T2K recent results on cross-section measurements

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NUFACT2017, Uppsala University
September 25th 2017

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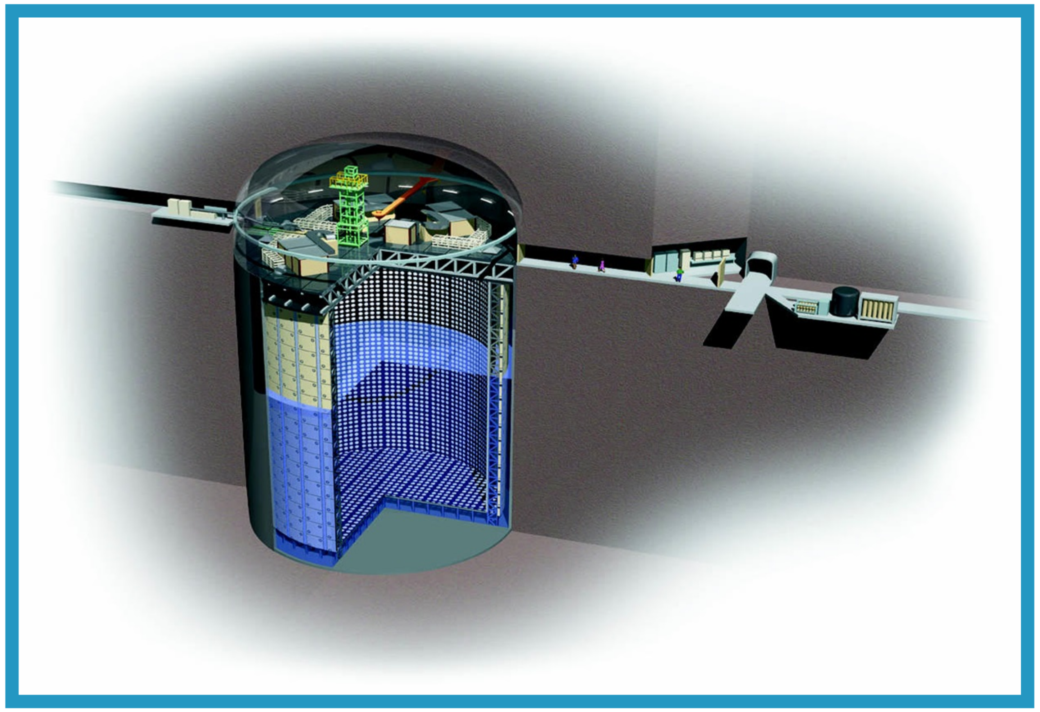
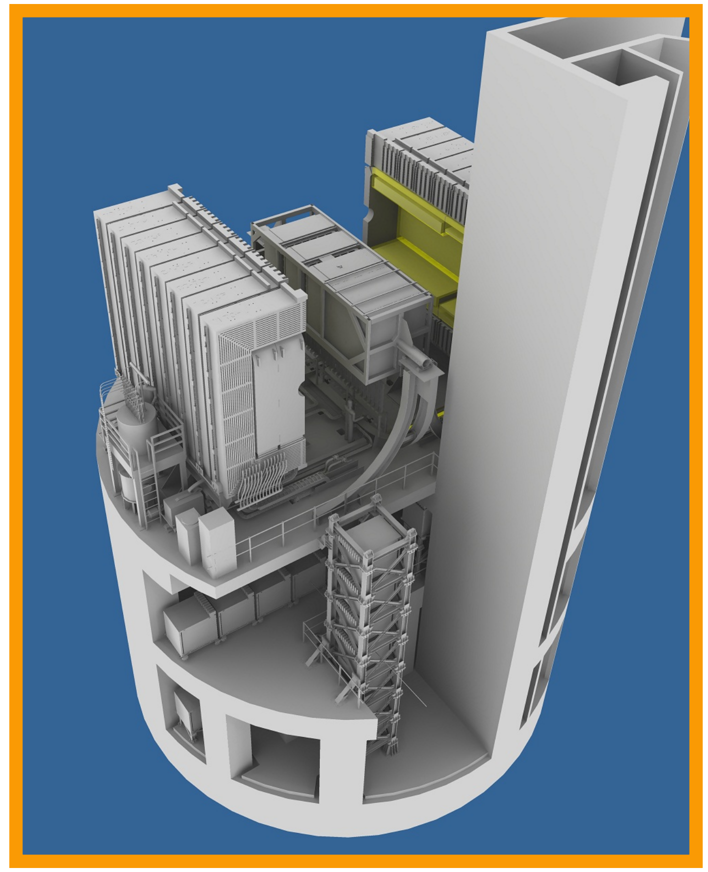
INFN Napoli

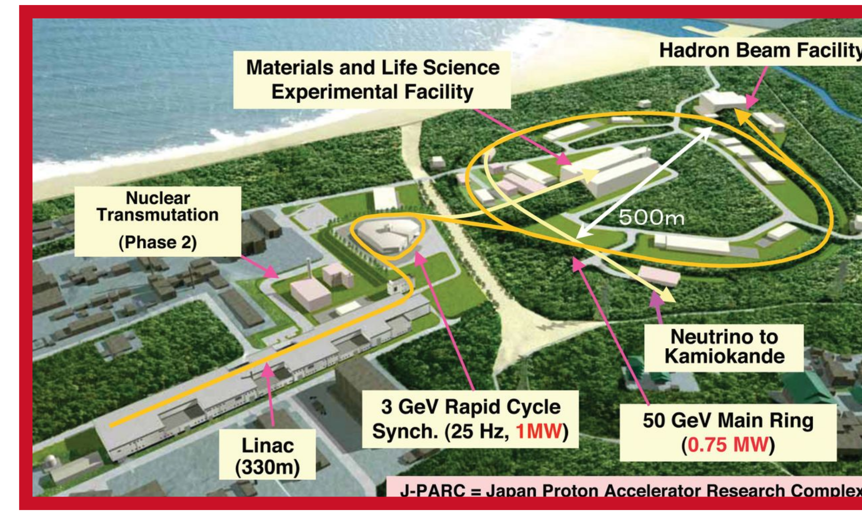
Overview

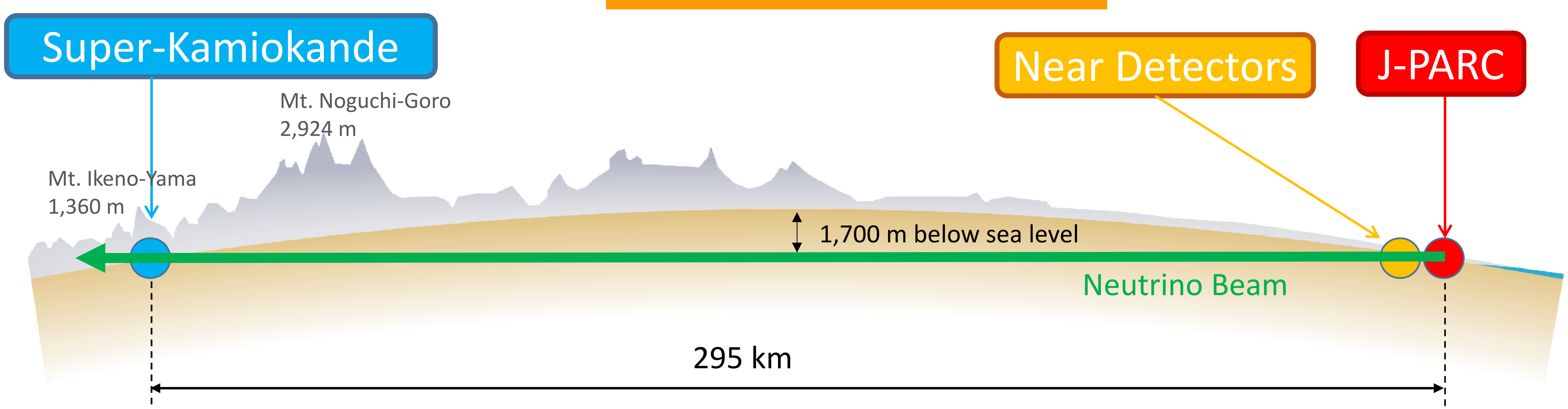
- Experimental setup
- Neutrino interactions at T2K
- Motivation for measuring cross sections
- Recent cross-section results
- Future work and summary

The T2K experiment

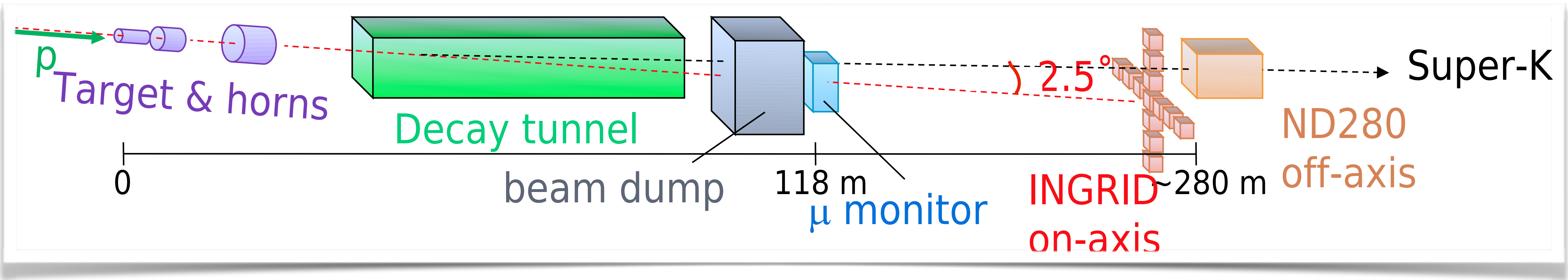




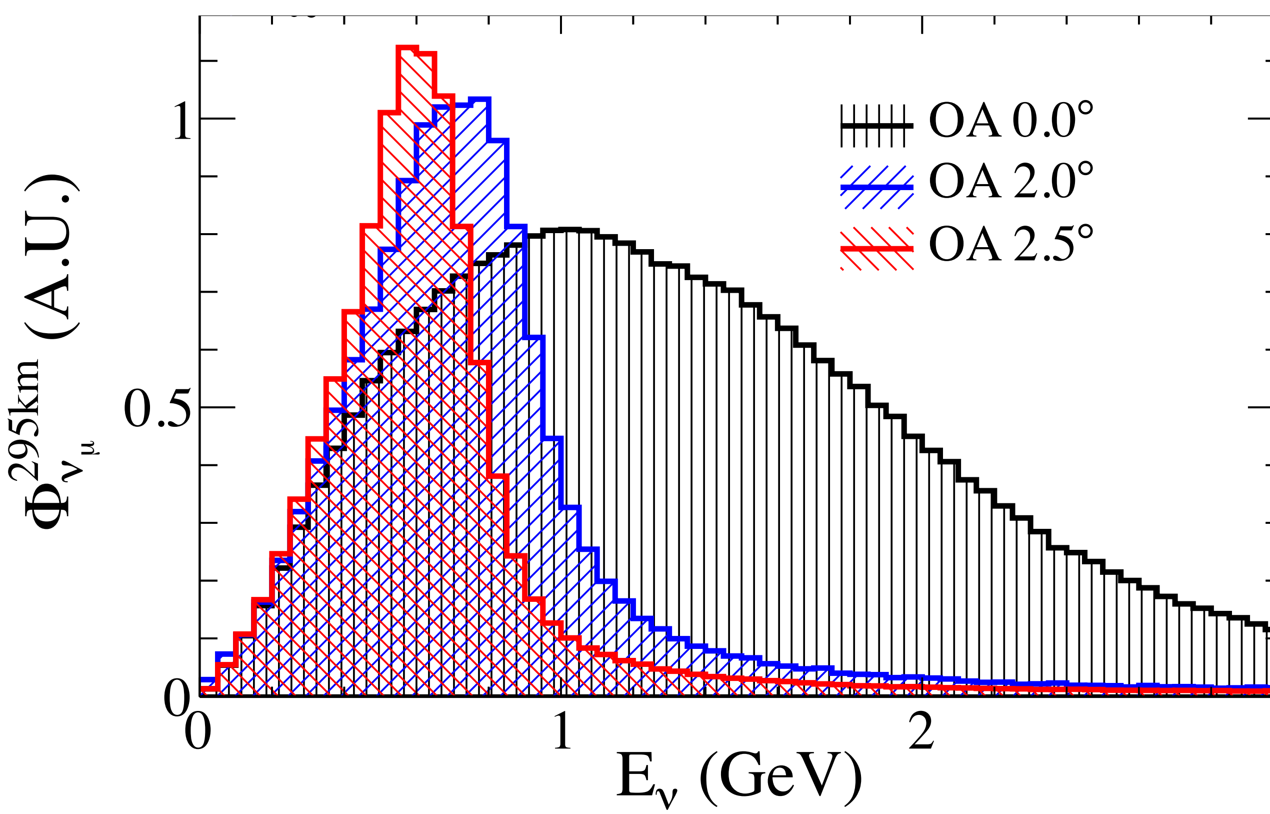




T2K Flux

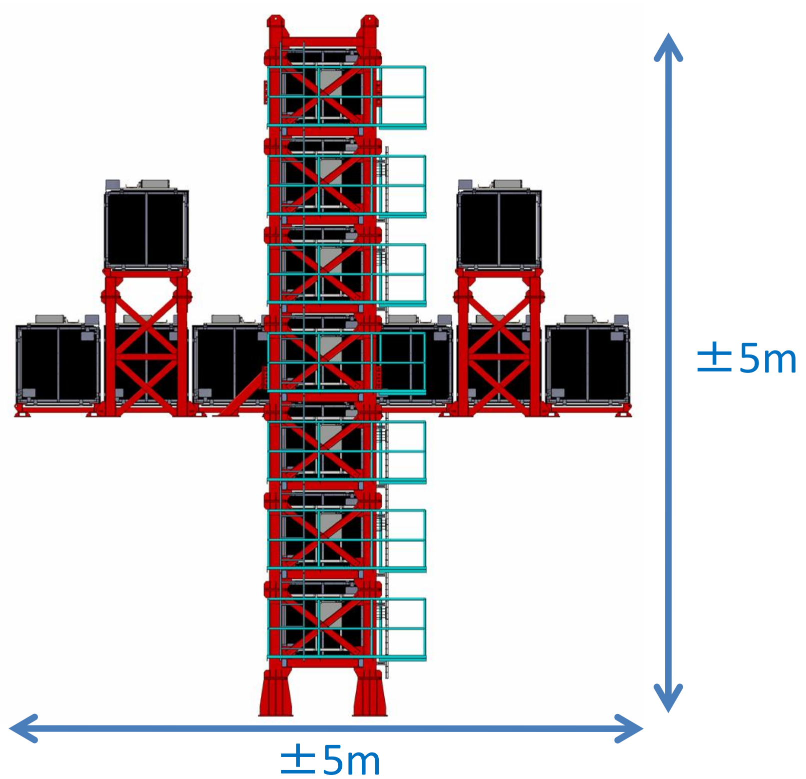


- Beam 2.5° off the direction to the far detector
- Narrow beam centered around 0.6 GeV
- Reduce ν_e component from *K* decays
- Flux estimation by hadron production measurements from NA61/SHINE



The Near Detector complex

Where T2K cross-section measurements have been performed!

