Exploring nuclear effects with transverse imbalances

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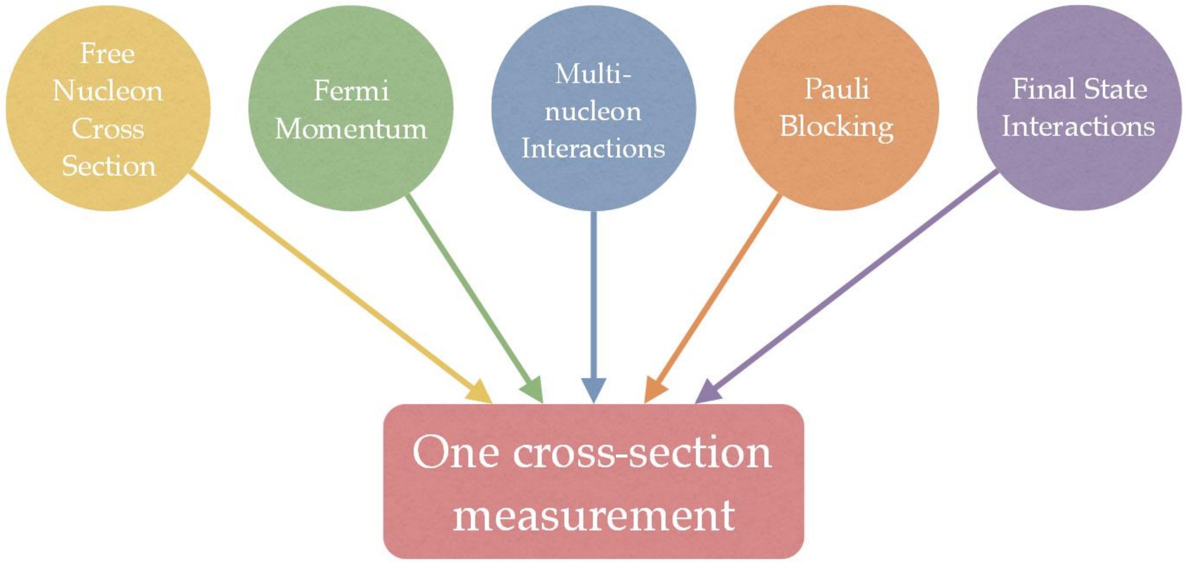
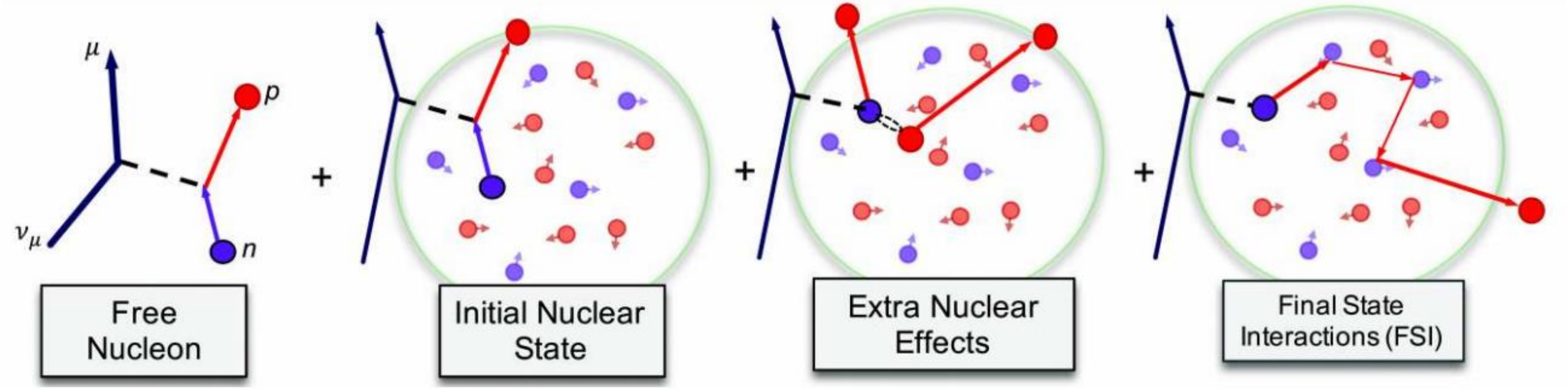
Overview

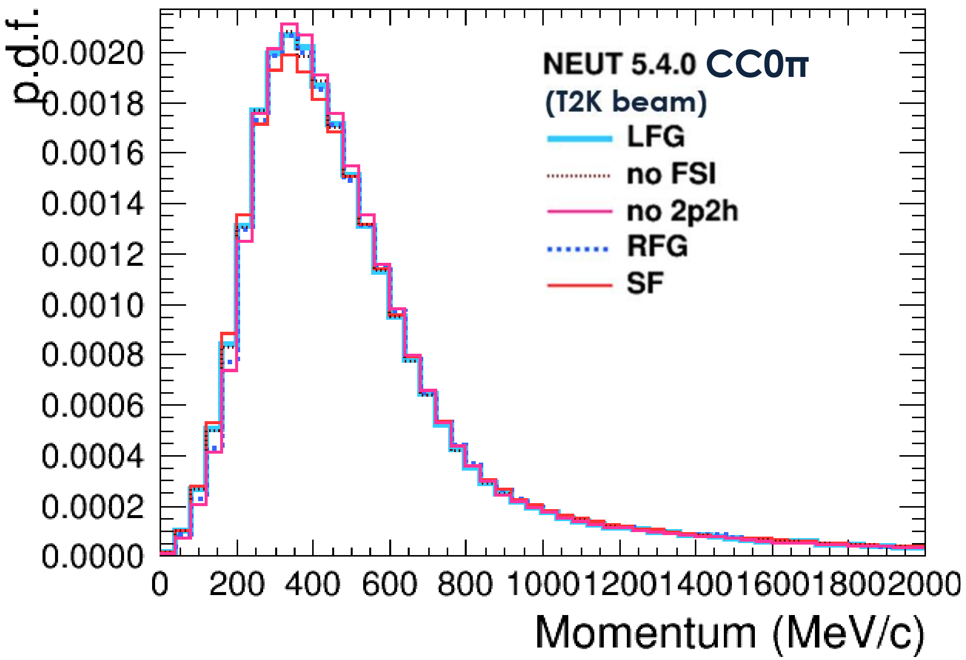
- What are transverse kinematics and why should we care?
- Current measurements: T2K and MINERvA
- What can we learn from these?
- The future of transverse measurements

What we want to learn about



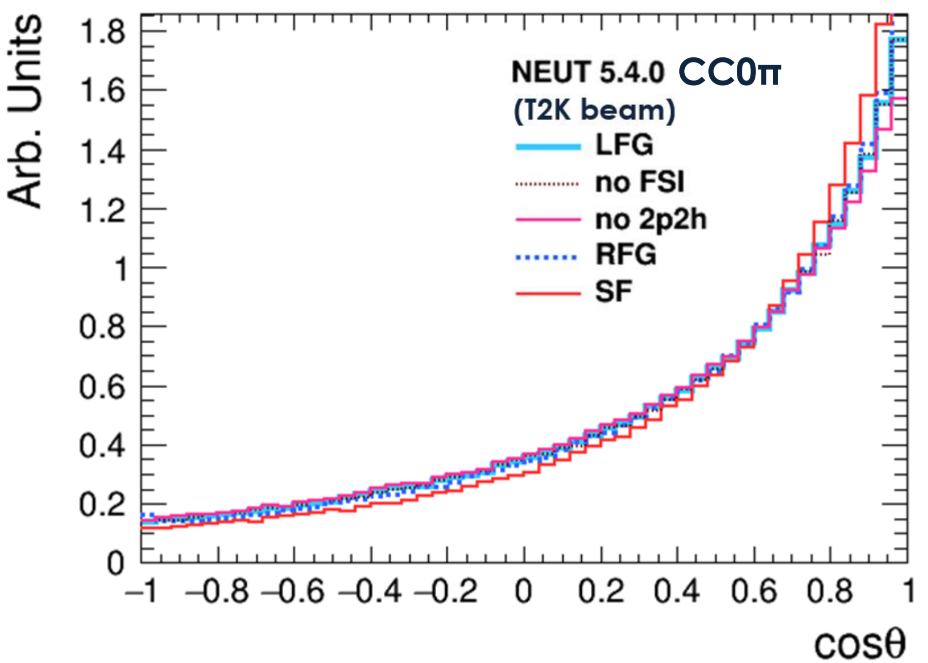


Which observables?

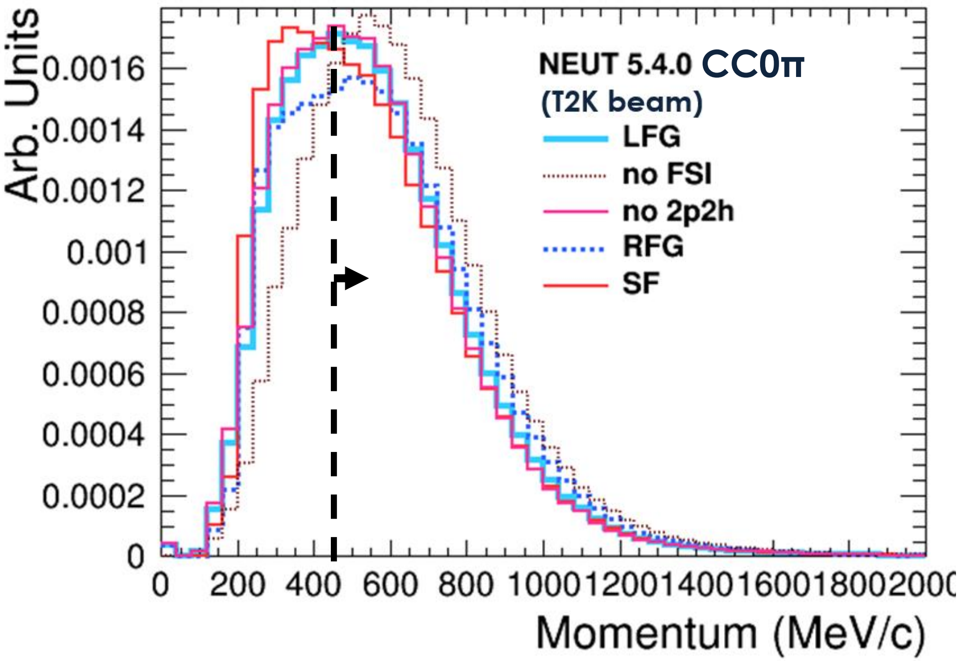


Muon kinematics?

Model separation doesn't look great …

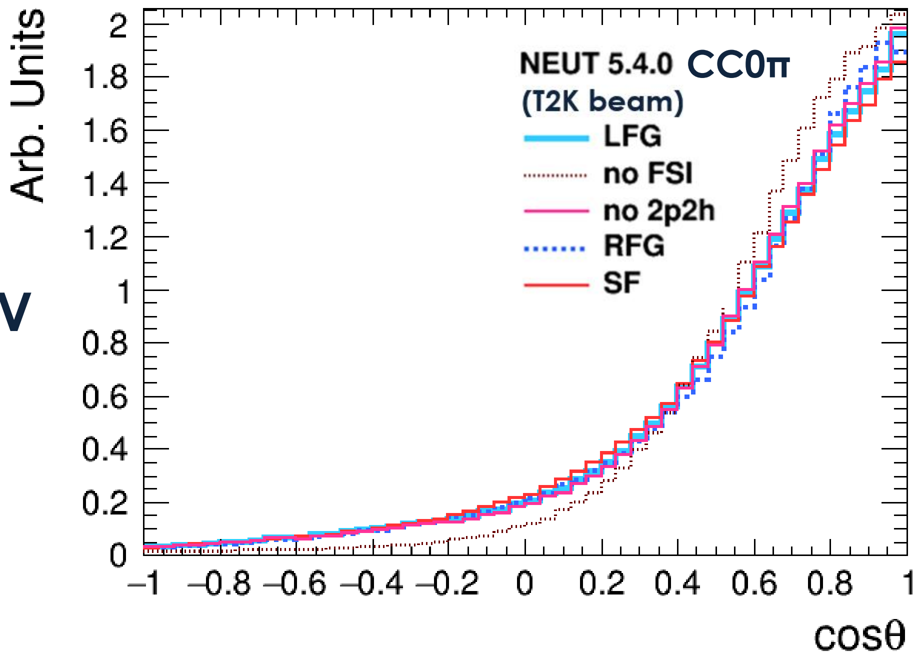


Which observables?

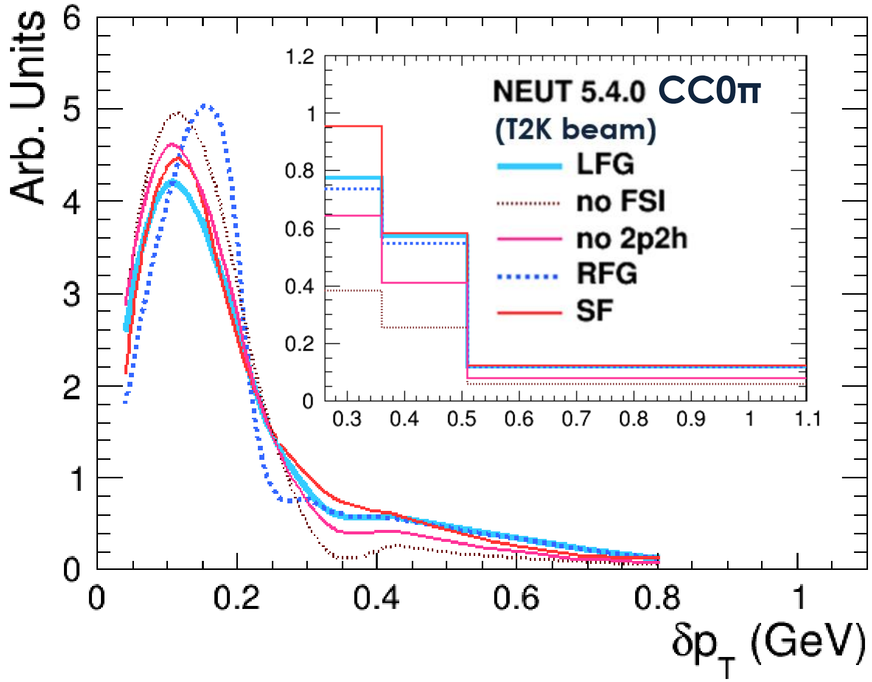


What about proton kinematics?

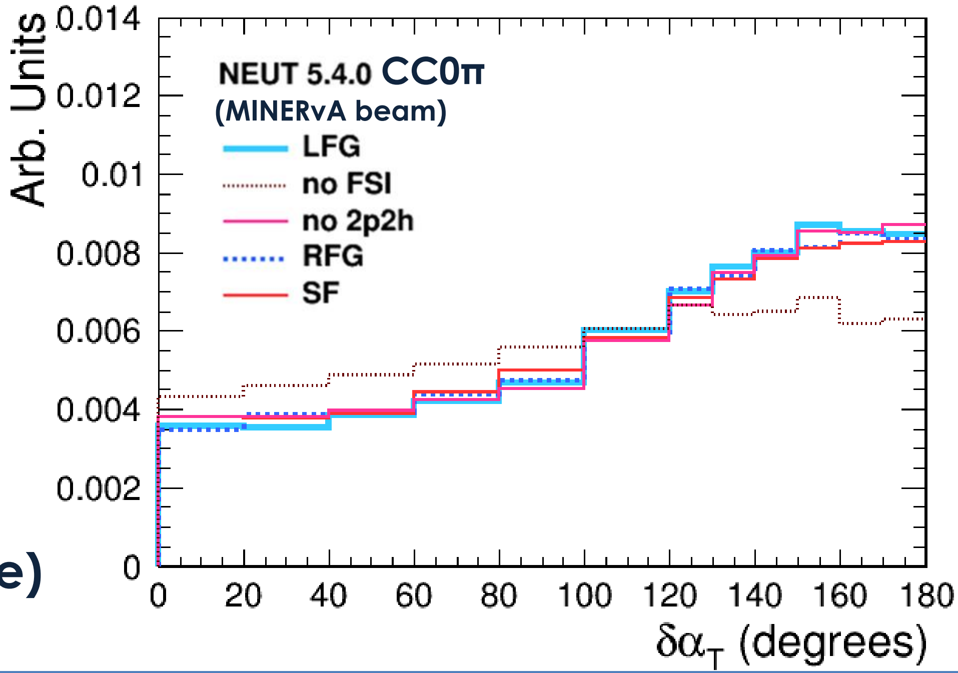
Still not so good above the 450 MeV that detectors are sensitive …



Which observables?



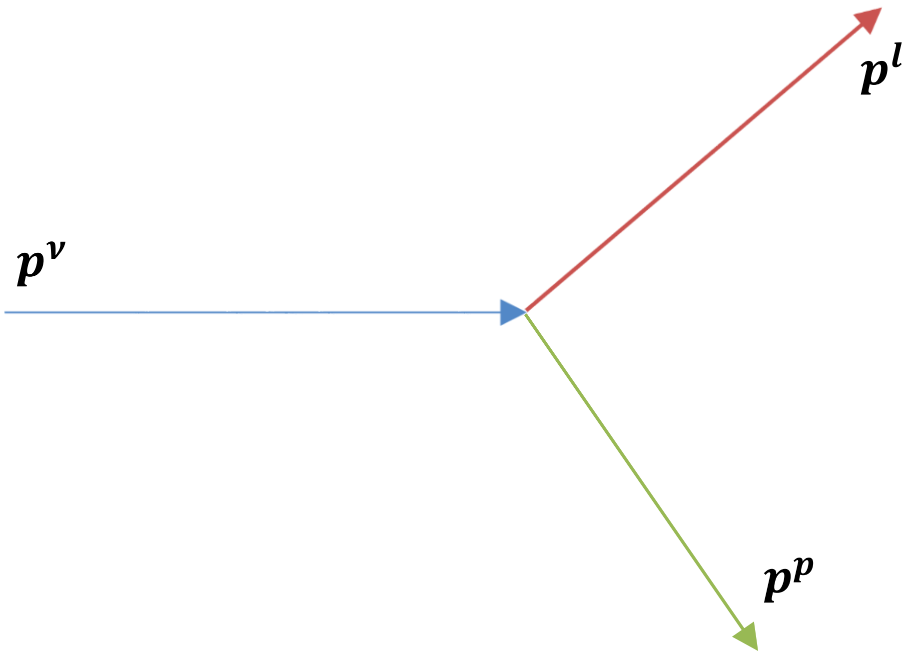
How about a combination of both?

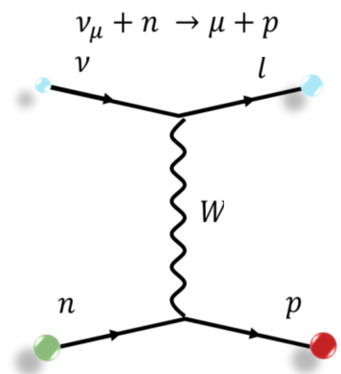


Looking much more interesting!

(And here we've limited ourselves to a kinematic region that detectors cans see)

