# Probing nuclear effects in neutrino CC1$\pi^+$ interactions with **Transverse Kinematic Imbalance** measurement in T2K

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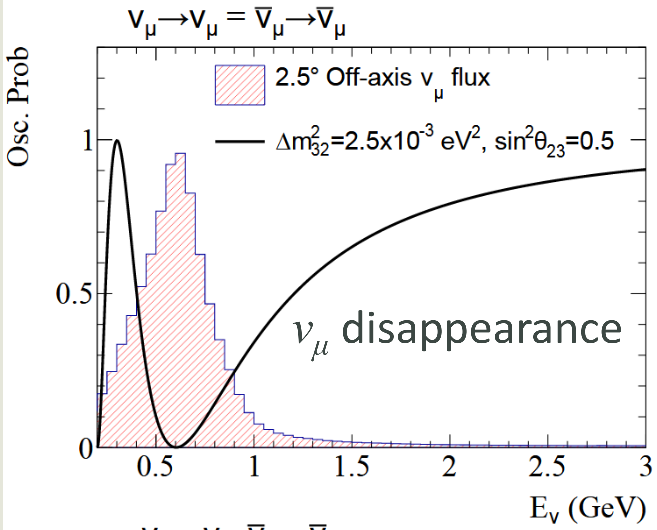
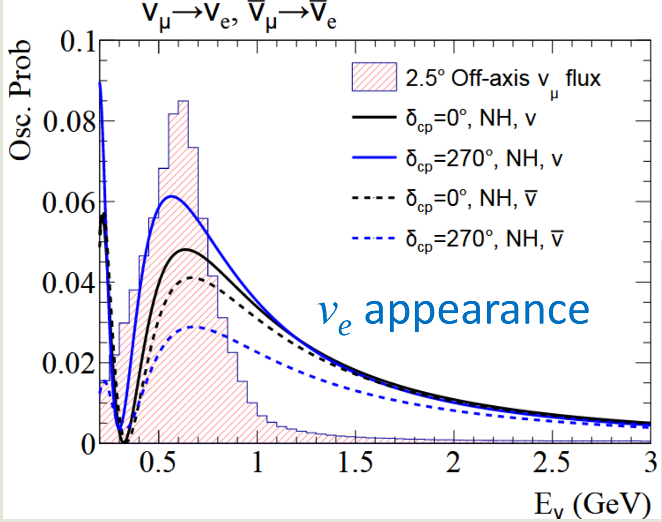




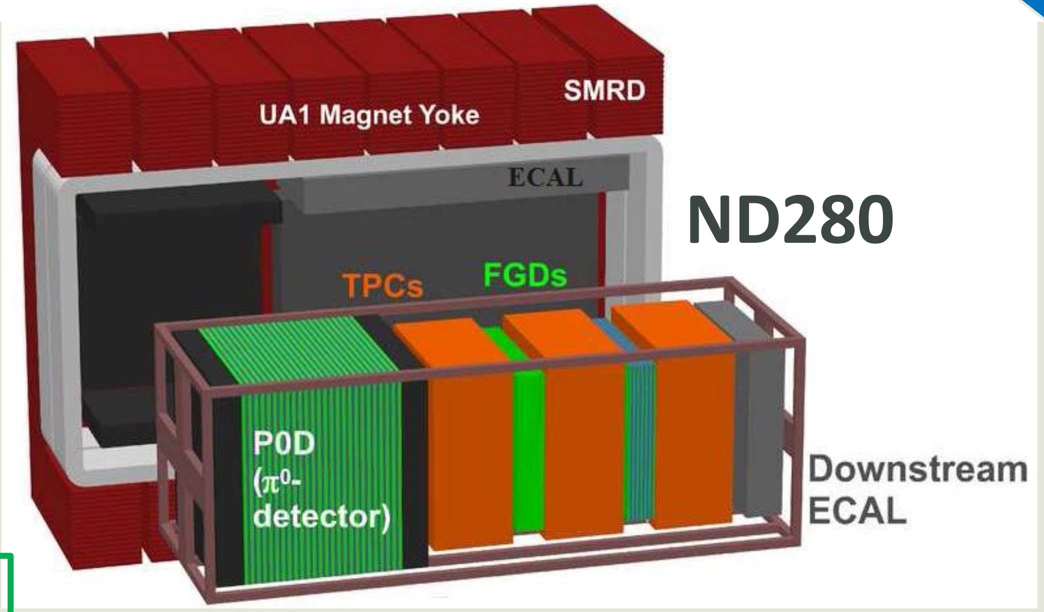
T2K Plenary talk@Mon 22/2
By Mathieu Guigue

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

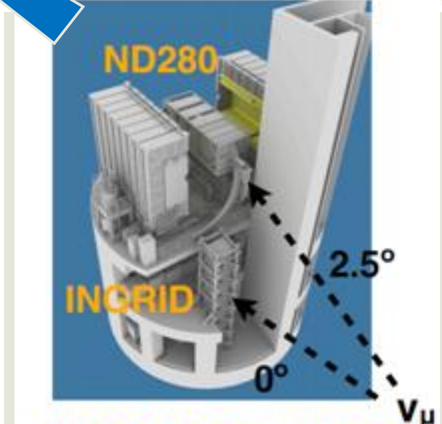
Interaction cross-section

Neutrino flux

Detector effects

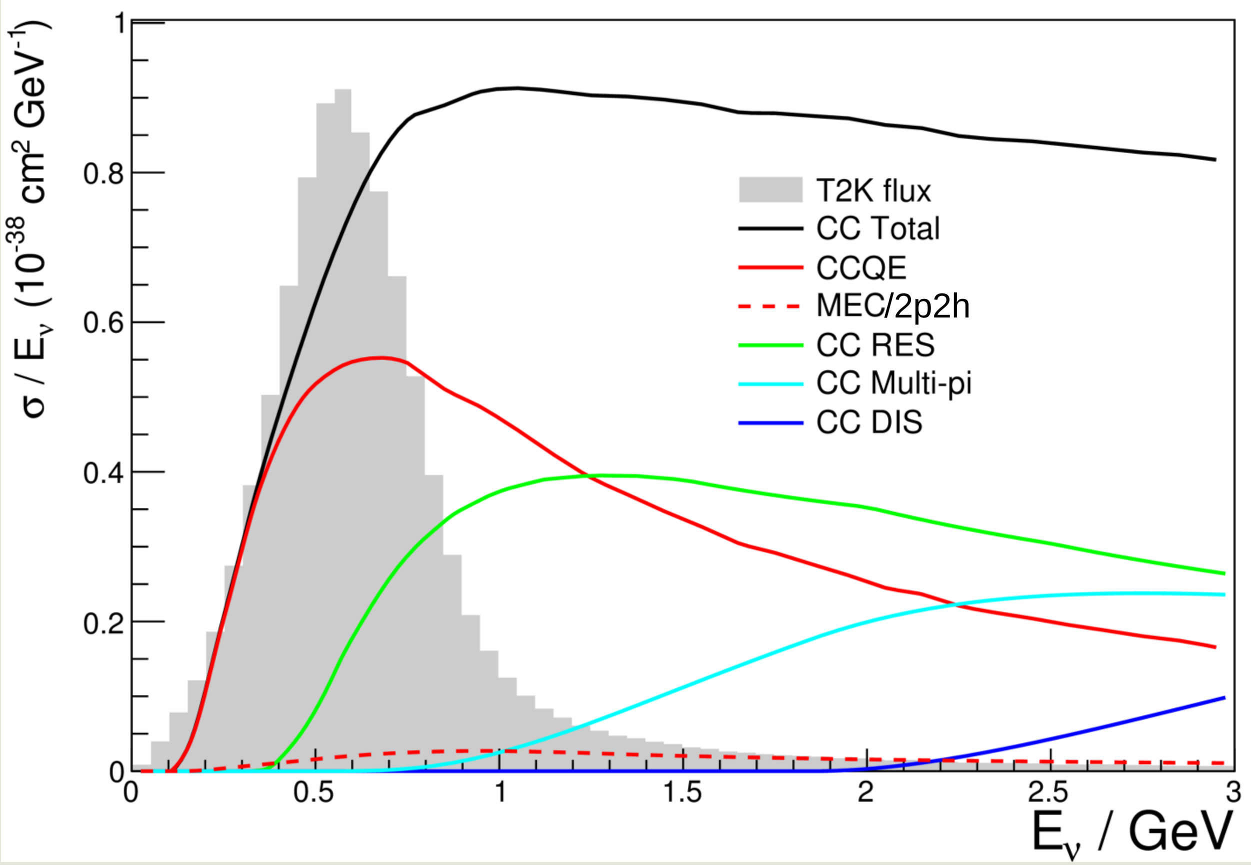



ND280

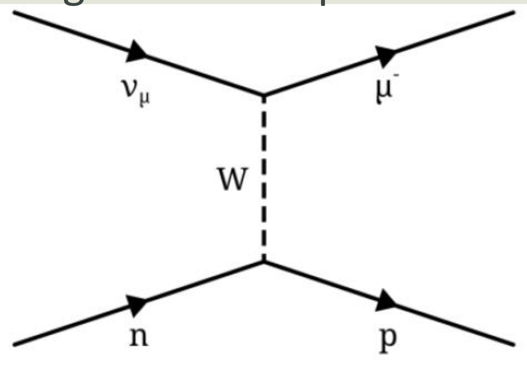



INGRID (on-axis) and ND280 (off-axis)

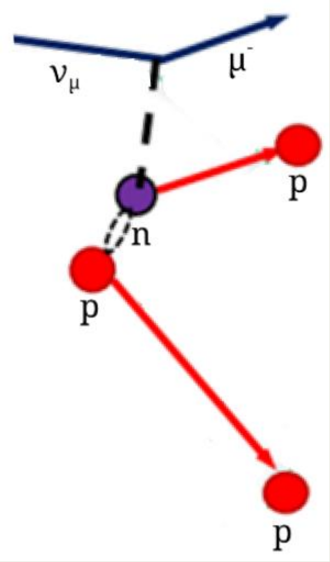
# Neutrino interactions at T2K



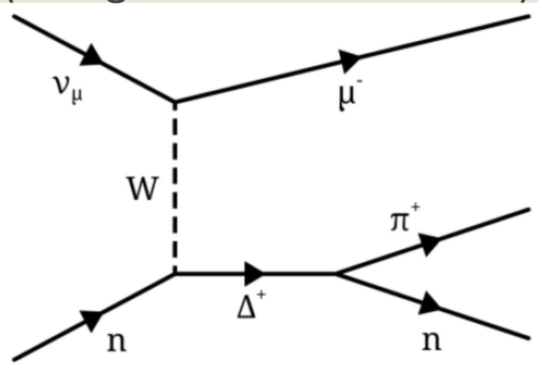

CCQE
(Charged-current quasi-elastic)




