Nucleons from neutrino interactions

and why ν oscillations need ν interaction measurements!

Stephen Dolan

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The precision era of ν oscillations

Latest results

- **Indication of CP violation!**
- Currently largely limited by statistics … but not for long!

T2K

HYPER K

NOvA

SBN Program

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

The precision era of ν oscillations

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Current systematic uncertainties

Source (T2K)	$N(\nu_e)$
Binding Energy	7.1%
Total Syst.	**8.8%**

Nature **580**, 339-344 / arXiv:2101.03779

Source (NOvA)	$N(\nu_e)$
$\sigma_{\nu N}$ and FSI	7.7%
Total Syst.	**9.2%**

Phys. Rev. D **98**, 032012

- Current results use ~100 $\nu_e + \bar{\nu}_e$, expect **1000-2000** for DUNE/HK
- ~2-3% stat. precision on CP asymmetry

The precision era of ν oscillations

Latest results

- **Indication of CP violation!**
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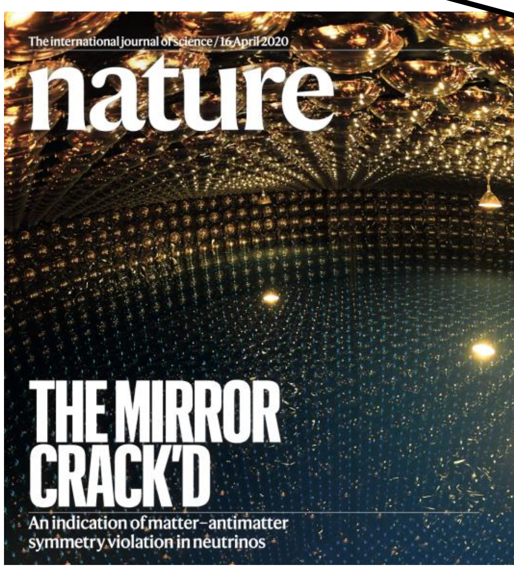
  st... for long!

Neutrino interaction uncertainties must be reduced for DUNE/Hyper-K to succeed

...rtainties



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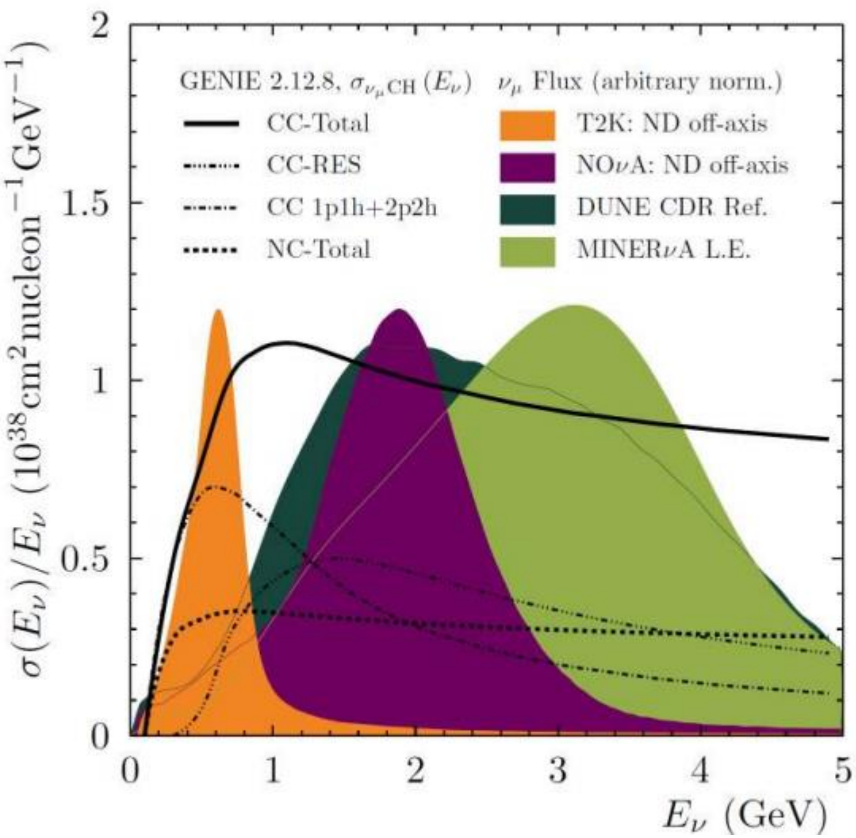
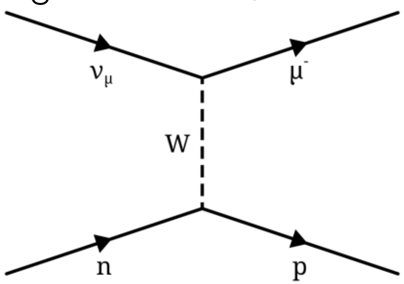
Neutrino interactions

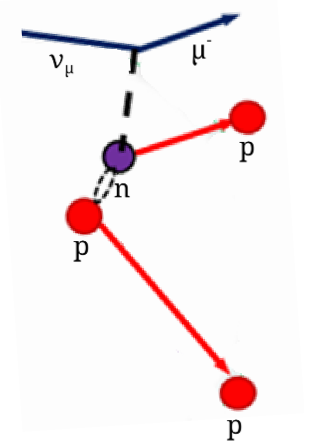


Key challenge: estimating E_ν

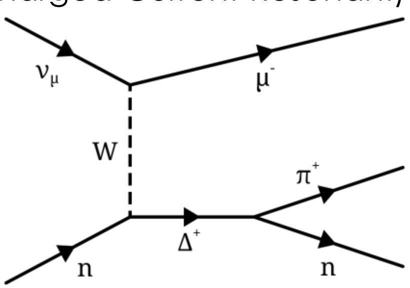
CCQE (1p1h)
(Charged-Current Quasi-Elastic)



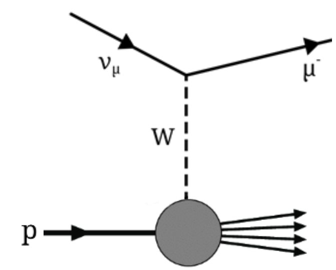
CC 2p2h
(2 particle, 2 hole)



CCRES
(Charged-Current Resonant)

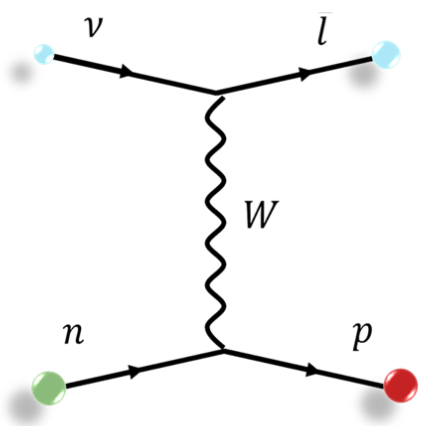


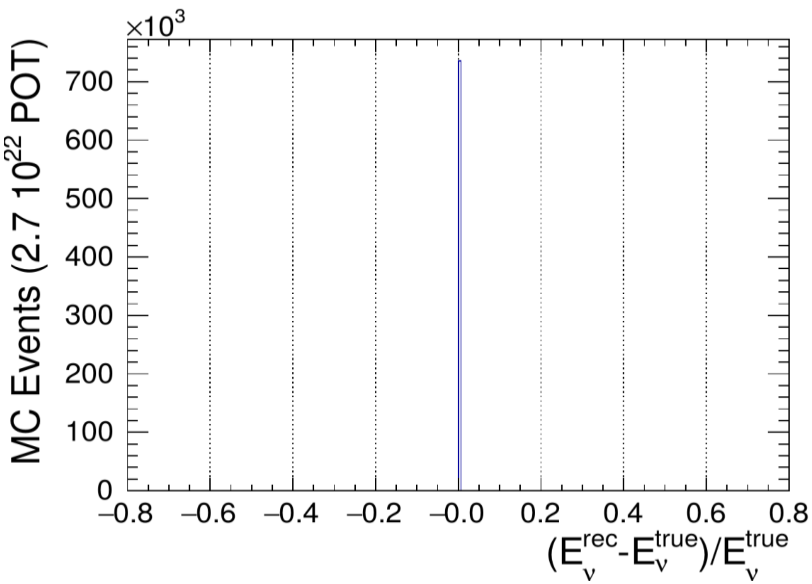
CCDIS
(Deep Inelastic Scattering)



Nuclear effects and E_ν (T2K/HK)

CCQE (1p1h)

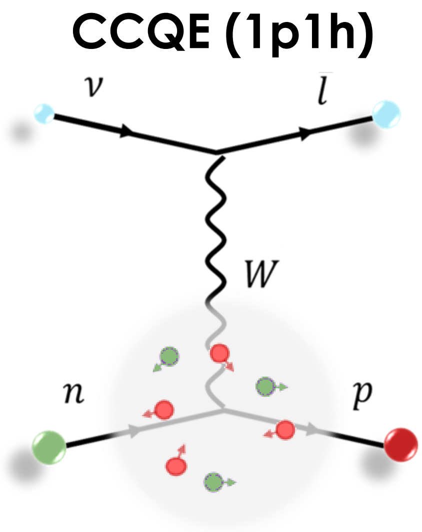


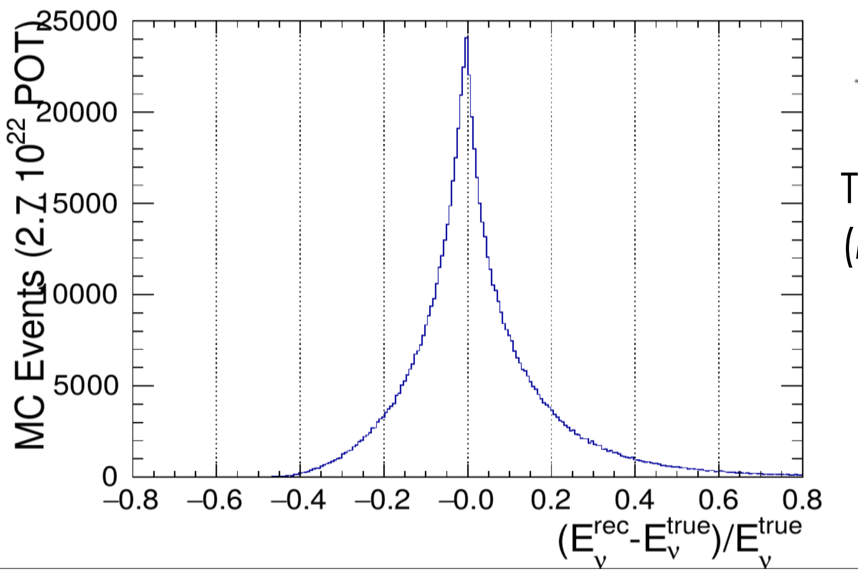


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Proxy for E_ν from lepton kinematics is perfect only for **CCQE elastic scattering** off a **stationary nucleon**

Nuclear effects and E_ν (T2K/HK)





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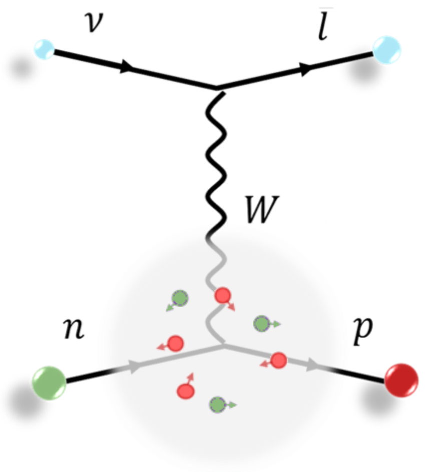
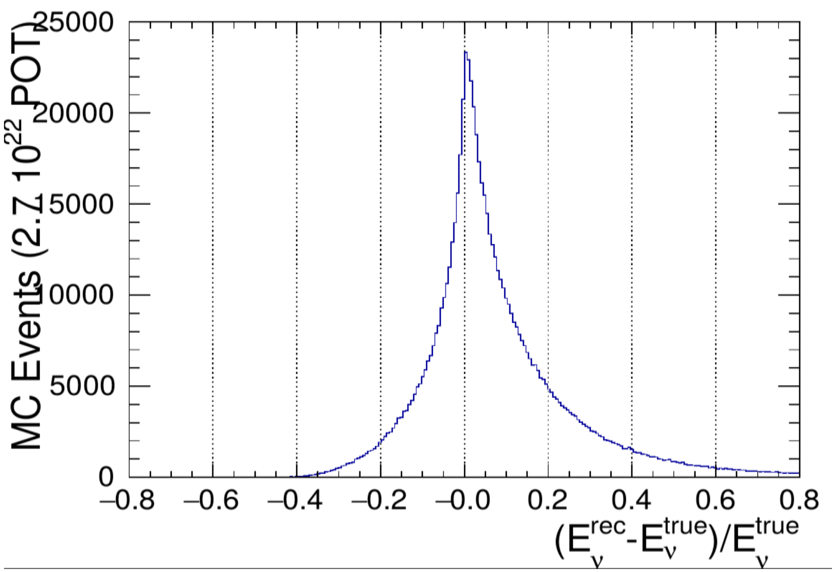
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

Nuclear effects and E_ν (T2K/HK)

CCQE (1p1h)





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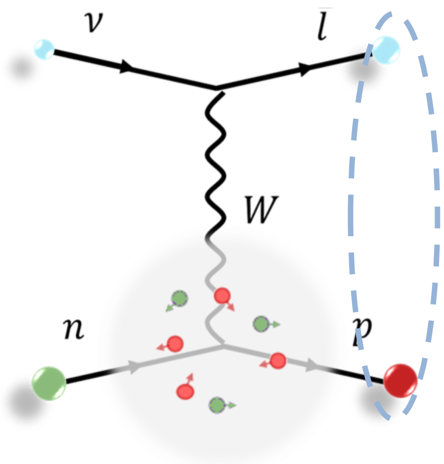
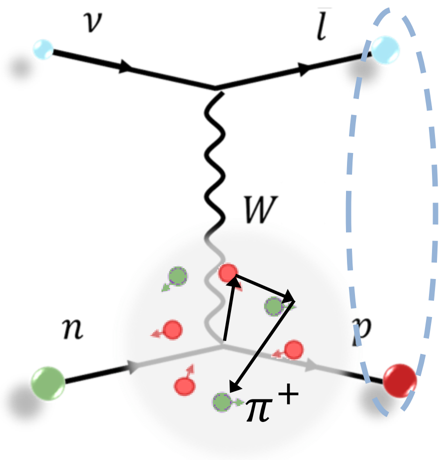
The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

Nuclear effects and E_ν (T2K/HK)

CCQE (1p1h)

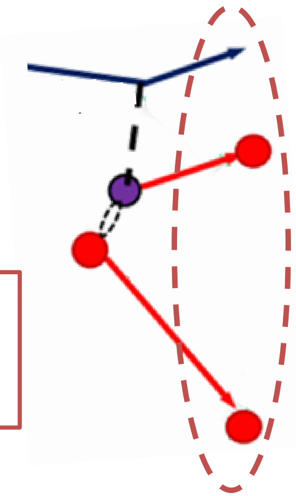


CCRES

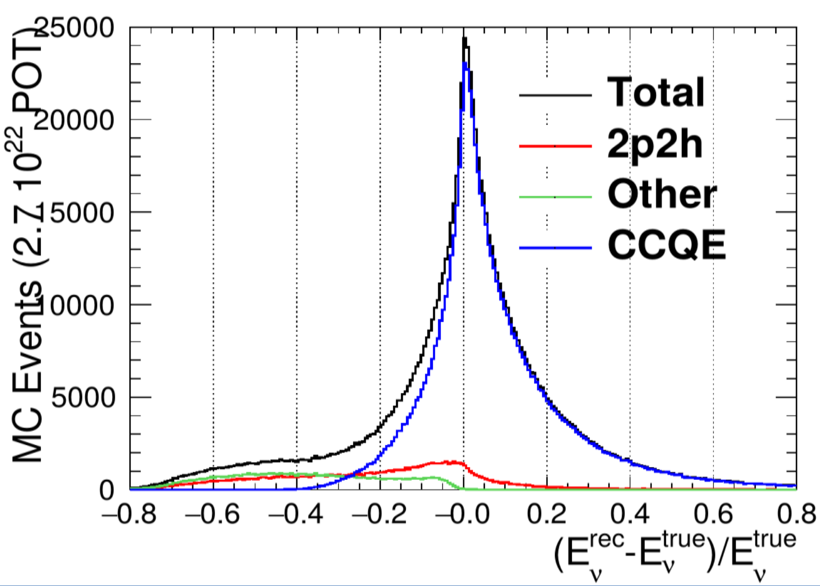


Final state interactions (FSI) can cause different interaction modes to have the same final state

2p2h



Interactions off a bound state of two nucleons can result in **2p2h** final states



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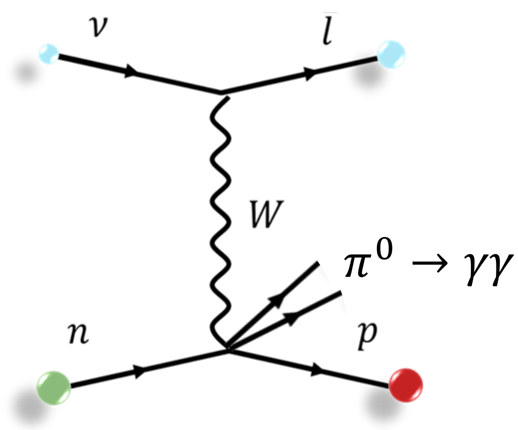
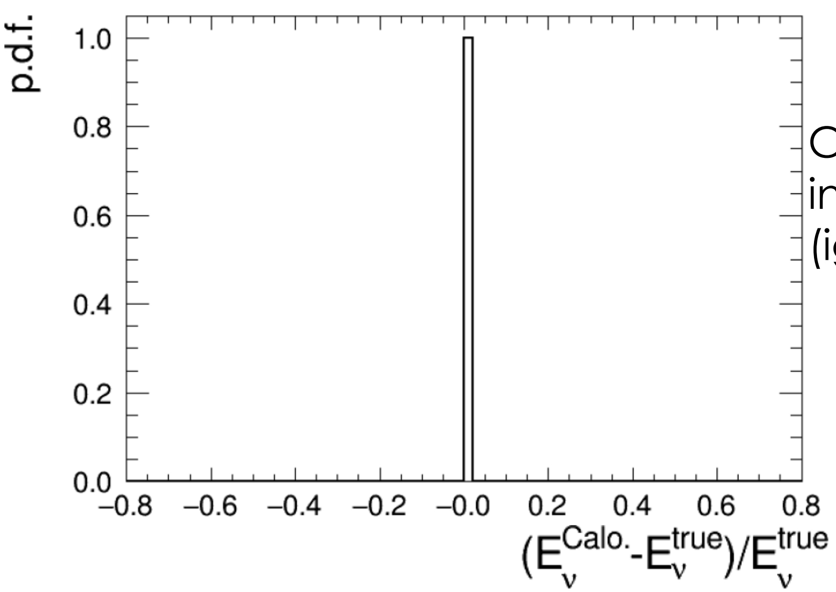
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

