Precision Measurements of the PMNS Parameters with T2K Data

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(on behalf of **the T2K Collaboration**)

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@University of Mississippi

THE UNIVERSITY OF WINNIPEG

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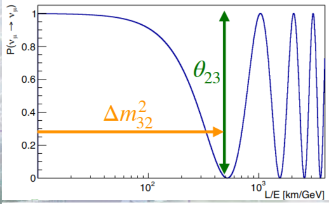
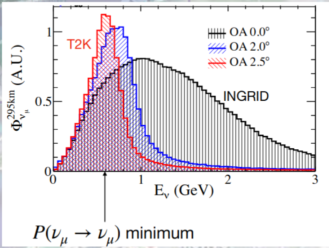
T2K

Neutrino Oscillations along T2K baseline

(Previous Talk by Joe Walsh)

Oscillations and Precision



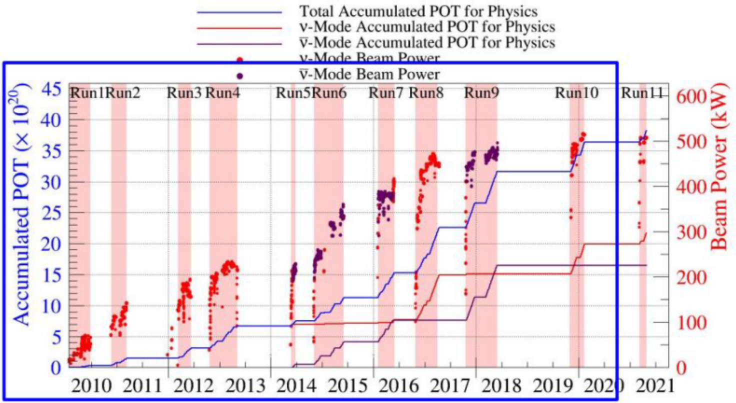


- 295km baseline
- First Osc. maximum at 0.6 GeV
- 2.5° off axis beam energy
- Measure Δm^2_{32}, θ_{23} from disappearance mode
- Systematic uncertainty important for precision in oscillation results.

Measuring Event Rates at **Far** and **Near** Detectors:

$$\mathbf{N}(\vec{x}) = \Phi(E_\nu) \cdot \sigma(E_\nu, \vec{x}) \cdot \epsilon(E_\nu) \cdot P_{ab}(E_\nu, \Delta m^2_{ij}, \theta_{ij})$$

The T2K Data for this Analysis:



OA2020 results: Run 1-10

ν mode : 1.99006×10^{21} (54.7%)

$\bar{\nu}$ mode : 1.65053×10^{21} (45.3%)

Data taken with SK Gd: Run 11:

ν-mode POT (FHC) : 2.116 x 10^{21}

ν̄-mode (RHC) POT : 1.651 x 10^{21}

Total delivered: 3.818x10^{21}

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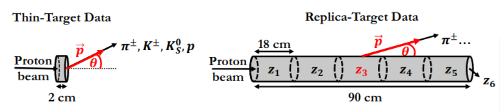
The Analysis Schematics: already explained by Joe in previous talk. Quick Reminder

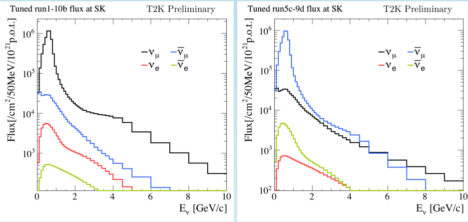
Flux Predictions and Improvements:

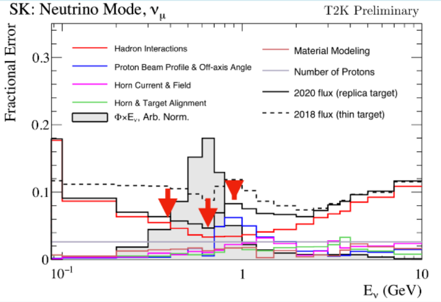


- Hadron production simulations by Fluka, propagations by GEANT3 (GCALOR)
- Interactions constrained with NA61/SHINE (CERN) data, also from beam monitor/INGRID
- New T2K graphite replica target is used, instead of thin target.
- Flux uncertainties **reduced from 8% to 5%**
- Wrong-sign comp. in $\bar{\nu}$-mode → An extra set of sample for analysis.

