Neutrino-Nucleus Interaction Cross-Section Measurements at T2K

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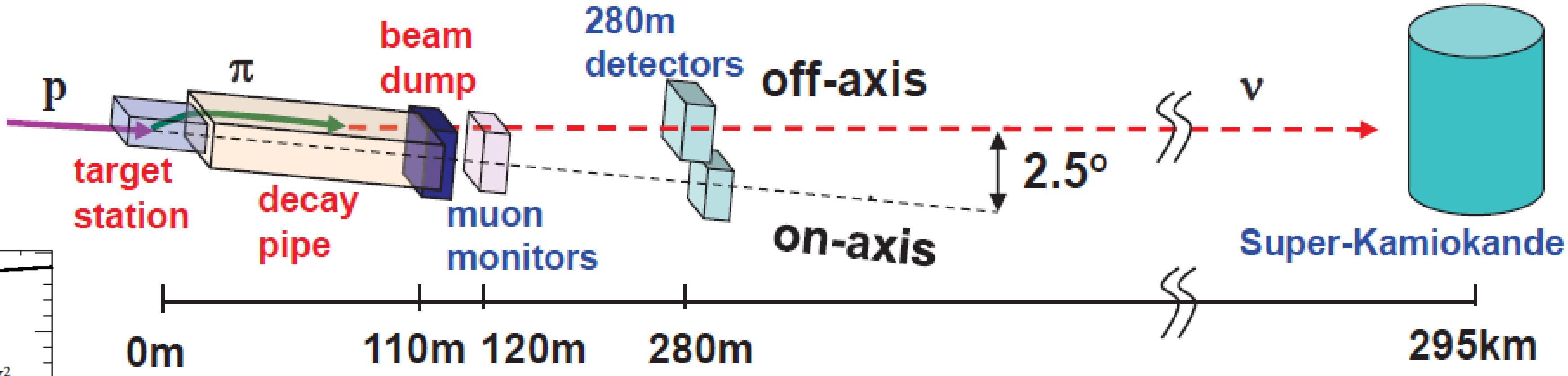
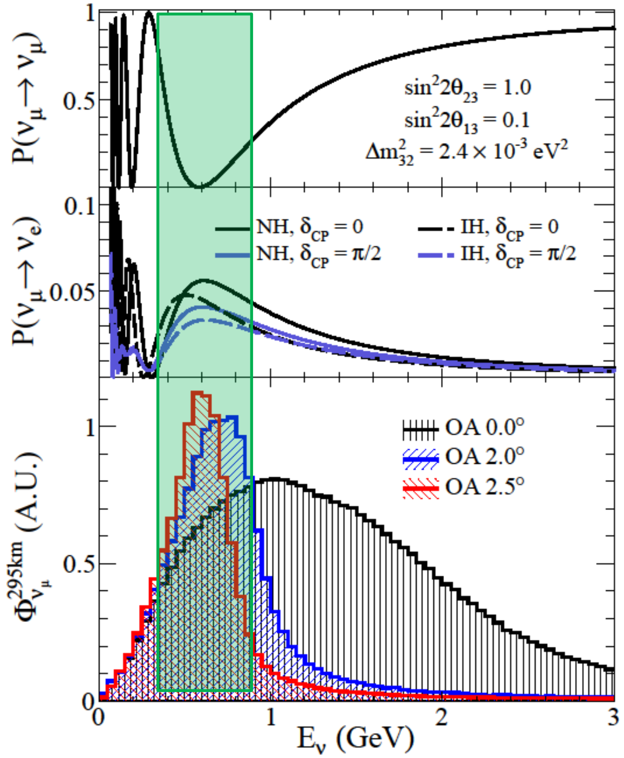
Overview

- Brief introduction to T2K experiment and the near detectors
- Highlights from recent cross-section measurements at the T2K near detectors: variety of measurements on different targets, fluxes, detectors, neutrino and anti-neutrino flavours – **test T2K cross-section model and uncertainties on multiple neutrino spectra**
  - CC-ν_e and CC-$\bar{\nu}_e$ inclusive on plastic (2.5° off-axis detectors)
  - NC single gamma production (2.5° off-axis detectors)
  - CC-ν_μ 0π on plastic and water (2.5° off-axis detectors)
  - CC-ν_μ charged-current inclusive on plastic, water and iron (On-axis detectors)
  - CC-$\bar{\nu}_\mu$ 0π 0proton on plastic and water (1.5° off-axis detectors)
- Summary

T2K long-baseline neutrino oscillation experiment in Japan

See Laura Kormos talk from Friday morning





- Off-axis narrow band ν_μ beam to far and near detectors
  - Enhanced signal at oscillation maximum
  - Reduce high-energy tail background

  - Measurements of the ν_e appearance and ν_μ disappearance
  - Currently searching for CP-violation in the neutrino sector

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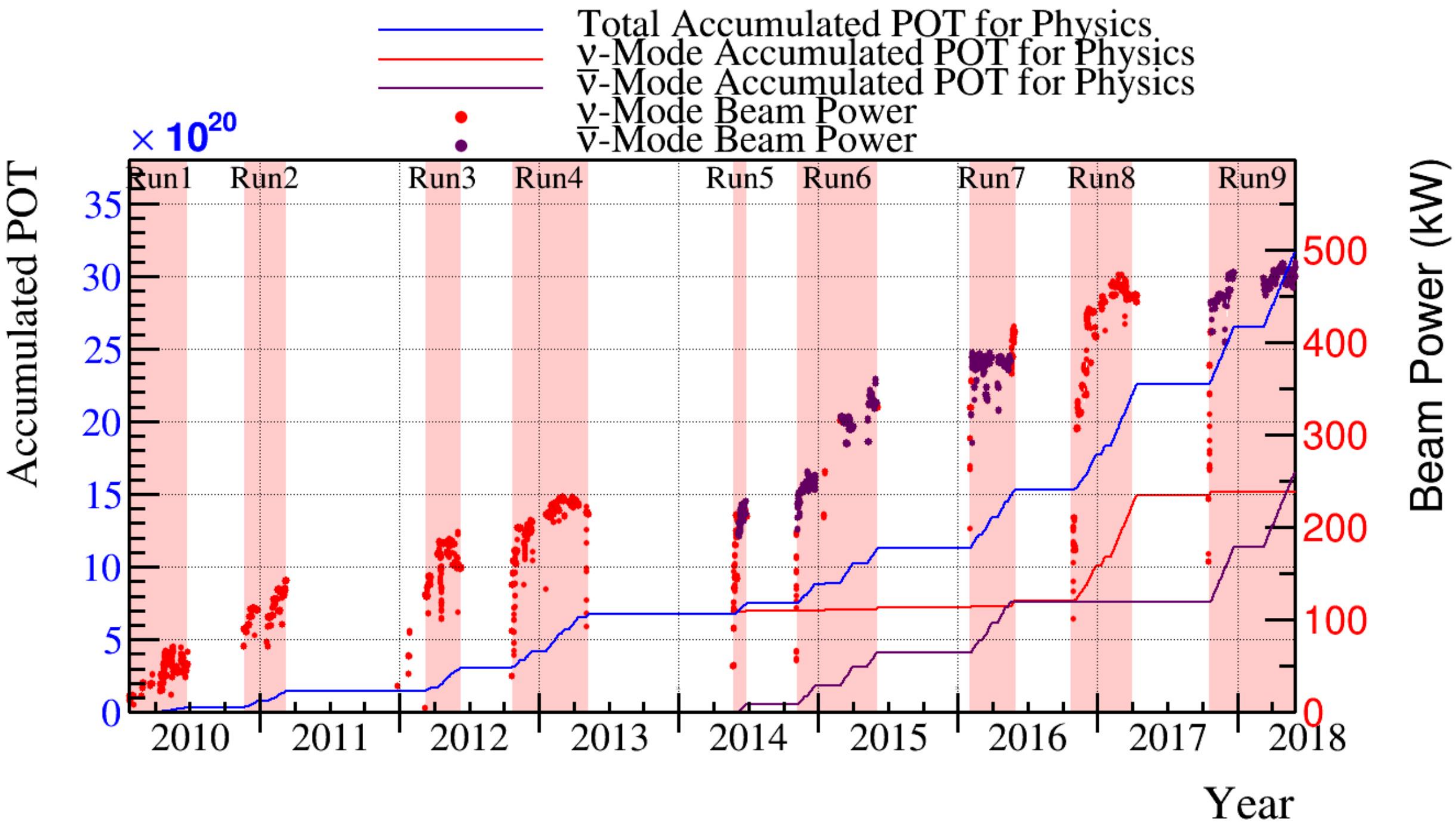
T2K accumulated protons-on-target (POT)



23 Jan. 2010 – 31 May 2018

POT total: 3.16×10^{21}

$\boldsymbol{\nu}$-mode 1.51×10^{21} (47.83%)

$\bar{\nu}$-mode 1.65×10^{21} (52.17%)

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Importance of neutrino cross-sections to neutrino oscillations

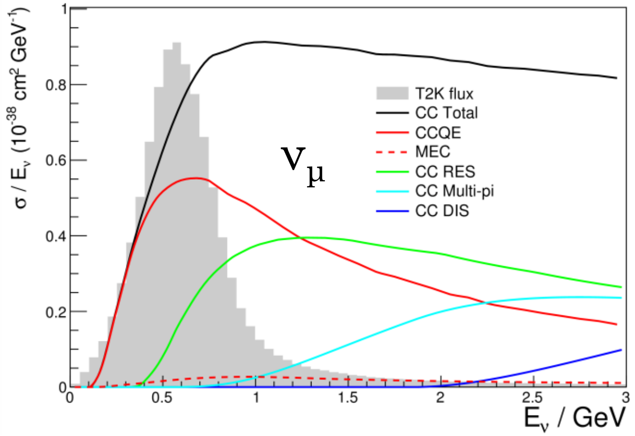
- Good neutrino interaction model is essential to reduce neutrino oscillation systematic uncertainties
  - Need a variety of measurements on different targets and for all neutrino and anti-neutrino flavours
- Differences between near – far detectors
  - Target, acceptance, flux

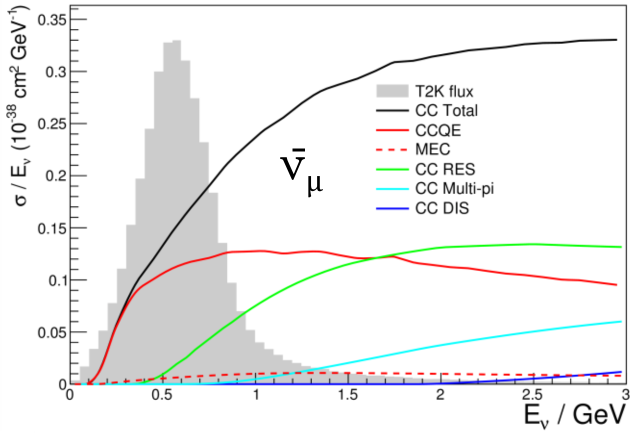
Phys. Rev. Lett. 121, 171802, 2018

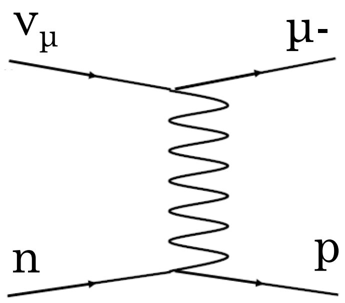
TABLE I. Systematic uncertainty on far detector event yields.