Not a good proxy for non-CCQE events: 2p2h and CC1π with pion abs. FSI

Nuclear effects and E_ν (SBN/DUNE/NOvA)



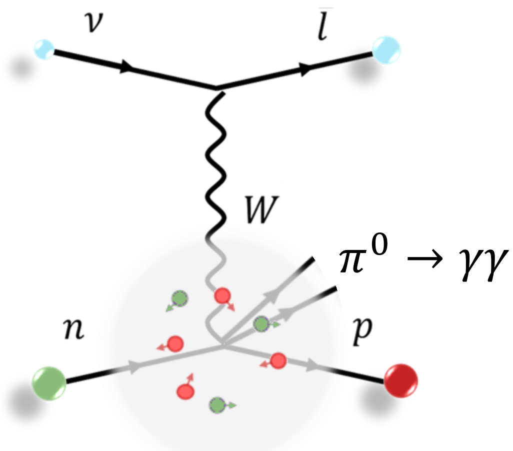


$$E_\nu^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

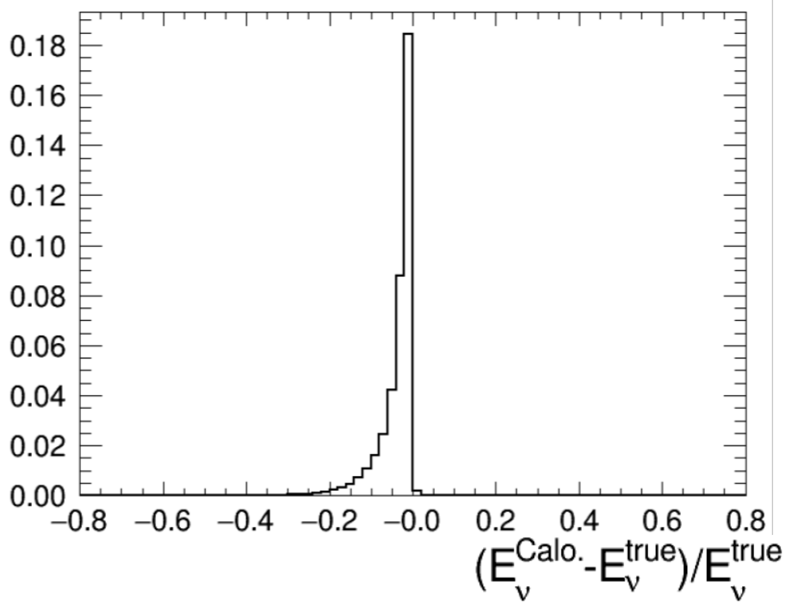
Calculation from calorimetry is perfect only for interactions **without neutrons and charged pions** (ignore heavier mesons here) off a **stationary nucleon**

Usefulness is not restricted to QE-like interactions (no final state pions)

Nuclear effects and E_ν (SBN/DUNE/NOvA)



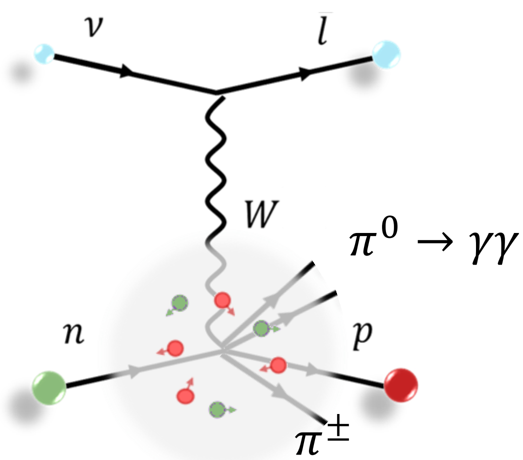
All events without n or $\pi^\pm$



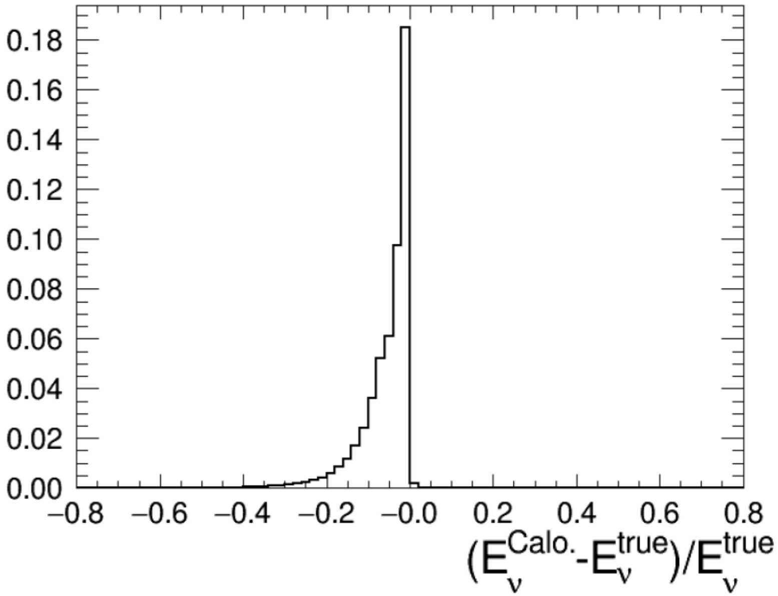
$$E_\nu^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

Impact of initial state effects (Fermi motion and removal energy) smaller than in QE approach

Nuclear effects and E_ν (SBN/DUNE/NOvA)



All events without n



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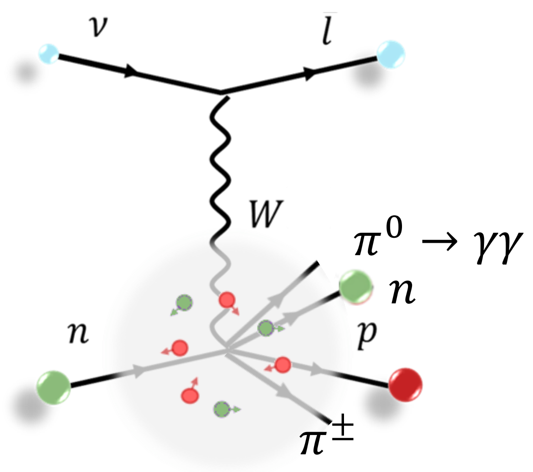
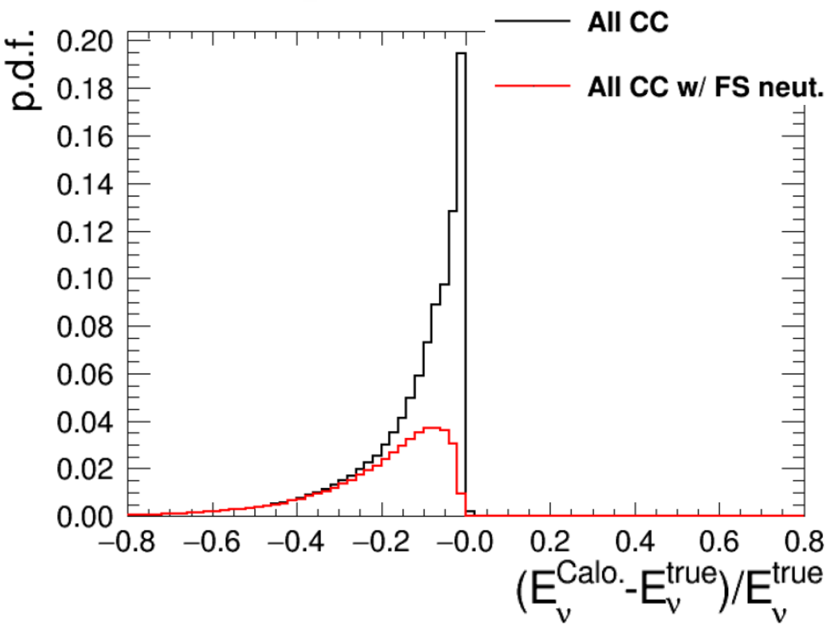
Impact of initial state effects (Fermi motion and removal energy) smaller than in QE approach

Charged pion masses also play a fairly small role

Nuclear effects and E_ν (SBN/DUNE/NOvA)





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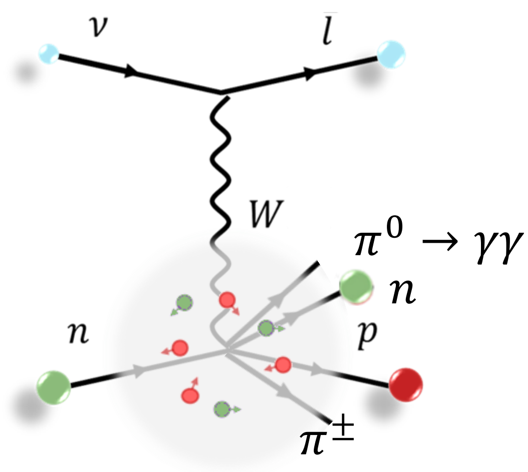
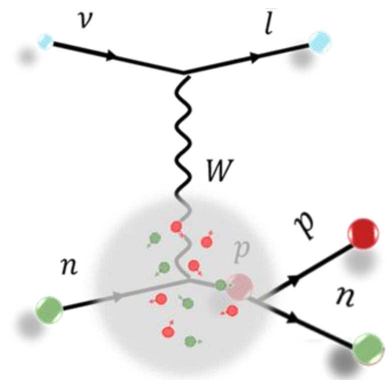
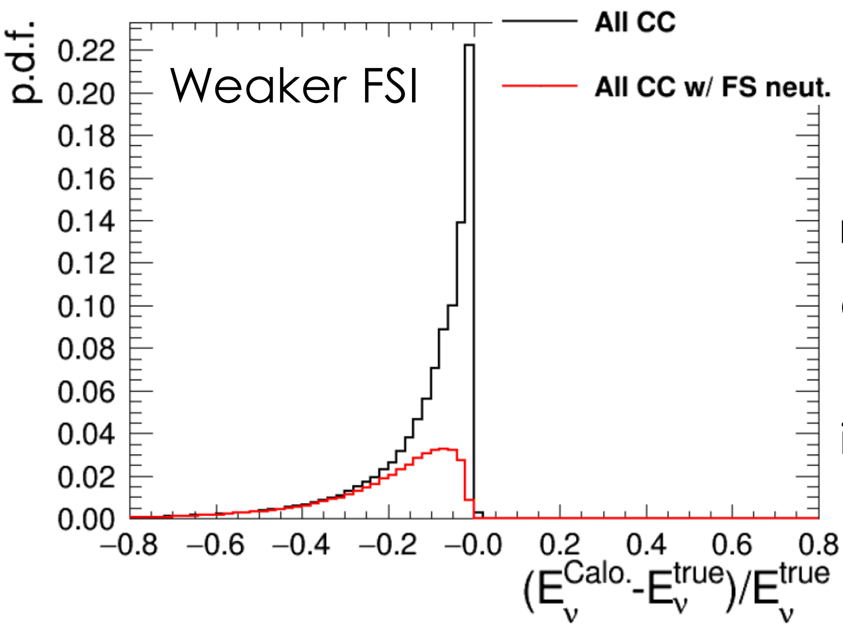
Fraction of E_ν in **Neutrons** is critical

Nuclear effects and E_ν (SBN/DUNE/NOvA)



Final State Interactions (FSI)





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Impact of initial state effects (Fermi motion and removal energy) smaller than in QE approach

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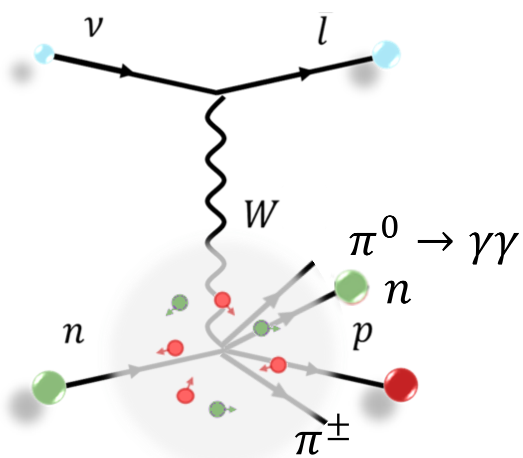
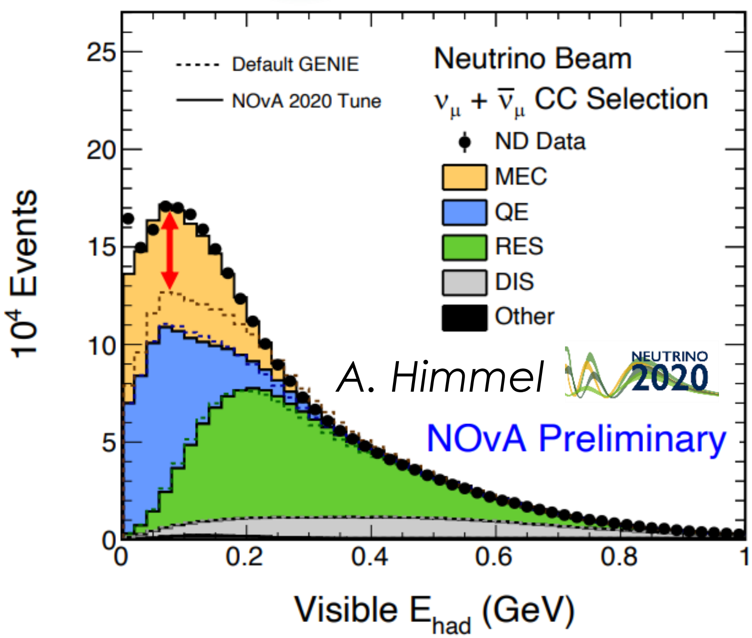
Fraction of E_ν in **Neutrons** is critical – affected importantly by FSI (and more important for $\bar{\nu}$)

Nuclear effects and E_ν (SBN/DUNE/NOvA)





- Complex interaction topologies make E_{had} tough to model
- NOvA find strong data/simulation discrepancy at low E_{had} (before applying a 2p2h modification)
- Covered by generous systematics, but this must be better understood for DUNE

What we need to know (a non exhaustive list!)

T2K/HK

("kinematic" E_ν proxy)

Critical

- Nuclear ground state: **Fermi motion** and "**binding energy**"
- **2p2h** and **pion absorption FSI** contributions to 0π final states

Important

- Impact of **nucleon FSI** on $\sigma(\nu_e)/\sigma(\nu_\mu)$ (see backups for details)
- Differences between interactions on Carbon and Oxygen

SBN/DUNE/NOvA

("calorimetric" E_ν proxy)

Critical

- Neutron production:
  - **FSI**
  - **2p2h**
  - DIS hadronisation

Important

- Charged pion multiplicities (e.g. from **FSI**)
- Nuclear ground state
- Differences between interactions on Carbon and Argon

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("kinematic" E_ν proxy)

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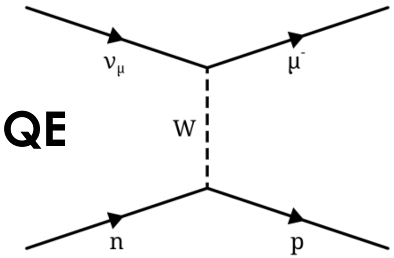
Neutrino interaction modelling is crucial all upcoming experiments, but different experiments have different priorities: **complimentary approaches**!


KEEP CALM
AND
MEASURE dσ/dx

What can we measure?

Interaction Modes

CCQE



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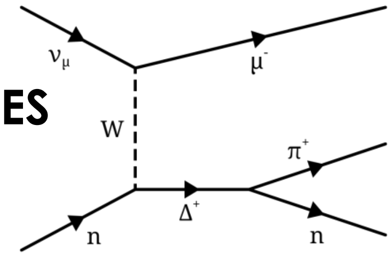
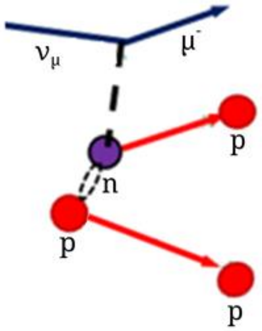
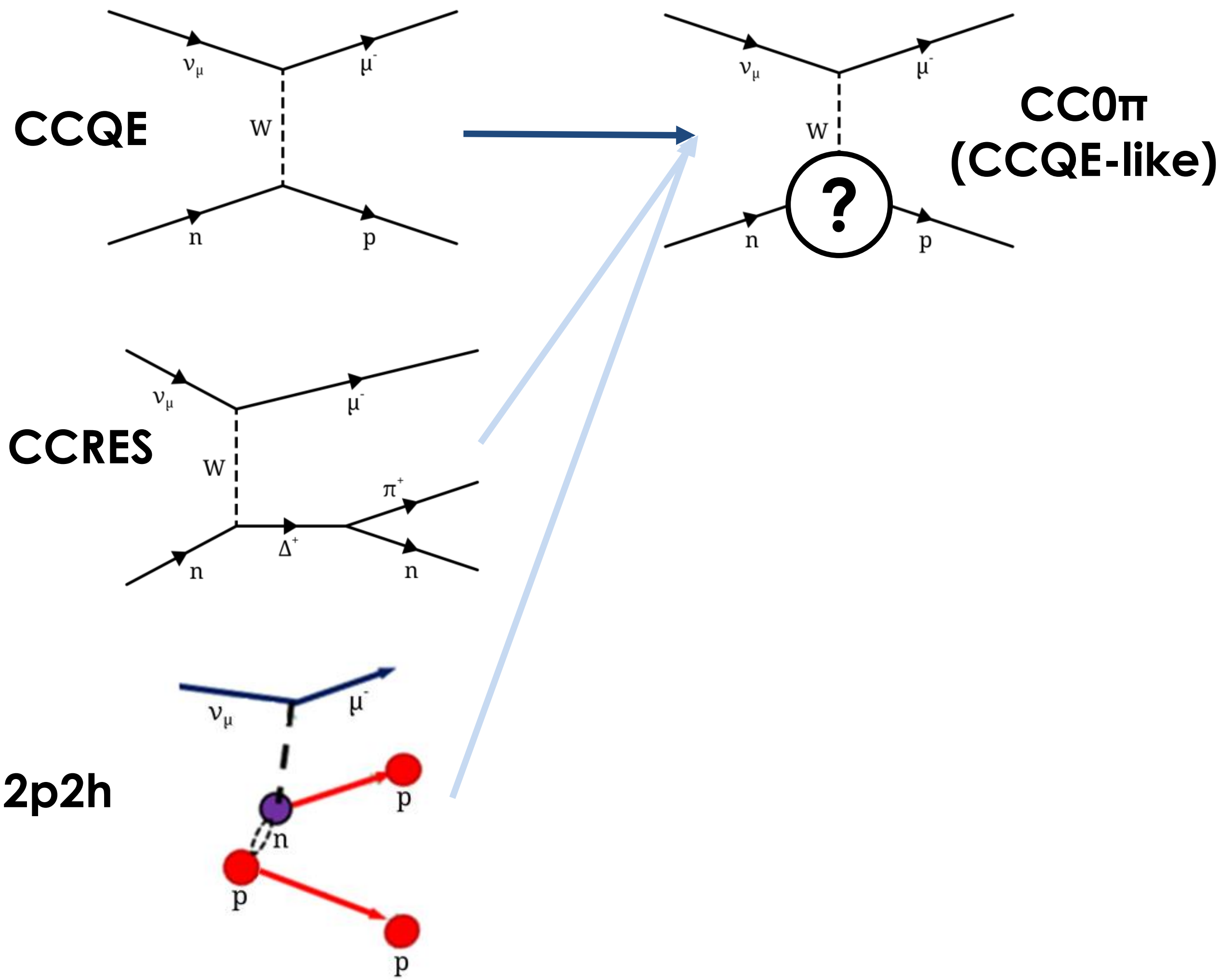


2p2h



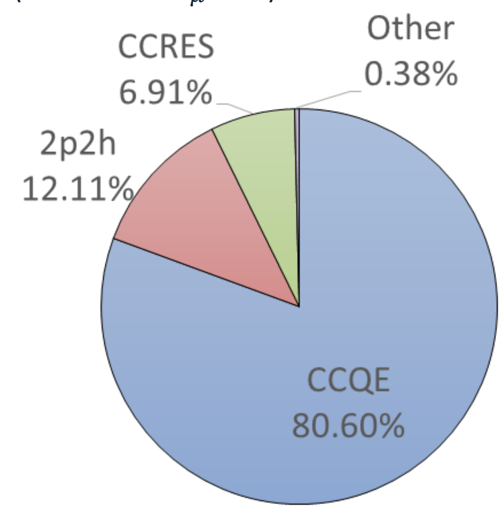
What can we measure?