2p2h
(2particle-2hole)

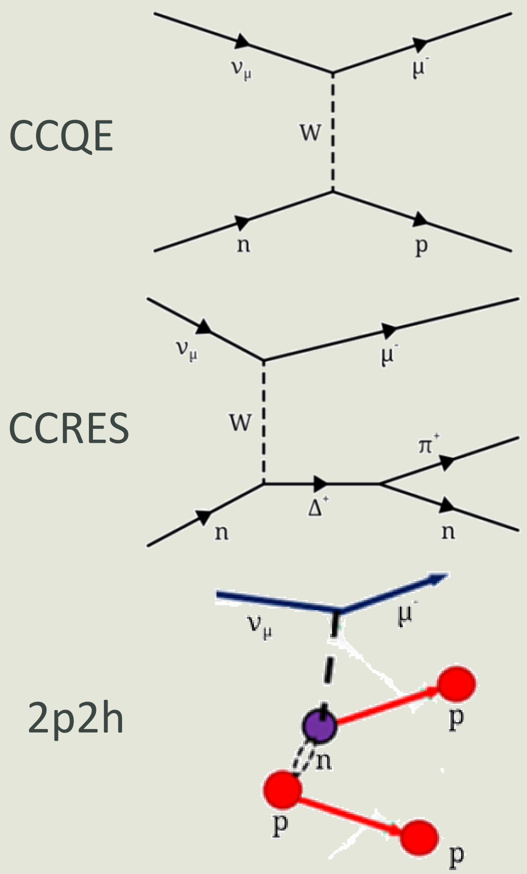



CCRES
(Charged-current resonant)

