UNIVERSITY OF OXFORD

T2K

T2K Neutrino Cross-Section Results

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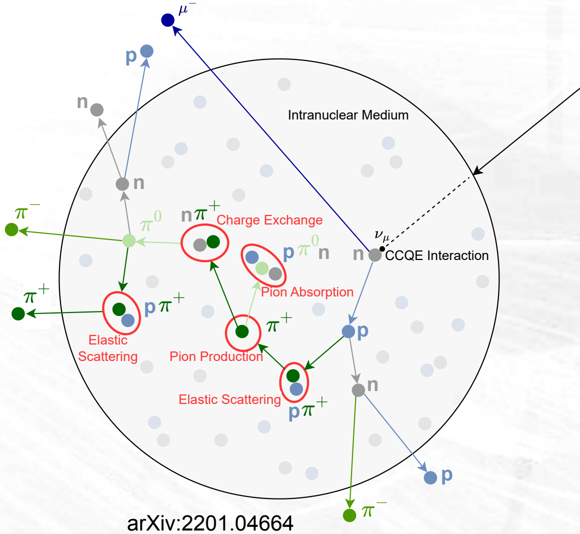
for the T2K Collaboration

Latest physics results and
cross-section measurements

Parallel session III: Neutrino masses, states and interactions

Otranto, Lecce, Italy
7th September 2024

NOW 2024
Neutrino Oscillation Workshop

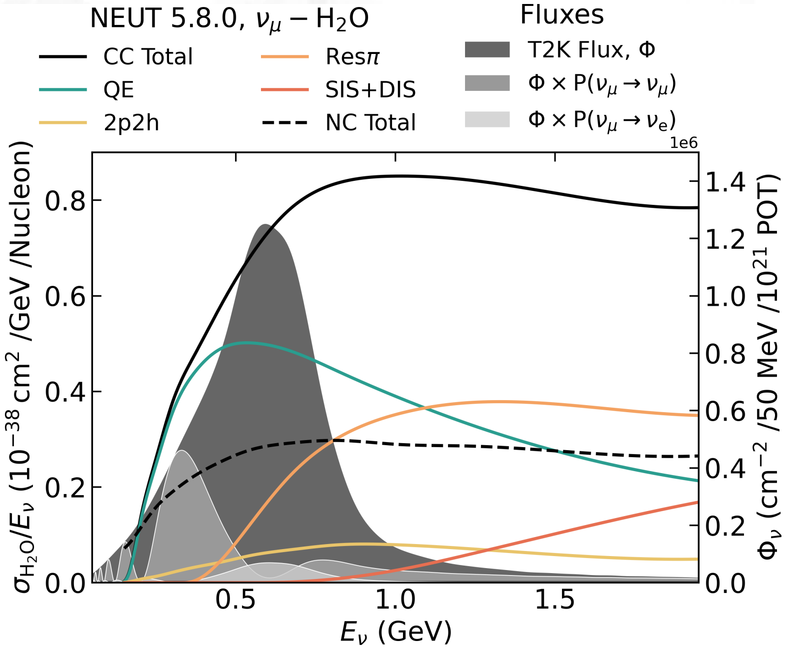


arXiv:2201.04664

Neutrino Oscillations

Need neutrino cross sections

For more details on neutrino oscillations in T2K+SK, see talk from Monday by Daniel Barrow on T2K and T2K+SK results



Plot from L. Pickering

- Neutrino *mass* and *weak* eigenstates are related via the PNMS-matrix:

usually parametrized by:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Neutrino mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$

CP-violating phase: δ_{CP}

- Neutrino event rate:

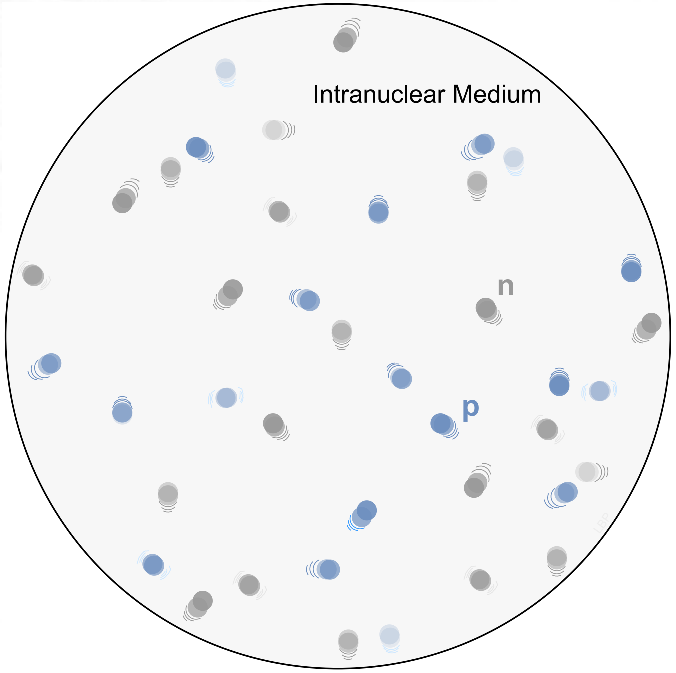
Need to know neutrino energy

Flux | Cross Section | # targets | Detector Efficiency

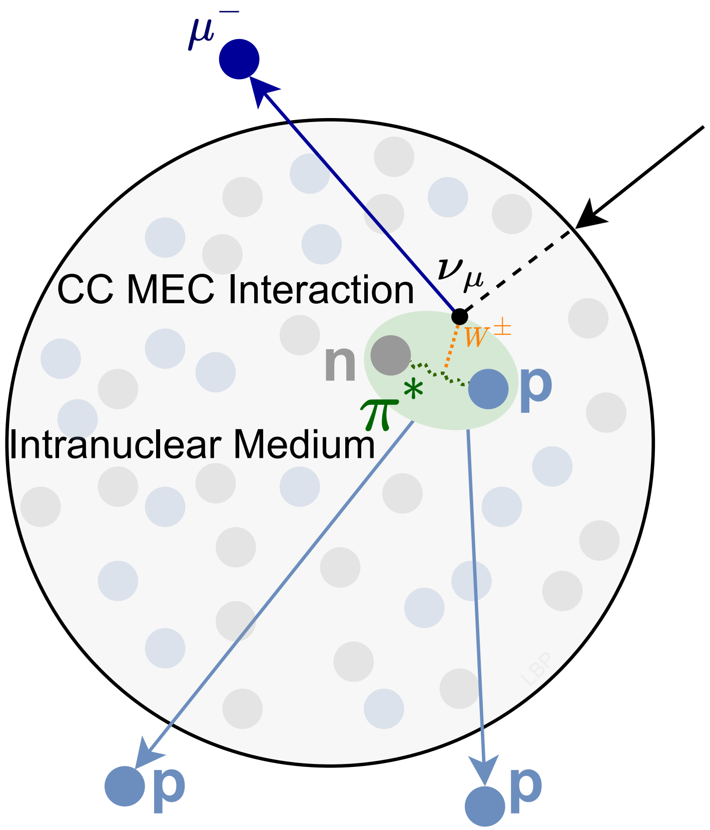
$$R^{FD}_{\alpha\rightarrow\beta}(E^{reco}_\nu) = \int_{E_{min}}^{E_{max}} \Phi_\alpha(E^{true}_\nu) \cdot \sigma^i_\beta(E^{true}_\nu, E^{reco}_\nu) \cdot \sum_j N_j \cdot \varepsilon_\beta(E^{true}_\nu, E^{reco}_\nu) \cdot P_{\alpha\rightarrow\beta}(E^{true}_\nu)$$

Nuclear Effects

Initial State Effects

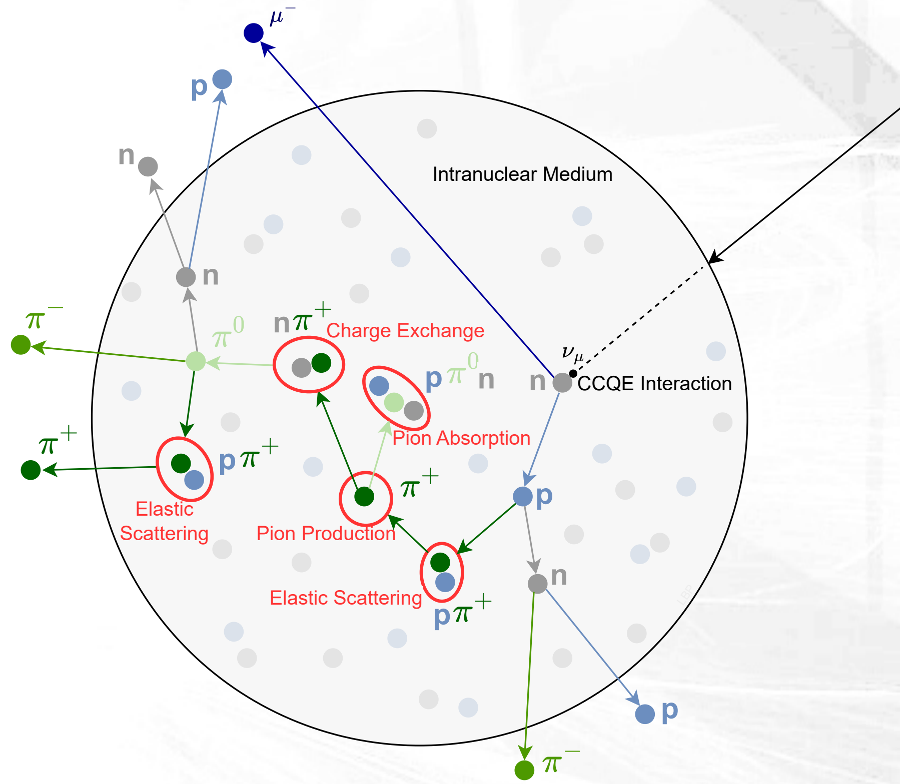


Meson Exchange Currents



LBP:FERMILAB-MASTERS-2020-03

Final State Interactions



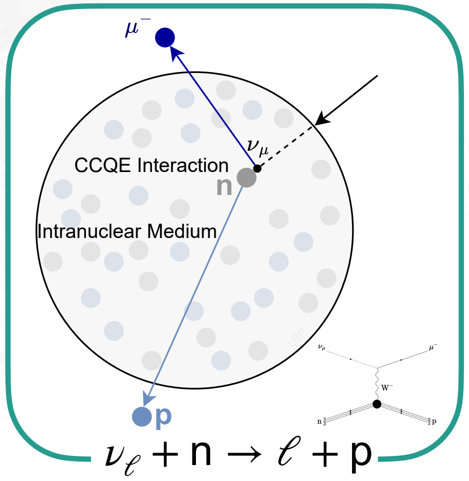
arXiv:2201.04664

Neutrino-Nucleus Cross Section

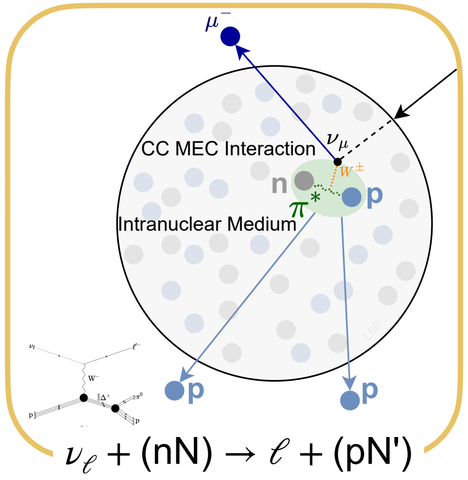
For more details, see talk yesterday by Benjamin Messerly on Understanding neutrino cross sections

Charged-Current (CC) Interaction Modes

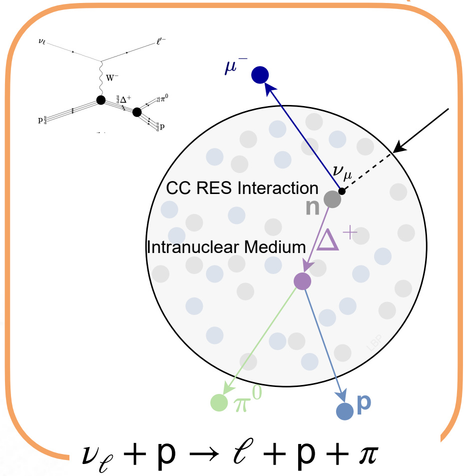
Quasi-Elastic (QE)



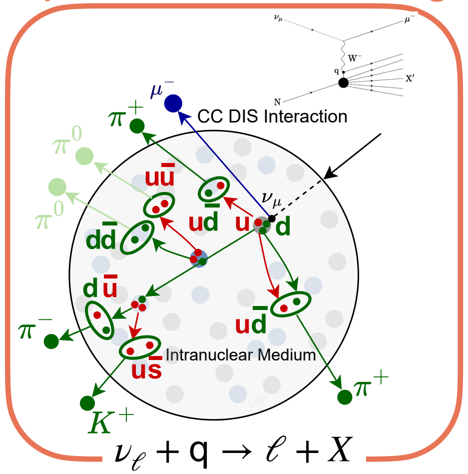
2particle-2hole (2p2h)

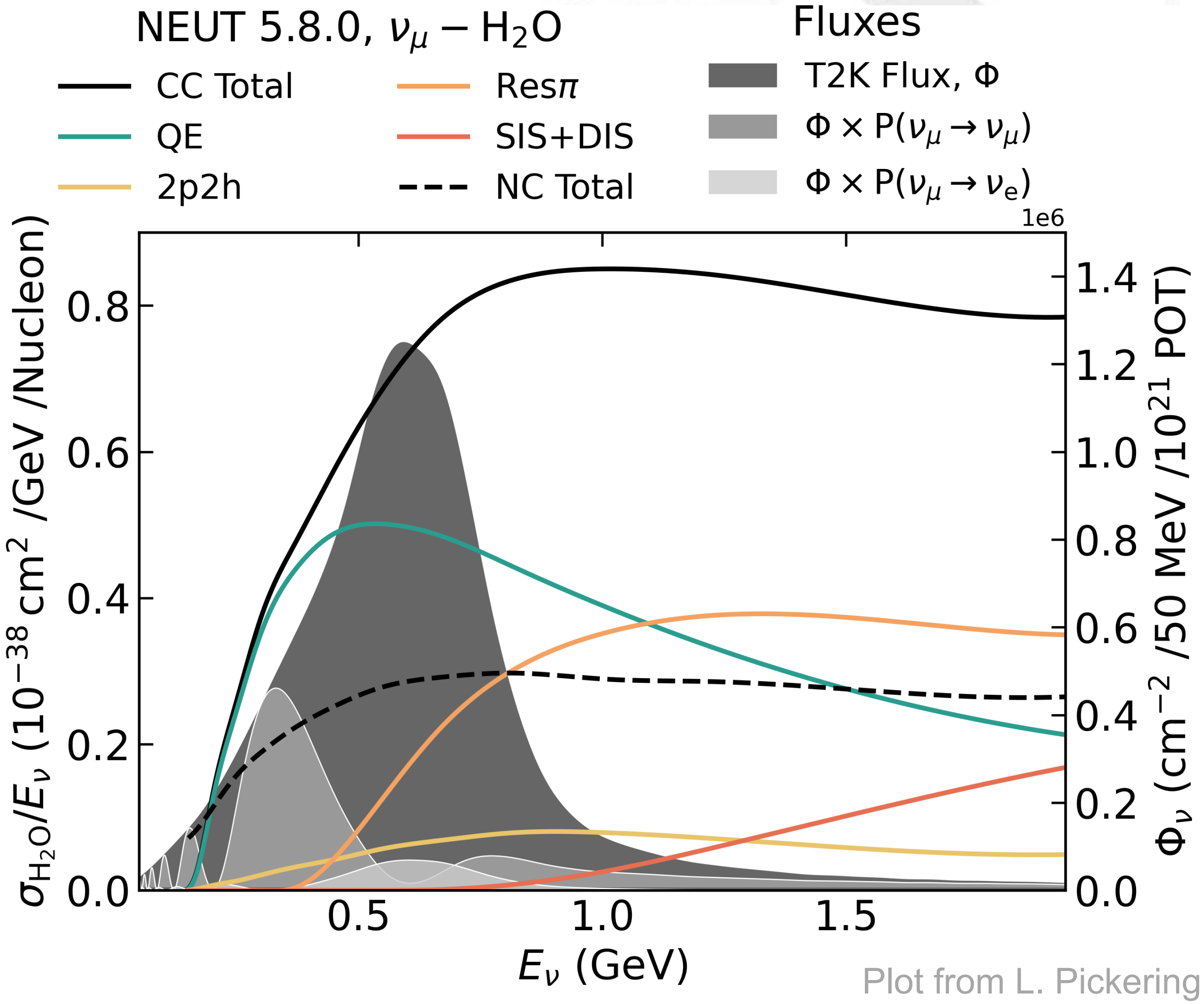


RESonance excitation (RES)



Deep Inelastic Scattering (DIS)





Plot from L. Pickering

T2K Cross-Section Results

- Inclusive $\overset{(-)}{\nu}_\mu$ Charged-Current Cross Section
- $\overset{(-)}{\nu}_\mu$ Charged-Current 1 π Cross Section
- Inclusive $\overset{(-)}{\nu}_e$ Charged-Current Cross Section
- $\overset{(-)}{\nu}_e$ Charged-Current 1 π Cross Section
- $\overset{(-)}{\nu}_\mu$ Charged-Current 0π Cross Section
- $\overset{(-)}{\nu}$ Neutral-Current π^0 Cross Section
- $\overset{(-)}{\nu}$ Quasi-Elastic-like Neutral-Current 0π Cross Section (γ-ray obs.)

$\sigma^{CC\text{-}inc}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CC\text{-}inc}_{\nu_\mu-C}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-CH,Fe}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-Fe}$ (INGRID), $\sigma^{CC\text{-}inc}_{\nu_\mu-C,O,H,Cu}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-C,dd}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-H_2O,C,Fe}$

$\sigma^{CC\text{-}inc}_{\overset{(-)}{\nu}_e}$: $\sigma^{CC\text{-}inc}_{\nu_e-C}$, $\sigma^{CC\text{-}inc}_{\nu_e-H_2O}$, $\sigma^{CC\text{-}inc}_{\nu_e-plastic}$

$\sigma^{CC0\pi}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CCQE0\pi}_{\nu_\mu-C}$, $\sigma^{CCQE0\pi}_{\nu_\mu-C,off-axis}$, $\sigma^{CC0\pi}_{\nu_\mu-C_8H_8}$, $\sigma^{CC0\pi}_{\nu_\mu-H_2O}$, $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (TKI), $\sigma^{CC0\pi}_{\nu_\mu,\bar{\nu}_\mu-CH}$, $\sigma^{CC0\pi}_{\nu_\mu-O+C}$, $\sigma^{CC0\pi}_{\bar{\nu}_\mu-H_2O}$, $\sigma^{CC0\pi}_{\nu_\mu-H_2O,C}$ (INGRID+ WAGASCI), $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (ND280+ INGRID), $\sigma^{CC0\pi}_{\nu_\mu-H_2O,CH}$ (WAGASCI- BabyMIND)

$\sigma^{NC0\pi}_{\overset{(-)}{\nu}}$: $\sigma^{NC0\pi}_{\nu-O}$, $\sigma^{NC0\pi}_{\nu,\bar{\nu}-O}$

$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CC1\pi\text{-}COH}_{\nu_\mu-C}$, $\sigma^{CC1\pi^+}_{\nu_\mu-H_2O}$, $\sigma^{CC1\pi}_{\nu_\mu-CH}$, $\sigma^{CC1\pi}_{\nu_\mu-CH}$ (TKI), $\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu-C}$

$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_e}$: $\sigma^{CC1\pi}_{\nu_e-CH}$

$\sigma^{NC1\pi}_{\overset{(-)}{\nu}}$: $\sigma^{NC1\pi^0}_{\nu,\bar{\nu}-H_2O}$, $\sigma^{NC1\pi^+}_{\nu,\bar{\nu}-CH}$

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

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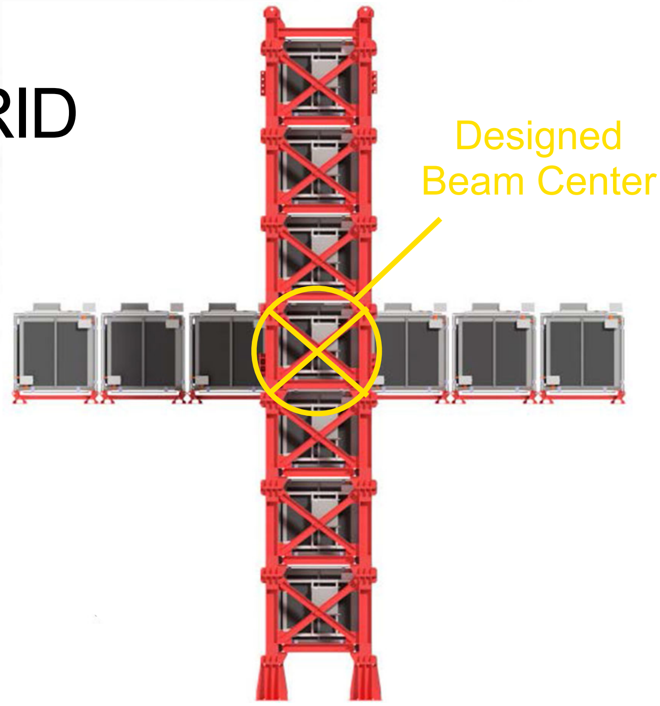
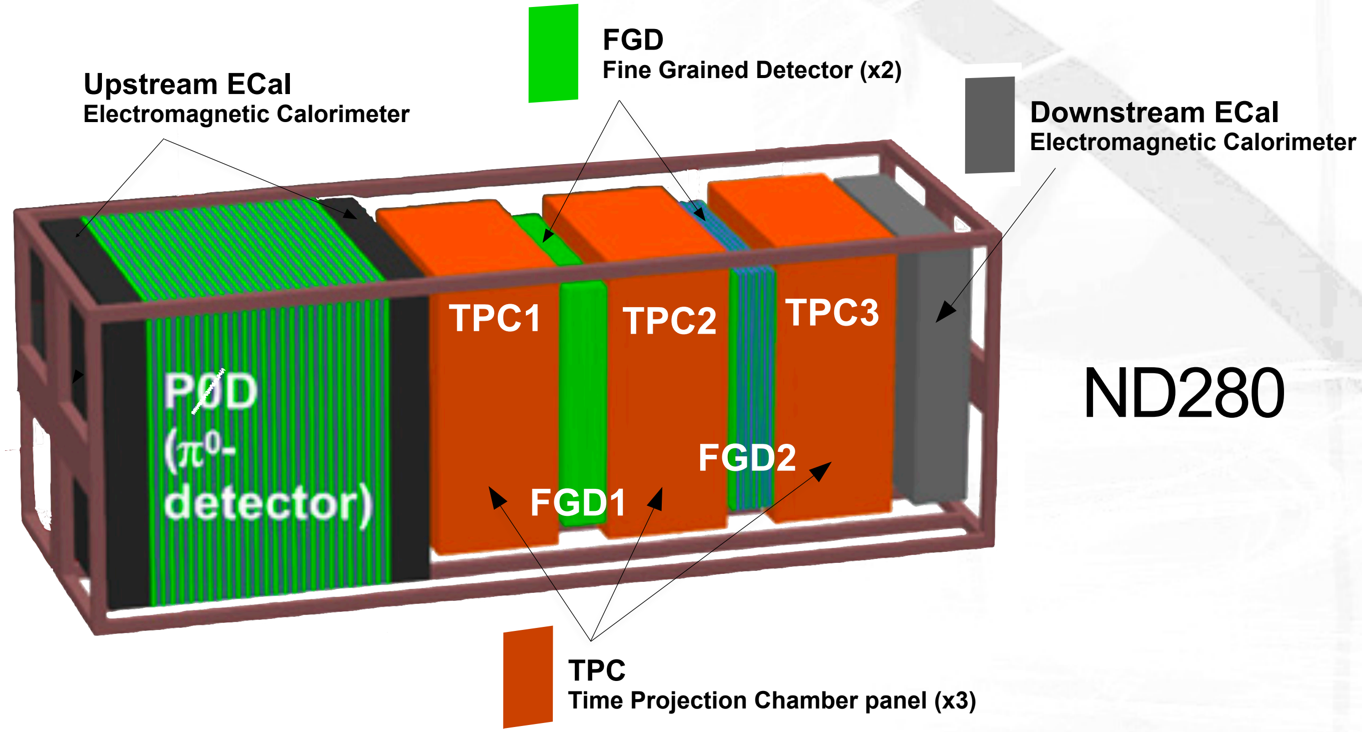
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

T2K Near Detectors - Nuclear Targets





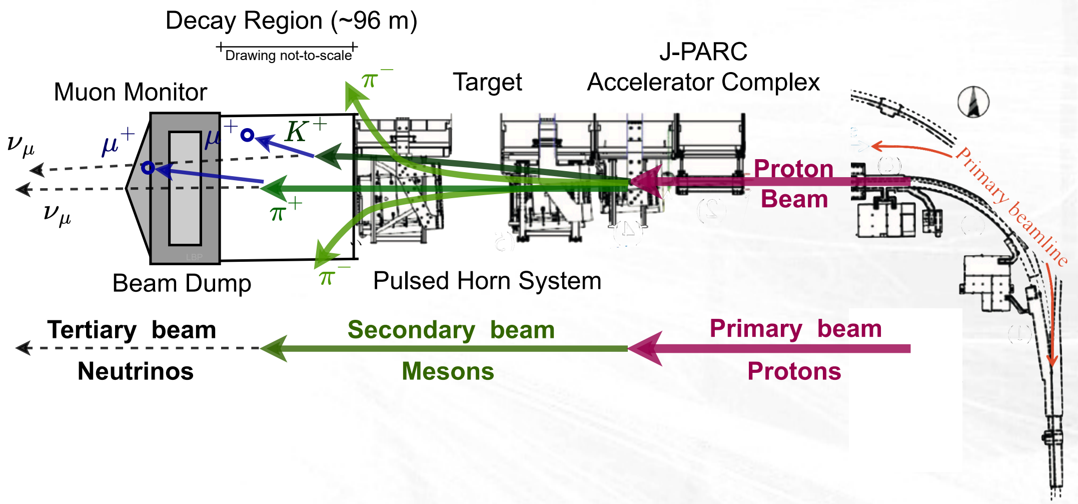
- *Standard Module*: mostly iron (**Fe**) plates, some plastic scintillator (hydrocarbon: **CH**) planes
- *Proton Module*: mostly plastic scintillator (**CH**) planes

Figure adapted from: T2K ND280 Upgrade - TDR

- *PØD*: scintillating bars (mostly carbon: **C**) alternating with either water (**H_2O**) target/brass (**$CuZn_X$**) foil or lead (**Pb**) foil
- *FGD1*: polystyrene scintillator (C_8H_8, majority of atoms are carbon (**C**))
- *FGD2*: polystyrene scintillator (**C**) and water (**H_2O**)

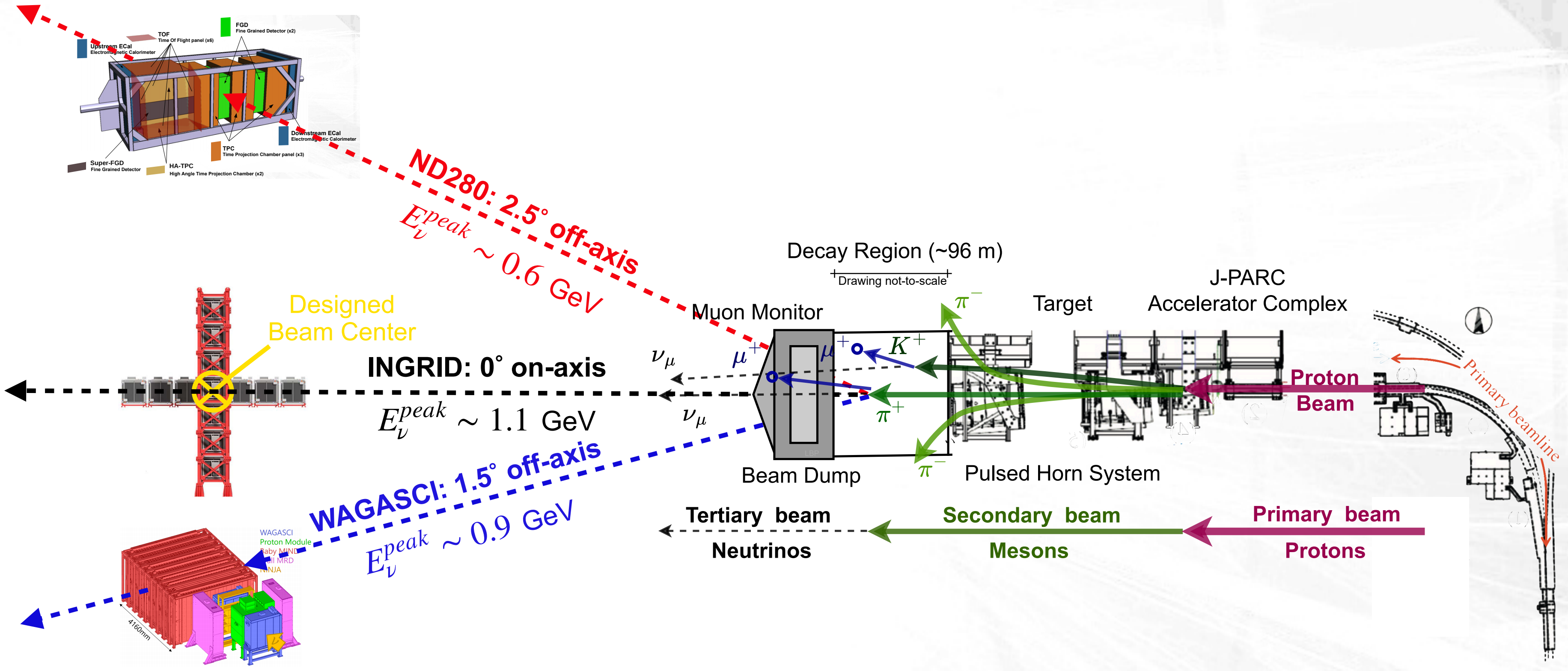
Figure adapted from: The T2K experiment

T2K Near Detectors



This figure uses images adapted from [T2K ND280 Upgrade - TDR] and [The T2K Experiment].

T2K Near Detectors



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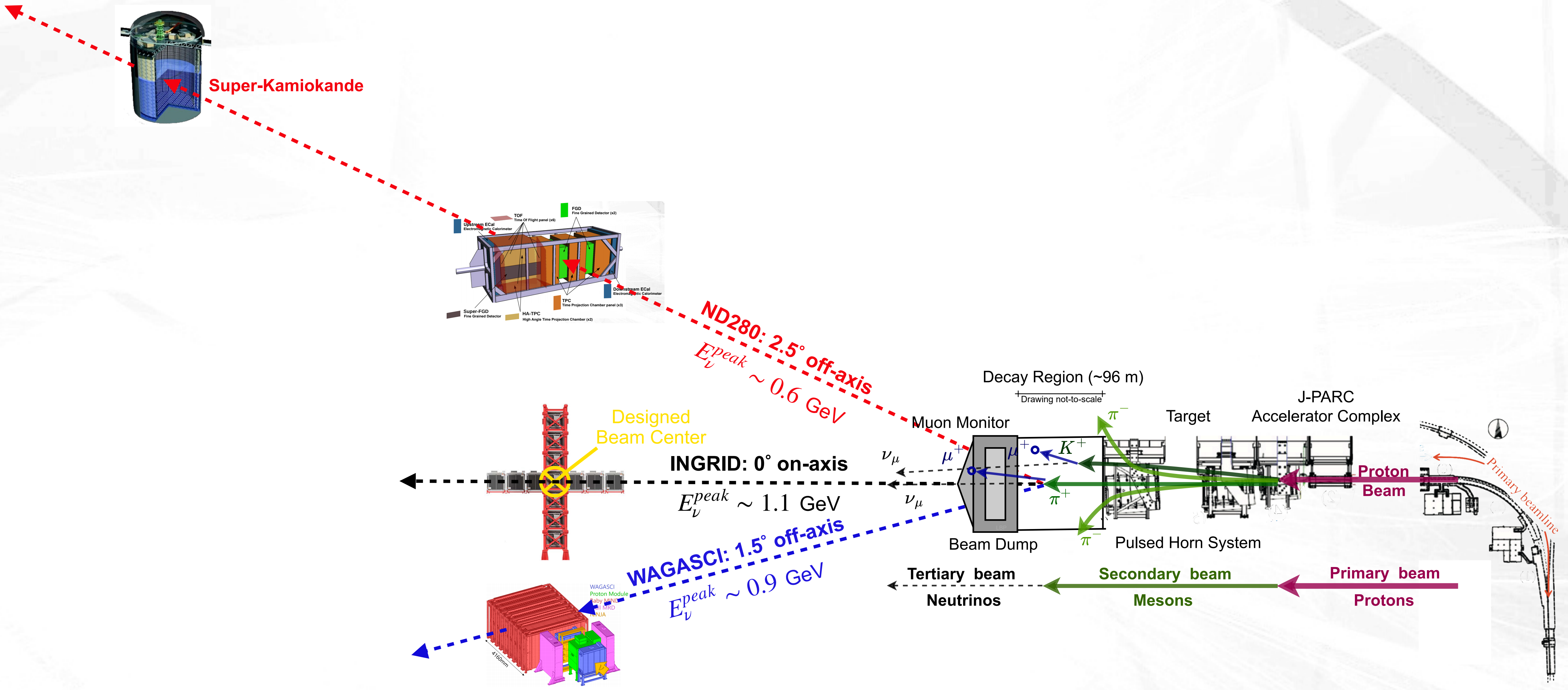

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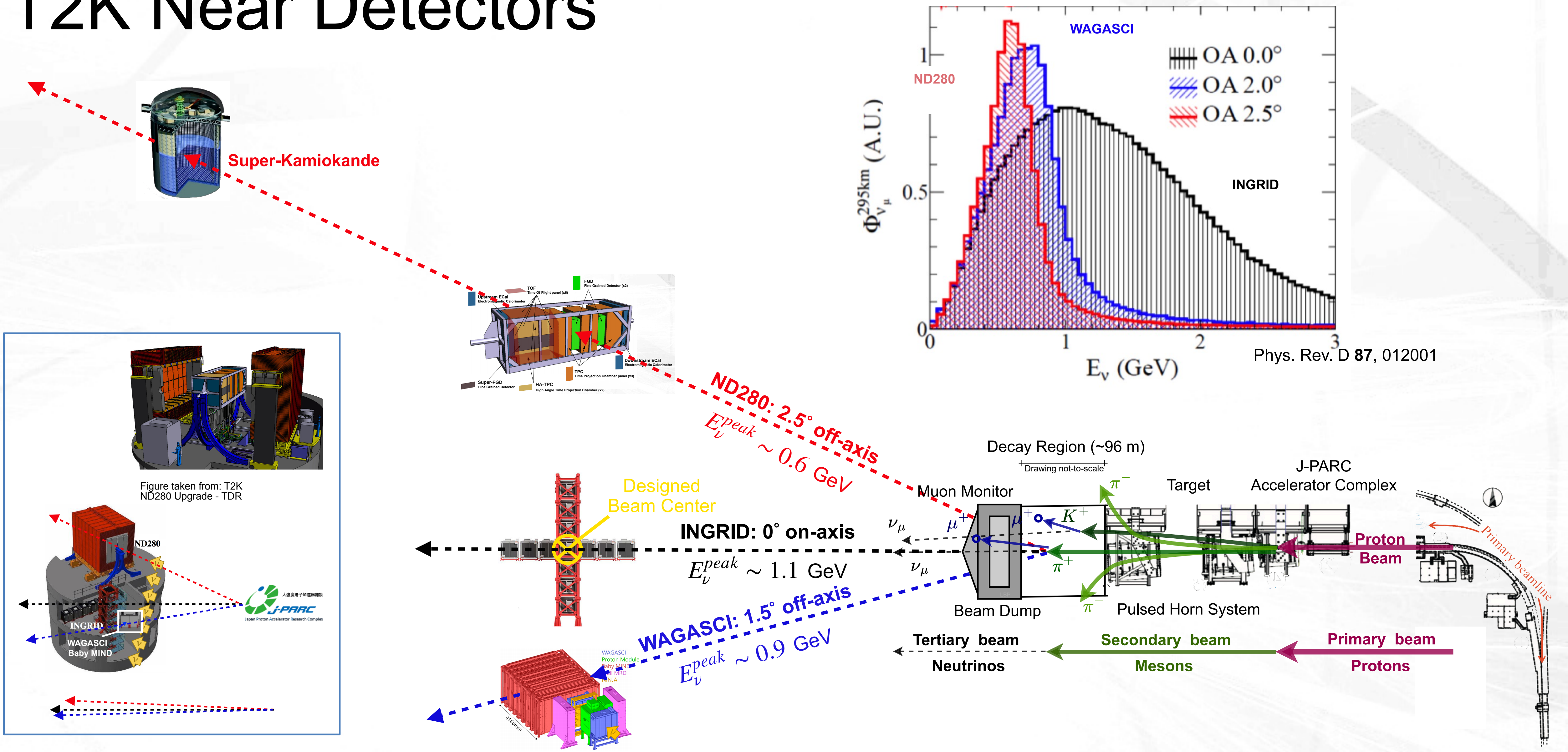