Interaction Modes | **Interaction Topologies**



- We measure what our detector actually sees
- But this contains all sorts of physics …

Interaction modes in CC0π topology:
(NEUT, T2K ν_μ flux)



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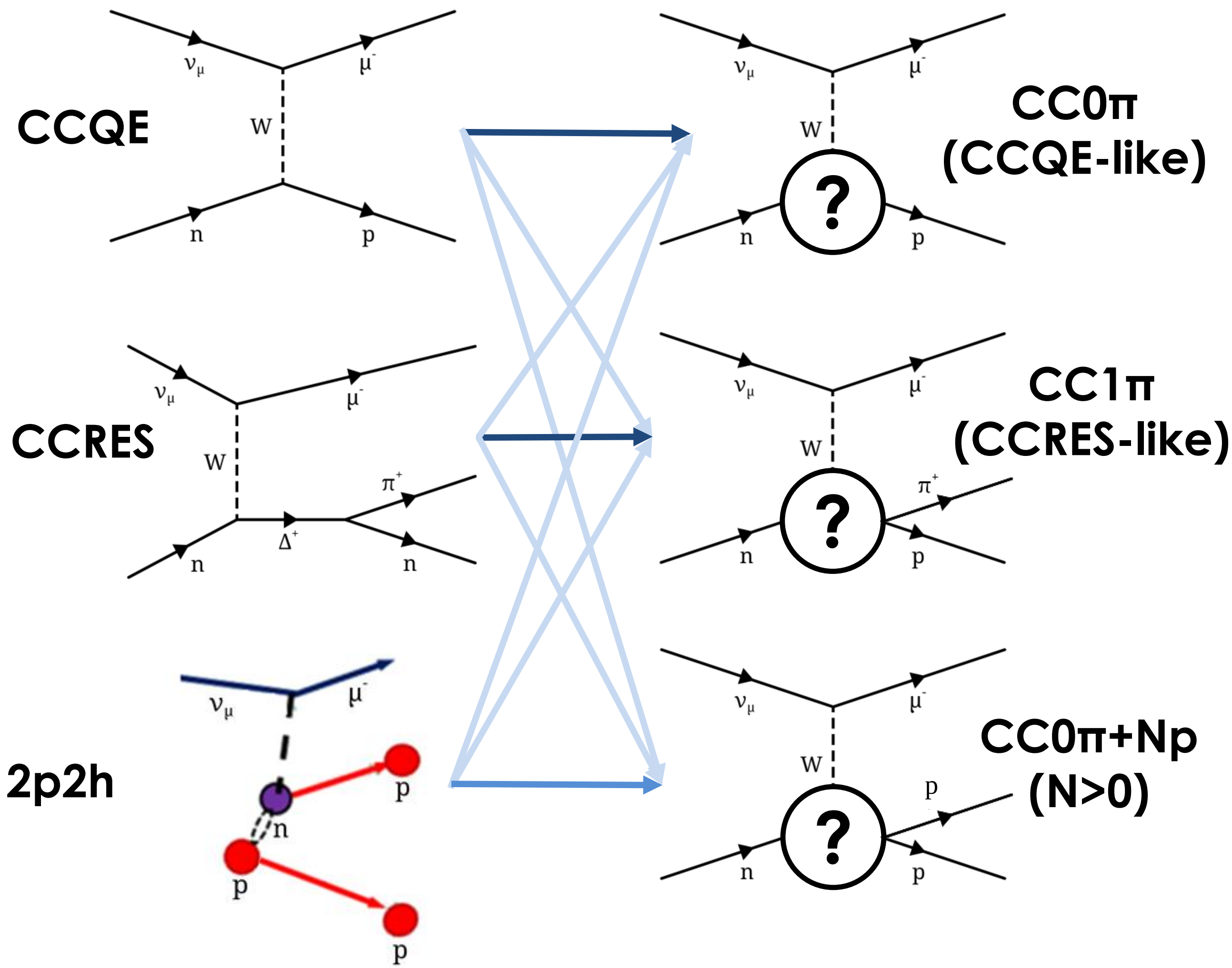
Interaction Modes | **Interaction Topologies**



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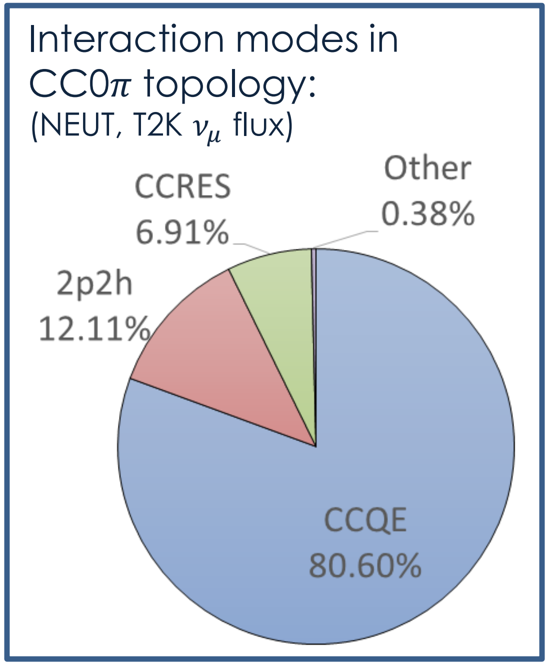

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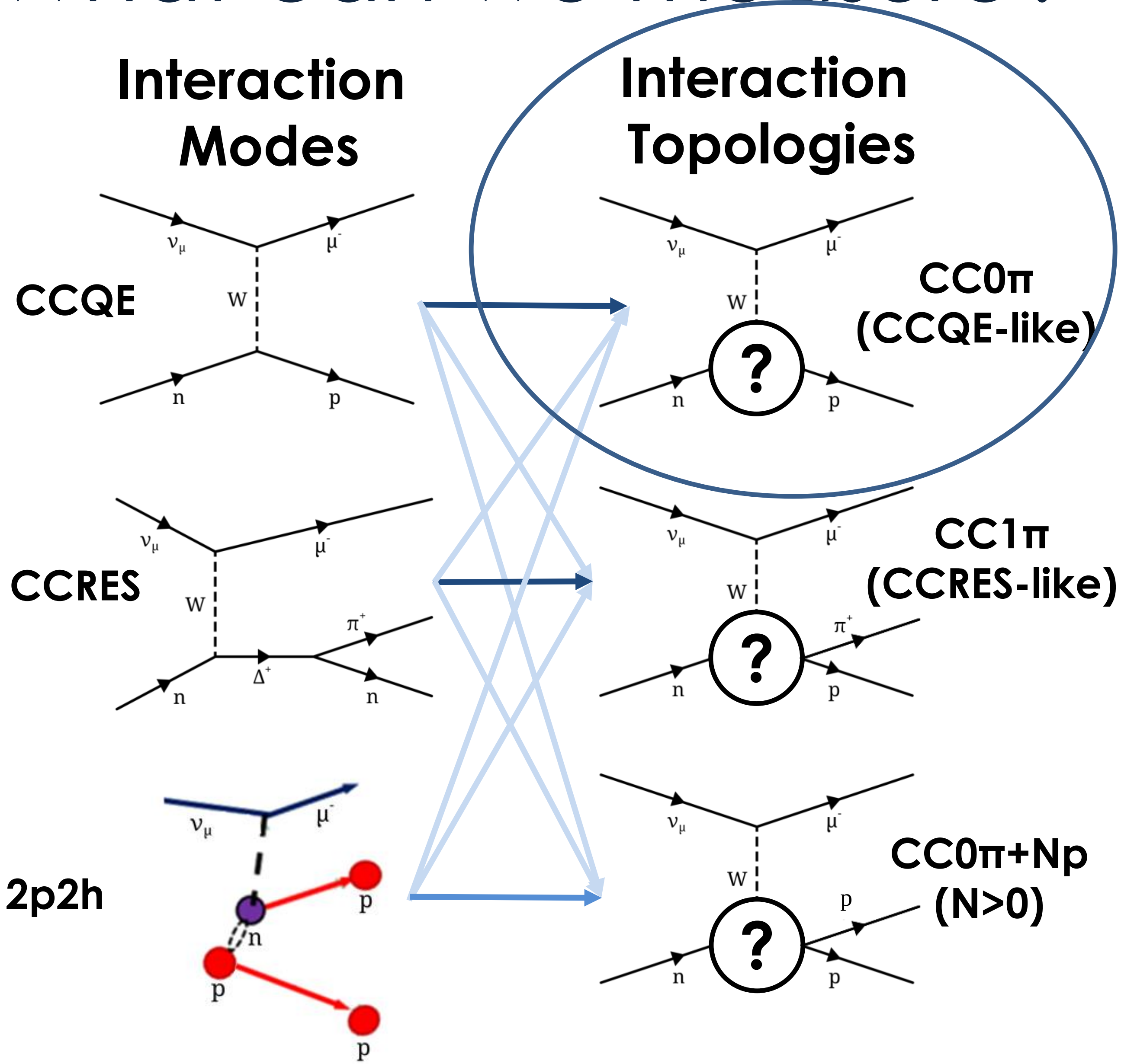

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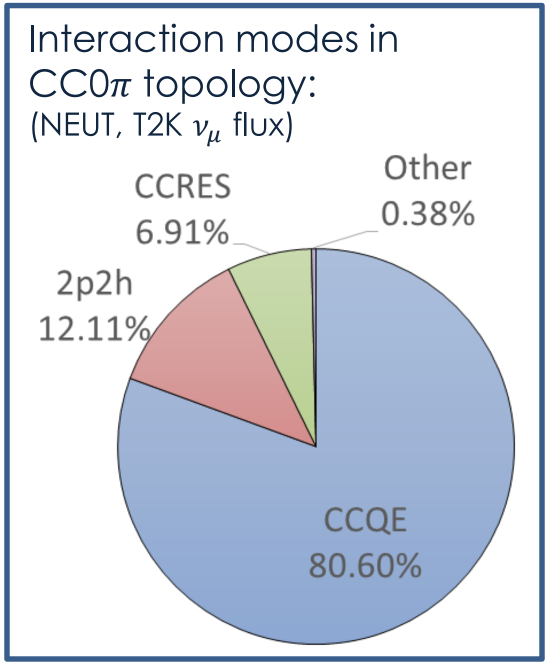
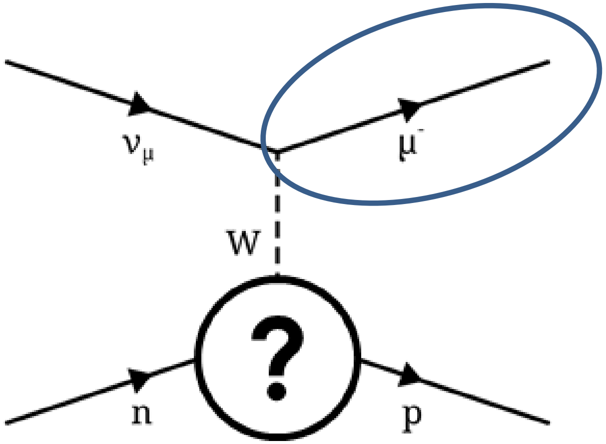


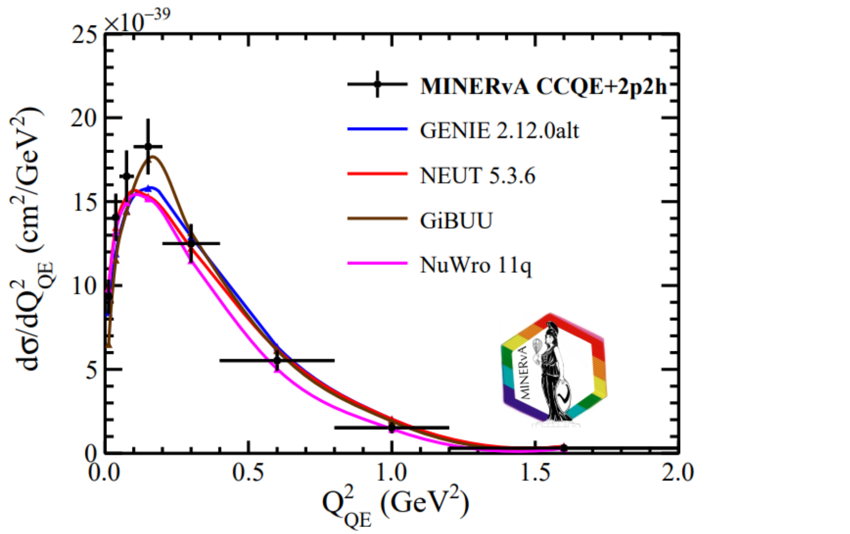
Which observables?

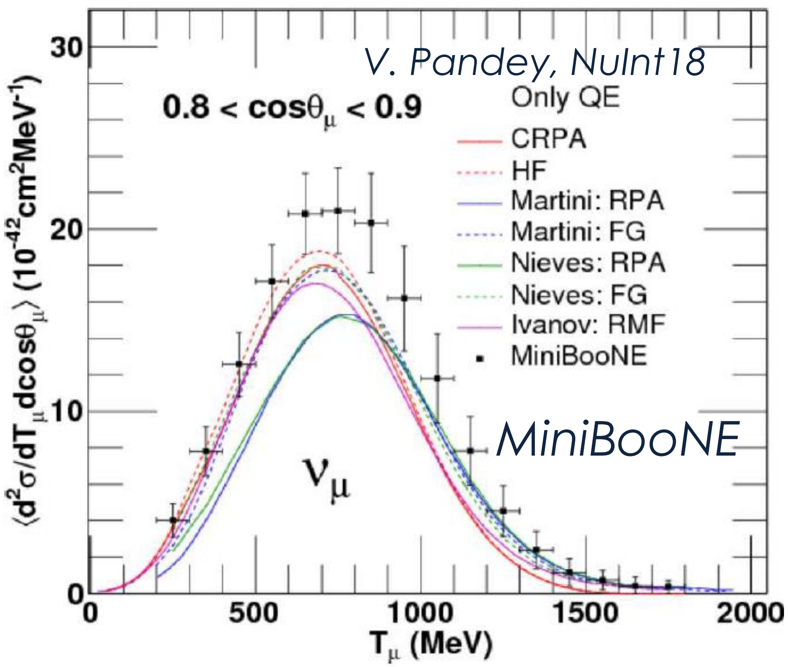
Just the lepton?

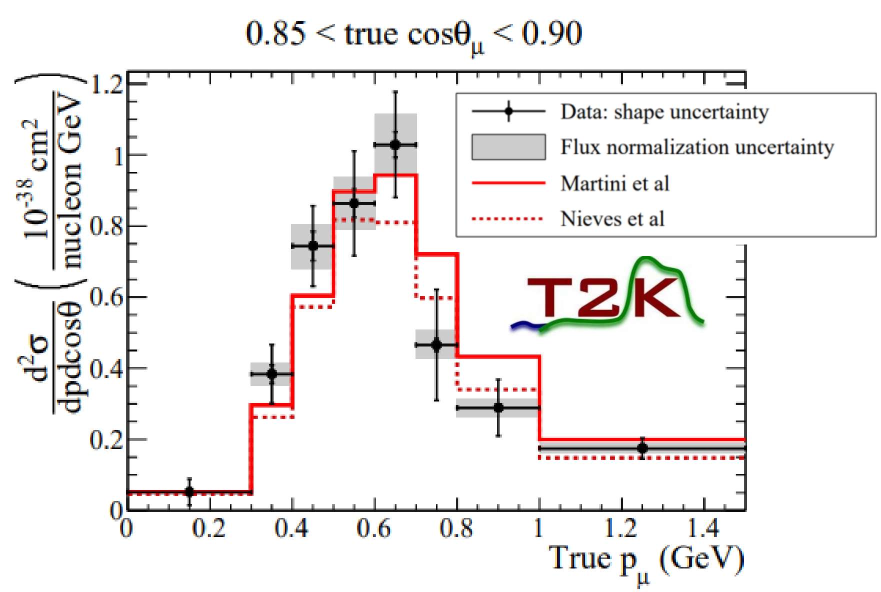


Which observables?

- Models can broadly describe data
- But the wide-band nature of neutrino beams means the impact of nuclear effects is “smeared out”
- Dramatically different models give very similar predictions!







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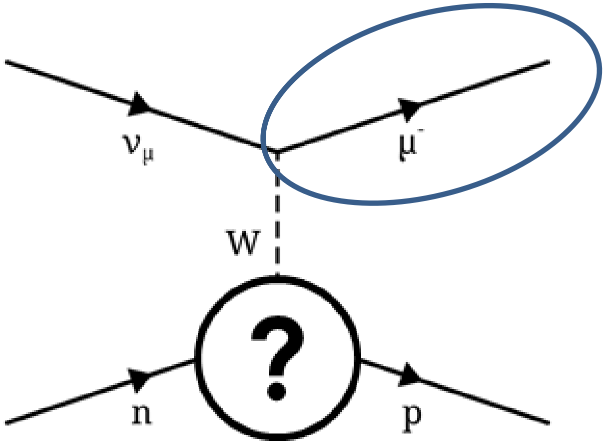
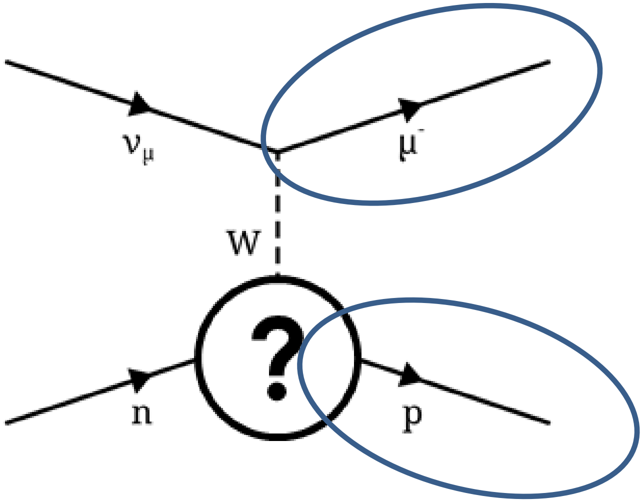


Difficult to untangle nuclear effects due to wide band neutrino fluxes.

