T2K and T2K+SK Joint Fit

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on behalf of the T2K Collaboration

NuFACT 2024

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Neutrino Oscillations

Oscillations characterised by Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

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

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

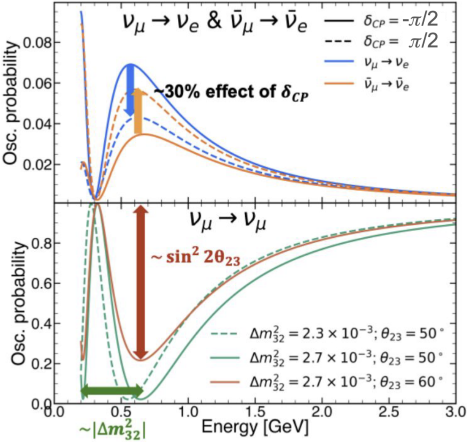
Atmospherics and LBL	Reactors and LBL	Solar and Reactors
$\theta_{23} \sim 45^\circ$	$\theta_{13} \sim 10^\circ$	$\theta_{12} \sim 35^\circ$
$\|\Delta m^2_{32}\| \sim 2.5 \times 10^{-3}$ eV^2	δ_{CP} unknown	$\Delta m^2_{21} \sim 7.5 \times 10^{-5}$ eV^2

Long baseline (LBL) experiments:

$\rightarrow$ Provide the most precise measurements of θ_{23} and $|\Delta m^2_{32}|$

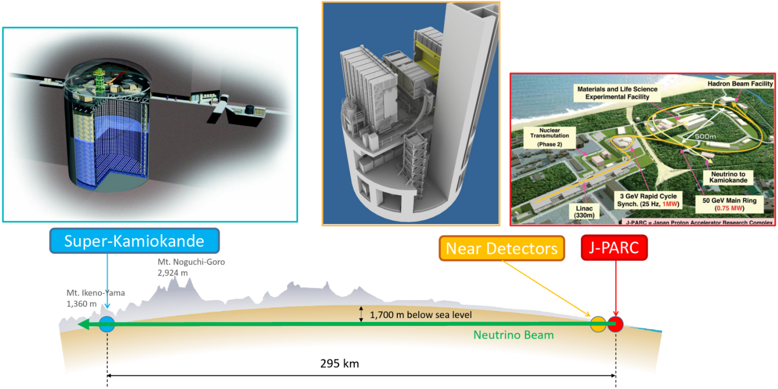
$\rightarrow$ δ_{CP} and the sign of Δm^2_{32} are unknown but accessible to LBL

Accelerator Neutrino Oscillations



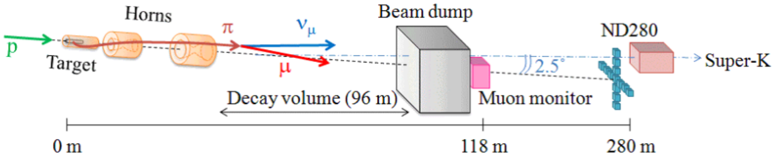
- δ_{CP} modifies neutrino/antineutrino appearance ($\nu_\mu \to \nu_e$) probability:
  - → Circular modulation over 2π period
  - → Asymmetric effect
- Disappearance probability ($\nu_\mu \to \nu_\mu$):
  - → $\sin^2 2\theta_{23}$ modulates amplitude
  - → Frequency of oscillation $\sim |\Delta m^2_{23}|$

The T2K Experiment

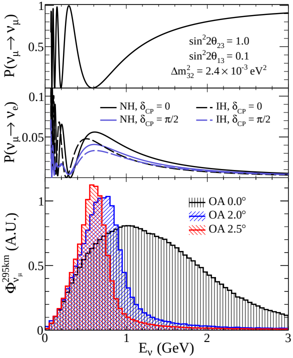


- ν_e and $\bar{\nu}_e$ appearance $\rightarrow$ determine θ_{13} and δ_{CP}
- ν_μ and $\bar{\nu}_\mu$ disappearance $\rightarrow$ precise measurement of θ_{23} and $|\Delta m^2_{32}|$
- Neutrino cross-section measurements $\rightarrow$ see talk by Laura Munteanu

T2K Beam

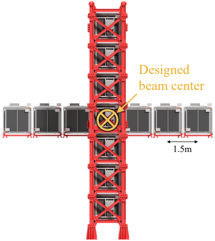


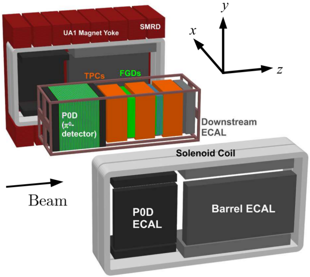
- 30 GeV proton beam extracted from J-PARC main ring onto graphite target
  - → Produces hadrons: mostly pions and kaons
- Hadrons are charge-selected and focused by three magnetic horns
  - → Select positive hadrons to produce predominantly ν_μ beam
  - → Select negative hadrons to produce predominantly $\bar{\nu}_\mu$ beam
- Beam directed 2.5° away from SK



Near Detectors

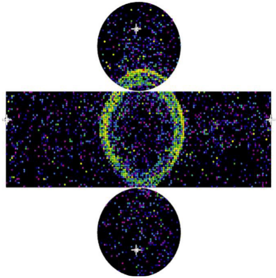
- 280 m downstream of beam target
- INGRID: on-axis detector
  - → Monitor beam intensity, direction & stability
  - → Constrain flux systematics
- ND280: off-axis detector
  - → Same 2.5° off-axis angle as SK
  - → Consists of several sub-detectors in a 0.2 T magnetic field
  - → Measure neutrino interactions, intrinsic ν_e contribution and wrong-sign background
  - → Constrain flux and cross-section uncertainties



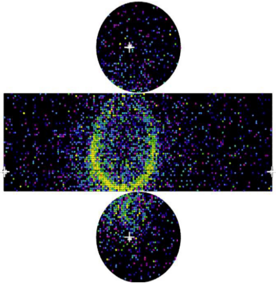


Super-Kamiokande

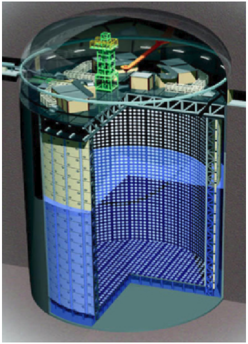
- 2.5° off-axis
- 50 kton water Cherenkov detector
- Doped with 0.03% $Gd_2(SO_4)_3$ in 2022 to improve neutron tagging efficiency



muon

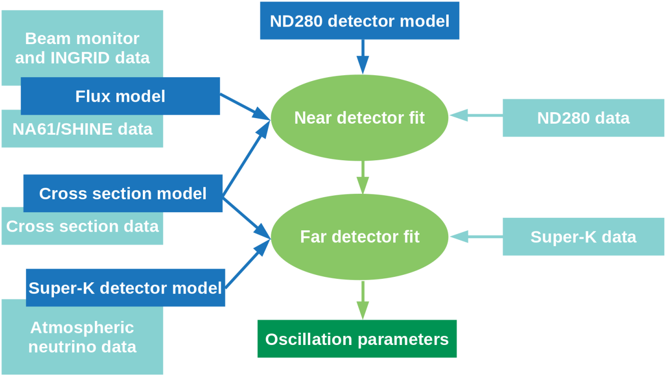


electron



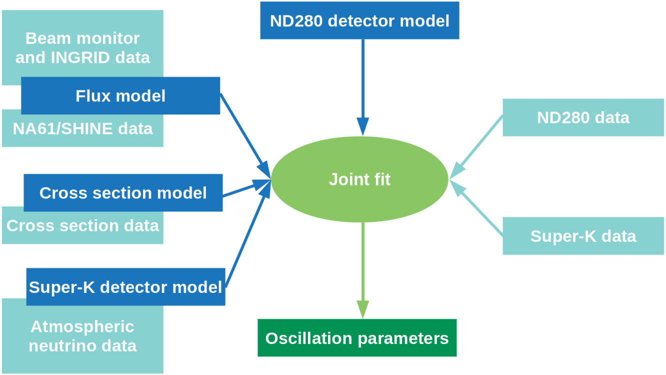
- Excellent particle identification capability
- $< 1\%$ μ misidentified as e
- μ produce sharp rings
- e produce fuzzy rings

