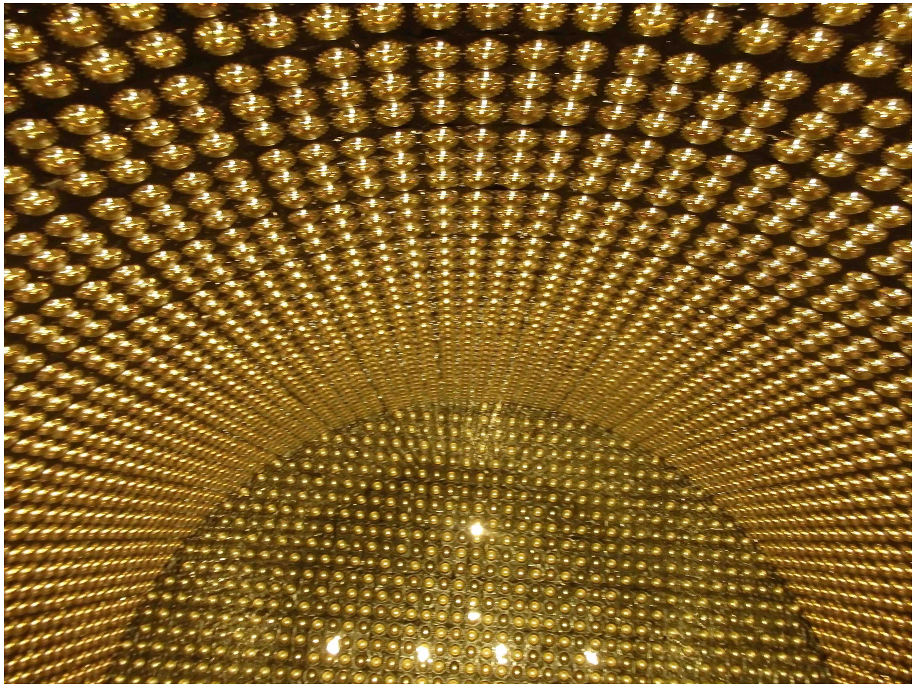
Overview and update from T2K

Dr Laura Kormos
on behalf of the
T2K Collaboration

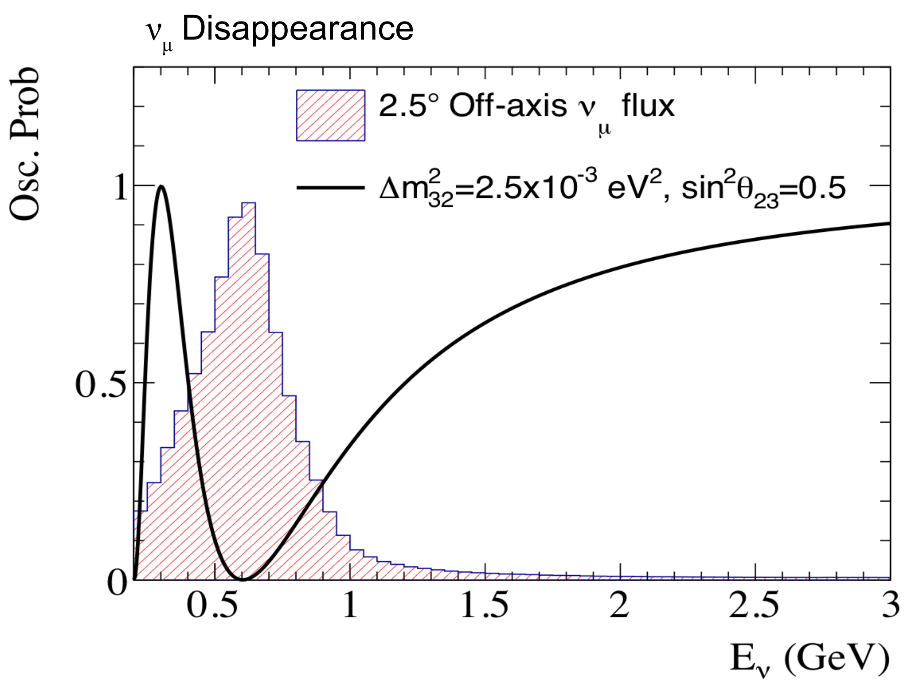
- T2K (Tokai to Kamioka)
- Updates
- Latest oscillation results
- Latest cross-sections
- Other recent T2K news
- Upcoming excitement

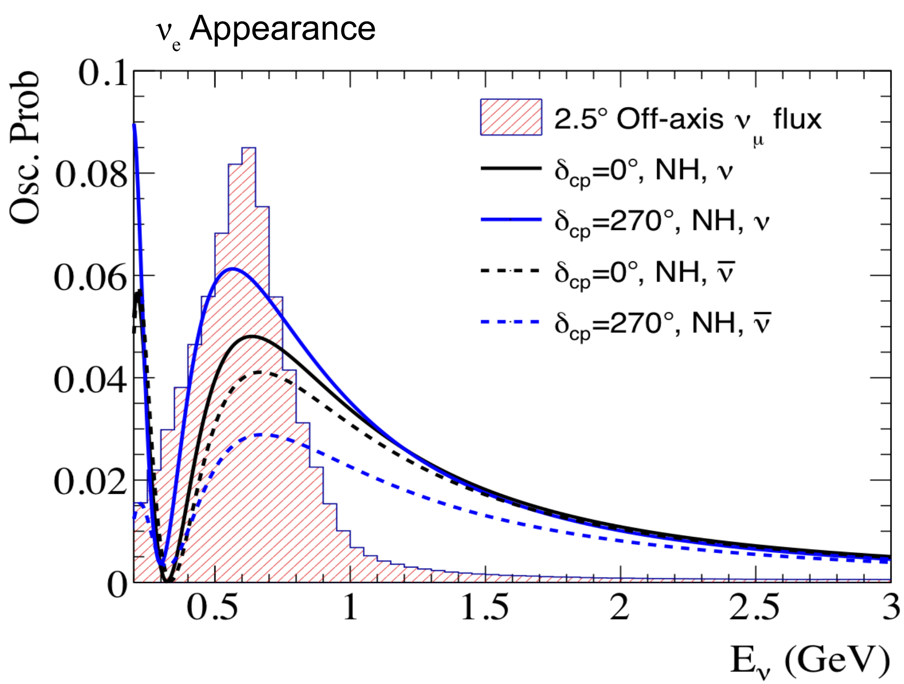


T2K
Tokai to Kamioka

- J-PARC beam
  - ν_μ , $\bar{\nu}_\mu$
- Near detectors:
  - INGRID on-axis
  - ND280 off-axis
- Far detector:
  - Super-Kamiokande (SK) off-axis

Oscillations at T2K



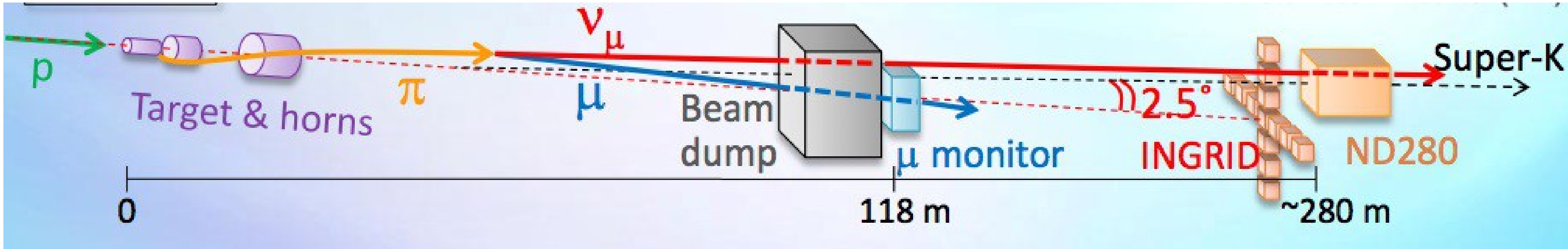


- LO* dependence on $\sin^2 2\theta_{23}$
  - hard to distinguish $\theta_{23}>45°$ from $\theta_{23}<45°$
- LO dependence on $|\Delta m^2_{32}|$
  - doesn't depend on sign of mass splitting

(* Leading Order)

- LO dependence on $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$
  - can separate $\theta_{23}>45°$ from $\theta_{23}<45°$
- Sub-leading dependence on $\sin(\delta_{CP})$
  - can detect CP violation (~30% effect)
- Sub-leading dependence on $\pm\Delta m^2_{32}$
  - ~10% matter effect

The T2K beam

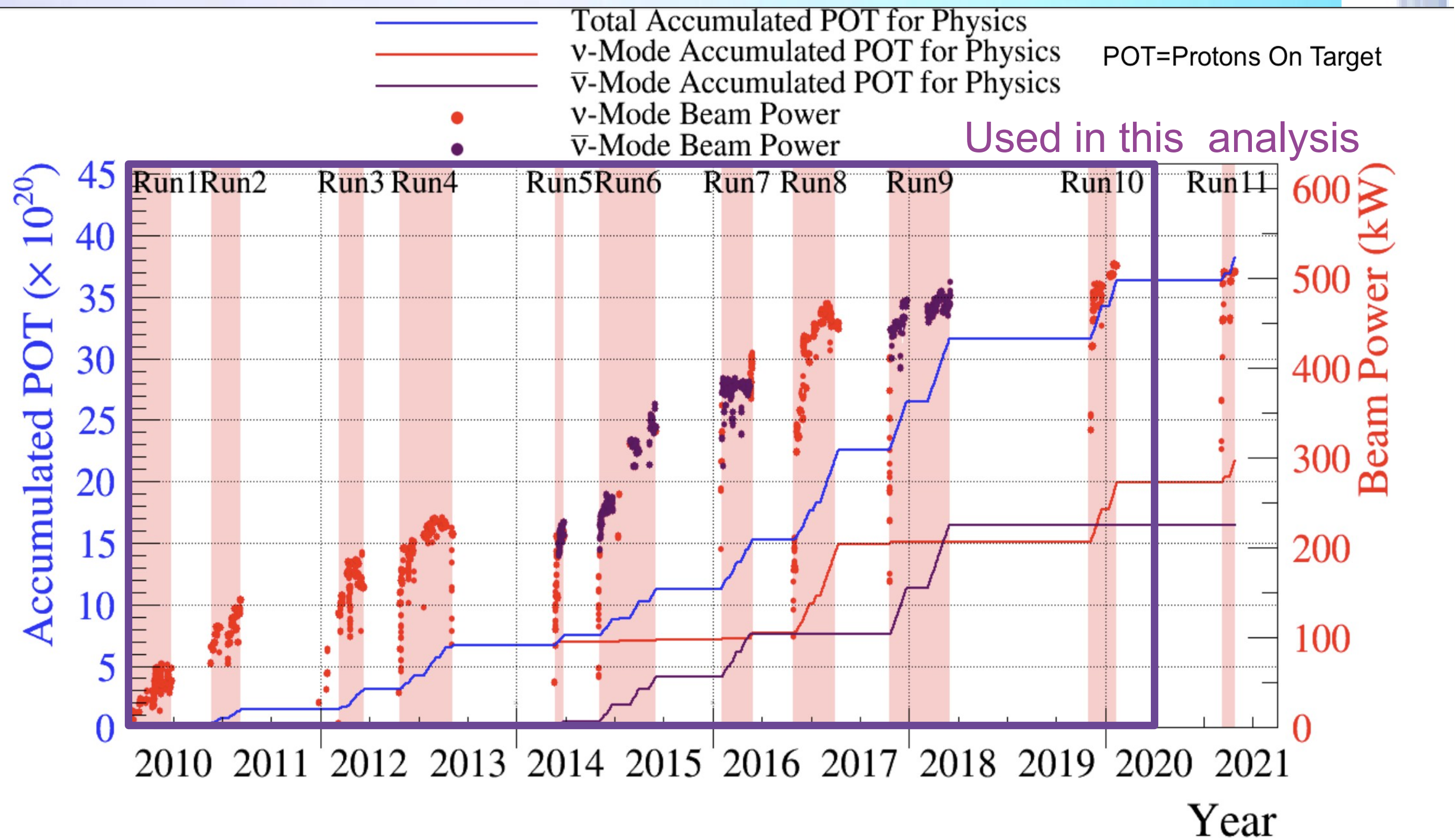


- Primarily ν_μ beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (forward horn current, FHC, or neutrino mode)
- Reverse polarity for $\bar{\nu}_\mu$ beam:

  $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

  (reverse horn current, RHC, or antineutrino-mode)

POT=Protons On Target



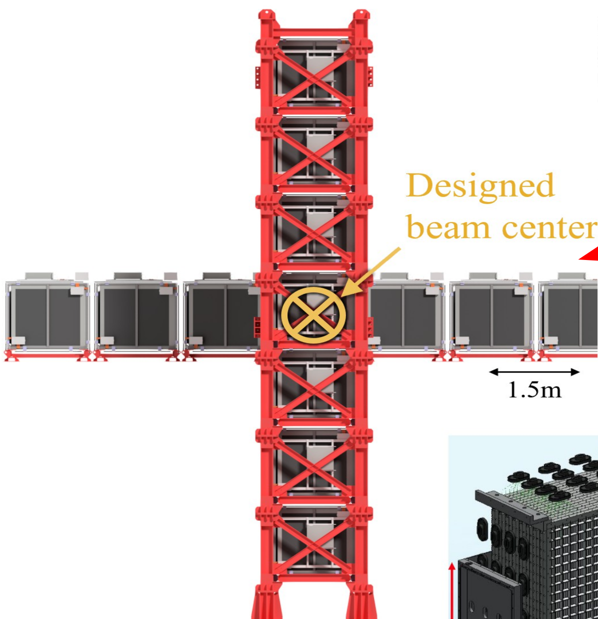
23 Jan 2010 – 27 Apr 2021
POT Total: 3.82×10^{21}
(maximum power 522.6 kW)

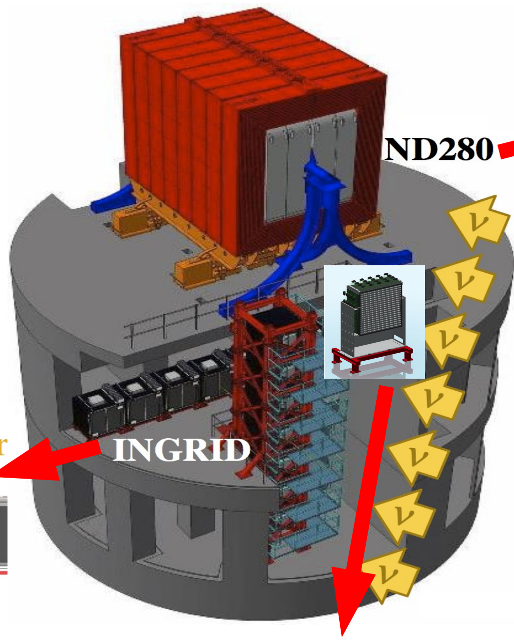
ν-mode: 2.17×10^{21} (56.8%)
$\bar{\nu}$-mode: 1.65×10^{21} (43.2%)

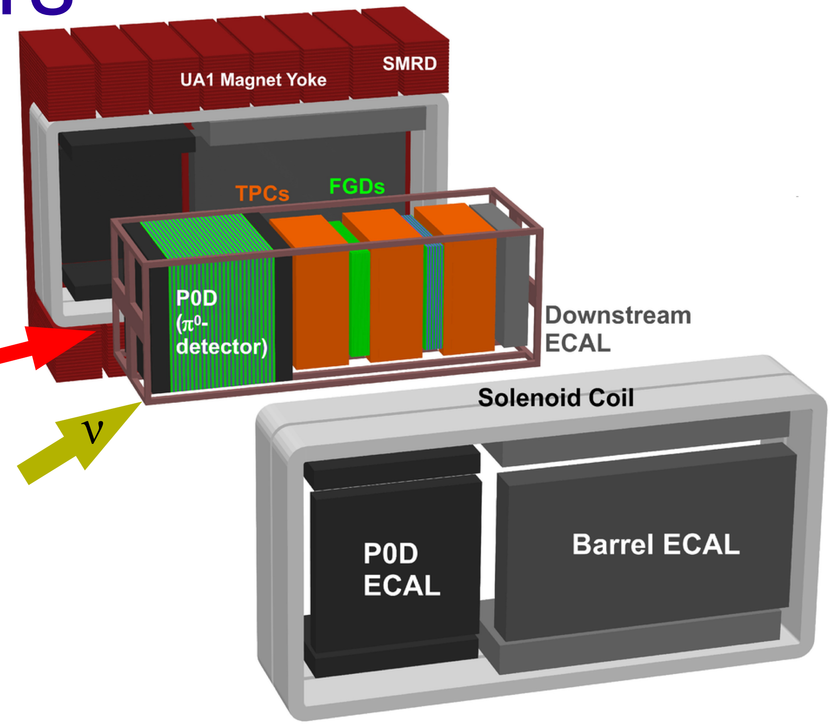
Near detectors

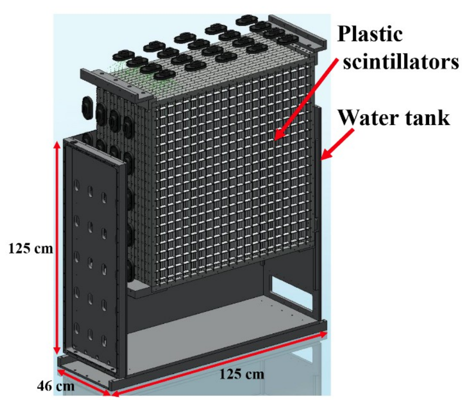
INGRID

- Identical modules in cross
- Iron and plastic scintillator tracking calorimeter
- Monitors ν, $\bar{\nu}$ beam direction and stability









