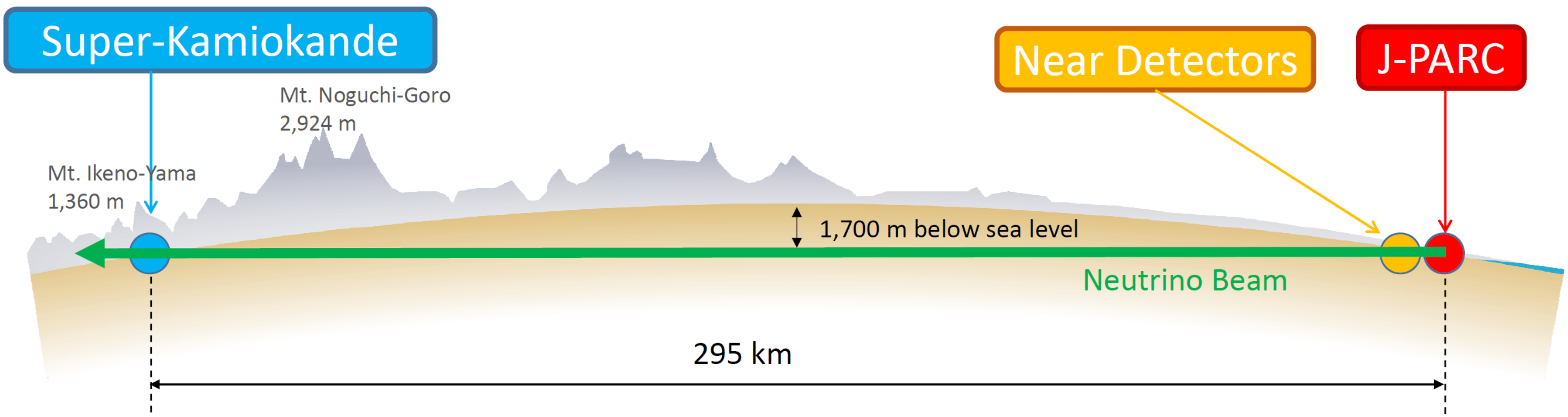
Recent cross section results from the T2K experiment

Clarence Wret
On behalf of the T2K collaboration

NuFact 2018
Virginia Tech, Blacksburg

The T2K experiment

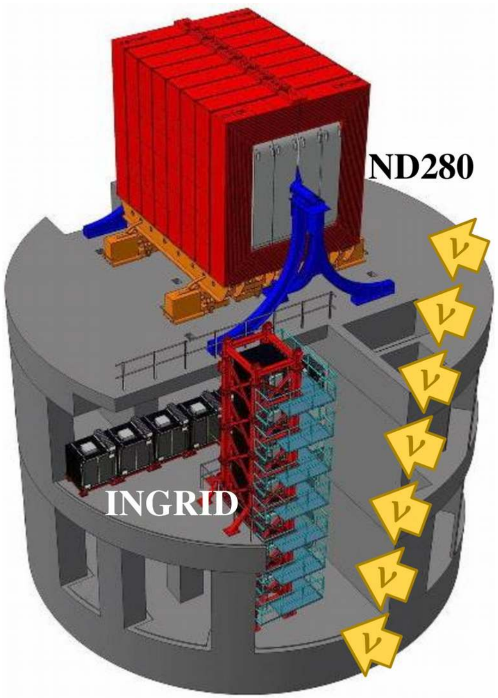
- Long baseline neutrino oscillation experiment



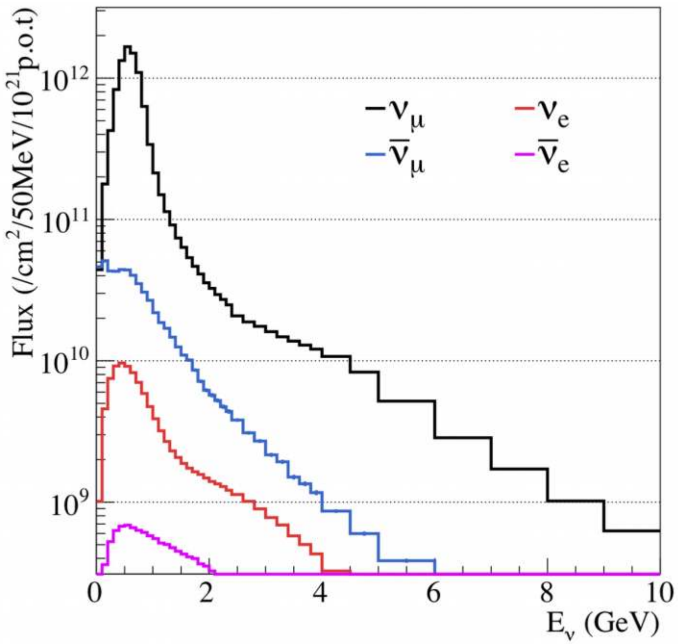
- Near detectors – 280 m from target
  - Constrains flux before oscillation and interaction physics
  - **Measurements of neutrino cross sections for the community**
  - Exotic measurements, e.g. steriles and HNL
- Far detectors – 295 km from target
  - Apply model constraints from near detector and external data, add-on SK detector model and neutrino oscillations

Near detectors

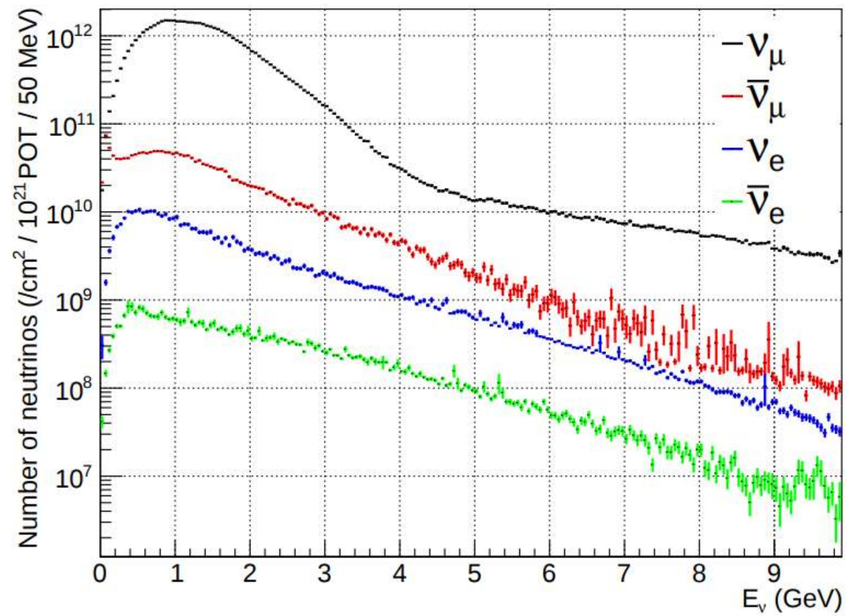
- Fluxes: ν_μ and anti-ν_μ dominated with different E_ν
  - ND280: 2.5° off-axis, 0.6 GeV narrow band
  - INGRID: On-axis, 1.3 GeV wide band



ND280 flux (off-axis)



INGRID flux (on-axis)



- Multiple targets in INGRID and ND280: C_8H_8, H_2O, Ar, Pb, Fe
- More detectors being rolled in!

ND280 sub-detectors

TPC: Time Projection Chamber:

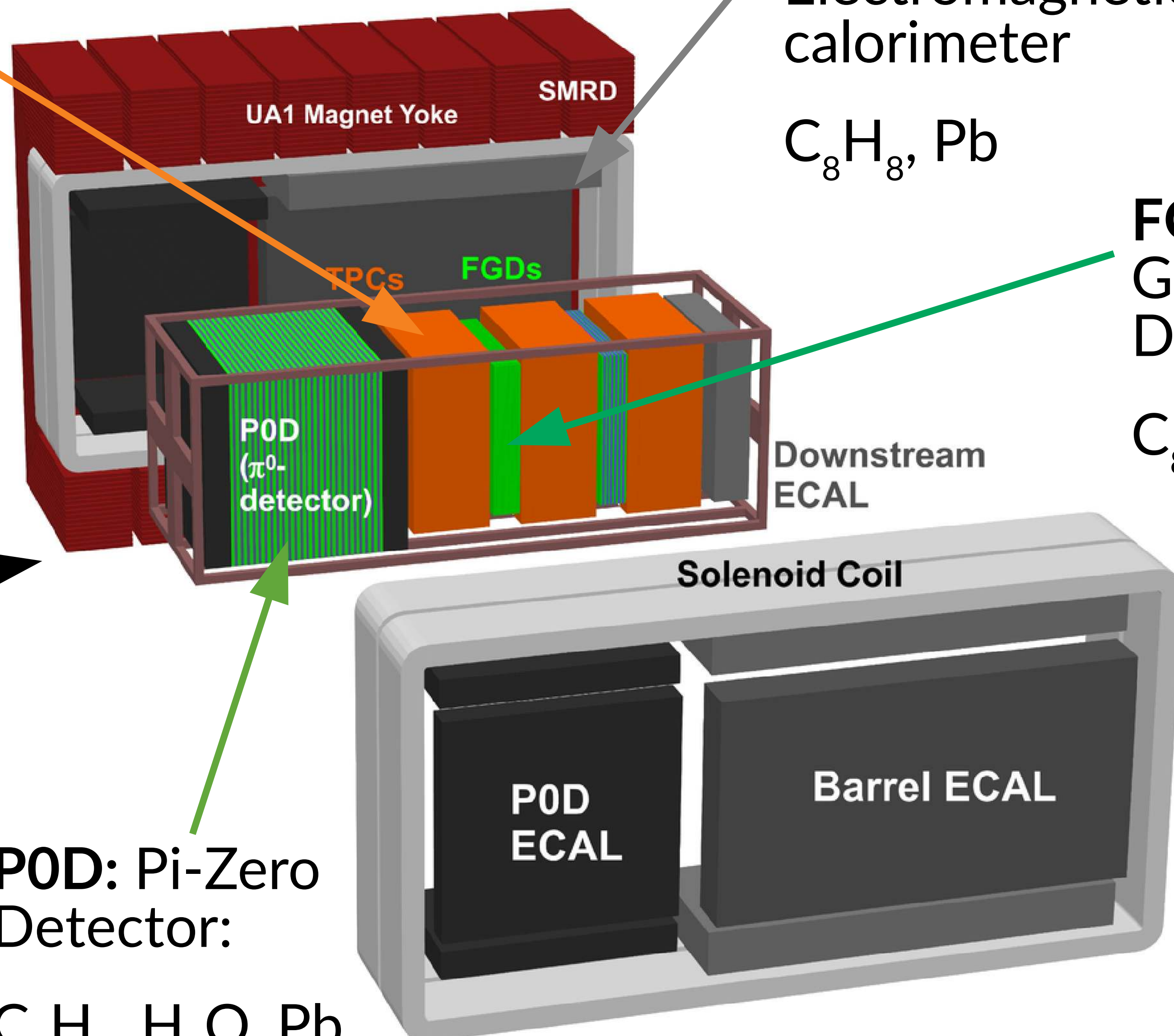
Gaseous Ar

ECAL: Electromagnetic calorimeter

C_8H_8, Pb

FGD: Fine Grained Detector:

C_8H_8, H_2O



V

V

V

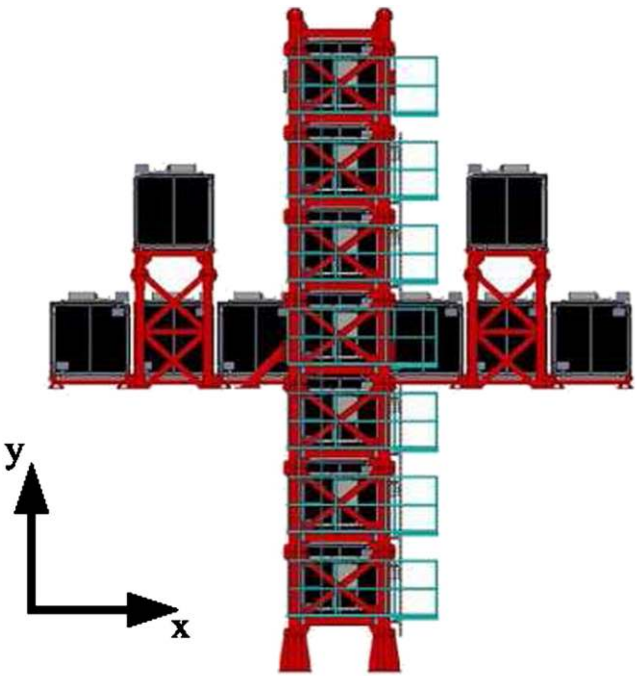
V

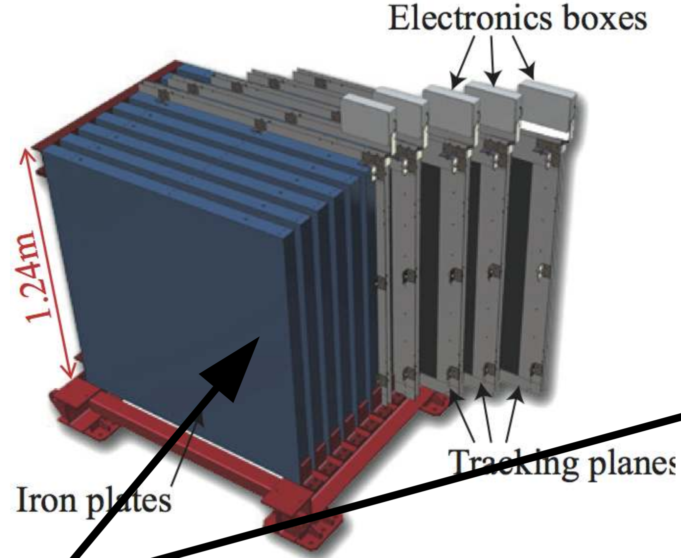
P0D: Pi-Zero Detector:

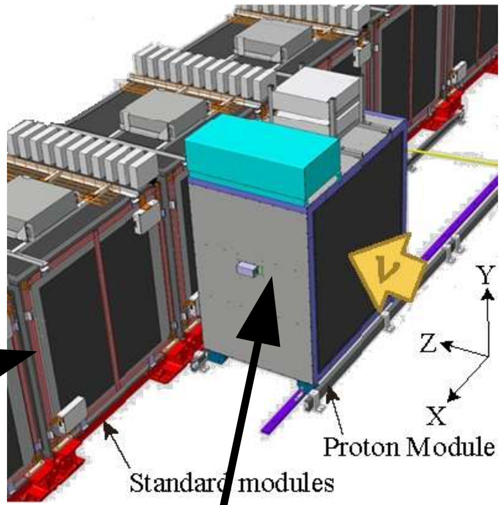
C_8H_8, H_2O, Pb

INGRID detector

- Organised in cross pattern for beam direction measurements







INGRID:
C_8H_8, Fe plates

Proton Module:
Fully C_8H_8

- Proton module for dedicated cross section modules
  - No iron plates: fully plastic scintillator

Relevance to oscillations

$$\overbrace{R(\vec{\mathbf{x}}) = \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(\nu_A \to \nu_B)$$

$$\underbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(\nu_A \to \nu_B)}_{\text{Far}}$$

- Modelling relates observables (e.g. p_μ θ_μ) to neutrino energy, E_ν, which determines the oscillation parameters
- Near and far detectors don't cancel systematics perfectly
  - E_ν spectrum is different in the far detector
  - Acceptance, efficiency and targets differs in the detectors
- Data predominantly from ν_μ: model used to predict ν_e from ν_μ

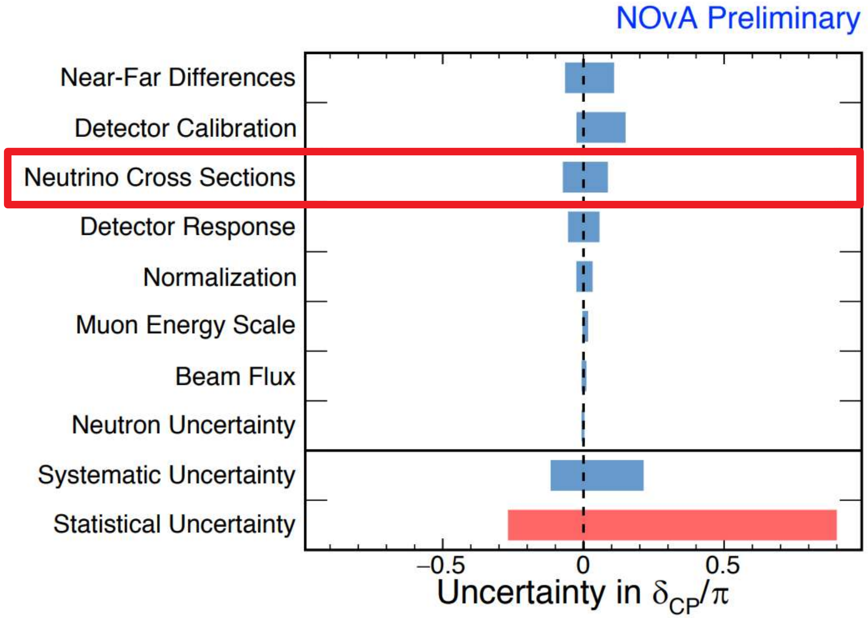
- Require few percent cross section systematics in current and future oscillation experiments
- *WG2 Goals for the Meeting*, K. Niewczas, Mon. 11.15am

