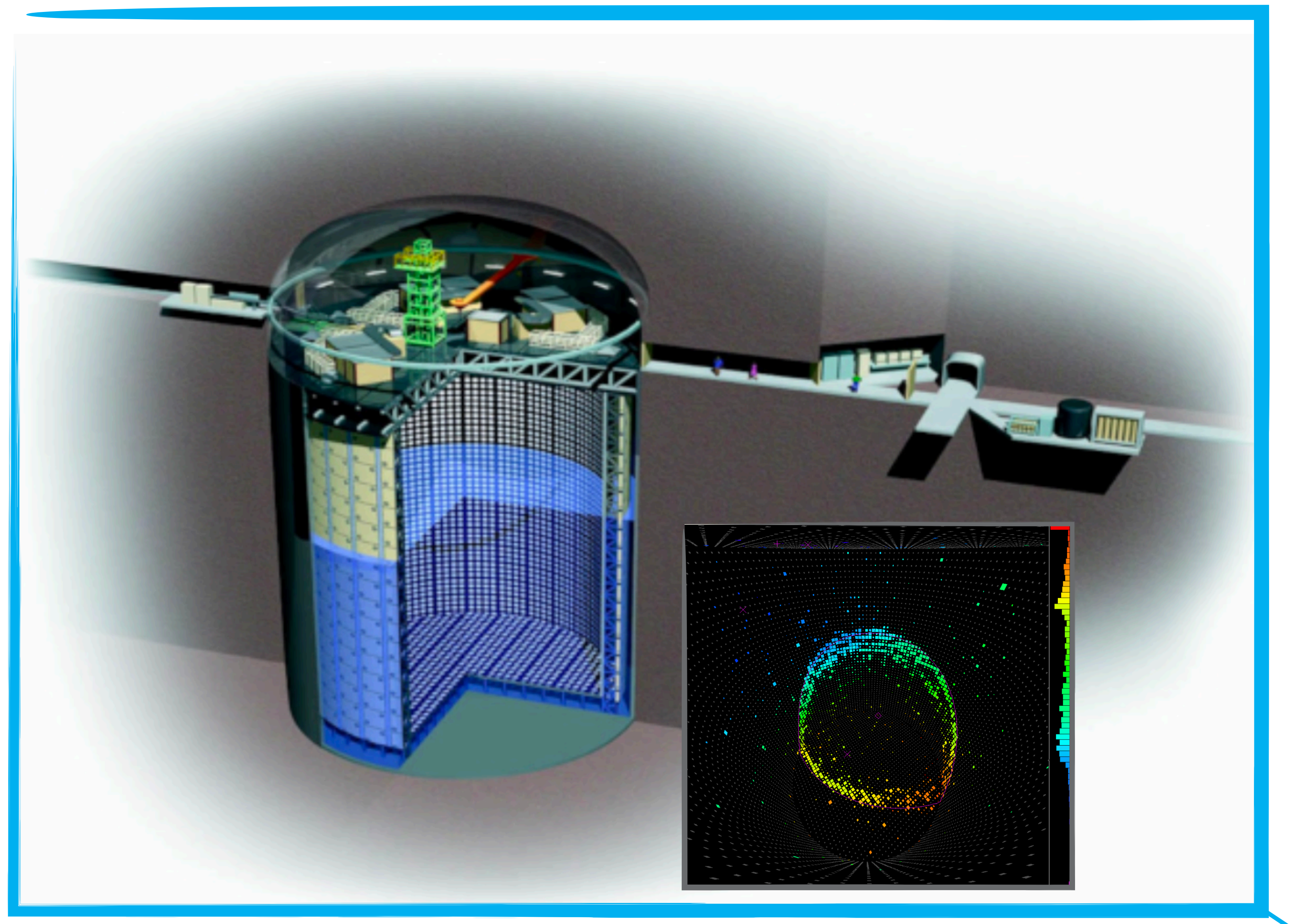
Recent T2K Results on Neutrino Cross-Sections

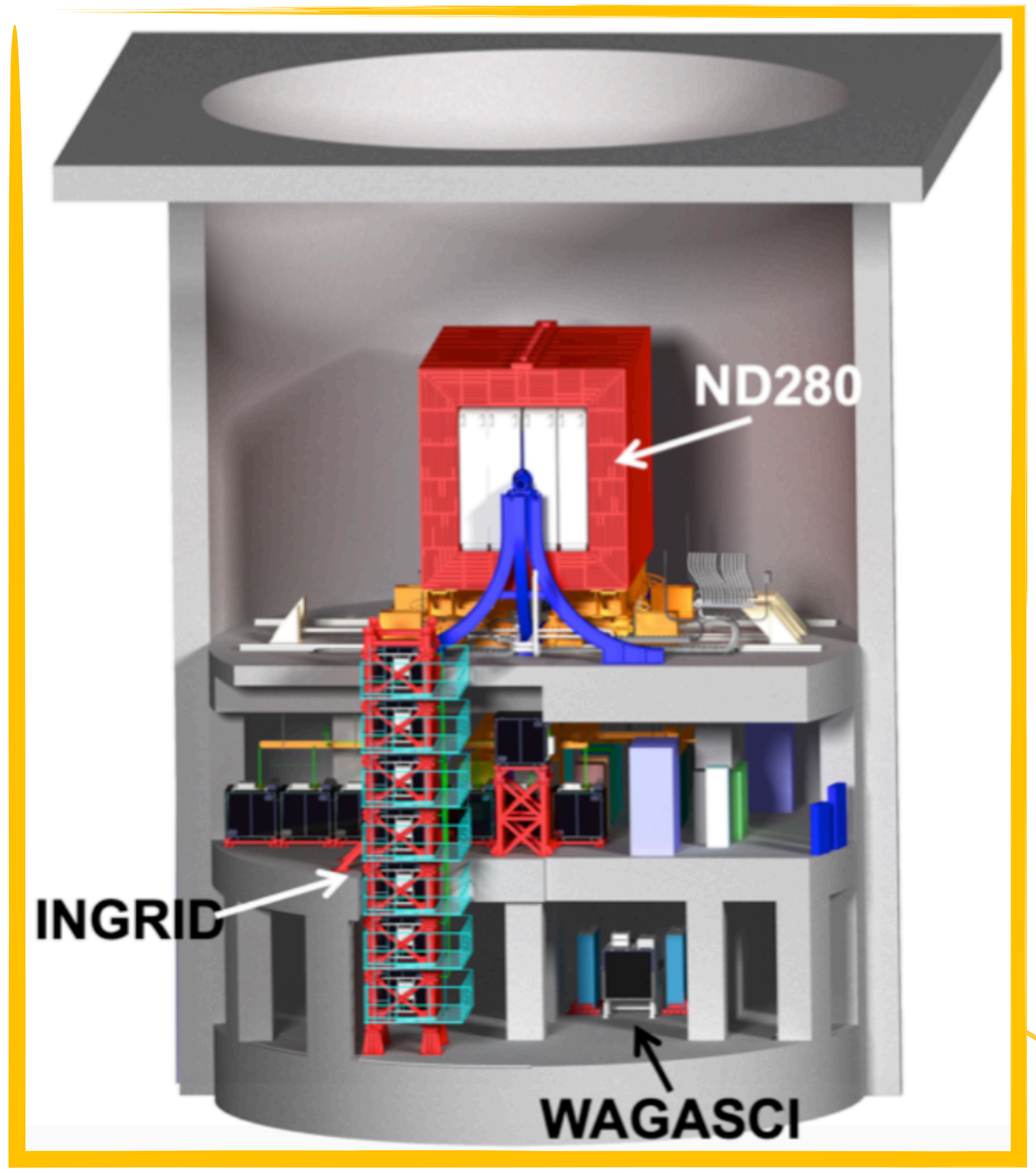
Alexander Izmaylov for the T2K Collaboration

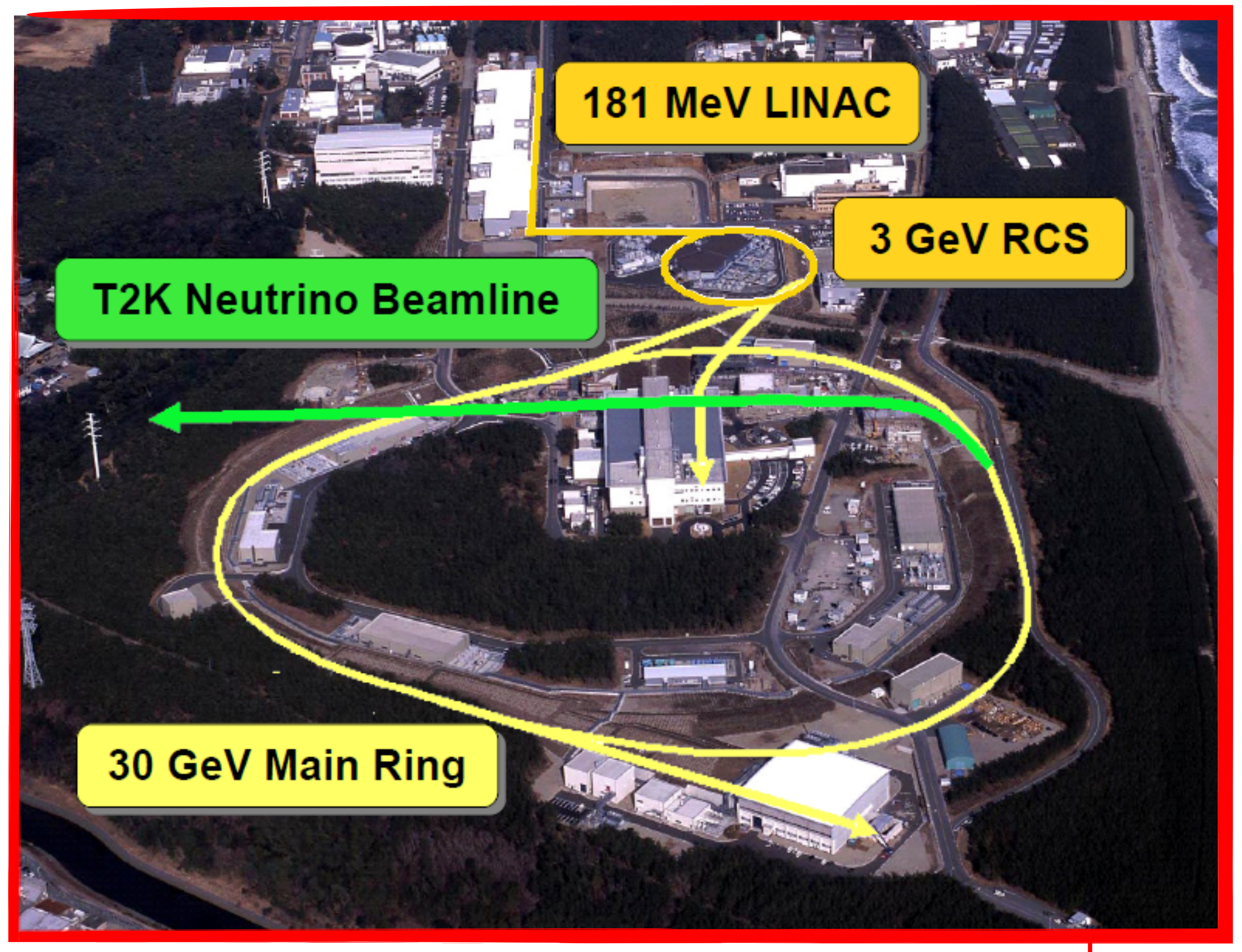
INR RAS

29th International Symposium on Particles, String and Cosmology (**PASCOS 2024**)
Quy Nhon, Vietnam, 7-13 July, 2024.

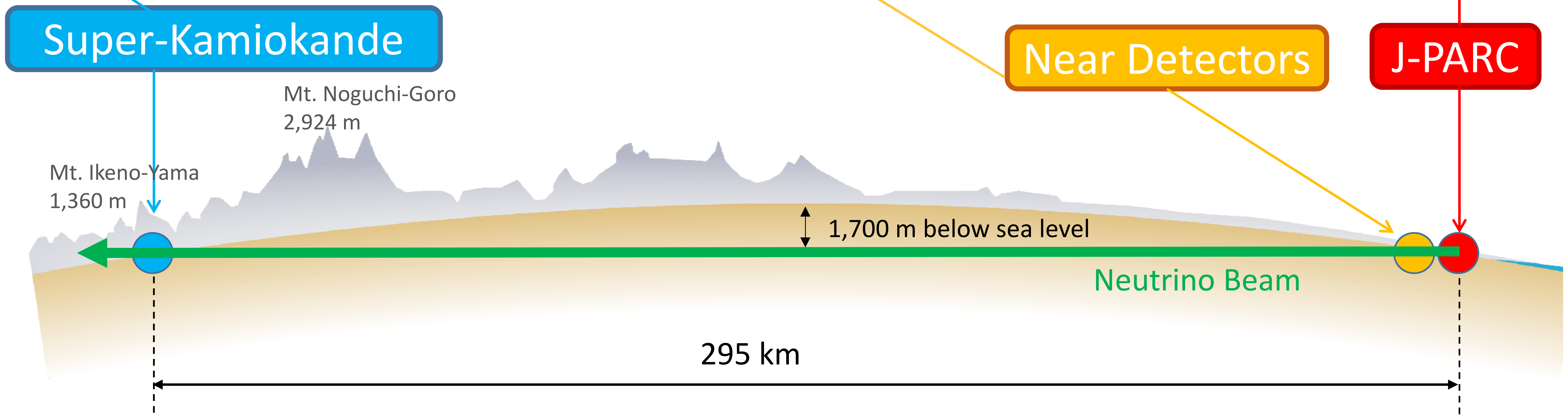
The T2K Experiment



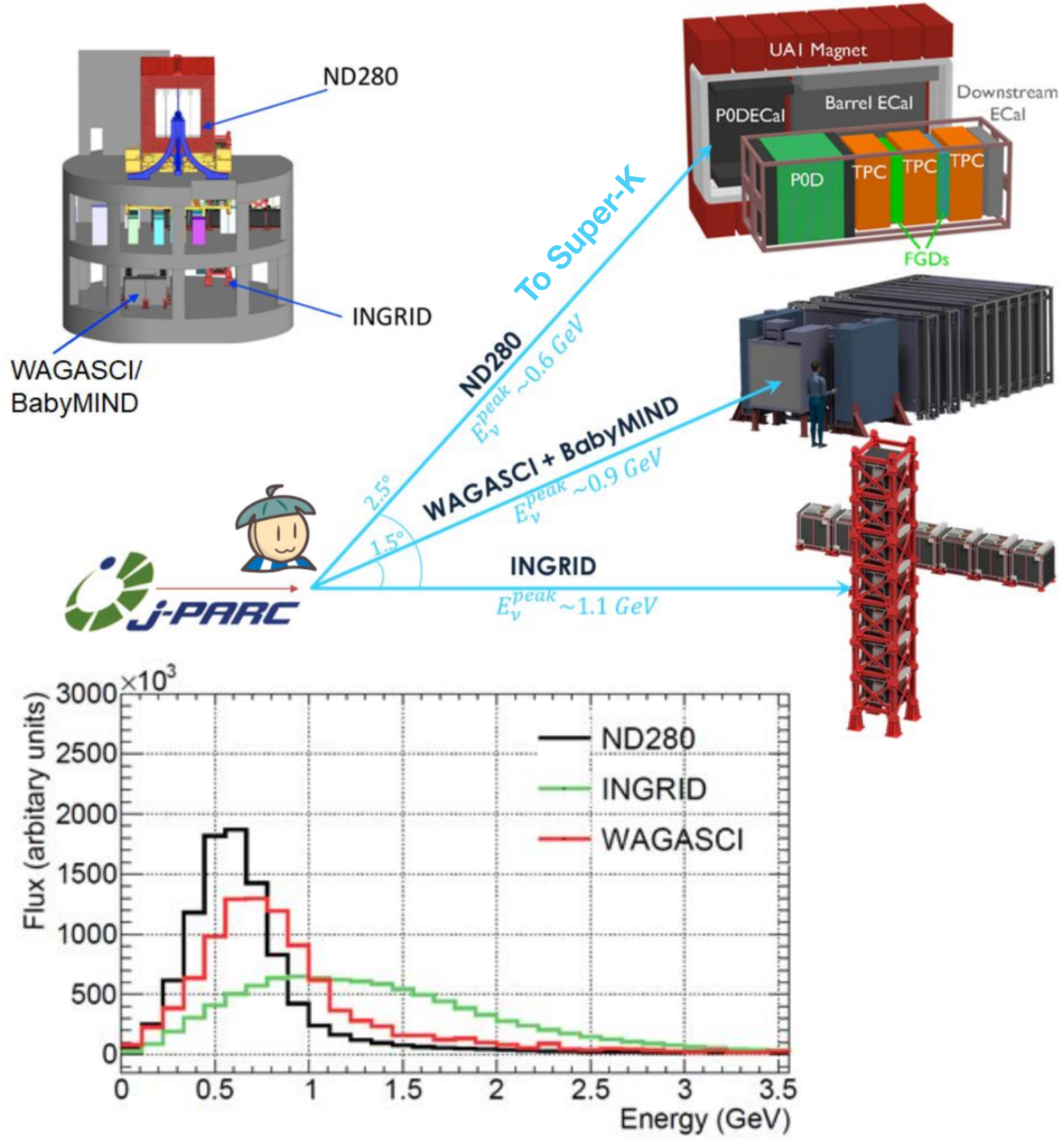




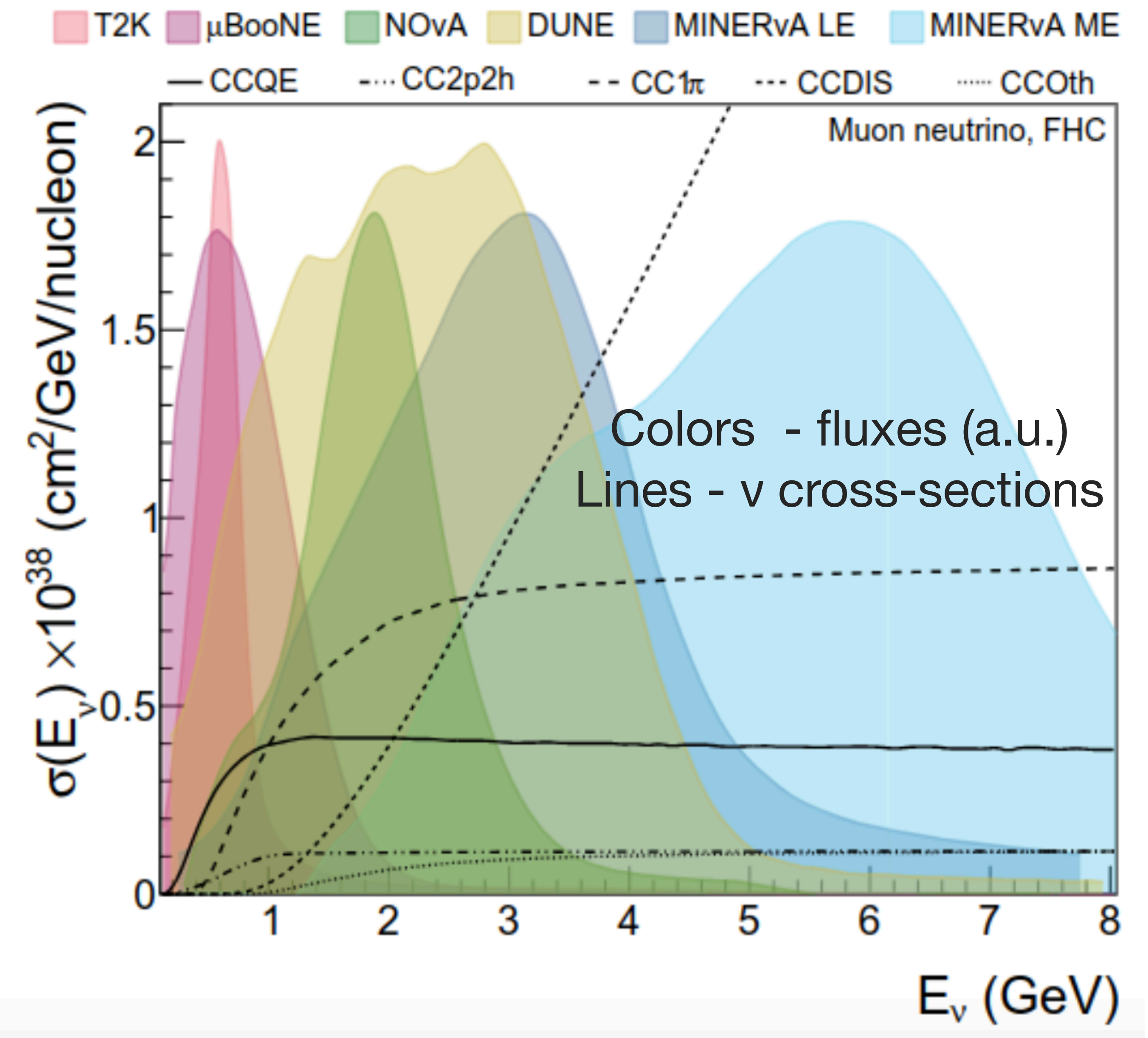
- Hunting accelerator neutrinos since 2010
- Precise measurements of PMNS and lepton CPV probes
- See T2K plenary talk by Son Cao on oscillation studies



T2K Near Detector Complex



- Multiple detectors at different off-axis angles
- Potential to probe different E_ν spectra of the same neutrino beam
- Potential to disentangle flux and neutrino interactions impacts
- Test models using different fluxes



- T2K @ sub-GeV ν energy
- Peaks at ~0.6 GeV with 2.5° off-axis
- Less energetic than other actors in the field [1]
- T2K can run with enhanced
  - ν_μ-mode beam
  - $\bar{\nu}_\mu$-mode beam

[1] C.Wret talk at NuInt2024

Neutrino XSec Impacts on Oscillation Analysis (OA)

- XSec studies have direct impact on PMNS oscillations measurements and CPV search
- Systematics in current long-baseline experiments ~dominated by neutrino interaction uncertainties
- Not a major issue for current projects as CPV is stat. limited
- Need to further improve the constrains for high-precision measurements in Hyper-K and DUNE era

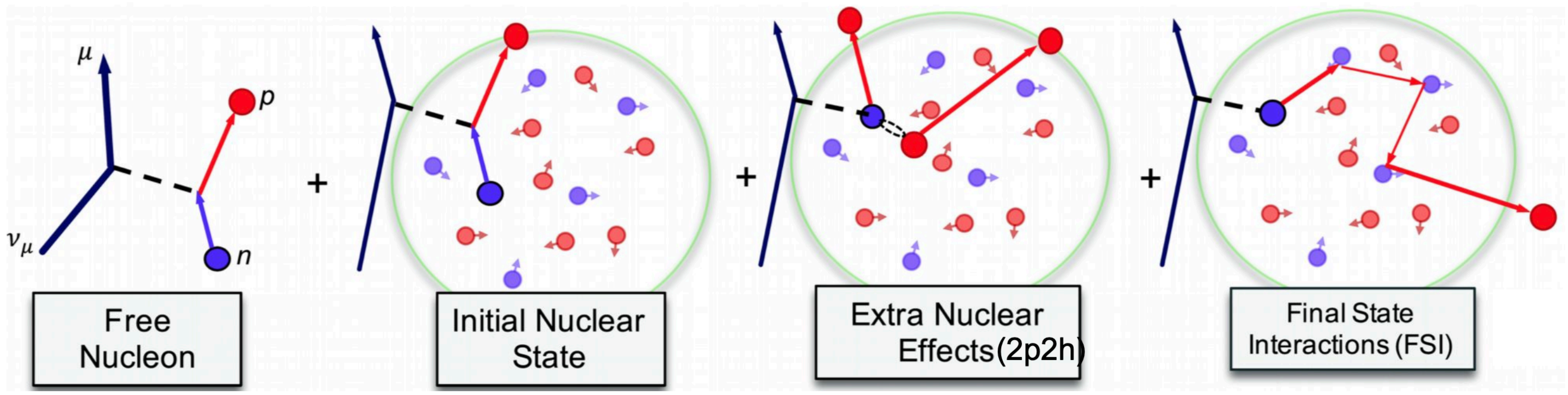
$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi^{far}(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi^{near}(E_\nu) \otimes D^{near}(\vec{x})}$$

