Latest Results and Future Prospects from T2K

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on behalf of the T2K Collaboration

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Neutrino Oscillations

- Neutrino oscillation is a consequence of non-degenerate neutrino masses and flavour mixing. Flavour states are linear superpositions of mass states with a mixing matrix as :

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

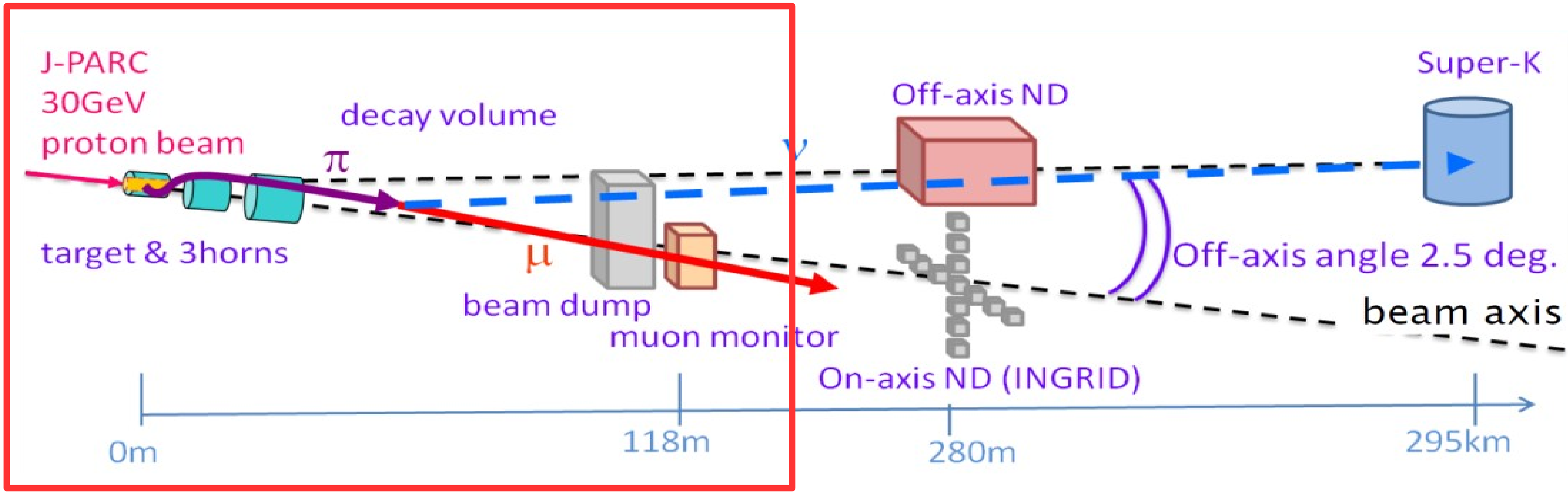
- Neutrinos are produced and interact in the flavour states, and propagate as the mass states. Therefore, a neutrino can change its flavour in flight. → **Neutrino Oscillation!**

- Neutrino oscillations are observed in
  - solar and atmosphere neutrinos detected on Earth.
  - accelerator- or reactor-produced neutrino beam measured at detectors far from its production.

Tokai-to-Kamioka

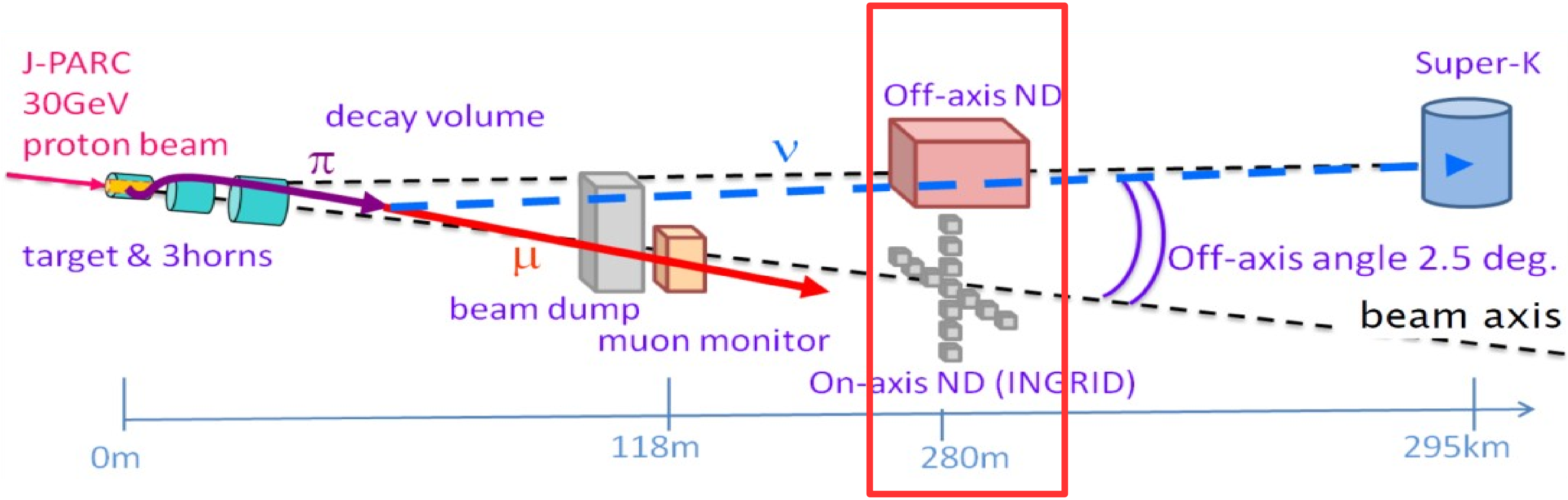
- Long-baseline neutrino oscillation experiment in Japan.
- ~500 collaborators, 62 institutes, 11 countries.

T2K Design



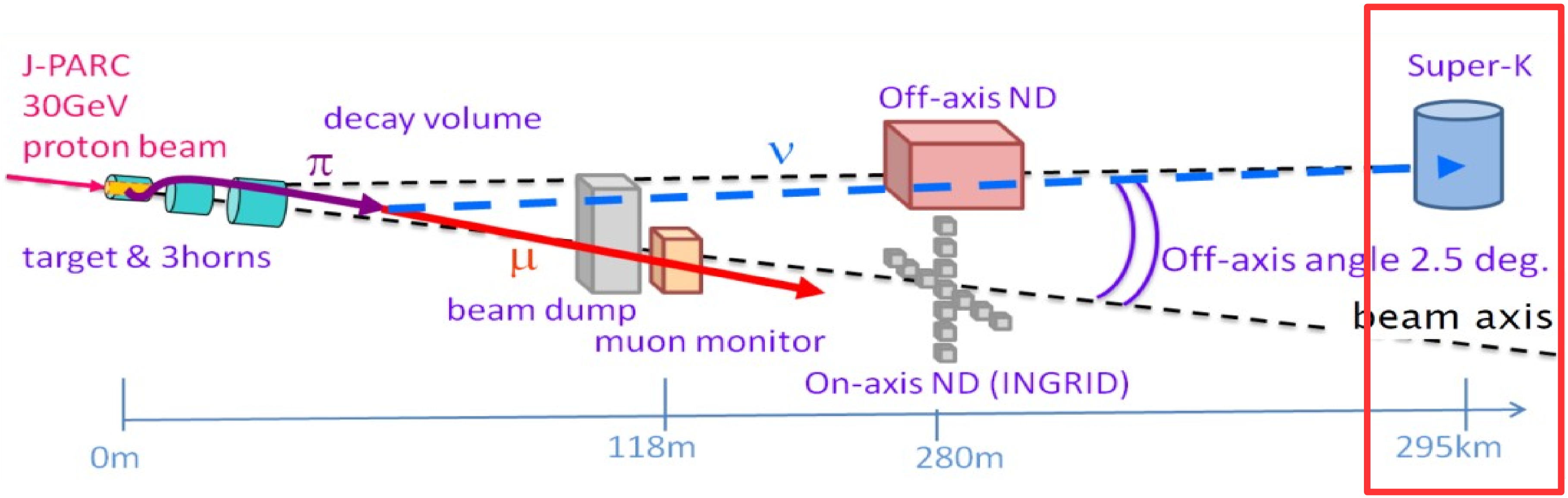
Beam Facilities

T2K Design



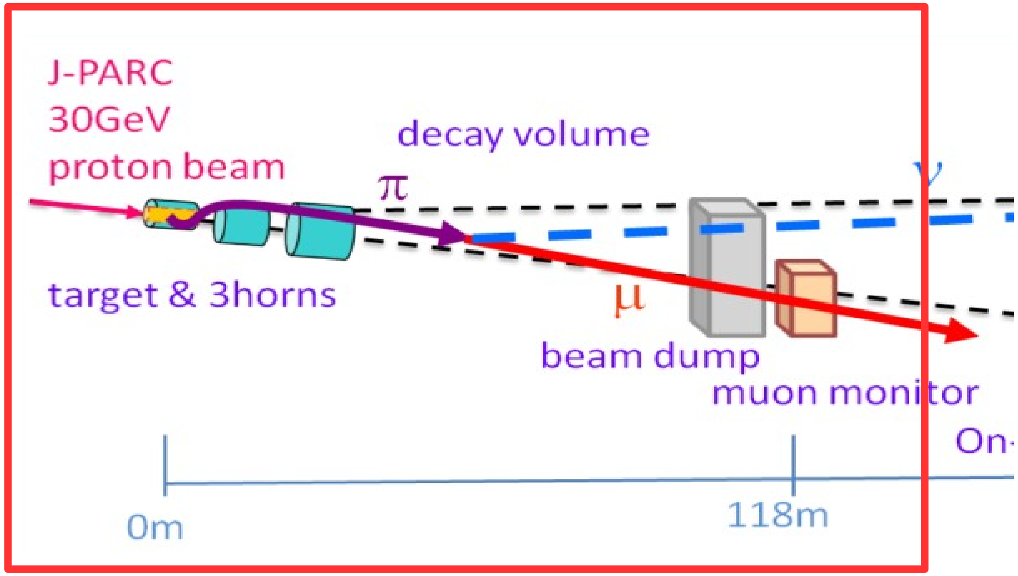
Near Detectors

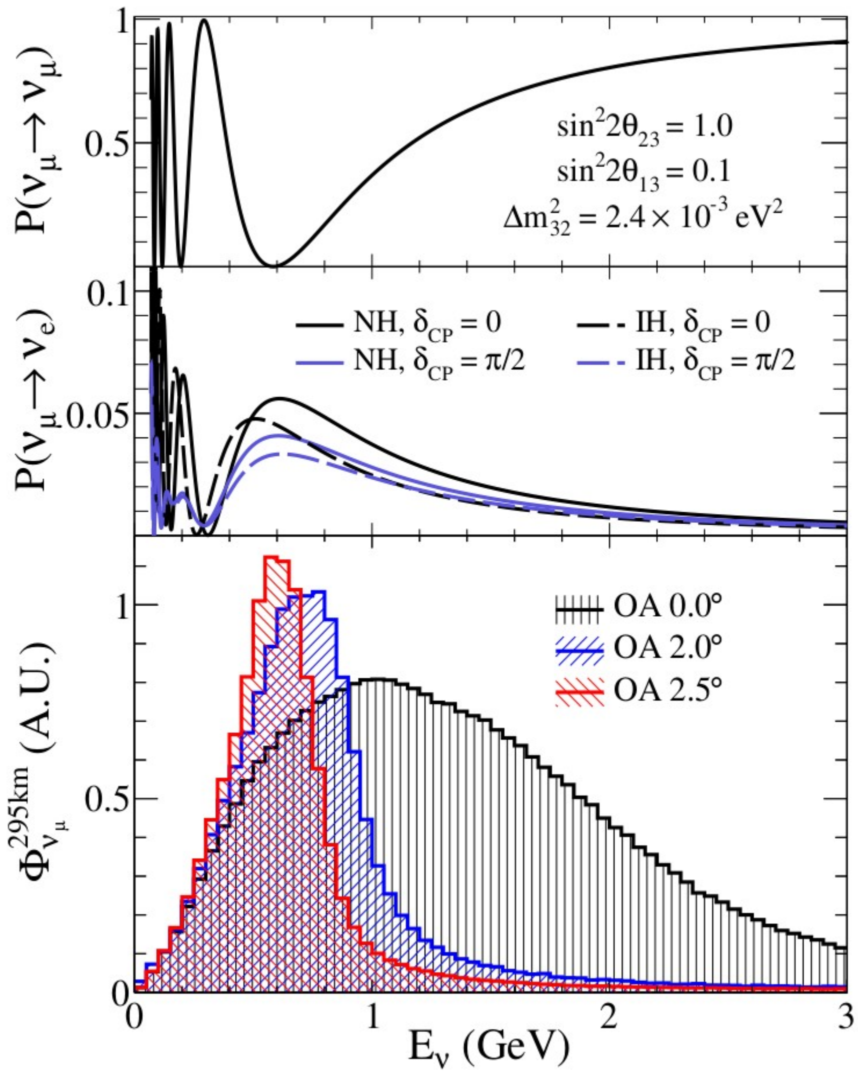
T2K Design



Far Detector

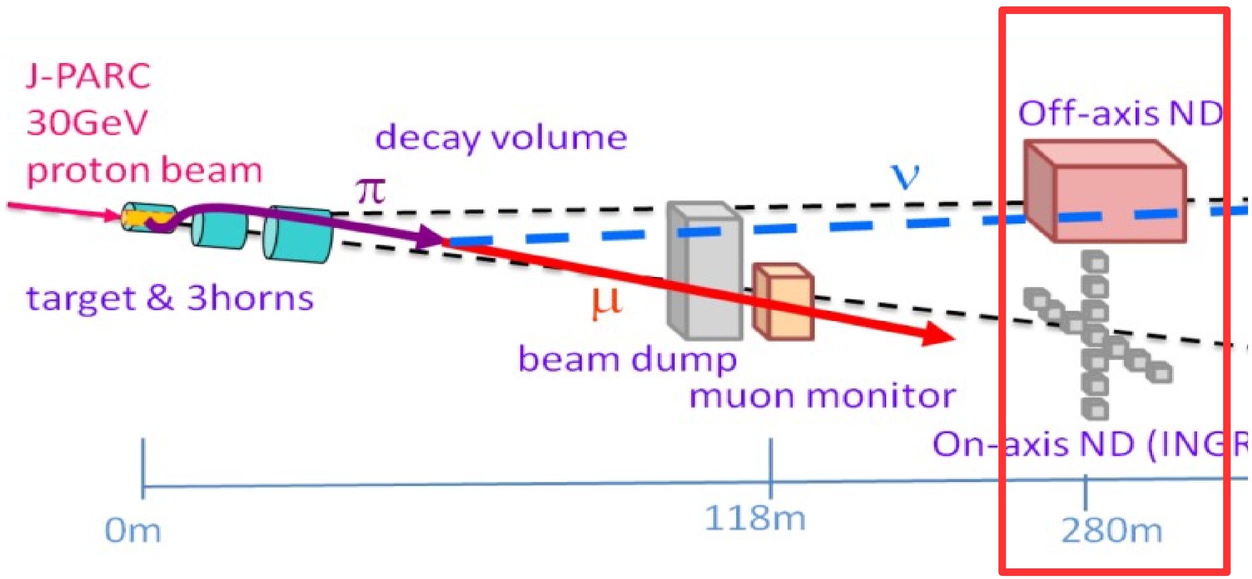
T2K Beam

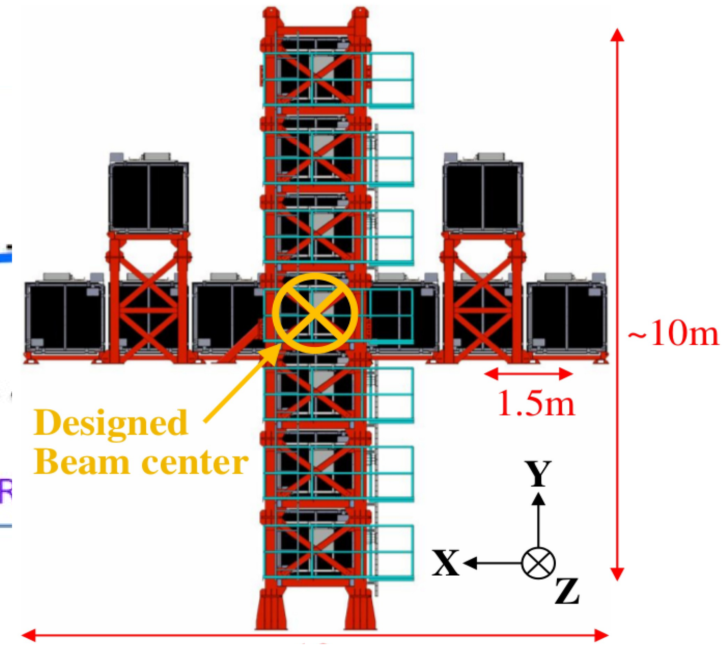




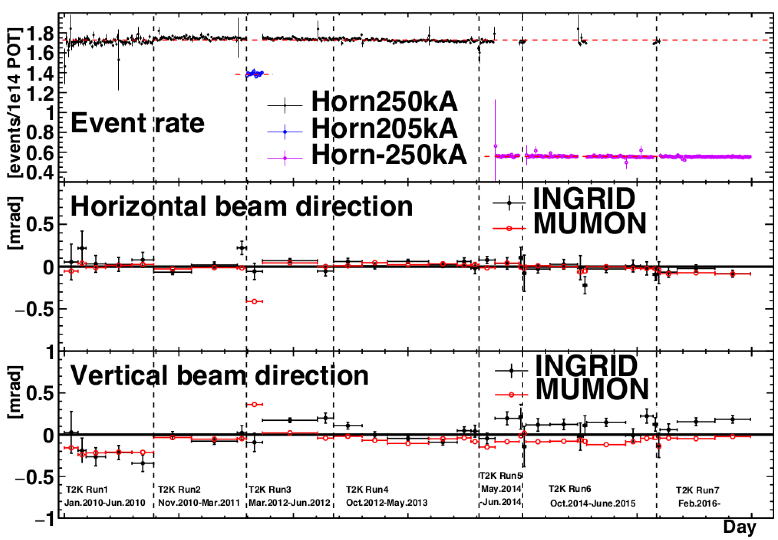
- 30 GeV proton beam on graphite target to produce secondary particles.
- The secondary particles decay in the decay volume to produce neutrinos.
- Off-axis configuration (2.5 degrees).

