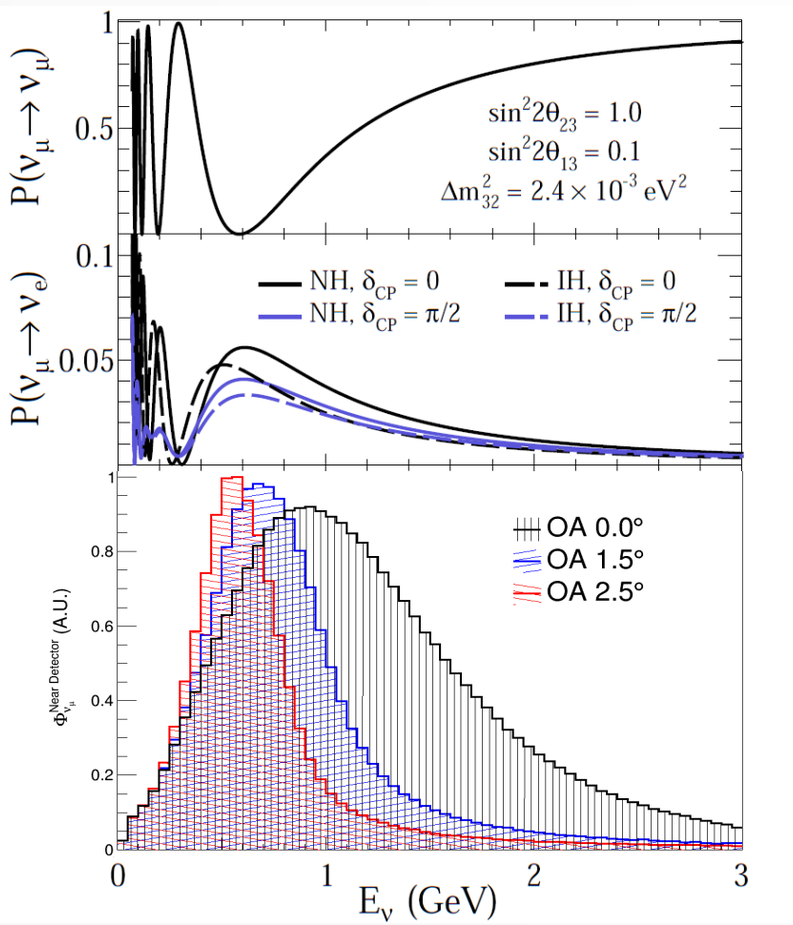
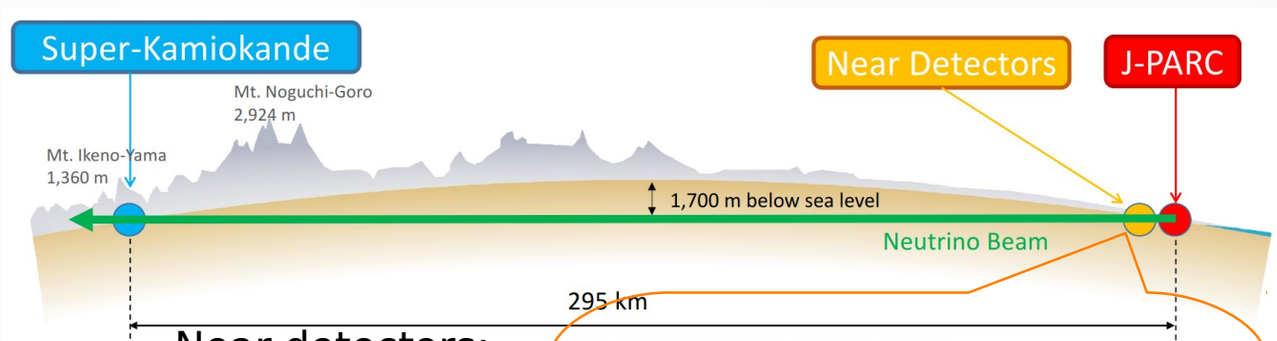
Measurements of Neutrino Interaction Cross Sections at T2K

Grzegorz Żarnecki for the T2K collaboration
National Centre for Nuclear Research

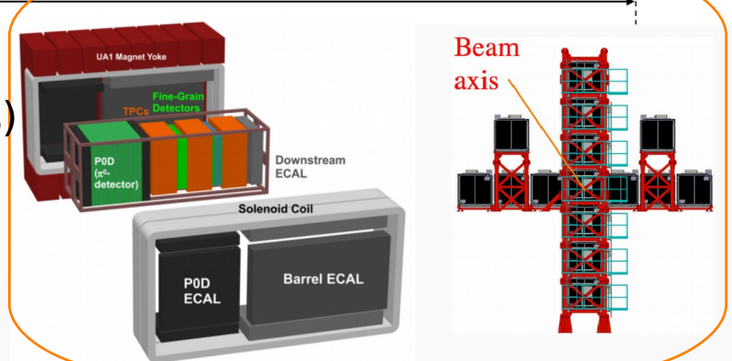
grzegorz.zarnecki@ncbj.gov.pl

T2K experiment





Near detectors:
INGRID (on-axis)
WAGASCI (off-axis)
ND280 (off-axis)

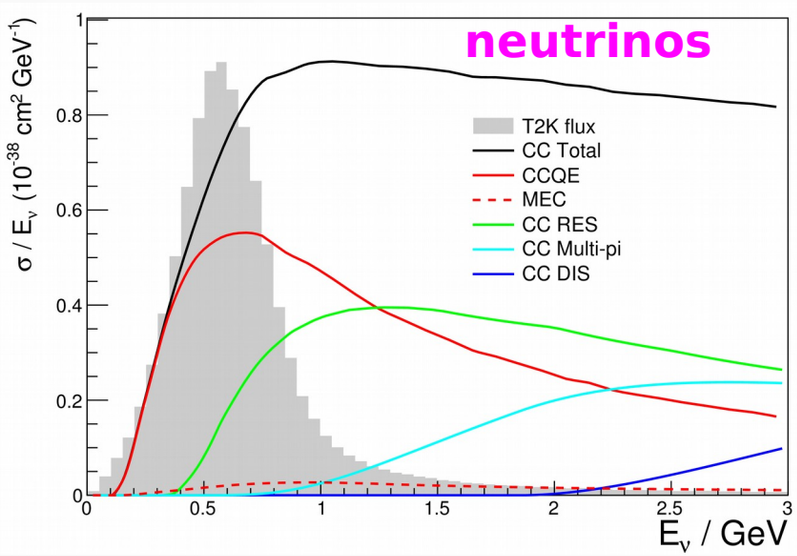


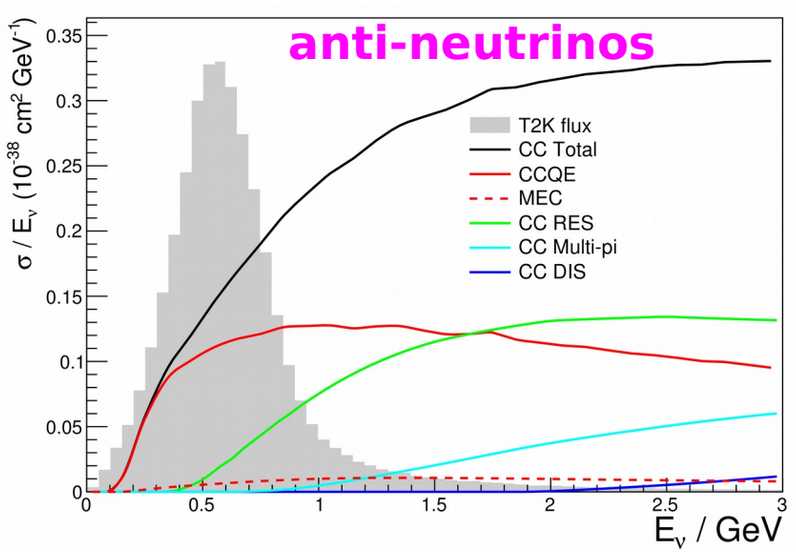
flux #targets

$$R = \sum_{\alpha} \phi_\alpha \times \sigma_\beta \times N \times \epsilon \times P(\nu_\alpha \to \nu_\beta)$$

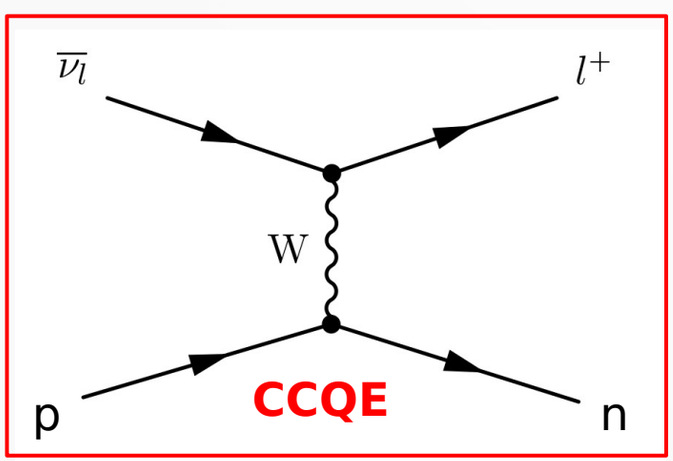
cross section detection efficiency oscillation probability

