Neutrino Cross-Section Measurements at T2K

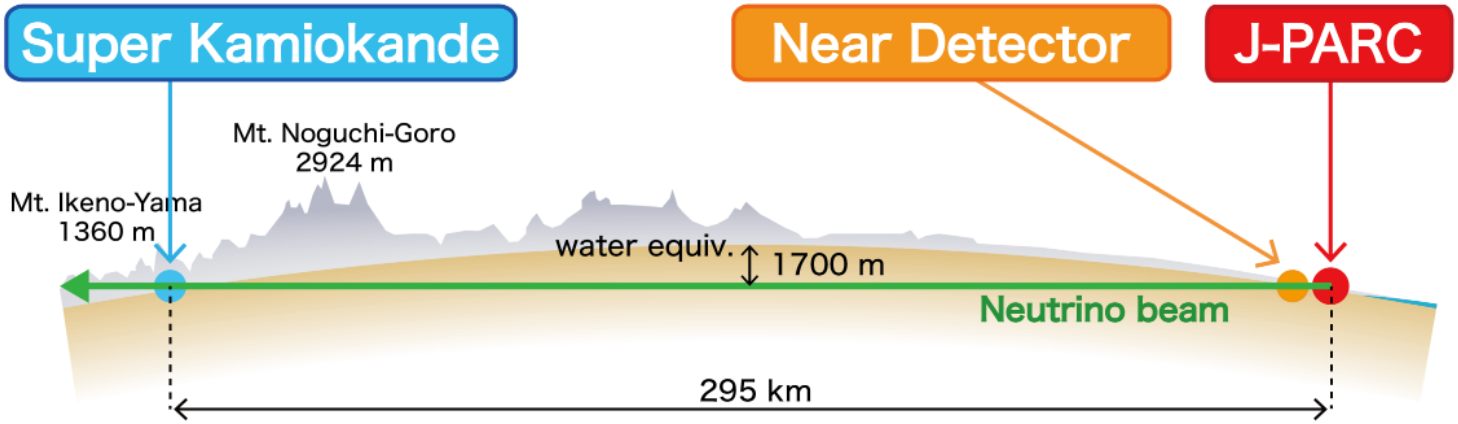
Matthew Malek (on behalf of the T2K Collaboration)

16th March 2017

XVII International Workshop on Neutrino Telescopes

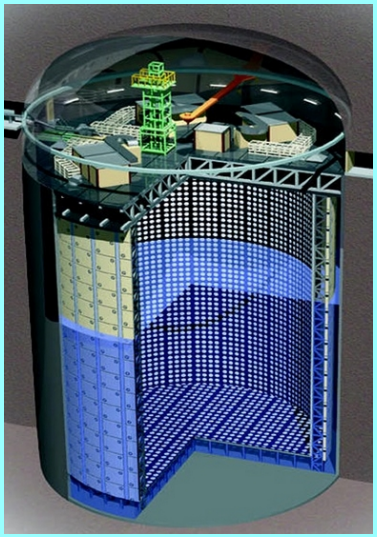
The T2K Experiment

The University Of Sheffield.



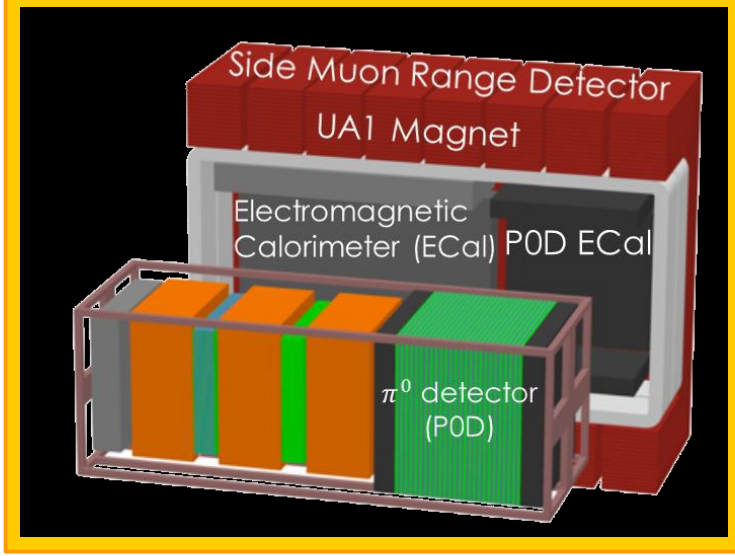
See talks from:
T. Nakaya (Monday)
A. Izmaylov (Tuesday)

Far Detector (off-axis) Super-Kamiokande

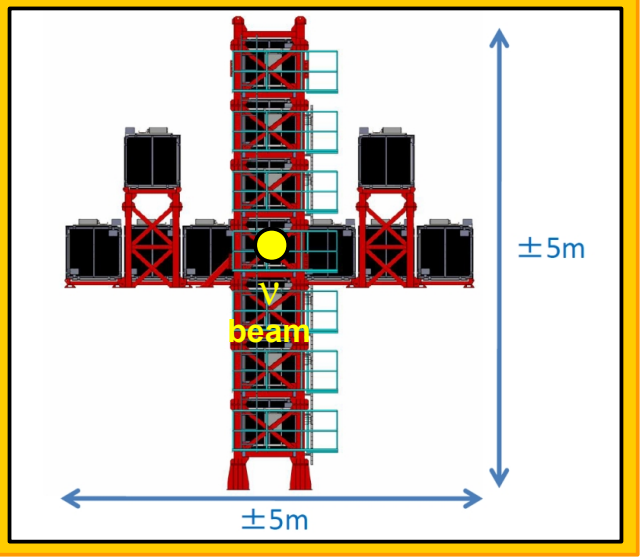


Near Detectors

Off-axis: ND280



On-axis: INGRID



Off-Axis Design

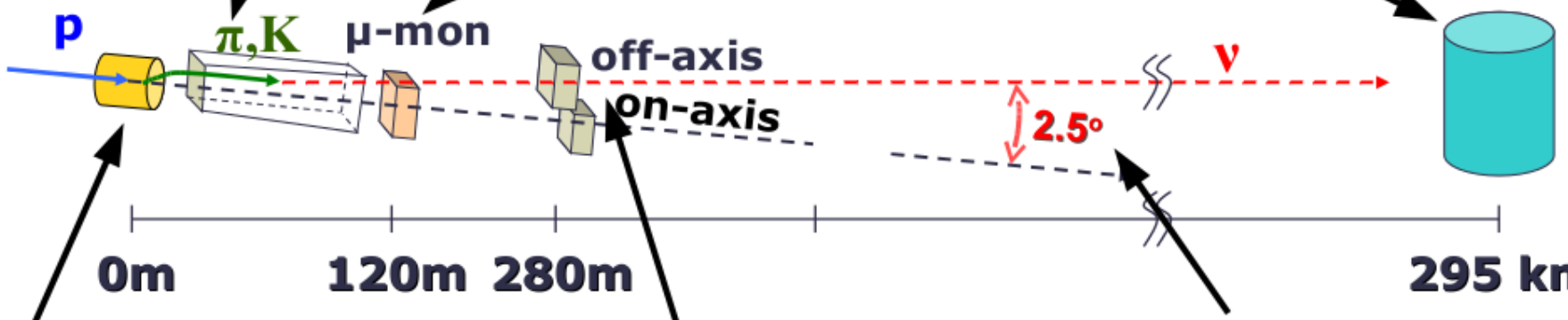
The University Of Sheffield.

30 GeV proton beam from J-PARC

Pions, kaons, muons decay in 96 m decay volume

MUMON measures muons from pion decay

Off-axis **far detector** at 295 km: Super-Kamiokande (SK) water cherenkov detector measures oscillated flux



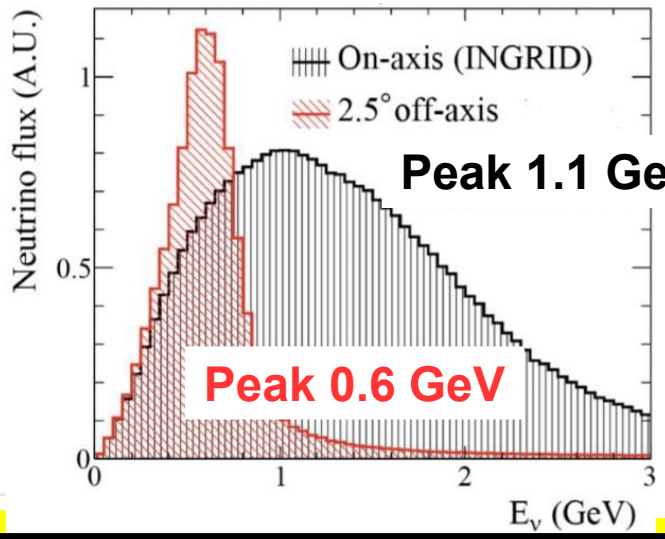
Beam on graphite target

3 magnetic horns focus positively charged hadrons

At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

Off-axis **near detector**: ND280 detector measures spectra for various neutrino interactions

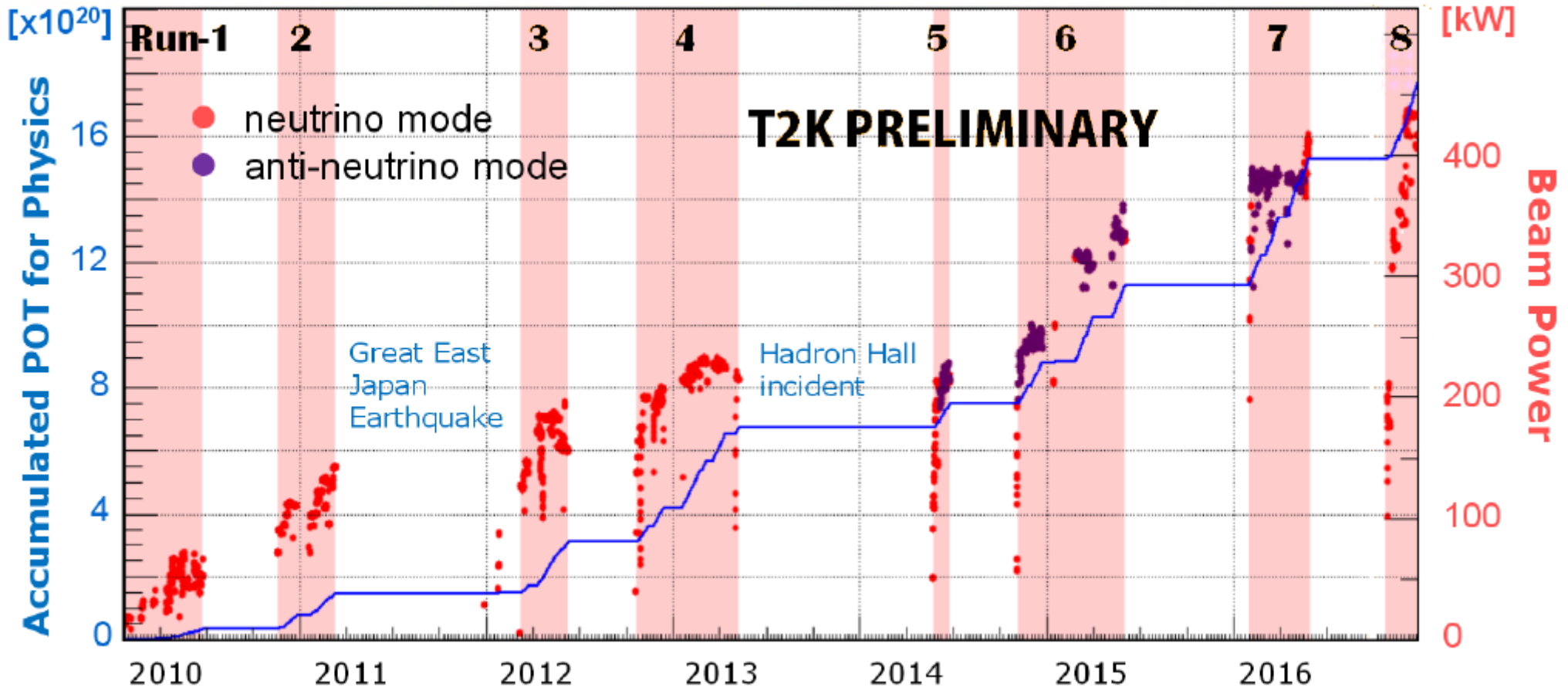
Off-axis = narrow band beam



T2K Data Taking

The University Of Sheffield.

P.O.T. = Protons On Target



Beam power continuously improving!

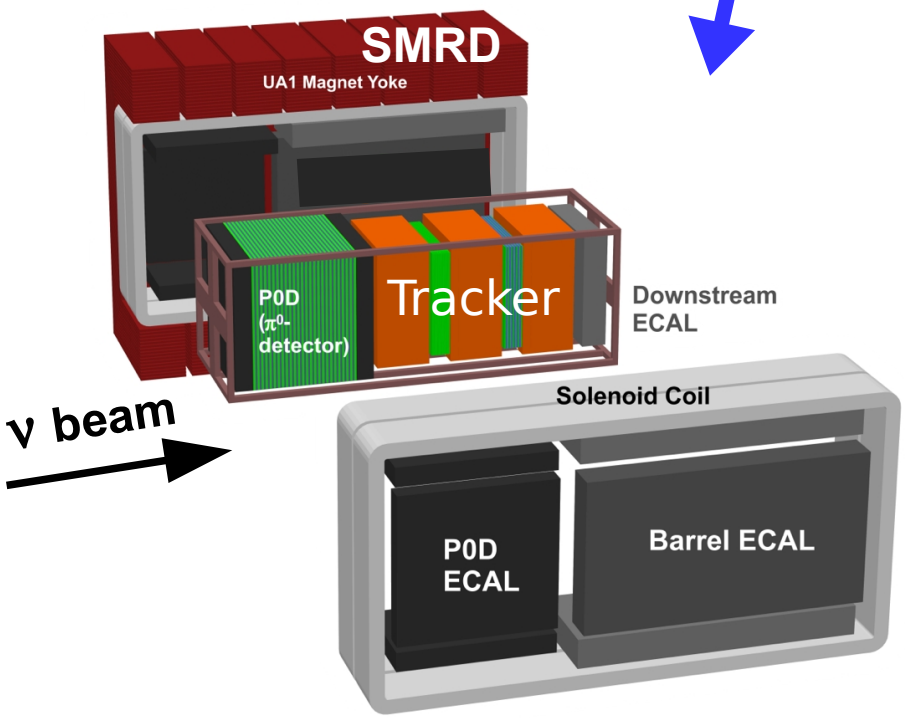
- Current power ~470 kW (2017) is <u>double</u> 2014 value of ~225 kW

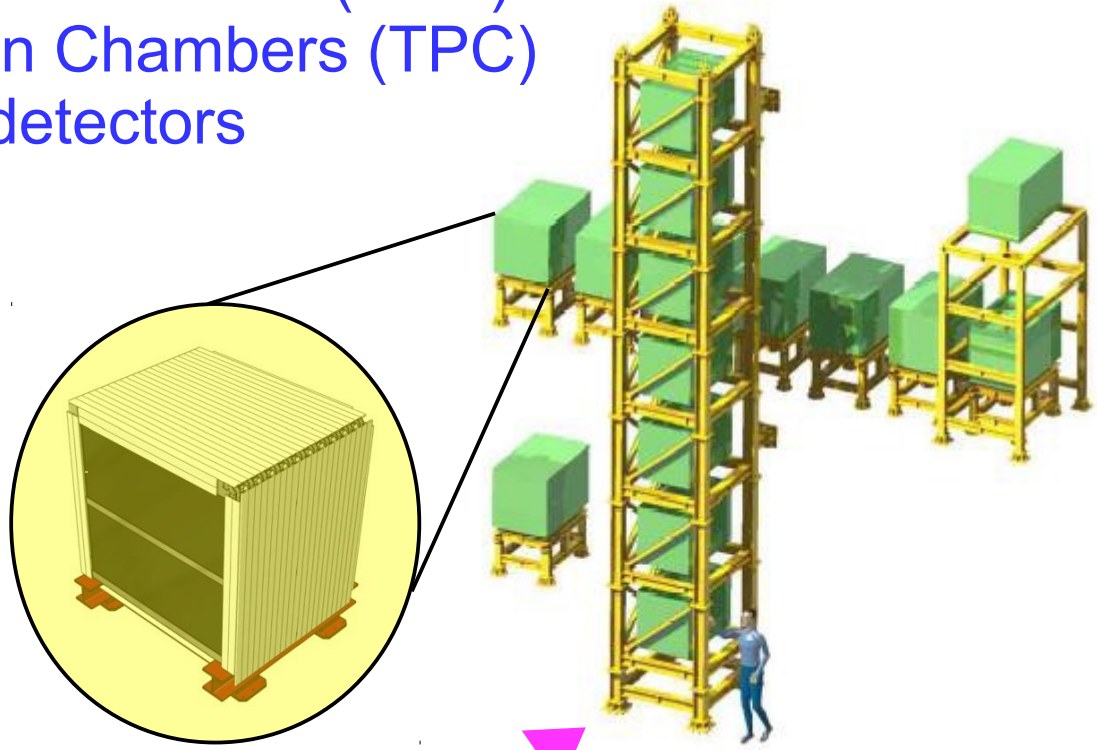
The Near Detector Suite

The University Of Sheffield.

