T2K

NEUTRINO CROSS-SECTION MEASUREMENTS

Lukas Koch
for the T2K Collaboration
NuFACT 2023

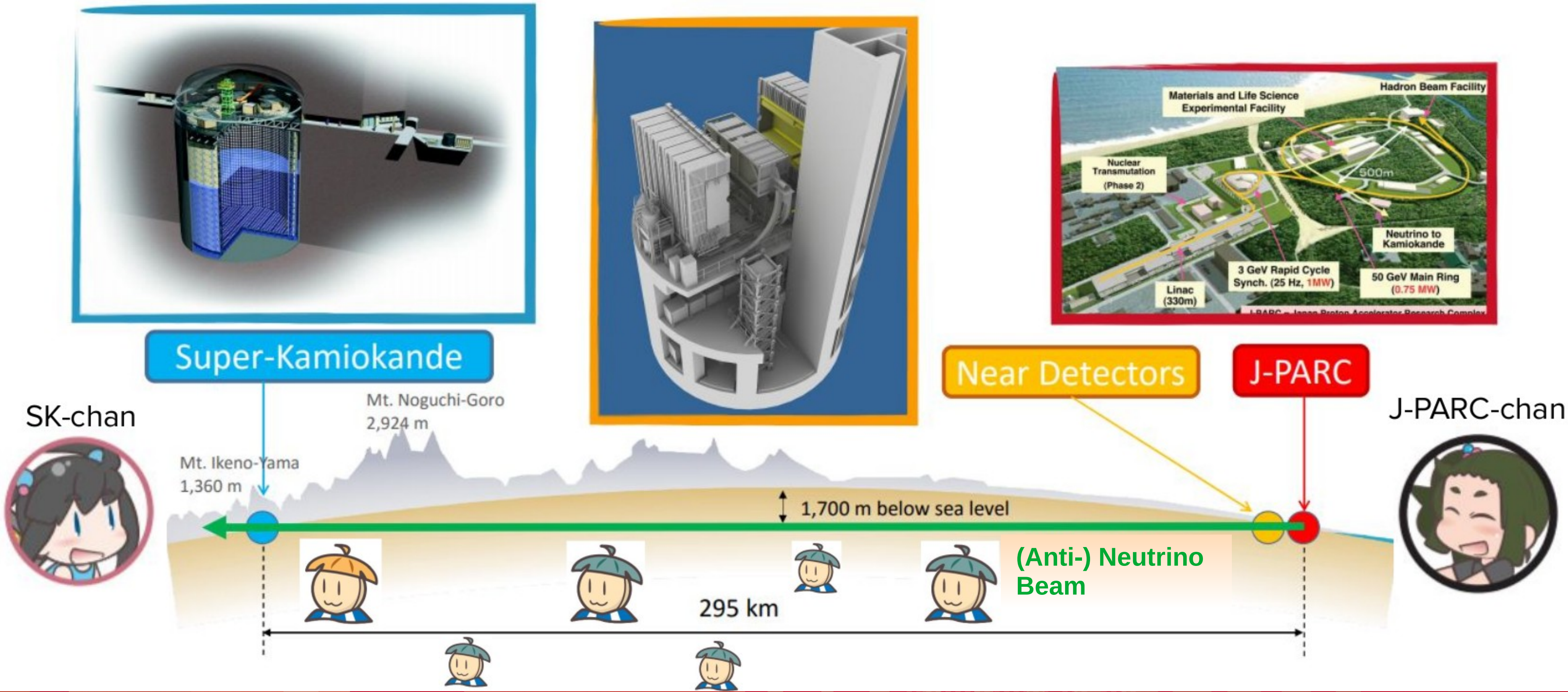
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

TABLE OF CONTENTS

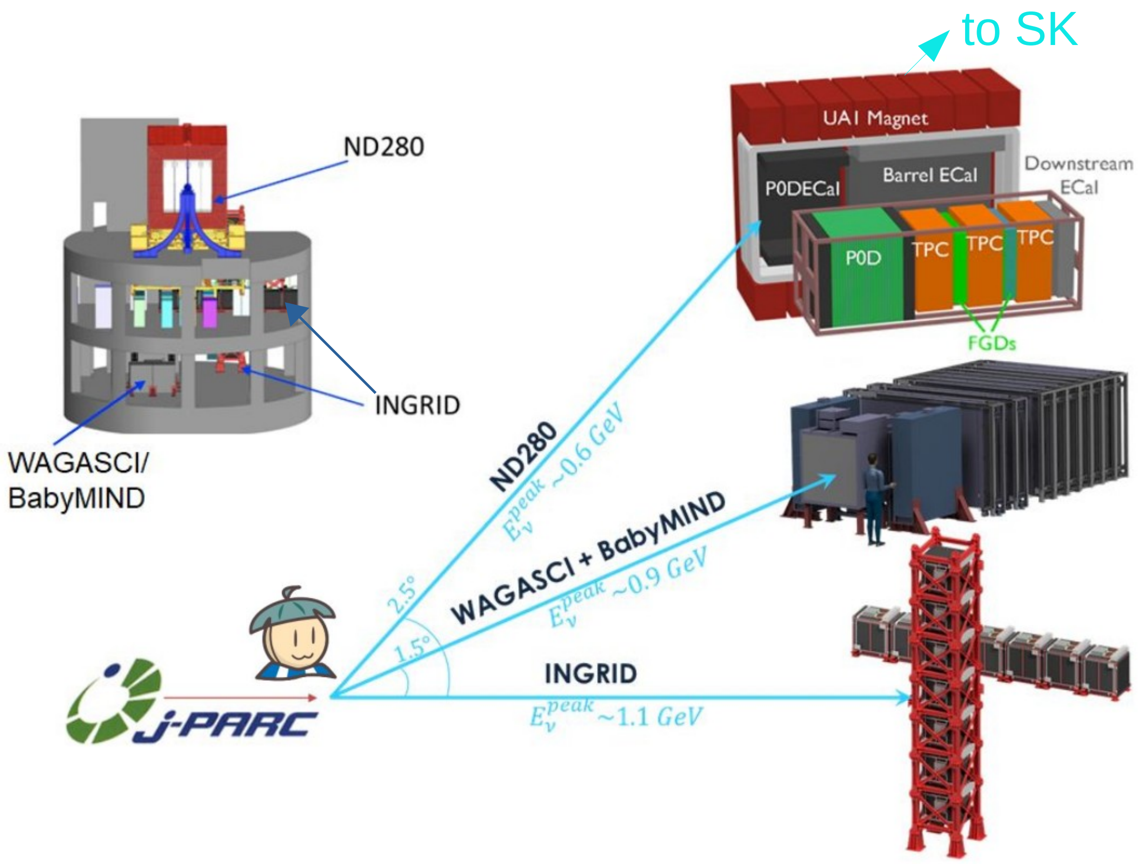
- The T2K experiment
- Recent official results
  - Charged current coherent on carbon
  - Combined on- and off-axis $0\pi^{+/-}$
- Upcoming measurements
  - Intermediate angle $0\pi^{+/-}$ and combination of all angles
  - Kaon production
- Outlook

THE T2K EXPERIMENT

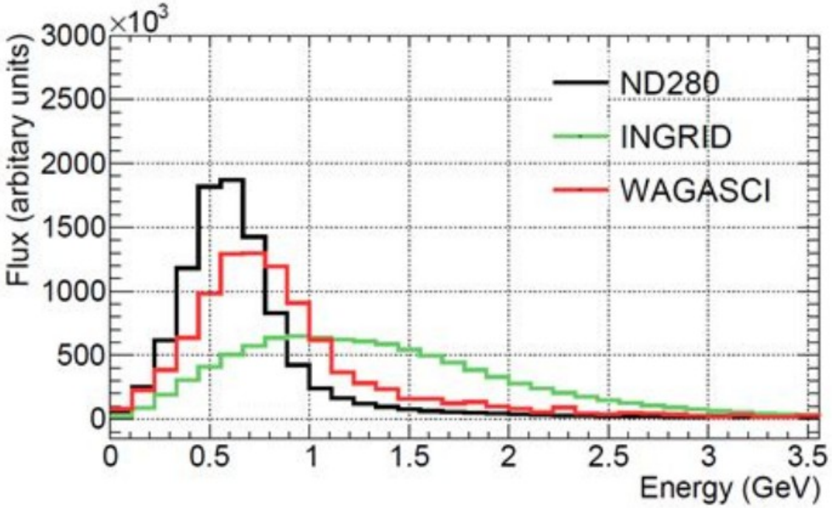
Character illustrations by AKIMOTO Yuki @ higgstan.com
https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/files/NF-pamph-EN.pdf



THE NEAR DETECTOR COMPLEX



Multiple different detectors
Different angles → different E_ν spectra
Disentangle flux and cross-section effects



IMPORTANT FOR OSCILLATION

- Cross sections have direct influence on current oscillation measurements
  - Big part of syst. Uncertainties of T2K δ_{CP} measurement
- Will need to constrain further as cross section models evolve to reach future physics goals @ Hyper-Kamiokande