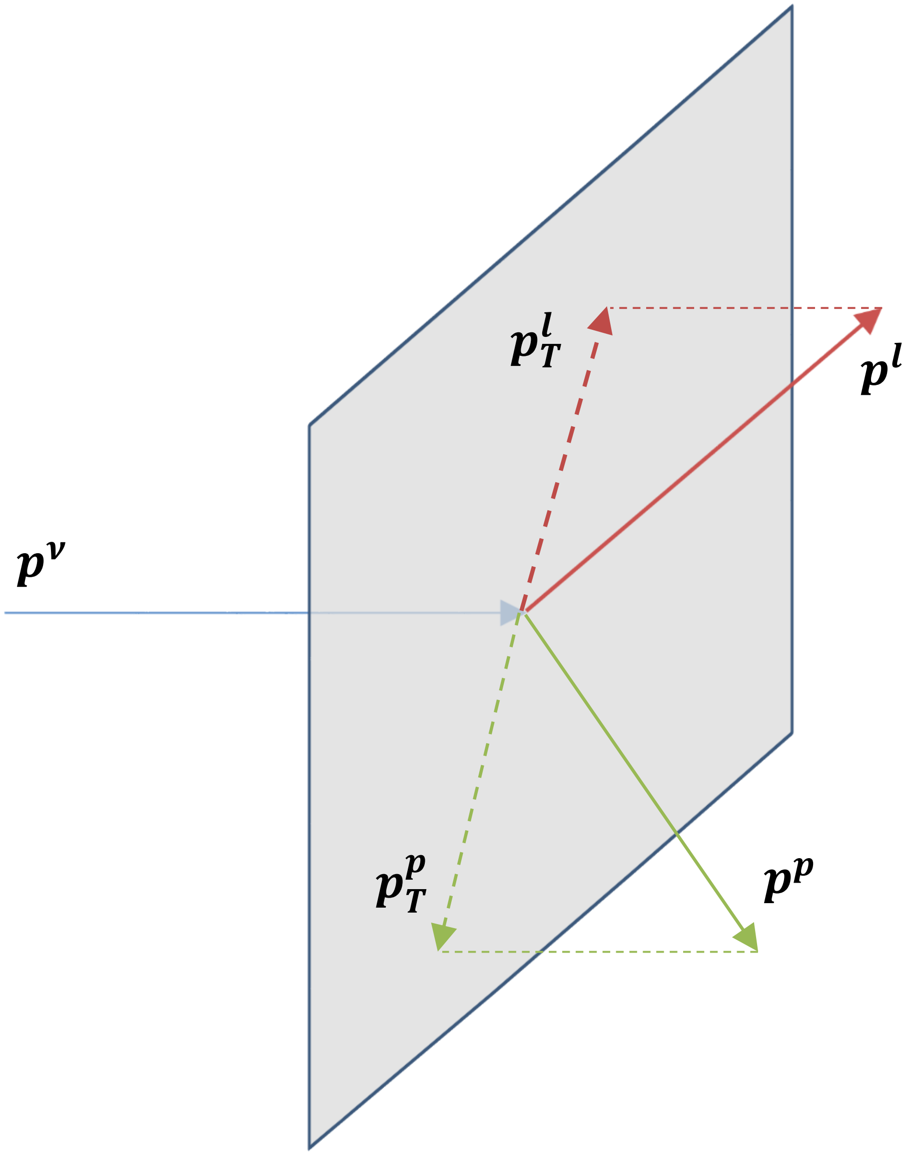
Single Transverse Variables

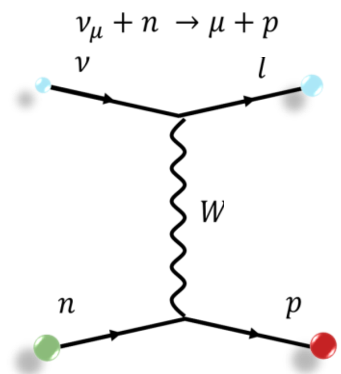




No nuclear Effects

Single Transverse Variables

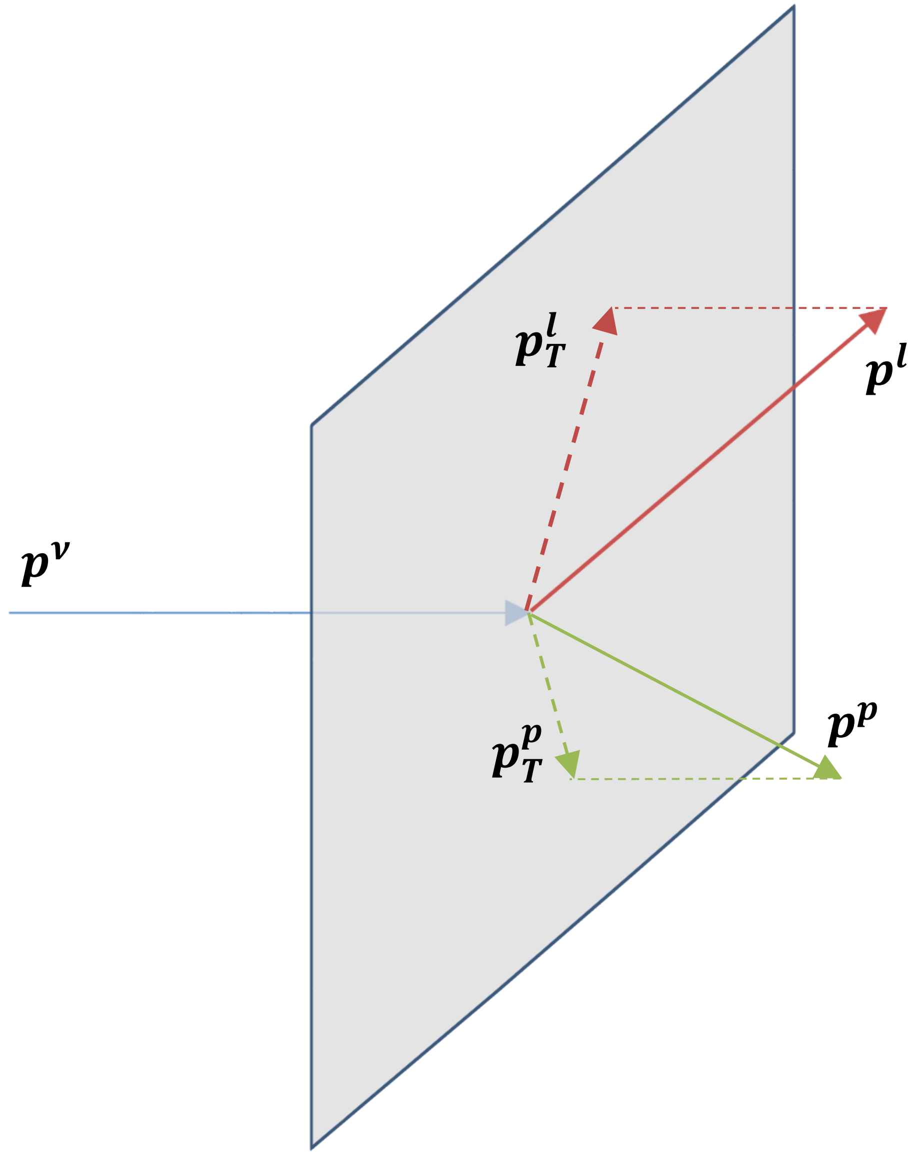




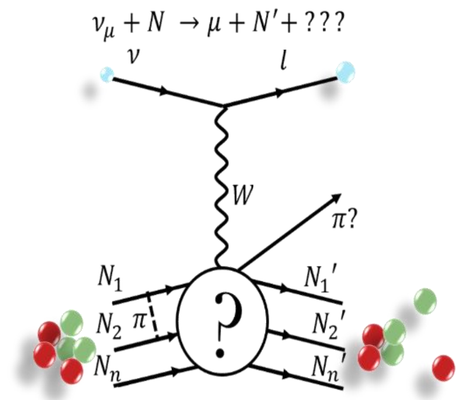
No nuclear Effects

$$p_T^l = -p_T^p$$

Single Transverse Variables



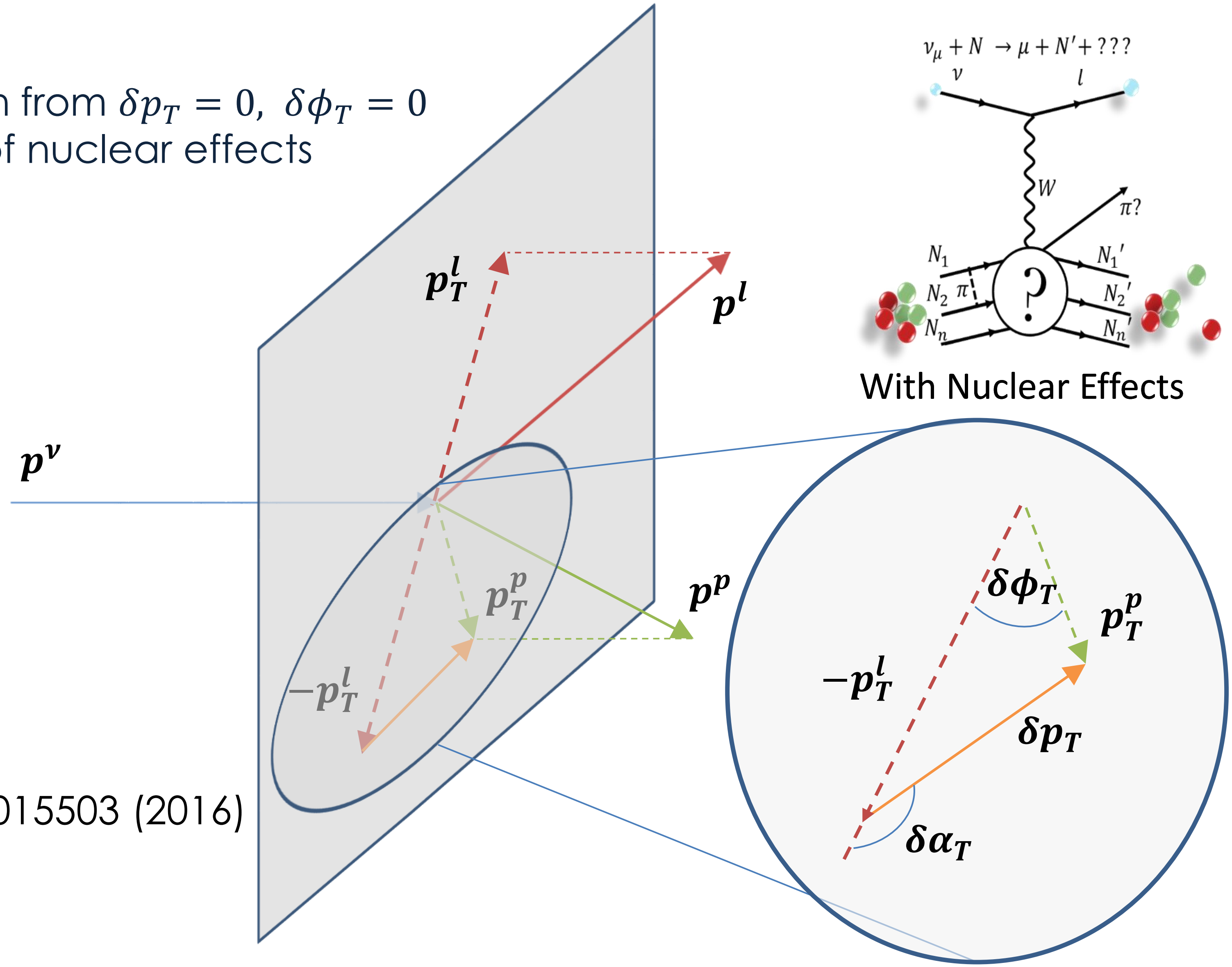
$$p_T^l \neq -p_T^p$$



With Nuclear Effects

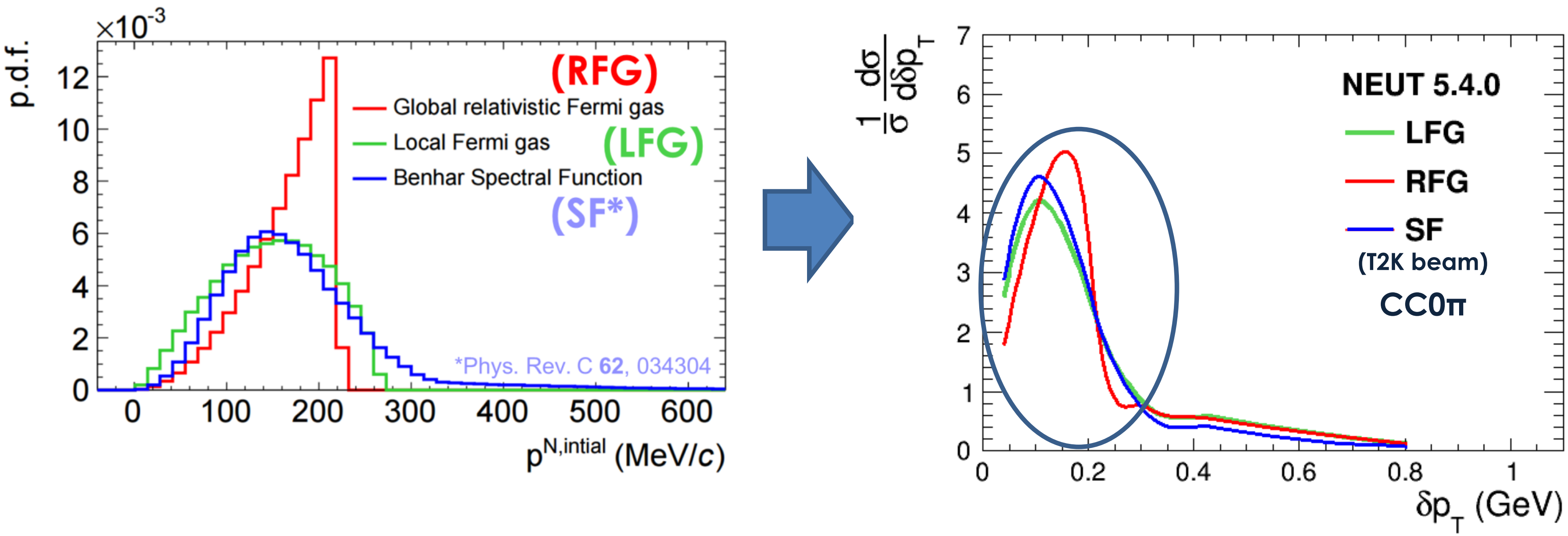
Single Transverse Variables

- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects



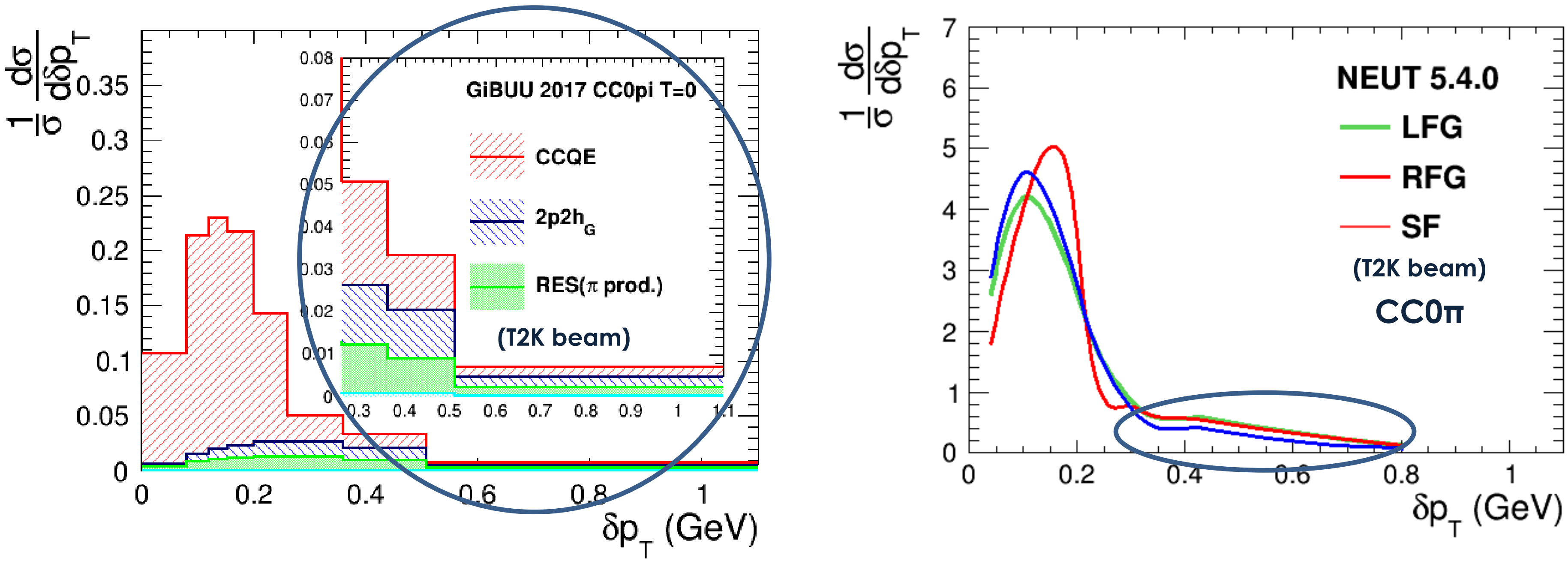
Phys. Rev. C **94**, 015503 (2016)

STV model discrimination - δp_T



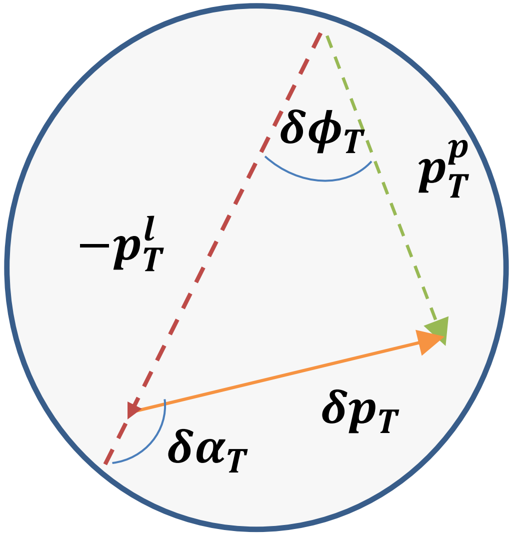
- In the absence of other nuclear effects, δp_T *is* the transverse projection of the Fermi motion.
- Since this motion is isotropic, $\delta p_T \rightarrow$ Fermi motion

STV model discrimination - δp_T

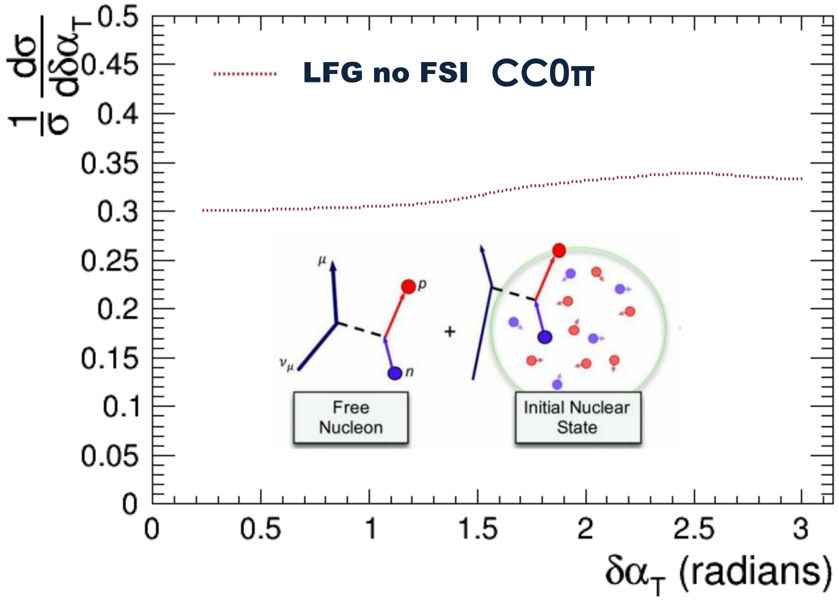


- In the absence of other nuclear effects, δp_T *is* the transverse projection of the Fermi motion.
- Since this motion is isotropic, $\delta p_T \rightarrow$ Fermi motion
- Cross section beyond the Fermi momentum must come from physics beyond RFG → 2p2h, FSI, SRCs …

STV model discrimination - $\delta\alpha_T$

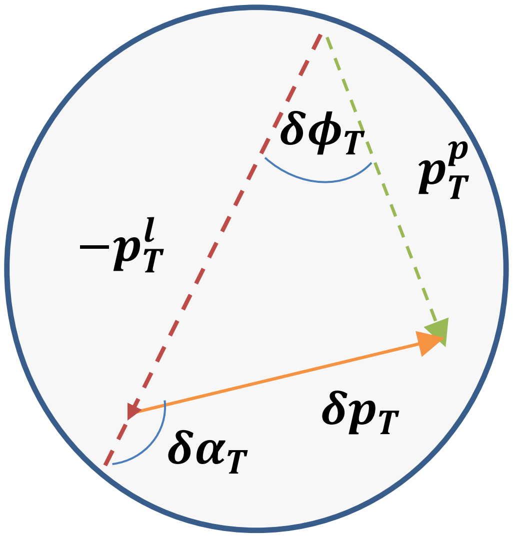


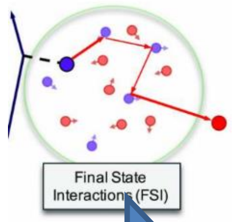
Consider imbalance from only Fermi motion



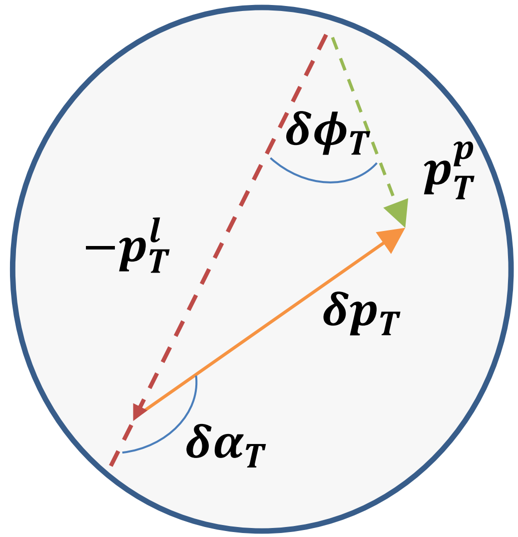
Fermi motion is isotropic so no preferred $\delta\alpha_T$ direction

STV model discrimination - $\delta\alpha_T$

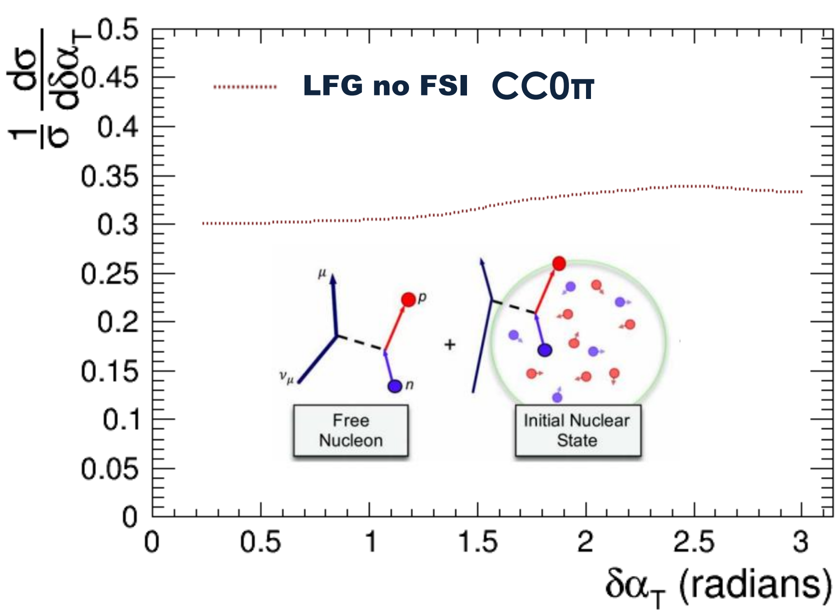


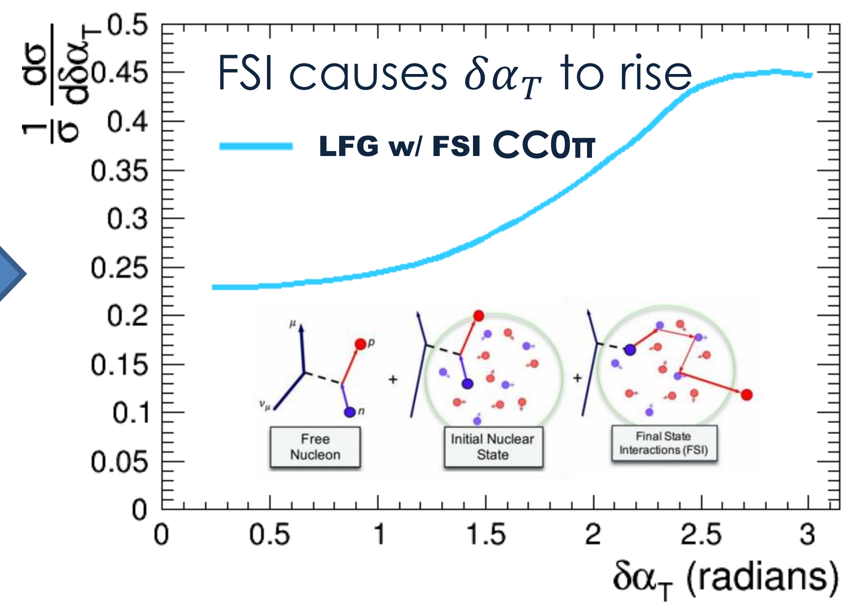


Deceleration of proton from FSI

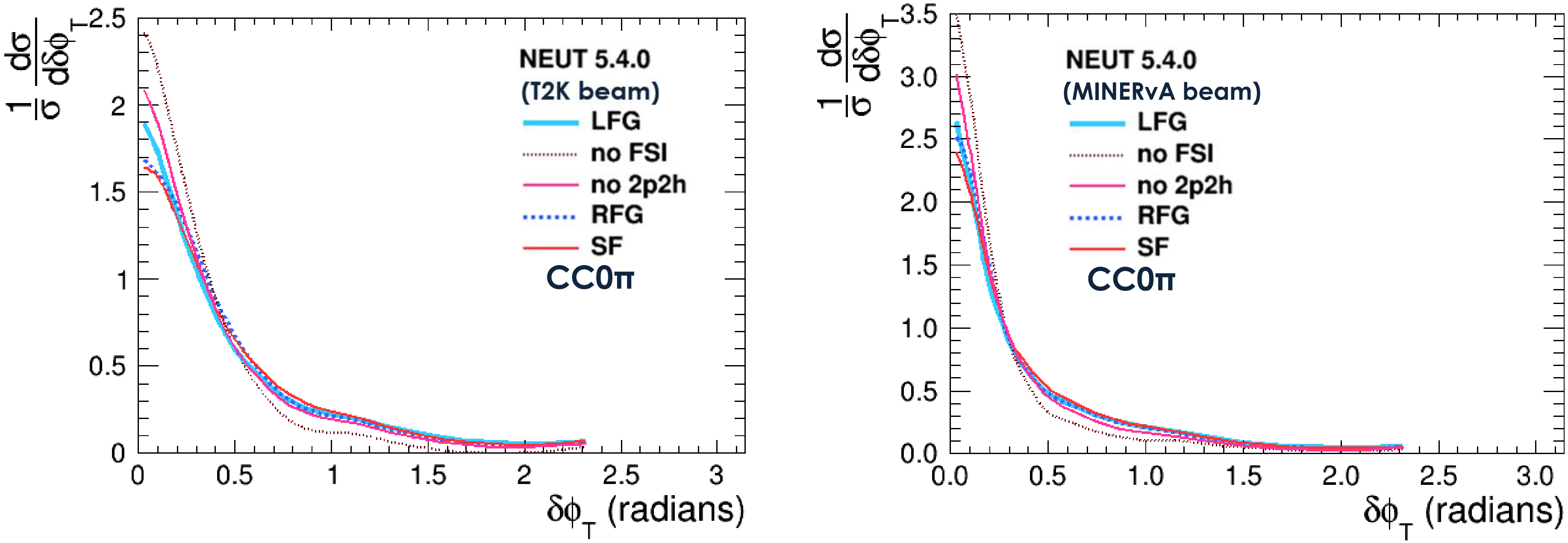


= larger $\delta\alpha_T$





STV model discrimination - $\delta\phi_T$



- A more general measure of transverse imbalance, more 2p2h and FSI give a larger contribution in the tail
- Not quite as powerful as δp_T and $\delta\alpha_T$
- But only requires outgoing particle angles and not their momentum → **much better detector resolution on $\delta\phi_T$**

Overview

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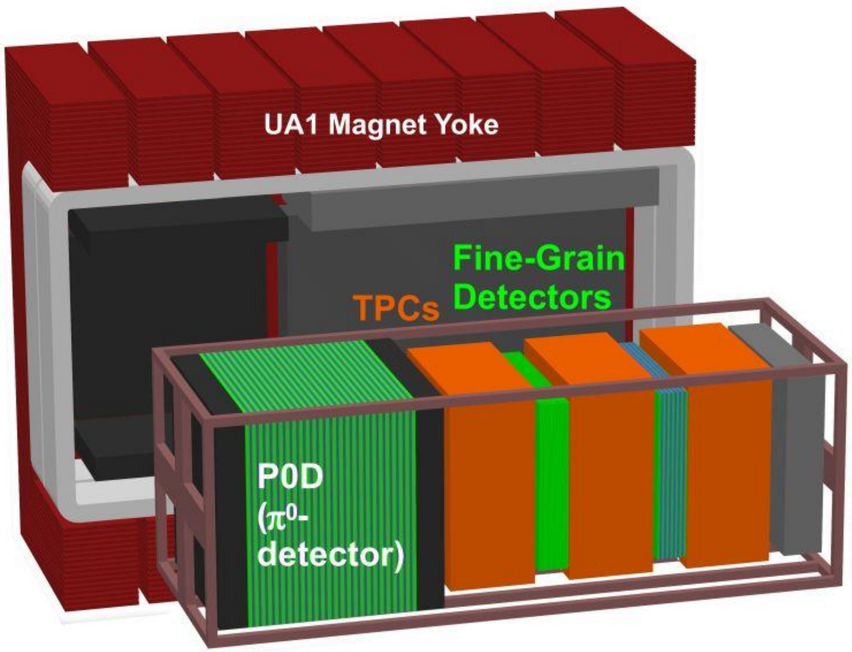
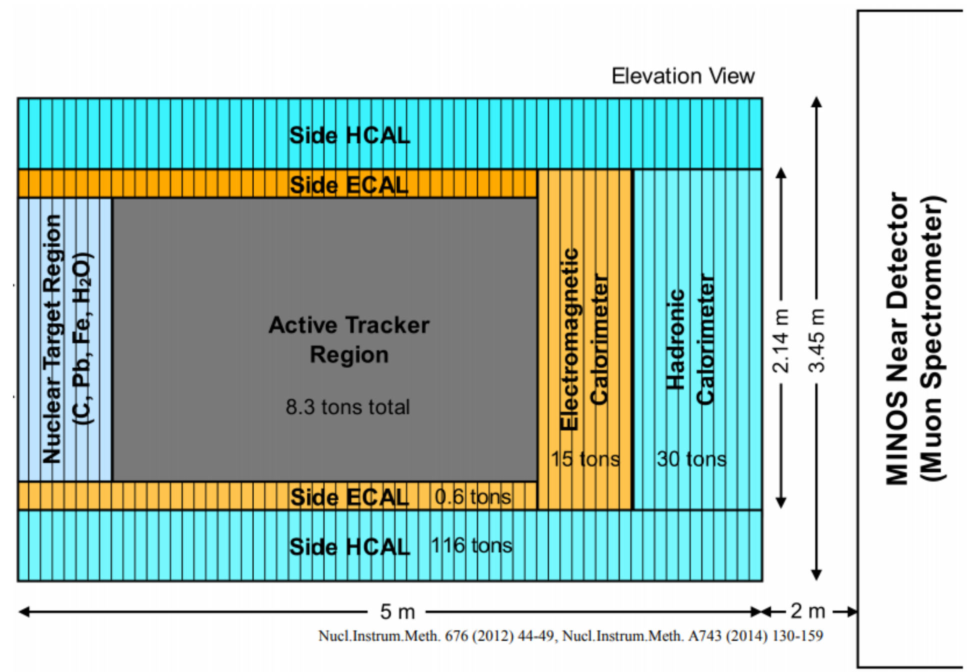
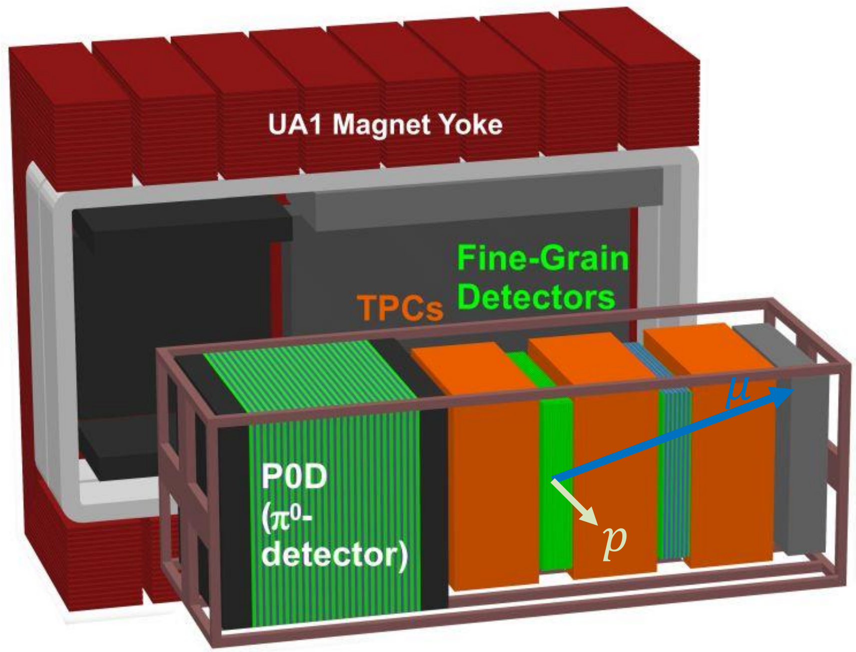
The players

