track Multiplicity

Particle range

Electromagnetic energy reconstruction

Hadronic interactions

Neutrino Oscillations

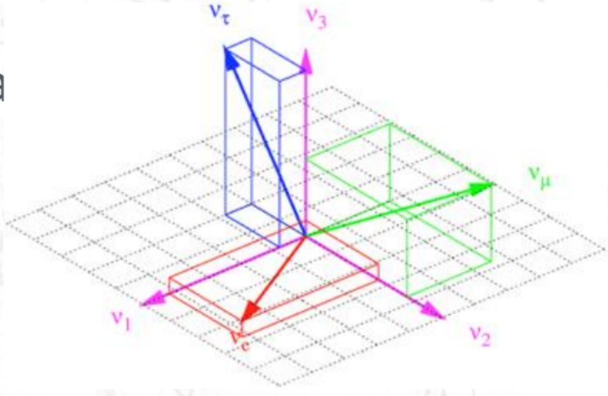
Neutrino oscillations

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

Flavour eigenstates	Lorentz eigenstates
$(\nu_e, \nu_\mu, \nu_\tau)$	(ν_1, ν_2, ν_3)
state of the neutrino interactions	states of the neutrino propagation in space

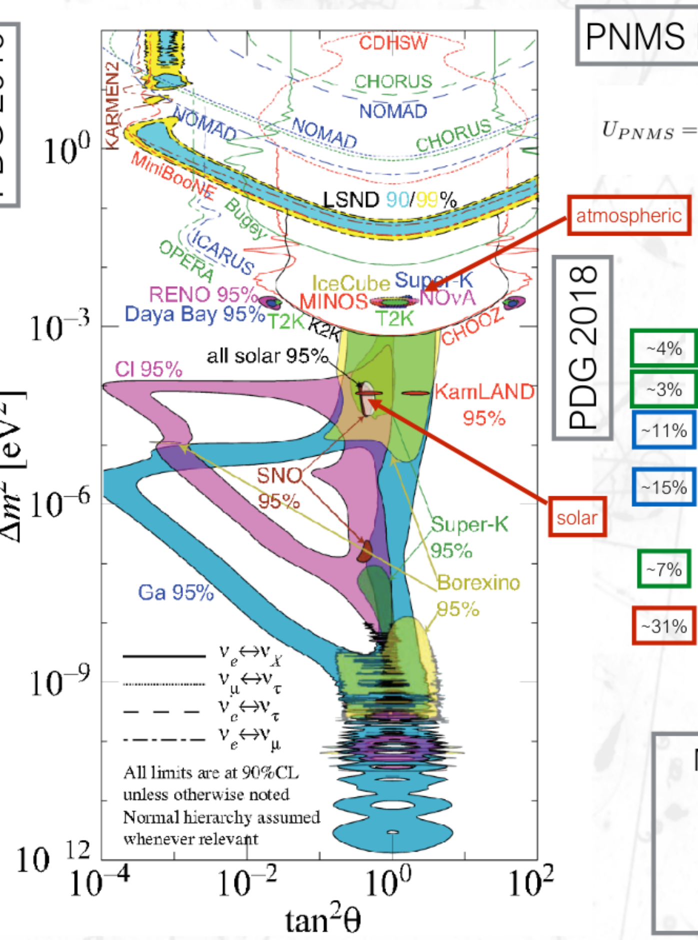
Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$\begin{pmatrix}\nu_e & \nu_\mu & \nu_\tau\end{pmatrix} = U_{PNMS}\begin{pmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{pmatrix}$$



Oscillation parameters

PDG 2016



PNMS Matrix

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

PDG 2018

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

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

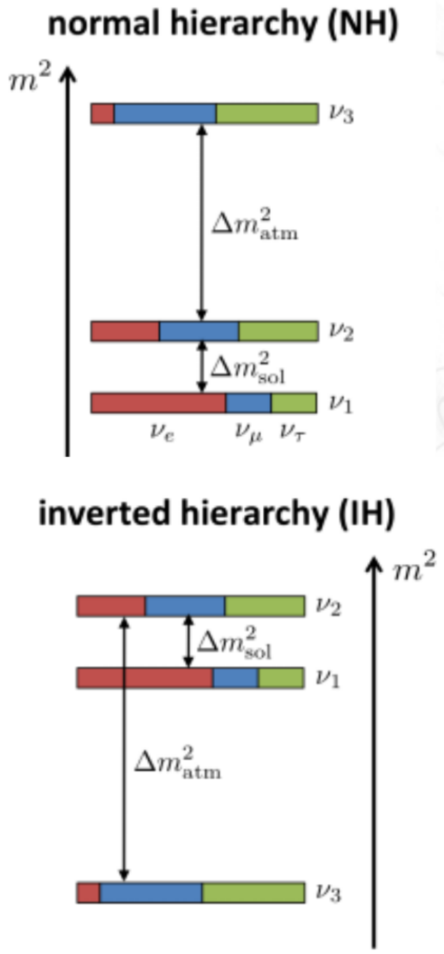
- Oscillations is a quantum interference phenomenon that depends on the (quadratic) mass difference:

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

- Due to matter effects in solar neutrinos we know:

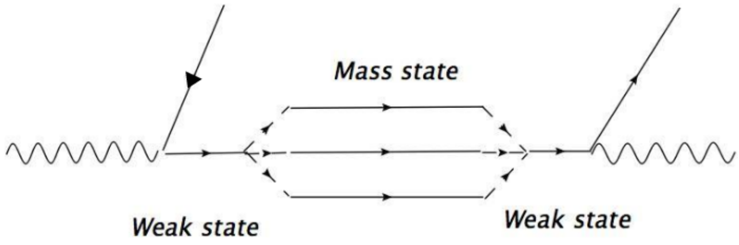
$$\Delta m^2_{12} > 0$$

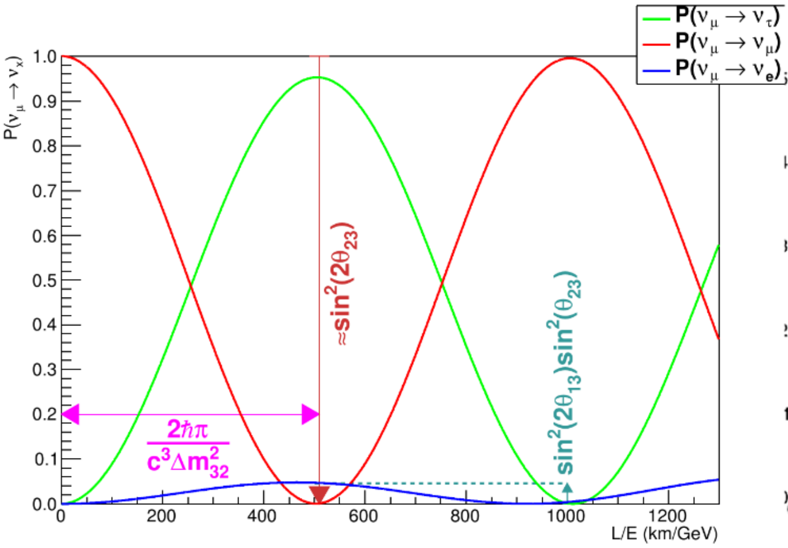
- Hierarchy determines the ordering of the masses. Traditionally:
    - Normal: $m_1 < m_2 < m_3$
    - Inverted: $m_3 < m_1 < m_2$

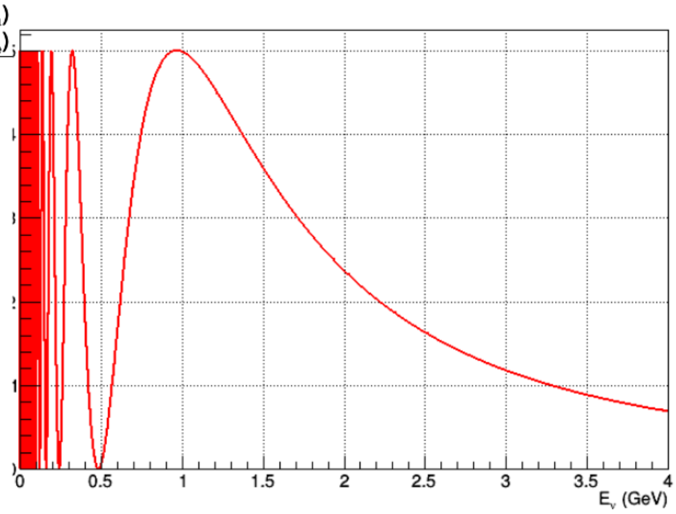


Neutrino oscillations

- 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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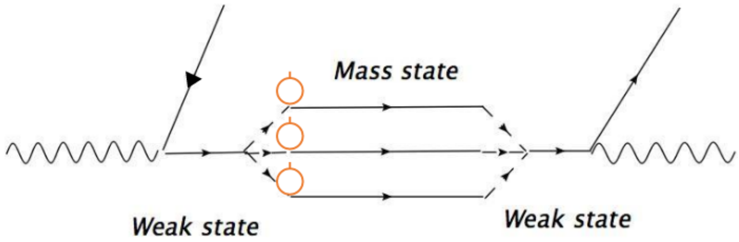

