SFGD Fiber Quality Check, Photo by Vladimir Baranov

T2K

Tokai-to-Kamioka Experiment

令和4年度東京大学宇宙線研
共同利用研究成果発表会

2023-02-22

Lukas Berns (Tohoku U)
for the T2K Collaboration

ν-oscillation

(interaction) (propagation)

For neutrinos flavor basis ≠ Hamiltonian basis.

→ Flavor (ν_e | ν_μ | ν_τ) oscillates over $L \times \Delta m^2 / E$,

amplitude controlled by (PMNS) mixing matrix U:

atmospheric **reactor** **solar**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$

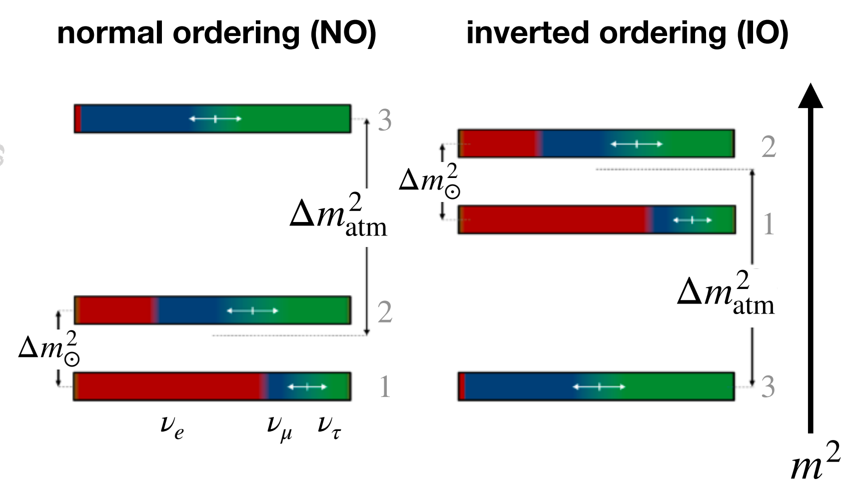
$s_{ij} \equiv \sin\theta_{ij}$

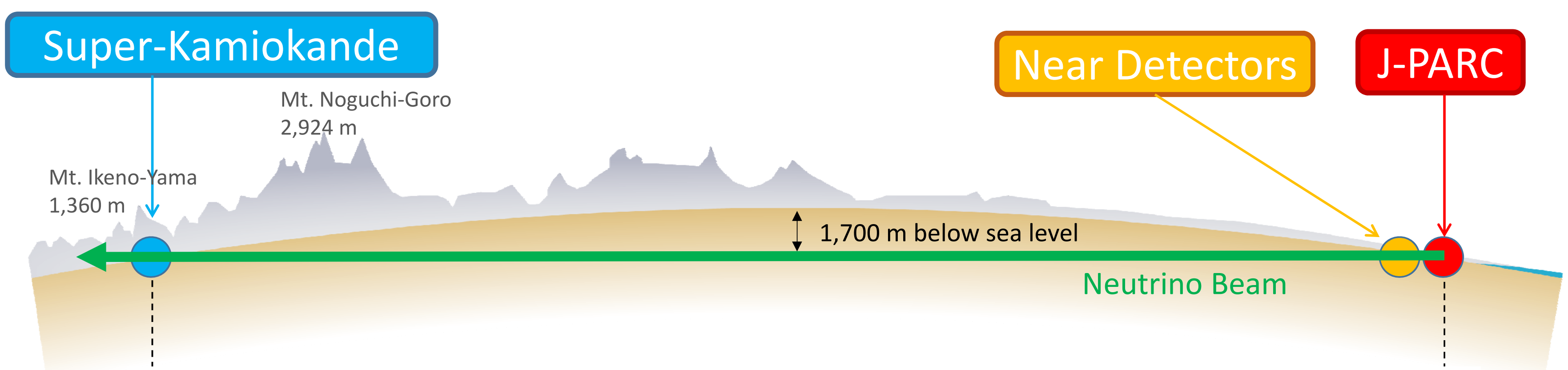
Open questions:

- value of $\delta_{\rm CP}$ → if $\sin\delta_{\rm CP} \neq 0$, CP violation
- sign of Δm^2_{32} (mass ordering)
- is θ_{23} maximal? octant? (i.e. $\theta_{23} < \frac{\pi}{4}$ or $\theta_{23} > \frac{\pi}{4}$)

important params for cosmology (leptogenesis...) and 0ν2β searches

flavor symmetries?





For $\delta_{\rm CP}$,MO look for $\nu/\bar{\nu}$ difference of $\nu_\mu \to \nu_e$ appearance

note: wrong-sign ν_μ and intrinsic ν_e backgrounds neglected for illustration

$\nu_\tau, \nu_\tau, \nu_\tau, \nu_e, \nu_e, \nu_\mu, \nu_\mu$ ← Neutrino mode ← $\nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$

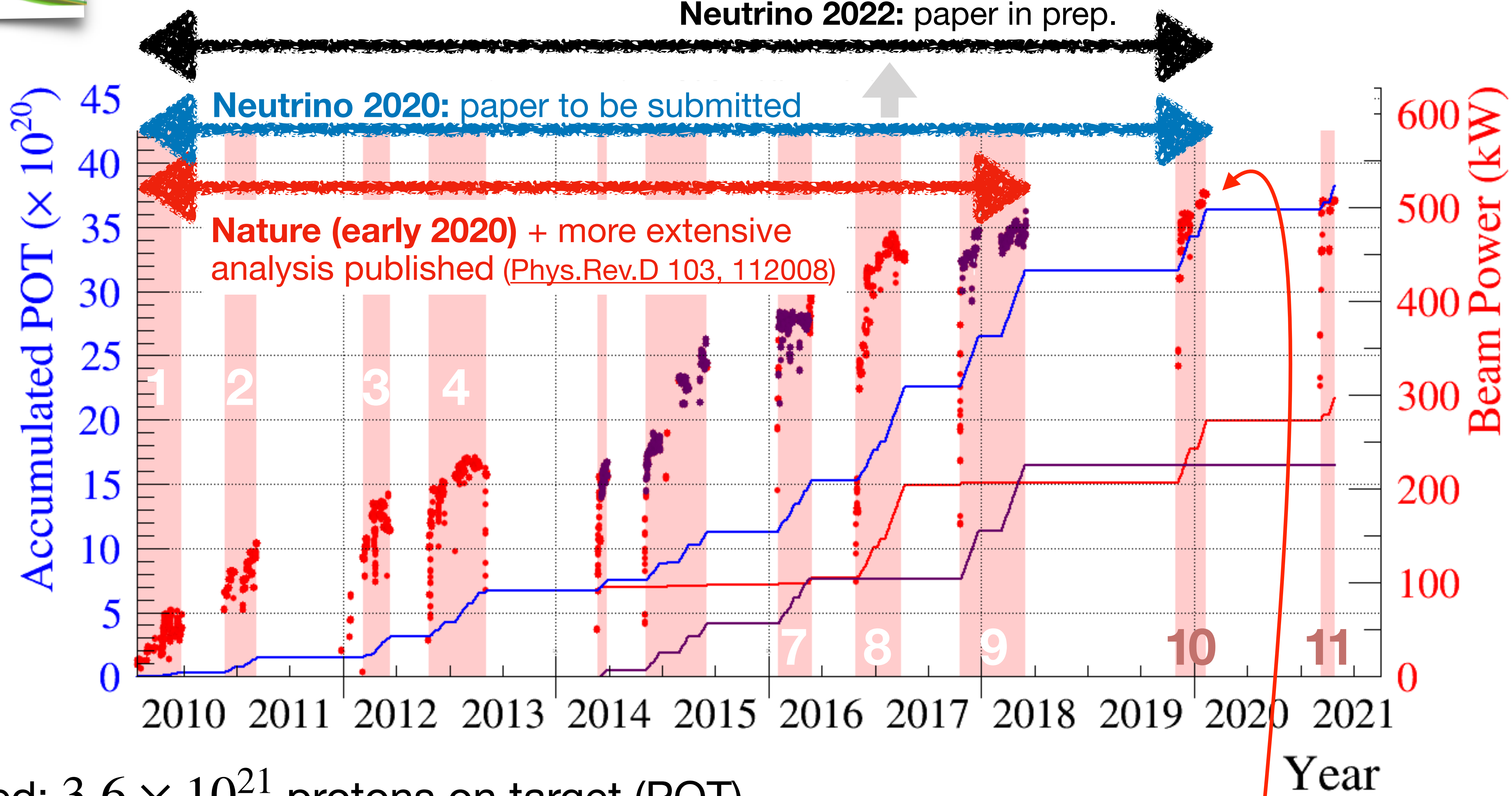
$\bar{\nu}_\tau, \bar{\nu}_\tau, \bar{\nu}_\tau, \bar{\nu}_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\mu$ ← Anti-neutrino mode ← $\bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu$

Dataset

same data,
many analysis improvements!

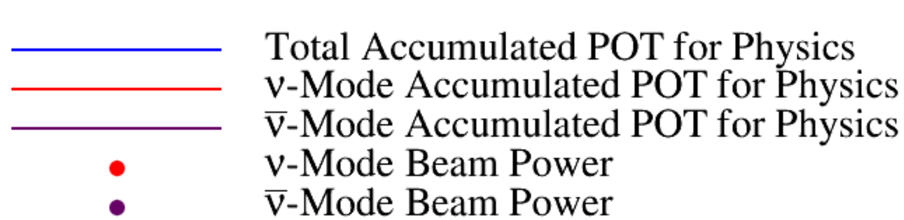
This talk

Neutrino 2022: paper in prep.



Analyzed: 3.6×10^{21} protons on target (POT)

ν-mode : $\bar{\nu}$-mode $\sim 6:5$



515 kW operation!

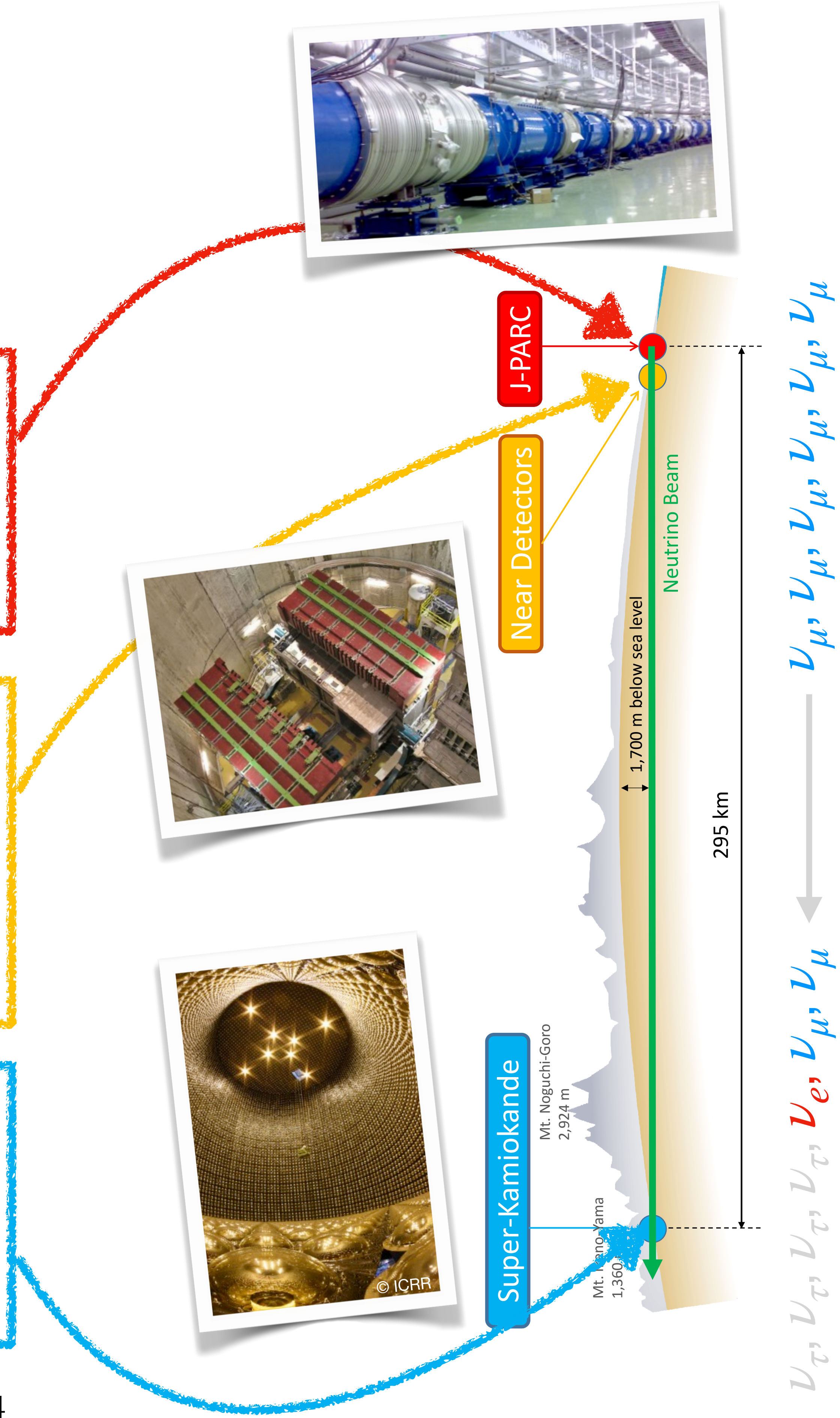
Additional run 11 data taken early 2021 (with Gd at SK), not used in this analysis

Analysis strategy

- Beam monitors + hadron production experiments
  → **neutrino flux**

- ND280 measurements
  + interaction model
  + external constraints
  → **unoscillated flux × xsec**

- 6 samples at SK
  → ν_μ **disappearance +**
  ν_e **appearance**



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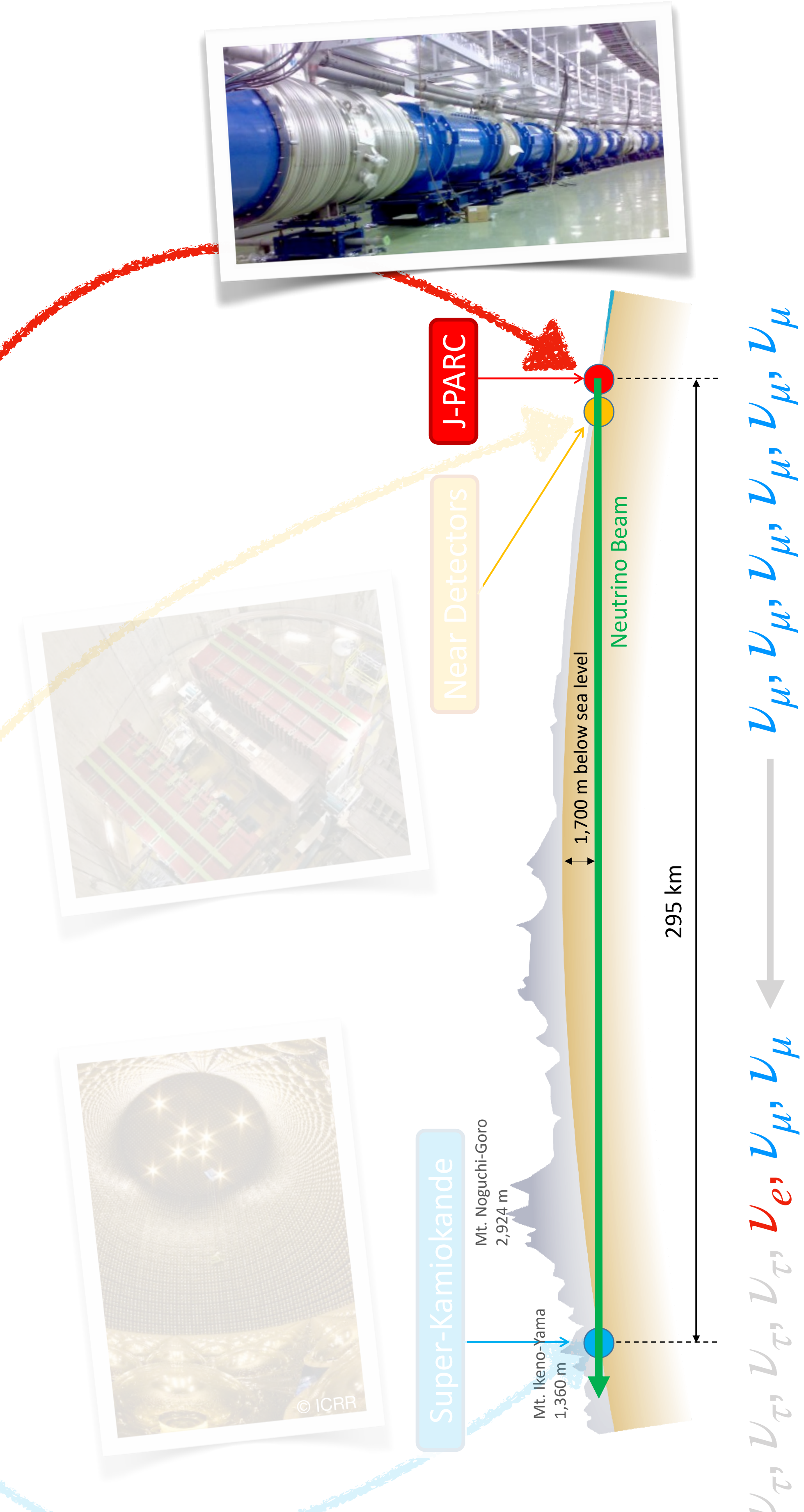

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- Beam monit
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→ neutrino

- ND280 me
+ interactio
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→ unosci