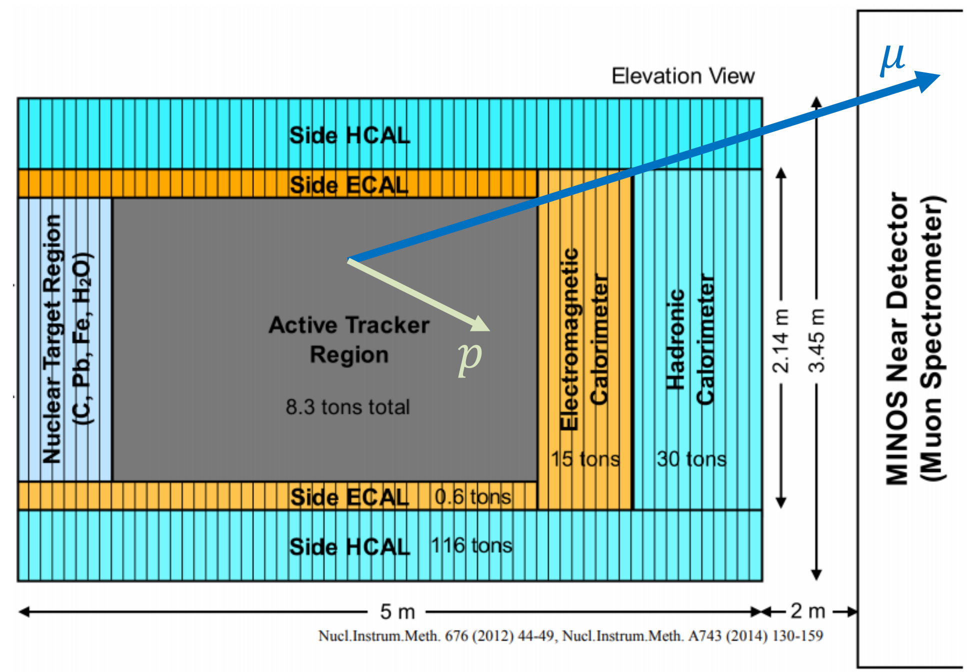




Scintillator tracker

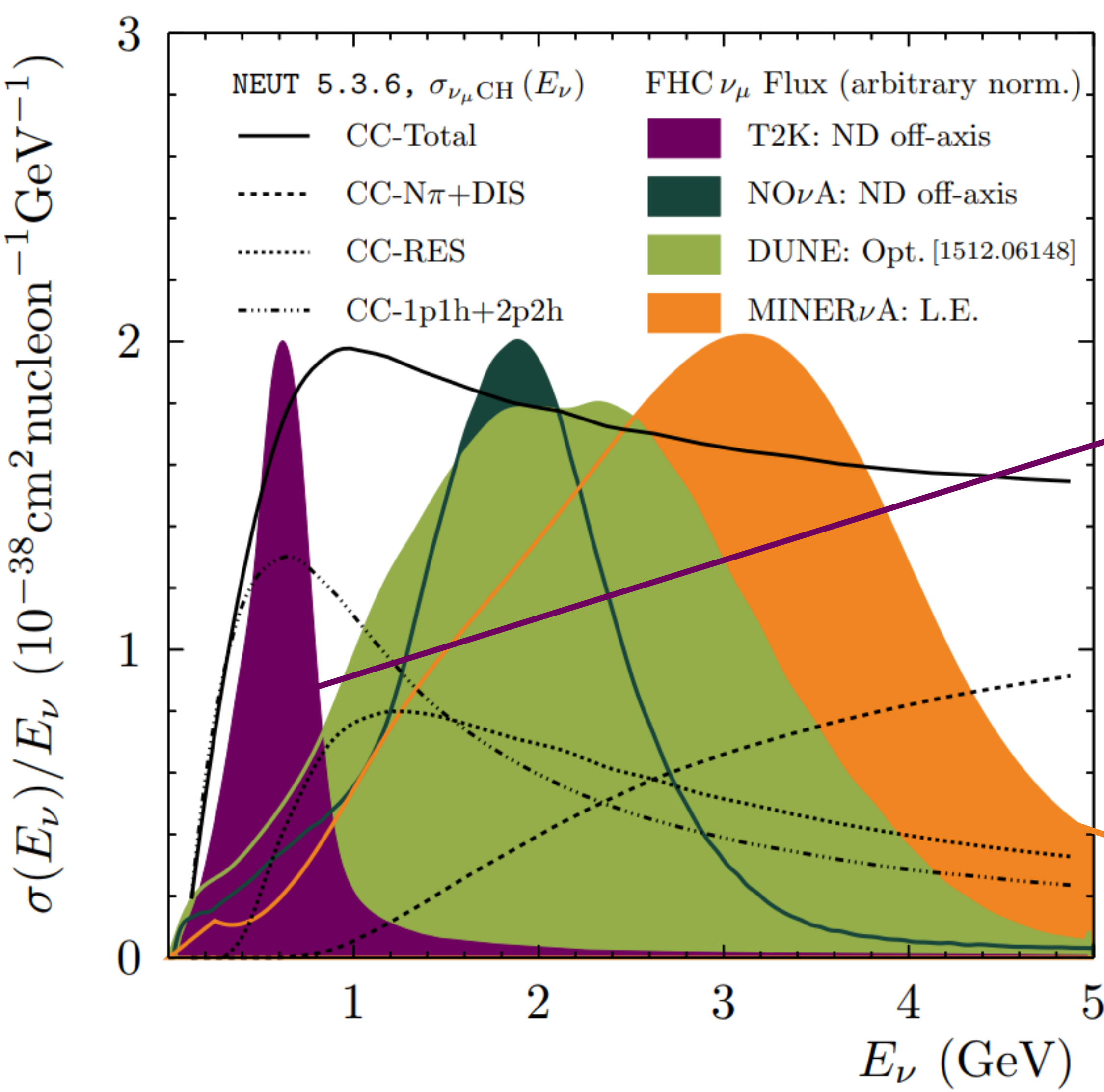
Signal: $\nu_\mu CC0\pi + Np\ (N > 0)$





Scintillator tracker

The fluxes



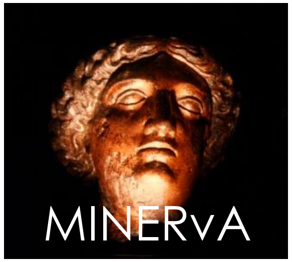
$E_\nu \sim 1\ GeV$

$E_\nu \sim 3\ GeV$

Kinematic constraints

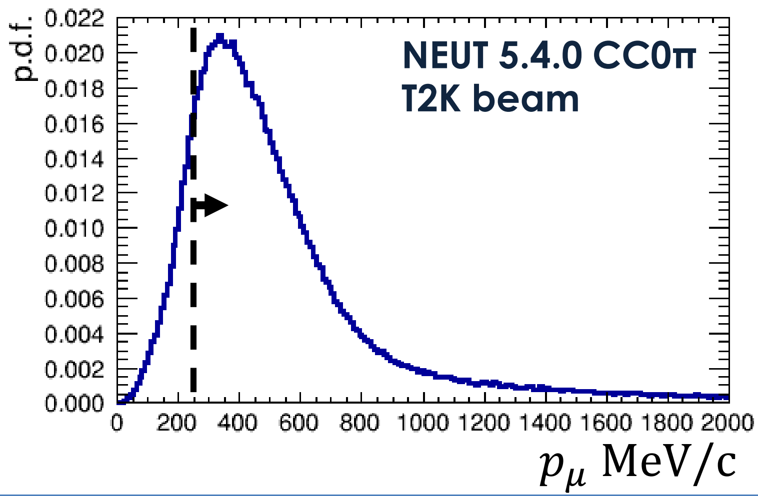
arXiv: 1802.05078

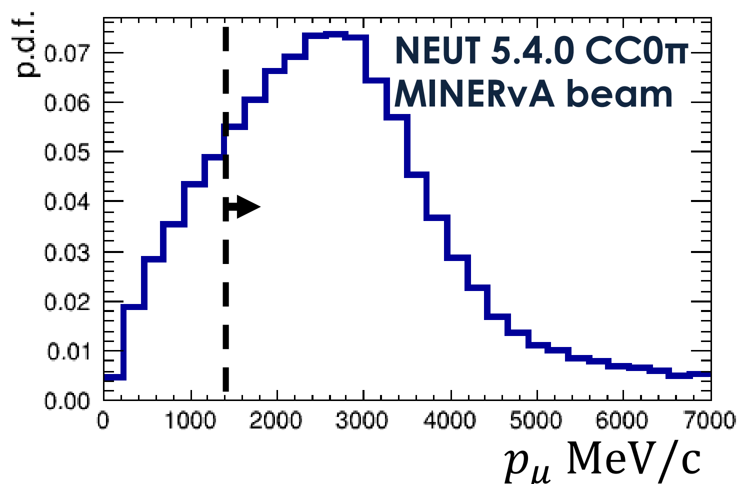
$p_\mu > 250\ MeV/c$



arXiv: 1805.05486

$1.5 < p_\mu < 10\ GeV/c$





Kinematic constraints

arXiv: 1802.05078

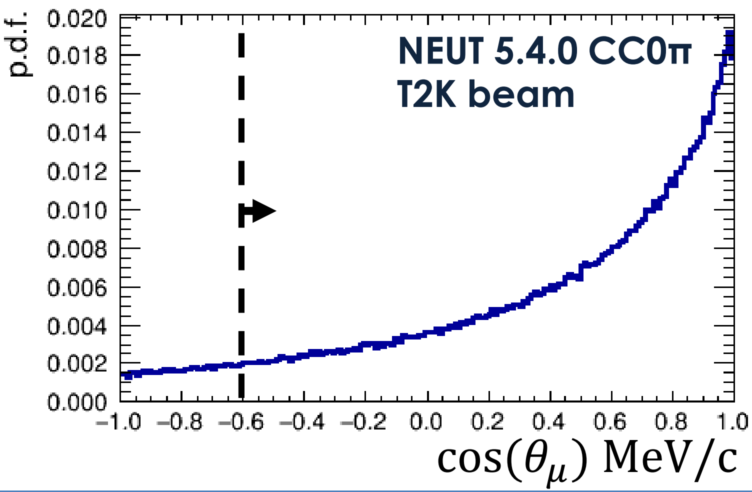
$p_\mu > 250\ MeV/c$

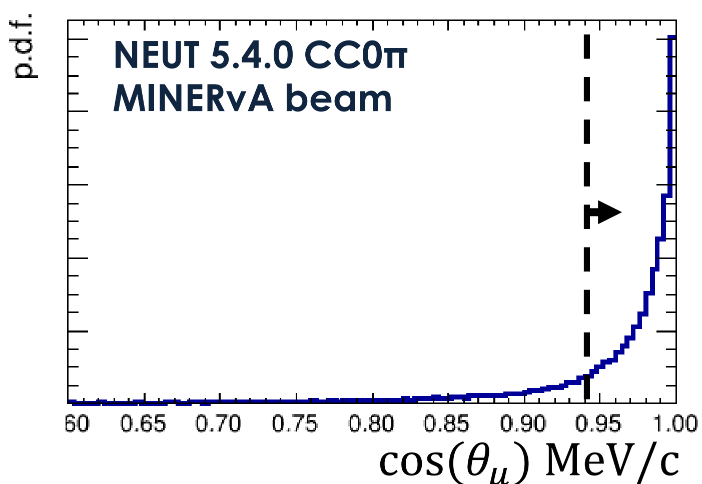
$\cos\theta_\mu > -0.6$

arXiv: 1805.05486

$1.5 < p_\mu < 10\ GeV/c$

$\theta_\mu < 20°$





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$p_\mu > 250\ MeV/c$

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$450 < p_p < 1000\ MeV/c$

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$1.5 < p_\mu < 10\ GeV/c$

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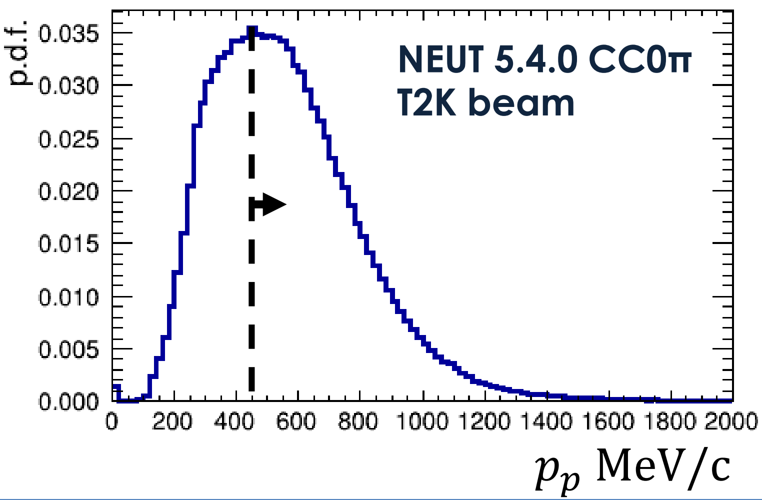
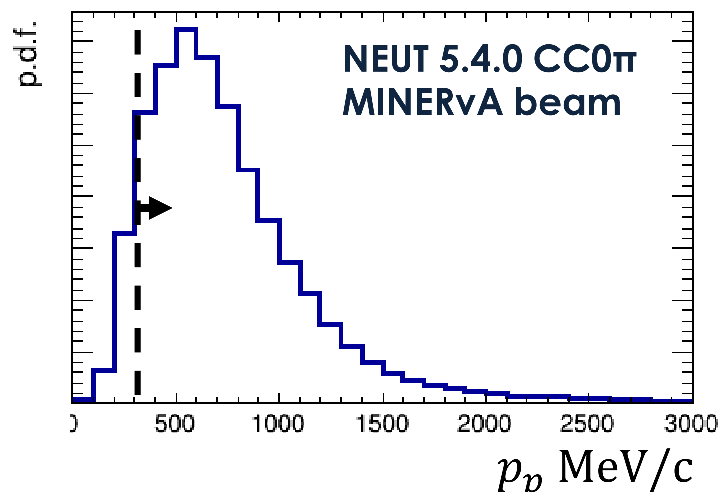
$450 < p_p < 1200\ MeV/c$





Kinematic constraints

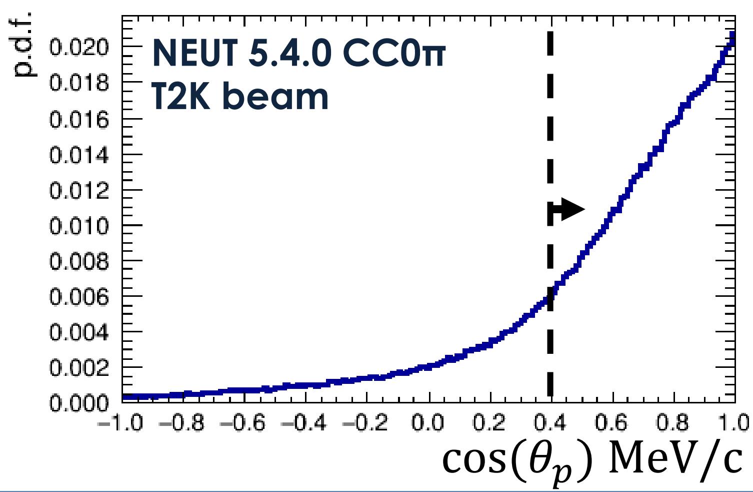
arXiv: 1802.05078

$p_\mu > 250\ MeV/c$

$\cos\theta_\mu > -0.6$

$450 < p_p < 1000\ MeV/c$

$\cos\theta_p > 0.4$



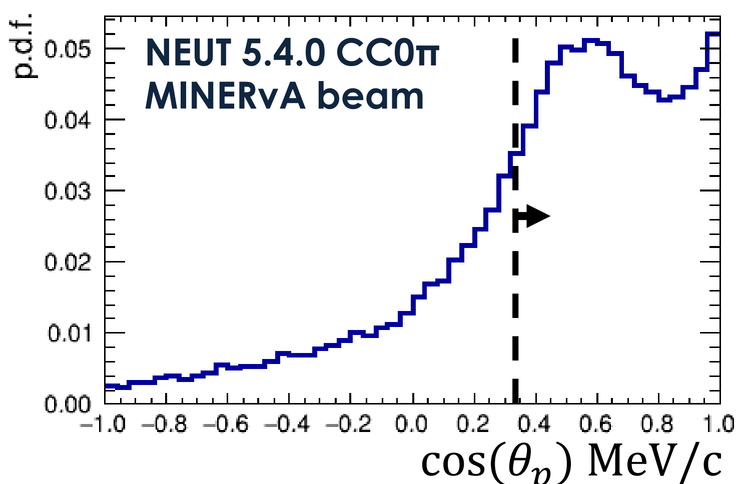
arXiv: 1805.05486

$1.5 < p_\mu < 10\ GeV/c$

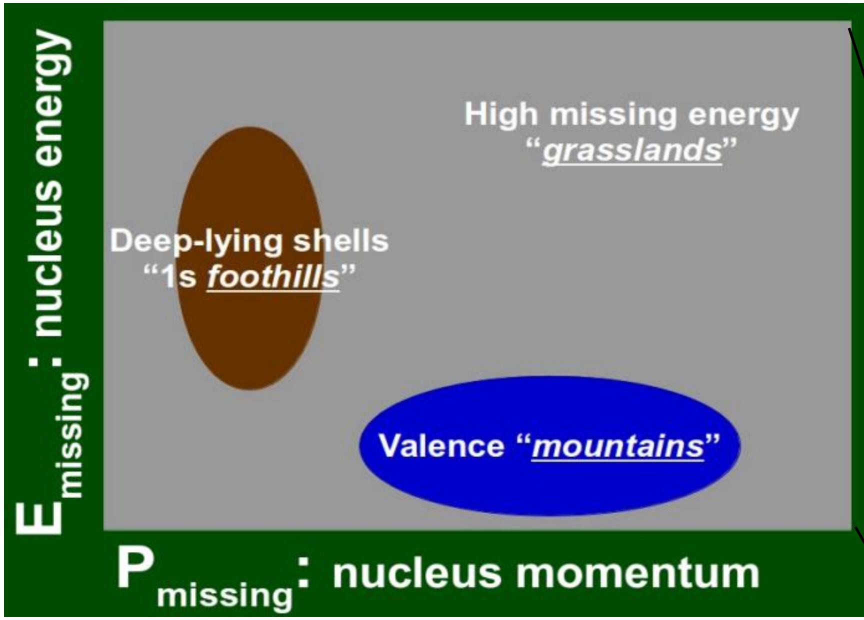
$\theta_\mu < 20°$

$450 < p_p < 1200\ MeV/c$

$\theta_p < 70°$

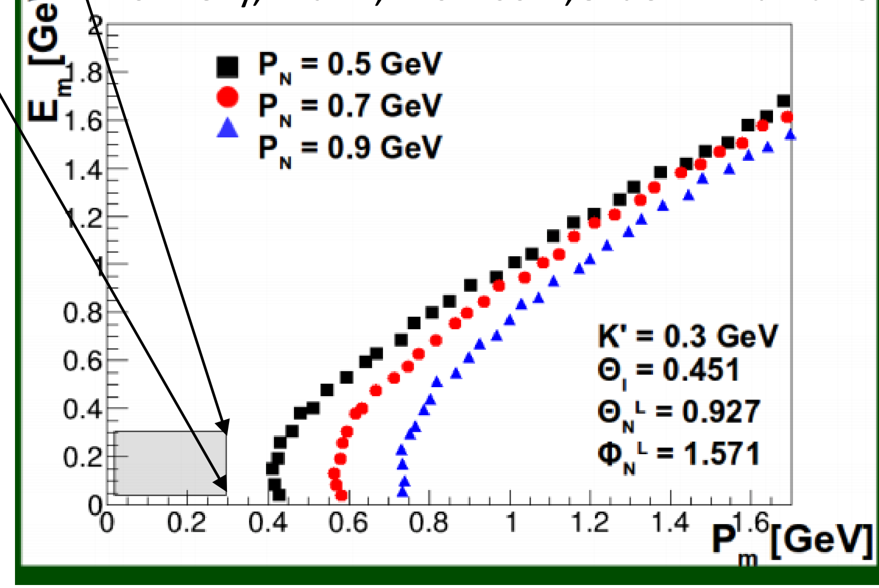


We may be way off the map!



We've been shown a "map" of where we can expect our models to work …

Donnelly, Mahn, Morrison ,Orden – Nuint 18



Overview

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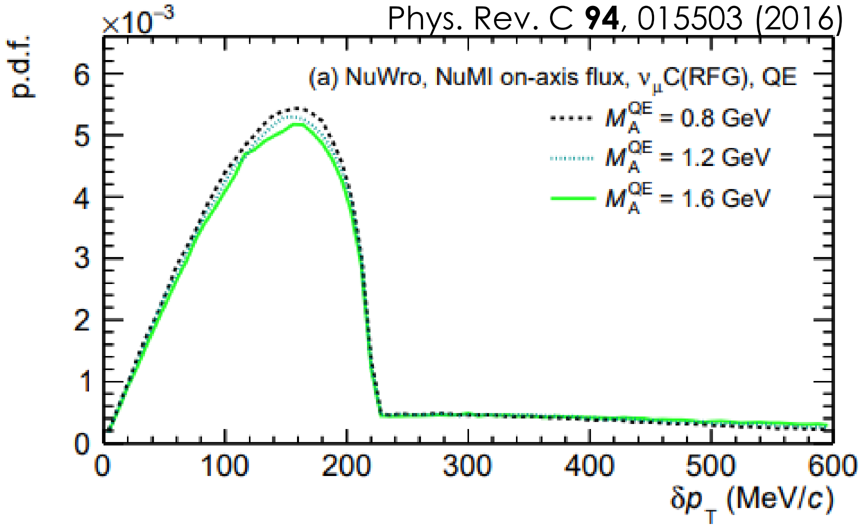
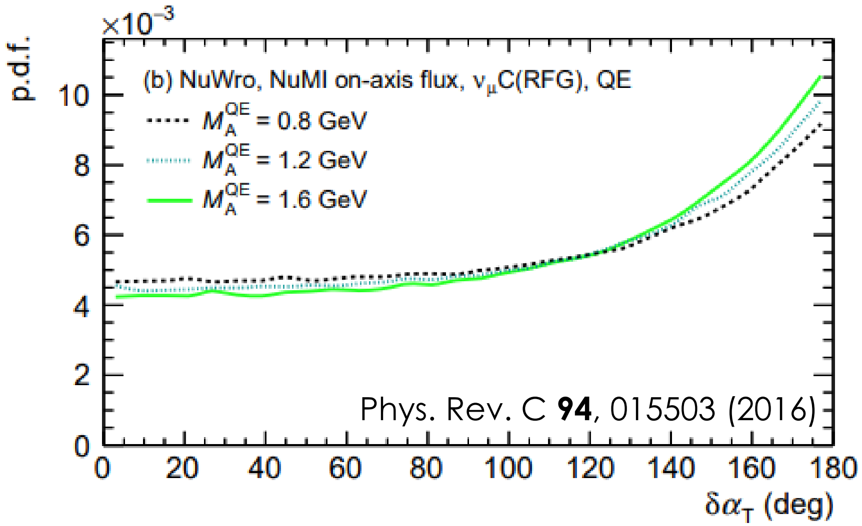
Shape only vs full xsec

Will mostly focus on showing "shape-only" results: $\frac{1}{\sigma}\frac{d\sigma}{dx}$

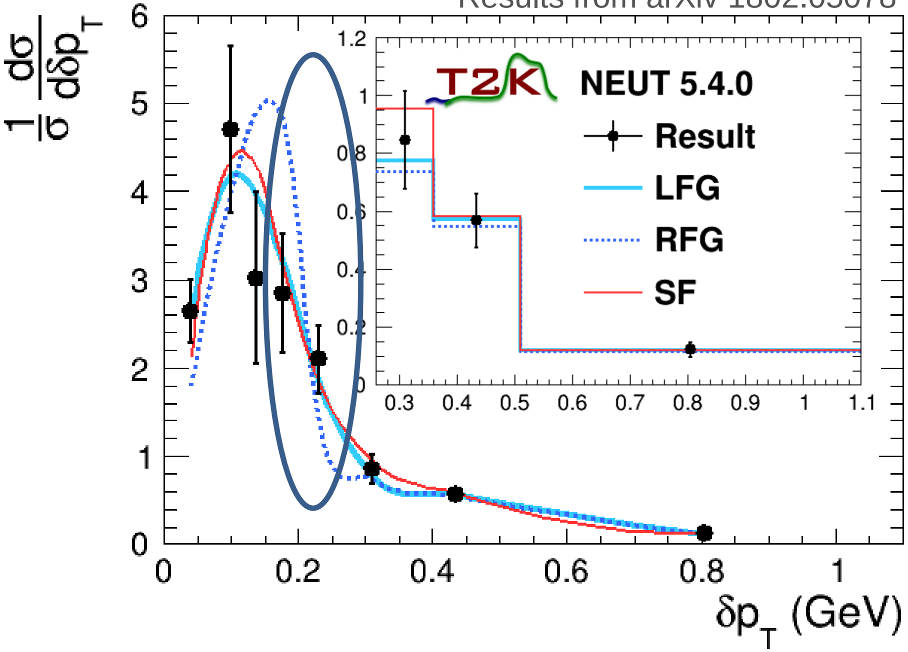
- Avoids the potential to misinterpret the results due to uncertain flux normalisation
- Hides the impact of some nucleon-level physics
  - E.g. M_A^{QE} does not alter the shape of the STVs
  - No possibility of mixing up the impact of 2p2h and M_A^{QE}



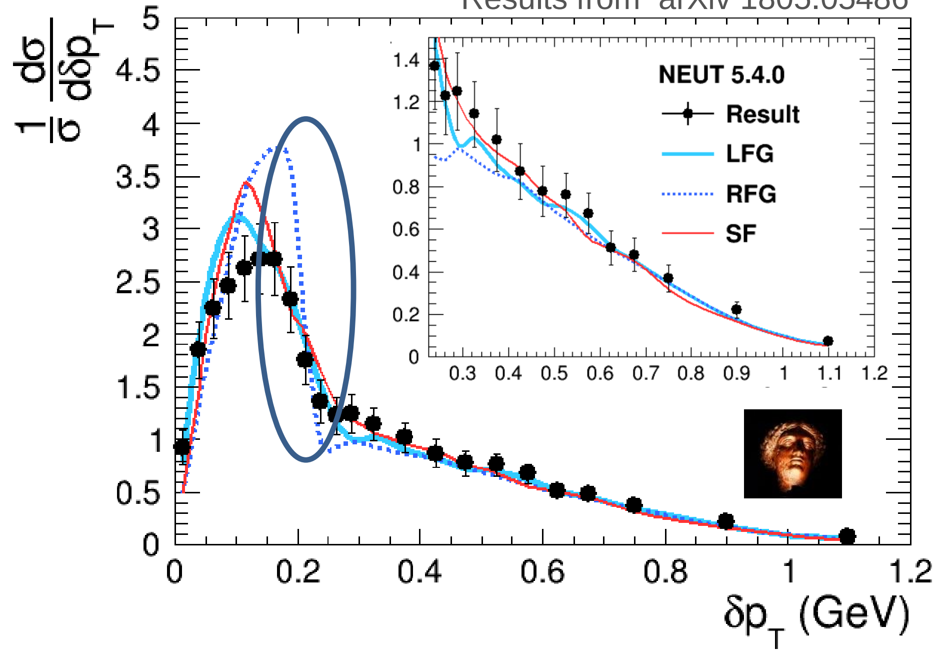


Sensitivity to nuclear models

Results from arXiv 1802.05078

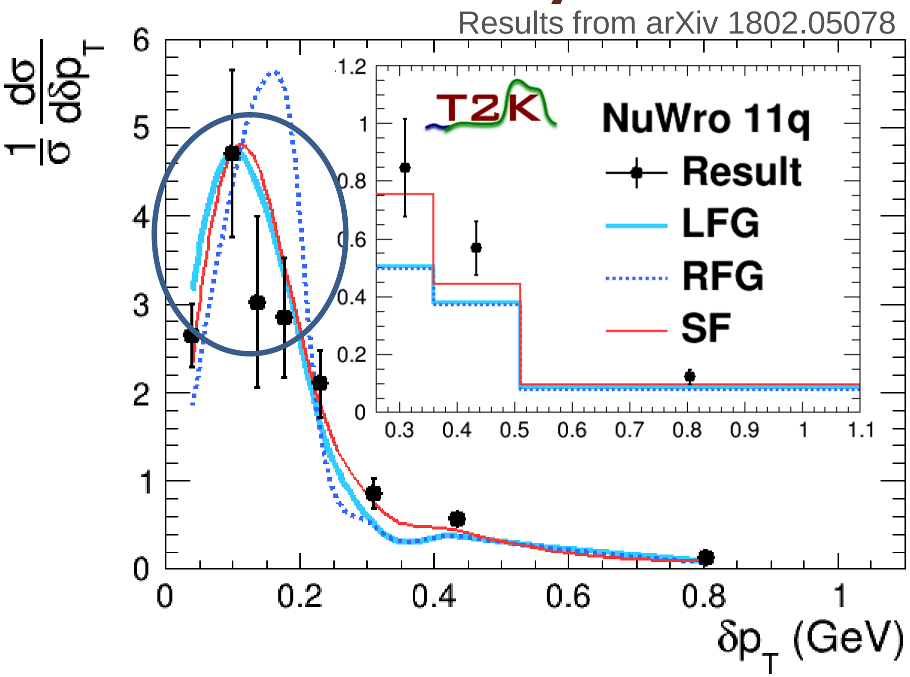


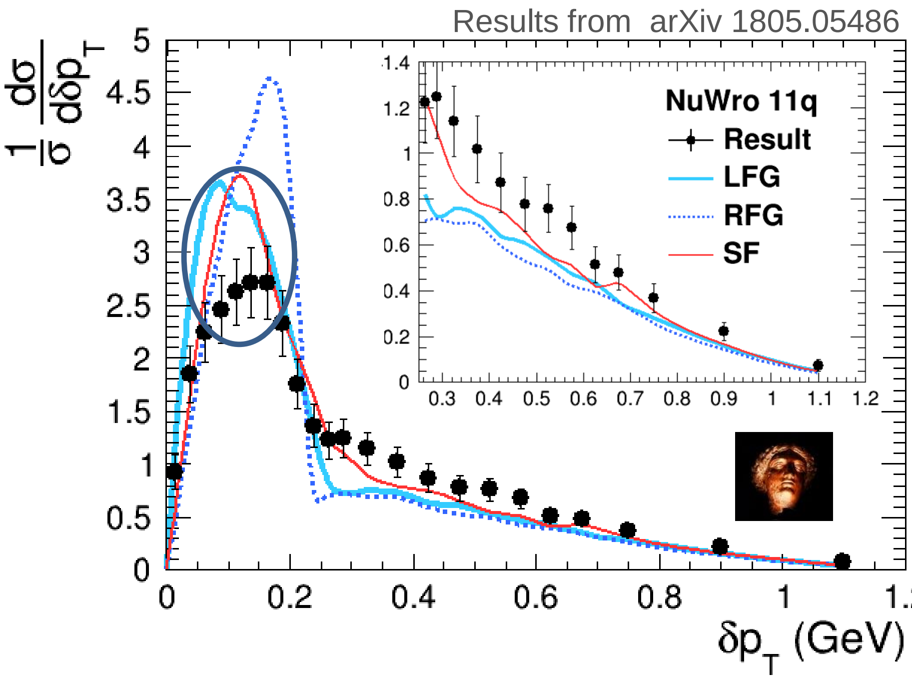
Results from arXiv 1805.05486



- The bulk of the distribution does not have the "Fermi-cliff" present in RFG models – **rejection of RFG model**
- No model separation in the tail → not surprising since this is dominated by other 2p2h and FSI effects

Sensitivity to nuclear models





- In general similar conclusions from NuWro
- For MINERvA result NuWro over/under estimates the bulk/tail (more on this next!).