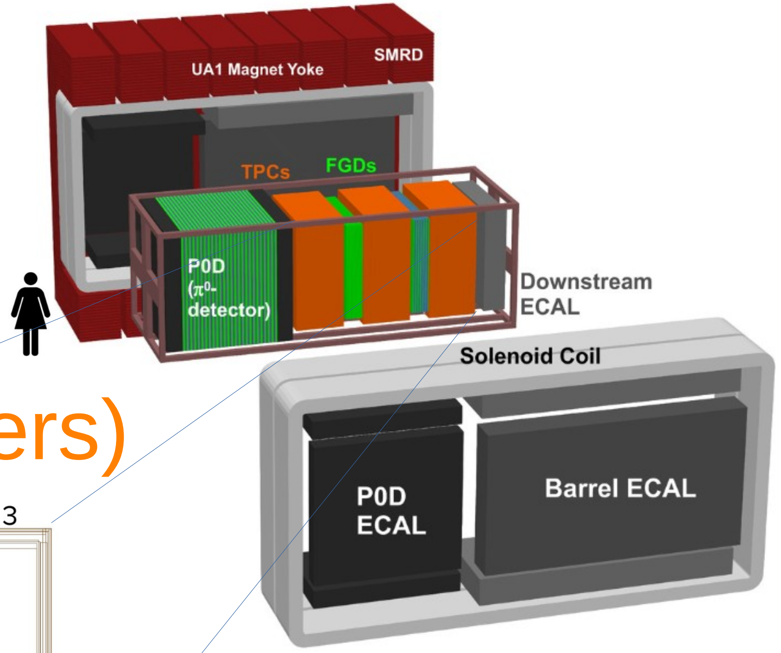
Error source	1-Ring μ ν	1-Ring μ $\overline{\nu}$	1-Ring e ν	1-Ring e $\overline{\nu}$	1-Ring e ν 1 d.e	$\nu / \overline{\nu}$
Flux and (ND unconstrained)	14.3	11.8	15.1	12.2	12.0	1.2
cross-section (ND constrained)	3.3	2.9	3.2	3.1	4.1	2.7
SK Detector	2.4	2.0	2.8	3.8	13.2	1.5
SK FSI + SI + PN	2.2	2.0	3.0	2.3	11.4	1.6
Nucleon Removal Energy	2.4	1.7	7.1	3.7	3.0	3.6
$\sigma(\nu_e)/\sigma(\overline{\nu}_e)$	0.0	0.0	2.6	1.5	2.6	3.0
NC1γ	0.0	0.0	1.1	2.6	0.3	1.5
NC Other	0.3	0.3	0.2	0.3	1.0	0.2
$\sin^2\theta_{23}$ and Δm^2_{21}	0.0	0.0	0.5	0.3	0.5	2.0
$\sin^2\theta_{13}$ PDG2018	0.0	0.0	2.6	2.4	2.6	1.1
All Systematics [%]	5.1	4.5	8.8	7.1	18.4	6.0

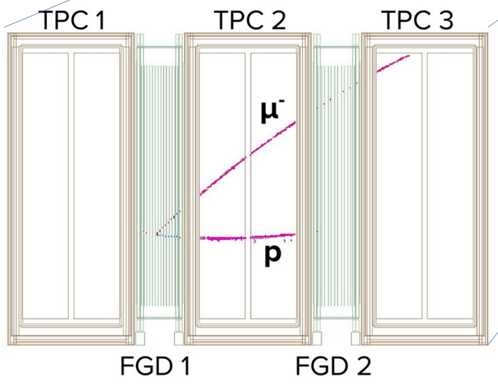
[Phys. Rev. D 103, 112008 (2021)]

Recent official results

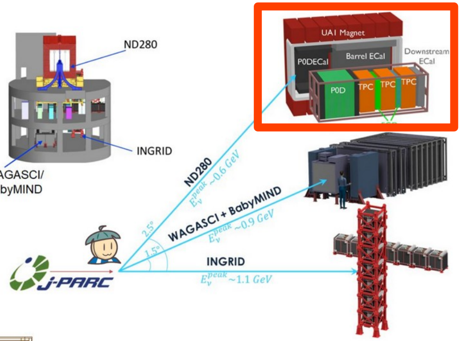
THE OFF-AXIS DETECTOR ND280

- Most important bits today:
- FGD (Fine Grained Detector)
  - Active CH target
- TPCs (Time Projection Chambers)
  - PID (Particle ID)
  - Momentum
- Magnet

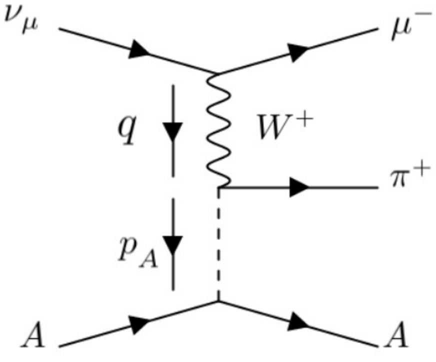




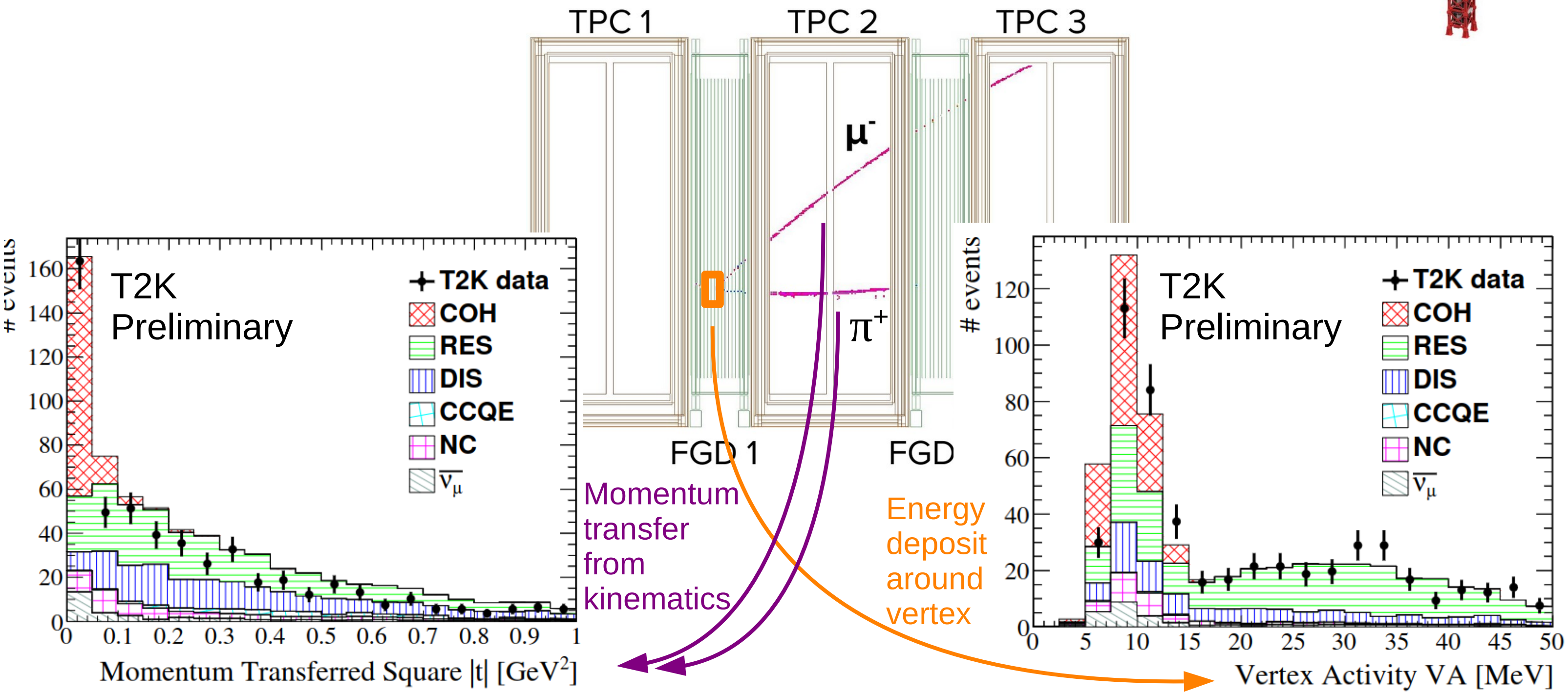
CHARGED CURRENT COHERENT ON C @ ND280



- Different from “true” coherent NC

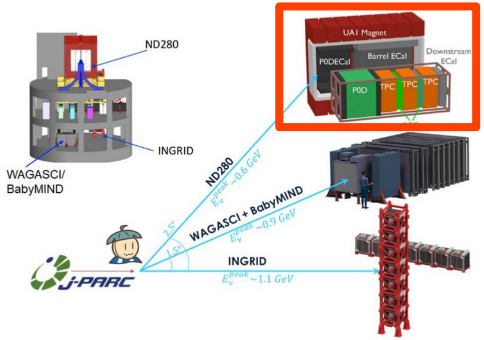


$$|p_A|^2 = |q - p_\pi|^2 = |t|$$

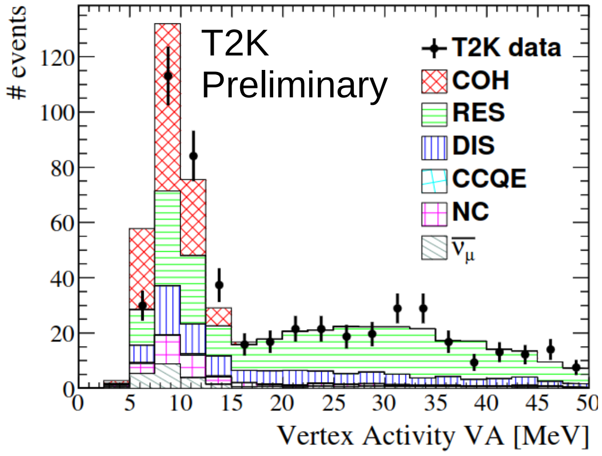


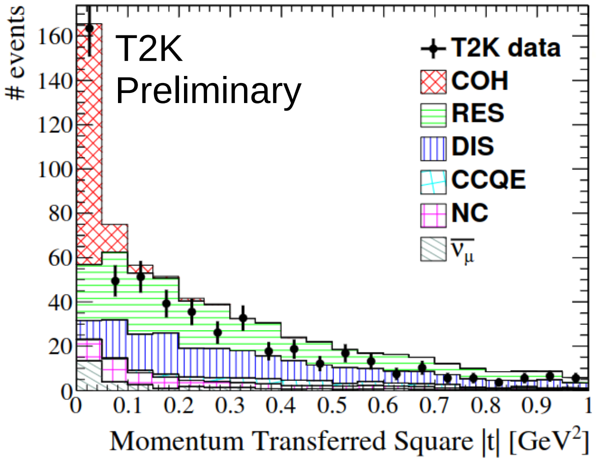
[arXiv: coming soon]

