# Recent Cross-section Results from the T2K Experiment

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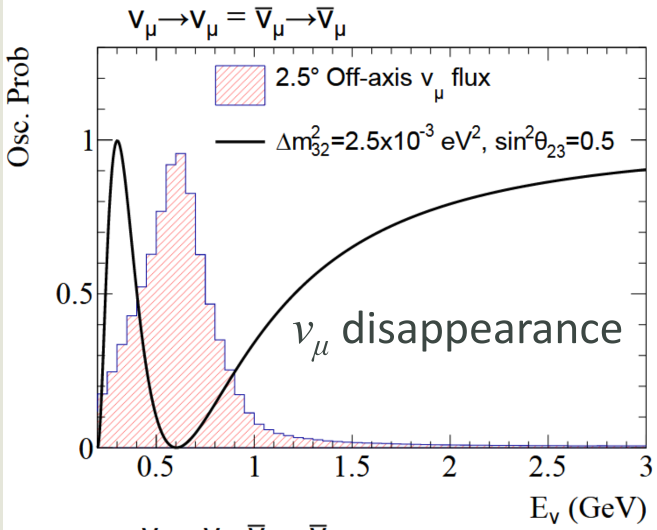
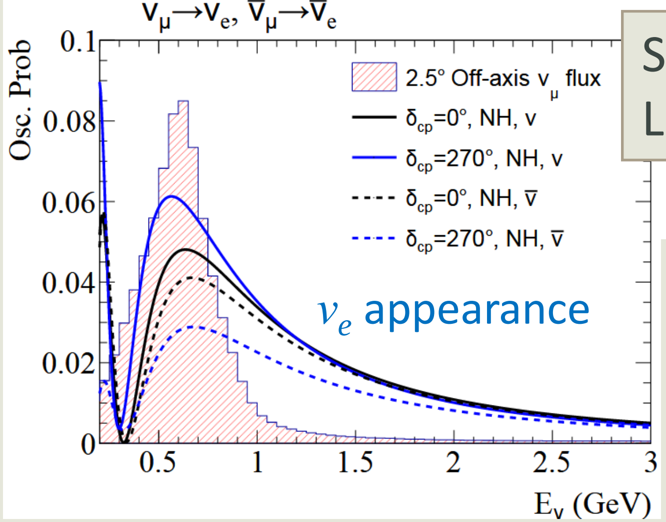
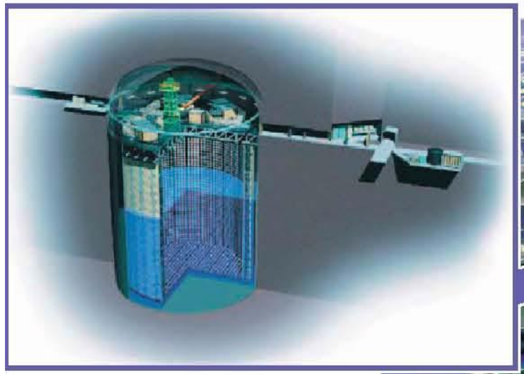


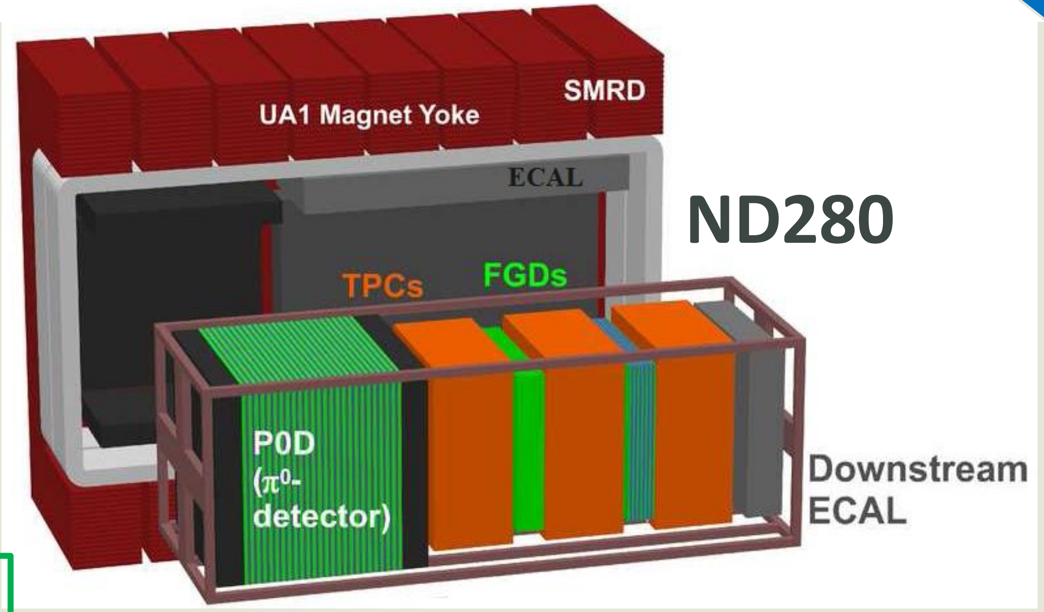



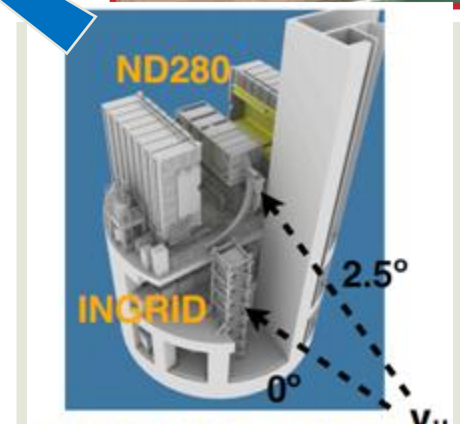

# T2K

J-PARC Main Ring
(KEK-JAEA, Tokai)

See osc talk by Laura Munteanu




ND280




INGRID (on-axis) and ND280 (off-axis)

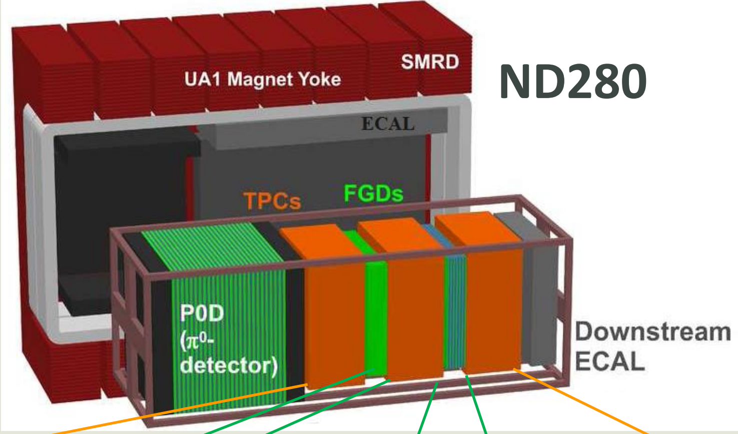
$$N_\mu(E_\nu)=\sigma(E_\nu)\Phi(E_\nu)\varepsilon(E_\nu)$$