Phys. Rev. D **87**, 012001

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$\overset{(-)}{\nu}_\mu$ Charged-Current 1 π Cross Section

Inclusive $\overset{(-)}{\nu}_e$ Charged-Current Cross Section

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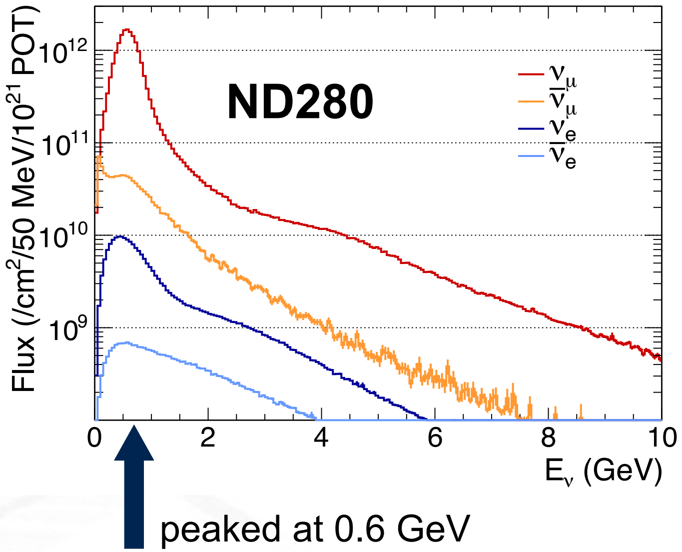
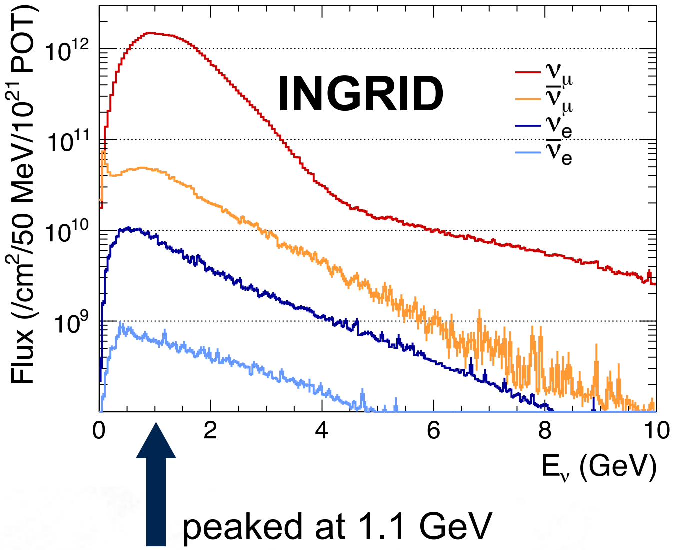
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

ν_μ-CC0π Interactions with **correlated energy spectra**

$\sigma^{CC0\pi}_{\nu_\mu-CH}$ (ND280+ INGRID)
Phys. Rev. D **108**, 112009



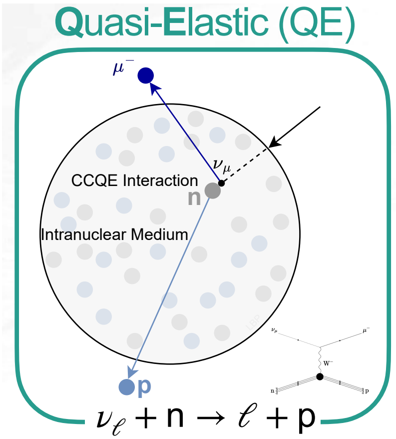
peaked at 0.6 GeV

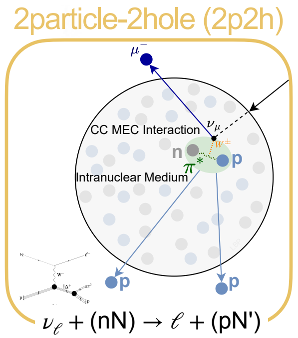


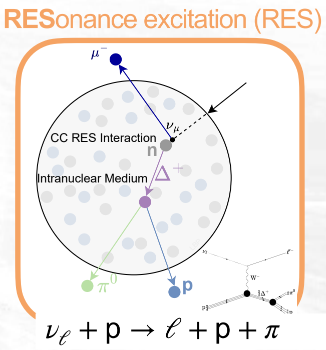
peaked at 1.1 GeV

- Goal of using correlated energy spectra **in a joint analysis**:
  - Study *energy dependence* of neutrino interactions
  - Reduce cross-section *uncertainties*
- Use energy spectra from two T2K detectors:
  - ND280: narrow energy-band off-axis flux peaked at 0.6 GeV
  - INGRID: wide(r) energy-band on-axis flux peaked at 1.1 GeV
- Dominant interaction mode:

Sub-dominant interaction modes:







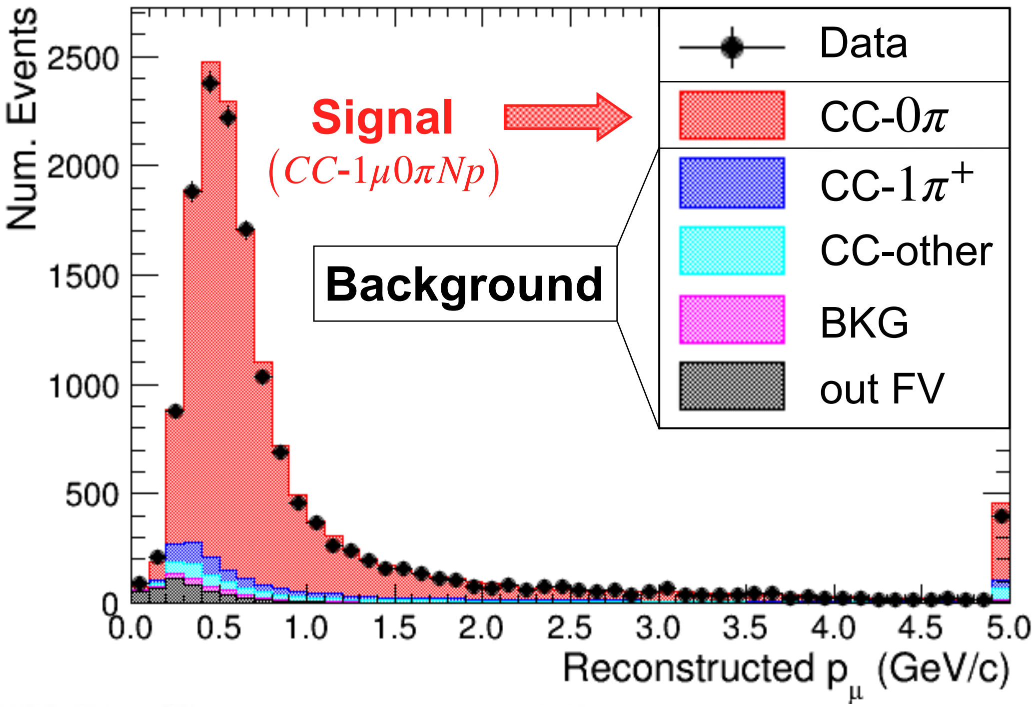
ν_μ-CC0π Interactions with **correlated energy spectra**

$\sigma^{CC0\pi}_{\nu_\mu-CH}$ (ND280+ INGRID)

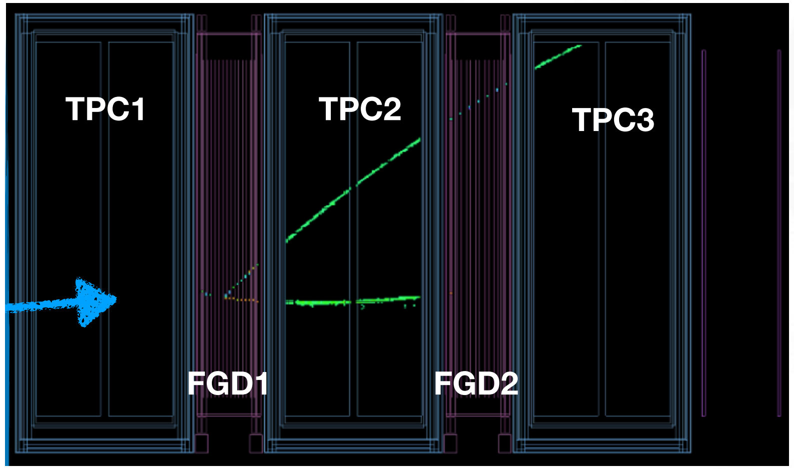
Phys. Rev. D **108**, 112009

- Signal definition: CC-1$\mu 0\pi N$p with

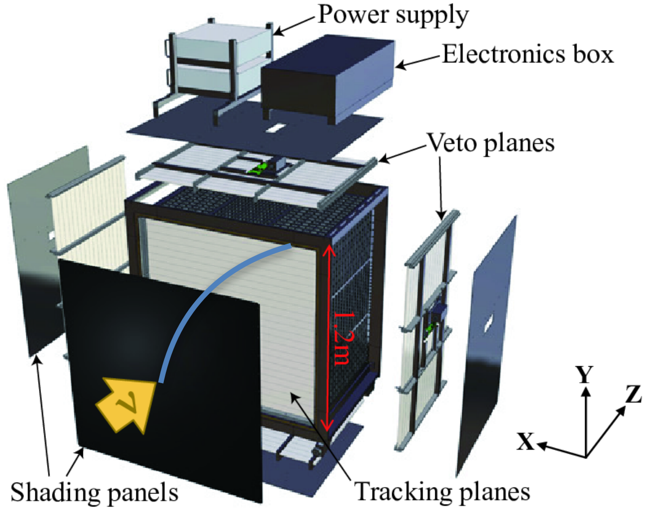
Particle	Momentum p [GeV/c]	Angle θ
μ^- (in INGRID)	< 0.35	$< 60°$



- Signal samples with ν vertex in FGD1 (ND280):



- Signal samples with ν vertex in Proton Module (INGRID):

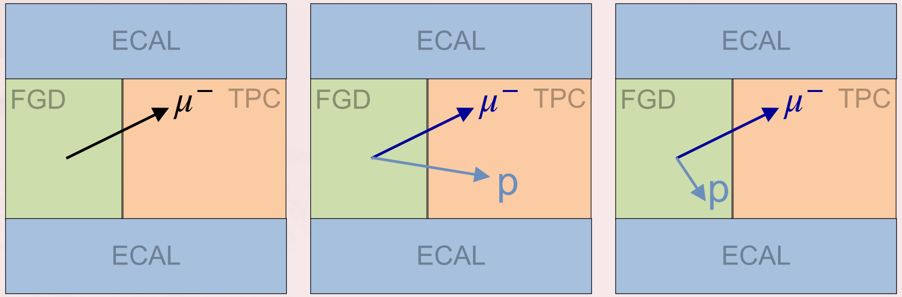


ν_μ-CC0π Interactions with **correlated energy spectra**

Signal: CC-1$\mu 0\pi N$p

$\sigma^{CC0\pi}_{\nu_\mu-CH}$ (ND280+ INGRID)
Phys. Rev. D **108**, 112009

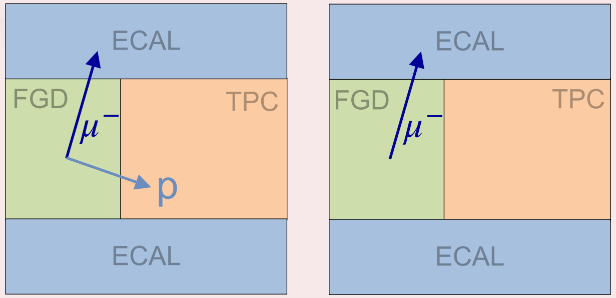
Sample I (μTPC) Sample II (μTPC + pTPC) Sample III (μTPC + pFGD)



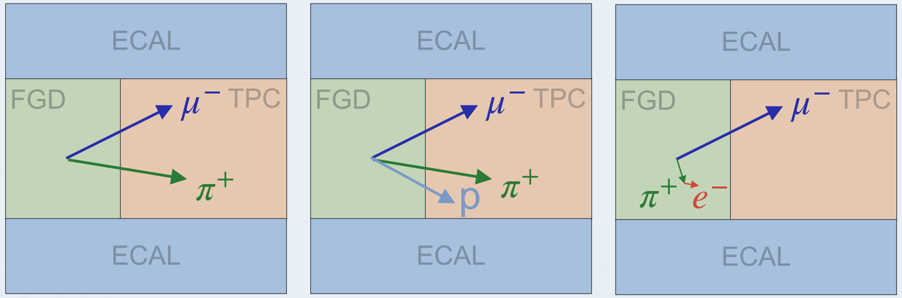
ND280

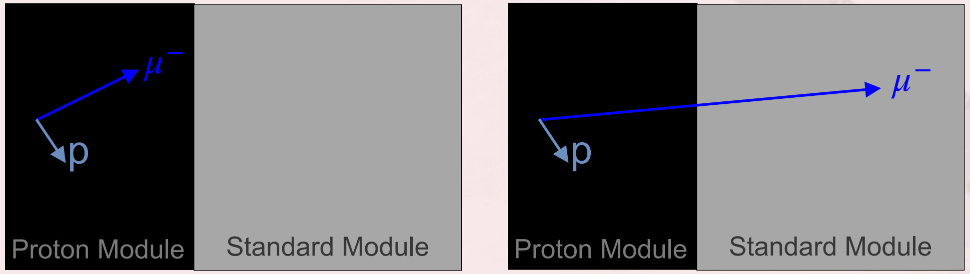
- Control sample: CC-1μX
- Vertex and target: Plastic scintillator in FGD1

Sample IV (μFGD + pTPC) Sample V (μFGD)



Sample VI (CC-1π^+) Sample VII (CC-other) Sample VIII (CC-Michel)

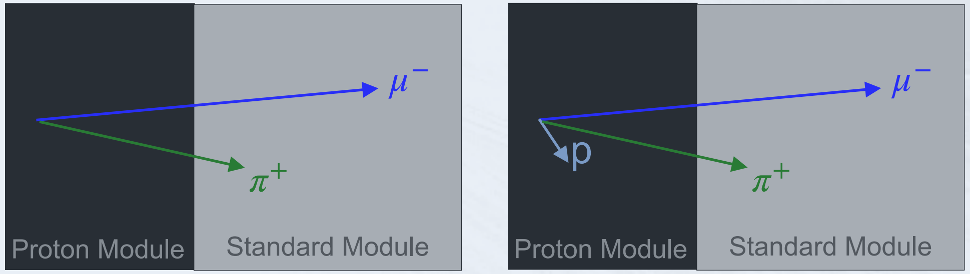




INGRID

- Control sample: CC-1$\mu 1\pi$(0-1)p
- Target: Scintillator in Proton Module

$p_\mu > 0.35$GeV and $\cos(\theta_\mu) > 0.5$ $\left(\theta_\mu < 60^\circ\right)$



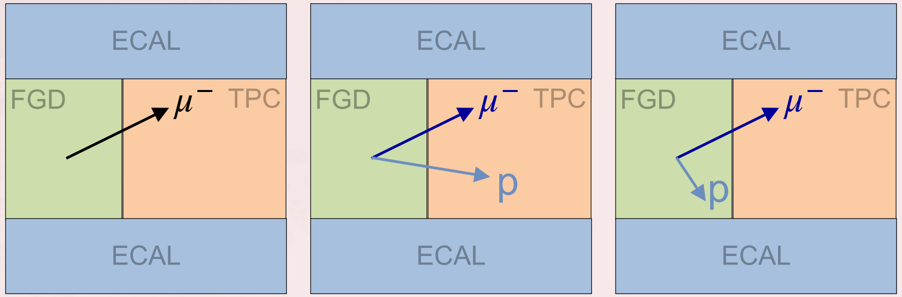
ν_μ-CC0π Interactions with **correlated energy spectra**

Signal: CC-1$\mu 0\pi N$p

$\sigma^{CC0\pi}_{\nu_\mu - CH}$ (ND280+ INGRID)
Phys. Rev. D **108**, 112009

ND280

Sample I (μTPC) | Sample II (μTPC + pTPC) | Sample III (μTPC + pFGD)



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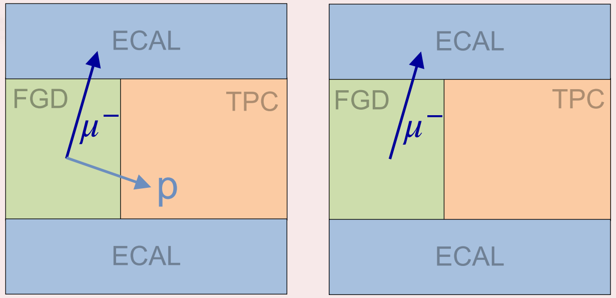
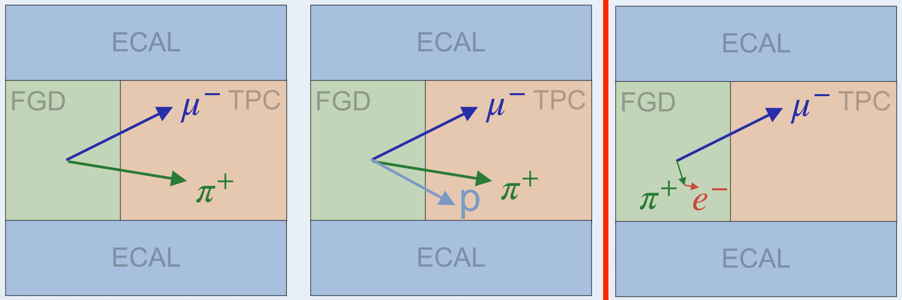
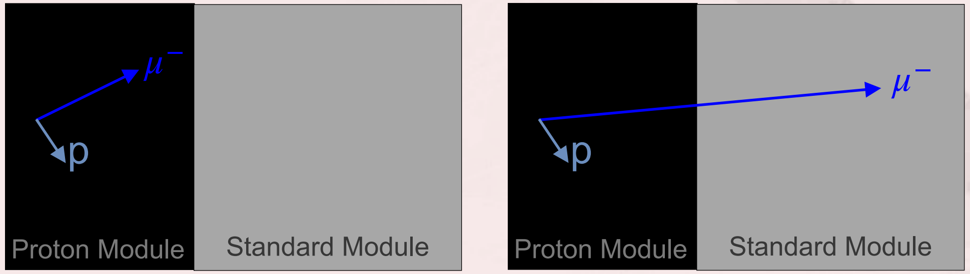


- Control sample: CC-1μX
- Vertex and target: Plastic scintillator in FGD1

Sample VI (CC-1π^+) | Sample VII (CC-other) | Sample VIII (CC-Michel)

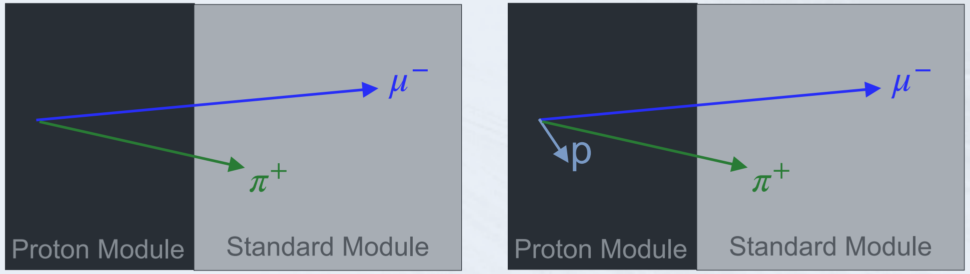


INGRID



- Control sample: CC-1μ1π(0-1)p
- Target: Scintillator in Proton Module

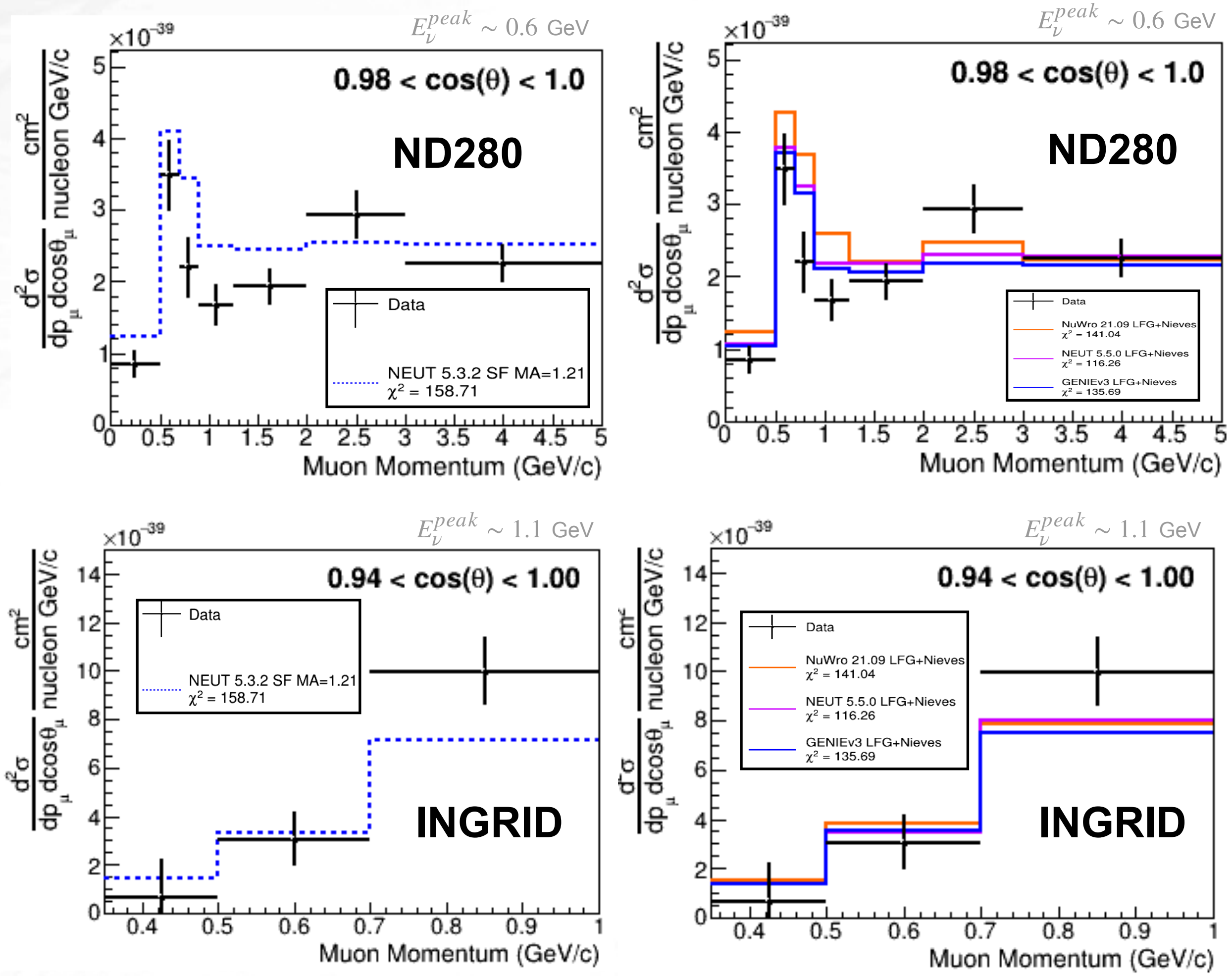
$p_\mu > 0.35$GeV and $\cos(\theta_\mu) > 0.5$ $\left(\theta_\mu < 60^\circ\right)$



ν_μ-CC0π Interactions with **correlated energy spectra**

Extracted Cross-Section

$\sigma^{CC0\pi}_{\nu_\mu - CH}$ (ND280+ INGRID)
Phys. Rev. D **108**, 112009



- PRISM-like analysis with two fluxes
- Ability to compare correlated results to naive sum
- Tensions between generator predictions and data
- Deficit of data wrt predictions at forward angles
- Data-MC agreement quantified by χ^2-values:

Model	ND280	INGRID	Joint
Nominal MC (NEUT)	136.34	18.21	158.71
NEUT LFG+Nieves	106.46	11.46	116.26
NEUT SF+Nieves $M_A = 1.03$	194.88	14.36	209.18
NEUT SF+Nieves $M_A = 1.21$	158.71	9.98	170.93
NuWro SF+Nieves	122.74	15.68	137.02
NuWro LFG+Nieves	125.88	12.75	141.04
NuWro LFG+SuSAv2	121.57	11.13	135.38
NuWro LFG+Martini	138.86	12.46	155.68
GENIE BRRFG+EmpMEC	141.40	12.80	156.05
GENIE LFG+Nieves	125.50	14.45	135.69
degrees of freedom:	58	12	70

T2K Cross-Section Results

- Inclusive $\overset{(-)}{\nu}_\mu$ Charged-Current Cross Section
- $\overset{(-)}{\nu}_\mu$ Charged-Current 1 π Cross Section
- Inclusive $\overset{(-)}{\nu}_e$ Charged-Current Cross Section
- $\overset{(-)}{\nu}_e$ Charged-Current 1 π Cross Section
- $\overset{(-)}{\nu}_\mu$ Charged-Current 0π Cross Section
- $\overset{(-)}{\nu}$ Neutral-Current π^0 Cross Section
- $\overset{(-)}{\nu}$ Quasi-Elastic-like Neutral-Current 0π Cross Section (γ-ray obs.)

$\sigma^{CC\text{-}inc}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CC\text{-}inc}_{\nu_\mu-C}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-CH,Fe}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-Fe}$ (INGRID), $\sigma^{CC\text{-}inc}_{\nu_\mu-C,O,H,Cu}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-C,dd}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-H_2O,C,Fe}$

$\sigma^{CC\text{-}inc}_{\overset{(-)}{\nu}_e}$: $\sigma^{CC\text{-}inc}_{\nu_e-C}$, $\sigma^{CC\text{-}inc}_{\nu_e-H_2O}$, $\sigma^{CC\text{-}inc}_{\nu_e-plastic}$

$\sigma^{CC0\pi}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CCQE0\pi}_{\nu_\mu-C}$, $\sigma^{CCQE0\pi}_{\nu_\mu-C,off-axis}$, $\sigma^{CC0\pi}_{\nu_\mu-C_8H_8}$, $\sigma^{CC0\pi}_{\nu_\mu-H_2O}$, $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (TKI), $\sigma^{CC0\pi}_{\nu_\mu,\bar{\nu}_\mu-CH}$, $\sigma^{CC0\pi}_{\nu_\mu-O+C}$, $\sigma^{CC0\pi}_{\bar{\nu}_\mu-H_2O}$, $\sigma^{CC0\pi}_{\nu_\mu-H_2O,C}$ (INGRID+ WAGASCI), $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (ND280+ INGRID), $\sigma^{CC0\pi}_{\nu_\mu-H_2O,CH}$ (WAGASCI- BabyMIND)

$\sigma^{NC0\pi}_{\overset{(-)}{\nu}}$: $\sigma^{NC0\pi}_{\nu-O}$, $\sigma^{NC0\pi}_{\nu,\bar{\nu}-O}$

$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CC1\pi\text{-}COH}_{\nu_\mu-C}$, $\sigma^{CC1\pi^+}_{\nu_\mu-H_2O}$, $\sigma^{CC1\pi}_{\nu_\mu-CH}$, $\sigma^{CC1\pi}_{\nu_\mu-CH}$ (TKI), $\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu-C}$

$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_e}$: $\sigma^{CC1\pi}_{\nu_e-CH}$

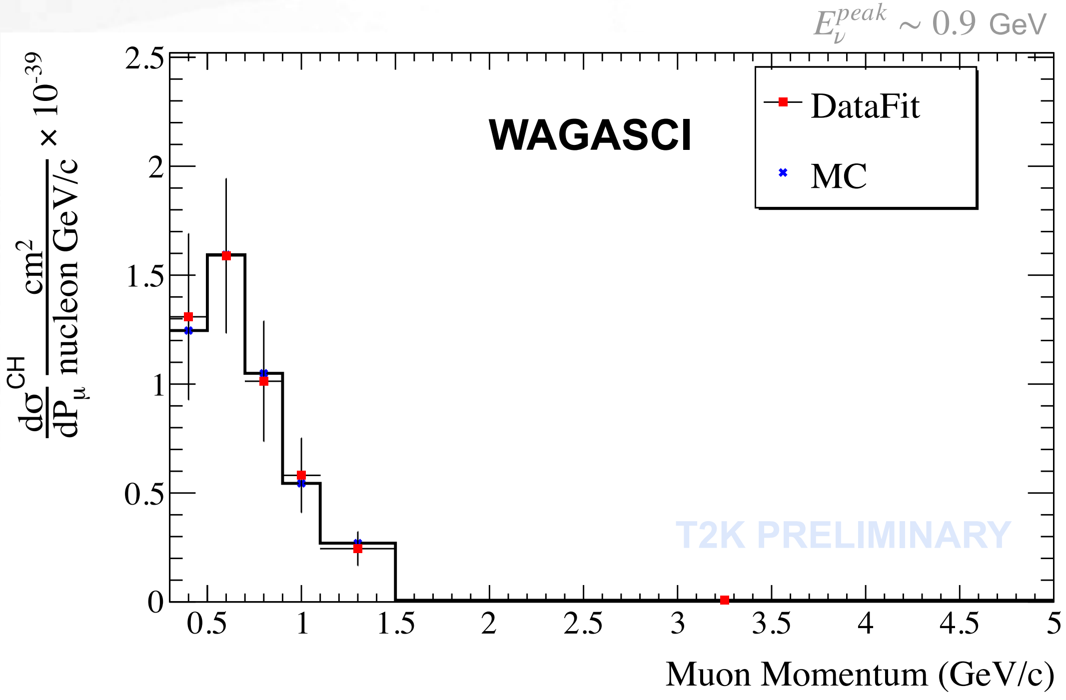
$\sigma^{NC1\pi}_{\overset{(-)}{\nu}}$: $\sigma^{NC1\pi^0}_{\nu,\bar{\nu}-H_2O}$, $\sigma^{NC1\pi^+}_{\nu,\bar{\nu}-CH}$

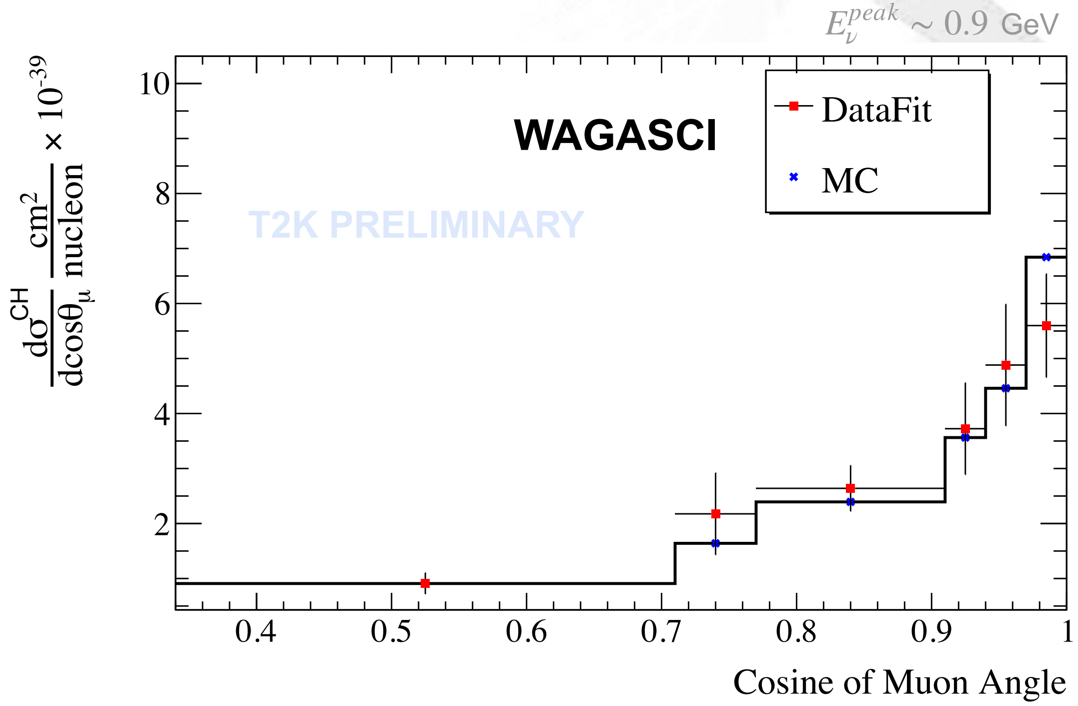
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

ν_μ-CC0π Measurement by **WAGASCI**

$\sigma^{CC0\pi}_{\nu_\mu - H_2O,CH}$ (WAGASCI-BabyMIND)
publication in preparation

Extracted Cross-Section





Model	χ^2 in momentum binning			χ^2 in angle binning		
	CH	H_2O	total	CH	H_2O	total
NEUT nominal	0.493	5.619	6.673	4.040	5.082	9.005
NEUT alternative version	1.827	5.550	7.611	4.279	6.615	11.29
GENIE	1.086	6.030	7.667	2.199	4.783	6.955
Post fit by the ND fit	1.318	5.547	7.424	3.217	5.169	8.208

degree of freedom: 12

- Possibility of adding CC0π measurement with WAGASCI to add a third flux to the PRISM analysis of Phys. Rev. D 108, 112009 with ND280 and INGRID

T2K Cross-Section Results

Inclusive $\overset{(-)}{\nu}_\mu$ Charged-Current Cross Section

$\overset{(-)}{\nu}_\mu$ Charged-Current 1 π Cross Section

Inclusive $\overset{(-)}{\nu}_e$ Charged-Current Cross Section

$\overset{(-)}{\nu}_e$ Charged-Current 1 π Cross Section

$\overset{(-)}{\nu}_\mu$ Charged-Current 0π Cross Section

$\overset{(-)}{\nu}$ Neutral-Current π^0 Cross Section

$\overset{(-)}{\nu}$ Quasi-Elastic-like Neutral-Current 0π Cross Section (γ-ray obs.)