Oscillation Analysis Strategy



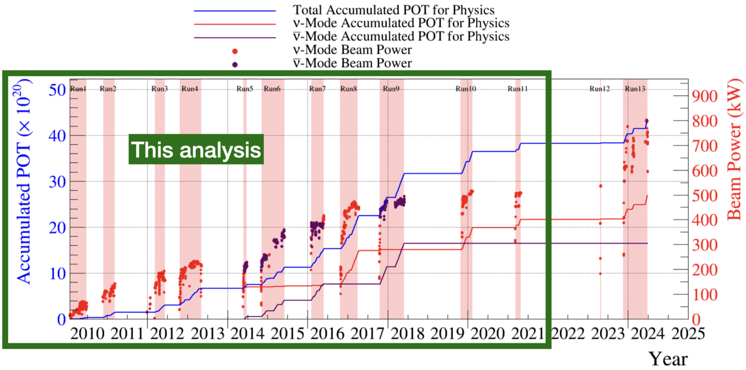
- Sequential analysis: first fit near detector data, then fit SK data
- Both fitting approaches produce consistent results

Oscillation Analysis Strategy



- Joint analysis: simultaneous fit to near and far detector data
- Both fitting approaches produce consistent results

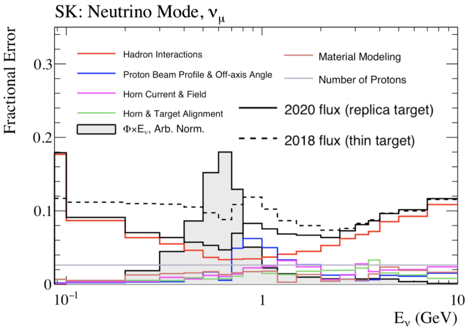
Latest T2K Oscillation Analysis

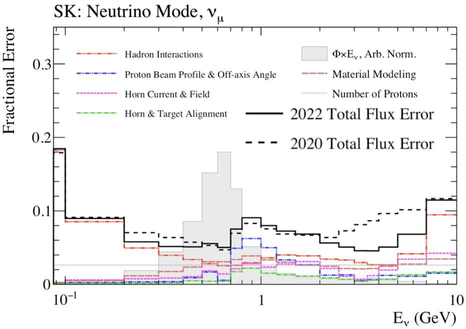


- Updates since 2022 analysis:
  - → 10% more data in neutrino mode
  - → Improved SK detector systematics treatment
  - → Added selection cuts to distinguish decay electrons and neutrons at SK
- See talk by Ed Atkin

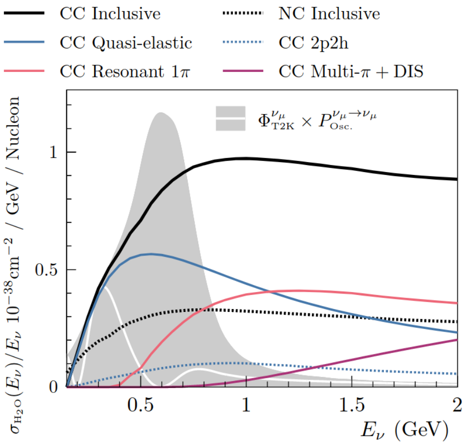
Flux Model

- Use NA61/SHINE hadron production data with replica T2K target to inform flux model
  - → Eur. Phys. J. C 76, 617 (2016), Eur. Phys. J. C 76, 84 (2016)
  - → Reduces flux uncertainty from ∼10% to ∼5% around flux peak
  - → Increases nominal ν_μ and ν_e fluxes
  - → Reduce uncertainties at higher energies





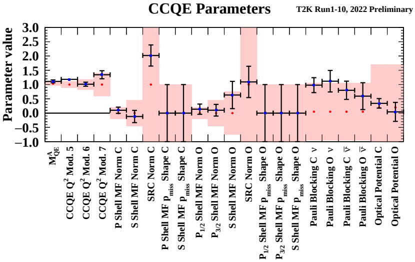
Cross-section Model

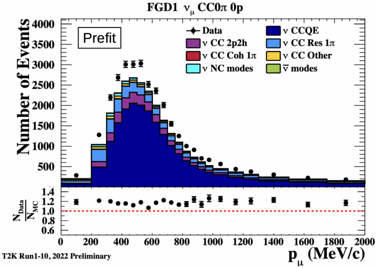


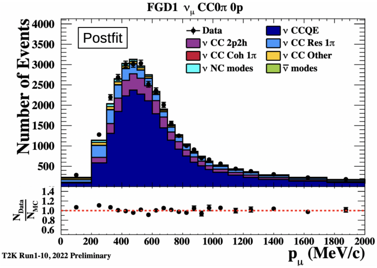
- Dominated by CCQE interactions at T2K energies
  - → Spectral Function model from Behnar et al.
  - → Paper on parameterisation
- Significant contributions from 2p2h and resonant interactions
  - → Valencia model for 2p2h
  - → Rein-Sehgal with lepton mass corrections for single pion production
- Mismodelling can lead to biases in neutrino energy reconstruction
  - → Constrain cross-section model with near detector data

Near Detector Fit

- 22 samples separated by:
  - → Beam configuration
  - → Lepton candidate charge
  - → Target (CH/H_2O)
  - → Number of pions, protons and photons
- See talk by Ewan Miller



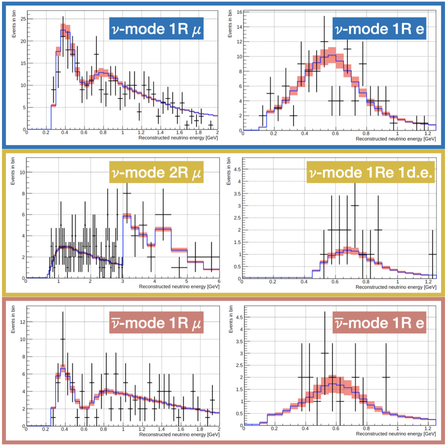




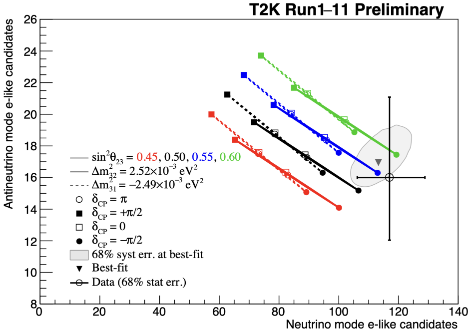
SK Samples

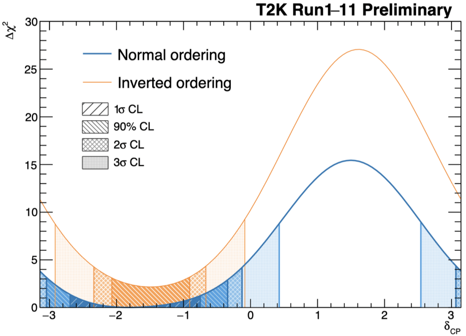
- 2 samples 1R μ-like/e-like in ν-mode $\rightarrow$ CCQE enhanced
- 2 samples CC1π enhanced (2 rings or additional decay electron)
- 2 samples 1R μ-like/e-like in $\bar{\nu}$-mode $\rightarrow$ CCQE enhanced
- New detector covariance matrix at SK
  - $\rightarrow$ Significantly reduces systematics in 1Re1d.e. sample
  - $\rightarrow$ See talk by Michael Reh