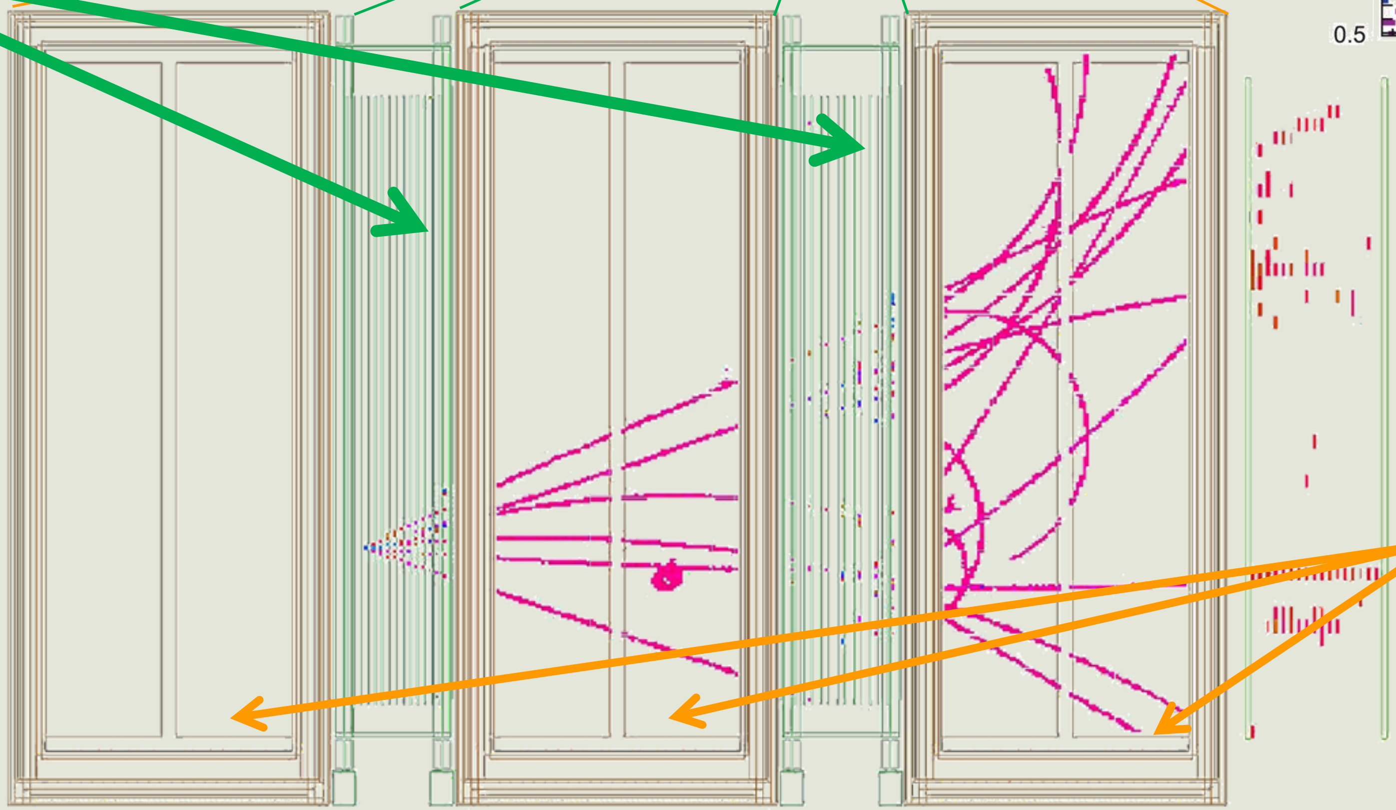
Interaction cross-section

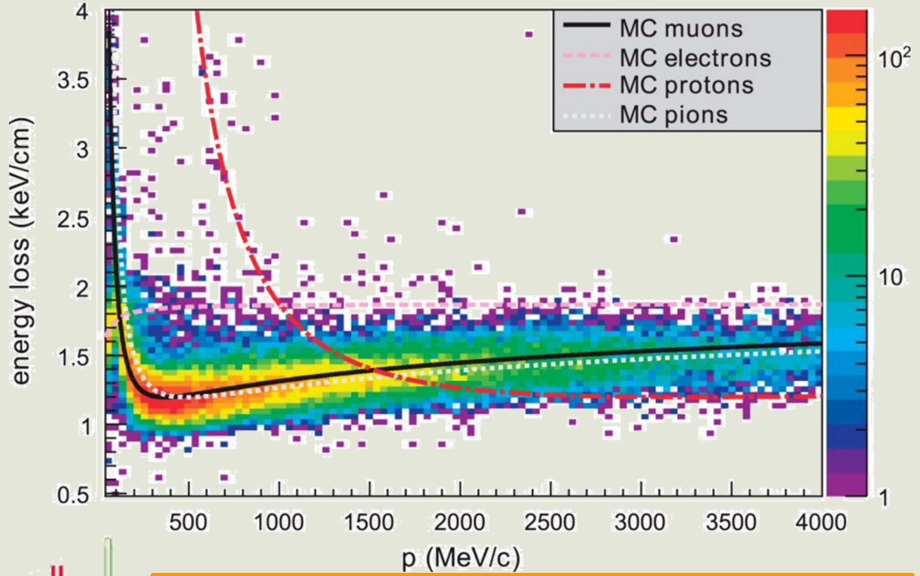
Neutrino flux

Detector effects

**Fine Grained Detectors (FGD 1 &2):**
- $\nu$ interaction target
- CH scintillator trackers
- alt $H_2O$ layers in FGD2

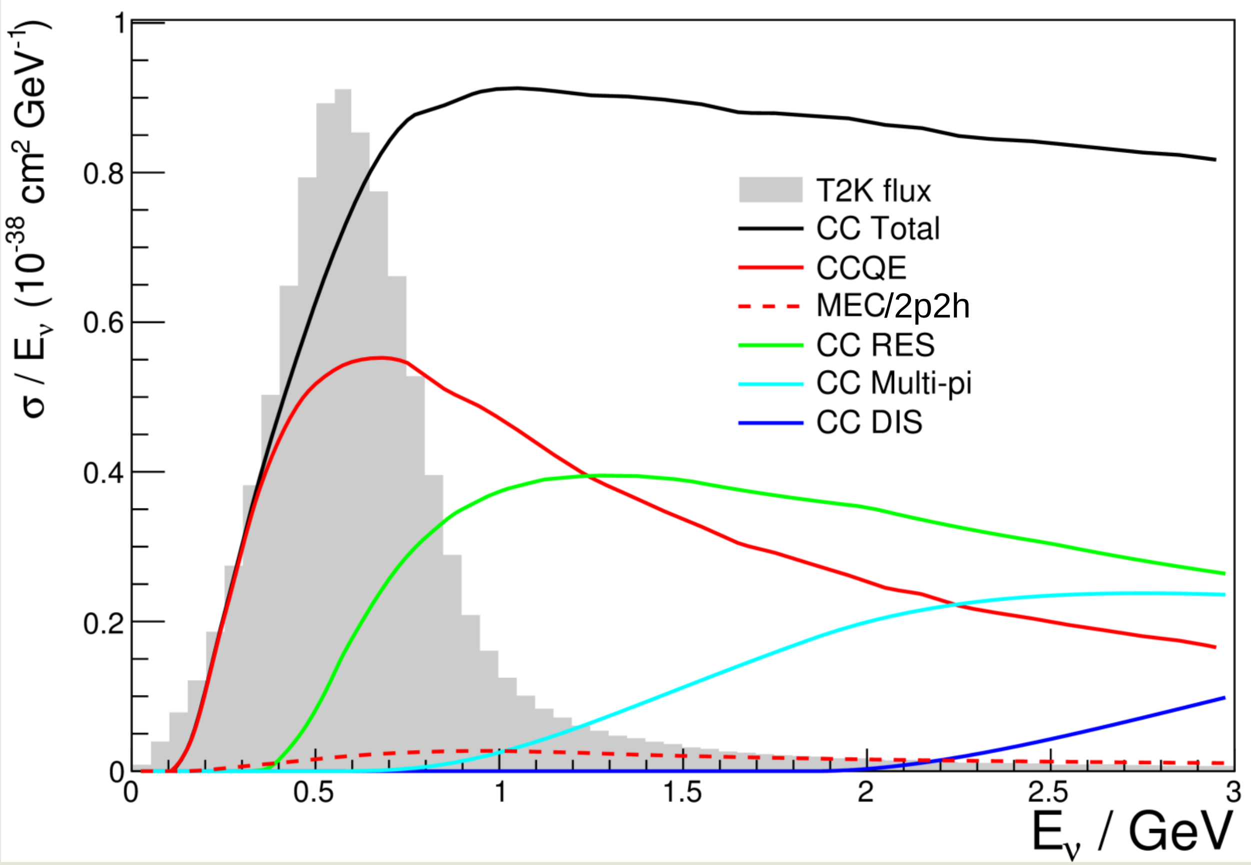


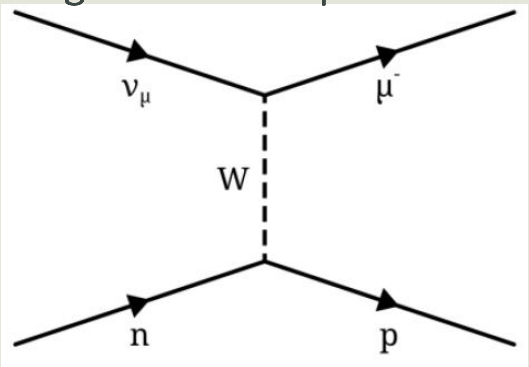



**Time Projection Chambers (TPC 1, 2 & 3):**
- Excellent tracking
- High-res charged particle mom
- Accurate PID

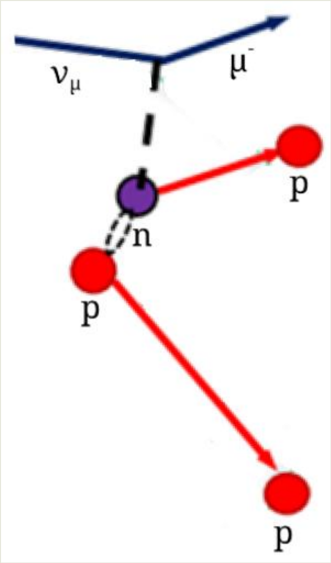
# Neutrino interactions at T2K



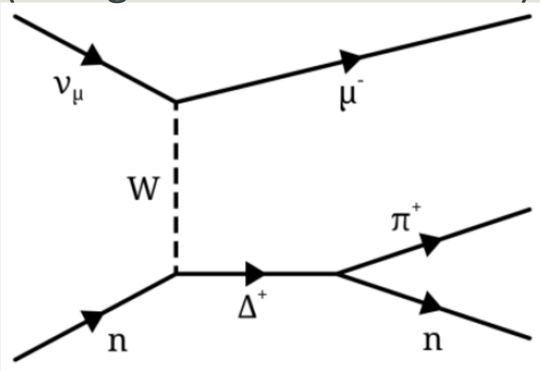

CCQE
(Charged-current quasi-elastic)



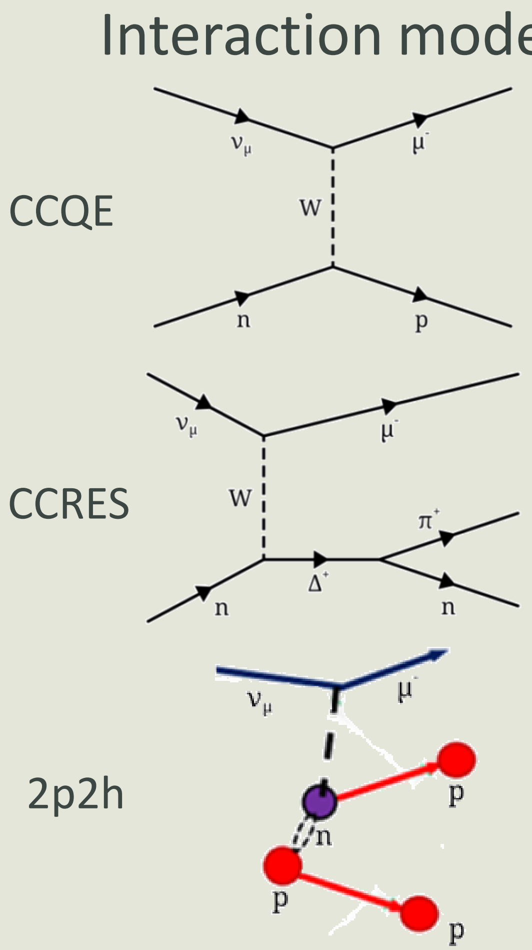

2p2h
(2particle-2hole)

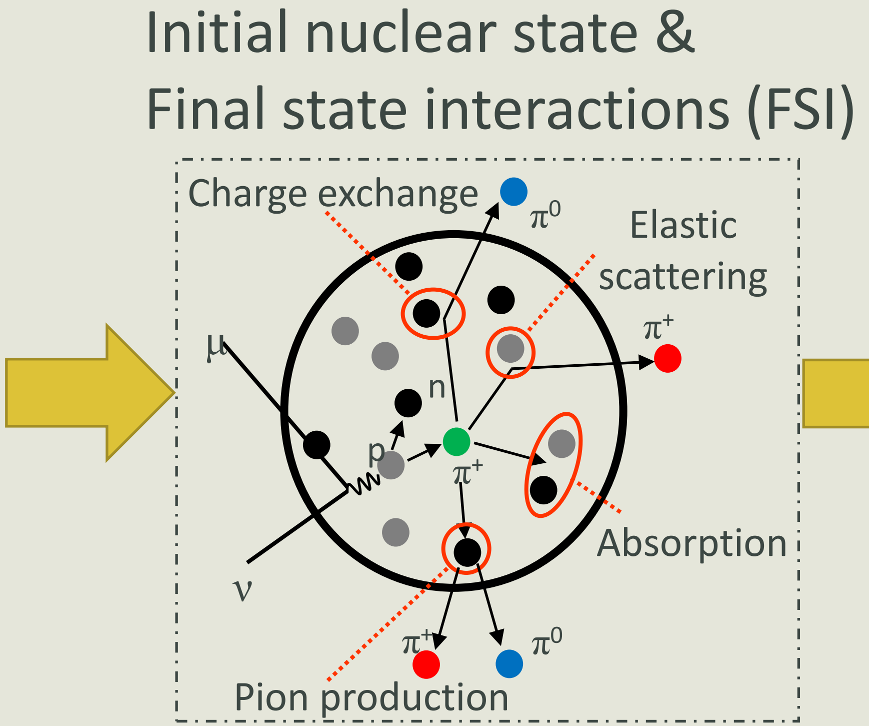


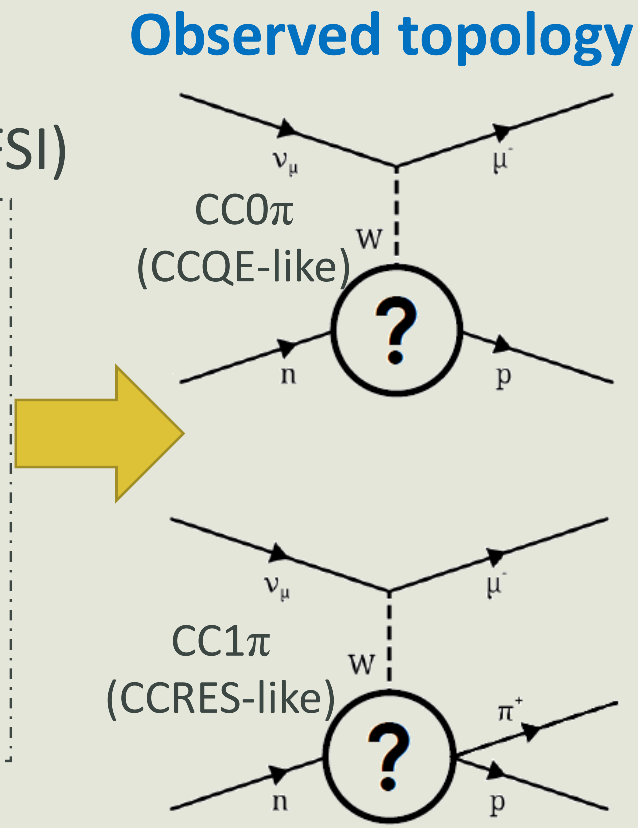

CCRES
(Charged-current resonant)