T2K Near Detectors

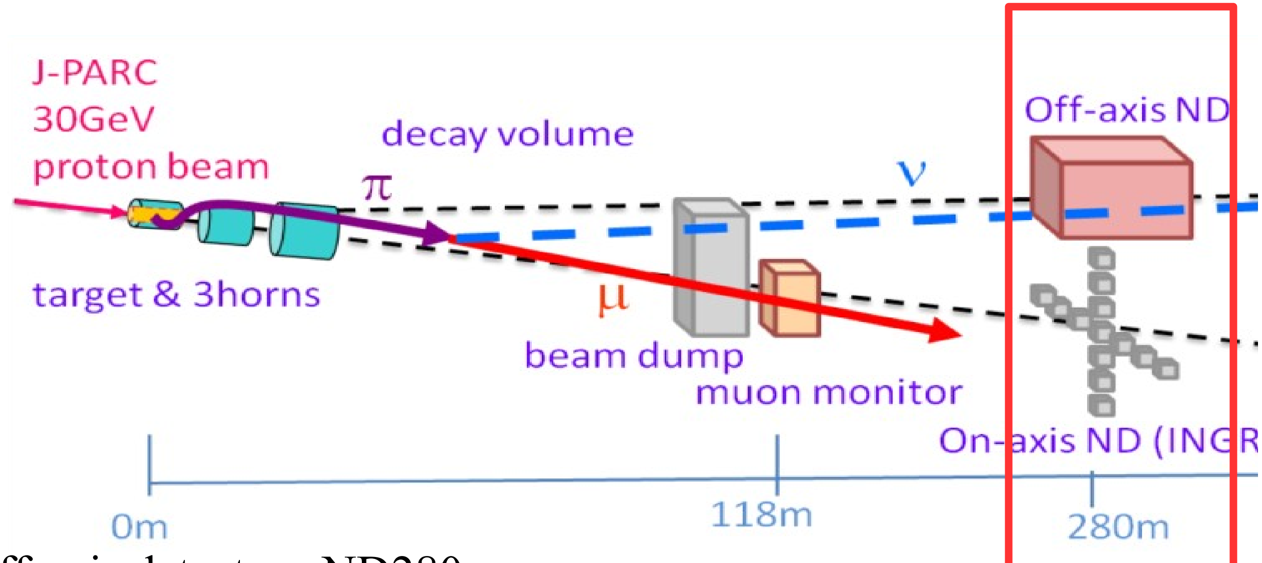


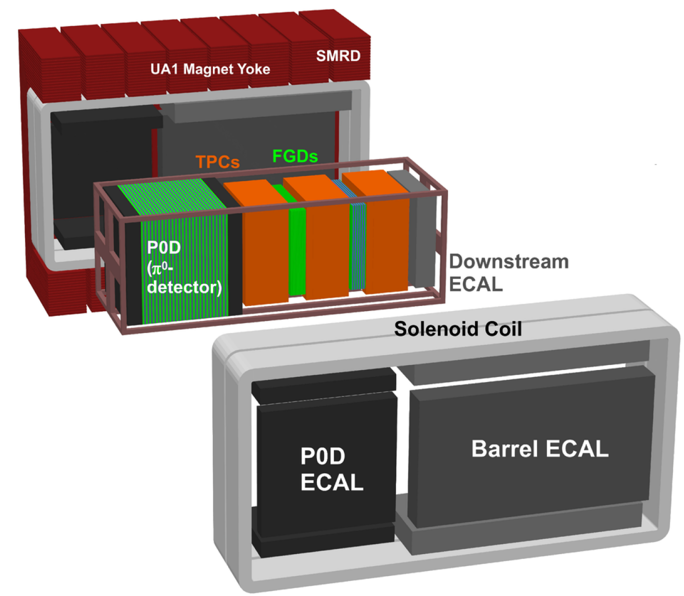


- On-axis detector : INGRID
- Iron/Scintillator detectors.
- Measure beam profile and event rates on daily basis.

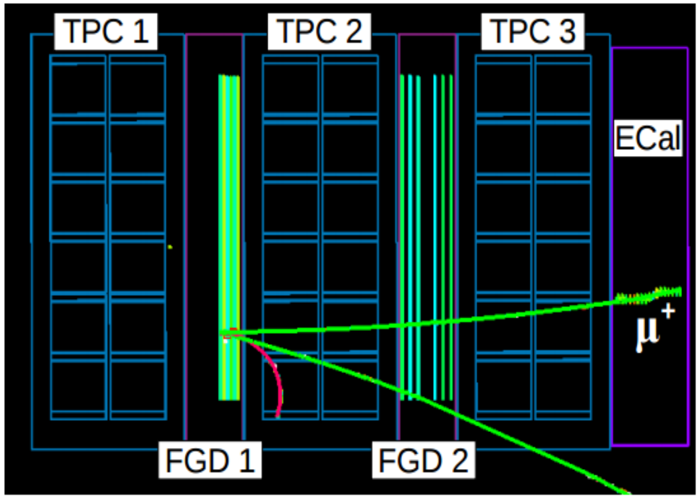


T2K Near Detectors



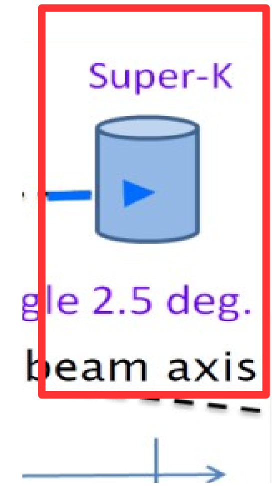


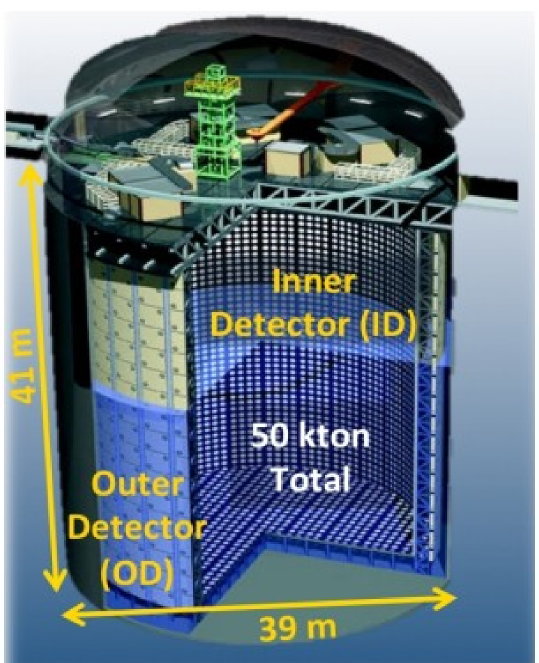
- Off-axis detector : ND280
- Detectors are enclosed in the magnet.
- Trackers
  - 3 Time Projection Chambers (TPCs)
  - 2 Fine-grained Detectors (FGDs)
- π^0-detector (P0D) is placed in front of the trackers.
- Electromagnetic calorimeters (ECAL) surround the trackers and P0D. Muon range detectors are installed in between the magnet.

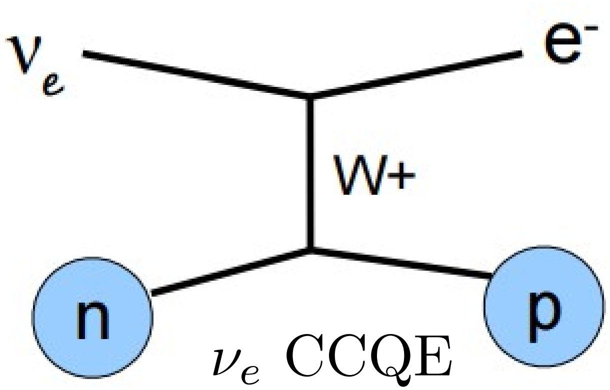


T2K Far Detector

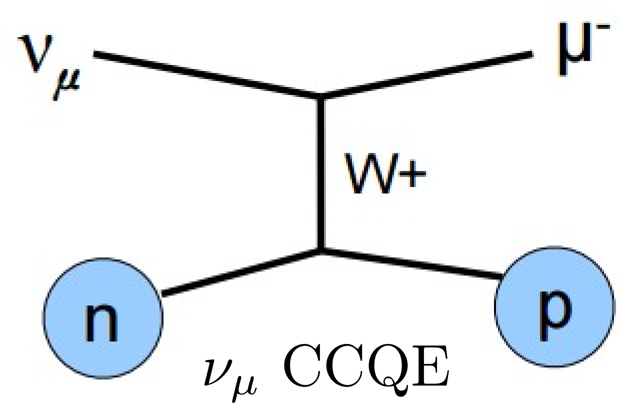
- 50 kiloton water-Cherenkov detector.
- Charged particles above Cherenkov threshold produce Cherenkov light detected by the PMTs.
- T2K signal : single ring events for charged-current quasi-elastic (CCQE) interactions of muon/electron neutrinos.







ν_e Appearance signal



ν_μ Disappearance signal

T2K Far Detector

- 50 kiloton water-Cherenkov detector.
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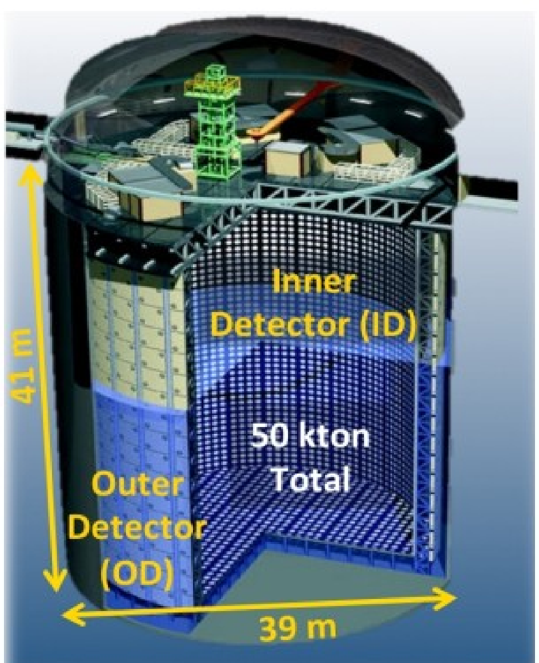
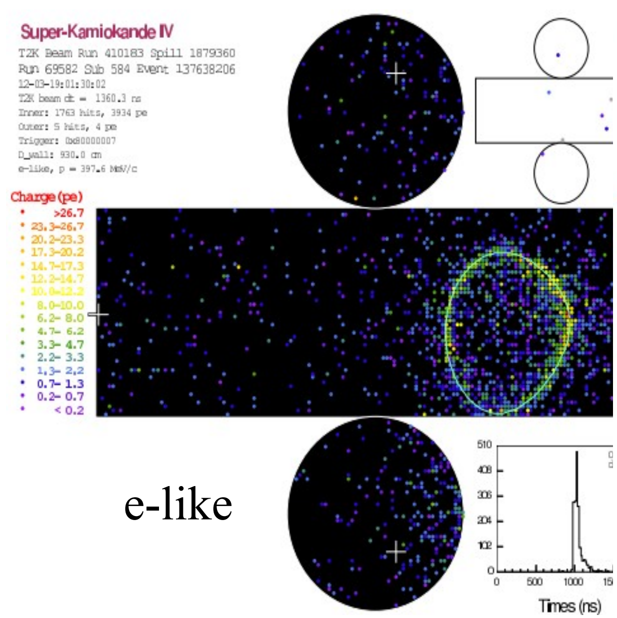
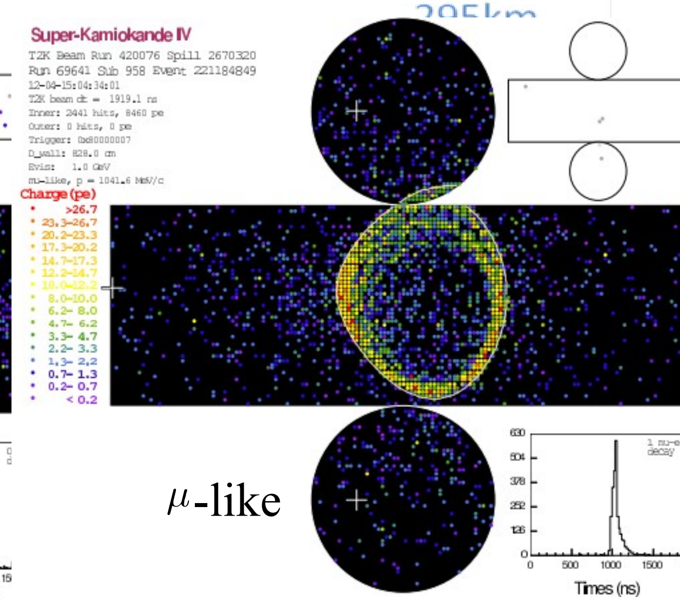
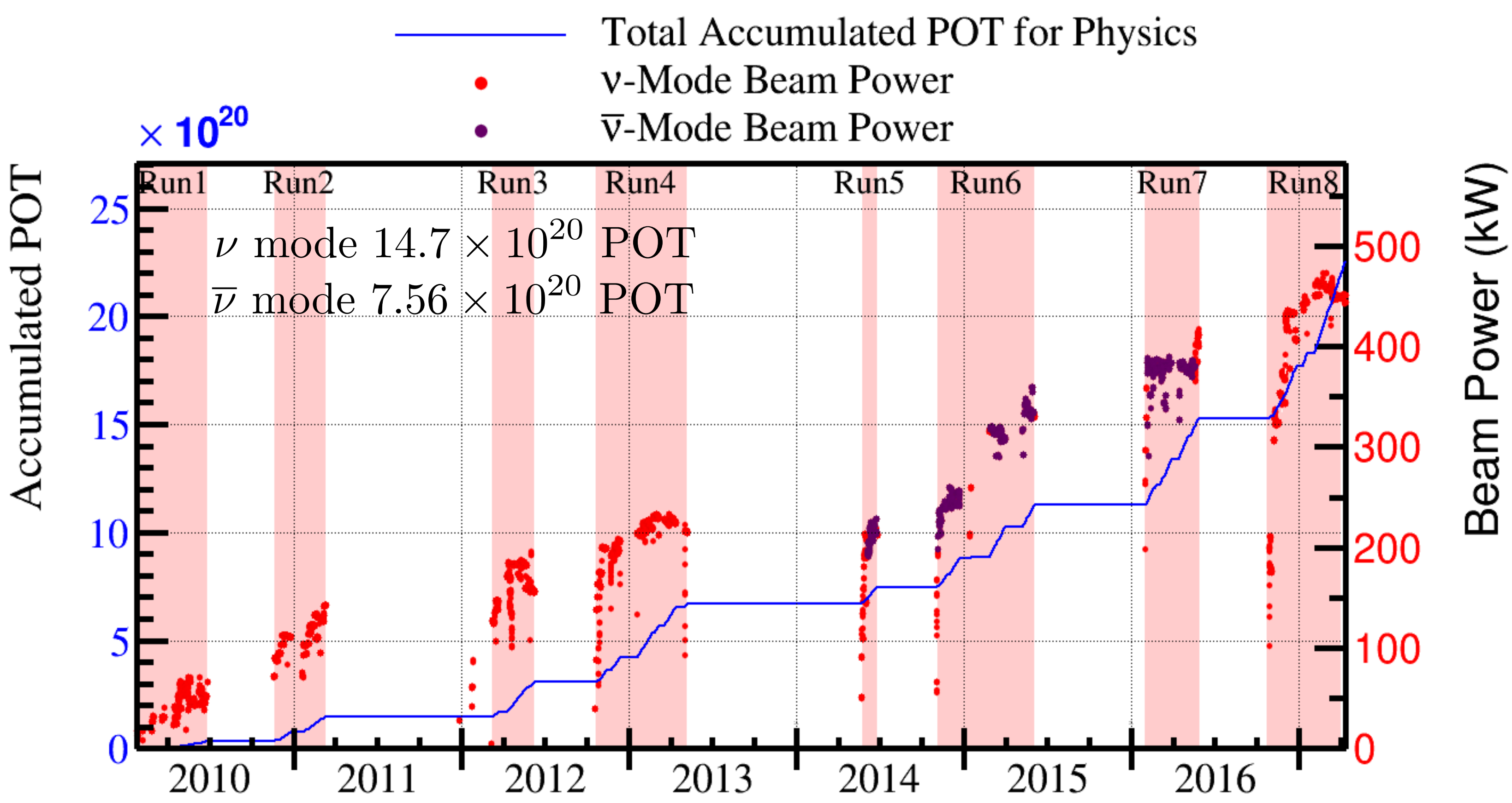






POT History

- Data collected : protons on target (POT) history.



Oscillations at T2K

Oscillations at T2K

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

$$P(\overline{\nu}_\mu \to \overline{\nu}_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

Same

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta_{31}]}{(1-x)^2}$$
$$+ \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31})}{x} \frac{\sin[(1-x)\Delta_{31}]}{(1-x)} \left(-\sin\delta_{CP} \sin\Delta_{31} + \cos\delta_{CP} \cos\Delta_{31}\right)$$

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1+x)\Delta_{31}]}{(1+x)^2}$$
$$+ \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31})}{x} \frac{\sin[(1+x)\Delta_{31}]}{(1+x)} \left(+\sin\delta_{CP} \sin\Delta_{31} + \cos\delta_{CP} \cos\Delta_{31}\right)$$

$$*\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E_\nu}, \; x = \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2_{31}}$$

Opposite signs for the matter effects terms and CP phase!

Neutrino/anti-neutrino oscillation probabilities with matter effects.