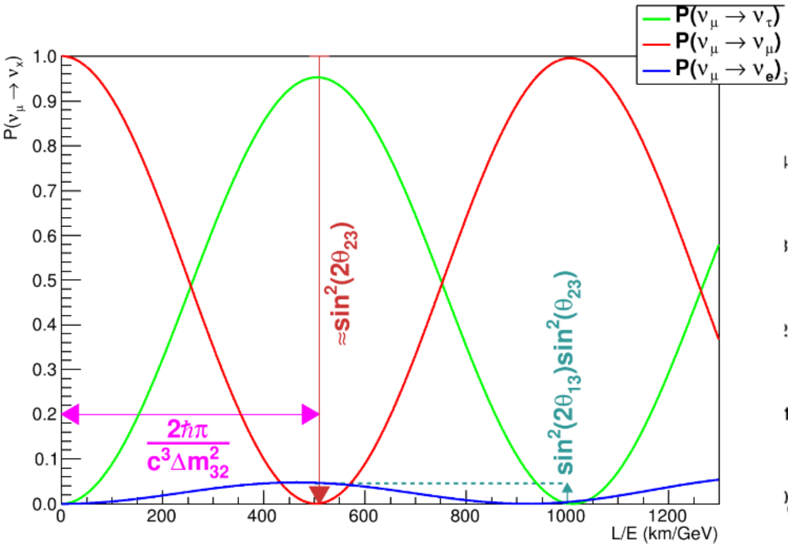

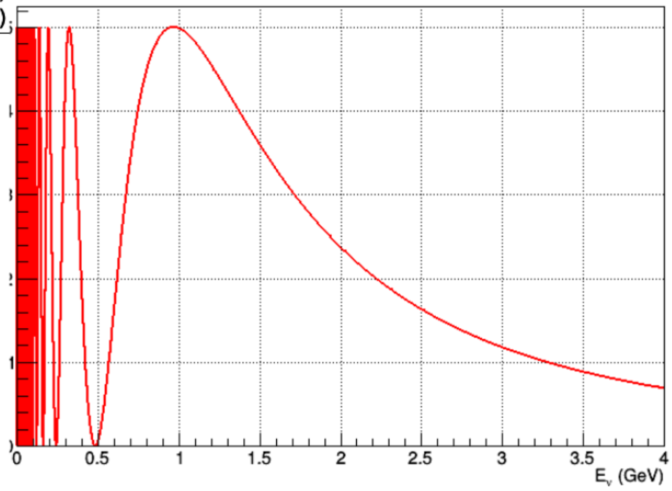

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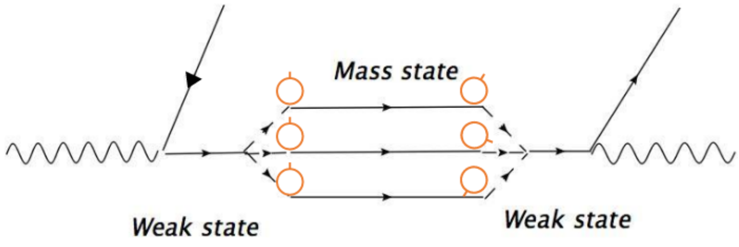
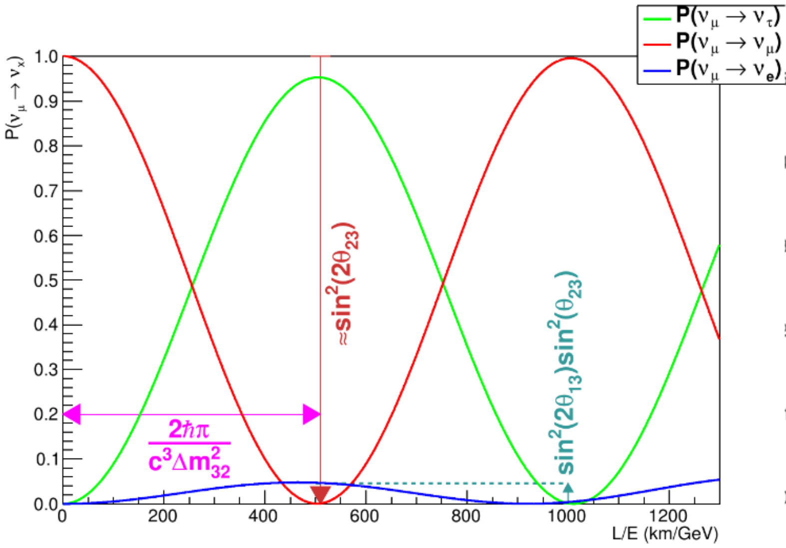
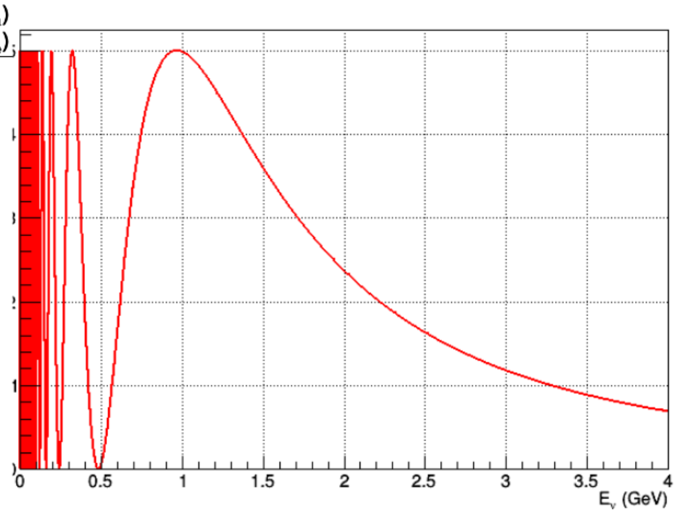
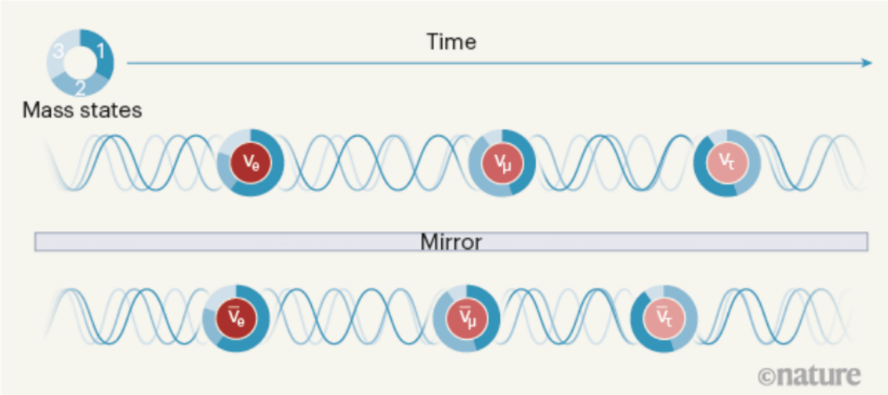






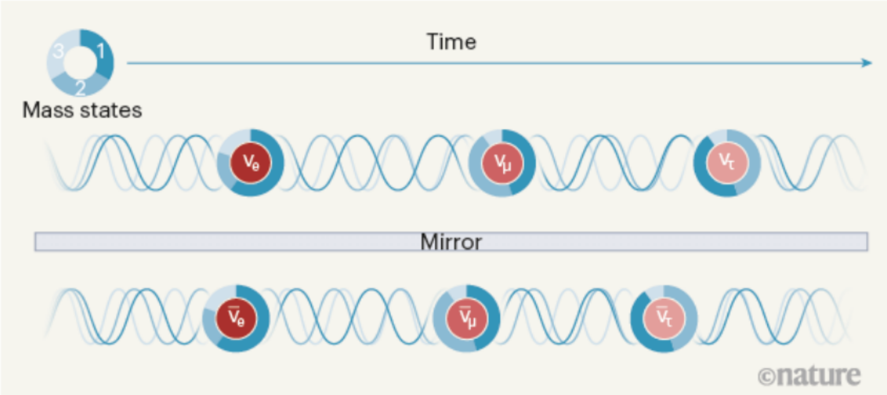
CP Asymmetry



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

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right) \mp \frac{1.27\Delta m^2_{21}L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right) \quad (2)$$

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



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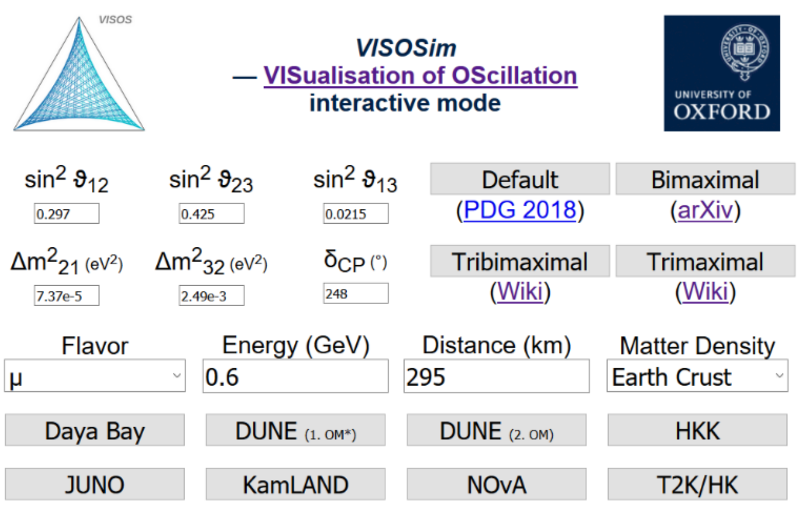
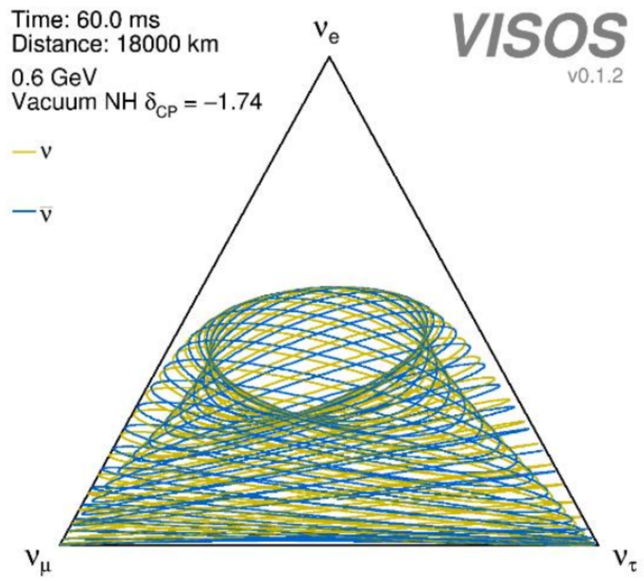
OIY (Oscillate It Yourself)

- 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/





CP Violation and the Matter-Antimatter Asymmetry

CP violation

- 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

CP violation

- 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):