The ND280 detector sits 2.5º off-axis along the line to Super-K

- Tracking via two Fine-Grained Detectors (FGD) sandwiched between three Time Projection Chambers (TPC)
- Also calorimeters and muon detectors
- Carbon and water targets
- 0.2 T magnetic field





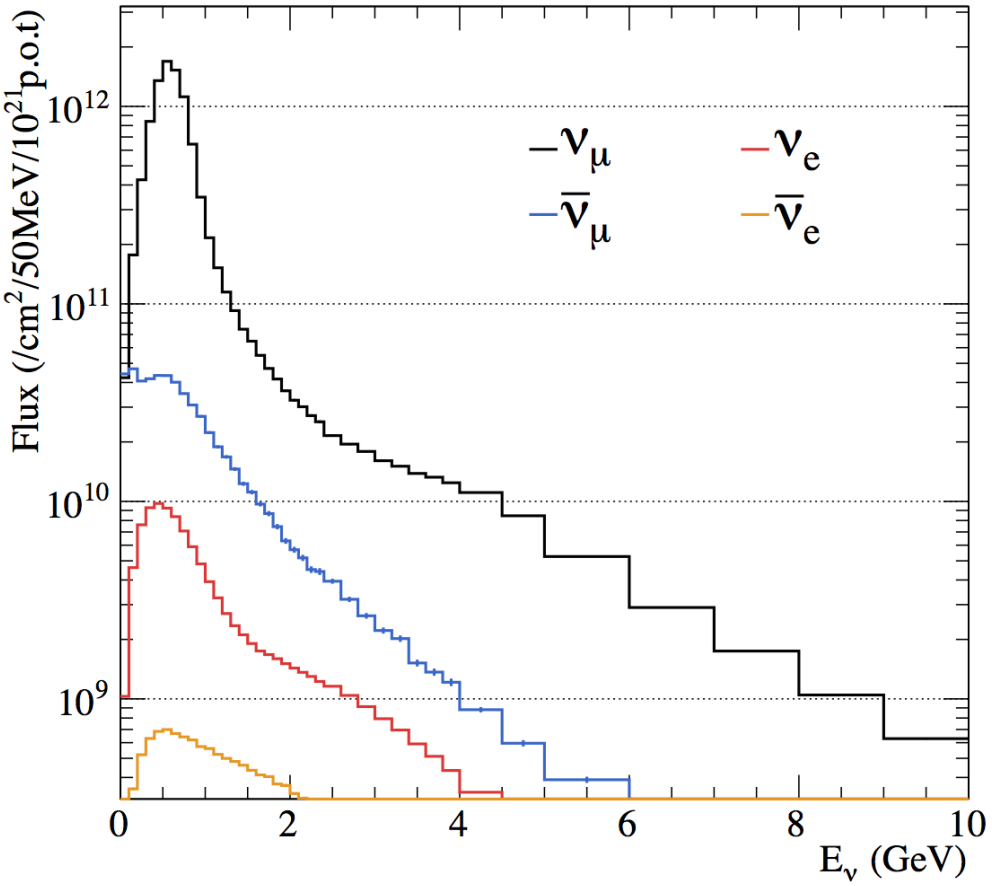
The INGRID detector sits on-axis (0º)

- Carbon and iron targets
- Monitors beam direction
- Tracks beam rate

Neutrino Fluxes @ ND280

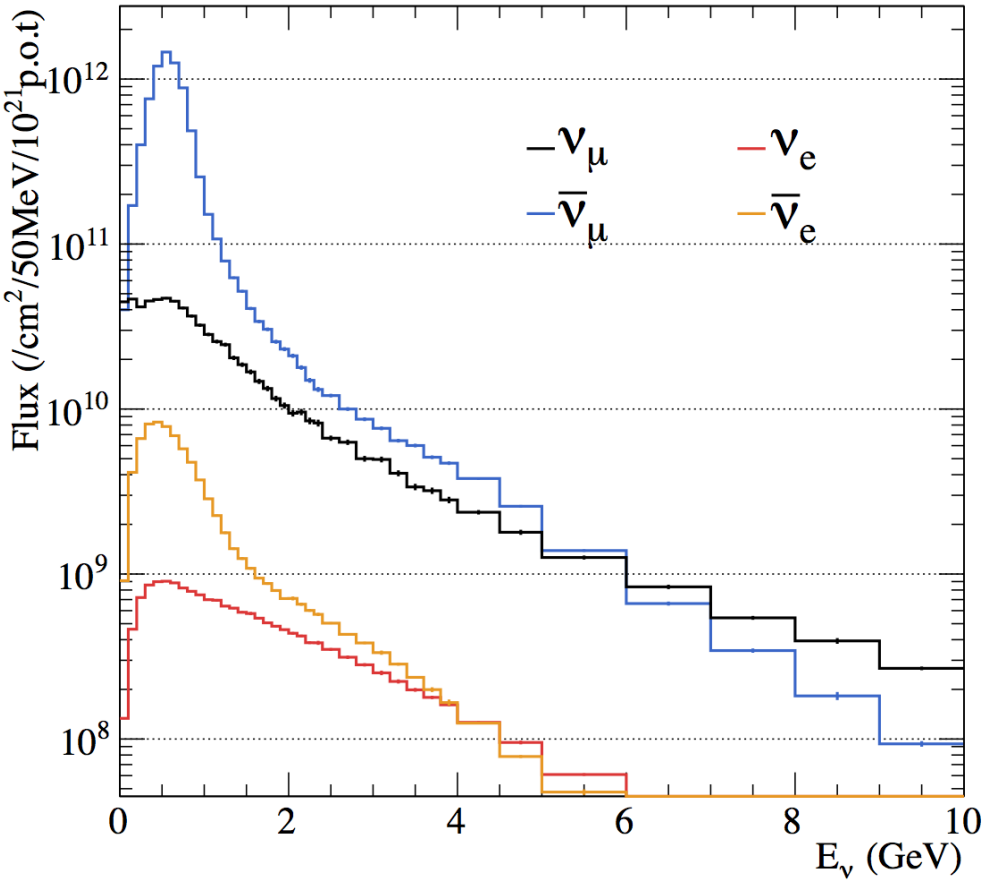
The University Of Sheffield.

Forward Horn Current



(or "Neutrino mode")

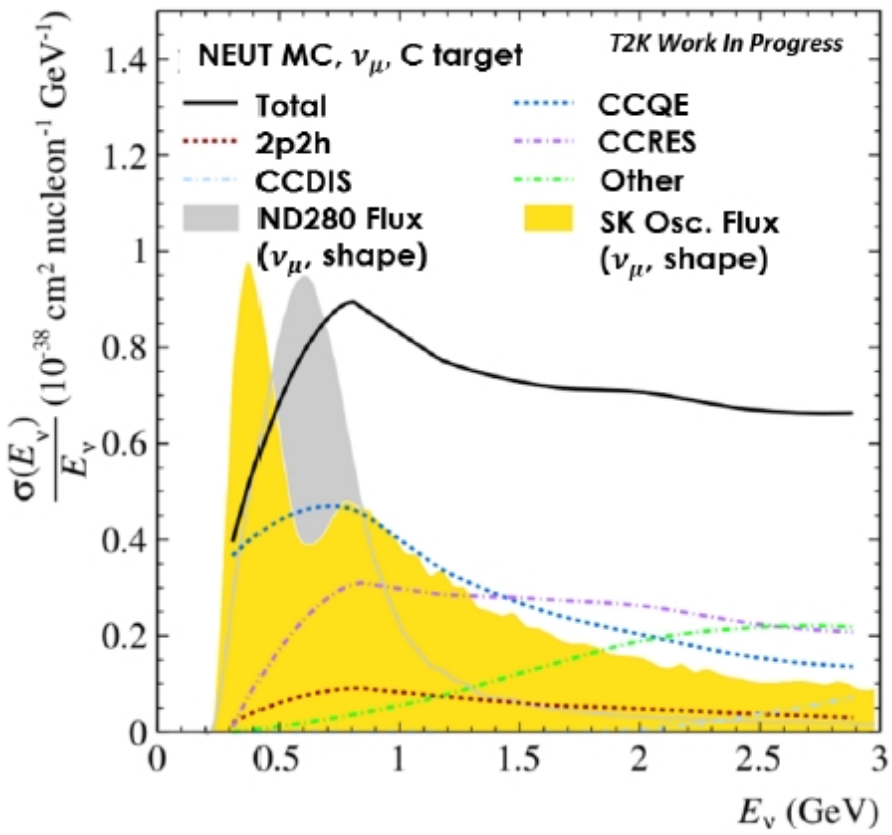
Reverse Horn Current



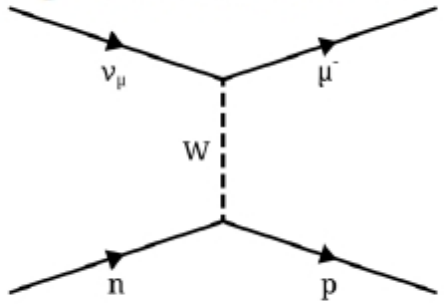
(or "Anti-neutrino mode")

ν Interactions @ T2K

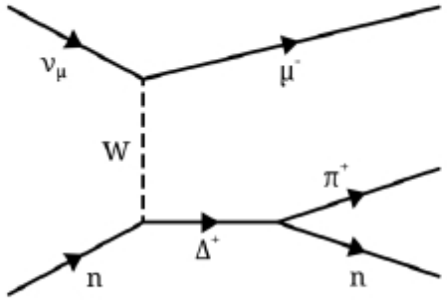
The University Of Sheffield.



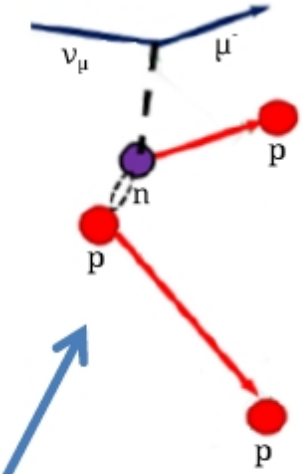
CCQE
(Charged-Current Quasi-Elastic)



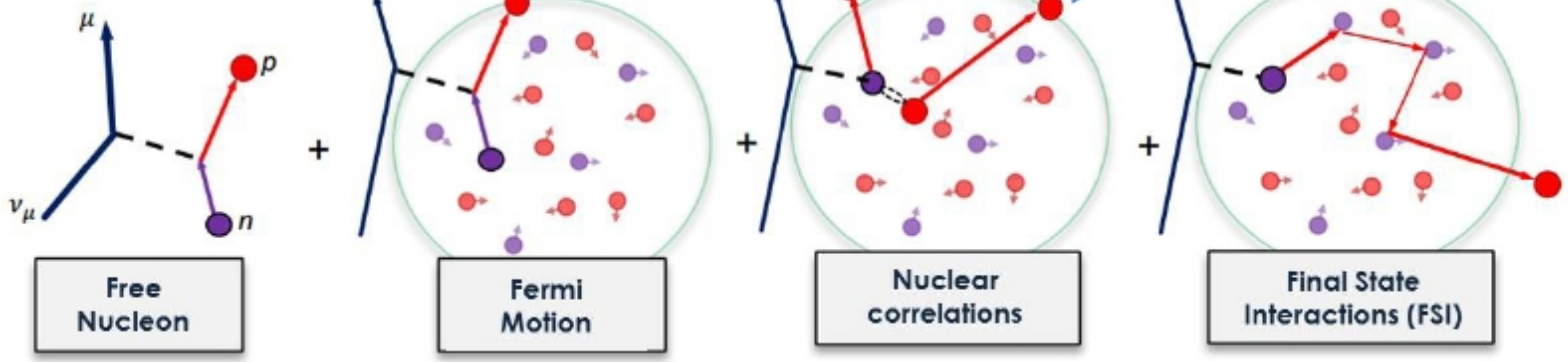
CCRES
(Charged-Current Resonant)



2p2h
(2 particle – 2 hole)