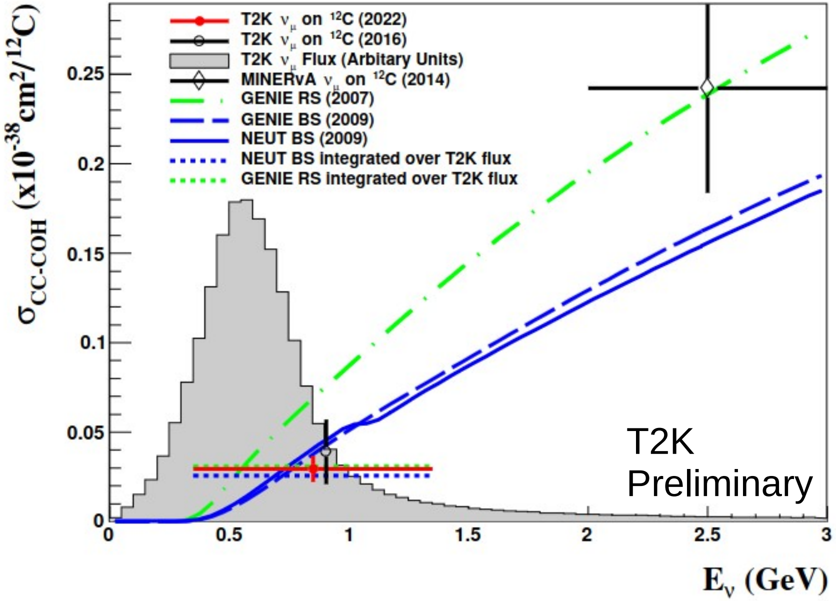
CHARGED CURRENT COHERENT ON C @ ND280



- Update of 2016 ν_μ measurement
- Reduced uncertainties → Better constrain of oscill. background
- Compatible with both Berger Sehgal (NEUT) and Rein Sehgal (GENIE)



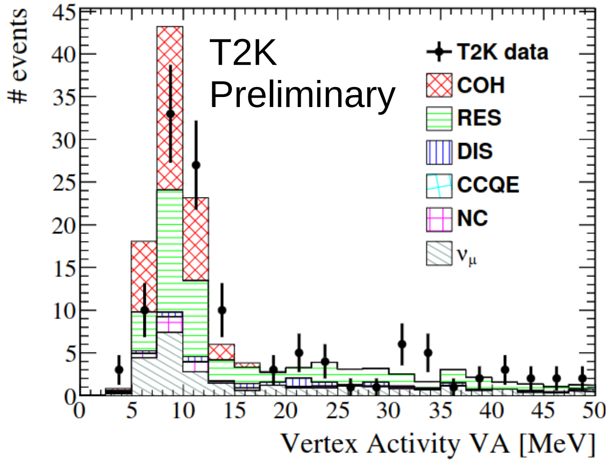


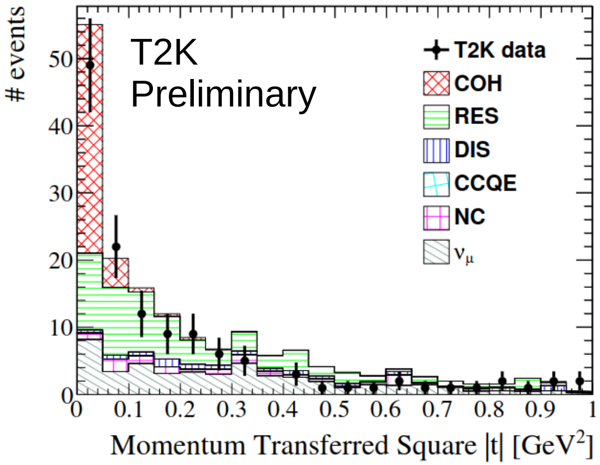


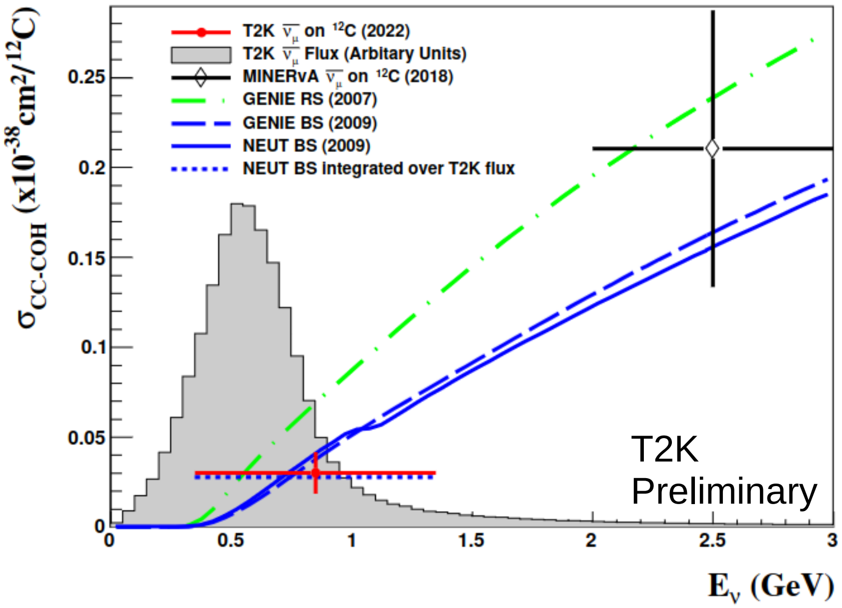
[arXiv: coming soon]

CHARGED CURRENT COHERENT ON C @ ND280

- Our first anti-ν_μ measurement
- Compatible with Berger Sehgal (NEUT)
  - Rein Sehgal not excluded (GENIE)



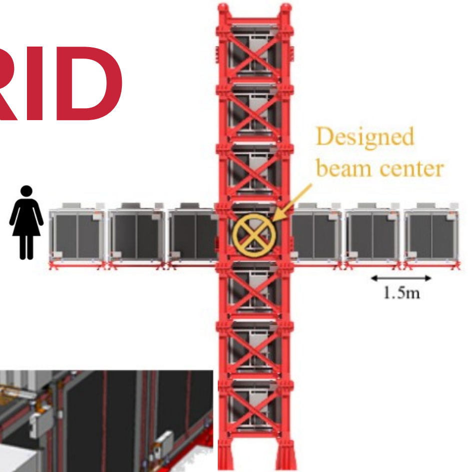


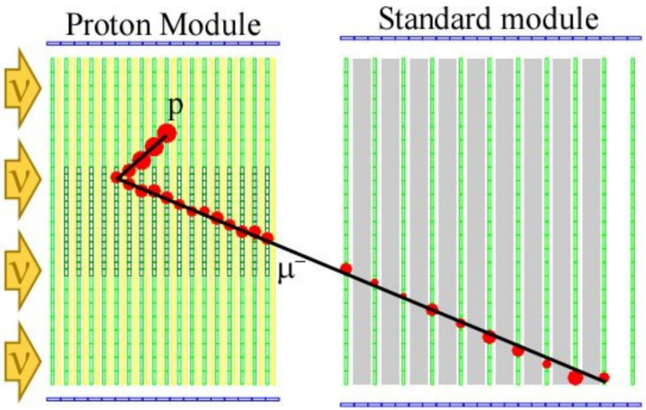


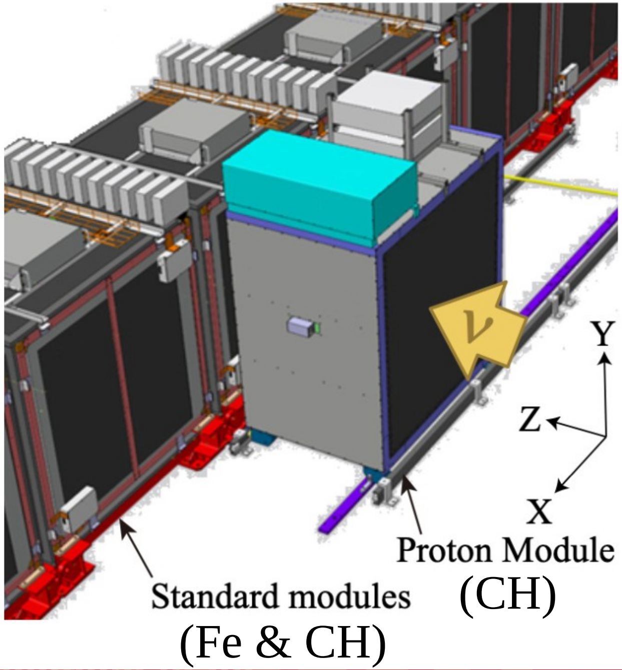
[arXiv: coming soon]

