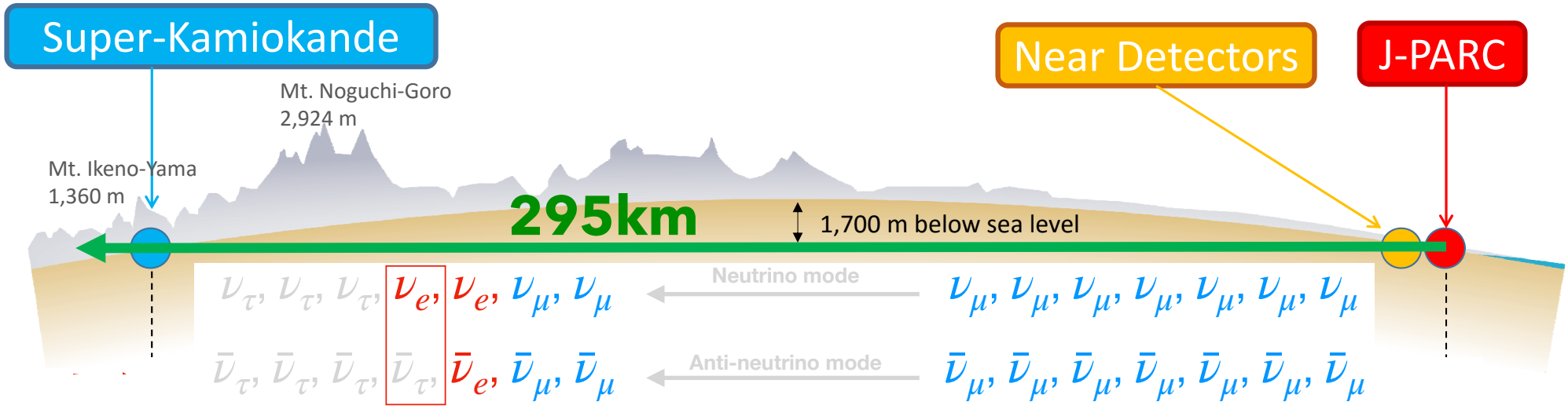
T2K

2024/2/19, NPB2024

Ken Sakashita (KEK/J-PARC) for T2K collaboration

T2K experiment



~570 members, 78 institutes,

14 countries(incl. CERN)

Open questions about neutrino oscillation

- **CP violation ?**

  $\delta_{CP} \neq 0$ and π ?

Matter-antimatter asymmetry

- **What is the neutrino mass ordering ?**

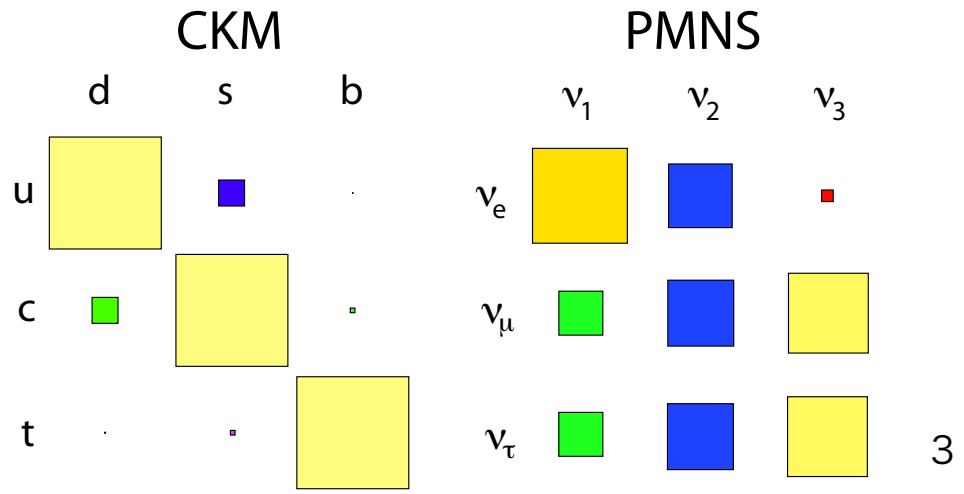
  $m_2 < m_3$ or $m_2 > m_3$?

impacts to 0νββ
→origin of ν mass

- **$\theta_{23} = \pi/4$?**

  or $\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$?
  (octant)

Flavor symmetry model

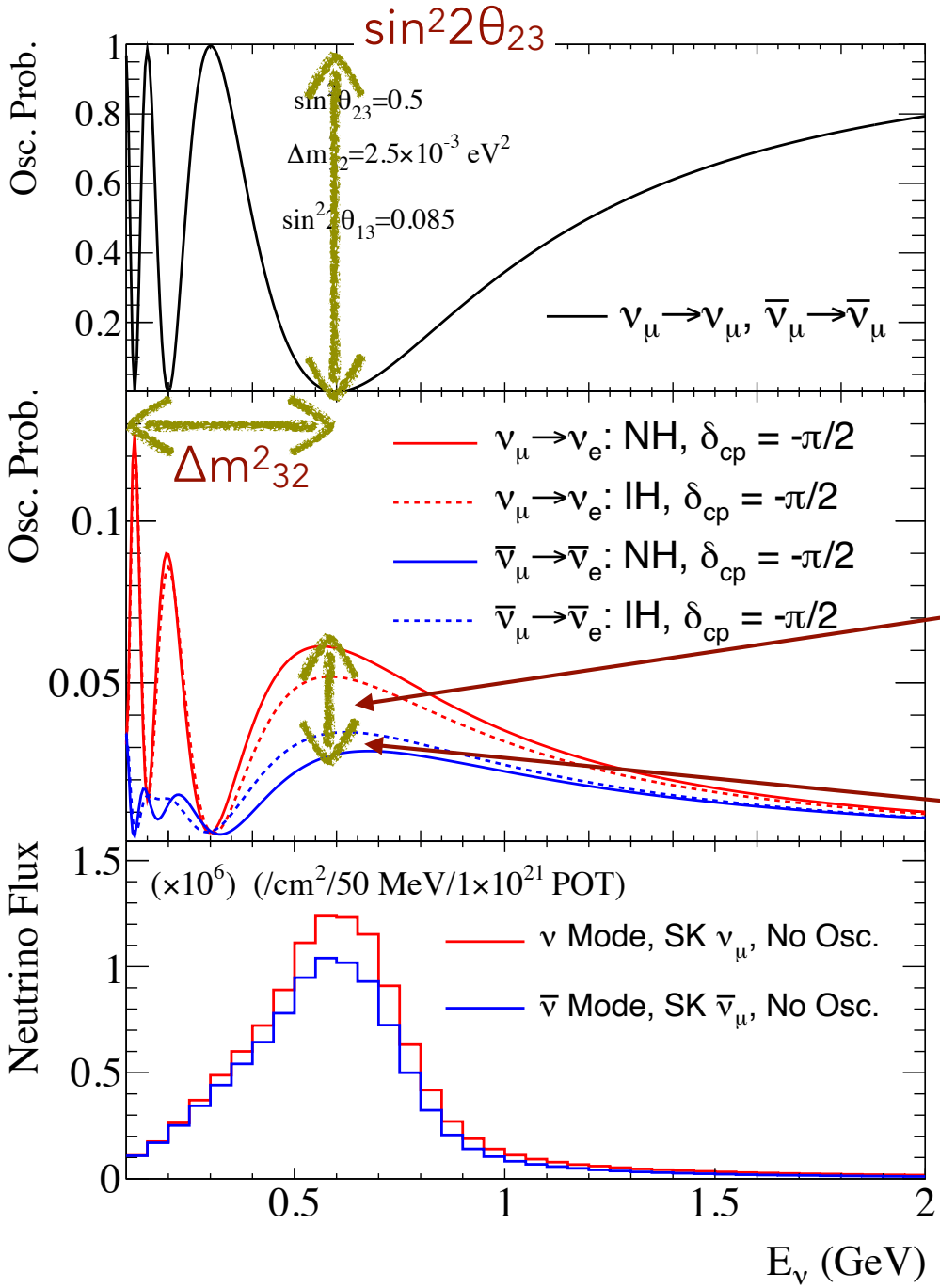


Area ~ U^2
S.Stone, PoS(ICHEP2012)933

Contents

- Introduction
- Latest oscillation analysis results [improvements]
- Joint oscillation analysis [diff. L & E]
- T2K enters a new phase
- Summary

What can we know neutrino oscillation from T2K ?



precise measurement of
$\sin^2 2\theta_{23}$, Δm^2_{32}

of ν_e vs # of $\bar{\nu}_e$

~ ±30% (large CPV effect)

