Neutrino Interactions

Part 2: The Nucleus Strikes Back

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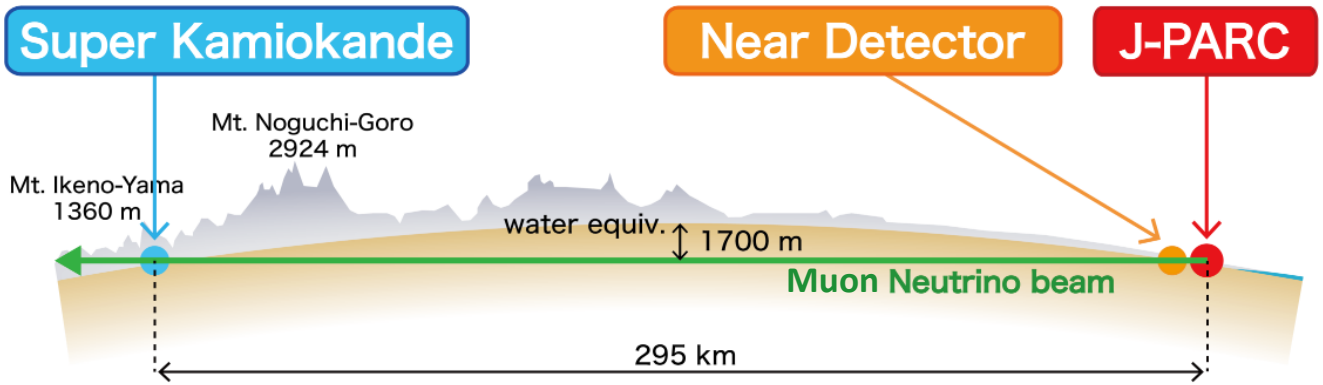
Summary so far

- The Weak Interaction
  - Point-like scattering is "easy" to calculate
  - Chirality is crucial for neutrino/anti-neutrino cross-section differences
- Neutrino-nucleon interactions
  - Separation into QE, RES and DIS
  - QE: almost calculable with some form (fudge) factors
  - RES: much more difficult, lots of diagrams to consider
  - DIS: easy for *inclusive* high Q^2, hard at low Q^2, hadronic side a total guess
  - RES-DIS transition is poorly understood but potentially important for DUNE
- Neutrino-nucleus interactions
  - Nuclear effects: there are lots of them, they can significantly alter the nucleon-level cross section
  - Lots of options for ground state modelling and how to build cross sections
  - Not all models can predict everything!

Overview

- The Weak Interaction
  - Historical Overview
  - Point-like scattering
- Neutrino-nucleon interactions
  - QE, RES and DIS
- Neutrino-nucleus interactions
  - Nuclear effects
  - Ground state modelling
- Why do we care?
  - Neutrino interactions for neutrino oscillations
  - Neutrino energy reconstruction
- Neutrino-nucleus interaction measurements
  - Inclusive successes and exclusive failures
- Where did it all go wrong? (Neutrino event generators)
  - Limitations of our simulations
- Don't Panic! The future of neutrino interactions

The T2K Experiment



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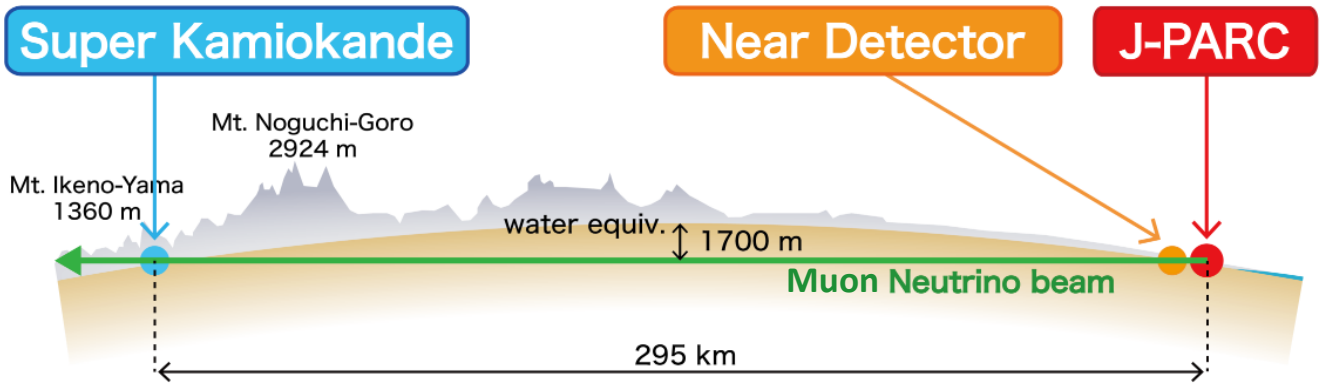

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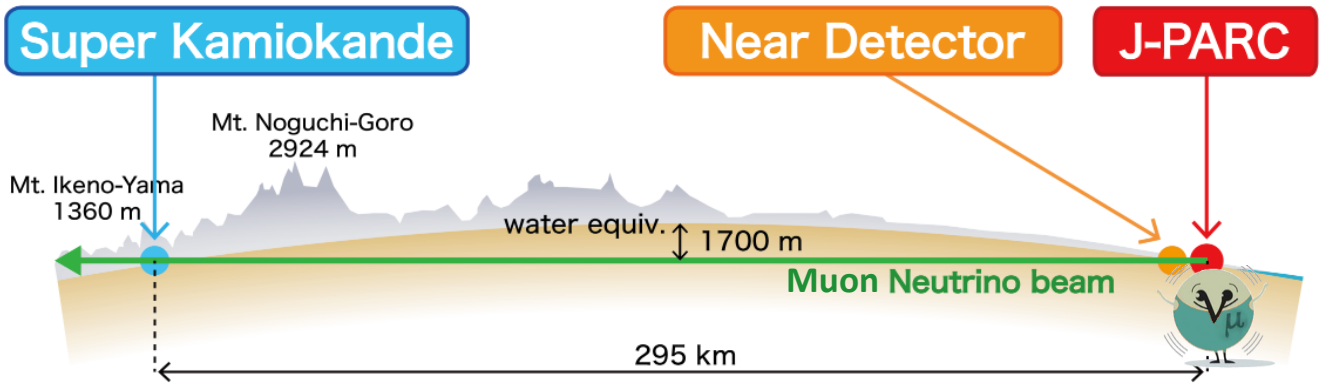

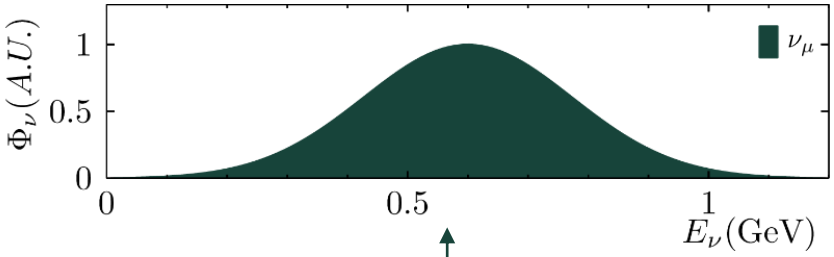

Produce predominantly ν_μ neutrino *or anti-neutrino* beam

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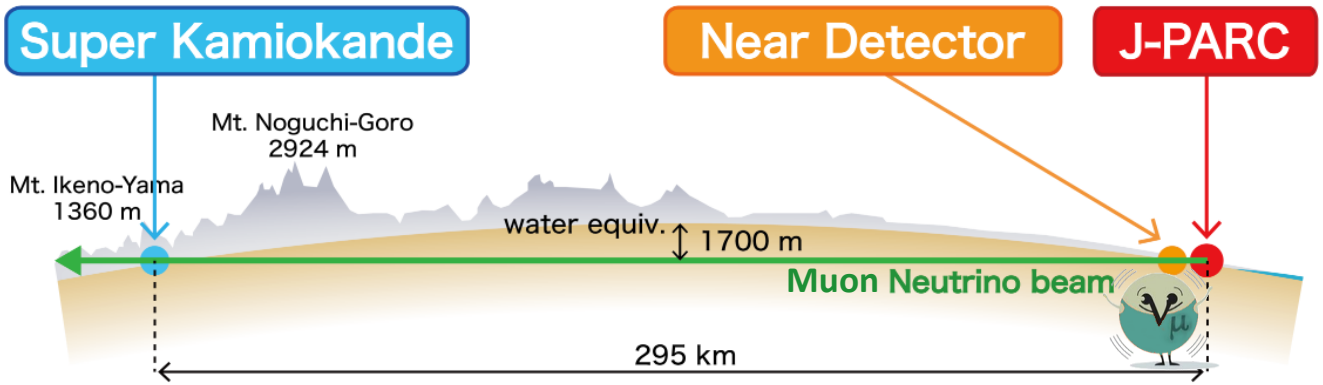
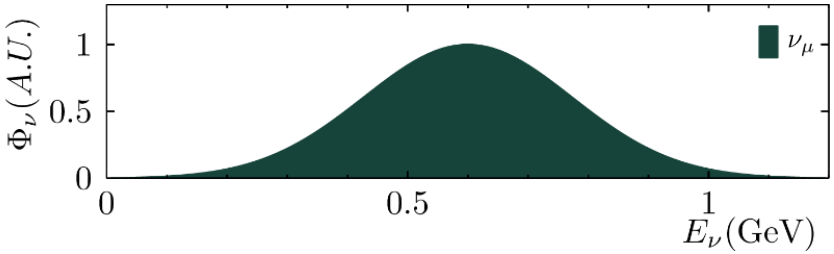
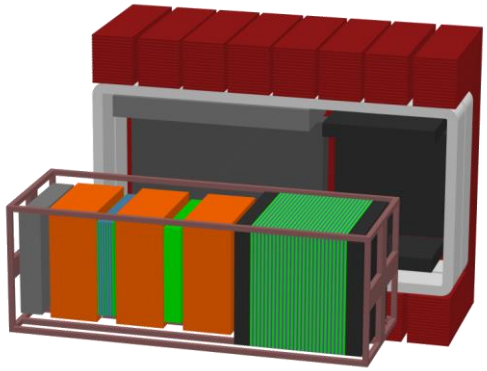




Near Detector
ND280



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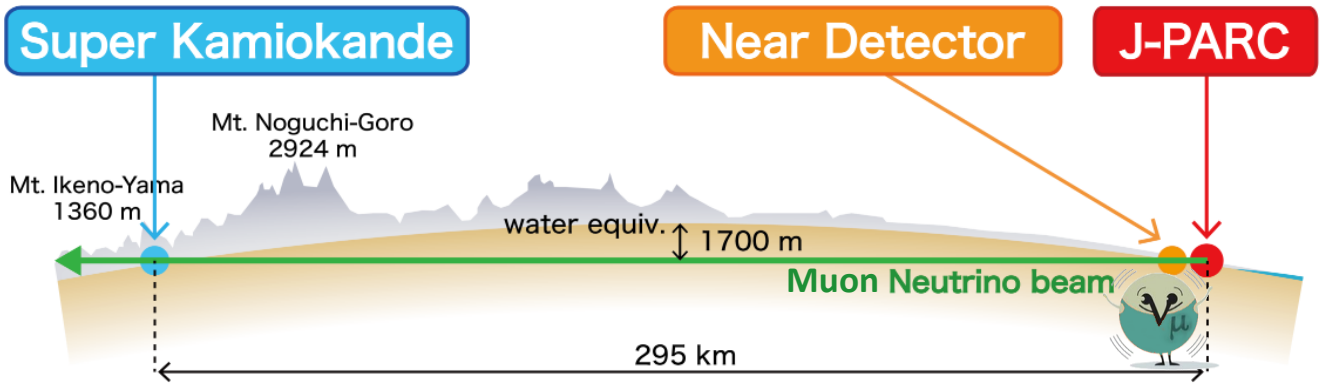

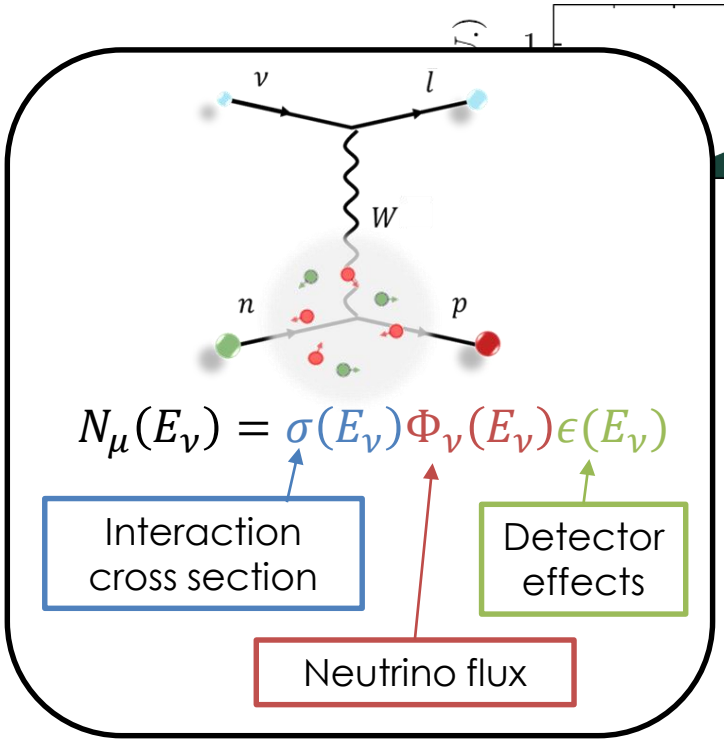

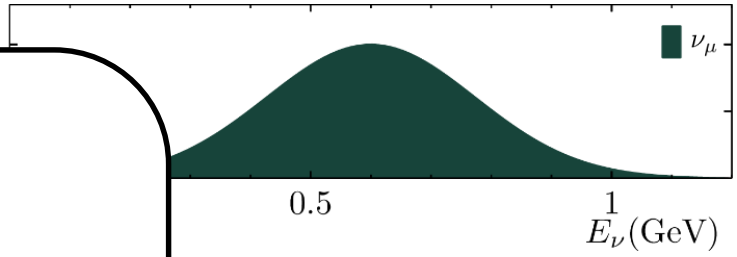

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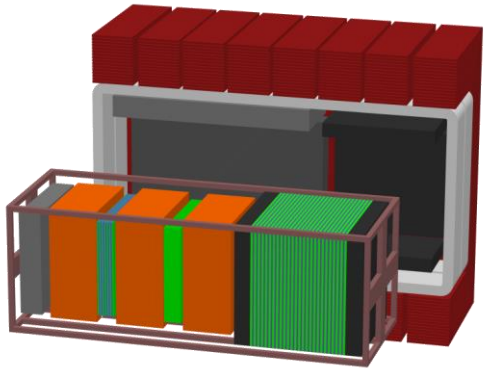

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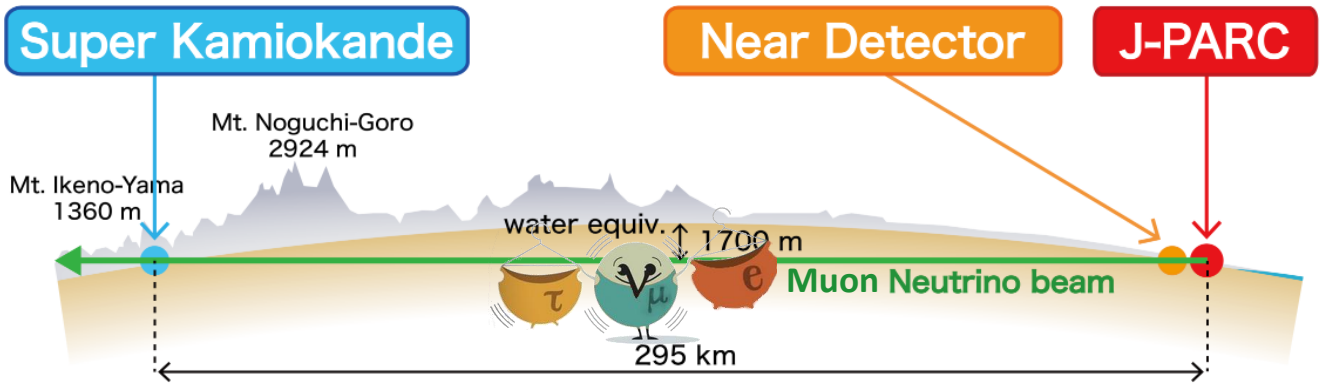

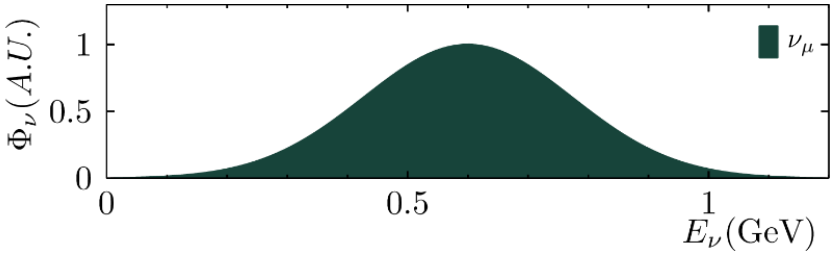

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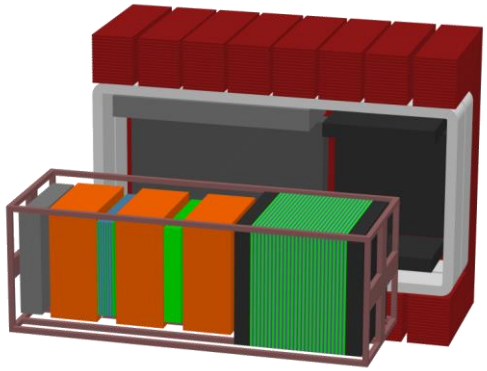

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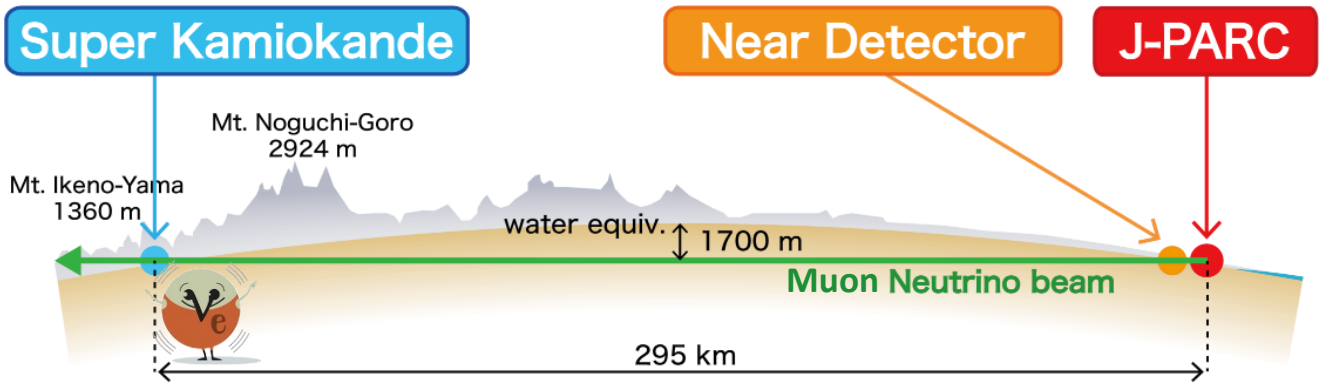

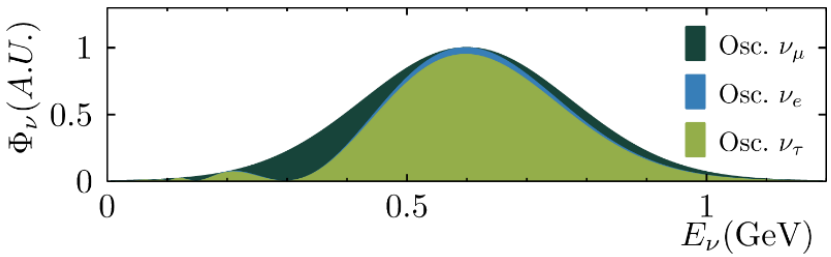

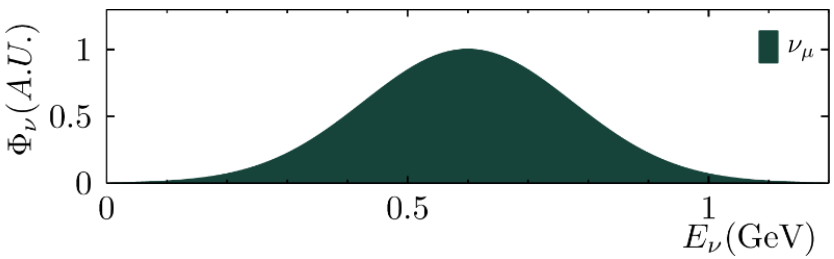

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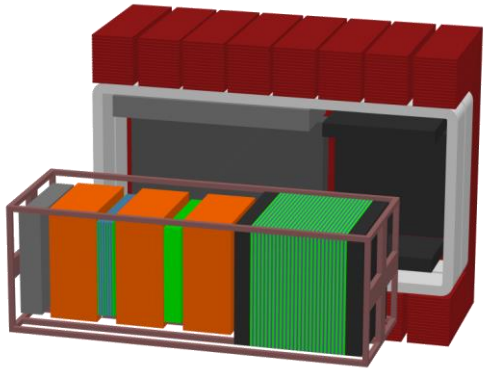

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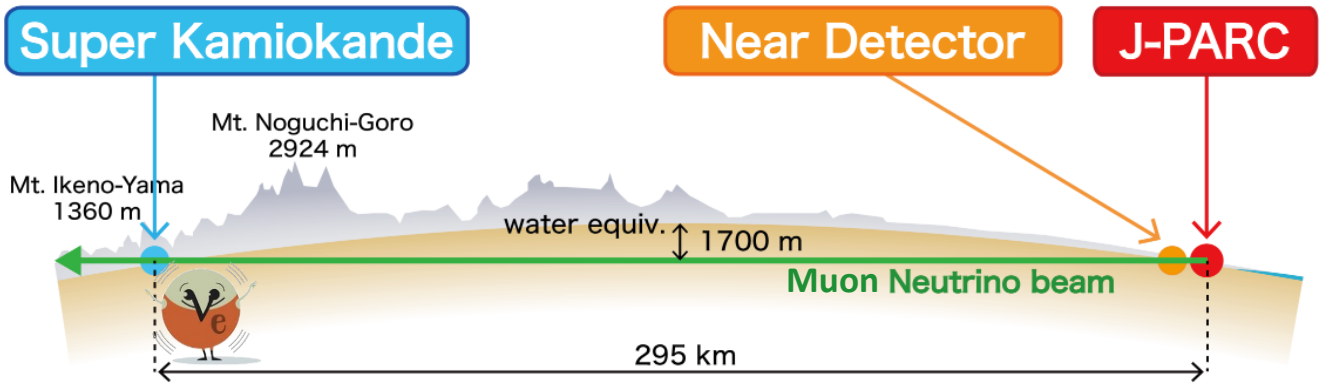
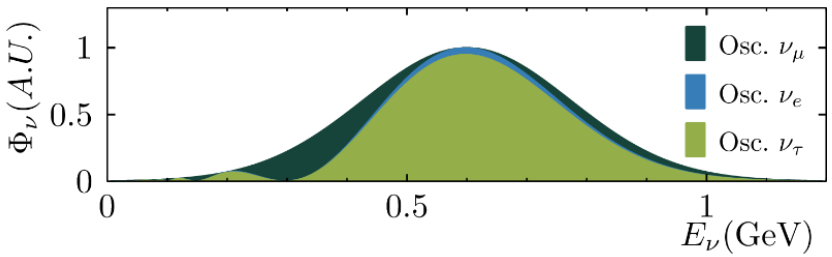
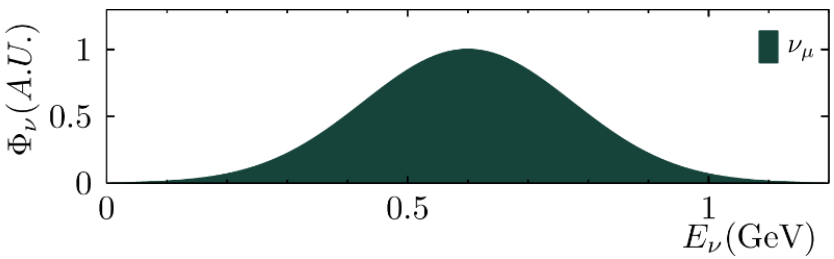
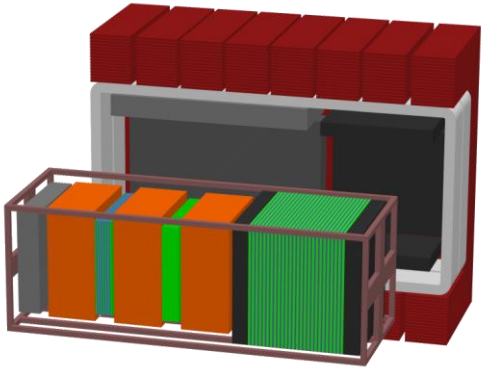






Far Detector
Super-Kamiokande

Near Detector
ND280



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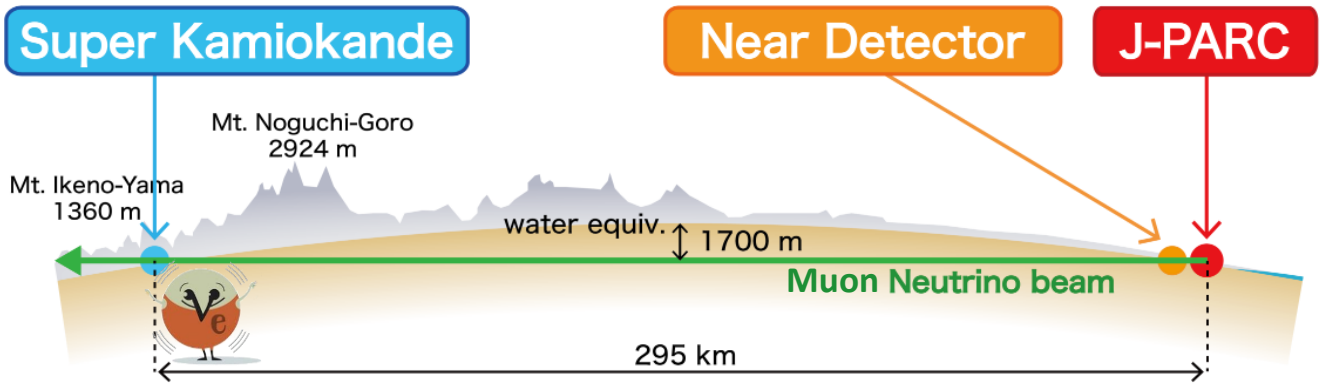

