New T2K oscillation measurements with updated analysis

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On behalf of the T2K collaboration
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IRN Neutrino
IJCLab, Orsay
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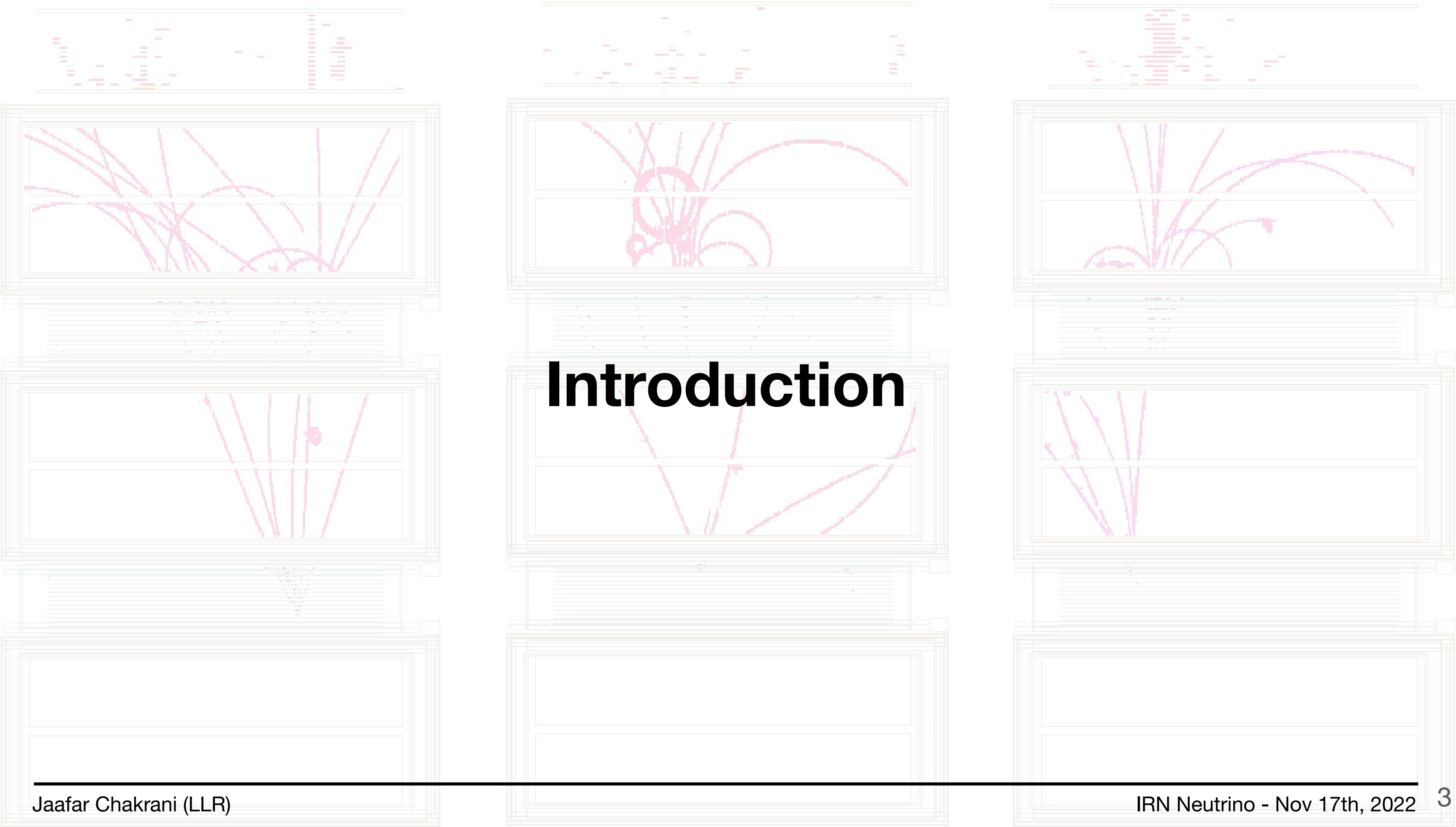
ÉCOLE POLYTECHNIQUE
INSTITUT POLYTECHNIQUE DE PARIS
IN2P3 Les deux infinis
Physique des 2 Infinis et des Origines

Outline

- Introduction
- Updates to the oscillation analysis
- Oscillation measurement results
- What's next?
- Summary



Introduction

What do Long-Baseline Experiments measure?

- Mass and flavor states mixing: $|\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i} \, |\nu_\alpha\rangle$

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

$$c_{ij} = \cos(\theta_{ij})$$
$$s_{ij} = \sin(\theta_{ij})$$

- Long-baseline experiments are sensitive to:
  - Atmospheric parameters $(\theta_{23}, \Delta m^2_{32})$ through $\nu_\mu/\bar{\nu}_\mu$ disappearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

  - $(\delta_{CP}, \theta_{23})$ through $\nu_e/\bar{\nu}_e$ appearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \overset{(+)}{-} O(\delta_{CP})$$

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If $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ then matter and anti-matter could behave differently in the lepton sector
$\longrightarrow$ CP violation!

This could shed light on the matter/anti-matter asymmetry in the Universe

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What do Long-Baseline Experiments measure?

$$\ldots U_{\alpha i} \, |\nu_\alpha\rangle$$

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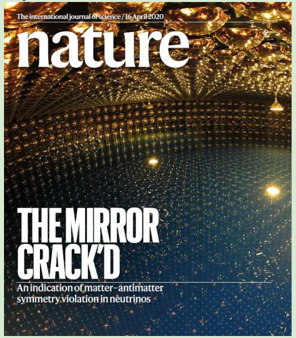
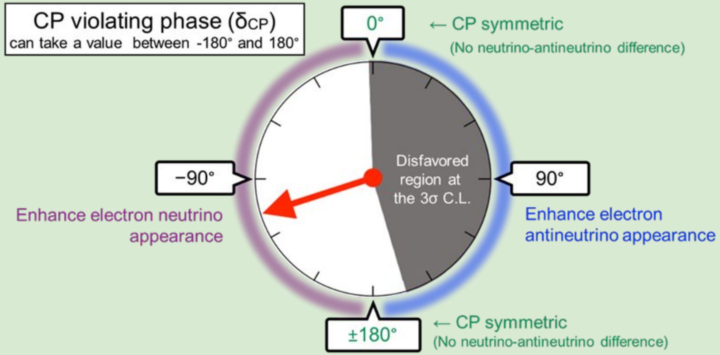
First hints by T2K

April 2020



- CP conservation is excluded at a 2σ level
- Preference for a ~maximal CP violation



…ance

$$\ldots \frac{\ldots^2_{32} L}{\ldots E} \Big)$$

$$\ldots L \Big) \; (\mp) O(\delta_{CP})$$

If $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ then matter and anti-matter could behave differently in the lepton sector
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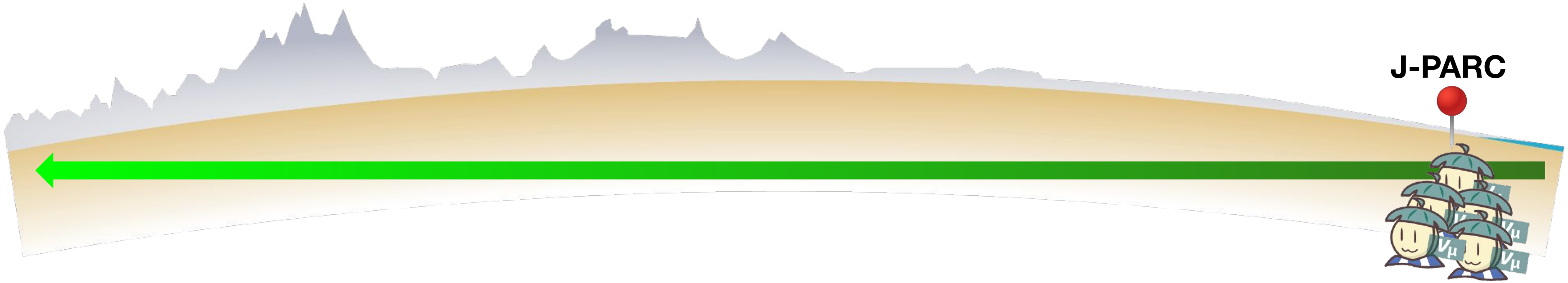
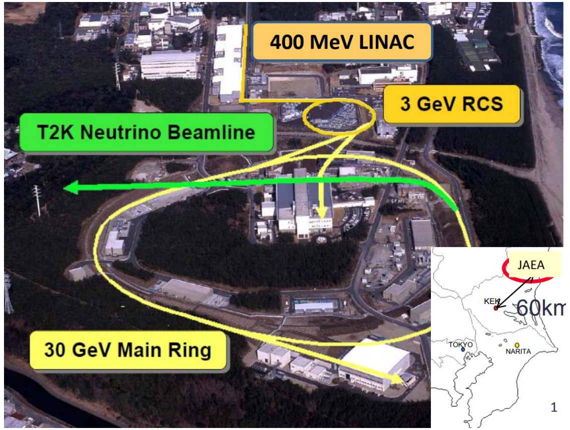
T2K experiment



- Proton beam on graphite target
- Produced hadrons decay into muon (anti-)neutrinos



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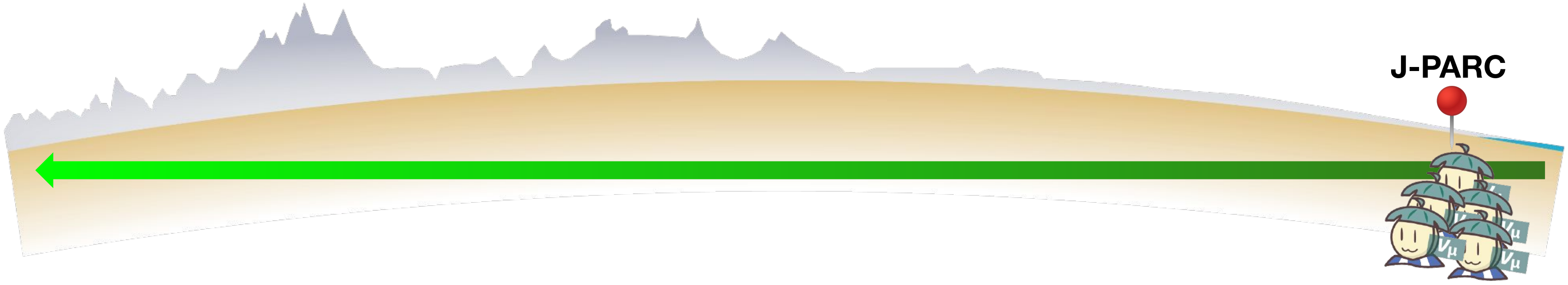

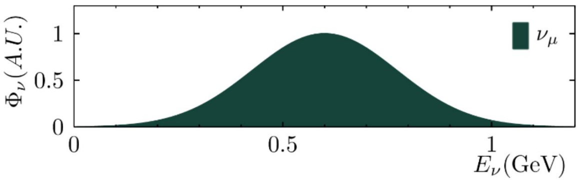

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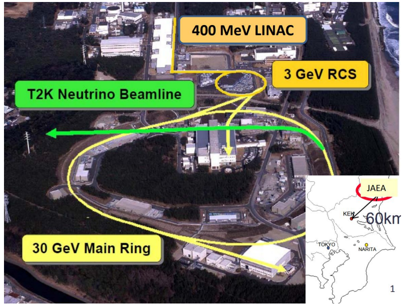

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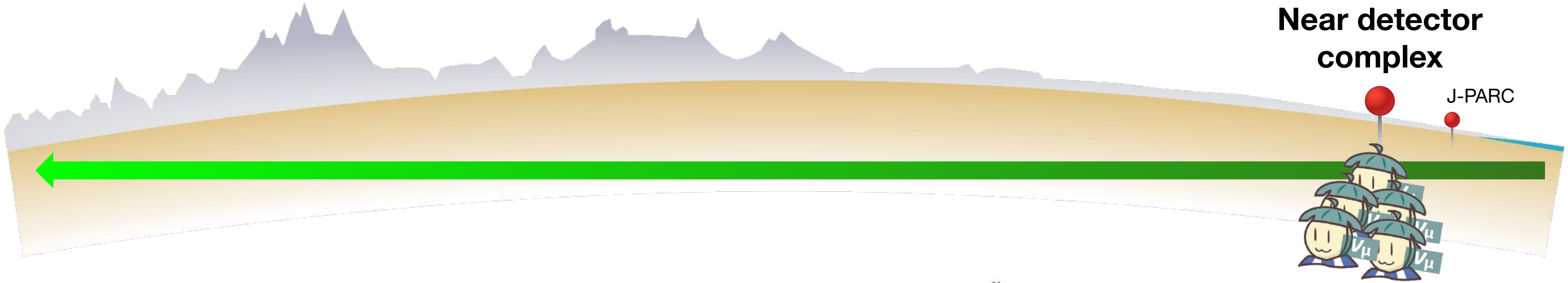
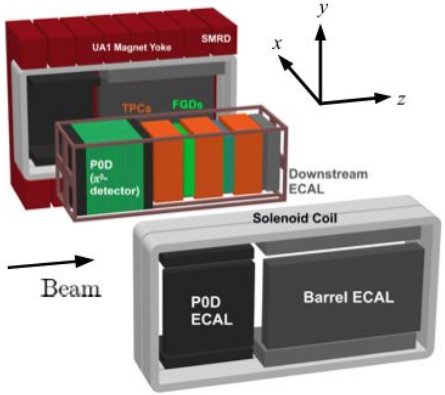
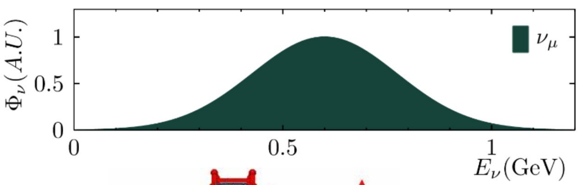
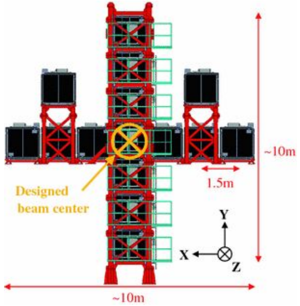