δ_{CP}

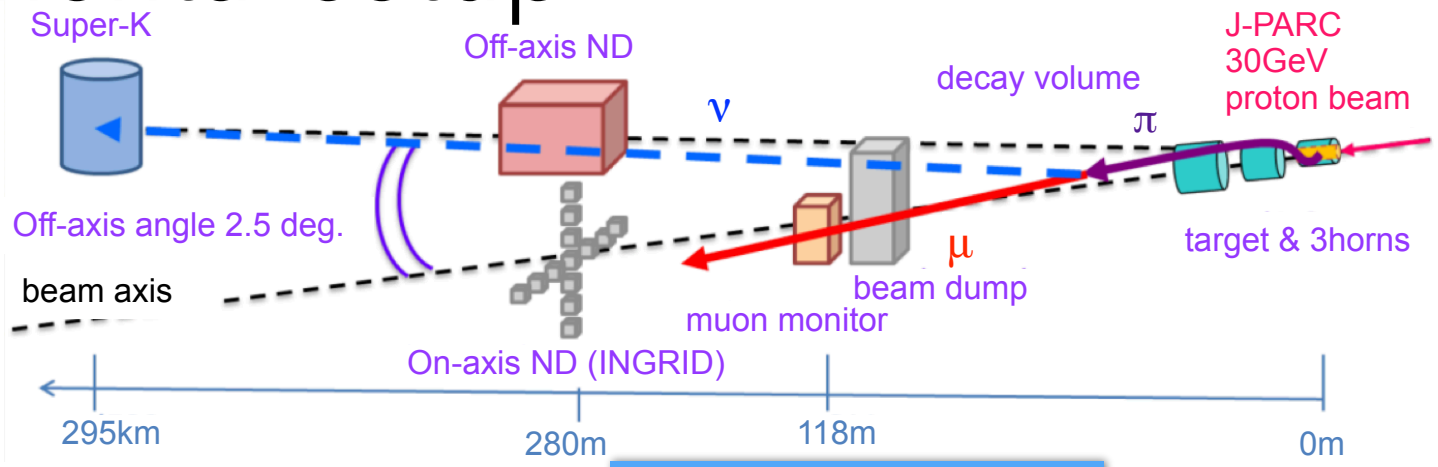
small matter effect $\text{sign}(\Delta m^2_{32})$

L = 295km

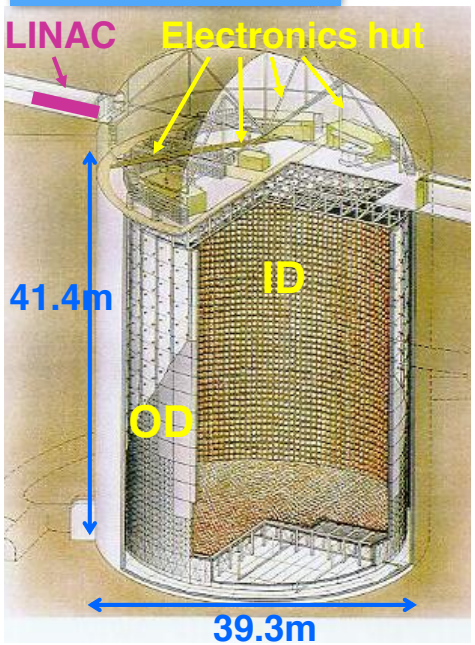
<E_ν> ~0.6GeV

Unique aspects of the T2K

Experimental setup

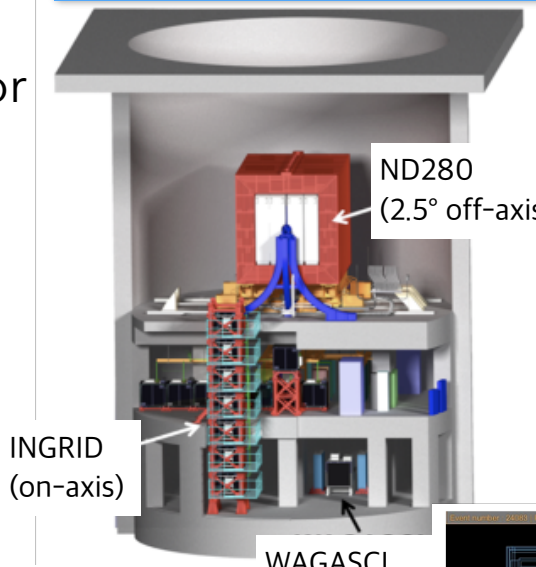


Far detector (FD)

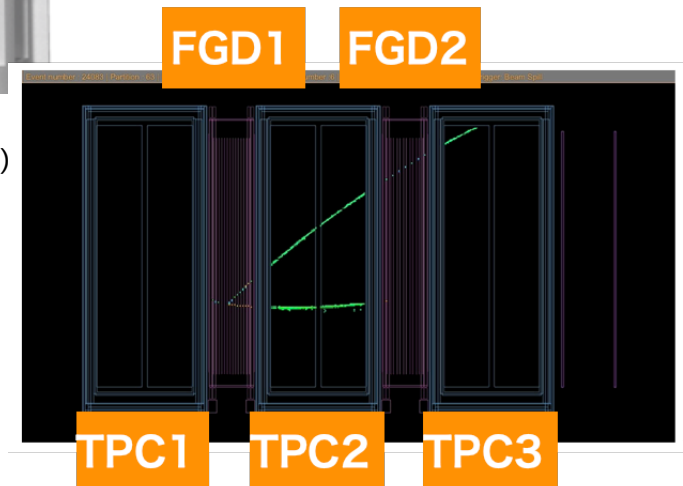


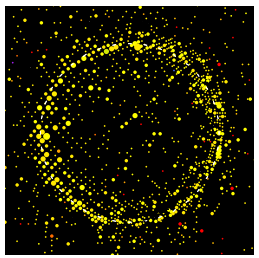
- 50kton water Cherenkov detector
- 4π acceptance
- **Recently, 0.03% Gd loaded**
  → enable use of neutron tagging

Near detector (ND)

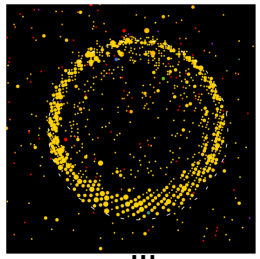


- ND280 det. in 0.2T UA1 magnet
- **Various ν-N interaction measurements**
- **ND280 upgrade is in progress**





ν_e-like



ν_μ-like

- Good e-like/μ-like separation (less than 1% mis-PID@1GeV, single ring)

Latest oscillation analysis results

data before 2020 + analysis improvements (shown at Neutrino2022)

What are the improvements ?

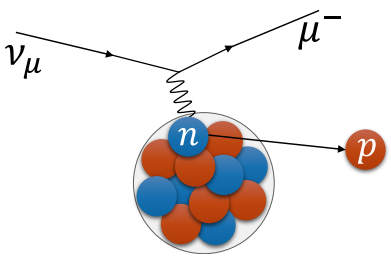
$$N_{FD}(E_{rec}) = \sum_{E_t} \Phi_{FD}(E_t) P_{osc}(E_t) \sigma(E_t) \epsilon_{FD}(E_t, E_{rec})$$

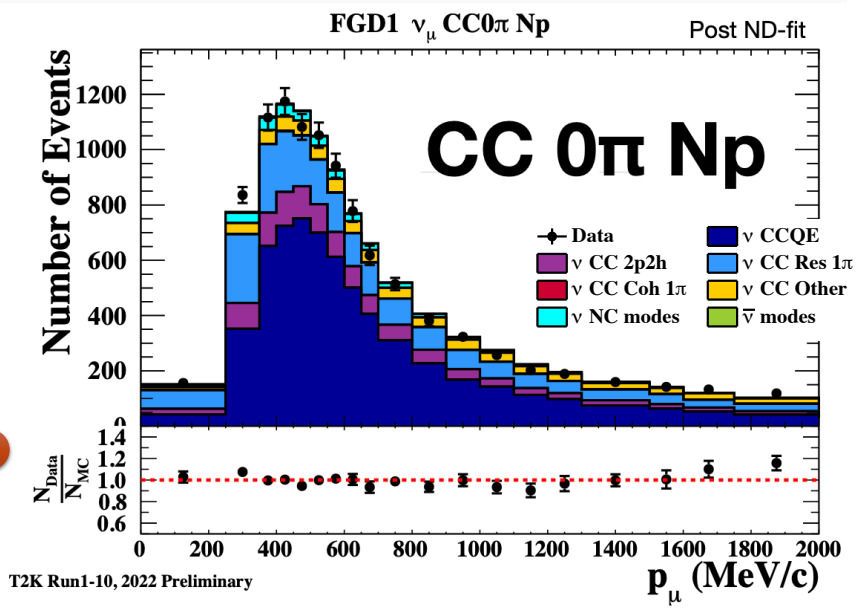
E_t:true ν energy, ε:efficiency

constraint using Near Detector (ND) data

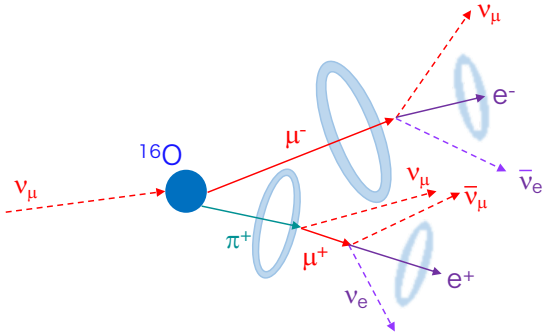
New modeling of flux based on horn water, NA61/SHINE 2010 replica target data