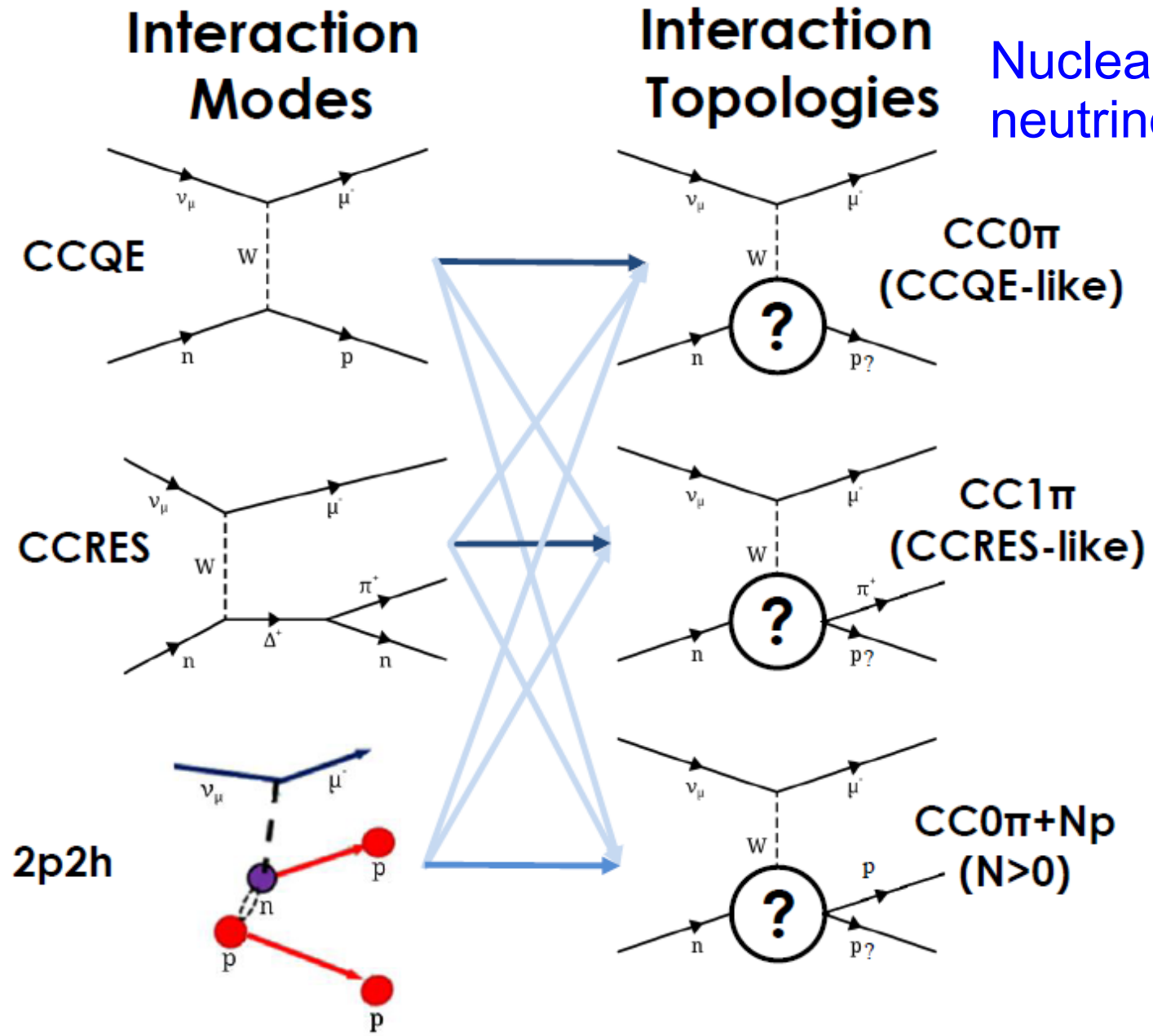
Nuclear Effects



Diagrams by Patrick Stowell

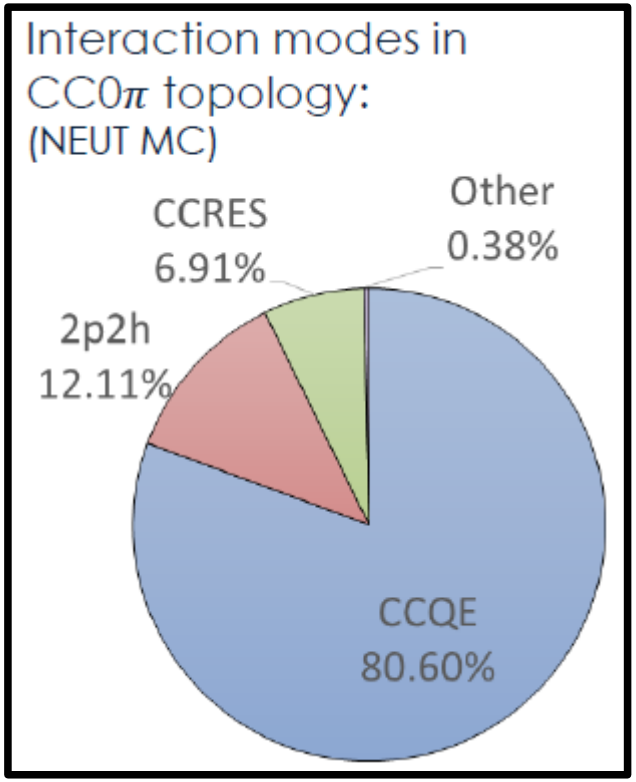
Event Topologies

The University Of Sheffield.

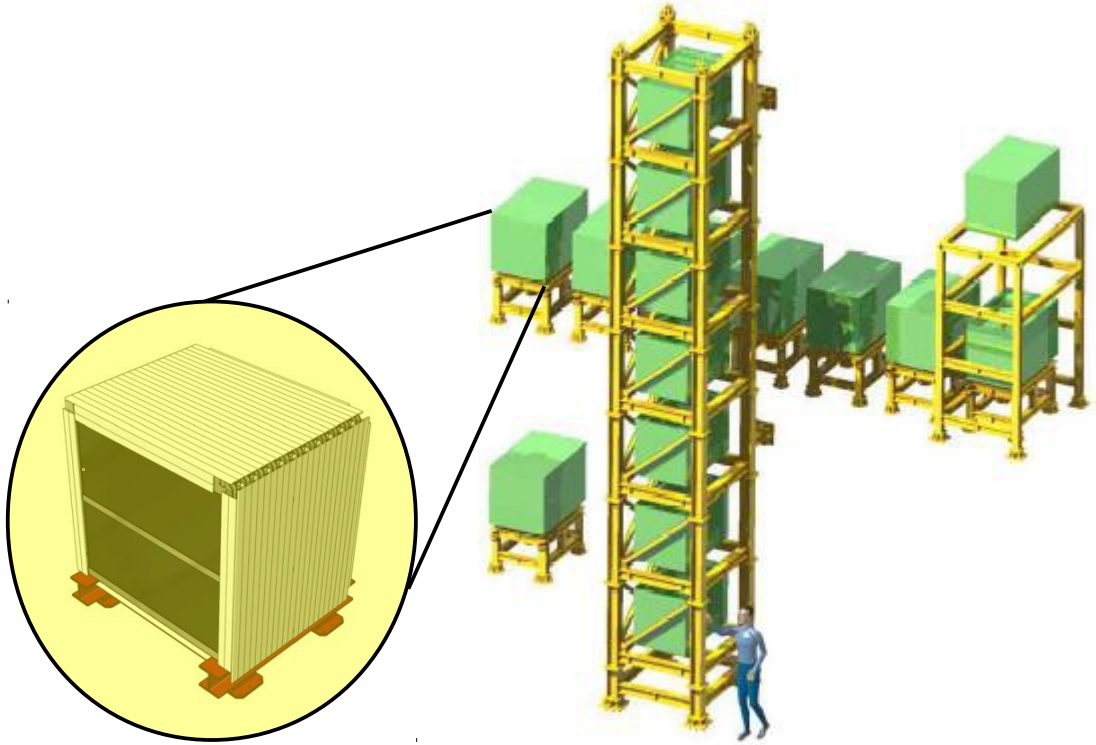


Nuclear effects can mask the neutrino interaction mode.

Measurements based on experimental event topologies.



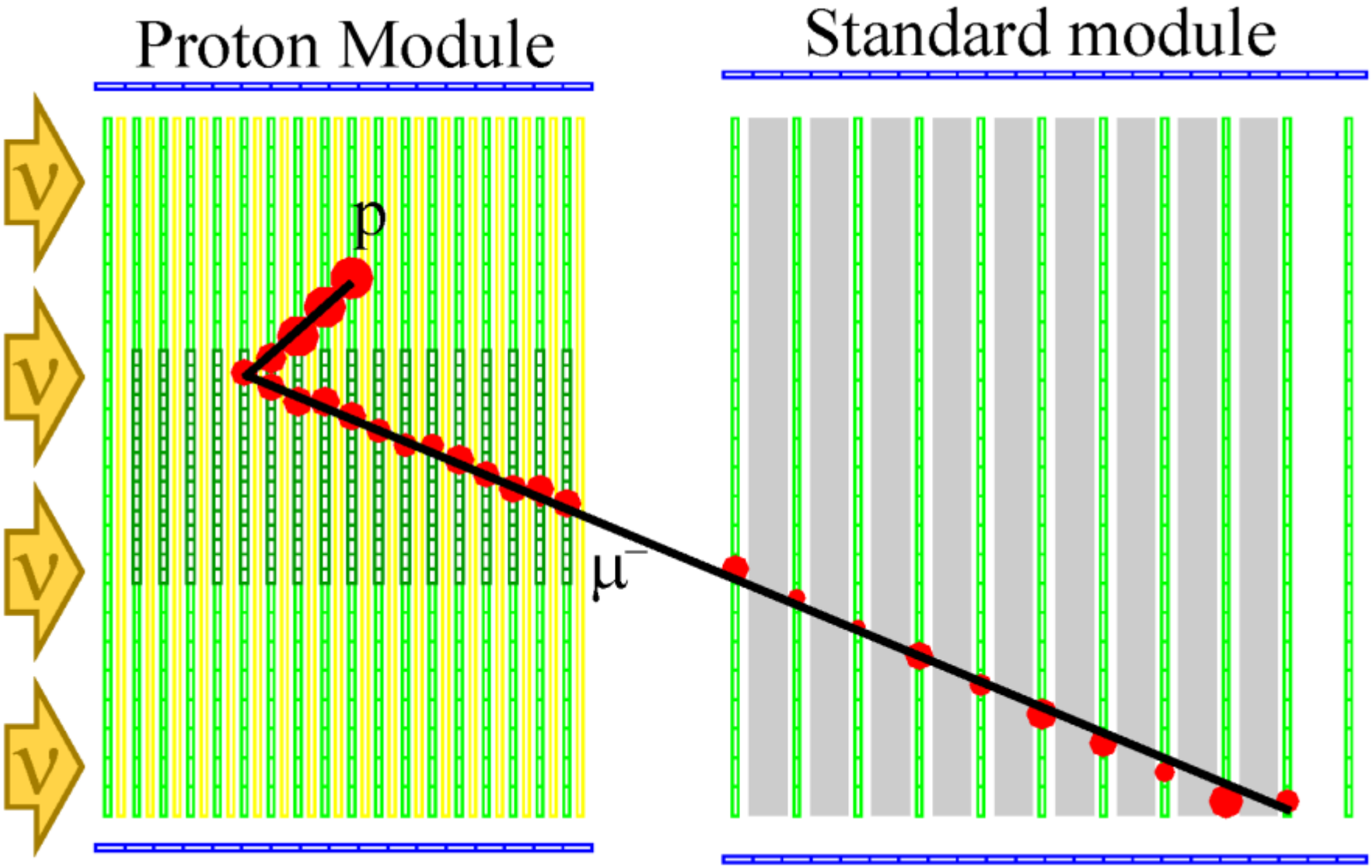
On-Axis Results from INGRID



ν_μ CCQE on Carbon

The University Of Sheffield.

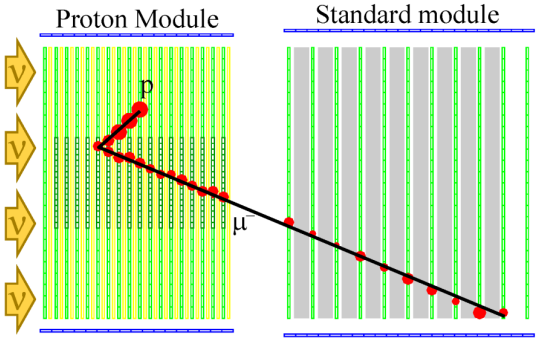
Uses the proton module in front of central INGRID module

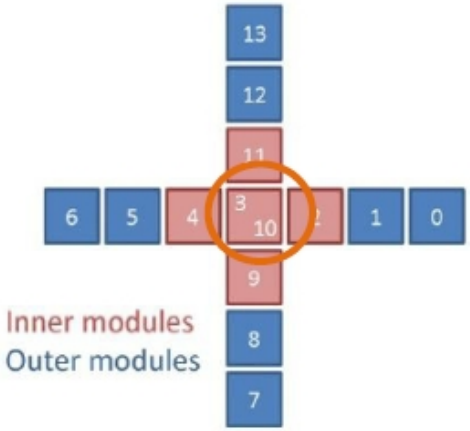


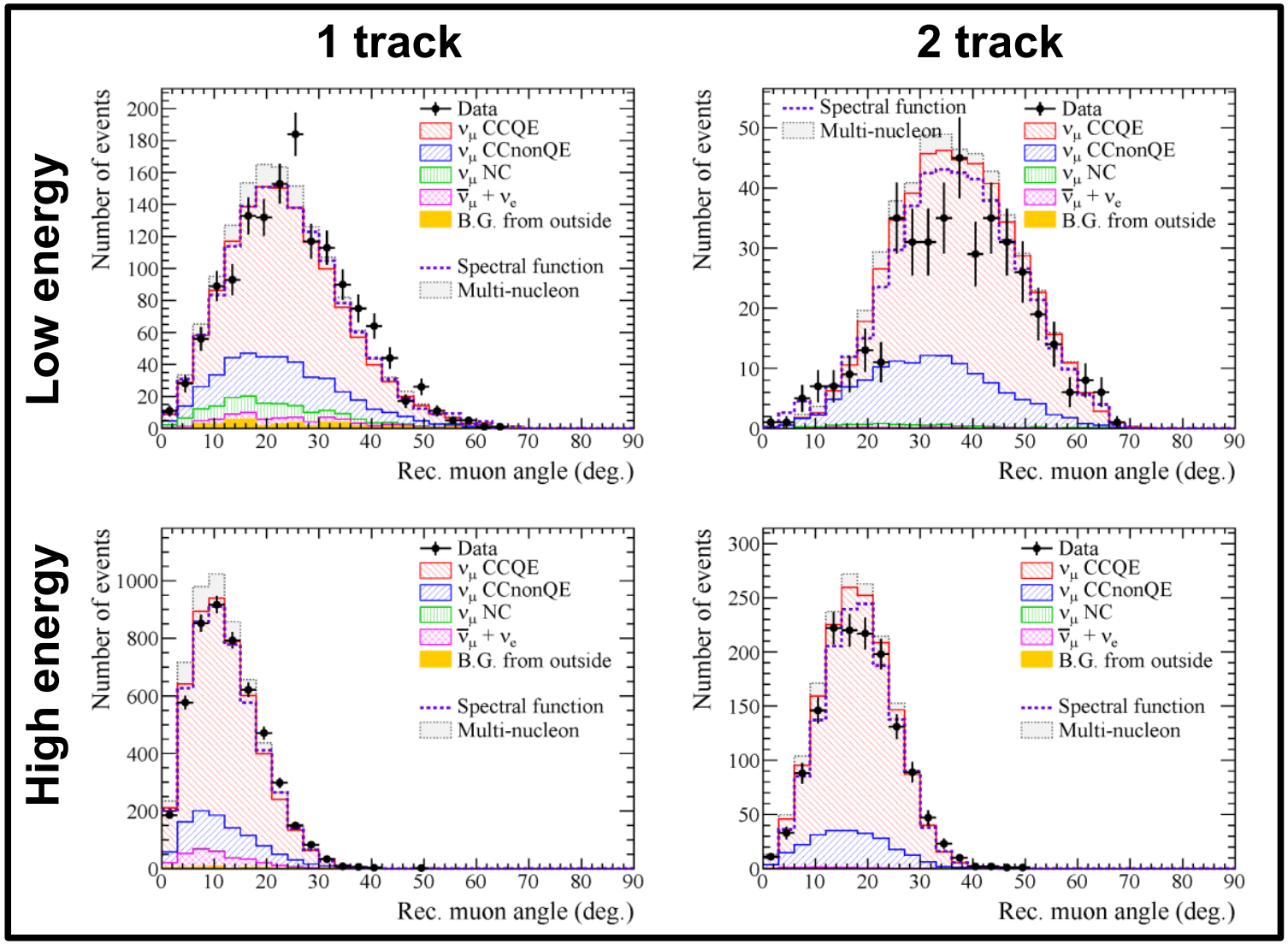
ν_μ CCQE on Carbon

The University Of Sheffield.