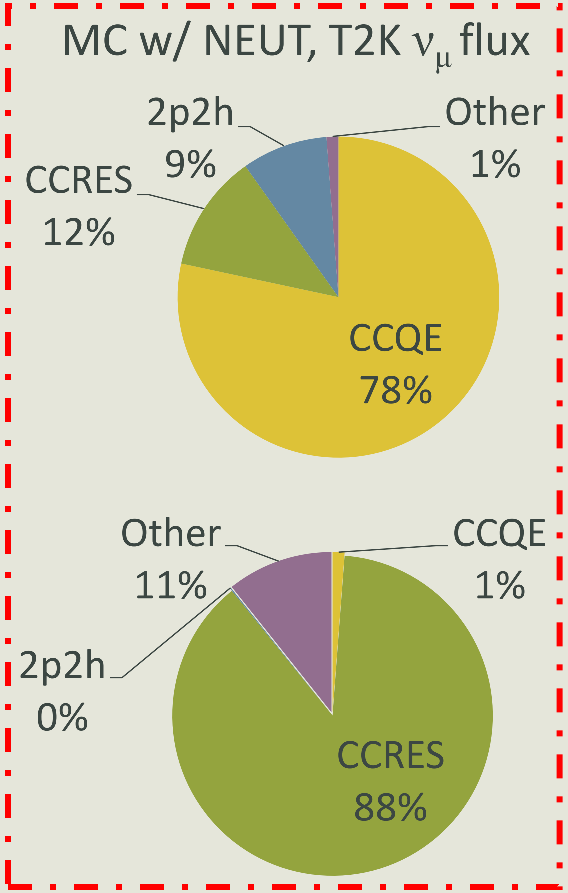


# Neutrino interaction measurements at T2K



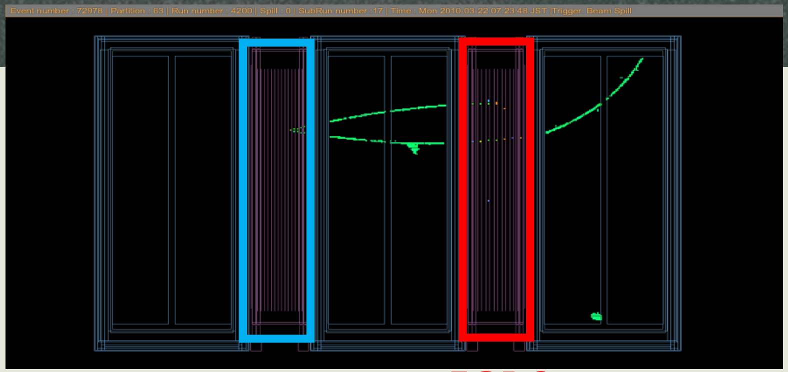



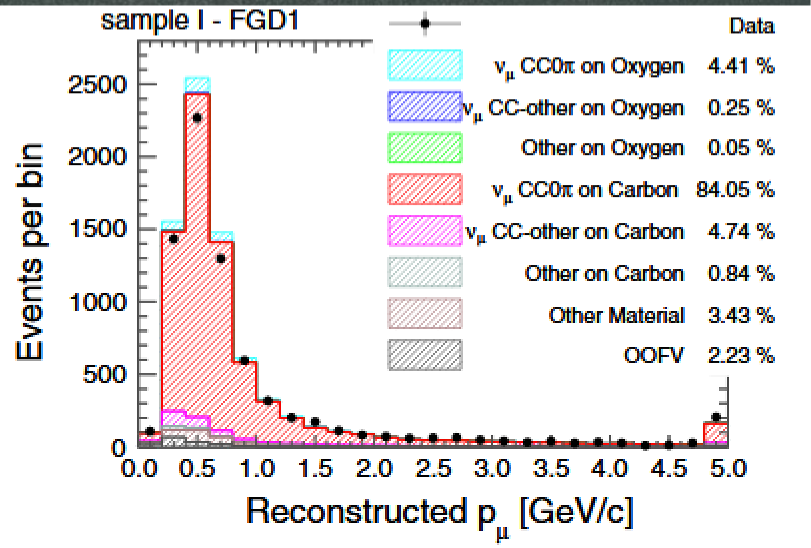



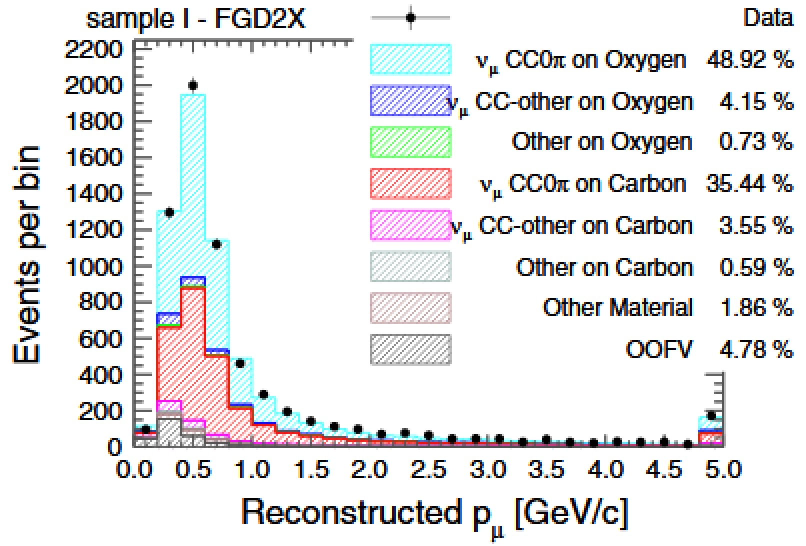



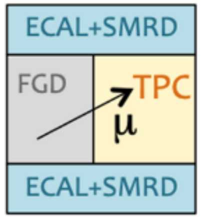
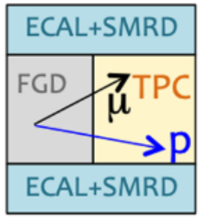
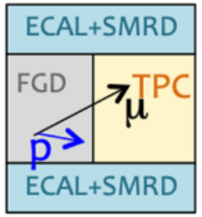
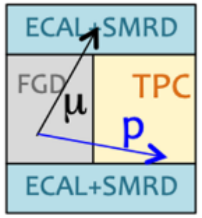
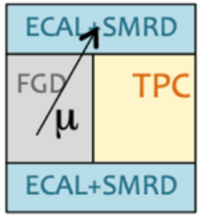
# Joint Carbon + Oxygen CC0π cross-section at T2K

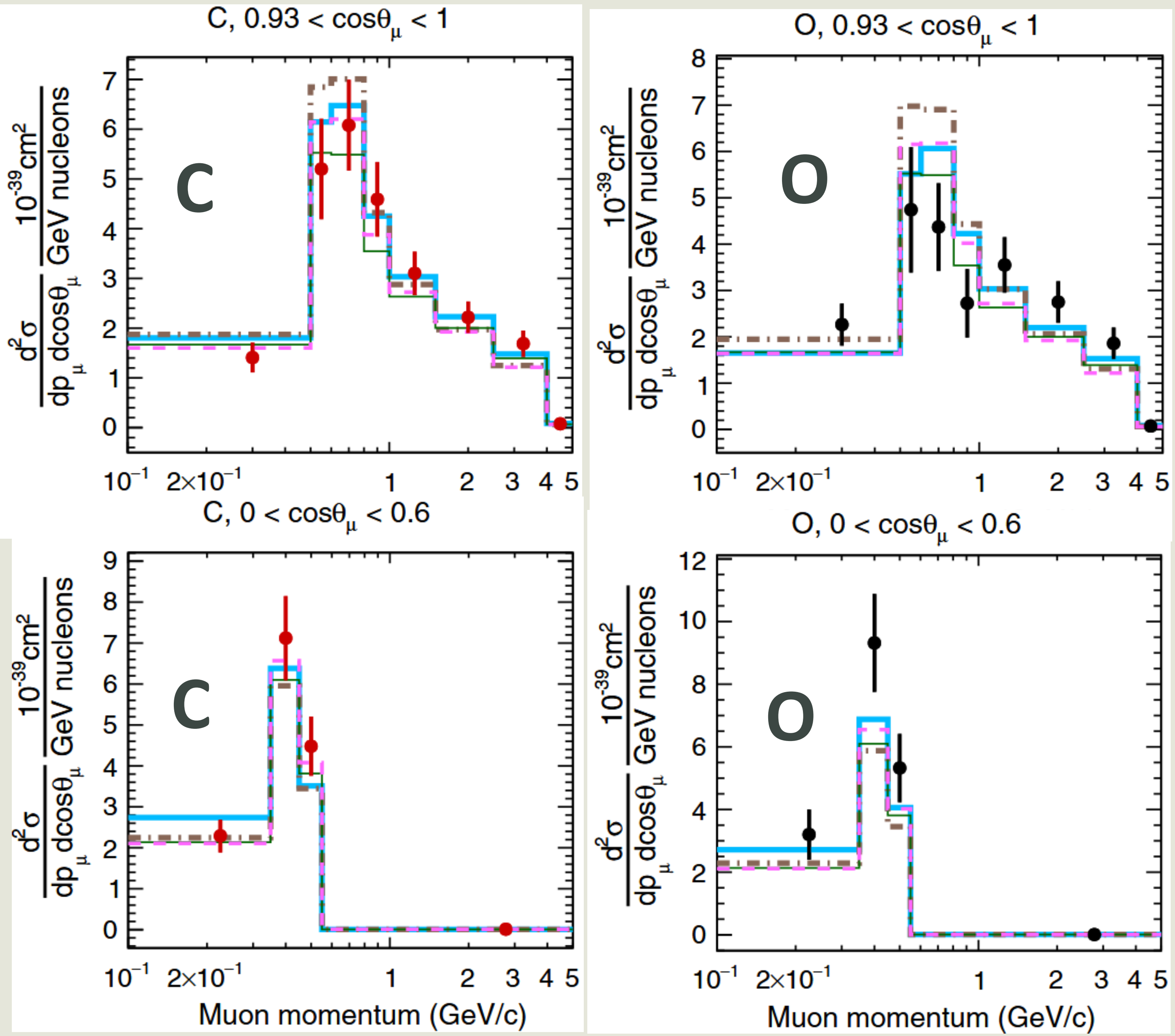
- Simultaneous fit of C & O interactions →
- C & O double differential cross-sections, C/O ratio
- **Phys. Rev. D 101, 112004 (2020)**




| | I – μTPC | II – μTPC+pTPC | III – μTPC+pFGD | IV – μFGD+pTPC | V – μFGD |
|---|---|---|---|---|---|
| **Signal sample** |  |  |  |  |  |
| **Description** | Single μ candidate tracked in TPC | Both μ and *p* candiates are tracked in the TPC | μ tracked in the TPC and : • 1*p* tracked in the FGD • or multi *p* | μ tracked in FGD/Ecal and: • 1 *p* tracked in the TPC • or 1 *p* tracked in the TPC + multi *p* • or multi *p* | $\mu_{FGD}$ only reconstructed in the FGD/ Ecal |