New ND samples (18→22): Separated events by π, p, γ multiplicity to constrain ν-N int. model



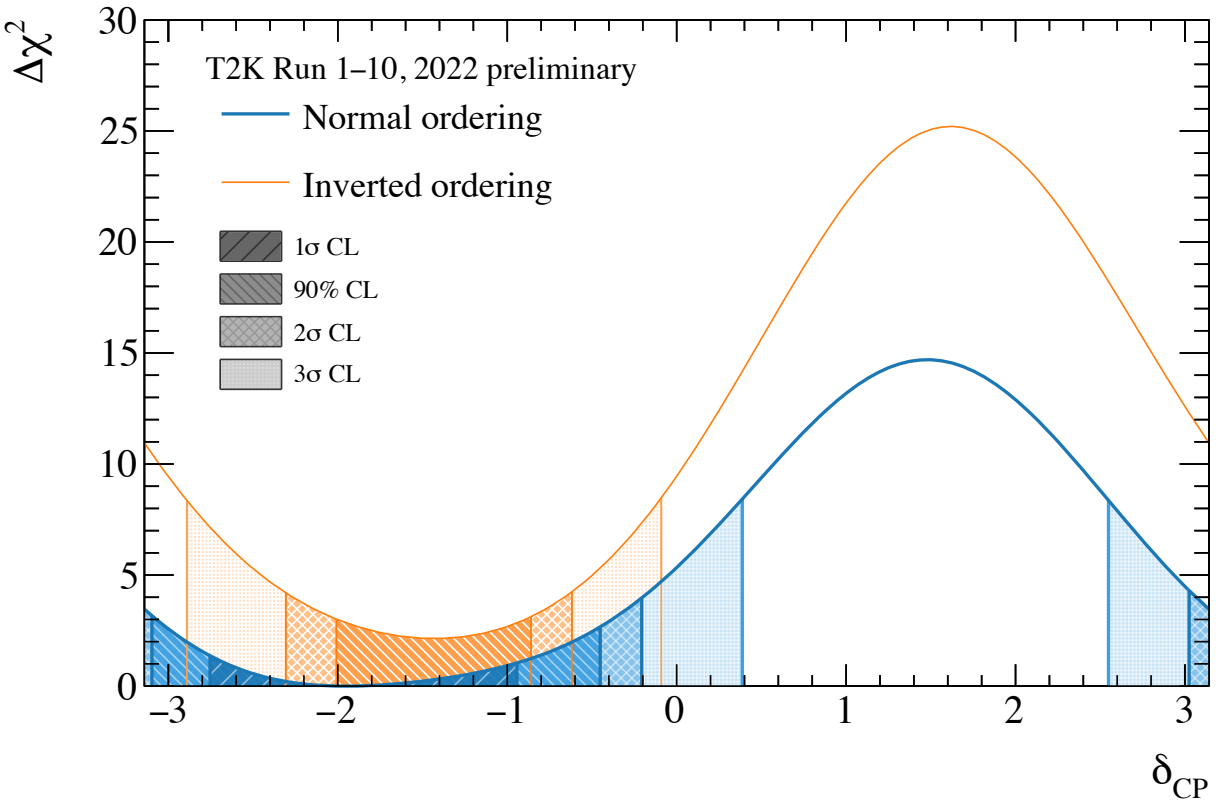


New FD samples (5→6 samples): Added multi-ring muon-like events



Further improvements (more additional event samples etc..) are under preparation

Results on neutrino CP violation

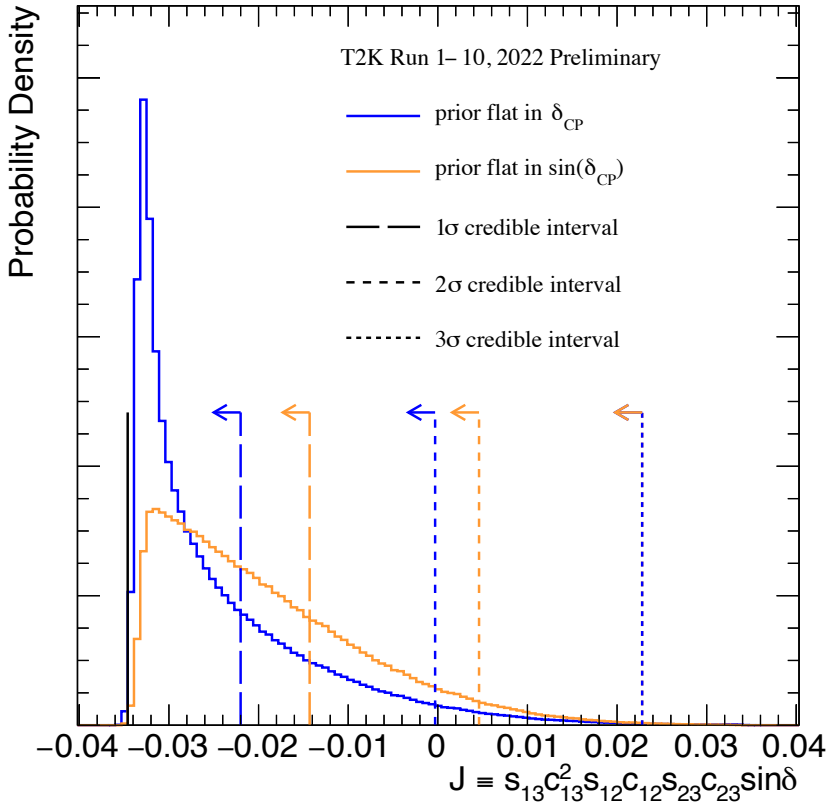


Large region of δ_{CP} excluded at 3σ.
CP conservation is excluded at 90% C.L.

Weak preference of normal ordering

Jarlskog invariant

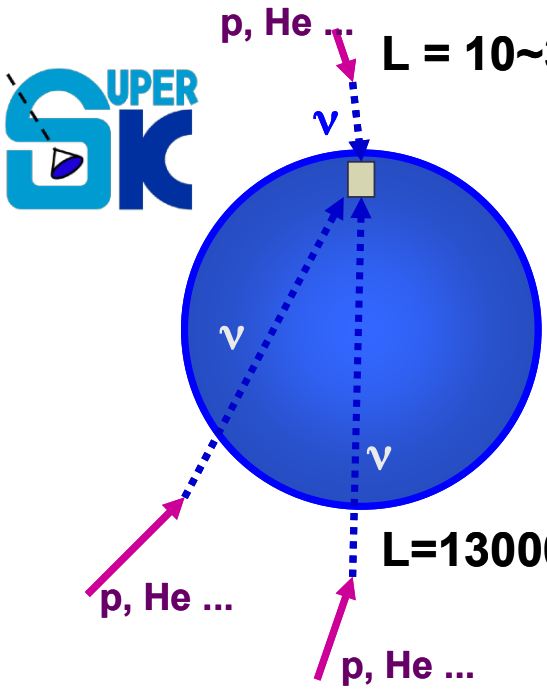
$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$

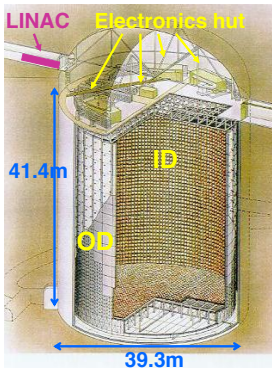


T2K data prefers largest (negative) CP violation.

Joint oscillation analysis

- Different energies, baselines can resolve the degeneracies between mass ordering and δ_{CP} and/or θ_{23} octant and δ_{CP}
- It is important to study possible correlations in the systematics errors between the experiments