Oscillations at T2K

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

$$P(\overline{\nu}_\mu \to \overline{\nu}_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

$\Rightarrow$ $|\Delta m^2_{32}|$, $\sin^2 2\theta_{23}$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta_{31}]}{(1-x)^2}$$

$$+\left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31})}{x} \frac{\sin[(1-x)\Delta_{31}]}{(1-x)} \Big(-\sin\delta_{CP} \sin\Delta_{31} + \cos\delta_{CP} \cos\Delta_{31} \Big)$$

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$$+\left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31})}{x} \frac{\sin[(1+x)\Delta_{31}]}{(1+x)} \Big(+\sin\delta_{CP} \sin\Delta_{31} + \cos\delta_{CP} \cos\Delta_{31} \Big)$$

$\Rightarrow$ Δm^2_{32} : sign can be determined by the matter effect
$\sin^2 \theta_{23}$ instead of $\sin^2 2\theta_{23}$
$\sin^2 2\theta_{13}$, δ_{CP}

Oscillations at T2K

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

$$P(\overline{\nu}_\mu \to \overline{\nu}_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta_{31}]}{(1-x)^2}$$

$$+ \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31})}{x} \frac{\sin[(1-x)\Delta_{31}]}{(1-x)} \left(-\sin\delta_{CP} \sin\Delta_{31} + \cos\delta_{CP} \cos\Delta_{31} \right)$$

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⇒ Joint Analysis : combine $\nu/\overline{\nu}$ oscillations

Analysis Overview

- Compare the neutrino events observed at SK to the MC predictions. The MC predictions involve modelling of the flux, the neutrino interactions and detection efficiency as :

$$N_{SK}^{prediction} \sim \sum_{i}^{flavours} P(\nu_i \to \nu_k)\Phi_i^{SK}\sigma_k\epsilon_{SK} \text{ (predicted number of } \nu_k \text{ at SK ; } k = e, \mu)$$

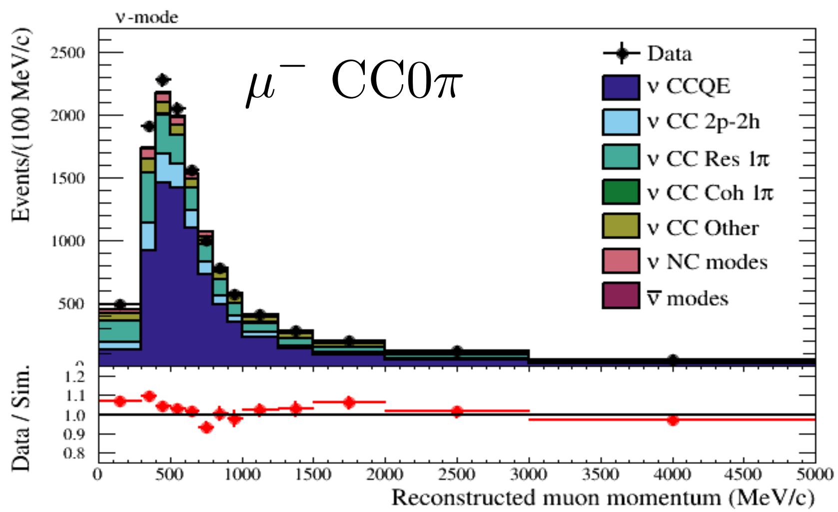
- ND280 measurements are used to constrain the flux and neutrino interaction uncertainties. Charged-current neutrino interactions are included in ND280 samples as :

ν mode : μ^- CC0π , μ^- CC1π , μ^- CCNπ in FGD1/2

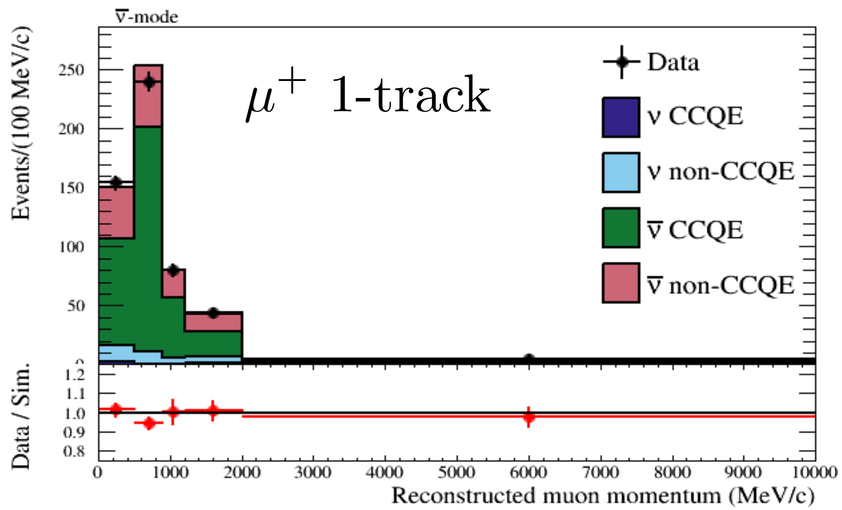
$\bar{\nu}$ mode : μ^+ 1-track , μ^+ N-track , μ^- 1-track , μ^- N-track in FGD1/2

See more details on systematics in the analysis at *Systematic Uncertainties in Neutrino Oscillation Measurements* by D. Hadley; September 27th;

ND280 Fit

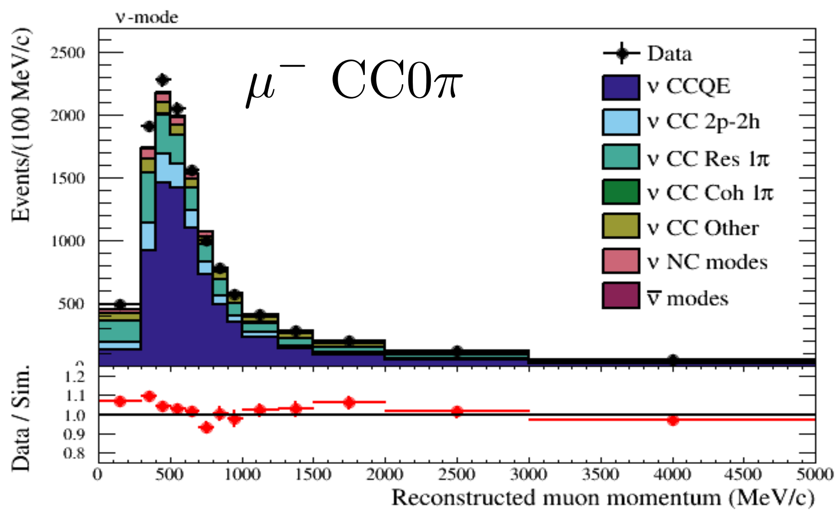


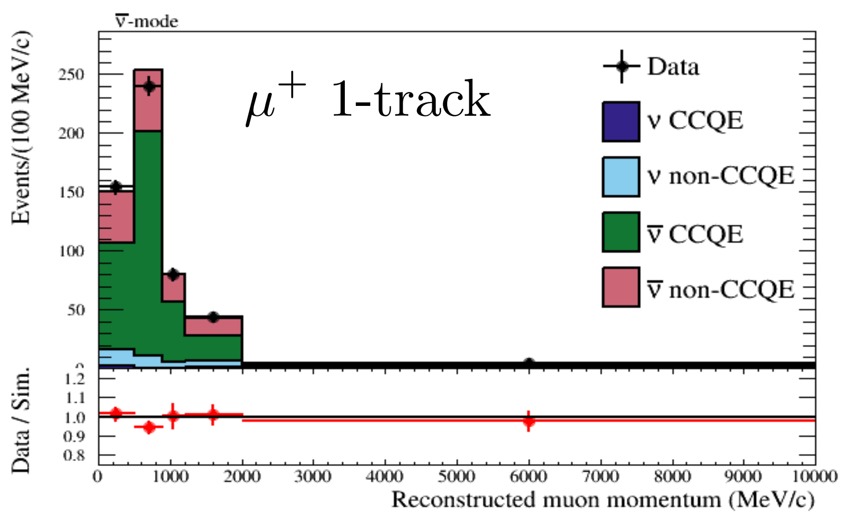
ν-mode
μ^- CC0π
Data
ν CCQE
ν CC 2p-2h
ν CC Res 1π
ν CC Coh 1π
ν CC Other
ν NC modes
$\bar{\nu}$ modes
Events/(100 MeV/c)
Data / Sim.
Reconstructed muon momentum (MeV/c)



$\bar{\nu}$-mode
μ^+ 1-track
Data
ν CCQE
ν non-CCQE
$\bar{\nu}$ CCQE
$\bar{\nu}$ non-CCQE
Events/(100 MeV/c)
Data / Sim.
Reconstructed muon momentum (MeV/c)

ND280 Fit





Flux Predictions

- proton beam properties/flux
- hadronic production on graphite
- propagation/decay of hadrons

Neutrino Interaction Models

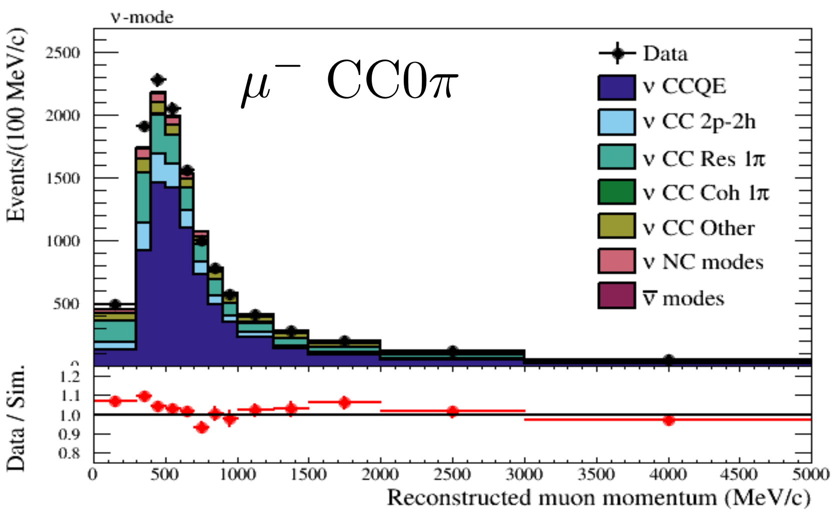
- nuclear models
- axial mass M_A^{QE}
- 2p-2h contributions
- and other more...

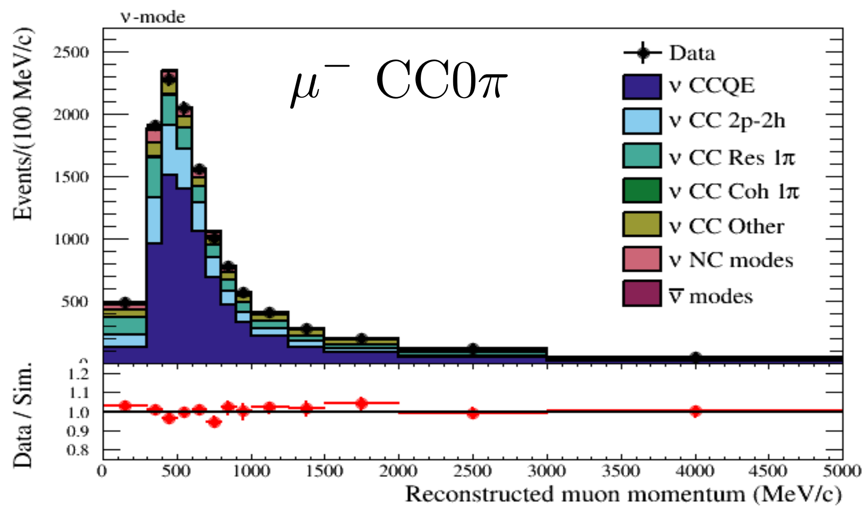
Flux and neutrino interaction model parameters are fit to ND280 data.

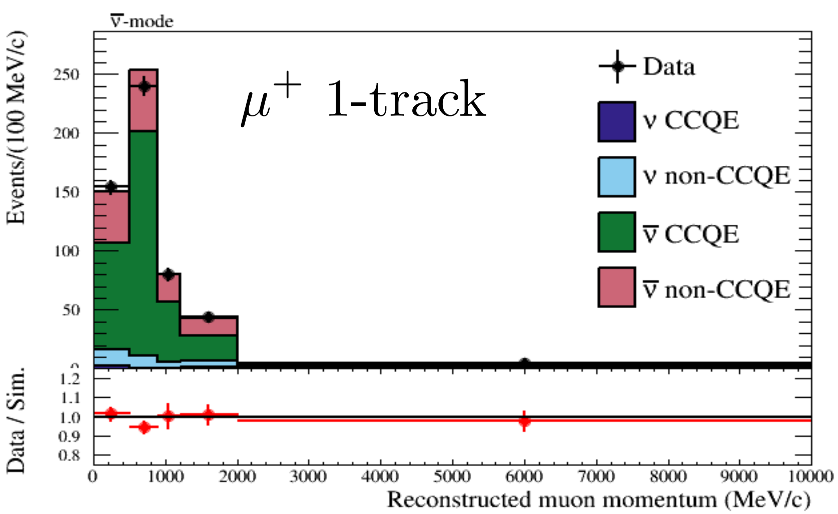
→ constrain the parameters!

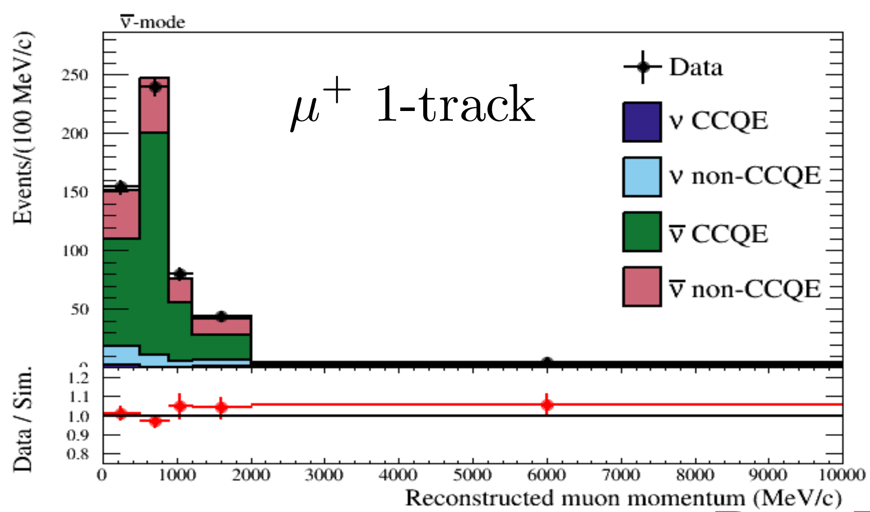
→ reduce the uncertainties!

ND280 Fit



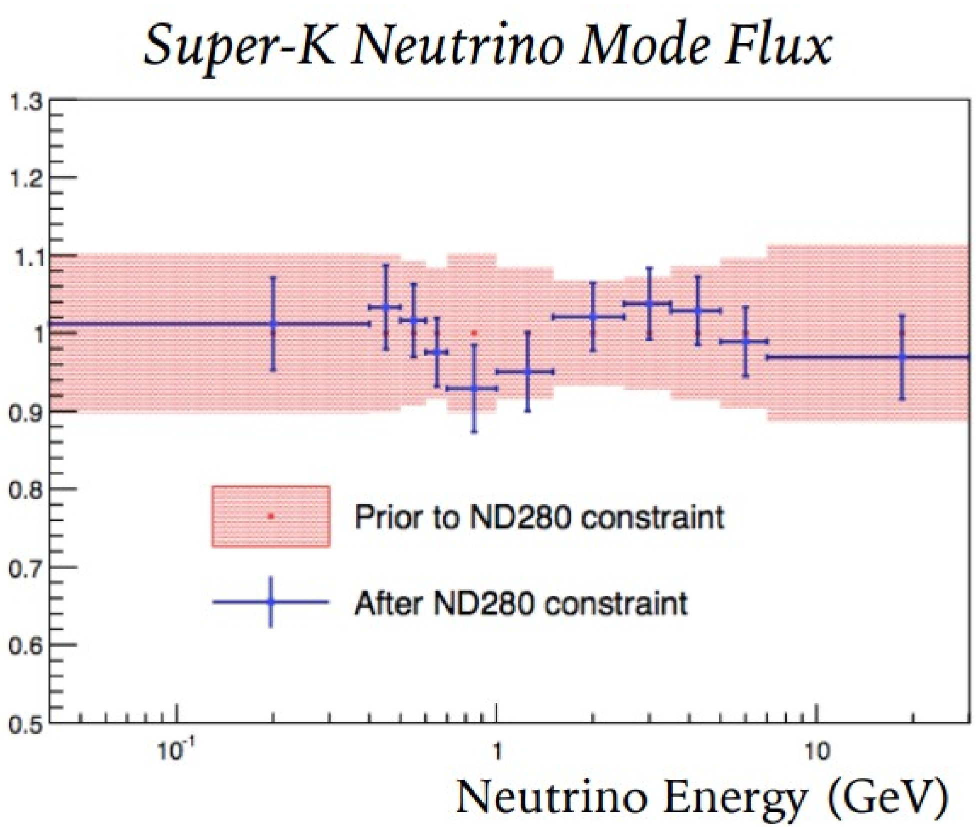


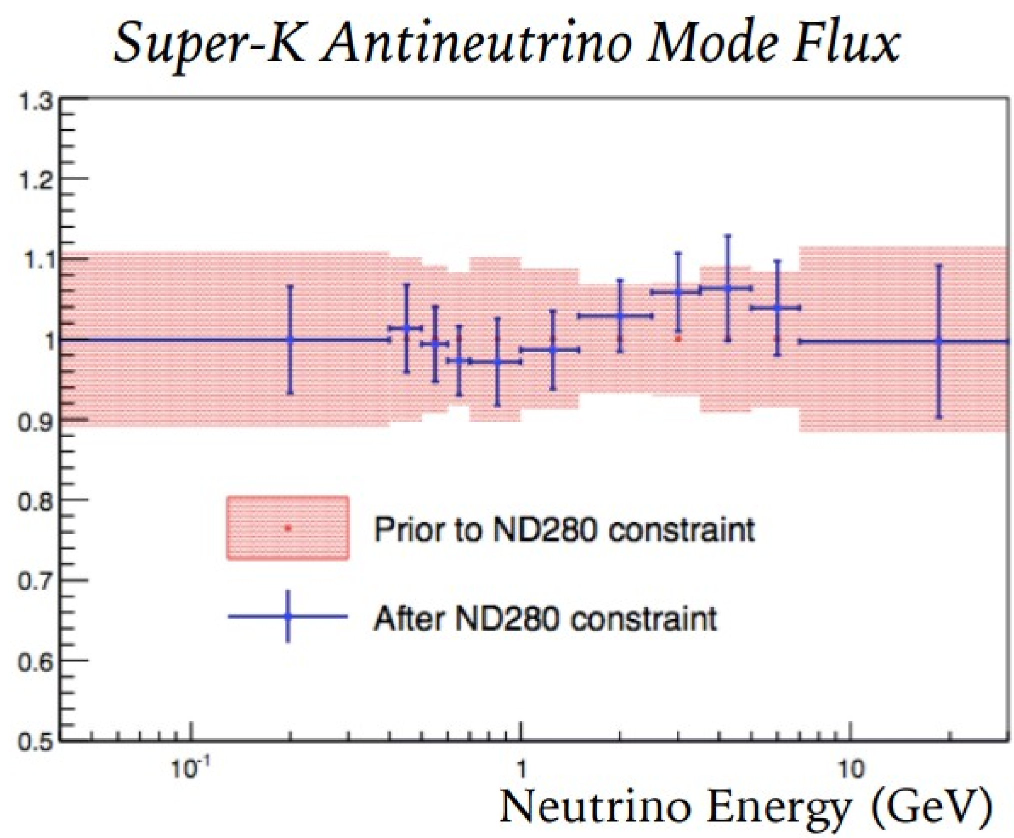




Post-Fit

ND280 Fitted Parameters

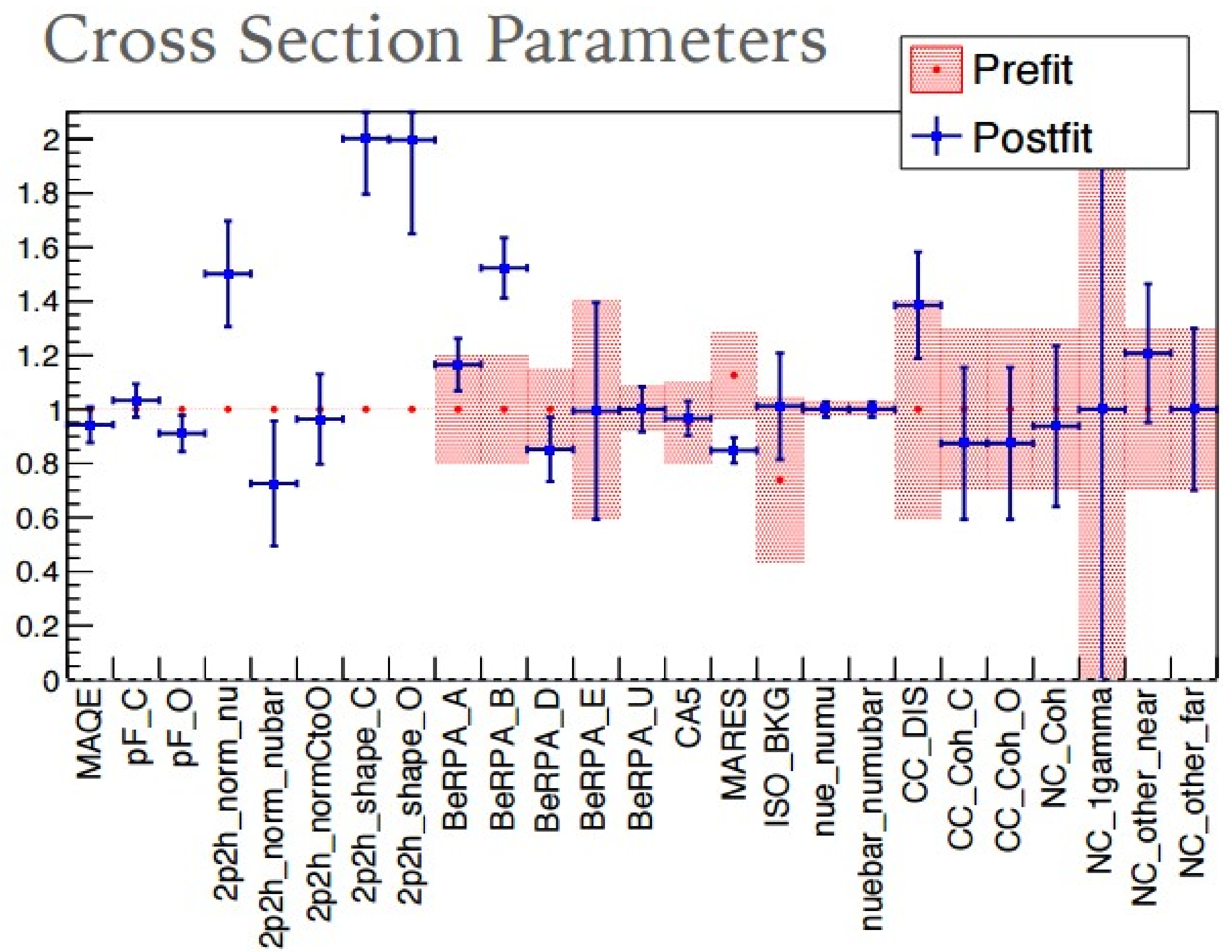




Flux parameters are updated after ND280 fit.
Post-fit parameters and covariance matrices are input to the oscillation analysis.