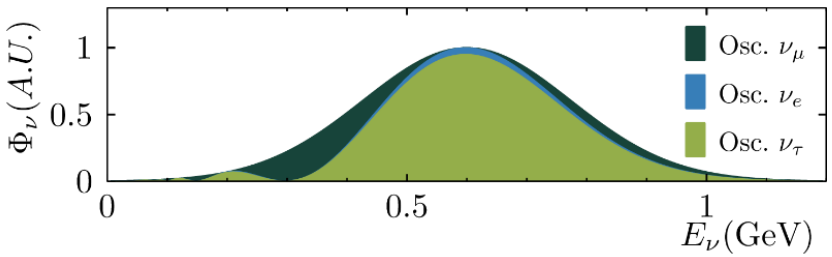

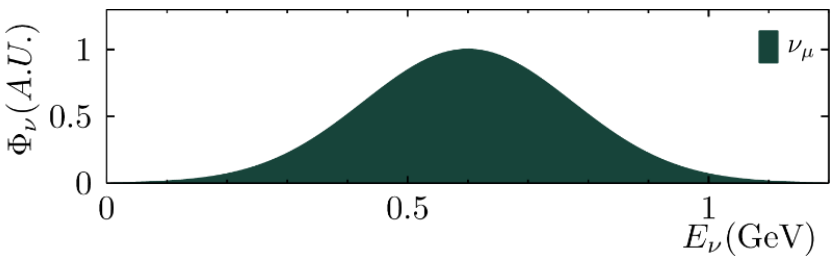

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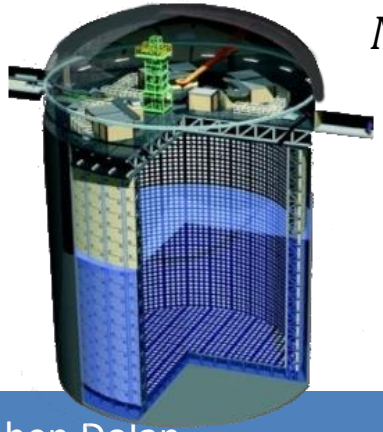


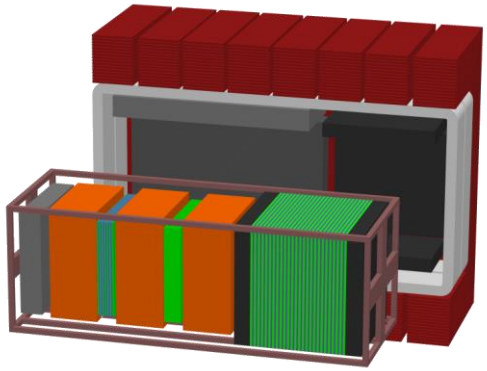
$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Oscillation probability

PMNS Mixing
δ_{CP} θ_{13}
Δm^2_{32} θ_{23}

$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Near Detector
ND280



Neutrino Interactions at T2K

$$N_\ell(E_\nu) = P(\nu_\mu \to \nu_\ell)(E_\nu)\, \sigma(E_\nu)\, \Phi_\nu(E_\nu)\, \epsilon(E_\nu)$$

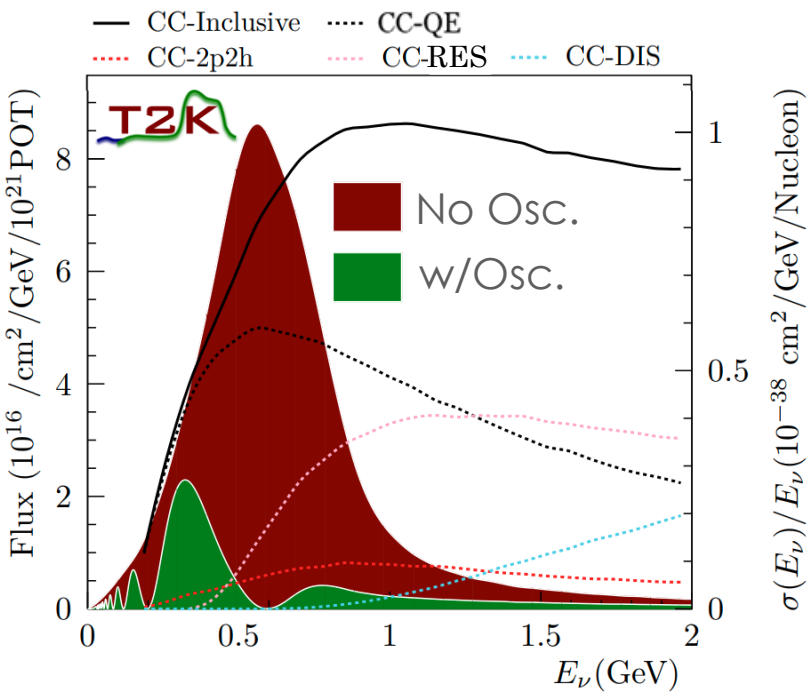
$N_\ell(E_\nu)$ = Event rate

$P(\nu_{\ell'} \to \nu_\ell)(E_\nu)$ = Oscillation probability

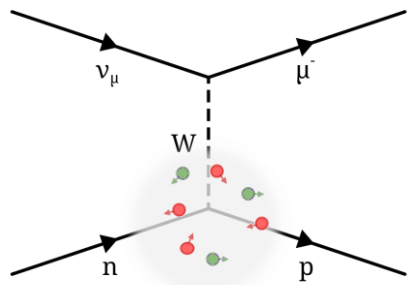
$\Phi_\nu(E_\nu)$ = Neutrino flux

$\epsilon(E_\nu)$ = Detector efficiency

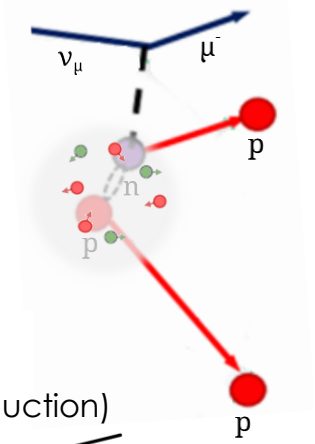
$\sigma_\ell(E_\nu)$ = Interaction cross section



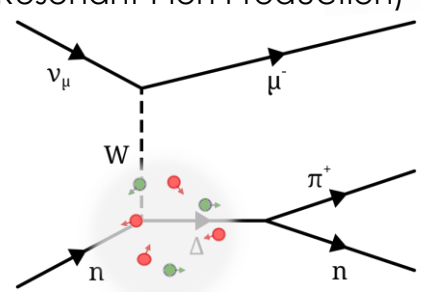
CCQE
(Charged-Current Quasi-Elastic)



CC2p2h
(2 particle, 2 hole)



CCRES
(Resonant Pion Production)



ν oscillations need ν cross sections

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- Need to know $\Phi \times \sigma$ in order to interpret N_ℓ as $P(\nu_\mu \to \nu_\ell)$

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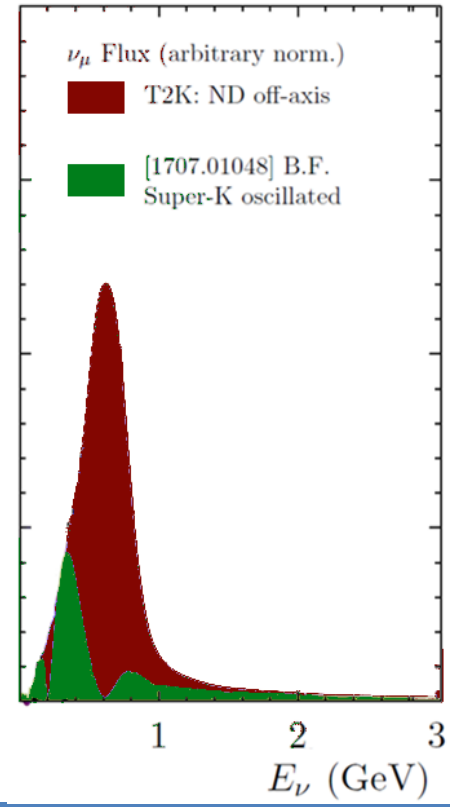
- Near / far ratios don't fully cancel this:
  - Dramatic change in E_ν distribution
  - ν_μ at ND vs ν_e at FD (for appearance)
  - Different ND/FD design, acceptance



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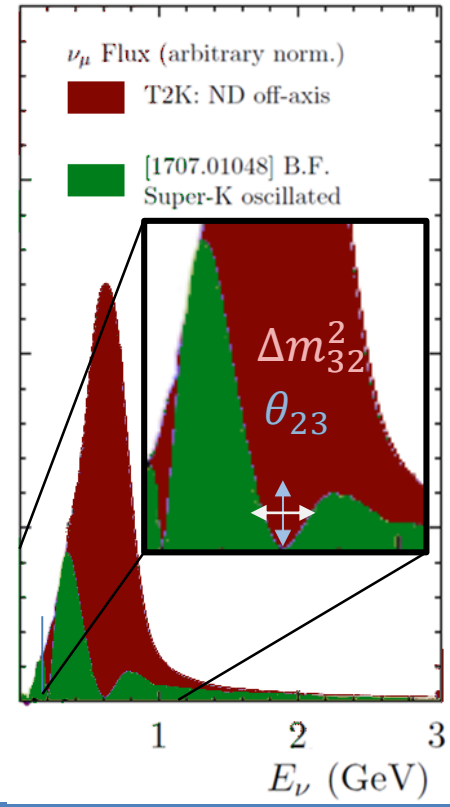
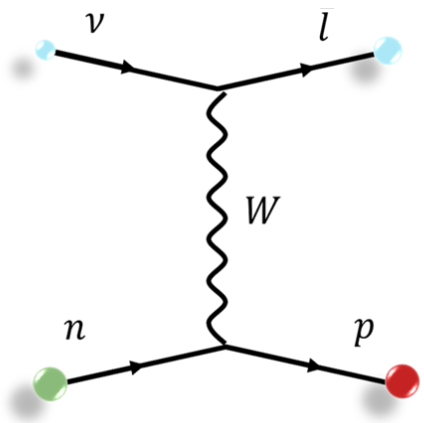
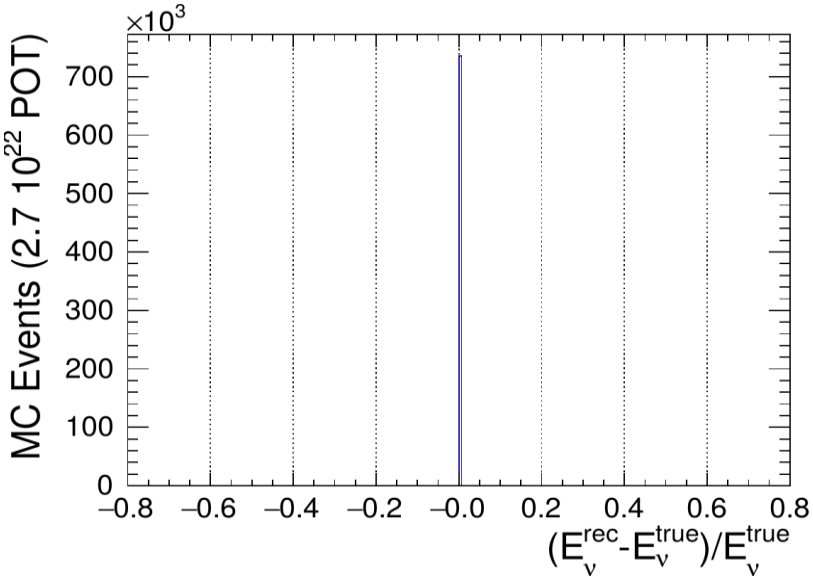
  - Different ND/FD design, acceptance
- Not just counting experiments: Require a model to relate E_ν^{reco} to E_ν^{true}



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 exact only for **CCQE elastic scattering** off a **stationary nucleon**

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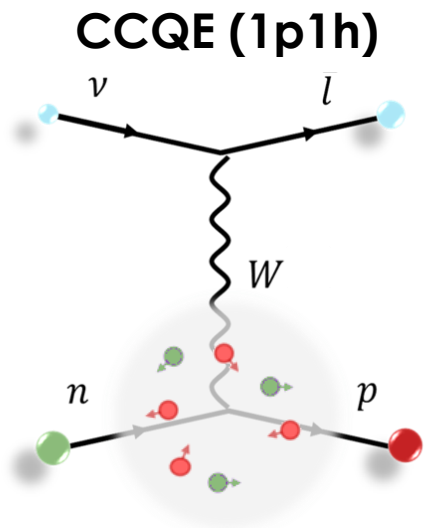

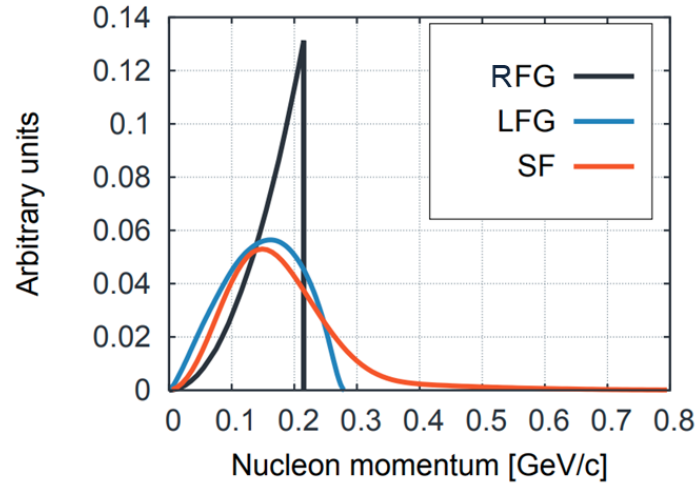

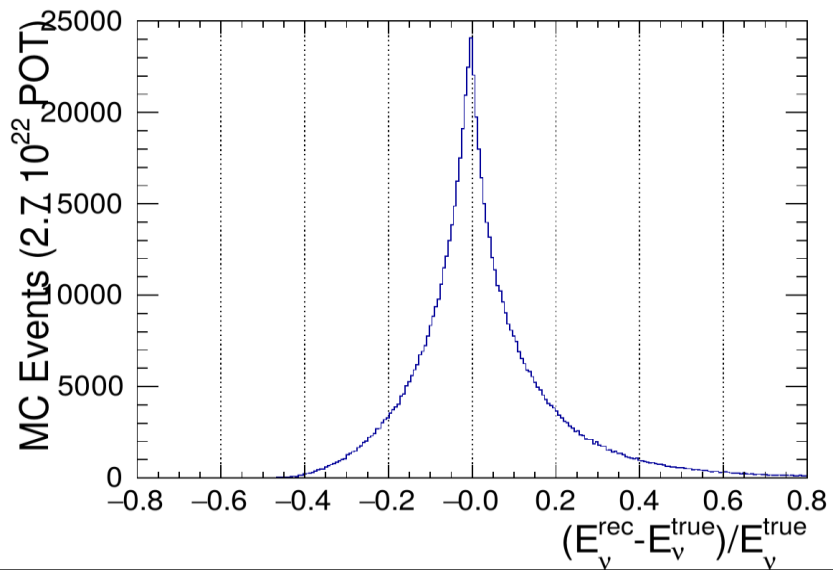

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The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

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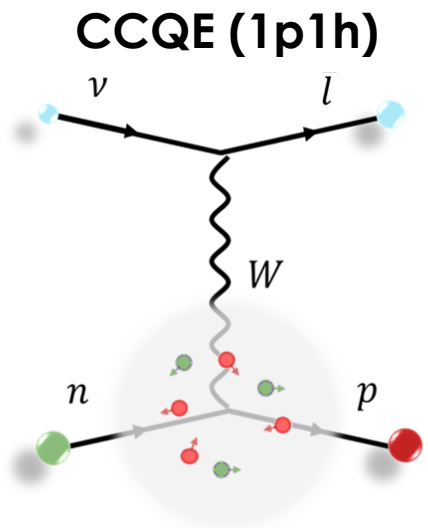
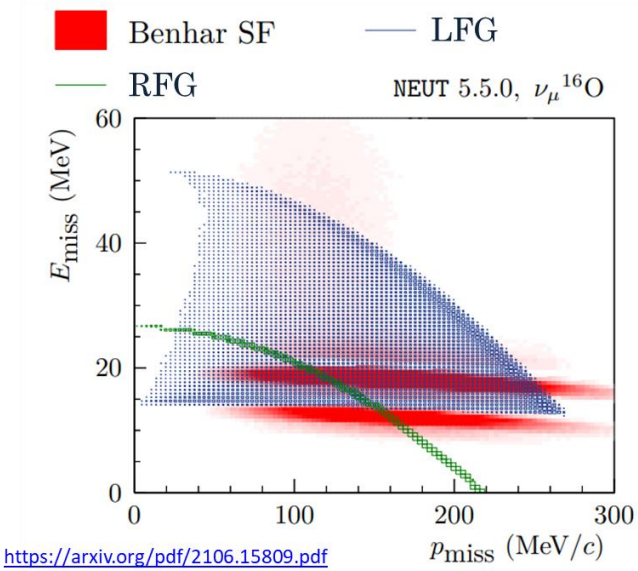
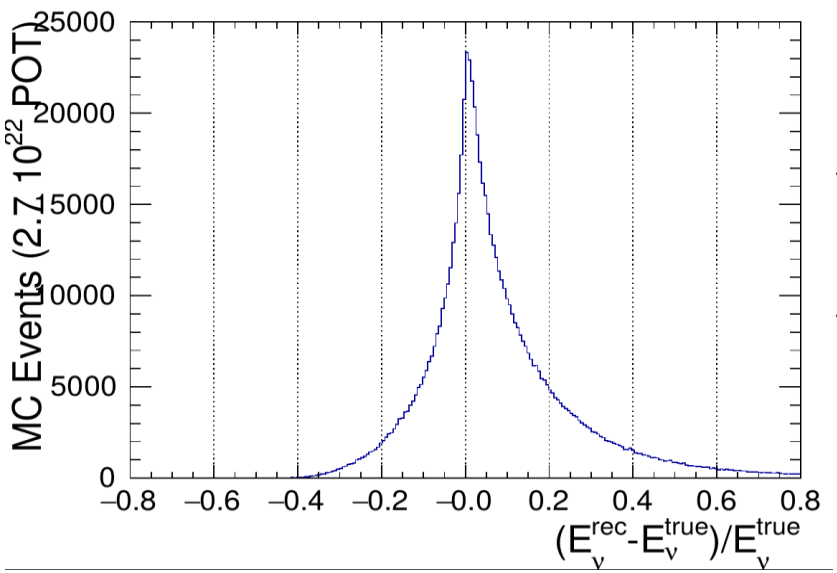




https://arxiv.org/pdf/2106.15809.pdf



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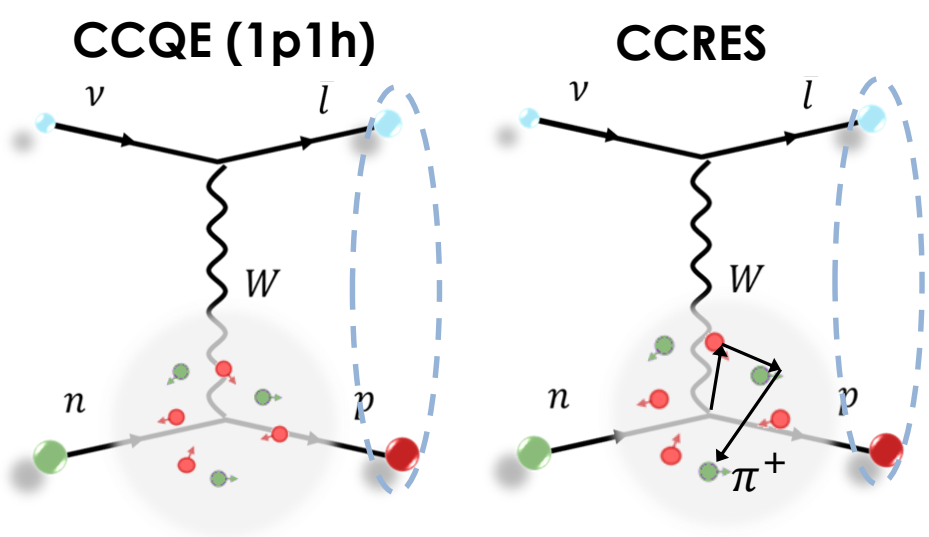
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

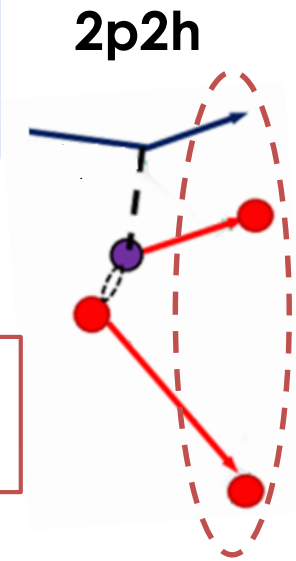
The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

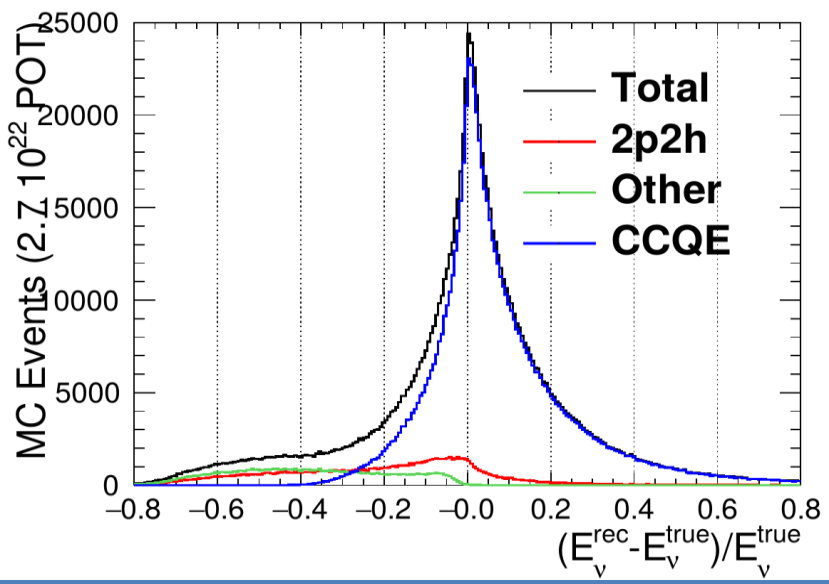
Nuclear effects and E_ν (T2K/HK)



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

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





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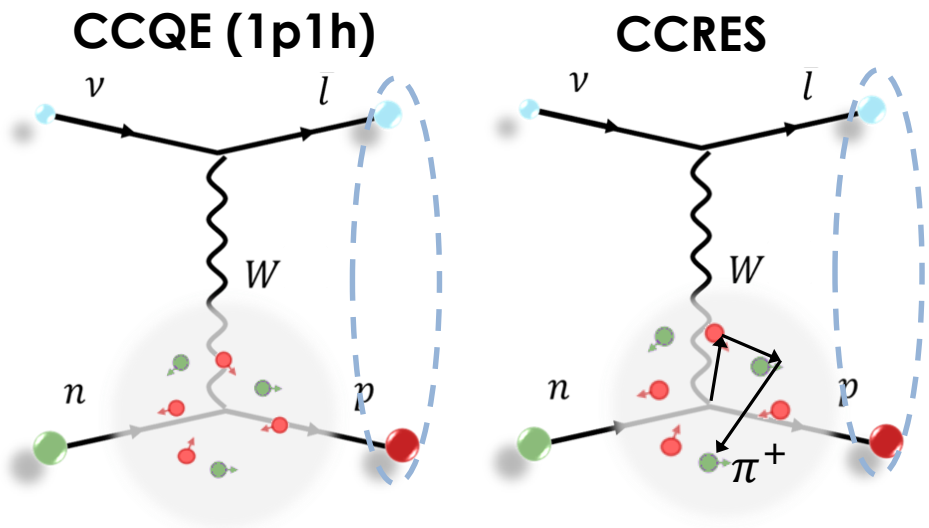
The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

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

Nuclear effects and E_ν (T2K/HK)



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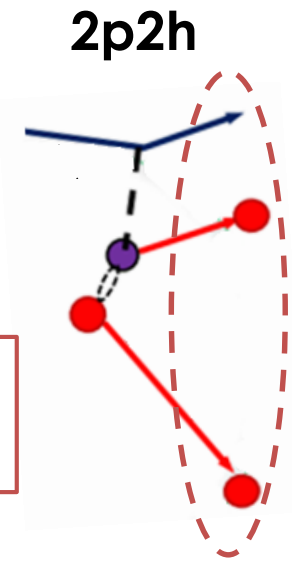
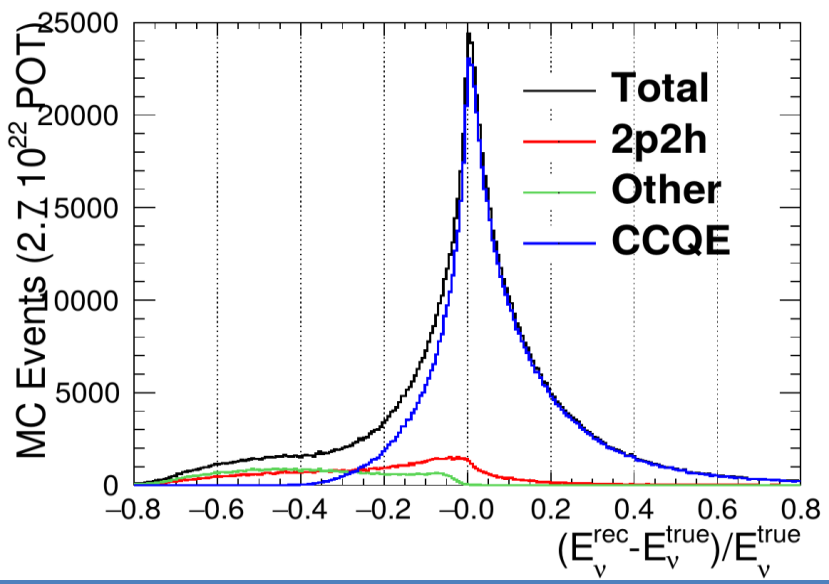
Interactions off a bound state of two nucleons can result in **2p2h** final states





