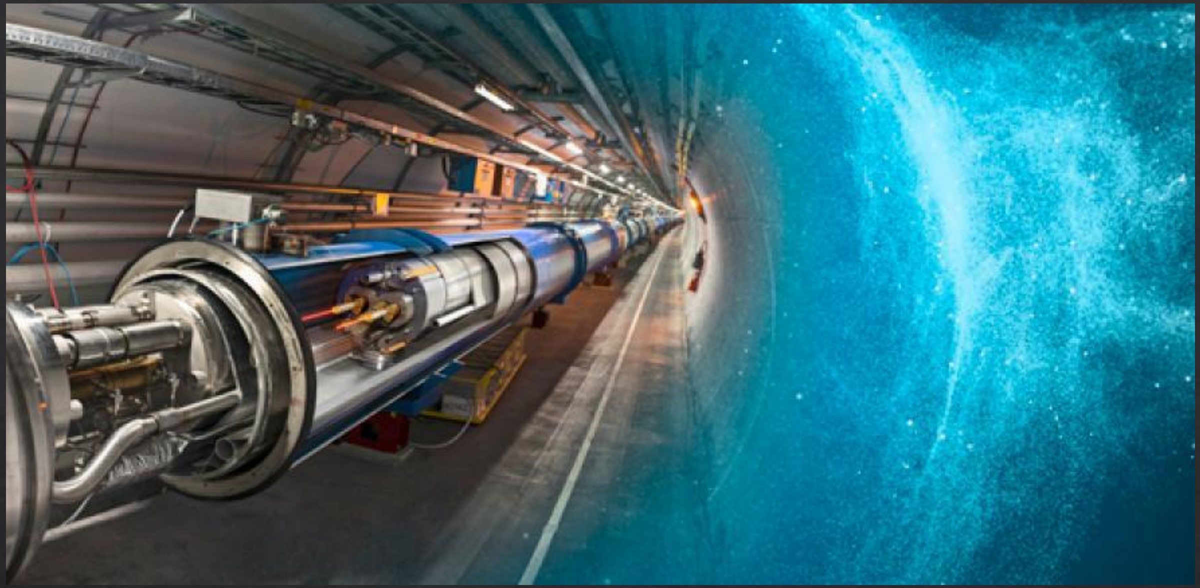

First Pan-African Astro-Particle and Collider Physics Workshop

The T2K Experiment

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University of Liverpool

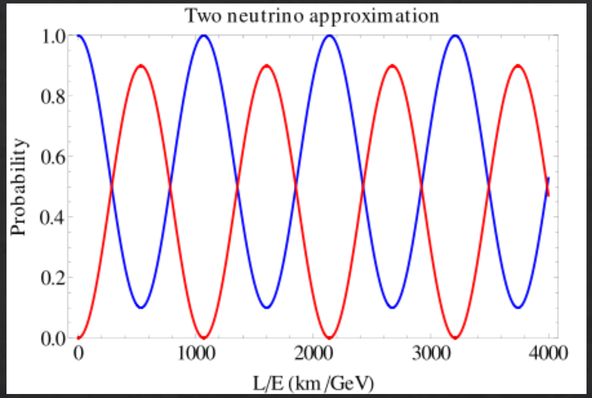
T2K

UNIVERSITY OF LIVERPOOL

Neutrino Oscillations

With 2 flavours:

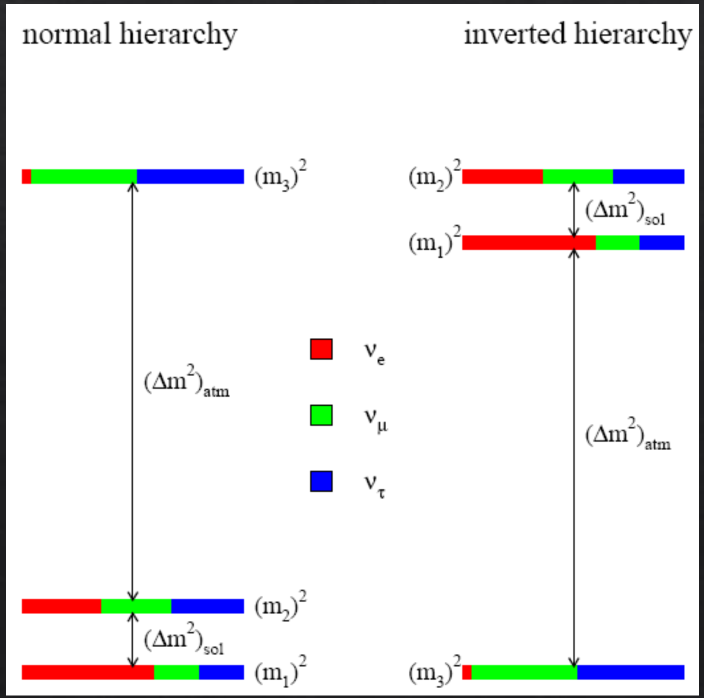
$$p(\nu_\alpha \rightarrow \nu_\beta) = sin^2 2\theta sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



Neutrinos are an exciting area of physics ripe for new discoveries and more Nobel prizes

Neutrino mixing is characterised by the PMNS matrix.

$$\mathbf{U}_{PMNS} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

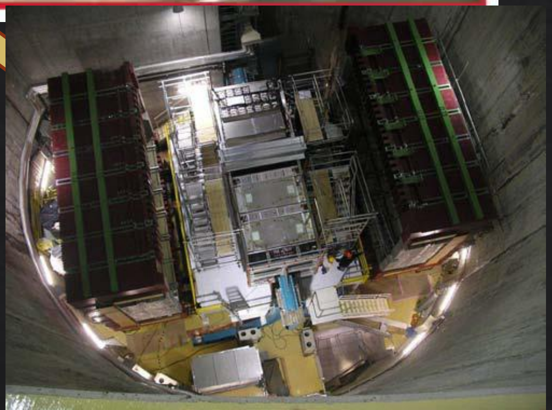


Can we complete this picture?
- CP Violating Phase δ
- Mass Ordering.
- Is θ_{23} < or > 45°? (The Octant)