ND280 Fitted Parameters

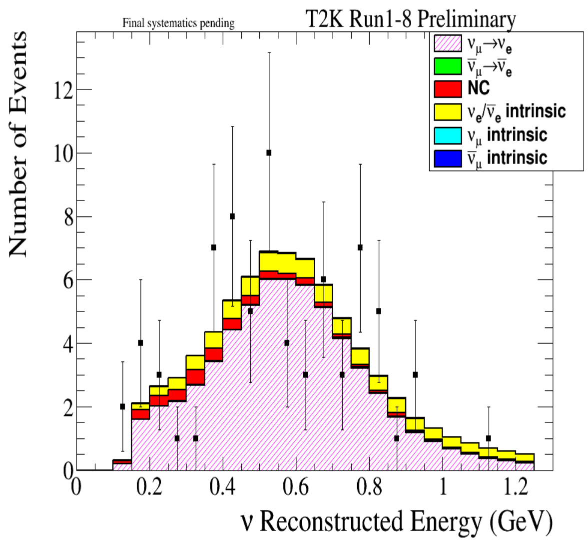
See more details at
The T2K cross-section results and prospects from the oscillation perspective
by K. Nakamura; September 26th;



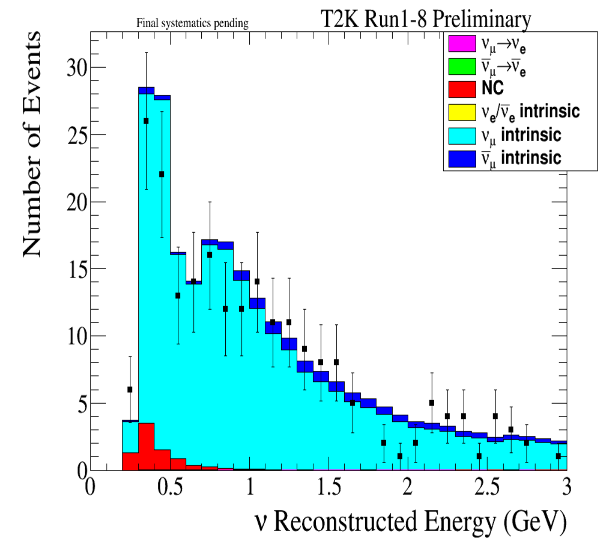
Cross-section parameters are updated after ND280 fit.
Large changes to the cross-section models.
Post-fit parameters and covariance matrices are input to the oscillation analysis.

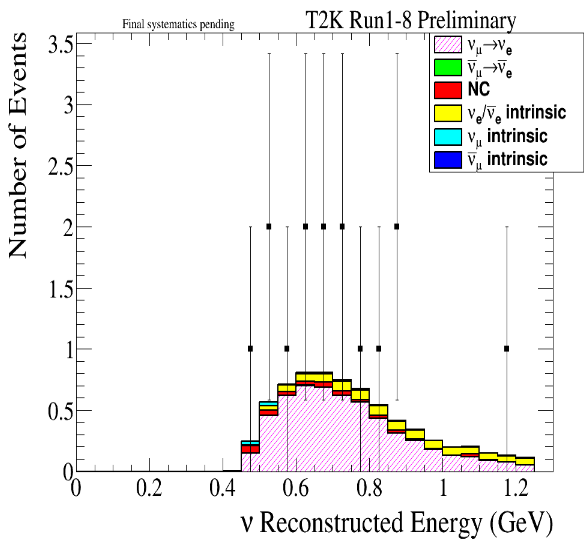
SK Data

ν_e candidates



ν_μ candidates



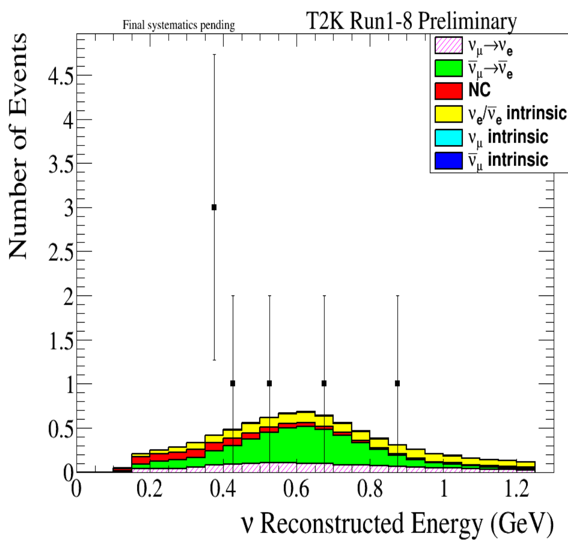


- Observed events at SK with neutrino beam.
- New fiducial volume and reconstruction algorithm!
  - 30 % more statistics with better purity/efficiency.
- Three samples :
  - ν_e CCQE (1e ring) (top-left)
  - ν_e CC1π^+(1e ring) (bottom-left)

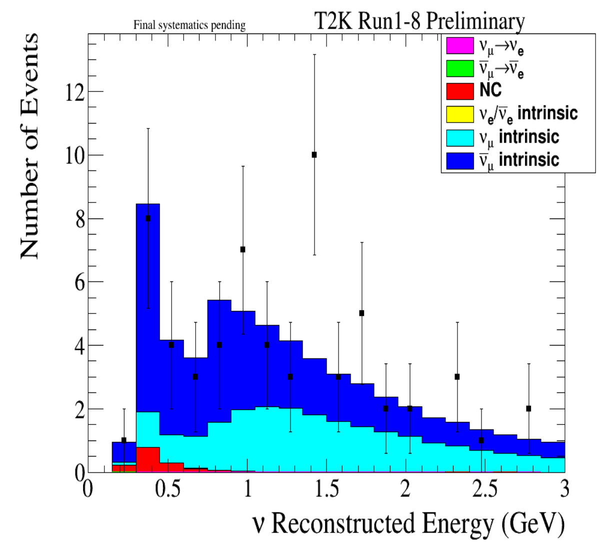
    $\longrightarrow$ additional delayed ring from the Michel electron.
  - ν_μ CCQE (1μ ring) (top-right)

SK Data

$\overline{\nu}_e$ candidates



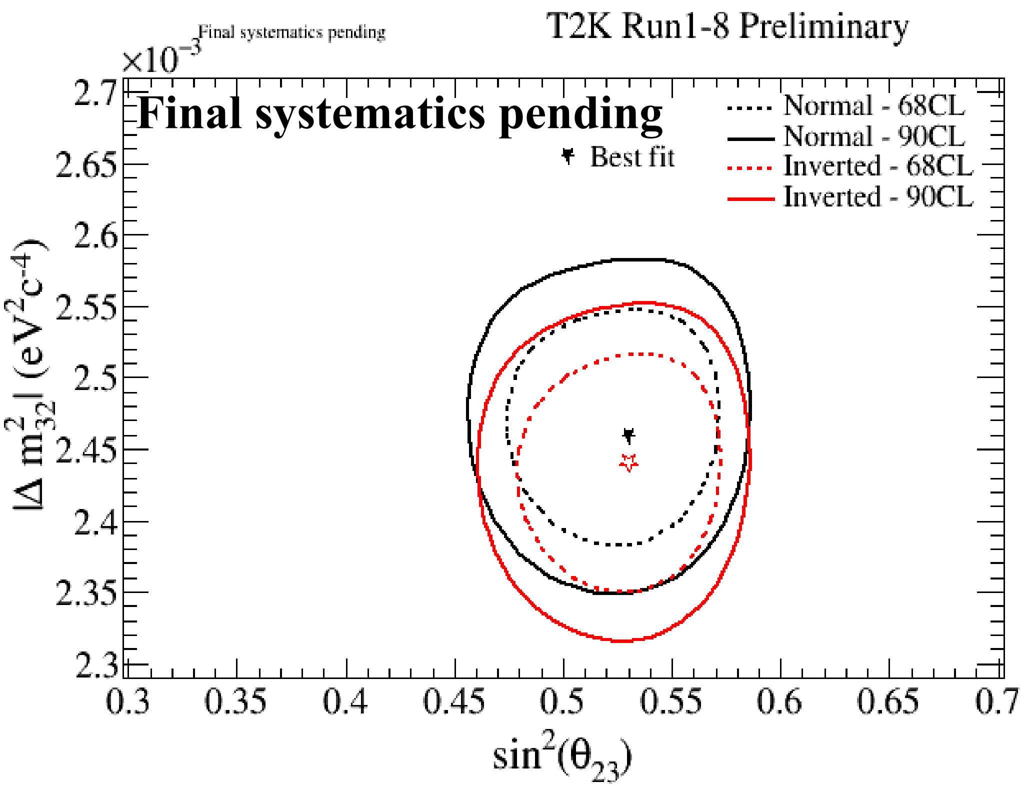
$\overline{\nu}_\mu$ candidates



- Observed events at SK with anti-neutrino beam.
- New fiducial volume and reconstruction algorithm!
  - 30 % more statistics with better purity/efficiency.

- Two samples :
  - $\overline{\nu}_e$ CCQE (1e ring) (top-left)
  - $\overline{\nu}_\mu$ CCQE (1μ ring) (top-right)
- No single pion sample here due to π^- absorption.

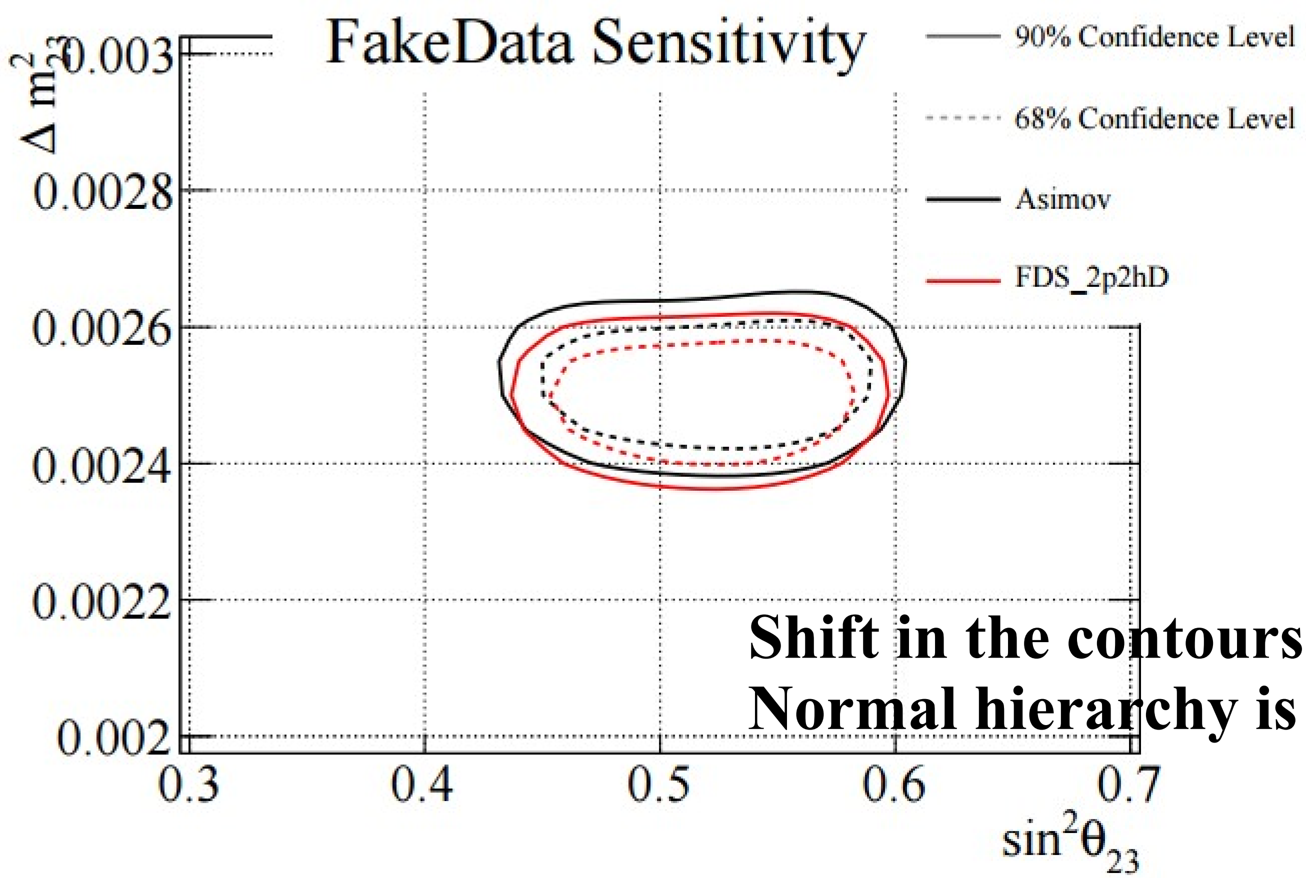
Results



- With reactor constraint :
  - $\sin^2 2\theta_{13} = 0.085 \pm 0.05$
- Consistent with maximal mixing.
- Preliminary contours. Update expected from neutrino interaction model uncertainties.

See more details at *Oscillation results and plans from the T2K experiment* by P. Dunne; September 27^{th};

Results : Possible Impact

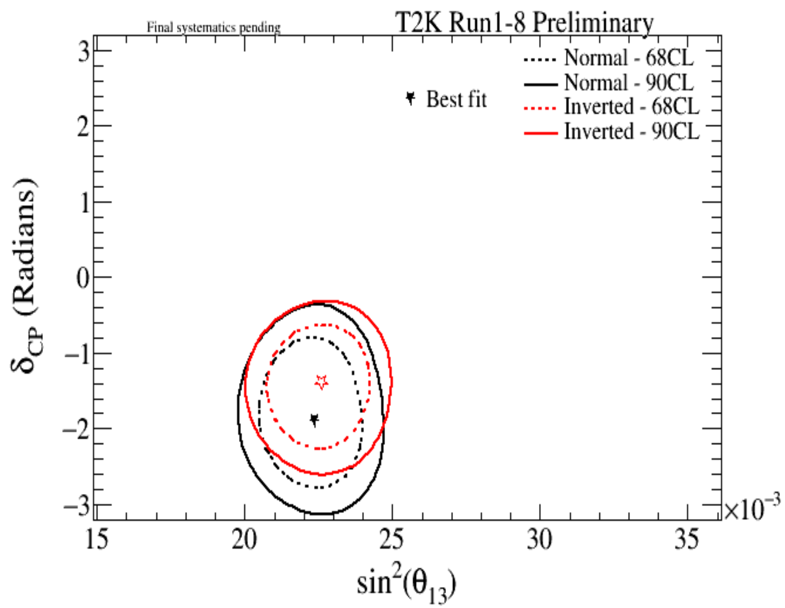


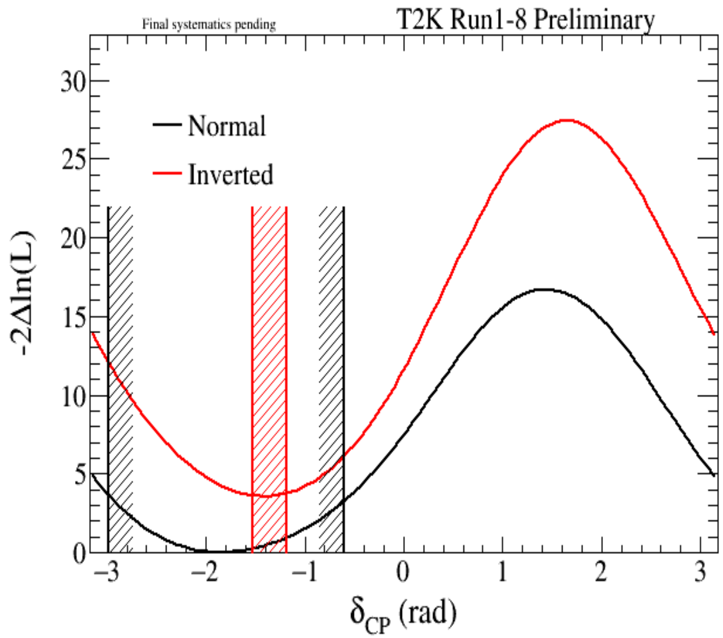
Shift in the contours.
Normal hierarchy is assumed.

(a) $\sin^2\theta_{23}$–Δm^2_{23}

See more details at *The T2K cross-section results and prospects from the oscillation perspective* by K. Nakamura; September 26th;

Results





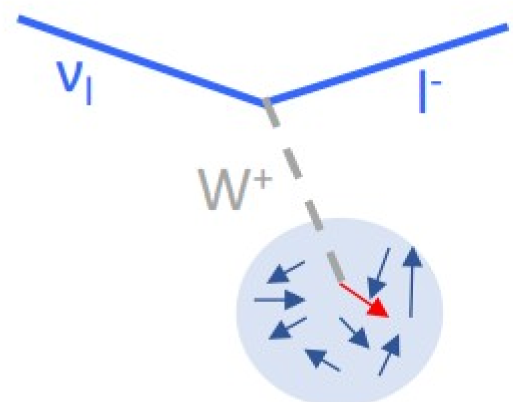
- With reactor constraint : $\sin^2 2\theta_{13} = 0.085 \pm 0.05$
- $\sin \delta_{CP} = 0$ is excluded at 2σ.
- 2σ C.L. intervals are shown on the right plot.