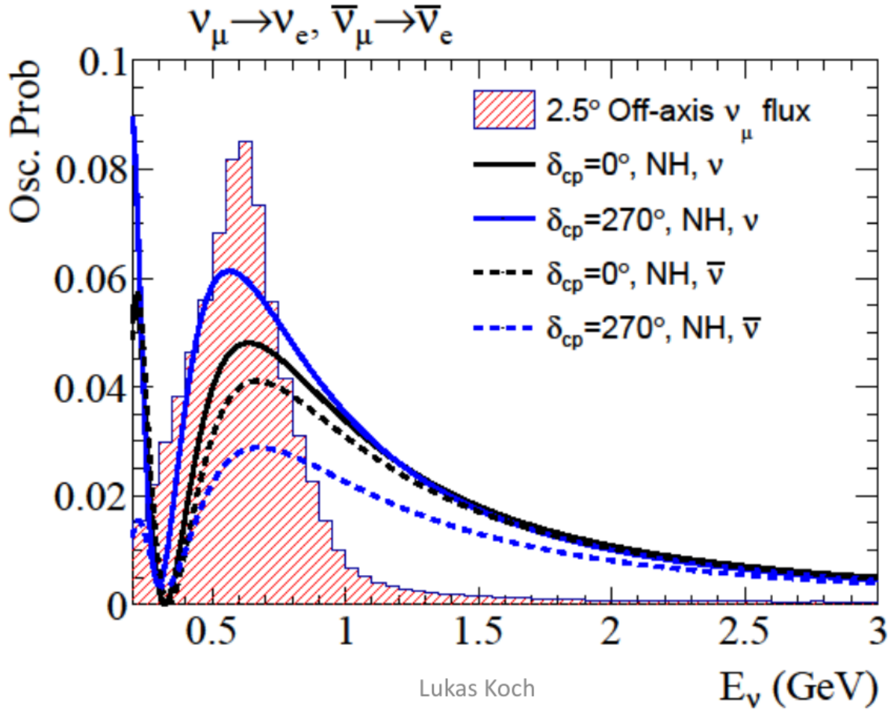
$$J_{\mathrm{CP,l}} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{\mathrm{CP}} \approx 0.033\sin\delta_{\mathrm{CP}} \quad (1)$$

  - In quark sector (CKM matrix): $(J_{\mathrm{CP},q} = 3\times10^{-5})$
- CP violation is a necessary condition, not sufficient
  - Still need beyond standard model processes for other Sakharov conditions

T2K's δ_{CP} Measurement

Principle

- 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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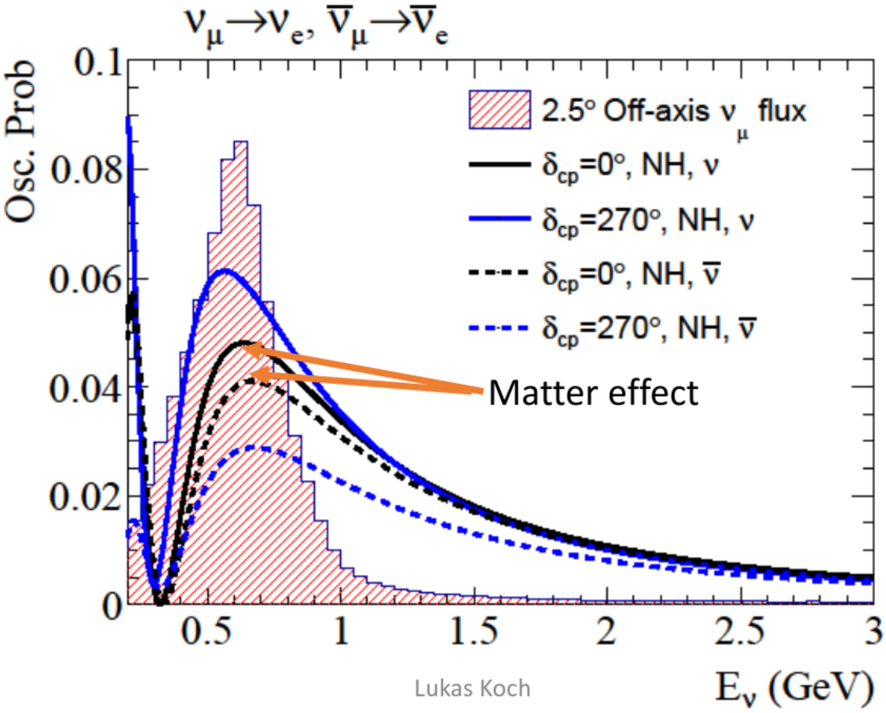

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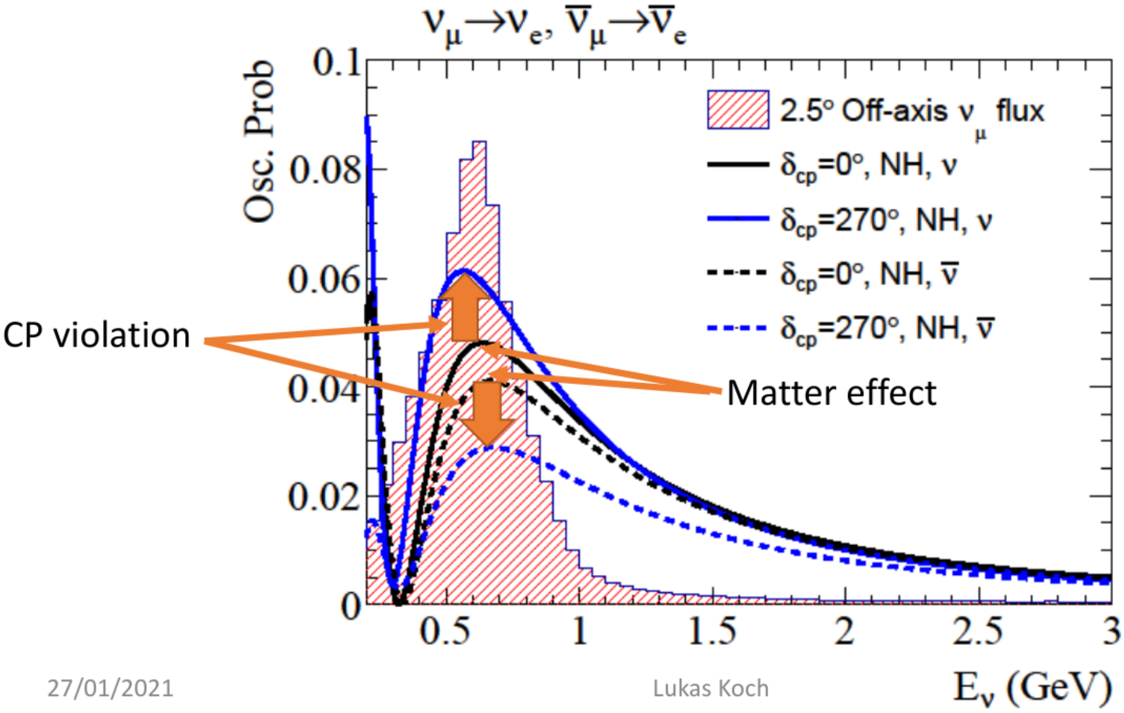
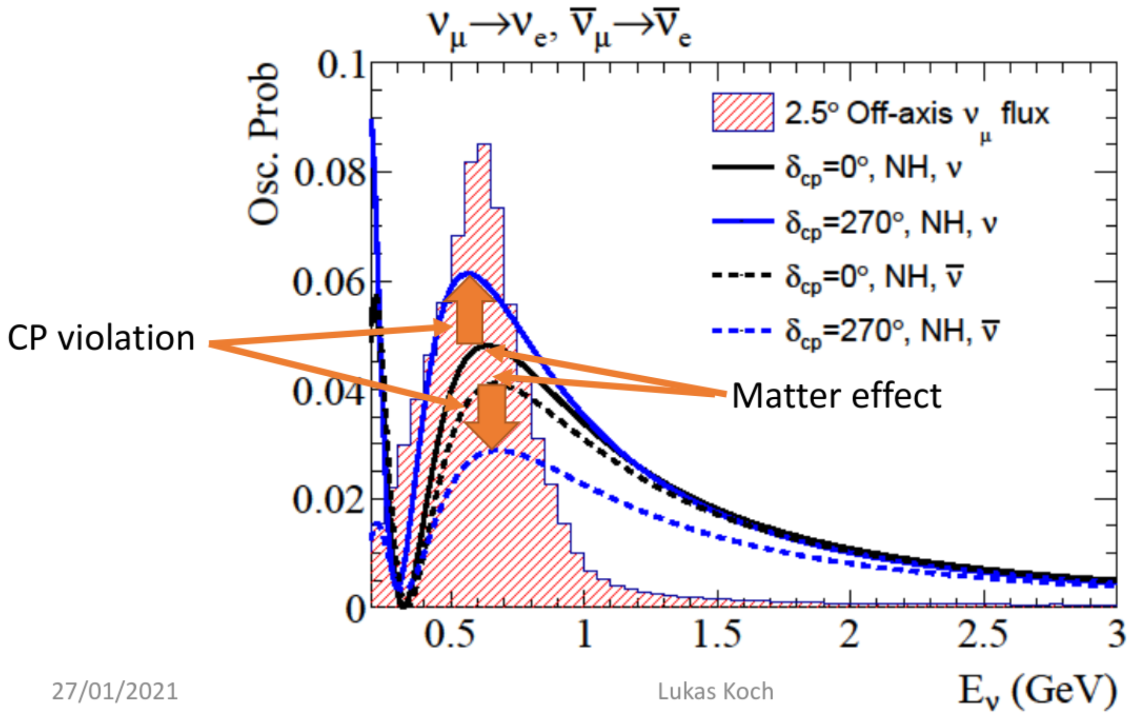


