Recent neutrino cross section results from the Tokai-to-Kamioka (T2K) experiment

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On behalf of the T2K Collaboration
Given at 21st Recontres du Vietnam, 22-25 July 2025, ICISE, Quy Nhon, Vietnam

Science and
Technology
Facilities Council

Tokai-to-Kamioka (T2K) Experiment

International collaboration: 565 members from 75 institutions in 15 countries (as of 1 July 2025)

Far detector "measures" the oscillated beam composition

Super-Kamiokande

295 km baseline for neutrino oscillations

Upgrade completed in May 2024!

Near Detector Complex (280 m from production) "measures" the initial beam composition

(Anti-)neutrino beam (~600 MeV) produced at J-PARC

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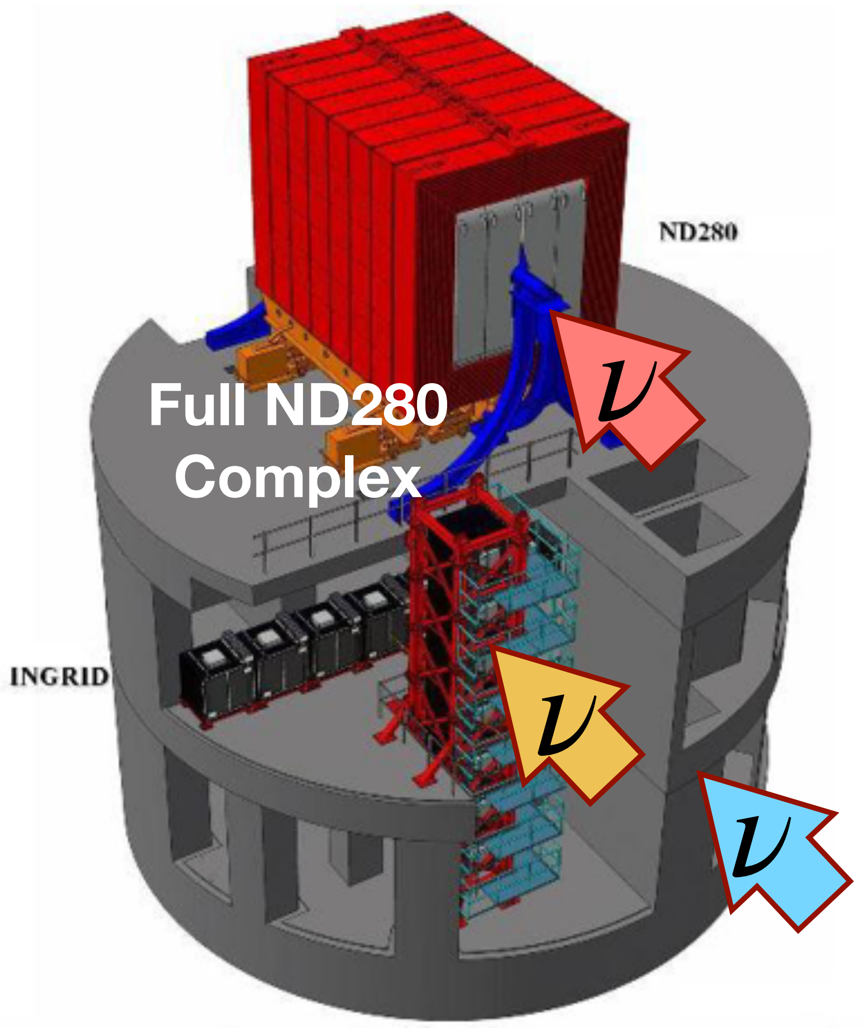
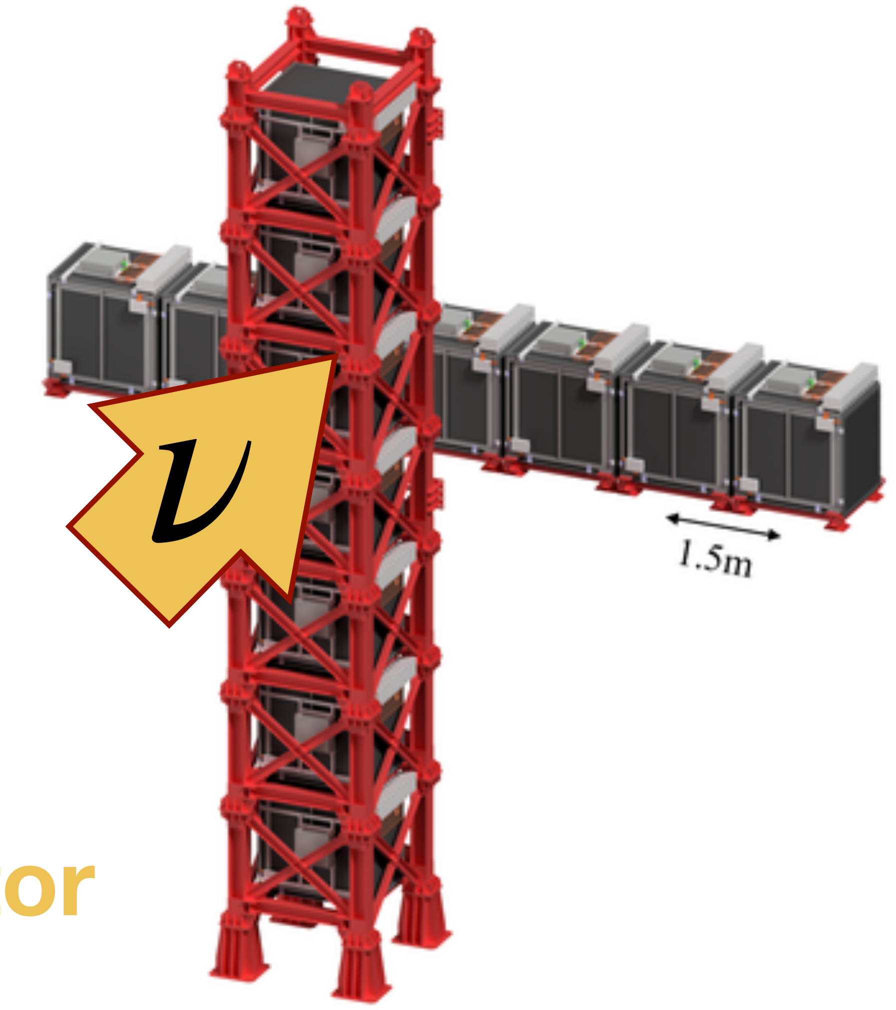
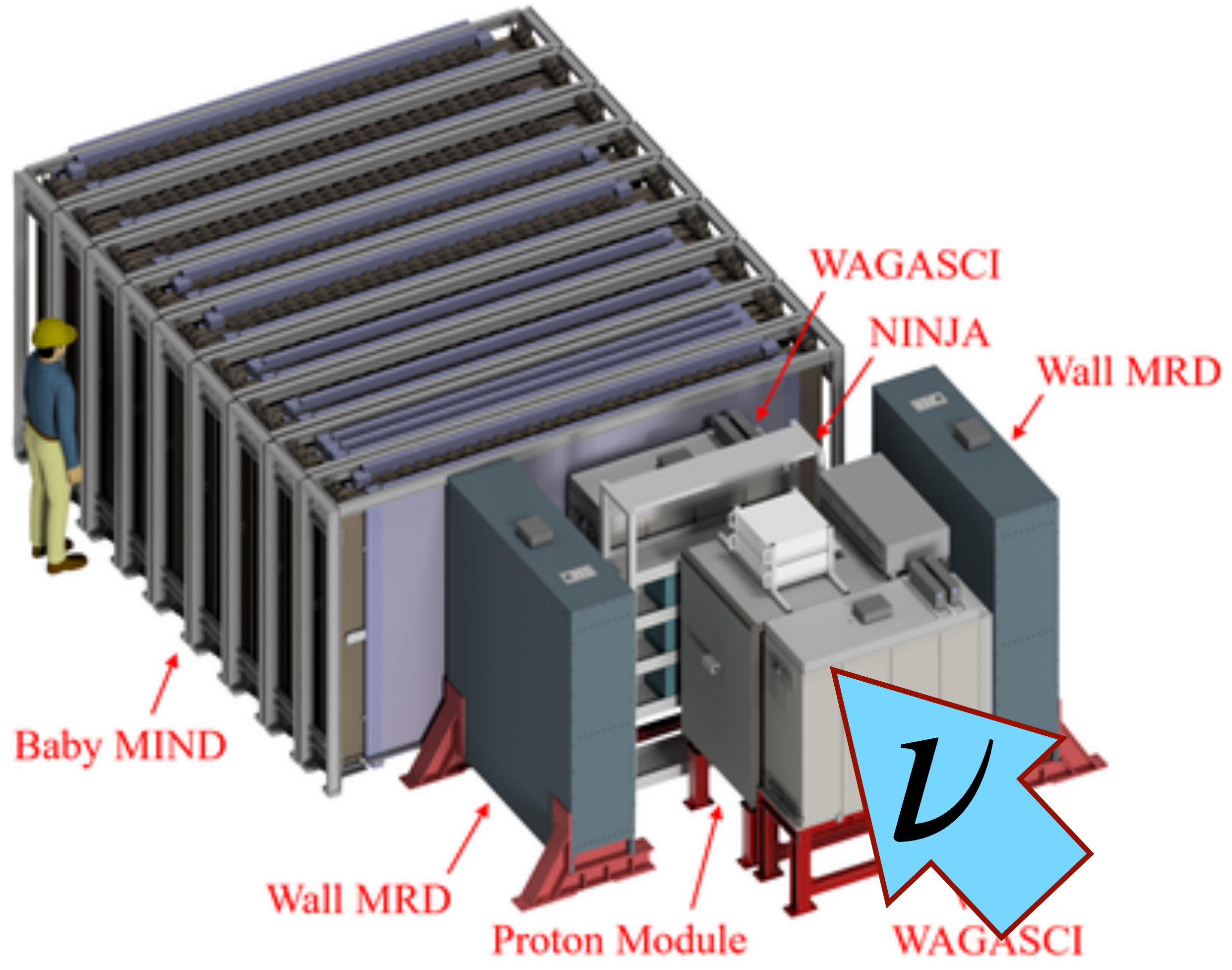
T2K’s near detector physics programme

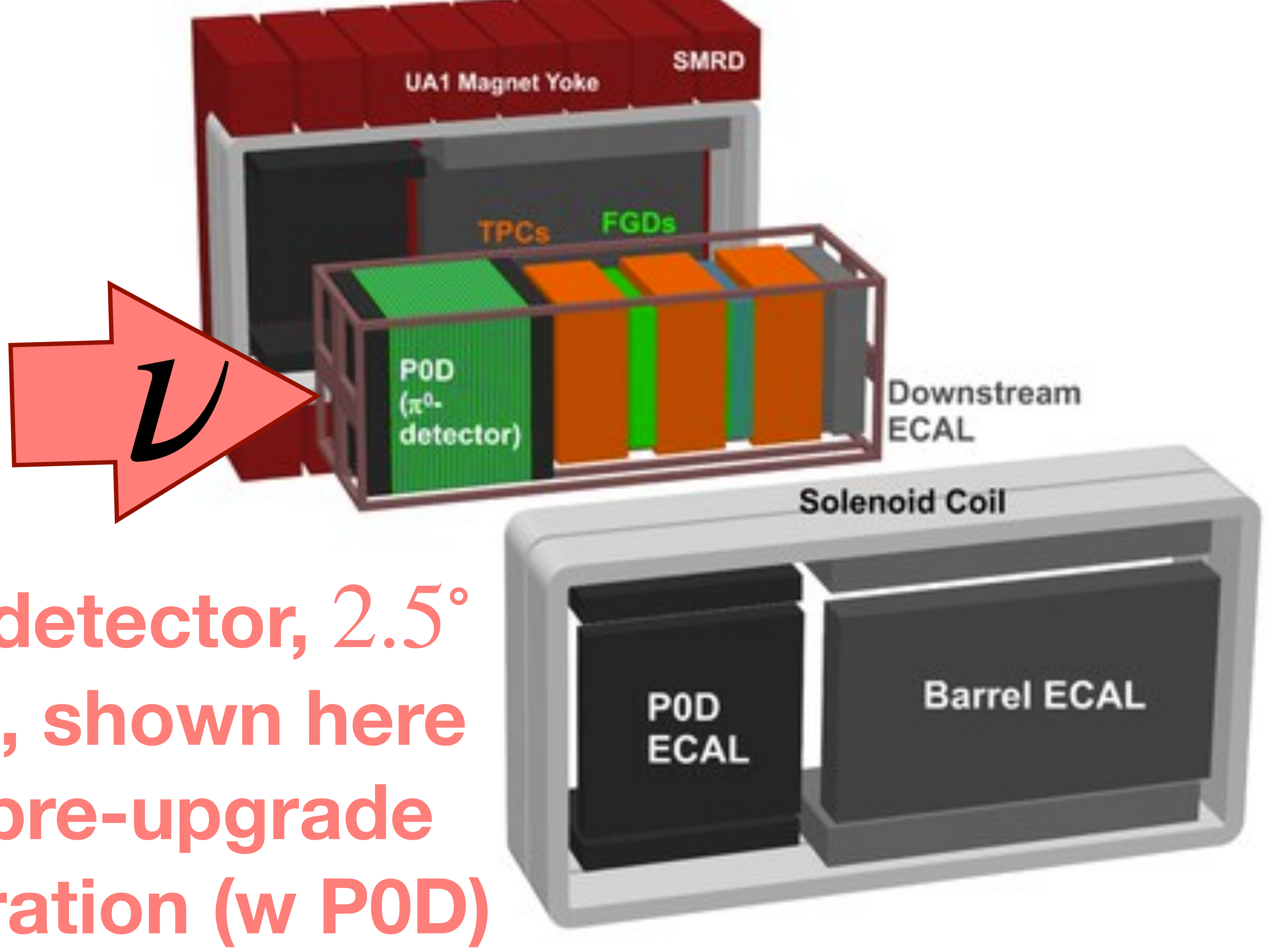




INGRID detector (on-axis)



WAGASCI and BabyMIND detectors, 1.5° off-axis



ND280 detector, 2.5° off-axis, shown here is the pre-upgrade configuration (w P0D)

- Unmagnetised detector, consisting of 16 identical modules, each made of alternating iron (Fe) and plastic (CH) layers
- Used to constrain non-hadronic beam systematics (e.g. off-axis angle on a run-by-run basis), and to monitor beam profile stability
- Also measures cross sections for neutrino interaction models

- Water/CH lattice neutrino target (WAGASCI) with a magnetised (1.5 T) iron and scintillator (BabyMIND) muon range tracking detector
- Plans to start using in oscillation analyses, and already producing cross section results

- Magnetised (0.2 T) composite detector: 2 Fine Grained Detectors (2x 0.8 t target mass, mostly C_8H_8 and water) sandwiched between 3 vertical Time Projection Chambers (PID and momentum measurements) + P0D (mostly carbon alternating with water target, lead foil or brass foil) + ECal + SMRD (high energy muon range)
- Main constraint of flux and cross section model parameters in the oscillation analysis + rich suite of cross section measurements

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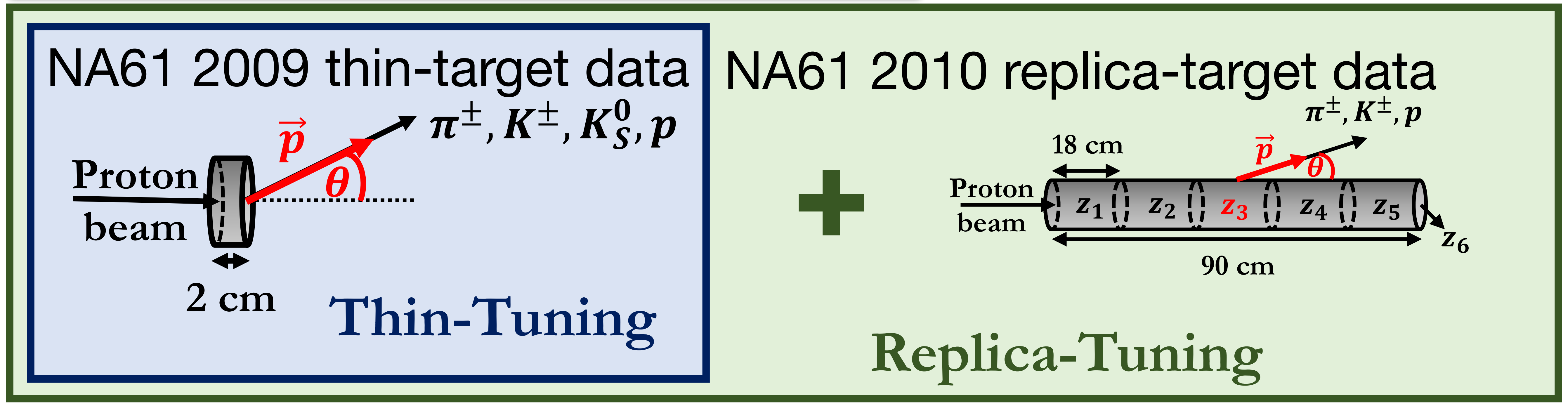
Neutrino flux model