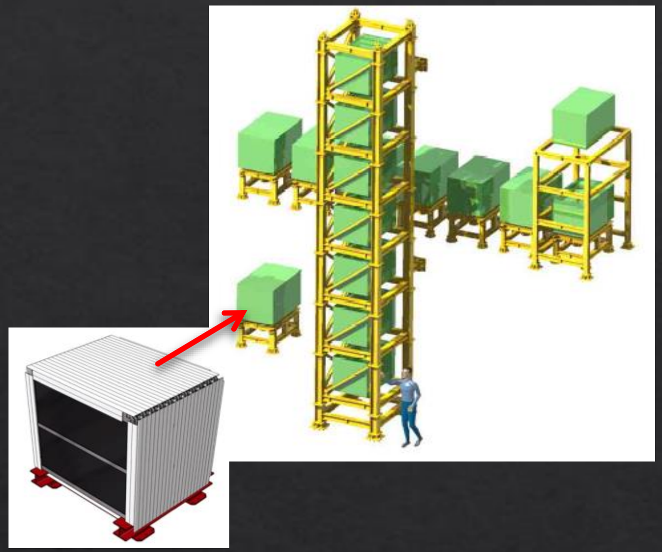
How can we answer these questions with T2K?
- Look for ν_e appearance in the ν_μ beam
- How does this differ for neutrino and antineutrino beams?

Can we find CP violation at the 3σ level before the next generation?

The T2K Experiment

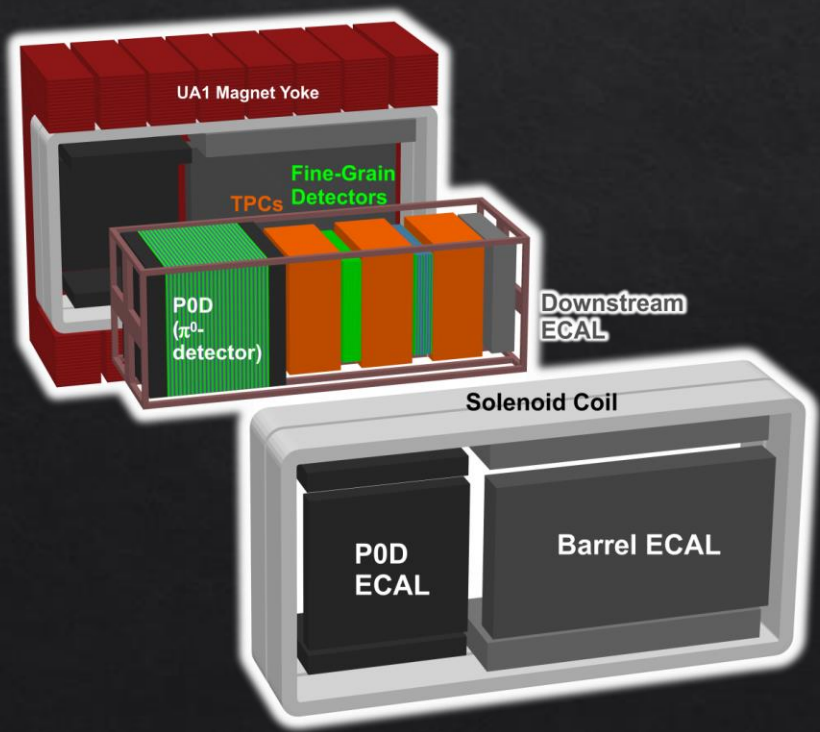


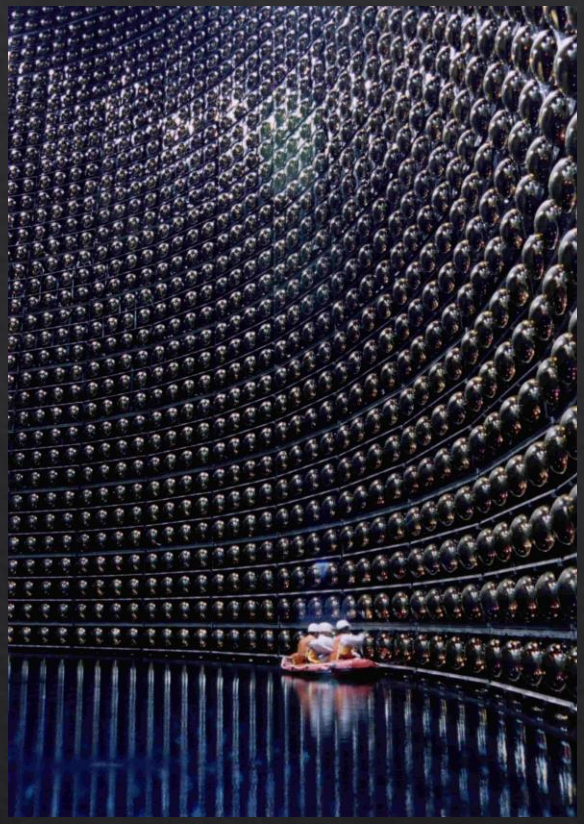
- 295km baseline – matter effect small
- Narrow band neutrino beam Epeak ~600 MeV
- First measurements using off-axis beam technique
- Near detector complex to measure beam before oscillation

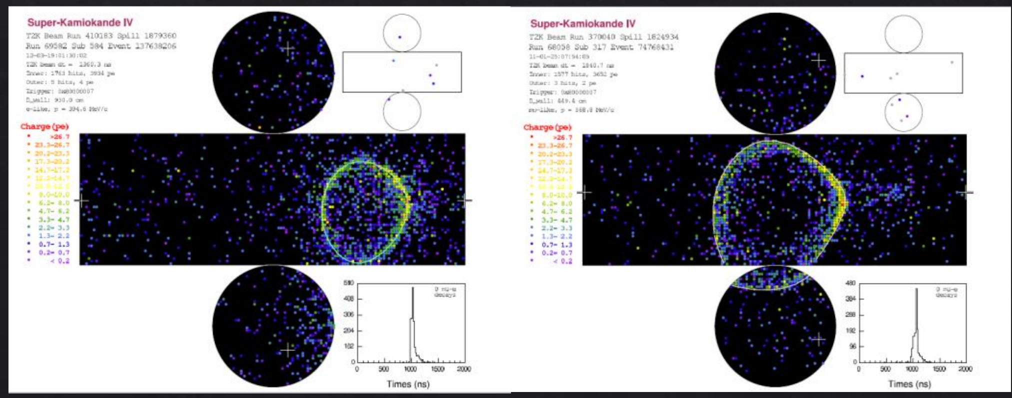


The Detectors

- Near detectors
  - Ingrid
    - On axis
    - Neutrino beam monitoring
  - ND280
    - Off axis
    - Flux and cross section measurements
- SK
  - 50 kton water Cherenkov
  - Excellent μ/e separation