Relevance to oscillations

- Large systematics at T2K and NOvA long-baseline oscillation experiments

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

T2K August 2018, https://arxiv.org/pdf/1807.07891.pdf

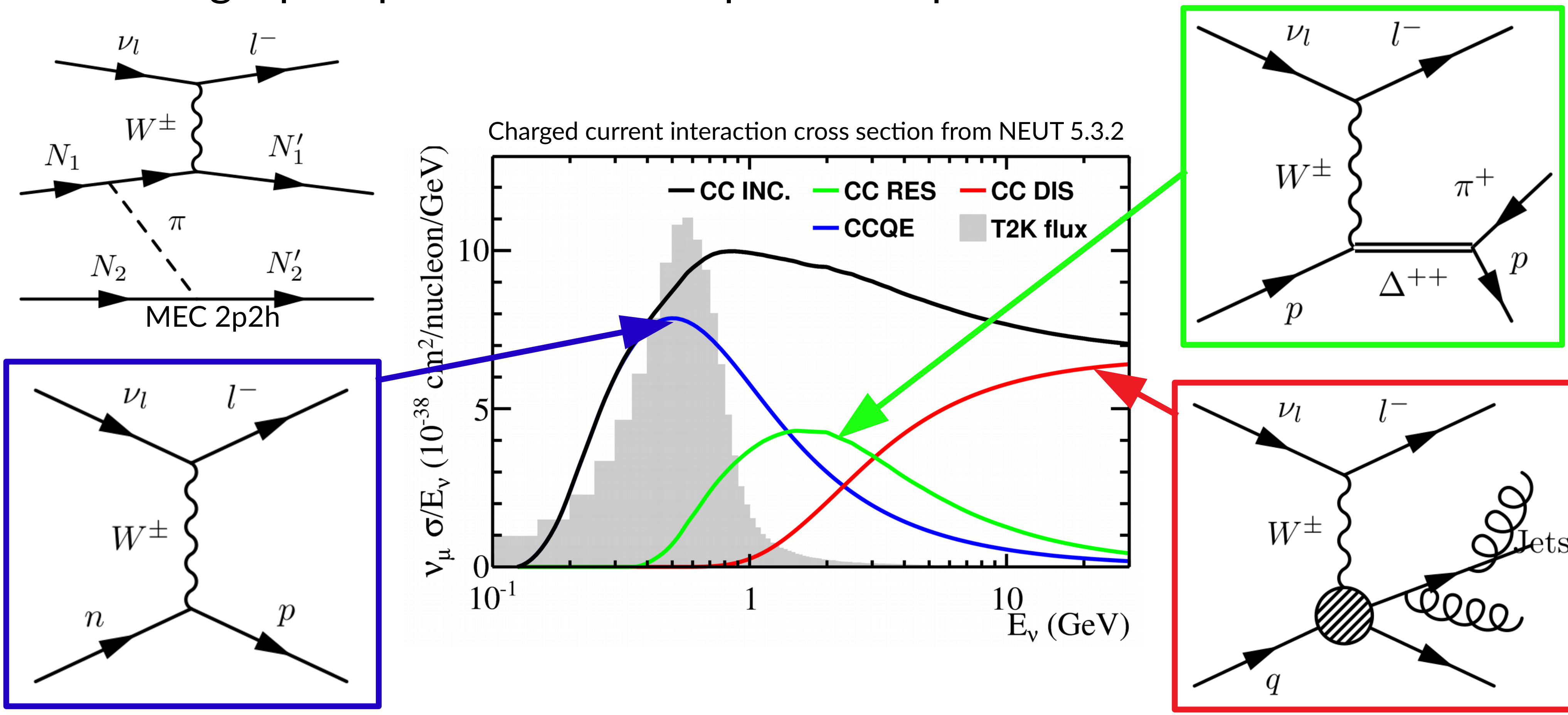


NOvA Wine and Cheese, A. Himmel, June 15, 2018

- After NOvA calibration, neutrino interactions dominant for δ_{CP}
  - *Details of the NOvA oscillation analyses*, E. Smith, Thu. 2pm
  - *Details of the T2K oscillation analyses*, D. Sgalaberna, Thu. 2.30pm
  - *NOvA Cross Section Model / Oscillation Needs*, J. Wolcott, Fri. 2pm
  - *T2K Cross Section Model / Oscillation Needs*, C. Wret, Fri. 2.30pm

Neutrino cross sections

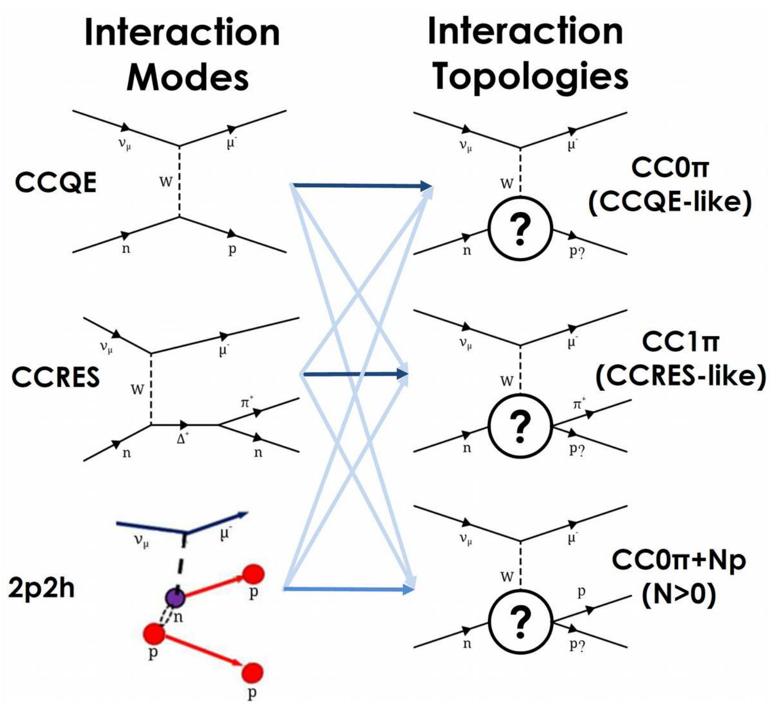
- Cross section landscape at T2K primarily the CCQE interaction
  - 2p2h interaction shares the CCQE final state (“0π” or CCQE-like)
  - Single pion productions with pion absorption

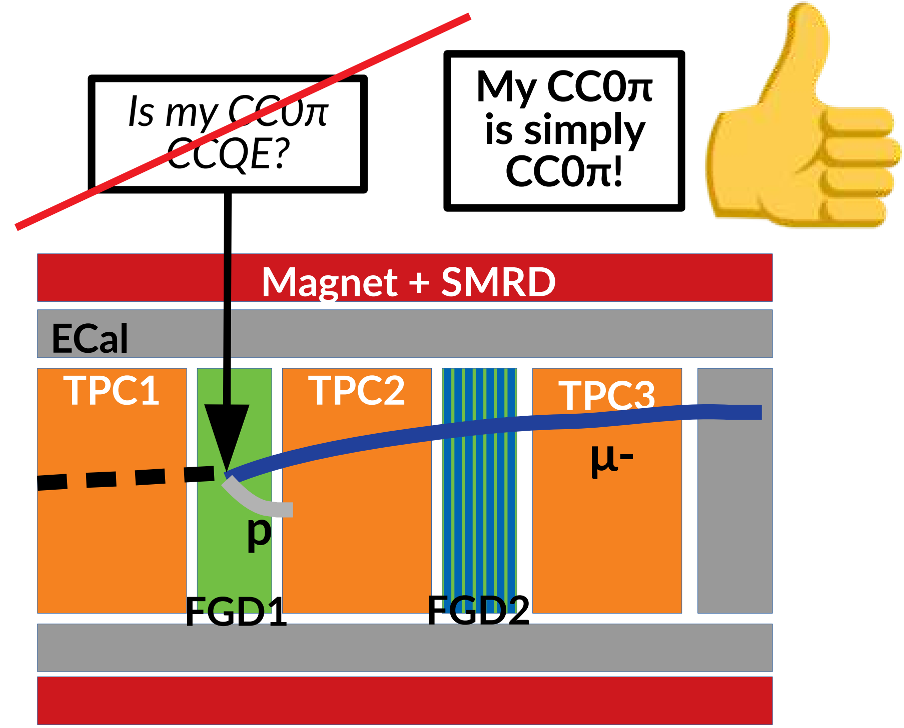


- Signal at T2K-SK is CC0π → Historically the focus of T2K measurements
  - 1π^0 is background for ν_e appearance, NC1$\pi^\pm$ is background for ν_μ disapp.

T2K cross section strategy

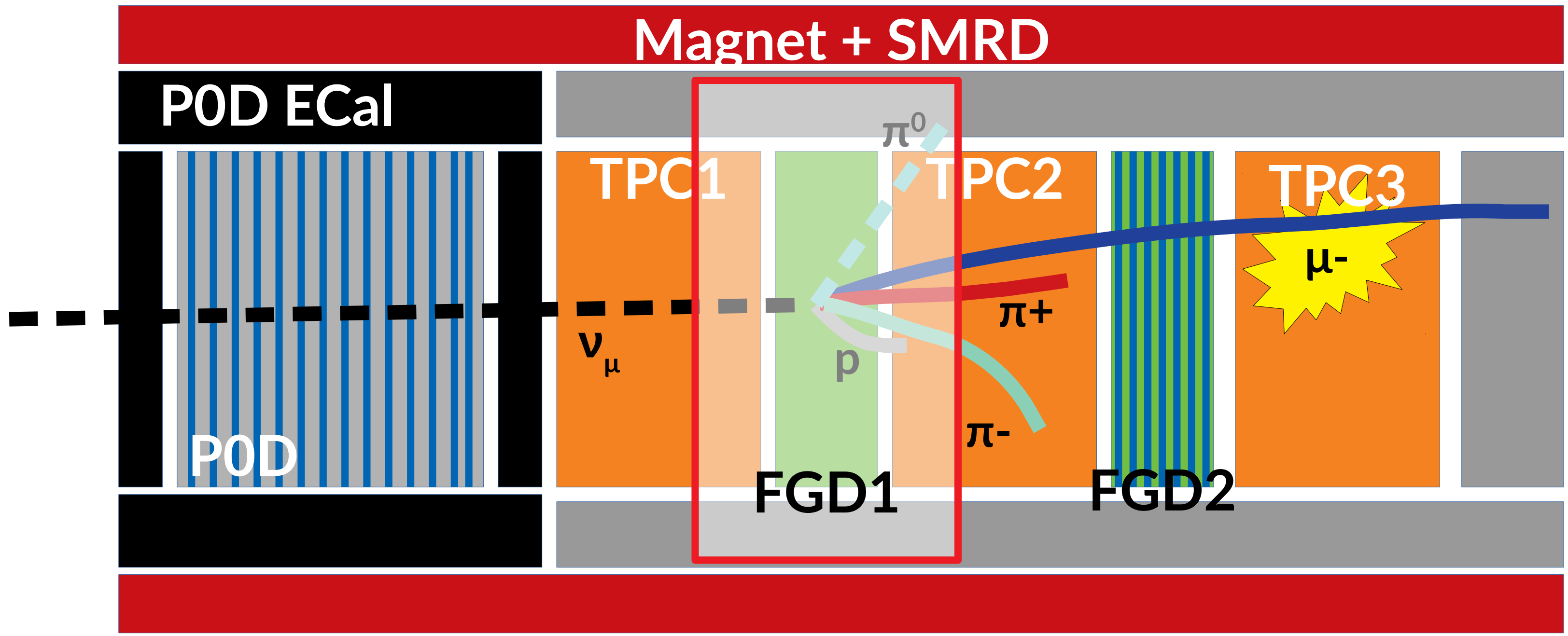
- Cross section signal definition by observed final state topology
  - Can't see nucleon-level interaction from detector and FSI processes





- Inclusive CC or NC selection, and count the pions and nucleons
  - CC0π, CC0π1p, CC1π$^+$, NCπ^0, etc
- Removes large (but not all!) model dependence in extracted cross section from background subtraction

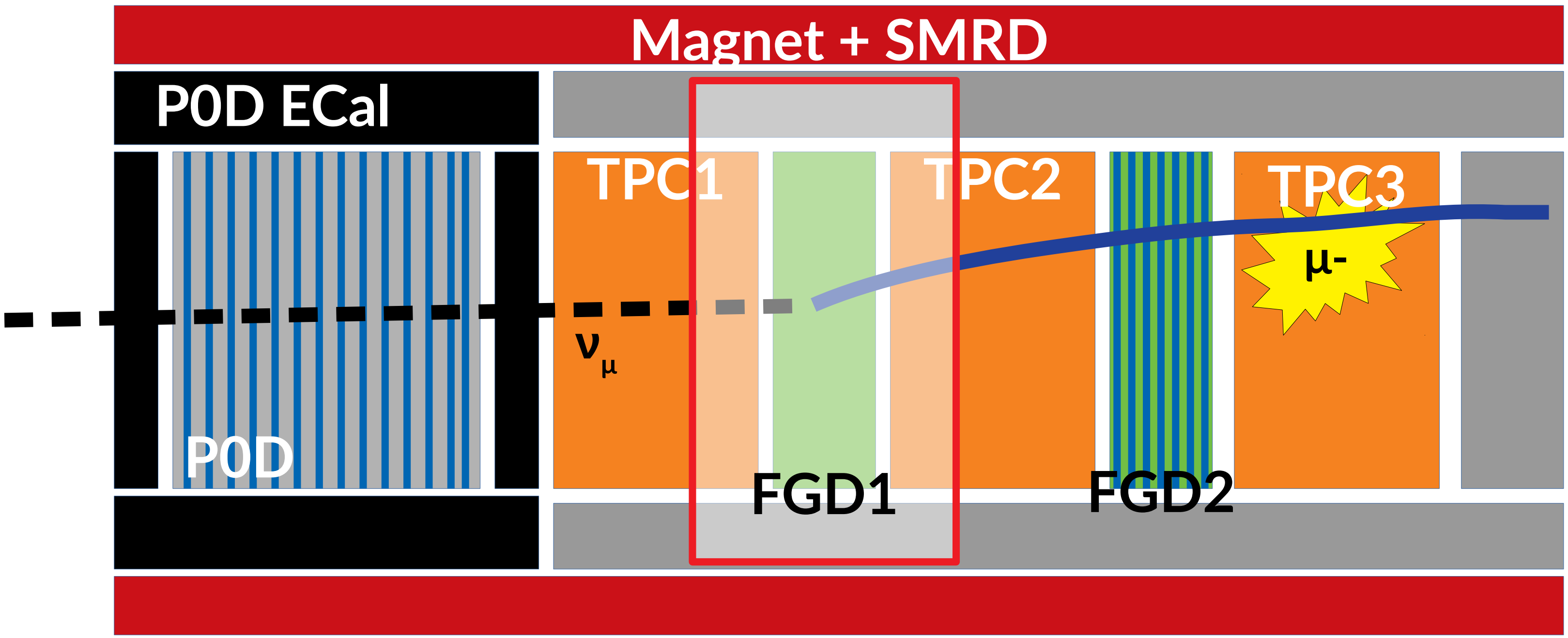
T2K cross section strategy



- <u>Measurements of inclusive p_μ $\cos\theta_\mu$ in sub-detector</u>
- Make exclusive 0π measurement on muon
- Make exclusive 1π measurement on muon
- Make above measurements in separate detector
- Move beyond the muon kinematics

Improved understanding detector+intera

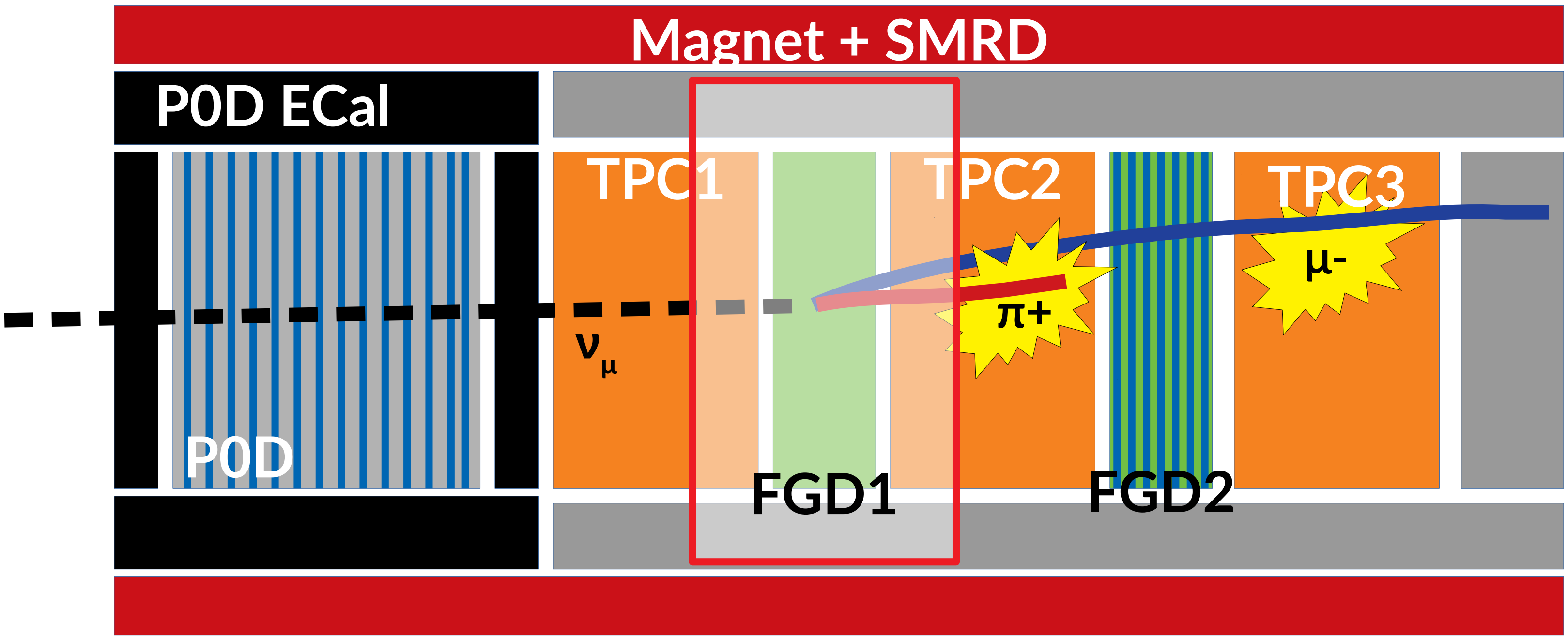
T2K cross section strategy



- Measurements of inclusive p_μ $\cos\theta_\mu$ in sub-detector
- <u>Make exclusive 0π measurement on muon</u>
- Make exclusive 1π measurement on muon
- Make above measurements in separate detector
- Move beyond the muon kinematics

Improved understanding detector+interaction

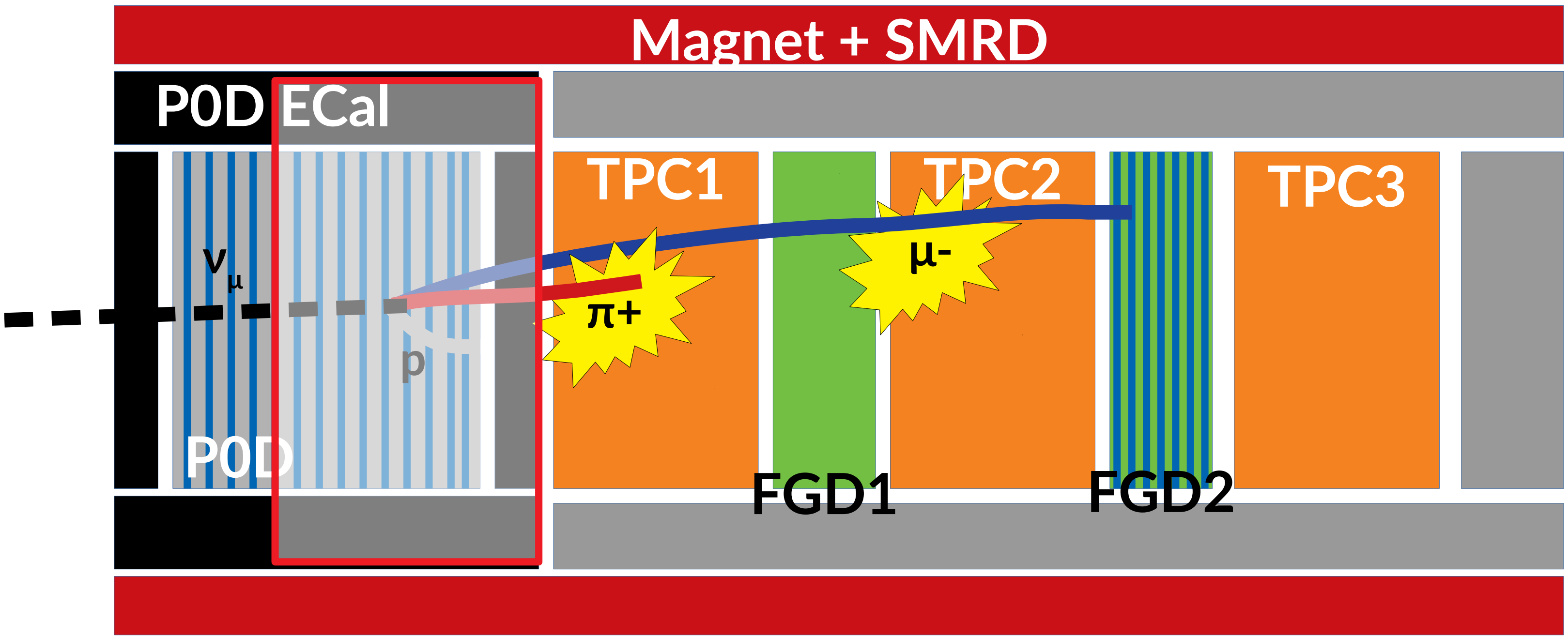
T2K cross section strategy



- Measurements of inclusive p_μ $\cos\theta_\mu$ in sub-detector
- Make exclusive 0π measurement on muon
- <u>Make exclusive 1π measurement on muon</u>
- Make above measurements in separate detector
- Move beyond the muon kinematics