- Flux tuning involves constraining the modelled hadron production with external data, most importantly NA61 data, but also data from other experiments (HARP, BNL, Eichten *et al*, Allaby *et al* etc)
- Applying this tuning brings us to flux uncertainties at the ~6% level at the flux peak

External hadron production data usage:



NA61 2009 thin-target data

Thin-Tuning

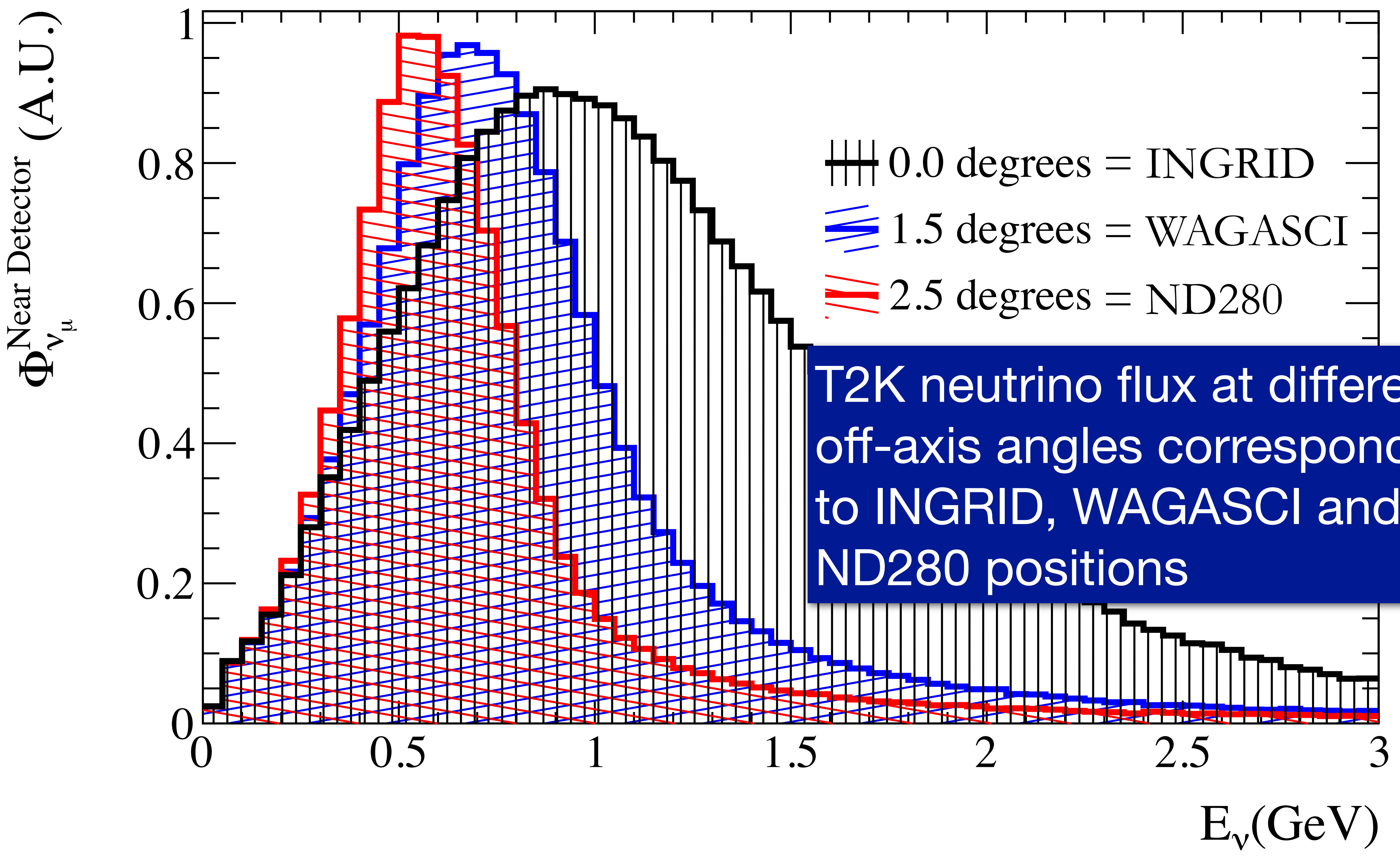
NA61 2010 replica-target data

Replica-Tuning

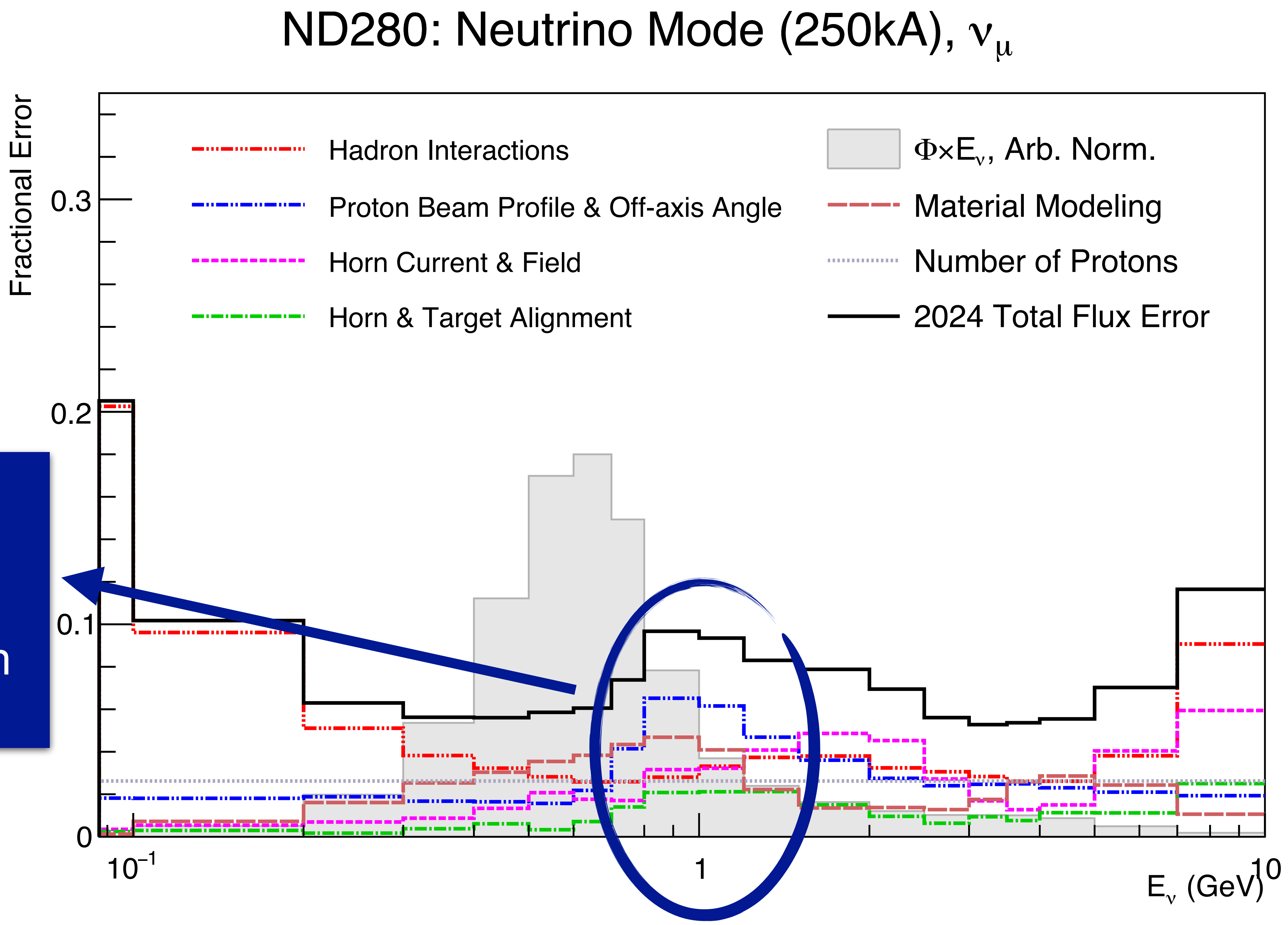
NA61 2009 thin-target data:
Eur. Phys. J. C 76, 84 (2016)

NA61 2010 replica-target data:
Eur. Phys. J. C 79, 100 (2019)

T2K replica-target mounted at NA61



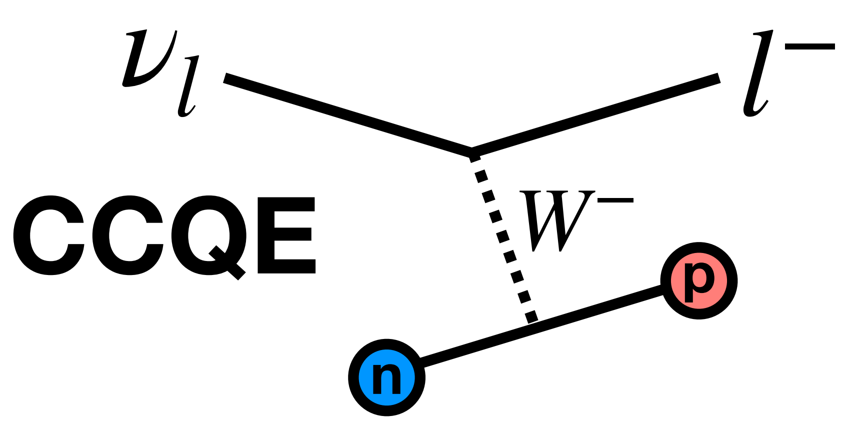
T2K neutrino flux at different off-axis angles corresponding to INGRID, WAGASCI and ND280 positions

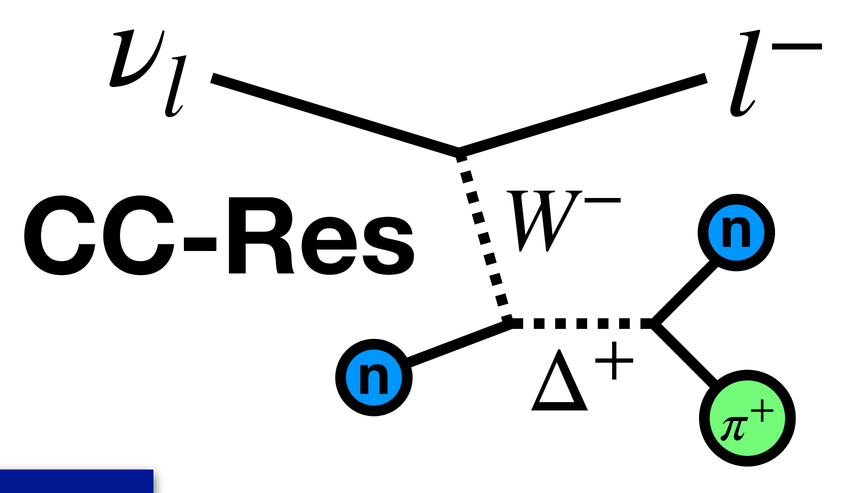


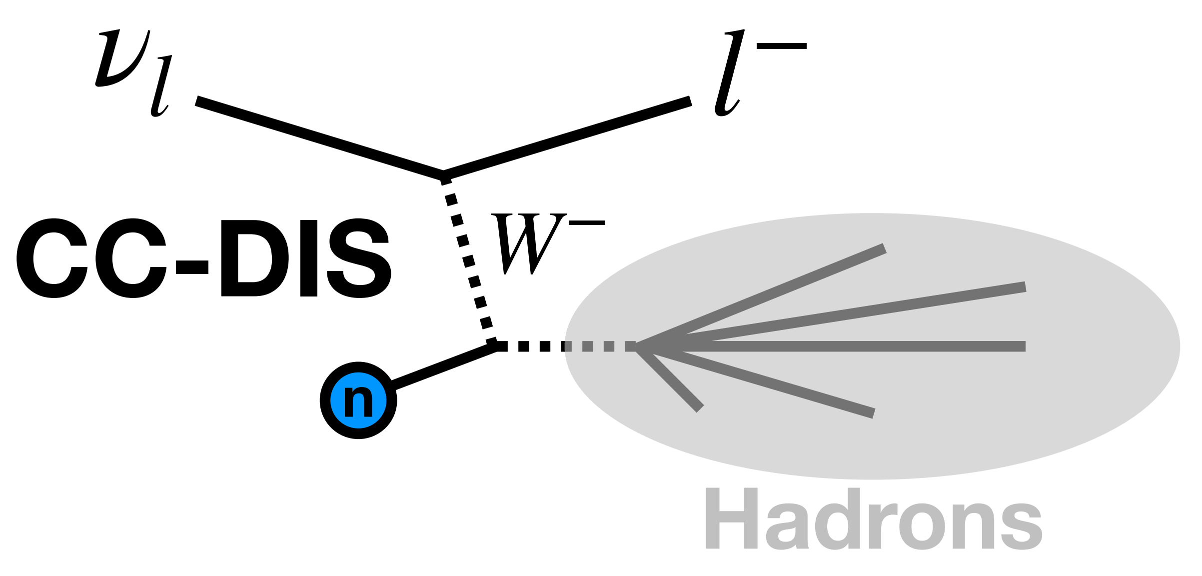
Slightly higher error due to contributions from material modelling and proton beam profile

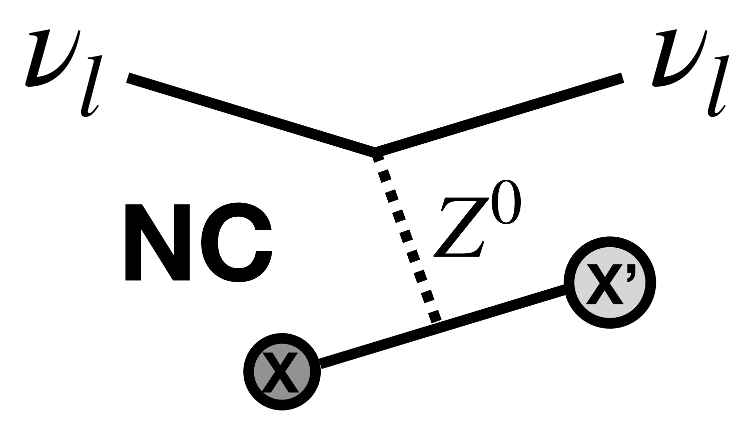
Neutrino interaction models

- At ~0.6 GeV peak beam energy, neutrinos interact via **charged current quasi-elastic (CCQE)** scattering, with subdominant contributions from, **resonant CC1π (CC-Res)** and **deep-inelastic (DIS)** scattering







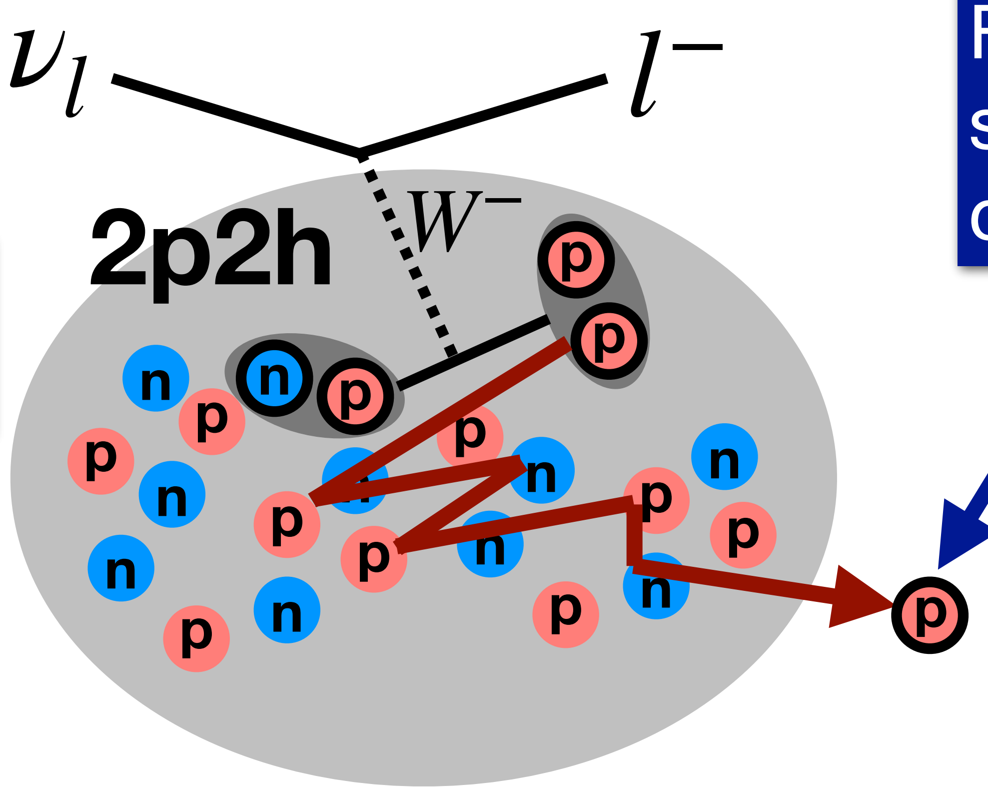


Free-nucleon-level interaction channels

T2K also probes neutral current (NC) interaction channels

- But the target nucleons are not free, and the nuclear medium introduces various nuclear effects e.g. initial nuclear state modelling (Fermi motion), multi-nucleon "2p2h" correlations, final state interactions (FSI) etc.