Sensitivity to nuclear models

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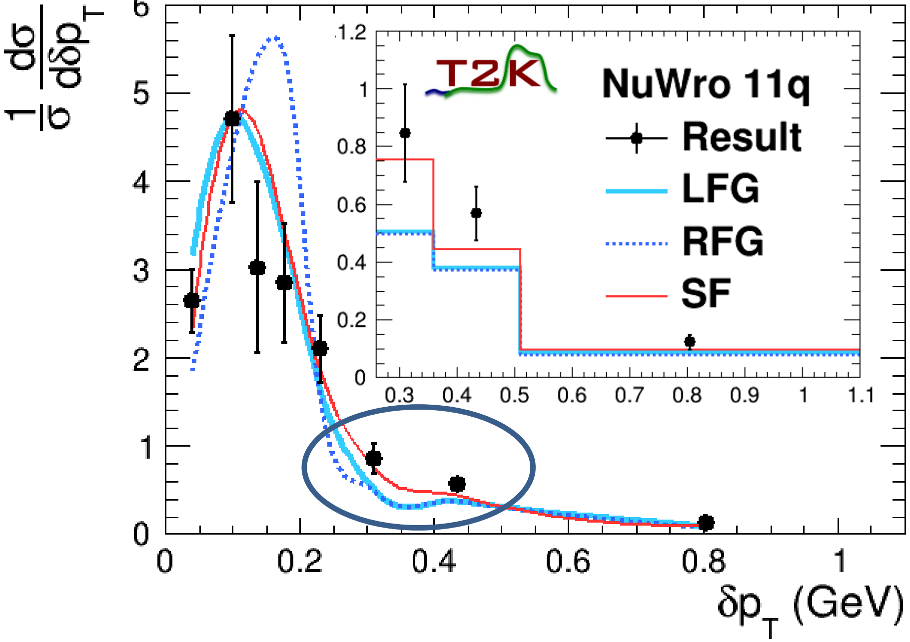

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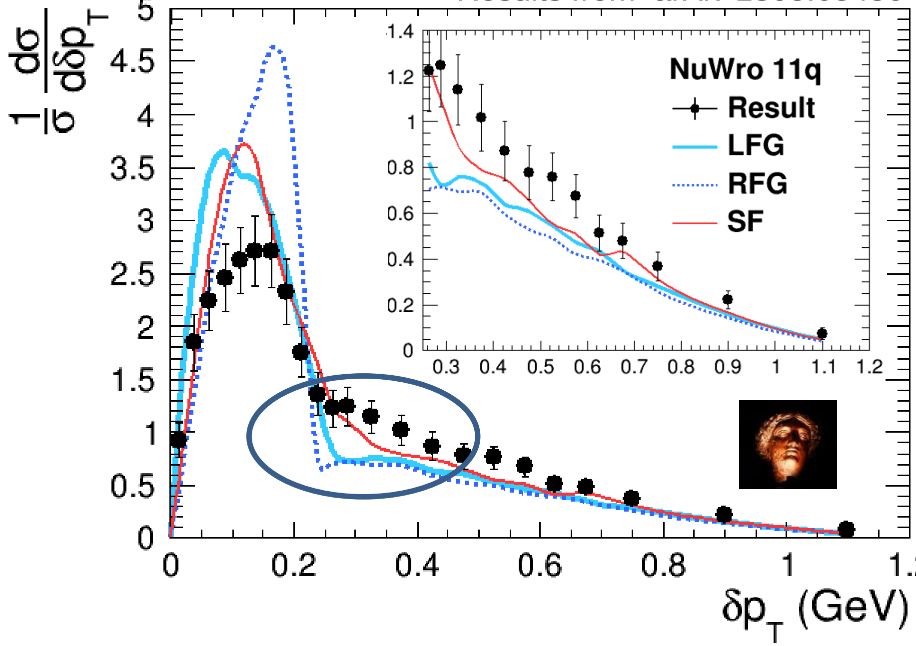
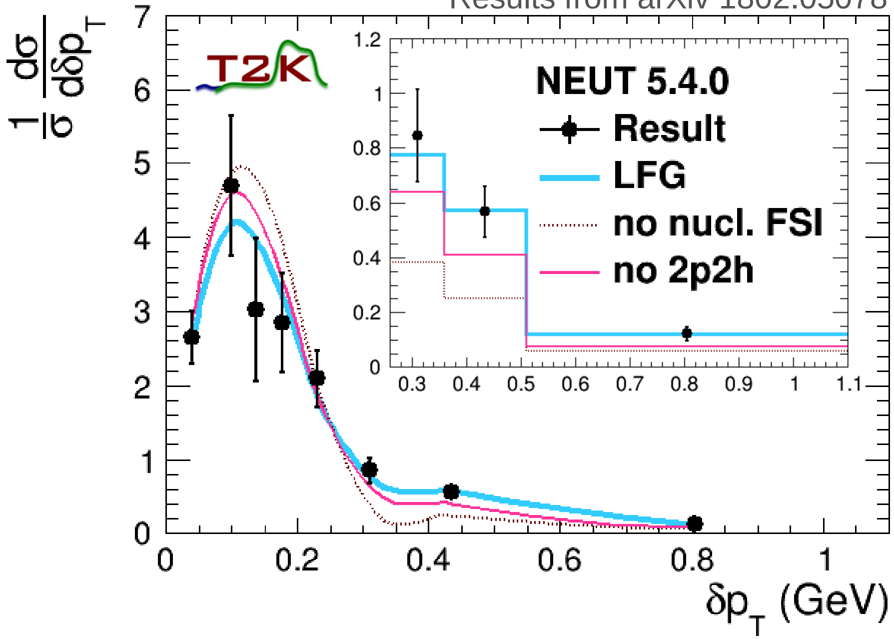


- In general similar conclusions from NuWro
- For MINERvA result NuWro over/under estimates the bulk/tail (more on this next!).
- SF appears important to fill in the "dip" region (SRCs extend the initial state nucleon momentum distribution)

Sensitivity to 2p2h and FSI

Results from arXiv 1802.05078



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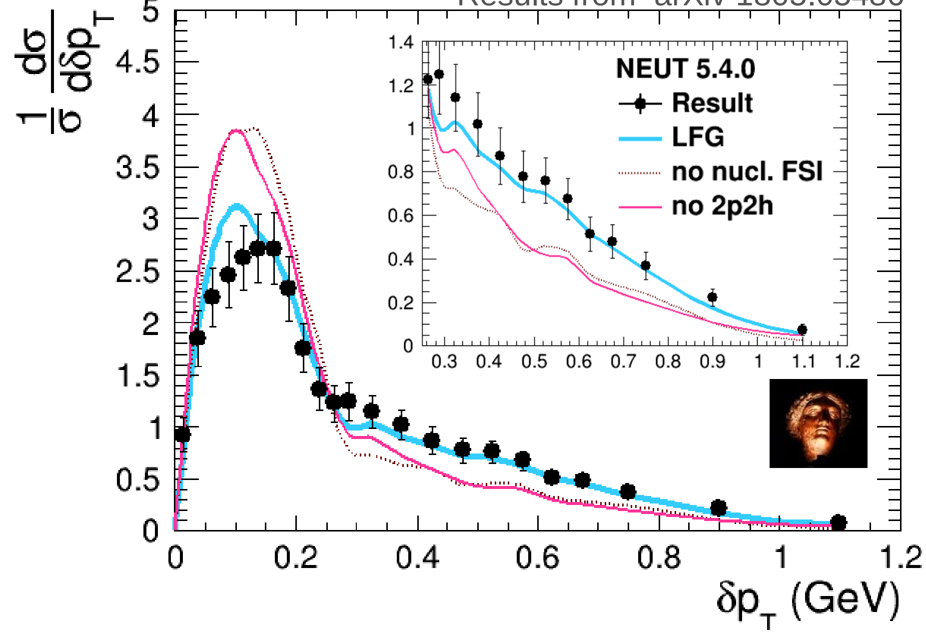

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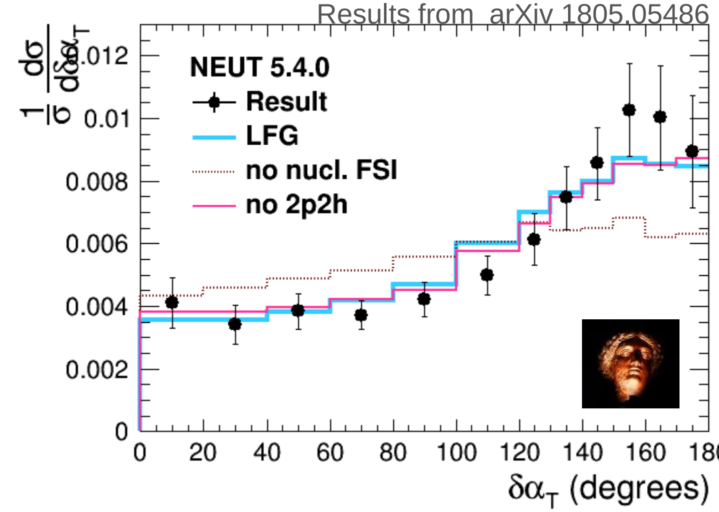
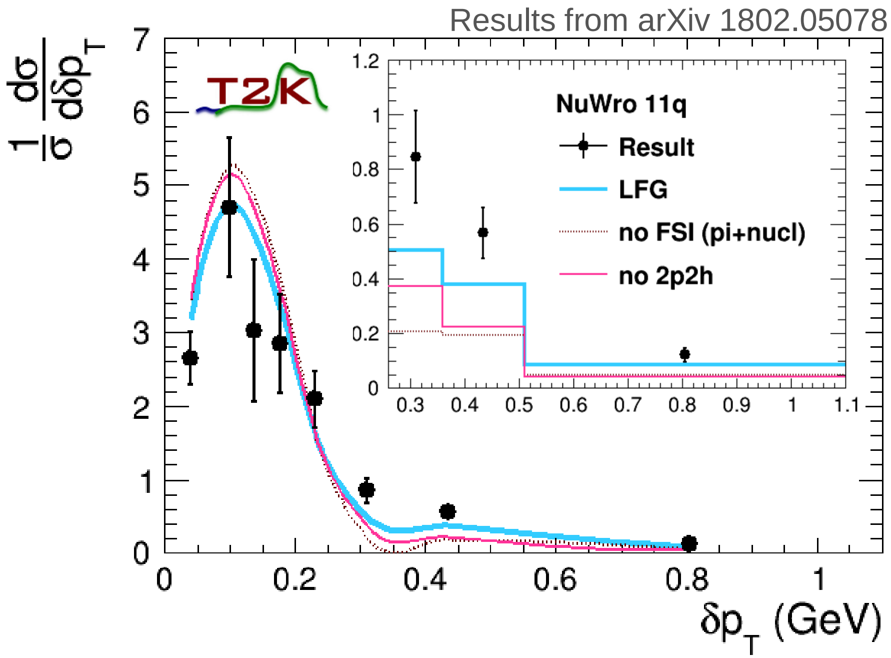
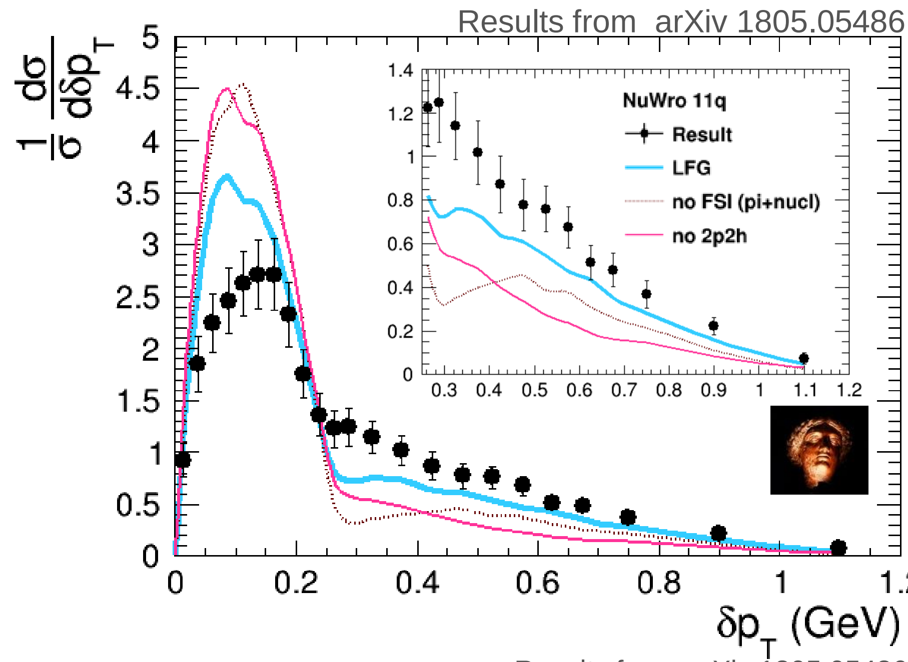


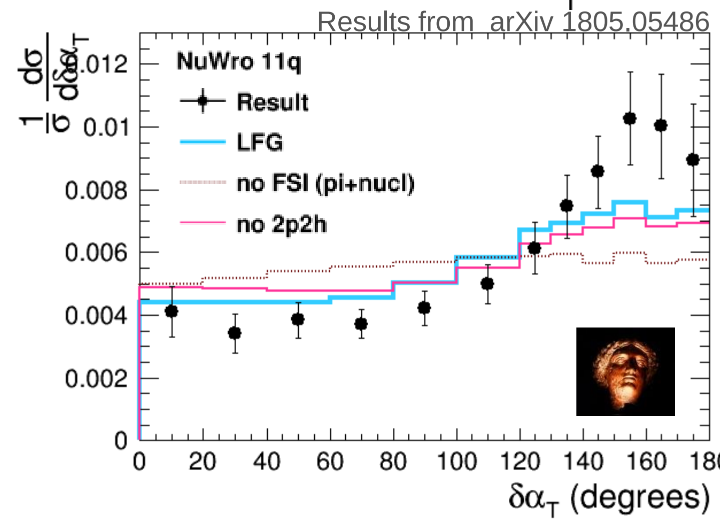
- 2p2h strength seems about right.
- In NEUT, $\delta\alpha_T$ breaks the degeneracy between 2p2h and FSI.

Sensitivity to 2p2h and FSI

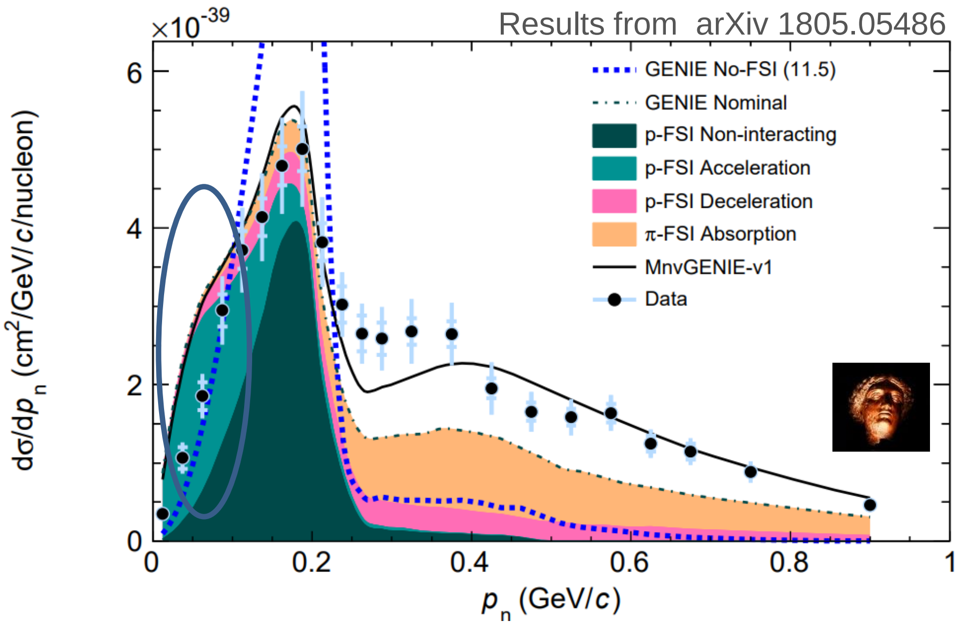


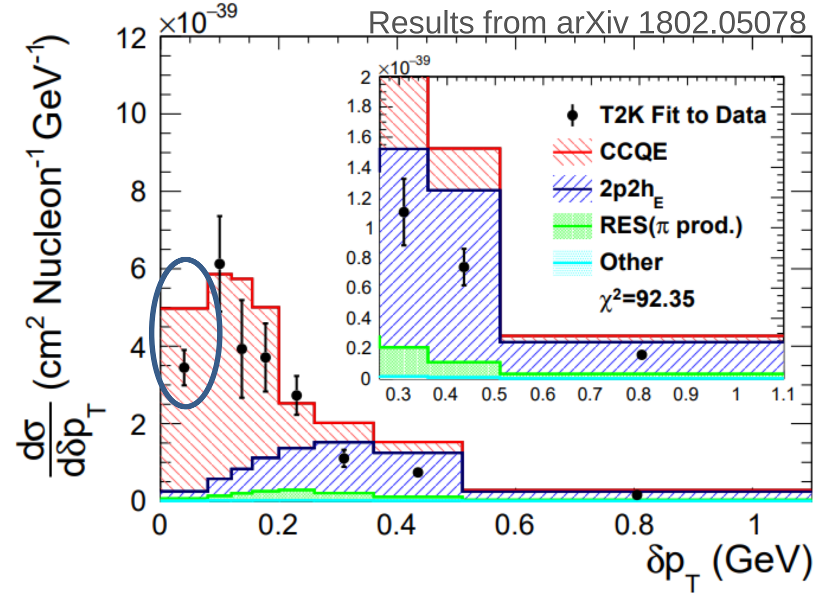


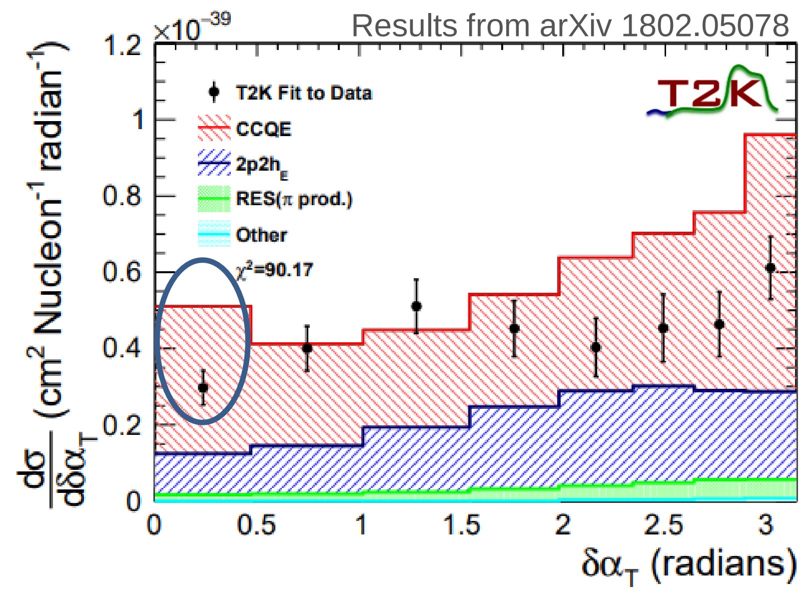
- 2p2h strength is the same, but now too few events in the tails!
- Difference is the 1p1h and FSI models. NuWro FSI too weak?



FSI in GENIE

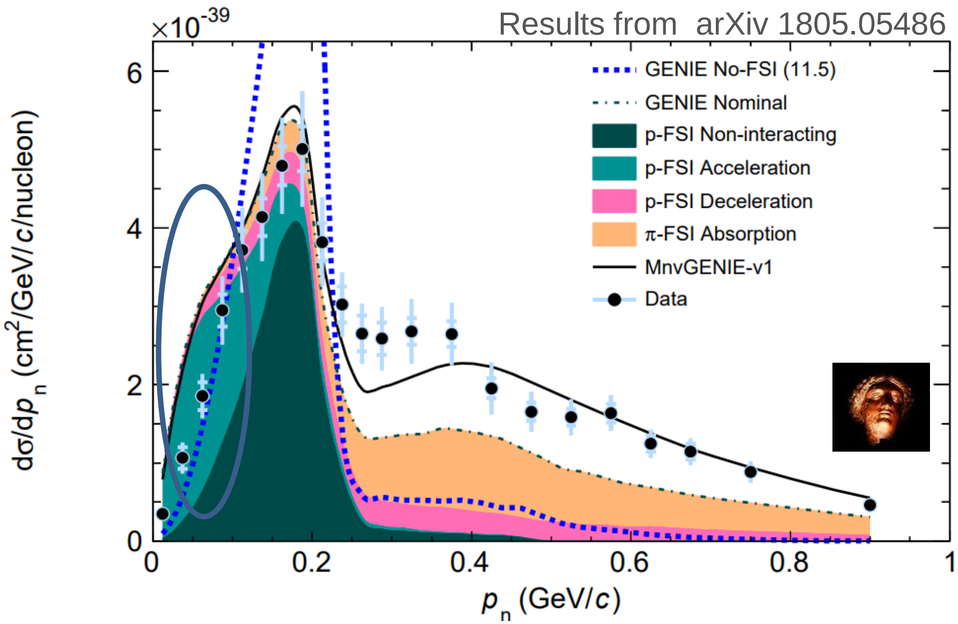


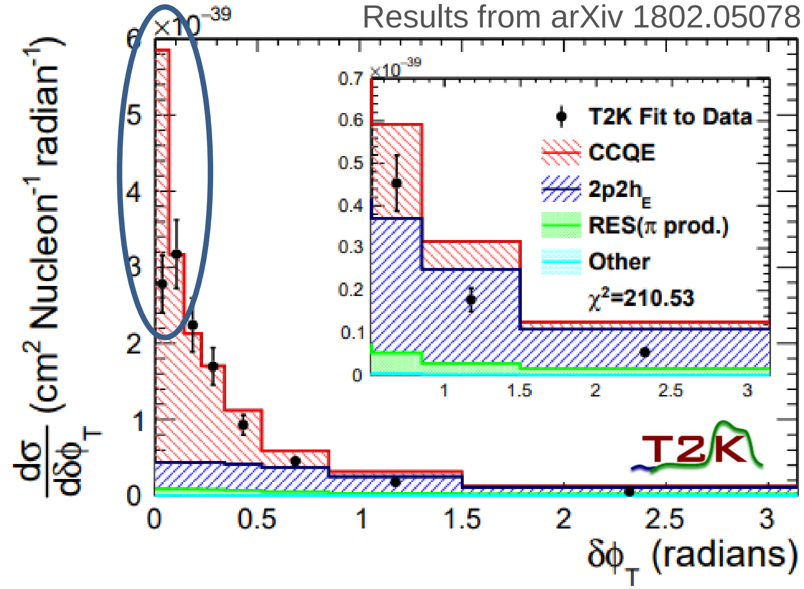


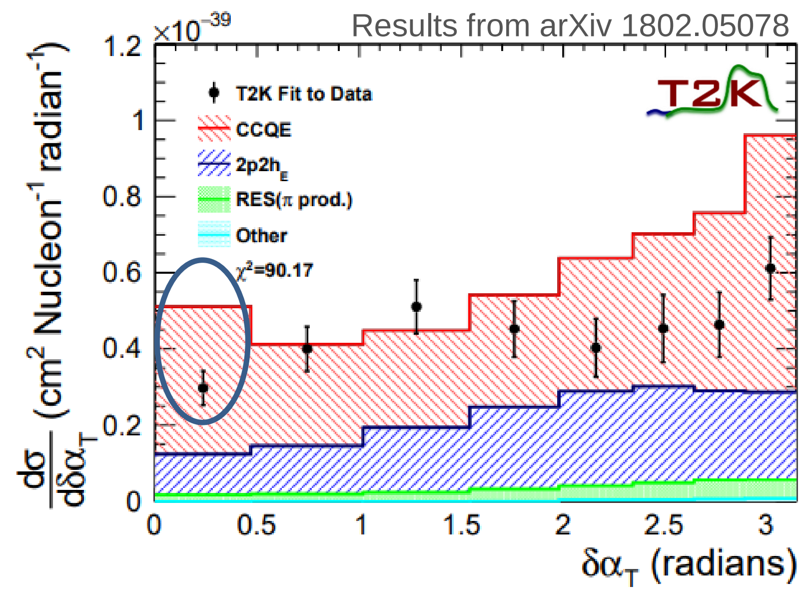


- Accelerating ("elastic") FSI in GENIE's default model causes some odd features in the STV not seen in the results

