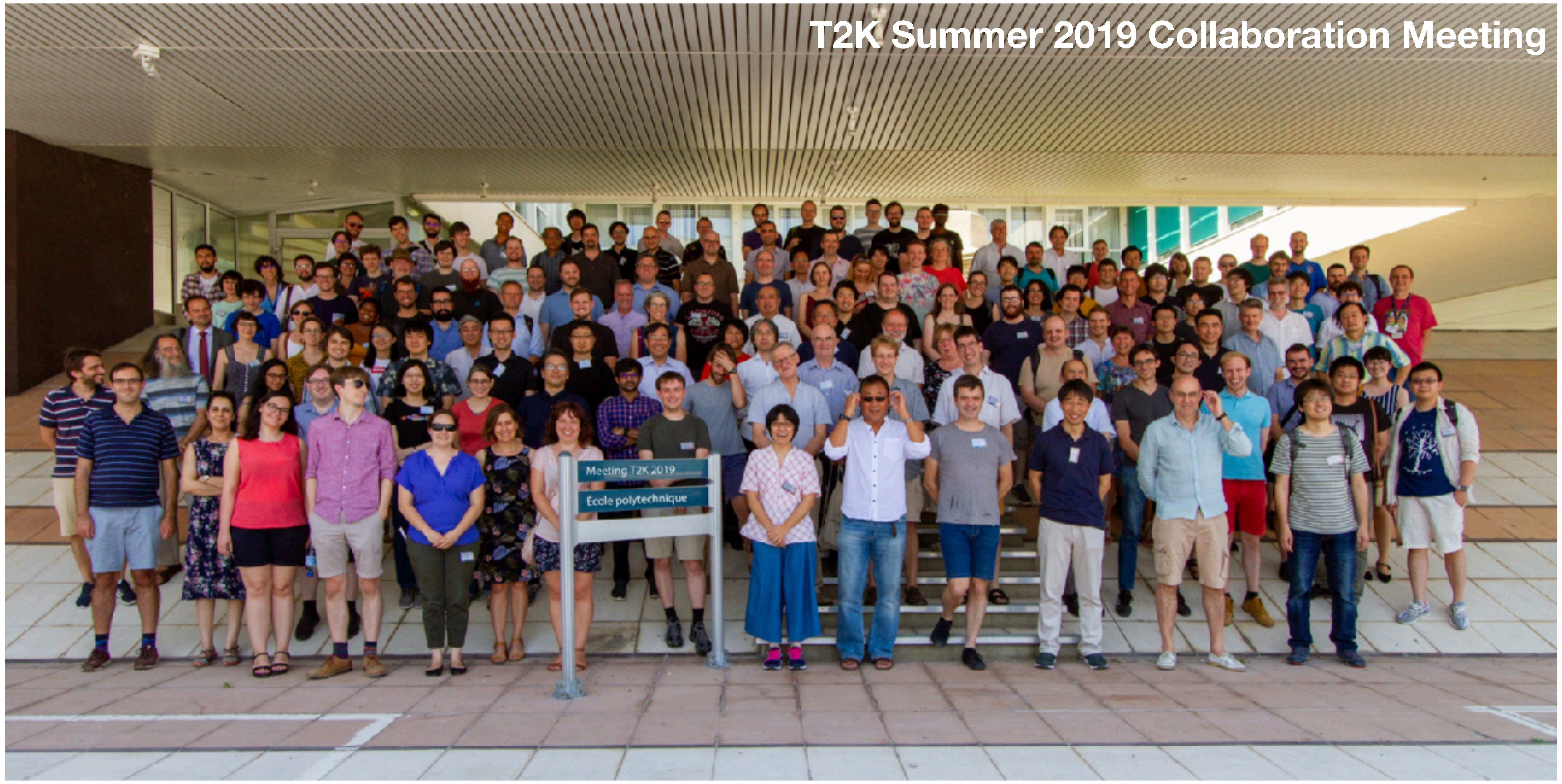
The T2K Experiment: Status, Results and Prospects

Mathieu Guigue for the T2K Collaboration

XIX International Workshop on Neutrino Telescopes — February 22nd 2021

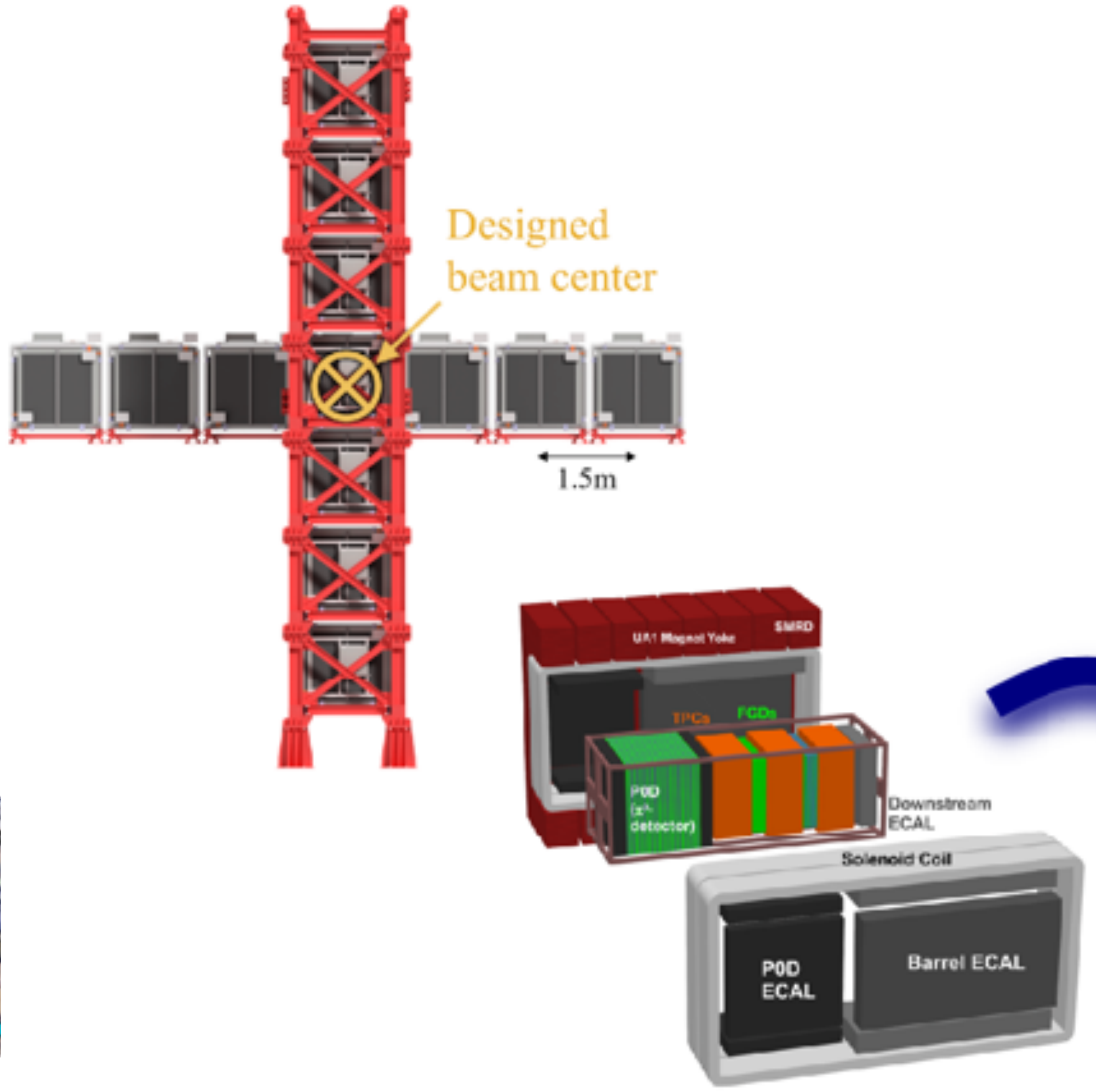
A short introduction on neutrino oscillations

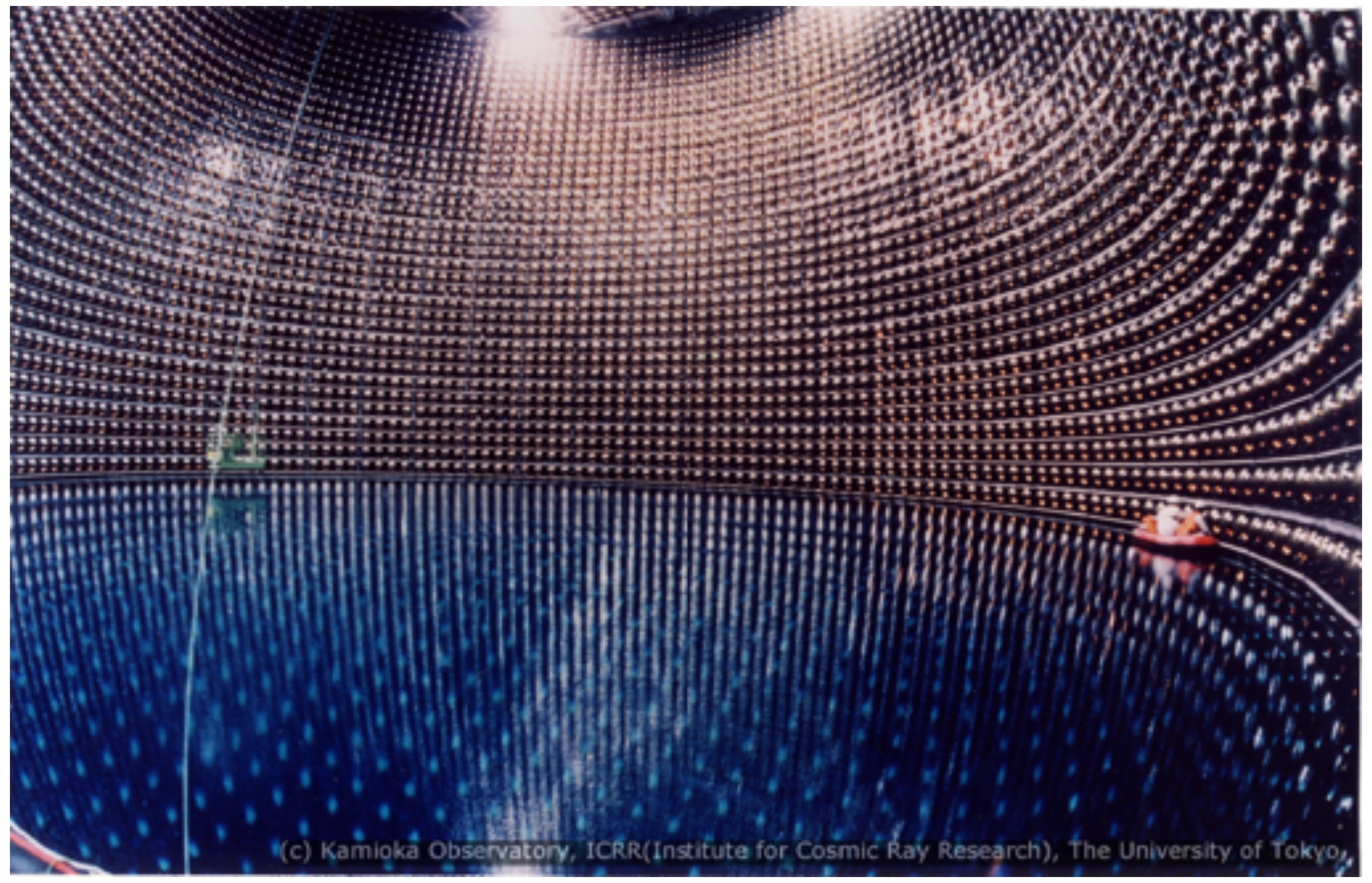
T2K Collaboration



~500 members over 12 countries and 69 institutes

From Tokai To Kamioka

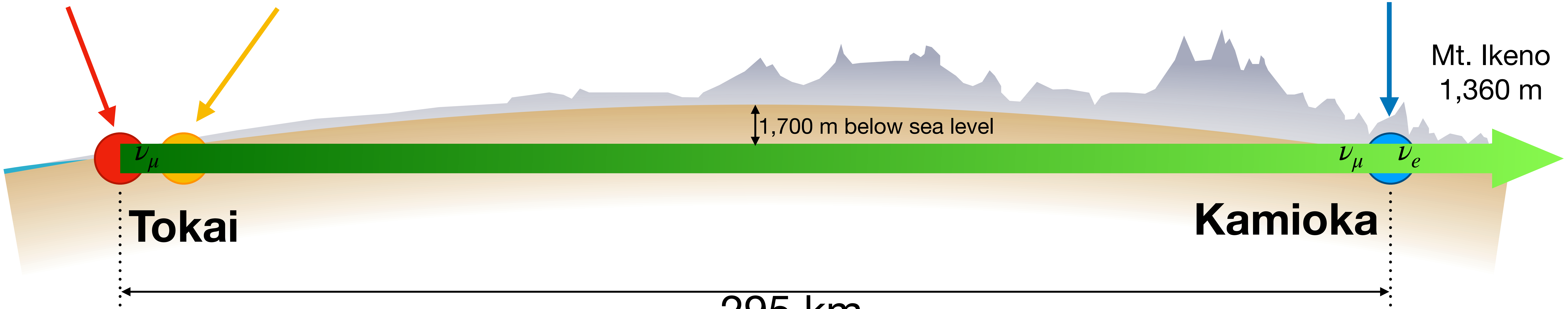




J-PARC

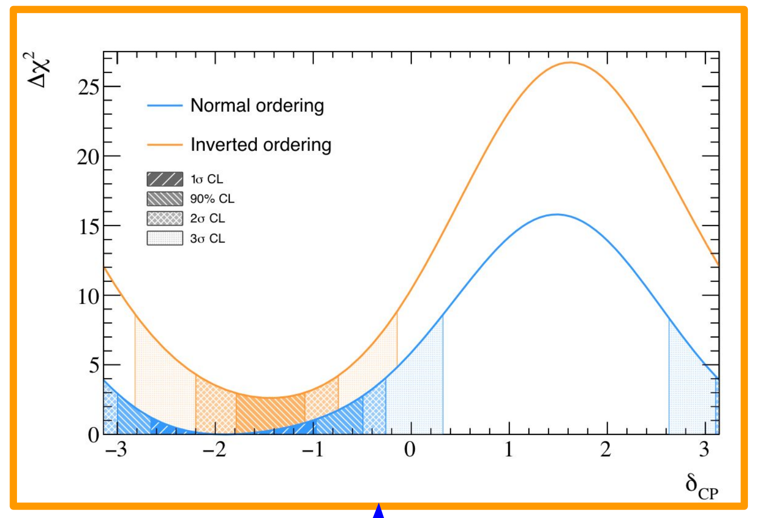
Near Detectors

Super-Kamiokande



Oscillation analysis strategy

$\delta_{CP}, \ \sin^2\theta_{13}, \ \Delta m^2_{32} \ldots$

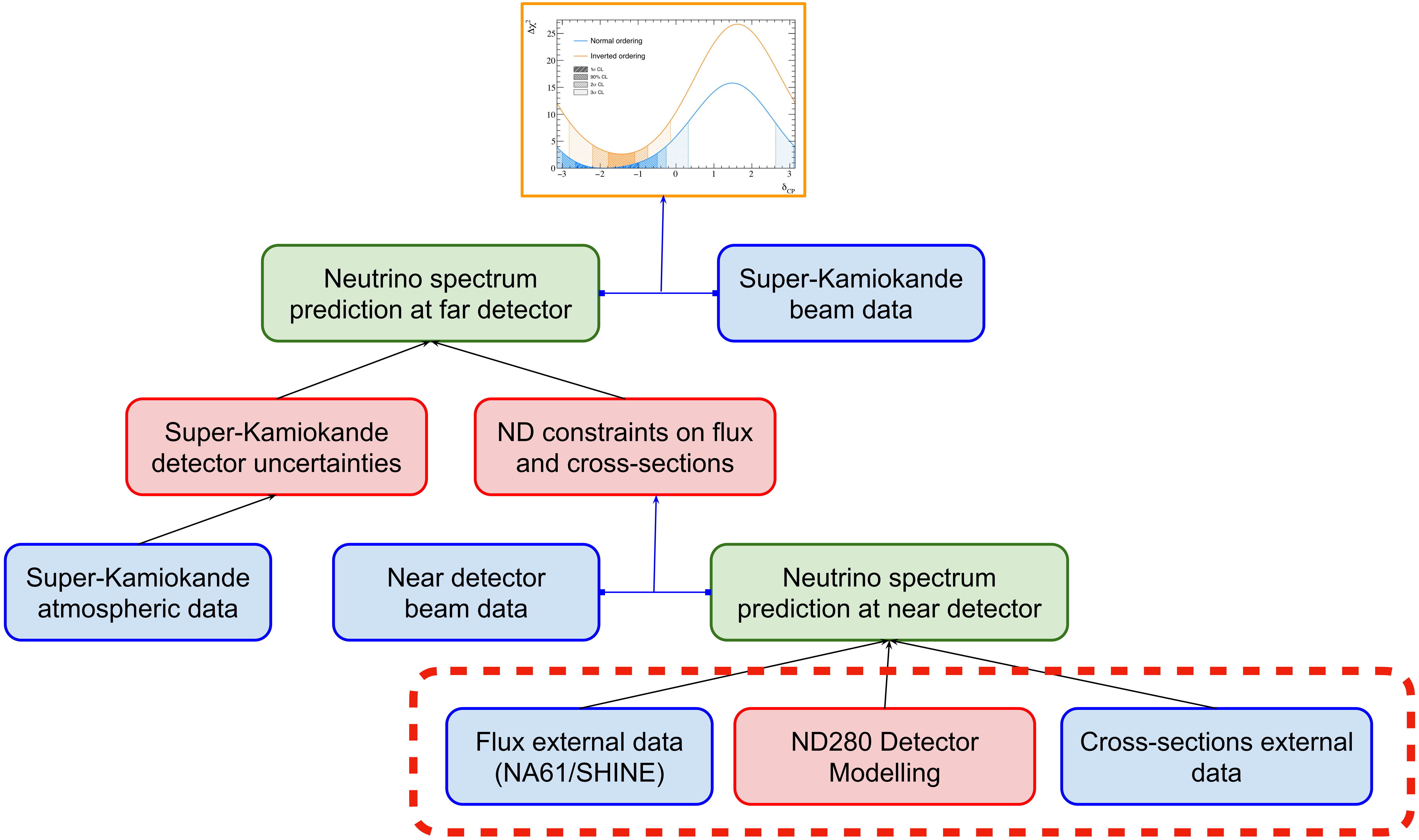


Neutrino spectrum prediction at far detector

Super-Kamiokande beam data

Oscillation analysis strategy

$\delta_{\mathrm{CP}},\ \sin^2\theta_{13},\ \Delta m^2_{32}\dots$

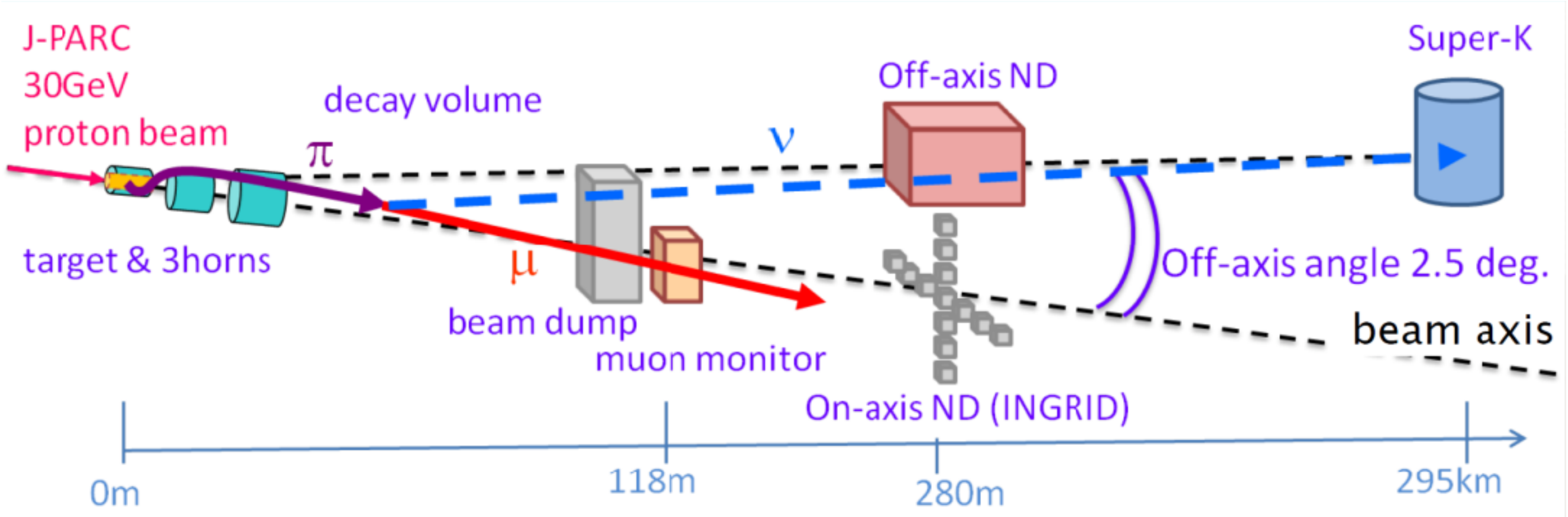


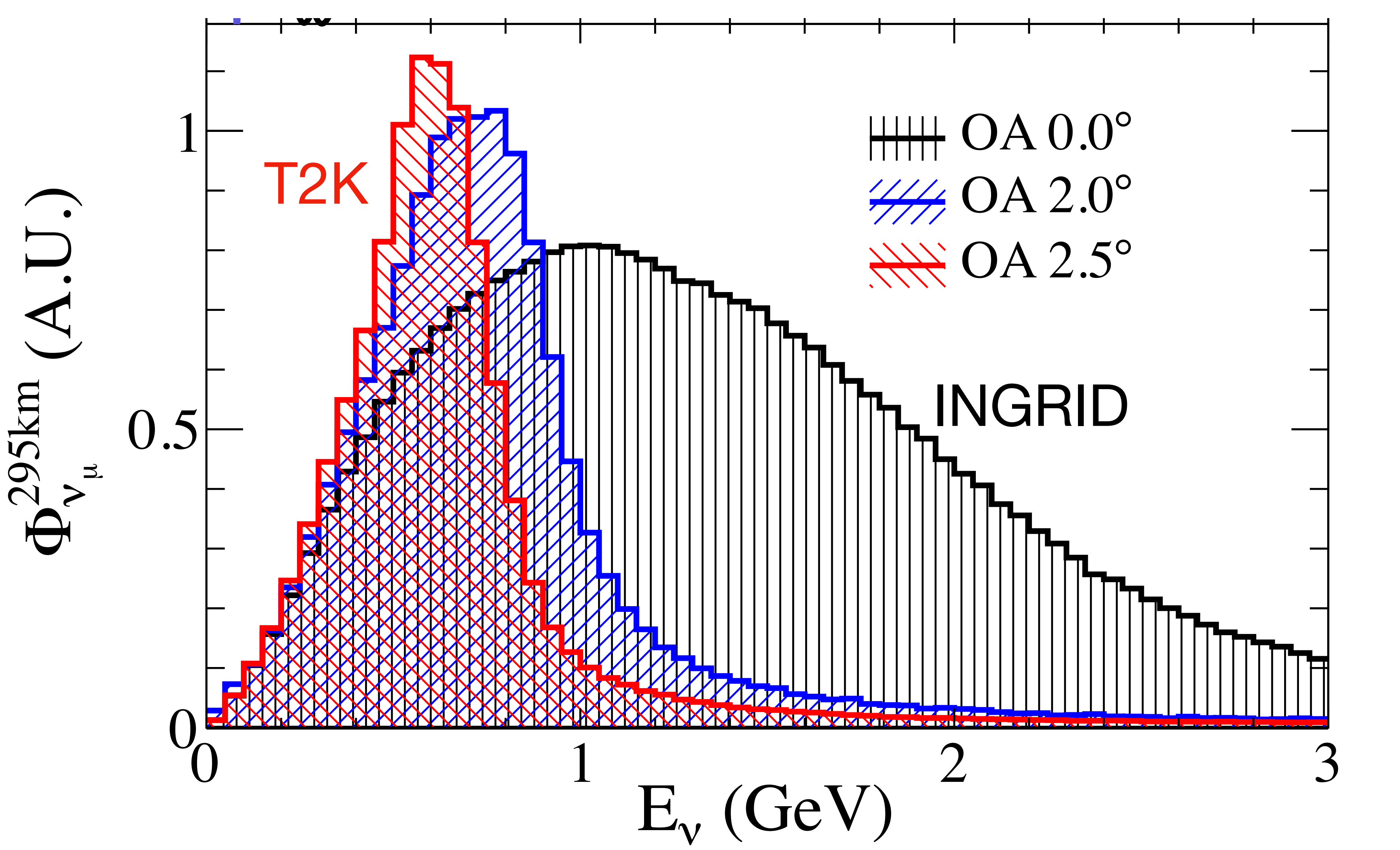
Muon neutrinos production at J-PARC

Produced from decaying hadrons generated by Protons On graphite Target (POT) at J-PARC

