Pion Contributions to “0π” events

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with helpful commentary from S. Dolan
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2019-06-06

WG Charge

Comparison of Pion production contributions to 0pi final states:

- **What it is:** Neutrino data to probe "quasielastic and dip" region response are necessarily contaminated with pion production where the pion is absorbed or otherwise "stuck" inside the nucleus and does not appear in the final state.
- **Work goals:** understand specifically how the convolution of primary pion production processes and FSI models in different generators results in different predictions:
  - Compare primary production models without FSI.
  - To what extent is the difference in the primary production model versus being in the FSI? Can we identify specific kinematic regions with differences between models?
  - Are there approaches or tests that could improve the reliability of this prediction in generators?

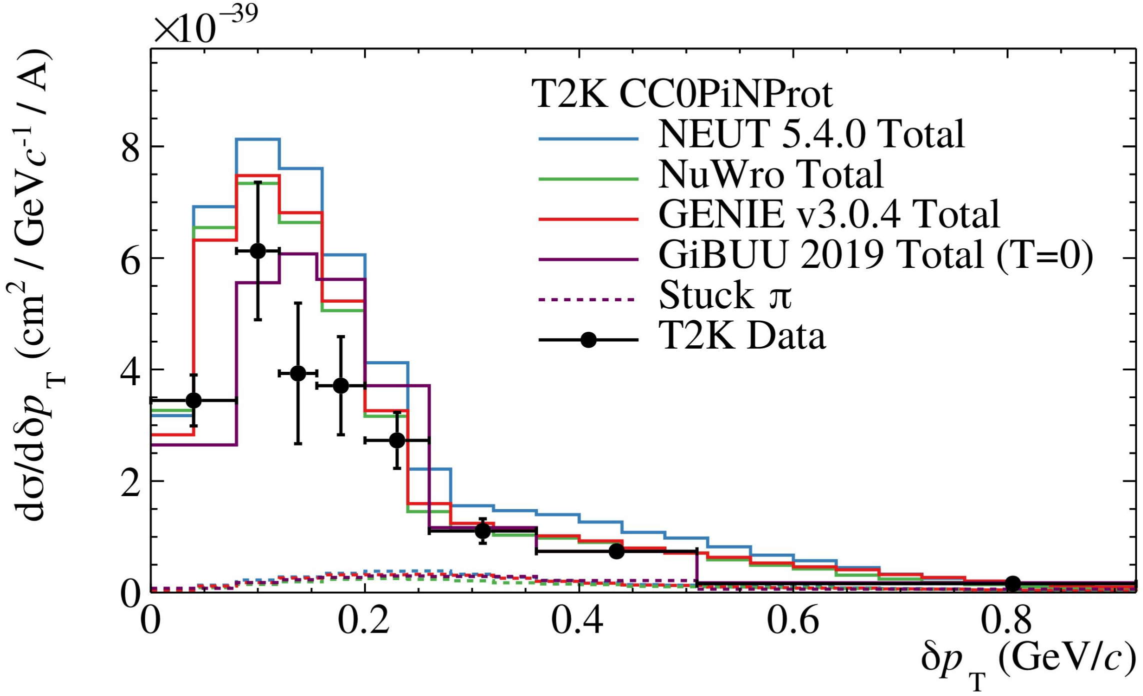
Questions we're going to try to ask:

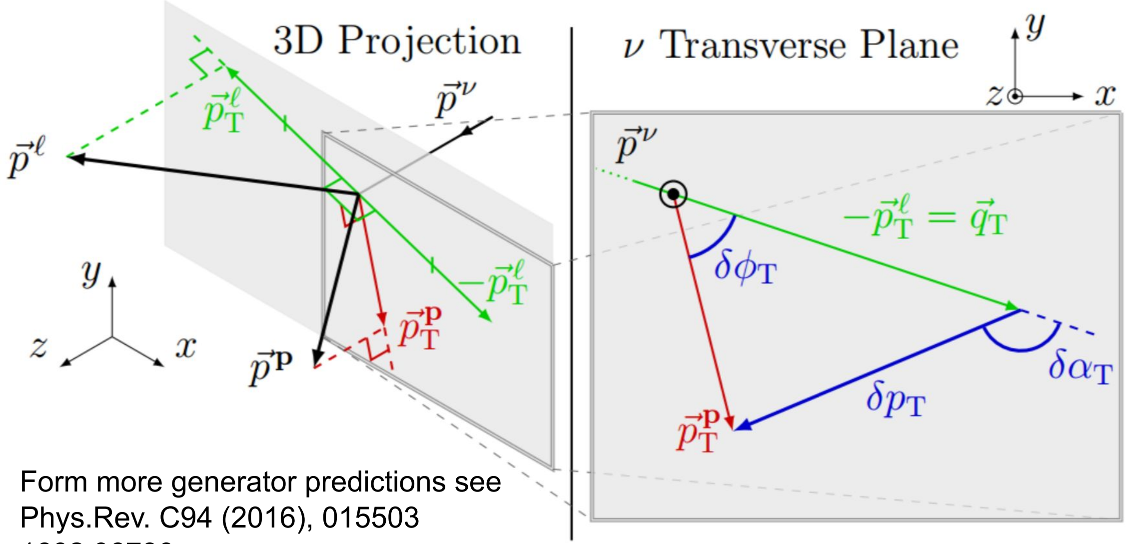
- How do the absolute predictions for stuck pions compare across different generators?
  - Do they show up in the same kinematic regions?

- How do the relative predictions for stuck pions compare across different generators?
  - Are the fractions comparable in the same kinematic regions?

Approach

- Compare generator predictions of 0Pi signal definitions used by current experiments.
    - Lepton variables unlikely to show much sensitivity, and largely flux dependent
    - No pion variables in a 0Pi sample...
    - Look at lepton-hadron correlations!
    - Look at energy ‘evolution’
- Much of this has been done before, but brought together here for discussion of where might be interesting to go next!
- Try not to overlap with the FSI group too much...



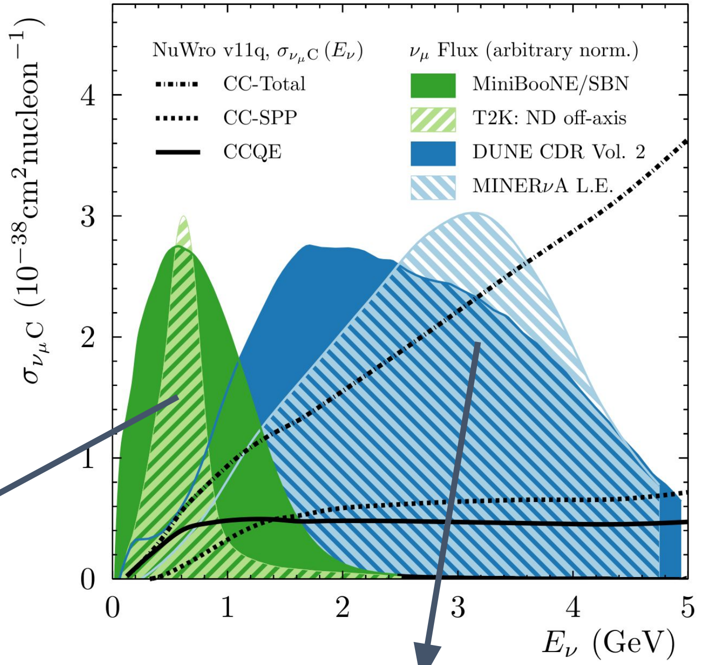


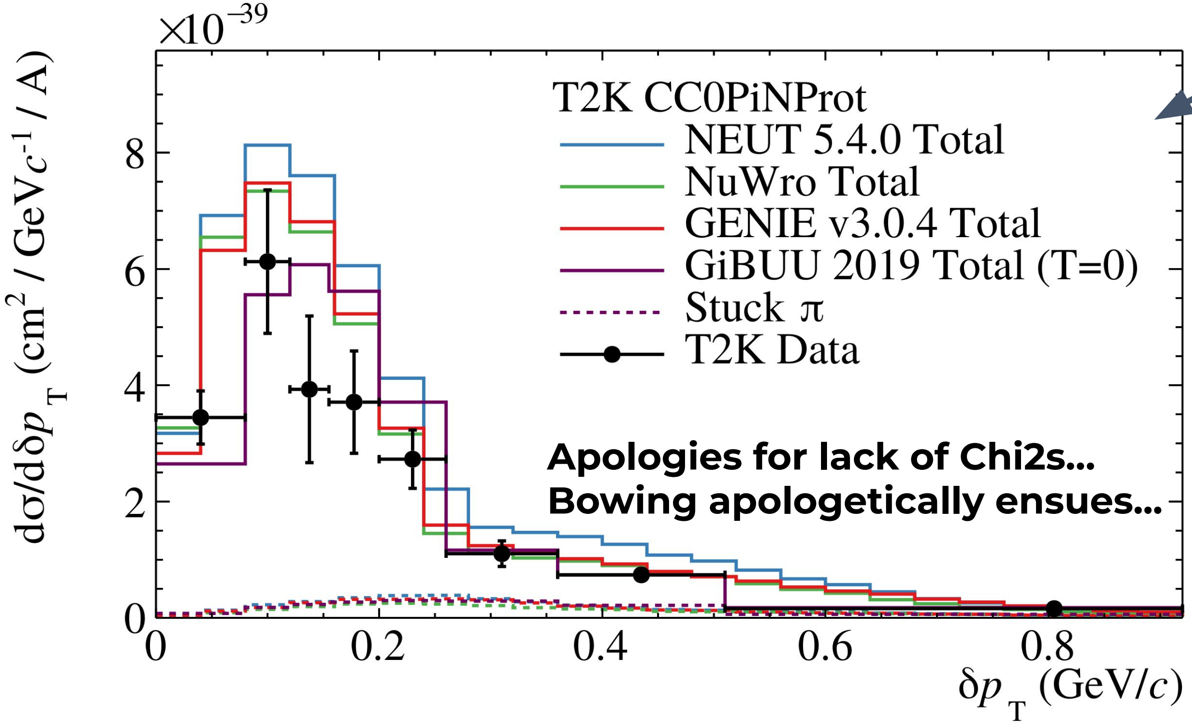
Form more generator predictions see
Phys.Rev. C94 (2016), 015503
1602.06730
1606.04403

https://doi.org/10.1016/j.physrep.2018.08.003

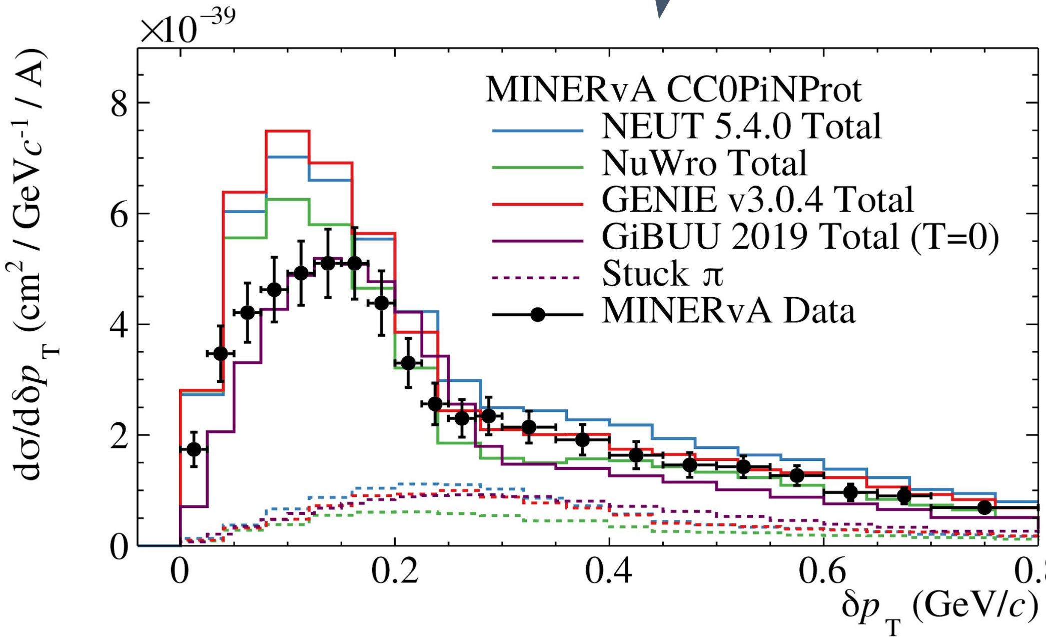
Data Comparison: δp_T

- T2K: 1802.05078
- MINERvA: 1805.05486
- (GENIE norm may not be quite right to a few %, its fine for here, but probably not best to show these plots as is elsewhere)





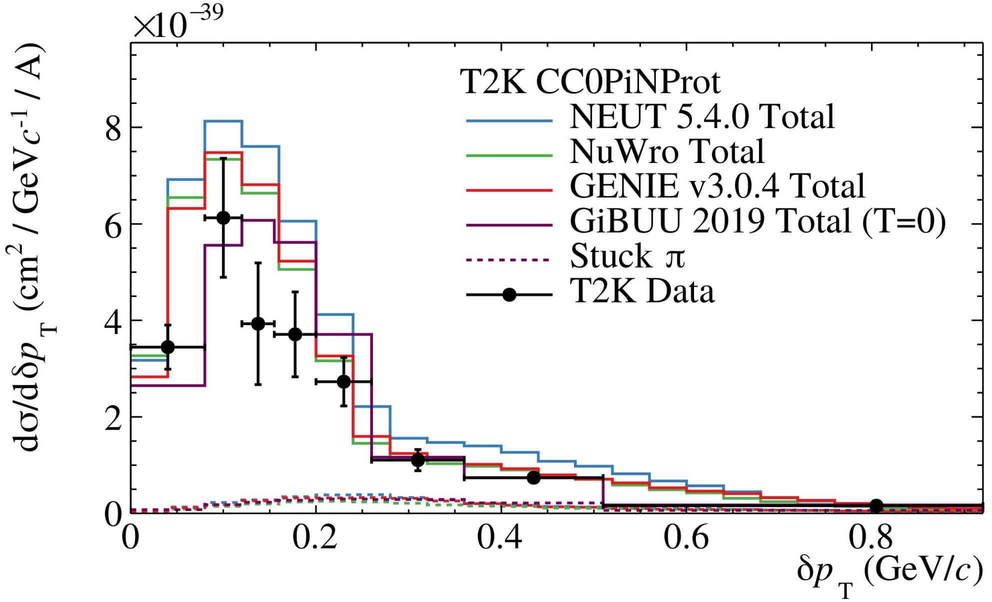
Apologies for lack of Chi2s...
Bowing apologetically ensues...