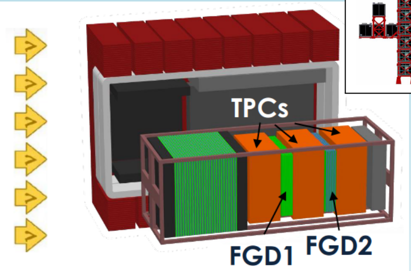
Being Worked upon:–

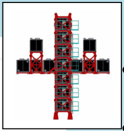
- New: NA61/SHINE replica-target 2010 data to be used, adds Kaons and proton yields and overall larger statistics
- Uncertainty to reduce to 4%. *Stay Tuned!!*





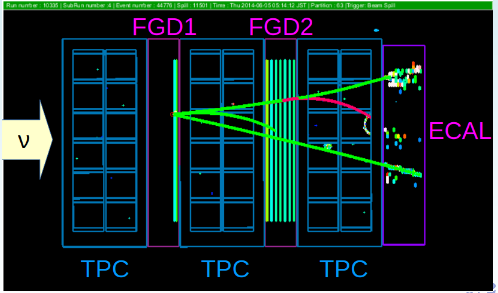
The Near Detectors of T2K:



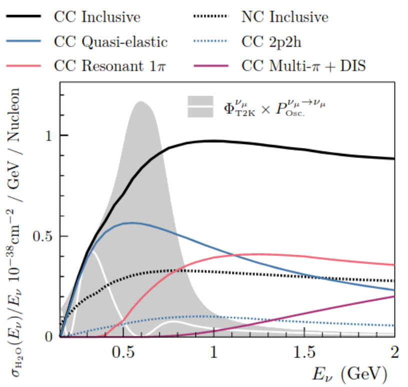


- On-axis INGRID detector (Scintillator/Fe) -monitor beam stability, spill counts
- 2.5° off-axis composite detector, 0.2 T $\vec{B}$:
  - 2 Fine Grained scintillating detectors FGD1 (CH) and FGD2 (CH,H2O)
  - 3 Time Projection Chambers (TPCs)
  - ECal surrounding inner detectors
  - One Upstream detector, and SMRDs

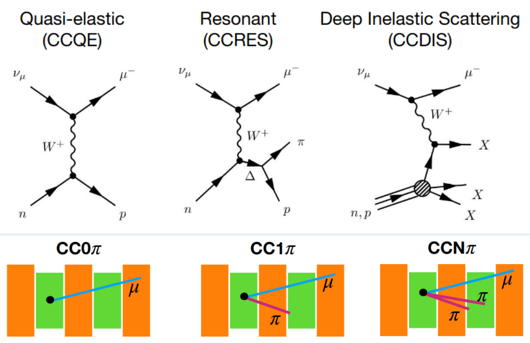
- FGDs as neutrino targets, tracker
- TPC for PID, tracking
- Magnetic field: charge and momentum
- Constraints on cross-section models, followed by Near Detector Fitting.



Neutrino Interactions



- Three main interaction channels:
  - **CCQE** (and 2p2h); CC-RES; CC-DIS
- ND samples selected by topology based on reconstructed pion multiplicity



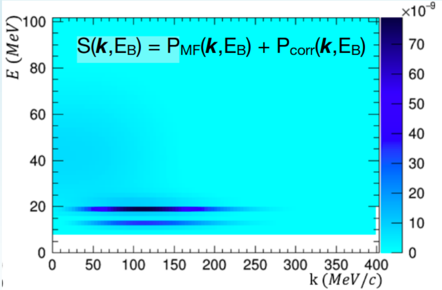
- Cross-Section Measurements → Updating Neutrino Interaction Models.
- T2K updates NEUT, iteratively.
- To use in ND-Fits

- Several Neutrino Cross Section Results Published, and more going on.