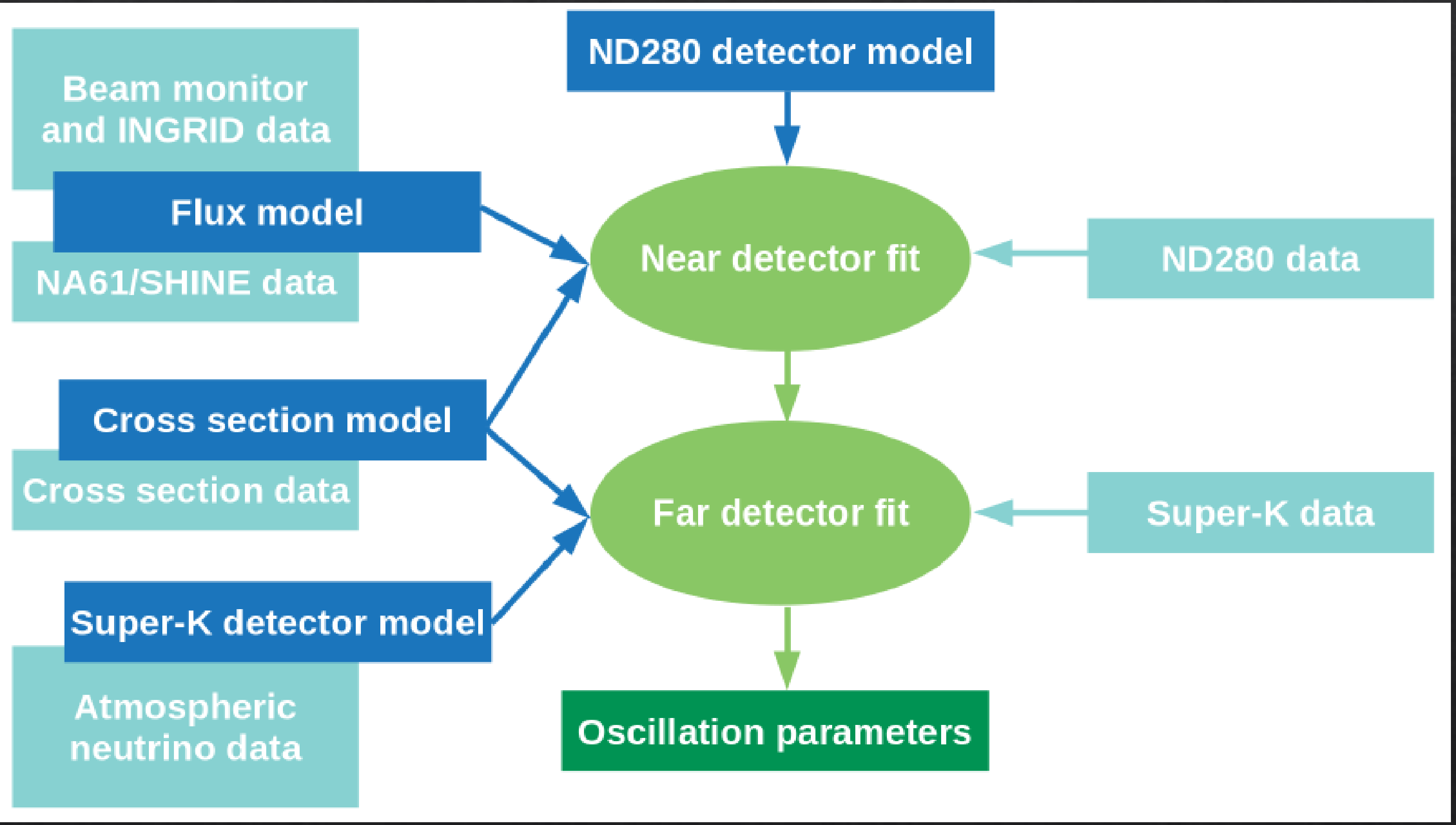






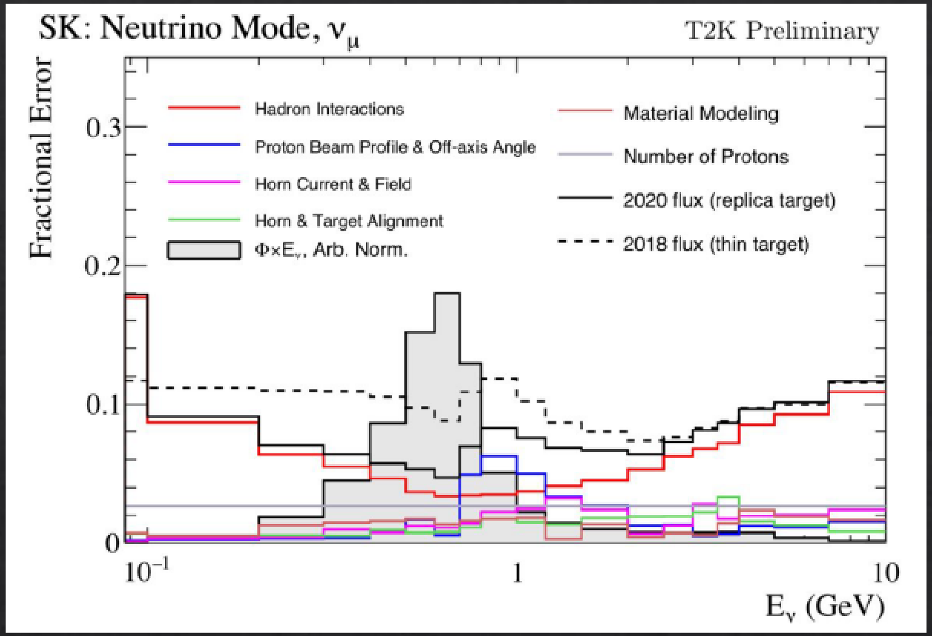
Analysis Strategy

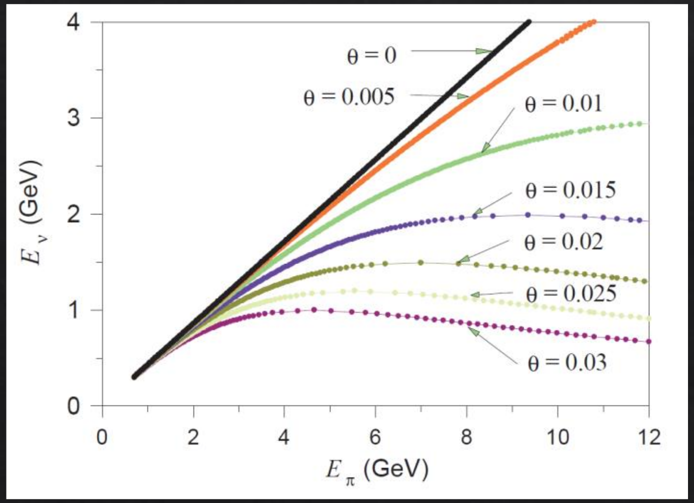
- Multiple approached producing consistent results
  - Frequentist and Bayesian
- Near Detector data
  - Constrain flux*cross section
  - Predicts event rate at far detector
- Separated and joint fit used in different approaches

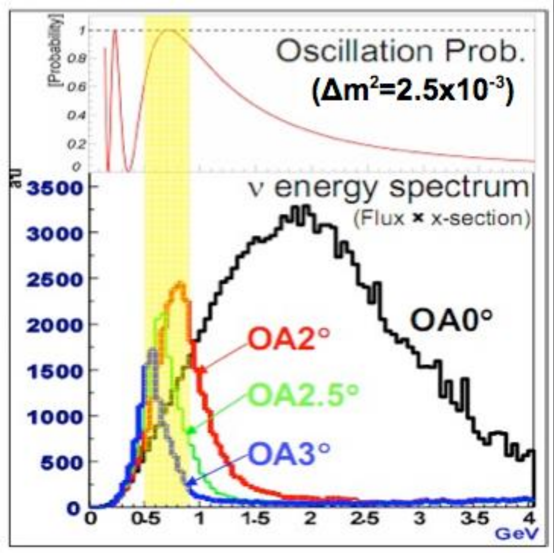


