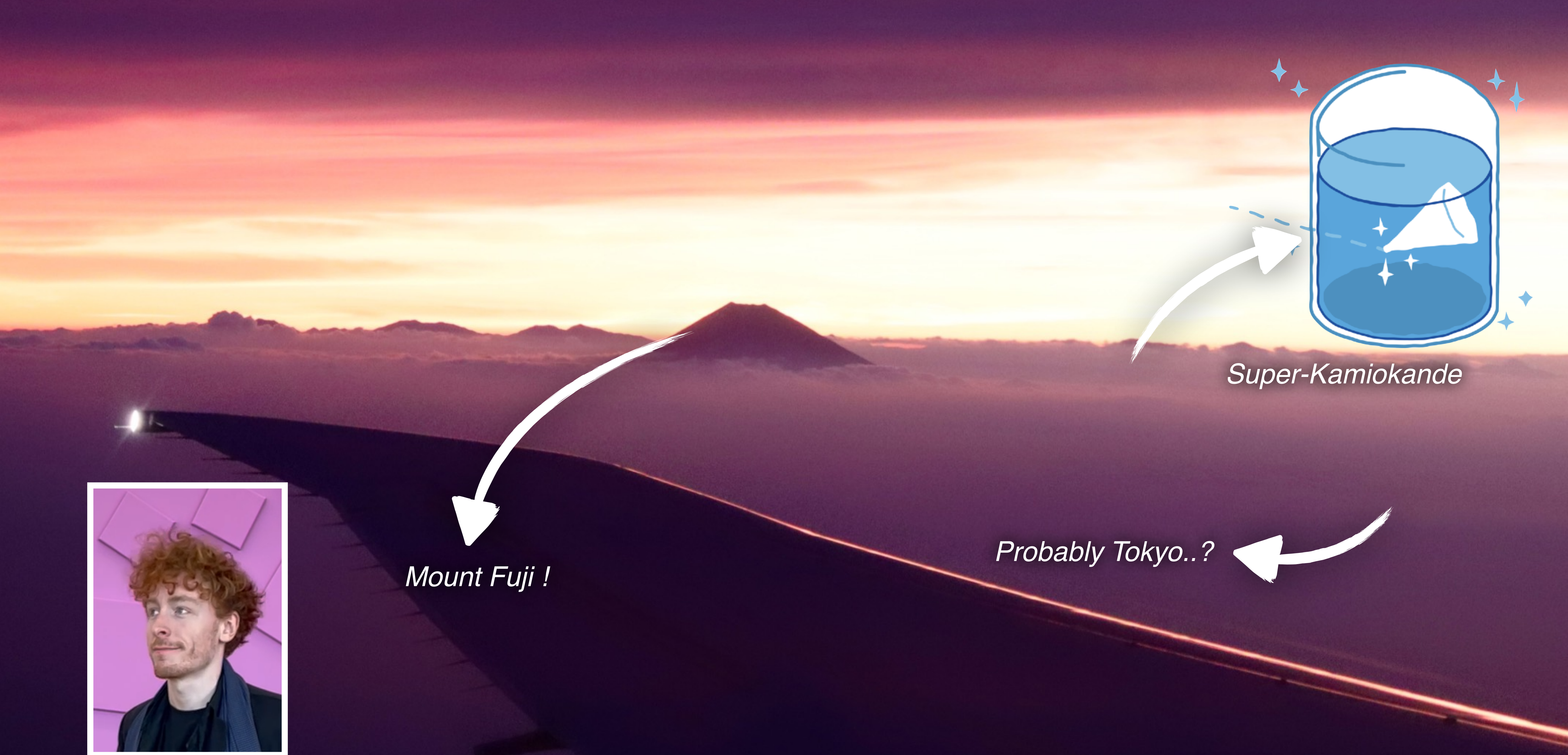
T2K latest oscillation results

Adrien Blanchet
For the T2K collaboration

NuFACT 2023: The 24th International Workshop on Neutrinos from Accelerators
2023-08-25 - Seoul / South Korea

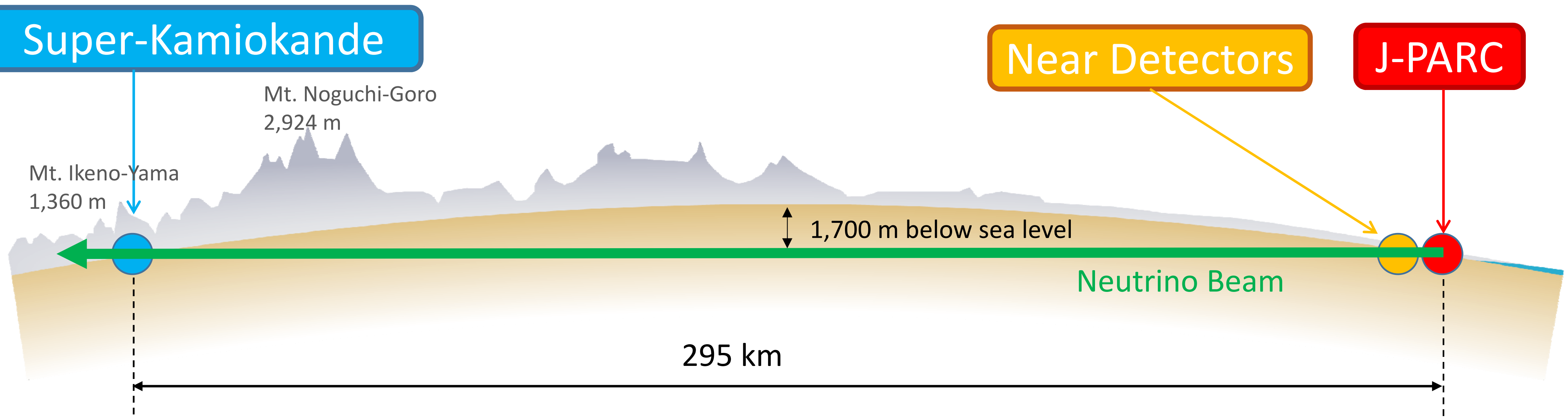


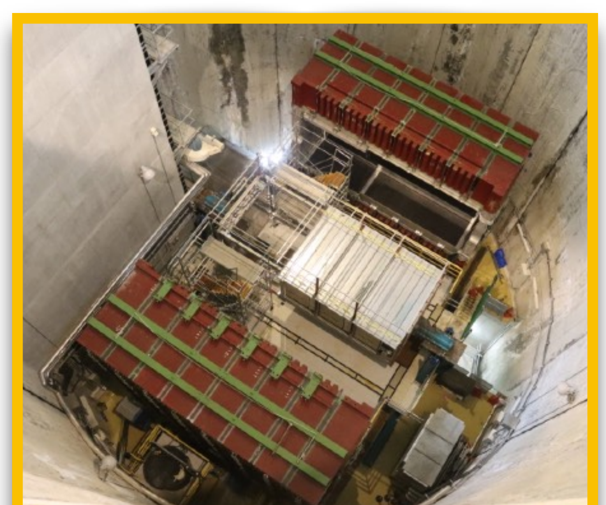
A flight to Japan in June 2023

The T2K experiment

~500 collaborators across 14 countries and 75 institutes

See **Daniel Cherdack** talk for the global summary!

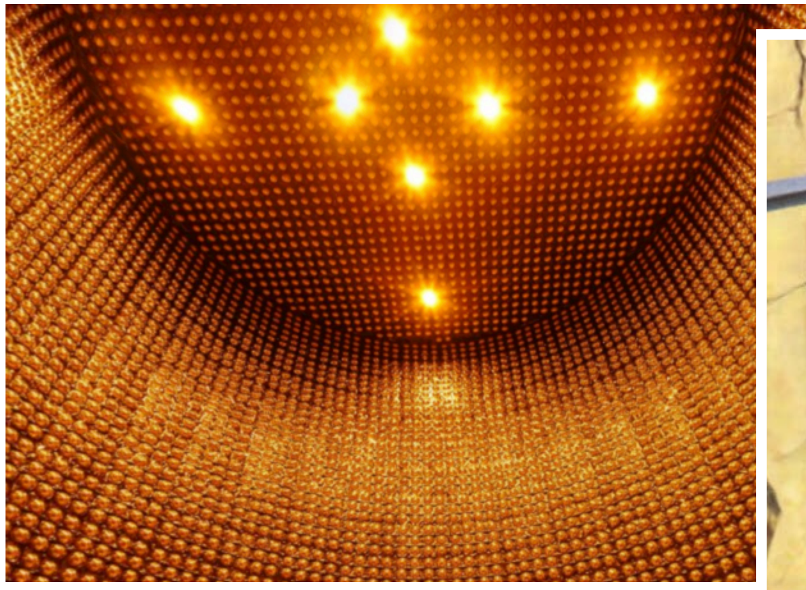


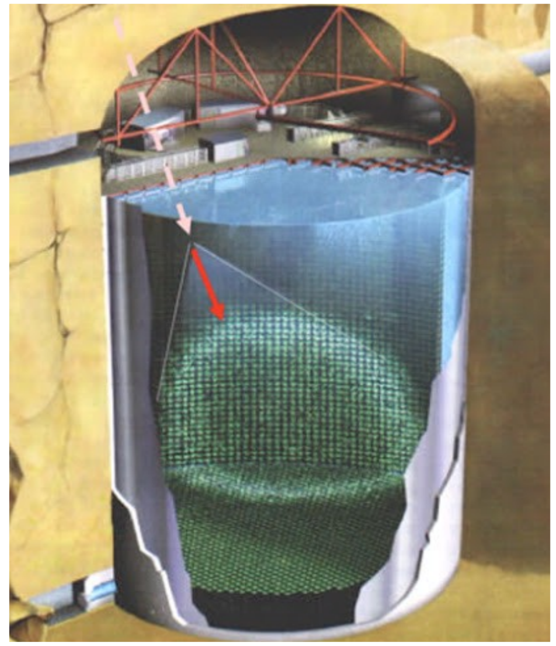


$\nu_\tau, \nu_\tau, \nu_\tau, \nu_\tau, \nu_\tau, \nu_e, \nu_\mu, \nu_\mu \longleftarrow \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$

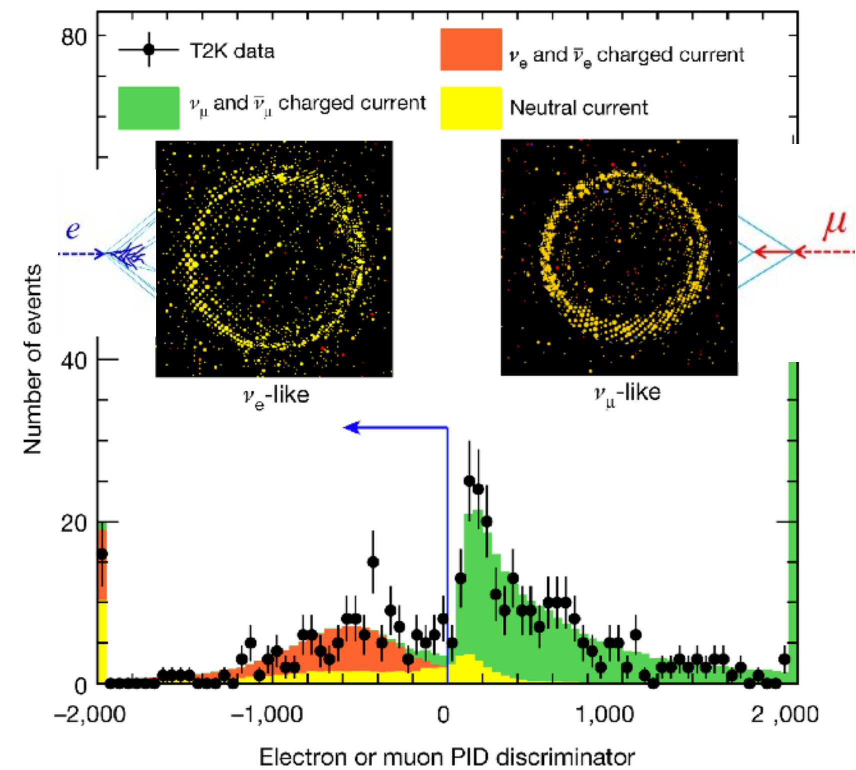
- Measure oscillation parameters with accelerator neutrinos
- Understand better neutrino interactions with matter