Source [%]	ν_μ	ν_e	$\nu_e\pi^+$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	2.4	7.8	4.1	1.7	4.8
Flux & ND280-constrained cross sec.	3.3	3.2	4.1	2.7	2.9
SK detector systematics	2.4	2.9	13.3	2.0	3.8
Hadronic re-interactions	2.2	3.0	11.5	2.0	2.3
Total	5.1	8.8	18.4	4.3	7.1

11 – 14 % before near detector constraints





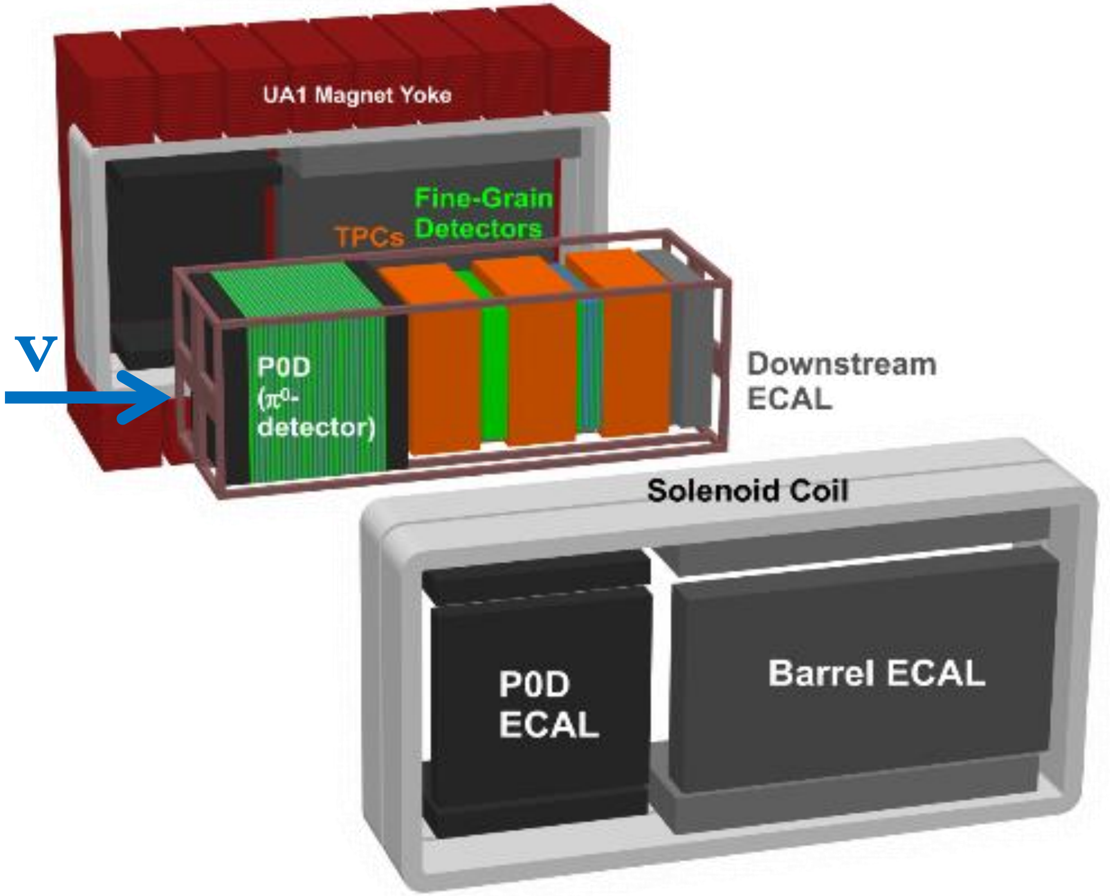


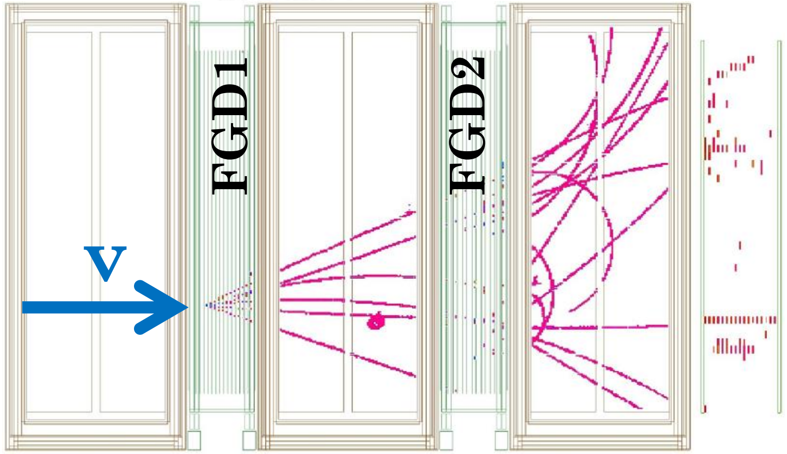
Neutrino charged-current quasi elastic (CCQE) – T2K far detector golden channel

Neutrino cross-section measurements at the T2K near detectors at **2.5° off-axis**

Near detector at 2.5° off-axis (ND280)

- 2.5° off-axis to measure neutrino interactions and estimate the background contamination
- Refurbished UA1 magnet - 0.2T field
- Front optimized to measure π^0 interactions (P0D) on water/plastic
- Rear optimized to measure charged-current interactions
  - 2 Fine-Grained Detectors (FGD)
    - First is plastic (FGD1), the other is plastic + water (FGD2)
  - 3 Time Projection Chambers (TPC) following the P0D and the FGDs
    - Tracking, dE/dx
- Surrounded by the electromagnetic calorimeter and muon detector





Nucl. Instrum. Meth. A 659, 106 (2011)

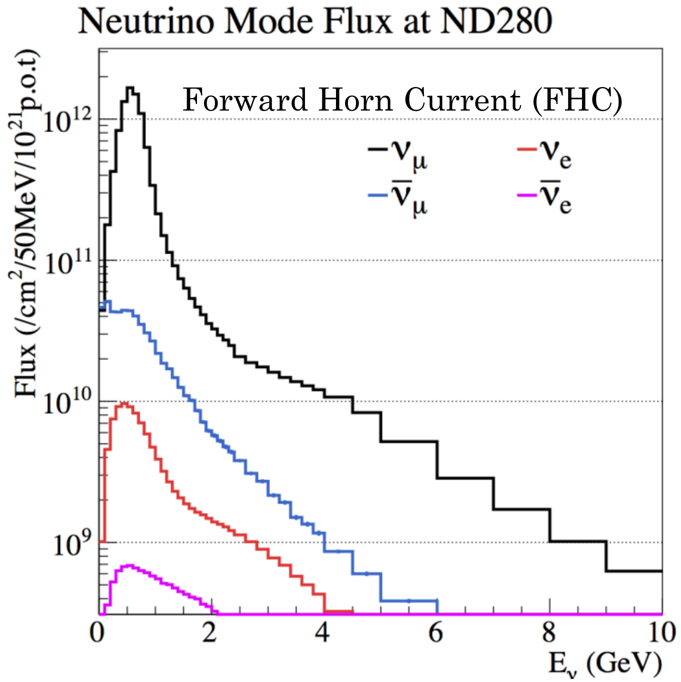
Electron (anti-)neutrinos at ND280

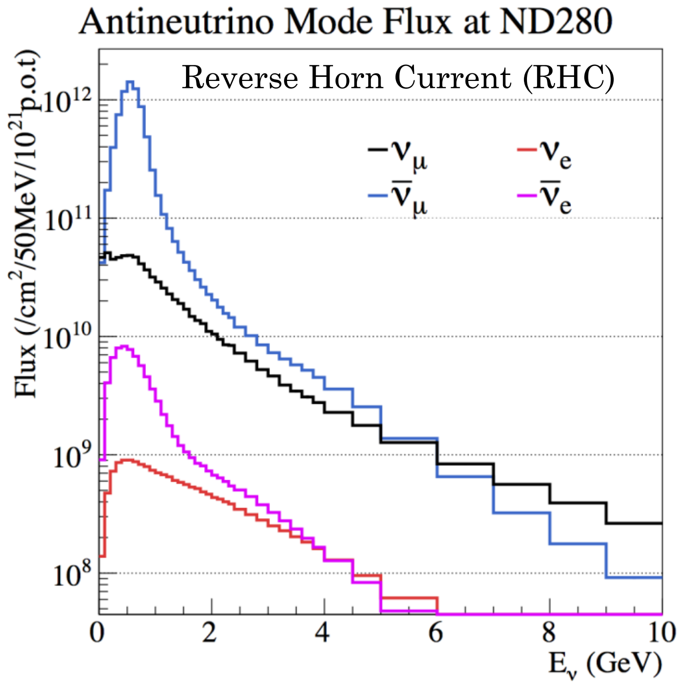
- First T2K CC-ν_e cross-section measurement on plastic published in 2014 (Phys. Rev. Lett. 113, 241803, 2014)

- New measurement with twice the neutrino mode statistics and including the anti-neutrino mode data until 2017
  - First CC-$\bar{\nu}_e$ measurement after Gargamelle in 1978

- Challenging analysis
  - ν_e is only ~1.5% of the neutrino beam
  - Perfect particle identification to select electrons and remove muons, pions and protons
  - Large (π^0) backgrounds from charged-current and neutral-current ν_μ interactions in and outside the FGDs
  - CC-$\bar{\nu}_e$ selection in neutrino mode is currently not used due to tiny statistics and low purity

- CC-ν_e/CC-$\bar{\nu}_e$ is the only irreducible background at the far detector neutrino analyses for ν_e ($\bar{\nu}_e$) appearance