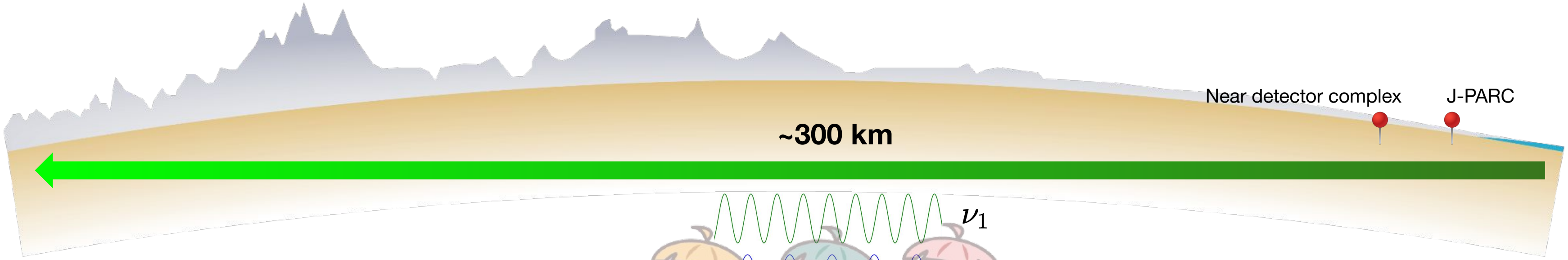


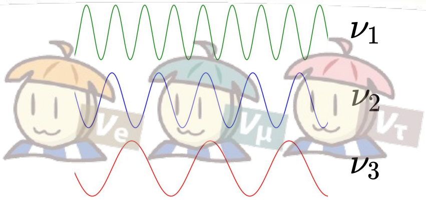


- Measure unoscillated neutrino flux:
  - Electron neutrino and wrong-sign contaminations
  - Neutrino-nucleus interactions

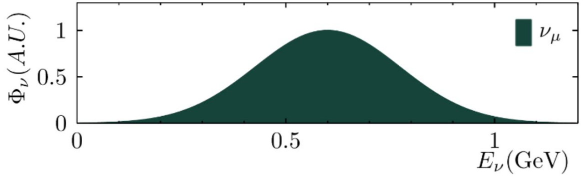
$\longrightarrow$ Reduce **systematic uncertainties**

T2K experiment





$$|\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i} \, |\nu_\alpha\rangle$$



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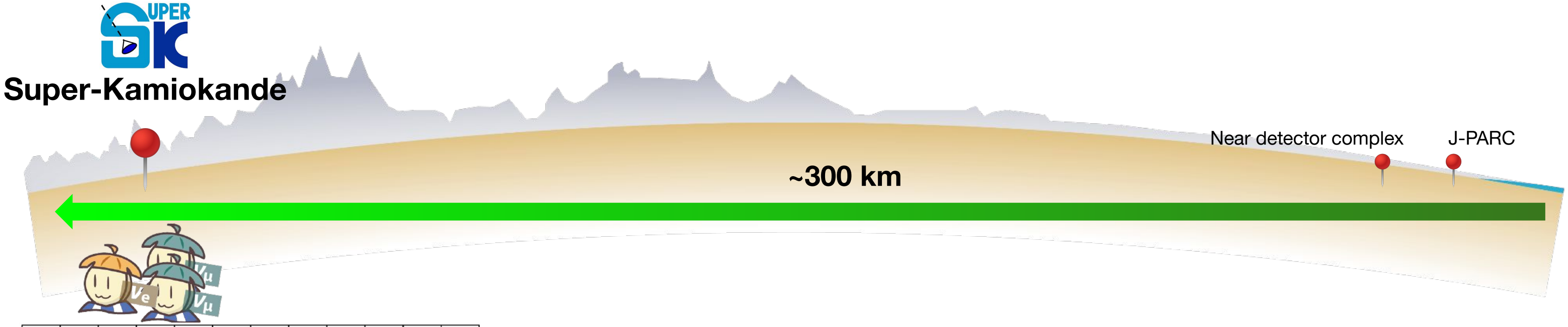

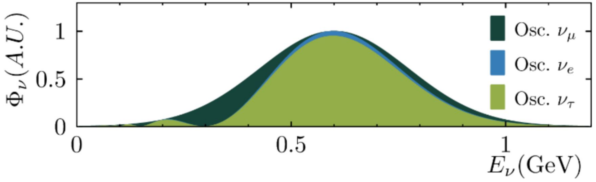

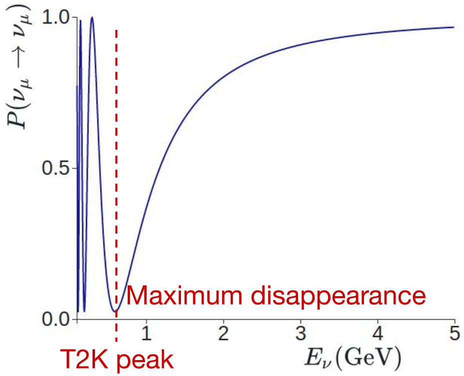

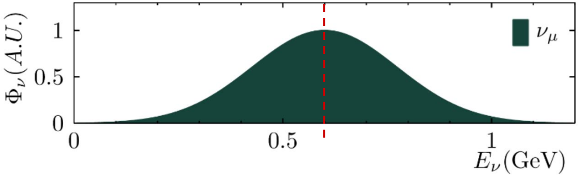

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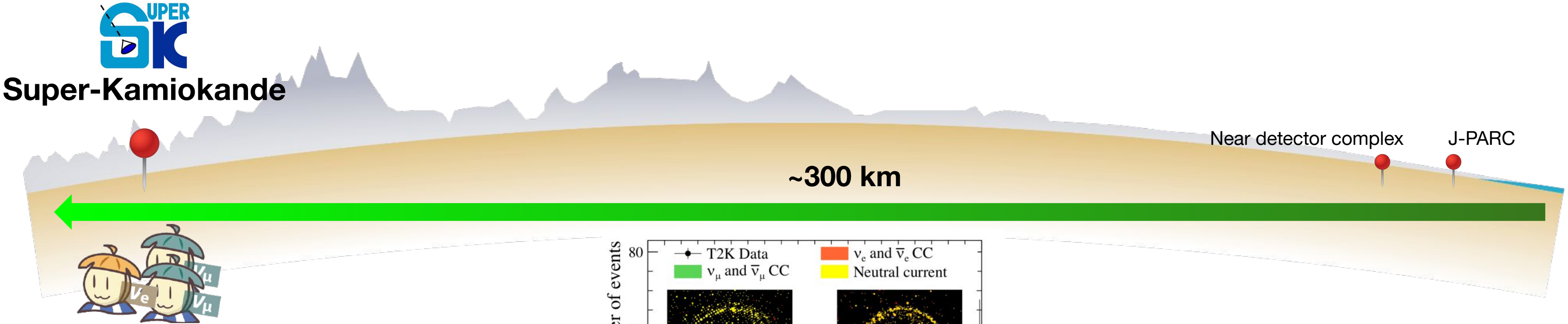
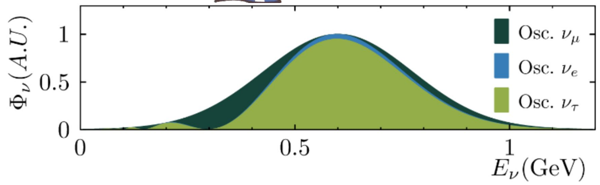
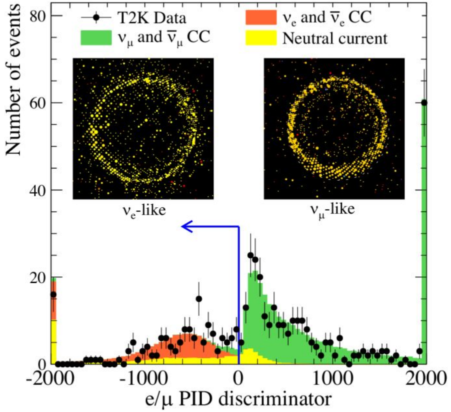
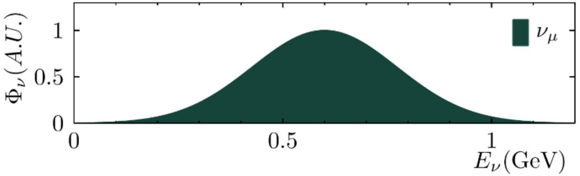
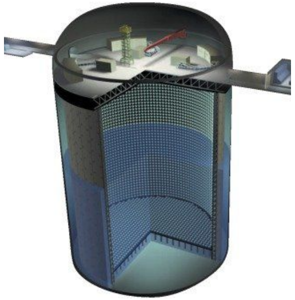




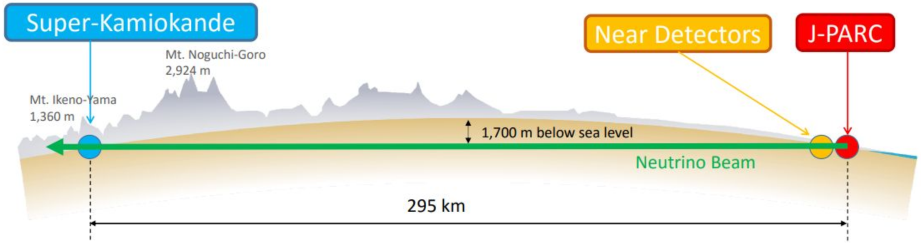






- 50 kt water Cherenkov detector
- Measurement of:
  - Electron neutrino vs. muon neutrino PID by ring pattern
  - Neutrino energy

T2K Oscillation Analysis strategy



Flux model | Detector model | Neutrino interaction model

$$N_{\nu_\alpha}^{ND}(E_\nu) = \Phi_{\nu_\alpha}^{ND}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma_{\nu_\alpha}^{ND}(E_\nu)$$

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- Far/Near ratio does not fully cancel systematic uncertainties, *e.g.*:

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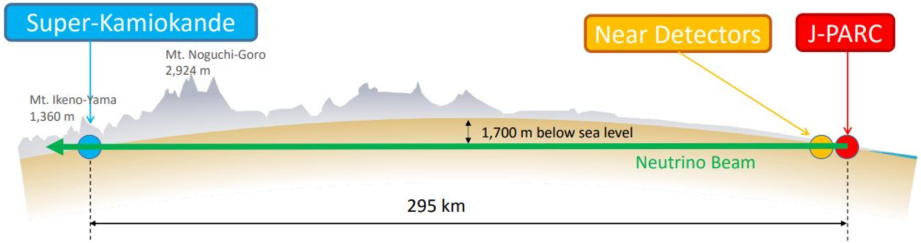

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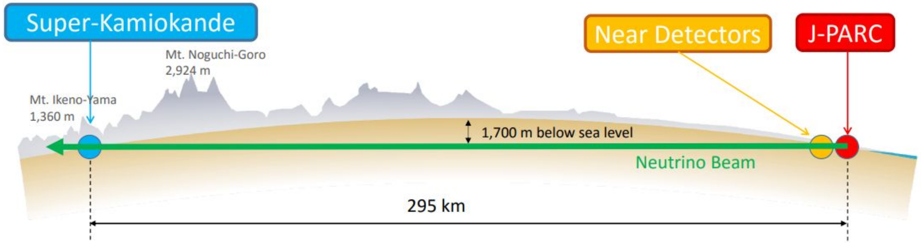

Flux model · **Detector model** · **Neutrino interaction model**

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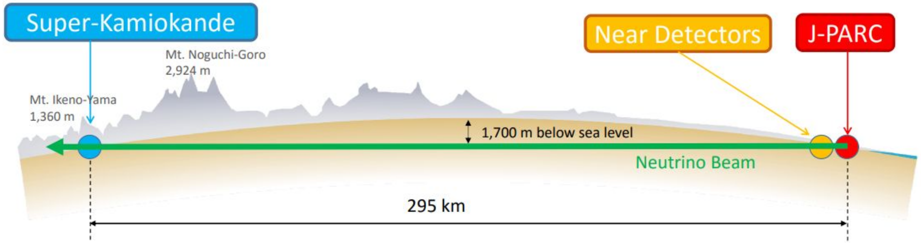

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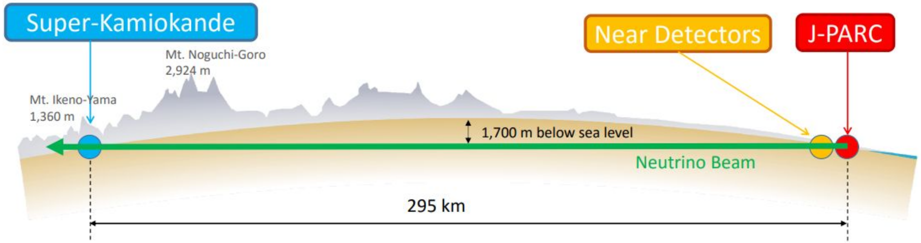
    - Mainly $\nu_\mu(\bar{\nu}_\mu)$ at ND interacting with CH $\longrightarrow$ use model to infer interactions of $\nu_\mu/\nu_e(\bar{\nu}_\mu/\bar{\nu}_e)$ on H_2O

T2K Oscillation Analysis strategy



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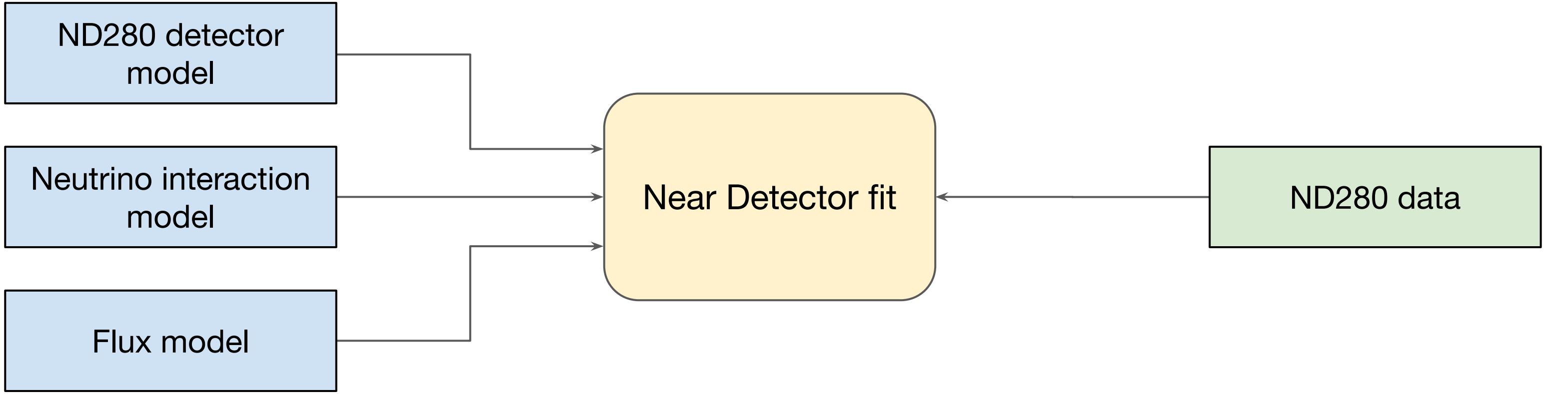
↪ **T2K's approach is to propagate the constraints on the flux and the neutrino interaction models from the ND to the FD**