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

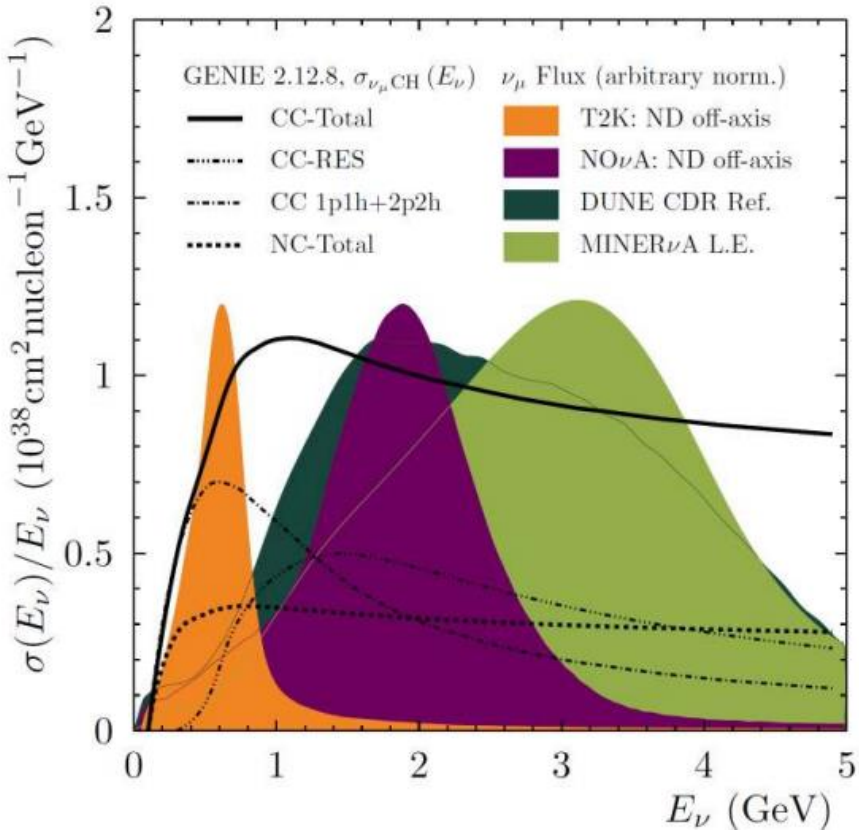
First-order effects

Fermi motion causes a **smearing** on E_ν^{QE}

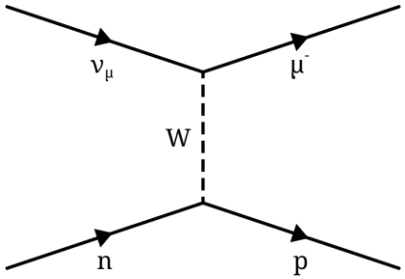
Nuclear removal energy effects introduce a **bias**

2p2h and pion abs. *FSI* cause further **bias**

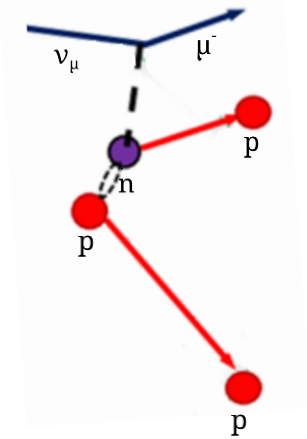
Neutrino interactions



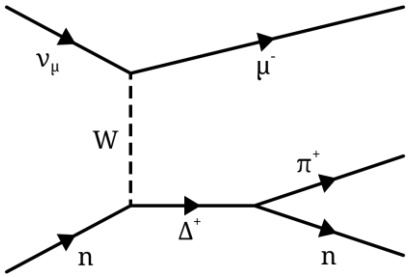
CCQE (1p1h)
(Charged-Current Quasi-Elastic)



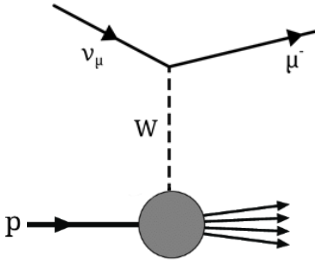
CC 2p2h
(2 particle, 2 hole)



CCRES
(Charged-Current Resonant)

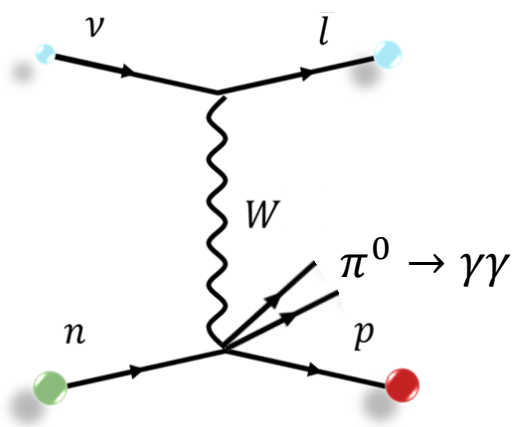


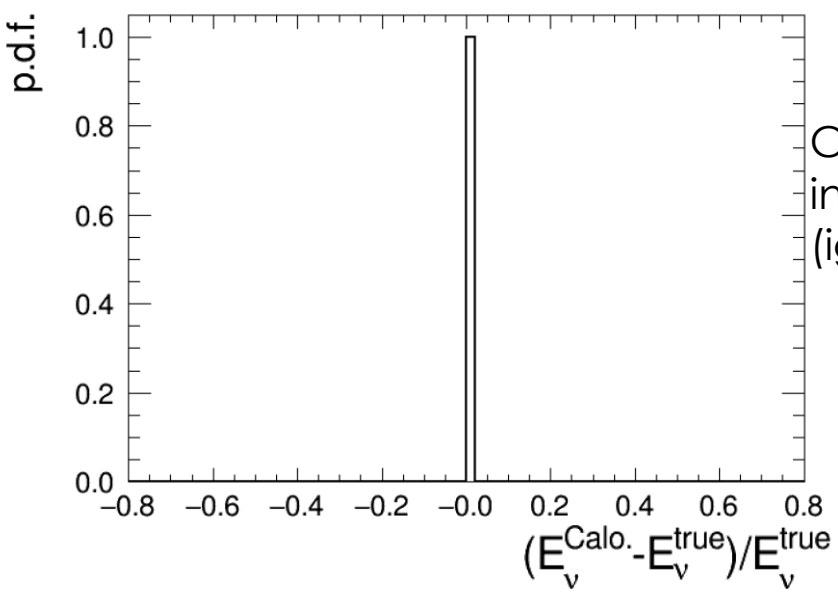
CCDIS
(Deep Inelastic Scattering)



Key challenge: estimating E_ν

Nuclear effects and E_ν (SBN/DUNE/NOvA)



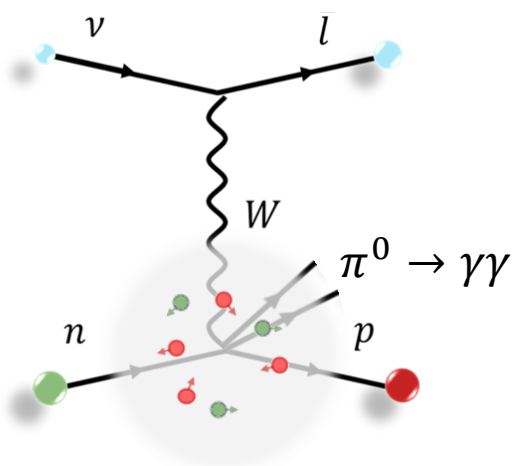


$$E_\nu^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

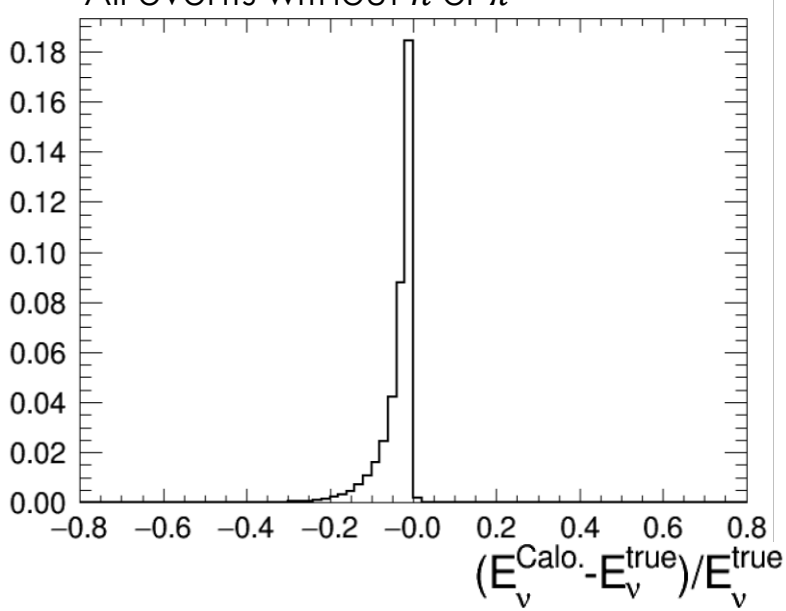
Calculation from calorimetry is exact only for interactions **without neutrons and charged pions** (ignore heavier mesons here) off a **stationary nucleon**

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

Nuclear effects and E_ν (SBN/DUNE/NOvA)



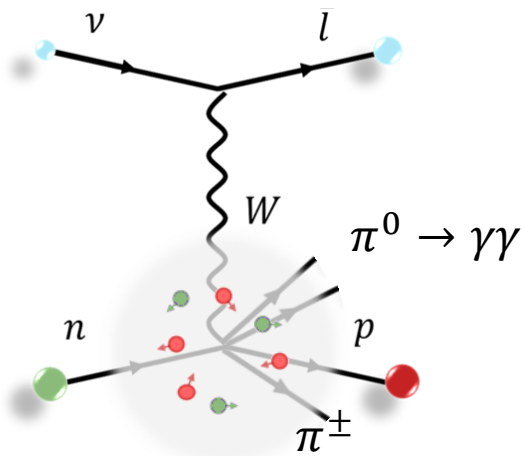
All events without n or $\pi^\pm$



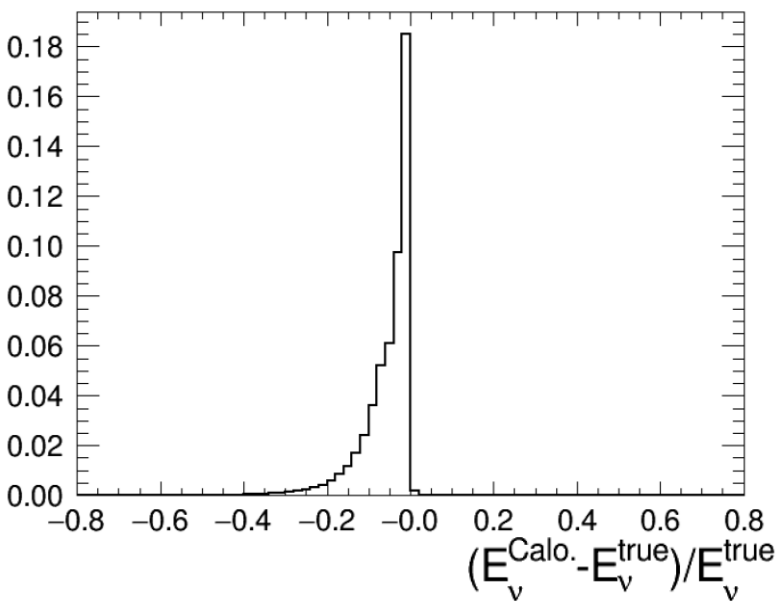
$$E_\nu^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

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

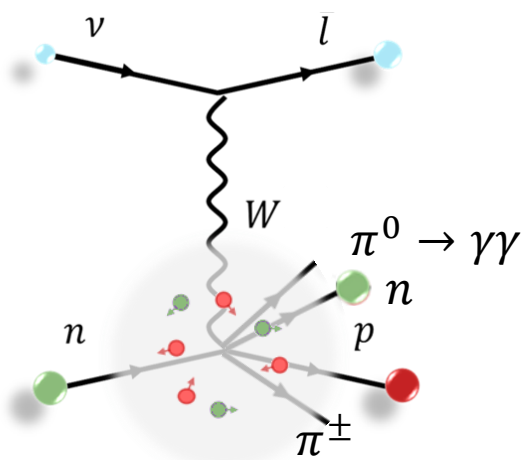


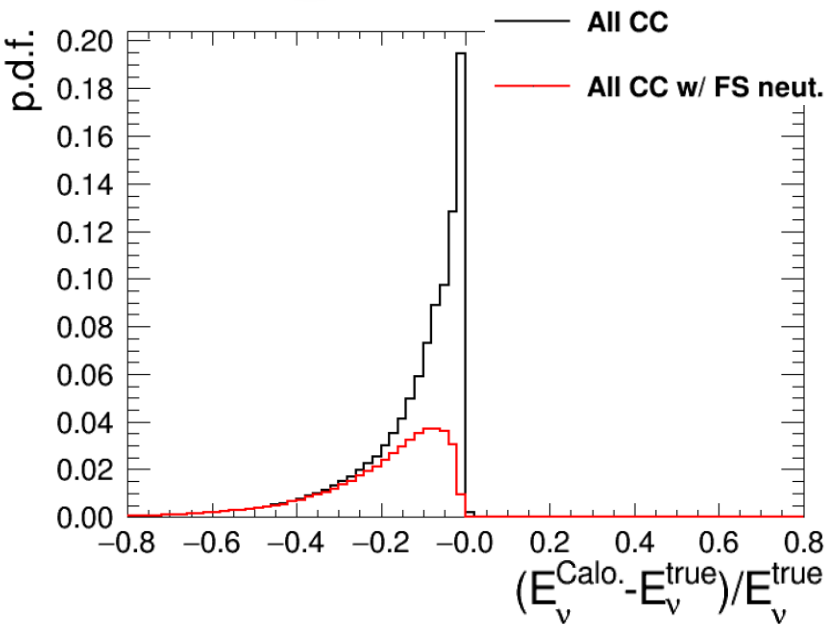
$$E_\nu^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

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

Charged pion masses also play a fairly small role

Nuclear effects and E_ν (SBN/DUNE/NOvA)





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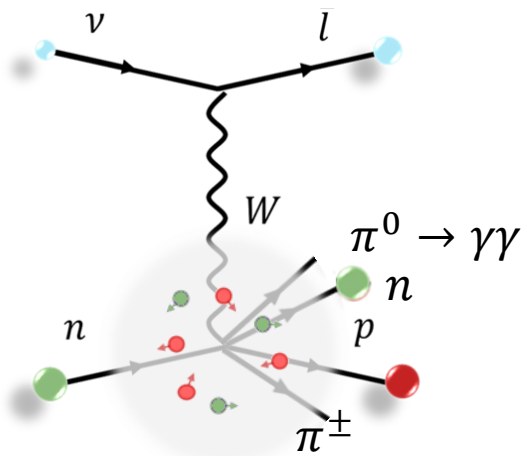
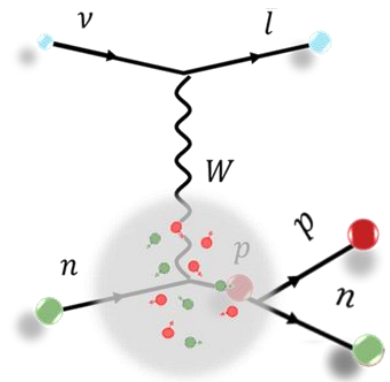
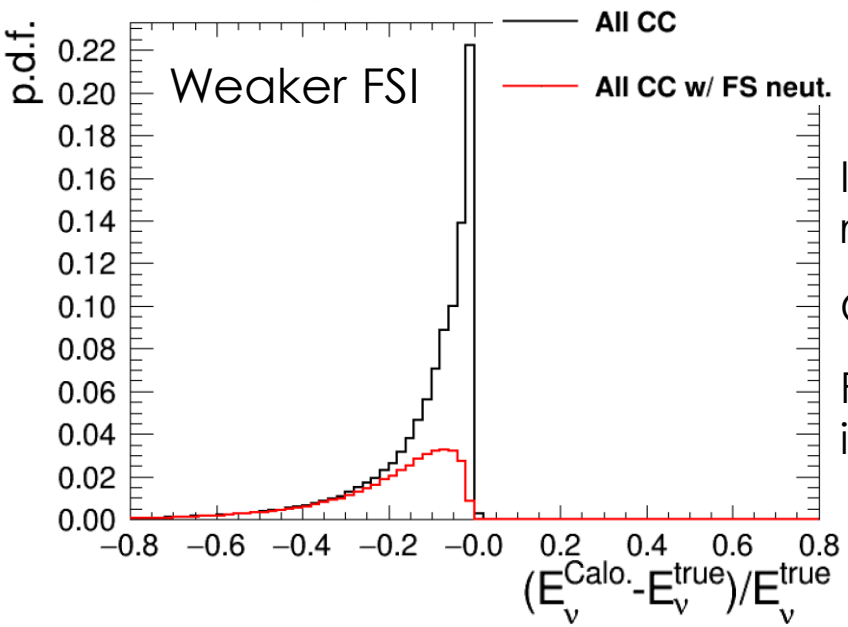
Fraction of E_ν in **Neutrons** is critical

Nuclear effects and E_ν (SBN/DUNE/NOvA)



Final State Interactions (FSI)





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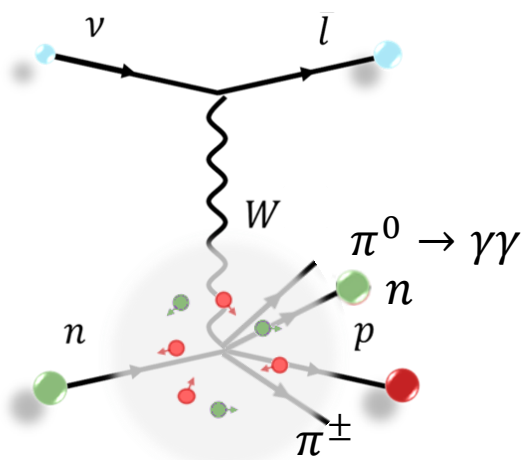
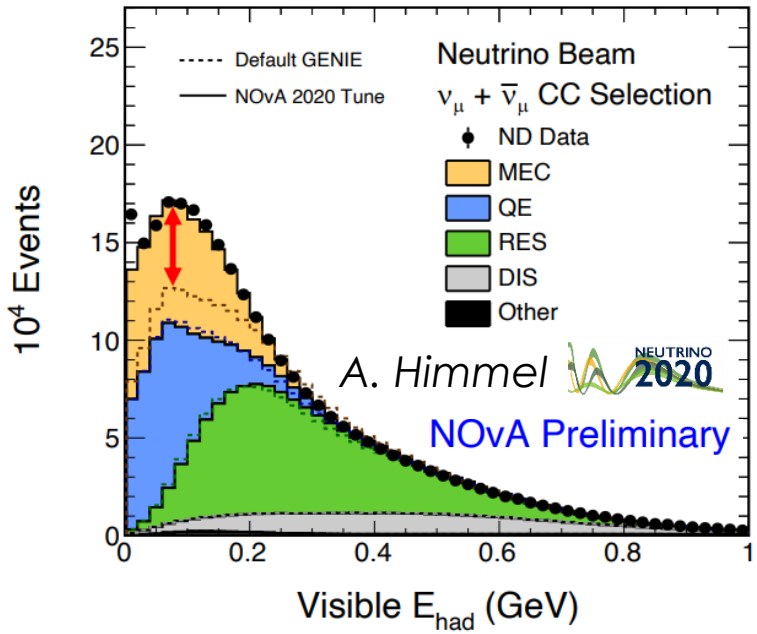
Impact of initial state effects (Fermi motion and removal energy) smaller than in QE approach

Charged pion masses also play a fairly small role

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)



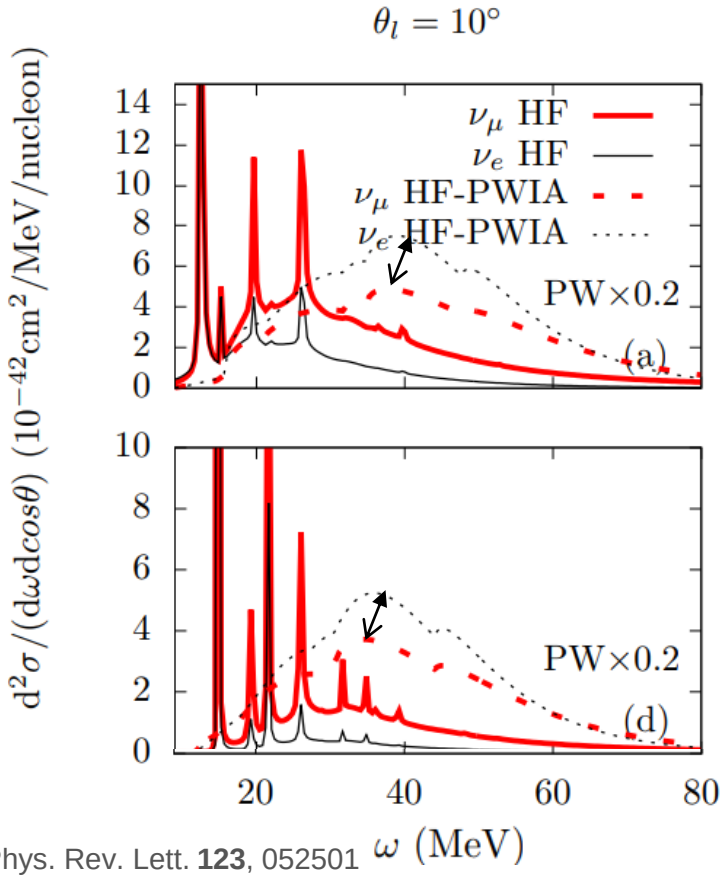


- Complex interaction topologies make E_{had} tough to model
- NOvA find strong data/simulation discrepancy at low E_{had} (before applying a 2p2h modification)
- Covered by generous systematics, but this must be better understood for DUNE

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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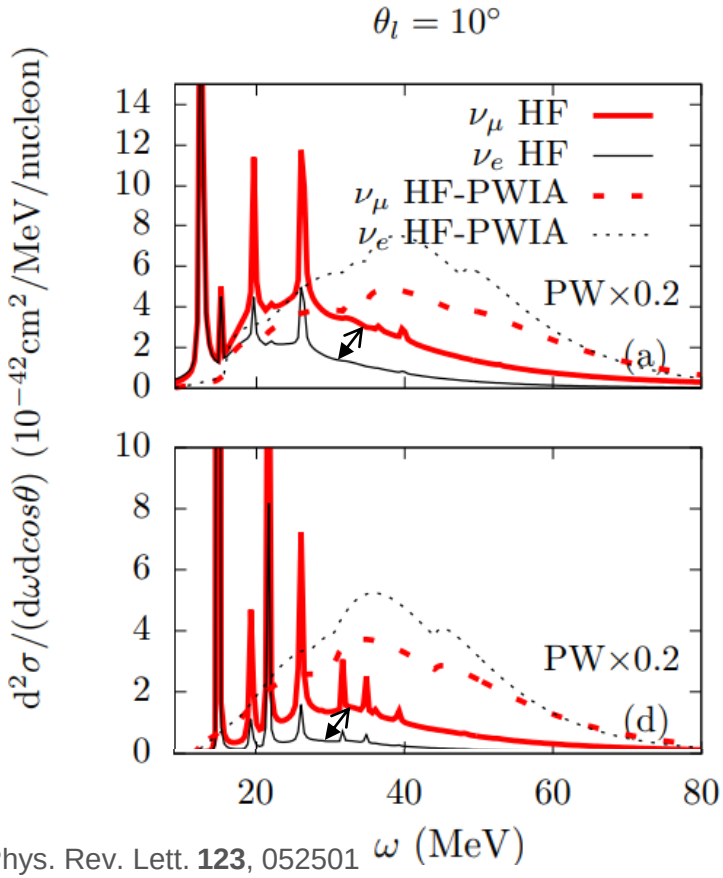


Phys. Rev. Lett. **123**, 052501

- 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): $\sigma(\nu_e) < \sigma(\nu_\mu)$

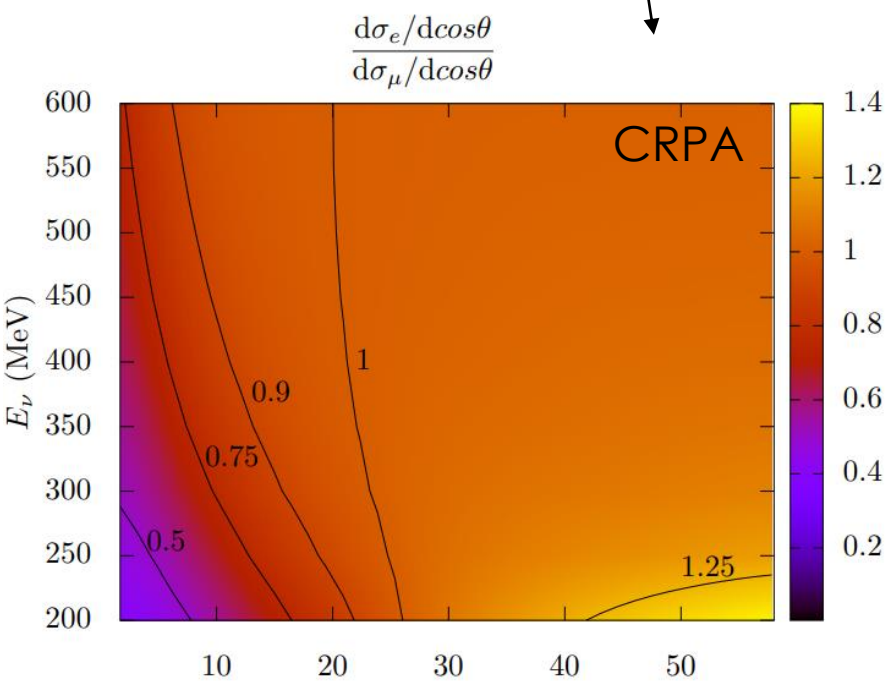
Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

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

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

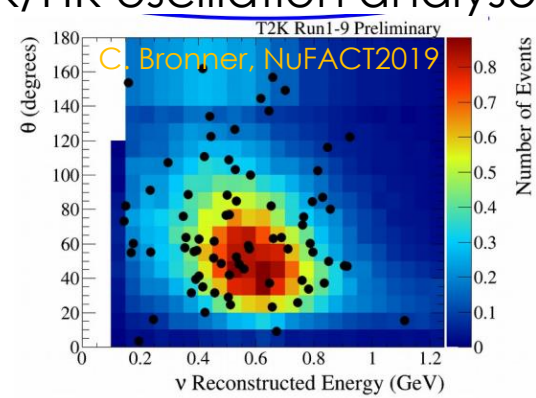
	$E_\nu = 200\ MeV$		$E_\nu = 600\ MeV$	
Model	5°	60°	5°	60°
RFG (w/PB)	0.64	1.61	0.97	1.03
SF (full)	1.41	1.92	1.04	1.03
CRPA	~0.5	~1.4	~0.9	~1.0

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



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

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



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 $\sigma(\nu_e)/\sigma(\nu_\mu)$
- 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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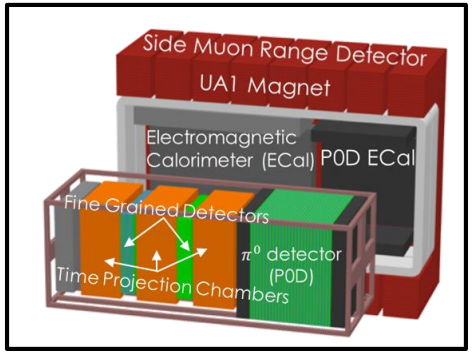
- Nuclear ground state
- Differences between interactions on Carbon and Argon

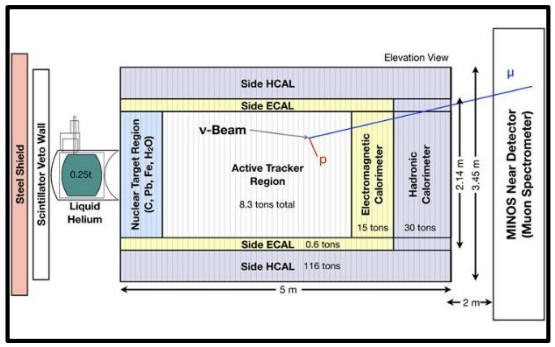
Neutrino interaction modelling is crucial for all upcoming experiments, but different experiments have different priorities: **complimentary approaches**!

