Rencontres de Moriond 2024

Latest activities and results from T2K

Phill Litchfield

for the T2K collaboration

2024/03/29

Outline

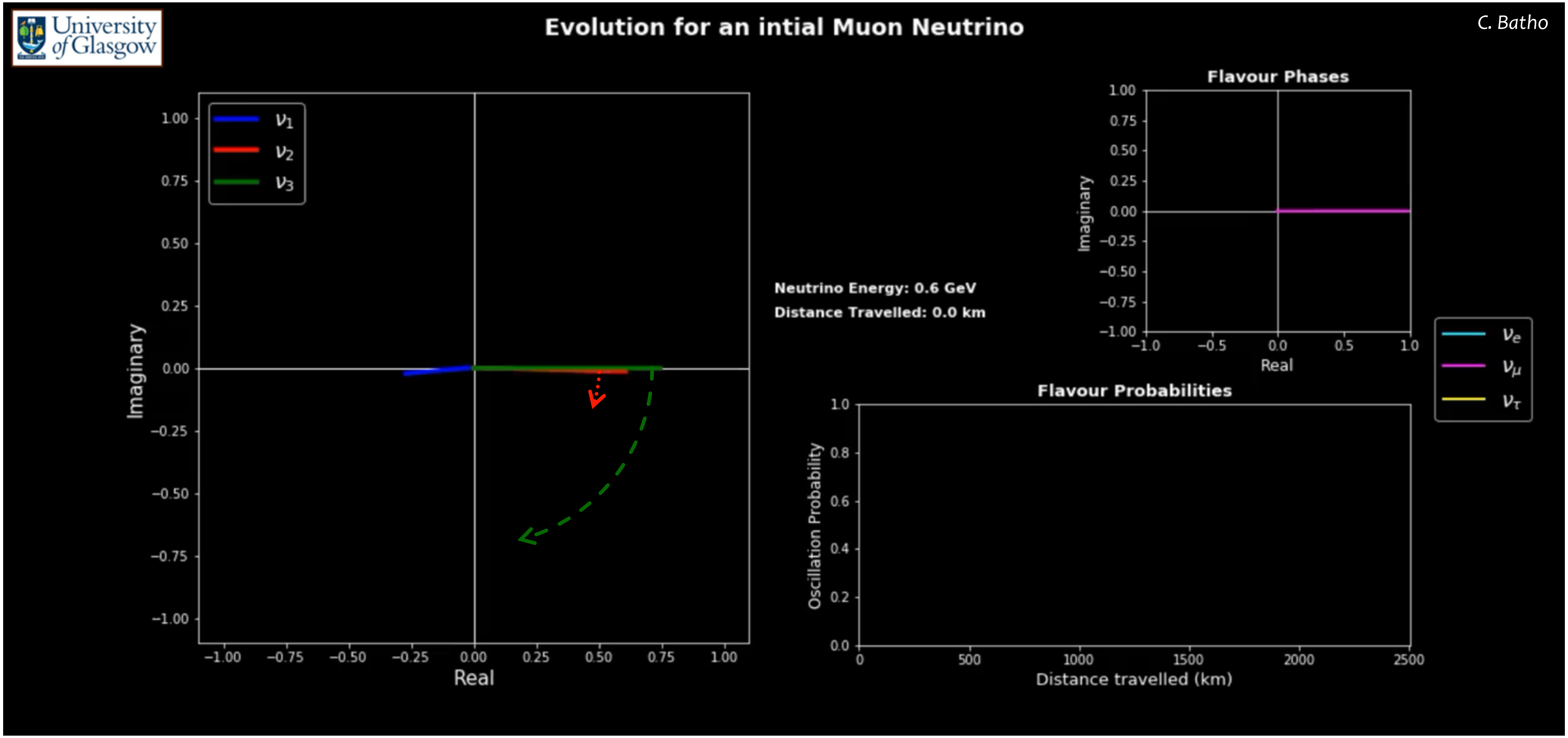
What I will cover:

- **T2K recent operations and renewal**
- **Latest T2K-only results** (2023)
- **T2K combination with Super-K atmospherics**
- **The near future: ND280 upgrade**

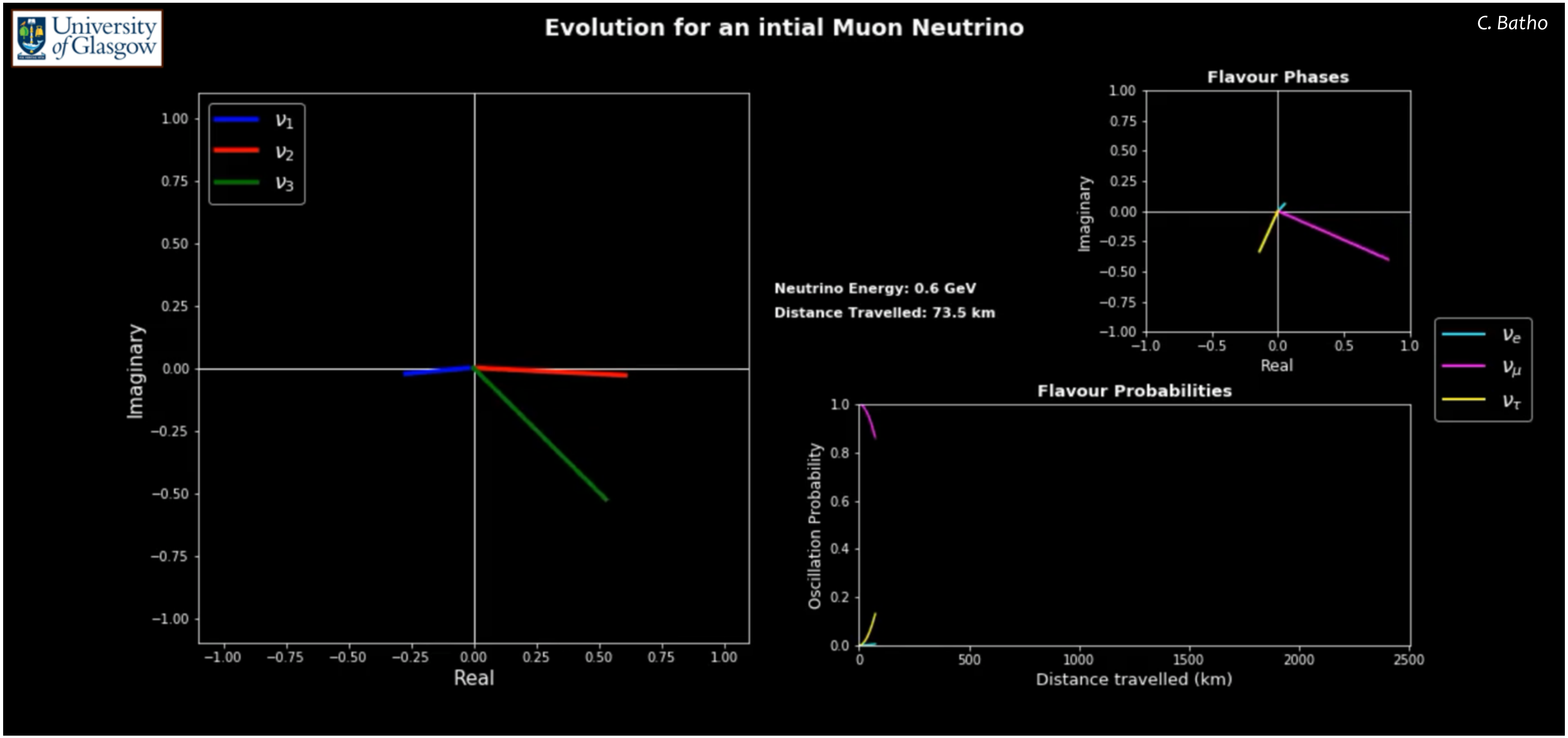
Not covered in this talk:

- Cross-section results
- T2K + NOνA combination. (Mayly Sanchez)
- SK stand-alone, inc. Gd (Andrew Santos)