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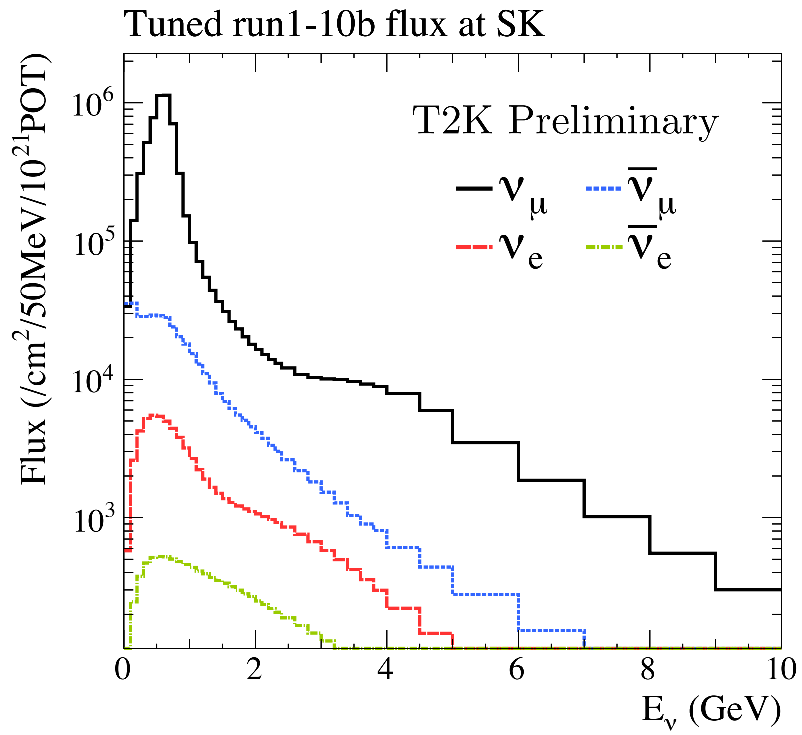
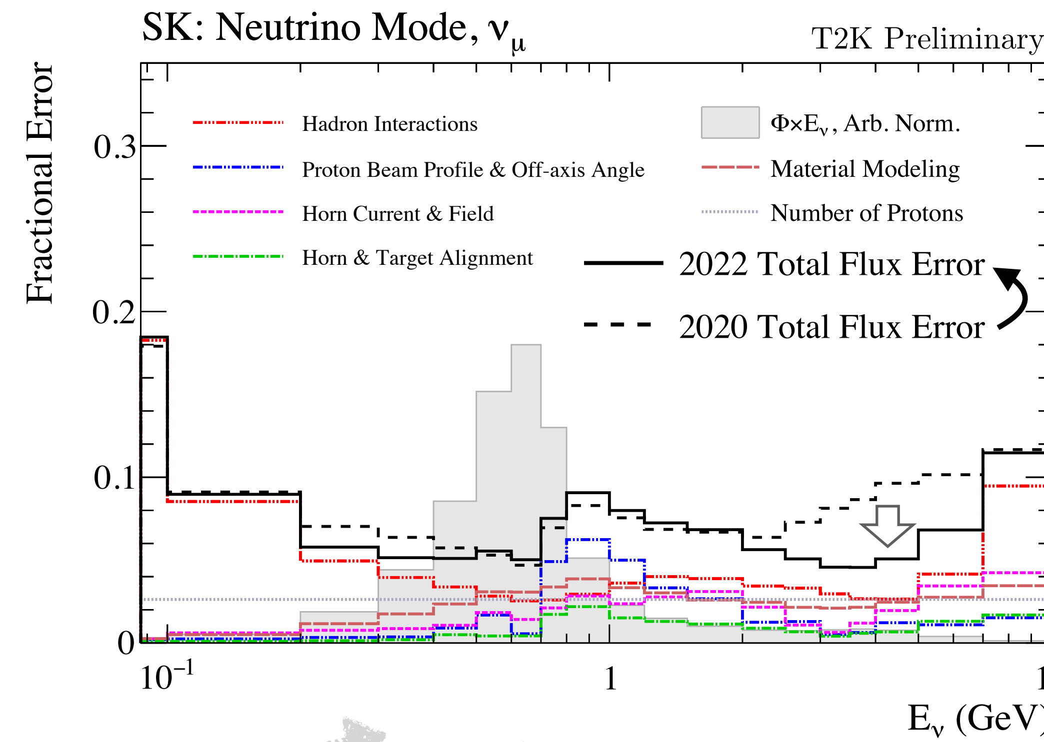
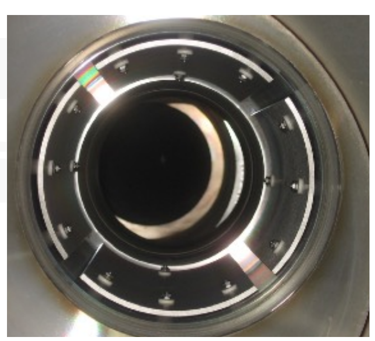
→ ν_μ disap
ν_e appe





Beam line modeling



← Beam monitors

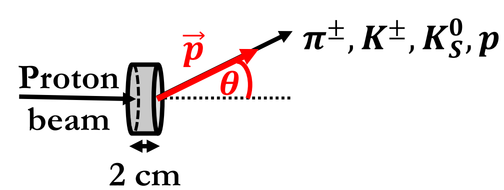
More realistic modeling of cooling water in horns slightly increased uncertainty at flux peak

Hadron production experiments

Hadron interaction uncertainty at high-E reduced thanks to higher-statistics **NA61** measurement that includes **kaon** yields from **replica** of T2K target.

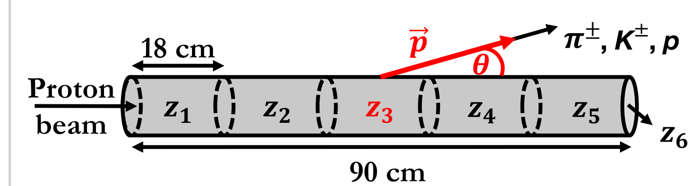
K,p in previous analysis

Thin target data
Mainly Eur. Phys. J. C (2016) 76:84



K,p in this analysis

Replica target data
Eur. Phys. J. C (2019) 79:100



An
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- Beam m
productio
→ neutri

- ND280 m
+ interac
+ externa
→ unosc

- 6 sample
→ ν_μ dis
ν_e app

New NA61/SHINE measurements, and experiments to understand horn cooling water distributions are being performed for further reduction of systematics

Photo from summer 2022
(by Eric D. Zimmerman, NA61/SHINE)

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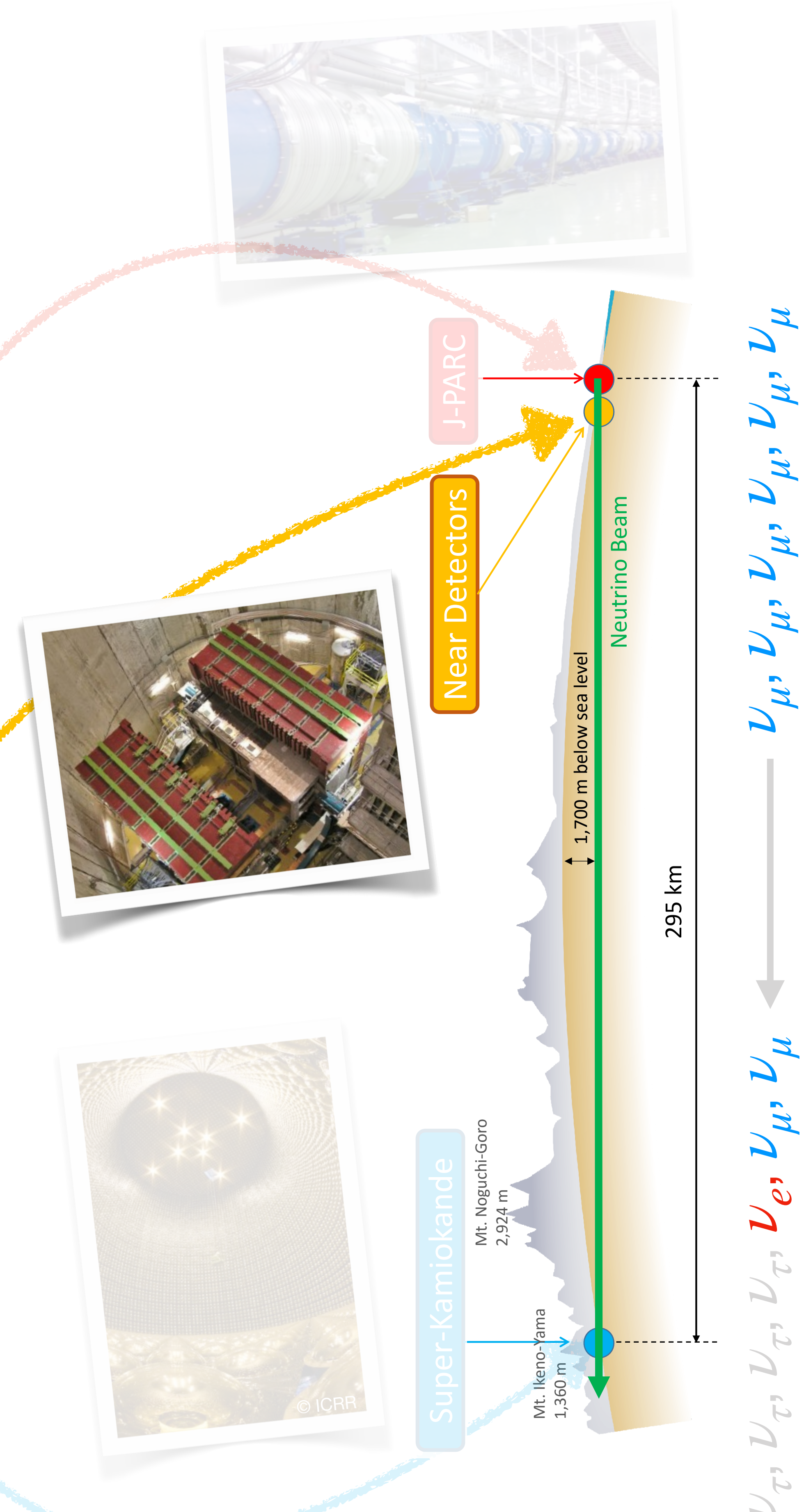

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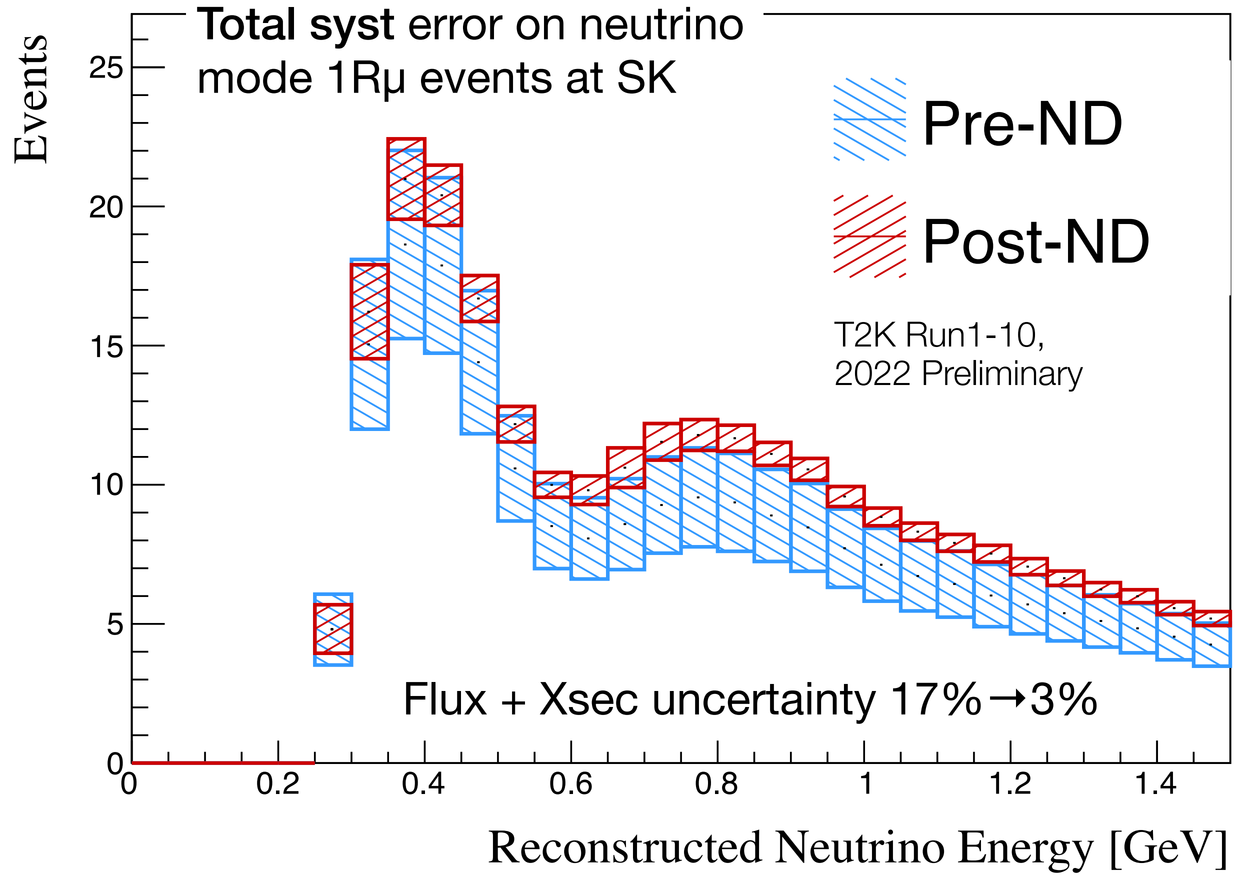


22 samples = (5×1+3×2)×2
separated by

1. π,p,γ multiplicity
   → interaction mode
2. lepton charge
   → wrong-sign bkg
   (in antineutrino mode)
3. C / C+O target
   → ν+O xsec

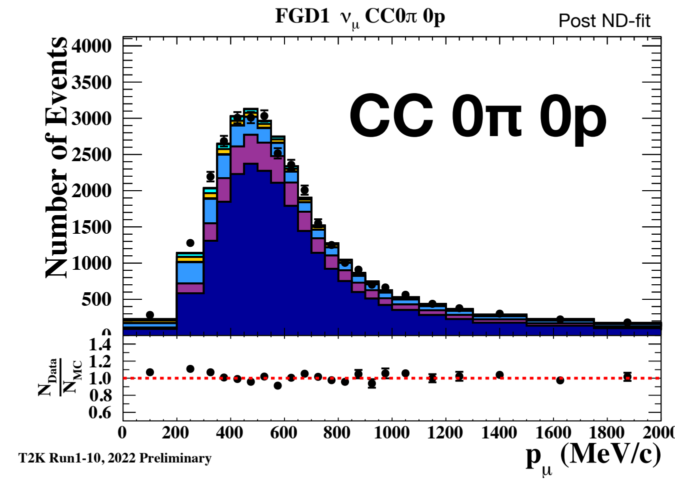
ND fit p-value: **10.9%** (> 5% threshold)

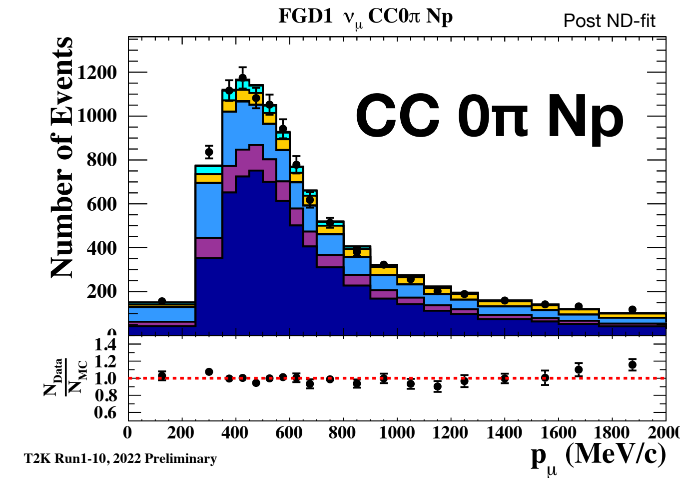
Analysis strategy

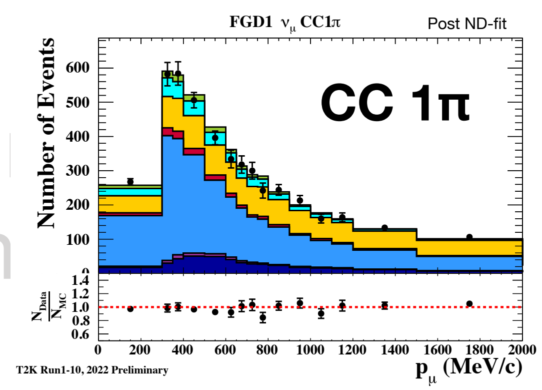
- Beam monitors + hadron production experiment → **neutrino flux**

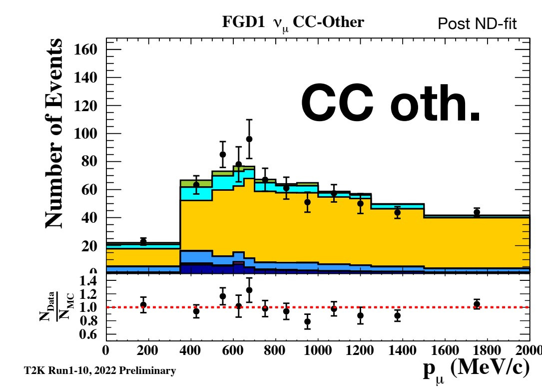
- ND280 measurements + interaction model + external constraints → **unoscillated flux × xsec**

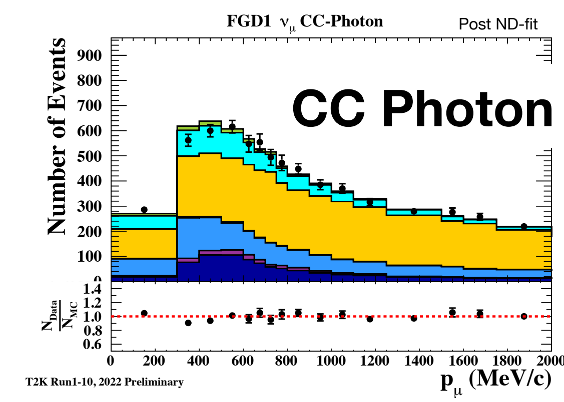
- 6 samples at SK → ν_μ **disappearance +** ν_e **appearance**