THE ON-AXIS DETECTOR INGRID

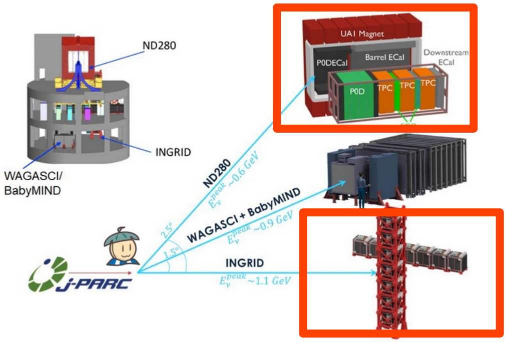
- Standard modules for beam monitoring
  - Actually span off axis-angles
- Proton module for cross sections
  - On-axis
  - PID via dE/dx & track length
  - Momentum by track length



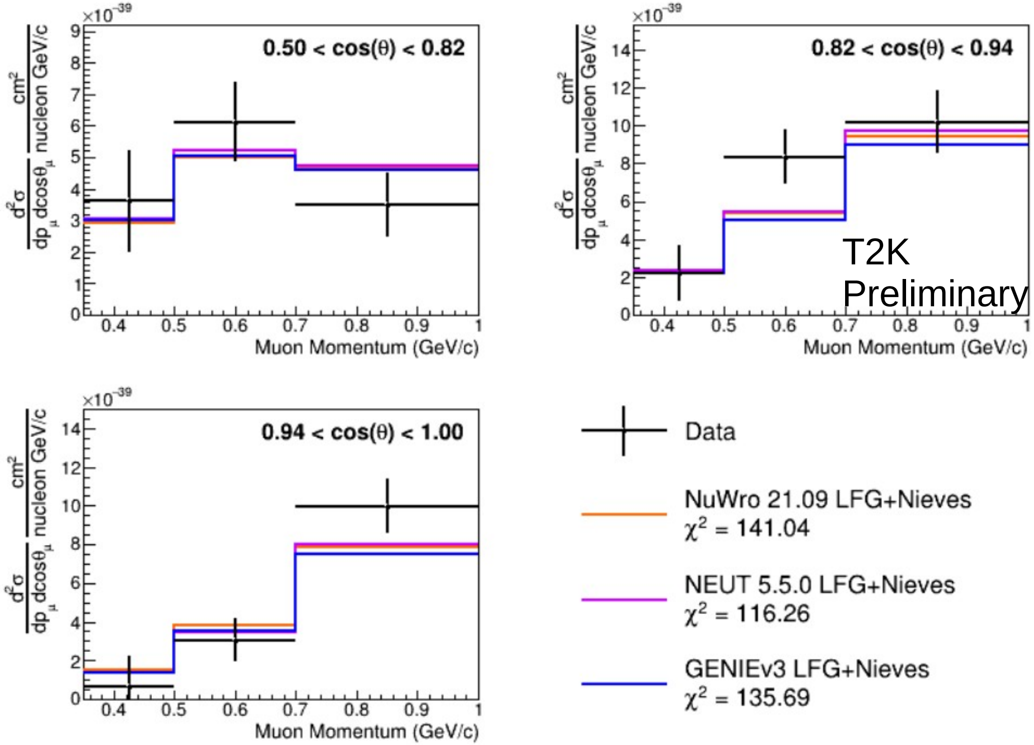




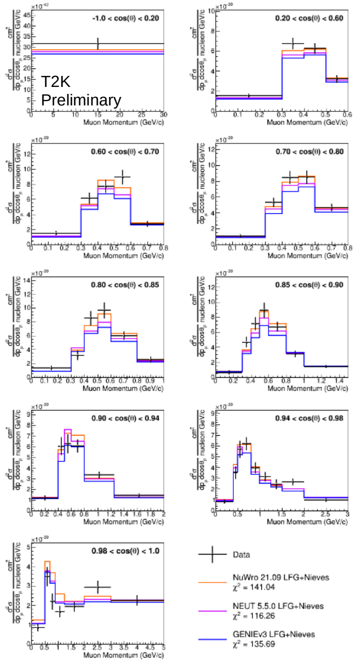
COMBINED ON-OFF-AXIS CHARGED CURRENT 0 PIONS



- INGRID on-axis
- ND280 off-axis
- No charged pions in final state
- Combined fit, fully correlated result for two fluxes
- Differential in muon kinematics
- 70 XSEC bins
  - 58 ND280
    12 INGRID
  - All models insufficient

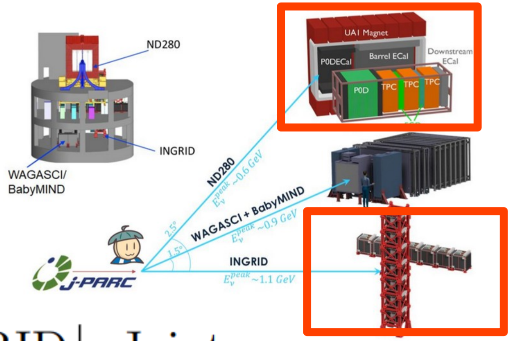


[arXiv:2303.14228]



Overflow not shown

COMBINED ON-OFF-AXIS CHARGED CURRENT 0 PIONS



- INGRID on-axis
- ND280 off-axis
- No charged pions in final state
- Combined fit, fully correlated result for two fluxes
- Differential in muon kinematics
- 70 XSEC bins
  - 58 ND280
    12 INGRID
  - All models insufficient

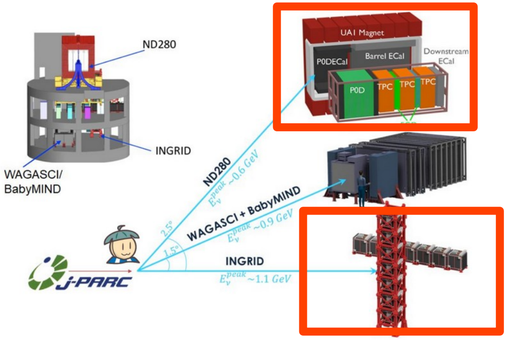
Model	ND280	INGRID	Joint
Nominal MC (NEUT)	136.34	18.21	158.71
NEUT LFG+Nieves	106.46	11.46	116.26
NEUT SF+Nieves $M_A = 1.03$	194.88	14.36	209.18
NEUT SF+Nieves $M_A = 1.21$	158.71	9.98	170.93
NuWro SF+Nieves	122.74	15.68	137.02
NuWro LFG+Nieves	125.88	12.75	141.04
NuWro LFG+SuSAv2	121.57	11.13	135.38
NuWro LFG+Martini	138.86	12.46	155.68
GENIE BRRFG+EmpMEC	141.40	12.80	156.05
GENIE LFG+Nieves	125.50	14.45	135.69

T2K Preliminary

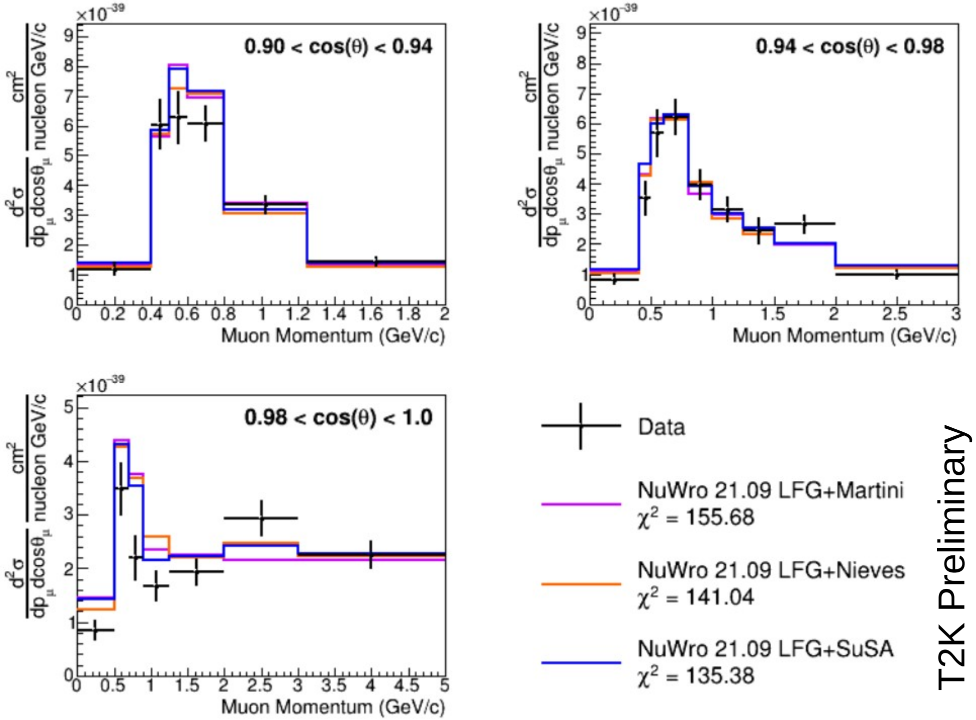
Squared Mahalanobis distances (χ^2)

[arXiv:2303.14228]

COMBINED ON-OFF-AXIS CHARGED CURRENT 0 PIONS



- INGRID on-axis
- ND280 off-axis
- No charged pions in final state
- Combined fit, fully correlated result for two fluxes
- Differential in muon kinematics
- 70 XSEC bins
  - 58 ND280
    12 INGRID
  - All models insufficient