T2K Oscillation Analysis strategy



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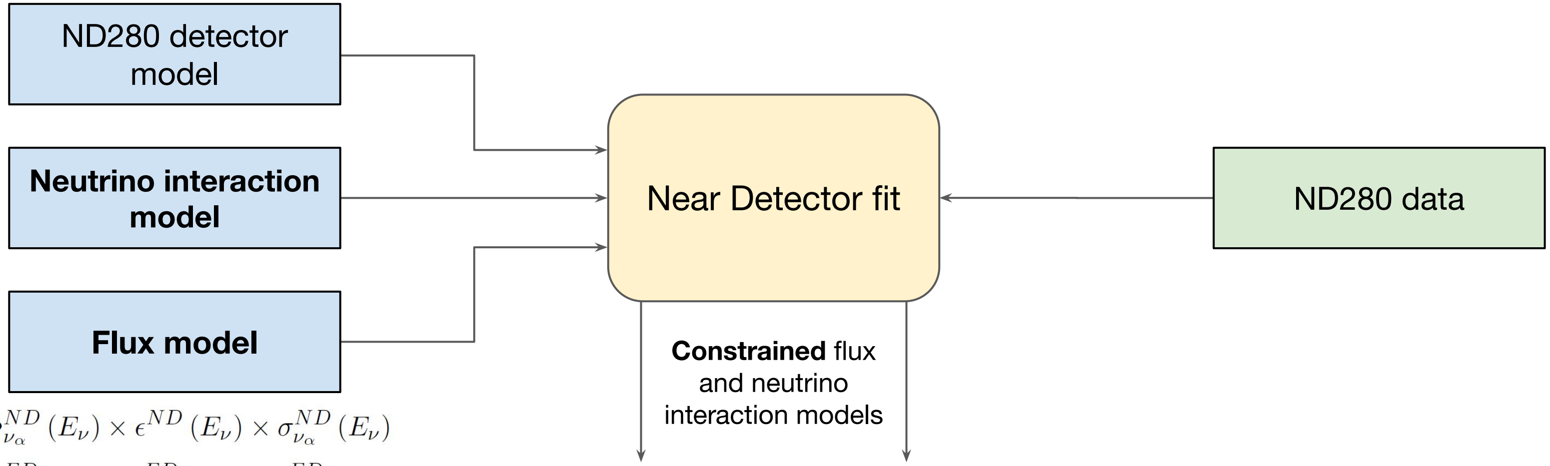

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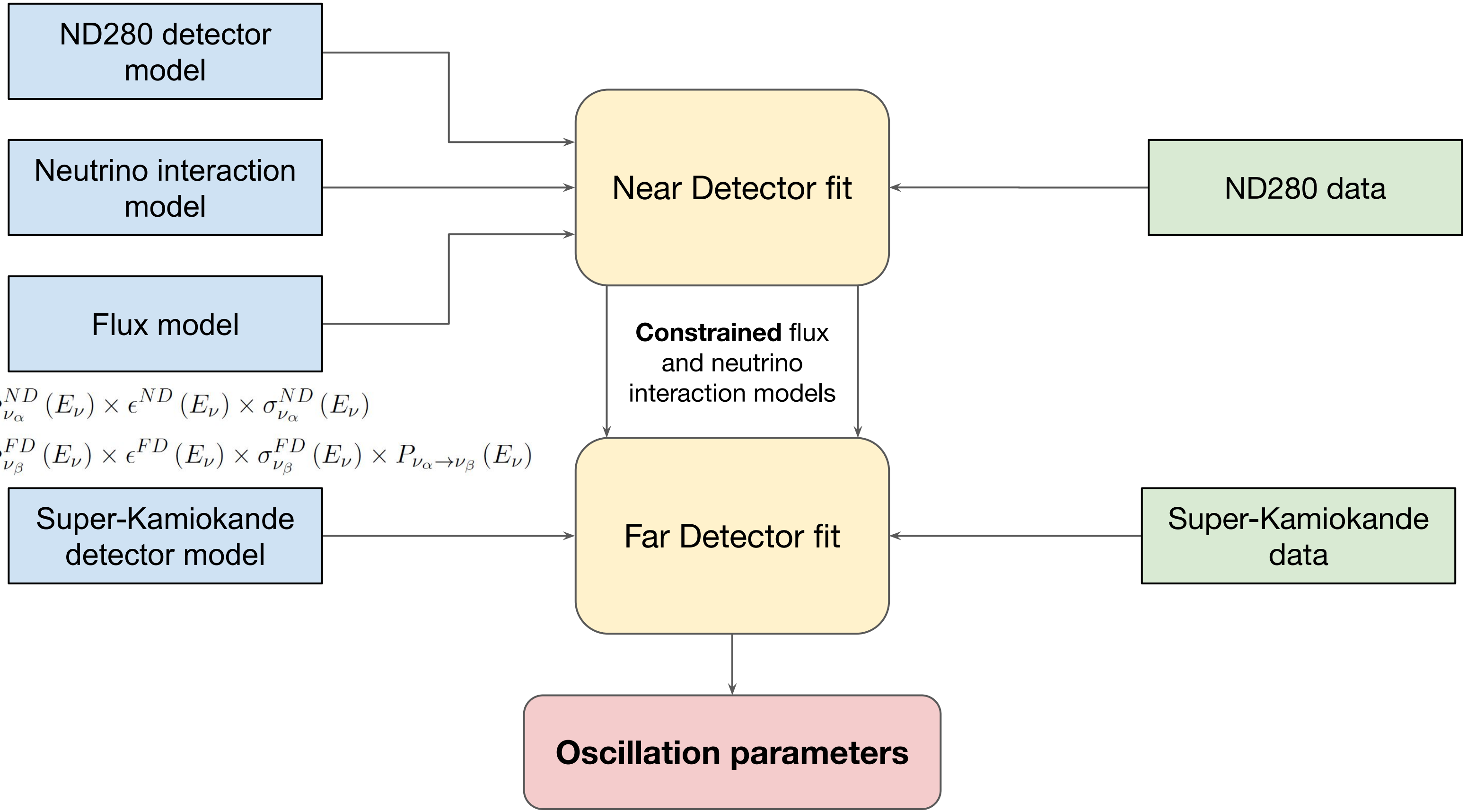

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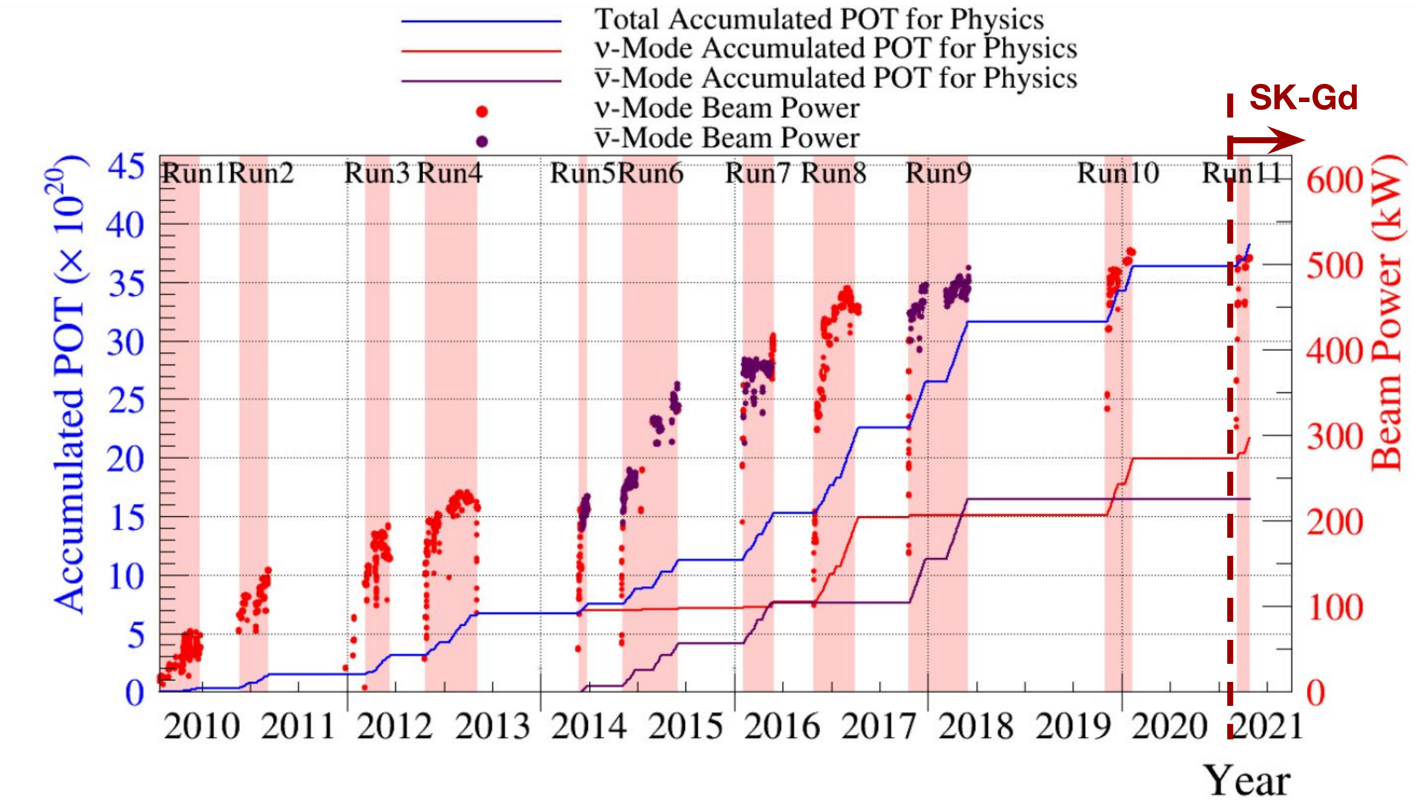
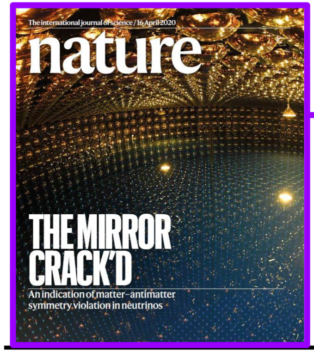
Updates to the oscillation analysis

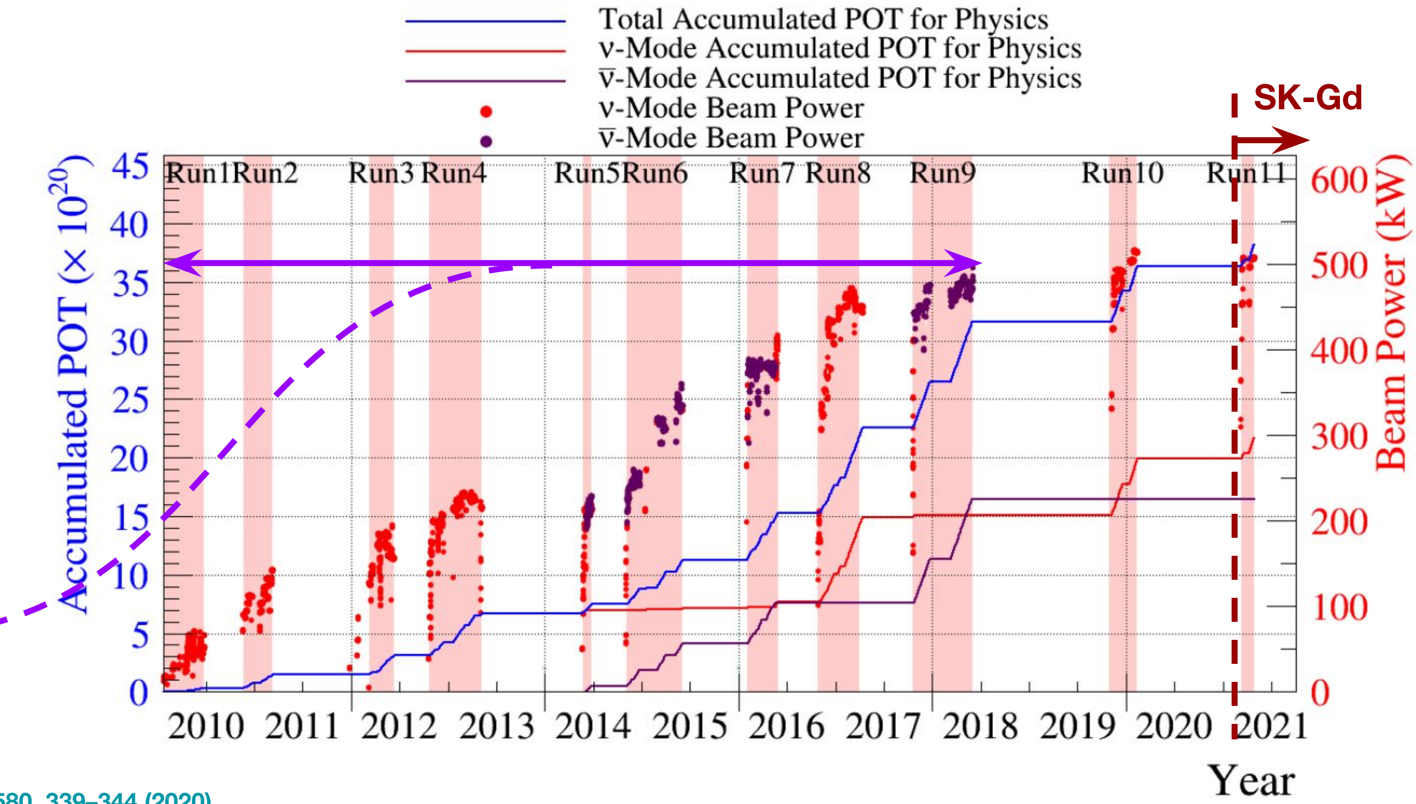
Dataset



Total Accumulated POT for Physics
ν-Mode Accumulated POT for Physics
ν̄-Mode Accumulated POT for Physics
ν-Mode Beam Power
ν̄-Mode Beam Power
SK-Gd
Run1 Run2 Run3 Run4 Run5 Run6 Run7 Run8 Run9 Run10 Run11
Accumulated POT (× 10^20)
Beam Power (kW)
0 5 10 15 20 25 30 35 40 45
0 100 200 300 400 500 600
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021
Year