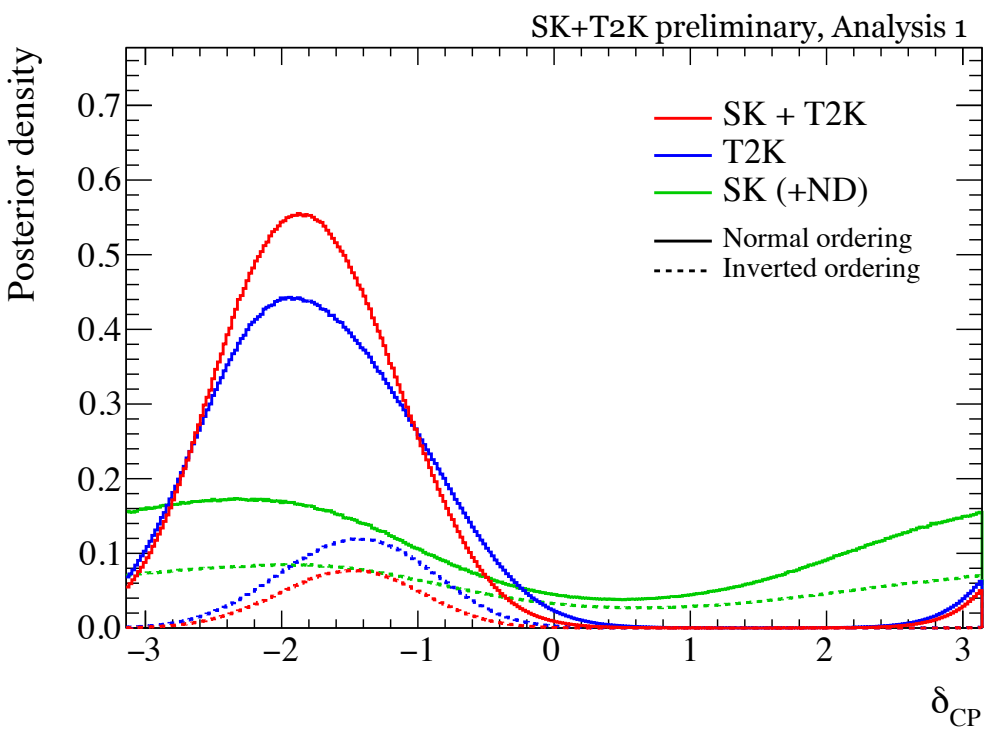
Slide from A. Himmel, Neutrino 2020

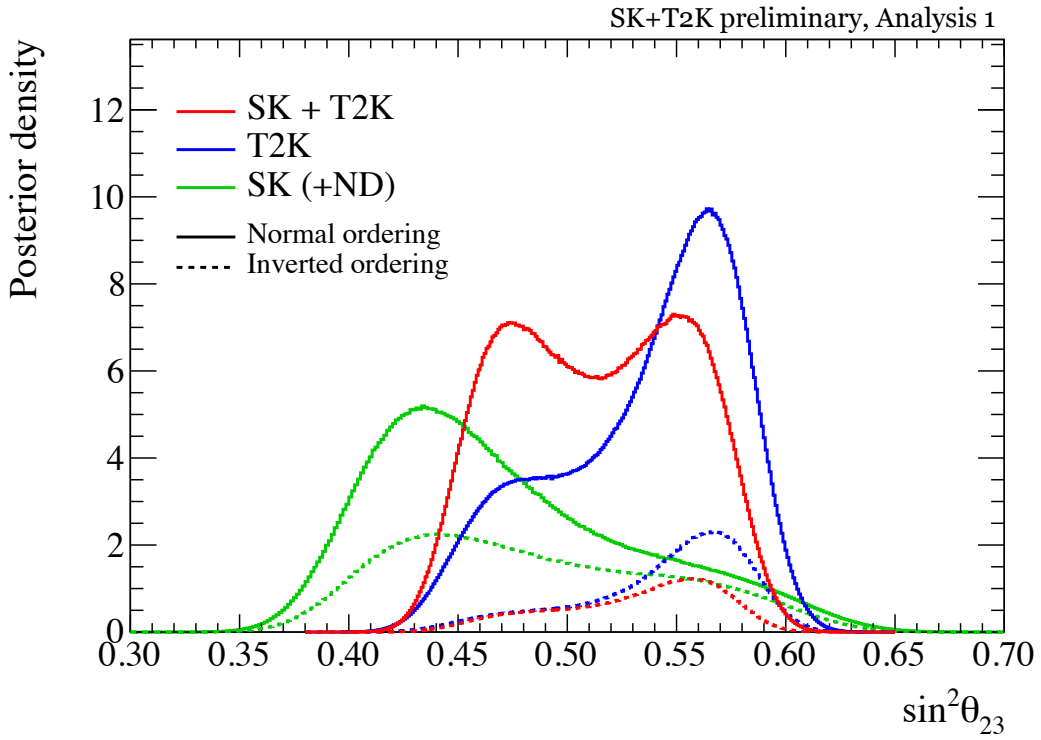
atmospheric
+ accelerator

T2K, SK, NOvA can provide complementary information

	T2K	NOvA
Baseline	295km	810km
Peak neutrino energy	0.6 GeV	2 GeV
CP effect	32%	22%
Matter effect	9%	29%

SK+T2K combined results





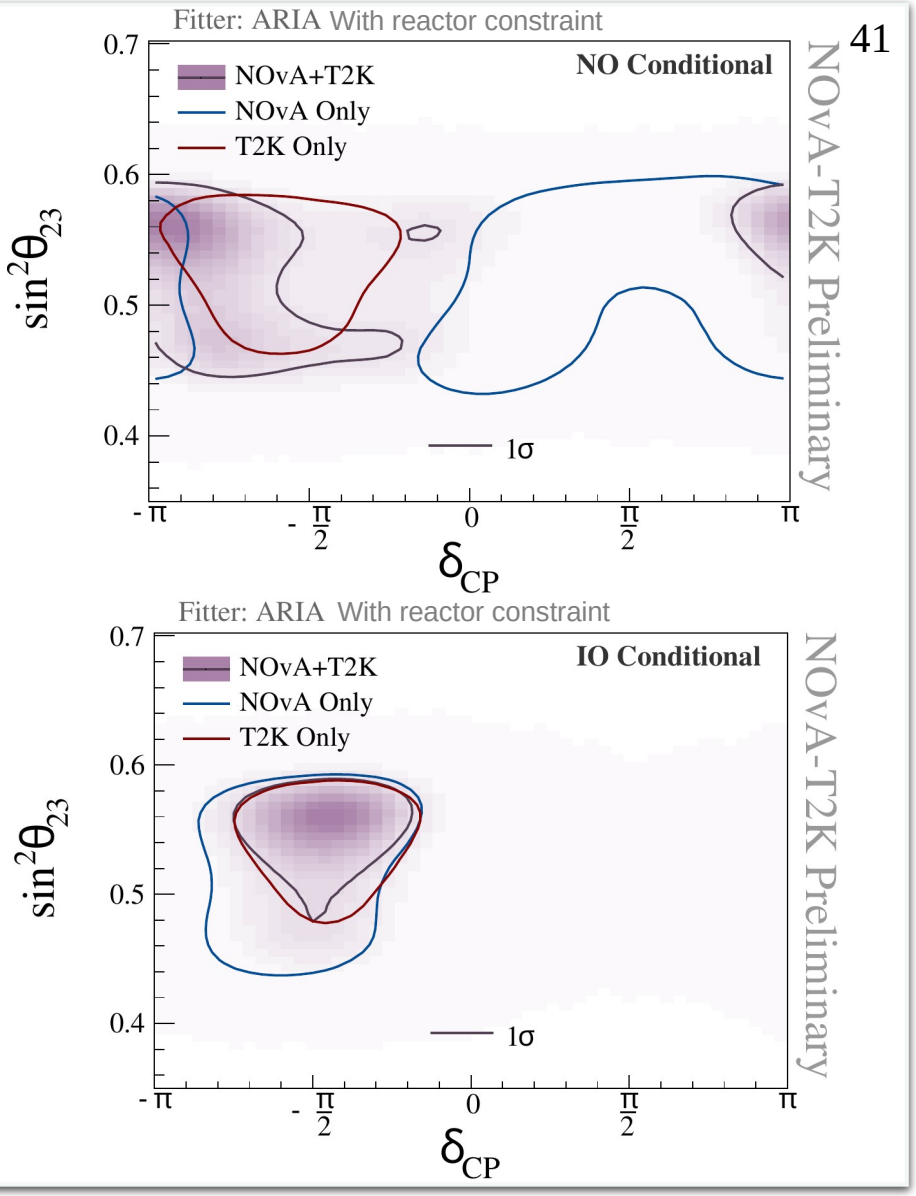
- CP conservation ($\delta_{CP}=0, \pi$) is excluded around 2σ. SK provides additional rejection of $\delta_{CP}=0$
- Weak preference for normal ordering with 90% posterior probability
- Joint fit has no strong octant preference

NOvA+T2K combined results

Comparison with NOvA-only & T2K-only fits

- The joint analysis **relieves differences in the Normal Ordering** where the individual experiments prefer slight different parameter regions.

- **Joint-fit gains sensitivity in the Inverted Ordering** where there was significant overlap in the posterior probability for the individual experiments.