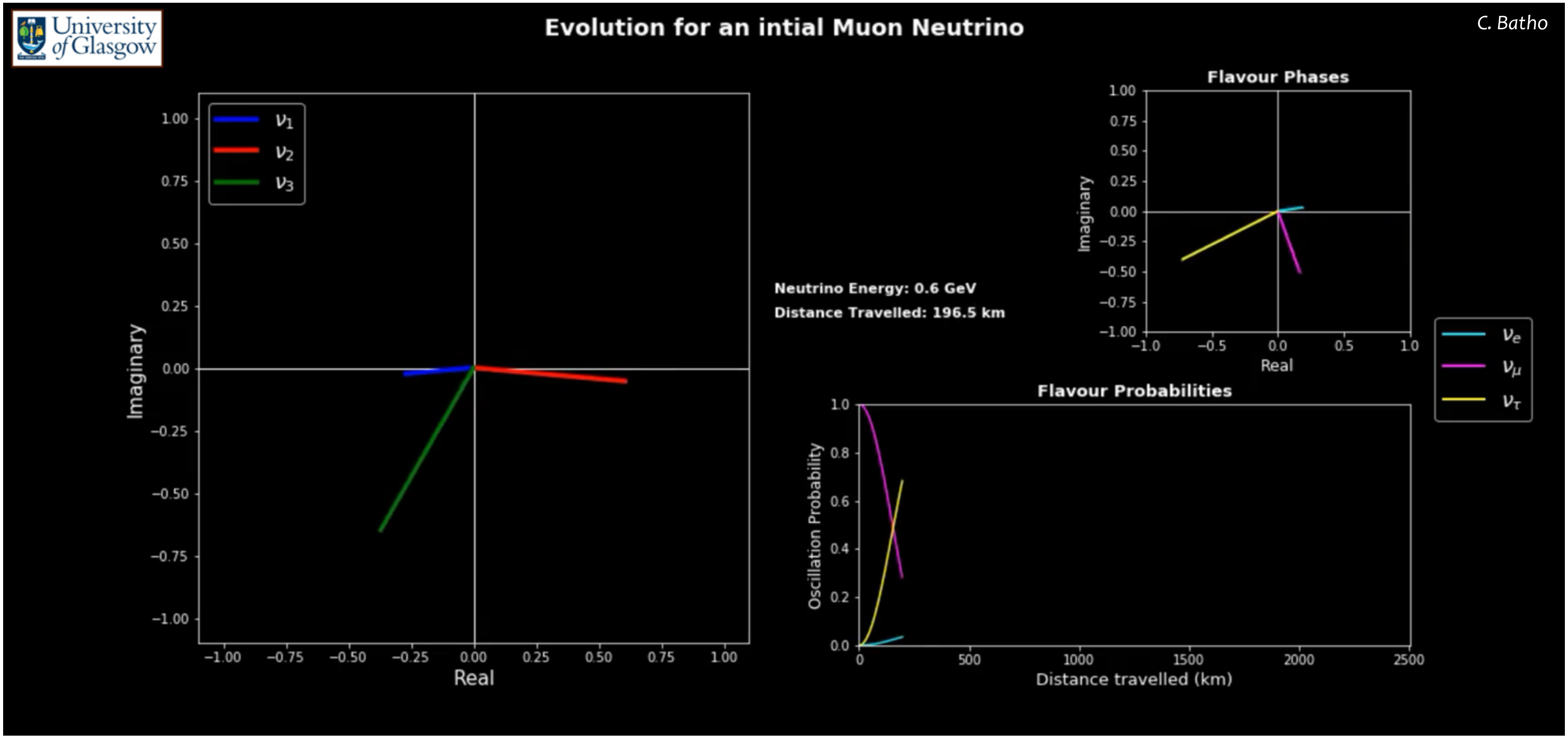
Muon neutrino initial state



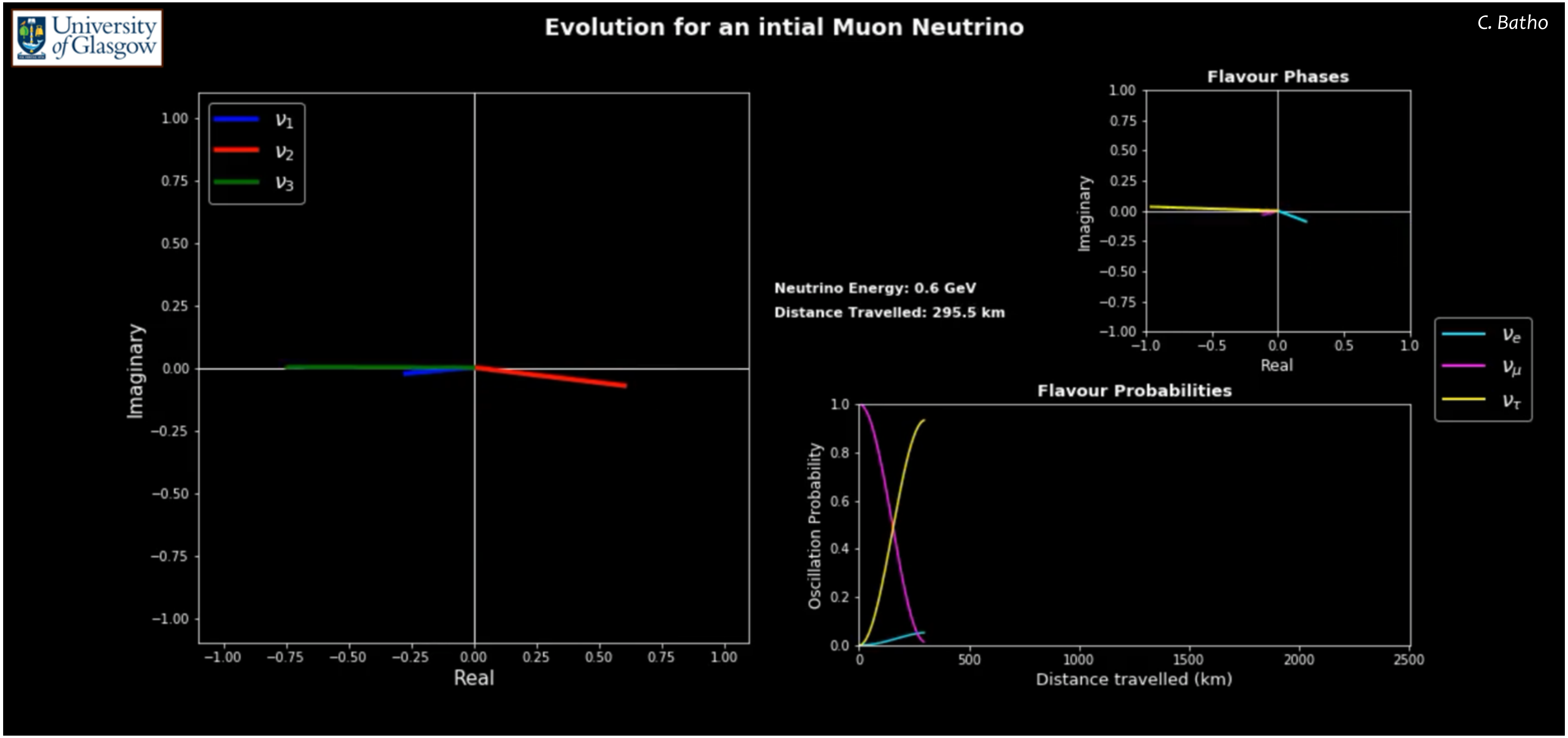
After 74km / 0.6GeV



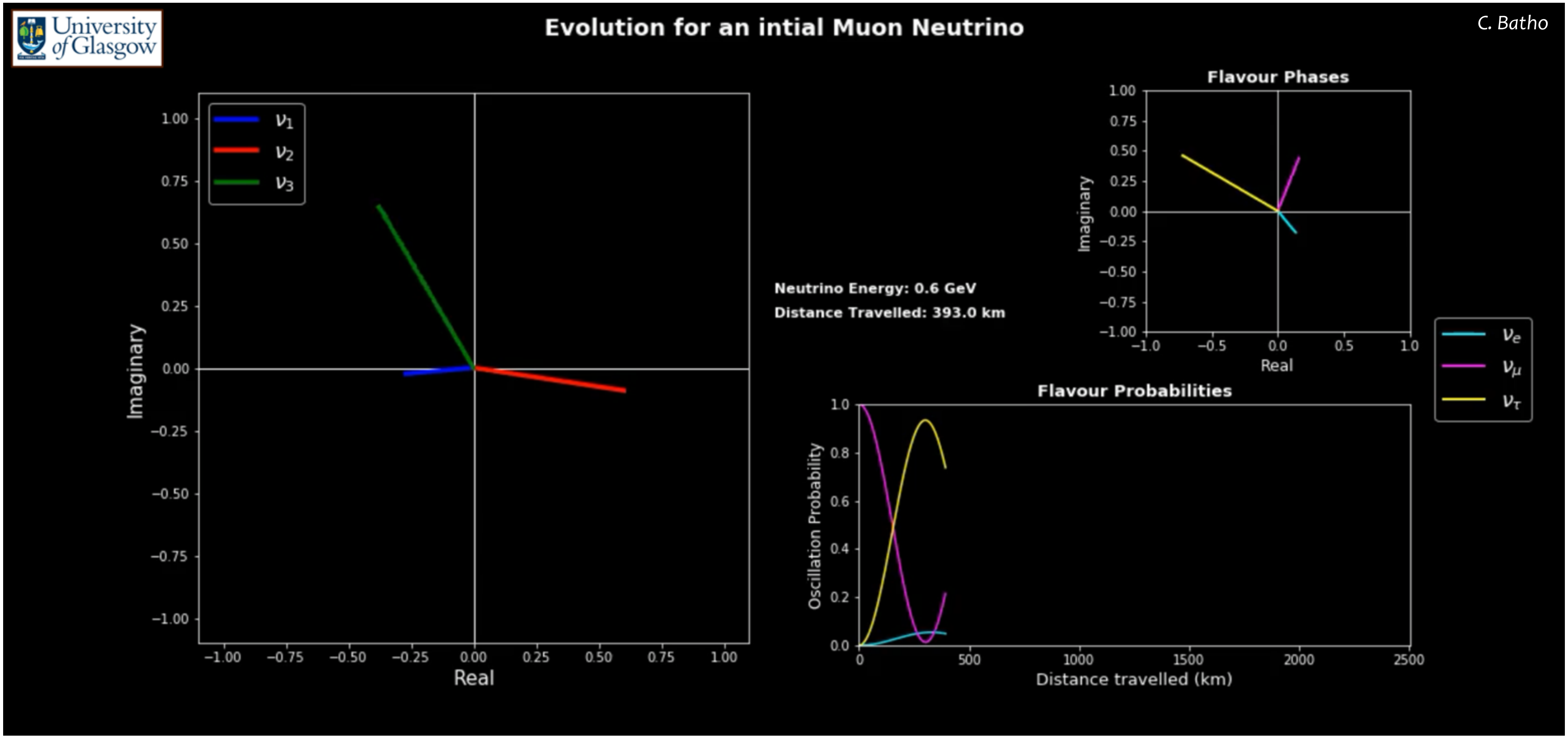
After 195km / 0.6GeV



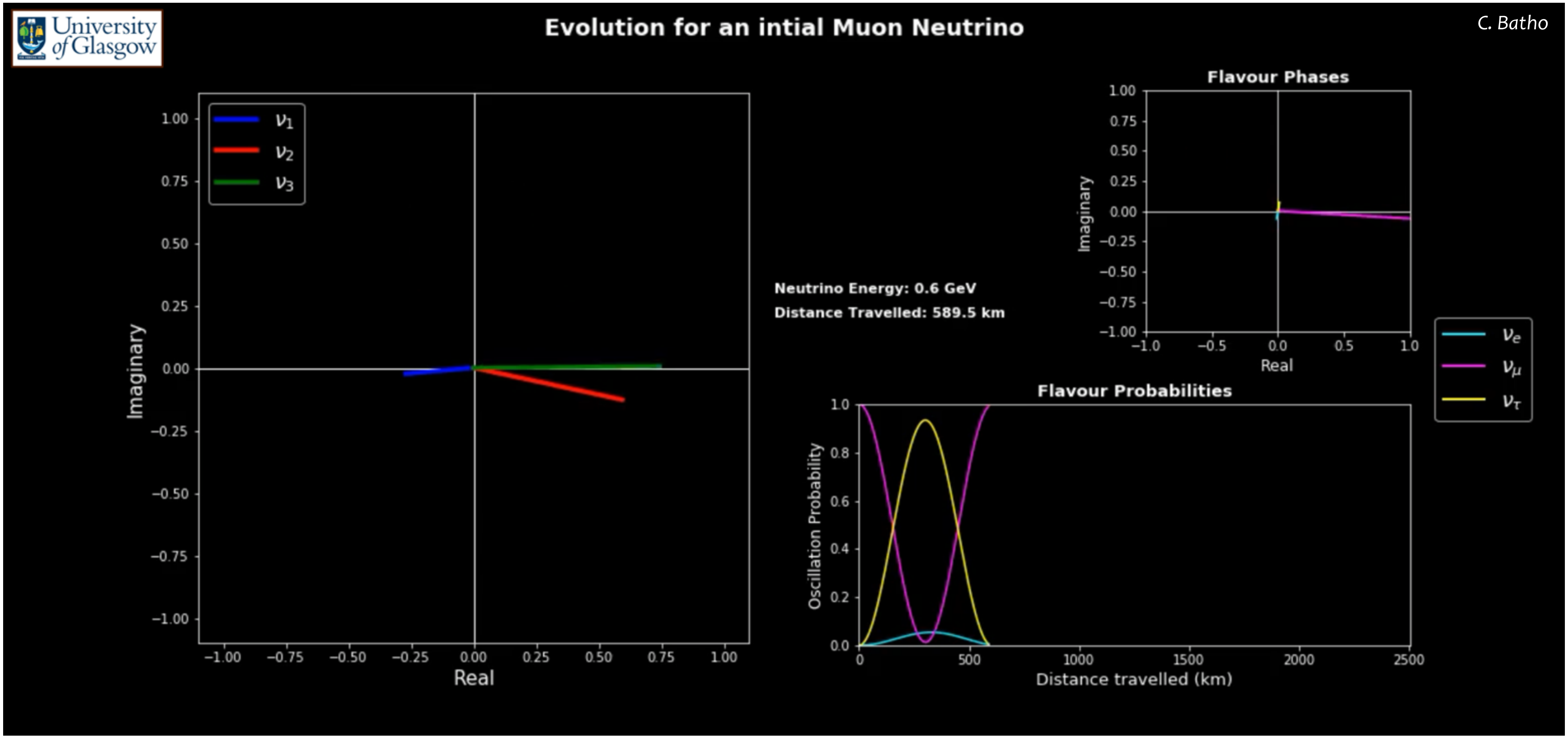
T2K Baseline: 295km / 0.6GeV



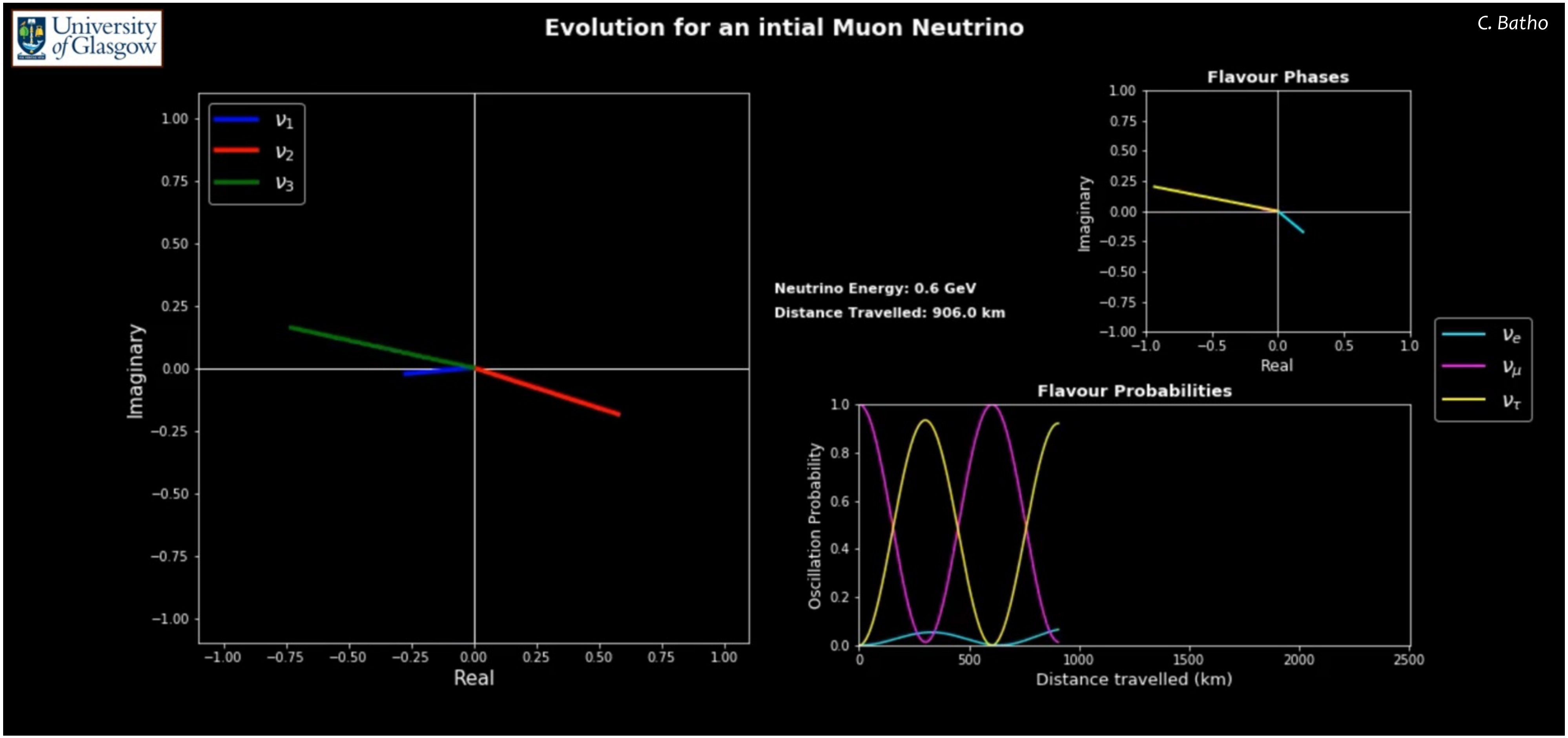
After 393km / 0.6GeV



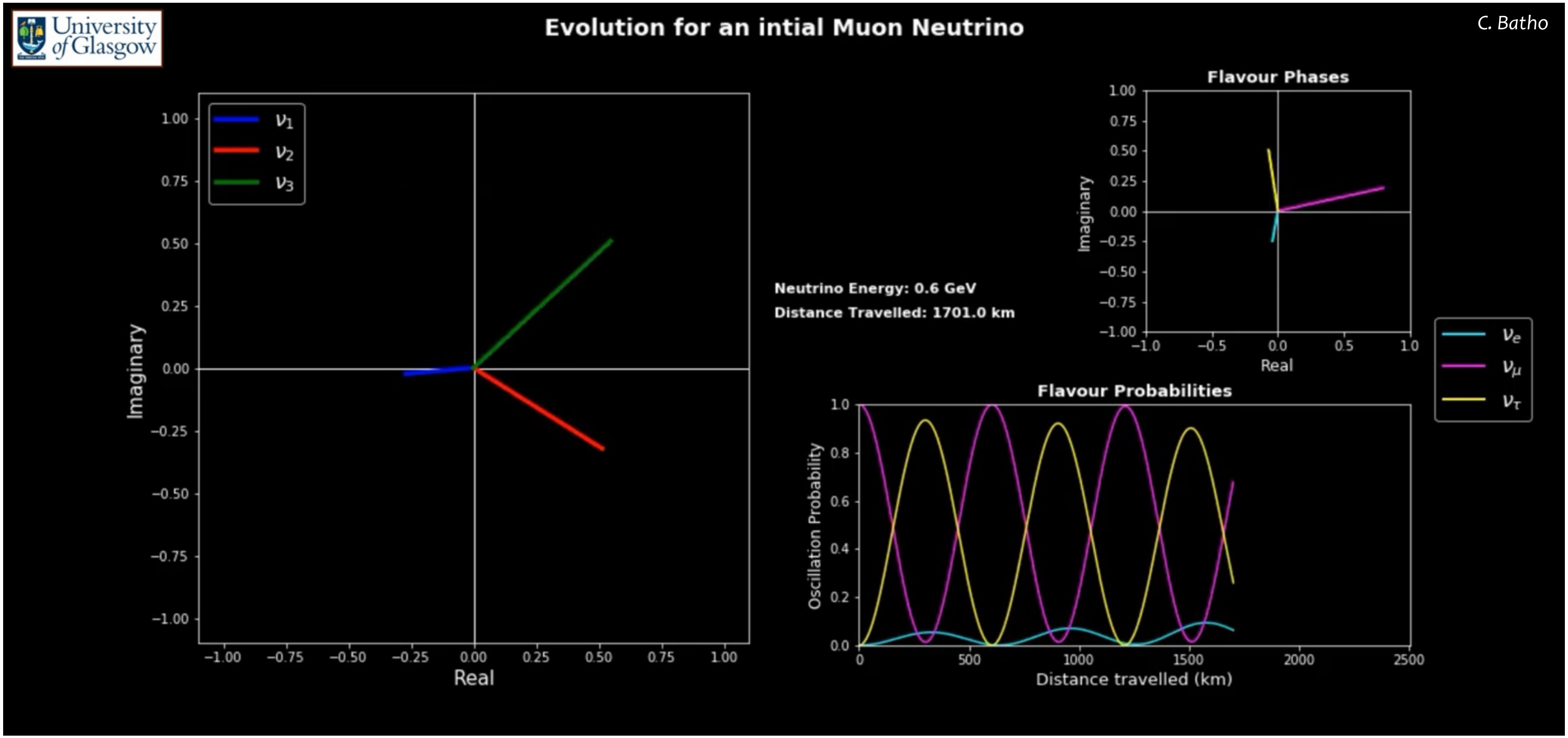
Almost a ν_μ: 589km / 0.6GeV



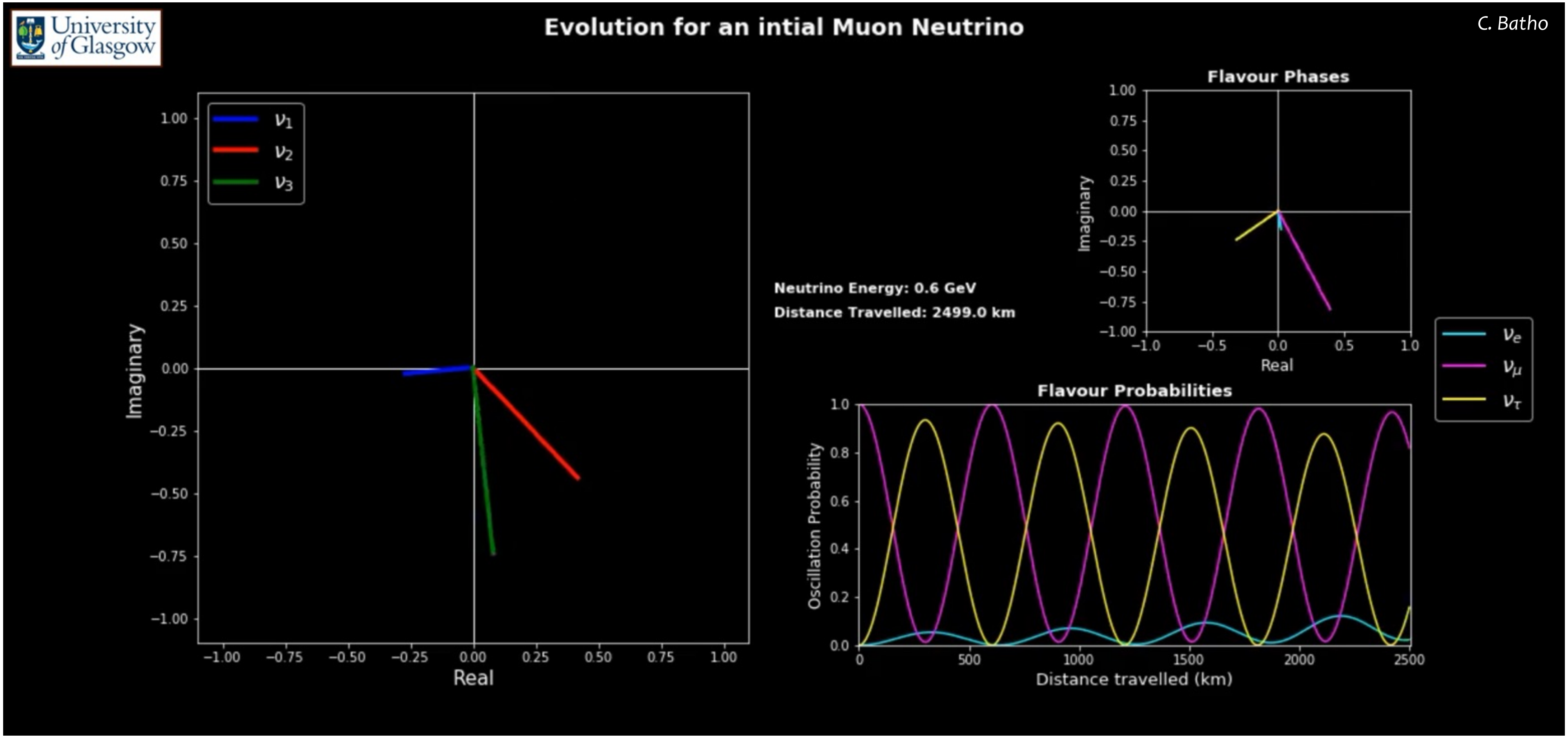
Second minimum: 906km / 0.6GeV



After 1700km / 0.6GeV