Neutrino interactions and event topologies

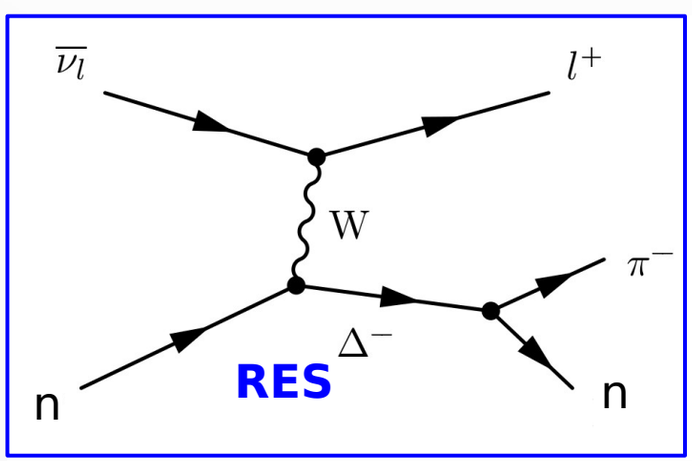




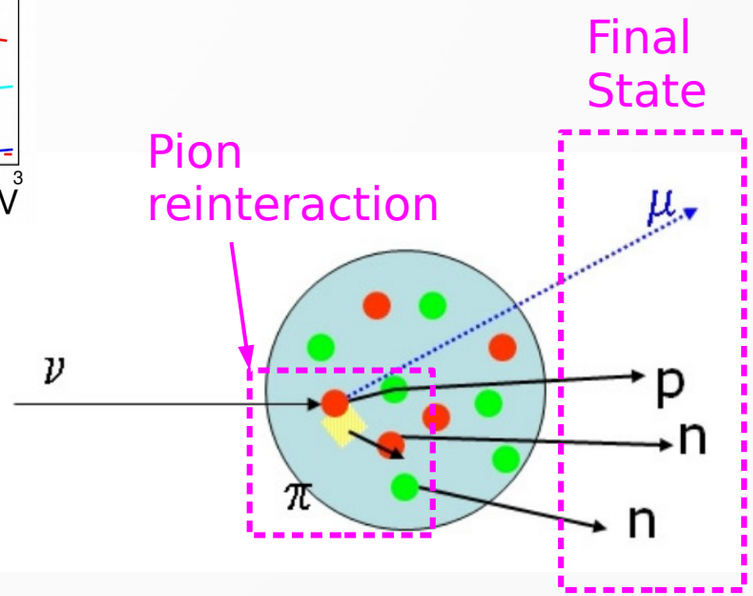
At T2K energy scale mostly quasielastic and resonant interactions occur.



CC quasielastic interaction – dominating in **CC0π topology**



CC resonant interaction – dominating in **CC1π topology**



Events are classified according to their final state topology.

T2K cross section measurements

Multiple targets: hydrocarbon, water, iron, argon

Multiple angles w.r.t. neutrino beam axis – different energies

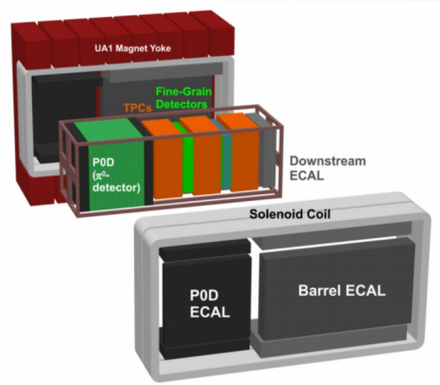
Neutrino and anti-neutrino beam modes

Possibility to study interactions relevant for T2K oscillation analysis (CC0π, CC1π on C, O), explore nuclear effects and measure rare processes.

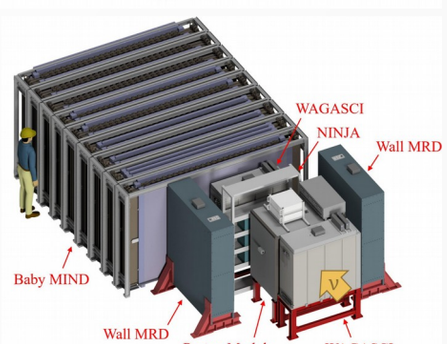
Blind analysis approach, fake data studies

Reducing model dependencies by selection studies, binning optimisation, phase-space reduction, accurate choice of observables.

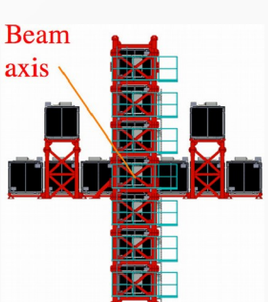
ND280
2.5 deg
off-axis



WAGASCI
1.5 deg
off-axis



INGRID
on-axis



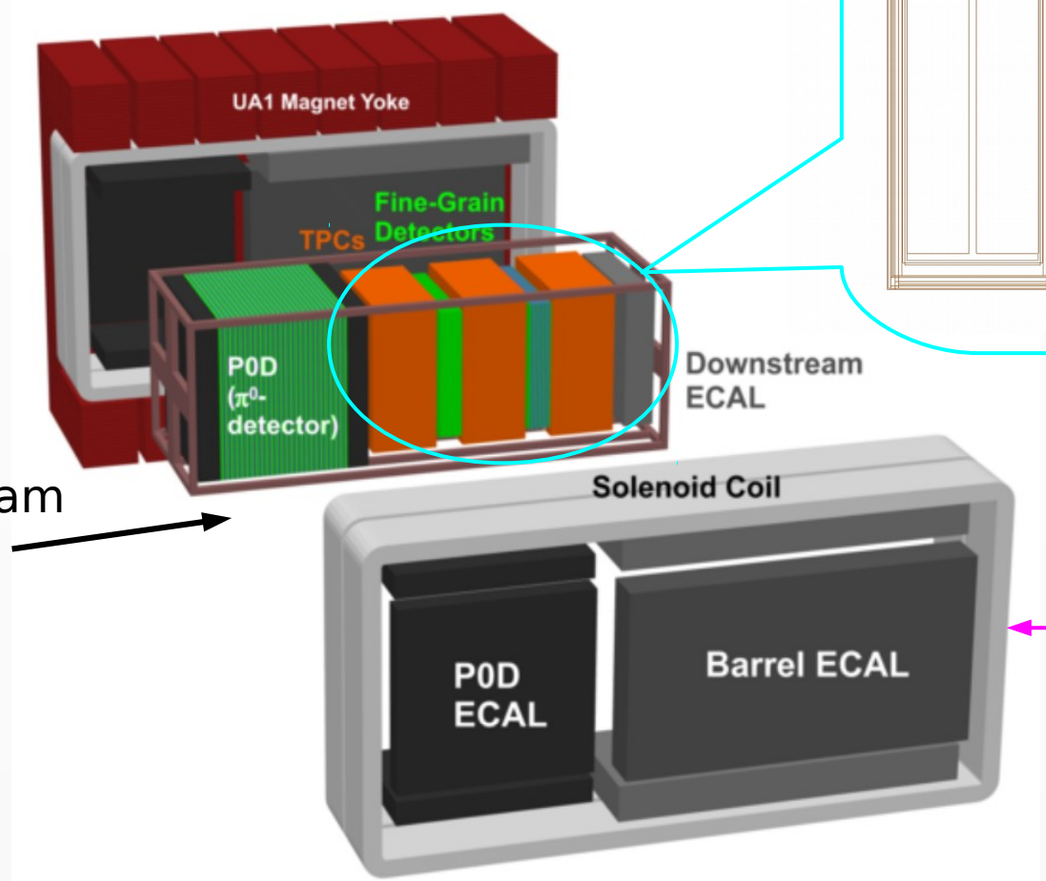
ND280

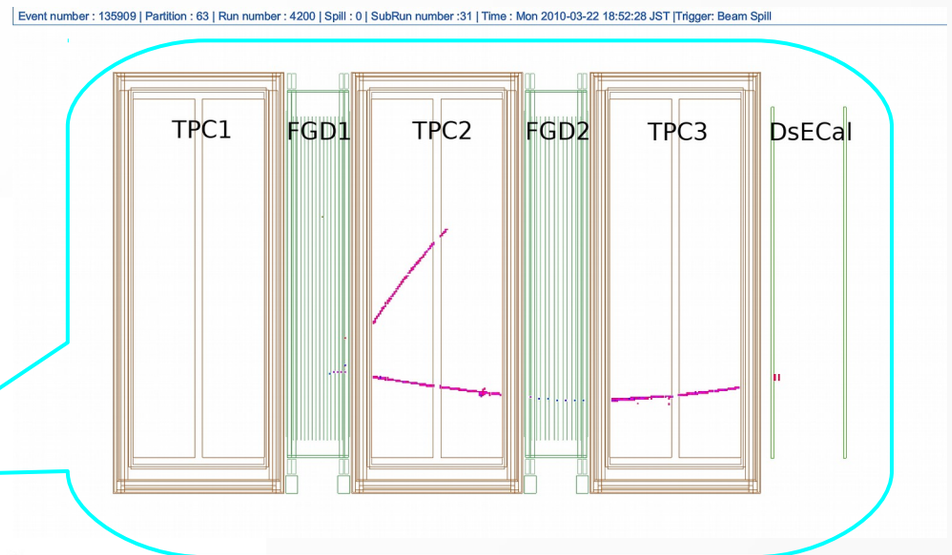
Tracker region: 2 Fine Grain Detectors (FGDs) + 3 gaseous Time Projection Chambers (TPCs).

FGDs provide interaction target **(FGD1: CH, FGD2: CH+H_2O)** and tracking of low energy particles.

TPCs allow for particle identification via energy loss dE/dx measurement and provide excellent tracking.

Exploded view of ND280





Data event display

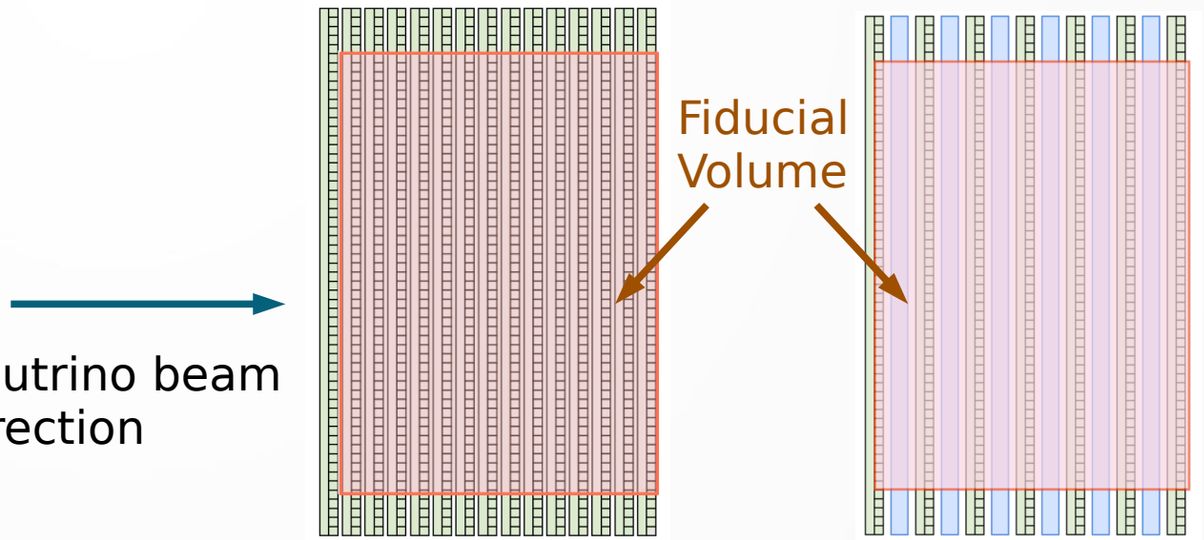
Refurbished UA1 magnet generates the magnetic field of 0.2 T.