Schematic example of some of the nuclear effects



Looks like CCQE after FSI, even though it was scattering off of a correlated nucleon pair

- We define states based on the final track topology observed in the detector *after* nuclear effects e.g. for CC interactions CC0π, CC1π and CC-Other

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Neutrino interaction models

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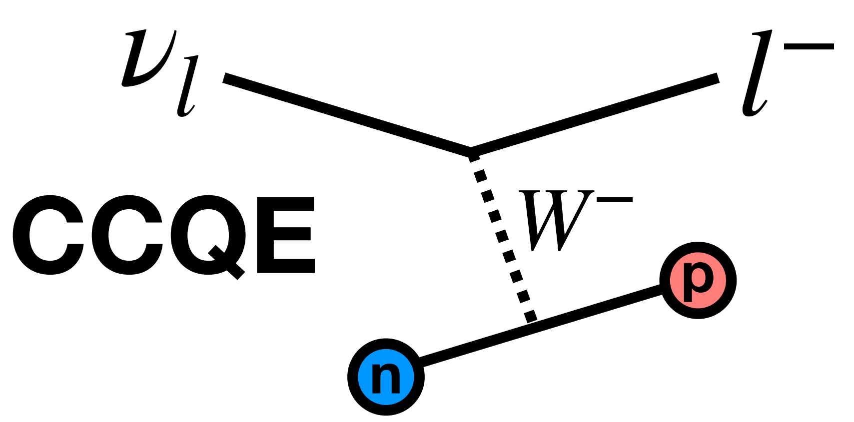
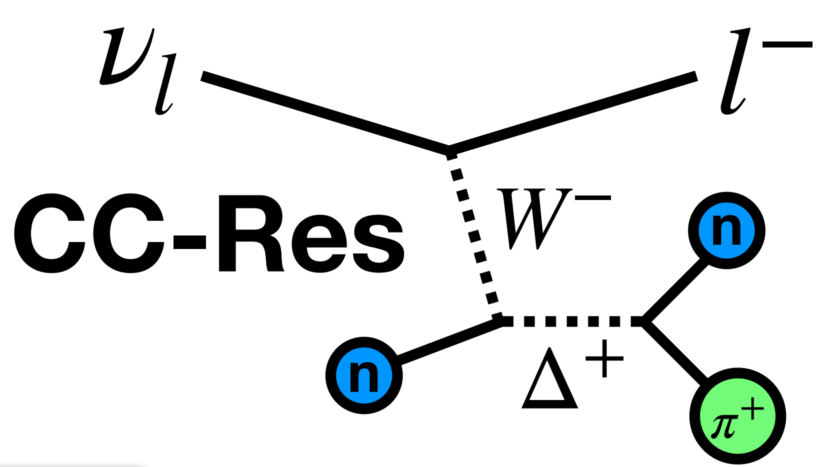
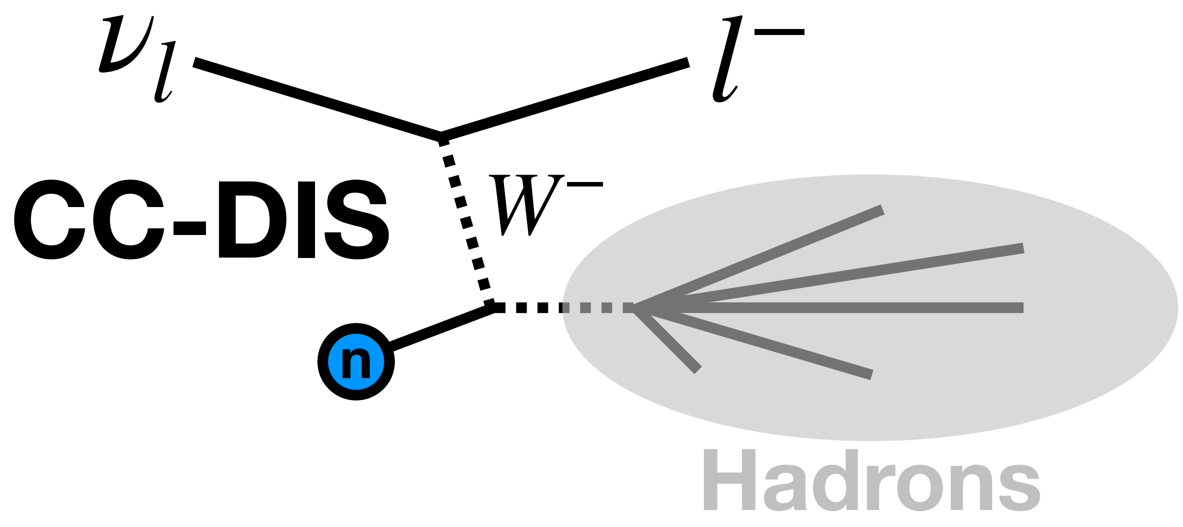
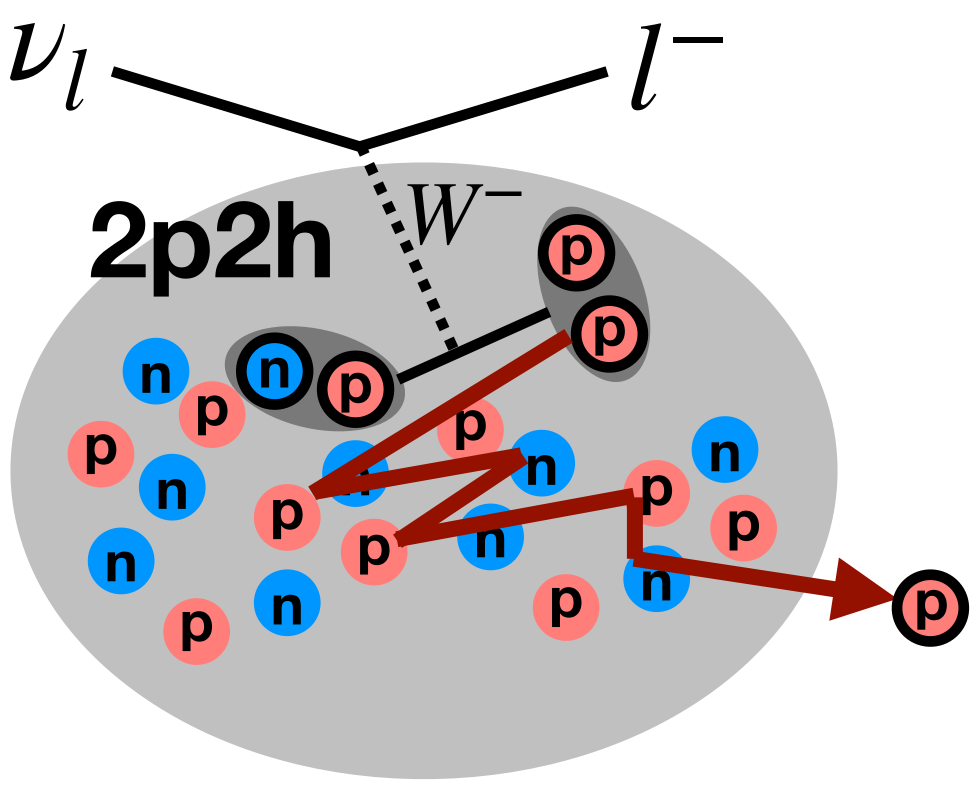


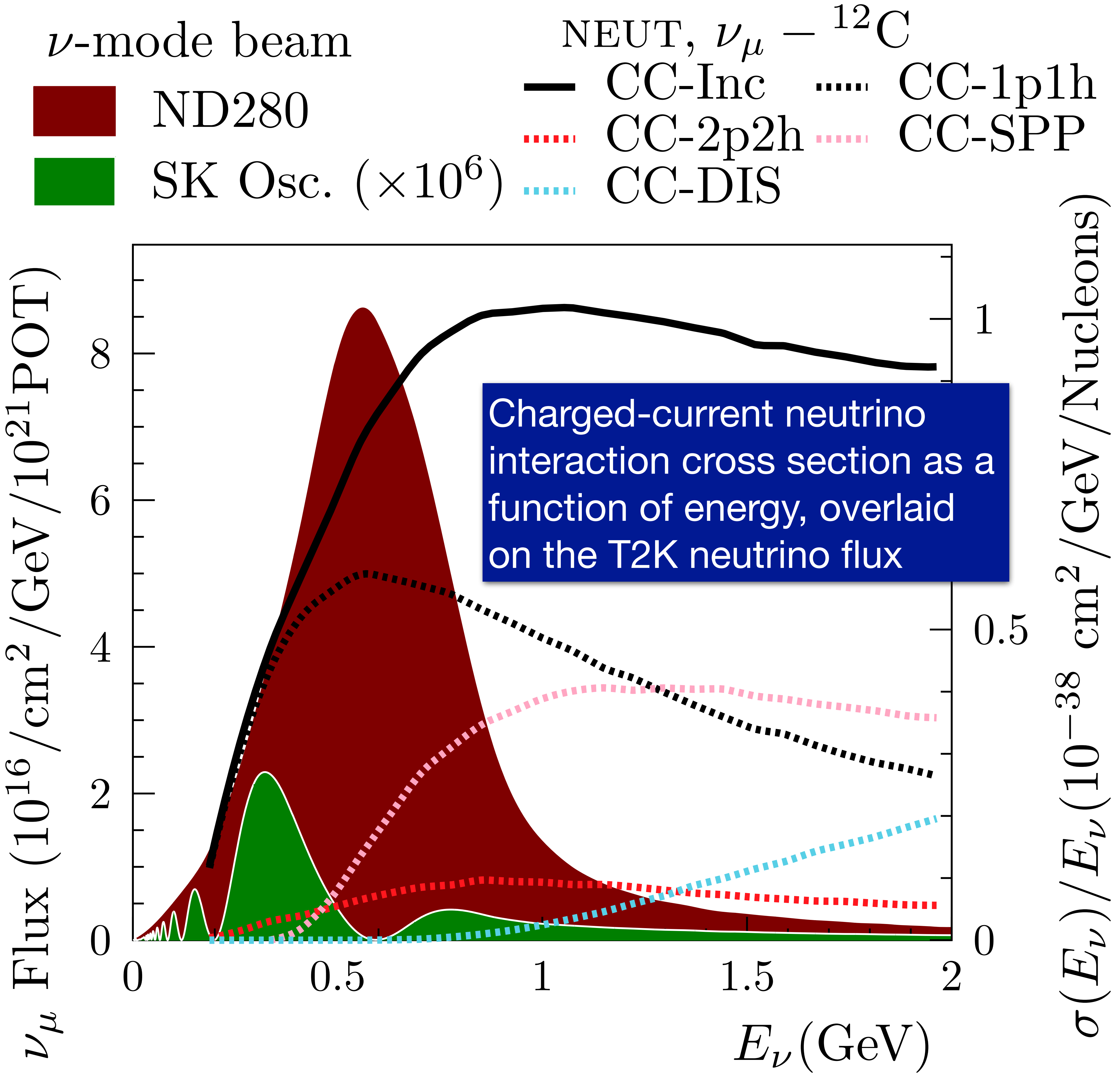


Free-nucleon-level interaction channels



Nuclear effects folded in





Charged-current neutrino interaction cross section as a function of energy, overlaid on the T2K neutrino flux

Cross section measurement history with the T2K beam

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
$\sigma^{CC-inc}_{\overset{(-)}{\nu}_{\mu}}$	On C (FGD1)	On Fe, CH (INGRID)		On Fe (INGRID)	On C, O, H, Cu (P0D)	2D on C (FGD1)	On water, C, Fe (INGRID)			Inclusive $\overset{(-)}{\nu}_{\mu}$ charged-current		
$\sigma^{CC-inc}_{\overset{(-)}{\nu}_{e}}$		On C (FGD1)	On water (P0D)					nu+anti-nu, on CH (FGD1)		Inclusive $\overset{(-)}{\nu}_{e}$ charged-current		
$\sigma^{CC0\pi}_{\overset{(-)}{\nu}_{\mu}}$	$\overset{(-)}{\nu}_{\mu}$ charged-current pionless	QE on C (INGRID)	QE on C (FGD1)	On CH (FGD1)	On water (P0D)	TKI, On CH (FGD1)	nu+anti-nu, on CH (FGD1)	On O, C (FGDs)	Anti-nu, on water (P0D)	On water, CH (WAGASCI +PM)	On CH (ND280+ INGRID)	On water, CH (WAGASCI-BabyMIND)
$\sigma^{NC0\pi}_{\overset{(-)}{\nu}}$		On O (Super-K)					QE on O, nu+anti-nu (Super-K)			$\overset{(-)}{\nu}$ neutral-current pionless		
$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_{\mu}}$	$\overset{(-)}{\nu}_{\mu}$ charged-current with a pion in the final state			COH on C (FGD1)	On water (FGD2)			1 pi+, on CH (FGD1)	1 pi+, TKI, on C (FGD1)		COH on C, nu+anti-nu	
$\sigma^{CC\pi}_{\overset{(-)}{\nu}_{e}}$	$\overset{(-)}{\nu}_{e}$ charged-current with a pion in the final state											Pion(s), on CH (FGD1)
$\sigma^{NC1\pi}_{\overset{(-)}{\nu}}$	$\overset{(-)}{\nu}$ neutral-current with a pion in the final state					1 pi0, on water (P0D)					1 pi+, on CH (FGD1), PRL & PRD	