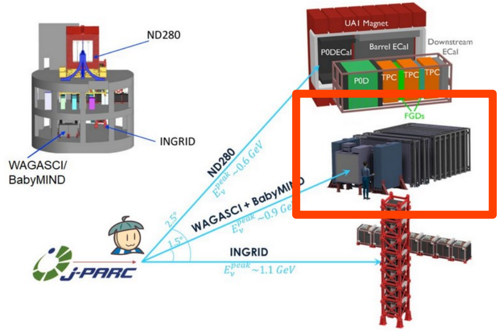
[arXiv:2303.14228]

Most tension in on-axis, forward-going, low- to medium-momentum region

Consistent with other results

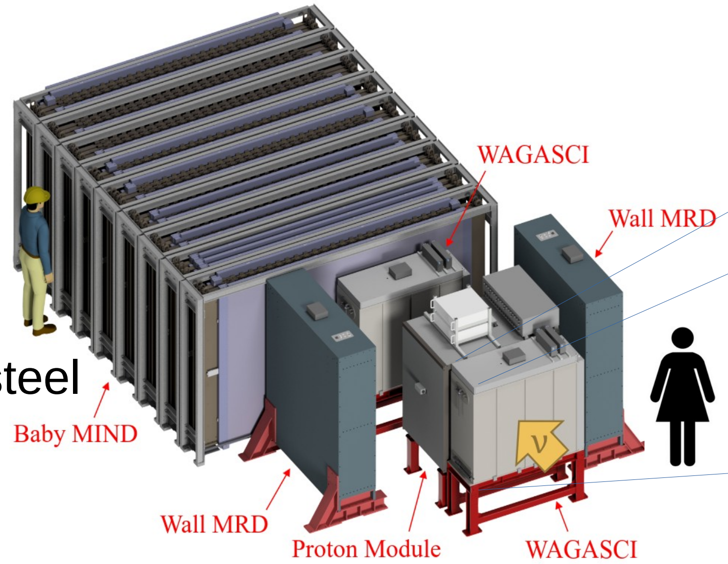
Coming soon

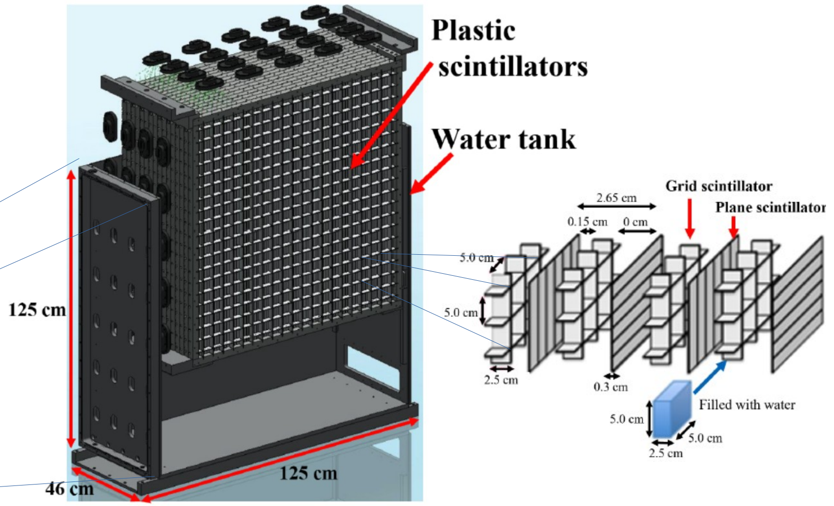
INTERMEDIATE ANGLE WAGASCI & BABYMIND



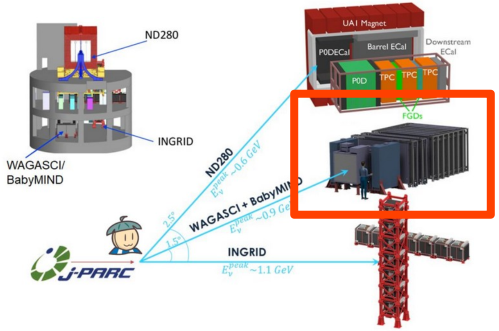
- CH and water target WAGASCI
- CH target Proton Module (from INGRID)
- Muon spectrometer BabyMIND
- Muon Range Detectors (MRD)

CH &
Magnetised steel



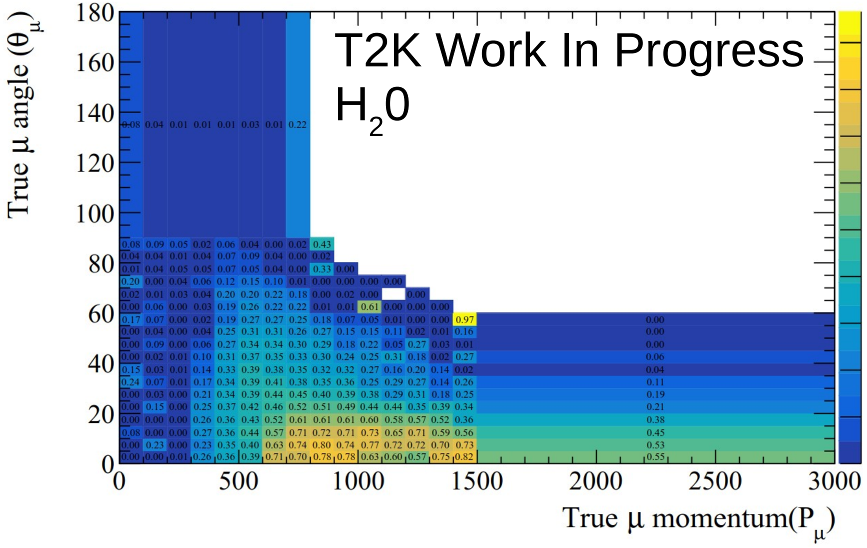


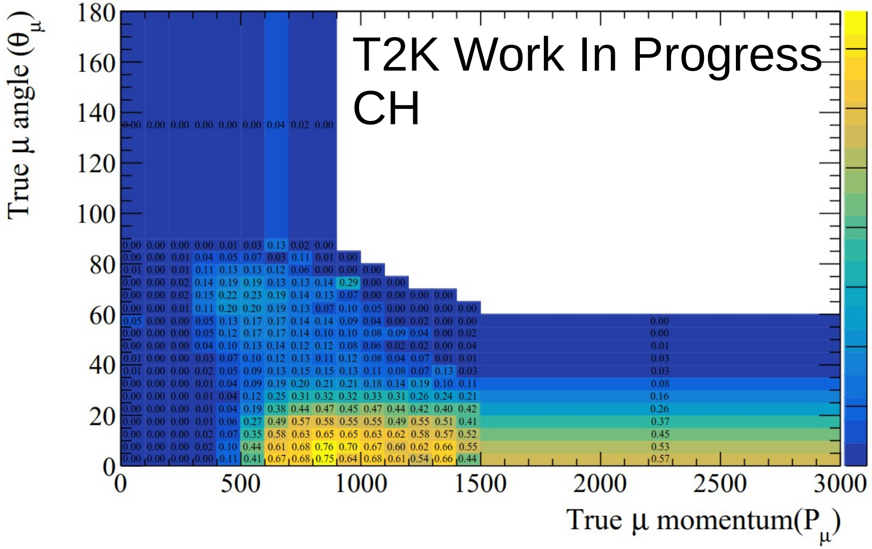
INTERMEDIATE ANGLE CHARGED CURRENT 0 PIONS



- No charged pions in final state
- Complex detector geometry
- Complex acceptance
- Overall efficiency of ~20% and purity of 50% – 60% (depending on sample)

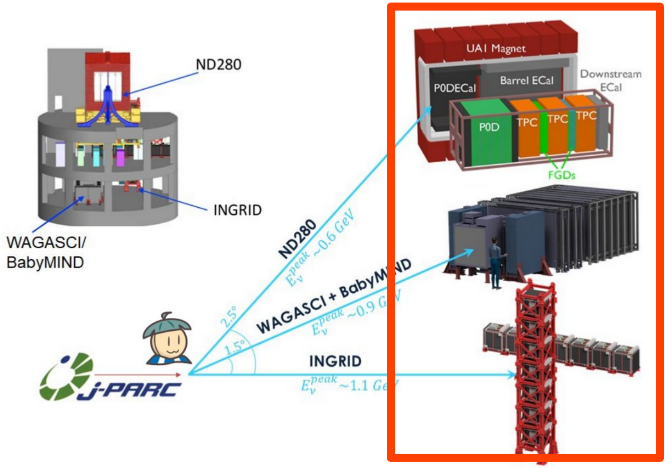
$$\nu_\mu + A \rightarrow \mu^- + 0\pi^\pm + X$$

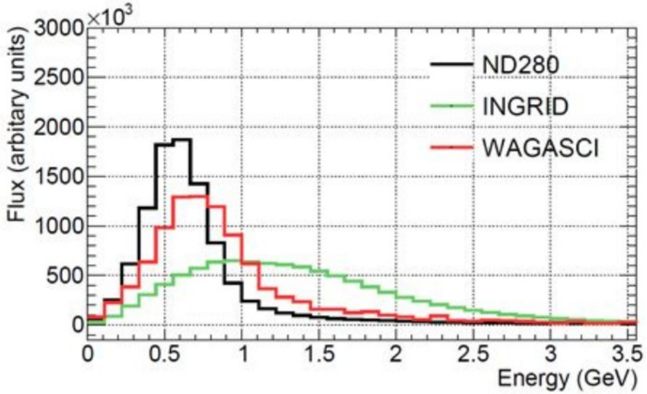




FUTURE: COMBINE ALL DETECTORS

- Work ongoing to harmonize analyses of different detectors
  - Currently all use separate softwares
  - Minimise friction of combined analyses
- Aim: combine data of all angles, targets, interaction topologies
  - Maximise use of data
  - Disentangle flux & cross sections
  - Test & develop models

