T2K Latest Results and Plans

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On behalf of the T2K collaboration

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Lake Louise Winter Institute
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T2K

Neutrino Oscillations

Oscillations described by the PMNS matrix:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

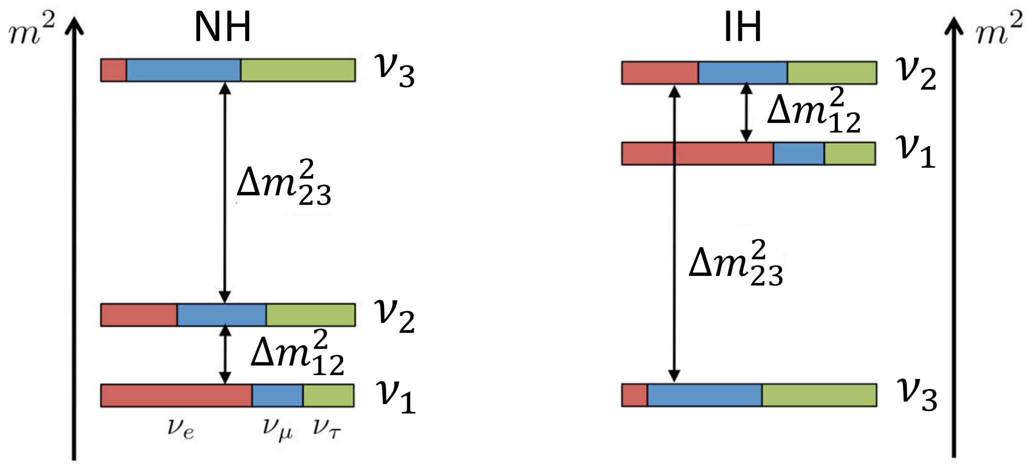
$$s_{ij} = \sin\theta_{ij}\,, c_{ij} = \cos\theta_{ij}$$

For a muon neutrino in T2K:

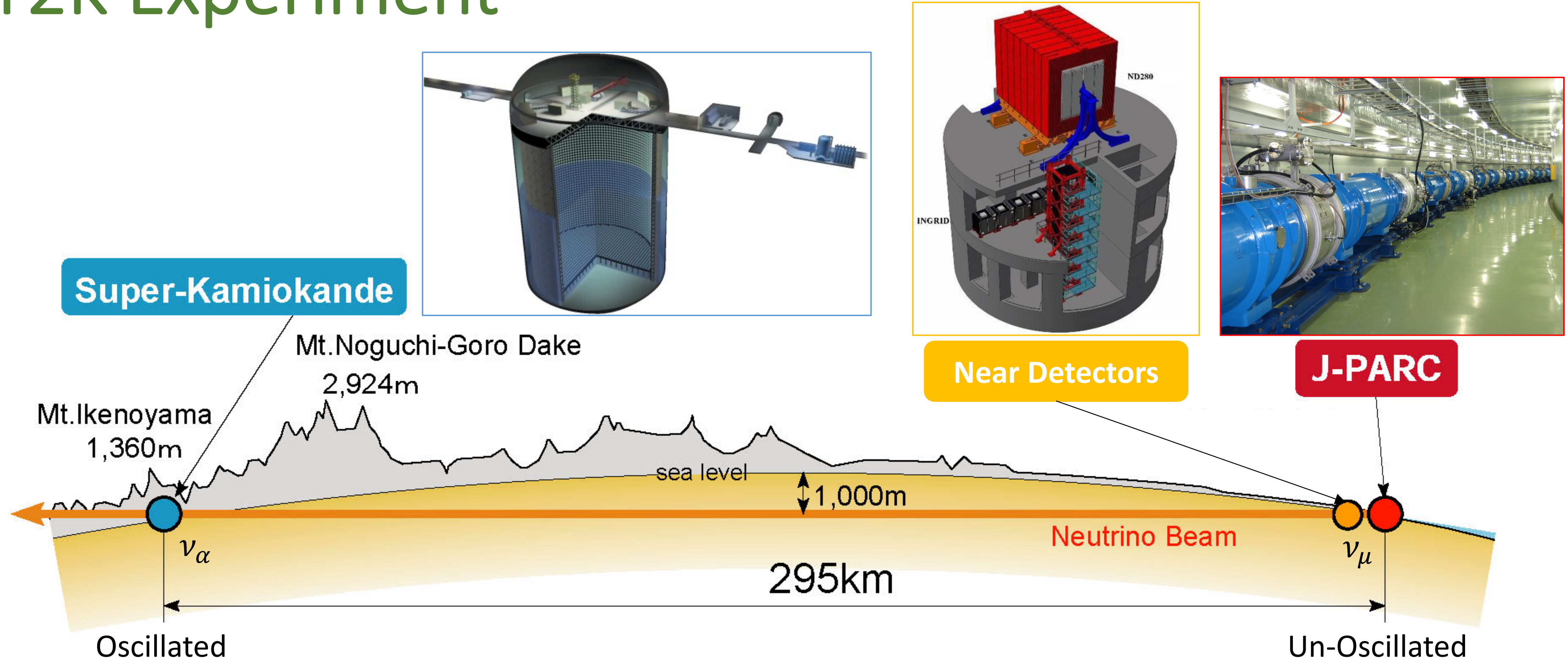
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{1.27\,\Delta m^2_{31}[eV^2]L[km]}{E_\nu[GeV]}\right) + O(\delta_{CP})$$

What questions is T2K answering?

1. What are the precise values of θ_{23}, θ_{13} and $|\Delta m^2_{32}|$?
2. Is there significant CP violation in the neutrino sector?
3. Do we have sensitivity to neutrino mass hierarchy?

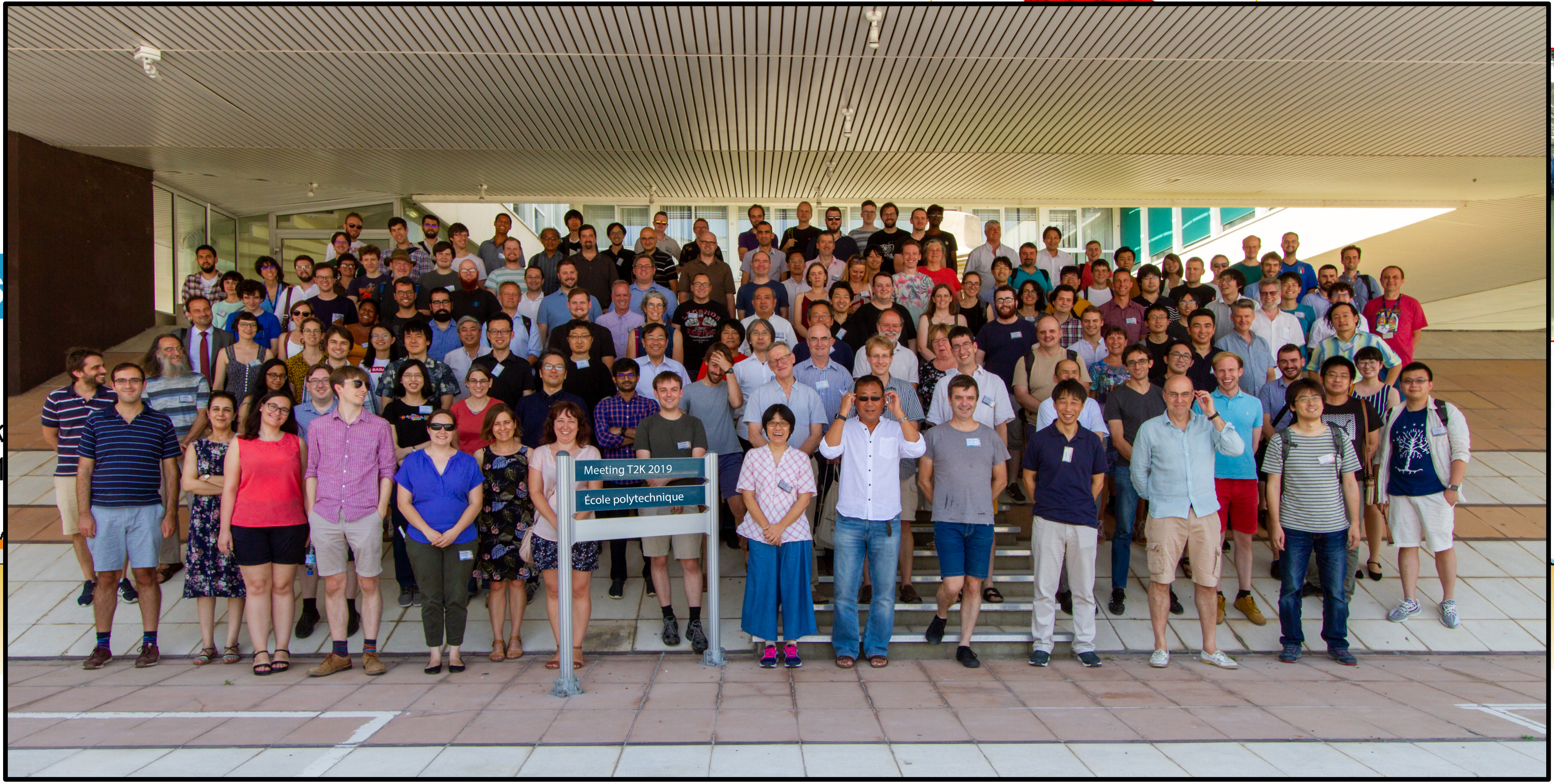


T2K Experiment



- ν and $\bar{\nu}$ beam modes
- Several cross section measurements, exotic searches, etc.

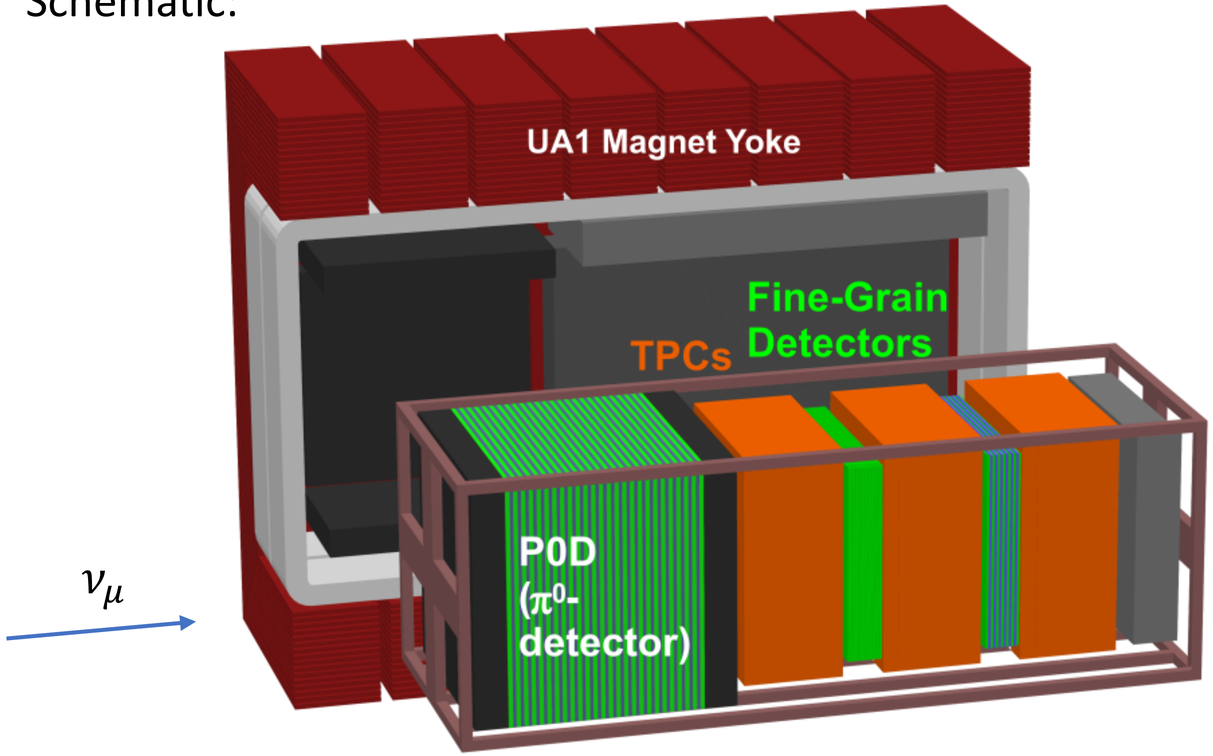
T2K Experiment



Over 500 collaborators from 76 institutions in 14 countries

The Near Detector

Schematic:

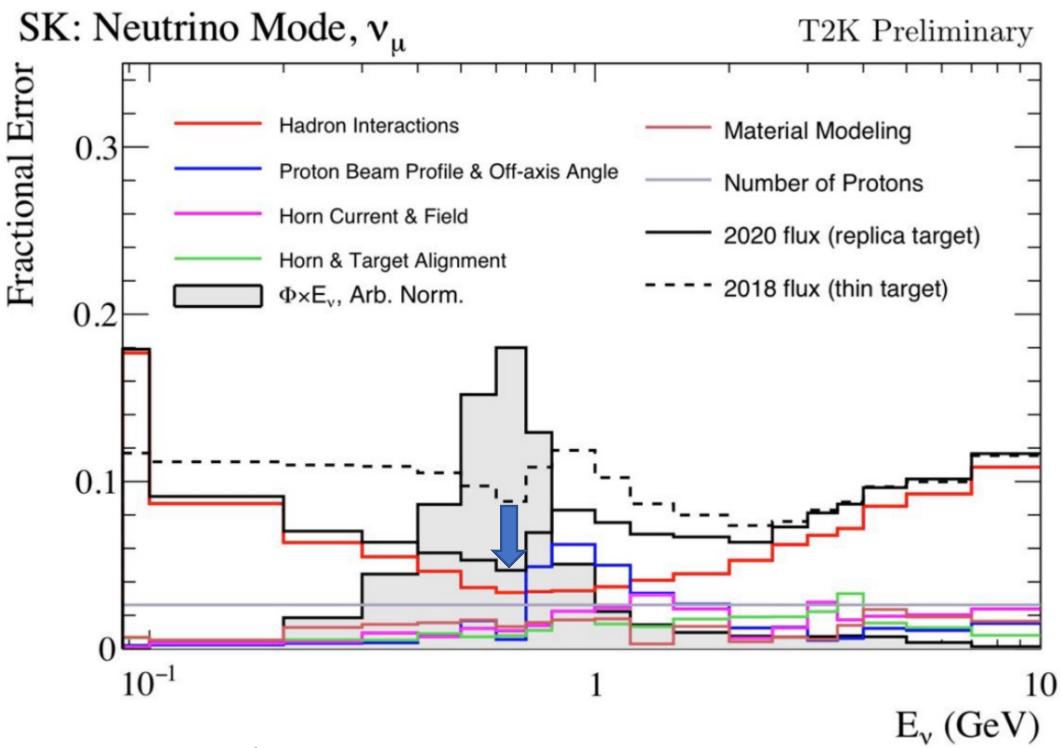


Purpose: Constrains flux and cross section systematics at FD

- Samples depend on target, ν or $\bar{\nu}$ and number of pions

Flux

Flux uncertainty ~5% at flux peak



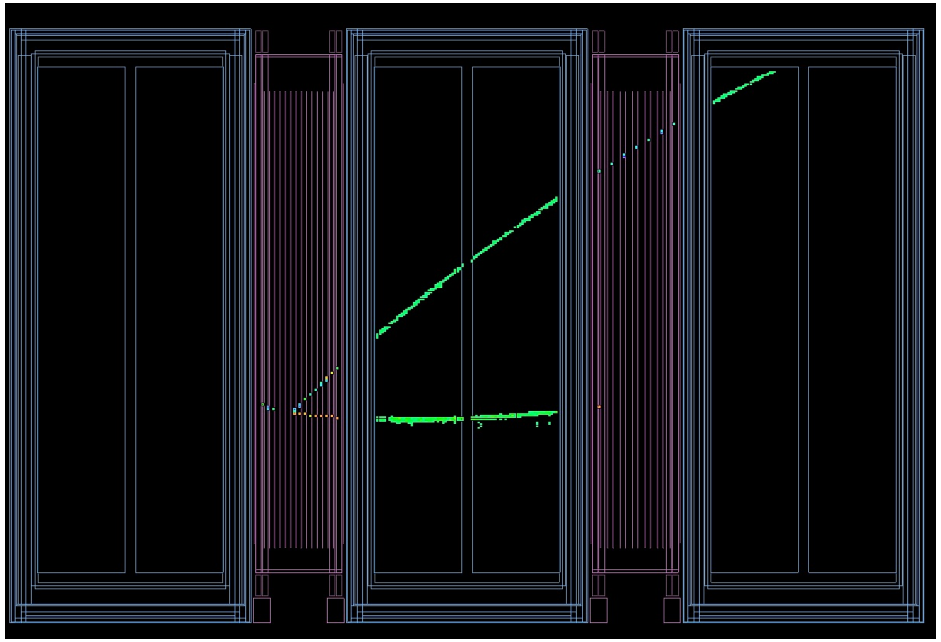
Cross Section

Dominated by CC Quasi-Elastic interactions

- '2p2h' and CC 1π resonant at higher energies

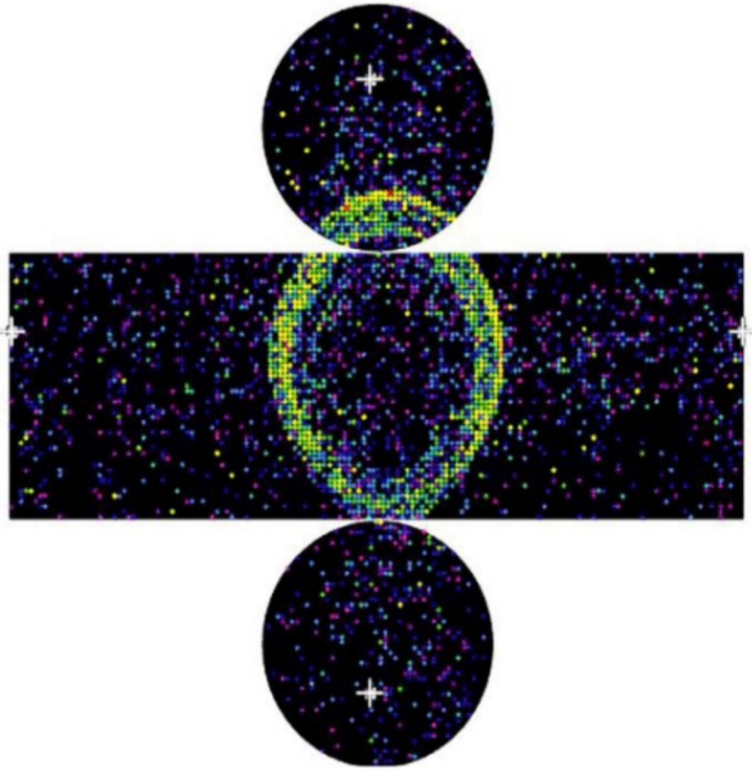
Observations in the Detectors

Near Detector:



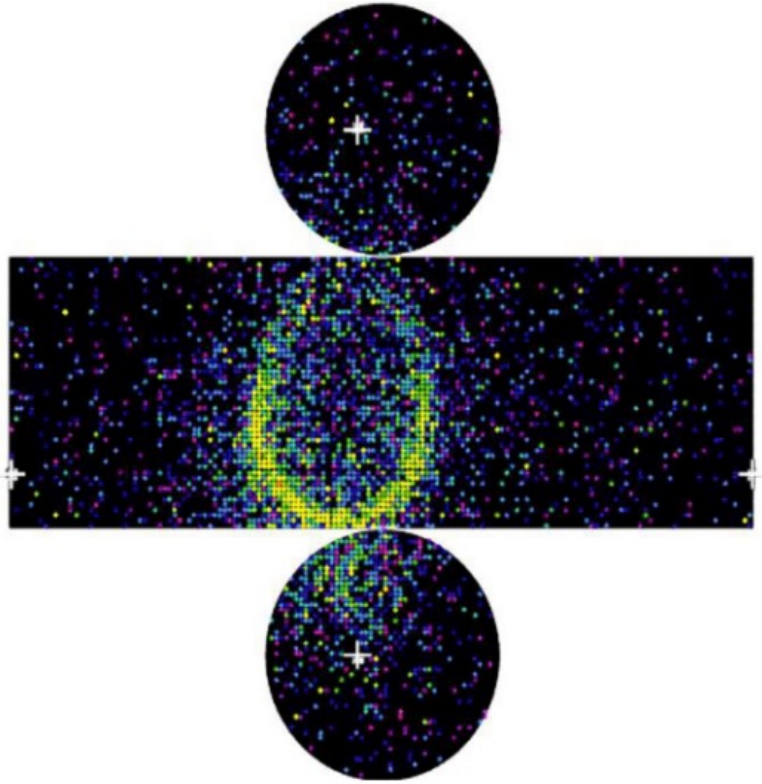
Far Detector:

Muon



'Sharp'

Electron

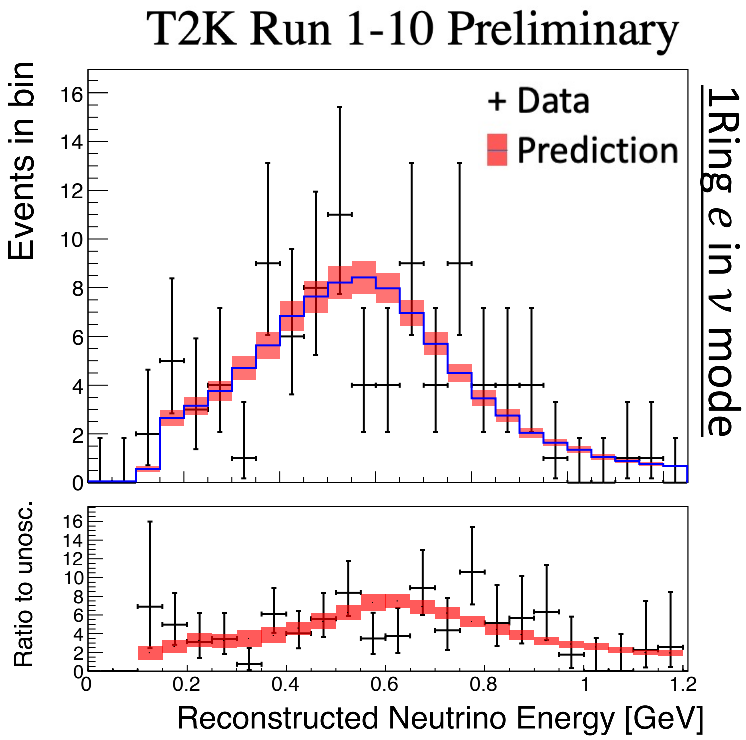


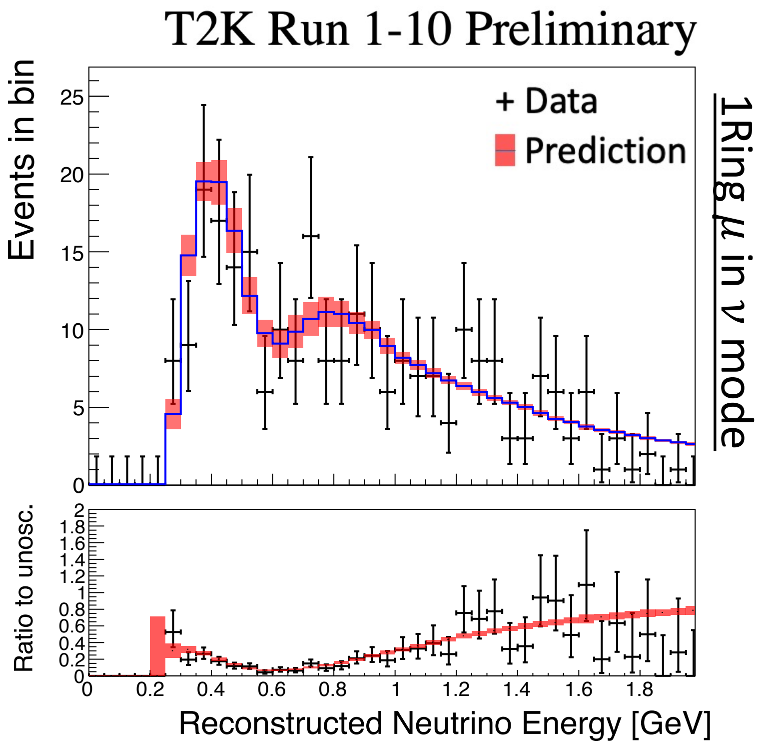
'Fuzzy'