Uses the proton module in front of central INGRID module
Data divided into samples based on topology and energy



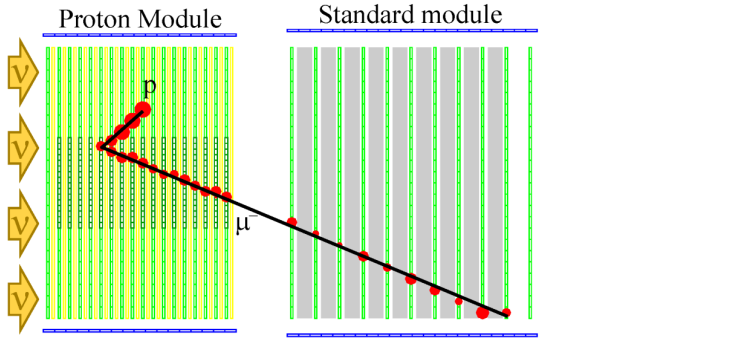


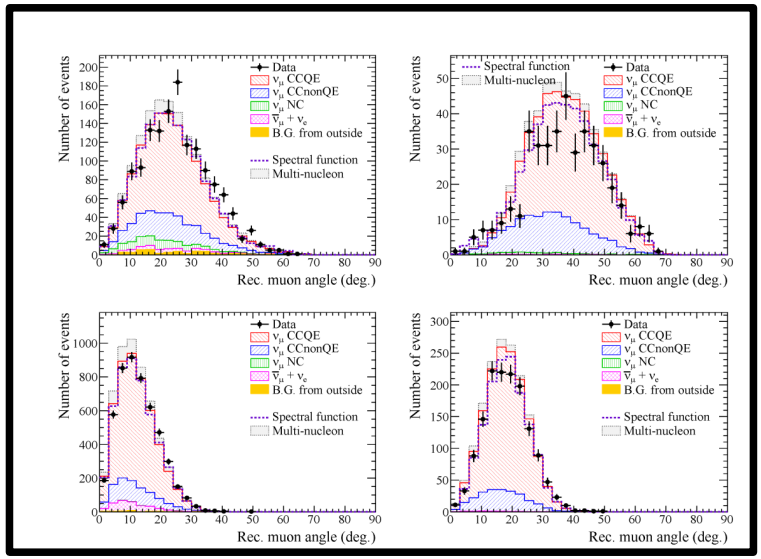


ν_μ CCQE on Carbon

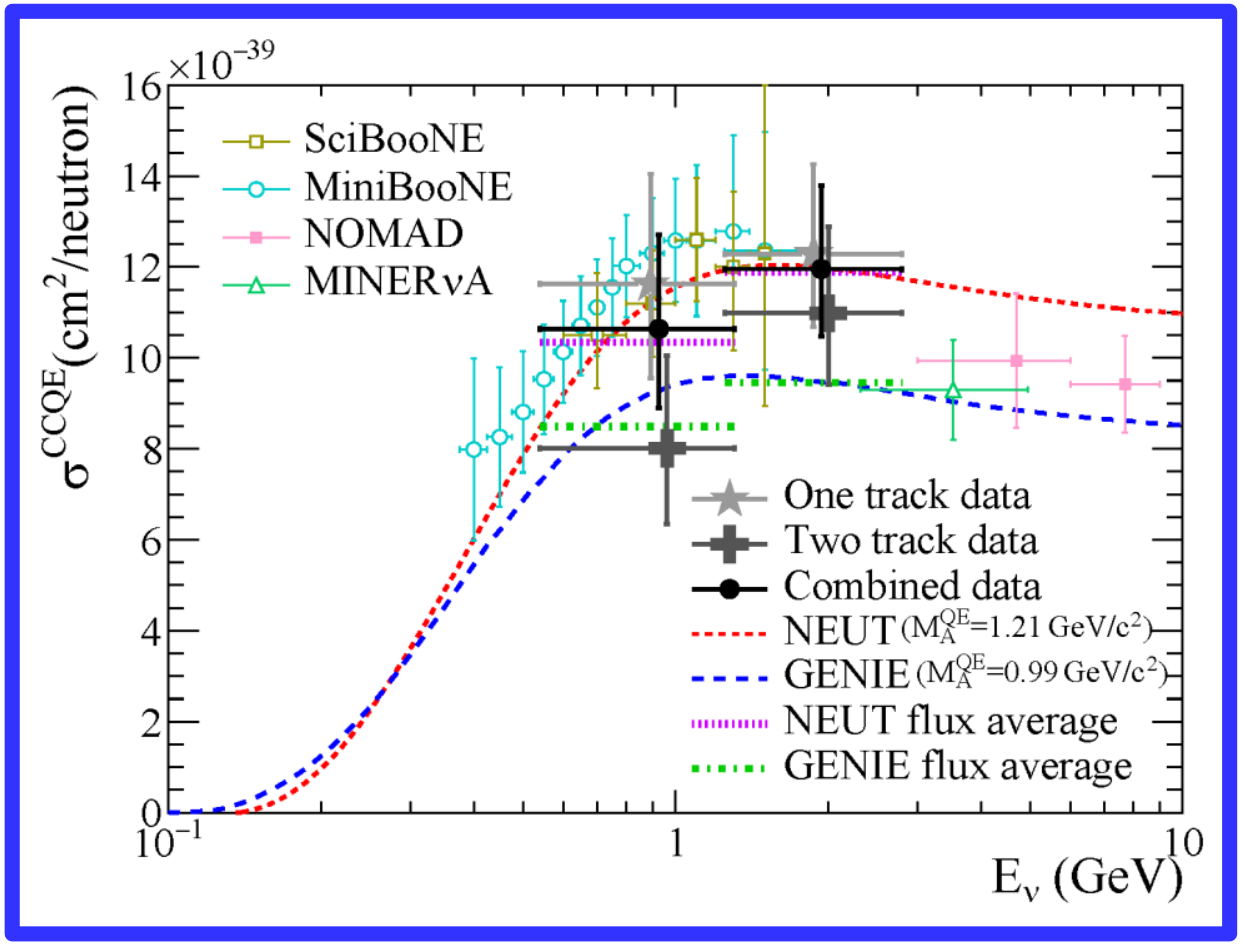
The University Of Sheffield.

Uses the proton module in front of central INGRID module
Data divided into samples based on topology and energy





6.4 x 10^{20} P.O.T. in Neutrino mode



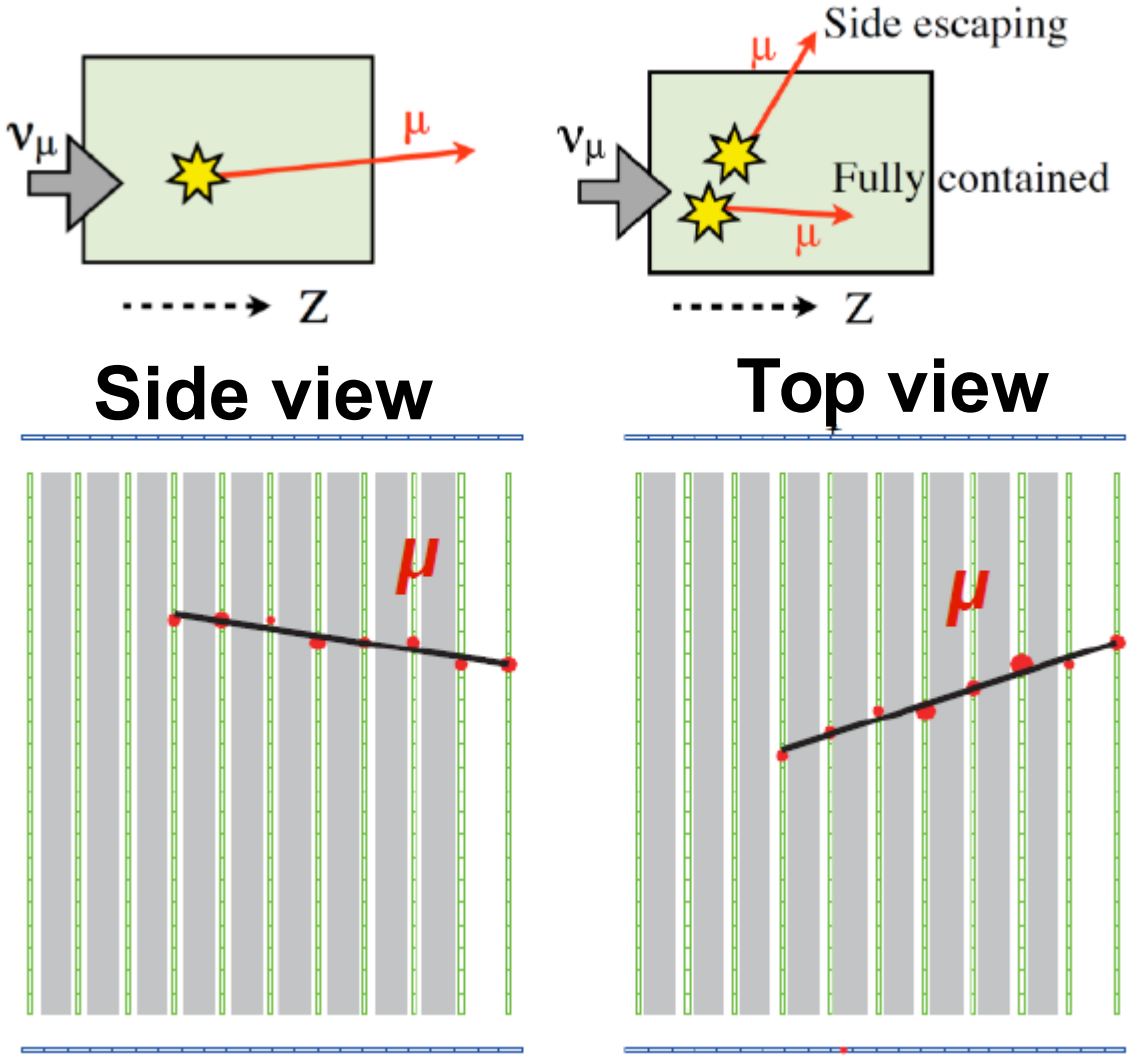
Data cannot distinguish between NEUT & GENIE

Published in PRD **91**:112002 (2015)

ν_μ CC-inclusive on Iron

The University Of Sheffield.

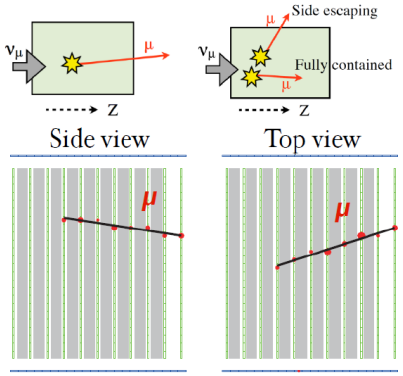
Exploits different fluxes in different INGRID modules

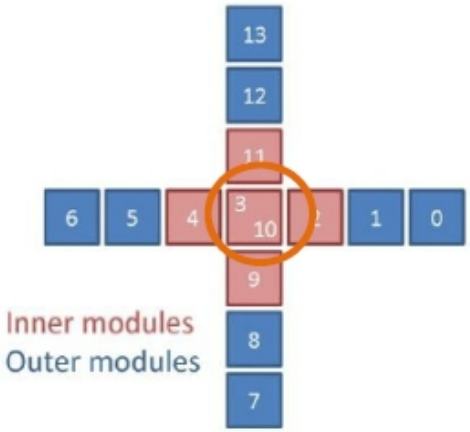


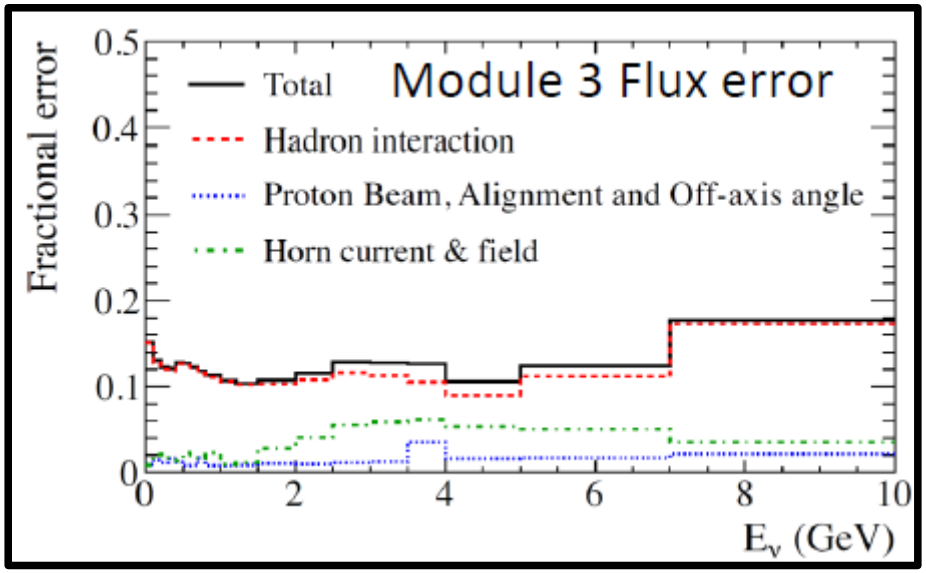
ν_μ CC-inclusive on Iron

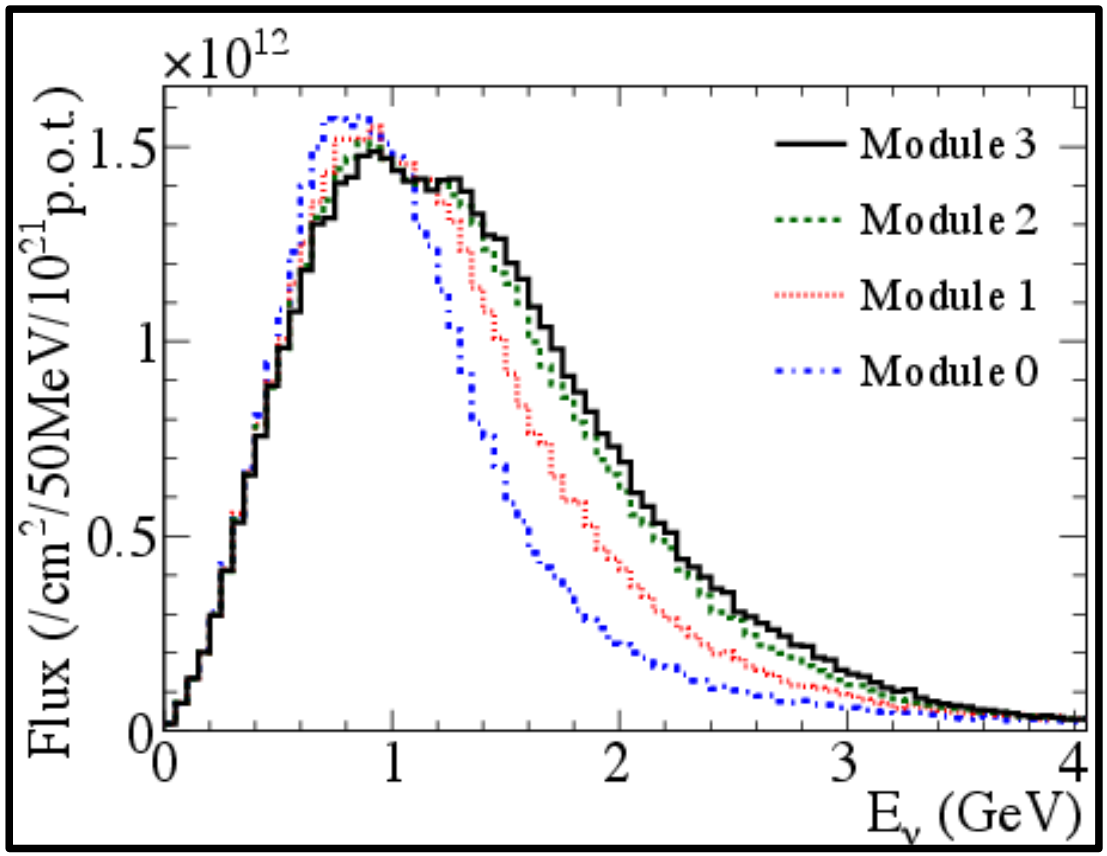
The University Of Sheffield.