Improved understanding detector+intera[...]n

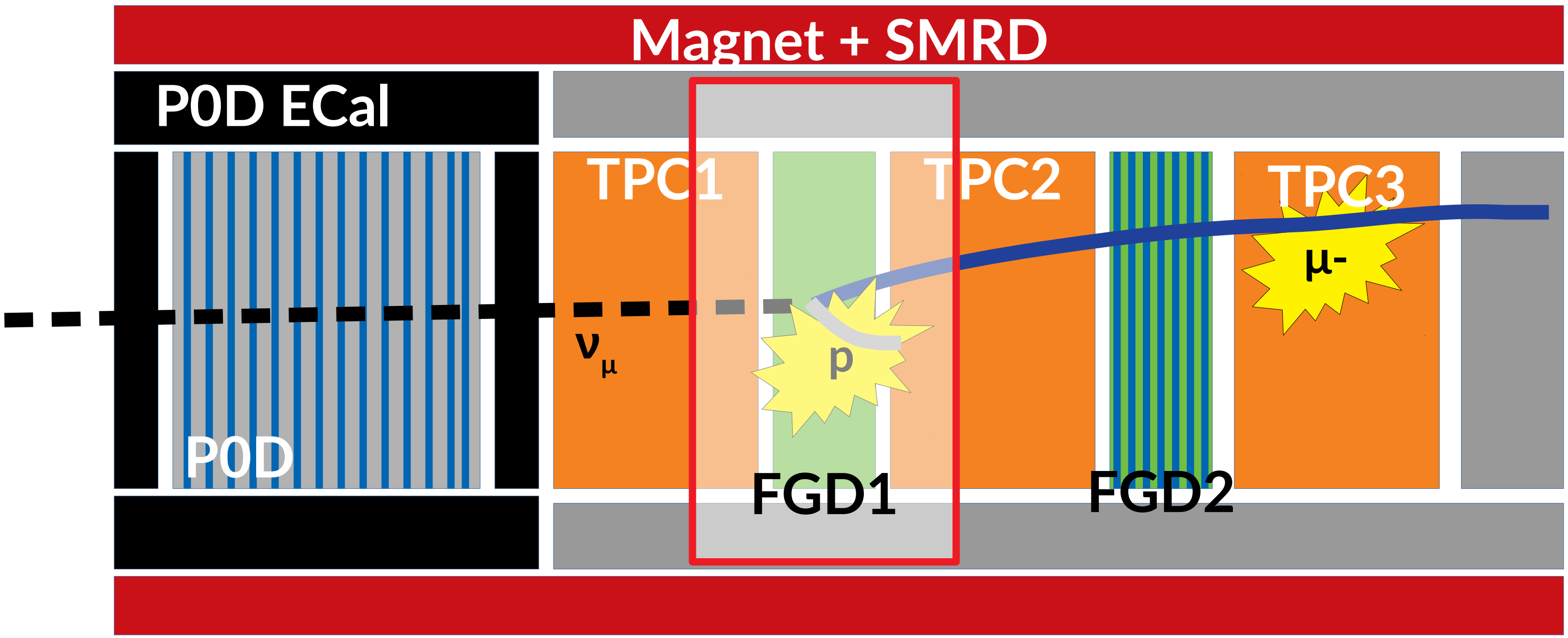
T2K cross section strategy



- Measurements of inclusive p_μ $\cos\theta_\mu$ in sub-detector
- Make exclusive 0π measurement
- Make exclusive 1π measurement
- Make above measurements in separate detector
- Move beyond the muon kinematics

Improved understanding detector+intera

T2K cross section strategy

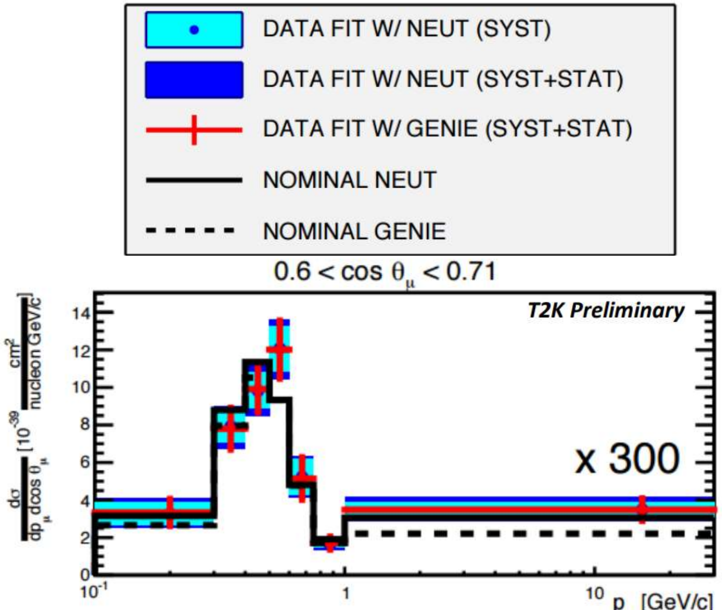


- Measurements of inclusive p_μ $\cos\theta_\mu$ in sub-detector
- Make exclusive 0π measurement on muon
- Make exclusive 1π measurement on muon
- Make above measurements in separate detector
- Move beyond the muon kinematics

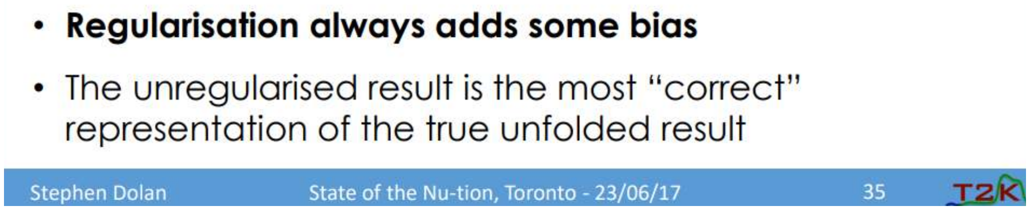
Improved understanding of detector and interaction

T2K cross section strategy

- NEUT and GENIE neutrino interaction generators with full detector simulation, with small NuWro production (plans for GiBUU)
  - Test unfolding methods, detector effects, model dependence



T2K CC-inclusive result with different input analysis simulation, A. Garcia

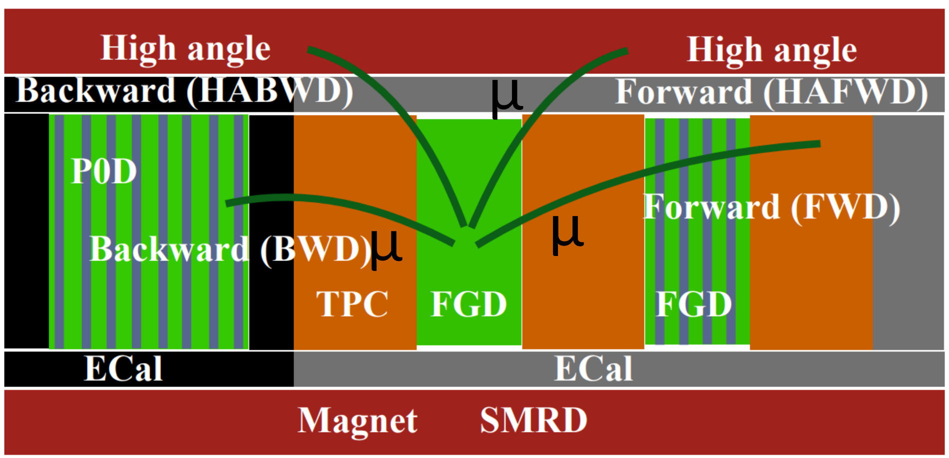


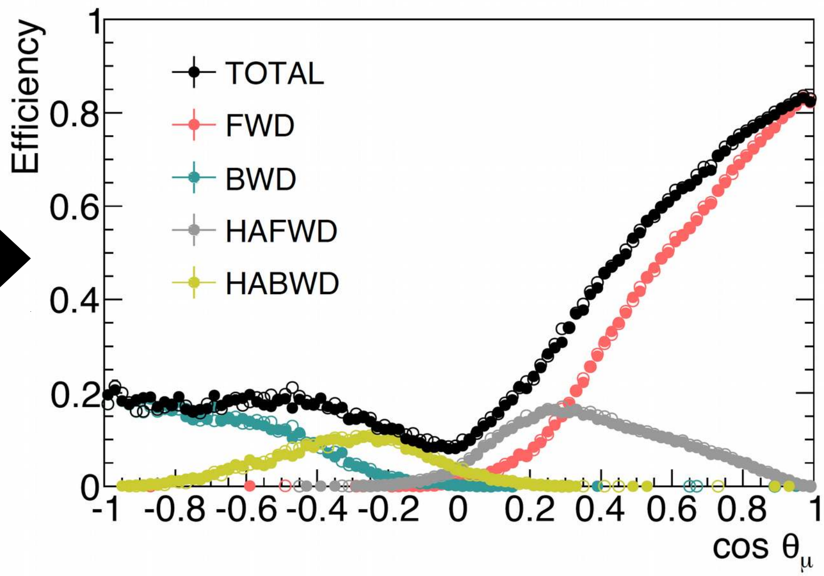
Unfolding biases in neutrino cross sections, S. Dolan

- Increasing interest in unfolding (or folding) techniques and efficiency biases
  - e.g. PRD 93, 112012 used D'Agostini vs template fitting
  - Co-organised State of the Nu-tion workshop with MINERvA (NuInt 2018), discussing analysis techniques at each experiment

CC-inclusive

- Large extension of previous FGD1 (C_8H_8) result
  - Including high angle and backward going muon candidates
  - 5x increase in statistics
  - Systematics improvements in flux and reconstruction

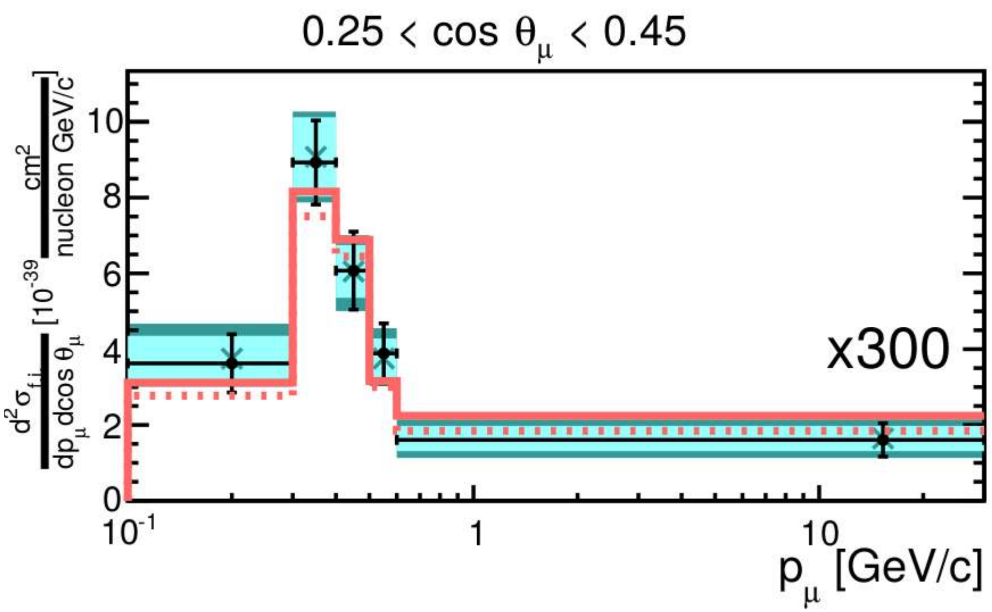


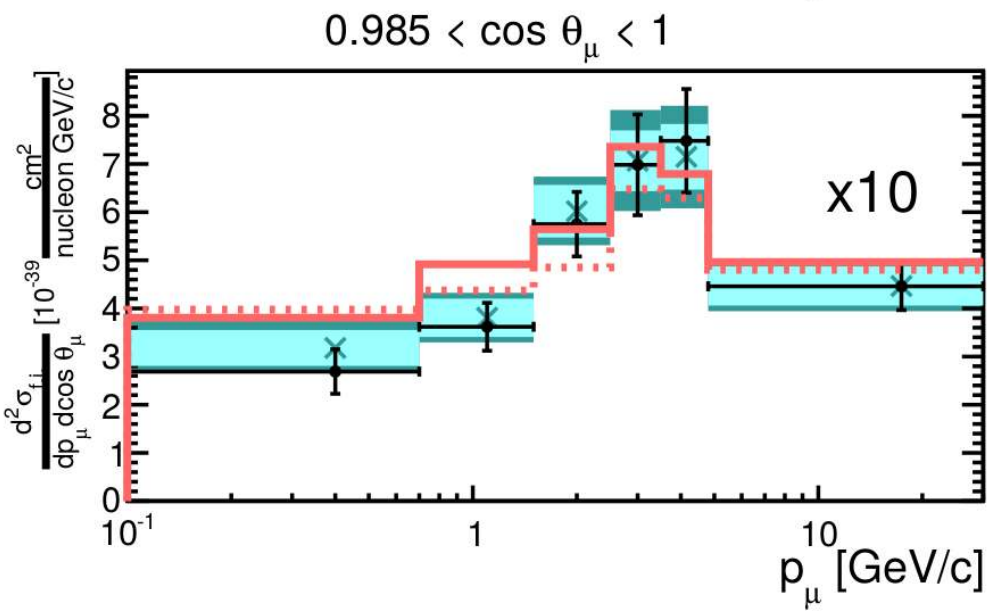


- Minimally model dependent
  - Detector unfolding tested with multiple models and generators
- Takes ND280 closer to SK-like acceptance

CC-inclusive

- Consistent differences between NEUT 5.3.2 and GENIE 2.8.0 throughout the phase space: roughly normalisation





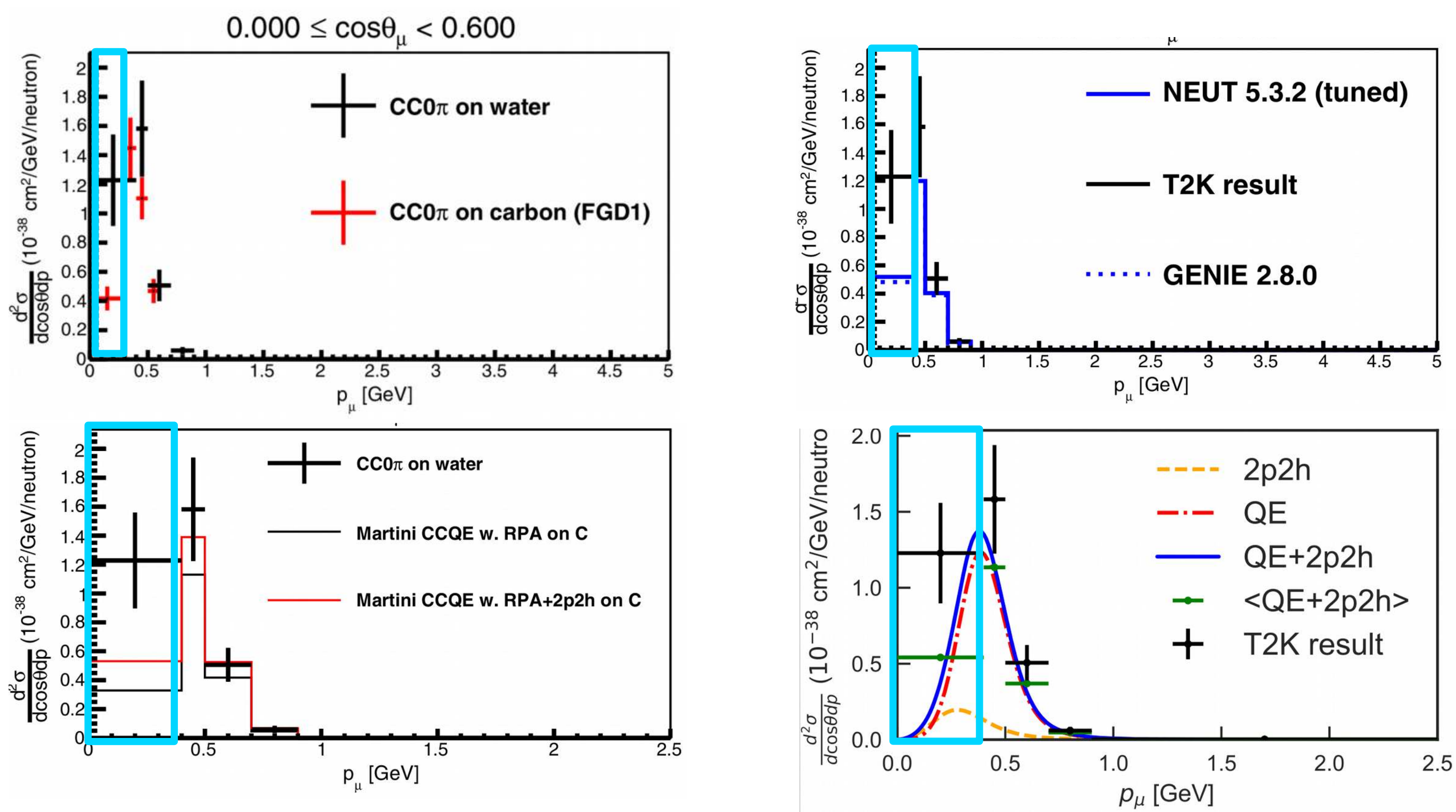
- Expanded selection possible in future 0 and 1π analyses: on towards exclusive channels!
- Being incorporated into the ND280 fitting for OA
  - *Details of the T2K oscillation analyses*, D. Sgalaberna, Thu. 2.30pm

PRD93 112012
PRD97 012001

CC0π

S. Bolognesi, A. Furmanski, T. Campbell, T. Yuan

- Previous result on FGD1 C_8H_8 compared to first H_2O measurement
- C_8H_8 vs H_2O is crucial systematic for T2K ND280 → SK propagation

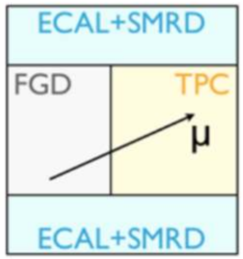
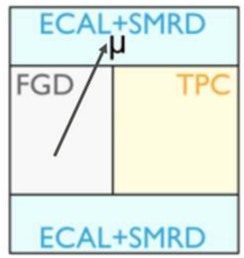
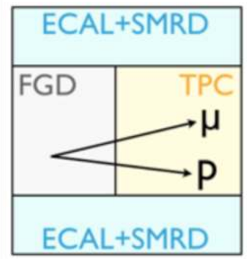
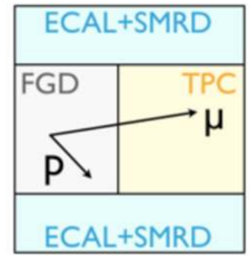
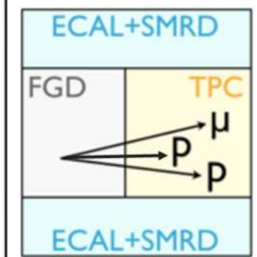
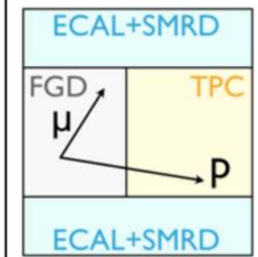