The Far Detector

Five oscillation samples:

- 1 μ-like ring in ν and $\bar{\nu}$ modes
- 1 e-like ring in ν and $\bar{\nu}$ modes
- 1 e-like ring + Michel electron ring in ν mode





Near detector Constraint:

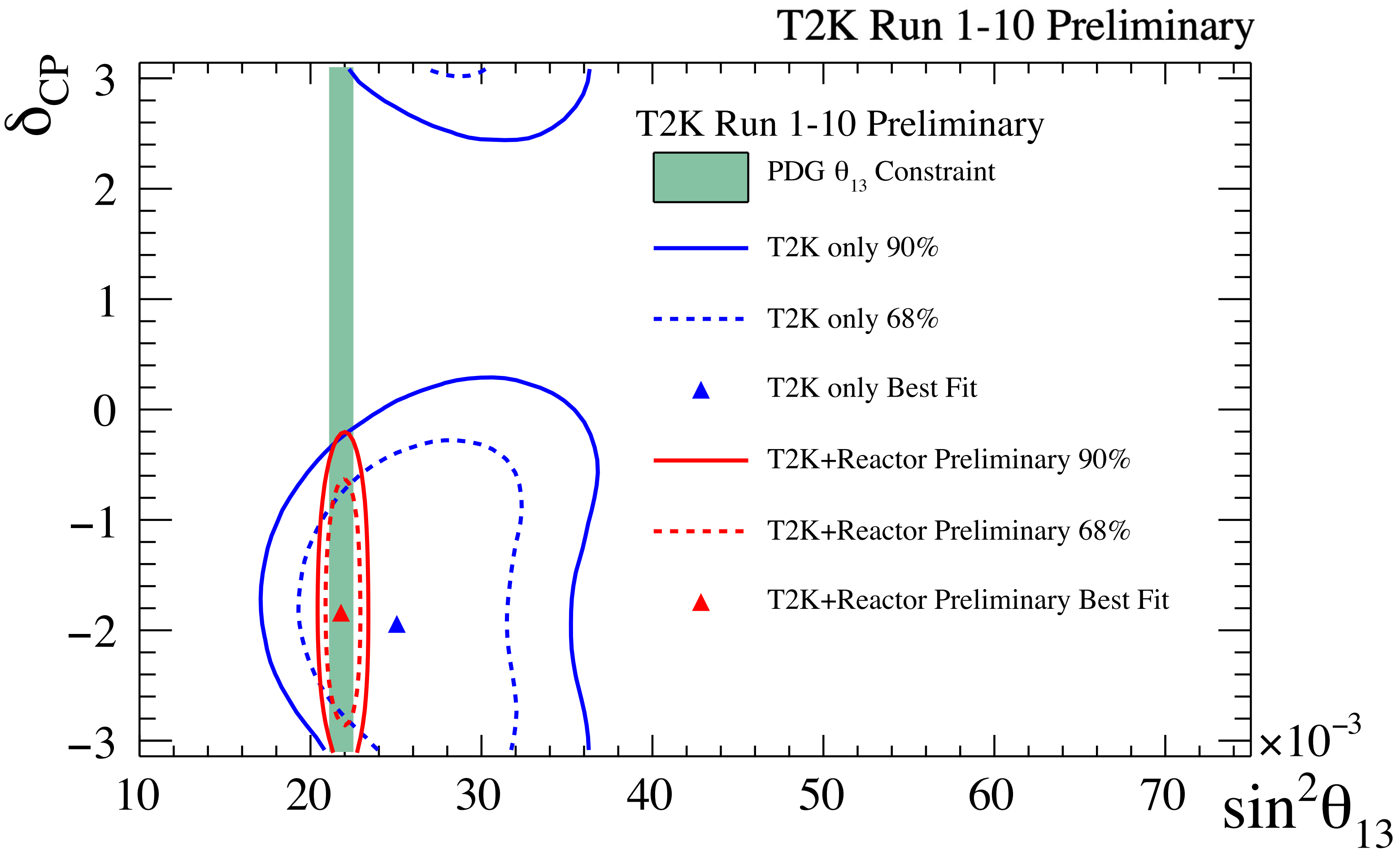
Uncertainty on Event Rate	1Rμ		1Re		
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π^+
Pre-ND	13.0%	12.0%	13.8%	12.7%	18.7%
Post-ND	3.0%	4.0%	4.7%	5.9%	14.3%

Measuring Oscillation Parameters

Measuring θ_{13}

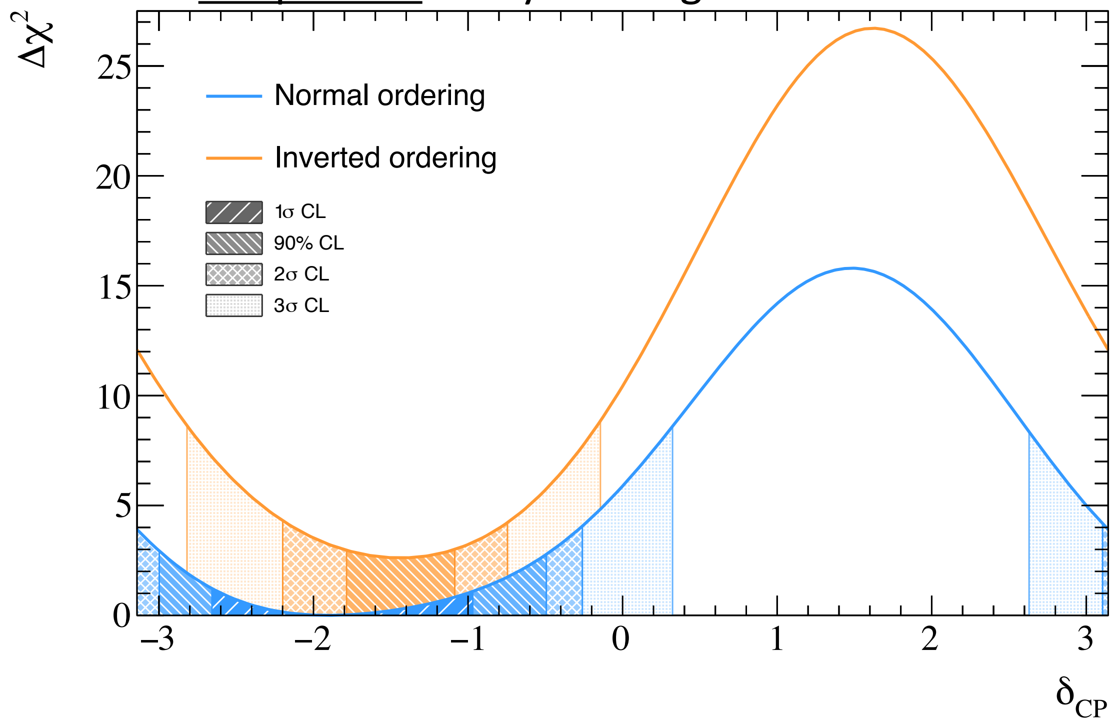
- Two measurements of θ_{13}:
  - → T2K-only
  - → T2K with the PDG constraint
- T2K-only intervals consistent with PDG
  - → Better than 1σ

Focus on results using PDG constraint

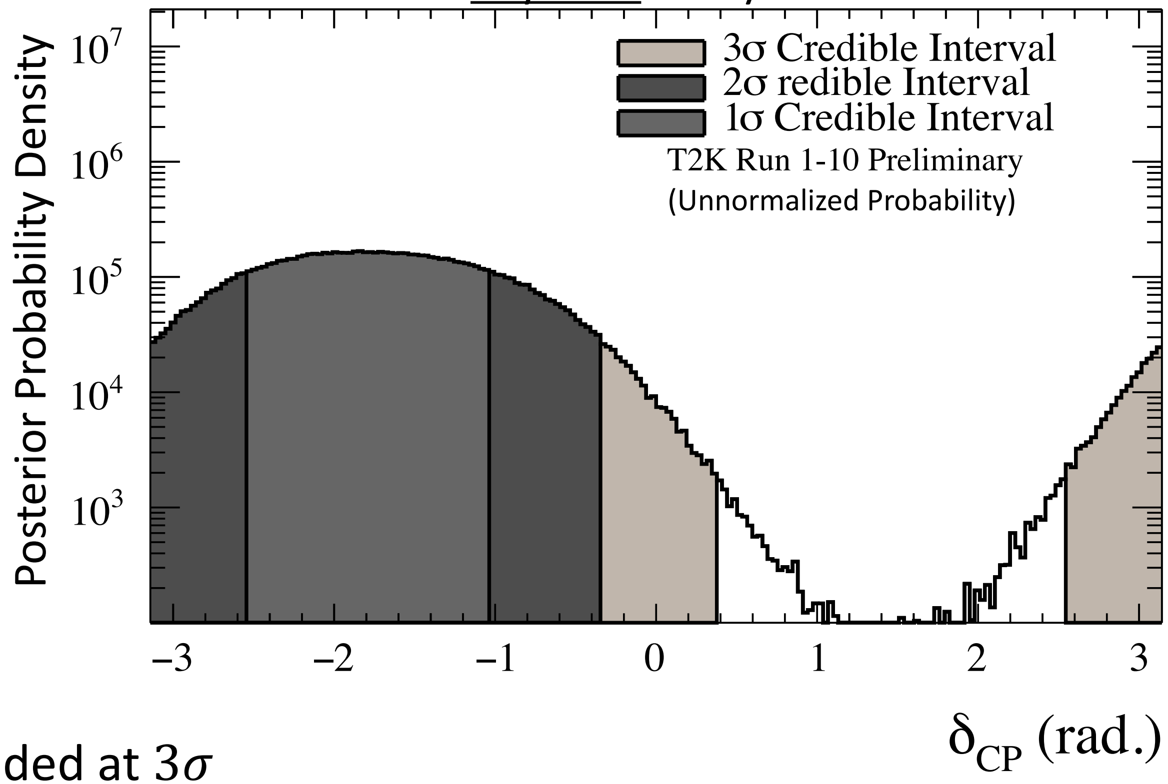


Measuring δ_{CP} (CP-Violation)

Frequentist Analysis using Feldman Cousins:

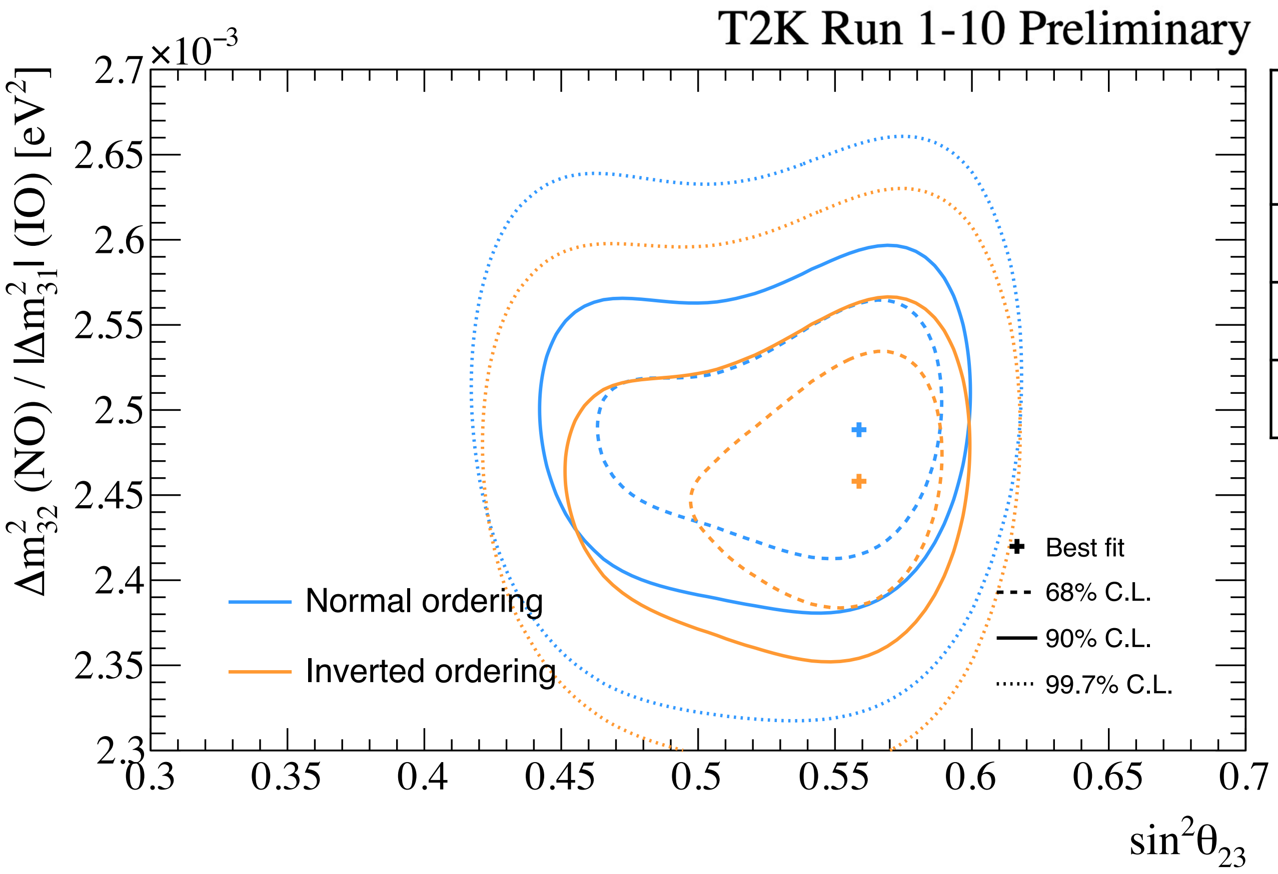


Bayesian Analysis:



- 35% of values excluded at 3σ
- CP conservation ($\delta_{CP} = 0, \pi$) disfavored at 90%
- Robustness studies performed with alternative models
  - → Minor shifts in 90% intervals
  - → Conclusions unchanged

Measuring θ_{23} and Δm^2_{32}



Bayes' Factors (Taken from Posterior Probability Density):

Posterior Probability	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	**0.808**
IH ($\Delta m^2_{32} < 0$)	0.035	0.157	0.192
Sum	0.230	**0.770**	1.000

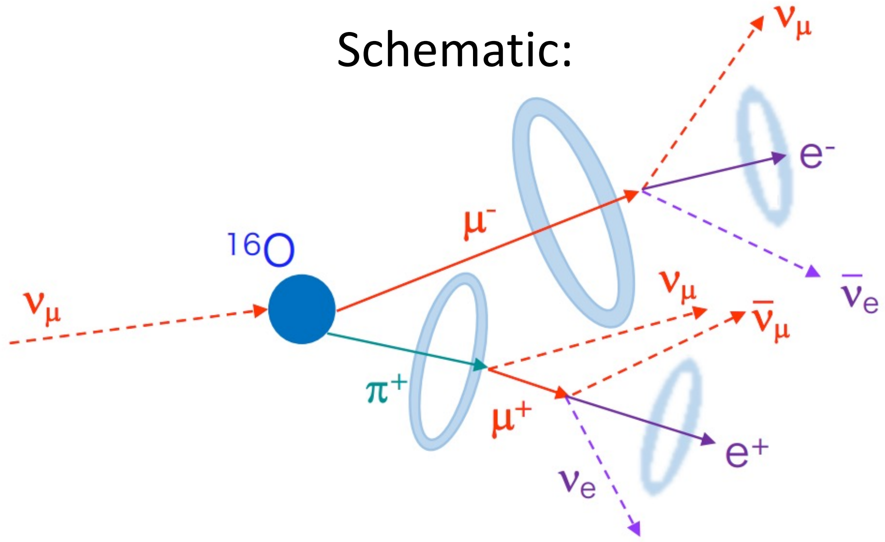
- Data has slight preference for upper octant and normal hierarchy

Future of T2K

Far Detector Updates

New Sample: ν_μ CC events with 2 μ-like rings and 1 or 2 decay electrons

Schematic:



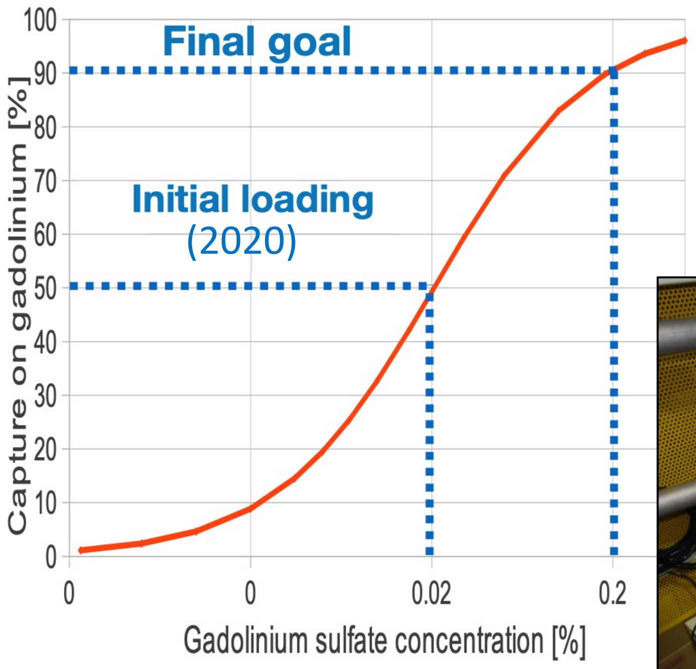
π ring similar to μ ring due to similar mass

Benefits:

- $\sim$20% more events selected at SK
- Expected to increase sensitivity to θ_{23} and $|\Delta m^2_{32}|$

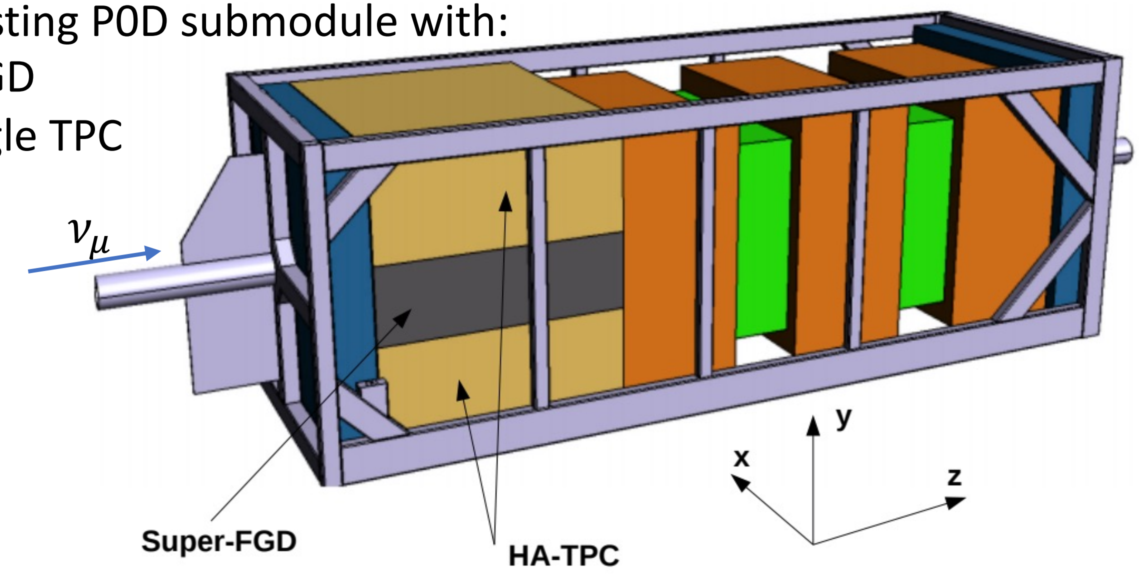
SK-Gd: Doping Super-K with Gadolinium

- Enhances detection of neutrons from ν interactions
- Larger signal from Gadolinium capture

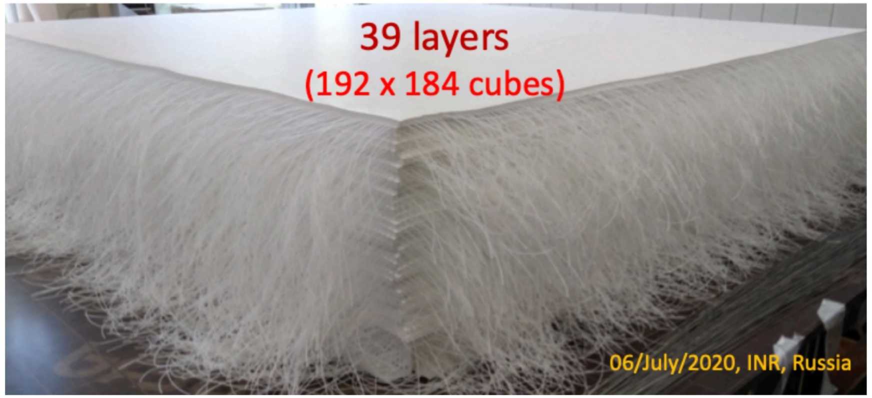


Near Detector Upgrade

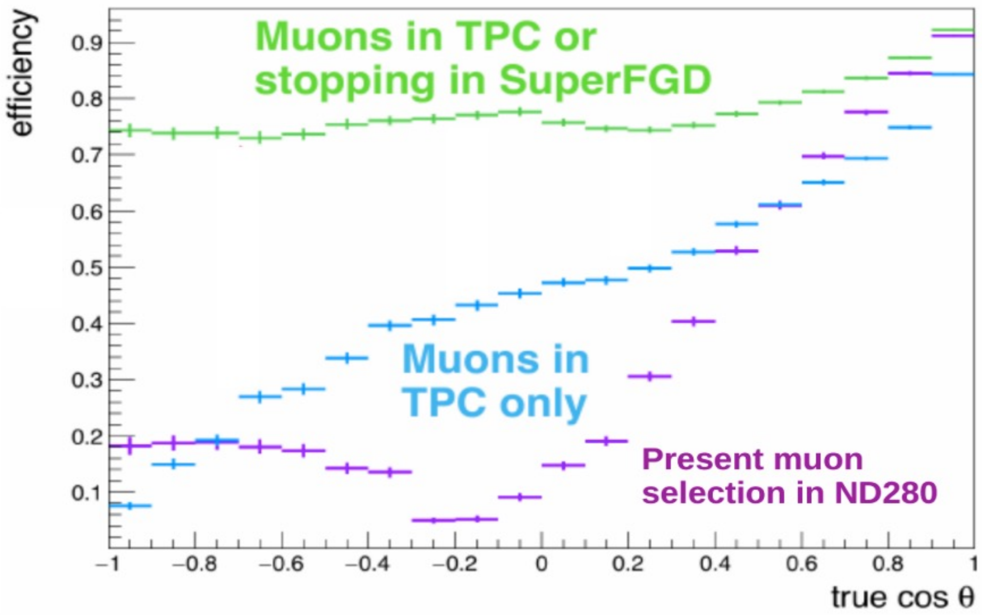
Replace existing P0D submodule with:
- Super-FGD
- High Angle TPC