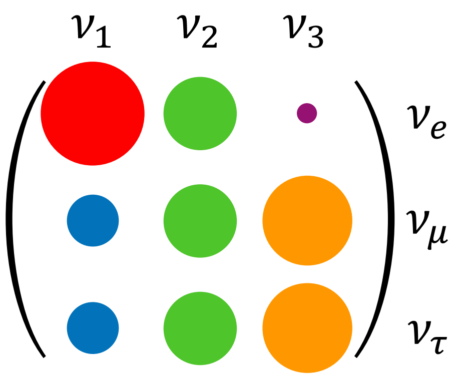
After 2500km / 0.6GeV



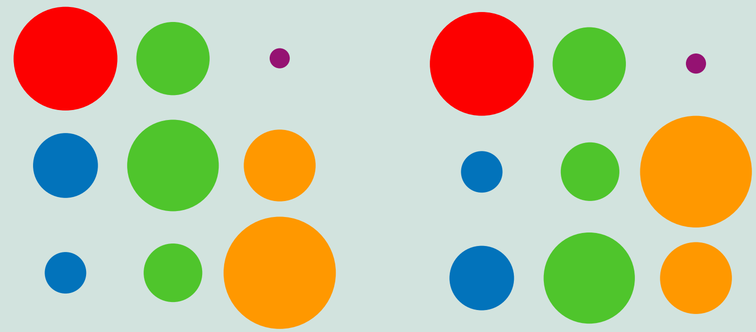
Now: precision measurement — can't approximate as a single sub-matrix.

- We know *fairly* well what the mixing matrix looks like:

$|U_{\mathrm{PMNS}}|^2 \simeq$

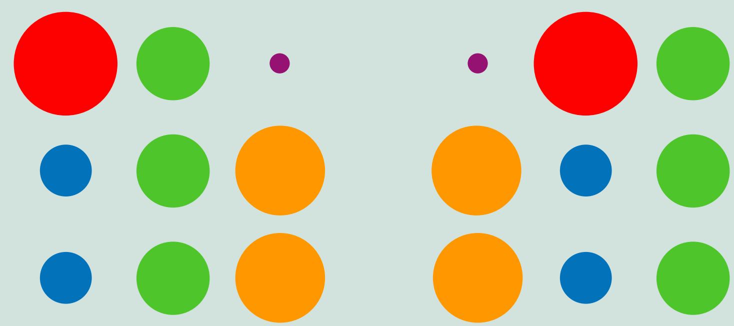


Octant degeneracy



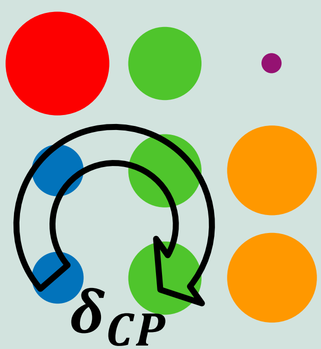
Lower ($\theta_{23} < 45°$) Upper ($\theta_{23} > 45°$)

Mass Ordering [Hierarchy]



Normal (NO) Inverted (IO)