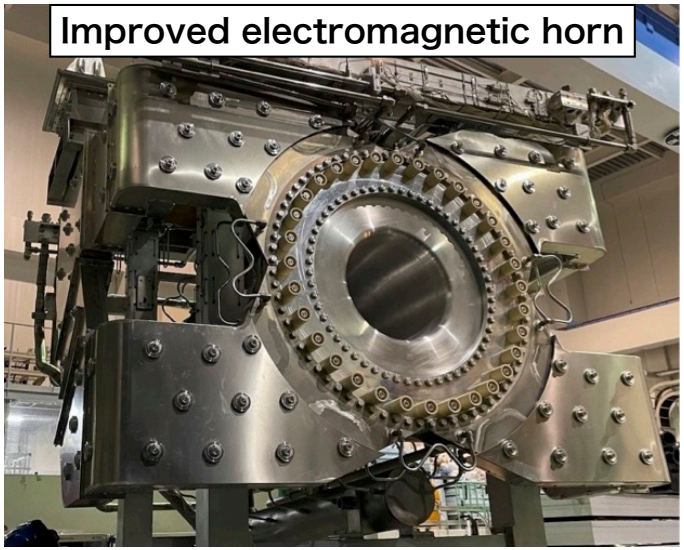


Slide by Ed Atkins (ICL) at KEK seminar 16 Feb 2024
(also FNAL Wine&Cheese seminar by Zoya Vallari)

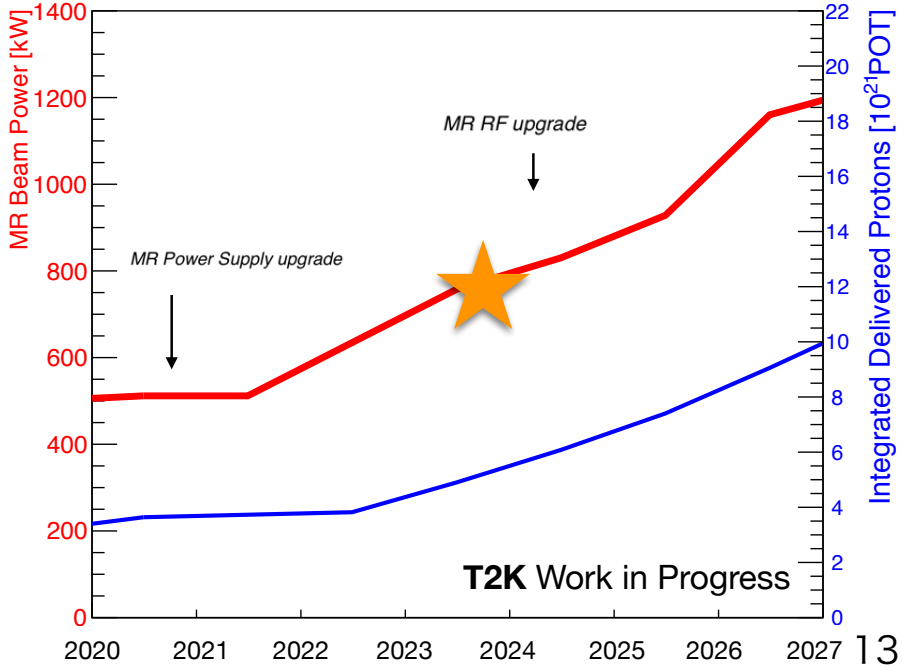
T2K enters a new phase

J-PARC accelerator/beamline upgrade

- Magnet power supply of accelerator was upgraded for faster cycle (2.48s → 1.36s)
- New electromagnetic horn with improved cooling capacity was installed. Horn power supply was also upgraded.
- Successfully achieved 710kW stable operation with 320kA of horn current
- Also, 760kW continuous operation for 40mins on 2023/Dec/25



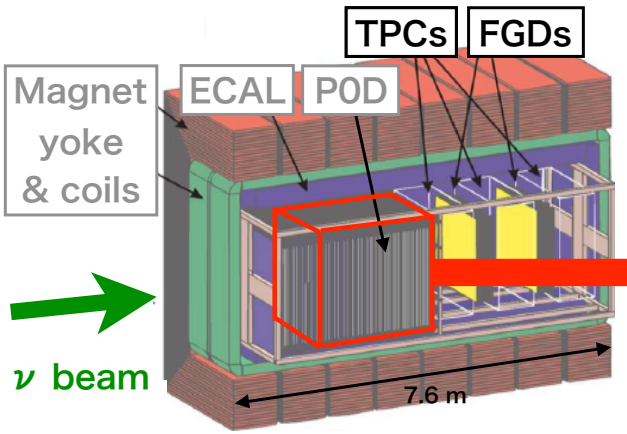
T2K Projected POT (Protons-On-Target)



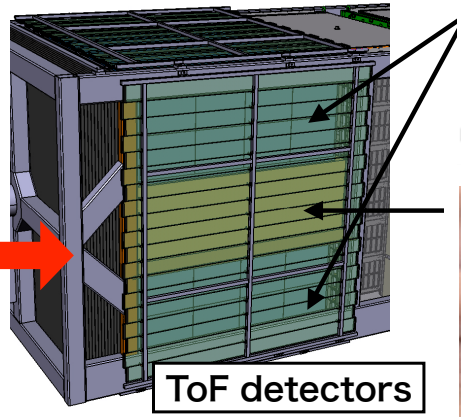
x ~1.5 more neutrinos/second compared to before the upgrade !!
(beam power & horn)
Still in progress toward 1.3MW