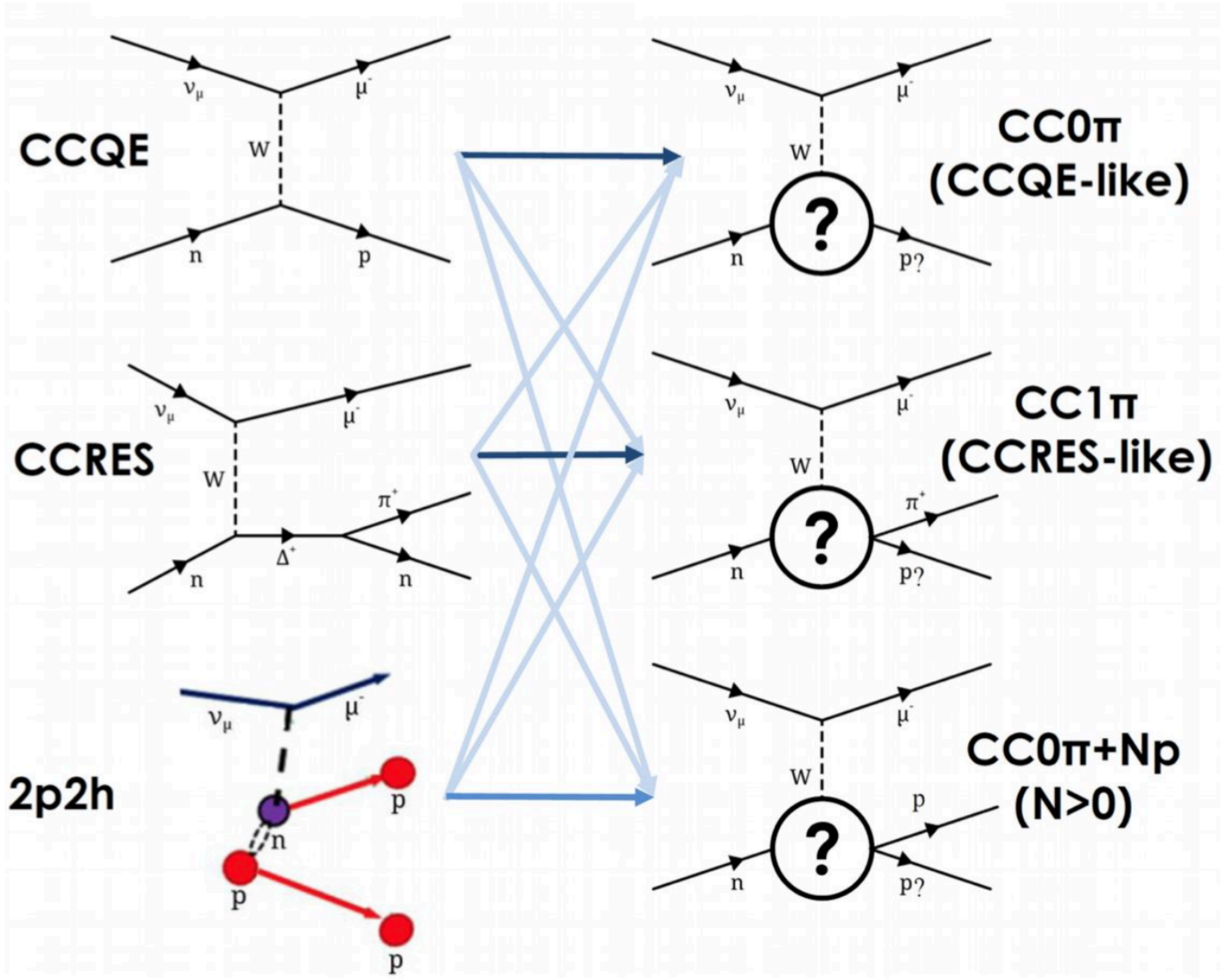
Error source (%)	ν mode SK e-like ring	anti-ν mode, SK e-like ring	ratio e ν/anti-ν
Flux	2.8	3.0	2.2
ν xsec (ND tuned)	3.8	3.5	2.4
ν sec (all)	4.8	4.8	4.4
Flux + xsec (ND tuned)	2.9	2.7	2.3
Flux + xsec (all)	4.1	4.3	4.4
Super-K	2.7	5.1	4.0
Total	4.9	6.7	5.9

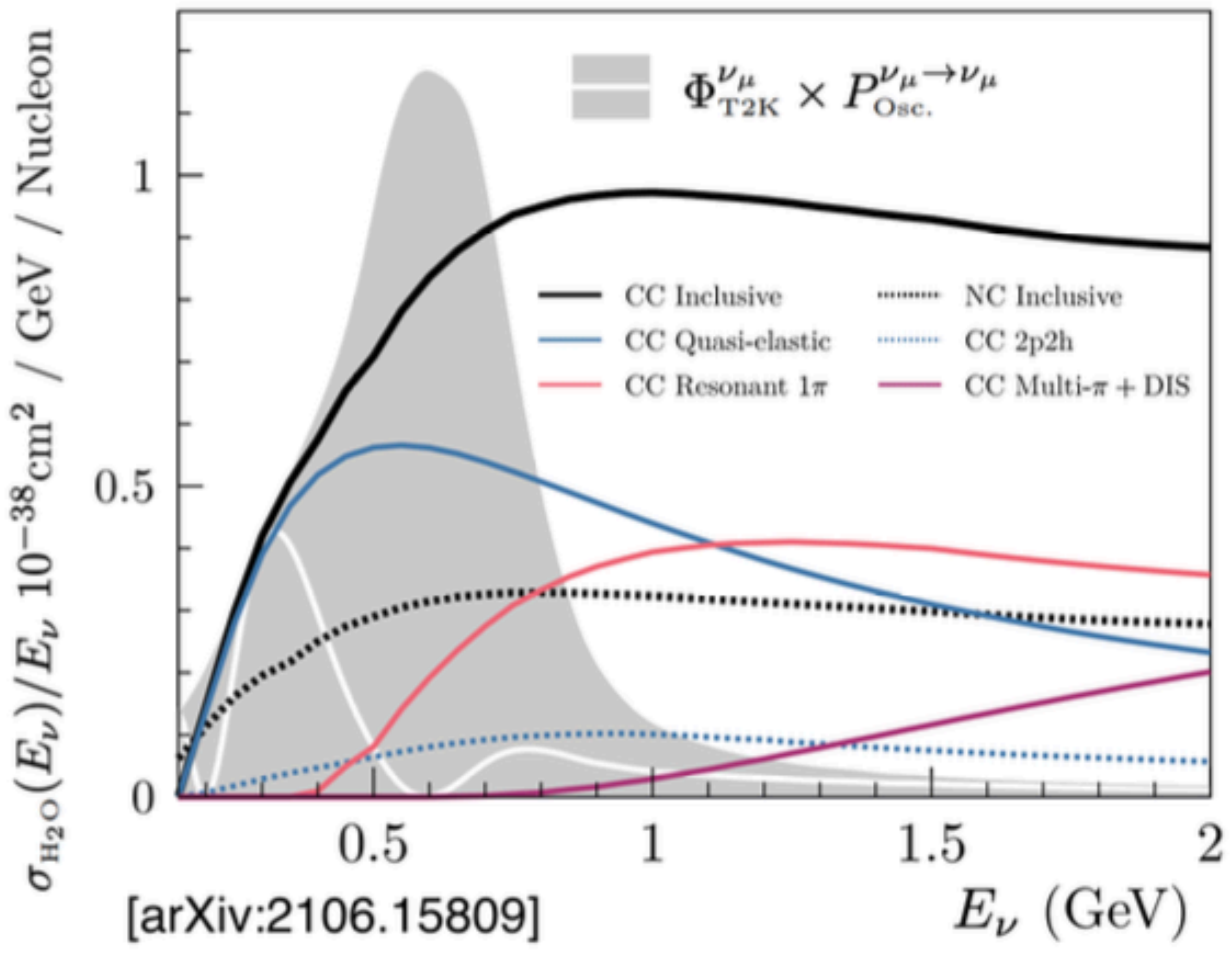
* From T2K plenary talk by Son Cao on oscillation analysis

Measuring Neutrino Interactions

- Complex nuclei as targets in detectors: scintillators (CH), H_2O, liquid Ar etc
- Initial reactions on nucleons convoluted with nuclear effects
- Define signal based on final state reconstructed observables in detectors
- Generally split by
  - ν flavour → μ/e lepton
  - Interaction mode: CC/NC
  - π and proton multiplicities
- $$\frac{d\sigma}{dx_i dy_j} = \frac{N_{ij}^{signal}}{\epsilon_{ij}\Phi N_{nucleons}^{FV}} \times \frac{1}{\Delta x_i \Delta y_j}$$
- Extract cross-section in true variables` bins
- Unfolding detector effects, integrated flux and efficiency correction using binned-likelihood template fitting [2]







[2] A.Cudd et al talk NuSTEC CEWG Seminar; and e.g. T2K Collab. Phys.Rev.D 108 (2023) 11, 112009

Outline

- Recent highlights from T2K cross-section studies

  1. **Published: Near-detector on/off-axis joint measurement of $\nu_\mu CC0\pi^\pm$**

  - **Preliminary:**

    2. **Intermediate detector WAGASCI/BabyMIND — $\nu_\mu CC0\pi^\pm$**

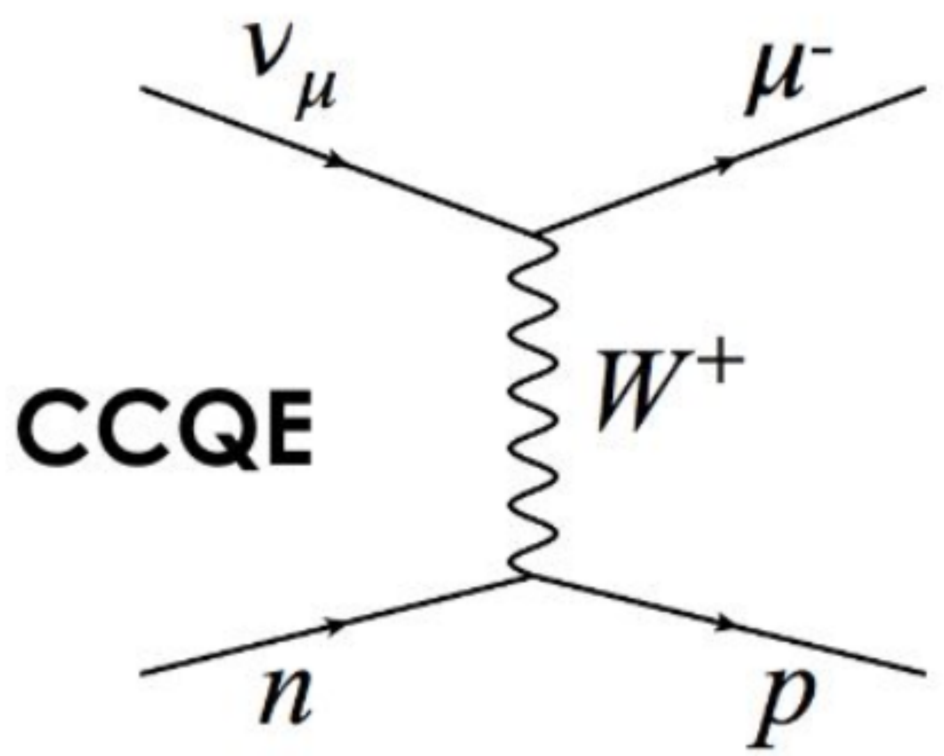
    3. **T2K off-axis ND280 — $\nu_e CC\pi^+$**

    4. **T2K off-axis ND280 — $NC1\pi^+$**

  5. **Work in progress: T2K off-axis ND280 $\nu_\mu CC\ K^+$ production**

- Cross-sections in different interaction channels, detector observables measured as a function of true (usually kinematic) variables

  - 1D, 2D… "differential" cross-sections $\frac{d\sigma}{dp_\mu}, \frac{d\sigma}{d\cos\theta_\mu}, \frac{d\sigma}{dp_p}, \frac{d^2\sigma}{dp_\mu \cdot d\cos\theta_\mu} \ldots$

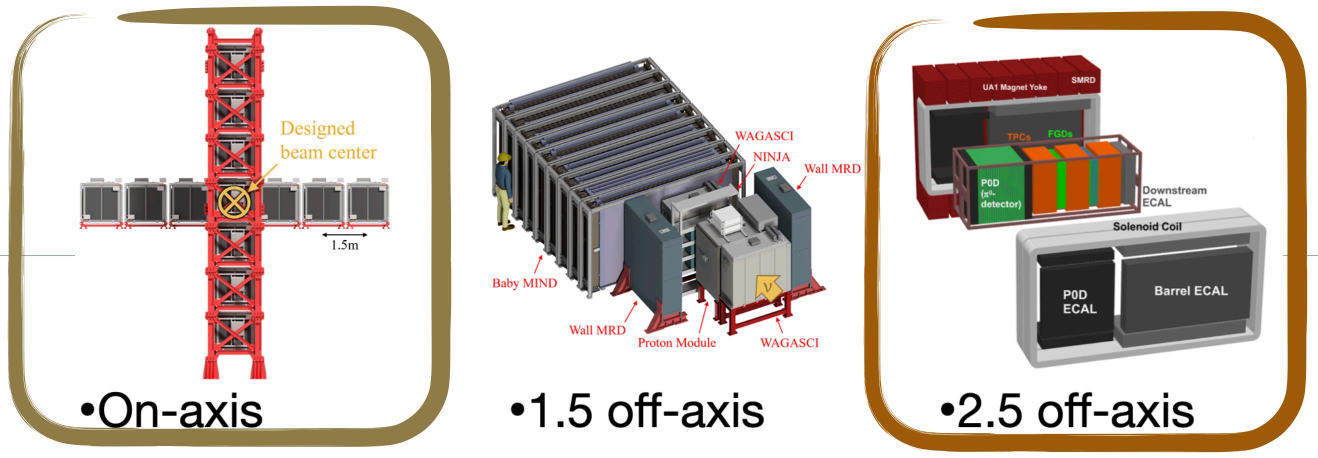


- Ultimate goal — in experiments collect a wide range of measurements over different fluxes, targets, ν species, interaction products to develop and tune theoretical models

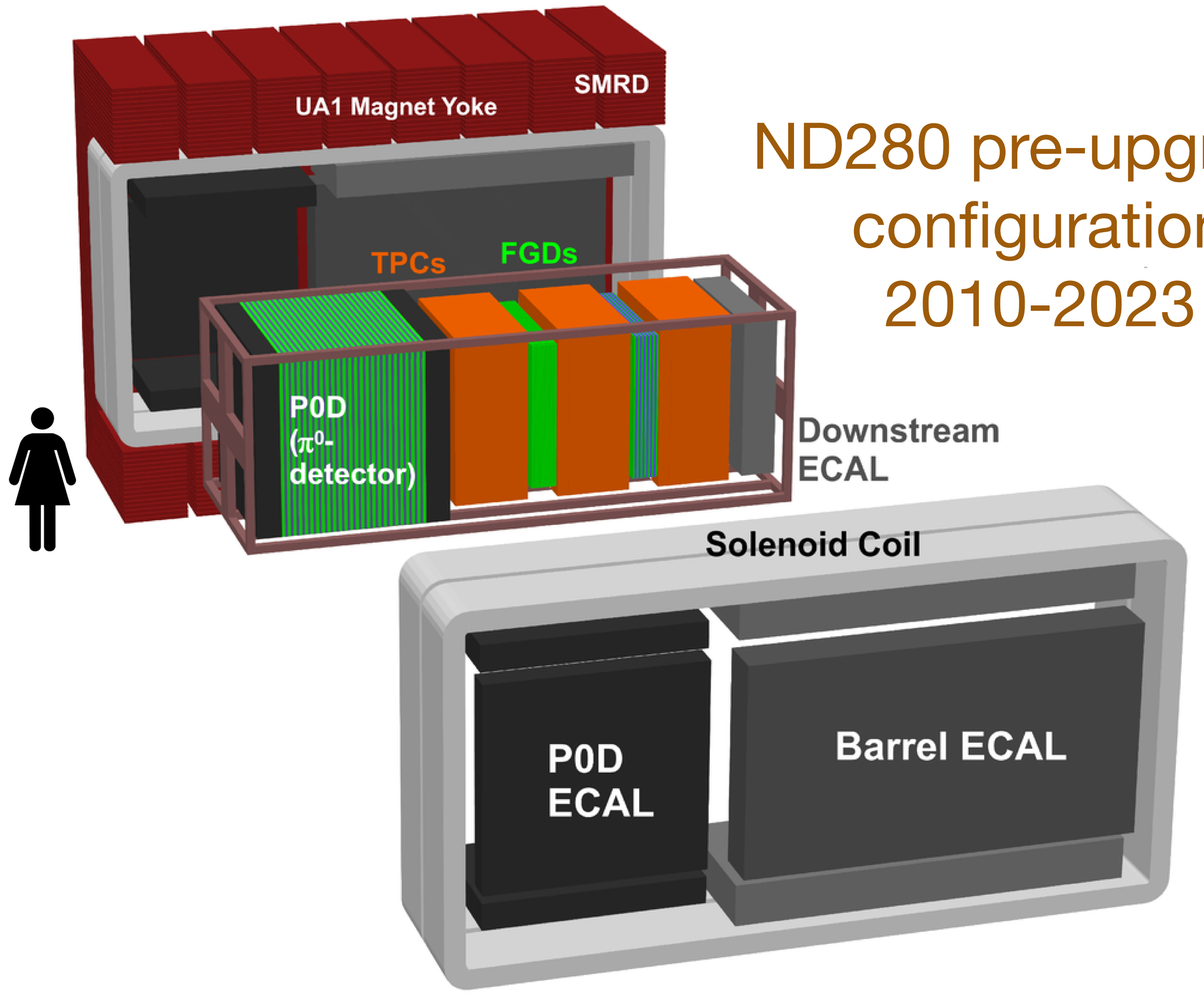
  - Further realised in "neutrino generators" — simulation engines to describe neutrino interactions in detector media: NEUT [3] (primary in T2K), GENIE [4], NuWro[5] etc

[3] Acta Phys. Polon. B 40, 2477 (2009) [4] Nucl. Instrum. Meth. A 614, 87 (2010) [5] Nucl. Phys. B Proc. Suppl. 229-232, 499 (2012)

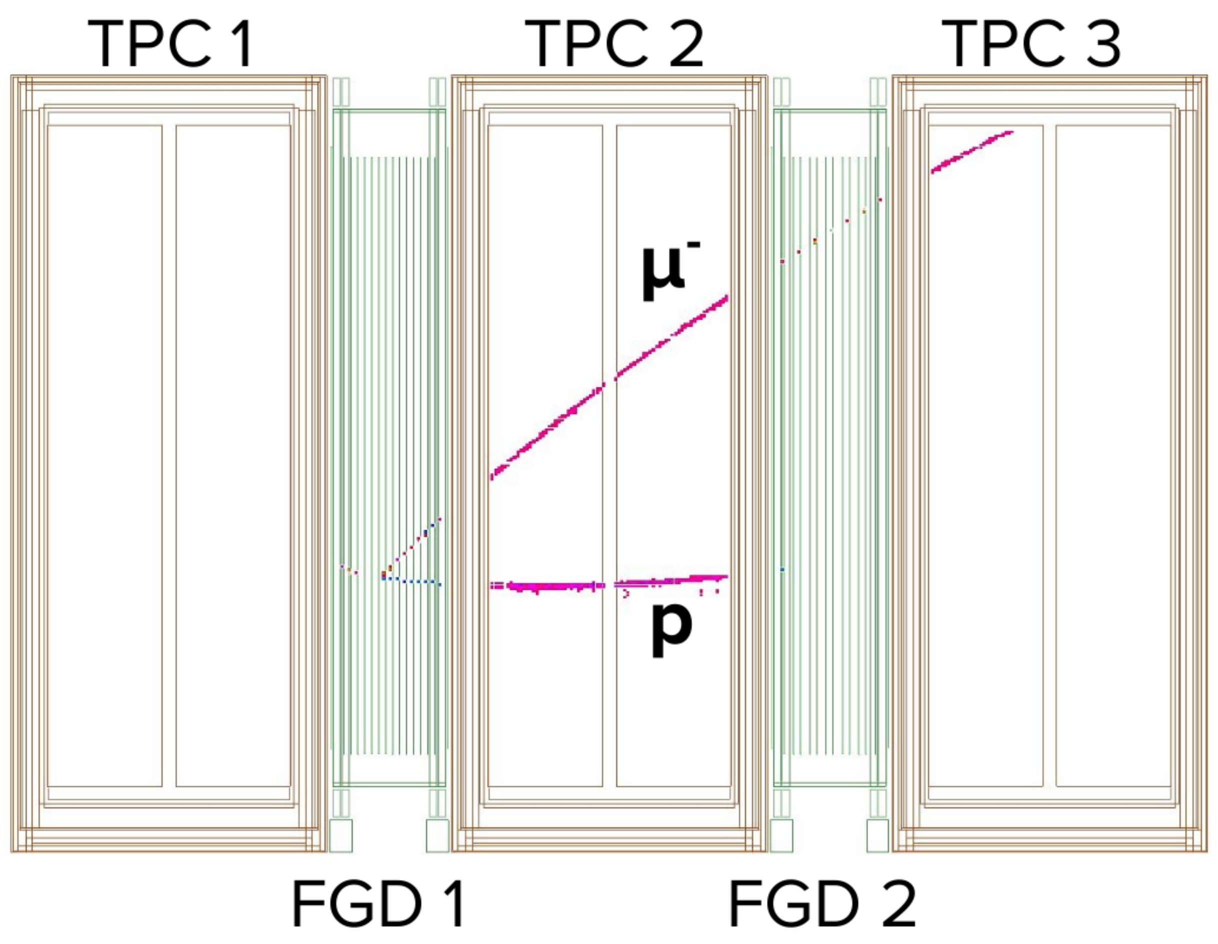
1. Joint On/Off-axis ν_μ CC0π analysis



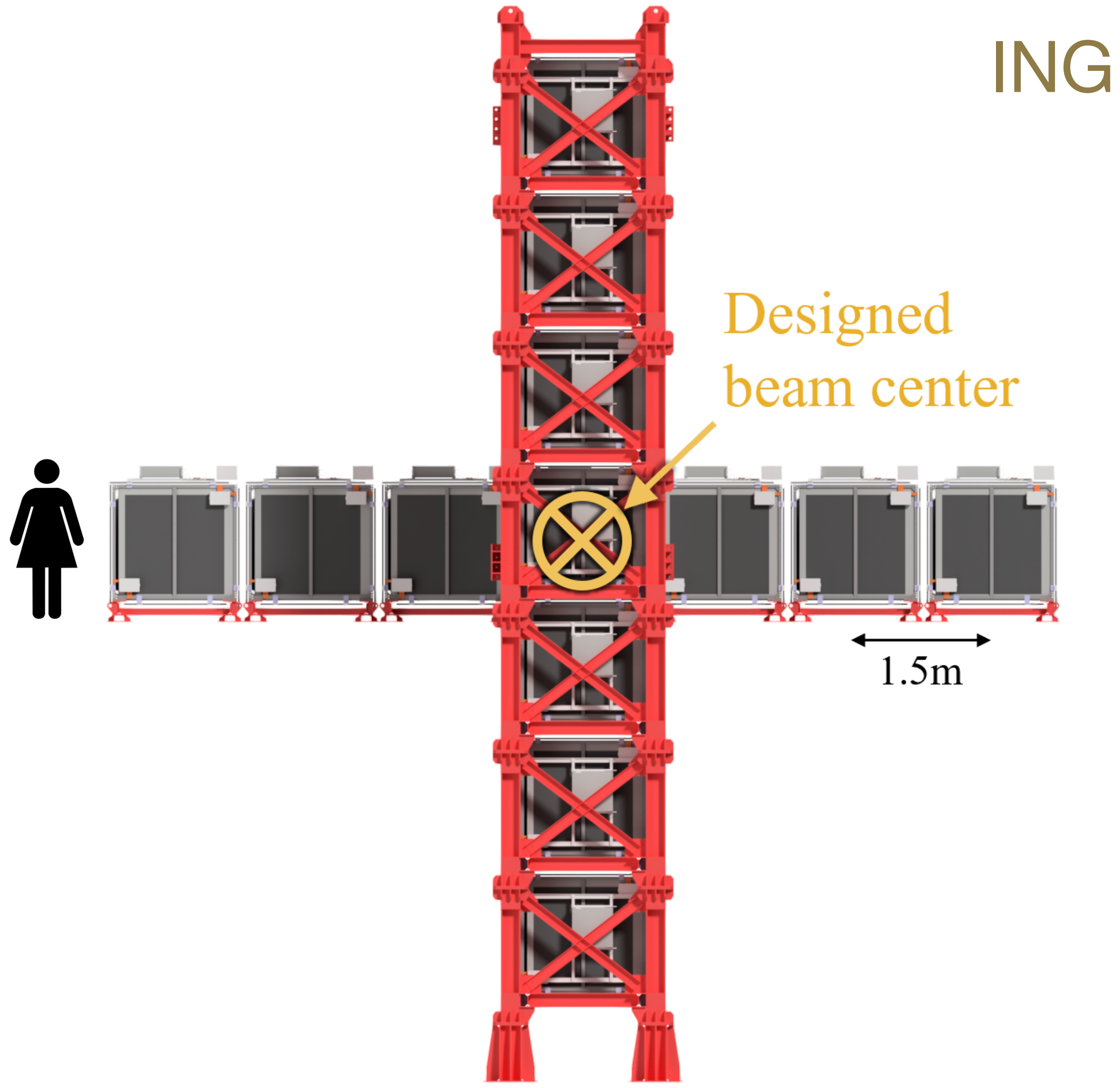
- Study ν_μ CC interactions on CH w/o pions in the final state @ two detectors [6]
- 2.5° off-axis ND280
  - 0.2 T field
  - FGD1/2 plastic scintillator targets + additional H_2O in FGD2
  - Gaseous Ar TPCs, ECals, π^0 module, muon-range detectors
- On-axis INGRID
  - Iron-scintillator sandwich modules for beam monitoring
  - Proton CH module for XSec
  - PID and momentum from dEdX and track length