Exploits different fluxes in different INGRID modules
Fit cross section using different event topologies





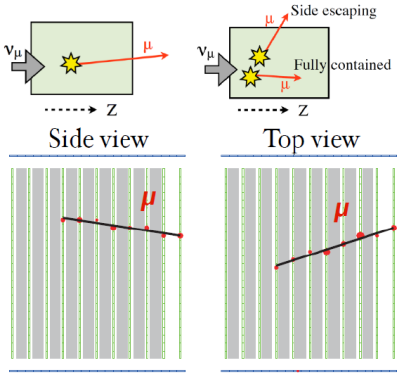




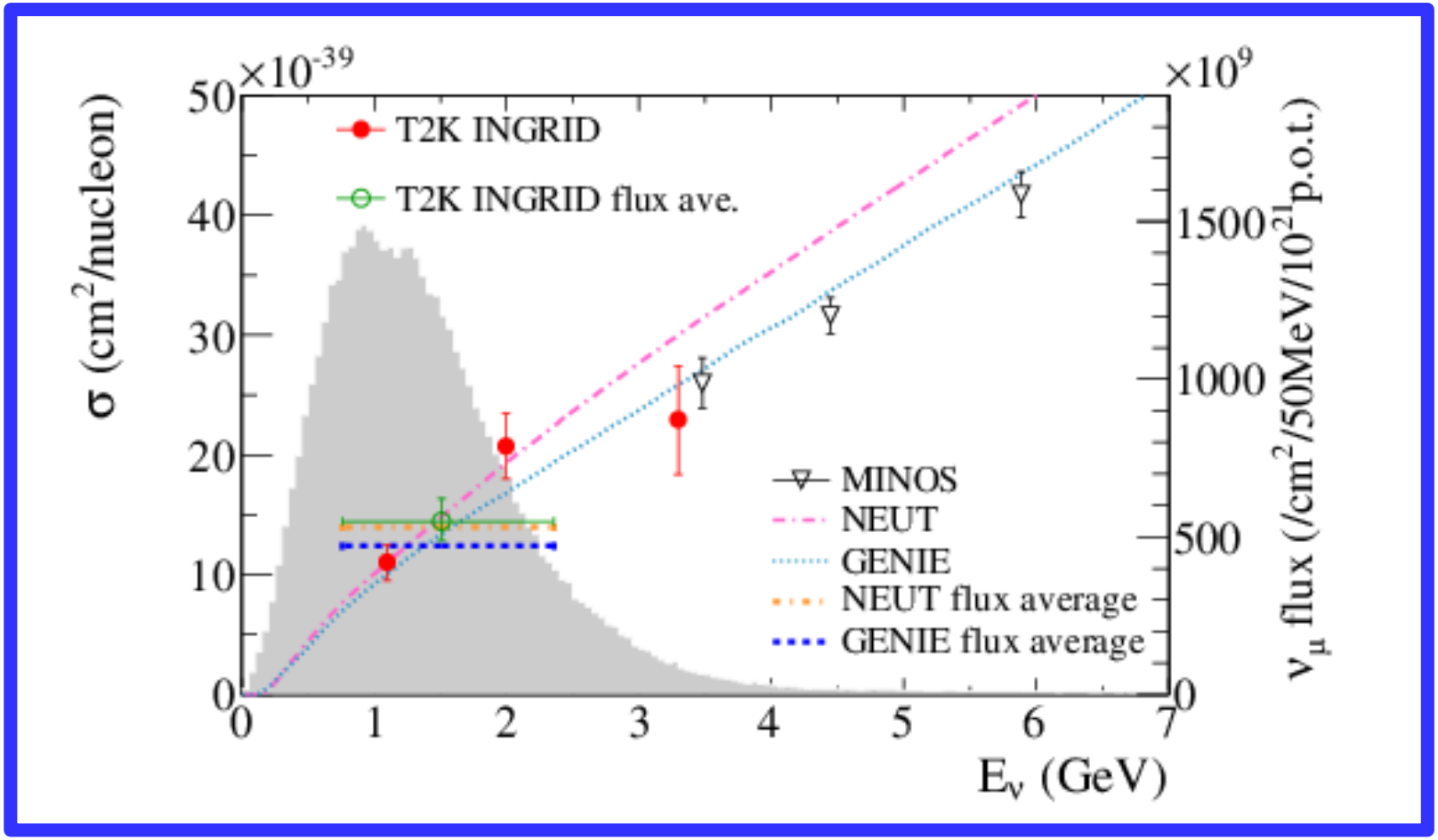
ν_μ CC-inclusive on Iron

The University Of Sheffield.

Exploits different fluxes in different INGRID modules
Fit cross section using different event topologies



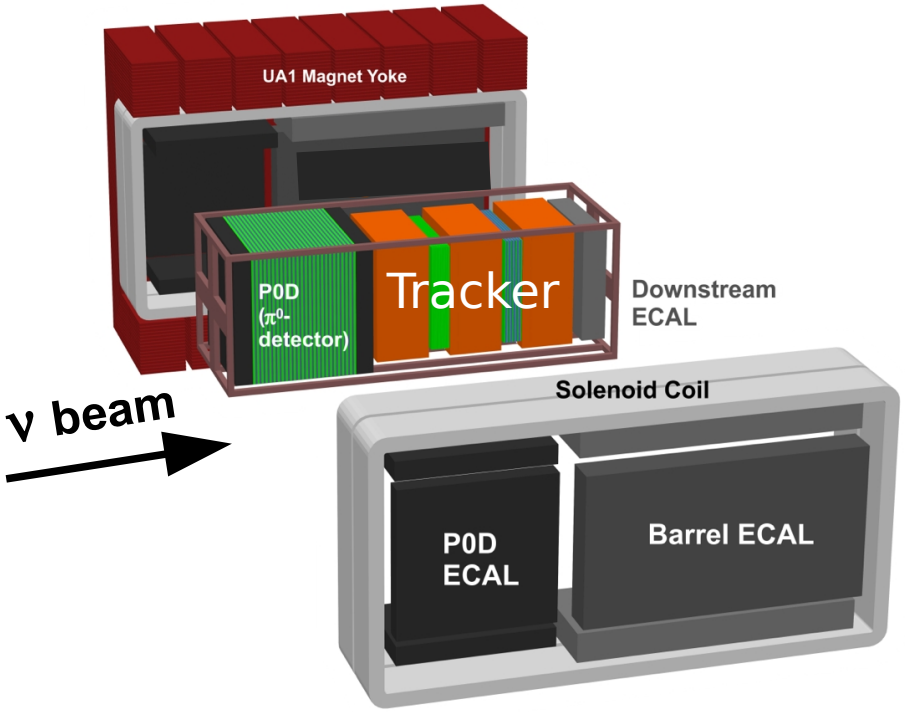
6.27 x 10^{20} P.O.T. in Neutrino mode



Published in PRD **93**:072002 (2016)

Extends energy range; no disagreement w/ models

Off-Axis Results from ND280

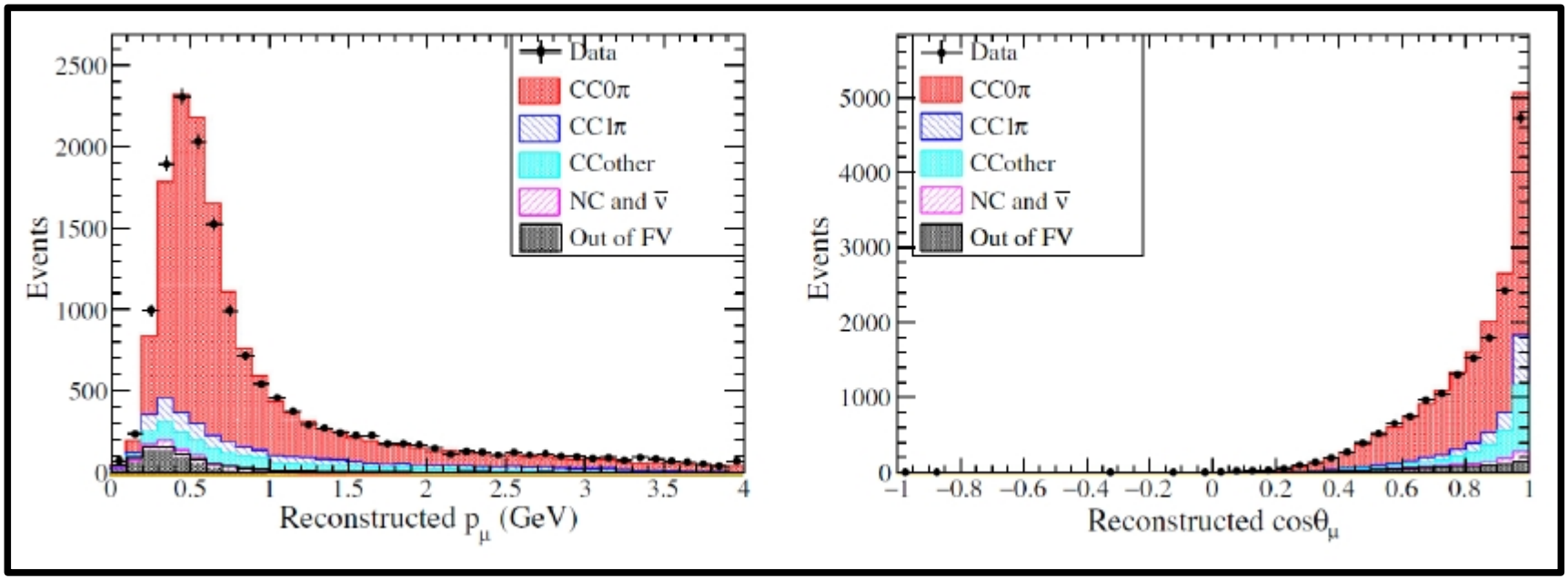


ND280 Tracker: CC0π

The University Of Sheffield.

Primary channel used in T2K oscillation analyses

- Use FGD1 as a CH target alongside TPC for tracking
- Interactions with correlated nucleons are important
  - Use models from Martini and Nieves
- Two analyses with different selection & cross-section extraction
  - Fit with additional samples to extend phase space
  - Bayesian unfolding in restricted phase space



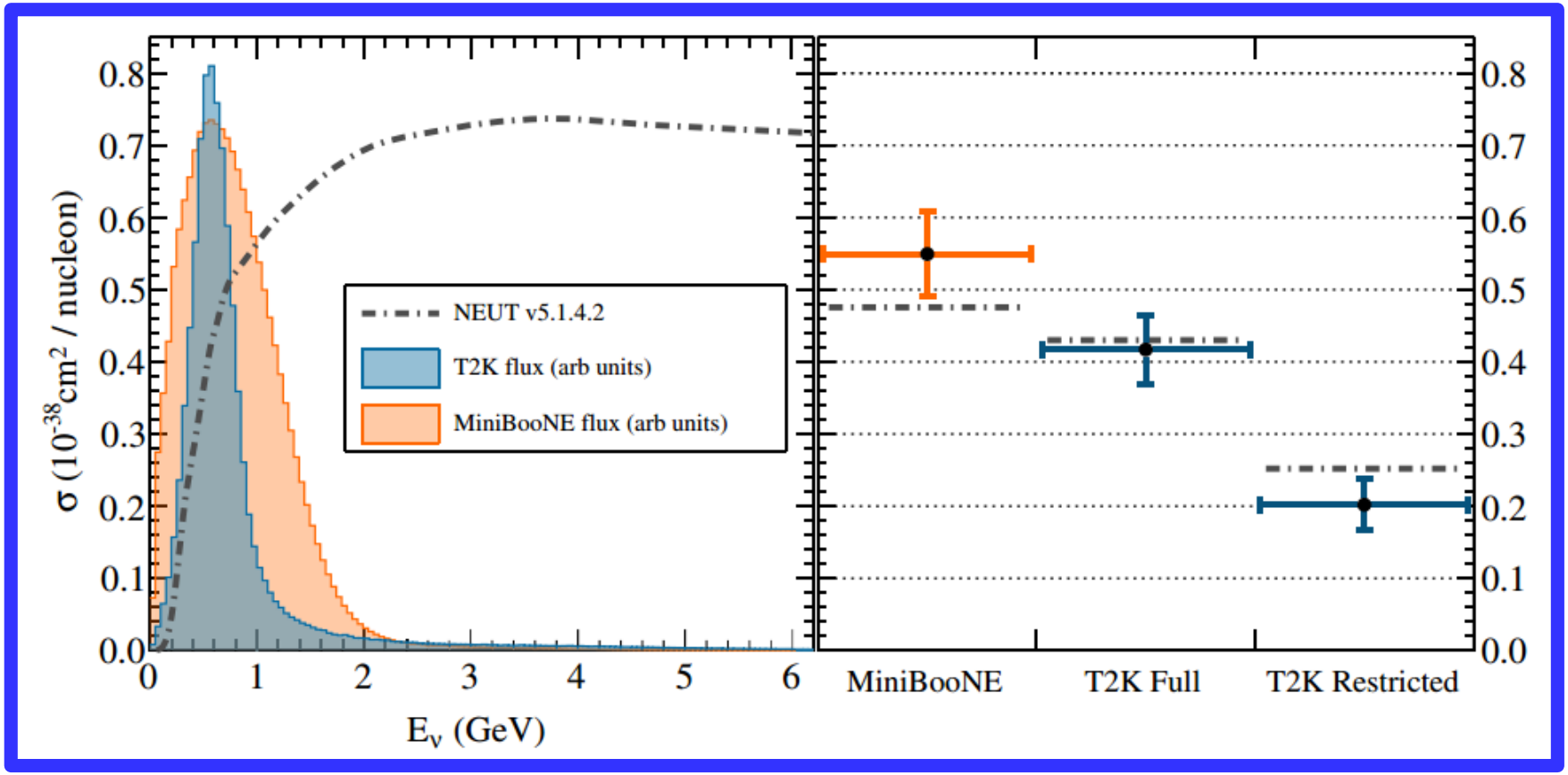
ND280 Tracker: CC0π

The University Of Sheffield.