Wagasci

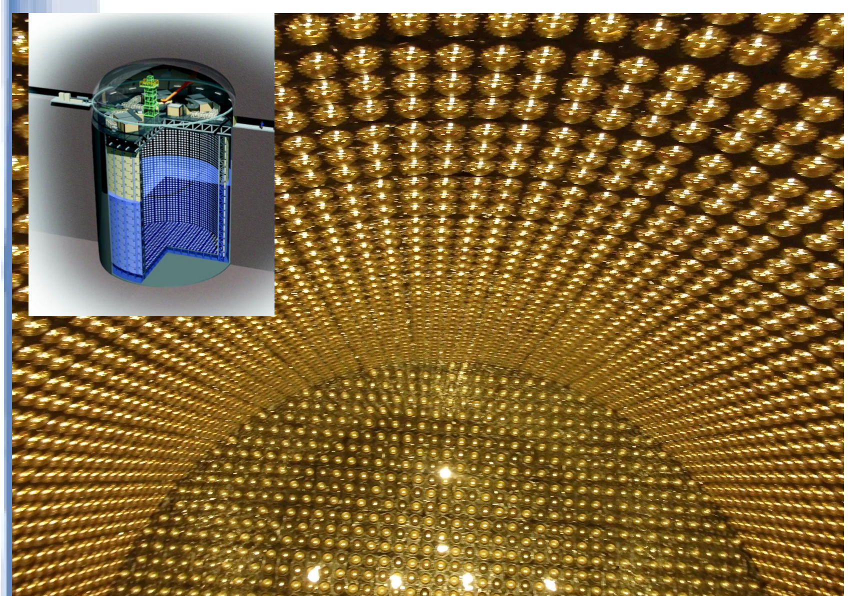
- Water target
- Immersed scintillator planes
- 1.5° off-axis

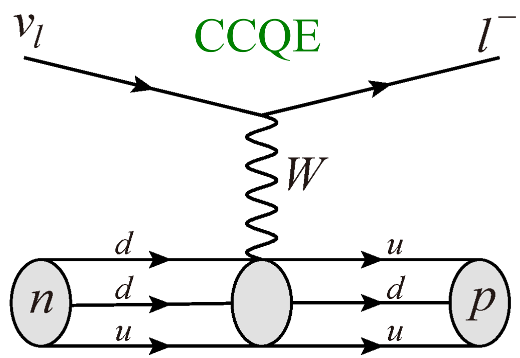
ND280

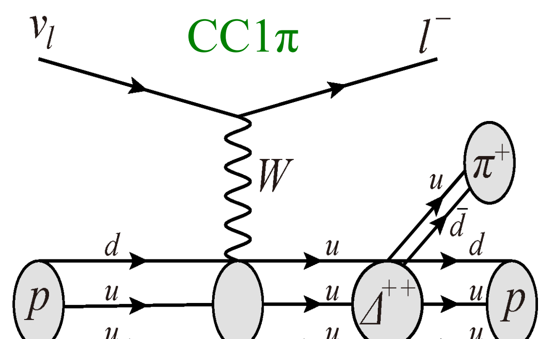
- **Off-axis (2.5°) detector**
- 0.2 T magnet
- Trackers, calorimeters, muon range detectors
- Water, carbon, lead, targets.
- Beam ν_e, flux, cross sections, exotics

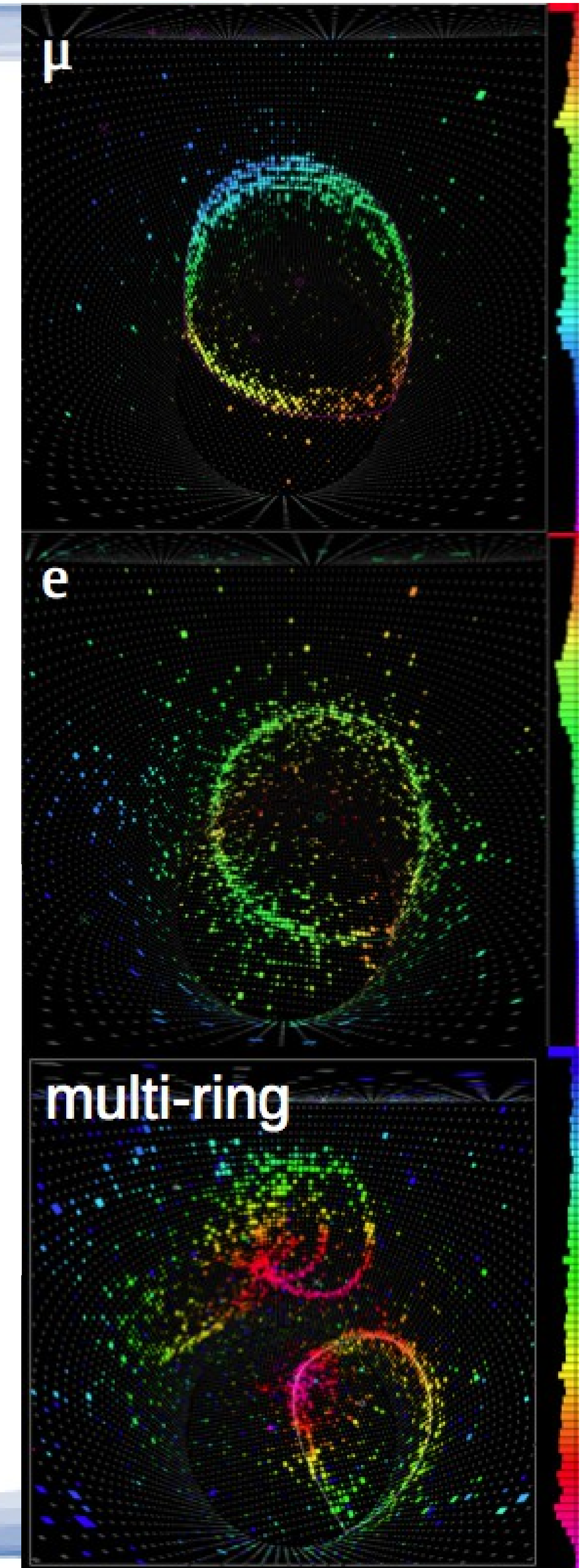
Far detector: Super-Kamiokande (SK)

- 50 kton Water-Cherenkov detector
- 2.5° off axis (same as ND280)
- Excellent e/μ separation, π^0 rejection
- Select 1-ring, CCQE-enriched sample
- Select CC1π^+ sample (neutrino-mode)
- ν kinematics derived from lepton



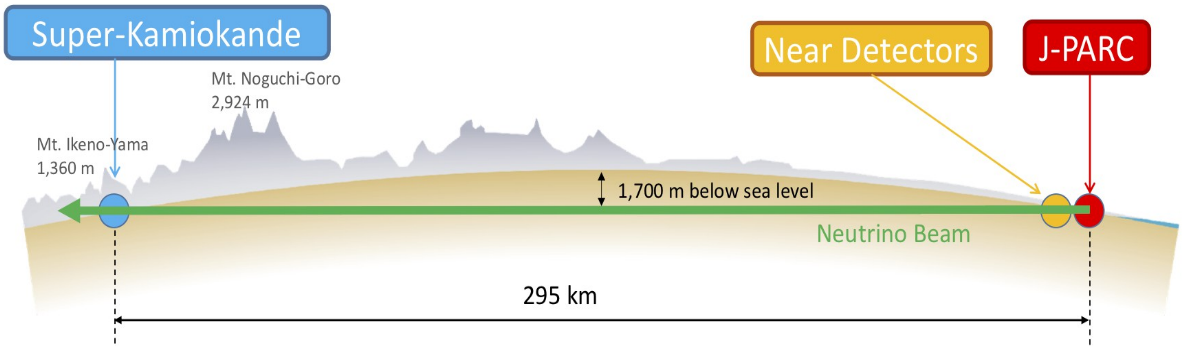






T2K oscillation analysis overview

- Measure N events at Near Detector, ND
- Tune the models to fit the ND data
- Compare tuned models to Far Detector, FD, data to extract oscillation probability (P_{Osc})



Φ, σ, ε, P_{Osc} all depend on E_ν

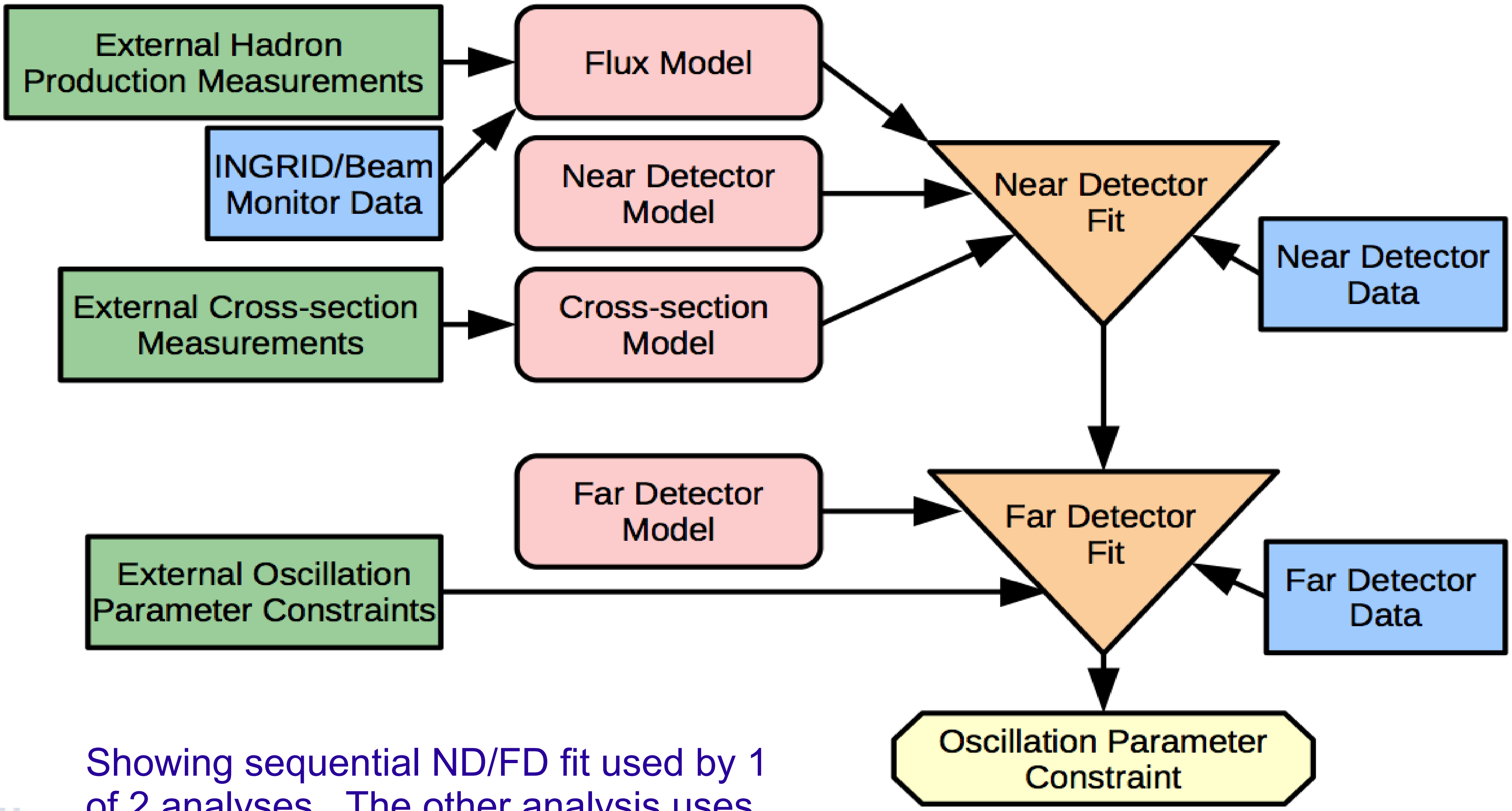
full shape analysis

- $N_{ND} \sim \Phi_{ND} \bullet \sigma_{ND} \bullet \varepsilon_{ND}$

  Observable Flux Cross section Detector response

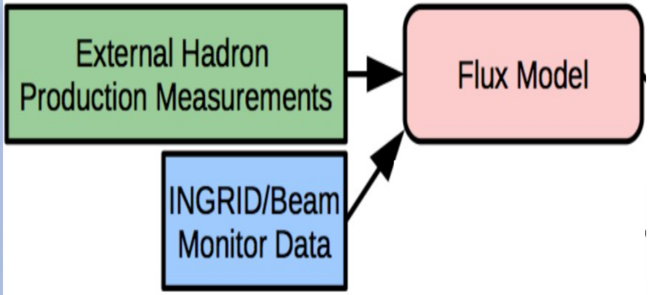
- $N_{FD} \sim \Phi_{FD} \bullet \sigma_{FD} \bullet \varepsilon_{FD} \bullet \mathbf{P_{Osc}}$

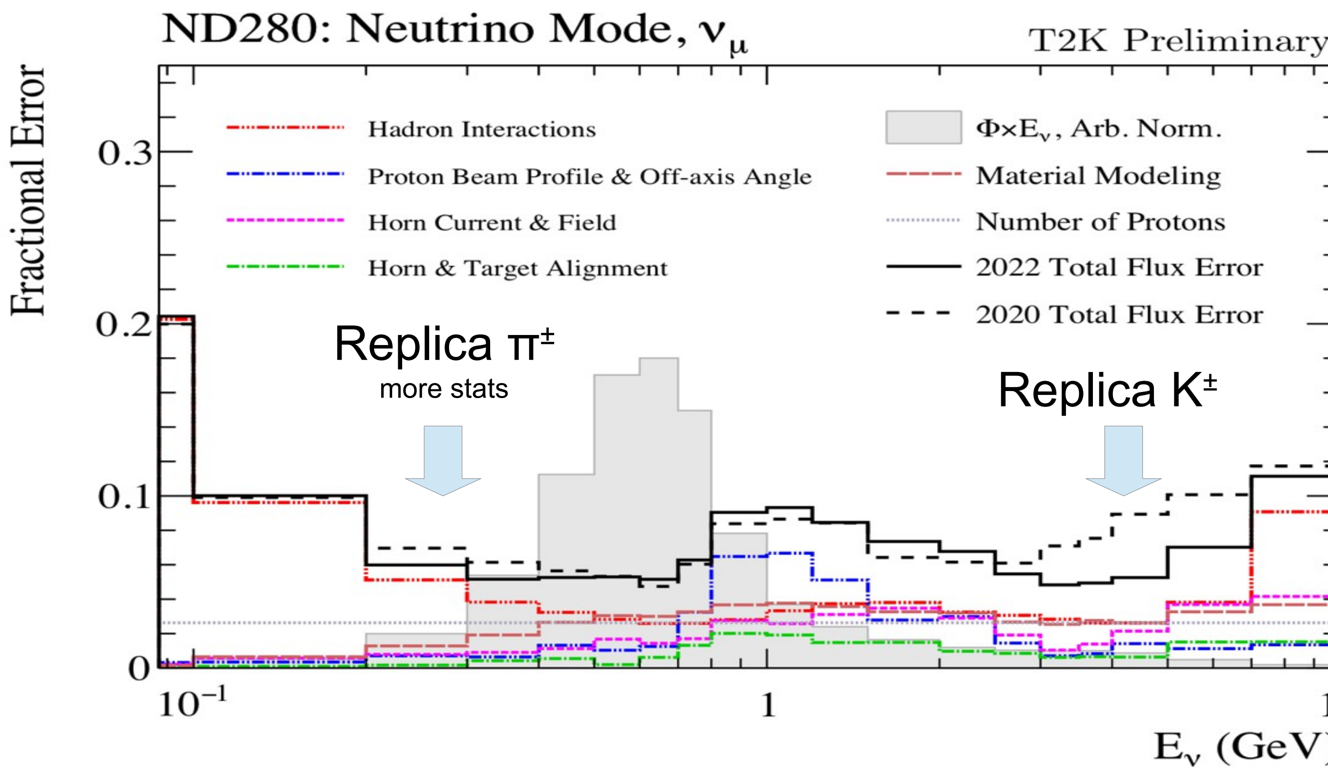
T2K oscillation analysis overview



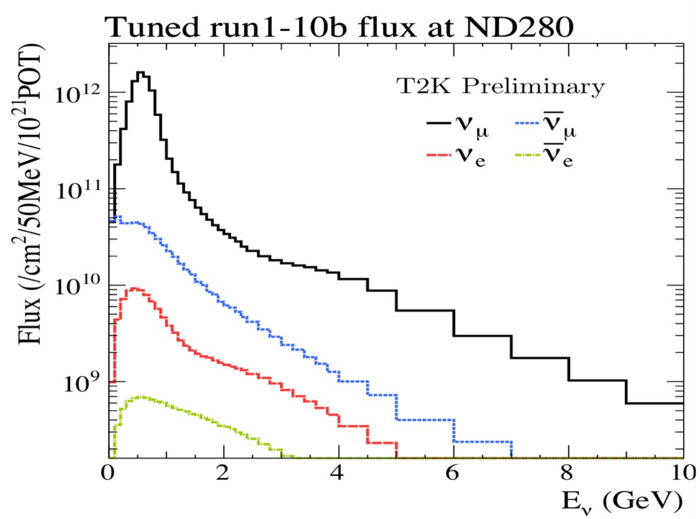
Showing sequential ND/FD fit used by 1 of 2 analyses. The other analysis uses simultaneous fit to ND/FD.

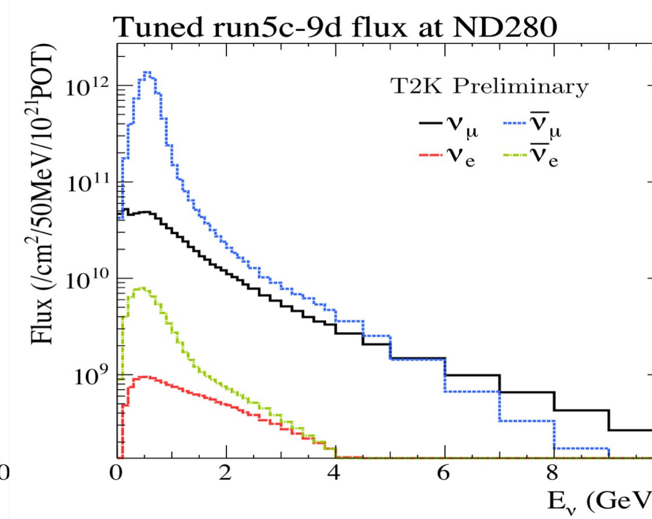
Flux prediction and uncertainties





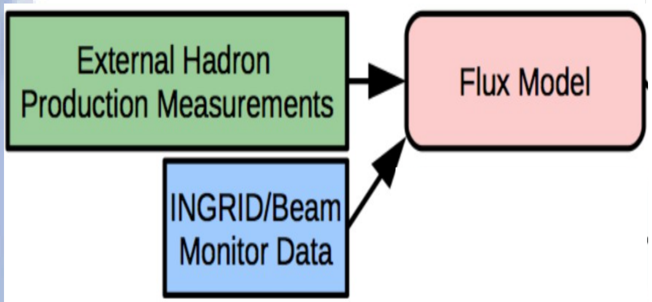
- Flux simulation (FLUKA/GEANT3/ GCALOR)
- Tuned using external data (NA61/SHINE hadron production measurements)
- UPDATE: Moved from using 2009* to 2010** T2K replica target data.
  - more statistics for $\pi^\pm$ production.
  - adds $K^\pm$ and p data.