Sample	Last Analysis	This Analysis
ν-mode 1R μ	3.4%	3.2%
ν-mode 1R e	5.2%	4.9%
ν-mode 2R μ	4.9%	3.9%
ν-mode 1Re 1d.e.	14.3% →	6.3%
$\bar{\nu}$-mode 1R μ	3.9%	5.0%
$\bar{\nu}$-mode 1R e	5.8%	6.7%



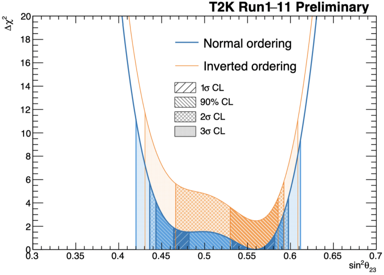
T2K Oscillation Analysis Results

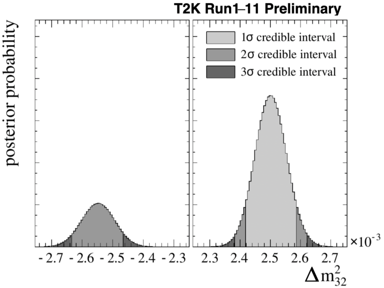




- Best-fit δ_{CP} value $\sim -\pi/2$
- CP-conserving values are within 2σ interval

T2K Oscillation Analysis Results



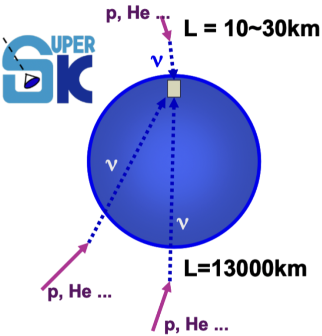


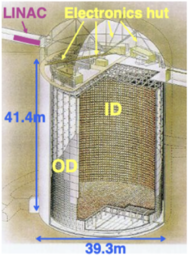
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IO ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00

- Bayes Factor B(NO/IO) = 3.3
- Bayes Factor $B(\theta_{23} > 0.5/\theta_{23} < 0.5) = 2.6$
- Weak preference for normal ordering and upper octant

Joint Analyses

- Two joint analyses released in 2023
- T2K (beam) + NOνA (beam)
  - $\rightarrow$ See next talk for details
- T2K (beam) + SK (atmospherics) - Arxiv 2405.12488
  - $\rightarrow$ T2K data (5 samples) POT: 3.6×10^{21} - Eur. Phys. J. C 83, 782
  - $\rightarrow$ SK-IV data (18 samples) 3244 days - PTEP 2019 5, 054F01





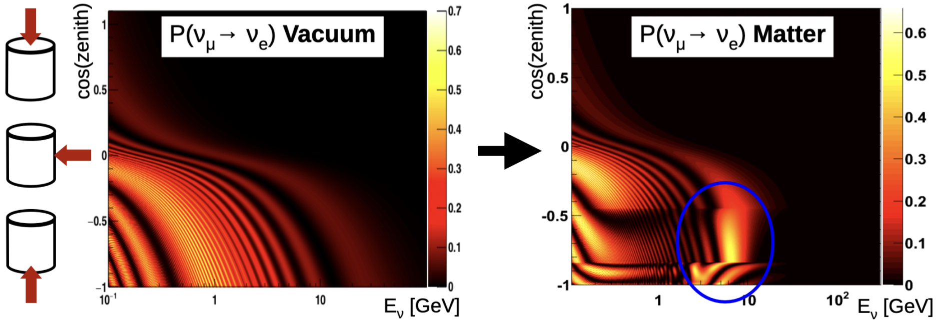
atmospheric
+ accelerator

Complementary information

Atmospheric Oscillations in SK

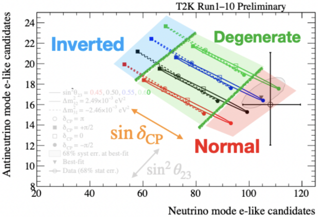
- Resonant-induced matter effects between 2 and 10 GeV in up-going neutrinos
  - $\rightarrow$ Enhancement of ν in NO; enhancement of $\bar{\nu}$ in IO
  - $\rightarrow$ Sensitivity to θ_{23} octant
  - $\rightarrow$ Effect not degenerate with δ_{CP}

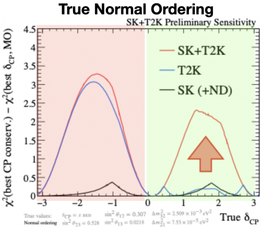
Atmospheric neutrino oscillation probability (normal ordering)

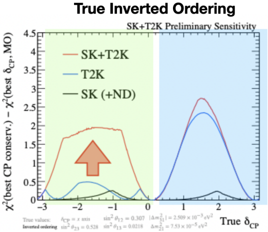


T2K+SK Joint Analysis

- T2K has good sensitivity to δ_{CP} but mild sensitivity to mass ordering
- SK has better sensitivity to mass ordering than δ_{CP}
- Joint analysis breaks degeneracies between δ_{CP} and mass ordering

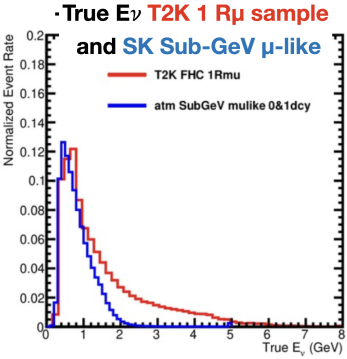


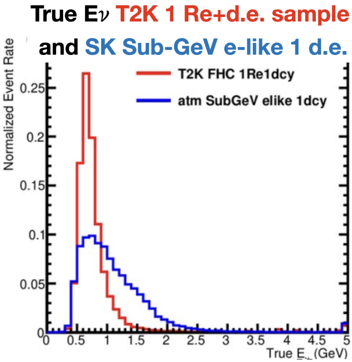




T2K+SK Systematics Model

- Energy spectra of T2K samples and low energy SK samples overlap
  - → Correlated systematics: T2K near detector can be used to constrain cross-section uncertainties for low energy atmospheric samples



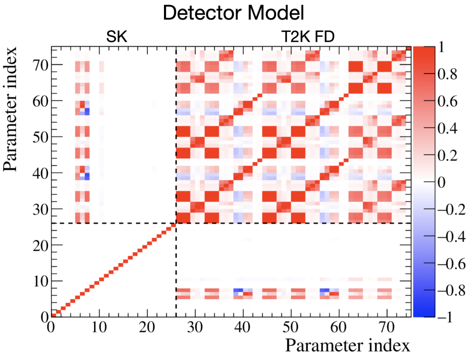


T2K+SK Systematics Model

Interaction Model Summary

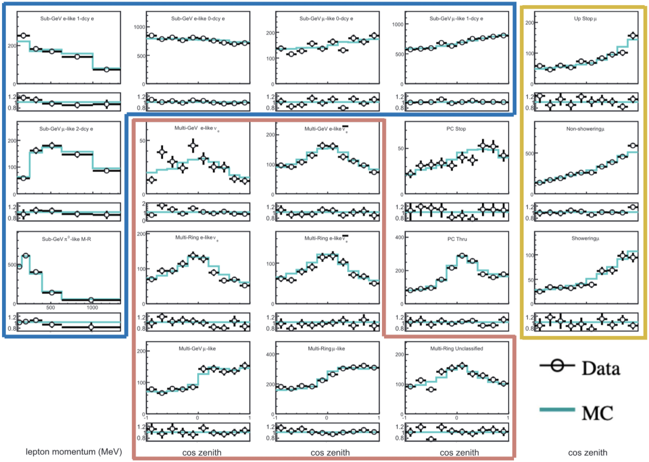
	"Low-energy" samples SK FC sub-GeV and T2K	"High-energy" samples SK FC multi-GeV, PC, Upmu
Charged Current Quasi-Elastic (CCQE)	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2 parameters)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	+ extra ν_e/ν_μ xsec diff. error	
Two particles two holes (CC2p2h)	T2K model w/ND280	SK model (100% error) + T2K-style shape error
Resonant Interactions	T2K model w/ND280 + new p_π shape uncertainty + extra NC1π^0 uncertainties	SK model for 3 dials also in T2K model, use more recent, larger T2K priors
Deep inelastic	T2K model w/ND280	SK model
Tau neutrino interactions	SK model (25% normalization error) correlated in low-E/highE	
Final State Interactions	T2K model w/ND280	T2K model w/o ND280 (mostly same as SK model)
Secondary Interactions	T2K model, correlated in low-E/high-E not applied to SK Upmu samples	