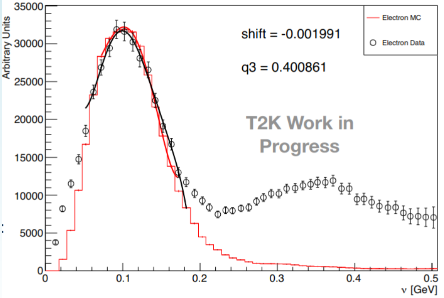
Click to see "List of Recent Results"

Cross Section Modelling and Improvements (CCQE)

- Significant updates applied on NEUT 5.4.0 model (arxiv:2106.15809)
- RFG+RPA model earlier → Spectral Function Model used now.
- Shell model built largely from electron-scattering data; Nuclear ground states better defined; and better outgoing nucleon kinematics
- New $|q_3|$-dependent removal energy treatment from comparing NEUT to electron scattering data (q_3=3-momentum transfer in nuclear models)
- To apply a correction for the q_3 shift observed in the data

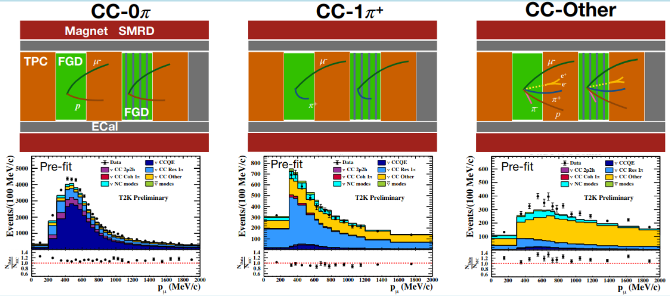


*O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Nucl. Phys., A579:493–517, 1994

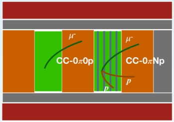


Electron data:arXiv:nucl-ex/0603032v1

ND Samples and Improvements

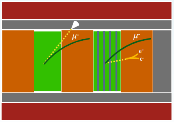


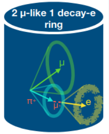
- **For Current Analysis:** 6-ν+12-$\bar{\nu}$ = 18 samples
- Larger Statistics than earlier
- Topology based selections: CC0π, CC1π, CC-Other
- Constrain CCQE, CCRES, CCDIS channels



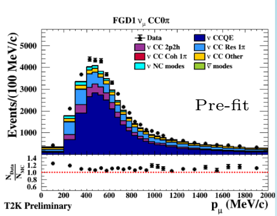
New samples at ND and SK for upcoming analyses:

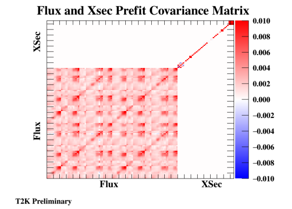
- p/γ-tagging: Selections based on
  -charge depositions & PIDs in ECAL,
  -e/p likelihood in ECAL; p-likelihood in TPCs
  -energy depositions in FGD
  - Photons produce topologies relatable to EM-showers in ECal.
- Purity in samples to improve by ~5-10%

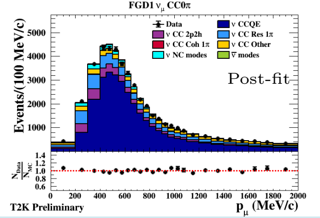




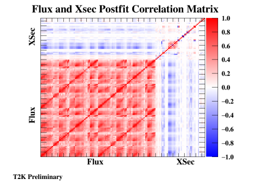
Near Detector Fits



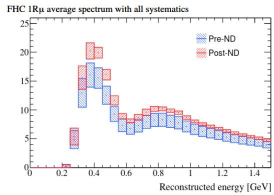


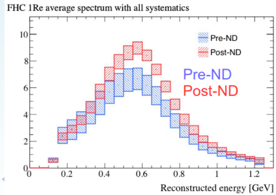


- Prefit ND sample + Constraints from Flux and Cross section Models → Postfit ND distribution
- An extended binned likelihood fit to the ND sample
- Introduces anticorrelations between flux and cross-section uncertainties
- Model after fit reproduces well the data (p-value of 0.74)



- FD prediction of the spectra at SuperK; Flux and cross-section uncertainties in CC0π samples reduce from ∼13% to ∼4%