See more details at *Oscillation results and plans from the T2K experiment* by P. Dunne; September 27th;

Cross sections at T2K

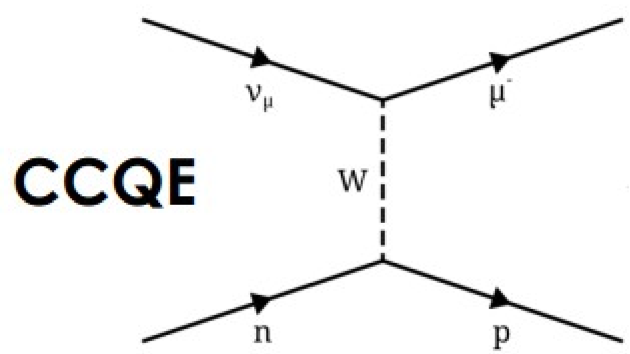
Neutrino Interactions

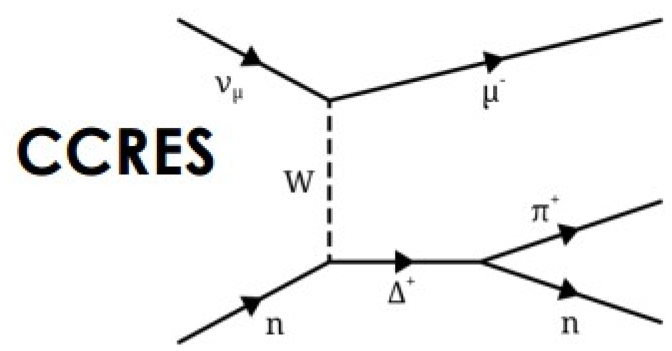
- Accurate knowledge of the neutrino interaction reduces uncertainties on the oscillation analysis.
- Probe the weak interaction.
- Probe nuclear effects.
  - Final State Interaction (FSI)
  - Multi-nucleon processes



Cross sections at T2K

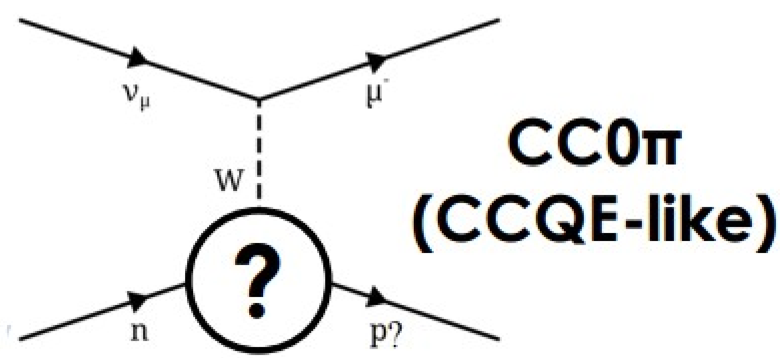
- **Targets** : carbon and oxygen
- **Interaction Channels** : main signal at T2K is charged-current quasi-elastic (CCQE) scattering with significant backgrounds from Charged-current resonance (CCRES) which is sub-dominant channel at T2K energy.

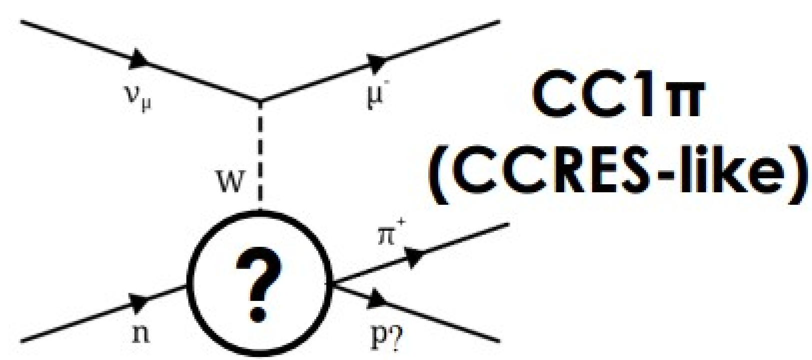




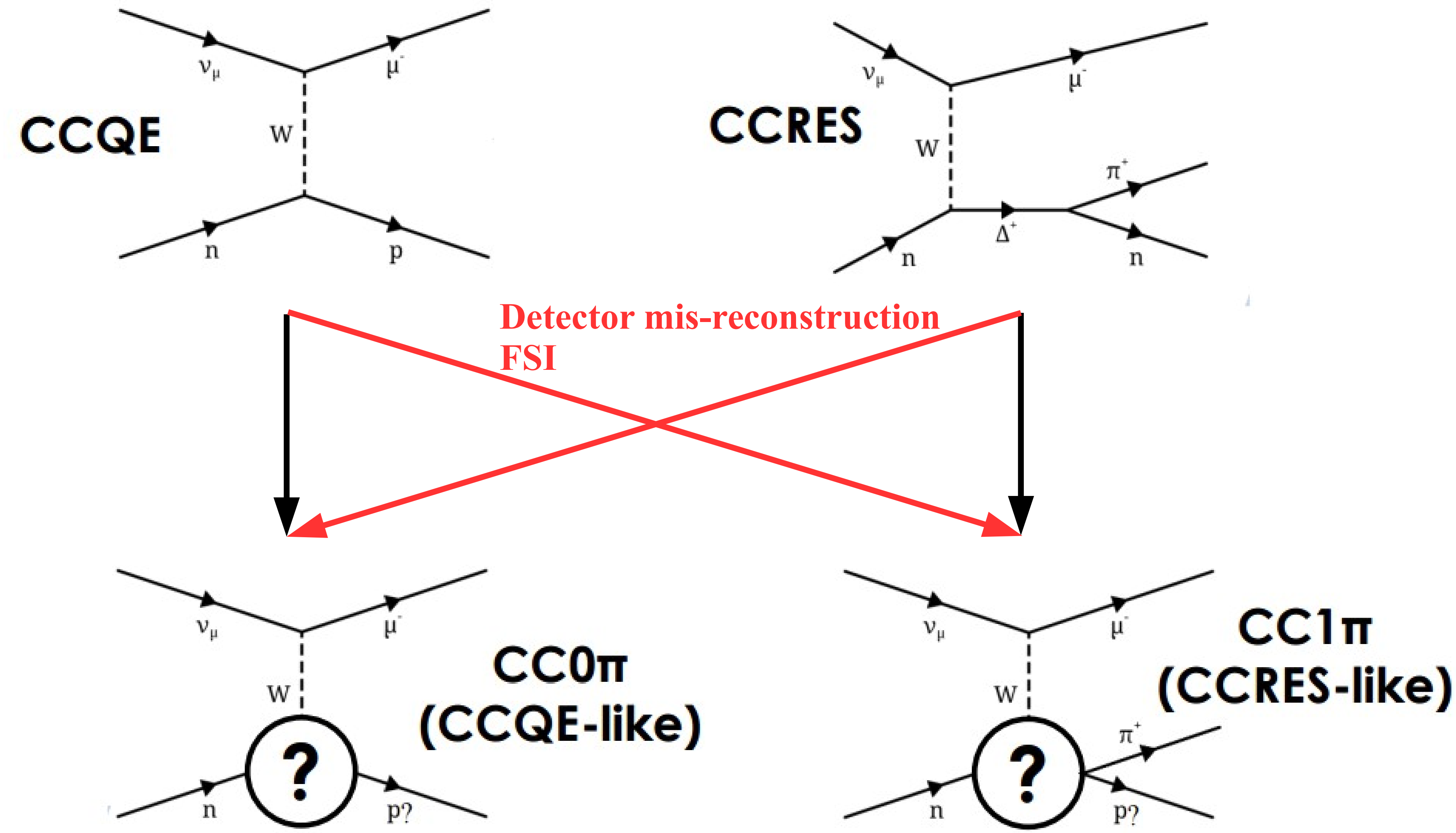
Cross sections at T2K

- **Targets** : carbon and oxygen
- **Interaction Channels** : main signal at T2K is charged-current quasi-elastic (CCQE) scattering with significant backgrounds from Charged-current resonance (CCRES) which is sub-dominant channel at T2K energy. As we only can observe the interactions by final state particles, signals are defined as final state topology.



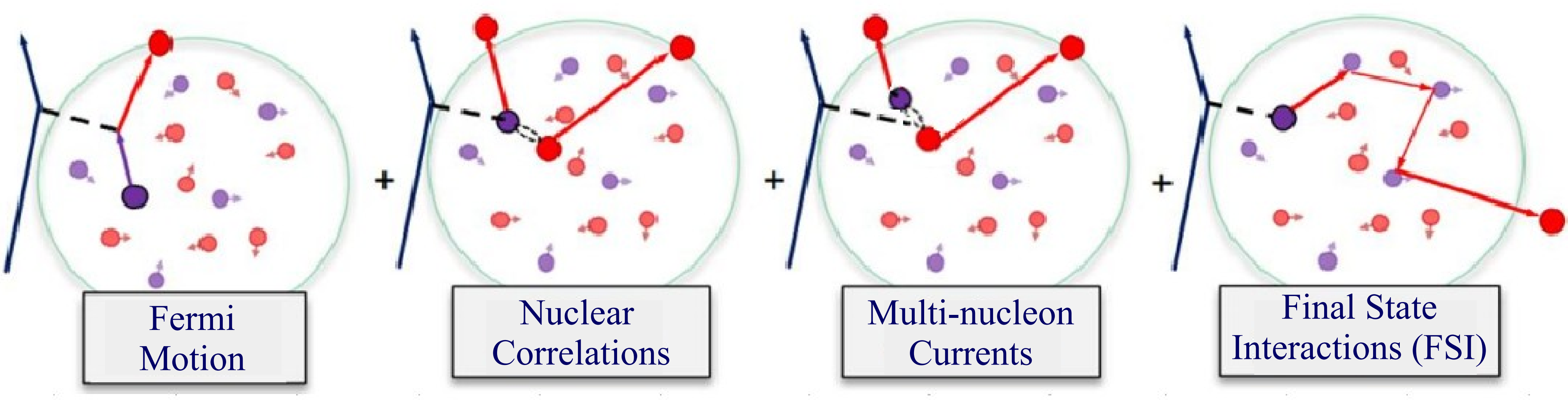


Cross sections at T2K

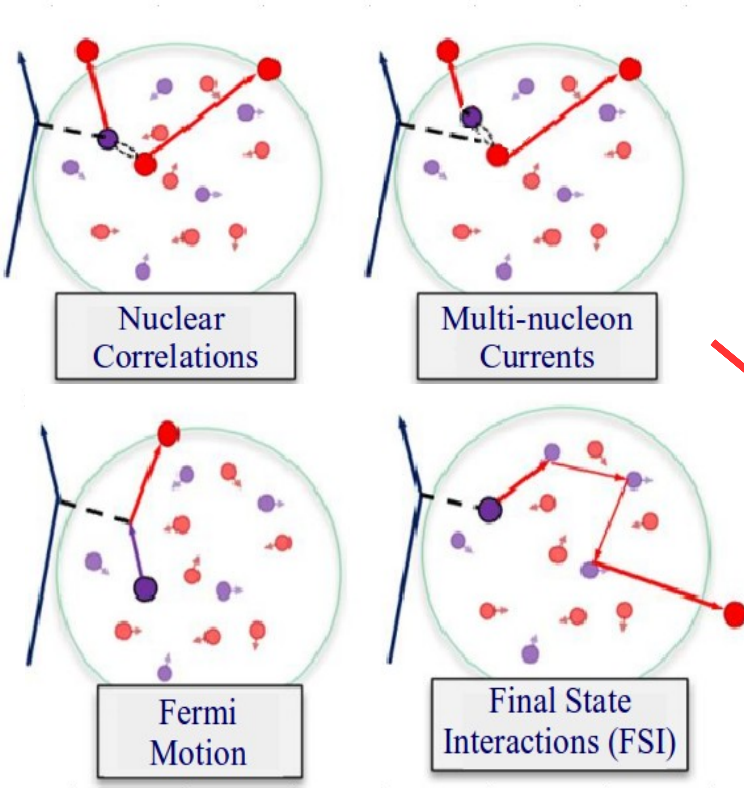


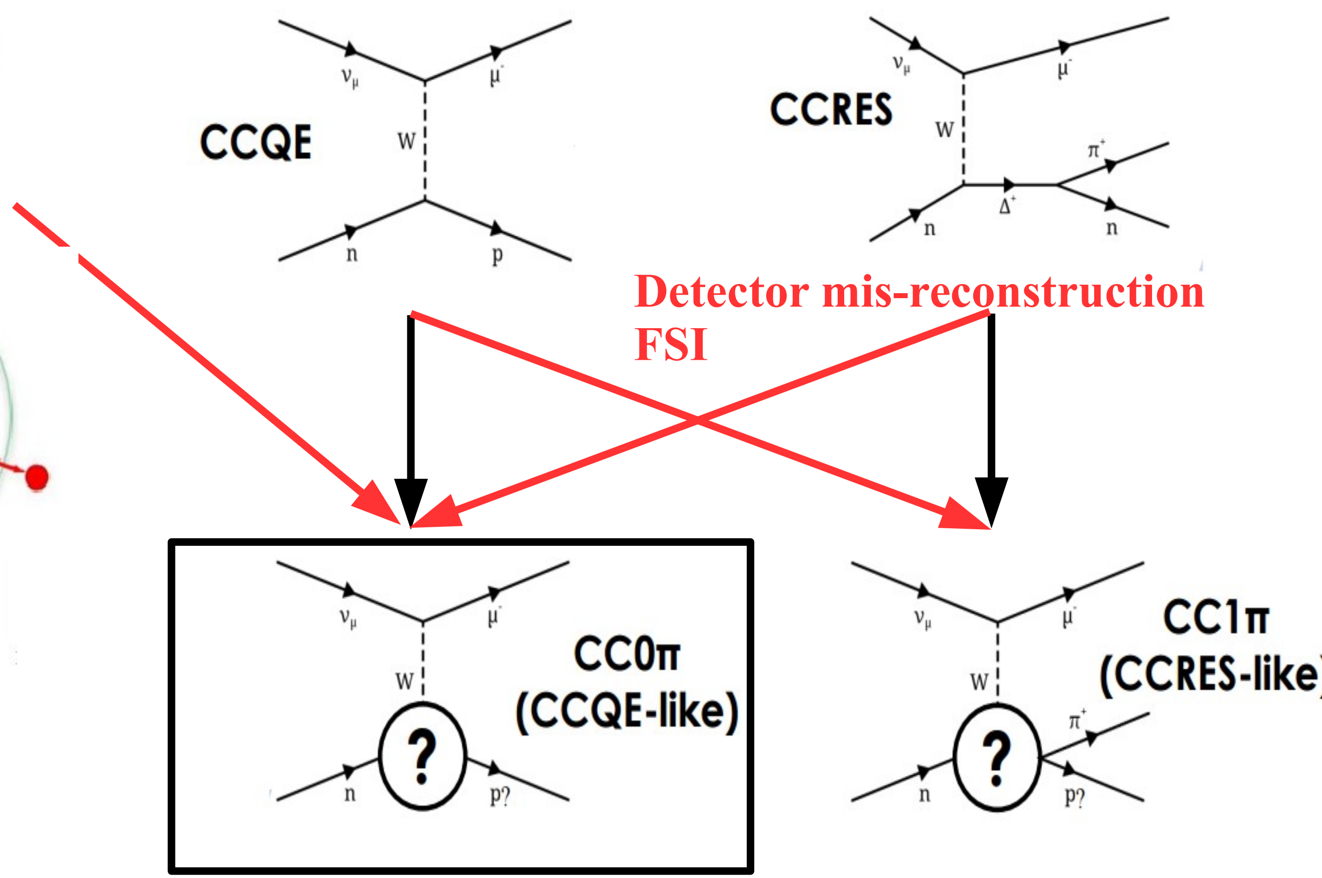
Cross sections at T2K

- **Targets** : carbon and oxygen
- **Interaction Channels** : main signal at T2K is charged-current quasi-elastic (CCQE) scattering with significant backgrounds from Charged-current resonance (CCRES) which is sub-dominant channel at T2K energy. As we only can observe the interactions by final state particles, signals are defined as final state topology.



Cross sections at T2K



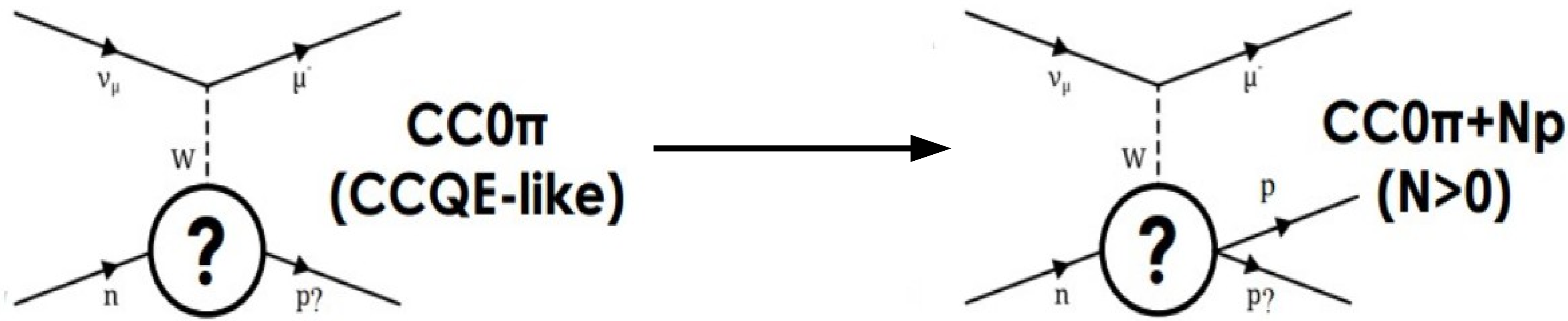


Main signal

Multi-nucleon ejection

Alter the CCQE kinematics

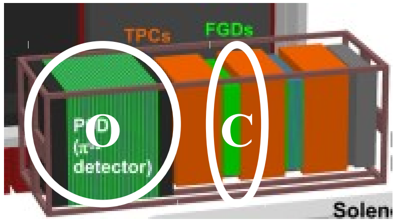
Cross sections at T2K



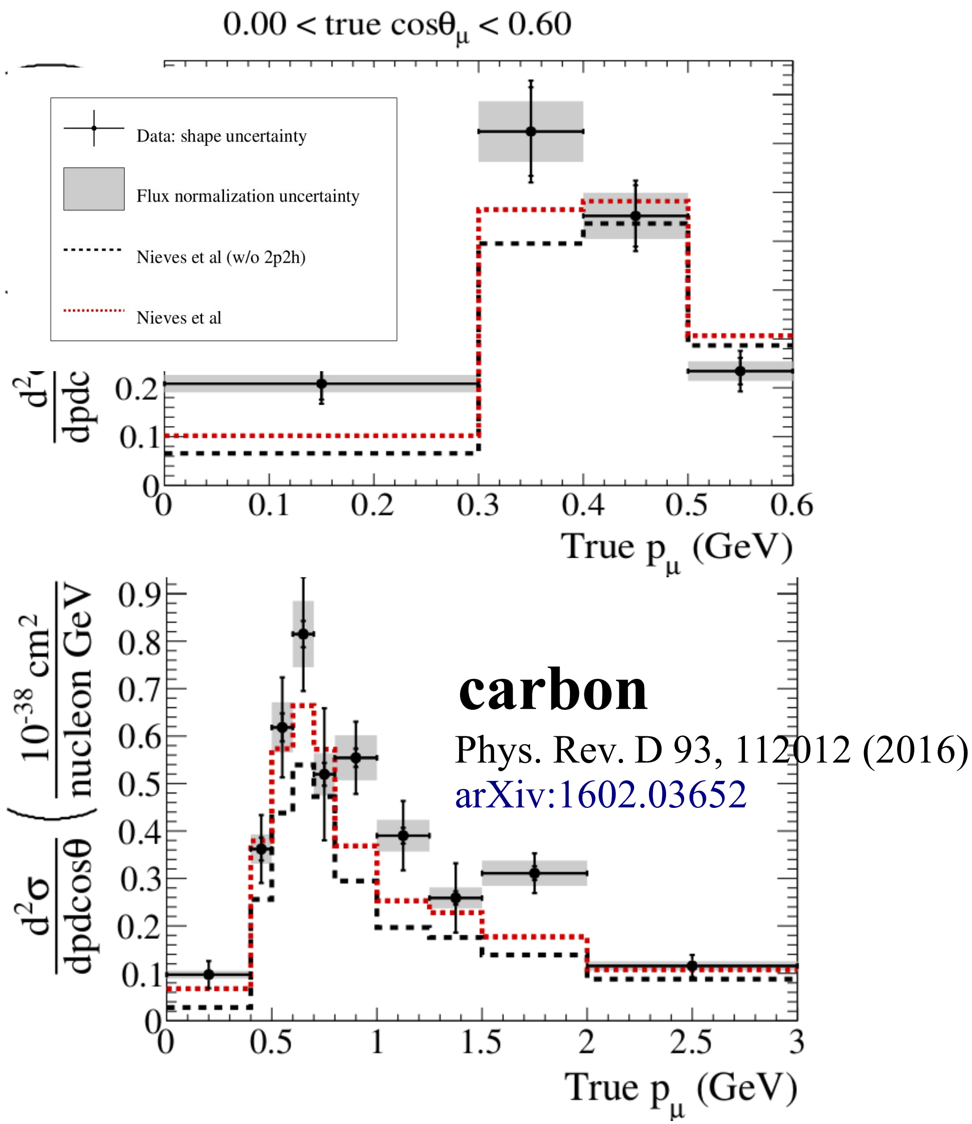
started looking at hadronic side to probe nuclear effects!