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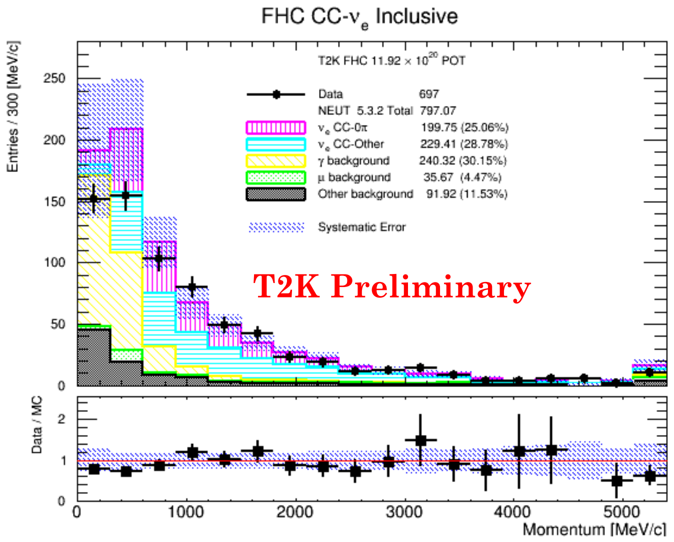
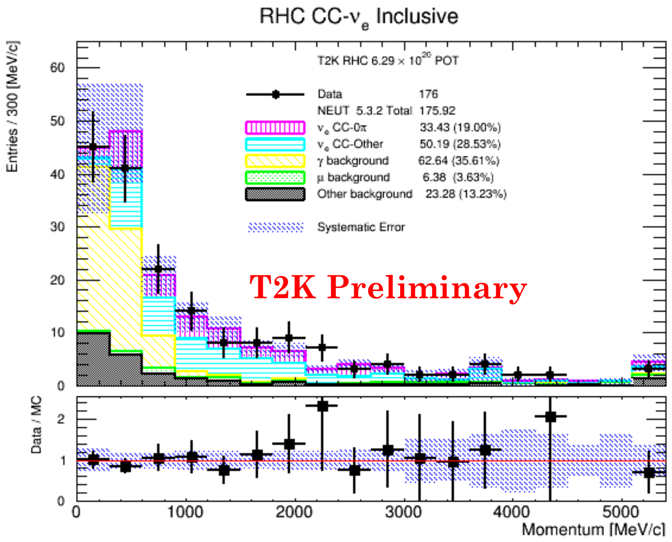
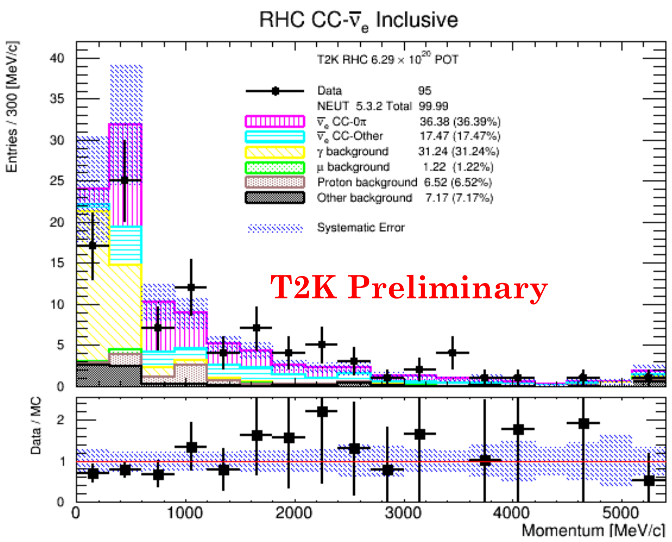
CC-ν_e and CC-$\bar{\nu}_e$ inclusive selections in FGD1

- Low momentum region is dominant by the gamma background
  - Data – MC discrepancy but large systematic uncertainties
  - ~1/3 of the gamma background is coming from external photons

- Gamma background in each selection is controlled by an independent control sample selecting e-e+ pairs







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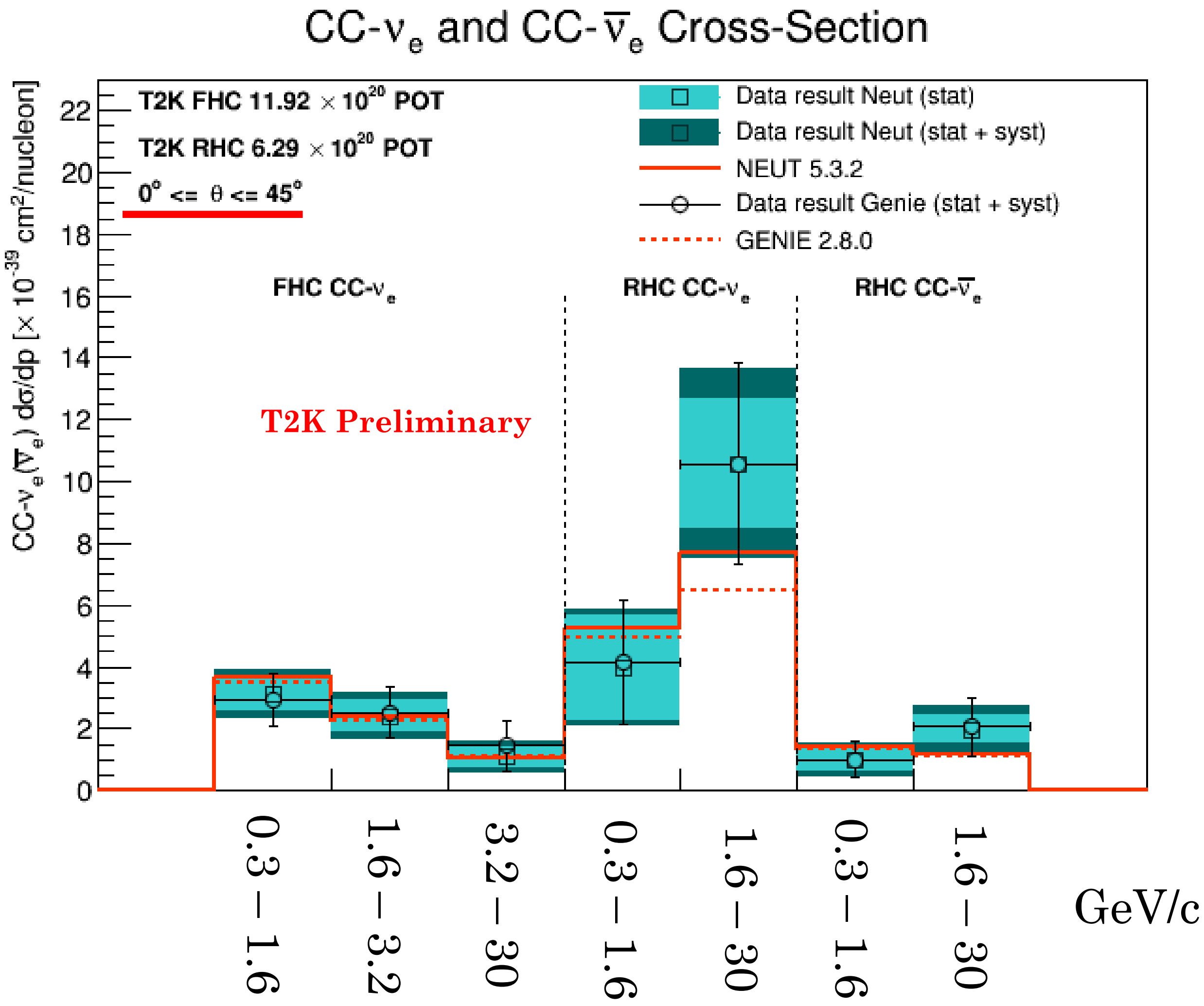
CC-ν_e and CC-$\bar{\nu}_e$ inclusive cross-sections on plastic

- CC-ν_e and CC-$\bar{\nu}_e$ selections and their corresponding gamma control samples are fitted simultaneously
- Limited phase-space ($\theta < 45^\circ$ and p > 300 MeV/c) due to detector acceptance effects
- Cross-section results agree within errors with the Neut and Genie neutrino generator models



See also poster 761

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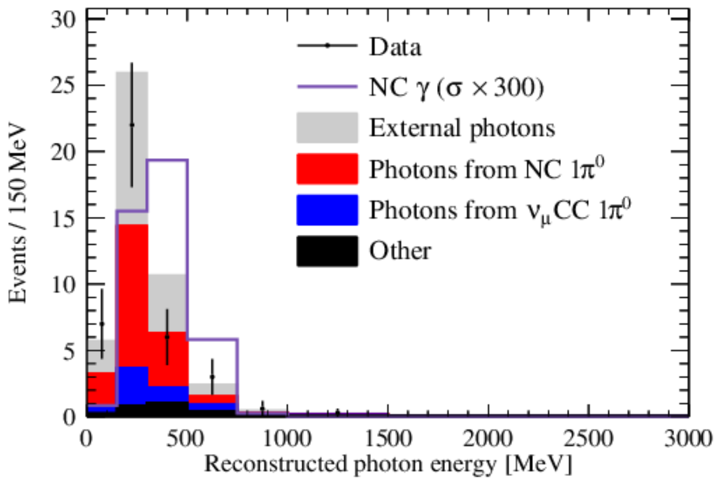
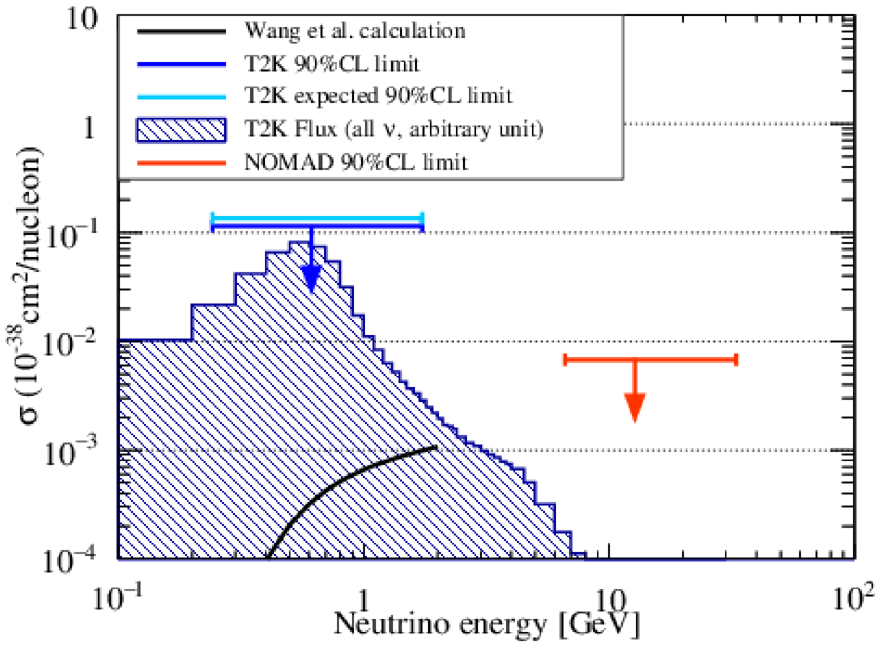
NC single photon production

- Select FGD1 – TPC e-e+ pairs with low invariant mass
- Background dominant from NC $1\pi^0$ and external photons