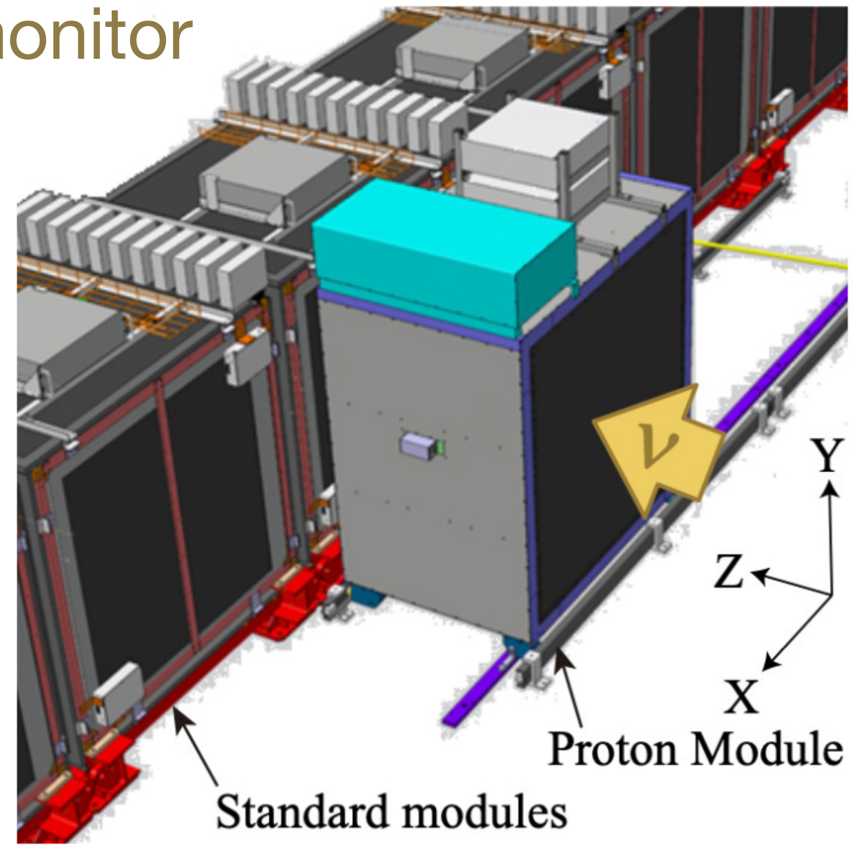


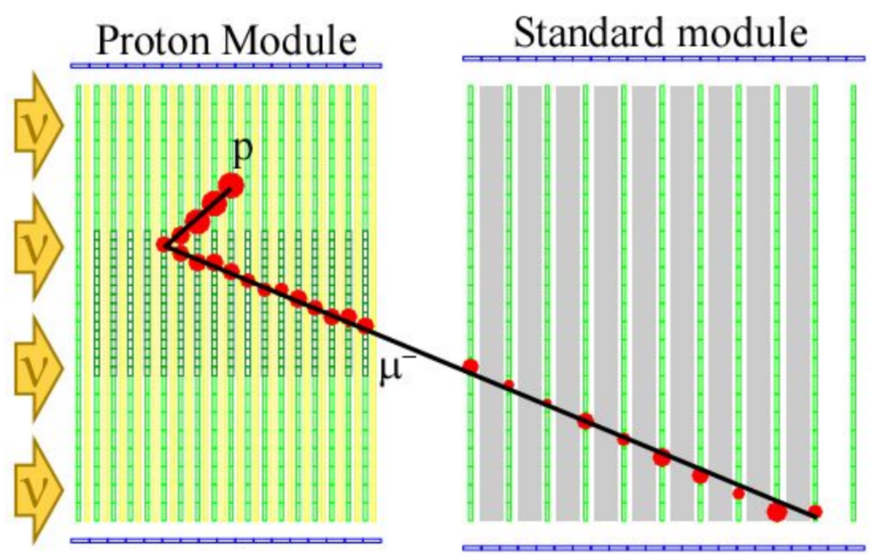
ND280 pre-upgrade configuration 2010-2023



INGRID ν-beam monitor

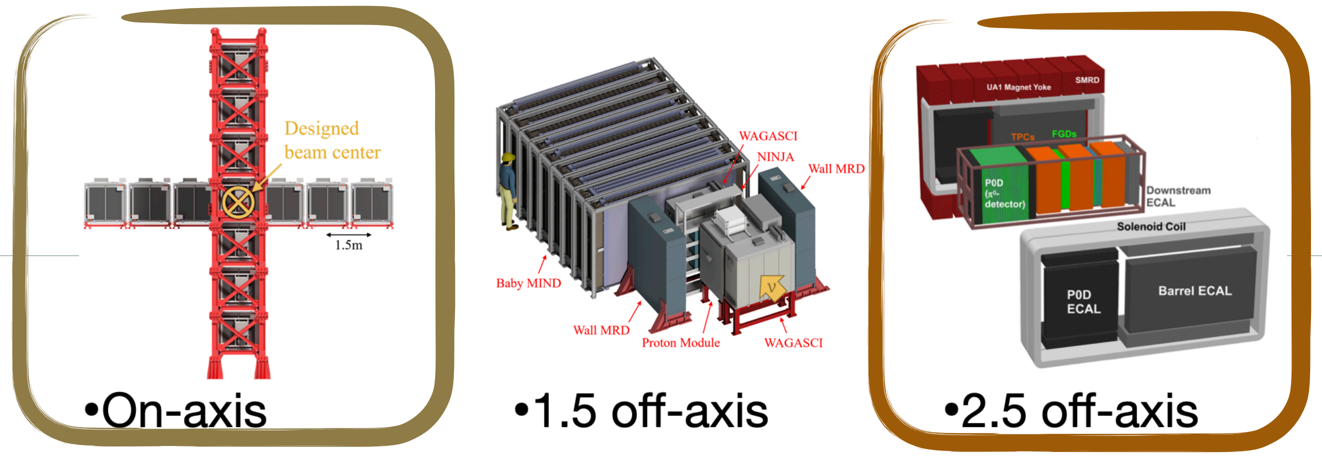




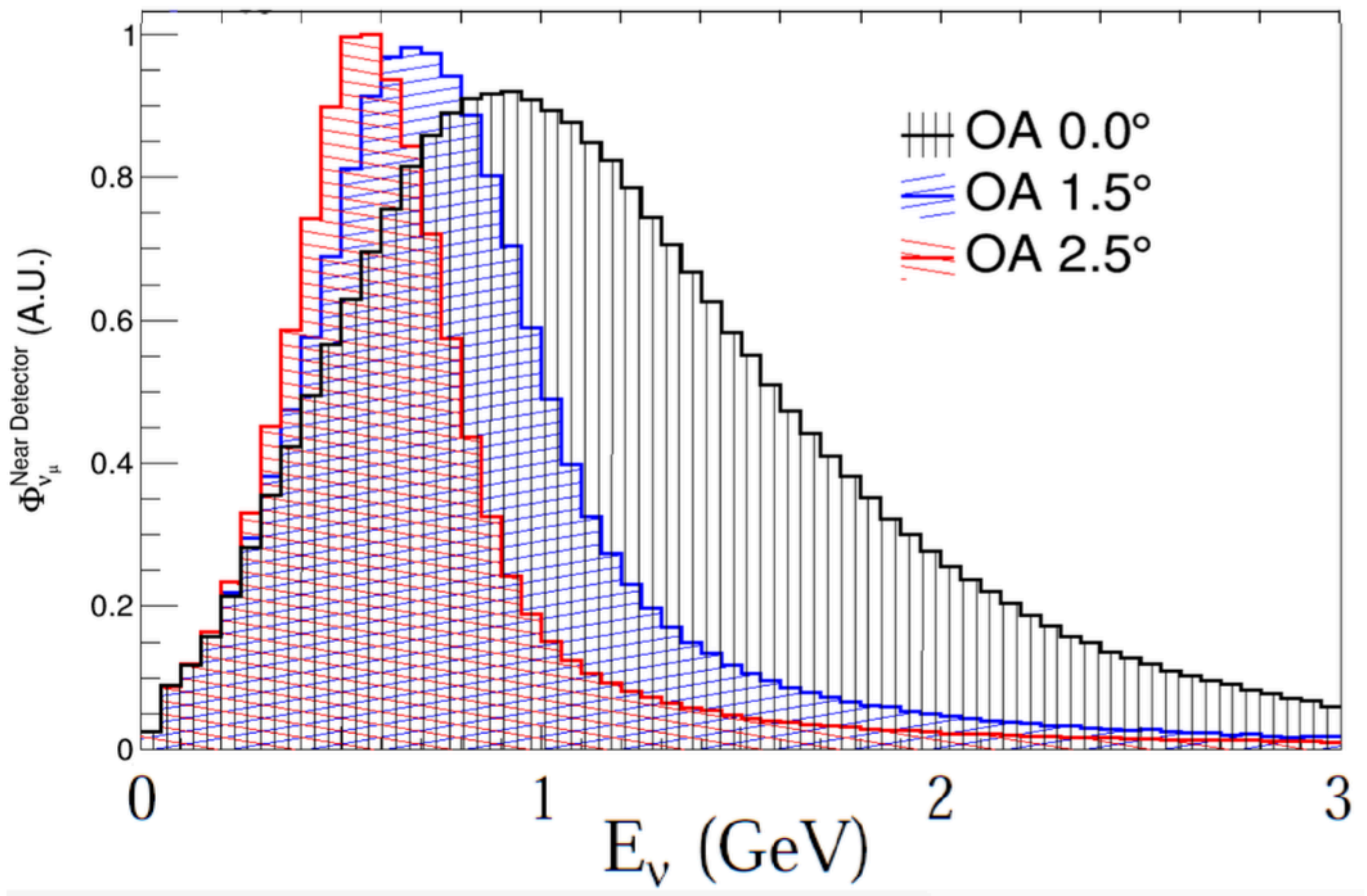


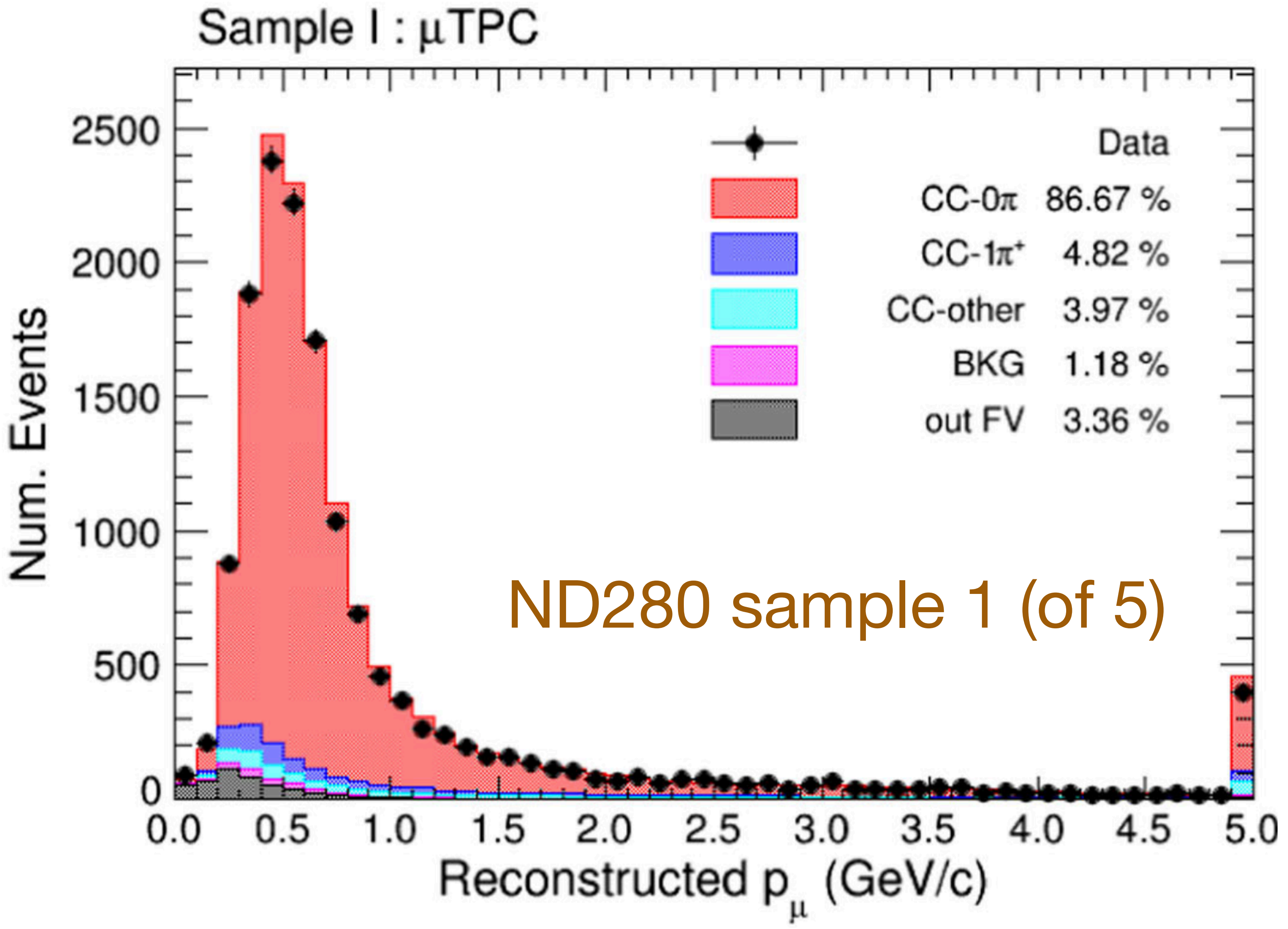
[6] T2K Collab. Phys.Rev.D 108 (2023) 11, 112009

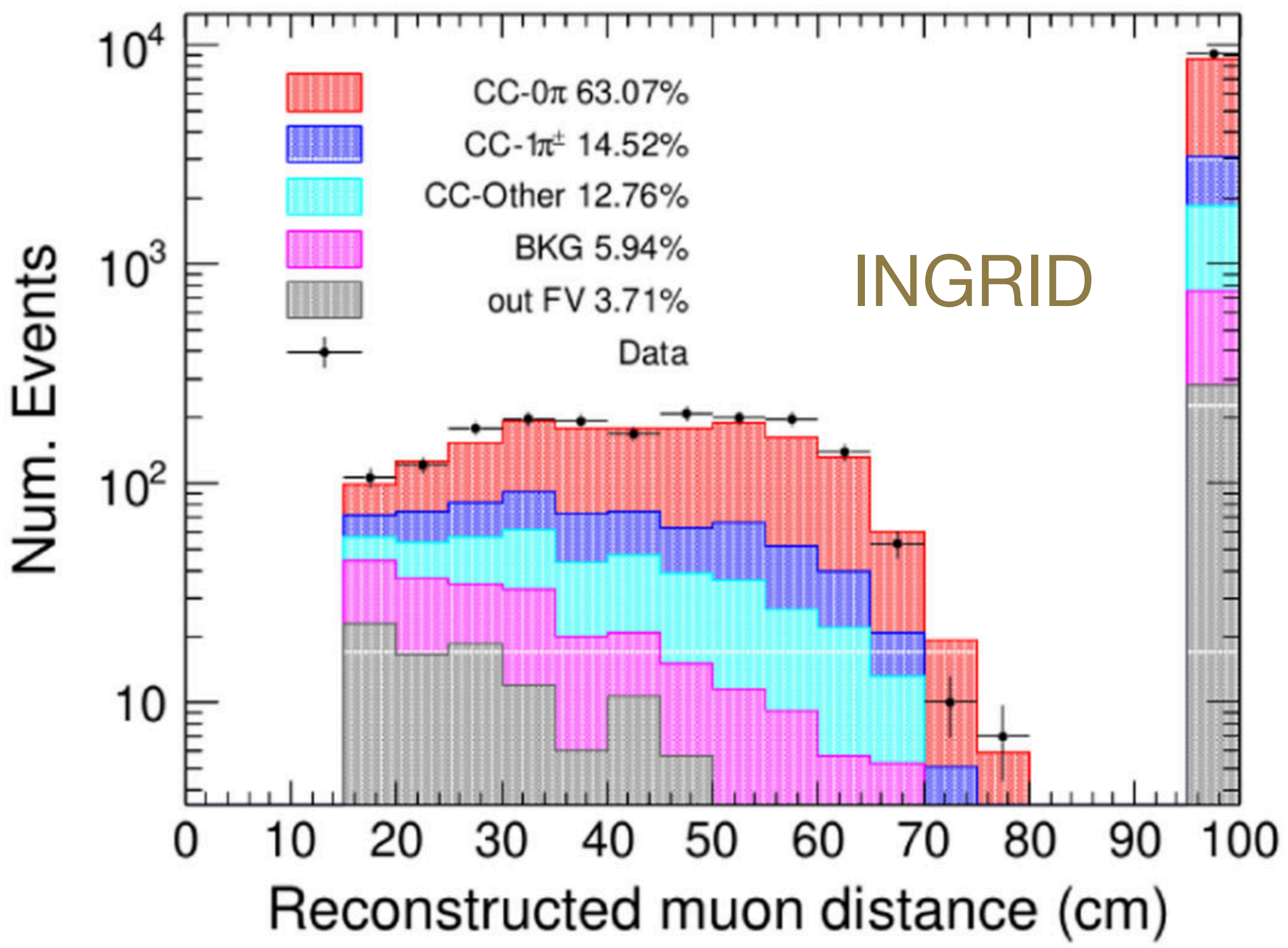
1. Joint On/Off-axis ν_μ CC0π analysis



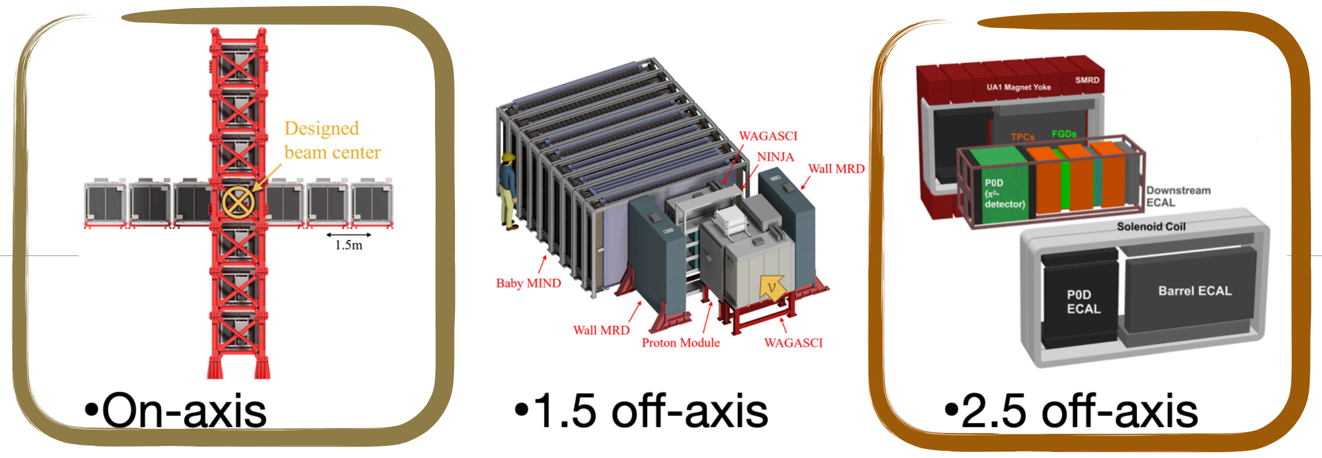
- $\nu_\mu + CH \rightarrow \mu^- + O\pi^\pm + Np$
- Simultaneous measurement with two different fluxes
- 2D differential cross-sections in muon kinematics
- 6 samples for (p_μ, $\cos\theta_\mu$)
  - 5 samples in ND280 for different muon and proton topologies
  - One INGRID sample
- First time in T2K correlated energy spectra has been used in a cross-section analysis
  - Correlated resulting cross-sections
  - Reduced flux uncertainty