High energy mostly based on SK



- Same detector simulation and reconstruction used in both experiments
  - → Correlated detector systematics included in joint analysis

SK Atmospheric Samples



Multi-GeV samples

- $\rightarrow$ Sensitive to mass ordering and θ_{23} octant

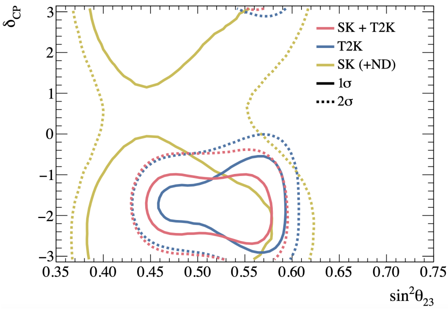
Sub-GeV samples

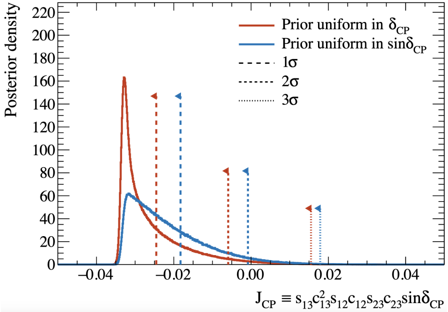
- $\rightarrow$ Sensitive to δ_{CP}

Upward-going muons

- $\rightarrow$ Sensitive to $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$ octant

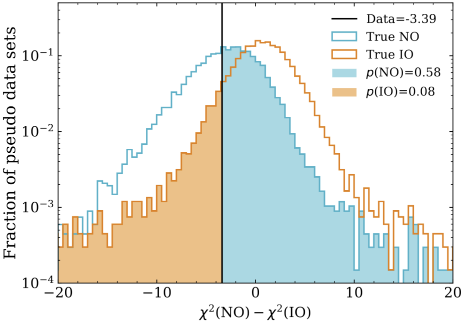
T2K+SK Oscillation Analysis Results: θ_{23} and δ_{CP}

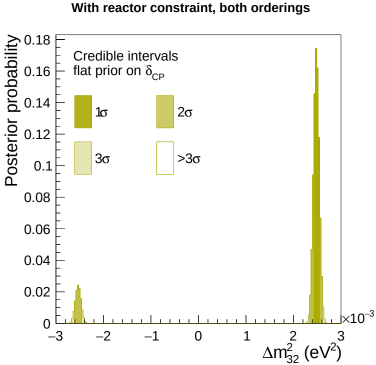




- T2K and SK prefer different octants for θ_{23}
  - → Joint analysis has weaker constraint than individual experiments and higher probability of maximal mixing
- The CP-conserving value of the Jarlskog invariant ($J_{CP} = 0$) is excluded with a significance varying between 1.9σ and 2.0σ
- Frequentist analyses find a p-value of 0.050 for a CP conservation hypothesis defined as $J_{CP} = 0$

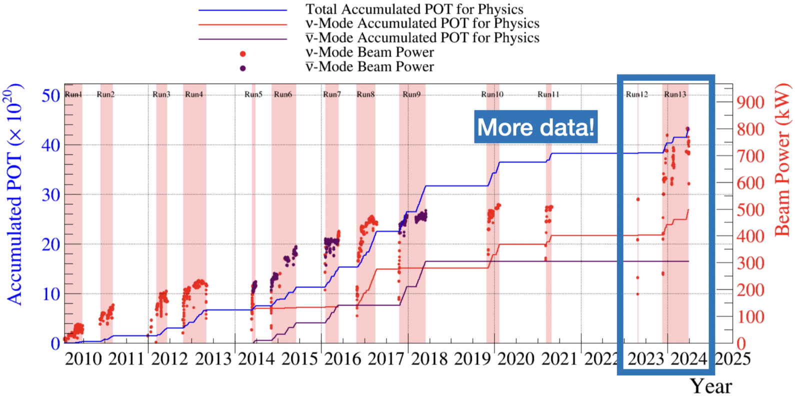
T2K+SK Oscillation Analysis Results: mass ordering





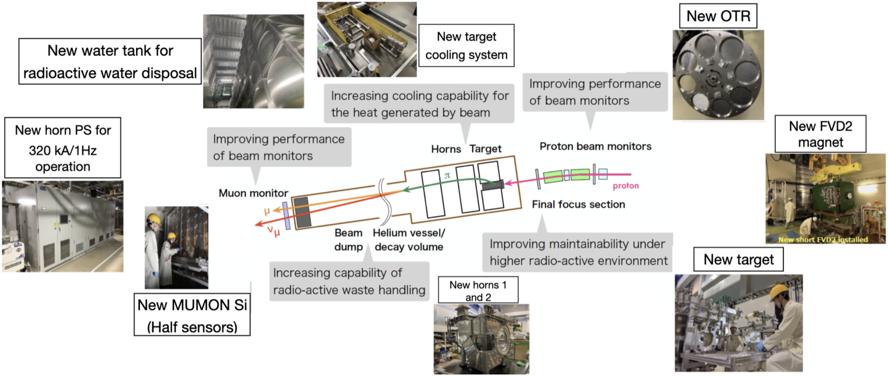
- Slight preference for normal ordering
- Frequentist p-values = 0.58 for NO, 0.08 for IO
  - → Corresponds to 1.64σ deviation assuming equal prior probabilities
- Bayesian analysis gives Bayes factor B(NO/IO) = 8.98
  - → c.f. T2K analysis B(NO/IO) = 3.3

Future Plans for T2K



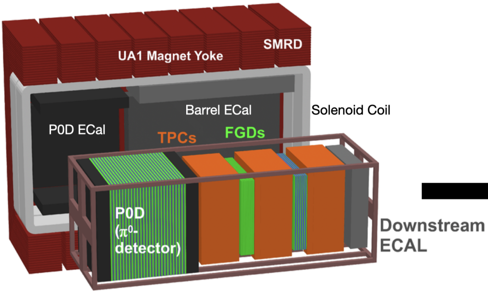
- More data taken in 2023/2024
- Beamline upgrades → 750 kW achieved in December 2023
- ND280 upgrade installed and took first data

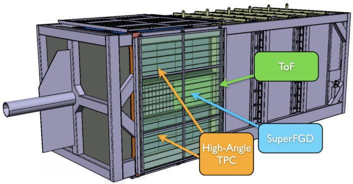
Beamline Upgrades



- Replacement of Main Ring power supplies to allow for higher repetition rate from 2.48 s to 1.36 s
- Horn being operated at 320 kA instead of 250 kA
  $\rightarrow$ 10% increase in neutrino flux
- Beam power increased to 800 kW in June 2024

ND280 Upgrade

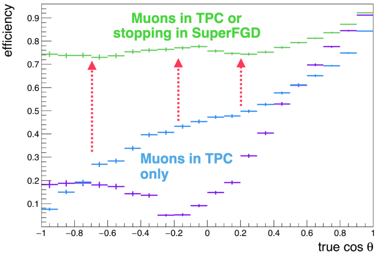


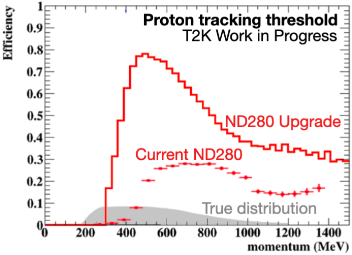


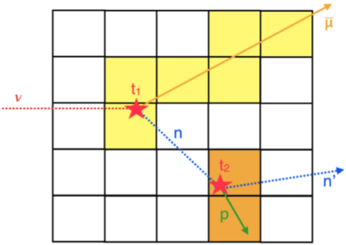
- To address limitations of ND280, replace PØD with three new subdetectors:
  - → SuperFGD: highly segmented target material with excellent tracking capability → see my talk later today
  - → High Angle TPCs: measure momentum, charge and particle ID with better angular acceptance → see talk by Samira Hassani
  - → Time-of-Flight: precise timing information to reject backgrounds and improve reconstruction