Super-FGD being assembled:
- Finished end of 2022
- Data taking soon after



Benefits:
- Improved efficiency for Muon reconstruction

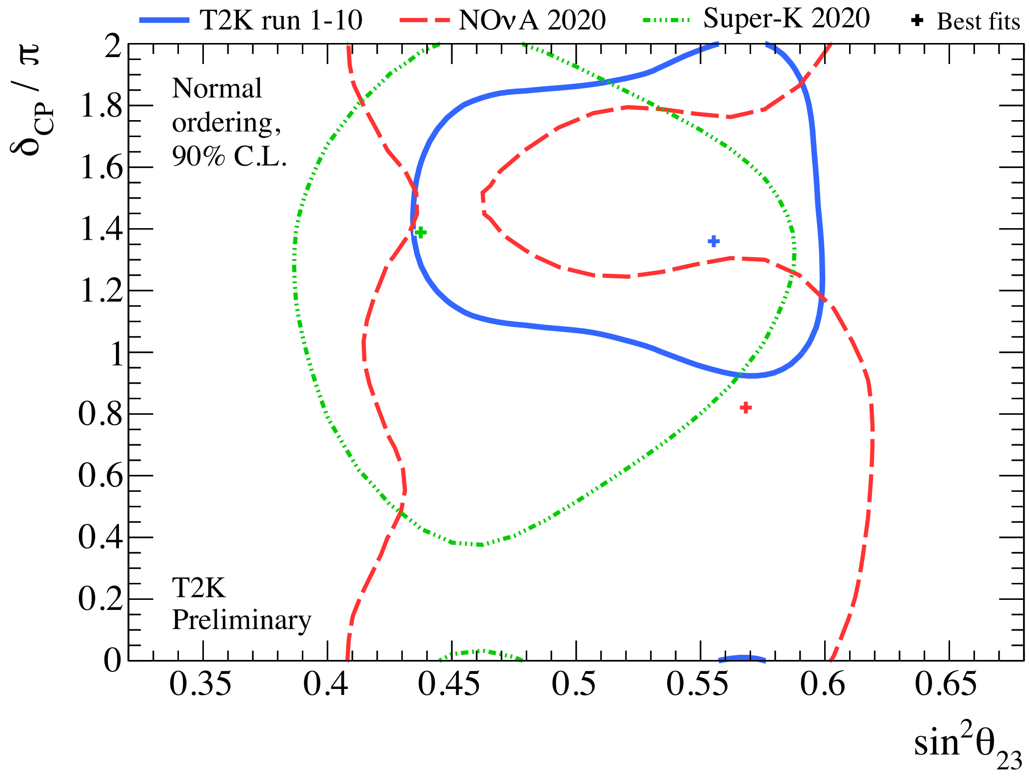


- Lower proton threshold
- Improved event vertexing
- Increased target mass

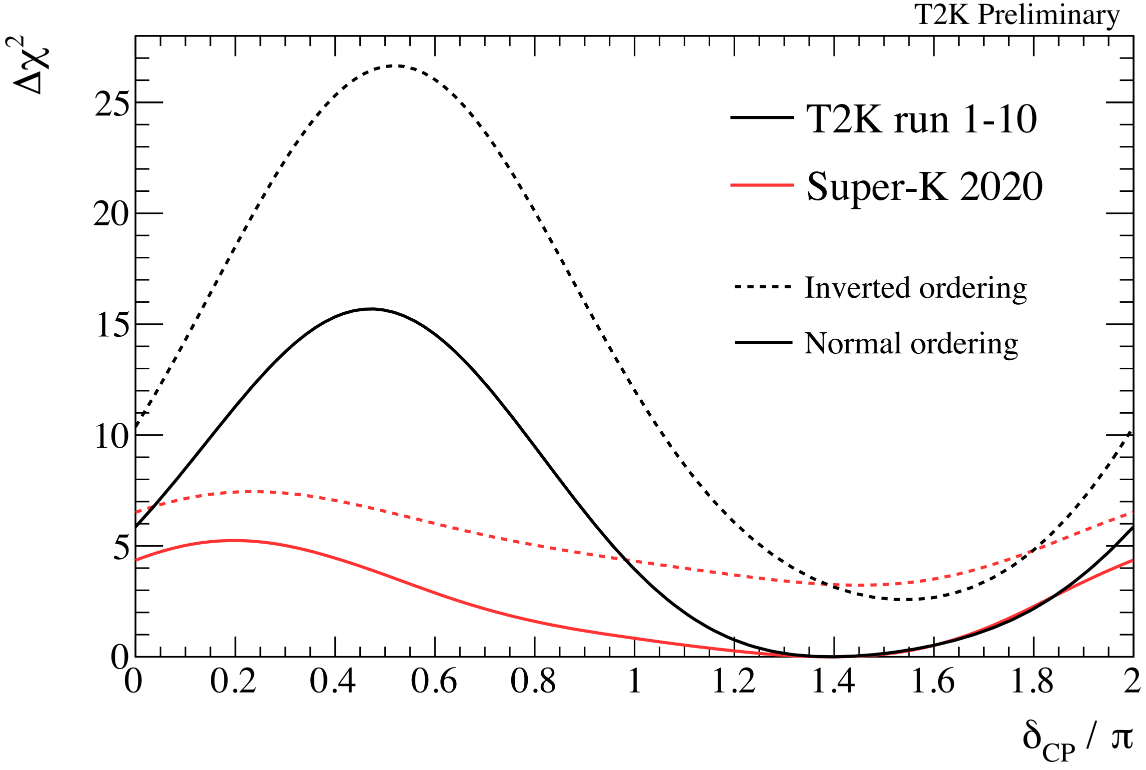
Reduction of crucial systematic uncertainties

Joint Oscillation Parameter Fits Underway

T2K-NOνA



T2K-SK



- Joint fits with NOνA and Super-Kamiokande experiments
- Different energies and baselines
- Consistent statistical treatment using full experiment likelihood

Summary

- T2K experiment is a long baseline neutrino oscillation experiment:
  - → Producing world-leading measurements of oscillation parameters
- Latest oscillation results indicate:
  - → Charge Parity conservation is excluded at 90% confidence level
  - → Slight preference for normal hierarchy and upper octant
- Exciting program of upgrades planned:
  - → Inclusion of new oscillation samples
  - → Gadolinium doping in far detector
  - → Upgrade of near detector hardware
- Joint oscillation fits are being conducted with SK and NOνA to maximize impact data taken

Backup Slides

T2K Beam

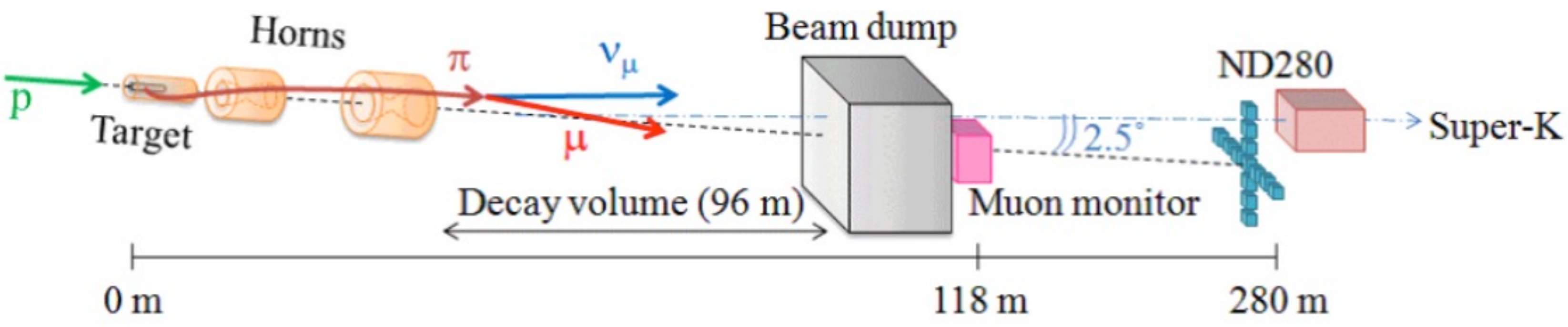
30 GeV proton beam incident on graphite target:

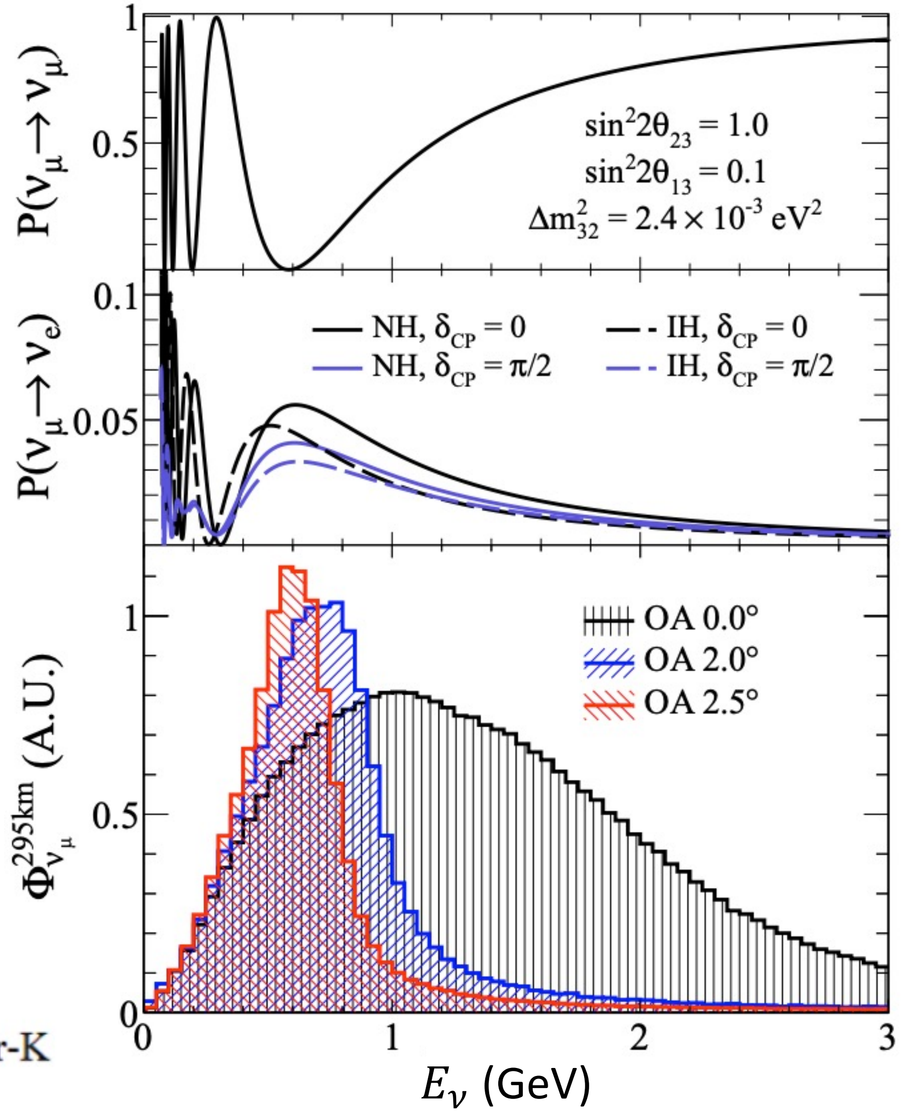
- Generates hadrons; mostly pions and kaons

Magnetic horns select charge of hadron beam:

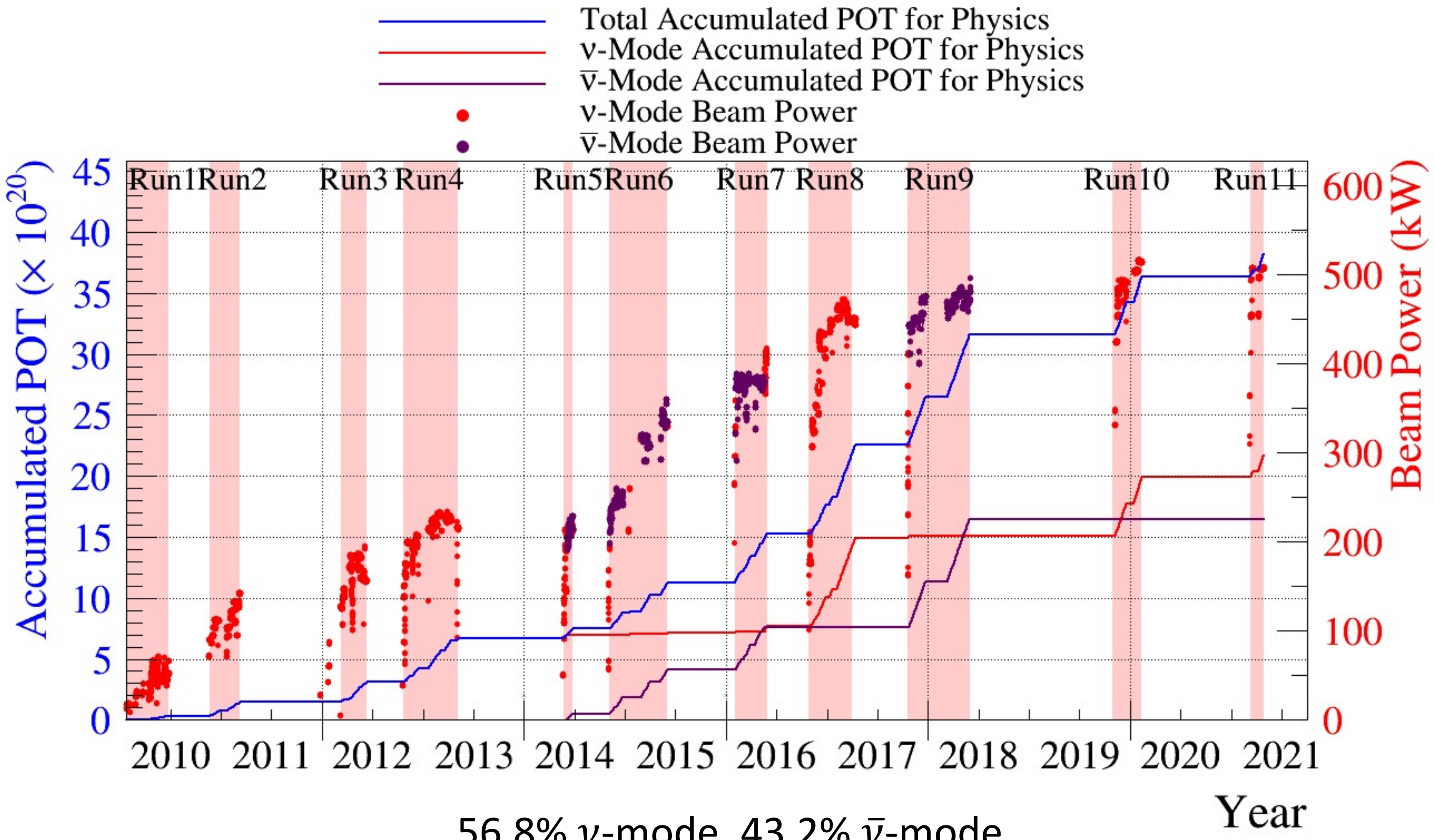
- ν_μ beam generated by selection positive hadrons
- $\bar{\nu}_\mu$ beam generated by selection negative hadrons