Dataset

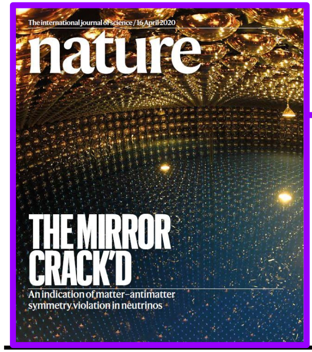




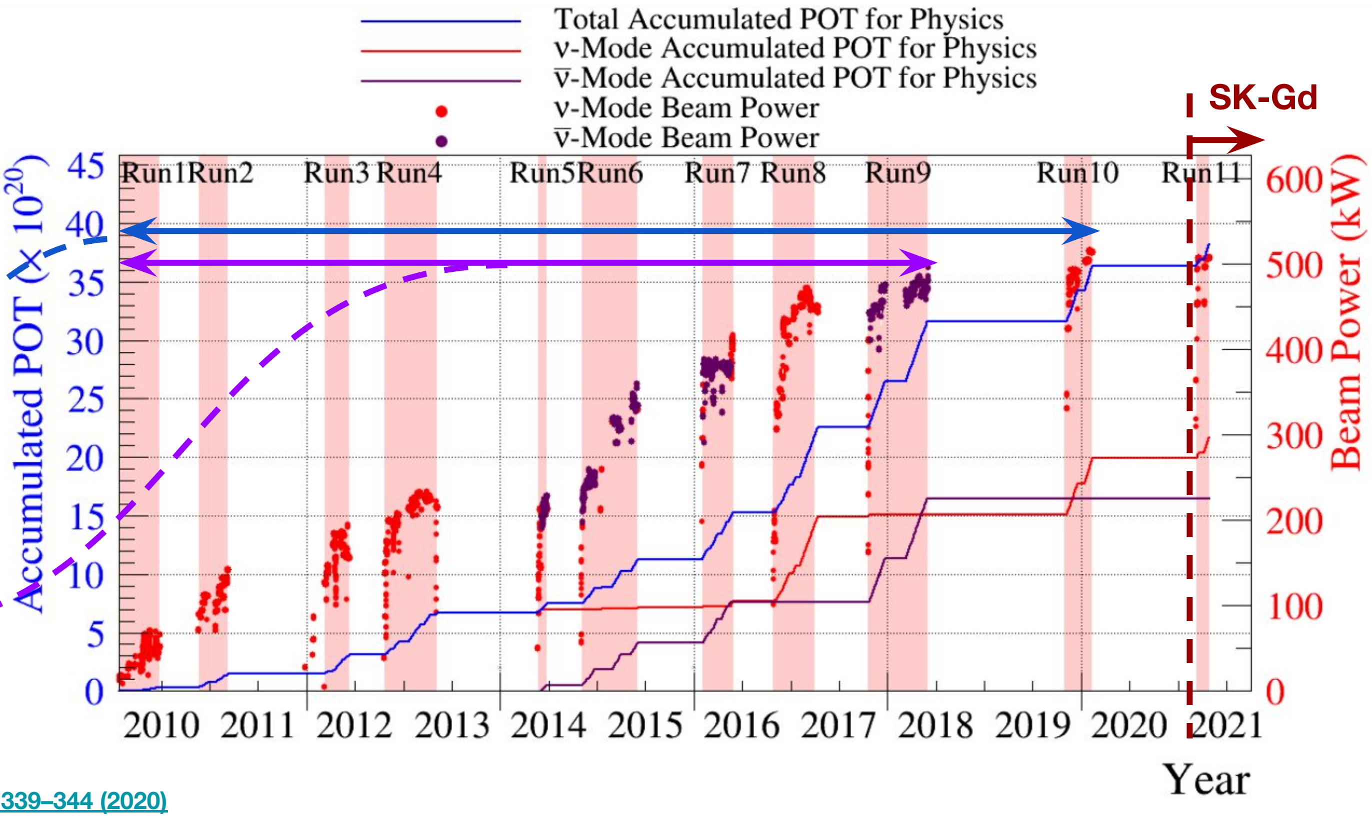
Nature 580, 339–344 (2020)

Phys.Rev.D 103, 112008

Dataset



[Talk at the IRN Neutrino of December 2021 by A. Blanchet]



[Nature 580, 339–344 (2020)]
[Phys.Rev.D 103, 112008]

Dataset

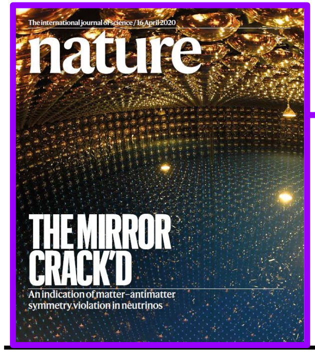
Same data
A lot of analysis improvements

NEUTRINO SEOUL 2022

This talk

NEUTRINO 2020

[Talk at the IRN Neutrino of December 2020 by A. Blanchet]



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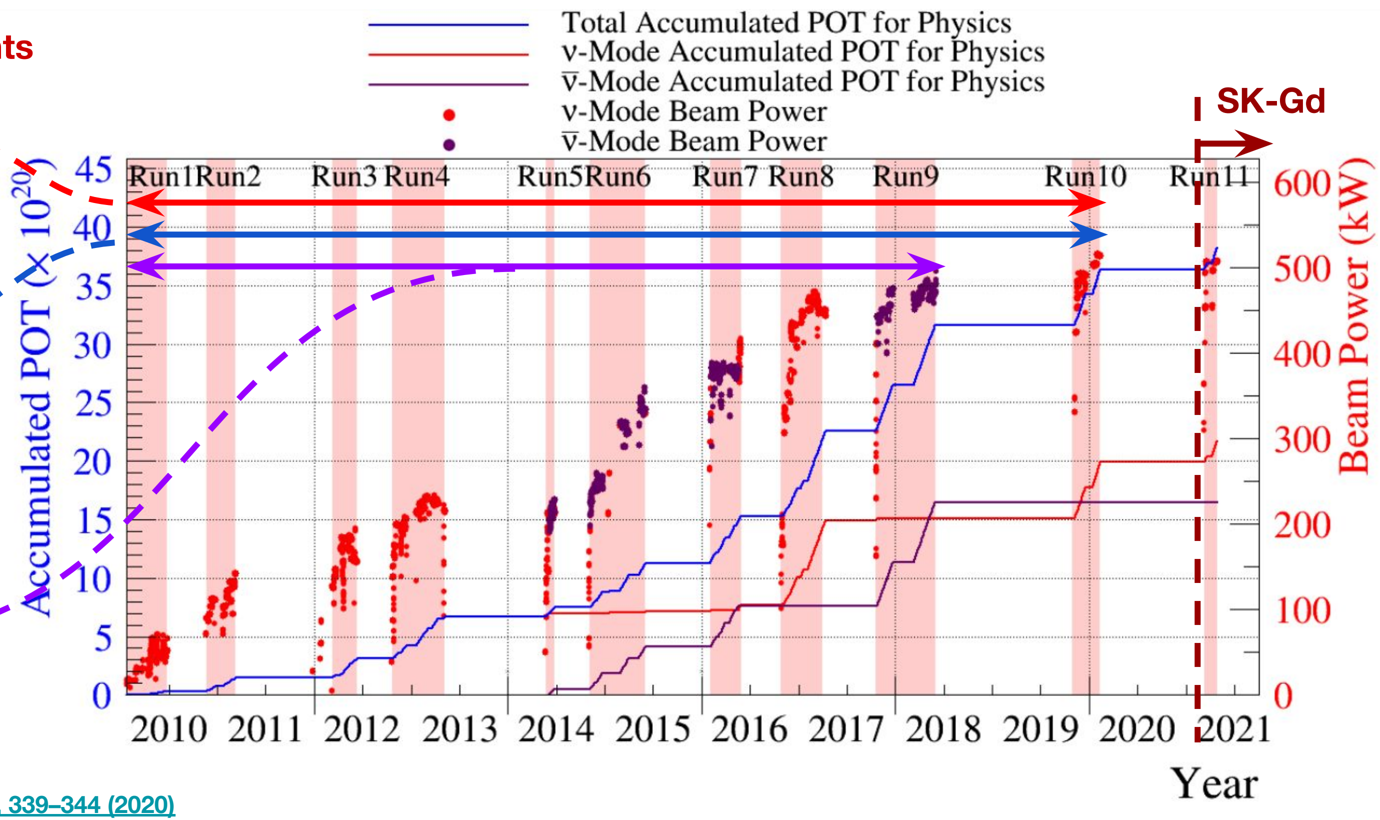
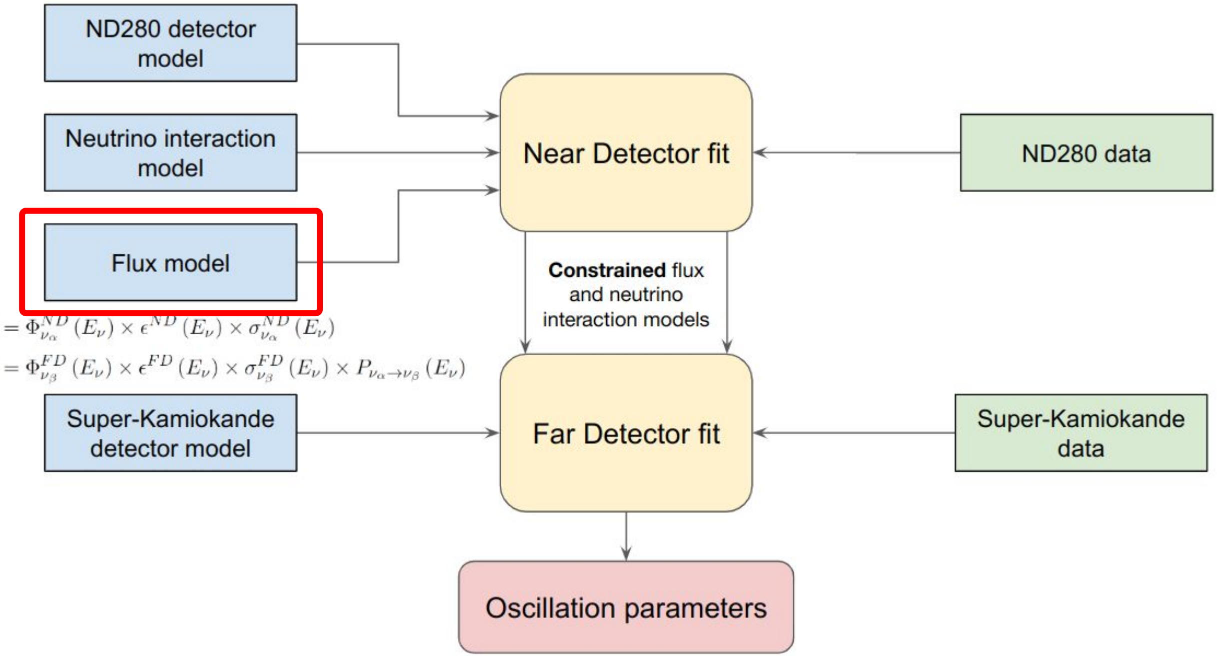


New flux model uncertainties



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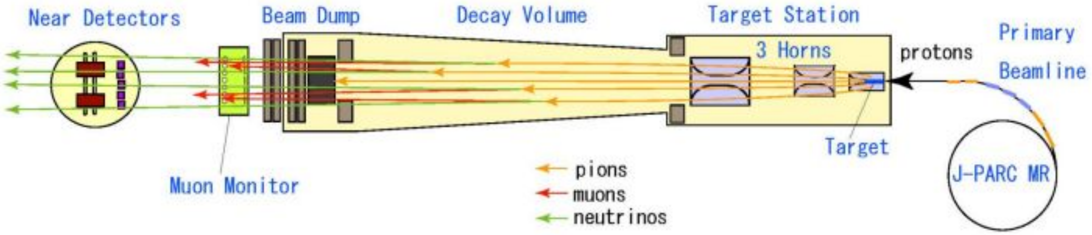
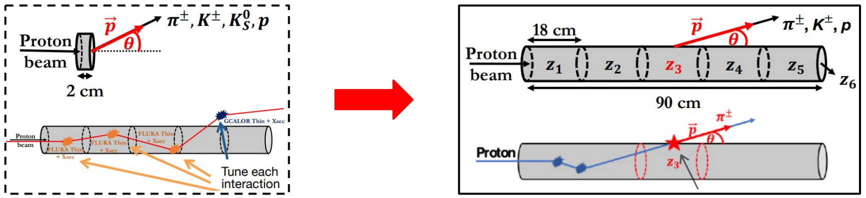
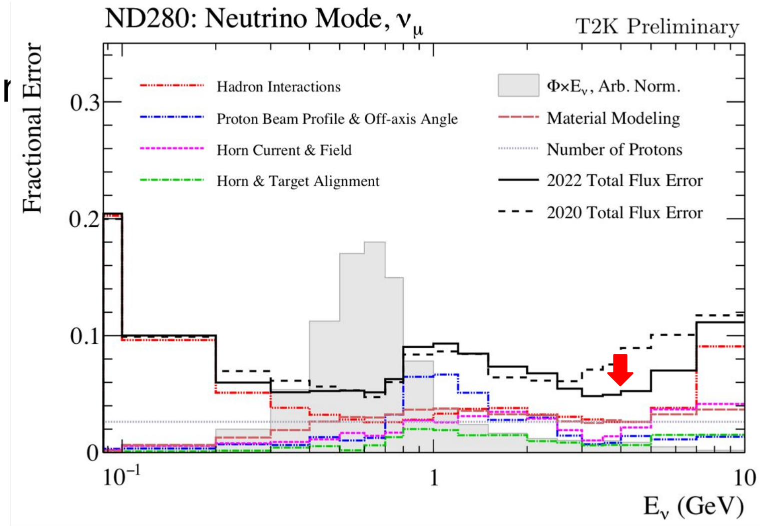