- Low momentum, high angle region under-predicted throughout
  - Region of largest difference between water and carbon: nuclear effect?
- Complimentary anti-ν_μ cross section, coming to arxiv

CC0π

S. Dolan, P. Bartet-Friburg, J. Kim, X. Lu

- New selections enable proton kinematic measurements with p_p > 450 MeV

	μTPC (1 track)	μFGD (1 track)	$\mu TPC + pTPC$	$\mu TPC + pFGD$	μTPC + multi p	$\mu FGD + pTPC$
Sample						
Description and number of measured events	• Single μ candidate tracked in TPC • **8874 events**	• Single μ candidate tracked in FGD and stopped in ECal • **1585 events**	• Both μ and p candidates are tracked in TPC • **1785 events**	• μ candidate is tracked in TPC • p candidate is tracked in FGD only • **1592 events**	• μ candidate is tracked in TPC • Multi p candidates, leading p is in TPC • **131 events**	• μ candidate is tracked in FGD only • p candidate is tracked in TPC • **1068 events**

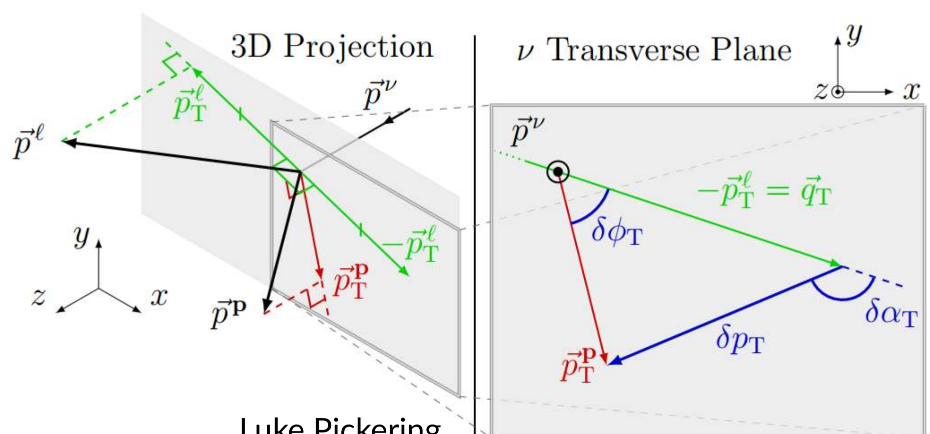
- Selections with proton candidate sensitive to nuclear effects, e.g.
  - Transverse to neutrino direction
  - 2D inferred $p_p^{\text{inferred}} \cos\theta_\mu$

$$\overrightarrow{p}_p^{inferred} = (-p_\mu^x, -p_\mu^y, -p_\mu^z + E_\nu),$$

$$\Delta p_p = |\overrightarrow{p}_p^{measured}| - |\overrightarrow{p}_p^{inferred}|,$$

$$\Delta\theta_p = \theta_p^{measured} - \theta_p^{inferred},$$

$$|\Delta \mathbf{p}| = |\overrightarrow{p}_p^{measured} - \overrightarrow{p}_p^{inferred}|.$$

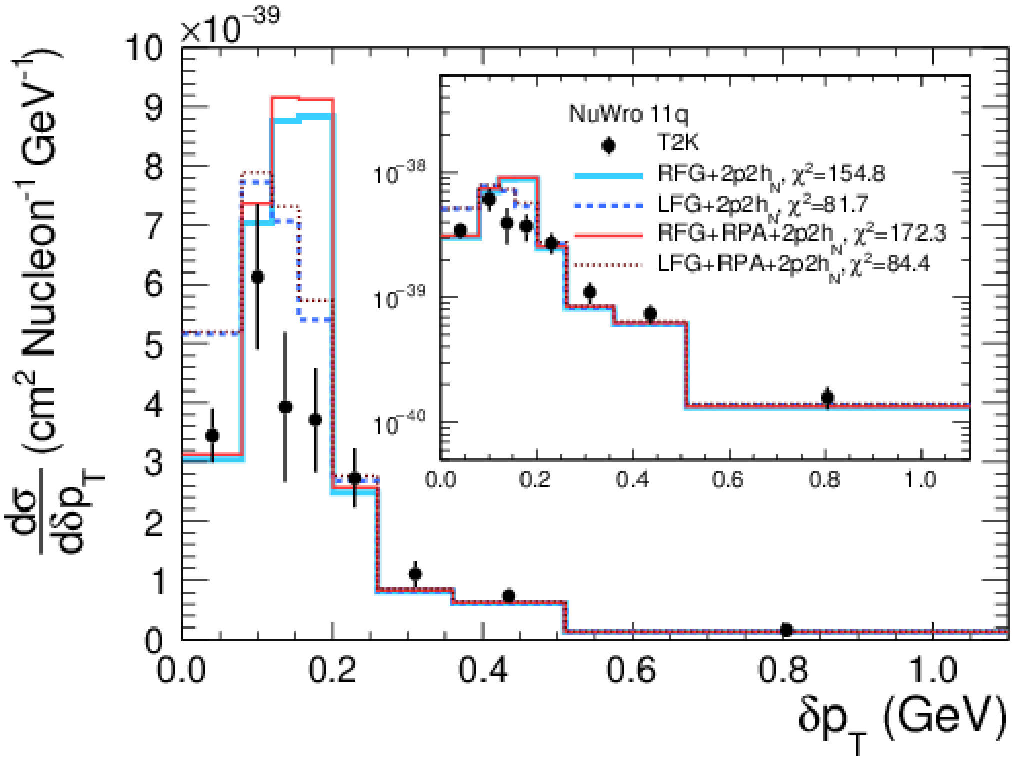


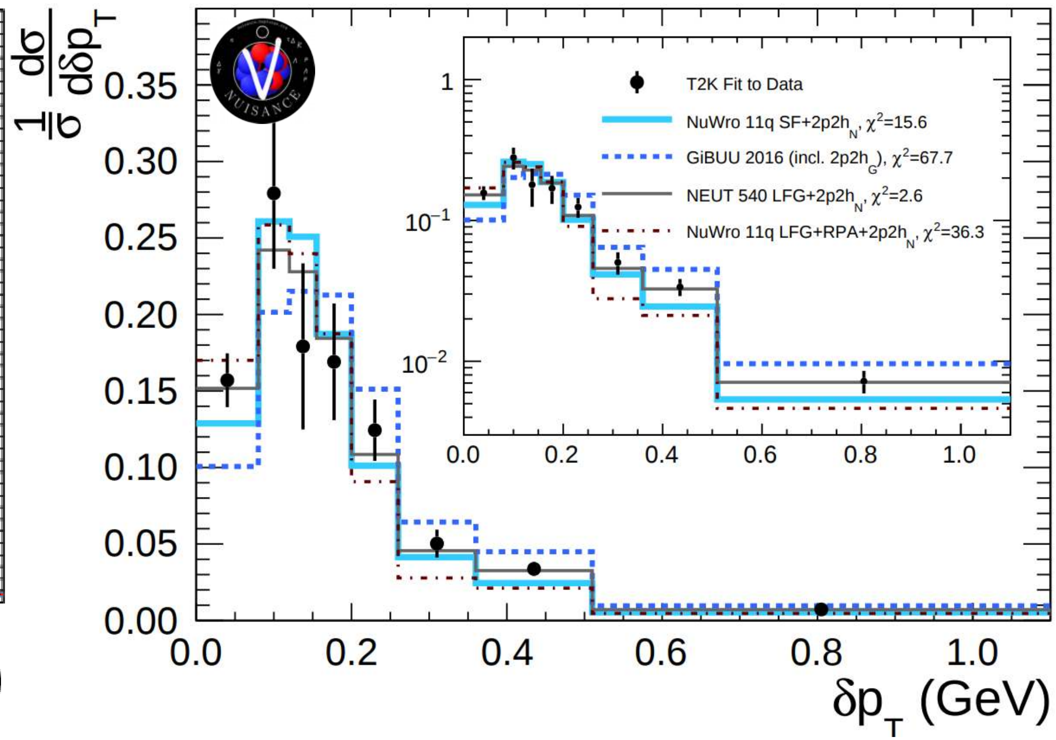
arXiv:1802.05078

CC0π

S. Dolan, P. Bartet-Friburg, J. Kim, X. Lu

- Weaknesses of nuclear models exposed, although no clear winner (yet?)





- Generally disfavours simplistic nuclear models (RFG) and requires 0π enhancement, e.g. 2p2h, and generally favours RPA
- The power of the transverse variables clearly demonstrated!
- 2D cross sections of inferred proton momentum and muon variables

arXiv:1802.05078
arXiv:1804.09488

CC0π future

S. Dolan, X. Lu, T. Campbell, C. Riccio, L. Maret, B. Quillain, M. Licciardi

- Effort at T2K and MINERvA to probe nuclear model together
  - Authors working closely together with generator experts
  - *MINERvA Cross Section Results*, X. Lu, Tue. 2pm

T2K + MINERvA =

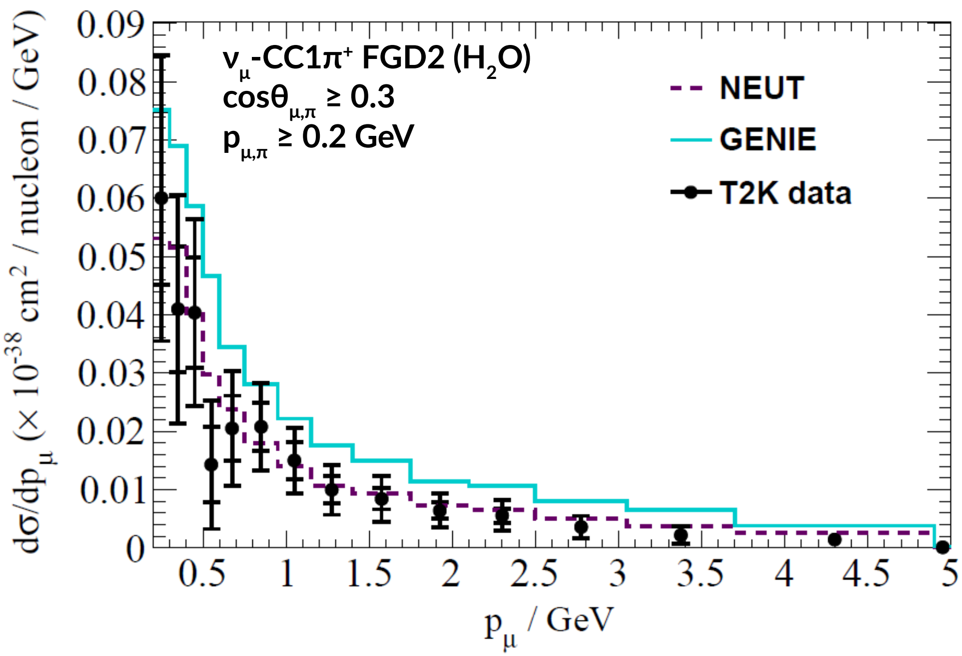
- Complementary target and anti-neutrino analyses underway
  - Anti-ν_μ on H_2O in P0D, coming to arxiv
  - Simultaneous ν_μ and anti-ν_μ on C_8H_8, coming to arxiv
- INGRID proton module with proton track multiplicity analysis

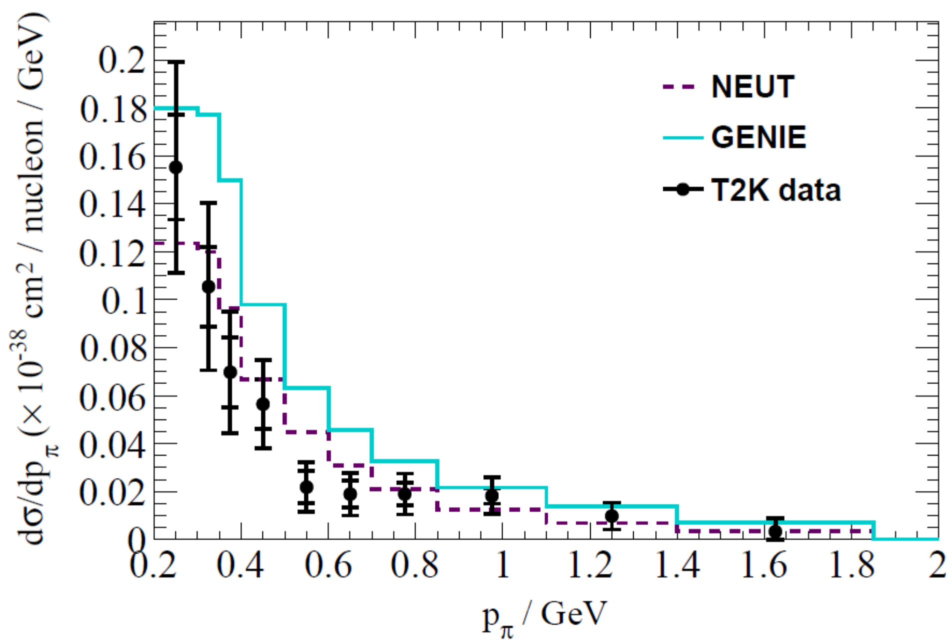
PRD 95 012010

CC1$\pi^{\pm}$

L. Cremonesi, J. Schwehr, M. Hogan, D. Cherdack

- Important background for T2K oscillation (signal at NOvA and DUNE)
  - Nuclear model less tested with 1π data; clever analyses needed!
- CC1π^+ H_2O FGD2 analysis saw too large GENIE cross section
  - Low statistics limits the power of the data: next analyses doubles



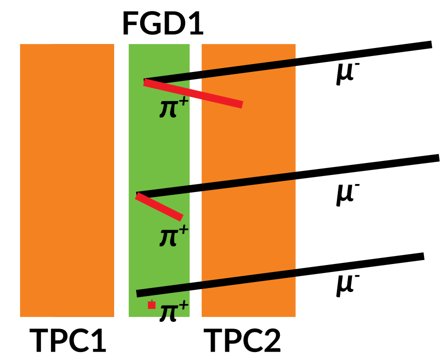


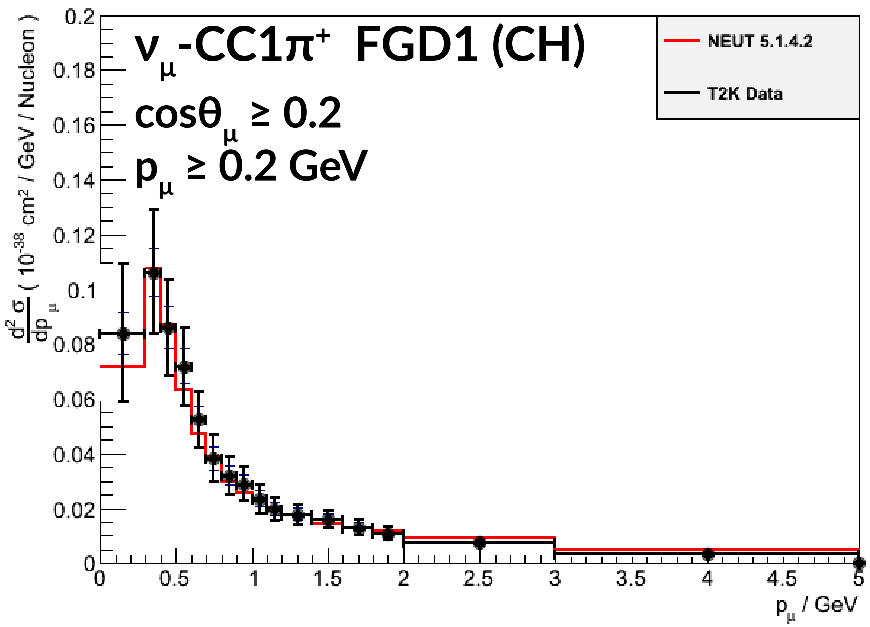
- Complementary selection on P0D, coming to arxiv
  - Different detector with larger statistics and acceptance
  - P0D fiducial target (not H_2O only)

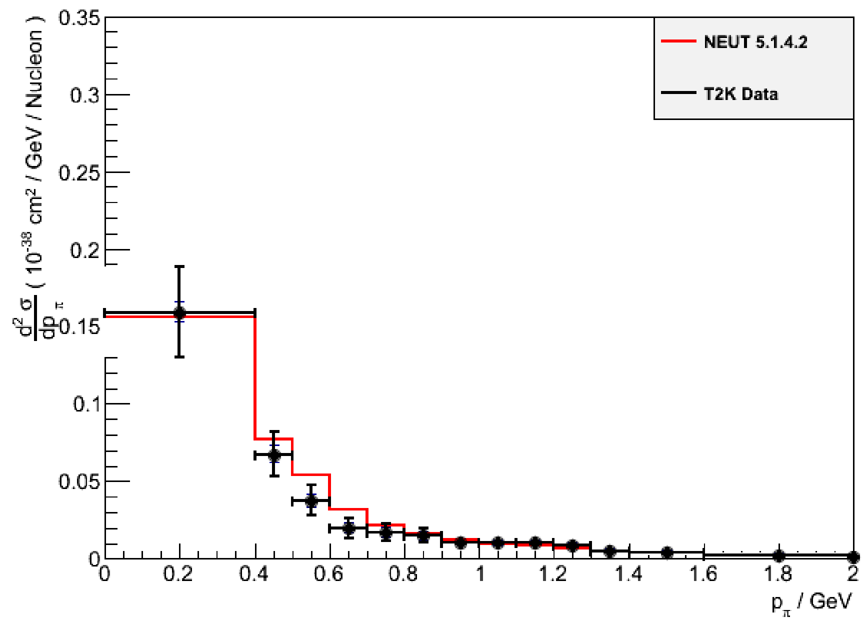
$CC1\pi^{\pm}$

R. Castillo,
B. Quillain, M. Licciardi

- C_8H_8 in FGD1 analysis in preparation for PRD, arxiv soon
  - Much larger data set and different target
  - Pion selection by TPC or FGD track, or delayed Michel
- Correlated observables and derived quantities
  - Shine light on pion FSI and nuclear effects





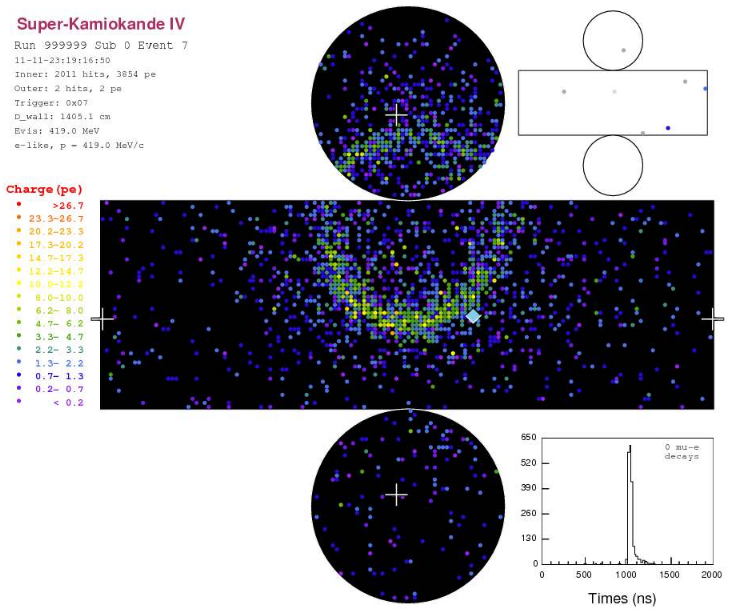


- Proton module with target comparisons and 2D, coming to arxiv
- Future analyses: anti-ν_μ and wrong-sign pion production, particle and selection correlations, multiple targets comparisons