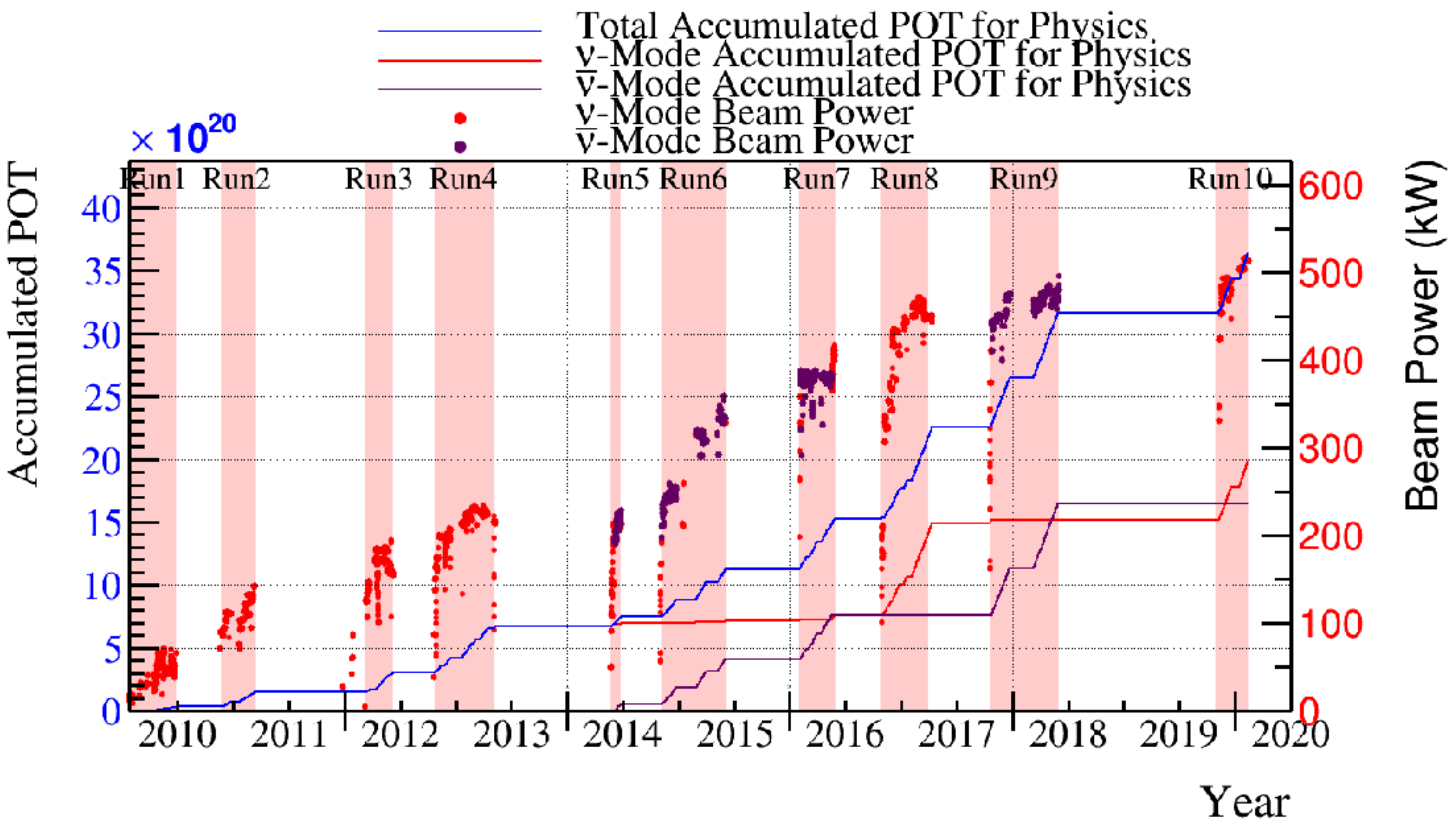
- Decay volume ~ 100 m long
- Magnetized "horns" to select hadrons charge → enrichment in ν_μ or $\bar{\nu}_\mu$
- Muon flux monitoring after beam dump

2.5° off-axis beam for ND and SK





Data taking status

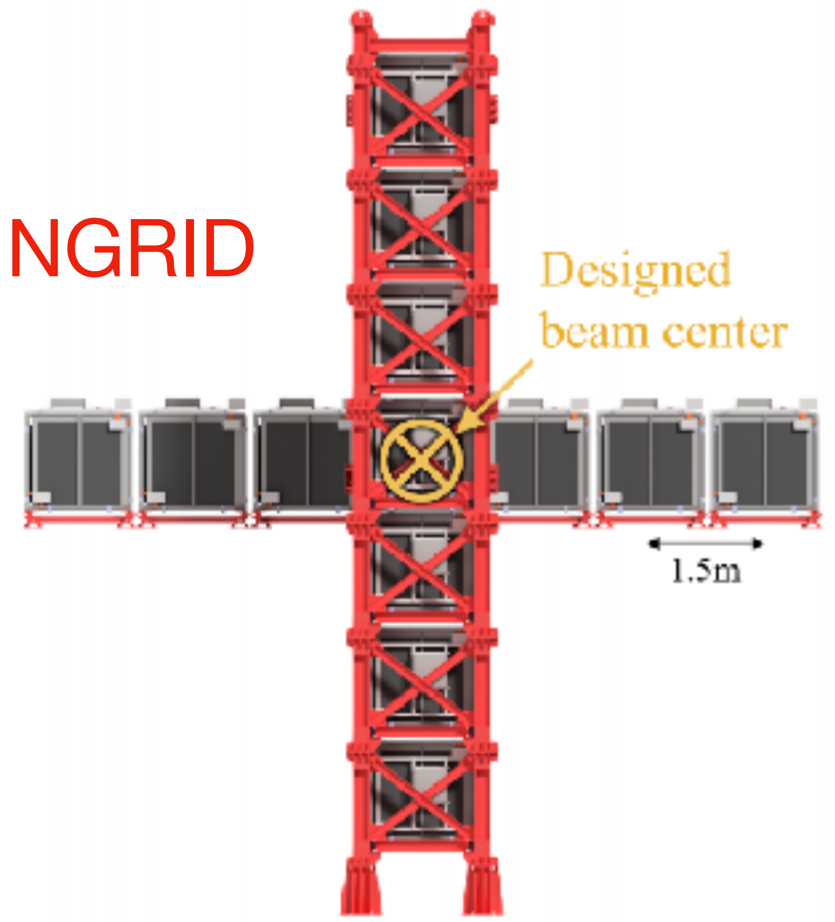


Steady increase in beam power: **515 kW this year**

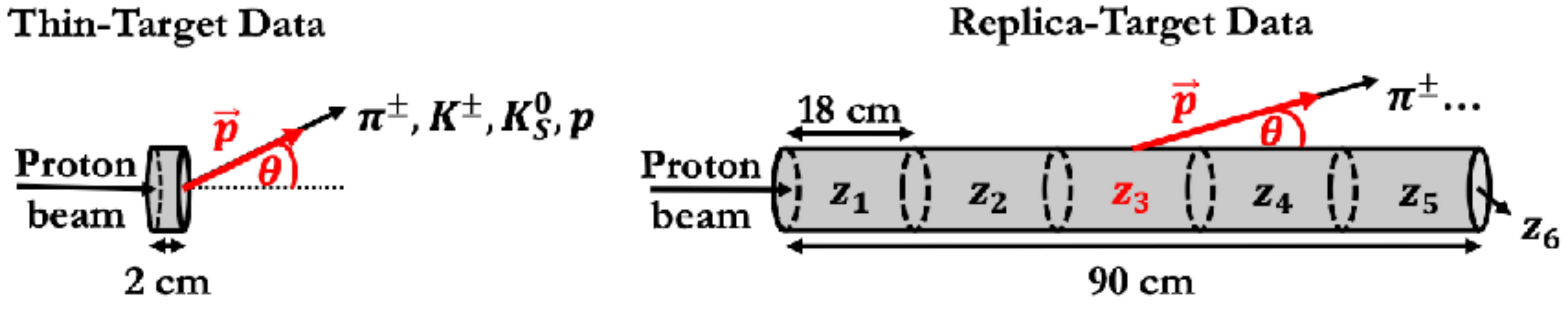
Run 1-10: 1.97×10^{21} POT in ν mode and 1.63×10^{21} POT in $\bar{\nu}$ mode

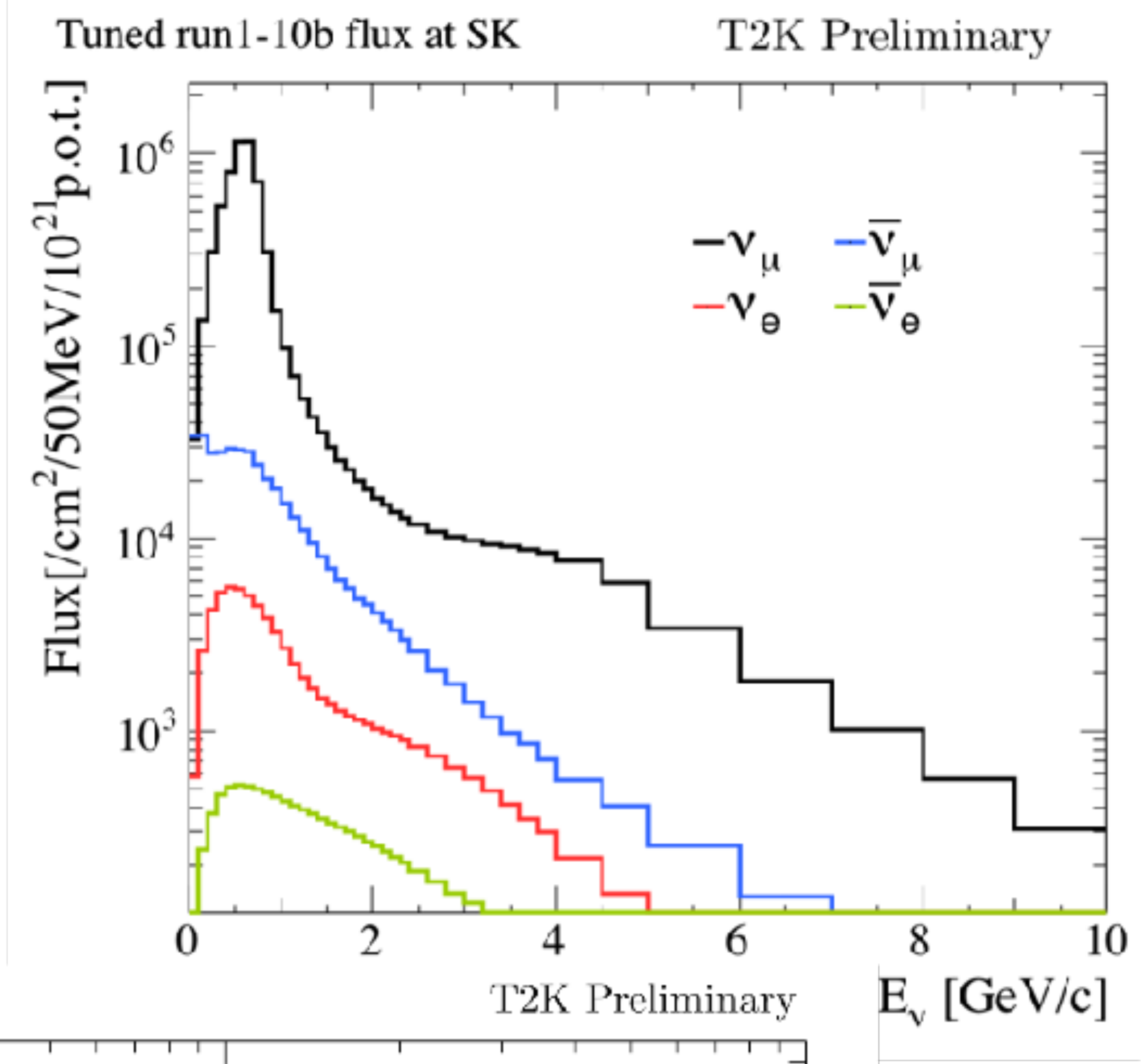
Flux constraints

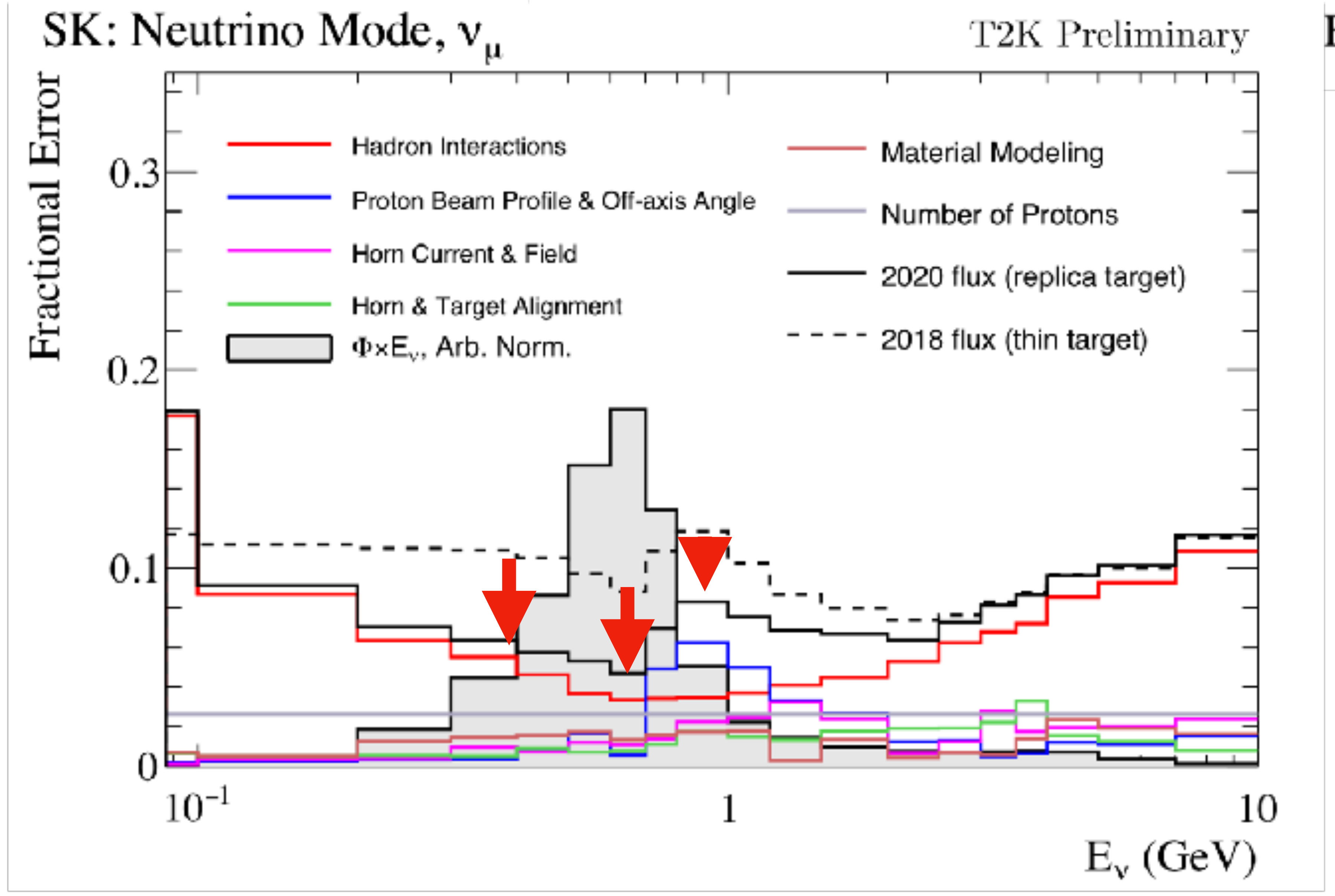
INGRID



NA61/SHINE@CERN







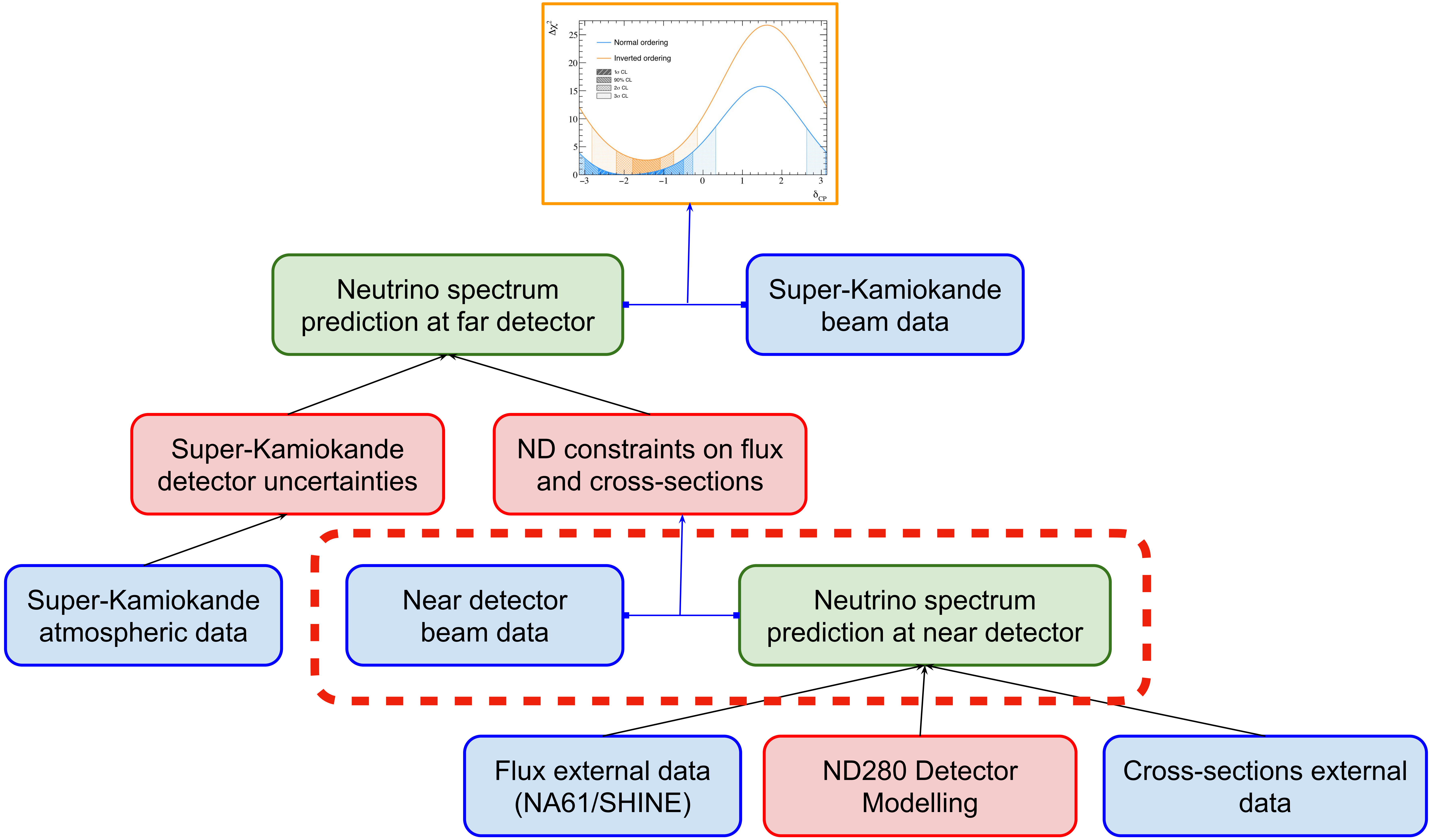
Monitoring of neutrino beam intensity and direction by INGRID on-axis detector

Simulations hadron production by Fluka
- Tuning on NA61/SHINE data from CERN
- **New:** T2K graphite replica target