- The neutrino beam is obtained from 30 GeV protons fired at a graphite target, and the polarity of the horns allows to choose neutrino or antineutrino beam
- External measurements from NA61/SHINE on T2K replica target allow to reduce high-E uncertainties

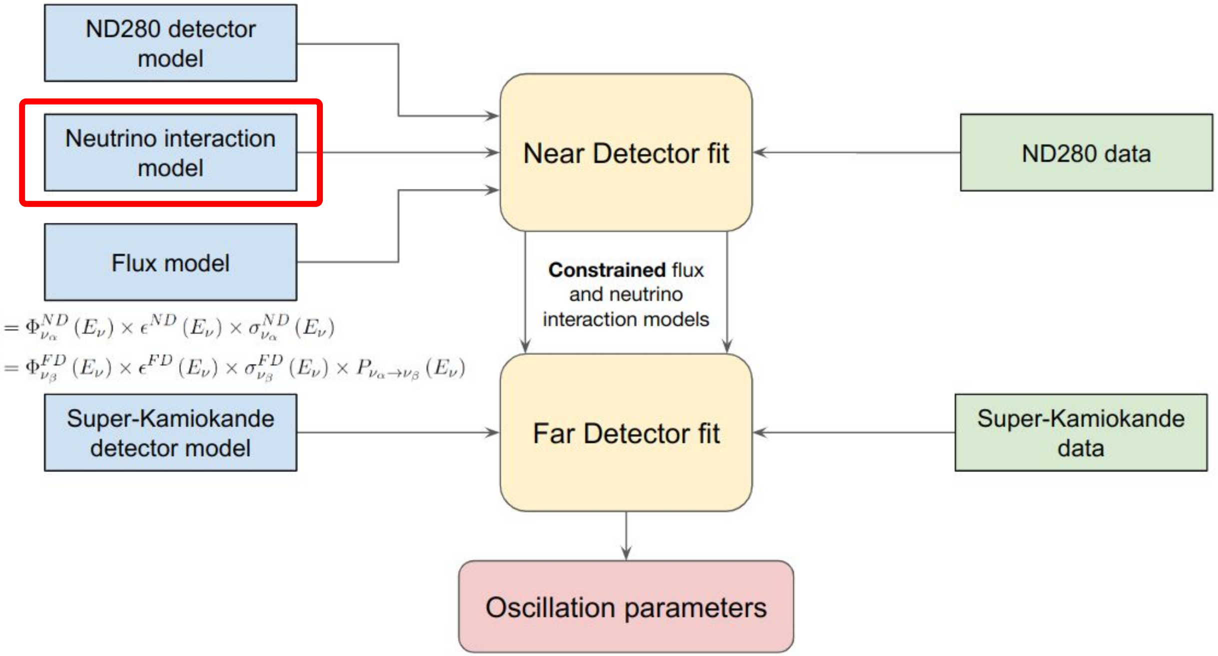


Eur. Phys. J. C76, 617 (2016)

Eur. Phys. J. C79, 100 (2019)



New neutrino interaction model uncertainties



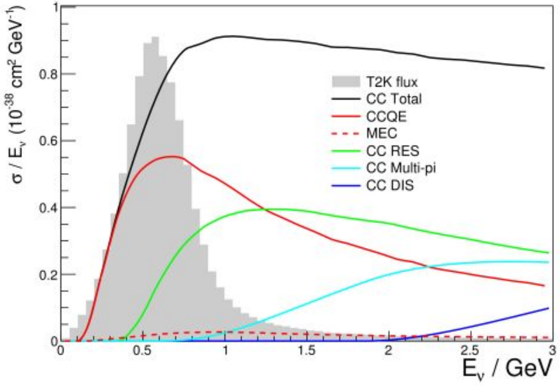
$$N_{\nu_\alpha}^{ND}(E_\nu) = \Phi_{\nu_\alpha}^{ND}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma_{\nu_\alpha}^{ND}(E_\nu)$$

$$N_{\nu_\beta}^{FD}(E_\nu) = \Phi_{\nu_\beta}^{FD}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma_{\nu_\beta}^{FD}(E_\nu) \times P_{\nu_\alpha \to \nu_\beta}(E_\nu)$$

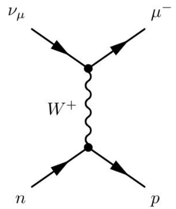
New neutrino interaction model uncertainties

Significant improvements to the interaction model:

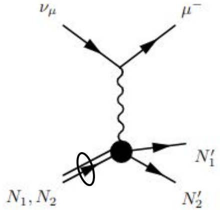
- **Charged-Current Quasi-Elastic (CCQE):** based on the Benhar Spectral Function model built from electron scattering data
  New uncertainties on: (see talk from previous IRN Neutrino)
  - The nuclear shell structure
  - Low energy transfer region with Pauli Blocking and optical potential
- **Proton tagging uncertainties:**
  - Nucleon FSI
  - Improved description of 2p2h pn/nn pairs contribution
- **CC Resonant (CCRES):**
  - New tune to bubble chamber data
  - New resonance decay uncertainties
  - Effective inclusion of binding energy uncertainty



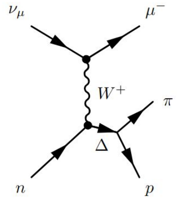
CCQE



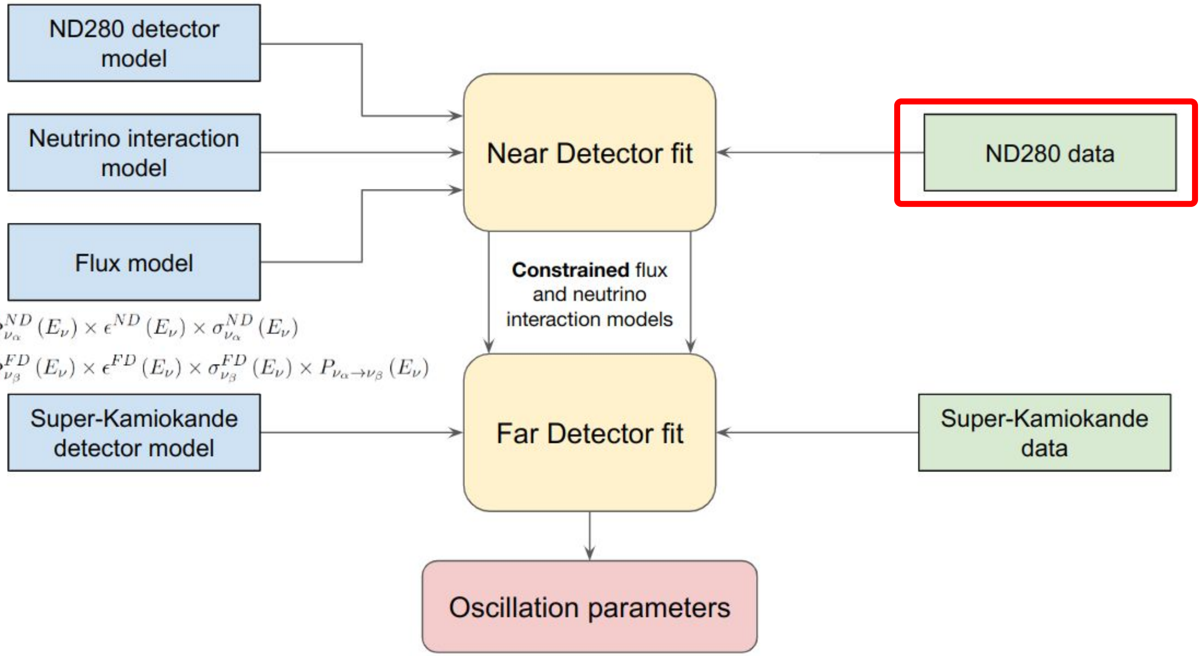
2p2h



CCRES



New Near Detector samples



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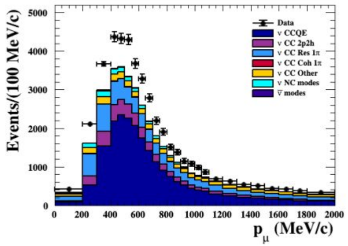
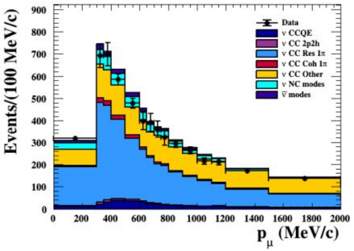
New Near Detector samples

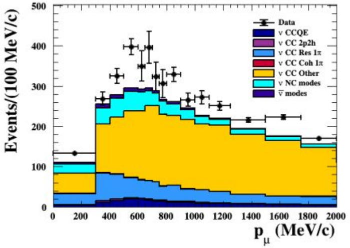
2020



(a) FGD1 FHC ν_μ 0π



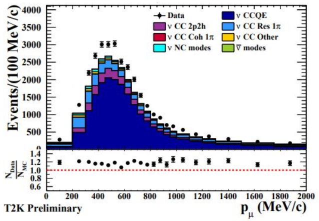
(b) FGD1 FHC ν_μ 1π



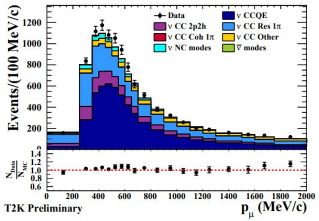
(c) FGD1 FHC ν_μ Other

- New **proton** & **photon** tagged samples
- Total number of samples: **18** → **22**