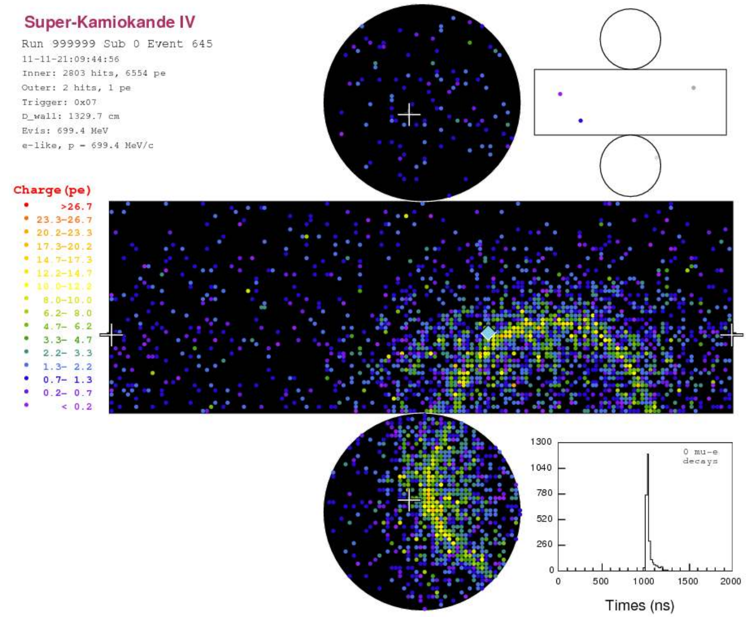
CC/NCπ^0

M. Lawe, C. Pidcott, A. Izmaylov, M. Batkiewicz, Z. Vallari

- Backgrounds for T2K-SK oscillation signal



True π^0 reconstructed as e at SK



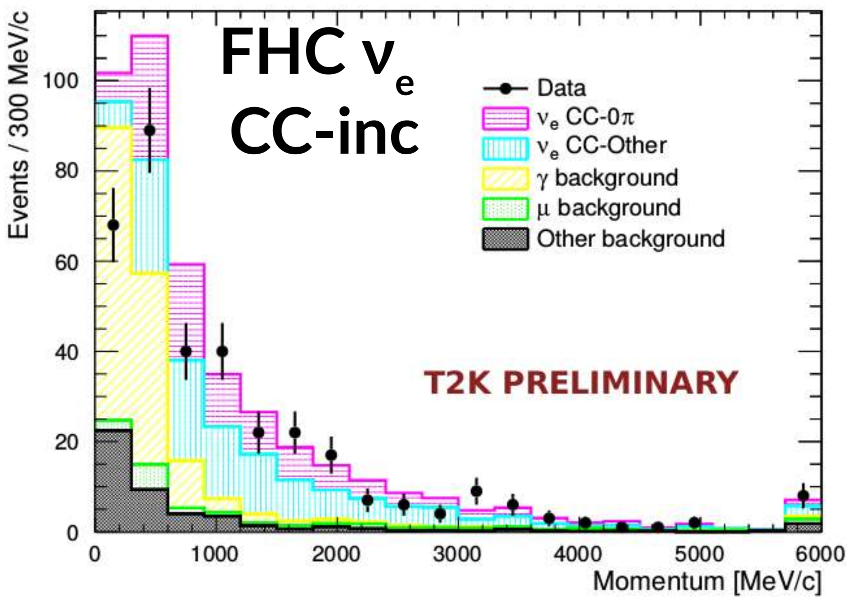
True e reconstructed as e at SK

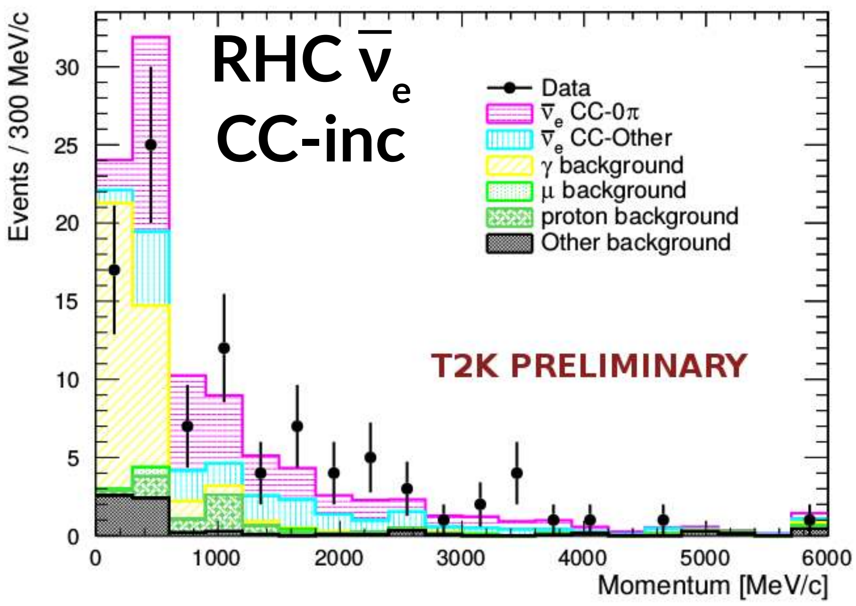
- ν_μ and anti-ν_μ, charged and neutral current selections in FGD and P0D are developed
- NC1π^0 in P0D on H_2O rates PRD 97 032002
- New NC1π^0 analysis approaching, CC1π^0 analysis is ongoing
- Large systematics involved

ν_e interactions

S. King, G. Christodoulou, B. Jamieson, P. Lasorak, Y. Wang

- Intrinisic beam background for $\nu_\mu \rightarrow \nu_e$ oscillation
- Very sparse amount of external data on ν_e interaction
- ν_e and anti-ν_e CC-inclusive and ν_e CC0π selections developed

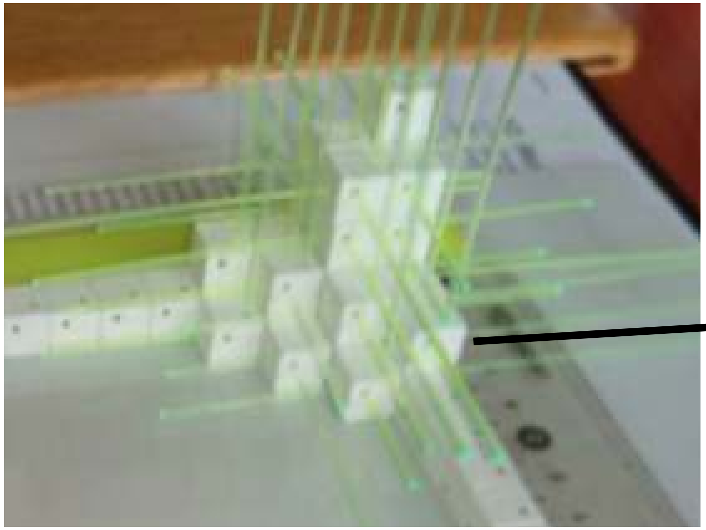


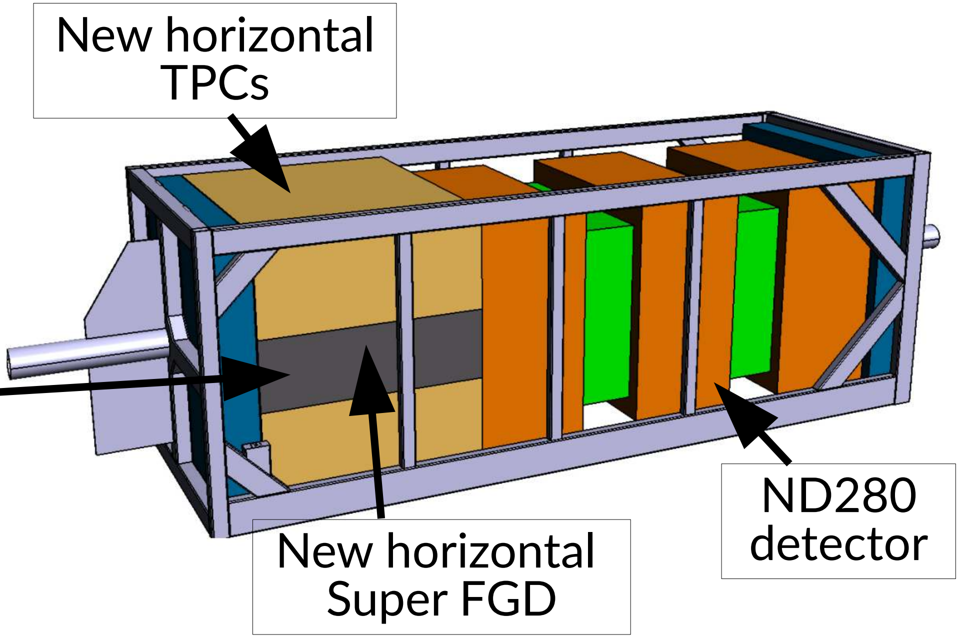


- Photon backgrounds large below 500 MeV
- P0D selections being developed

ND280 Upgrades

- Upgrade programme at J-PARC for T2K-II (~2021) and beyond
- Super FGD (JINST 13 P02006, CERN-SPSC-P357) – Install 2021
  - Segmented 1cm^3 cubes FGD sandwiched by two TPCs
  - Excellent vertexing and proton measurements
  - 80%+ efficiency in $\cos\theta_\mu$

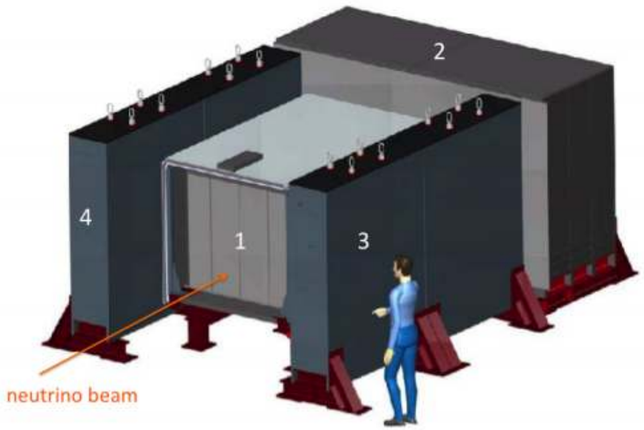


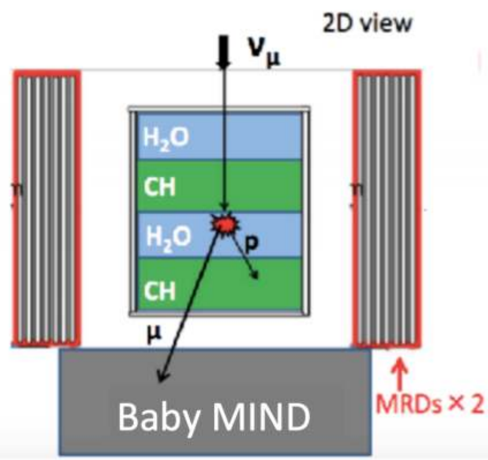


- High Pressure TPC, movable water Cherenkov detector (ν-PRISM)
- *T2K Near Detector Upgrades and Plans for T2HK*, T. Lux, Wed. 1pm

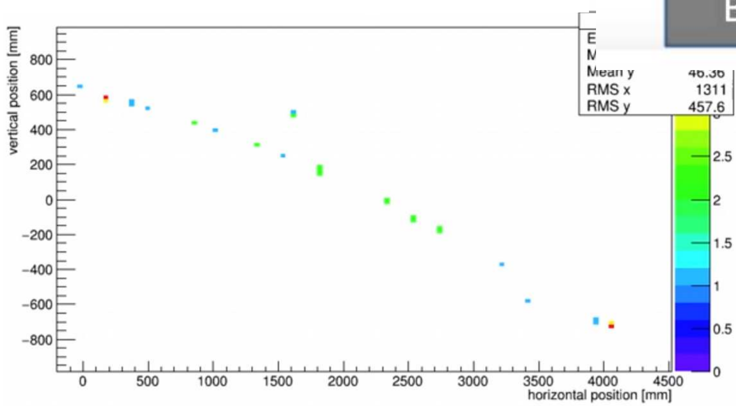
ND280 Upgrades

- WAGASCI and Baby MIND (JINST 12 C07028) detectors
  - Segmented cubic CH/H_2O (WAGASCI) and MRD+Baby MIND





Baby MIND moved into pit, Y. Uchida, Dec 2017



Baby MIND muon tracking in T2K beam spill, E. Noah

- Installed and running well: being integrated into T2K frameworks
- *<u>WAGASCI, S.-P. Hallsjo, Thur. 5pm</u>*

Conclusion

- Neutrino interaction systematics are critical for oscillation analyses and path forwards
- T2K provides community with data from different fluxes, detectors and interaction targets
- Neutrino interaction cross section programme is mature
  - Inclusive selections with expanded phase space
  - Topological selections with kinematics correlating particles, moving beyond the muon and pion
  - π^0 and ν_e selections pushing forwards
- Large increases in data as J-PARC ramps up power
- ND280 upgrades focussing on proton measurements and vertex activity are being evaluated

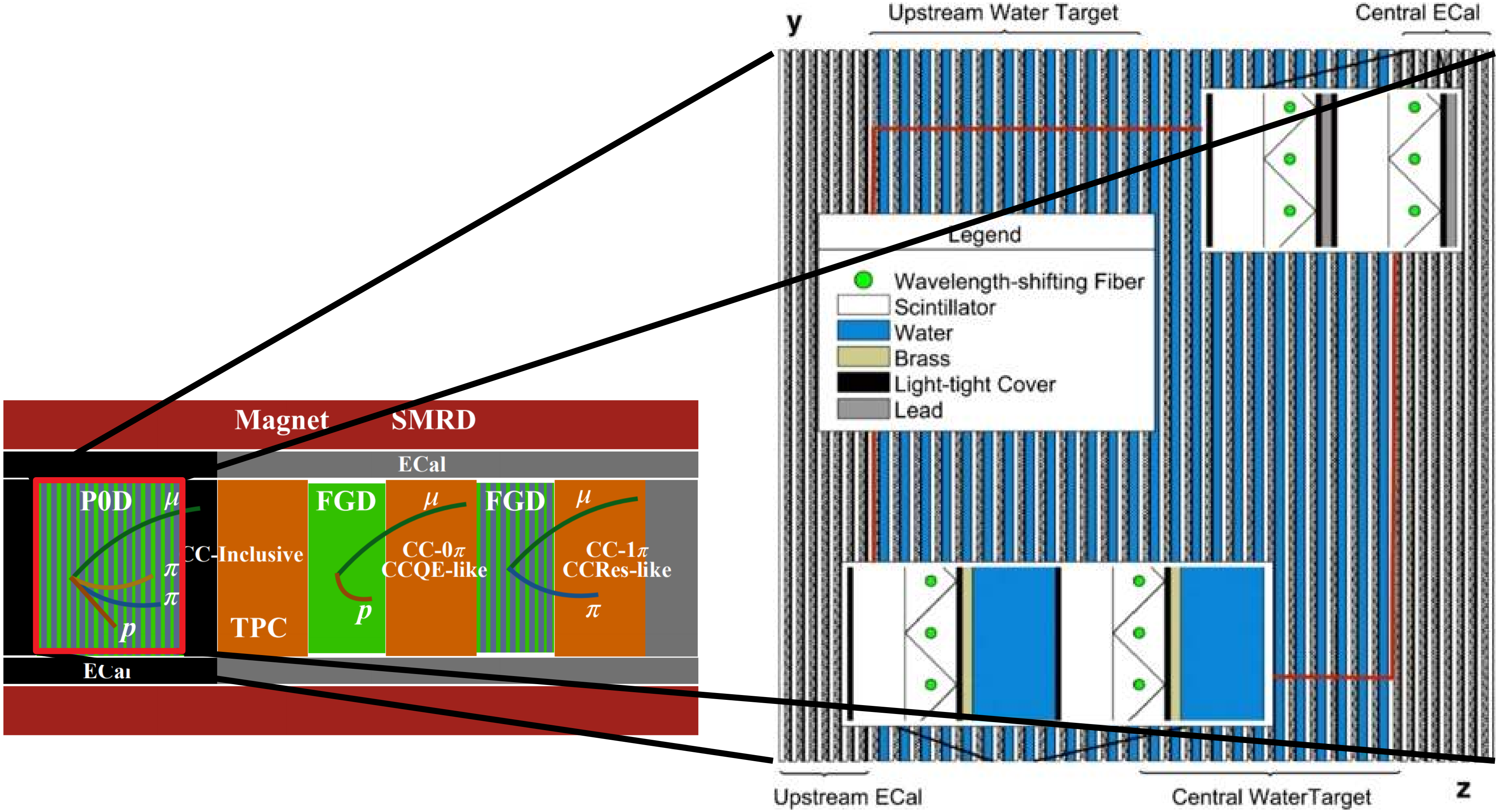
Thank you!