ND280 Upgrade Physics Benefits

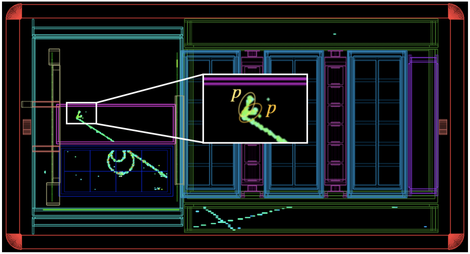
- Higher efficiency for backwards and high-angle muons
- Lower proton reconstruction threshold
- Reconstruct neutron kinematics event by event for the first time

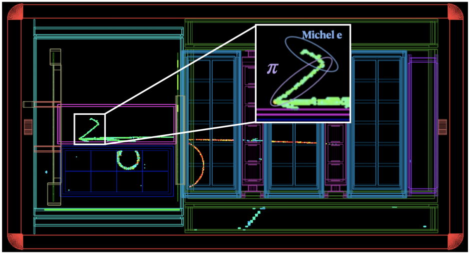






First Neutrino Interactions in ND280 Upgrade

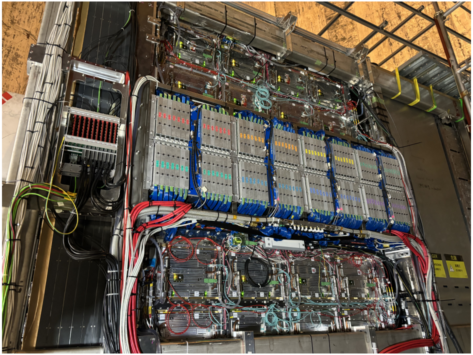


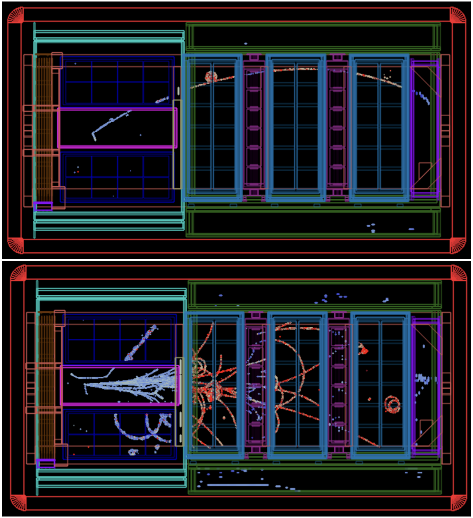


- First beam data taken in November/December 2023 and February 2024 with SFGD, bottom HAT and four TOF panels

ND280 Upgrade Complete

- Upgrade installation complete and first data with fully upgraded ND280 in June 2024





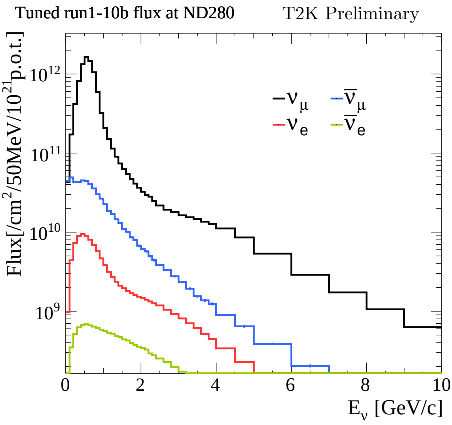
Summary

- T2K is a long baseline experiment aiming to make precise measurements of θ_{23} and Δm^2_{32}, looking to distinguish the neutrino mass ordering, and searching for CP violation
- New T2K oscillation analysis includes 10% more data in neutrino mode and improved detector systematics
  - $\rightarrow$ CP conservation excluded at 90% CL
  - $\rightarrow$ Weak preference for normal ordering and upper octant
- Presented joint analysis with SK
  - $\rightarrow$ The CP-conserving value of the Jarlskog invariant is excluded with a significance varying between 1.9σ and 2.0σ
- See next talk for T2K+NOνA results
- Lots of exciting developments coming for T2K with beamline and detector upgrades