CP Violation

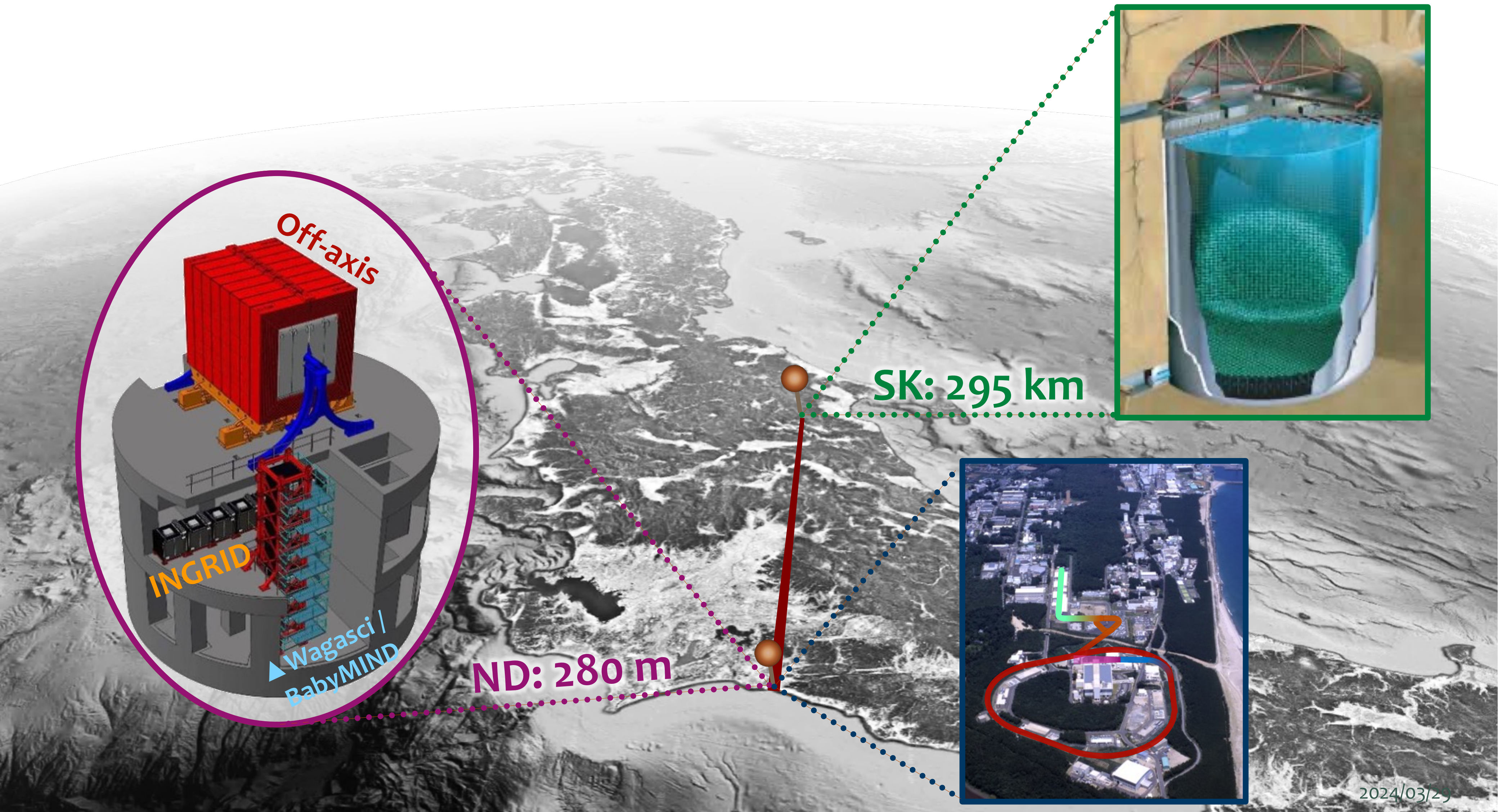


Complex mixing of these 4 elements causes

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Key parameter: $\boldsymbol{\delta_{CP}}$

Spatial orientation



Temporal orientation

Feb '24: More beam data with ND280 upgrade

'24

25 Dec '23: 760kW achieved!

(**28 Nov:** >750 kW permission)

Aug '23: First operation with ND280 upgrade

Nov '23: Horn current up to 320kA

Autumn 2023: Latest T2K analysis

'23

(**Summer 2022:** 0.03% Gd at SK)

2022~23: ND280 upgrades

'22

2021~22: Beam upgrades

April 2021: Last run before upgrades (Max beam power 523kW)

▼ **2020:** End of run 10 (this data)

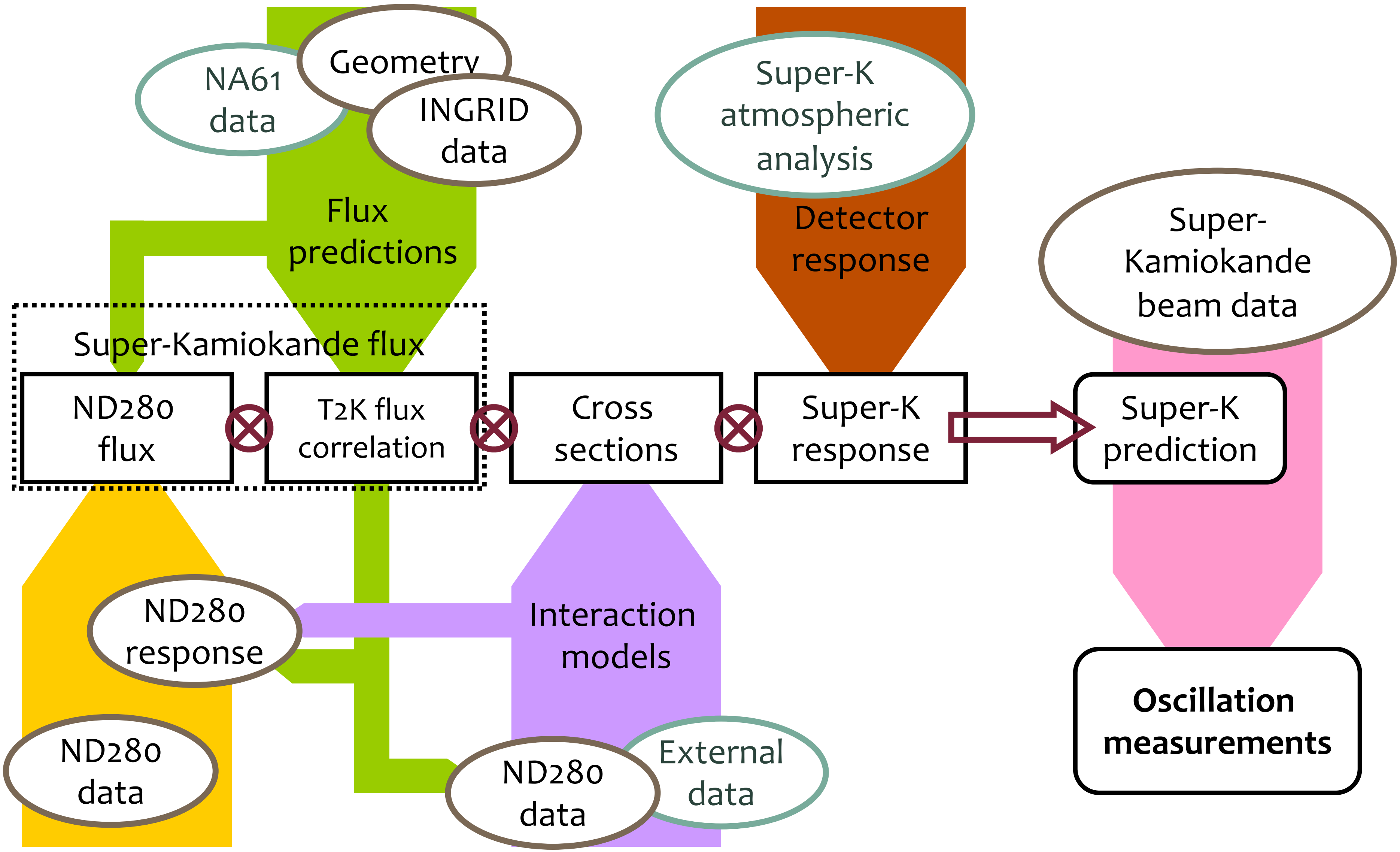
'21

T2K-only analysis

Eur.Phys.J.C 83 (2023) 9, 782

arXiv: 2303.03222 [hep-ex]

T2K Analysis strategy



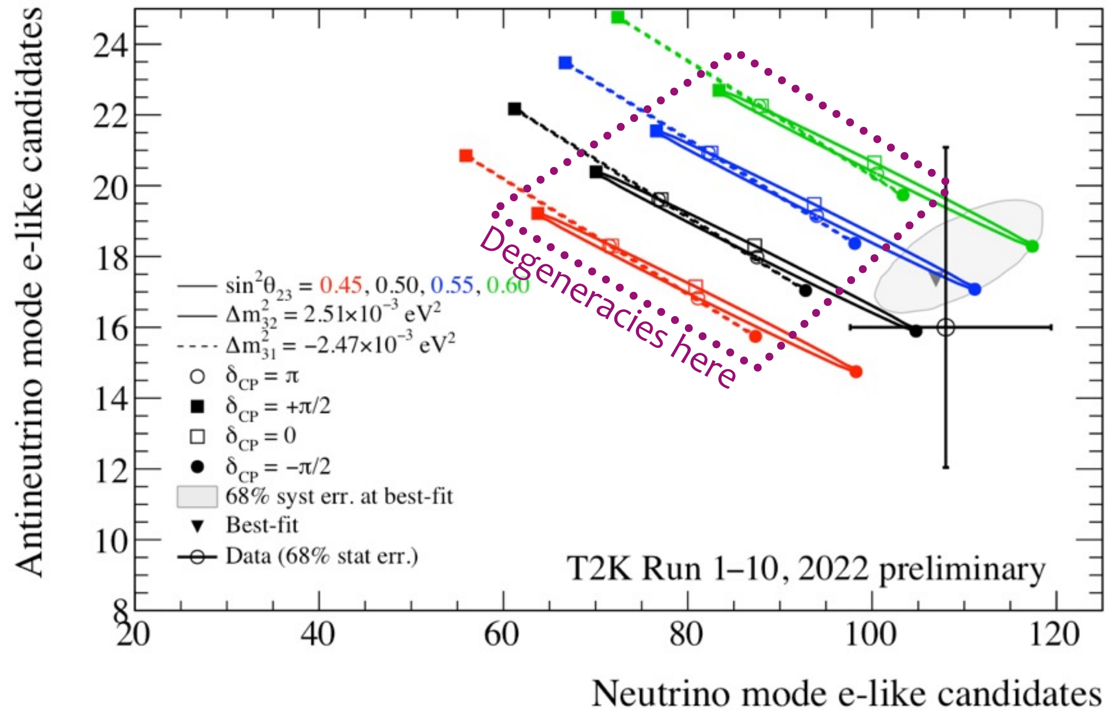
T2K-only latest results

CP violation:

- Find $\delta_{CP} = -0.63^{+0.31}_{-0.22}\,\pi$
- CPC values excluded at 90% CL

Preferences on octant degeneracy and Mass Ordering:

- Need all of Upper Octant + Normal Ordering + CPv to get the large (best fit) ν_e signal



T2K posterior probability		$\theta_{23} < \frac{\pi}{2}$	$\theta_{23} > \frac{\pi}{2}$
		0.23	0.77
$\Delta m^2_{32} > 0$	0.80	0.19	0.61
$\Delta m^2 < 0$	0.20	0.04	0.16

Updates from 2020

Same POT, but:

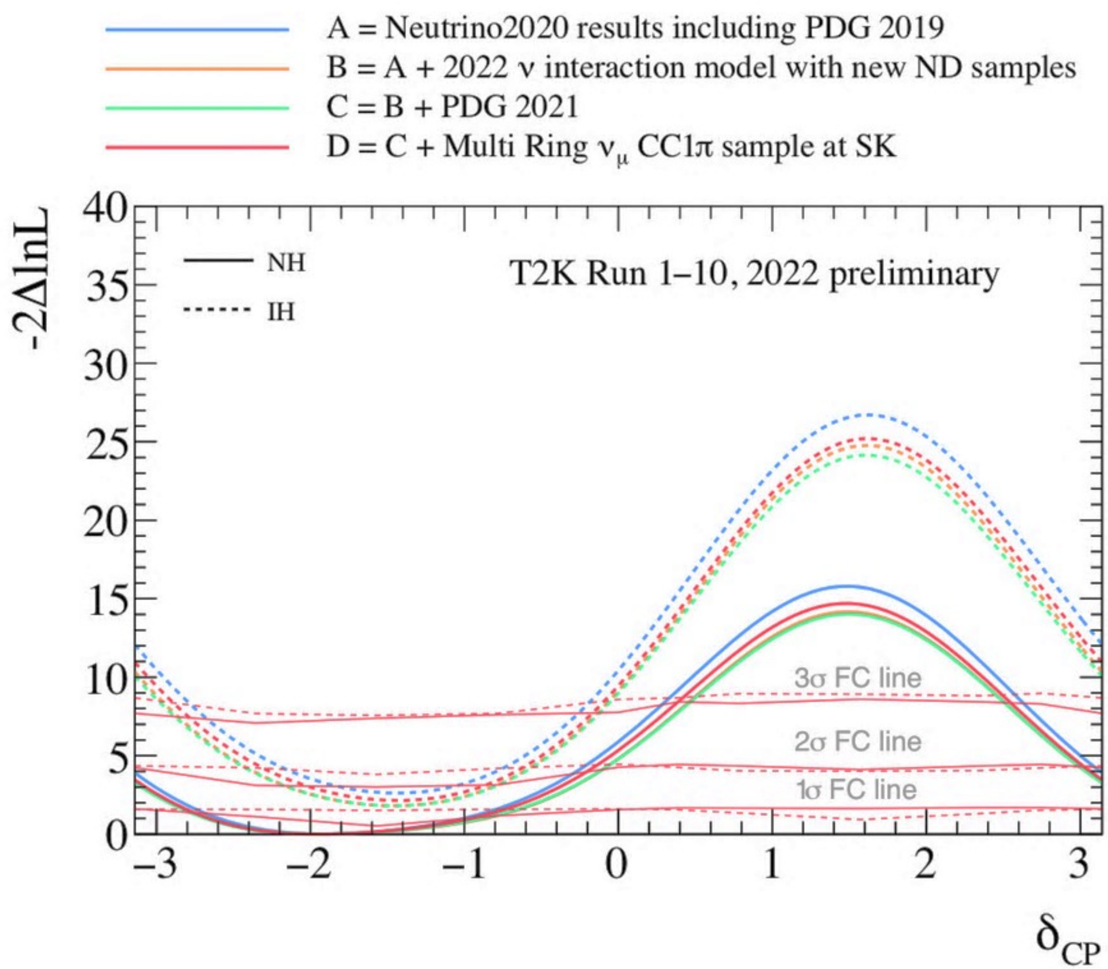
Updated the neutrino interaction model

Constrained by 106% more ND280 data

- Still allows more model variation → enlarged intervals, especially in Δm^2

Update reactor constraint on $\sin^2 2\theta_{13}$

Added ν_μ CC1π sample



University of Glasgow

T2K

T2K+SK analysis

Based on KEK-IPNS &
JPARC seminar 2023/12/20
https://kds.kek.jp/event/49194

(paper in preparation)