Beam axis is 2.5° degrees from SK





Data Collected



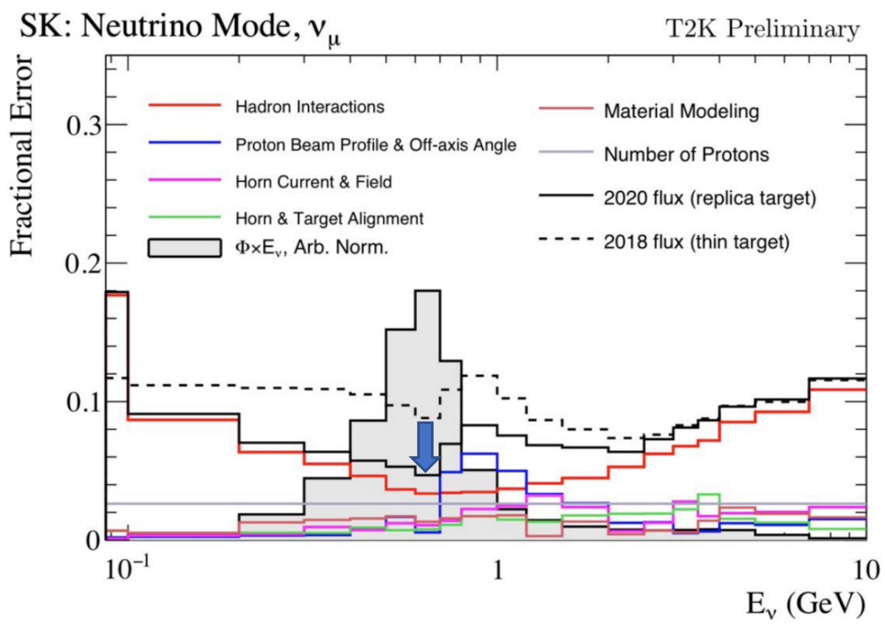
56.8% ν-mode, 43.2% $\bar{\nu}$-mode

Flux and Cross Section Systematic Updates

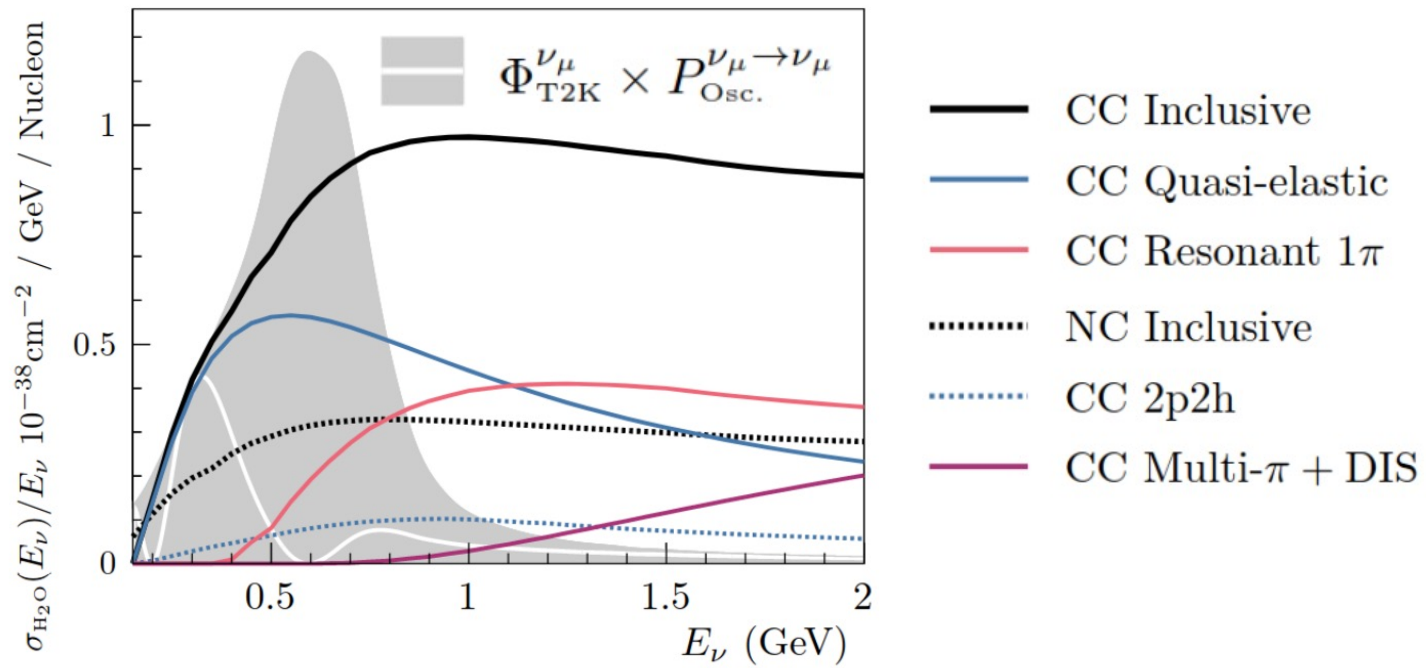
Flux

NA61/SHINE hadron production data

Reduces flux uncertainty from ~10% to ~5% at flux peak



Cross Section



Updates:

- CCQE nuclear initial state model updated to spectral function (SF)
- Removal energy treated as shift in lepton momentum with smaller uncertainty from SF model
- Energy dependent ‘2p2h’, correlated FSI between ND and FD,

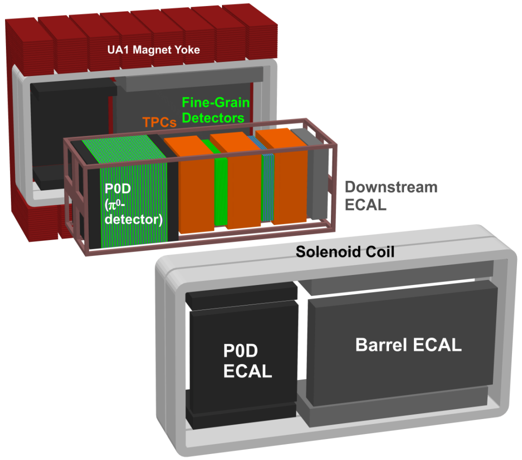
  + other improvements

T2K Detectors

Near Detectors:

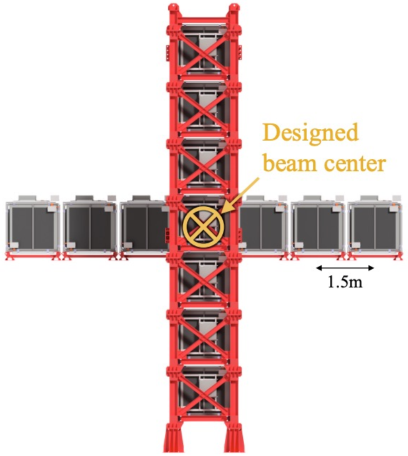
Situated 280m downstream of beam target

ND280



- 2.5° off beam axis
- Several sub detectors in 0.2T field
- Neutrino interactions, intrinsic ν_e and wrong-sign background
- Constrains flux and cross section systematics

INGRID

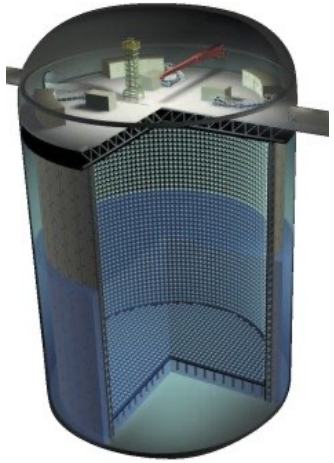


- On beam axis
- Iron-target with scintillator tracker
- Monitors beam intensity, direction and stability
- Constrains flux systematics

Far Detector:

Situated 295km downstream of beam target

Super Kamiokande

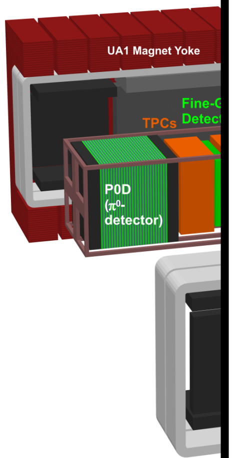


- 2.5° off beam axis
- 50 kton water Cherenkov detector
- No charge identification
- Particle ID via ring pattern;

Electrons more likely to scatter → ‘fuzzier’

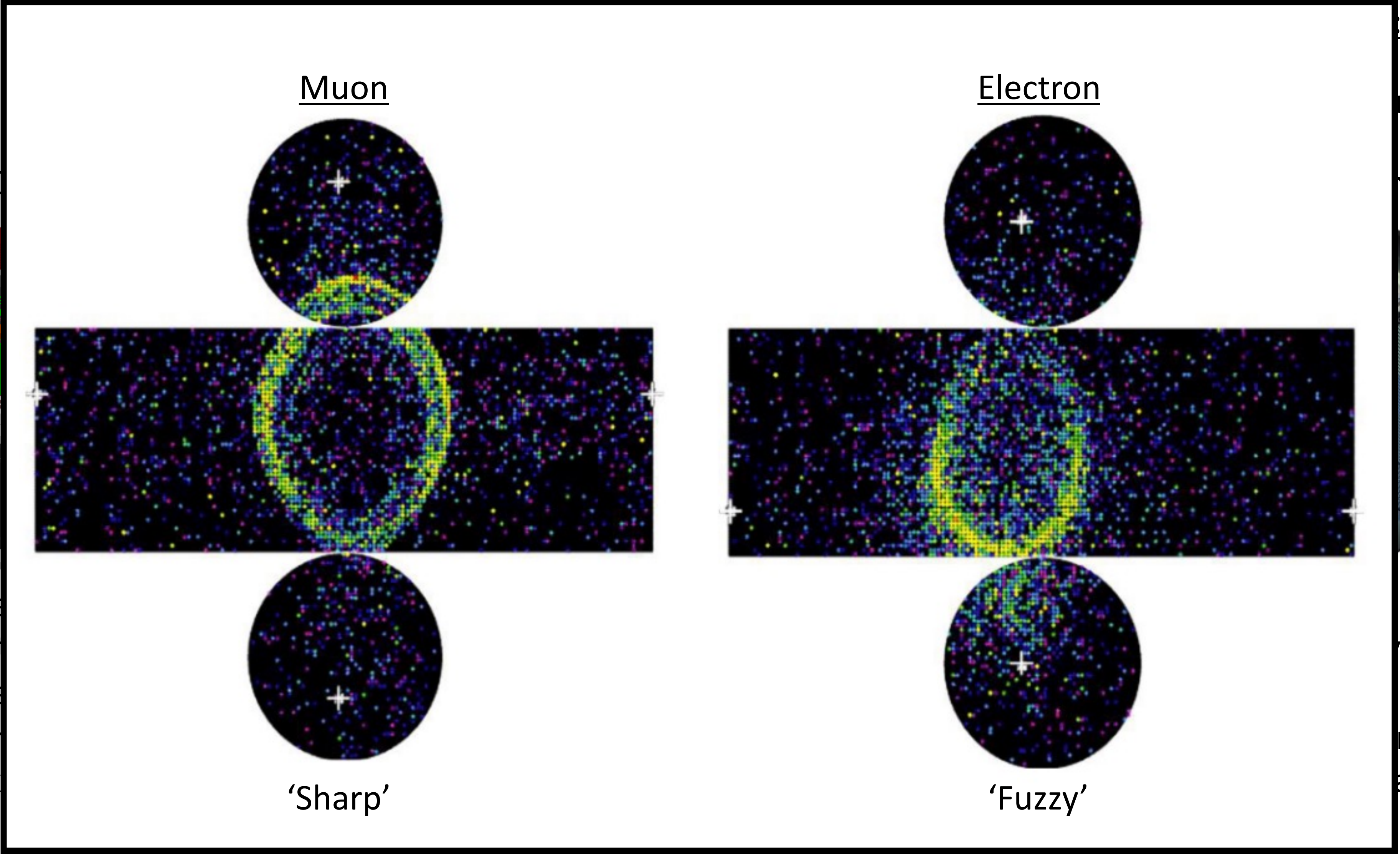
T2K Detectors

ND



m of beam target

nde



- 2.5° off beam a
- Several sub de
- Neutrino intera
  and wrong-sign
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detector

n;