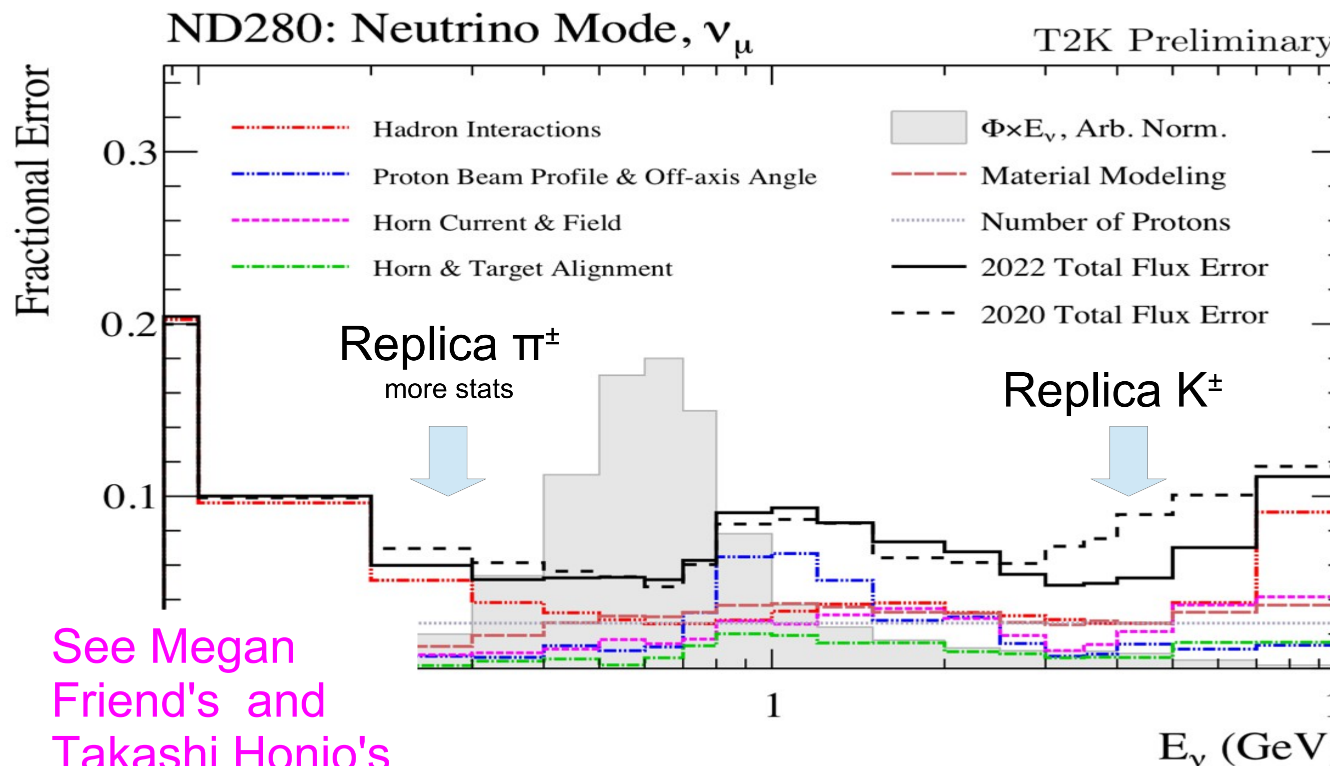




*Eur. Phys. J. C76, 617 (2016)
**Eur. Phys. J. C79, 100 (2019)

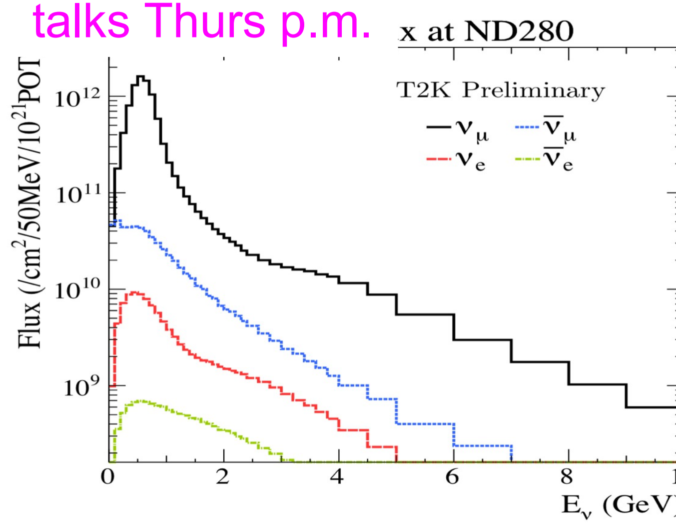
Flux prediction and uncertainties

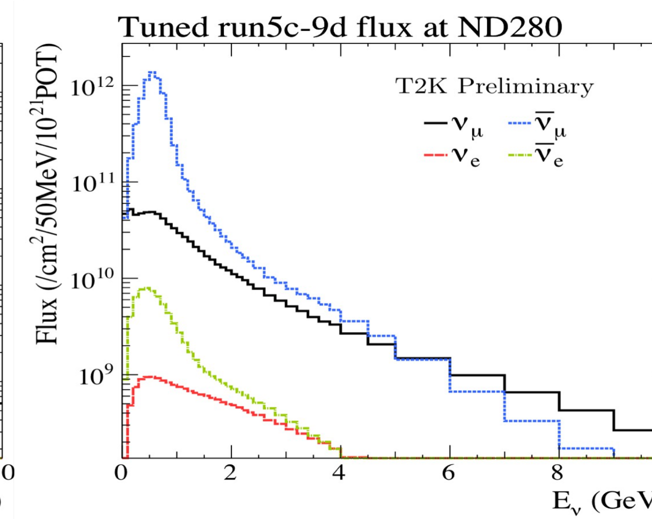




- Flux simulation (FLUKA/GEANT3/ GCALOR)
- Tuned using external data (NA61/SHINE hadron production measurements)
- UPDATE: Moved from using 2009* to 2010** T2K replica target data.
  - more statistics for $\pi^\pm$ production.
  - adds $K^\pm$ and p data.

See Megan Friend's and Takashi Honjo's talks Thurs p.m.





*Eur. Phys. J. C76, 617 (2016)
**Eur. Phys. J. C79, 100 (2019)

Cross-section models

External Cross-section Measurements → Cross-section Model

- NEUT generator tuned to external data from MINERνA, bubble chambers, etc, and to ND280 data.
-

- Updates:

CCQE:

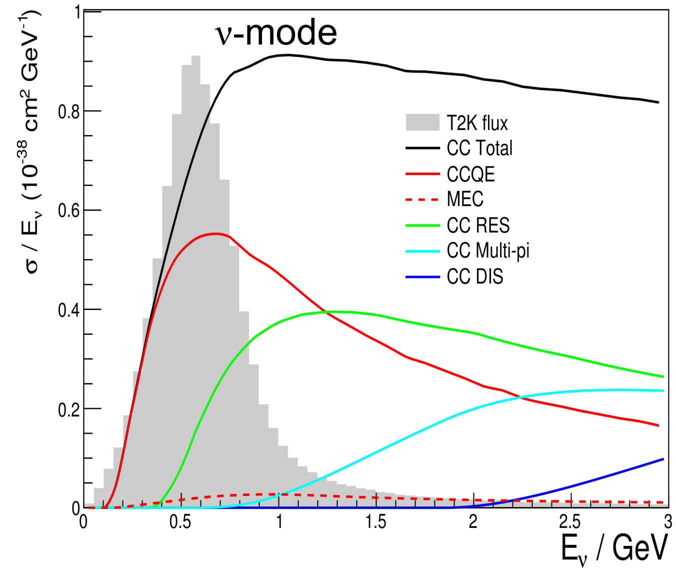
- Expanded parameterization of the spectral function (SF)
- Normalizations for Mean Field (MF) and Short Range Correlations (SRC)

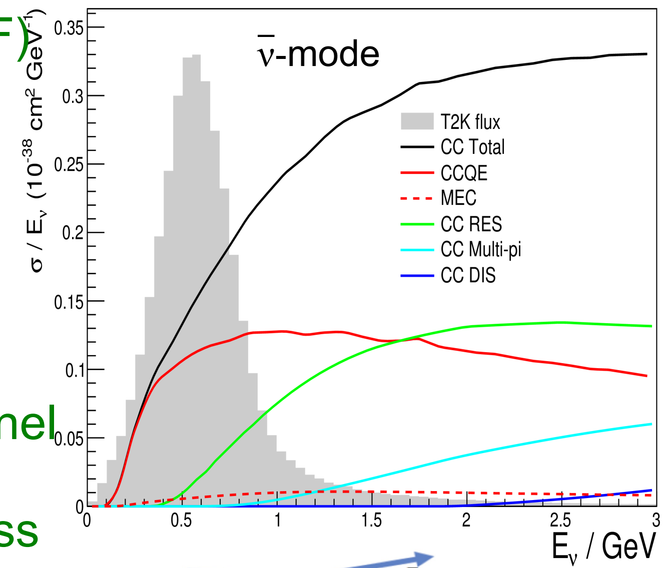
2p2h/MEC:

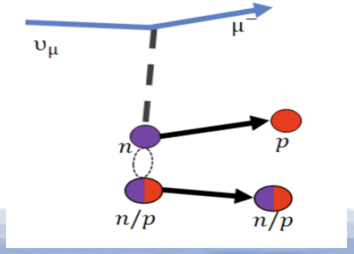
- Better description of 2p2h pn/nn pairs contribution

Other

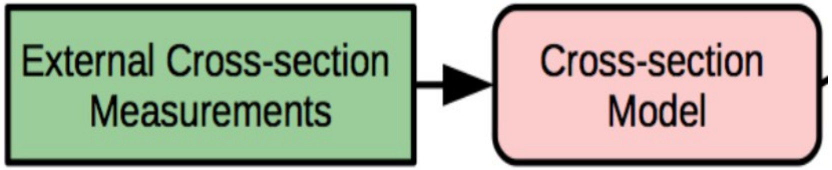
- New tune of resonance model
- Effective inclusion of binding energy for resonant channel
- New Nucleon Final State Interactions (FSI) uncertainty
- New multi-π uncertainty varying shape of hadronic mass and π multiplicity







Cross-section models



- NEUT generator tuned to external data from MINERνA, bubble chambers, etc, and to ND280 data.
-

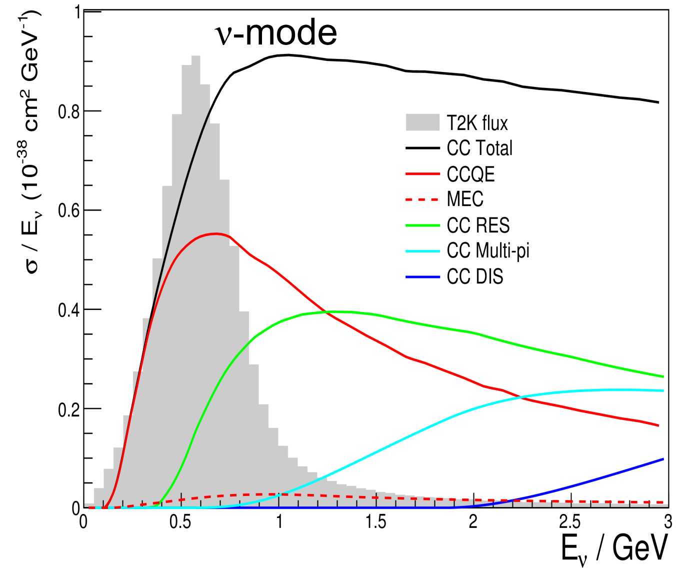
- Updates:

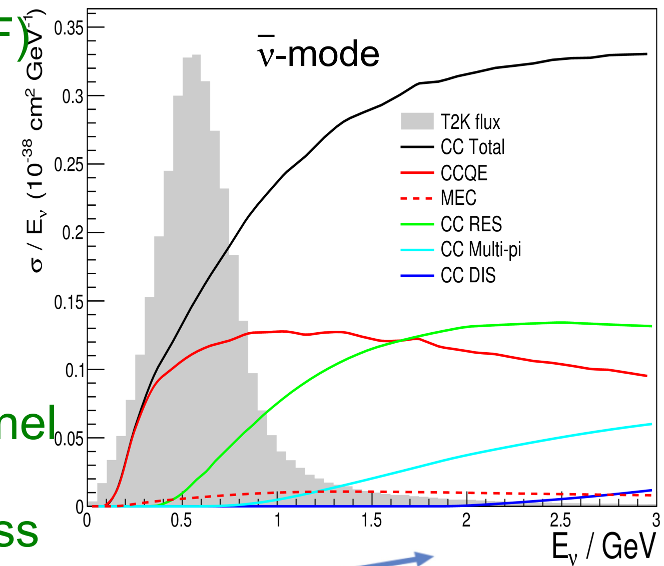
See Stephen Dolan's talk Tues p.m.

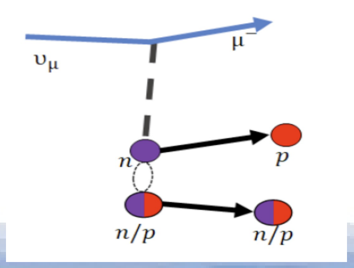
CCQE:
- Expanded parameterization of the spectral function (SF)
- Normalizations for Mean Field (MF) and Short Range Correlations (SRC)

2p2h/MEC:
- Better description of 2p2h pn/nn pairs contribution

Other
- New tune of resonance model
- Effective inclusion of binding energy for resonant channel
- New Nucleon Final State Interactions (FSI) uncertainty
- New multi-π uncertainty varying shape of hadronic mass and π multiplicity

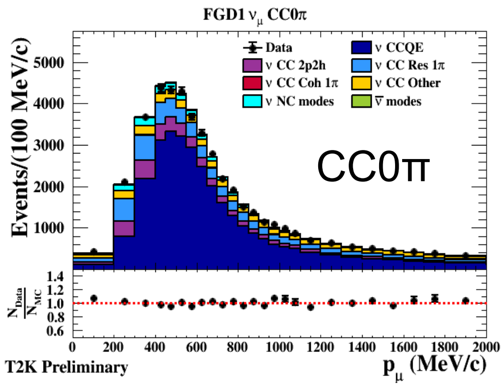


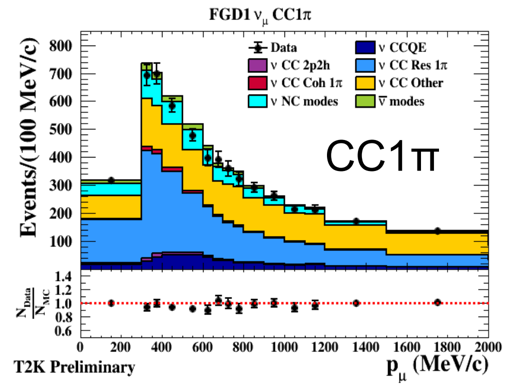


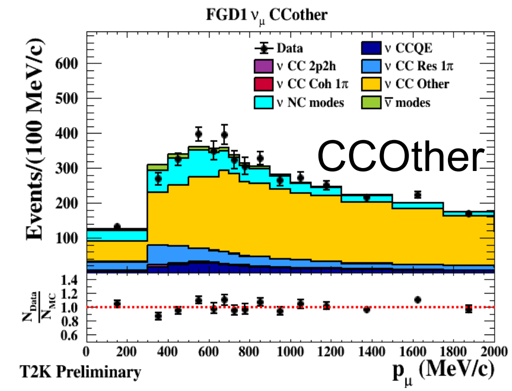


Update: New ND280 data samples

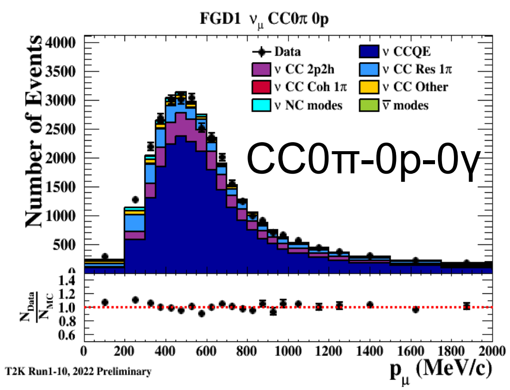
2020

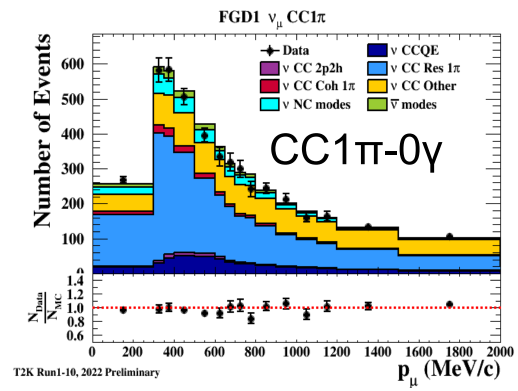


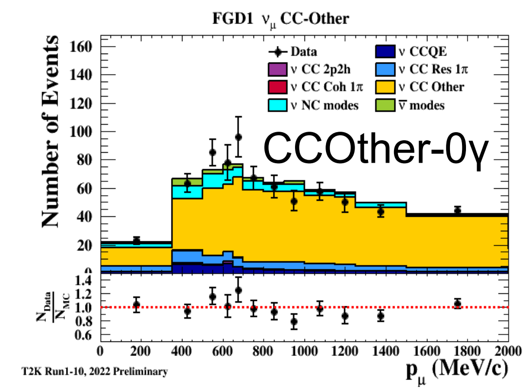


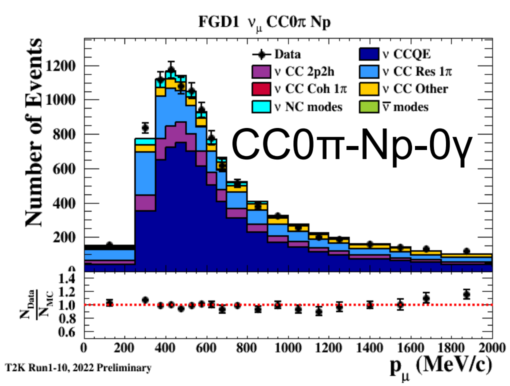


2022



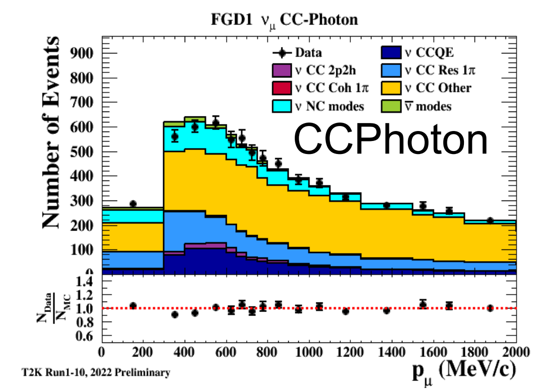






- Data
- ν CC 2p2h
- ν CC Coh 1π
- ν NC modes
- ν CCQE
- ν CC Res 1π
- ν CC Other
- $\bar{\nu}$ modes