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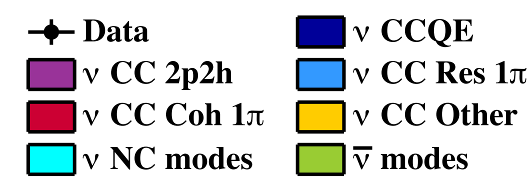
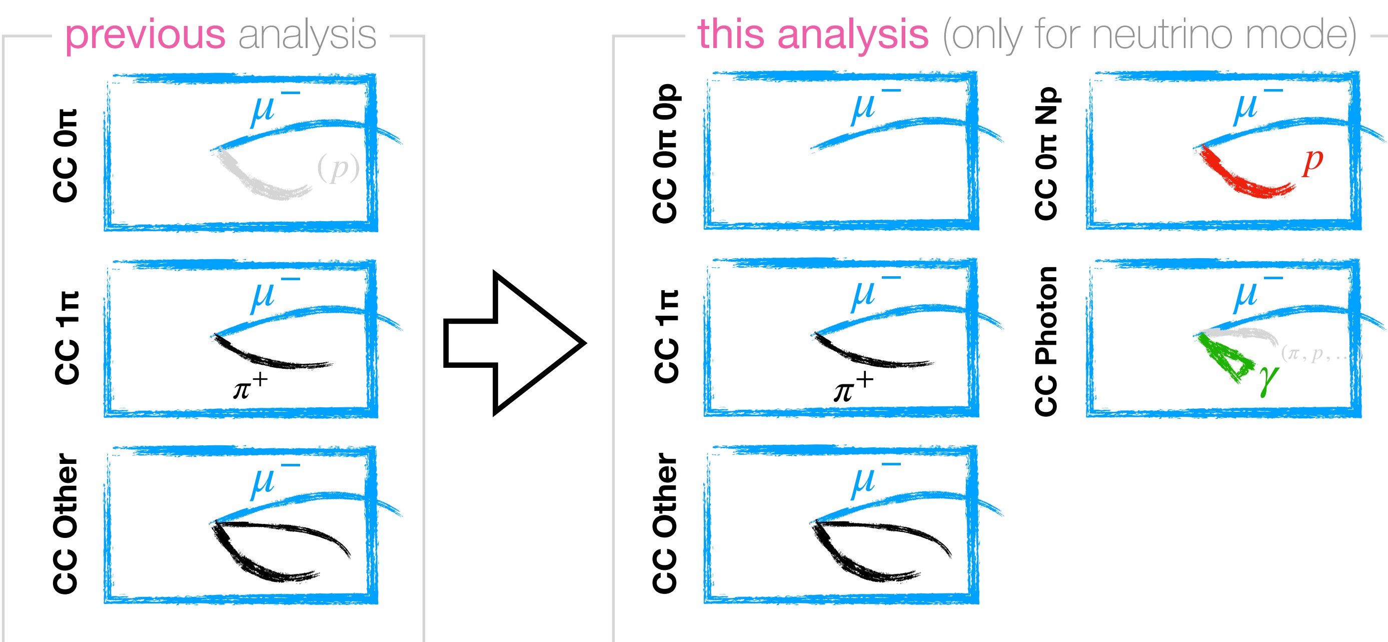


1. π,p,γ multiplicity
   → interaction mode

Finer sample separation in this analysis



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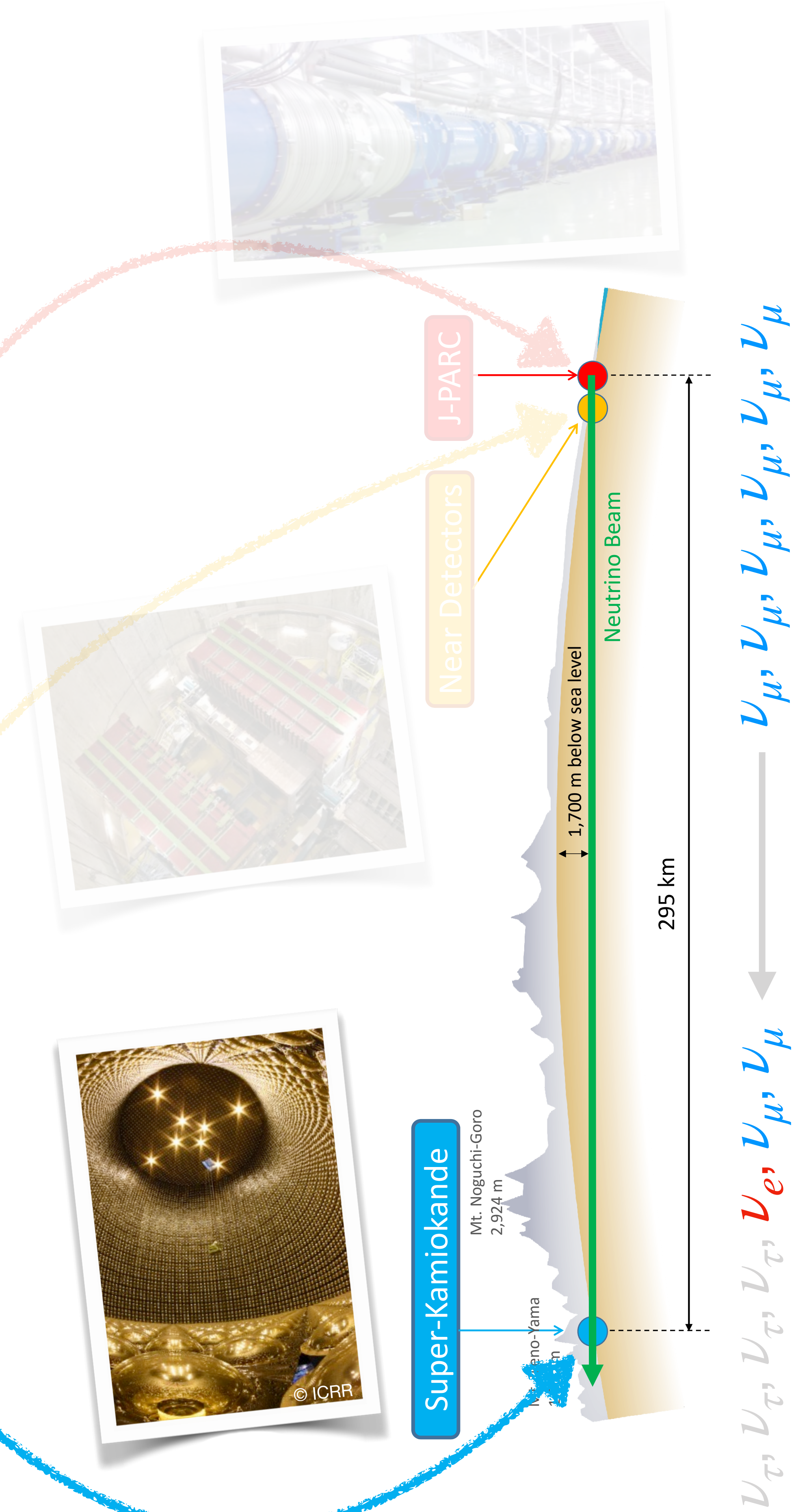

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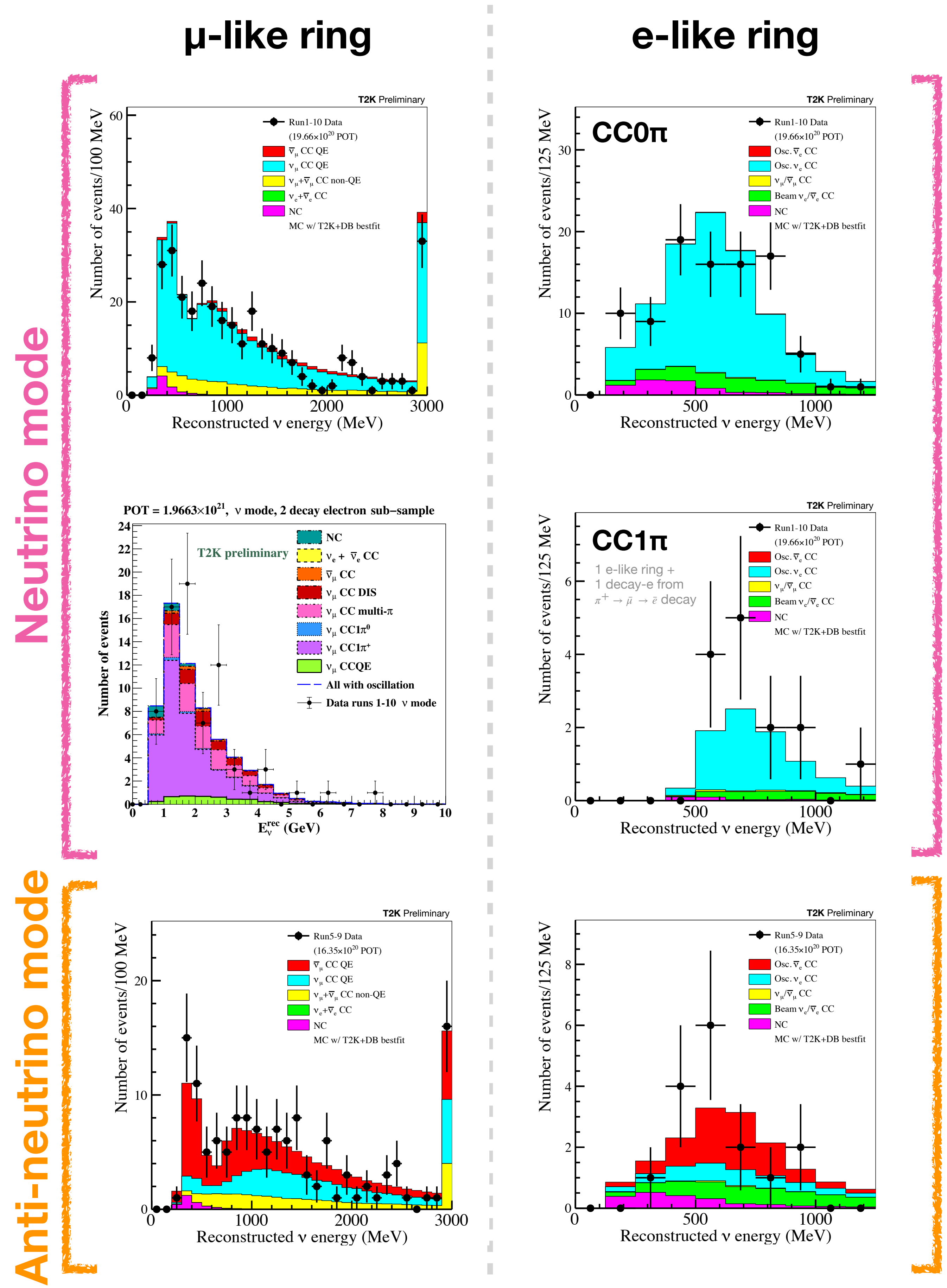
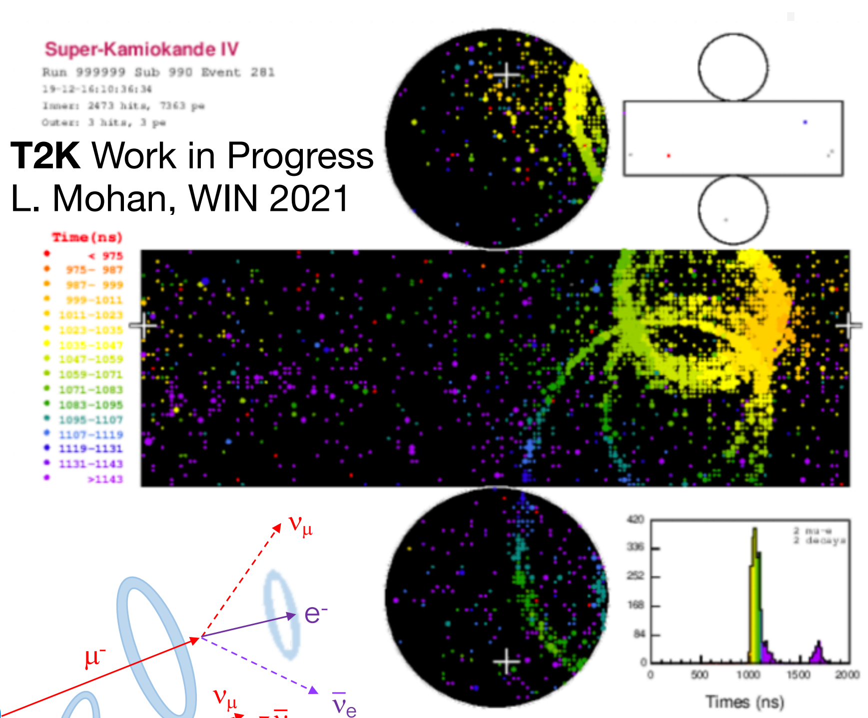
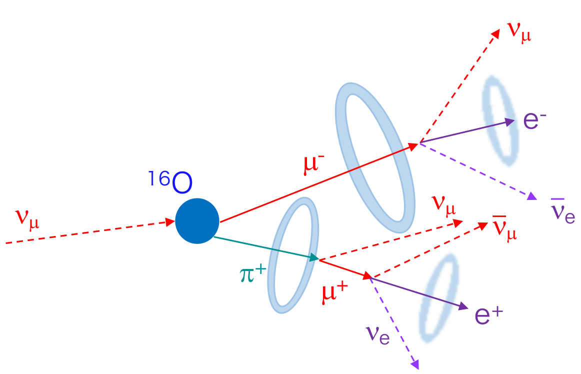


Multi-ring sample added for the first time

Analysis strategy



T2K Work in Progress
L. Mohan, WIN 2021



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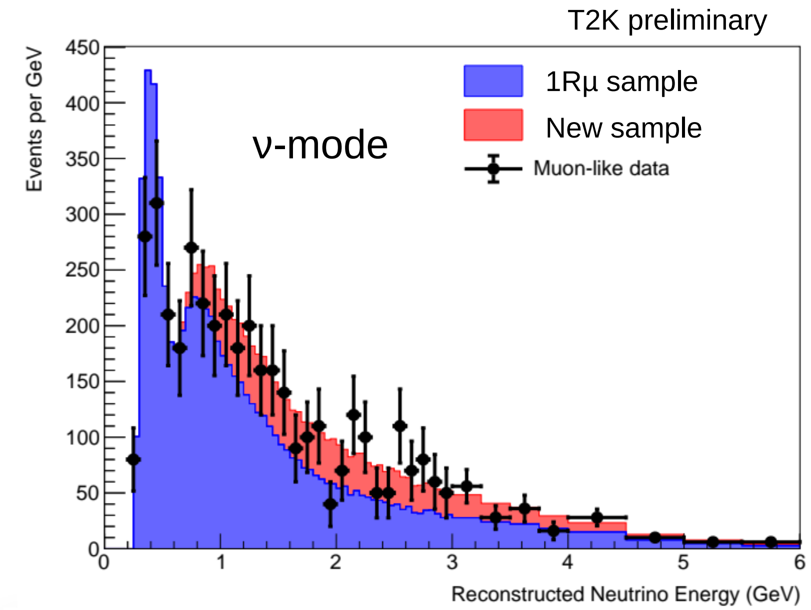
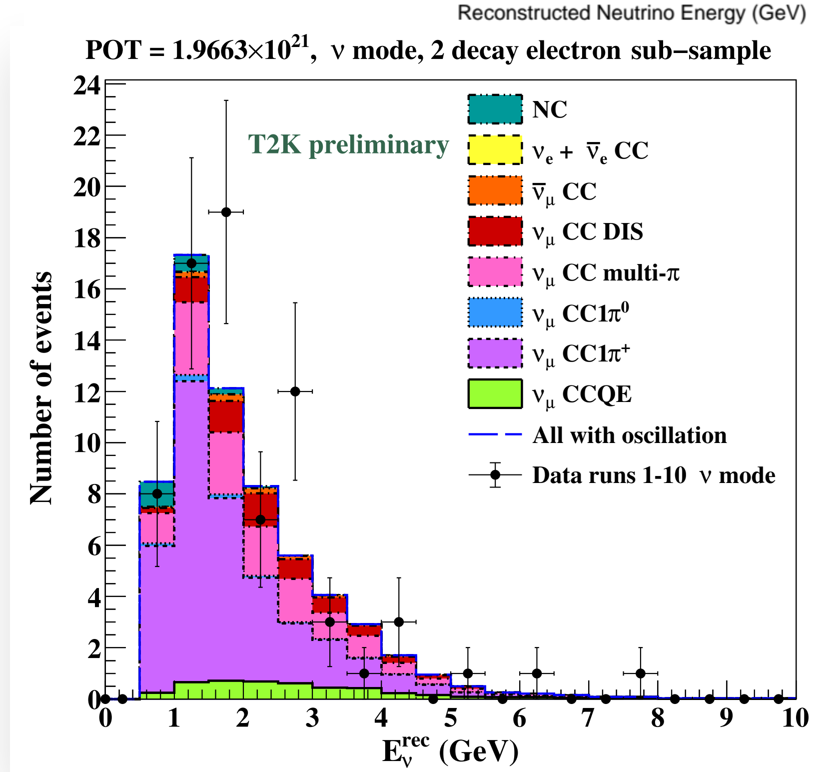
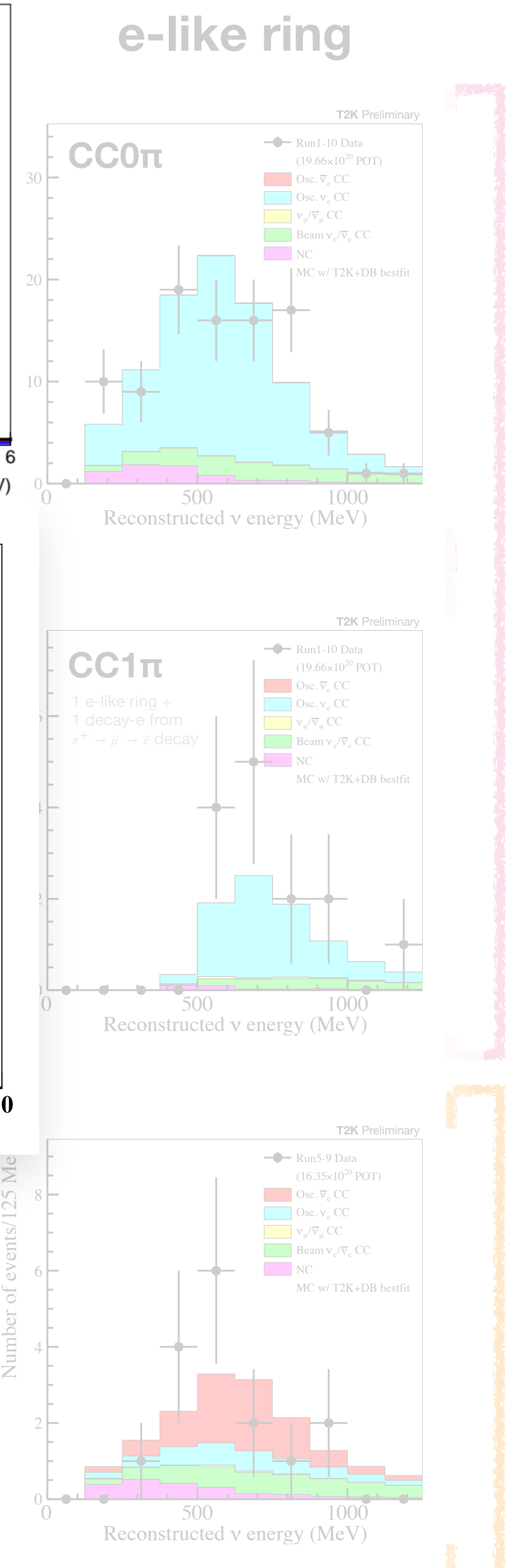
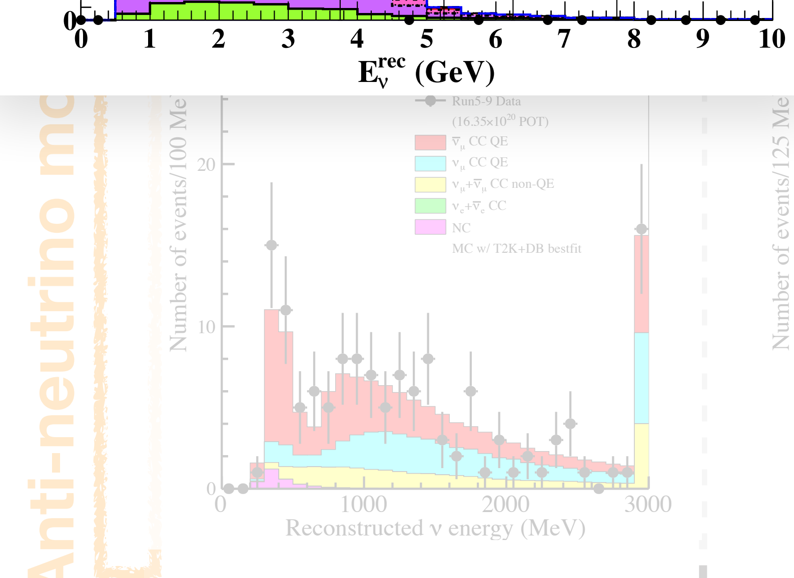




