Exploration of the Symmetry in Particle Physics with an Accelerator Neutrino Beam

T. Nakaya (Kyoto) for the A02 group

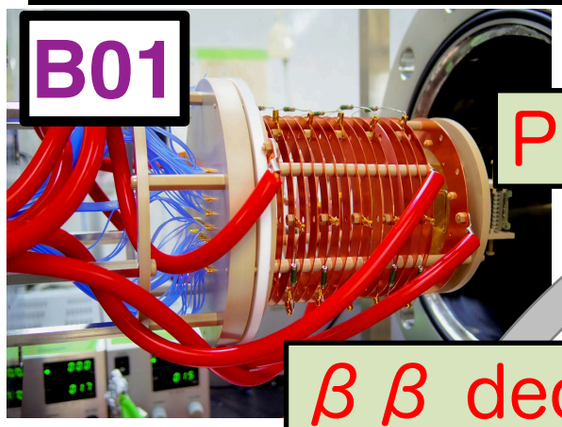
2023.3.29 @ Two infinities

Exploration of Particle Physics and Cosmology with Neutrinos

2018.7～2023.3 (A01-04, B01-02, C01-02)

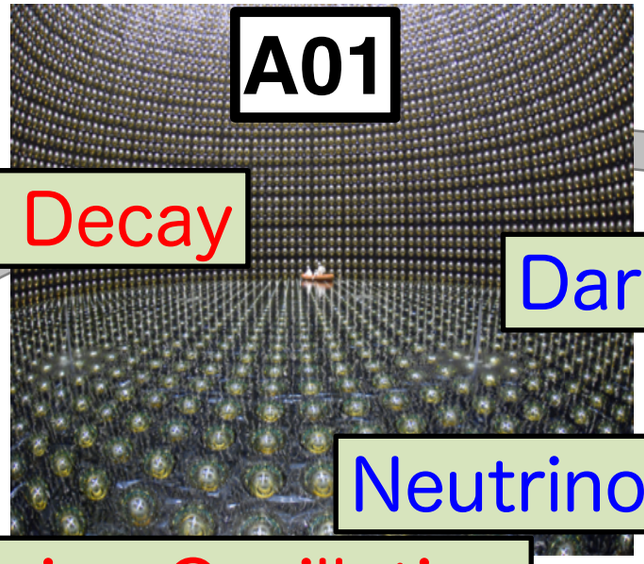
Particle Physics

Cosmology



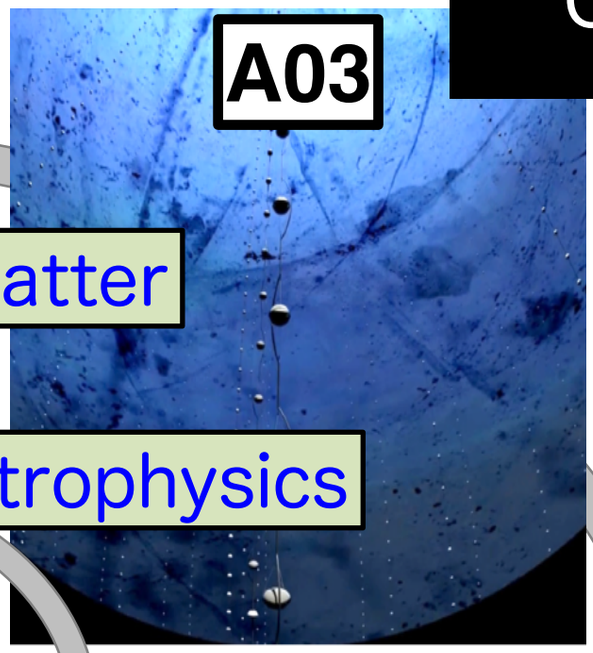
Proton Decay

$\beta\beta$ decay



Neutrino Oscillation

Dark Matter



Neutrino Astrophysics

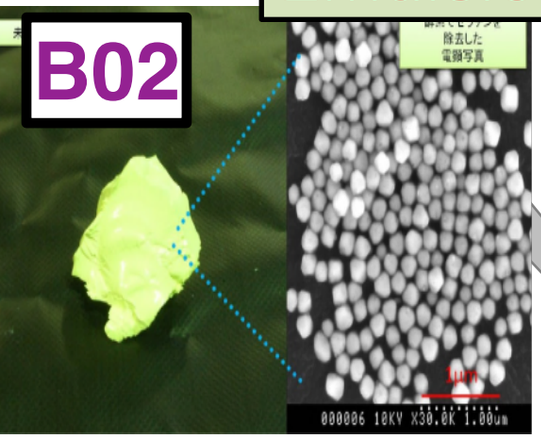
Inflation

A04

Neutrino mass

Neutrino Frontier

Emulsion



CP violation

Photon Sensor

theory

C01

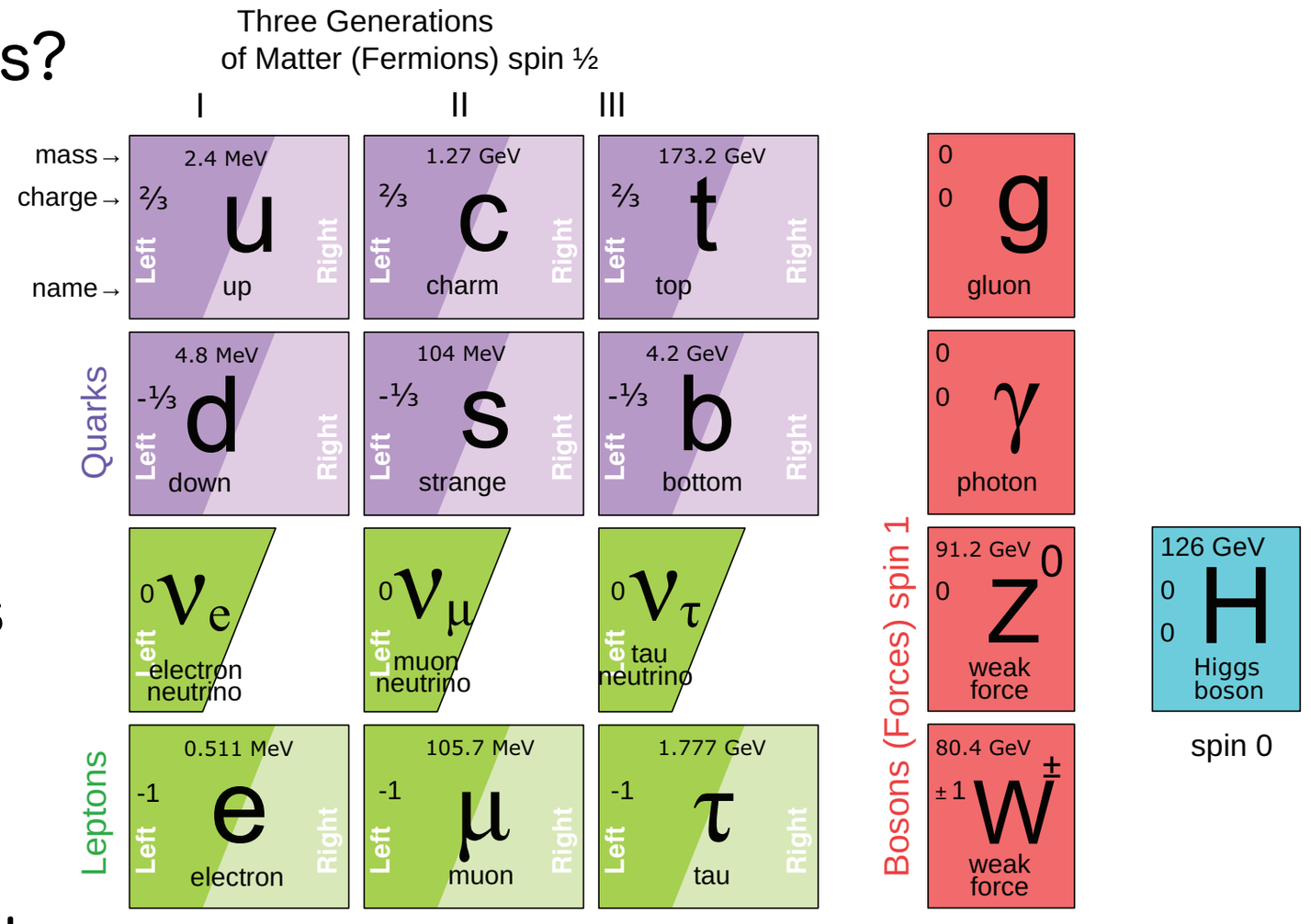
C02 New Physics

phenomenology

Introduction

- Neutrino mass and mixing (right handed neutrinos) are physics beyond the standard model.

- Tiny Neutrino mass
  - What is the origin of the mass?
- Flavor Symmetry
  - Between leptons and quarks
    - mass pattern
    - mixing pattern
    - the number of generations
- CP violation
  - the origin?