Highlighting Super-Kamiokande and ND280





Nature 580, 339–344 (2020)

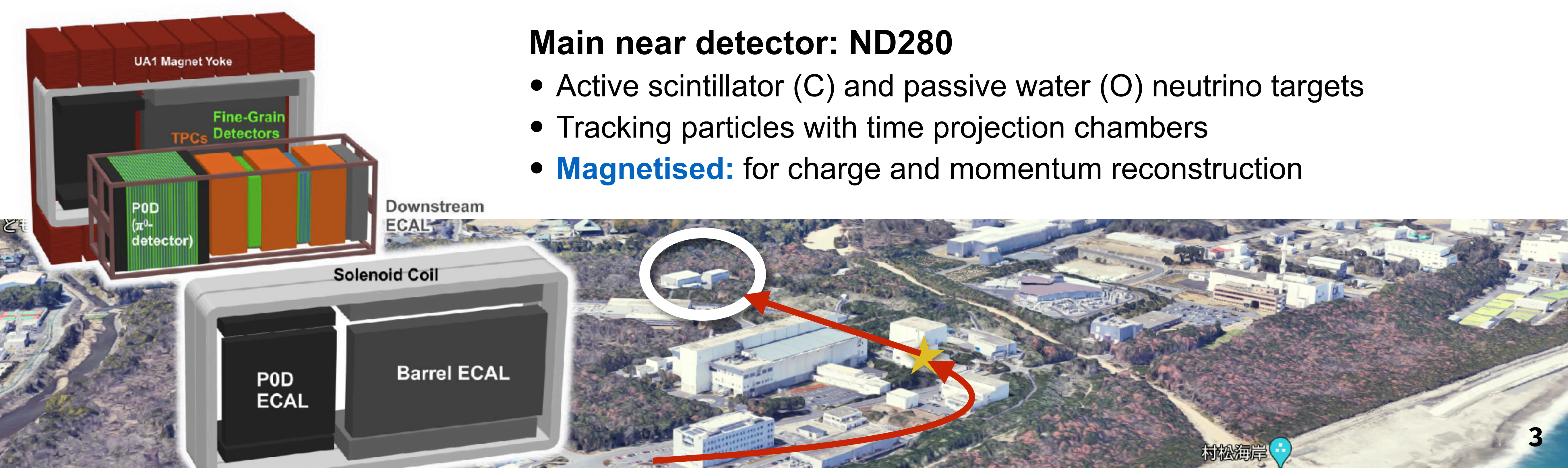


Super-Kamiokande

- Good particle identification using the ring shape and sharpness
- Neutrino energy reconstruction from lepton momentum and angle wrt beam direction
- **Not magnetised:** need near detector constraints for wrong-sign backgrounds

Main near detector: ND280

- Active scintillator (C) and passive water (O) neutrino targets
- Tracking particles with time projection chambers
- **Magnetised:** for charge and momentum reconstruction

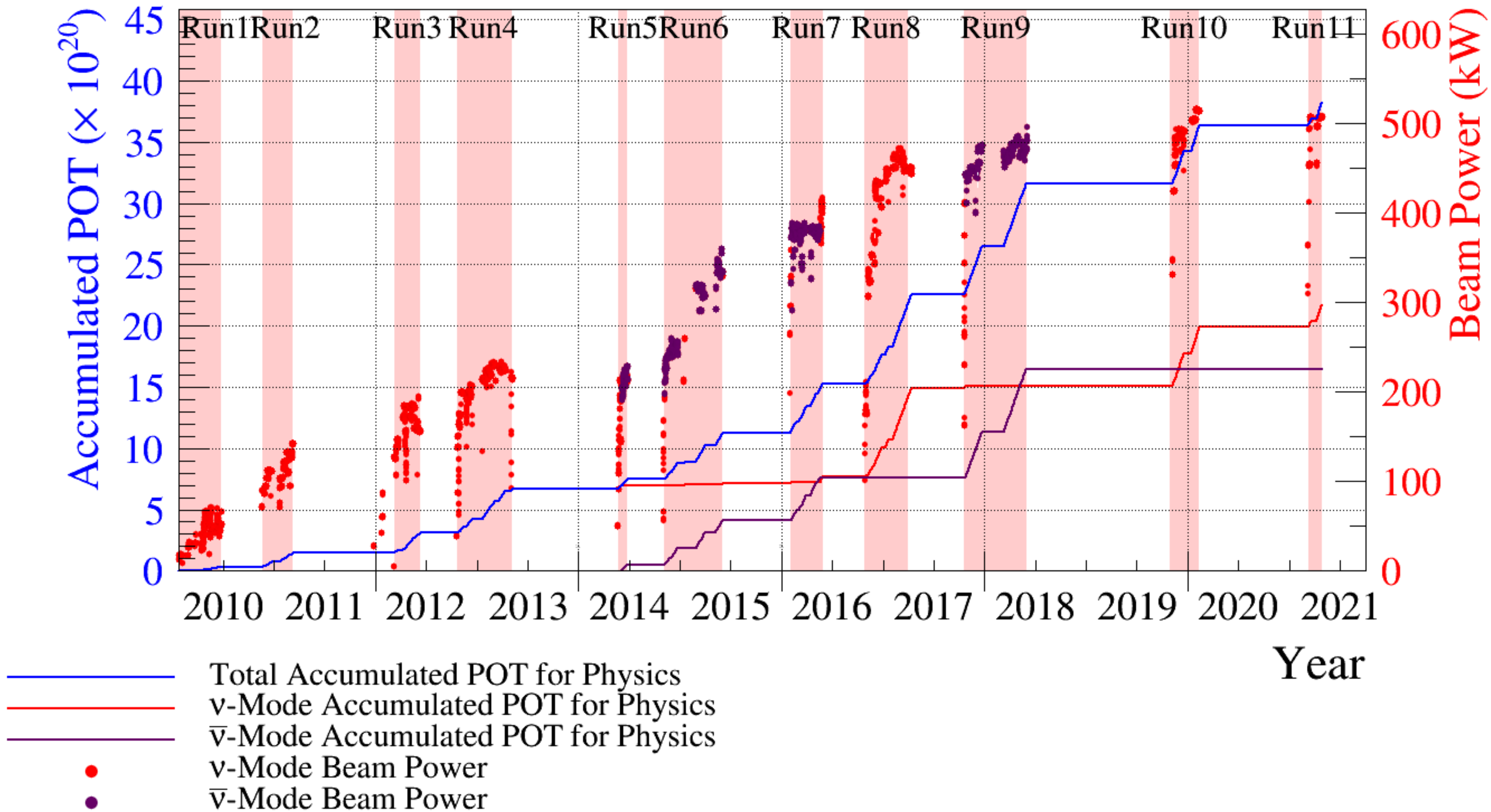


Oscillation analysis with 2022 data release

This talk — new samples (stat. increase) — presented at Neutrino 2022

Presented at Neutrino 2020, paper accepted in EPJC (arXiv: 2303.0322)

Nature (early 2020) — short paper **580, 339–344 (2020)**
Phys. Rev. D — long paper Phys.Rev.D 103, 112008

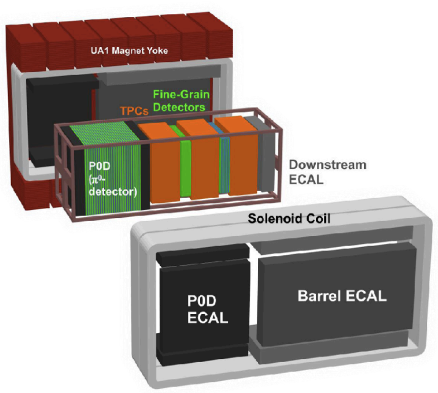


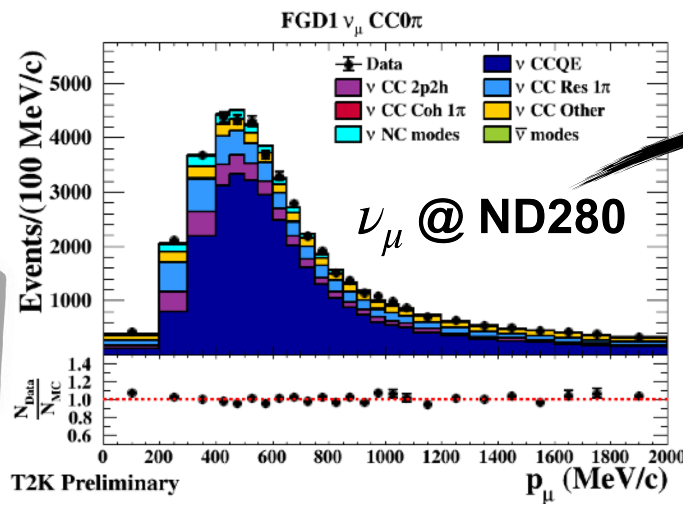
Overview and highlights of this analysis

$\left\{\text{Observed event rate @ SK}\right\} = \left\{\nu\ \text{Flux models}\right\} \times \left\{\nu\ \text{cross-section models}\right\} \times \left\{\text{SK detector model}\right\} \times \left\{\text{oscillation parameters}\right\}$