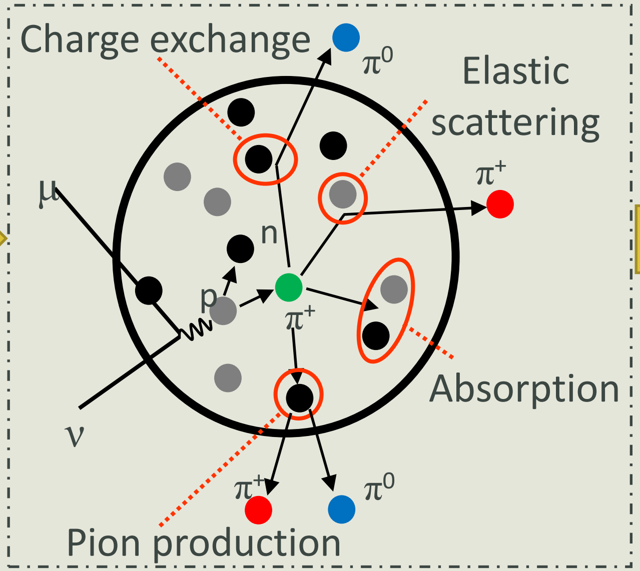


# Neutrino interaction measurements at T2K

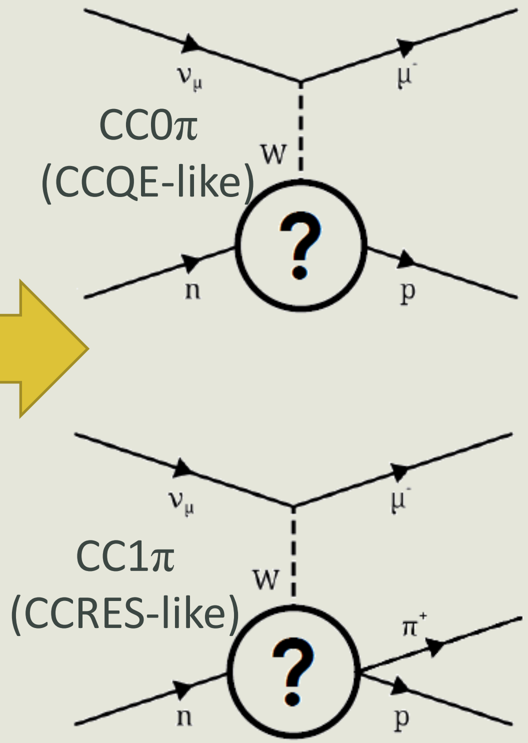
## Interaction mode

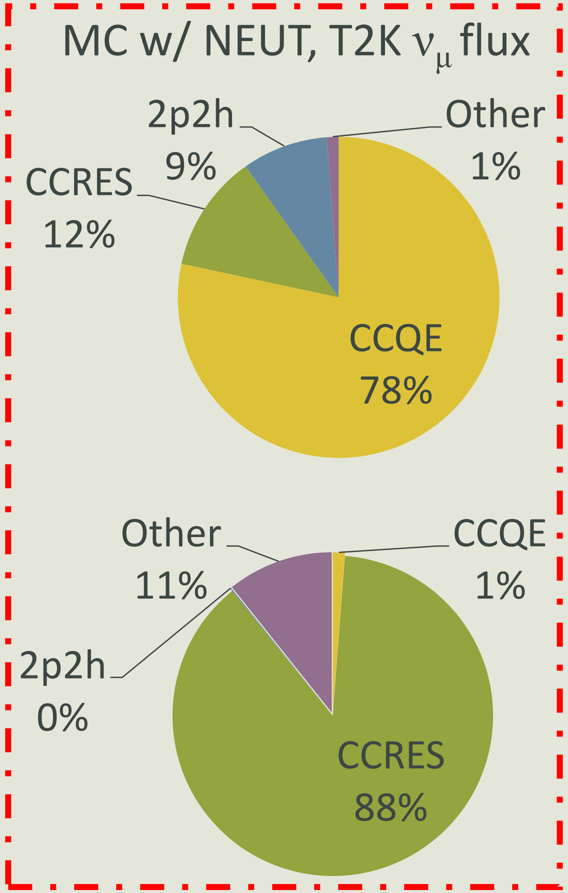



## Initial nuclear state & Final state interactions (FSI)



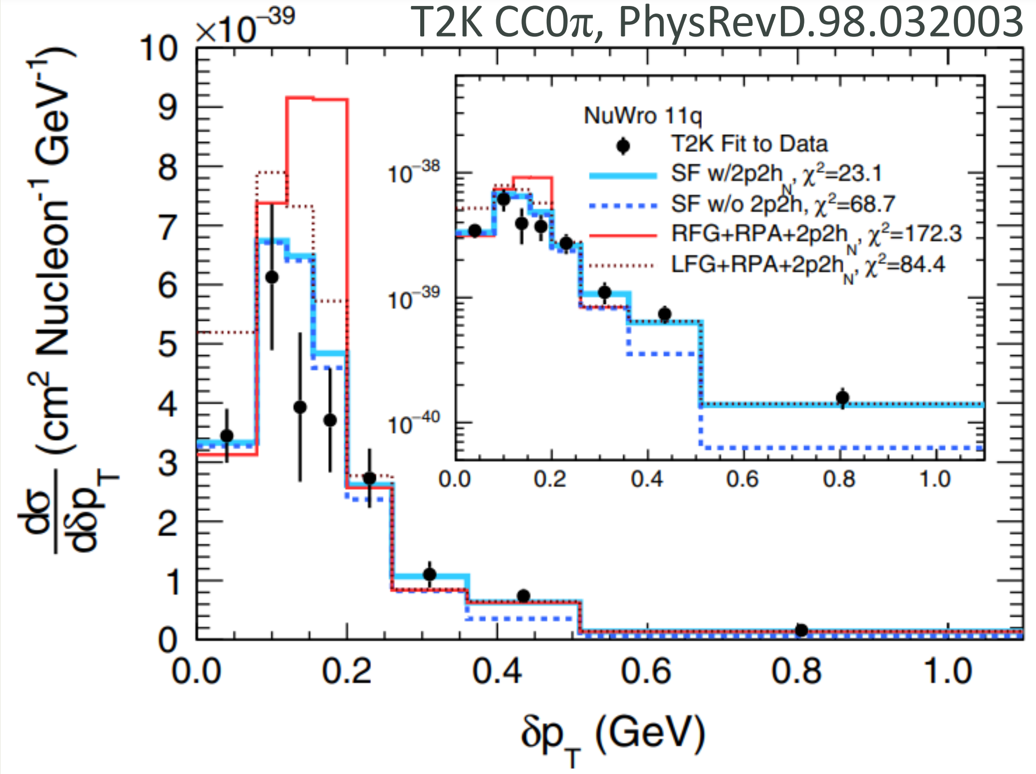

## Observed topology

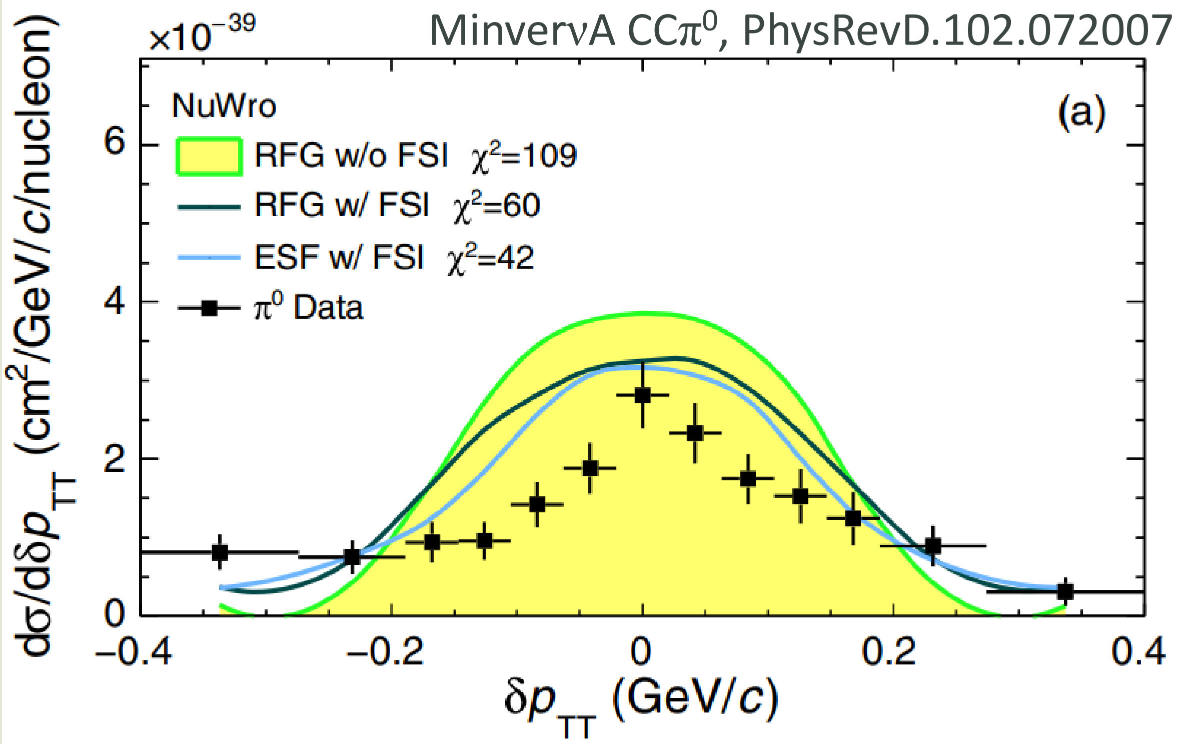


# Measurement of Transverse Kinematic Imbalance (TKI)

- Lepton-hadron correlations on the transverse plane to the initial neutrino direction → helps precisely identify intranuclear dynamics



# Measurement of TKI in CC1$\pi^+$Xp interaction at T2K

Preprint: arXiv:2102.03346

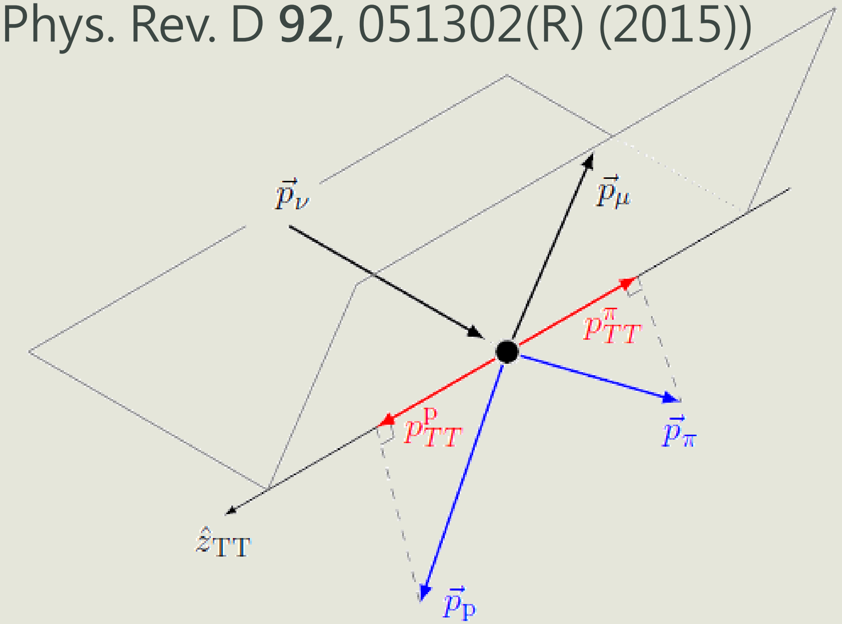
- $\nu_\mu$ CC1$\pi^+$ interaction on nucleus A with at least 1 proton in the final state:

$$\nu_\mu + \mathrm{A} \rightarrow \mu^- + \pi^+ + \mathrm{p} + \mathrm{A}'$$

- Double transverse momentum imbalance $\delta p_{TT}$ (Phys. Rev. D **92**, 051302(R) (2015))

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

- $\delta p_{TT}$=0 if no nuclear effects
- Initial Fermi motion and FSI cause a broad distribution



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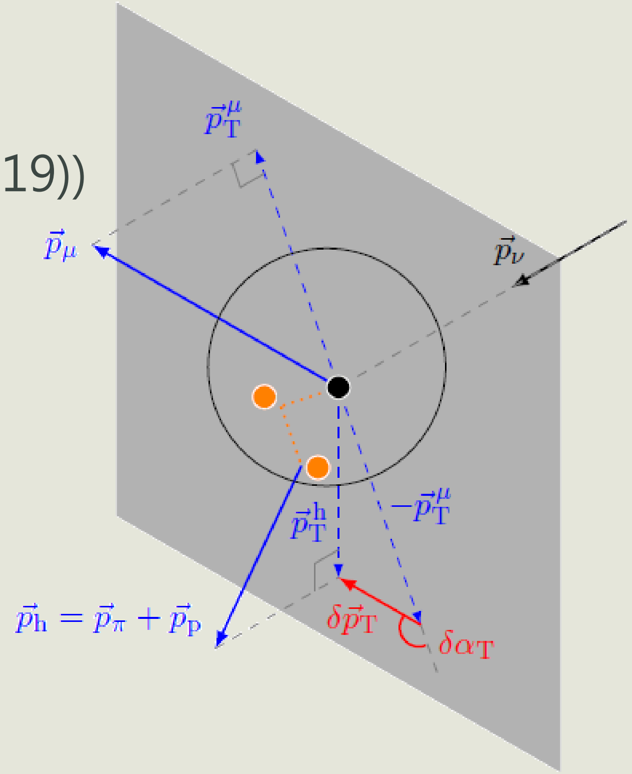
- Initial nucleon momentum $p_N$ (Phys. Rev. C **99**, 055504 (2019))

$$p_N = \sqrt{\delta \vec{p}_T^{\,2} + p_L^2} \quad \begin{cases} \delta \vec{p}_T = \vec{p}_T^{\,\mu} + \vec{p}_T^{\,\pi} + \vec{p}_T^{\,\mathrm{p}} \\ p_L = \dfrac{1}{2}\alpha - \dfrac{M_{\mathrm{A}'}^2 + \delta \vec{p}_T^{\,2}}{2\alpha} \\ \alpha = M_{\mathrm{A}} + p_L^{\mu} + p_L^{\pi} + p_L^{\mathrm{p}} - E^{\mu} - E^{\pi} - E^{\mathrm{p}} \end{cases}$$




- Probes the Fermi motion inside the nucleus
- FSI shift the peak and cause a long tail

# Measurement of TKI in CC1$\pi^+$Xp interaction at T2K

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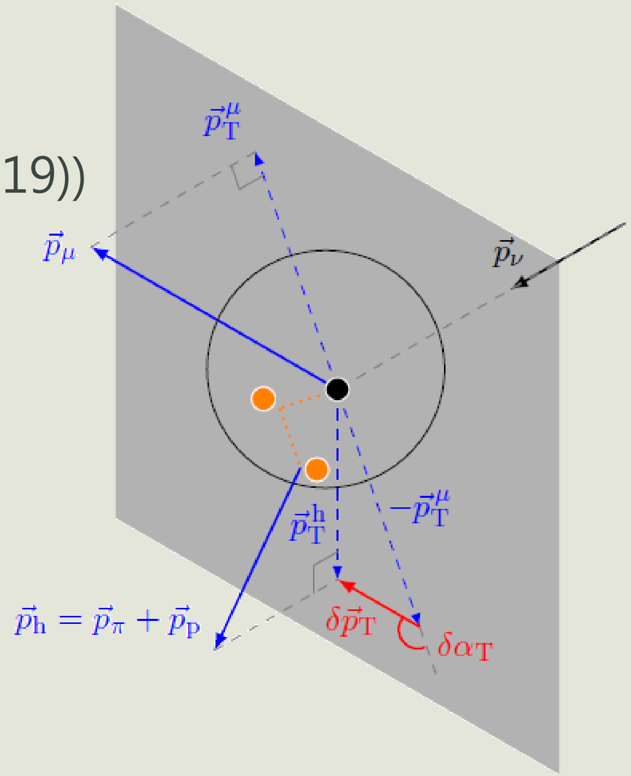
- Transverse boosting angle $\delta\alpha_T$ (Phys. Rev. C **99**, 055504 (2019))

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

- Isotropic Fermi motion causes a flat distribution
- FSI slow down hadrons and skew towards $\delta\alpha_T > 90^o$

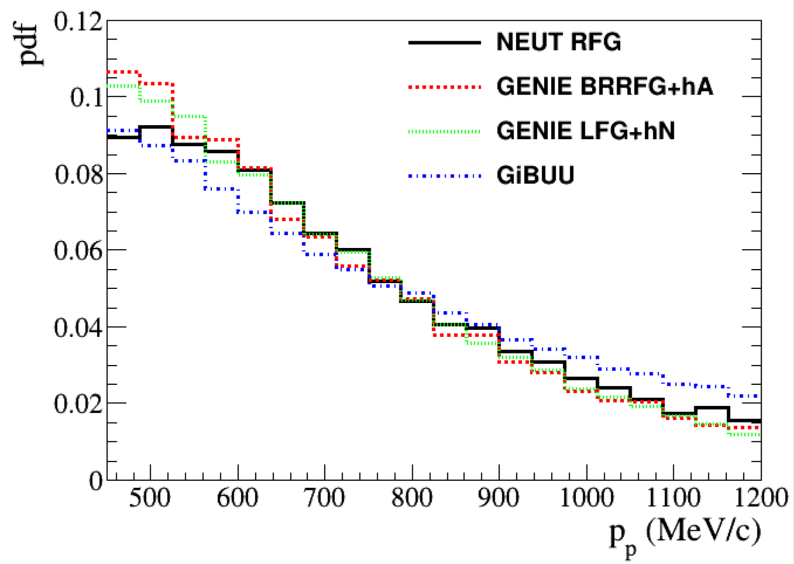


# $CC1\pi^{+}Xp$ Signal Definition

Preprint: arXiv:2102.03346

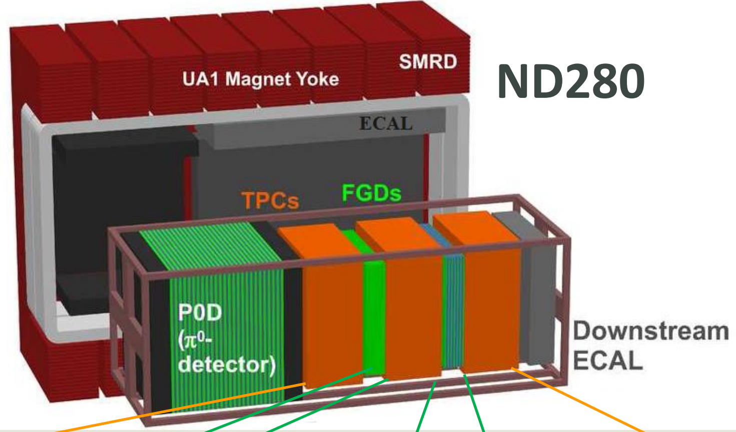
- Events with $1\mu^-$, $1\pi^+$ and no other mesons, at least 1 proton in the final state
- Phase space restrictions to mitigate model dependence in efficiency correction
- Three-particle final states lead to complicated efficiency dependency on high dimensional kinematic phase space
- Systematic parameters added to allow variation of underlying particle kinematics