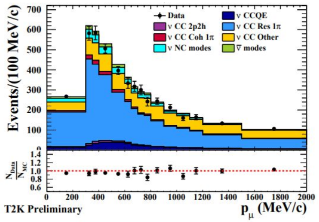
2022



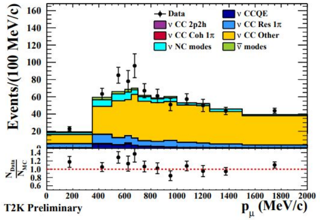
(a) FGD1 FHC CC0π-0p-0γ



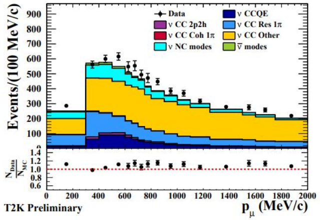
(b) FGD1 FHC CC0π-Np-0γ



(c) FGD1 FHC CC1π-0γ

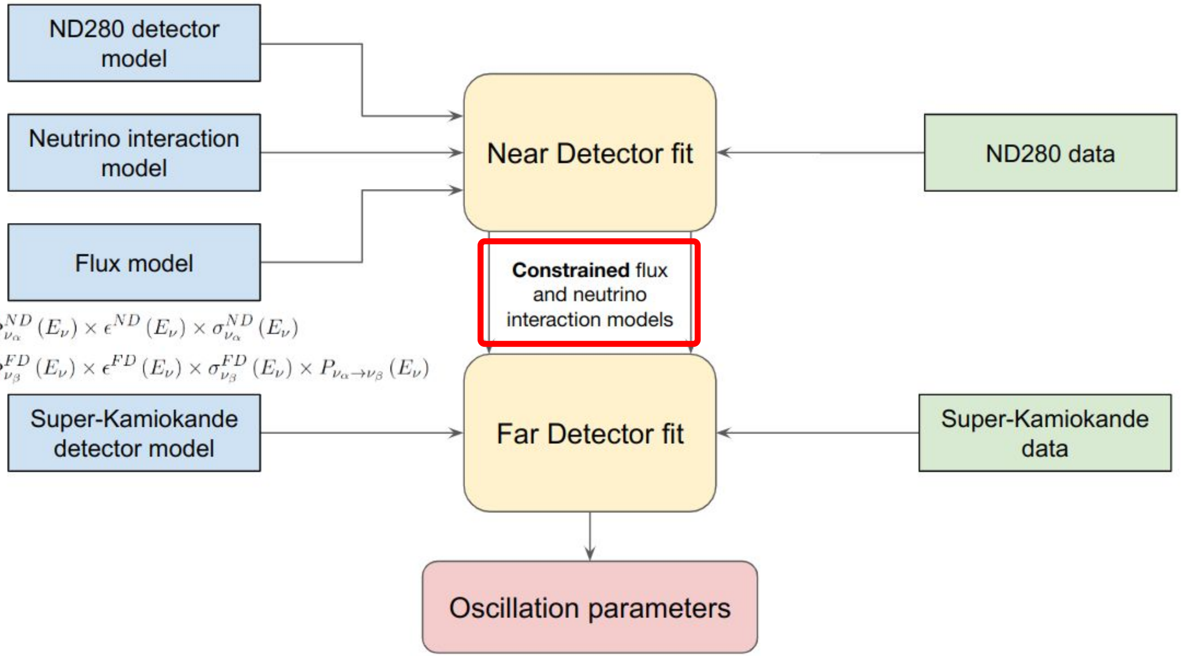


(d) FGD1 FHC CC-Other-0γ



(e) FGD1 FHC CC-Photon

Near Detector fit



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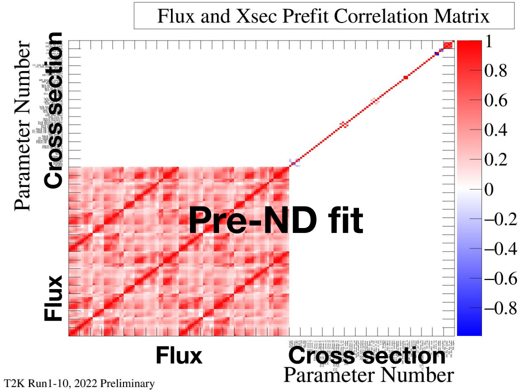
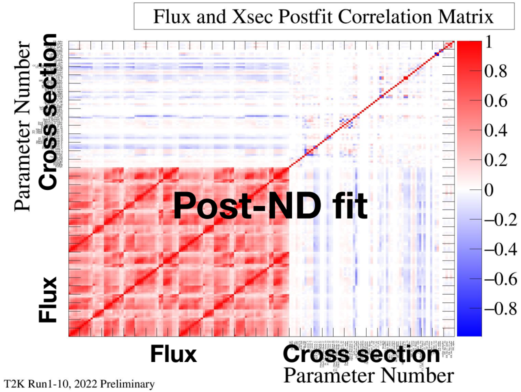
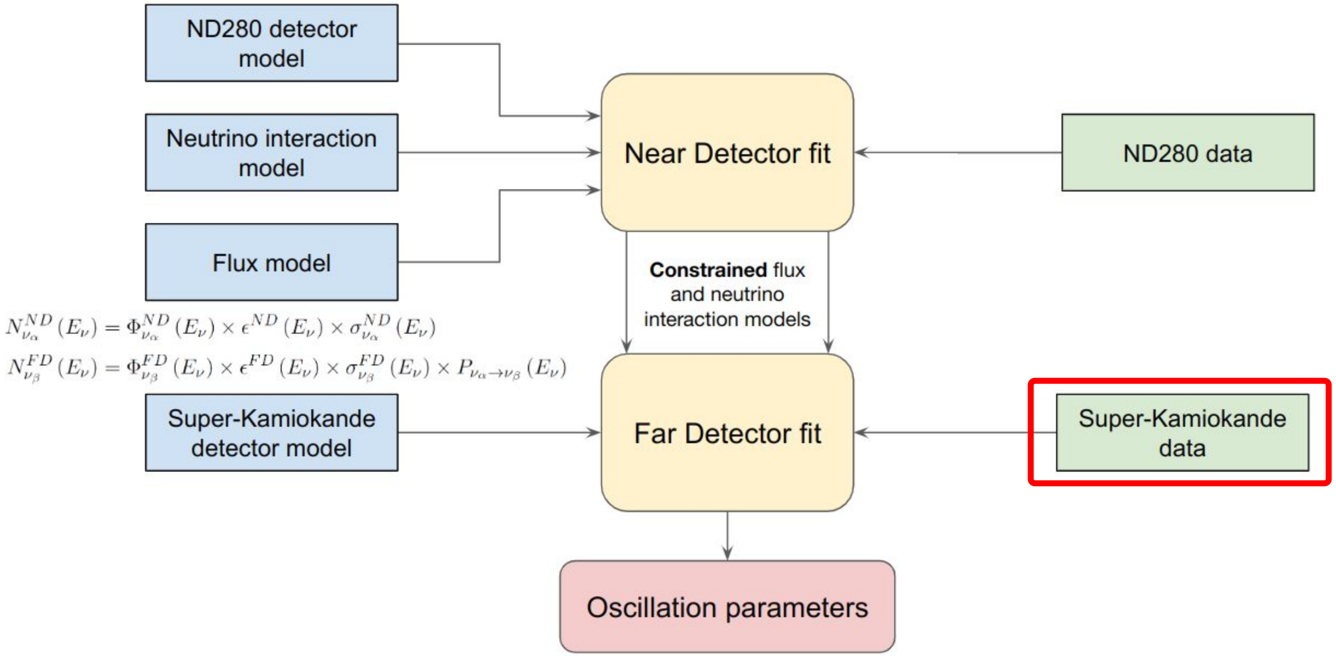
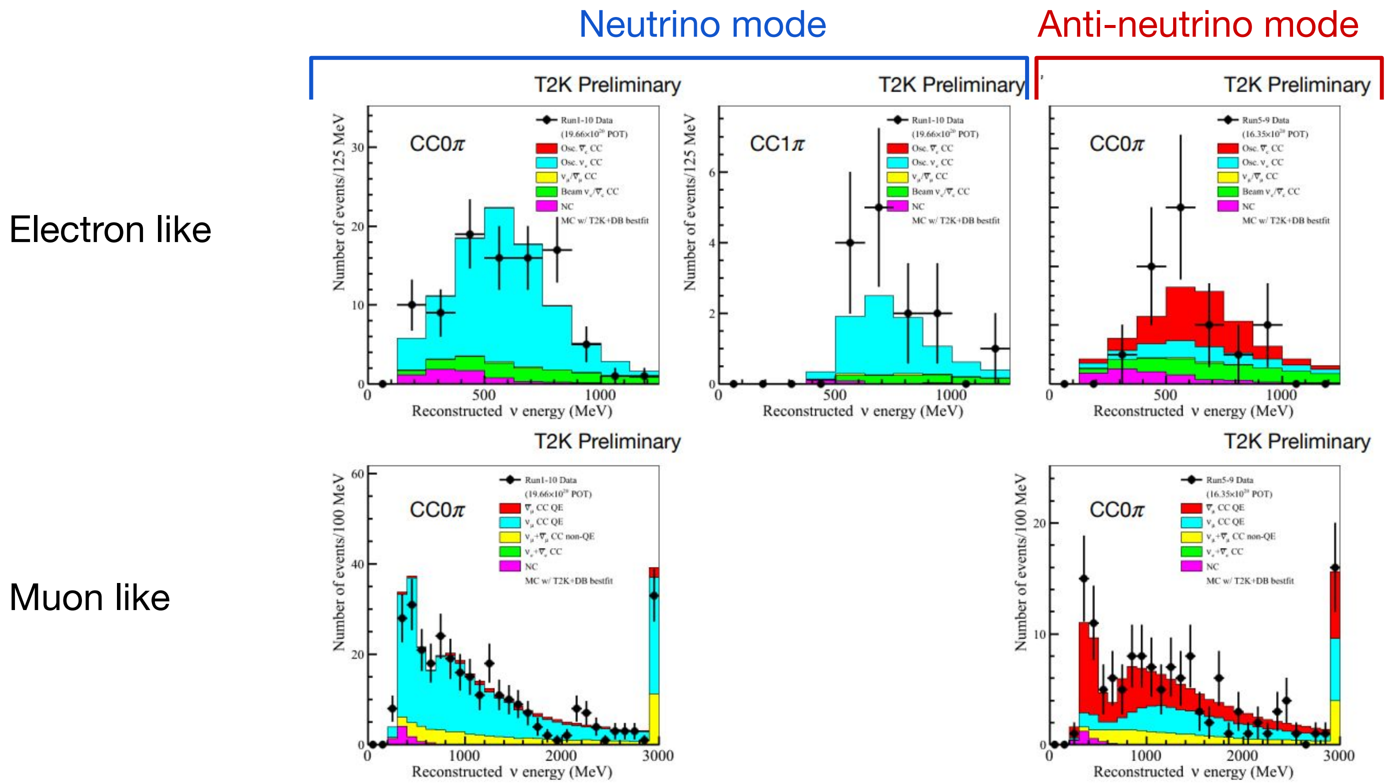