Constrained by ND280

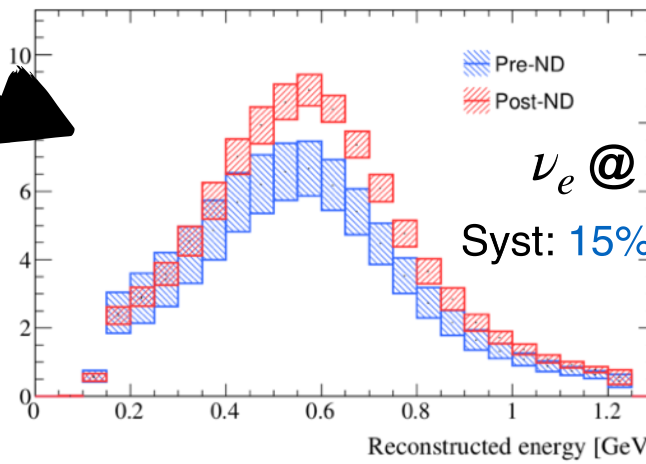
What we seek





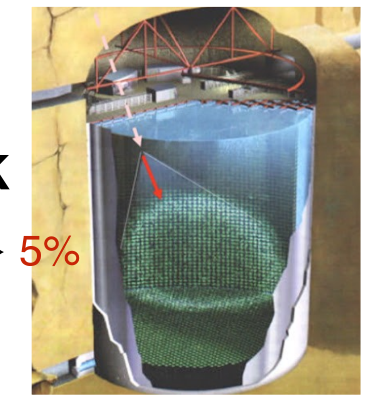
ν_μ @ ND280

Constrains and corrects *flux & cross-section systematics*



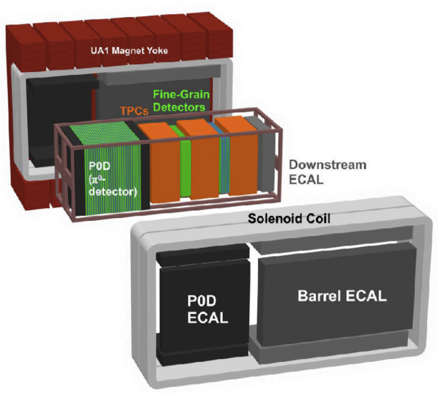
ν_e @ SK

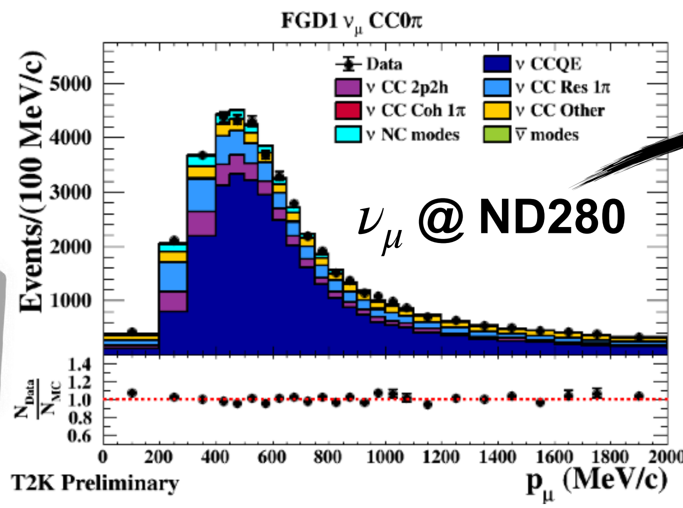
Syst: 15% → 5%



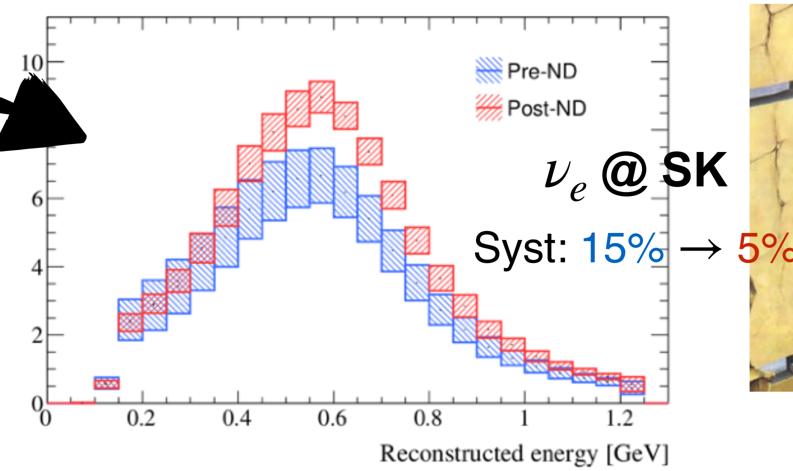
Overview and highlights of this analysis

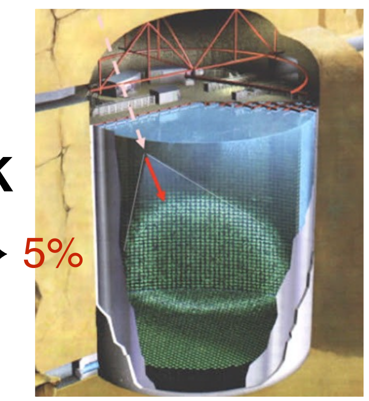
$$\left\{\begin{array}{c}\text{Observed}\\ \text{event rate}\\ \text{@ SK}\end{array}\right\} = \underbrace{\left\{\begin{array}{c}\nu\ \text{Flux}\\ \text{models}\end{array}\right\} \times \left\{\begin{array}{c}\nu\ \text{cross-section}\\ \text{models}\end{array}\right\}}_{\text{Constrained by ND280}} \times \left\{\begin{array}{c}\text{SK detector}\\ \text{model}\end{array}\right\} \times \underbrace{\left\{\begin{array}{c}\text{oscillation}\\ \text{parameters}\end{array}\right\}}_{\text{What we seek}}$$





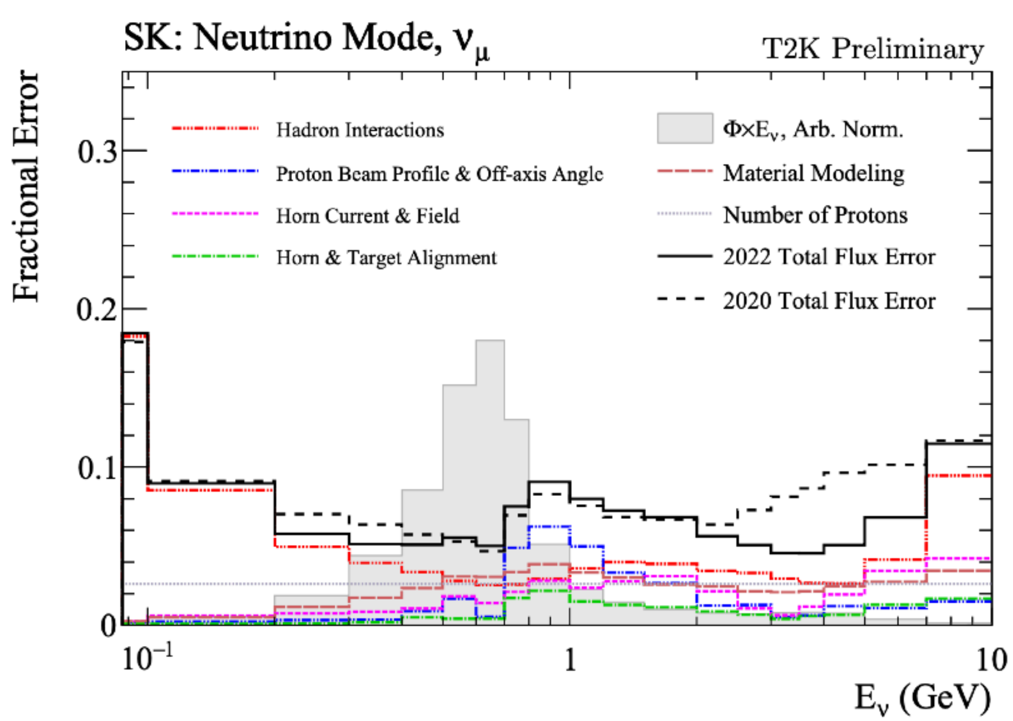
Constrains and corrects *flux & cross-section systematics*





Improved flux model

- More realistic beam line modelling + use of beam monitor data
- Using high-statistics NA61 2010 kaon dataset



See **Megan Friend** talk!

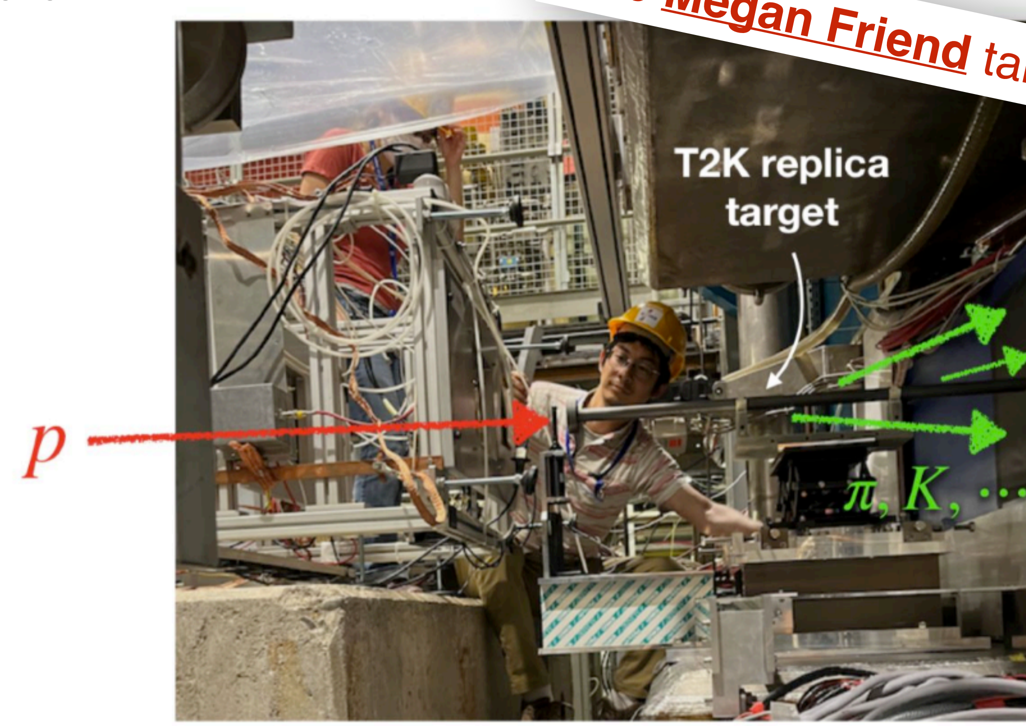
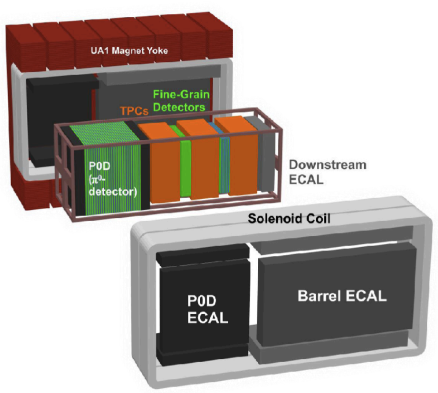
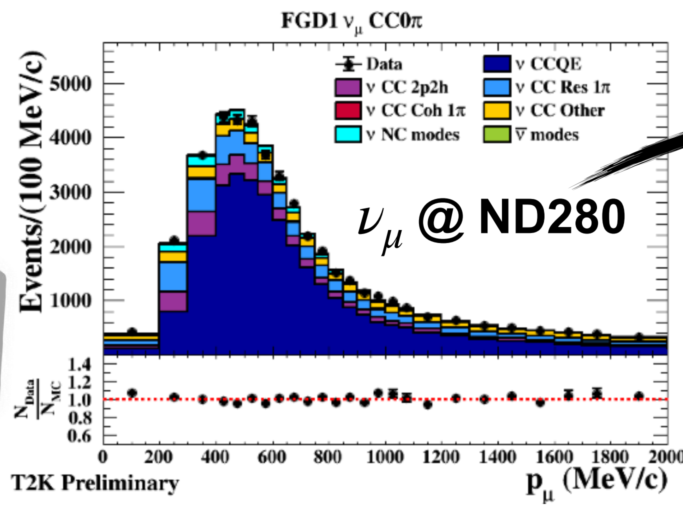


Photo from this summer
(by Eric D. Zimmerman, NA61/SHINE)

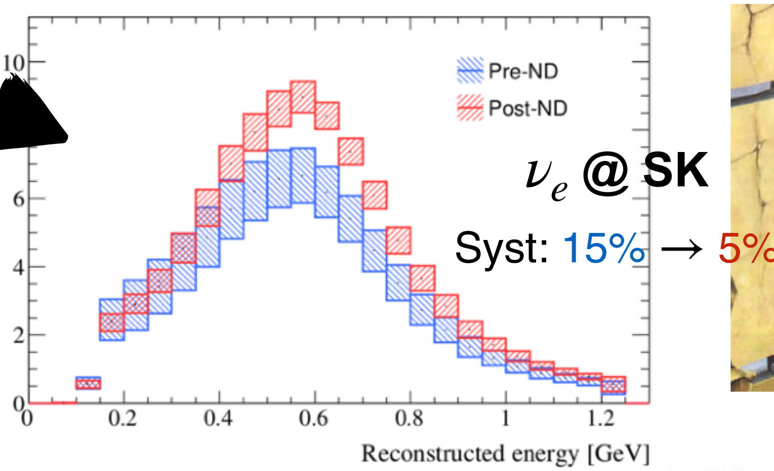
Overview and highlights of this analysis