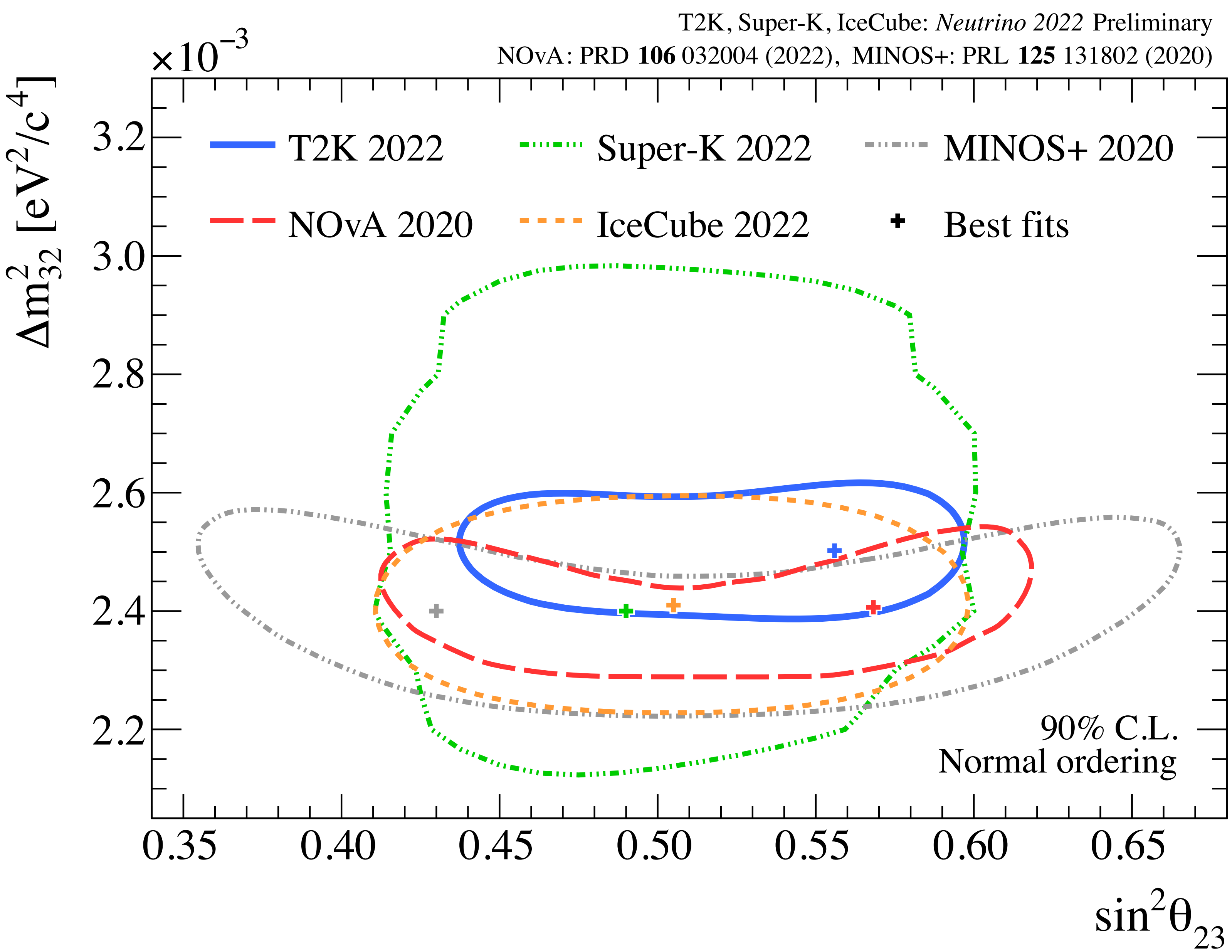




Multi-ring sample added for the first time

Δm^2_{32} vs. θ_{23}

Atmospheric mixing parameters

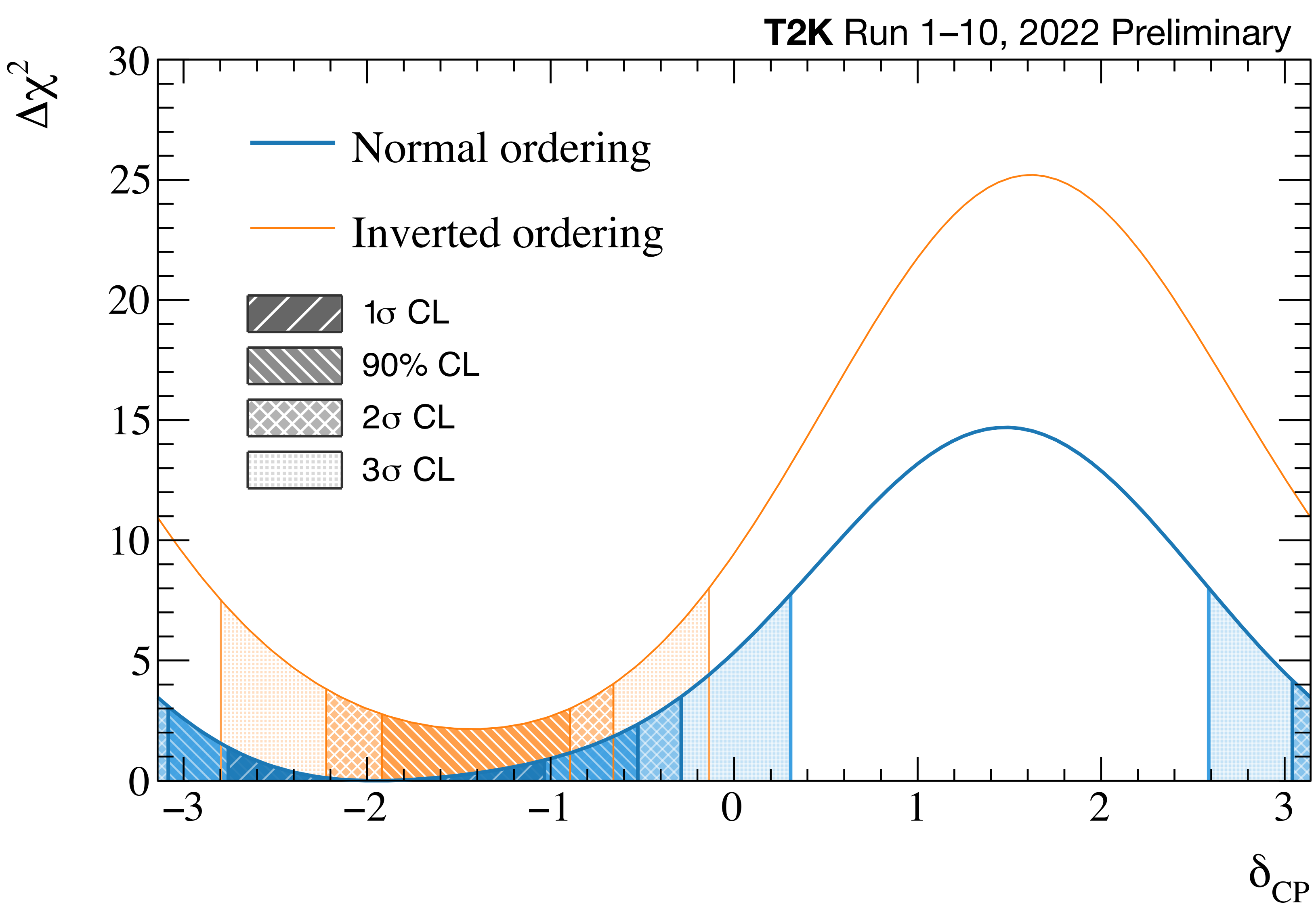


World-leading measurement of atmospheric params, still compatible with both θ_{23} octants

New interaction model and ND samples cause largest change compared to **2020**

Multi-ring ν_μCC1π sample only gives small contribution due to being above oscillation maximum

Constraints on δ_{CP} and mass ordering



Large region **excluded at 3σ**

CP-conservation $\{0, \pi\}$ **excluded at 90%**, π is within 2σ

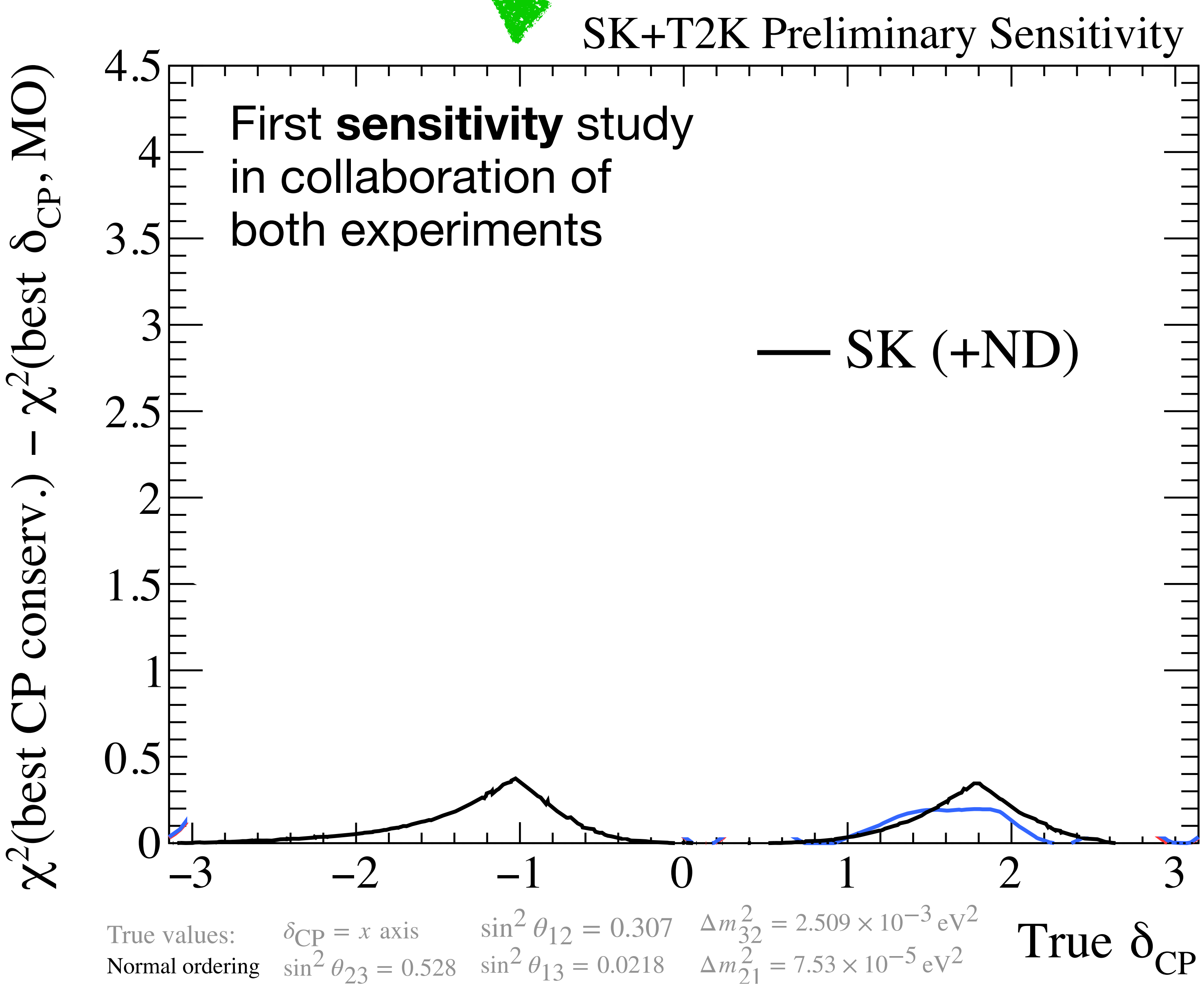
Weak preference of **normal ordering**

Slightly weaker compared to 2020 analysis, mainly due to updated model with new ND samples

SK + T2K
atmospheric + accelerator

Ongoing joint fits

NOvA + T2K
810 km / 295 km



- Joint fits between experiments with different oscillation baselines/ energies and detector technologies

→ expect increased sensitivity in δ_{CP}, mass ordering, θ_{23} octant **beyond** stats increase from resolved degeneracies and syst constraints

- important to understand potentially non-trivial syst. **correlations** between experiments

First results expected soon!

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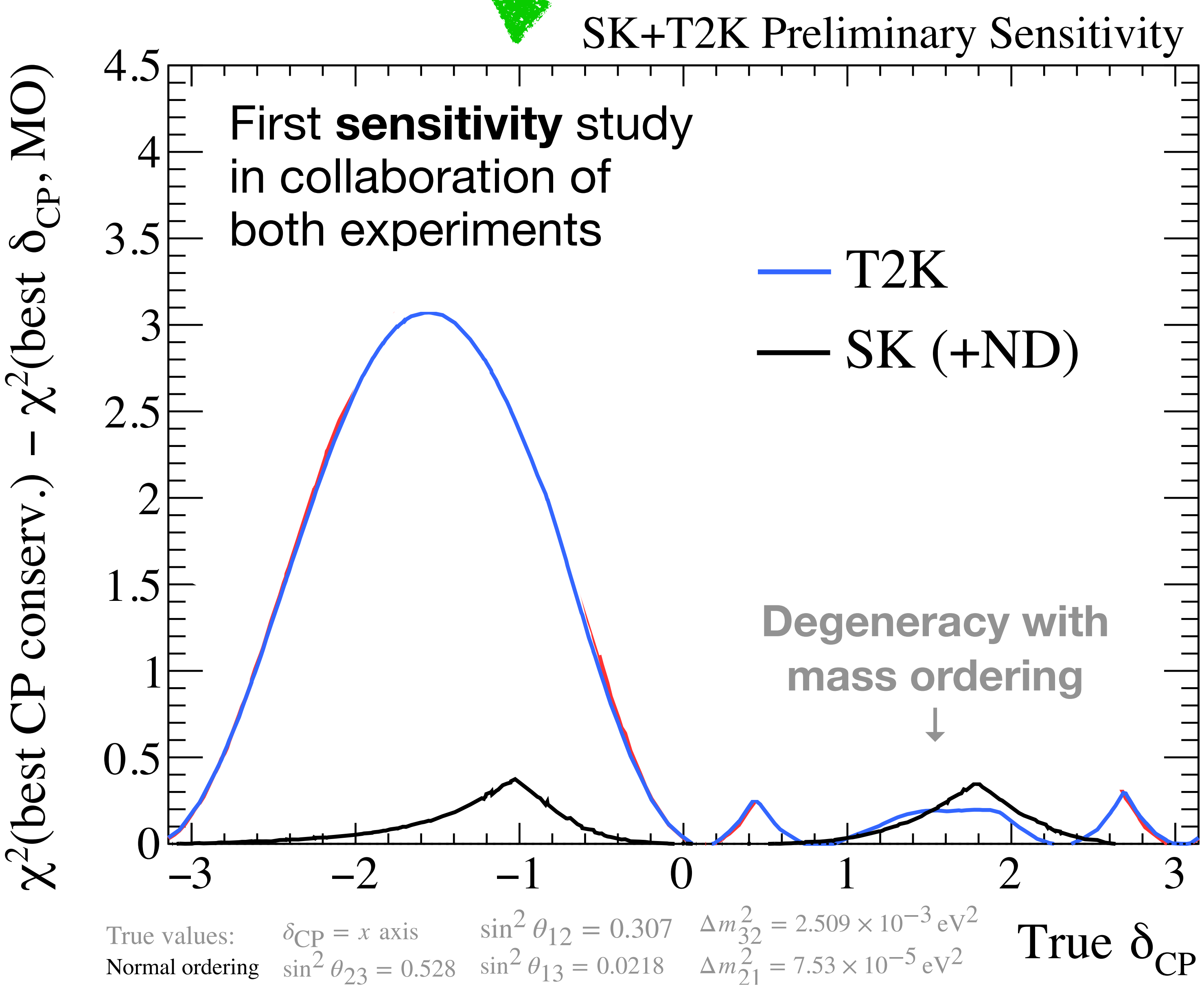