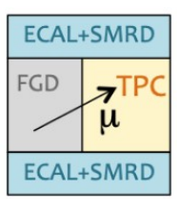
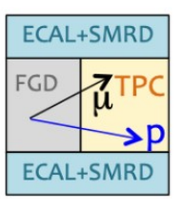
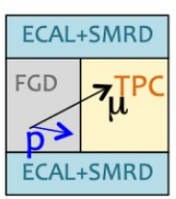
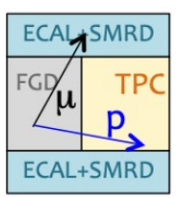
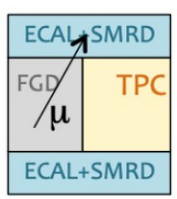
Simultaneous measurement of the ν_μ CC0π cross section on O and C at ND280 **(1)**

First joint O/C analysis

Signal events: single reconstructed μ^- track + any number of reconstructed proton tracks (sharing a common vertex).

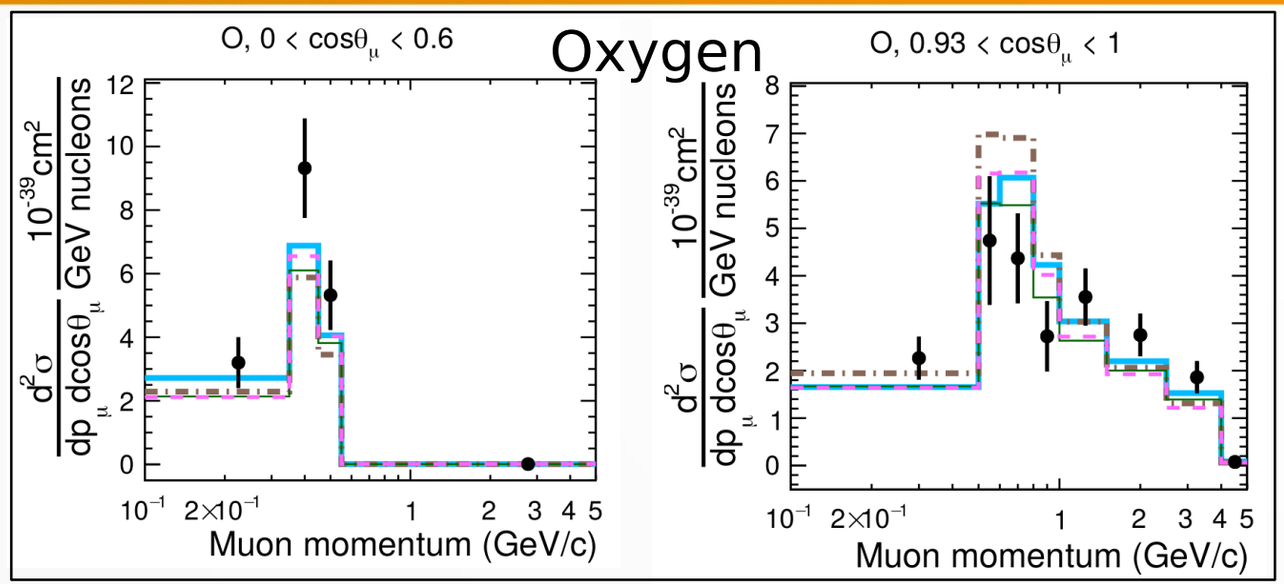
Signal samples categorised based on the vertex position (FGD1, FGD2X – carbon enhanced, FGD2Y – oxygen enhanced).

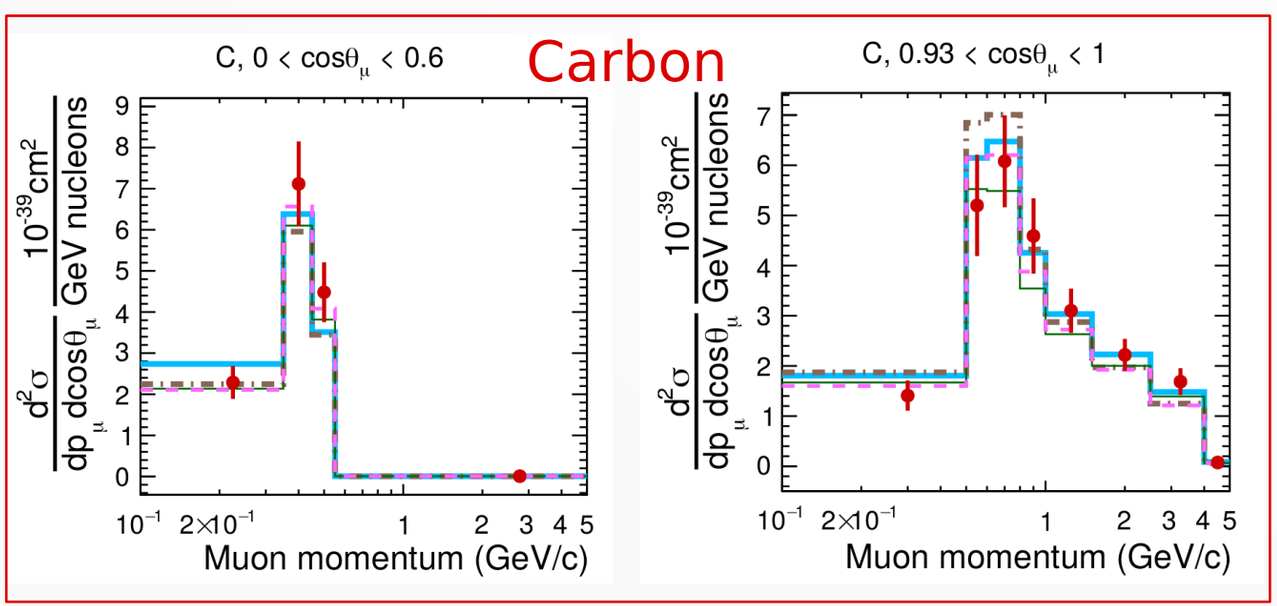


Signal sample	I – μTPC	II – μTPC+pTPC	III – μTPC+pFGD	IV – μFGD+pTPC	V – μFGD
					
Description	Single μ candidate tracked in TPC	Both μ and *p* candiates are tracked in the TPC	μ tracked in the TPC and : • 1*p* tracked in the FGD • or multi *p*	μ tracked in FGD/Ecal and: • 1 *p* tracked in the TPC • or 1 *p* tracked in the TPC + multi *p* • or multi *p*	μ_{FGD} only reconstructed in the FGD/ Ecal

Each XY module consists of two layers of scintillator bars oriented horizontally (X) and vertically (Y).

Simultaneous measurement of the ν_μ CC0π cross section on O and C at ND280 **(2)**





Results reported as double differential cross section (per nucleon) in μ kinematic variables. Correlations and ratio of the O/C cross sections provided.

Published in: Phys.Rev.D 101 (2020) 11, 112004

Results best described by local Fermi gas descriptions of the nuclear ground state with random phase aproximation suppression.

- Data
- GENIE v3 LFG hN (48.9)
- NuWro LFG (64.7)
- NEUT SF (110.3)
- RMF(1p1h)-SusaV2(2p2h) (90.6)

Joint On/Off axis ν_μ CC0π measurement on scintillator with FGD1 and the Proton Module **(1)**