  - matter dominant universe with Leptogenesis



Accelerator Neutrino Experiments in J-PARC

T2K

Gigantic detector

$\Phi_\nu^{SK}(E_\nu)$

$\Phi_\nu^{ND}(E_\nu)$

Neutrino Cross sections

Intense Beam

ν, ν, ν, ν

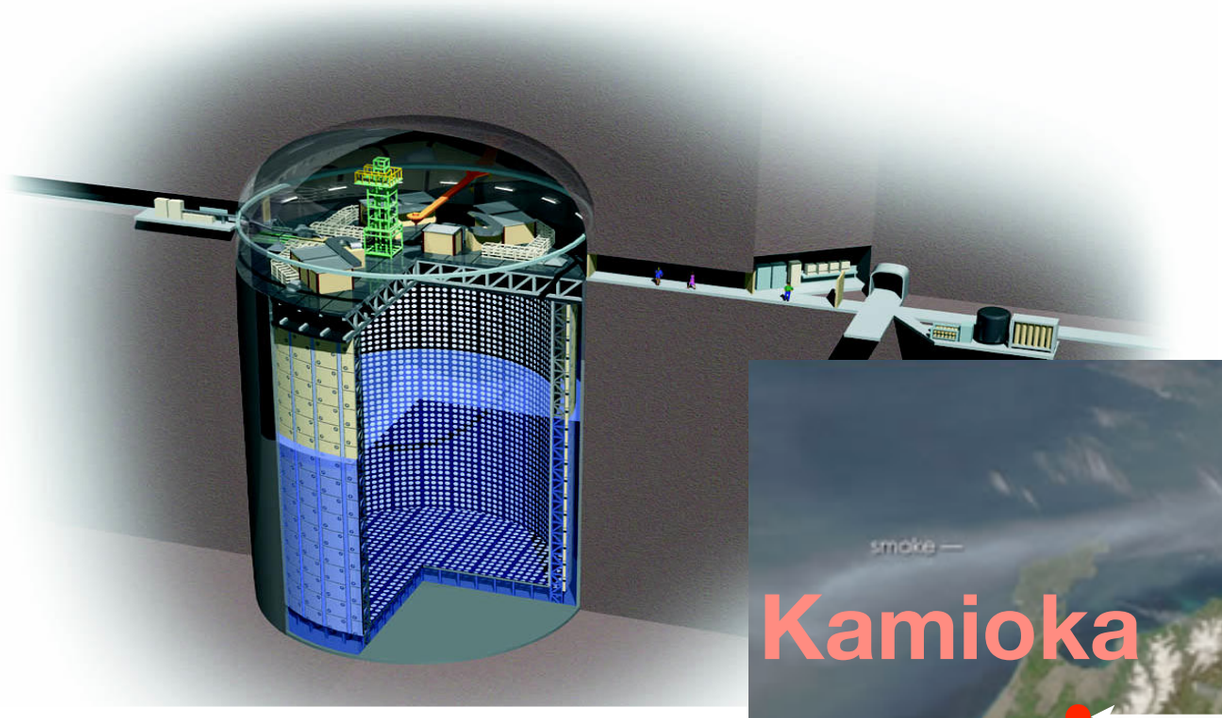
Oscillation

π, π, π, π, K

Proton Beam

ND280

NINJA



Credit: Super-K collaboration

Credit: J-PARC

$$N_{signal} = \Phi \times \sigma \times N_{target} \times \varepsilon \times P$$

Improvements of oscillation measurements

Φ — Higher Beam flux
- J-PARC
- Nu beam line

σ — Better understanding of Neutrino Cross Sections
- T2K ND280
- NINJA

$\varepsilon \times P$ — Osc. analysis
$\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$, Δm_{32}^2, δ_{CP}

→ ***Result***

Goals of this Grant-in-Aid project

<u>Study of symmetries in neutrino oscillations</u>

- **θ_{23} precisions better than 5%**
- **CP violation (δ_{CP}) with 99% CL for the maximum CPV**

① [J-PARC] Handling of the higher beam power with development of new beam monitors (16 electrodes BPM)