Flux uncertainties reduced from 8% to 5%

Oscillation analysis strategy

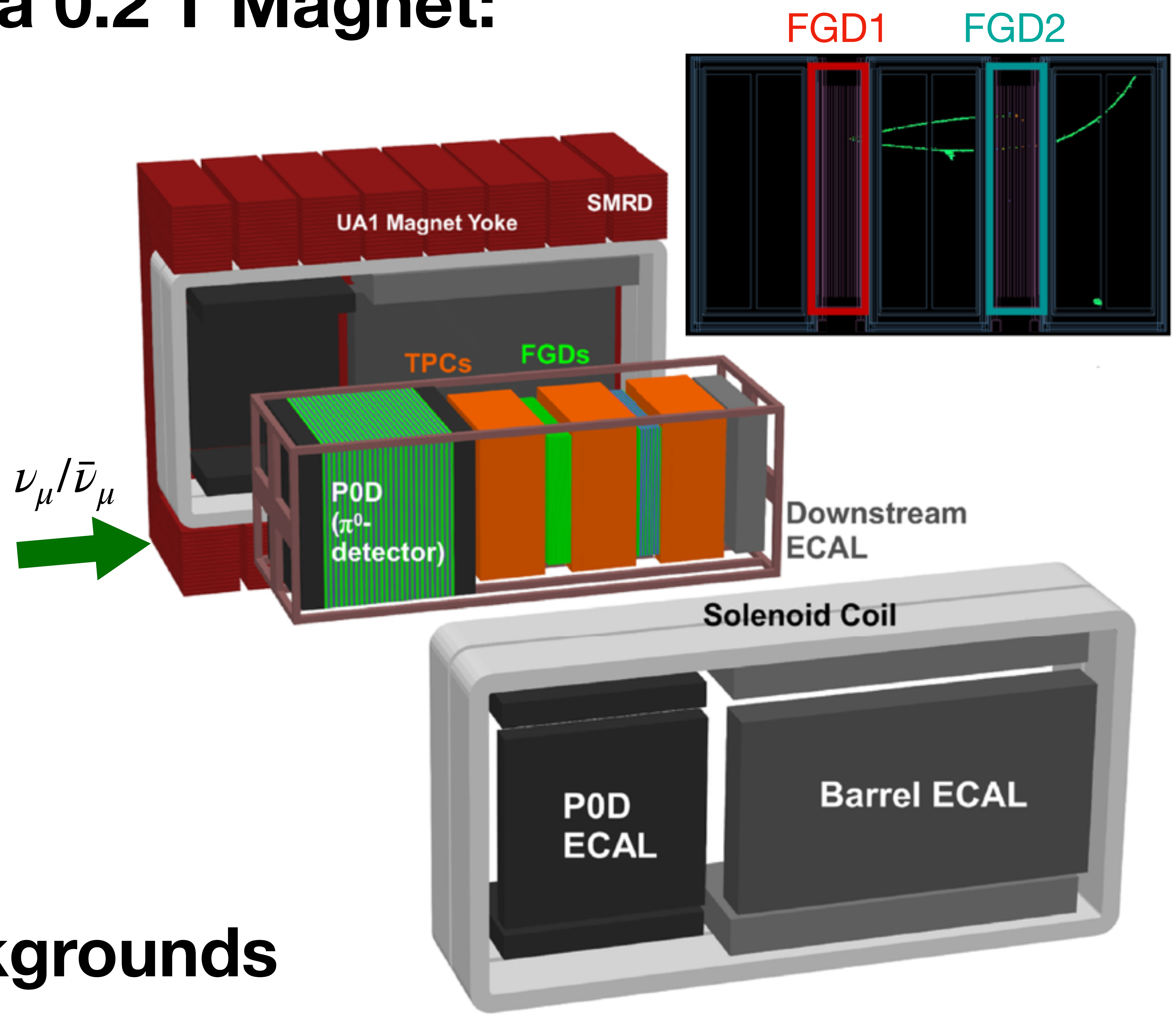
$\delta_{CP},\ \sin^2\theta_{13},\ \Delta m^2_{32}\ldots$



Off-axis Near Detector at 280m (ND280)

2.5° off-axis composite detector inside a 0.2 T Magnet:

- Two Fine Grained scintillating detectors FGD1 (C) and FGD2 (C,O)
- Three Time Projection Chambers (TPCs) between FGDs
- One Upstream π^0 detector
- ECal surrounding inner detectors

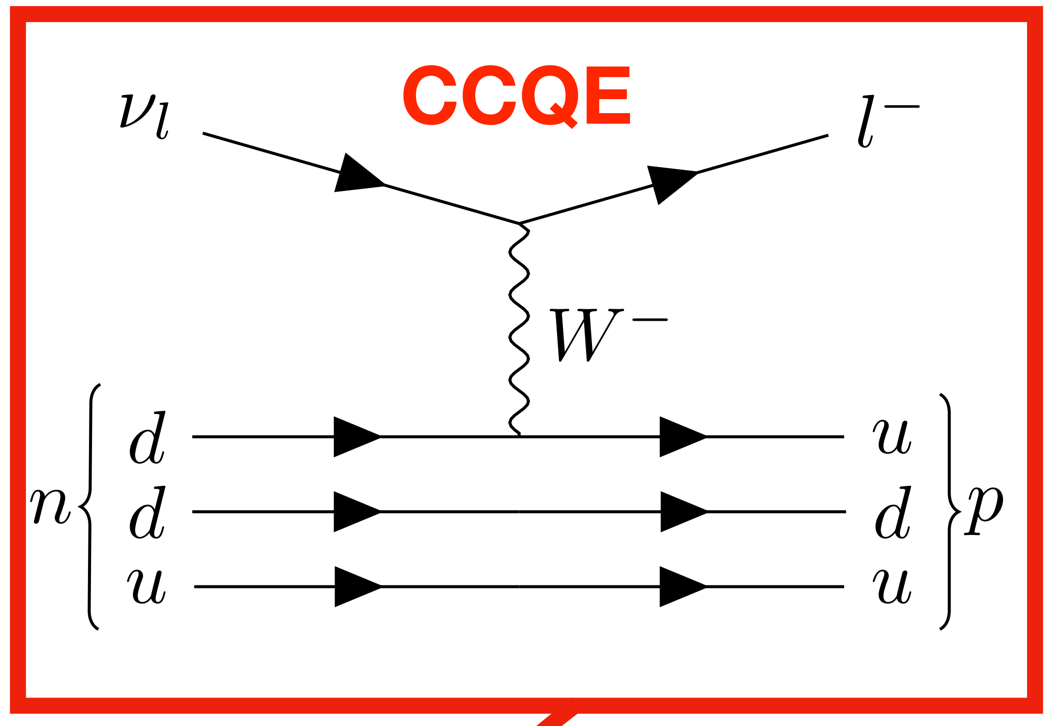


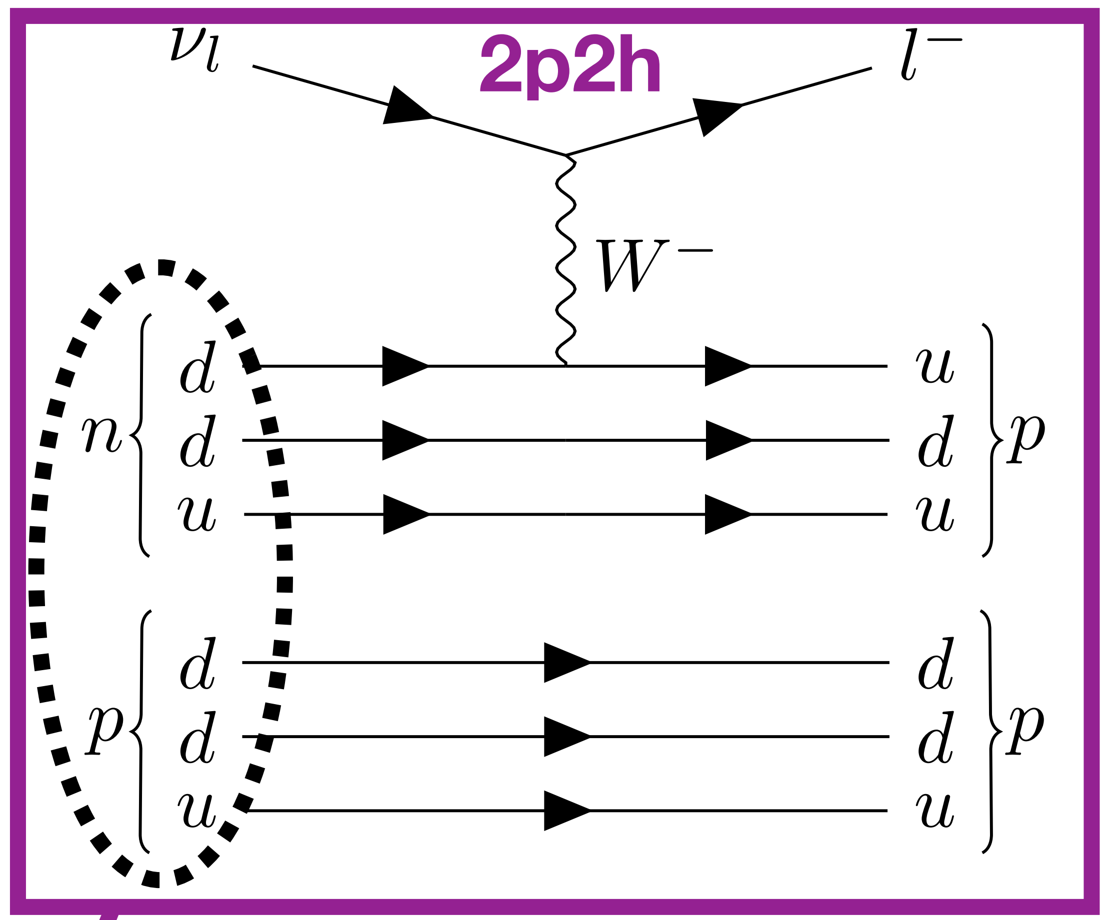
FGDs used as neutrino targets

Magnetization → charge and momentum

⇒ **Constraints on cross-sections, flux uncertainty model and wrong sign backgrounds**

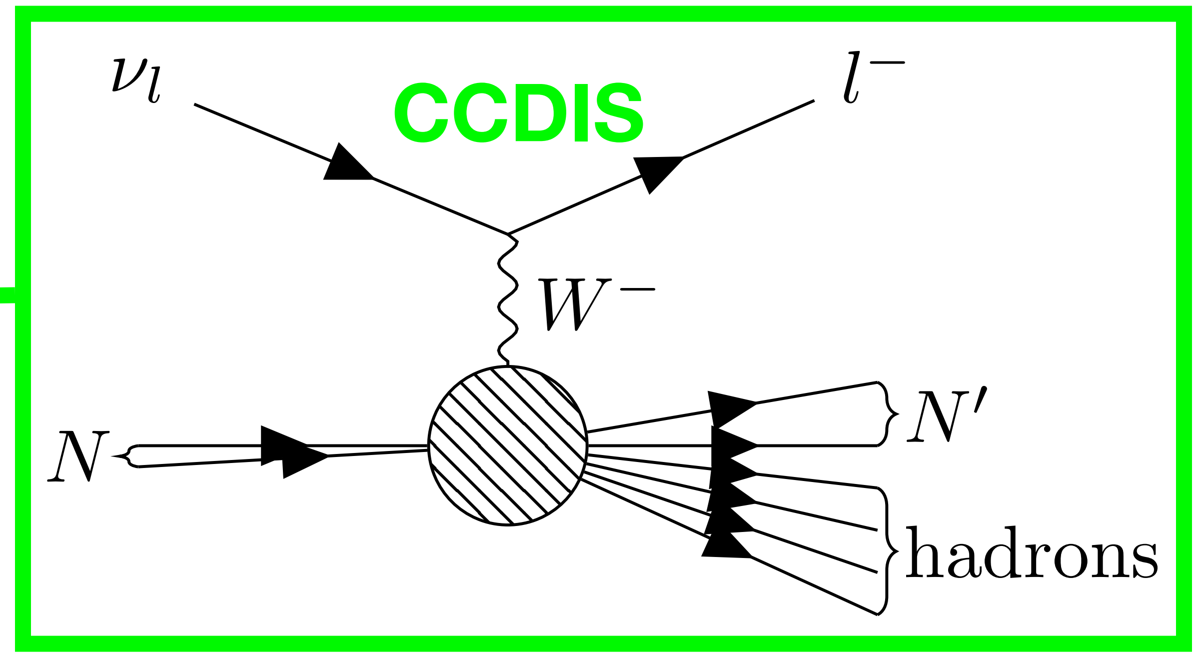
Neutrino interactions

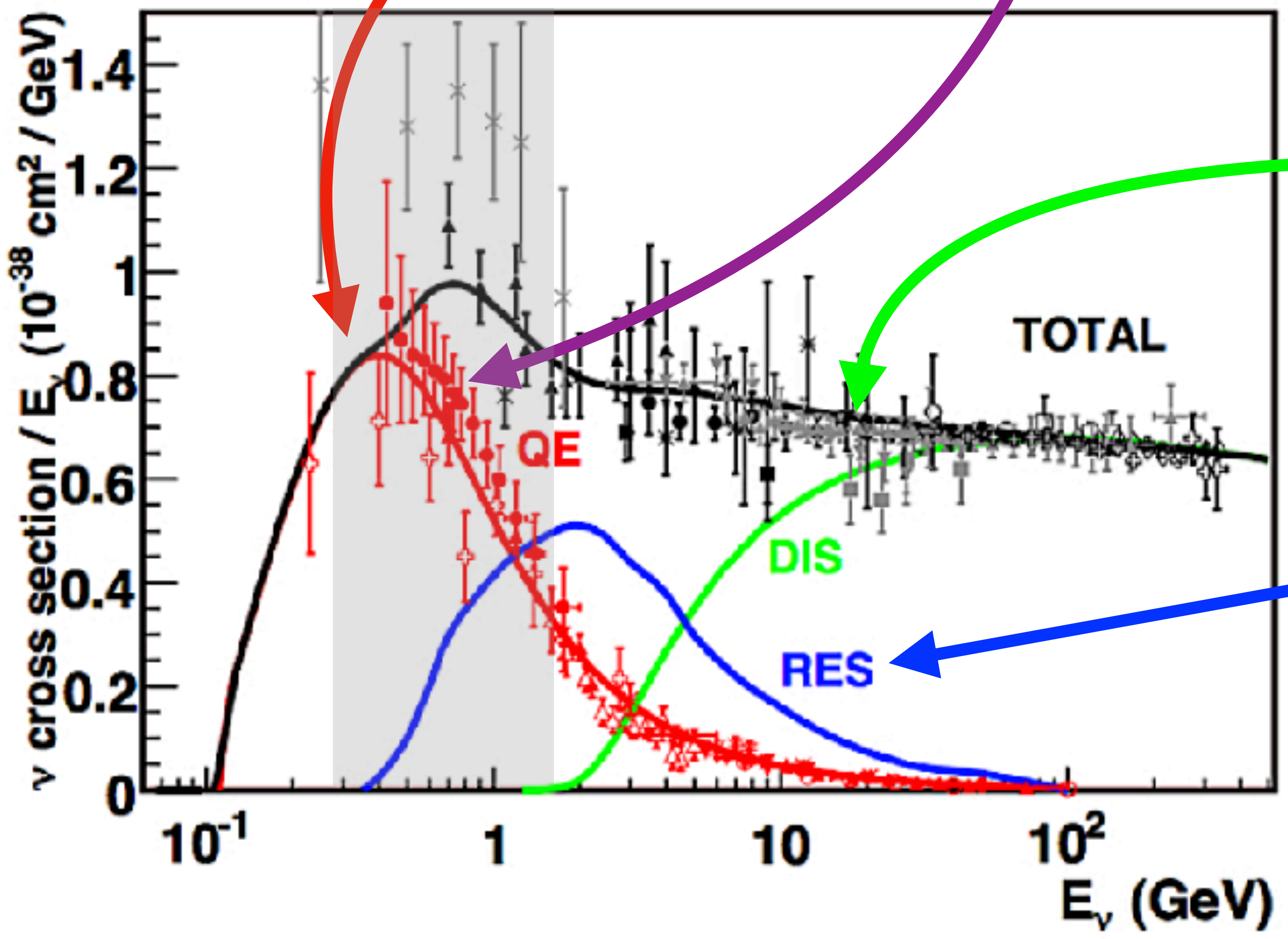


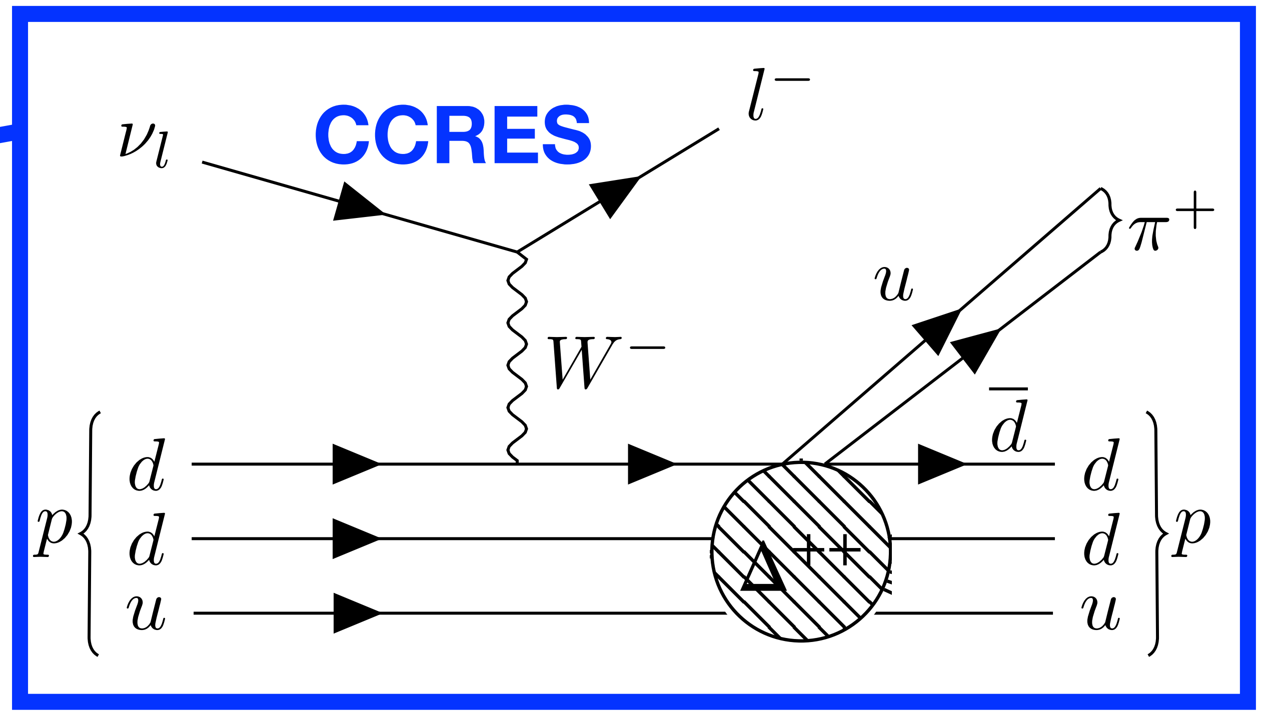


Three interactions channels:

- CCQE (and 2p2h)
- CC Resonant (RES)
- CC Deep Inelastic Scattering (DIS)





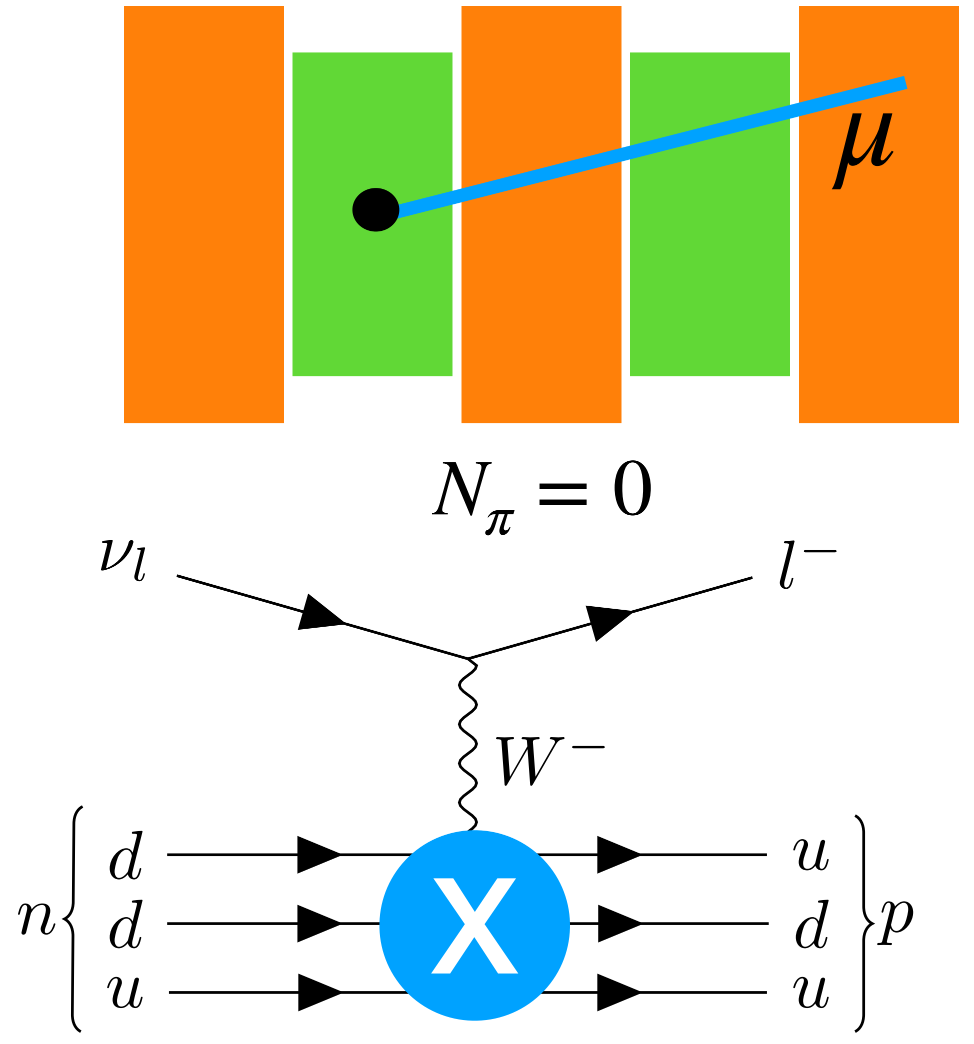


→ Define samples enriched in each of the processes using **reconstructed pion multiplicity**