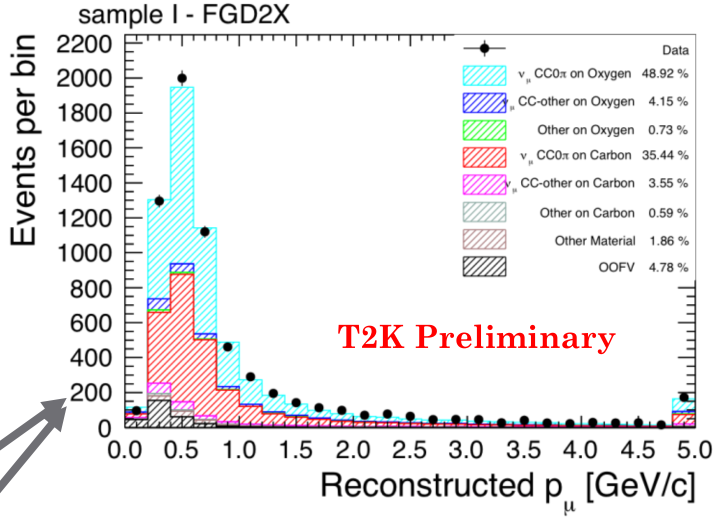


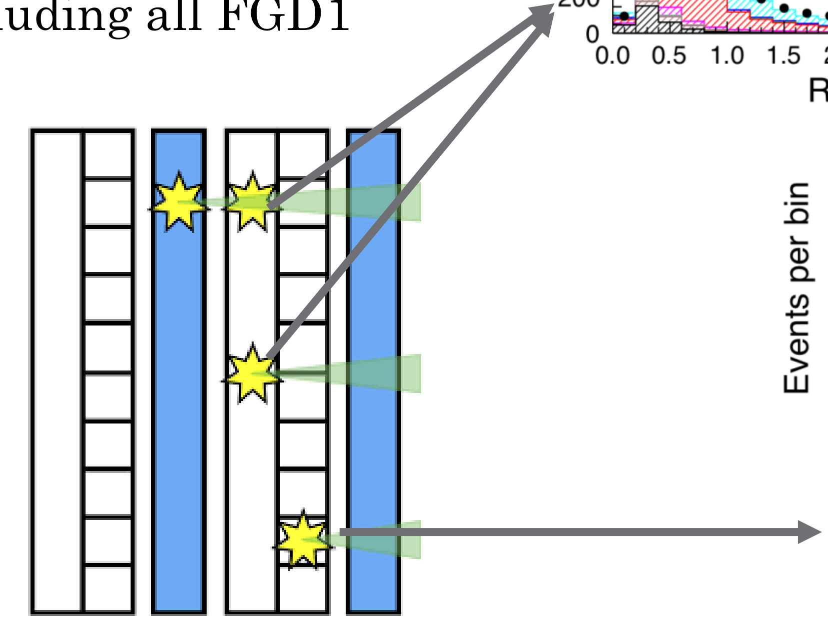
J. Phys. G 46, 08LT01 (2019)

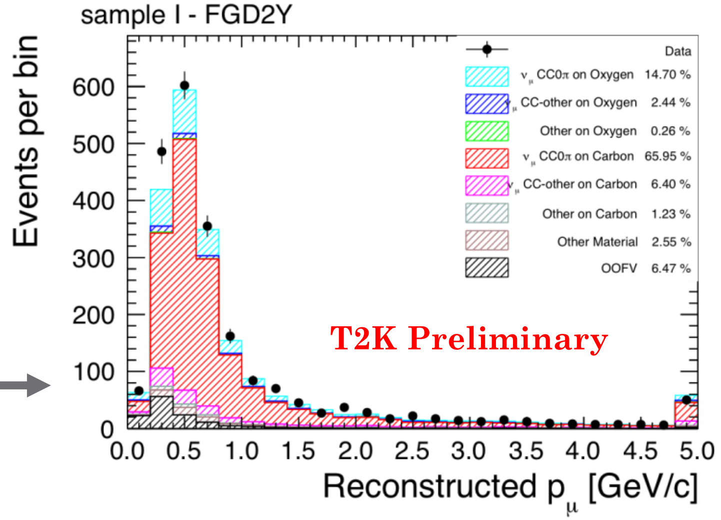
Important background process for the far detector electron-neutrino appearance searches

ν_μ CC-0π cross-section measurement on plastic and water

- Combined FGD1 + FGD2 analysis
- For FGD2 split events in two samples based on the interaction vertex to get a water enriched sample
- Extract the cross-sections using a simultaneous fit including all FGD1 and FGD2 samples

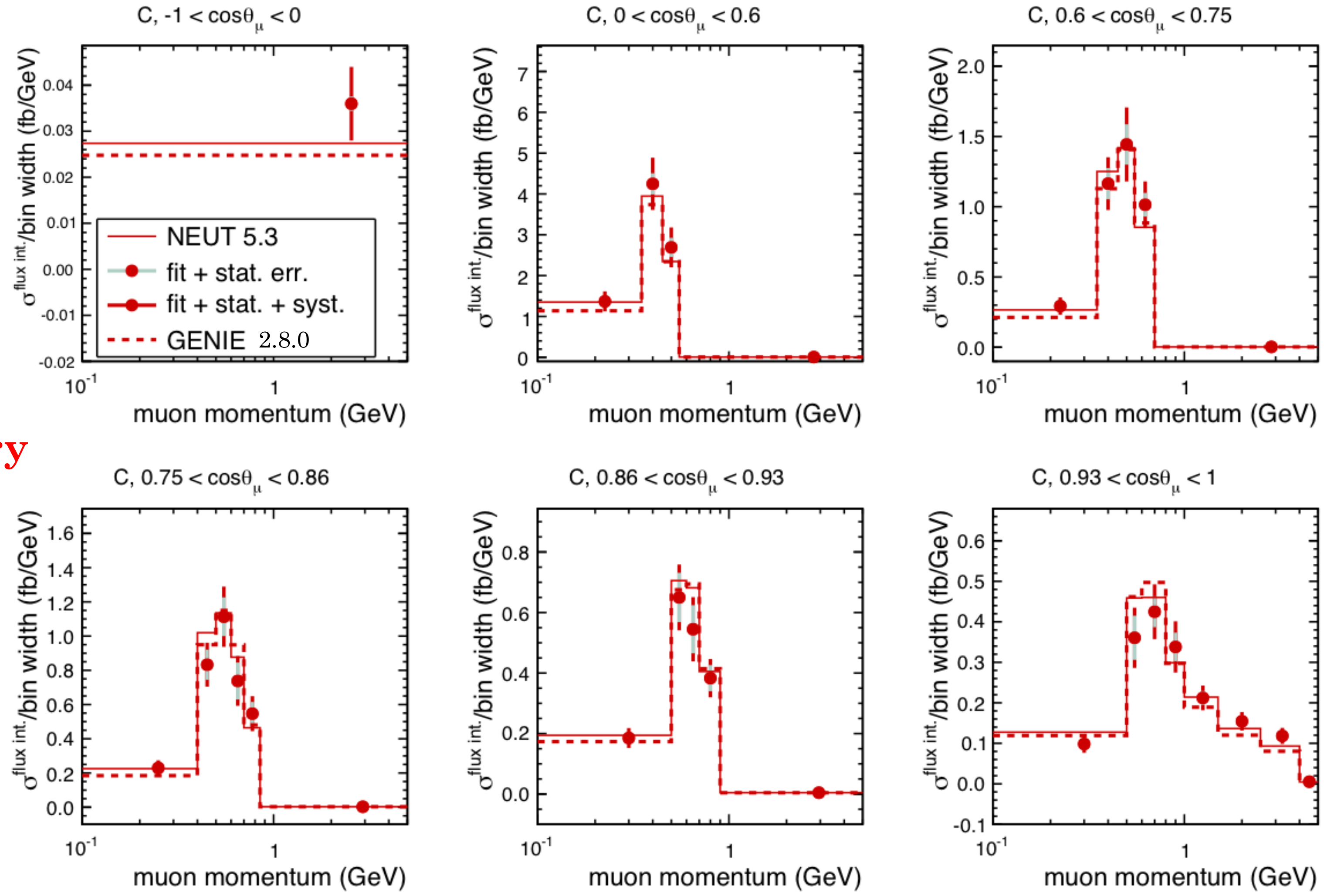






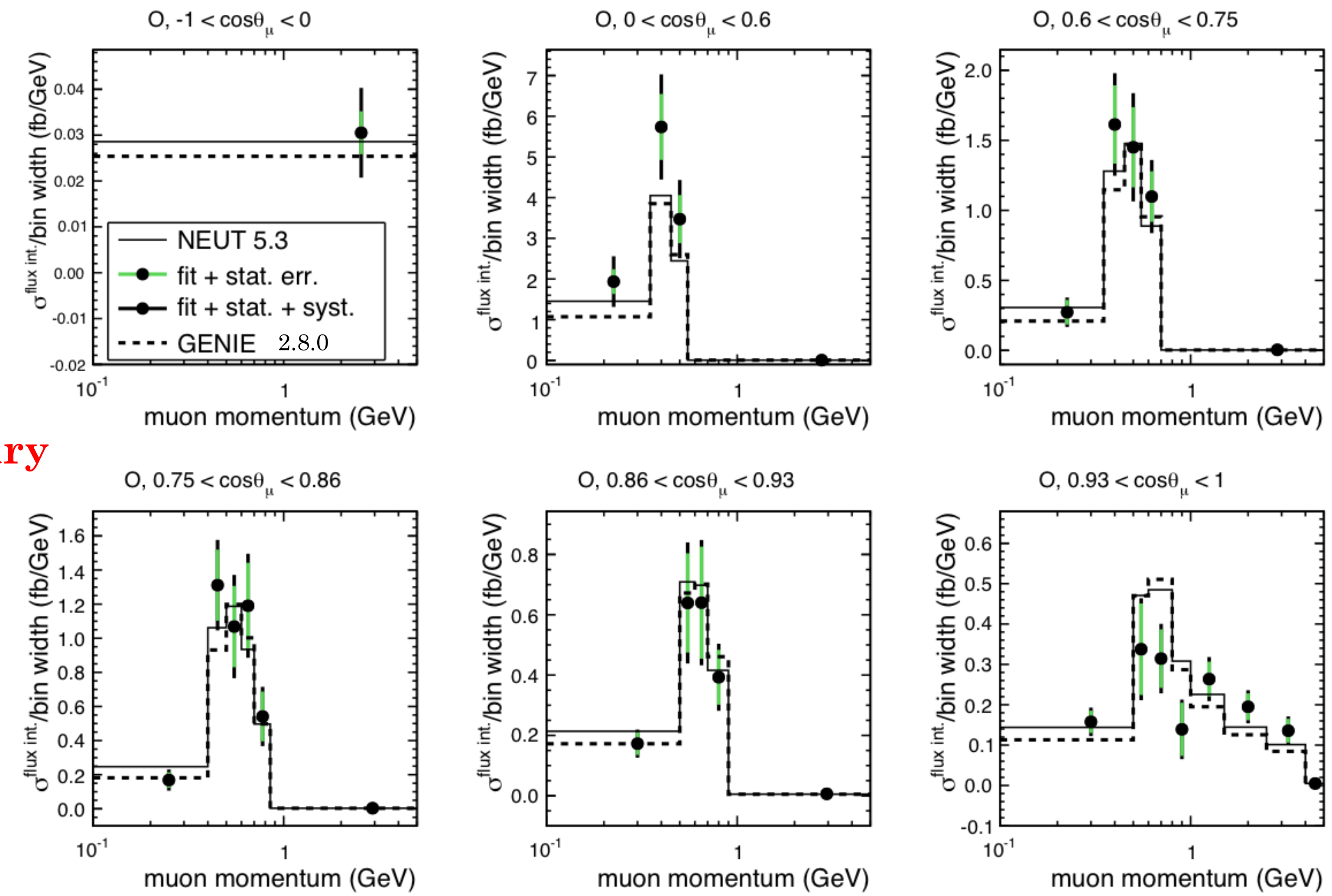
ν_μ CC-0π cross-section results on plastic