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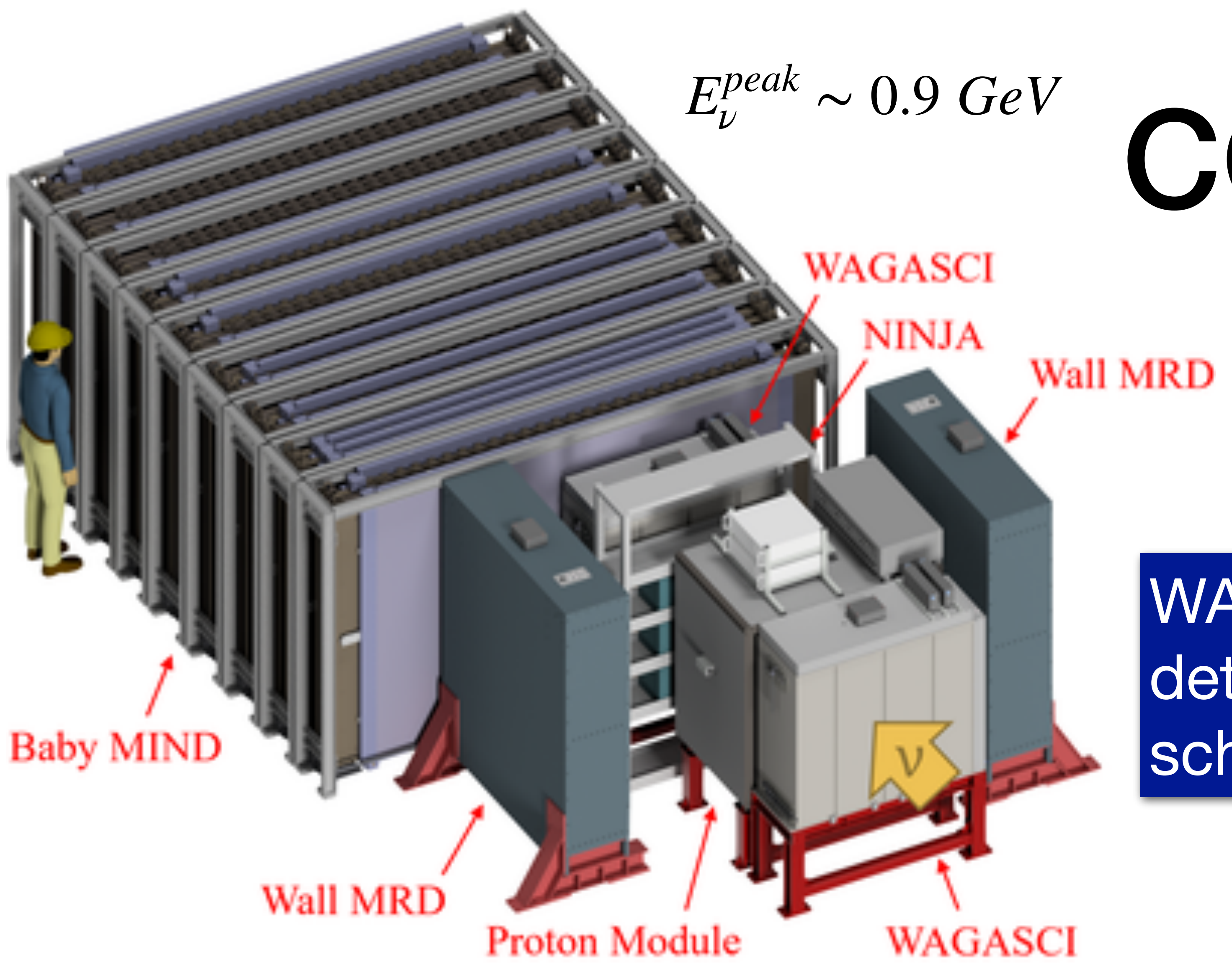
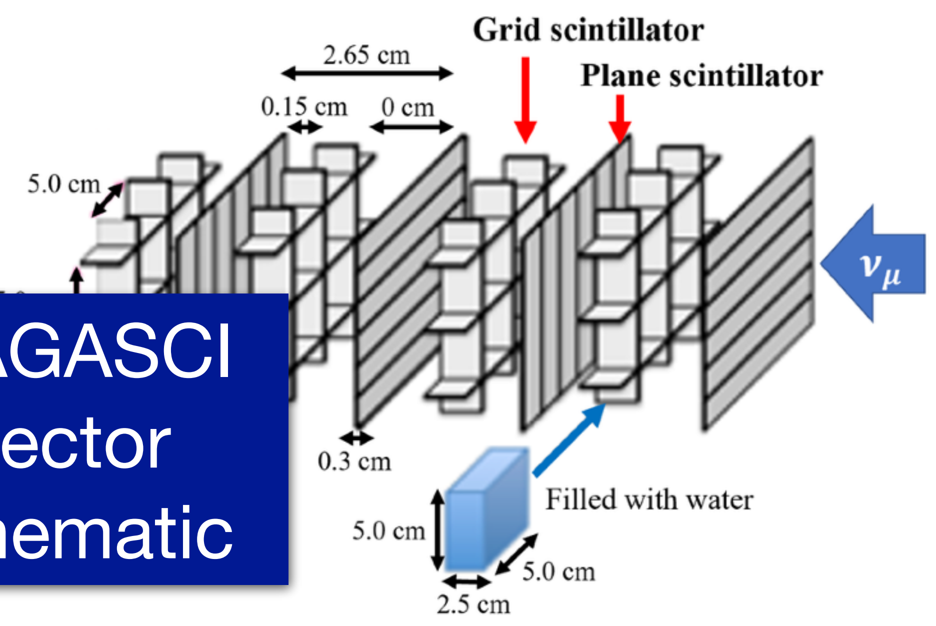
$\sigma^{CC-inc}_{\overset{(-)}{\nu}_{e}}$		On C (FGD1)	On water (P0D)					nu+anti-nu, on CH (FGD1)					Inclusive $\overset{(-)}{\nu}_{e}$ charged-current
$\sigma^{CC0\pi}_{\overset{(-)}{\nu}_{\mu}}$		QE on C (INGRID)	QE on C (FGD1)	On CH (FGD1)	On water (P0D)	TKI, On CH (FGD1)	nu+anti-nu, on CH (FGD1)	On O, C (FGDs)	Anti-nu, on water (P0D)	On water, CH (WAGASCI +PM)	On CH (ND280+ INGRID)	On water, CH (WAGASCI-BabyMIND)	$\overset{(-)}{\nu}_{\mu}$ charged-current pionless
$\sigma^{NC0\pi}_{\overset{(-)}{\nu}}$		On O (Super-K)					QE on O, nu+anti-nu (Super-K)						$\overset{(-)}{\nu}$ neutral-current pionless
$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_{\mu}}$				COH on C (FGD1)	On water (FGD2)			1 pi+, on CH (FGD1)	1 pi+, TKI, on C (FGD1)		COH on C, nu+anti-nu		$\overset{(-)}{\nu}_{\mu}$ charged-current with a pion in the final state
$\sigma^{CC\pi}_{\overset{(-)}{\nu}_{e}}$												Pion(s), on CH (FGD1)	$\overset{(-)}{\nu}_{e}$ charged-current with a pion in the final state
$\sigma^{NC1\pi}_{\overset{(-)}{\nu}}$						1 pi0, on water (P0D)					1 pi+, on CH (FGD1), PRL & PRD		$\overset{(-)}{\nu}$ neutral-current with a pion in the final state

CC0π ν_μ interactions on hydrocarbon and water

$E_\nu^{peak} \sim 0.9\ GeV$

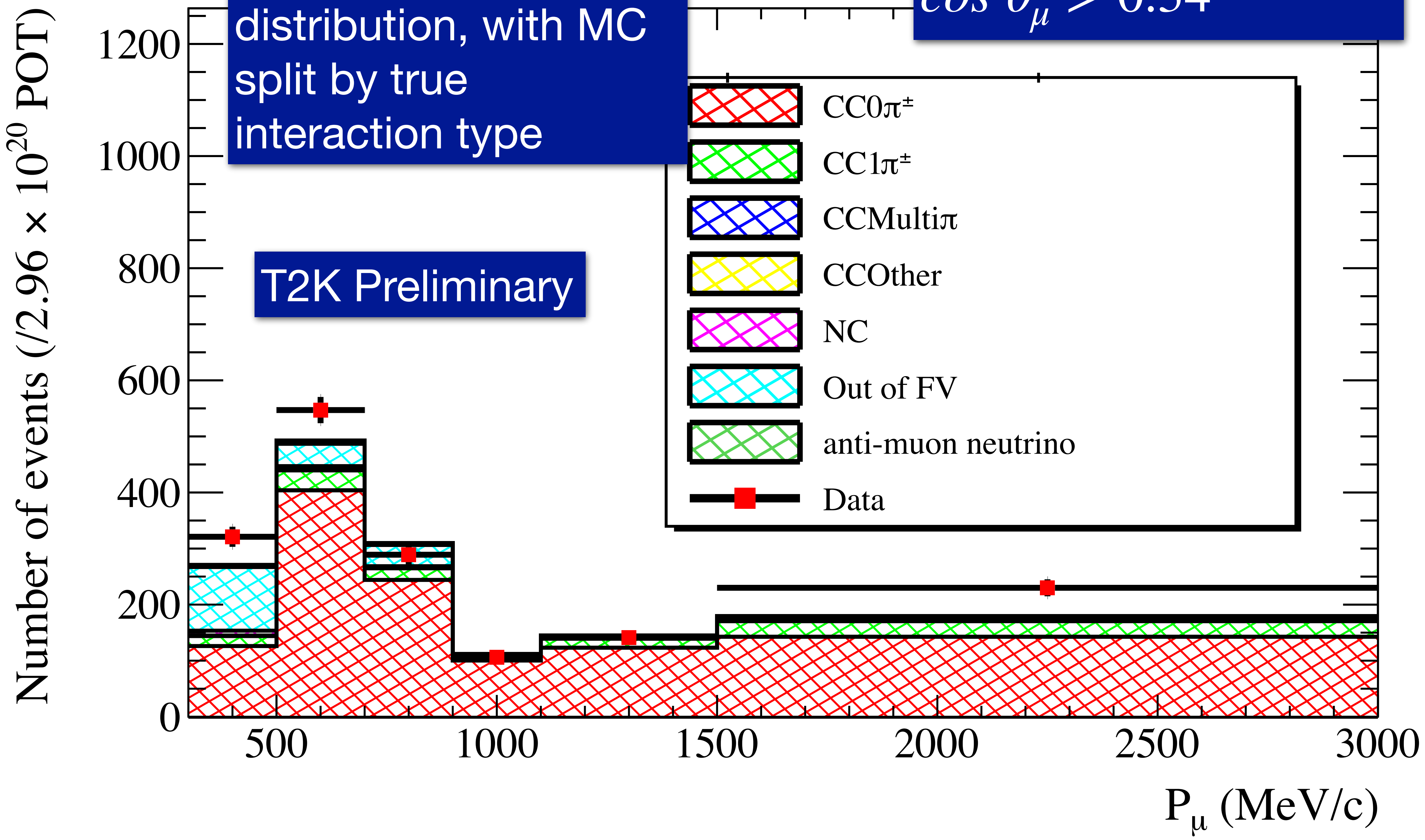




WAGASCI detector schematic

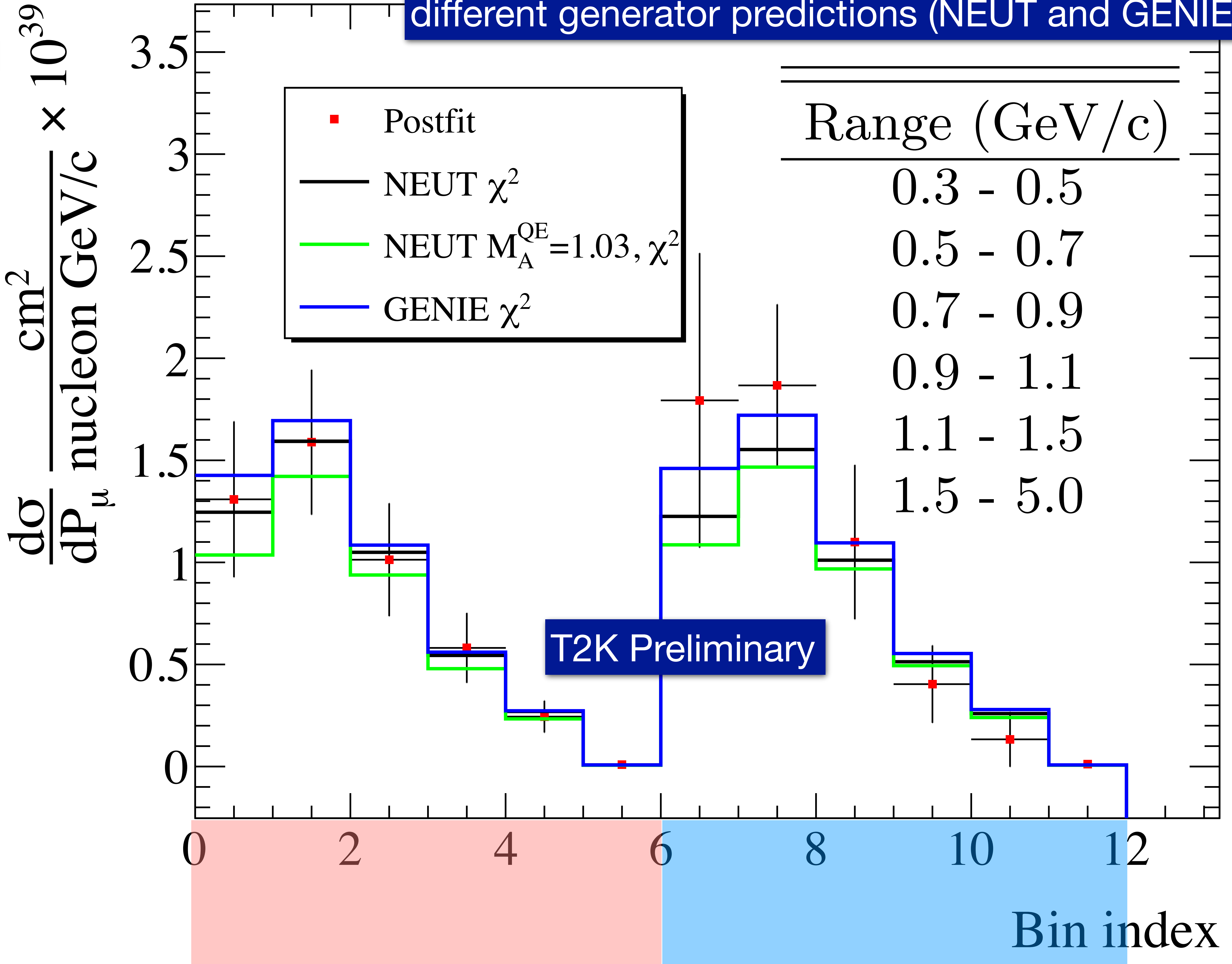
Signal definition
Pion: $p_\mu > 0.3\ GeV/c$, $cos\ \theta_\mu > 0.34$

Data vs. MC event distribution, with MC split by true interaction type



T2K Preliminary

Differential flux-integrated cross section result, in muon momentum phase space, compared against different generator predictions (NEUT and GENIE)



T2K Preliminary

Momentum bins 0-5
CH results

Momentum bins 6-11
H2O results

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Cross section measurement history with the T2K beam