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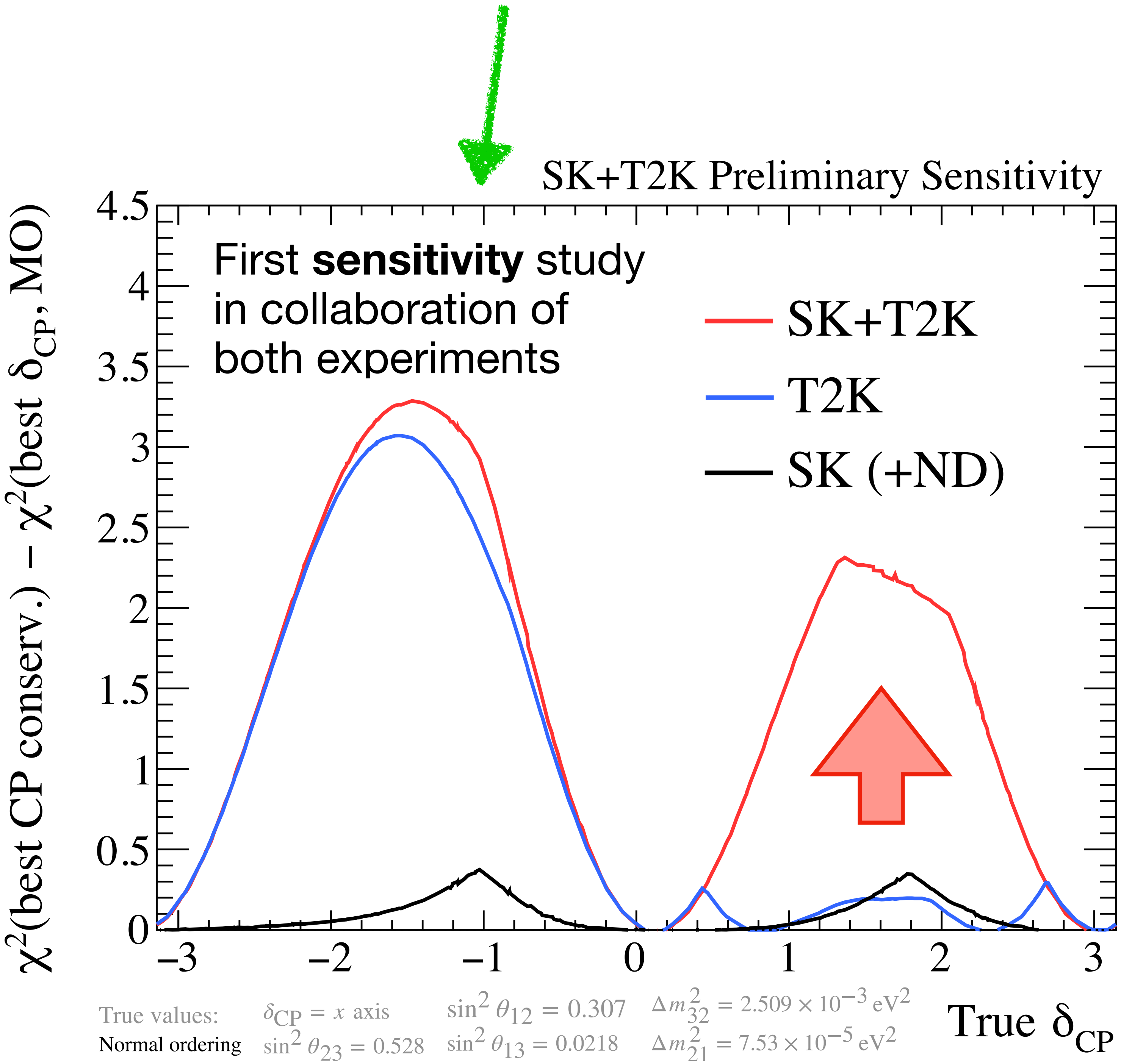

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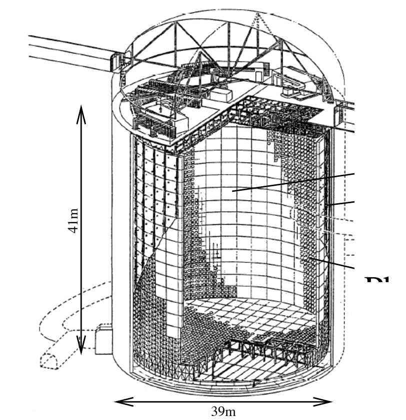
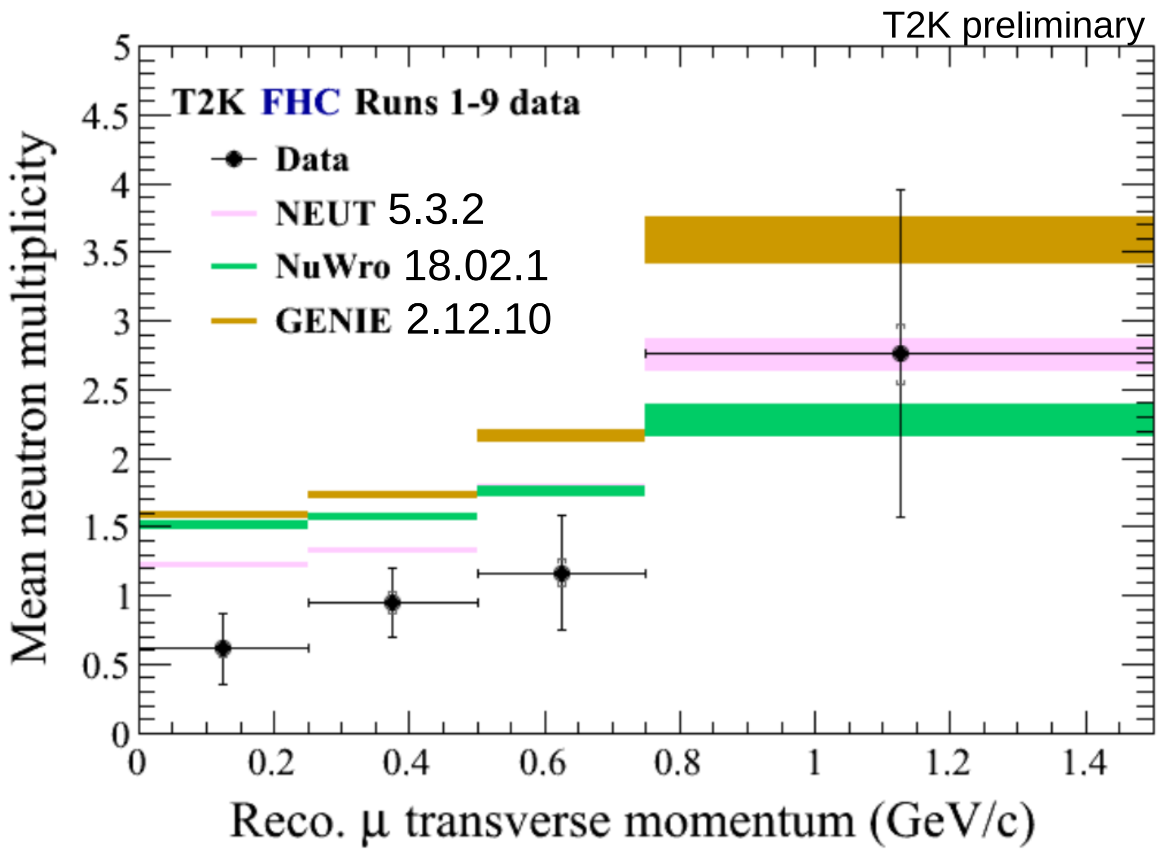
Neutrons at SuperK

(far detector)





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- Measured multiplicity using T2K beam, all generators over-predict
- Note: measurement uses data before adding Gd (H-capture)

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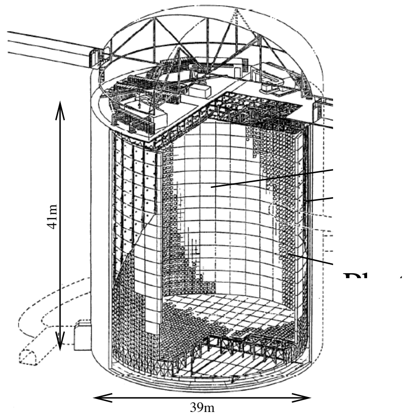

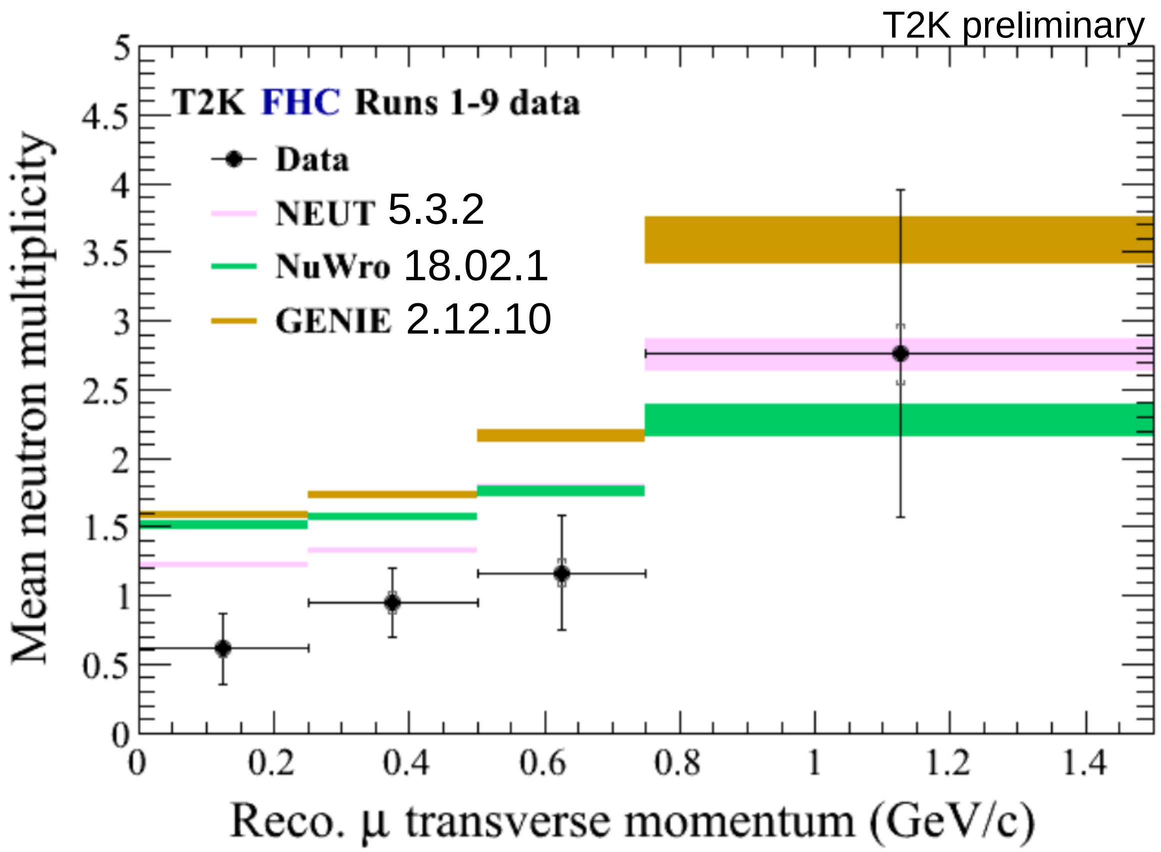

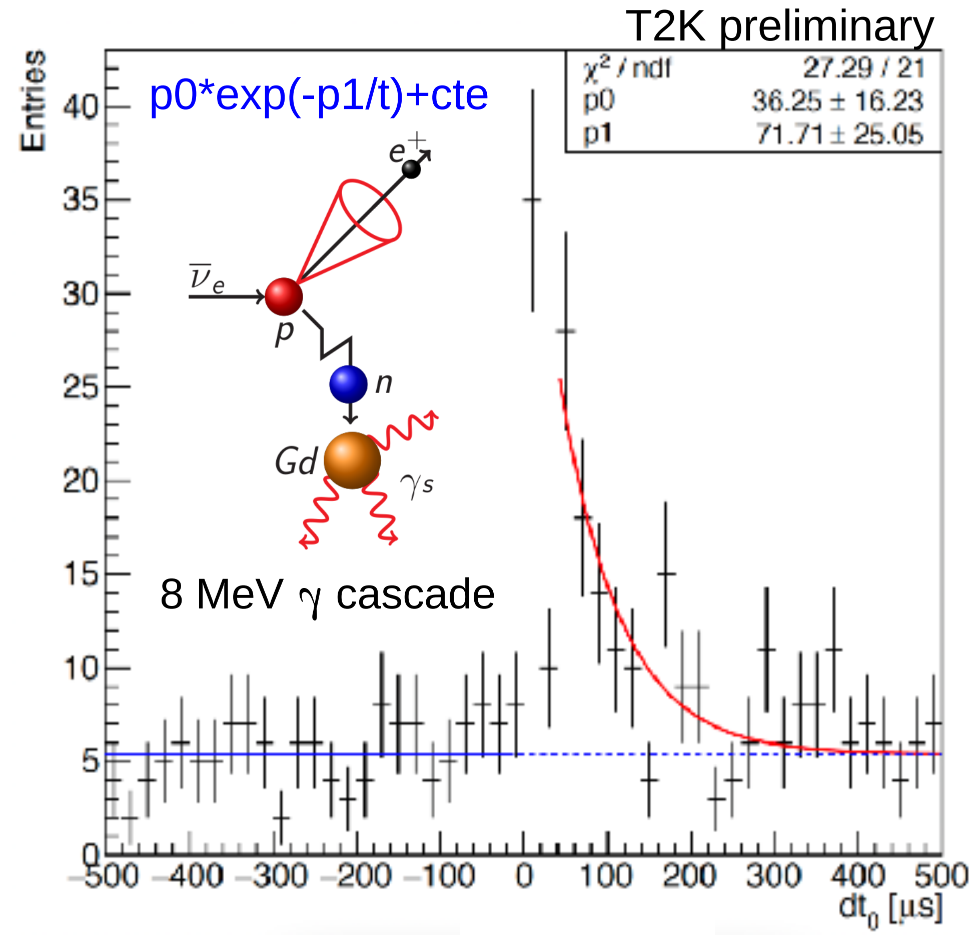

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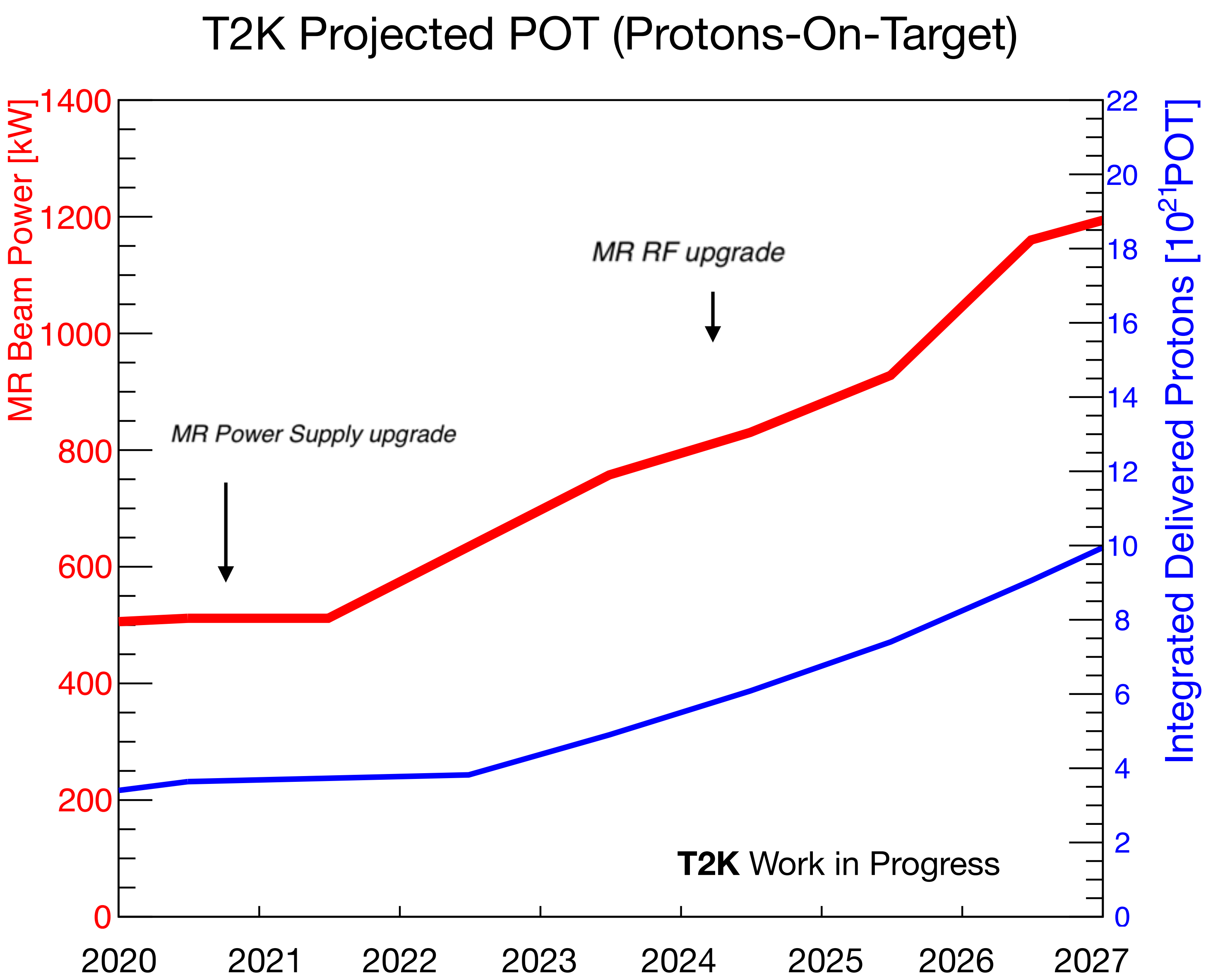
After addition of Gadolinium…