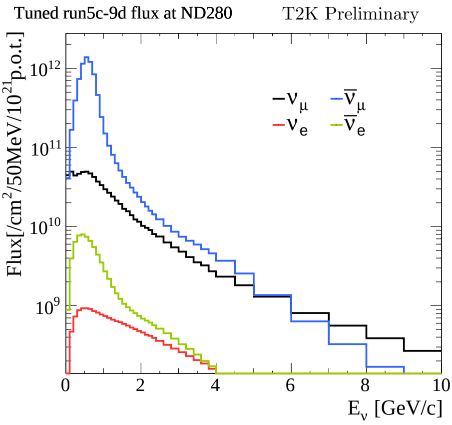
BACKUP

Beam Composition

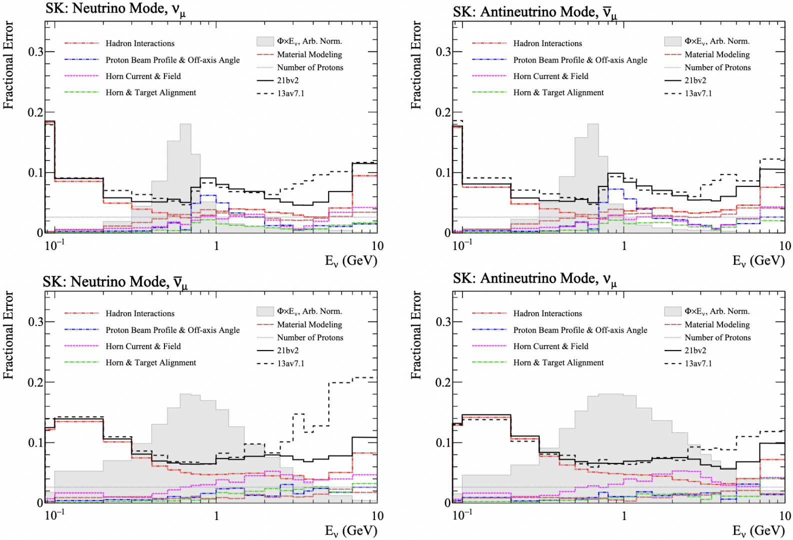
ν-mode



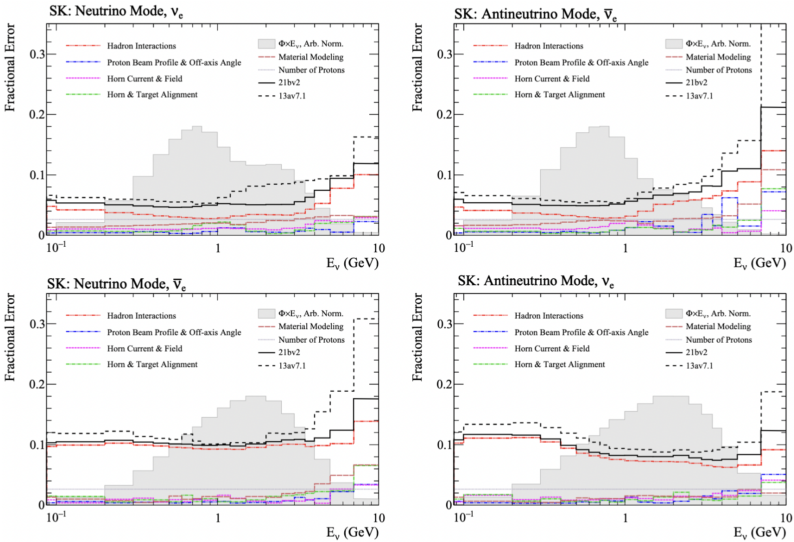
$\bar{\nu}$-mode



Flux Systematics: ν_μ

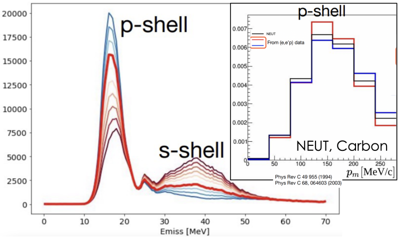


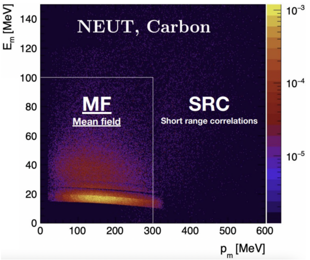
Flux Systematics: ν_e



Cross-Section Model: CCQE

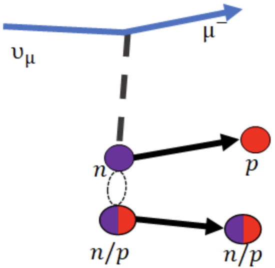
- Spectral Function model by Benhar et al. for nuclear structure
- 22 parameters for modifying lepton and nucleon kinematics
  - → Separated by C vs O and ν vs $\bar{\nu}$ where appropriate
- Change relative occupancy and shape of momentum distributions within nuclear shells
- Removal energy (E_{rmv}) treatment developed using scattering data
- Normalisation of the Short Range Correlation (SRC) contribution
- Inclusion of Pauli Blocking and optical potential

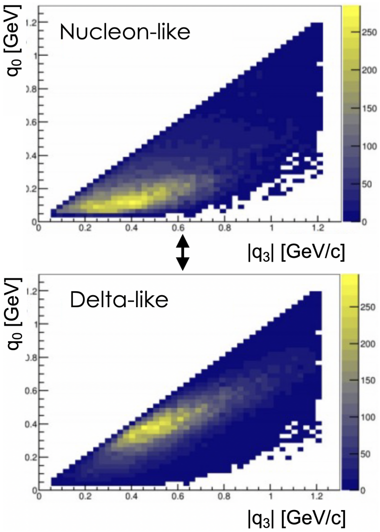




Cross-Section Model: 2p2h

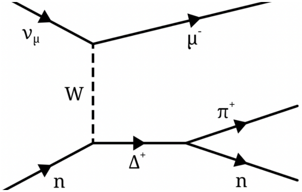
- Base model: Valencia 2p2h
- Parameters to control:
  - → Normalisation
  - → Shape
  - → Pair contributions - PN vs NN (NP vs PP in $\bar{\nu}$ mode)
  - → Energy dependence

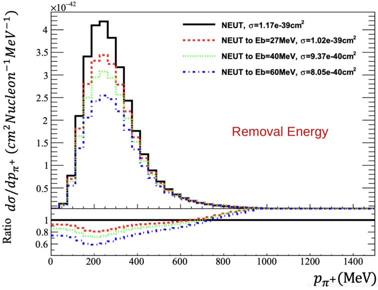


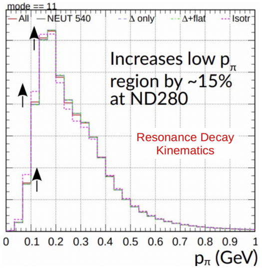


Cross-Section Model: Single Pion Production

- Base model: Rein-Sehgal with lepton mass corrections
- Parameters to control:
  - → Form factors - M_A^{RES} and C_A^5
  - → Non-resonant background
  - → Channel normalisations
  - → Removal energy
  - → Resonance decay kinematics

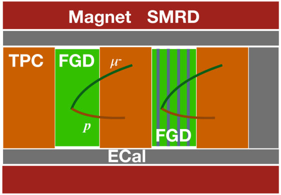


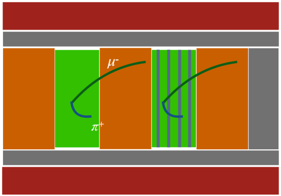


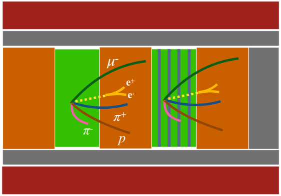


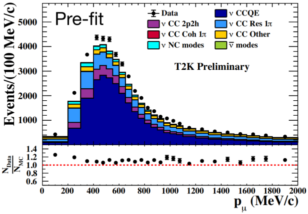
Near Detector Oscillation Samples: Previous Analysis

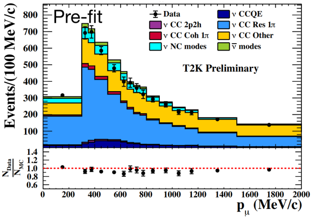
$CC0\pi$	$CC1\pi^+$	CC-Other

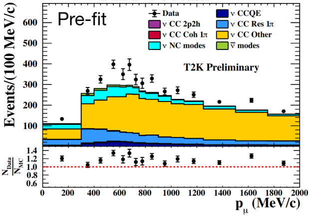










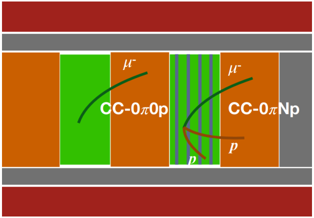


- Have equivalent selections in antineutrino mode, where wrong-sign background (ν_μ) is also selected

$\rightarrow$ 3 topologies $\times$ 2 FGDs $\times$ 3 neutrino flavour-mode combinations $=$ 18 samples in total

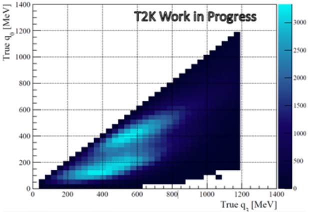
Near Detector Oscillation Samples: Latest Analysis

New samples in neutrino mode:

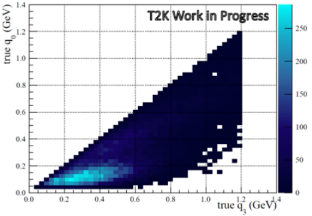


- Split CC0π sample based on presence or absence of **protons**
- Different sensitivity to nuclear effects:
  - → Separates (q_0, q_3) peaks in Valencia 2p2h model

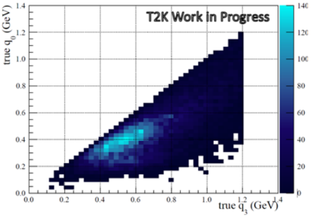
CC0π



CC0π0p

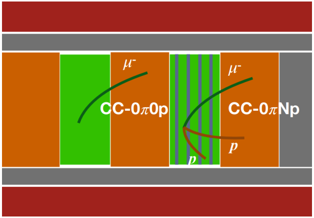


CC0πNp

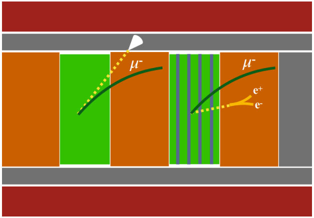


Near Detector Oscillation Samples: Latest Analysis

New samples in neutrino mode:

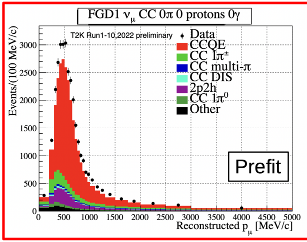


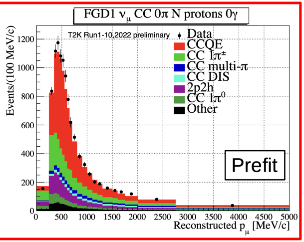
- Split CC0π sample based on presence or absence of **protons**
- Different sensitivity to nuclear effects:
  - $\rightarrow$ Separates (q_0, q_3) peaks in Valencia 2p2h model