FSI in GENIE

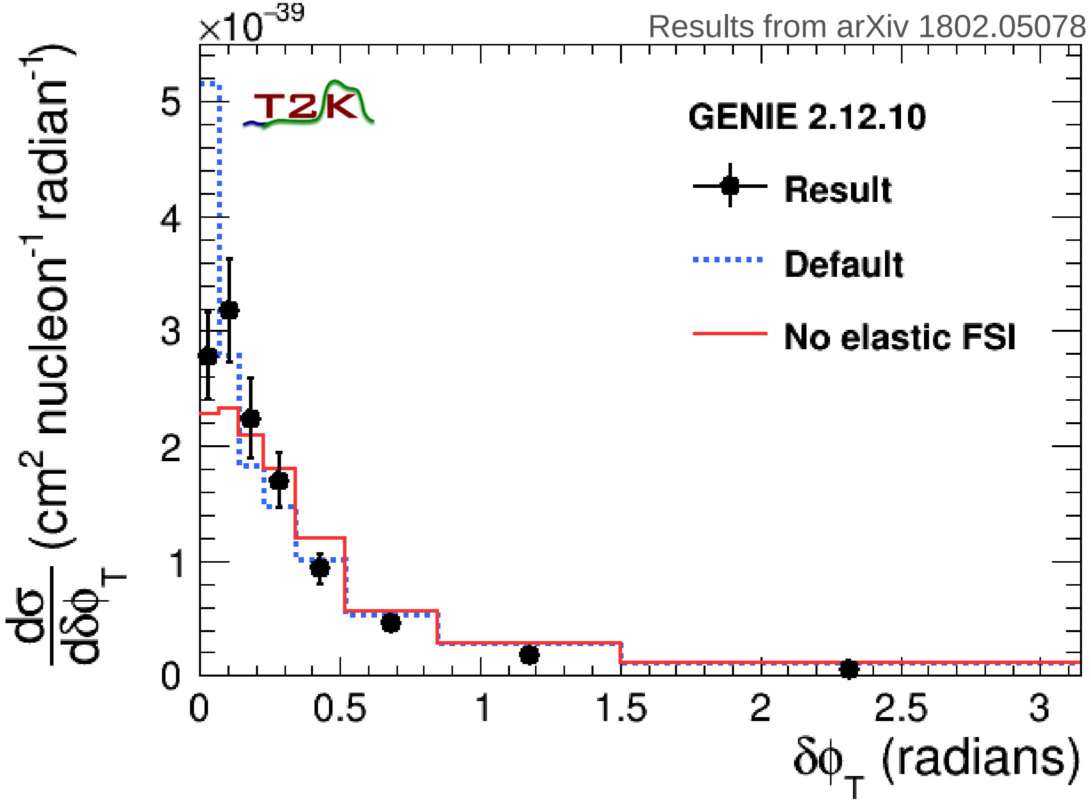






- Accelerating ("elastic") FSI in GENIE's default model causes some odd features in the STV not seen in the results
- Best probe of this is $\delta\phi_T$

FSI in GENIE



- Removing this "elastic" FSI gives comparisons much more compatible with the results

Exploring 2p2h using GiBUU

- GiBUU describes 2p2h in νN interactions by likening to known eN scattering (see previous talk).
- Link is via simple factors where the only free parameter is the isospin (T) of the initial state. E.g.: $W_1^{\nu} = \left(G_M^2 \frac{\omega^2}{\mathbf{q}^2} + G_A^2 \right) R_T^e \, 2(\mathcal{T}+1)$
  - Expect T=0 [Phys. Rev. C**92**, 024604]

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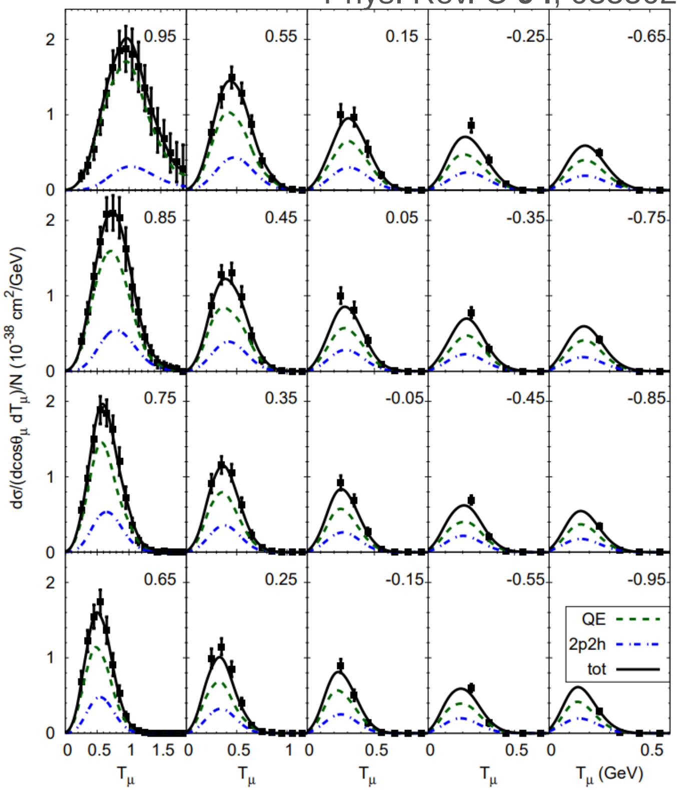
Phys. Rev. C **94**, 035502



- Expect T=0 [Phys. Rev. C**92**, 024604]
- T=1 gives near perfect agreement with MiniBooNE
- But this comes mostly from the result's normalisation – sensitive to flux normalisation error

Exploring 2p2h using GiBUU

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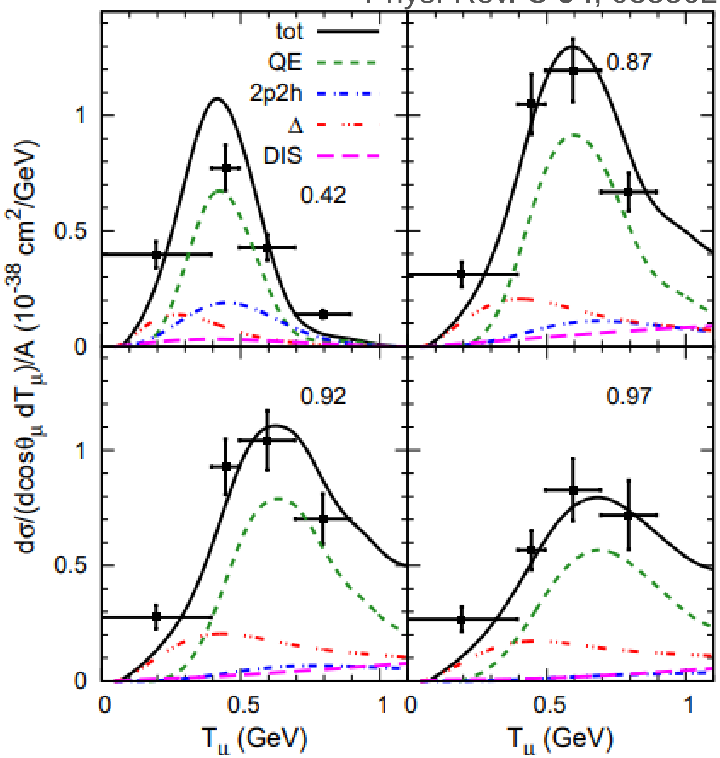
- Link is via simple factors where the only free parameter is the isospin (T) of the initial state. E.g.: $W_1^{\nu} = \left(G_M^2 \frac{\omega^2}{\mathbf{q}^2} + G_A^2 \right) R_T^e \, 2(\mathcal{T}+1)$

Phys. Rev. C **94**, 035502

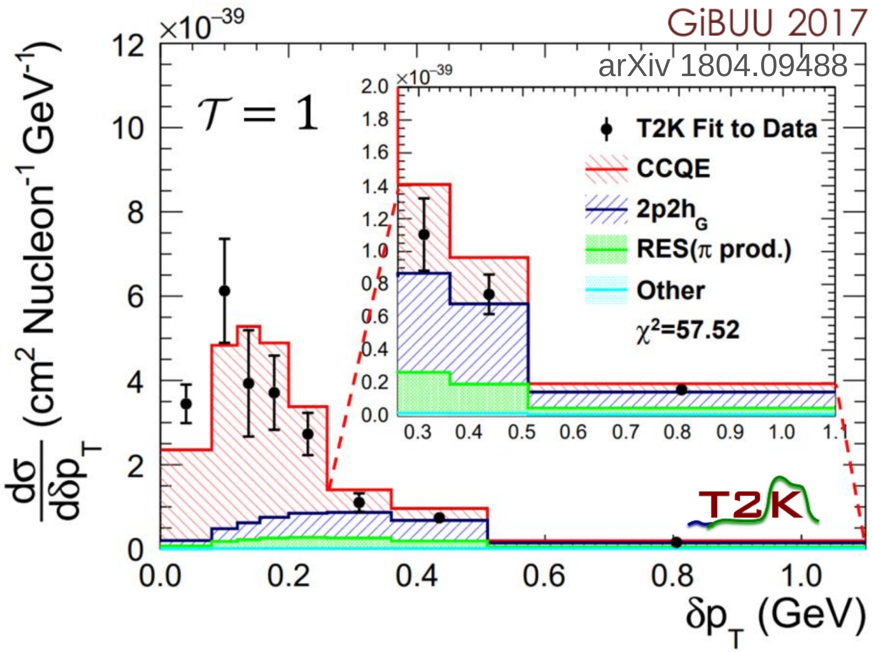


- Expect T=0 [Phys. Rev. C**92**, 024604]
- T2K results prefer T=0 but also susceptible to flux normalisation

> Presently available data thus do not allow to determine the neutrino-induced 2p2h processes to better than within a factor of 2. For this situation to change the flux would have to be known to significantly better than 10%.
> Phys. Rev. C **94**, 035502

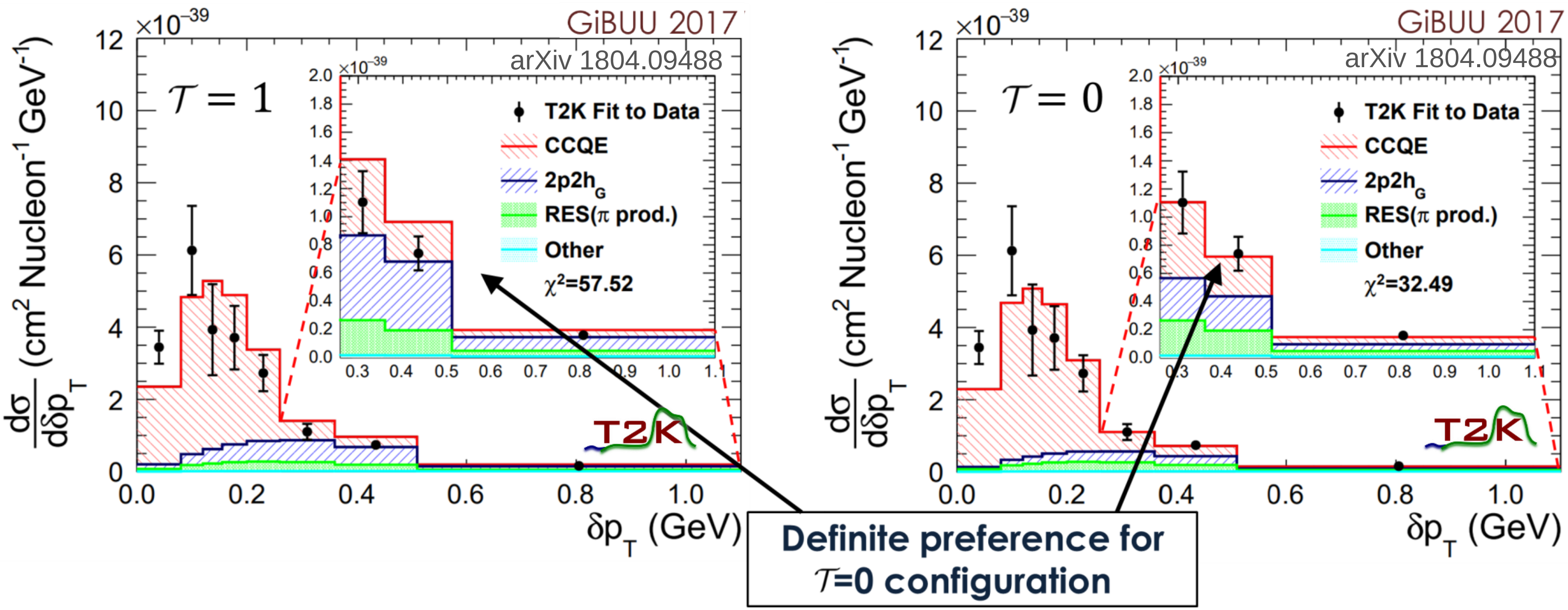
- Or maybe we just need more shape sensitivity to 2p2h …

Exploring 2p2h using GiBUU



- Looking at δp_T for GiBUU with T=1, the 2p2h contribution seems too strong

Exploring 2p2h using GiBUU

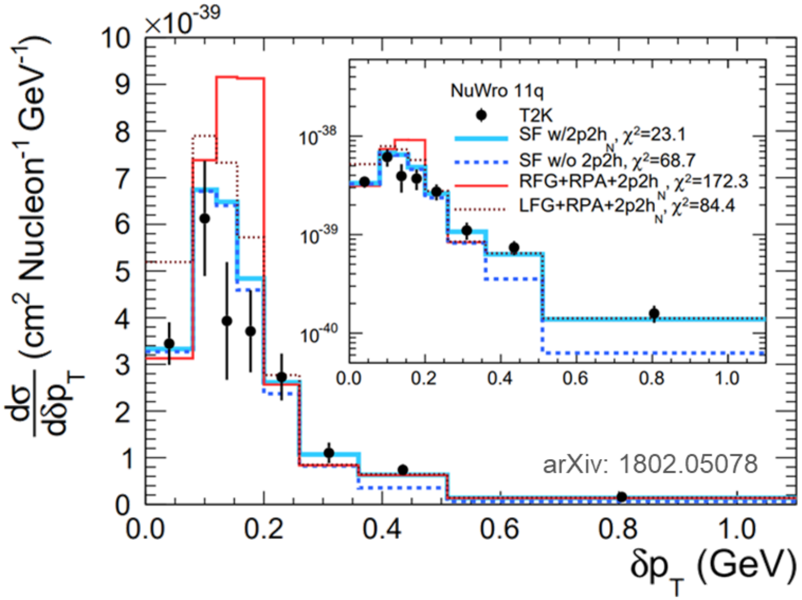


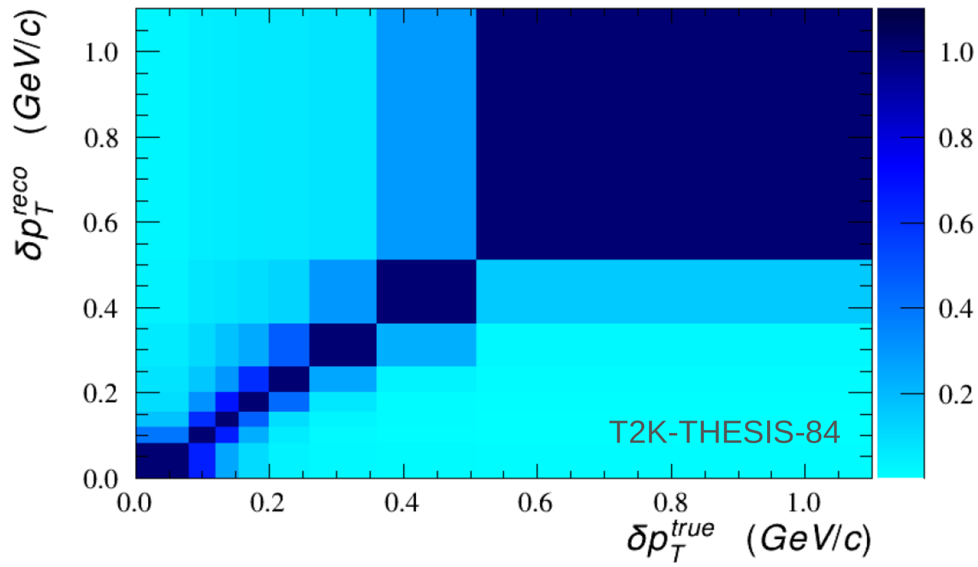
- T=0 looks much better! This time the conclusion is not sensitive to the flux normalisation
- For ^{40}Ar expect T=2 → strong enhancement factor. MicroBooNE results will be interesting …

Overview

- What are transverse kinematics and why should we care?
- Current measurements: T2K and MINERvA
- What can we learn from these?
- The future of transverse measurements

Finer binning?





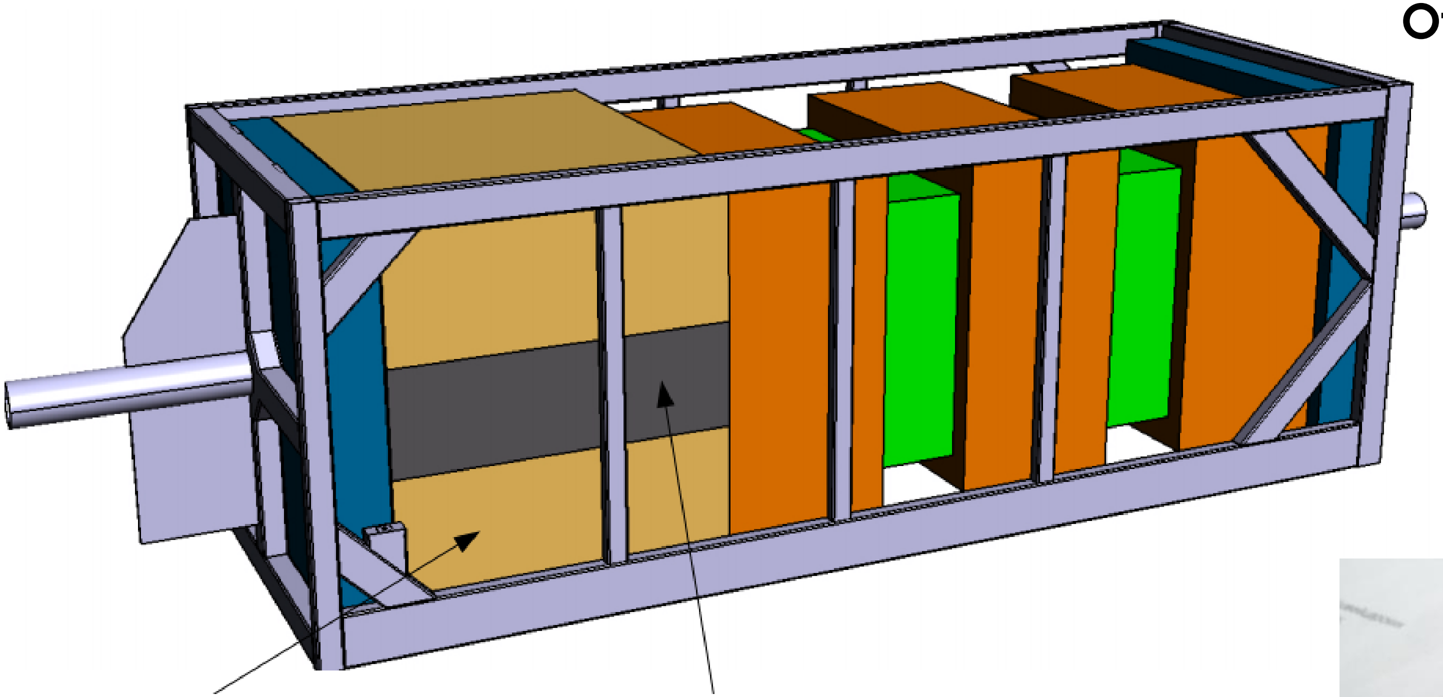
- T2K correlated-kinematics measurements are already quite limited by detector resolution
- Significantly finer binning not feasible without improved detector performance (or excessive regularisation)

Proposal - CERN-SPSC-P357

ND280 Upgrade (off axis)

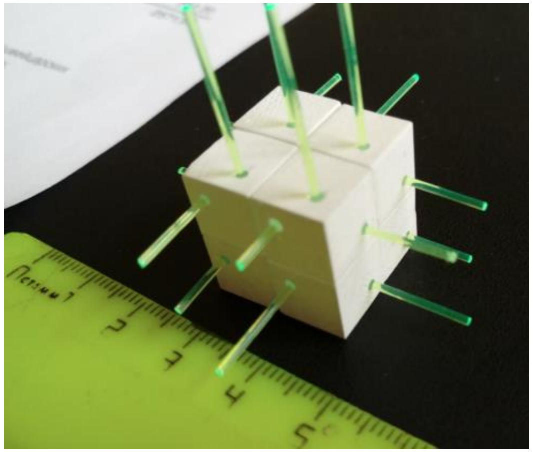
- Facilitates 4π acceptance with lower reconstruction thresholds

Peak E_ν
- On Axis ~ 1.1 GeV
- **Off Axis ~ 0.6 GeV**



Two new high-angle TPCs

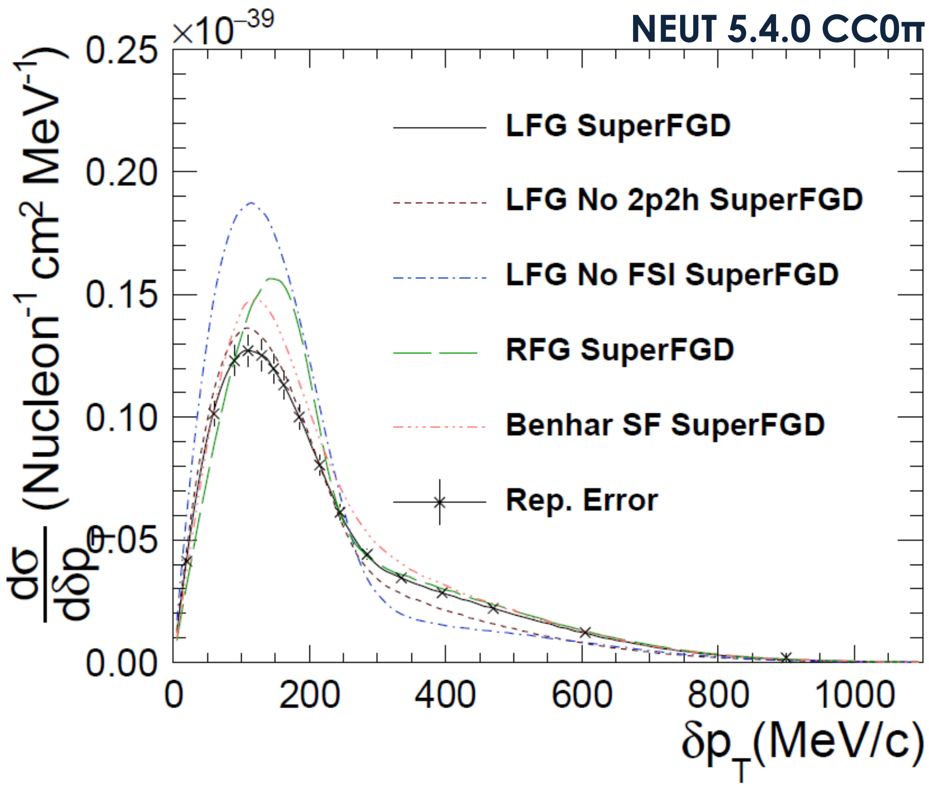
New finely segmented Scintillator detector (SuperFGD – arXiv1707.01785)

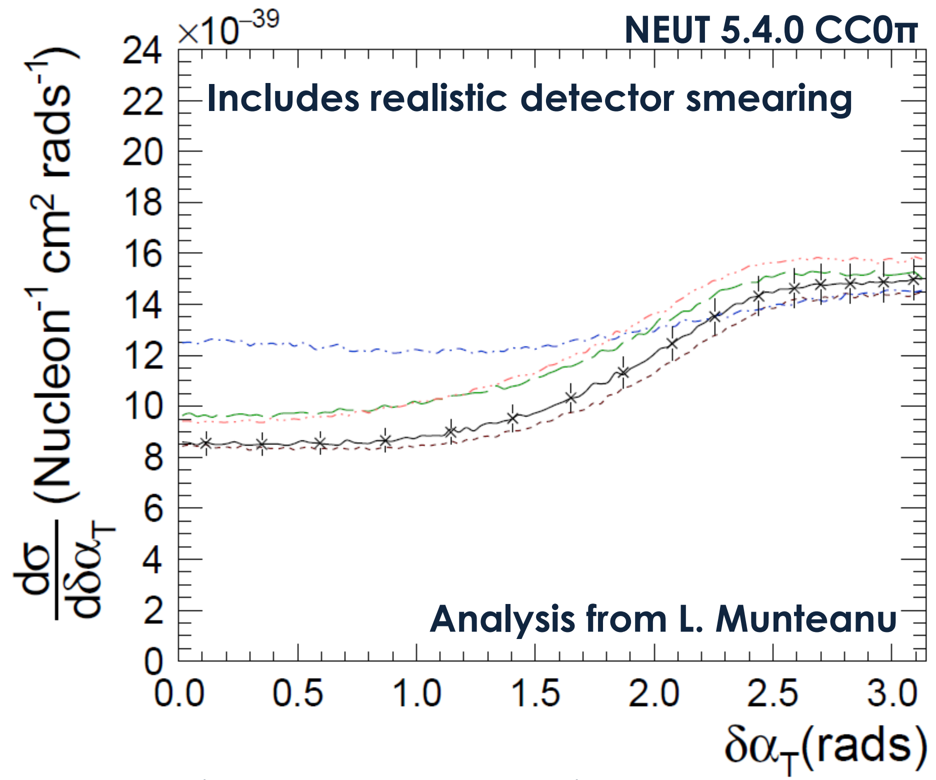


Ready by ~ 2021

Measuring the STV with ND280 upgrade

- More mass, more data, better acceptance: at least **50 times** more events than T2K analysis!
- With two times finer binning (assuming improved upgrade resolution) expect a ~5 times reduction in statistical error: ~13%→~3%

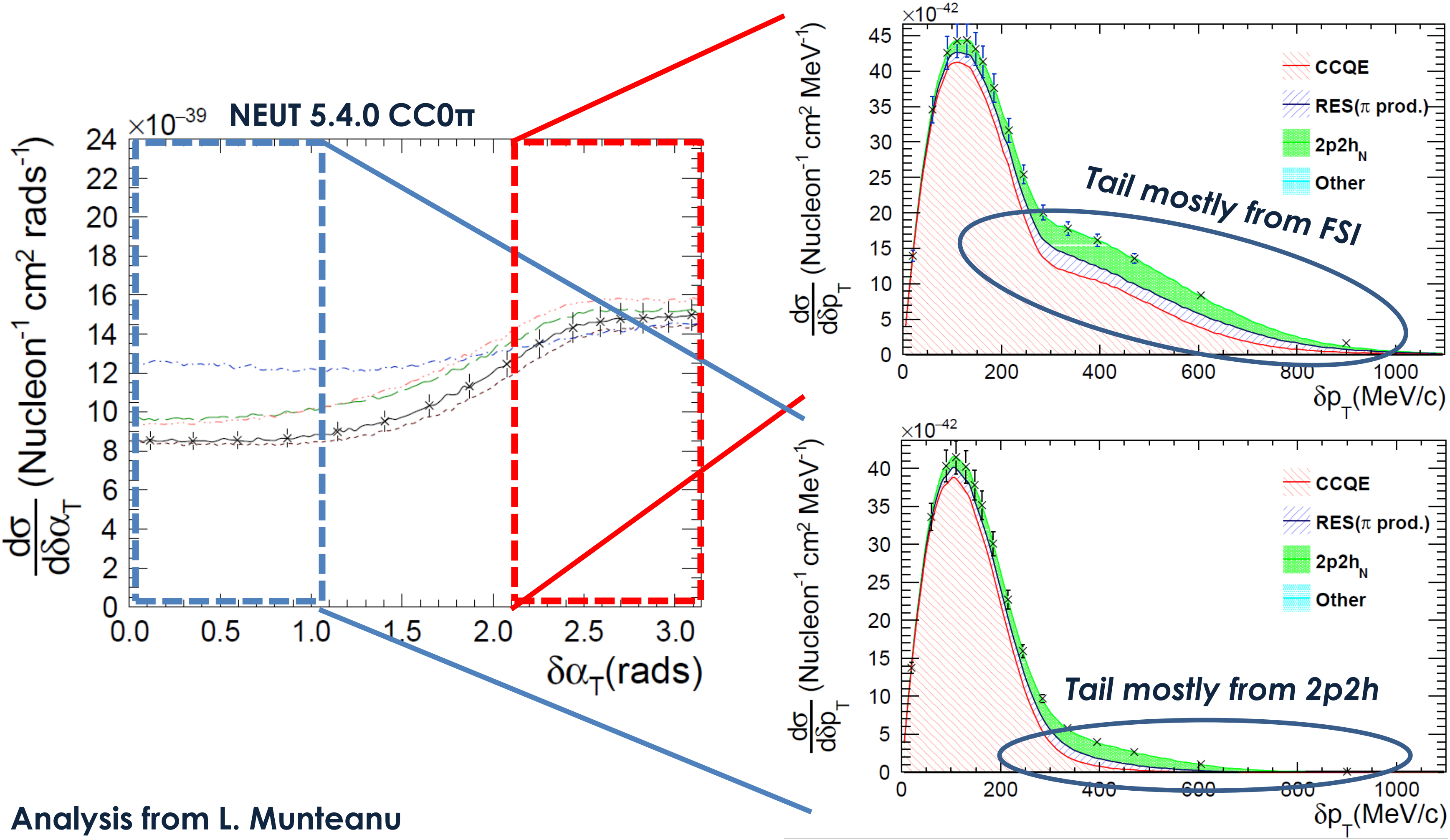




- Sensitive to all nuclear effects but can still be hard to disentangle them all …

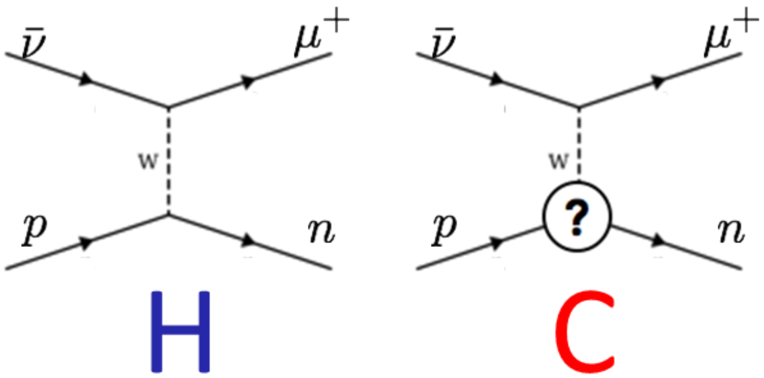
Multi-differential STV

- Measuring δp_T in bins of $\delta\alpha_T$ may allow excellent separation of 2p2h and FSI - makes use of high statistics from upgrade.