- $\chi^2$ dominated by high statistics forward bins
- Forward bins: favor more "simple" CCQE Fermi gas nuclear models (LFG), largely due to substantial "RPA" low energy transfer suppression
- High angle bins: LFG underestimates data. CCQE more affected by nucleon form factors, but cannot explain C/O difference
- Need to improve non-QE (2p2h, abs FSI) currently based on a Fermi-gas ground state

# Joint ν + anti-ν CC0π cross-section in FGD1(CH)

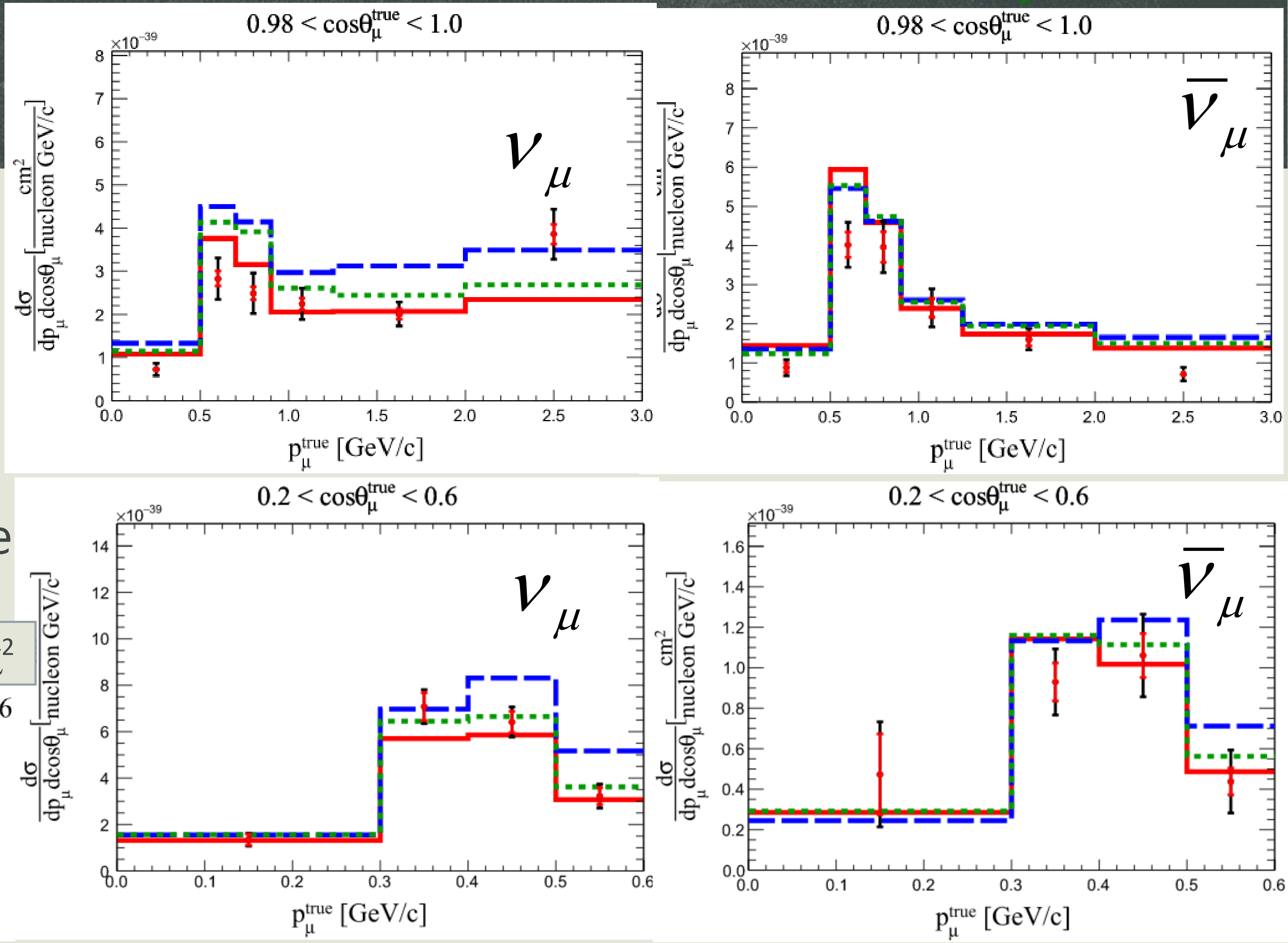
- **Phys. Rev. D 101, 112001 (2020)**
- Similar conclusions to C/O analysis
  - Need reduction of cross-section at forward angles, enhancement at higher angles for LFG
- Large $\chi^2$→no model describes the whole data well

2p2h model, Full (shape only) $\chi^2$

NEUT LFG+2p2h $\chi^2$ = 366.7(459.1)/116

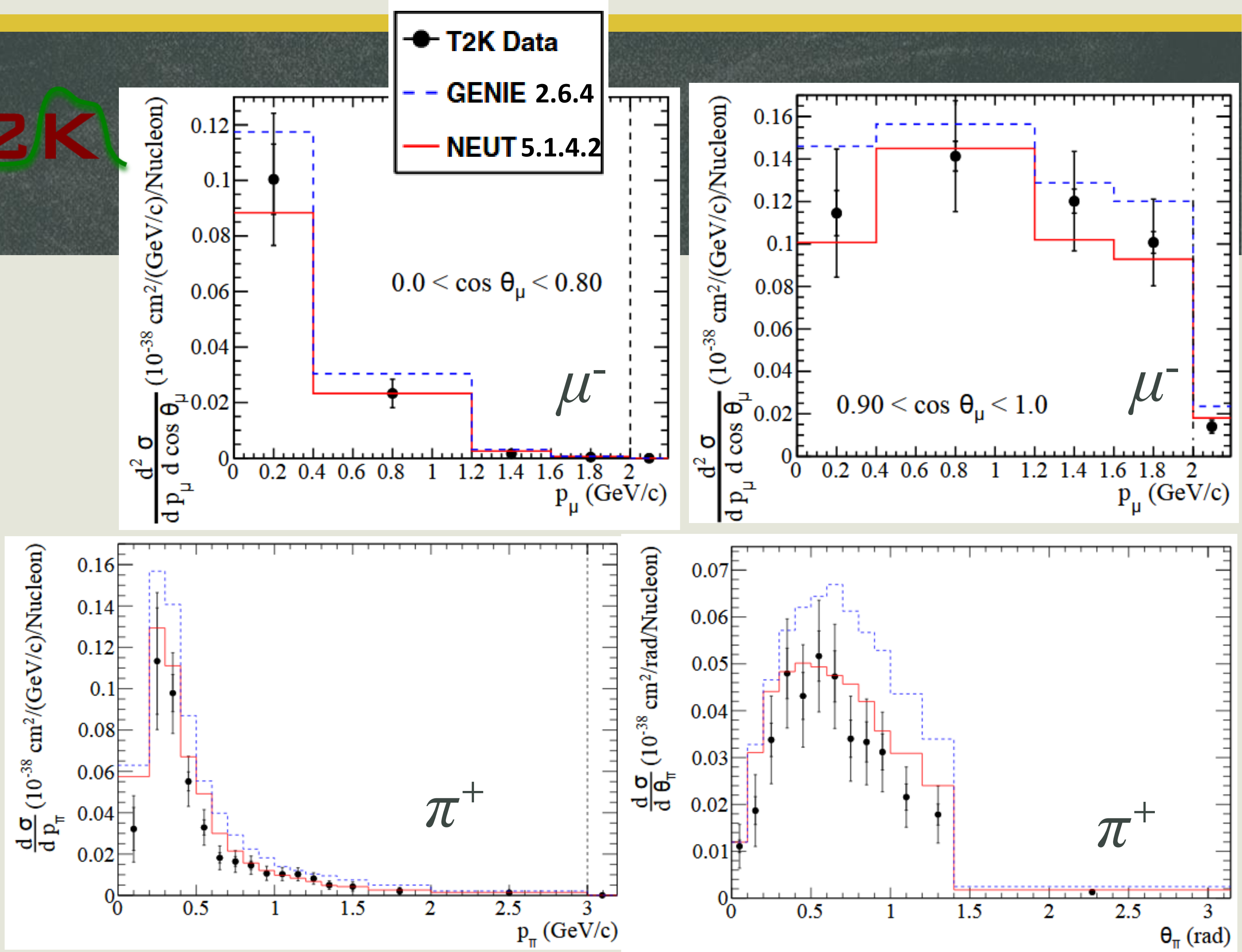
Martini et al. $\chi^2$ = 368.6(573.4)/96

SuSAv2 $\chi^2$ = 565.9(563.1)/116



# CC1$\pi^+$ cross-section at T2K

- "Uncharted territory"
  - Less theoretical input
  - Less data
- Models show mostly normalization differences
- Let's dig deeper…

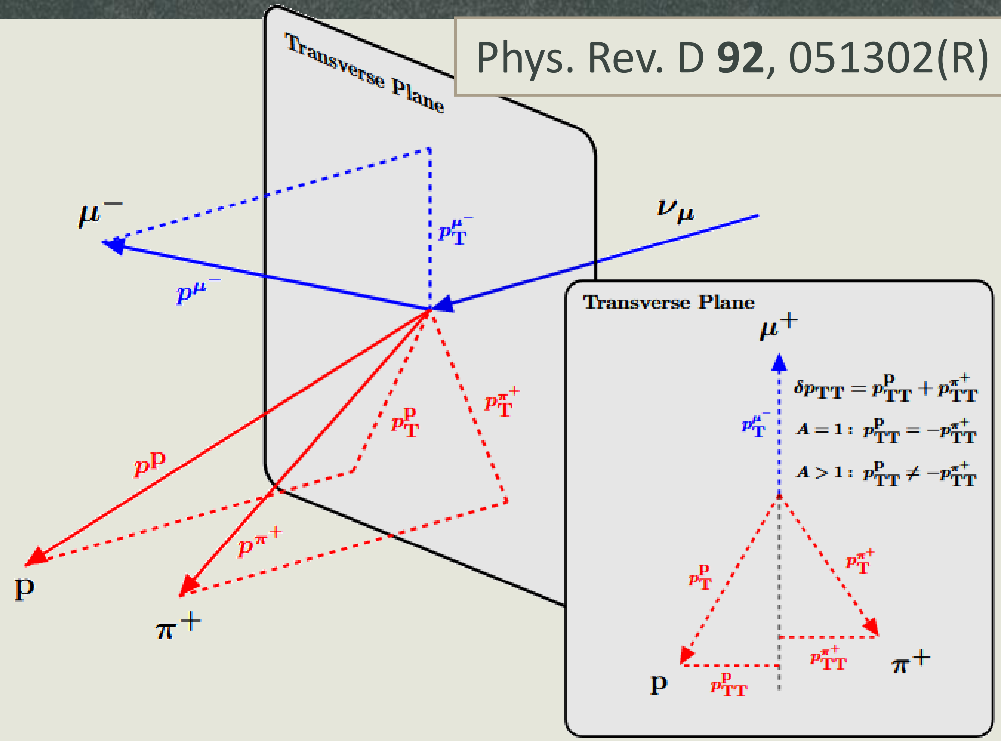



Phys. Rev. D 101, 012007 (2020)