T2K Breakthrough Prize Party

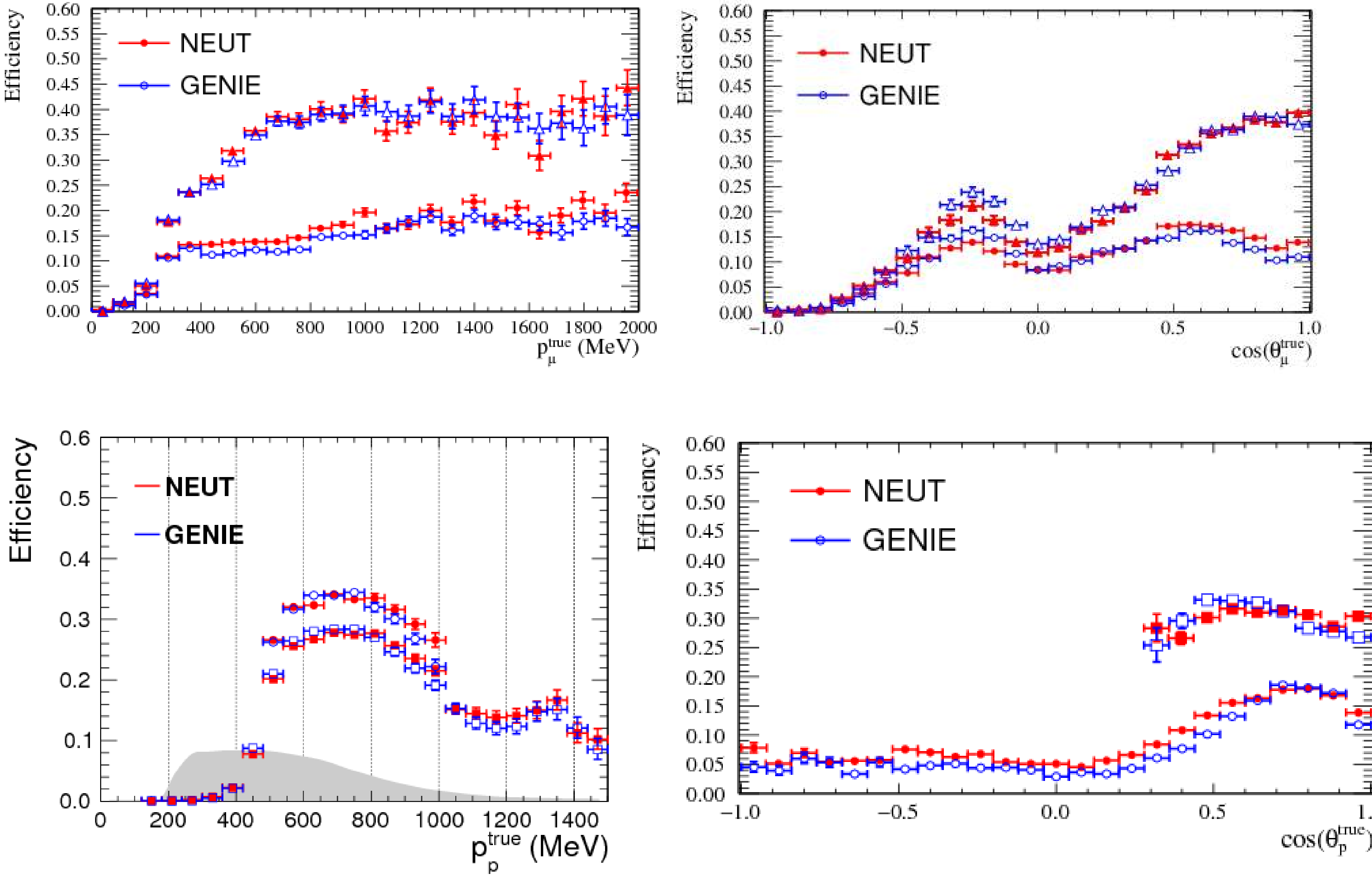
January 28th, 2016 at Kuji Sunpia Hitachi

Backups

P0D side view

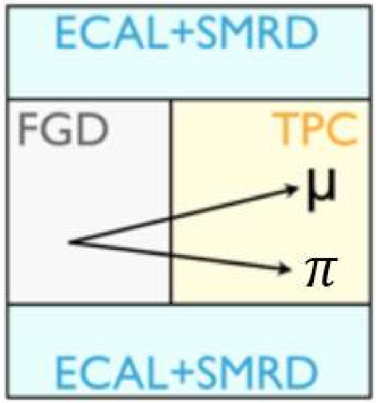
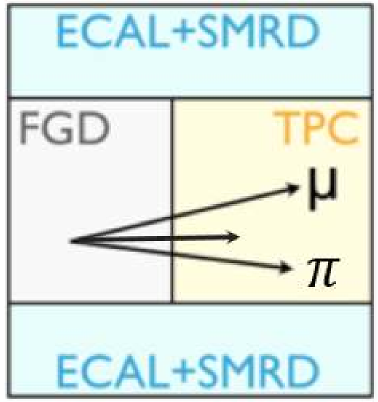


CC0π efficiencies

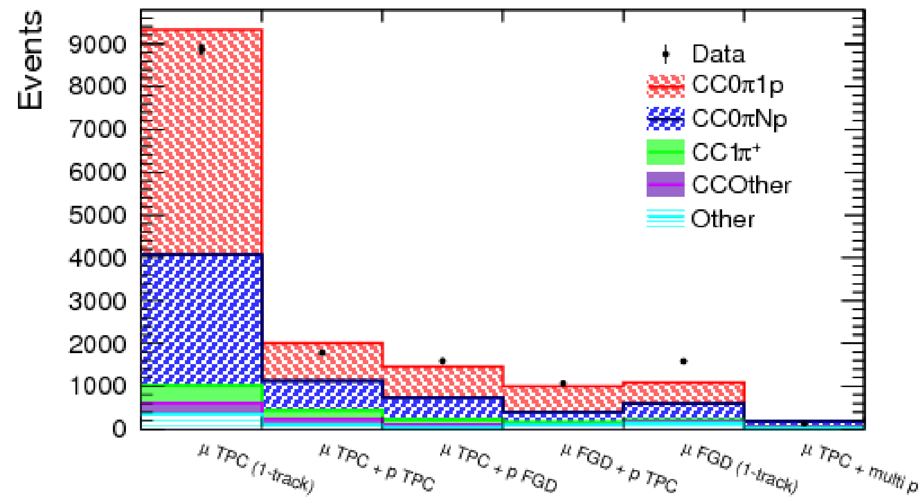


CC0π details

Control samples

Sample	$CC1\pi$ Control 	$CCOther$ Control 
Description and number of expected events	• Both μ and π candidates are tracked in TPC • **877 events**	• Both μ and π candidates are tracked in TPC • At least one extra TPC track • **1307 events**

Signal by topology

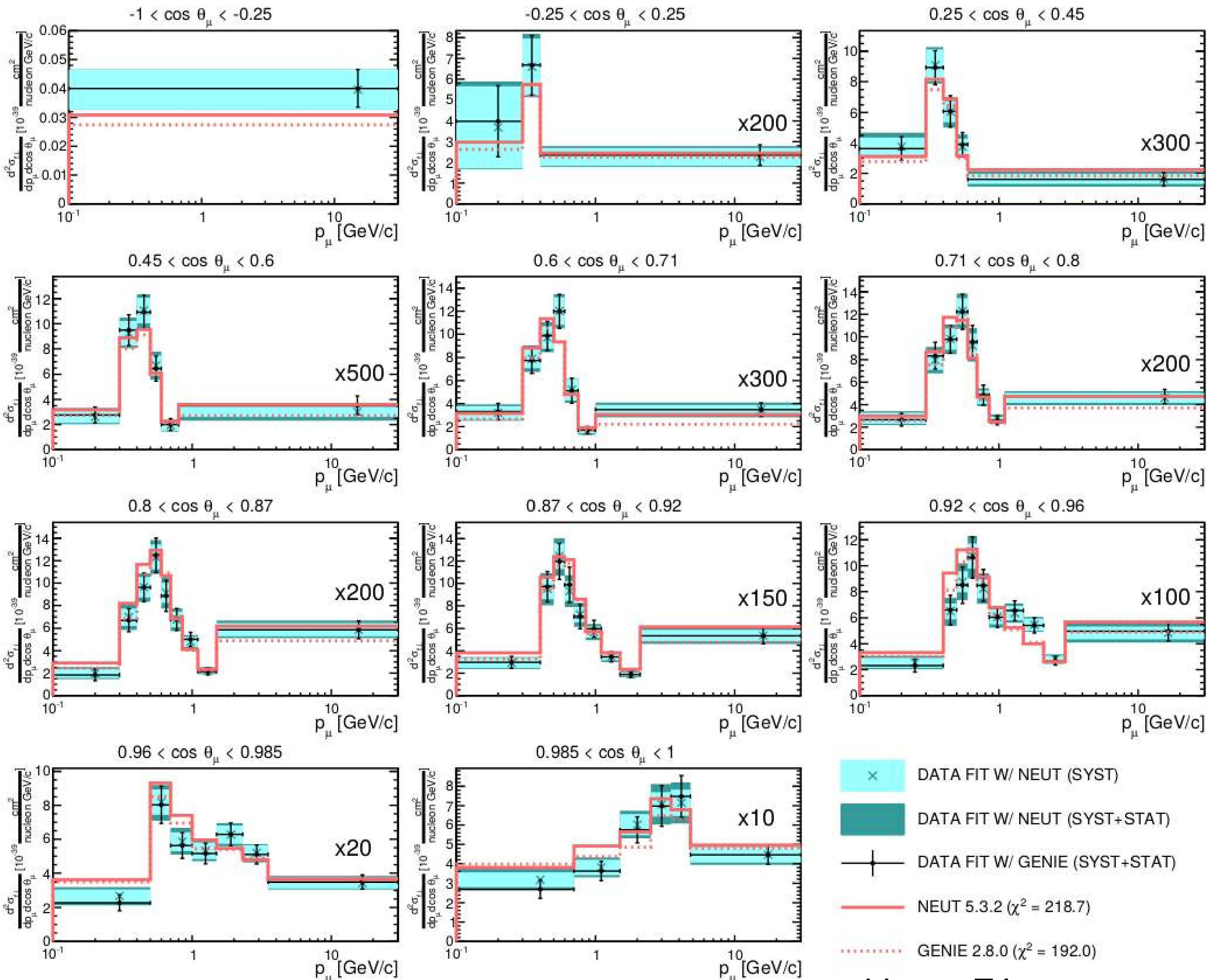


arXiv:1801.05148

CC-inclusive

A. Garcia

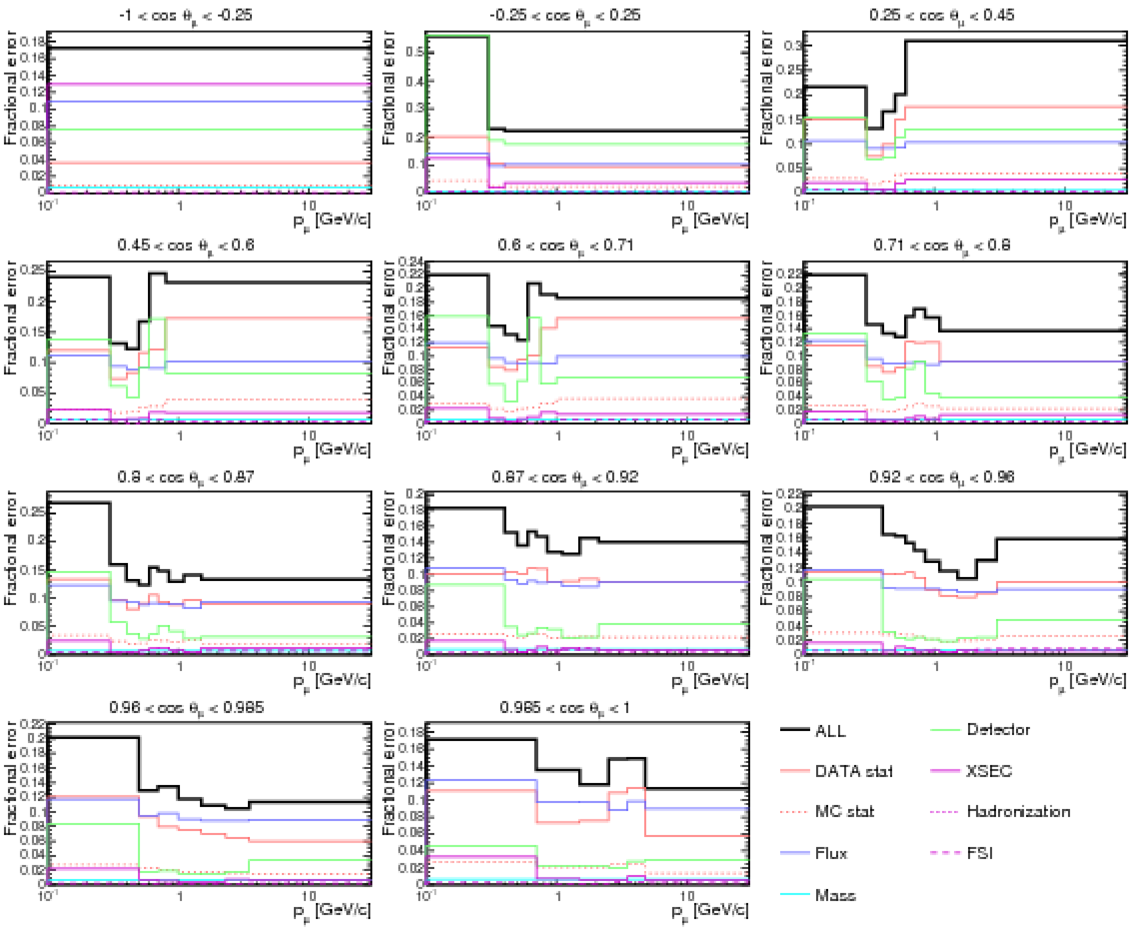
- Small preference (0.37 χ^2/N_{Bins}) for GENIE CC-inclusive model over NEUT
- Results invariant to model used in unfolding
- Similar anti-ν_μ selection finalised, measurement in preparation



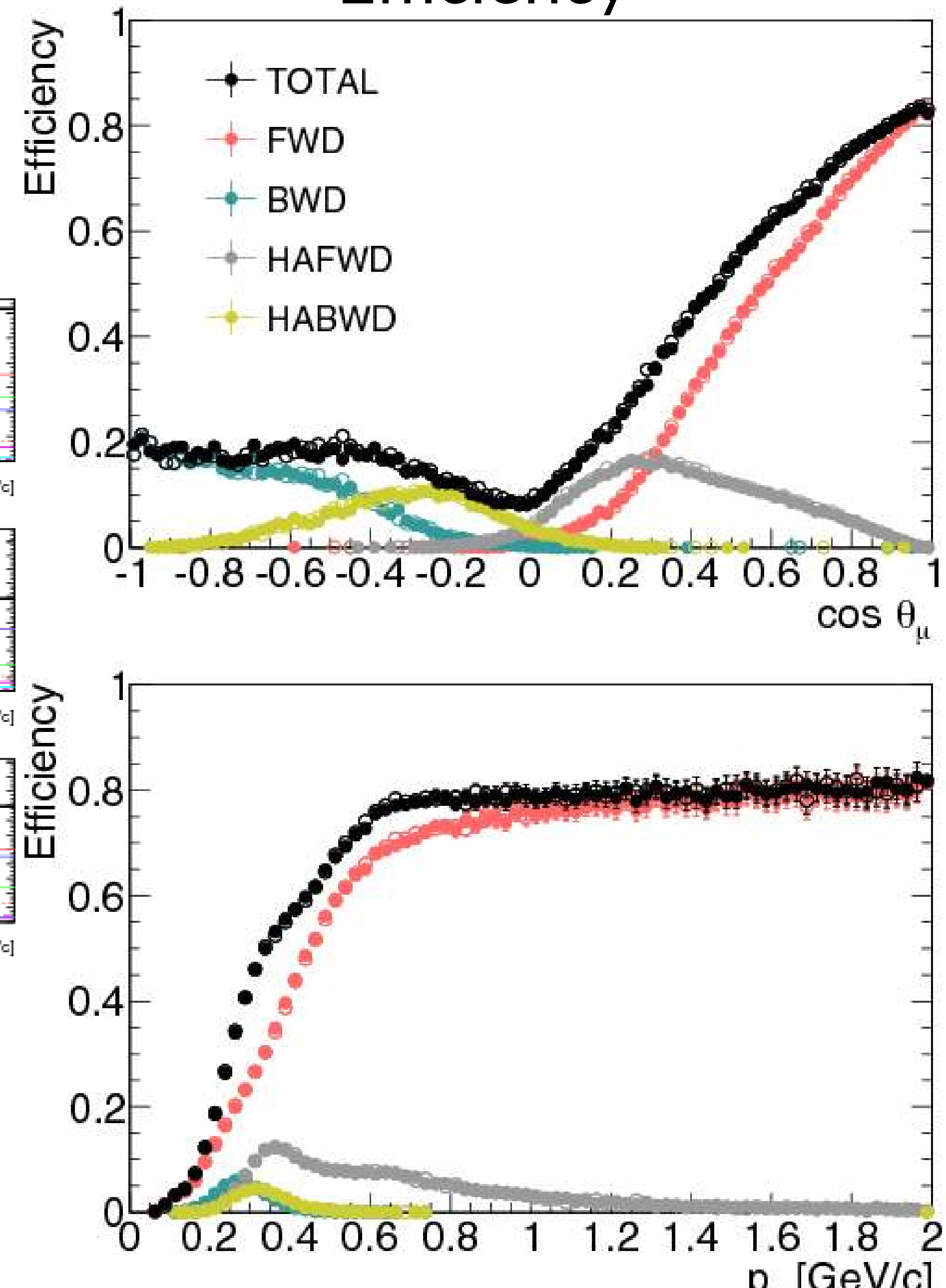
$N_{Bins} = 71$

CC inclusive details

Fractional errors



Efficiency



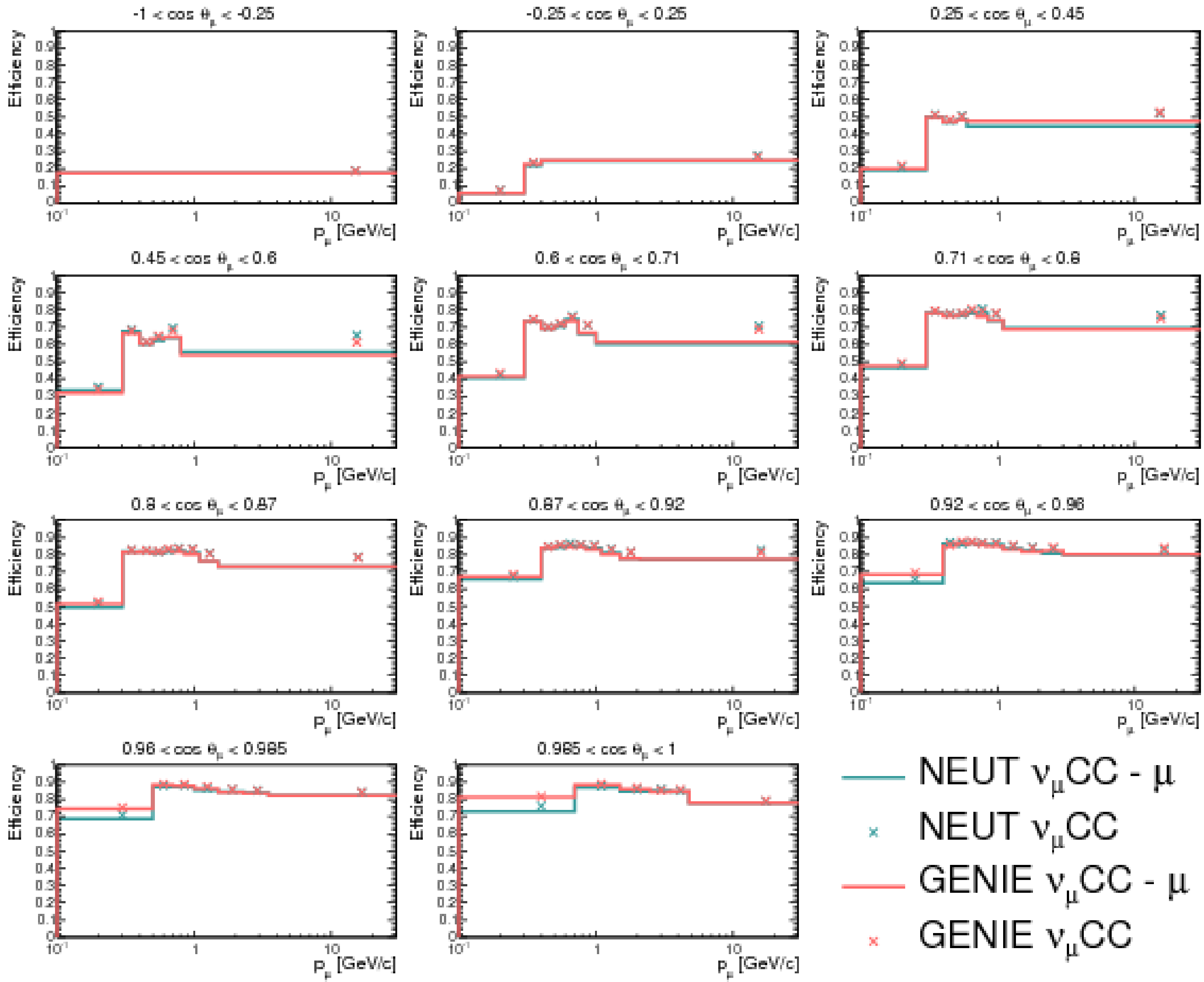
CC inclusive details

Event selection

Cut	FWD		BWD		HAFWD		HABWD	
	DATA	NEUT	DATA	NEUT	DATA	NEUT	DATA	NEUT
Quality	82155	81222 **32.3**	1861	1050 **58.5**	7225	7121 **41.8**	1582	1566 **48.9**
FV	50519	51648 **48.7**	1165	1025 **58.8**	5669	5764 **49.2**	1356	1360 54.1
μ PID	29140	29750 **81.6**	940	799 **73.6**	3712	3487 **71.7**	779	684 **72.7**
Veto	25669	26656 **89.4**	940	799 **73.6**	3270	3107 **79.2**	730	645 **75.9**
Ordering ν_μ**CC**$-\mu$[%]	25669	26656 **89.4**	940	799 **73.6**	3082	2857 **81.9**	682	591 **78.9**