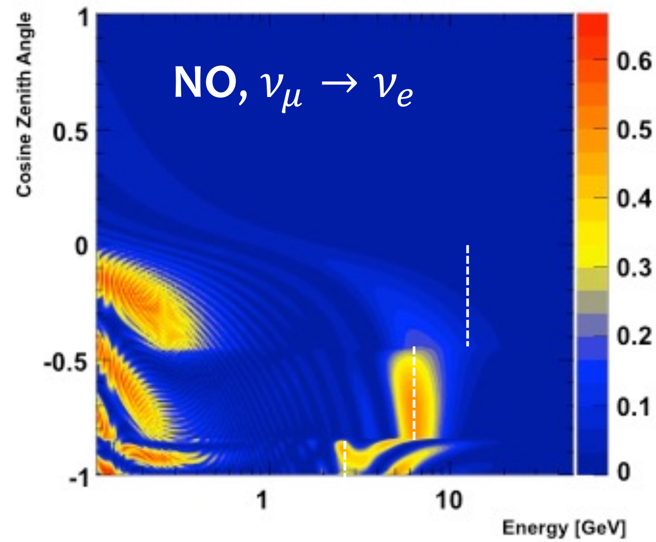
Combining T2K+SK: Degeneracies

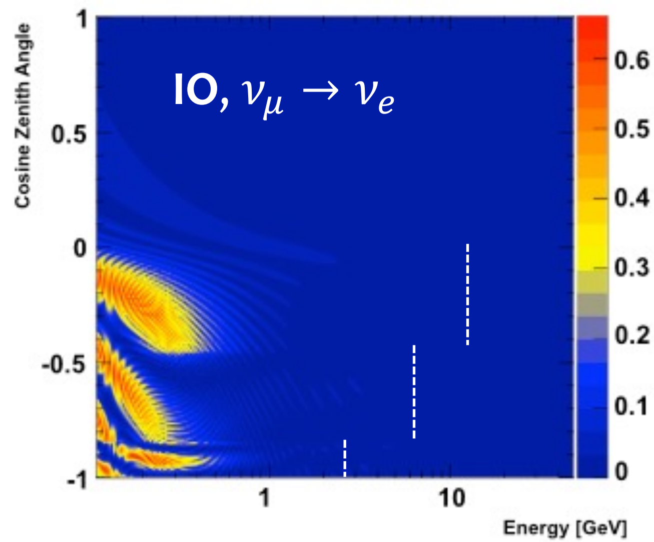
T2K very sensitive to $\sin\delta$ but lacks sensitivity to energy distortion caused by $\cos\delta$

- **SK can help resolve $\delta = 0$ vs π**

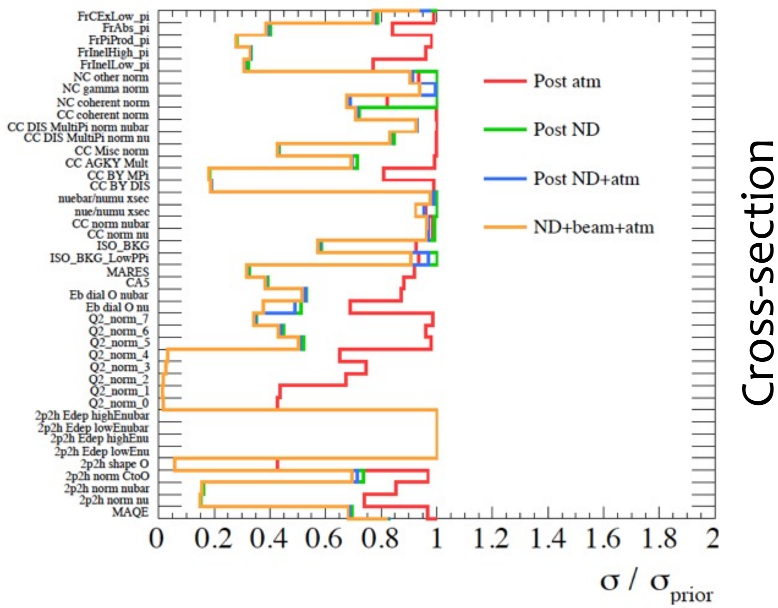
MSW resonance changes mixing drastically for high energy neutrinos:

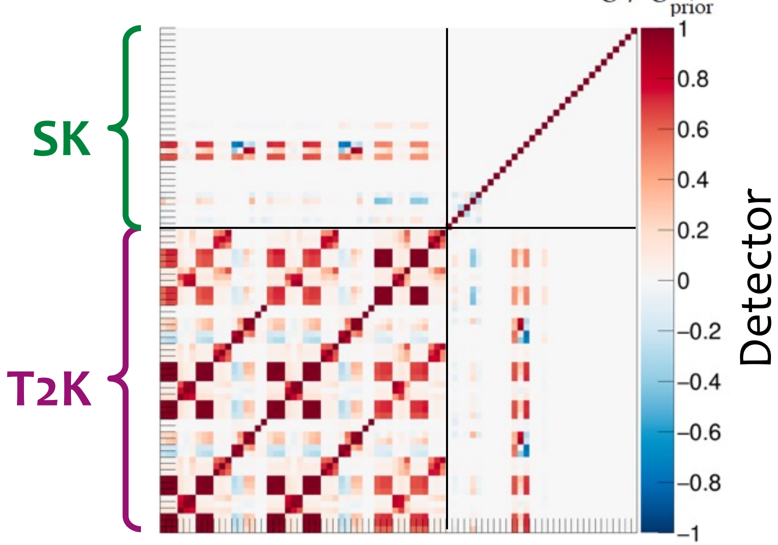
- $E_\nu \sim 13$ GeV (crust); ~ 2.5 GeV (core)
- Only for ν in NO, and $\bar{\nu}$ in IO (expect around $2\nu : 1\bar{\nu}$)
- **SK breaks T2K's MO – δ_{CP} degneracies**





Combining T2K+SK: Uncertainties





T2K has a well-understood narrow-band flux, and ND280 can identify many exclusive channels (μ^+ or μ^-, π, p)

- **ND280 fitting can be used to significantly improve many cross-section uncertainties.**

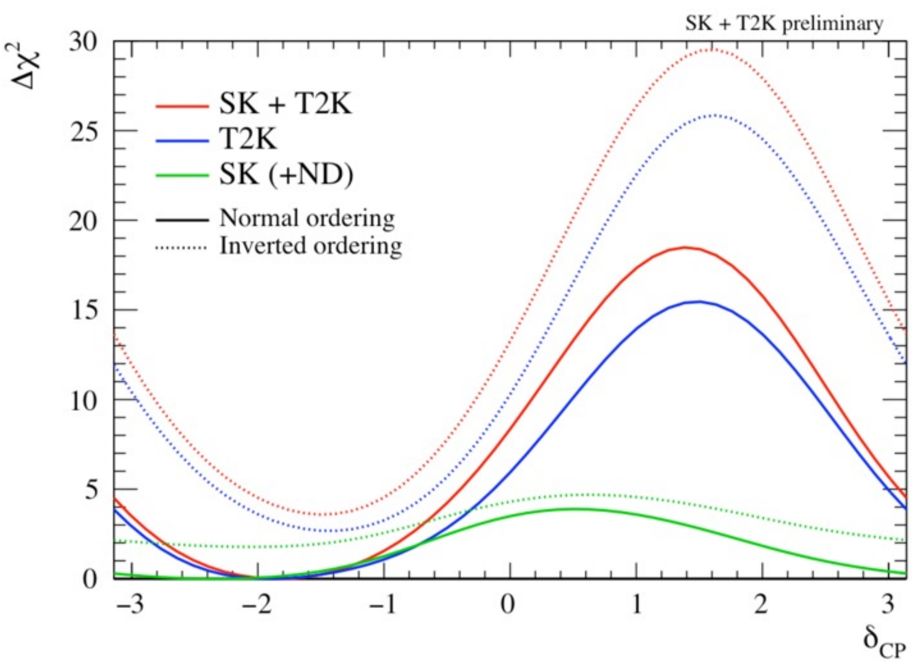
SK detector systematics are shared between T2K & SK (but act differently because of differences in spectrum)

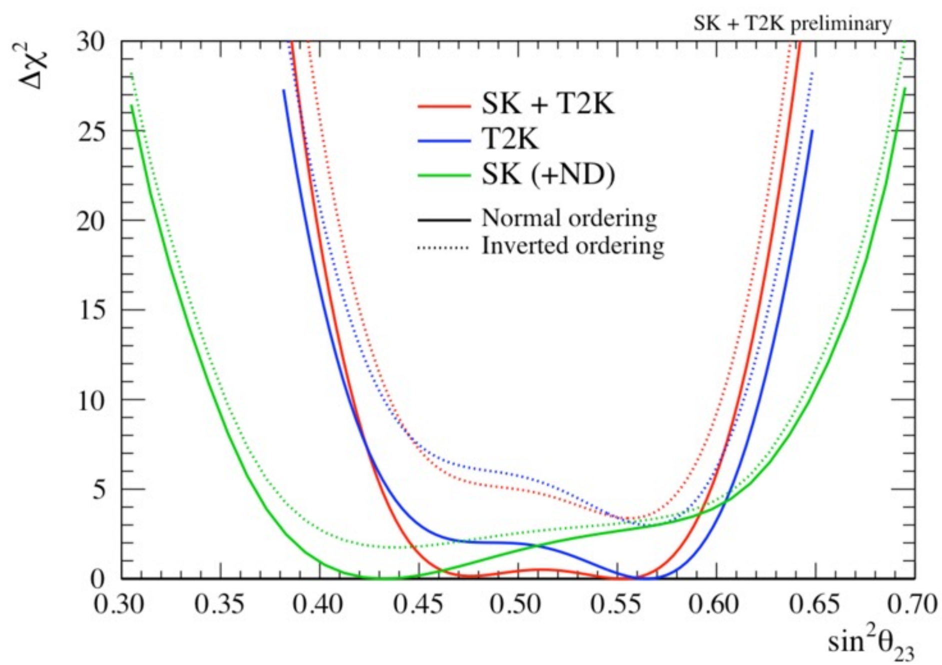
- **Construct full correlation for joint analysis**

T2K+SK results

- Opposite octant preference cancellation (esp. NH)
- NO preference increases slightly
- Main differences are in δ_{CP} and $\sin^2\theta_{23}$

T2K+SK posterior		$\theta_{23} < \frac{\pi}{2}$	$\theta_{23} > \frac{\pi}{2}$
		0.39	0.61
$\Delta m^2 > 0$	0.90	0.37	0.53
$\Delta m^2 < 0$	0.10	0.02	0.08