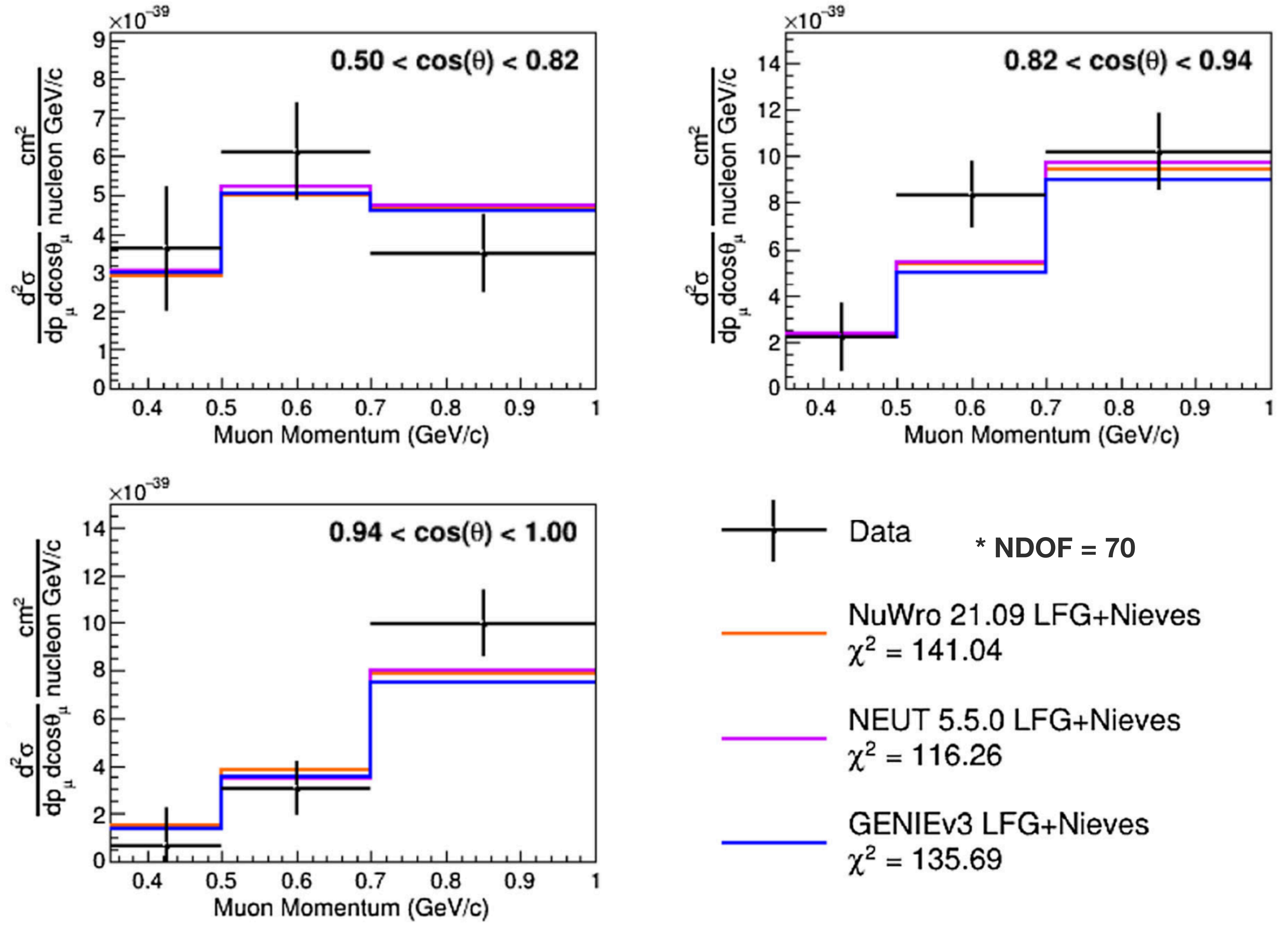




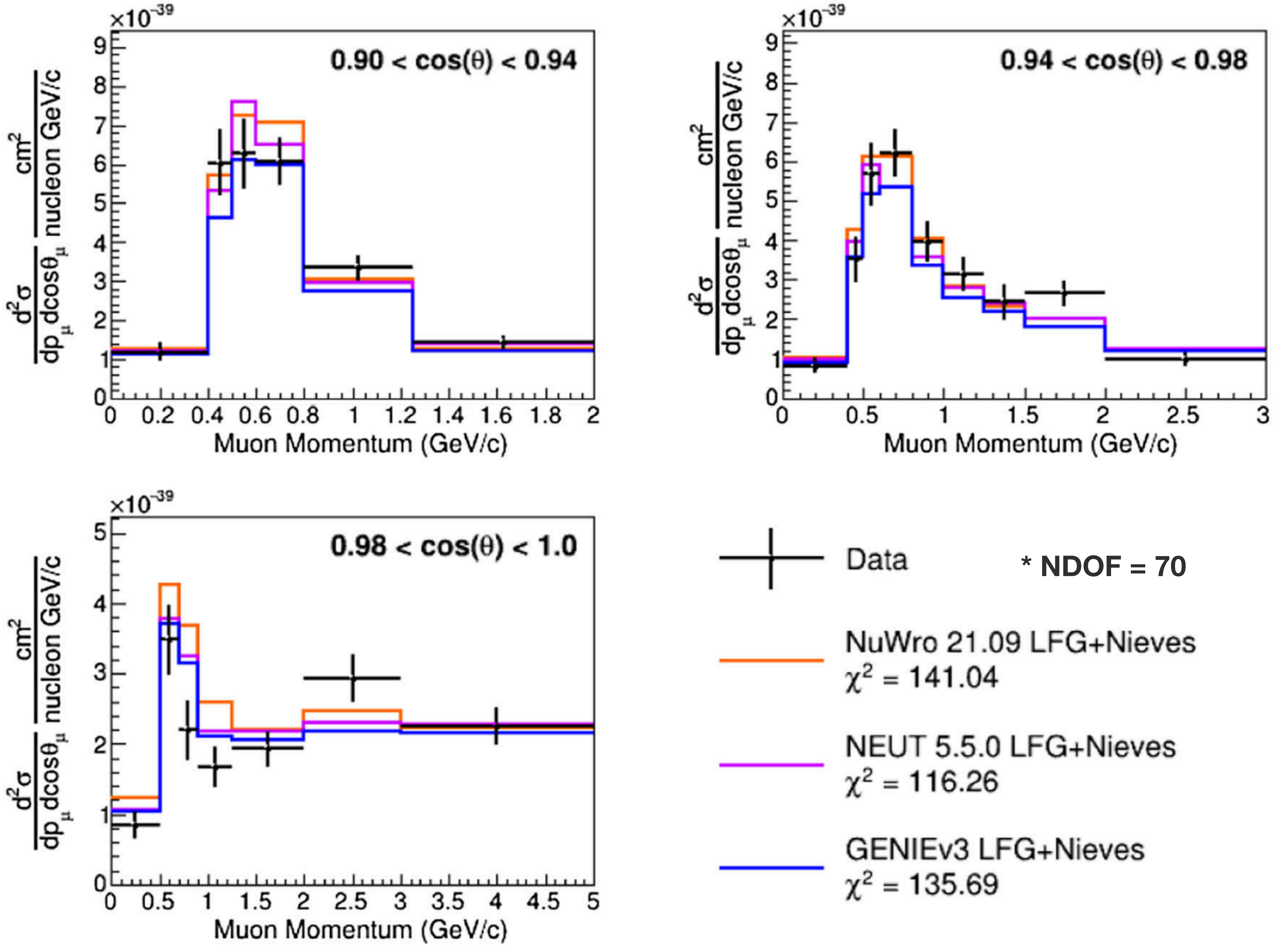
1. Joint On/Off-axis ν_μ CC0π analysis



INGRID samples



ND280 samples

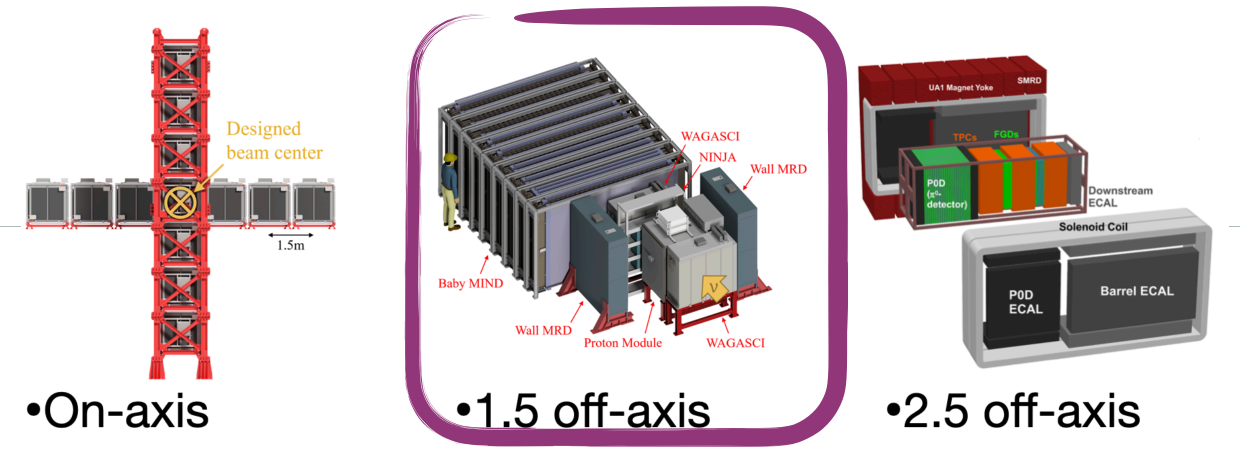


- Current models [7] “struggle” to describe data → further model development and analyses
  - Tensions in on-axis, forward-going, low- to medium- momentum range
- Potential for extensions with more detectors, channels and signals

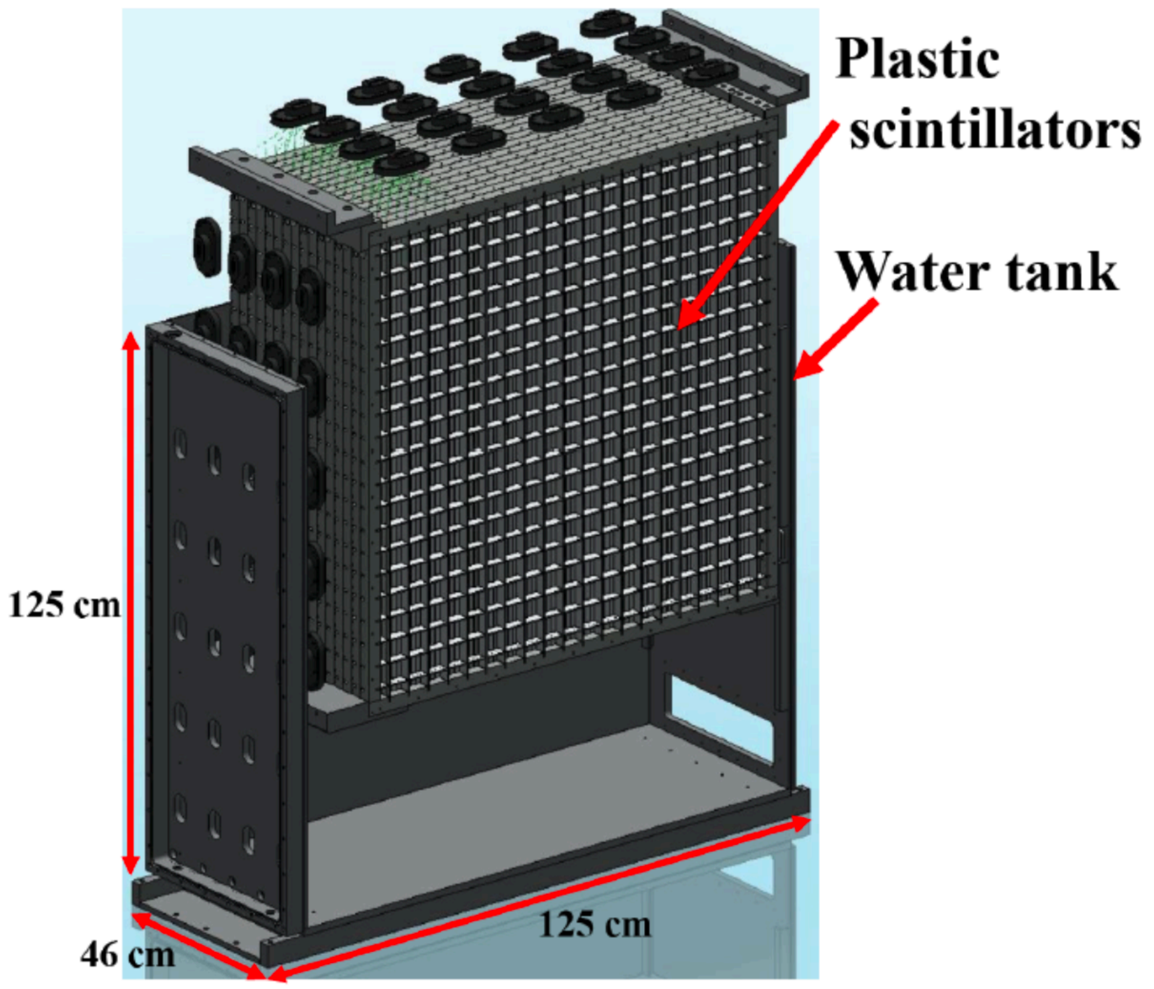
Results consistent with previous ND280 and INGRID measurements

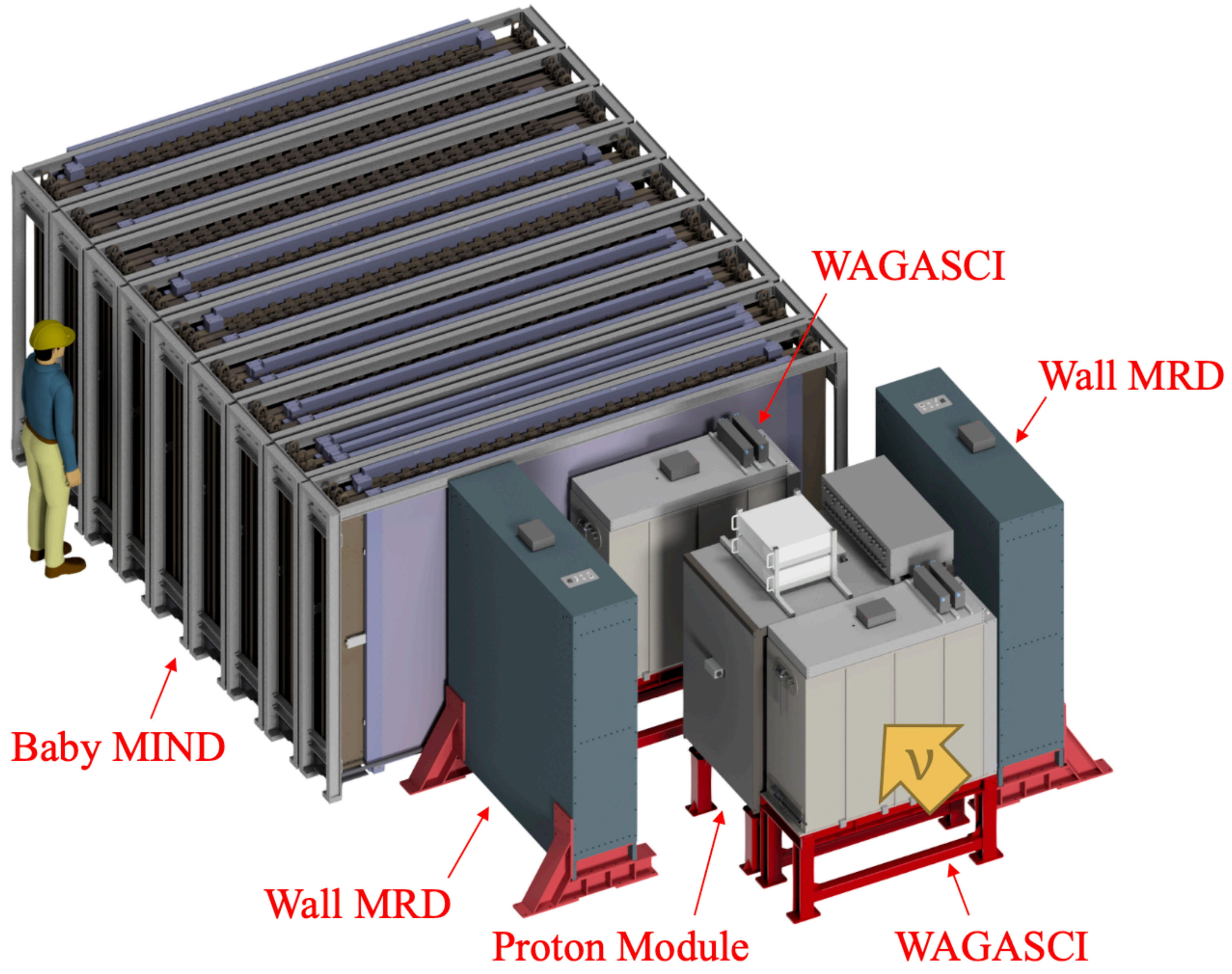
[7] Comparisons to models with NUISANCE framework. 2017 *JINST* 12 P01016

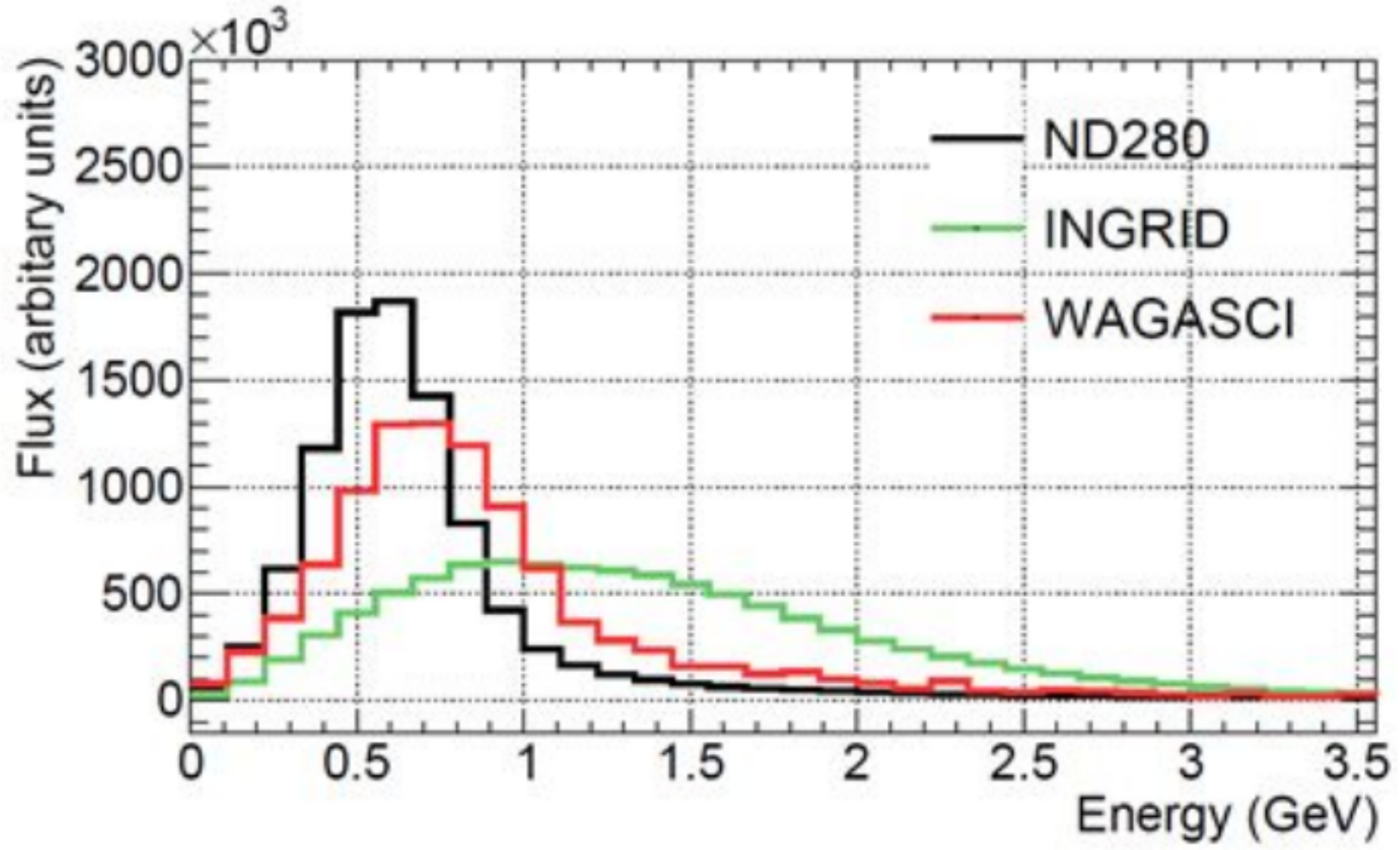
2. ν_μ CC0$\pi^\pm$ in WAGASCI/BabyMIND

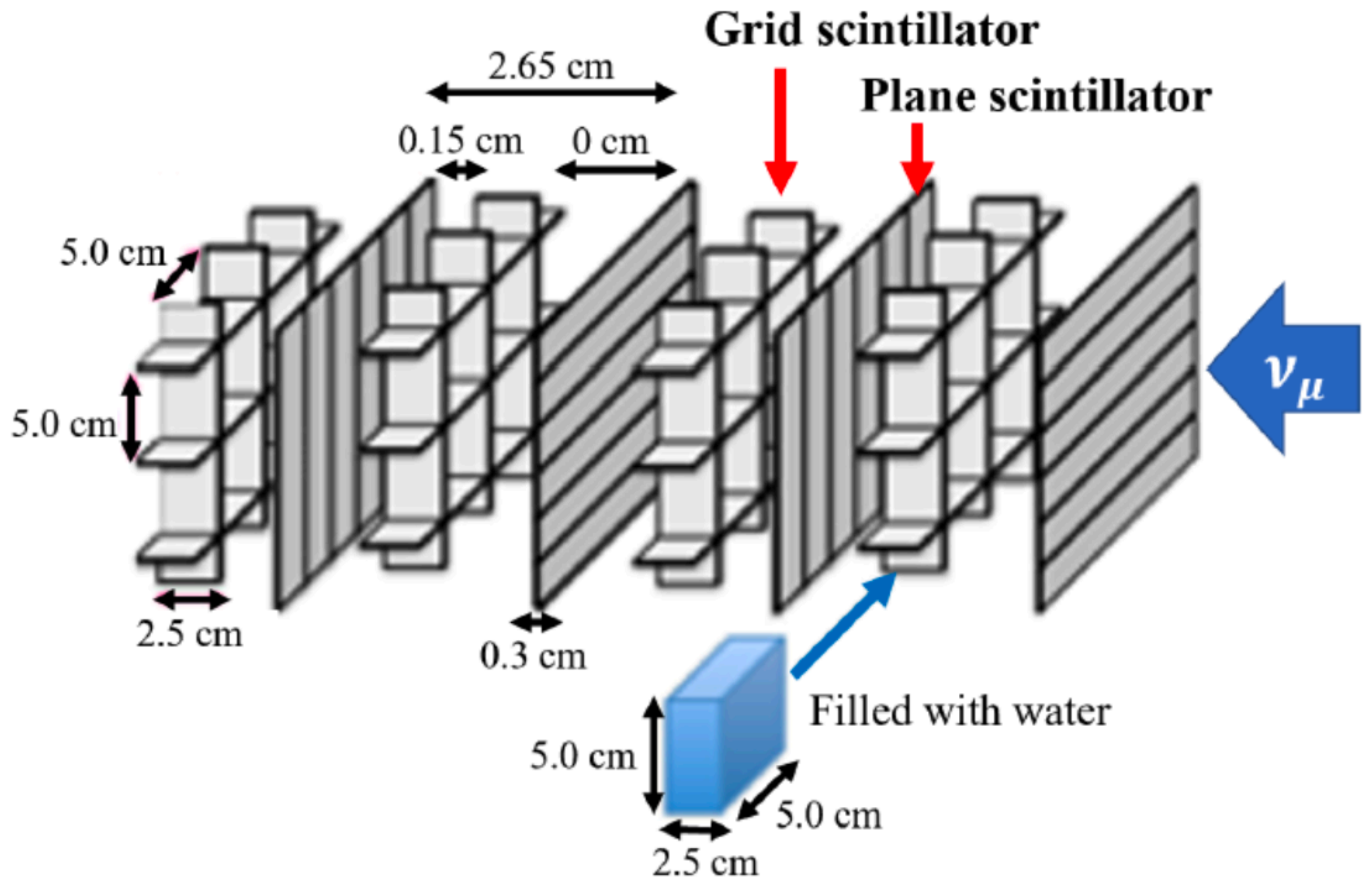


- Study of ν interactions on CH and H_2O enriched targets
  - WAGASCI: plane and grid-like plastic scintillators in a water tank
  - Proton module with plastic scintillator
  - Baby-MIND magnetised iron-scintillator planes
  - Muon-range detectors