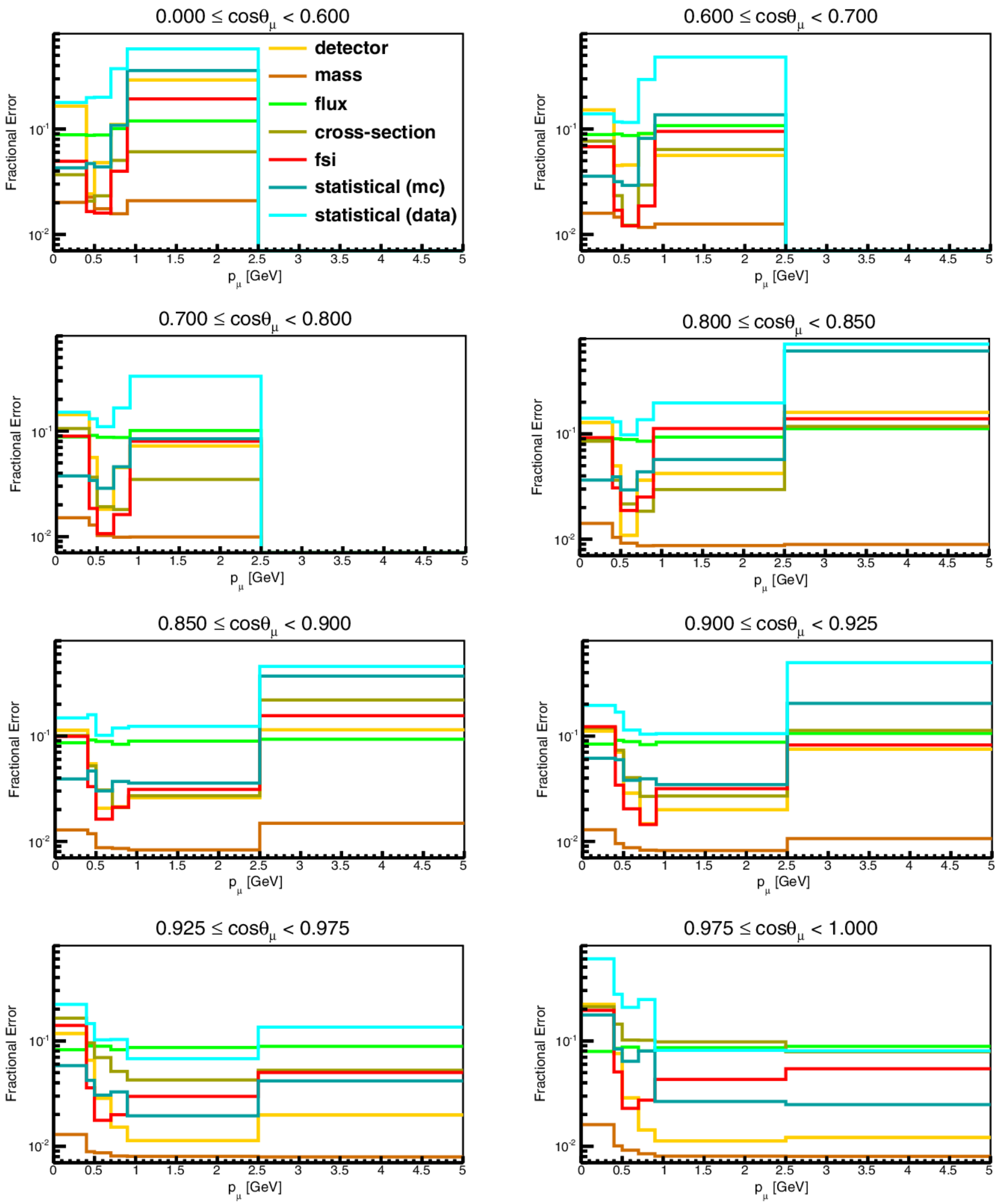
TABLE I. The selected number of events and signal purities percentage (in bold) in each sample as successive requirements are added for data and MC. The cut in last row refers to the priority order in cases where a muon candidate has been found in two samples.