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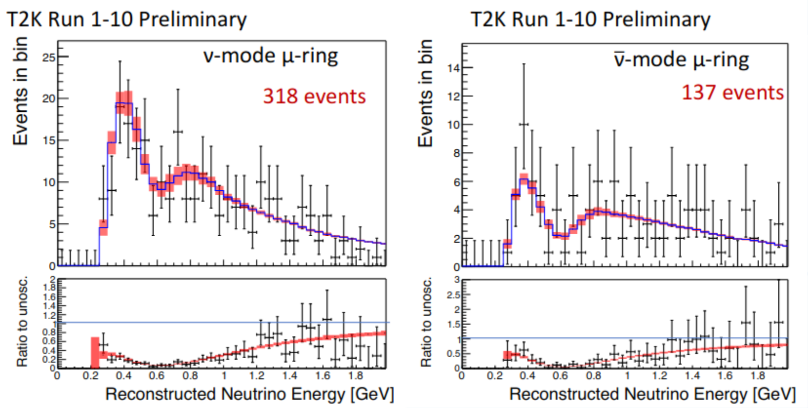
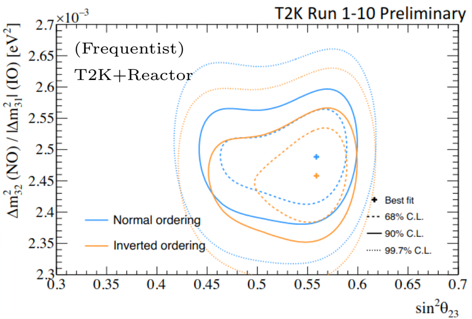
At the Far Detector (SuperK)

- 2 (of 5) samples with μ-like rings (one in ν-mode, one in $\bar{\nu}$-mode)
  (For Details on SK sample: See Joe's Talk)
- Systematic uncertainty: 3.0 (4.0)% in ν-mode ($\bar{\nu}$-mode)



The Current PMNS Precision Status:



Super-K Sample	pre-ND fit error	post-ND fit error
ν_μ 1Rμ	11.1%	3.0%
$\bar{\nu}_\mu$ 1Rμ	11.3%	4.0%
ν_e 1Re	13.0%	4.7 %
$\bar{\nu}_e$ 1Re	12.1%	5.9%
ν_e 1Re1d.e.	18.7%	14.3%

- Analysis using five SK samples for T2K Run 1-10:
  -Upper octant preference (77.1% prob),
  -Normal Ordering of Mass hierarchy preferred at 80.8%
- Frequentists confidence intervals (left) agree with the Bayesian credible intervals (below).

$\sin^2\theta_{23}$:–

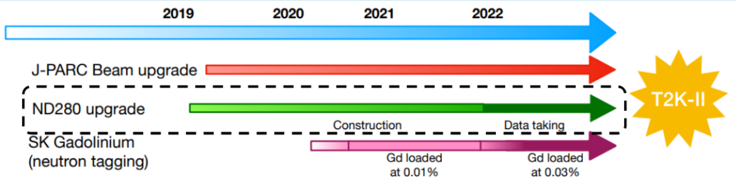
(Bayesian)

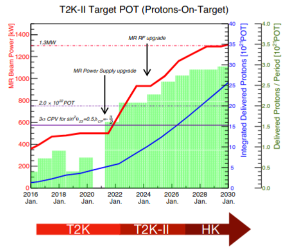
	Hierarchy	Most Probable Value	Range
T2K only	Normal	0.471	[0.452, 0.508] and [0.530, 0.568]
	Inverted	0.469	[0.449, 0.508] and [0.531, 0.565]
	Both	0.471	[0.451, 0.508] and [0.530, 0.567]
T2K + reactor	Normal	0.559	[0.504, 0.583]
	Inverted	0.560	[0.519, 0.585]
	Both	0.559	[0.507, 0.584]