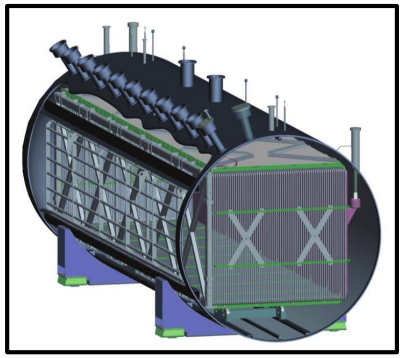

KEEP CALM
AND
MEASURE dσ/dx

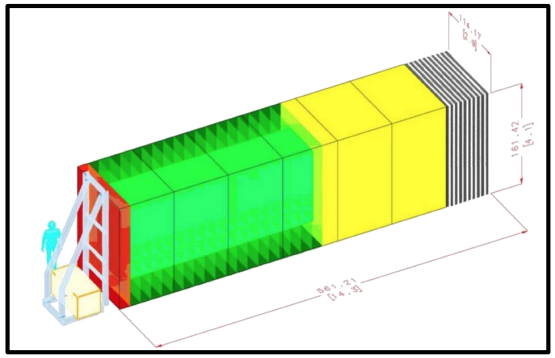
Overview

- The Weak Interaction
  - Historical Overview
  - Point-like scattering
- Neutrino-nucleon interactions
  - QE, RES and DIS
- Neutrino-nucleus interactions
  - Nuclear effects
  - Ground state modelling
- Why do we care?
  - Neutrino interactions for neutrino oscillations
  - Neutrino energy reconstruction
- Neutrino-nucleus interaction measurements
  - Inclusive successes and exclusive failures
- Where did it all go wrong? (Neutrino event generators)
  - Limitations of our simulations
- Don't Panic! The future of neutrino interactions

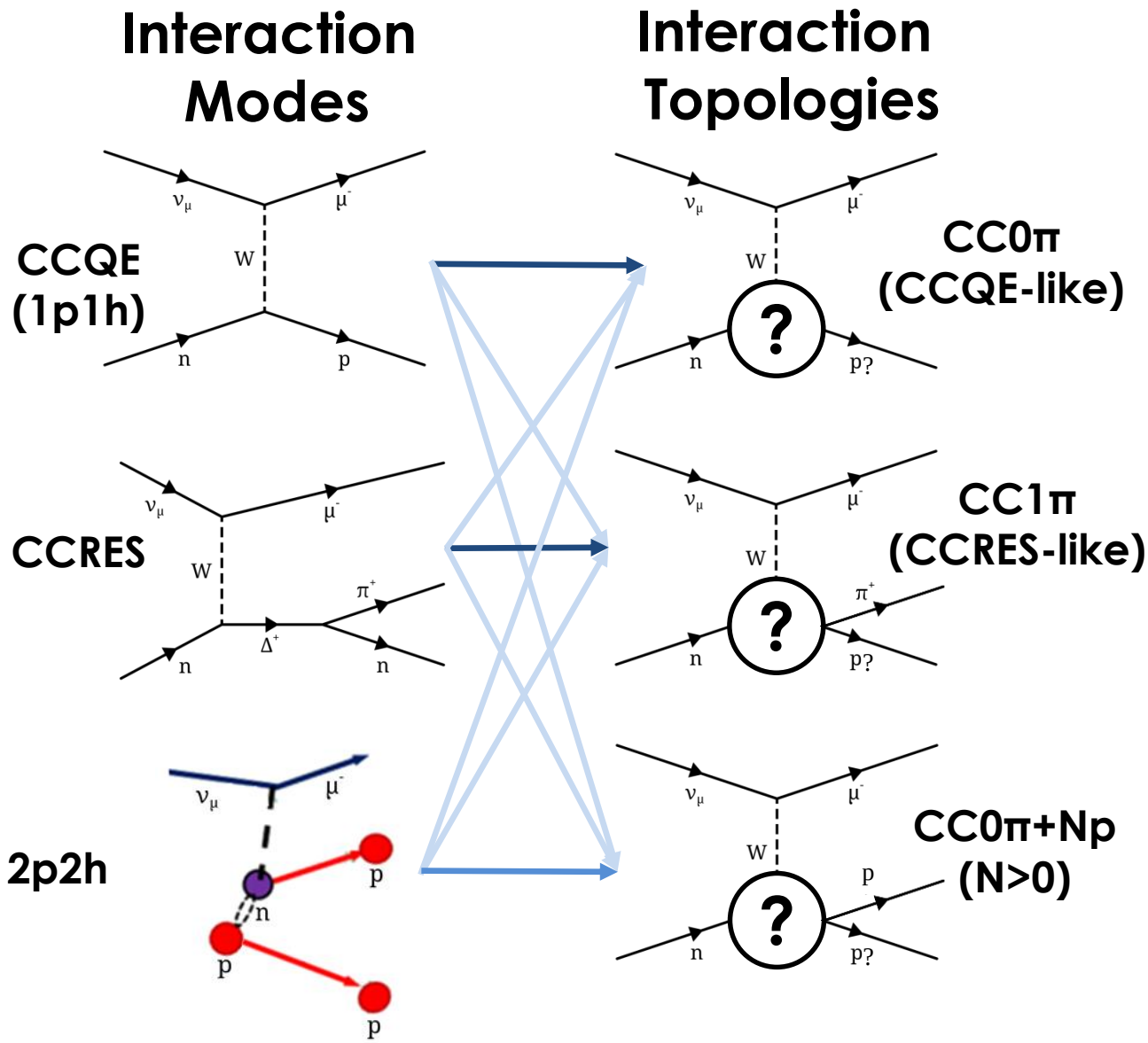




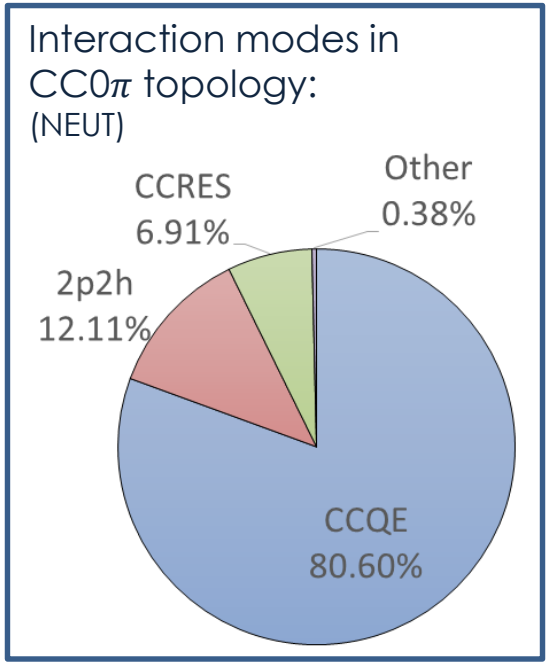




What can we measure

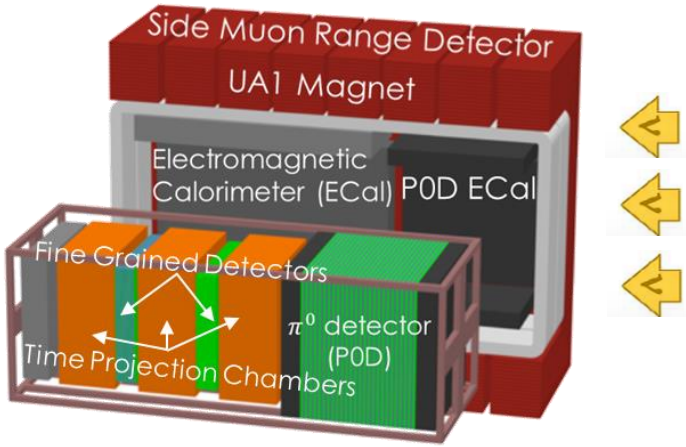


- Nuclear effects can hide the true interaction mode
- To minimise model dependence we measure interaction topologies



ND280 and MINERvA

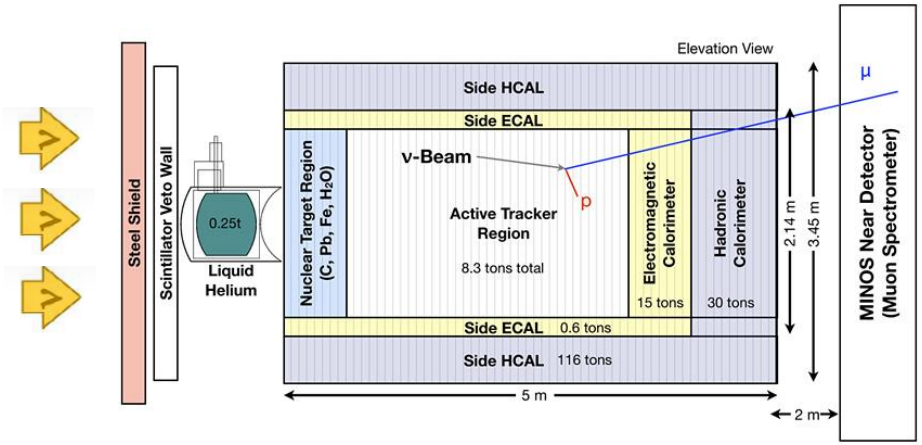
ND280 (Near detector for T2K)



Primary targets: CH, H_2O

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

MINERvA

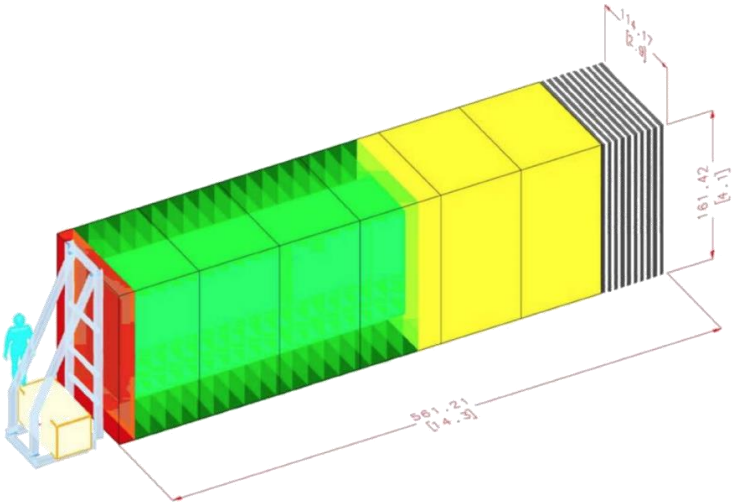


Primary targets: CH, Pb, Fe

Peak E_ν
- ME ~ 5.8 GeV
- LE ~ 3.2 GeV

NOvA and μBooNE

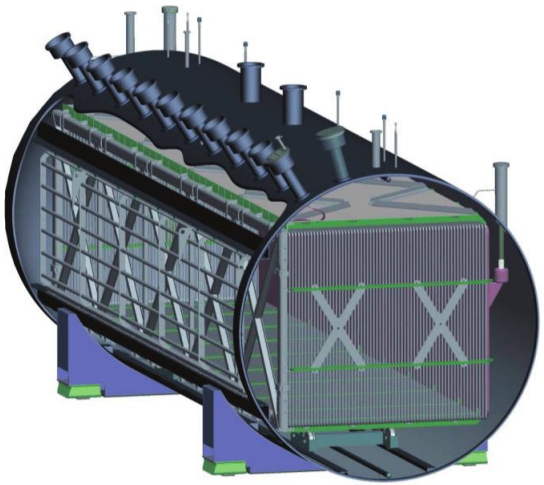
NOvA (Near detector)



Primary targets: "NOvA soup"
(Mostly C, H, Cl)

Peak E_ν: ~ 2 GeV

μBooNE



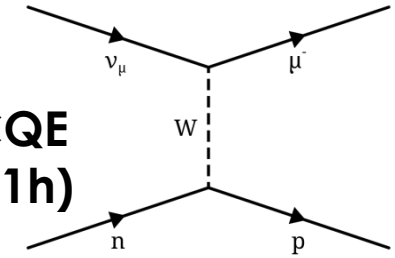
Primary targets: Ar

Peak E_ν: ~ 0.6 GeV

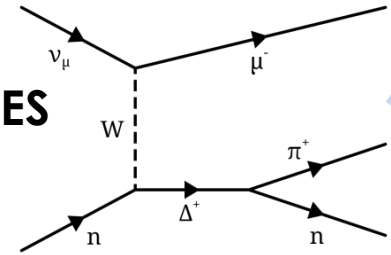
CC0π measurements

Interaction Modes

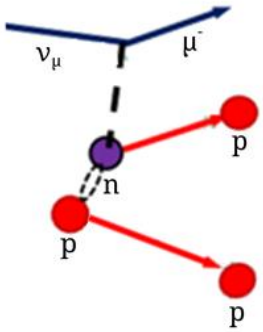
CCQE (1p1h)



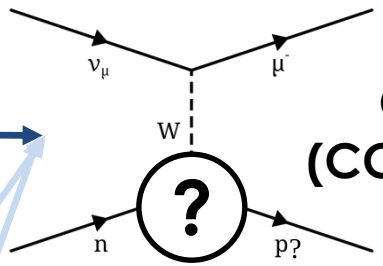
CCRES



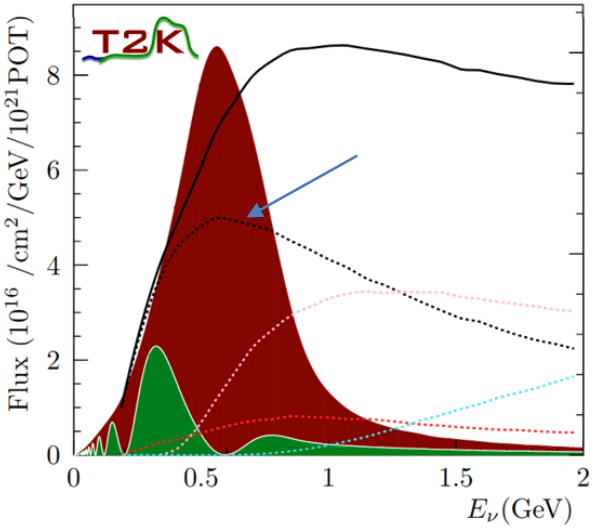
2p2h



Interaction Topologies



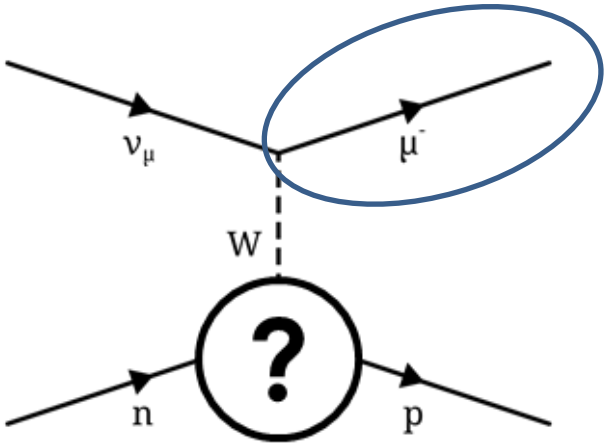
CC0π (CCQE-like)



- The thing we know "best"
- Dominant community focus for ~10 years
- Signal process for T2K/HK

Which observables?

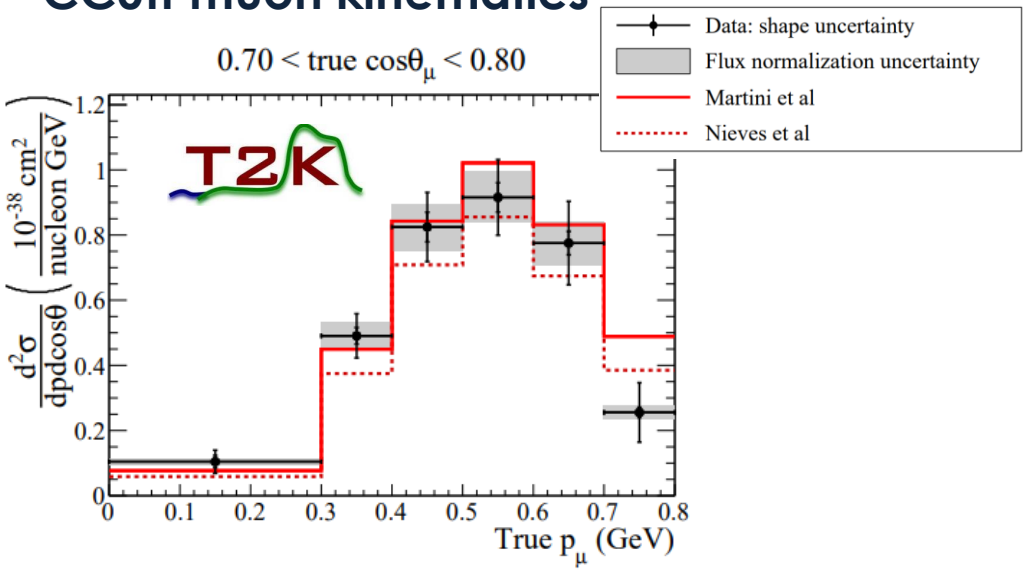
Just the muon?

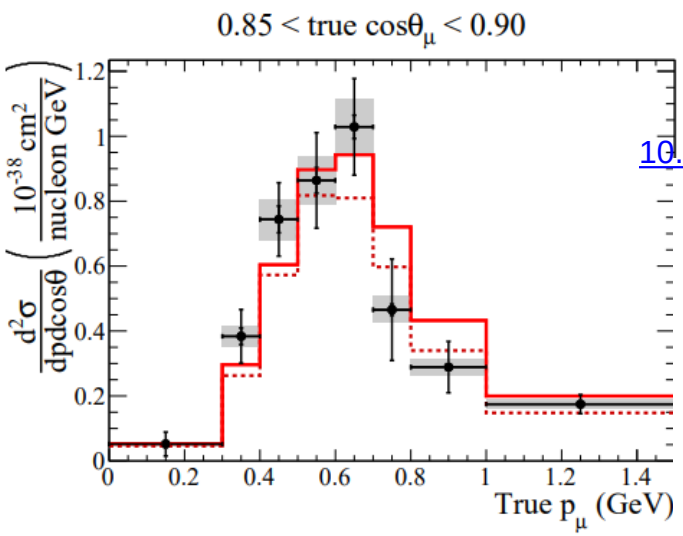


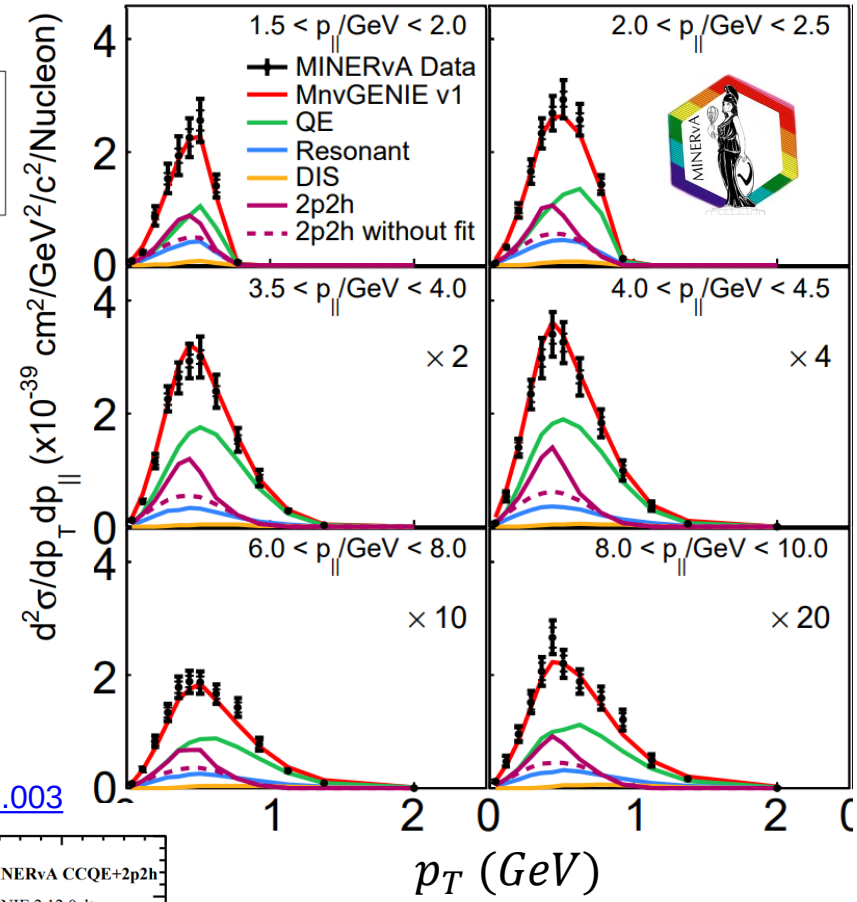
Our current models vs data

Phys. Rev. D **99**, 012004

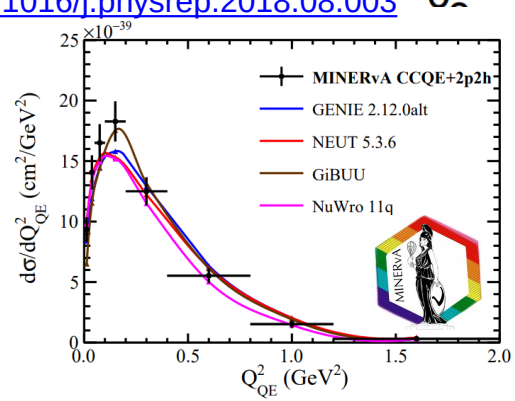
CC0π muon kinematics







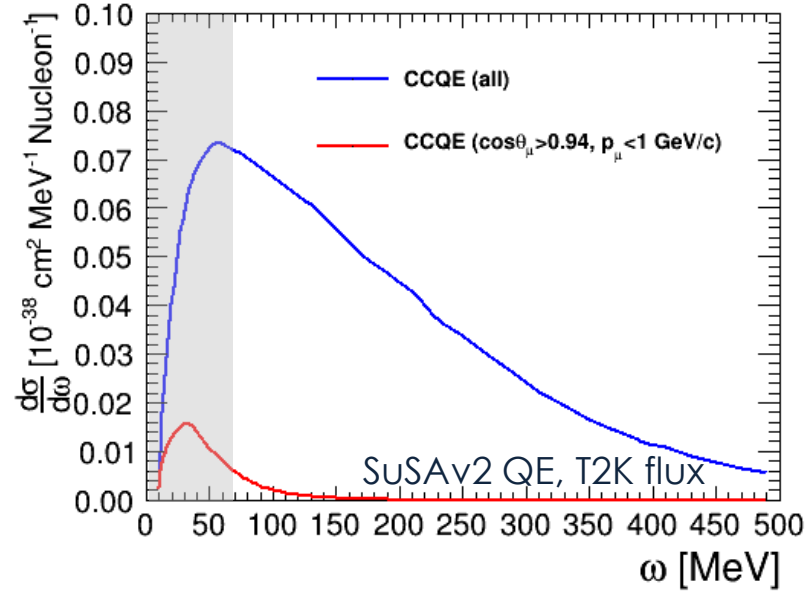
10.1016/j.physrep.2018.08.003

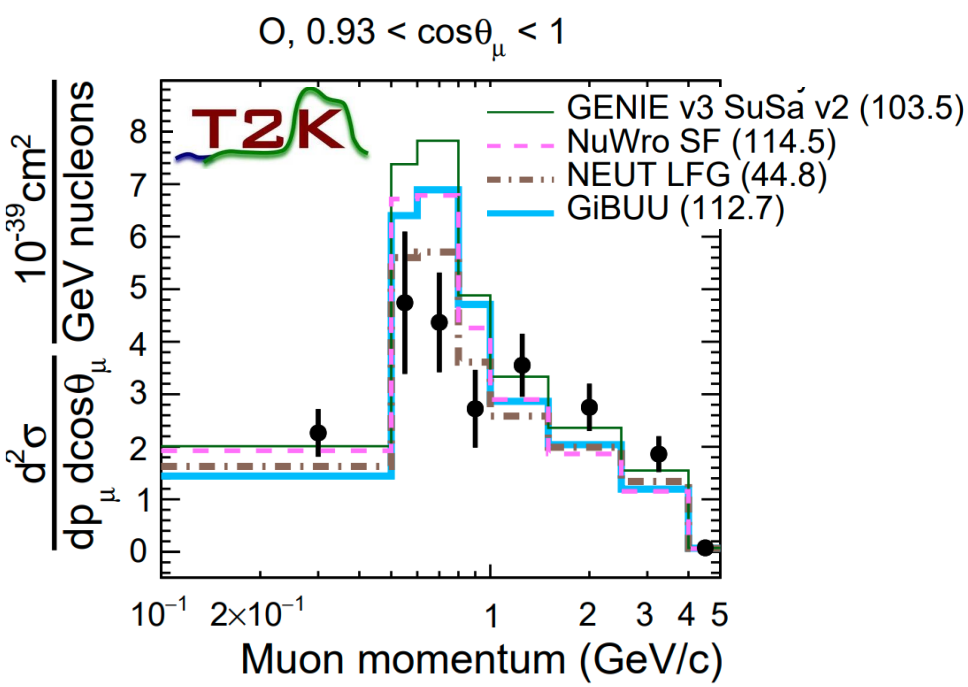


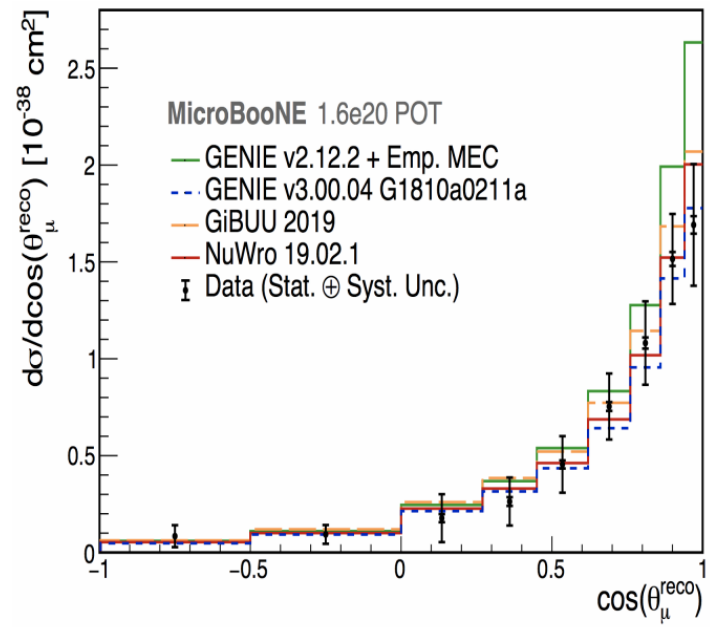
Agreement is sort of okay (by our poor standards).