- 5×10^{21} POT will be accumulated for high statistics

② [NINJA] Better understanding of neutrino interactions

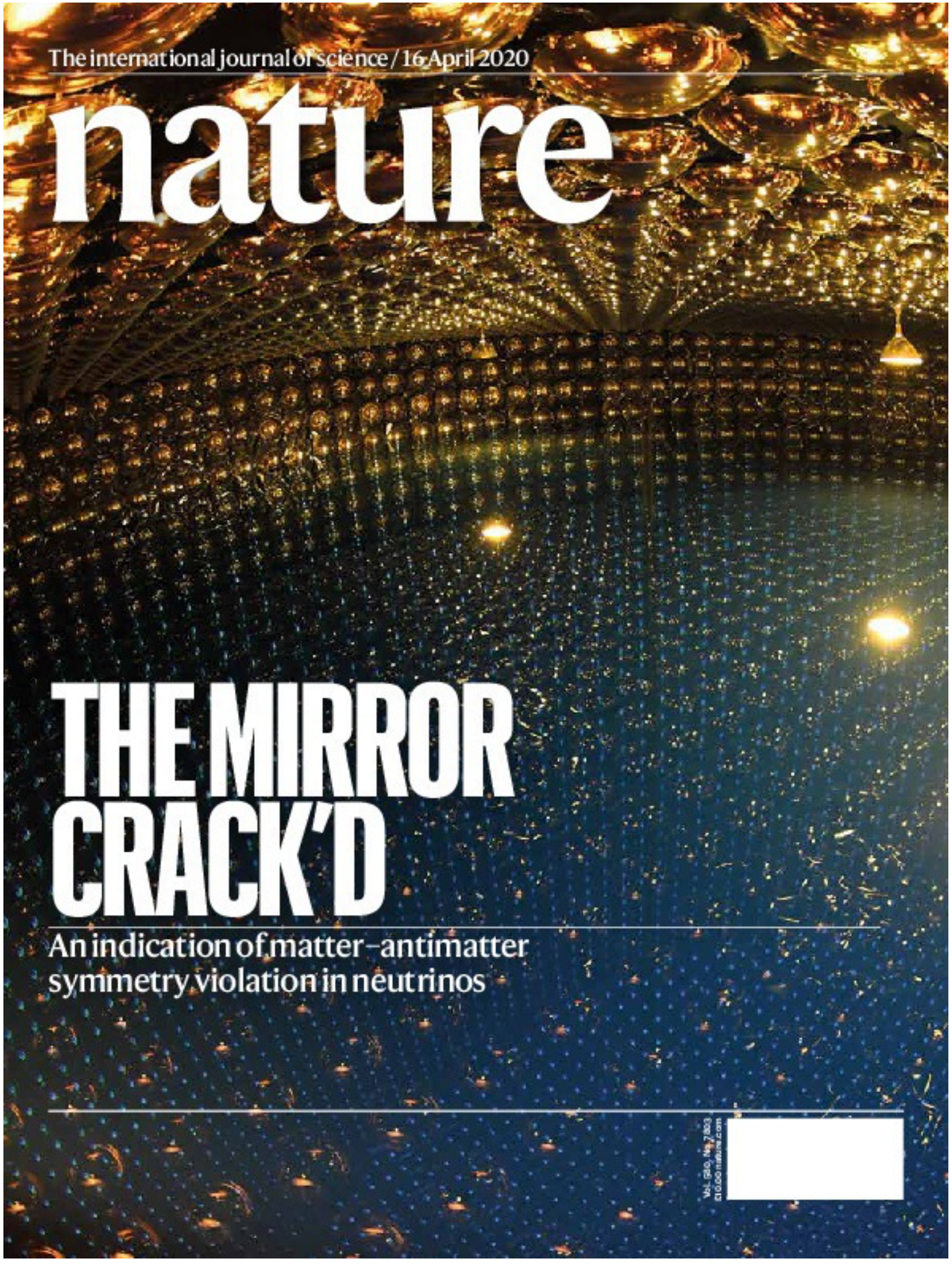
- 10% precision for neutrino cross sections

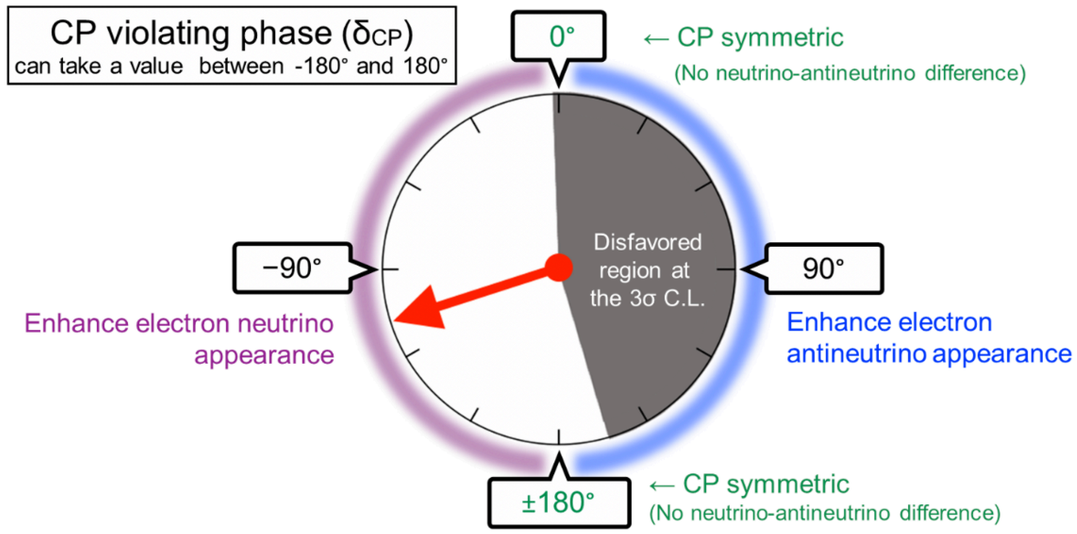
③ [T2K] Improvements of oscillation measurements

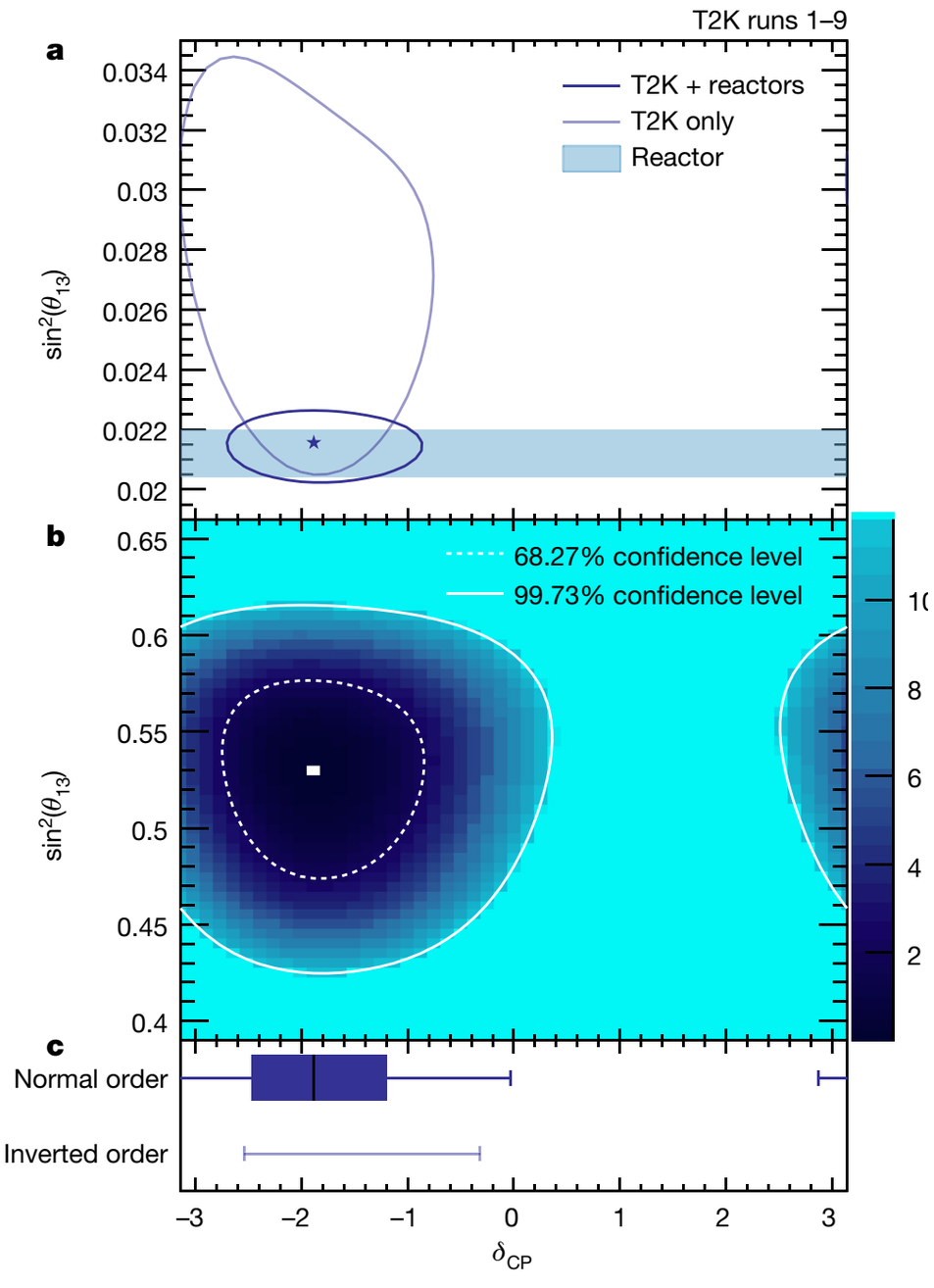
- θ_{23} precisions better than 5%
- CP violation (δ_{CP}) with 99% CL for the maximum CPV