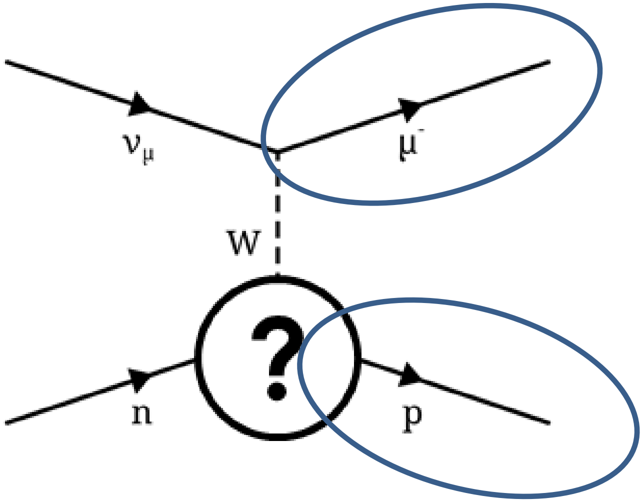
Which observables?

Lepton and proton?



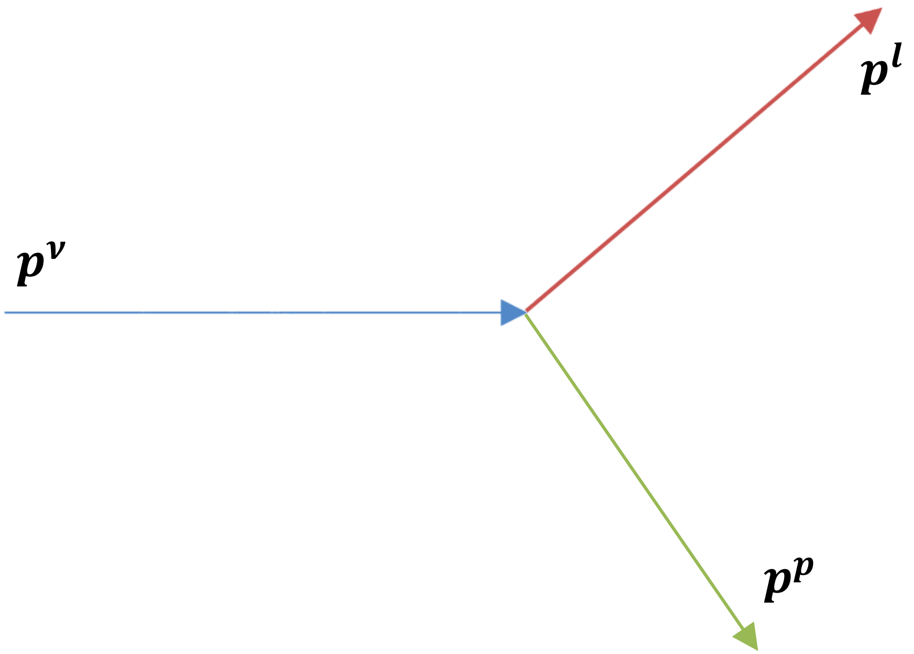
Which observables?

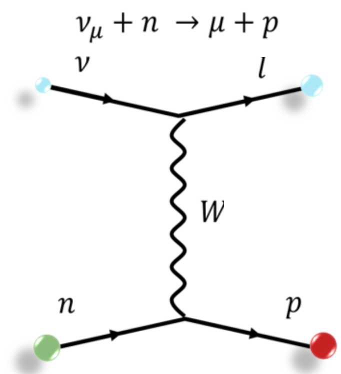
Lepton and proton?



Correlations between the muon and proton kinematics allow us to disentangle nuclear effects from neutrino energy

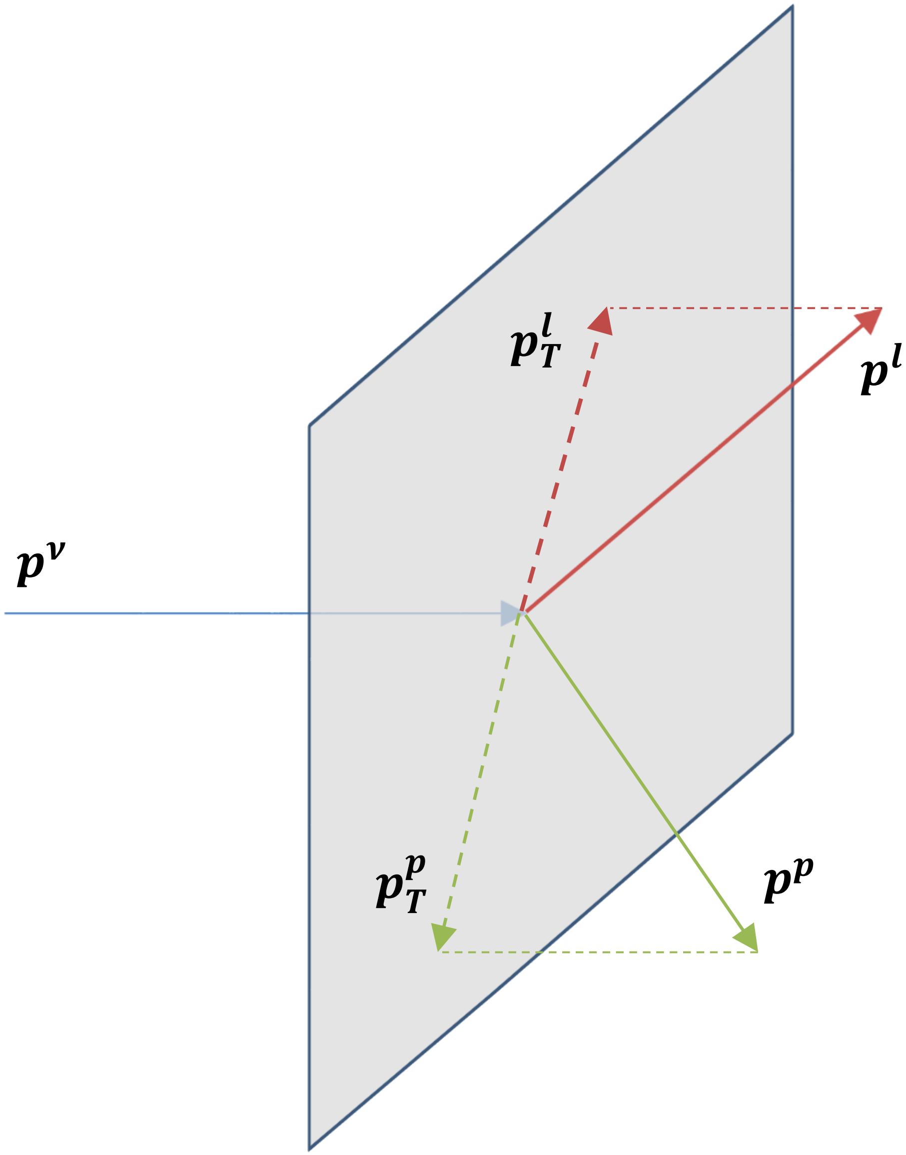
Single Transverse Variables

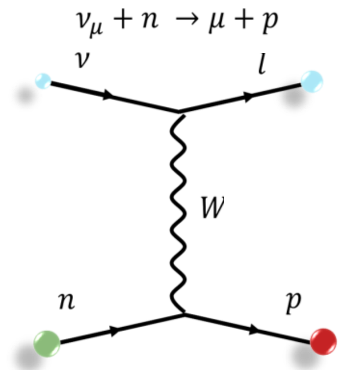




No nuclear Effects

Single Transverse Variables

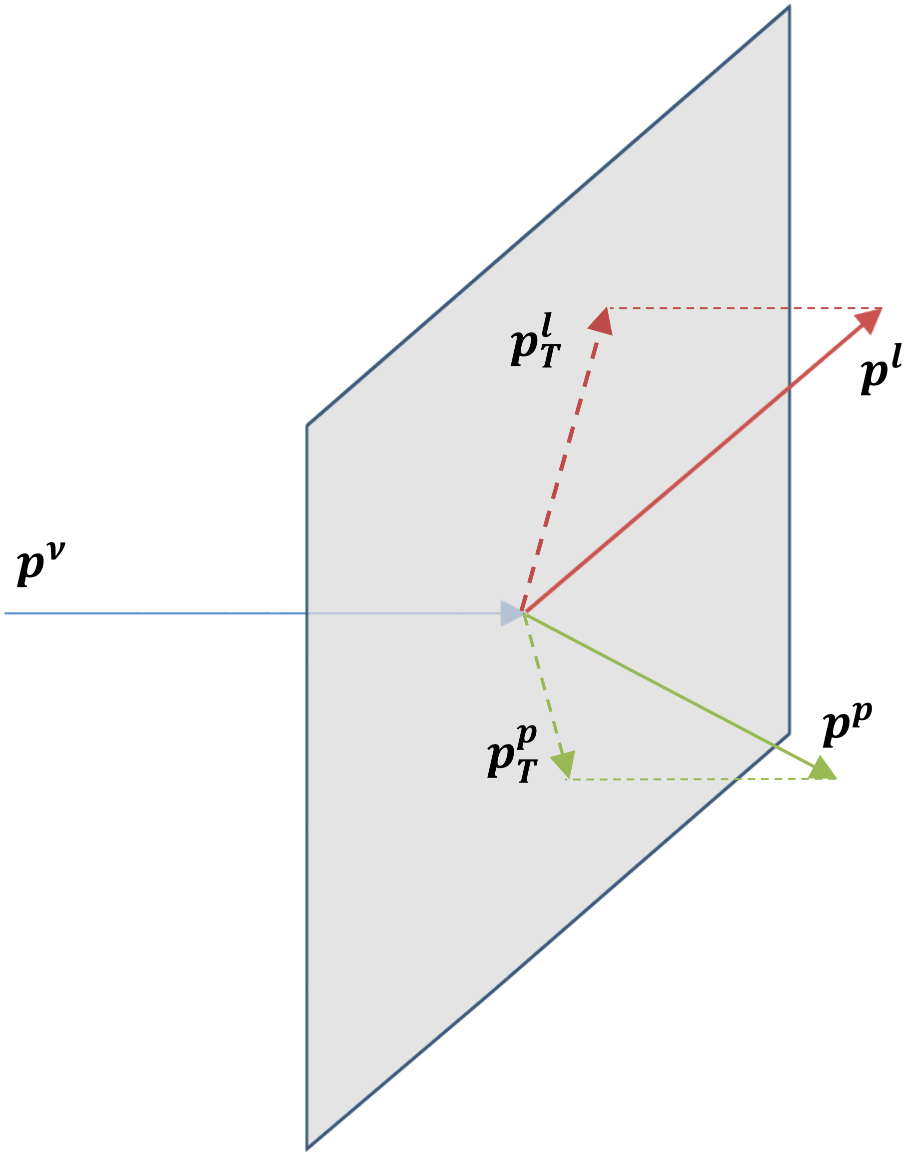


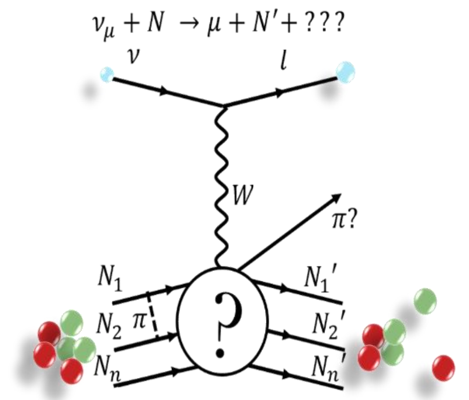


No nuclear Effects

$$p^{l}_{T} = -p^{p}_{T}$$

Single Transverse Variables



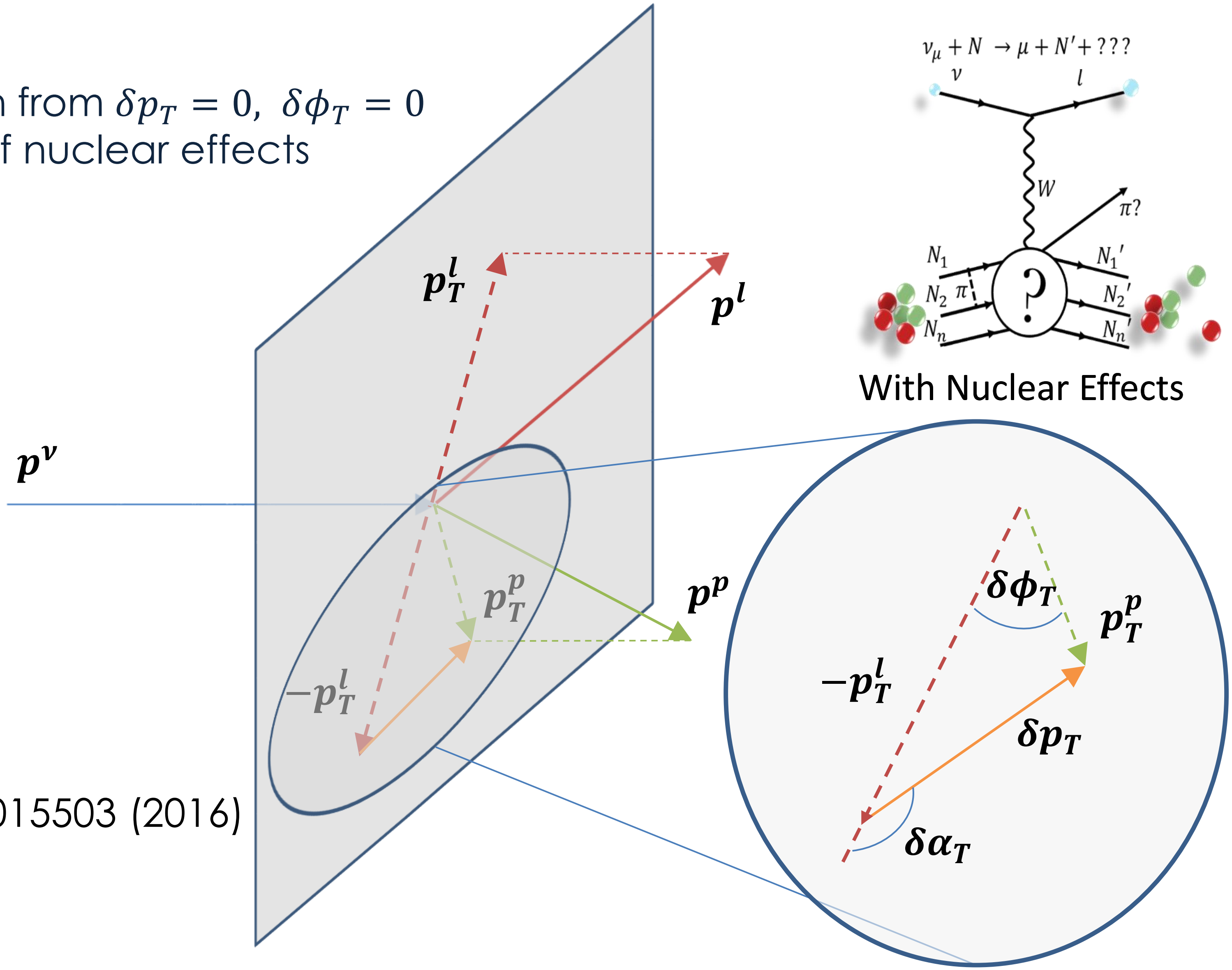


With Nuclear Effects

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

Single Transverse Variables

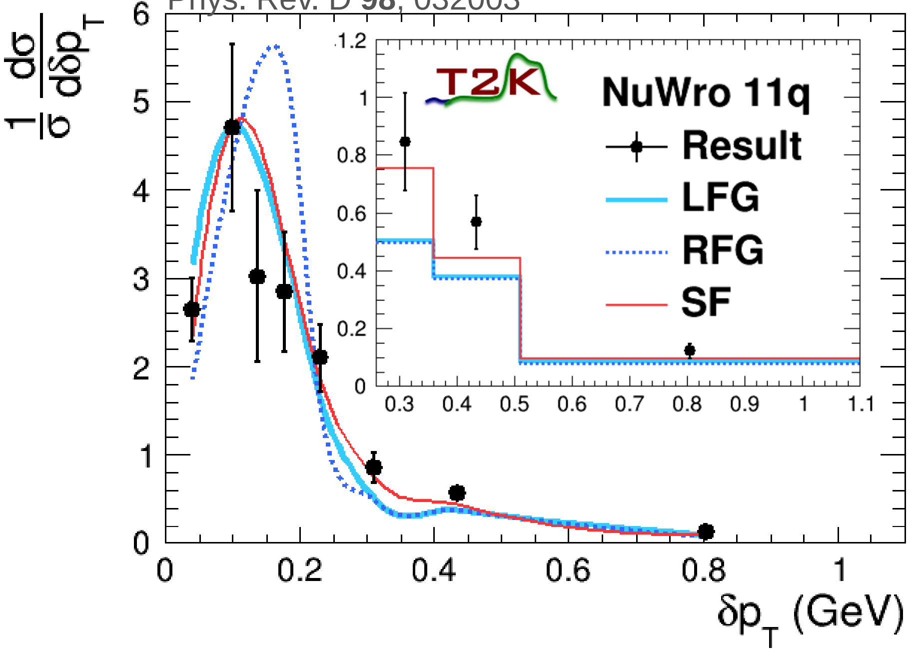
- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects



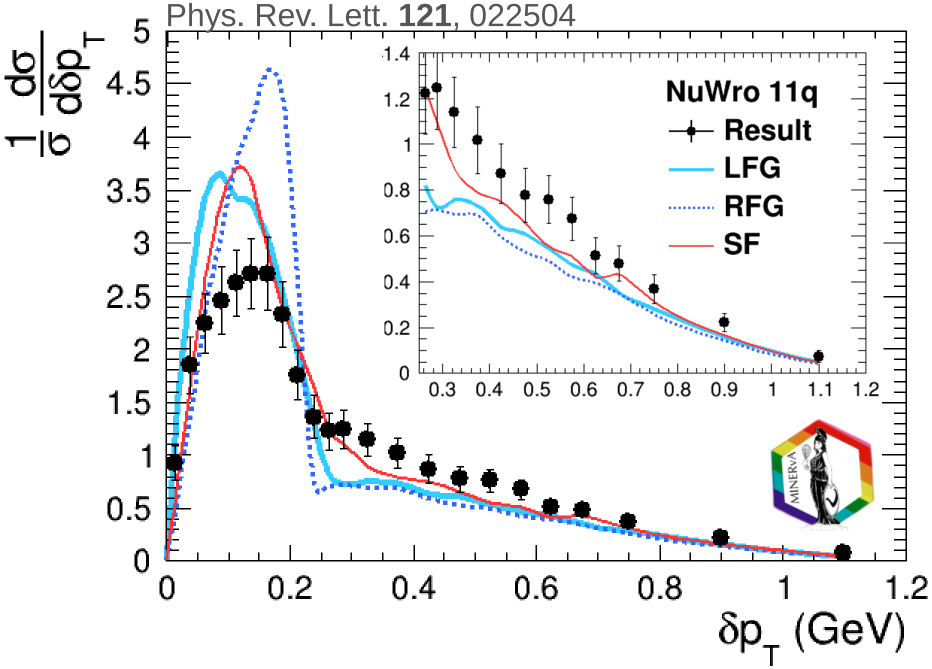
Phys. Rev. C **94**, 015503 (2016)