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
$\sigma^{CC-inc}_{\overset{(-)}{\nu}_{\mu}}$	On C (FGD1)	On Fe, CH (INGRID)		On Fe (INGRID)	On C, O, H, Cu (P0D)	2D on C (FGD1)	On water, C, Fe (INGRID)			Inclusive $\overset{(-)}{\nu}_{\mu}$ charged-current		
$\sigma^{CC-inc}_{\overset{(-)}{\nu}_{e}}$		On C (FGD1)	On water (P0D)					nu+anti-nu, on CH (FGD1)		Inclusive $\overset{(-)}{\nu}_{e}$ charged-current		
$\sigma^{CC0\pi}_{\overset{(-)}{\nu}_{\mu}}$	$\overset{(-)}{\nu}_{\mu}$ charged-current pionless	QE on C (INGRID)	QE on C (FGD1)	On CH (FGD1)	On water (P0D)	TKI, On CH (FGD1)	nu+anti-nu, on CH (FGD1)	On O, C (FGDs)	Anti-nu, on water (P0D)	On water, CH (WAGASCI +PM)	On CH (ND280+ INGRID)	On water, CH (WAGASCI-BabyMIND)
$\sigma^{NC0\pi}_{\overset{(-)}{\nu}}$		On O (Super-K)					QE on O, nu+anti-nu (Super-K)			$\overset{(-)}{\nu}$ neutral-current pionless		
$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_{\mu}}$	$\overset{(-)}{\nu}_{\mu}$ charged-current with a pion in the final state			COH on C (FGD1)	On water (FGD2)			1 pi+, on CH (FGD1)	1 pi+, TKI, on C (FGD1)		COH on C, nu+anti-nu	
$\sigma^{CC\pi}_{\overset{(-)}{\nu}_{e}}$	$\overset{(-)}{\nu}_{e}$ charged-current with a pion in the final state											Pion(s), on CH (FGD1)
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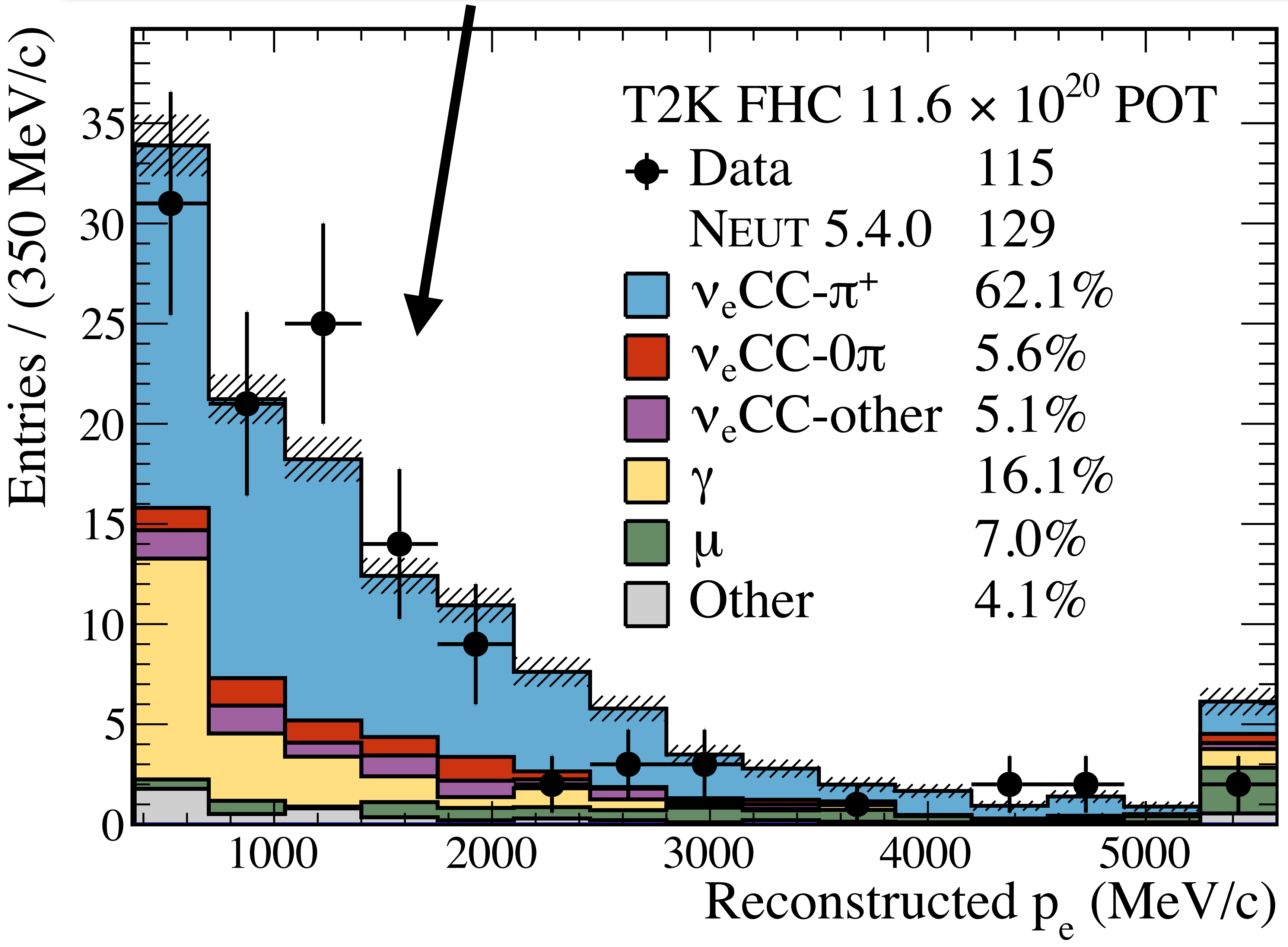
CCπ^+ ν_e interactions on hydrocarbon: signal selection & background

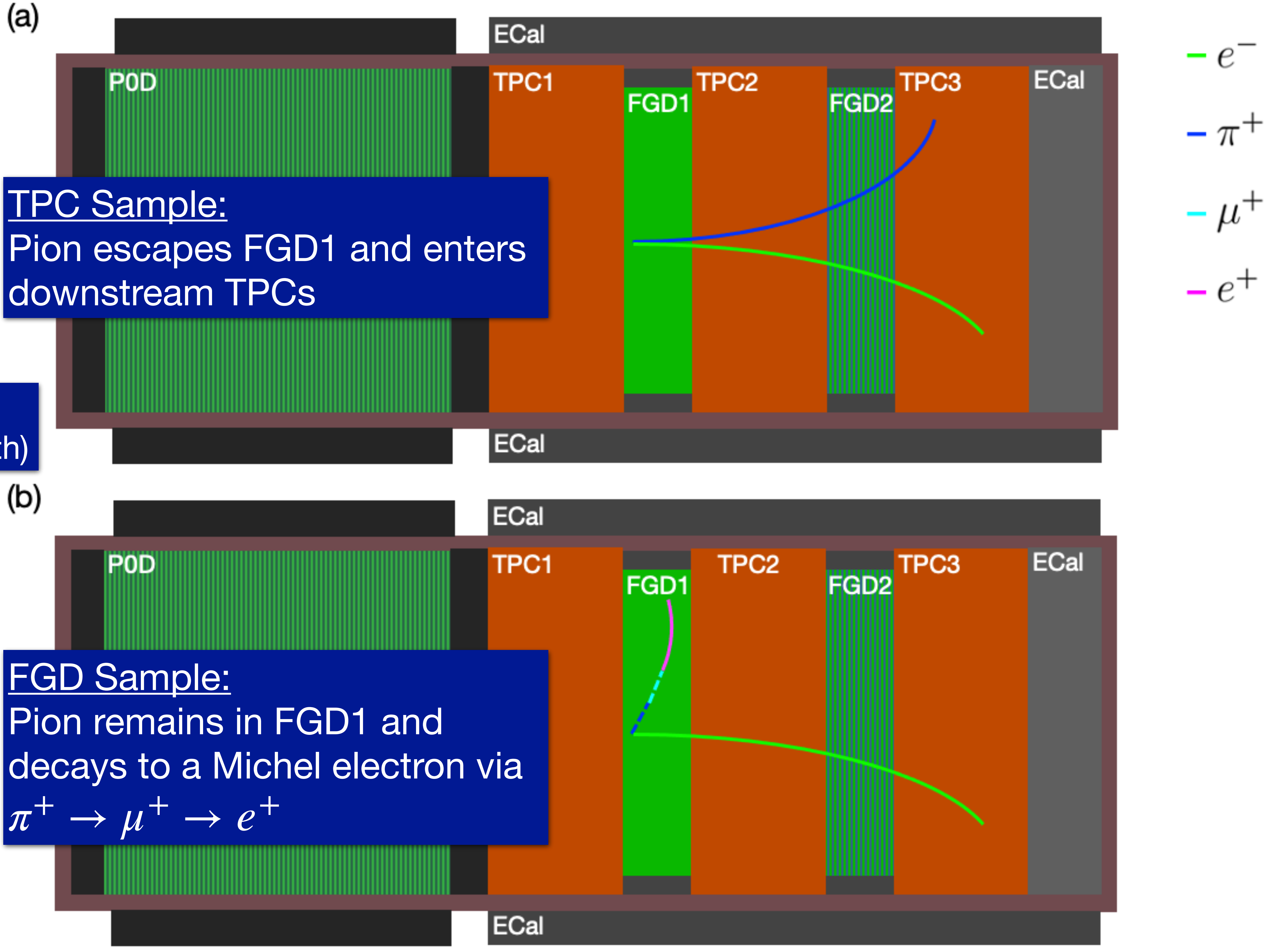
- CCπ^+ is the sub-dominant mode that contributes to the ν_e appearance signal in T2K/HK, and understanding it is important for better (δ_{CP}, θ_{13}) oscillation parameter constraints

<u>Signal definition</u>
Pions: $p_{\pi^+} < 1.5\ GeV/c$
Electron: $p_{e^-} \in [0.35, 30]\ GeV/c,\ cos\ \theta_{e^-} > 0.7$

Coloured stacked histograms show NEUT prediction broken down by signal and background types (from truth)



$E_\nu^{peak} \sim 0.6\ GeV$



<u>TPC Sample:</u>
Pion escapes FGD1 and enters downstream TPCs

<u>FGD Sample:</u>
Pion remains in FGD1 and decays to a Michel electron via $\pi^+ \rightarrow \mu^+ \rightarrow e^+$

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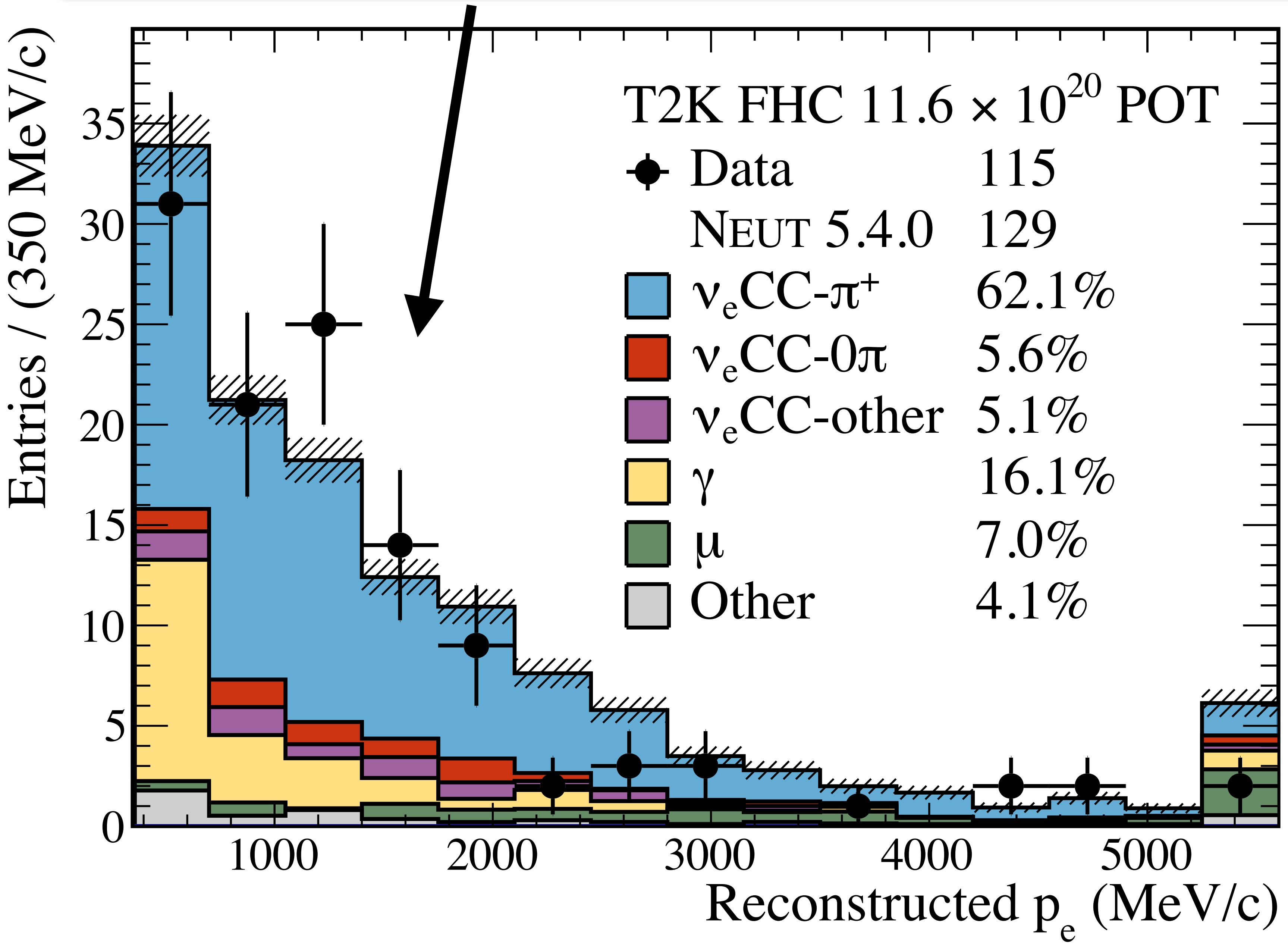
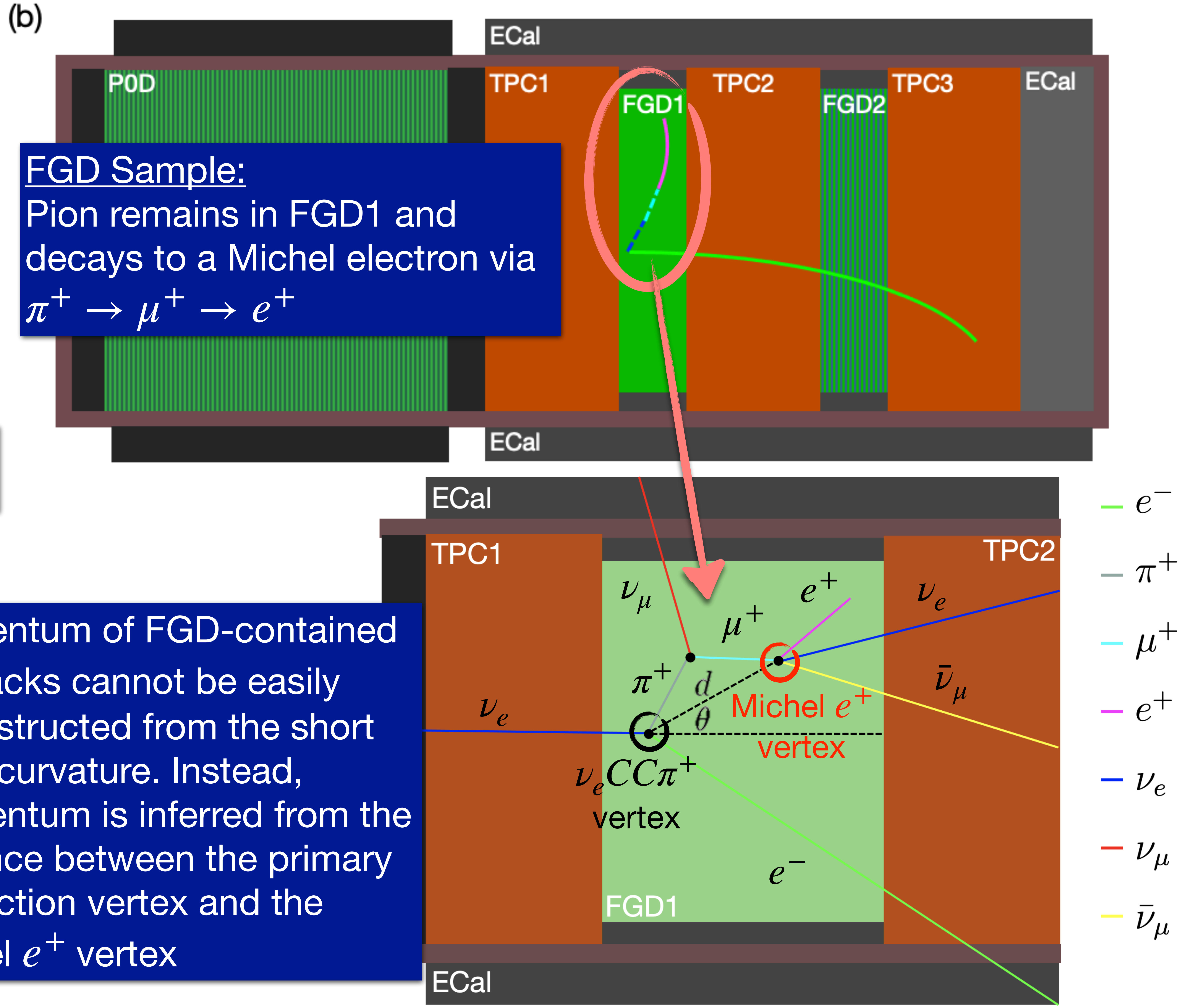