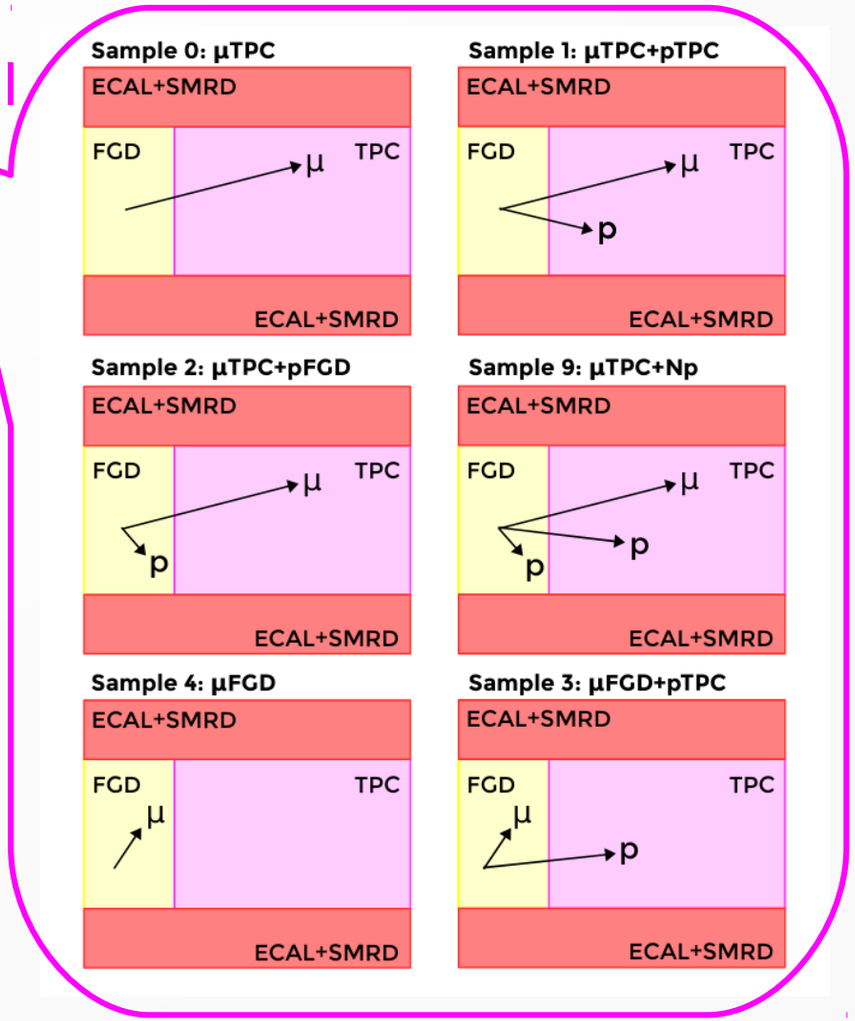
First on-axis/off-axis analysis

Two different flux spectra

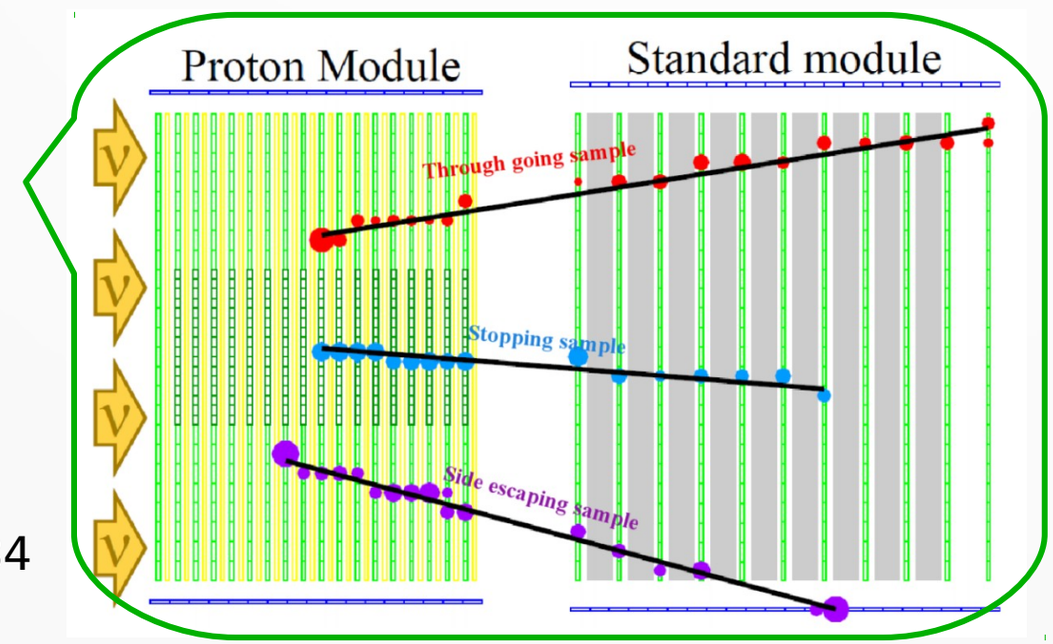
Possibility to study energy dependence of neutrino interactions

Flux constraints

ND280 signal samples



INGRID signal samples

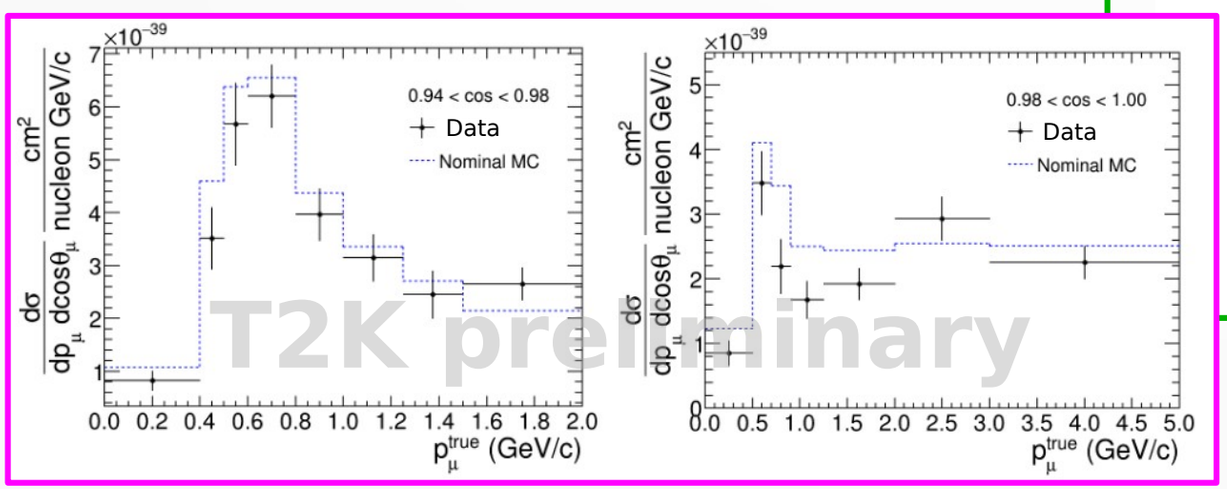


A. Cudd, T2K technical note 384

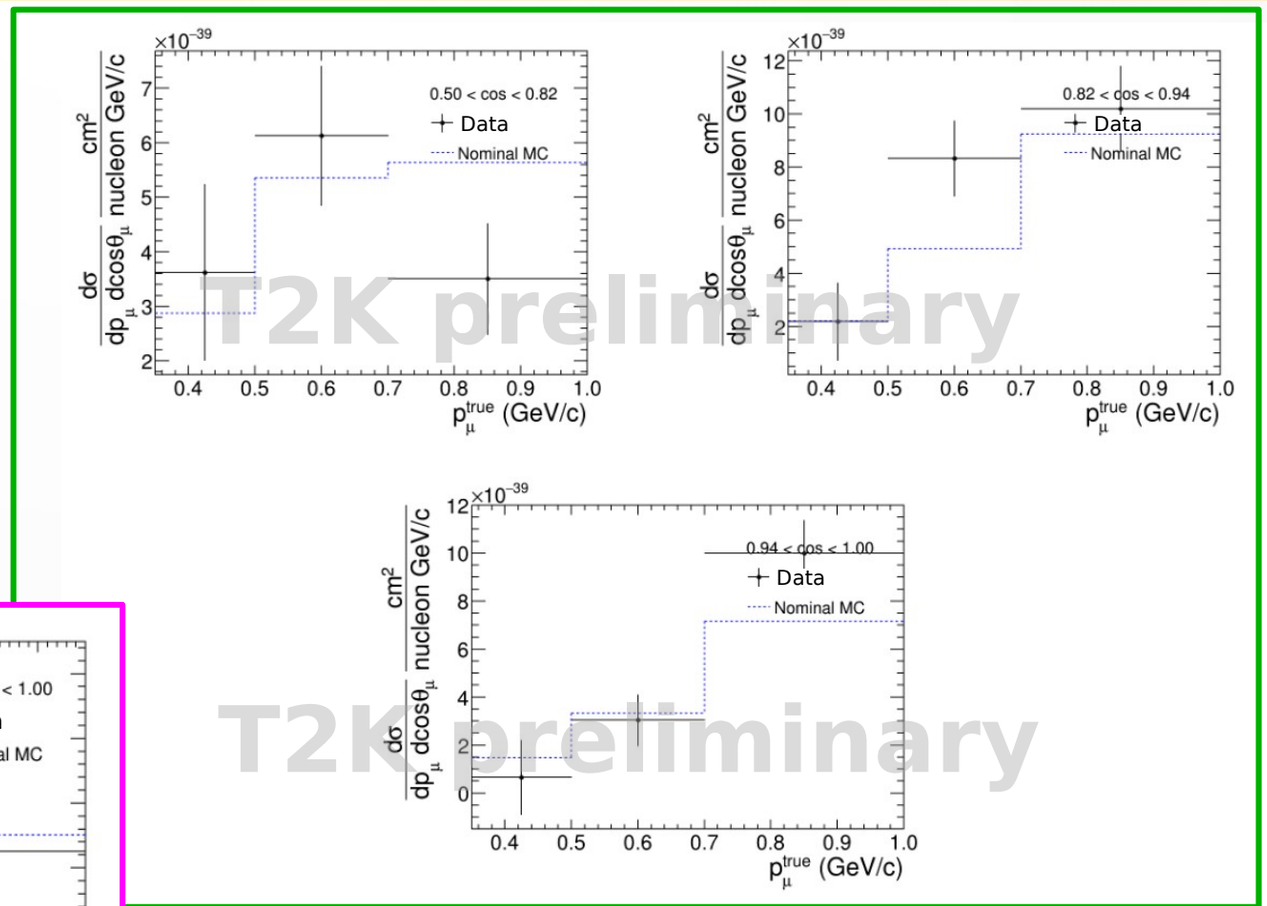
Joint On/Off axis ν_μ CC0π measurement on scintillator with FGD1 and the Proton Module **(2)**

Cross section is reported as flux integrated for on axis and off axis flux.

Publication in preparation!



ND280 extracted cross section bins



INGRID extracted cross section bins

Correlations fully available

Transverse kinematic imbalance (TKI) in ν_μ CC1π^+ production channel containing at least one proton **(1)**

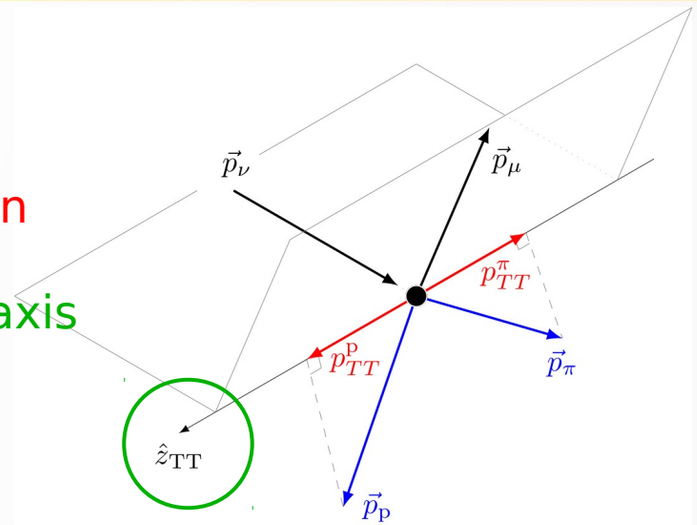
Limited knowledge of nuclear medium effects is one of the dominant systematic uncertainty sources in the oscillation analysis.