Primary channel used in T2K oscillation analyses

- **Result:** Flux-integrated double-differential **CC0π** cross section in final state muon kinematic variables [p_μ, $\cos(\theta_\mu)$]

5.73 x 10^{20} P.O.T. in Neutrino mode



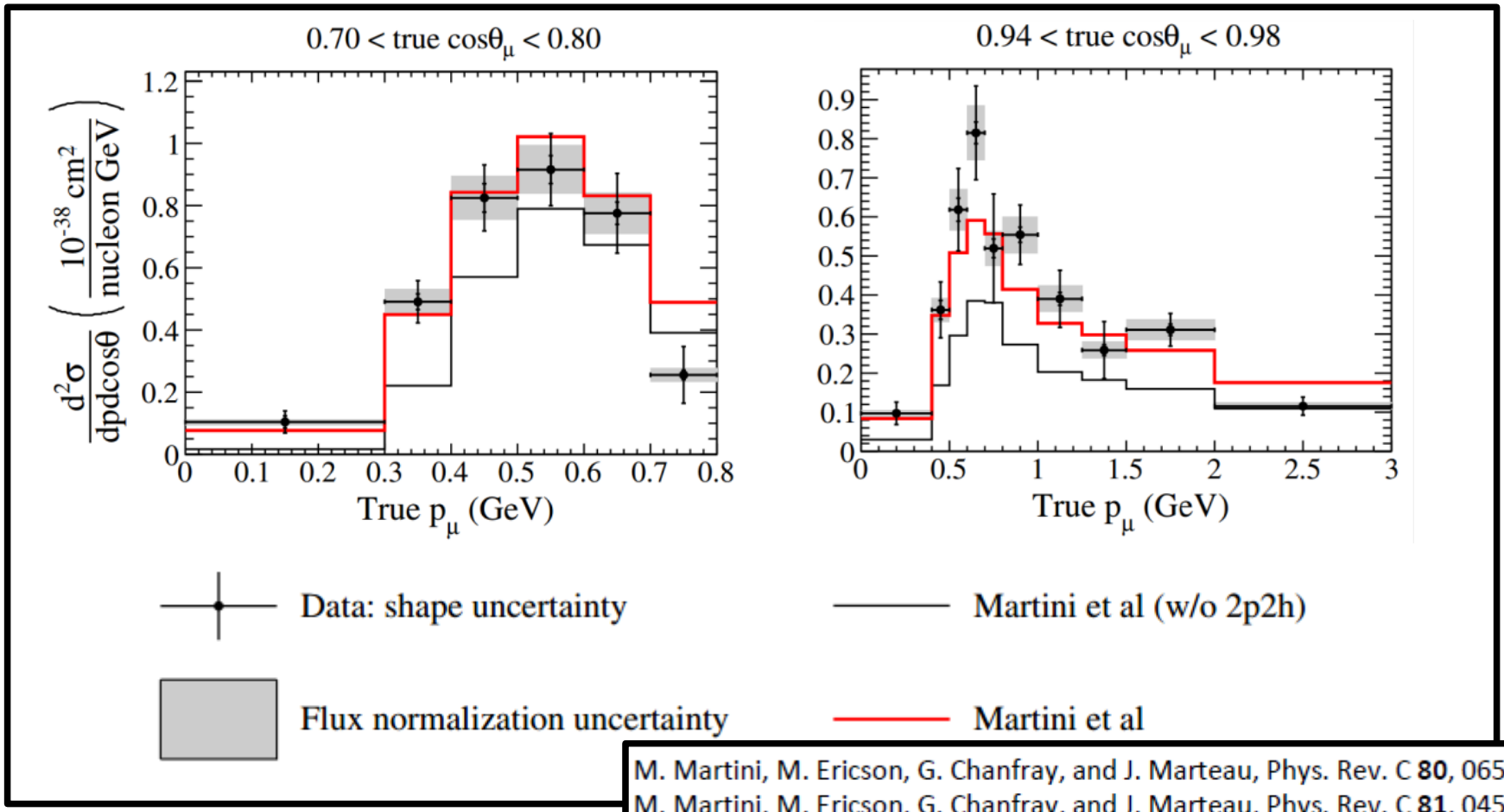
Published in PRD **93**:112012 (2016)

ND280 Tracker: CC0π

The University Of Sheffield.

Primary channel used in T2K oscillation analyses

- **Result:** Flux-integrated double-differential **CC0π** cross section in final state muon kinematic variables [p_μ, $\cos(\theta_\mu)$]
- Compared to Martini *et al*. Model **with** and **without** 2p2h



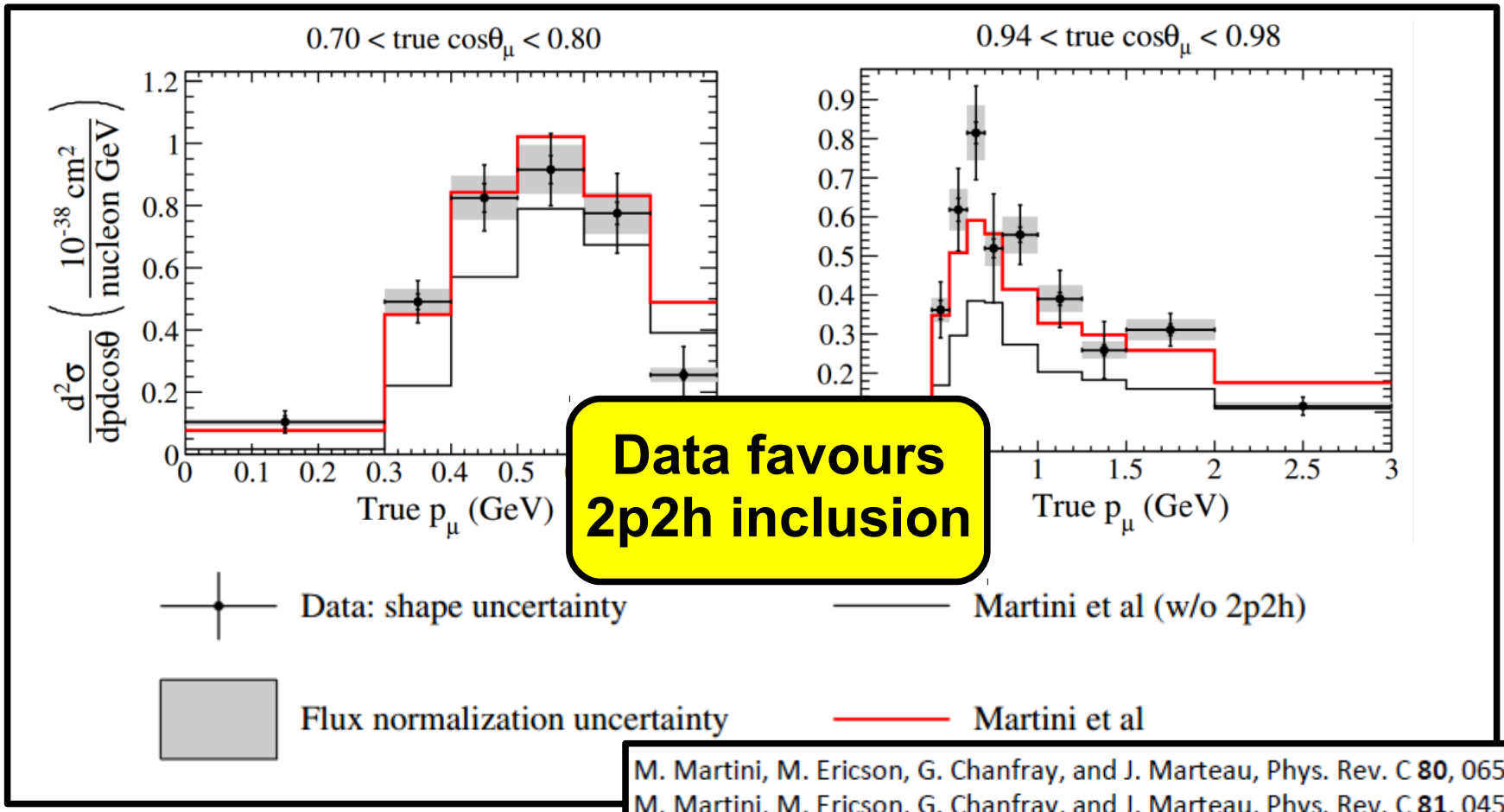
M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **80**, 065501 (2009)
M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **81**, 045502 (2010)

ND280 Tracker: CC0π

The University Of Sheffield.

Primary channel used in T2K oscillation analyses

- **Result:** Flux-integrated double-differential **CC0π** cross section in final state muon kinematic variables [p_μ, $\cos(\theta_\mu)$]
- Compared to Martini *et al*. Model **with** and **without** 2p2h

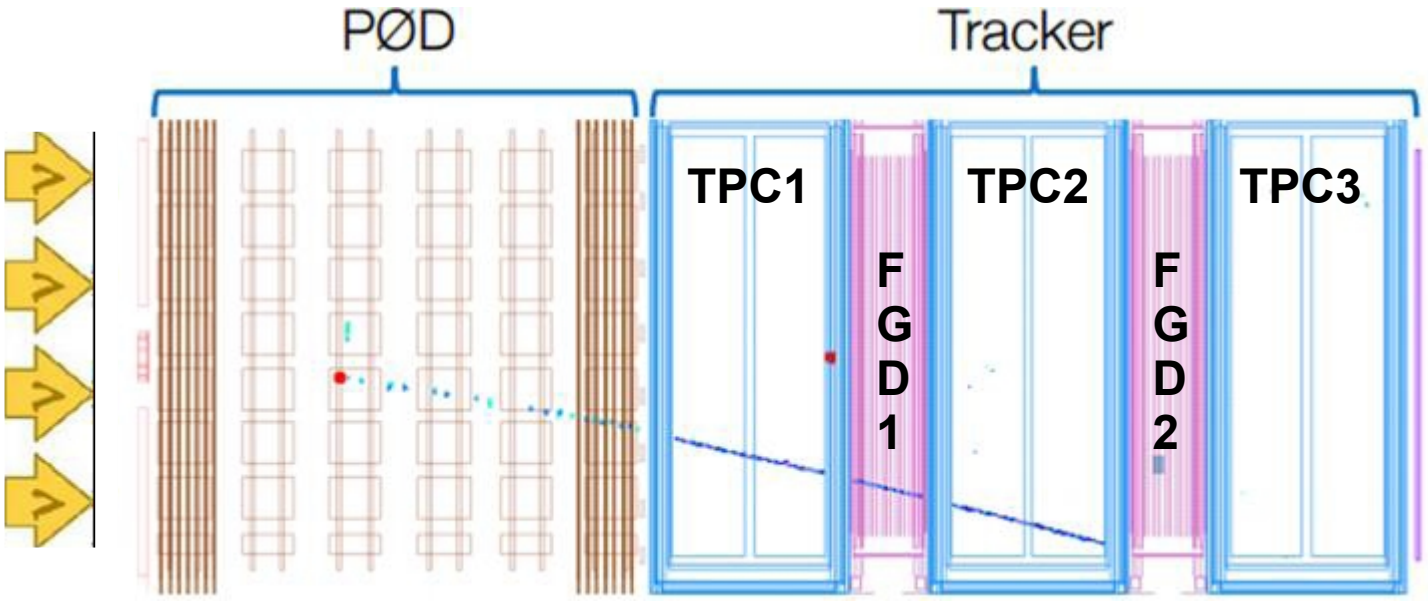


M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **80**, 065501 (2009)
M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **81**, 045502 (2010)

P0D CC0π on Water

The University Of Sheffield.

- Isolate CC0π events that (a) start in the π^0 detector (P0D), and also (b) have a muon enter the TPC for tracking:

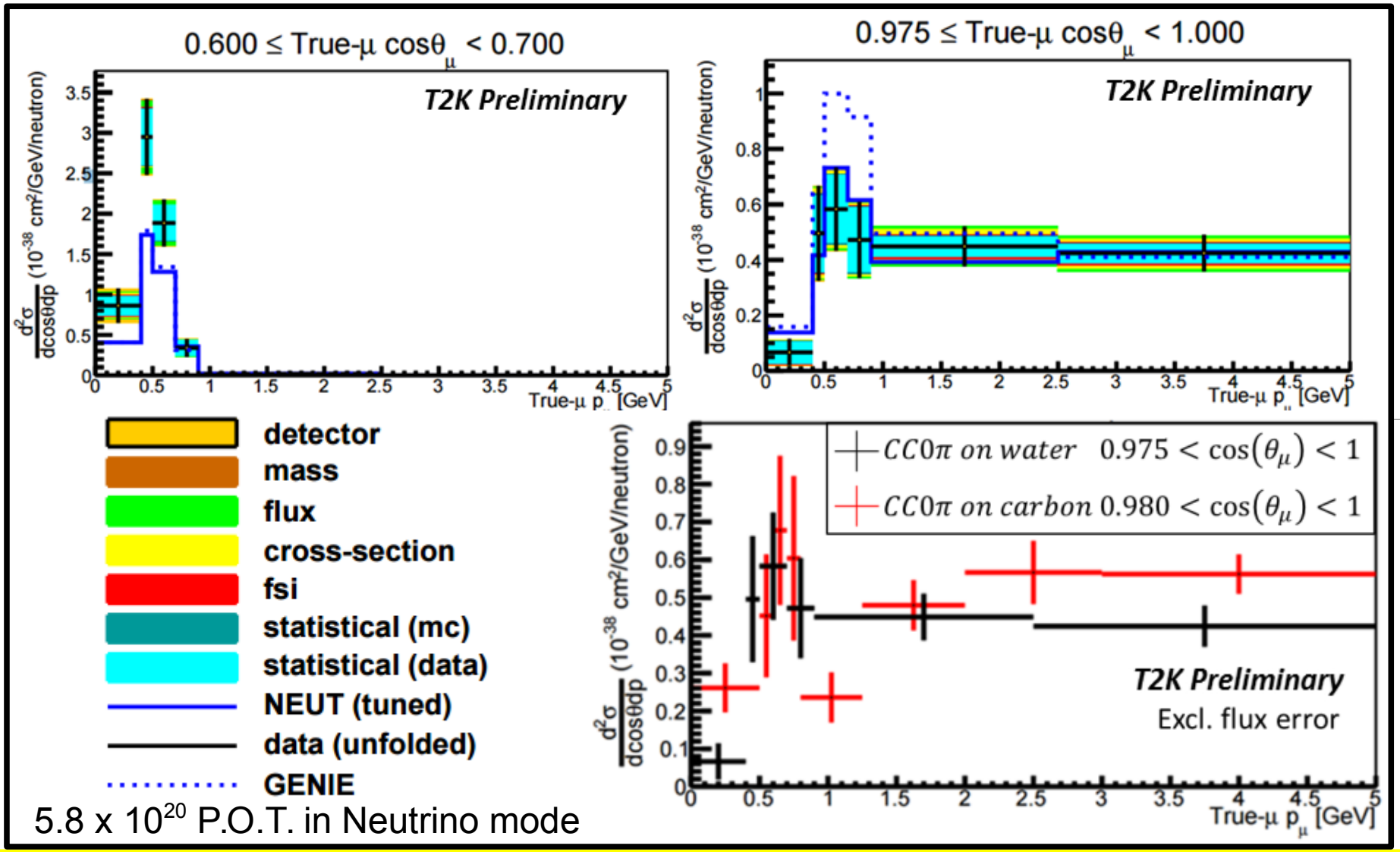


- Collect P0D data in both water-in and water-out modes
- Subtract water-out from water-in to get cross section on water

P0D CC0π on Water

The University Of Sheffield.