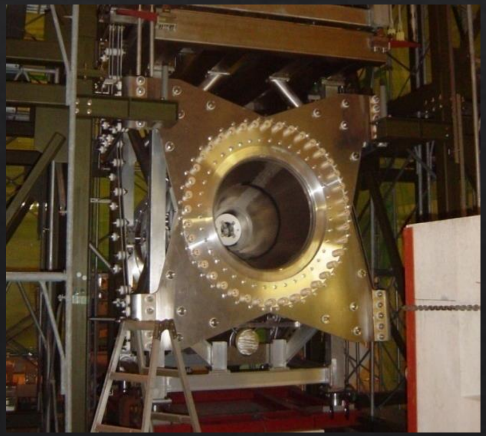
T2K Beam

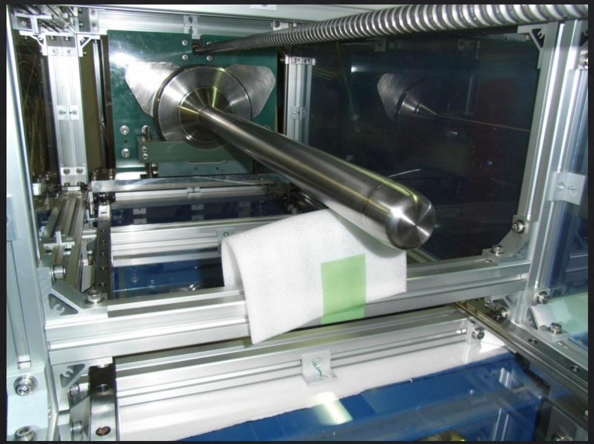
- 30 GeV protons on target
  - Produces pions which are collected by magnetic horns
  - Change sign of beam by changing horn current direction
- T2K uses the off-axis beam approach
  - Narrow band beam
  - More neutrinos you want and less you don’t
- Neutrino flux from beam simulation
  - Uncertainties constrained by use of NA61/SHINE T2K replica target data.