Measurements of TKI probe the lepton-hadron correlations on the plane that is transverse to incident neutrino direction.

Useful to understand intranuclear dynamics!

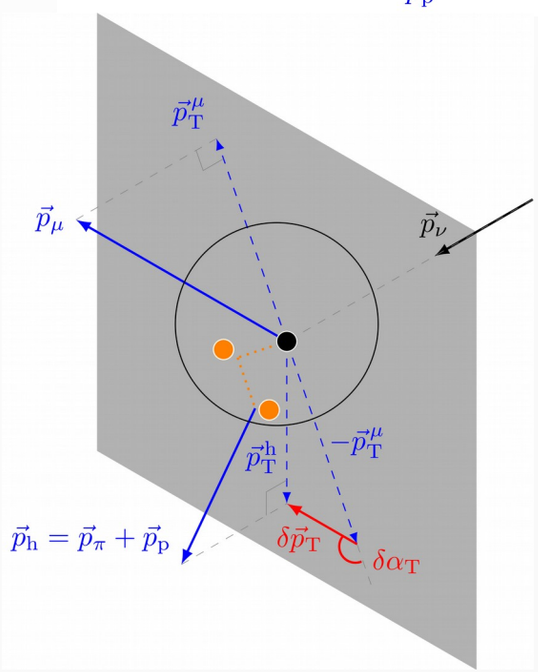
Observables based on measured μ, π, proton momenta.

proton/pion momentum projection on double transverse axis $\mathbf{z_{TT}}$



sum of the transverse momenta

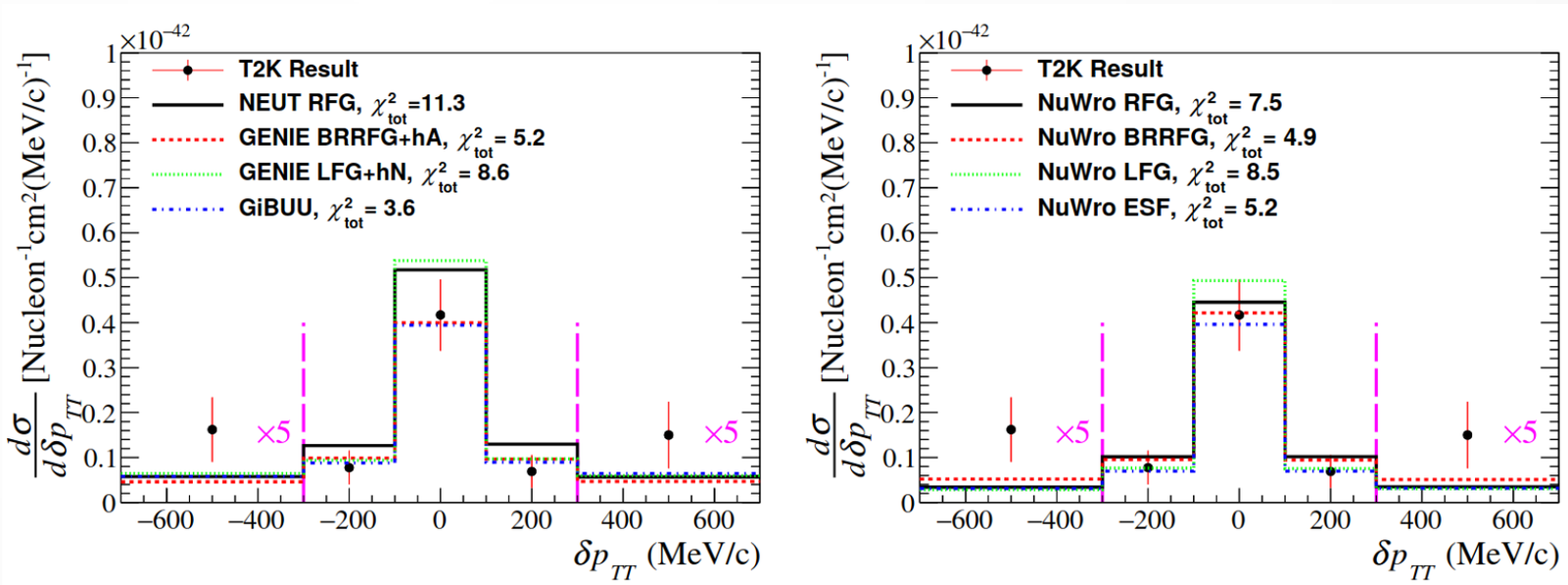
transverse boosting angle



Transverse kinematic imbalance (TKI) in ν_μ CC1π^+ production channel containing at least one proton **(2)**

Interactions in ND280's subdetector FGD1. Differential cross section on hydrocarbon reported in TKI observables.

Uncertainty dominated by statistical error.



Published in Phys.Rev.D 103 (2021) 11, 112009 (arXiv:2102.03346)

δp_{TT} – double transverse momentum imbalance (sum of proton and pion momentum projections on $\mathbf{z_{TT}}$)

Slight preference for GiBUU – more realistic nuclear ground state modelling (density- and momentum-dependent mean field). Data disfavour simple Fermi gas models (RFG and LFG).

ν_μ and $\bar{\nu}_\mu$ CC coherent pion production on carbon **(1)**

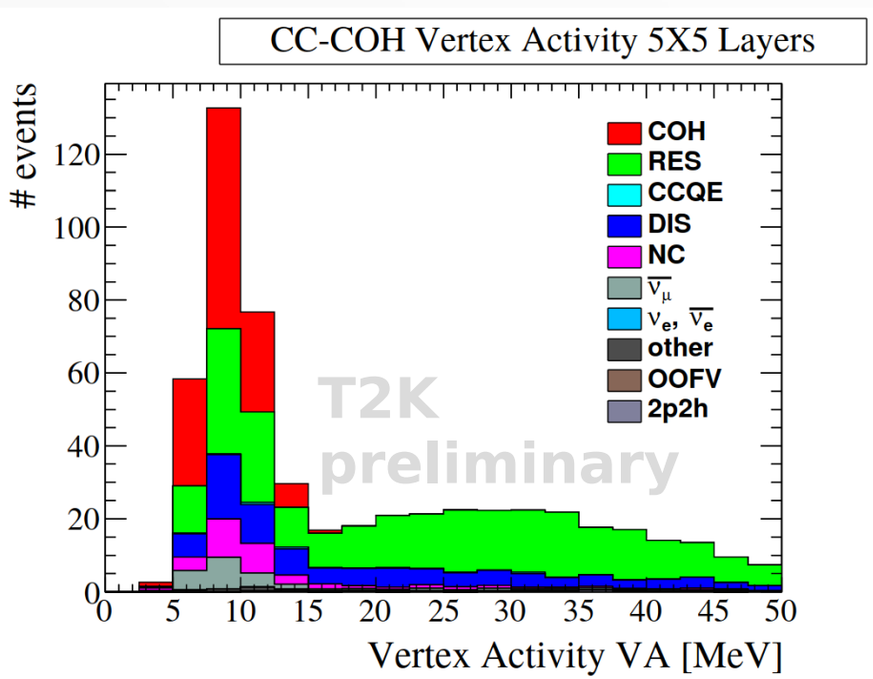
Rare interaction mode that is not well modelled theoretically.

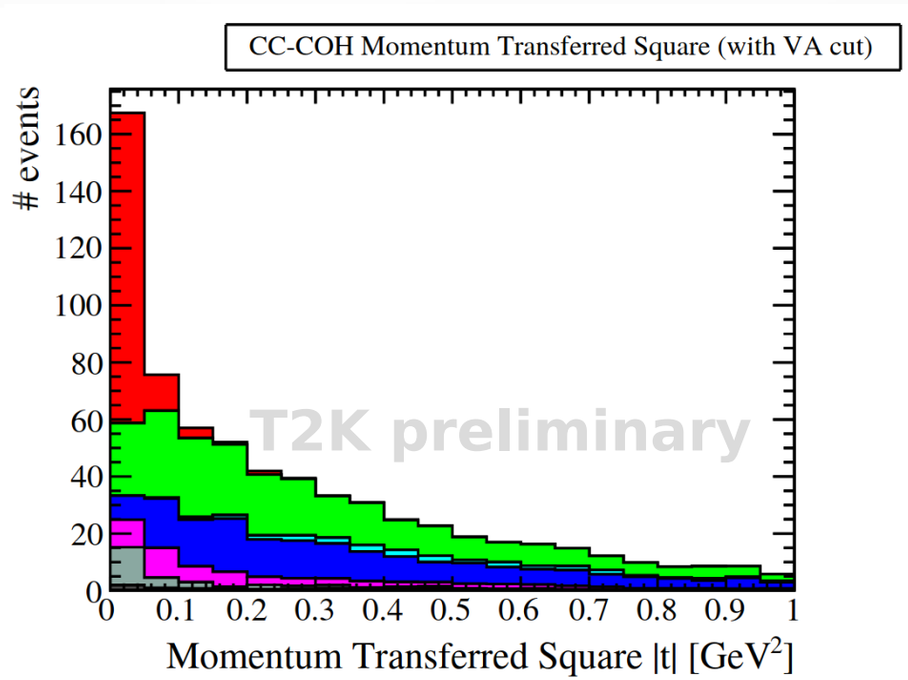
Interactions in ND280's subdetector FGD1. Signal selected as events with exactly two tracks (μ-like and π-like), low energy deposit around vertex and low momentum transferred squared.

$$\nu_l + N \rightarrow l^- + \pi^+ + N$$

$$\bar{\nu}_l + N \rightarrow l^+ + \pi^- + N$$

Recoiled nucleus remains in the ground state.