New

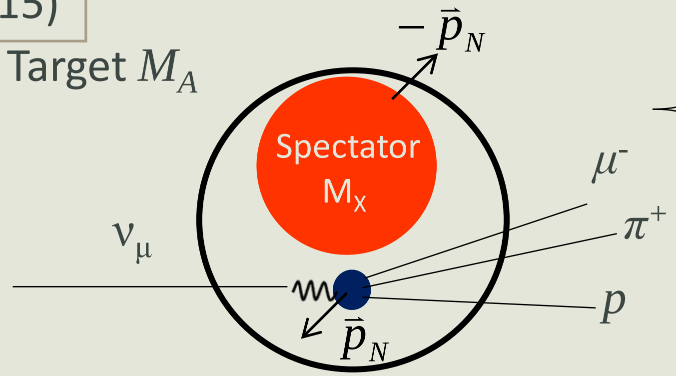
# CC1$\pi^+ p$ cross-section in transverse kinematic imbalance (TKI): Powerful tools to characterize nuclear effects

Phys. Rev. D **92**, 051302(R) (2015)




## Double transverse momentum imbalance

$$\delta p_{TT} = \frac{\vec{p}^{\,\nu} \times \vec{p}_T^{\,\mu}}{\left|\vec{p}^{\,\nu} \times \vec{p}_T^{\,\mu}\right|} \cdot (\vec{p}_T^{\,\pi} + \vec{p}_T^{\,p})$$

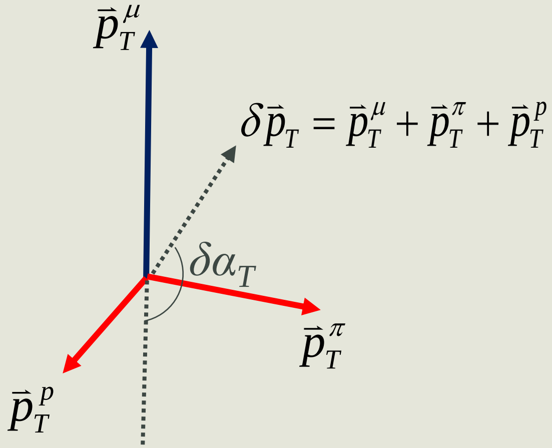



$$\begin{cases} \delta\vec{p}_T = \vec{p}_T^{\,\mu} + \vec{p}_T^{\,\pi} + \vec{p}_T^{\,p} \\ p_L = \frac{1}{2}\alpha - \frac{M_X^2 + \delta\vec{p}_T^{\,2}}{2\alpha} \\ \alpha = M_A + p_L^\mu + p_L^\pi + p_L^p - E^\mu - E^\pi - E^p \end{cases}$$

## Initial nucleon momentum

$$p_N = \sqrt{\delta\vec{p}_T^{\,2} + p_L^2}$$

Phys. Rev. C **99**, 055504 (2019)



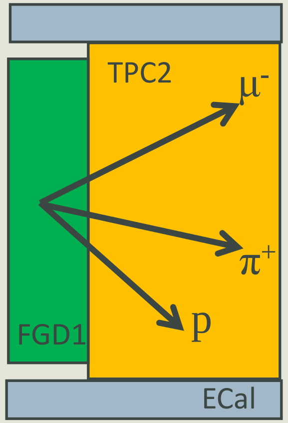

## Transverse boosting angle

$$\delta\alpha_T = \cos^{-1}\frac{-\vec{p}_T^{\,\mu} \cdot \delta\vec{p}_T}{p_T^\mu \, \delta p_T}$$

> 90°: hadronic systems decelerated by nuclear effects

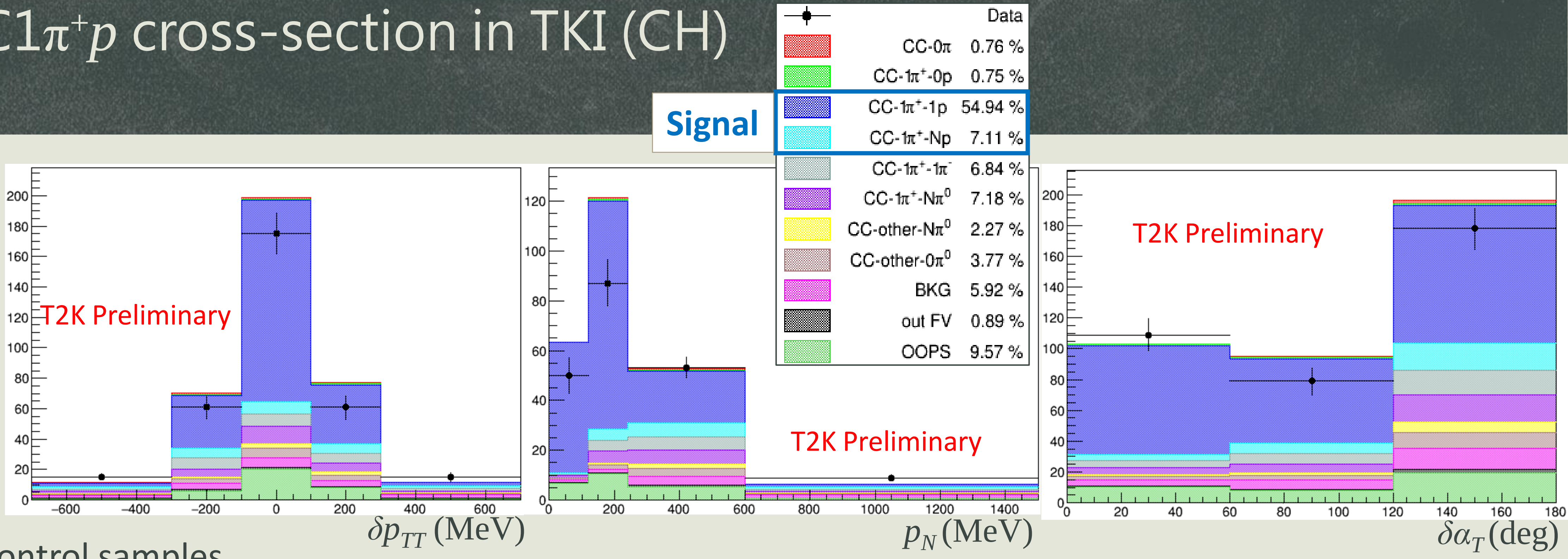
New

# CC1$\pi^+ p$ cross-section in TKI (CH)




Signal sample

& 4 CC-other control samples




Phase space restriction

| Particle | Momentum $p$ | Angle $\theta$ |
|---|---|---|
| $\mu$ | 250-7000 MeV | $< 70^o$ |
| $\pi^+$ | 150-1200 MeV | $< 70^o$ |
| $p$ | 450-1200 MeV | $< 70^o$ |

Unfolding

Maximum likelihood fit

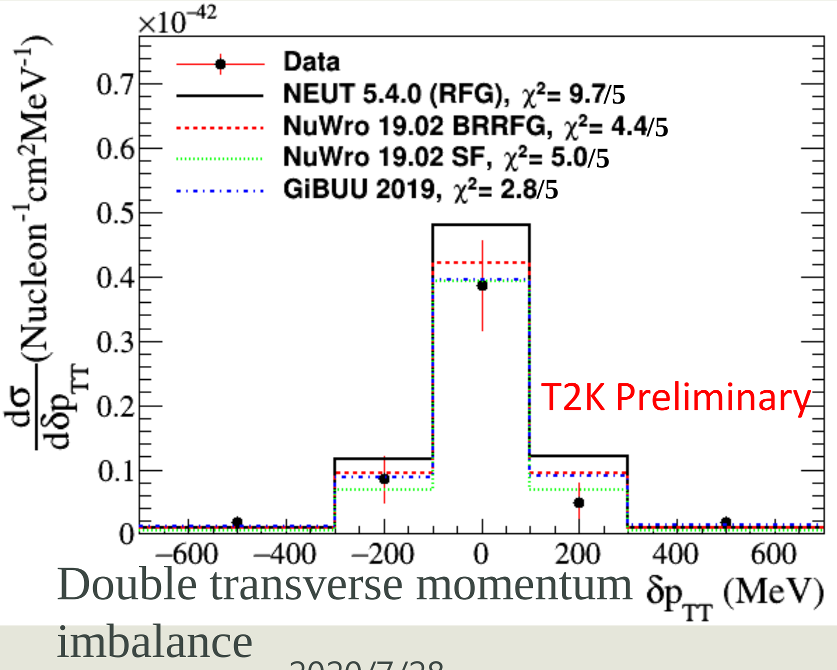
$$\frac{d\sigma}{dx_i} = \frac{N_i^{signal}}{\varepsilon_i \Phi N_{targets}^{FV}} \frac{1}{\Delta x_i}$$

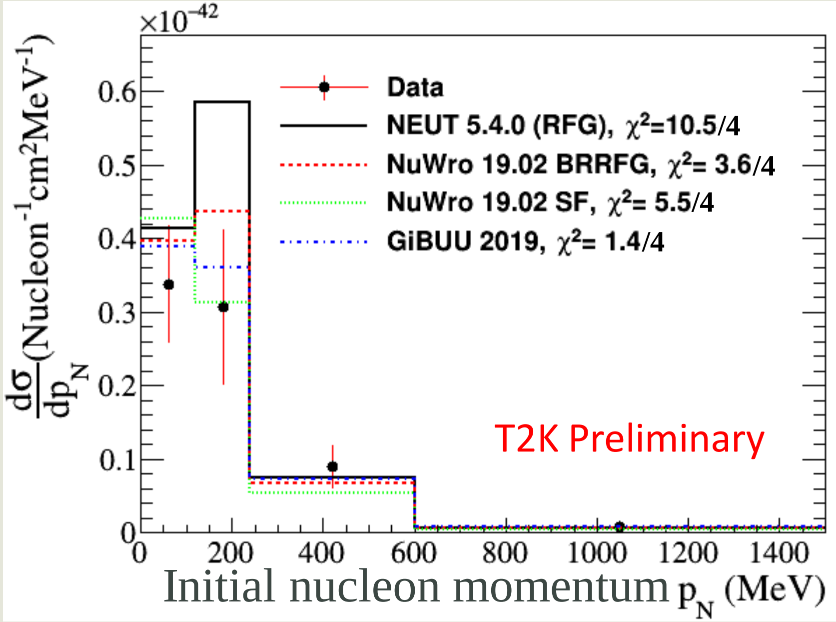
Efficiency, Flux integral, #Targets, Bin width