Principle

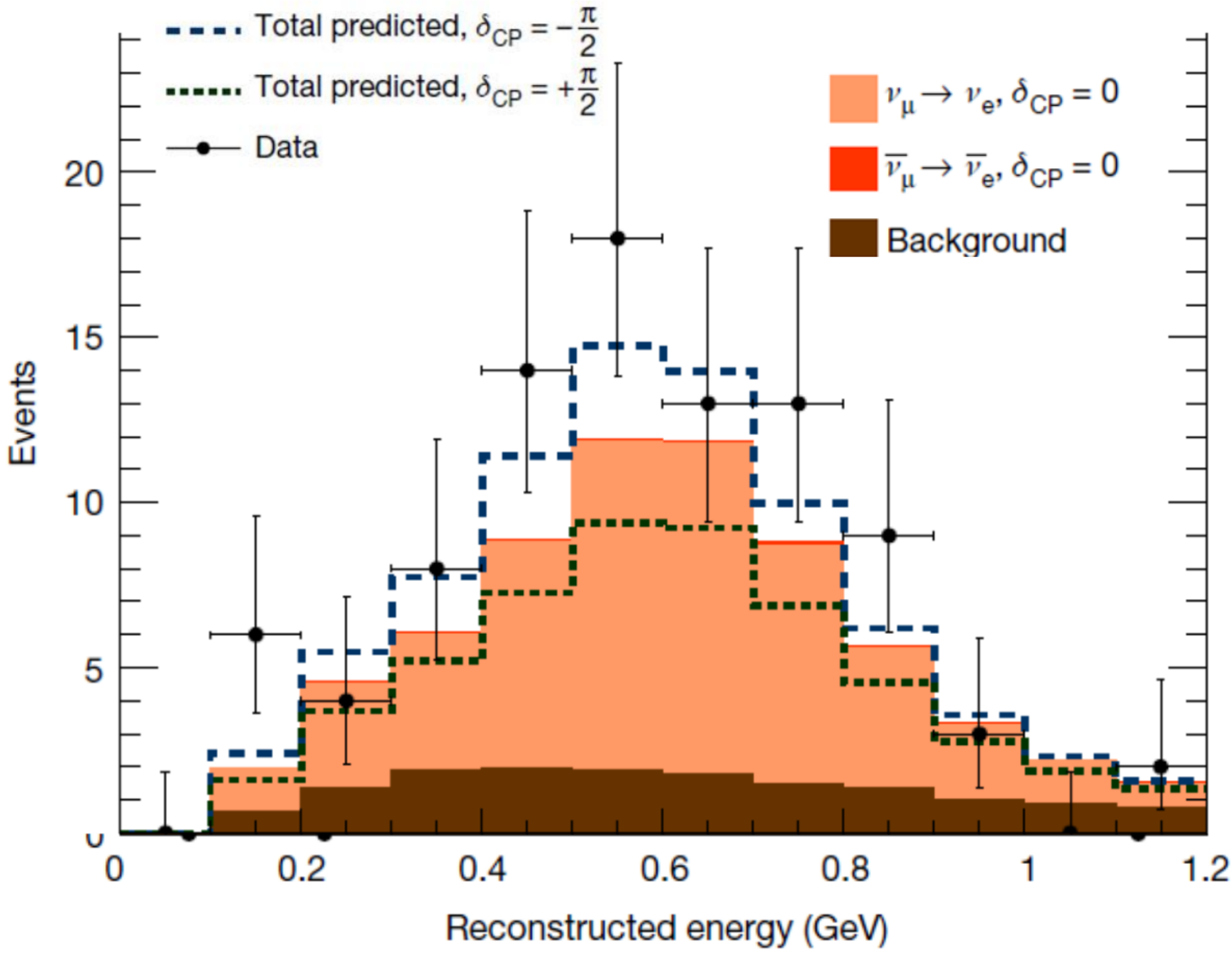
Summer Update 2020

- Count electron-
  - Both in neutrino and antineutrino beam mode
  - Data analysed here taken between 2009 and ~~2018~~ **2019**

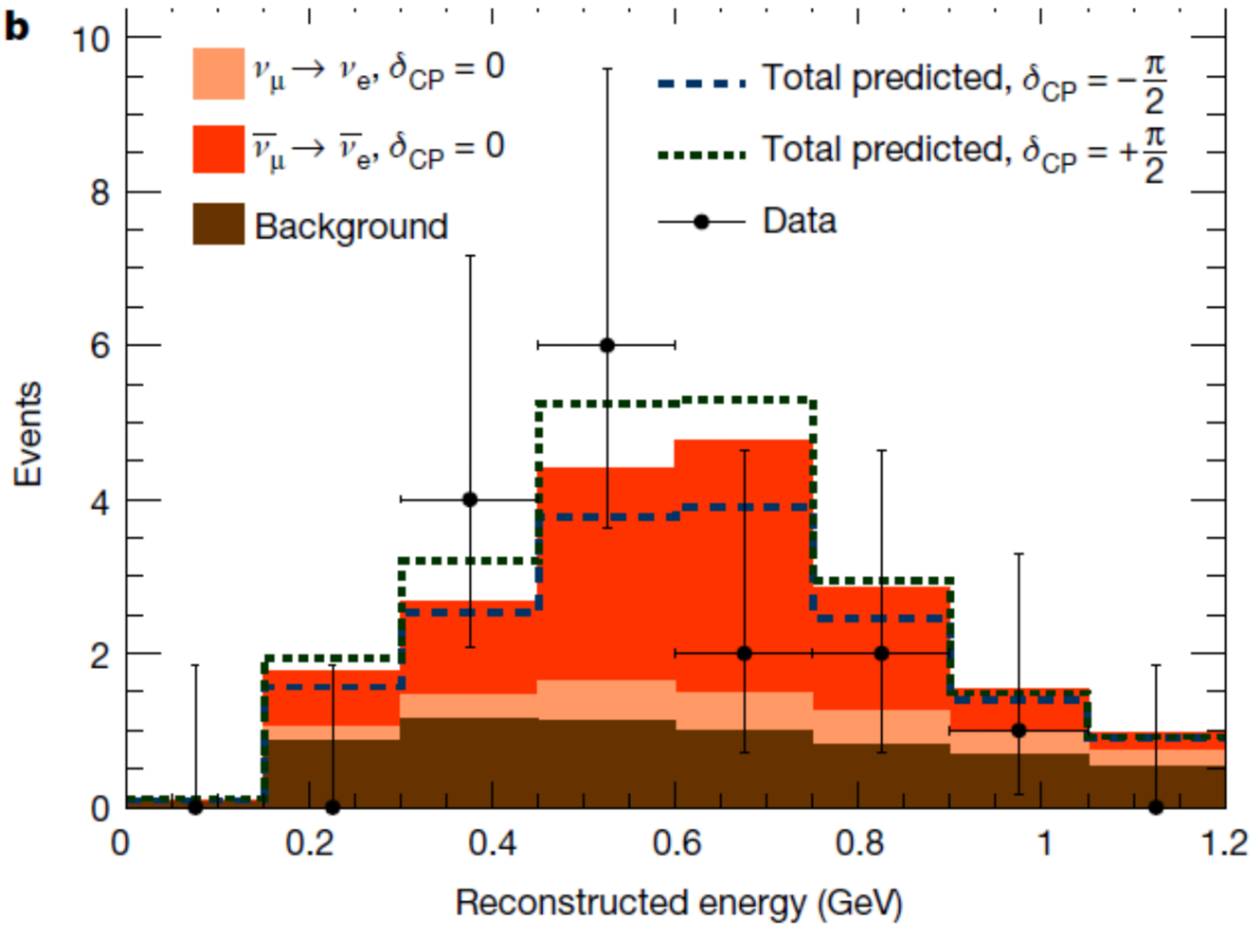
    32% increase of nu-mode data
- Compare with model expectations
  - Exclude parameter space that is incompatible with data



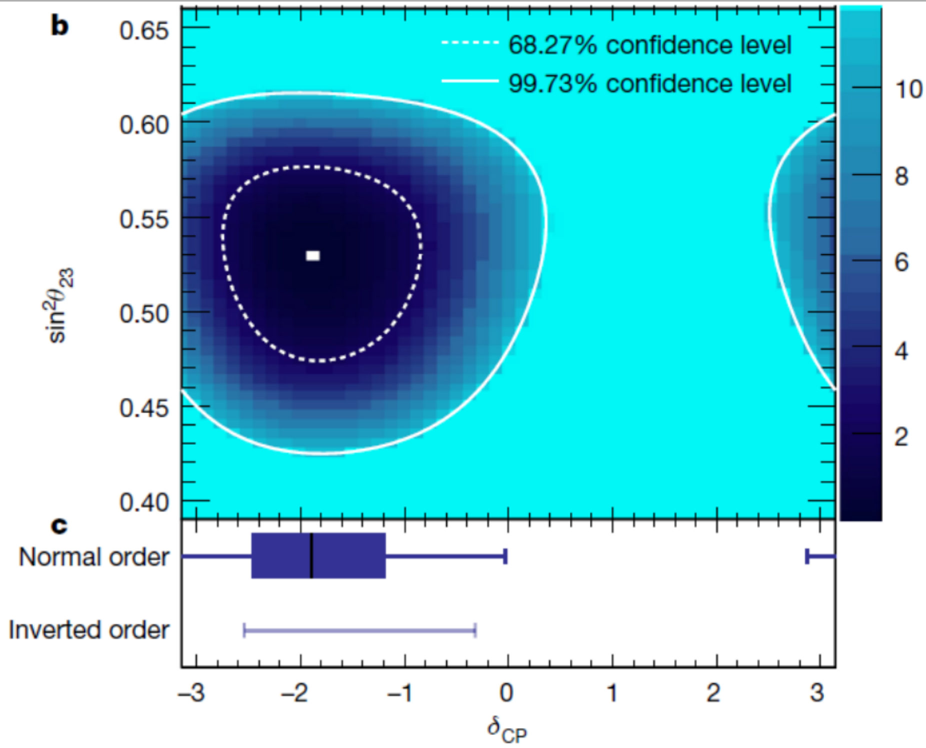
SK $\nu_e/\bar{\nu}_e$ candidates, neutrino mode



SK $\nu_e/\bar{\nu}_e$ candidates, antineutrino md.