→ Constrain cross-section models for each interaction

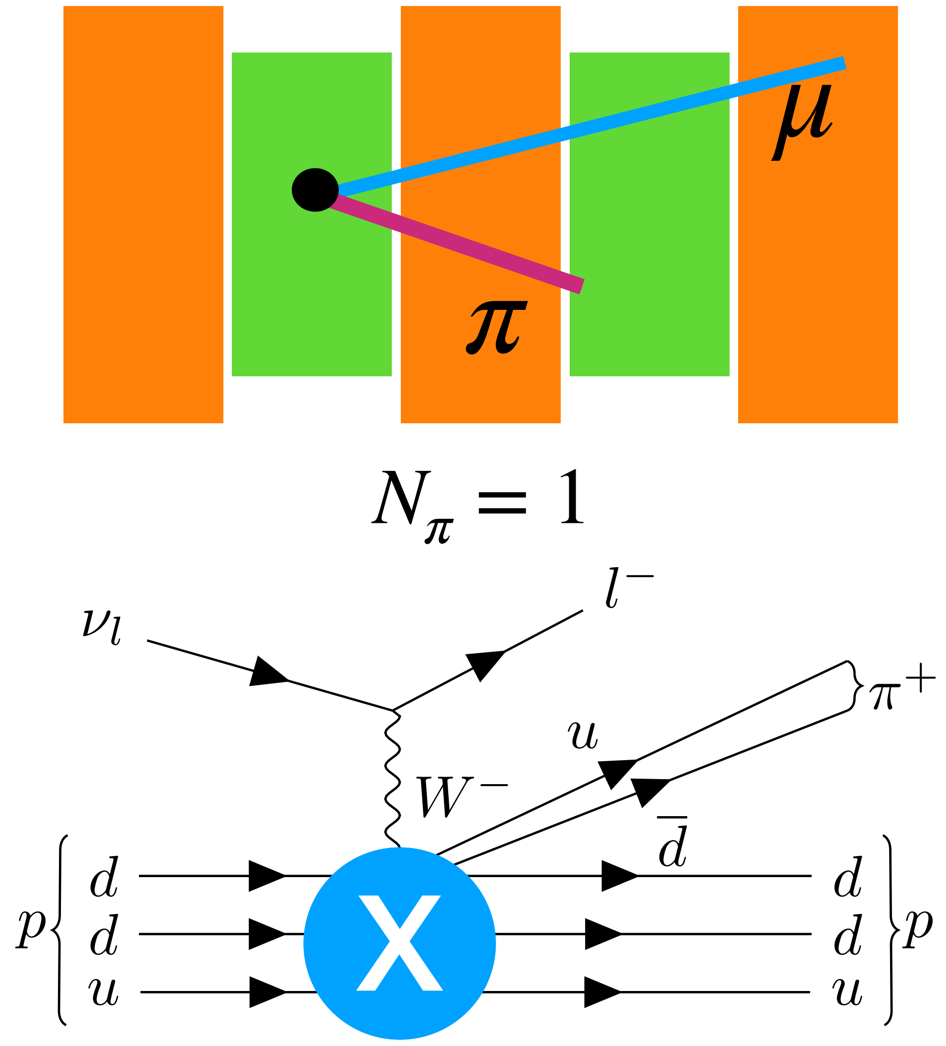
ND280 samples

CC0π



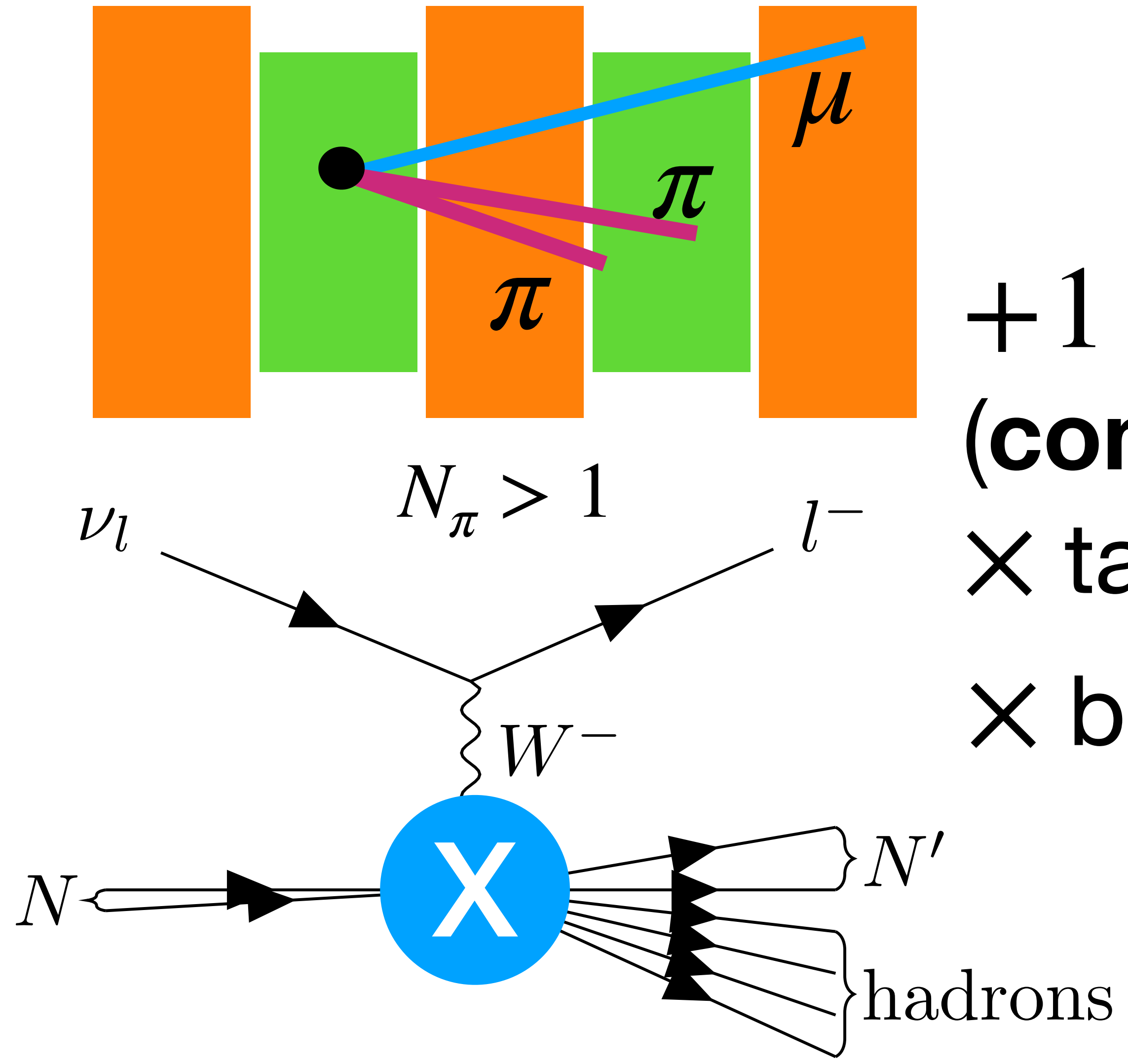
~CCQE + 2p2h

CC1π



~CCRes

CCNπ

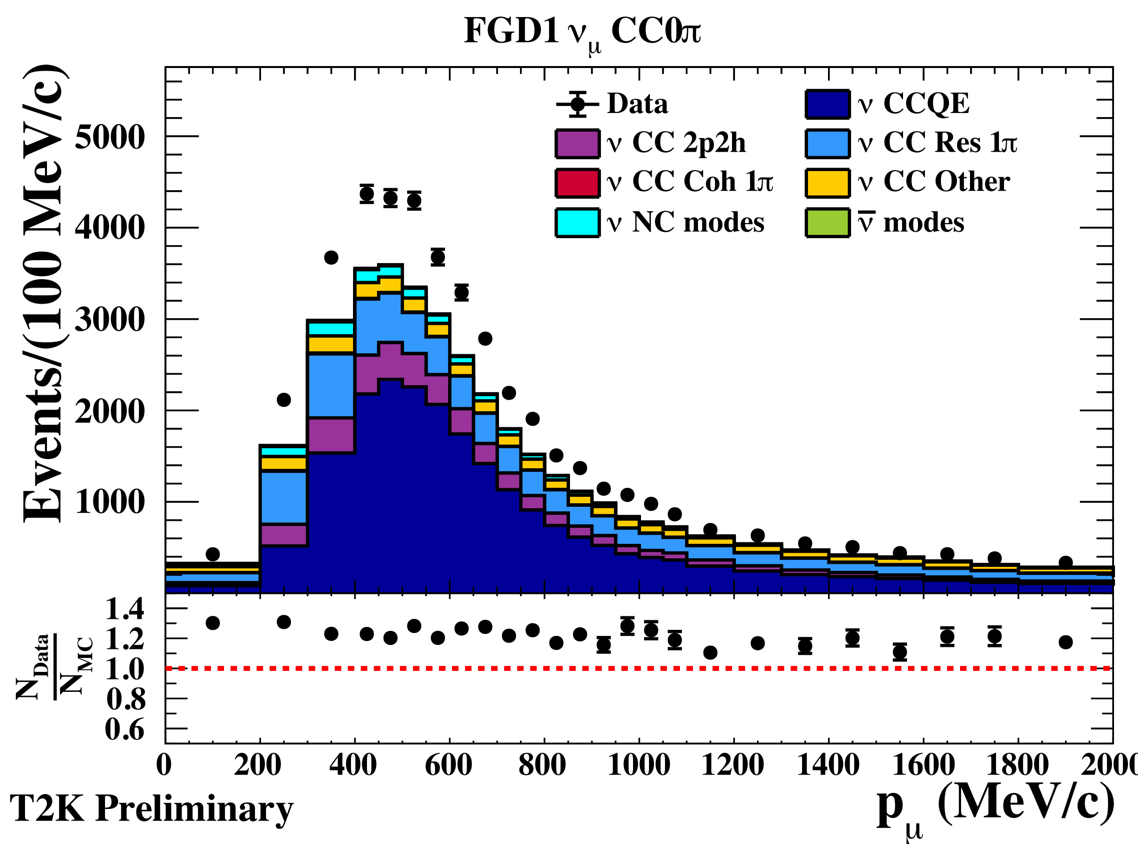


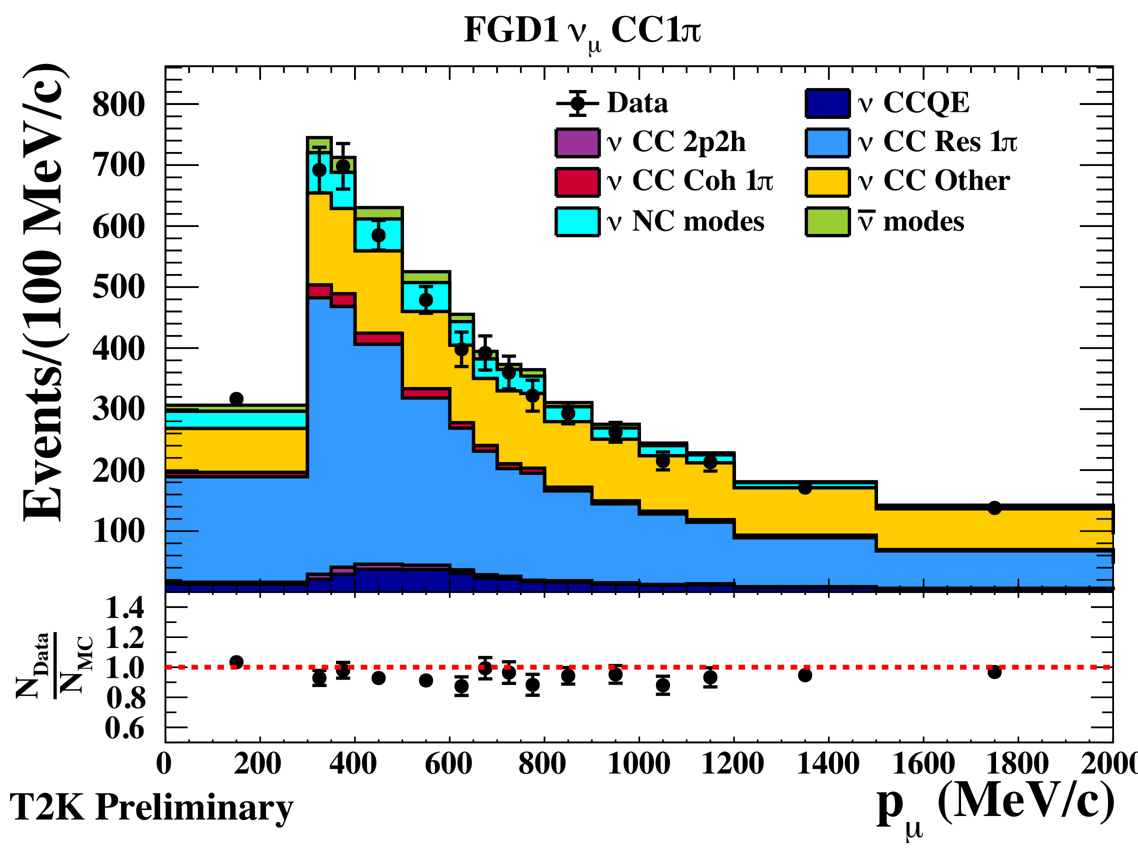
~CCDIS

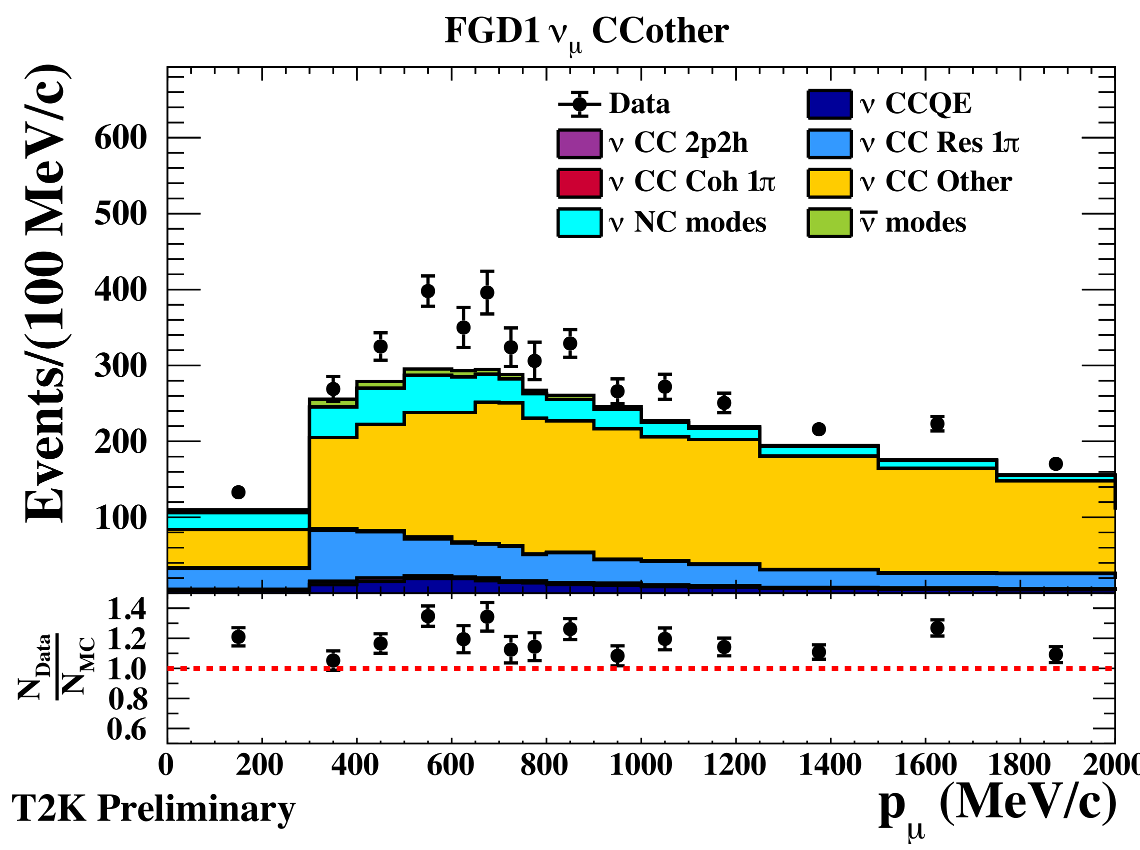
$+1$ sample ν events in anti-ν beam mode (**constrain wrong-sign background**)

$\times$ target detector (FGD1 or FGD2)

$\times$ beam mode (ν or anti-ν)







Near detector fit

Modeling of neutrino cross-sections
- Tuning of baseline nuclear model (Spectral Function)
- 2p2h modeling: new uncertainty on energy dependence
- Improvements of nucleon-nucleus binding energy (momentum shift)
- Improved parametrization of CCDIS and CCNπ models

Data from run 2-9

1.15×10^{21} POT in ν mode and 0.83×10^{21} POT in $\bar{\nu}$ mode

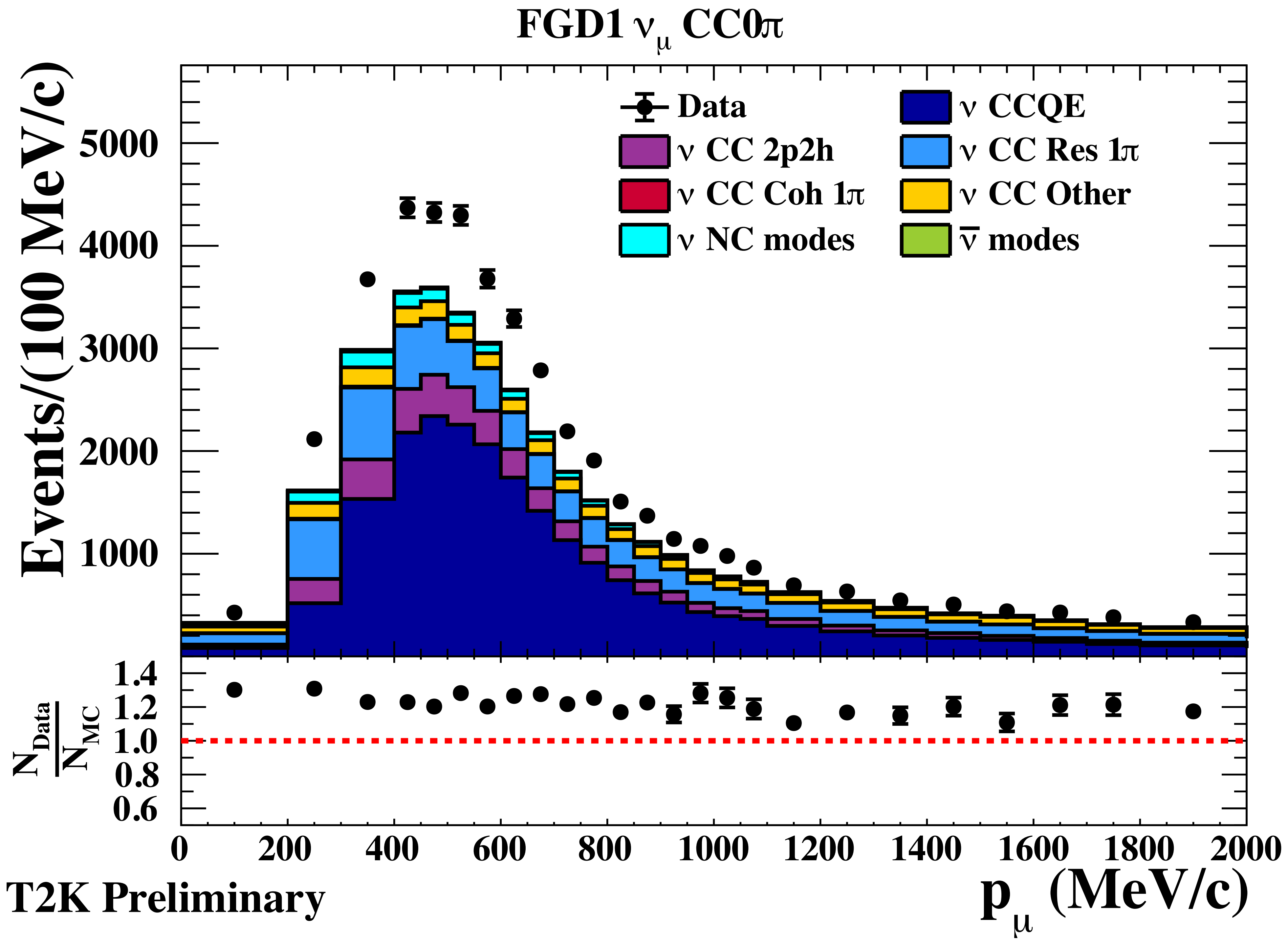
Near detector fit

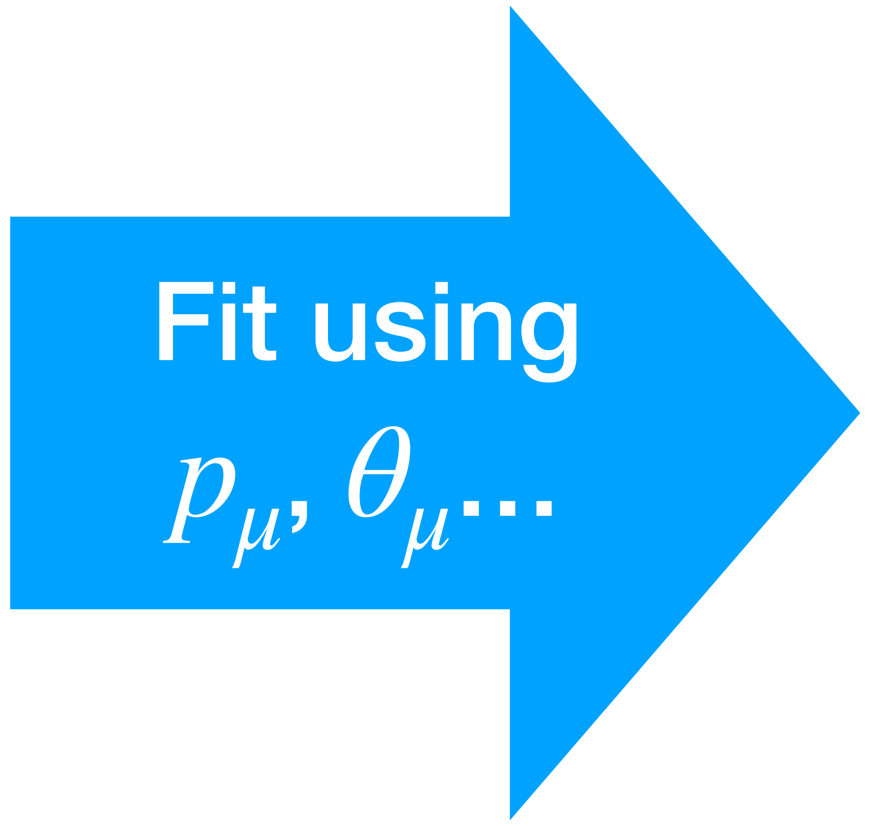
Modeling of neutrino cross-sections

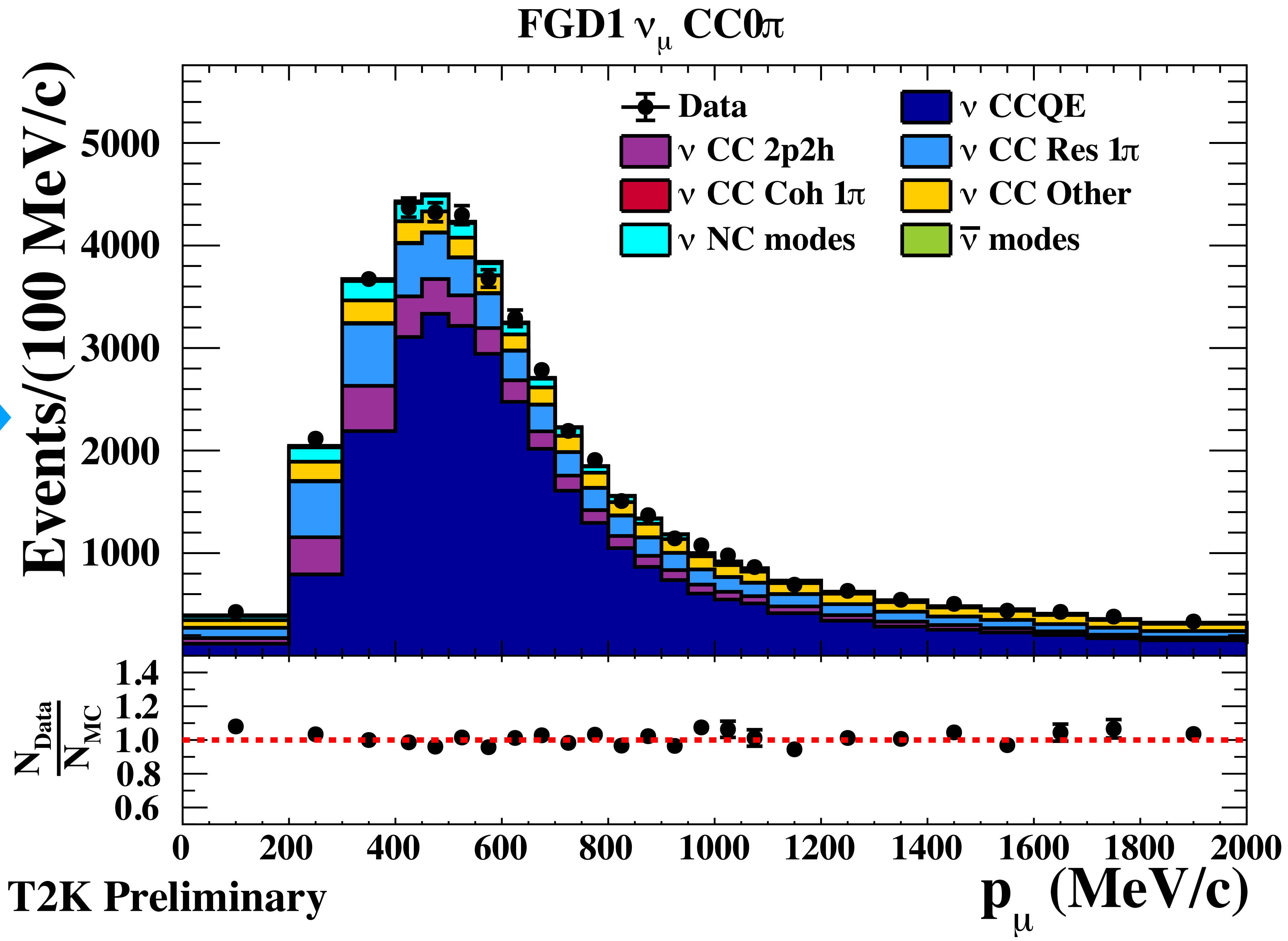
Model after fit reproduces well the data (p-value of 0.74)