T2K and NINJA presentations

- T2K results today at 14:30 by. Dr. Tatsuya KIKAWA
  - *Recent results and future prospects from the T2K experiment*
- NINJA results today at 17:45 by Dr. Tsutomu FUKUDA
  - *Precise measurement of Neutrino Interactions at J-PARC in the NINJA experiment*

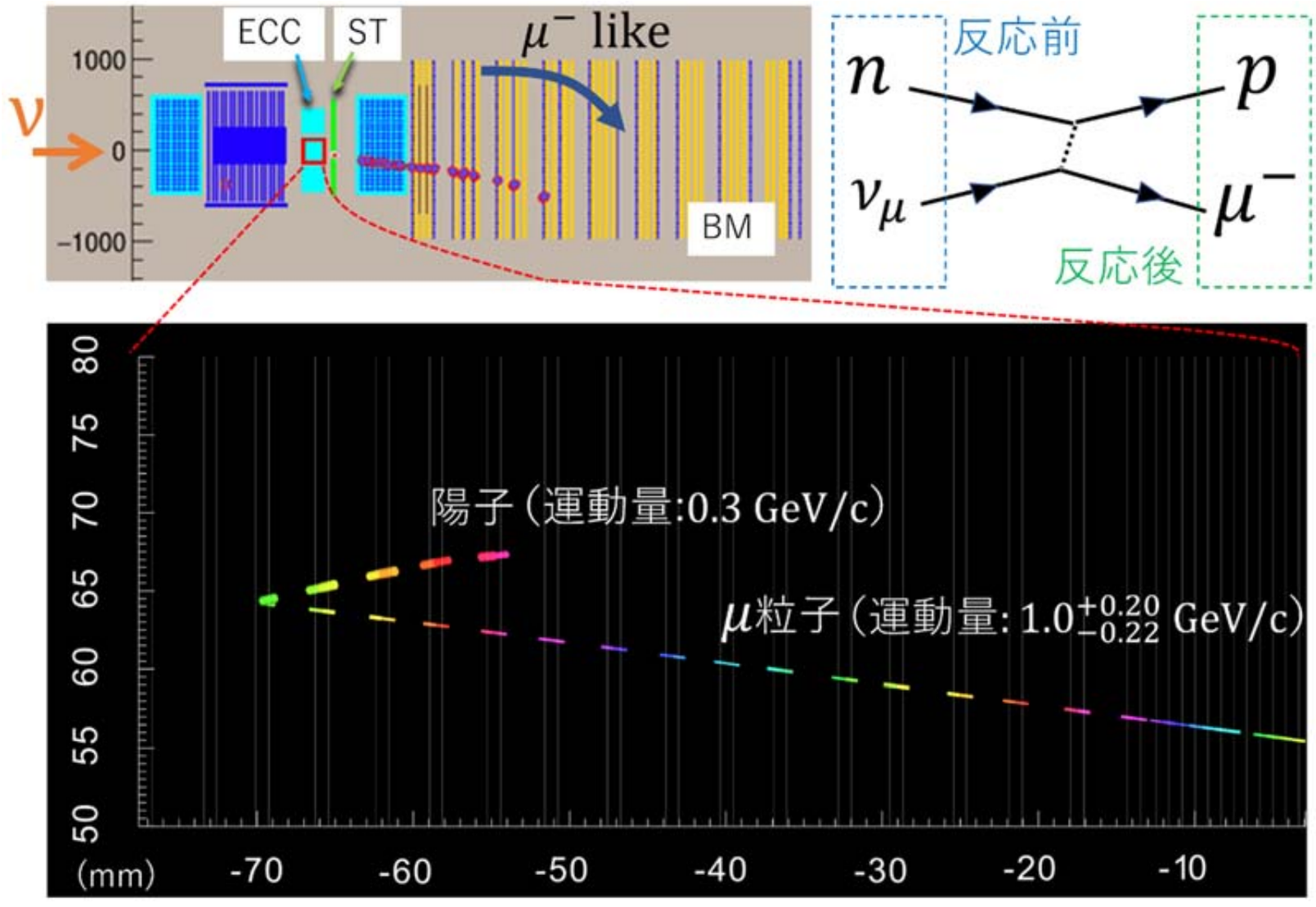

The international journal of science / 16 April 2020
nature
THE MIRROR CRACK'D
An indication of matter–antimatter symmetry violation in neutrinos


CP violating phase (δCP)
can take a value between -180° and 180°
0°
← CP symmetric
(No neutrino-antineutrino difference)
−90°
90°
Disfavored region at the 3σ C.L.
Enhance electron neutrino appearance
Enhance electron antineutrino appearance
±180°
← CP symmetric
(No neutrino-antineutrino difference)


T2K runs 1–9
a
T2K + reactors
T2K only
Reactor
sin²(θ13)
b
68.27% confidence level
99.73% confidence level
c
Normal order
Inverted order
δCP