Exponential decrease of #events *after* beam timing consistent with Gd capture time constant (115 μs)

Aim to measure neutron multiplicity on Gadolinium in future

Beam line upgrade

- Increase **beam power** from ~500 kW to 1.3 MW via upgrades to main ring power supply and RF (mostly increased rep rate)
- Many upgrades to neutrino beam line (target, beam monitors, …) ongoing to accept 1.3 MW beam



TDR: arXiv:1908.05141 [physics.ins-det]

Beam line upgrade

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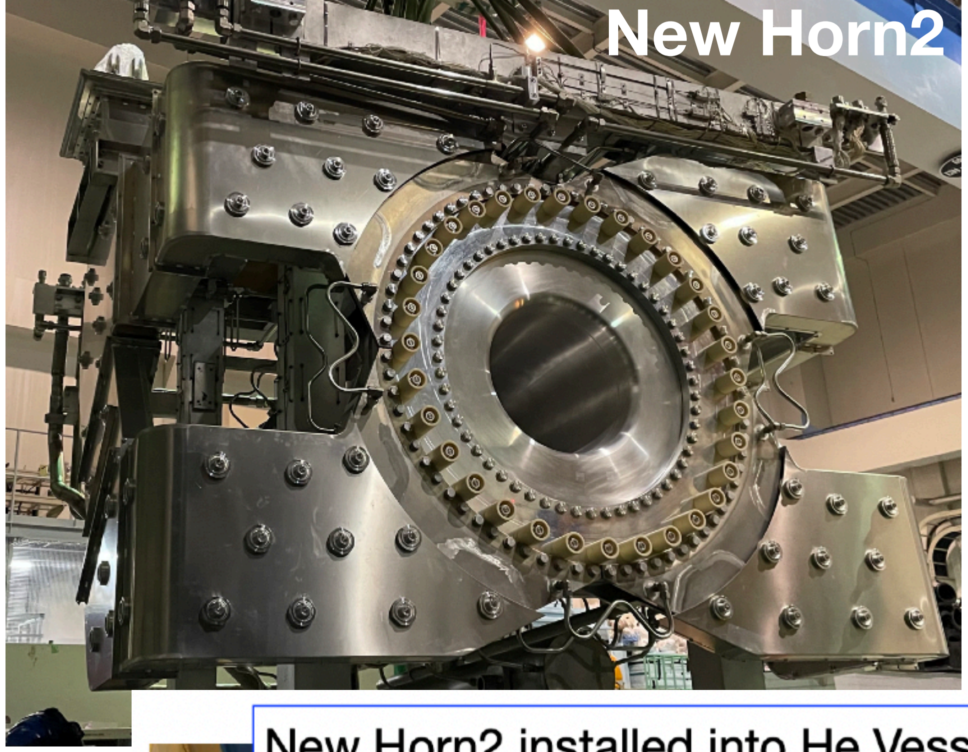
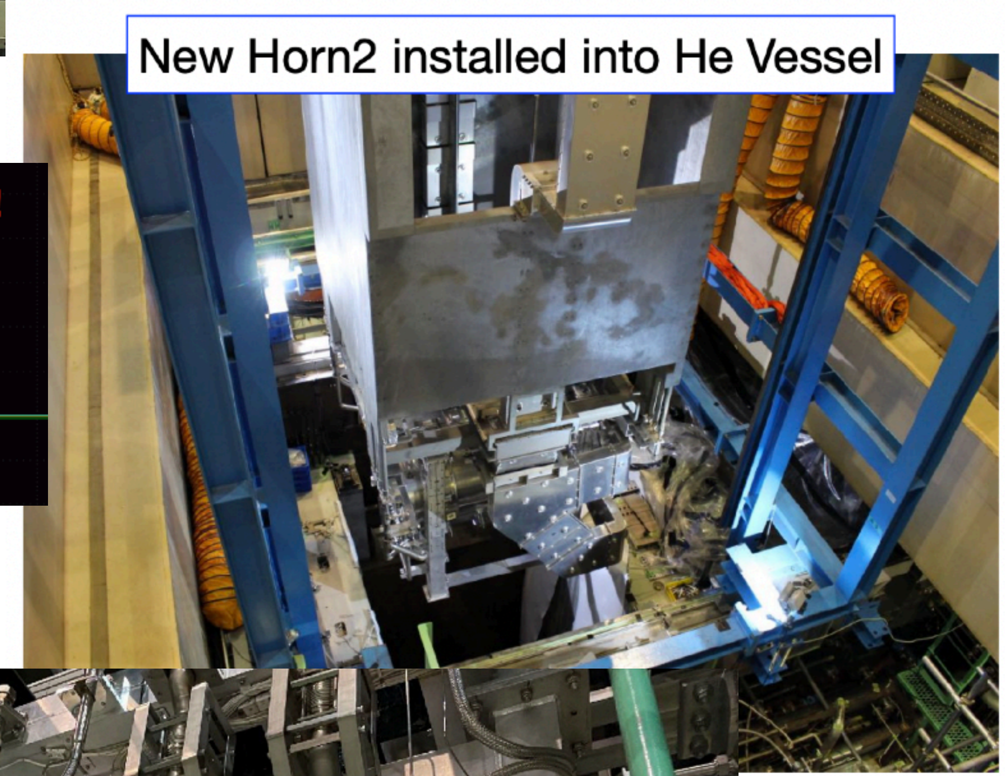
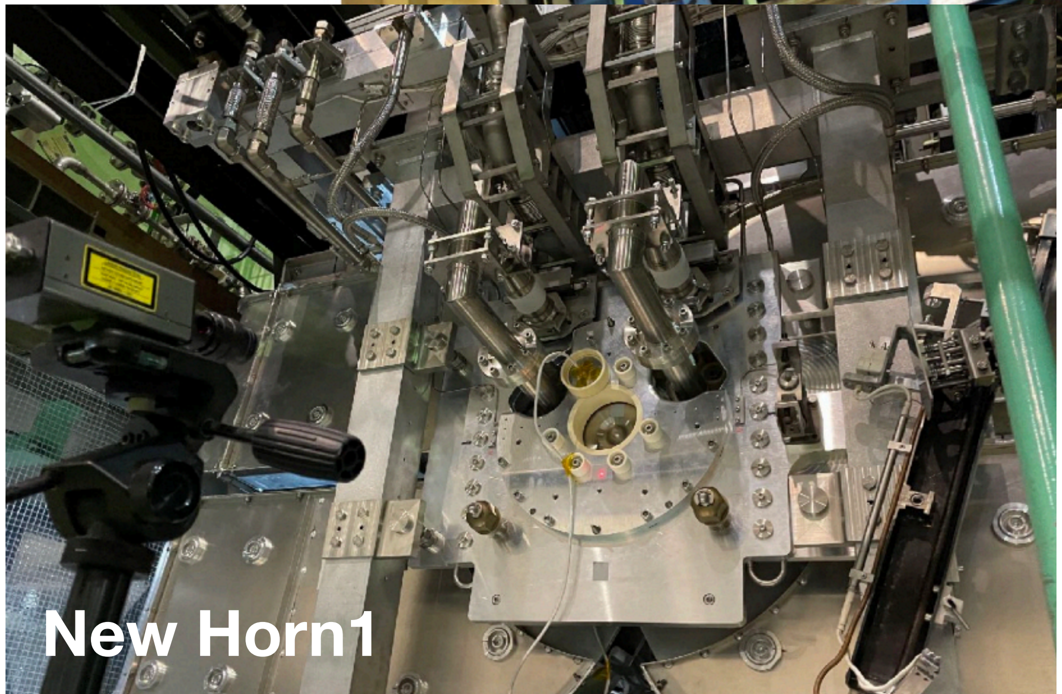
- Many upgrades to neutrino beam line (target, beam monitors, …) ongoing to accept 1.3 MW beam
- Increase **horn current** 250 kA → 320 kA for ~10% more ν/beam-power and reduced wrong-sign background

Aiming for 320 kA operation in next run (end of April)!







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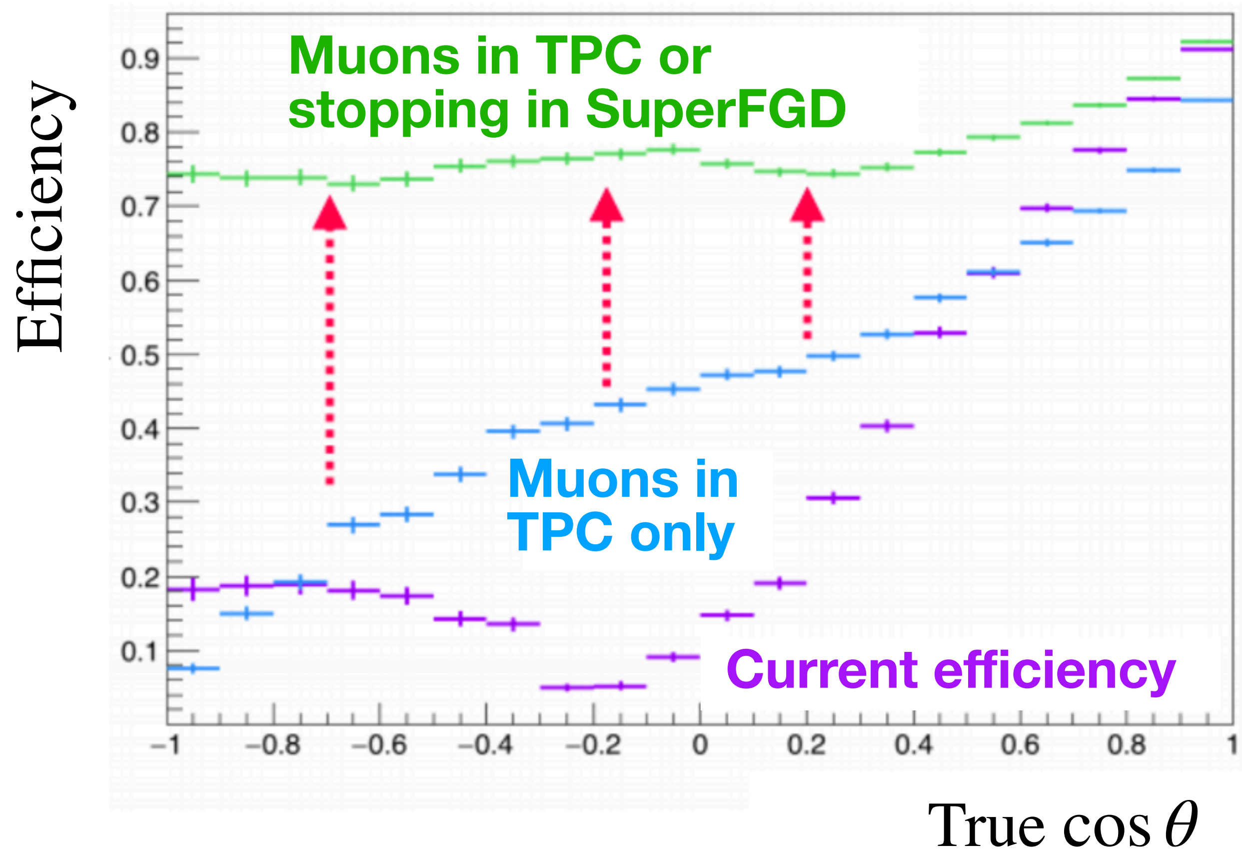
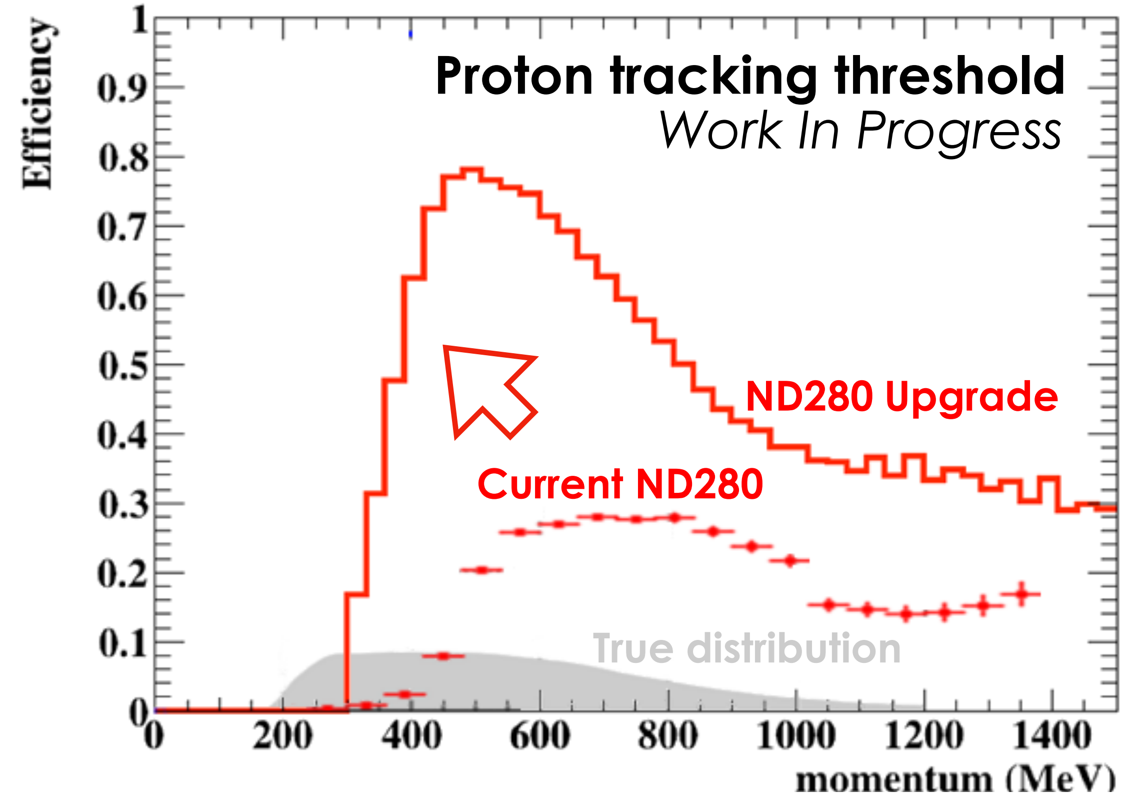




ND280 upgrade

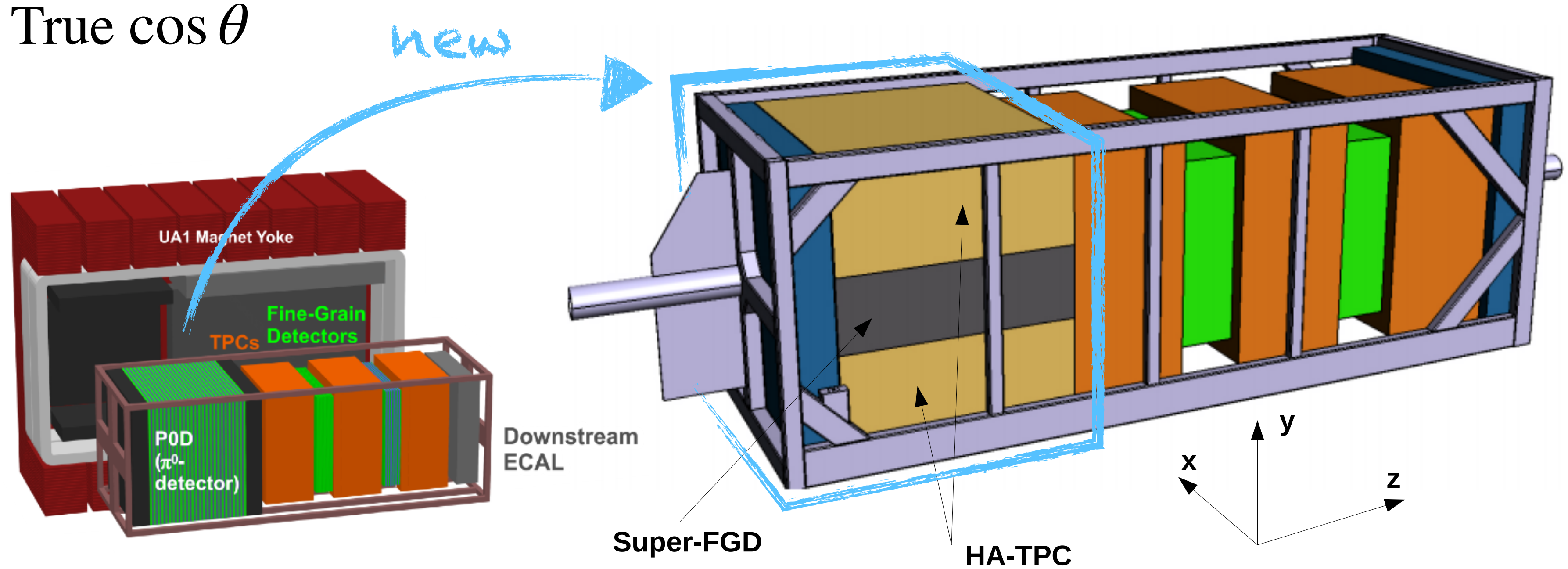
Replace **P0D** with
3D scintillation detector +
high-angle TPCs +
TOF enclosure