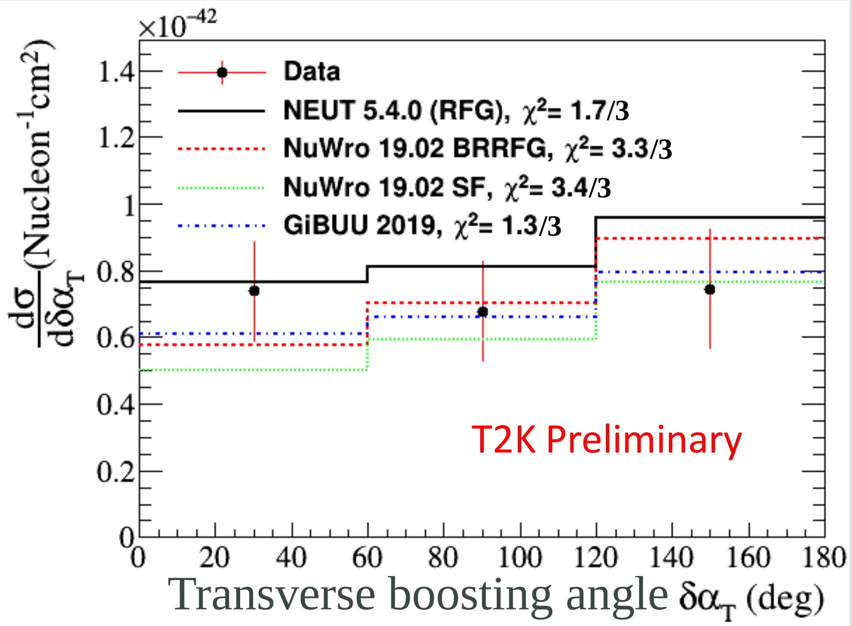
New

# $CC1\pi^+p$ cross-section in TKI (CH)

- Data slightly prefers more sophisticated nuclear models
- Carbon cross-section correlated with hydrogen (~20%)
- $\delta p_{TT}$ & $p_N$ more sensitive to initial nuclear model
- $\delta\alpha_T$ more sensitive to FSI (flat w/o FSI)



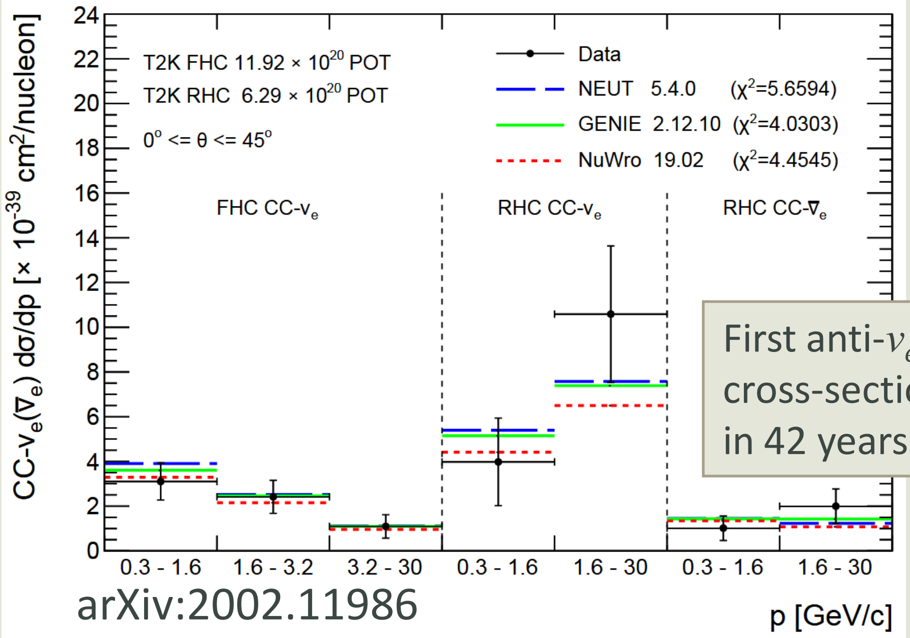



# cross-sections outlook

- More joint measurements
  - On/off axis, C/O/$\nu$/$\bar{\nu}$,0π/1π…
- New measurements of hadronic kinematics
  - TKI, calorimetry, $\pi/p$ kinematics…
- $\nu_e$ /NC interactions

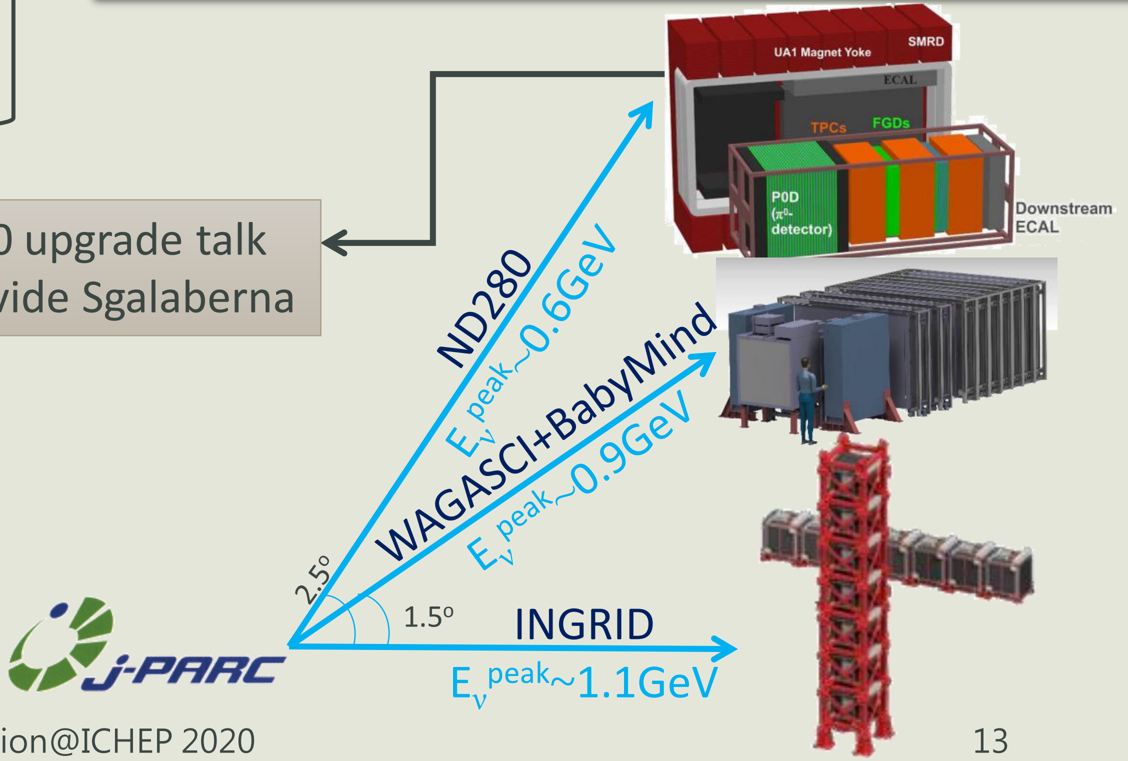
Validate theoretical models in all aspects & understand neutrino interactions in (next-gen) oscillation experiments




First anti-$\nu_e$ cross-section in 42 years!!

arXiv:2002.11986

ND280 upgrade talk by Davide Sgalaberna



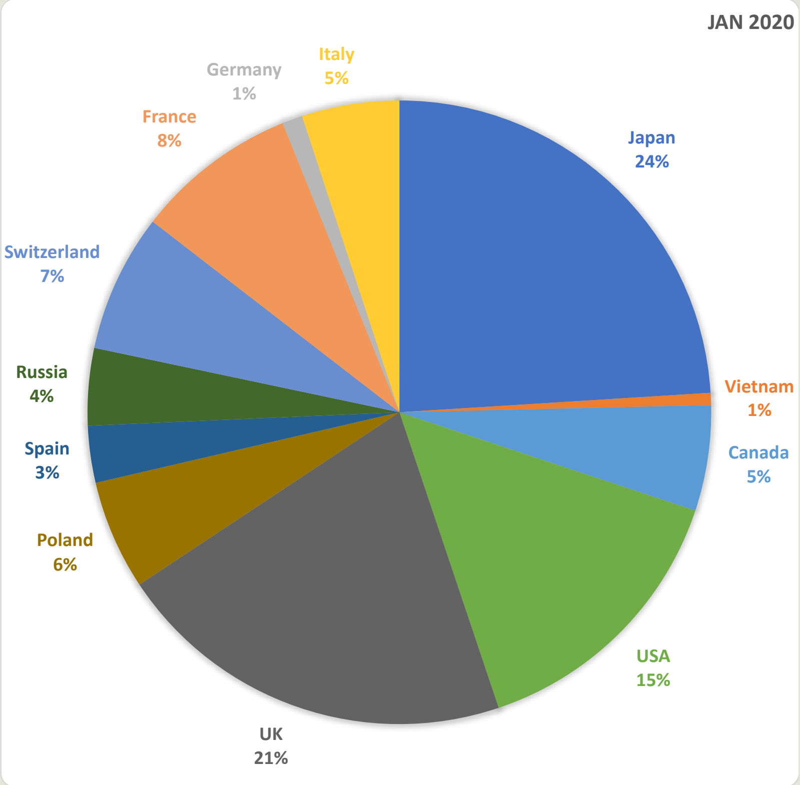
# The T2K Collaboration (2020)

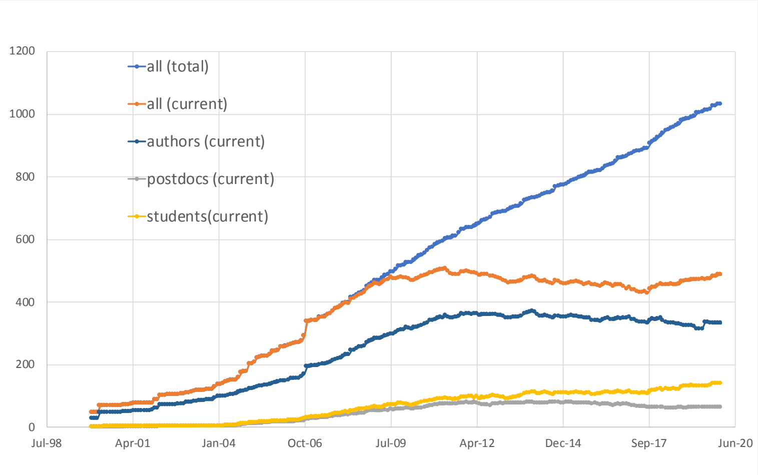
~500 members, 69 Institutes, 12 countries

| Asia | 117 |
|---|---|
| Japan | 114 |
| Vietnam | 3 |

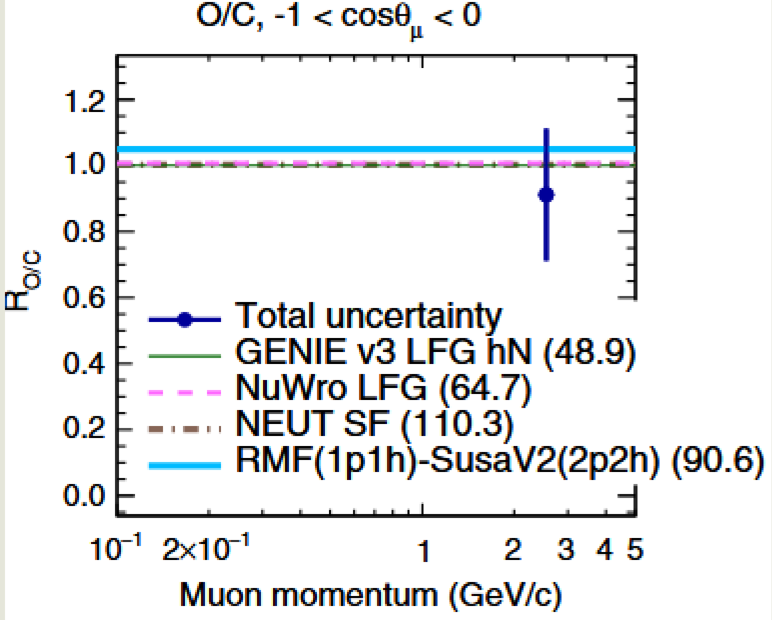
| Americas | 96 |
|---|---|
| Canada | 26 |
| USA | 70 |