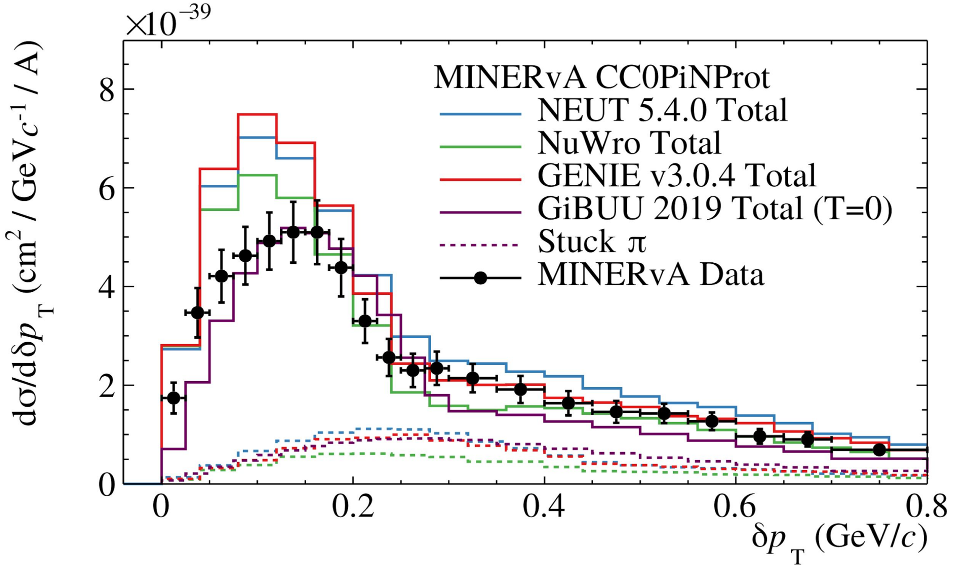
Signal definitions

- T2K: 1802.05078
- MINERvA: 1805.05486
- (GENIE norm may not be quite right to a few %, its fine for here, but probably not best to show these plots as is elsewhere)

500 MeV < pp
250 MeV < pmu, 1 < cos(theta_mu) < -0.6

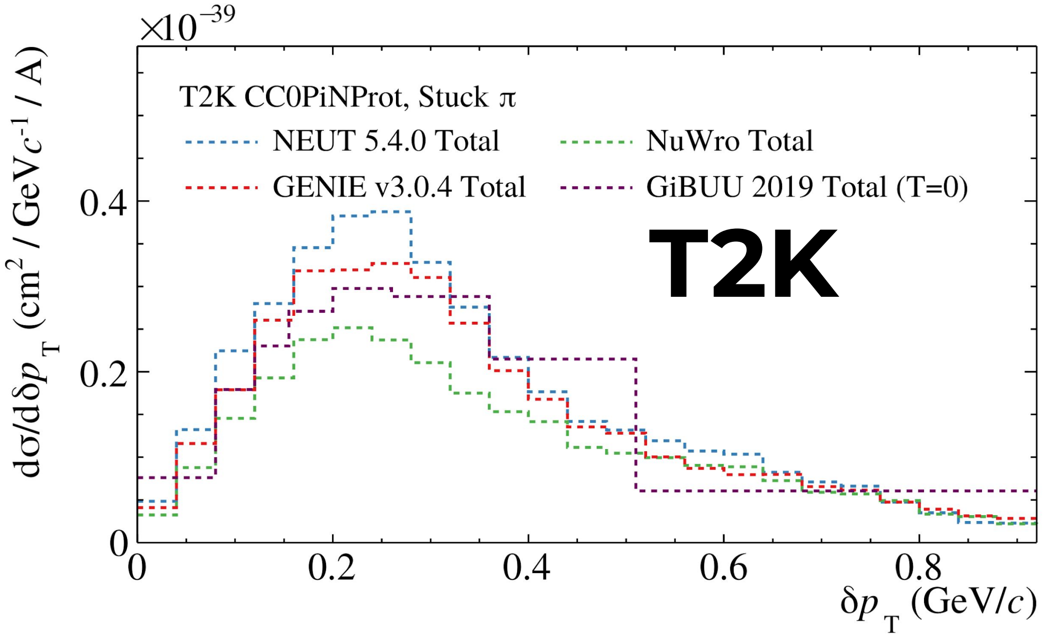


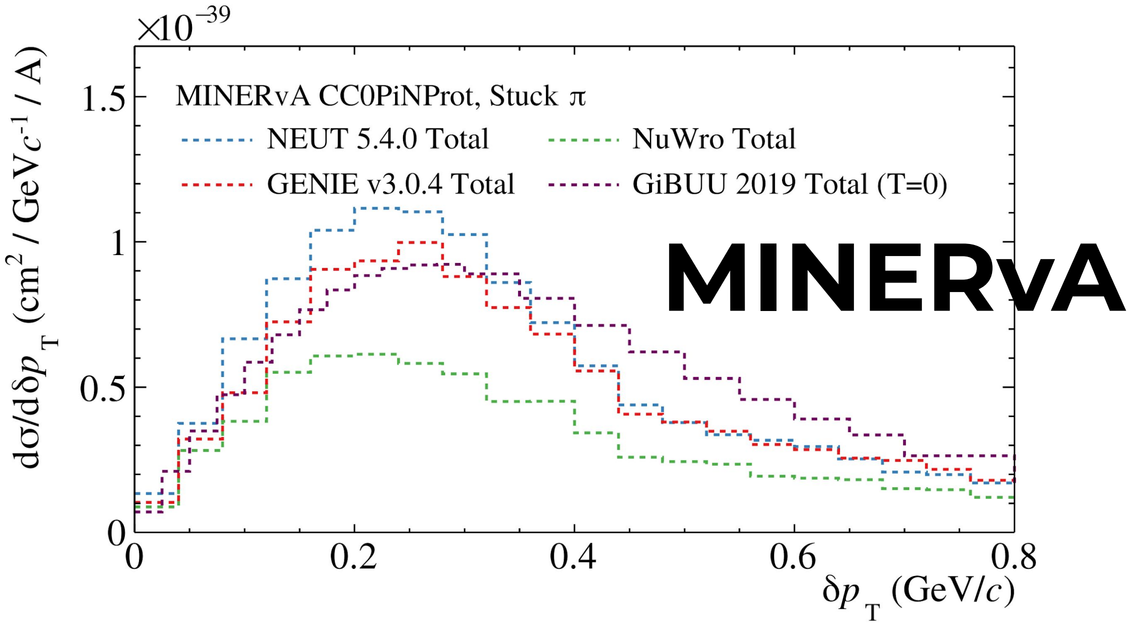
450 < pp < 1200 MeV, 0 < theta_p < 70°
1.5 < pmu < 10 GeV, 0 < theta_mu < 20°

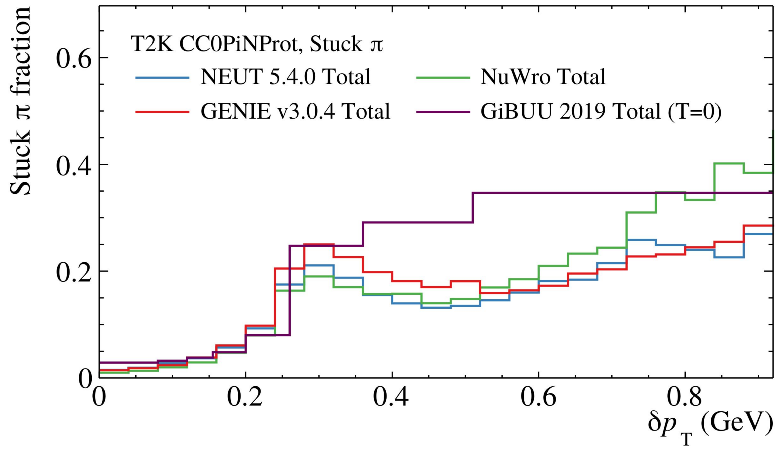


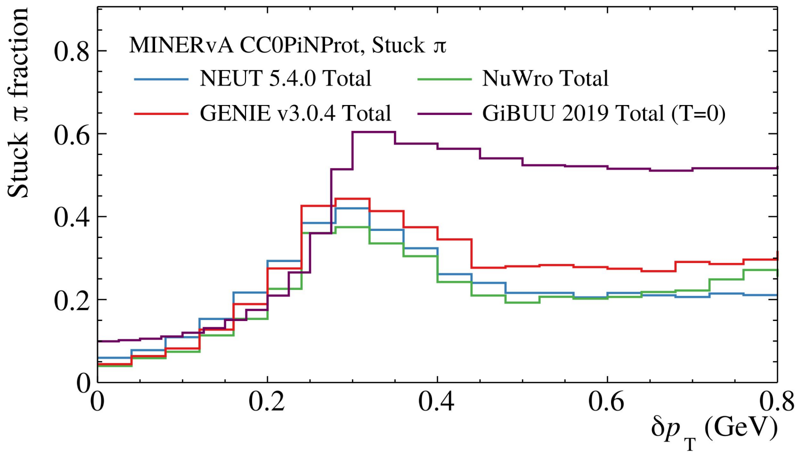
Stuck pion rate: δp_T

- Energy evolution is similar for all generators.
- Total contributions differ, but fractional is similar between generators.
- GiBUU 1pi fraction is higher in the tail due to weaker 2p2h (Isospin of inital NN pairs, T = 0) and strongest absolute SPP/pi abs.