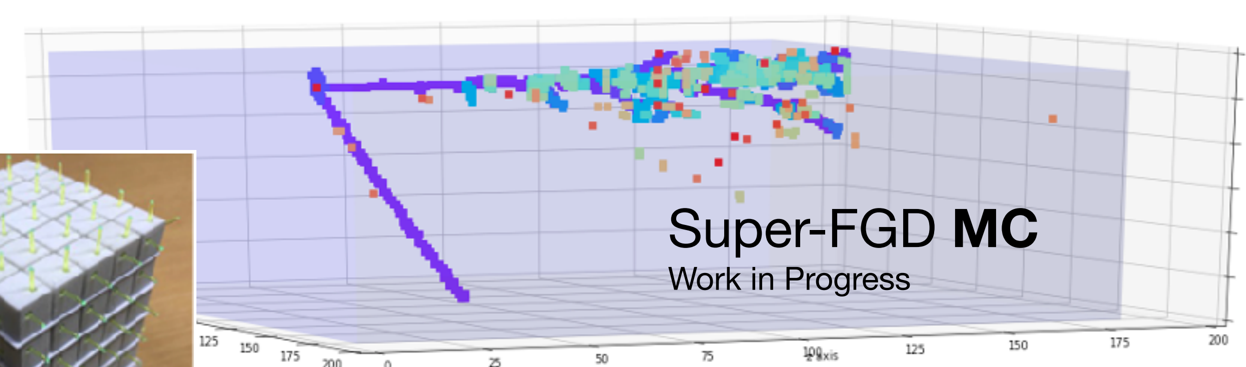
→ 4π acceptance like SK

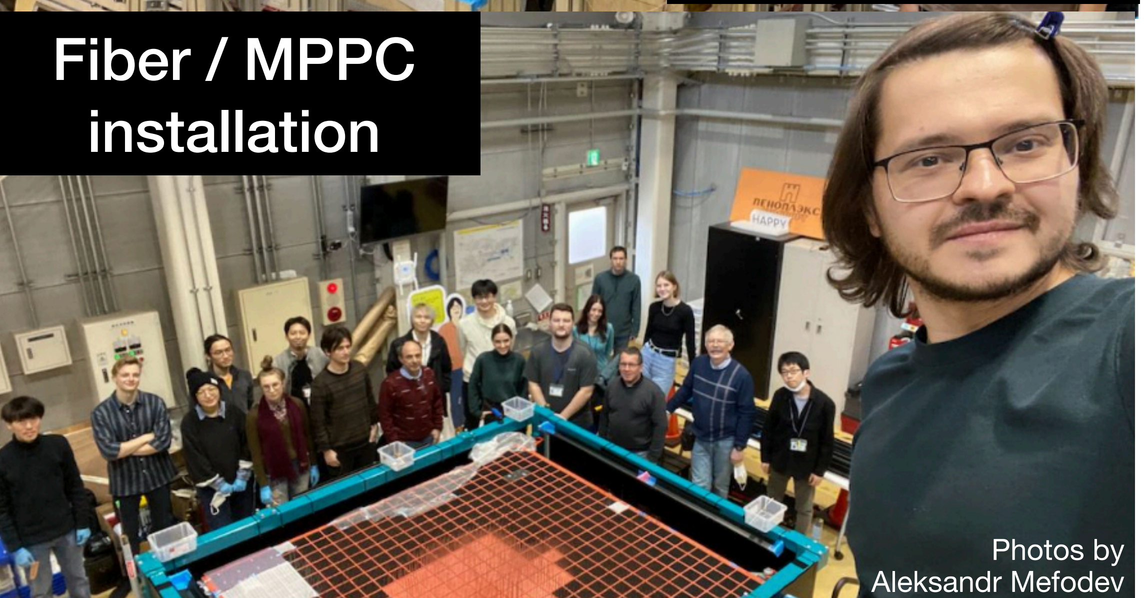
→ lower (proton) mom. threshold

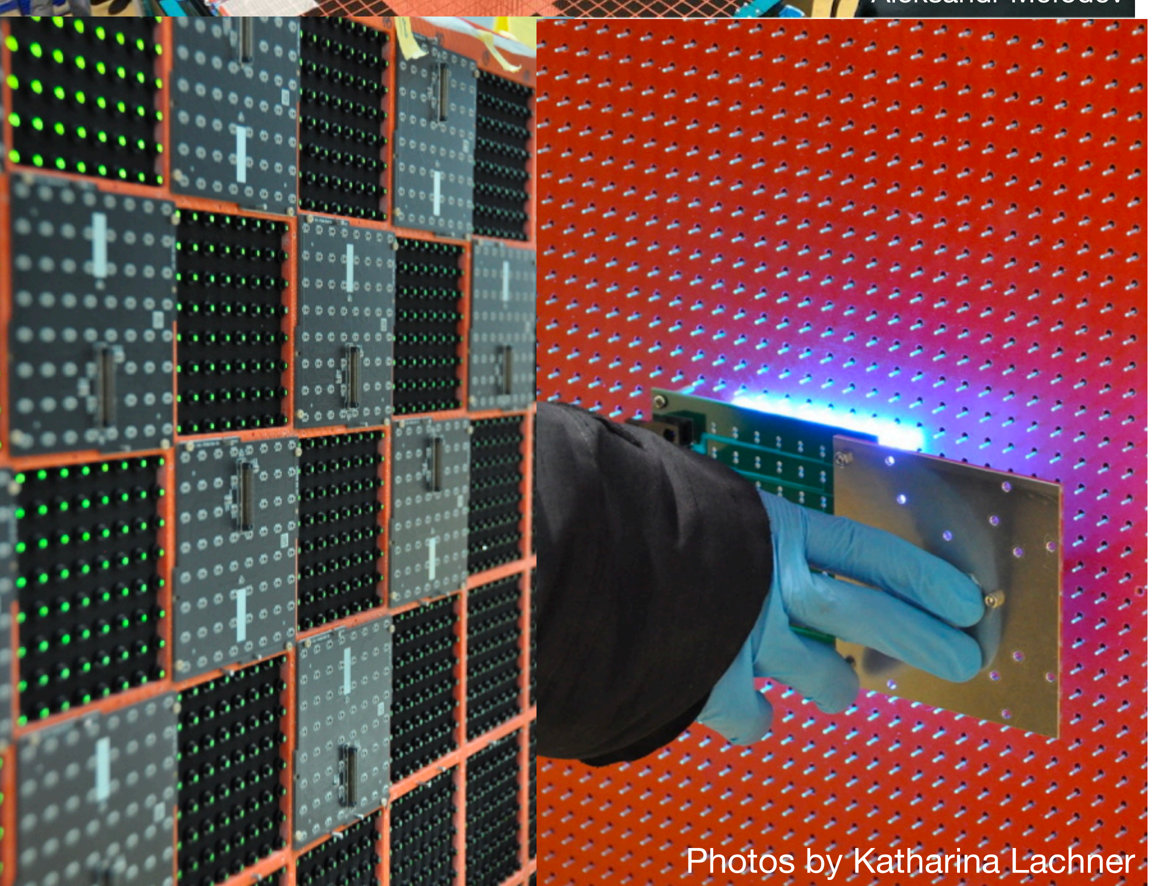
→ ~2x larger target mass

Reduce xsec systematics and better understanding of nuclear effects.

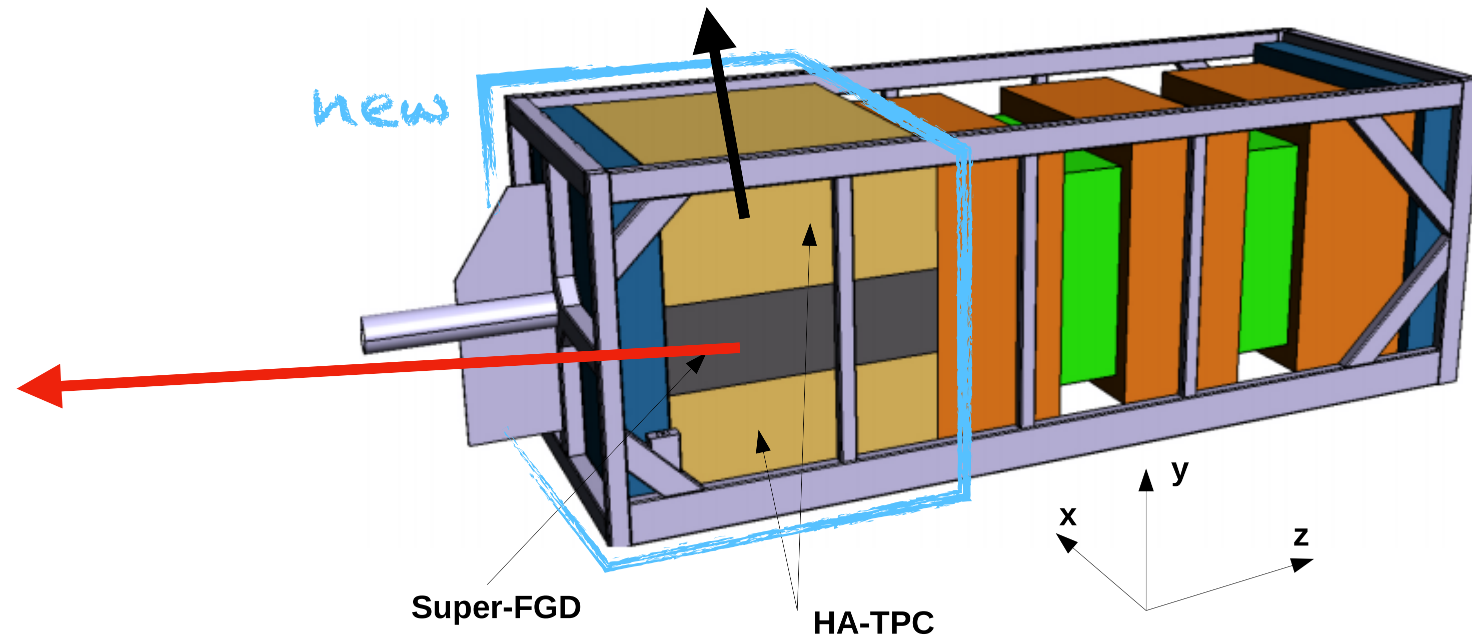








F. Sanchez, J-PARC PAC, Jan 2023



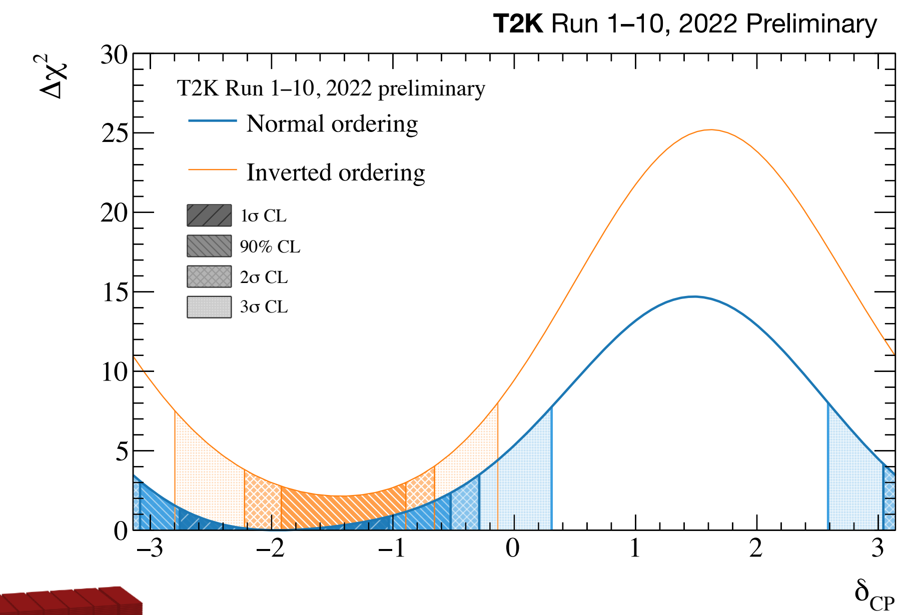
Problems leading to non-uniformity in High Angle TPCs understood and fixed → production progressing

Super-FGD construction at J-PARC well on track

Aiming for commissioning / installation of most components in autumn to be ready for beam

Summary

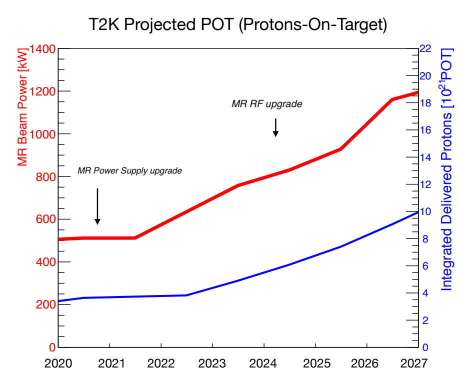
- Latest **T2K** neutrino oscillation results using 3.6×10^{21} protons on target, with **many improvements** at each level of analysis.

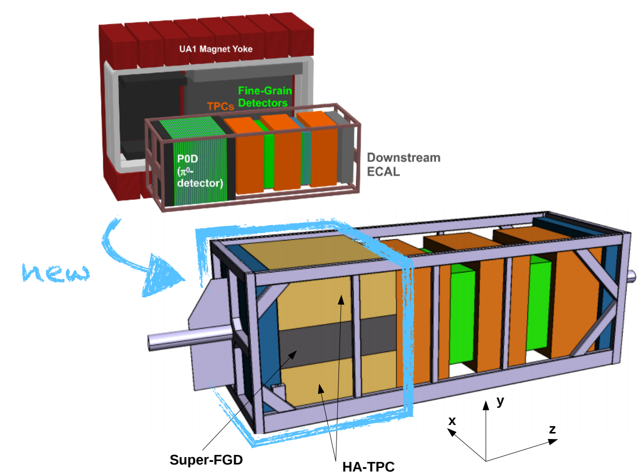


- **CP** conserving values of δ_{CP} excluded at 90%, **large range** excluded at 3σ.

- Many ongoing upgrades to the experiment
  - new near detectors
  - stronger beam, horns

- Exciting physics ahead coming with beam starting in April and NDup ready* for data in autumn
  * full detector at end of year





stay tuned!

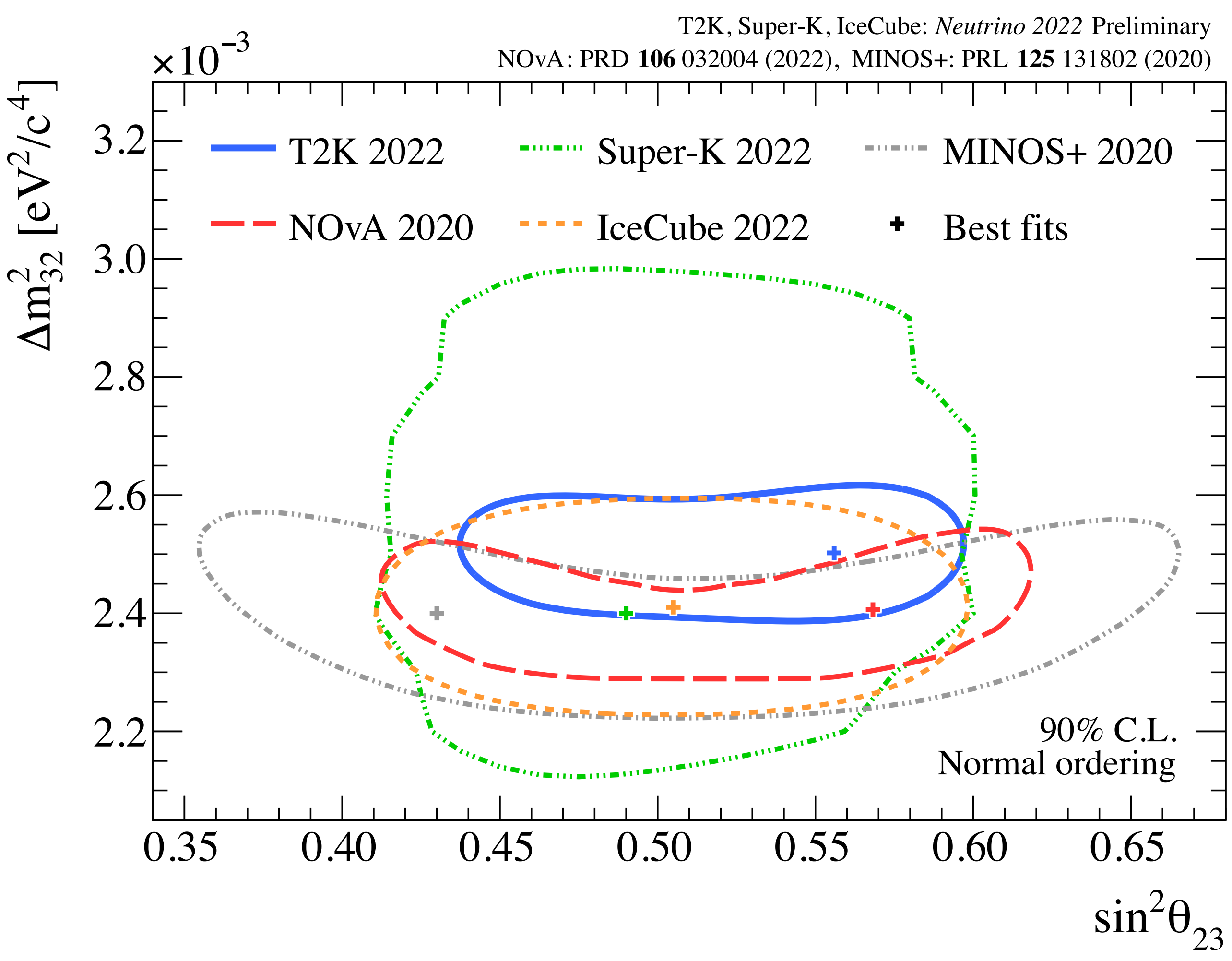
Approved budget:
100,000 JPY for travels