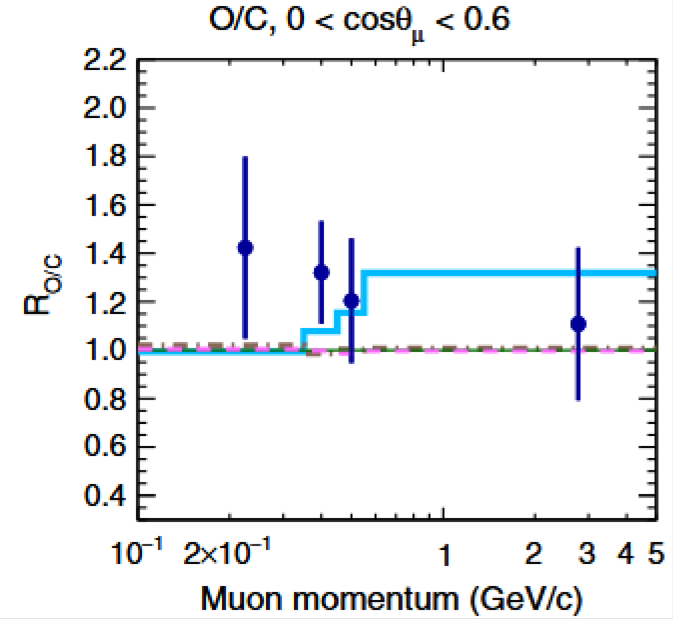
| Europe | 262 |
|---|---|
| France | 40 |
| Germany | 5 |
| Italy | 24 |
| Poland | 27 |
| Russia | 19 |
| Spain | 14 |
| Switzerland | 34 |
| UK | 99 |

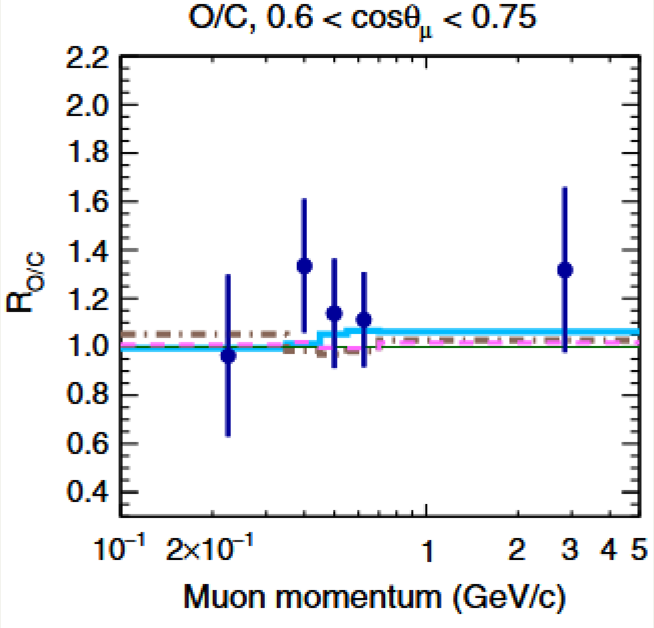


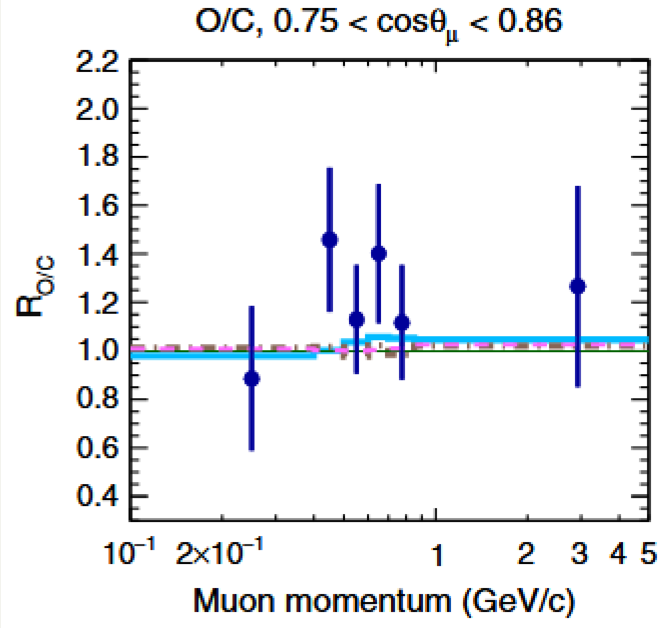



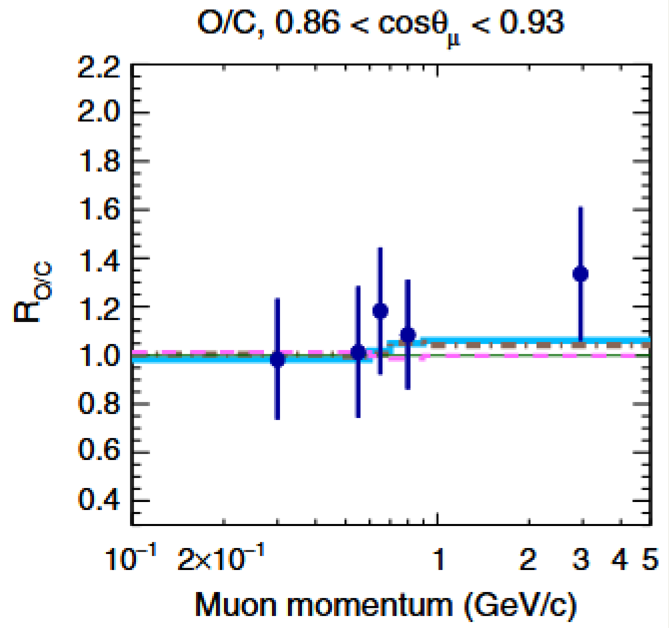
# Backup


O/C, -1 < cosθ_μ < 0
R_O/C
Muon momentum (GeV/c)
Total uncertainty
GENIE v3 LFG hN (48.9)
NuWro LFG (64.7)
NEUT SF (110.3)
RMF(1p1h)-SusaV2(2p2h) (90.6)


O/C, 0 < cosθ_μ < 0.6
R_O/C
Muon momentum (GeV/c)


O/C, 0.6 < cosθ_μ < 0.75
R_O/C
Muon momentum (GeV/c)


O/C, 0.75 < cosθ_μ < 0.86
R_O/C
Muon momentum (GeV/c)


O/C, 0.86 < cosθ_μ < 0.93
R_O/C
Muon momentum (GeV/c)

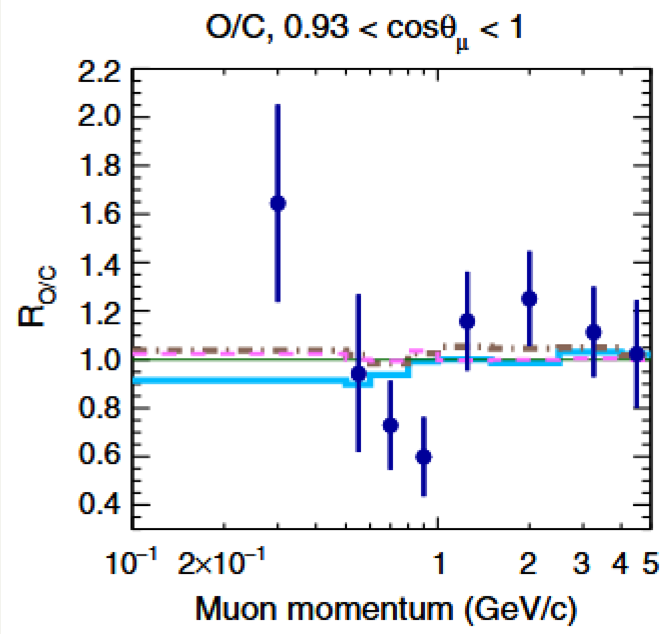
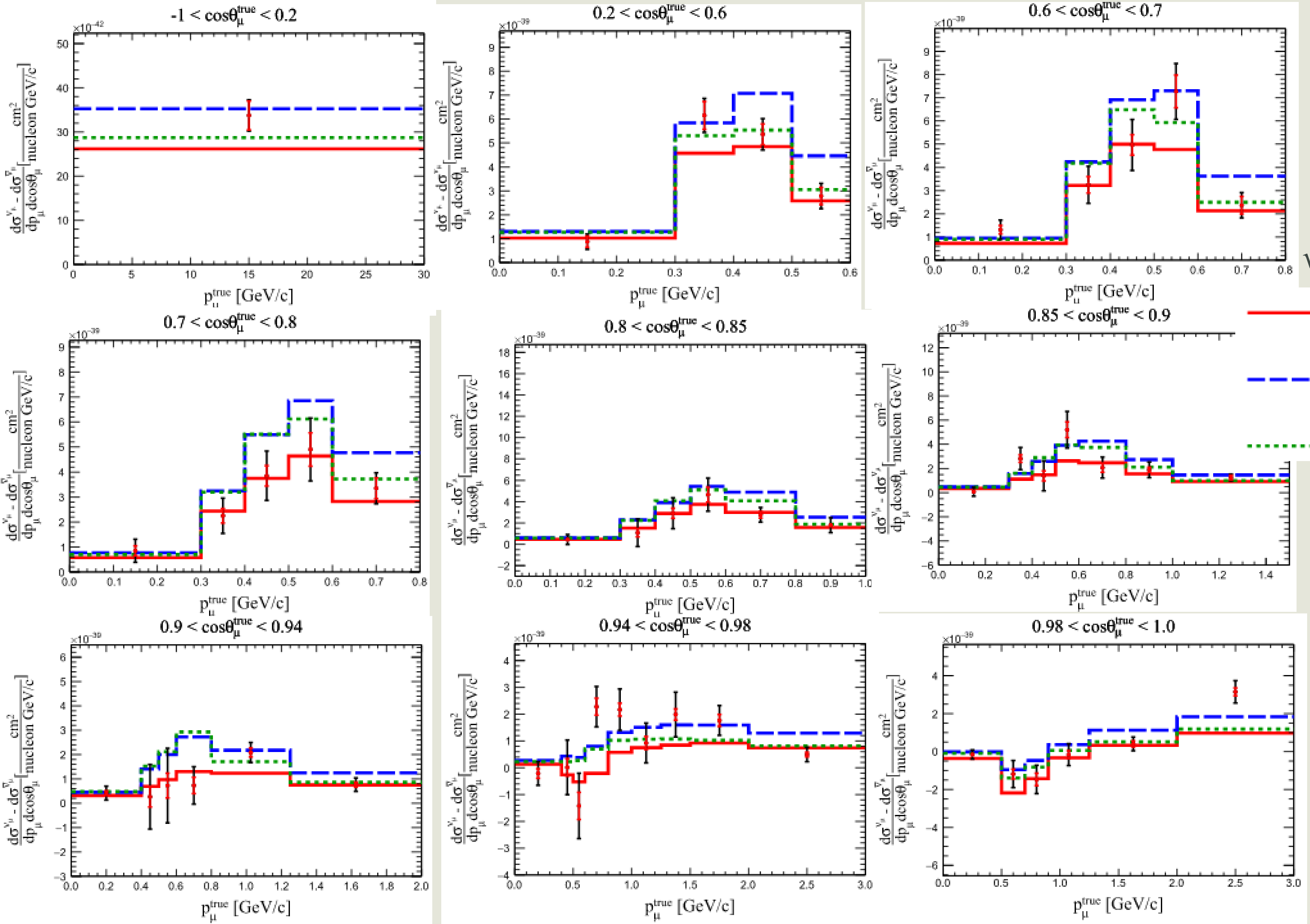