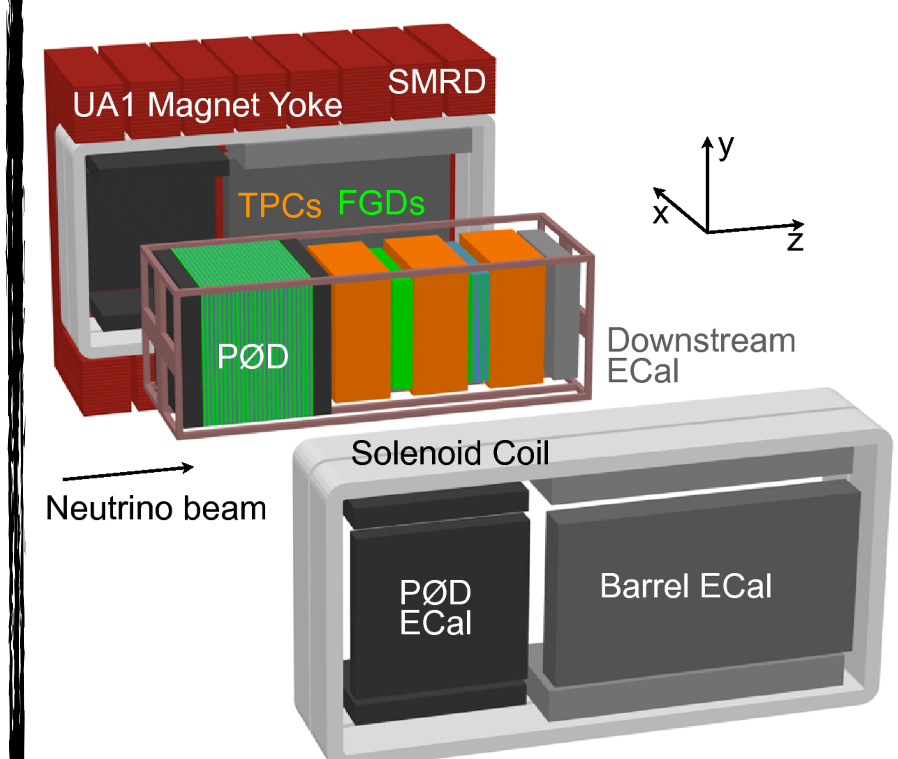


INGRID on-axis detector:

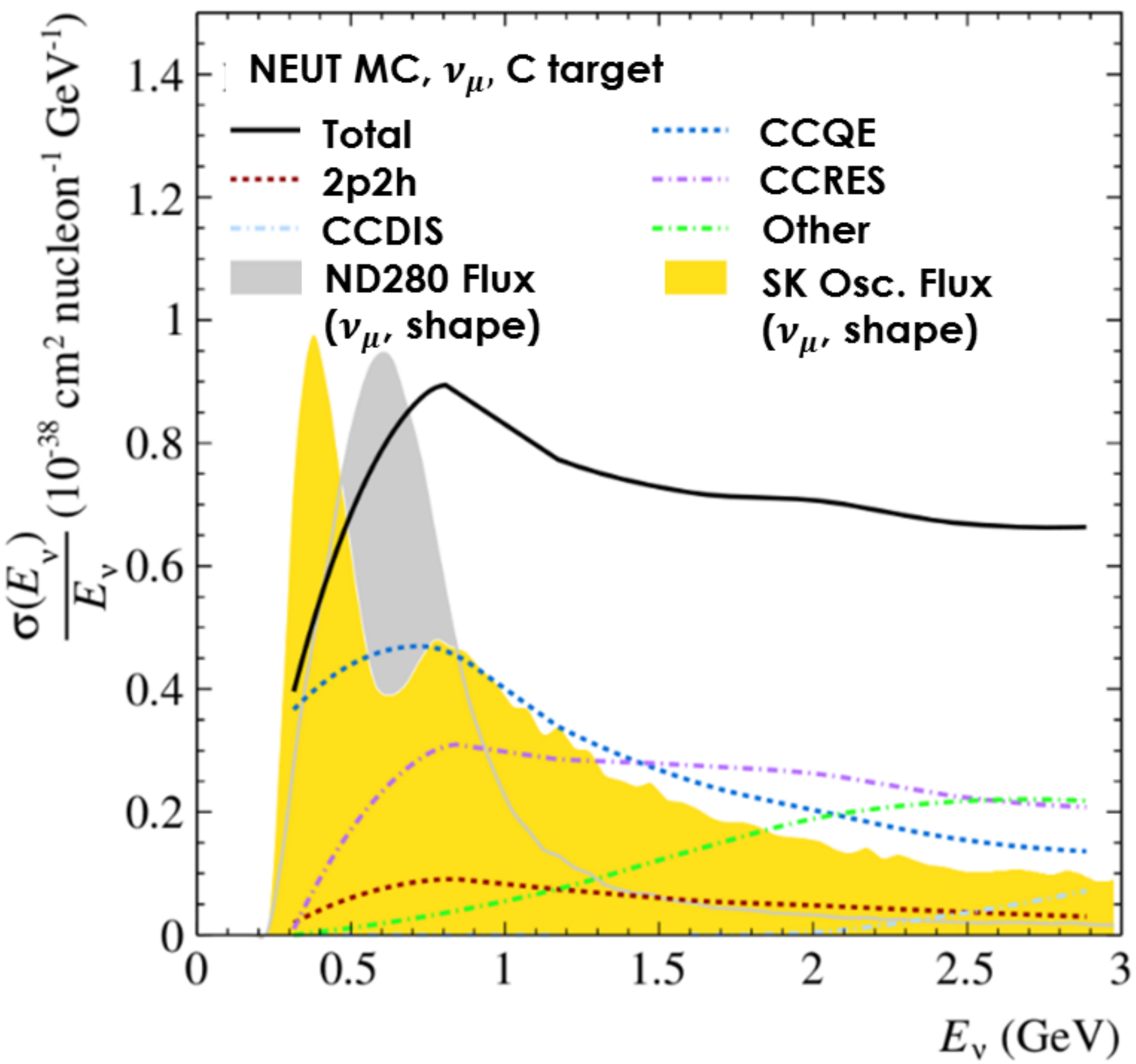
- Monitor the beam direction
- 14 modules arranged as a cross and other 2 outside the main cross target: CH+Fe
- Extra module - Proton Module target: CH

ND280 off-axis detector located 280 m from the target:

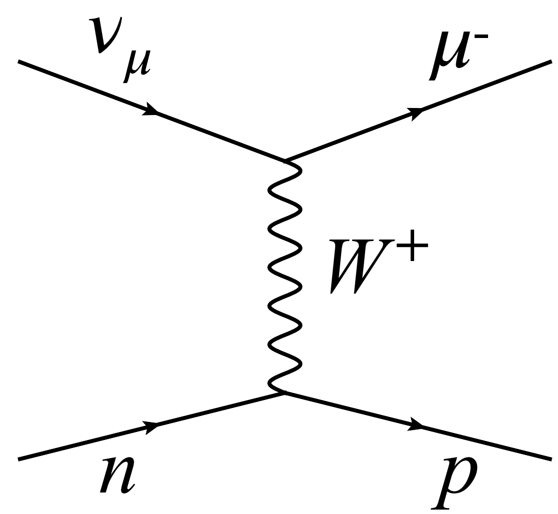
- π^0 detector P0D target: CH+H2O
- 3 Time Projection Chambers (TPC)
- 2 Fine-grained detectors FGD target: CH+H2O
- Electromagnetic calorimeters (ECal)
- UA1 refurbished Magnet instrumented with side muon range detector (SMRD)



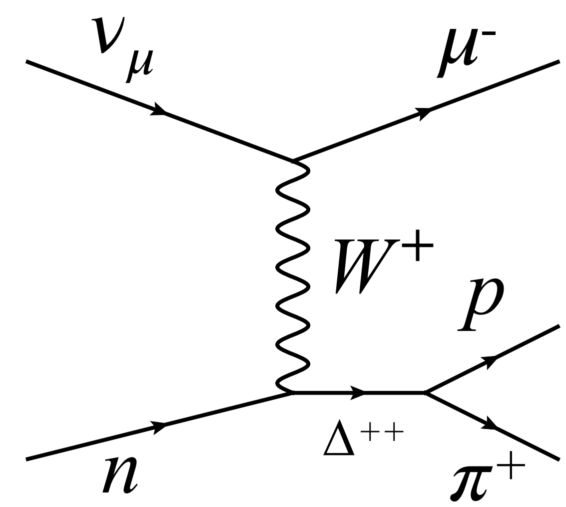
Relevant ν interactions at T2K



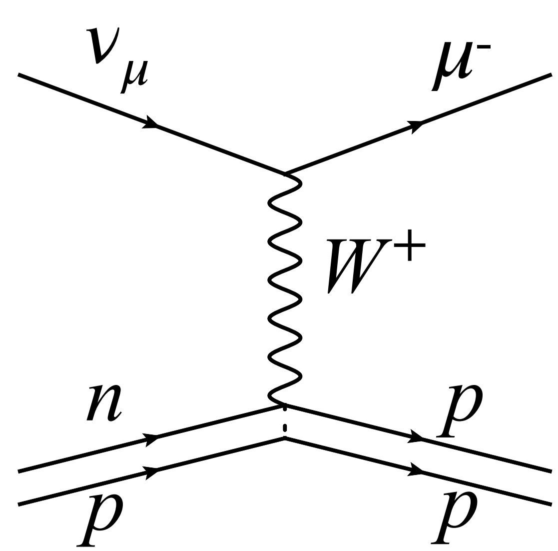
CCQE
(Charged-Current Quasi-Elastic)



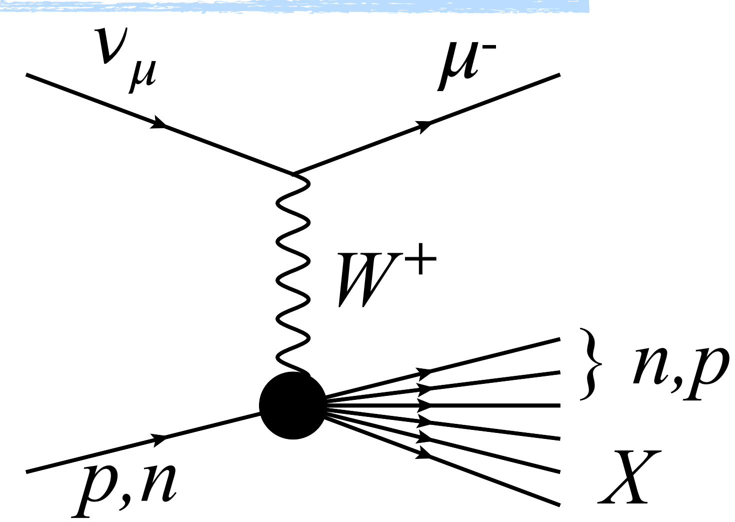
CCRES
(Charged-Current Resonant pion production)



2p2h
(2 particle 2 hole)

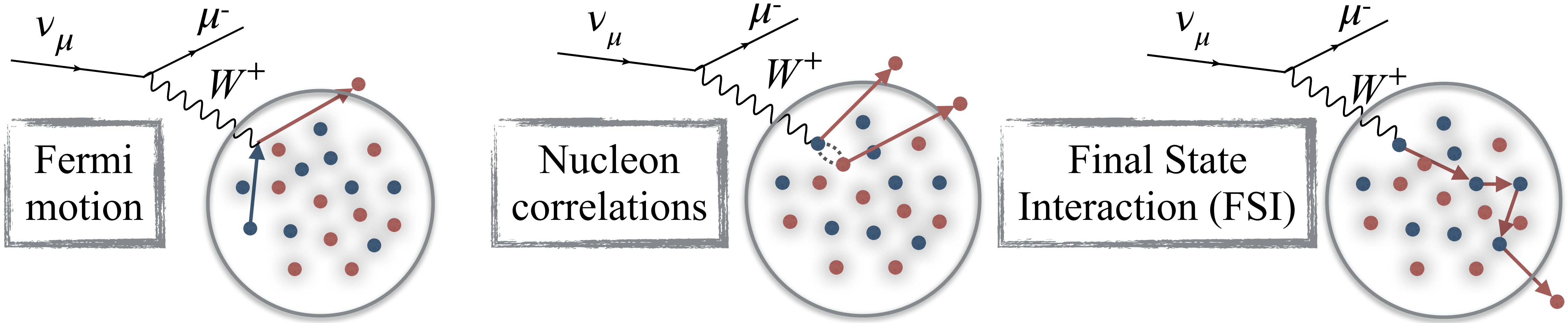


CCDIS
(Charged-Current Deep Inelastic Scattering)

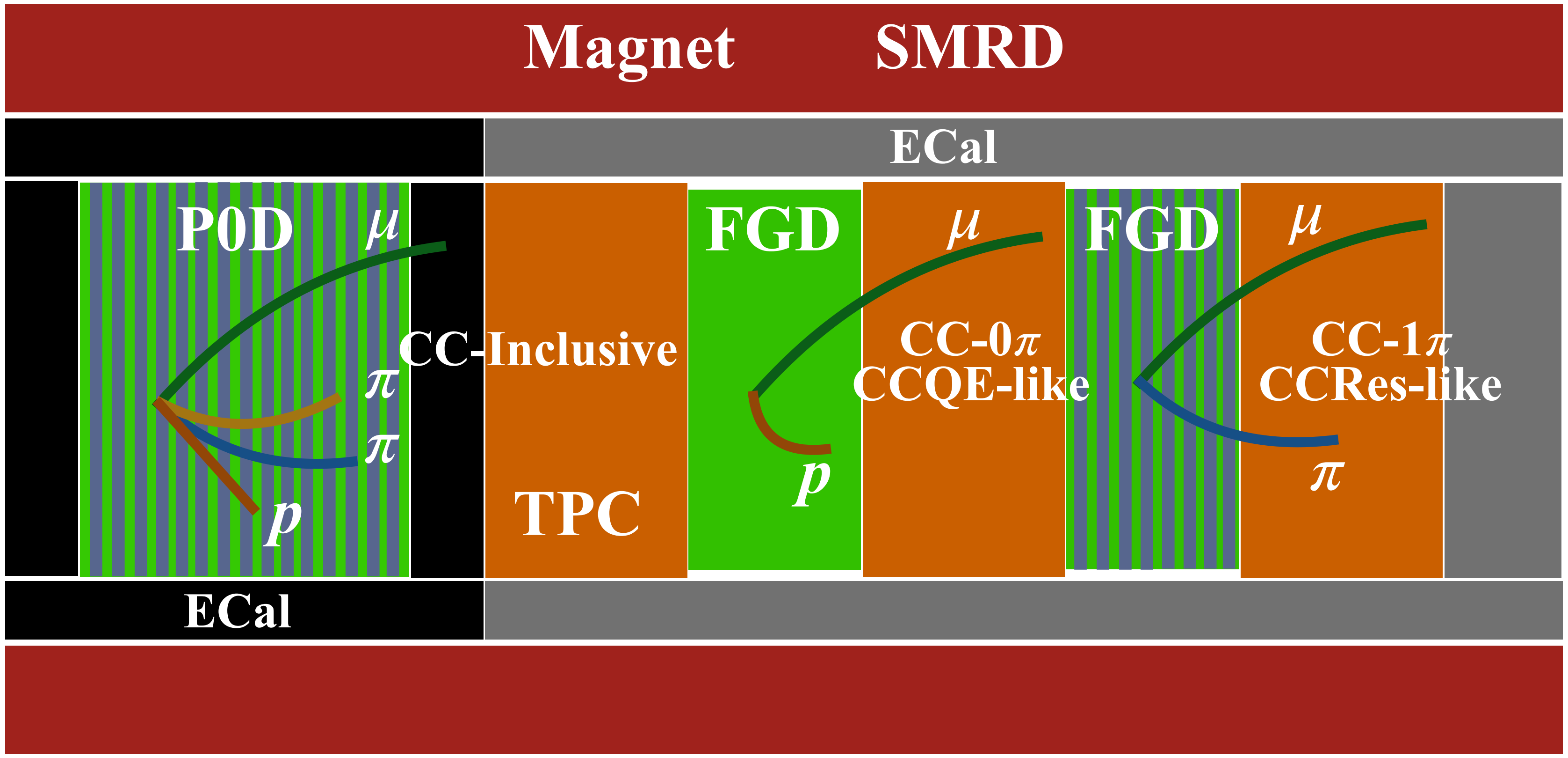


What can we measure?

Nucleons bound in the nucleus ⇒ Nuclear effect!



- **Nuclear** and **detector effects** obfuscate interaction mode
- Minimise the model dependence measure interaction topologies



Event generators

- Neutrino MC Generators connect the true and observed event topologies and kinematics
- Every observable is a convolution of flux, interaction physics and detector effects
- Re-weighting tools allow to assess uncertainties and tune the physics models
- T2K official generators are **NEUT** and **GENIE**
- We compare our results against different models: **GIBUU**, **NuWro**

Why cross-sections measurement

For more detail see talk by D. Hadley on Wednesday

Neutrino scattering understanding is crucial for the interpretation of neutrino oscillation since it affects background estimation and energy reconstruction.

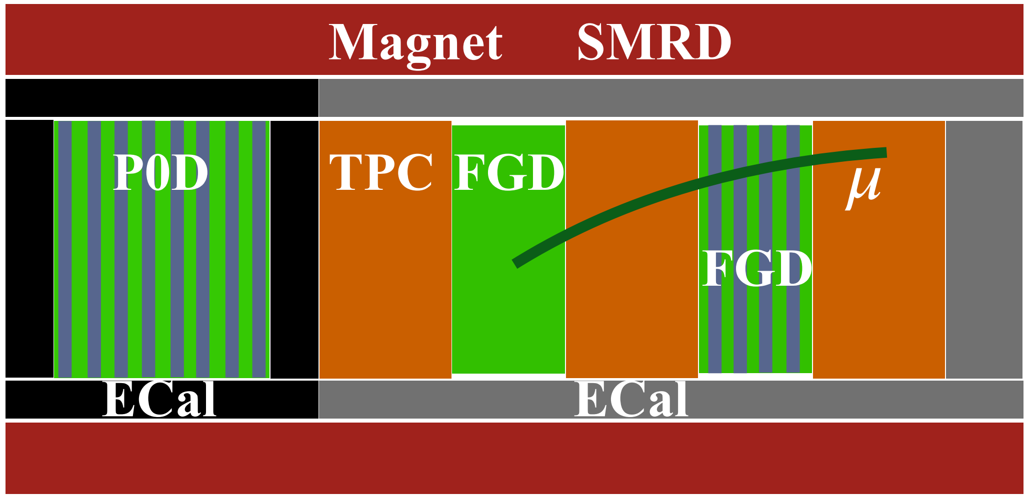
One of the **largest systematic uncertainties** in neutrino oscillation comes from neutrino interaction uncertainty.