New Far Detector sample



New Far Detector sample

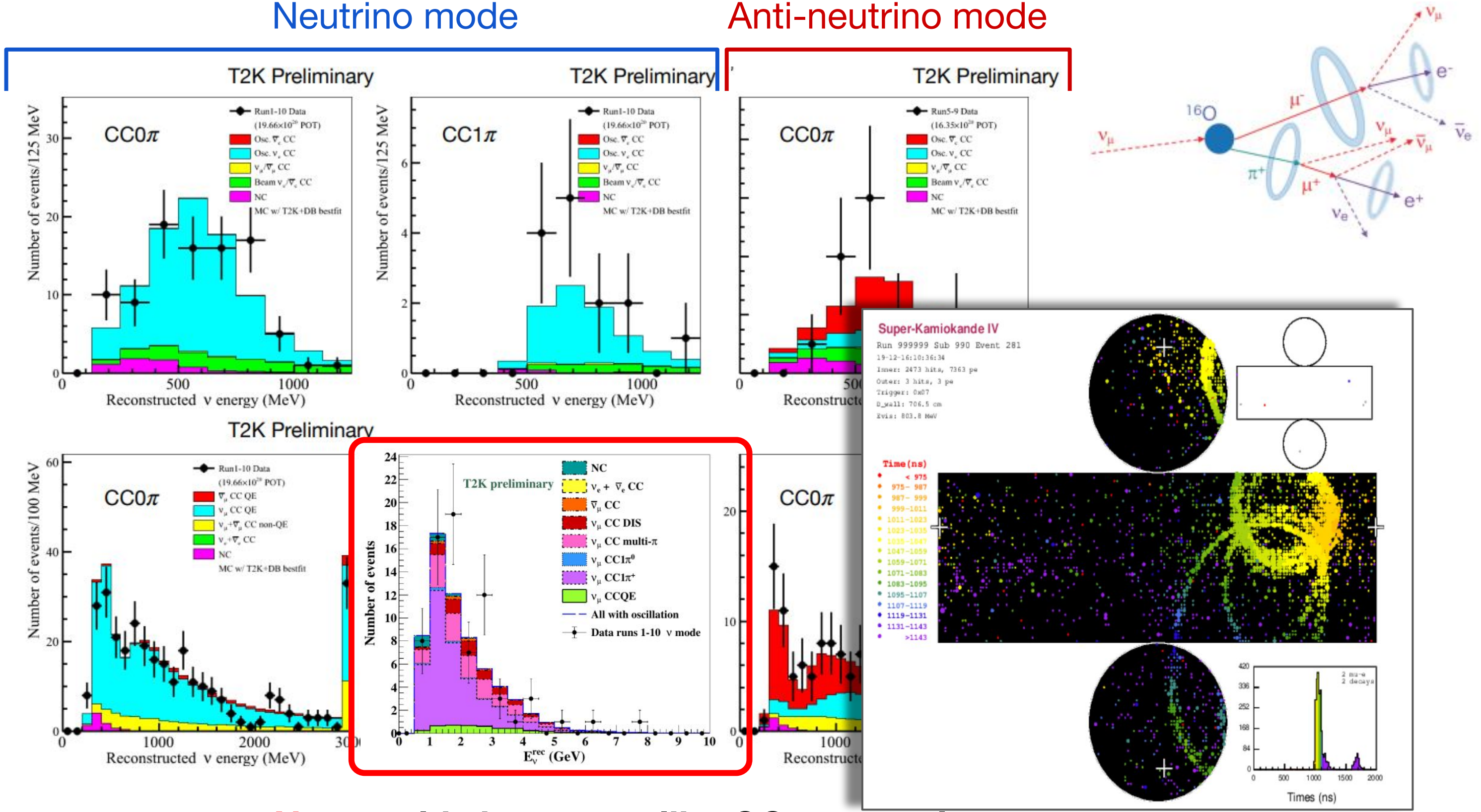


New Far Detector sample

Neutrino mode | Anti-neutrino mode

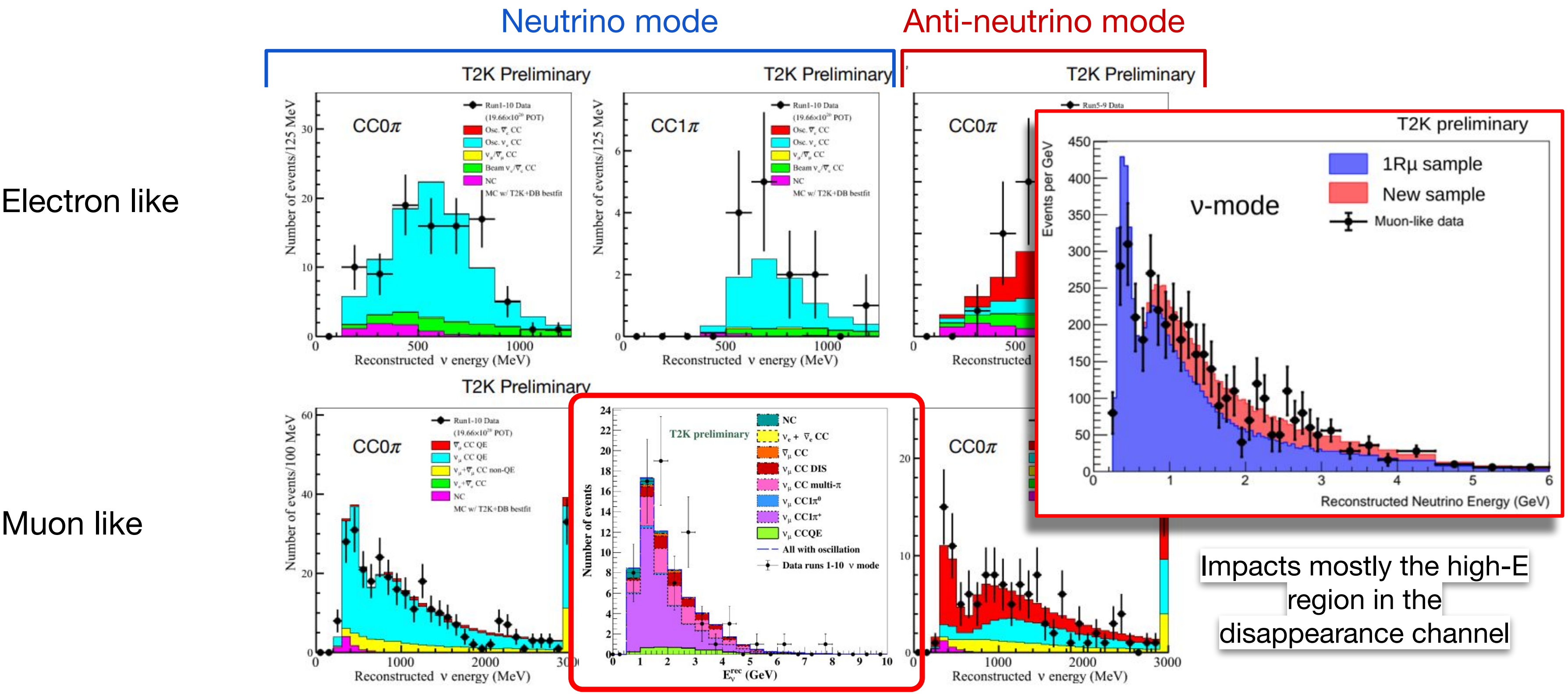
Electron like

Muon like



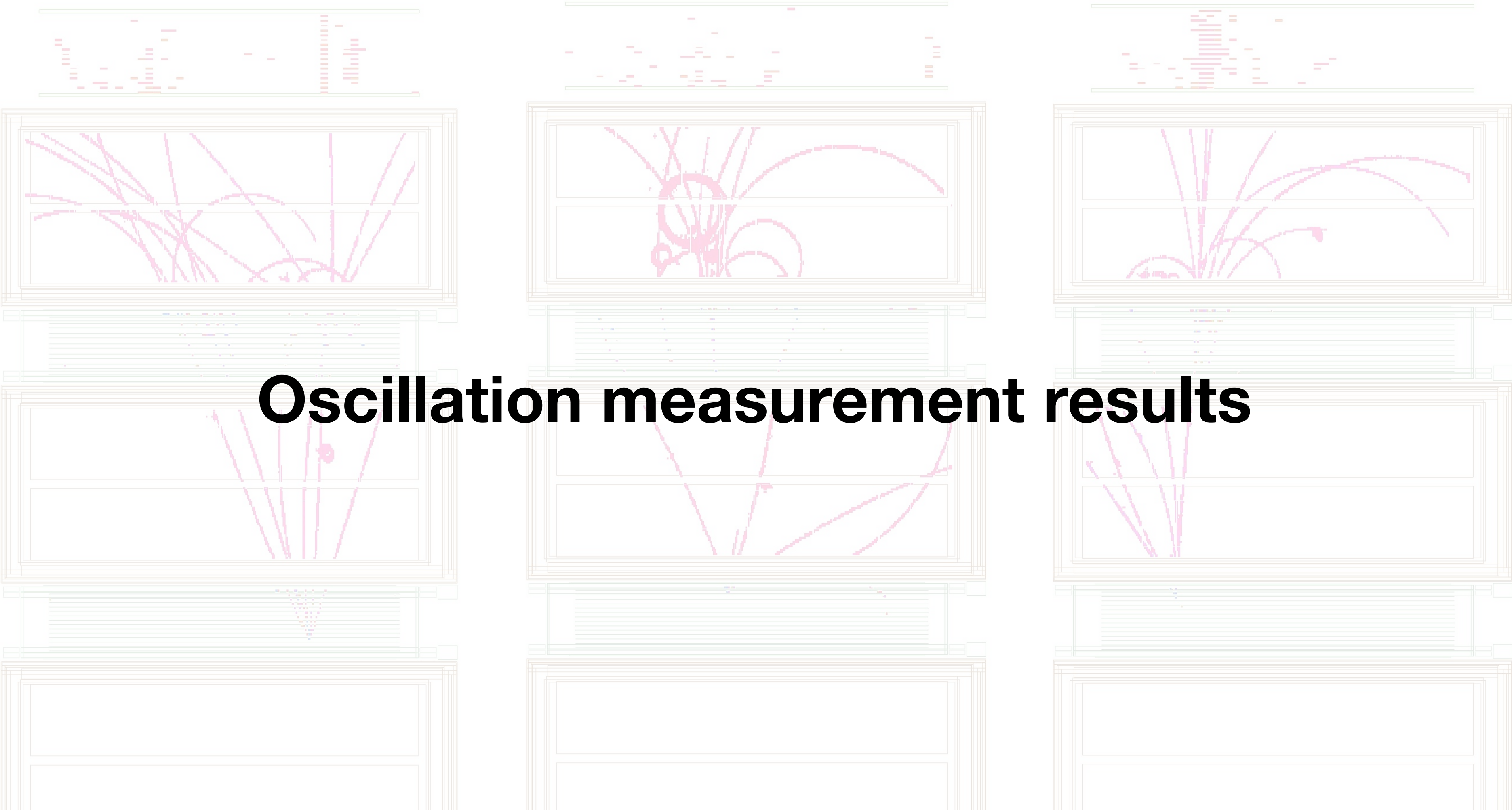
New multi-ring muon-like CC1π sample

New Far Detector sample



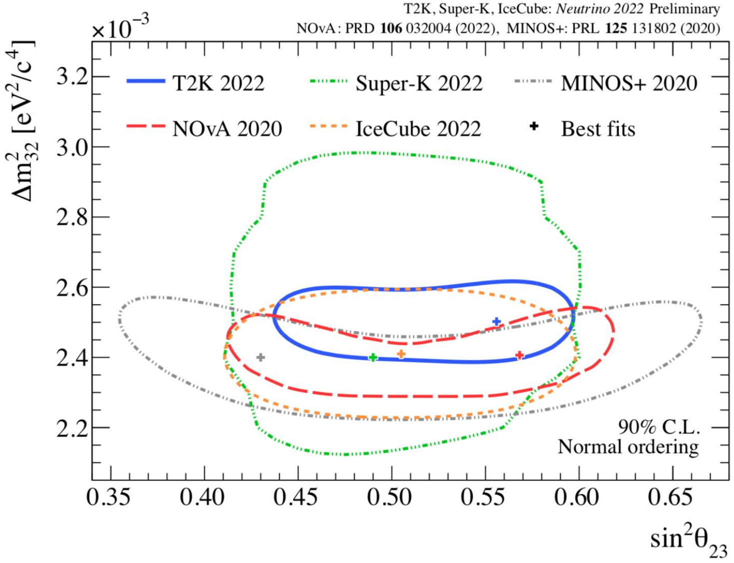
Impacts mostly the high-E region in the disappearance channel

New multi-ring muon-like CC1π sample



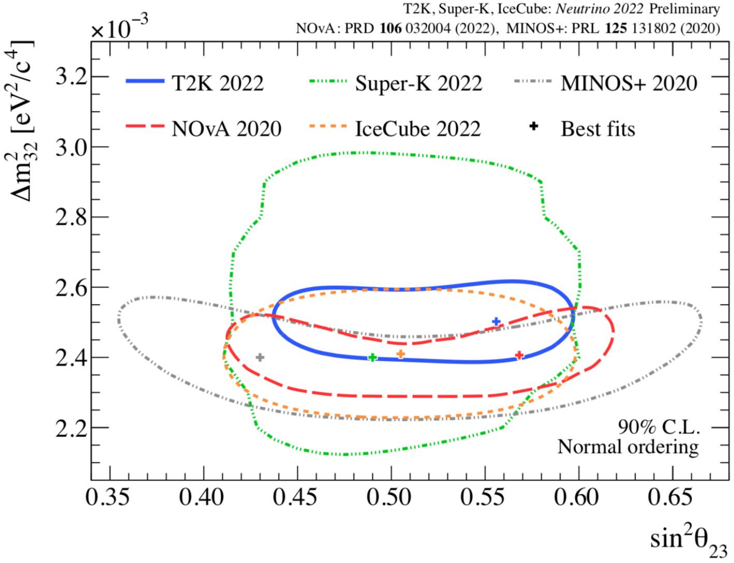
Oscillation measurement results

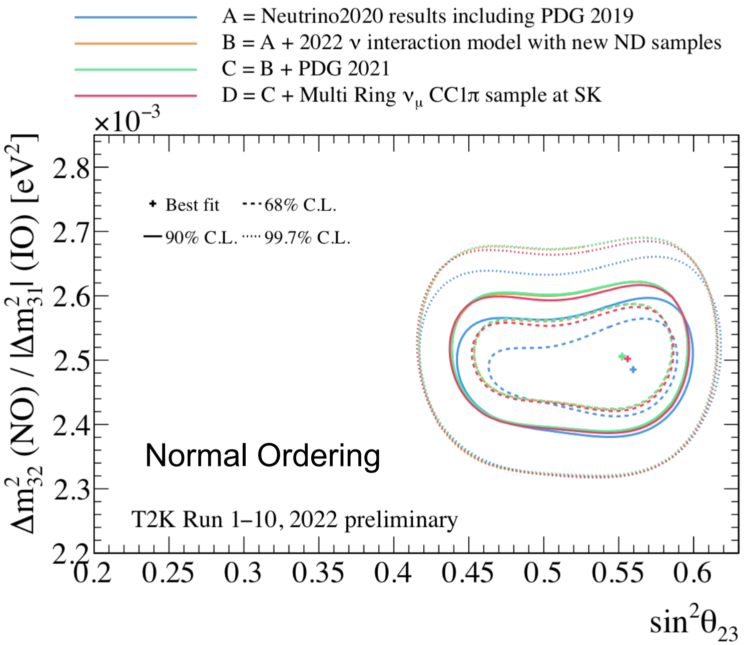
Disappearance: atmospheric parameters constraints



- **World leading measurements of the atmospheric parameters**
- Still compatible with both octants, with a weak preference for the upper octant

Disappearance: atmospheric parameters constraints

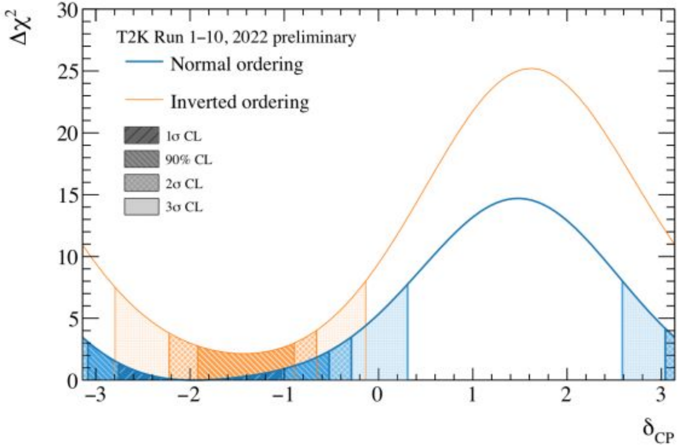




- **World leading measurements of the atmospheric parameters**
- Still compatible with both octants, with a weak preference for the upper octant
- The difference w.r.t. the 2020 results is largely due to the updated interaction model

Appearance: CP-violating phase constraints

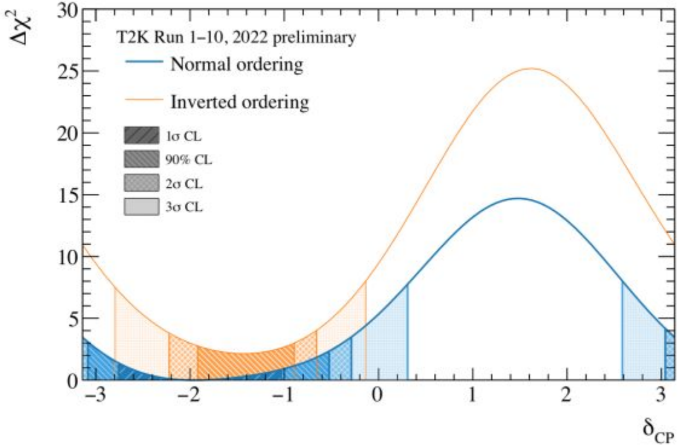
With reactor constraints

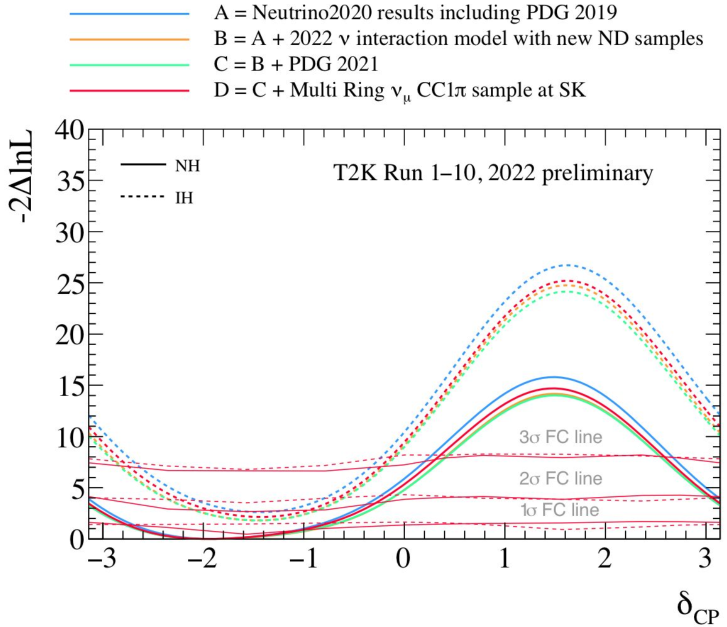


- 2020 conclusions unchanged: preference for ~maximal CP violation and exclusion of CP-conserving values at 90% C.L

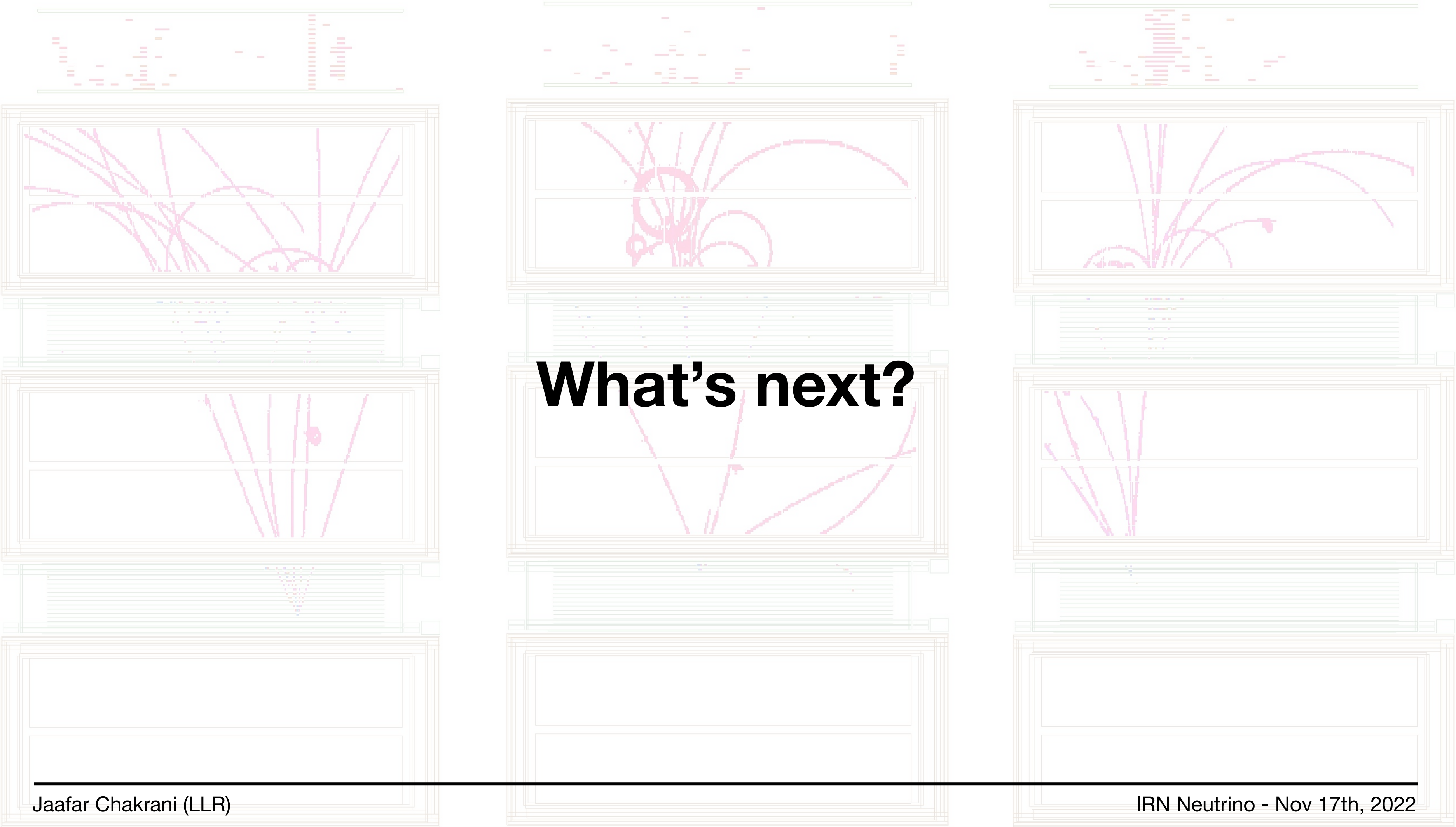
Appearance: CP-violating phase constraints

With reactor constraints





- 2020 conclusions unchanged: preference for ~maximal CP violation and exclusion of CP-conserving values at 90% C.L
- Slightly reduced constraints w.r.t. 2020 results due to the updated interaction model

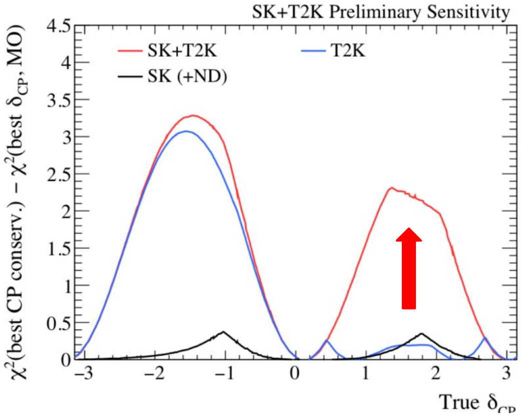


What’s next?