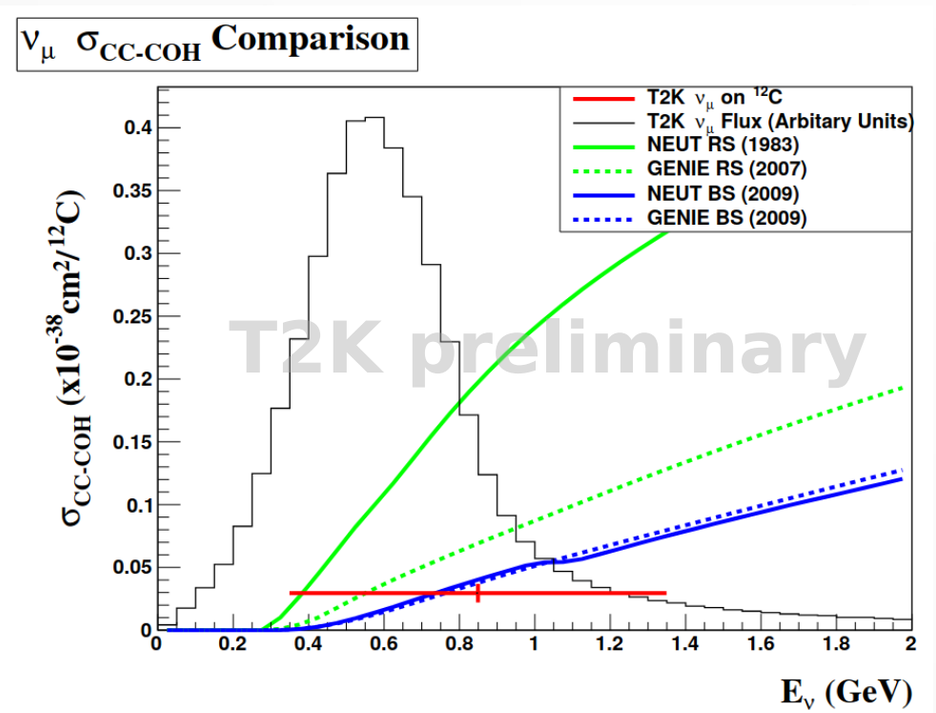


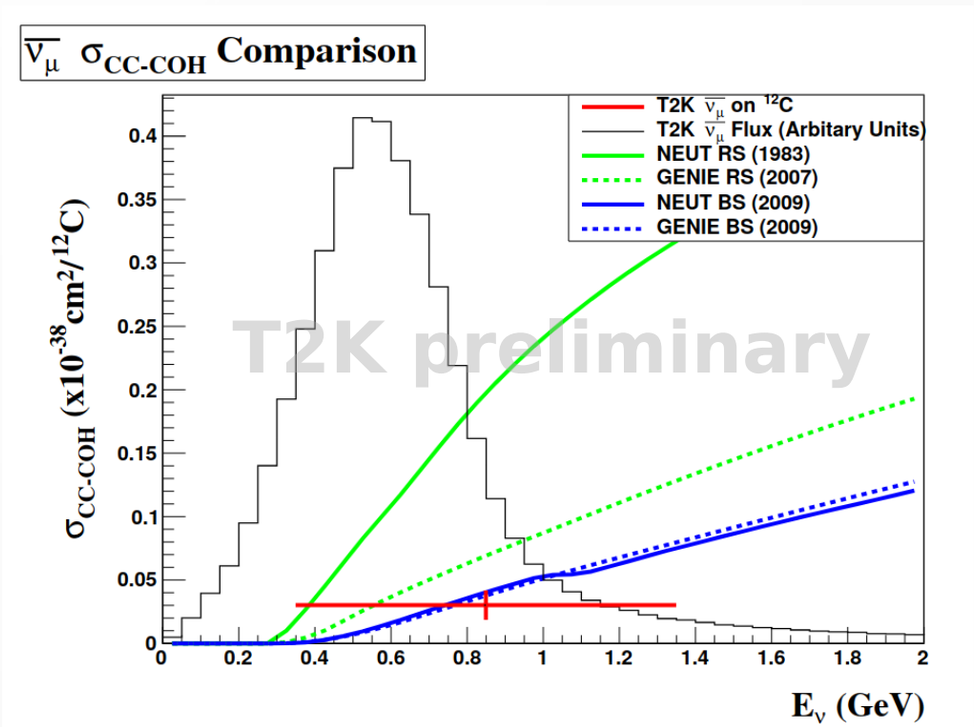
M. Yu, T2K technical note 391

ν_μ and $\bar{\nu}_\mu$ CC coherent pion production on carbon **(2)**

Due to statistical limitations the cross section (per nucleus) is reported as a single energy bin.

Firstly, the cross section for the entire FGD1 is calculated. Then the result is rescaled based on FGD1 composition and a scaling function F(A) to get cross section on carbon (for the plots below $F(A) = A^{1/3}$). **Publication in preparation!**

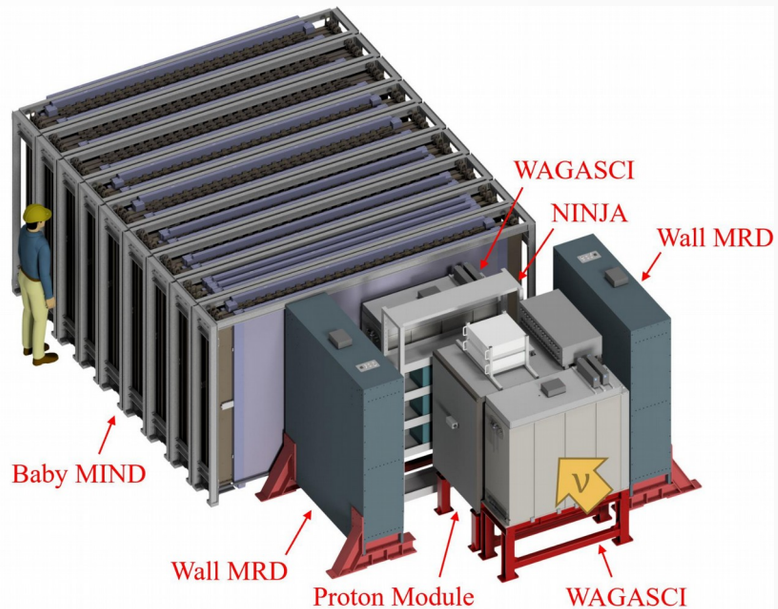




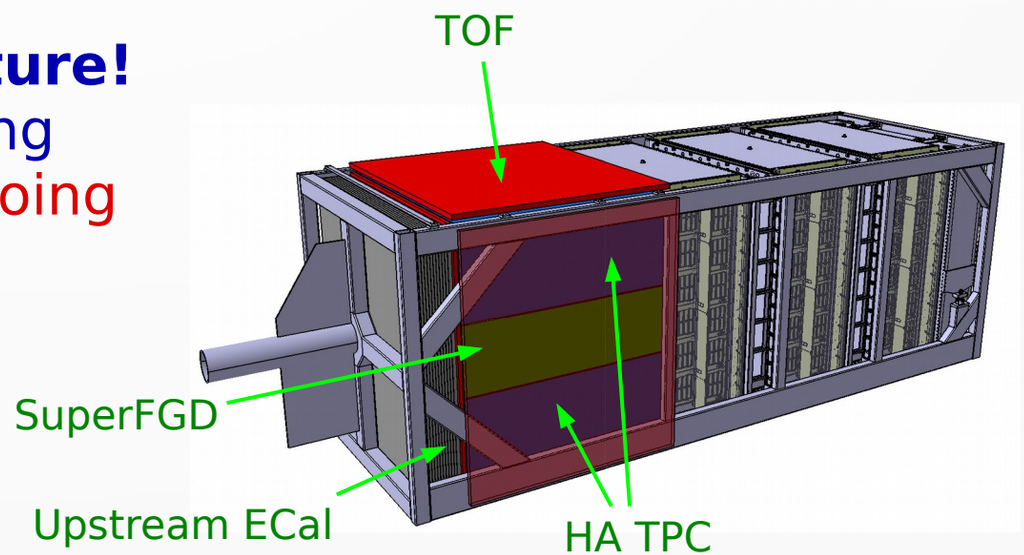
Summary and outlook

Cross section measurements validate neutrino interaction models and allow to constrain systematic uncertainties in oscillation analysis.

Experimental setup of T2K near detectors provides possibility for measurements on multiple targets at several beam angles.



Many new results expected in future!
-several ND280 CC1π analyses ongoing
-CC0π measurement in WAGASCI ongoing
-joint ND280/WAGASCI analysis
-cross section measurements
in upgraded ND280



Backup

1.5 deg off-axis detectors (current setup)