NINJA physics analysis started

Press release in October 20, 2020



精密測定により素粒子ニュートリノの謎の解明を目指す
NINJA 実験の物理解析が開始！

J-PARC Accelerator and Neutrino beam

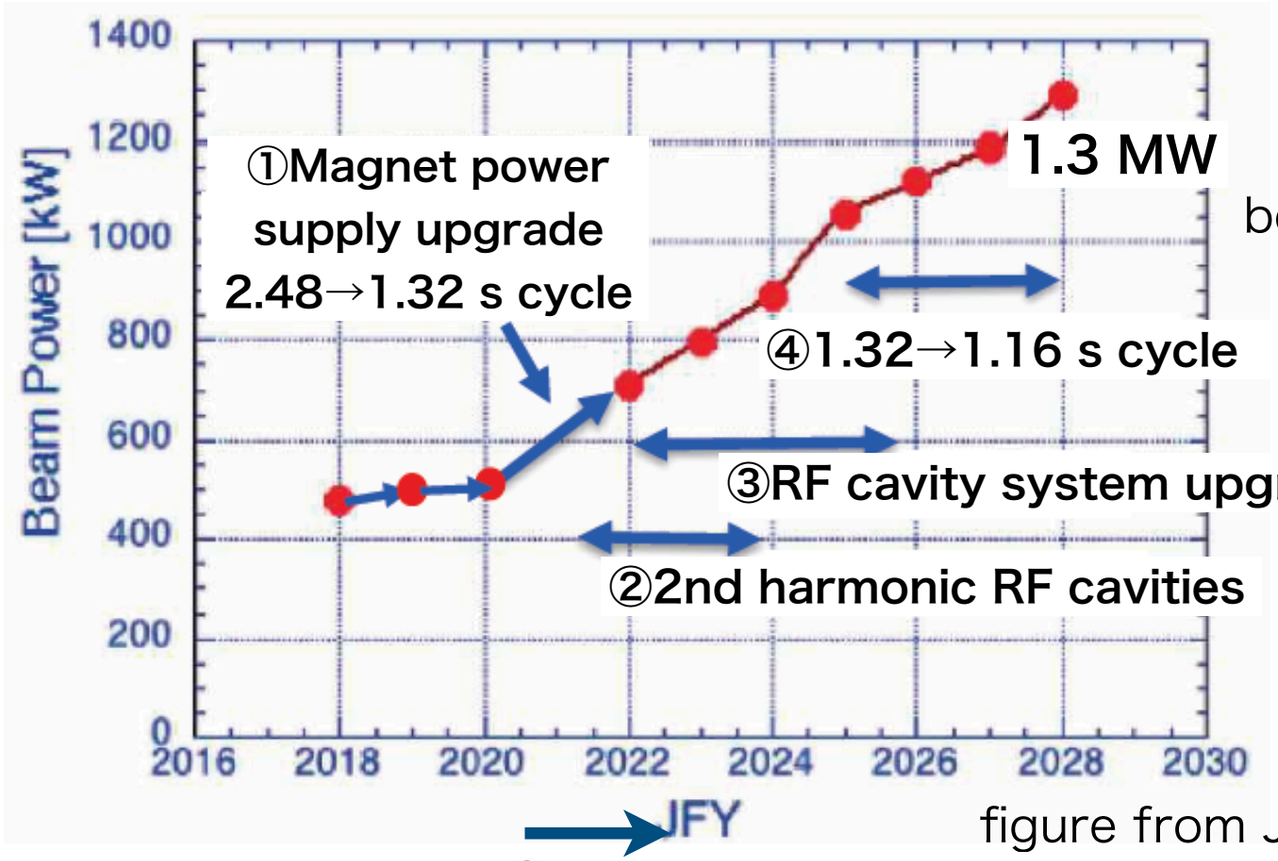
by Dr. Aine Kobayashi @ Exploration of Particle Physics and Cosmology with Neutrino work shop 2022