Prefit → Postfit

CC0π





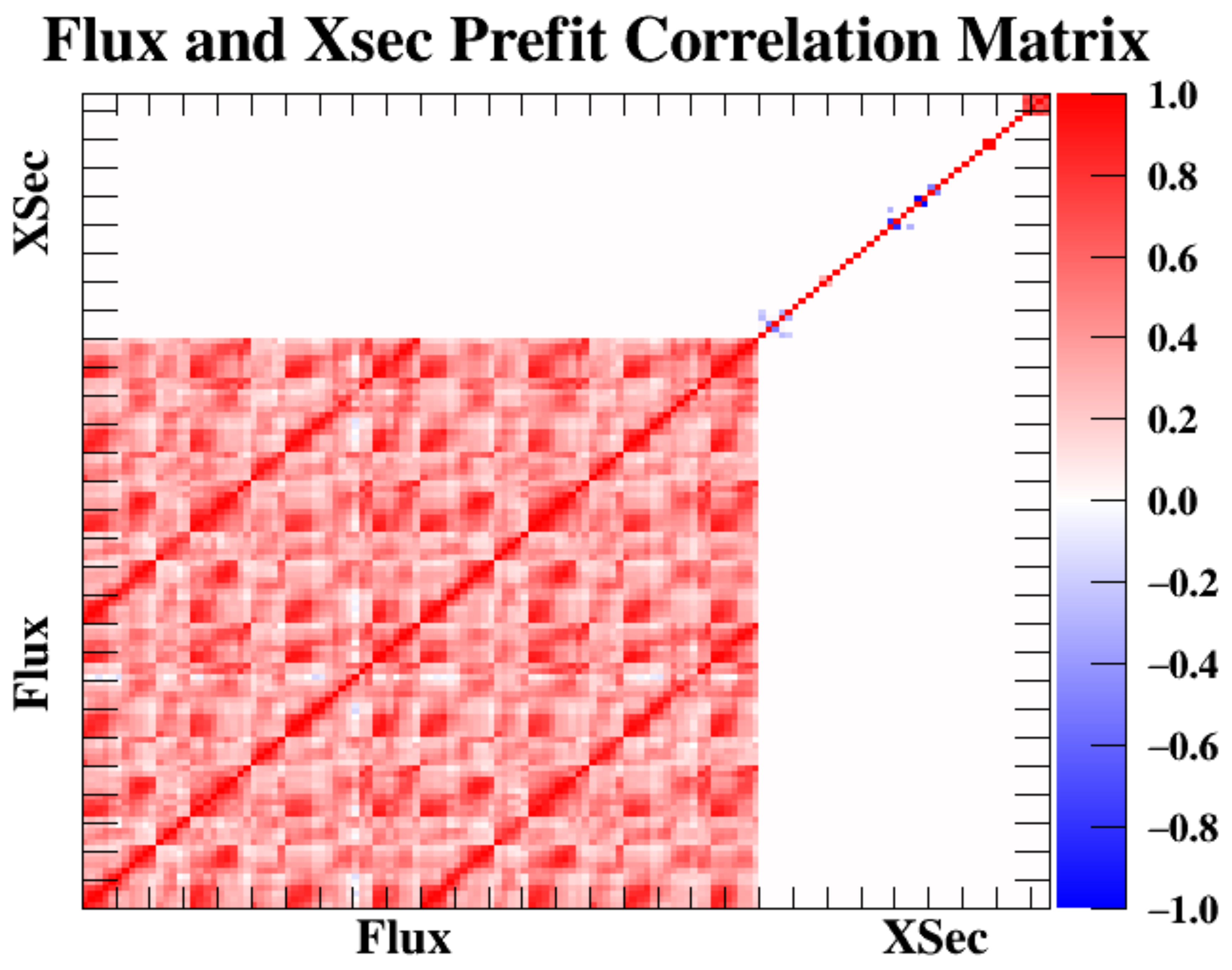


Near detector fit

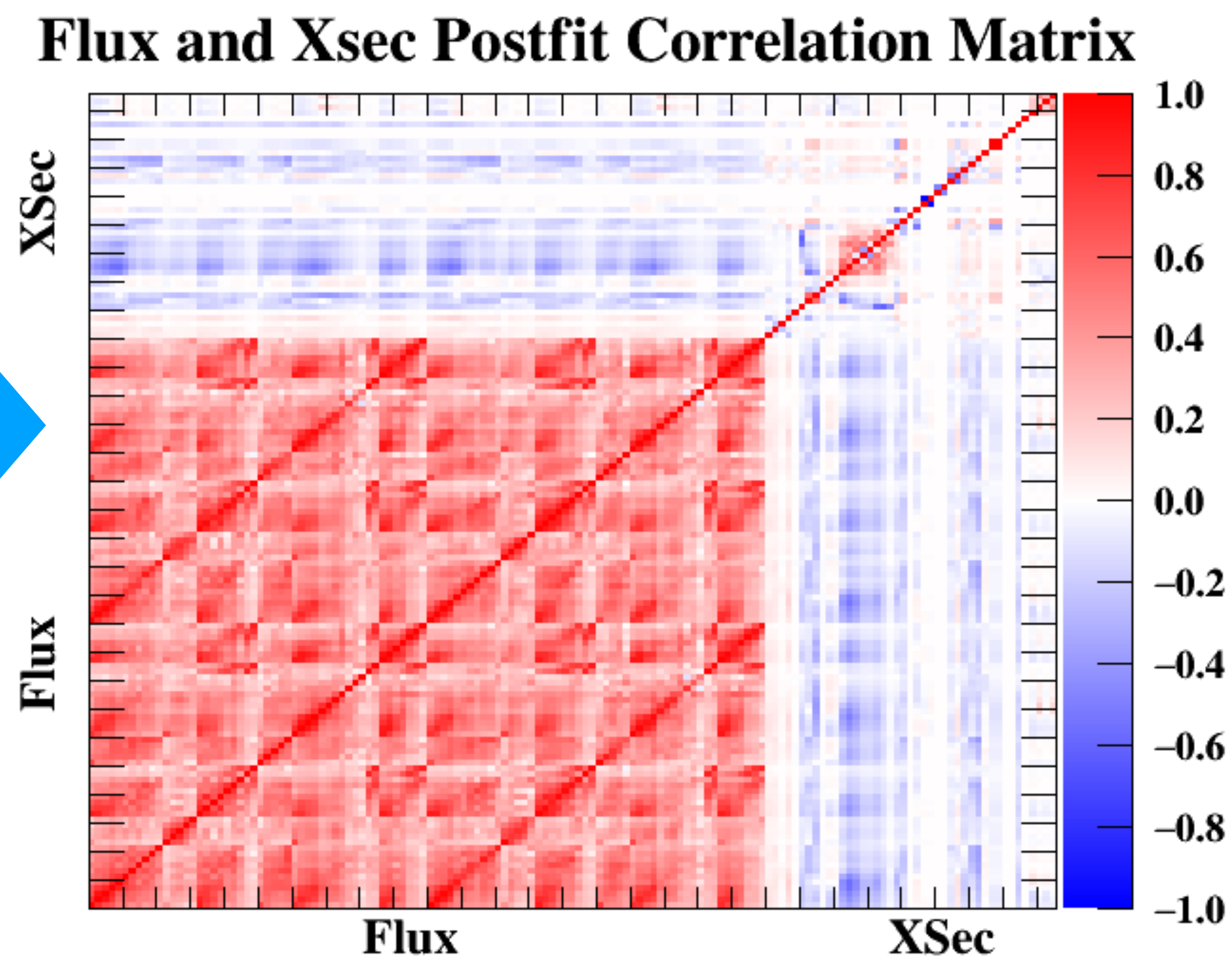
Modeling of neutrino cross-sections

Model after fit reproduces well the data (p-value of 0.74)

Introduction of anti-correlations between flux and cross-section parameters due to fit



T2K Preliminary



T2K Preliminary

Near detector fit

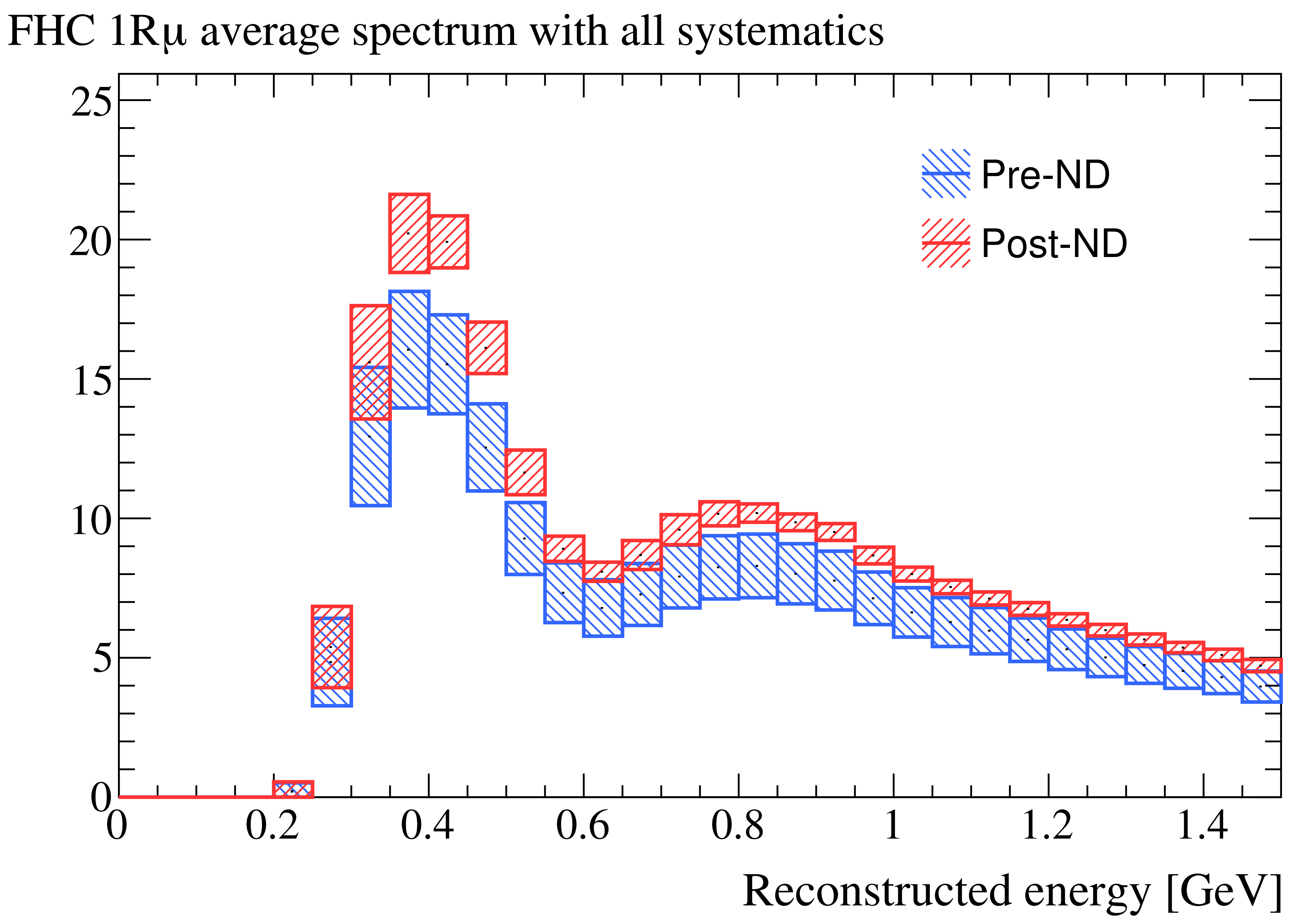
Modeling of neutrino cross-sections

Model after fit reproduces well the data (p-value of 0.74)

Introduction of anti-correlations between flux and cross-section parameters due to fit

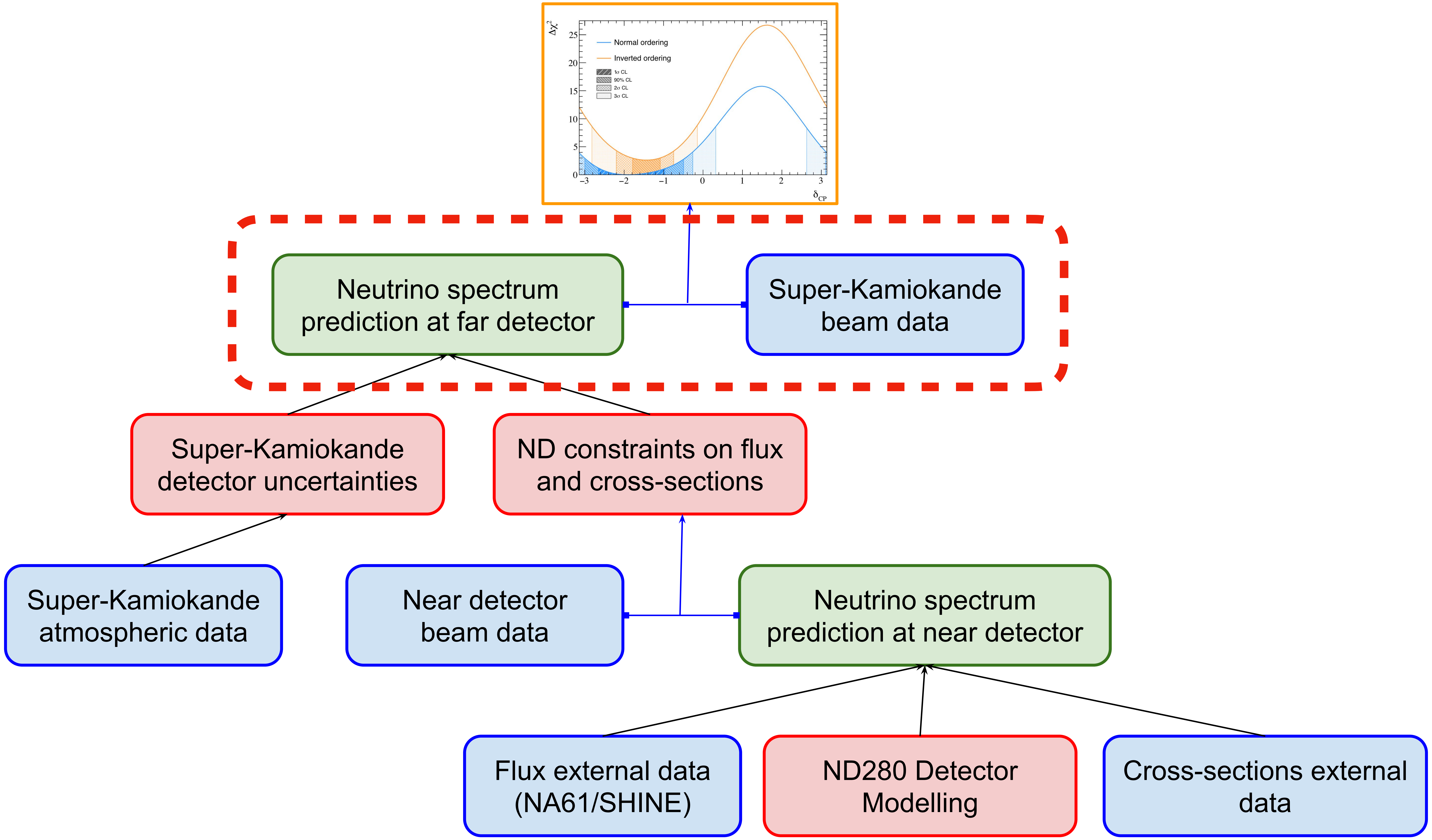
→**Flux and cross-section uncertainties reduction from ~13% to ~4%**