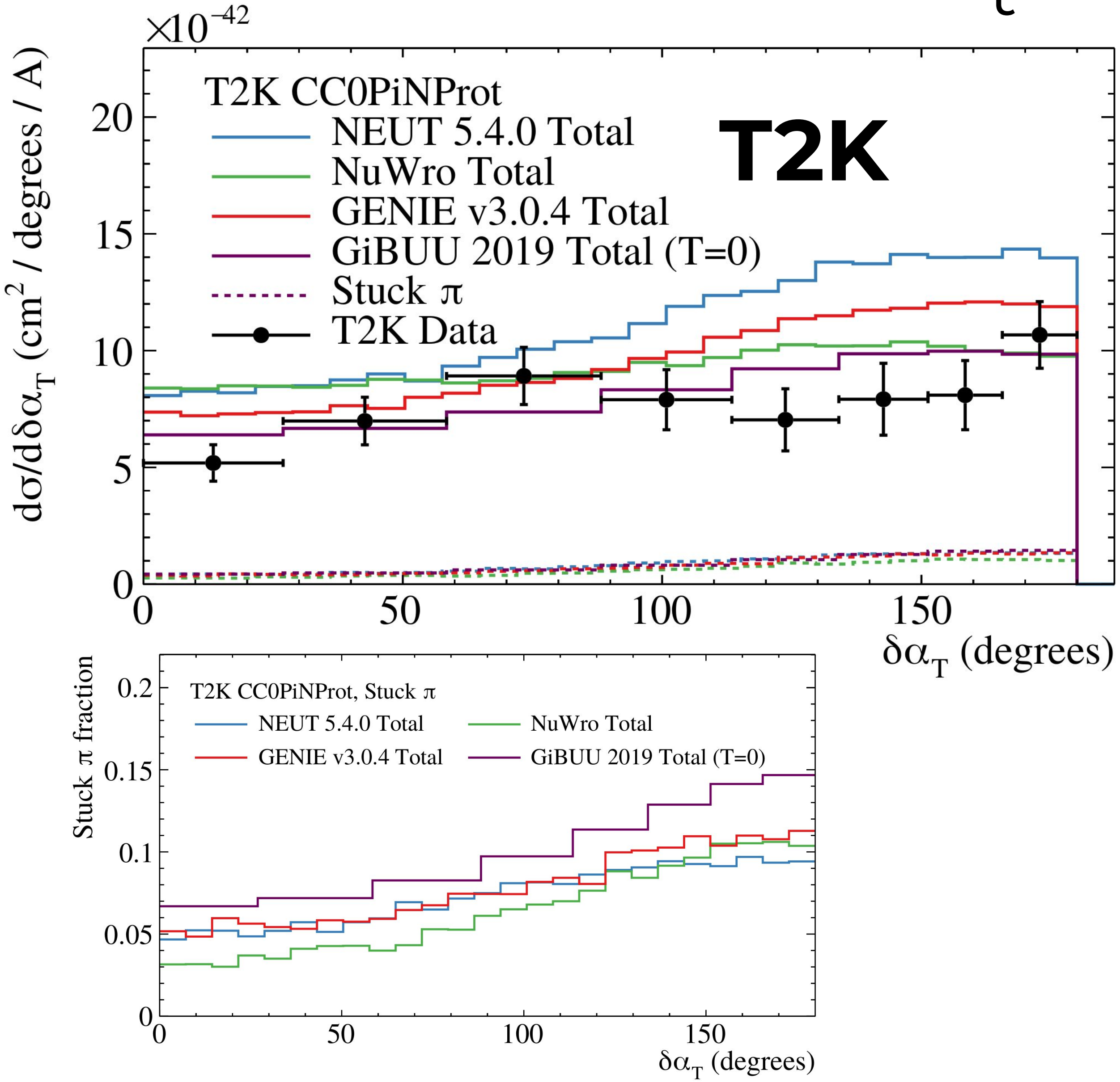


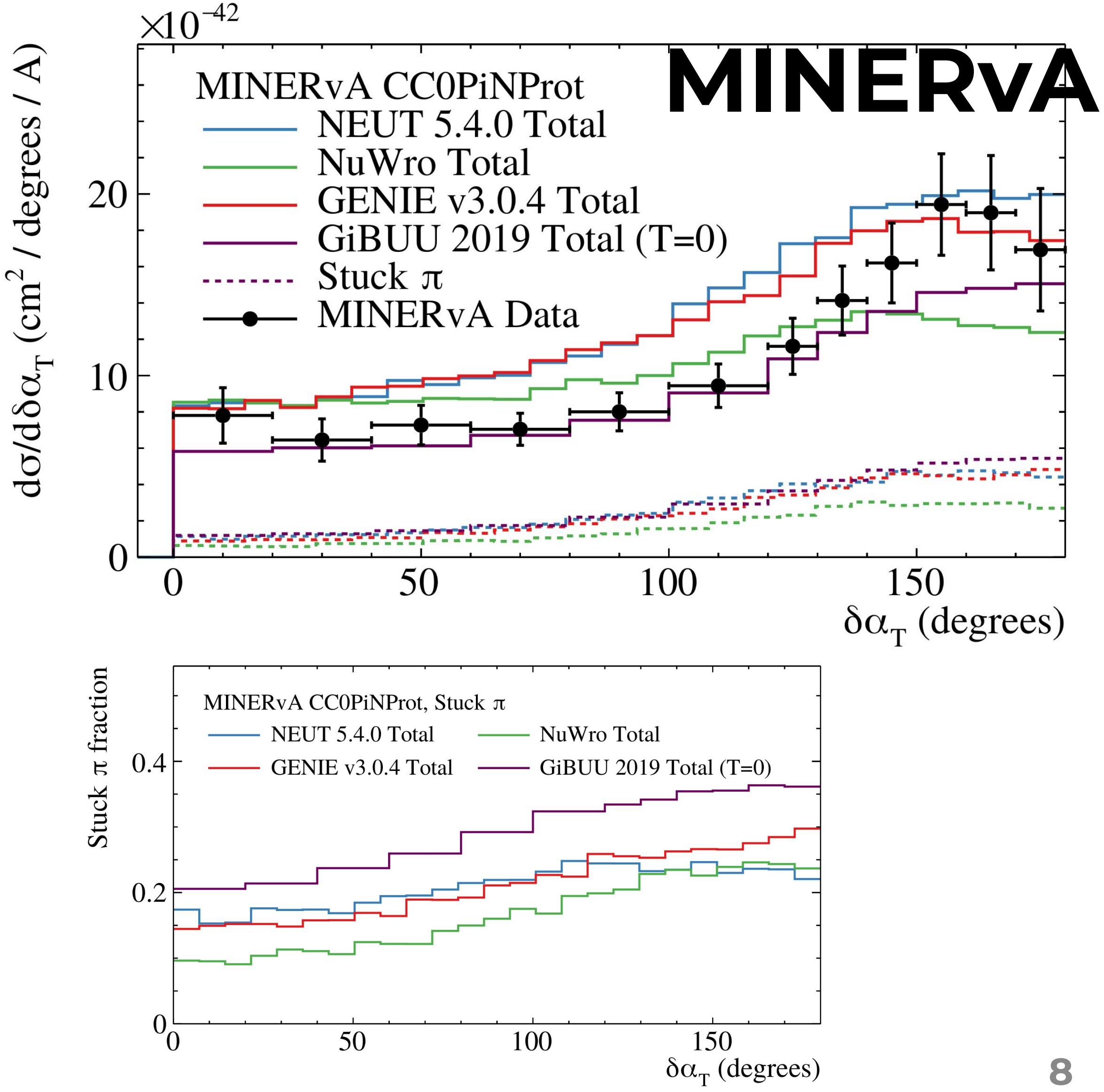




Stuck pion rate: $\delta\alpha_t$

QEL-pure at low **δαt**
FSI and stuck pion rich at higher **δαt**

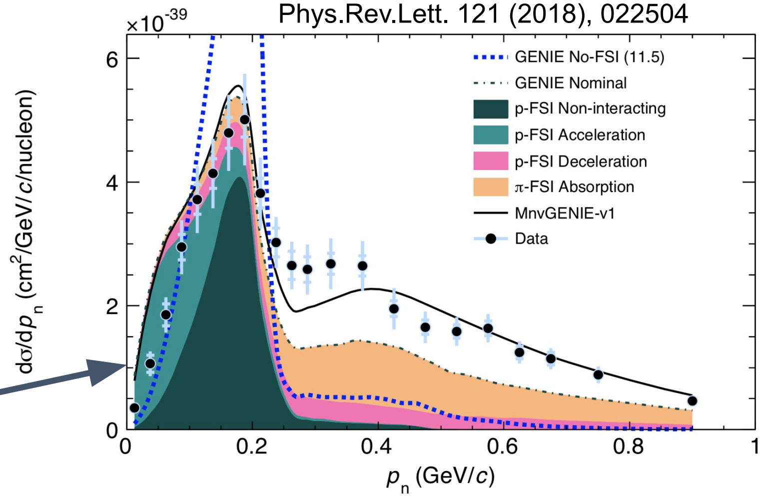


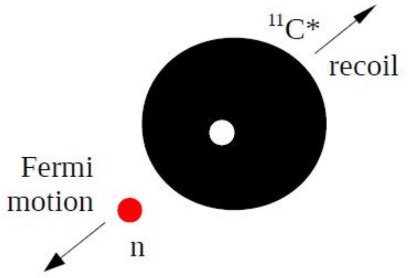


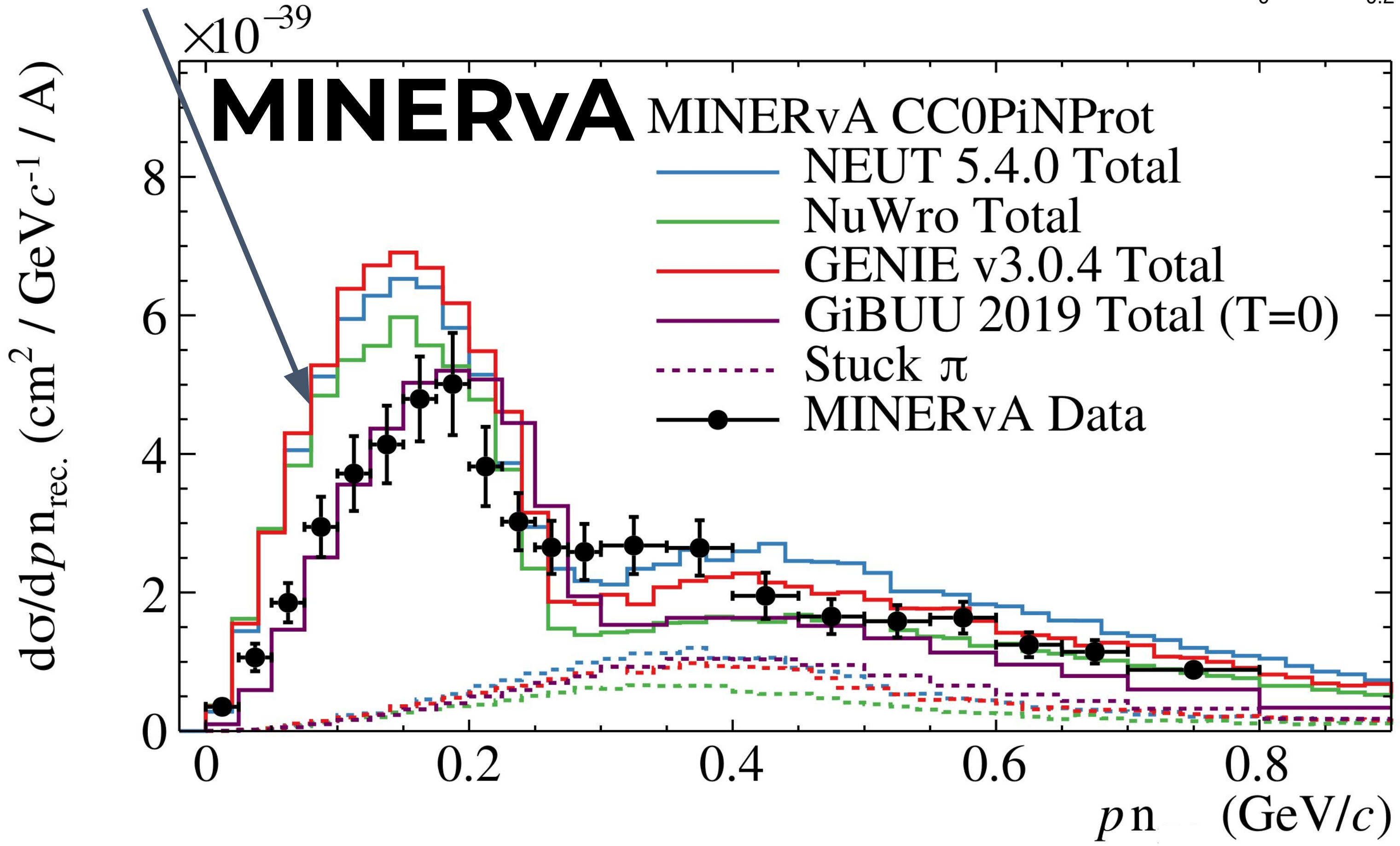
pn

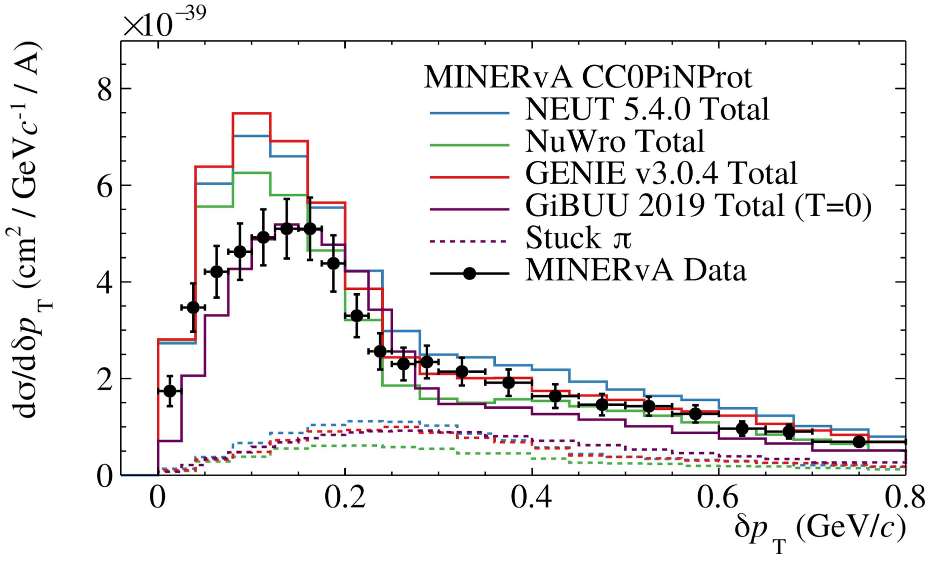
Phys.Rev. C95 (2017) 065501, see definition in BACKUP

- S. Dolan: Relative to dpt, stuck pions more away from QEL peak **(all non-QE, see later, backup)**
- GENIE V304 below no longer has elastic hA, less lumpy



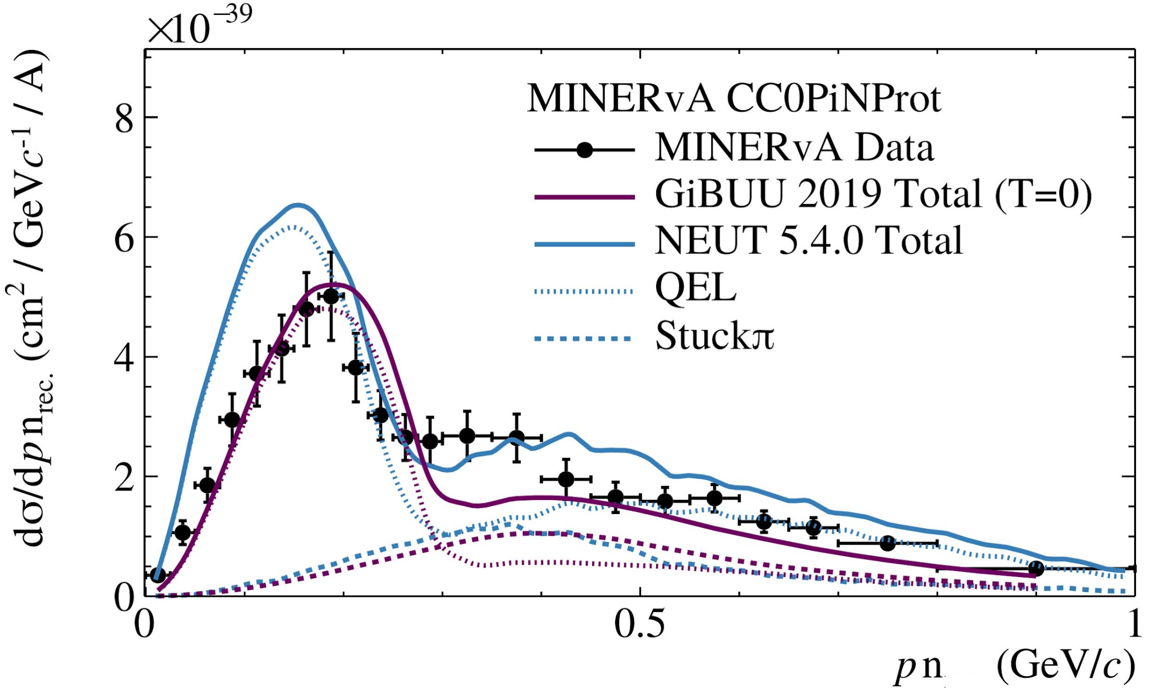


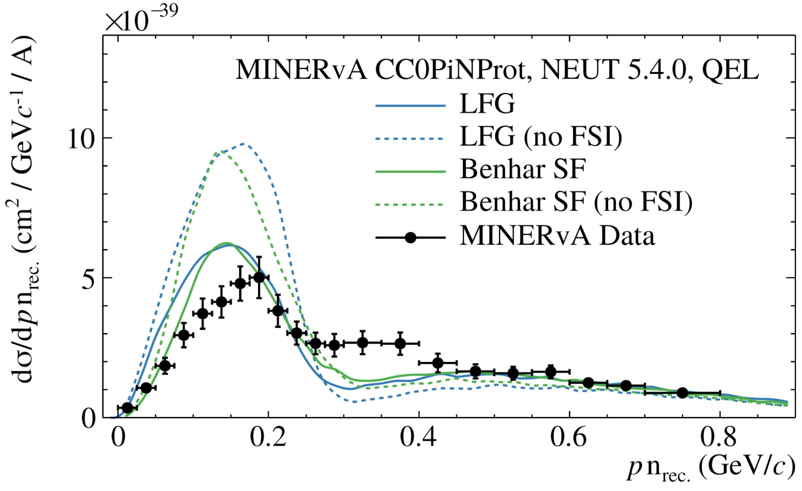


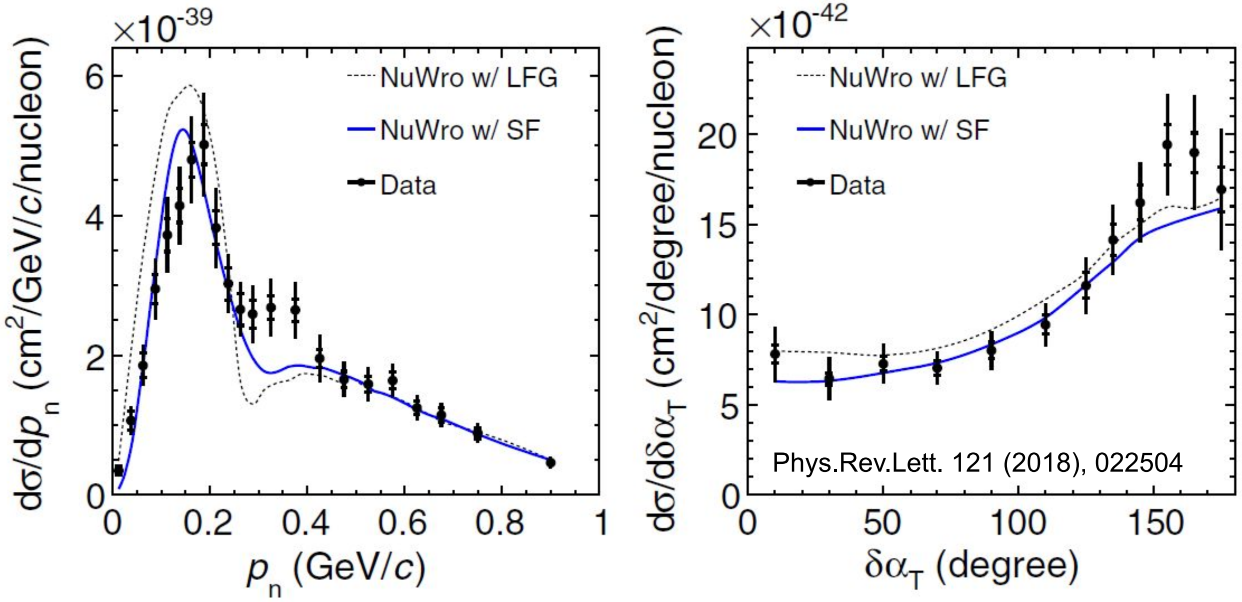


More pn

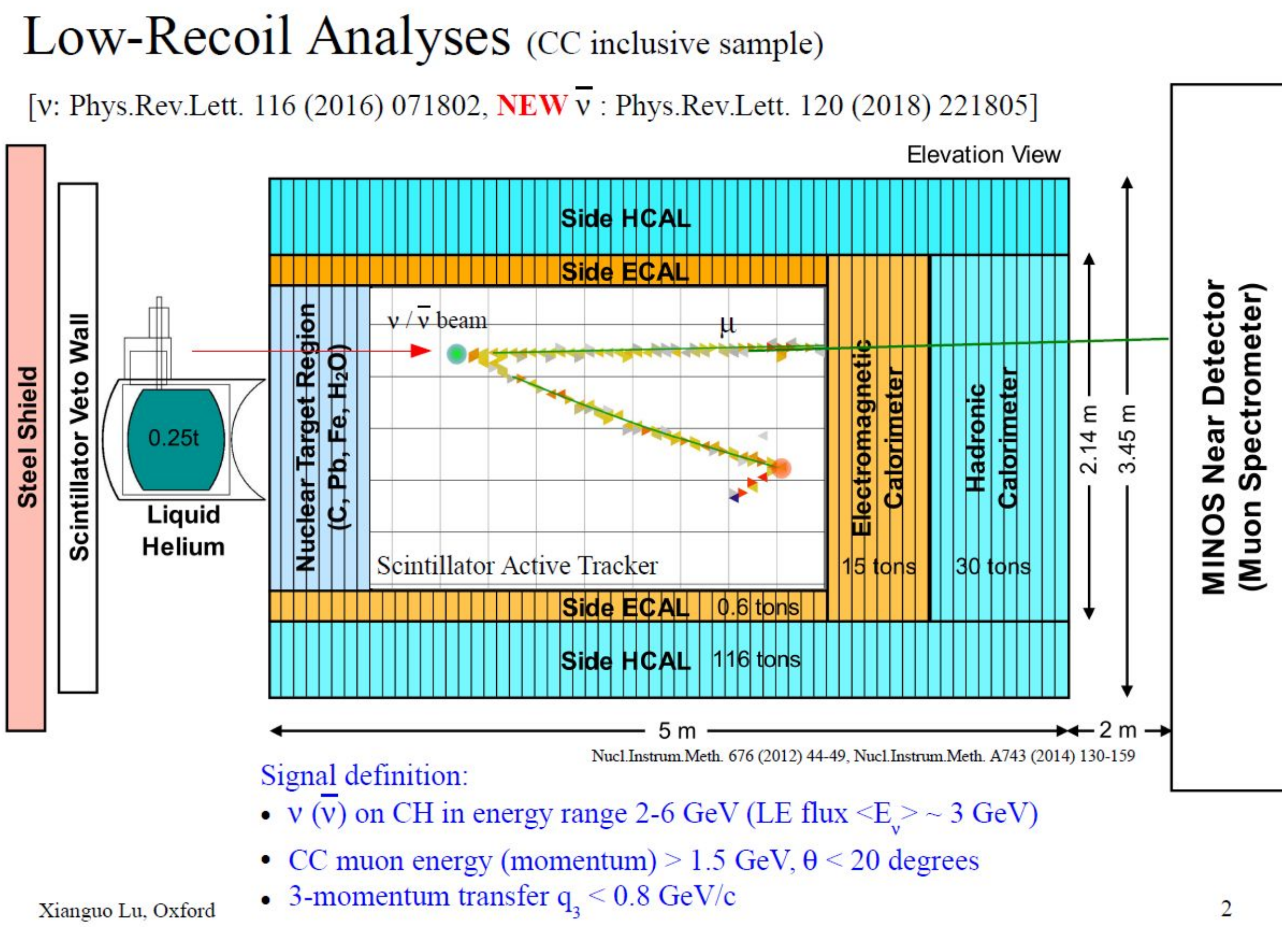
- Also wanted to look at stuck pi vs. 2p2h
  - GiBUU predicts no second peak for QEL, but NEUT does.
- And FSI/Nuclear momentum/binding model changes:
  - LFG/SF in NEUT qualitatively similar, **contrary to NuWro**
  - FSI mostly interacts with signal selections
- May be interesting to look at energy evolution as well...(see last BACKUP)