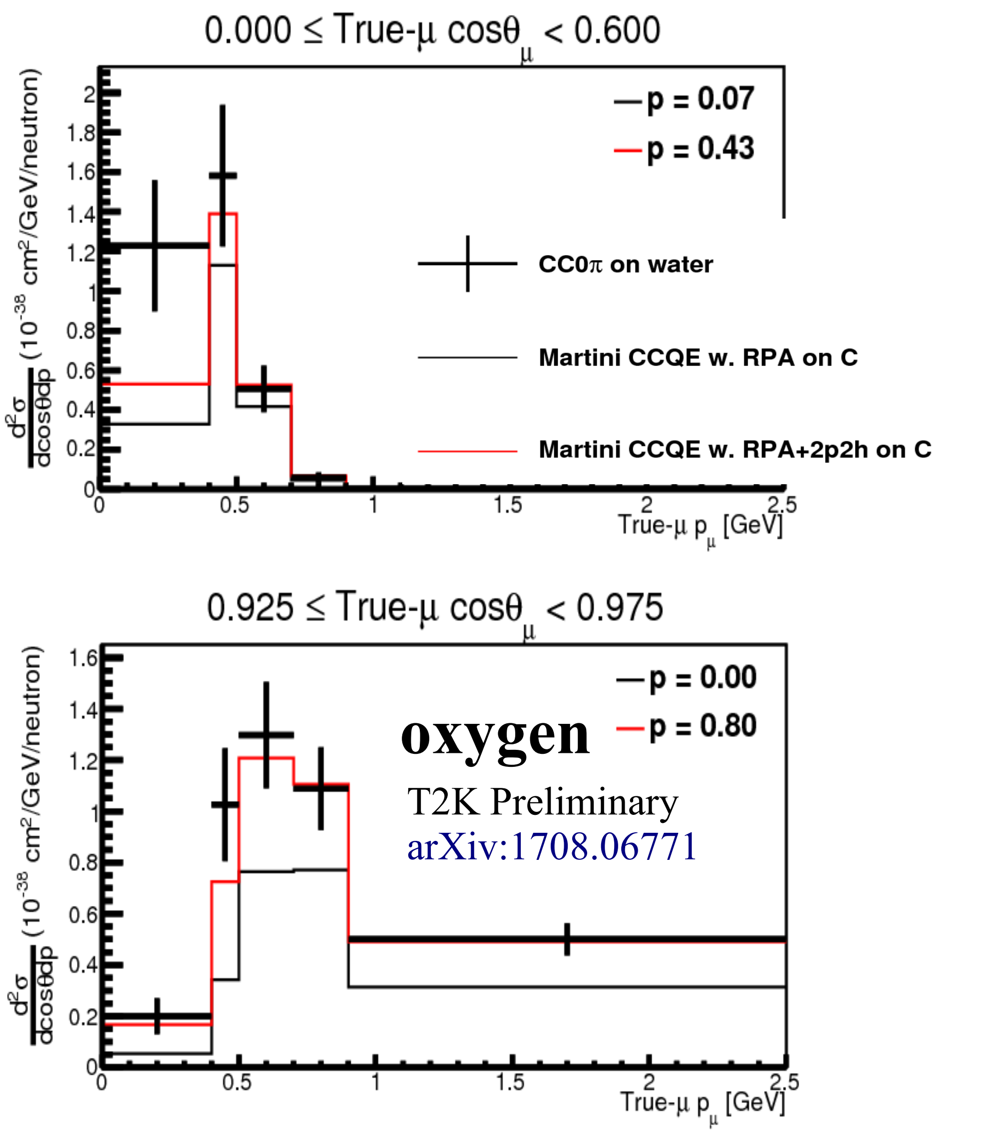
This talk will focus on the $\mathrm{CC}0\pi$ and $\mathrm{CC}0\pi\mathrm{N}p$ measurements.
See more details at *T2K recent results of cross section measurements* by C. Riccio; September 25th;

Results



- CC0π double-differential cross section in **muon** kinematics.

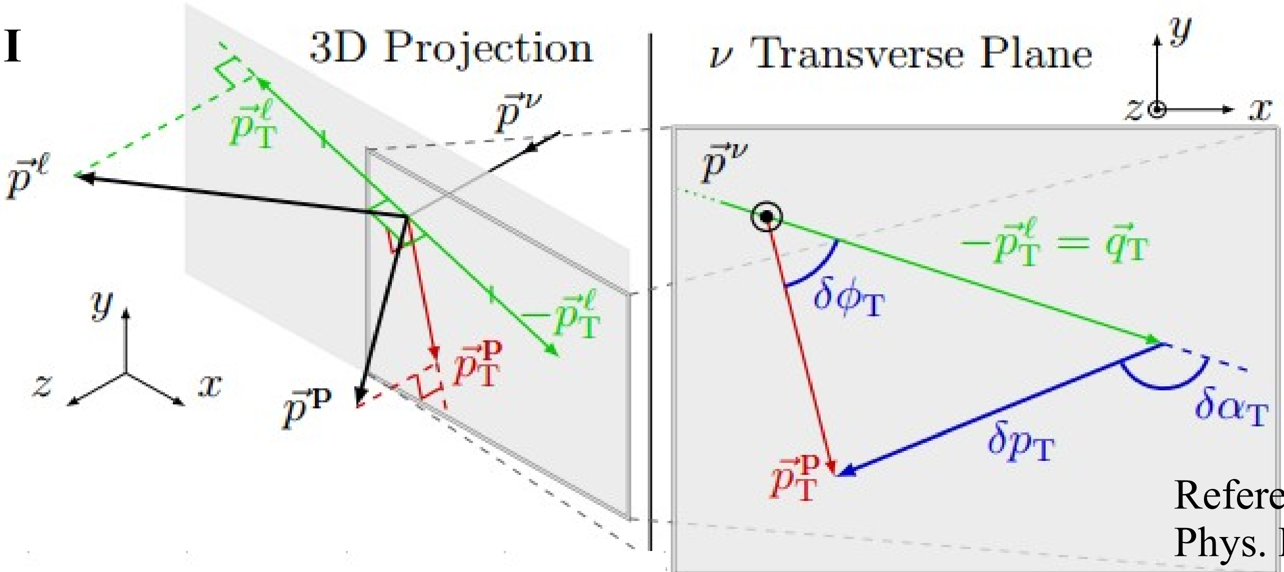




Results

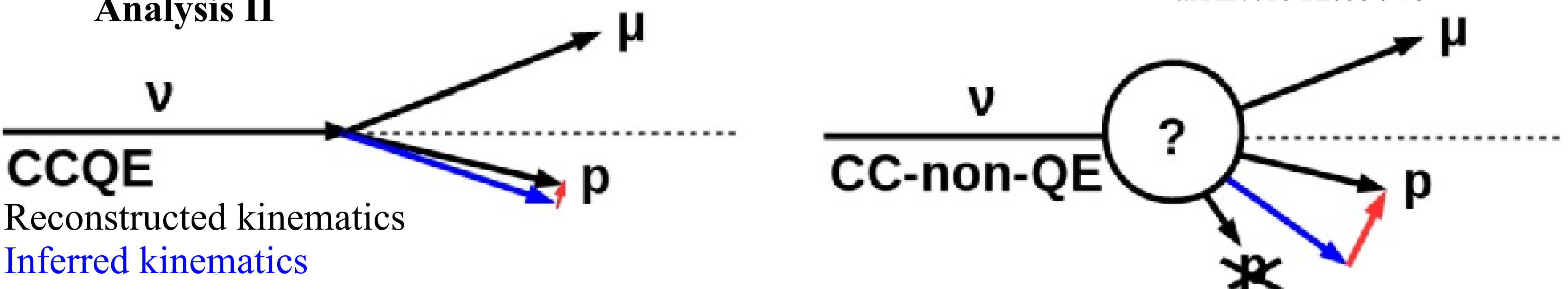
- $\mathrm{CC0}\pi\mathrm{N}p$ differential cross section in **proton** related variables.
- Two analyses with different sets of variables.

Analysis I



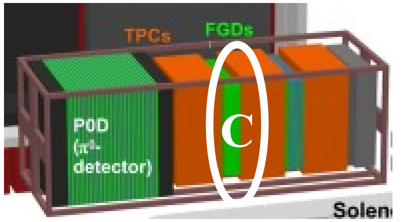
Reference :
Phys. Rev. C 94, 015503
arXiv:1512.05748

Analysis II

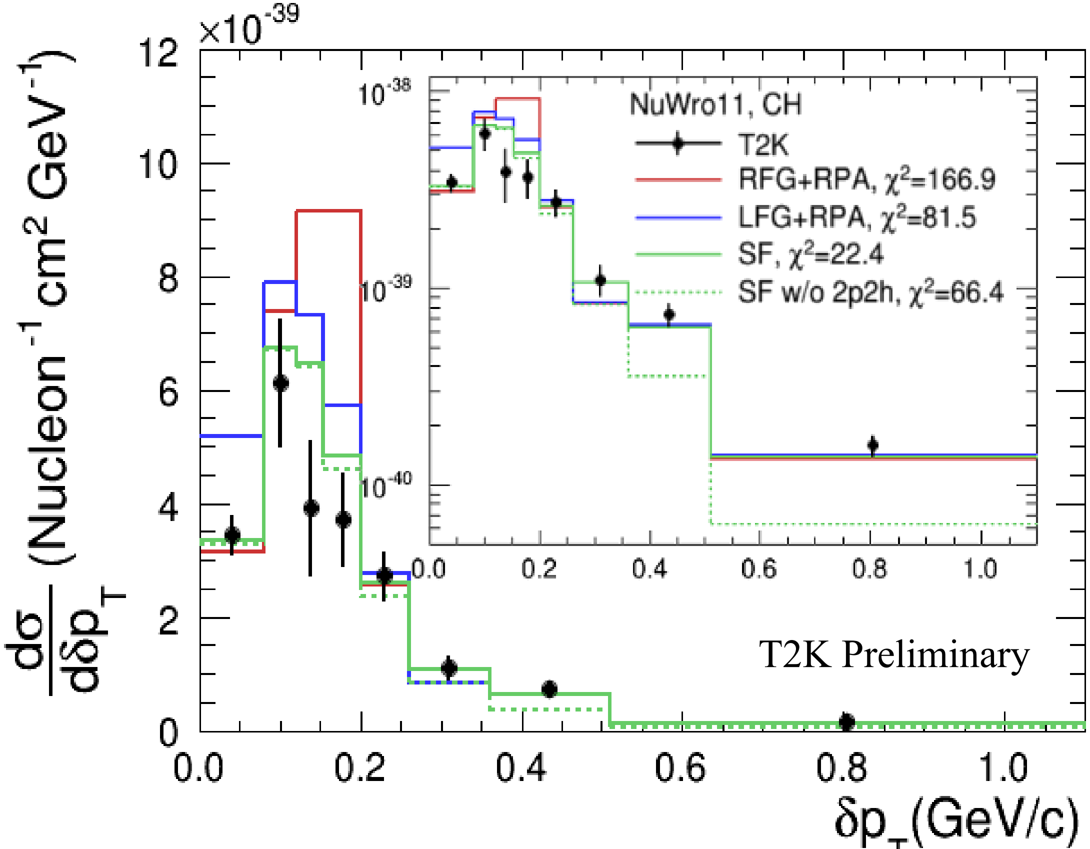


Reconstructed kinematics
Inferred kinematics
Difference

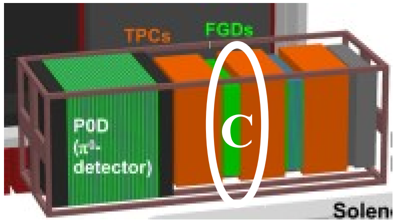
Results



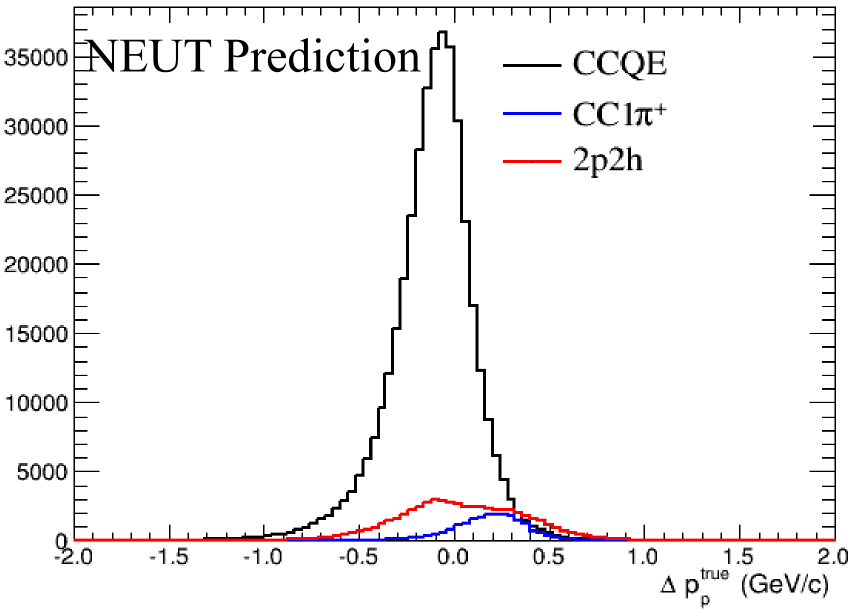
- $\mathrm{CC}0\pi\mathrm{N}p$ differential cross section in single transverse variables.
- Analysis I : Project proton/muon kinematics on the transverse plane of the neutrino beam.
- Shows interesting sensitivity to numerous nuclear effects.



Results

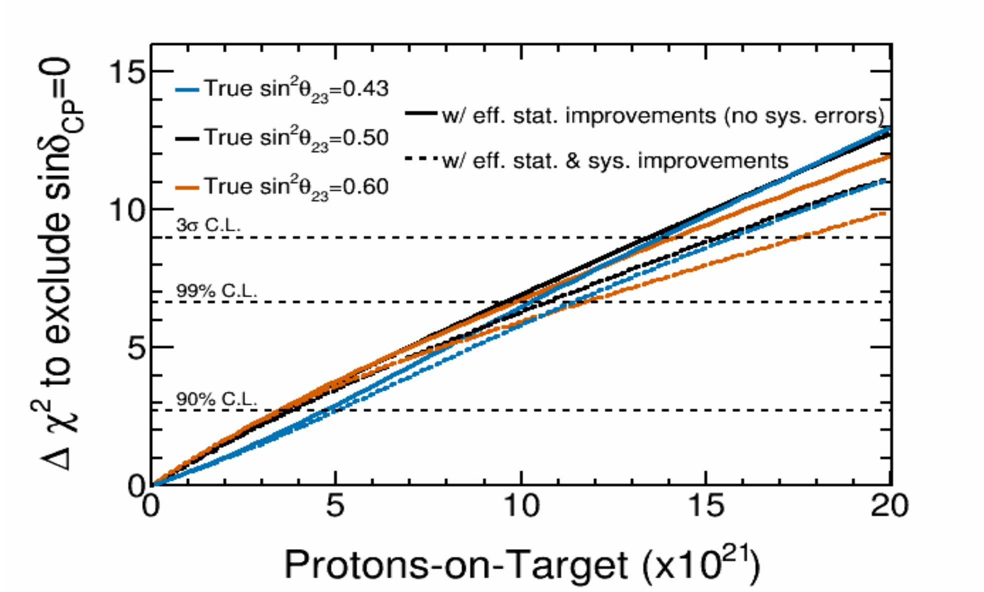


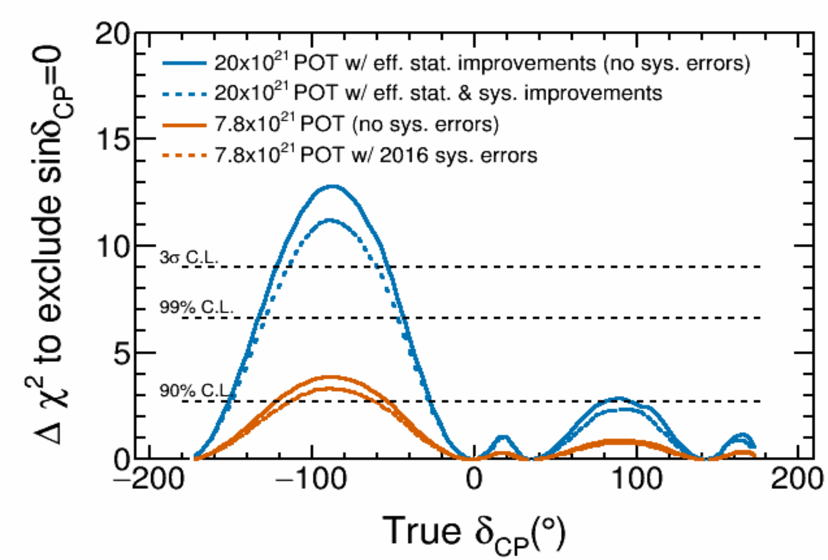
- $\mathrm{CC}0\pi\mathrm{N}p$ differential cross section in proton kinematic imbalance.
- Analysis II : Inferred proton kinematics from muon kinematics, and compared to the observed proton kinematics, expecting imbalance for any non-CCQE contributions.
- Momentum difference in different interaction modes.
  - Deviation for non-CCQE contributions.
  - CCQE distribution is centred at zero with some deviation due to FSI (e.g. proton re-scattering).