O/C, 0.93 < cosθ_μ < 1
R_O/C
Muon momentum (GeV/c)

TABLE V. $\chi^2_{tot}$ ($\chi^2_{shape}$) calculated as in Eq. (9) [Eq. (10)] for the full measurement of oxygen and carbon cross sections per nucleon, for oxygen and carbon neglecting the last $\cos\theta_\mu$ bin, for oxygen only, for carbon only and for the O/C ratio. The number of degrees of freedom (ndof) for each $\chi^2_{tot}$ comparison is also shown.

| Generator | Result | Total $\chi^2$ (shape only) (ndof = 58) | $\chi^2$ w/o last $\cos\theta_\mu$ bin (ndof = 50) | Only O $\chi^2$ (ndof = 29) | Only C $\chi^2$ (ndof = 29) | O/C ratio $\chi^2$ (ndof = 29) |
|---|---|---|---|---|---|---|
| NEUT 5.4.1 LFG | regularised | 44.8 (58.6) | 17.9 (21.1) | 26.0 (34.5) | 15.2 (20.1) | 30.8 |
| | unregularised | 44.4 (62.3) | 17.3 (22.5) | 26.4 (39.1) | 14.0 (19.4) | 30.6 |
| NEUT 5.4.0 SF | regularised | 111.0 (156.8) | 45.3 (69.0) | 50.0 (77.6) | 40.1 (58.3) | 31.7 |
| | unregularised | 116.8 (166.7) | 45.1 (70.1) | 53.7 (86.5) | 38.6 (56.2) | 32.2 |
| NuWro 18.2 LFG | regularised | 64.7 (83.7) | 21.0 (30.5) | 31.9 (45.0) | 23.5 (31.5) | 33.1 |
| | unregularised | 66.8 (88.7) | 21.1 (32.1) | 32.9 (49.9) | 22.6 (30.6) | 33.5 |
| NuWro 18.2 SF | regularised | 114.5 (180.1) | 50.2 (80.9) | 50.1 (86.1) | 44.8 (70.3) | 34.2 |
| | unregularised | 119.2 (189.0) | 48.7 (80.9) | 52.7 (94.8) | 42.6 (67.4) | 33.9 |
| Genie 3 LFG hN | regularised | 48.9 (58.5) | 22.3 (24.6) | 24.9 (32.1) | 18.4 (22.3) | 33.5 |
| | unregularised | 46.6 (60.0) | 20.1 (23.8) | 24.7 (35.6) | 16.3 (20.4) | 34.0 |
| Genie 3 LFG hA | regularised | 55.4 (62.0) | 22.9 (25.5) | 27.8 (34.3) | 19.8 (22.3) | 32.3 |
| | unregularised | 52.9 (62.0) | 21.0 (24.5) | 27.7 (37.0) | 17.7 (20.4) | 32.6 |
| Genie 3 SuSAv2 | regularised | 103.5 (105.4) | 39.0 (44.7) | 50.6 (57.3) | 35.8 (36.8) | 29.8 |
| | unregularised | 110.3 (111.3) | 40.3 (45.6) | 55.4 (62.8) | 35.1 (35.5) | 30.1 |
| RMF (1p1h) | regularised | 90.6 (97.5) | 48.2 (60.5) | 31.4 (37.8) | 43.9 (51.3) | 31.3 |
| + SuSAv2 (2p2h) | unregularised | 95.8 (102.2) | 49.3 (60.7) | 34.0 (42.1) | 41.9 (48.1) | 30.7 |
| GiBUU | regularised | 112.7 (117.0) | 47.2 (50.6) | 46.8 (58.0) | 46.6 (46.1) | 39.3 |
| | unregularised | 107.5 (112.2) | 41.7 (46.8) | 43.5 (56.0) | 41.0 (41.2) | 37.0 |

## ν + anti-ν CC0π difference




NEUT LFG+2p2h $\chi^2$ = 79.5(113.8)/58

Martini et al. $\chi^2$ = 119.6(289.8)/48

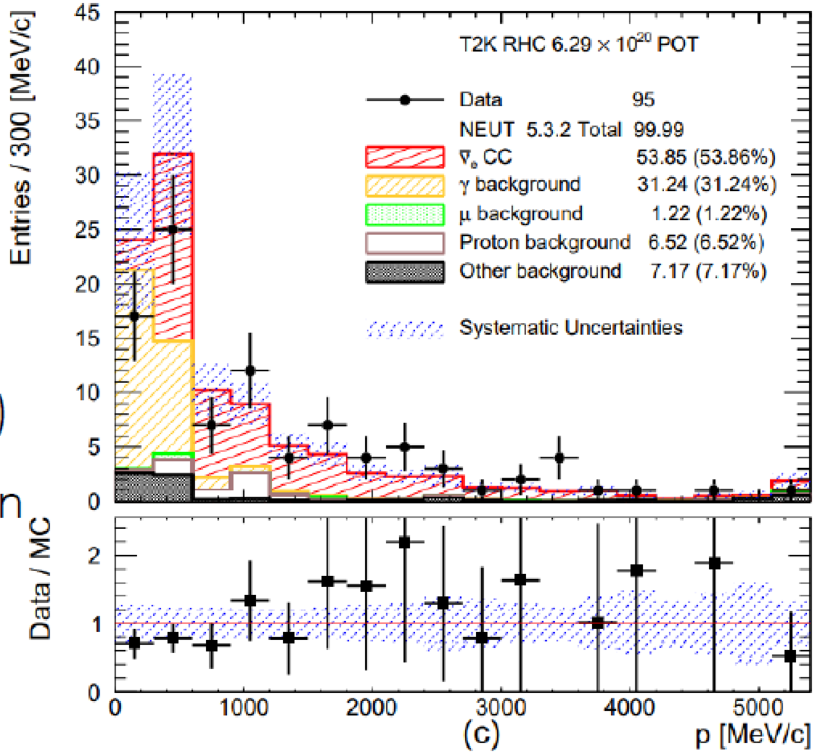
SuSAv2 $\chi^2$ = 119.2(137.9)/58

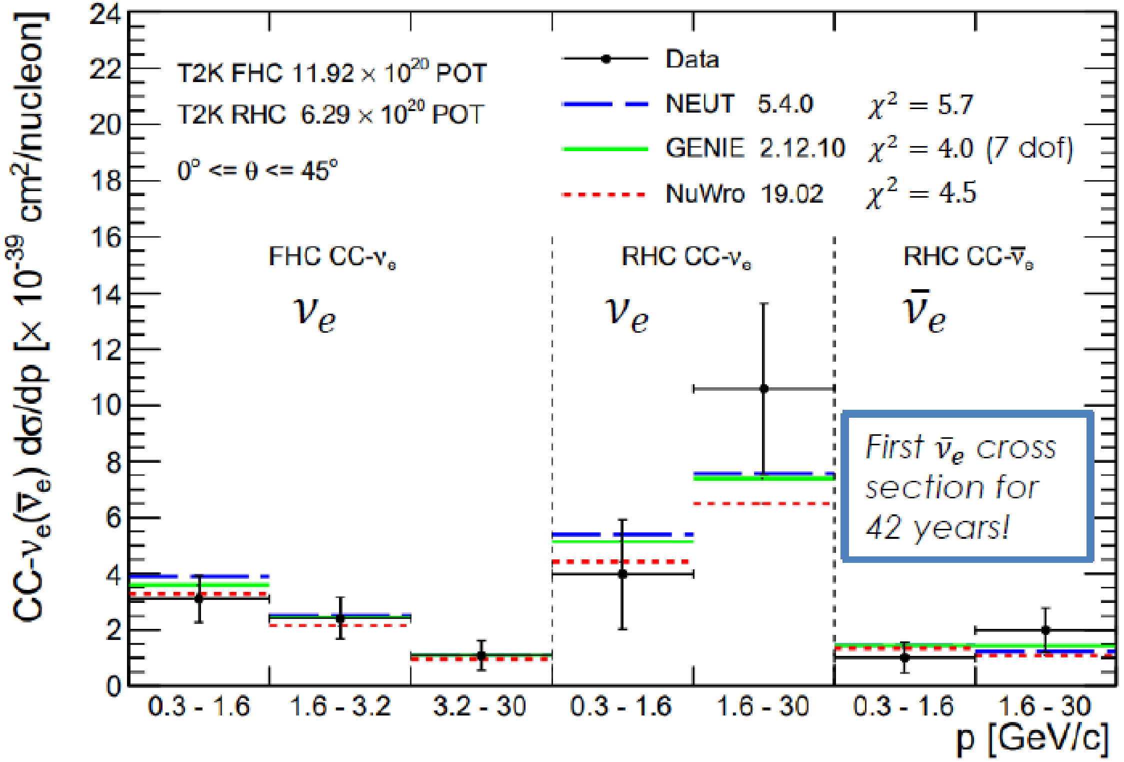
# Electron neutrino measurement

arXiv:2002.11986

## Selection

- Identify interactions of intrinsic $\overset{(-)}{\nu}_e$ contribution to flux ($\nu_e$ is ~1% of the $\nu_\mu$) when running to produce predominantly $\nu_\mu$ (FHC) and $\bar{\nu}_\mu$ (RHC)
- Major background at low reconstructed electron momentum from photons (largely from $\pi^0$ decay)
- This is constrained with a dedicated control region




## Cross section Measurement

- Detector acceptance limits measurement to: $p_e > 300$ MeV/c, $\theta_e < 45°$
- Large statistical uncertainties
- Good agreement with event generators