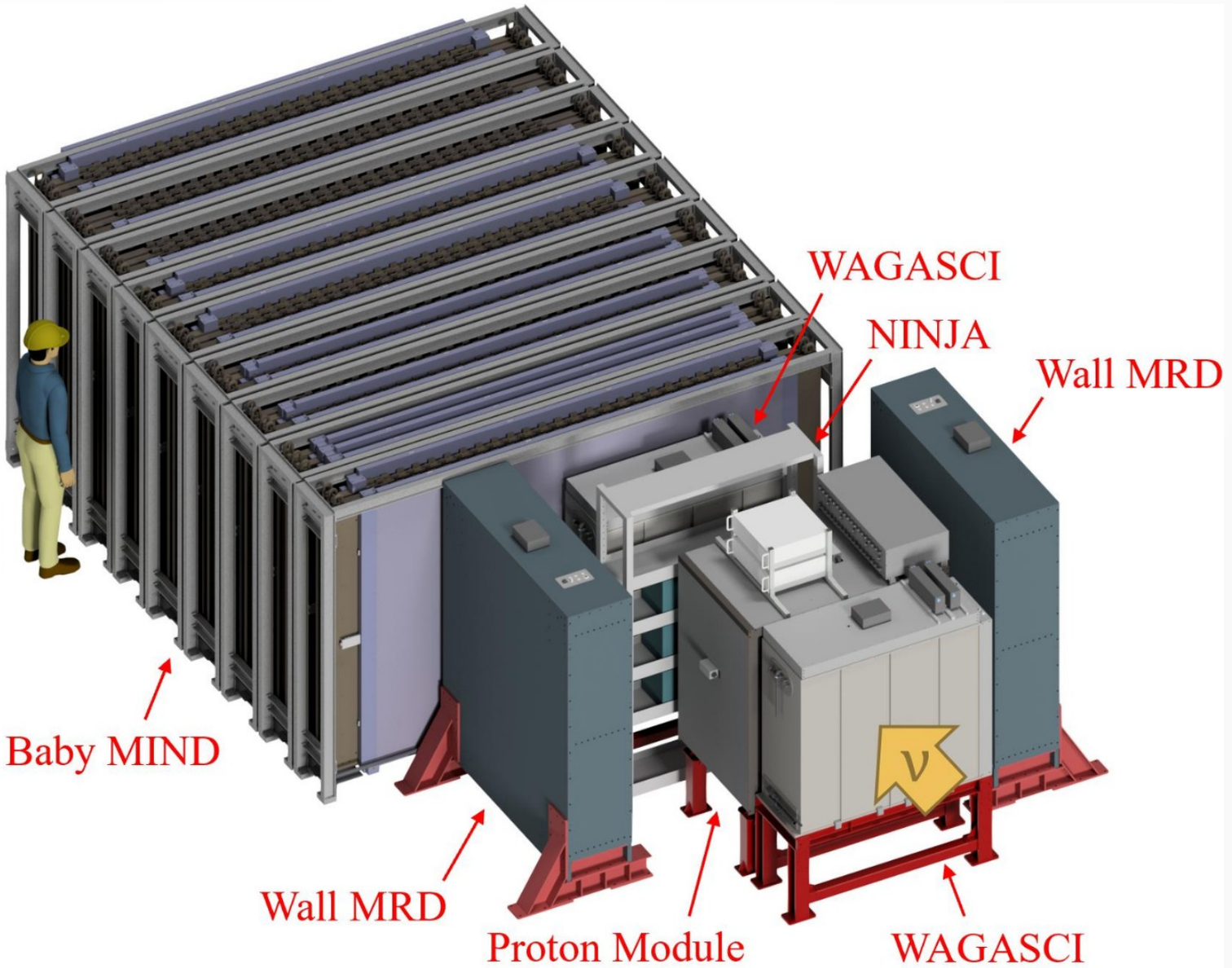
Baby MIND – 33 magnetised iron modules and 18 scintillator modules

WAGASCI – three dimensional grid structure of scintillators + water

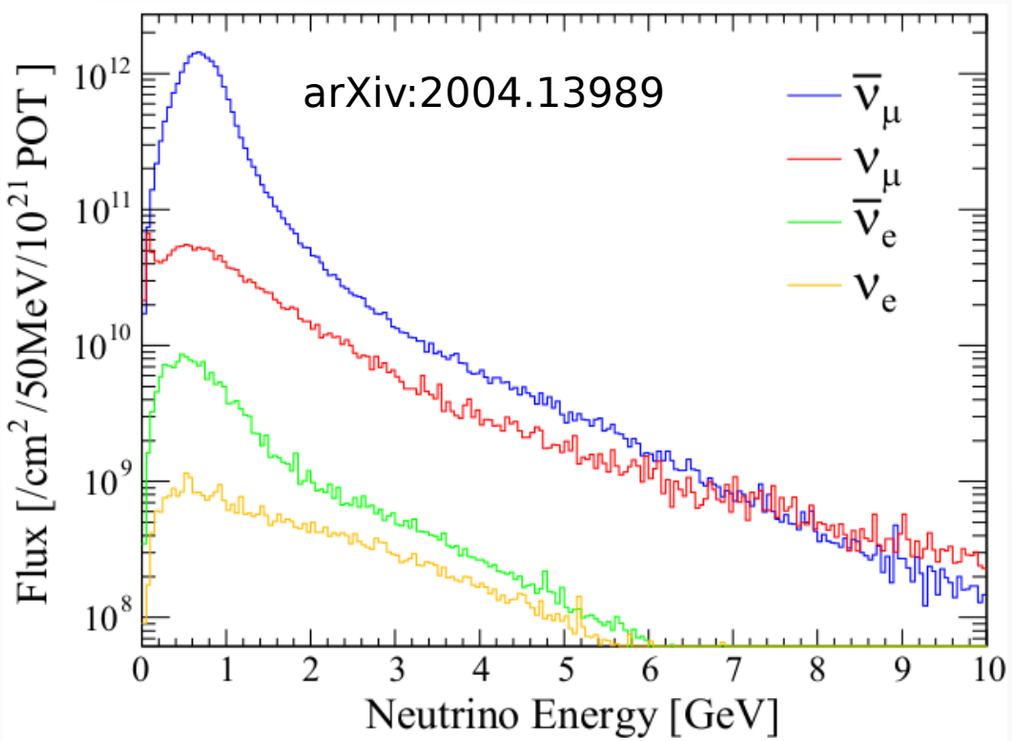
NINJA – nuclear emulsion films + steel plates

Wall Muon Range Detectors (MRDs) – iron + scintillator

Proton Module – fully active scintillator tracking detector



Proton Module+WAGASCI+INGRID module (old setup)



Predicted fluxes at the WAGASCI module (anti-neutrino beam mode)

Proton Module – fully active scintillator tracking detector

WAGASCI – scintillator bars + water target (80% of fiducial volume)

INGRID module – scintillator tracking planes + iron plates

$\bar{\nu}_\mu$ and $\bar{\nu}_\mu+\nu_\mu$ CC0π0p cross sections on H_2O and CH at mean antineutrino energy of 0.86 GeV

Data collected from October 2017 to May 2018.
Statistics of 7.91×10^{20} POT

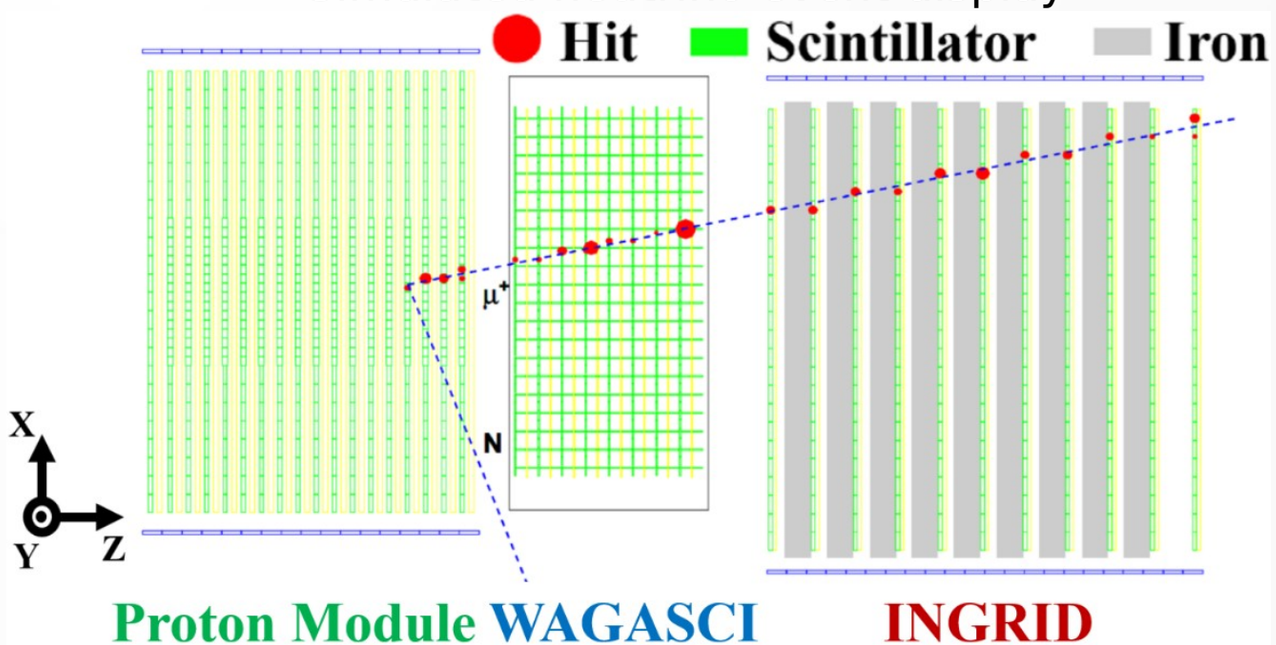
Events having more than one track excluded.

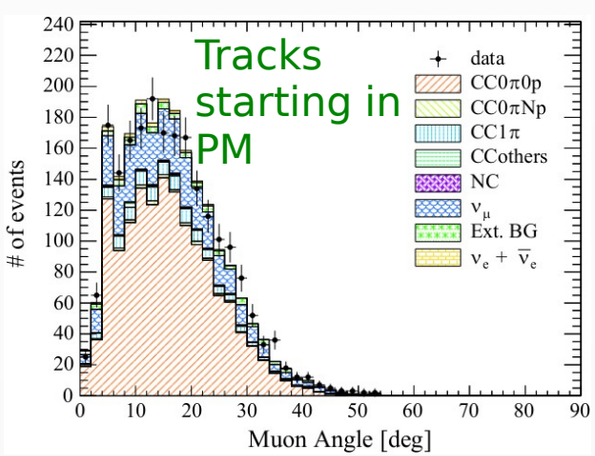
Reconstructed μ track starting in Proton Module or WAGASCI.

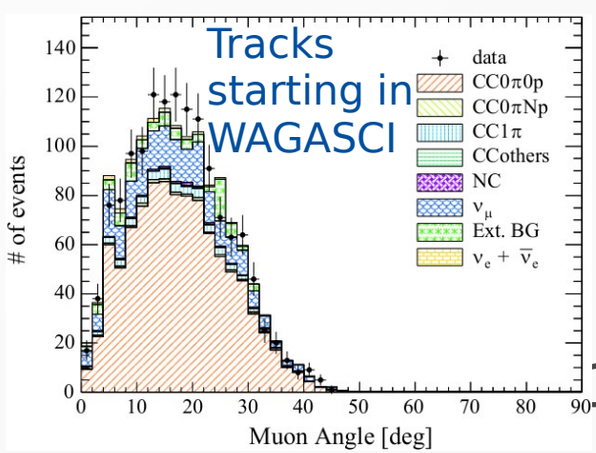
Angular acceptance based on (extrapolated) track's range.