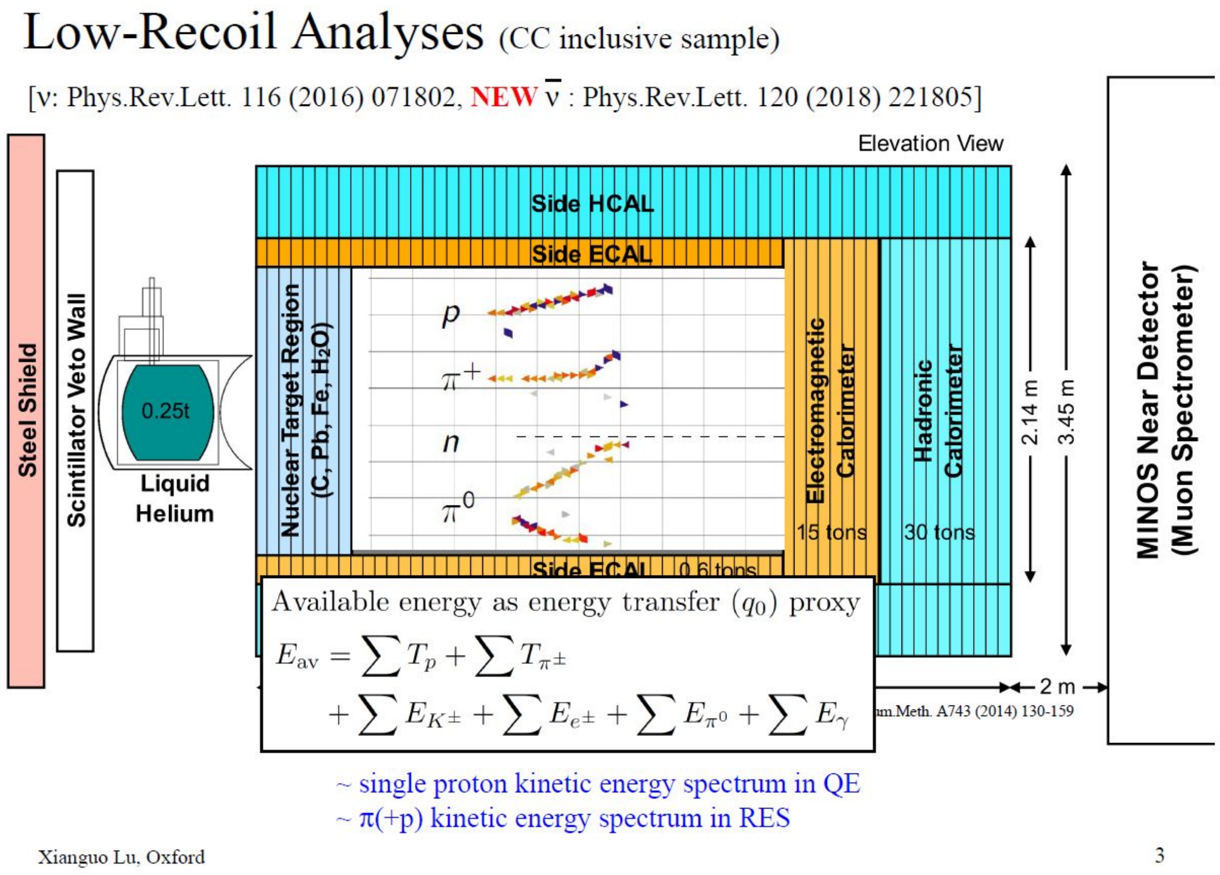






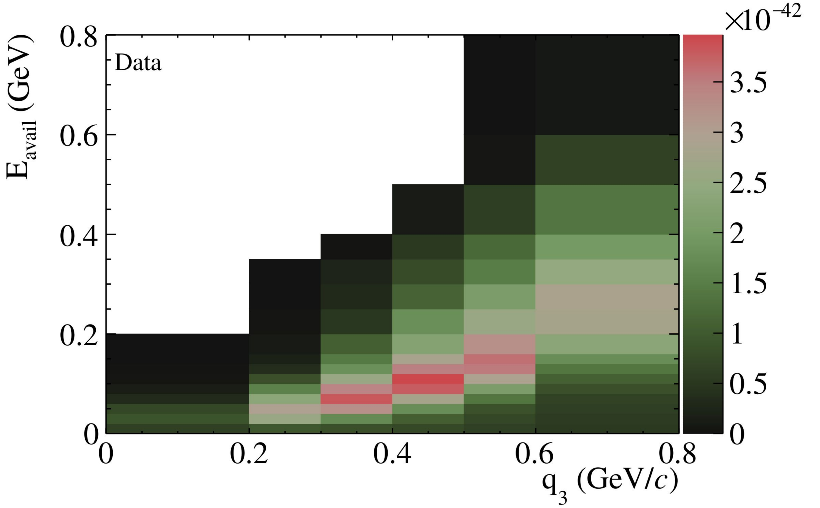
MINERvA Low Recoil

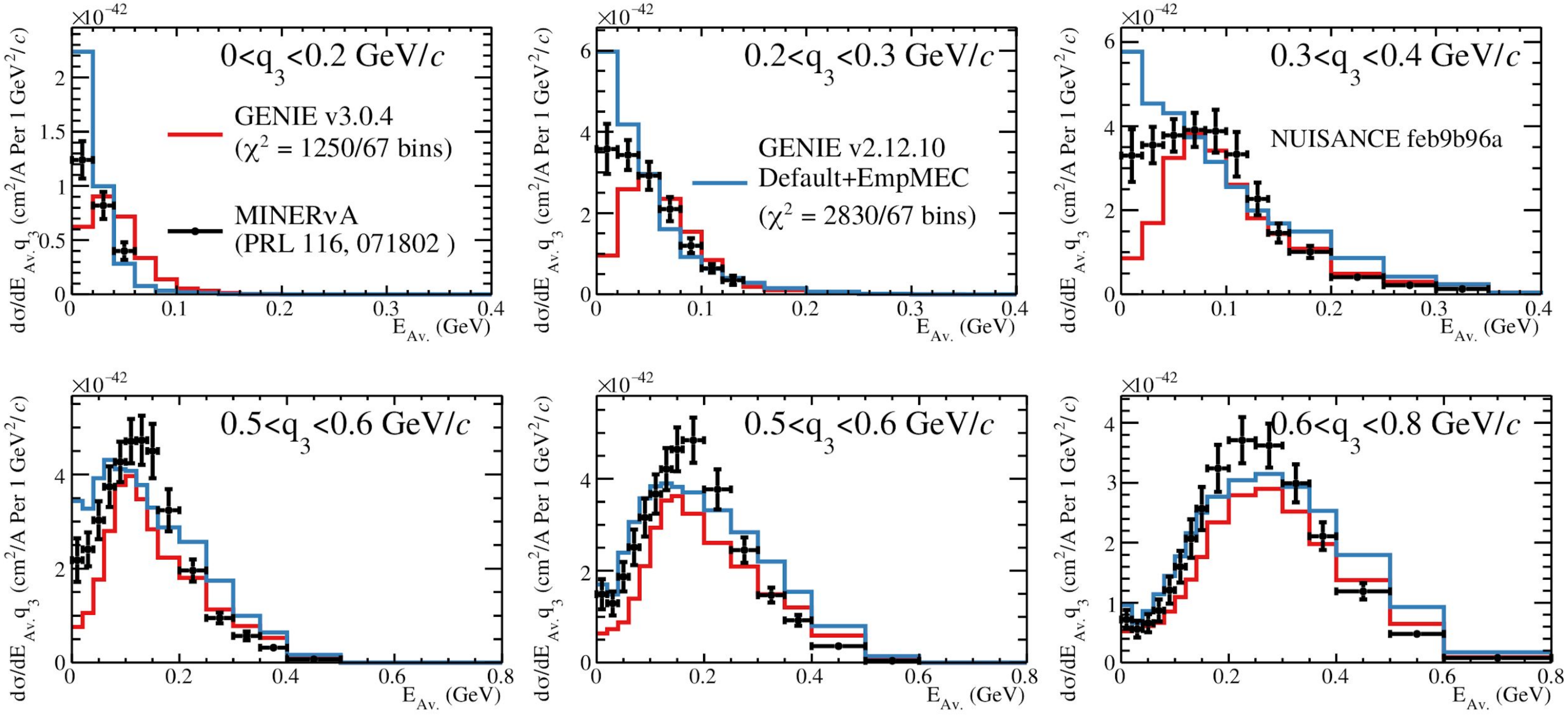




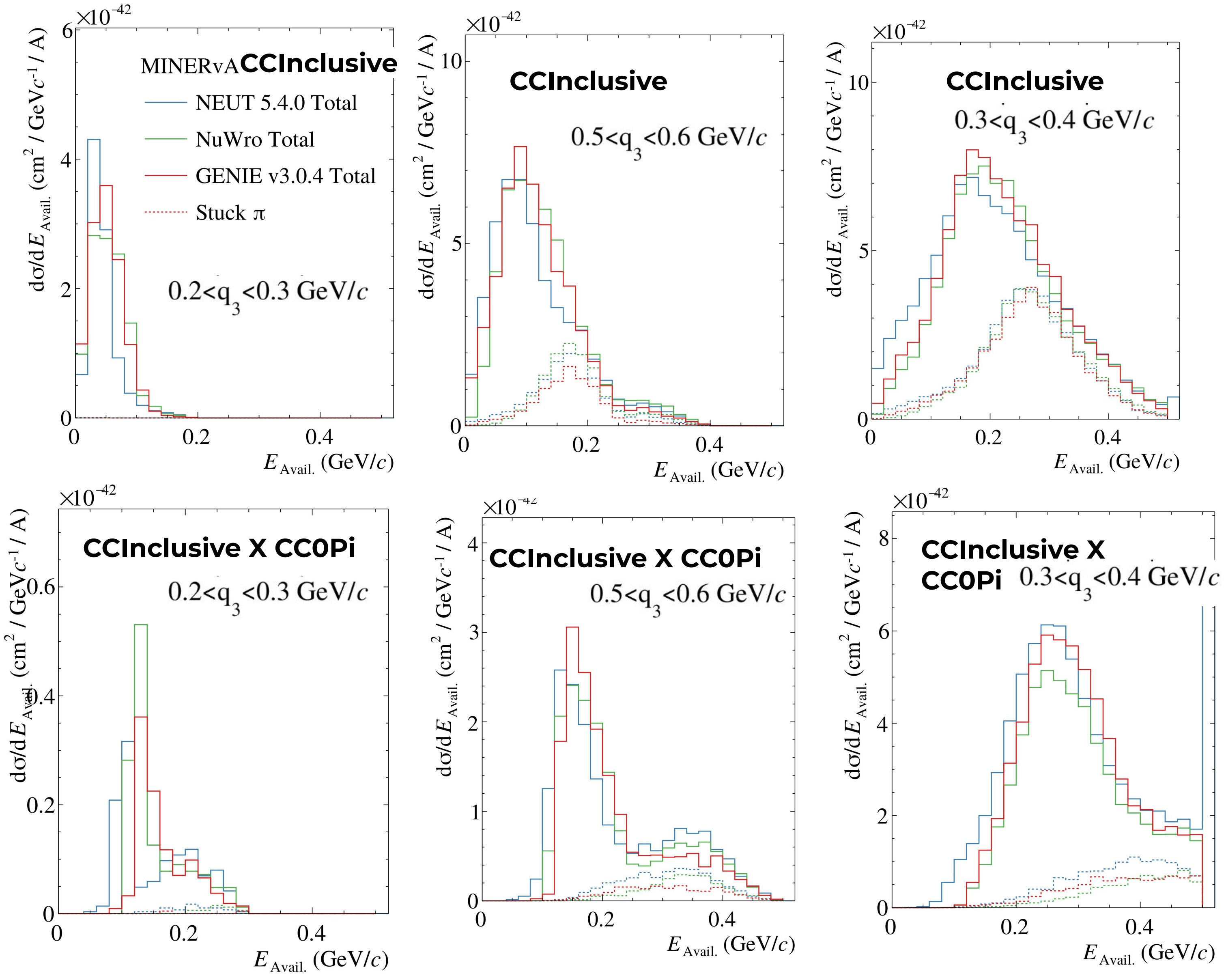
MINERvA Low Recoil

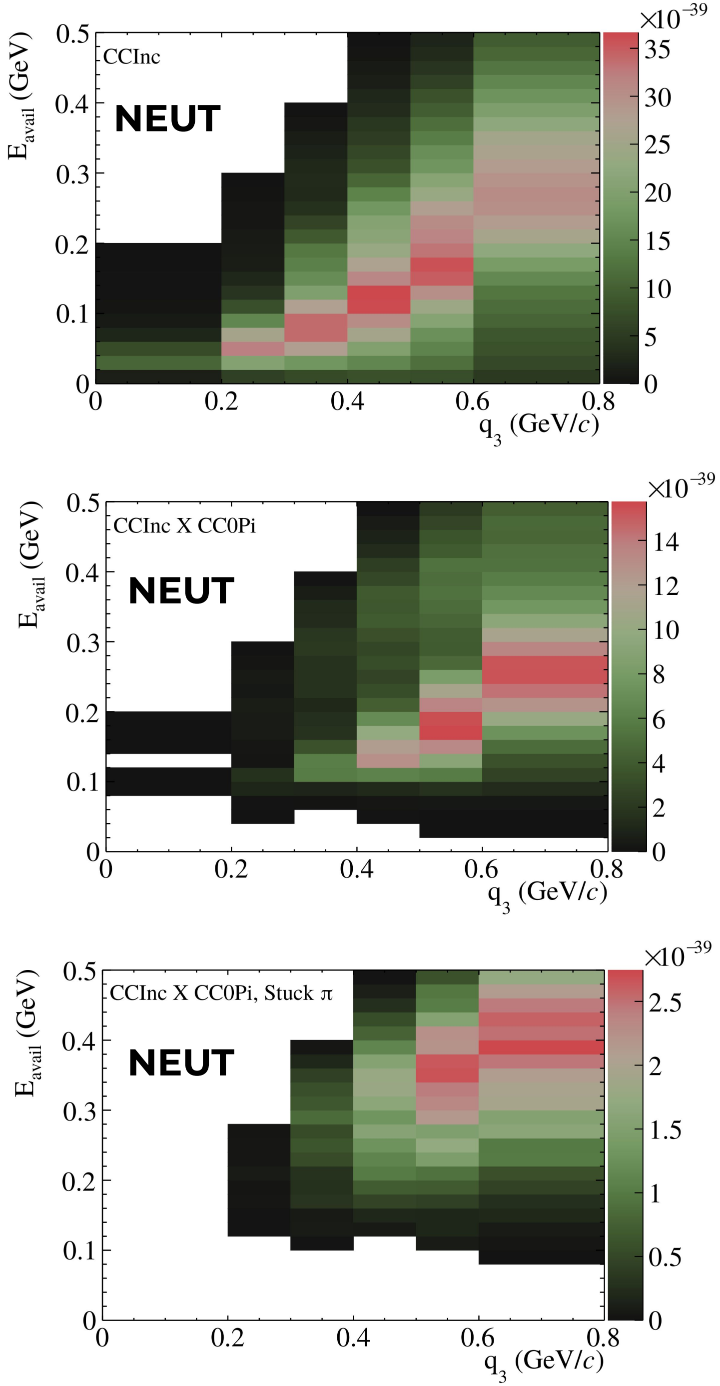
- Another lepton/hadron correlation observable:
  - Visible Lep.+Had. E → reconstructed Enu → q3:EAvail
- Data uses CCInclusive selection
- Finally a chi2...





MINERvA Low Recoil: Effect of applying 0Pi STV selection --aka Luke's travels in generator land





Experimental Implications

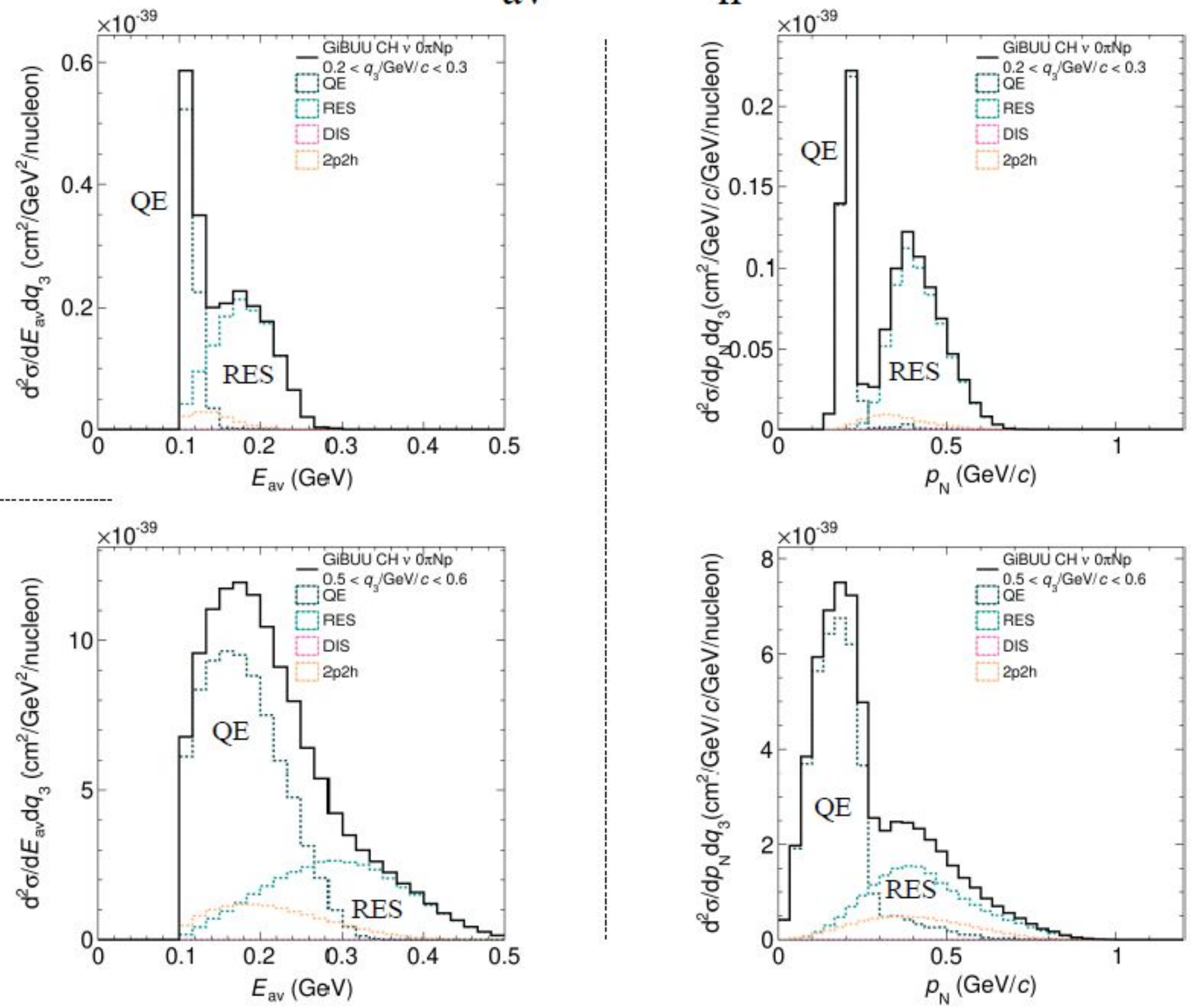
* GiBUU https://gibuu.hepforge.org/trac/wiki

p_n can provides QE/RES separation at high q3 (> 1 GeV/c)