$\sigma^{CC\text{-}inc}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CC\text{-}inc}_{\nu_\mu-C}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-CH,Fe}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-Fe}$ (INGRID), $\sigma^{CC\text{-}inc}_{\nu_\mu-C,O,H,Cu}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-C,dd}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-H_2O,C,Fe}$

$\sigma^{CC\text{-}inc}_{\overset{(-)}{\nu}_e}$: $\sigma^{CC\text{-}inc}_{\nu_e-C}$, $\sigma^{CC\text{-}inc}_{\nu_e-H_2O}$, $\sigma^{CC\text{-}inc}_{\nu_e-plastic}$

$\sigma^{CC0\pi}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CCQE0\pi}_{\nu_\mu-C}$, $\sigma^{CCQE0\pi}_{\nu_\mu-C,off-axis}$, $\sigma^{CC0\pi}_{\nu_\mu-C_8H_8}$, $\sigma^{CC0\pi}_{\nu_\mu-H_2O}$, $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (TKI), $\sigma^{CC0\pi}_{\nu_\mu,\bar{\nu}_\mu-CH}$, $\sigma^{CC0\pi}_{\nu_\mu-O+C}$, $\sigma^{CC0\pi}_{\bar{\nu}_\mu-H_2O}$, $\sigma^{CC0\pi}_{\nu_\mu-H_2O,C}$ (INGRID+ WAGASCI), $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (ND280+ INGRID), $\sigma^{CC0\pi}_{\nu_\mu-H_2O,CH}$ (WAGASCI- BabyMIND)

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$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_e}$: $\sigma^{CC1\pi}_{\nu_e-CH}$

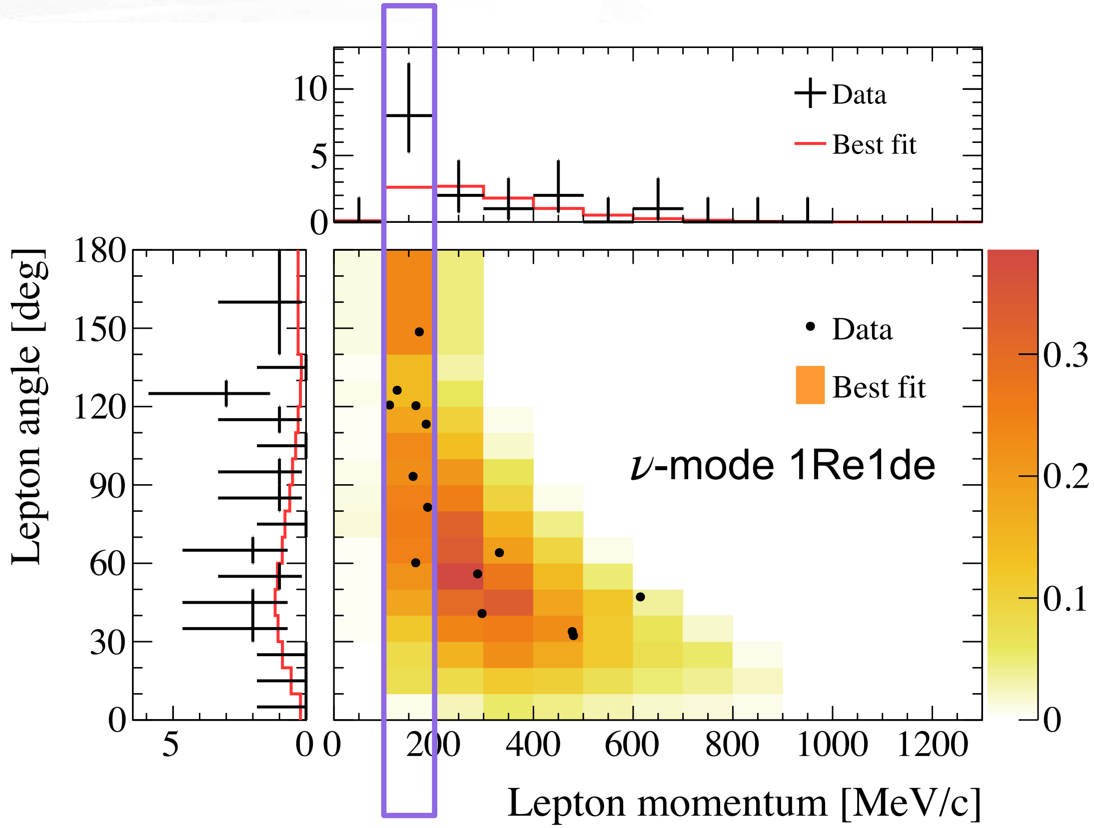
$\sigma^{NC1\pi}_{\overset{(-)}{\nu}}$: $\sigma^{NC1\pi^0}_{\nu,\bar{\nu}-H_2O}$, $\sigma^{NC1\pi^+}_{\nu,\bar{\nu}-CH}$

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

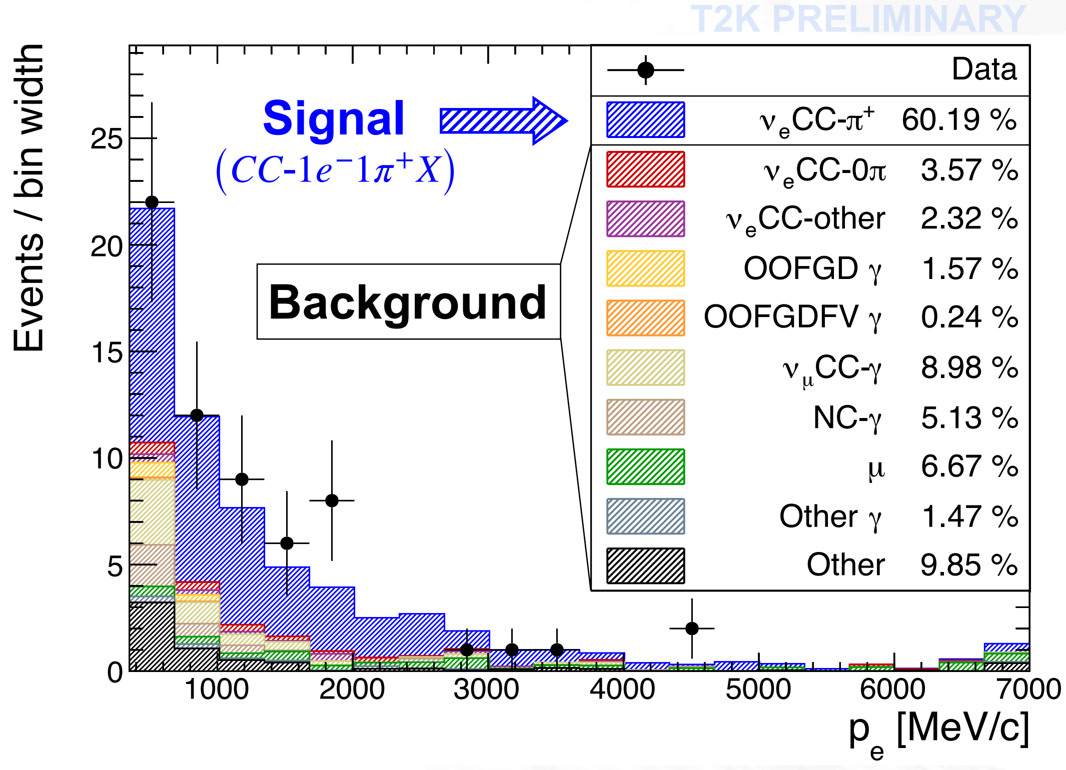
ν_e-CC$1\pi^{\pm}$ Interactions

Motivation and Signal Definition

- Michel-electrons in Super-Kamiokande



Particle	Momentum p [GeV/c]	Angle θ
e^-	$0.35 - 30$	$< 46°$
π^+	< 1.5	



ν_e-CC$1\pi^{\pm}$ Interactions

$\sigma_{\nu_e-CH}^{CC1\pi}$ publication in preparation

Signal Definition

Particle	Momentum p [GeV/c]	Angle θ
e^-	$0.35 - 30$	$< 46°$
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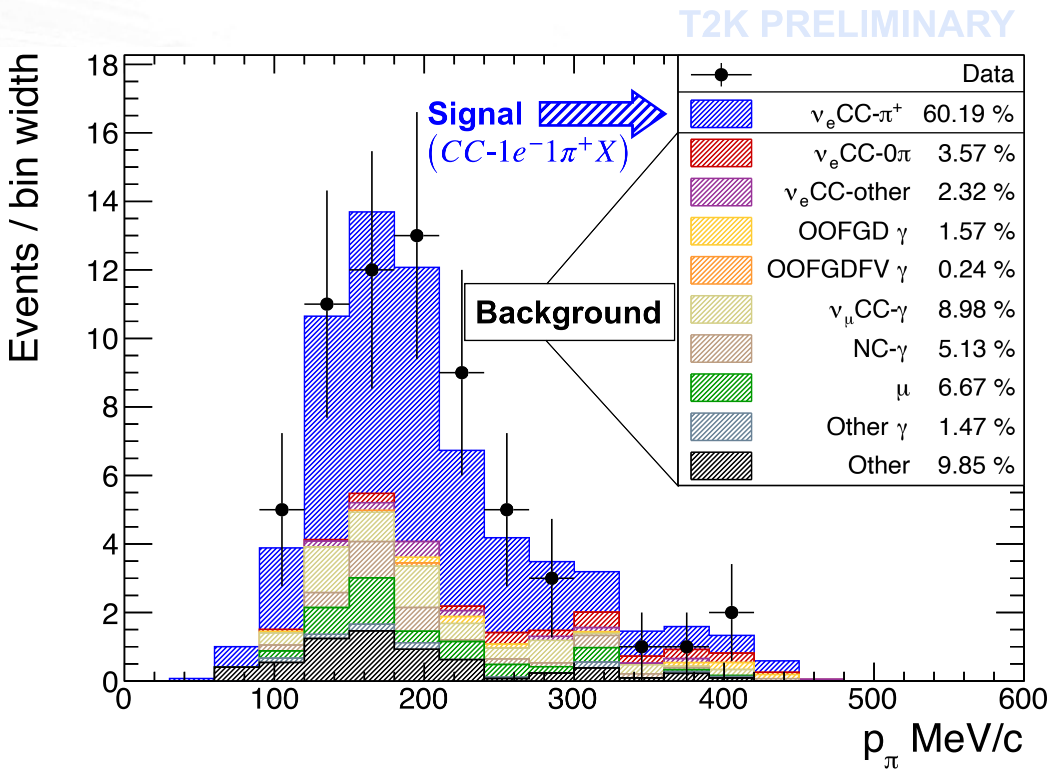
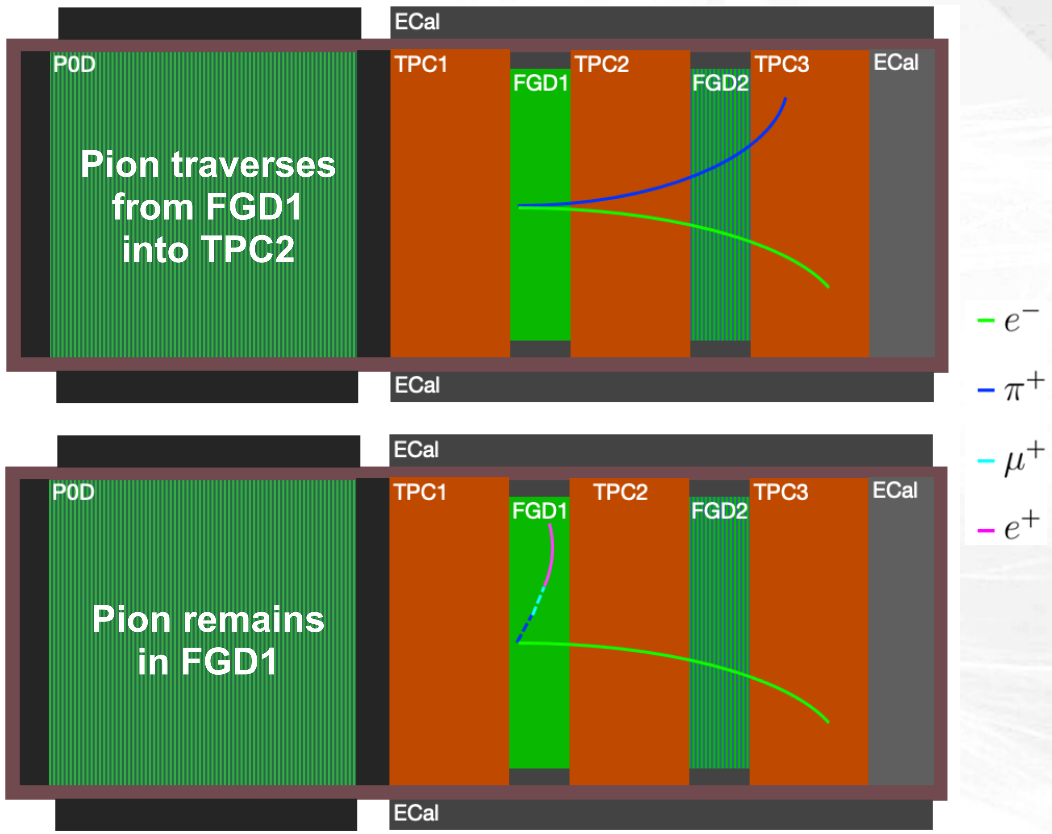


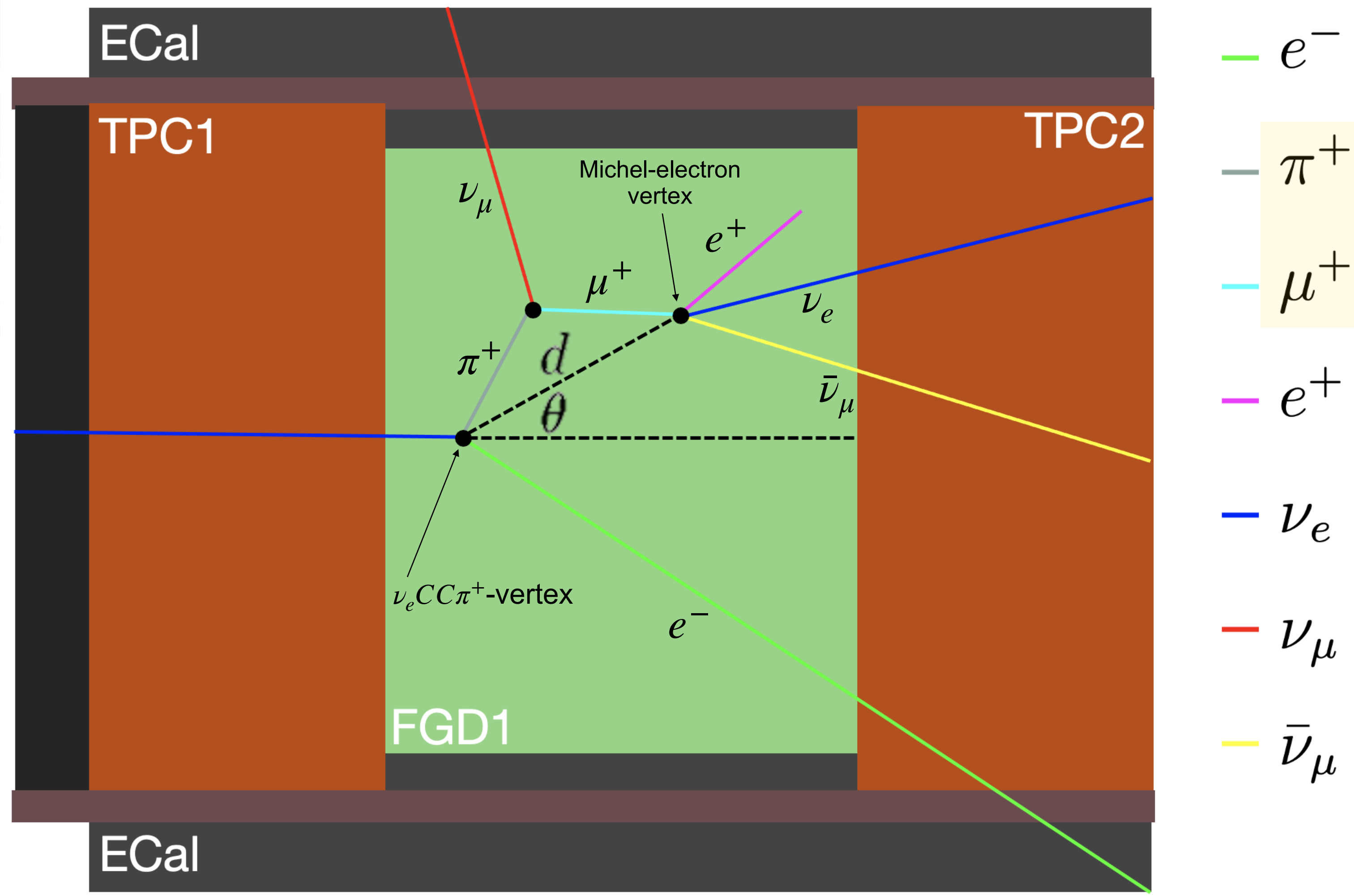
- Signal samples with ν vertex in FGD1:



ν_e-CC$1\pi^{\pm}$ Interactions

$\sigma^{CC1\pi}_{\nu_e-CH}$ publication in preparation

Pion Kinematics Reconstruction from Michel Electrons

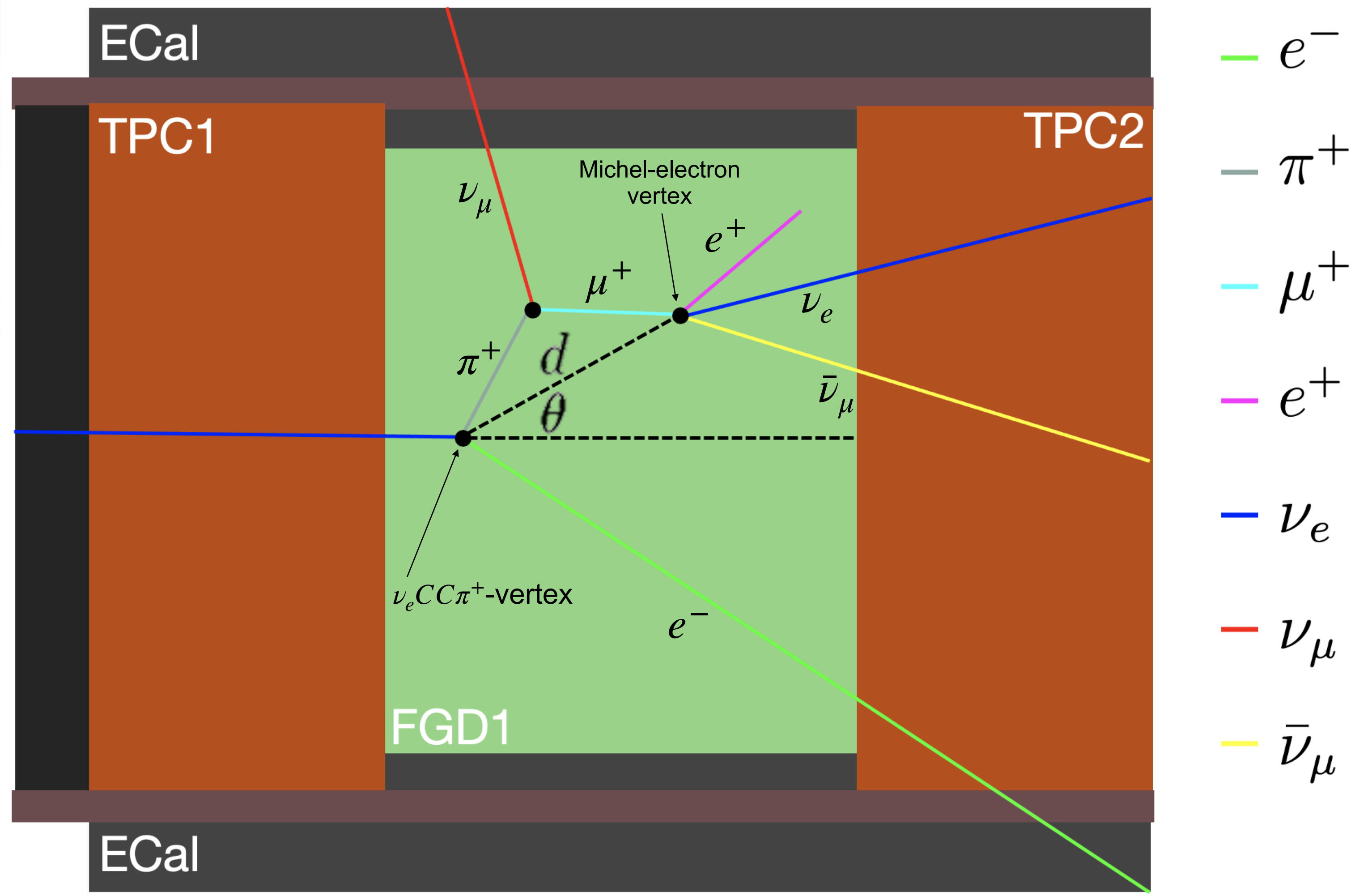


Note: Track lengths are exaggerated to show distance d and angle θ describing the original $\nu_e CC\pi^+$ vertex and the Michel-electron vertex.

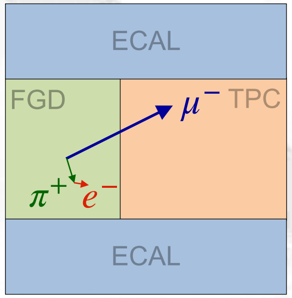
ν_e-CC$1\pi^{\pm}$ Interactions

$\sigma^{CC1\pi}_{\nu_e-CH}$ publication in preparation

Pion Kinematics Reconstruction from Michel Electrons



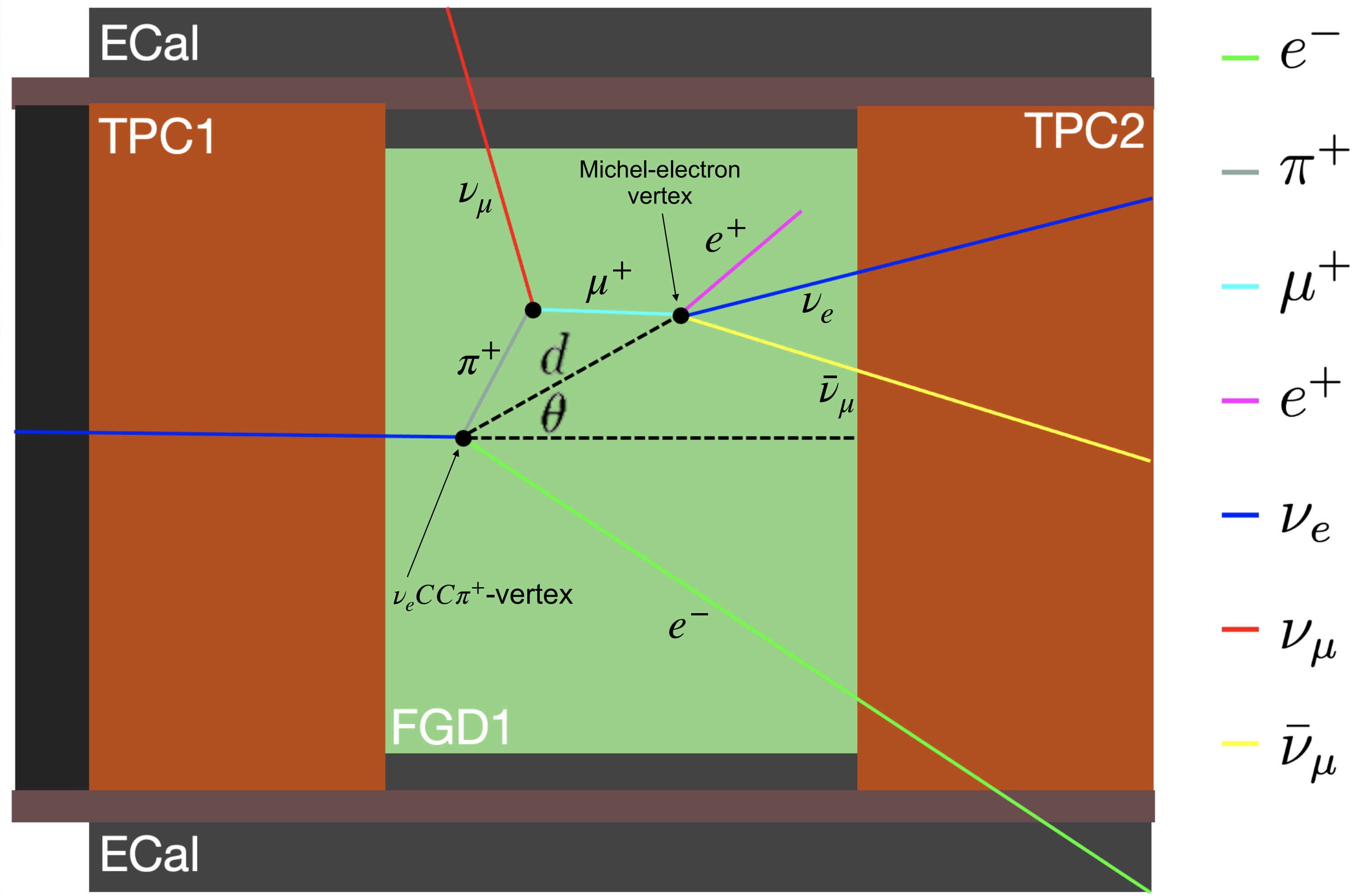
This method was first developed in a $\nu_\mu CC1\pi^+$-analysis. More details can be found in the upcoming publication.



ν_e-CC$1\pi^{\pm}$ Interactions

$\sigma^{CC1\pi}_{\nu_e-CH}$ publication in preparation

Pion Kinematics Reconstruction from Michel Electrons



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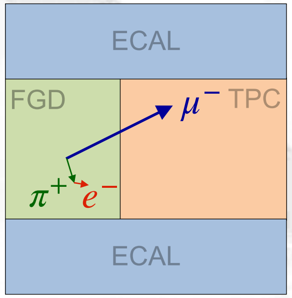
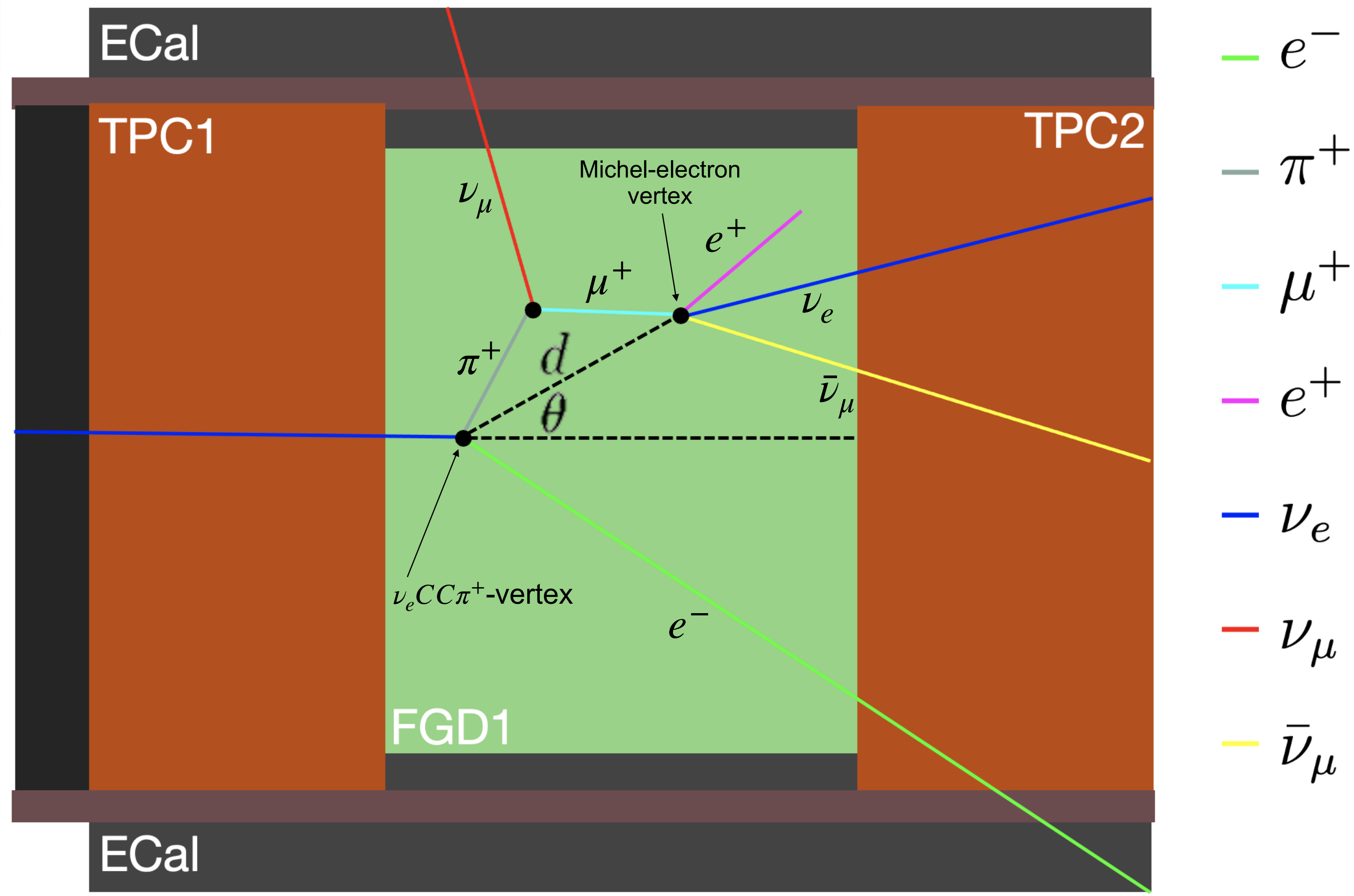


$$p_\pi = c_0 \cdot d^{c_1} + c_2$$

ν_e-CC$1\pi^{\pm}$ Interactions

$\sigma^{CC1\pi}_{\nu_e-CH}$ publication in preparation

Pion Kinematics Reconstruction from Michel Electrons



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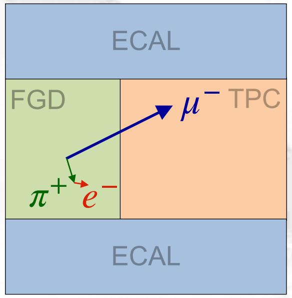
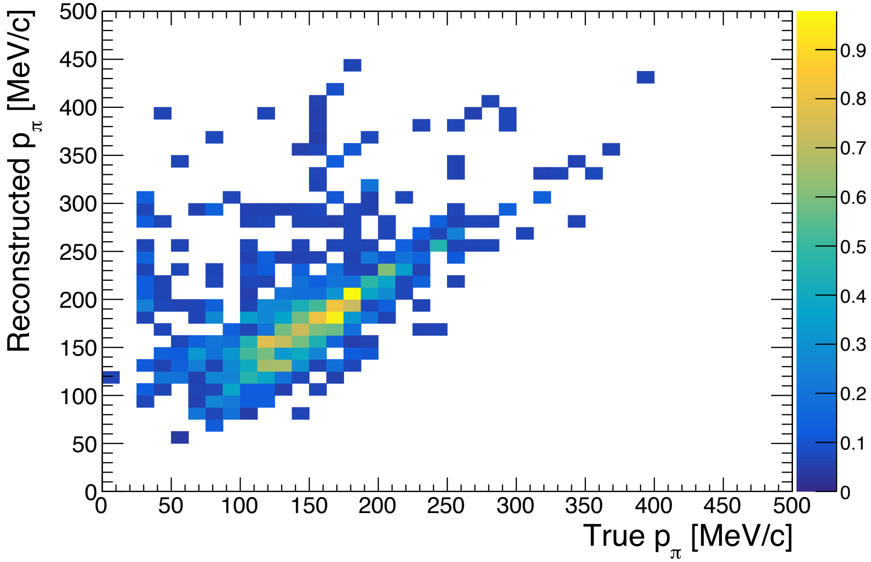
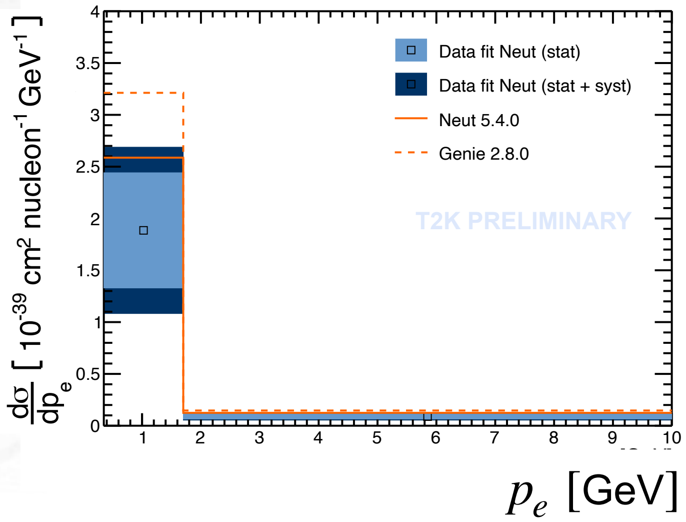


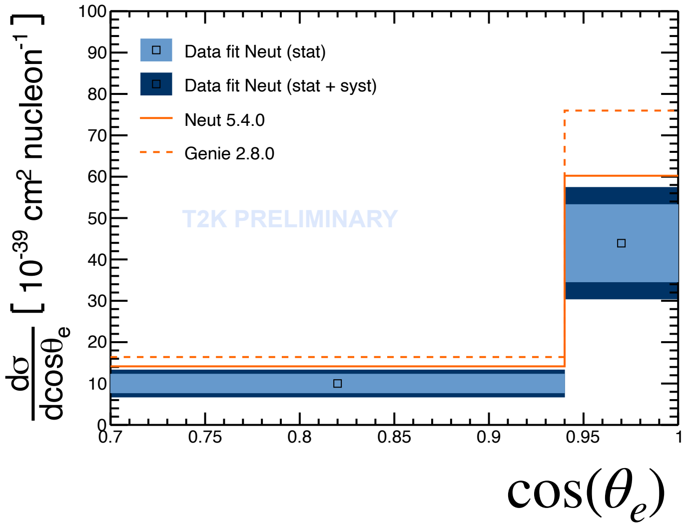
$$p_\pi = c_0 \cdot d^{c_1} + c_2$$

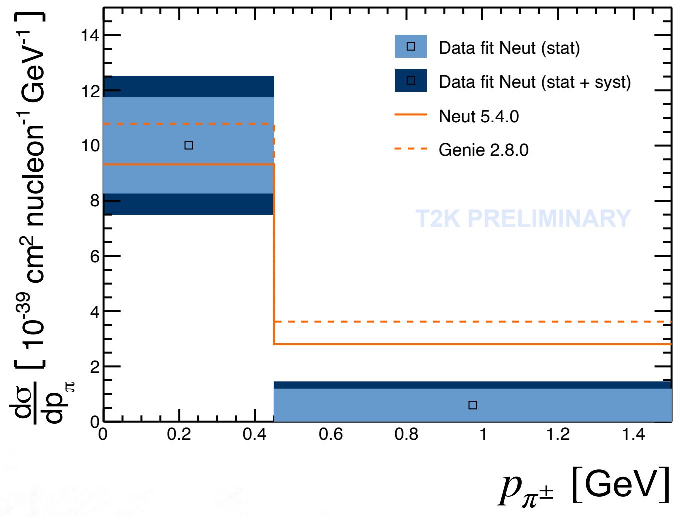


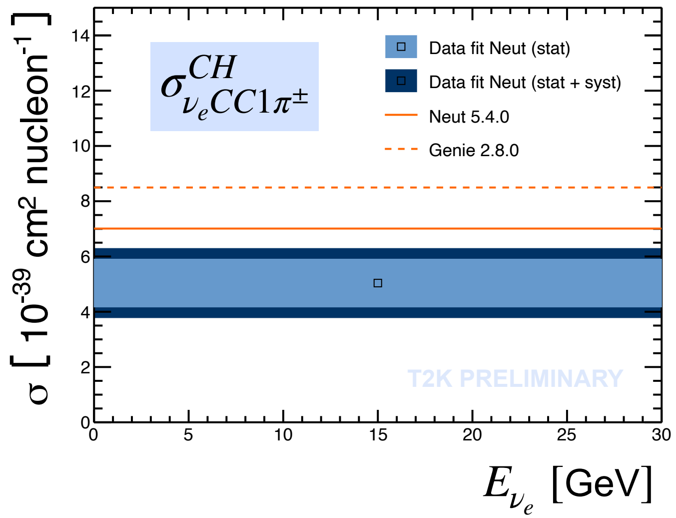
ν_e-CC$1\pi^{\pm}$ Interactions

$\sigma^{CC1\pi}_{\nu_e-CH}$ publication in preparation









- Tendency for overestimation of models, especially for upper pion-momentum region
- Total ν_eCC$1\pi^{\pm}$ cross section slightly lower than inclusive result in JHEP10 (2020) 114

$$\left(\sigma^{CH,prior}_{\nu_e CC\text{-}inc} = (6.62 \pm 1.32(\text{stat.}) \pm 1.30(\text{syst.})) \times 10^{-39}\ \text{cm}^2\ \text{nucleon}^{-1}\right)$$

$$\sigma^{CH}_{\nu_e CC1\pi^{\pm}} = (5.04 \pm 1.20) \times 10^{-39}\ \text{cm}^2\ \text{nucleon}^{-1}$$

Cross-section uncertainty

Source	Error
Detector	5.6%
Flux	6.8%
Interaction model	7.8%
Target mass	0.7%
Total systematic	11.7%
Total statistical	16.3%

dominant source of uncertainty!