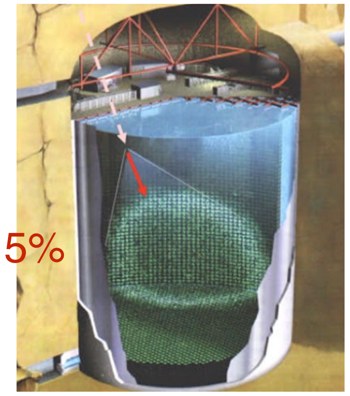
$$\left\{\text{Observed event rate @ SK}\right\} = \underbrace{\left\{\nu \text{ Flux models}\right\} \times \left\{\nu \text{ cross-section models}\right\}}_{\text{Constrained by ND280}} \times \left\{\text{SK detector model}\right\} \times \underbrace{\left\{\text{oscillation parameters}\right\}}_{\text{What we seek}}$$





Constrains and corrects *flux & cross-section systematics*



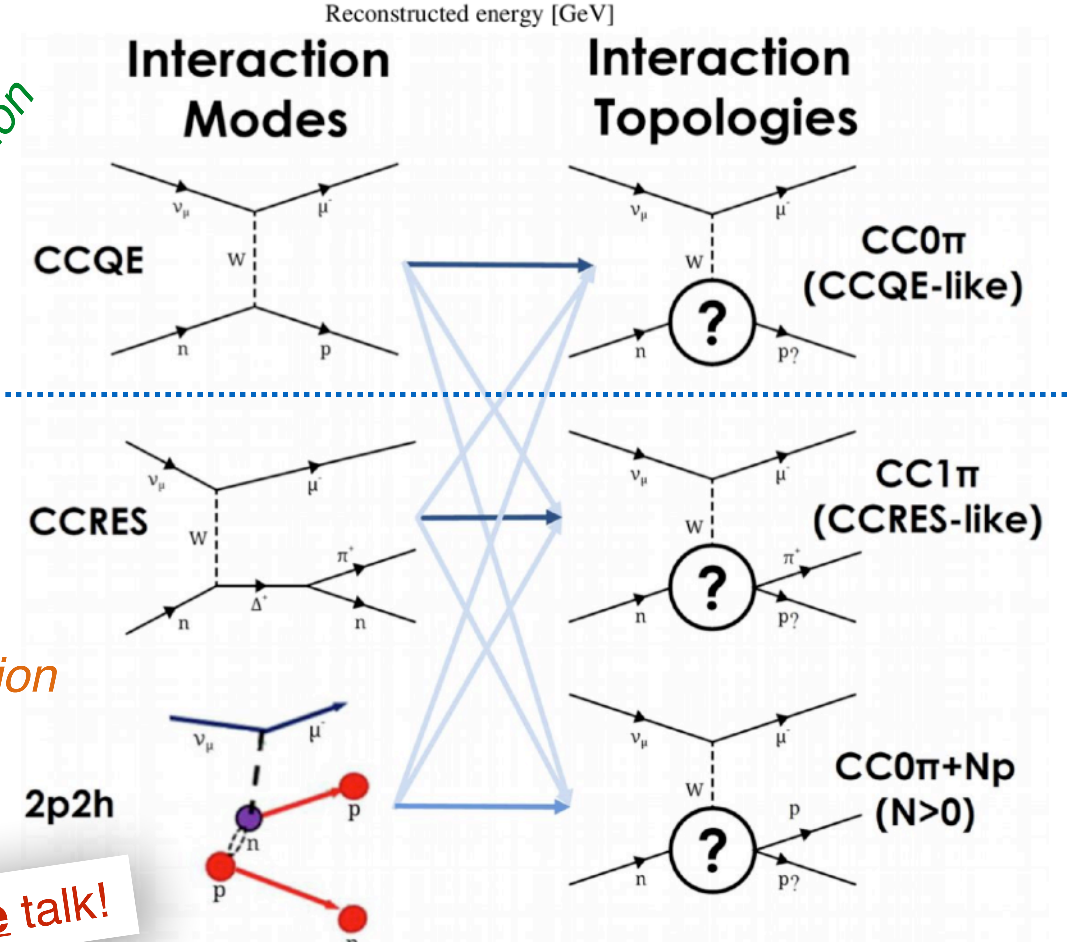


Updates to our interaction models

- Improved CCQE based on **Spectral Function model**
  - *uncertainties on nucl. shell structure*
  - *Improved momentum transfert modelling: optical potential, Pauli blocking…*
- Uncertainties for tagging protons:
  - *2p2h separation in pp and pn*
  - *nucleon FSI*
- Resonant pion production mode
  - *new uncertainties including effective binding energies*

Good E_ν reconstruction

Mis-reconstruction of E_ν

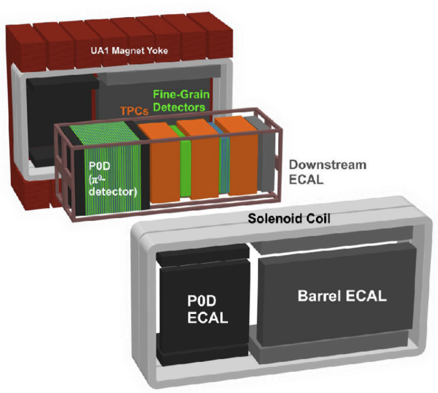


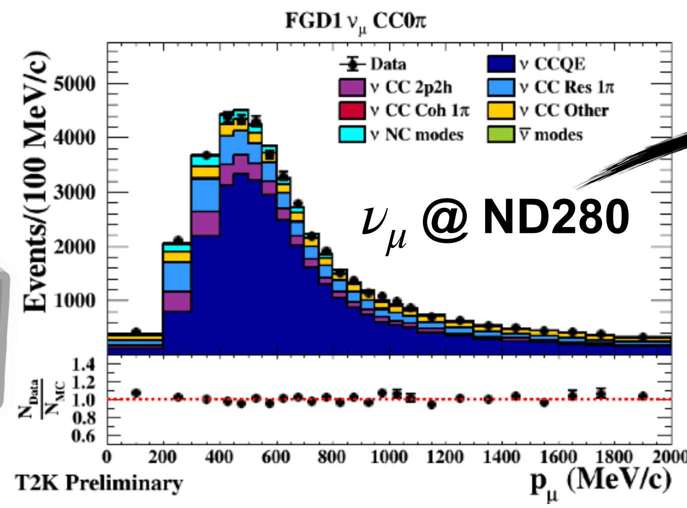
See **Tristan Doyle** talk!

Overview and highlights of this analysis

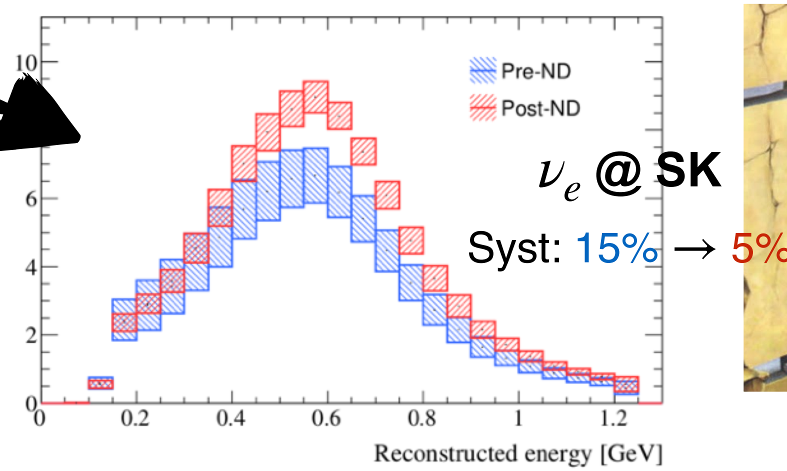
$\left\{ \begin{array}{c} \text{Observed} \\ \text{event rate} \\ \text{@ SK} \end{array} \right\} = \left\{ \begin{array}{c} \nu \text{ Flux} \\ \text{models} \end{array} \right\} \times \left\{ \begin{array}{c} \nu \text{ cross-section} \\ \text{models} \end{array} \right\} \times \left\{ \begin{array}{c} \text{SK detector} \\ \text{model} \end{array} \right\} \times \left\{ \begin{array}{c} \text{oscillation} \\ \text{parameters} \end{array} \right\}$

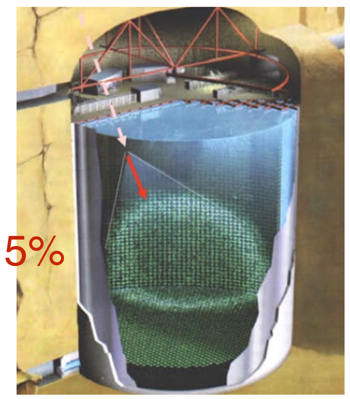
Constrained by ND280 — What we seek





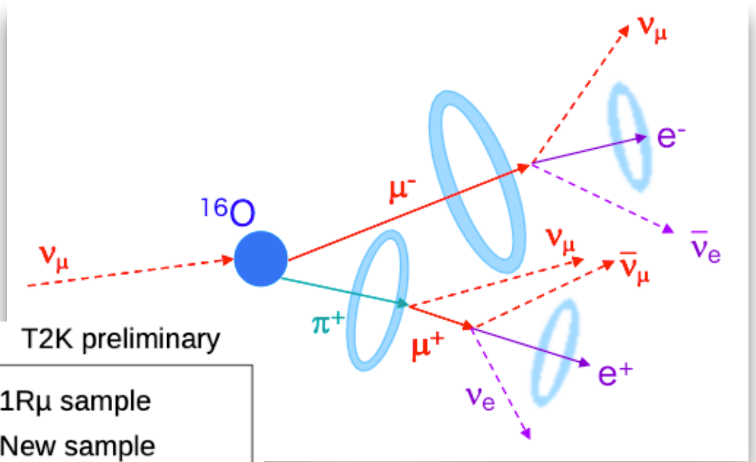
***Constrains and corrects** flux & cross-section systematics*