Published in PTEP 2021 4, 043C01 (arXiv:2004.13989)

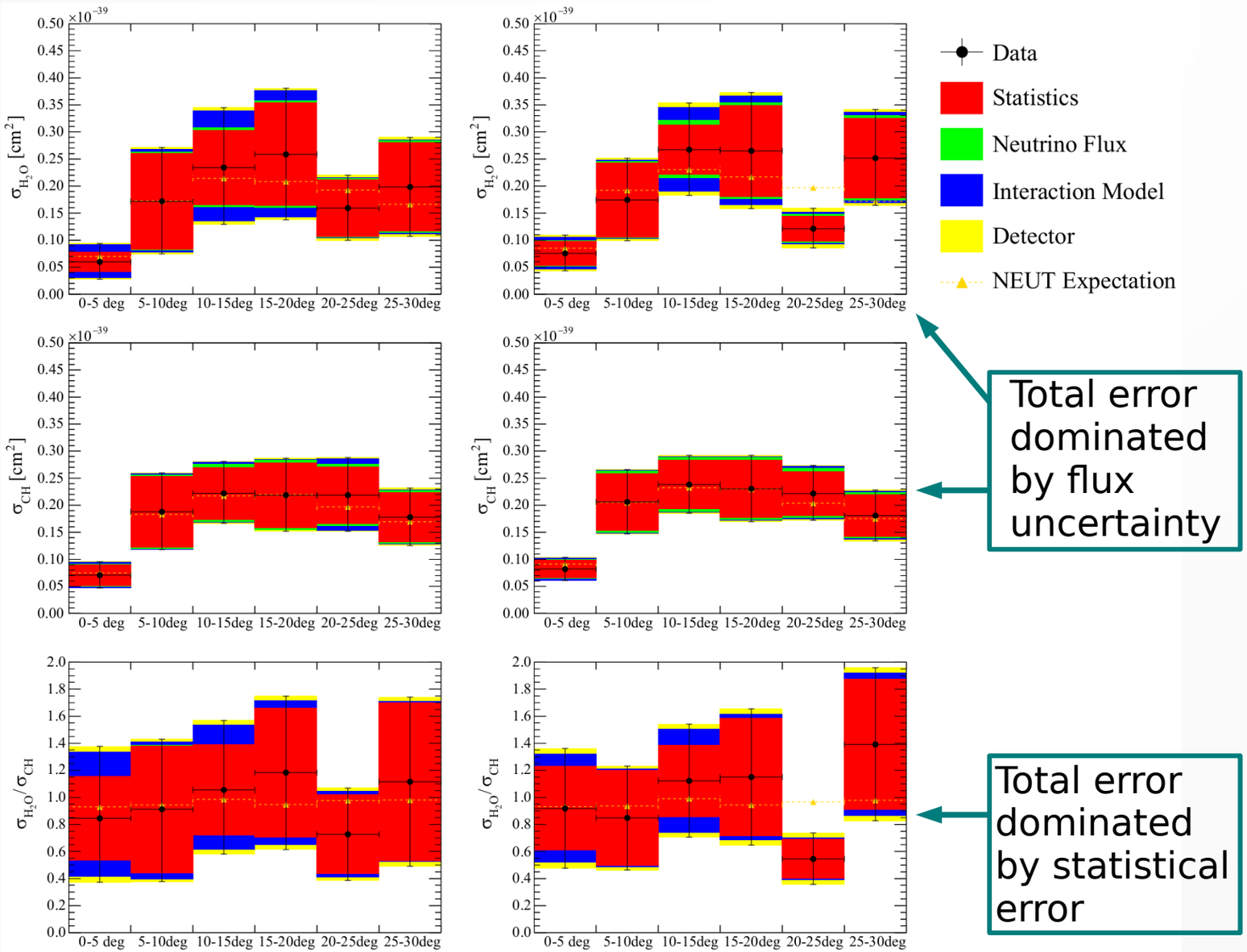
Simulated neutrino event display







$\bar{\nu}_\mu$ and $\bar{\nu}_\mu+\nu_\mu$ CC0π0p cross sections on H_2O and CH at mean antineutrino energy of 0.86 GeV



Total error dominated by flux uncertainty

Total error dominated by statistical error

Cross section reported as flux integrated.

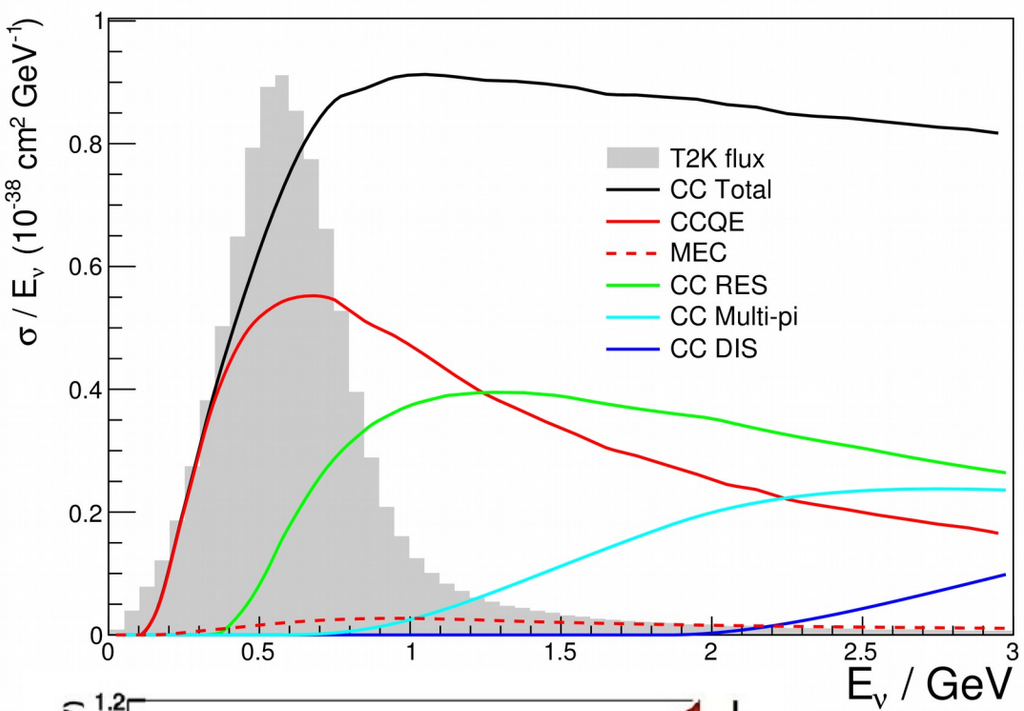
Result extracted by background subtraction. Estimated background in WAGASCI plastic scintillators based on selected event rate in the Proton Module.

Overall good agreement with NEUT MC predictions, with some discrepancy in 20-25deg region.

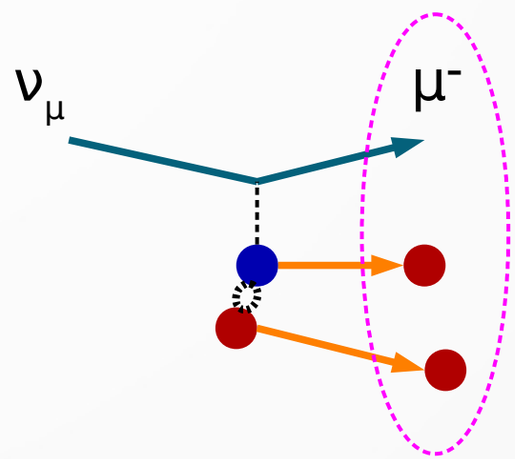
Signal and background samples

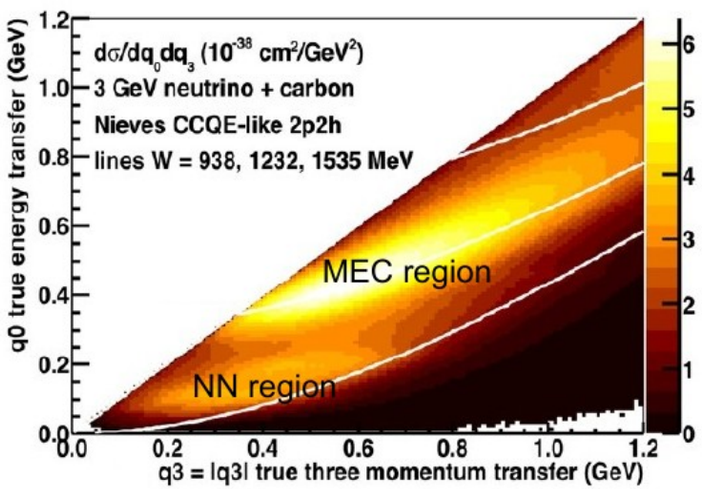
Analysis	Signal samples	Background samples
Simultaneous measurement of the ν_μ CC0π cross section on O and C at ND280	single reconstructed μ^- track + any number of reconstructed proton tracks	single reconstructed μ^- track + reconstructed π^+ track or multiple π signatures
Joint On/Off axis ν_μ CC0π measurement on scintillator with FGD1 and the Proton Module	ND280: single reconstructed μ^- track + any number of reconstructed proton tracks INGRID: single μ-like track starting in Proton Module	ND280: single reconstructed μ^- track + π^+ signature INGRID: CC1π^+ sample
Transverse kinematic imbalance (TKI) in ν_μ CC1π^+ production channel containing at least one proton	single reconstructed μ^- track + single reconstructed π^+ track + any number of reconstructed proton tracks	single reconstructed μ^- track + single reconstructed π^+ track + any number of reconstructed proton tracks + π^- or π^0 signatures
ν_μ and anti-ν_μ CC coherent pion production on carbon	exactly two reconstructed tracks: single μ-like track + single π-like track	events with high momentum transferred squared or events with more than 3 FGD1 track segments
anti-ν_μ and anti-ν_μ+ν_μ CC0π0p cross sections on H_2O and CH at mean antineutrino energy of 0.86 GeV	single reconstructed μ-like track and no other tracks	multi-track events

2p2h final state



Neutrino interaction on a bound state of two nucleons can lead to **2p2h** final state (topology with two nucleons ejected from the nucleus). **Meson exchange current (MEC)** interaction is the dominant source of this effect.





The 2p2h cross section for the Nieves model (arXiv:1102.2777) in the true three-momentum transfer q3 and true energy transfer q0 phase-space. Plot from T2K tech-note 315.