T2K Preliminary



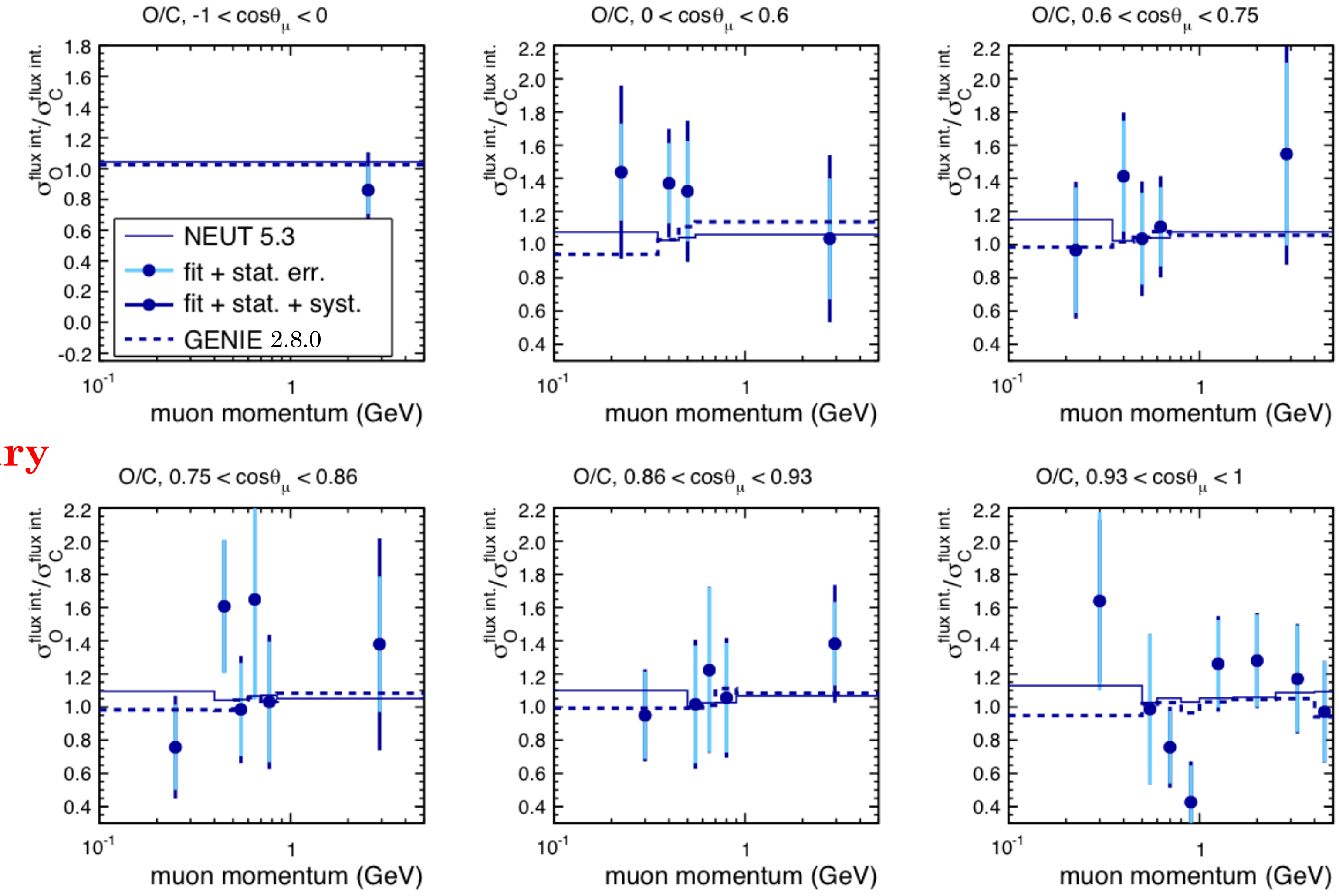
ν_μ CC-0π results cross-section results on water

T2K Preliminary



CC-ν_μ 0π water/plastic ratio

T2K Preliminary



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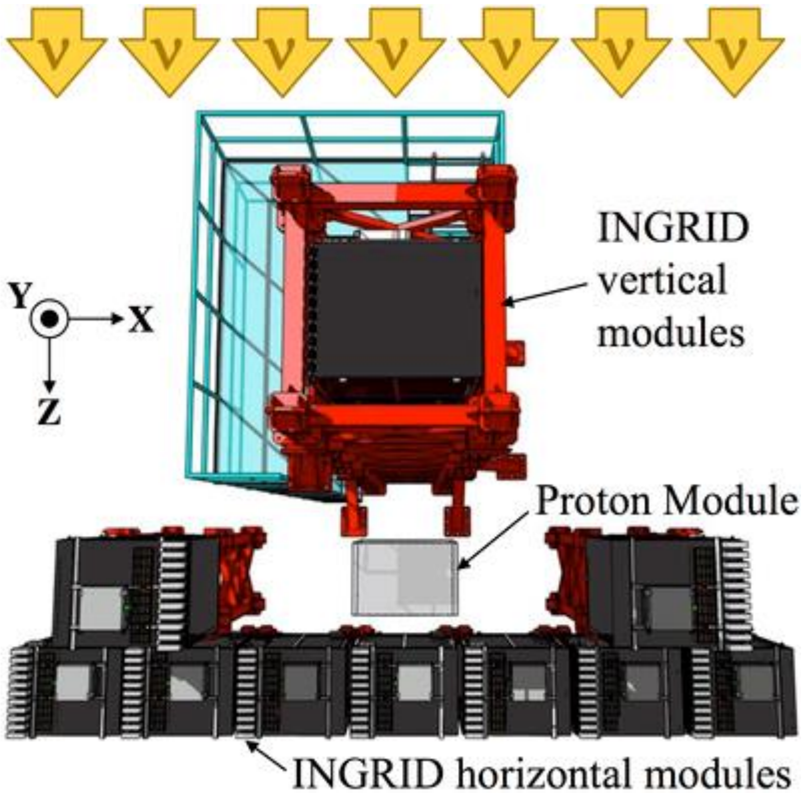
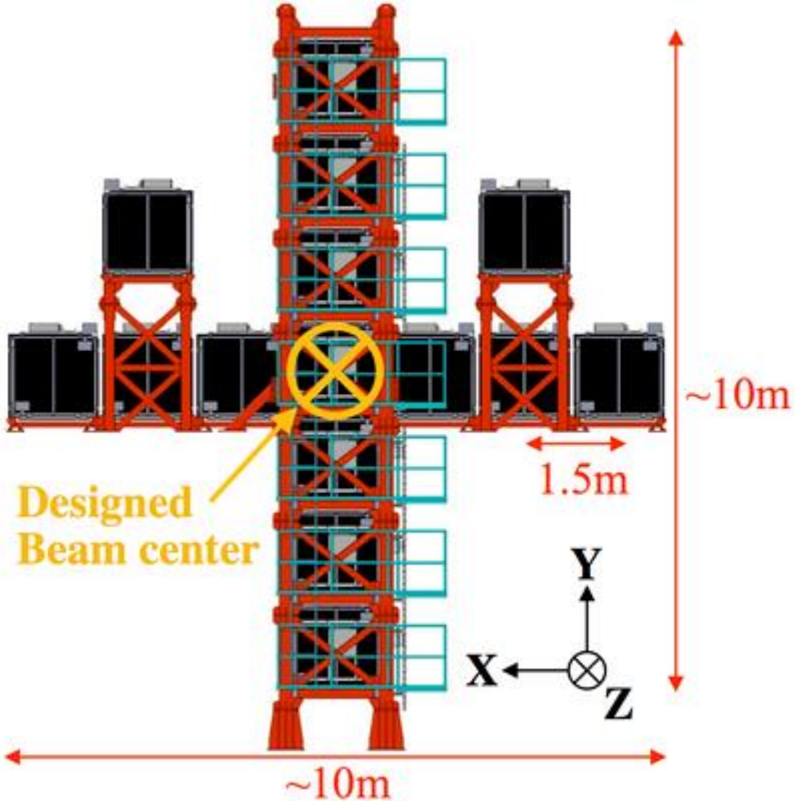
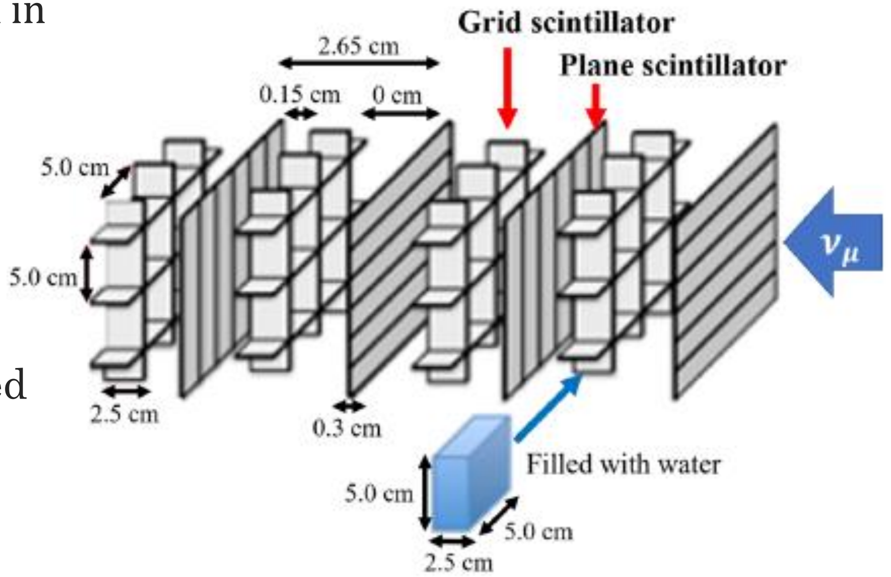
Neutrino cross-section measurements at the T2K near detectors **on-axis**

Near detectors on-axis



- INGRID
  - Continuous beam monitor
  - Iron (96%)
- Proton module
  - Plastic scintillator
  - 5.89×10^{20} POT collected in neutrino mode
- Water module
  - Water (80%) + plastic (20%)
  - 7.25×10^{20} POT collected in neutrino mode