2016 oscillation analysis	ν_μ 1 muon-like ring	ν_e 1 electron-like ring	$\bar{\nu}_\mu$ 1 muon-like ring	$\bar{\nu}_e$ 1 electron-like ring
ν flux w/o ND280	7,6%	8,9%	7,1%	8,0%
ν flux w/ND280	3,6%	3,6%	3,8%	3,8%
ν cross section w/o ND280	7,7%	7,2%	9,3%	10,1%
ν cross section w ND280	4,1%	5,1%	4,2%	5,5%
ν flux+cross section	2,9%	4,2%	3,4%	4,6%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%
Super-K detector	3,9%	2,4%	3,3%	3,1%
Total w/o ND280	12,0%	11,9%	12,5%	13,7%
Total w/ ND280	5,0%	5,4%	5,2%	6,2%

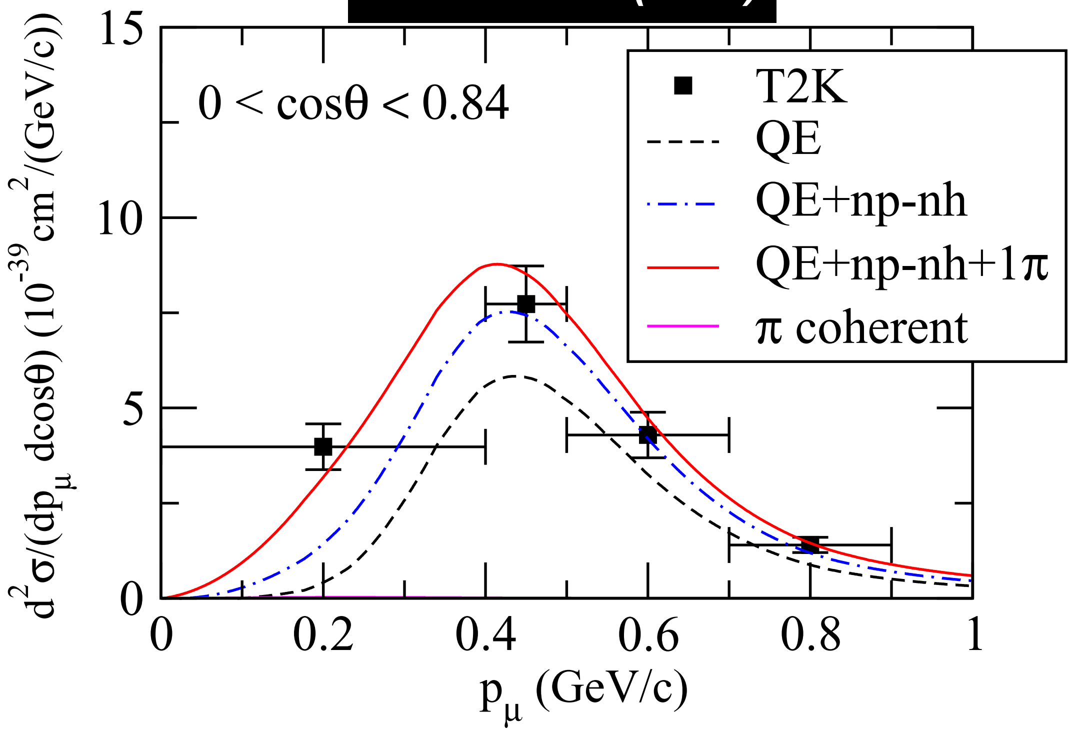
ν_μ CC Inclusive on CH

Already published a ν_μ CC inclusive cross section on CH using FGD1 as target:
Phys. Rev. D 87, 092003

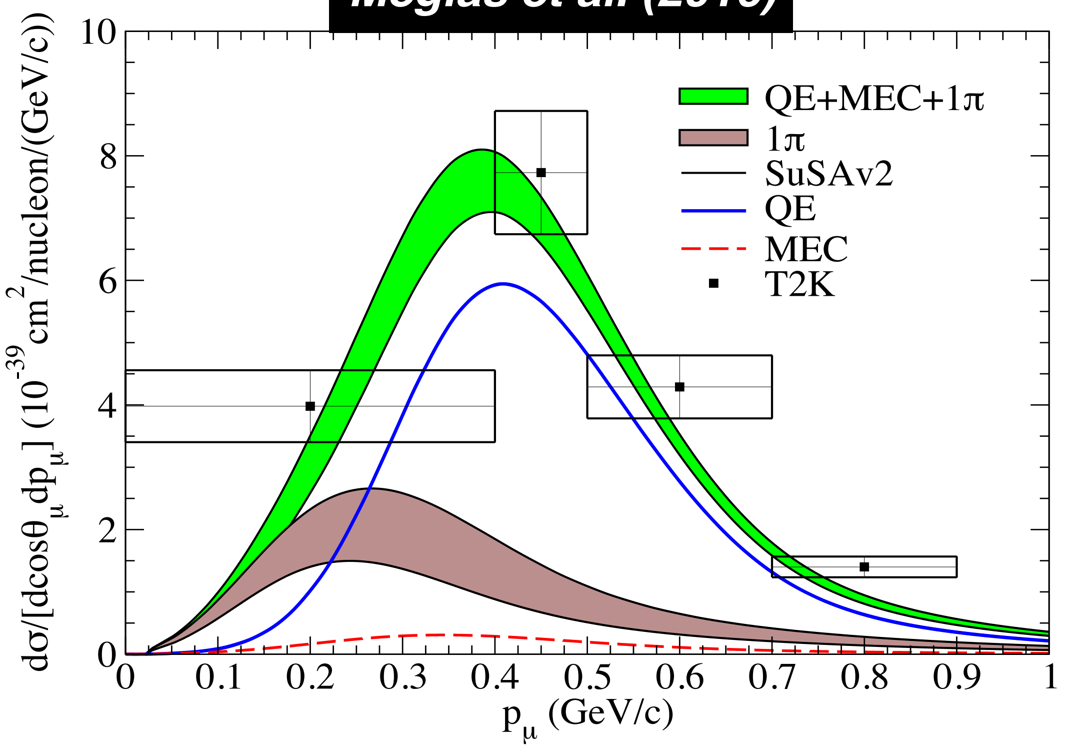
- Data tested against different models
- Limited statistics
- Phase space restricted to forward region of the outgoing muon



Martini et al. (2014)



Megias et al. (2016)

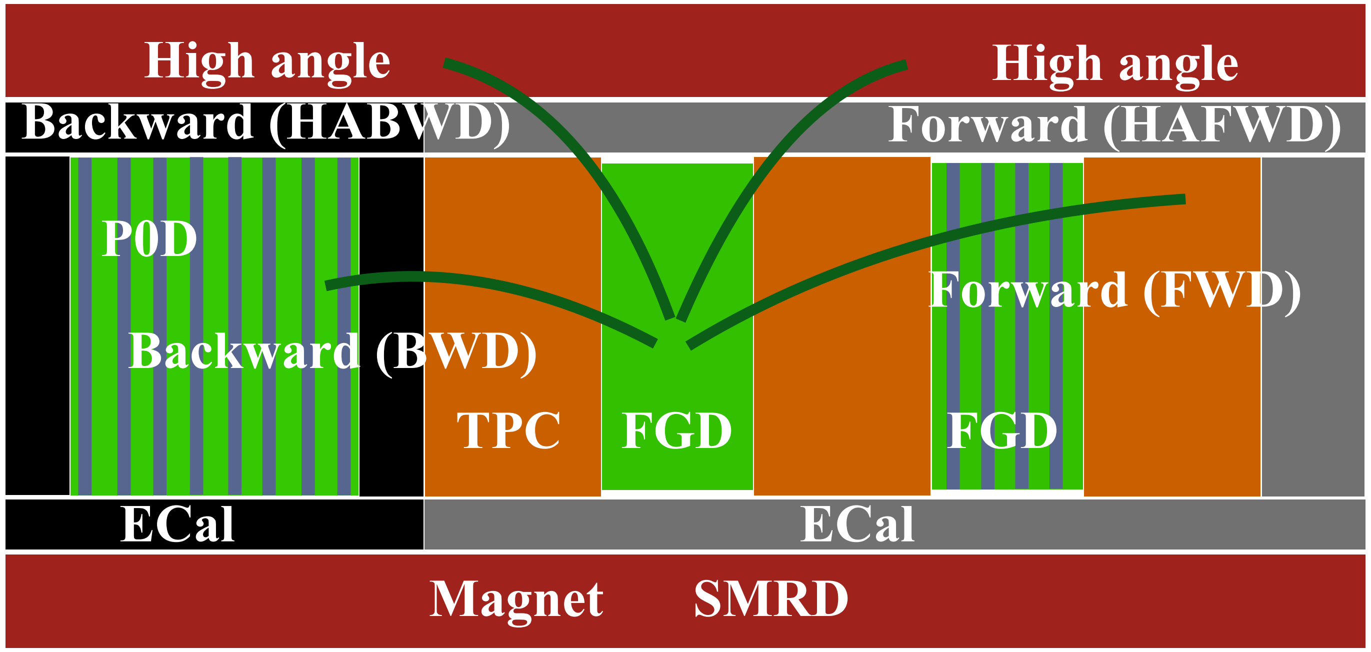


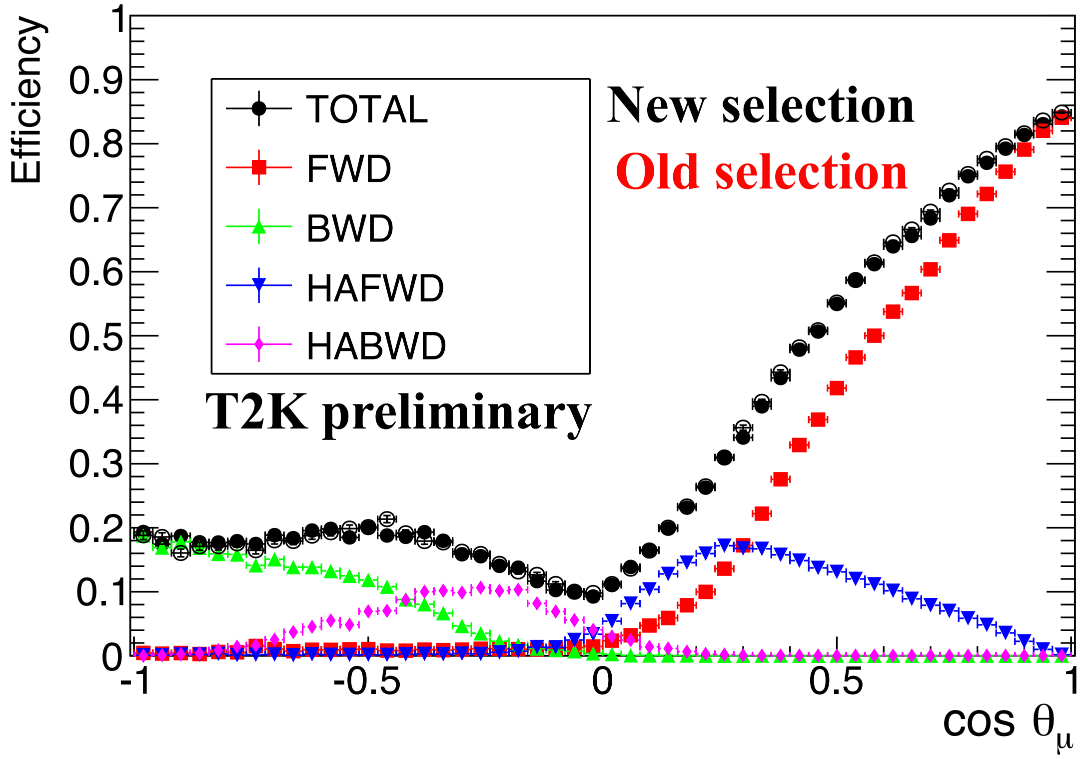
ν_μ CC Inclusive on CH

Next generation analysis!

New features of the revisited analysis:

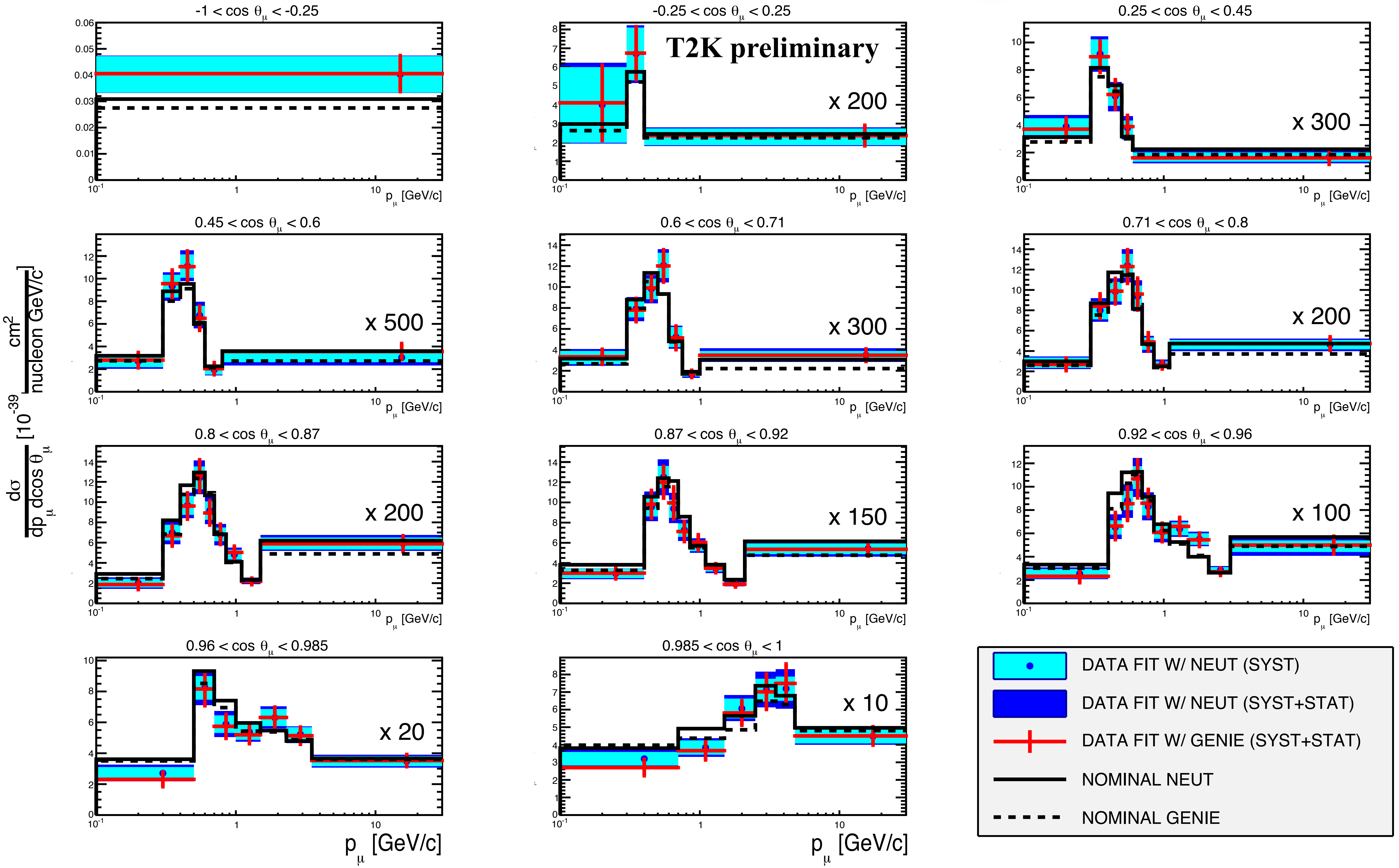
- Statistics has been increased by a factor of five
- Increased angular acceptance for high-angle and backward-going muons using the timing information between the sub-detectors
- Increased purities and efficiency
- Used a maximum likelihood fit instead of the bayesian unfolding
- Flux integrated cross section to avoid neutrino energy dependence
- Background constrained with two sidebands