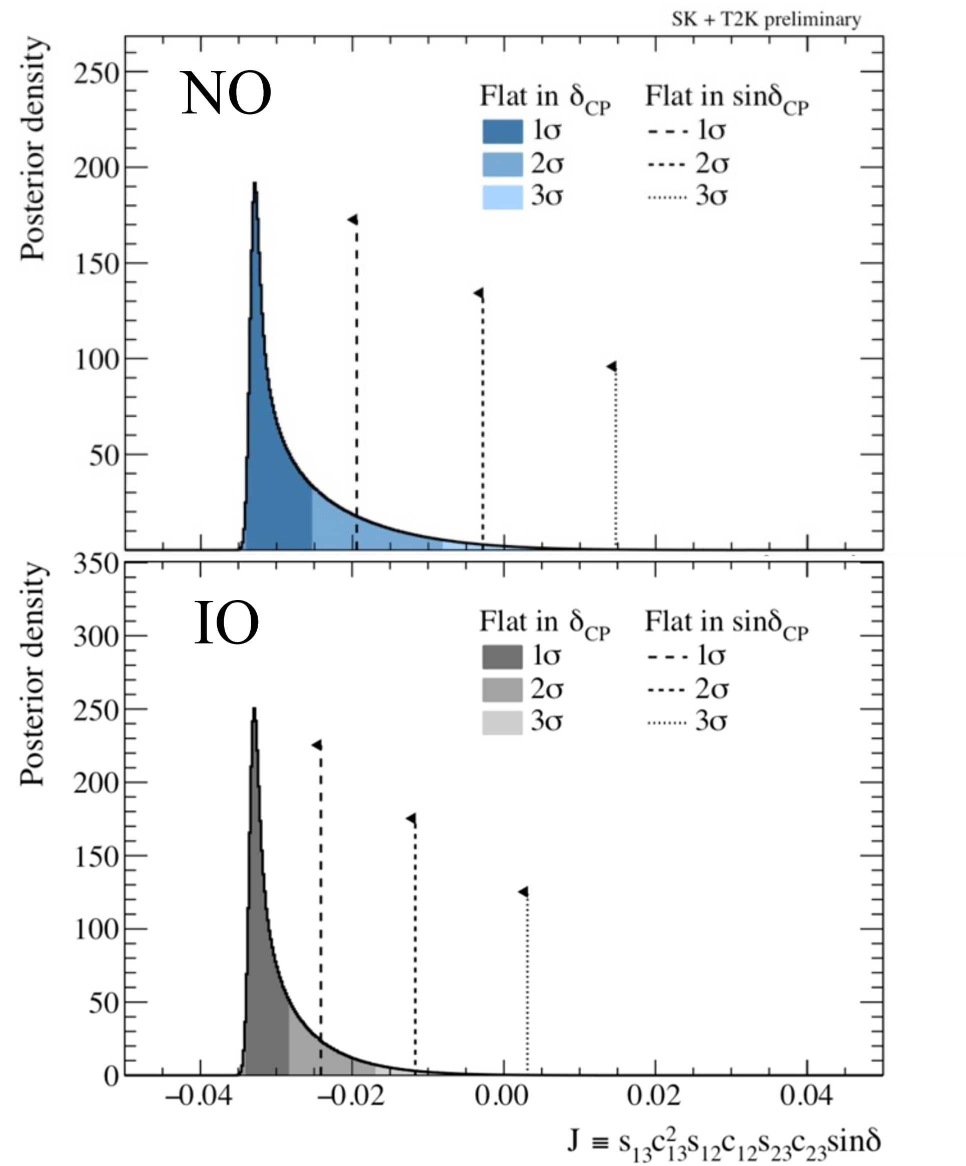
Bayes intervals and CP conservation

Couple of ways to quantify CP:

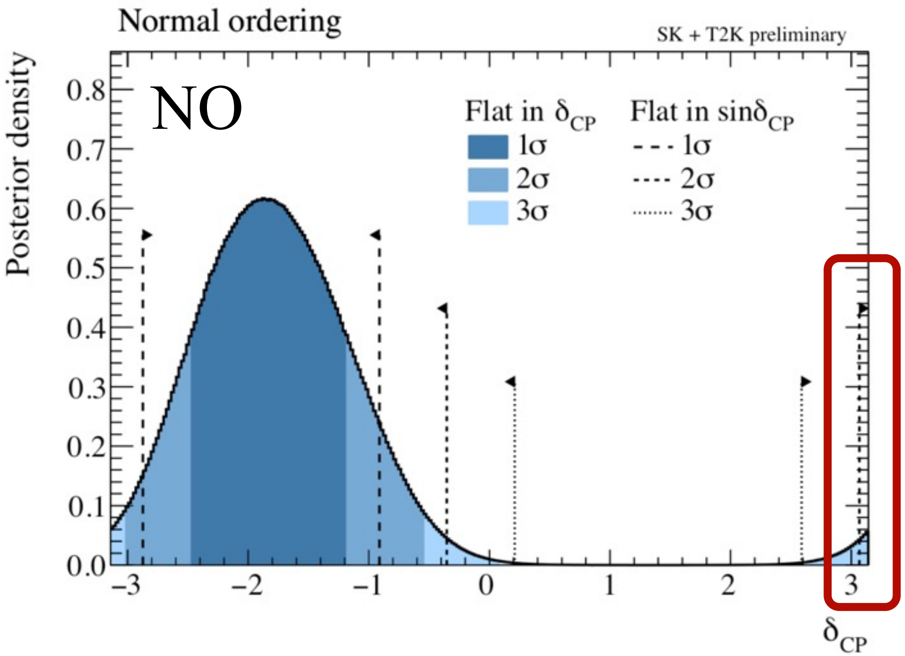
- $J_{CP} = \mathbb{Im}\left[U_{e2}U^*_{\mu2}U^*_{e1}U_{\mu2}\right]$ **is the parameterisation-invariant measure.**
- But historically reported using δ_{CP} which has two CP conserving points $\{0, \pi\}$
  - Equivalent to $\theta_{13} \leftrightarrow -\theta_{13}$

Bayes methods also need a prior.

- Common choices are flat in δ_{CP} or flat in $\sin\delta_{CP}$
  - I prefer flat in δ_{CP} ~ SU(3) — these histograms.



T2K-SK result on CPC



We usually highlight the most conservative conclusion.

For some combinations of prior, MO, and parameterisation: **the CPC conserving point $\delta = \pi$ is still included within 2σ.**

- Plus larger than expected effects in $CC1\pi^+$ systematic study.

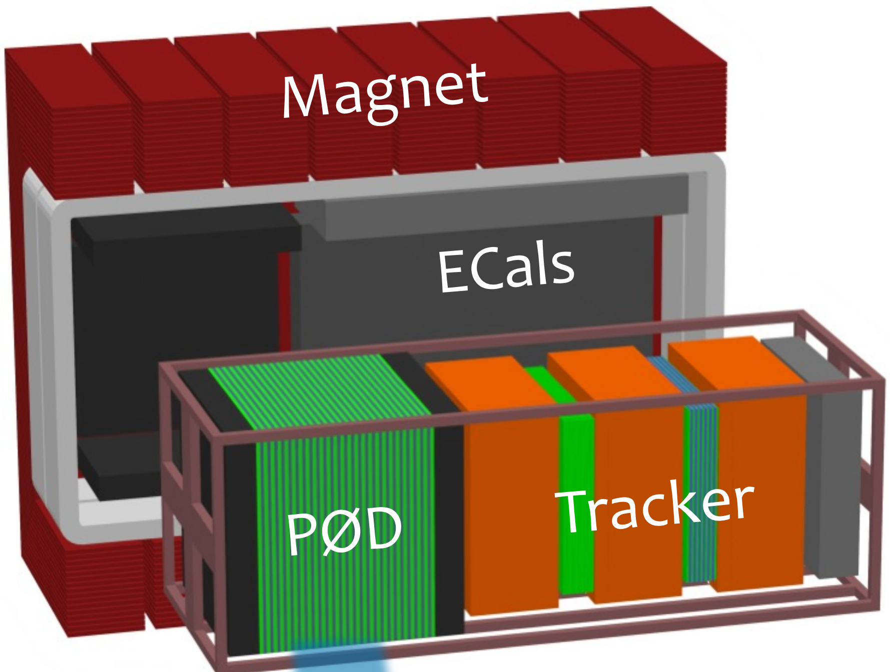
- **Frequentist analysis will also be in the paper (soon) but this only gets around the prior dependence, and is otherwise pretty consistent.**

Personal interpretation:

- Every approach puts CP conservation as disfavoured by 'about' 2σ, the question is whether it is 'a bit below' or 'a bit above'.

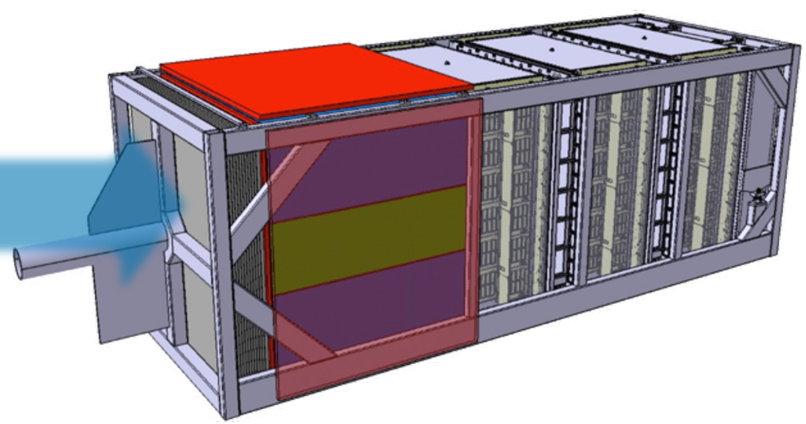
ND280 Upgrade

ND280 upgrade



Replacement High-angle tracker:

- As target mass /vertex det: **Super-FGD** (3D scintillator)
- Two **High-Angle TPCs**
- All surrounded by high resolution **Time-of-Fight** panels

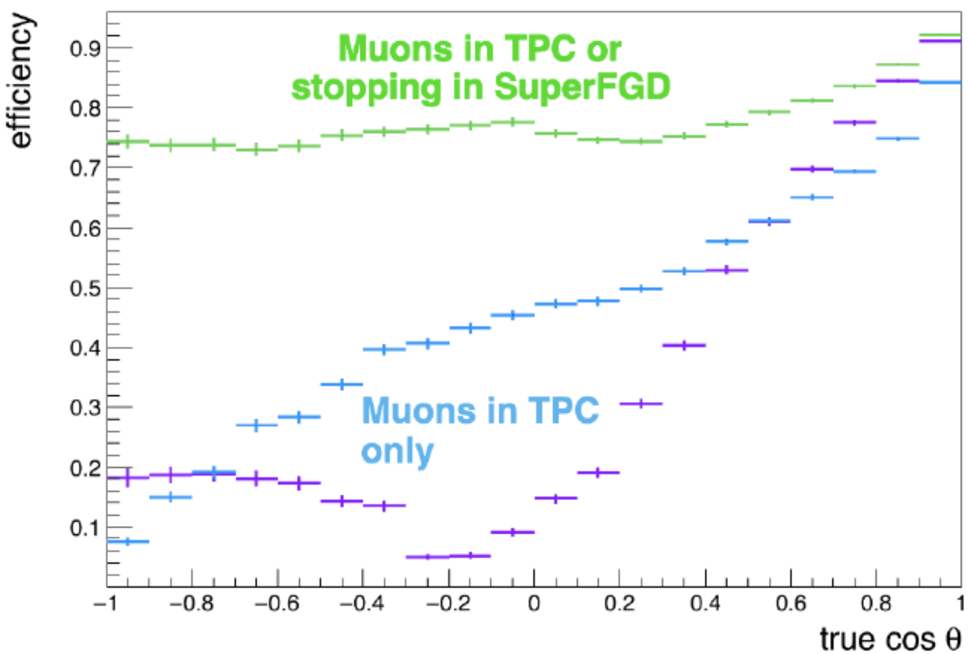


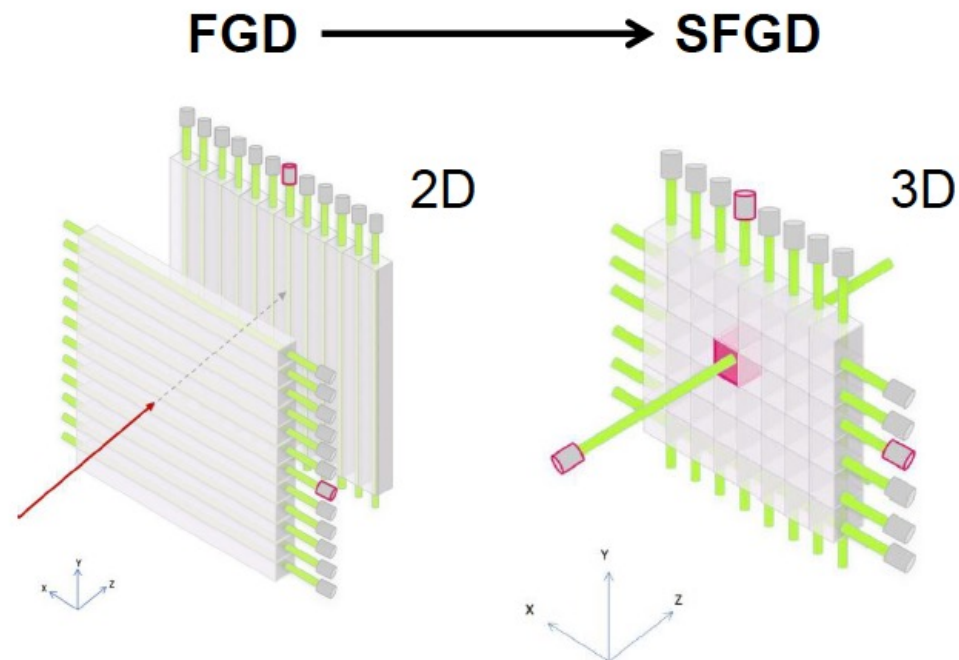
PØD intended to control π^0 B/G in the case θ_{13} was very small.