E_{av} vs. p_n

q3 0.2-0.3 GeV/c

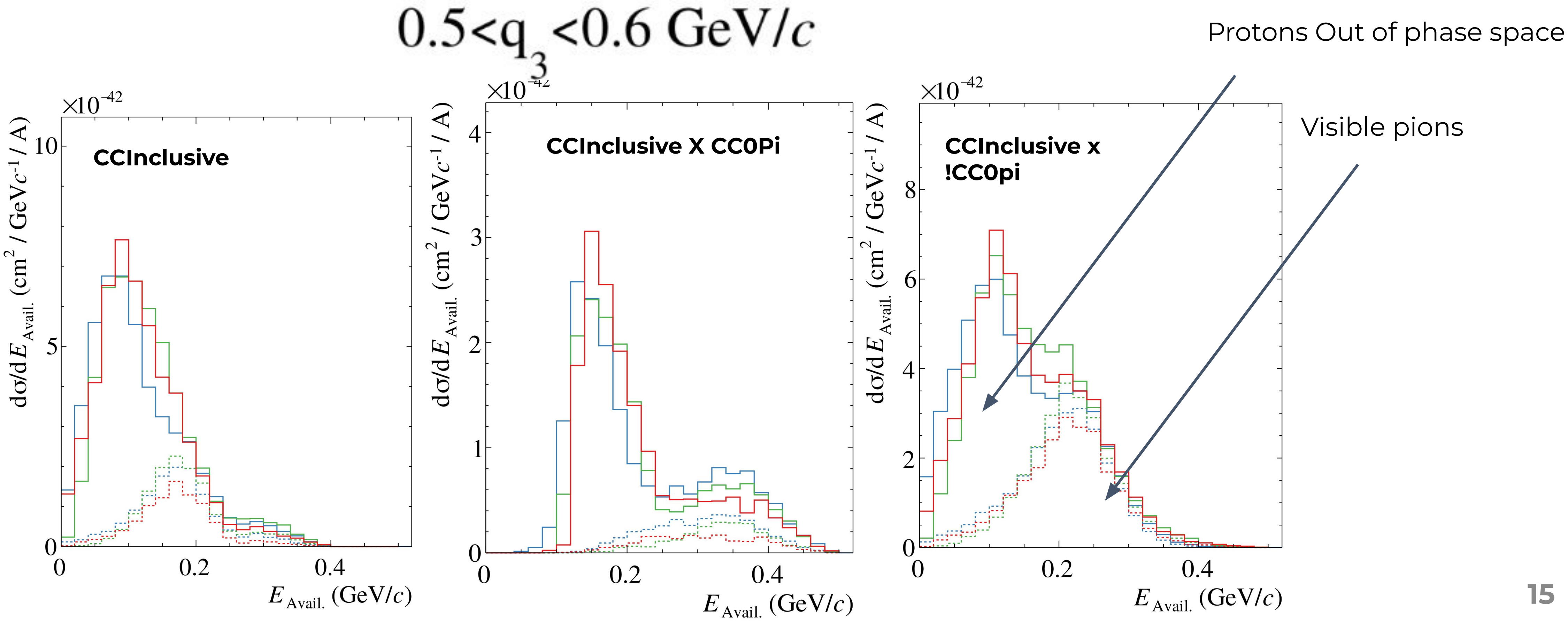
q3 0.5-0.6 GeV/c



* Compare q3-evolution of QE/RES/2p2h location: only 2p2h moves (GiBUU)

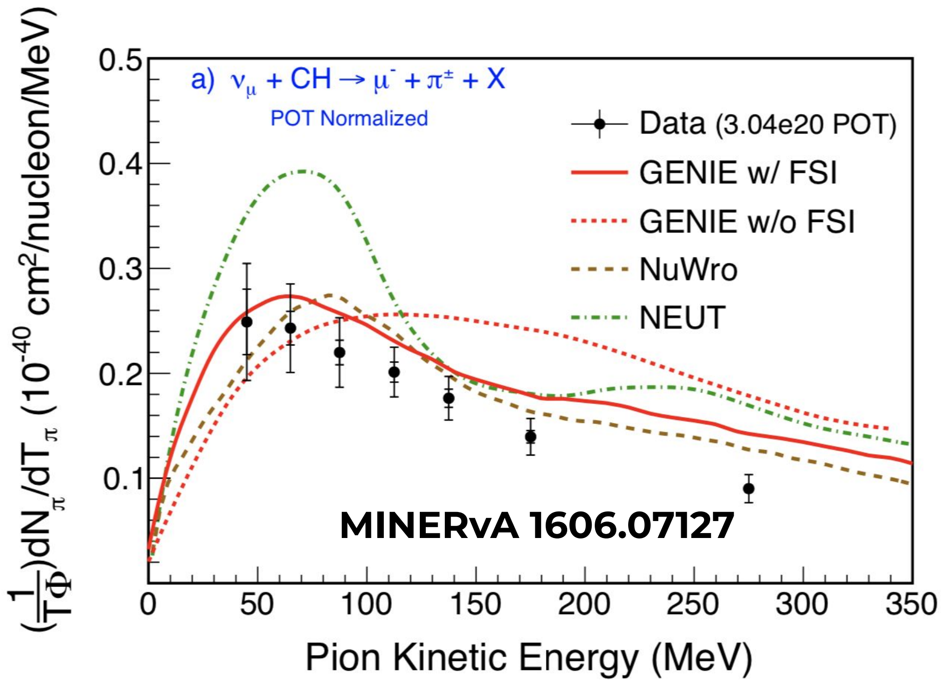
0Pi Background subtraction

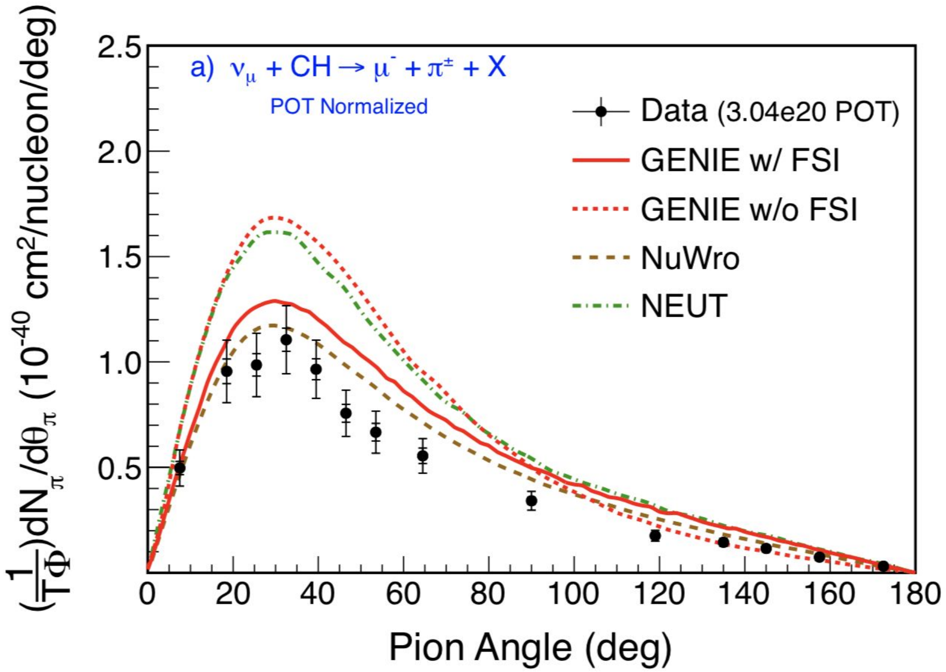
- Not discussed in detail here, but the experimental accessibility of these clues will rely on the background subtraction, detector resolution, and signal definitions:
  - The backgrounds to **0Pi** should be foregrounds in other samples so that simultaneous constraints can be be obtained for multiple channels.



Primary production models

- Combinations of CC0Pi, CCInc, and CC1 or NPi together will begin to constrain which regions are richer in stuck pions.
  - Depending on detector resolution and selection capabilities and analysis signal definitions, FSI moves events between these three types of selections
  - **They can only hide for so long!**





Summary

- How do the predictions for stuck pions compare across different generators?
- Absolute Levels:
  - The absolute levels of stuck pion predictions vary by +-25%
  - NEUT predicts highest level, NuWRO predicts lowest level
  - GENIE and GIBUU both in between the two extremes
  - Stuck pions to first order show up in the same kinematic regions
- Fraction of true SPP events
  - NuWRO, GENIE, NEUT all have similar fractions -- variations are mostly total xsec differences.
  - GIBUU has 2x larger SPP fraction at high δp_T because of stronger SPP/pi abs and weaker 2p2h.

Final Comments

- Updated truth studies of lepton-hadron 0pi samples from T2K and MINERvA:
  - Generators predict significant separation power in dpt, pn, and visible energy.
  - Continued, high statistics, carefully-designed experimental probes of 0pi, 1pi, and inclusive and comparisons to ever evolving models is how we're going to progress…
- Didn't get to:
  - Further energy evolution (Booster, DUNE, off axis)
  - Different nuclear targets (NOvA soup, Ar40)
  - More FSI on/off and pion production comparisons to dig in to observed differences.

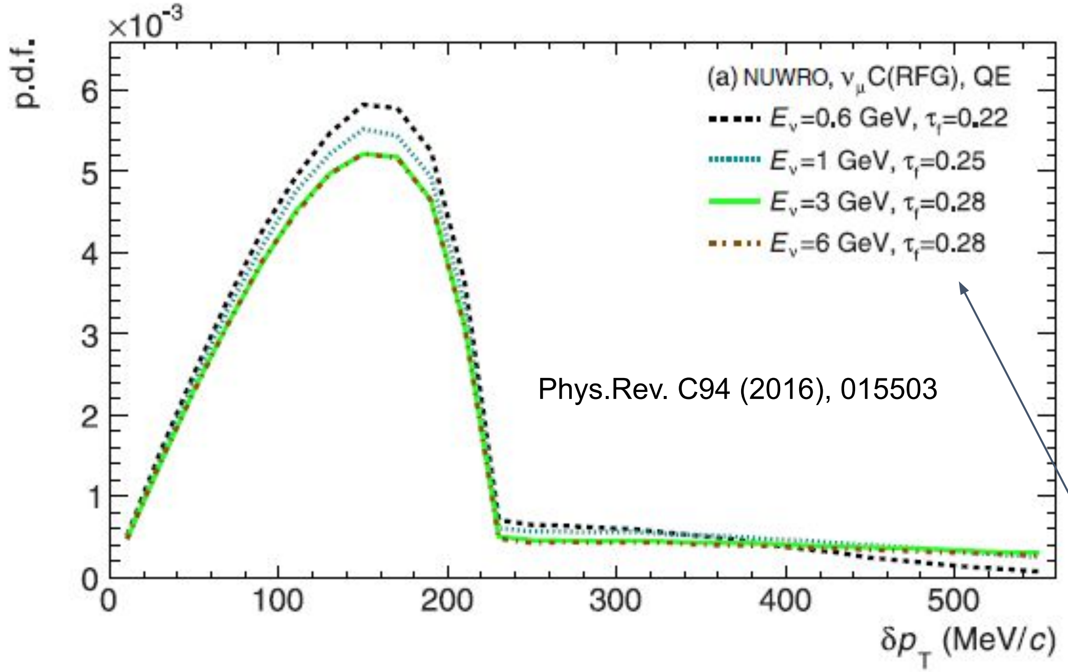

"That's all Folks!"
MINERvA
T2K
u
d̄
SEASON
TM & © WBEL (s17)

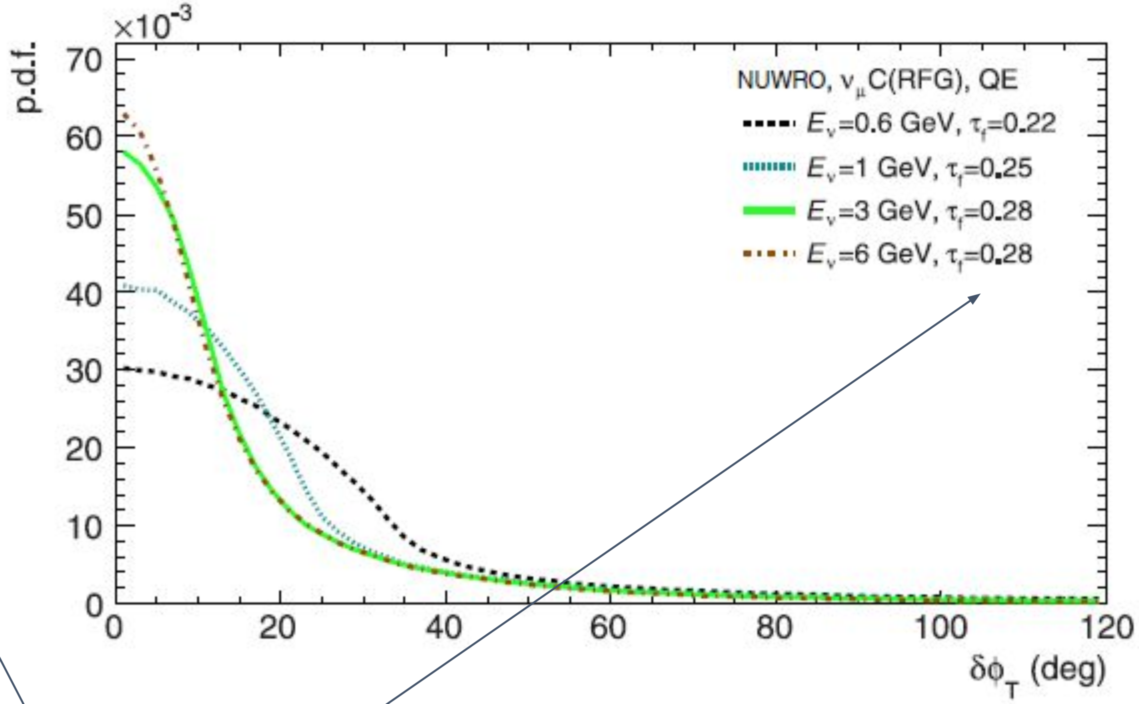
Summary: How does FSI change Unstuck pions?