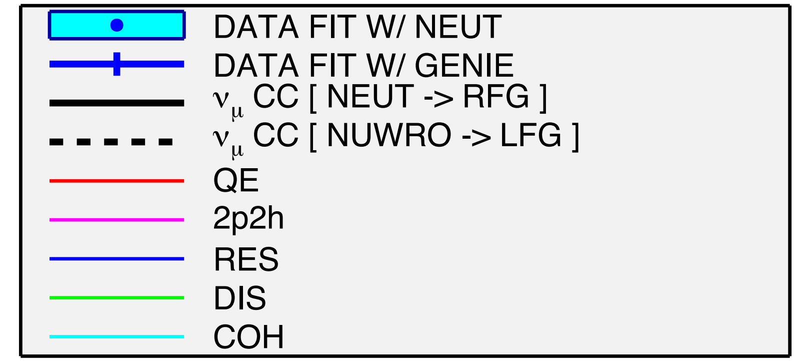


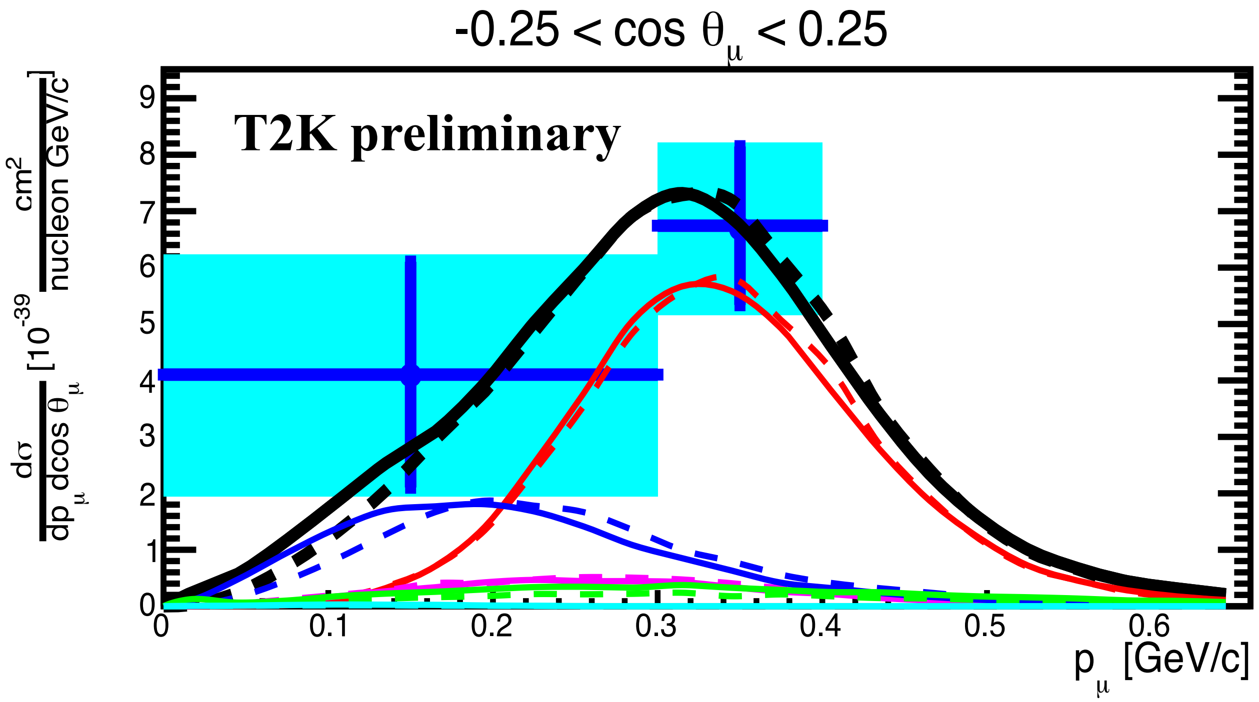
ν_μ CC Inclusive on CH

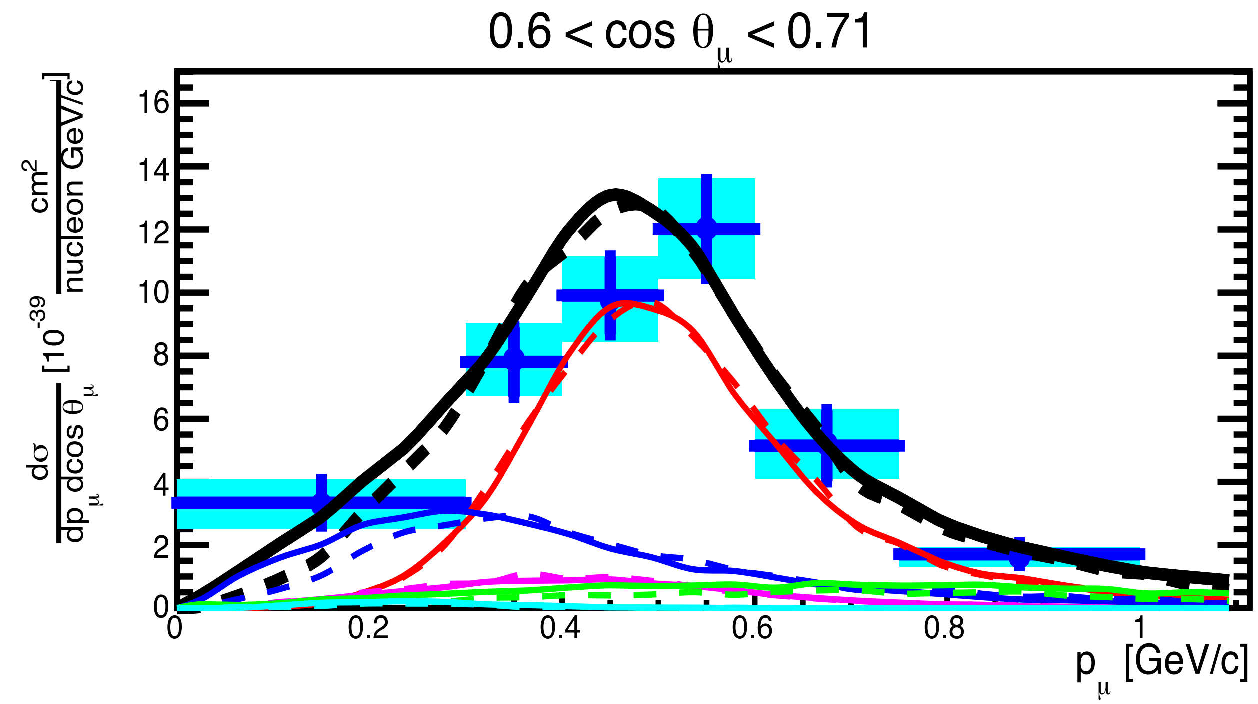
Publication in preparation!

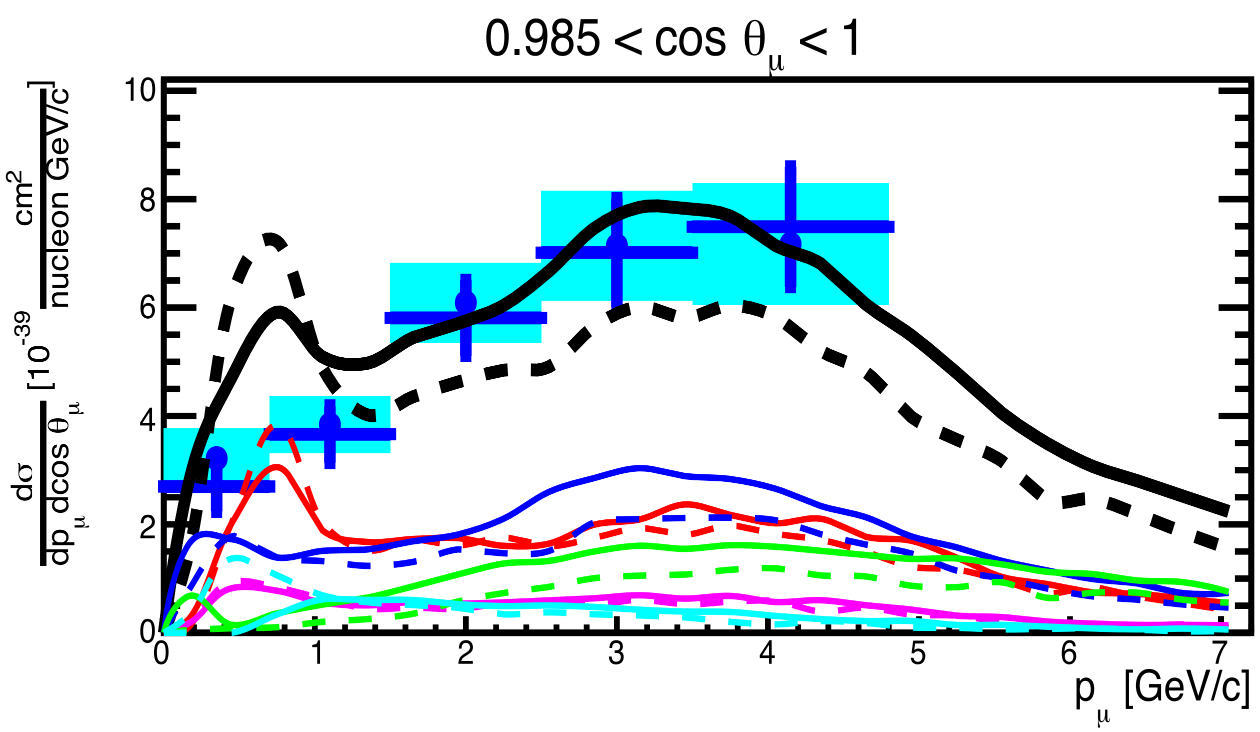


ν_μ CC Inclusive on CH





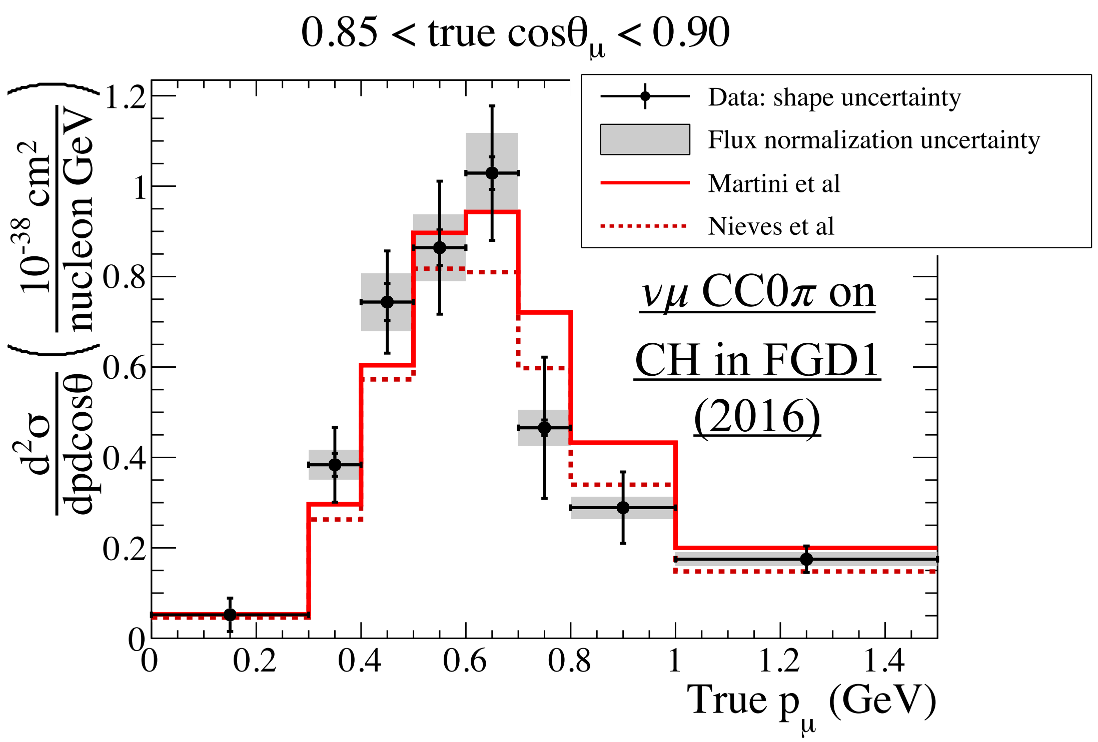


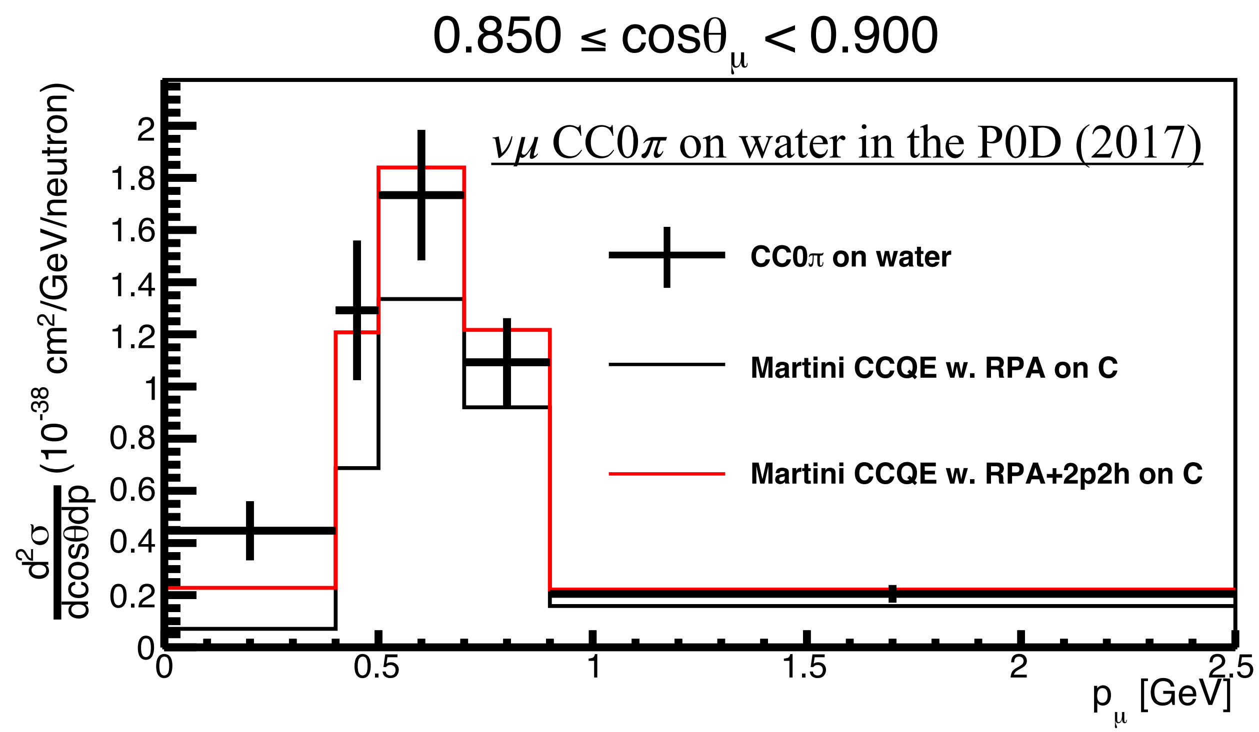


NEUT using Relativistic Fermi Gas (RFG) as nuclear model and NuWro using Local Fermi Gas (LFG) overestimate the cross section in low momentum bins

ν_μ CC0π on CH and water

CC0π: CCQE-like + 2p2h





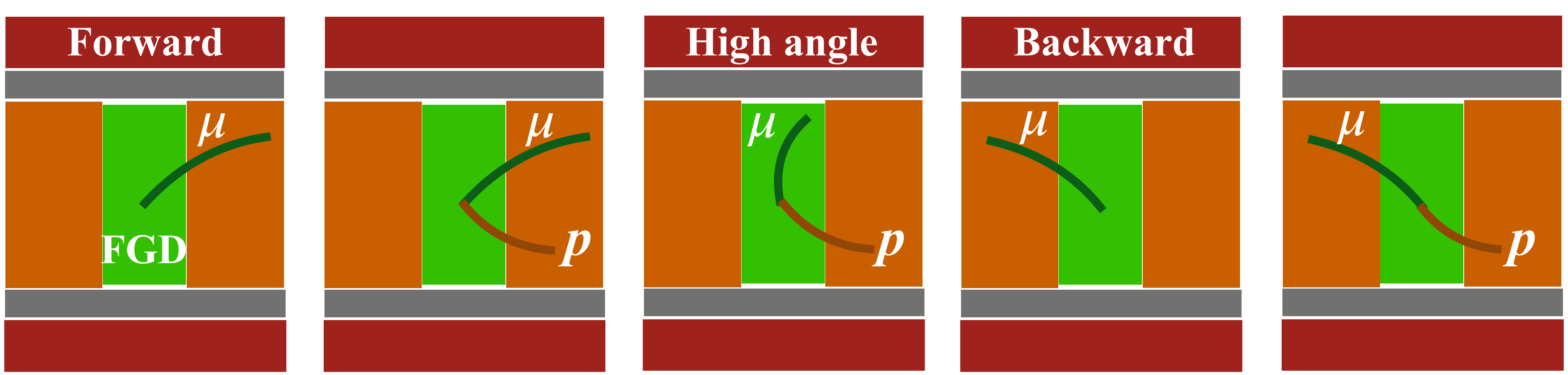
- Next step: CC0π cross section in muon and proton kinematics
- Can give more and new information on nuclear effects
- Nuclear effects are very difficult to model
- Need to be less dependent on simulation