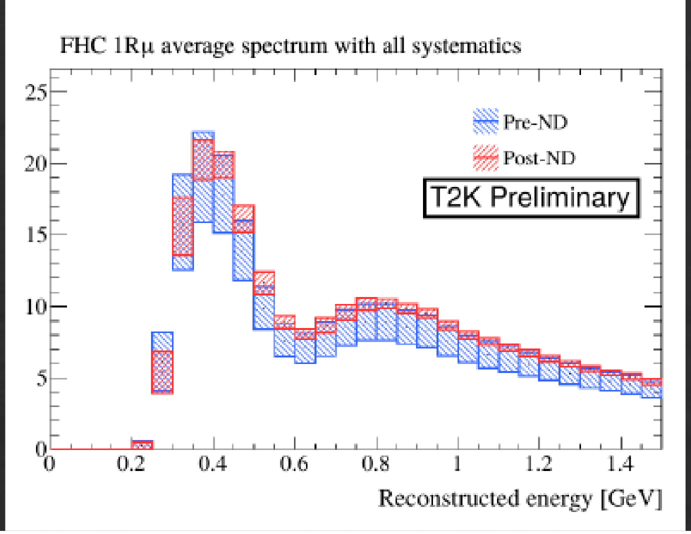


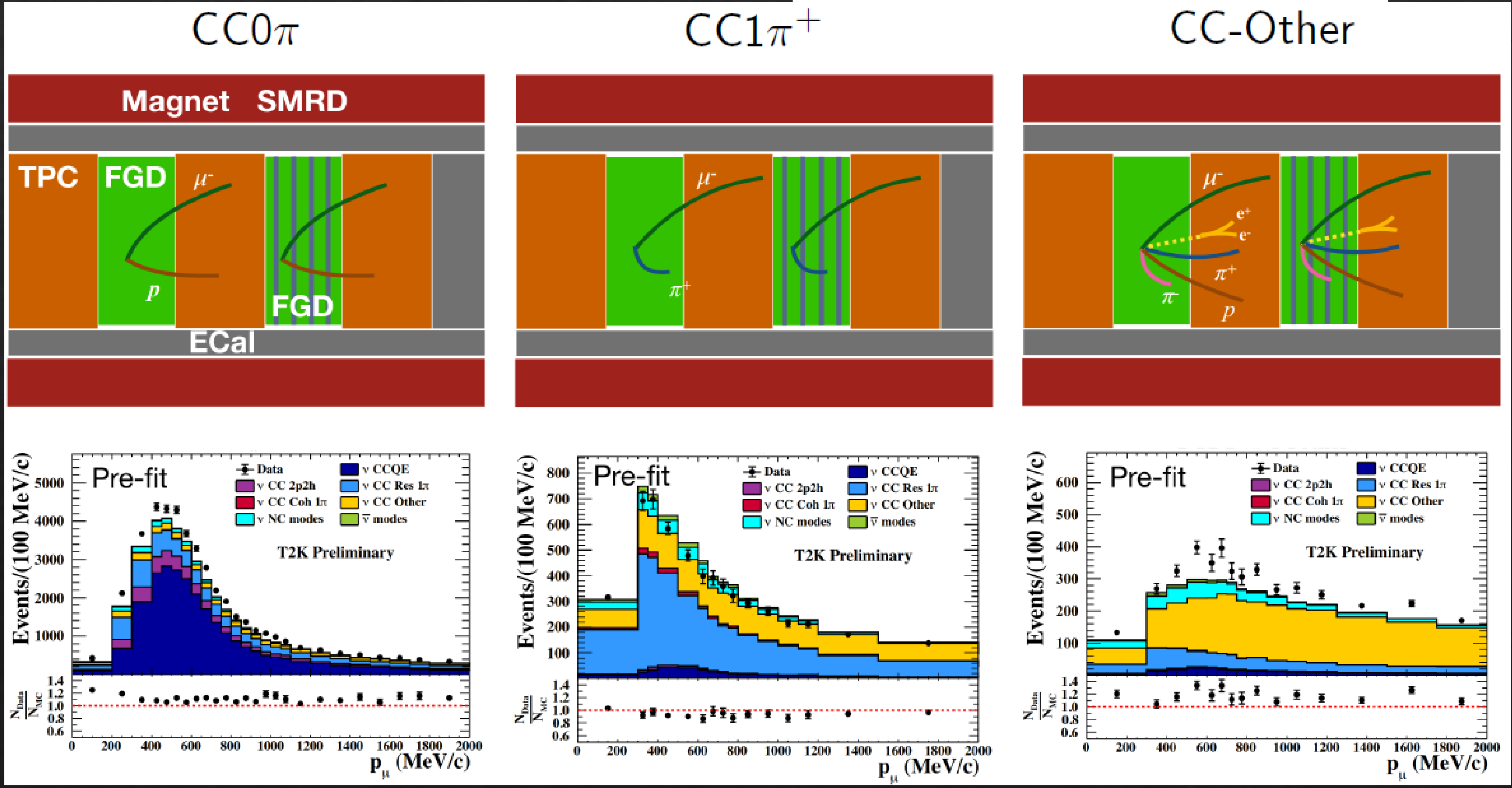


Horns and Target

Near Detector Results

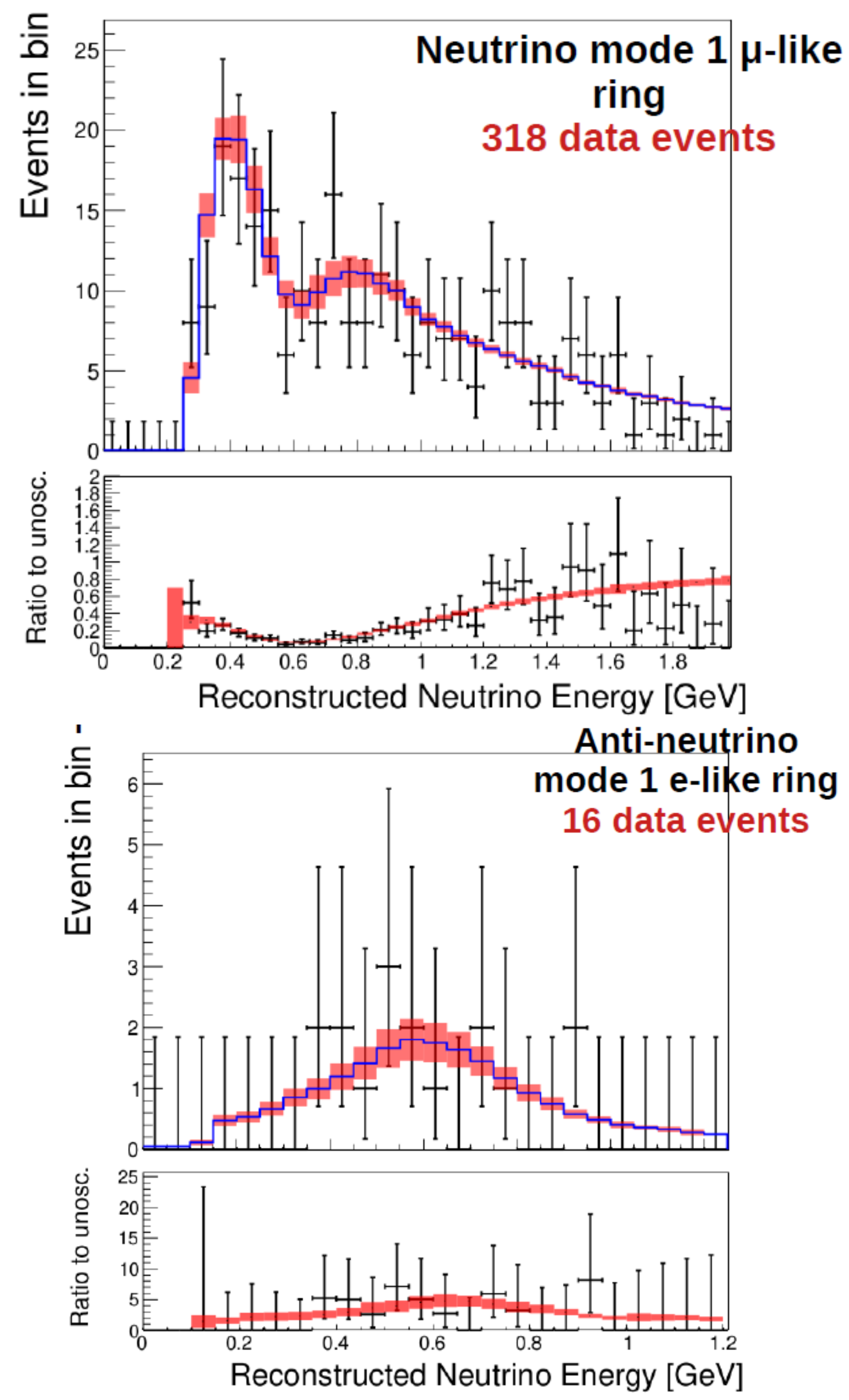
- Fit a set (18) of neutrino and antineutrino samples
- Constrains
  - Flux parameters
  - Cross section model parameters
- Correlation between the two further reduces uncertainty in SK prediction
  - 13% → 4.7% uncertainty in 1 ring electron like samples post fit
- New samples to come
  - NC π^0
  - Hadron Kinematics
- Neutrino cross section measurements