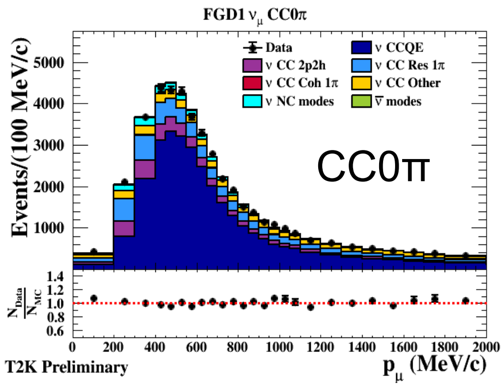
All postfit

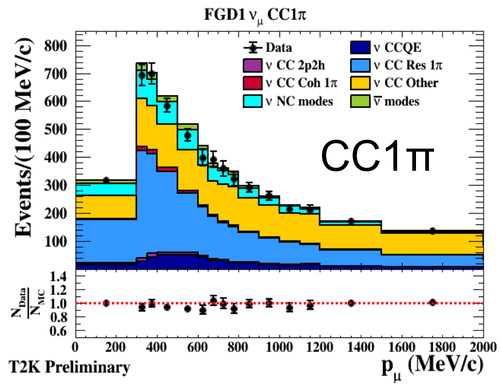


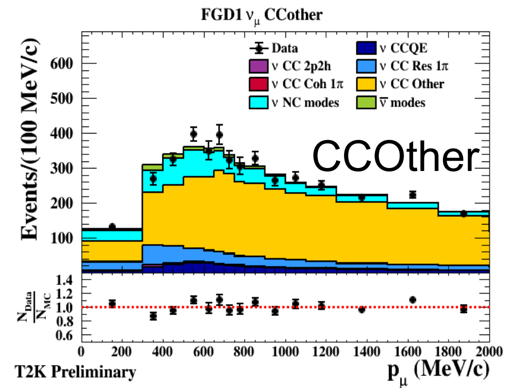
Update: New ND280 data samples

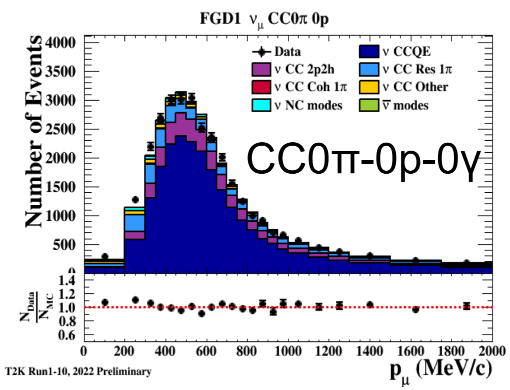
2020

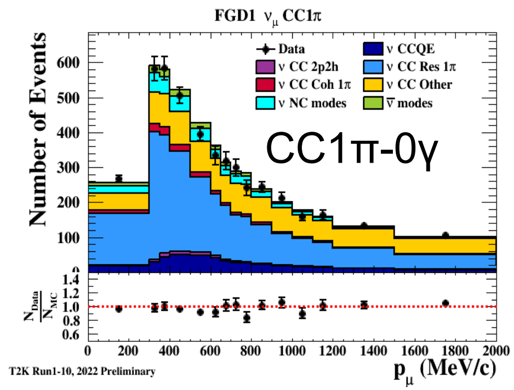
2022

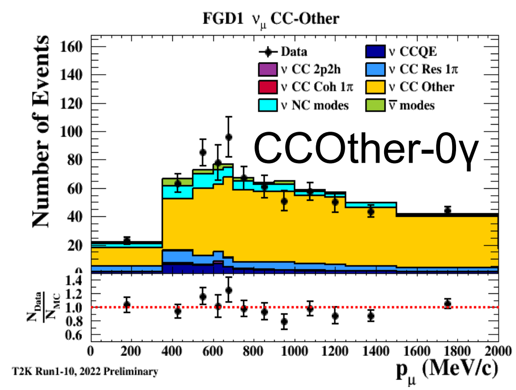


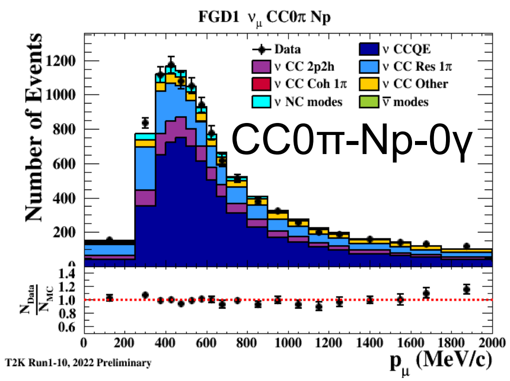




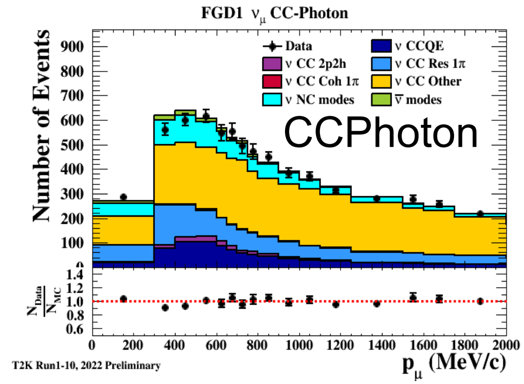






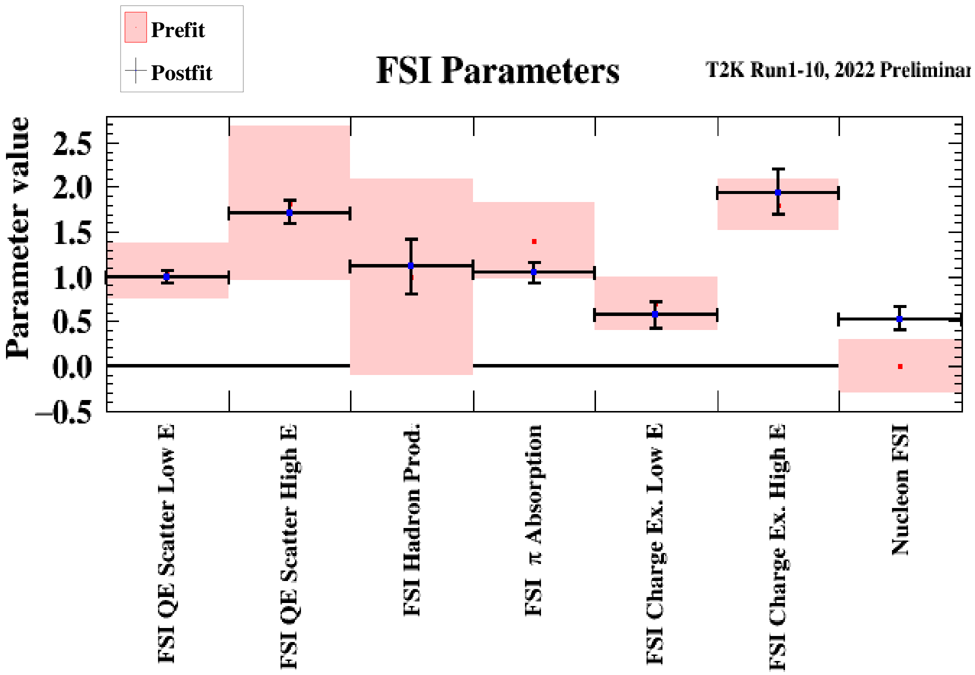


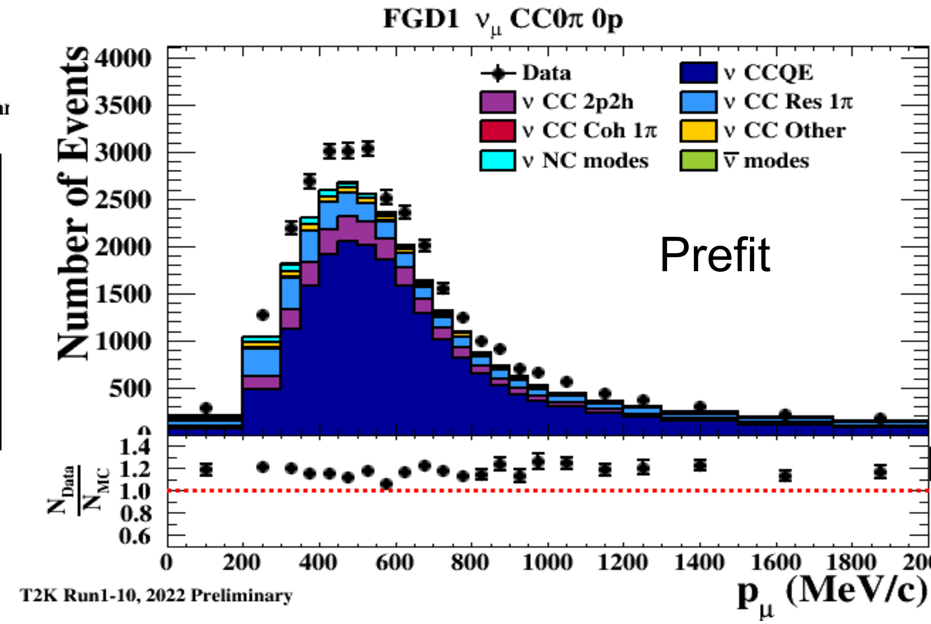
See Callum Wilkinson's talk Thurs a.m.



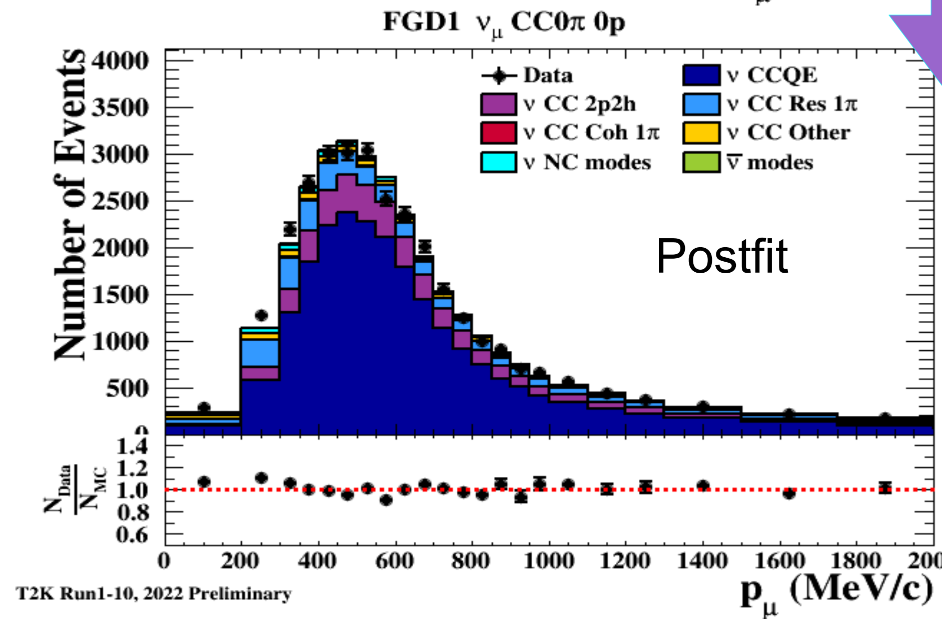
All postfit

ND280 data fitting and constraints





Data fit



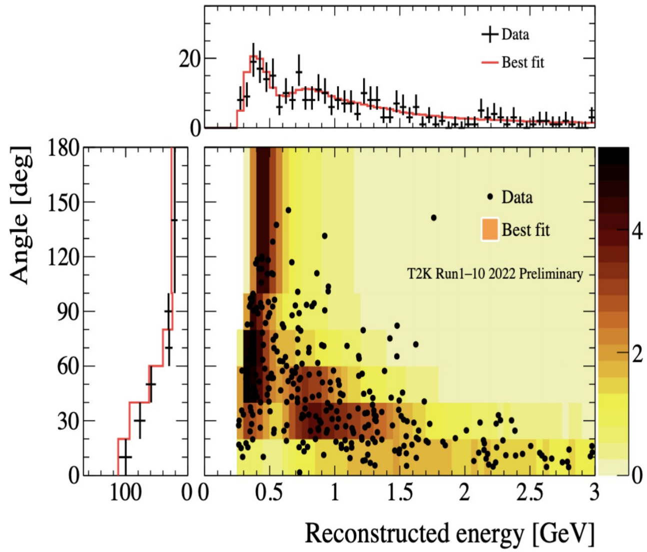
- Showing only 1 (CC-0π-0p-0 γ, ν-mode) of 22 ND280 data samples: 10 samples in ν-mode and 12 in $\bar{\nu}$-mode
- Fit tunes ~1000 parameters (showing only FSI cross-section parameters)