Forward Angles

- The very forward region is especially sensitive to interactions with low energy transfer (ω)
- Things don't look so good here …







Phys. Rev. Lett 123,131801 (2019)

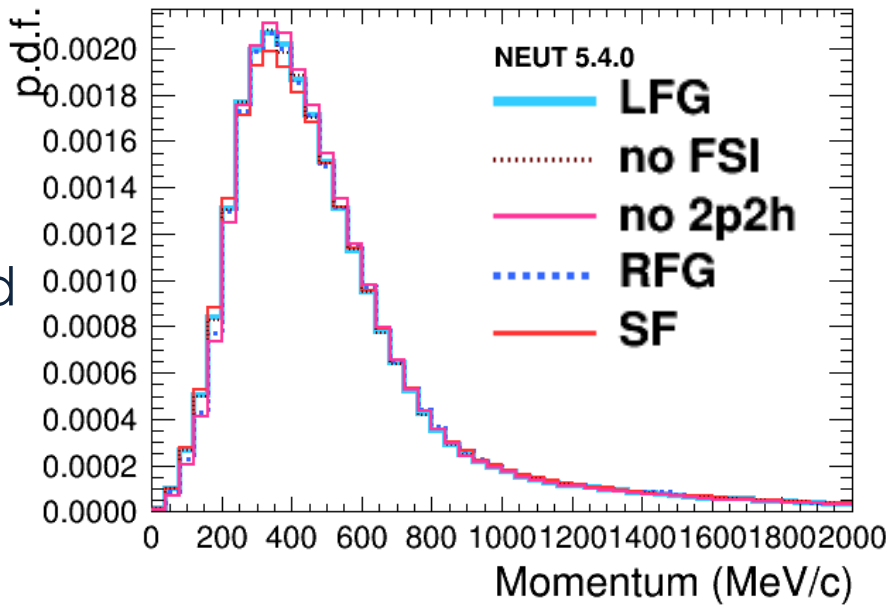
What to measure?

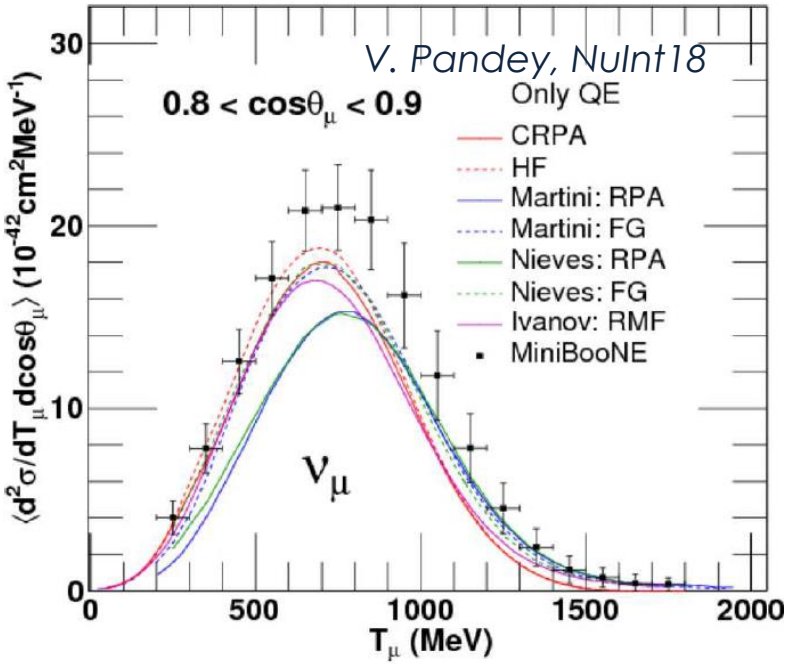
Muon kinematics?

✓ Muon kinematics can be predicted directly from most theories

X But most theories predict very similar things in muon kinematics (apart from at forward angles)

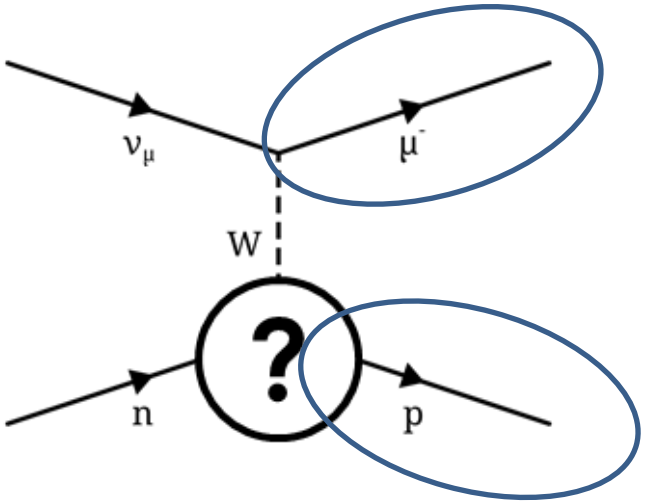
X Differences are often normalisation changes: can be hidden under a flux error





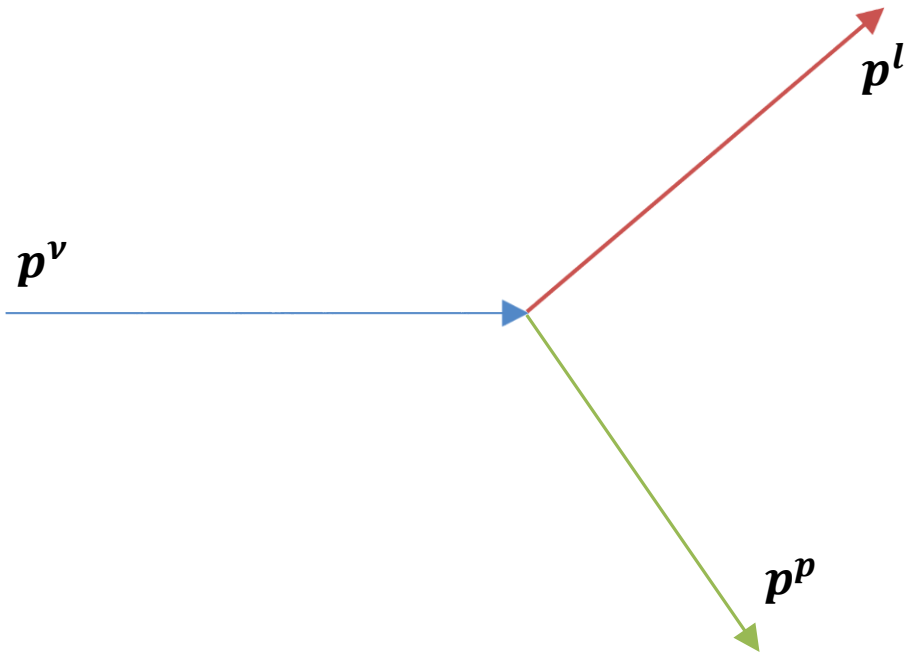
Which observables?

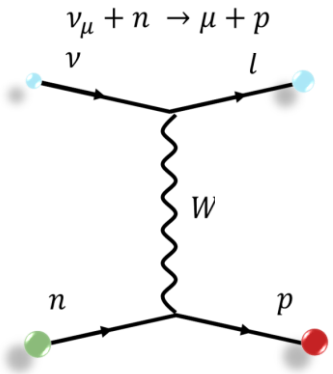
Lepton and proton?



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

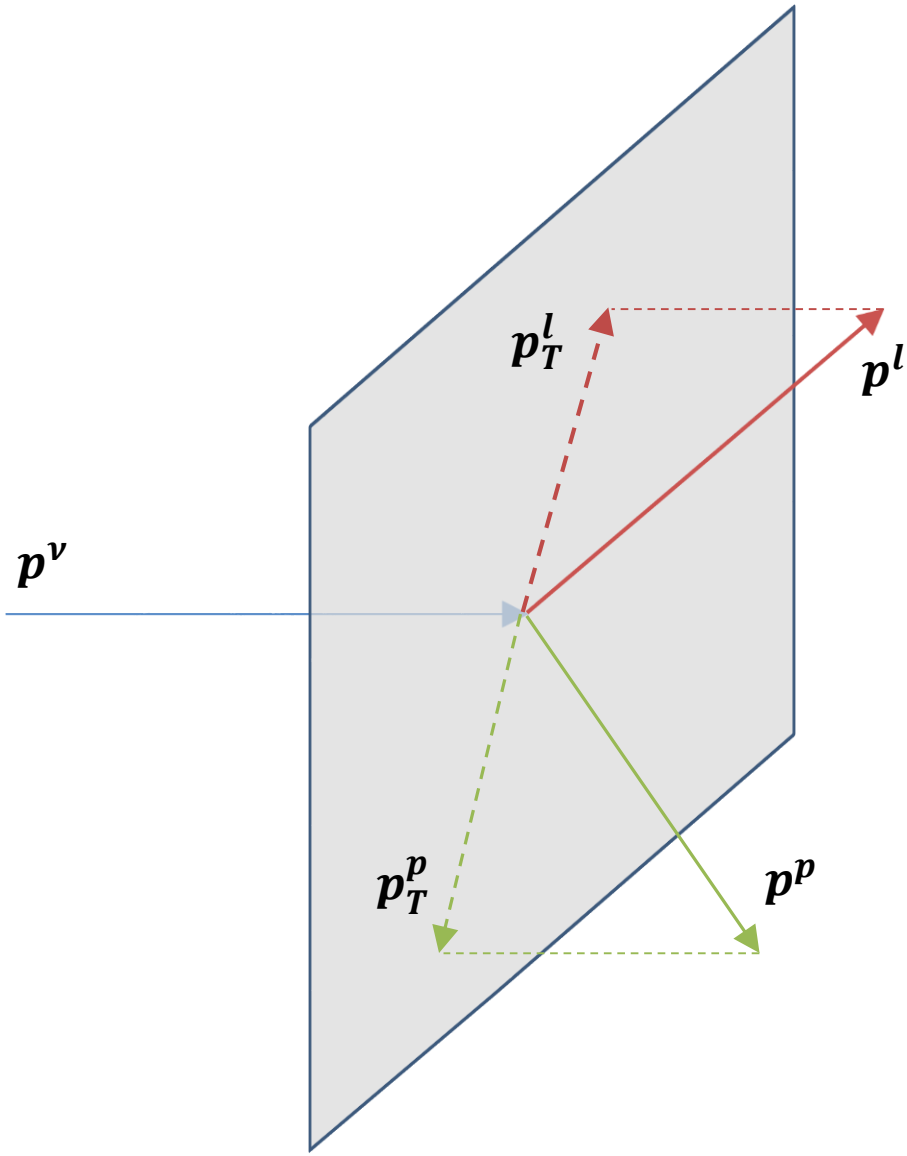
Single Transverse Variables

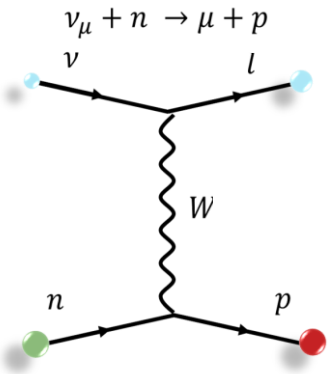




No nuclear Effects

Single Transverse Variables

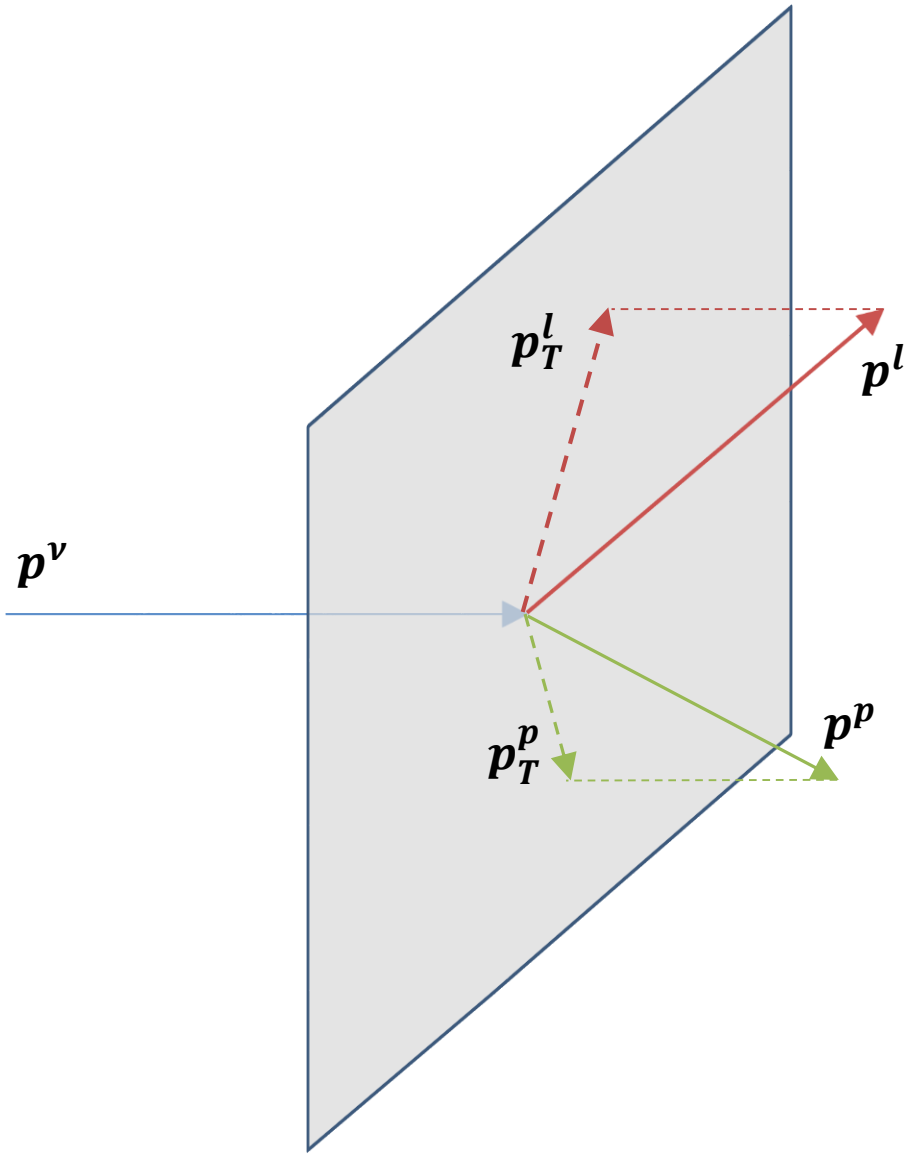




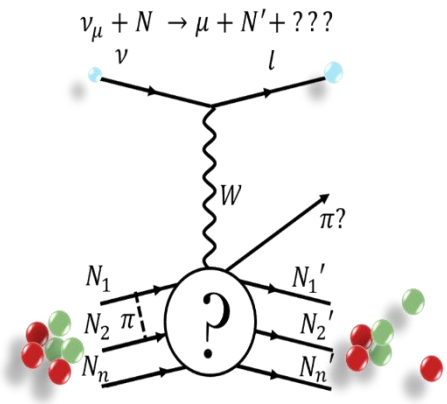
No nuclear Effects

$$\boldsymbol{p_T^l} = -\boldsymbol{p_T^p}$$

Single Transverse Variables



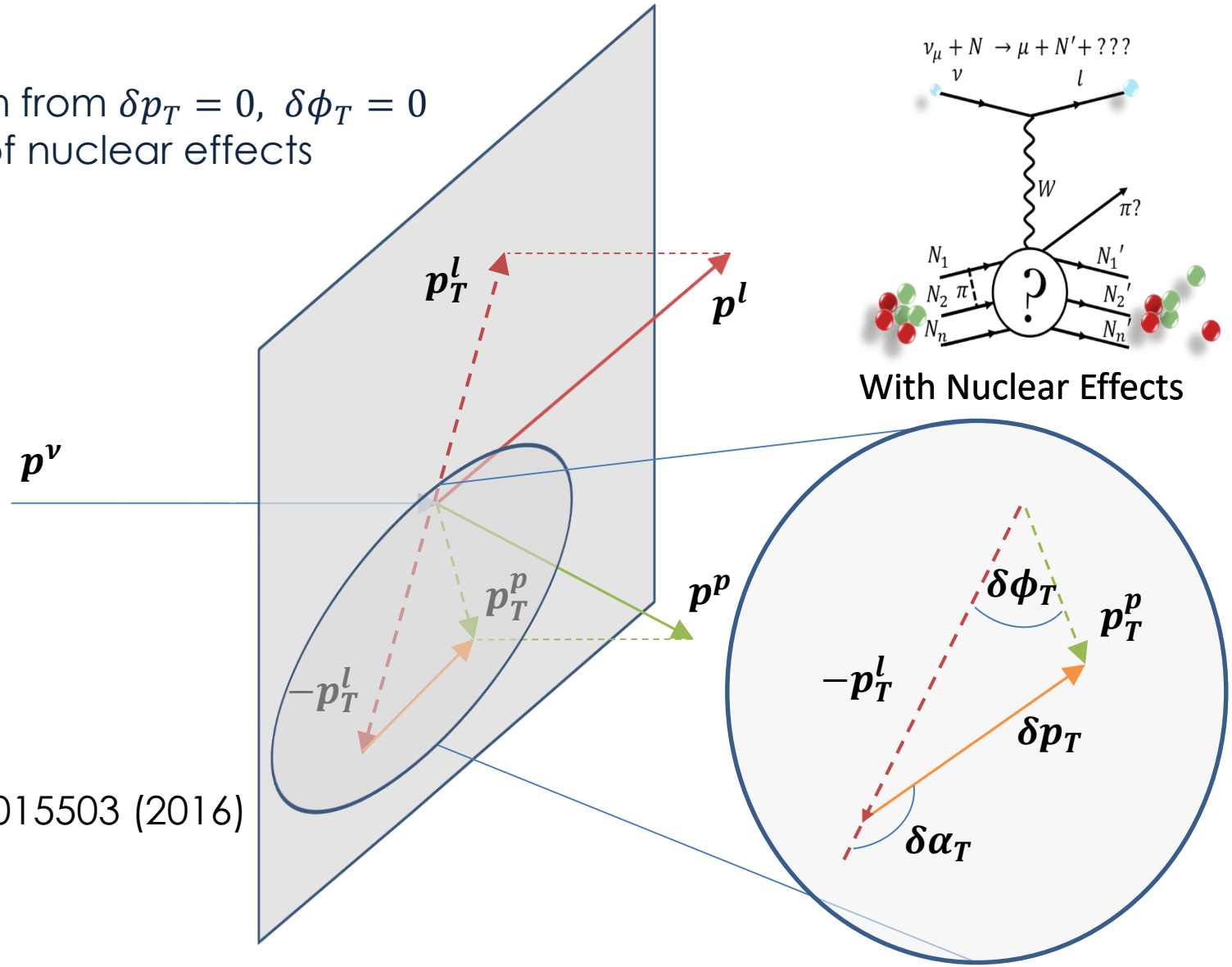
$$p_T^l \neq -p_T^p$$



With Nuclear Effects

Single Transverse Variables

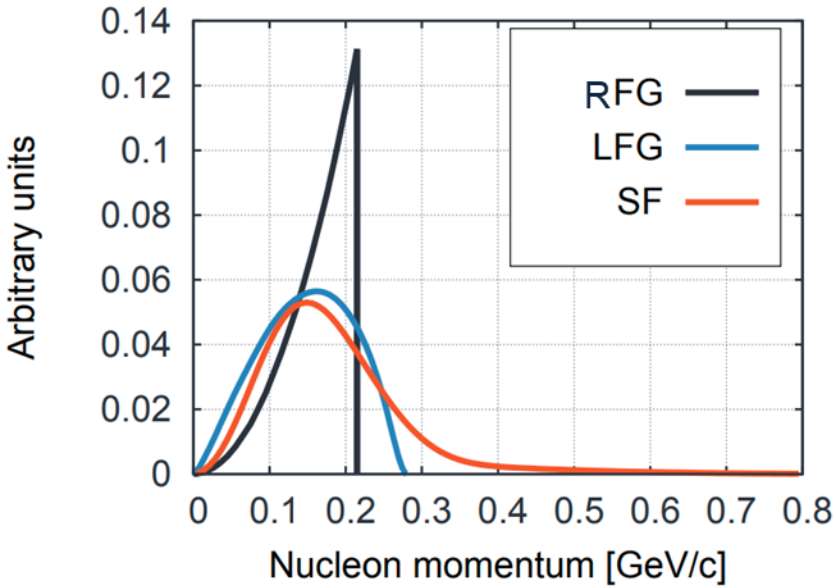
- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects

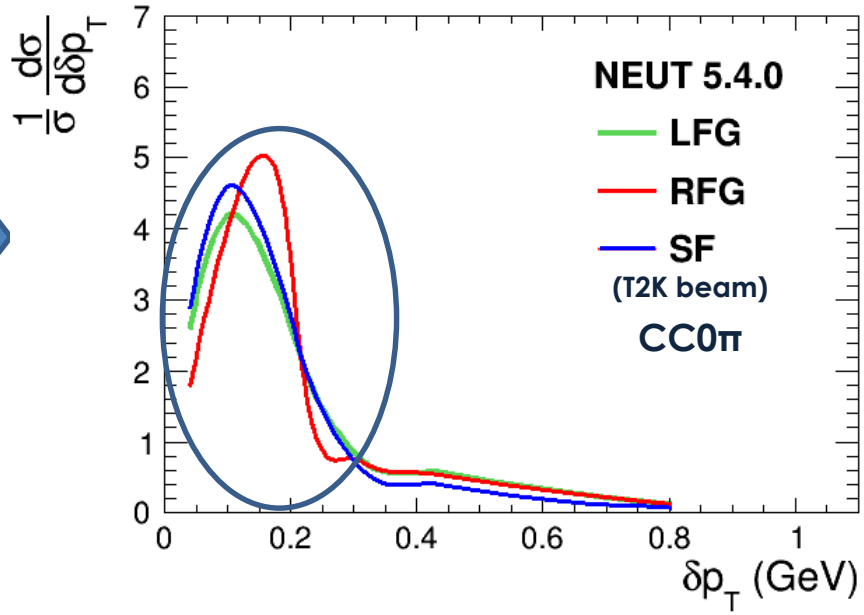


With Nuclear Effects

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

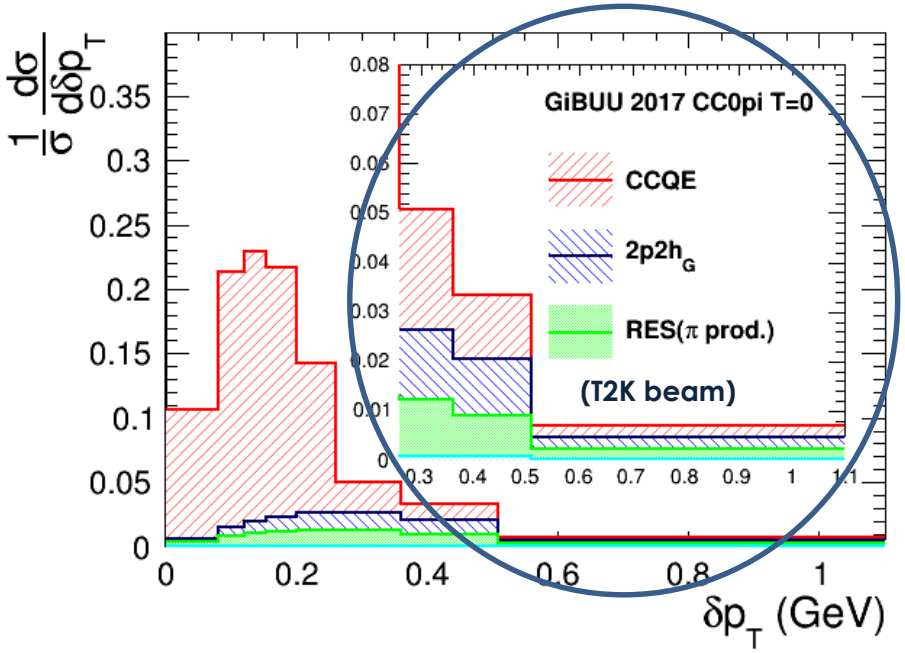
STV model discrimination - δp_T

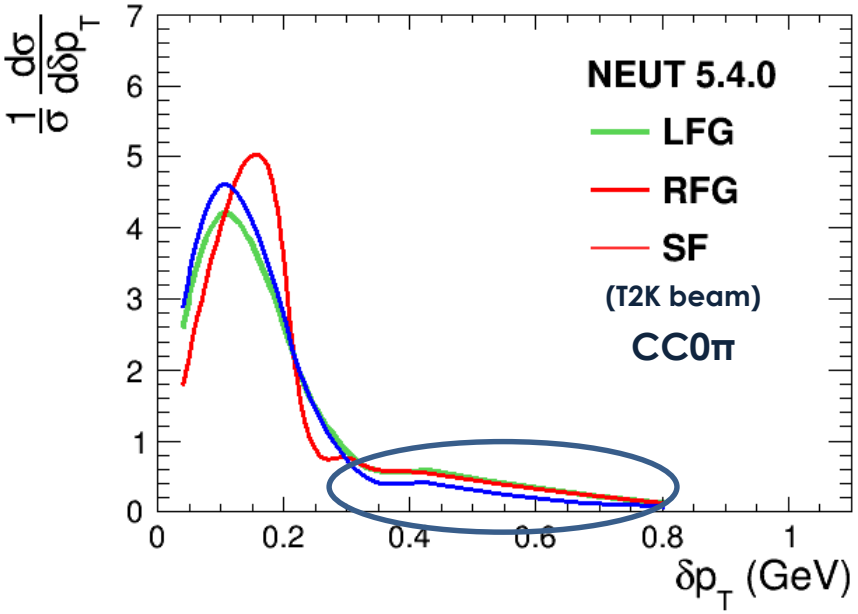




- In the absence of other nuclear effects, δp_T *is* the transverse projection of the Fermi motion.
- Since this motion is isotropic, $\delta p_T \rightarrow$ Fermi motion