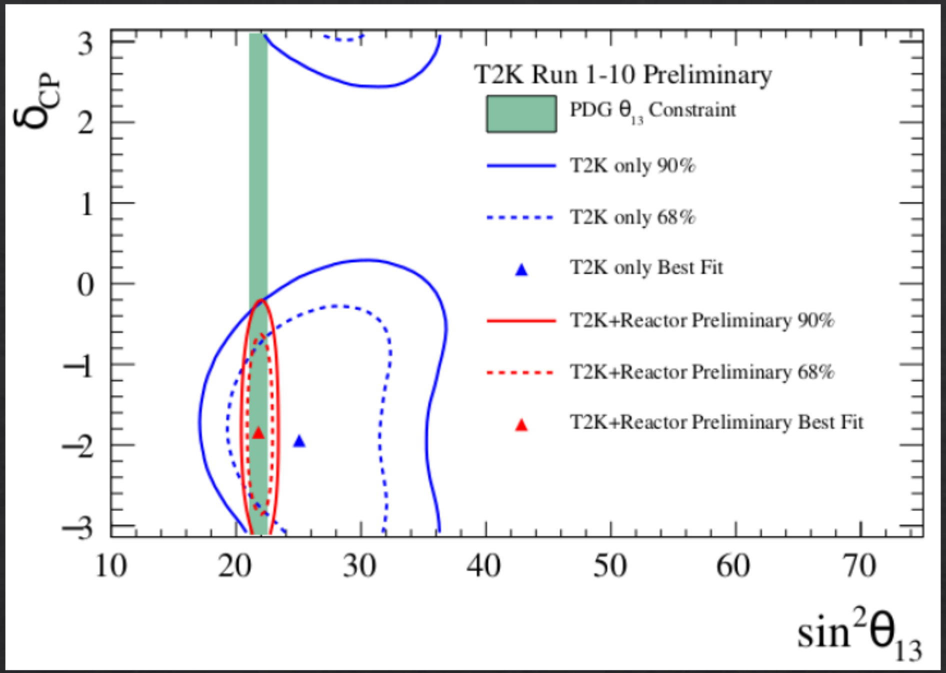
Super-Kamiokande Data

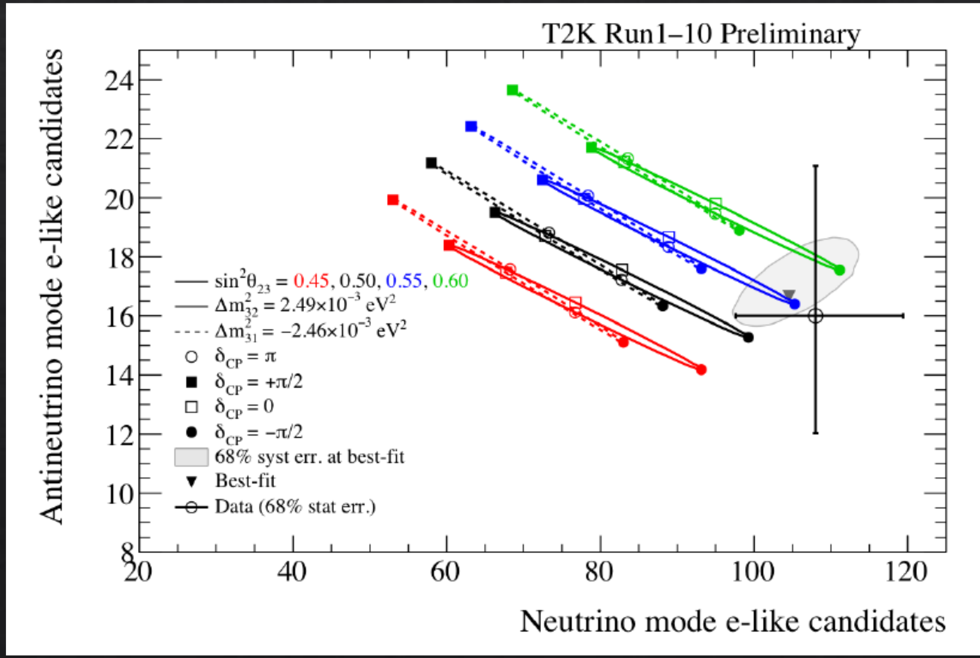
- 5 data samples
  - Single Ring mu-like, neutrino and antineutrino mode
  - Single Ring e-like, neutrino and antineutrino mode
  - Single Ring e-like + 1 Michel electron, neutrino mode
- Work underway to add more CCπ samples
- Detector systematics from fit to atmospheric neutrino sample