→Spectra prediction at far detector

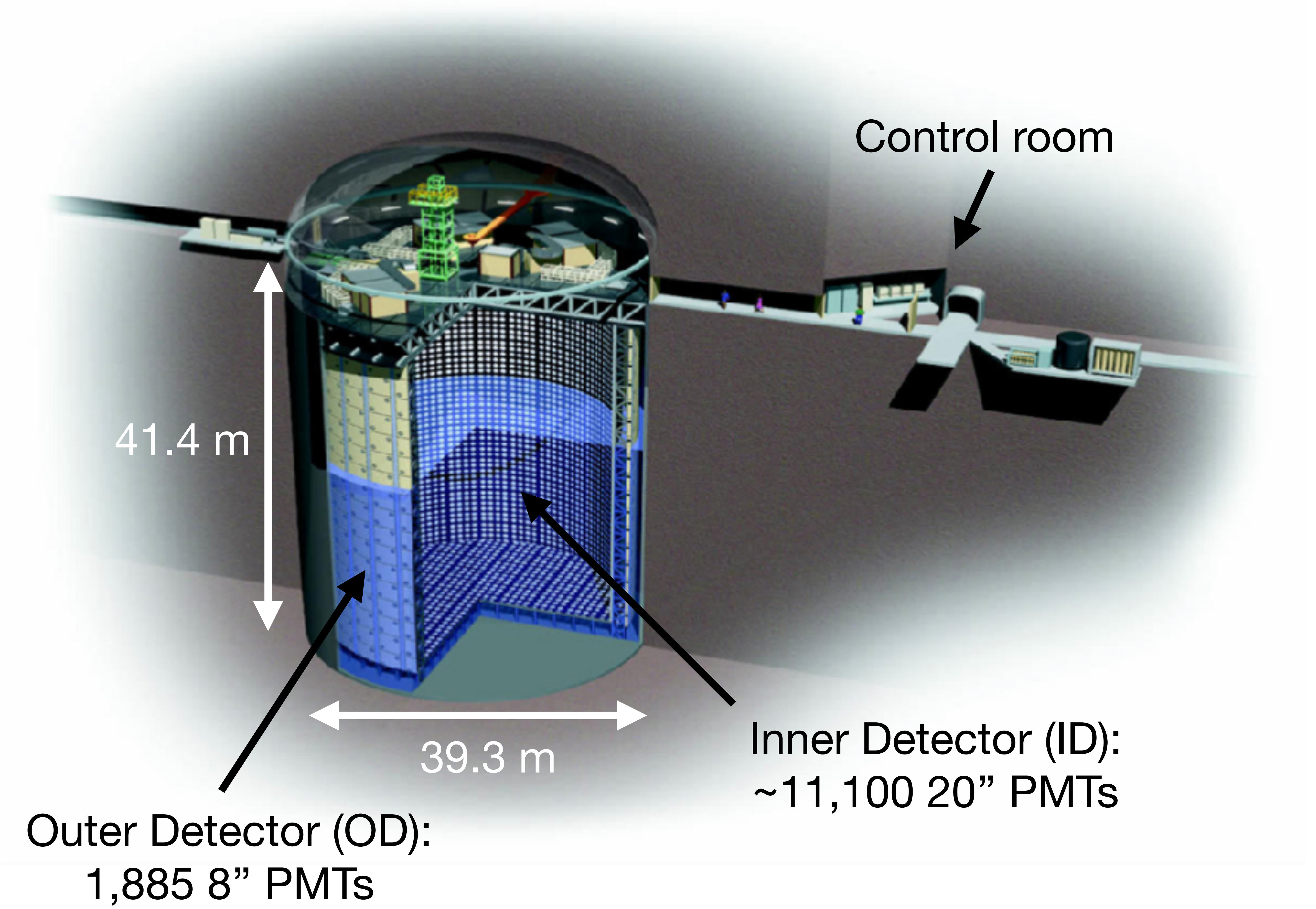


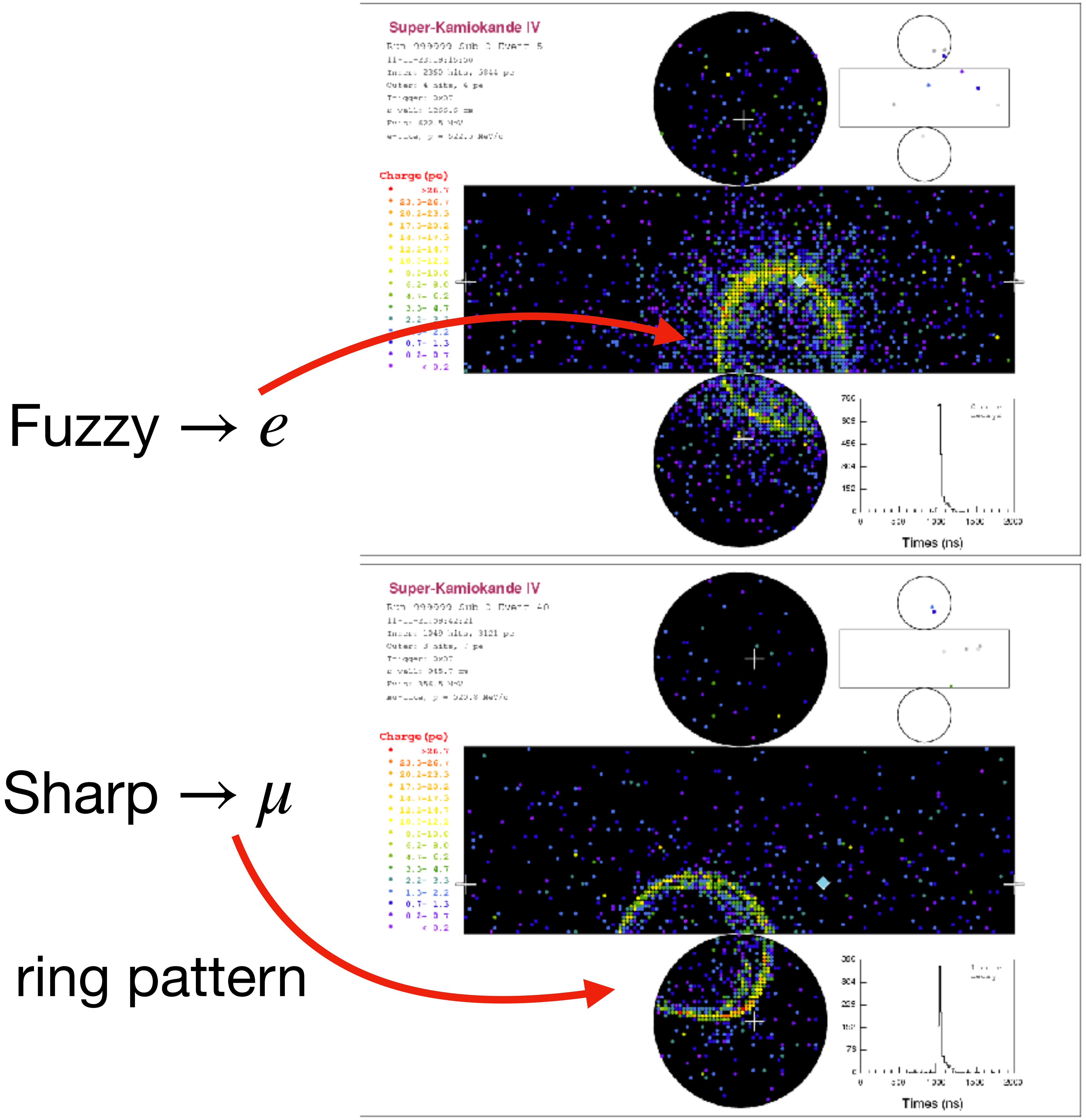
Oscillation analysis strategy

$\delta_{CP},\ \sin^2\theta_{13},\ \Delta m^2_{32}\dots$



Off-axis Far Detector: Super Kamiokande





50 kton of purified water → 22.5 kton fiducial

1000 m under Mount Ikeno

e-μ identification et kinematics using Cherenkov ring pattern

No charge identification (contrary to ND280)

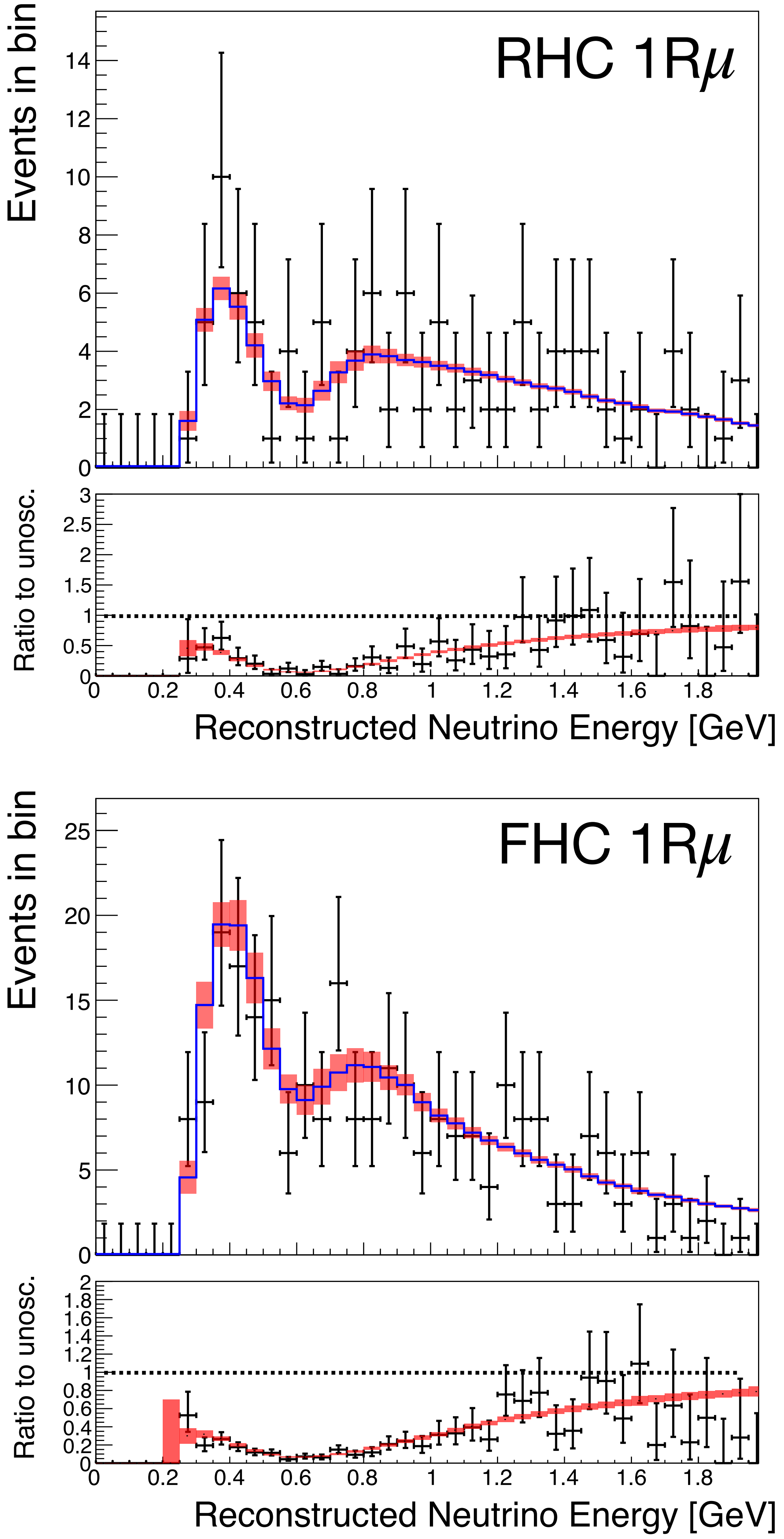
Super-Kamiokande samples

Selection based on ring counting and shape

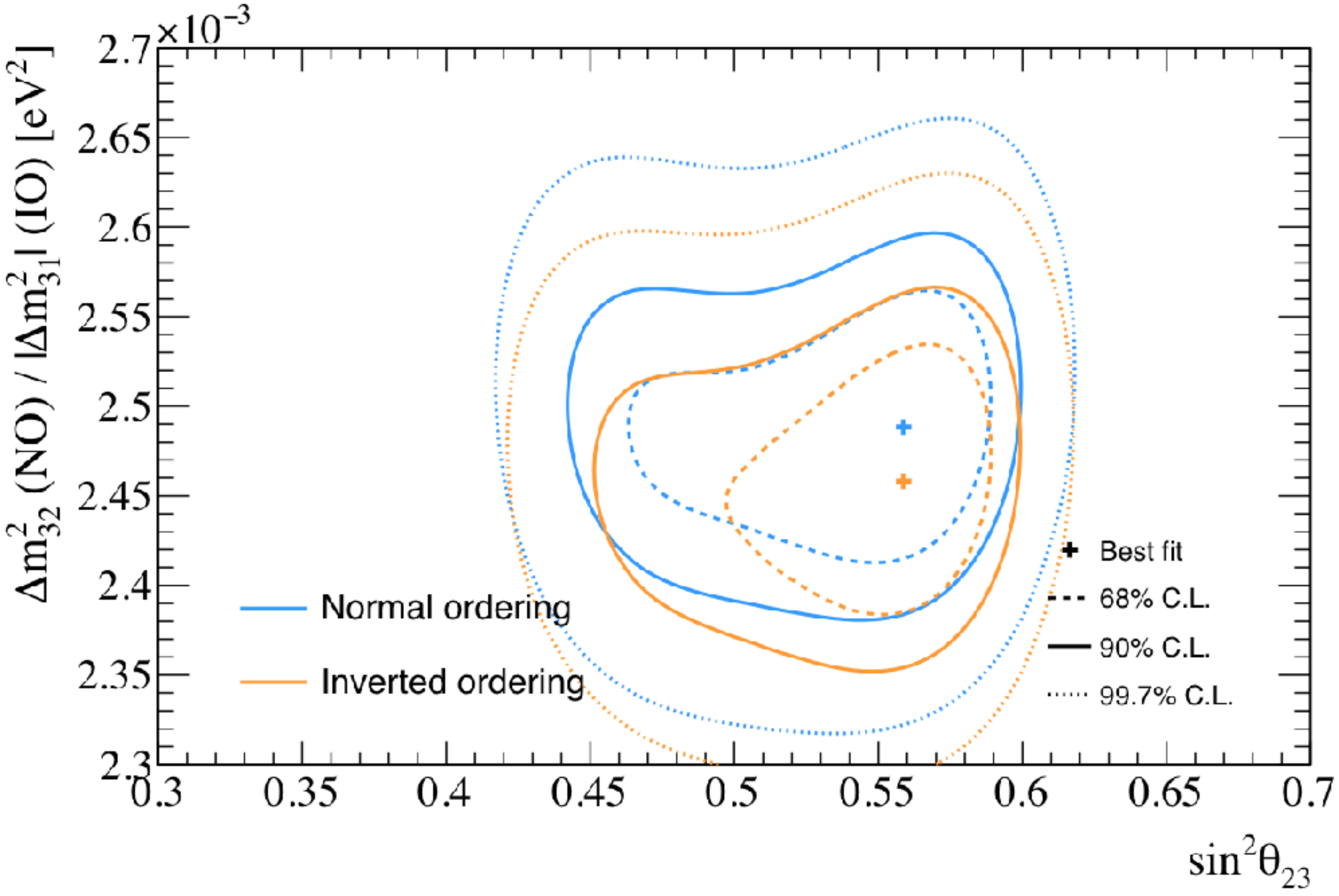
- Two samples with 1 μ-like ring (ν mode and anti-ν mode) $\rightarrow$ ν_μ-CC0π
- Two samples with 1 e-like ring (ν mode and anti-ν mode) $\rightarrow$ ν_e-CC0π
- One sample with 1 e-like ring + 1 Michel electron ring $\rightarrow$ ν_e-CC1π

Sample	FHC 1Rμ	RHC 1Rμ	FHC 1Re	RHC 1Re	FHC 1Re1de
Total uncertainty (after fit) [%]	3.0	4.0	4.7	5.9	14.3
Total uncertainty (before fit) [%]	11.1	11.3	13.0	12.1	18.7