Current measurements

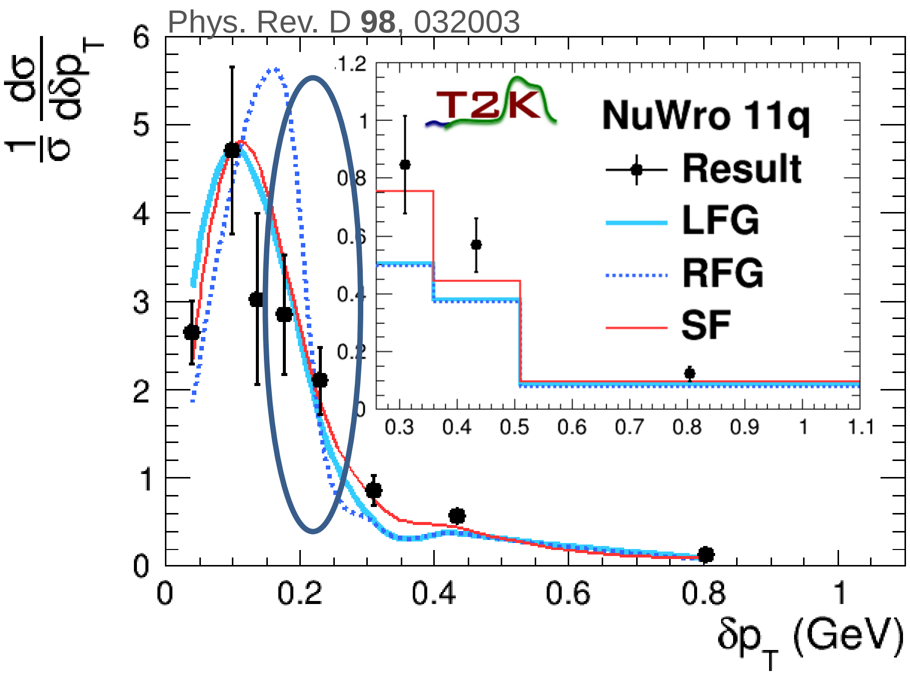
Phys. Rev. D **98**, 032003

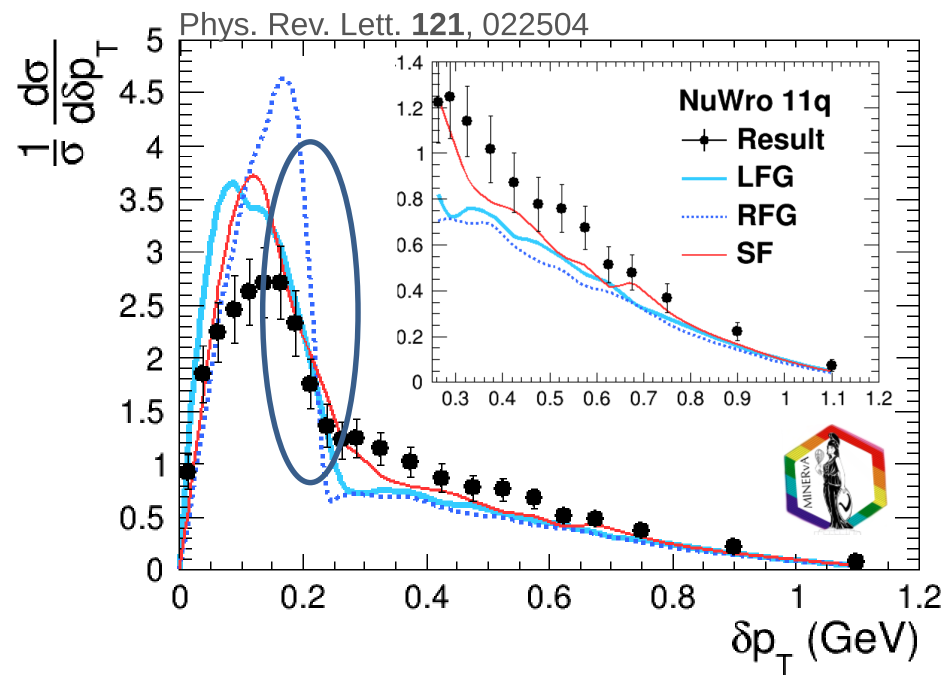


Phys. Rev. Lett. **121**, 022504



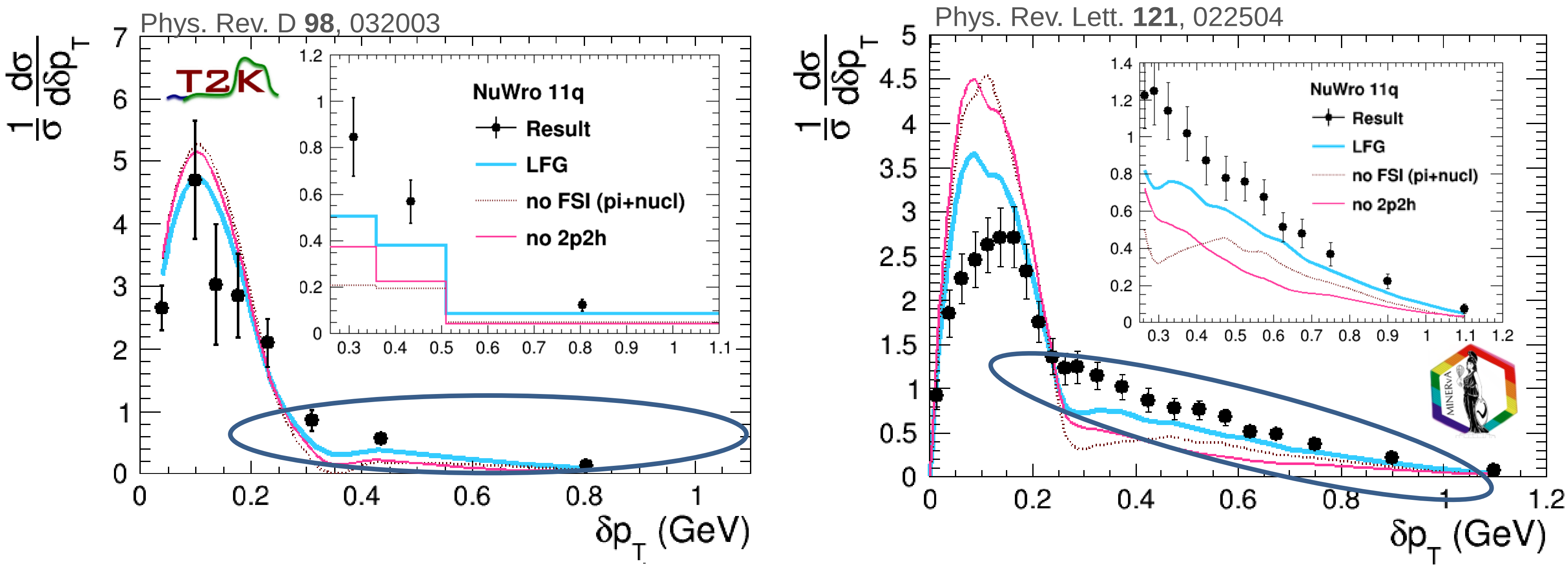
Current measurements





- The bulk of the distribution is sensitive to initial state nuclear effects
- But none of the models are able to provide a complete description of the data …

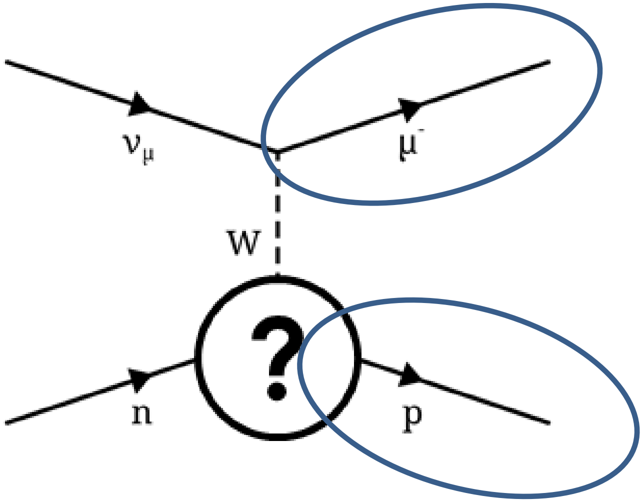
Current measurements



- The tail is more sensitive to 2p2h and FSI effects
- But, again, no model can describe the observations
- Clearly we have work to do in our modelling of nuclear effects!

Which observables?

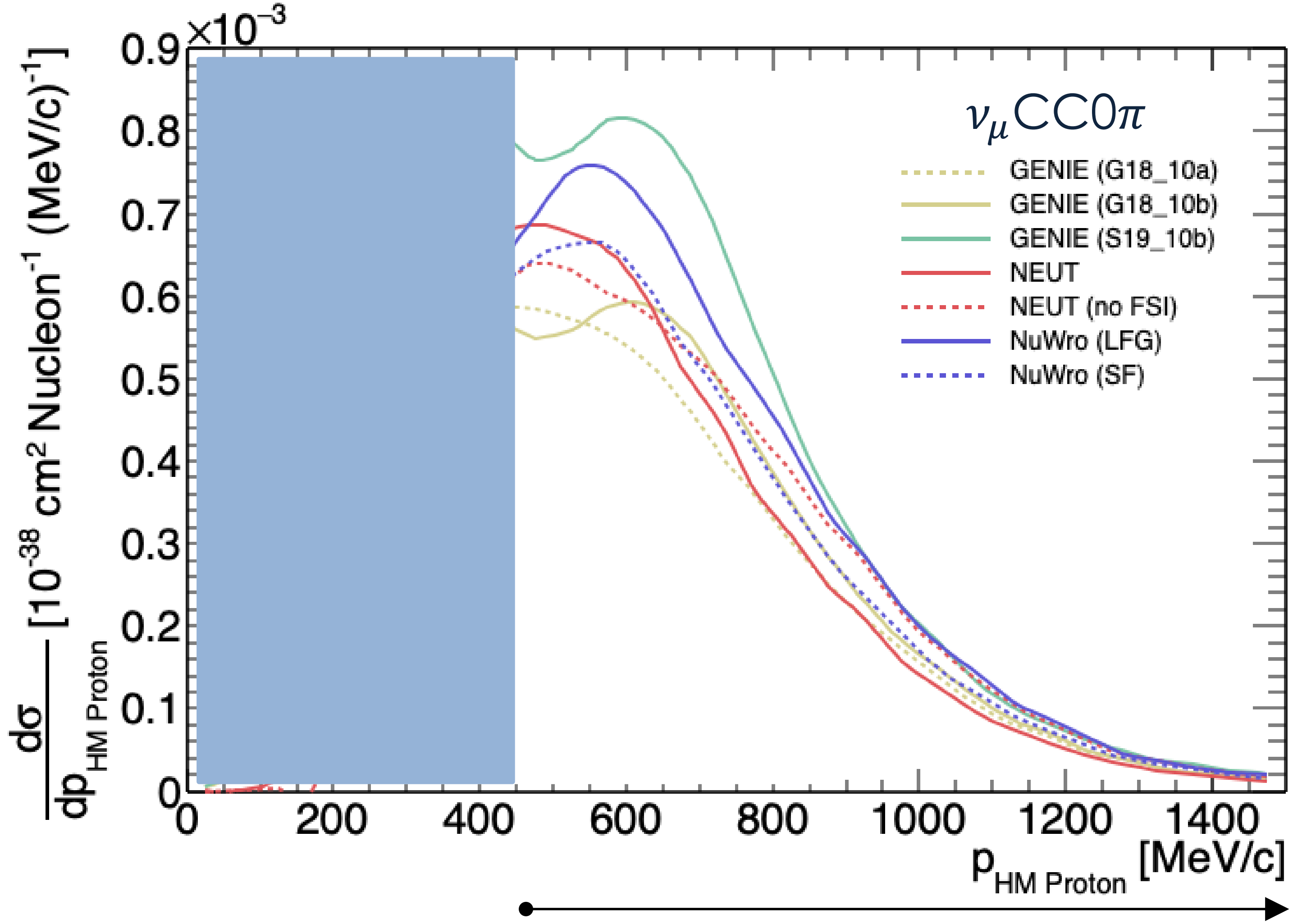
Lepton and proton?



Correlations between the muon and proton kinematics allow us to disentangle nuclear effects from neutrino energy

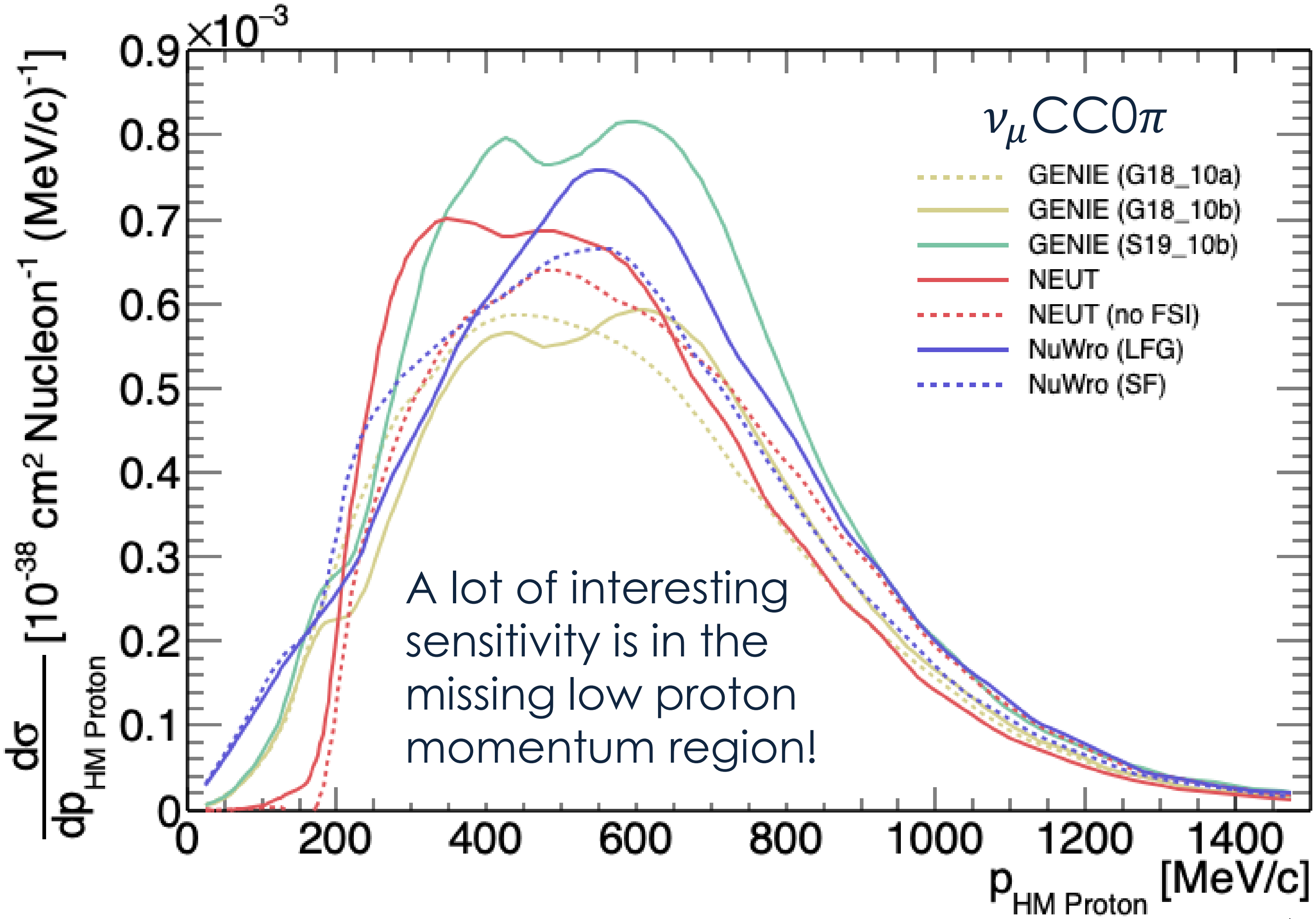
However, limited detector acceptance means low statistics and that we don't see the full story …