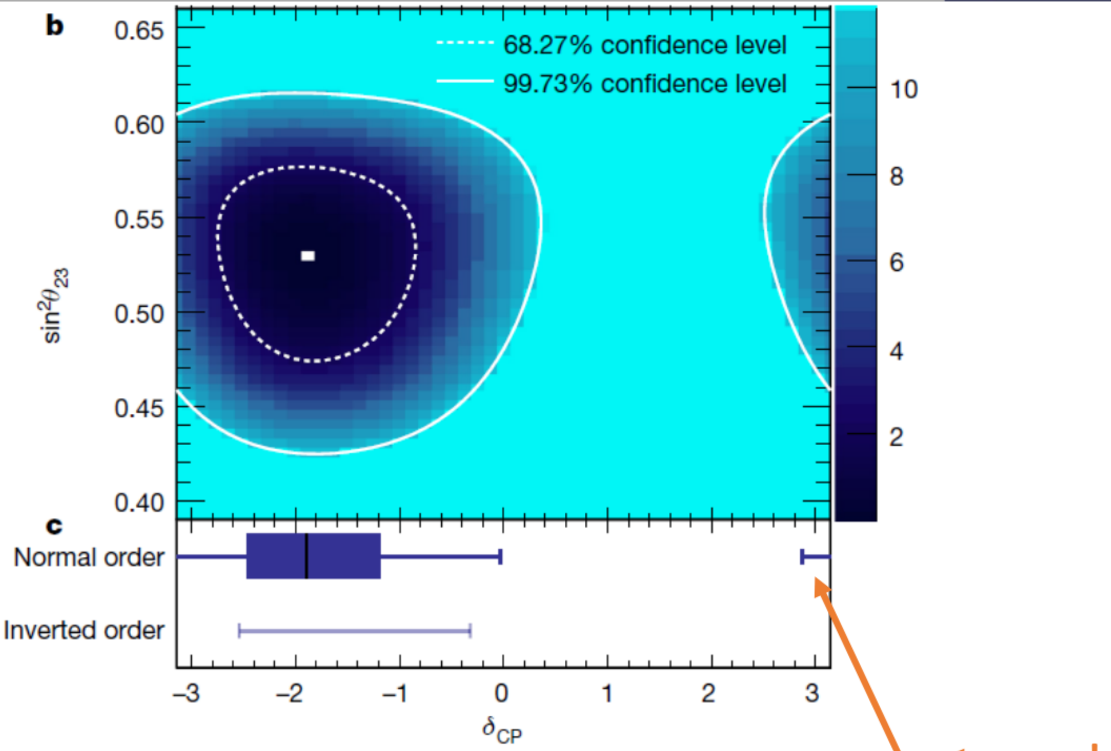


Result



- 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

Result



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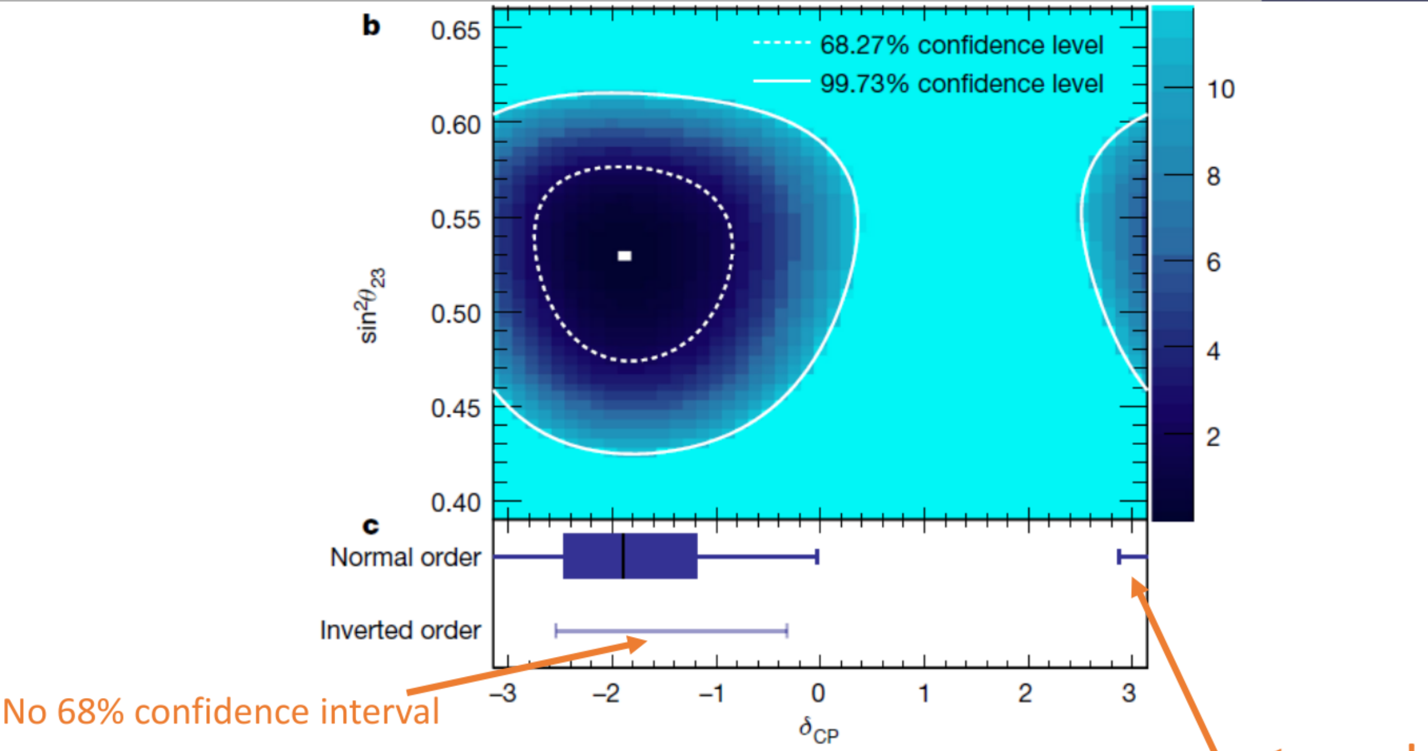

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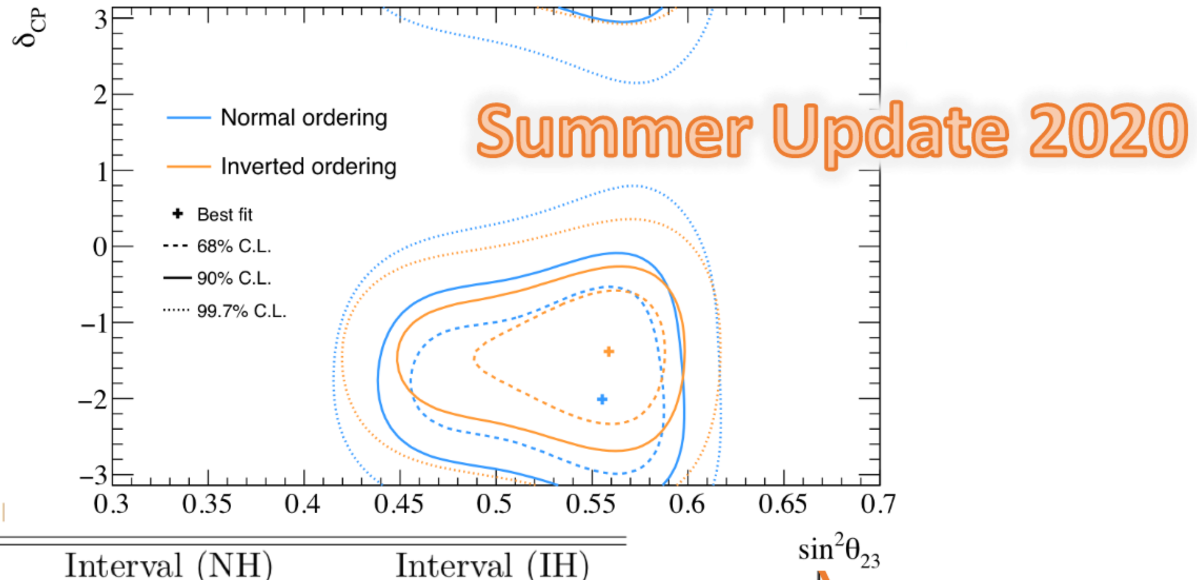

Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.66, -0.97]$	
90%	$[-3.00, -0.49]$	$[-1.79, -1.09]$
2σ	$[-\pi, -0.26] \cup [3.11, \pi]$	$[-2.20, -0.75]$
3σ	$[-\pi, 0.32] \cup [2.63, \pi]$	$[-2.82, -0.14]$

$< -\pi$!

δ_{CP}:

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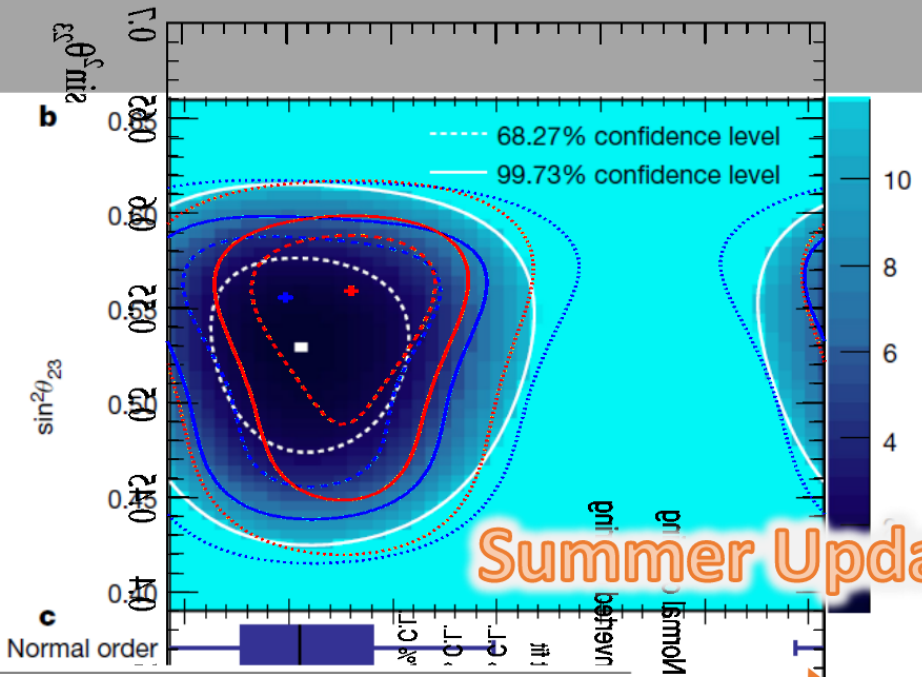