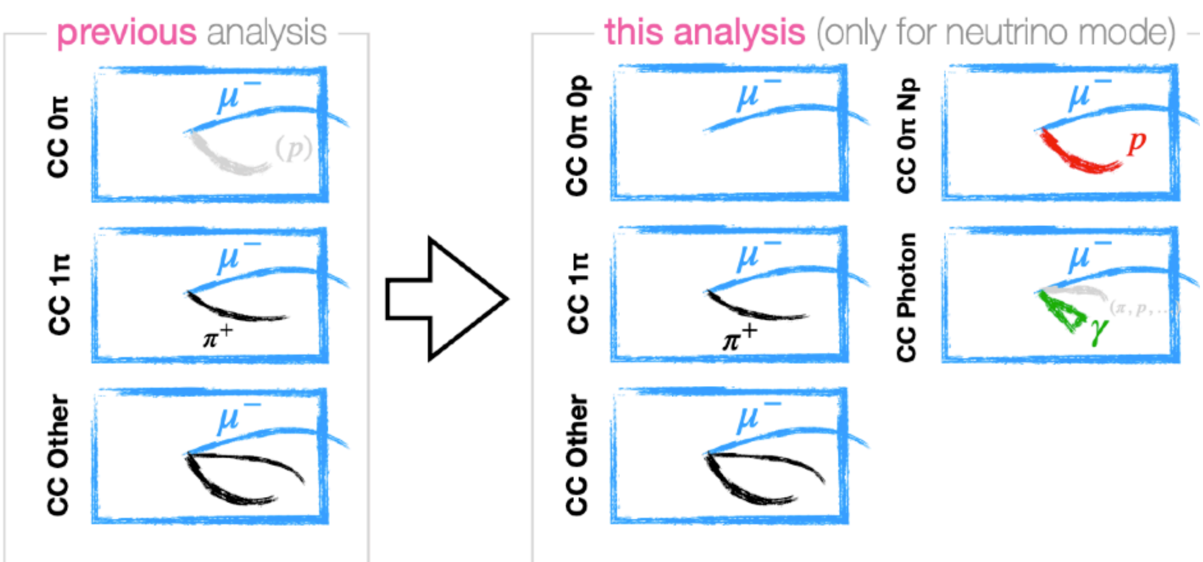


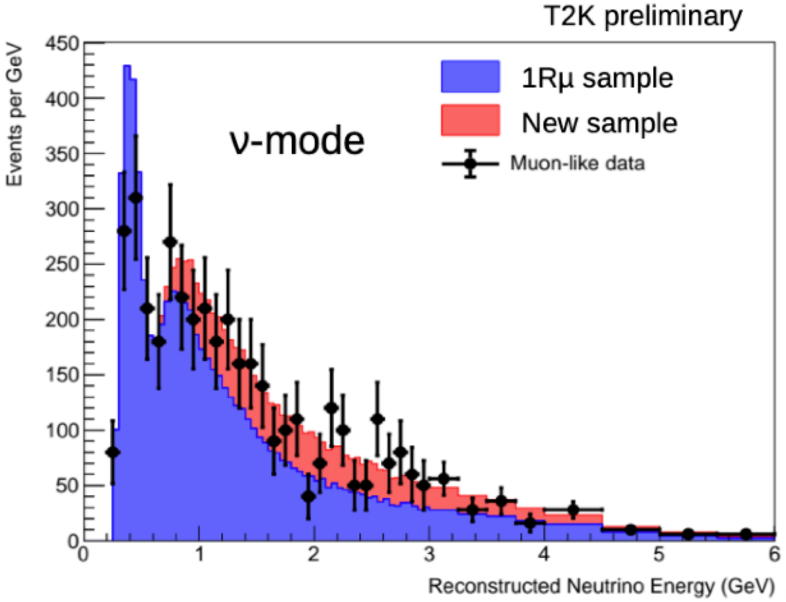


New samples

- 22 samples in ND280 now also separated by p, γ presence
- 1 numuCC1Pi sample in SK + adding multiring events



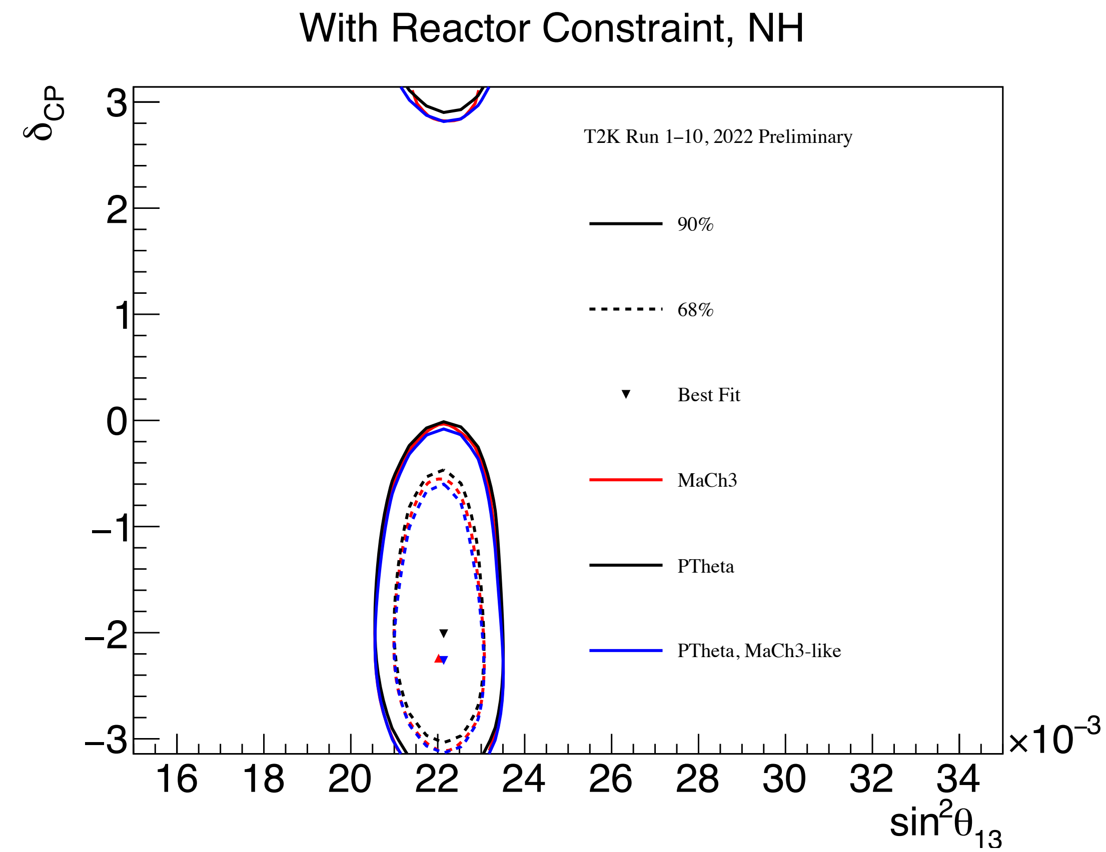




Robustness studies

Complementary fitting approaches

- (Semi-)Frequentist approach: (**P-Theta software**)
  - Using FD data only + constraints from ND as prior
  - Feldman-Cousins approach for estimating C.L.
- Bayesian credible intervals: (**MaCh3 software**)
  - Metropolis-Hastings MCMC algorithm
  - Joint ND + FD
- Very **similar results** in both approaches!

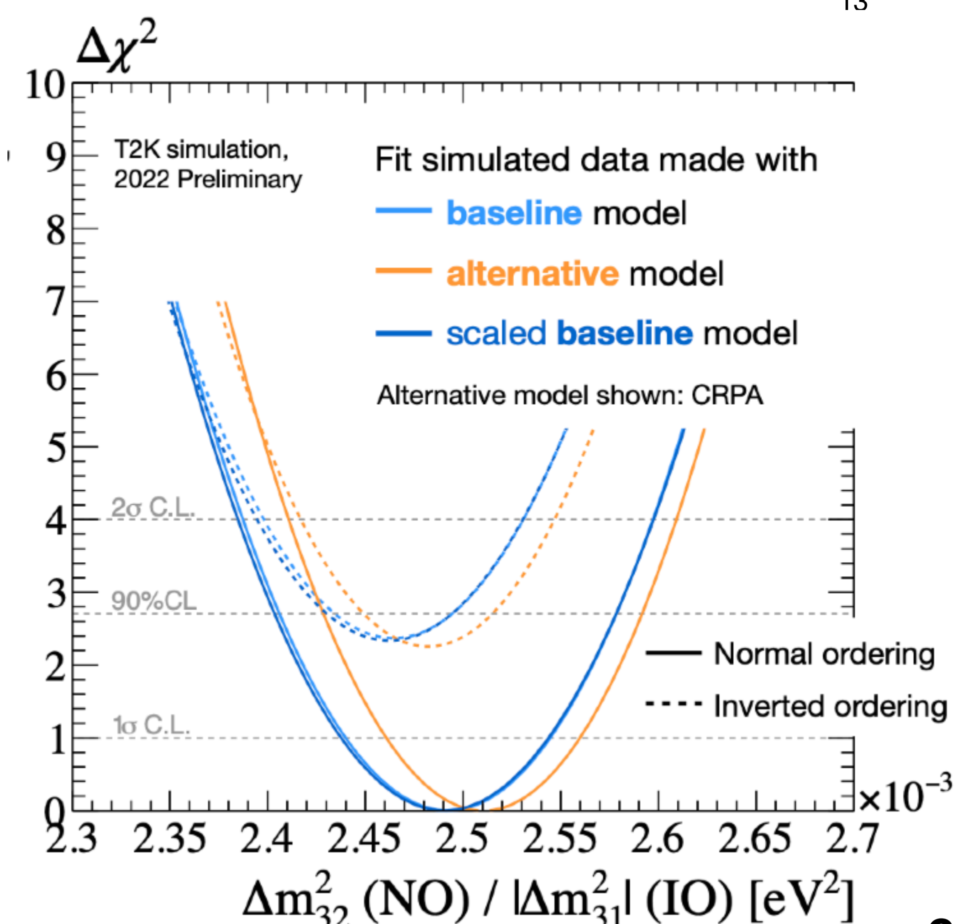


Alternative model studies

- Test how our parametrisation of the systematics is able to absorb mismodeling of interaction channels
- Using fits to “simulated data” from theory or data-driven **alternative interaction models, pion production, nuclear models…**
- Quantify biases induced on oscillation parameters

- No bias observed for θ_{23}
- Small effect on δ_{CP} but no change of the main conclusions
- **Small bias observed for Δm^2_{32}**
  - Additional gaussian uncertainty added to compensate:

$\pm 2.7 \times 10^{-5} \mathrm{eV}^2$



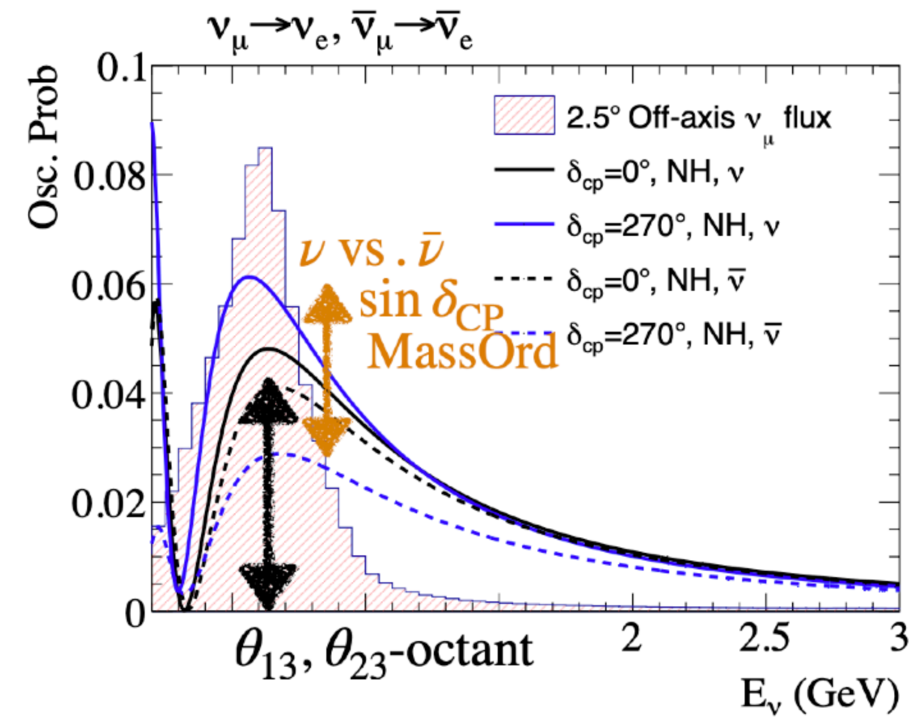
2022 (latest) oscillation results — δ_{CP}