ν_μ CC0π using μ+p kinematics

Selection and analysis strategy:

- Check if there are zero, one or more than one protons in the final state;
- Increase the angular acceptance for high-angle and backward-going muons using the timing information between the sub-detectors
- Used a maximum likelihood fit
- Background (CC resonant and CC DIS) constrained with two sidebands

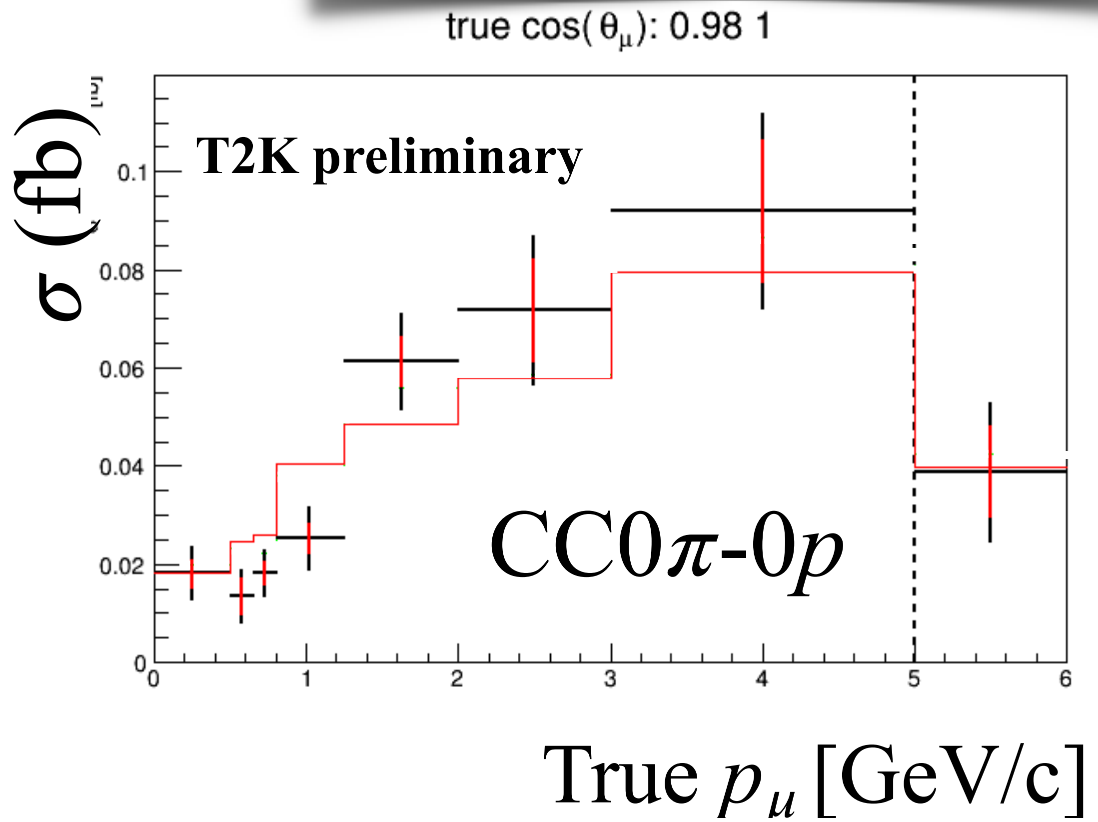
Signal selection

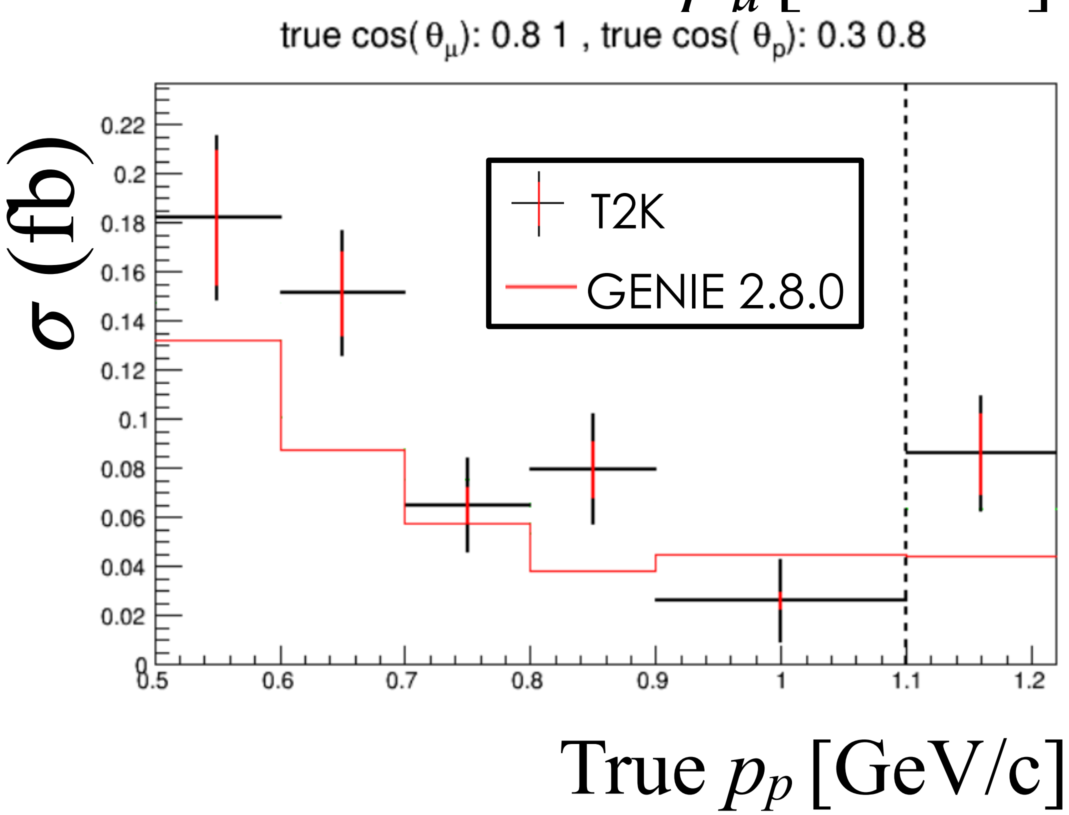


ν_μ CC0π using μ+p kinematics

Publication in preparation!

- Cross section extracted as function of the muon momentum and angle for CC0π-0p
- Cross section extracted as function of the muon and proton angle and muon momentum for CC0π-1p with momentum greater that 500 MeV/c
- Observed interesting excess over GENIE (w/o 2p2h)

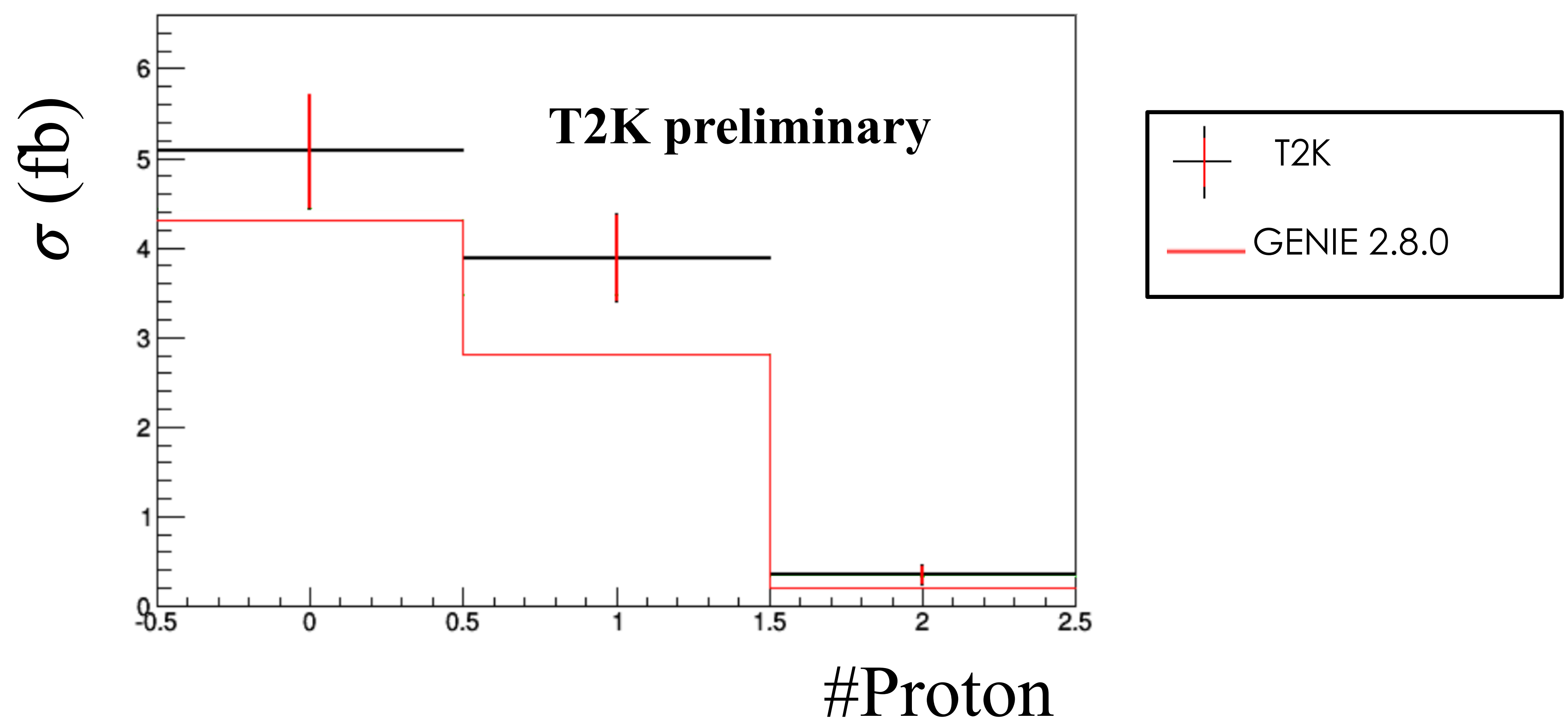




ν_μ CC0π using μ+p kinematics

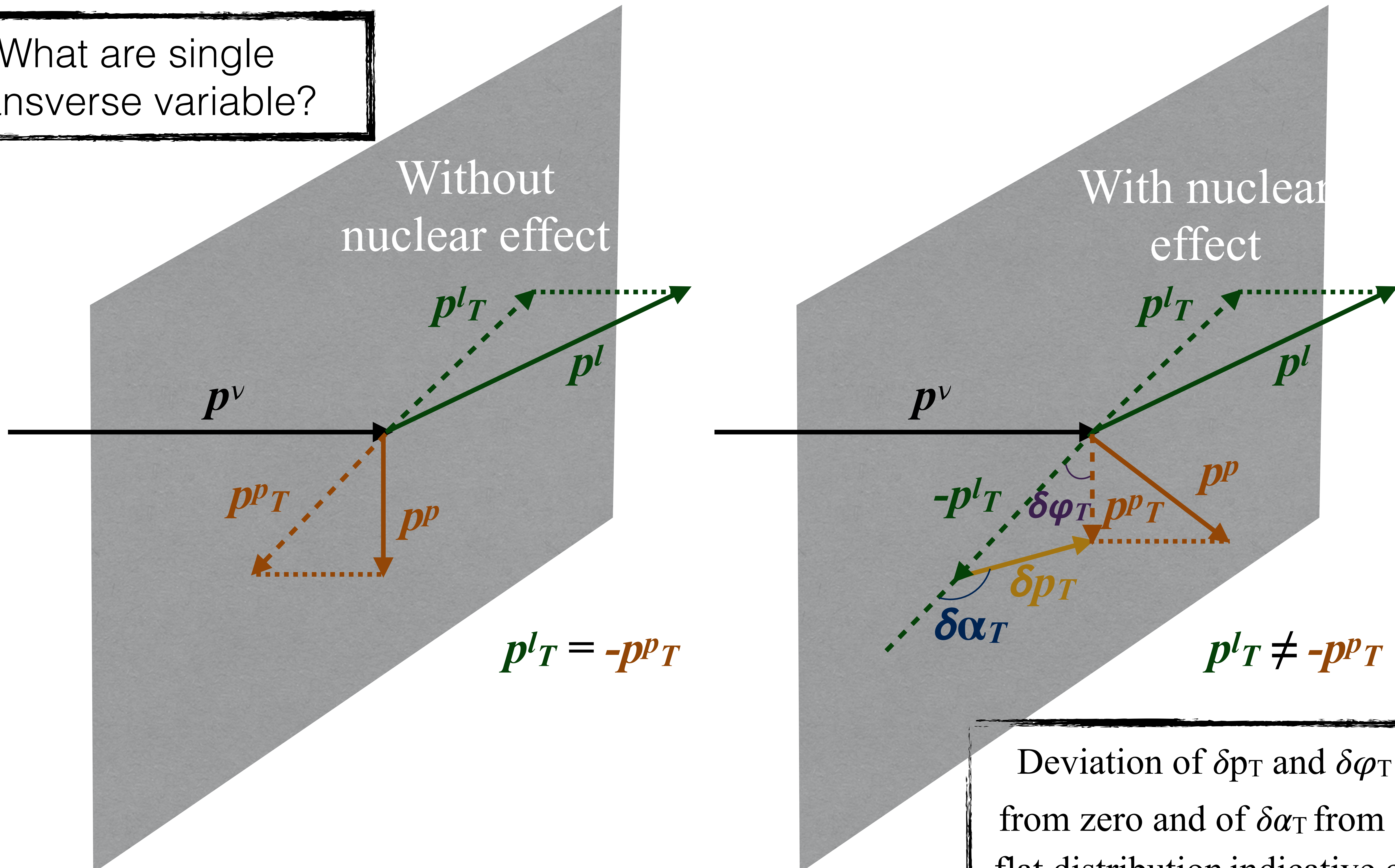
Publication in preparation!

- Cross section extracted also as a function of the number of protons with momentum greater that 500 MeV/c
- Observed interesting excess over GENIE (w/o 2p2h)
- More comparison under preparation



ν_μ CC0π using single transverse variables

What are single transverse variable?



Deviation of δp_T and $\delta\varphi_T$ from zero and of $\delta\alpha_T$ from a flat distribution indicative of nuclear effects

X.-G. Lu et al., Phys. Rev. C 94, 015503 (2016)

ν_μ CC0π with single transverse variables

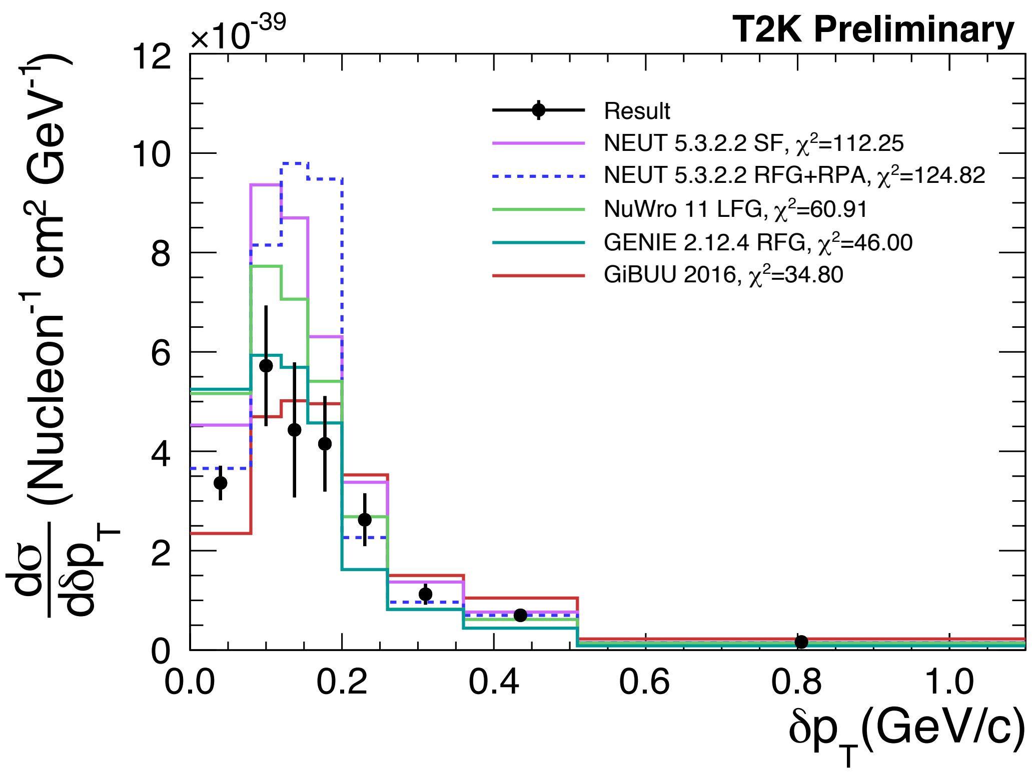
Publication in preparation!