T2K Cross-Section Results

- Inclusive $\overset{(-)}{\nu}_\mu$ Charged-Current Cross Section
- $\overset{(-)}{\nu}_\mu$ Charged-Current 1 π Cross Section
- Inclusive $\overset{(-)}{\nu}_e$ Charged-Current Cross Section
- $\overset{(-)}{\nu}_e$ Charged-Current 1 π Cross Section
- $\overset{(-)}{\nu}_\mu$ Charged-Current 0π Cross Section
- $\overset{(-)}{\nu}$ Neutral-Current π^0 Cross Section
- $\overset{(-)}{\nu}$ Quasi-Elastic-like Neutral-Current 0π Cross Section (γ-ray obs.)

Channel	Results (2013 → 2024)
$\sigma^{CC\text{-}inc}_{\overset{(-)}{\nu}_\mu}$	$\sigma^{CC\text{-}inc}_{\nu_\mu-C}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-CH,Fe}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-Fe}$ (INGRID), $\sigma^{CC\text{-}inc}_{\nu_\mu-C,O,H,Cu}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-C,dd}$, $\sigma^{CC\text{-}inc}_{\nu_\mu-H_2O,C,Fe}$
$\sigma^{CC\text{-}inc}_{\overset{(-)}{\nu}_e}$	$\sigma^{CC\text{-}inc}_{\nu_e-C}$, $\sigma^{CC\text{-}inc}_{\nu_e-H_2O}$, $\sigma^{CC\text{-}inc}_{\nu_e-plastic}$
$\sigma^{CC0\pi}_{\overset{(-)}{\nu}_\mu}$	$\sigma^{CCQE0\pi}_{\nu_\mu-C}$, $\sigma^{CCQE0\pi}_{\nu_\mu-C,off-axis}$, $\sigma^{CC0\pi}_{\nu_\mu-C_8H_8}$, $\sigma^{CC0\pi}_{\nu_\mu-H_2O}$, $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (TKI), $\sigma^{CC0\pi}_{\nu_\mu,\nu_{\bar{\mu}}-CH}$, $\sigma^{CC0\pi}_{\nu_\mu-O+C}$, $\sigma^{CC0\pi}_{\bar{\nu}_\mu-H_2O}$, $\sigma^{CC0\pi}_{\nu_\mu-H_2O,C}$ (INGRID+ WAGASCI), $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (ND280+ INGRID), $\sigma^{CC0\pi}_{\nu_\mu-H_2O,CH}$ (WAGASCI- BabyMIND)
$\sigma^{NC0\pi}_{\overset{(-)}{\nu}}$	$\sigma^{NC0\pi}_{\nu-O}$, $\sigma^{NC0\pi}_{\nu,\bar{\nu}-O}$
$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_\mu}$	$\sigma^{CC1\pi\text{-}COH}_{\nu_\mu-C}$, $\sigma^{CC1\pi^+}_{\nu_\mu-H_2O}$, $\sigma^{CC1\pi}_{\nu_\mu-CH}$, $\sigma^{CC1\pi}_{\nu_\mu-CH}$ (TKI), $\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu-C}$
$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_e}$	$\sigma^{CC1\pi}_{\nu_e-CH}$
$\sigma^{NC1\pi}_{\overset{(-)}{\nu}}$	$\sigma^{NC1\pi^0}_{\nu,\bar{\nu}-H_2O}$, $\sigma^{NC1\pi^+}_{\nu,\bar{\nu}-CH}$

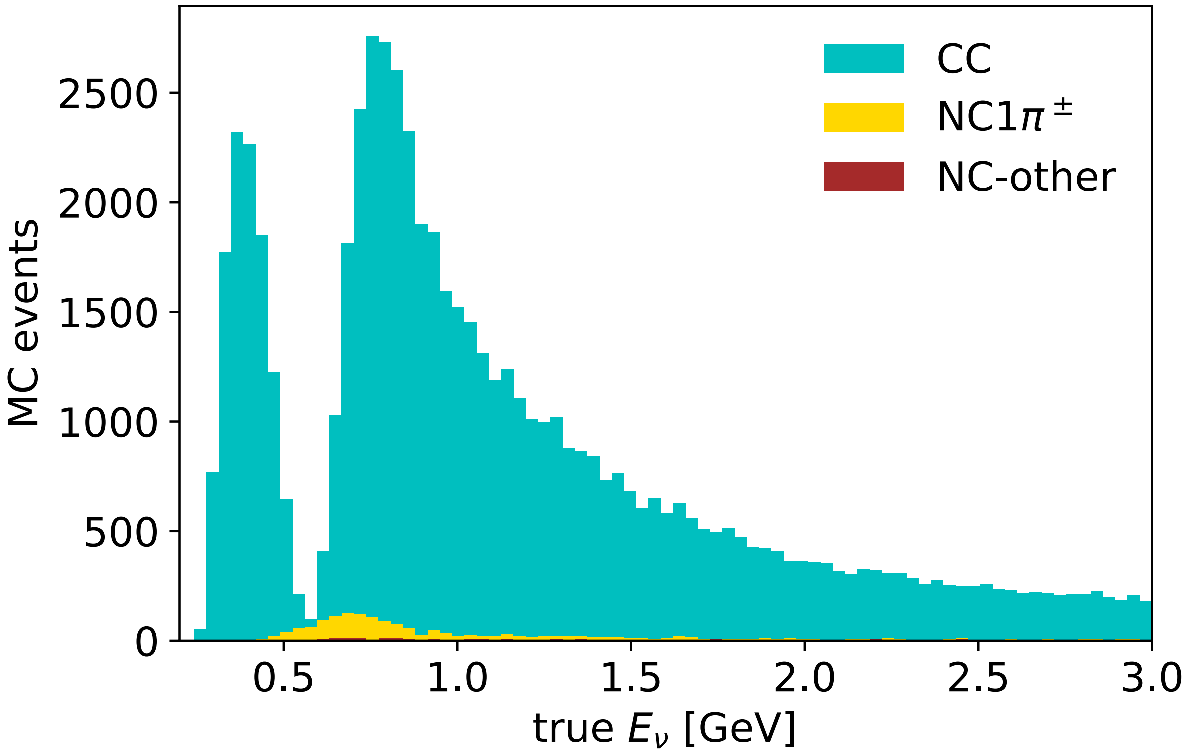
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

Neutrino-NC1π^+ Interactions on Hydrocarbon

$\sigma^{NC1\pi^+}_{\nu,\bar{\nu}-CH}$ publication in preparation

- Motivation:
  - NC1$\pi^\pm$ and CC0π look similar in SK

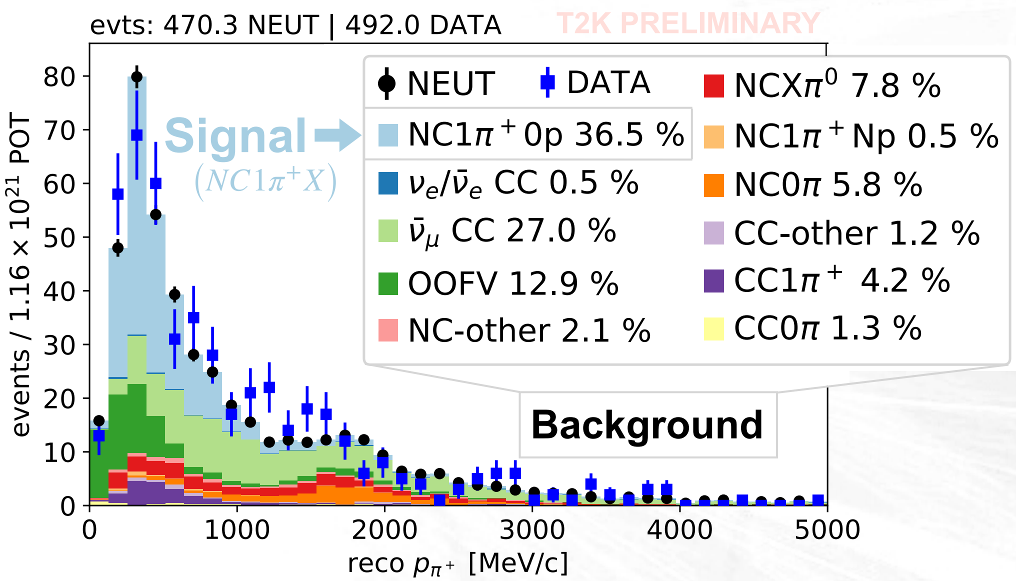
Oscillated (muon-disappearance) selected SK 1μ-ring sample events



- Signal definition: NC1π^+0p where

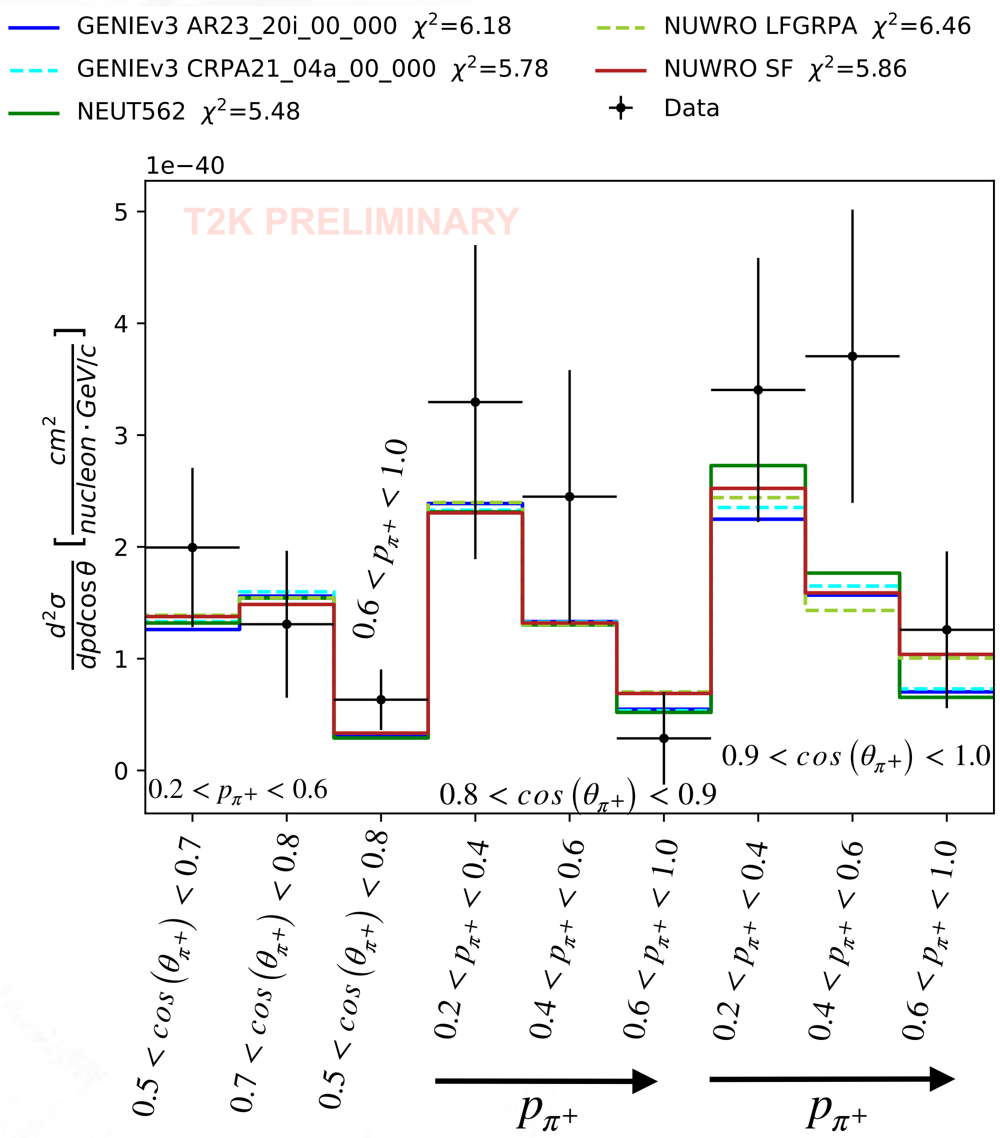
Particle	Momentum p [GeV/c]	Angle θ
π^+	$0.2 - 1.0$	$< 60°$
p	< 0.2	

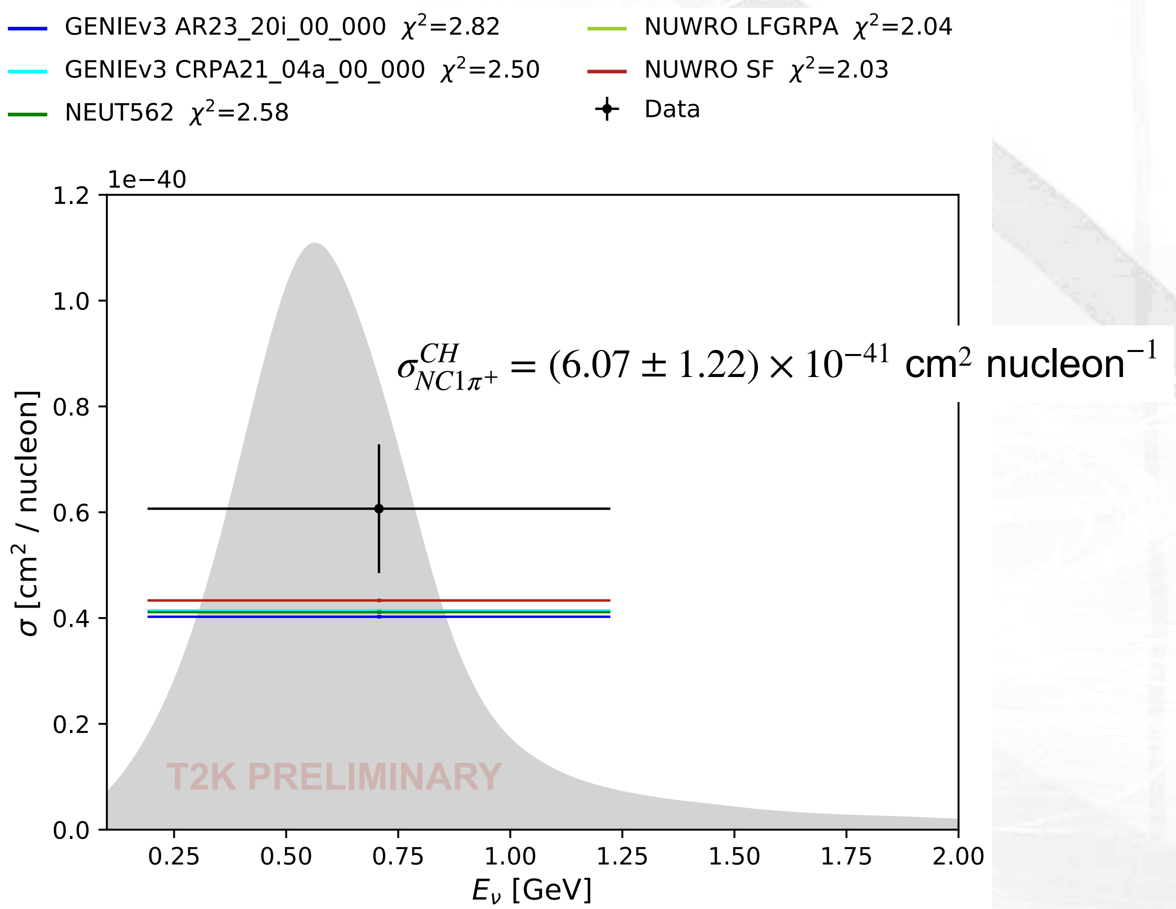
Proton momentum condition makes this count as 0p



Neutrino-NC$1\pi^+$ Interactions on Hydrocarbon

$\sigma^{NC1\pi^+}_{\nu,\bar{\nu}-CH}$ publication in preparation





T2K Cross-Section Results

Inclusive $\overset{(-)}{\nu}_\mu$ Charged-Current Cross Section

$\overset{(-)}{\nu}_\mu$ Charged-Current 1 π Cross Section

Inclusive $\overset{(-)}{\nu}_e$ Charged-Current Cross Section

$\overset{(-)}{\nu}_e$ Charged-Current 1 π Cross Section

$\overset{(-)}{\nu}_\mu$ Charged-Current 0π Cross Section

$\overset{(-)}{\nu}$ Neutral-Current π^0 Cross Section

$\overset{(-)}{\nu}$ Quasi-Elastic-like Neutral-Current 0π Cross Section (γ-ray obs.)

$\sigma^{CC\text{-}inc}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CC\text{-}inc}_{\nu_\mu-C}$ $\sigma^{CC\text{-}inc}_{\nu_\mu-CH,Fe}$ $\sigma^{CC\text{-}inc}_{\nu_\mu-Fe}$ (INGRID) $\sigma^{CC\text{-}inc}_{\nu_\mu-C,O,H,Cu}$ $\sigma^{CC\text{-}inc}_{\nu_\mu-C,dd}$ $\sigma^{CC\text{-}inc}_{\nu_\mu-H_2O,C,Fe}$

$\sigma^{CC\text{-}inc}_{\overset{(-)}{\nu}_e}$: $\sigma^{CC\text{-}inc}_{\nu_e-C}$ $\sigma^{CC\text{-}inc}_{\nu_e-H_2O}$ $\sigma^{CC\text{-}inc}_{\nu_e-plastic}$

$\sigma^{CC0\pi}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CCQE0\pi}_{\nu_\mu-C}$ $\sigma^{CCQE0\pi}_{\nu_\mu-C,off-axis}$ $\sigma^{CC0\pi}_{\nu_\mu-C_8H_8}$ $\sigma^{CC0\pi}_{\nu_\mu-H_2O}$ $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (TKI) $\sigma^{CC0\pi}_{\nu_\mu,\bar{\nu}_\mu-CH}$ $\sigma^{CC0\pi}_{\nu_\mu-O+C}$ $\sigma^{CC0\pi}_{\bar{\nu}_\mu-H_2O}$ $\sigma^{CC0\pi}_{\nu_\mu-H_2O,C}$ (INGRID+ WAGASCI) $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (ND280+ INGRID) $\sigma^{CC0\pi}_{\nu_\mu-H_2O,CH}$ (WAGASCI- BabyMIND)

$\sigma^{NC0\pi}_{\overset{(-)}{\nu}}$: $\sigma^{NC0\pi}_{\nu-O}$ $\sigma^{NC0\pi}_{\nu,\bar{\nu}-O}$

$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_\mu}$: $\sigma^{CC1\pi\text{-}COH}_{\nu_\mu-C}$ $\sigma^{CC1\pi^+}_{\nu_\mu-H_2O}$ $\sigma^{CC1\pi}_{\nu_\mu-CH}$ $\sigma^{CC1\pi}_{\nu_\mu-CH}$ (TKI) $\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu-C}$

$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_e}$: $\sigma^{CC1\pi}_{\nu_e-CH}$

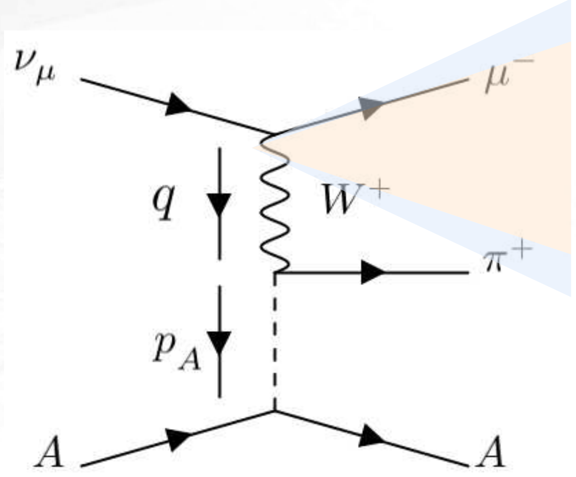
$\sigma^{NC1\pi}_{\overset{(-)}{\nu}}$: $\sigma^{NC1\pi^0}_{\nu,\bar{\nu}-H_2O}$ $\sigma^{NC1\pi^+}_{\nu,\bar{\nu}-CH}$

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

ν_μ Coherent Charged Pion Scattering on Carbon

$\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu-C}$ Phys. Rev. D **108**, 092009

Coherent charged pion production from a neutrino coherently scattering off a nucleus:

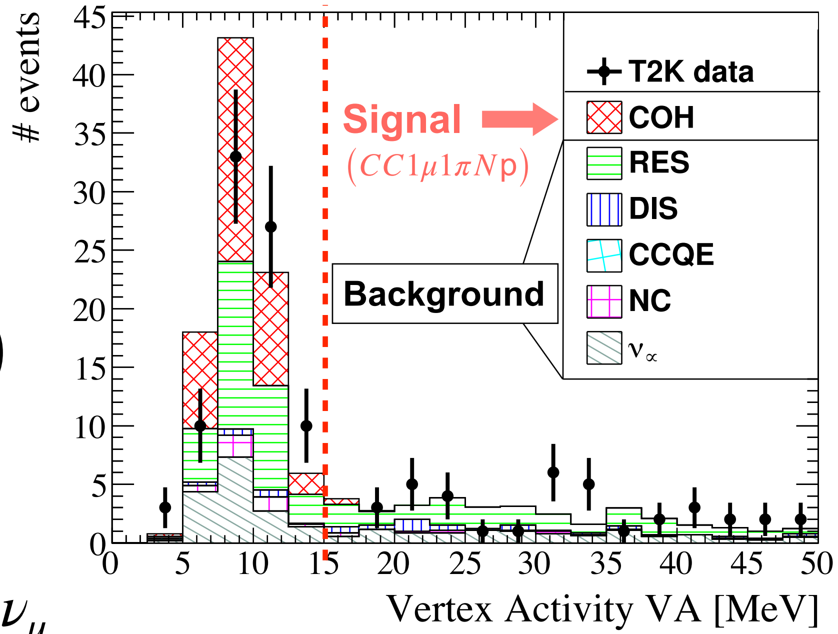


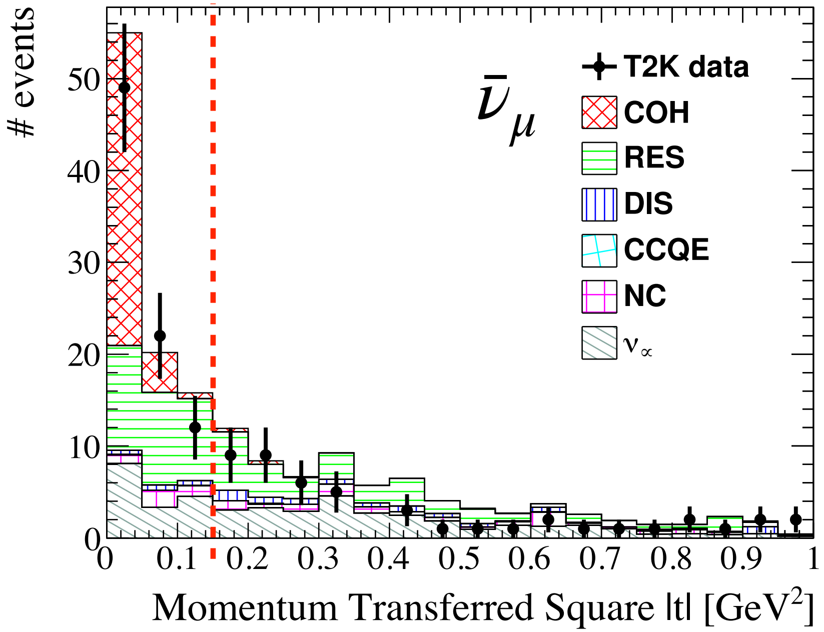
$$\overset{(-)}{\nu}_\mu + A \to \mu^{\overset{(+)}{-}} + \pi^{\overset{(-)}{+}} + A$$

$p_\mu > 0.2$GeV and $\cos(\theta_\mu) > 0.8$ $(\theta_\mu < 37^\circ)$

$p_\pi > 0.2$GeV and $\cos(\theta_\pi) > 0.6$ $(\theta_\pi < 53^\circ)$

- Event selection: CC$1\mu1\pi N$p and require
  - low vertex activity (hadrons $\lesssim$15 MeV VA in 5cm^2 volume around vertex)
  - low 4-momentum transfer to nucleus ($\lesssim$0.15 GeV^2)



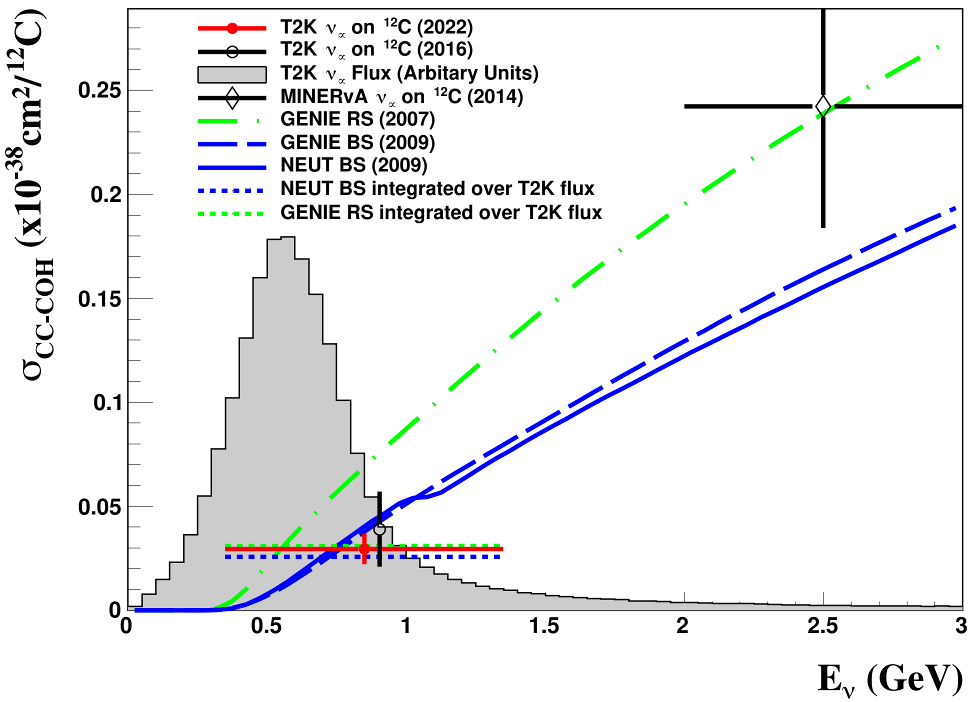


analogously for ν_μ

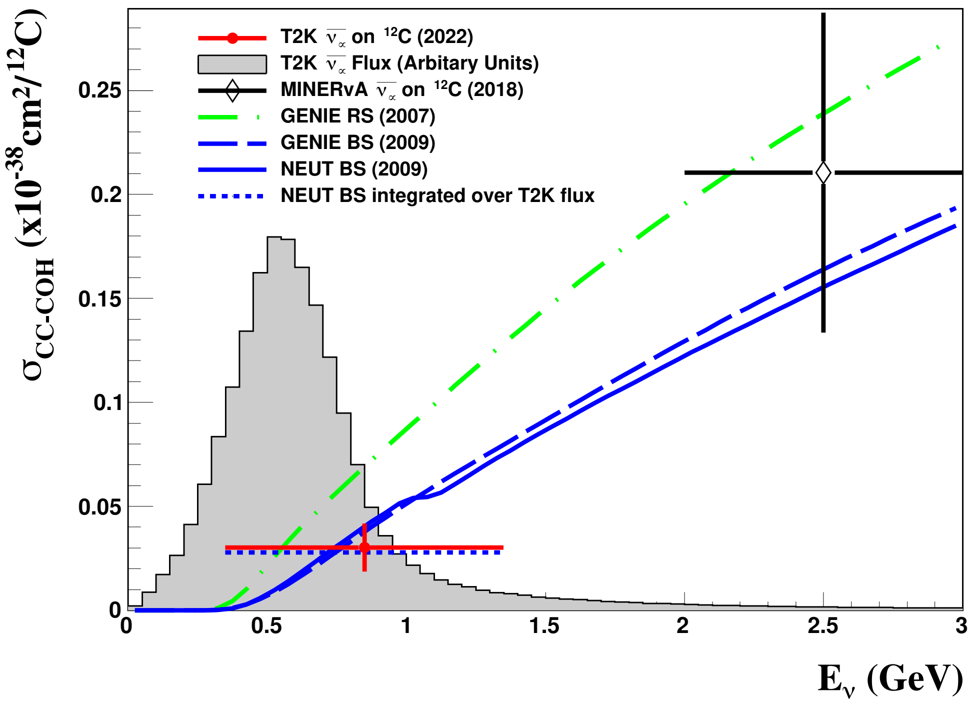
ν_μ Coherent Charged Pion Scattering on Carbon

- First measurement of $\bar{\nu}_\mu$ CC-COH cross section at mean energy less than 1GeV! $\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu - C}$ Phys. Rev. D **108**, 092009
- ν_μ CC-COH cross section consistent with previous 2016 T2K result ($\sigma^{CC1\pi\text{-}COH}_{\nu_\mu - C}$ Phys. Rev. Lett. **117**, 192501) with the fractional total uncertainty reduced from 46% to 23 %.