CC inclusive details

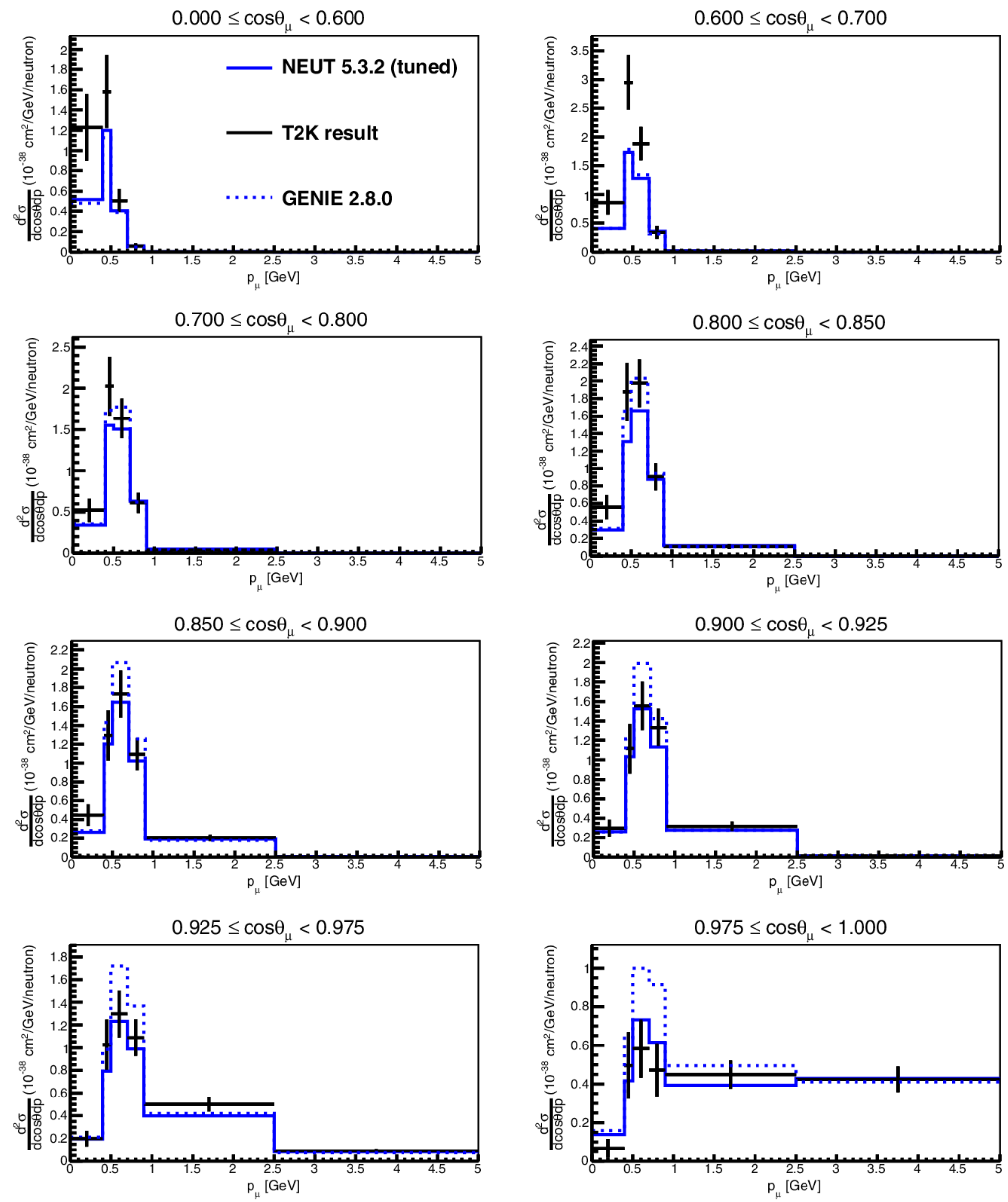


P0D CC0π details

Fractional errors

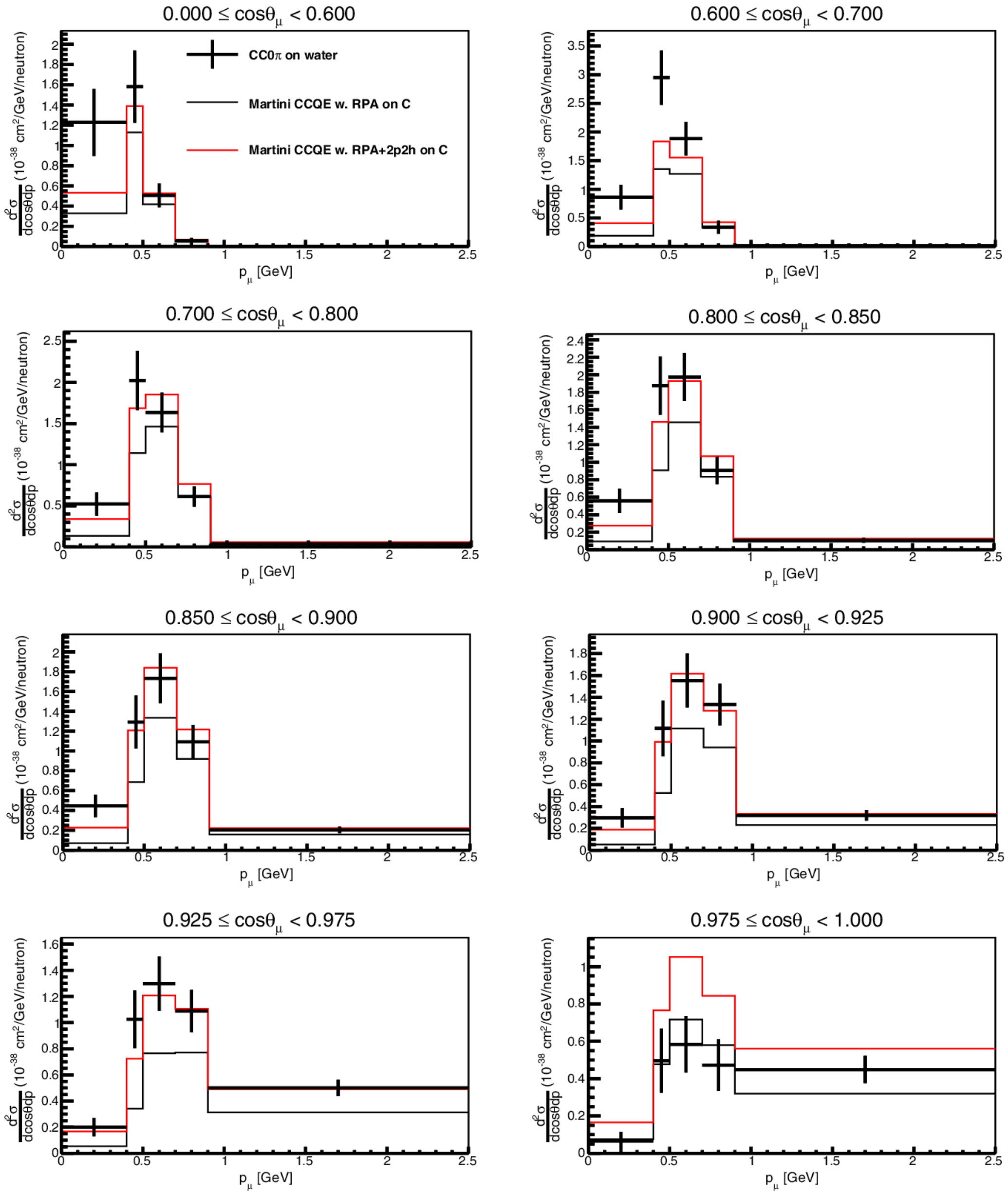


GENIE and NEUT comparison

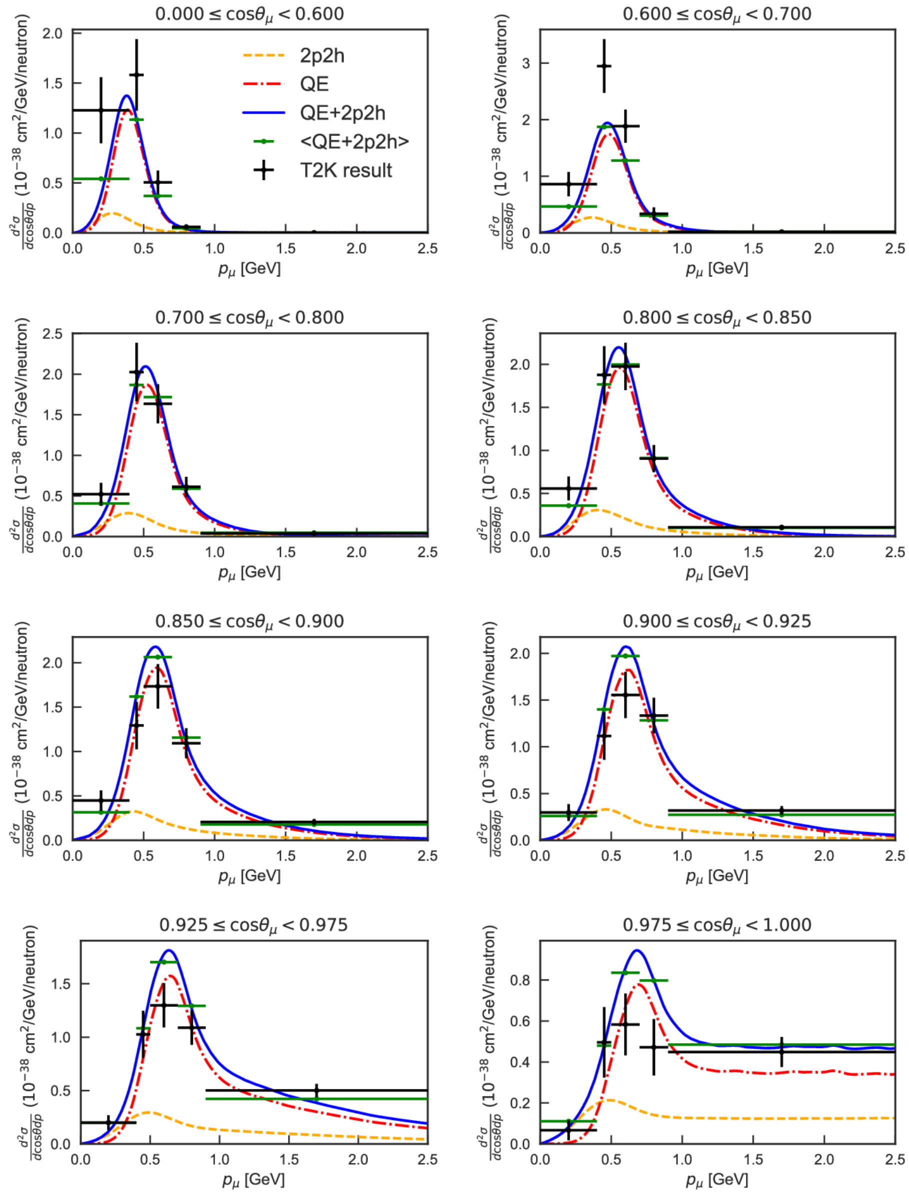


P0D CC0π details

Martini comparisons

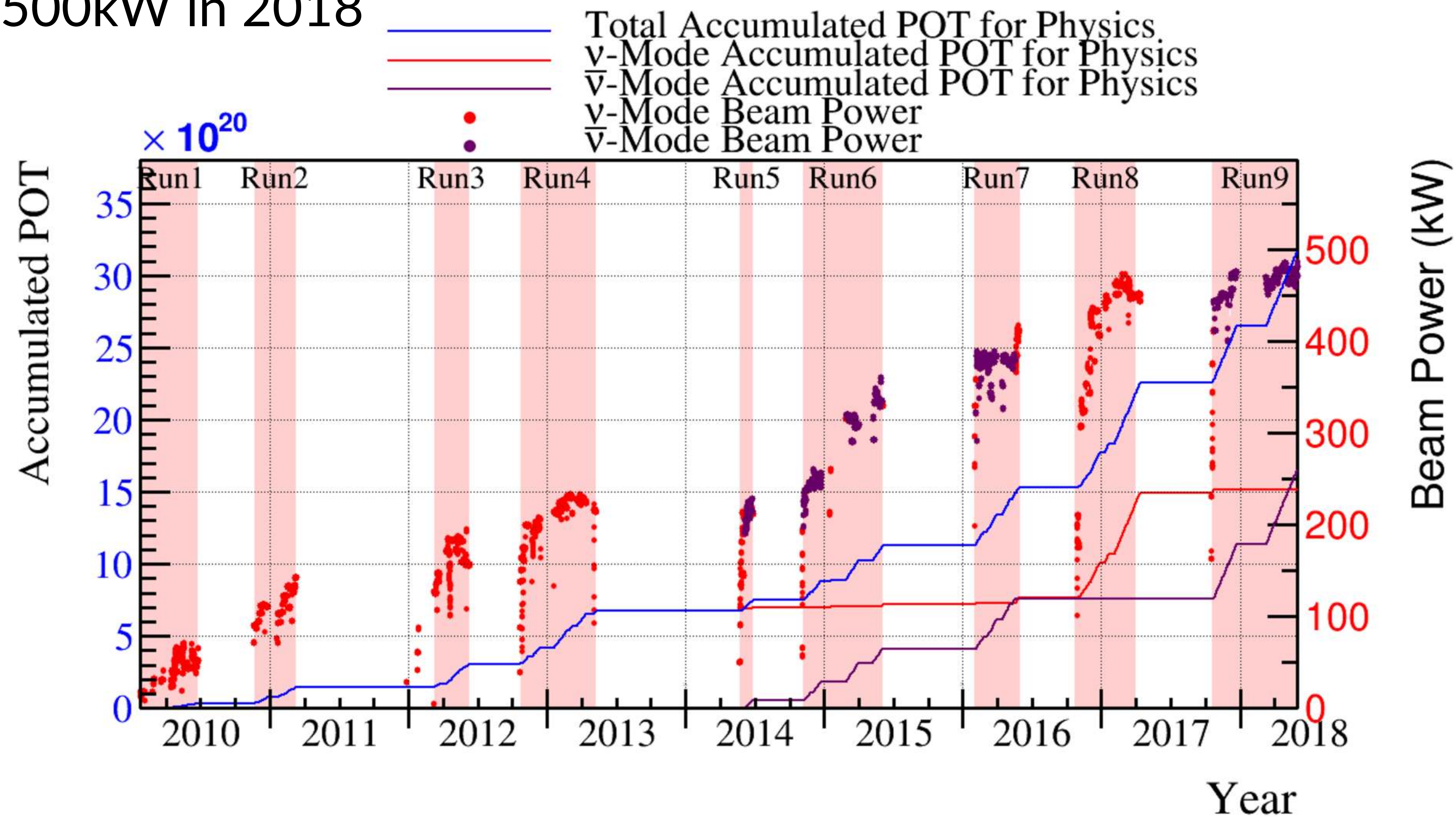


SuSA comparisons



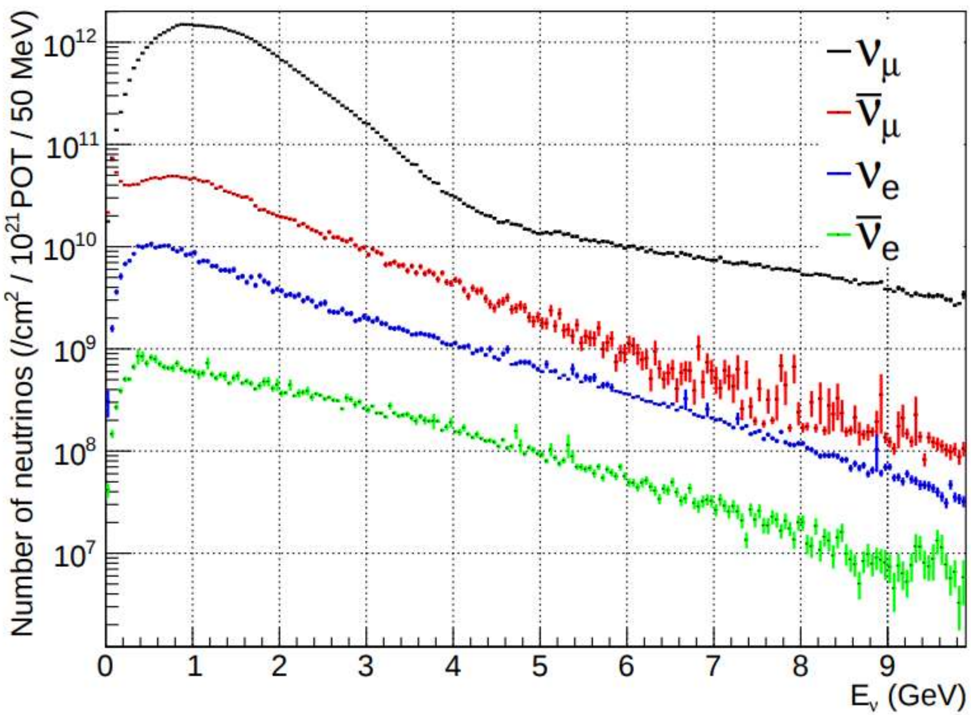
T2K beam performance

- 1.51E21 POT FHC
- 1.65E21 POT RHC
- 500kW in 2018

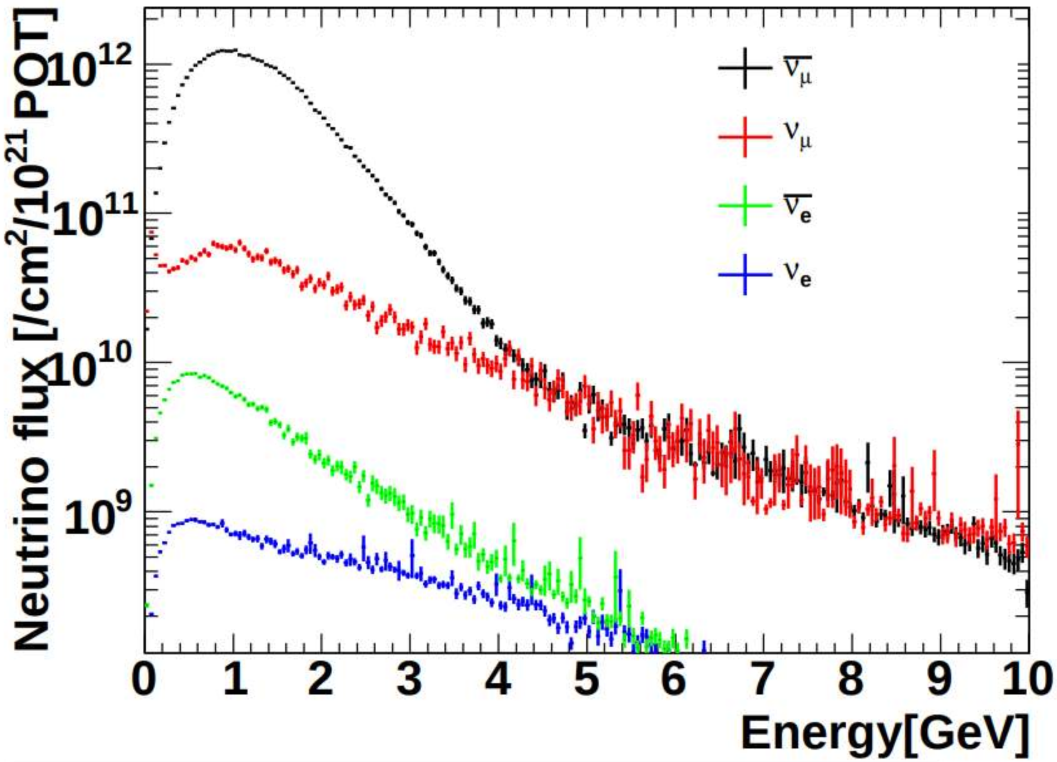


INGRID flux

Forward horn current

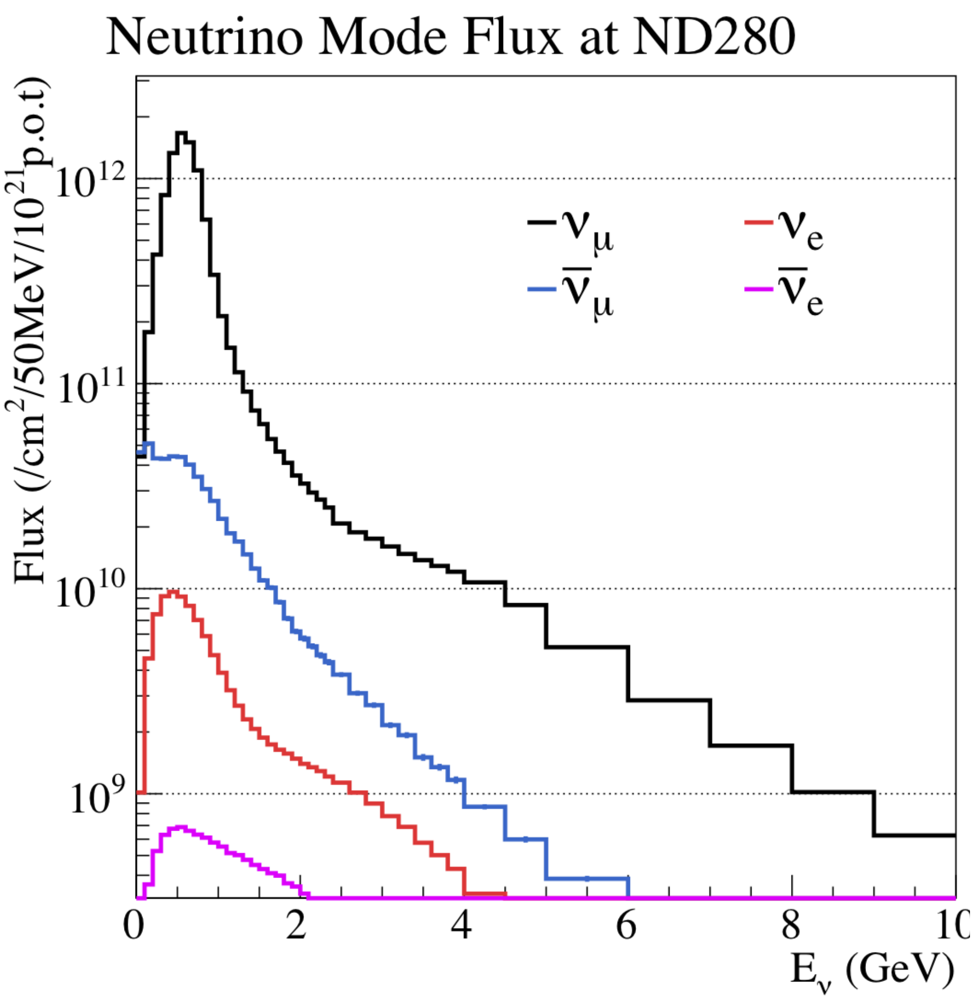


Reverse horn current

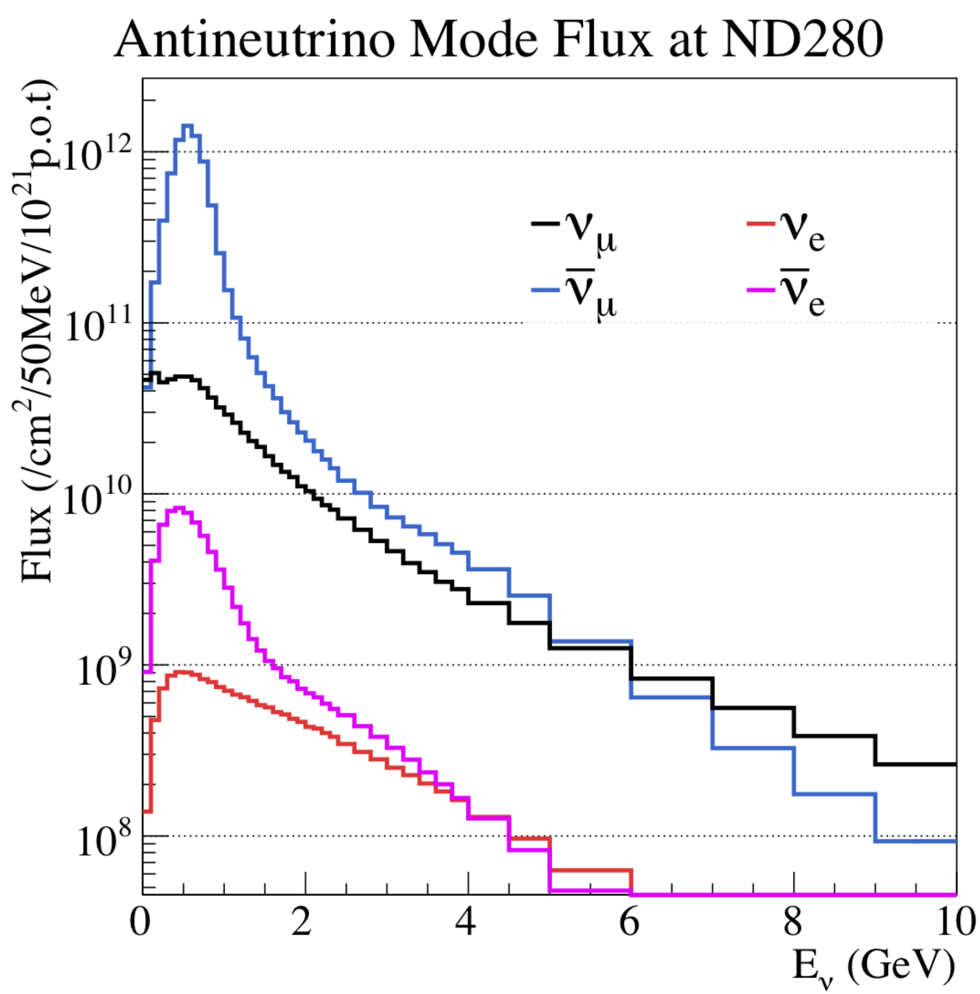


ND280 flux

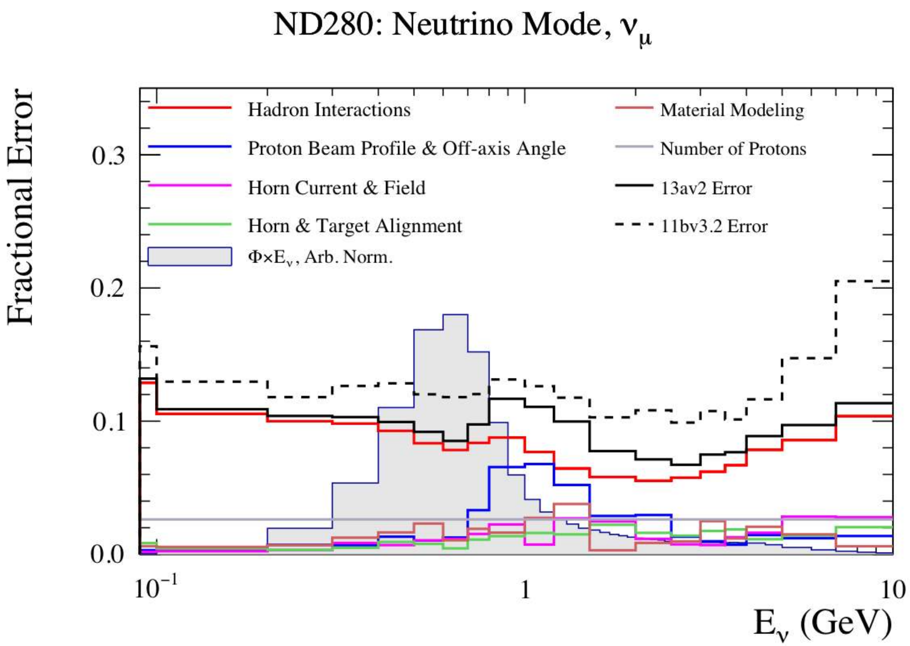
Forward horn current

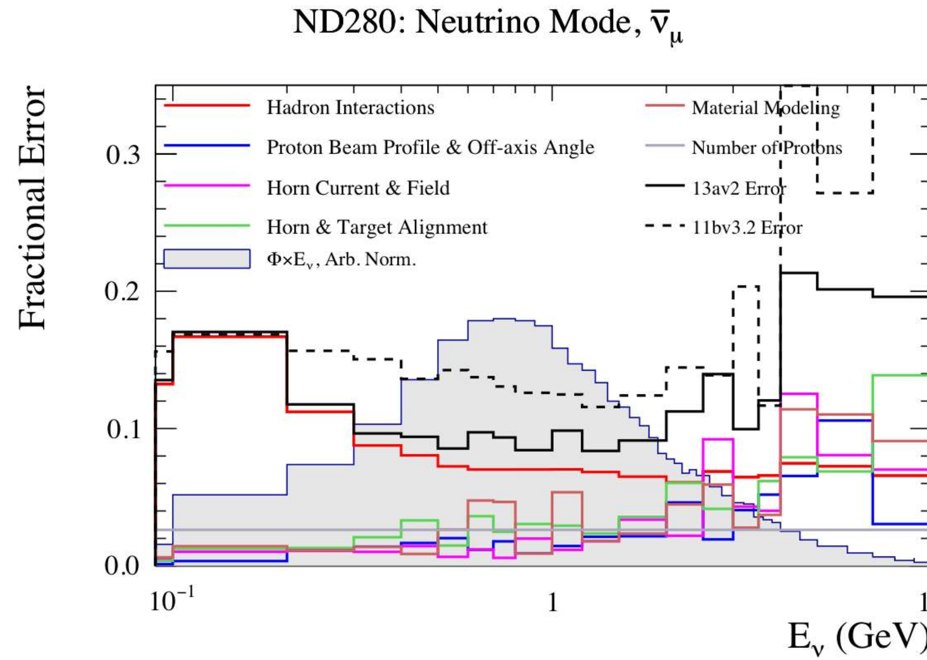


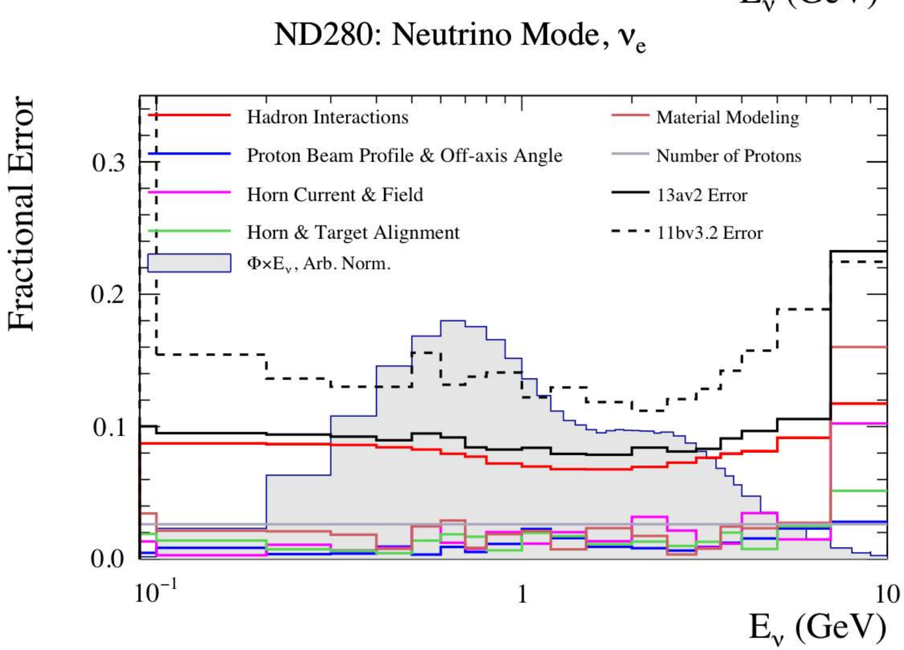
Reverse horn current

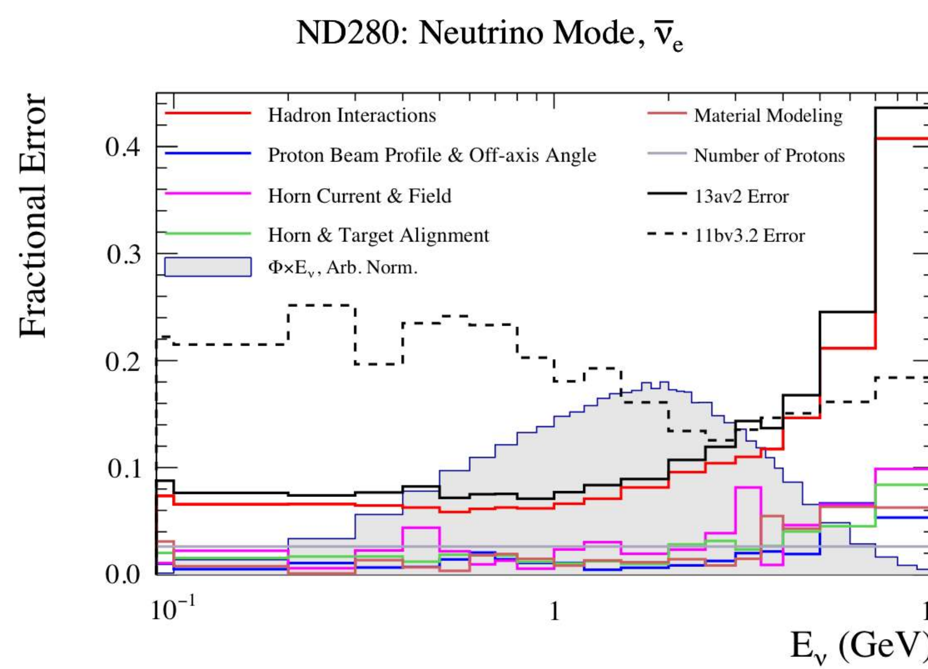


Flux uncertainties FHC









Flux uncertainties RHC