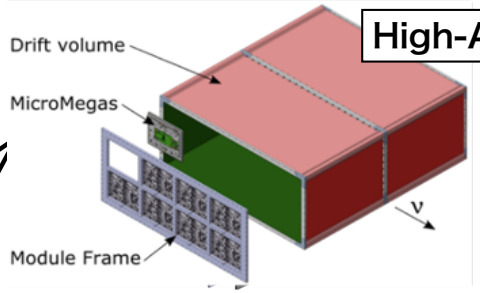
T2K ND280 upgrade

Current ND280

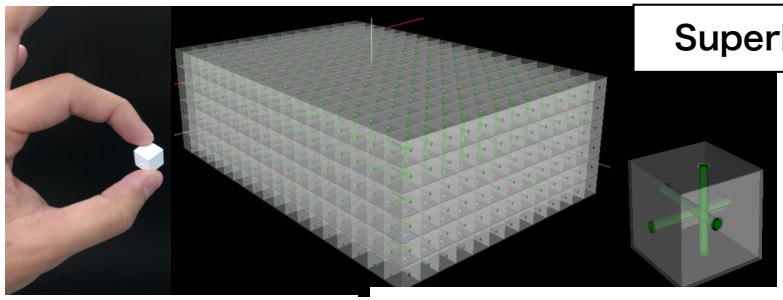


Upgraded ND280

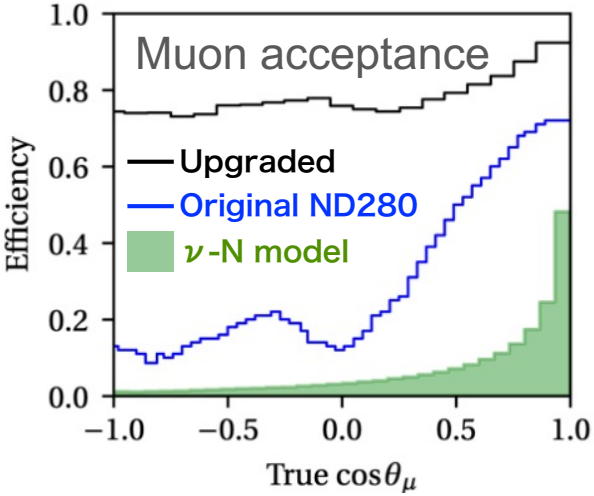


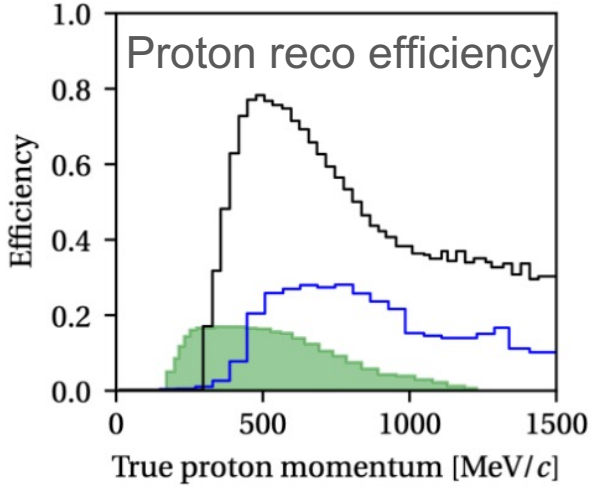


2×10^6 of 1cm^3 scintillator cubes



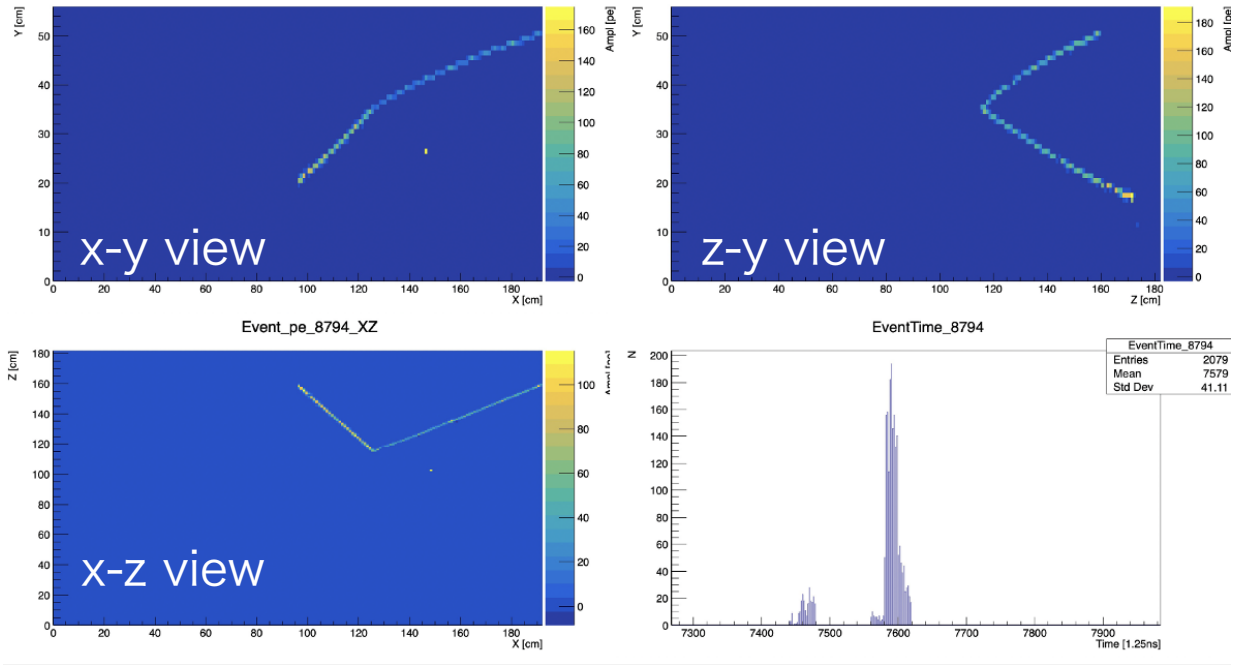
New capability to deeply understand neutrino interactions





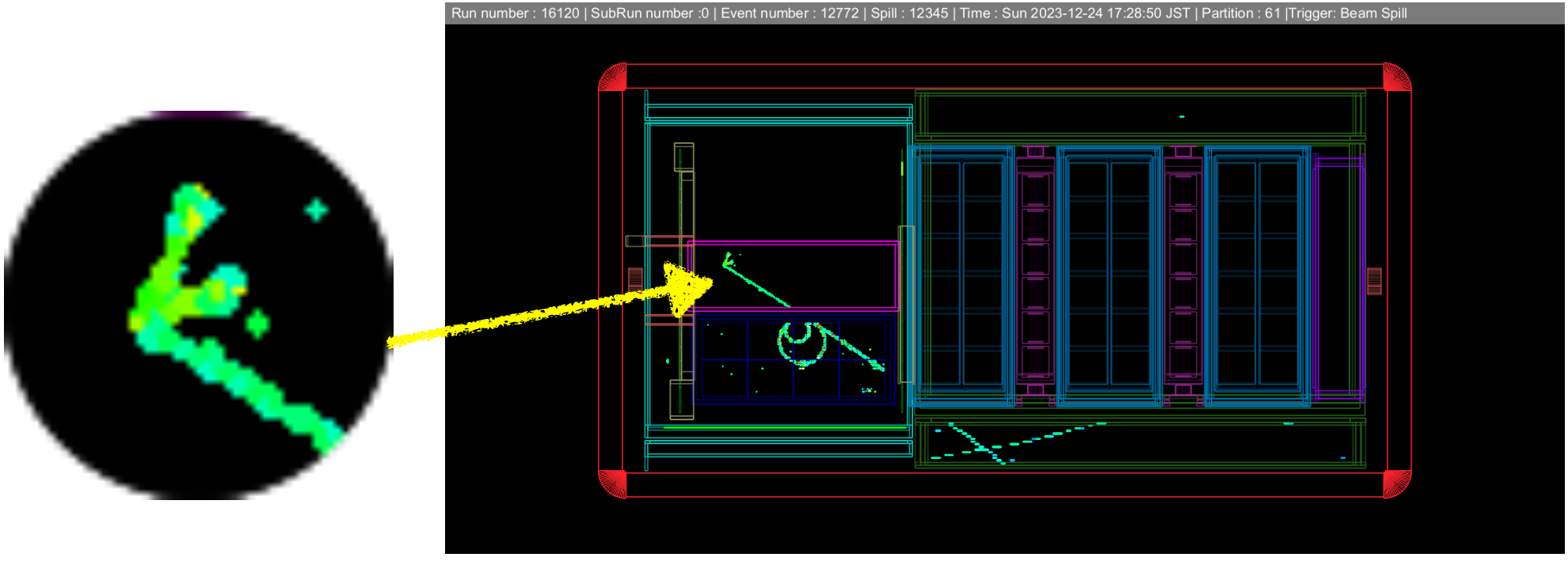
- New detectors (SuperFGD, High-Angle TPC, TOF) are partially installed into UA1-magnet

An event display of SFGD (3 directions)



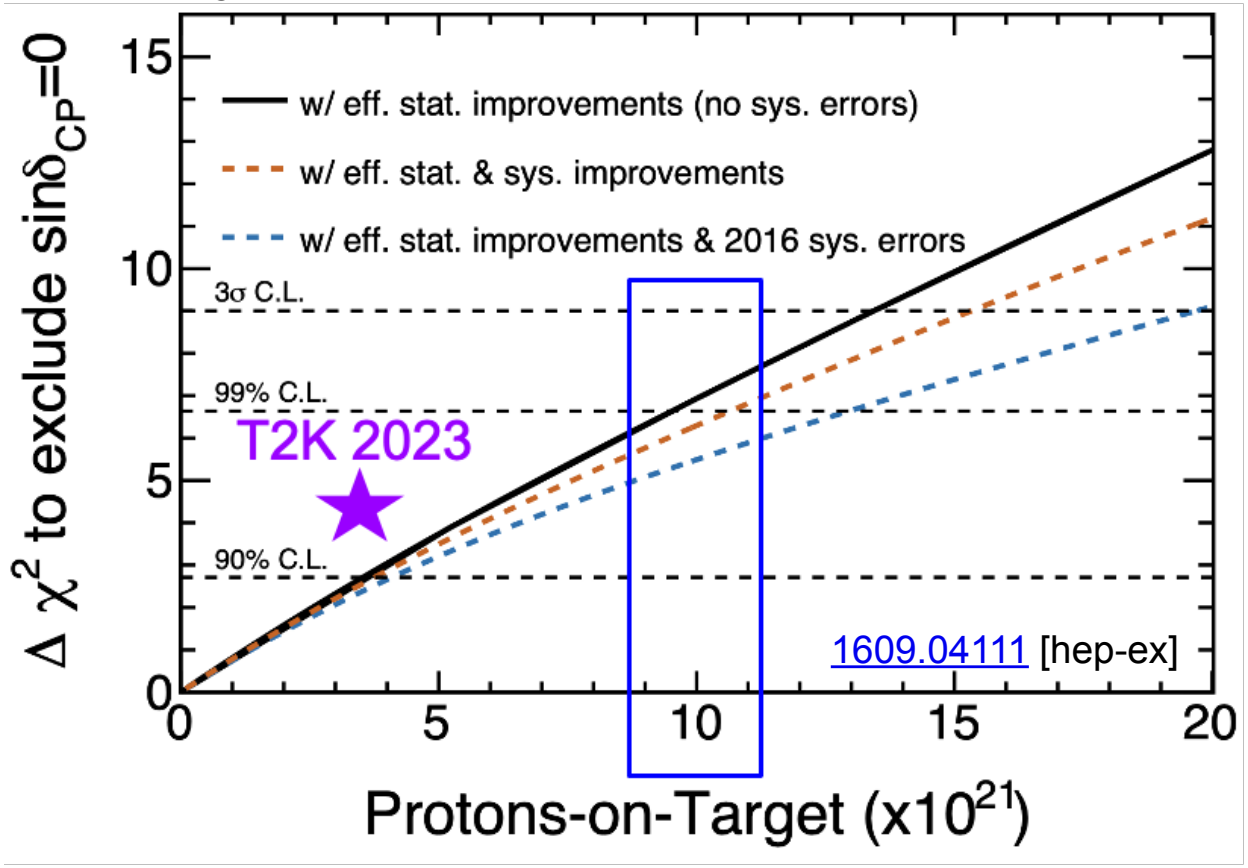
Commissioning with neutrino beam has been started !