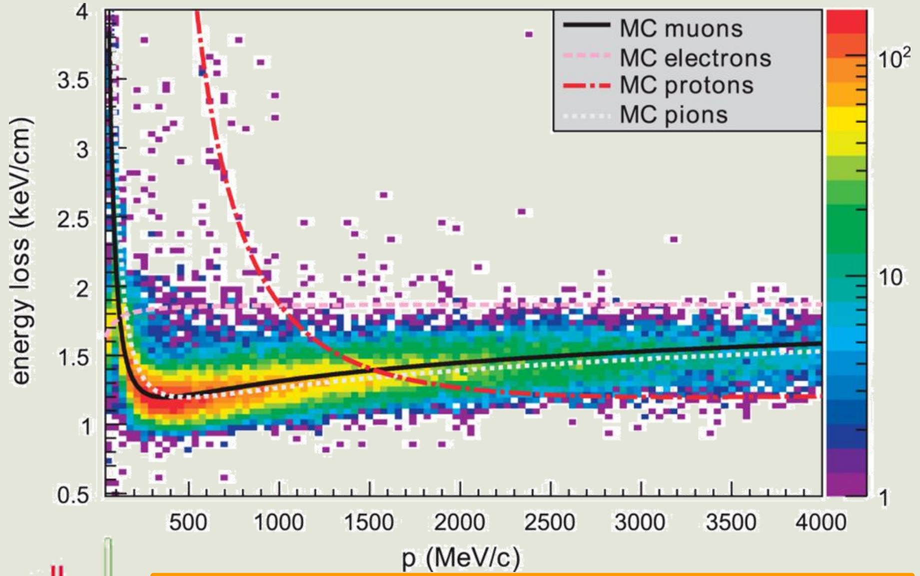
| Particle | Momentum $p$ | Angle $\theta$ |
|---|---|---|
| $\mu^-$ | 250-7000 MeV/c | $< 70^o$ |
| $\pi^+$ | 150-1200 MeV/c | $< 70^o$ |
| p | 450-1200 MeV/c | $< 70^o$ |

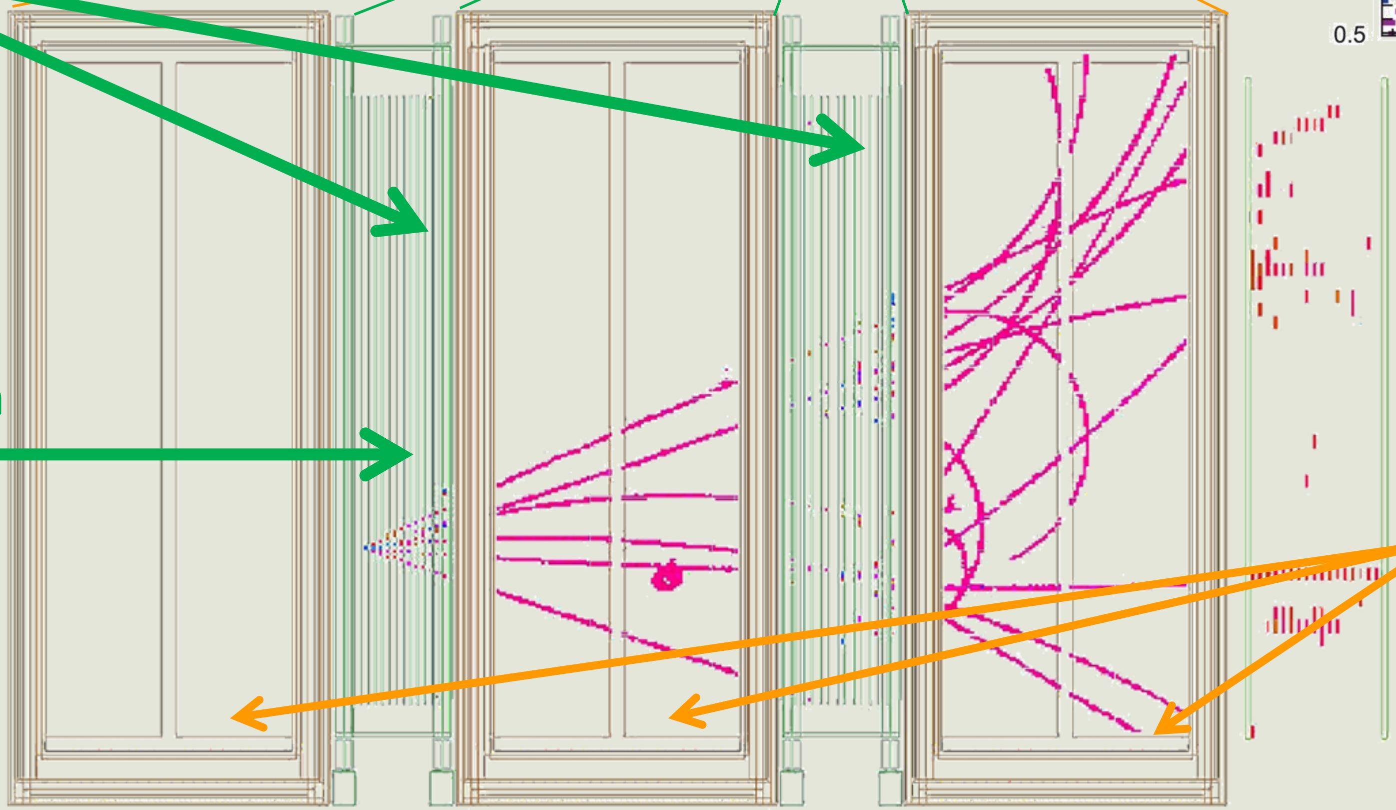


**Fine Grained Detectors (FGD 1 &2):**

- $\nu$ interaction target
- CH scintillator trackers
- alt $H_2O$ layers in FGD2



**FGD1: target in this analysis**

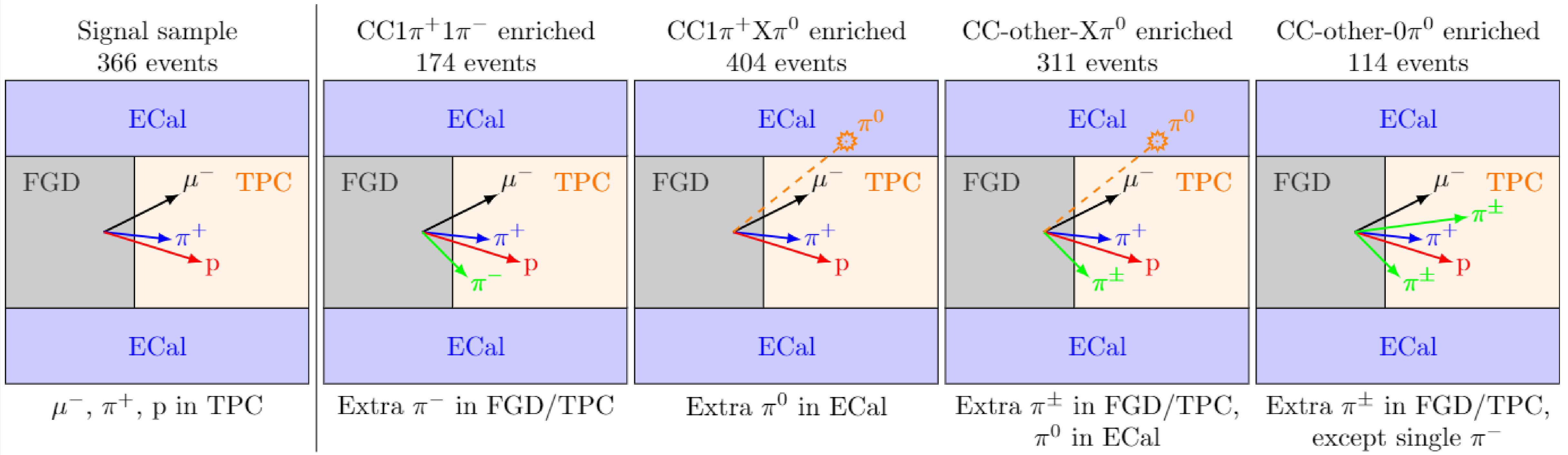
**Time Projection Chambers (TPC 1, 2 & 3):**