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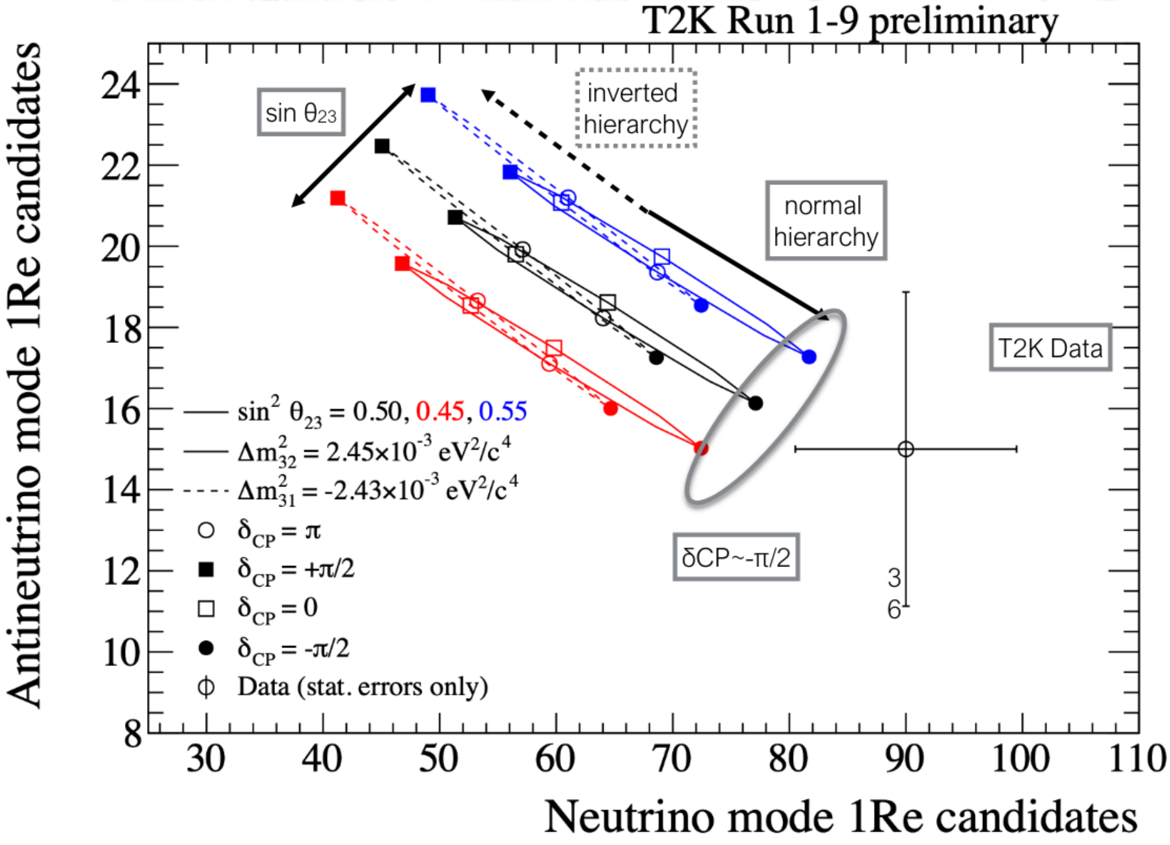
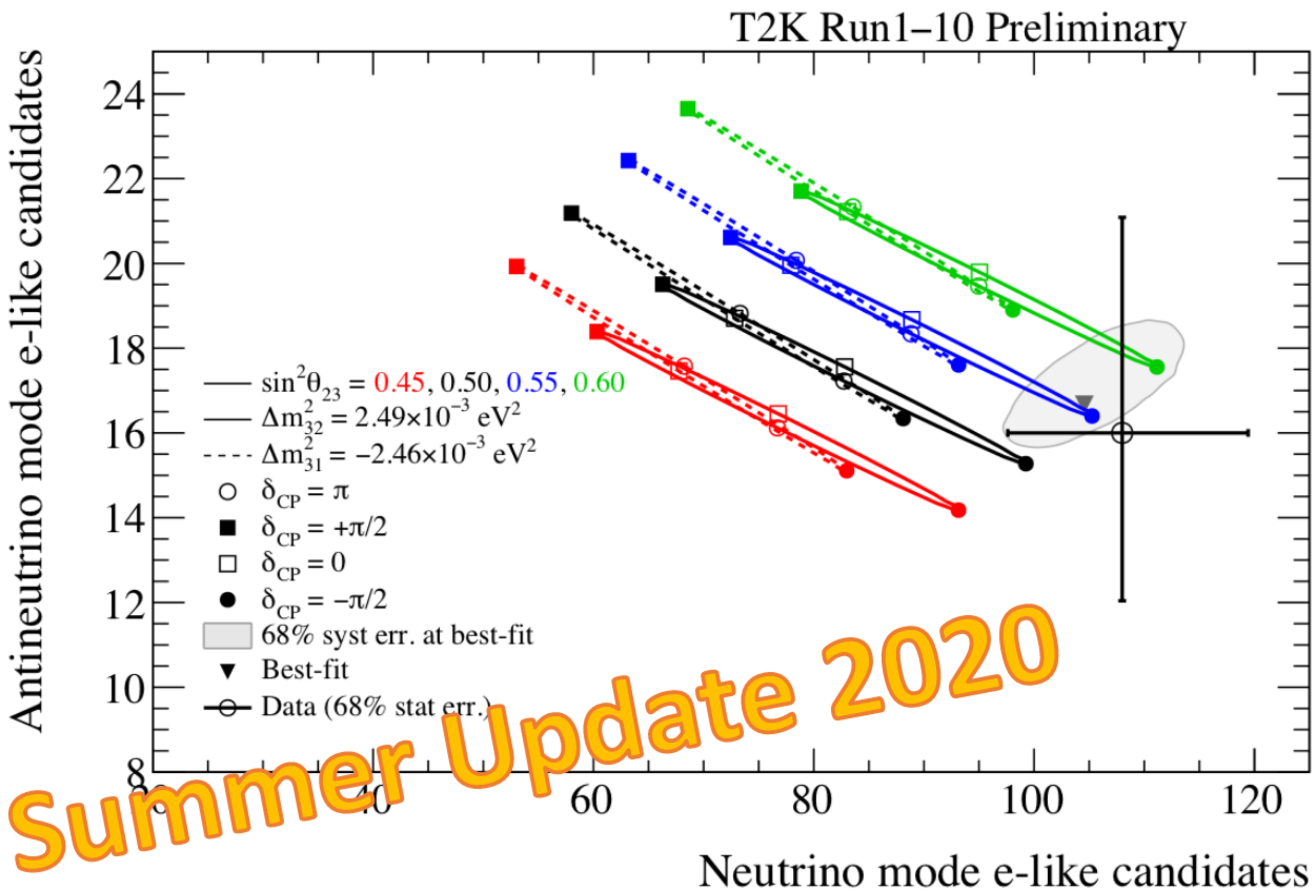


ν energy dependency is not reflected in this plot



ν energy dependency is not reflected in this plot

$\nu_e/\bar{\nu}_e$ samples overview

c		1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\delta_{CP} = -\frac{\pi}{2}$	$\nu_\mu \to \nu_e$	59.0	3.0	5.4
	$\bar{\nu}_\mu \to \bar{\nu}_e$	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
  - ~17% → ~9% in single lepton samples
  - ~22% → ~19% in pion sample
- Largest uncertainties from neutrino interaction models
  - “Largest individual contribution” 7.1% of total 8.8%

$\nu_e/\bar{\nu}_e$ samples overview

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Delayed electron = pion

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	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Data
FHC 1Rμ	346.61	345.90	346.57	347.38	318
RHC 1Rμ	135.80	135.45	135.81	136.19	137
FHC 1Re	96.55	81.59	66.89	81.85	94
RHC 1Re	16.56	18.81	20.75	18.49	16
FHC 1R ν_e CC1π^+	9.30	8.10	6.59	7.79	14
FHC 1Rμ ($E_{rec} < 1.2\,\mathrm{GeV}$)	209.14	208.80	209.11	209.57	191
RHC 1Rμ ($E_{rec} < 1.2\,\mathrm{GeV}$)	68.09	67.90	68.09	68.30	71

Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	[illegible]	18.4%
Data	[illegible]	15	15

Improved SK calibration and eventer processing

Summer Update 2020

"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%, […]"

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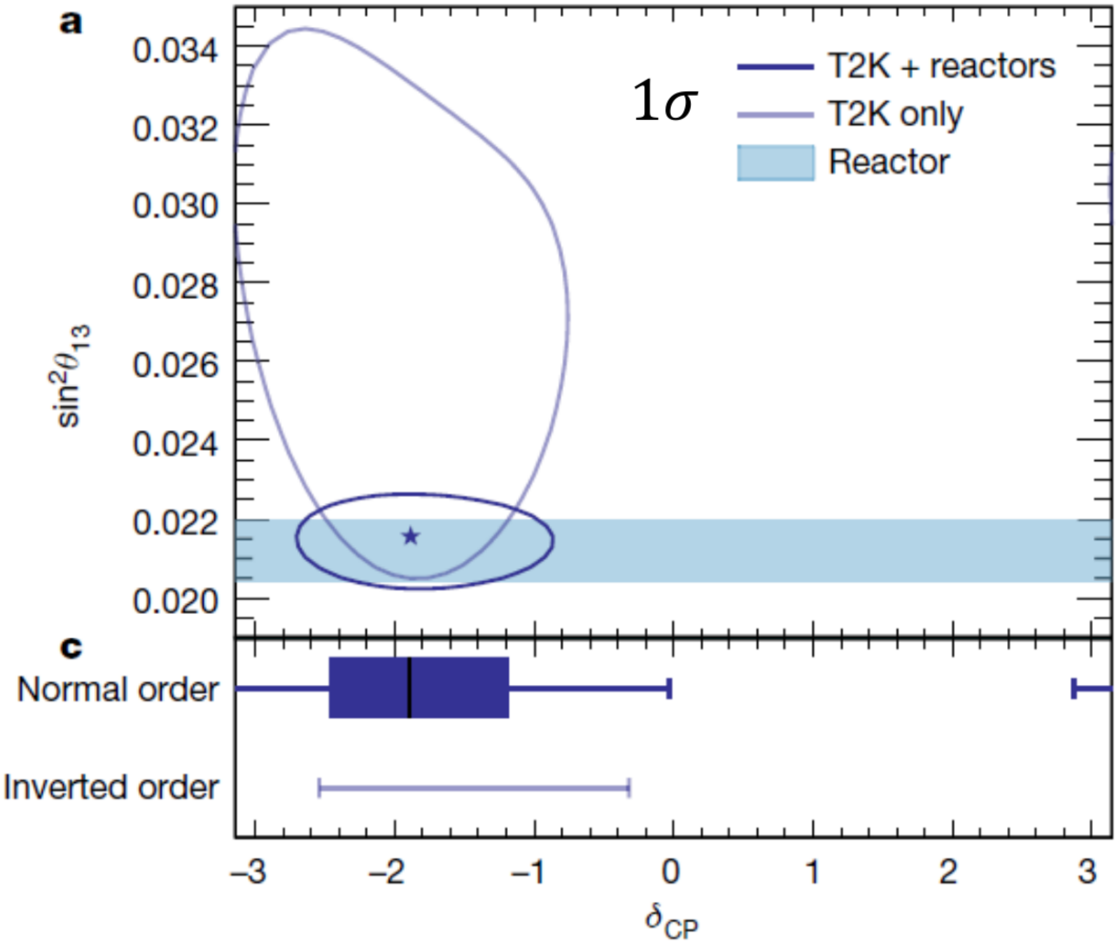
Reactor constraint