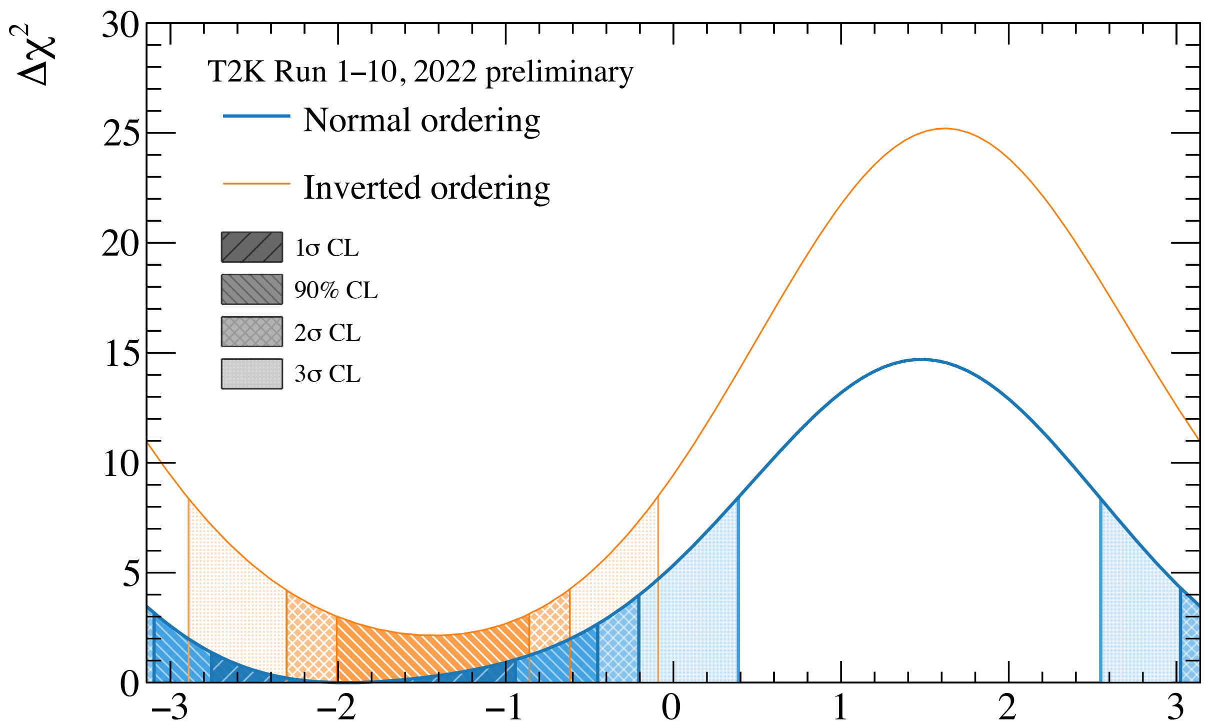
Adding reactor oscillation angle as an external constraint

- θ_{13} constraints of T2K are consistent with reactor antineutrino experiments (PDG value)

Results on the CP phase measurement

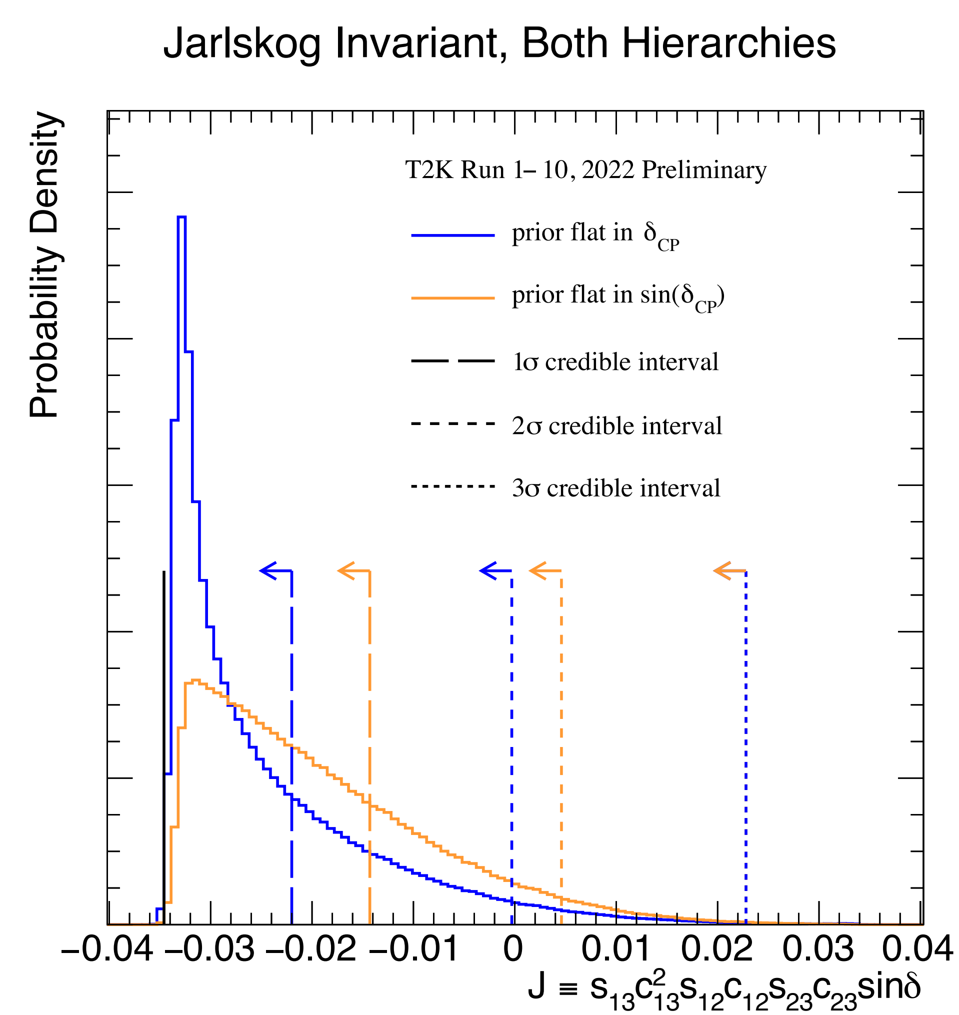
- Large region **excluded at 3σ**
- CP-conservation values ($\sin\delta_{CP} = 0$) **excluded at 90% C.L.**
- Weak preference of **normal ordering**





Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.75, -0.94]$	
90%	$[-3.10, -0.45]$	$[-2.01, -0.86]$
2σ	$[-\pi, -0.21] \cup [3.02, \pi]$	$[-2.31, -0.62]$
3σ	$[-\pi, 0.39] \cup [2.55, \pi]$	$[-2.89, -0.09]$