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



$E_{\bar{\nu}}^{peak} \sim 0.85$ GeV



$\sigma^{^{12}C,\ COH}_{\nu_\mu} = (2.98 \pm 0.37(\text{stat.}) \pm 0.31(\text{syst.})^{+0.49}_{-0.00}(Q^2\text{model}) \times 10^{-40}\ \text{cm}^2)$

$\sigma^{^{12}C,\ COH}_{\bar{\nu}_\mu} = (3.05 \pm 0.71(\text{stat.}) \pm 0.39(\text{syst.})^{+0.74}_{-0.00}(Q^2\text{model}) \times 10^{-40}\ \text{cm}^2)$

Summary and Outlook

- ~ 30 T2K cross-section publications on CC, NC muon- and electron-(anti-)neutrino interactions on various targets

  $\sigma^{CC\text{-}inc,0\pi,1\pi^{\pm}}_{\overset{(-)}{\nu}_{\mu},\overset{(-)}{\nu}_{e}-C,CH,O,H_2O,Fe}$

- More and more joint measurements (correlated energies, other experiments)

  $\sigma^{CC0\pi}_{\nu_\mu-CH}$ (ND280+ INGRID) Phys. Rev. D **108**, 112009

- More work to be done for better generator-data agreement
- Novel technique for low-momentum pion kinematics reconstruction

  $\sigma^{CC1\pi}_{\nu_e-CH}$ **publication in preparation**

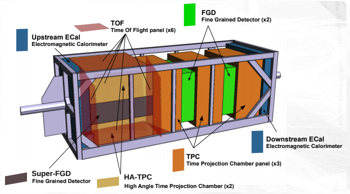
- Understanding of non-negligible backgrounds (NC$1\pi^+$) for neutrino oscillation experiments

  $\sigma^{NC1\pi^+}_{\nu,\bar{\nu}-CH}$ **publication in preparation**

- Data-based tuning for enhanced flux prediction

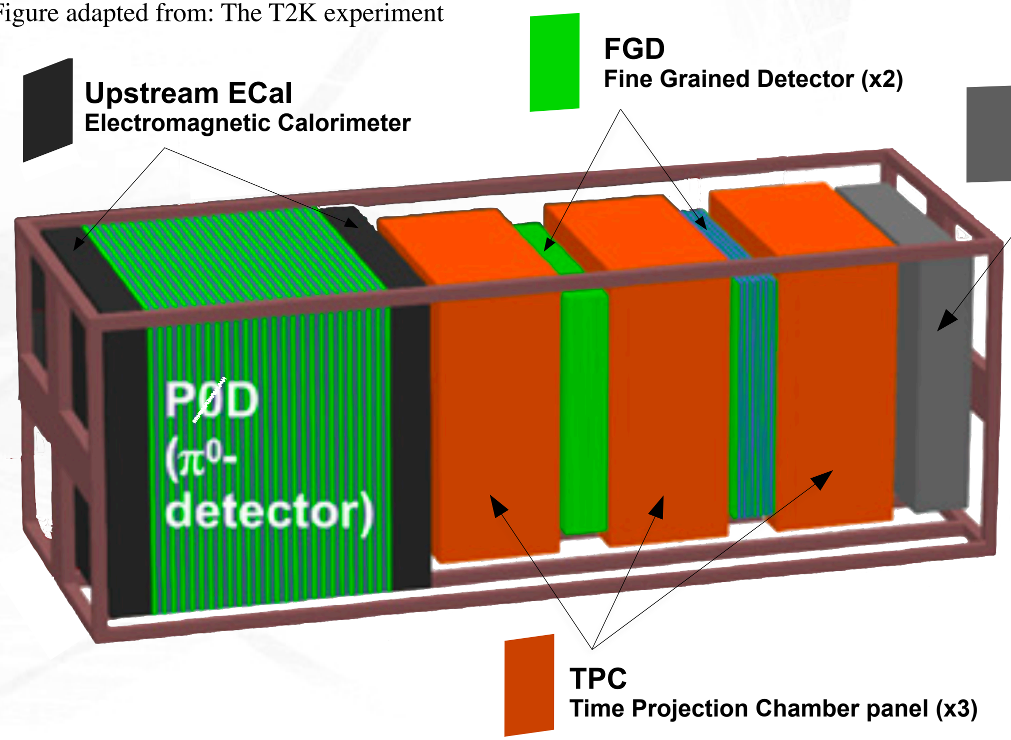
  $\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu-C}$ Phys. Rev. D **108**, 092009

- J-PARC accelerator upgrade will increase beam power → higher rate of data taking
- ND280 upgrade will increase detector capabilities, angle coverage, better low momentum tracking and provide more target mass



- Upcoming publications on NC-$1\pi^+$, ν_eCC-1π on CH, updated $\nu_\mu CC\text{-}1\pi$ on CH and H_2O, NC-π^0 on H_2O, CC-$1K^+$ on CH and more.
- More details on T2K results at https://t2k-experiment.org/publications/

Figure adapted from: The T2K experiment



T2K Near Detectors

ND280 Upgrade

For more details, see talk from Wednesday by Lorenzo Magaletti on T2K upgrades: near detector and beam

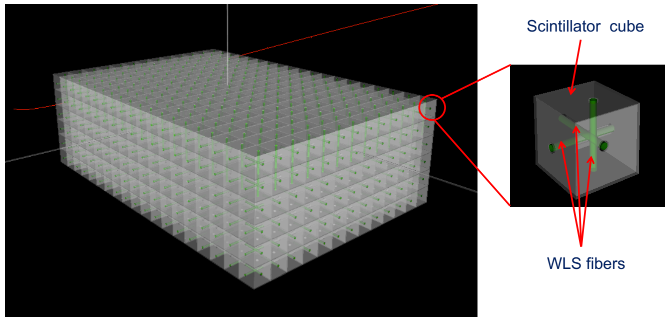


Figure 2.1: Schematic concept of the SuperFGD structure. The size of each cube is 1 × 1

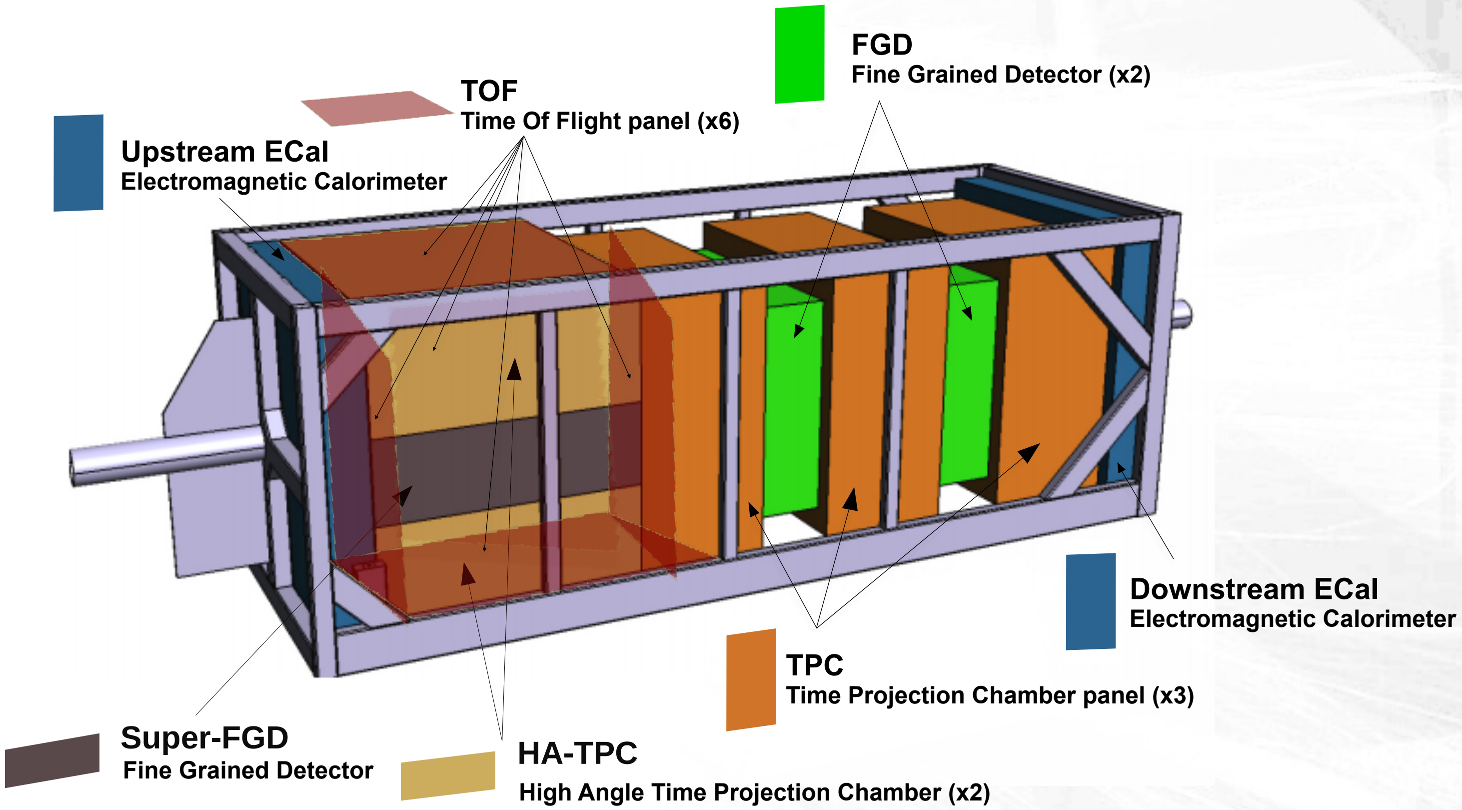
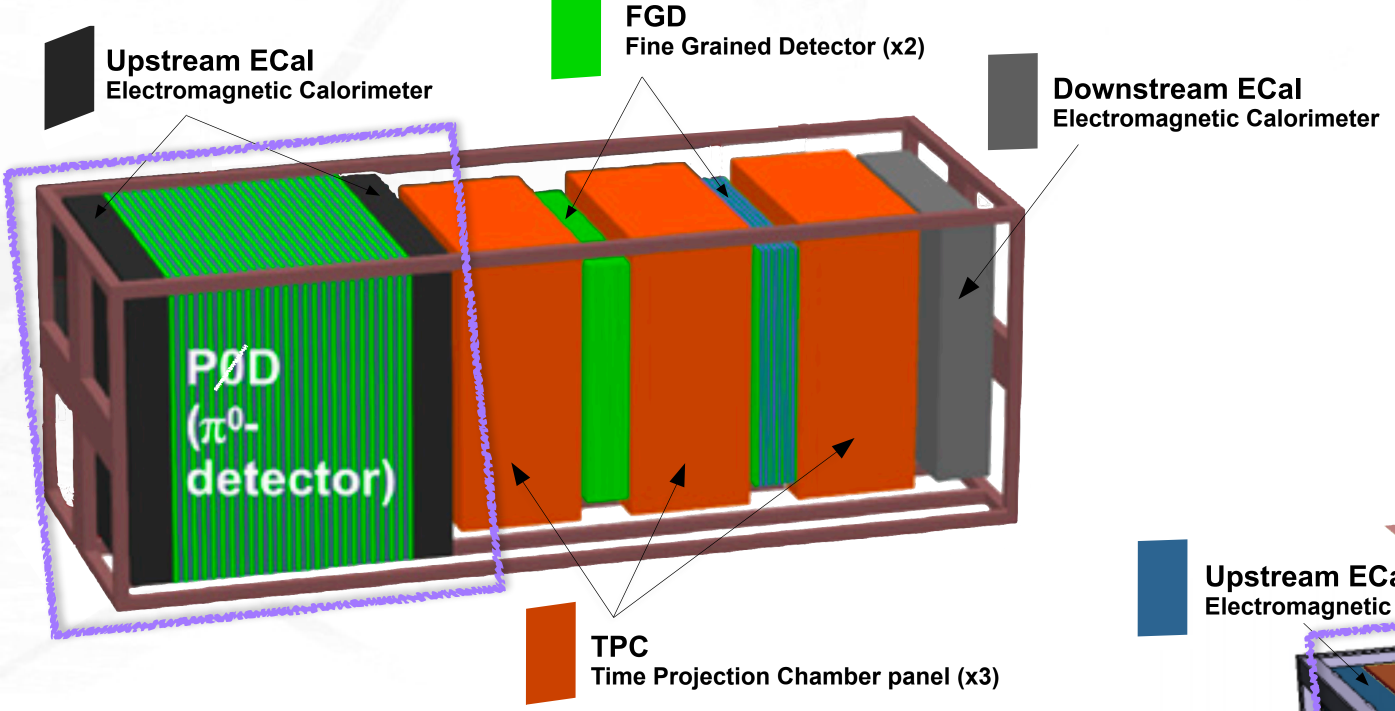


Figure adapted from: T2K ND280 Upgrade - TDR

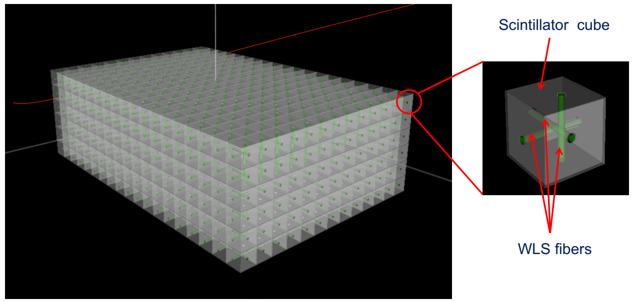
Figure adapted from: The T2K experiment



- ND280 Upgrade:
  - Replace Pi-zero Detector (PØD) with
    - SFGD
    - 2 HA-TPCs
    - 6 TOF panels
  - Reduce systematic errors from ~6% to ~4%

T2K Near Detectors

ND280



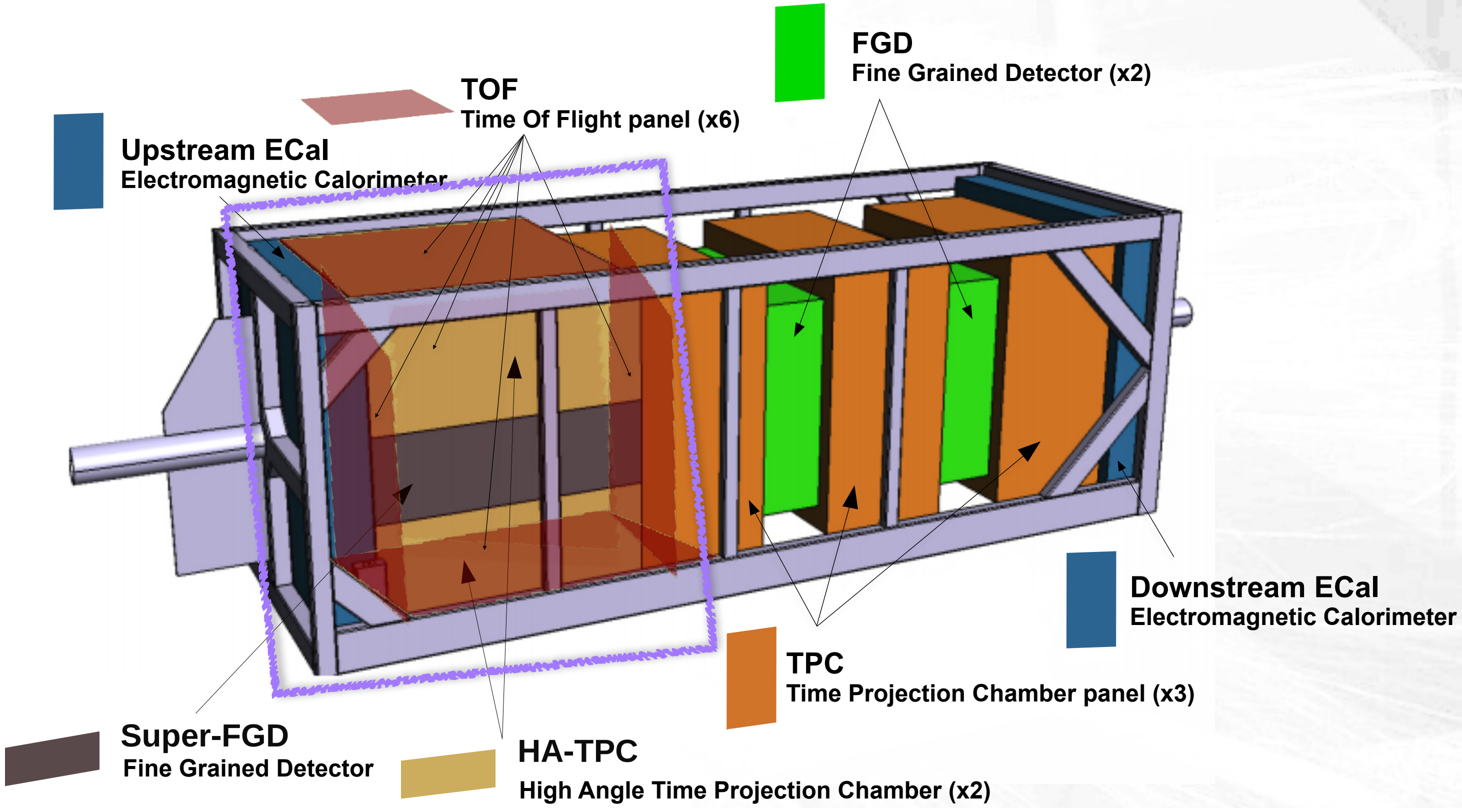
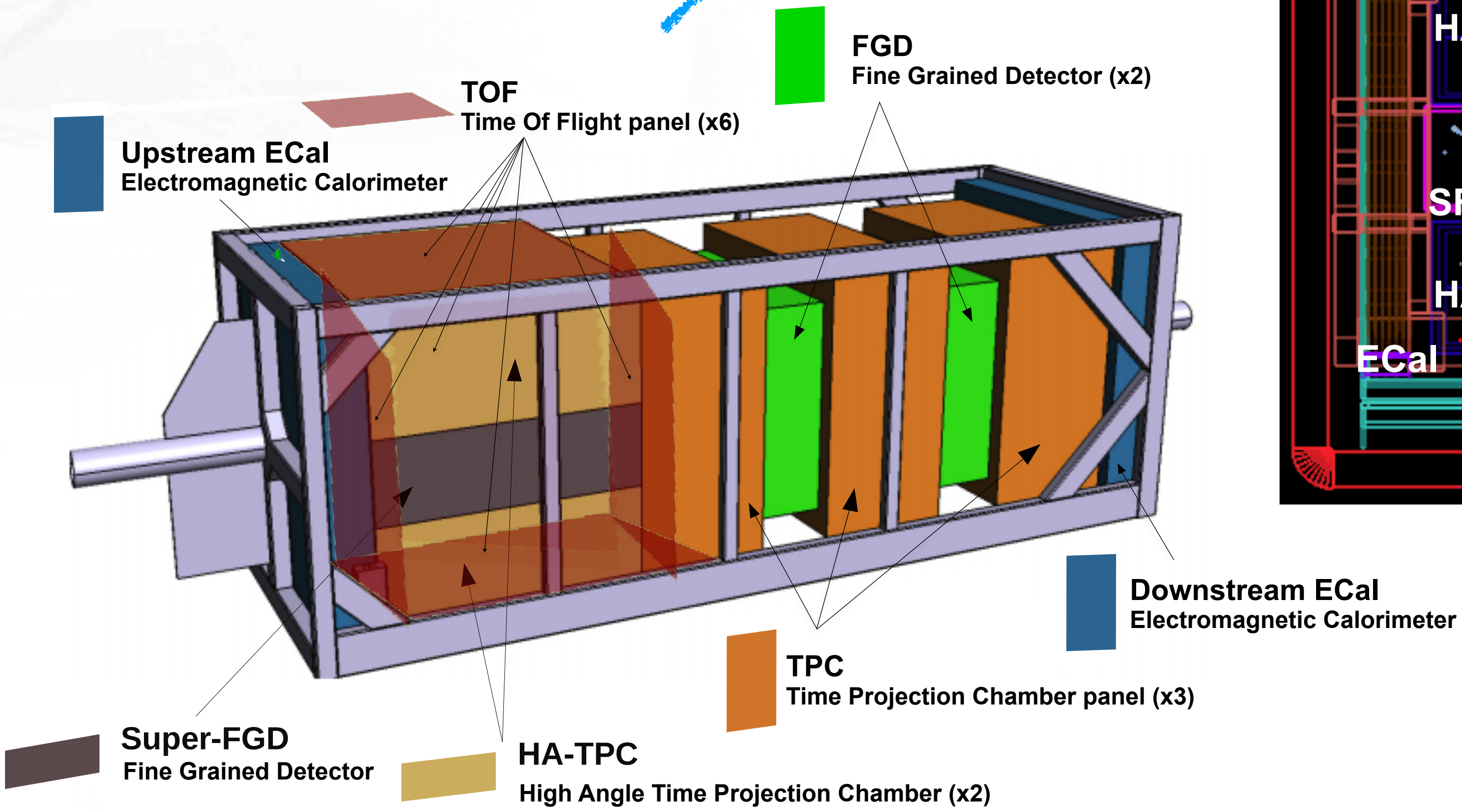


Figure adapted from: T2K ND280 Upgrade - TDR

T2K Near Detectors

ND280 Upgrade



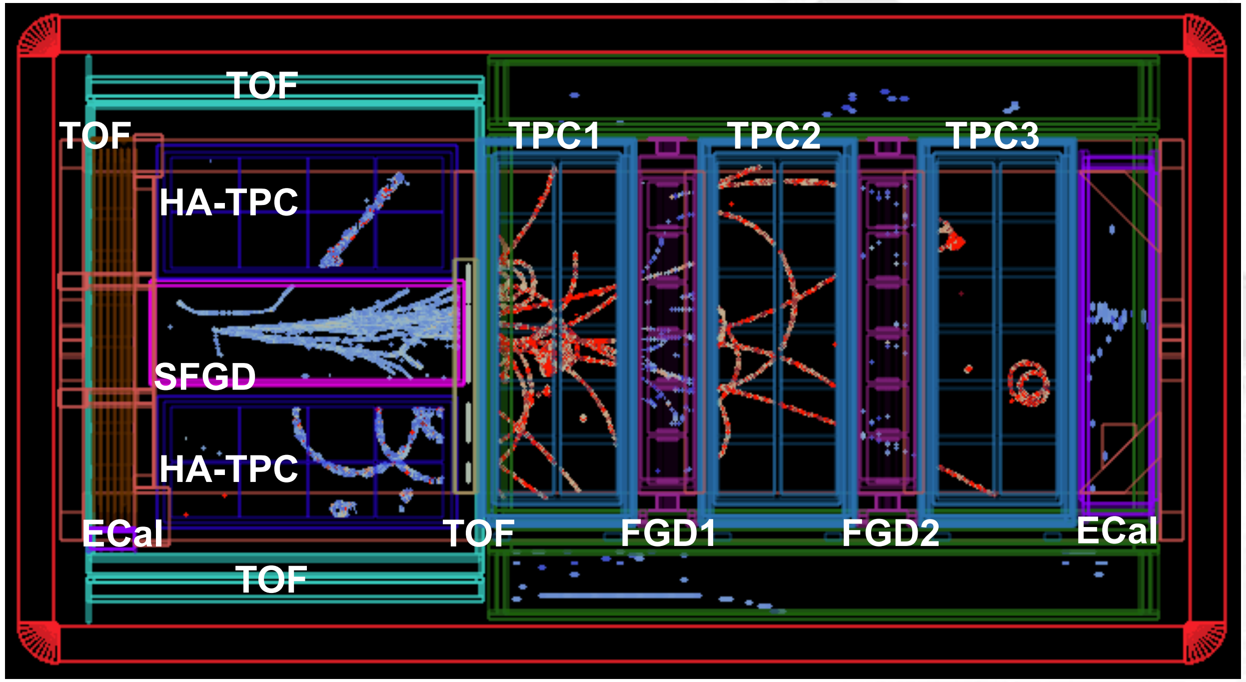


Figure adapted from: T2K ND280 Upgrade - TDR

ND280 DAQ expert and upgrade work in February and March 2024.

Backup

T2K Cross-Section Results

Inclusive $\overset{(-)}{\nu}_\mu$ Charged-Current Cross Section	$\sigma^{CC\ inc}_{\overset{(-)}{\nu}_\mu}$
Inclusive $\overset{(-)}{\nu}_e$ Charged-Current Cross Section	$\sigma^{CC\ inc}_{\overset{(-)}{\nu}_e}$
$\overset{(-)}{\nu}_\mu$ Charged-Current 0π Cross Section	$\sigma^{CC\ 0\pi}_{\overset{(-)}{\nu}_\mu}$
$\overset{(-)}{\nu}$ Quasi-Elastic-like Neutral-Current 0π Cross Section (γ-ray obs.)	$\sigma^{NC\ 0\pi}_{\overset{(-)}{\nu}}$
$\overset{(-)}{\nu}_\mu$ Charged-Current 1π Cross Section	$\sigma^{CC\ 1\pi}_{\overset{(-)}{\nu}_\mu}$
$\overset{(-)}{\nu}_e$ Charged-Current 1π Cross Section	$\sigma^{CC\ 1\pi}_{\overset{(-)}{\nu}_e}$
$\overset{(-)}{\nu}$ Neutral-Current π^0 Cross Section	$\sigma^{NC\ 1\pi}_{\overset{(-)}{\nu}}$

- Phys. Rev. D **95**, 012010 — Jan. 2017, on H_2O
- Phys. Rev. D **101**, 012007 — Jan. 2020, on CH
- Phys. Rev. D **97**, 012001 — Jan. 2018, ν_μ on H_2O
- Phys. Rev. D **97**, 032002 — Feb. 2018, $\nu + \bar{\nu}$ π^0 prod. on H_2O
- PTEP 043C01 — Mar. 2021, on H_2O, CH (INGRID+WAGASCI)
- Phys. Rev. D **93**, 072002 — Apr. 2016, on Fe (INGRID)
- Phys. Rev. D **87** 092003 — May, 2013, on C
- Phys. Rev. D **101**, 112001 — June 2020, $\nu_\mu + \bar{\nu}_\mu$ on CH
- Phys. Rev. D **93**, 112012 — June 2016, on C_8H_8
- Phys. Rev. D **101**, 112004 — June 2020, on O+C
- Phys. Rev. D **91**, 112002 — June 2015, QE on C (on-axis)
- Phys. Rev. D **91**, 112010 — June 2015, on H_2O
- Phys. Rev. D **98** 012004 — July 2018, double-differential on C
- Phys. Rev. D **103**, 112009 — June 2021, on CH (nuclear effects)
- T2K-TN-412 — 2024, $\nu + \bar{\nu}$ π^+ prod. on CH
- Phys. Rev. D **96** 052001 — Sep. 2017, on C, O, H, Cu
- Phys. Rev. D **102**, 012007 — July 2020, $\bar{\nu}_\mu$ on H_2O
- Phys. Rev. D **90** 052010 — Sep. 2014, on CH, Fe
- T2K-TN-445 — 2024, on H_2O, CH (WAGASCI-BabyMIND)
- Phys. Rev. D **98**, 032003 — Aug. 2018, on CH (nuclear effects)
- Phys. Rev. D **90**, 072012 — Oct. 2014, ν on O
- T2K-TN-450 — 2024, ν_e on CH
- JHEP10 (2020) 114 — Oct. 2020, differential and total on plastic scintillator
- Phys. Rev. Lett. **117**, 192501 — Nov. 2016, COH on C
- Phys. Rev. D **108**, 092009 — Nov. 2023, $\nu_\mu + \bar{\nu}_\mu$ COH on ^{12}C
- PTEP 093C02 — Sep. 2019, on H_2O, C, Fe
- Phys. Rev. D **92**, 112003 — Dec. 2015, QE on C (off-axis)
- Phys. Rev. D **100**, 112009 — Dec. 2019, $\nu + \bar{\nu}$ on O
- Phys. Rev. D **108**, 112009 — Dec. 2023, ND280 + INGRID
- Phys. Rev. Lett. **113**, 241803 — Dec. 2014, on C

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

T2K Cross-Section Results

Inclusive $\overset{(-)}{\nu}_\mu$ Charged-Current Cross Section	$\sigma^{CC\ inc}_{\overset{(-)}{\nu}_\mu}$
Inclusive $\overset{(-)}{\nu}_e$ Charged-Current Cross Section	$\sigma^{CC\ inc}_{\overset{(-)}{\nu}_e}$
$\overset{(-)}{\nu}_\mu$ Charged-Current 0π Cross Section	$\sigma^{CC\ 0\pi}_{\overset{(-)}{\nu}_\mu}$
$\overset{(-)}{\nu}$ Quasi-Elastic-like Neutral-Current 0π Cross Section (γ-ray obs.)	$\sigma^{NC\ 0\pi}_{\overset{(-)}{\nu}}$
$\overset{(-)}{\nu}_\mu$ Charged-Current 1π Cross Section	$\sigma^{CC\ 1\pi}_{\overset{(-)}{\nu}_\mu}$
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Phys. Rev. D **95**, 012010 — Jan. 2017, on H_2O

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Phys. Rev. D **91**, 112002 — June 2015, QE on C (on-axis)

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Phys. Rev. D **103**, 112009 — June 2021, on CH (nuclear effects)

T2K-TN-412 — 2024, $\nu + \bar{\nu}$ π^+ prod. on CH

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Phys. Rev. D **102**, 012007 — July 2020, $\bar{\nu}_\mu$ on H_2O

Phys. Rev. D **90** 052010 — Sep. 2014, on CH, Fe

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JHEP10 (2020) 114 — Oct. 2020, differential and total on plastic scintillator

Phys. Rev. Lett. **117**, 192501 — Nov. 2016, COH on C

Phys. Rev. D **108**, 092009 — Nov. 2023, $\nu_\mu + \bar{\nu}_\mu$ COH on ^{12}C

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Phys. Rev. D **92**, 112003 — Dec. 2015, QE on C (off-axis)

Phys. Rev. D **100**, 112009 — Dec. 2019, $\nu + \bar{\nu}$ on O

Phys. Rev. D **108**, 112009 — Dec. 2023, ND280 + INGRID

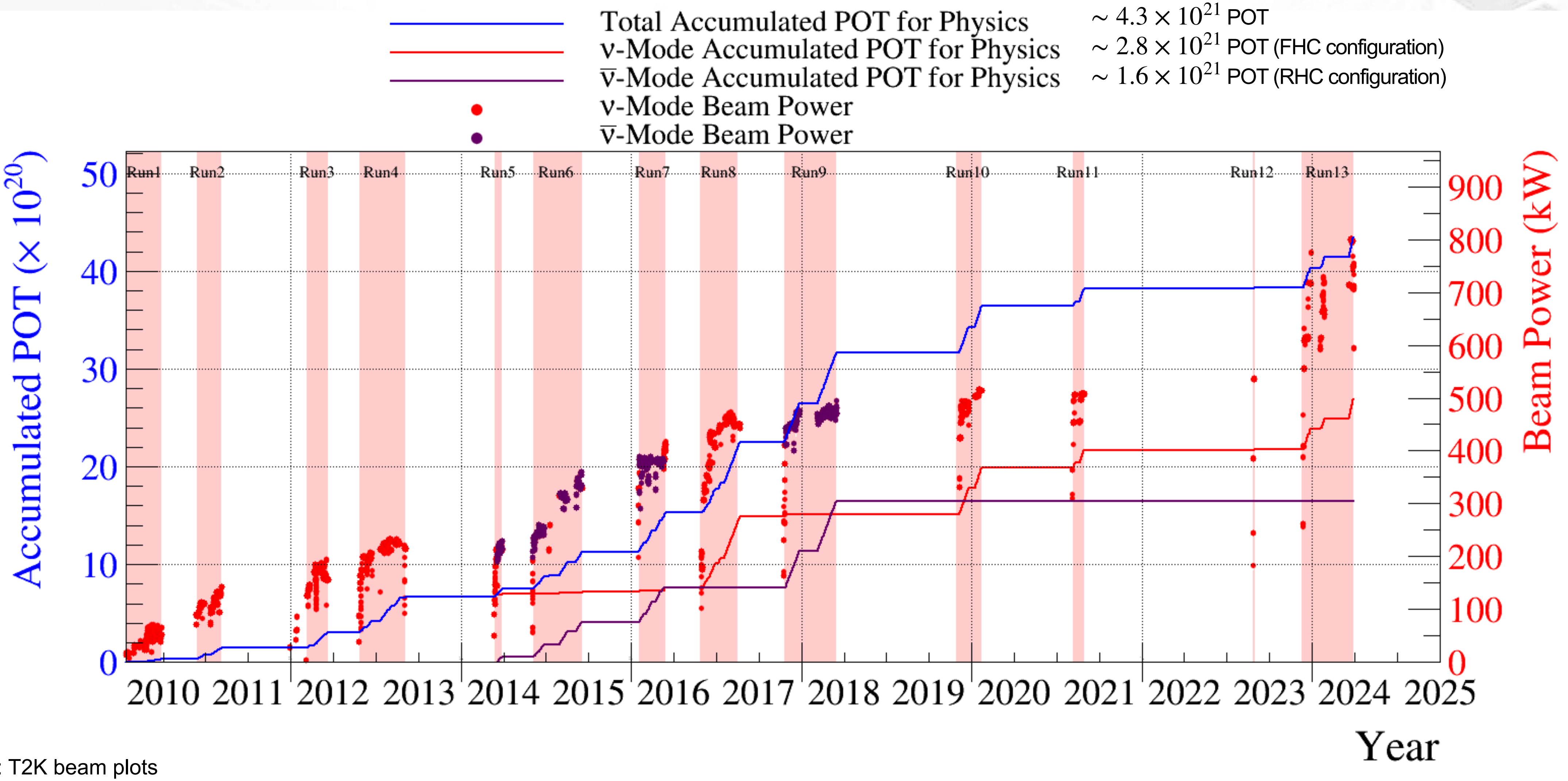
Phys. Rev. Lett. **113**, 241803 — Dec. 2014, on C

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

T2K Data-Taking

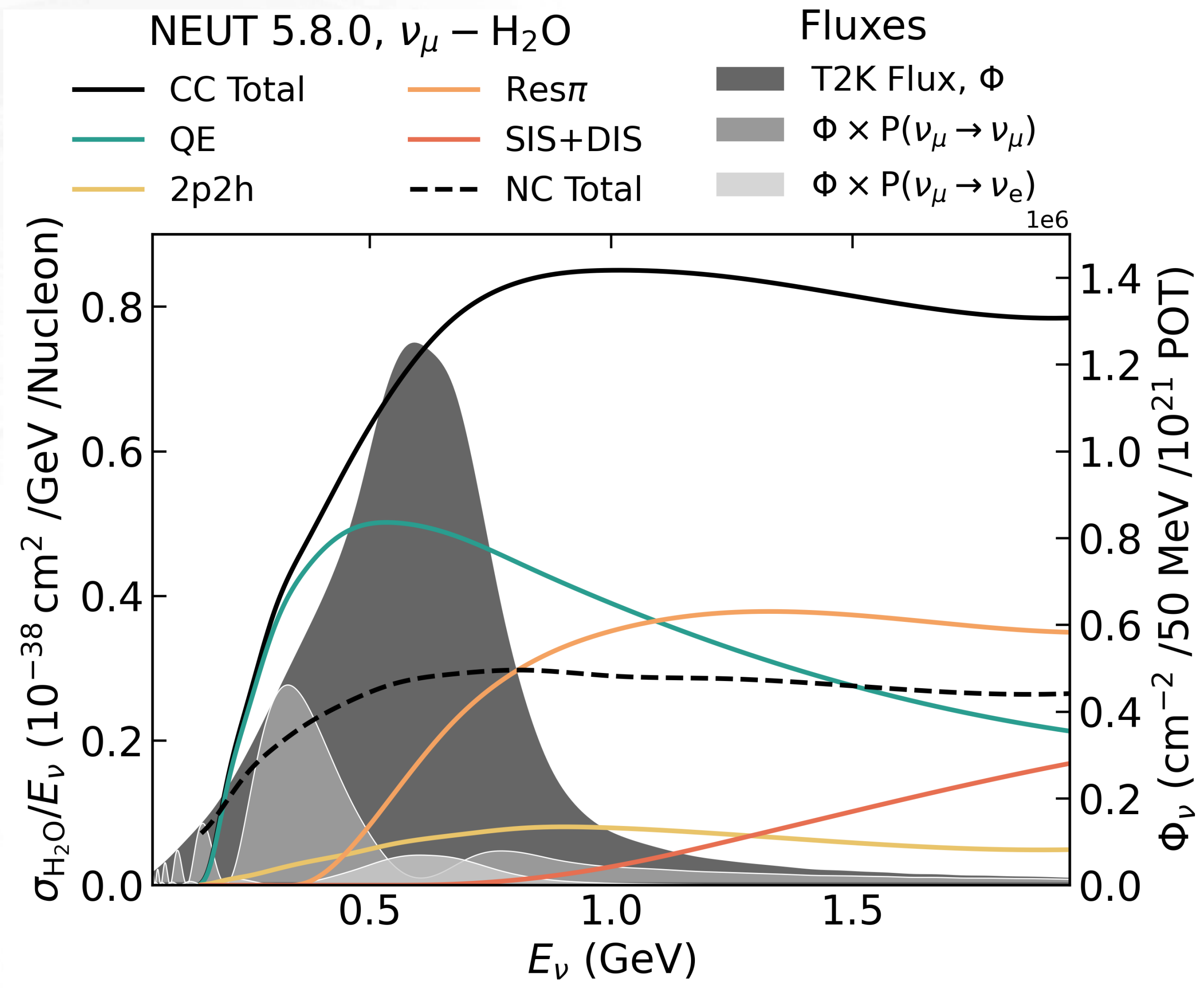
<u>Accumulated POT to date collected from 2010-2024 in 13 runs:</u>

$\sim 4.3 \times 10^{21}$ POT
$\sim 2.8 \times 10^{21}$ POT (FHC configuration)
$\sim 1.6 \times 10^{21}$ POT (RHC configuration)



Source: T2K beam plots

Cross-Section Extraction



Plot from L. Pickering

$$\frac{d\sigma}{dx_i} \propto \frac{\sum_i (N_i^{sig} - B_i^{bkg})}{\epsilon_i \Phi_\nu N_{target} \Delta x_i}$$