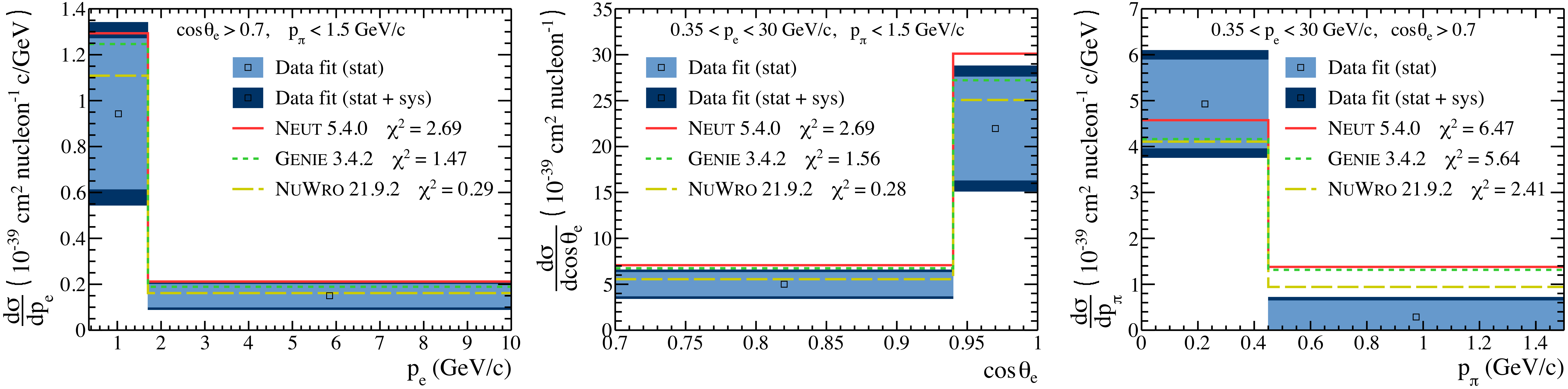
FGD Sample:
Pion remains in FGD1 and decays to a Michel electron via $\pi^+ \rightarrow \mu^+ \rightarrow e^+$

Momentum of FGD-contained π^+ tracks cannot be easily reconstructed from the short track curvature. Instead, momentum is inferred from the distance between the primary interaction vertex and the Michel e^+ vertex

CCπ^+ ν_e interactions on hydrocarbon: results

Differential flux-integrated cross section result, in the (p_e, $cos\ \theta_e$, p_{π^+}) phase space, compared against different generator predictions (NEUT, GENIE and NuWro)

- For a complete description see arXiv:2505.00516v1



Uncertainty source	Fractional error on σ [%]
Detector response	5.7
Flux model	6.8
Interaction model	7.8
Target mass	0.7
Total statistical	20.6
Total systematic	11.7

Systematics dominated by the interaction modelling uncertainty

Generator	σ (10^{-39} cm^2 nucl^{-1})	p-value
NEUT 5.4.0	3.51	0.30
GENIE 3.4.2	3.25	0.59
NUWRO 21.9.2	2.84	0.89
Data	2.52 ± 0.60	-

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$\sigma^{CC-inc}_{\overset{(-)}{\nu}_e}$		On C (FGD1)	On water (P0D)					nu+anti-nu, on CH (FGD1)		Inclusive $\overset{(-)}{\nu}_e$ charged-current		
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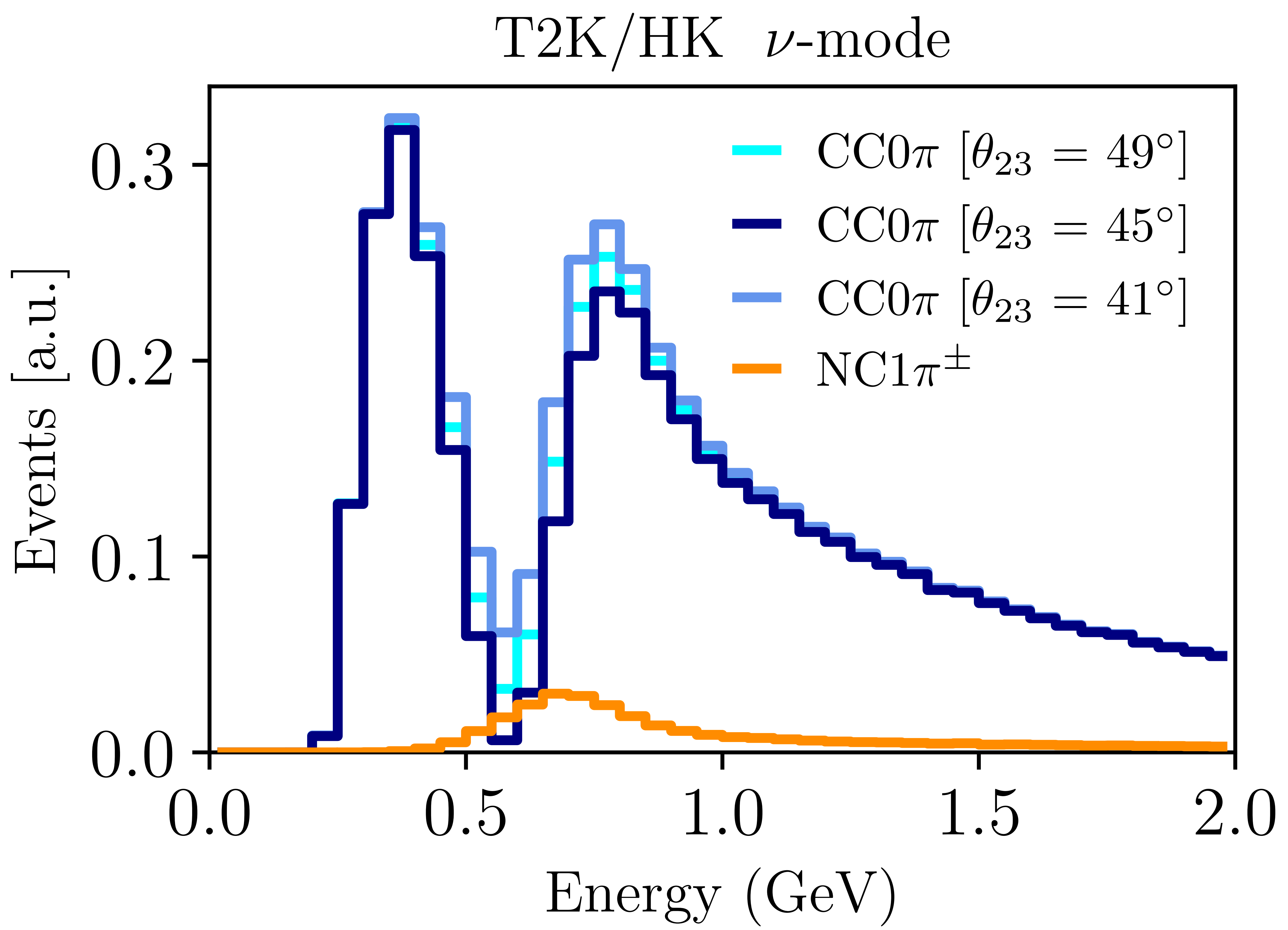
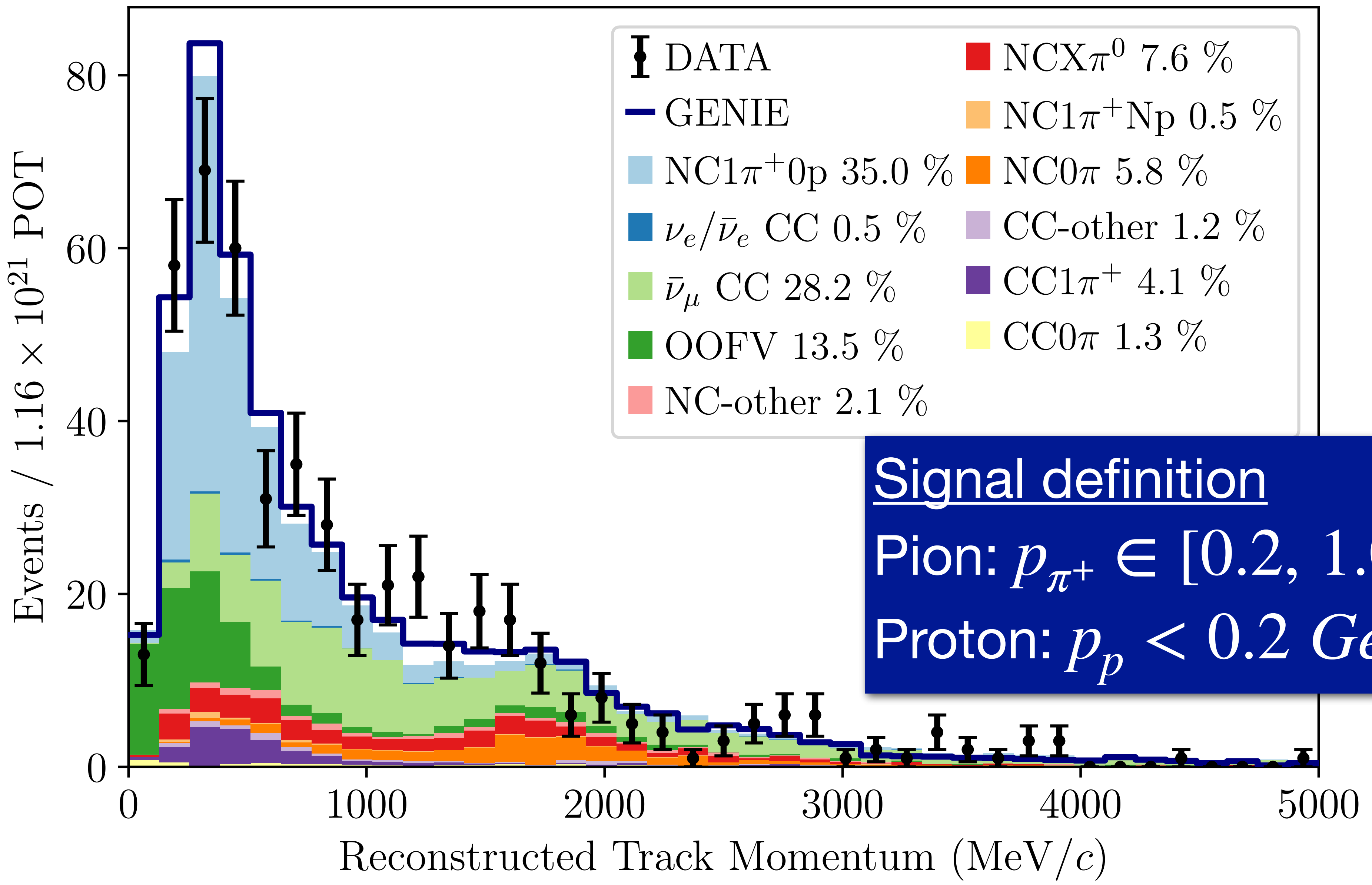
$\sigma^{NC0\pi}_{\overset{(-)}{\nu}}$		On O (Super-K)					QE on O, nu+anti-nu (Super-K)			$\overset{(-)}{\nu}$ neutral-current pionless		
$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_\mu}$	$\overset{(-)}{\nu}_\mu$ charged-current with a pion in the final state			COH on C (FGD1)	On water (FGD2)			1 pi+, on CH (FGD1)	1 pi+, TKI, on C (FGD1)		COH on C, nu+anti-nu	
$\sigma^{CC\pi}_{\overset{(-)}{\nu}_e}$	$\overset{(-)}{\nu}_e$ charged-current with a pion in the final state											Pion(s), on CH (FGD1)
$\sigma^{NC1\pi}_{\overset{(-)}{\nu}}$	$\overset{(-)}{\nu}$ neutral-current with a pion in the final state					1 pi0, on water (P0D)						1 pi+, on CH (FGD1), PRL & PRD

NC1π^+ neutrino interactions on hydrocarbon: signal selection & background

- At T2K/HK, NC1$\pi^\pm$ interactions where the pion is misidentified for a muon contribute a significant background to ν_μ events around the oscillation dip where the ν_μ oscillation probability is maximal