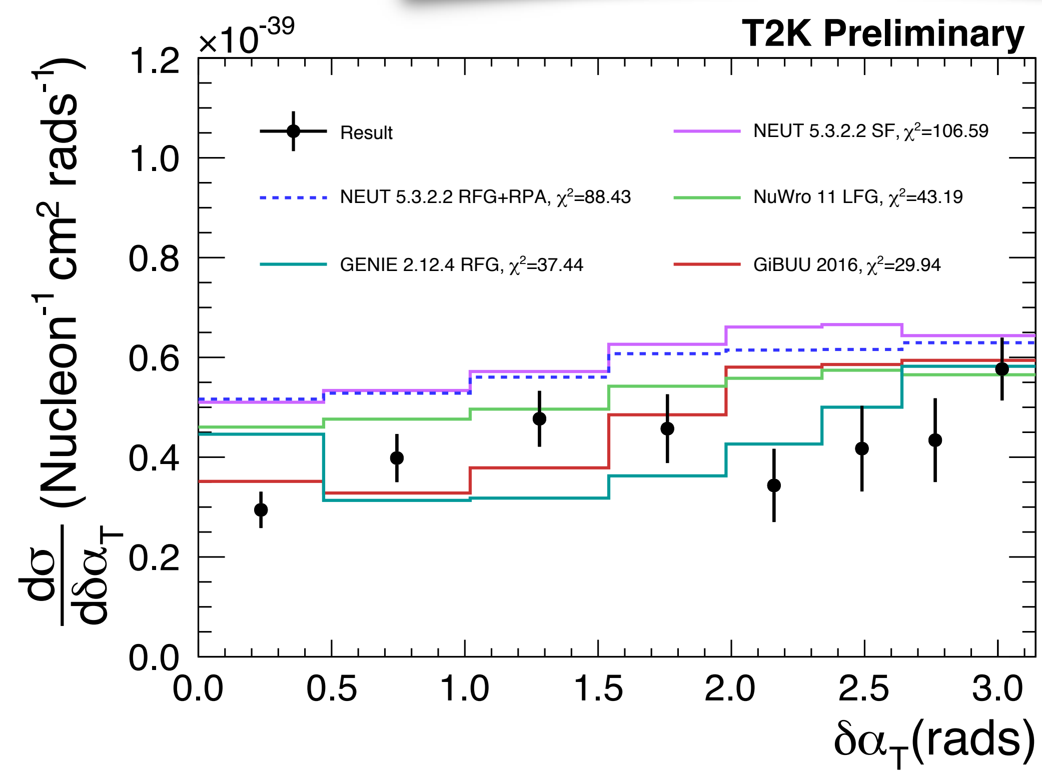
Analysis strategy:

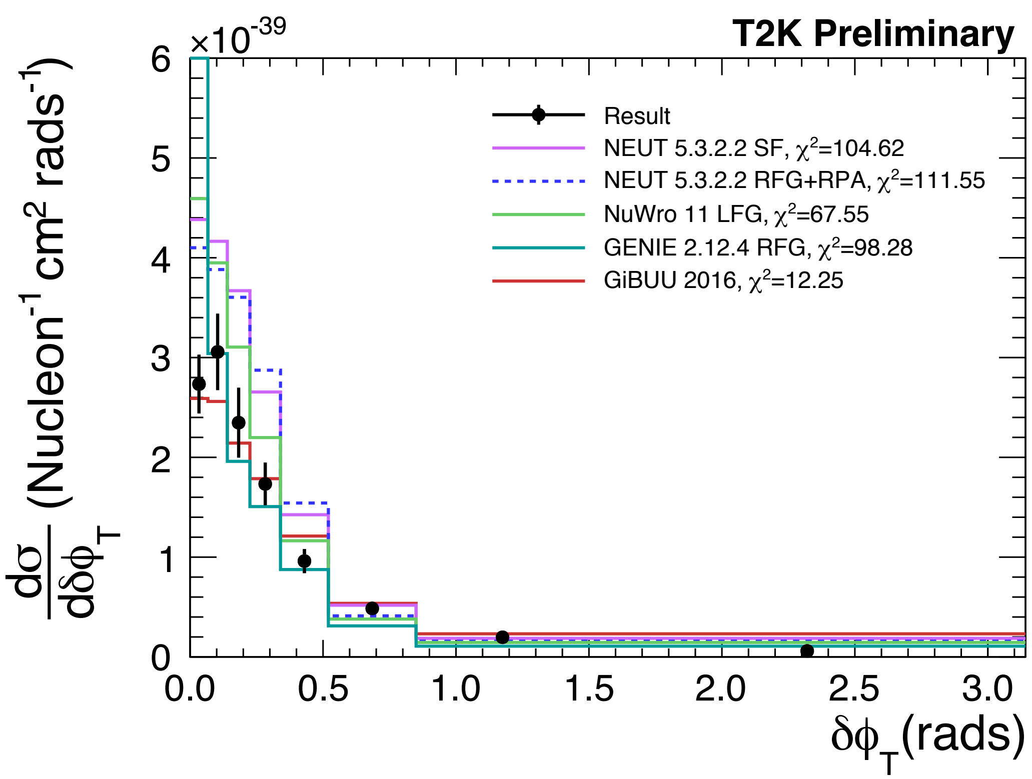
- Same selection used for CC0π with proton kinematics
- Measure flux-integrated cross section in bins of single transverse variable
- Restrict the phase space essential to mitigate model-dependence:
  - $p_\mu > 250$ MeV/c $\cos\theta_\mu > -0.6$
  - $450\ MeV/c < p_p < 1\ GeV/c$ $\cos\theta_p > 0.4$
- Cross section extracted using a maximum likelihood fit with a regularization method

ν_μ CC0π with single transverse variables

Publication in preparation!







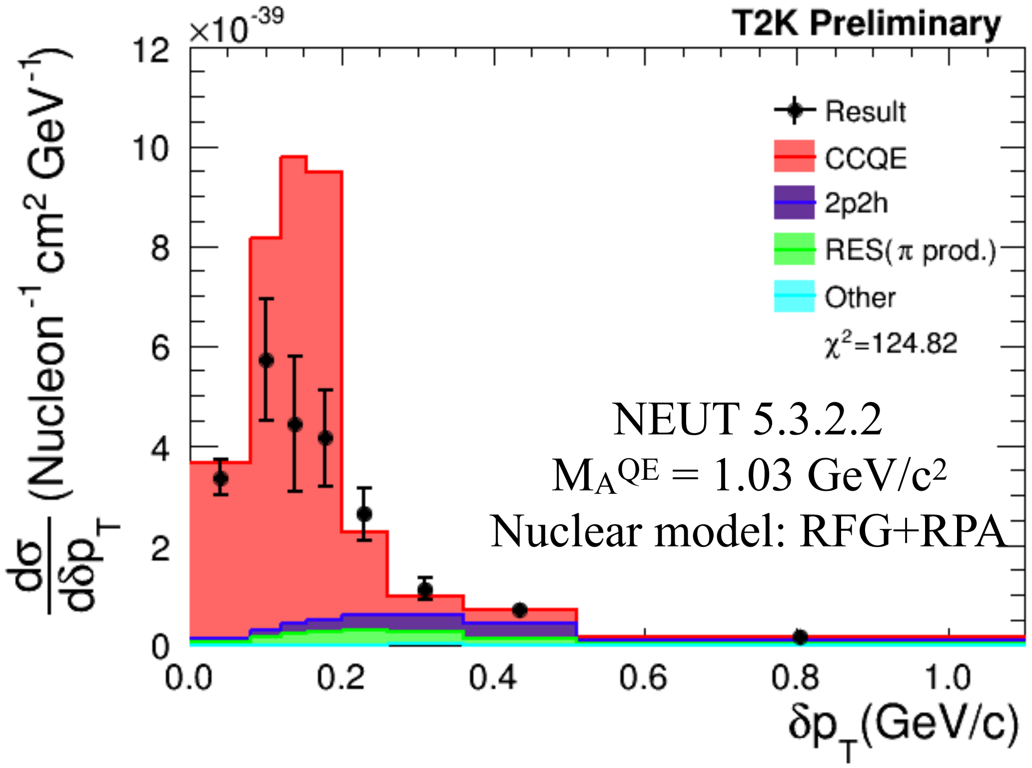
Data strongly disfavor RFG in favor of LFG and Spectral Function

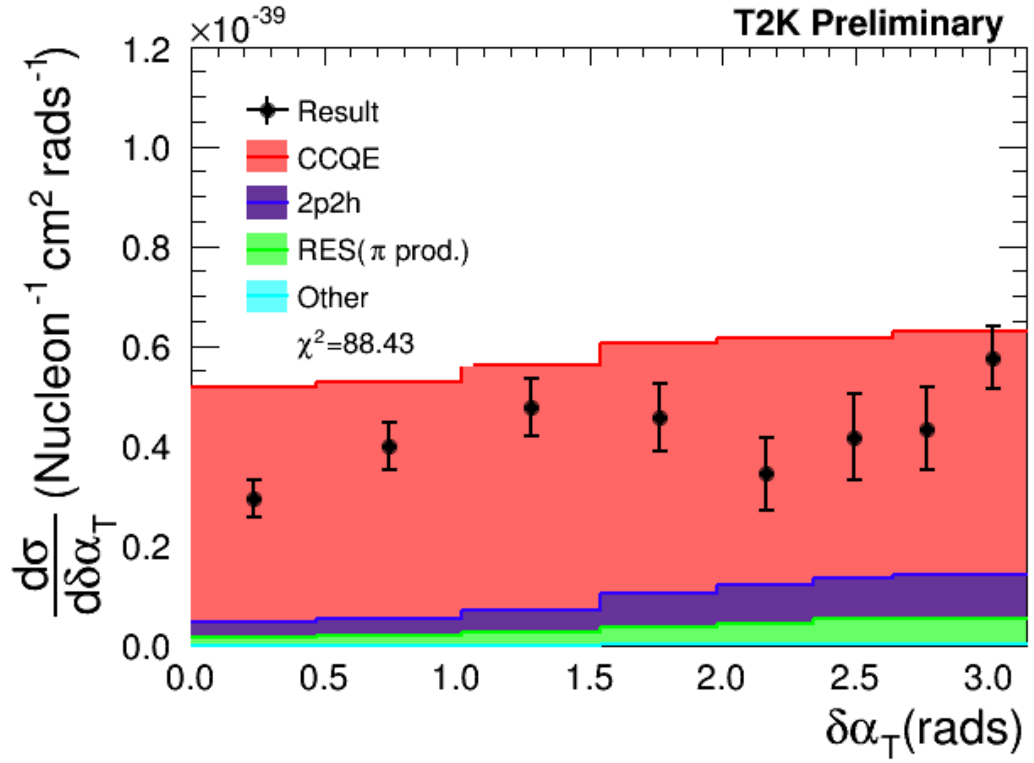
GIBUU with very different FSI seems close to data

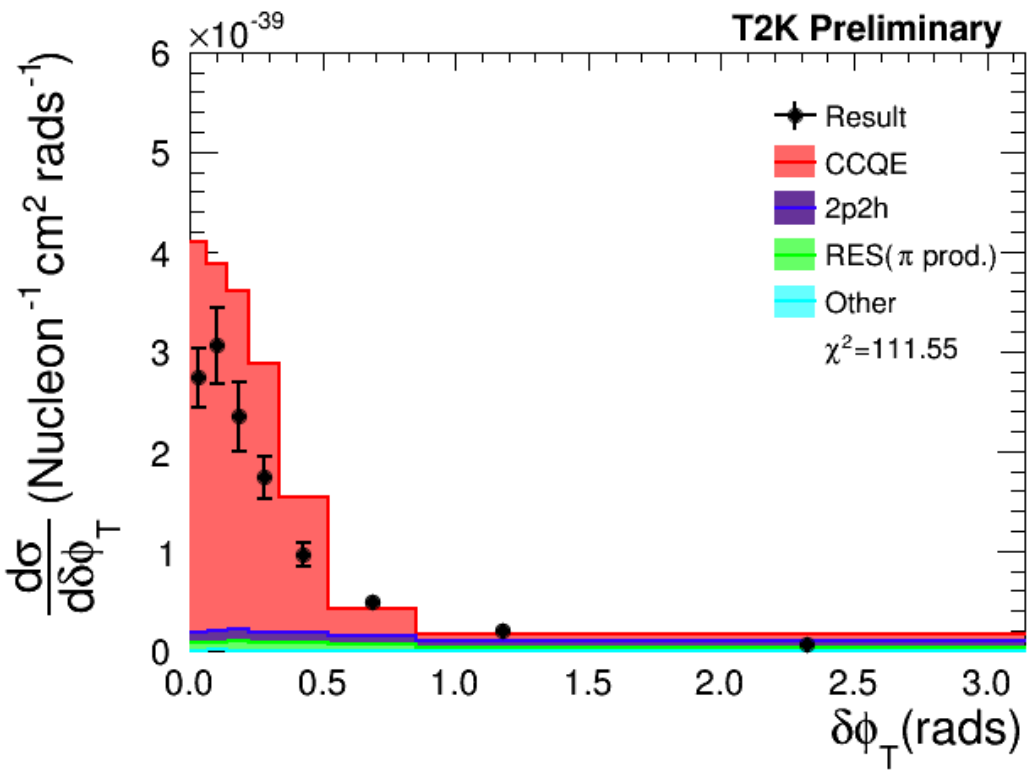
GENIE shape in first bin of each STV related to FSI model (“hA”)

ν_μ CC0π with single transverse variables

Publication in preparation!







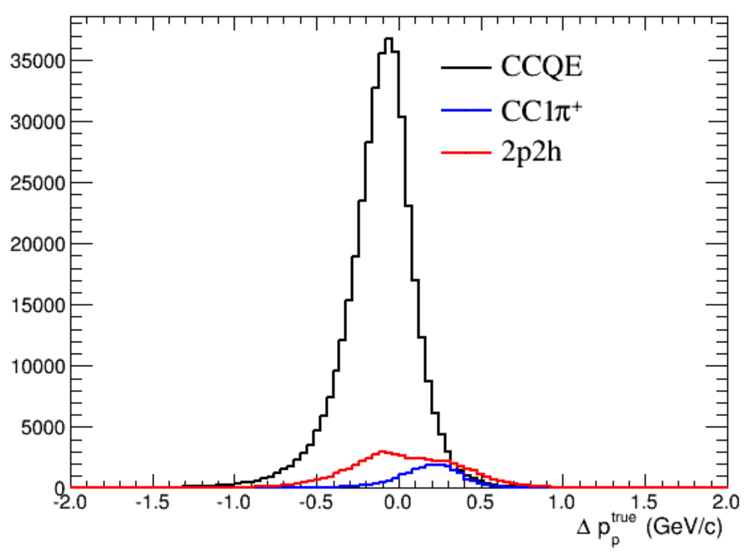
The tails in δp_T and $\delta\phi_T$ and the extent of the rise at large $\delta\alpha_T$ partially isolate the effects of Fermi Motion from 2p2h

ν_μ CC0π with inferred proton kinematics

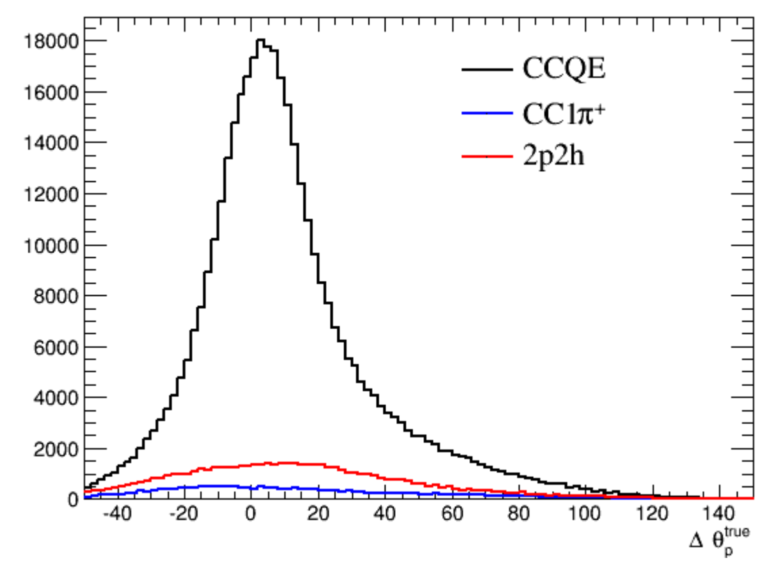
Analysis Ongoing!