- Excellent tracking
- High-res charged particle mom
- Accurate PID

# Event selection in FGD1 (CH)

Preprint: arXiv:2102.03346

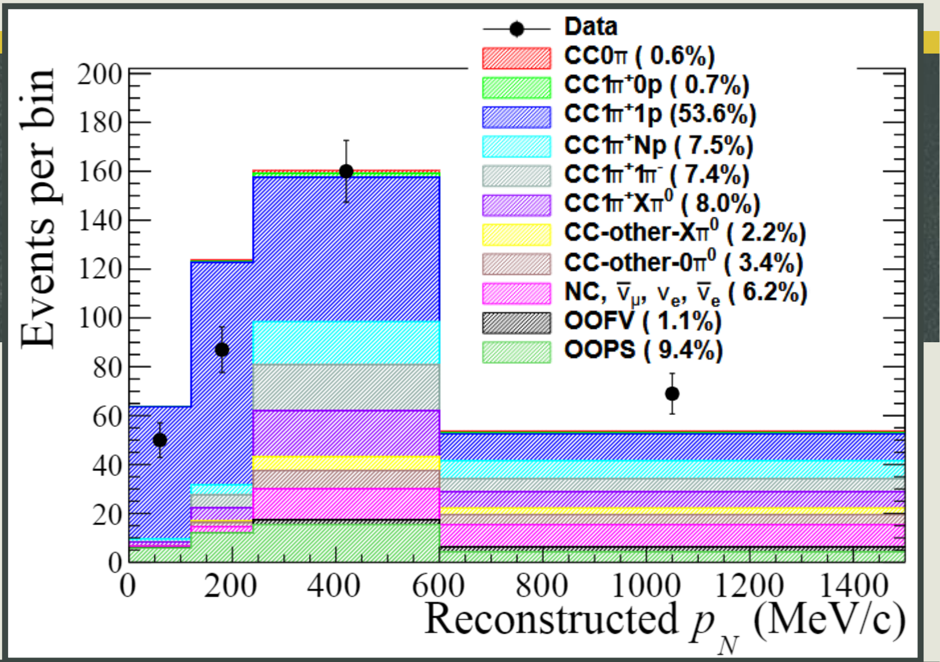
- One signal sample to select signal events
- Four control samples to constrain multi-pion background

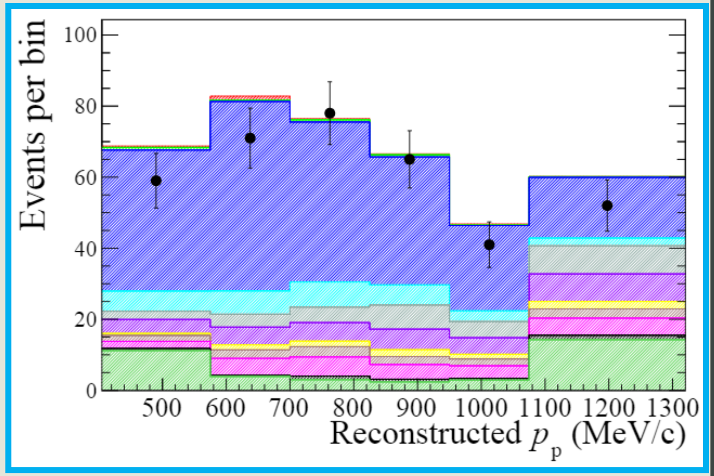


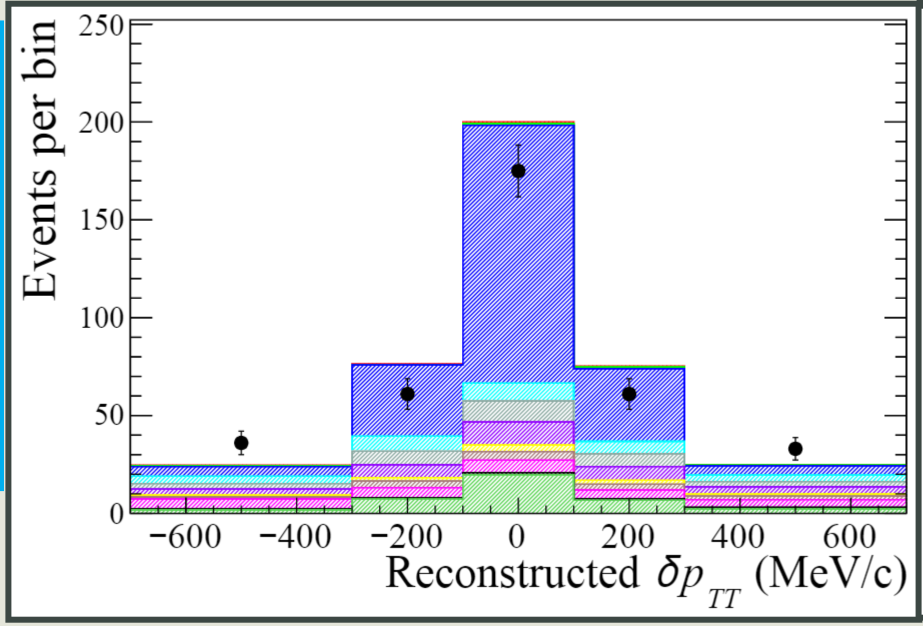
# Signal sample

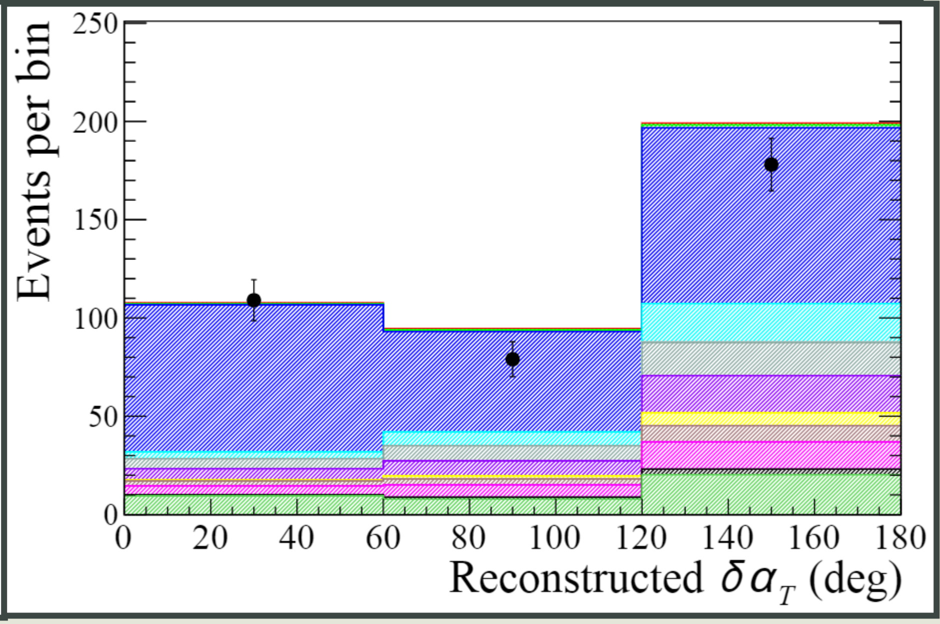
Preprint: arXiv:2102.03346

- 2D binning in one **TKI variable** vs. **proton momentum** for better efficiency correction



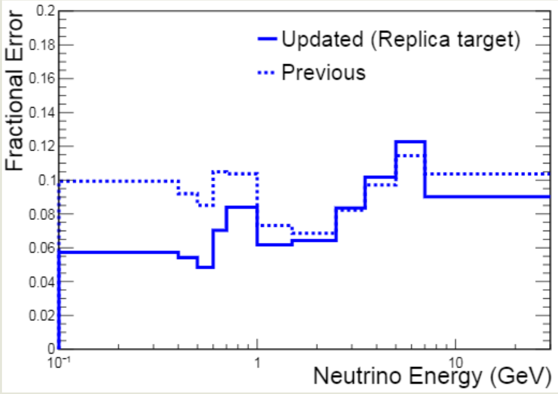



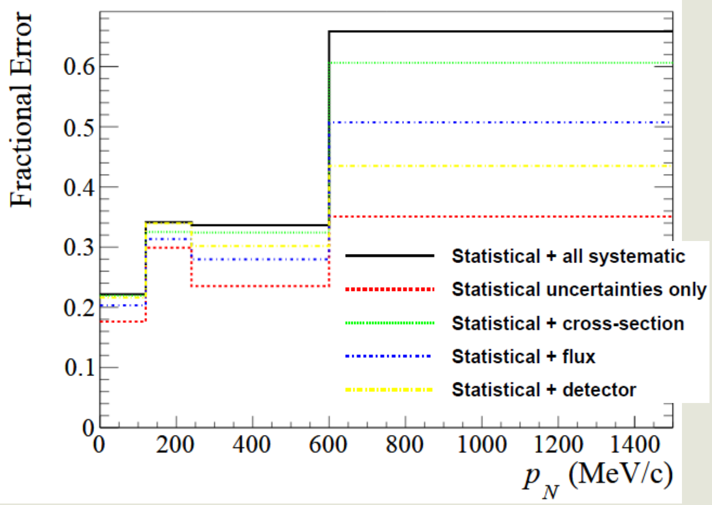
# Systematic uncertainties

Preprint: arXiv:2102.03346

Use of principle component analysis to reduce fit dimensionality

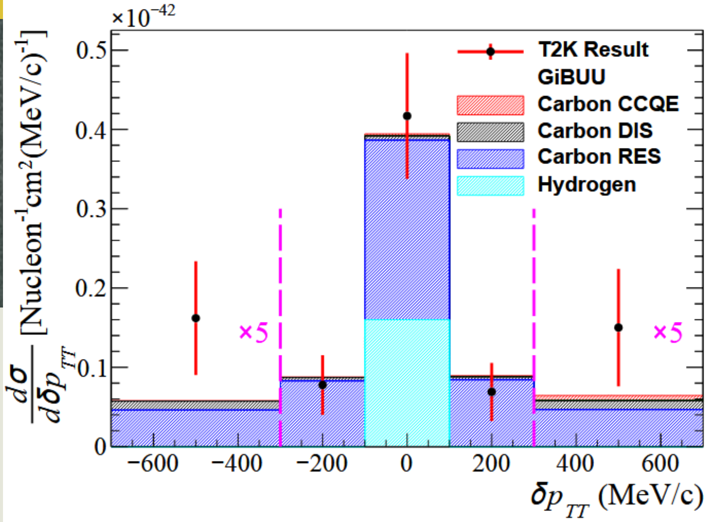
- Neutrino flux: improved with replica target measurement at NA61/SHINE (Eur.Phys.J. C79 (2019) no.2, 100)
- Detector responses: biggest contribution from proton secondary interactions (SI) and $\pi^0$-tagging uncertainty. Pion SI uncertainty reduced by ~40%.
- Neutrino cross-section and interaction model:
  - RES parameters such as $M_A^{RES}$ and $C_5^A$
  - DIS and pion FSI parameters
  - Additional parameters varying signal particle kinematics
    - Δ-resonance mass width
    - Nucleon FSI overall interaction probability
    - Ad hoc variations binned in signal particle momenta and angles