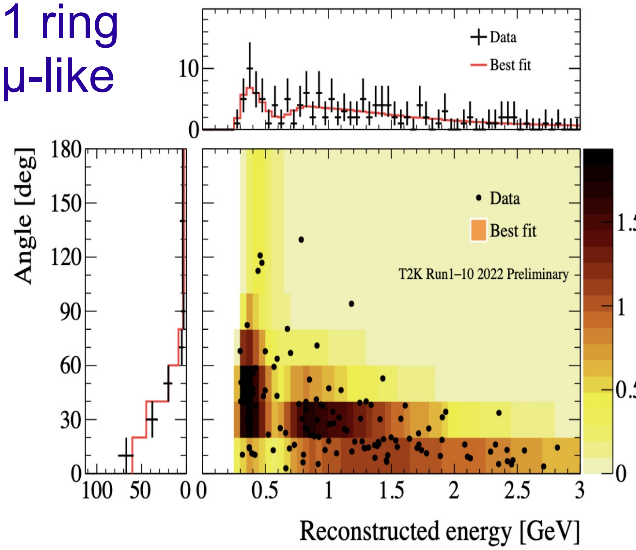
SK Samples

ν-mode

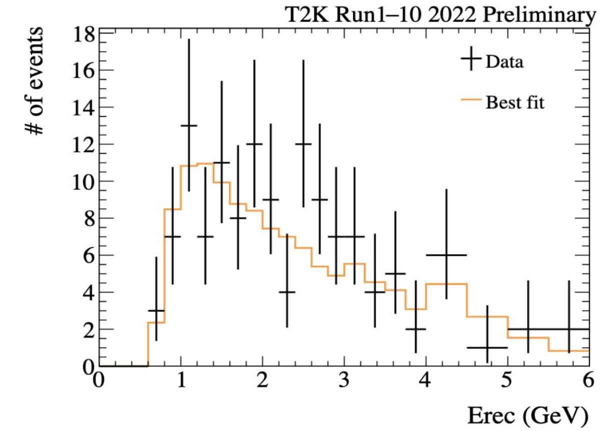
$\bar{\nu}$-mode

1 ring μ-like



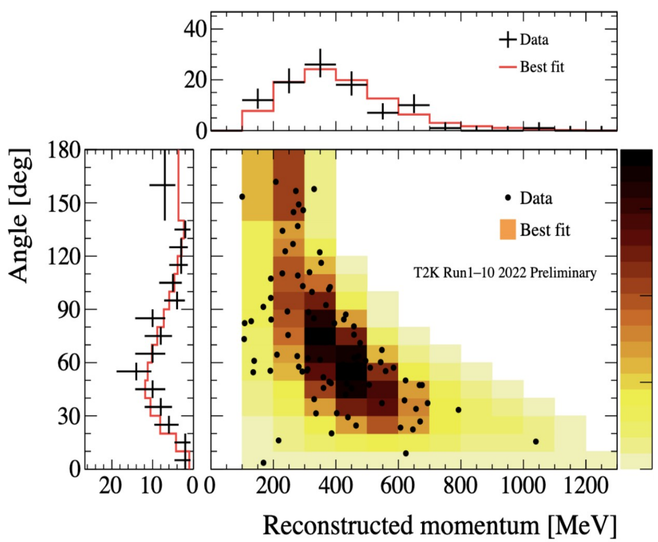


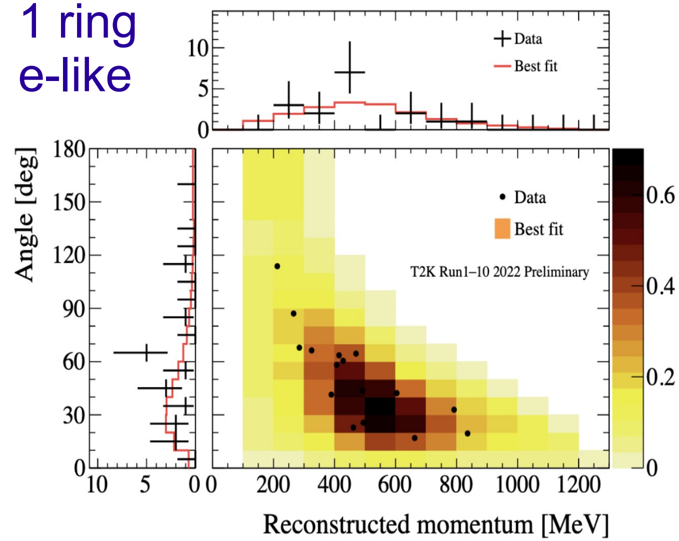
New: ν-mode ν_μ CC1π^+

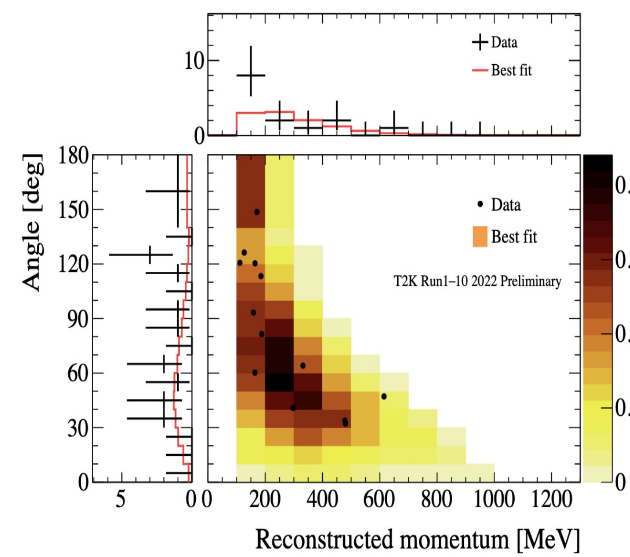


complements existing ν_e CC1π^+

1 ring e-like

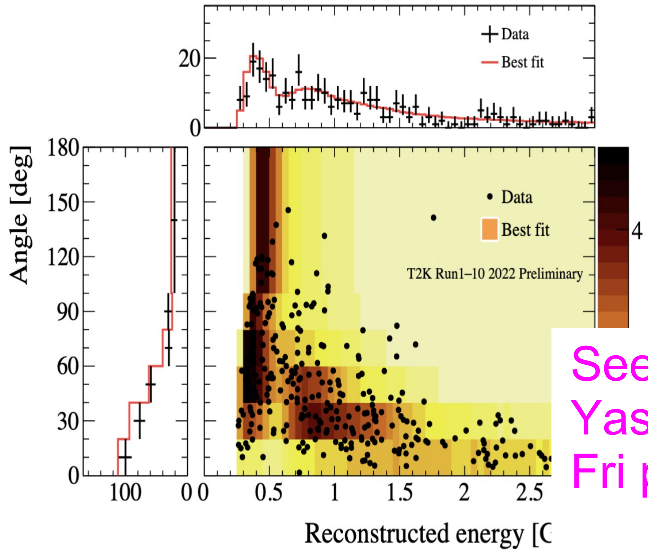






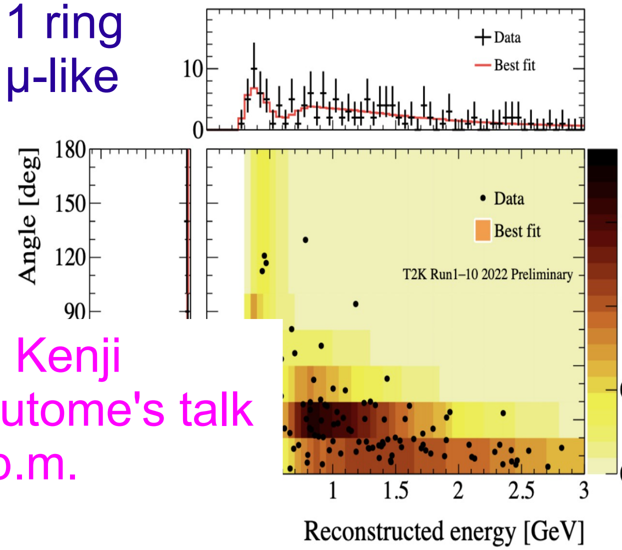
SK Samples

ν-mode



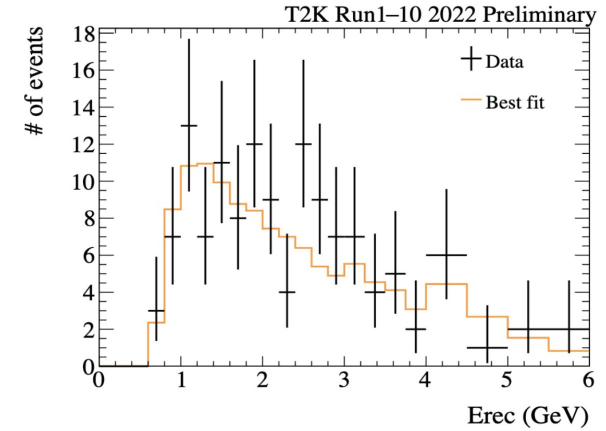
$\bar{\nu}$-mode

1 ring μ-like



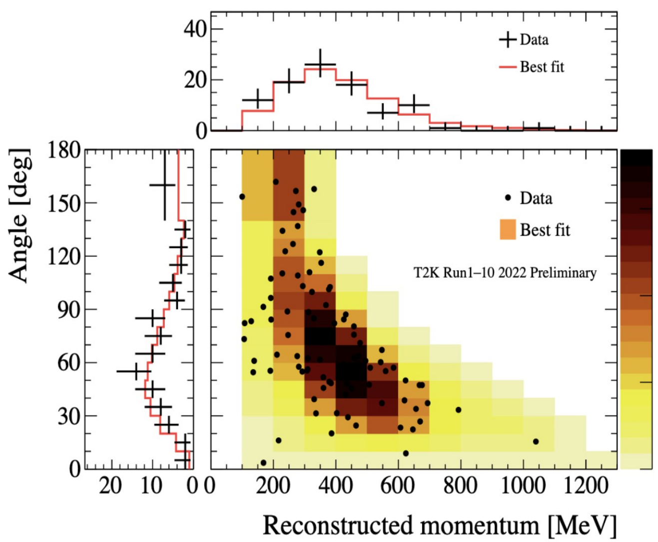
See Kenji Yasutome's talk Fri p.m.

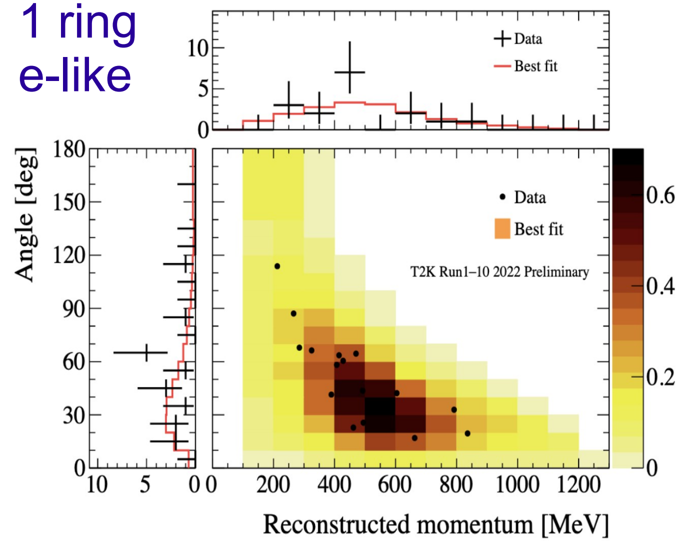
New: ν-mode ν_μ CC1π^+

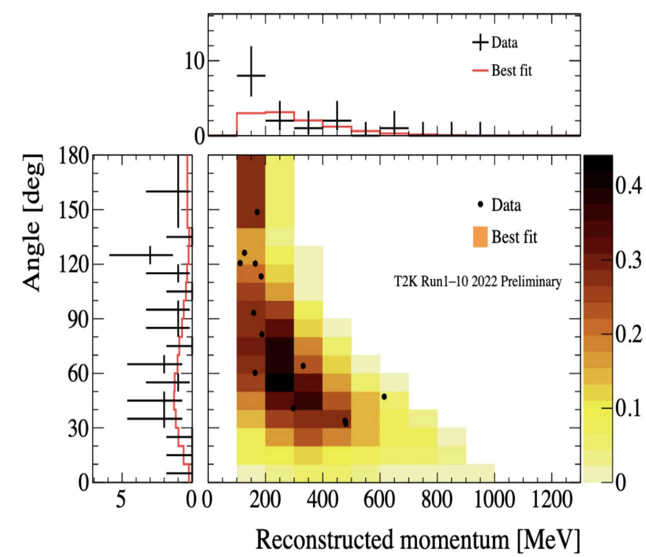


complements existing ν_e CC1π^+

1 ring e-like







Joint analysis with ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$

Frequentist with likelihood fit to
- p_{lep}/θ_{lep} for $\nu_e/\bar{\nu}_e$
- E_{rec} for $\nu_\mu/\bar{\nu}_\mu$
- sequential fit ND then FD

2 analysis frameworks

Bayesian with Markov Chain MC
- E_{rec} for $\nu_\mu/\bar{\nu}_\mu$
- E_{rec}/θ_{lep} for $\nu_e/\bar{\nu}_e$
- simultaneous fit ND and FD

SAMPLE	PREDICTED					OBSERVED
	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=+\pi/2$	$\delta_{cp}=\pi$	$\delta_{cp}=-2.18$	
ν-mode μ CCQE	358.7	358.0	358.6	359.4	359.1	318
$\bar{\nu}$-mode μ CCQE	139.4	139.1	139.4	139.8	139.6	137
ν-mode e CCQE	99.1	83.6	68.6	84.1	96.5	94
$\bar{\nu}$-mode e CCQE	17.0	19.4	21.4	19.1	17.3	16
ν-mode e CC1π+	10.9	9.5	7.7	9.1	10.5	14
ν-mode μ CC1π+	118.5	118.0	118.5	119.0	118.8	134

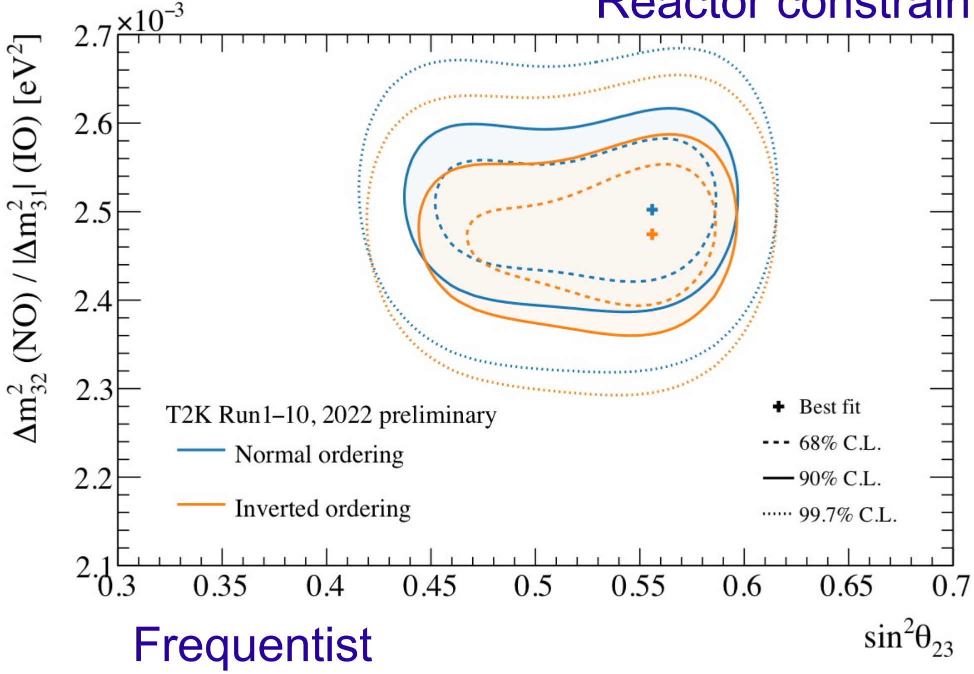
Best fit

Events observed at SK vs predictions calculated with osc. and syst. parameters (except δ_{CP}) at best fit, including NO.

Less events than predicted for ν-mode 1 ring μ-like sample.
- Goodness of fit p-value for this sample is 0.04 (rate only) and 0.35 (rate+shape)
- Considering look-elsewhere-effect, p-value is above our 5% threshold

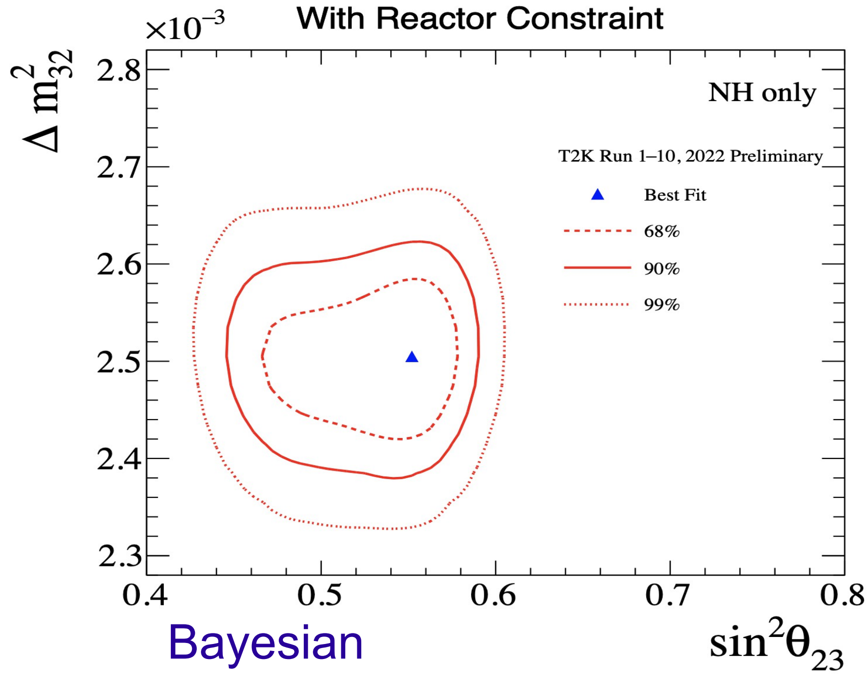
Atmospheric parameters

Reactor constraints applied.



Frequentist

- Best fit in the upper octant.
- Lower octant still consistent within 68% CL.



Bayesian

Feldman-Cousins confidence intervals for $\sin^2\theta_{23}$

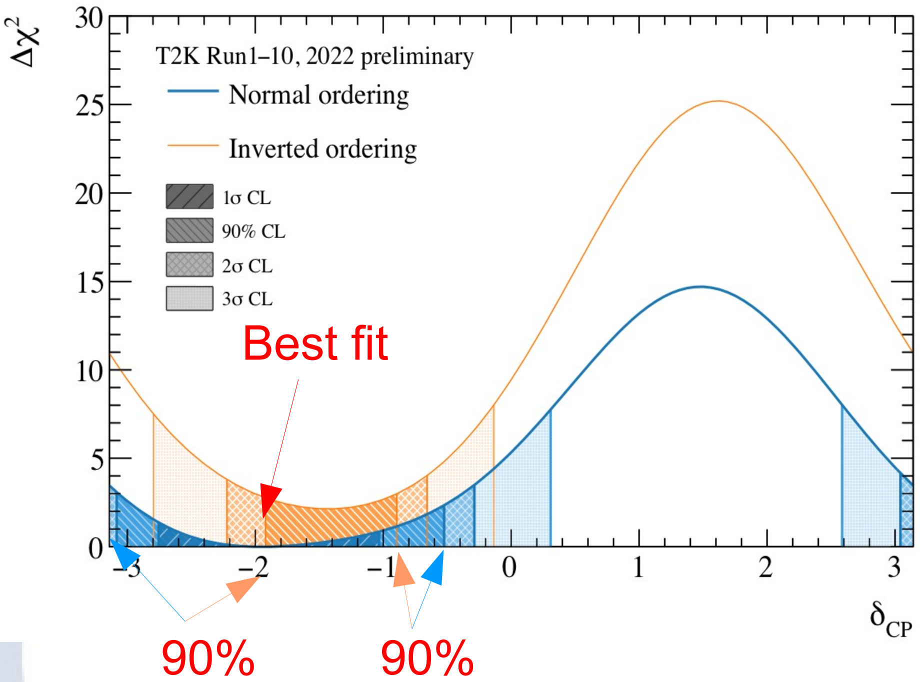
Confidence level	Interval (NH)	Interval (IH)
1σ	$[0.460, 0.491] \cup [0.526, 0.578]$	
90%	$[0.444, 0.589]$	$[0.525, 0.582]$
2σ	$[0.437, 0.594]$	$[0.459, 0.588]$

T2K Run 1-10, preliminary

θ_{13} and δ_{CP}

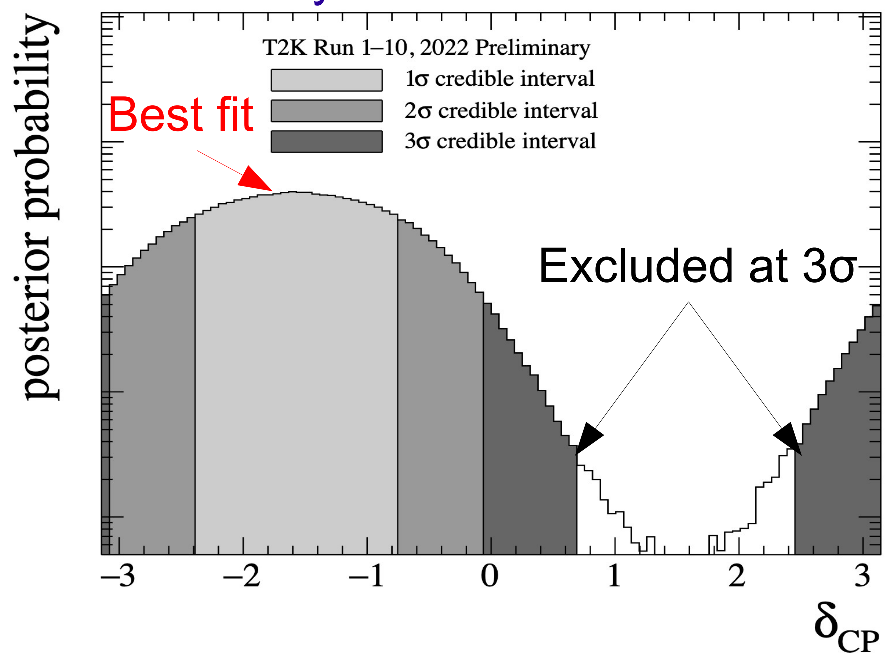
Reactor constraints applied.