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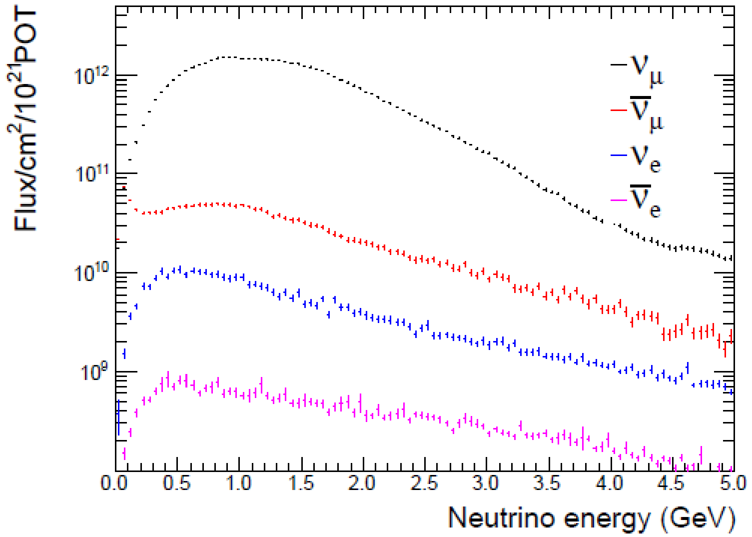
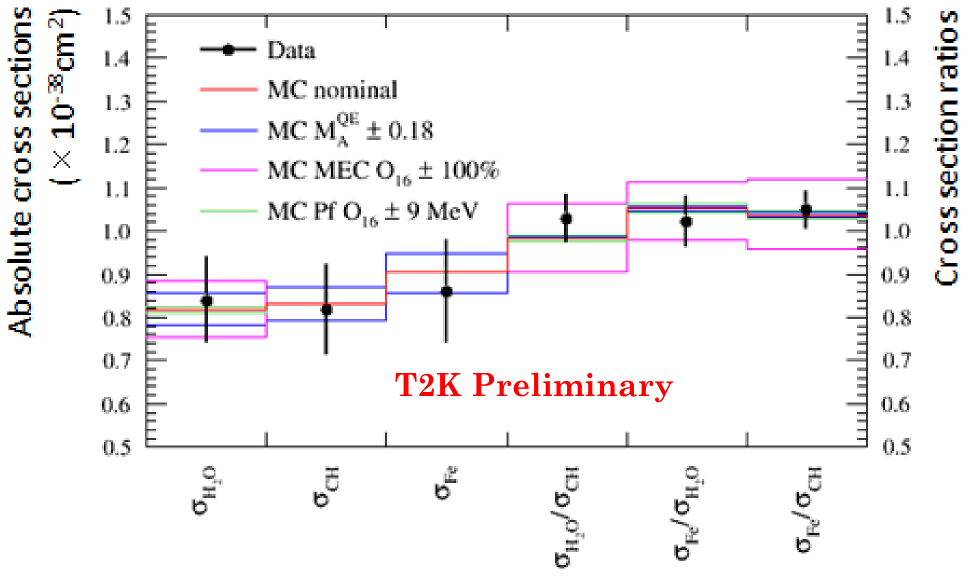
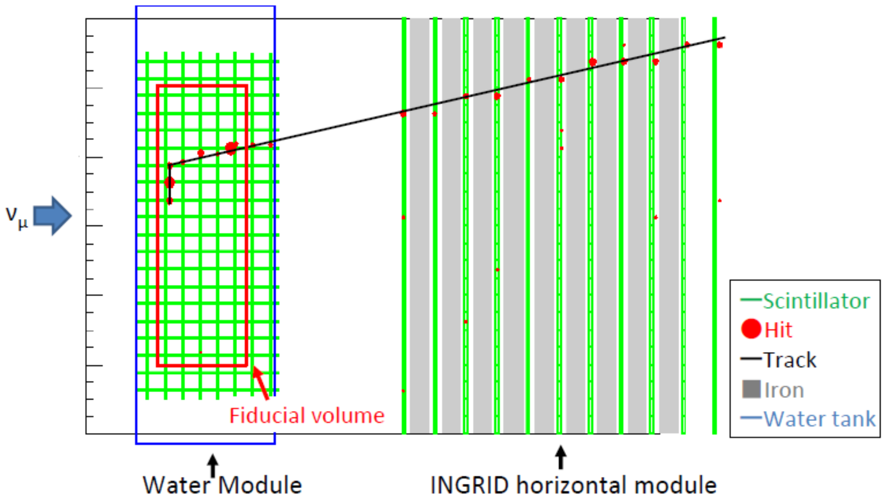
arXiv:1904.09611

CC-ν_μ charged-current cross sections on water, hydrocarbon and iron

- Phase-space
  - $p_\mu > 0.4$ GeV/c and $\theta_\mu < 45^\circ$
- First neutrino cross-section ratios for water / CH and water / iron
- Most precise neutrino cross-section measurement on water in the low-GeV energy range



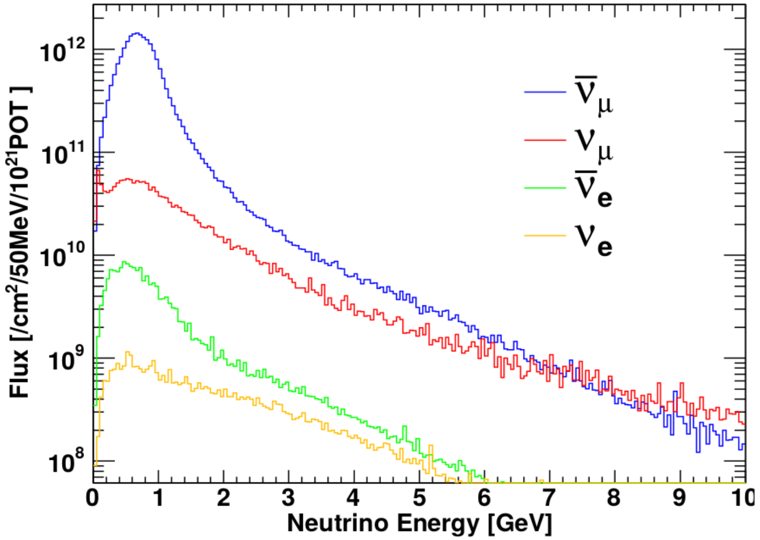


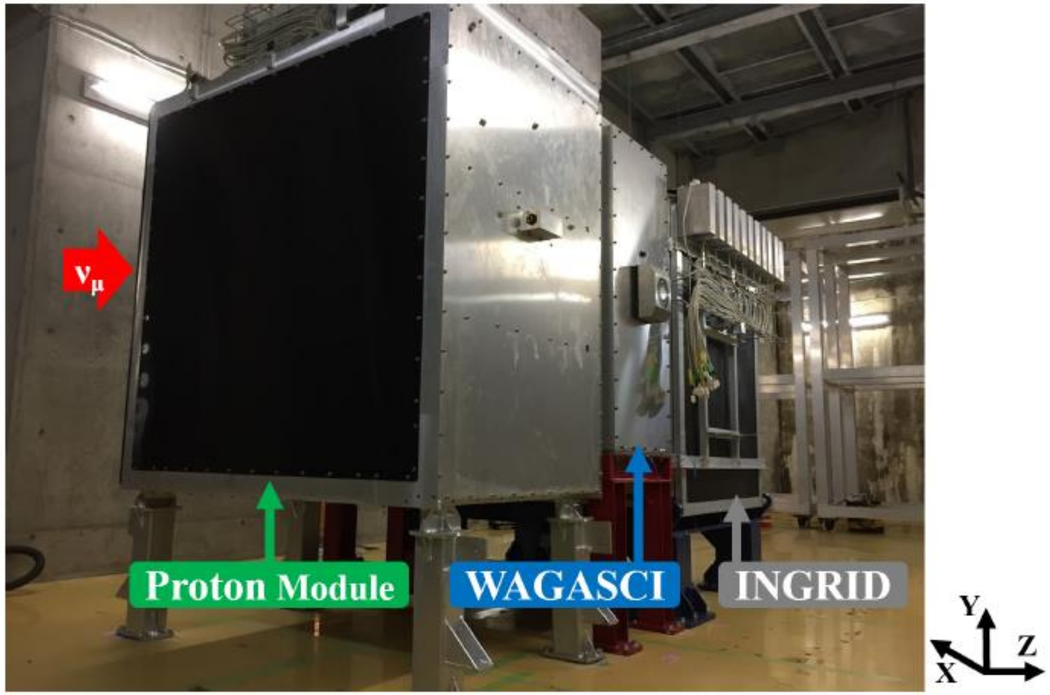


Neutrino cross-section measurements at the T2K near detectors at **1.5° off-axis**

Near detectors at 1.5° off-axis

- Vertex in proton module or water module
- INGRID is used for muon tracking
- Detector system is not magnetized
  - No separation between neutrinos and anti-neutrinos
- 7.91×10^{20} POT collected in anti-neutrino mode from October 2017 until May 2018