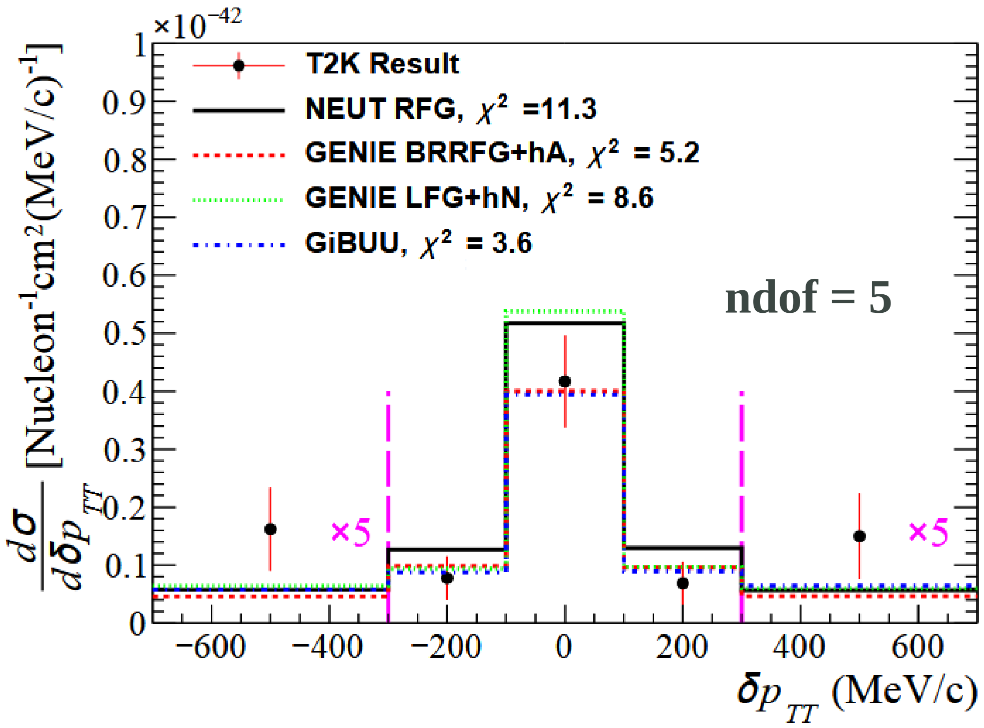



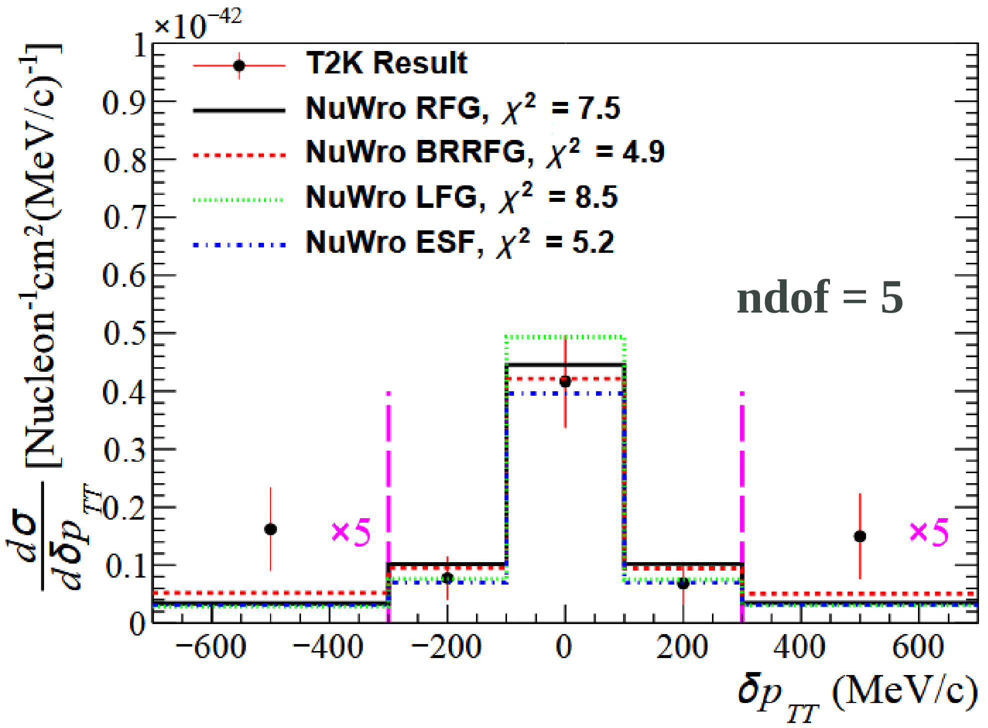
# Results

Preprint: arXiv:2102.03346




- Model sensitivity comes mostly from central bins
- Tail mostly contributed by FSI



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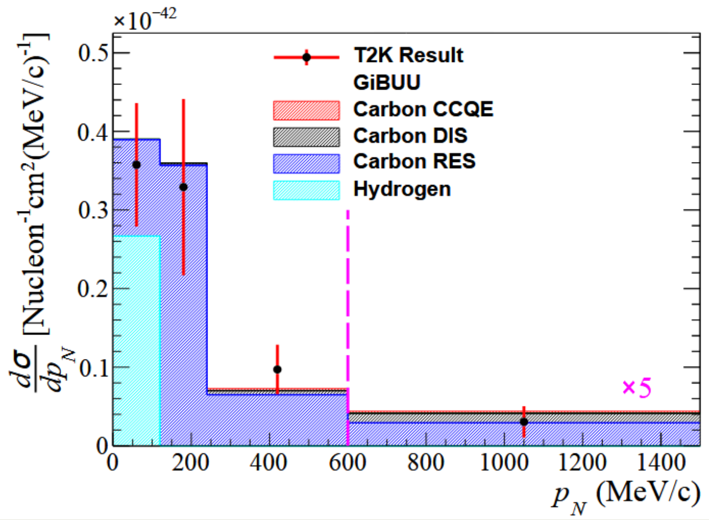
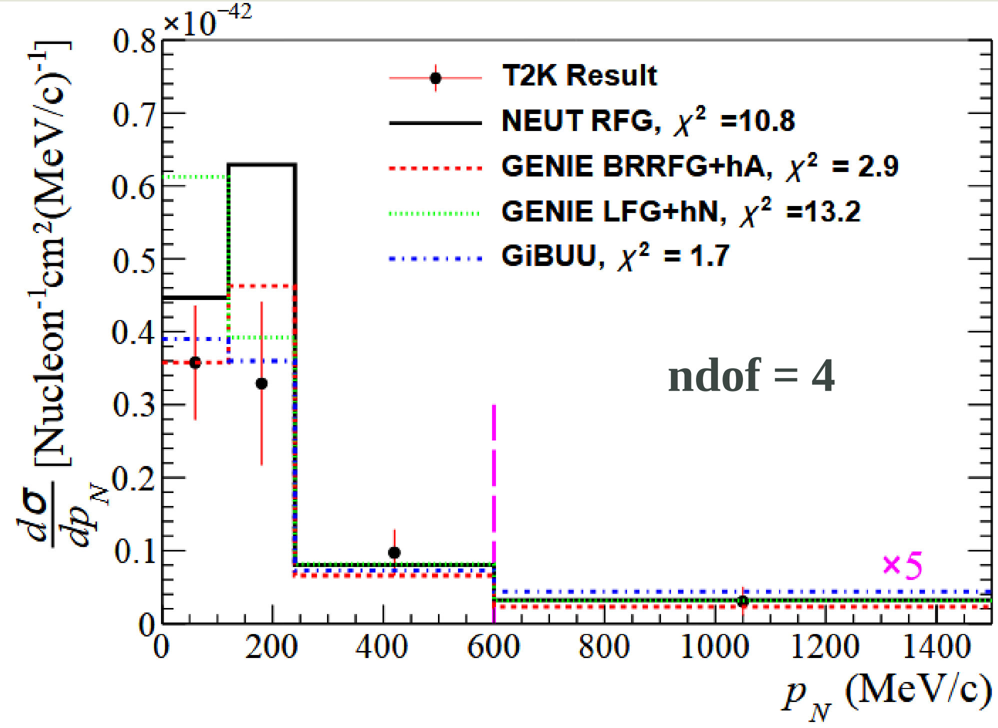
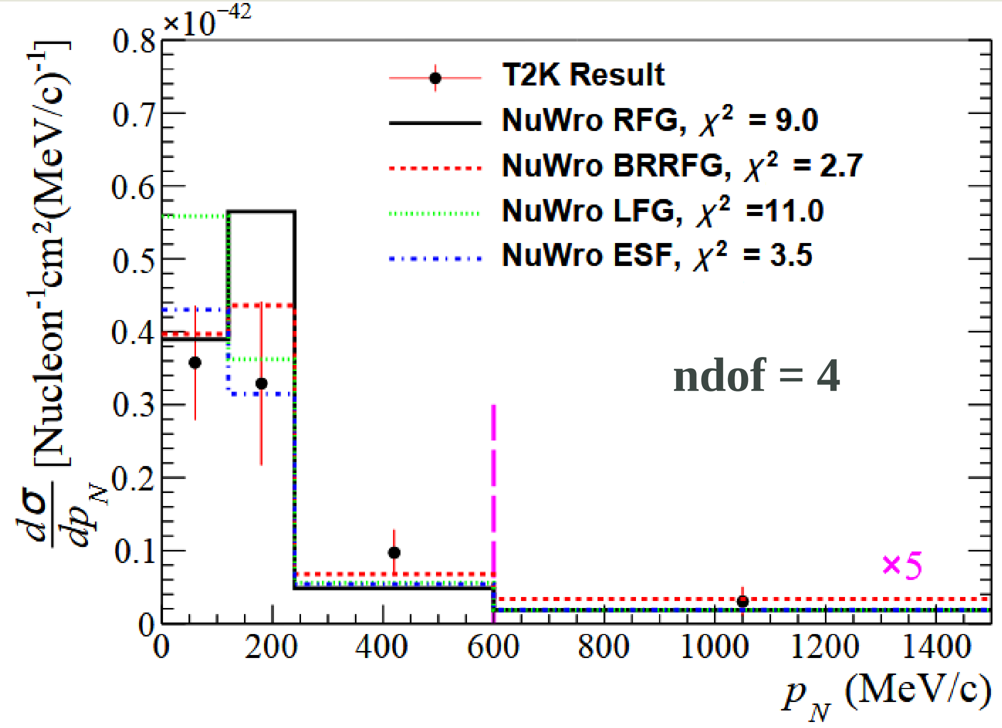