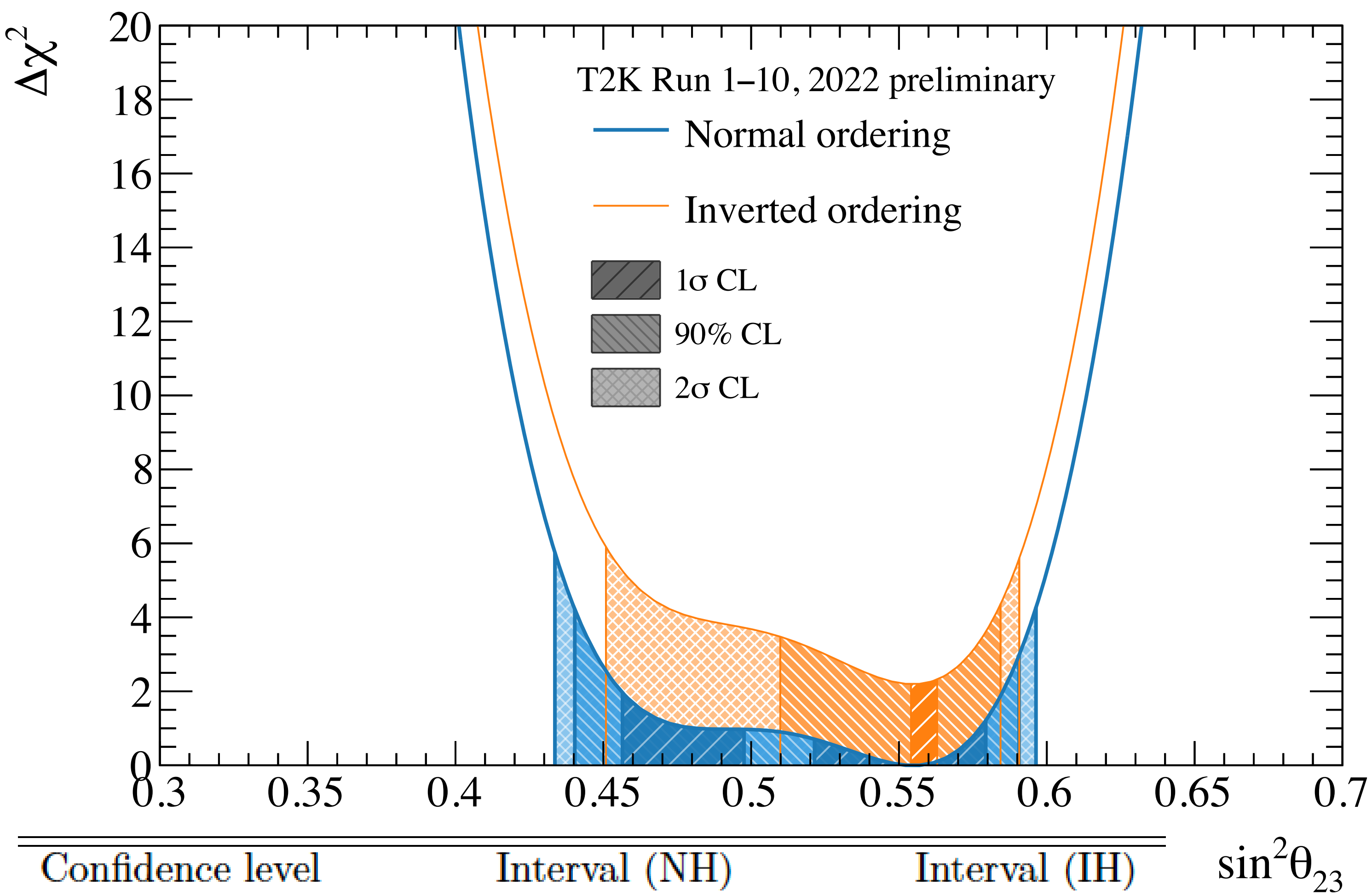
T2K Run 1-10, preliminary



2022 (latest) oscillation results – $\Delta m^2_{32}, \theta_{23}$

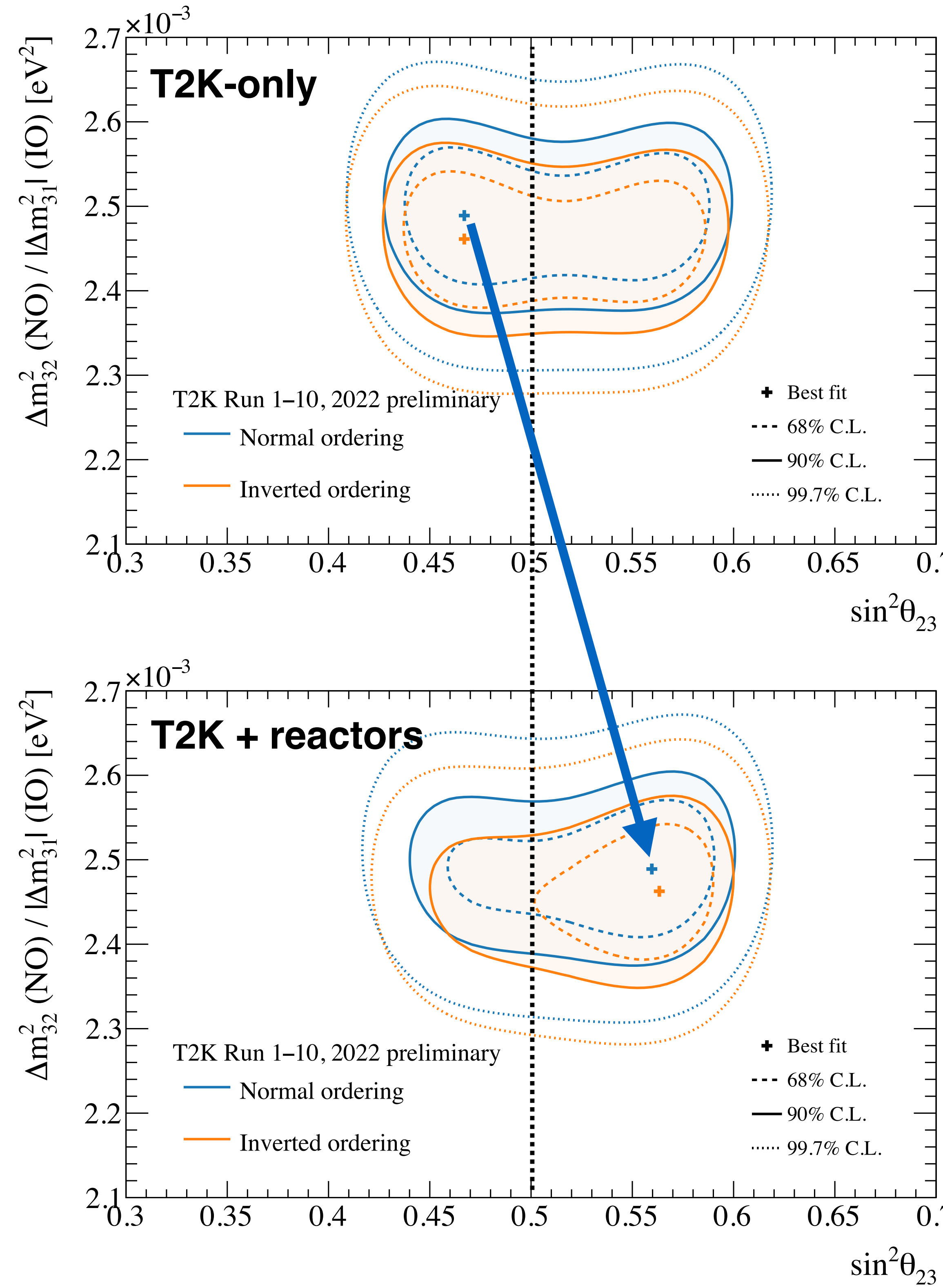
World-leading measurement of atmospheric params

- Sensitivity mainly from $\nu_\mu/\bar{\nu}_\mu$ disappearance samples
- Very weak **preference for the upper octant**
- Multiring events addition allows constraining in a more robust way the CC1pi part of the model



Confidence level	Interval (NH)	Interval (IH)
1σ	$[0.456, 0.498] \cup [0.521, 0.579]$	$[0.554, 0.563]$
90%	$[0.440, 0.591]$	$[0.510, 0.584]$
2σ	$[0.434, 0.596]$	$[0.451, 0.591]$

T2K Run 1-10, preliminary



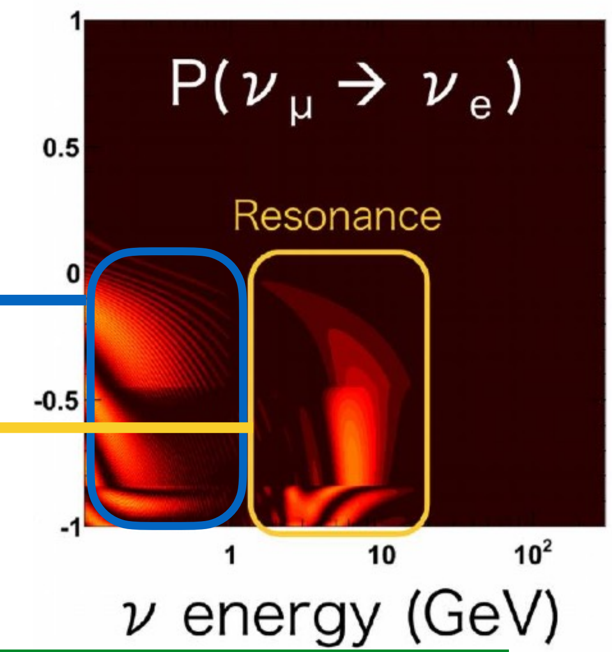
(atmospheric - ν) + T2K (accelerator - ν)

Motivation for joint fit: example with SK atmospheric neutrinos

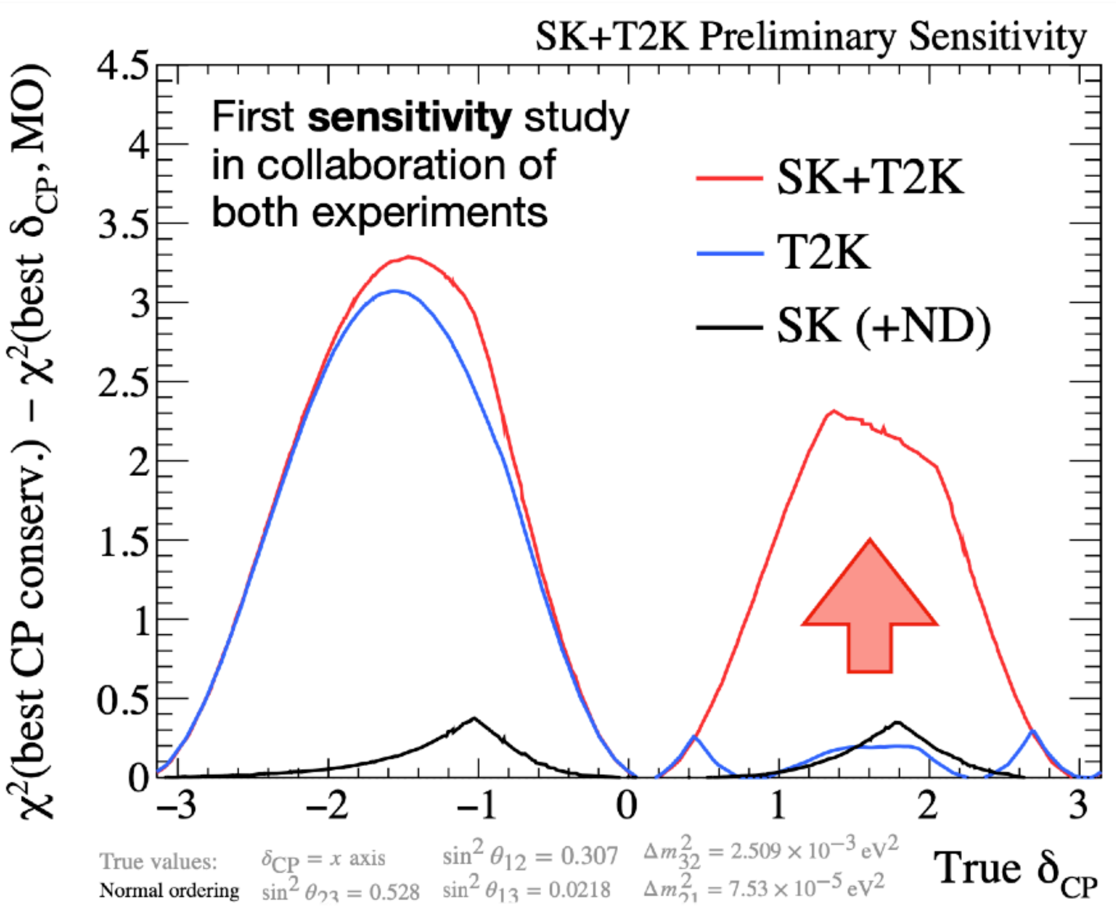
- Use sub-GeV + multi-GeV atmospheric neutrino sample
- Great decoupling between δ_{CP} and Mass Ordering (MO)
- However: **MO highly dependent on $\sin^2(2\theta_{atm})$…**
- … for which the world leading measurement is carried by T2K!

Sub-GeV Neutrino
Better sensitivity in δ_{CP}

Multi-GeV Neutrino
Better sensitivity in MO



T2K constraint on θ_{23} → **Improves** → **SK constraint on MO** → **Breaks degeneracy** → **T2K constraint on δ_{CP}**



Systematic treatment challenges:

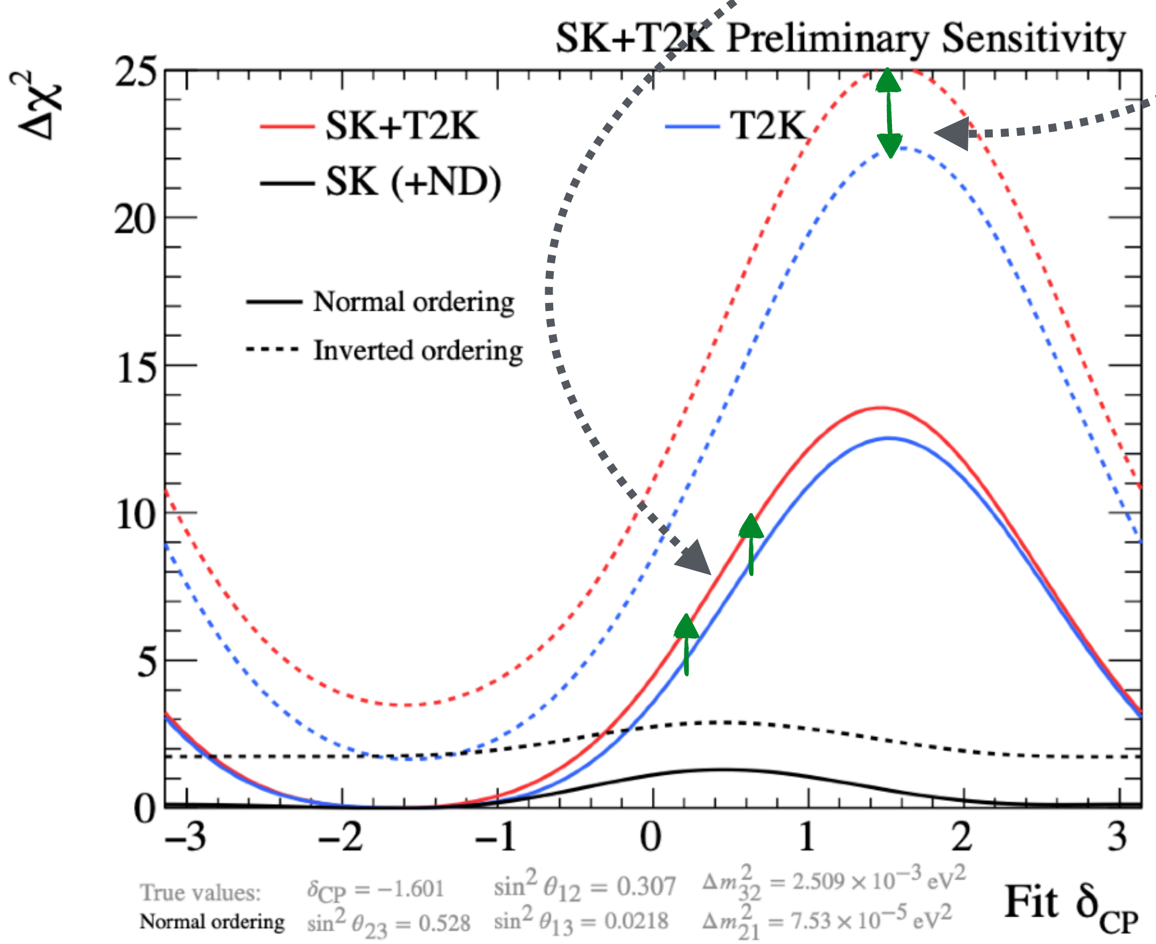
- Overlapping energy region (Sub-GeV)
  - Shared **interaction model** to capture correlations
  - Benefit from **ND constraints on atmospheric samples**
- Same detector: Super-Kamiokande
  - Systematic uncertainties due to **detector modelling should be fully correlated**