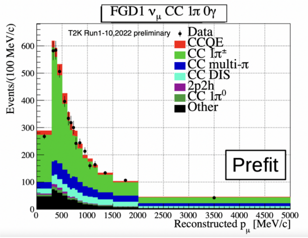


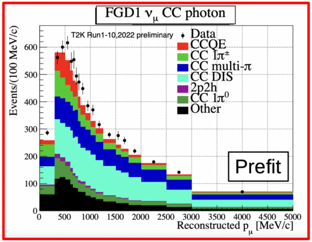
- Isolate CCπ^0 interactions by looking for **photons** in the ECals and TPCs
- Contributions from DIS (30%), multi-pion production (20%) and resonant π^0 production (24%)
- Improves purities of other ND samples

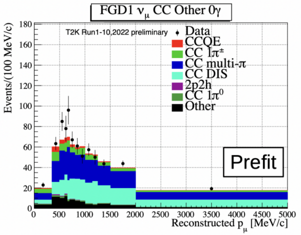
Near Detector Oscillation Samples: Latest Analysis







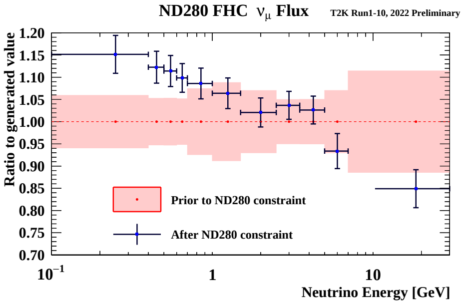


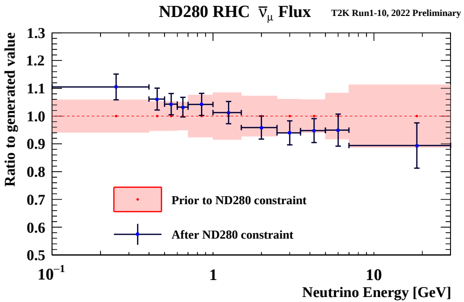


- 5 samples per FGD in neutrino mode
- Antineutrino mode selection unchanged
- 22 samples in total

Postfit Constraints on Flux Parameters

- Significant increases at low energy for both ν_μ and $\bar{\nu}_\mu$
- At flux peak (0.6 GeV) increase ν_μ by $\sim$10% and $\bar{\nu}_\mu$ by $\sim$7%
- Flux prediction at SK constrained through correlation with ND280 flux parameters

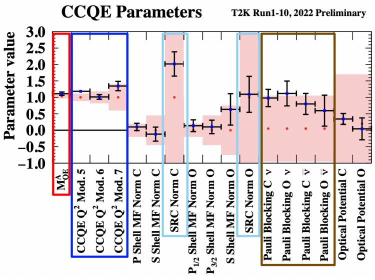


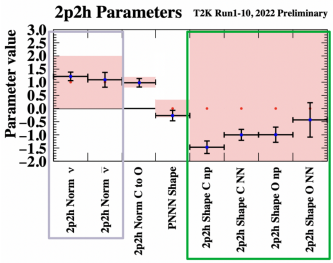


Although shifts seem large, incur a χ^2 penalty of $\sim$ 60 for 100 flux parameters

Postfit Constraints on CCQE and 2p2h Parameters

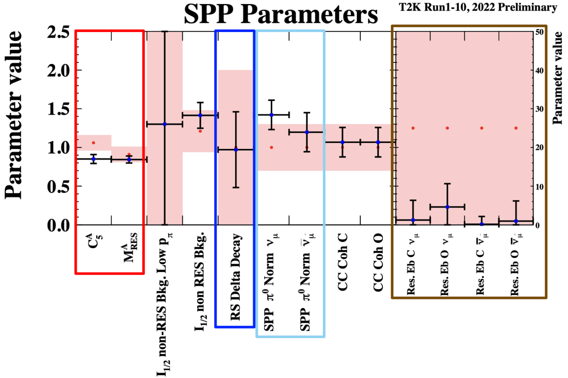
- M_A^{QE} increased above prior, CCQE high Q^2 cross section increased, Short Range Correlations (SRC) normalisation increased
- Pauli Blocking increased
  - $\rightarrow$ Changes low Q^2 region of CC0π0p with little impact on CC0πNp
- 2p2h normalisation increased by $\sim$20% for ν and $\sim$5% for $\bar{\nu}$
  - $\rightarrow$ Less than previous analysis due to correlations with SRC
- 2p2h shape parameters pulled towards non-Δ region
  - $\rightarrow$ Shift 2p2h towards low q_0





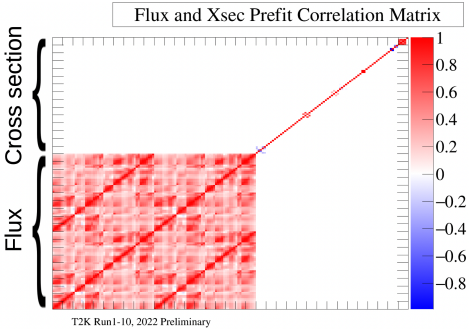
Postfit Constraints on SPP Parameters

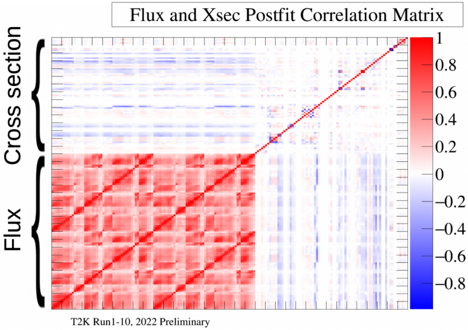
- Form factors M_A^{RES} and C_A^5 pulled below prior value
- RS delta decay remains at prior favouring Δ-like decay
- π^0 normalisations increased above prior values, more for ν_μ than $\bar{\nu}_\mu$
- Removal energy parameters pulled almost to 0



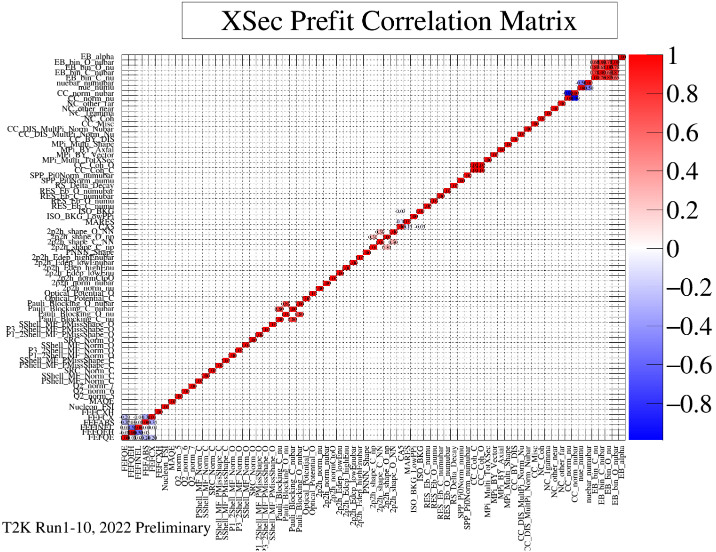
Parameter Correlations

- Strongest correlations between degenerate parameters
- Anticorrelations introduced between flux and cross-section parameters due to strong constraints on event rate
- ND detector systematic parameters not propagated to SK