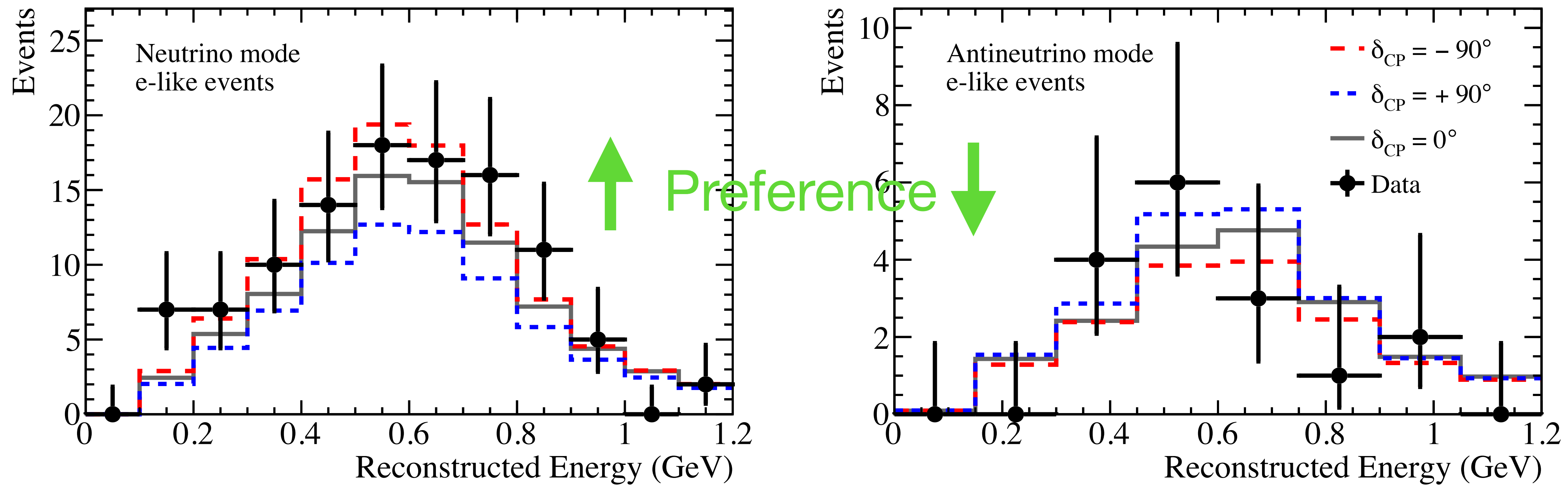
Disappearance analysis



Preference for upper octant

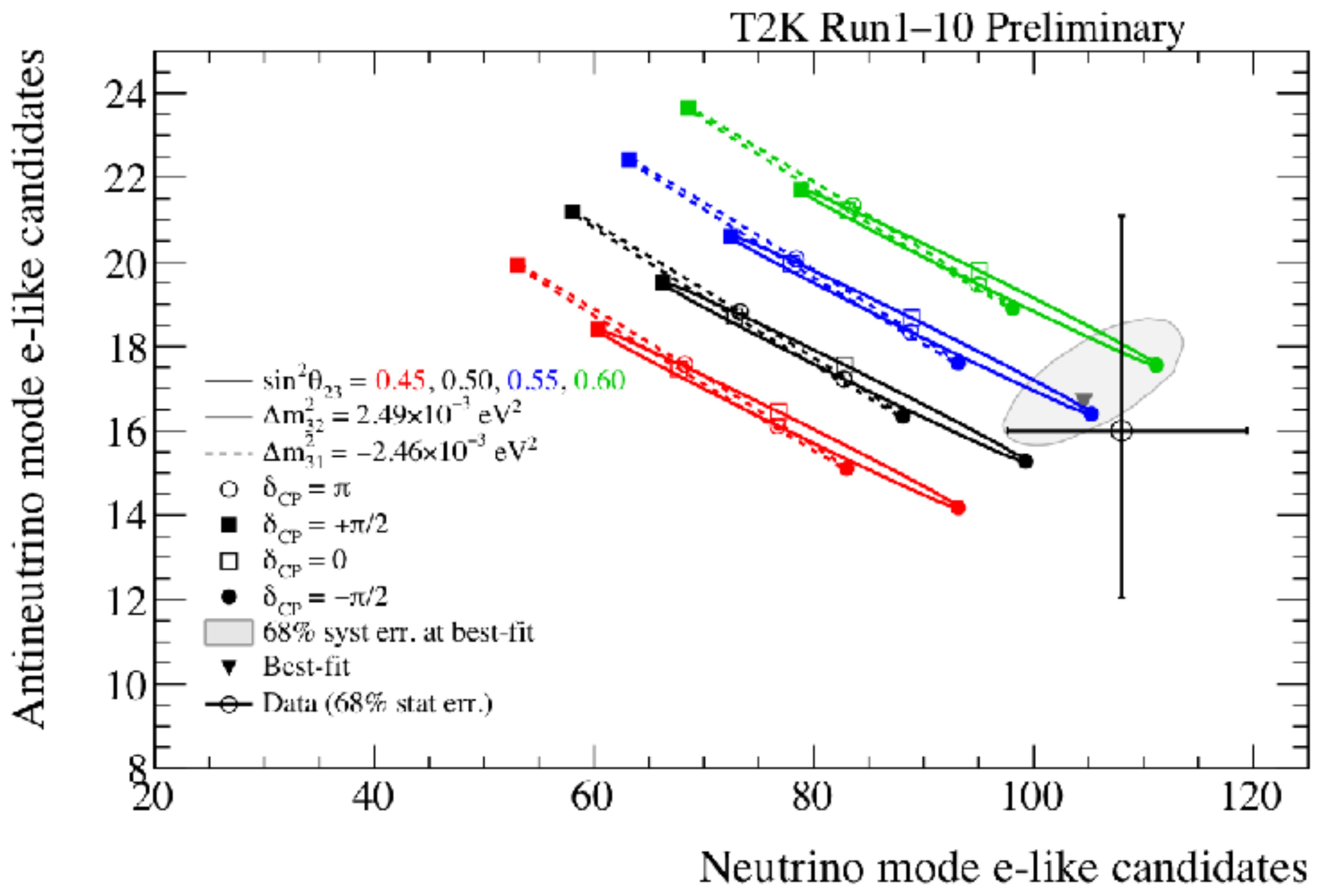


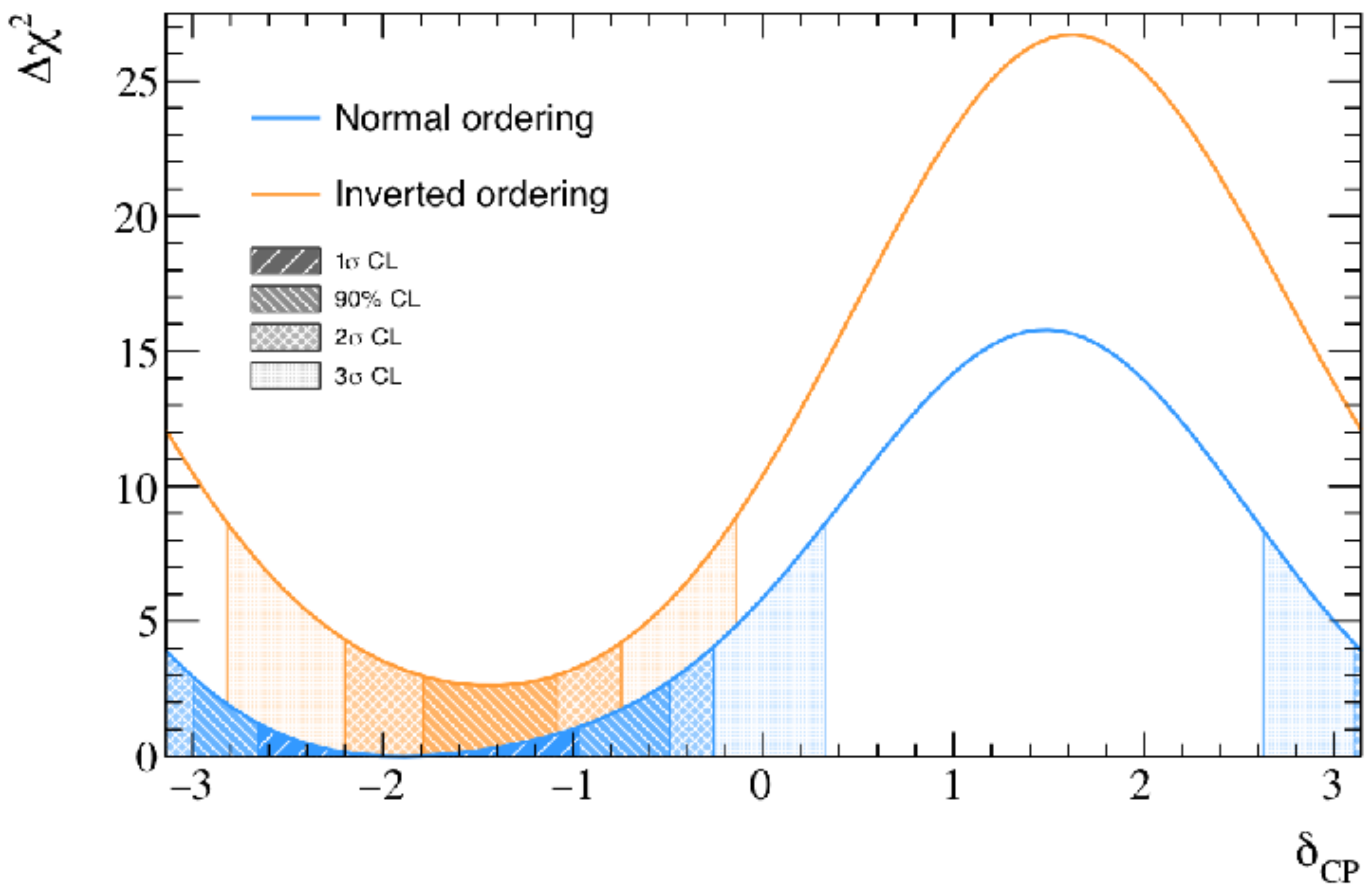
Appearance results



Preference for more ν e-like events and less anti-ν e-like events

$$\rightarrow \delta_{CP} = -\frac{\pi}{2} \text{ favored}$$

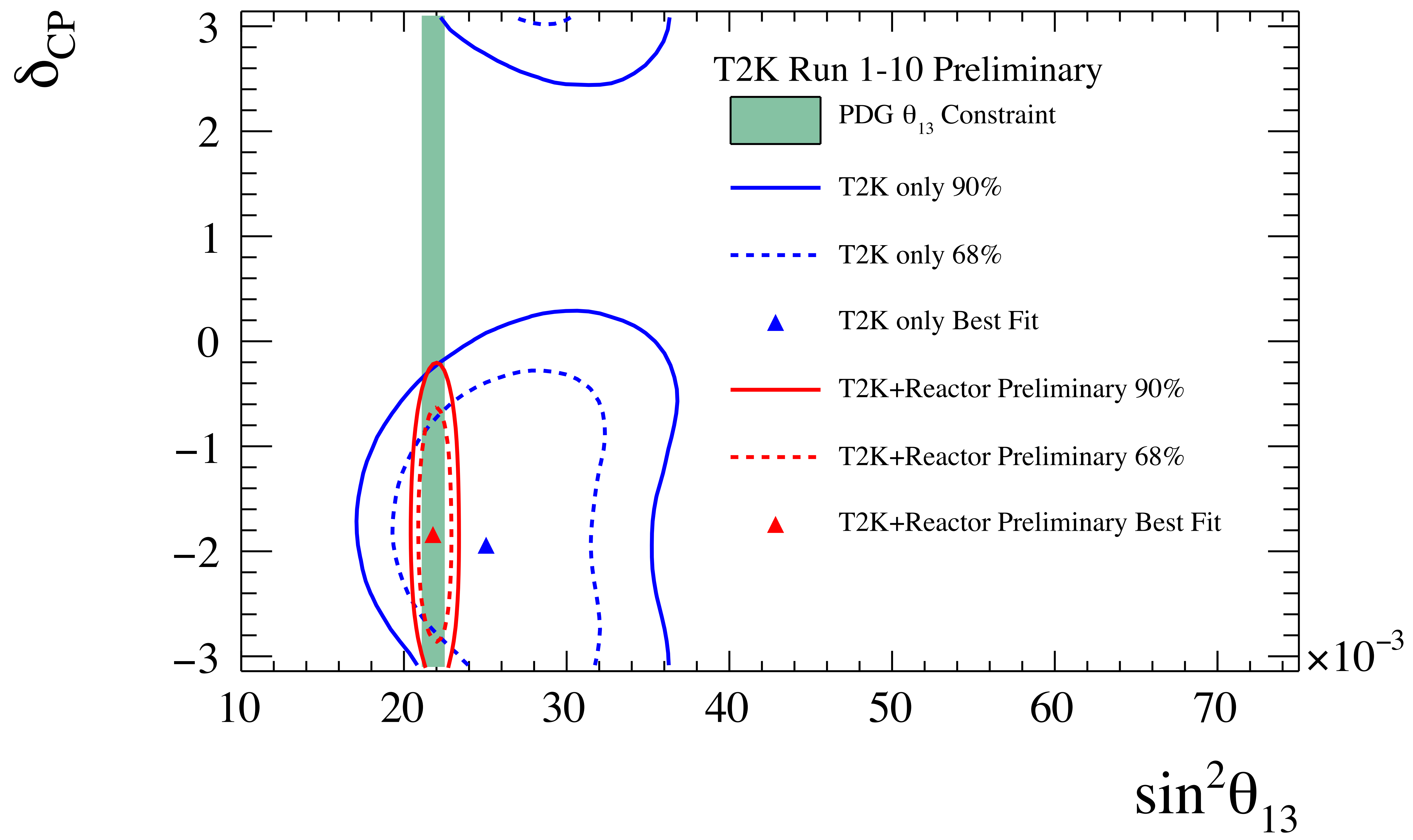




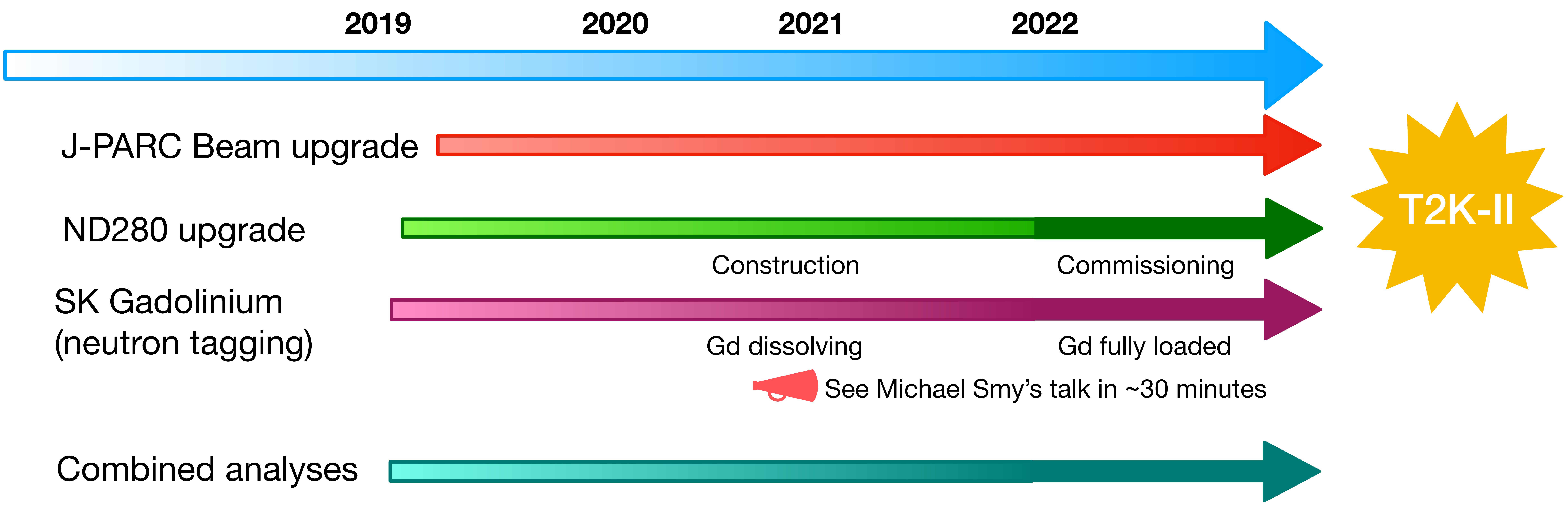
Reactor constraints impact on δ_{CP} vs θ_{13}

Constraints on θ_{13} compatible with PDG2019 at better than 1σ

Using PDG2019 constraint on θ_{13}, better constraint on δ_{CP}



T2K's Bright Future



Combined analyses

Experiments with different neutrino energies have different oscillation probabilities (and potentially different systematic uncertainties)

Two on-going combined analyses efforts:

- T2K beam and Super-Kamiokande atmospheric data
  → very long baseline and higher energy neutrino more sensitive to mass ordering
- T2K and NOνA beam data
  → different baseline and systematic uncertainties

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J-PARC beam upgrade

LPNHE PARIS

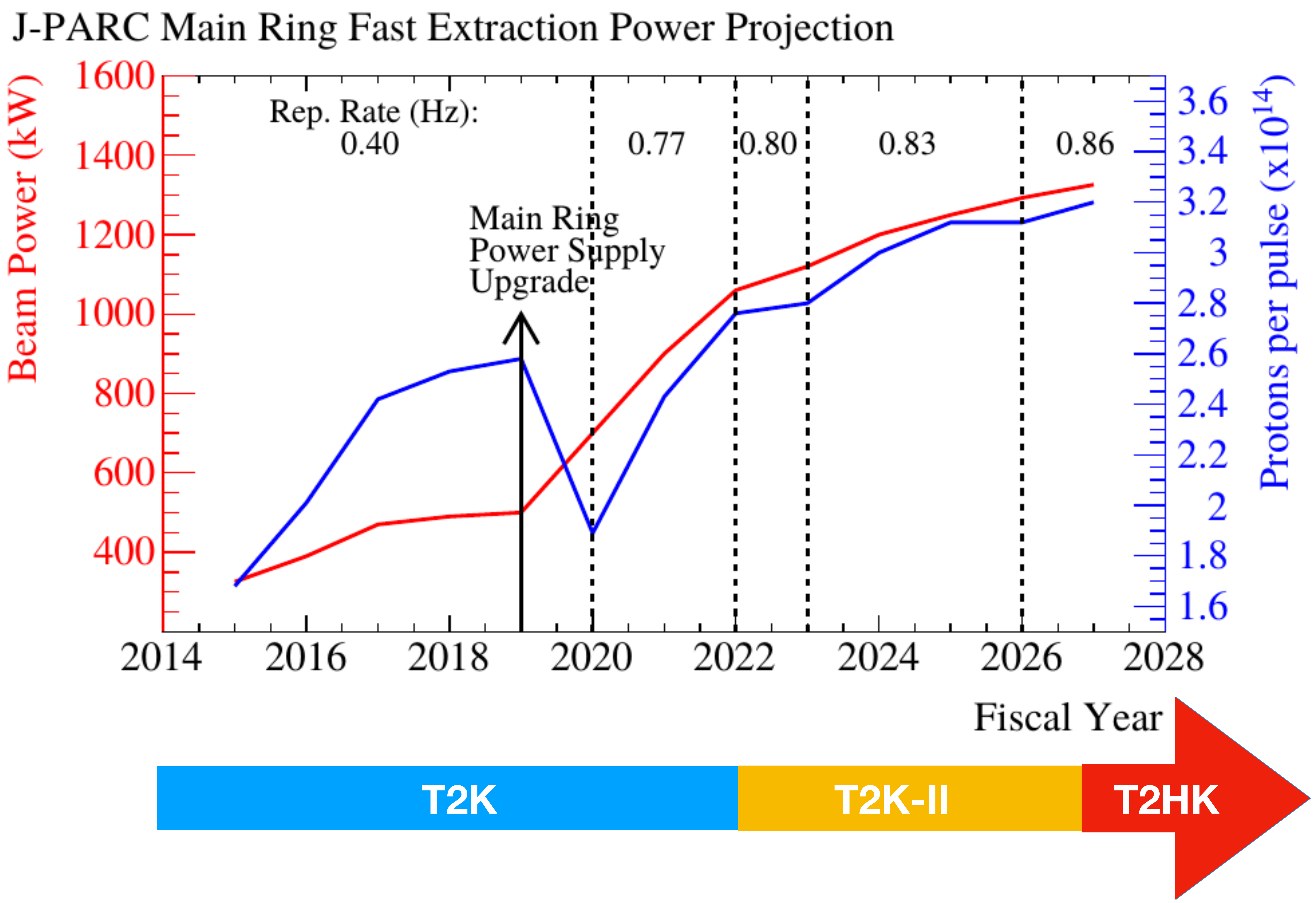
J-PARC main ring upgrades on-going

- 2x more pulse per second
(One pulse every 1.3 seconds)

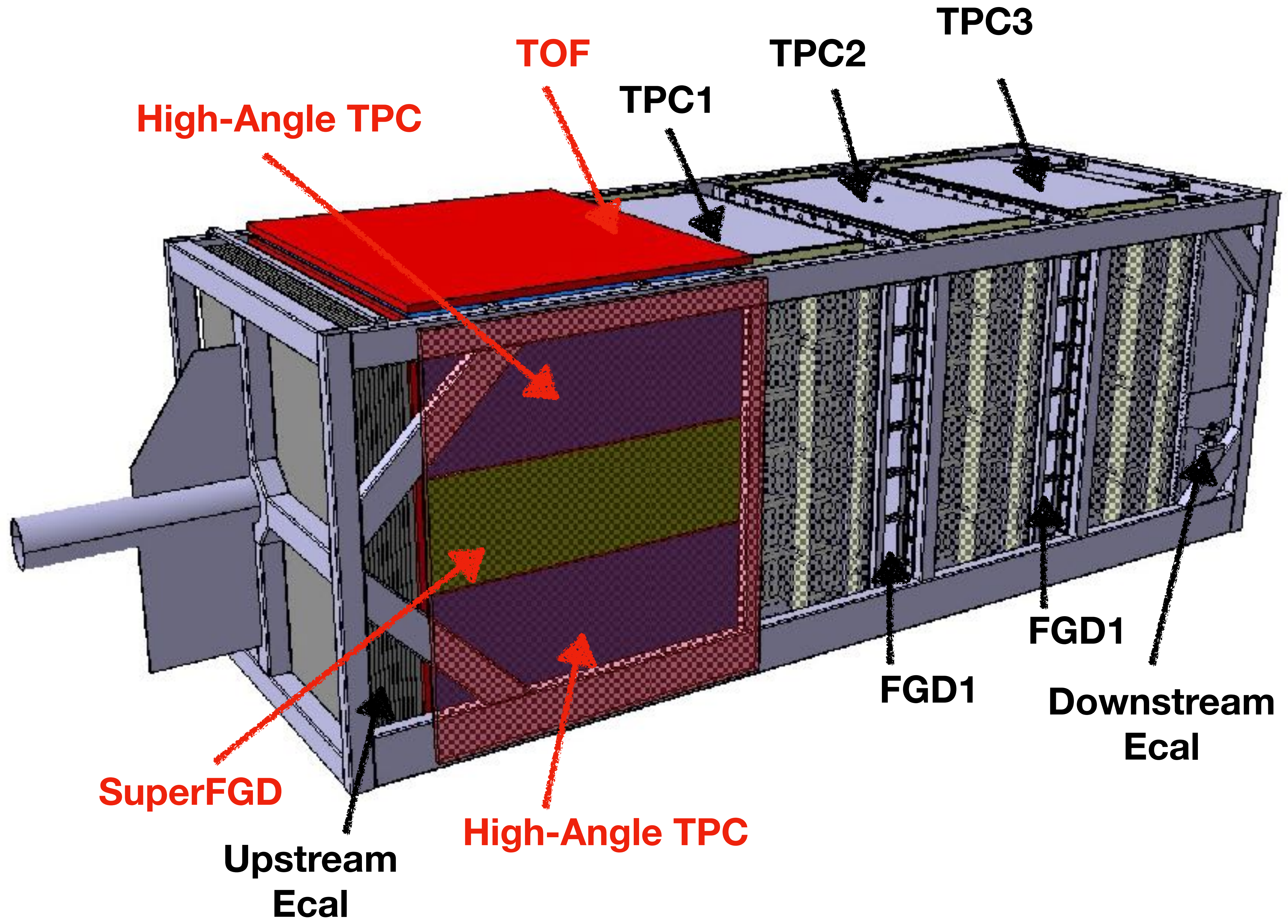
- Increase power from 515 kW
to up to 1.3 MW

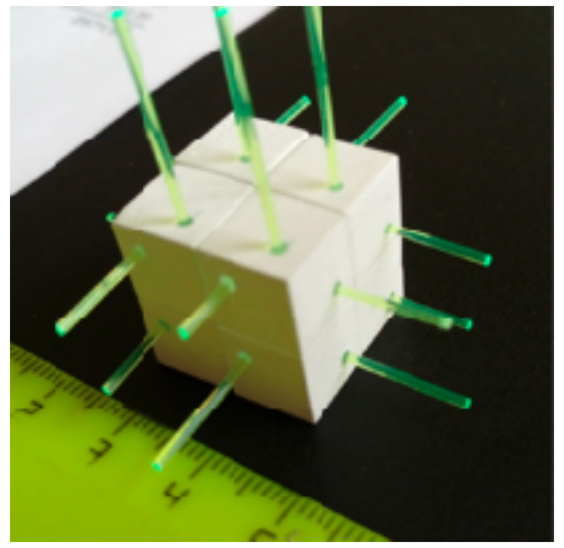
→ Boost statistics during T2K-II

→ Prepare for Hyper-Kamiokande

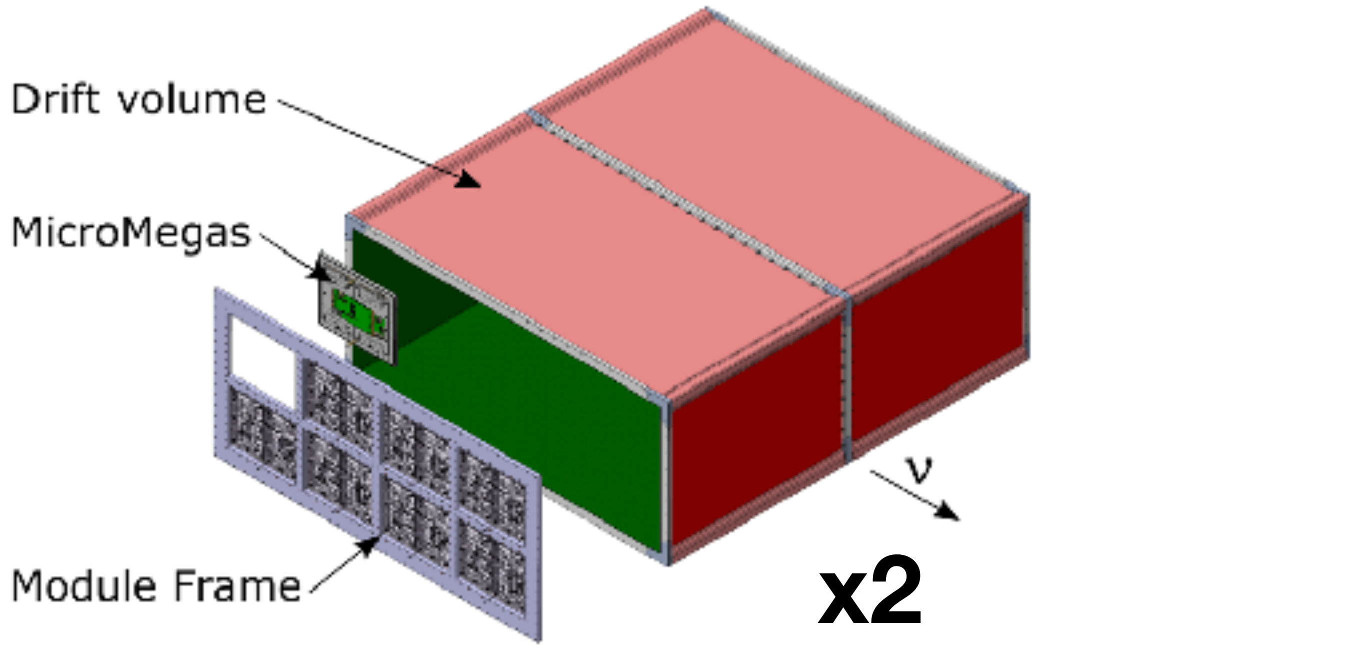


ND280 Upgrade

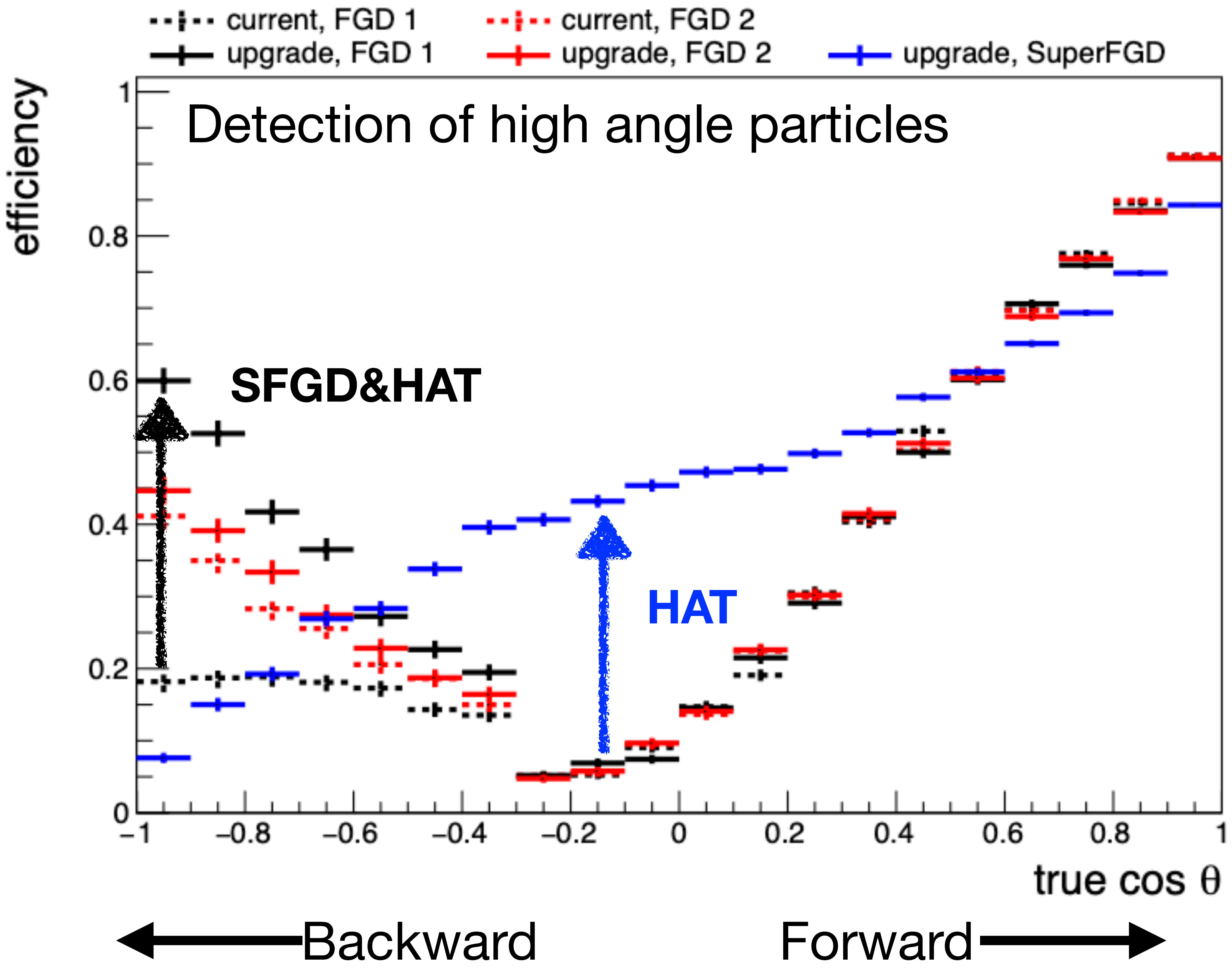




x1,000,000



x2



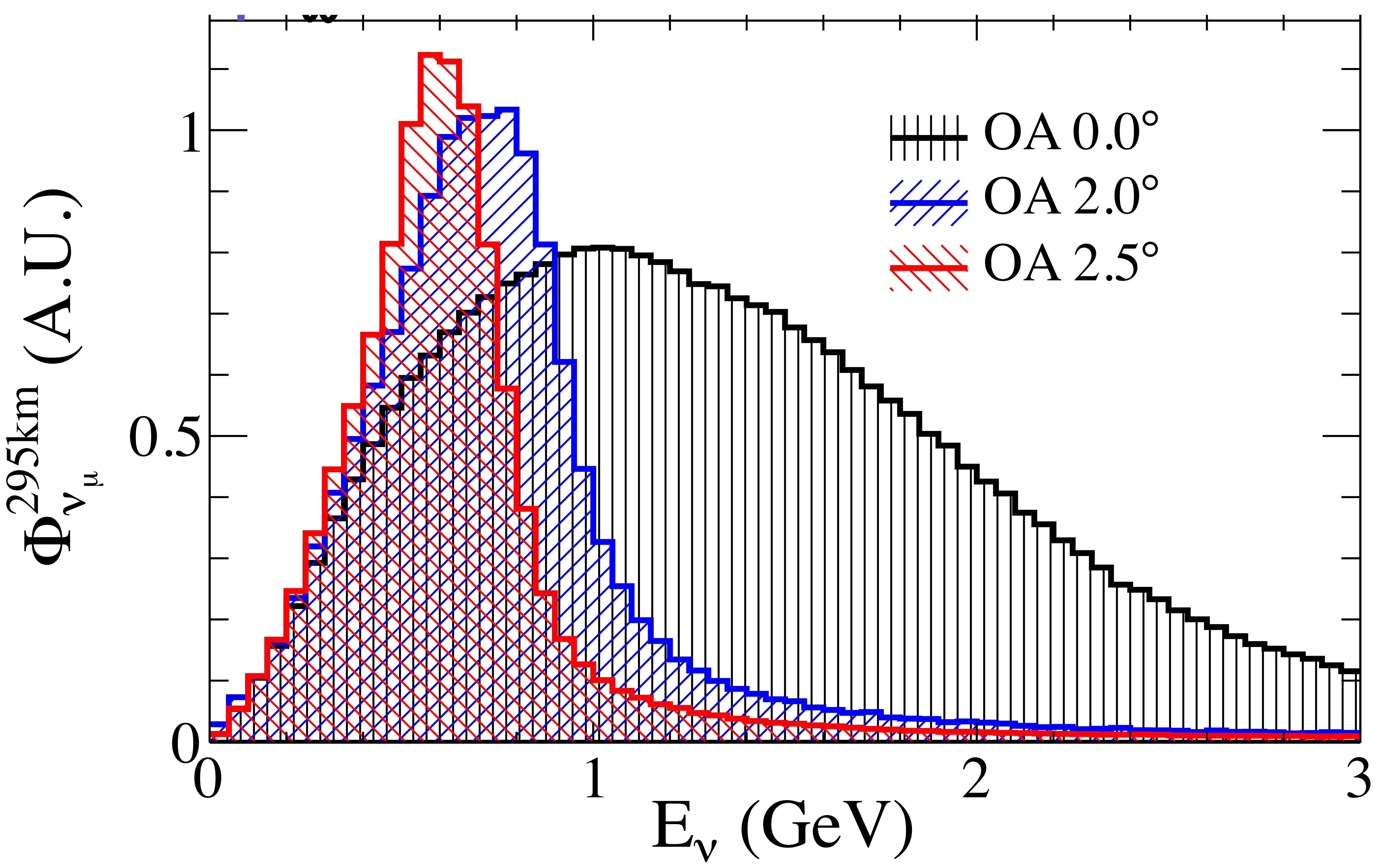
New ν target (SuperFGD) with 1 cm^3 scintillator cubes
High-Angle TPCs using resistive MicroMegas
Time-Of-Flight detector