- Turned out to be large

Higher angle acceptance

- **Existing tracker design** works best for forward going tracks
- **New tracker** can reconstruct high-angle recoils (→ large Q^2); better match for SK acceptance





Lower tracking threshold

- Alternating planes of FGD require minimum $\gtrsim 4\text{cm}_z$ track
- 3D Super-FGD needs $\gtrsim$ 2cm and is much more isotopic.

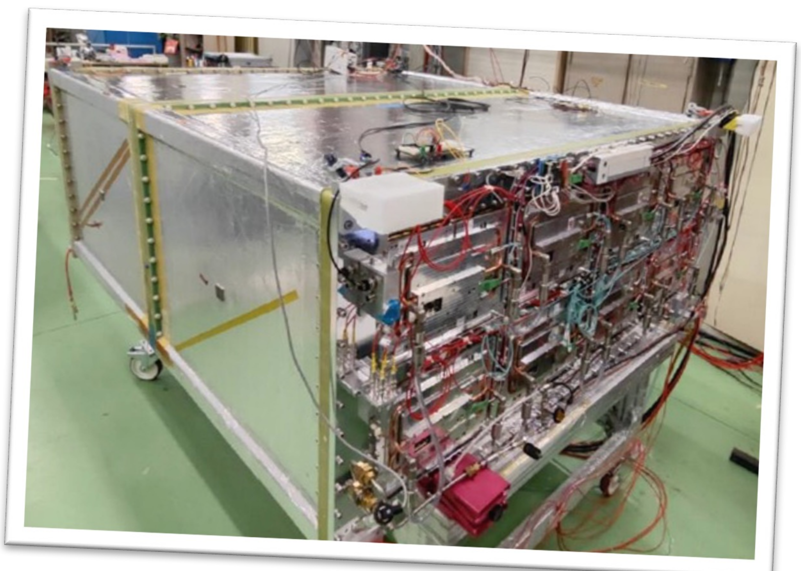
Maybe some installation pics?

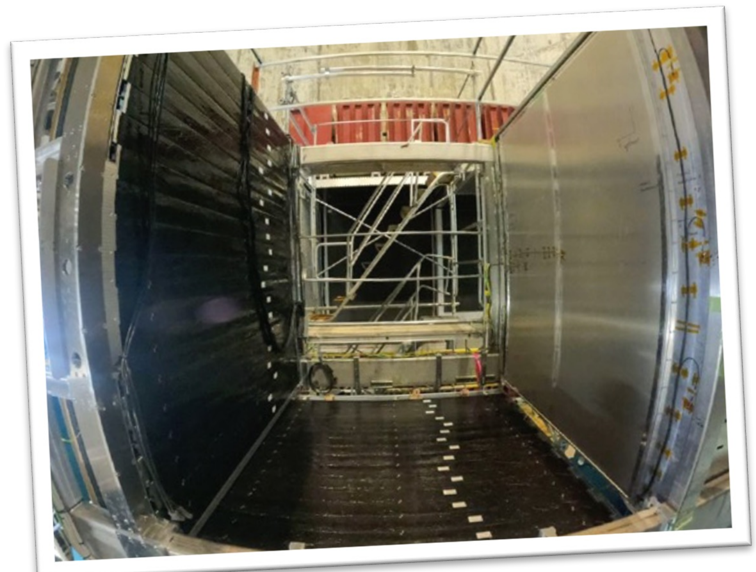
- Most of upgrade now installed.
- Top HA-TPC taking cosmics at CERN

◀ S-FGD during assembly, with guide fibre

▼ Installing ToF into ND280

▼ Checkout of Bottom HA-TPC

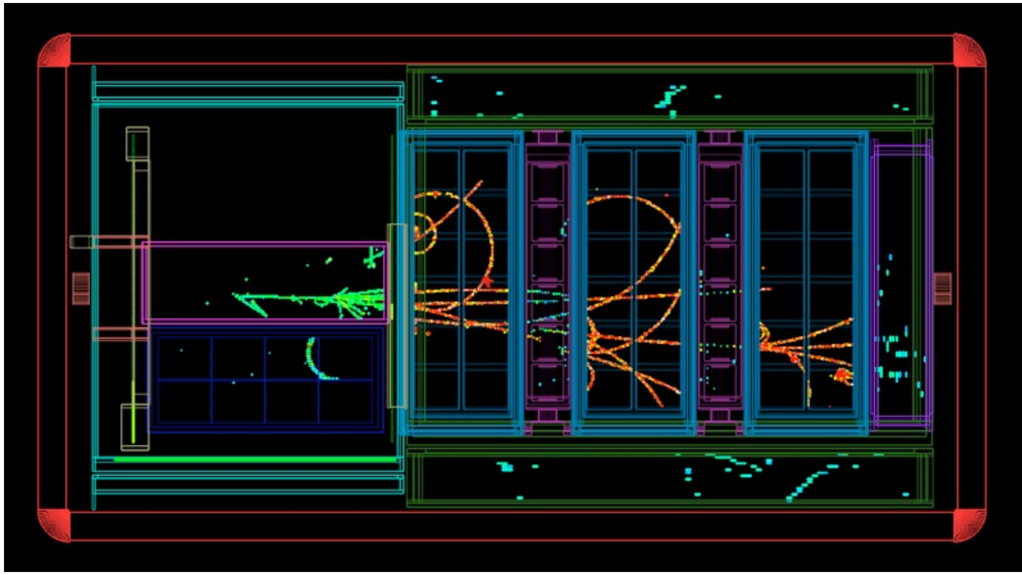


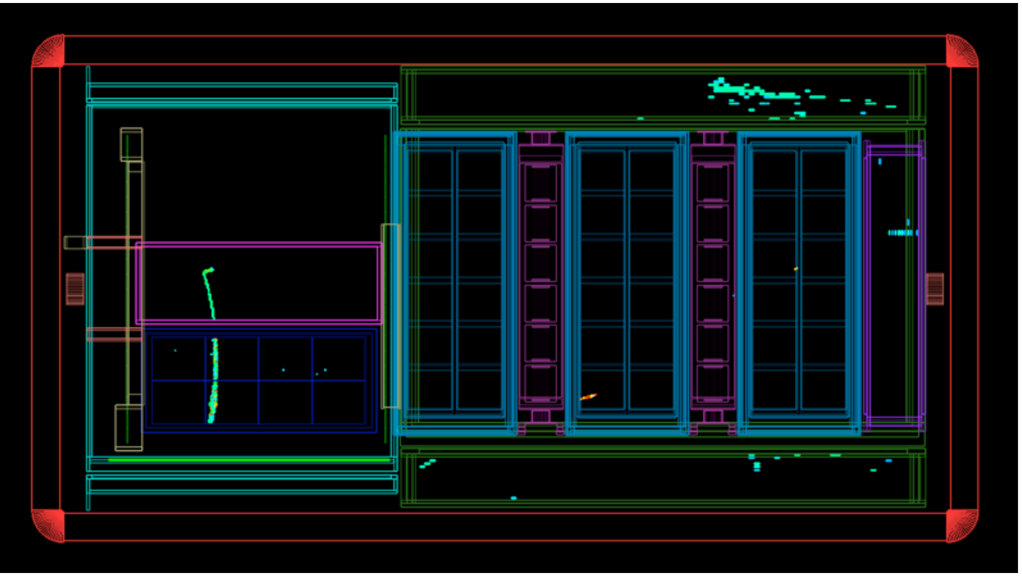


Event displays (December 2023)

[Looks like a…] **very high angle** muon, with forward-going **recoil proton**

- Would struggle to reconstruct this in the 'classic' tracker





Very busy event showing ND280 'classic' and upgrade detectors together

- Notice **higher resolution** of SuperFGD compared to original FGDs

Summary

T2K has been through an extensive renewal period

- Beam, ND280 (& SK) have all seen significant upgrades since 2021

Collaboration has been busy making significant improvements to analysis frameworks

- Significant additions to interaction physics model
- Integration of substantial new ND280 data set
- Oscillation analyses have expanded methods to make full combination with SK (& NOνA — next talk!)

Looking forward to new data that can make use of all these improvements

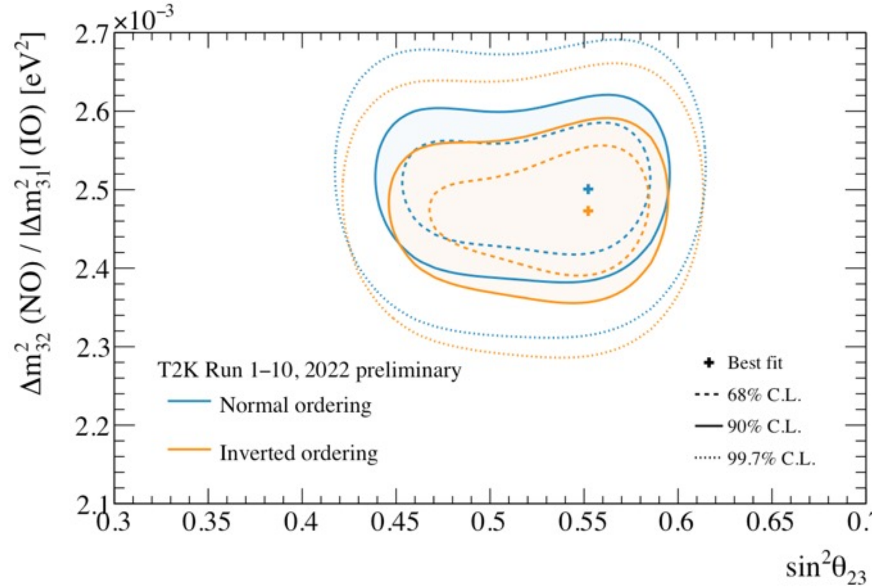
Reserves

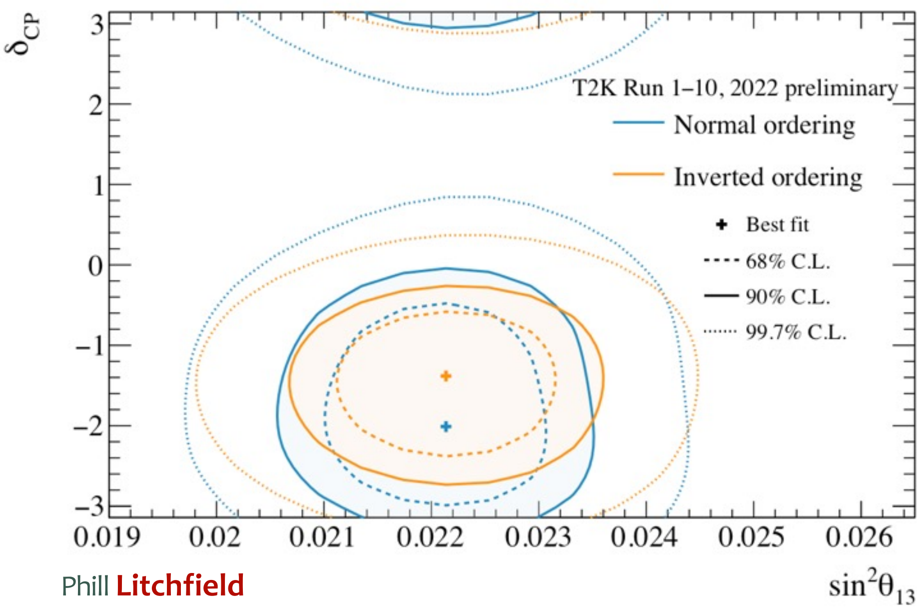
2024/03/29

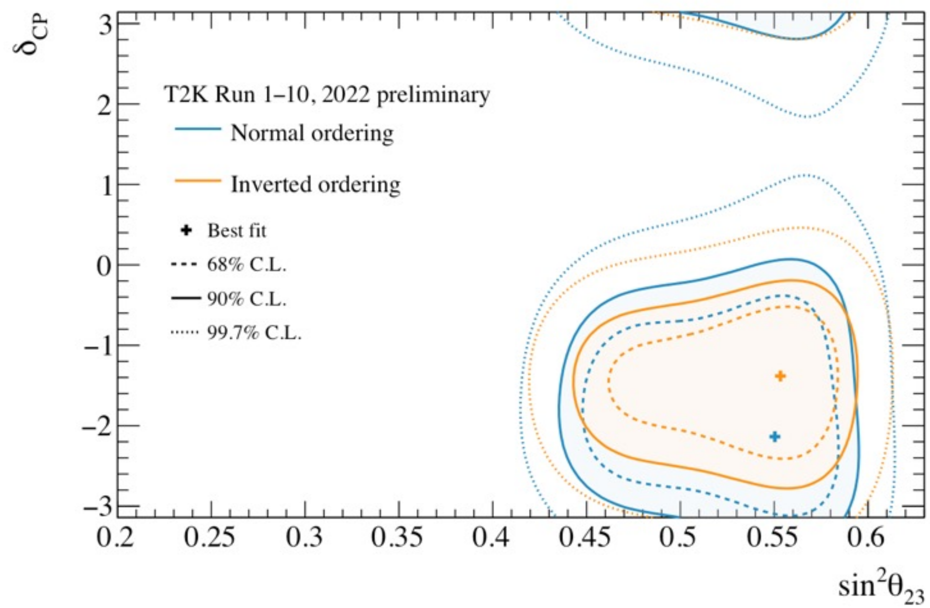
T2K-only latest results

- Find $\delta_{CP} = -0.63^{+0.31}_{-0.22}\,\pi$
- CPC values excluded at 90% CL