J-PARC MR beam power upgrade plan

more protons, faster cycle, less beam loss

Power = Energy × Number of protons per pulse / Cycle time

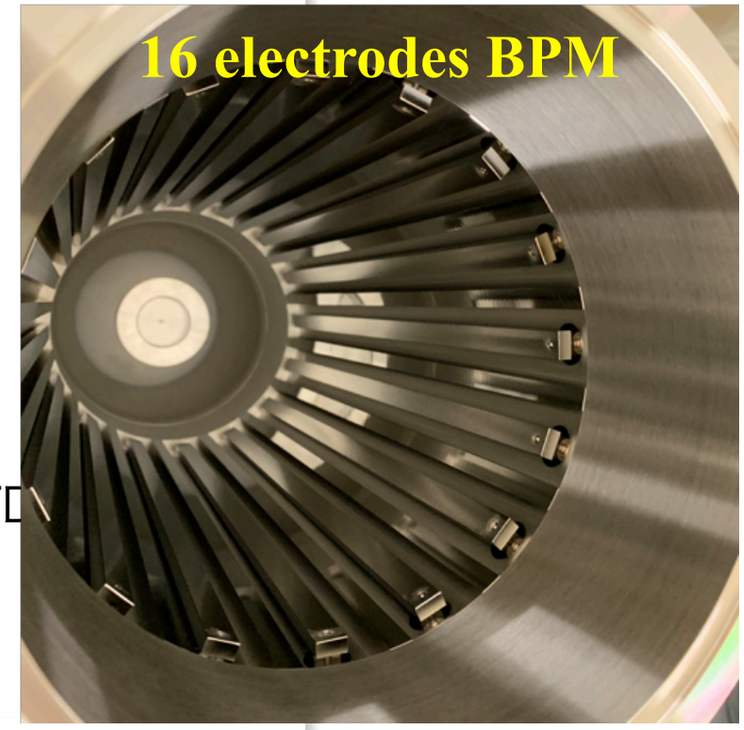
keep 30 GeV　　30 % up　　half

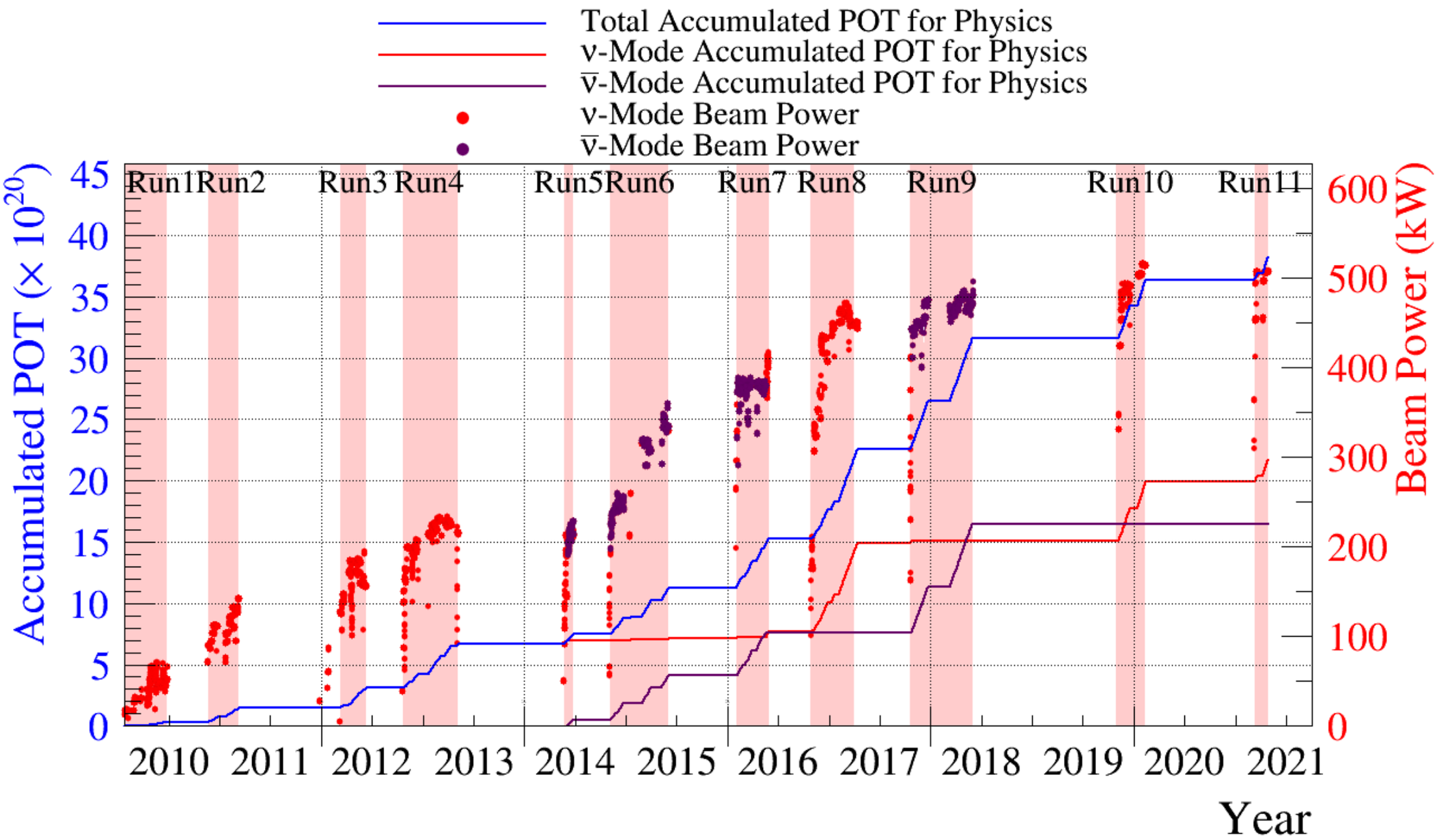


beam loss requiments

figure from J-PARC TD

⑤ Collimetor system
⑥ Injection/FX system
⑦ Beam monitors





23 Jan 2010 – 27 Apr 2021
POT Total: 3.82×10^{21}
(maximum power 522.6 kW)

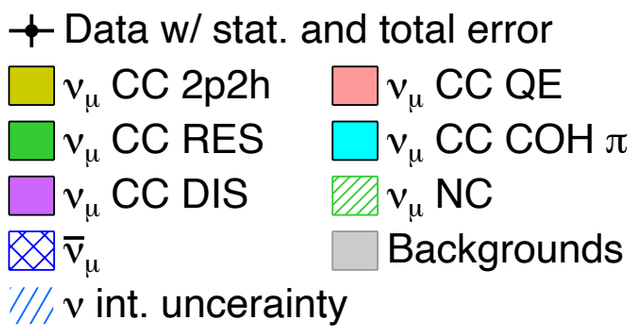
ν-mode: 2.17×10^{21} (56.8%)
$\bar{\nu}$-mode: 1.65×10^{21} (43.2%)

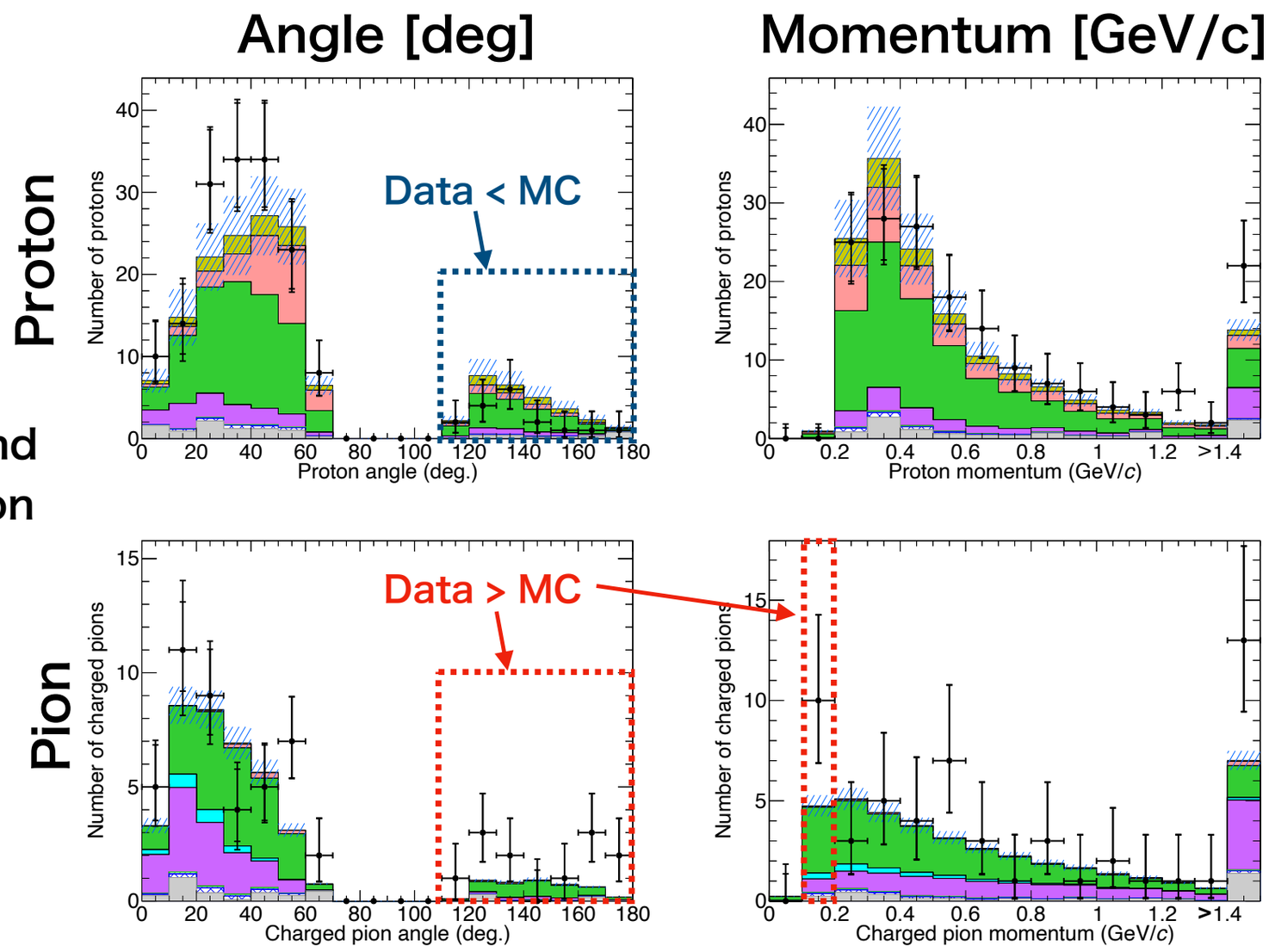
Neutrino Cross-section results from NINJA

Iron target results

Water target results are coming!