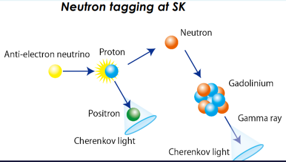
Δm^2_{32}:–

	Hierarchy	Most Probable Value	Range
T2K only	Normal	2.487×10^{-3} eV^2	$[2.437, 2.537] \times 10^{-3}$ eV^2
	Inverted	2.457×10^{-3} eV^2	$[2.407, 2.507] \times 10^{-3}$ eV^2
T2K + reactor	Normal	2.485×10^{-3} eV^2	$[2.436, 2.536] \times 10^{-3}$ eV^2
	Inverted	2.456×10^{-3} eV^2	$[2.406, 2.506] \times 10^{-3}$ eV^2

T2K-II: Upgrades in Beam, ND and FD ongoing







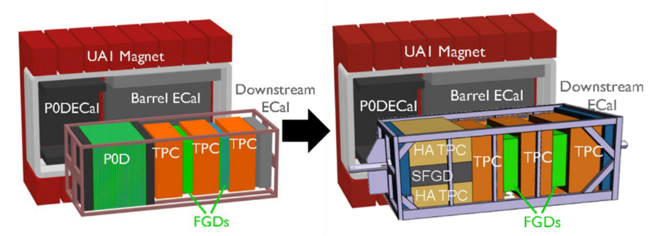
JParc-ν-Beam and SuperK:

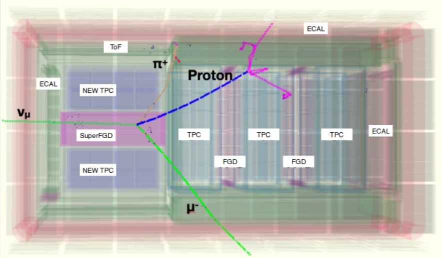
Beam power

500 kW	$\rightarrow$ ~900 kW	$\rightarrow$ ~1.3 MW
Today	***~2024***	***~2028***

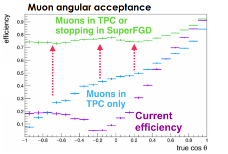
- Replacing two of the beam's magnetic focussing horns
- Upgrading horn power supply to enable faster beam repetition rate
- Improving the beam target cooling capability
- SuperK: Run-11 data taken with Gd-loaded to 0.01%, undergoing analysis.

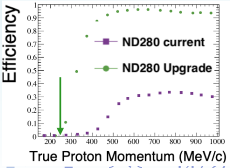
The ND Upgrade





- To overcome limited proton/neutron acceptance
- Improved pion tracking thresholds; decay electron tagging; wider phase space





- Can measure kinematics of untracked pions using decay electron position!
- More sensitive ~5 times higher efficiency

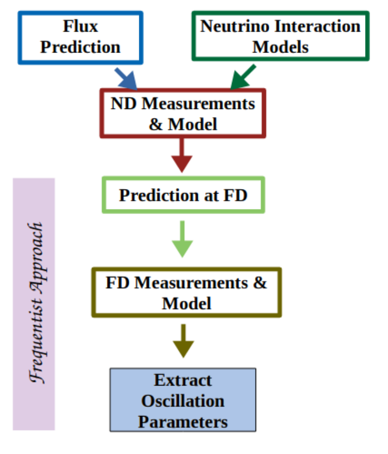
Summary

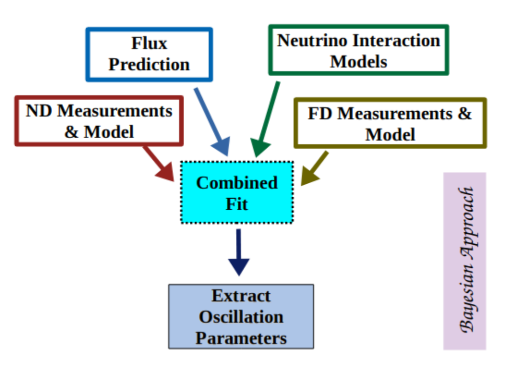
- Latest neutrino oscillation results from T2K, using 3.8×10^{21} POT data shown today.
- Slight preference for Non-maximal mixing; Upper octant & Normal Ordering MH preferred.
- **Newer Results Coming SOON**, with Improved Sample Selection, Reduced Predicted Flux Uncertainties, and more Robust Cross Section Models, ... *Stay Tuned!!*
- Many Cross Section Measurements completed, more going on.
- T2K-neutrino Interaction Model being updated with every iteration of Oscillation Analysis. NEUT seeing multiple improvements in near future.
- A complete set of uncertainties on semi-inclusive models will be crucial for upcoming oscillation measurements
- T2K-II upgrade process ongoing, higher beam power, more efficient detector systems.
- Other ongoing activities: T2K+NOvA and T2K+SK combined analyses.