Frequentist



Bayesian

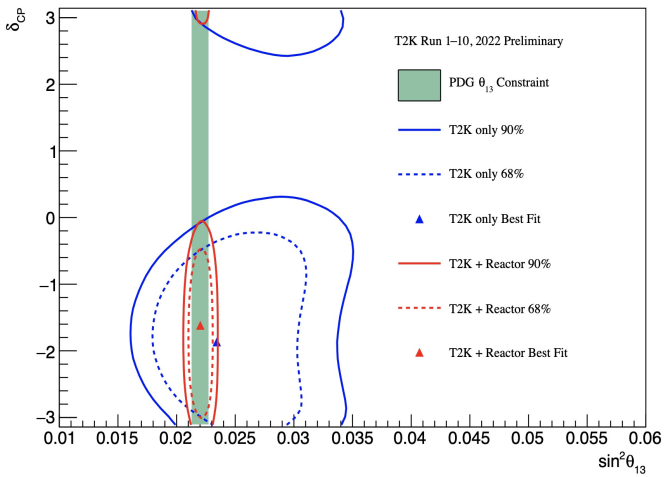
Marginalised over MO



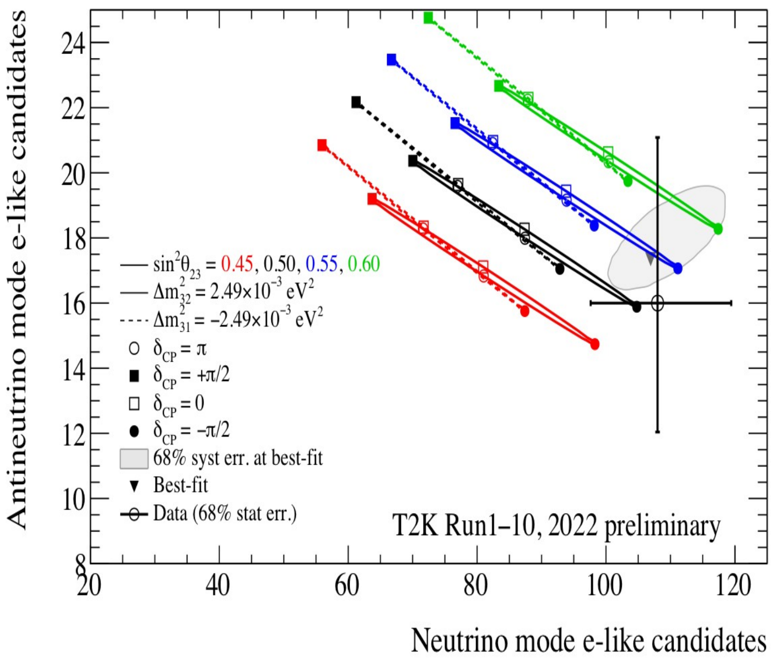
Feldman-Cousins confidence intervals for δ_{CP}

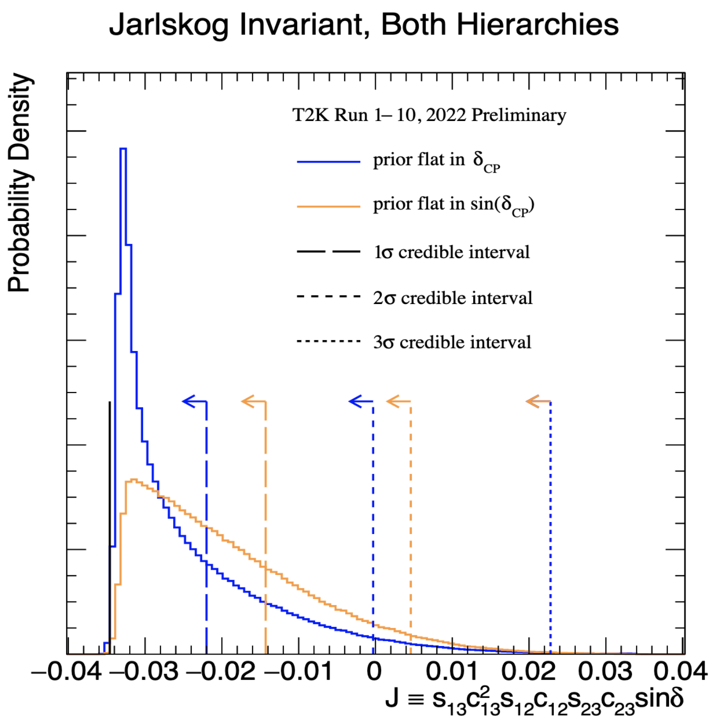
Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.76, -1.03]$	
90%	$[-3.08, -0.52]$	$[-1.92, -0.89]$
2σ	$[-\pi, -0.29] \cup [3.04, \pi]$	$[-2.22, -0.66]$
3σ	$[-\pi, 0.31] \cup [2.59, \pi]$	$[-2.80, -0.14]$

T2K Run 1-10, preliminary



More oscillation results





Jarlskog Invariant: $J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$

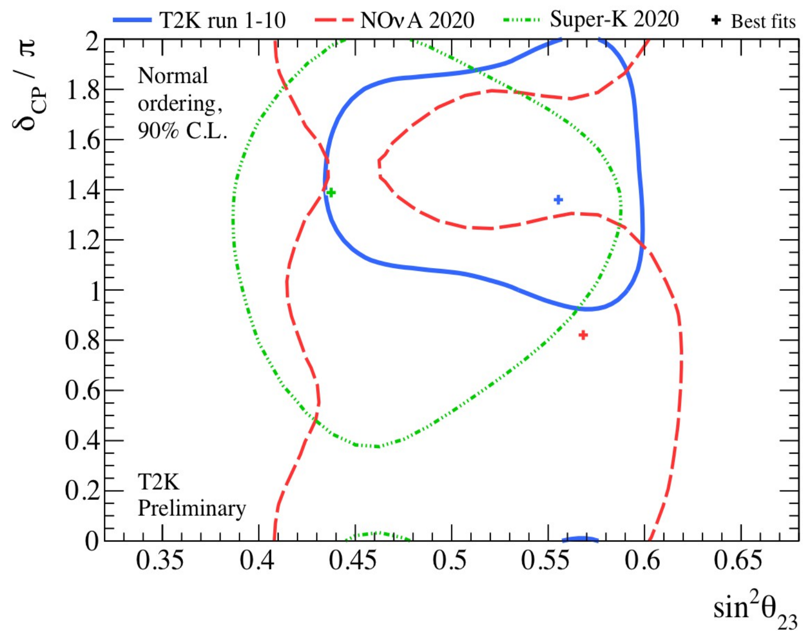
Bayesian posterior probabilities (with reactor constraint)

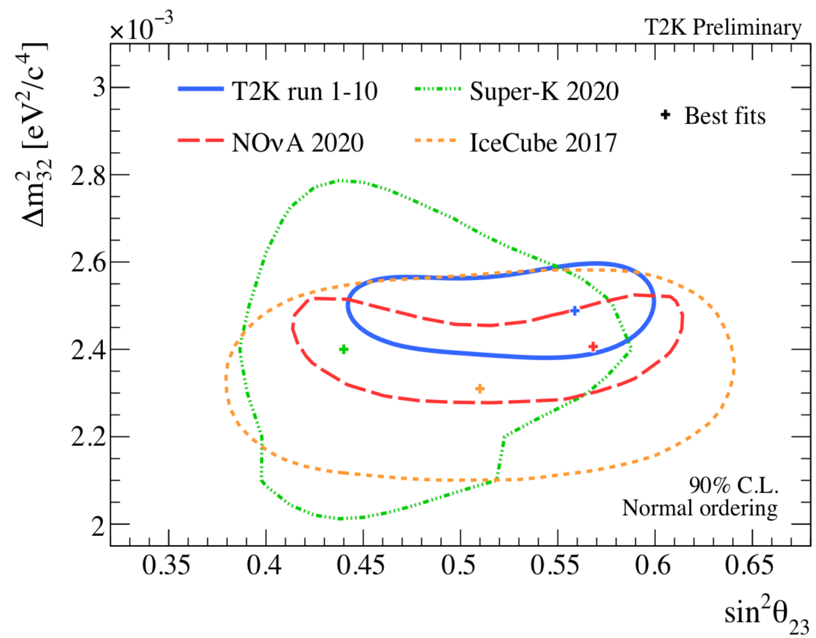
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.20	0.54	0.74
IH ($\Delta m^2_{32} < 0$)	0.05	0.21	0.26
Sum	0.25	0.75	1.000

Jarlskog invariant is independent of PMNS parameterization.

Comparisons to other experiments

Normal ordering, 2020 analyses



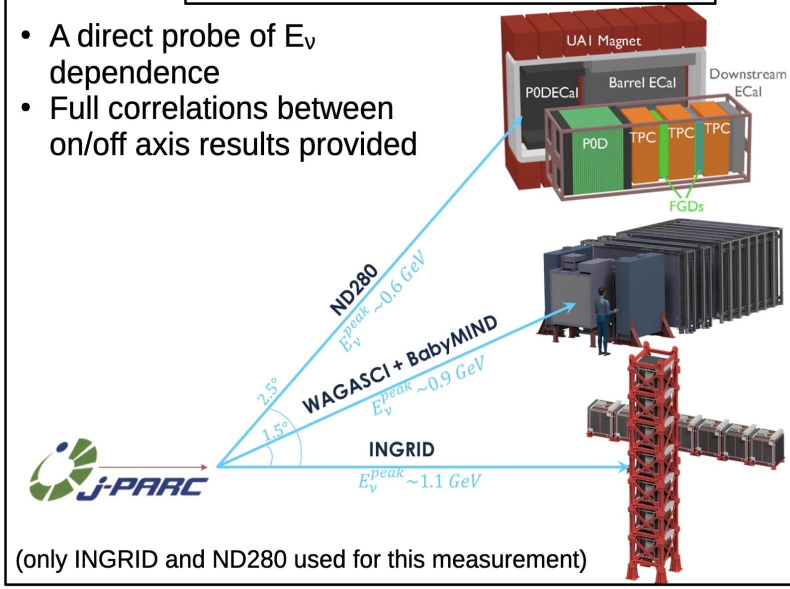


- At 90% CL, δ_{CP} consistent with SK best fit. NOvA best fit just outside contour. Contours overlap.
- At 90% CL, θ_{23} contours overlap. T2K and NOvA both prefer upper octant. SK prefers lower.

Cross sections – ND measurements

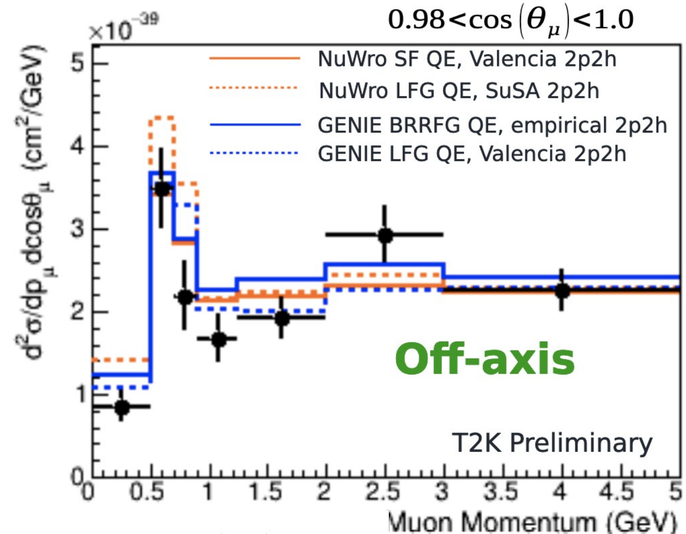
Joint On/Off axis measurements

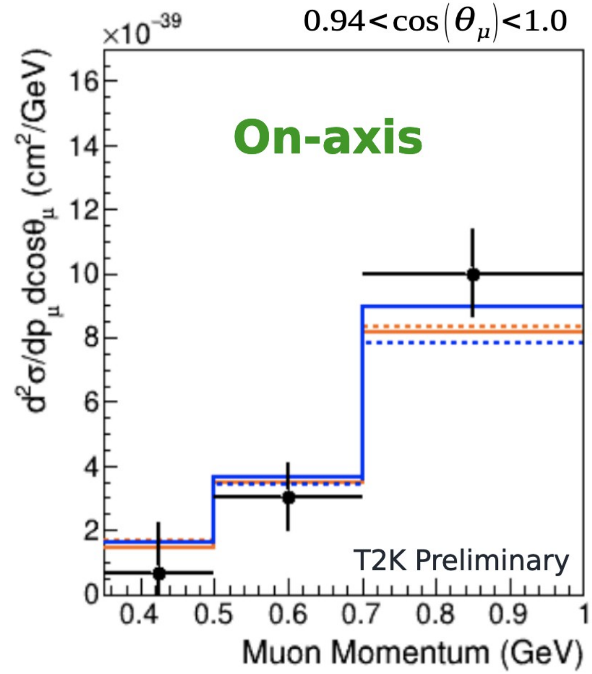
- A direct probe of E_ν dependence
- Full correlations between on/off axis results provided



(only INGRID and ND280 used for this measurement)

- Mature cross-section programme.
- Joint analyses
  - On-axis, off-axis, C/O, $\nu_\mu/\bar{\nu}_\mu$
  - Probe physics most relevant to oscillation analysis
  - Low-rate measurements (CC-coherent on C)



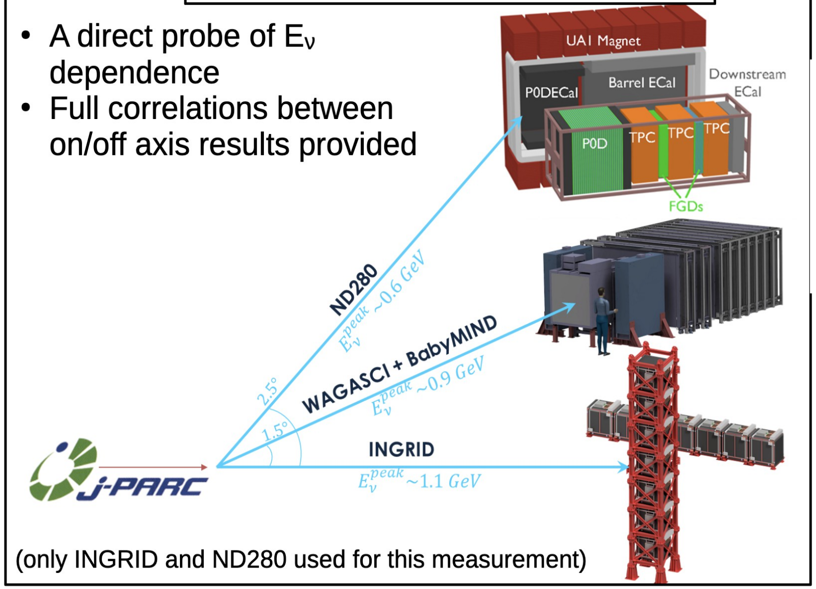


CC0π simultaneous on-/off-axis fit

Cross sections – ND measurements

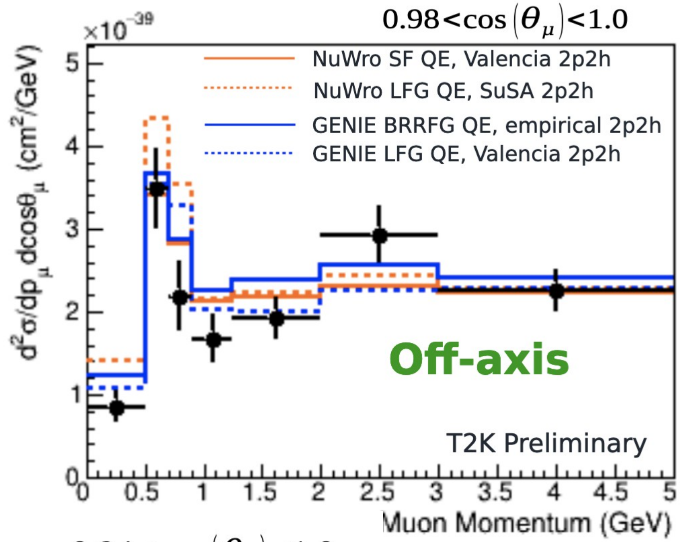
Joint On/Off axis measurements

- A direct probe of E_ν dependence
- Full correlations between on/off axis results provided

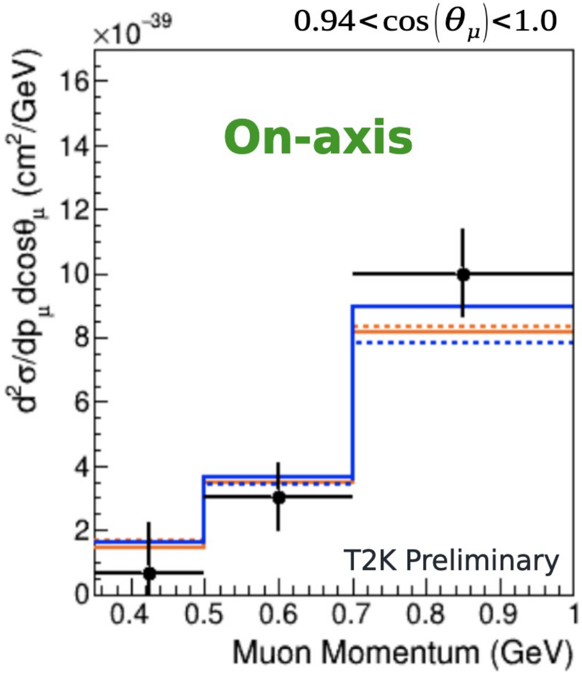


(only INGRID and ND280 used for this measurement)

See Andrew Cudd's talk Friday p.m.