- Result also uses reactor neutrino results as constraint

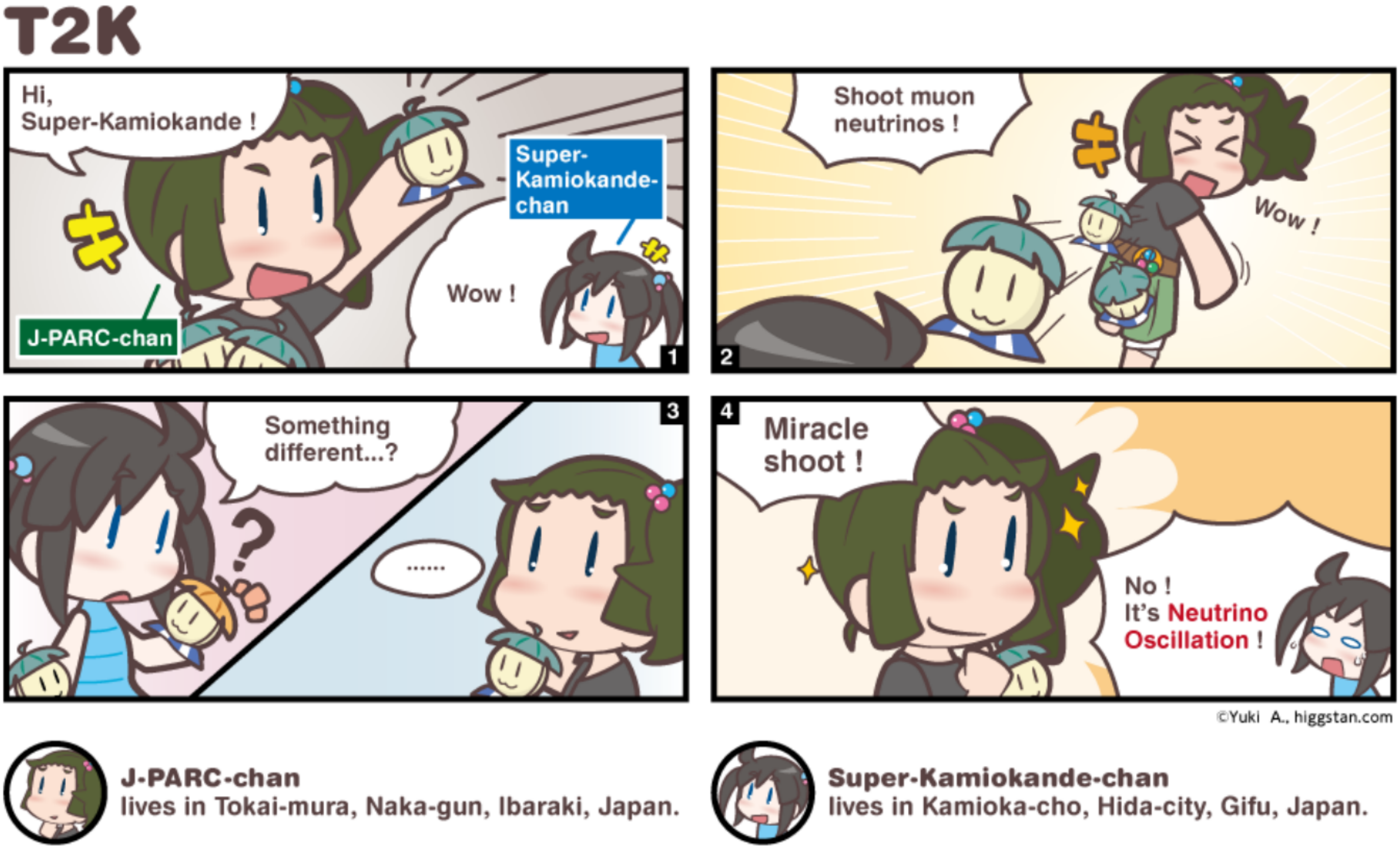
Summary

- 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
  - Summer 2020 update yields slightly wider confidence regions
- 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

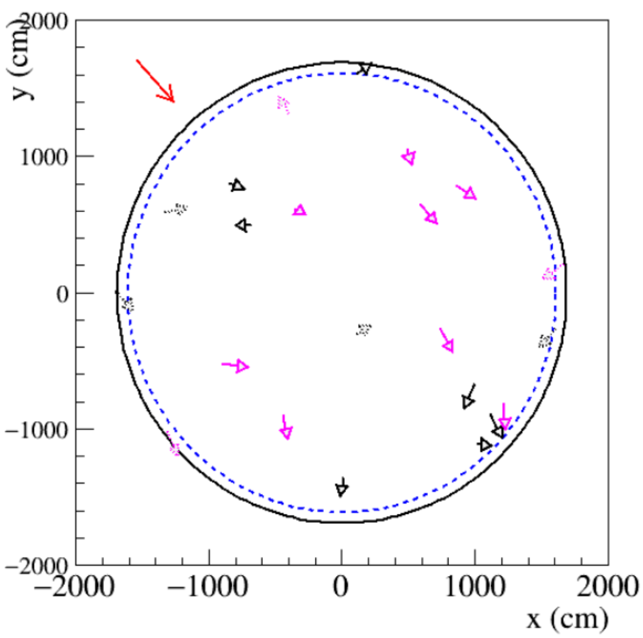
Thank you!

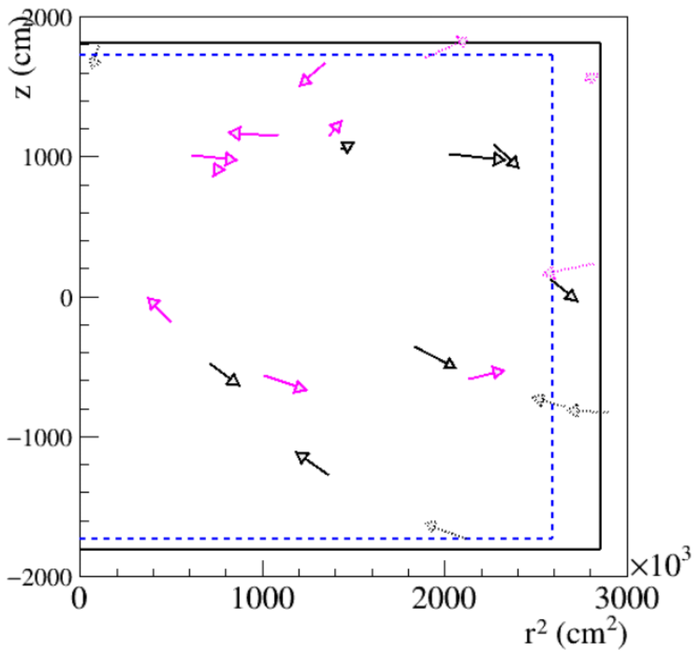
Thank you!

http://higgstan.com/4koma-t2k/



$\bar{\nu}_e$ vertex distribution





Systematic uncertainties

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- Constrained by near detector fits
  - 13% - 17% → 4% - 9% in single lepton samples
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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