- RFG and LFG models strongly disfavored at small $p_N$
- Over-prediction in the peak region for all models



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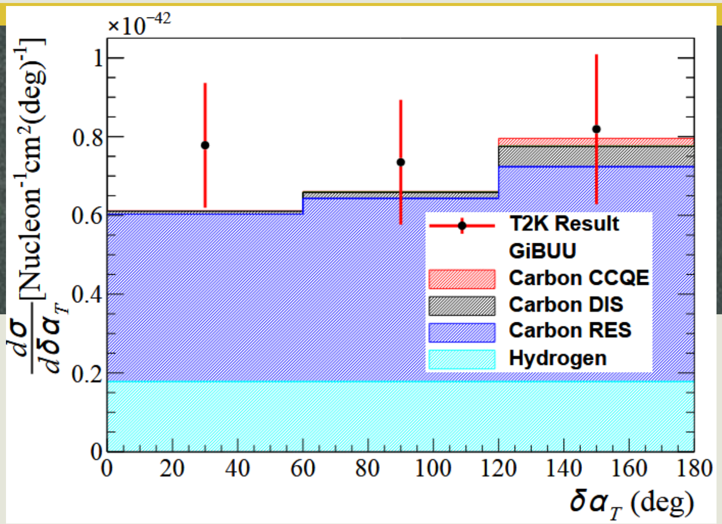
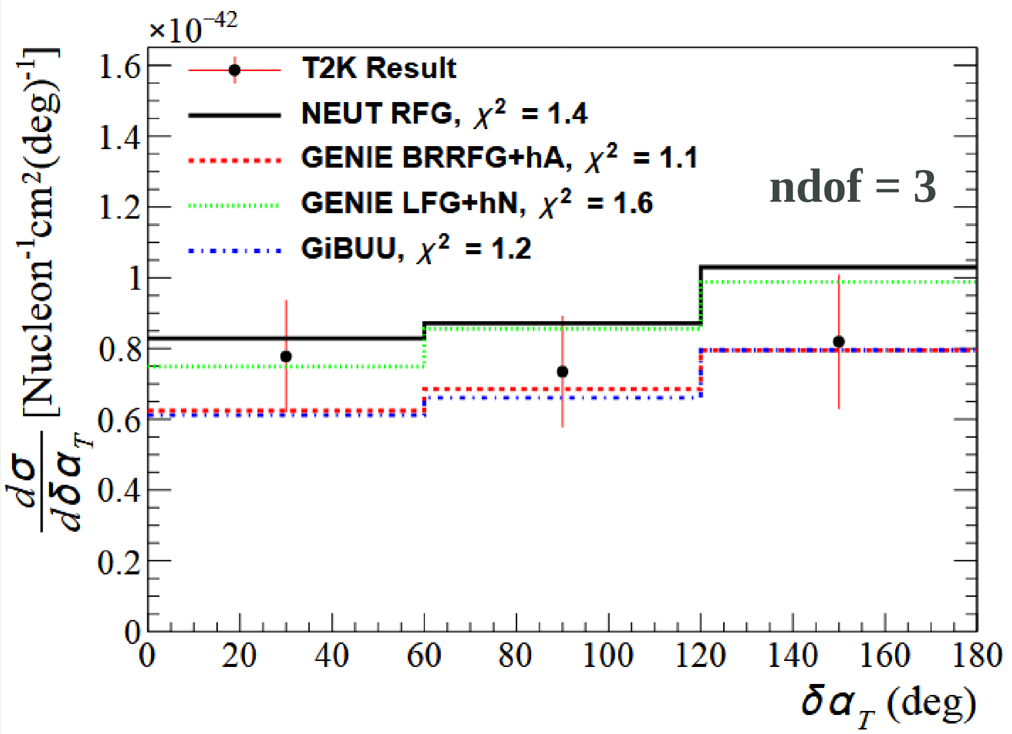
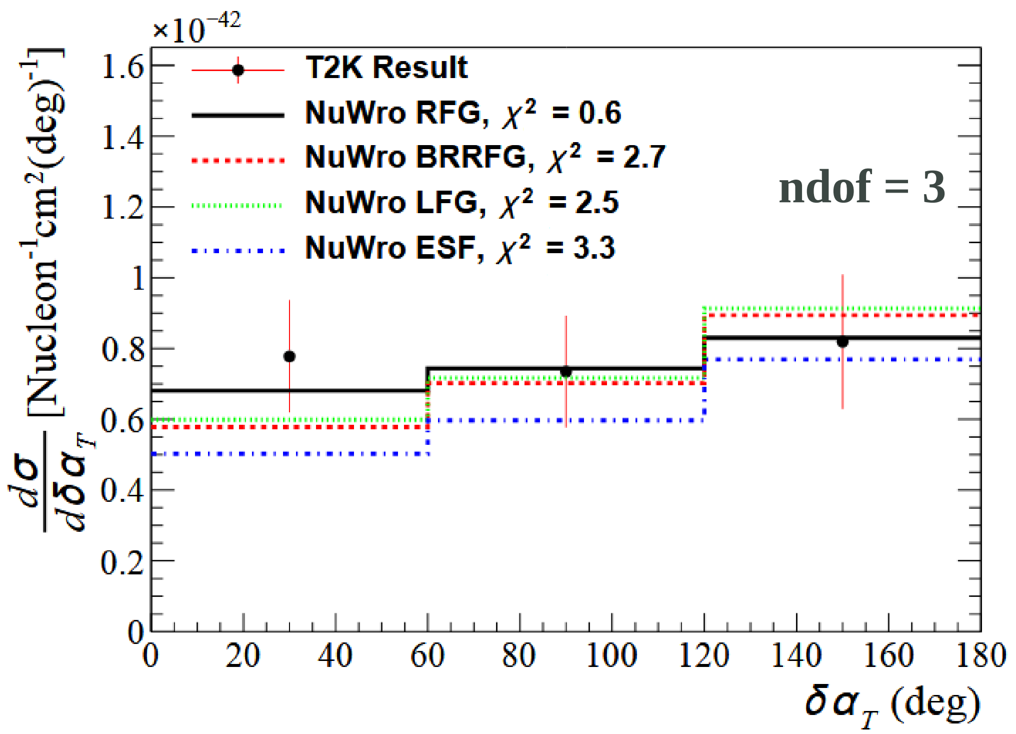


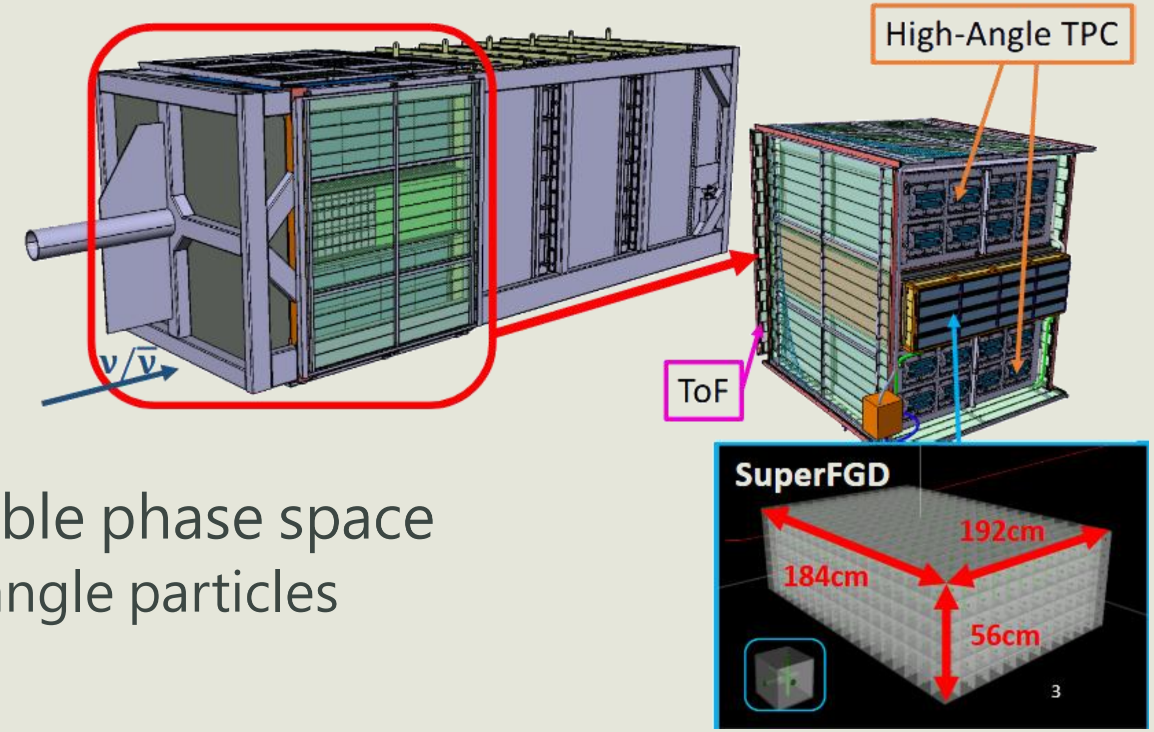

- Curvature strongly dependent on FSI
- Current phase space restrictions limit our sensitivity



# Summary

- TKI provides a novel way to constrain nuclear effects in neutrino interactions such as initial nuclear state and FSI
- First measurement of TKI in CC1$\pi^+$ interaction
  - simple Fermi gas models poorly describe initial nuclear states
  - sensitivity in FSI is limited by tight phase space restrictions
- Coming ND280-upgrade expands the measurable phase space
  - SFGD and high-angle TPC for low energy/high angle particles
  - Isolate interactions on hydrogen