- Measurement of charged hadrons from muon neutrino interactions on iron.





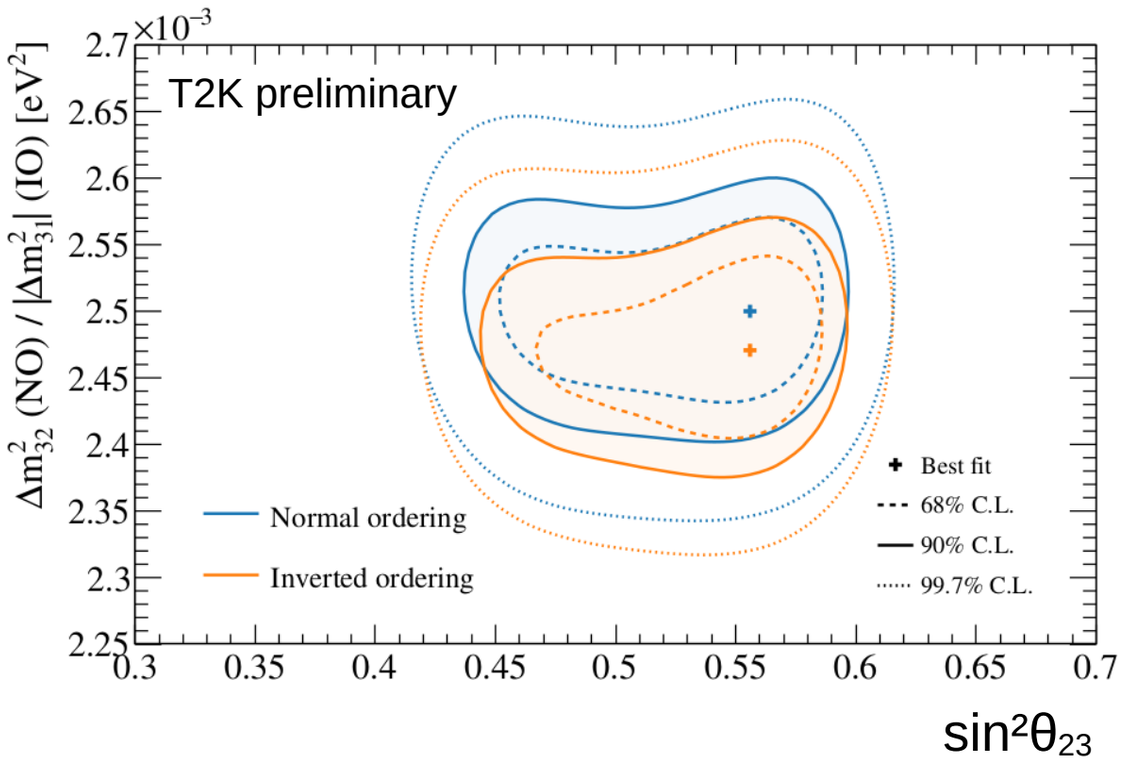
Some discrepancies have found b/w the data and MC prediction

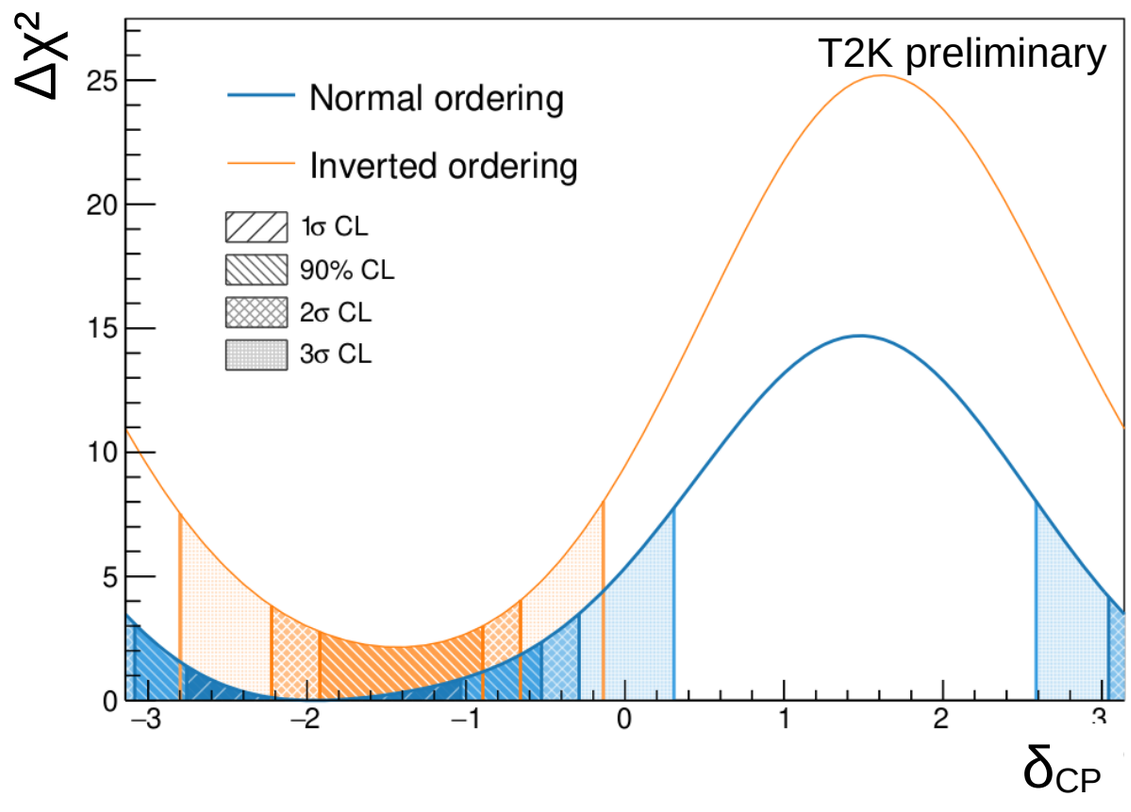
- Mean neutrino energy = 1.49 GeV
- 4.0 × 10^{19} protons on target
- 183 events

Phys. Rev. D 106, 032016 (2022)

Latest Oscillation results from T2K

- Best fit in the upper θ_{23} octant, but lower octant still allowed at the 1σ level
- CP-conserving values of δ=0 and δ=π outside of 90% CL intervals





Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

by Dr. Christophe Bronner @ Exploration of Particle Physics and Cosmology with Neutrino work shop 2022

Achievements

① [J-PARC] We accumulated 3.8 x 10^{21} POT before 2021.

- Goal: 5 x 10^{21} POT will be accumulated for high statistics

② [NINJA] Cross section results with Iron target. Results with Water target are coming (1/9 data has been shown).

- Goal: 10% precision for neutrino cross sections

③ [T2K] New results released at Neutrino 2022.