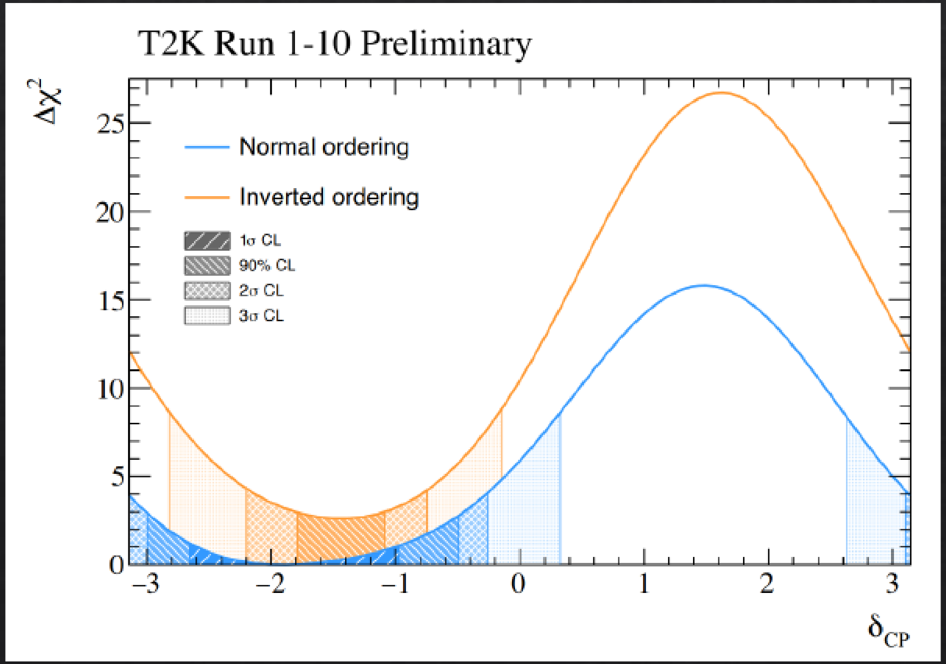


Limits on CP violation

- Disfavour CP conserving values at 90% CL
- 35% of values excluded at 3σ
  - Marginalised over the mass ordering

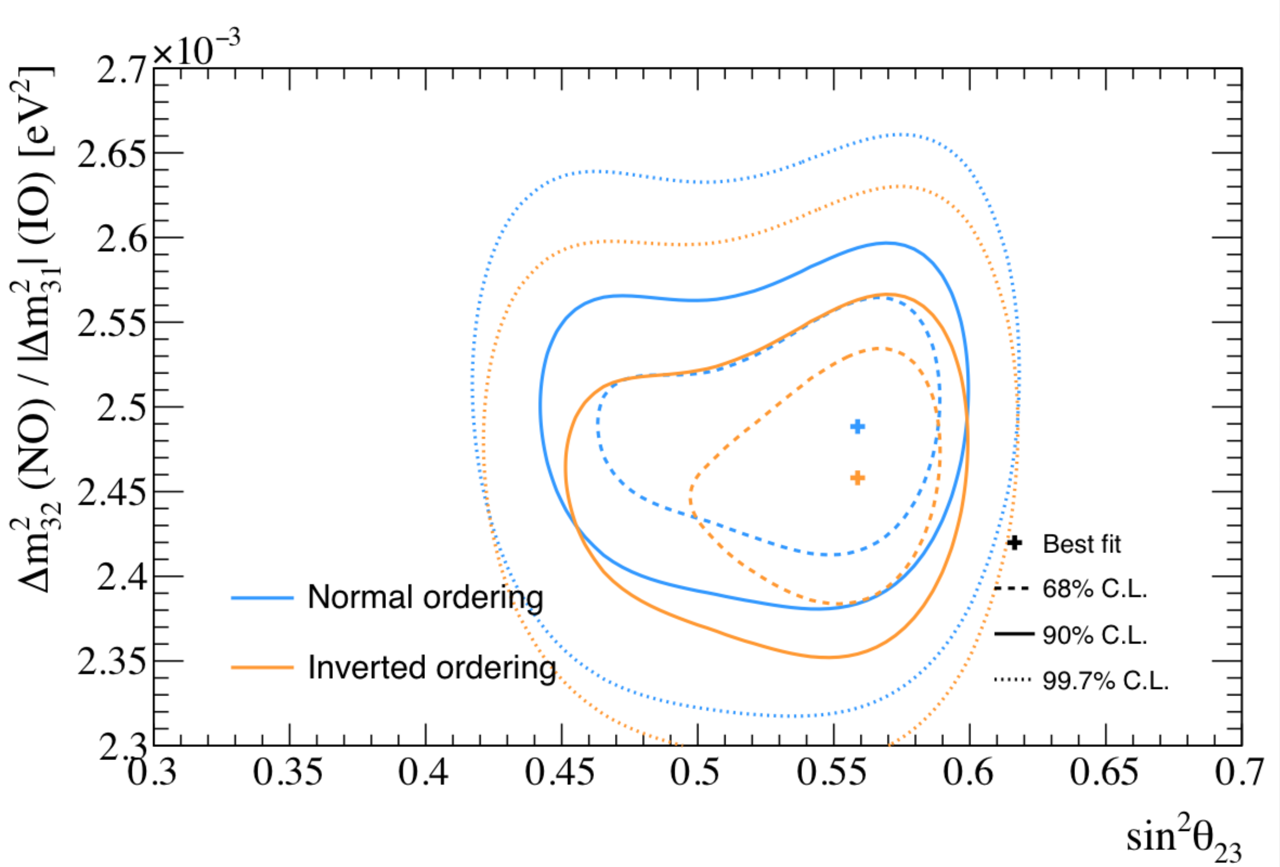






θ_{23} and Δm^2_{32} Results

- Still consistent with maximal mixing
- Slight preference for upper octant and normal ordering

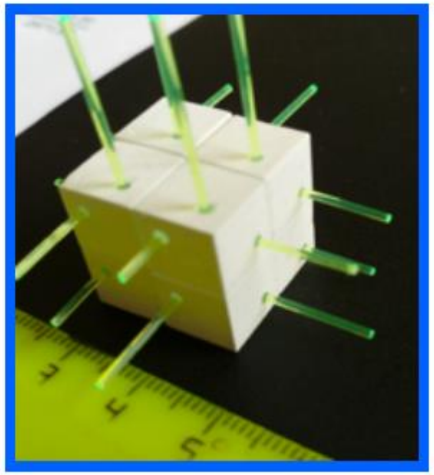


Bayesian Fit Results

Posterior Probability	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IO ($\Delta m^2_{32} < 0$)	0.035	0.157	0.192
Sum	0.230	0.770	1.000