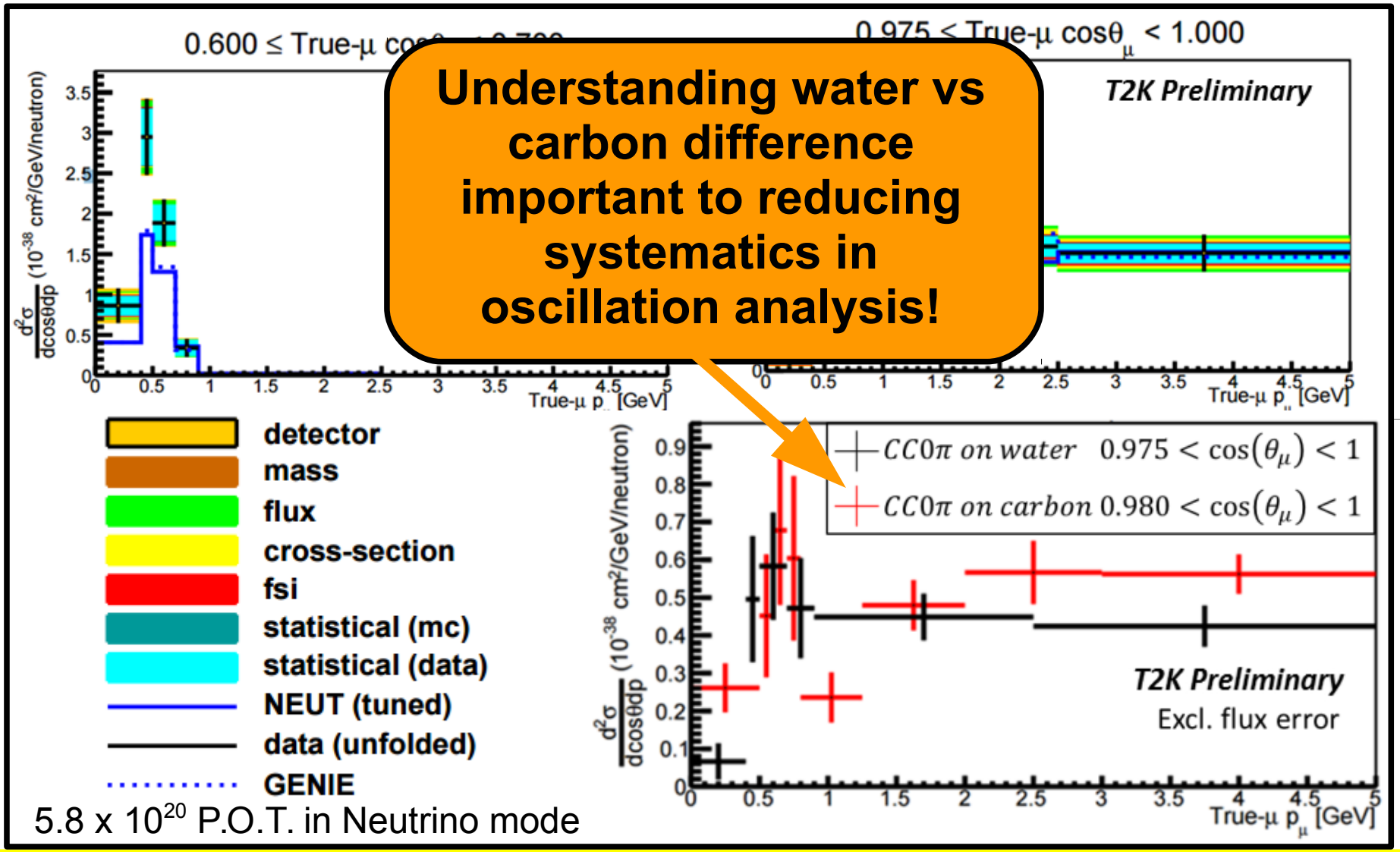
- **Result:** Flux-integrated double-differential **CC0π** cross section on water in final state muon kinematic variables [p_μ, $\cos(\theta_\mu)$]



P0D CC0π on Water

The University Of Sheffield.

- **Result:** Flux-integrated double-differential **CC0π** cross section on water in final state muon kinematic variables [p_μ, $\cos(\theta_\mu)$]



ND280 CC1π^+ Cross Sections

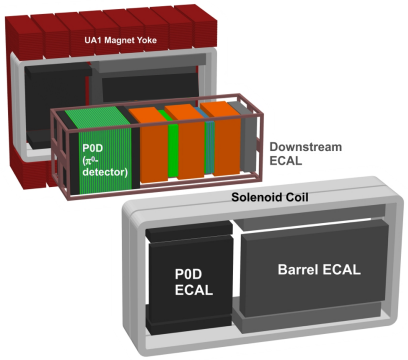
The University Of Sheffield.

We can exploit the tracking capabilities of the ND280 to reconstruct more complicated final states:

- **CC1π^+** events have two MIP-like tracks
  - Muon and pion kinematics can be measured
  - Possible to identify pions via Michel electrons in FGD
  - Veto multi-π events from extra tracks and π^0 veto from the electromagnetic calorimeter (ECAL)

Measuring these additional channels improves our understanding of neutrino cross sections, including:

- FGD1 → Carbon cross section
- FGD2 → Water cross section
- Coherent production



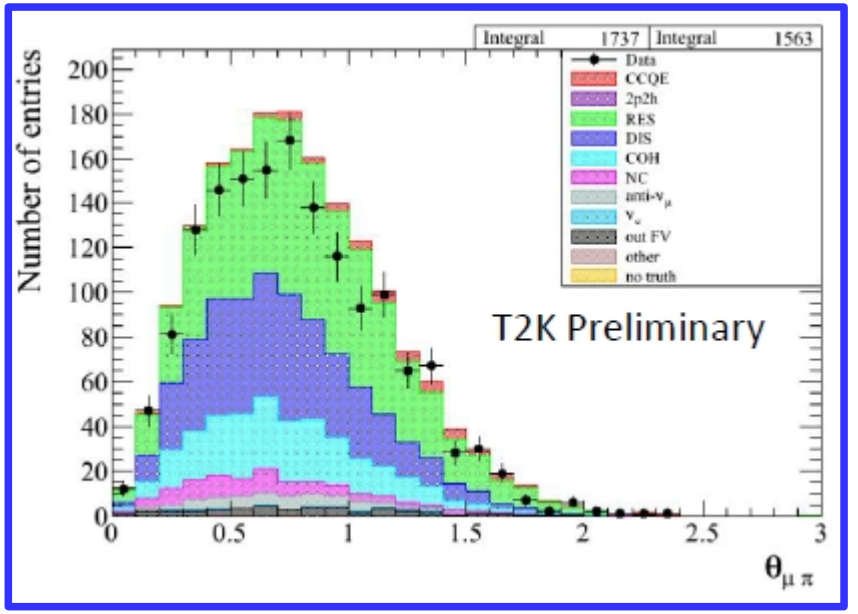
CC1π^+ X-section on Carbon

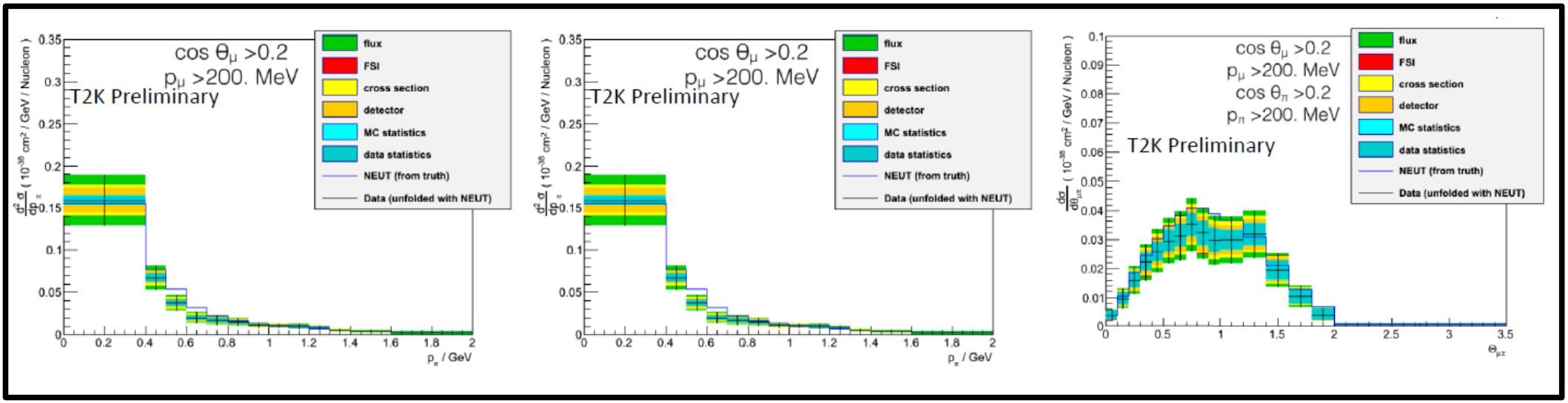
The University Of Sheffield.

5.6 x 10^{20} P.O.T. in Neutrino mode

Analysis of multiple tracks gives access to additional variables

Bayesian unfolding used, with control samples for backgrounds



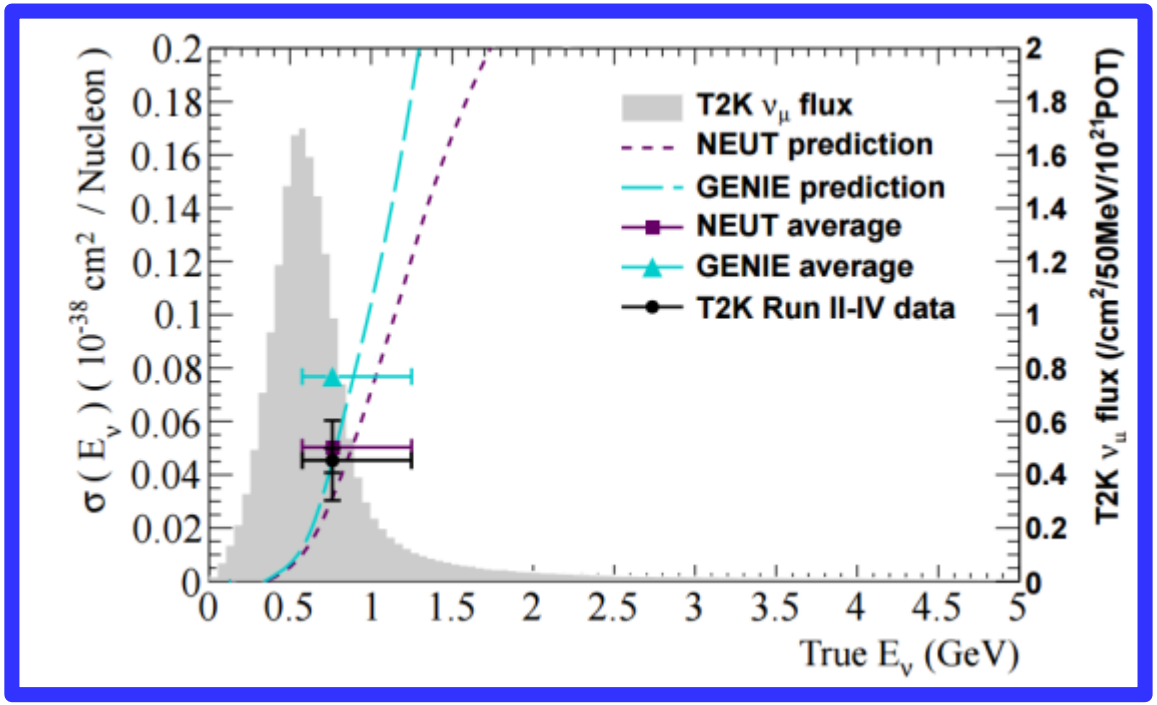


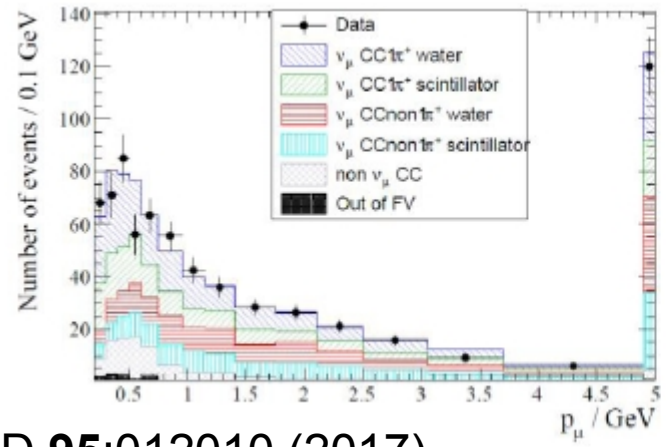
CC1π^+ X-section on Water

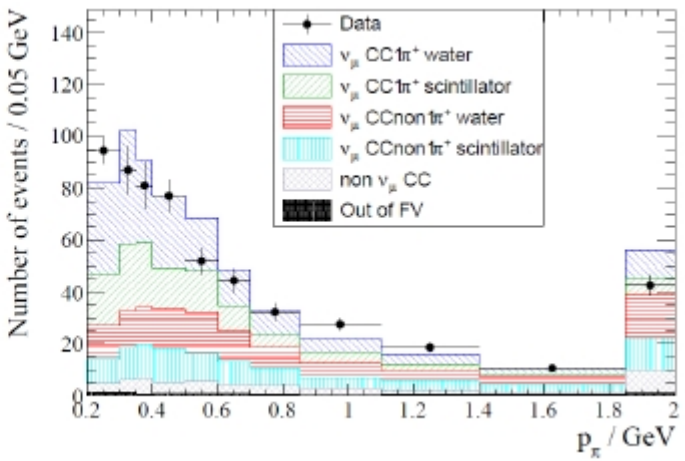
The University Of Sheffield.

- Create carbon-enriched and water-enriched samples in FGD2 based on reconstructed vertex
- Use Bayesian unfolding (w/ BG subtraction)

5.6 x 10^{20} P.O.T. in Neutrino mode







Published in PRD **95**:012010 (2017)

Coherent π^+ Production

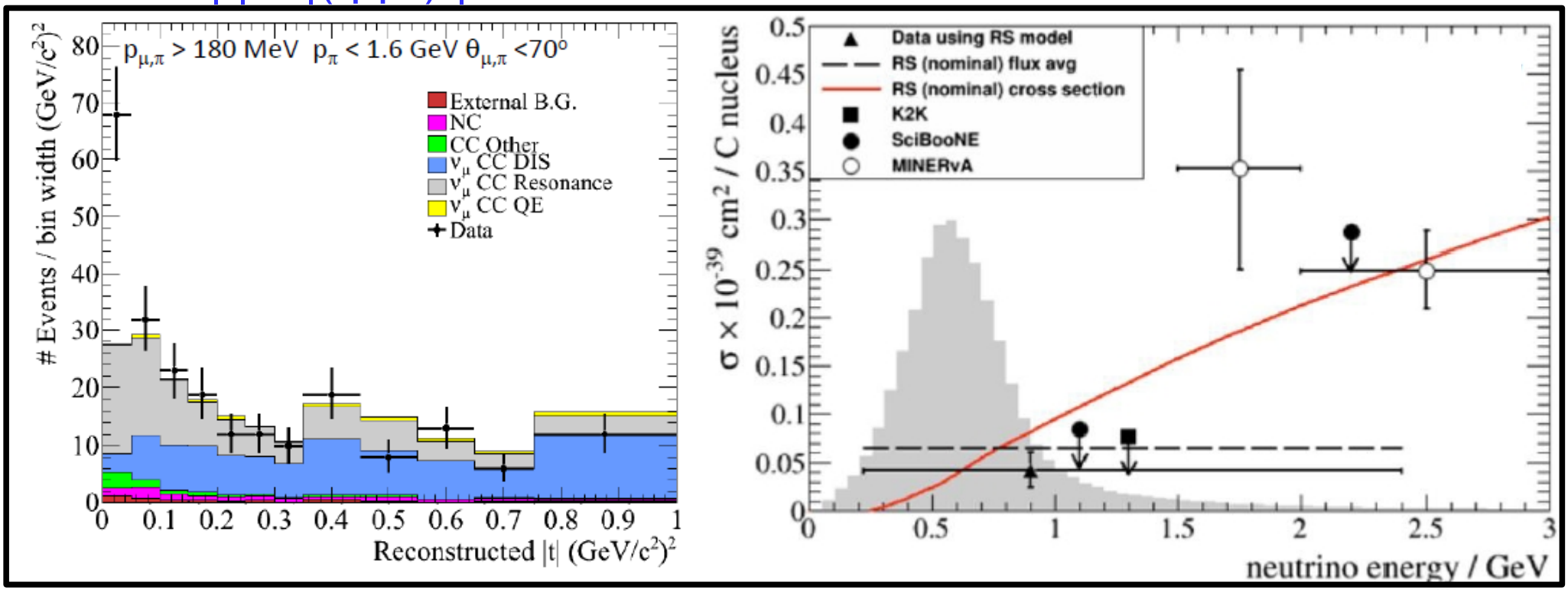
The University Of Sheffield.