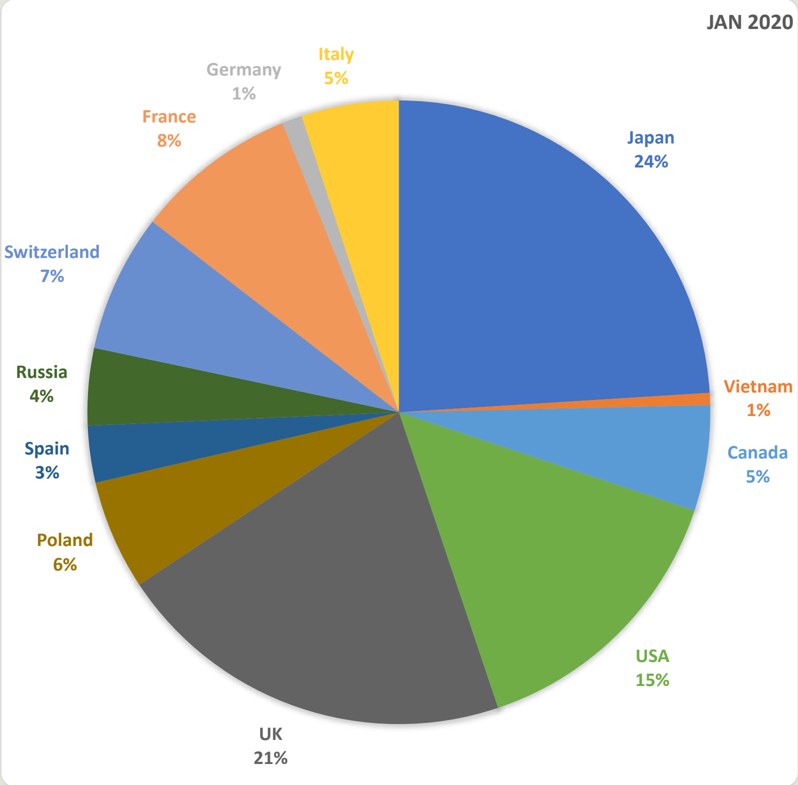
# The T2K Collaboration (2020)

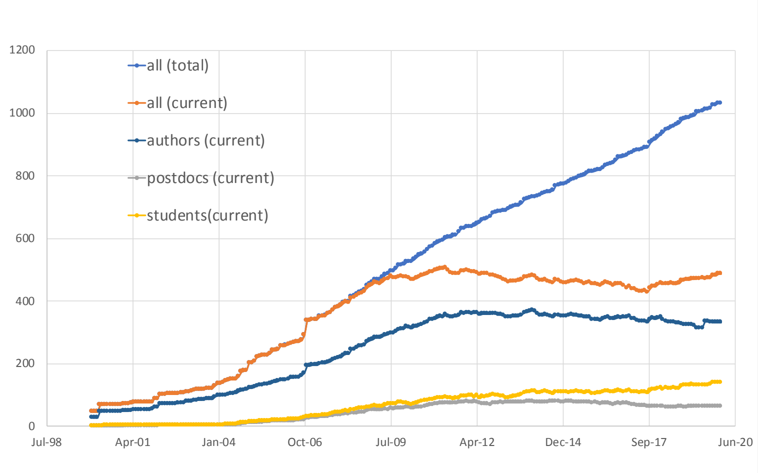
~500 members, 69 Institutes, 12 countries

| 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

# Unregularized binned likelihood fit

Preprint: arXiv:2102.03346

- Minimizing the negative log-likelihood ( $\chi^2$ ):

$$\chi^2 = -2\log(L) = -2\log(L_{\text{stat}}) - 2\log(L_{\text{syst}})$$

- Proper handle of finite MC statistics with Barlow-Beeston method*

$$\chi^2_{\text{stat}} = -2\log(L_{\text{stat}}) = \sum_{j}^{\text{reco. bins}} 2\left(\beta_j N_j^{\text{MC}} - N_j^{\text{obs}} + N_j^{\text{obs}} \log\frac{N_j^{\text{obs}}}{\beta_j N_j^{\text{MC}}} + \frac{(\beta_j - 1)^2}{2\sigma_j^2}\right)$$

- Barlow-Beeston scaling parameter $\beta_j \to 0$ when relative variance $\sigma_j \to 0$

$$\beta_j = \frac{1}{2}\left(-(N_j^{\text{MC}}\sigma_j^2 - 1) + \sqrt{(N_j^{\text{MC}}\sigma_j^2 - 1)^2 + 4N_j^{\text{obs}}\sigma_j^2}\right)$$

* Proceedings of the PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding, 10.5170/CERN-2011-006

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- Systematic penalty term from prior knowledge on nuisance parameters

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

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- Effects of fit parameters propagated to reconstructed bin $j$ in signal and control samples

$$N_j^{\mathrm{MC}} = \sum_i^{\mathrm{true\,bins}} (c_i w_{i,j}^{\mathrm{sig}} N_{i,j}^{\mathrm{sig}} + w_{i,j}^{\mathrm{bkg}} N_{i,j}^{\mathrm{bkg}})$$

Signal template parameters without prior constraints (thus unregularized)

No. of signal and background events in the truth bin $i$, contributing to the reconstructed bin $j$

Event weights from systematic variations

# Cross-section extraction and error propagation

Preprint: arXiv:2102.03346

- Generate a large number of sets of variations of parameters from post-fit covariance, re-evaluate every variable for each set, calculate cross section and construct uncertainties

$$\frac{d\sigma}{dx_i} = \frac{N_i^{\text{signal}}}{\varepsilon_{\text{i}} \Phi N^{\text{FV}}_{\text{nucleons}} \Delta x_i}$$

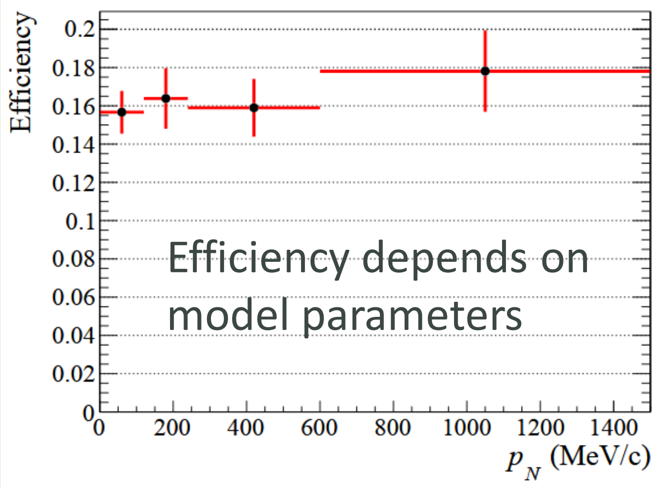
Number of signal events

Selection efficiency

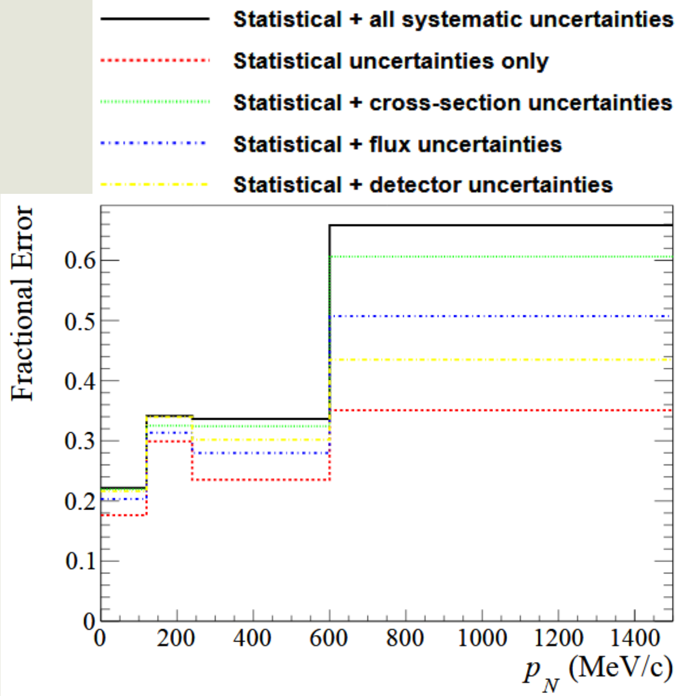
Flux integral, ~5% uncertainty from post-fit flux parameters

Number of target nucleons

Bin width

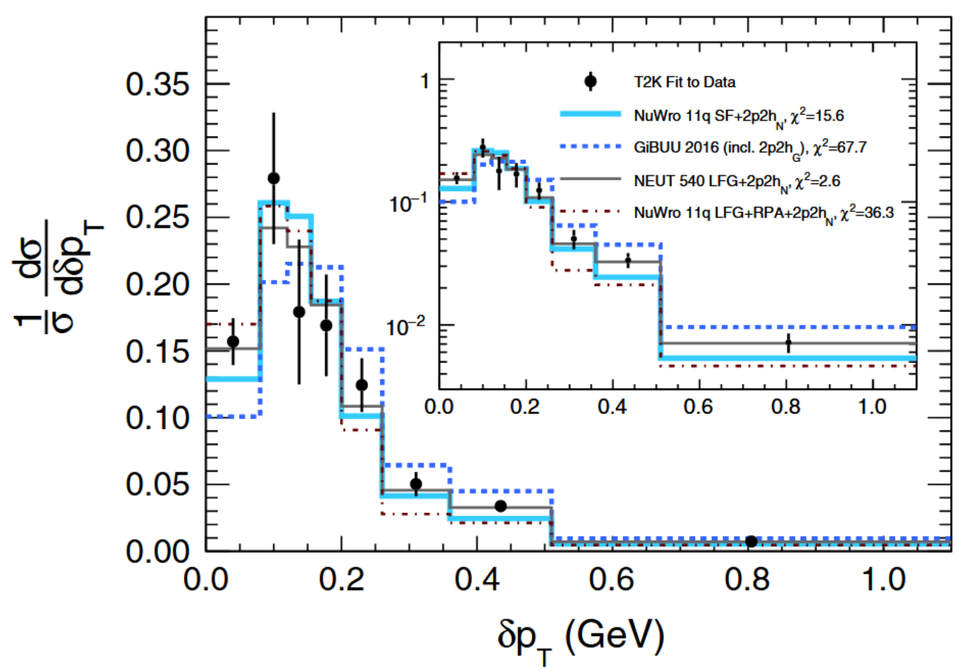



Efficiency depends on model parameters



# Comparison to previous TKI measurements

- CC0π in T2K (PhysRevD.98.032003)
- Much worse agreement in $\delta p_T (\sim p_N)$ for GiBUU, problem in nuclear ground state modelling? 2p2h strength could be one reason (Phys. Rev. C 98, 045502 (2018))




- CC$\pi^0$ in MinvervA (PhysRevD.102.072007)
- More curved $\delta\alpha_T$ due to difference in phase space restrictions and neutrino energy