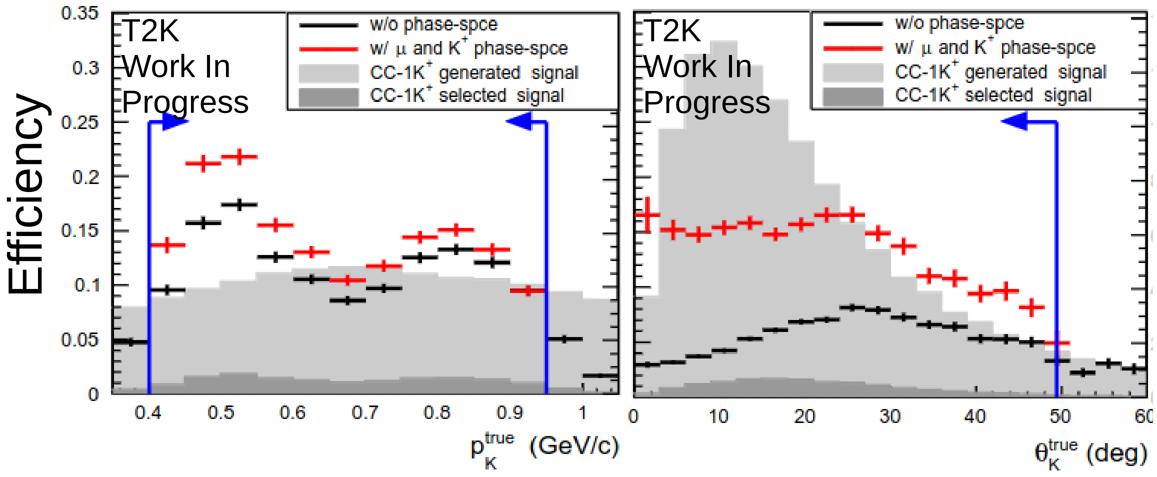


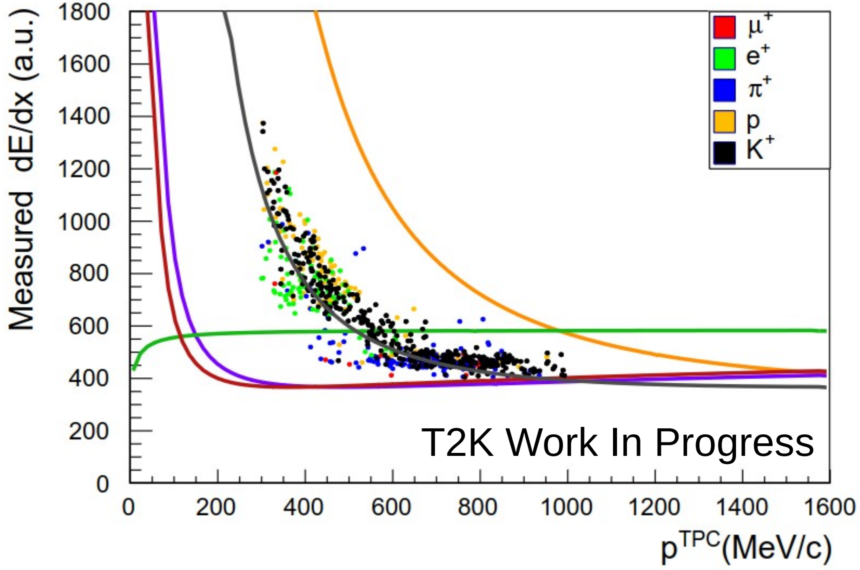


KAONS @ ND280

- Kaons are important for proton decay searches at SK and HK
- First Kaon production measurement at T2K
- Efficiency ~15%, Purity ~45%

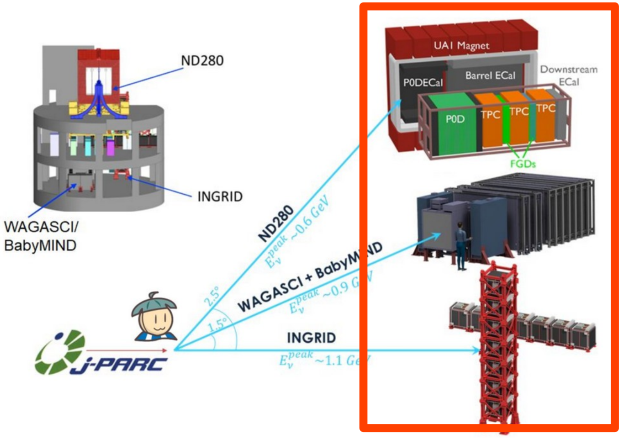
$$\nu_\mu + n \to \mu^- + K^+ + \Lambda^0,$$
$$\nu_\mu + n \to \mu^- + K^+ + K^- + p,$$
$$\nu_\mu + p \to \mu^- + K^+ + \bar{K}^0 + p,$$
$$\nu_\mu + p \to \nu_\mu + K^+ + \Lambda^0.$$
$$\nu_\mu + p \to \mu^- + K^+ + p,$$
$$\nu_\mu + n \to \mu^- + K^+ + n.$$

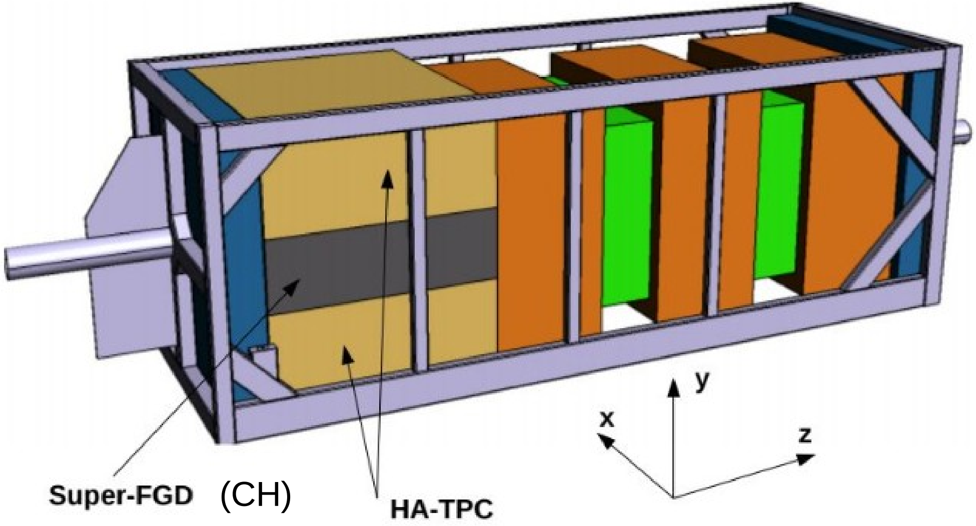




OUTLOOK

- Better integration of all detectors
  - Harmonized software
  - More combined measurements
  - Correlate all the things!
- Many measurements in the pipeline
  - ν_μCC1K^+ on CH @ ND280
  - CC0π on water and CH @ Wagasci
  - NC1$\pi^{0/+}$ on CH/$H_2$0 @ ND280
  - (anti-)ν_μCC1$\pi^{+(-)}$ on CH/$H_2$0 @ ND280
  - ...
- Detector upgrade happening as we speak
  - Better coverage of high angles
  - Neutron kinematics
  - [See] [these] [previous] [talks]





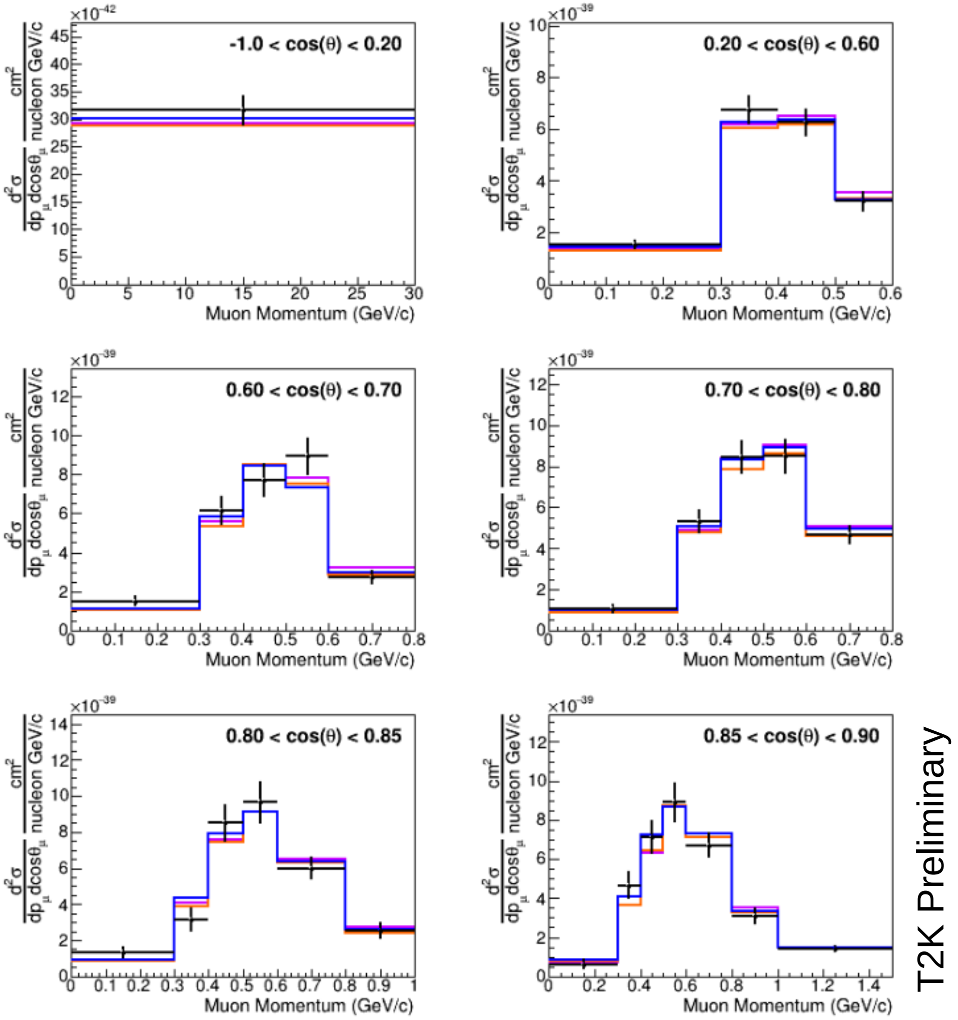
Thank you!