Thank you !

Back ups:

Quick Reminder of the Analysis Pipeline





Both yield consistent results

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List of Recent Cross Section Results

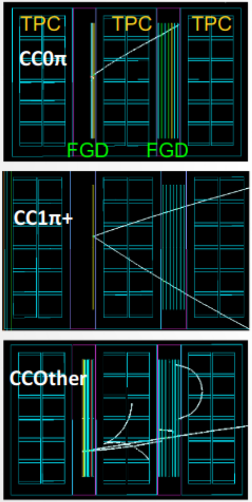
- First measurements of the Transverse Kinematics Imbalance in ν_μ CC1π+Np interactions (PhysRevD.103.112009 (2021))
- The First muon anti-neutrino CC0π cross section measurement on water (PhysRevD.102.012007(2020))
- The first combined ν_μ and $\bar{\nu}_\mu$ double differential CC0π cross section on CH (PhysRevD.101.112001(2020))
- The first combined ν_μ double differential CC0π cross section on oxygen and carbon (PhysRevD.101.112004(2020))
- The first CC0π measurement using one of the WAGASCI module (PTEP 2021, Issue 4(2021))
- The first T2K CC1π^+ cross section on CH (PhysRevD 101.012007(2020))
- Electron (anti)neutrino charged current inclusive cross sections (J.High Energ. Phys. 2020,114)

More Analyses ongoing:

- On-/off-axis combined analysis
- Different channels: CC Coherent, CC1π on different targets
- Combined interaction channels
- More measurements with the new detectors at 1.5° off-axis: WAGASCI, BabyMIND.

Back to Neutrino Interactions

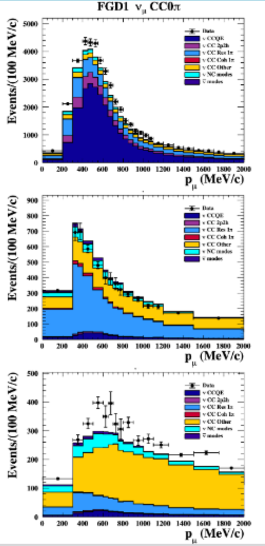
ND Samples :