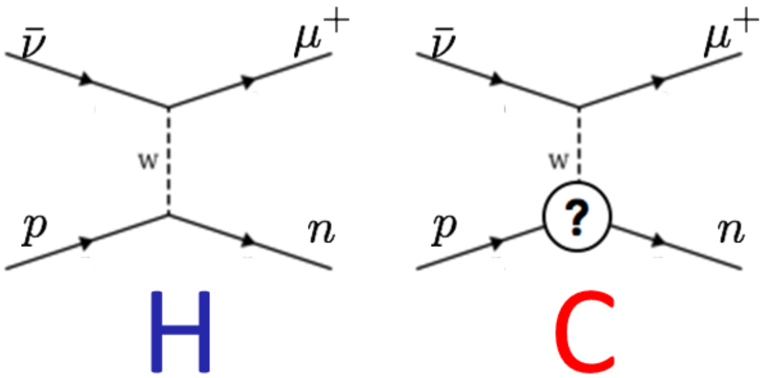
Analysis from L. Munteanu

Identification of H interactions



- $\bar{\nu}_\mu CC0\pi$ allows a H contribution
- H has no nuclear effects, so no transverse imbalance

Identification of H interactions



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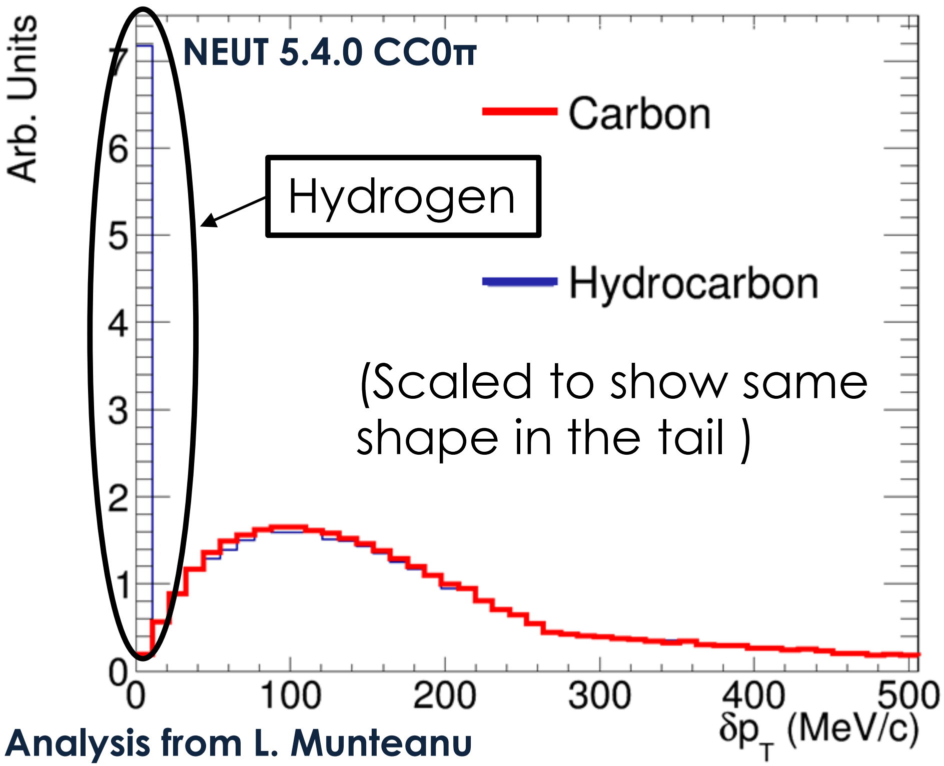

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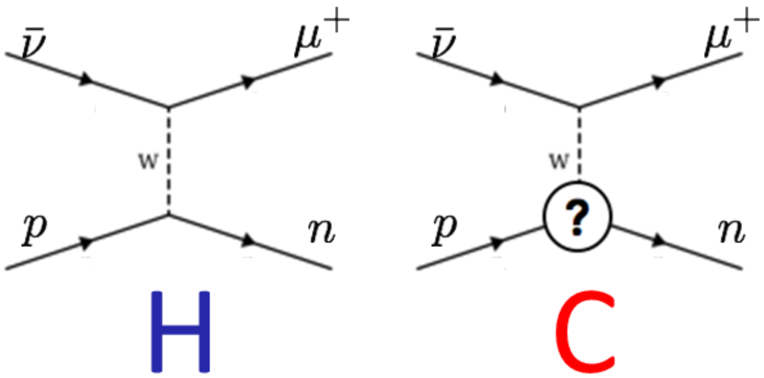
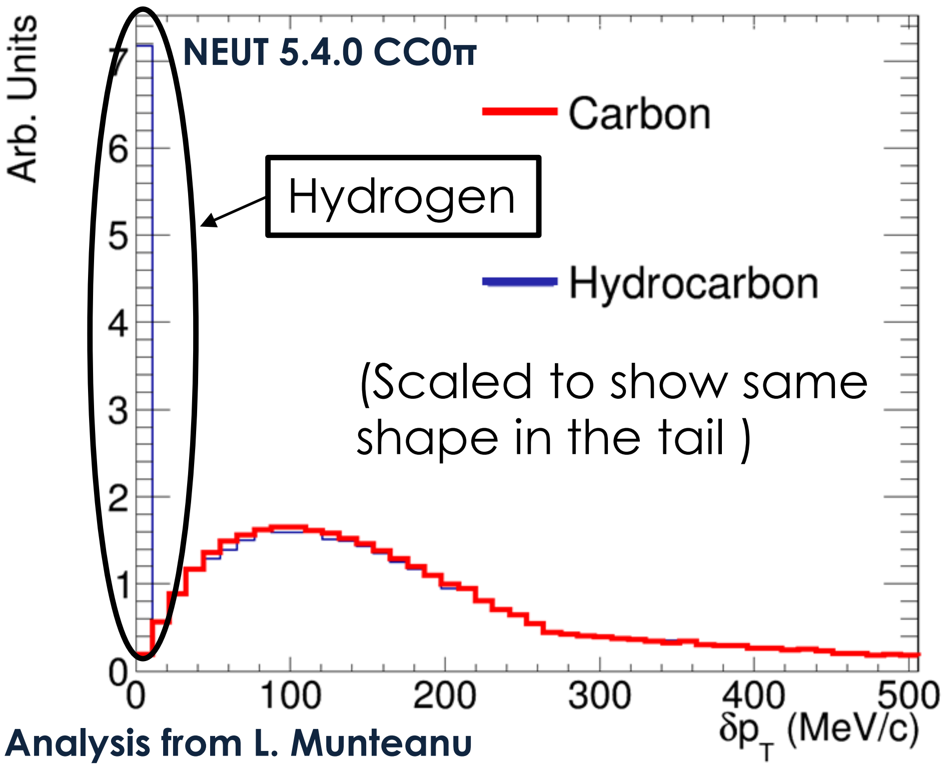


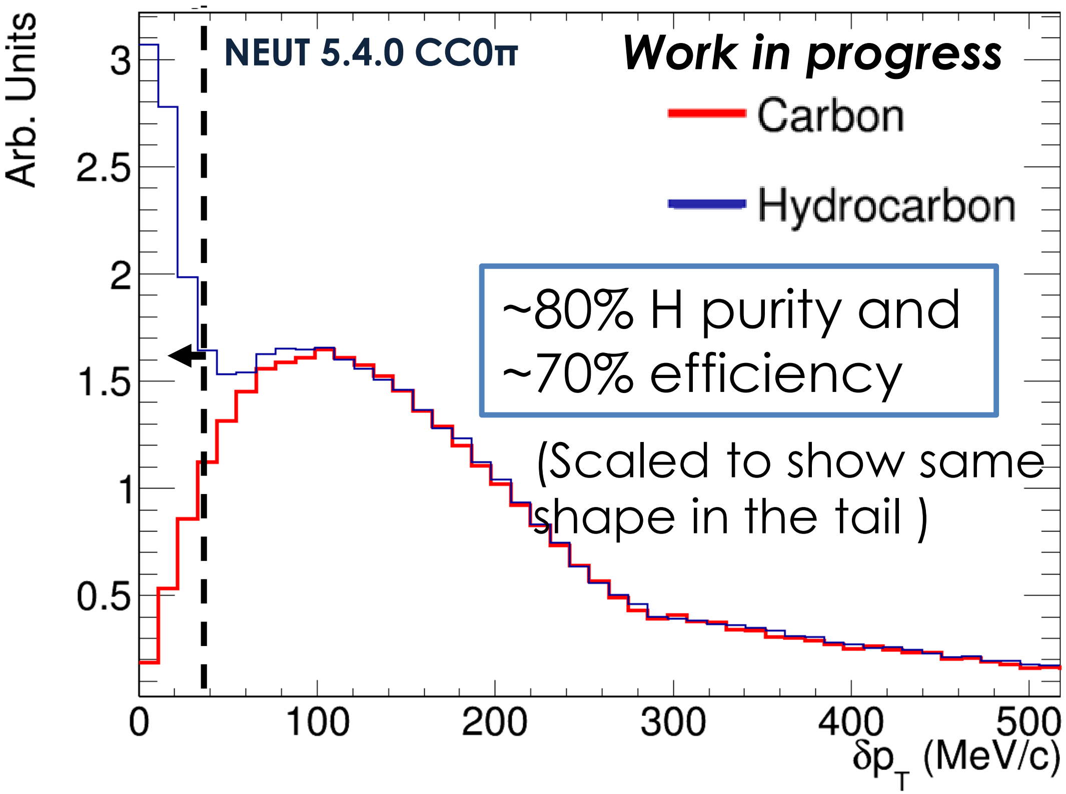


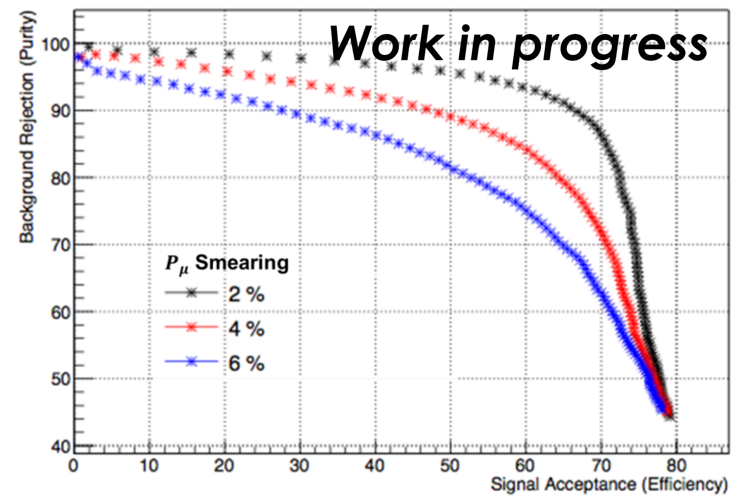
Analysis from L. Munteanu

- $\bar{\nu}_\mu CC0\pi$ allows a H contribution
- H has no nuclear effects, so no transverse imbalance
- Could use STV to extract H and make a ~ nuclear-effect free cross-section!
- Factorise nuclear from nucleon physics
- Can also have near perfect kinematic neutrino energy reconstruction

Can you do this in a real detector!?

- Assume conservative neutron detection capabilities of a SuperFGD (comparable to what MINERvA have shown)





- With ND280 upgrade this gives enough statistics for a double-differential hydrogen enhanced measurement

- Work in progress – let me know if you are interested!

Analysis from L. Munteanu

Summary

- The single-transverse variables offer a novel probe of nuclear effects in νN interactions
- T2K and MINERvA have measured them!
- **Sensitive to nuclear models**: RFG is disfavoured and results hint at a need for SF-like SRCs
- **Sensitive to FSI**: GENIE's elastic component disfavoured.
- **Sensitive to 2p2h**: no need for an empirical enhancement within NEUT 5.4.0 and sensitive to T in GiBUU model
- Future measurements may be able to more accurately probe 2p2h through **combining $\boldsymbol{\delta p_T}$ and $\boldsymbol{\delta \alpha_T}$**
- Possibility of using STVs and neutron-tagging to **access hydrogen interactions**

Thank you for listening

If you want to find out more:

Phys. Rev. C **94**, 015503 (07/16) – Initial suggestion of using the STV

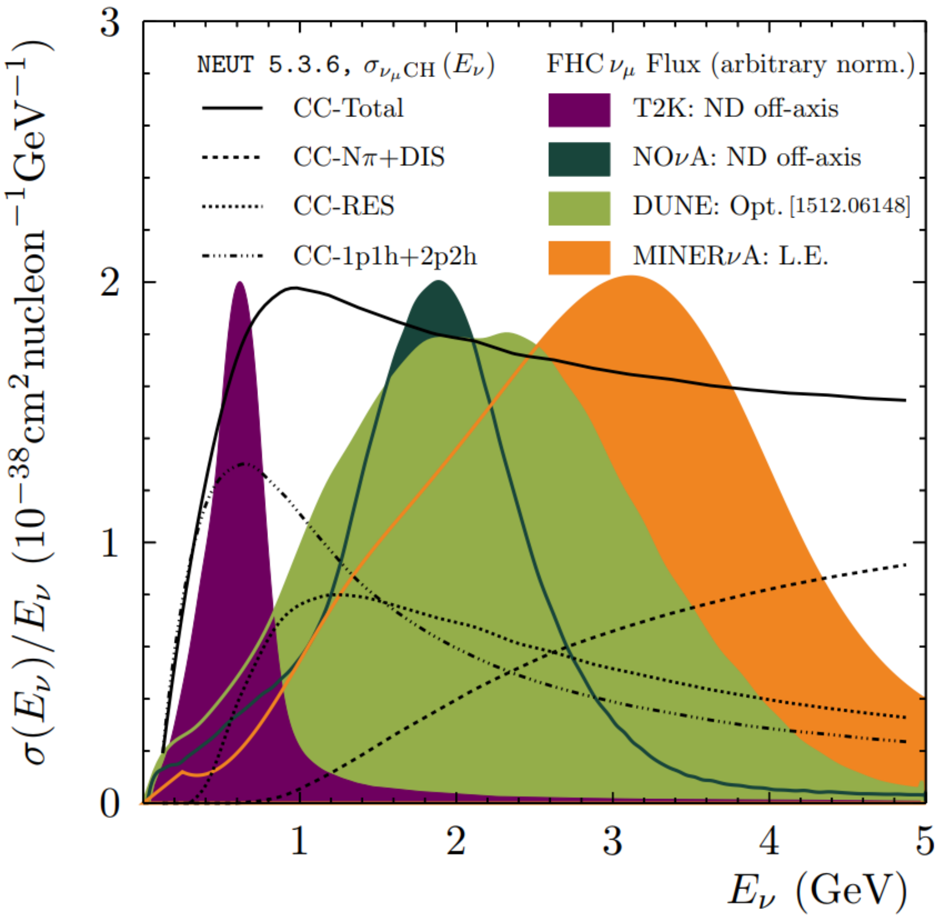
arXiv: 1802.05078 (02/18) – T2K measurement of transverse variables

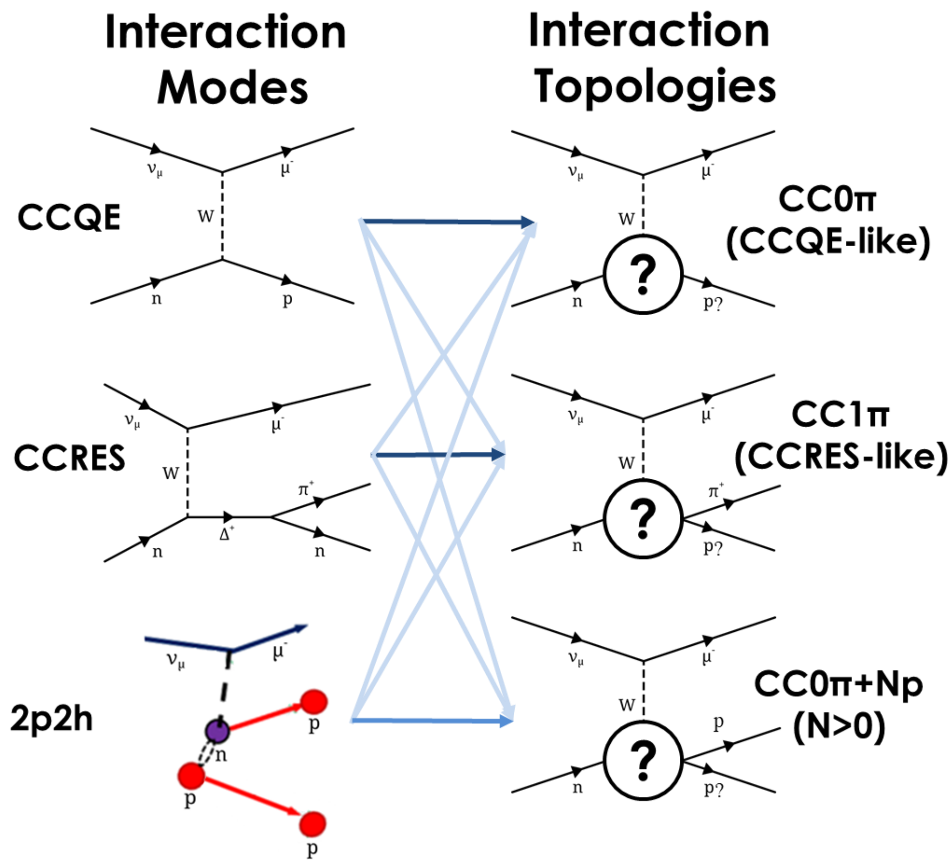
arXiv: 1804.09488 (04/18) – Analysis of T2K result in GiBUU framework

arXiv: 1805.05486 (05/18) – MINERvA measurement of transverse variables

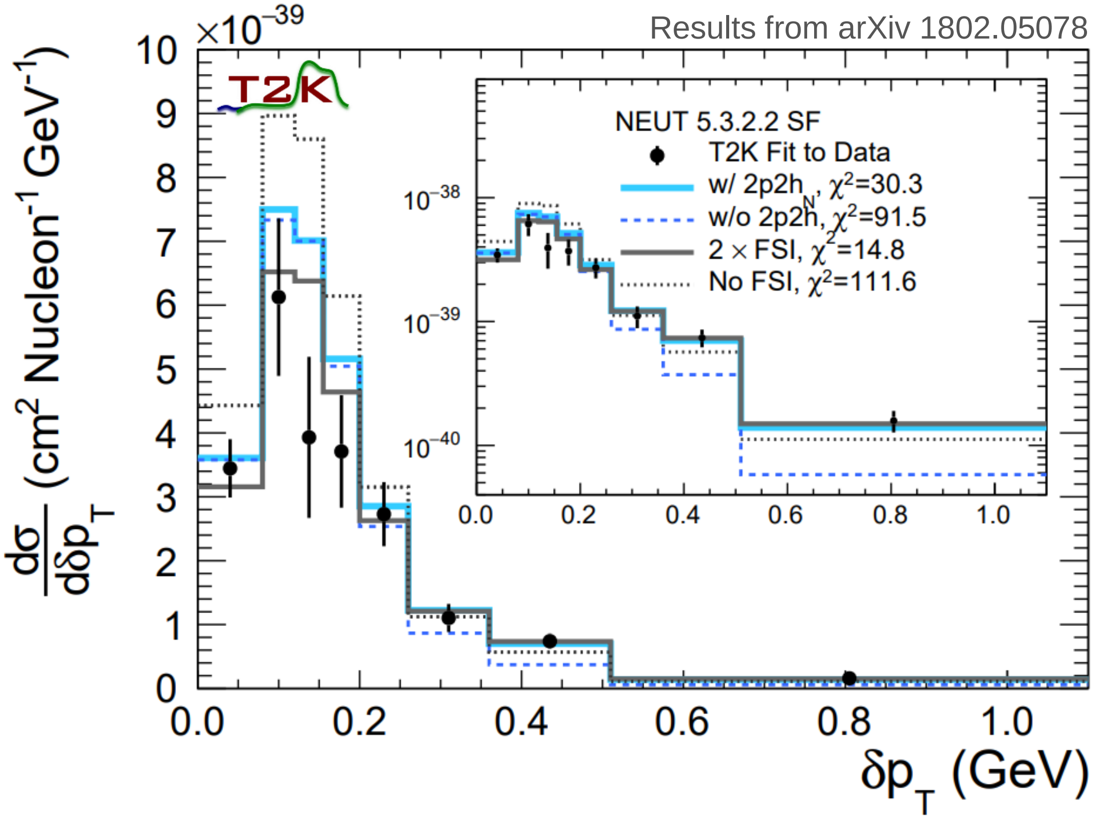
BACKUPS

What can be measured





Sensitivity to 2p2h and FSI



- Considering 100% variations of the mean-free path between scattering in the NEUT FSI cascade model
- At least some 2p2h contribution still required

ND280 vs Upgrade - exposure

Current ND280 results

- Limited kinematic phase-space: $p_\mu > 250\ MeV/c$
  $\cos(\theta_\mu) > -0.6$
  $450\ MeV/c < p_\mu < 1\ GeV/c$
  $\cos(\theta_p) > 0.4$
- ~30% integrated efficiency
- 1 ton fiducial mass
- $\sim 6 \times 10^{20}$ P.O.T

Super FGD potential

- Barely limited kinematic phase-space: $p_\mu > 50\ MeV/c$
  $300\ MeV/c < p_\mu < 1\ GeV/c$
  No angular restrictions
- ~60% integrated efficiency
- 2 ton fiducial mass
- $\sim 8 \times 10^{21}$ P.O.T

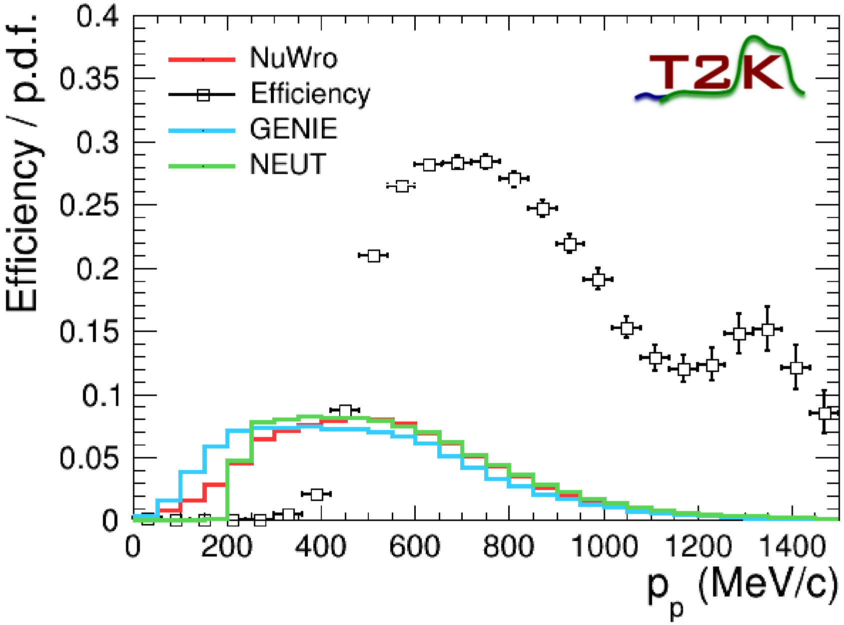
- At least **50 times more events**
- With two times finer binning (assuming improved upgrade resolution) expect a ~5 times reduction in statistical error: ~13%→~3%

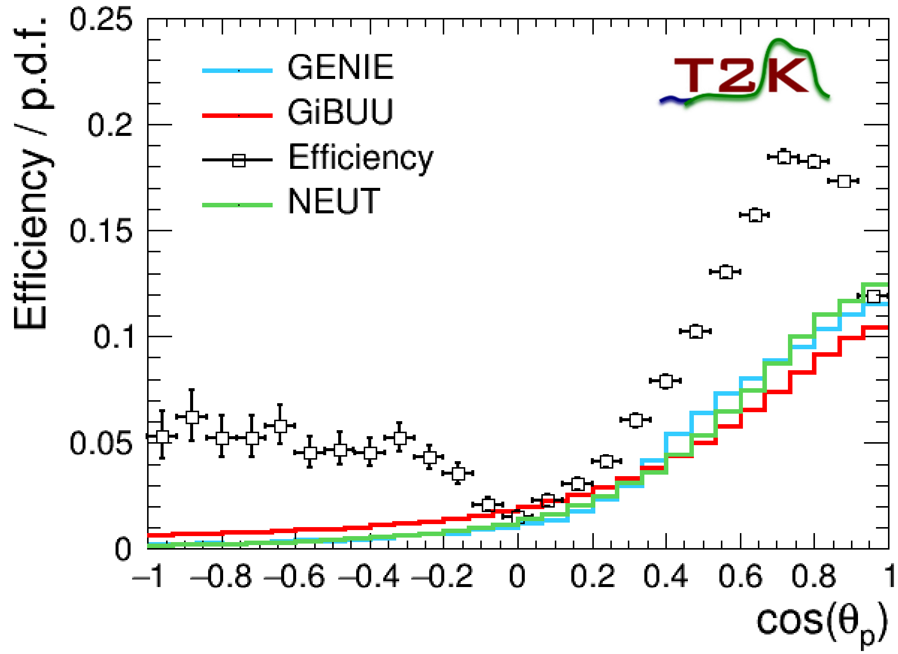
Kinematic constraints

- Need to correct for the detector efficiency (ϵ) when we calculate a cross section:

$$\frac{d\sigma}{dx_i} = \frac{N_{sig}}{\Phi_\nu T \epsilon_i}$$

Kinematic constraints



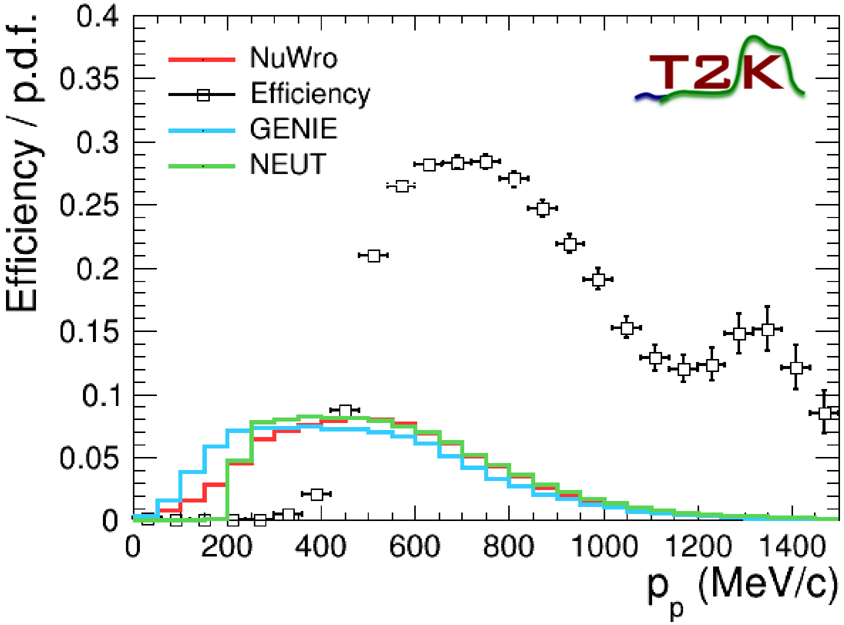


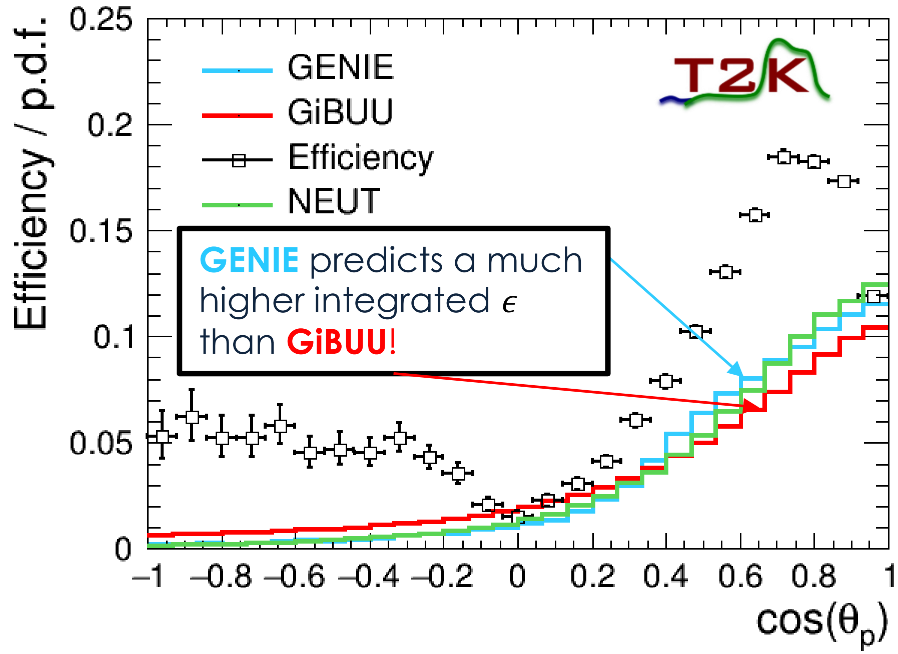
- Need to correct for the detector efficiency (ϵ) when we calculate a cross section:

$$\frac{d\sigma}{dx_i} = \frac{N_{sig}}{\Phi_\nu T \epsilon_i}$$

- But how do we know ϵ for a bin of the STV? We've integrated over the particle kinematics!