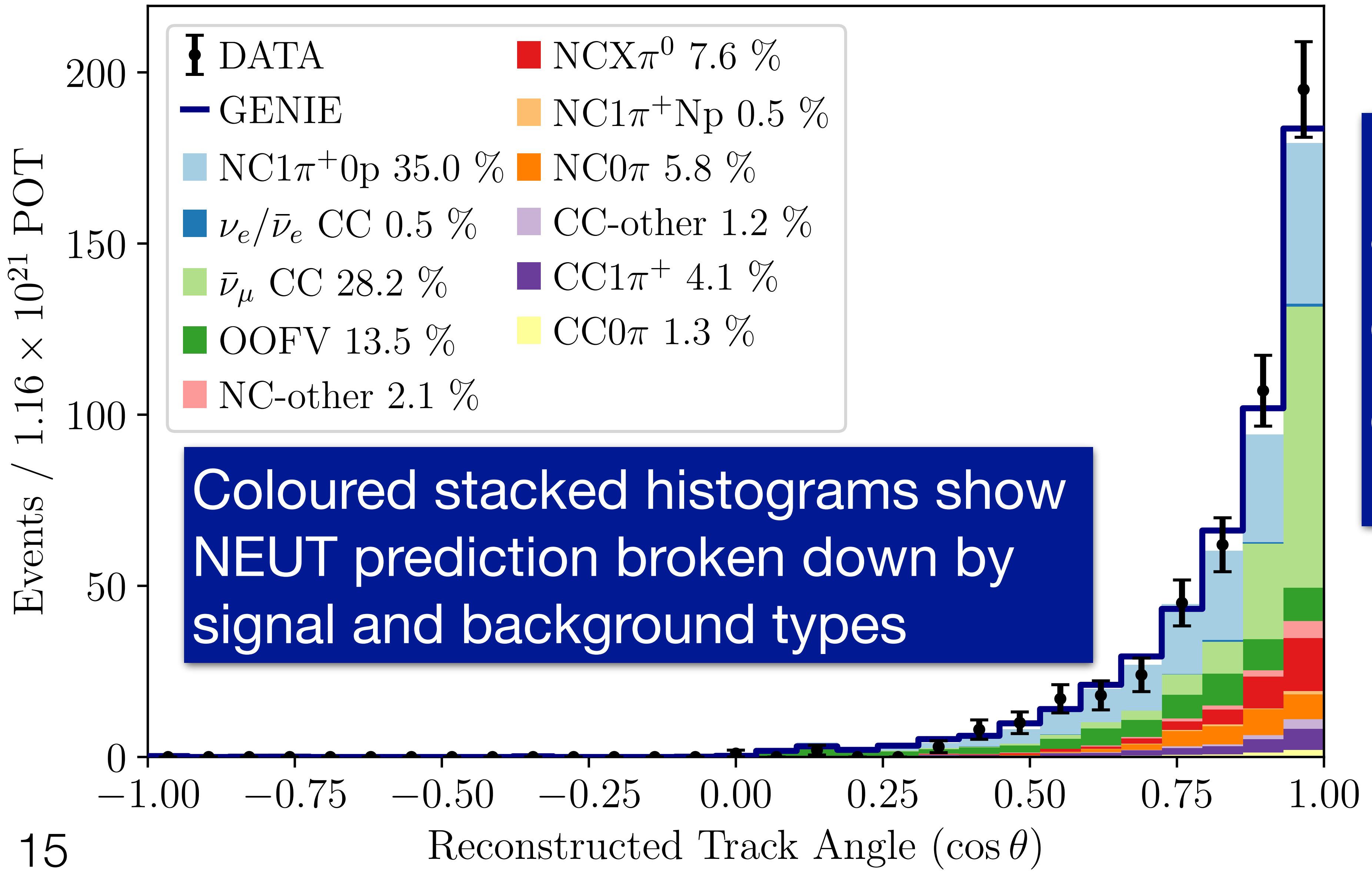




Signal definition

Pion: $p_{\pi^+} \in [0.2, 1.0]\ GeV/c, \theta_{\pi^+} < 60°$

Proton: $p_p < 0.2\ GeV/c$



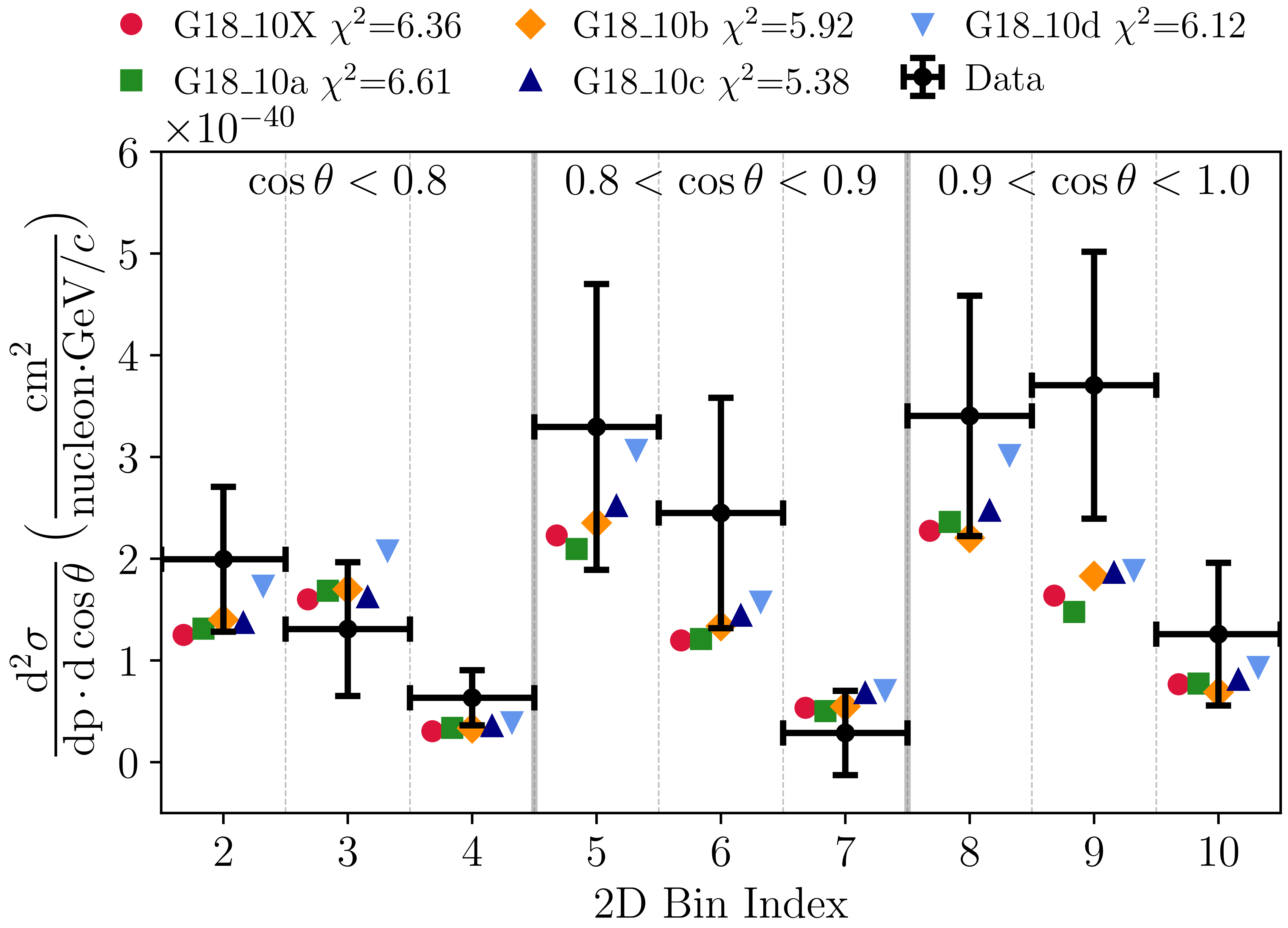
Coloured stacked histograms show NEUT prediction broken down by signal and background types

Largest background are $\bar{\nu}_\mu$ CC events, despite $\bar{\nu}_\mu$ making up only ~2.3% in the ν mode of operation

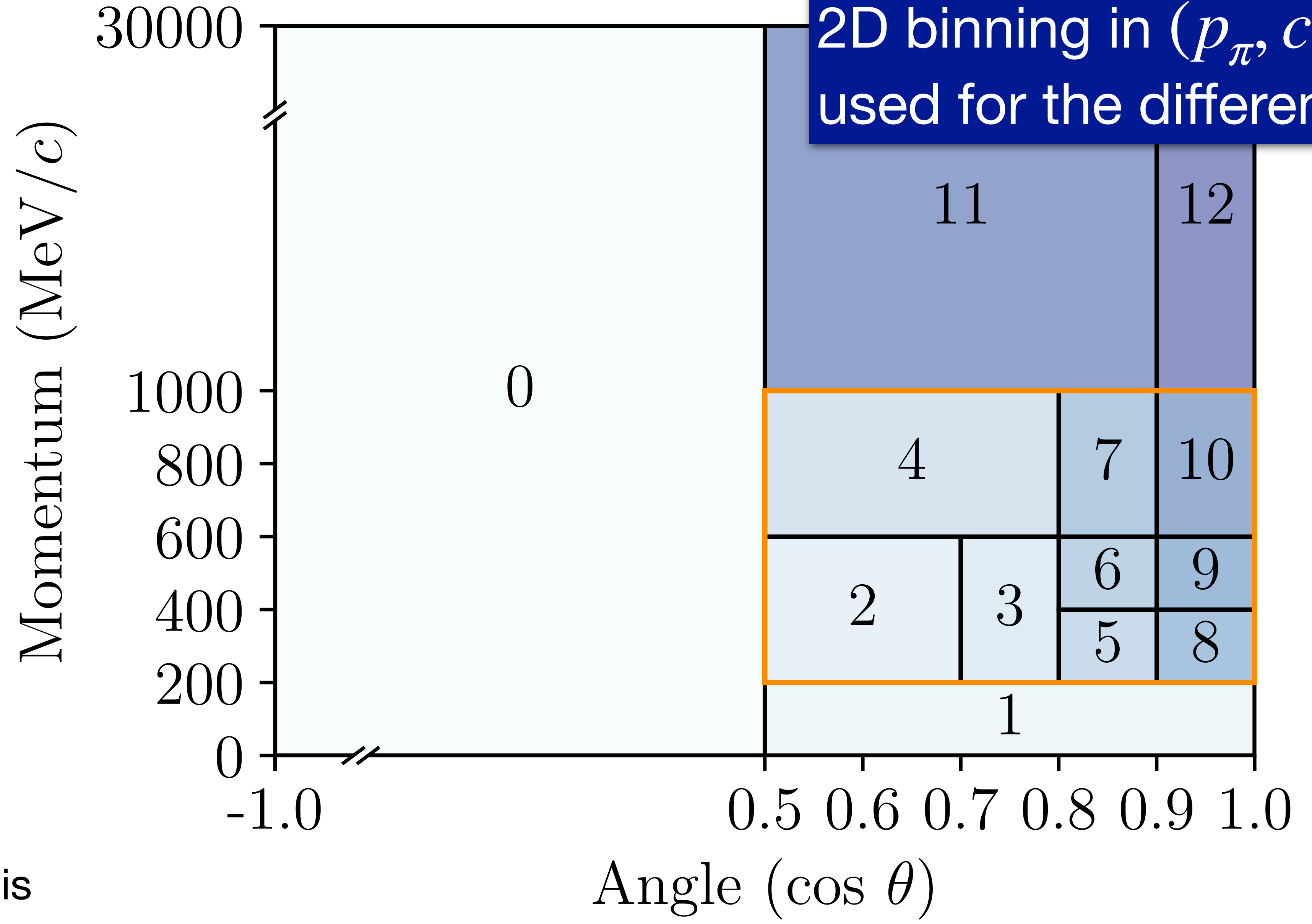
NC1π^+ neutrino interactions on hydrocarbon: results

- First measurement in this channel since Gargamelle and ANL bubble chamber experiments
- In the process of publication as a joint PRL and PRD release (arXiv:2503.06843v3 and arXiv:2503.06849v3)

Differential flux-integrated cross section result, comparison against different FSI models

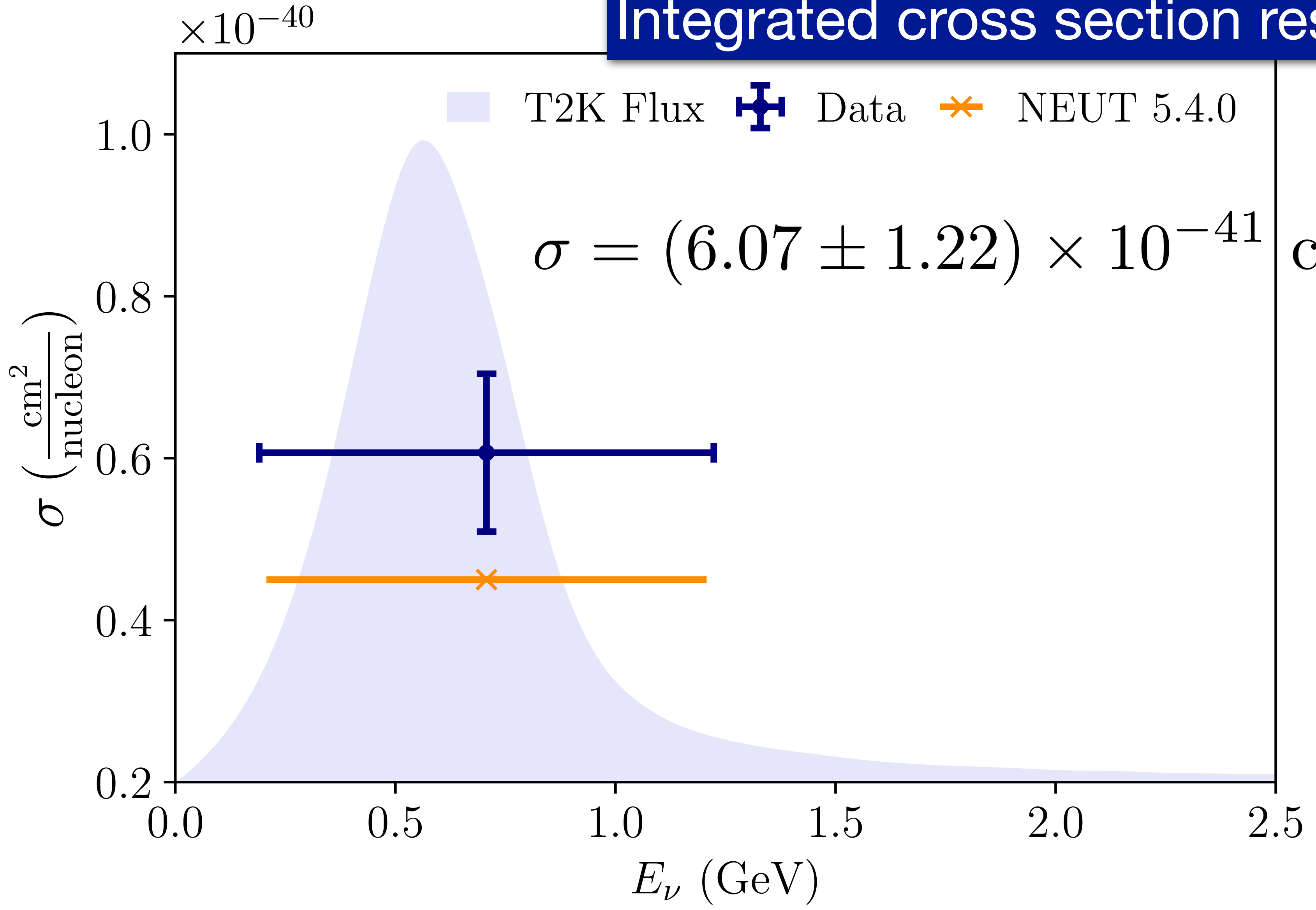


2D binning in $(p_\pi, cos\ \theta_\pi)$ used for the differential result



For this analysis
$E_\nu^{peak} \sim 0.6\ GeV$

Integrated cross section result



$$\sigma = (6.07 \pm 1.22) \times 10^{-41}\ cm^2/nucleon$$

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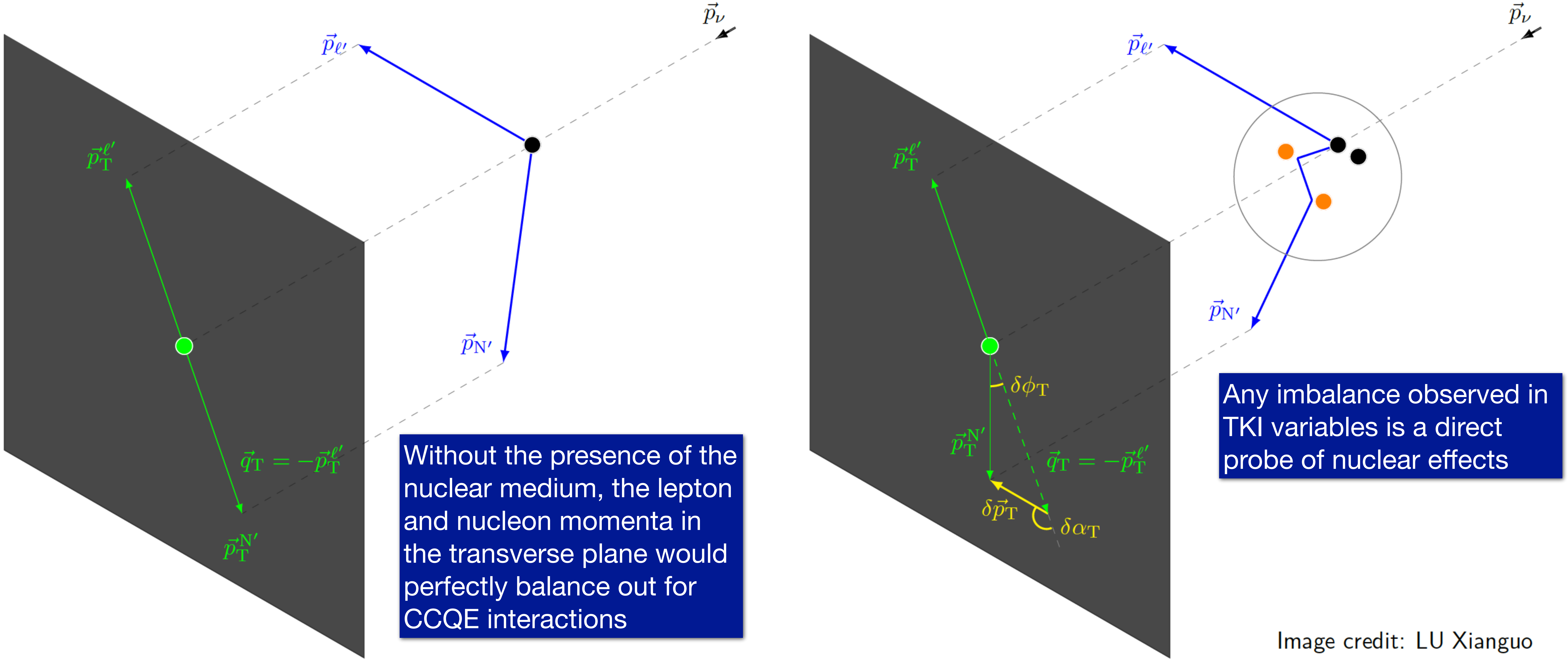
Transverse kinematic imbalance measurements

- Motivation: transverse kinematic imbalance (TKI) variables (defined in the plane perpendicular to neutrino motion) are a powerful direct probe of nuclear effects

- This T2K concept has been pioneered in Phys. Rev. C 94, 015503 (2016)



Without the presence of the nuclear medium, the lepton and nucleon momenta in the transverse plane would perfectly balance out for CCQE interactions

Any imbalance observed in TKI variables is a direct probe of nuclear effects

Image credit: LU Xianguo

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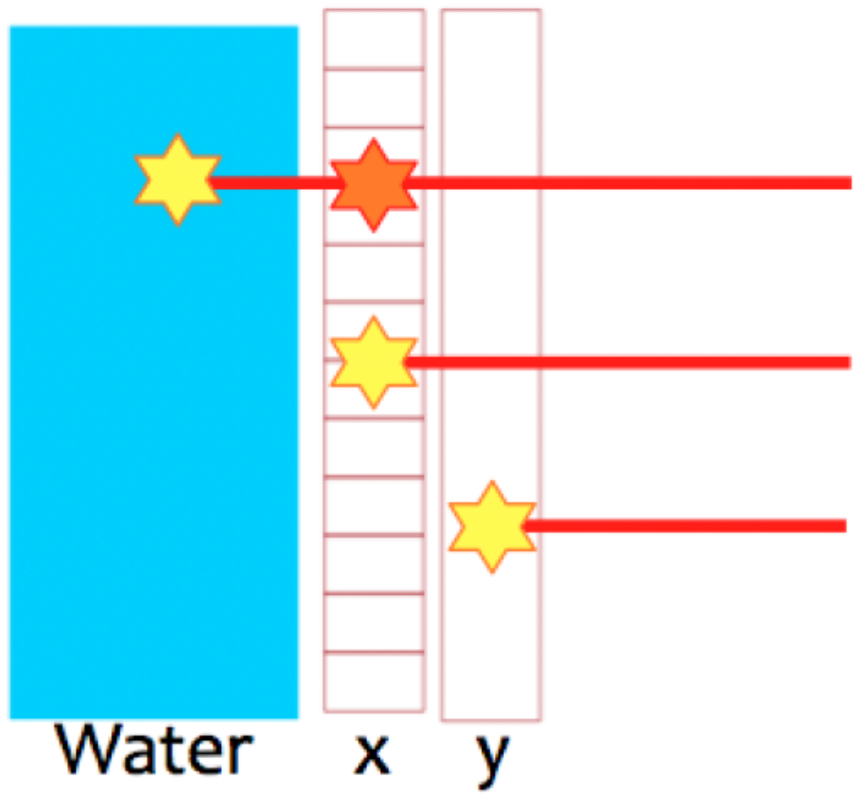
Upcoming results: new TKI measurement ($\nu_\mu CC0\pi Np$)