- Goal: θ_{23} precisions better than 5%
- Goal: CP violation (δ_{CP}) with 99% CL for the maximum CPV

Prospect and Summary

- J-PARC is now ready to provide the high beam power of 700~800 kW.
- Full data of water targets in NINJA are on process, and will be released soon.
- Oscillation analysis in T2K is improved.
- It becomes more exciting to take and analyze neutrino beam data in T2K and NINJA. Stay tuned!

Backup

Latest Oscillation results from T2K

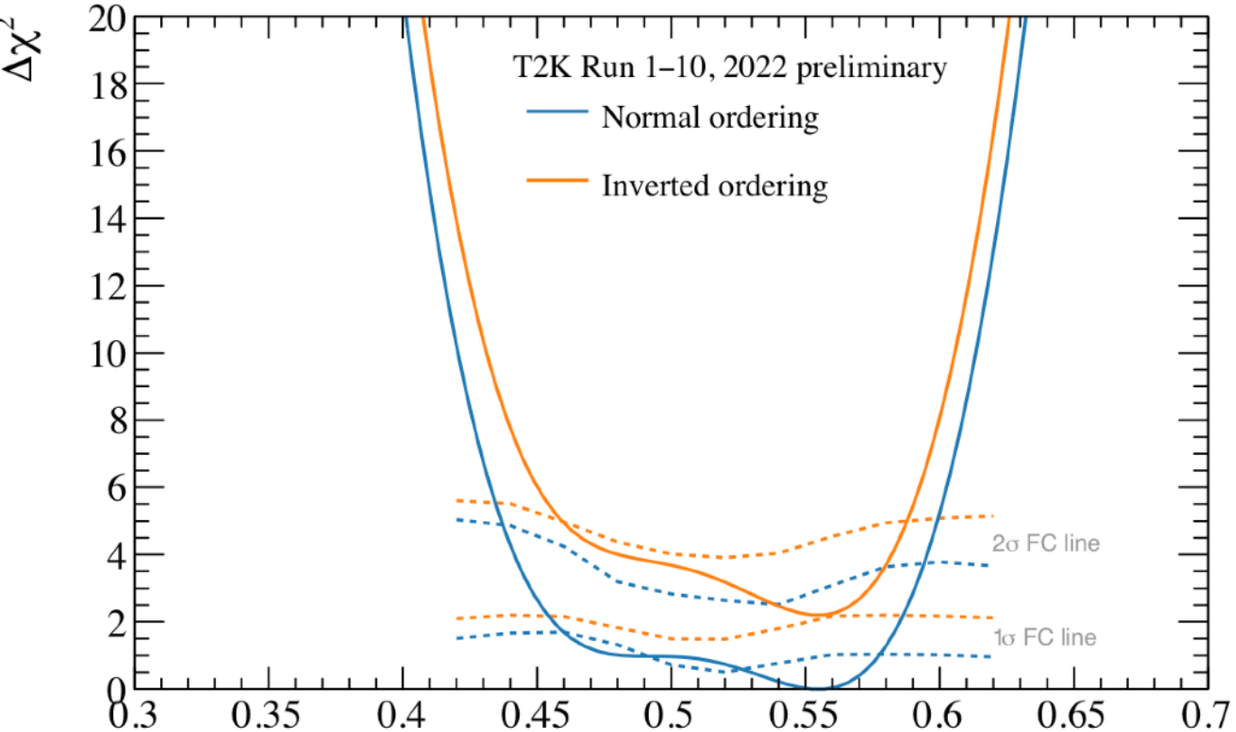


Table 35: Feldman-Cousins confidence intervals for $\sin^2\theta_{23}$.

Confidence level	Interval (NH)	Interval (IH)
1σ	$[0.460, 0.491] \cup [0.526, 0.578]$	
90%	$[0.444, 0.589]$	$[0.525, 0.582]$
2σ	$[0.437, 0.594]$	$[0.459, 0.588]$

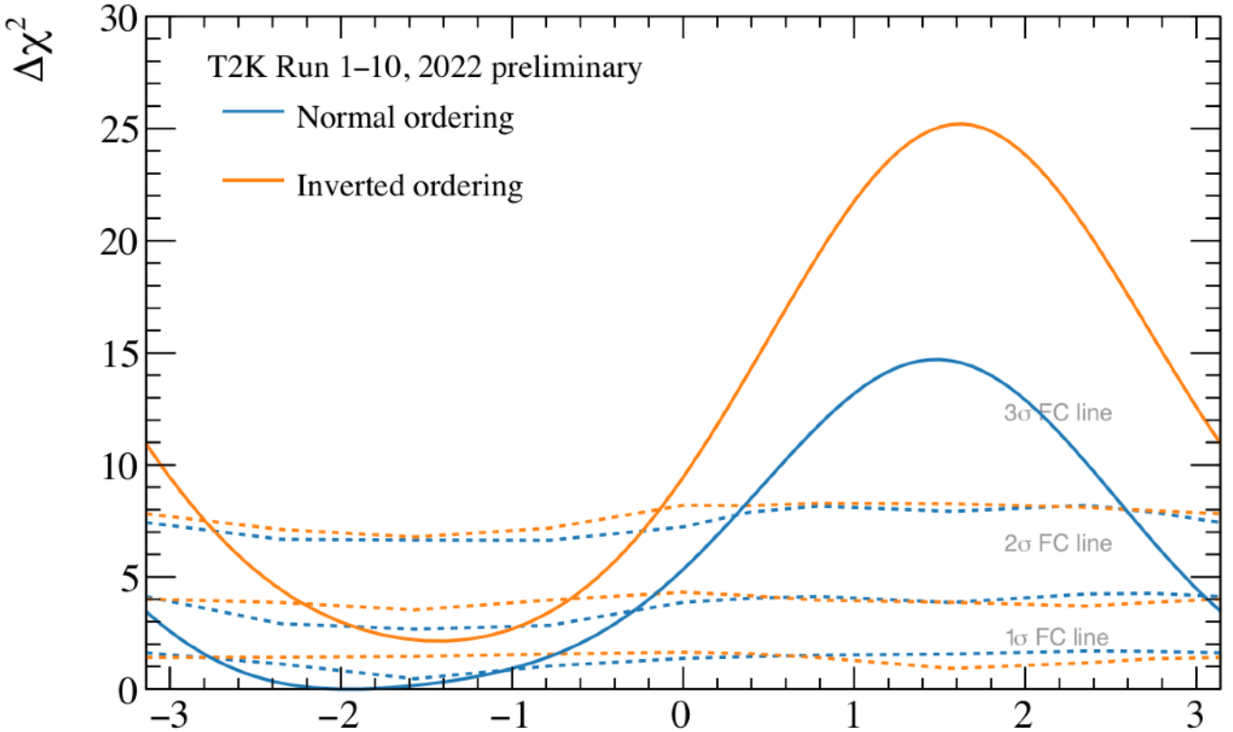


Table 34: Feldman-Cousins confidence intervals for δ_{CP}.

Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.76, -1.03]$	
90%	$[-3.08, -0.52]$	$[-1.92, -0.89]$
2σ	$[-\pi, -0.29] \cup [3.04, \pi]$	$[-2.22, -0.66]$
3σ	$[-\pi, 0.31] \cup [2.59, \pi]$	$[-2.80, -0.14]$