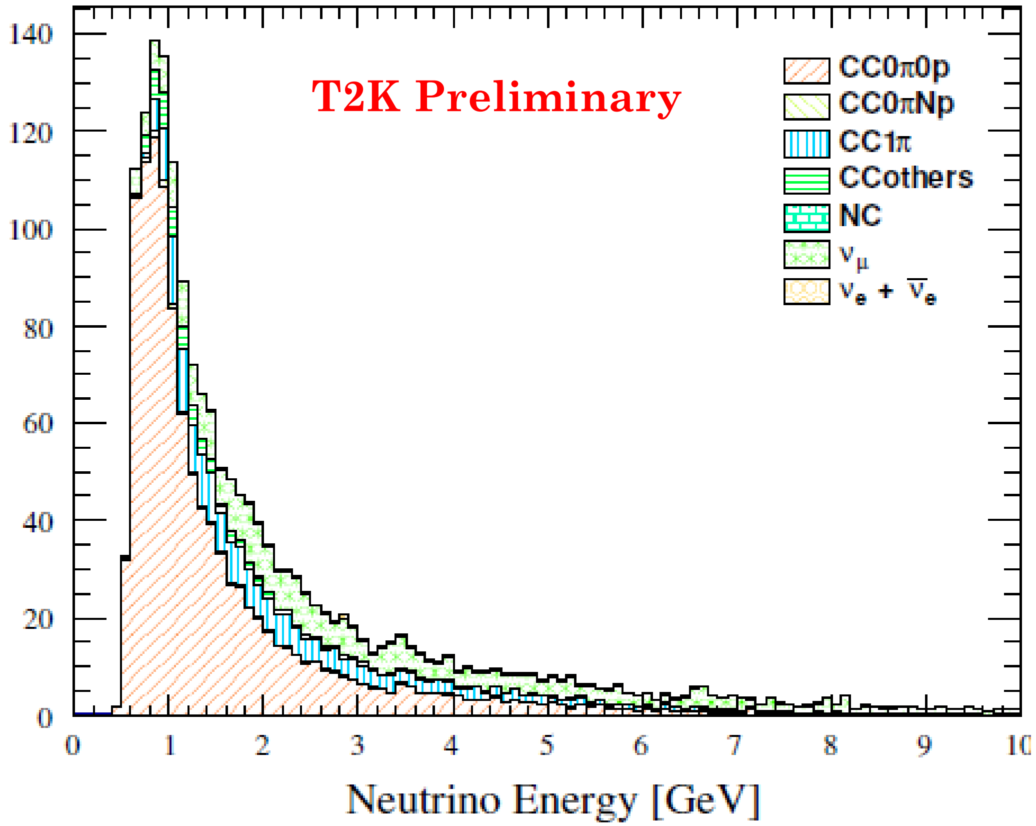




See also next talk by Etam Noah

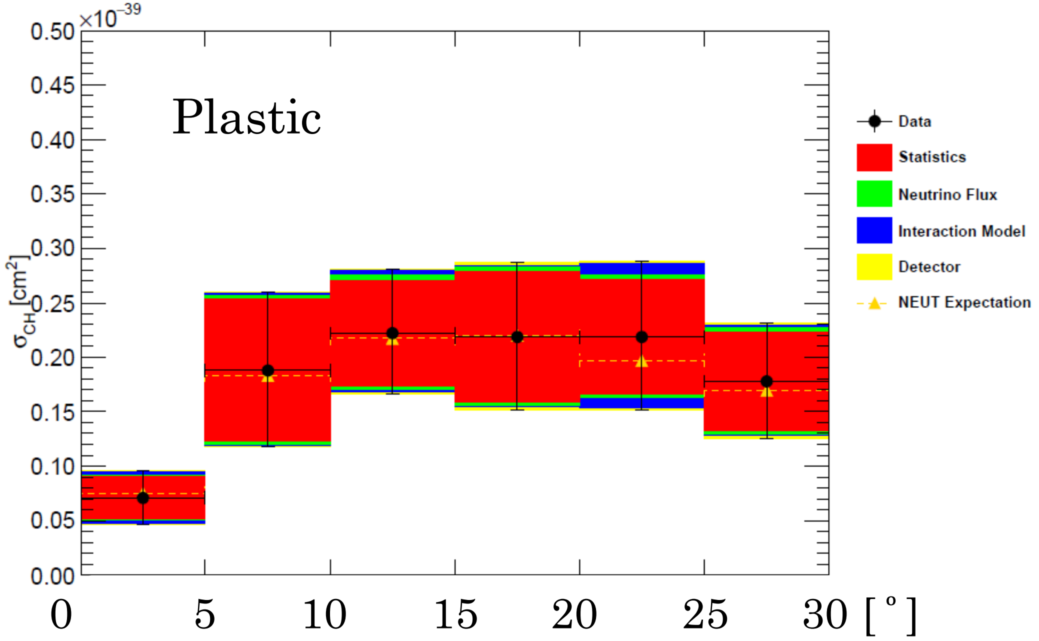
CC-$\bar{\nu}_\mu$ 0π 0proton selection

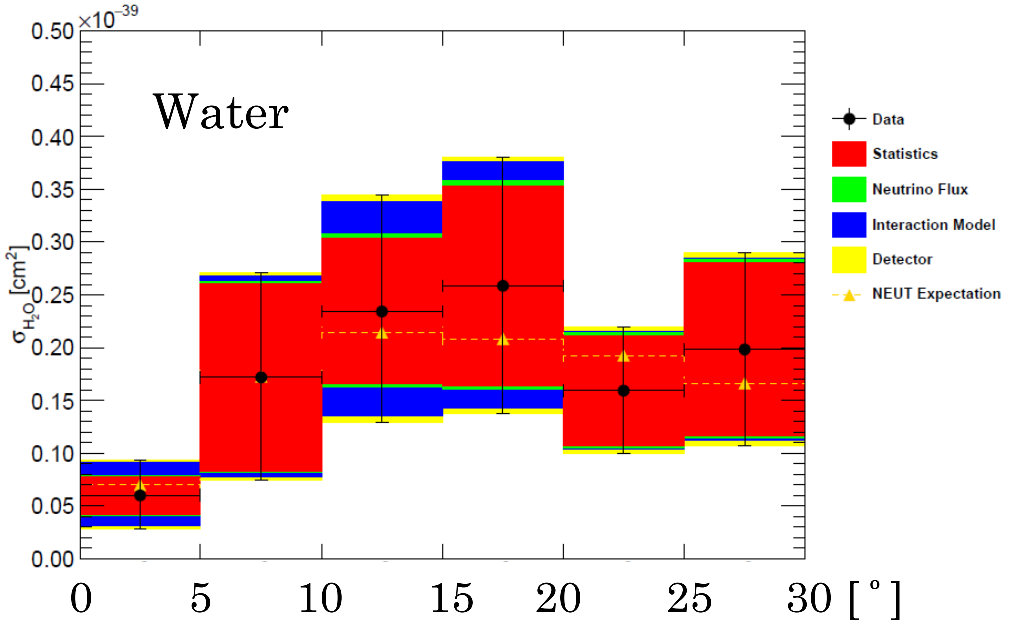
- Neutrino vertex either in WAGASCI or proton module
- Phase-space
  - $p_\mu > 0.4$ GeV/c and $\theta_\mu < 30^o$
  - No pions: $p_\pi > 0.2$ GeV/c and $\theta_\pi < 70^o$
  - No protons: $p_p > 0.6$ GeV/c and $\theta_p < 70^o$
- Large neutrino background with larger cross-sections
  - Measure both CC-$\bar{\nu}_\mu$ and CC-$\bar{\nu}_\mu$ + CC-ν_μ cross-sections



See also poster 764

CC-$\bar{\nu}_\mu$ 0π 0proton cross-section measurement on plastic and water





T2K Preliminary

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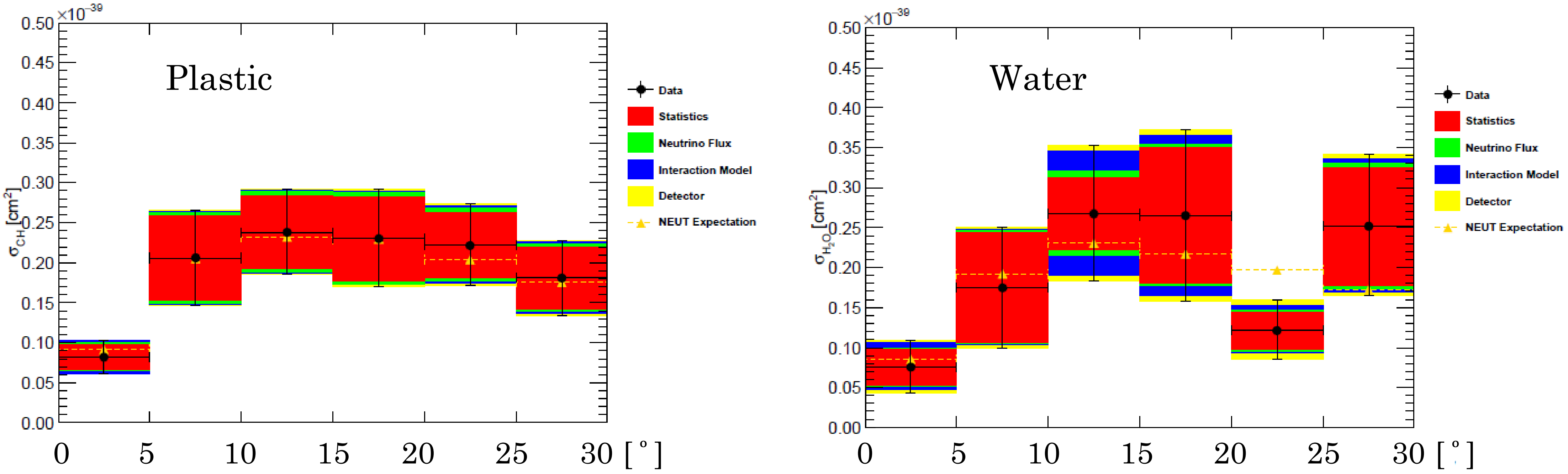
CC-$\bar{\nu}_\mu$ + CC-ν_μ 0π 0proton cross-section measurement on plastic and water



T2K Preliminary

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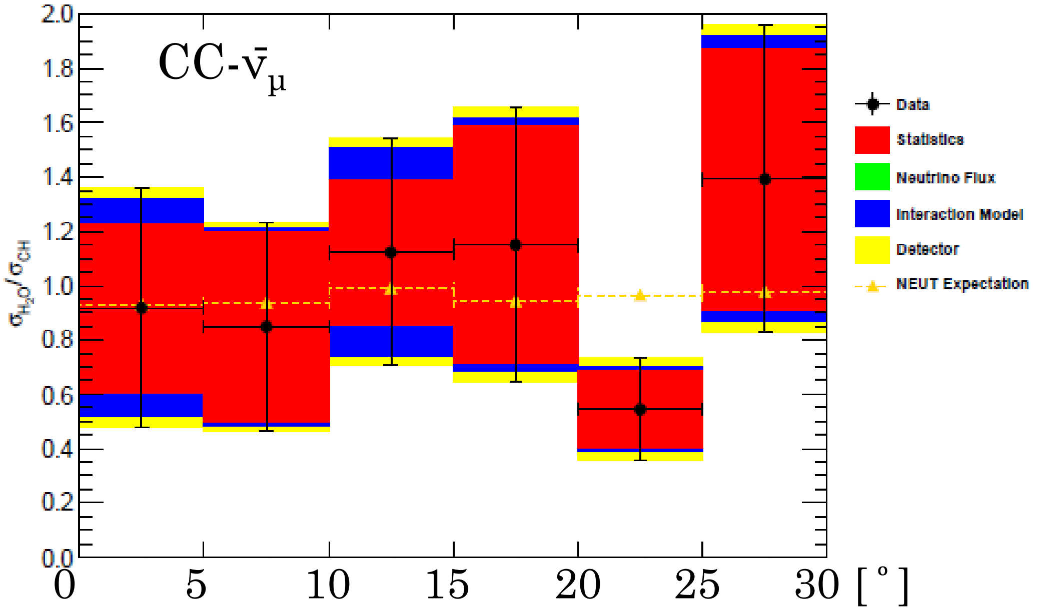
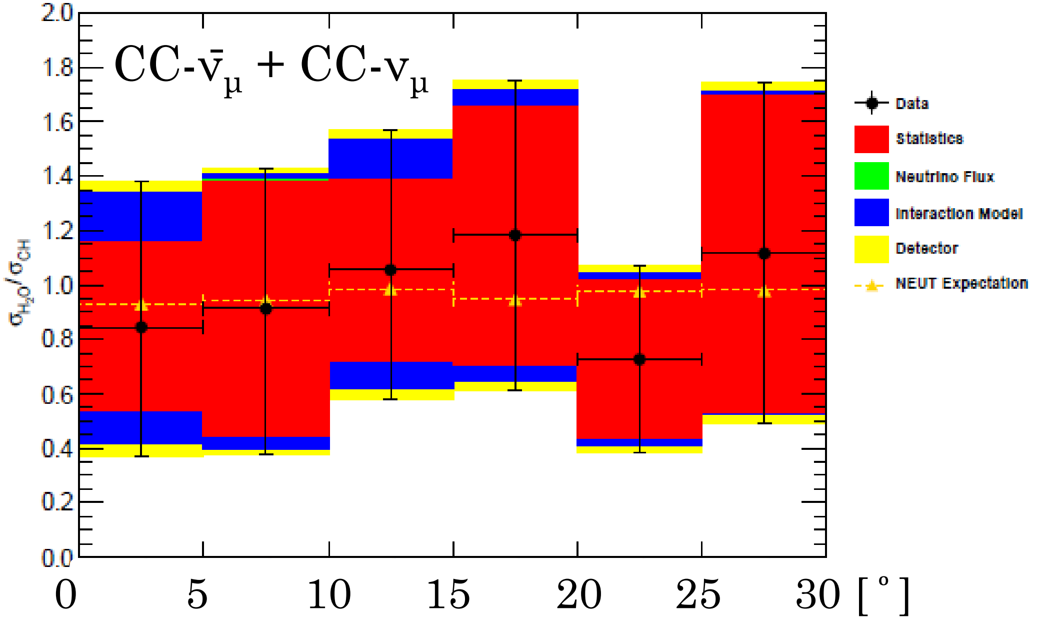
CC-$\bar{\nu}_\mu$ + CC-ν_μ 0π 0proton cross-section water/plastic ratio