Kinematic constraints





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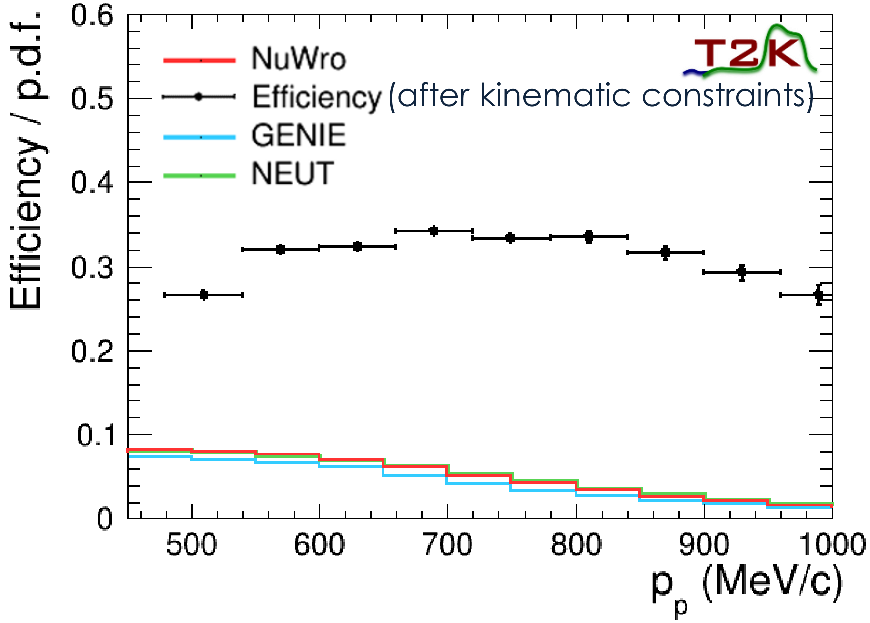
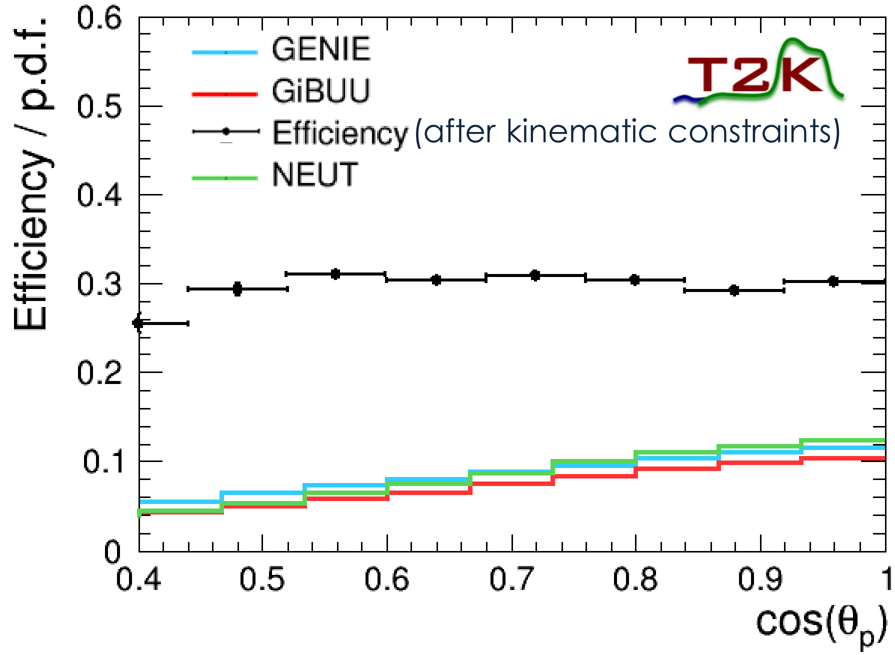
$$\frac{d\sigma}{dx_i} = \frac{N_{sig}}{\Phi_\nu T \epsilon_i}$$

- But how do we know ϵ for a bin of the STV? We've integrated over the particle kinematics!

- Can only get ϵ by using a model to predict the particle kinematics in each bin of the STV → model dependent ϵ → **result biased to input sim**.

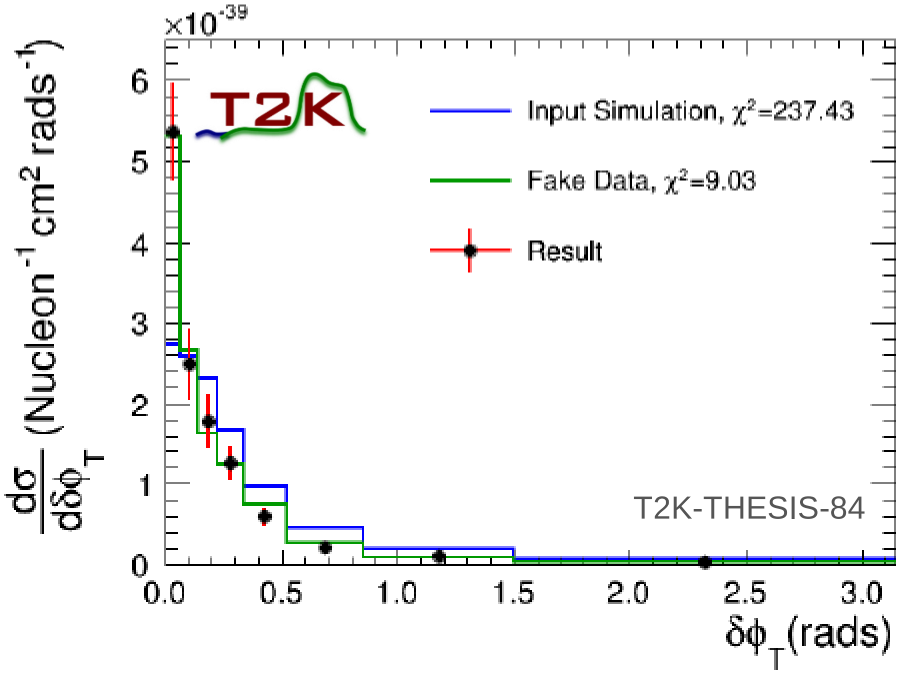
Kinematic constraints

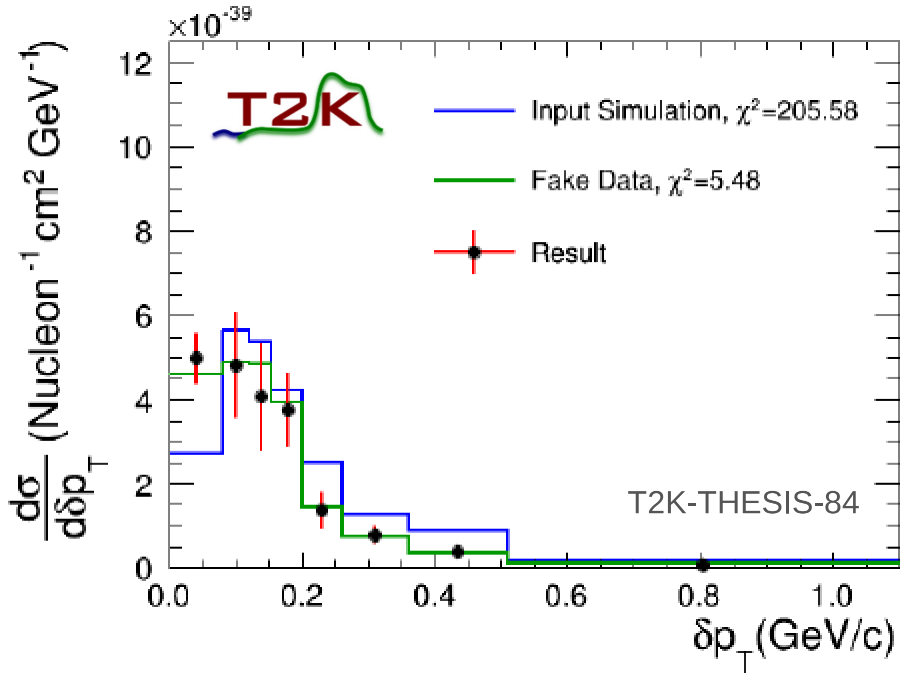




- Kinematic constraints can give us a **flat efficiency** in the underlying kinematics
- In this case the shape of the input model doesn't alter the efficiency → **model independent correction**!
- Essential that experiments ensure unbiased efficiency corrections or we won't learn anything!

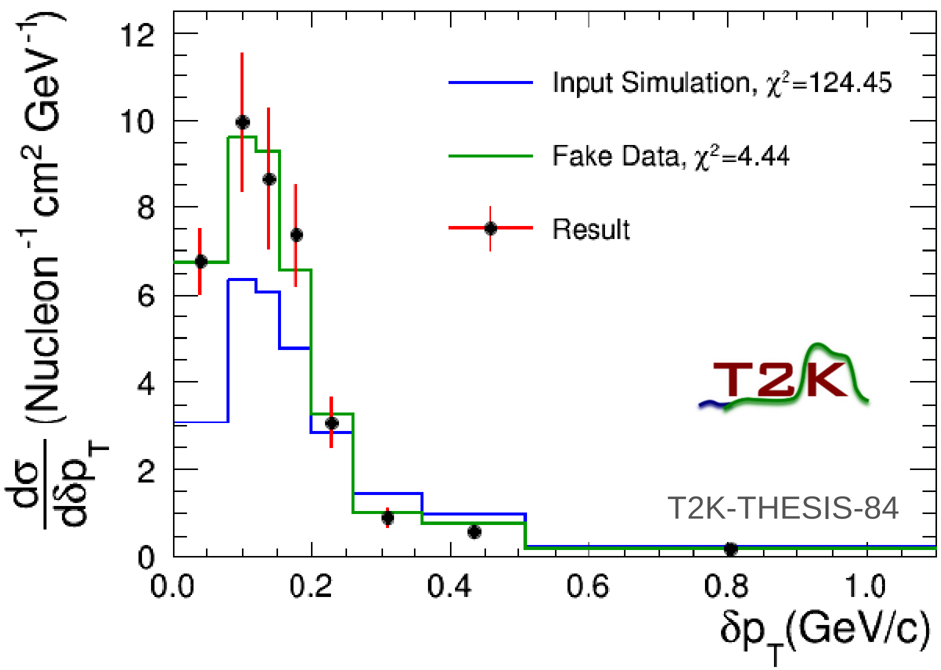
Can we trust the results?

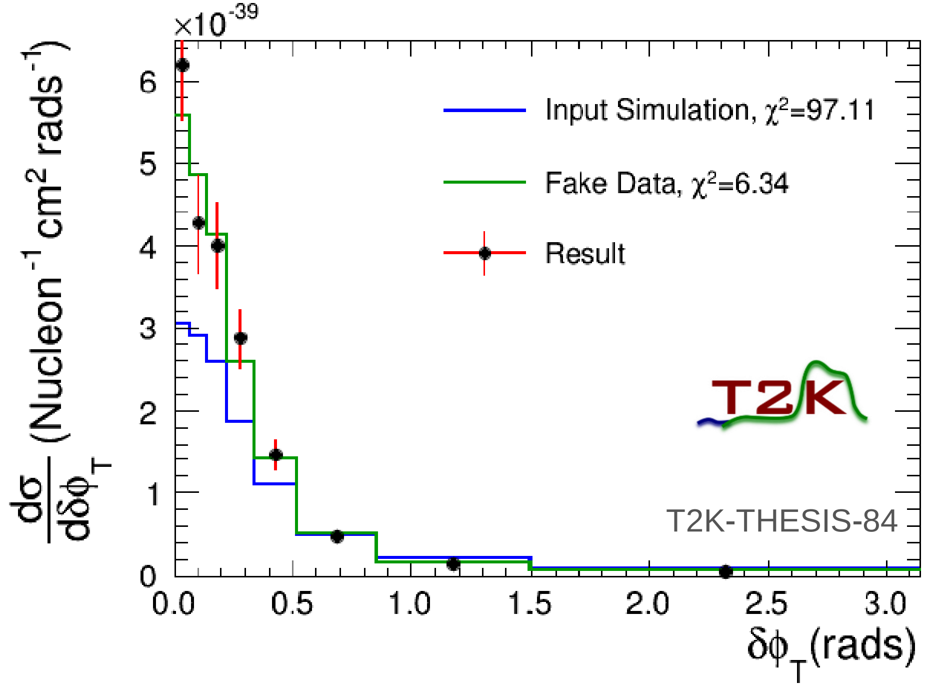




- Yes! Extensive care was taken to avoid model dependence.
- Above is an example of extracting a cross section from fake data produced from GENIE using our NEUT reference model as a template.

Can we trust the results?





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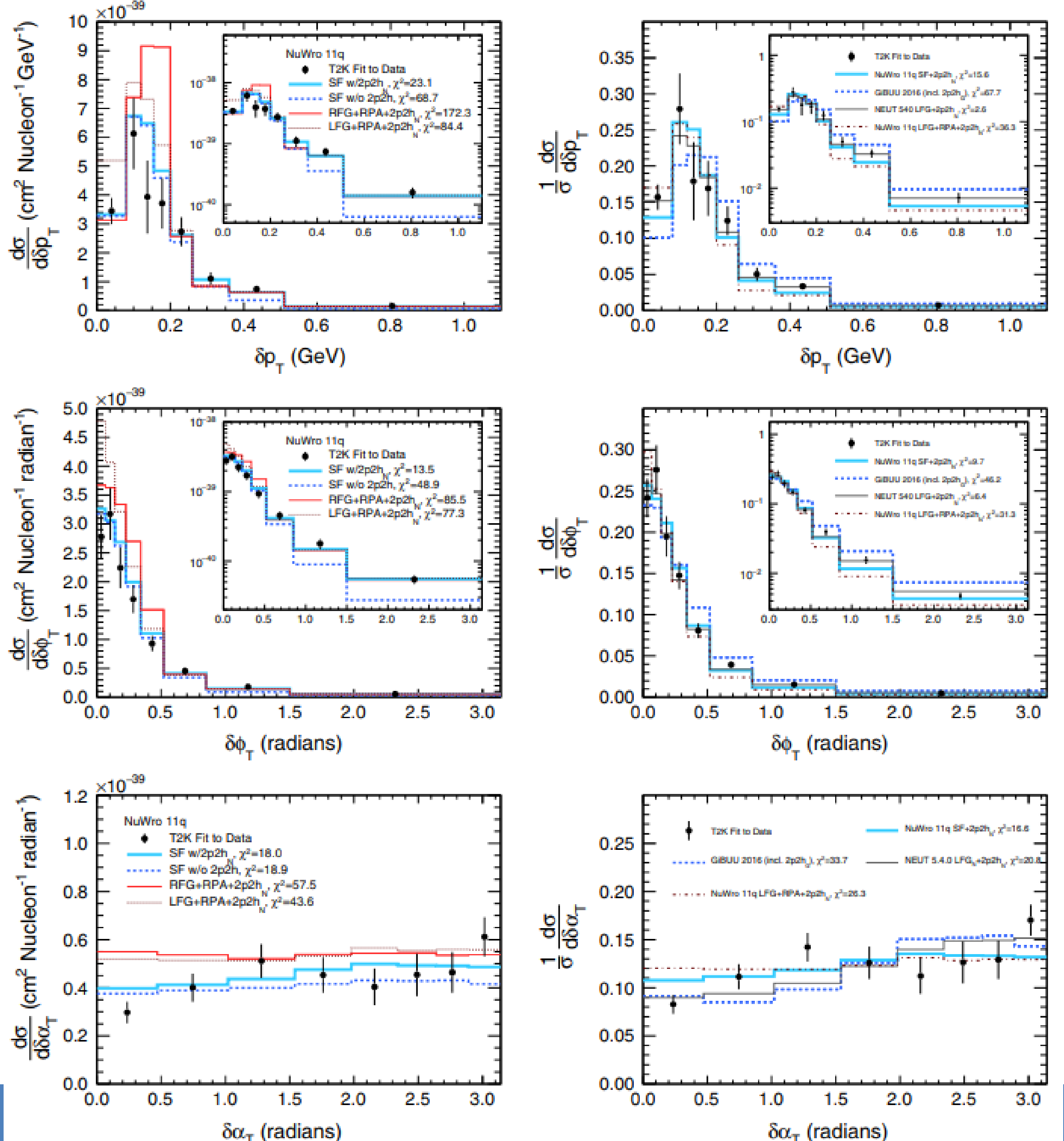
More from T2K

arXiv: 1802.05078



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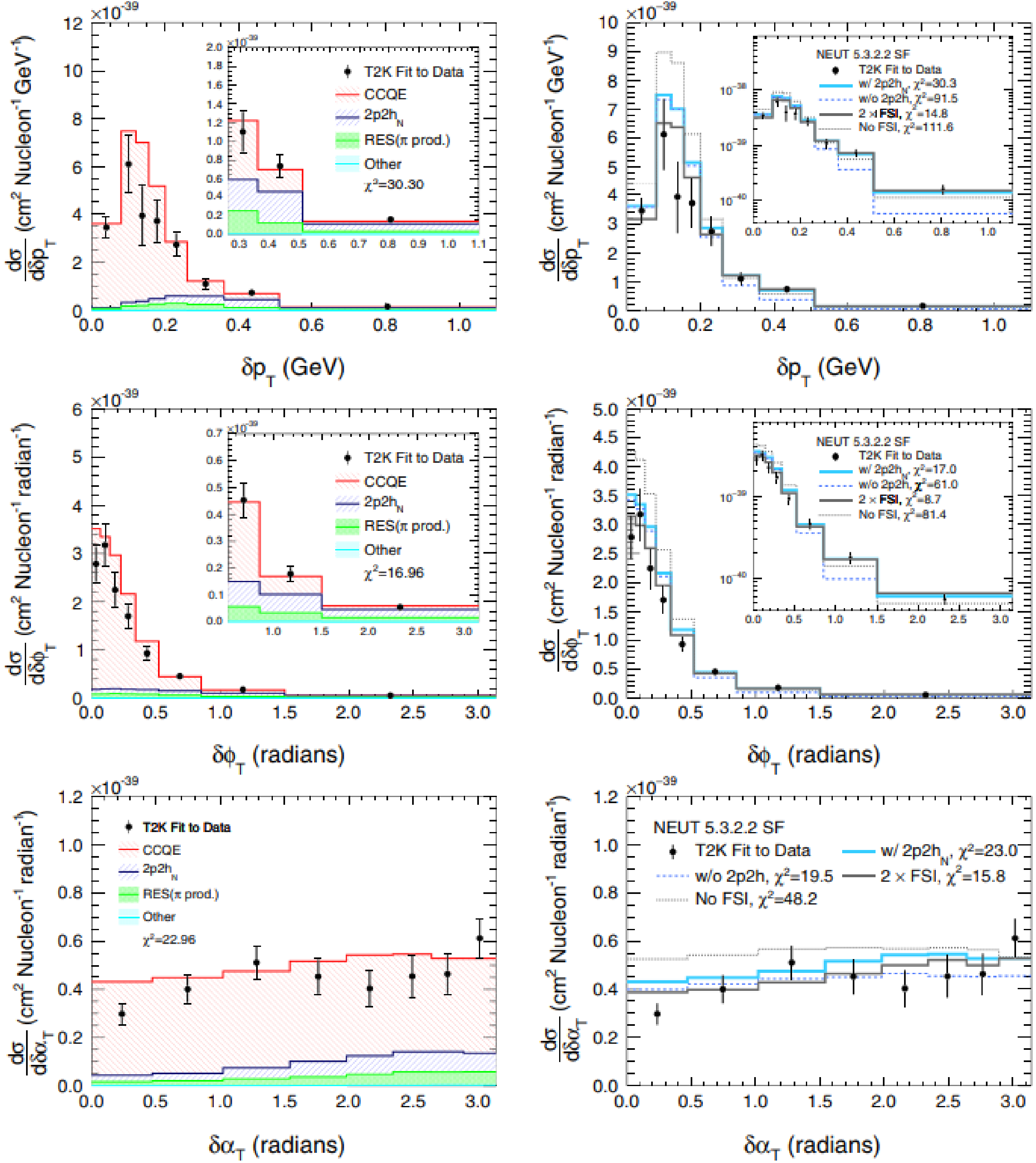
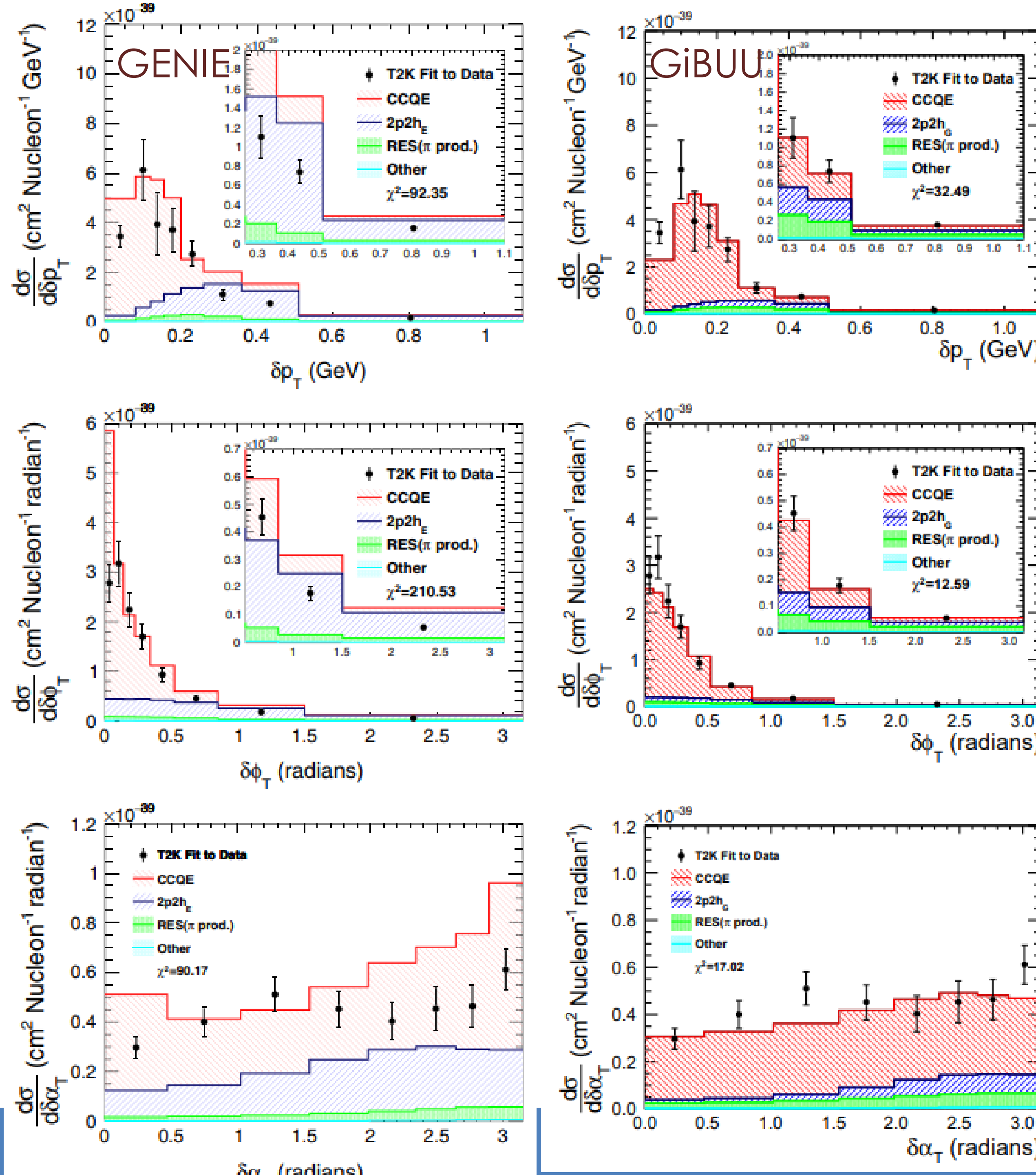


More from T2K

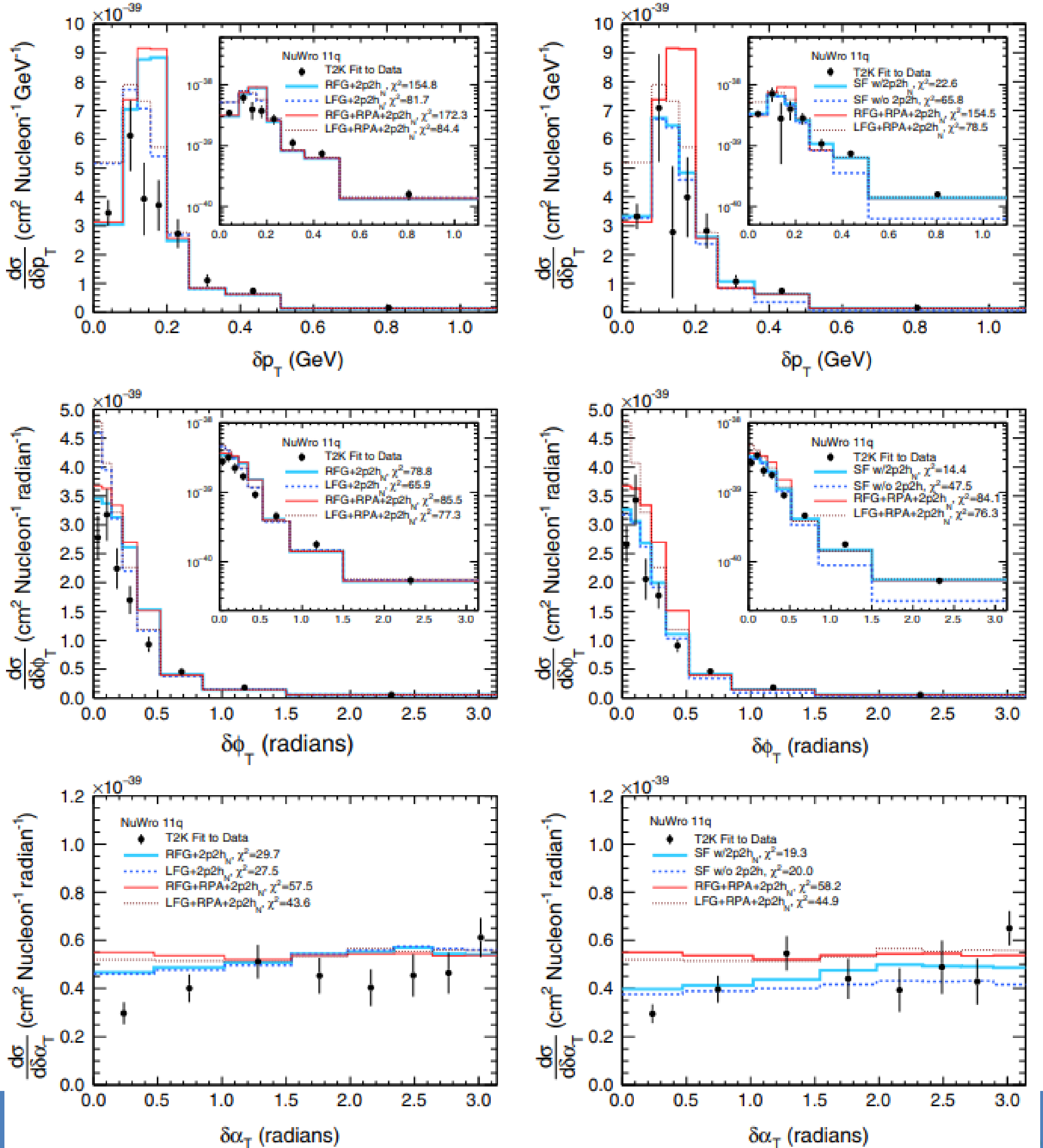
arXiv: 1802.05078

arXiv: 1804.09488



More from T2K

arXiv: 1802.05078



More from T2K

arXiv: 1802.05078

TABLE IX. The full and shape-only χ^2 comparisons to the δp_T result with nominal and no regularization. The table is ordered by the size of the no-regularization shape-only χ^2. More details of these models can be found in Sec. IV A.