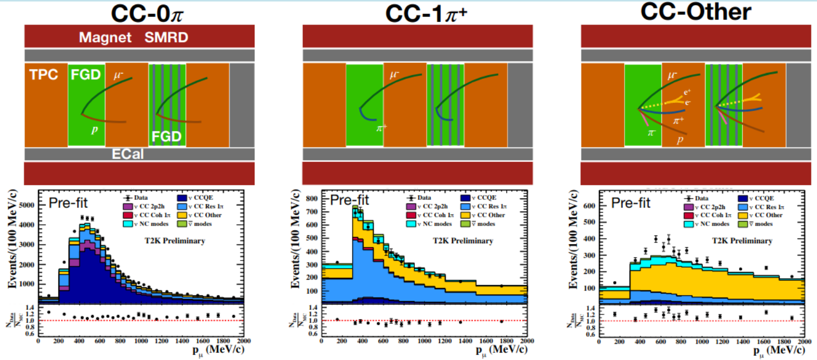
CC 0π – dominated by **CC QE**

CC 1π⁺ – enhanced in **resonant pion production**

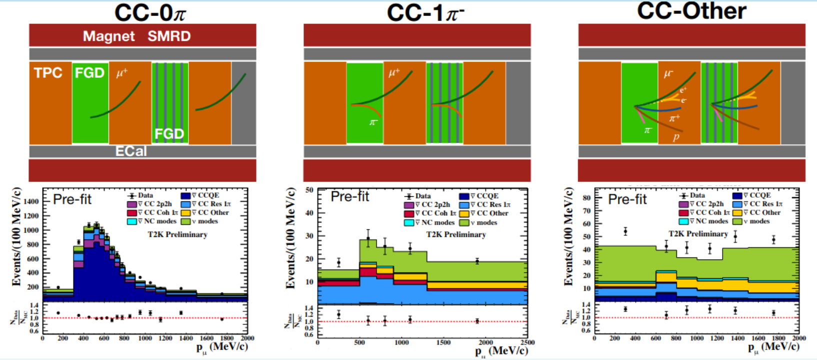
CC Other – mostly **DIS**



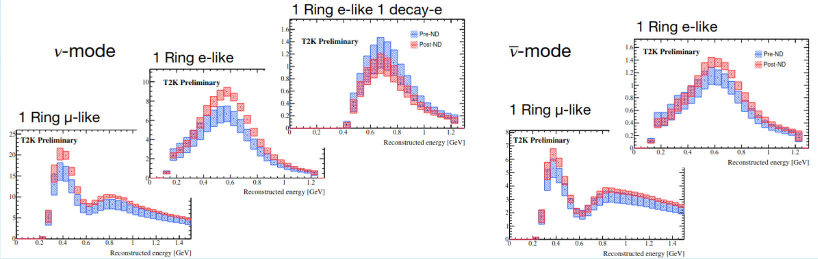
ND Sample nu OA2020

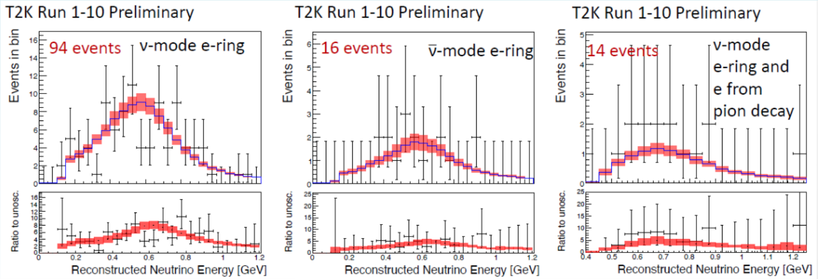


ND Sample nubar OA2020

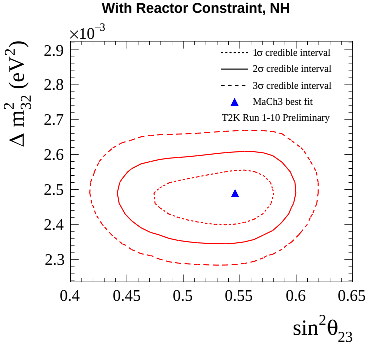


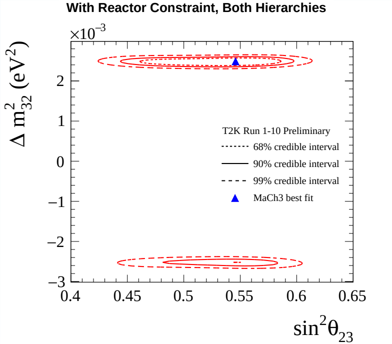
SK Predicted OA2020, and the 3-of-5 samples





PMNS Results Bayesian:

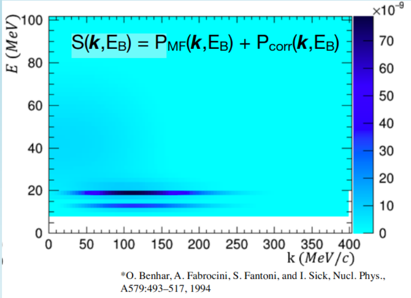




The Current PMNS Precision Status: More Systematics Details

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

The Spectral function:



- SF: Defines a nucleon ground state; as a probability function of finding a nucleon with a particular Nuclear removal energy (E_B) and Momentum (k)
- P_{MF}: pdf for Single nucleon from primary vertex; Nucleons in Mean-Field potential; Shell model built from QE (e,e'p) data
- P_{corr}: pdf for Two nucleons from primary vertex. Made of short range correlated nucleons (∼20%).

The Oscillation Probability:

Appearance

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

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

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

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

ν vs. $\bar{\nu}$ sign change

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

Disappearance

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