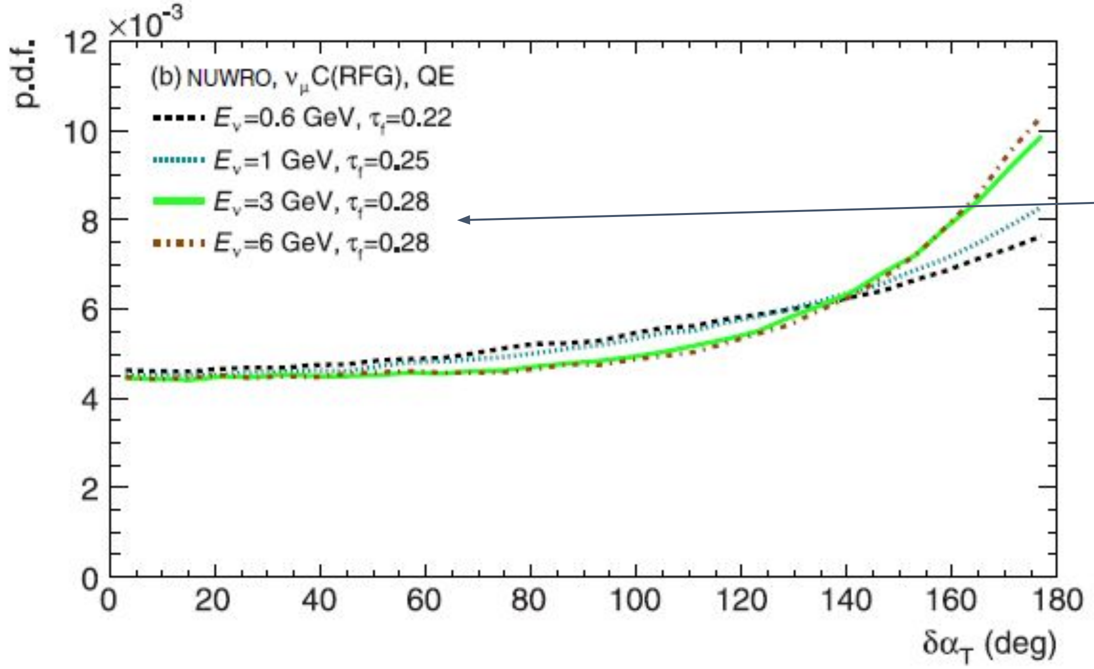
pion absorption will move 1pi events to 0pi events (might be useful to mention the trivial fact that inclusive cross section is insensitive to FSI)

- For GENIE:
  - Adding FSI makes “unstuck” pion energy spectrum softer, peak moves from 100MeV to 60MeV
  - No large changes seen in pion angular distribution, a little less forward peaked but barely
  - Adding FSI reduces overall strength of pion production by about 20% at 3.5GeV energies

- Comparing GENIE, NEUT, NuWro: pion kinetic energy spectrum from NEUT differs from GENIE and NuWro which have similar spectra
- All 3 generators have similar pion angular spectra







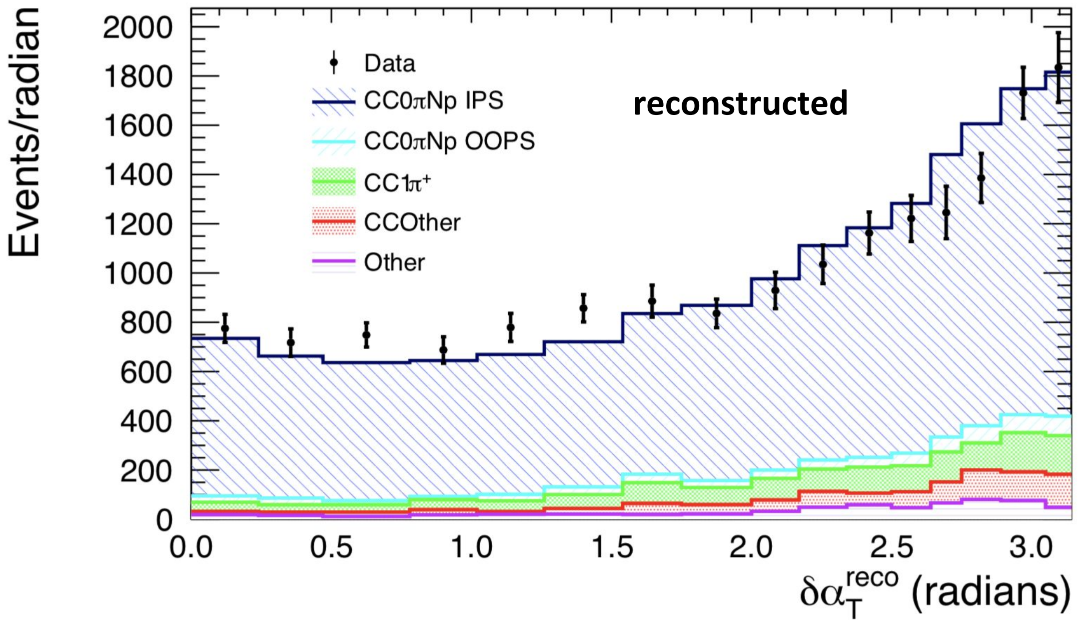
Tau here is the probability of the final-state proton to experience FSI extracted from NuWro at different neutrino energies ~ 1 - transparency

As neutrino energy goes up, proton momentum starts to saturate, so is the FSI probability.

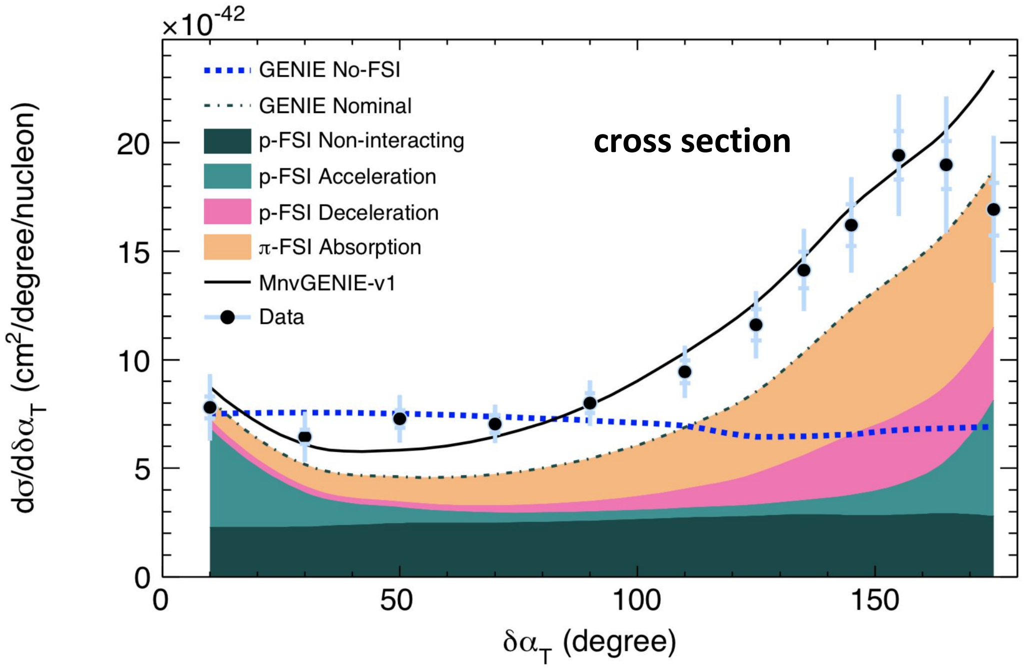
For pure QE events, FSI has only moderate dependence on neutrino energy.

This is the clearest place stuck pions show up:

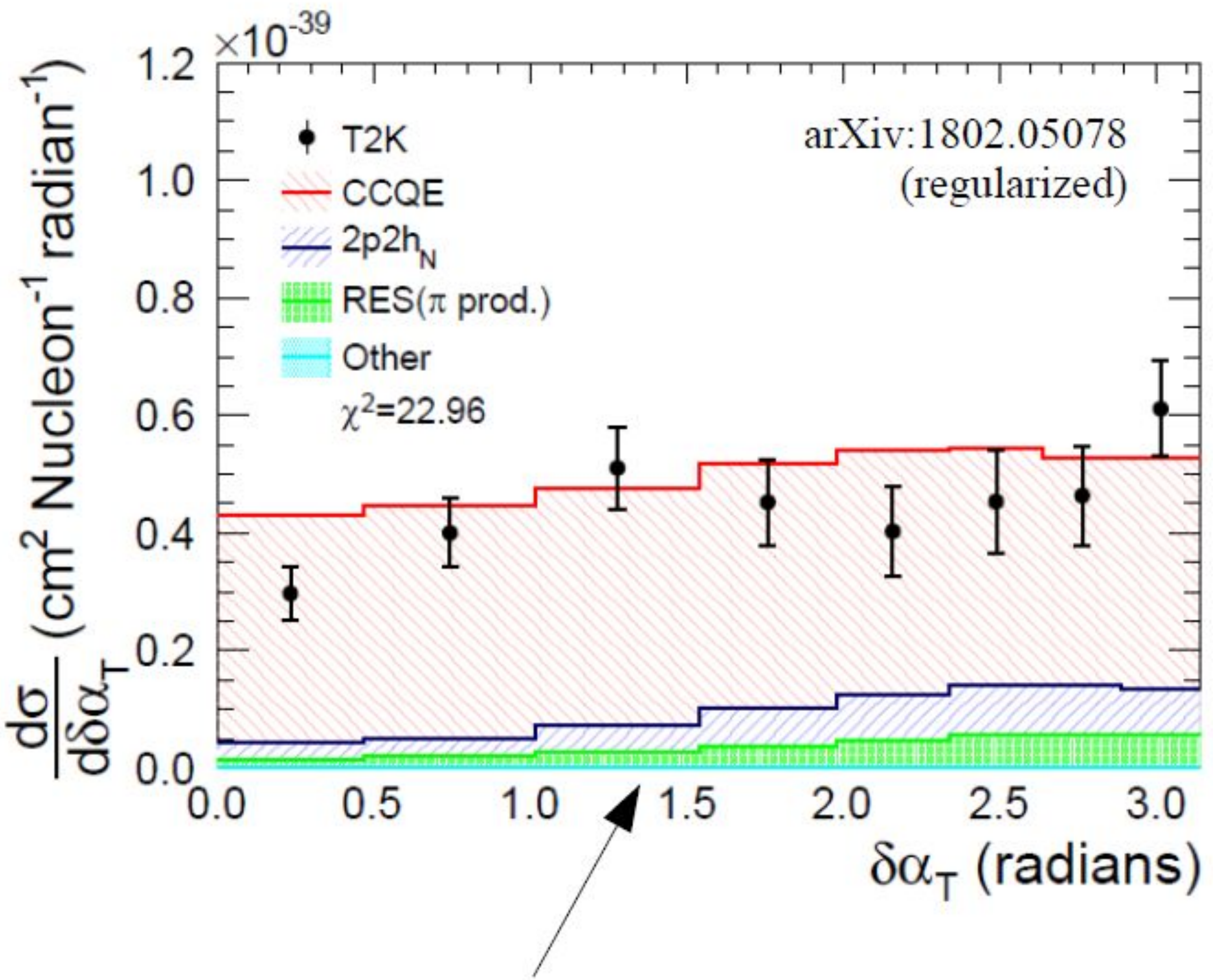
- $\delta\alpha_T$ (and p_n comparing T2K and MINERvA, see much more stuck pions at MINERvA energies



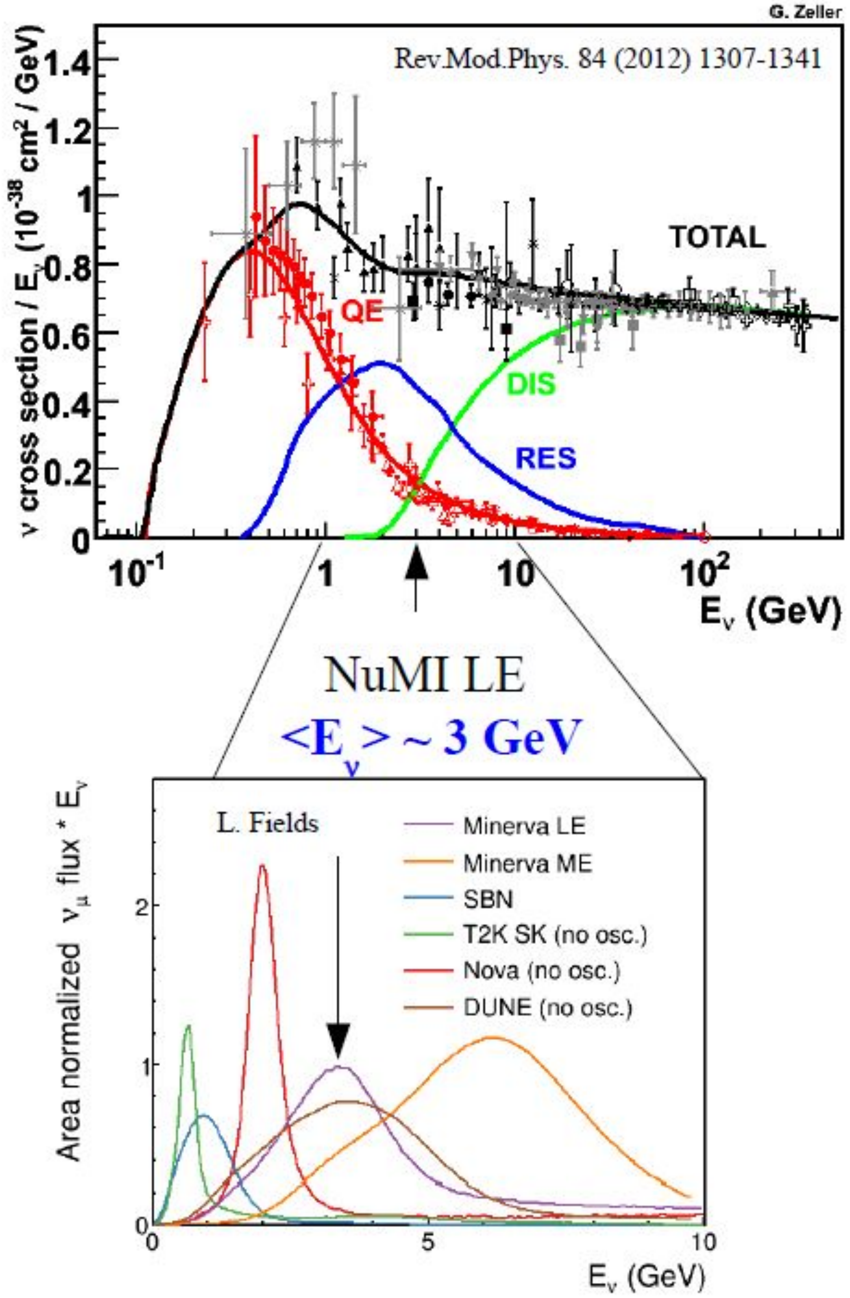
T2K: 1802.05078

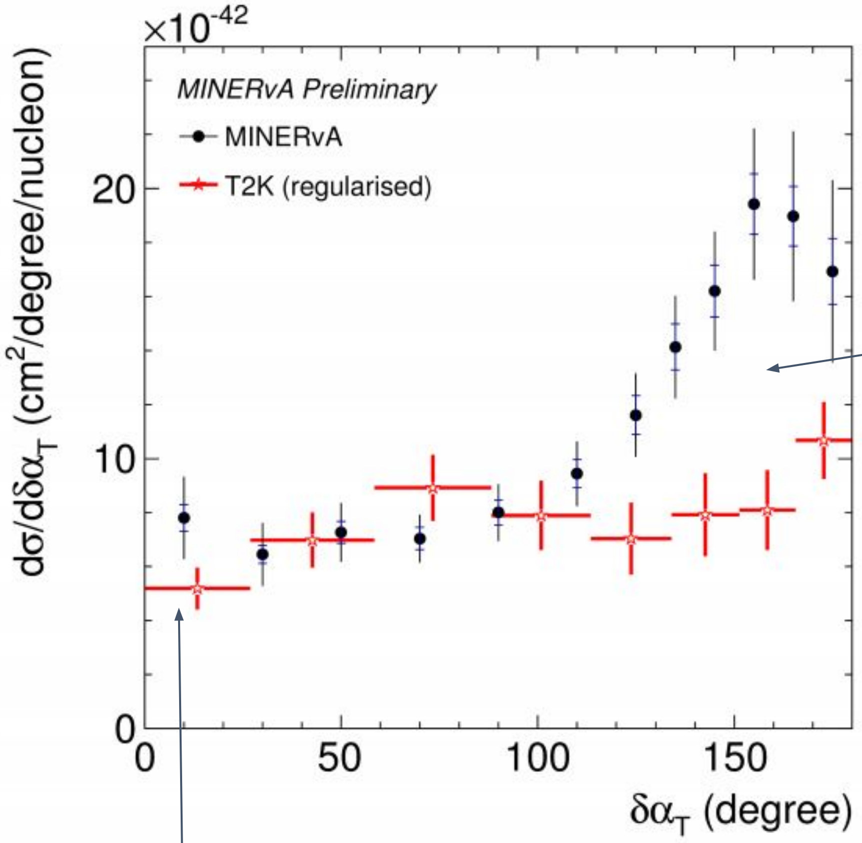


MINERvA: 1805.05486



MINERvA-T2K difference mainly due to RES:
Very small resonance contribution at T2K