ND280 Upgrade

- Upgrade near detector to improve granularity, high angle and backwards tracking
  - New technologies and enhanced sensitivity
- Installation by March 2023
- Beam power upgrade in progress



1x1x1 cm^3 cubes
Polystyrene scintillator
1.5% paraterphenyl
0.01% POPOP
Chemical etched reflector
WLS fiber Kuraray Y11 2-clad (∅=1mm)

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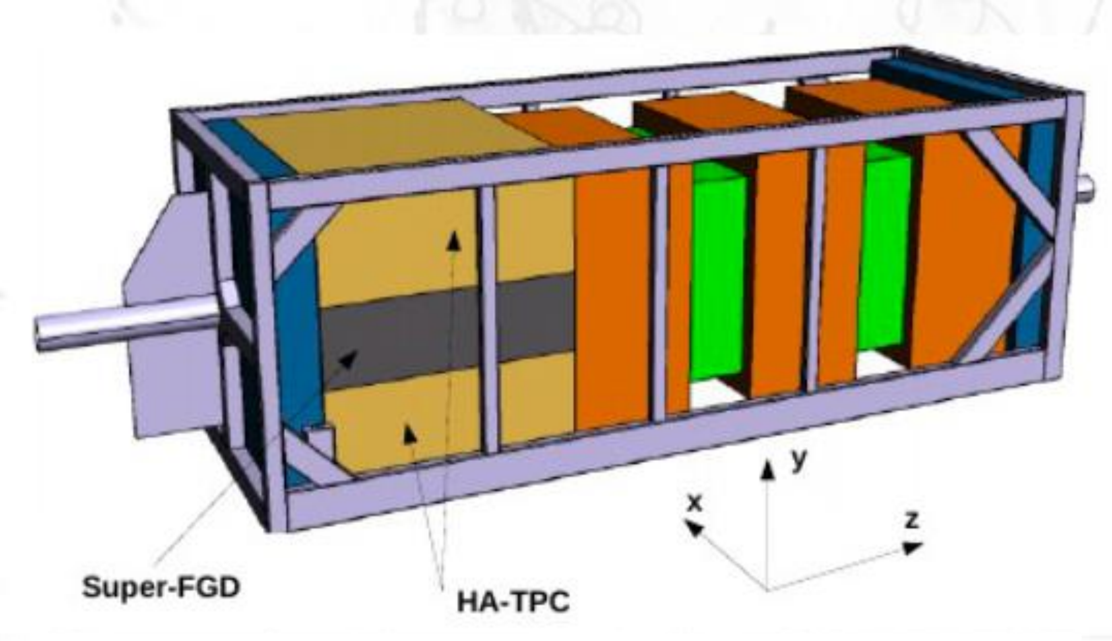
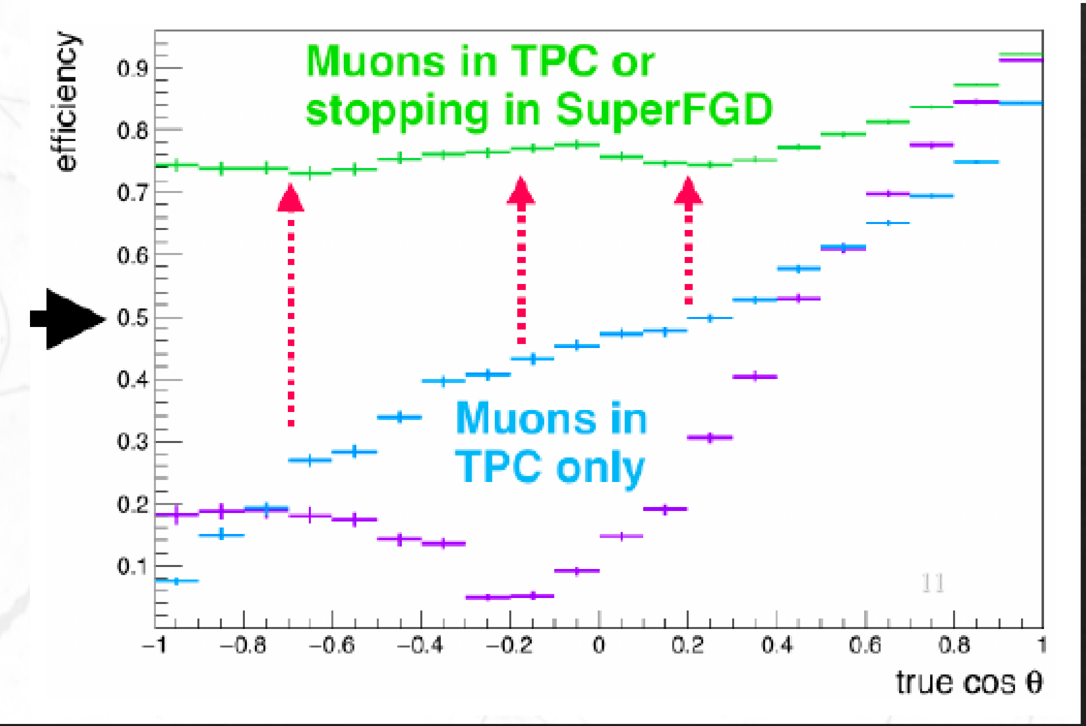
NIM A936 (2019) 136-138

Super FGD





Future Prospects

- We expect new exciting data between now and the start of Hyper-Kamiokande
- ND280 Upgrade
  - Contribute to reduced systematic uncertainties
  - Improvements to cross section model
- Beam power upgrade
  - More statistics
- SK-Gd
  - Neutron sensitivity in far detector from 2020
- All improvement expected online for next run from 2023

- T2K is developing joint fits with Nova and Super-Kamiokande
- Improved reach from combinations
- Correlated systematics and different analysis techniques requires joint working groups
  - Joint analyses are up and running
- First results expected for 2023

Summary

- T2K Oscillation Results
  - CP violation
  - θ_{23} and Δm^2_{32}
- T2K Upgrades
  - ND280 Upgrade
  - Beam Power Upgrade
  - SK-GD
- Joint fits
  - Nova
  - Super-Kamiokande

- All detector elements critical as we push for 3σ sensitivity

- New technologies and techniques
- Enhanced sensitivity and reach

- Reach for the ultimately sensitivity of the current generation