Proton momentum thresholds



The range of proton momentum current experiments are sensitive to

Proton momentum thresholds



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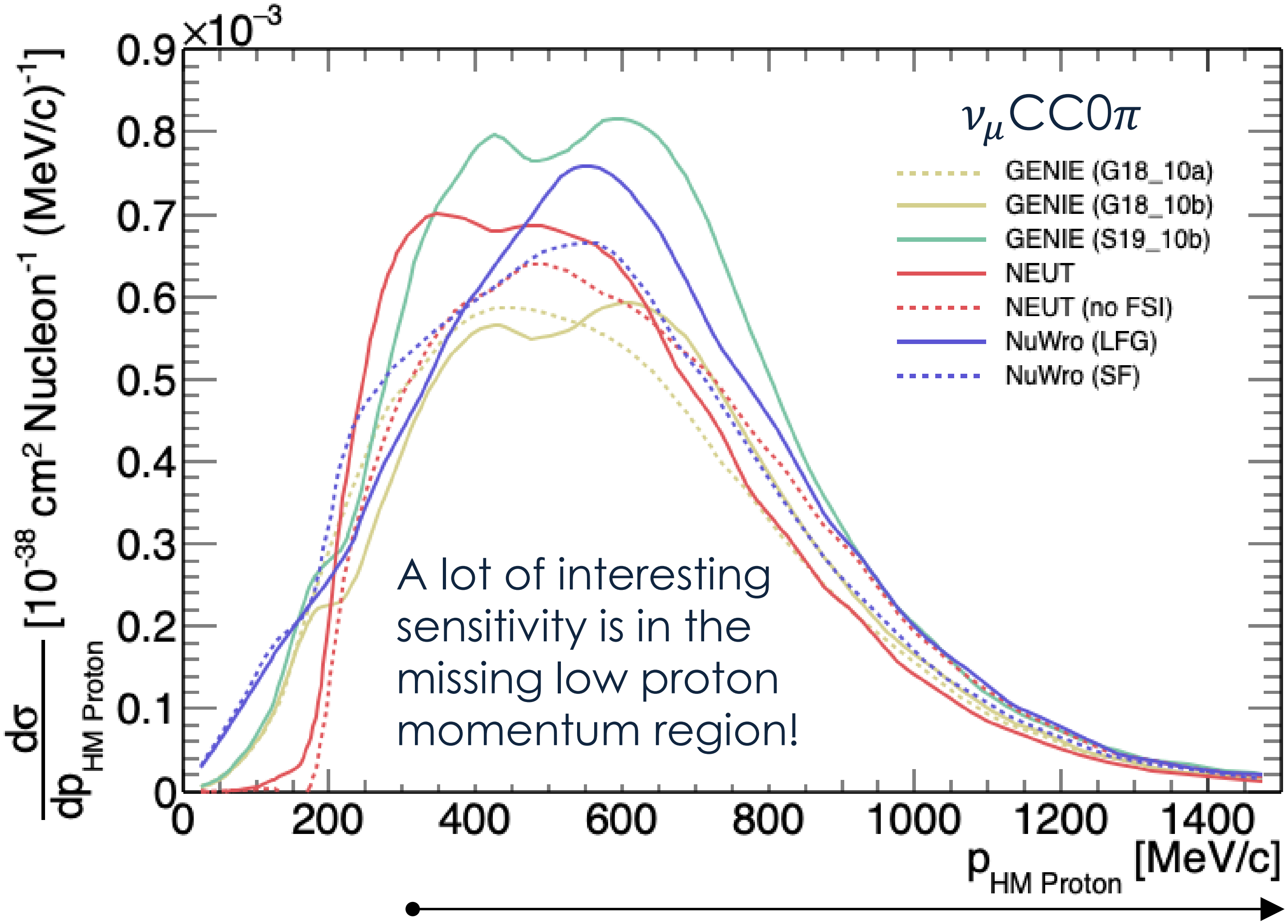
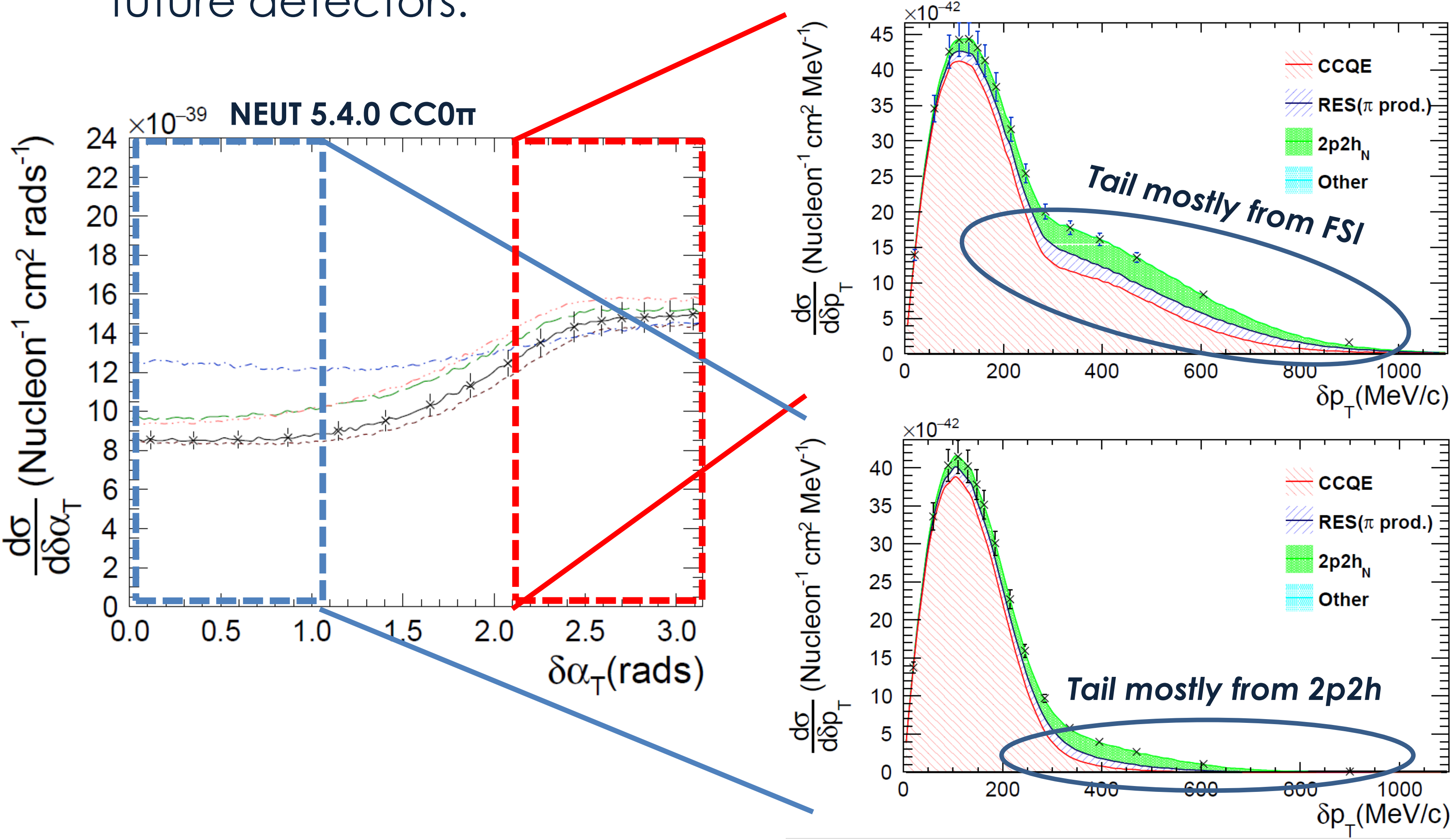


The range of proton momentum ND280 Upgrade and LAr detectors can access

Enhanced sensitivity

- Measuring δp_T in bins of $\delta \alpha_T$ may allow excellent separation of nuclear effects - makes use of high statistics / low thresholds from future detectors.



Summarising current measurements

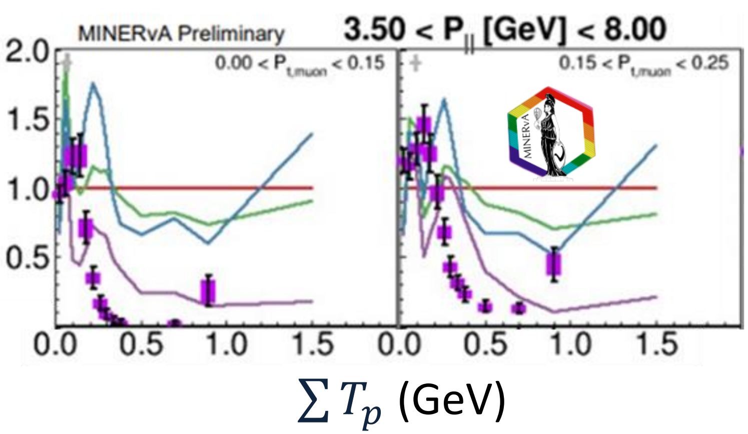
- ✓ T2K, MINERvA and others have made a wide range of innovative cross-section measurements aimed to target the nuclear physics most pertinent to future oscillation analyses

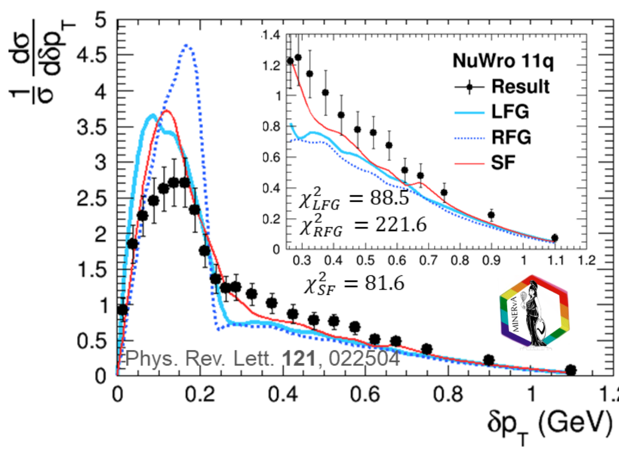
Summarising current measurements

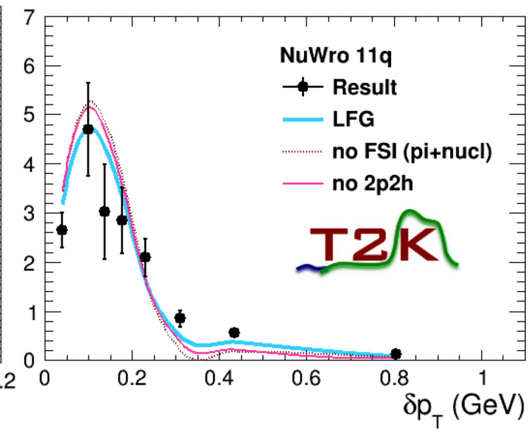
✓ T2K, MINERvA and others have made a wide range of innovative cross-section measurements aimed to target the nuclear physics most pertinent to future oscillation analyses

X None of our current simulations are able describe more than the lepton kinematics …

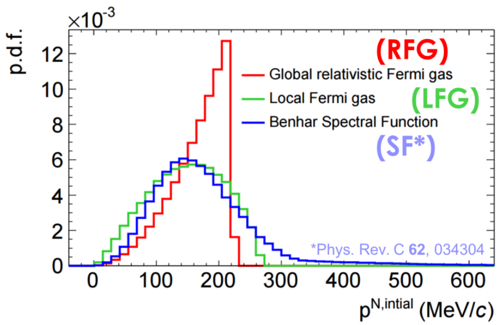
- It's critical to continue making new measurements with better detectors!

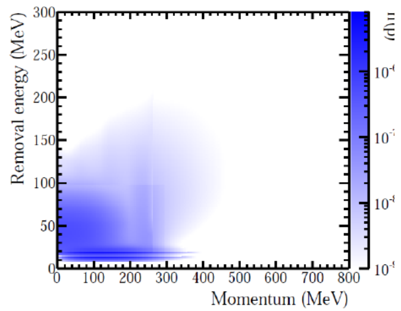


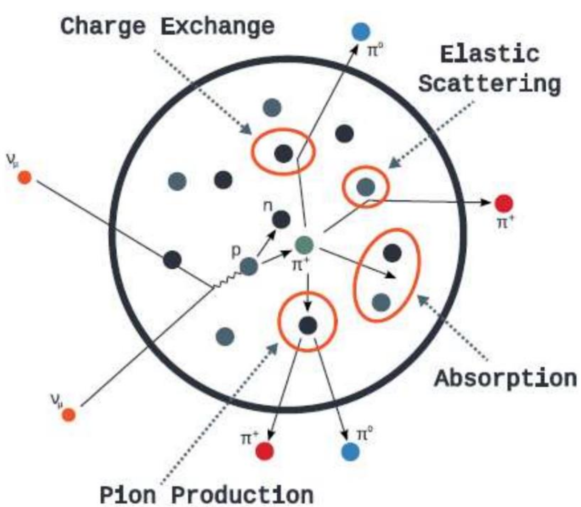


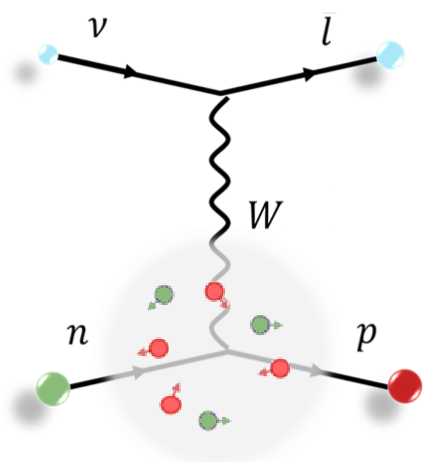


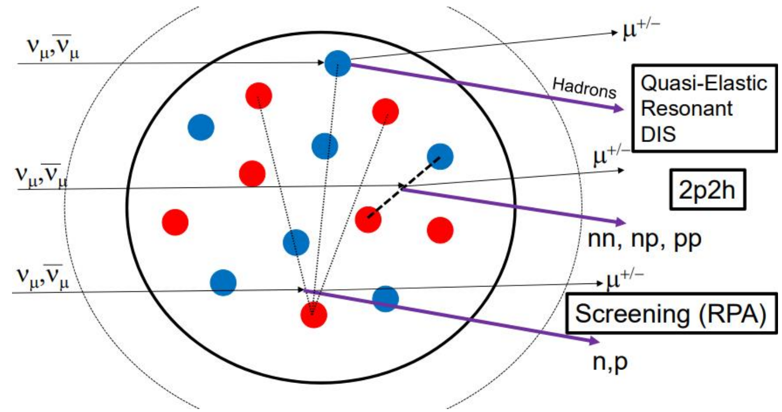
Nuclear targets are hard …

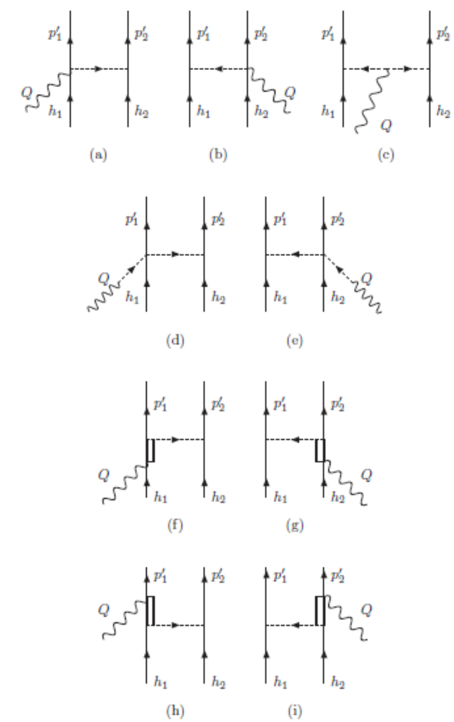




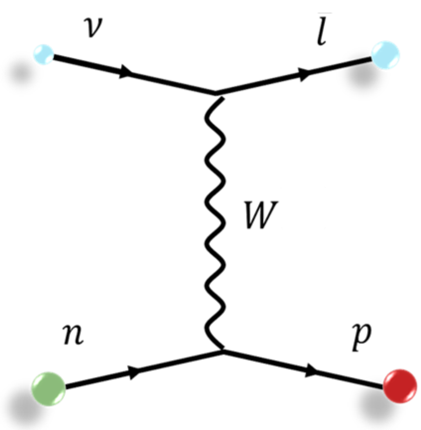








… nucleon targets are not



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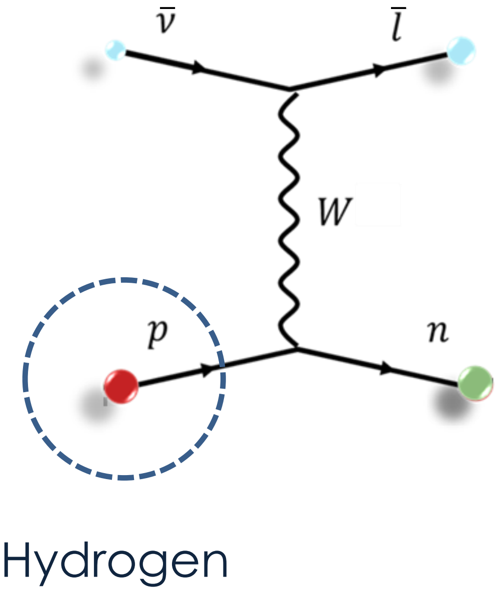

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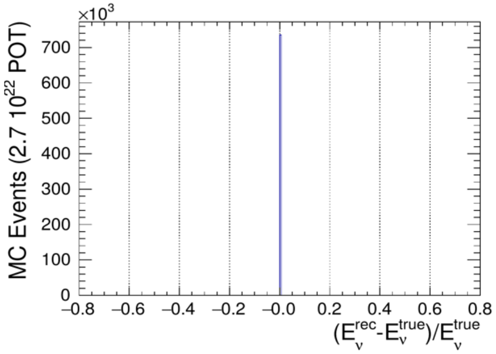
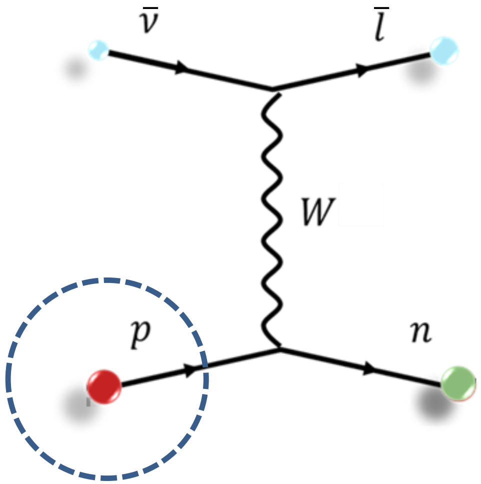


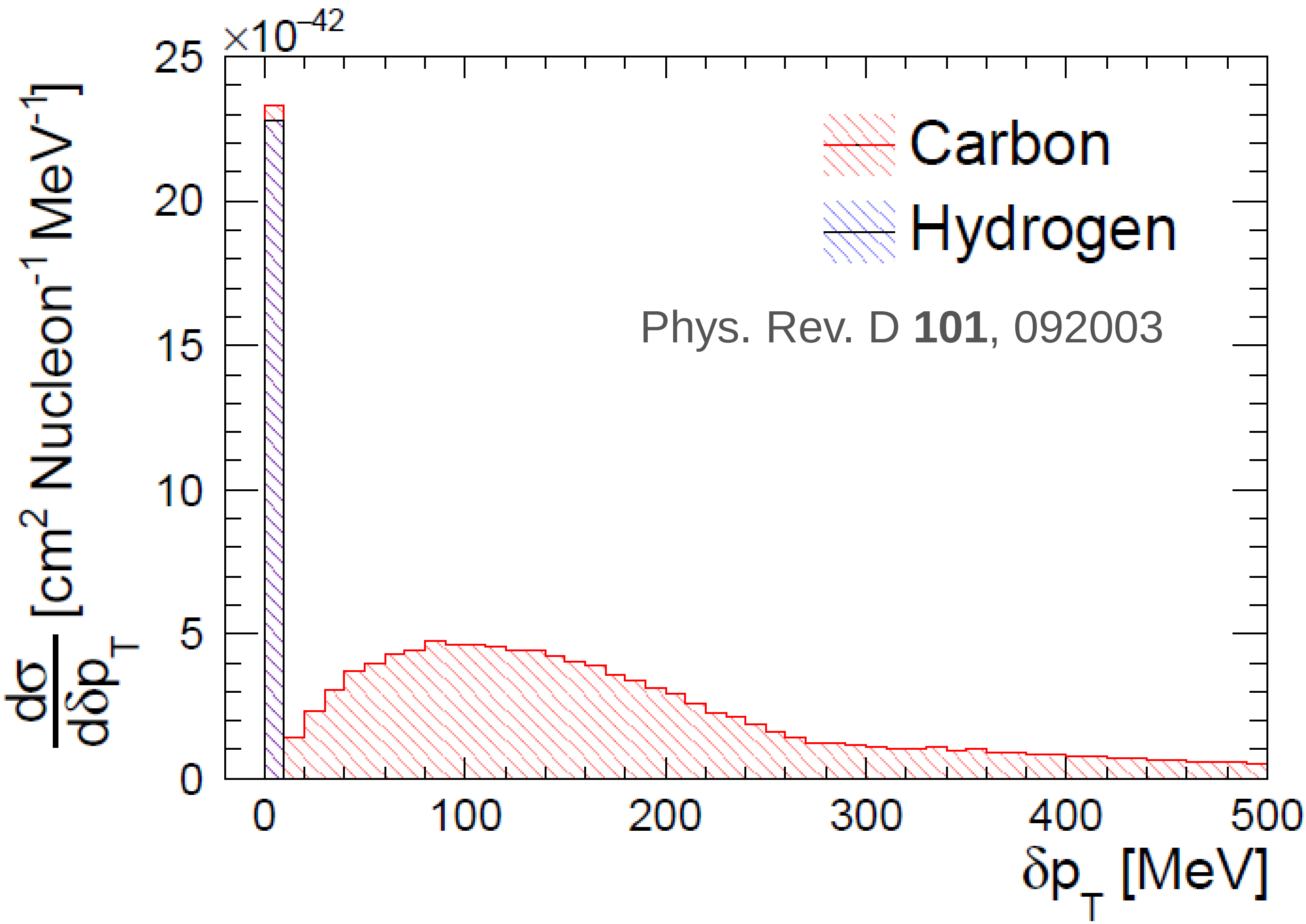
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Proxy for E_ν from lepton kinematics is perfect only for **CCQE elastic scattering** off a **stationary nucleon**