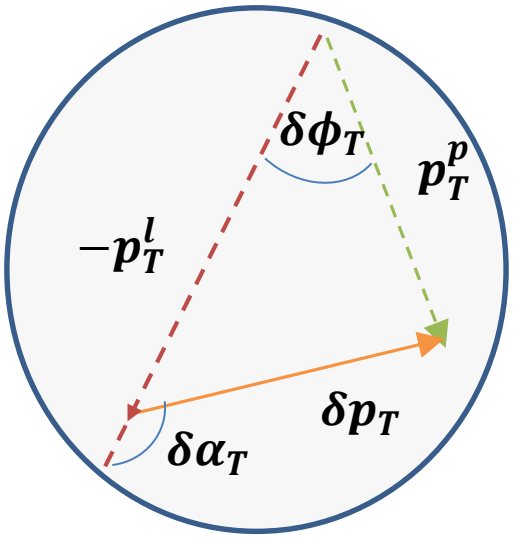
STV model discrimination - δp_T



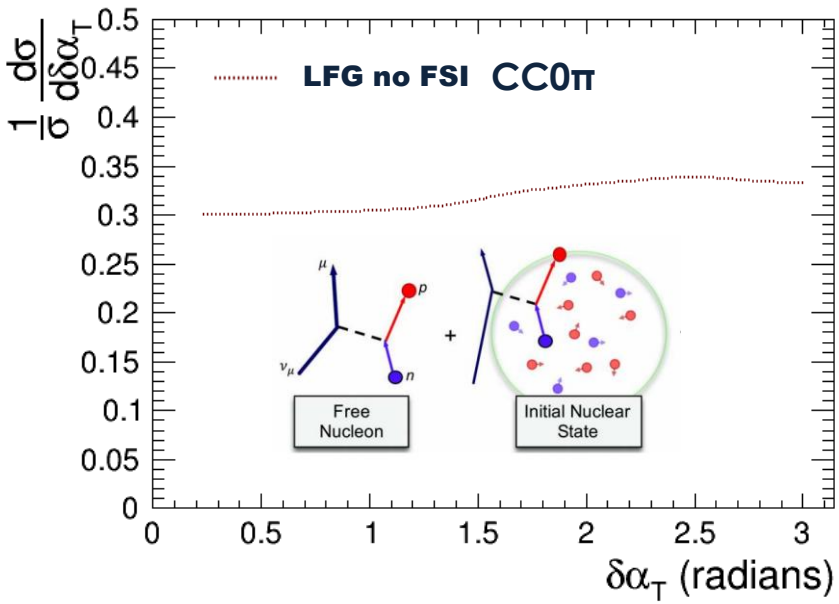


- In the absence of other nuclear effects, δp_T *is* the transverse projection of the Fermi motion.
- Since this motion is isotropic, δp_T → Fermi motion
- Cross section beyond the Fermi surface must come from physics beyond RFG → 2p2h, FSI, SRCs …

STV model discrimination - $\delta\alpha_T$

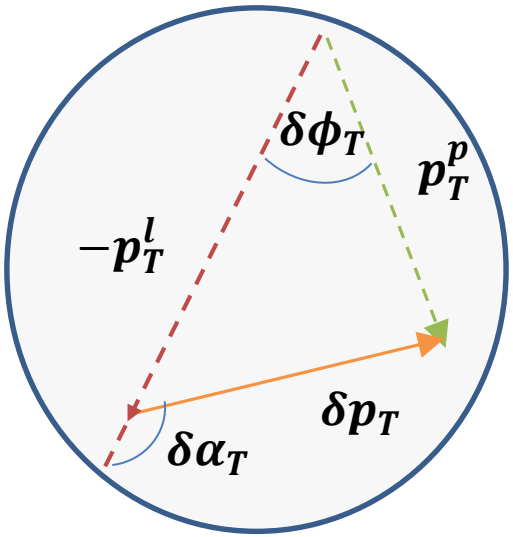


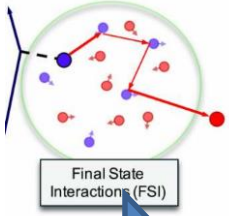
Consider imbalance from only Fermi motion



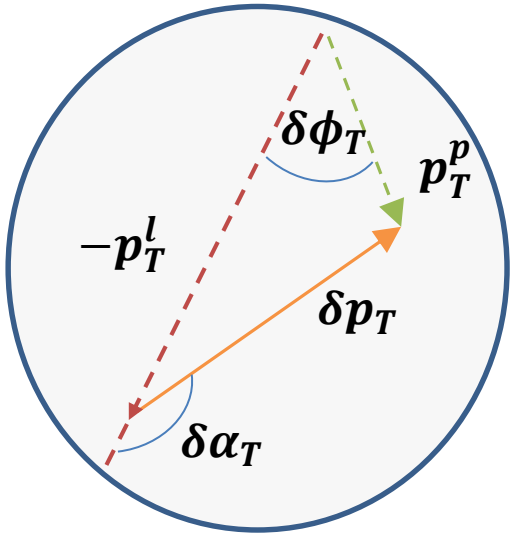
Fermi motion is isotropic so no preferred $\delta\alpha_T$ direction

STV model discrimination - $\delta\alpha_T$

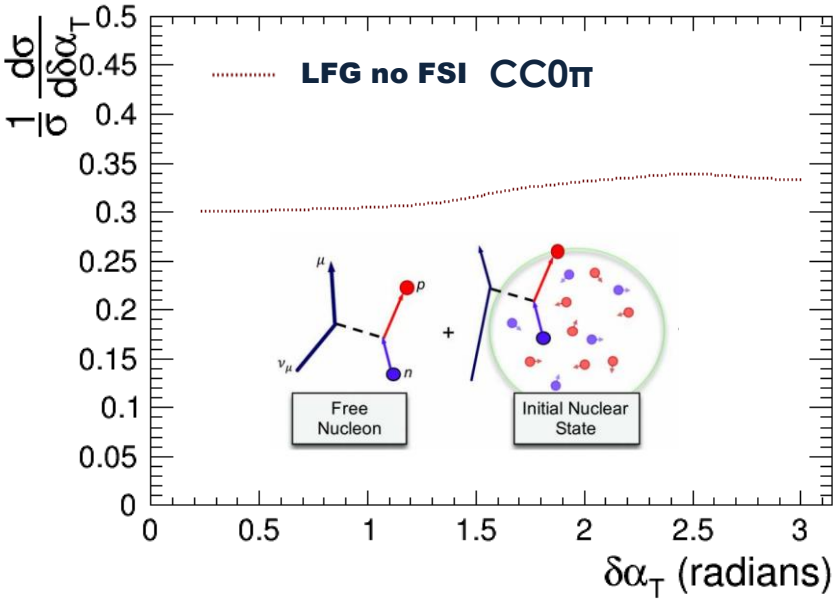


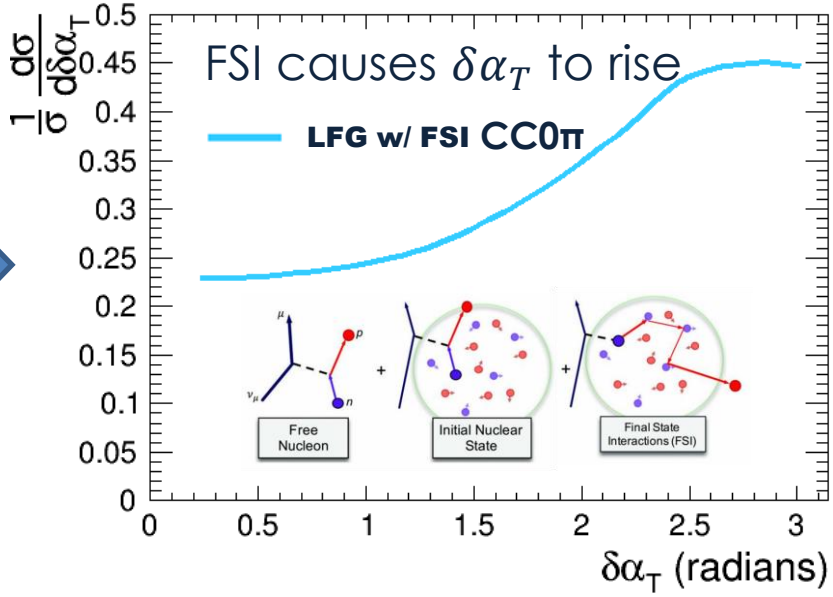


Deceleration of proton from FSI



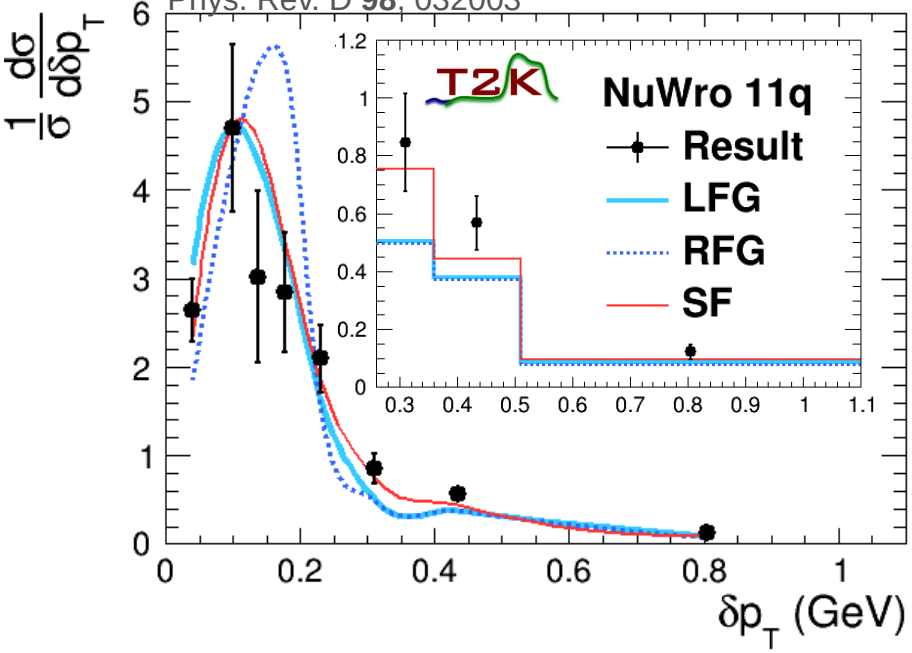
= larger $\delta\alpha_T$



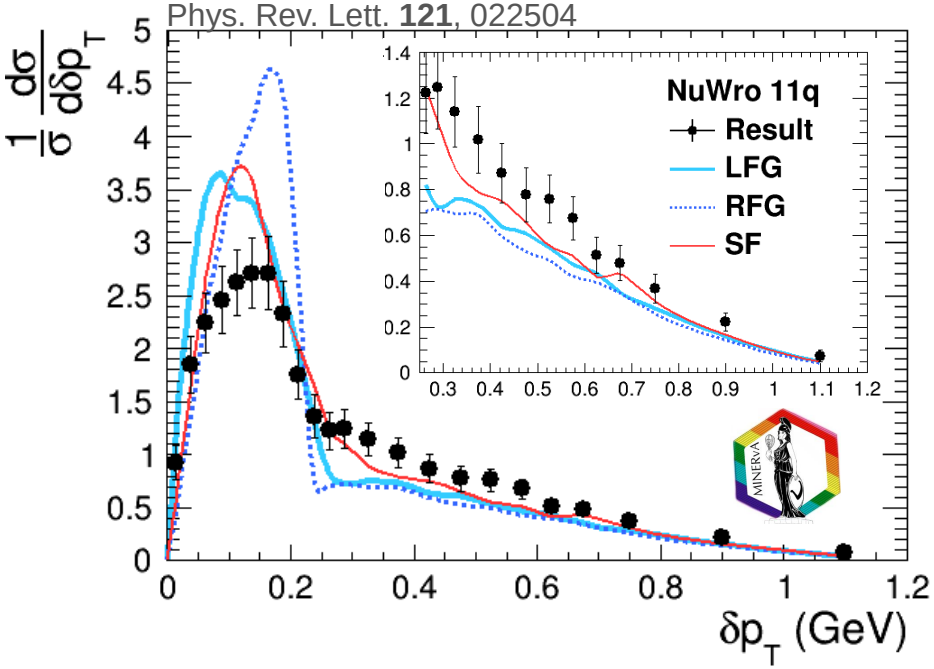


Current measurements

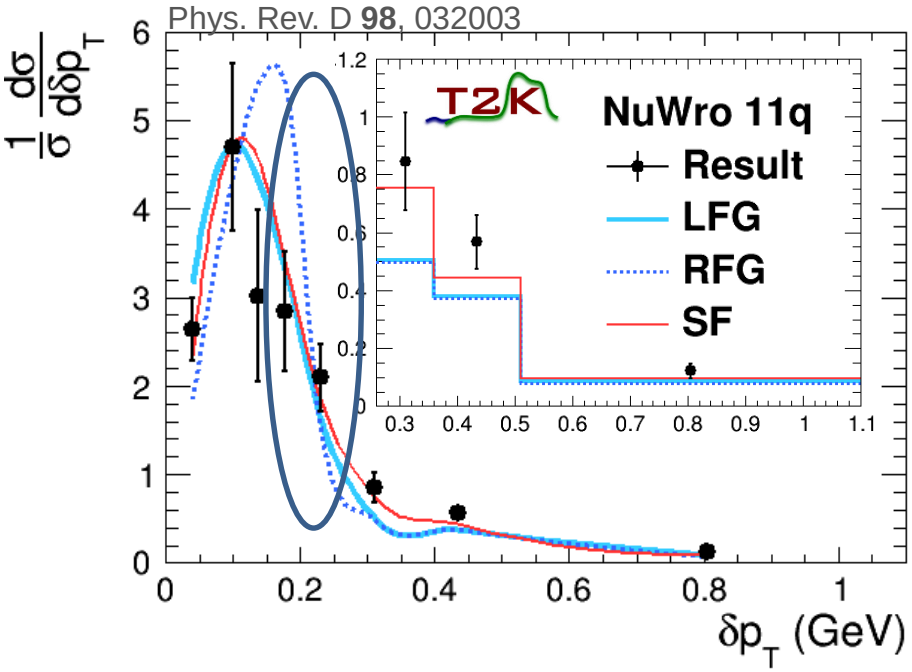
Phys. Rev. D **98**, 032003

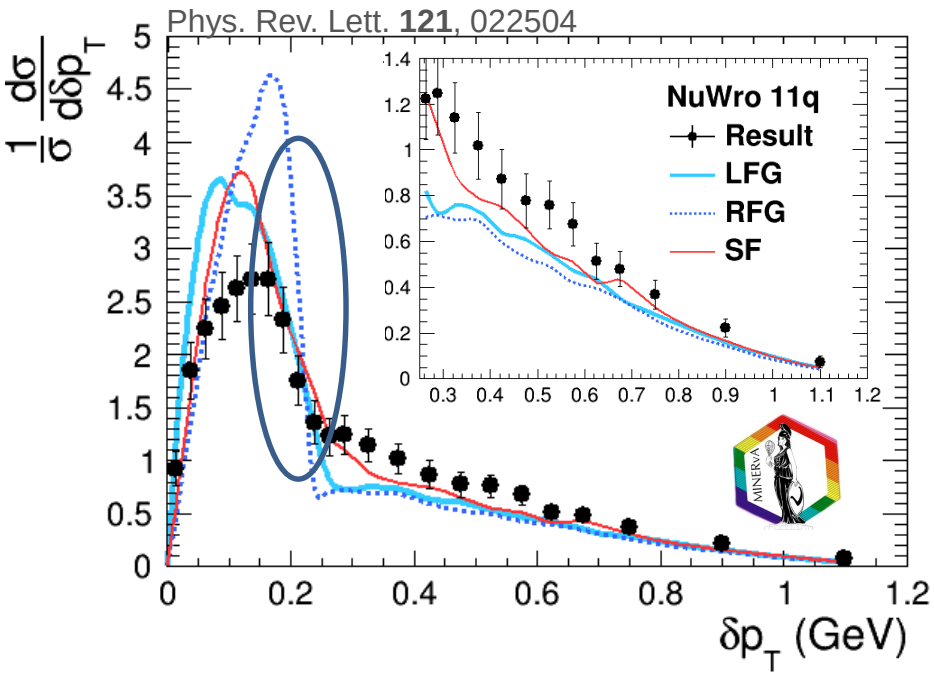


Phys. Rev. Lett. **121**, 022504



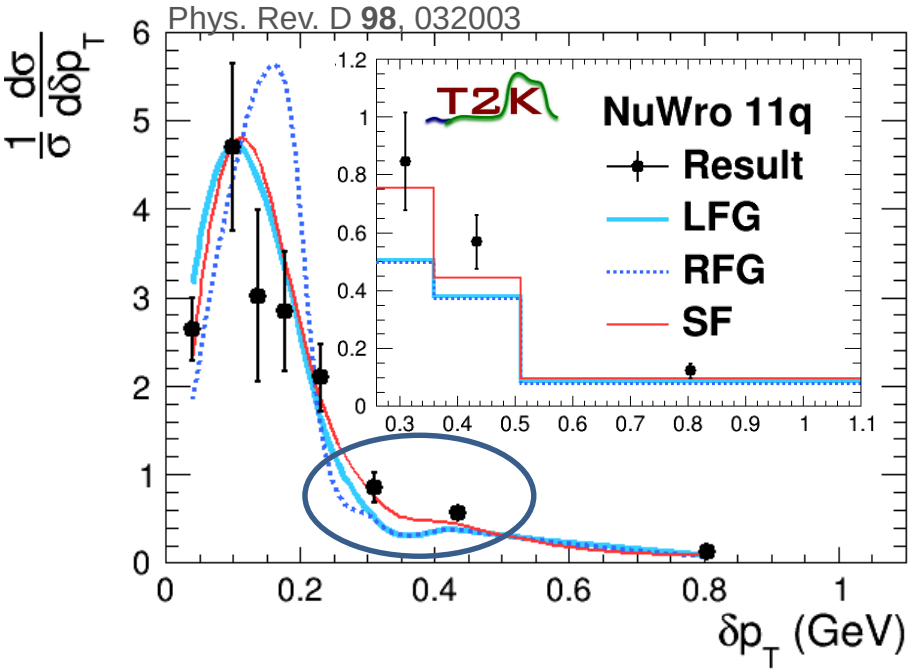
Current measurements

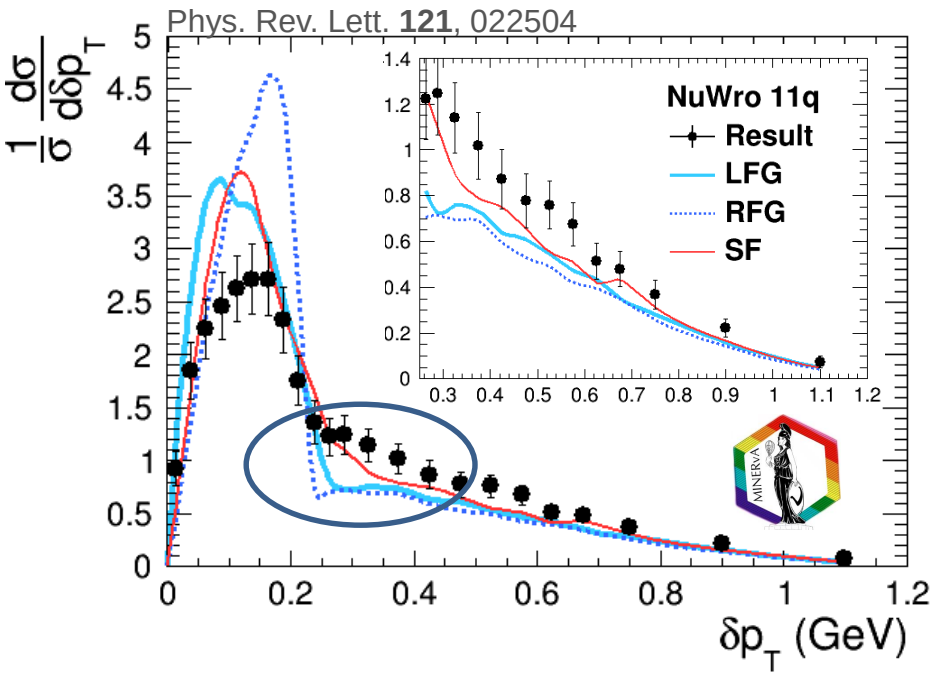




- The bulk of the distribution does not have the "Fermi-cliff" present in RFG models – **rejection of RFG model**

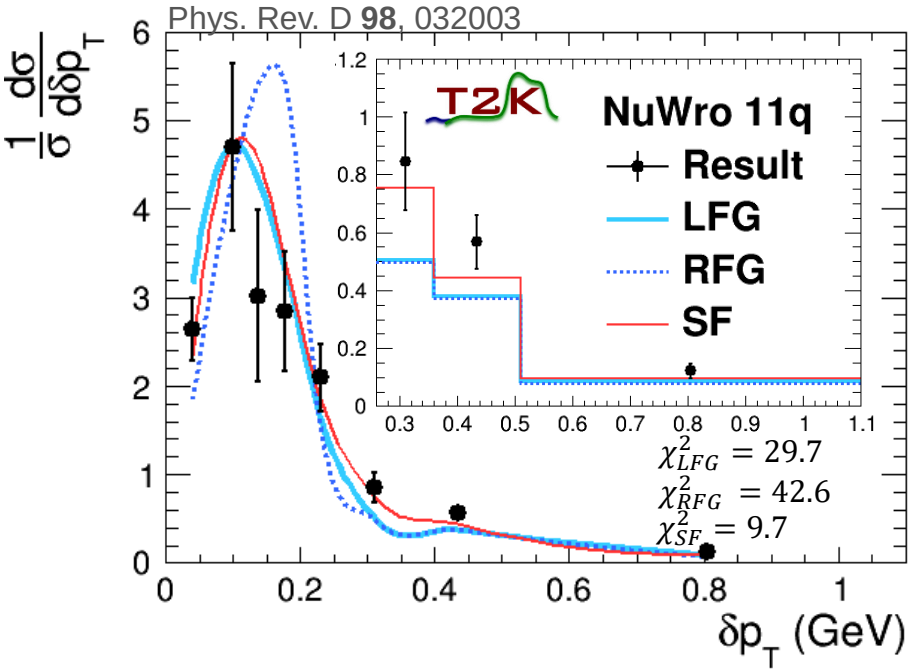
Current measurements

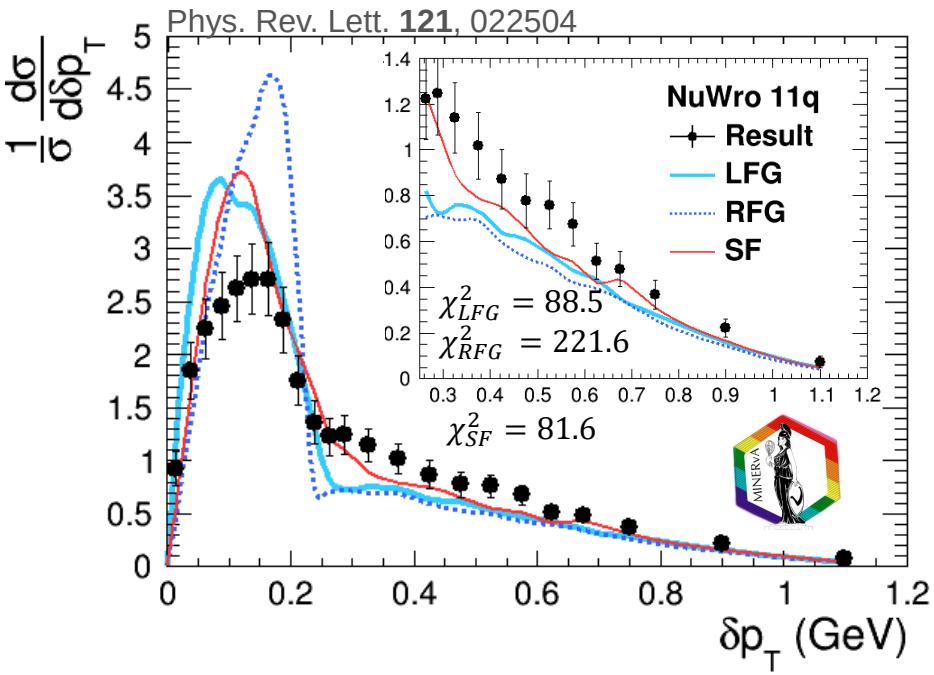




- The bulk of the distribution does not have the "Fermi-cliff" present in RFG models – **rejection of RFG model**
- SF appears important to fill in the "dip" region (SRCs extend the initial state nucleon momentum distribution)

Current measurements

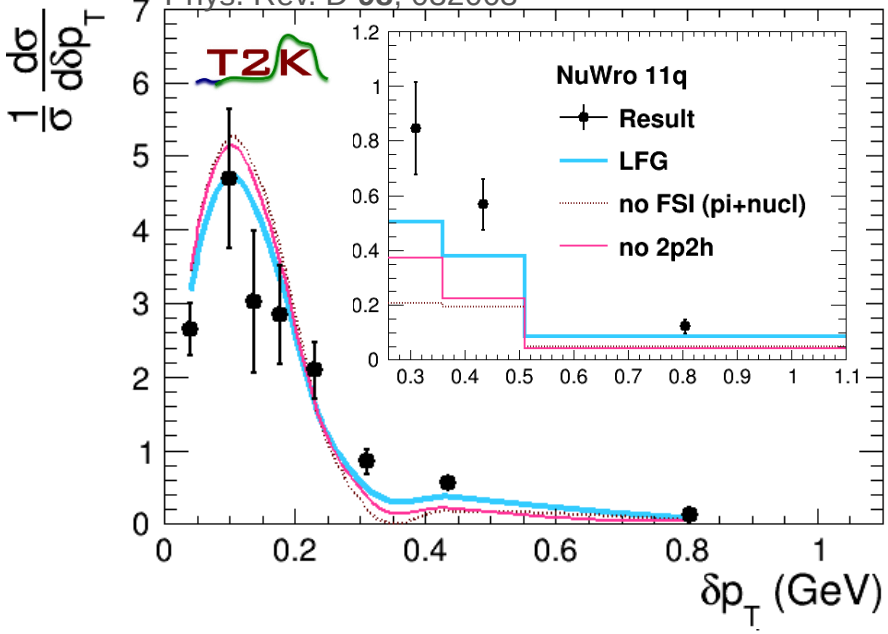




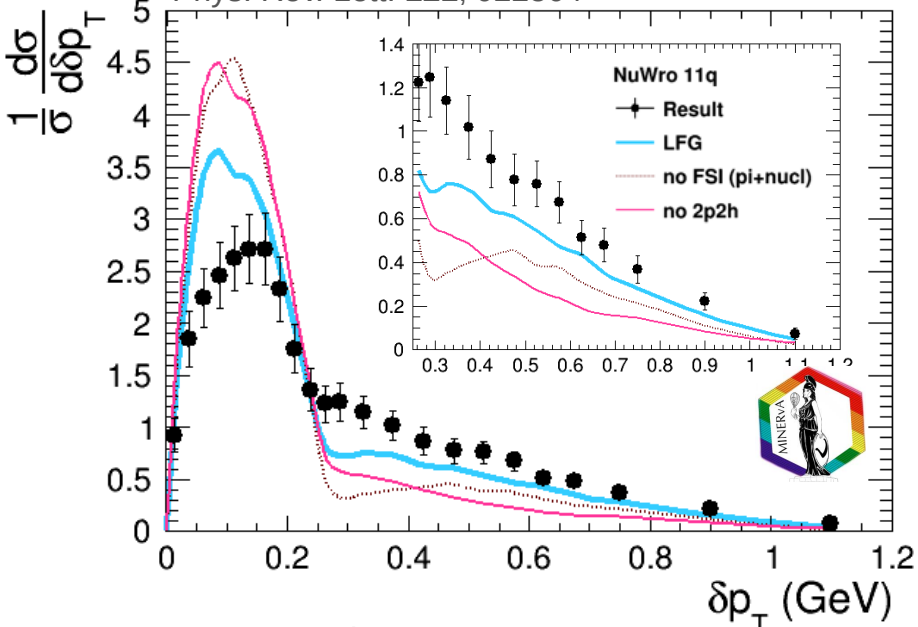
- The bulk of the distribution does not have the "Fermi-cliff" present in RFG models – **rejection of RFG model**
- SF appears important to fill in the "dip" region (SRCs extend the initial state nucleon momentum distribution)
- None of the models are able to fully describe the results