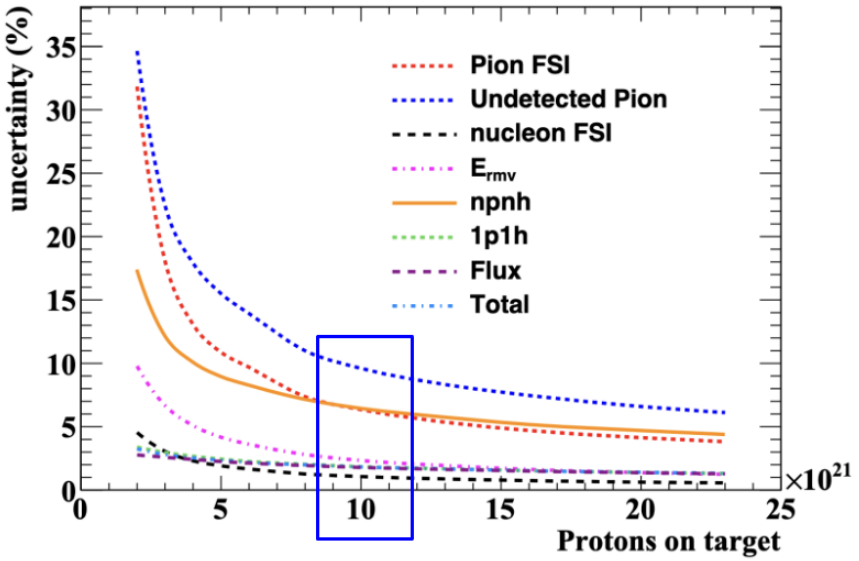
An event display of upgraded ND280



Prospects

$\delta_{CP} = -\pi/2$





Phys.Rev.D 105 (2022) 3, 032010

2108.11779 [hep-ex]

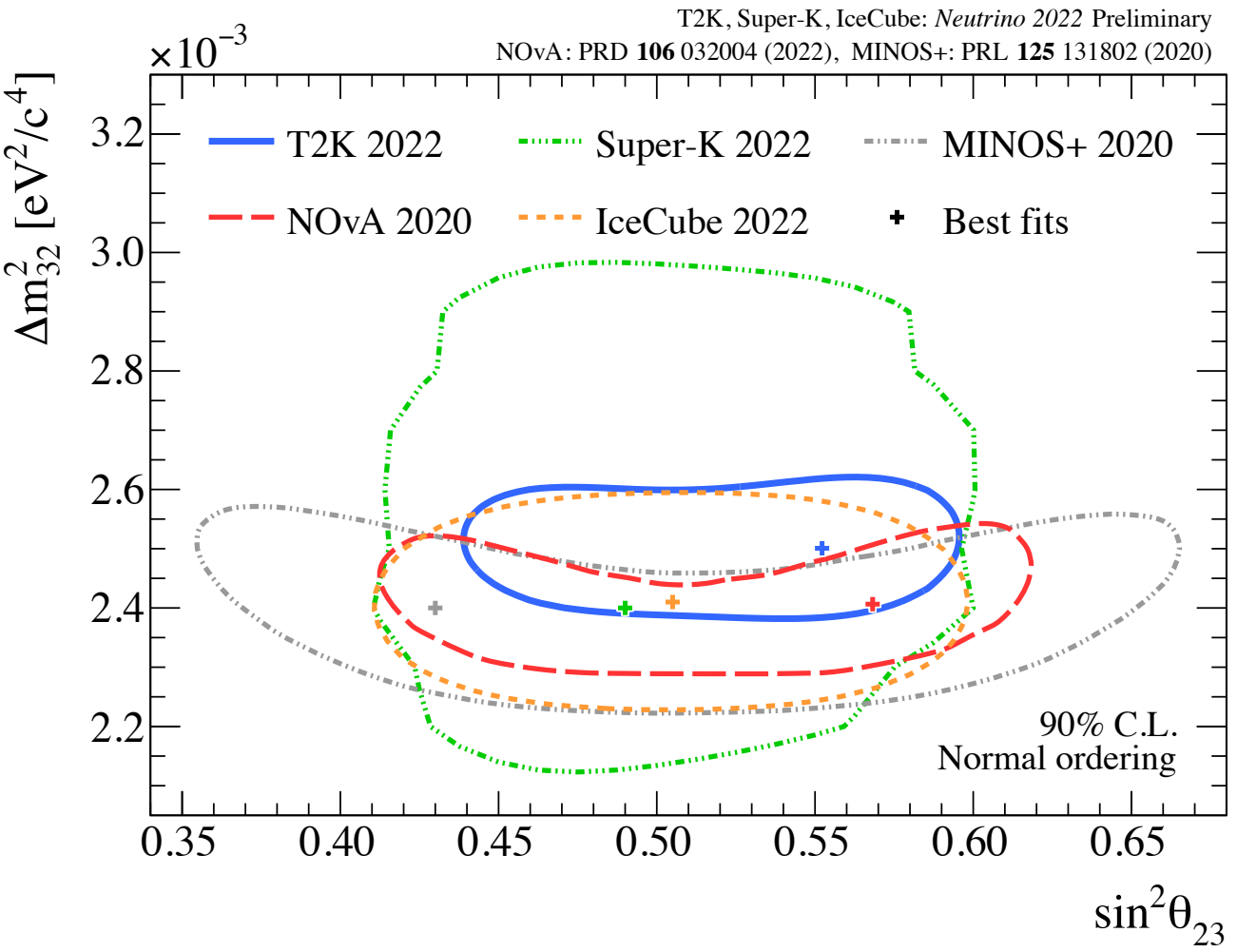
- With 10 x 10^{21} POT, T2K will have world leading CPV sensitivity
- It is crucial to reduce systematic errors, and this will be achieved with the upgraded ND280 data

Summary

- Conservation of CP symmetry excluded at 90% C.L. (latest T2K results with several improvements)
- New results from two joint analyses : SK+T2K and NOvA+T2K
- T2K enters a new phase with significantly improved sensitivity for neutrino oscillation
  - Started data taking with upgraded accelerator neutrino beam and new detectors
  - Stay tuned for exciting results in future !

backup

Δm^2_{32} and θ_{23}

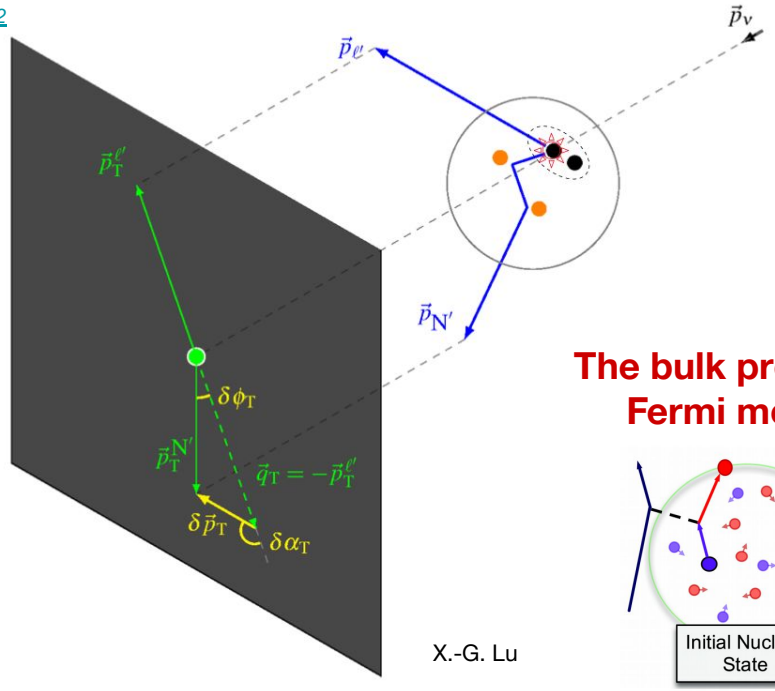


- World-leading measurement of atmospheric parameters ($|\Delta m^2_{32}|$ precision is ~3% level)
- Still compatible with both θ_{23} octants

New observables: transverse kinematic imbalance

For more details, see:
* *Phys Rev C 94, 015503*
* *Talk by X.-G. Lu at NEUTRINO2022*