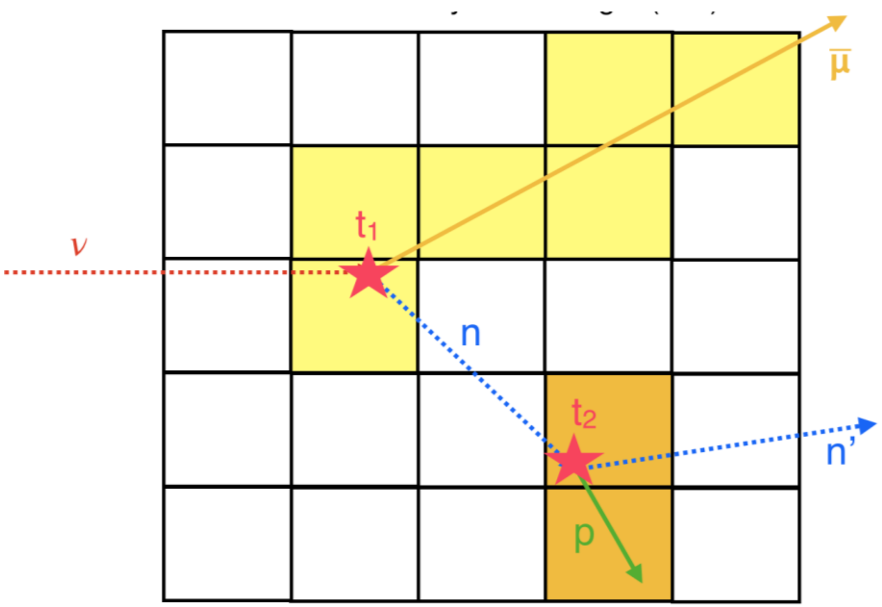
Hydrogen

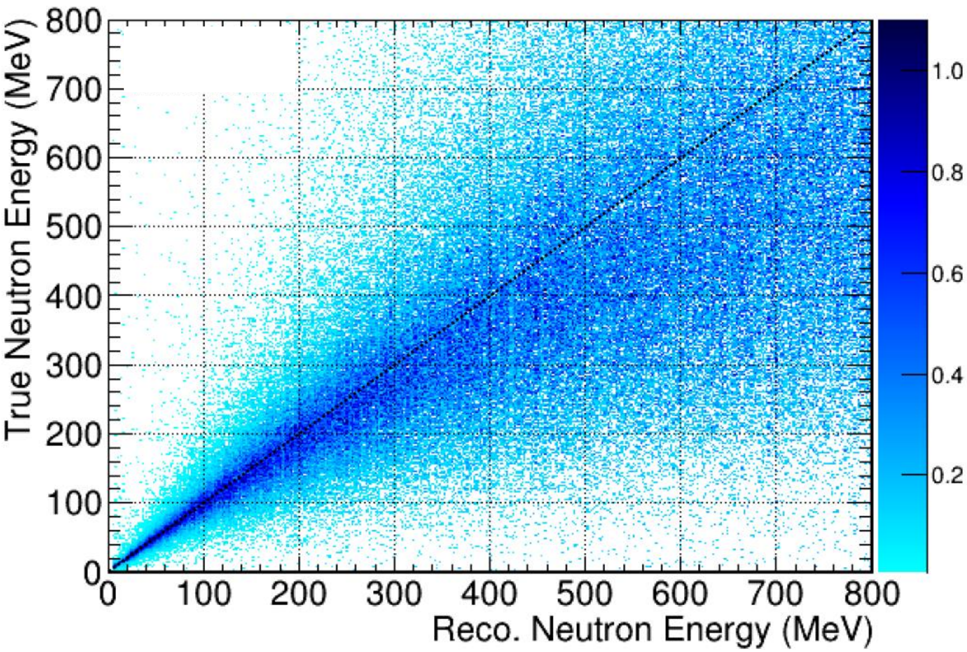
Separating H in CH (scintillator)



Neutrons with a 3D scintillator detector

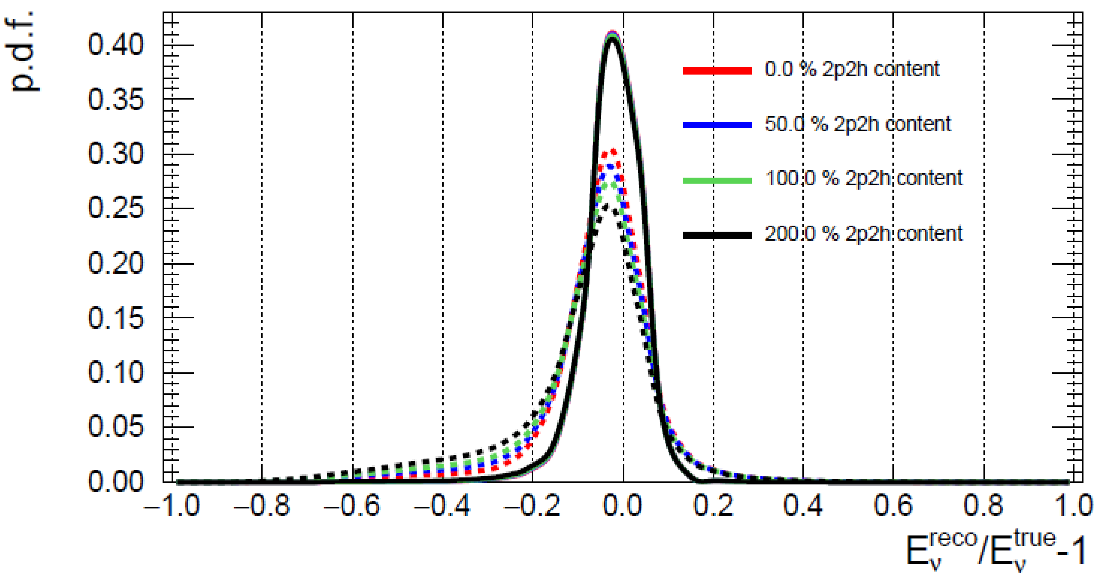
- Can look for neutrons via their re-interaction within a detector
- If the path is long enough (>20 cm) neutron energy is measured using the time of flight with resolution 15-30% (for ~1 ns timing resolution)



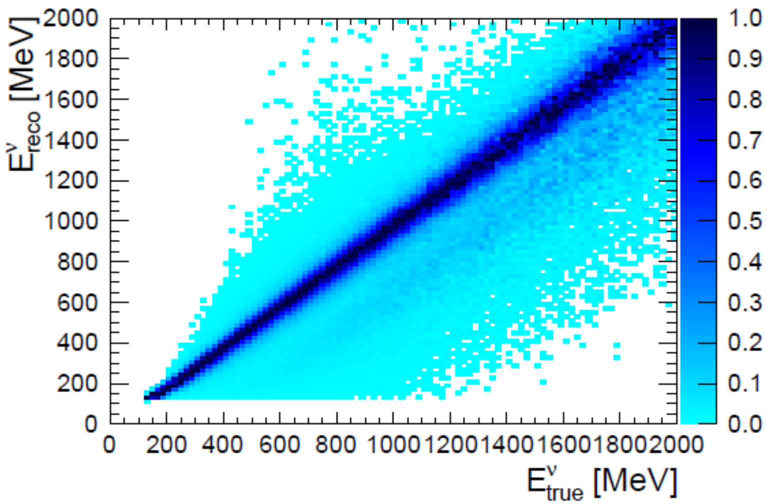


Phys. Rev. D **101**, 092003

Reconstructing the anti-neutrino flux

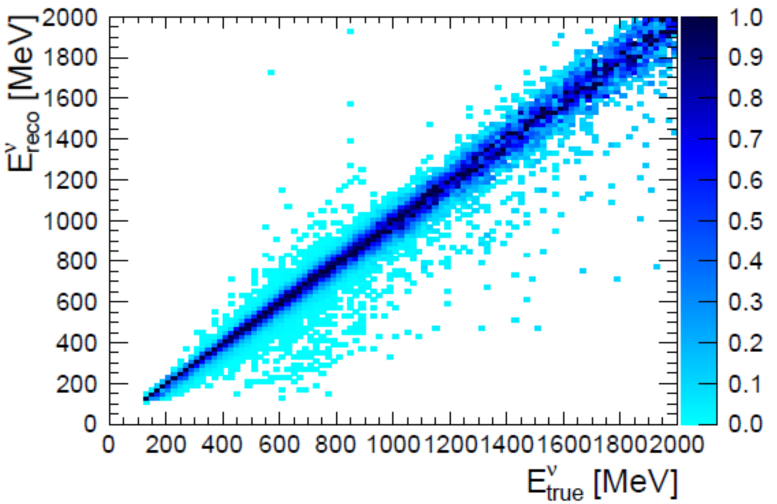


- Improved E_ν resolution
  - RMS: 15% → 7%
- Insensitive to nuclear effects (even the carbon events are the ones that aren't much affected)
- In-situ anti-neutrino flux measurement!



$\delta p_T > 40\ MeV$

lever arm > 10cm



Phys. Rev. D **101**, 092003

Summary

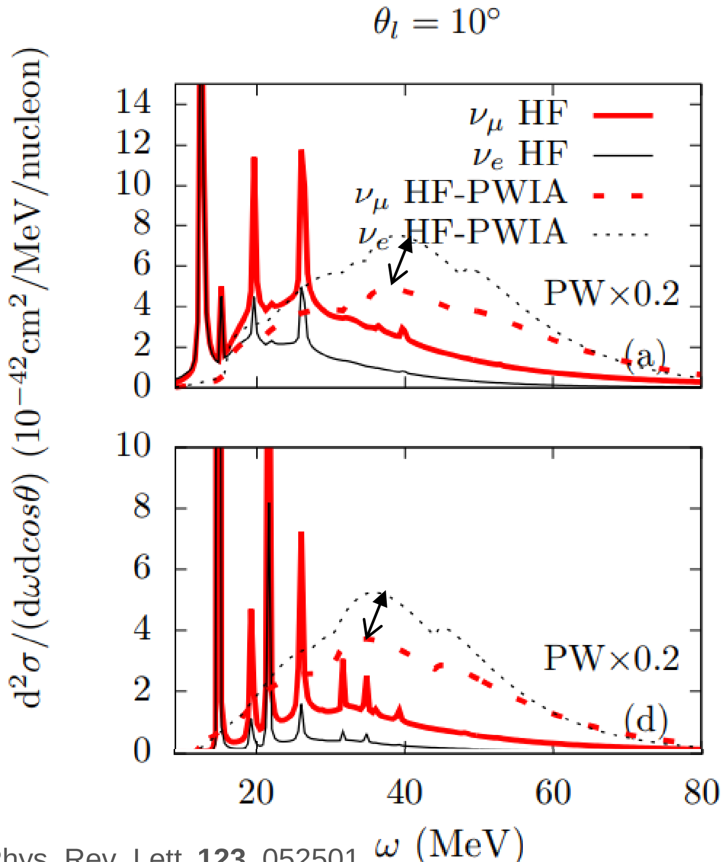
- To avoid future oscillation analyses becoming **pre-maturely limited by systematic uncertainties**, *it is essential to better understand nuclear effects in neutrino-nucleus interactions*
- Nuclear effects can only be effectively understood by **measuring outgoing lepton and nucleon kinematics**
- Current measurements are limited by detector capabilities, but already **indicate a poor modelling of the essential processes**
- **Future measurements of nucleons** from neutrino interactions and **continued collaboration with the nuclear theory community** are critical
- Measuring neutrons from neutrino interactions offers the possibility of interesting new measurements

Backups

Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

- Ratio of ν_e to ν_μ critical for future oscillation analyses
  - Measure ν_μ at ND but need to know about ν_e to measure δ_{CP}

- This is also subject to subtleties in the nuclear physics…



Phys. Rev. Lett. **123**, 052501

- If the outgoing nucleon exits the nucleus as a "plane wave" (no FSI): $\sigma(\nu_e) > \sigma(\nu_\mu)$

Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

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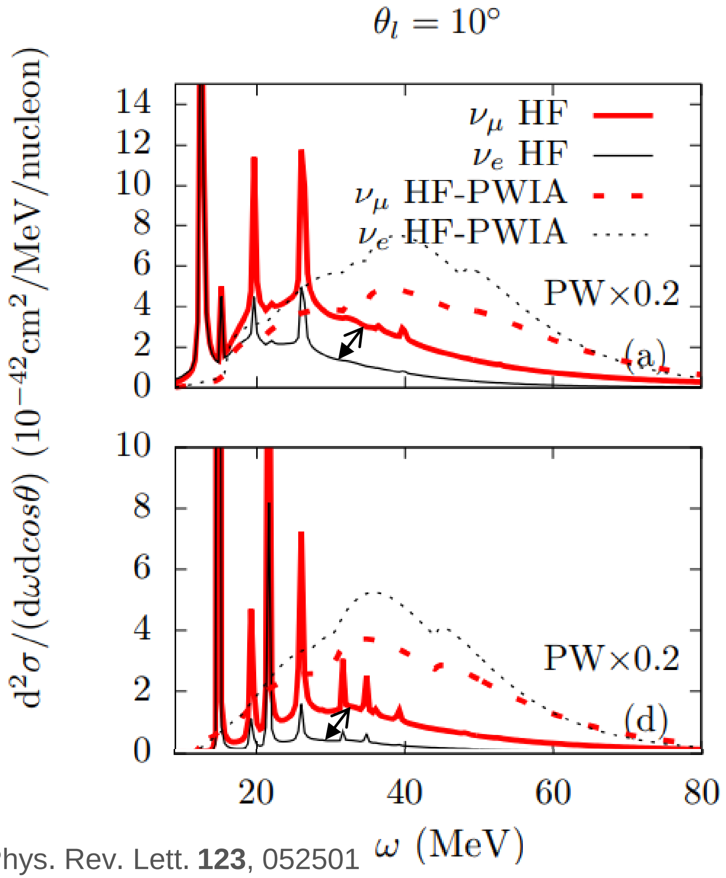


Phys. Rev. Lett. **123**, 052501

- If the outgoing nucleon exits the nucleus as a "plane wave" (no FSI): $\sigma(\nu_e) > \sigma(\nu_\mu)$

- If the outgoing nucleon is distorted by the nuclear potential (FSI): $\sigma(\nu_e) < \sigma(\nu_\mu)$

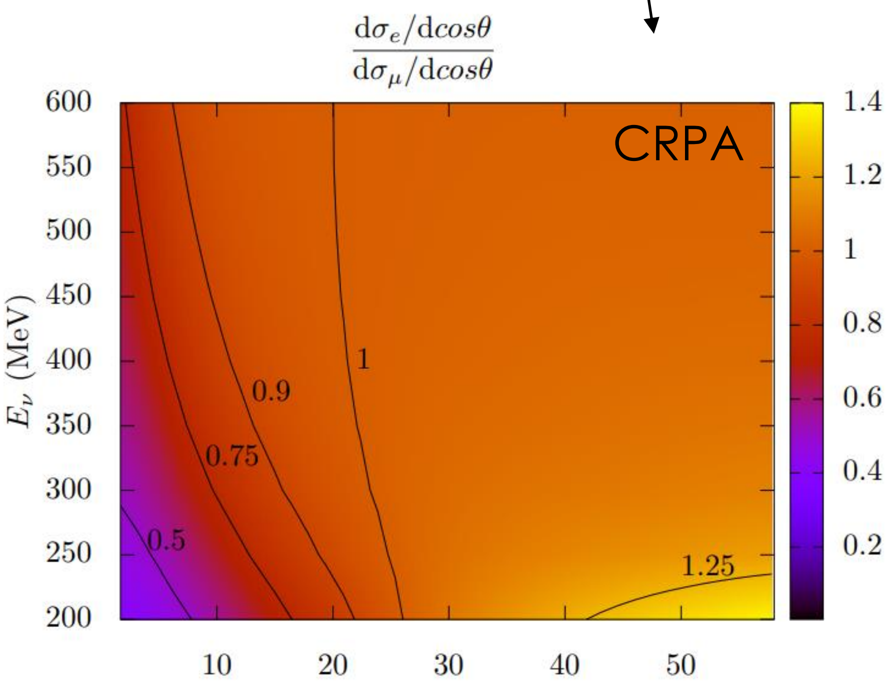
Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

- Different models can predict quite different cross section ratios!
- Important for T2K/HK!

$$\frac{d\sigma_e/d\cos\theta}{d\sigma_\mu/d\cos\theta}$$

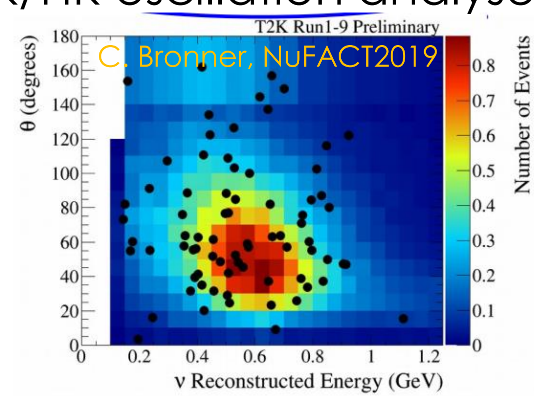
	$E_\nu = 200\ MeV$		$E_\nu = 600\ MeV$	
Model	5°	60°	5°	60°
RFG (w/PB)	0.64	1.61	0.97	1.03
SF (full)	1.41	1.92	1.04	1.03
CRPA	~0.5	~1.4	~0.9	~1.0