- Statistics will be almost doubled (11.61 x 10^20 POT) wrt the previous result and this analysis considers 2D correlations between TKI variables: $\delta p_T - \delta\alpha_T$ and $p_N - cos\ \theta_\mu$
- The addition of signal samples in FGD2, including an “oxygen-enhanced” sample that contains a significant contribution from interactions on water



$CC0\pi$ interactions on H_2O have the first hit in the X-layer of FGD2

$CC0\pi$ in the X-layer of FGD2 (C_8H_8)

$CC0\pi$ in the Y-layer of FGD2 (C_8H_8)

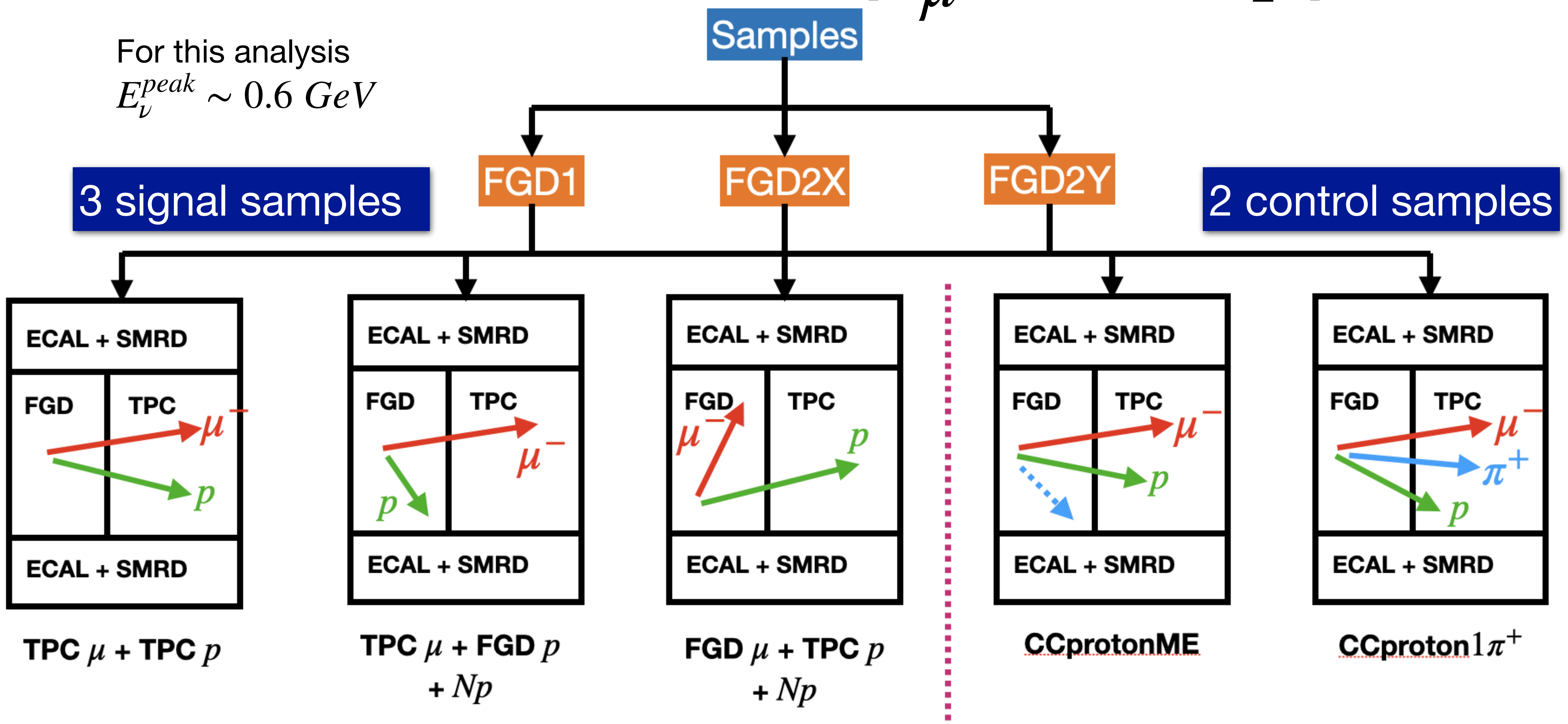
~75% overall signal purity, ~26% selection efficiency

Signal definition

Muon: $p_\mu \in [0.225,\ 10.0]\ GeV/c,\ cos\ \theta_\mu > -0.6$

Proton: $p_p \in [0.525,\ 1.1]\ GeV/c,\ cos\ \theta_\mu > 0.3$

For this analysis $E_\nu^{peak} \sim 0.6\ GeV$



TPC μ + TPC p

TPC μ + FGD p + Np

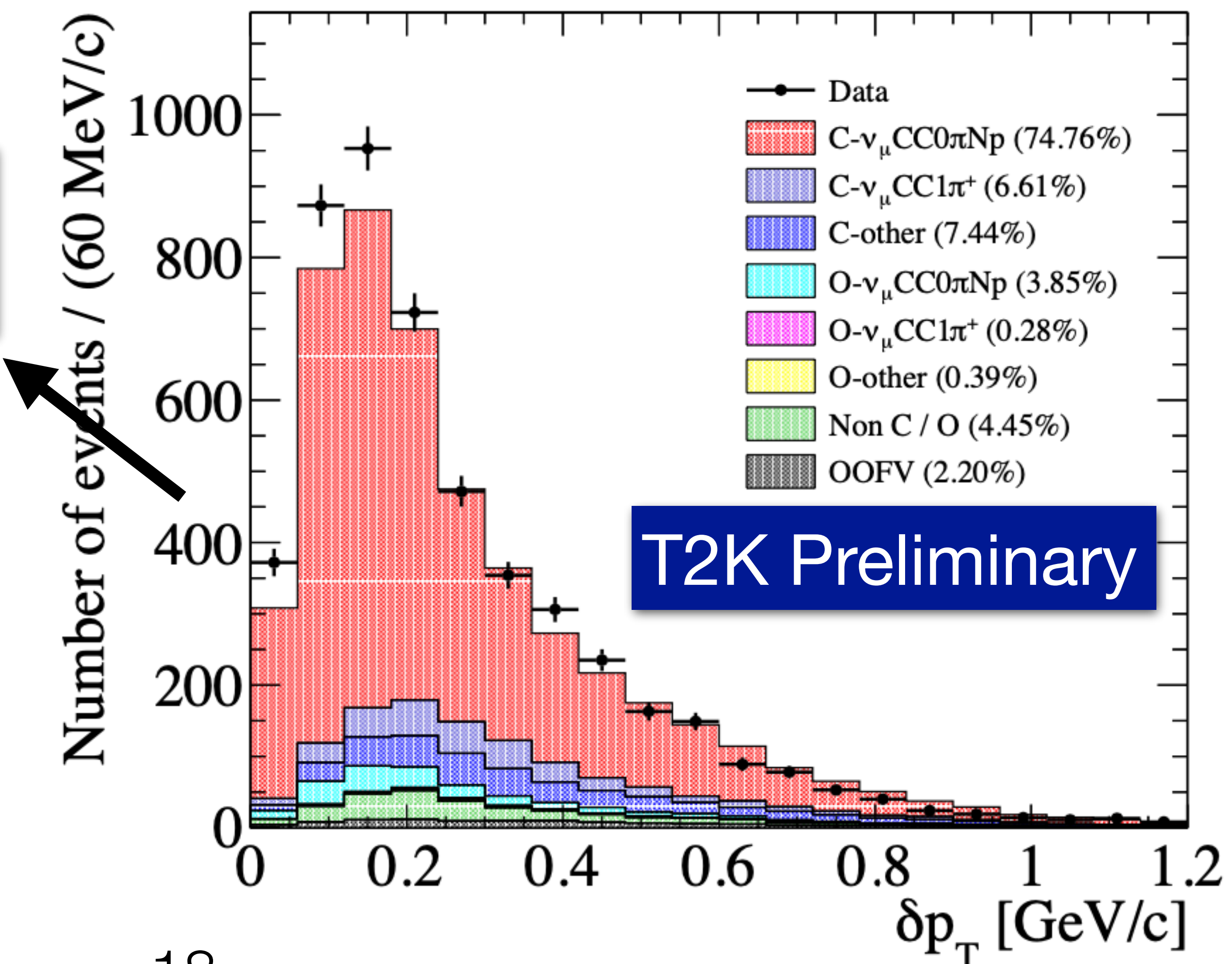
FGD μ + TPC p + Np

CCprotonME

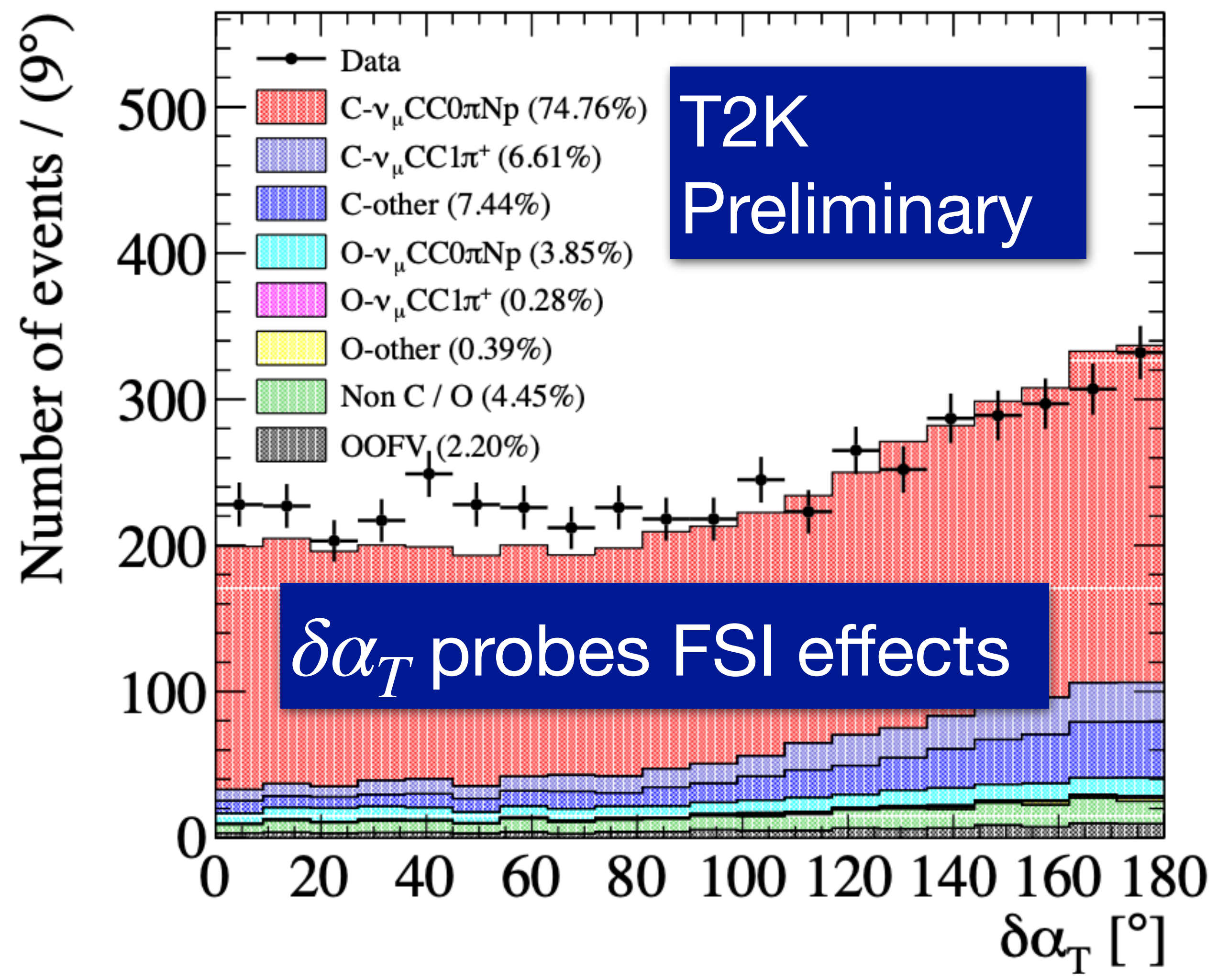
CCproton$1\pi^+$

Control Samples

δp_T is a good probe of Fermi motion at event peak, and 2p2h and FSI in the tail region



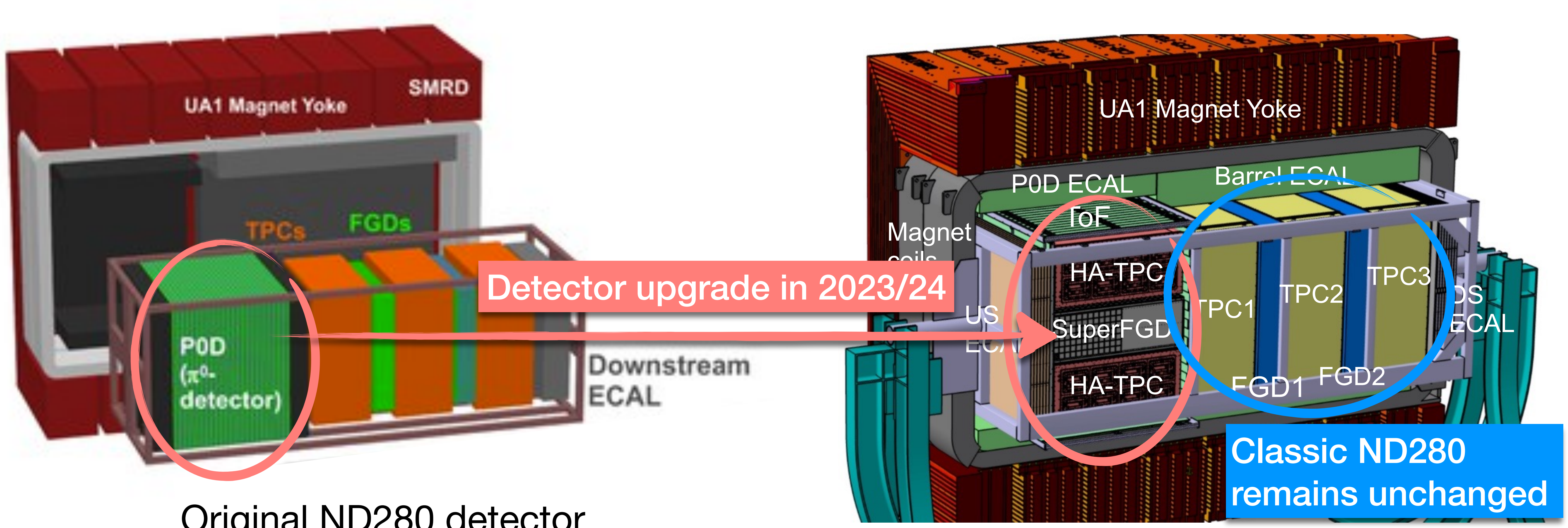
Signal sample FGD1



$\delta\alpha_T$ probes FSI effects

Conclusions

- T2K keeps producing a rich programme of cross section measurements that can benefit the wider community and feed into neutrino interaction model development
- Many new analyses are in progress - stay tuned!
- An upgrade of the ND280 detector has been completed in summer of 2024, the first data from which opens up a wealth of new opportunities for cross section measurements that probe new parts of phase space (wider acceptance, improved signal efficiency and purity etc)



Detector upgrade in 2023/24

Classic ND280 remains unchanged

Original ND280 detector
(2010-2023)

New ND280 detector
(Completed in 2024)

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Thank you very much!
Cảm ơn nhiều!

Backup Materials

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On behalf of the T2K Collaboration
Given at 21st Recontres du Vietnam, 22-25 July 2025, ICISE, Quy Nhon, Vietnam

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