Systematic uncertainties

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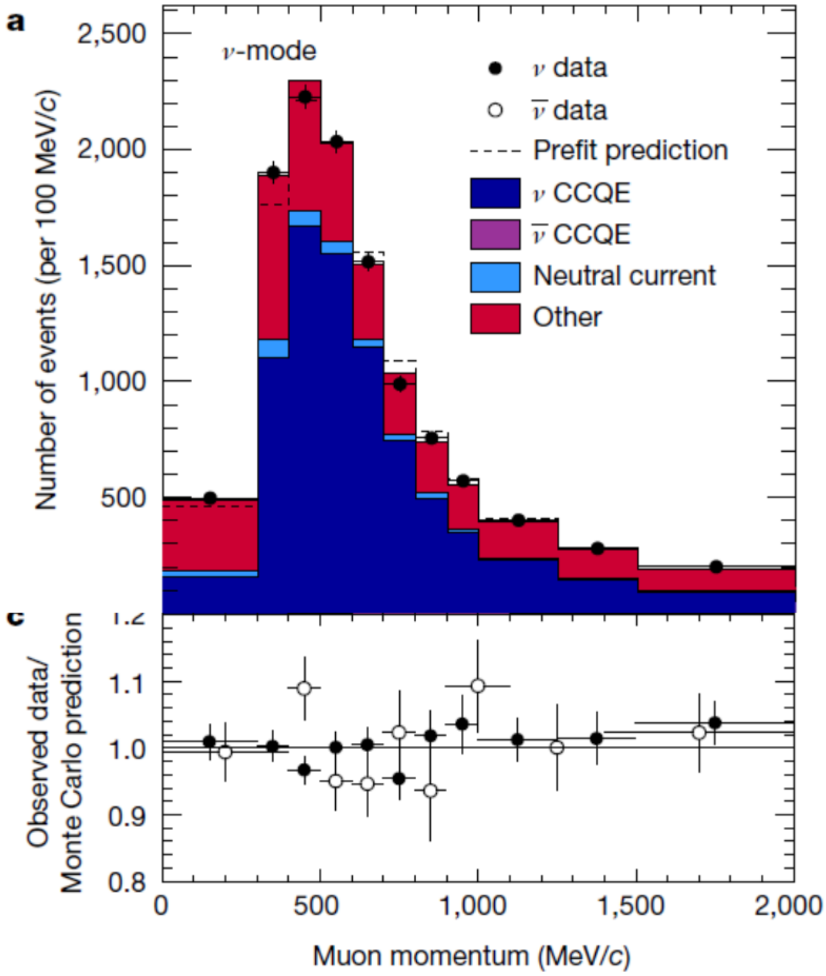
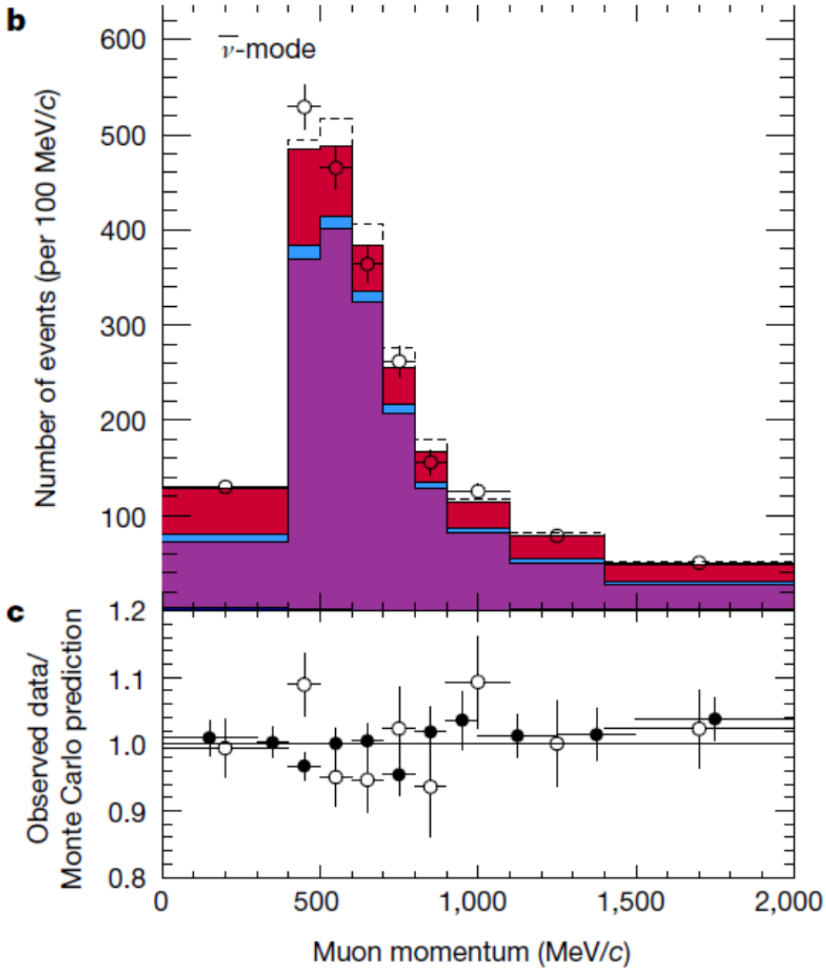
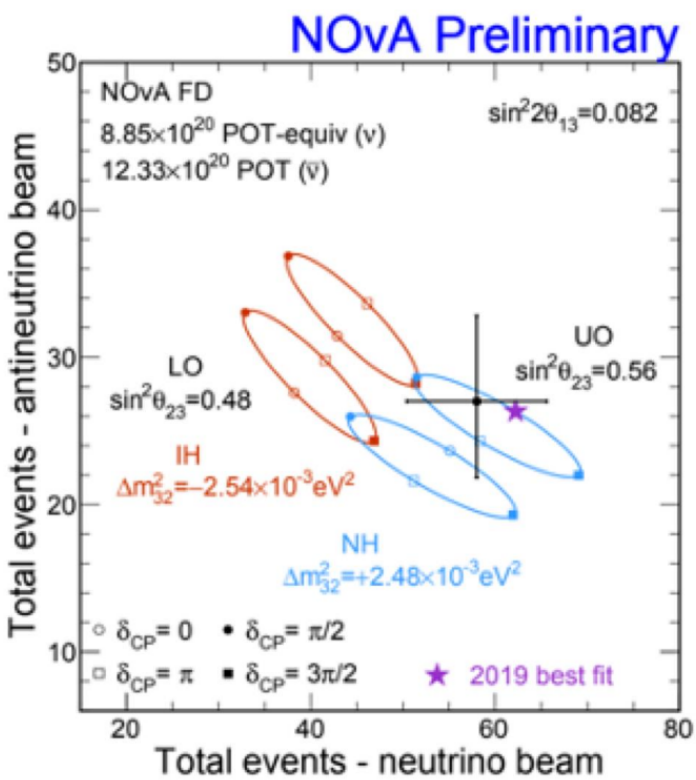
Near detector fit, FHC

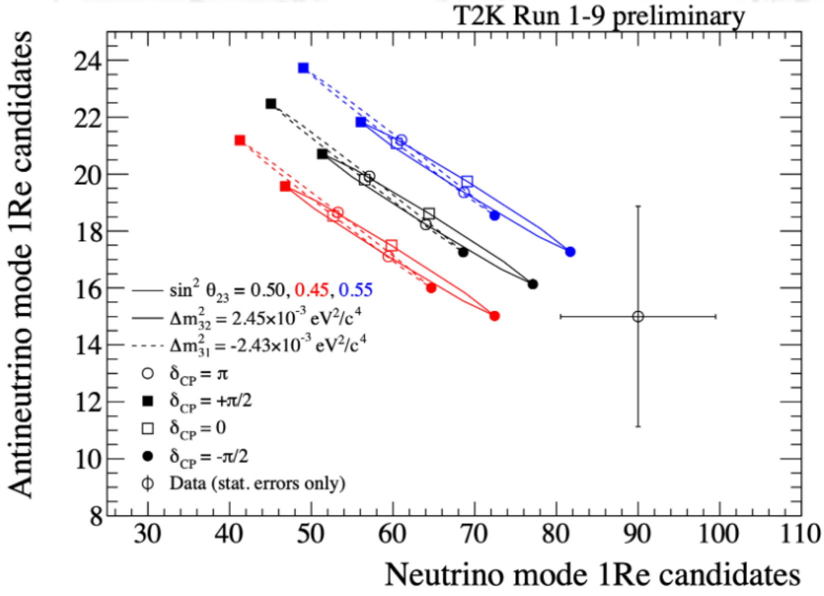


Near detector fit, RHC



Nova results





https://arxiv.org/abs/2009.08585

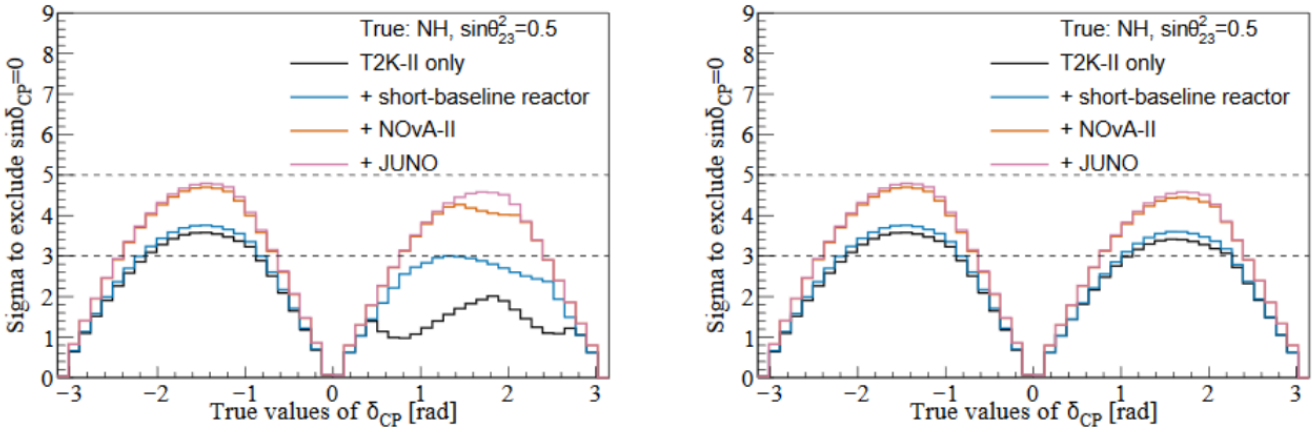


FIG. 5: CPV sensitivity as a function of the *true* value of δ_{CP} obtained with different analyses. *Normal* MH and $\sin^2\theta_{23} = 0.5$ are assumed to be *true*. Left (right) plot is with the *unknown* (*known*) *MH option.*

T2K-II, NOνA-II and JUNO

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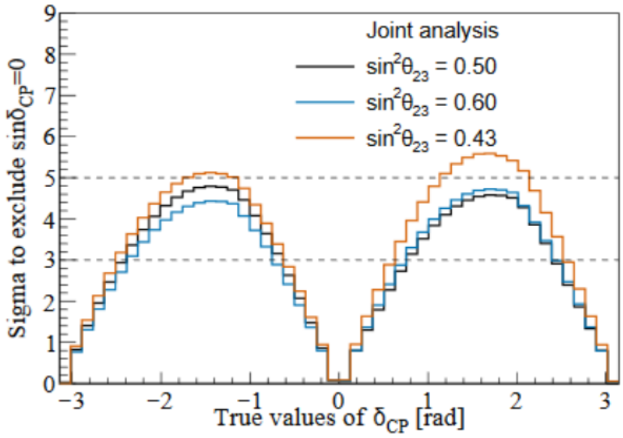
https://arxiv.org/abs/2009.08585



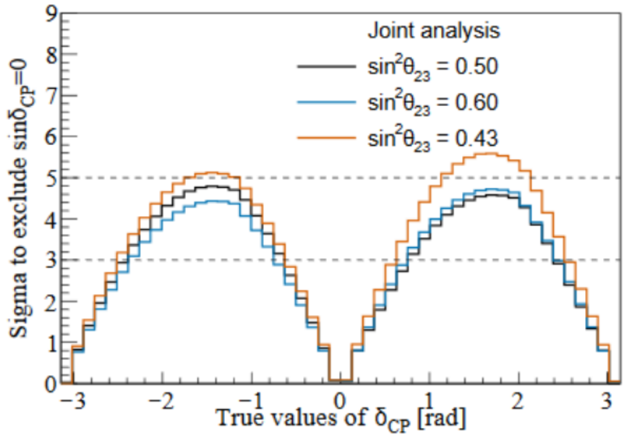


FIG. 6: CPV sensitivity as function of the *true* value of δ_{CP} obtained with a joint analysis of all considered experiments at different *true* $\sin^2\theta_{23}$ values (0.43, 0.5, 0.6). Left (right) plot is with the *unknown* (*known*) MH option.