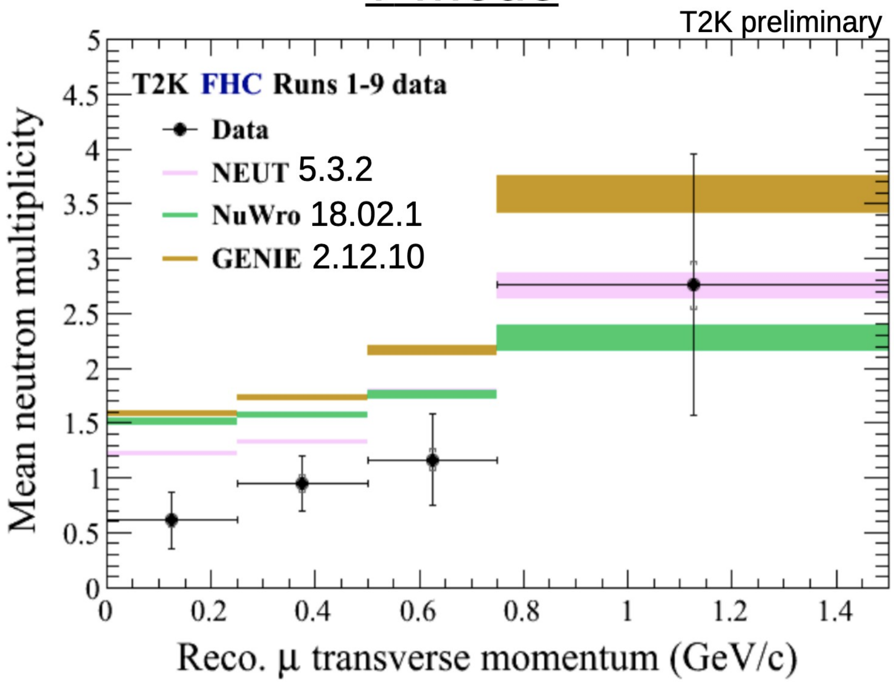
- Mature cross-section programme.
- Joint analyses
  - On-axis, off-axis, C/O, $\nu_\mu/\bar{\nu}_\mu$
  - Probe physics most relevant to oscillation analysis
  - Low-rate measurements (CC-coherent on C)



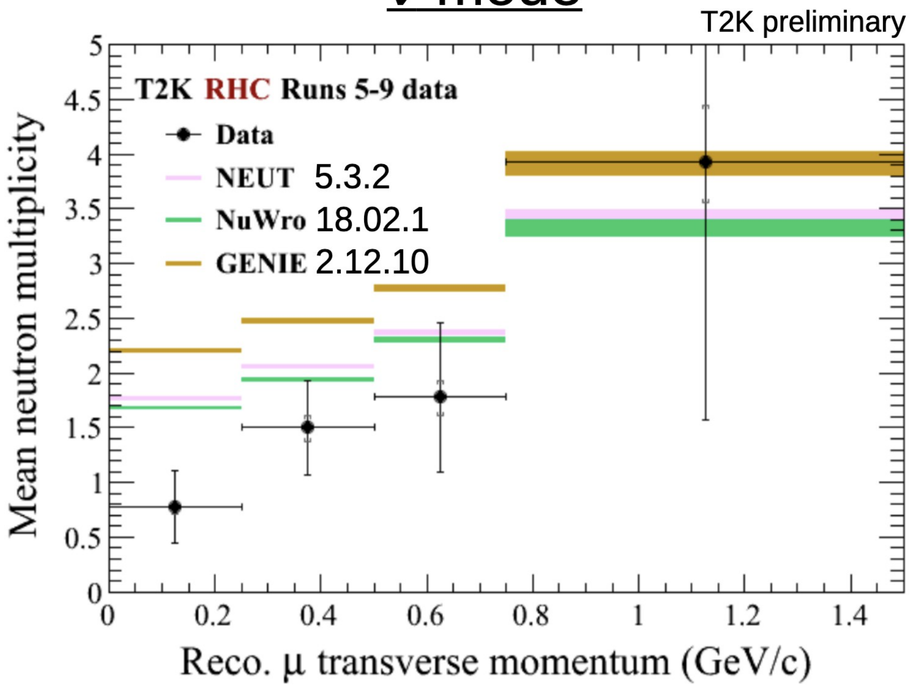
CC0π simultaneous on-/off-axis fit

Cross sections – neutron multiplicities at SK

ν-mode



$\bar{\nu}$-mode



- Neutron tagging in water Cherenkov detectors may separate $\nu/\bar{\nu}$, CC/NC ν interaction and reject backgrounds
- Thermalised neutrons are captured on H and produce 2.2 MeV γ.
- All generators considered found to over-predict neutron production

Future: Joint Analyses

T2K-NOvA

- Different baselines, energy ranges and detector technologies: complementarity to study oscillations
  - increased sensitivity
  - ability to break degeneracy between mass ordering and δ_{CP}

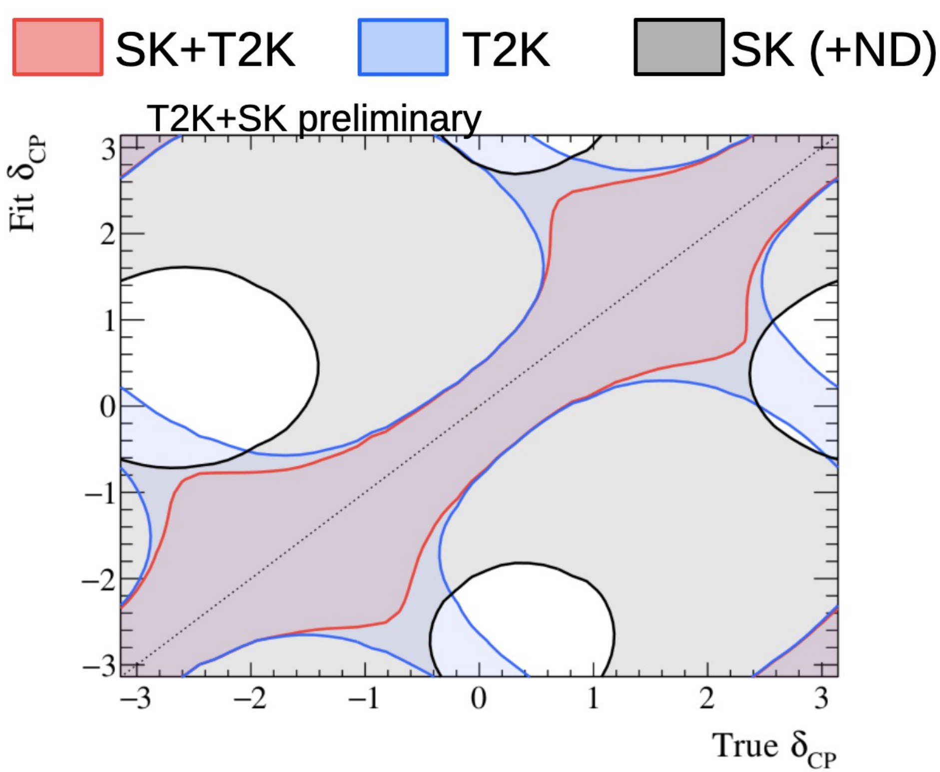
Experimental Property	T2K	NOvA
Proton beam energy	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection technology	Water Cherenkov	Segmented liquid scintillator bars
CP effect*	~30%	22%
Matter effect	9%	29%

*Minimum difference $\sin(\delta_{CP})$=0 and ±1, between ν and $\bar{\nu}$

T2K-SK atmospheric

- Joint fit can break degeneracy with $\cos(\delta_{CP})$ and mass ordering.
- Improved ability to reject wrong mass ordering and wrong θ_{23} quadrant.

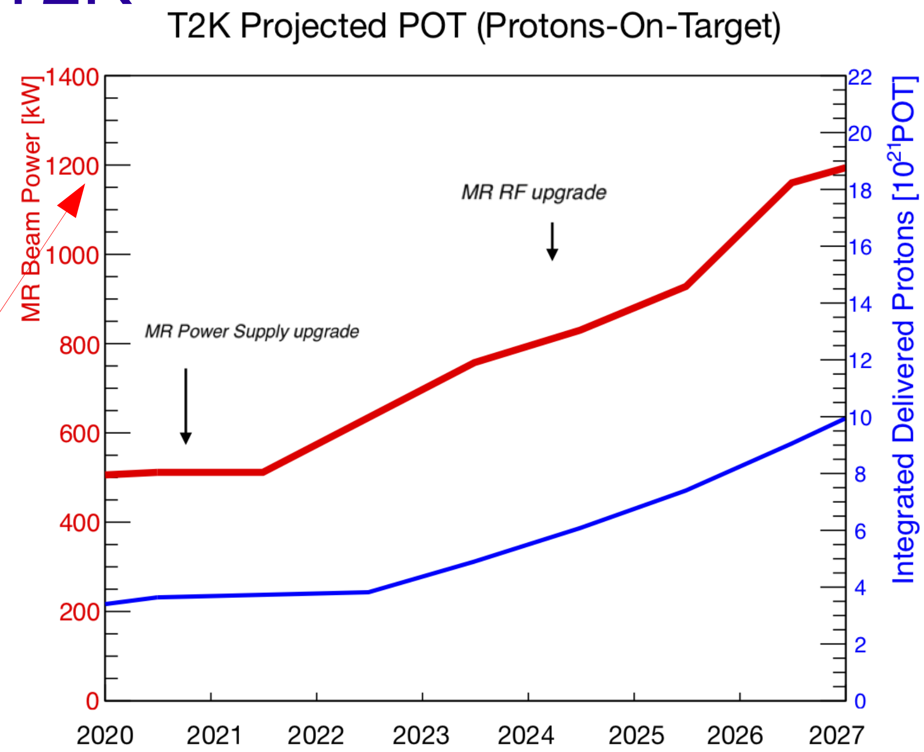
68% CL intervals for δ_{CP} as a function of true δ_{CP} assumed

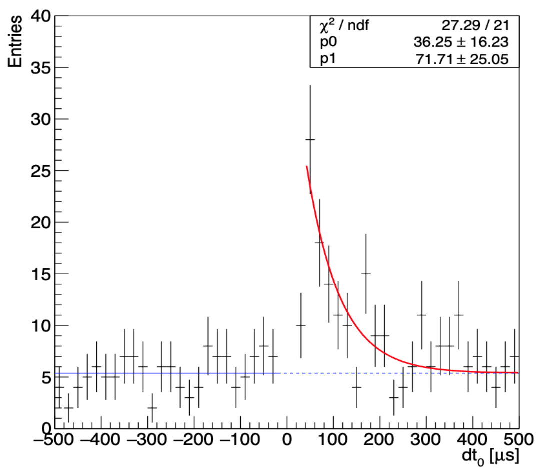


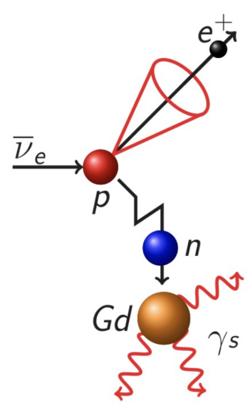
Future T2K

Beam upgrade

- Increased beam power
  - Proton beam reached 515 kW stable power before shutdown.
  - Higher intensity - reduced rep rate, higher horn current, ready early 2023
  - > 1 MW by 2027







8 MeV γ cascade

SK upgrade

- Gd now added to SK (not yet used in analysis but neutron signal seen)
  - enhance neutron detection
  - improve low-energy $\overline{\nu}_e$ detection
  - may provide wrong-sign background constraint in $\overline{\nu}_e$-mode data.

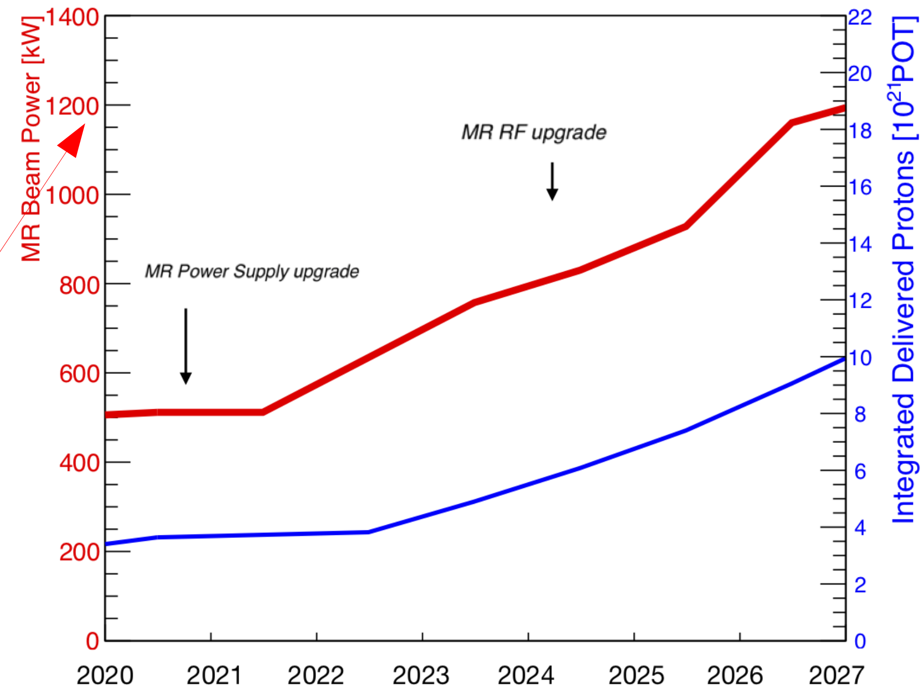
Future T2K

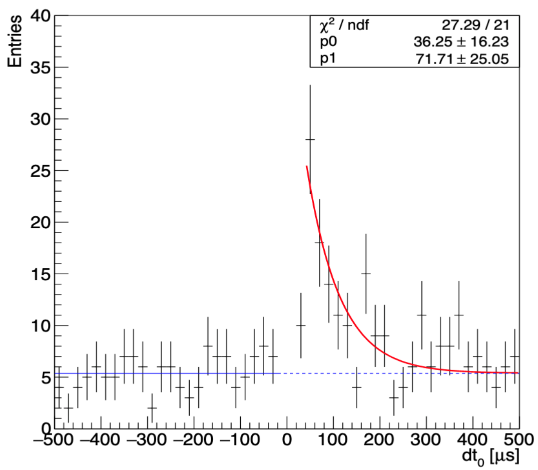
Beam upgrade

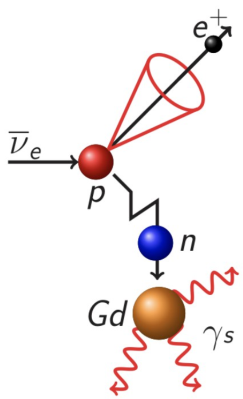
- Increased beam power
  - Proton beam reached 515 kW stable power before shutdown.
  - Higher intensity - reduced rep rate, higher horn current, ready early 2023

> 1 MW by 2027

See Takeshi Nakadaira's talk Wed a.m.







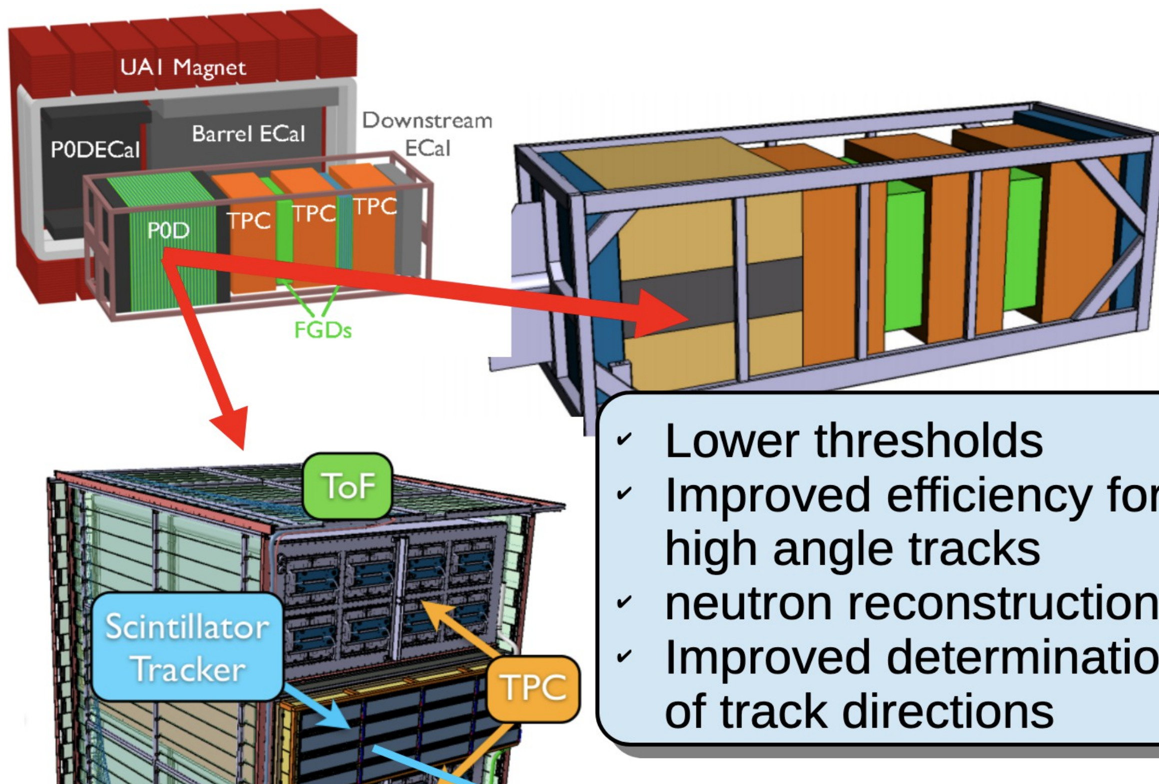
8 MeV γ cascade

SK upgrade

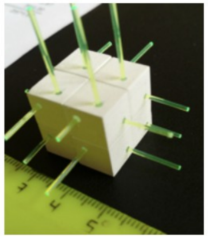
- Gd now added to SK (not yet used in analysis but neutron signal seen)
  - enhance neutron detection
  - improve low-energy $\overline{\nu}_e$ detection
  - may provide wrong-sign background constraint in $\overline{\nu}_e$-mode data.