Future Perspectives

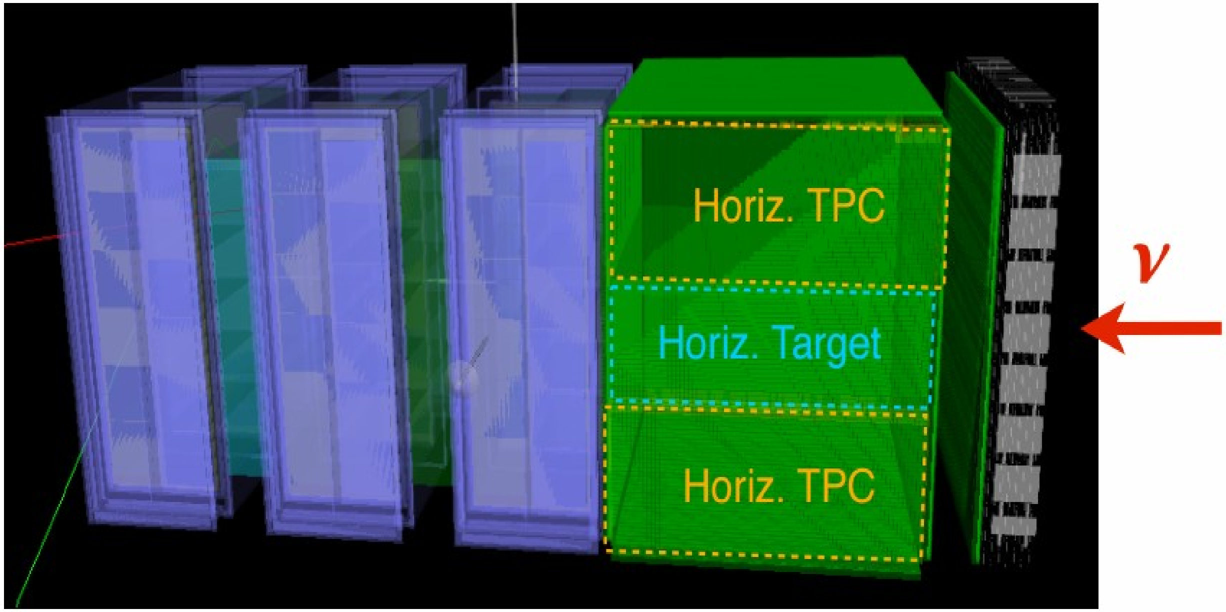
- Approved for 7.8×10^{21} POT by 2021, and proposal (arXiv:1609.04111) to extend the operation for 20.0×10^{21} POT with
  - Beam power upgrade : will be increased from 450 kW to 1.3 MW.
  - Possible near detector upgrade.
- Exclude CP conserving hypothesis at 3σ.
- Reduce the systematic uncertainties.





Future Perspectives

- New near detector design is proposed to have better acceptance and more target.
- Keeping the main trackers and replace P0D with two horizontal TPCs and a horizontal scintillator detector.



See more details at *Upgrade of the T2K near detector ND280: effect on oscillation and cross-section analyses* by M. Lamoureux; September 29th;

Conclusions

- Combined neutrino and anti-neutrino analysis with doubled neutrino statistics and improved SK measurements has been shown.
- CP conservation is disfavoured at 2σ C.L.
- $\mathrm{CC}0\pi$ measurements indicated the data is more in favour with multi-nucleon contributions. But we do not know how or how much it will contribute to the data.
  - started looking at hadronic side as well, moving to $\mathrm{CC}0\pi\mathrm{N}p$
- In addition to $\mathrm{CC}0\pi$ measurements, there are also other cross-section measurements such as $\nu_\mu\mathrm{CC}1\pi^+$, and $\overline{\nu}_\mu/\nu_e\mathrm{CC}$ inclusive.
- Proposal to extend run until 2026 to collect 3 times more POT. It will achieve 3σ sensitivity.

Back Up

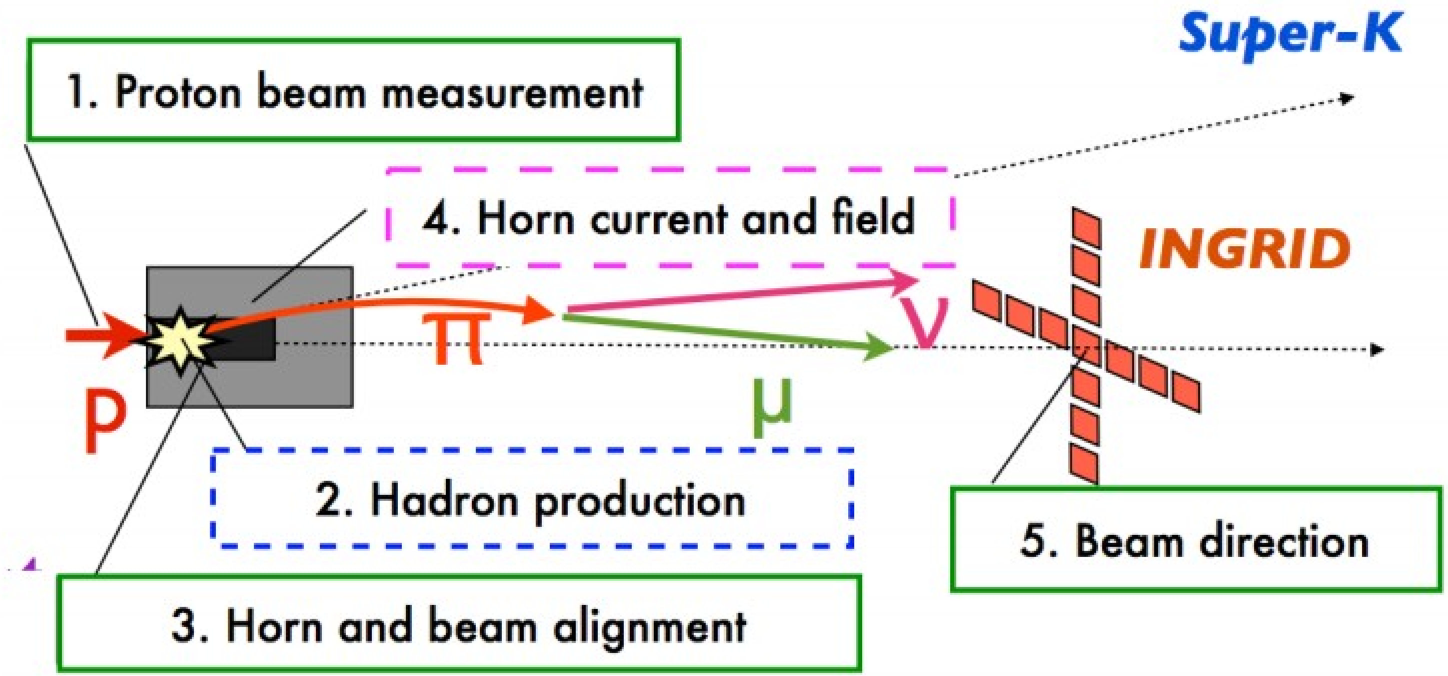
SK Updates

- Since 2016, there have been improvements on SK side.
  - New fiducial volume : ~ 30 % more statistics.
  - New sample : $\mathrm{CC}1\pi^+$ has been included.
    - Additional e-like ring is required for the michel electron.
    - Gain ~ 10 % more statistics.
    - Applied only to neutrino mode. For anti-neutrino mode, π^- is absorbed.
  - New reconstruction algorithm uses charge and time likelihood.
    - Selection efficiency and purity have been improved.

SK Systematics

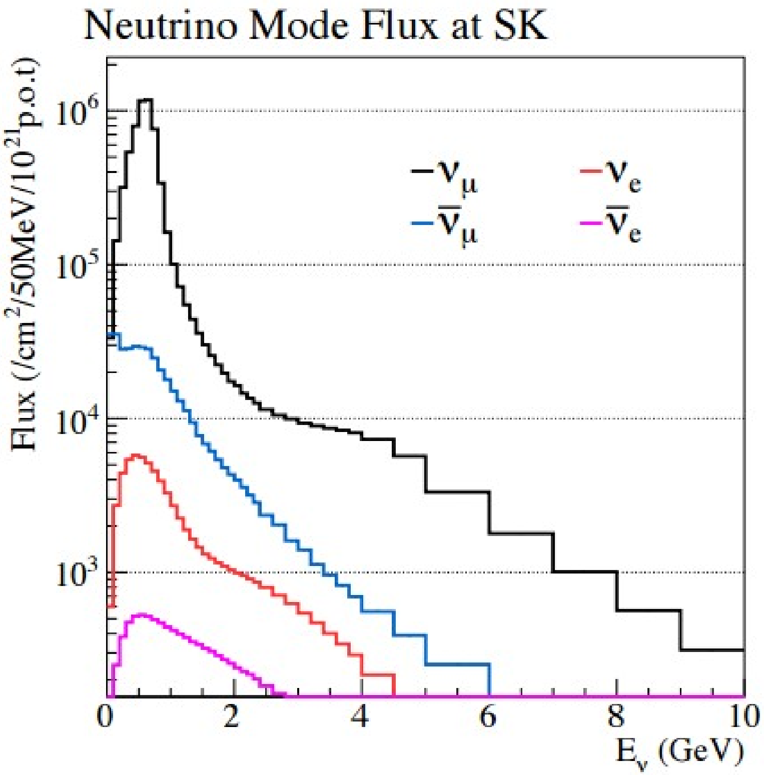
	% Errors on Predicted Event Rates, Osc. Parameter Set A					
	1R μ-Like		1R e-Like			
Error Source	FHC	RHC	FHC	RHC	FHC CC1π	FHC/RHC
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
ND280 const. flux & xsec	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Systematic Error	4.40	3.76	6.10	6.51	20.94	4.77

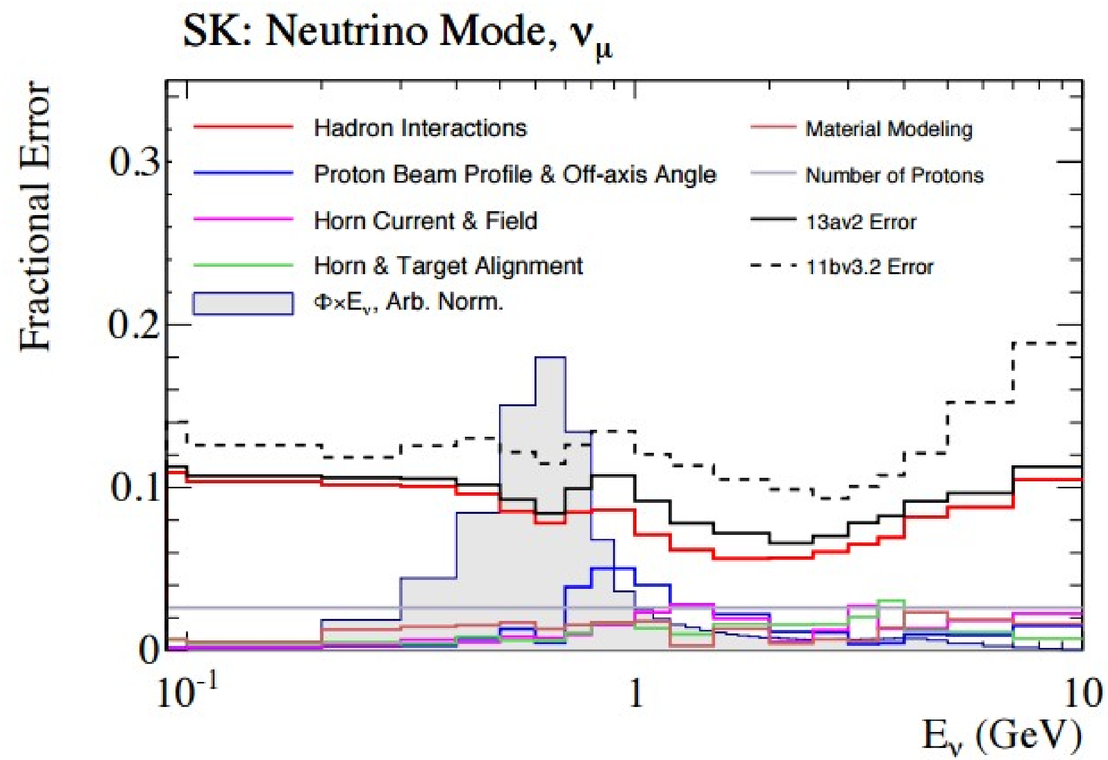
Flux Simulation Inputs



- The proton beam properties measured at the beam monitor.
- Hadron production on graphite is simulated (FLUKA2011) with external data from NA61/SHINE.
- Propagation of hadrons is simulated with GEANT3.
- INGRID measures the neutrino beam direction/centre.

Flux Predictions at SK





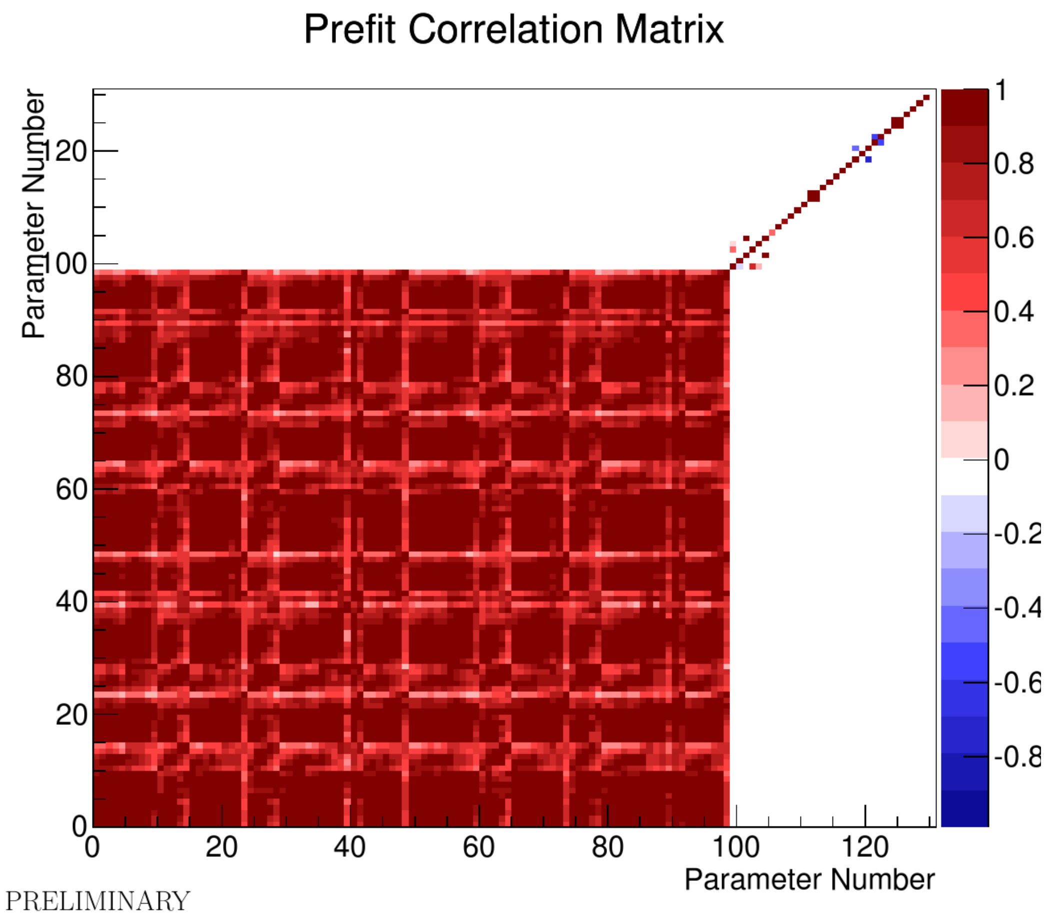
- The overall uncertainties on the flux prediction is 8~12 %.
- The main source of the uncertainties is hadron interaction modelling.

Systematics with Fit

Fractional uncertainties (%) on the observed neutrino events at SK.

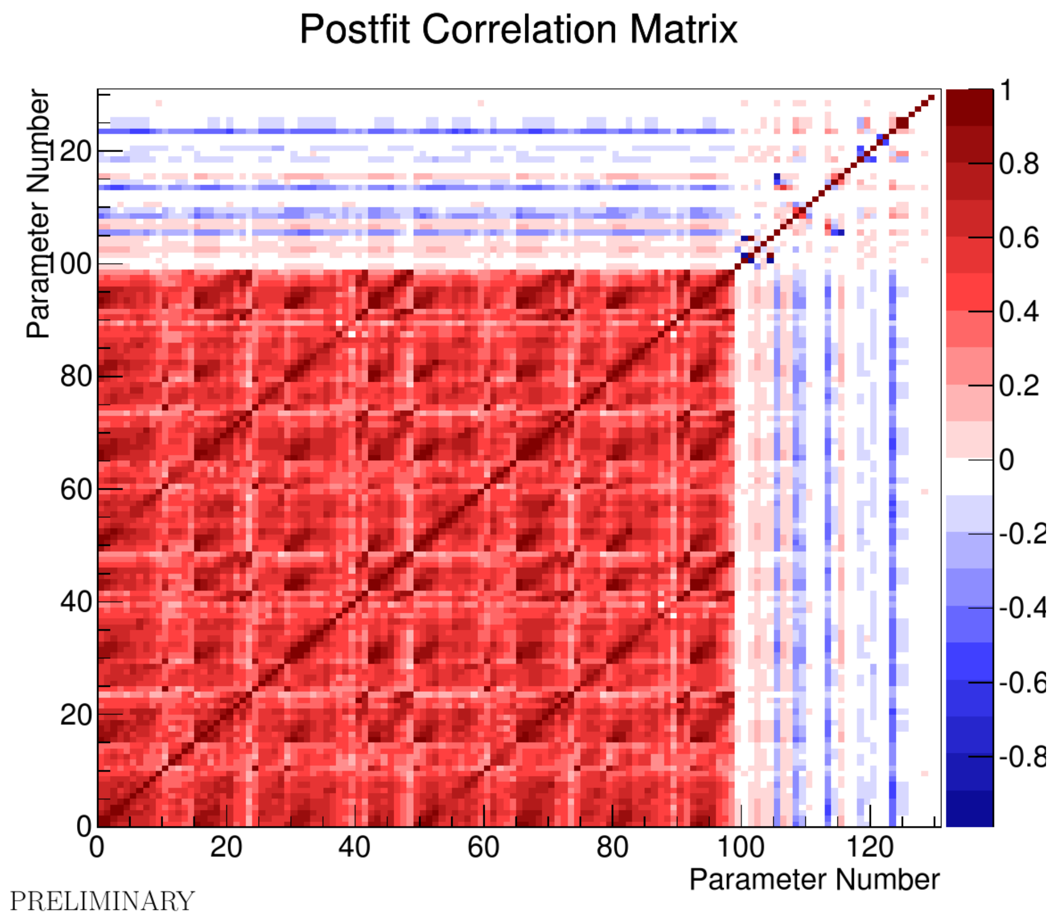
	ν_μ		ν_e		$\overline{\nu}_\mu$		$\overline{\nu}_e$	
	Pre-fit	Post-fit	Pre-fit	Post-fit	Pre-fit	Post-fit	Pre-fit	Post-fit
Flux	7.6	**2.9**	8.9	**4.2**	7.1	**3.4**	8.0	**4.6**
Cross section	7.7		7.2		9.3		10.1	
Total	12.0	**5.0**	11.9	**5.4**	12.5	**5.2**	13.7	**6.2**

ND280 Fitted Parameters



Correlation between parameters (flux and cross-section models) before ND280 fit.