T2K Preliminary

Previous T2K cross-section measurements

- Measurement of inclusive double-differential νμ charged-current cross section with improved acceptance (Phys.Rev. D98, 012004, 2018)
- Characterisation of nuclear effects in neutrino scattering with a measurement of final-state kinematics (Phys.Rev. D98, 032003, 2018)
- First measurement of the νμ charged-current cross section without pions in the final state on a water target (Phys.Rev. D97, 012001, 2018)
- Measurement of muon- antineutrino and neutrino charged-current inclusive cross sections and their ratio with the T2K off-axis near detector (Phys.Rev. D96, 2017)
- First Measurement of the Muon Neutrino Charged Current Single Pion Production Cross Section on Water with the T2K Near Detector (Phys.Rev. D95, 012010, 2017)
- Measurement of Coherent π+ Production in Low Energy Neutrino-Carbon Scattering (Phys. Rev. Lett.117, 192501, 2016)
- Measurement of double-differential muon neutrino charged-current interactions on C8H8 without pions in the final state using the T2K off-axis beam (Phys.Rev. D93, 112012, 2016)
- Measurement of the muon neutrino inclusive charged-current cross section in the energy range of 1-3 GeV with the T2K INGRID detector (Phys.Rev. D93 , 072002, 2016)
- Measurement of the νμ charged current quasi-elastic cross-section on carbon with the T2K on-axis neutrino beam (Phys. Rev. D 91, 112002, 2015)
- Measurement of the νμ CCQE cross section on carbon with the ND280 detector at T2K (Phys. Rev. D 92, 112003, 2015)
- Measurement of the inclusive νμ charged current cross section on iron and hydrocarbon in the T2K on-axis neutrino beam (Phys. Rev. D 90, 052010, 2014)
- Measurement of the Inclusive Electron Neutrino Charged Current Cross Section on Carbon with the T2K Near Detector (Phys. Rev. Lett. 113, 241803, 2014)
- Measurement of the neutrino-oxygen neutral-current interaction cross section by observing nuclear deexcitation γ rays (Phys. Rev. D 90, 072012, 2014)
- Measurement of the Inclusive NuMu Charged Current Cross Section on Carbon in the Near Detector of the T2K Experiment (Phys. Rev. D 87, 092003, 2013)

Summary

- **T2K has a rich and unique neutrino cross-section program**
  - Different neutrino fluxes (on-axis, different off-axis angles), targets, detectors, neutrino and anti-neutrino flavours
  - Vital to reduce systematic uncertainties for the neutrino oscillation measurements and CP-violation searches
  - Also important for the design of the next generation of long baseline neutrino oscillation experiments

- Highlights of the 2019 T2K cross-section measurements presented in this talk

- Many more to come…

BACK UP

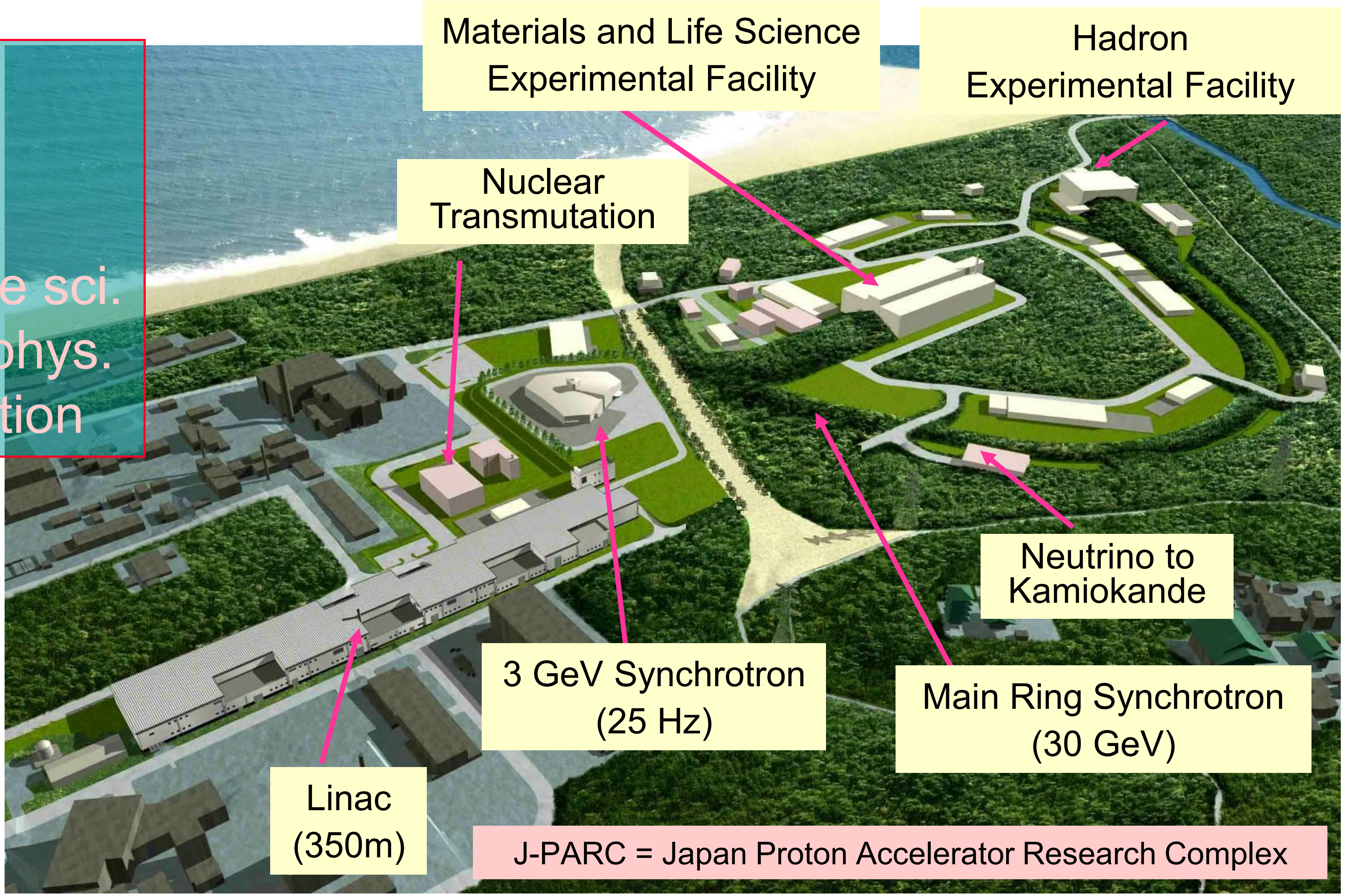
MW Proton Facility : J-PARC

Unique facility

3GeV+30GeV

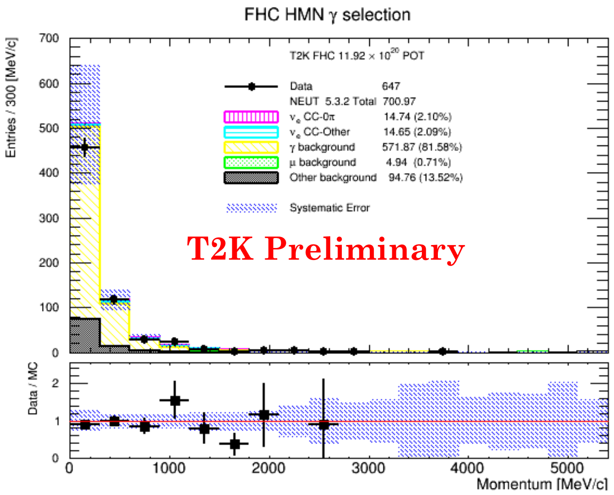
Multi-purposes

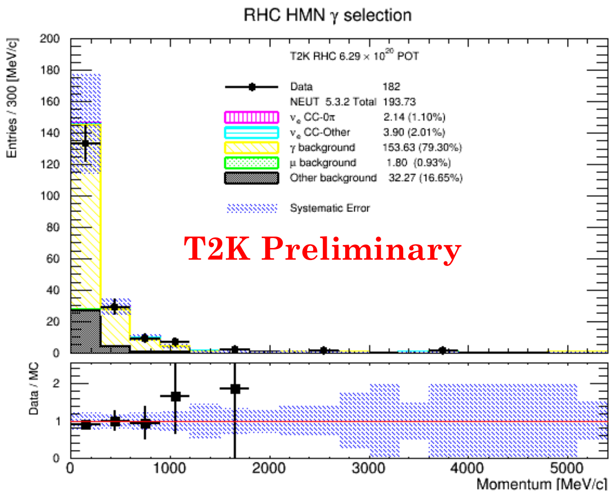
- Materials and life sci.
- Nucl. and part. phys.
- Nucl. transmutation

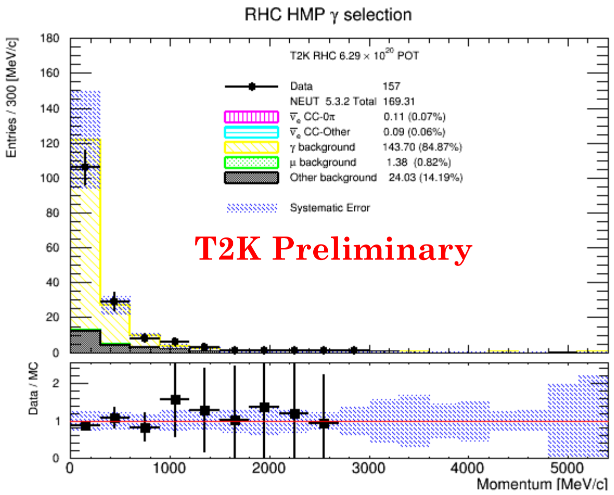


Gamma control samples for CC-ν_e selections

- Select FGD1 – TPC e-e+ tracks with low invariant mass
- Apply same veto cuts as the CC-ν_e analysis







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NC single gamma processes

N* = baryon resonance
M = neutral vector meson