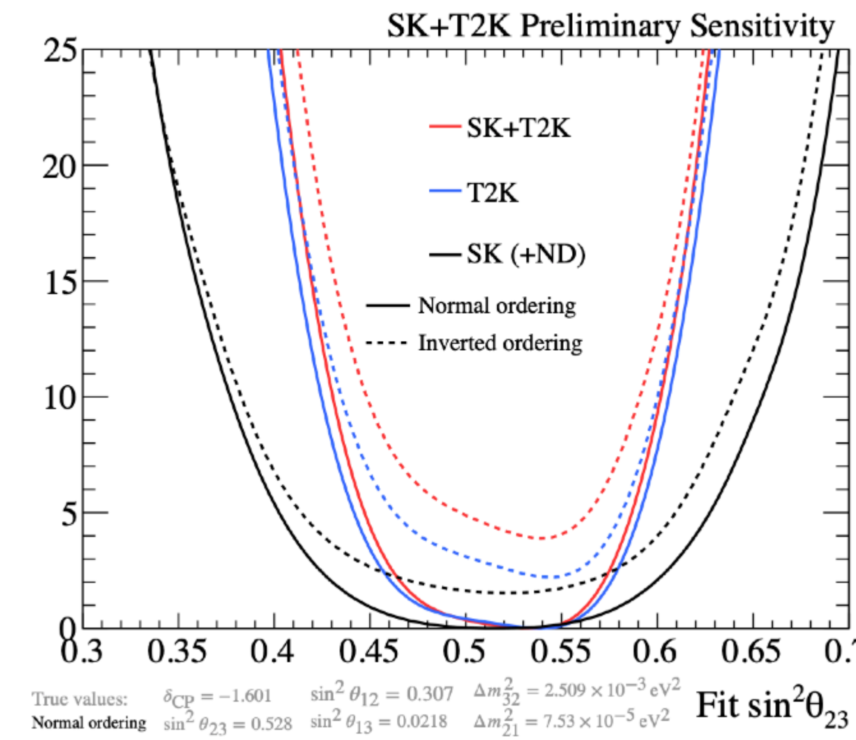
(atmospheric - ν) + T2K (accelerator - ν)

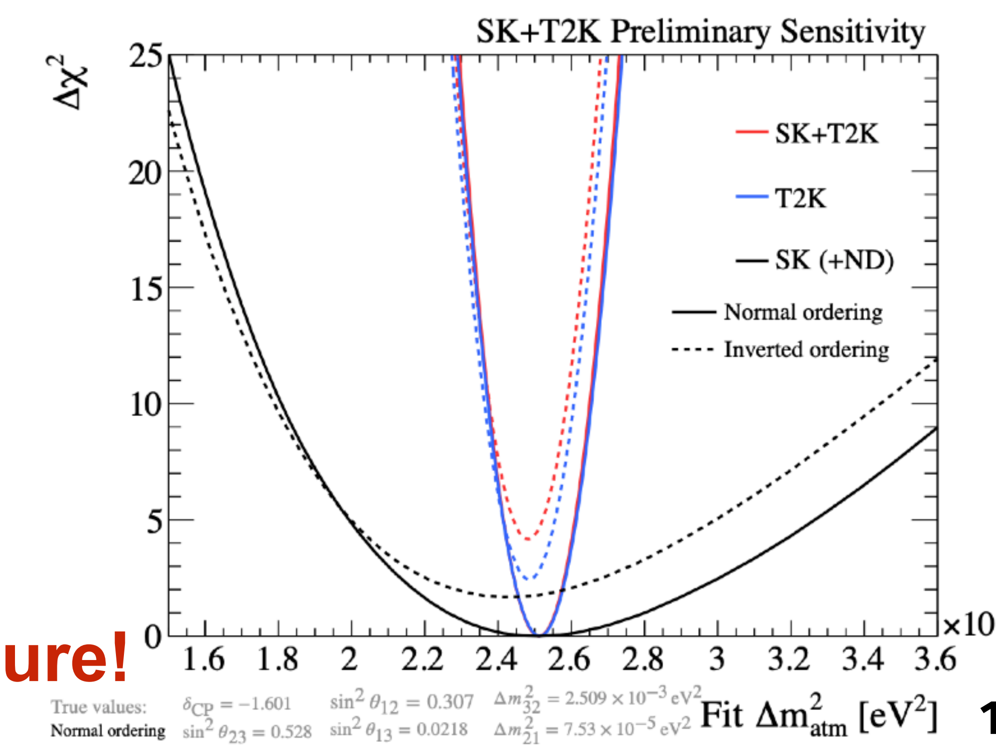
Preliminary sensitivity results

- Asimov sensitivities at true $\sin^2\theta_{23} = 0.528$, $\delta_{CP} = -1.601$, Normal Ordering
- Δm^2_{32} & θ_{23} constraint is dominated by T2K
- Main benefit of joint fit is that **both experiments are sensitive to MO**
- Noticeable **sensitivity boost for δ_{CP} in the ~0 region**

PoS NOW2022 (2023) 008

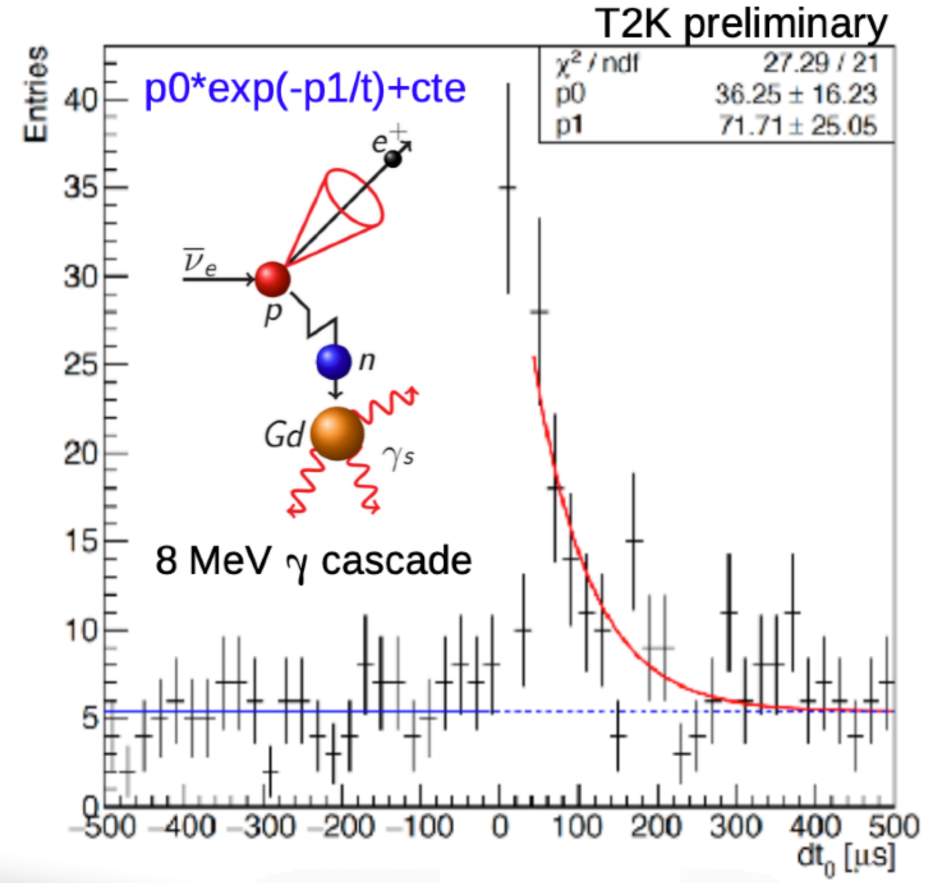






Stay tuned for the data results in the very near future!

Upcoming analyses



Finalising run 11 analysis: first data with SK-Gd!

- 9% more exposure in neutrino-mode samples
- SK-Gd 0.01% (now moving 0.03% for better neutron tagging)
- Measurement of neutrino int. with neutrons (NCQE, 2p2h,…)
- Retuning of selection + Improved evaluation of uncertainties on detector modelling and reconstruction

NOνA + T2K joint fit

- Different oscillation **baselines, energies and detector** tech.
- Important to understand systematic correlations

See **Charlie Naseby, Yukine Sato, Takeshi Nakadaira** and **Megan Friend** talks!

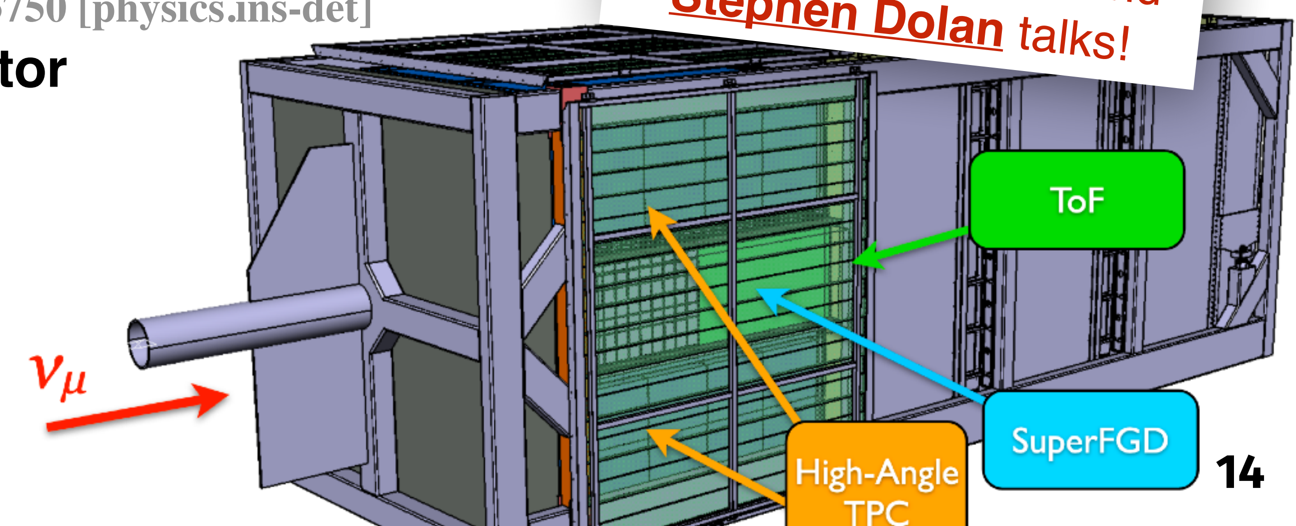
T2K extended runs

- Upgraded beamline TDR: arXiv:1908.05141 [physics.ins-det]
  - Increase **beam power from ~500 kW to 1.3 MW** via upgrades to main ring power supply and RF (mostly increased rep rate)
  - Increase **horn current 250 kA → 320 kA** for ~10% more neutrinos/beam-power and reduced wrong-sign background

See **Laura Munteanu, Dung Thi Nguyen, Katharina Lachner** and **Stephen Dolan** talks!

- Upgrading ND280 with new detectors: TDR: arXiv:1901.03750 [physics.ins-det]
  - A new neutrino target: **Super-Fine Grained Detector**
  - Two new trackers: **High-Angle TPCs**
  - **Time of Flight detector planes**

  - *Will allow to probe unreached phase-space*
  - *Reduce xsec systematics and better understanding of nuclear effects*



Summary

- Latest T2K neutrino oscillation results using 3.6×10^{20} protons on target
- **Many improvements** at each level of analysis
- CP conserving values of δ_{CP} **excluded at 90% C.L.**
- Weak preference for **normal ordering** and **upper octant**
- Ongoing joint analyses with SK and NOνA
- Exciting perspectives for the future with T2K phase-II