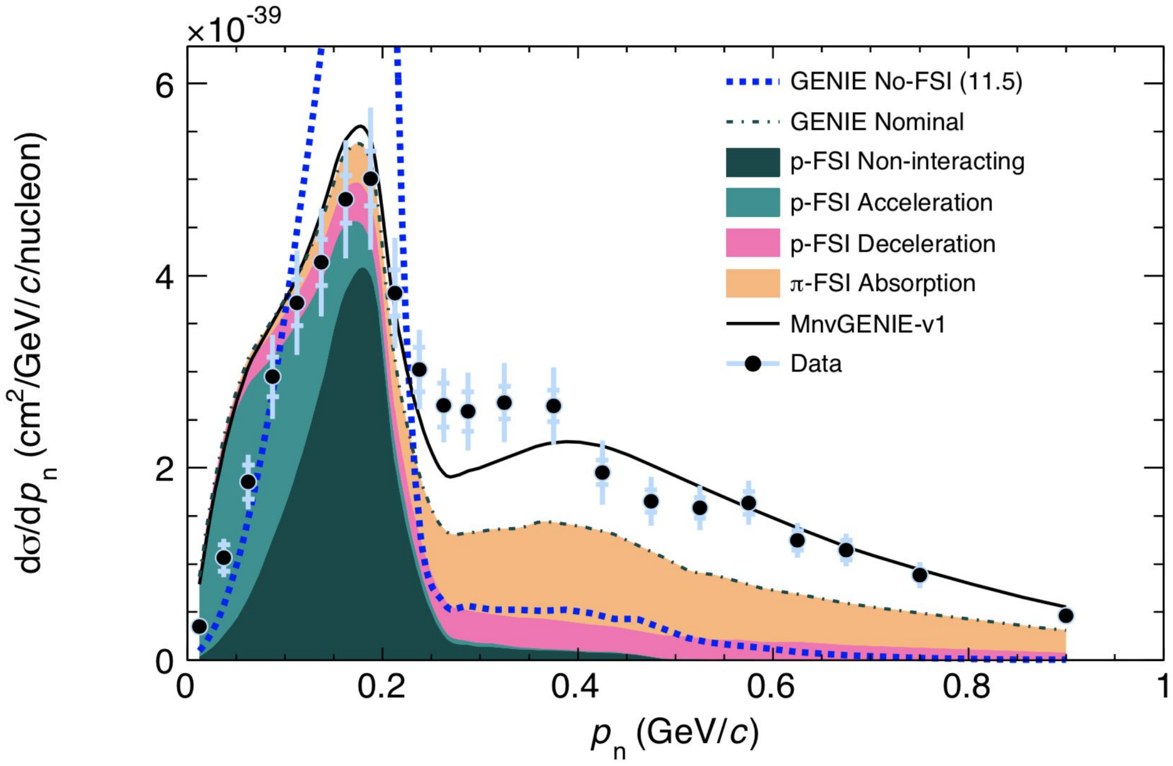


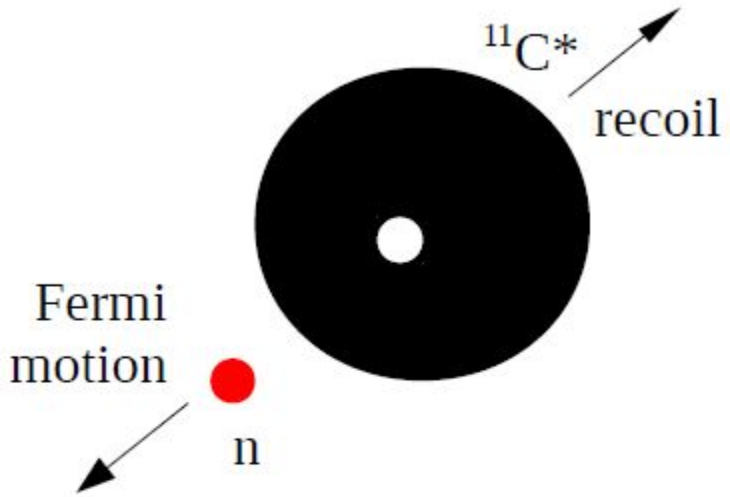
stuck pion is the major difference

in dat -> 0 region, pure QE is dominant.
Pure QE cross section starts to saturate at T2K energy
proton kinematic and proton FSI difference is sub-dominant

This is the clearest place stuck pions show up:

- p_n (Phys.Rev. C95 (2017) 065501, see BACKUP for definition) maybe the clearest place the “pions” can be separated:





MINERvA: 1805.05486

Questions to ask:

- How do the absolute predictions for stuck pions compare across different generators?
  - Do they show up in the same kinematic regions?
- How do the relative predictions for stuck pions compare across different generators?
  - Are the fractions comparable in the same kinematic regions?

Conclusions

- Absolute stuck pion predictions:

- Fractional Stuck Pion predictions:

What models are in which generators?

Stolen directly from Jan's slides this morning

Generator	Pion Producti on Model	FSI Model (for pions)
GENIE		hN is a cascade model; Oset et al; or hA which is an effective model
NEUT		for pions based on Oset et al computations with later fit to available pion-nucleus data
NuWRO		Oset et al calculations
GIBUU		Cascade Model

GiBUU

	Model Name	ν	e	Detailed electron mode implementation
COherent				
Quasi **E**lastic	QE[1]	+	+	The electron σ is calculated using the formfactor BBA2003 parametrization. For the neutrino cross section, the vector form factors are extracted from the electrons ones based on CVC, the axial form factor is using the dipole form with the axial vector constant, gA, taken from β decay, and Q2 dependence tuned to neutrino data.
Meson **E**x**C**hange	SuSA	+	+	?
	Empirical	+	+	The cross section for electrons is obtained from a data analysis by Bosted and Christy, and the neutrino one is then extracted based on the relations between the e and ν structure functions used by the Lyon group[2]
RESonance	Phenomenological FF	+	+	For the e σ calculation, the helicity amplitudes are determined in the MAID analysis[3] For σν , the vector form factors, C_{6V} C_{5V} C_{4V} , are extracted from the electrons ones based on the CVC. $C_{5A}(0)$ is obtained by fitting the available pion production data on an elementary target. C_{3V} is taking the modified dipole form. C_{3A} is set to zero. C_{6A} can be related to C_{5A} by PCAC. C_{5A} parametrization is given in Leitner et al..
Deep **I**nelastic **S**cattering	[4]	+	?	1. lepton interacts with a nucleon, modeled by Pythia (nucleon is treated as free or bound + Fermi motion, Pauli blocking). 2. (pre-)hadrons are propagated through the surrounding nuclear medium according to the BUU transport description. This is exactly the same for e and ν all other hadron-induced reactions on nuclei.

Genie

	Model Name	ν	e	Detailed electron mode implementation
COherent	Ahrens	+	-	
	Coherent pion	+	-	
Quasi **E**lastic	Rosenbluth	-	+	Stand alone code only for electrons
	Llewellyn Smith	+	+	Calculating for ν, if probe is electron modify coupling constants (release candidate for v3.2)
	SUSA	+	+	SDo: Works for nu and e in the same code using hadron tensor table framework (although of course the nu and e tensors are different). Inclusive model implementation.
	Nieves dipole	+	-	
	Nieves z exp	+	-	
Meson **E**x**C**hange	Empirical Dytman model	+	+	Calculating for ν, if probe is electron modify coupling constants.
	Nieves	+	-	
	SUSA	+	+	SDo: Works for nu and e in the same code using hadron tensor table framework (although of course the nu and e tensors are different). Inclusive model implementation. Can predict the different contributions from different initial state pairs for e and for nu.
RESonance	Rein Sehgal	+	+	Calculating for ν, if probe is electron modify coupling constants
	Berger Sehgal	+	+	Calculating for ν, if probe is electron modify coupling constants
Deep **I**nelastic **S**cattering	Bodek-Yang			

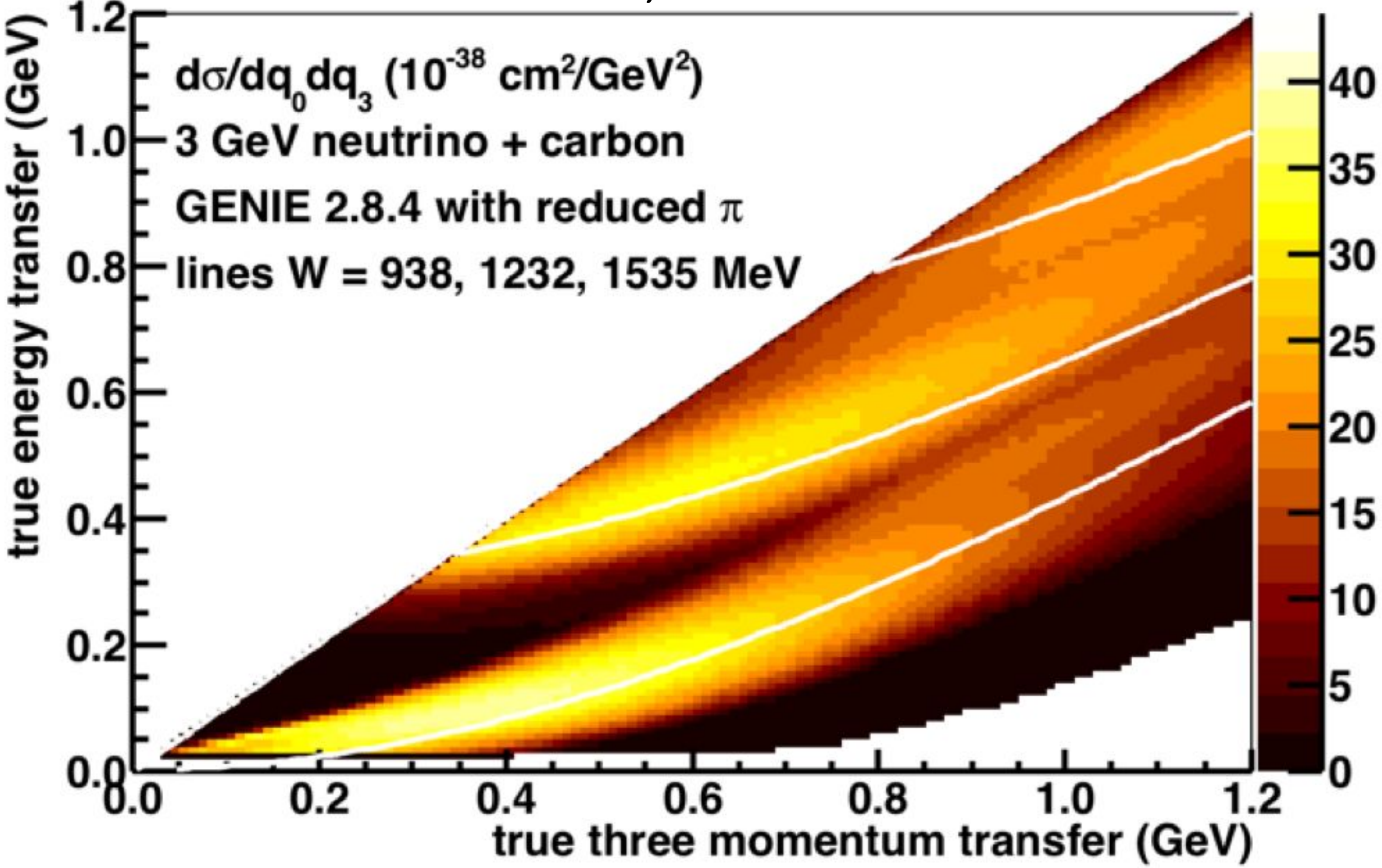
from Adi's talk on Monday

https://indico.ectstar.eu/event/53/contributions/1103/attachments/779/1007/190604_trentoE4NU.pdf

Other way to look for stuck pions

Consider the inclusi
momentum transfe
can be seen in neut

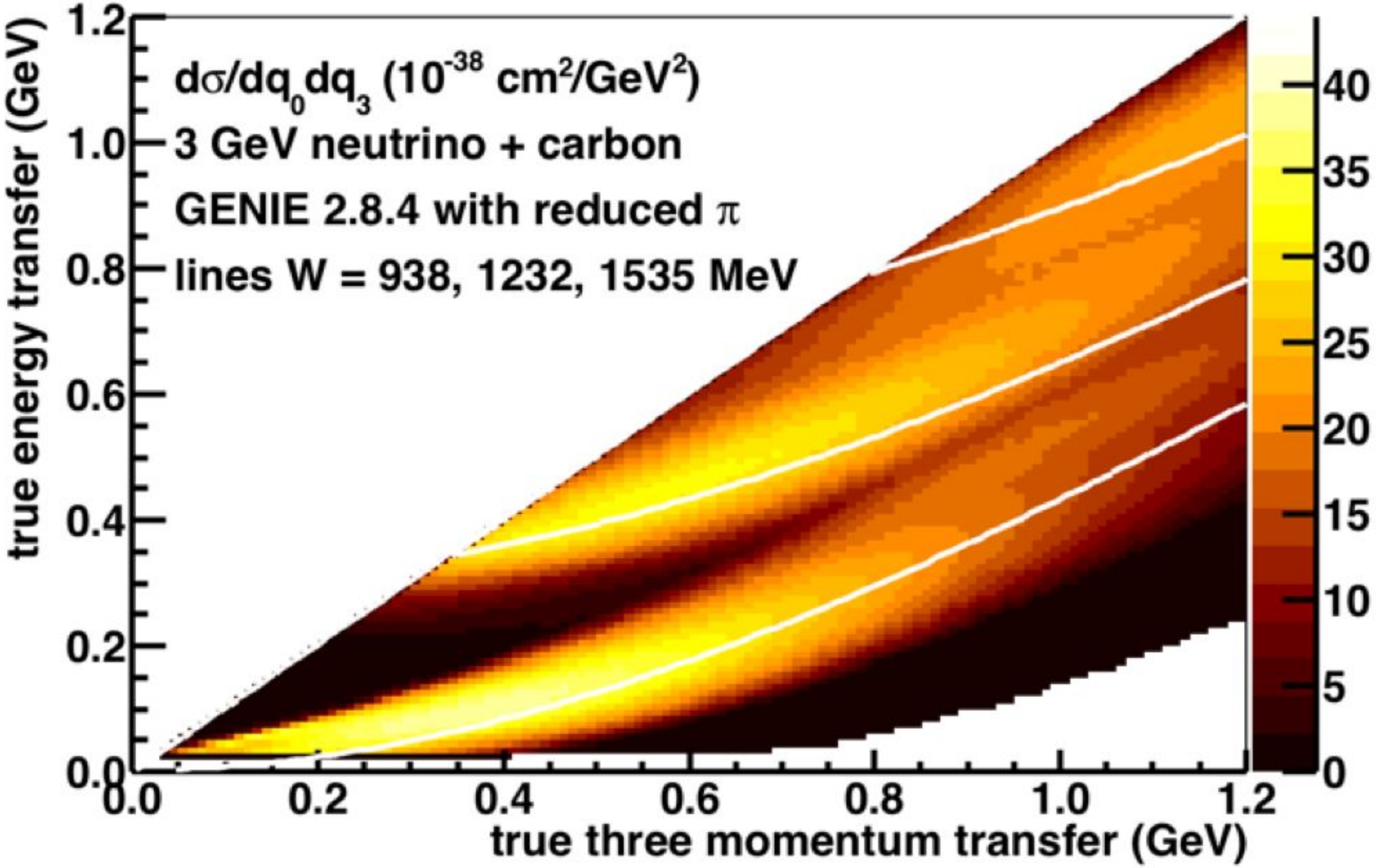
R. Gran, NuINT '17



Which events show up where?

Four kinds of events
- Quasi-elastic
- 2p2h events
- Pion production
  - (resonance ++)
- Stuck pion events

Where are the stuck



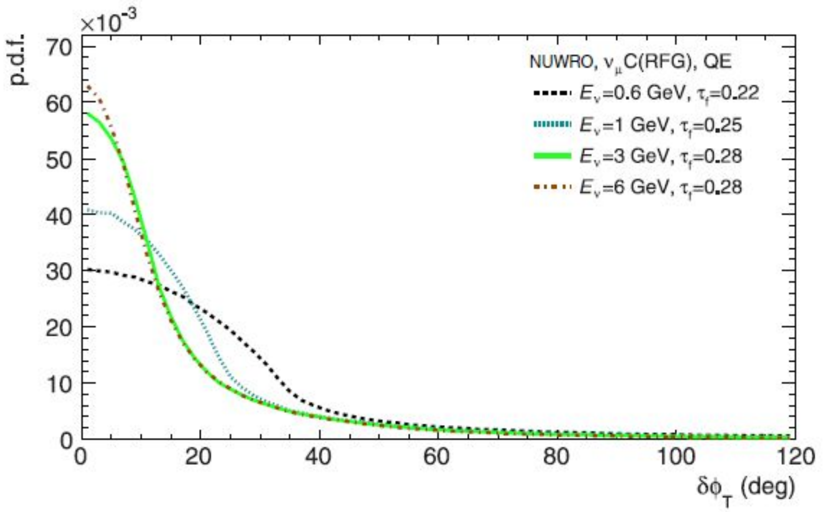
Please add the q0-q3 slides here to show the different components

What about nuclear dependence?

One way to separate out the role FSI plays could be to compare these signatures across different nuclear targets

Experimental resolution on both the Transverse Variables and the q0-q3 signatures will be very dependent on the target geometry.