N_i^{sig}: # selected signal events in bin i summed across all samples

B_i^{bkg}: # of background events in bin I

Φ_ν: neutrino flux

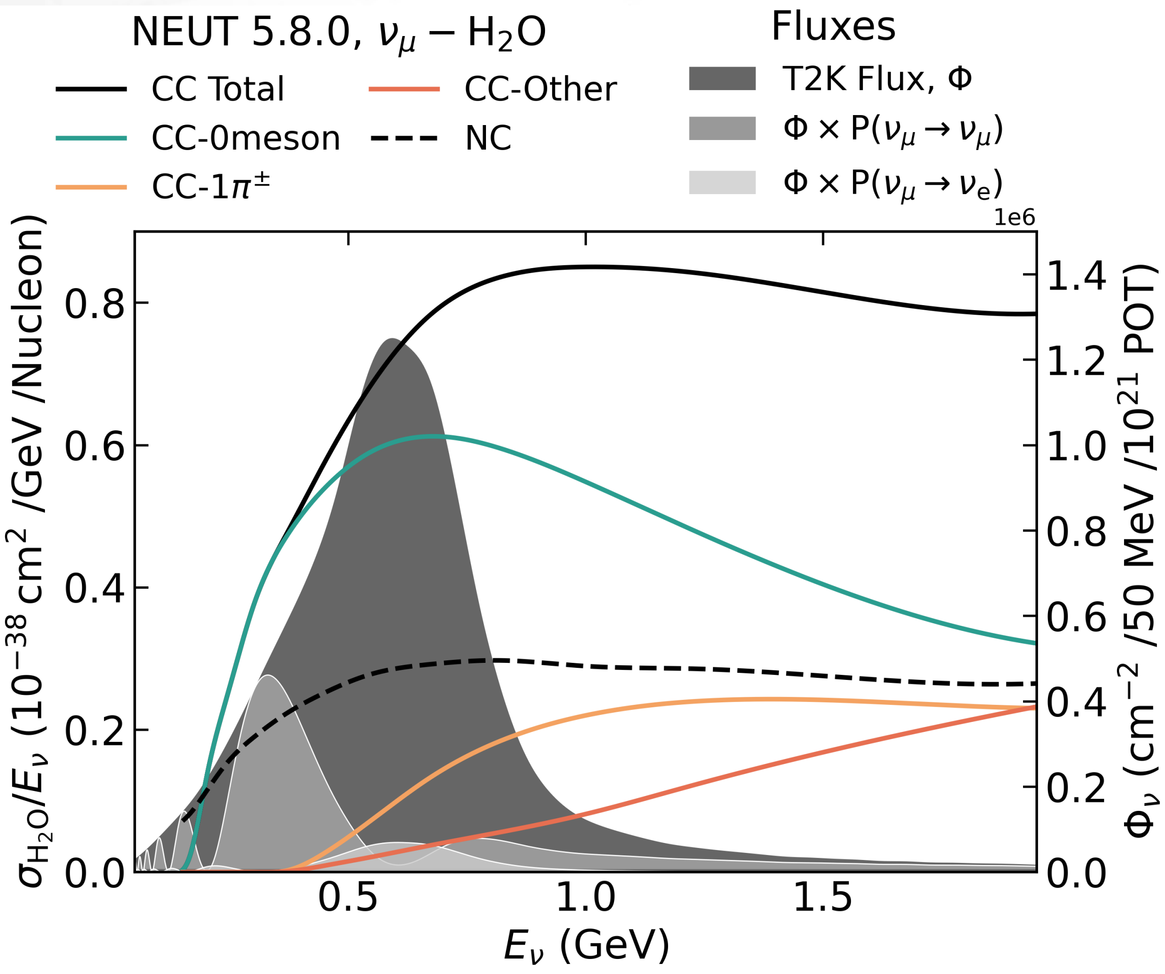
$N_{targets}$: # of targets

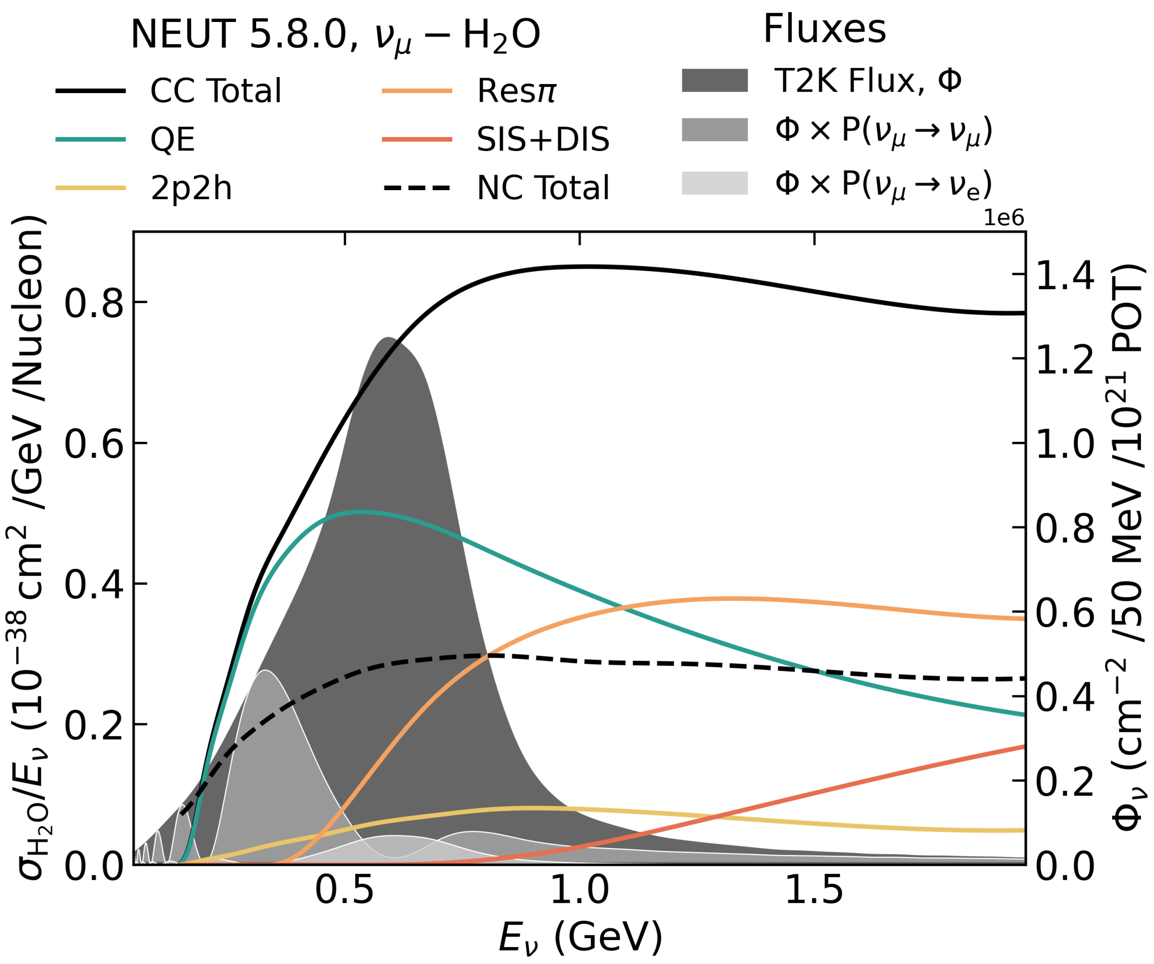
ϵ_i : bin-by-bin efficiency correction

x_i : kinematic variable

Neutrino-Nucleus Cross Section

Interaction Modes





Plots from L. Pickering

Further reference: Eur. Phys. J. Spec. Top. (2021) 230:4469-4481

T2K Flux and Cross Section

Interaction Modes, ND280 and SK flux prediction

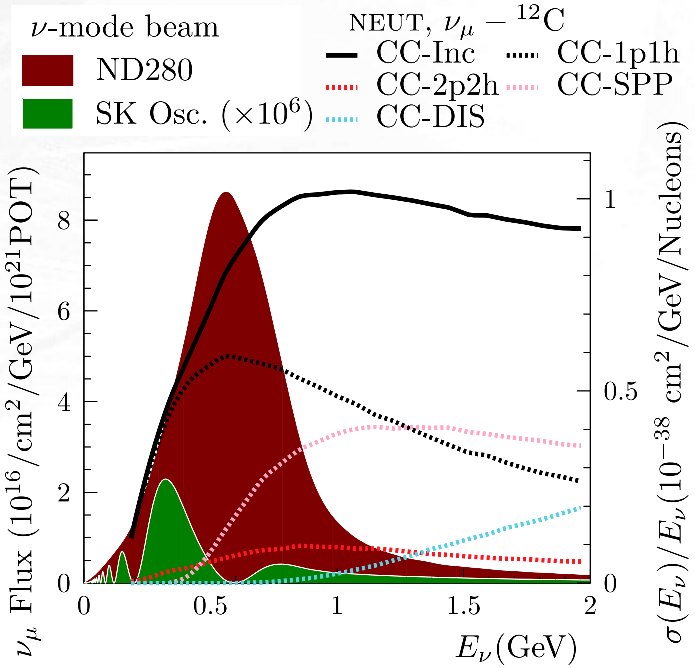
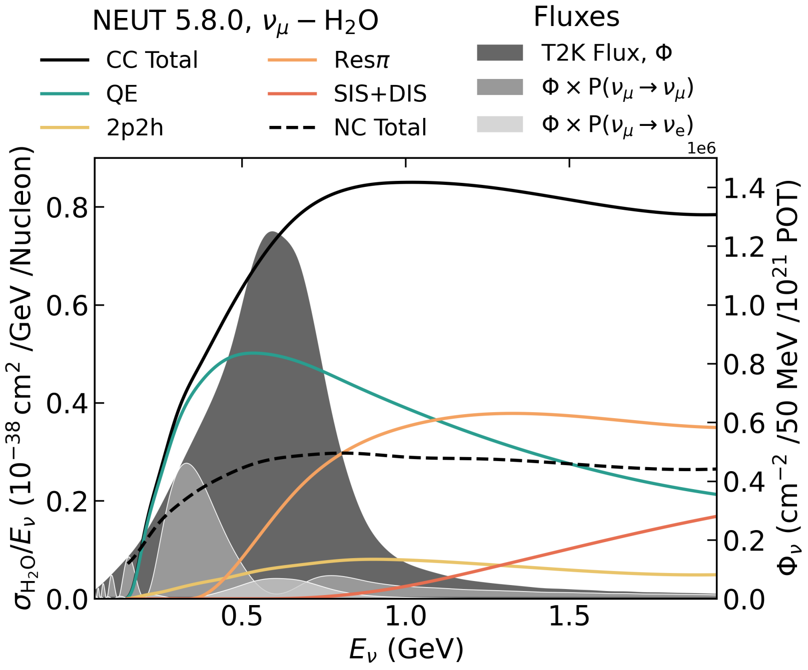


FIG. 3. The total charged-current cross section for muon neutrinos interacting with a carbon nucleus, as predicted by NEUT, overlaid on the ND280 muon neutrino flux, and an example oscillated muon neutrino flux at SK. The oscillation parameters used here are the best fit from the previous analysis [26]. The total (Inc) cross section is separated into 1p1h, 2p2h, single-pion production (SPP), and DIS channels.

Phys. Rev. D **103**, 112008



Plot from L. Pickering

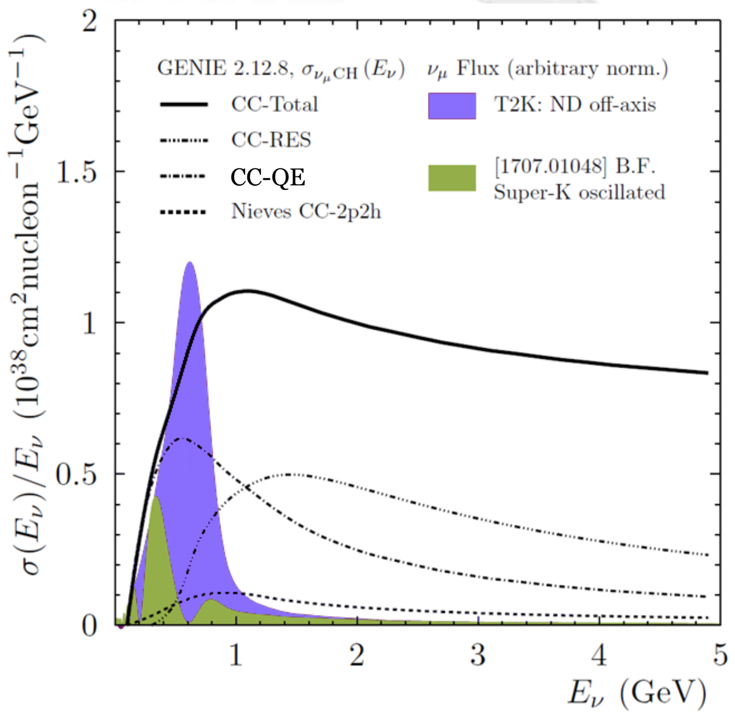


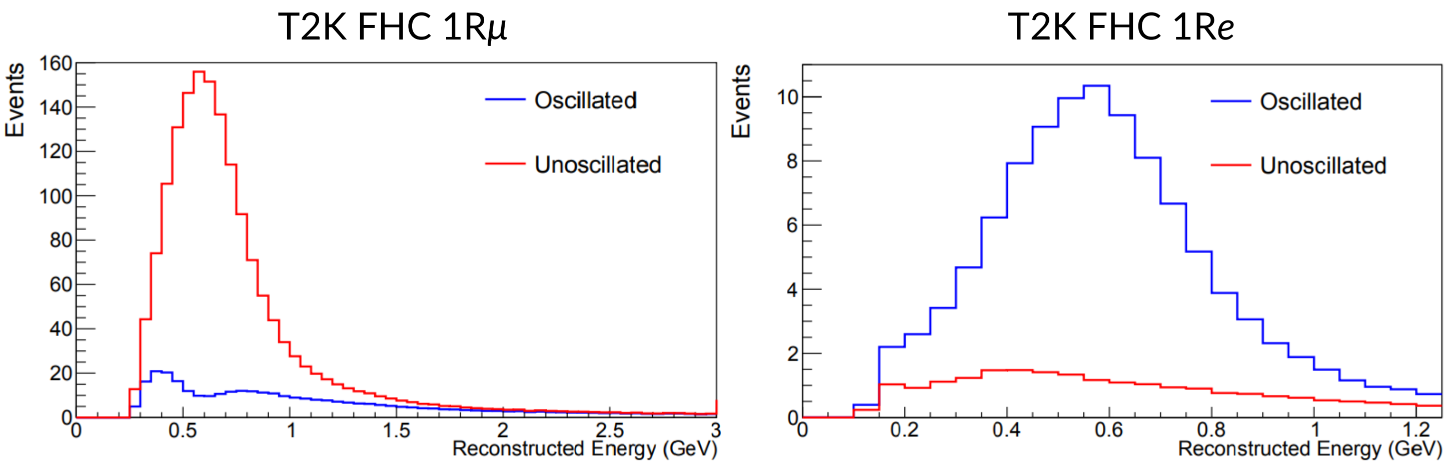
Figure taken from: Neutrino-Nucleus Interactions at T2K. Talk given at Neutrino2020 by Stephen Dolan inJune 2020.

T2K Flux and Cross Section

UNIVERSITY OF OXFORD

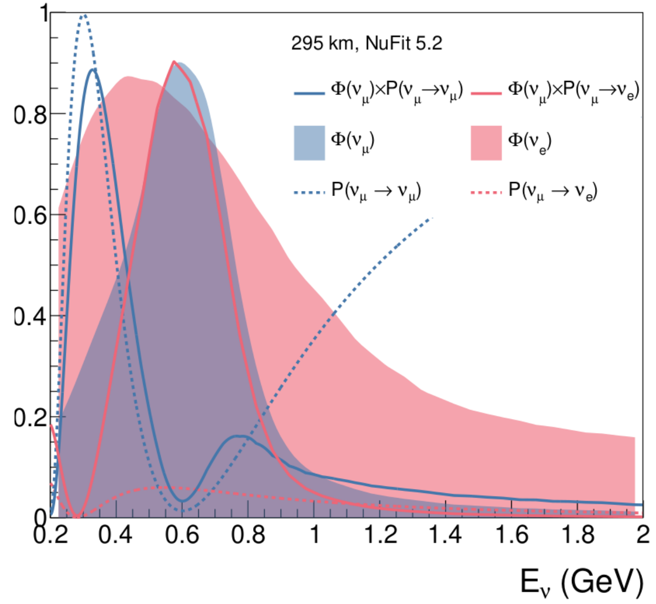
Introduction

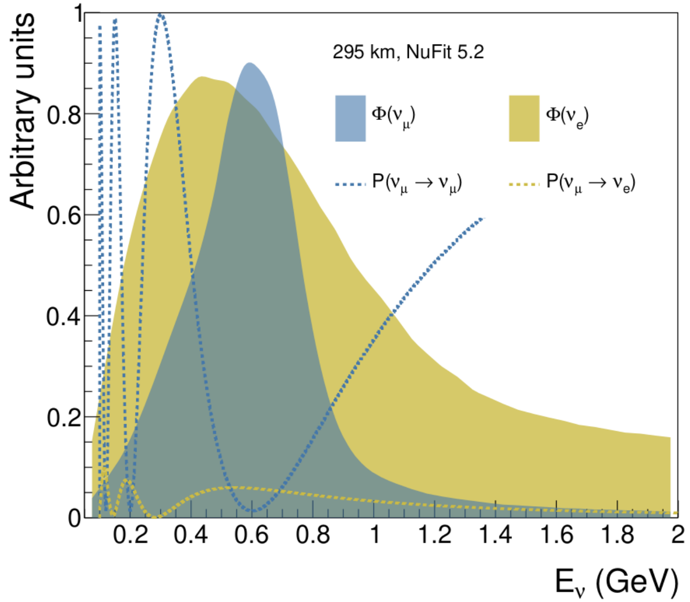
- Oscillation parameters change the rate and shape of the appearing and disappearing neutrinos



- Relies on the model prediction in the absence of oscillations
  - Constrain this model → constrain your oscillation parameters!
- Finding cross-section effects which are degenerate with oscillation parameters is the **nightmare** scenario

Clarence Wret 4

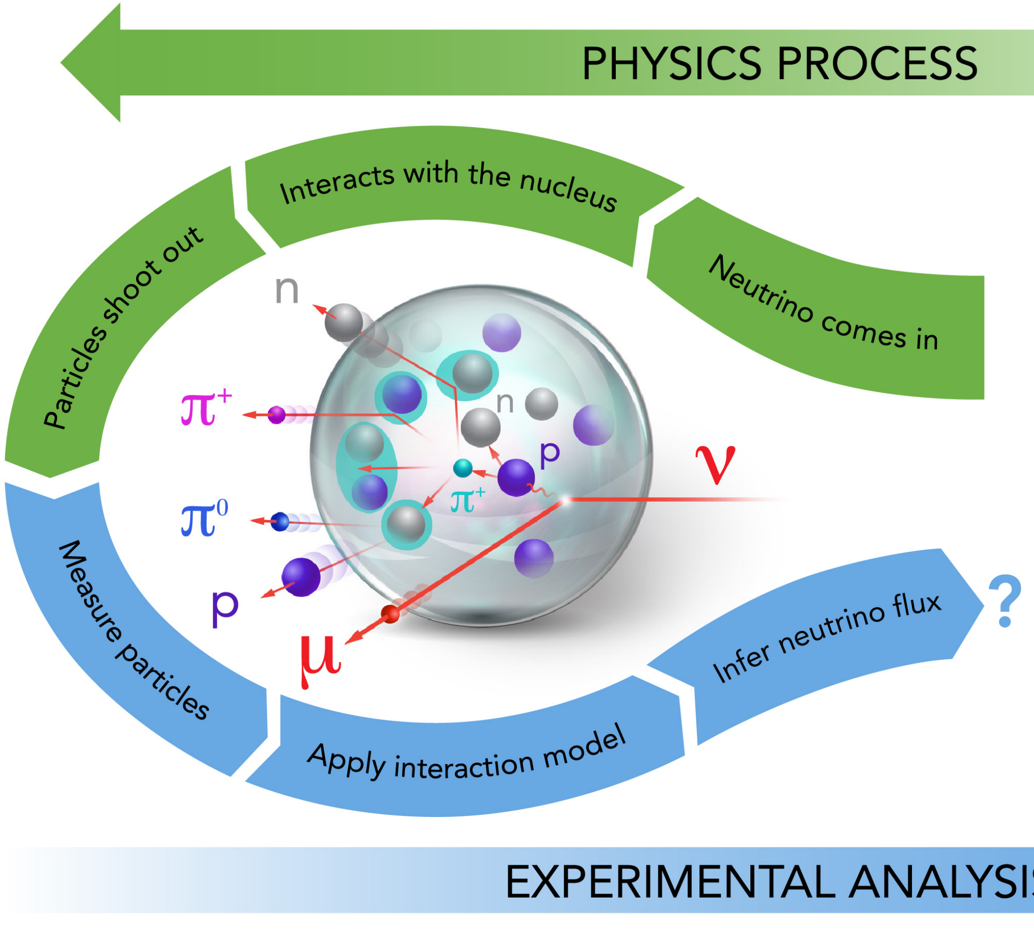


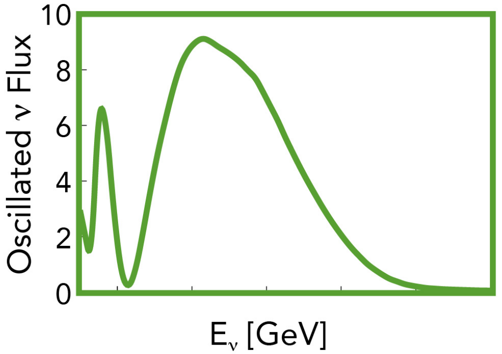


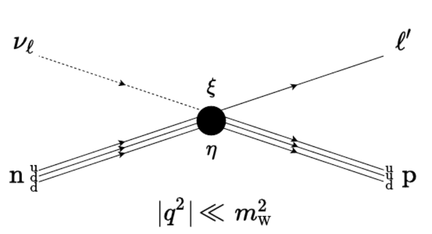
Figures taken from: Impact of neutrino interaction uncertainties on oscillation measurements. Talk given at NuInt2024 by Clarence Wret in April 2024.

Neutrino-Nucleus Cross Sections

Theory and Experiment







$$\bar{u}_{\ell'}(p_{\ell'})\left[-i\frac{g_W}{\sqrt{2}}\gamma^\xi\frac{1}{2}(1-\gamma^5)\right]u_{\nu_\ell}(p_{\nu_\ell})$$

$$i\frac{g_{\xi\eta}}{m_W^2}$$

$$\bar{u}_p(p_p)\left[-i\frac{g_W}{\sqrt{2}}V_{ud}\gamma^\eta\frac{1}{2}(1-\gamma^5)\right]u_n(p_n)$$

$$\frac{d\sigma}{d\Omega^*} = \frac{1}{64\pi^2 s}\frac{p_f^*}{p_i^*}\frac{G_F^2}{2}\underbrace{\langle p_{\nu_\ell}|\gamma_\xi(1-\gamma^5)|p_{\ell'}\rangle\langle p_{\ell'}|\gamma_\eta(1-\gamma^5)|p_{\nu_\ell}\rangle}_{\text{leptonic tensor}}\underbrace{?????????}_{\text{hadronic tensor}}$$

$$\sigma \propto L_{\xi\eta}W^{\xi\eta}$$

$$\frac{d\sigma}{dx_i} \propto \frac{\sum_j (N_j - B_j)}{\epsilon_i \Phi_\nu N_{targets} \Delta x_i}$$

N: # of signal events
B: # of background events
Φ_ν: flux
$N_{targets}$: # of targets
ϵ: efficiency

Nature **599**, 565-570 (2021)

Nuclear Effects

Final **S**tate **I**nteractions (FSIs)

- FSIs inside the nucleus:
  - (In)elastic Scattering
  - Pion Production
  - Absorption
  - Charge Exchange

- Particles that exit the nucleus are observable nucleus.

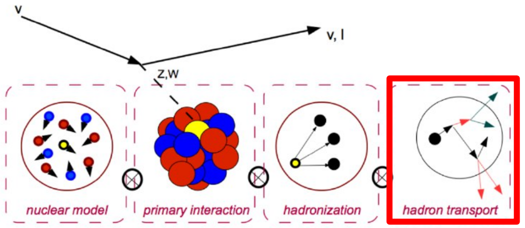
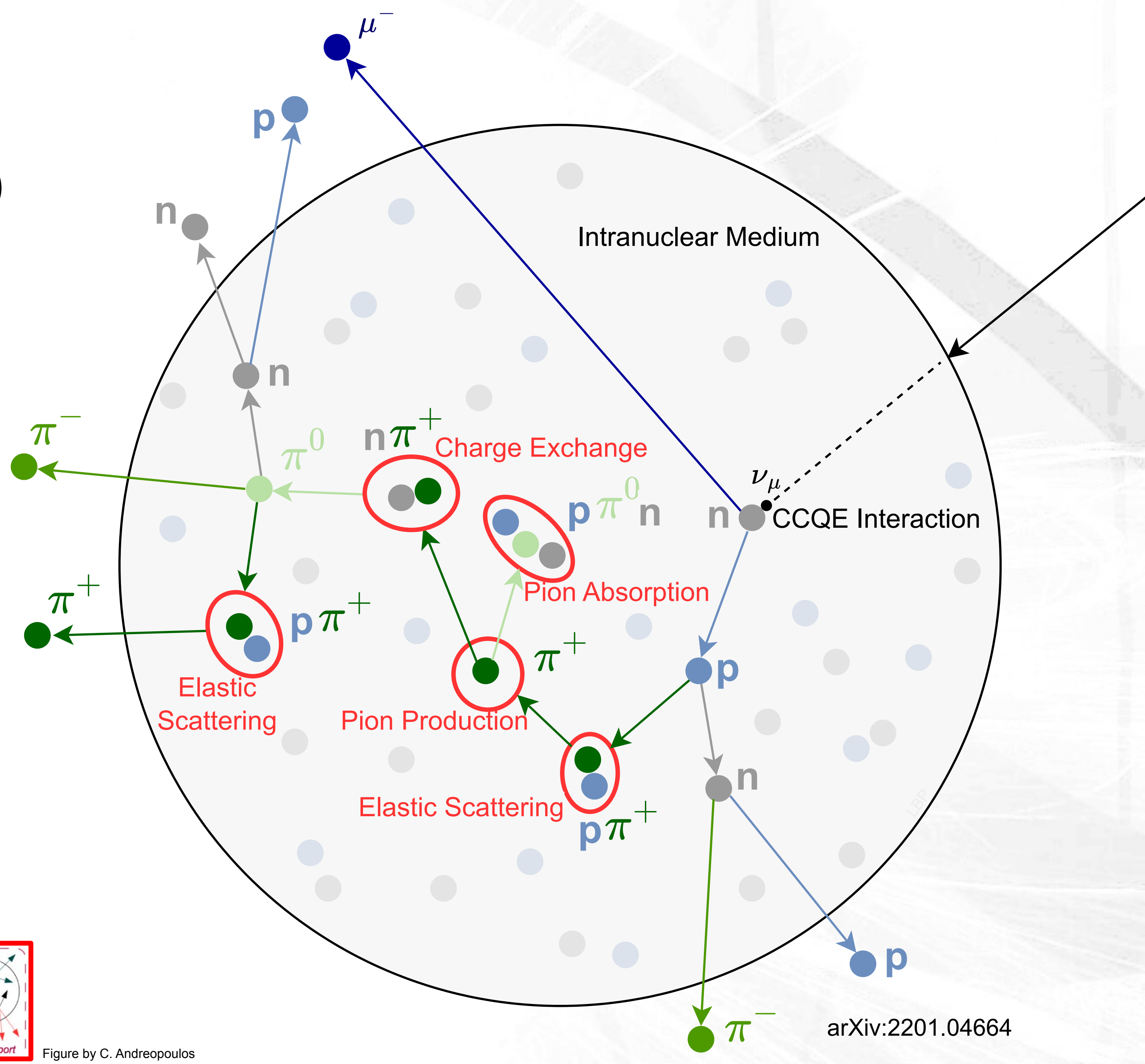


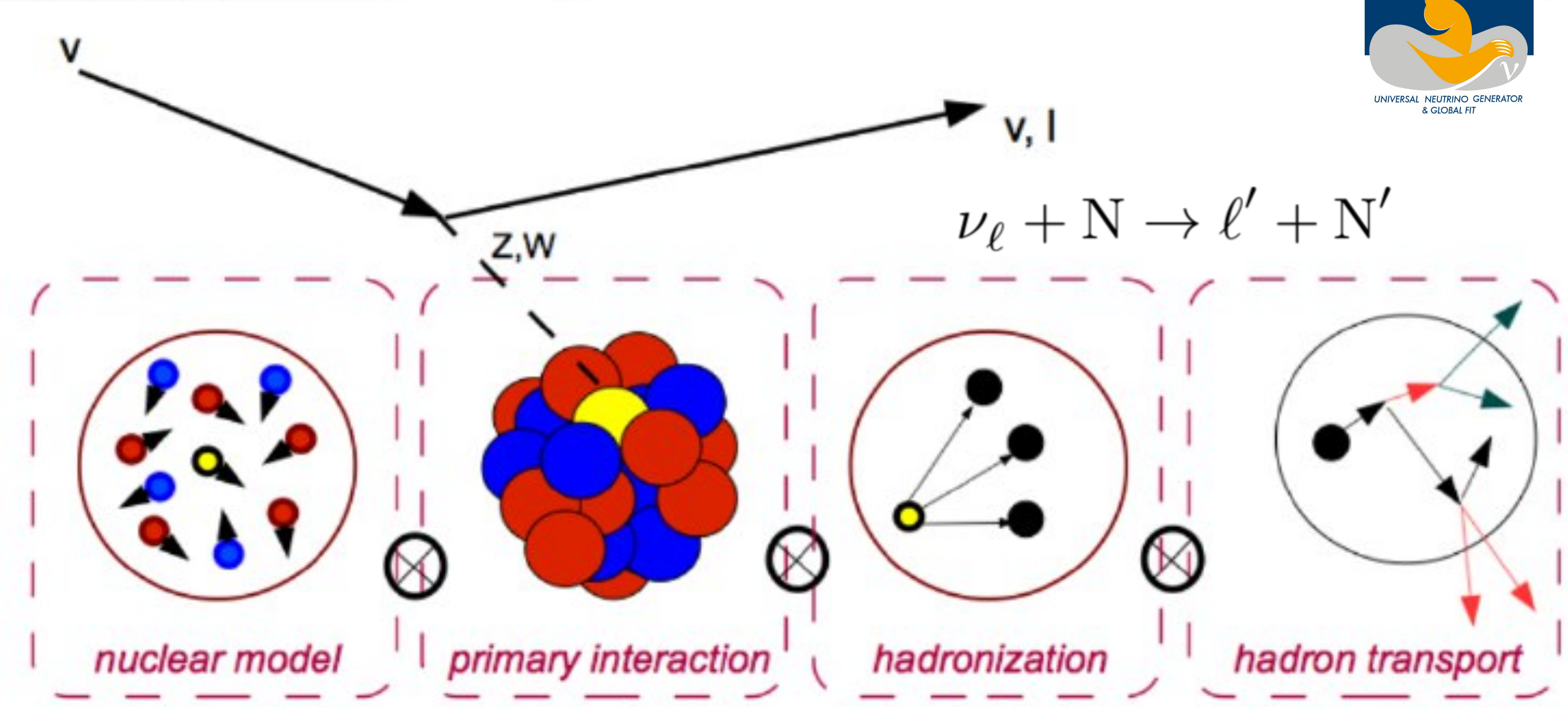
Figure by C. Andreopoulos



arXiv:2201.04664

Neutrino-Nucleus Interactions

Theoretical Predictions by Neutrino Event Generators



$$\nu_\ell + \mathrm{N} \rightarrow \ell' + \mathrm{N}'$$

Figure by C. Andreopoulos

Various neutrino event generators for different attempts in cross section predictions

Neutrino Event Generators

- Ambigous theoretical approach to cross-section calculation

  ➡ Different attempts in cross section predictions

  ➡ Various neutrino event generators to simulate neutrino-nucleus scattering

- Large gap between theory and experiment

  ➡ Need data from experiment

NEUT

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

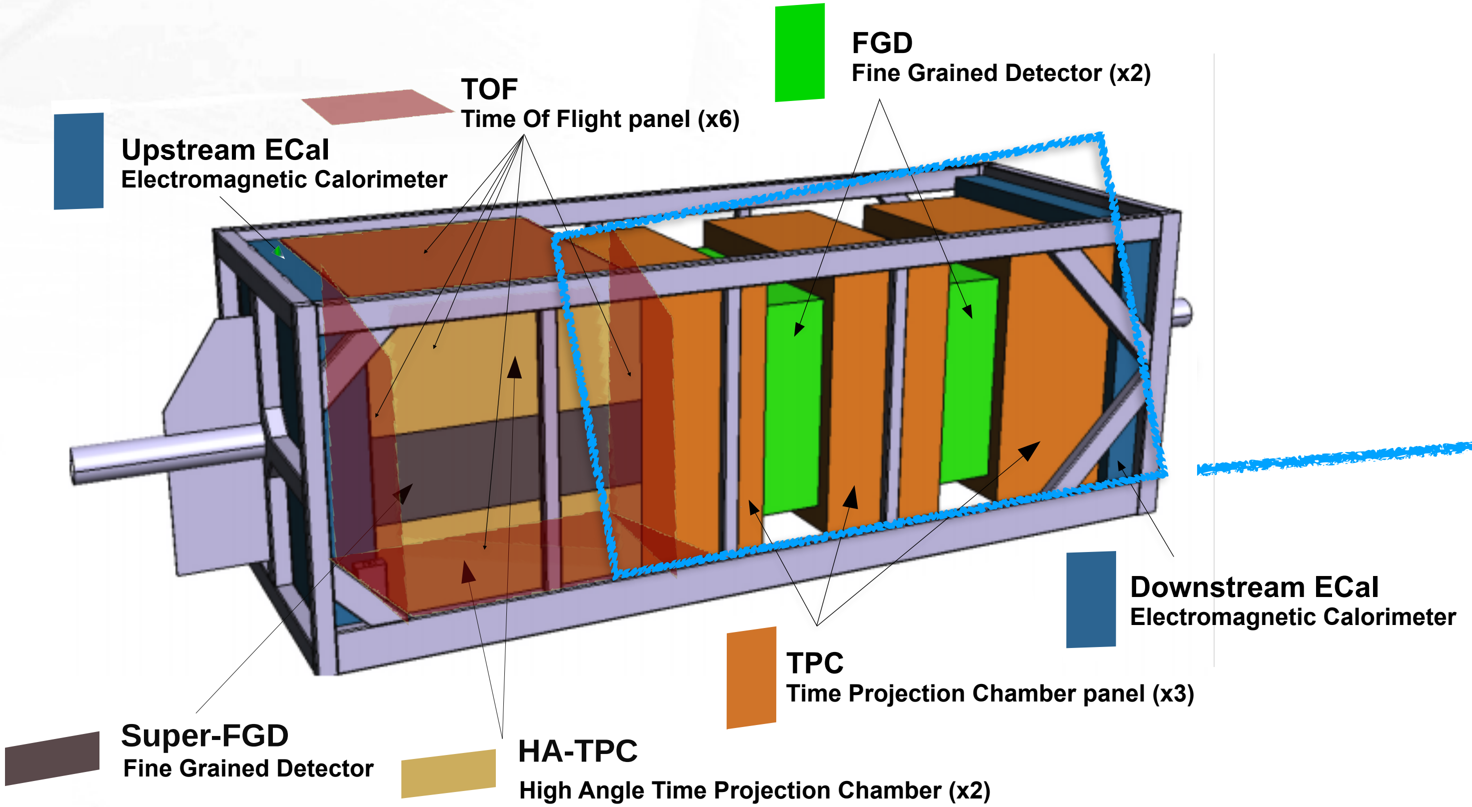
Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NuWro
Wrocław Neutrino Event Generator

For more details, see talk from Wednesday by Lorenzo Magaletti on T2K upgrades: near detector and beam