Tabulated from Phys. Rev. C **96**, 035501 and the left figure

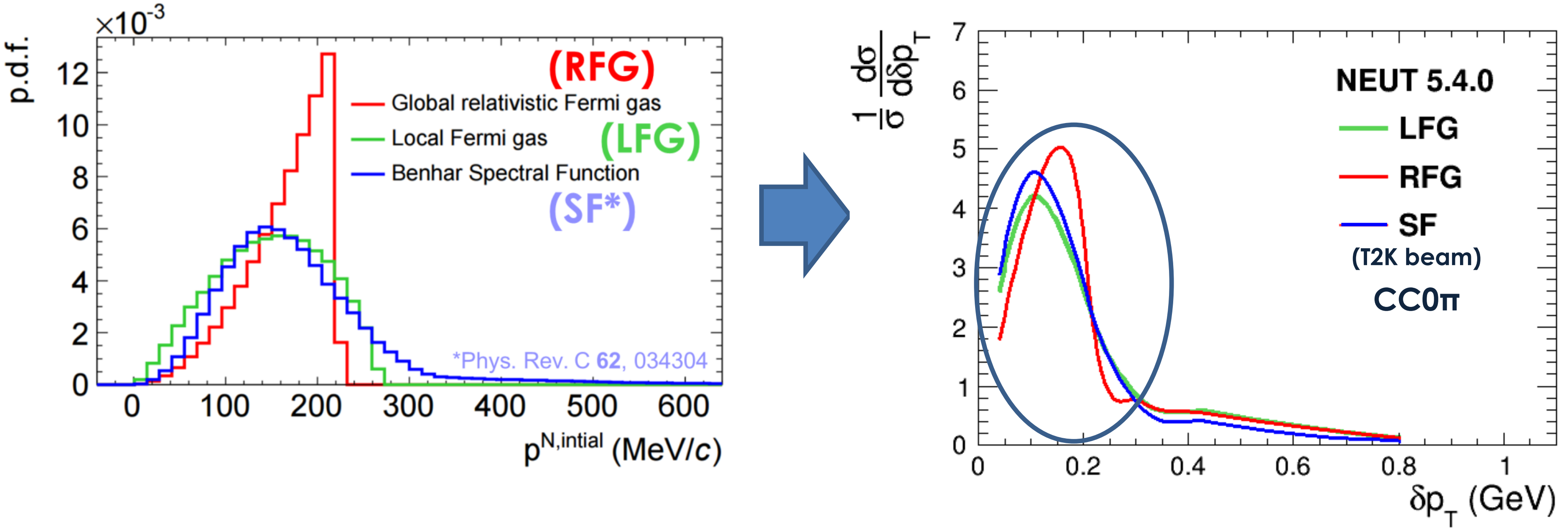


Phys. Rev. Lett. **123**, 052501 θ_l (degrees)

These differences are predicted in regions that are relevant to T2K/HK oscillation analyses

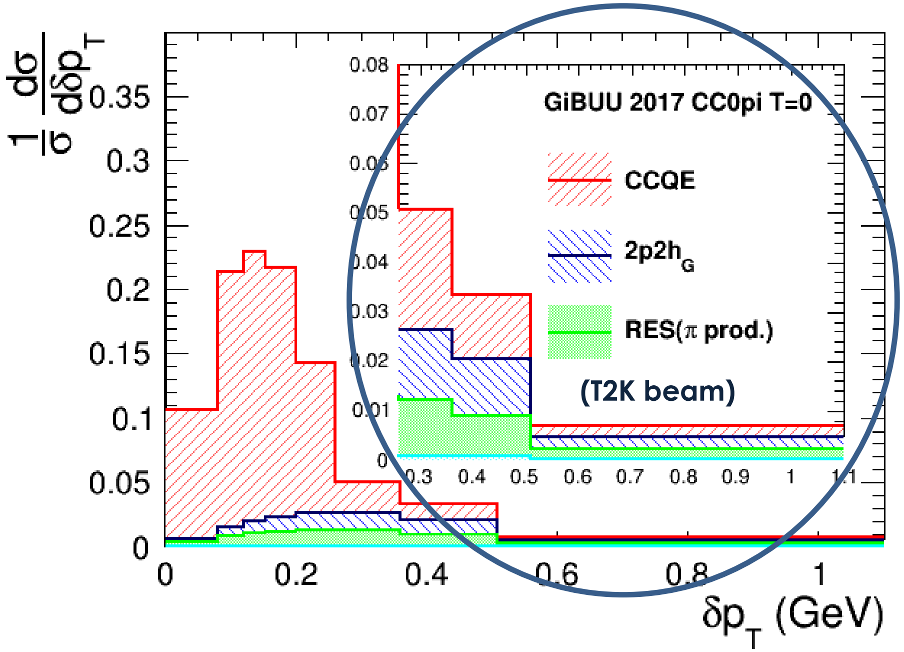


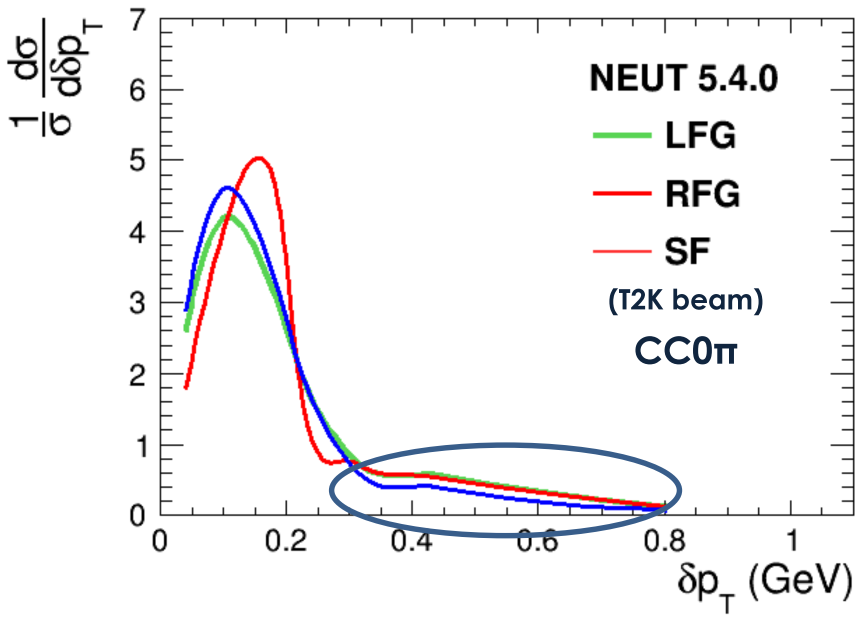
STV model discrimination - δp_T



- 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

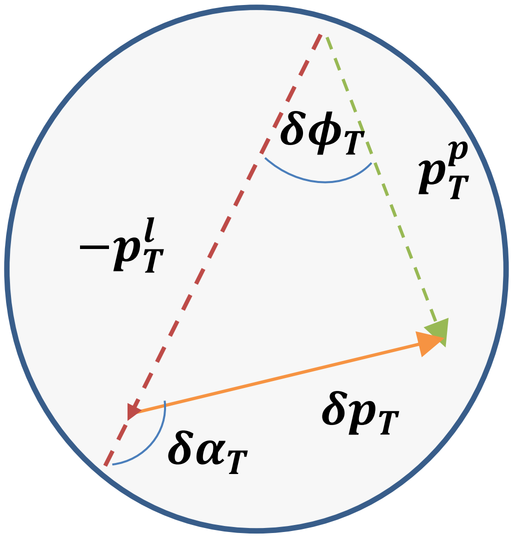
STV model discrimination - δp_T



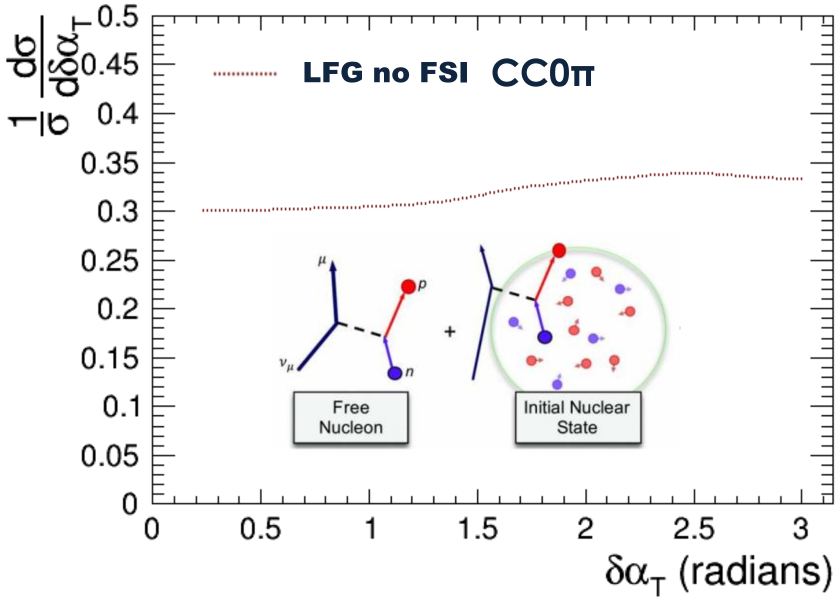


- In the absence of other nuclear effects, δp_T *is* the transverse projection of the Fermi motion.
- Since this motion is isotropic, $\delta p_T \rightarrow$ Fermi motion
- Cross section beyond the Fermi surface must come from physics beyond RFG → 2p2h, FSI, SRCs …

STV model discrimination - $\delta\alpha_T$

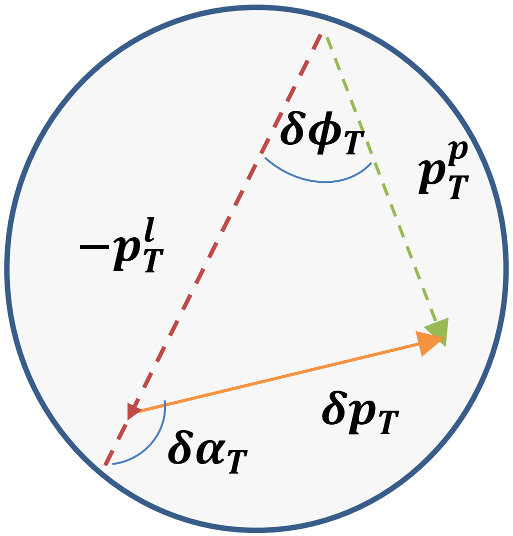


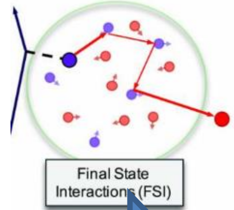
Consider imbalance from only Fermi motion



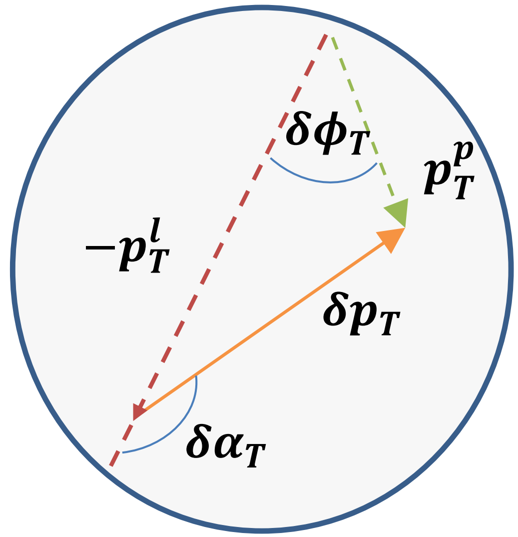
Fermi motion is isotropic so no preferred $\delta\alpha_T$ direction

STV model discrimination - $\delta\alpha_T$

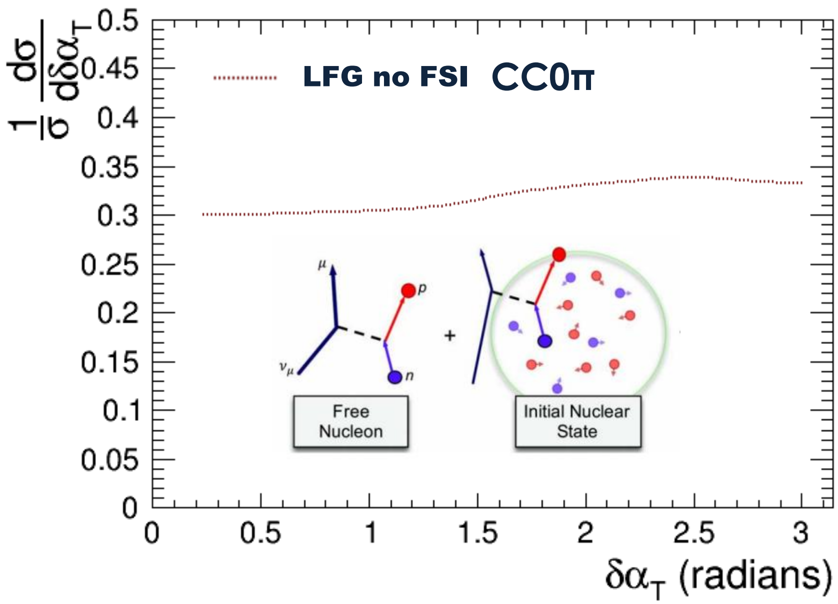


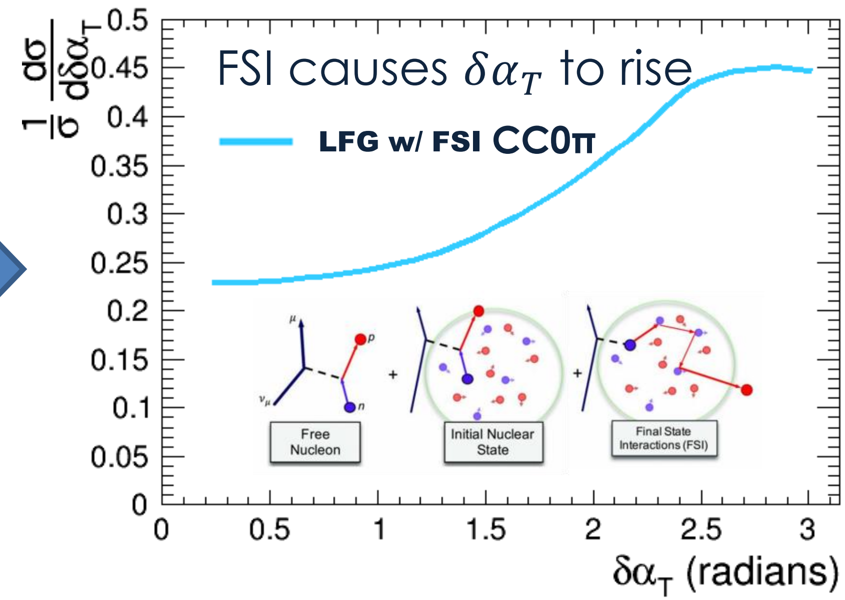


Deceleration of proton from FSI



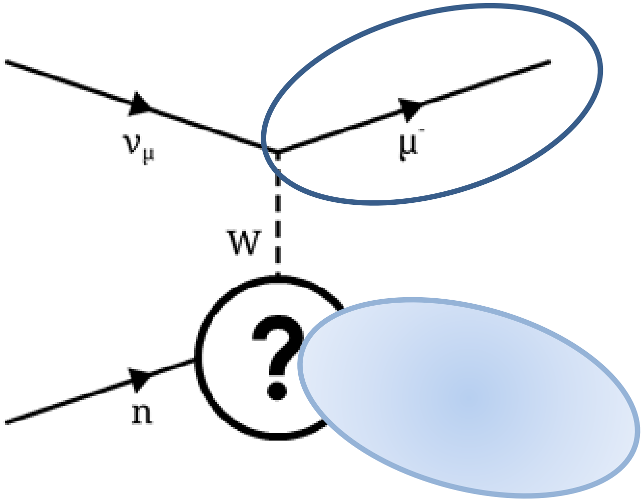
= larger $\delta\alpha_T$





Which observables?

Lepton and proton?



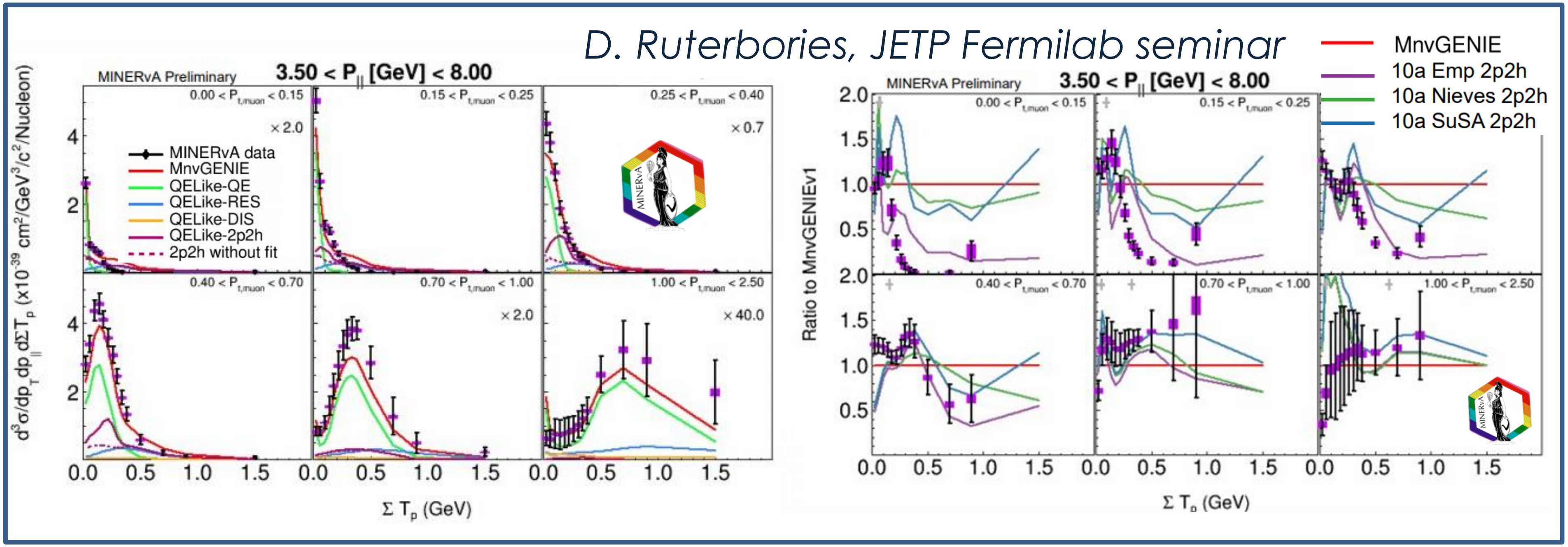
Correlations between the muon and proton kinematics allow us to disentangle nuclear effects from neutrino energy

However, limited detector acceptance means low statistics and that we don't see the full story …

To avoid this, we can rely on calorimetric methods (no need to reconstruct individual protons)

Calorimetric measurements

- Sum energy deposited in the detector not associated with lepton
  - Reject pions: excess energy is $\sum T_{proton}$
- Measure $d^3\sigma/dp_T^\mu dp_{||}^\mu d\sum T_p$



- **Best model agreement with data:** $\chi^2 = 5062/238$
- Worrisome for calerometric reconstruction of E_ν (DUNE/SBN/NOvA) …

End