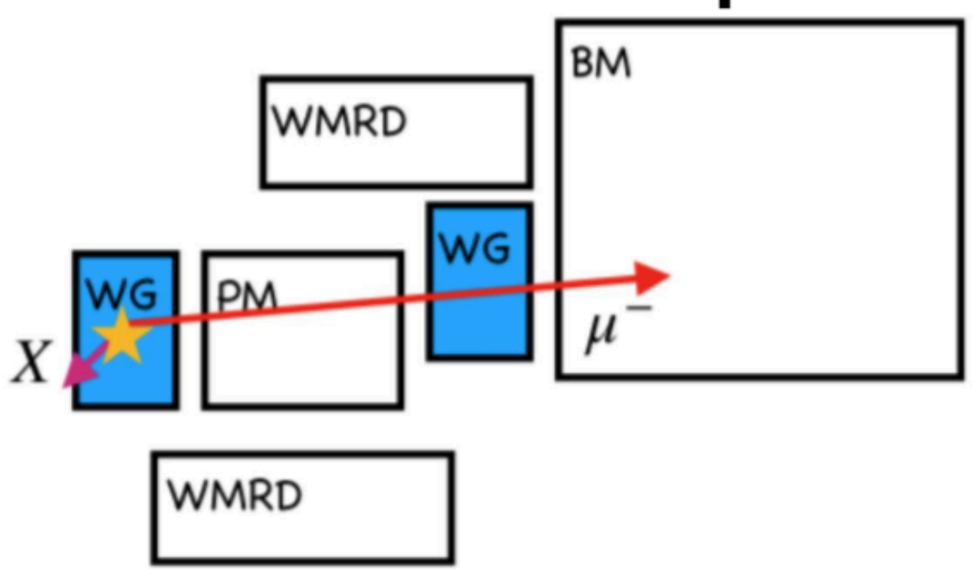








WAGASCI/BM top view



2. ν_μ CC0$\pi^\pm$ in WAGASCI/BabyMIND

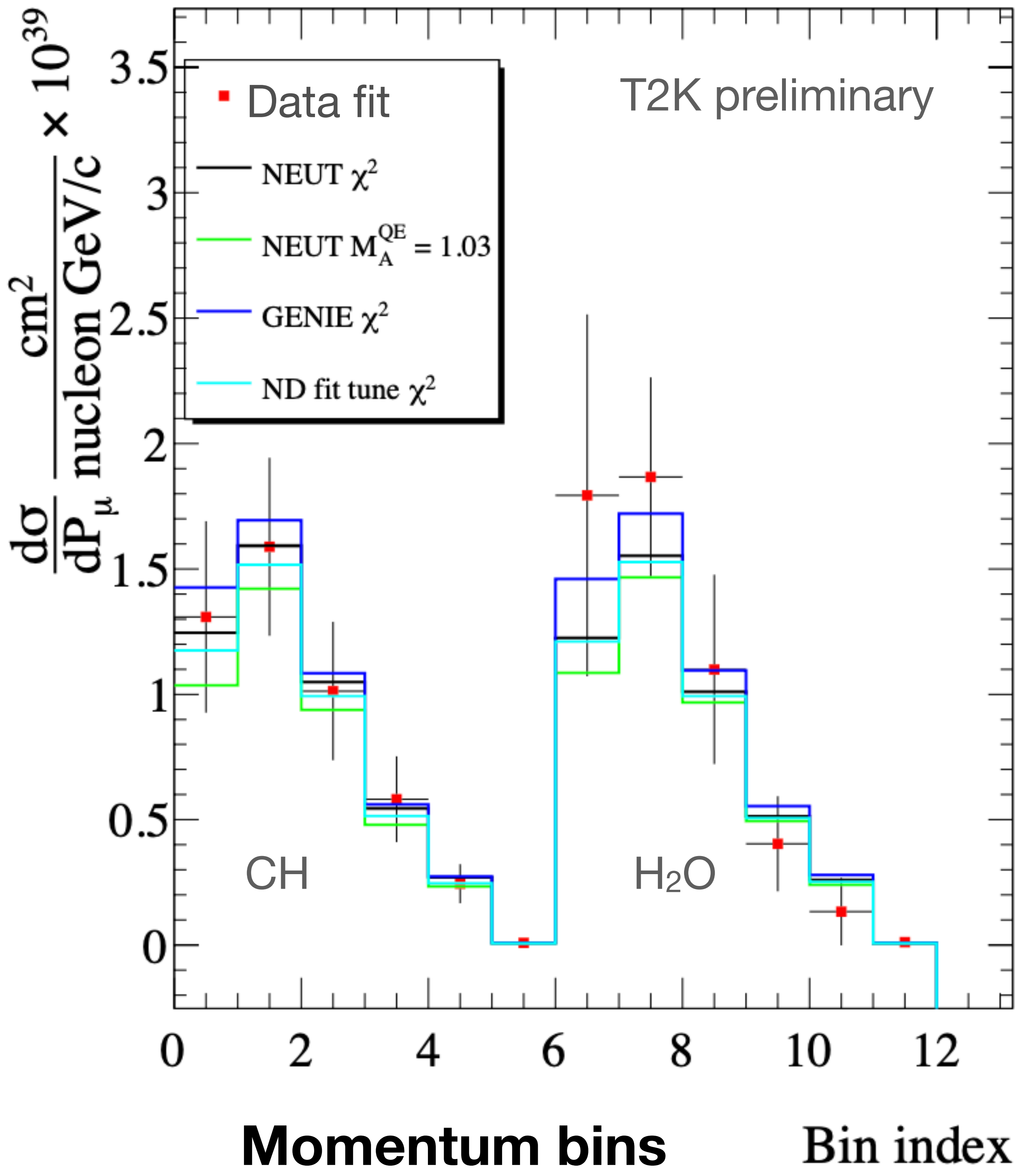
- $\nu_\mu + CH \rightarrow \mu^- + O\pi^\pm + X$
- Signal: a muon track and no charged pions in the final state
- 1D differential cross-sections for H_2O and CH targets in muon kinematic bins
- Phase-space restriction
    - p_μ > 300 MeV/c
    - θ_μ < 70°
- First physics results with the full WAGASCI/Baby-MIND setup
- No enough sensitivity to differentiate between models with the current stats
- Data-taking on-going

Analysis binning

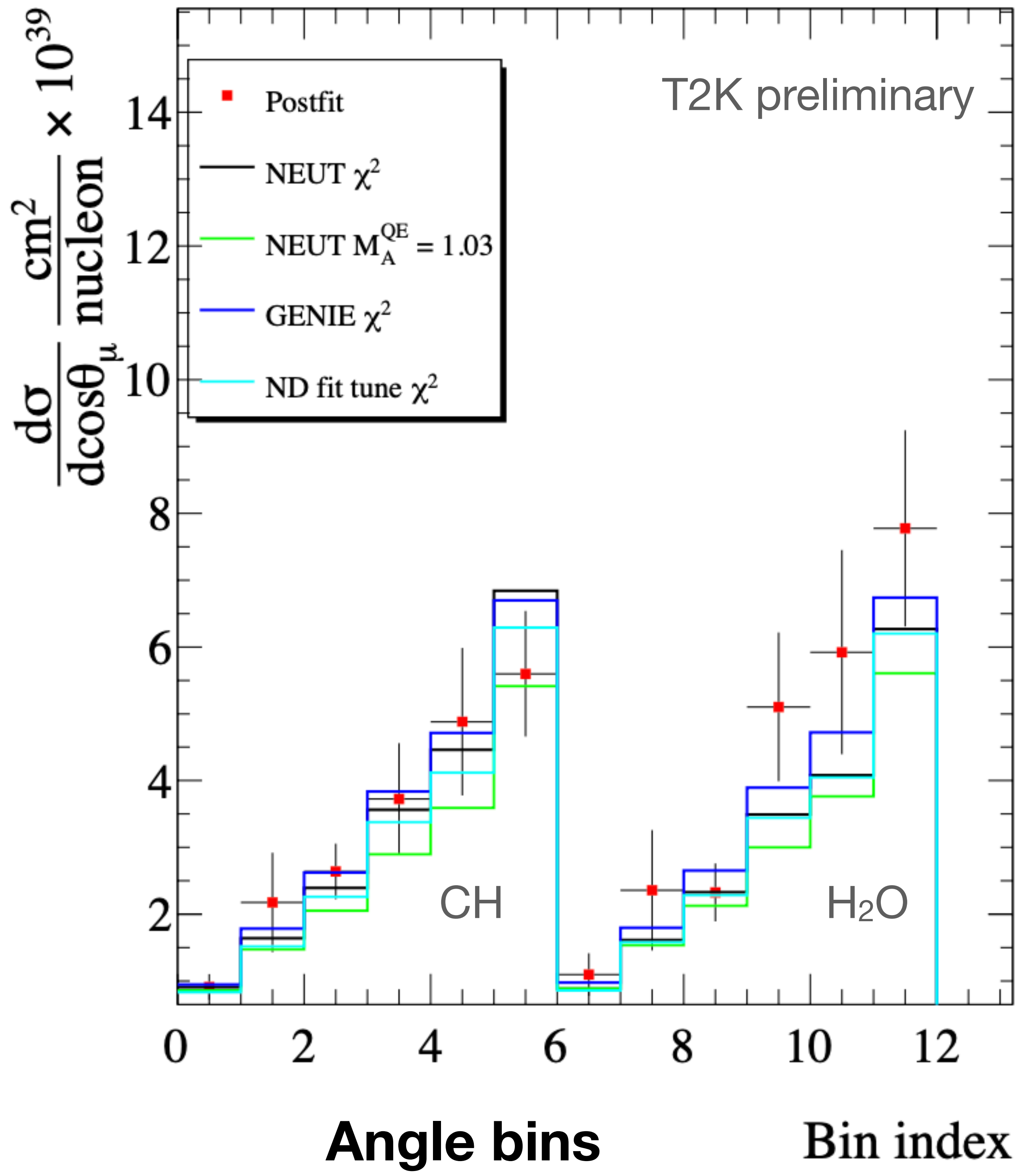
Momentum bins: 300, 500, 700, 900, 1100, 1500, 30000 (cosθ 0.34–1)

cosθ bins: 0.34, 1.0 0.34, 0.57, 0.71, 0.91, 0.94, 0.97, 0.98, 1 (momentum 300-30000)

0-5: bins for CH target, 6-11 bins for H_2O target



Momentum bins



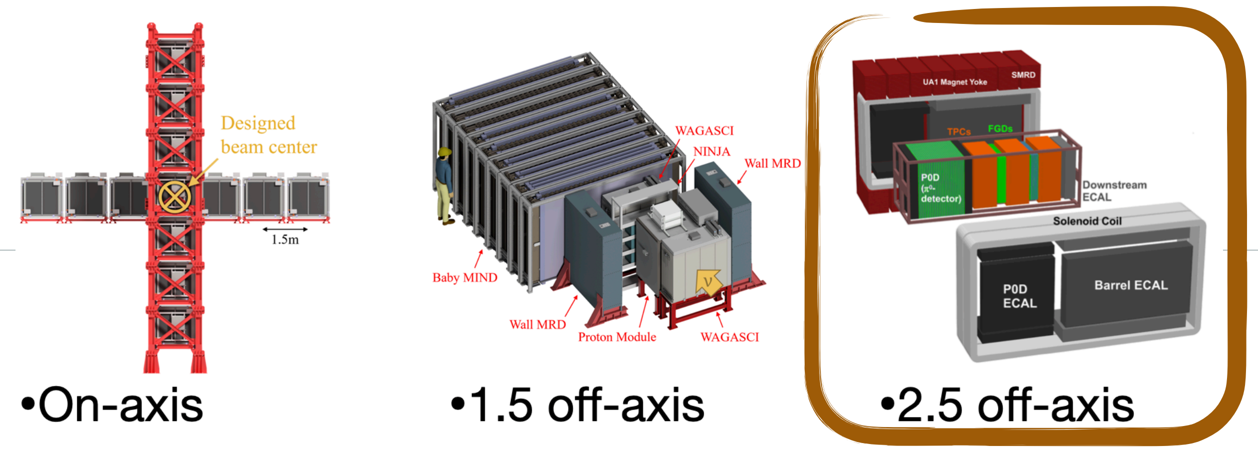
Angle bins

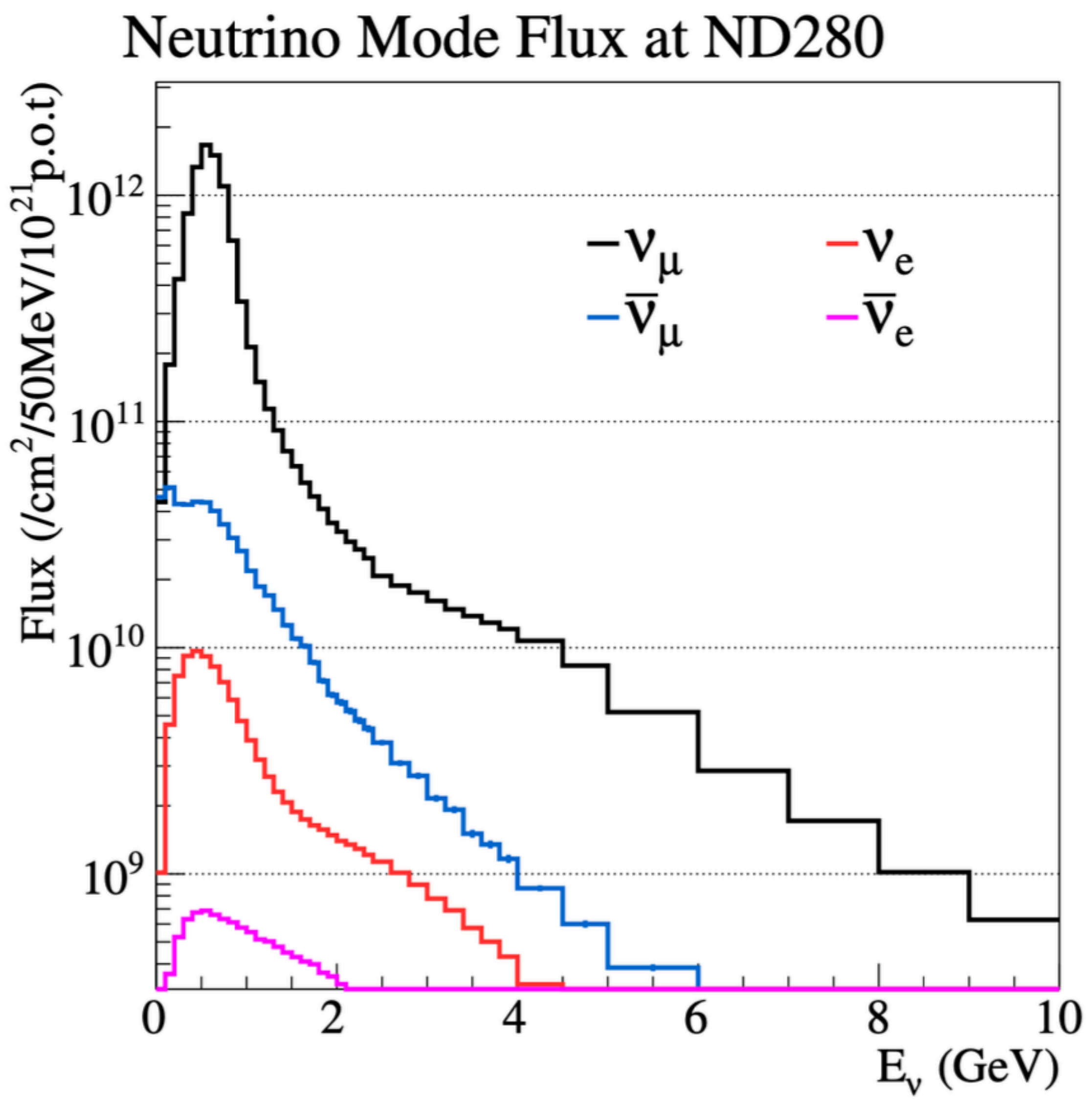
3. ν_e CCπ^+ Interactions

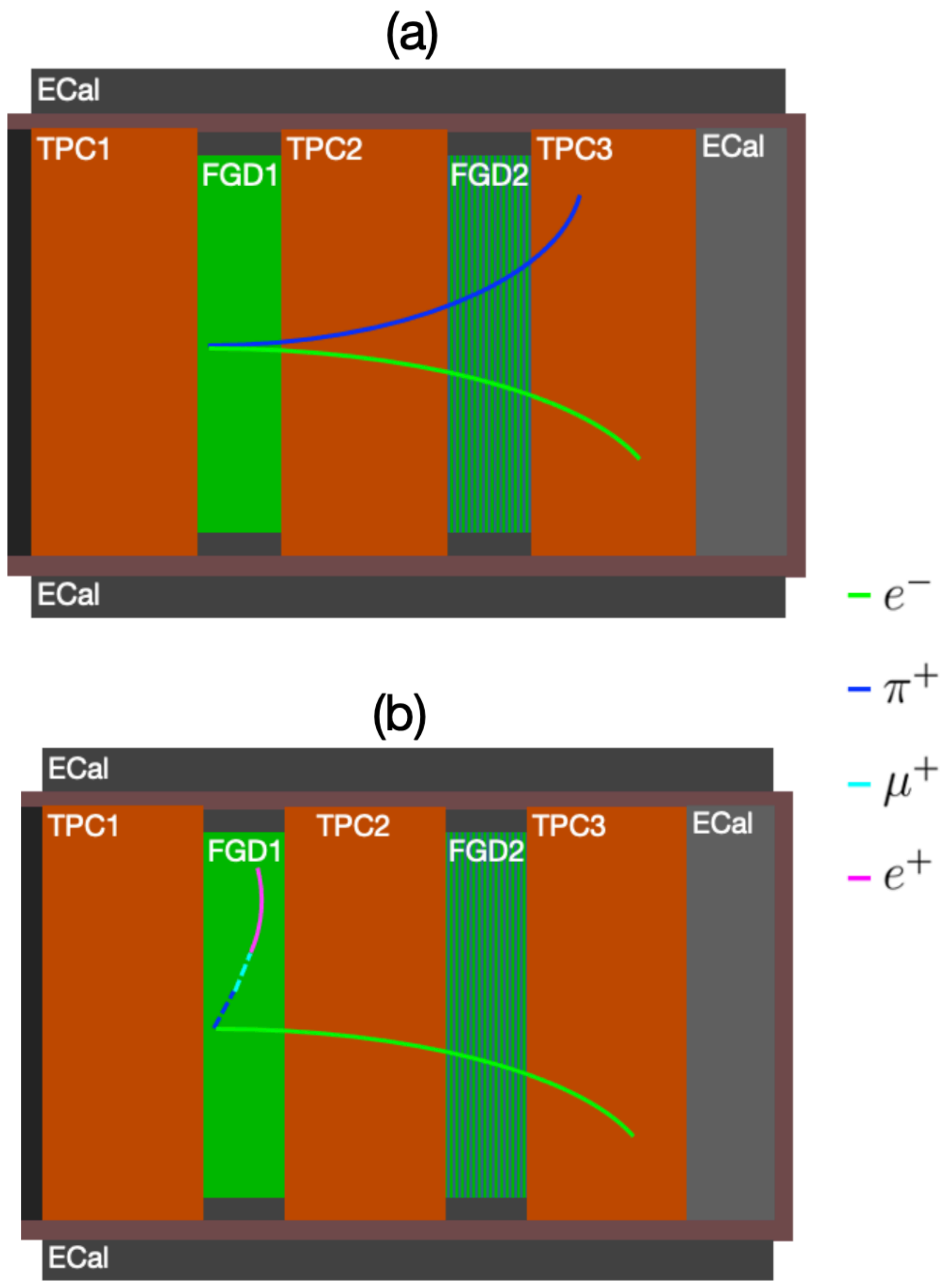
- Channel: $\nu_e CC\pi^+$ in FGD1 in ν-mode beam
- $\nu_e + CH \rightarrow e^- + \pi^+ + X$
- Contributes to appearance channel for CP-violation search
  - Important when reach higher statistics and reduced systematics
  - Statistically significant event excesses in far detector samples [8]
- Extends previous T2K inclusive ν_e/anti-ν_e CC measurement [9]

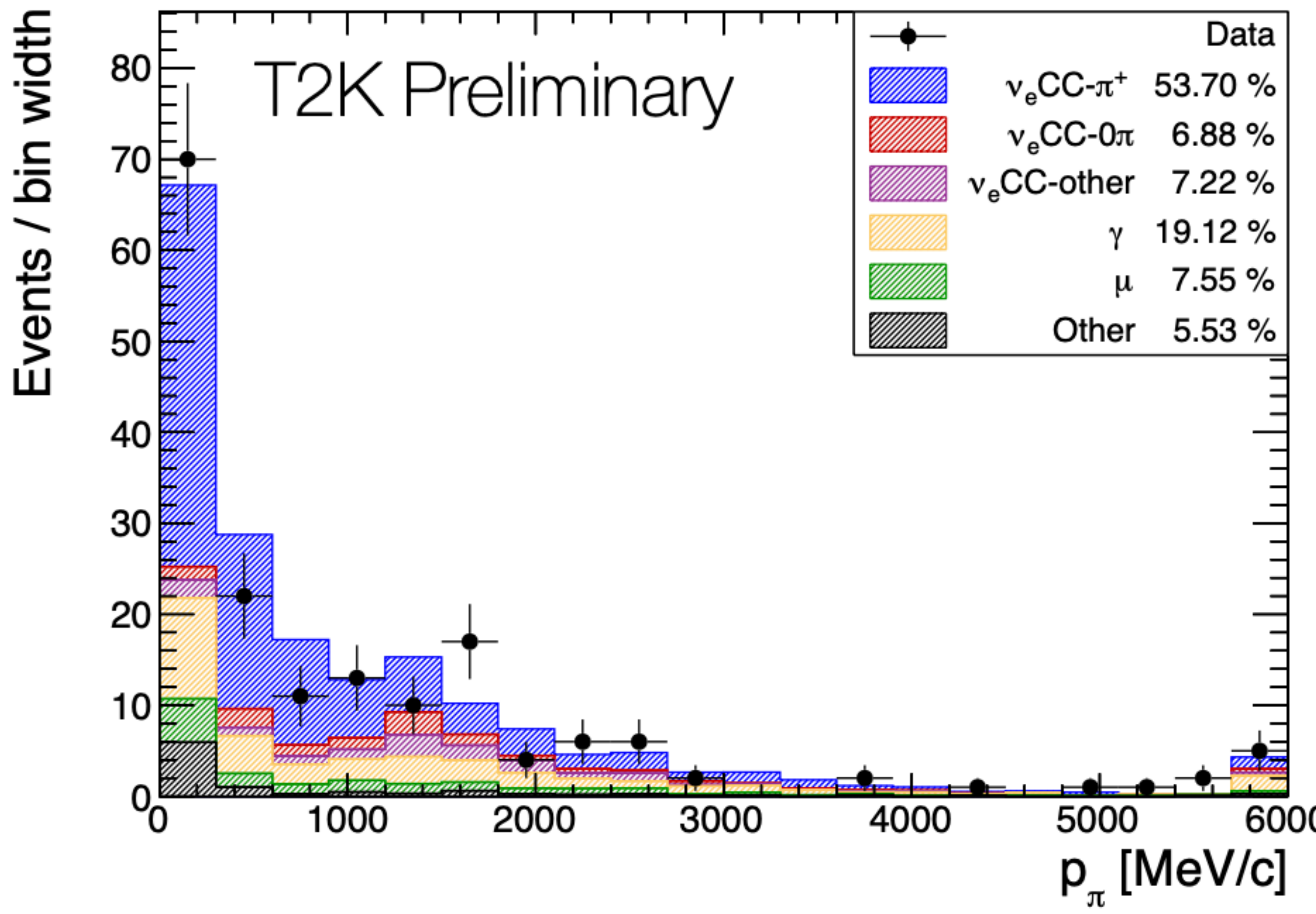
  a) Tag TPC pions with dE/dX

  b) Tag Michel electrons for FGD stopping pions → recover low momentum pions





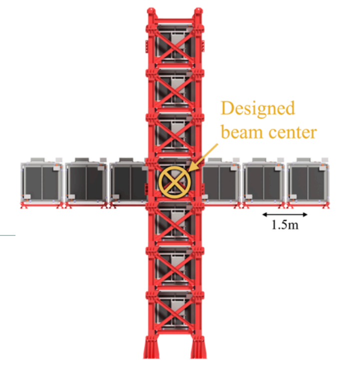




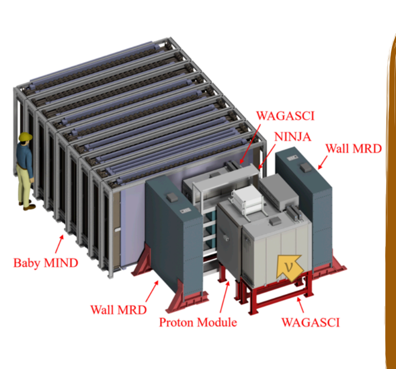
[8] T2K Collab., *Phys. Rev.* D103 (2021) 112008