T2K Near Detectors

ND280



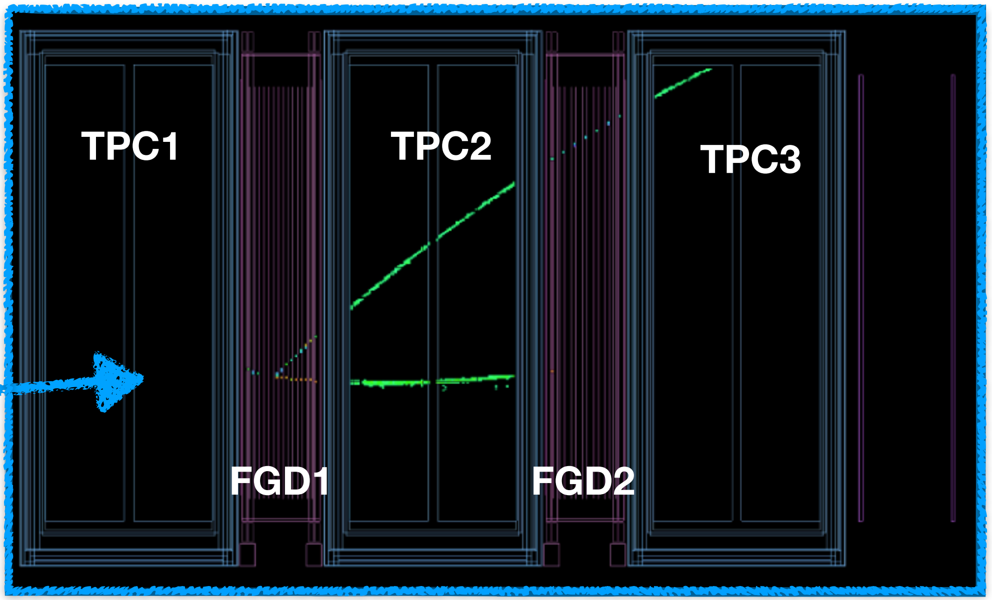
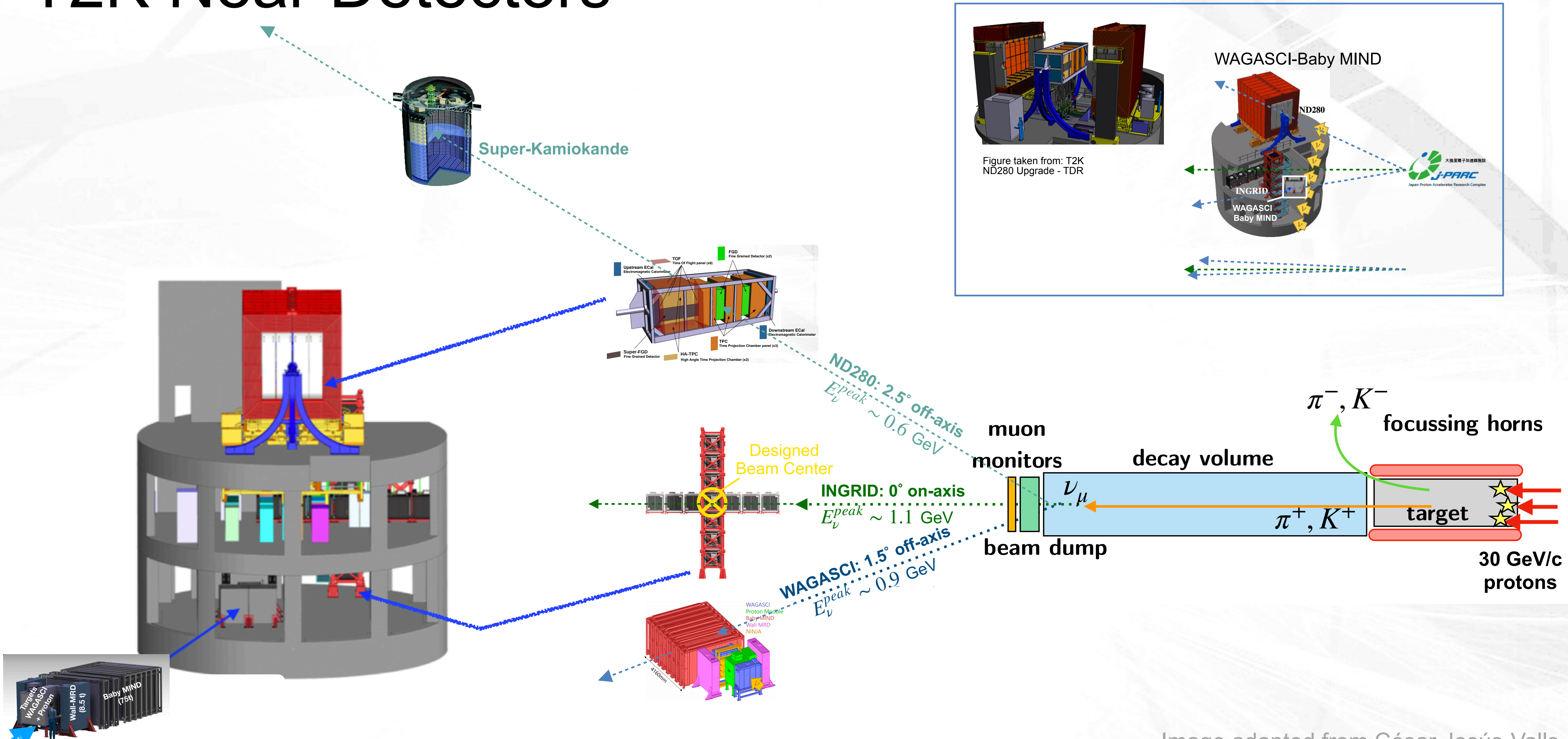


Figure adapted from: T2K ND280 Upgrade - TDR

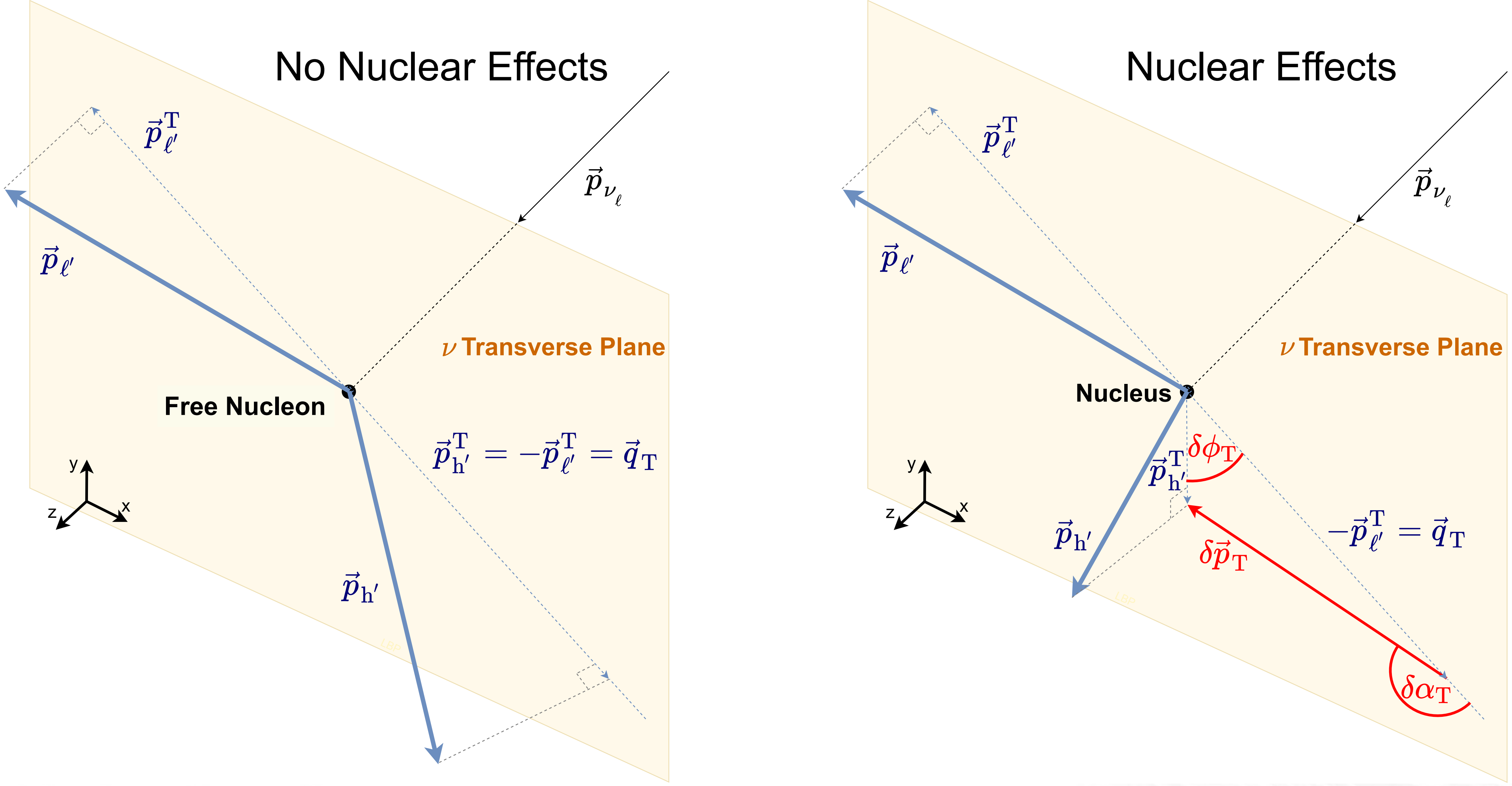
T2K Near Detectors



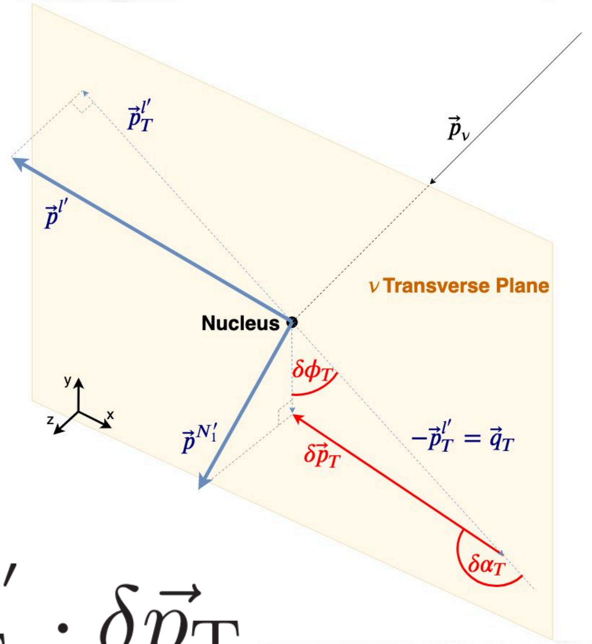
Figures adapted from: Recent measurements & prospects of WAGASCI-BabyMIND. Talk given at ICISE by Son Cao in August 2019.

Image adapted from César Jesús-Valls.

Transverse Kinematic Imbalance (TKI)



Transverse Kinematic Imbalance Variables



arXiv:2201.04664

- Any imbalance observed for CCQE interactions between lepton and hadron kinematics is a direct consequence of nuclear effects

- This imbalance (STKI) can be fully characterised by a set of three **S**ingle-**T**ransverse **V**ariables (STVs)

$$\delta\vec{p}_{\mathrm{T}} \equiv \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'}$$

$$\delta\alpha_{\mathrm{T}} \equiv \arccos\frac{-\vec{p}_{\mathrm{T}}^{\,\ell'}\cdot\delta\vec{p}_{\mathrm{T}}}{p_{\mathrm{T}}^{\ell'}\,\delta p_{\mathrm{T}}}$$

$$\delta\phi_T \equiv \arccos\frac{-\vec{p}_T^{\,l'}\cdot\vec{p}_T^{\,N'}}{p_T^{l'}\,p_T^{N'}}$$

$$\delta\vec{p} \equiv (\delta p_{\mathrm{L}},\ \delta\vec{p}_{\mathrm{T}})$$

Calculate Initial-State Momentum of Struck Neutron

- When energy of incoming neutrino is known (Truth Level Analysis):

$$E_\nu = p_L^\mu + p_L^\pi + p_L^p - \delta p_L \qquad \vec{0} = \vec{p}_T^{\,\mu} + \vec{p}_T^{\,\pi} + \vec{p}_T^{\,p} - \delta \vec{p}_T$$

- When energy of incoming neutrino is unknown (Reconstruction Level Analysis):

$$p_L = \frac{1}{2}(M_A + p_L^\mu + p_L^\pi + p_L^p - E_\mu - E_\pi - E_p) - \frac{1}{2}\frac{\delta p_T^2 + M_{A'}^2}{M_A + p_L^\mu + p_L^\pi + p_L^p - E_\mu - E_\pi - E_p}$$

M_A Initial target nucleus mass

$M_{A'}$ Residual nucleus Mass

- Initial nucleon momentum (probes Fermi motion inside the nucleus):

$$p_N = \sqrt{\delta p_T^2 + p_L^2}$$

Phys. Rev. D **103**, 112009 June 2021 on CH (nuclear effects)

First T2K measurement of transverse kinematic imbalance in the muon-neutrino charged-current single-π $^+$ production channel containing at least one proton

- Use energy spectra from two T2K detectors:
  - ND280: narrow energy-band off-axis flux peaked at 0.6 GeV
  - Dominant interaction mode: CCQE
- Data samples collected between 2010 and 2017 in ND280 corresponds to 11.6×10^{20} POT
- Signal definition: CC$1\mu 1\pi^+ Xp$ with

Particle	Momentum p	Angle θ
μ^-	250–7000 MeV/c	$< 70°$
π^+	150–1200 MeV/c	$< 70°$
p	450–1200 MeV/c	$< 70°$

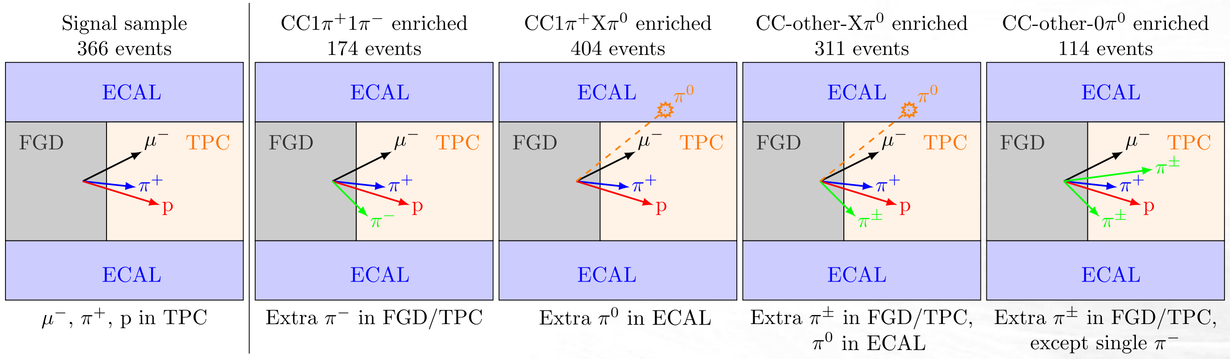
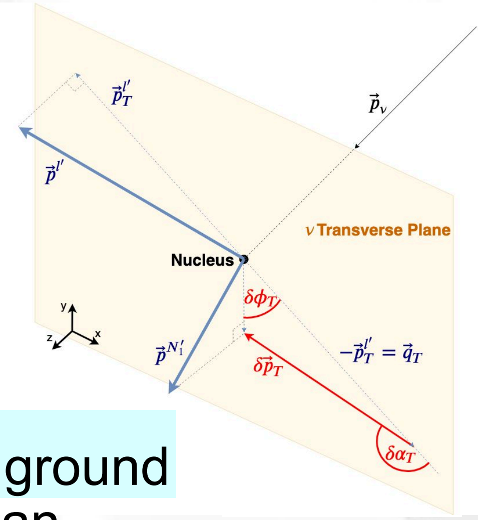


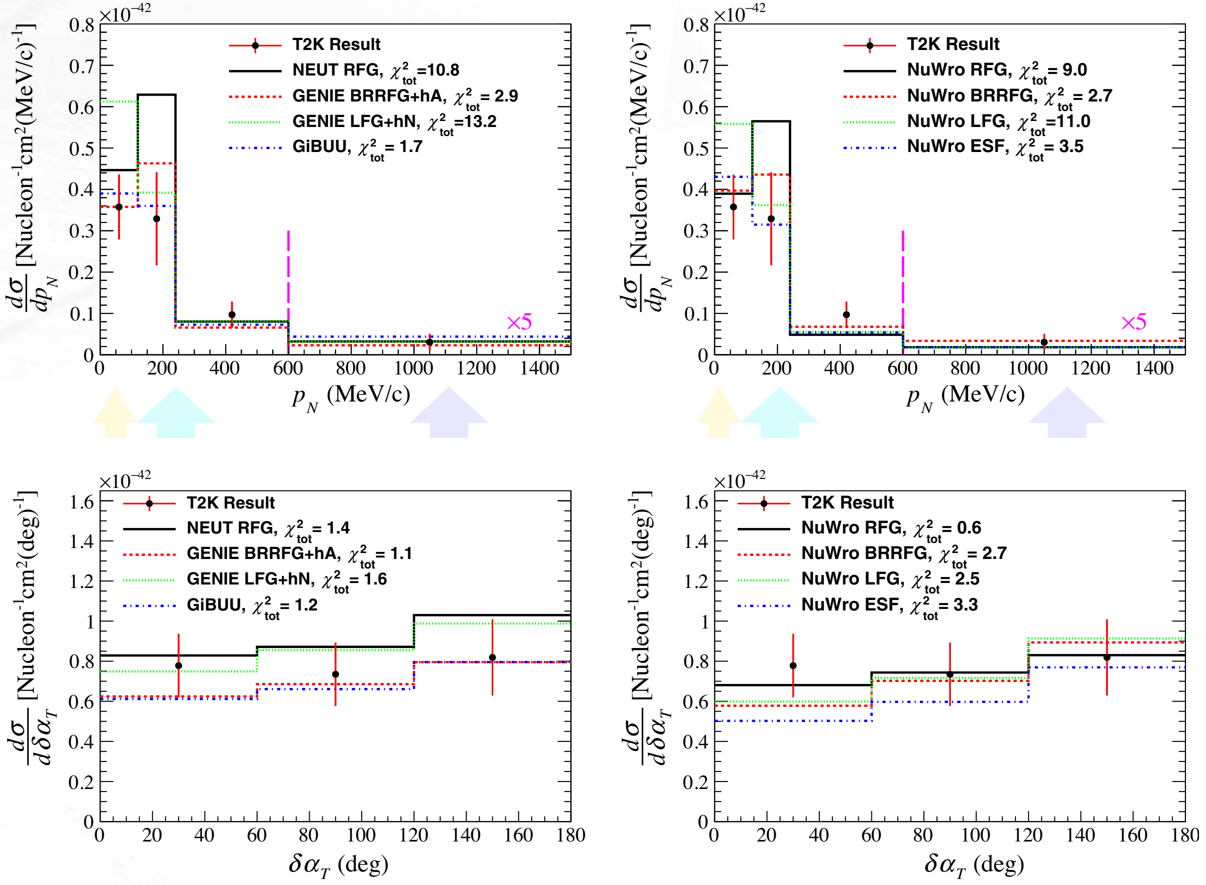
FIG. 5. Schematic representation of the signal sample (left) and control samples (right) selection, together with the number of events observed in data. Details of the selection criteria are described in Secs. V B and V C.

June 2021
Phys. Rev. D **103**, 112009 on CH (nuclear effects)

First T2K measurement of transverse kinematic imbalance in the muon-neutrino charged-current single-π^+ production channel containing at least one proton



arXiv:2201.04664



- Take-home messages:
  - *GiBUU* modeling of nuclear ground state (LFG-based), *better* than GENIE-, NuWro-, NEUT-LFG (incompatibility for $p_N < 120$ MeV/c)
  - Nucleon momentum peak in RFG disfavored
  - All FSI models (GiBUU: transport theory; else: cascade model) have similar predictions
  - $\delta\alpha_T$ sensitive to FSIs, but phase space restrictions limit sensitivity to FSI modeling (improvement with ND280 upgrade)

June 2021
Phys. Rev. D **103**, 112009
on CH (nuclear effects)

Muon-Neutrino-CC0π Interactions with **correlated energy spectra**

$\sigma^{CC0\pi}_{\nu_\mu - CH}$ (ND280+ INGRID)
Phys. Rev. D **108**, 112009

- Signal definition: CC-1$\mu 0 \pi N$p topology (ν_μ interaction with an outgoing muon, no pions and any number of other hadrons (visible protons) in the final state)
- Target material: Plastic scintillator in FGD1 (ND280) and Proton Module (INGRID)

- ND280 event selection:
  - Interaction vertex in FGD1
  - 5 signal definitions (0π):
    - Sample I: 1μ in TPCs
    - Sample II: 1μ($\geq$1)p in TPCs
    - Sample III: 1μ1p in TPCs
    - Sample IV: 1μ in FGD1 and 1p in TPCs
    - Sample V: 1μ in FGD1
  - Main backgrounds (control samples, $\geq 1\pi^+$):
    - Sample VI: 1$\mu 1\pi^+$ in TPCs
    - Sample VII: 1$\mu 1\pi^+$1track in TPCs
    - Sample VIII: 1μ1e in FGD1

- INGRID event selection:
  - Interaction vertex in Proton Module
  - Signal definition:
    - CC-1$\mu 0\pi$(0-1)p

      $p_\mu > 0.35$GeV and $\cos(\theta_\mu) > 0.5$ $\left(\theta_\mu < 60^\circ\right)$
  - Main background (control sample):
    - CC-1$\mu 1\pi$(0-1)p

Muon-Neutrino-CC0π Interactions with **correlated energy spectra**

Cross-Section Extraction

- Cross-Section as a function of true muon kinematics: $x = p_\mu \cos\left(\theta_\mu\right)$
- $\hat{N}^{sig}_i$: best-fit number of selected signal events in truth bin i summed across all samples
- ϵ_i : bin-by-bin efficiency correction
- $\hat{\Phi}$: Integral of the neutrino flux evaluated at the best-fit parameters

$\left(\hat{\Phi}^{ND280} = 2.29 \times 10^{13}\text{cm}^{-2} \pm 6.0\,\%\right.$ and $\left.\hat{\Phi}^{INGRID} = 3.14 \times 10^{13}\text{cm}^{-2} \pm 6.1\,\%\right)$

- $N_{nucleons}$: number of target nucleons in fiducial volume

$\left(N^{ND280}_{nucleons} = 5.53 \times 10^{29} \pm 0.67\,\%\right.$ and $\left.N^{INGRID}_{nucleons} = 1.76 \times 10^{29} \pm 0.38\,\%\right)$

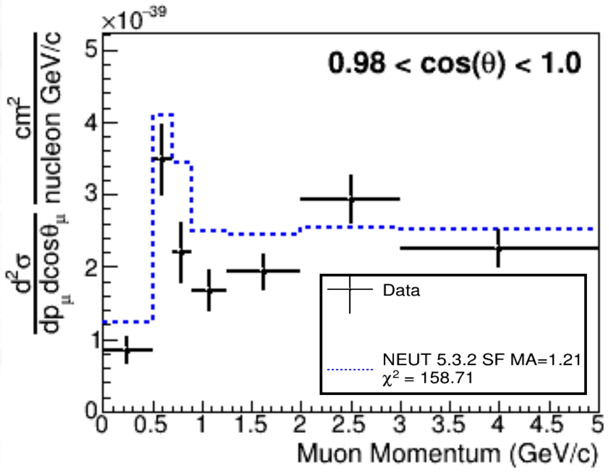
$$\frac{d\sigma}{dx_i} = \frac{\hat{N}^{sig}_i}{\epsilon_i \hat{\Phi} N_{nucleons} \Delta x_i}$$

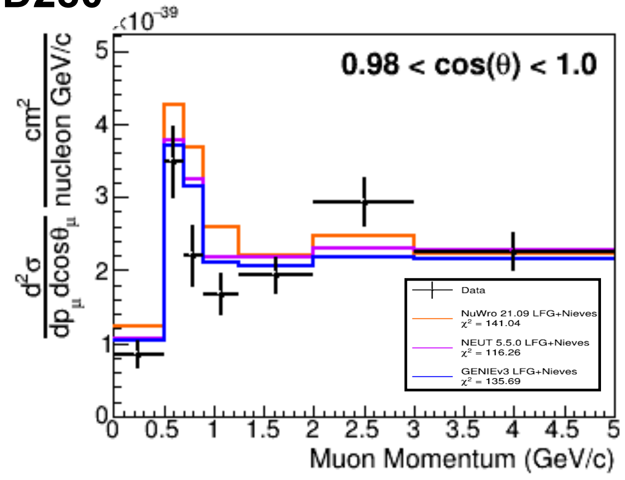
Pionless charged-current muon-neutrino cross sections on hydrocarbon with **correlated energy spectra** using ND280 and INGRID

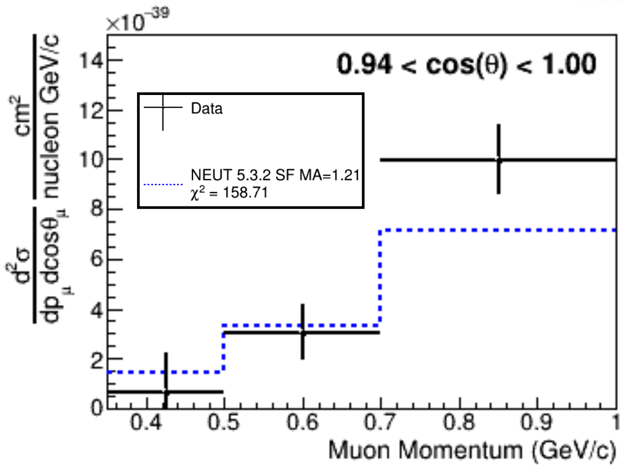
$\sigma^{CC0\pi}_{\nu_\mu - CH}$ (ND280+ INGRID)
Phys. Rev. D **108**, 112009

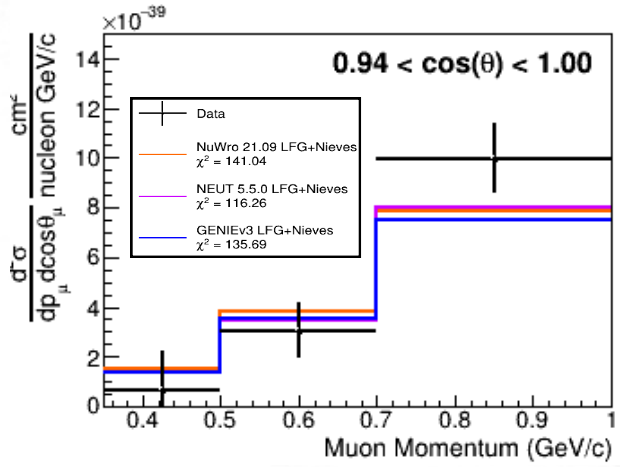
Extracted Cross-Section

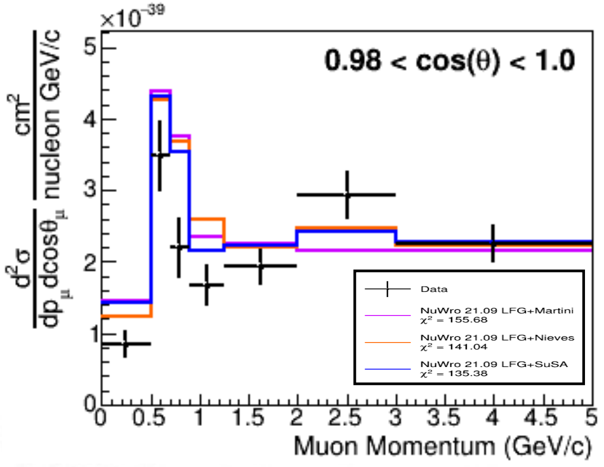
ND280 **INGRID**





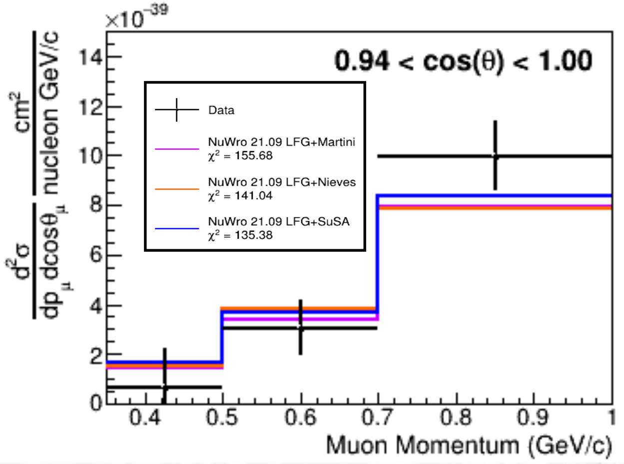






Model	ND280	INGRID	Joint
Nominal MC (NEUT)	136.34	18.21	158.71
NEUT LFG+Nieves	106.46	11.46	116.26
NEUT SF+Nieves $M_A = 1.03$	194.88	14.36	209.18
NEUT SF+Nieves $M_A = 1.21$	158.71	9.98	170.93
NuWro SF+Nieves	122.74	15.68	137.02
NuWro LFG+Nieves	125.88	12.75	141.04
NuWro LFG+SuSAv2	121.57	11.13	135.38
NuWro LFG+Martini	138.86	12.46	155.68
GENIE BRRFG+EmpMEC	141.40	12.80	156.05
GENIE LFG+Nieves	125.50	14.45	135.69
degrees of freedom:	58	12	70

- PRISM analysis with two fluxes
- Extend analysis to three energy spectra with WAGASCI-Baby MIND
- ND280 upgrade for enhanced angle coverage, low momentum tracking
- Ability to compare result with correlations to naive sum



ν_e-CC$1\pi^{\pm}$ Interactions

$\sigma^{CC1\pi}_{\nu_e-CH}$ publication in preparation

Kinematic Variables

- Signal definition: CC-$1e^{-}1\pi^{+}X$ with

Particle	Momentum p [GeV/c]	Angle θ
e^-	0.35 - 30	$< 46°$
π^+	< 1.5	
p		

- Background samples with vertex in FGD1:

ν_eCC0π - any ν_eCC interactions which produce no pions of any type.

ν_eCC-other - any ν_eCC interactions which produce no positive pions, but $\geq 1\pi^{0,-}$.

γ - interactions where pair production from a photon occurs ($\gamma \rightarrow e^+e^-$).

μ - interactions where the main electron candidate is a muon.

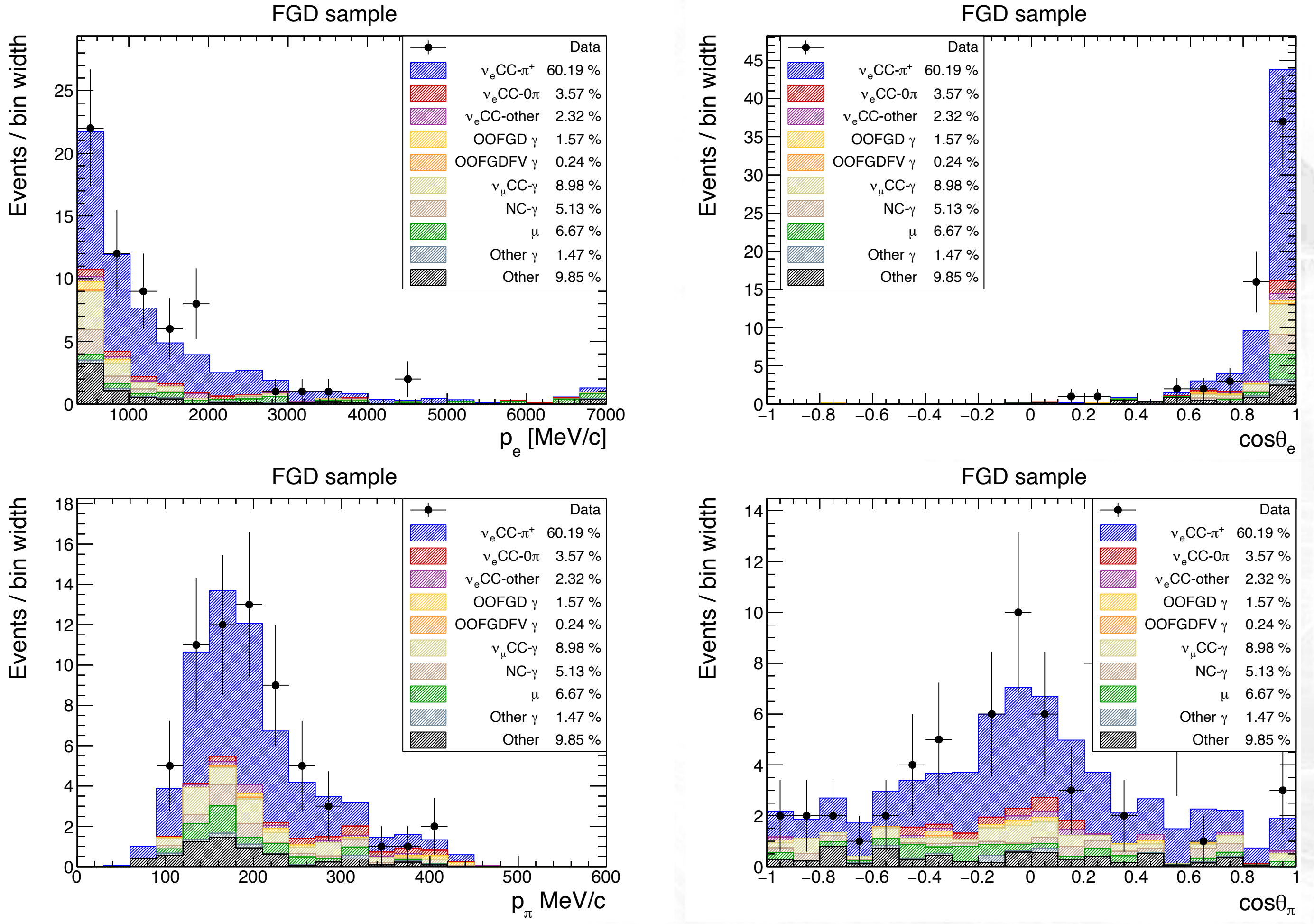
Other - any interaction not covered by the previous categories, or interactions which occur outside of the FGD1 FV.

OOOFGD γ - photon conversions which occur outside of FGD1.

OOFGDFV γ - photon conversions which occur within FGD1 but outside of the restricted FV.

ν_μCC-γ - photon conversions which originate from ν_μCCπ^0 events.

NC-γ - photon conversions which originate from any NCπ^0 event.