CC COH DETAILS

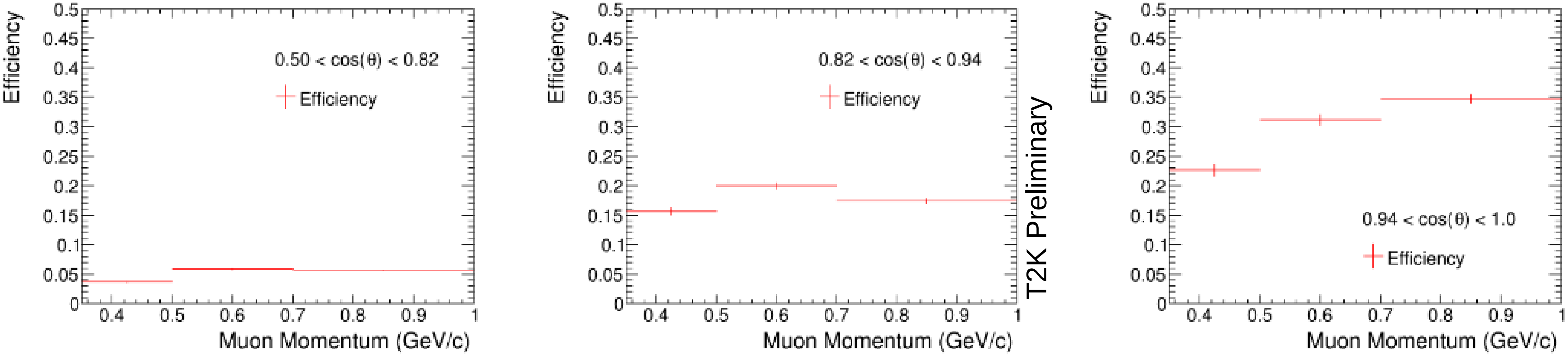
- ν: 1.1e21 POT
- Anti ν: 8.2e20 POT
- Signal
  - P_mu > 200 MeV/c
  - P_pi > 200 MeV/c
  - cos(theta_mu) > 0.8
  - cos(theta_pi) > 0.6
- Efficiency: 47% (30%)
- Purity: 42%

CC 0PI DETAILS

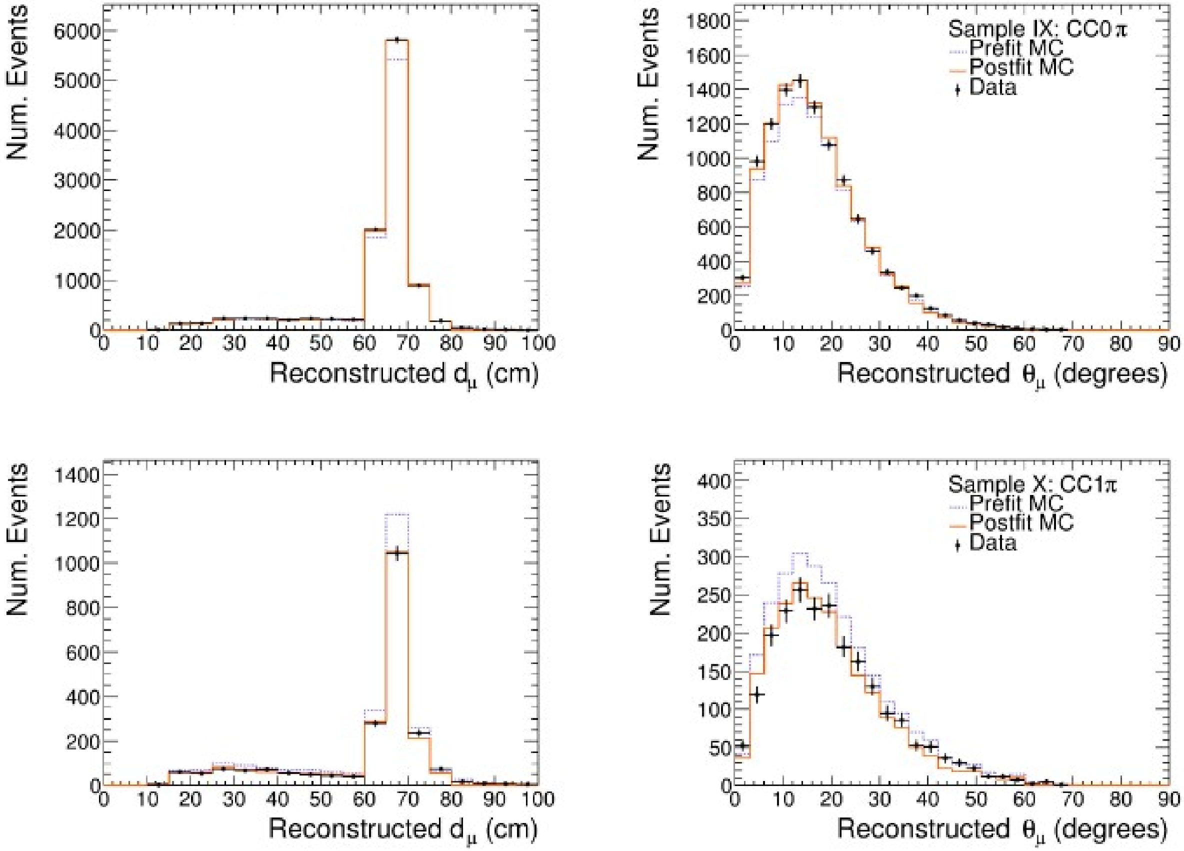
- ND280
  - 11.5e20 POT
  - Pur: 63% - 87%
  - Eff: 10% - 75%
- INGRID
  - 6.0e20 POT
  - Pur: 63%
  - Eff: 5% - 35%