ND280 upgrade

- Improved proton tracking.
- Improved muon angular acceptance.
- Changes to ND280 analysis samples to increase angular acceptance.



- ✓ Lower thresholds
- ✓ Improved efficiency for high angle tracks
- ✓ neutron reconstruction
- ✓ Improved determination of track directions



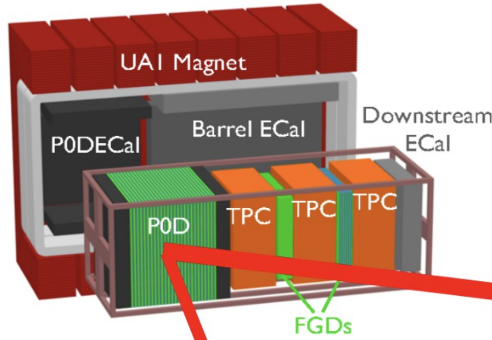
1 cm^3 cubes + WLS fibers

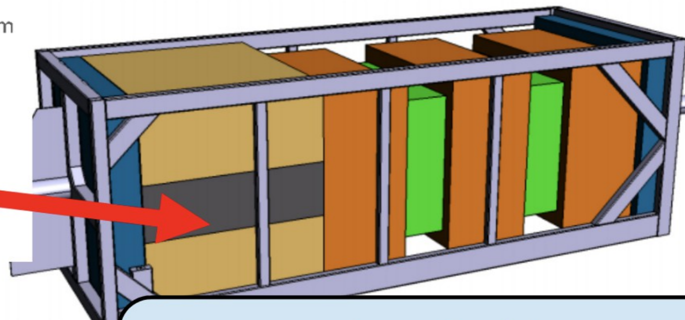
ND280 upgrade

See Aoi Eguchi's talk Thurs a.m.

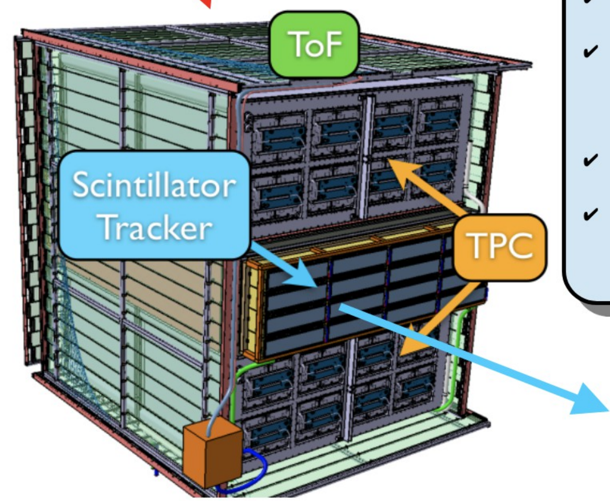
- Improved proton tracking.
- Improved muon angular acceptance.
- Changes to ND280 analysis samples to increase angular acceptance.

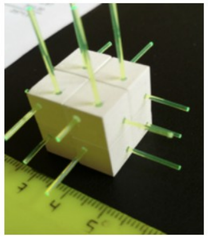
See Ciro Riccio's talk Thurs a.m.





- ✓ Lower thresholds
- ✓ Improved efficiency for high angle tracks
- ✓ neutron reconstruction
- ✓ Improved determination of track directions





1 cm³ cubes + WLS fibers

Summary

- T2K has a new analysis using the same data runs as last year, but using more of the data with more near detector samples, more far detector samples, and upgraded cross-section and flux models.
- δ_{CP} results from T2K remain consistent in favouring near-maximal CP violation, near $-\pi/2$. CP conservation continues to be excluded at 90% CL.
- T2K favours the upper octant for θ_{23} but is still consistent with lower octant and maximal values.
- Normal mass ordering is slightly favoured.
- Joint analyses with NOvA and SK have begun and have the power to address degeneracies.
- A major upgrade of T2K is well under way, including beam, near detectors, and far detector.

UK Research and Innovation

Extras

Oscillations at T2K

Appearance

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 \underline{s_{13}^2}\, \underline{s_{23}^2} \sin^2\Delta_{31} \times \left(1 \pm \frac{2\boxed{a}}{\Delta m_{31}^2}(1-s_{13}^2)\right)$$ Leading term

$$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Conserving

$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\frac{\boxed{a}L}{4E}(1-2s_{13}^2)$$ Matter effect

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \underline{\sin\delta} \sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Violating

$$+4s_{12}^2 c_{13}^2(c_{12}c_{23} + s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta)\sin^2\Delta_{21}$$ Solar term

ν vs. $\bar{\nu}$ sign change

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\quad \Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$ $\quad \boxed{a = 2\sqrt{2} G_F n_e E}$

θ_{13} dependence — Octant sensitivity — CP-odd phase

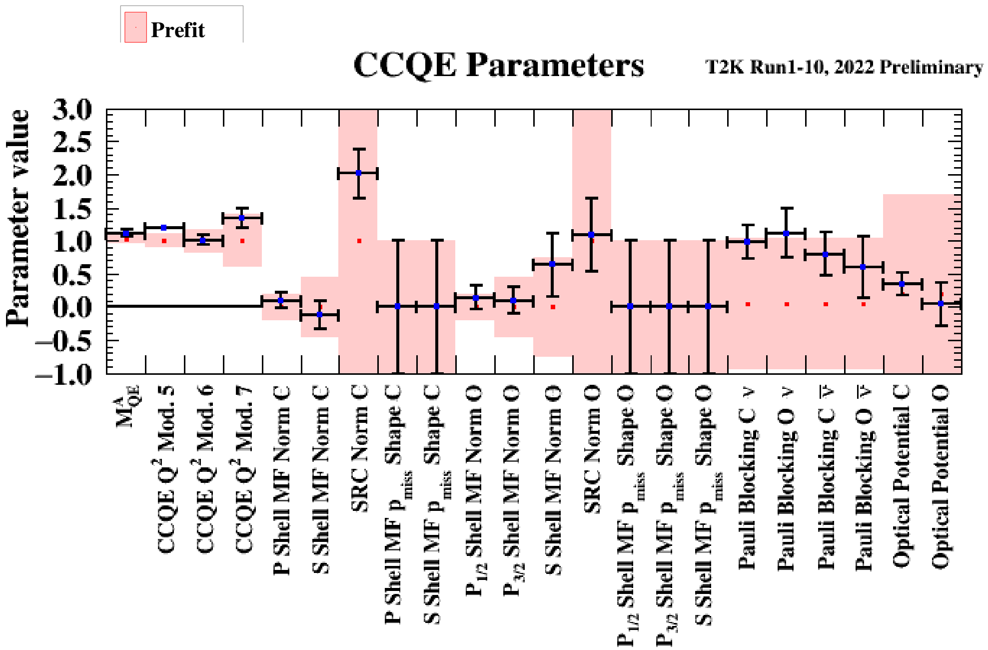
Disappearance

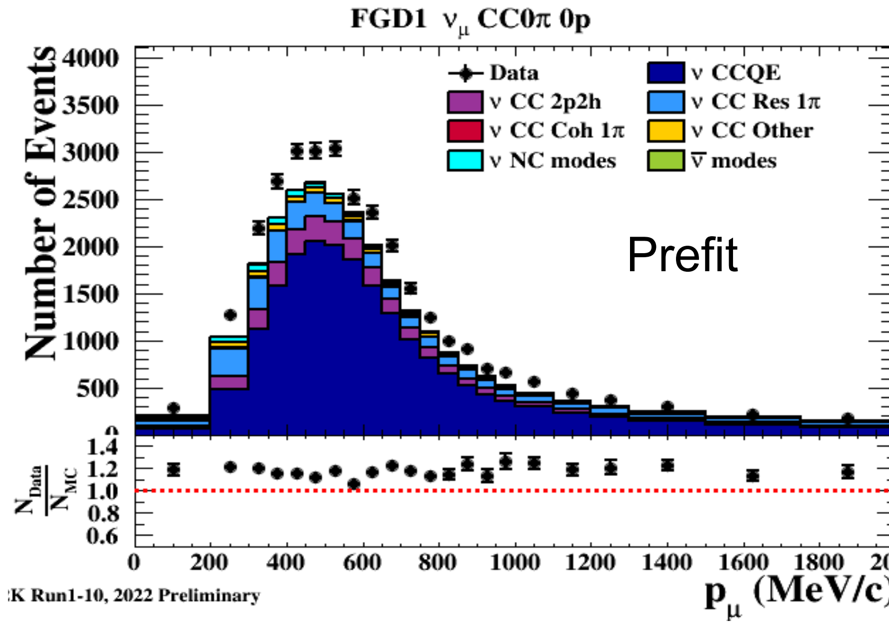
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\cos^4\theta_{13} \cdot \underline{\sin^2 2\theta_{23}} + \sin^2 2\theta_{13} \cdot \underline{\sin^2\theta_{23}}\right) \cdot \sin^2 \frac{\Delta m_{32}^2 \cdot L}{4E_\nu}$$

(Leading and next terms only)

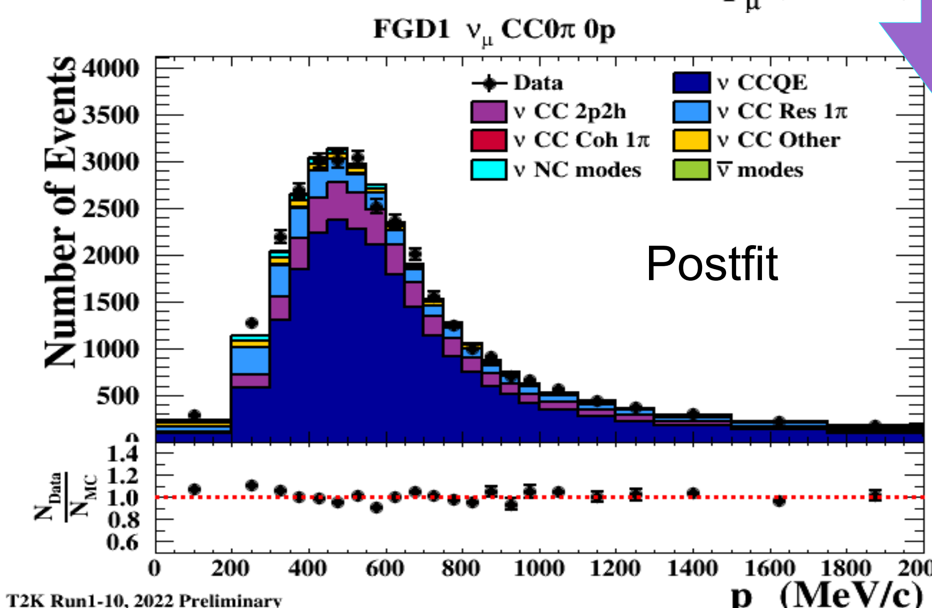
θ_{23} dependence — Octant sensitivity — $P_{PMNS}(\bar{\nu}_\mu \to \bar{\nu}_\mu) = P_{PMNS}(\nu_\mu \to \nu_\mu)$ **Test of CPT**

ND280 data fitting and constraints



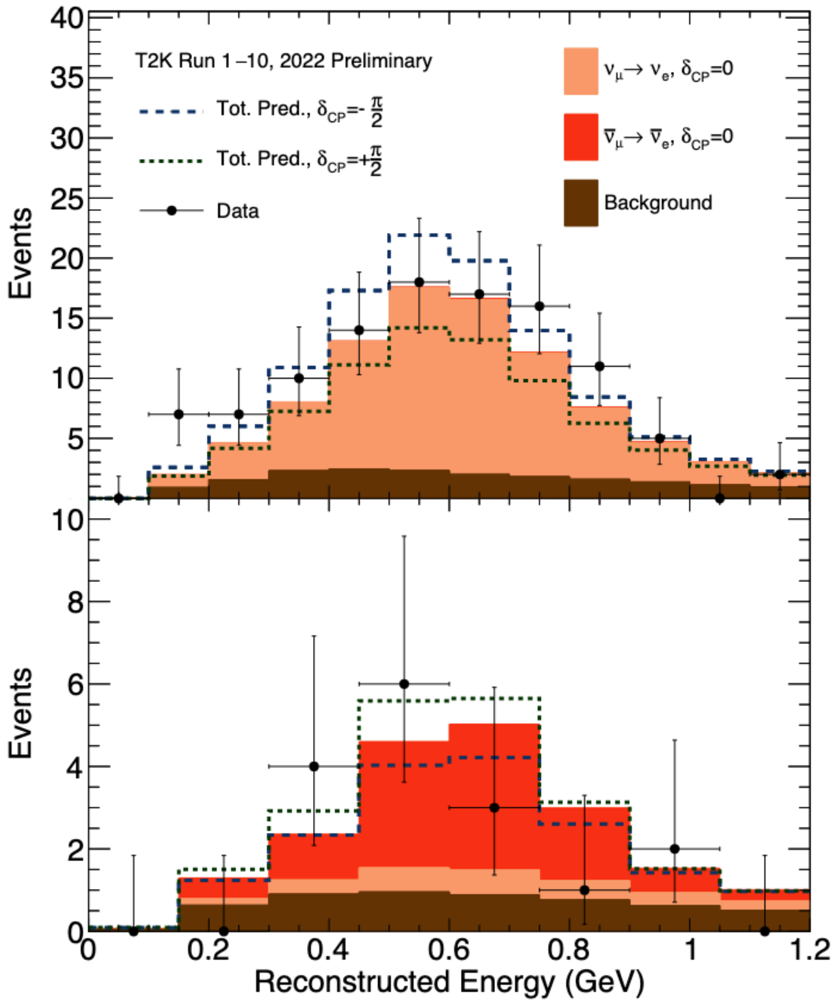


Data fit



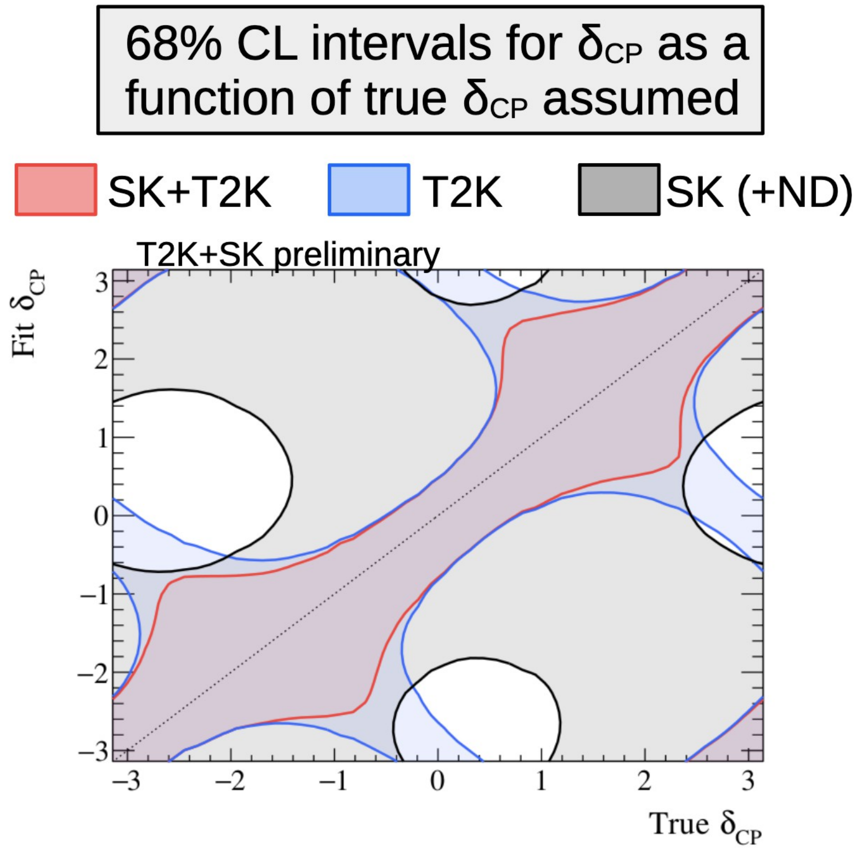
- ND280 fit: Based on extended binned likelihood fit as function of the muon kinematics (momentum and angle)
  - Found a prior model p-value of 11%, greater than our 5% threshold.

Electron-neutrino appearance



- Neutrino-mode (top) and antineutrino-mode (bottom) electron-like events. Data agrees with any value of deltaCP. Note the small amount of background, especially in neutrino-mode. Antineutrino-mode has some "wrong-sign" background.

Future: T2K beam -SK atmospheric ν joint analyses



- Sensitivity to δ_{CP} dominated by T2K.
- Joint fit can break degeneracy with $\cos(\delta_{CP})$ and mass ordering.
- Improved ability to reject wrong mass ordering and wrong θ_{23} quadrant.

“SK (+ND)”: T2K ND constraint on interaction uncertainties used for low E atmospheric samples

True values assumed: $\sin^2(\theta_{23})=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}$ ev^2/c^4, $\sin^2(\theta_{13})=0.0218$, NO