A search was conducted for coherent π^+ production on carbon.

In coherent production, ν interacts with full nucleus (not indiv. nucleons)

→ only the lepton and pion will leave the nucleus in the final state

- Look for a lack of vertex activity to select coherent production
- Look for excess of events at low 4-momentum transfer to nucleus
  - $|t| = |(q-p_\pi)^2|$



Published in PRL **117**:192501 (2016)

Low t excess obs. at 2.2σ → lower than models

Antineutrinos @ ND280

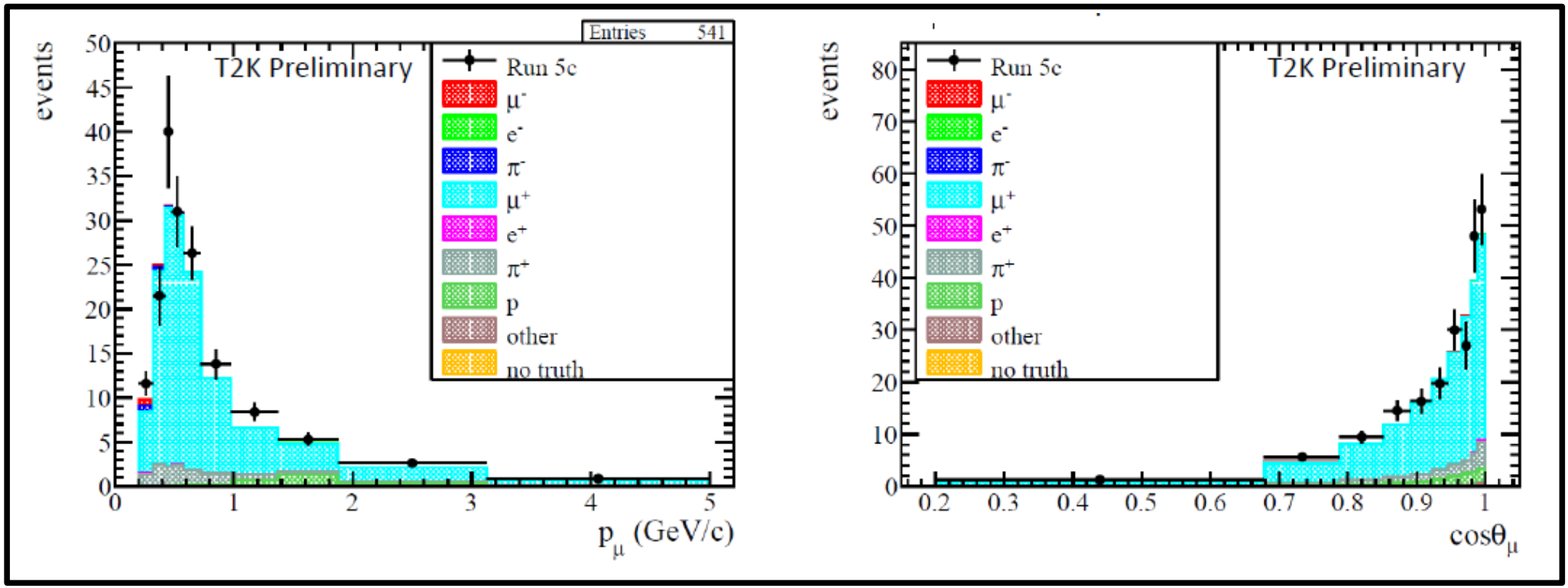
The University Of Sheffield.

Select highest momentum positive track (μ^+) from FGD-TPC:

– Quality cuts, particle ID, and veto cuts are then applied

– A control sample is used to minimize protons

- Can be difficult to distinguish from muons at 1 – 2 GeV

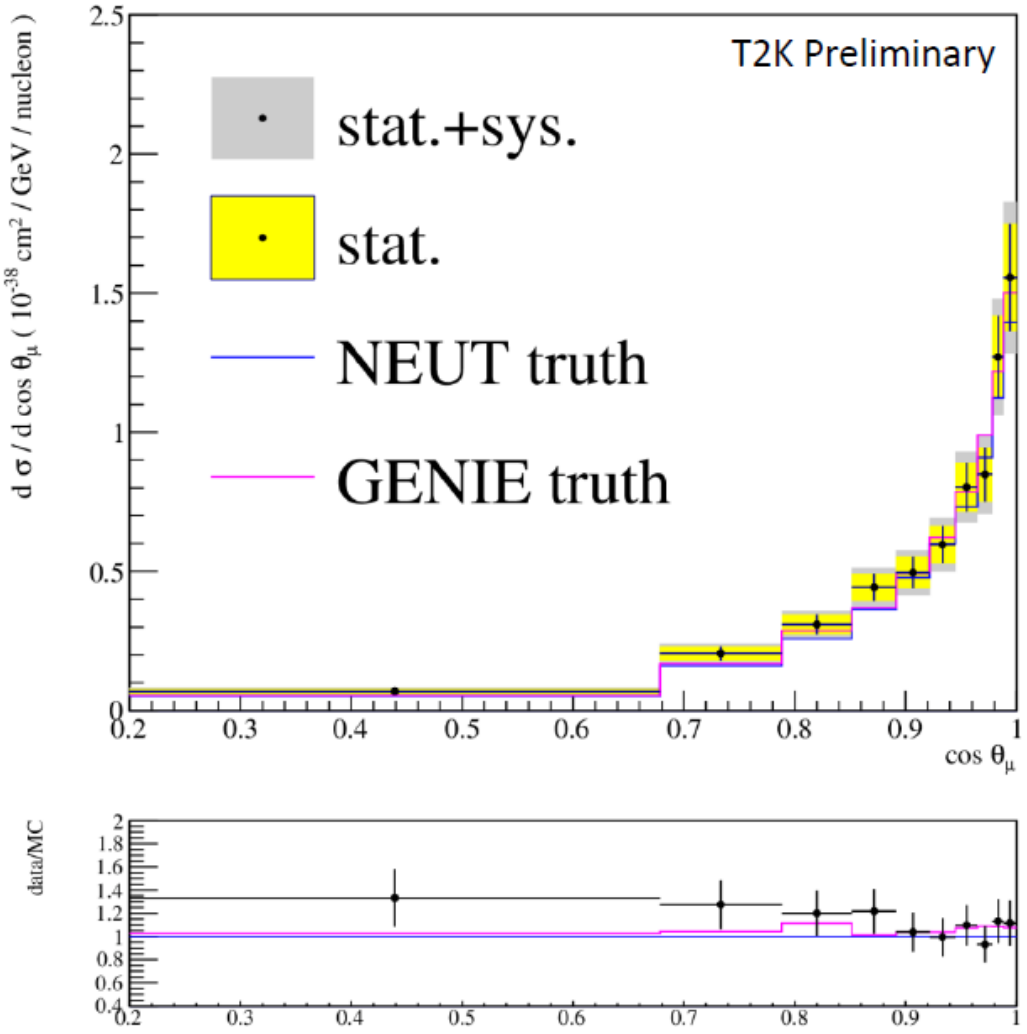


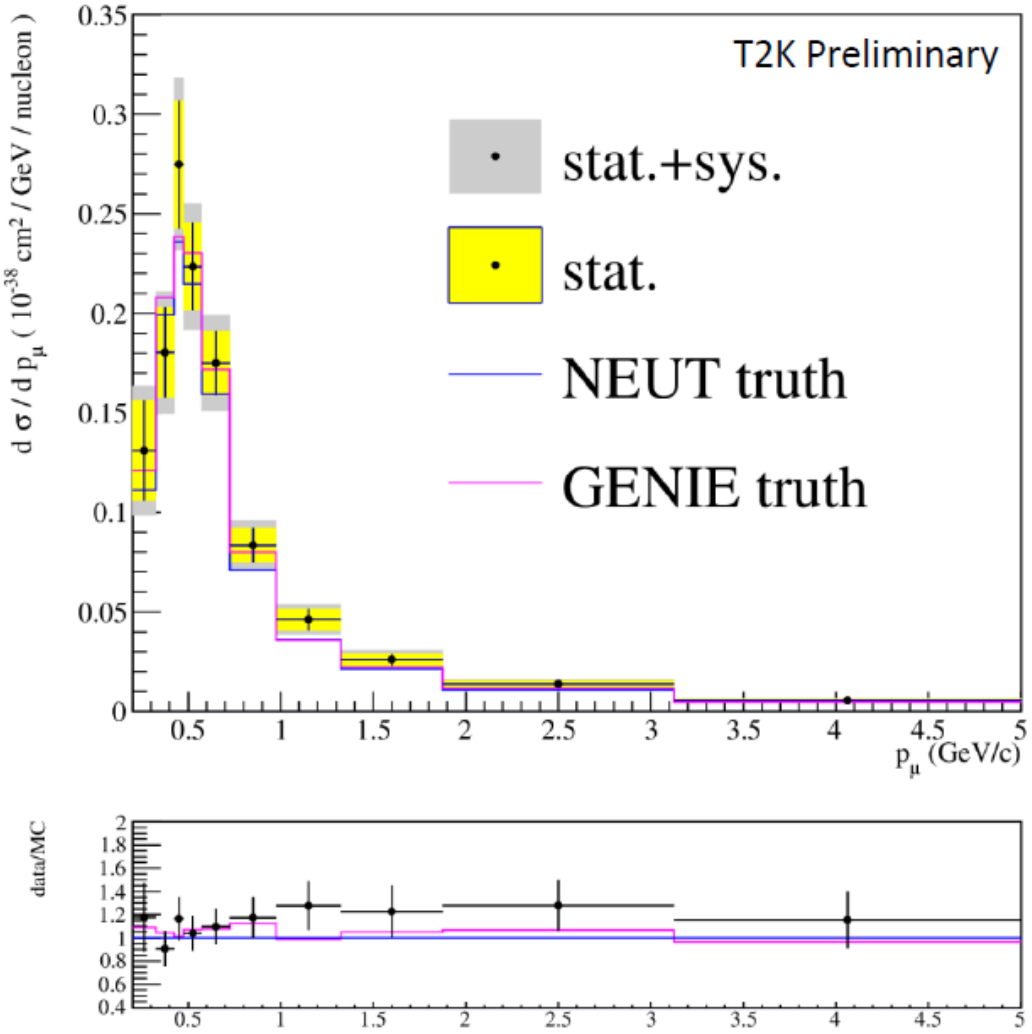
4.29 x 10^{19} P.O.T. in Antineutrino mode

$\bar{\nu}_\mu$ CC-Inclusive on Carbon

The University Of Sheffield.

Analysis uses FGD1 data in RHC ($\bar{\nu}$) mode





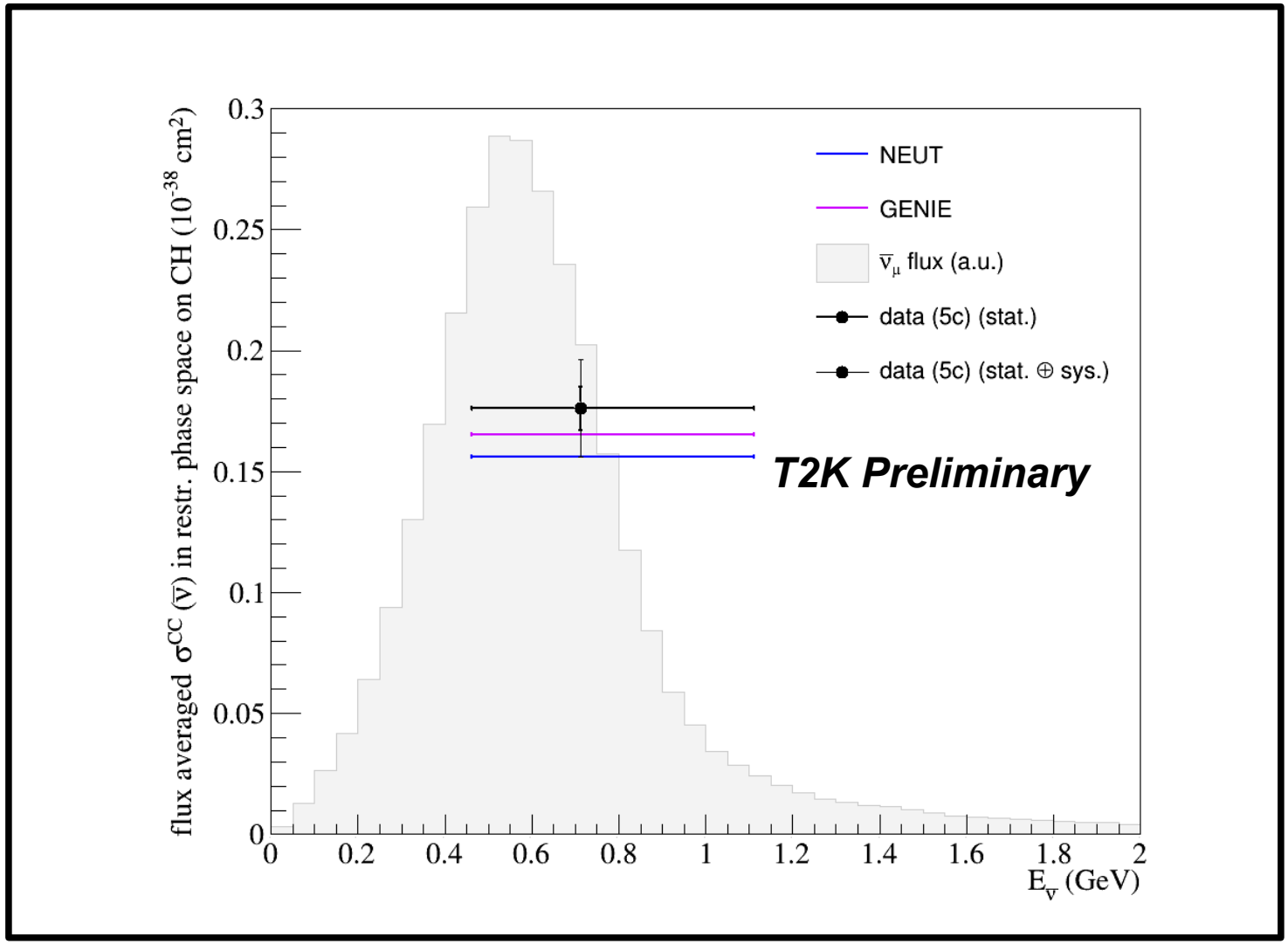
Good agreement w/ both NEUT & GENIE

4.29 x 10^{19} P.O.T. in Antineutrino mode

$\bar{\nu}_\mu$ CC-Inclusive on Carbon

The University Of Sheffield.

Results are differential cross sections in muon momentum & angle



T2K Run 5c = 4.29 x 10^{19} P.O.T. in Antineutrino mode

Summary & Conclusions

The University Of Sheffield.

- The T2K Near Detector suite can make precision cross-section measurements, as a supplement to its primary role in the oscillation analysis
- Cross-section results from T2K's neutrino mode are available now in both inclusive and exclusive channels
- Antineutrino cross-section measurements are being analysed, and first results are starting to emerge
- **Many more cross-section results to come!**

The University Of Sheffield.

Thank you for listening!