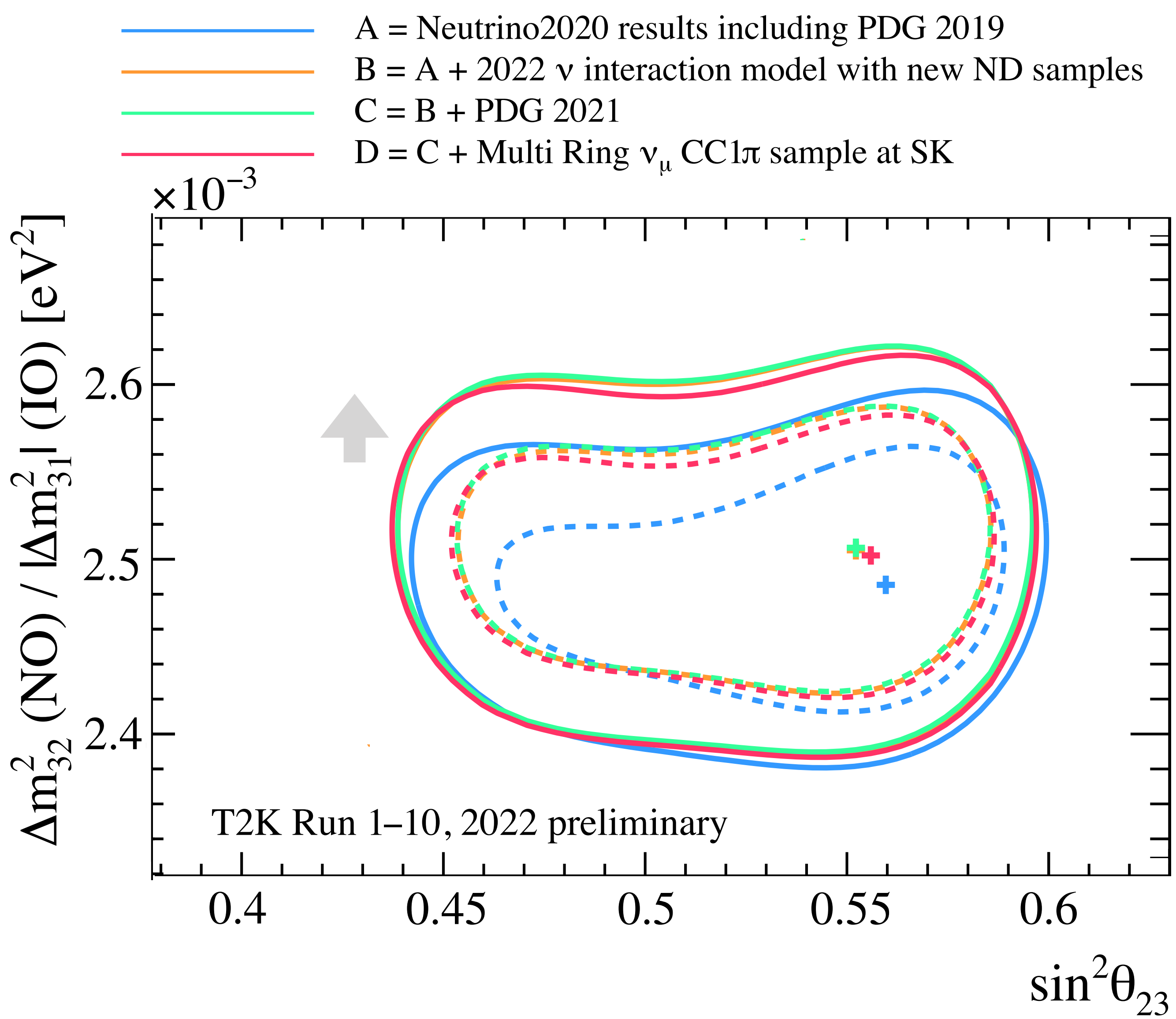
Thank you for continued support

backup

Δm^2_{32} vs. θ_{23}

Atmospheric mixing parameters

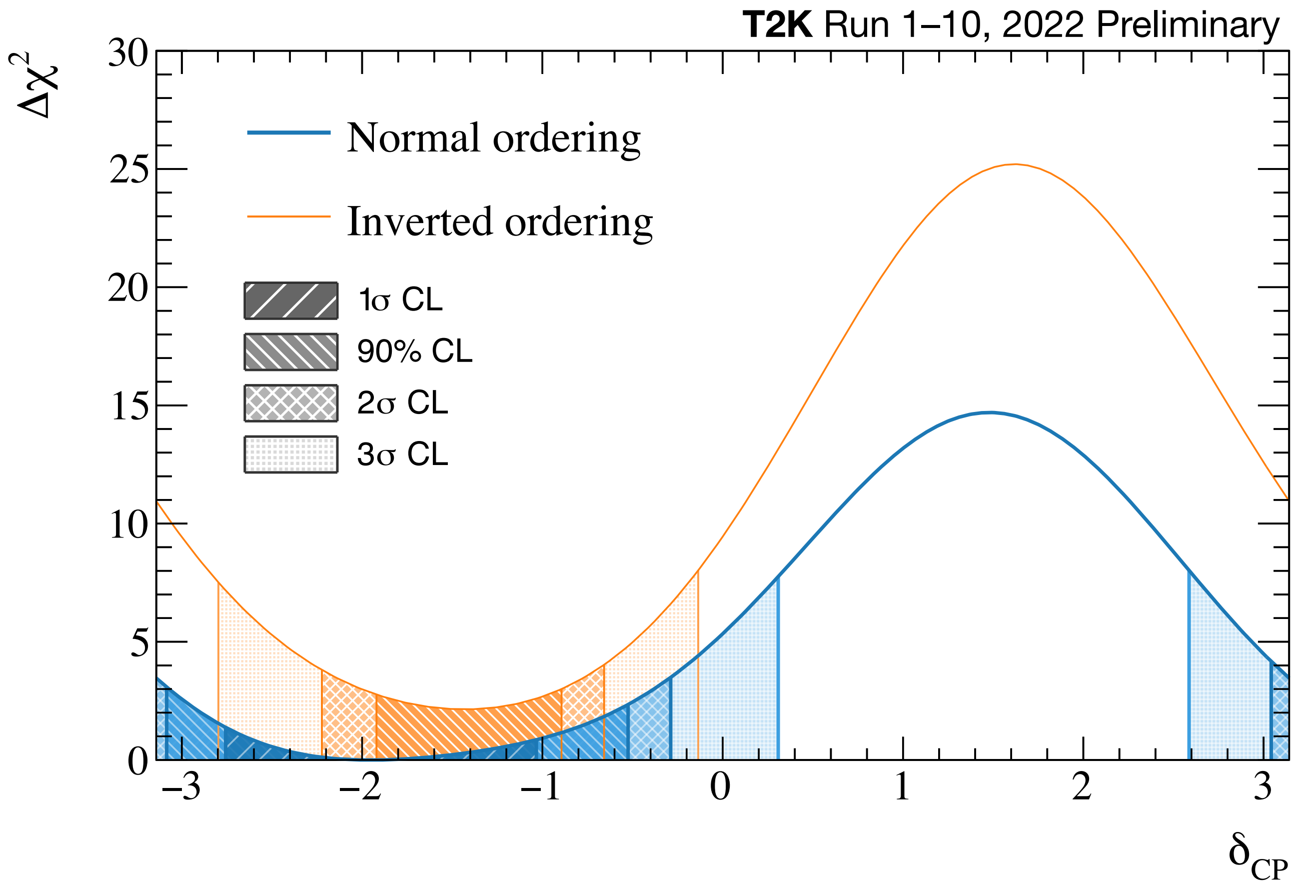


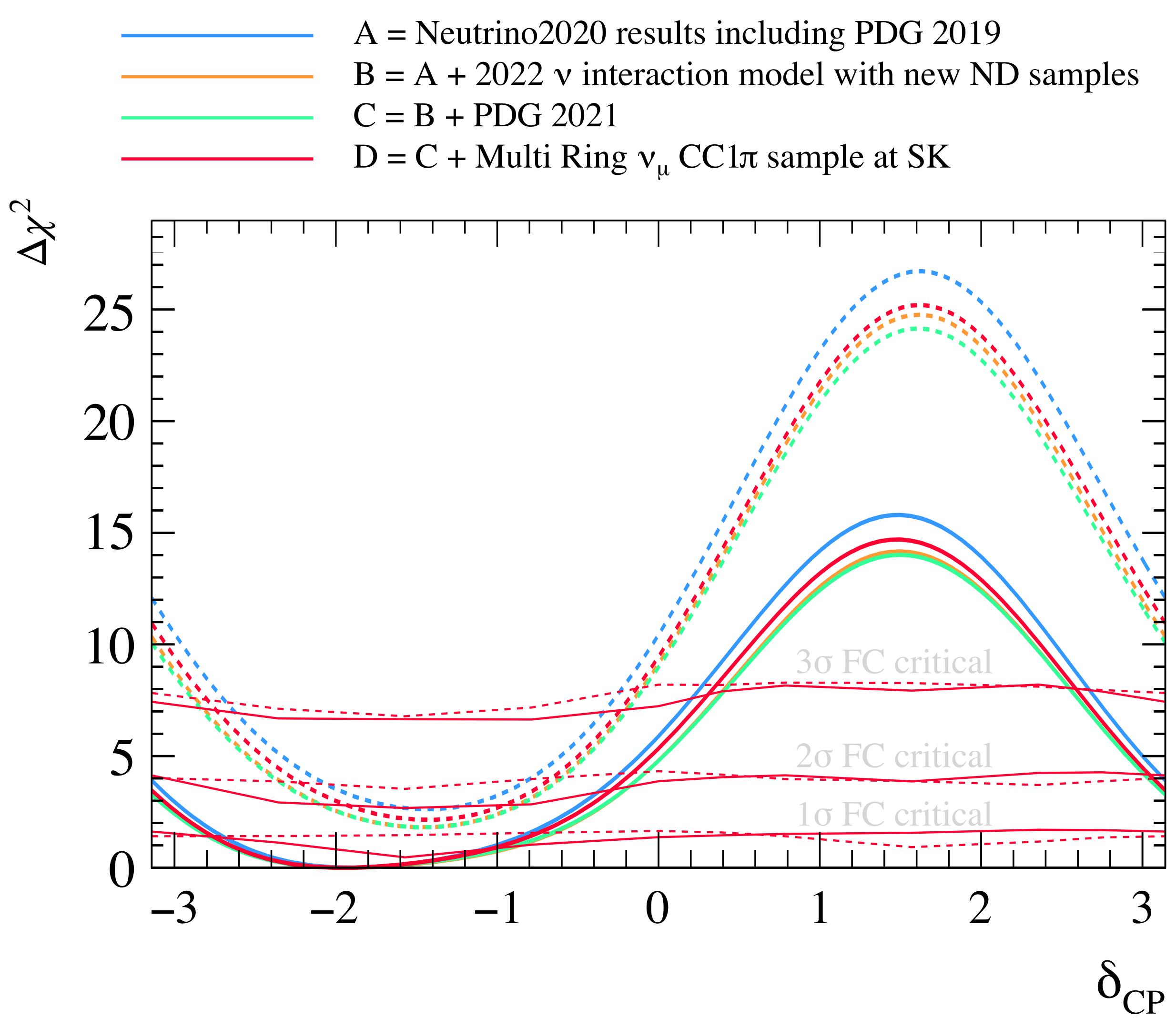


World-leading measurement of atmospheric params still compatible with both octants, very weakly preferring upper

- **New** interaction model and ND samples cause largest change compared to **2020**
- Multi-ring ν_μCC1π sample only gives small contribution due to being above oscillation maximum

Constraints on δ_{CP} and mass ordering





- Large region **excluded at 3σ**
- CP-conservation $\{0, \pi\}$ **excluded at 90%**, π is within 2σ
- In checks for biases caused by xsec model choices, left (right) 90% CI edge moves at most by 0.06 (0.05)
- Weak preference of **normal ordering**

- Slightly weaker constraint compared to 2020 analysis, mainly due to updated model with new ND samples

NOvA + T2K

810 km / 295 km

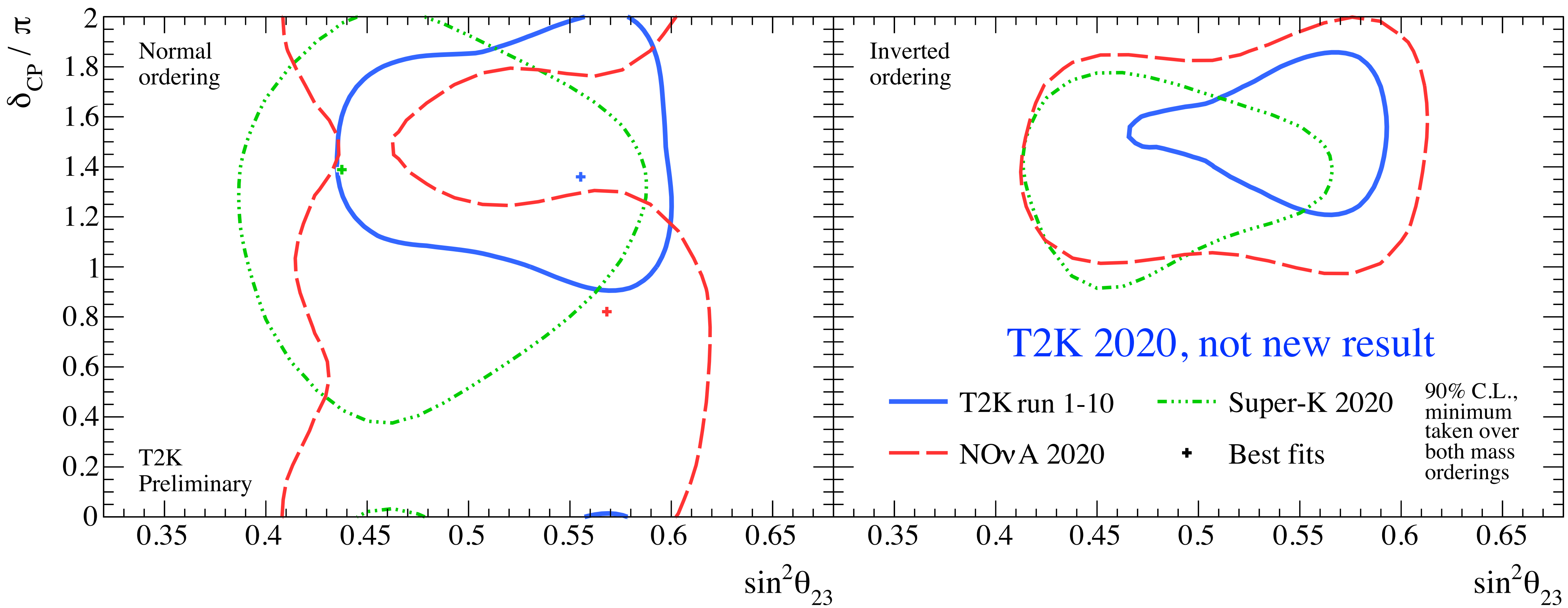
Ongoing joint fits

SK + T2K

atmospheric + accelerator

Comparison of released contours (not joint fit)

NOvA results: A. Himmel (2020) Zenodo, (preliminary)
SK results: Y. Nakajima (2020) Zenodo, (preliminary)
NOvA and T2K use Feldman-Cousins, SK use fixed $\Delta\chi^2$



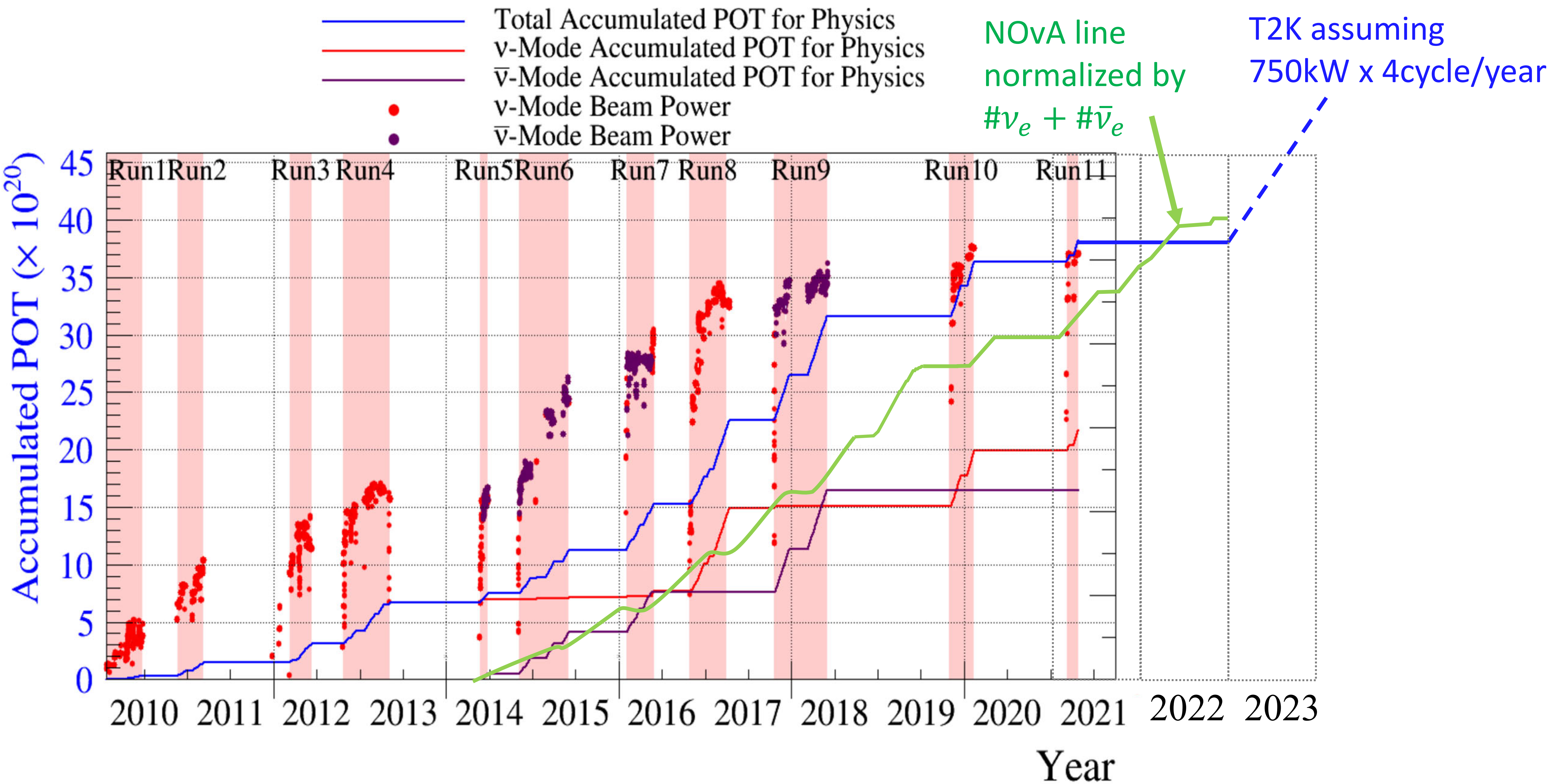
- Joint fits between experiments with different oscillation baselines/energies and detector technologies

→ expect increased sensitivity in δ_{CP}, mass ordering, θ_{23} octant
beyond stats increase from resolved degeneracies and syst constraints

- important to understand potentially non-trivial syst. **correlations** between experiments

First results expected soon!

Competition with NoVA



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%)

Slide taken from F. Sanchez, J-PARC PAC, Jan 2023