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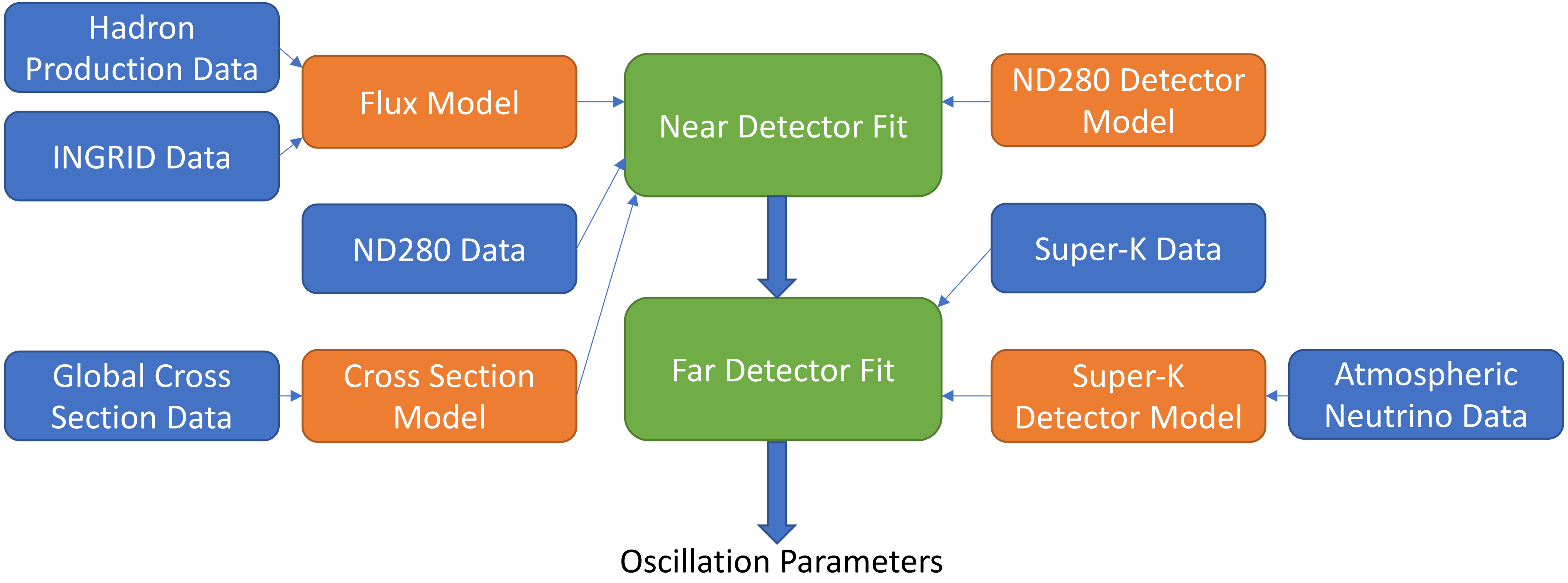
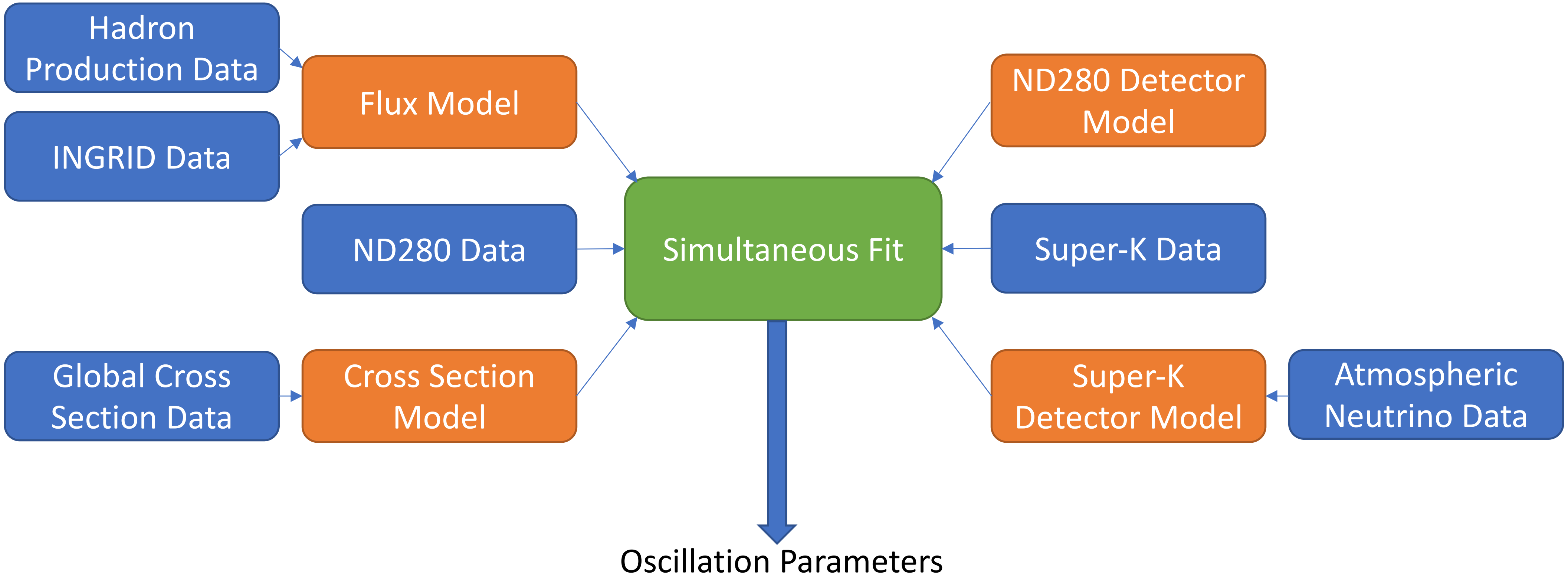
Analysis Strategy



Analysis strategy: Define a model and constrain it with data

Several fitter groups with analysis differences; bayesian vs. frequentist, sequential ND-FD fit vs. simultaneous fit

Analysis Strategy



Analysis strategy: Define a model and constrain it with data

Several fitter groups with analysis differences; bayesian vs. frequentist, sequential ND-FD fit vs. simultaneous fit