Joint fits

T2K-SK

- Common detector for the two experiments



- A joint fit could **resolve the degeneracy** between the mass ordering and the CP-violating phase
- First data result expected in less than a year!

T2K-NOvA

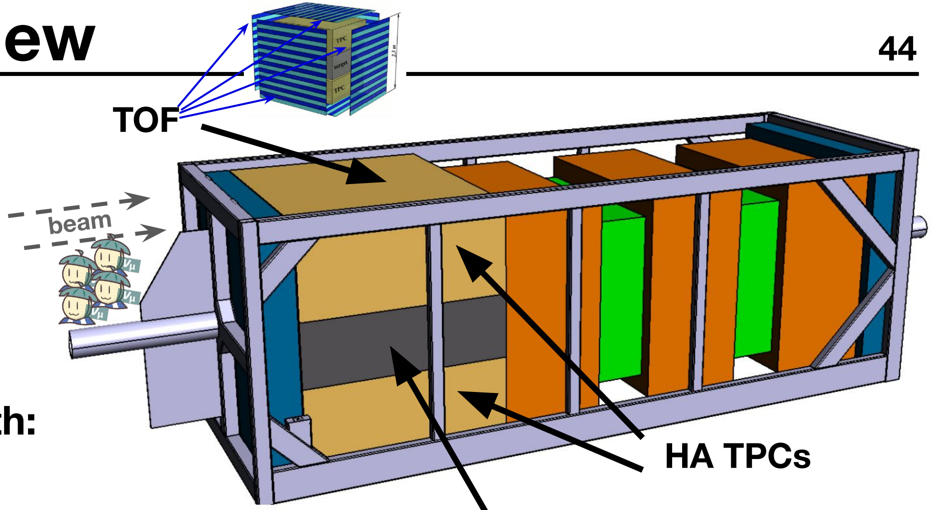
- Experiments with different baselines, beam energy, and detector technologies

Experimental Property	T2K	NOvA
Proton Beam Energy	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection Technology	Water Cherenkov	Segmented liquid sintillator bars

- The two collaborations are currently working on the joint fit, with a special care about the correlations between systematic uncertainties

T2K ND280 Upgrade Overview

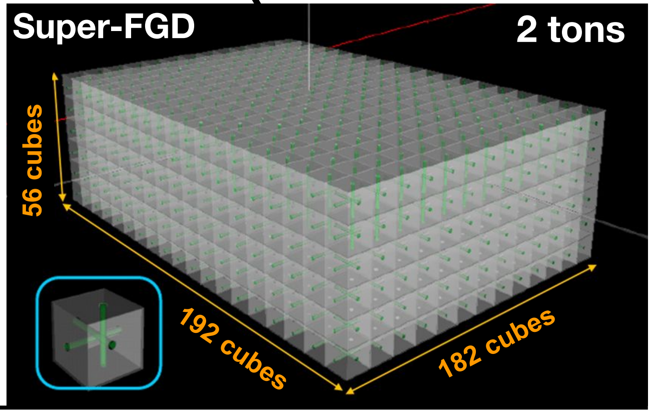
- Super-FGD: 2.10^6 1 cm^3 scintillator cubes
- New high-angle TPCs
- New Time Of Flight detector



The goal is to reduce the ND systematics with:

- Fully active target
- 4π acceptance for charged particles
- Lower proton momentum threshold (~300 MeV/c)
- Neutron kinematics reconstruction
- Larger statistics

↪ See expected performances in [previous IRN talk]



T2K ND280 Up

- Super-FGD: 2.10^6
- New high-angle TP
- New Time Of Flight

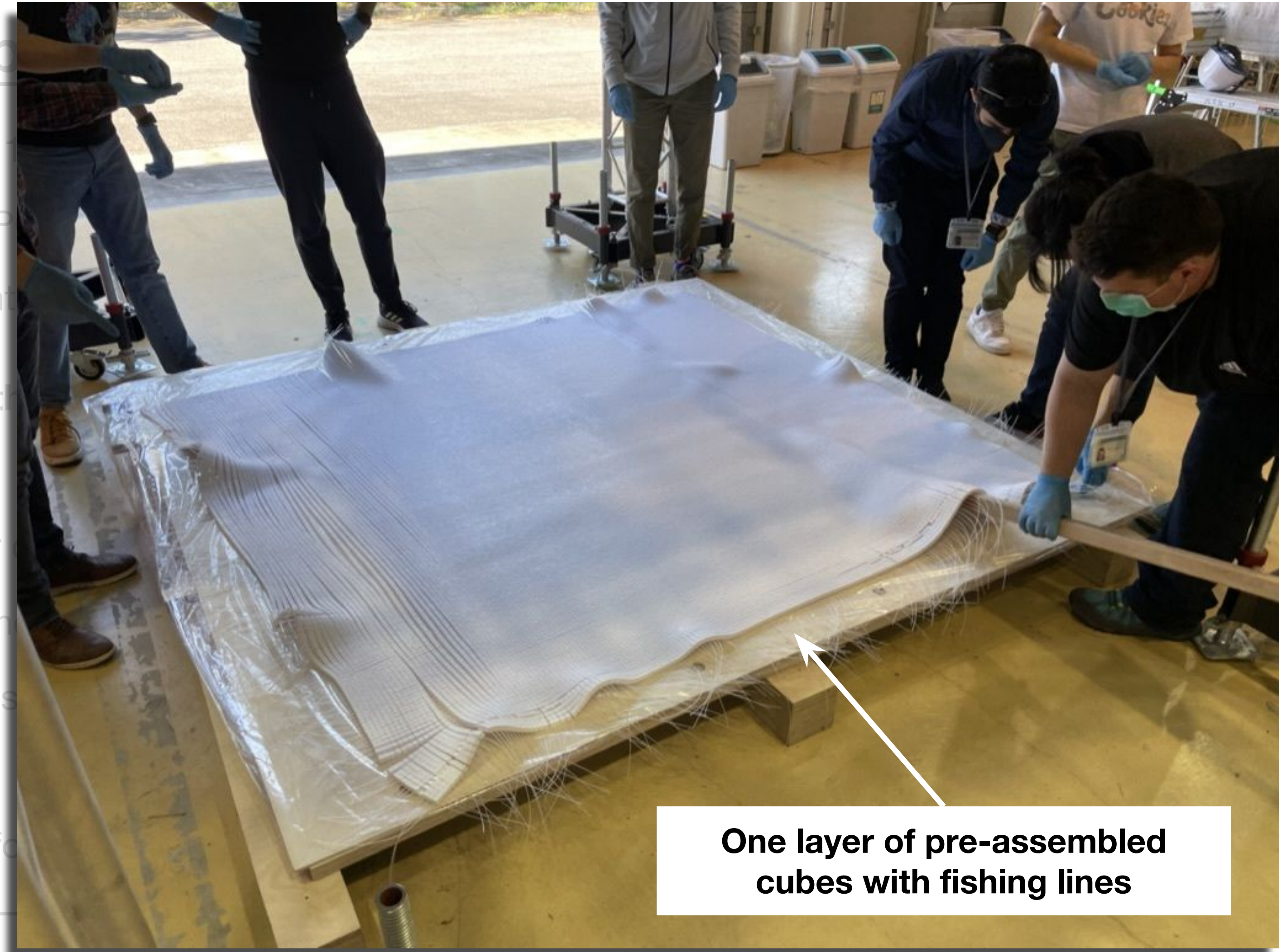
The goal is to reduce th

Few pictures of the ongoing Super-FGD assembly

target

- 4π acceptance for
- Lower proton mom
- Neutron kinematics
- Larger statistics

↪ See expected perf



T2K ND280 U

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Few pictures of the ongoing Super-FGD assembly

target

- 4π acceptance fo
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↪ See expected pe

T2K ND280 U

- Super-FGD: 2.10^6
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Few pictures of the ongoing Super-FGD assembly target

- 4π acceptance fo
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↪ See expected per

T2K ND280 Upgrade Overview

- Sup
- New
- New

The goal

- Fully
- 4π a
- Low
- Neu
- Larg

↪ See

TPCs

2 tons

2 cubes

First layer installed on: October 31st

Progress as of <u>two days ago</u>: 40/56 layers

Summary

Summary

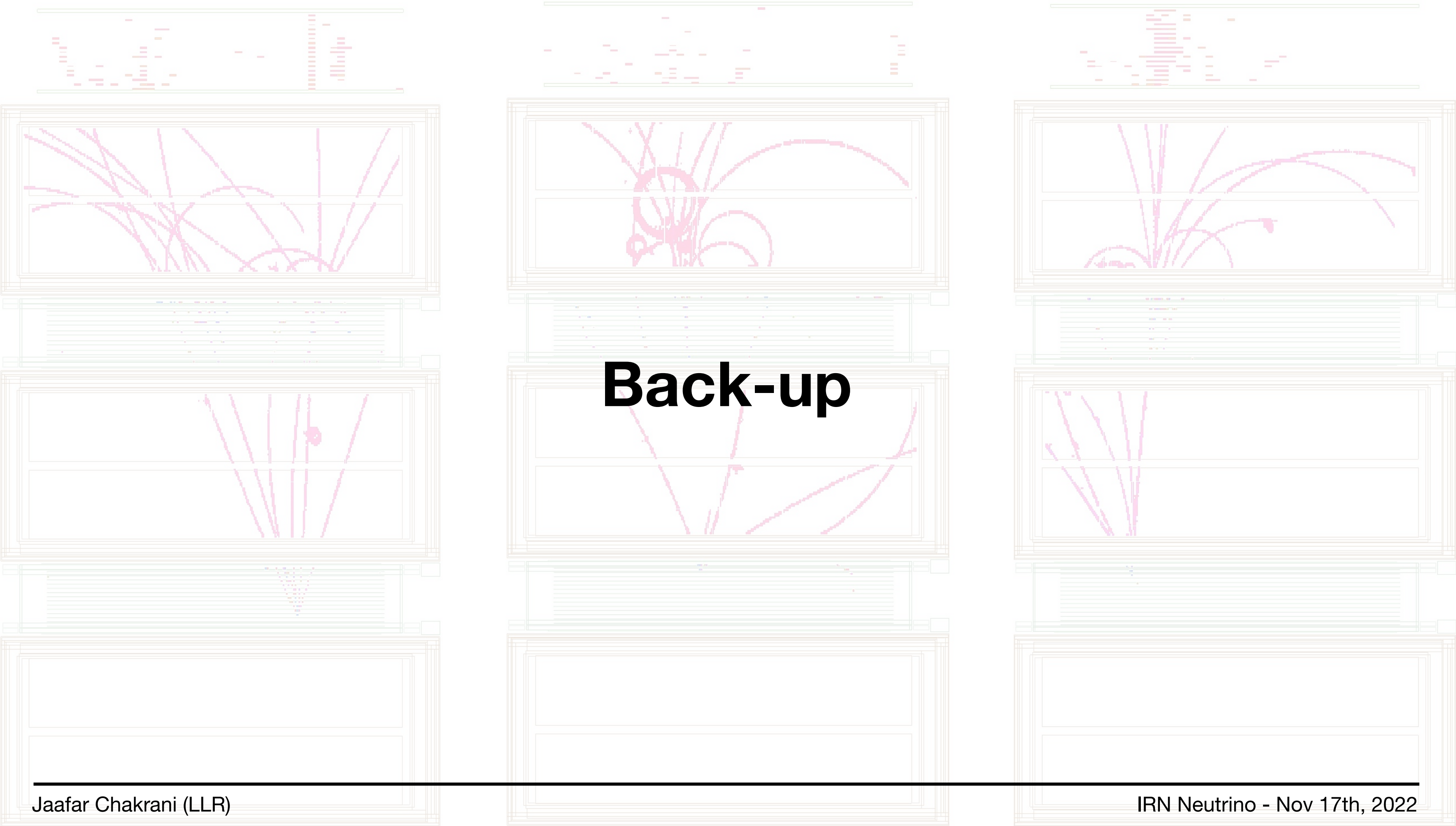
- T2K performed a substantial update at each level of the oscillation analysis
- The oscillation measurement results show:
  - CP conservation is still excluded at 90% C.L., with a slightly weaker constraint due to the updated interaction model
  - Normal ordering and upper octant are weakly preferred
- A bright future ahead:
  - Joint fits with SK and NOvA experiments
  - Upgraded beamline and near detector

T2K Collaboration

Online

T2K “hybrid” collaboration meeting, May 2022

Back-up



Bi-event plot