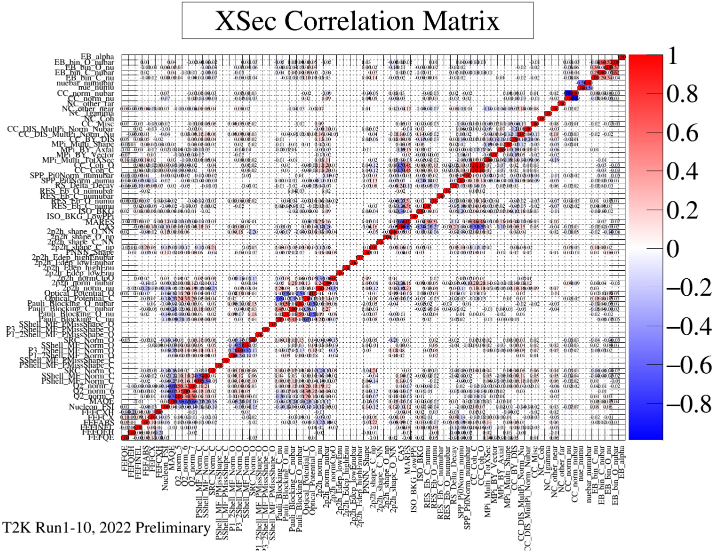




Cross-Section Correlations: Prefit



Cross-Section Correlations: Postfit

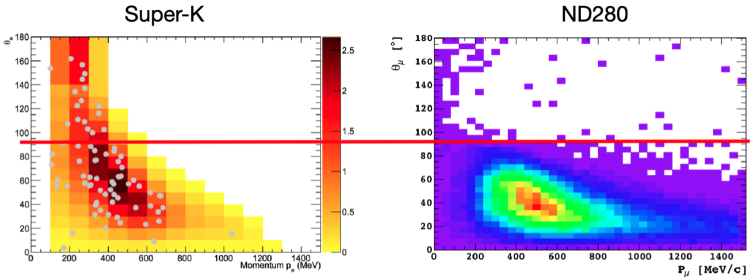


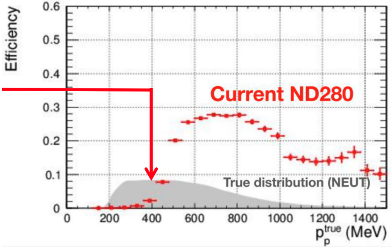
Systematic Uncertainties at the Near Detector

- Before ND fit, cross-section uncertainties are largest
- After fit, cross-section and flux are similar at 2.5-3.5%
- Detector uncertainties remain smallest: 2-5% before and 1-2% after

Sample	$\delta N/N(\%)$					
	Flux		Xsec		ND280	
	pri.	post.	pri.	post.	pri.	post.
FGD1 FHC CC0π-0p-0γ	5.0	2.7	11.8	2.8	1.8	1.2
FGD1 FHC CC0π-Np-0γ	5.5	2.8	11.7	3.2	3.5	2.2
FGD1 FHC CC1π-0γ	5.2	2.7	9.1	2.7	3.0	1.4
FGD1 FHC CC-Other-0γ	5.4	2.8	8.0	2.8	5.2	2.3
FGD1 FHC CC-Photon	5.5	2.8	8.5	2.8	2.8	1.8
FGD1 RHC CC0π	4.9	3.2	11.3	3.2	1.9	1.2
FGD1 RHC CC1π	4.6	3.1	10.3	3.0	4.2	2.6
FGD1 RHC CC-Other	4.5	2.9	9.3	3.0	3.5	2.0

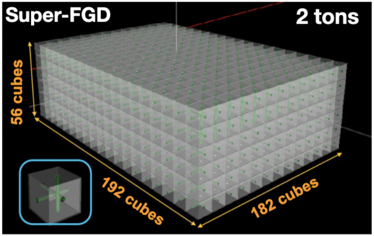
ND280 Limitations

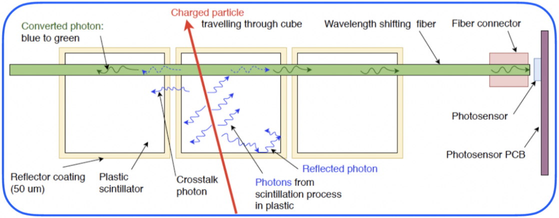


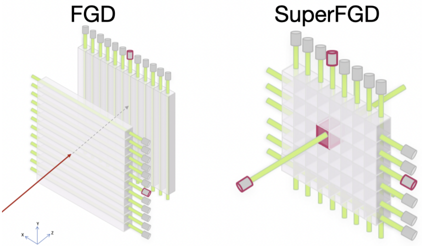


- Limited angular acceptance
- High proton reconstruction threshold

SuperFGD

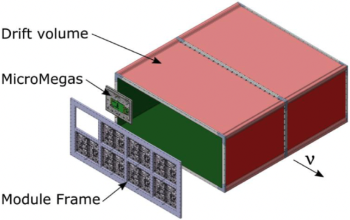






- 2 million optically isolated 1 cm^3 plastic scintillator cubes
- 56,000 wavelength shifting fibers
  - → Three orthogonal fibers per cube
  - → Each coupled to an MPPC

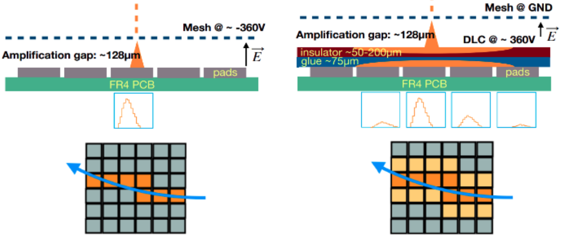
HAT



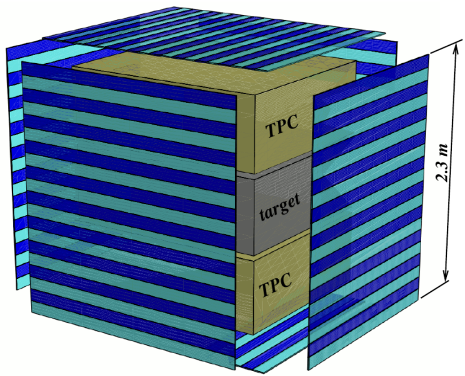
- Employs Encapsulated Resistive Anode Micromegas (ERAMs)
- Charge spread over several pads improves spatial resolution

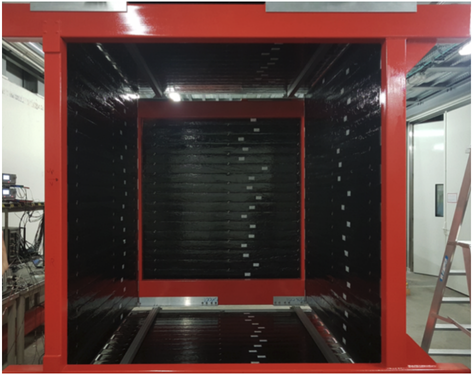
Existing vertical TPCs:
Bulk MicroMegas

New horizontal TPCs:
Resistive Anode MicroMegas



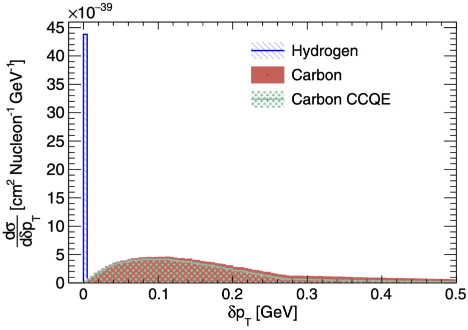
TOF

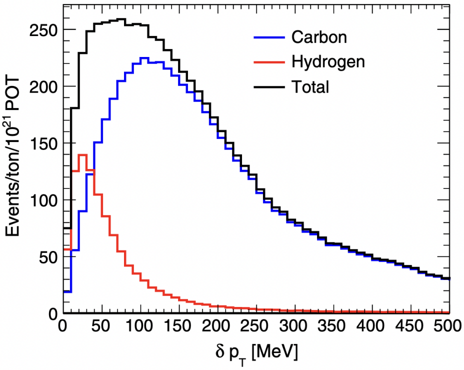




- Six plastic scintillator panels surrounding SFGD + HATs
- Double-ended readout of scintillator bars

Interactions on Hydrogen





PhysRevD.101.092003 (2020)