Current measurements

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

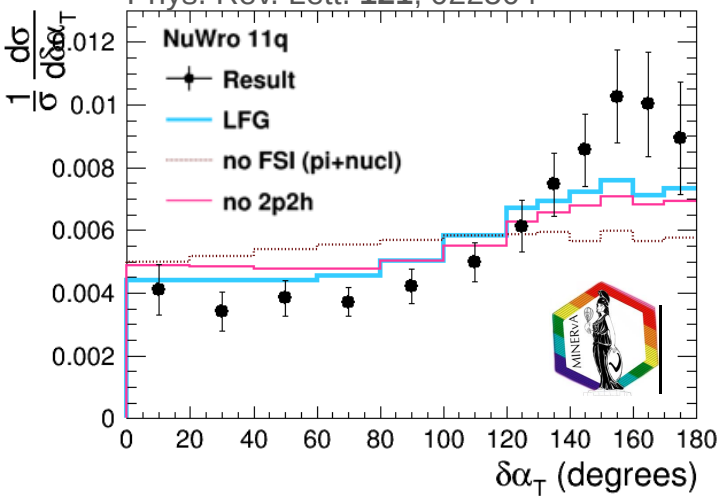


Phys. Rev. Lett. **121**, 022504



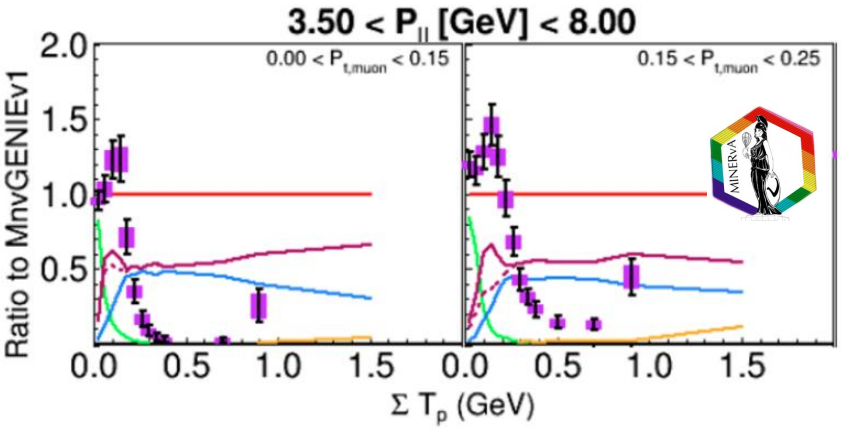
- Can try altering 2p2h and FSI in the models
- Clear preference to need 2p2h, but models are still in poor agreement with the results

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

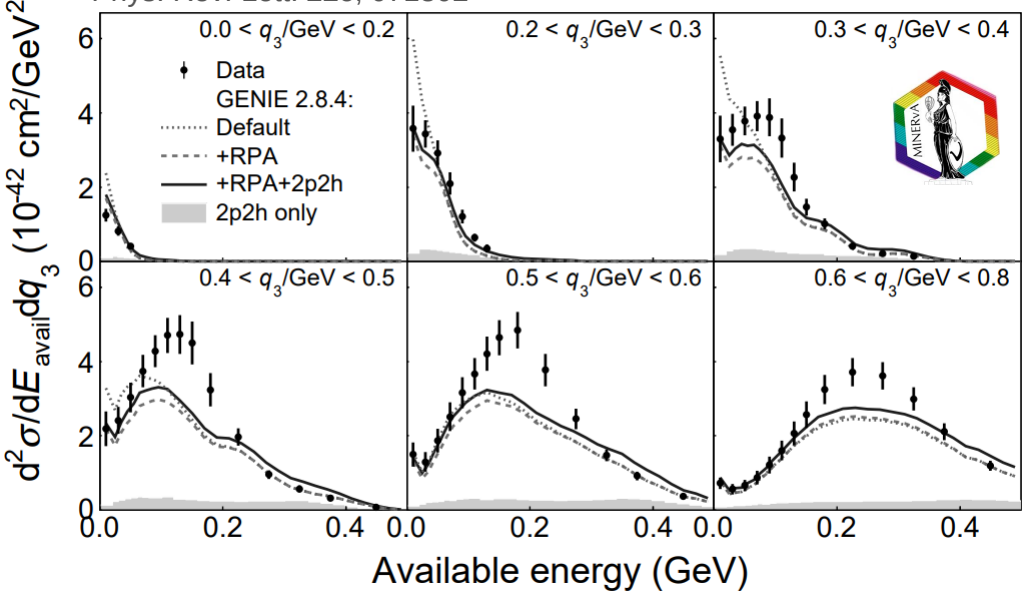


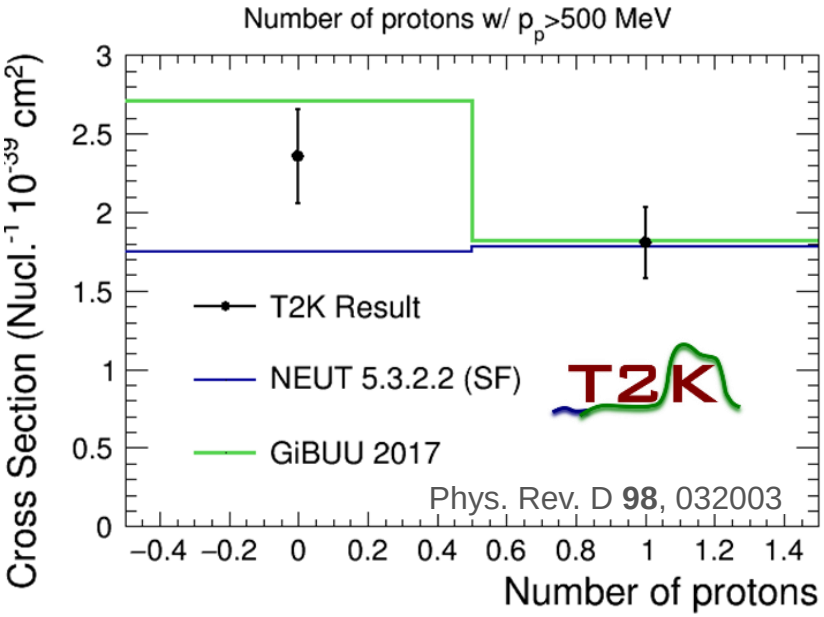
Current measurements

- This trend carries on when trying to describe most exclusive data



Phys. Rev. Lett. **116**, 071802

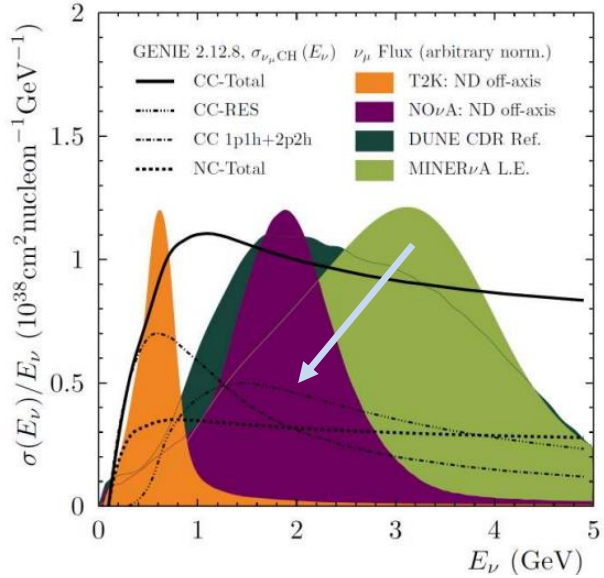




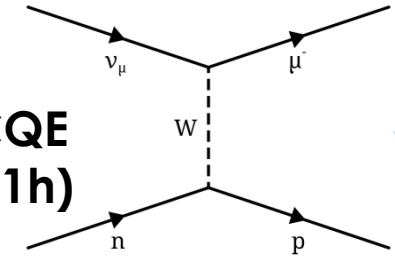
What can we measure

Interaction Modes

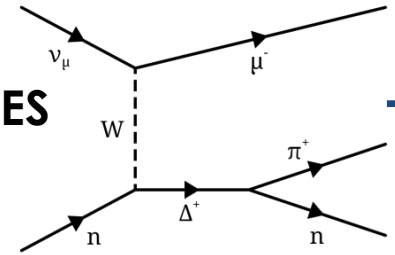
Interaction Topologies



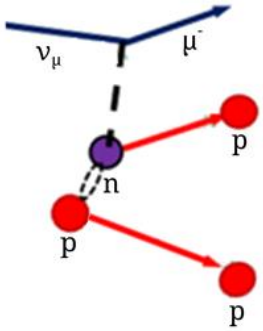
CCQE (1p1h)

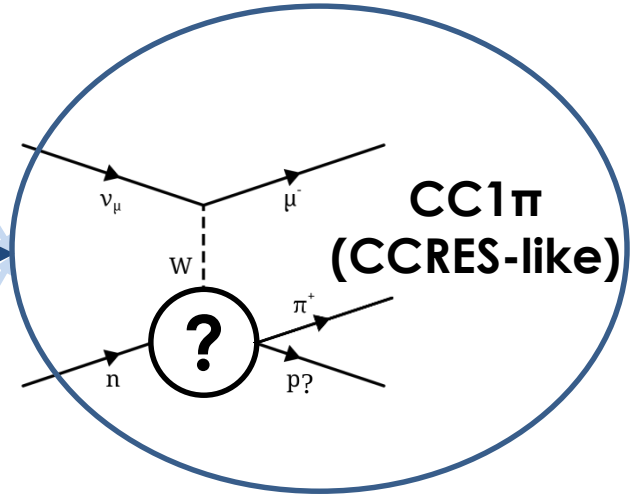


CCRES



2p2h





CC1π (CCRES-like)

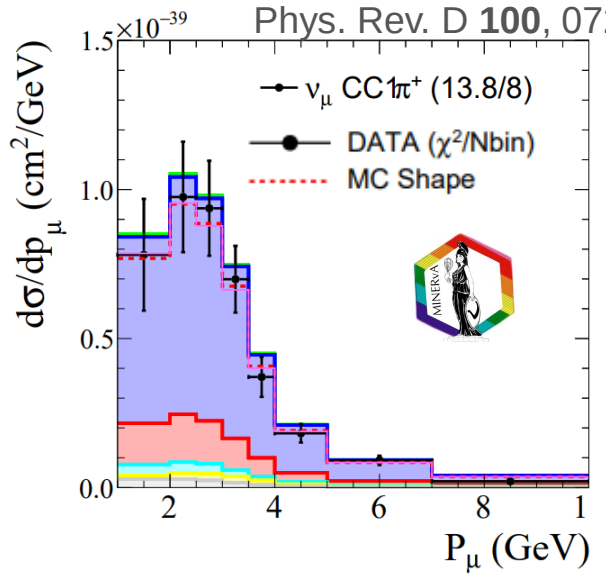
- Key contributor to all experiments
- The thing we don't understand well at all …

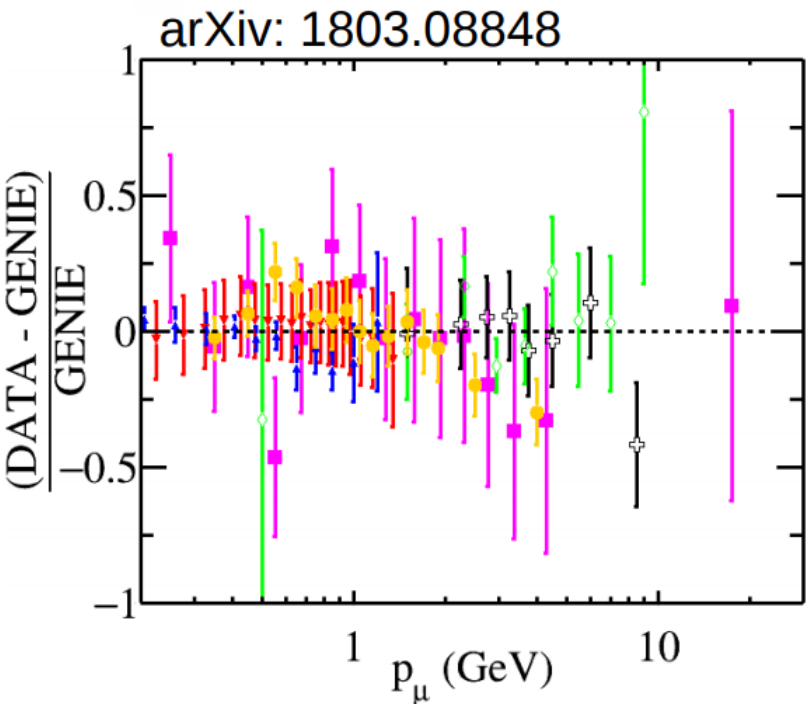
Pion production measurements

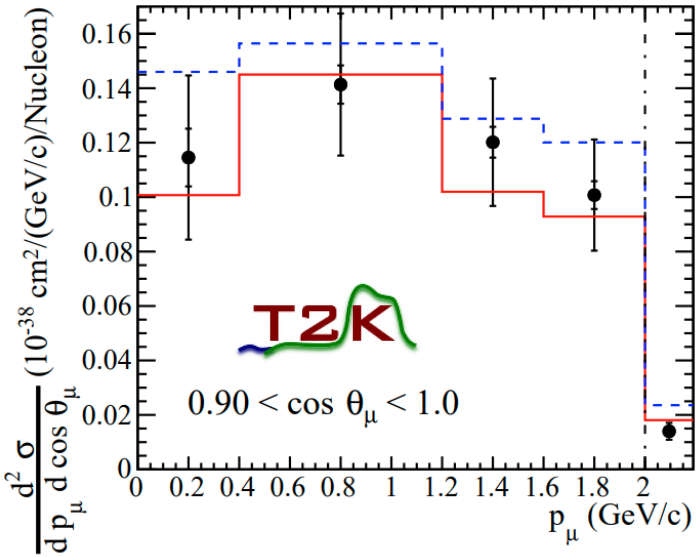
Similar story:

- Models generally able to predict lepton kinematics reasonably well
  - Even in the forward region!

Phys. Rev. D **100**, 072005





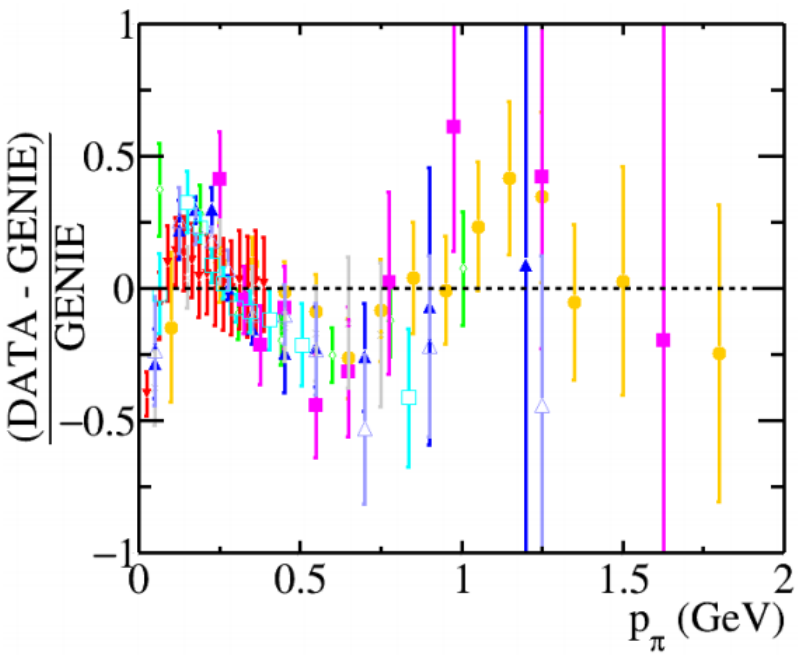


Phys. Rev. D **101**, 012007

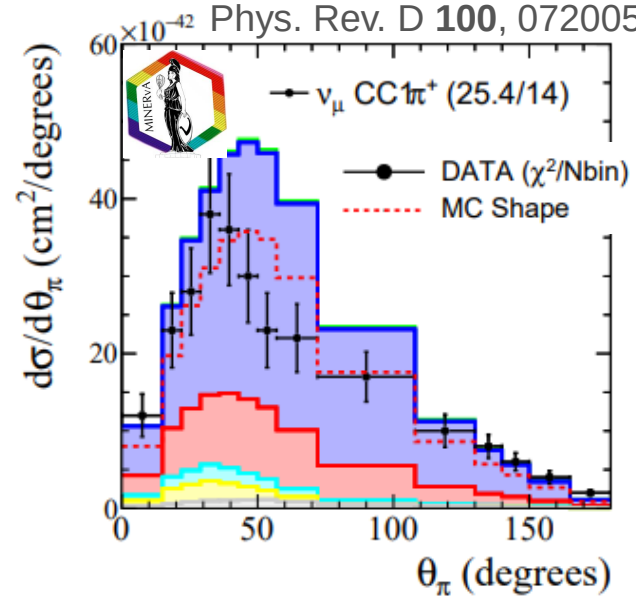
Pion production measurements

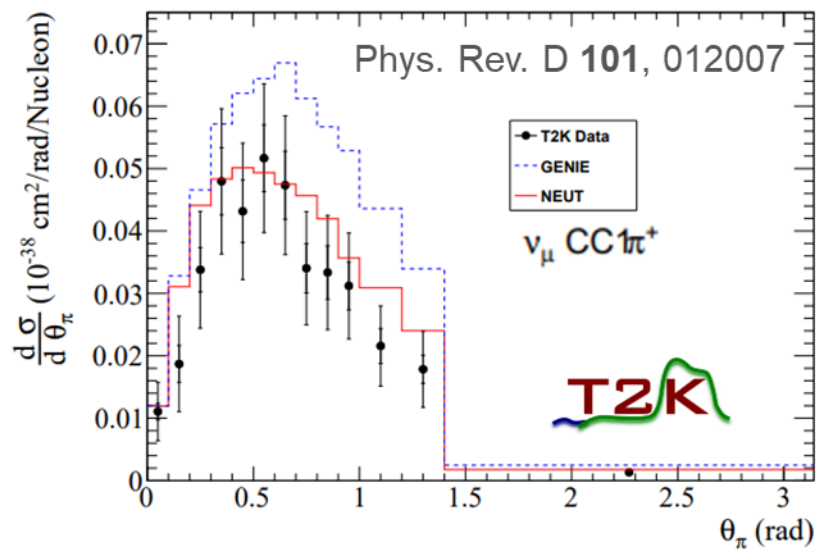
Similar story:

- Models generally able to predict lepton kinematics reasonably well
  - Even in the forward region!
- But pion kinematics are poorly described across experiments



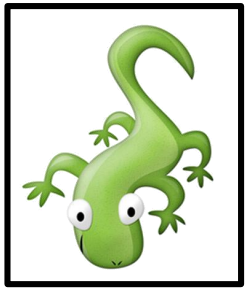
Phys. Rev. D **100**, 072005

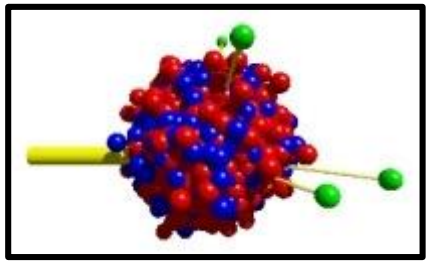




Overview

- The Weak Interaction
  - Historical Overview
  - Point-like scattering
- Neutrino-nucleon interactions
  - QE, RES and DIS
- Neutrino-nucleus interactions
  - Nuclear effects
  - Ground state modelling
- Why do we care?
  - Neutrino interactions for neutrino oscillations
  - Neutrino energy reconstruction
- Neutrino-nucleus interaction measurements
  - Inclusive successes and exclusive failures
- Where did it all go wrong? (Neutrino event generators)
  - Limitations of our simulations
- Don't Panic! The future of neutrino interactions





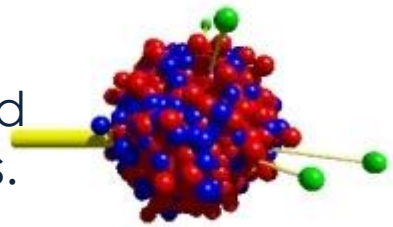
The Generators

GENIE: very widely used. Large development team. Used as default simulations by most Fermilab neutrino experiments.

NEUT: used primarily by the SK, T2K and HK collaborations. Smaller development team – updated to fill needs of experiments.

NuWro: wide range of models available. Driven more by theory than by experimental requirements. Only a few developers. (Also called the **W**r**O**claw **N**eutrino event **G**enerator)

GiBUU: a full theory in its own right, predicting nu/e/hadron scattering. Different philosophy than the other generators. Hard to use as a primary input for experiments. One/two developers.



The Generators

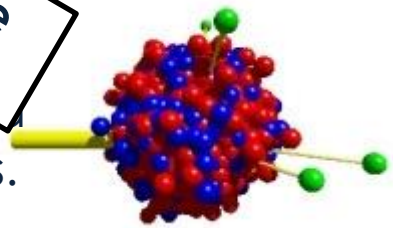
GENIE: very widely used. Large development team. Used as default simulations by most Fermilab neutrino experiments.

Caveat: not everything I say applies to all models in all these generators. Too much to cover in one talk!

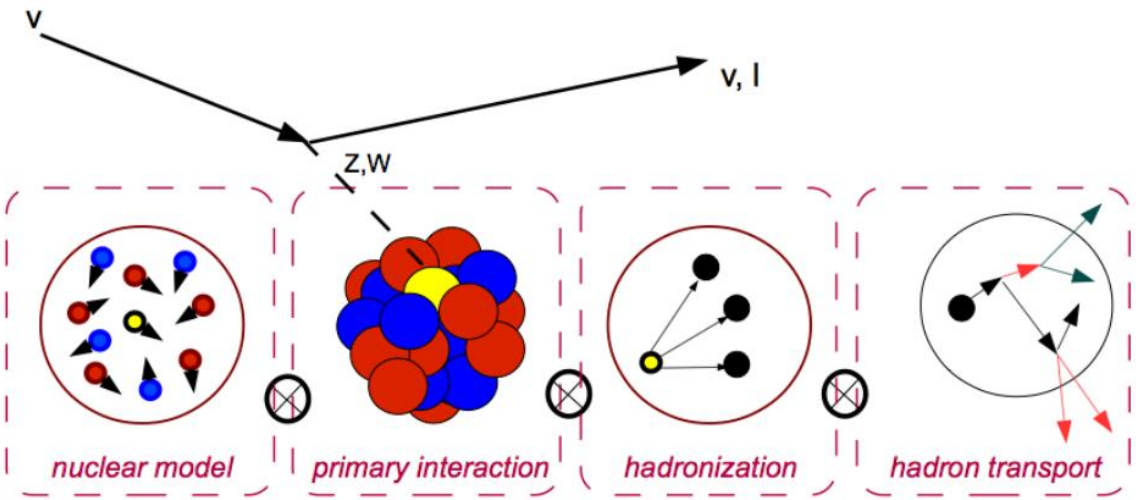
NEUT: used prim SK, T2K and HK collaborations. Smaller development team to fill needs of experiments.

NuWro: wide range of ilable. Driven more by theory than by experimental requi ly a few developers. (Also called the **W**r**O**claw **N**eutr enerator)

GiBUU: a full theory in its own right, predicting nu/e/hadro scattering. Different philosophy than the other generators. Ha to use as a primary input for experiments. One/two developers.