[9] T2K Collab., *JHEP* 10 (2020) 114

3. ν_e CCπ^+ Interactions



•On-axis



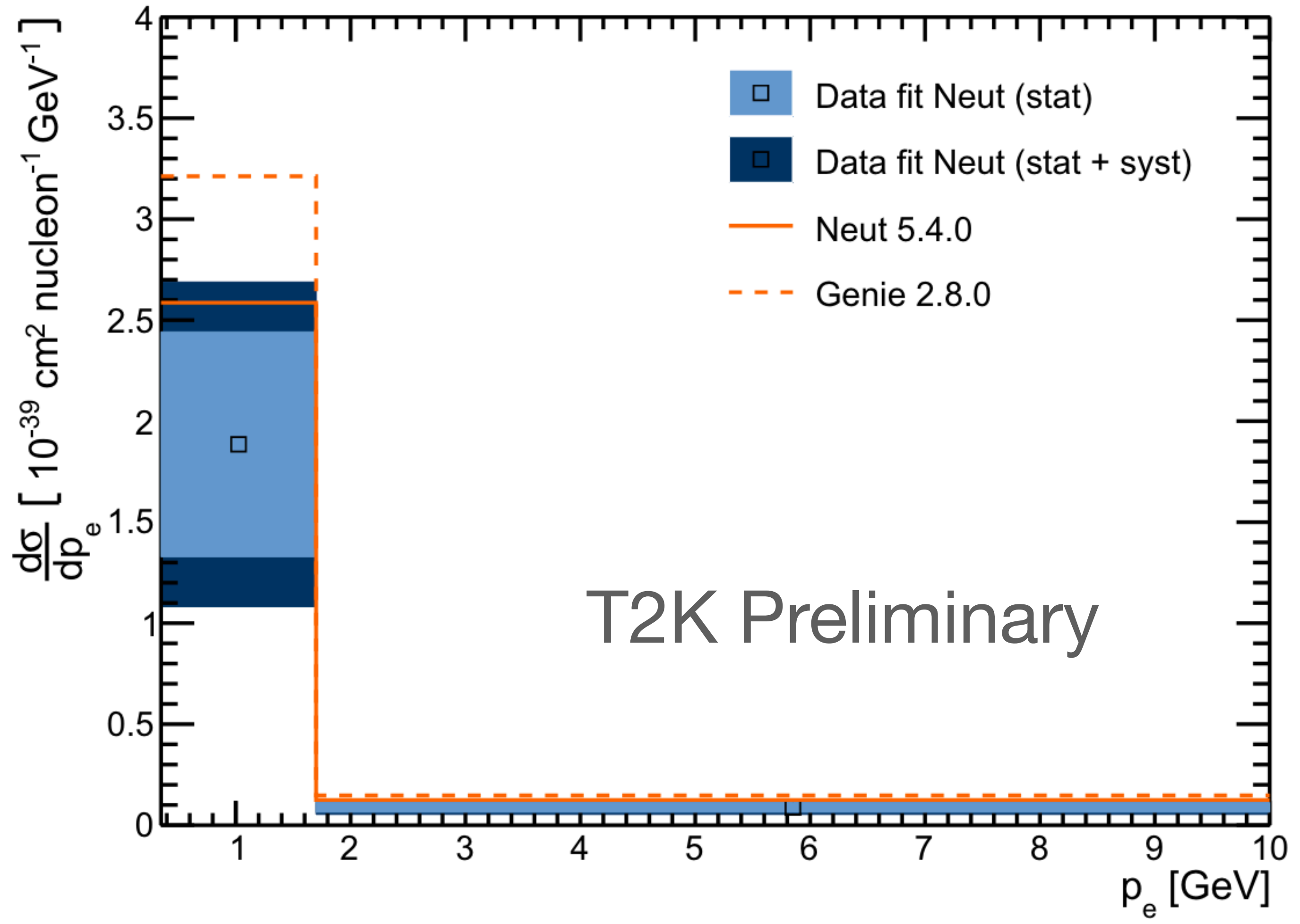
•1.5 off-axis

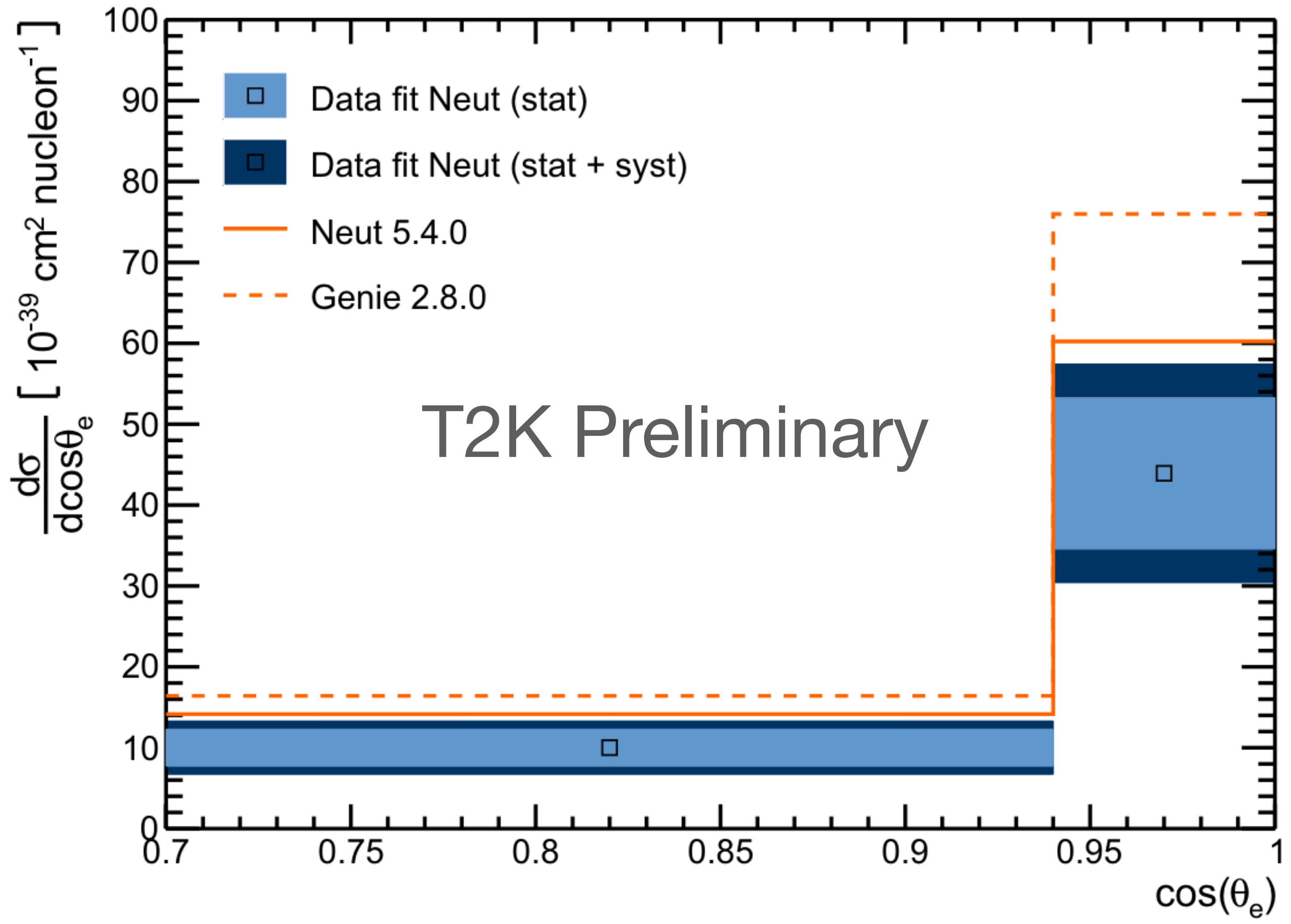
•2.5 off-axis

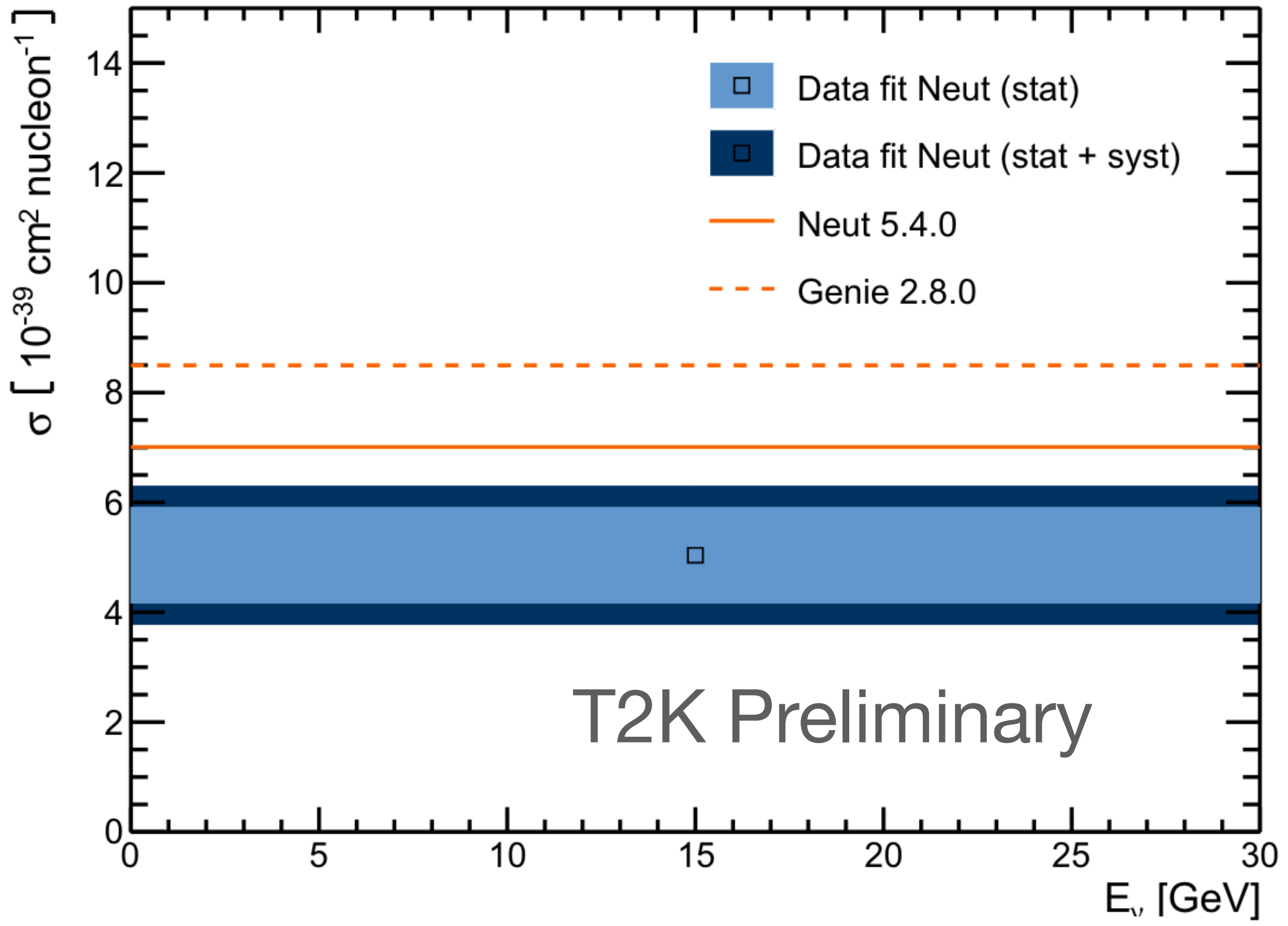
- $\nu_e + CH \rightarrow e^- + \pi^+ + X$
- Restricted phase-space
  - $0.35 < p_e < 30$ GeV/c, $\cos\theta_e > 0.7$,
  - $p_\pi < 1.5$ GeV/c
- Purity of ~60% with ~20% efficiency
- 3D measurement in p_e, $\cos\theta_e$ and p_π
- Stat. limited: 355 events predicted
- Results over-predicted by both NEUT (1.6σ) and GENIE (2.9σ)
- No indications of excesses

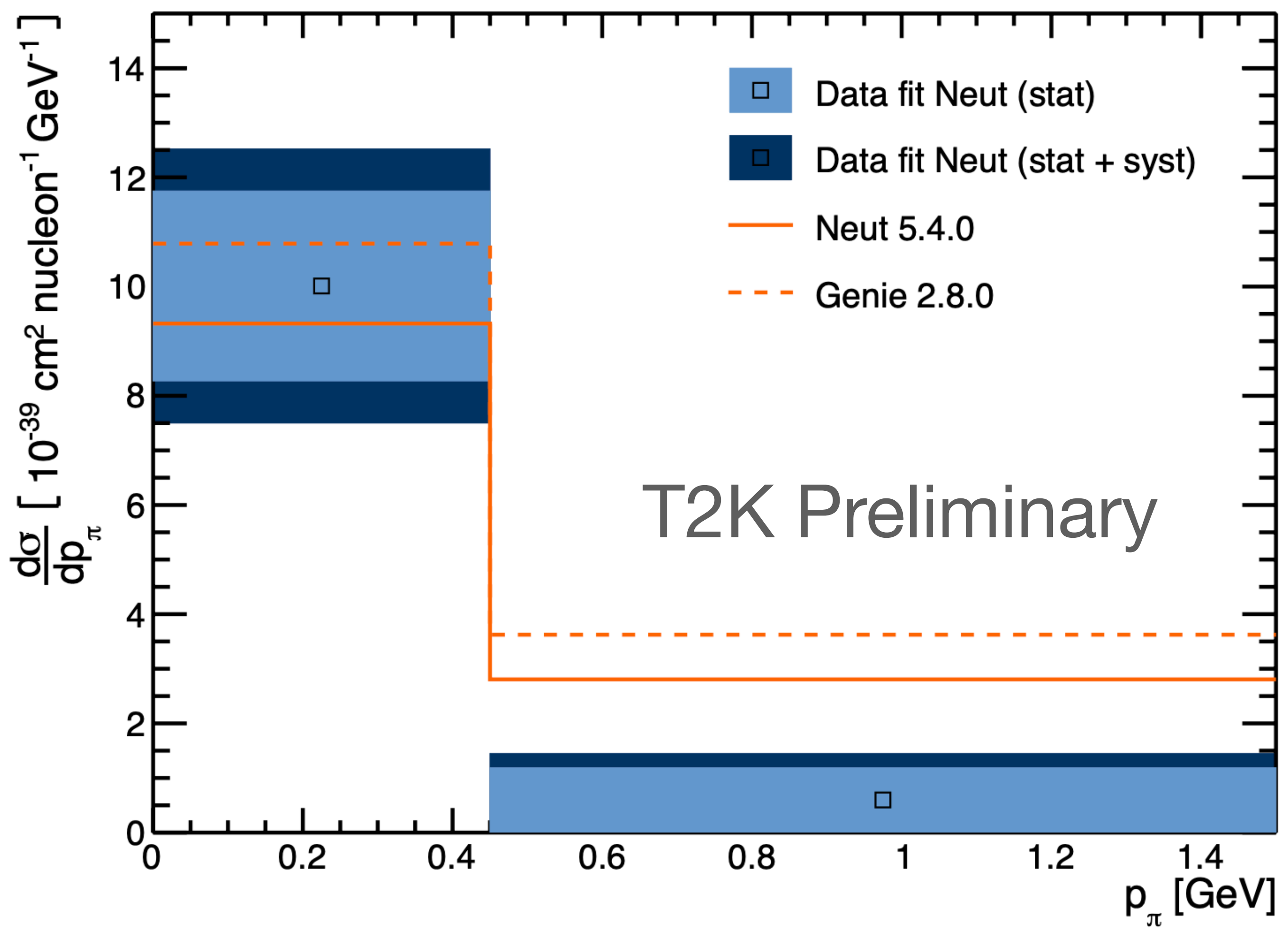
The total flux-integrated cross section:

$$\sigma = 5.04 \pm^{0.94(stat.)}_{0.73(syst.)} [10^{-39} \mathrm{cm}^2 \text{ nucleon}^{-1}]$$





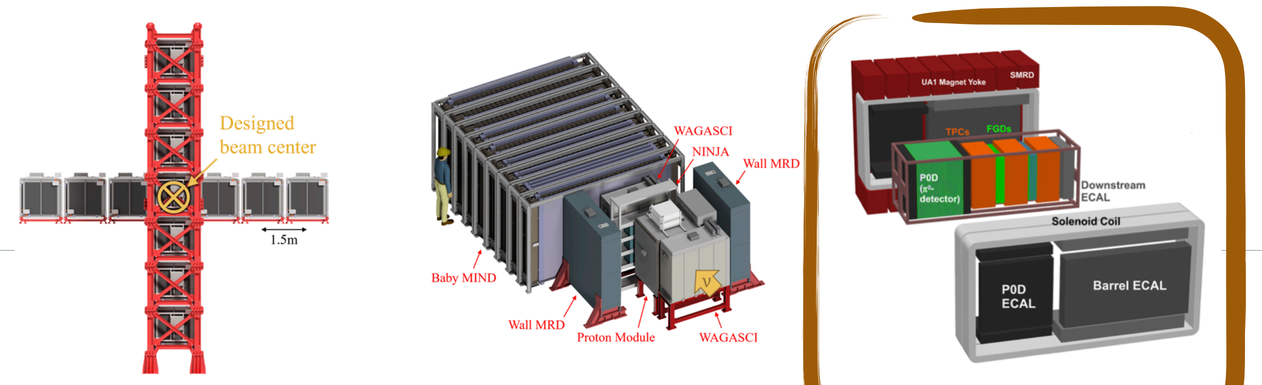




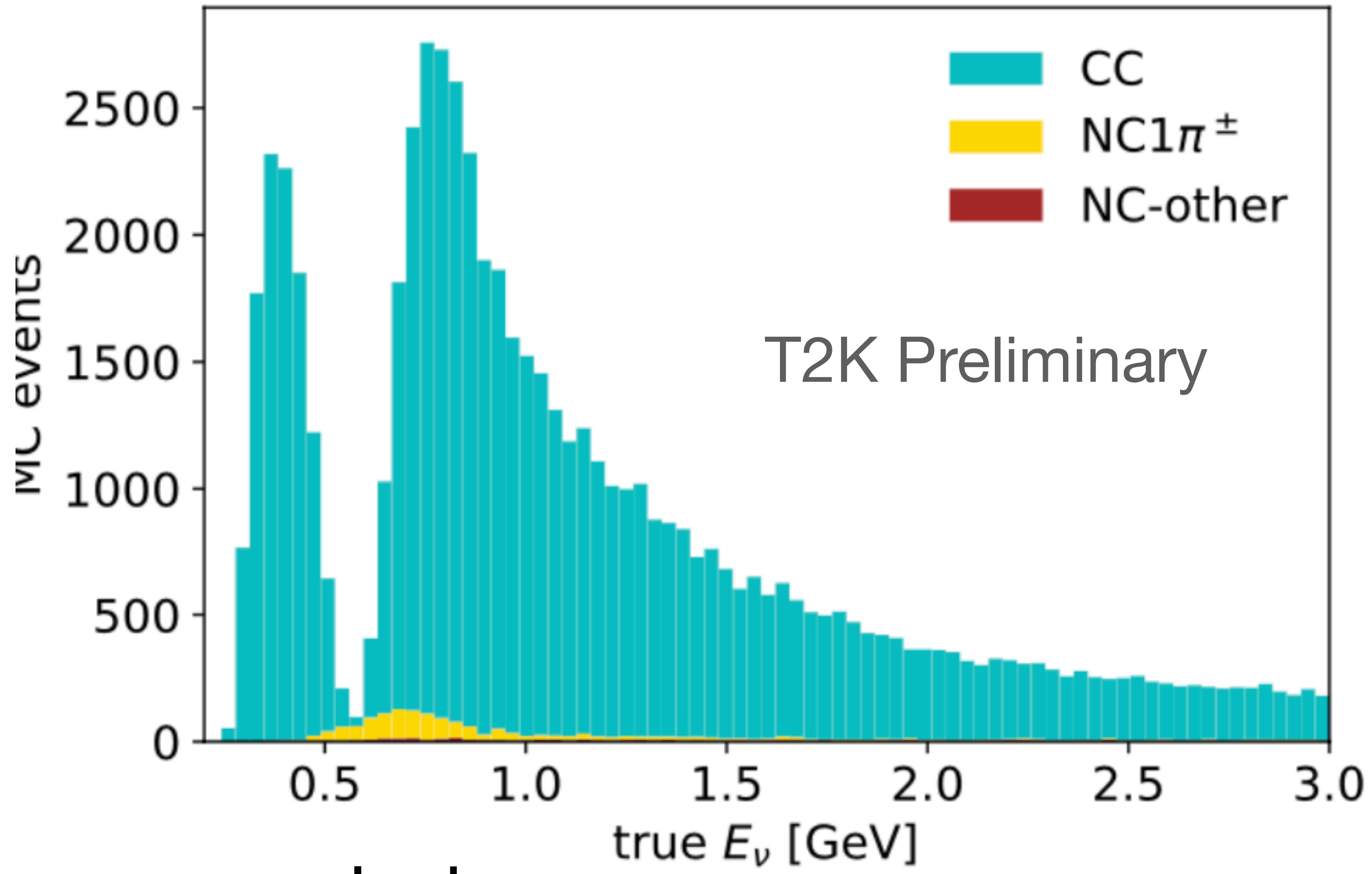
Summing up over 3D bins

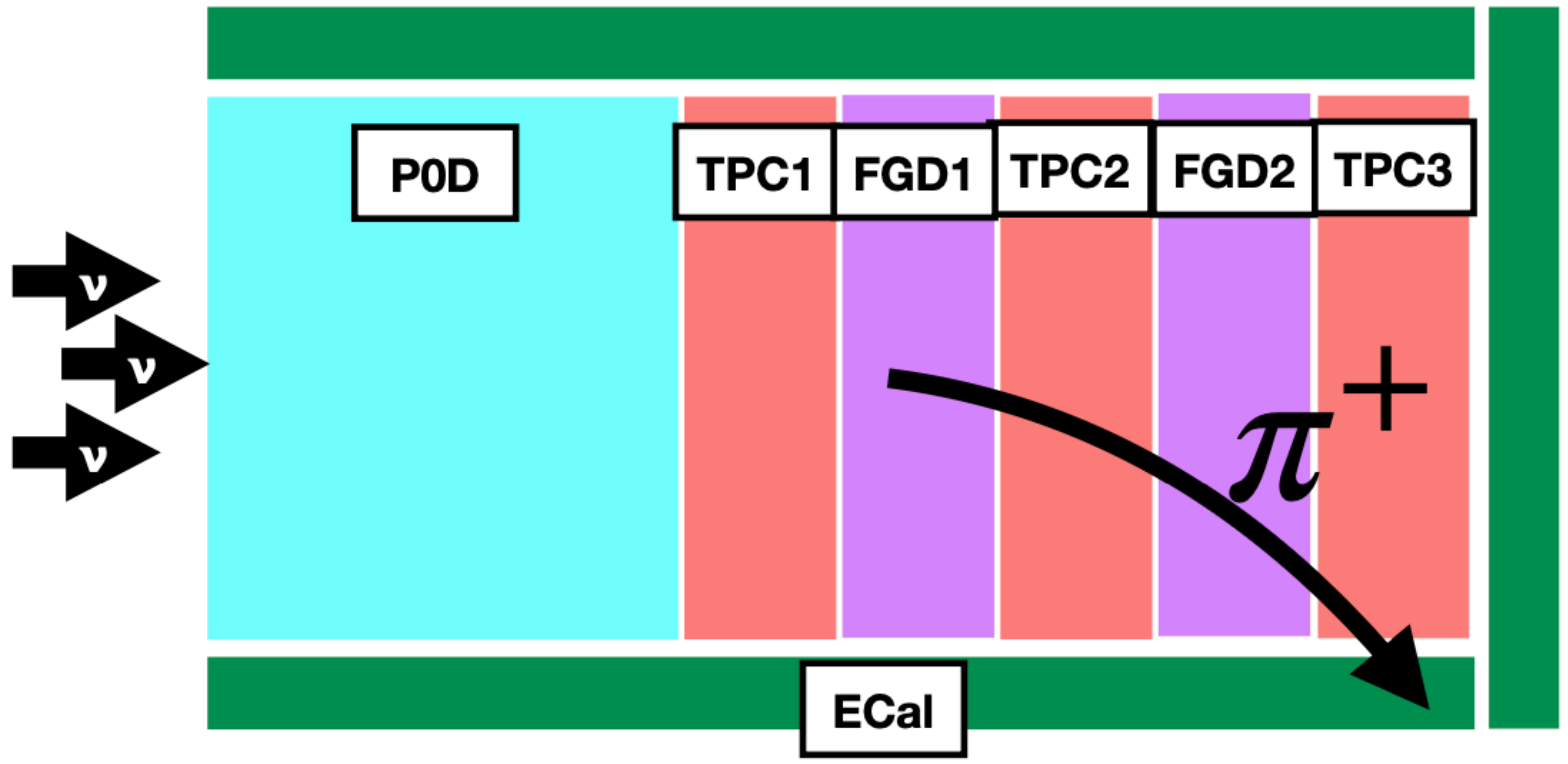
$$\sigma = \sum_{i=4}^{11} \sigma_i \Delta p_{e,i} \Delta\cos\theta_{e,i} \Delta p_{\pi,i}.$$