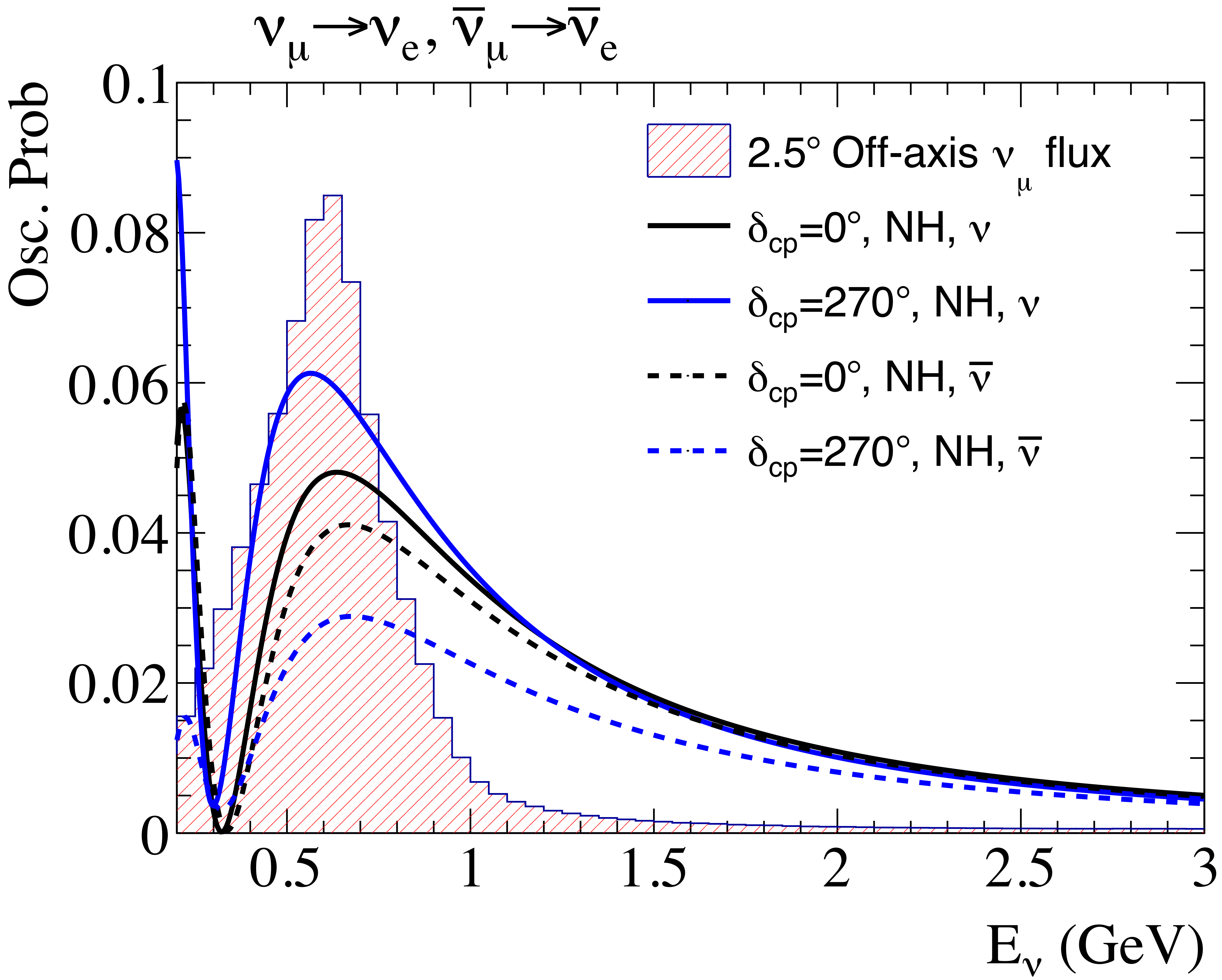
Target total mass: $2 \rightarrow 4$ tons

Summary

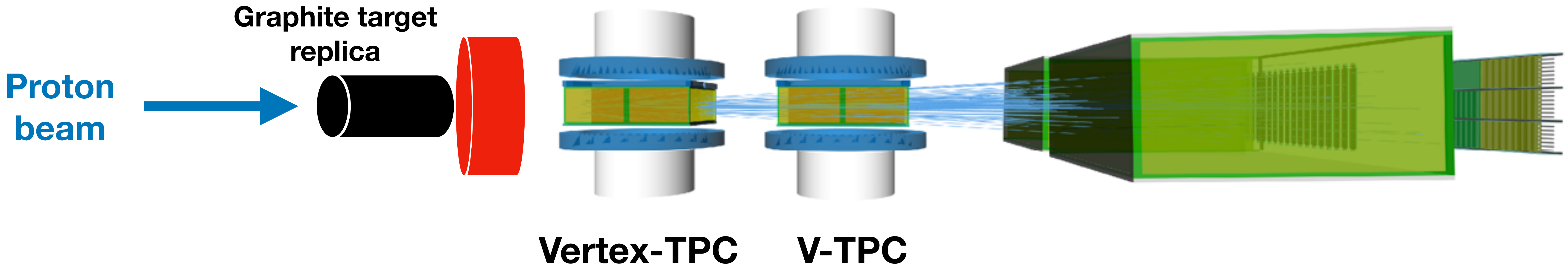
Backups

Off-axis technique



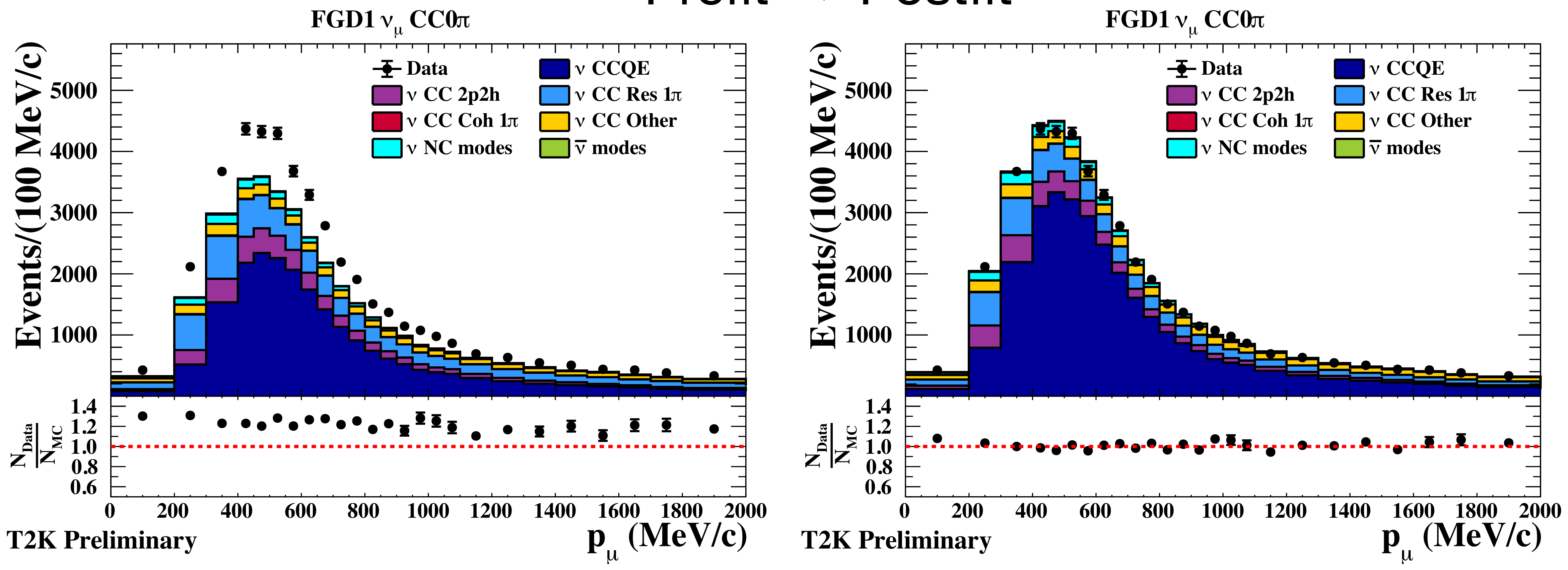


NA61/SHINE



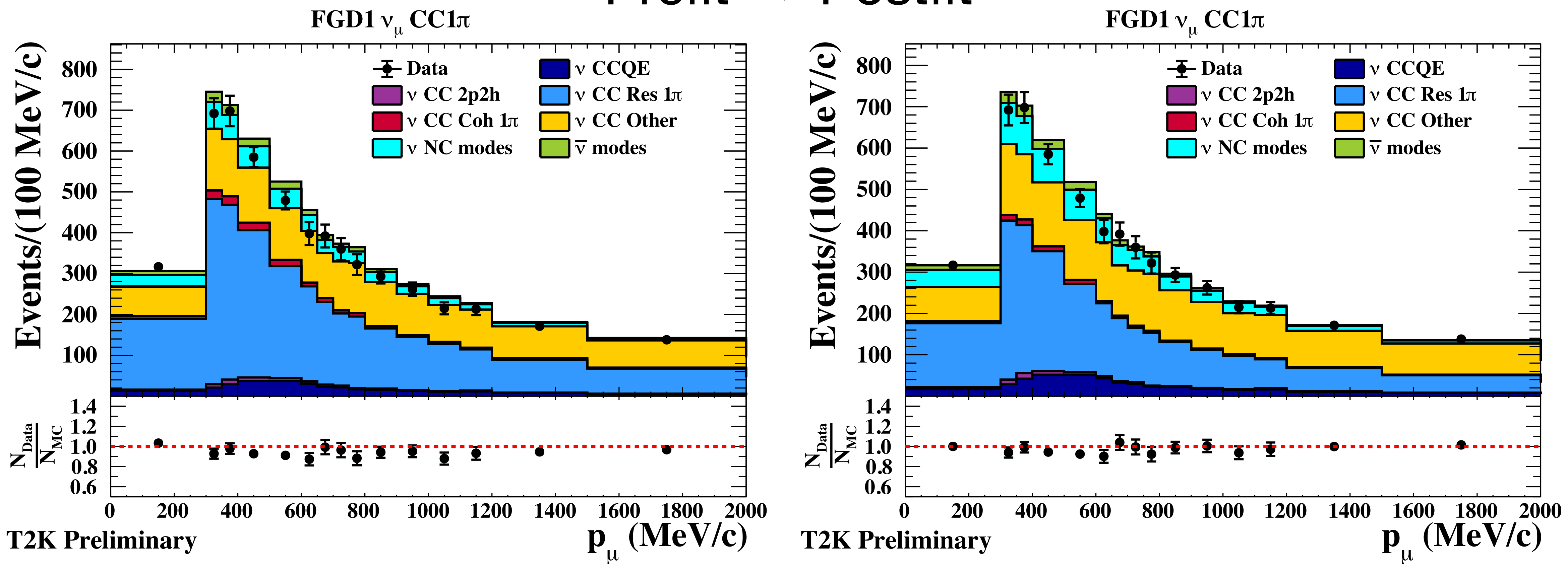
ND280 samples (continued)

Prefit → Postfit



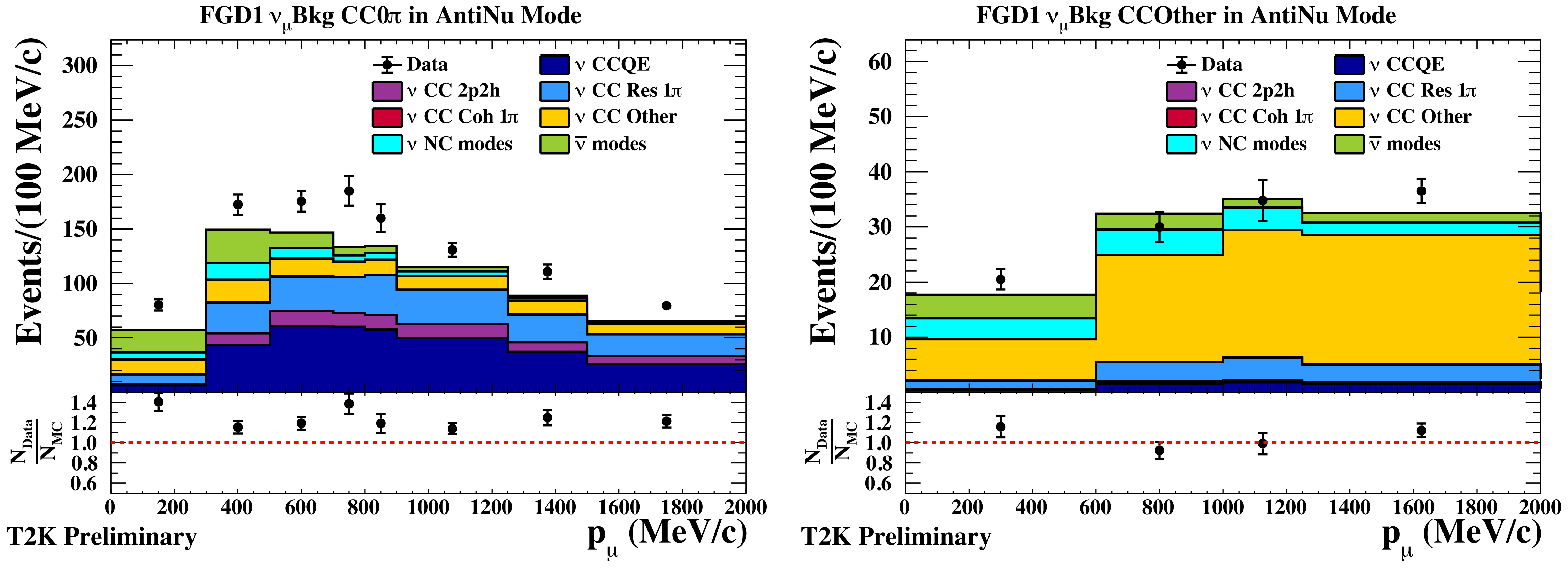
CC0π

Prefit → Postfit



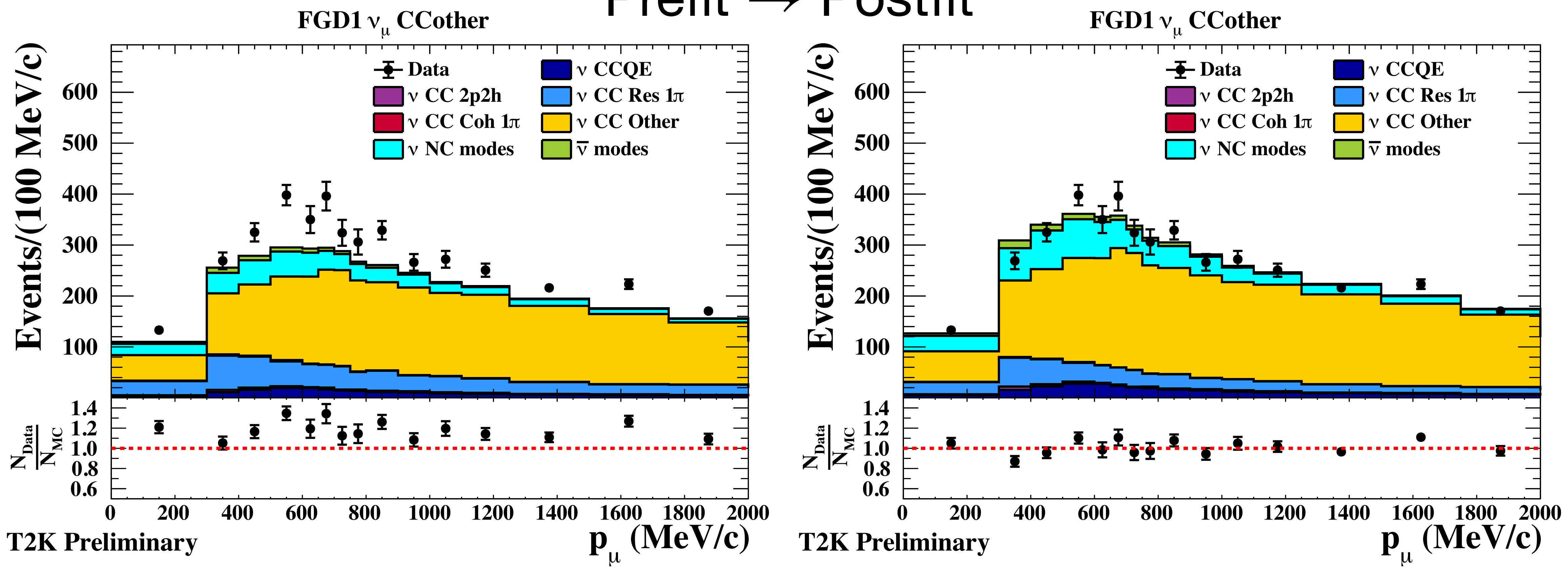
CC1π

Prefit → Postfit



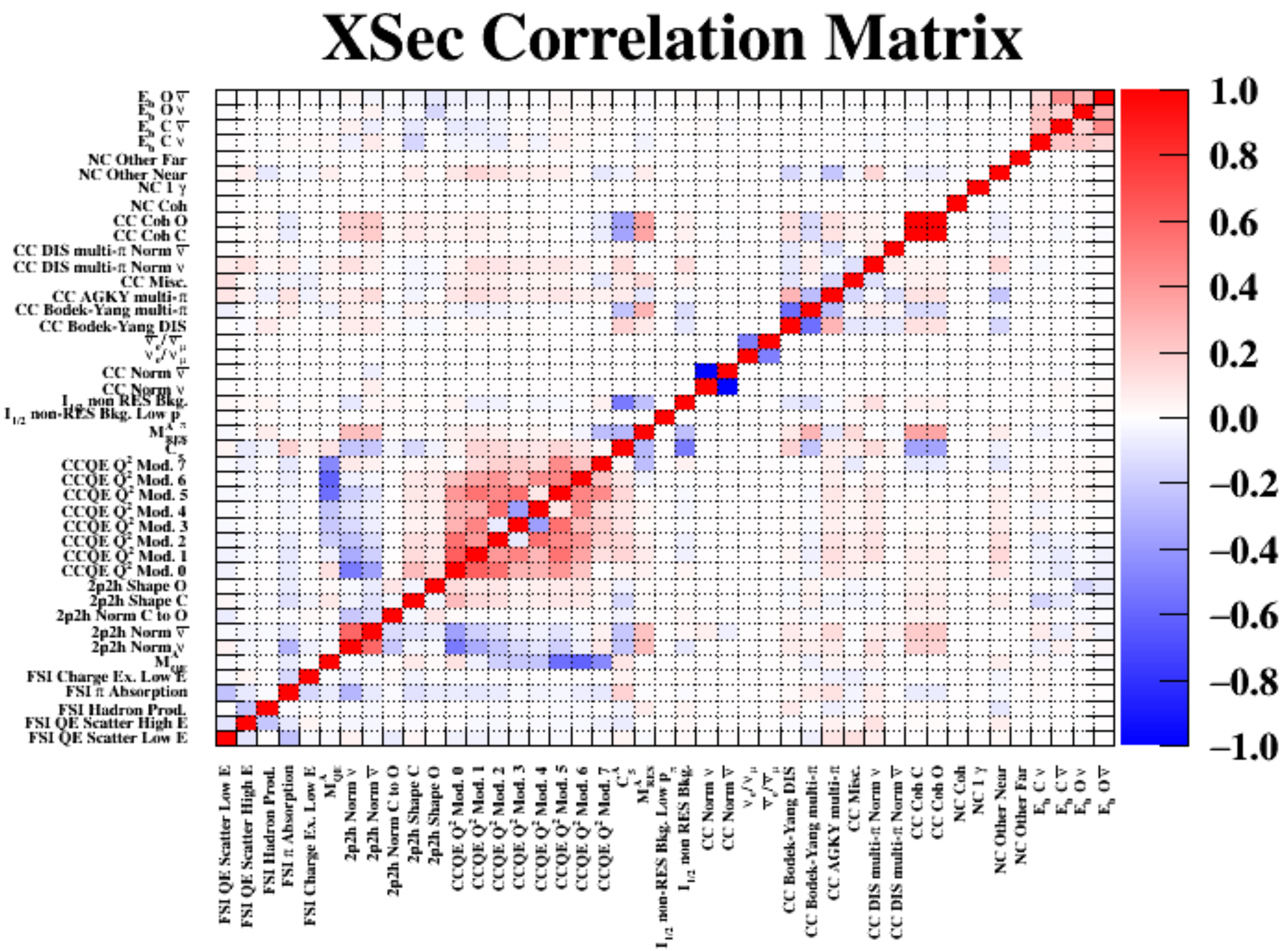
CCOther Background

Prefit → Postfit



CCNπ

Cross-section correlation matrix



T2K Preliminary