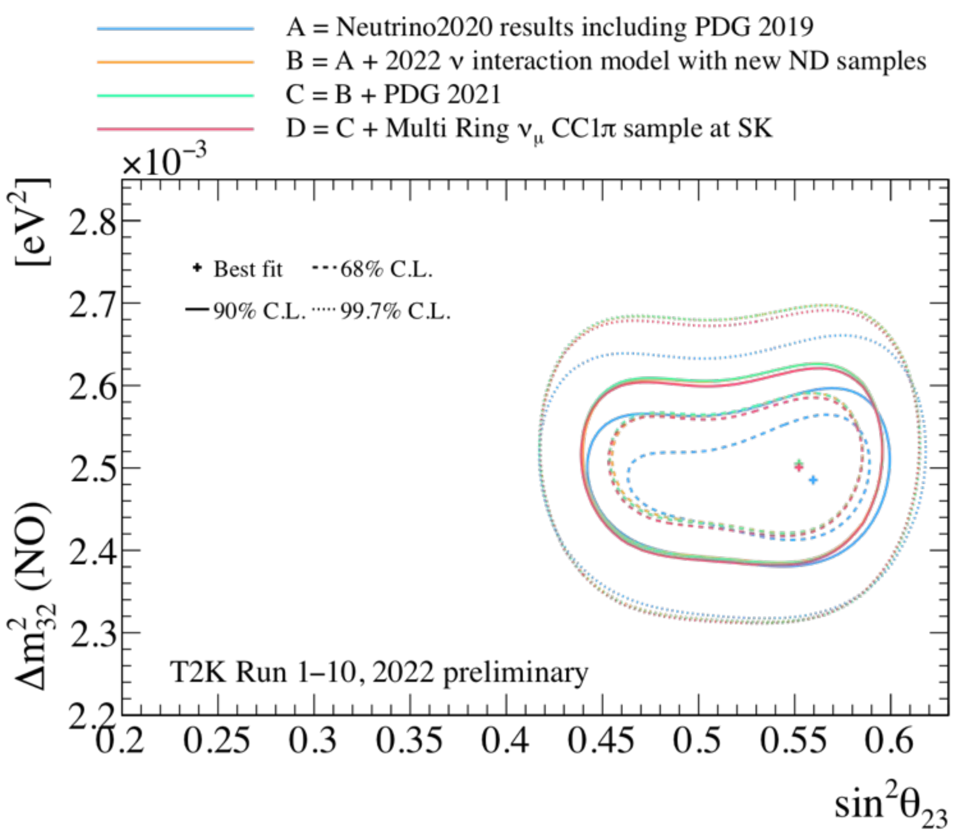
Posterior probability		$\theta_{23} < \frac{\pi}{2}$	$\theta_{23} > \frac{\pi}{2}$
		0.23	0.77
$\Delta m^2 > 0$	0.80	0.19	0.61
$\Delta m^2 < 0$	0.20	0.04	0.16

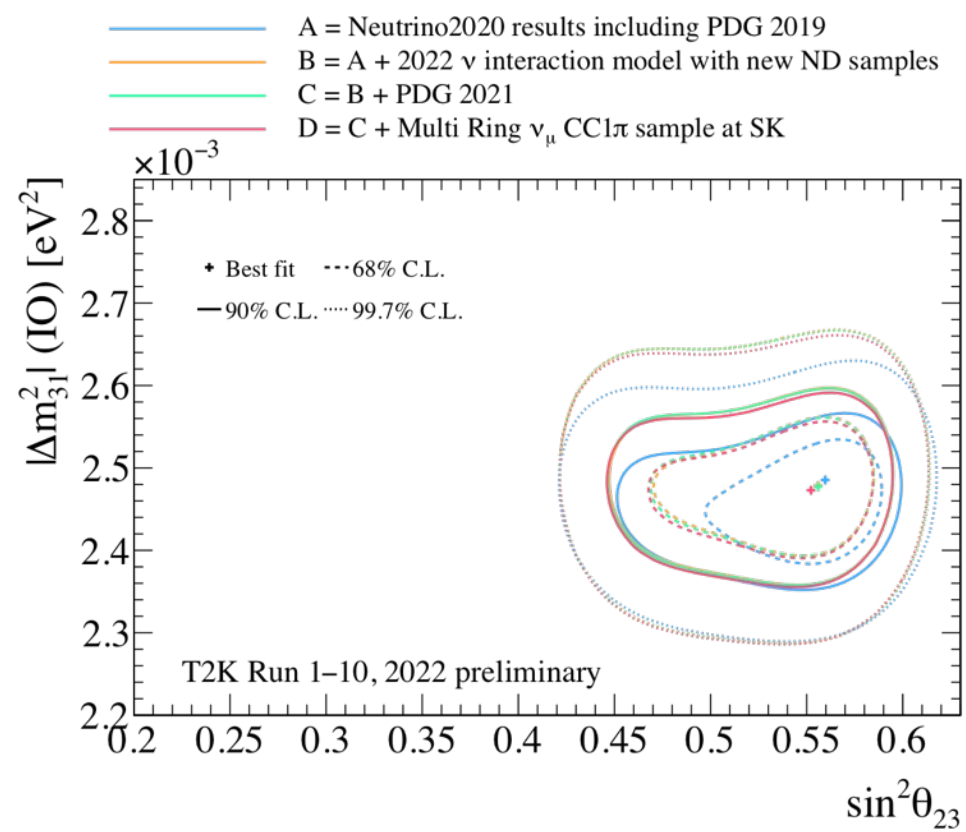




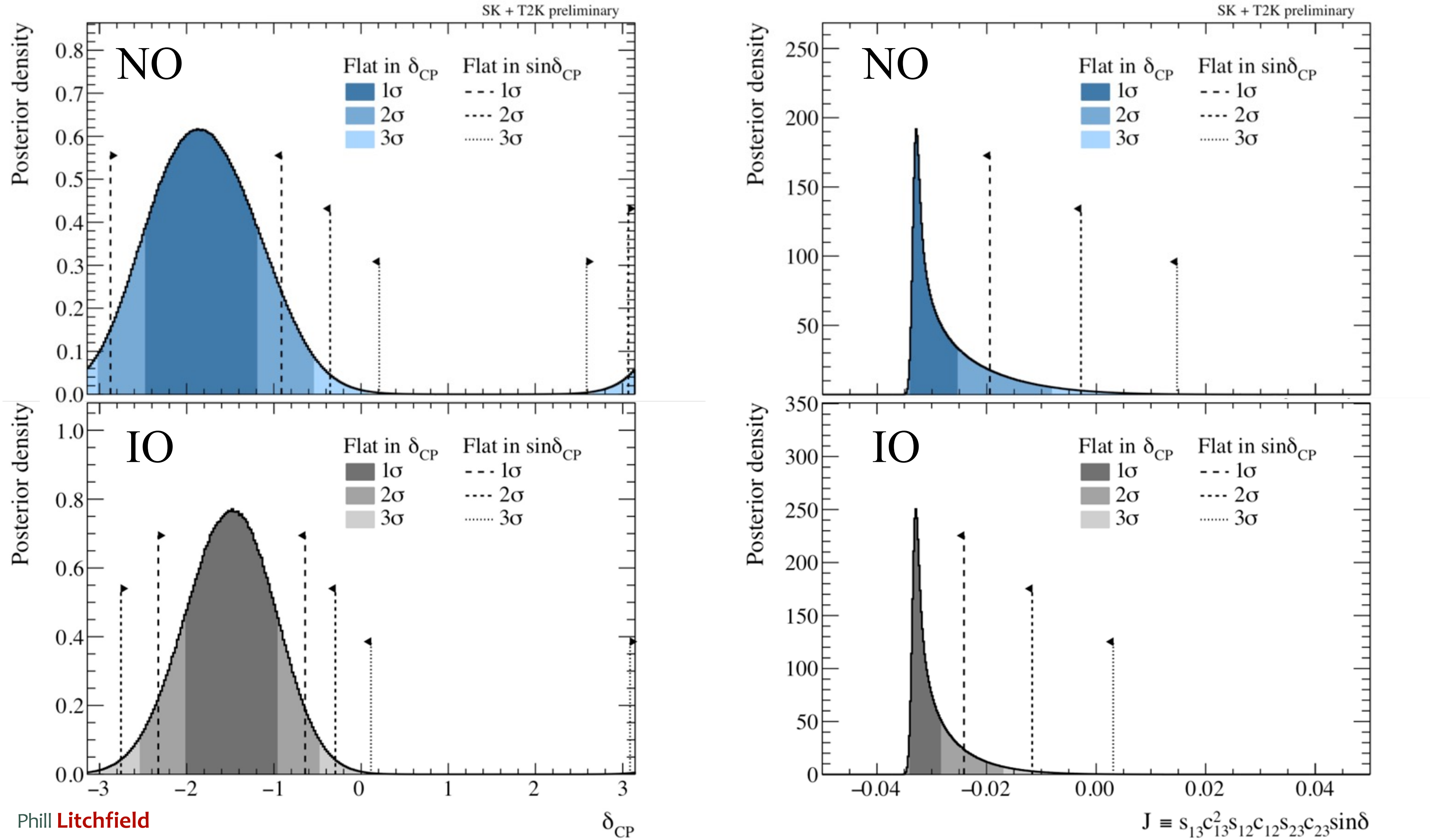


Disappearance: NO vs IO





Bayes intervals and CP



Matter effect in Earth

Matter effect dimensionless parameter:

$$2\sqrt{2}G_F n_e E \,/ \left|\Delta m^2_{31}\right|$$

Condition for matter term to dominate:

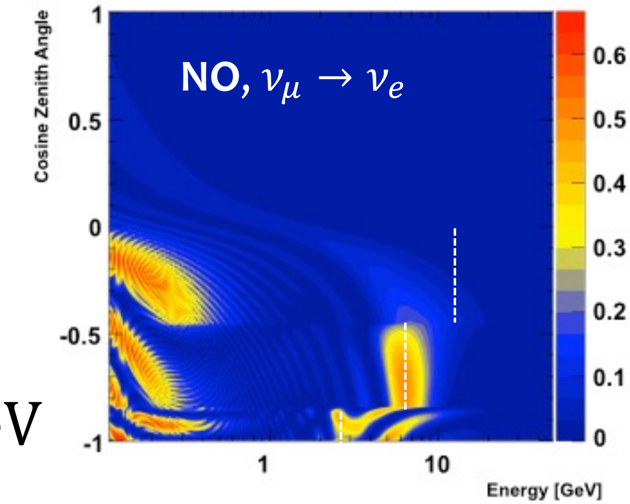
$$E \gtrsim \frac{\left|\Delta m^2_{31}\right|}{2\sqrt{2}G_F n_e} = \frac{33\ \mathrm{g\,cm^{-3}}}{\rho}\ \mathrm{GeV}$$

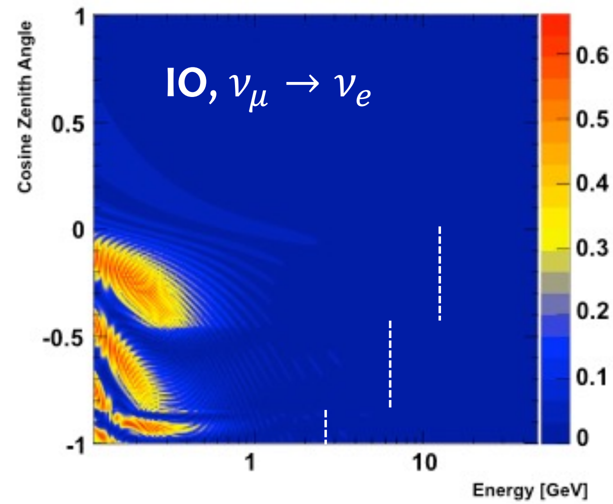
[Numbers from 2101.03779]

Crust/Upper mantle ($\rho \sim 2.6$): $E \gtrsim 13.\,\mathrm{GeV}$

Lower mantle ($\rho \sim 4.5$): $E \gtrsim 7.3\ \mathrm{GeV}$

Outer core ($\rho \sim 12$): $E \gtrsim 2.7\ \mathrm{GeV}$





Matter effect becomes important a bit below this