4. NC1π⁺ Interactions @ ND280



- NC1π± important for disappearance channel of OA
  - Currently in T2K has a 60% uncertainty
  - Now sub-dominant due to stats but crucial for precision measurements
- Previous studies at bubble chambers date back to > 40 years
  - Gargamelle (GGM) propane-freon BC [10]: 88 signal events, $p\nu \to \nu\pi^+ n$ event rate vs kinematics; $\nu n \to \nu\pi^- p$ also measured
  - ANL deuterium bubble chamber [11]: 54 signal events, $\nu n \to \nu\pi^- p$ xsec
- T2K ND280: final-state π⁺ in FGD1 and any number of protons p<200 MeV/c





Restricted phase-space analysis

$\cos\theta_{\pi^+} > 0.5$ and $0.2 < p_{\pi^+} < 1.0$ GeV			
Topology	Process	NEUT Events	GENIE Events
NC1π^+0p	$\bar{\nu} + p \to \bar{\nu} + n + \pi^+$	4.55	5.77
	$\nu + n \to \nu + n + \pi^0$	2.59	2.29
	$\nu + p \to \nu + n + \pi^+$	116.99	113.32
	ν + (n or p) $\to \nu$ + (n or p) + multi π	1.56	0.56

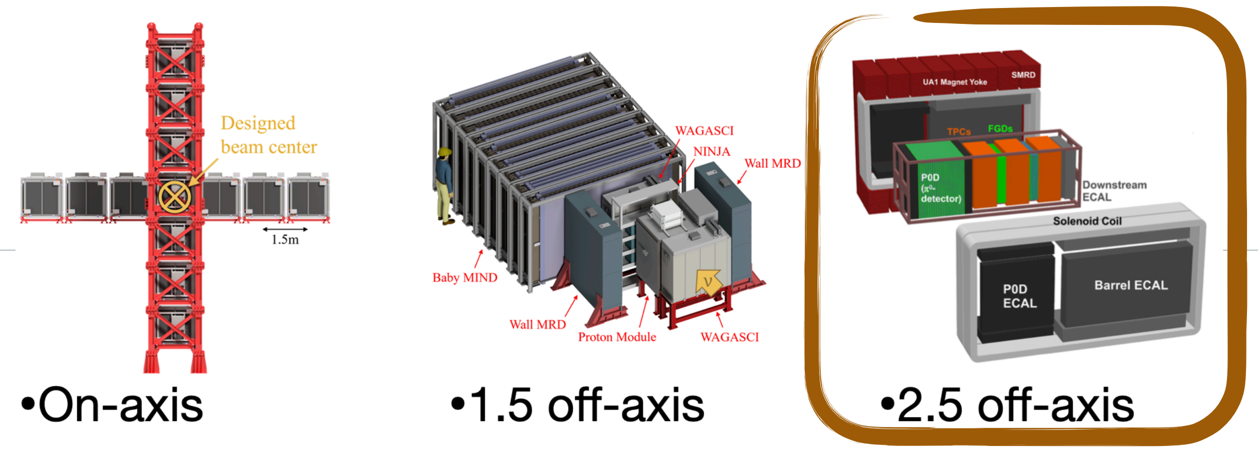
★~120 events

Largest signal sample ever studied

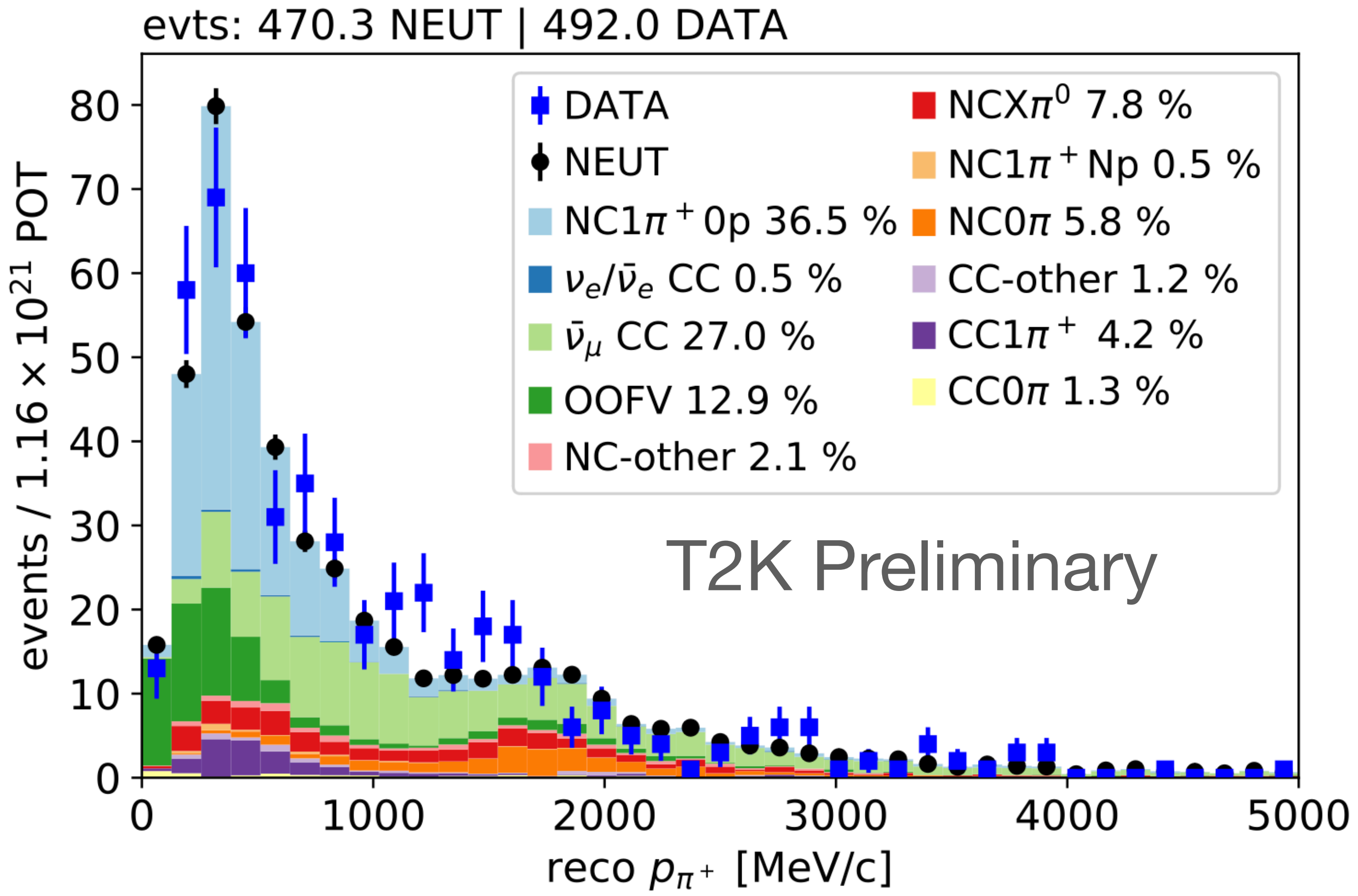
[10] GGM Nucl.Phys.B 135 (1978) 45-65

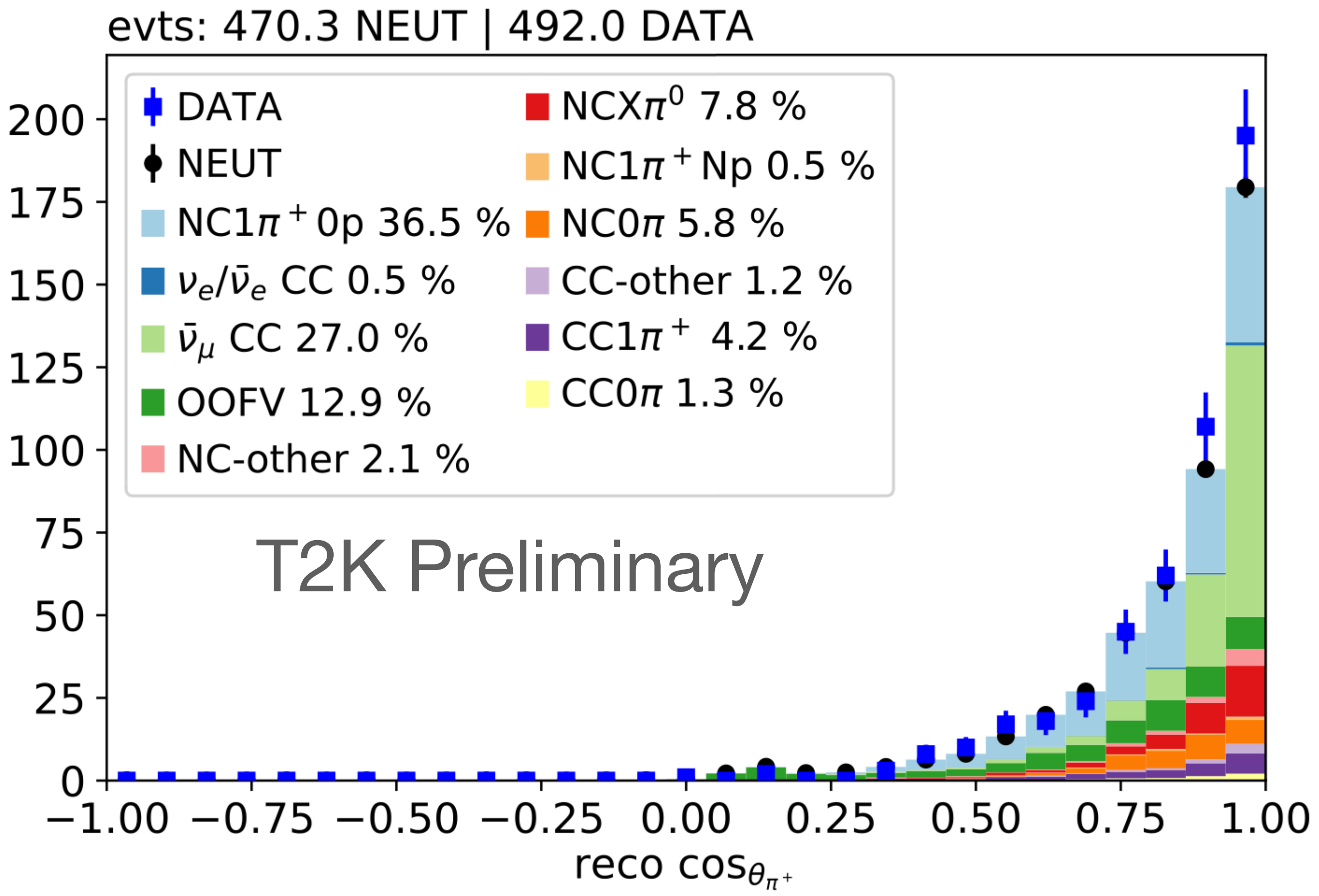
[11] ANL Phys.Lett.B 92 (1980) 363

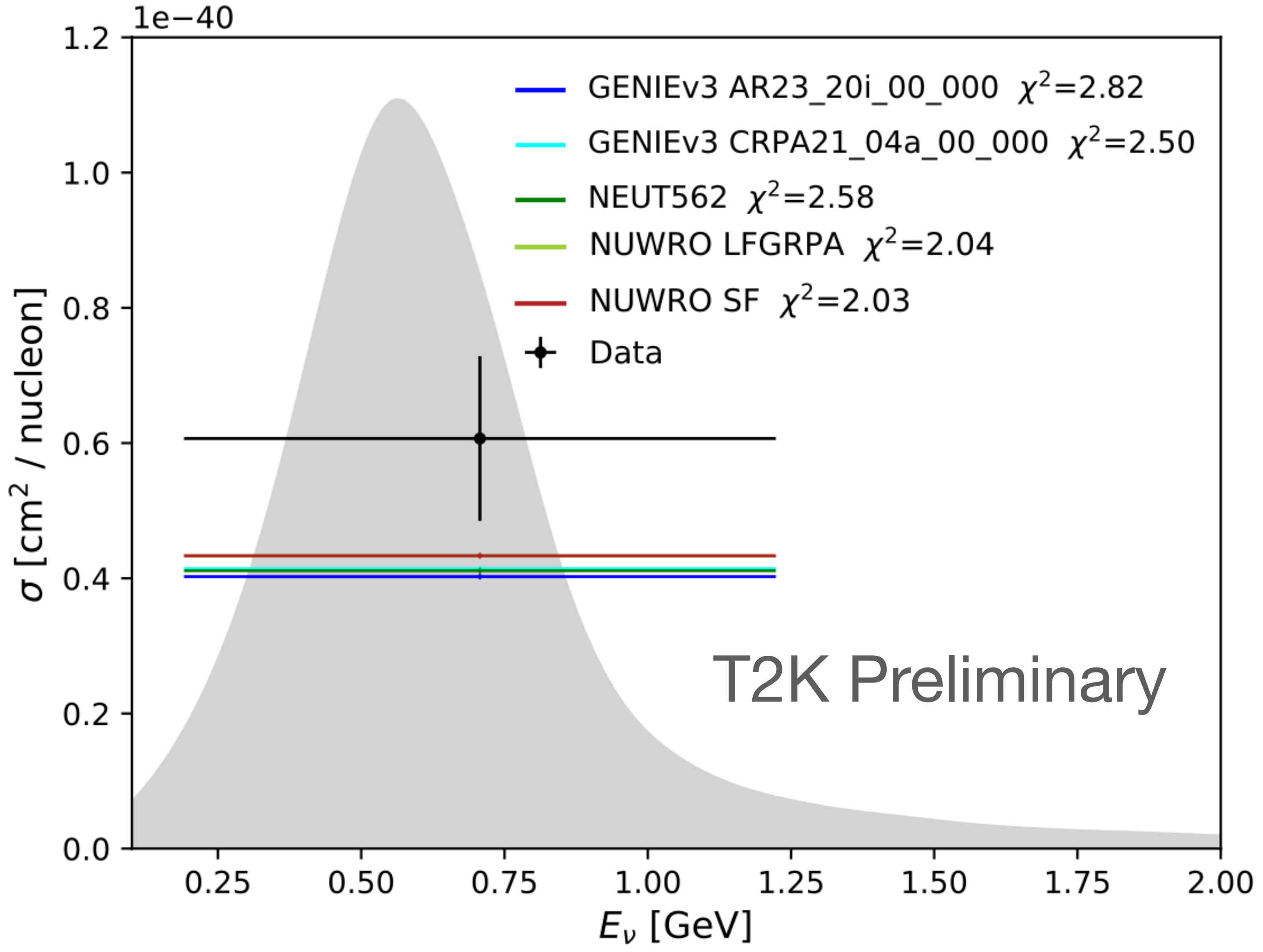
4. NC1π+ Interactions

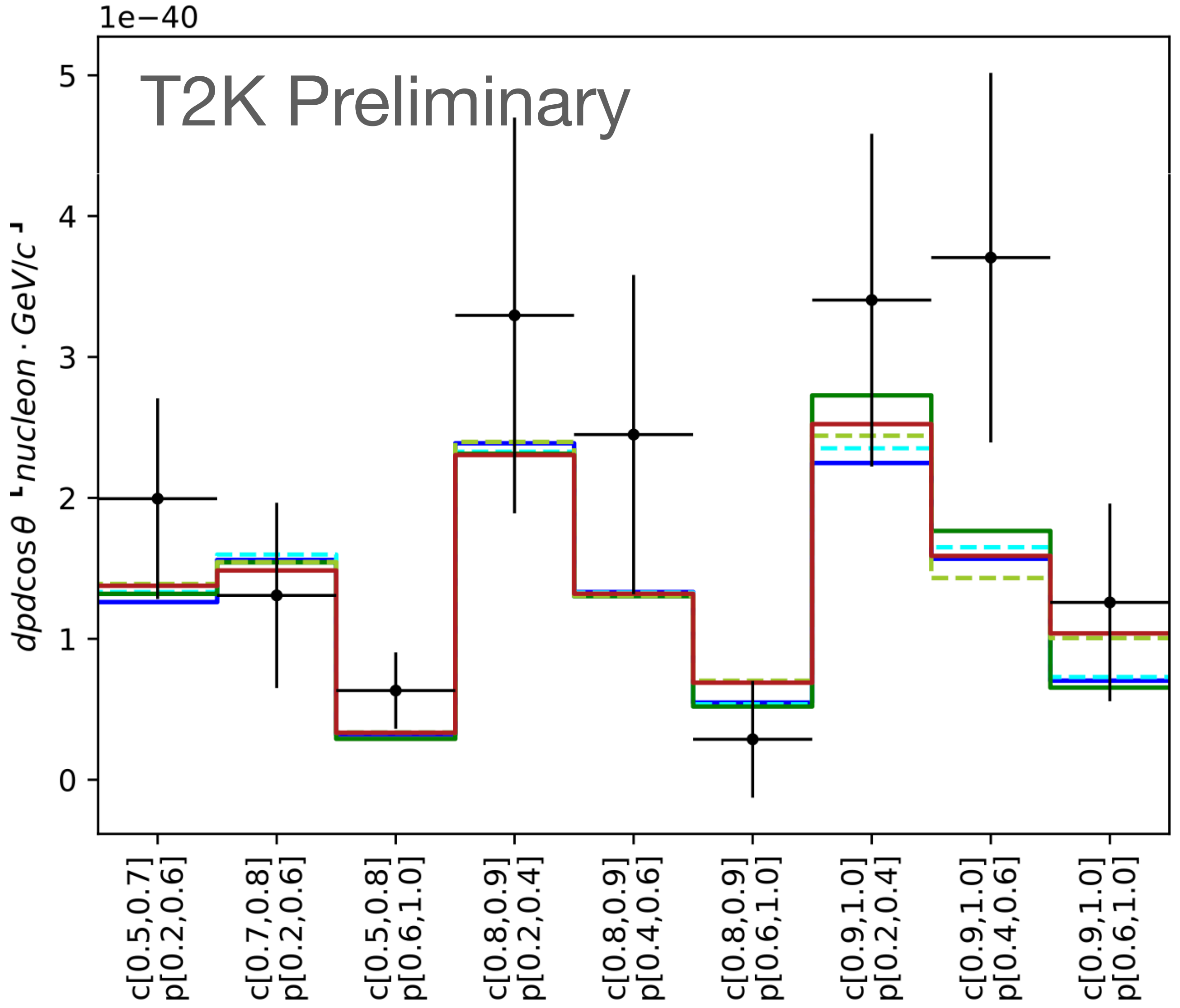


- $\nu/\bar{\nu} + CH \rightarrow \pi^+ + X$
- Selection with > 20% efficiency and 30-60% purity
- 2D differential measurement: p_π, $\cos\theta_\pi$
- Total cross-section result on CH
- $\sigma = 6.97 \pm 1.22 \times 10^{-41}$ cm^2/nucleon
  - 13% stat and 15% syst
- 1-1.5σ larger cross section result is preferred compared to most models
- First to provide new data on this channel since 1980
- First cross-section measurement on the NC1π+ channel