ND280 Fitted Parameters



Correlation between parameters (flux and cross-section models) after ND280 fit.

Likelihood Function

Measured (M) and predicted (N) number of events at SK

$$-ln(L) = \boxed{\sum_{i}^{N_{SKbins}} N_i^{SK}(\vec{o},\vec{p}) - M_i^{SK} + M_i^{SK} ln[M_i^{SK}/N^{SK}(\vec{o},\vec{p})]}$$

$$+\boxed{\frac{1}{2}\sum_{i}^{N_o^{const}}\sum_{j}^{N_o^{const}} \Delta o_i (V_{ij}^{o})^{-1}\Delta o_j} + \boxed{\frac{1}{2}\sum_{i}^{N_p}\sum_{j}^{N_p}\Delta p_i (V_{ij}^{p})^{-1}\Delta p_j.}$$

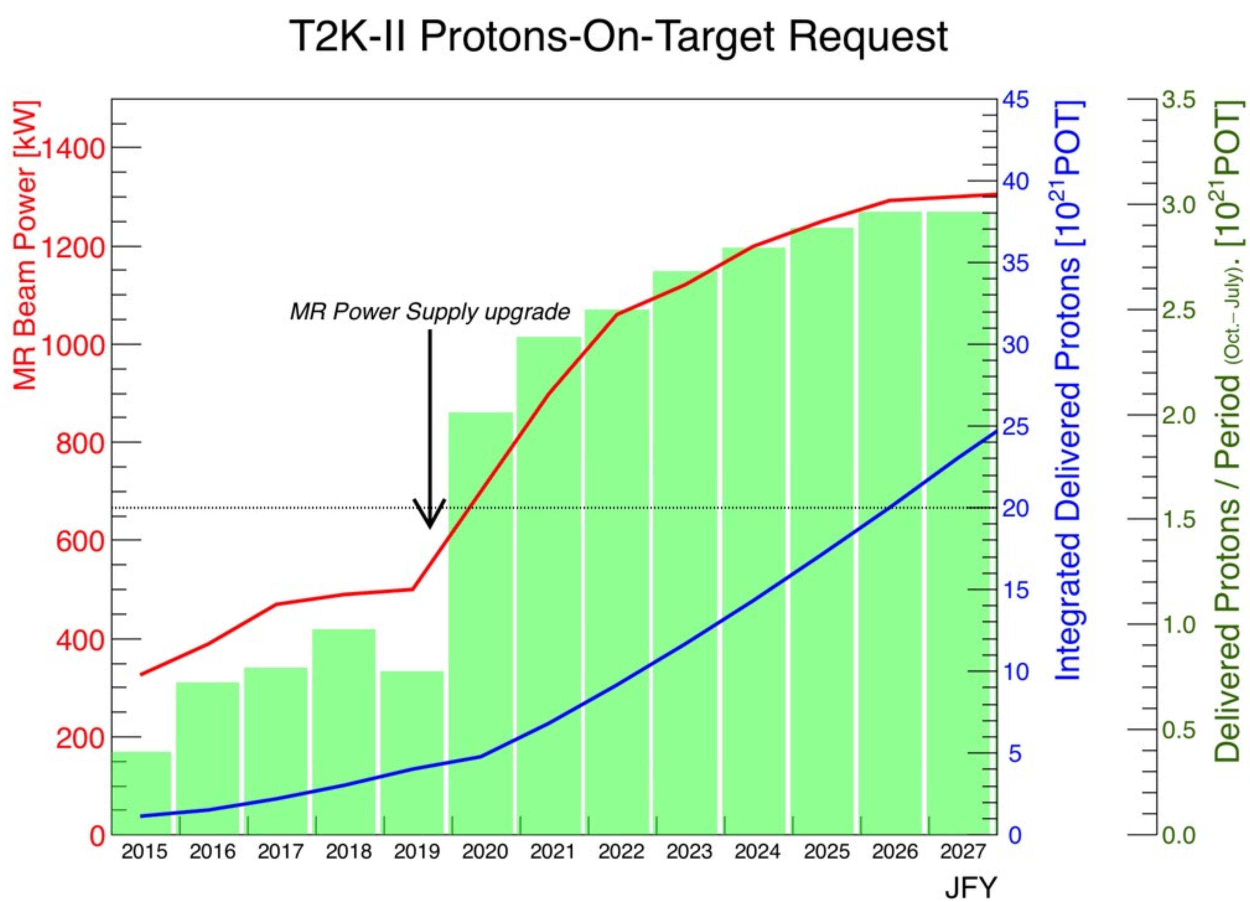
Penalty term due to
oscillation parameter systematics

Penalty term due to
model parameter systematics

Fakedata Studies

- Motivation : In ND280 fit, model and flux parameters are fitted simultaneously. What if there is 3p-3h in nature, not yet in MC?
  - Deficit in MC. ND280 fit can increase flux to overcome.
  - This fitted flux goes into SK and will alter the oscillation analysis.
- Fakedata studies examine any potential bias by a choice of cross-section models.
- Data-driven fakedata sets are generated to use. In MC, one of neutrino interaction modes are enhanced to account for the difference in data and model predictions.
  - ND280 and MINERvA data are used.

T2K-II POT Request



Assumed avg. MR beam power [kW]
Total Integrated POT by the end of JFY
Expected POT in Each T2K-Run Period (POT accumulated in Oct. ~ next Jun.)

Main Ring Plan

JFY	2015	2016	2017	2018	2019	2020	2021	2022
		New buildings		HD Target	Long shutdown			
FX power [kW] **SX power [kW]**	390 42	470 42	480-500 50	> 500 50-60	700 60-80	800 80	900 80-100	1060 100
Cycle time of main magnet PS **New magnet PS**	2.48 s		Mass production installation/test	2.48 s	1.3 s	1.3 s	1.3 s	1.3 s
High gradient rf system **2$^{\text{nd}}$ harmonic rf system**	Installation		Manufacture, installation/test					
Ring collimators	Add.coll imators (2 kW)				Add.colli. (3.5kW)			
Injection system **FX system**	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, FX septa manufacture /test							
SX collimator / Local shields						Local shields		
Ti ducts and SX devices with Ti chamber			ESS					

Neutrino Oscillations

- Neutrino mixing matrix in the standard 3-flavor mixing :

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

where $c_{12} = \cos\theta_{12}$, $s_{12} = \sin\theta_{12}$

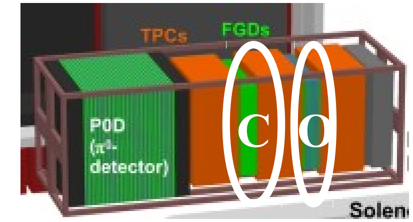
- There are six oscillation parameters : Δm^2_{21} , Δm^2_{32} , θ_{12} , θ_{23} , θ_{13} , δ_{CP}

- Global fits

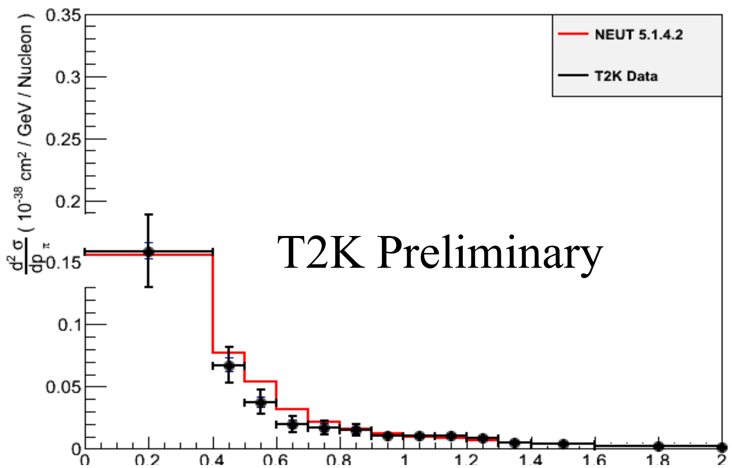
Parameter	best fit
$\Delta m^2_{21}(10^{-5}eV^2)$	$7.54^{+0.26}_{-0.22}$
$\lvert\Delta m^2_{32}\rvert(10^{-3}eV^2)$	$2.43 \pm 0.96 (2.38 \pm 0.06)$
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$	$0.437^{+0.033}_{0.023}(0.455^{+0.039}_{-0.031})$
$\sin^2\theta_{13}$	$0.0234^{+0.0020}_{-0.0019}(0.0240^{+0.0019}_{-0.0022})$

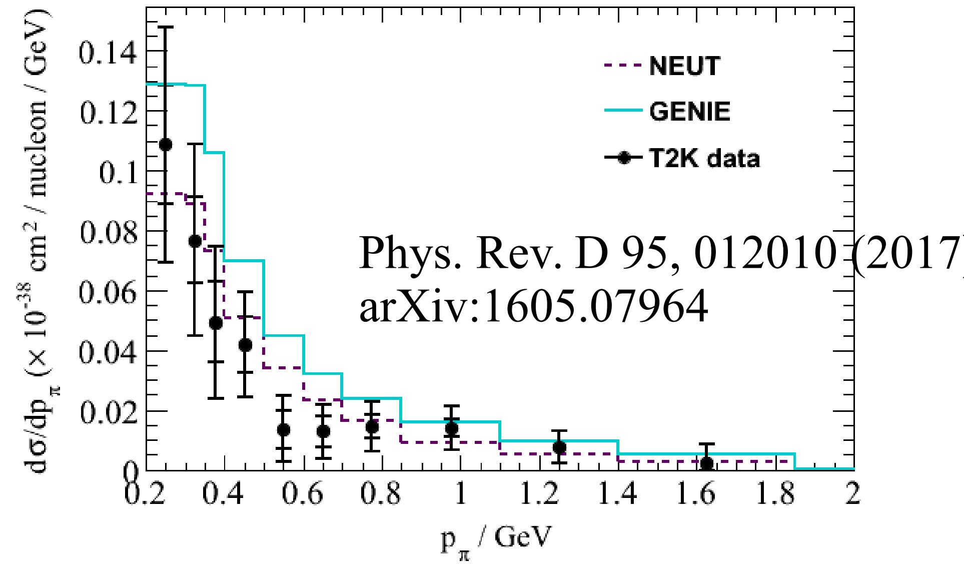
- Open Questions
  - Mass hierarchy
  - CP violation phase
  - Dirac or Majorana

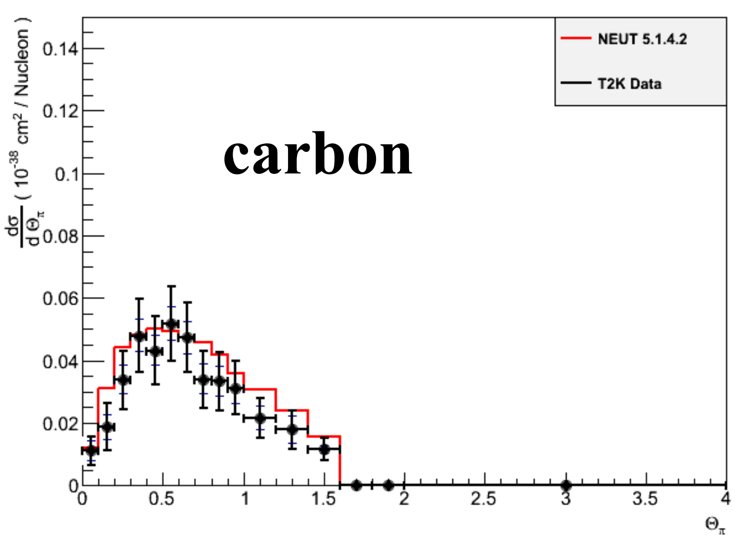
Cross-section Results

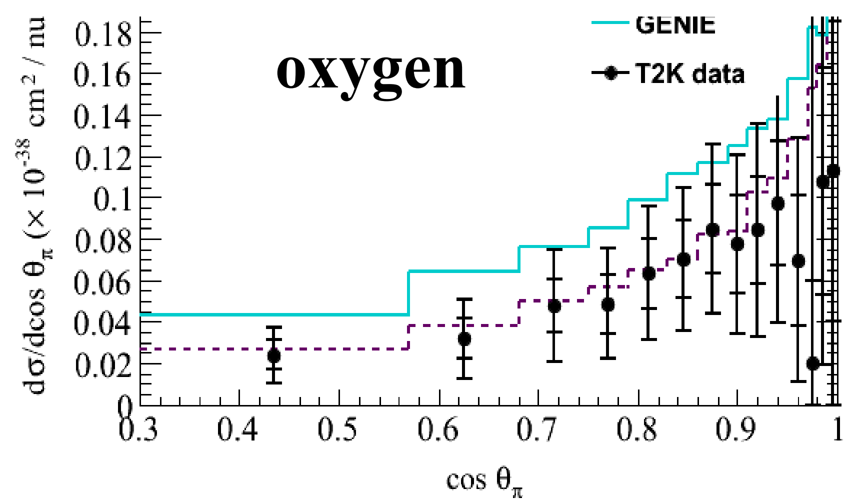


- $CC1\pi^{+}$ differential cross section in pion kinematics.

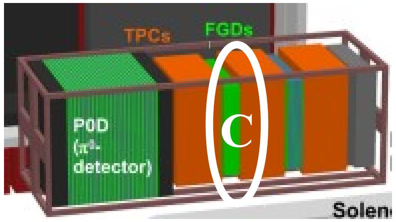




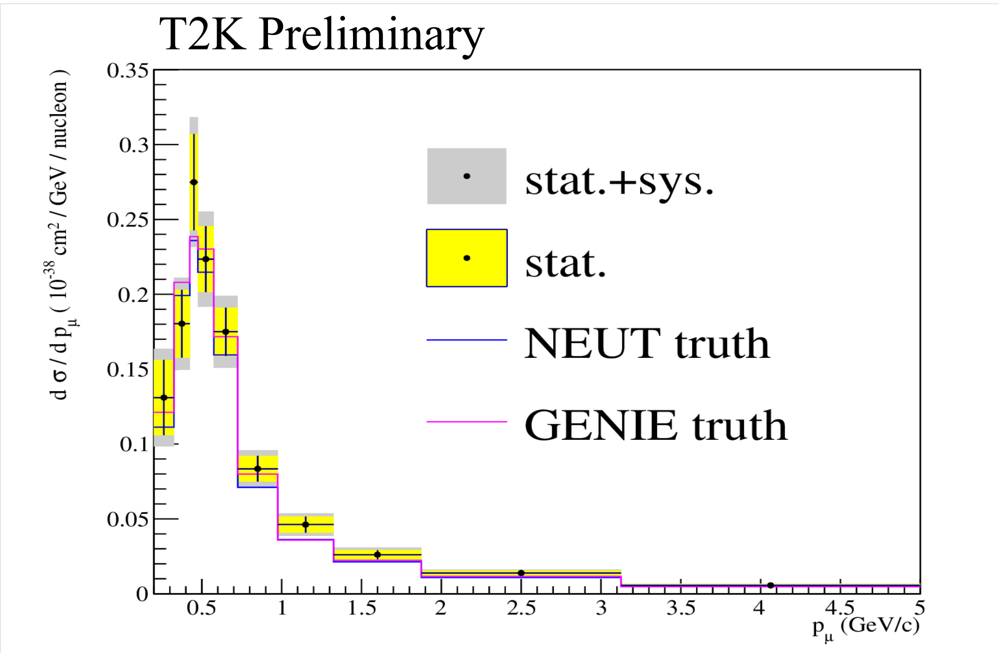


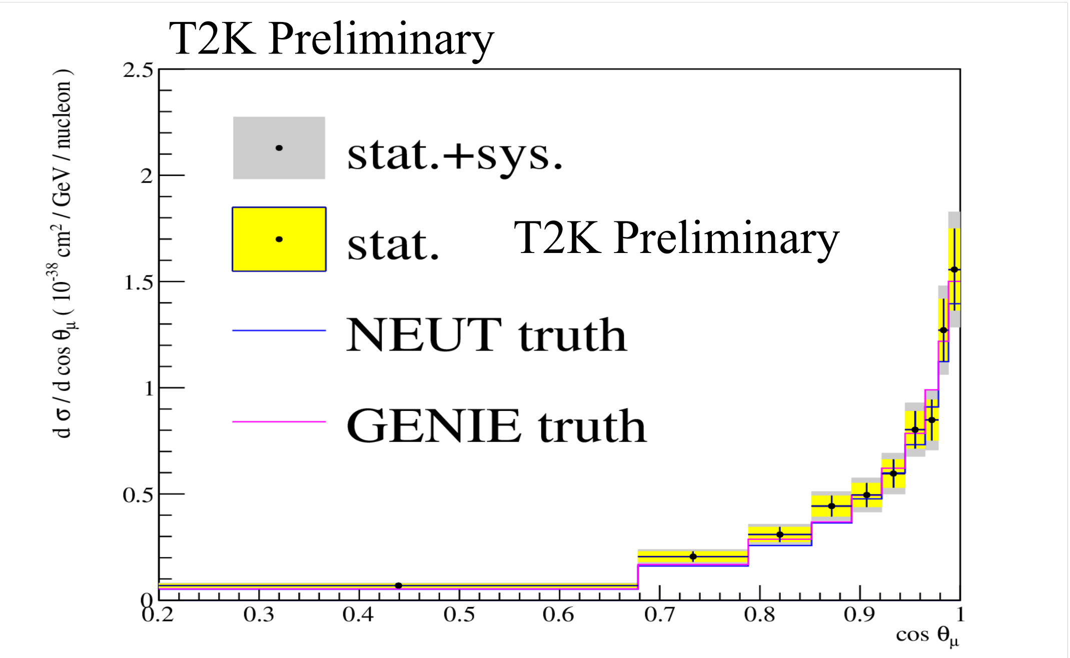


Cross-section Results



- Anti-neutrino CC inclusive on carbon.
- Differential cross section in muon kinematics.





Sensitivity to the Efficiency

Cross-section Extraction:

ν_μ inclusive CC cross-section measurement on C at T2K at NuInt 2017

Goal -> double-differential (p_μ,$\cos\theta_\mu$) cross section ν_μ CC inclusive on plastic*

*C[86%]H[7%]O[4%]

$$\frac{d\sigma}{dp_{\mu,i}dcos\theta_{\mu,j}} = \frac{N_{ij}^{CC-\mu}}{\epsilon_{ij}^{CC-\mu,MC}\Phi N_{nucleons}^{FV}\Delta p_{\mu,i}\Delta cos\theta_{\mu,j}}$$

- Efficiency correction using NEUT 5.3.0 and GENIE 2.8.0 predictions.
    - Discrepancies for low momentum muons going forward (in RES and DIS channels).