CC 0PI INGRID EFFICIENCY

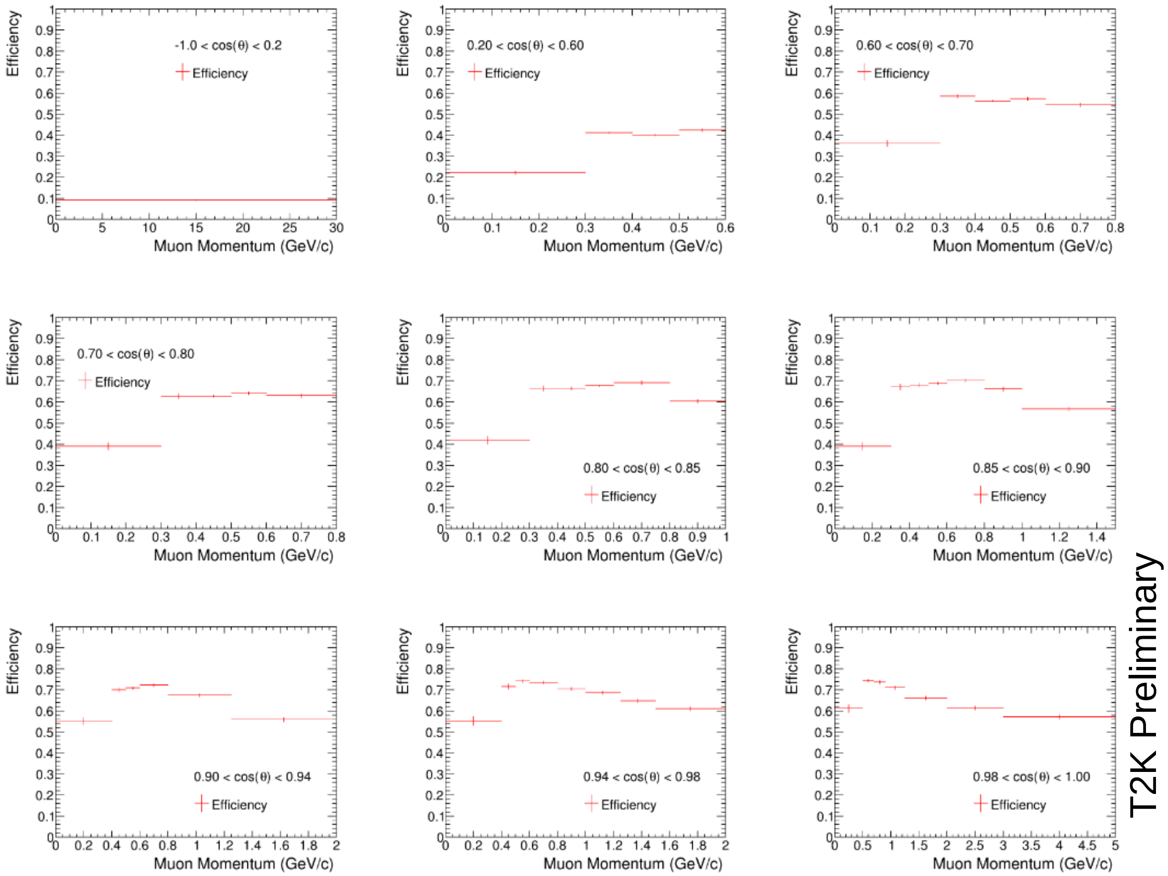


CC 0PI INGRID EVENT DISTRIBUTIONS

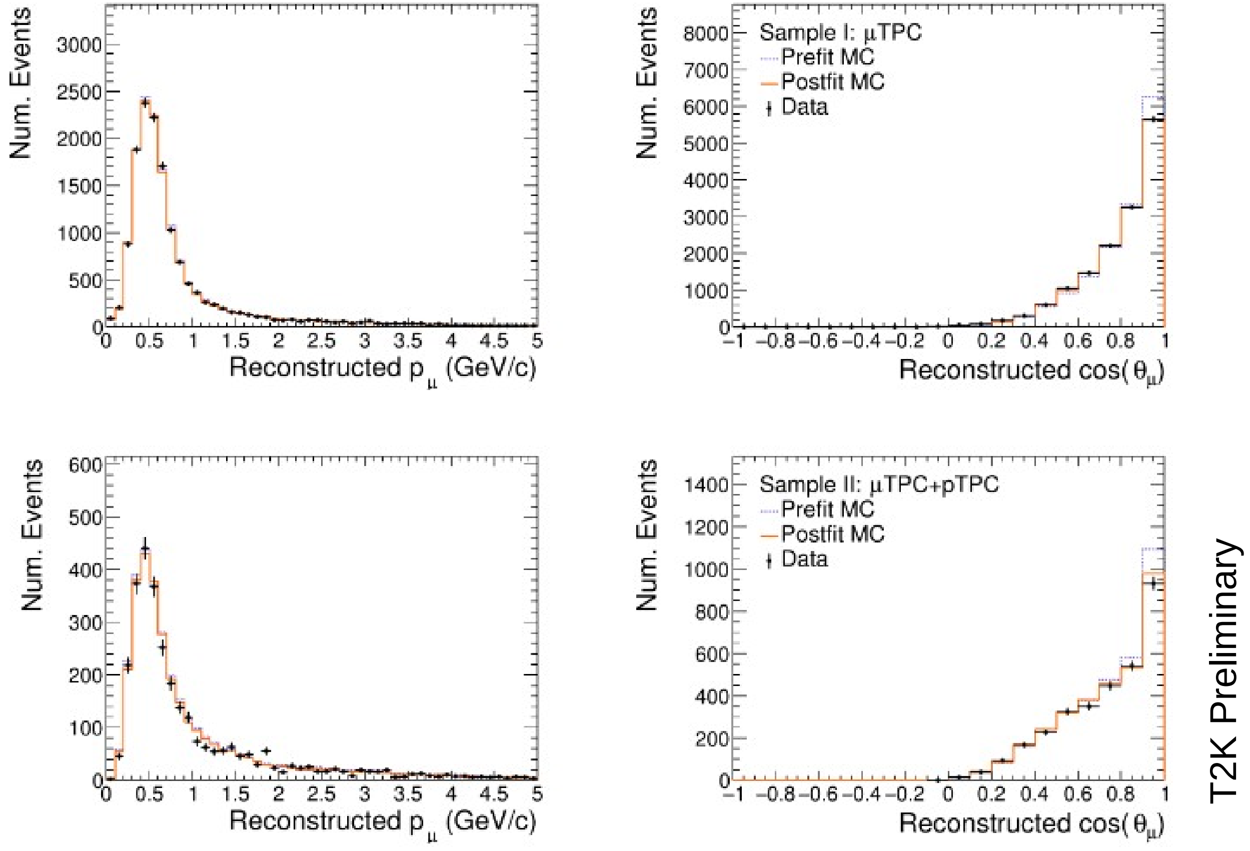


T2K Preliminary

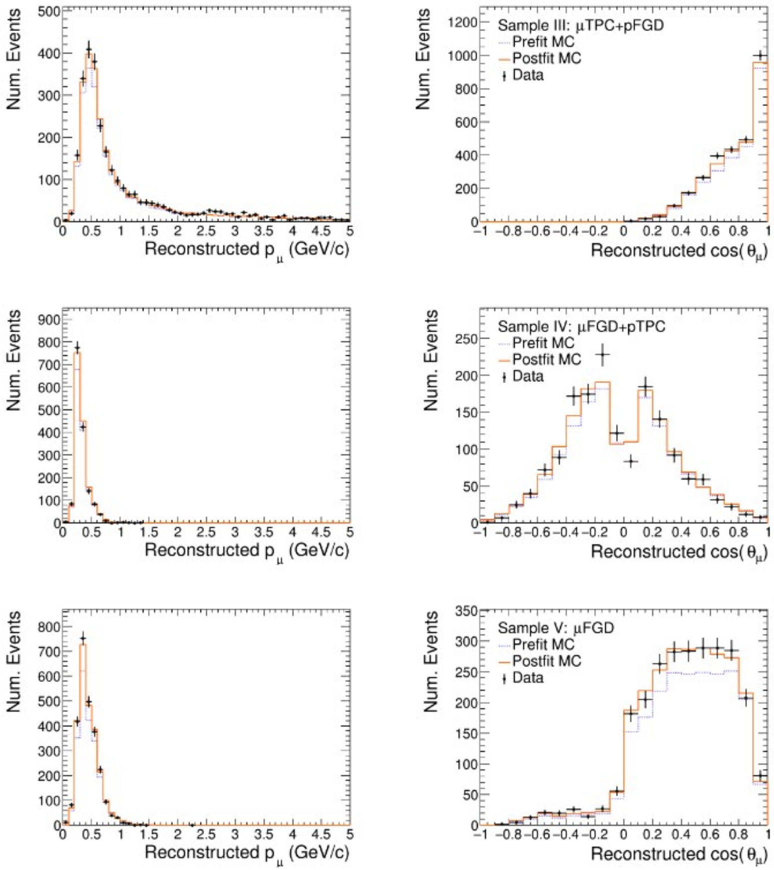
CC 0PI ND280 EFFICIENCY



CC 0PI ND280 EVENT DISTRIBUTIONS

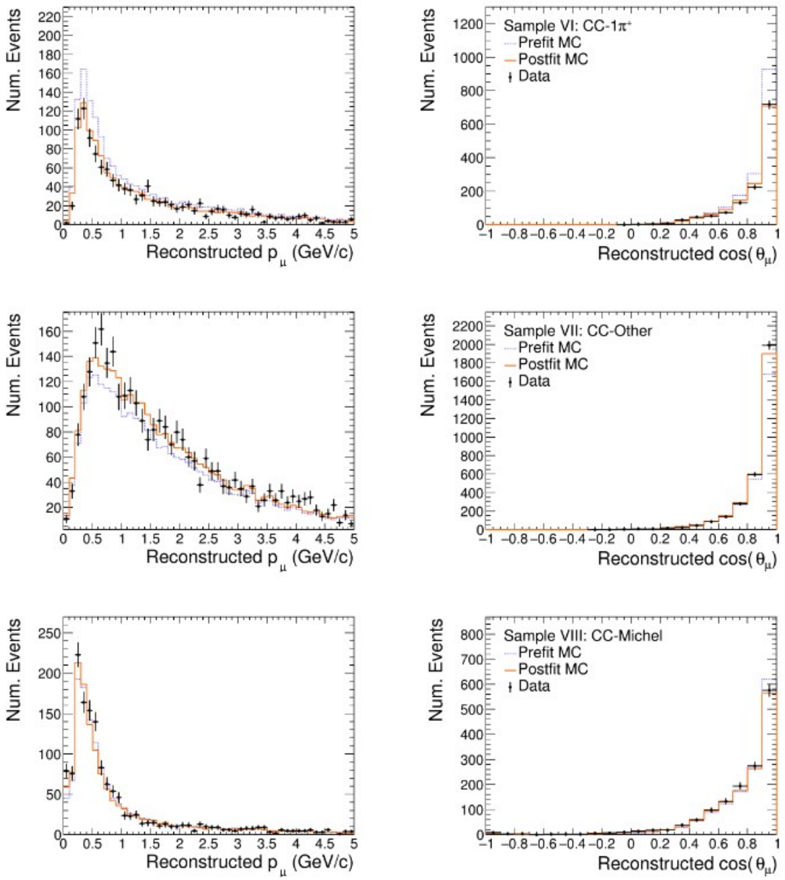


CC 0PI ND280 EVENT DISTRIBUTIONS



T2K Preliminary

CC 0PI ND280 EVENT DISTRIBUTIONS



T2K Preliminary

KAON DETAILS

- Kaon possible decay channel of proton $p \rightarrow K^+\bar{\nu}$
- Atmospheric neutrino backgrounds
  - NC $\nu_\mu p \rightarrow \nu_\mu K^+ \Lambda^0$
  - CC $\nu_\mu N \rightarrow \mu^- K^+ N$