	Full		Shape Only	
Generator	No Reg.	Nom. Reg.	No Reg.	Nom. Reg.
NEUT 5.4.0 ($\text{LFG}_N + 2p2h_N$)	31.6	30.4	3.38	2.60
NEUT 5.3.2.2 ($\text{SF} + 2p2h_N + 2 \times \text{FSI}$)	15.9	14.8	11.0	10.1
NEUT 5.3.2.2 ($\text{SF} + 2p2h_N$)	31.9	30.3	16.6	15.5
NuWro 11q ($\text{SF} + 2p2h_N$)	22.6	23.1	16.8	15.6
NuWro 11q ($\text{LFG} + 2p2h_N$)	81.5	81.7	39.0	15.6
NuWro 11q ($\text{LFG} + \text{RPA} + 2p2h_N$)	78.5	84.4	39.9	36.3
NEUT 5.3.2.2 ($\text{SF} + 2p2h_N + \text{No FSI}$)	114	112	42.9	41.4
GENIE 2.12.4 ($\text{RFG} + 2p2h_E$)	92.9	92.4	47.9	47.7
NuWro 11q (SF w/o 2p2h)	65.8	68.7	55.4	54.8
NEUT 5.3.2.2 (SF w/o 2p2h)	93.3	91.5	61.2	59.6
GiBUU 2016 ($\text{LFG} + 2p2h_G$)	77.0	78.9	66.1	59.6
NuWro 11q ($\text{RFG} + 2p2h_N$)	150	155	67.2	69.0
NuWro 11q ($\text{RFG} + \text{RPA} + 2p2h_N$)	155	172	68.6	70.4
GENIE 2.12.4 (RFG w/o 2p2h)	94.6	97.8	74.1	76.2

GiBUU 2017 T=0 32.5

More from T2K

arXiv: 1802.05078

TABLE X. The full and shape-only χ^2 comparisons to the $\delta\phi_T$ result with nominal and no regularization. The table is ordered by the size of the no-regularization shape-only χ^2. More details of these models can be found in Sec. IV A.

	Full		Shape Only	
Generator	No Reg.	Nom. Reg.	No Reg.	Nom. Reg.
NEUT 5.4.0 ($LFG_N + 2p2h_N$)	39.0	36.7	7.55	6.40
NEUT 5.3.2.2 ($SF + 2p2h_N + 2 \times FSI$)	9.95	8.70	7.71	6.57
NEUT 5.3.2.2 ($SF + 2p2h_N$)	18.4	17.0	9.59	8.45
NuWro 11q ($SF + 2p2h_N$)	14.4	13,5	10.8	9.70
NuWro 11q ($LFG + 2p2h_N$)	66.8	65.9	29.7.0	29.0
NEUT 5.3.2.2 ($SF + 2p2h_N$ + No FSI)	81.5	81.4	30.5	30.1
NuWro 11q ($LFG + RPA + 2p2h_N$)	76.3	77.3	32.1	31.3
NuWro 11q ($RFG + RPA + 2p2h_N$)	84.7	85.5	40.1	39.4
NuWro 11q (SF w/o 2p2h)	47.5	48.9	42.1	42.3
NuWro 11q ($RFG + 2p2h_N$)	79.3	78.8	42.6	42.0
NEUT 5.3.2.2 (SF w/o 2p2h)	60.6	61.0	43.7	43.8
GiBUU 2016 ($LFG + 2p2h_G$)	43.4	44.1	45.6	46.2
GENIE 2.12.4 ($RFG + 2p2h_E$)	208	211	114	115
GENIE 2.12.4 (RFG w/o 2p2h)	192	193	128	128

GiBUU 2017 T=0 12.6

More from T2K

arXiv: 1802.05078

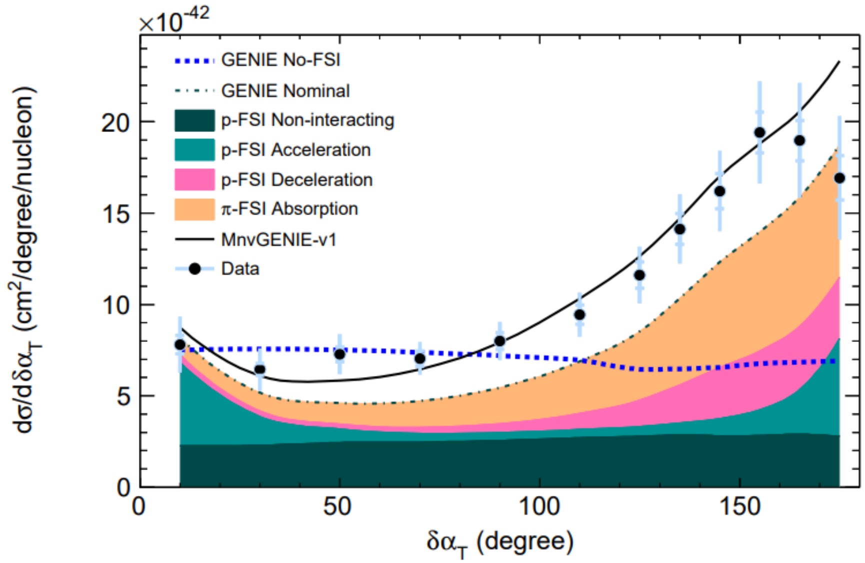
TABLE XI. The full and shape-only χ^2 comparisons to the $\delta\alpha_T$ result with nominal and no regularization. The table is ordered by the size of the no-regularization shape-only χ^2. More details of these models can be found in Sec. IV A.

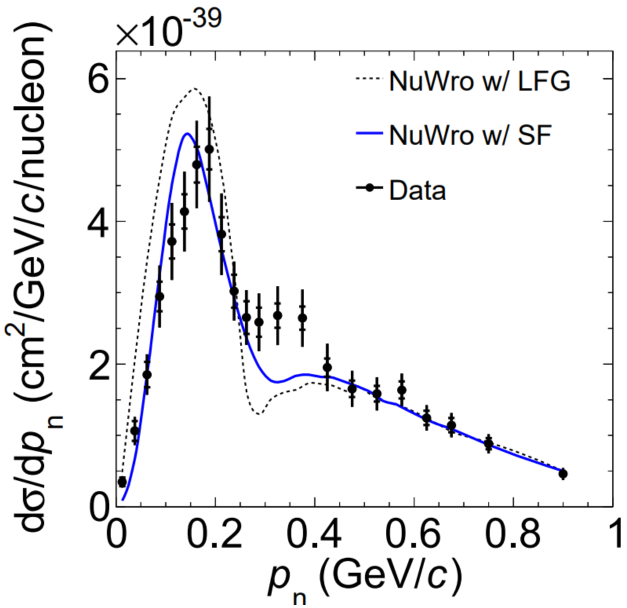
	Full		Shape only	
Generator	No reg.	Nom. reg.	No reg.	Nom. reg.
NEUT 5.3.2.2 (SF + $2p2h_N$ + 2 × FSI)	17.7	15.8	16.3	14.2
NuWro 11q (SF + $2p2h_N$)	19.3	18.0	18.6	16.6
NEUT 5.3.2.2 (SF + $2p2h_N$)	24.8	23.0	18.8	16.8
NuWro 11q (LFG + $2p2h_N$)	29.6	27.5	19.0	16.9
NuWro 11q (RFG + $2p2h_N$)	31.6	29.7	20.7	18.7
NEUT 5.3.2.2 (SF w/o 2p2h)	21.0	19.5	21.7	19.6
NEUT 5.4.0 (LFG_N + $2p2h_N$)	63.0	60.7	22.8	20.8
NuWro 11q (SF w/o 2p2h)	20.0	18.9	23.4	21.4
NEUT 5.3.2.2 (SF + $2p2h_N$ + No FSI)	49.9	48.2	28.3	26.3
NuWro 11q (LFG + RPA + $2p2h_N$)	44.9	43.6	28.6	26.3
GiBUU 2016 (LFG + $2p2h_G$)	41.3	40.2	35.5	33.7
NuWro 11q (RFG + RPA + $2p2h_N$)	58.2	57.5	38.1	35.8
GENIE 2.12.4 (RFG + $2p2h_E$)	88.5	90.2	40.1	39.6
GENIE 2.12.4 (RFG w/o 2p2h)	38.6	72.0	62.6	64.1

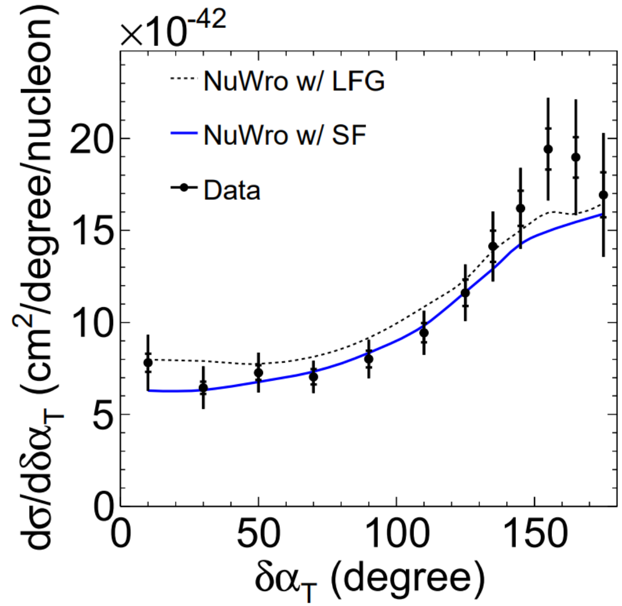
GiBUU 2017 T=0 17.9

More from MINERvA

arXiv: 1805.05486

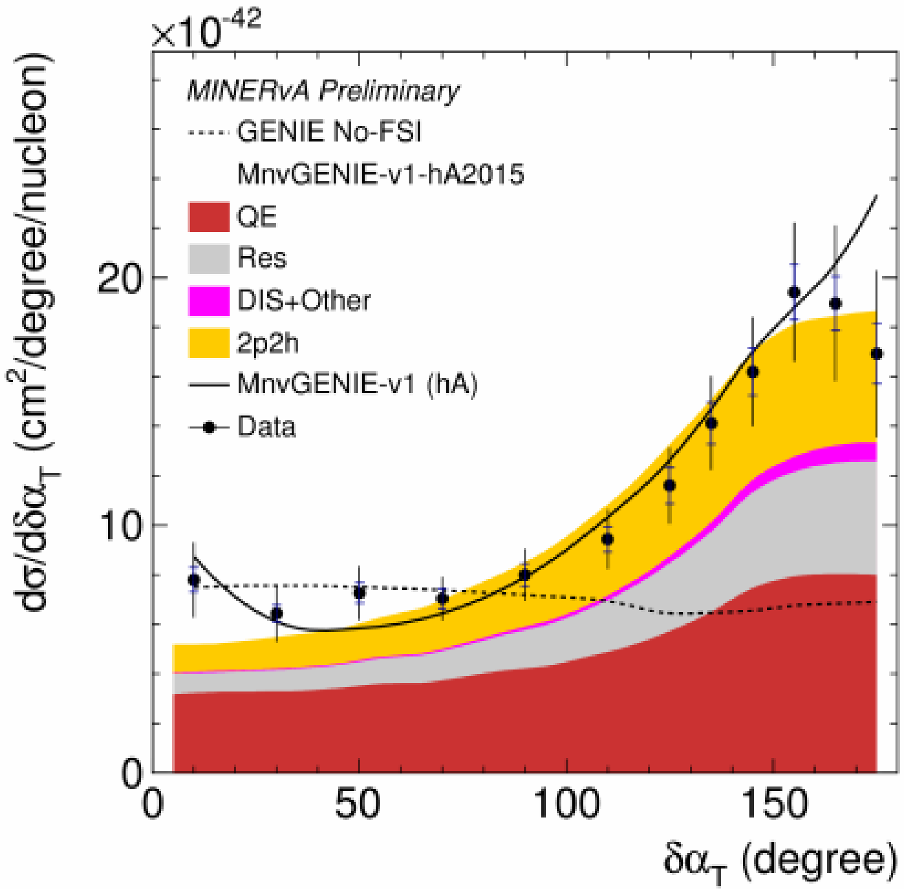


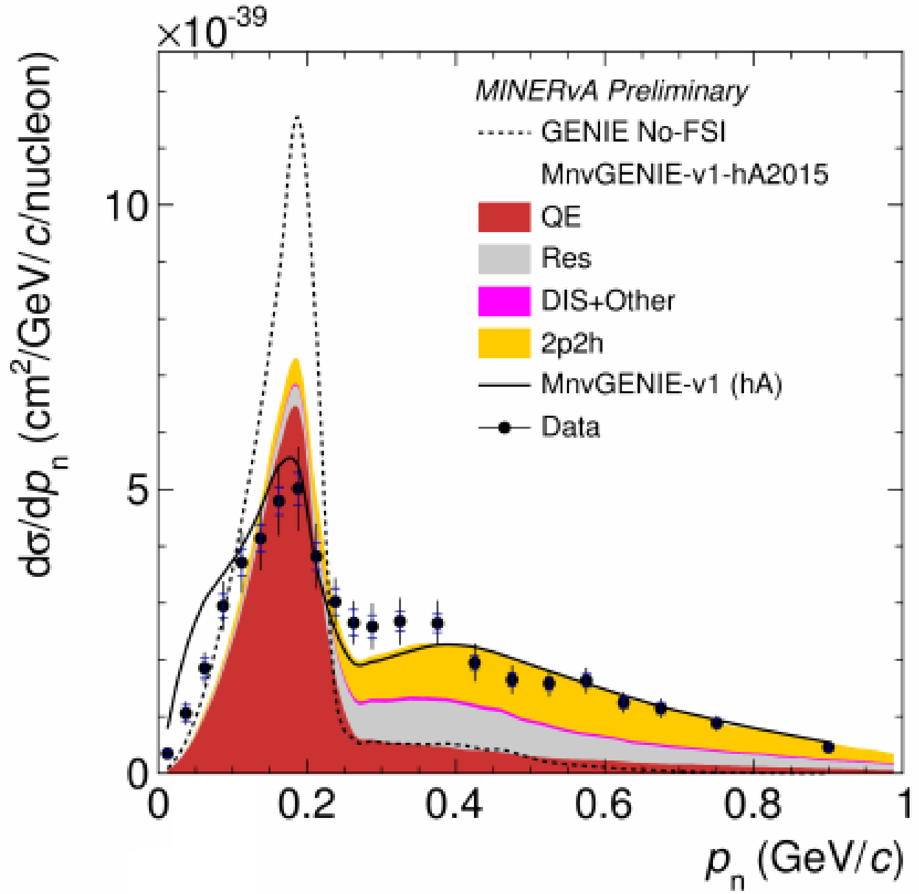




More from MINERvA

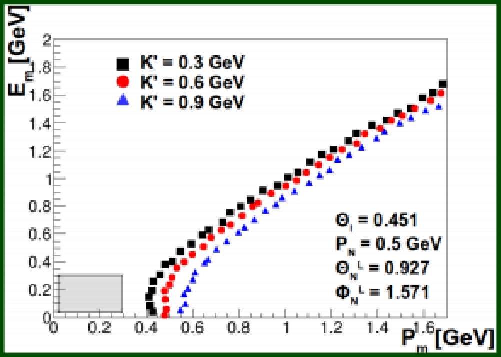
Xianguo Lu Fermilab wine and cheese





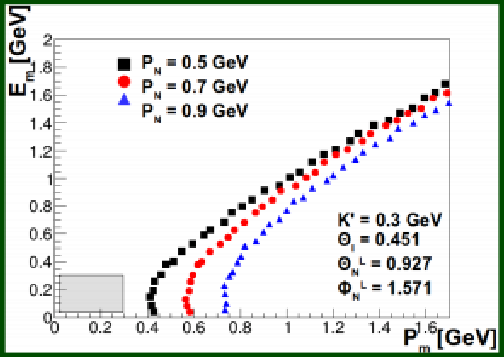
General Remarks and Conclusions

Muon Momentum



The data represented by the black squares are the same for each plot. The grey box represents the mountains and foothills regions. The parameters that are fixed are listed in the corner of each plot.

Proton Momentum



Regardless of what observable is being manipulated, as you increase the momentum of the neutrino, the rivers become more linear and quickly enter the grasslands region.

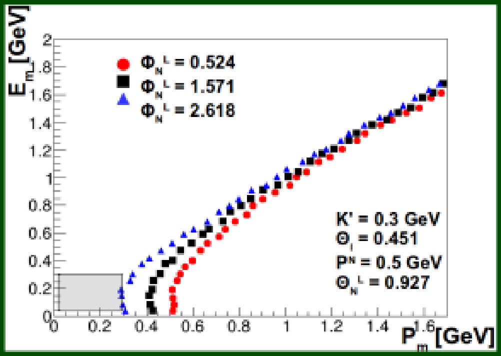
Analyzing the Nuclear Recoil System in Neutrino-Nucleus Reactions

T.W. Donnelly[1], K. Mahn[2], *J. Morrison*[2], J.W. Van Orden[3]

Even for low neutrino momentum, most of the rivers that have been calculated lie above the valence mountain region, where the bulk of the neutrino-nucleus cross section lives.

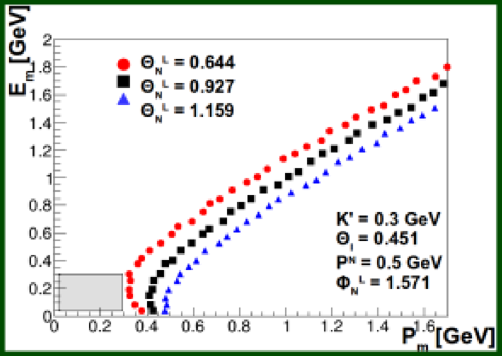
More work will need to be done in order to better understand the nuclear physics of the grasslands region and how the neutrino-nucleus cross section is distributed across these interactions.

Proton Azimuthal Angle



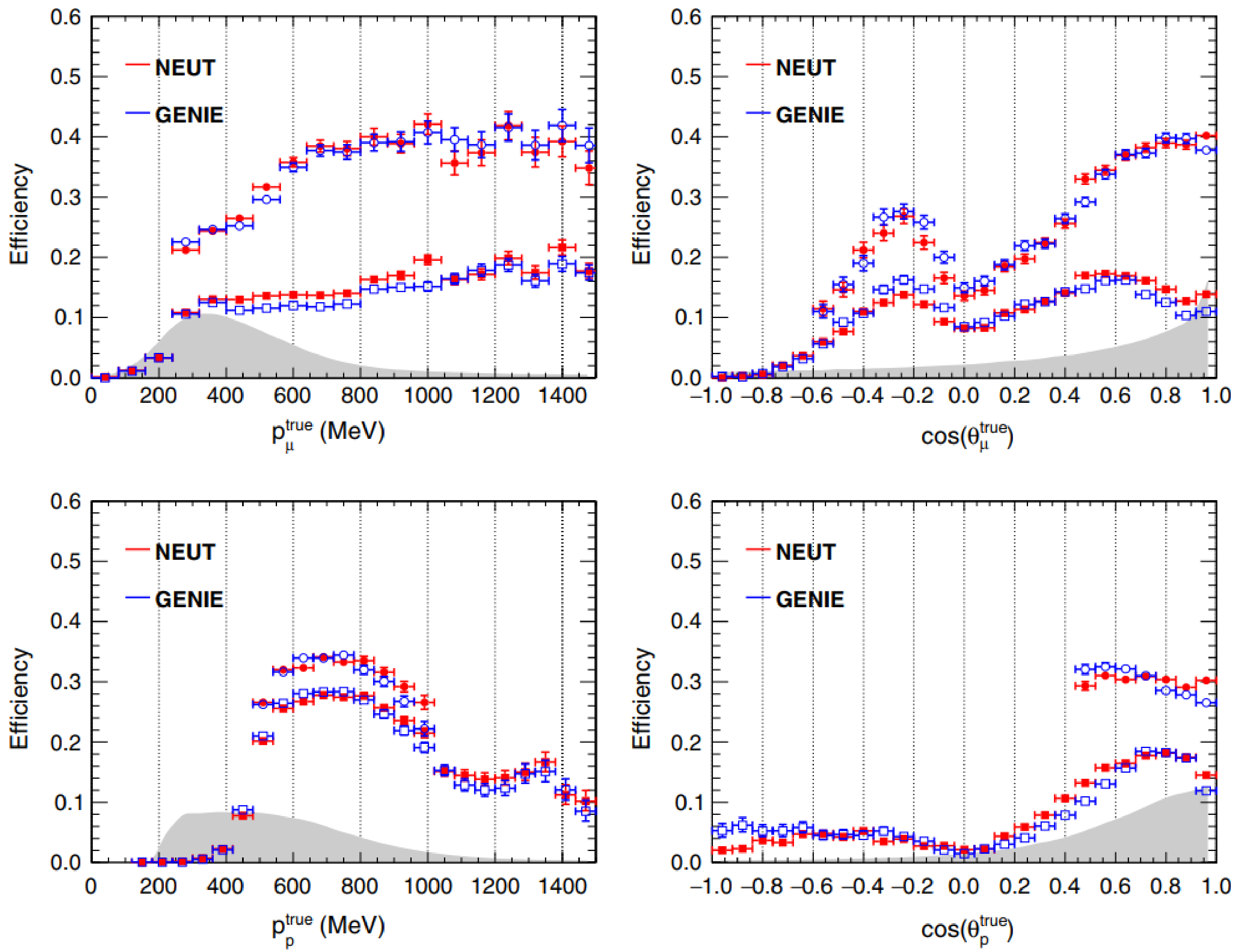
In order for experiments to probe the phase space covered by the valence mountains, sensitivies will likely need to be pushed lower. More studies will need to be performed to find how low the sensitivies must be.

Proton Polar Angle

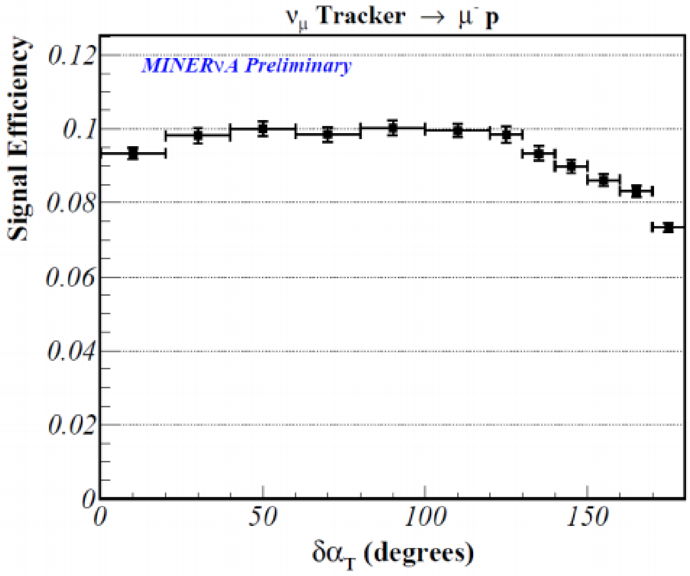


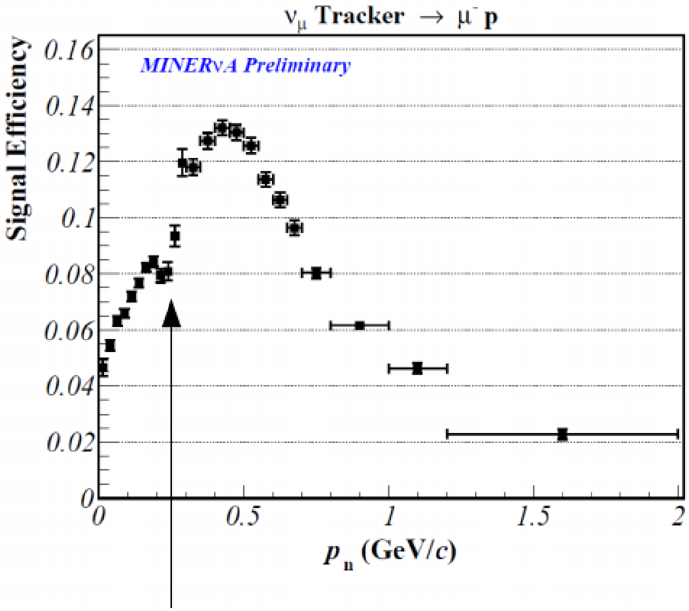
T2K Efficiency

arXiv: 1802.05078



MINERvA Efficiency / smearing





Overall efficiency: ~ 9%

Xianguo Lu, Oxford (Fermilab wine and cheese)

Peak region (see later slides)