ν_e-CC$1\pi^{\pm}$ Interactions

$\sigma^{CC1\pi}_{\nu_e-CH}$ publication in preparation

Event Selection

Cut	**All samples**
1	ND280 event quality
2	Track multiplicity
3	TPC quality
4	Main track electron PID
5	Main track muon PID
6	Main track pion PID
7	Main track muon PID (2nd seg)
8	ECal EM energy cut
9	MIP-EM cut
10	P0D veto
11	TPC veto

Cut	**TPC sample**	**FGD sample**	**TPC sideband**	**FGD sideband**
12	Pair track pion PID	Michel electron cut	Pair track pion PID	Michel electron cut
13	ECal polar angle veto	ECal upstream veto	ECal upstream veto	Reverse m_{inv} cut
14	m_{inv} cut	m_{inv} cut	Reverse m_{inv} cut	-
15	No FGD sample events	-	-	-

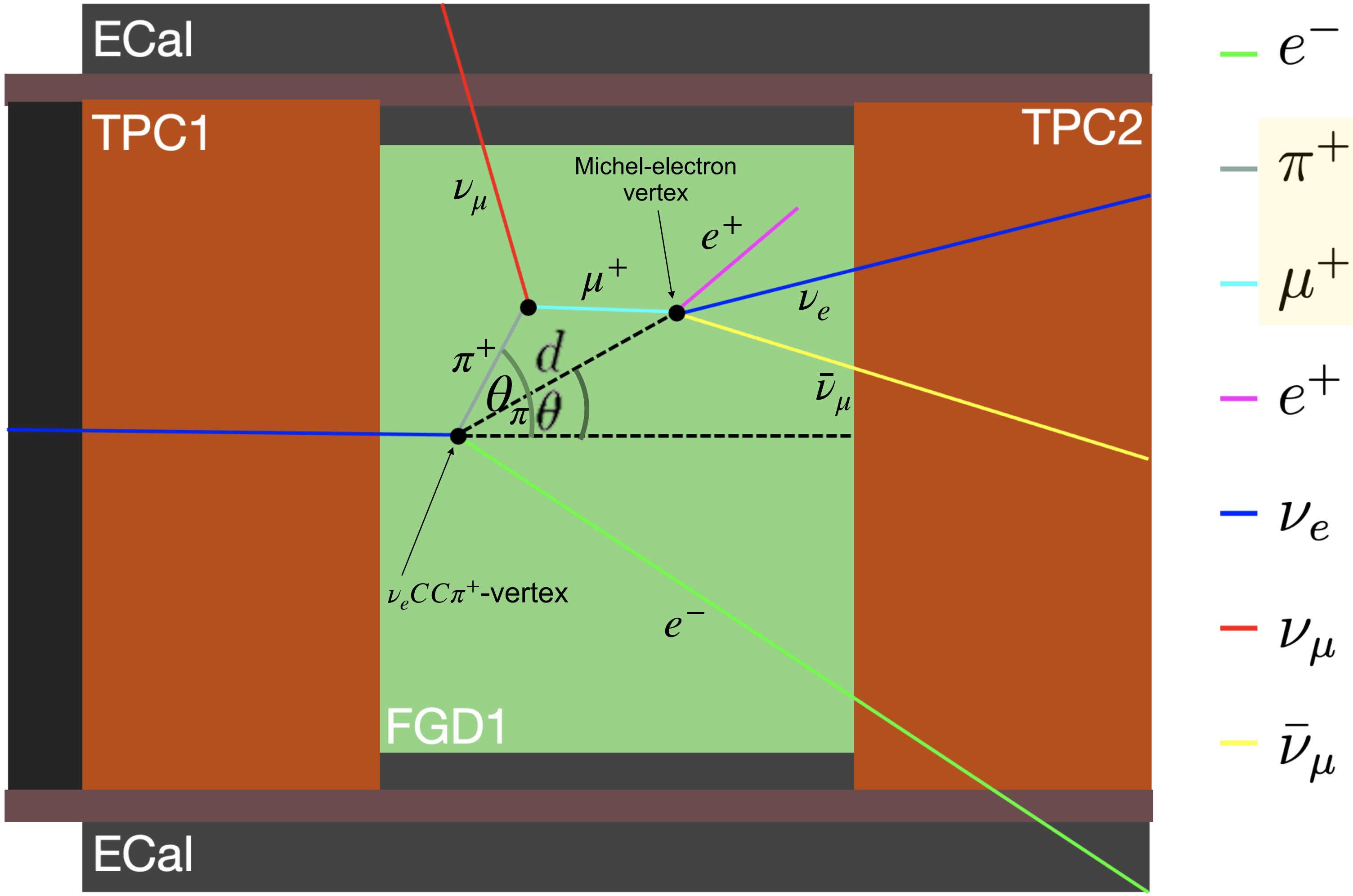
ν_e-CC$1\pi^\pm$ Interactions

Pion Kinematics Reconstruction from Michel Electrons

$$p_\pi = c_0 \cdot d^{c_1} + c_2$$

$$c_0 = 19.11 \pm 0.88 \text{ [MeV/mm]}$$
$$c_1 = 0.4154 \pm 0.0063$$
$$c_2 = 14.47 \pm 2.02 \text{ [MeV]}$$

$$\theta_\pi = \theta_{ME}$$



Note: Track lengths are exaggerated to show distance d and angle θ describing the original $\nu_e CC\pi^+$ vertex and the Michel-electron vertex.

This method was first developed in a $\nu_\mu CC1\pi^+$-analysis. More details can be found in T2K-TN-417.

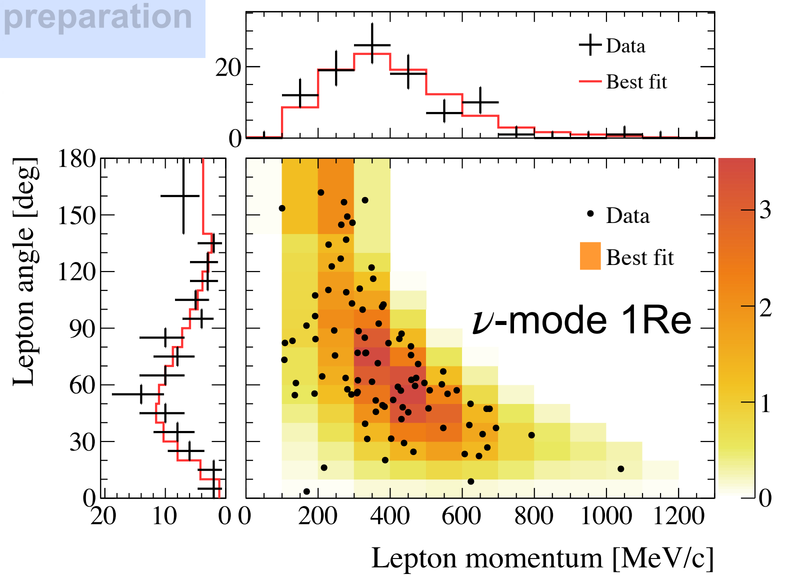
ν_e-CC$1\pi^{\pm}$ Interactions

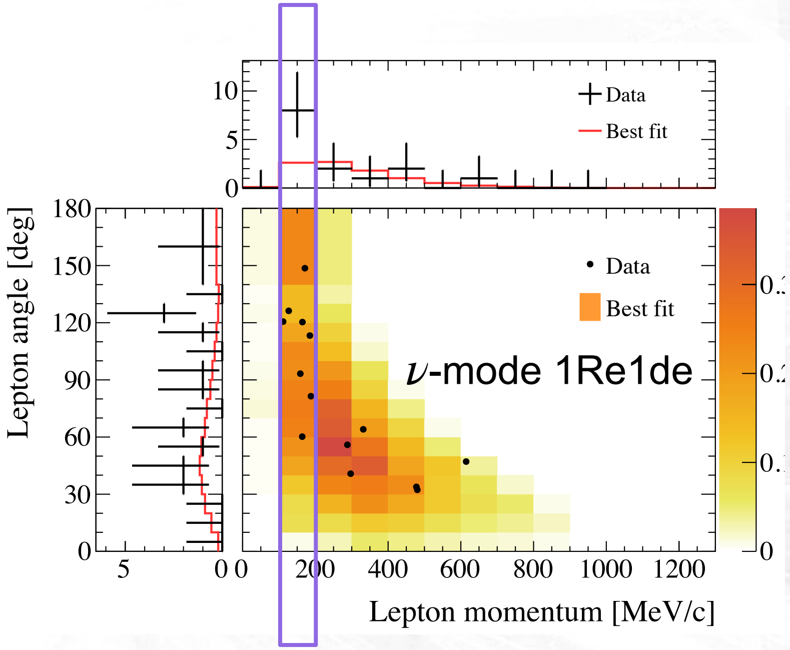
$\sigma^{CC1\pi}_{\nu_e-CH}$ publication in preparation

Pion Kinematics Reconstruction from Michel Electrons

- 1π events are a background for single-ring detection in Super-Kamiokande
  - **E**lectron-like single-**R**ing ($1Re$) sample
  - **E**lectron-like single-**R**ing with **d**elayed Michel **e**lectron ($1Re1de$) sample
- Method of low-momentum pion tagging by delayed Michel-electrons also important for far detector's (Super-Kamiokande) event reconstruction

Sample		Flux	Interaction	FD + SI + PN	Flux⊗Interaction (%)	Total (%)
		Uncertainty source (%)				
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)



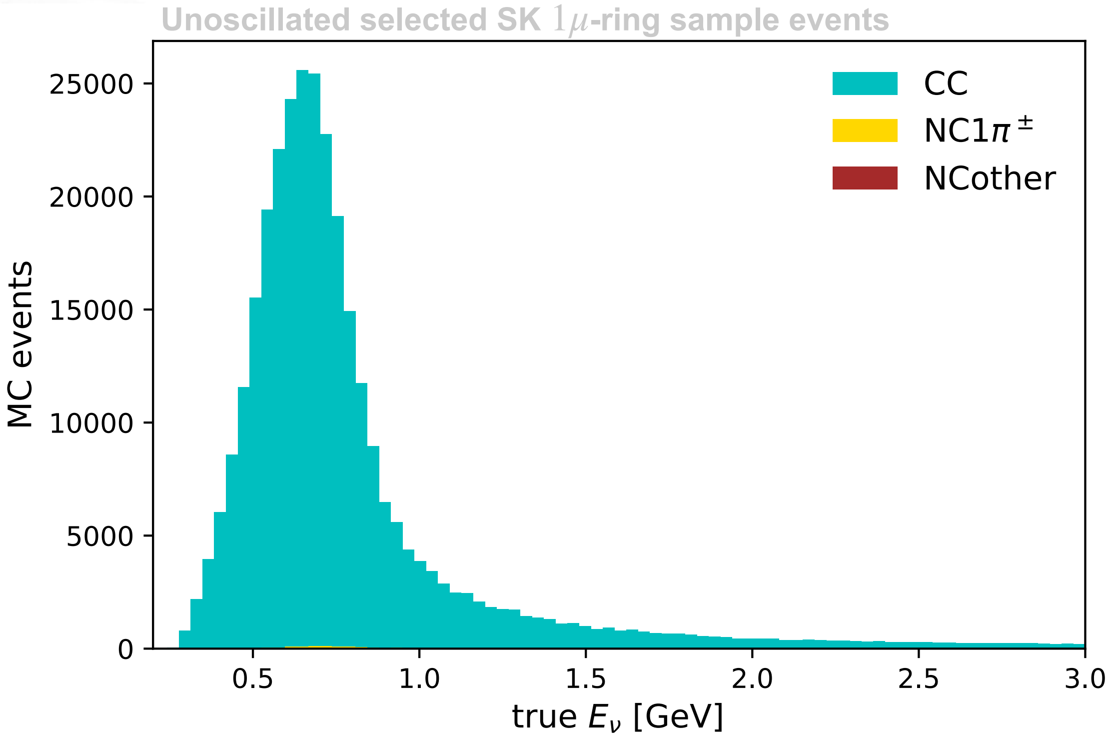


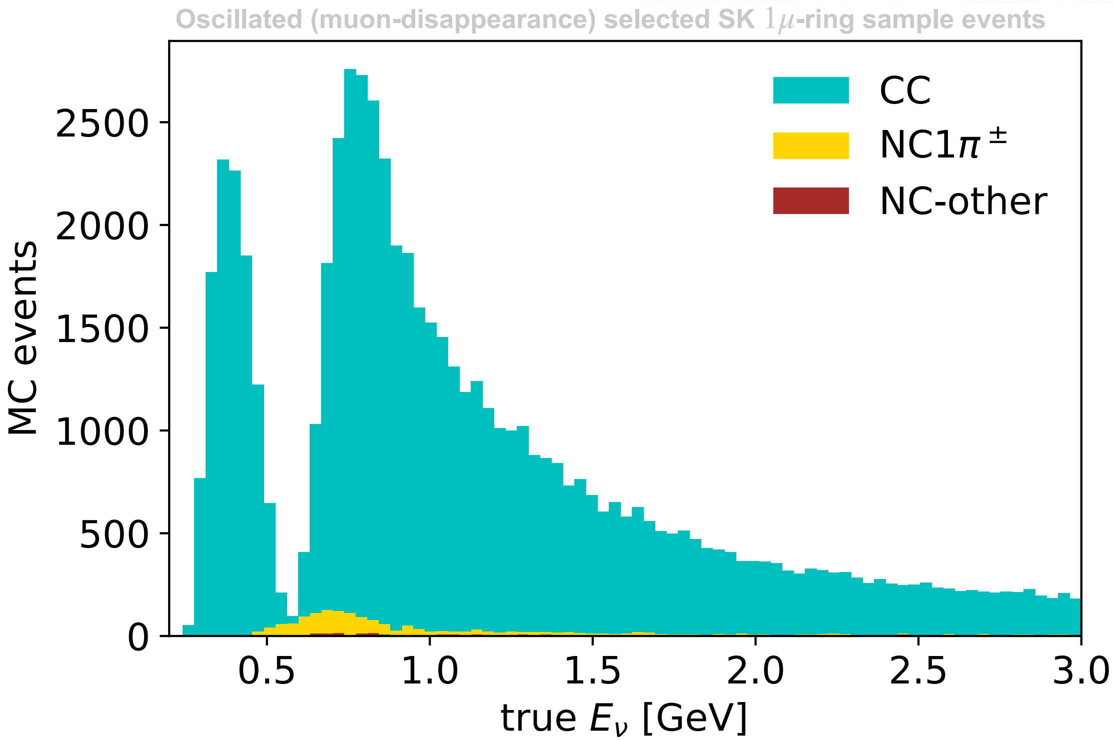
Eur.Phys.J.C 83 (2023) 9, 782

Neutrino-NC$1\pi^+$ Interactions on Hydrocarbon

Motivation

- Dip region in T2K's oscillated ($\nu_\mu \rightarrow \nu_\mu$) prediction has non-negligible NC $1\pi^\pm$ events due to similarity of μ and $\pi^\pm$ in water Cherenkov detectors!





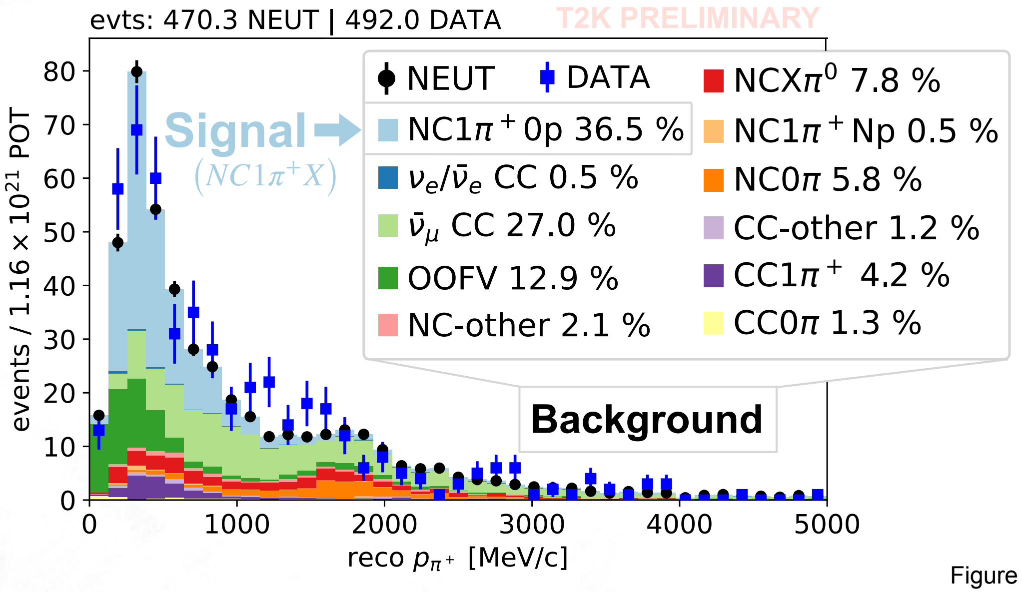
Neutrino-NC$1\pi^+$ Interactions on Hydrocarbon

$\sigma^{NC1\pi^+}_{\nu,\bar{\nu}-CH}$ publication in preparation

- Motivation:
  - NC$1\pi^\pm$ and CC0π look similar in SK
  - Signal definition: NC$1\pi^+$0p where

Proton momentum condition makes this count as 0p

Particle	Momentum p [GeV/c]	Angle θ
π^+	0.2 – 1.0	$< 60°$
p	< 0.2	



- Signal and background samples with ν vertex in FGD1:

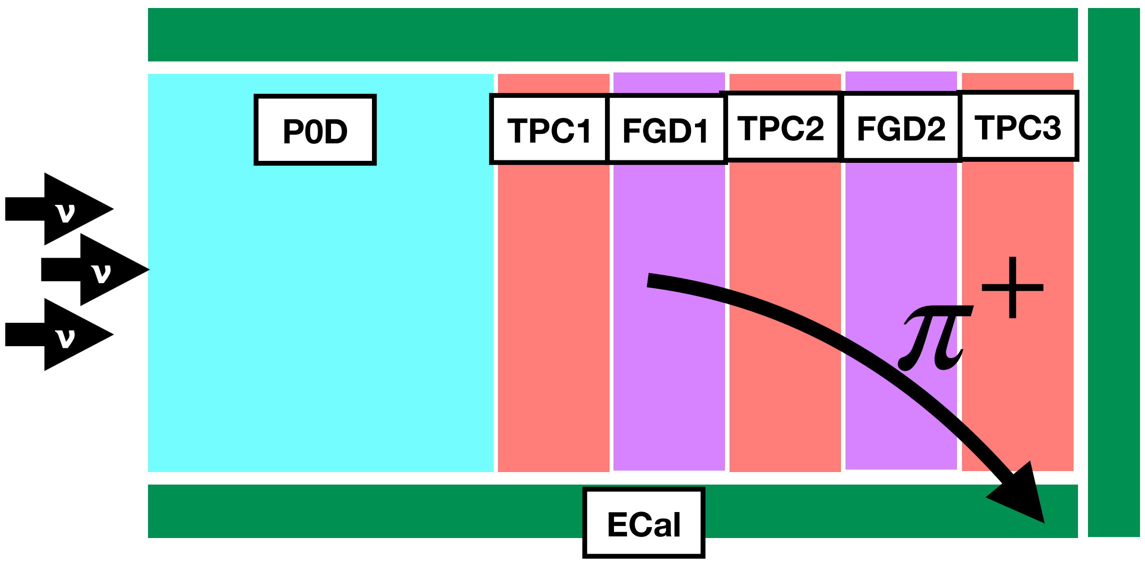
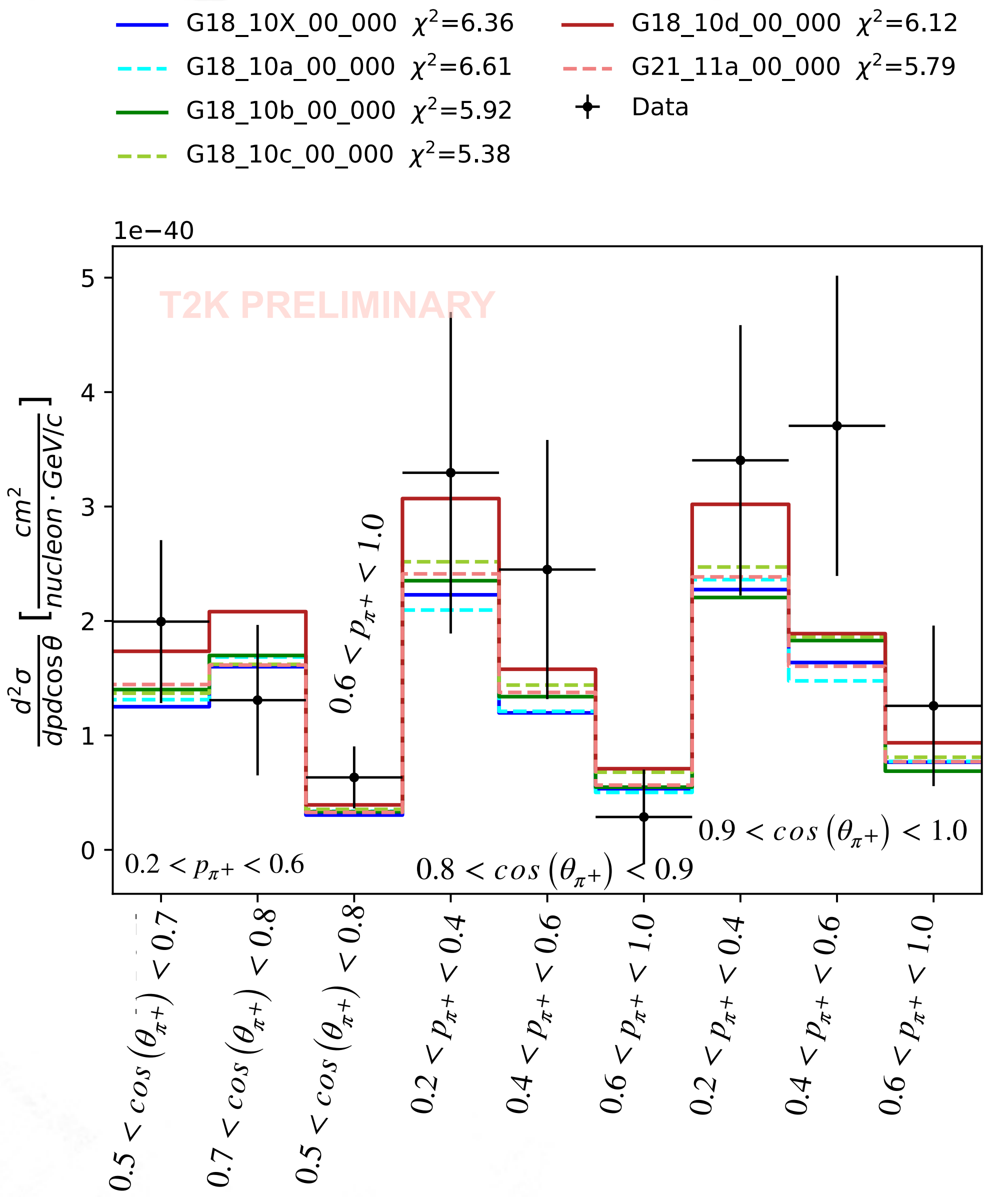
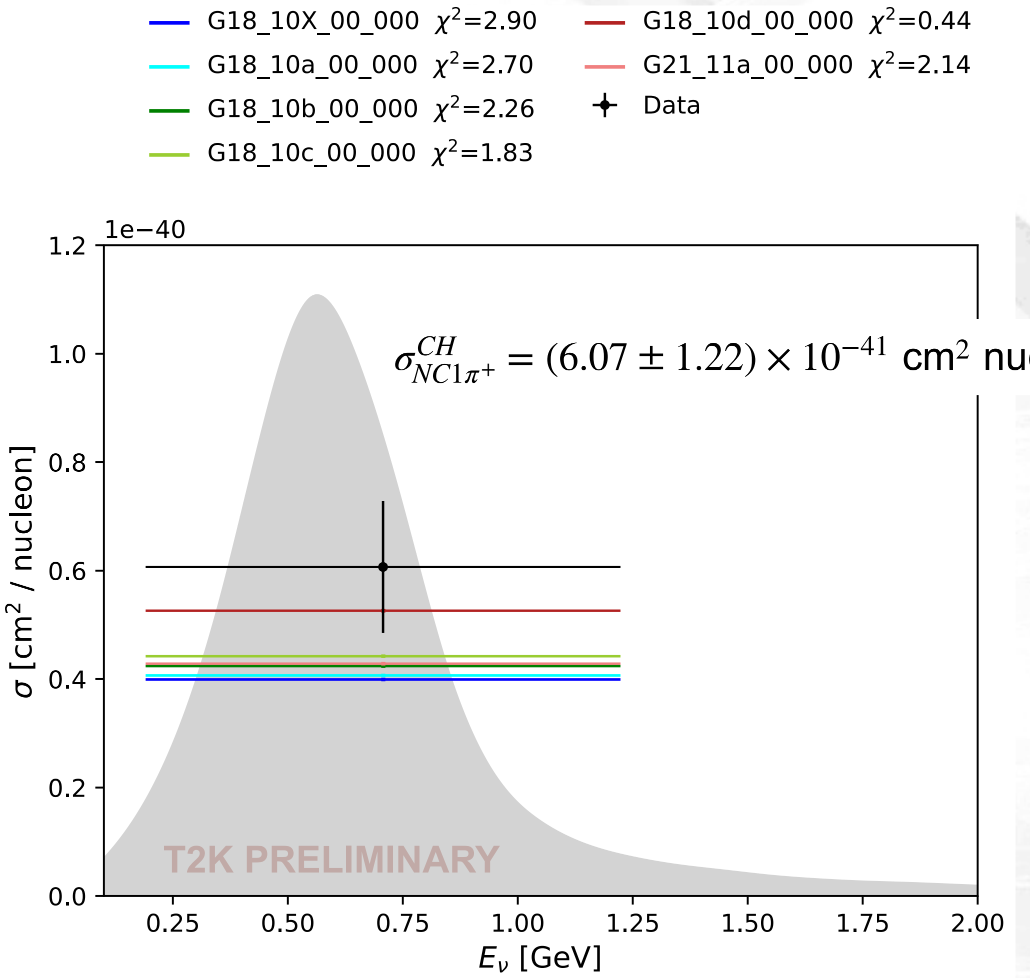


Figure taken from: T2K latest results and prospects on NC and CC pion production. Talk given at NuInt2024 by César Jesús-Valls in April 2024.

Neutrino-NC$1\pi^+$ Interactions on Hydrocarbon

$\sigma^{NC1\pi^+}_{\nu,\bar{\nu}-CH}$ publication in preparation





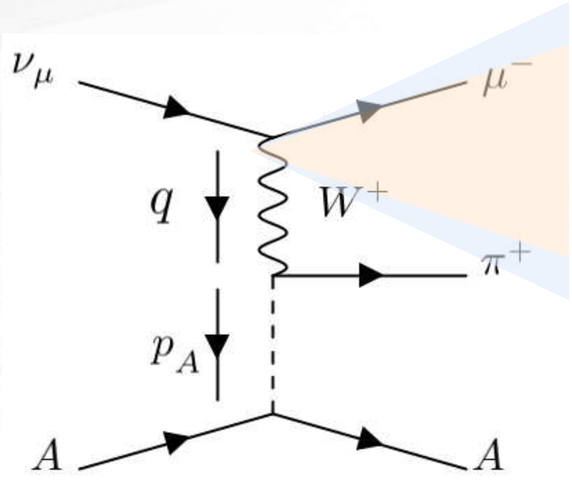
$$\sigma^{CH}_{NC1\pi^+} = (6.07 \pm 1.22) \times 10^{-41}\ \text{cm}^2\ \text{nucleon}^{-1}$$

- Data prefers Bertini Cascade (FSI) model

ν_μ-Coherent Charged Pion Scattering on Carbon

$\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu-C}$ Phys. Rev. D **108**, 092009

Coherent charged pion production from a neutrino coherently scattering off a nucleus:



$$\overset{(-)}{\nu}_\mu + A \rightarrow \mu^{\overset{(+)}{-}} + \pi^{\overset{(-)}{+}} + A$$

$p_\mu > 0.2$GeV and $\cos(\theta_\mu) > 0.8$ $\left(\theta_\mu < 37^\circ\right)$

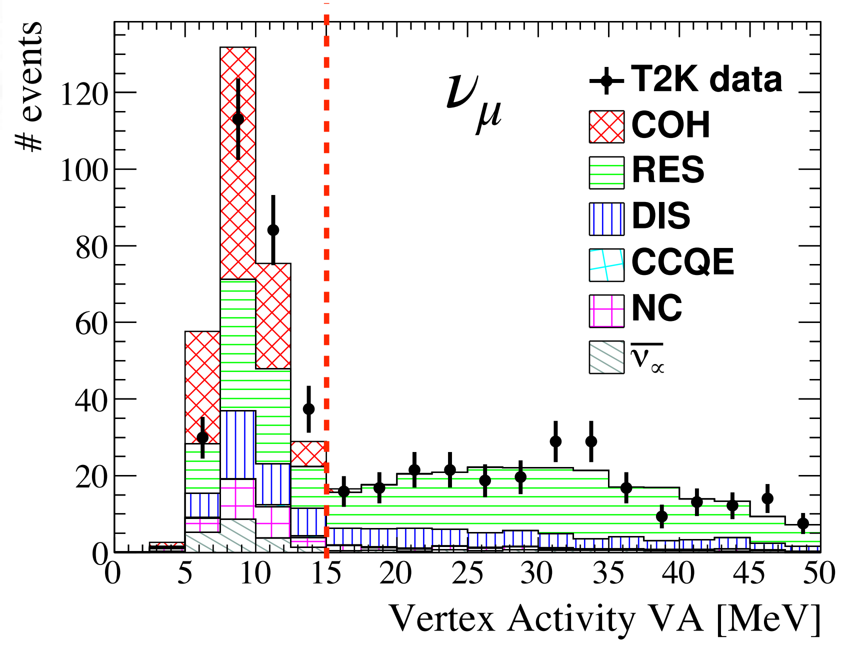
$p_\pi > 0.2$GeV and $\cos(\theta_\pi) > 0.6$ $\left(\theta_\pi < 53^\circ\right)$

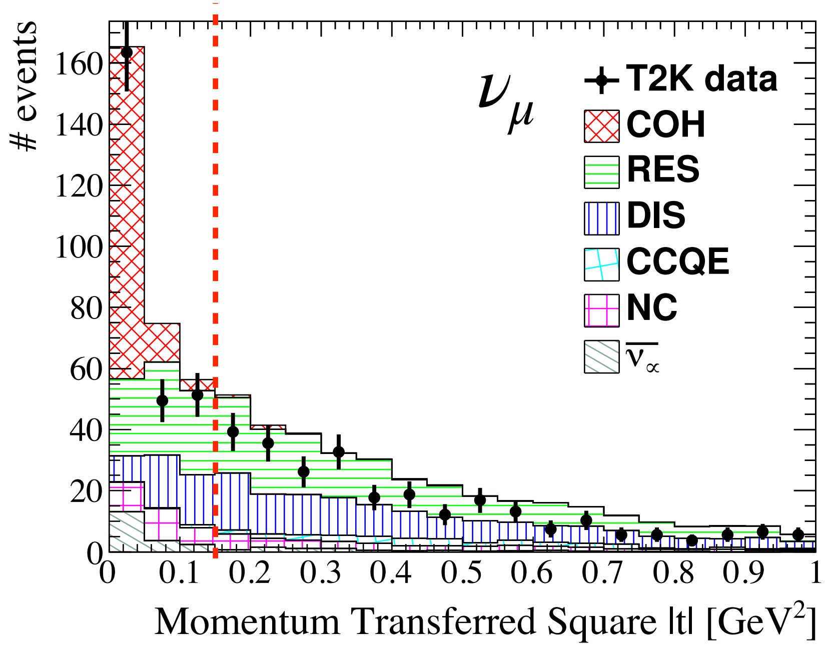
- Use energy spectra in Forward (FHC) and Reverse (RHC):
  - ν_μ: narrow energy-band off-axis flux peaked at 0.6 GeV
  - $\bar{\nu}_\mu$: wide(r) energy-band on-axis flux peaked at 1.1 GeV
- Data samples:
  - ν_μ: 11.54×10^{20} POT (collected 2010-2017 in FHC configuration)
  - $\bar{\nu}_\mu$: 8.15×10^{20} POT (collected 2014-2018 in RHC configuration)

ν_μ-Coherent Charged Pion Scattering on Carbon

$\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu-C}$ Phys. Rev. D **108**, 092009

- Event selection: CC$1\mu 1\pi X p$ and
  - require low vertex activity (hadrons $\lesssim$15 MeV vertex activity in 5cm^2 volume around vertex position)
  - Require low 4-momentum transfer to nucleus ($\lesssim$0.15 GeV^2)



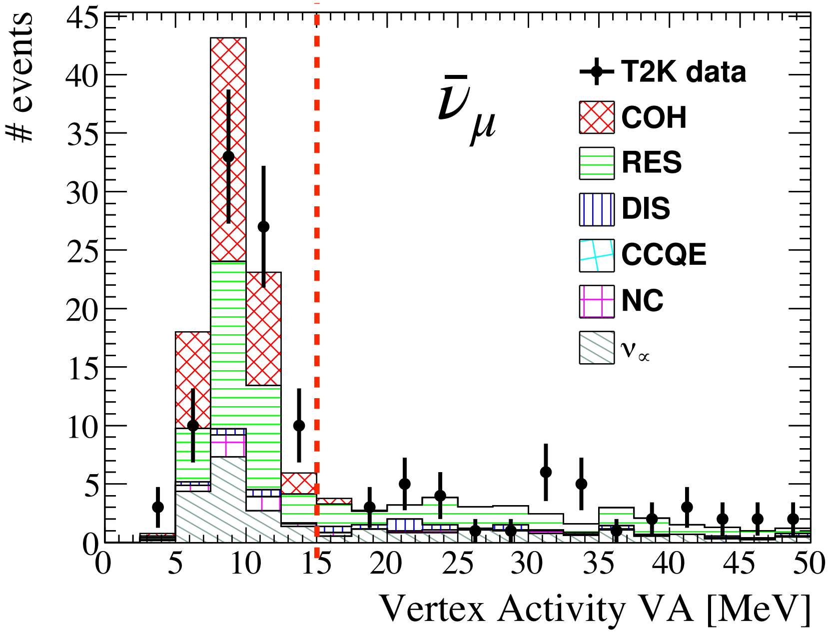


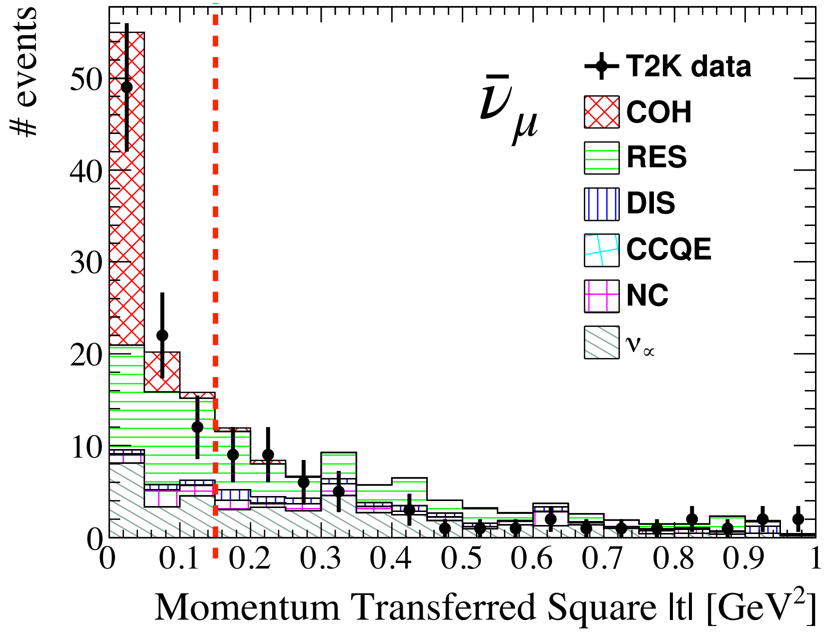
analogously for $\bar{\nu}_\mu$

ν_μ-Coherent Charged Pion Scattering on Carbon

$\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu-C}$ Phys. Rev. D **108**, 092009

- Event selection: CC$1\mu1\pi Xp$ and
  - require low vertex activity (hadrons $\lesssim$15 MeV vertex activity in 5cm^2 volume around vertex position)
  - Require low 4-momentum transfer to nucleus ($\lesssim$0.15 GeV^2)





analogously for ν_μ

ν_μ-Coherent Charged Pion Scattering on Carbon

$\sigma^{CC1\pi\text{-}COH}_{\nu_\mu,\bar{\nu}_\mu-C}$ Phys. Rev. D **108**, 092009

- Coherent Pion-Production Cross Section:

$$\sigma^{COH}_{\overset{(-)}{\nu}_\mu,FGD1} = \frac{N}{\epsilon\ \Phi\ T}$$

- N : number of COH events obtained by likelihood fitter
- ϵ : detector efficiency
- Φ : Integrated muon / anti-muon neutrino flux
- T : number of target nuclei

$$\sigma^{COH}_{\overset{(-)}{\nu}_\mu,C,1/3} = \sigma_C \sum_i \frac{F(A_i)}{F(A_C)}$$

- σ_C : COH cross section on carbon nuclei
- f_i : fractional composition of a given element
- $F(A) = A^{\frac{1}{3}}$: scaling function

	T2K (2022)	NEUT BS (2009)	GENIE RS (2007)
$\sigma_{\nu_\mu,\mathrm{FGD}}$	$3.00 \pm 0.37 \pm 0.31 \pm 0.49$	2.77	3.28
$\sigma_{\nu_\mu,\mathrm{C},1/3}$	$2.98 \pm 0.37 \pm 0.31 \pm 0.49$	2.57	3.09
$\sigma_{\bar{\nu}_\mu,\mathrm{FGD}}$	$3.07 \pm 0.71 \pm 0.39 \pm 0.75$	2.87	/
$\sigma_{\bar{\nu}_\mu,\mathrm{C},1/3}$	$3.05 \pm 0.71 \pm 0.39 \pm 0.74$	2.78	/