Analysis strategy:

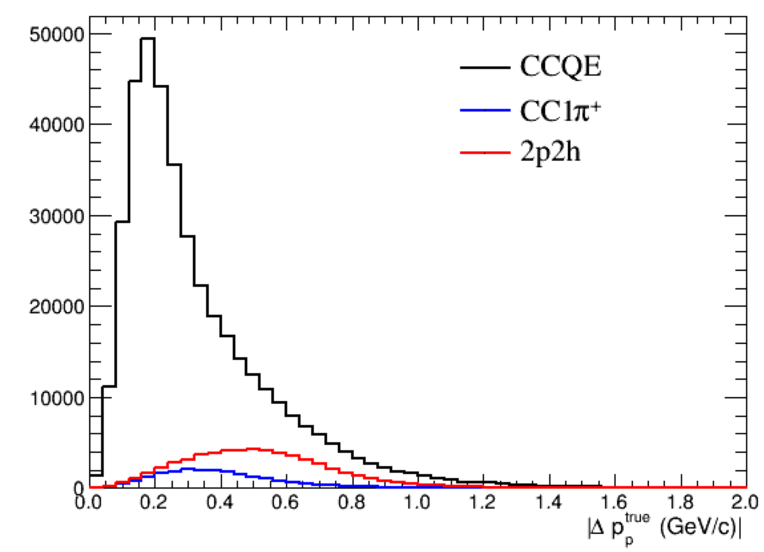
- Under hypothesis of stationary target and elastic scattering can infer proton kinematics from measured μ
- Non-zero imbalance between inference and measured proton indicates presence of nuclear effects or CC-non-QE interaction
- Same selection used for CC0π with proton kinematic



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



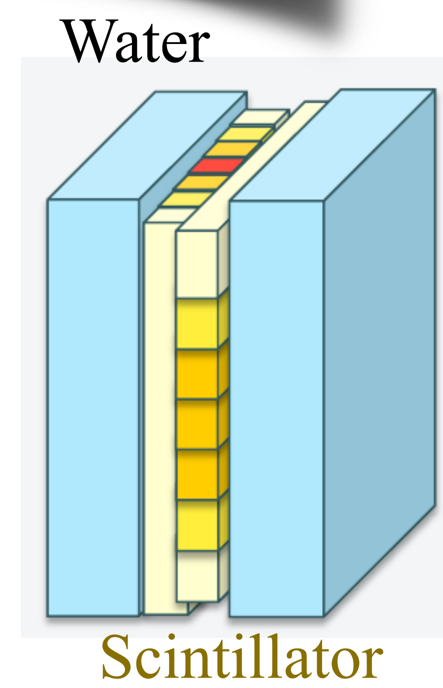
$\Delta\theta_p = \theta_p^{inferred} - \theta_p^{measured}$



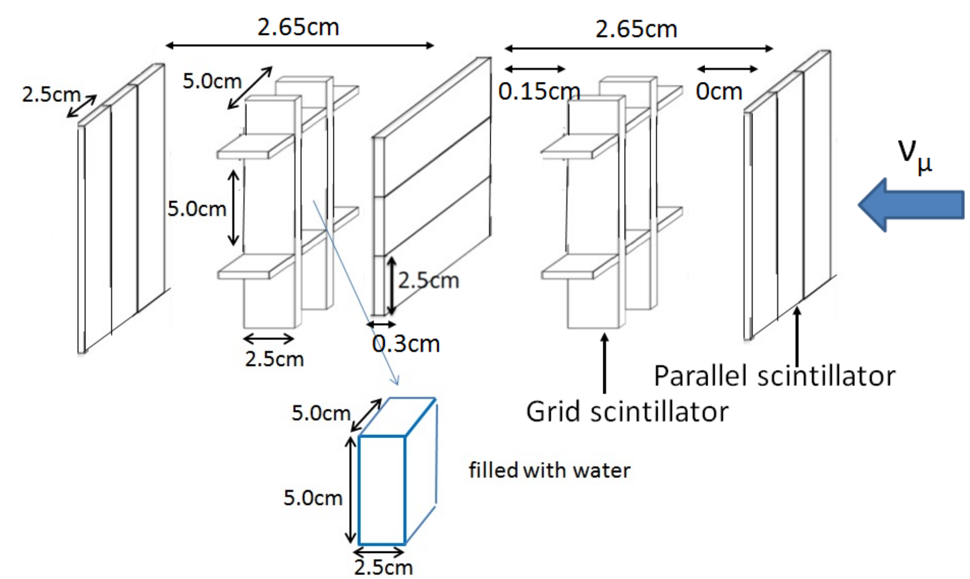
$|\boldsymbol{\Delta p}_p| = |\boldsymbol{p}_p^{inferred} - \boldsymbol{p}_p^{measured}|$

Ongoing measurements

Cross section on water coming soon!



- ν_μ **CC Inclusive water over carbon ratio:**
  - Use both FGDs
  - Cross section extracted in ν Energy
- ν_μ **CC Inclusive on water using INGRID**
  - Use INGRID new water module
  - Cross section extracted in μ-kinematics

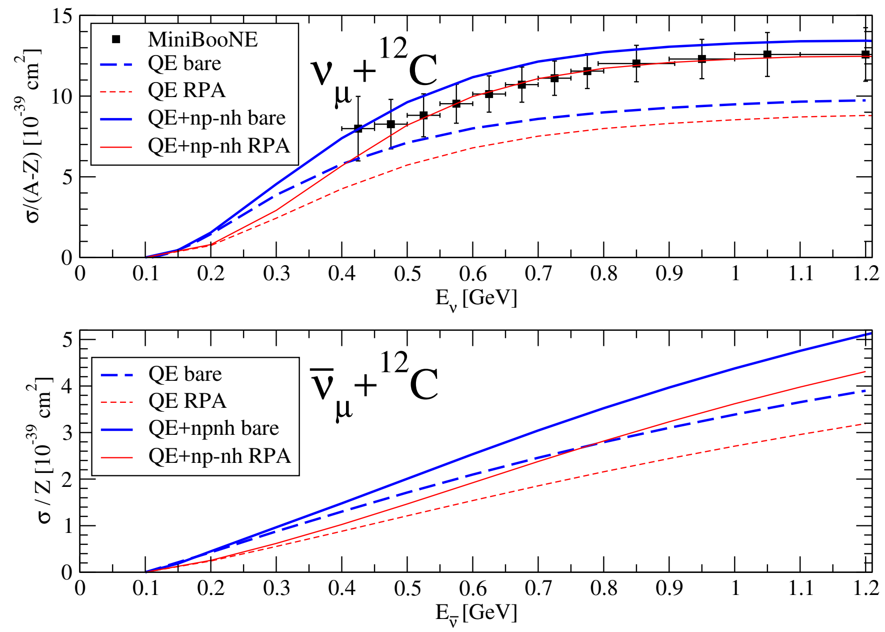


- ν_μ **CC0π water over carbon ratio:**
  - Use FGD2 water layers
  - Cross section extracted using matrix inversion method and extended binned likelihood in μ-kinematics
  - Next step: FGD1-FGD2 joint-fit: mitigate the water-carbon migration

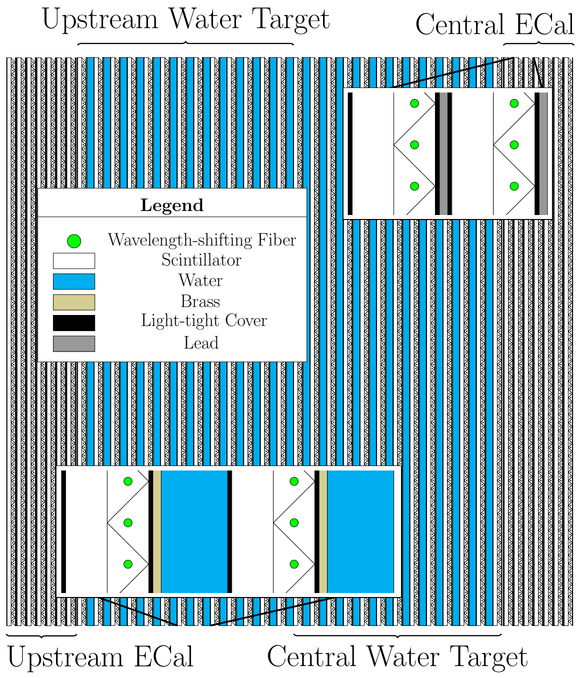
Ongoing measurements

- ν_μ - $\bar{\nu}_\mu$ **CC0π on CH :**
  - Joint fit of ν_μ - $\bar{\nu}_\mu$ CC0π cross section using extended binned likelihood
  - Cross section extracted in μ-kinematics
  - Evaluation of sum, difference and asymmetry

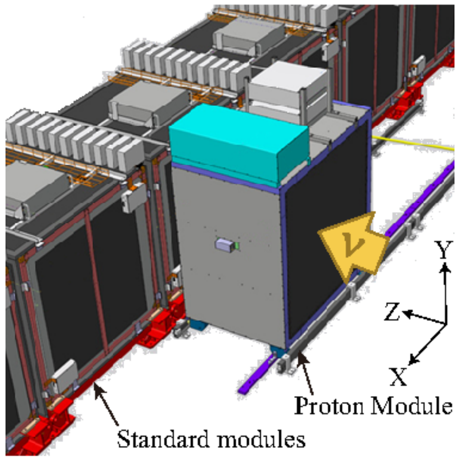
M. Martini et al., Phys. Rev. C81 (2010)



- $\bar{\nu}_\mu$ **CC0π on water:**
  - Use P0D water layers
  - ν_μ CC0π cross section using extended binned likelihood
  - Cross section extracted in μ-kinematics



- $\bar{\nu}_\mu$ **CC0π on CH:**
  - Use INGRID proton module
  - Cross section extracted in μ-kinematics



List of published measurements

- Phys.Rev. D87 (2013) no.9, 092003, “Measurement of the inclusive ν_μ charged current cross section on carbon in the near detector of the T2K experiment”
- Phys.Rev. D90 (2014) no.7, 072012, “Measurement of the neutrino-oxygen neutral-current interaction cross section by observing nuclear de-excitation γ rays”
- Phys.Rev.Lett. 113 (2014) no.24, 241803, “Measurement of the Inclusive Electron Neutrino Charged Current Cross Section on Carbon with the T2K Near Detector”
- Phys.Rev. D90 (2014) no.5, 052010, “Measurement of the inclusive ν_μ charged current cross section on iron and hydrocarbon in the T2K on-axis neutrino beam”
- Phys.Rev. D92 (2015) no.11, 112003, “Measurement of the ν_μ charged-current quasi-elastic cross section with ND280 detector at T2K”
- Phys.Rev. D91 (2015) no.11, 112002, “Measurement of the ν_μ charged current quasi-elastic cross-section on carbon with the T2K on-axis neutrino beam”
- Phys.Rev. D93 (2016) no.7, 072002, “Measurement of the muon neutrino inclusive charged-current cross section in the energy range of 1-3 GeV with the T2K INGRID detector”
- Phys.Rev. D93 (2016) no.11, 112012, “Measurement of double-differential muon neutrino charged-current interactions on C_8H_8 without pions in the final state using the T2K off-axis beam”
- Phys.Rev. D95 (2017) no.1, 012010, “First measurement of the muon neutrino charged current single pion production cross section on water with the T2K Near Detector”
- Phys.Rev.Lett. 117 (2016) no.19, 192501, “Measurement of Coherent π^+ Production in Low Energy Neutrino-Carbon Scattering”
- Phys.Rev.D96 052001 (2017), “Measurement of $\bar{\nu}_\mu$ and ν_μ charged current inclusive cross sections and their ratio with the T2K off-axis near detector”

Summary

- T2K near detectors provide a perfect opportunity to make precise cross-section measurements
- New inclusive cross-section measurement has been developed using new selection
- Measurement of the proton kinematics and single transverse variables very important to tune the model
- Many results with water as target are coming!
- Many anti-neutrino results in the near future!

Thank you for your attention

T2K Breakthrough Prize Party

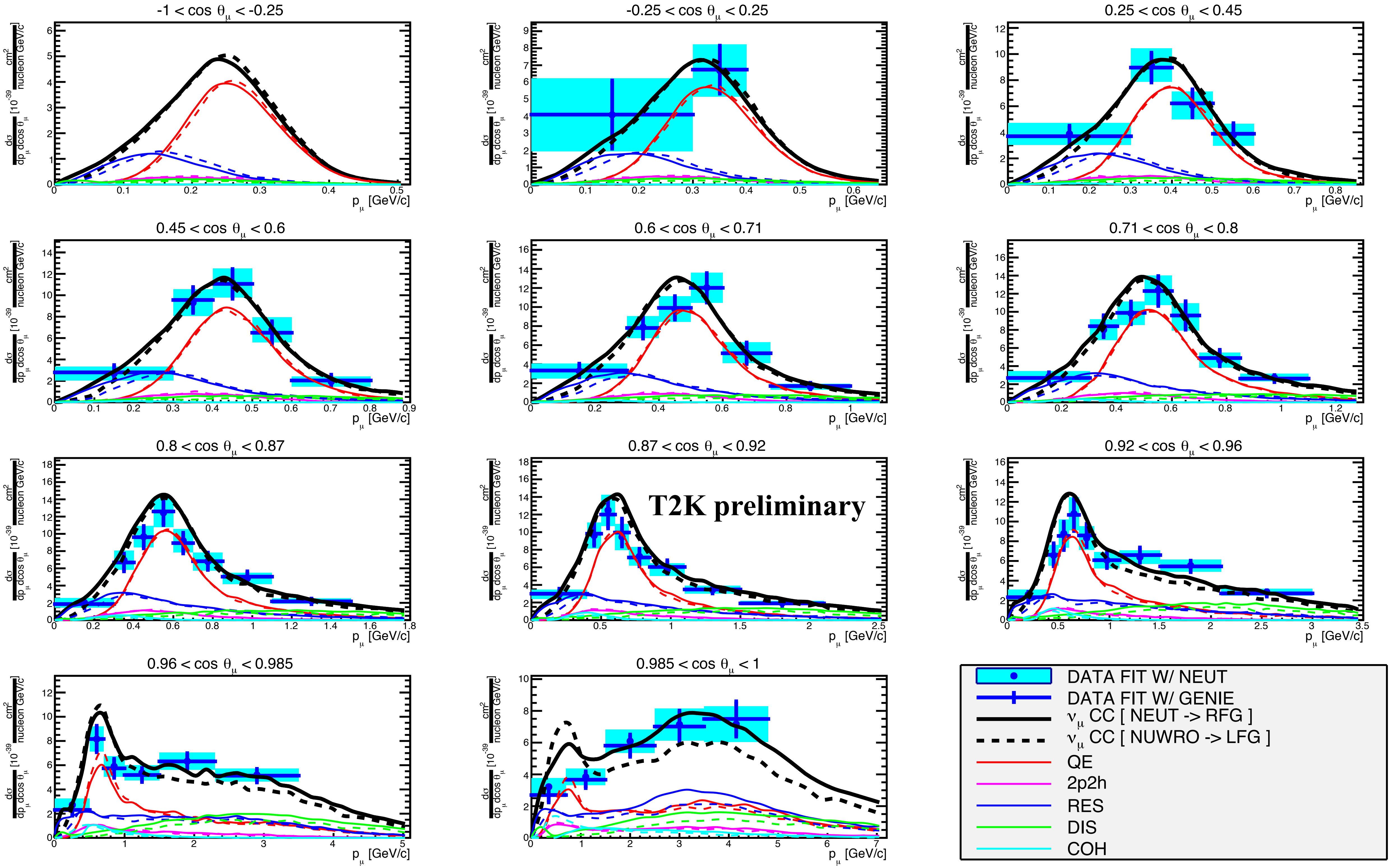
January 28th, 2016 at Kuji Sunpia Hitachi