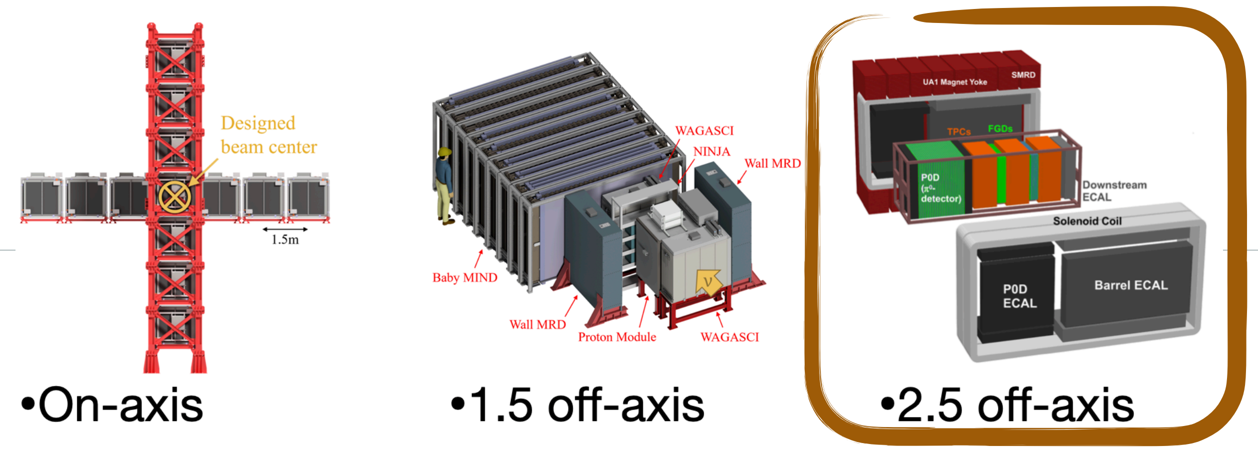








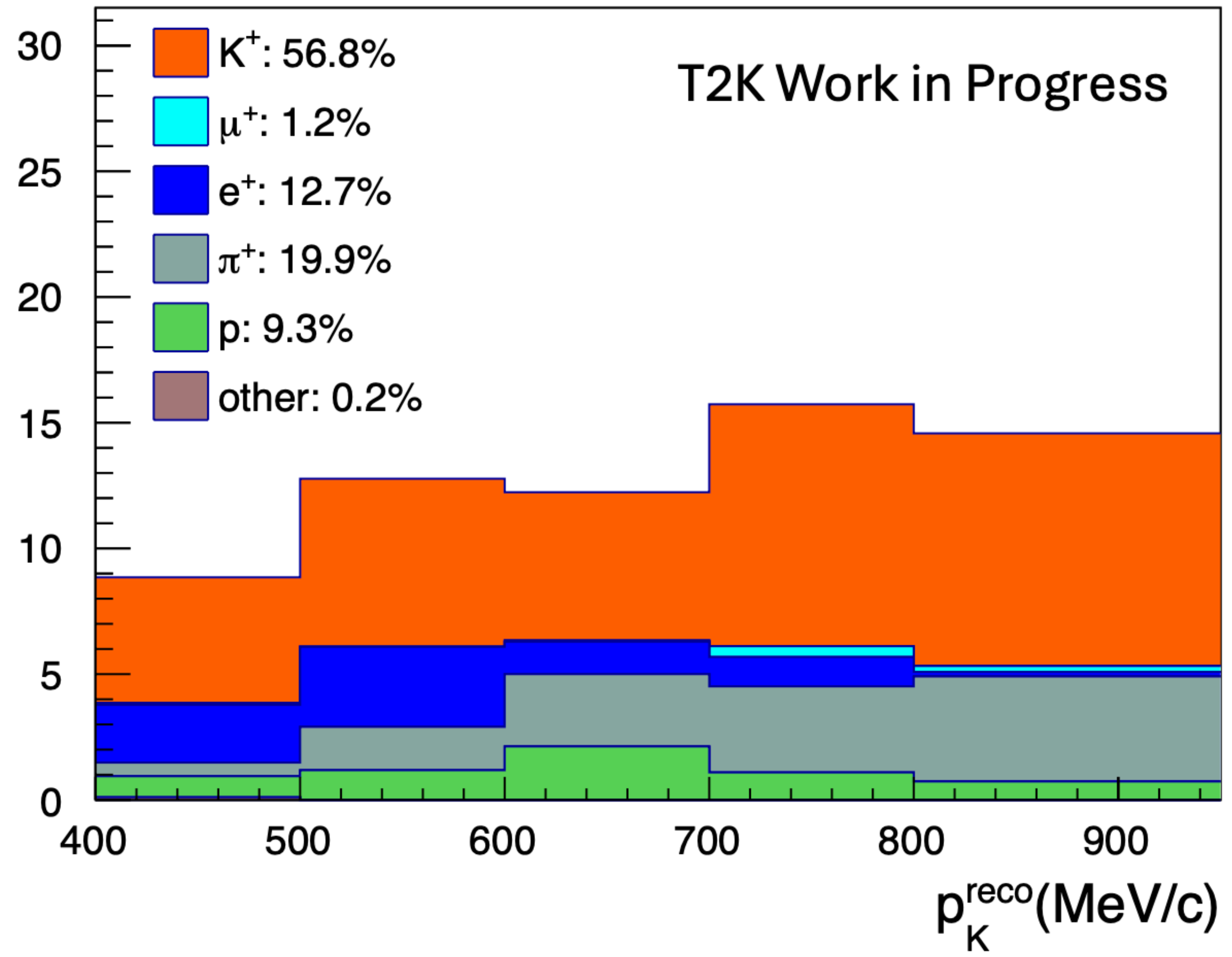
5. ν_μ CC K^+ Production @ ND280

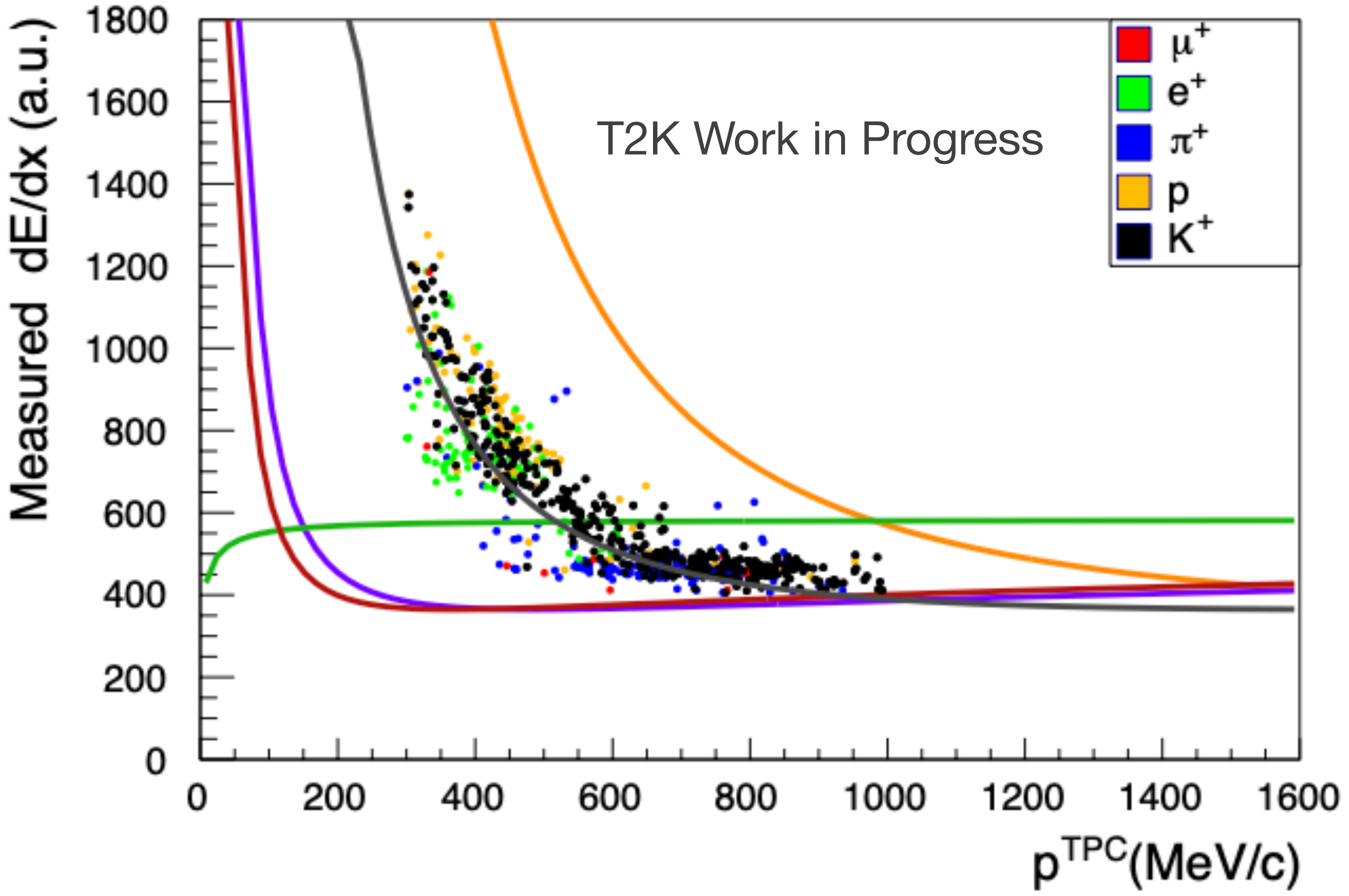


- Kaon production background for proton decay searches $p \rightarrow K^+ + \bar{\nu}$
- First kaon measurements in T2K
- Events in FGD1 with μ^- and K^+ tagged using TPC dEdX
- Efficiency ~15%, Purity ~50 %
- ~60 events expected (GENIE)
- Single bin XSec in the restricted phase-space
- Cross-sections vary up to 30% between generators
- Unblinded signal samples; results under T2K review

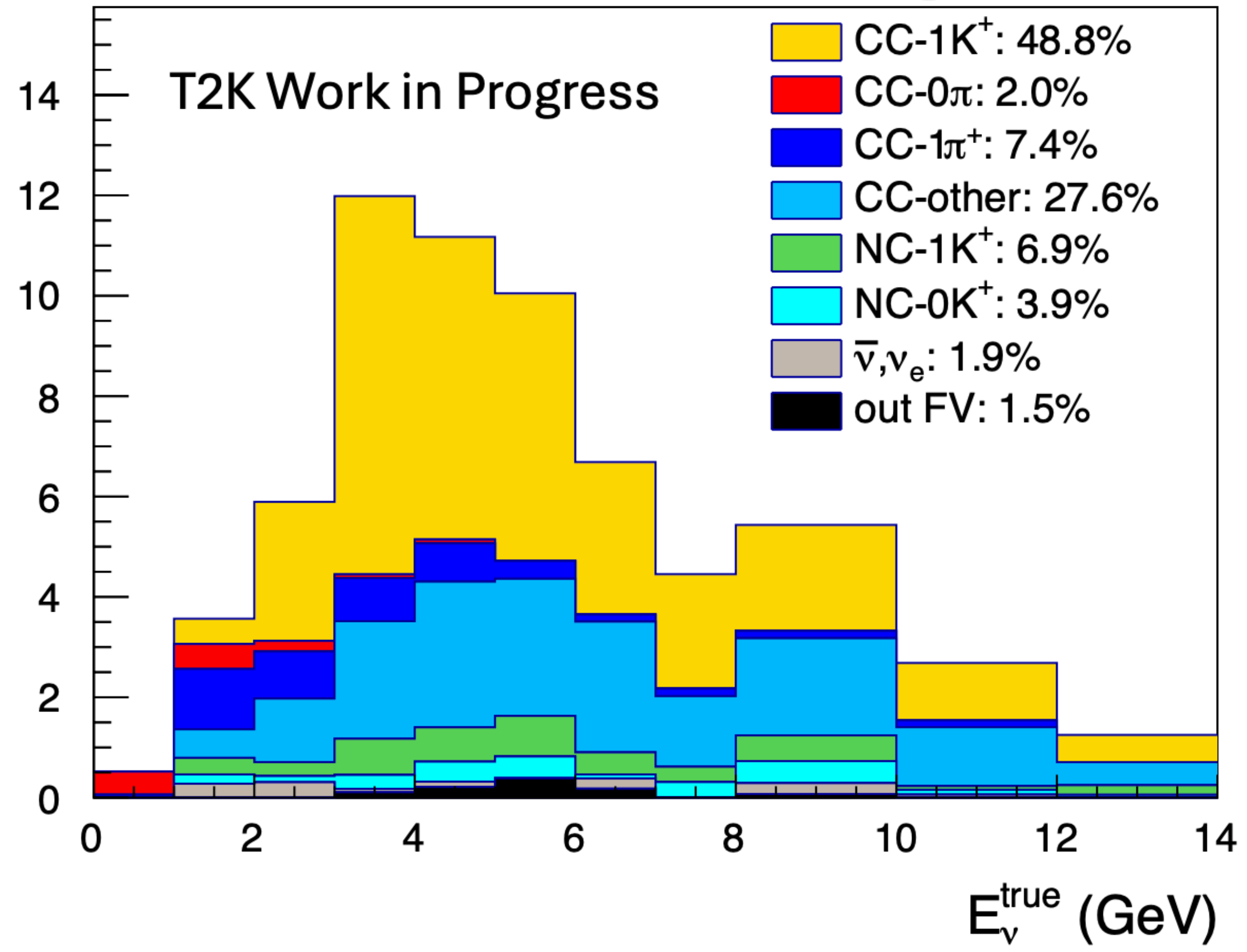
$$\nu_\mu + n \rightarrow \mu^- + K^+ + \Lambda^0,$$
$$\nu_\mu + n \rightarrow \mu^- + K^+ + K^- + p,$$
$$\nu_\mu + p \rightarrow \mu^- + K^+ + \bar{K}^0 + p,$$
$$\nu_\mu + p \rightarrow \nu_\mu + K^+ + \Lambda^0.$$
$$\nu_\mu + p \rightarrow \mu^- + K^+ + p,$$
$$\nu_\mu + n \rightarrow \mu^- + K^+ +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

Kaon momentum



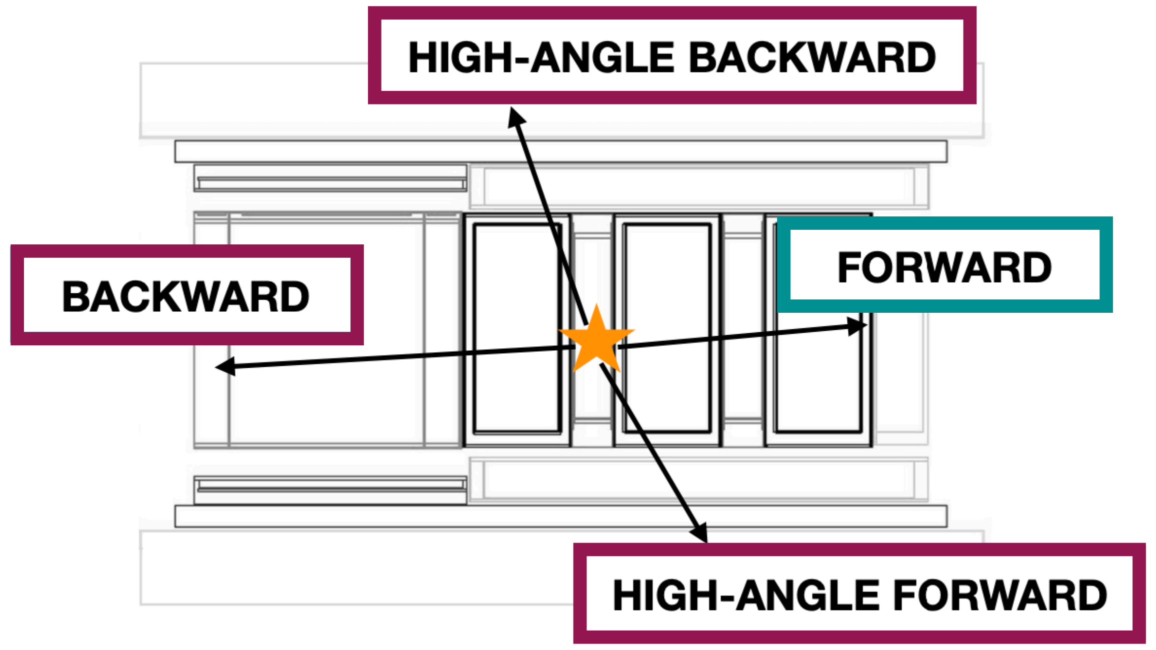


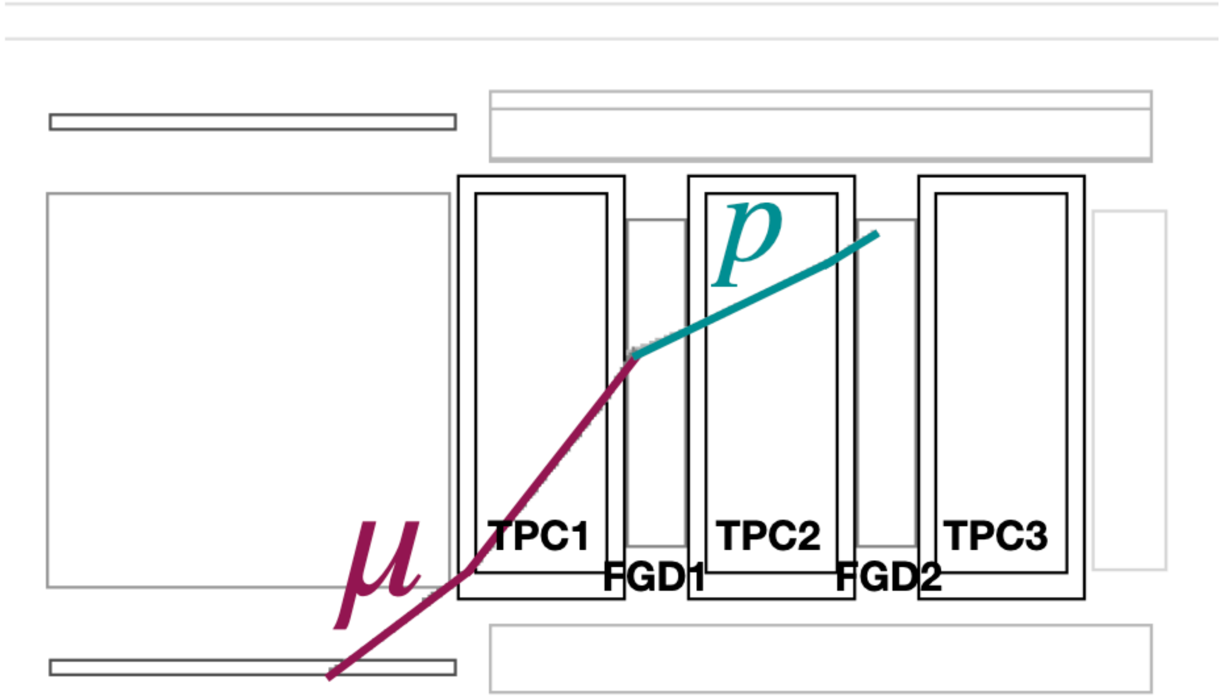
True neutrino energy



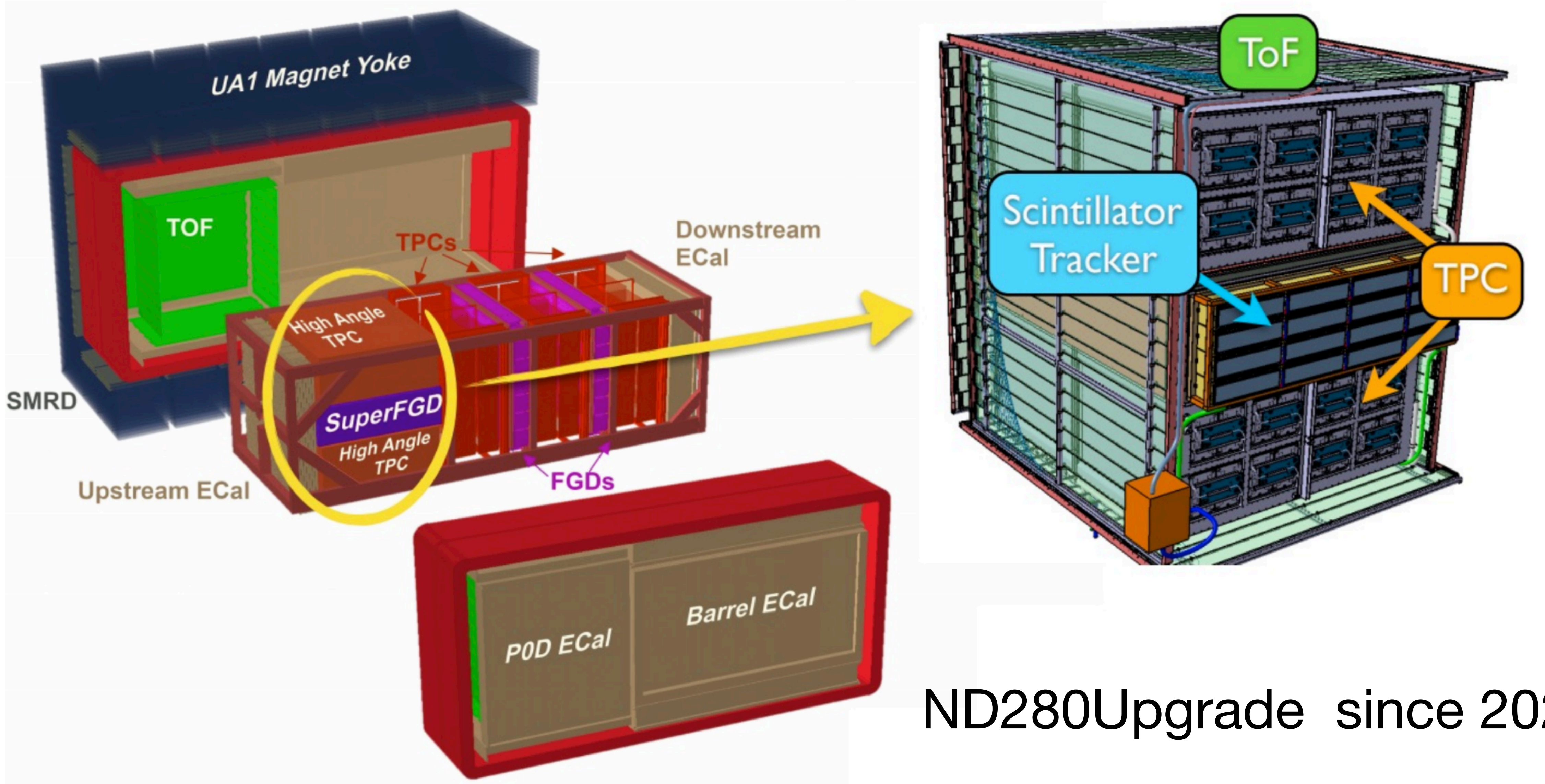
Outlook

- Exciting T2K XSec results being prepared for publication
  - WAGASCI/BabyMIND joint CH/water $\nu_\mu CC0\pi$
  - $\nu_e CC\pi^{+-}$ in ND280 on CH
  - $NC1\pi^+$ in ND280 on CH
  - ν_μCC kaon production in ND280 on CH
- Approaching finalisation and sharing
  - Anti-ν_μ $CC1\pi^-$ in ND280 on CH
  - $\nu_\mu CC1\pi^+$ in ND280 FGD1(CH)/FGD2(CH+$H_2$0)
  - $NC1\pi^0$ in ND280 P0D
  - NCE (1p0π) in ND280 on CH
- Being actively developed
  - CC0πNp in FGD1/FGD2 TKI* with improved proton PID
  - **CC0π and CC1π in ND280 FGDs using "4π" samples**
  - CC0πNp in FGDs with calorimetric variables
  - ν_μCC1π+ in ND280 P0D
  - **ν_μCC0π WAGASCI/Baby-MIND + ND280 joint analyses**
  - ν_μCC1π joint CH+$H_2$0 in WAGASCI/Baby-MIND
- **Unique opportunities for XSec studies with the recently upgraded ND280**





Topologies with large-angles wrt ν beam added for ND280 analyses



ND280Upgrade since 2023

See talk by Alejandro Ramirez on the recent news and thriving T2K ND physics program

* Transverse kinematic imbalance

Summary

- Scrupulous studies of neutrino reactions are crucial as we enter the era of the high-precision oscillation analyses and lepton CPV search
- T2K steadily provides novel neutrino cross-section measurements with many on-going and converging analyses
- Recent highlights on neutrino interactions in T2K with near-detectors:
  - Joint on/off-axis $\nu_\mu CC0\pi$ with potential extensions with more detectors, channels and samples
  - ND280: $\nu_e CC\pi^+$, $NC1\pi^+$ — the first result since 1980s(!)
  - WAGASCI/BabyMIND: $\nu_\mu CC0\pi^\pm$ — first physics with the full detector setup
- Rich opportunities for neutrino interactions studies with the upgraded T2K near detector ND280Upgrade