Nucleon bound within nuclear target

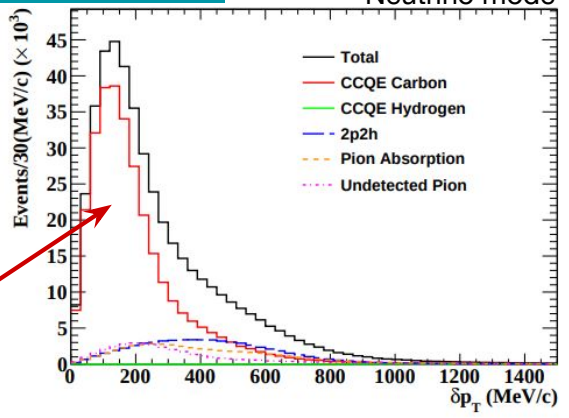


X.-G. Lu

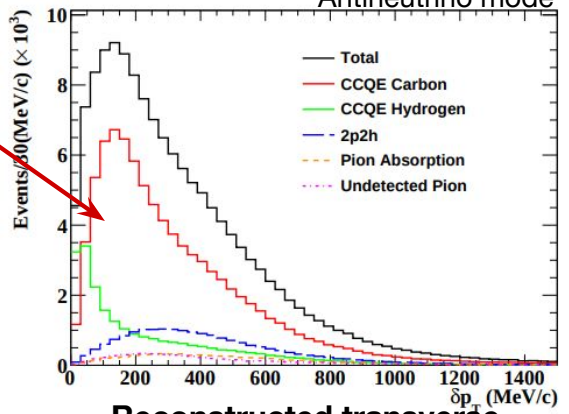
The bulk probes Fermi motion

Phys. Rev. D 105.032010

Neutrino mode

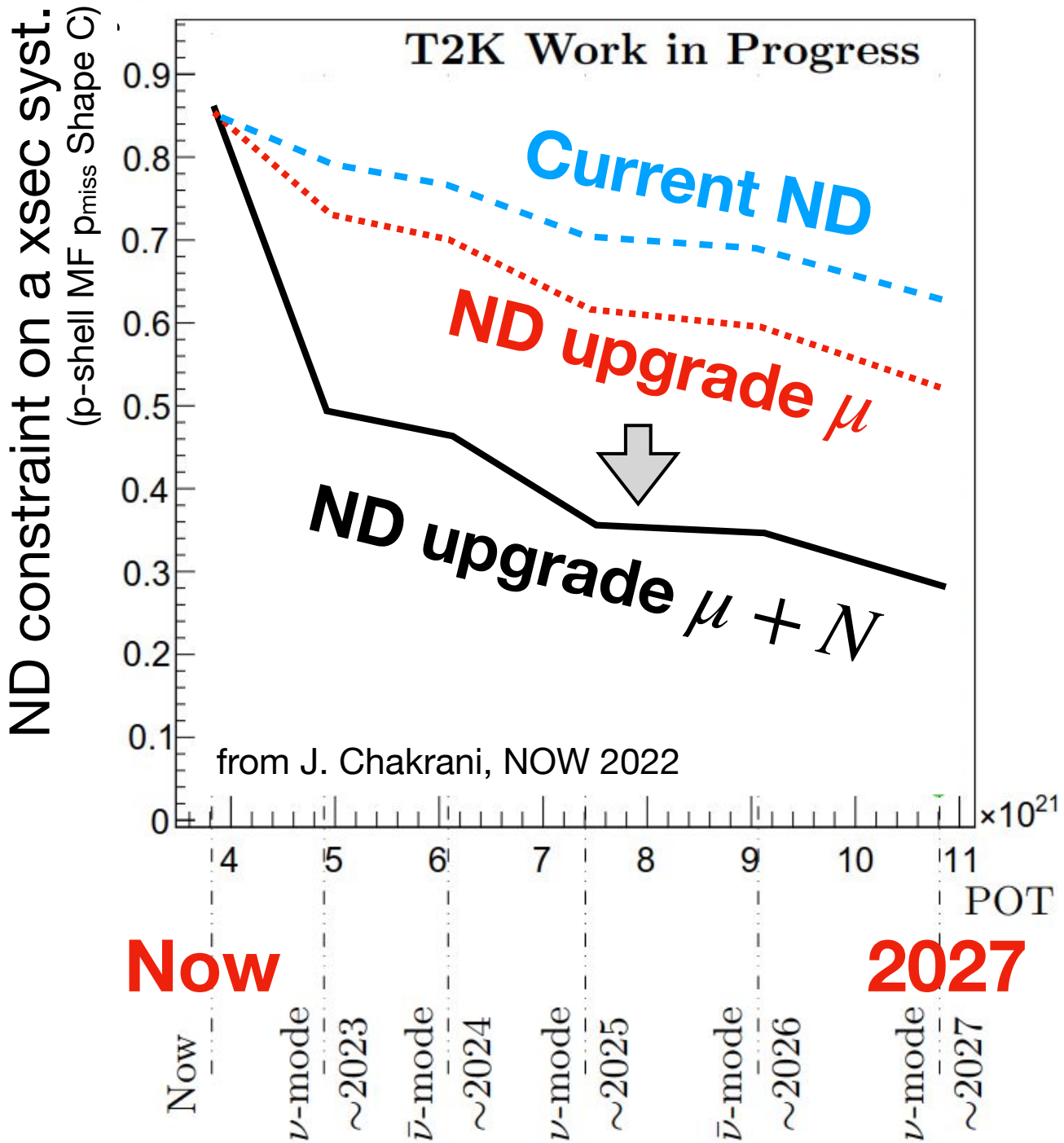


Antineutrino mode



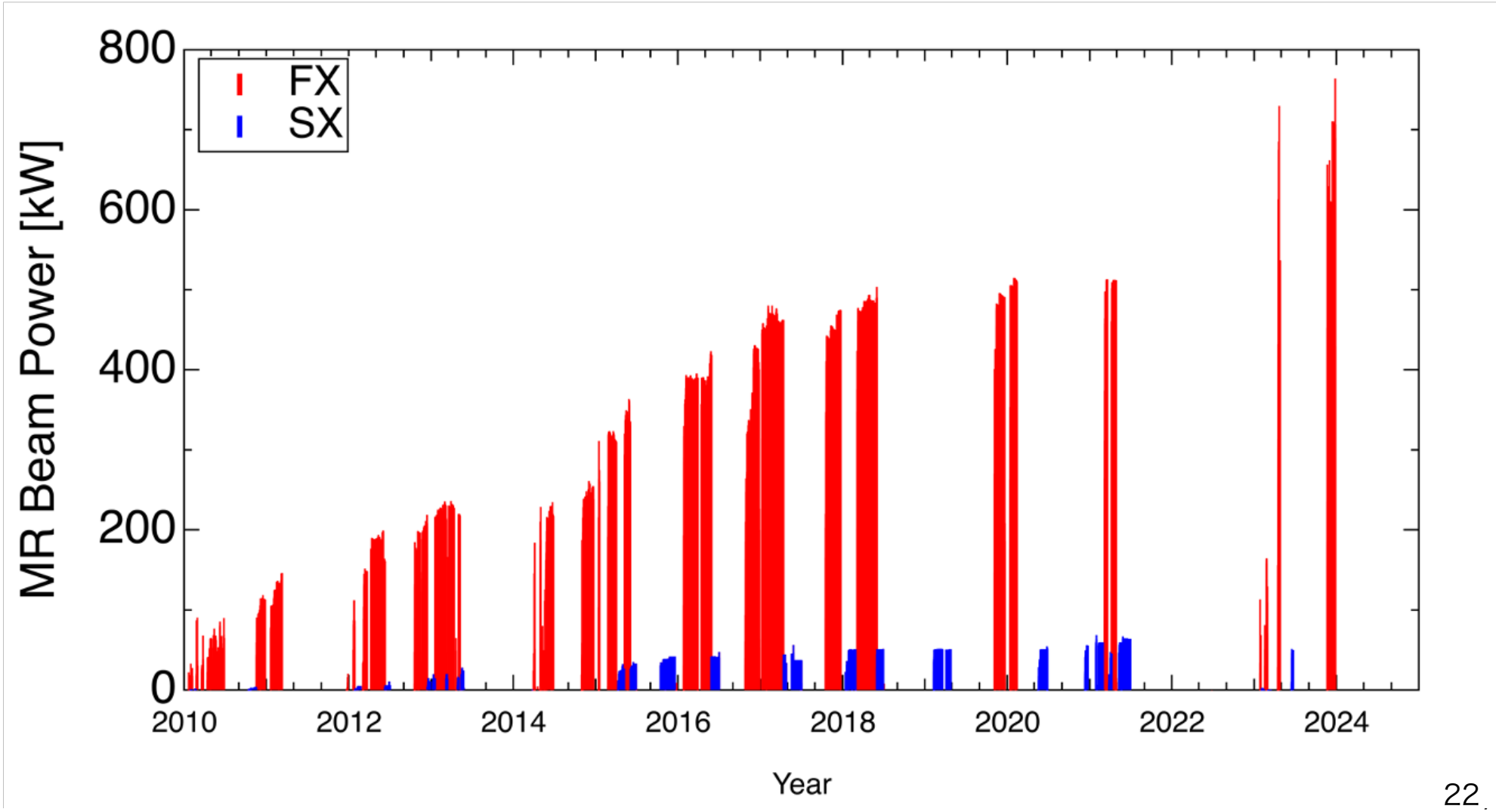
Reconstructed transverse momentum imbalance δp_T

- Need the reconstruction of both muons and nucleons
- Probe nuclear effects (Fermi motion, FSI, ...)


T2K Work in Progress
ND constraint on a xsec syst.
(p-shell MF p_{miss} Shape C)
Current ND
ND upgrade μ
ND upgrade $\mu + N$
from J. Chakrani, NOW 2022
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
4
5
6
7
8
9
10
11
×10^21
POT
Now
2027
Now
ν-mode
~2023
ν̄-mode
~2024
ν-mode
~2025
ν̄-mode
~2026
ν-mode
~2027

MR Beam Operation

- Hardware upgrade was completed for the 1.36 s operation by JFY2022.
- Beam tuning and FX operation were performed in April, Nov. and Dec. of 2023
- Beam power was gradually increased with beam tunings.
- Beam of 760 kW was successfully delivered on Dec. 25, 2023.



J-PARC neutrino beamline