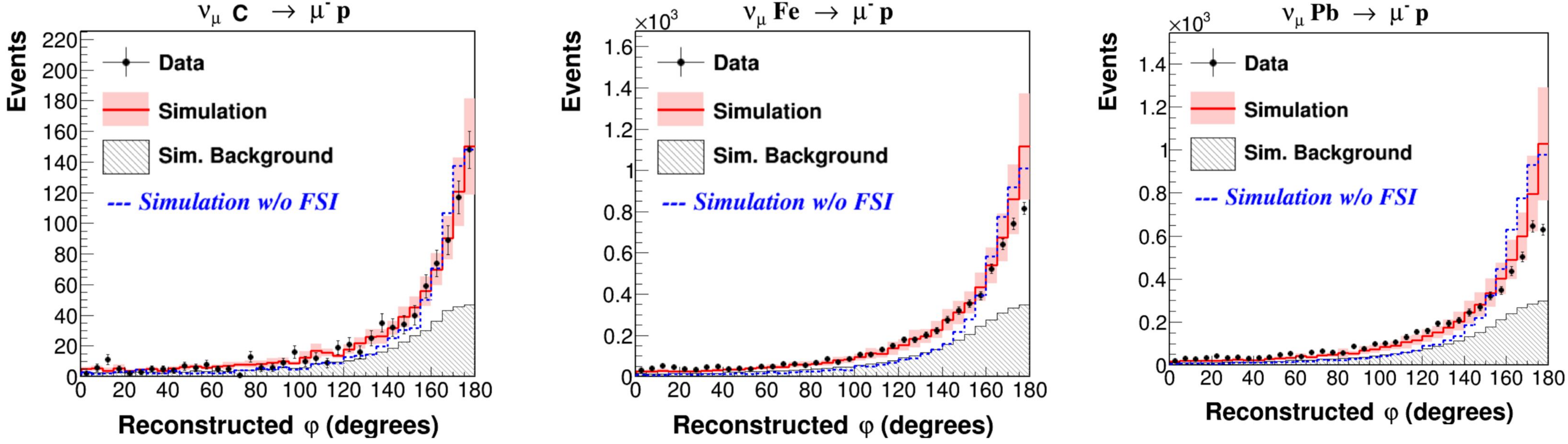
Reminder of “acoplanari



Comparison: φ (below) = π - $\delta\Phi_T$ plot shown

But this variable is energy dependent…neutri

the effect of FSI. Events are 1 proton, one muon events but with



MINERvA 1705.03791, Background is mostly real pions misidentified as protons

Conclusions

Question that could be a conclusion based on Luke's plots: is pion production correlated with stuck pion production?

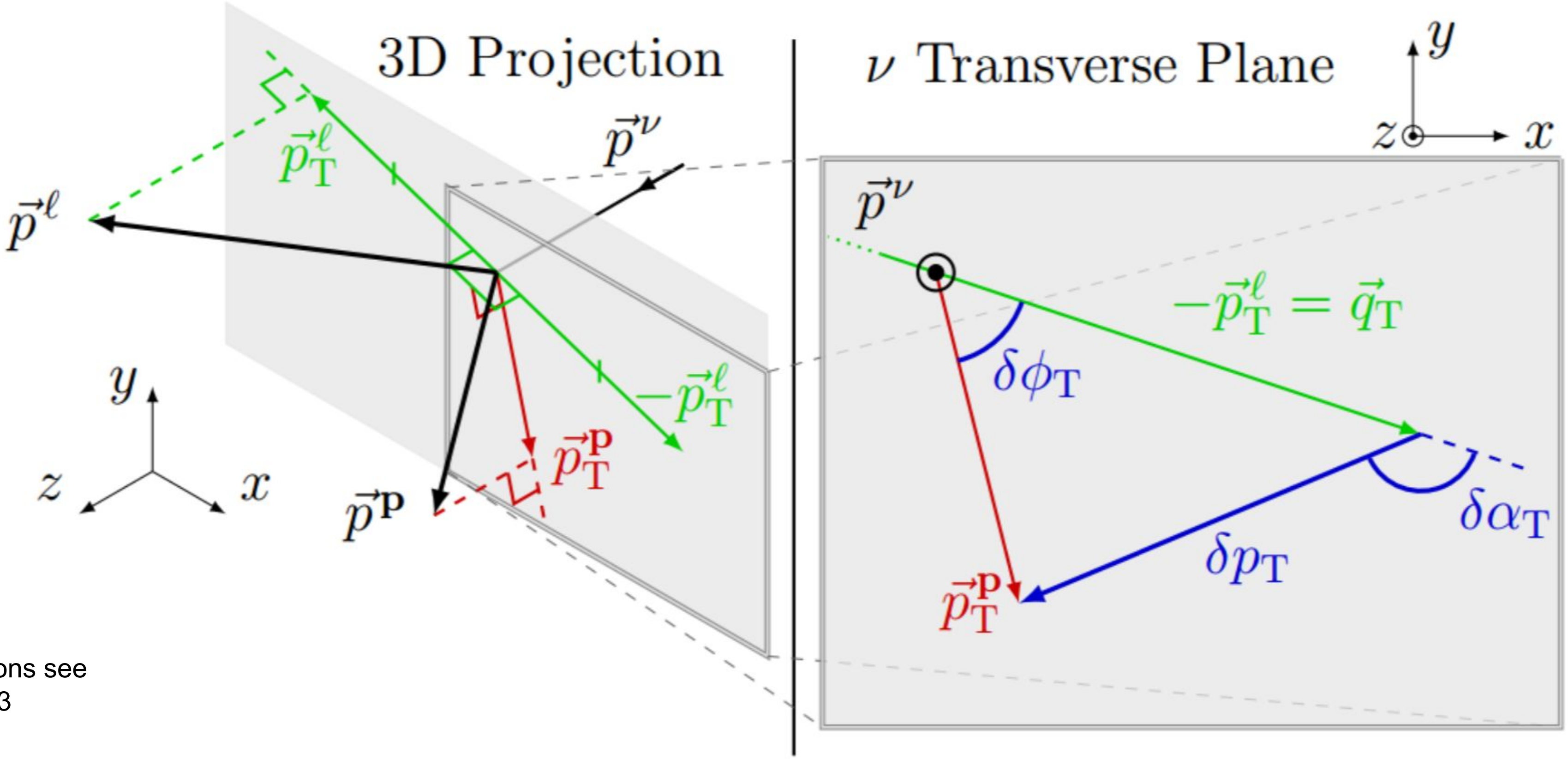
(comparing different generators...)

Question: can we untangle FSI effects from primary interaction effects by looking at identified pions (i.e. events with michel decays) versus unidentified pions?

BACKUP

Prediction for Stuck pions in “0π” sample

- One clear place this shows up is in transverse variables (T2K: 1802.05078,)



Form more generator predictions see
Phys.Rev. C94 (2016), 015503
1602.06730
1606.04403

A more general analysis of kinematic imbalance

Transverse: $0 = \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'} - \delta\vec{p}_{\mathrm{T}}$

Longitudinal: $E_\nu = p_{\mathrm{L}}^{\ell'} + p_{\mathrm{L}}^{\mathrm{N}'} - \delta p_{\mathrm{L}}$

New variable: $p_{\mathrm{n}} \equiv \sqrt{\delta p_{\mathrm{T}}^2 + \delta p_{\mathrm{L}}^2}$

[Furmanski, Sobczyk, Phys.Rev. C95 (2017) 065501]

Neutrino energy is unknown (in the first place), equations are not closed.

Assuming exclusive μ-p-A' final states
Use energy conservation to close the equations

$$E_\nu + m_{\mathrm{A}} = E_{\ell'} + E_{\mathrm{N}'} + E_{\mathrm{A}'}$$

$$E_{\mathrm{A}'} = \sqrt{m_{\mathrm{A}'}^2 + p_{\mathrm{n}}^2}$$

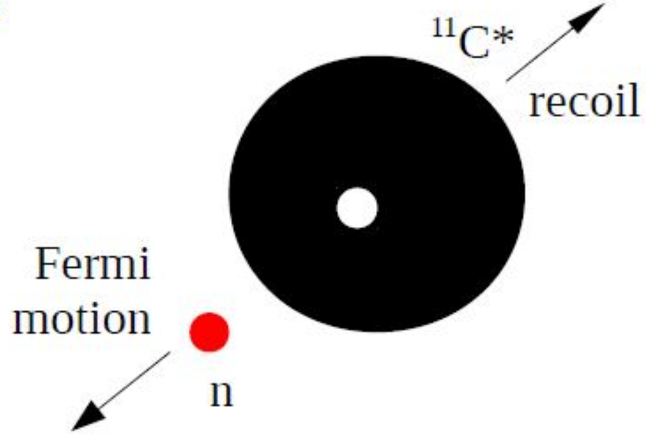
p_n: recoil momentum of the nuclear remnant

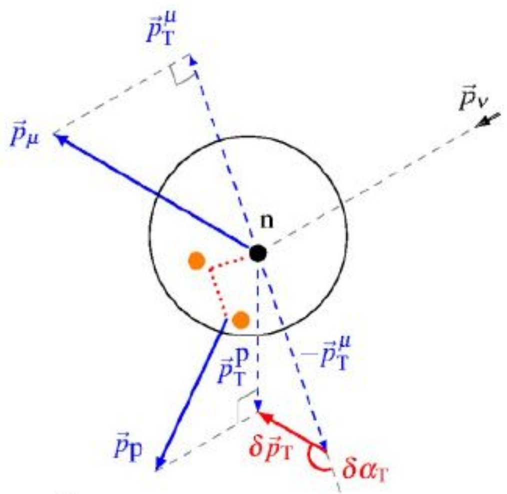
final-state

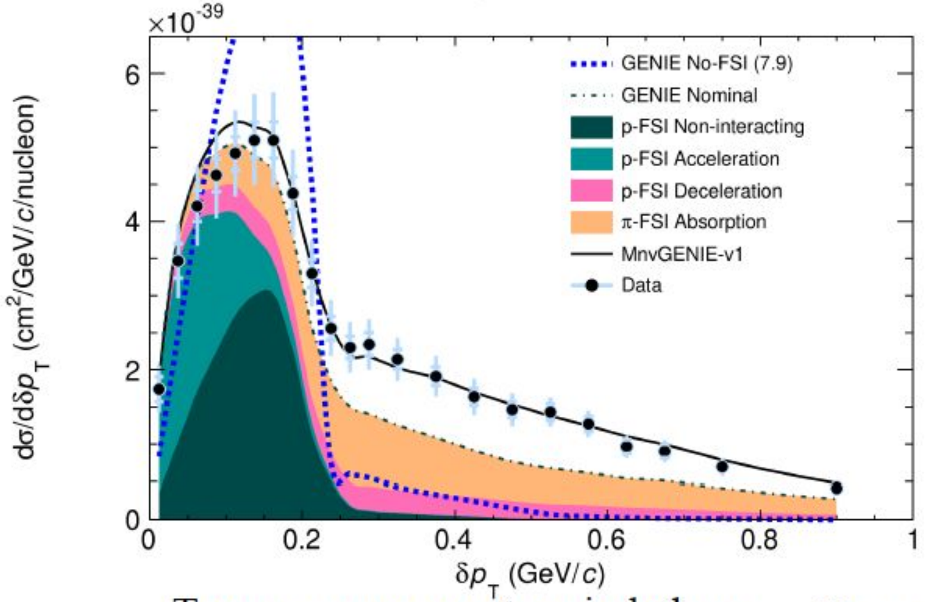
Dual Interpretation

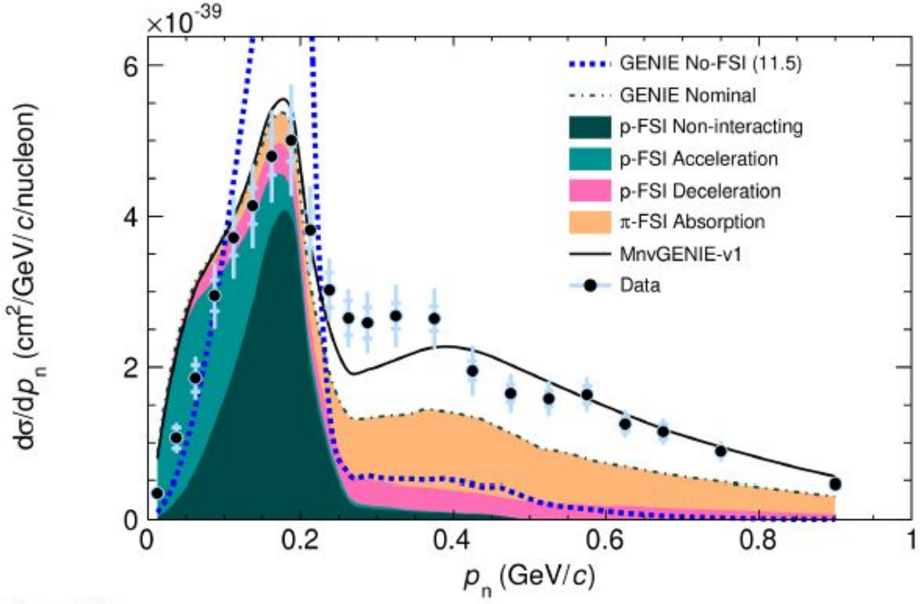
For CCQE, A' = ^{11}C*
No more unknowns
p_n: neutron Fermi motion

initial-state









Transverse momentum imbalance (missing pT) in CC0piNp sample

Upgraded with exclusivity constraint →

Initial neutron momentum

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Experimental Implications

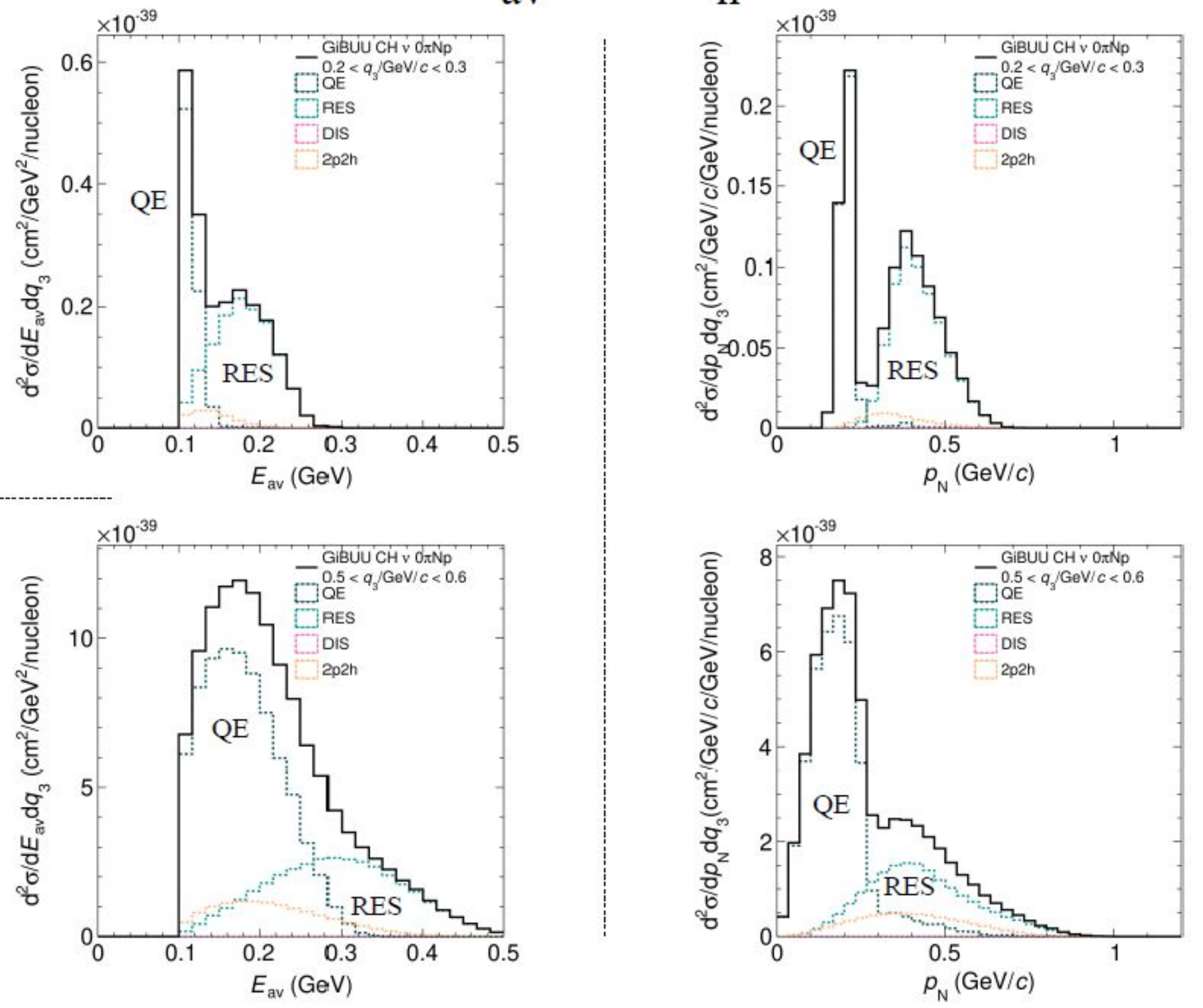
* GiBUU https://gibuu.hepforge.org/trac/wiki

p_n can provides QE/RES separation at high q3 (> 1 GeV/*c*)

E_{av} vs. p_n

q3 0.2-0.3 GeV/*c*

q3 0.5-0.6 GeV/*c*



* Compare q3-evolution of QE/RES/2p2h location: only 2p2h moves (GiBUU)