Backup

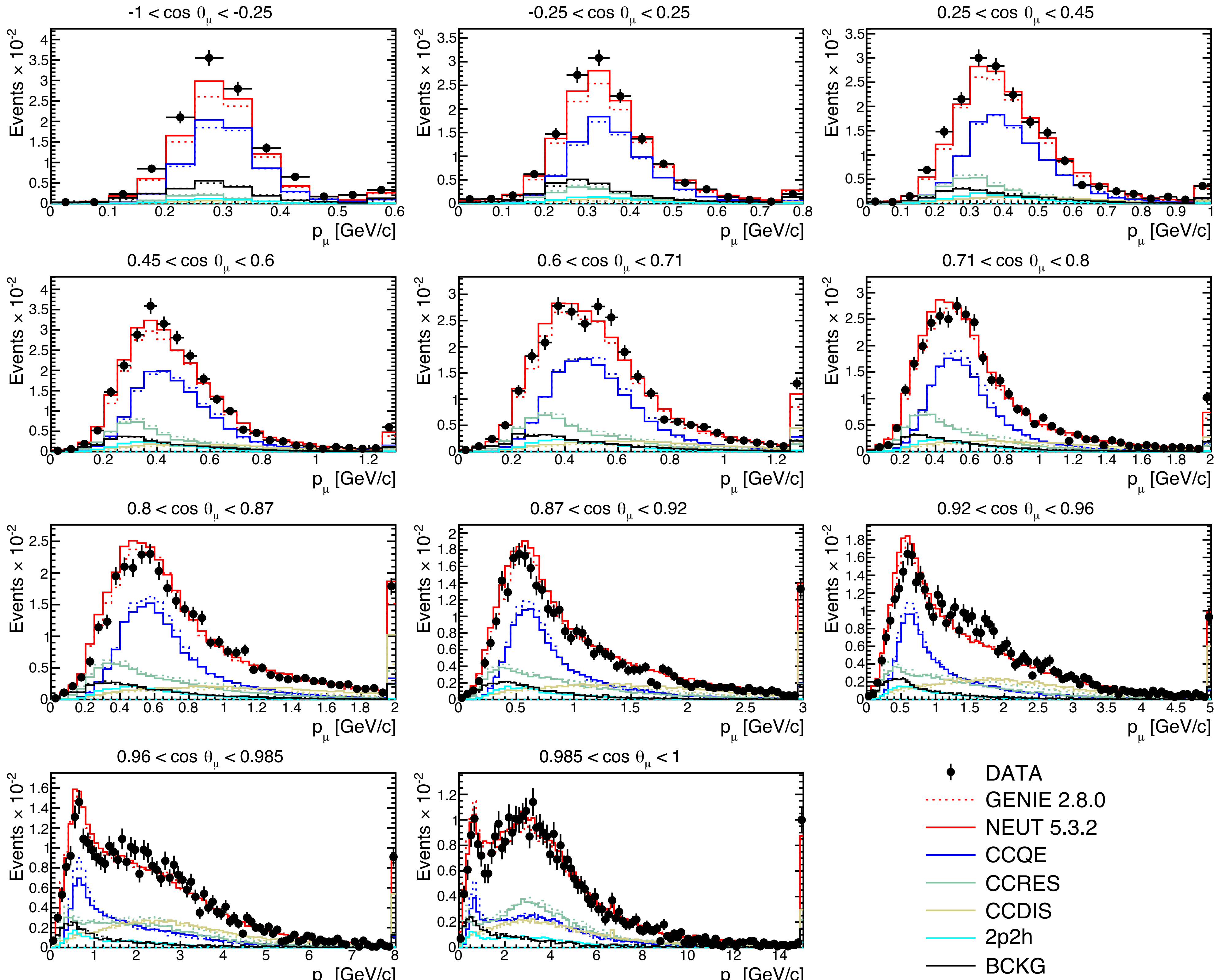
Event generators: details

	NEUT 5.3.2	GENIE 2.8.0
CCQE	SF (Benhar et al., 2000) BBA05 (Bradford et al., 2005) M_A^{QE} = 1.21 GeV/c^2 p_F [^{12}C] = 217 MeV/c E_B [^{12}C] = 25 MeV	RFG (Bodek et al., 1981) BBA05 (Bradford et al., 2005) M_A^{QE} = 0.99 GeV/c^2 p_F [^{12}C] = 221 MeV/c E_B [^{12}C] = 25 MeV
2p2h	Nieves et al., 2011	-
CCRES	W<2 GeV Rein-Sehgal, 1981 FF (Graczyk et al., 2008)	W<1.7 GeV Rein-Sehgal, 1981 FF (Kuzmin et al., 2016)
CCDIS	W>1.3 GeV (w/o single π) GRV98 PDF (Glück et al. 1998) BY corr. at low Q2 (Bodek et al. 2003)	W>1.7 GeV (for W<1.7 GeV is tuned) GRV98 PDF (Glück et al. 1998) BY corr. at low Q2 (Bodek et al. 2005)
Hadronization	W < 2 GeV KNO scaling (Koba et al. 1972) W > 2 GeV PYTHIA/JETSET	W < 2.3 GeV AGKY (Koba et al. 1972) 2.3 GeV < W < 3 GeV AGKY (Koba et al. 1972) + PYTHIA/JETSET W > 3 GeV PYTHIA/JETSET
FSI	Intra-nuclear cascade	Intra-nuclear cascade (INTRANUKE hA)

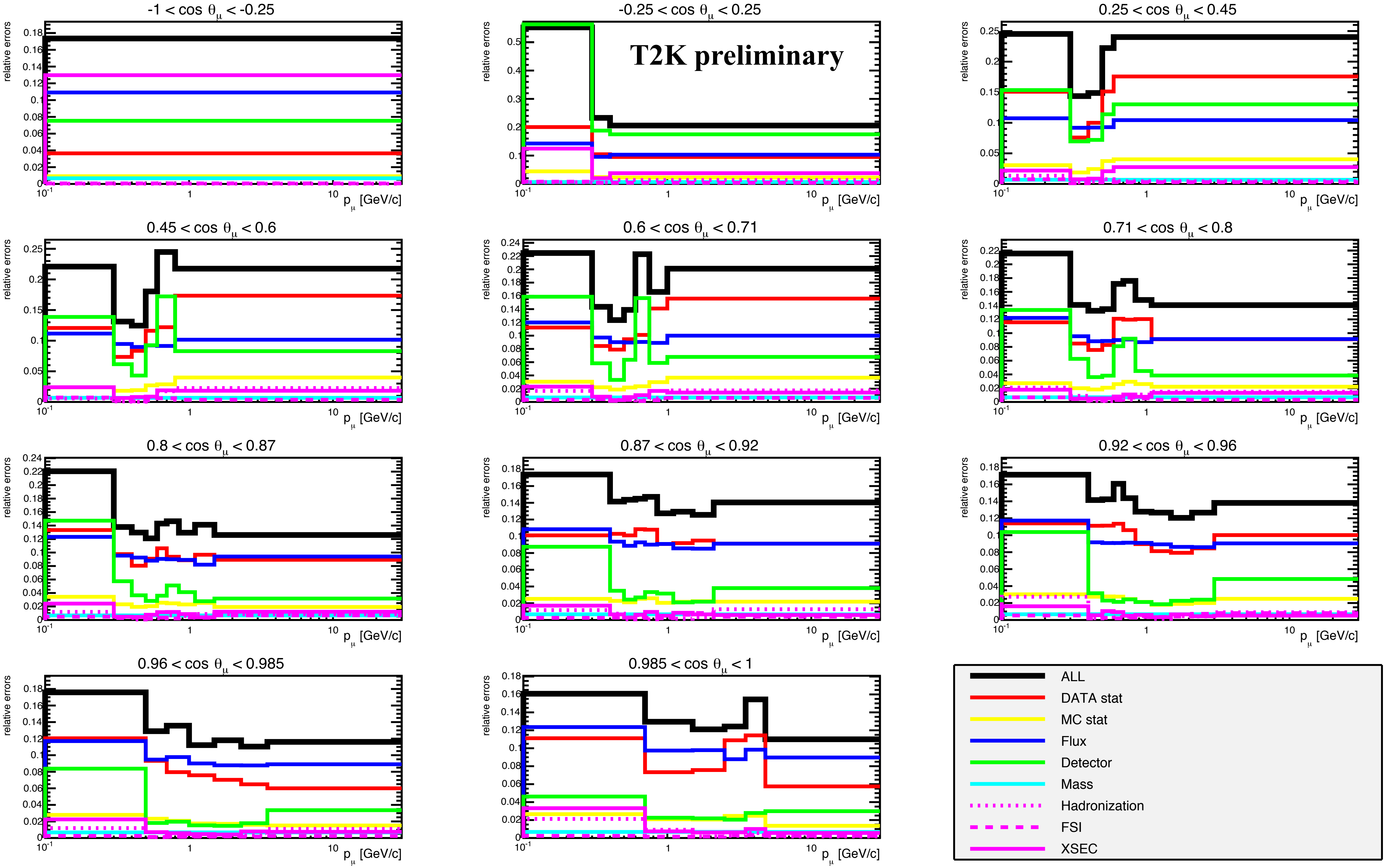
ν_μ CC Inclusive on CH



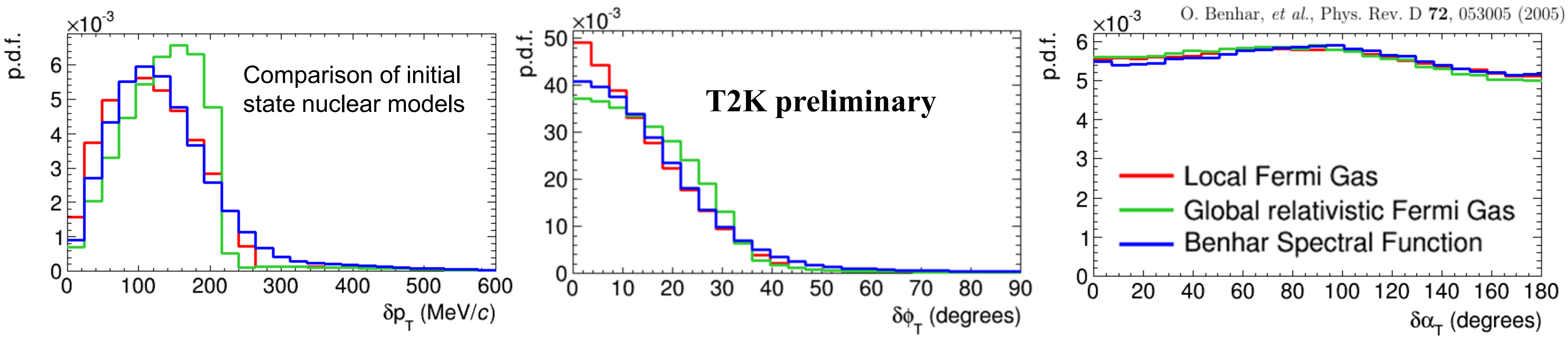
ν_μ CC Inclusive on CH



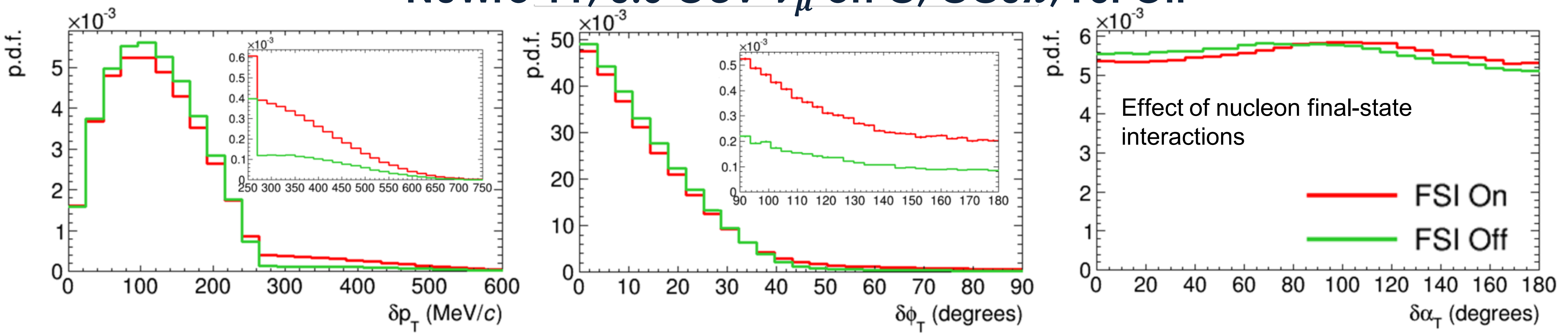
ν_μ CC Inclusive on CH



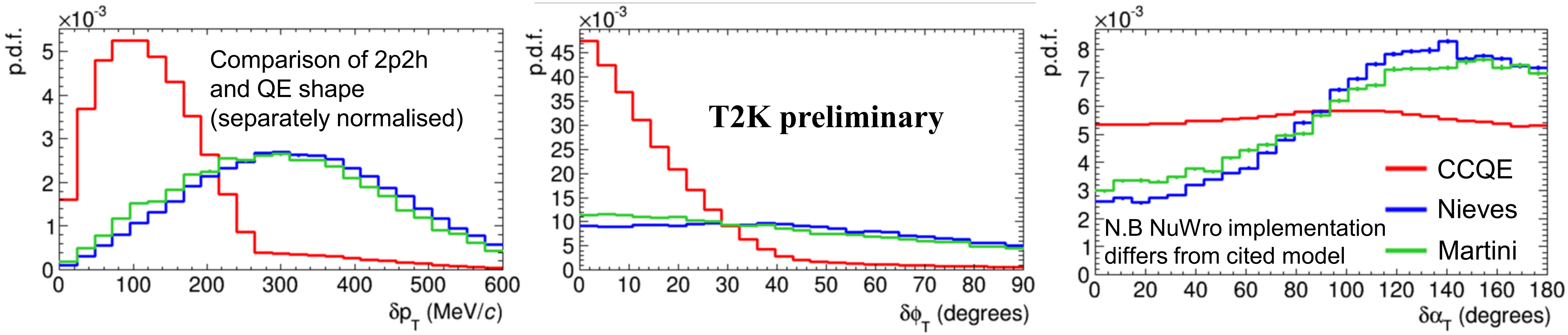
STV and FSI



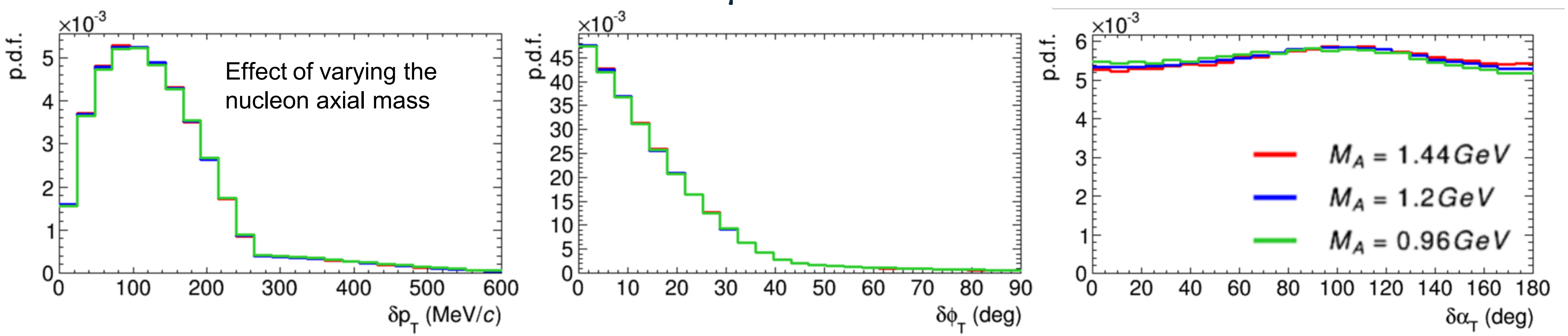
NuWro 11, 0.6 GeV ν_μ on C, CC0π, FSI Off



STV and MAQE



NuWro 11, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG



NuWro 11, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG

Extended binned likelihood fit

$$\chi^2 = \chi^2_{stat(fit\,goodness)} + \chi^2_{syst(penalty)} + \chi^2_{reg}.$$

$$\chi^2_{stat} = \sum_{j}^{recobins} 2(N_j^{MC} - N_j^{obs} + N_j^{obs} ln \frac{N_j^{obs}}{N_j^{MC}})$$

$$\chi^2_{syst} = (\vec{a}^{syst} - \vec{a}^{syst}_{prior})(V^{syst}_{cov})^{-1}(\vec{a}^{syst} - \vec{a}^{syst}_{prior})$$

$$\chi^2_{reg} = p_{reg} \sum_i (c_i - c_{i-1})^2$$