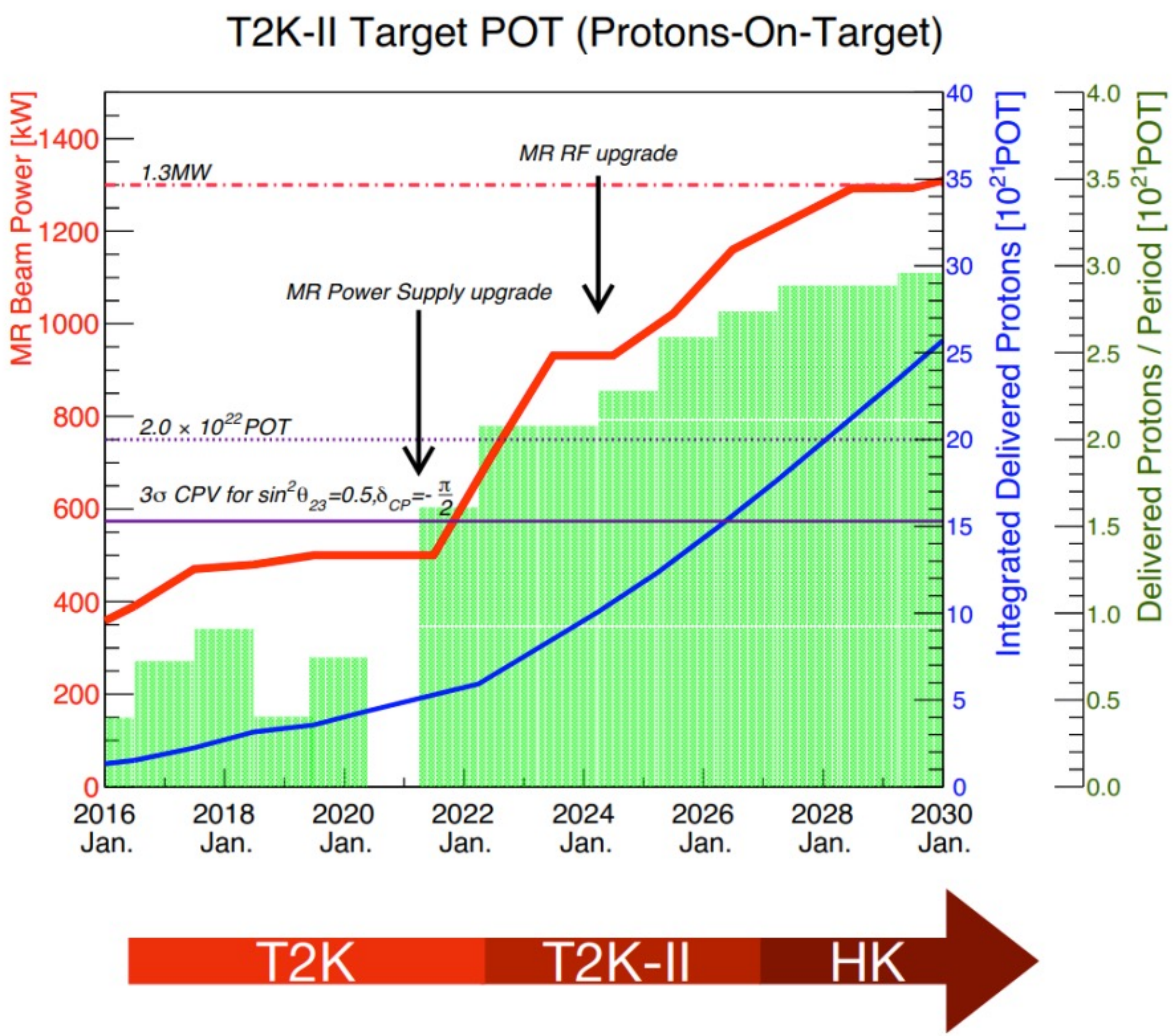
Beam Upgrade

Stable beam operation at 515kW

<u>Upgrades:</u>

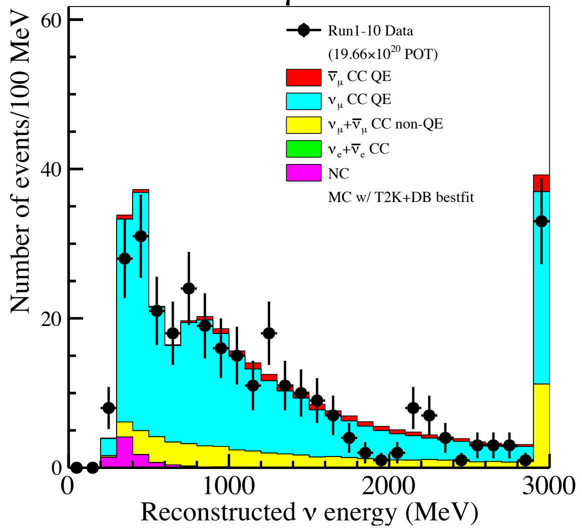
- Main ring power supply
- RF upgrade

Expect beam power > 1MW by 2027

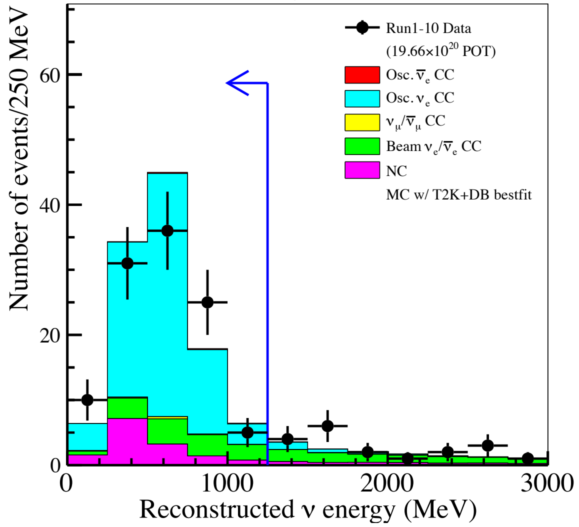


Far Detector Oscillation Samples

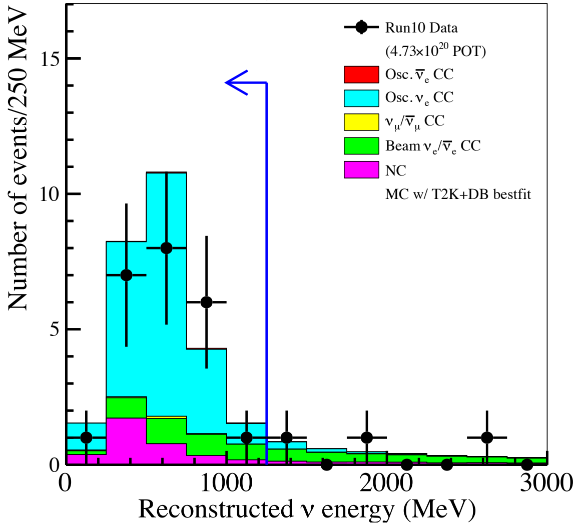
ν_μ 1Rμ



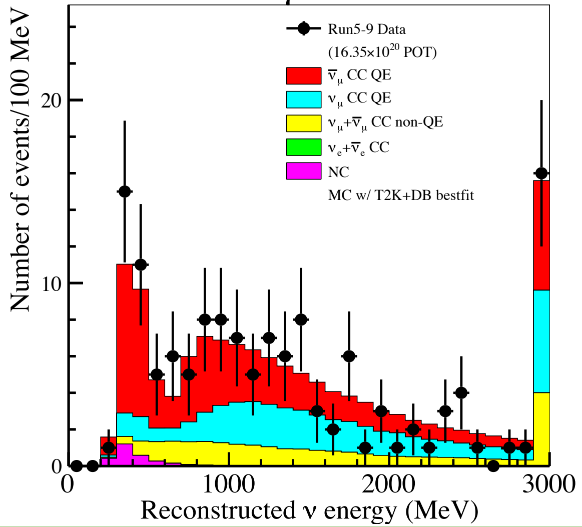
ν_e 1Re



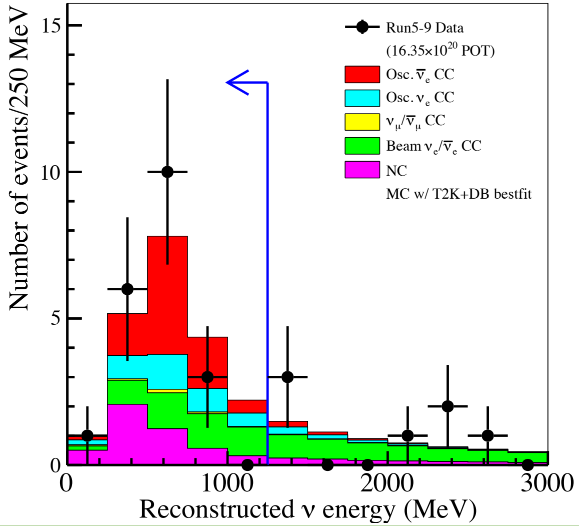
ν_e 1Re1de



$\bar{\nu}_\mu$ 1Rμ



$\bar{\nu}_e$ 1Re



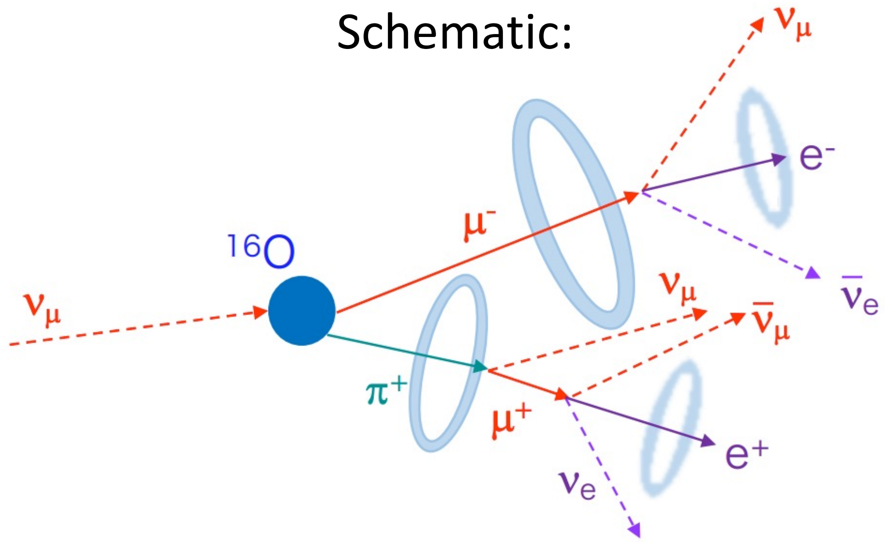
Five samples:

- 1 μ-like ring, 1Rμ, in ν and $\bar{\nu}$ modes
- 1 e-like ring, 1Re, in ν and $\bar{\nu}$ modes
- 1 e-like ring + Michel electron ring, 1Re1de, in ν mode

New Oscillation Samples

<u>Far Detector Sample</u>: ν_μ Charged Current events with 2 μ-like rings and 1 or 2 decay electrons

Schematic:



<u>Benefits:</u>

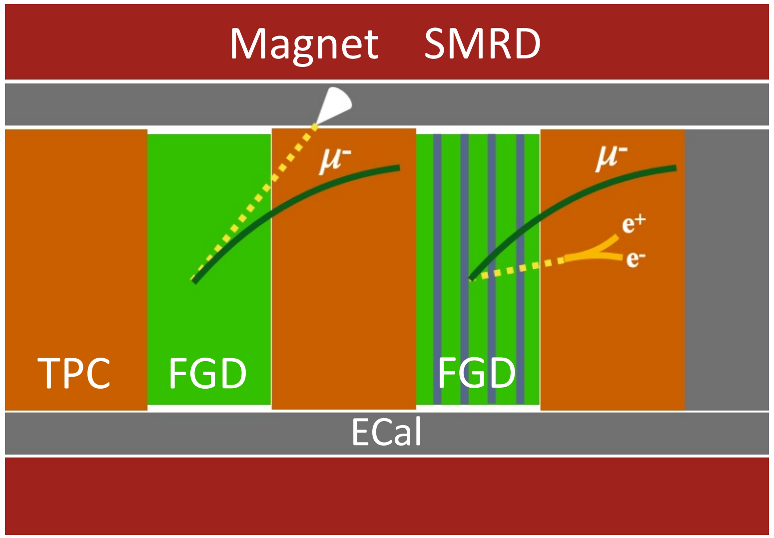
- $\sim$20% more events selected at SK
- Expected to increase sensitivity to θ_{23} and $|\Delta m^2_{32}|$

<u>Near Detector</u>:

Split CC0π sample depending on presence of protons:

- Different sensitivity to nuclear effects (cross section modelling will be updated)

Isolate CCπ^0 interactions by looking at photons in ECal and any e^+e^- pairs in the TPC:

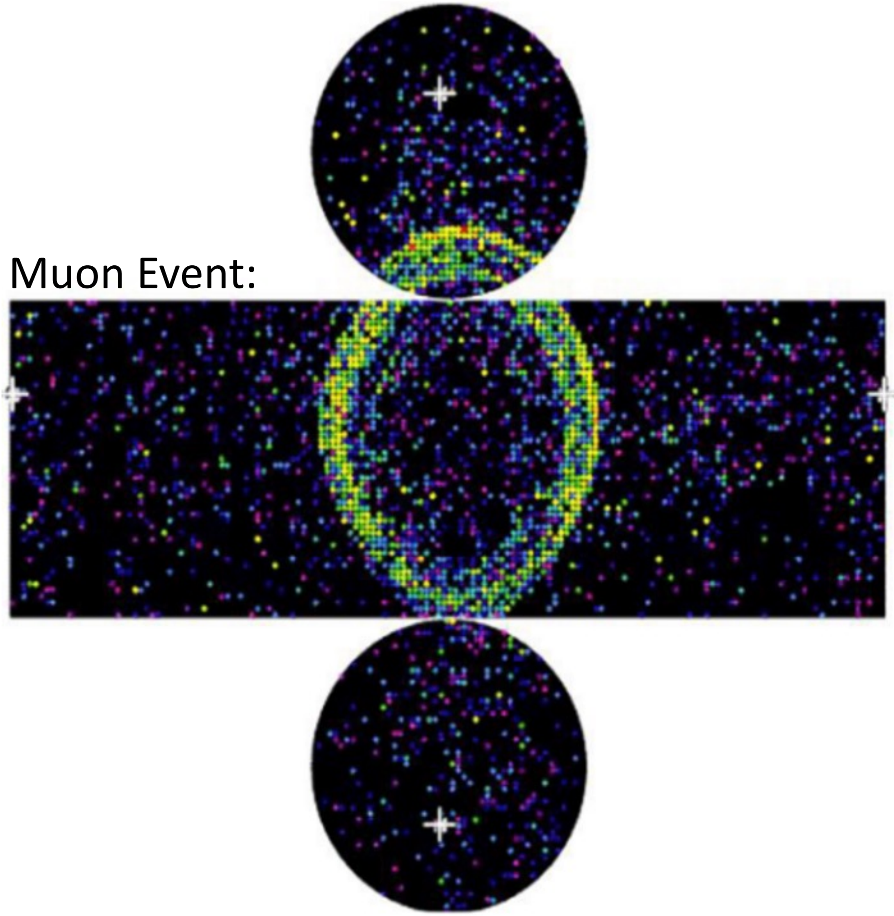


Improves sample purities (CC0π and CC1π^+) and constrains new sample at the far detector

Observations at the Far Detector

Observe Cherenkov rings in SK:

Muon Event:



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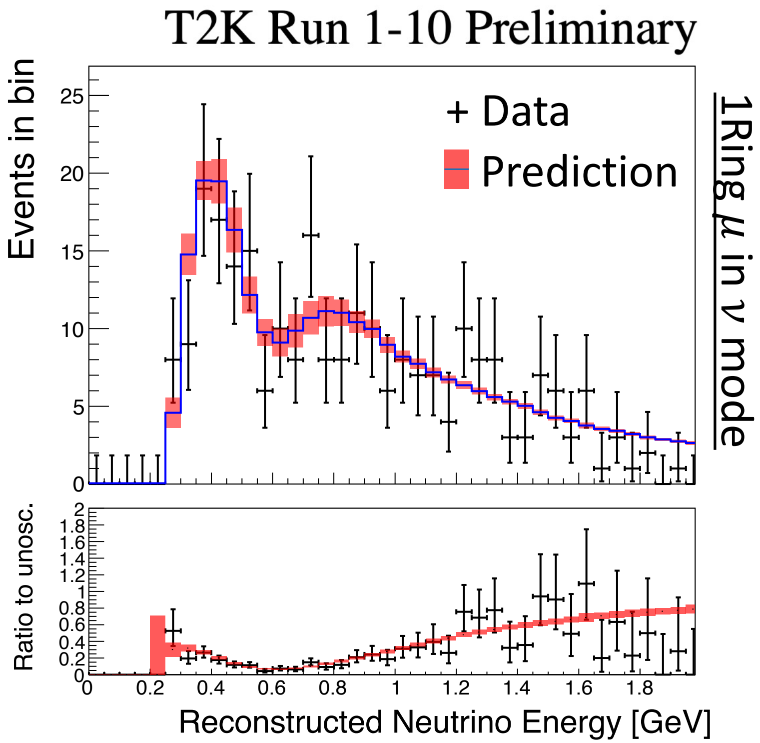

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