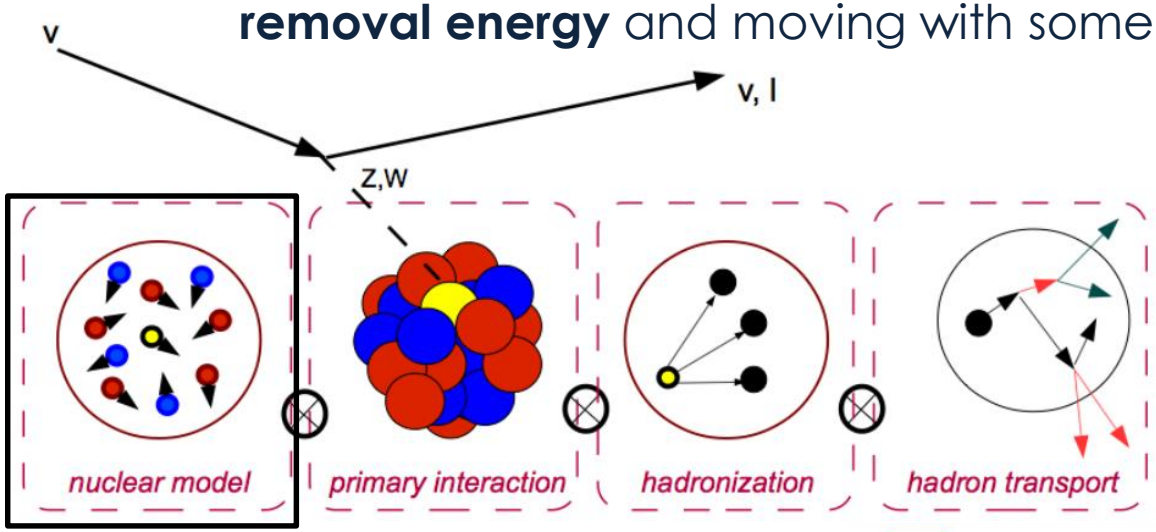


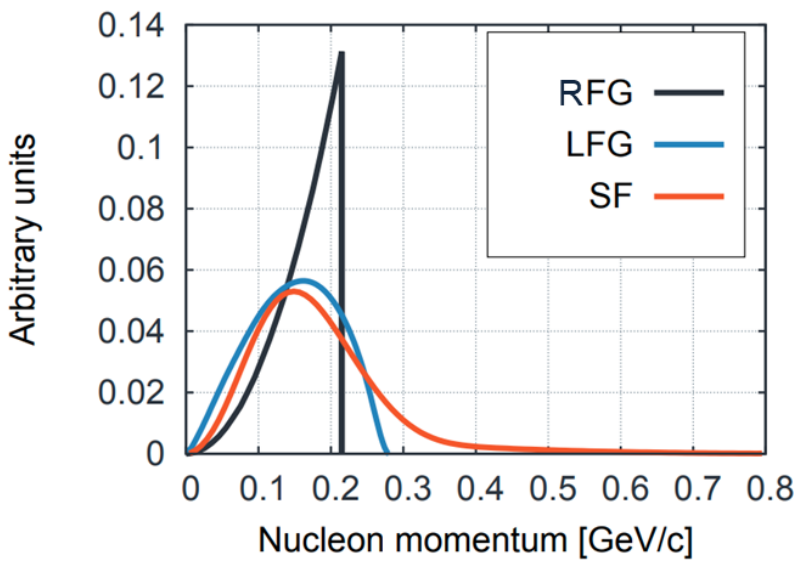
A generator's view of νN scattering

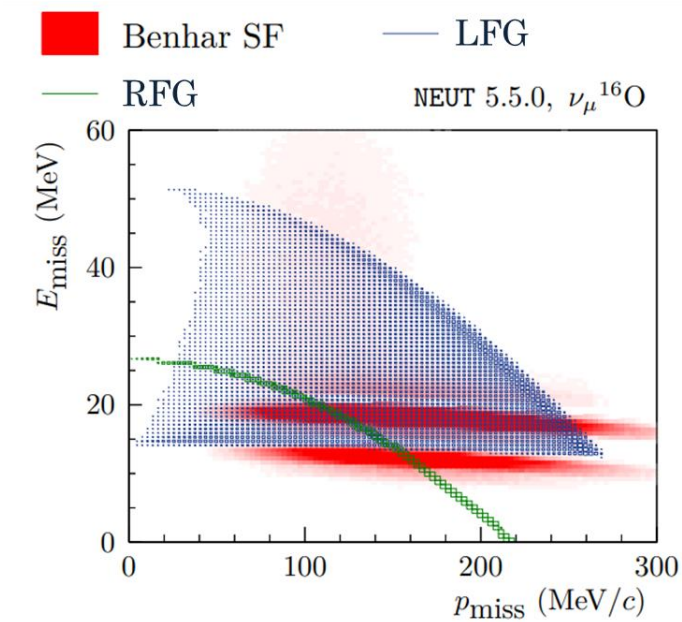


Fermi motion

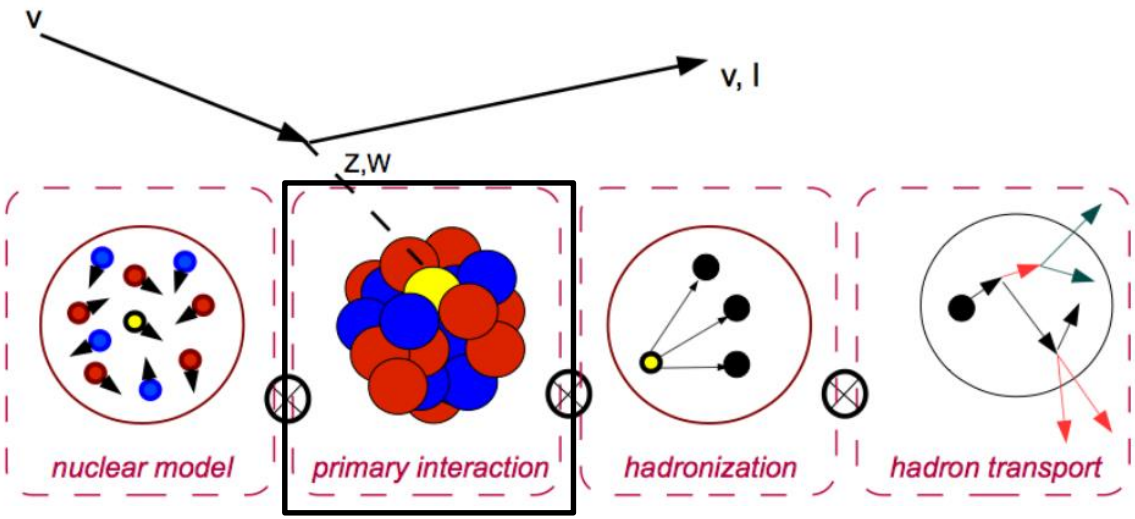
- Start with a nucleon inside the nucleus, bound with some **removal energy** and moving with some **Fermi motion**





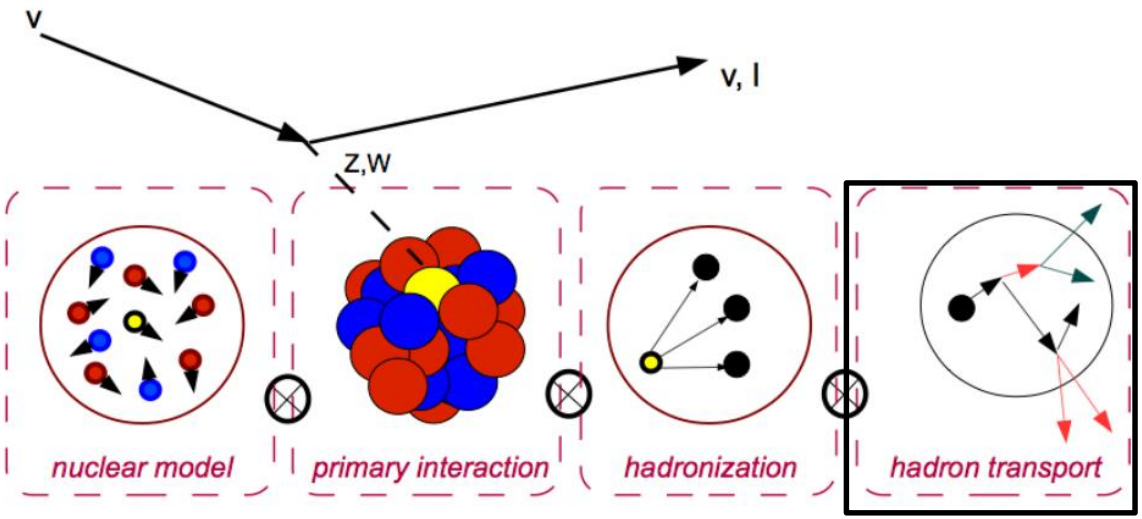


Neutrino-nucleon interaction

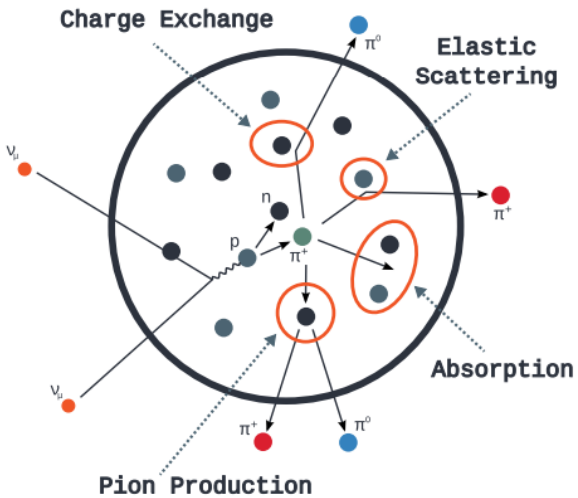


- We have a nucleon, now let's interact with it

Final state interactions

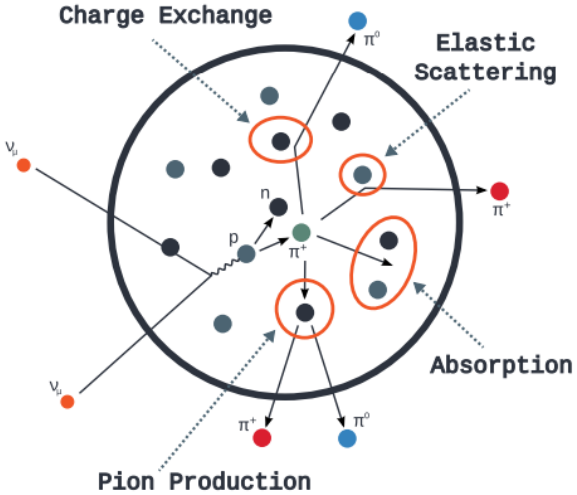


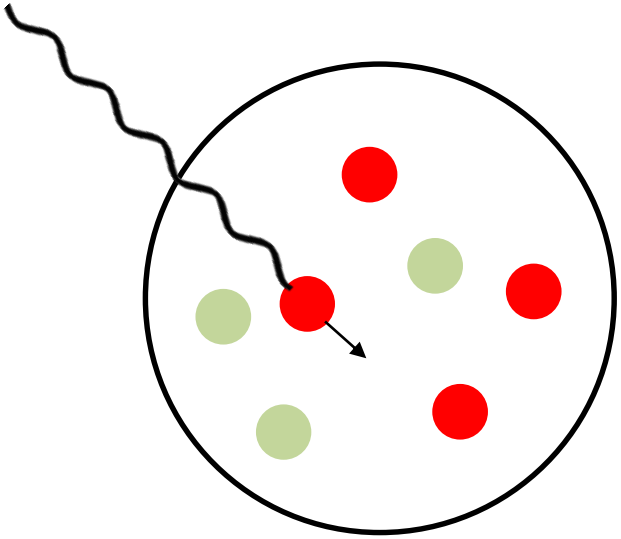
- We now have a nucleon inside the nucleus, it should probably bounce around a bit before it gets out: **Final State Interactions**



Final state interactions

- Intranuclear cascade models: classical billiard ball scattering within the nucleus





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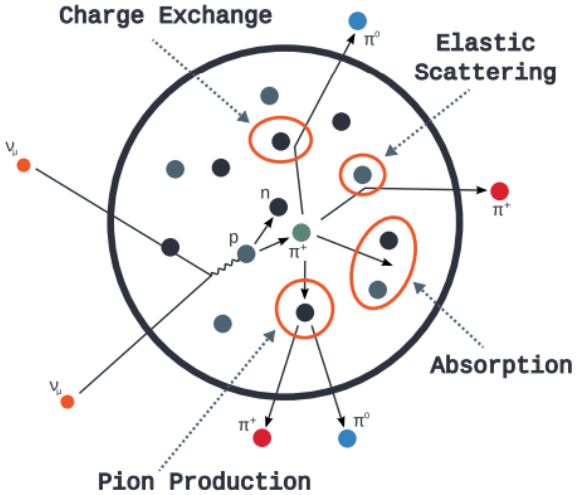

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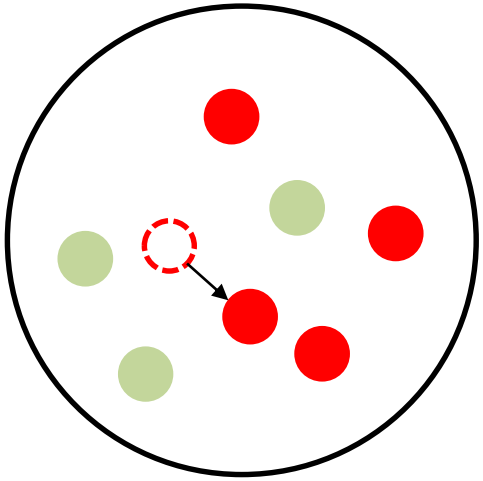

Final state interactions

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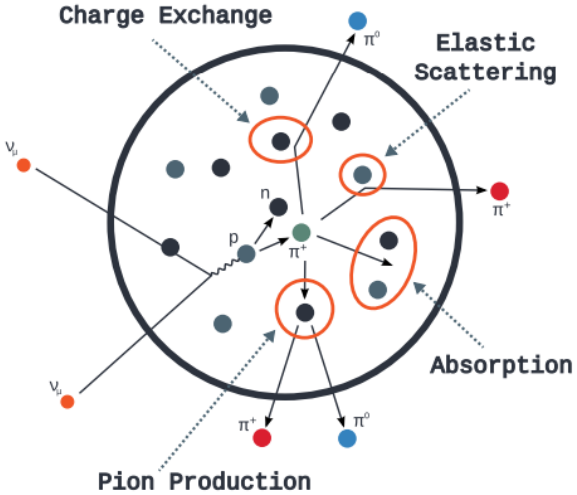

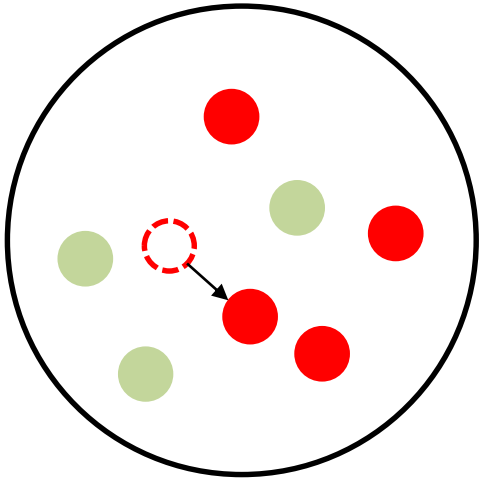

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Final state interactions

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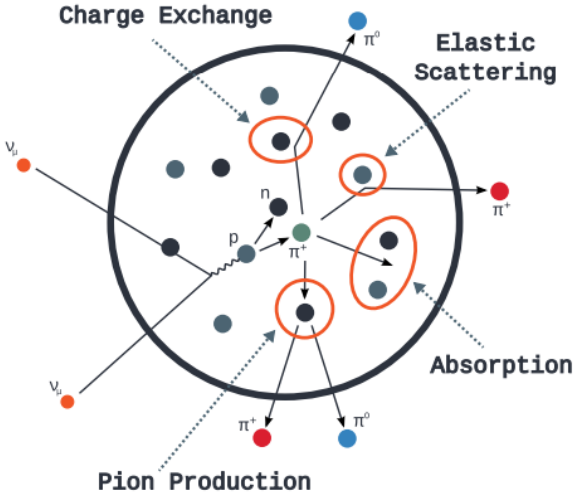

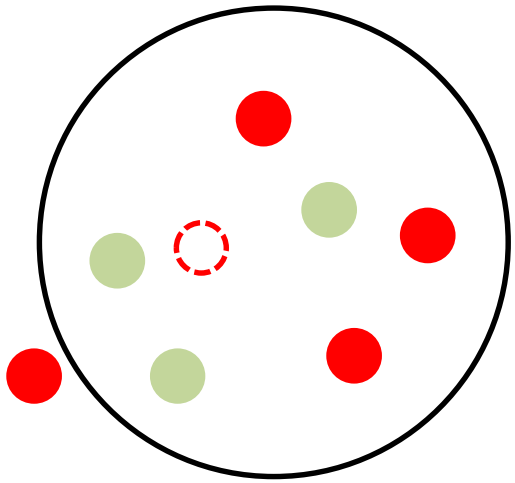

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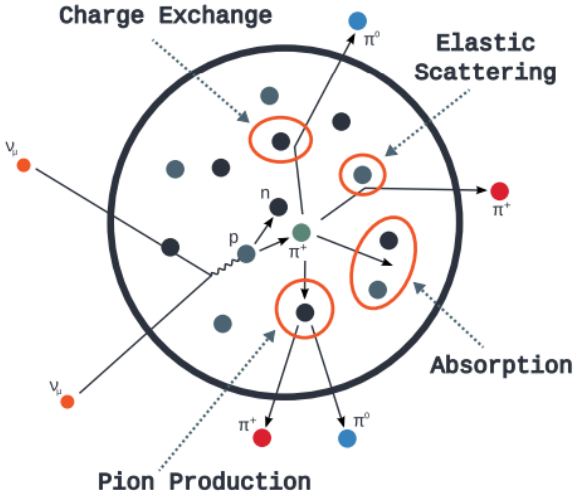

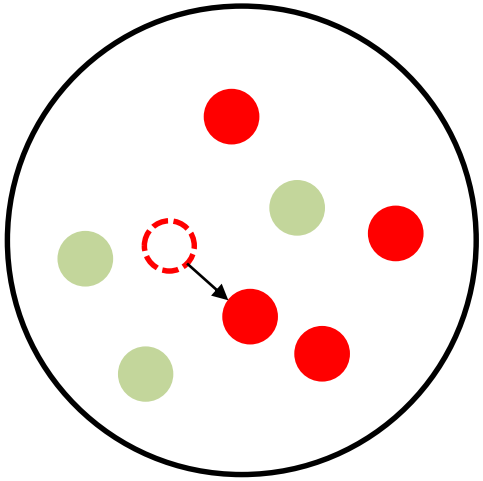

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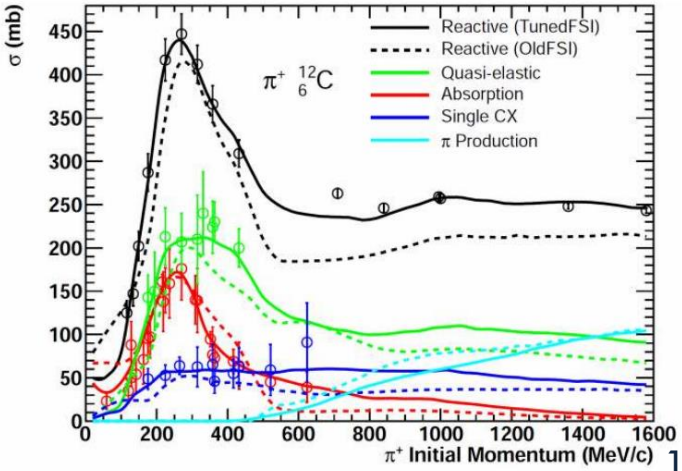

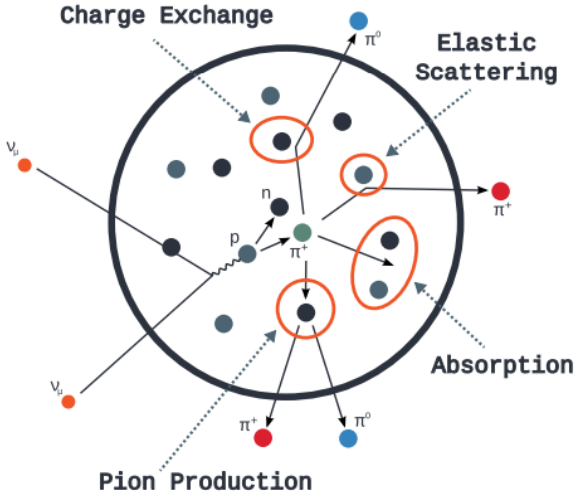

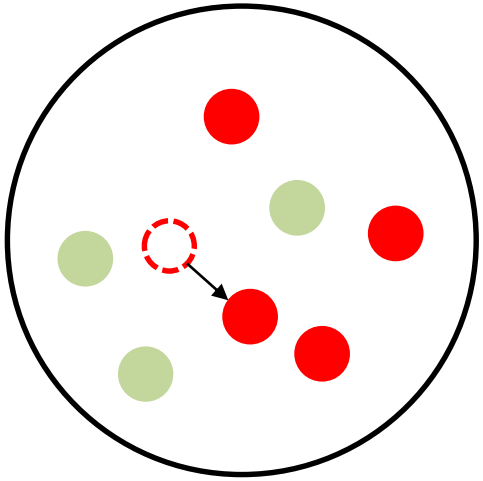

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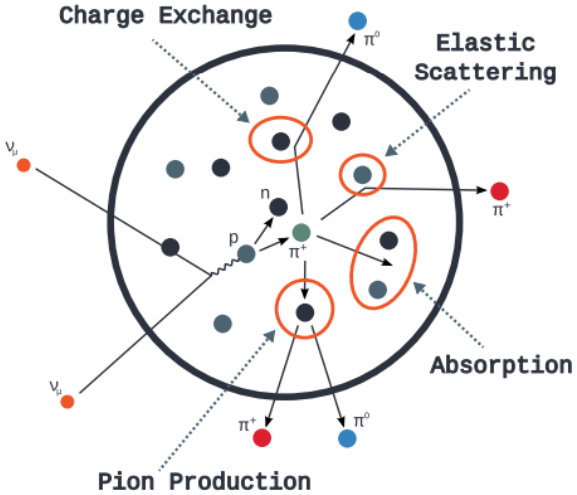
2. Check whether it's outside the nucleus, if it is add this particle to the final state and stop FSI for it
3. Use MC methods to determine if it interacts or not, if it does choose a process according to its cross section

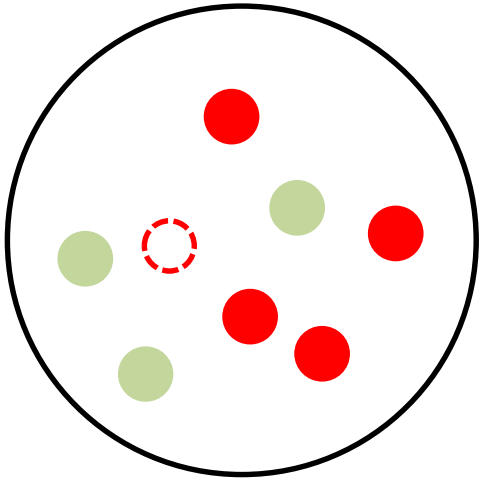
See e.g.: Phys. Rev. D **99**, 052007

Final state interactions

- Intranuclear cascade models: classical billiard ball scattering within the nucleus



Absorption



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4. Generate the interaction

Final state interactions

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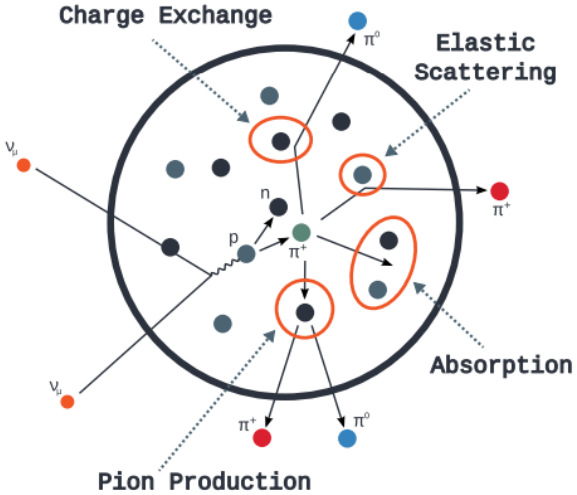
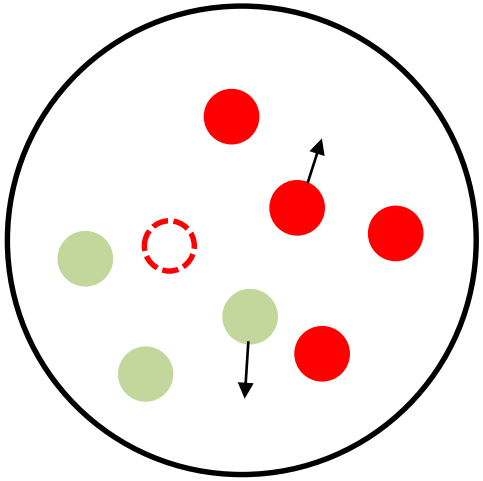


Charge Exchange



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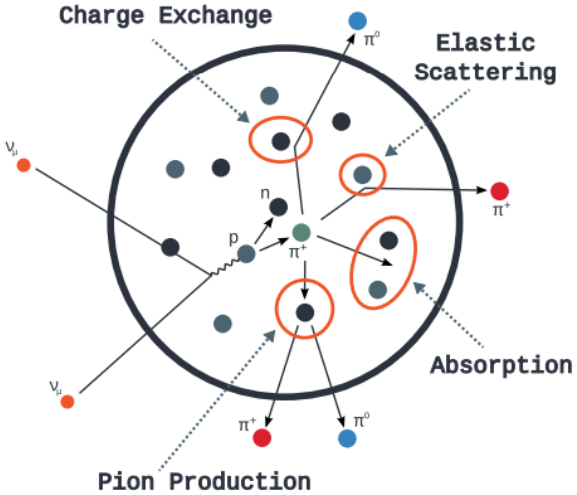
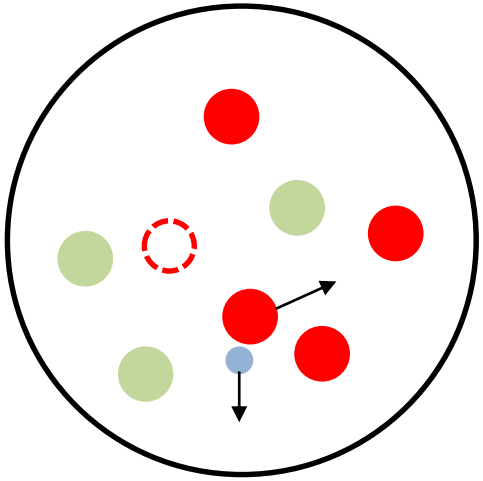


Pion Production



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Final state interactions

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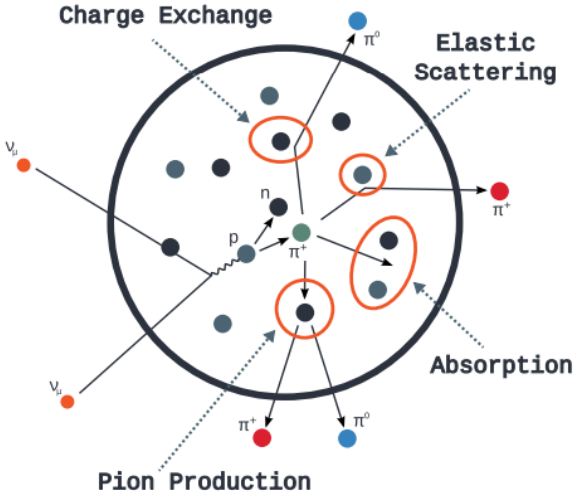
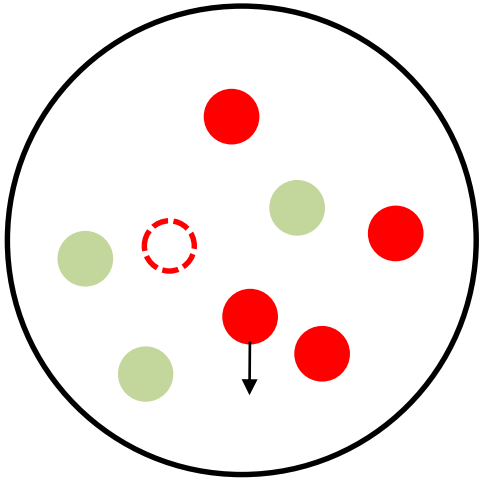


Elastic scatter



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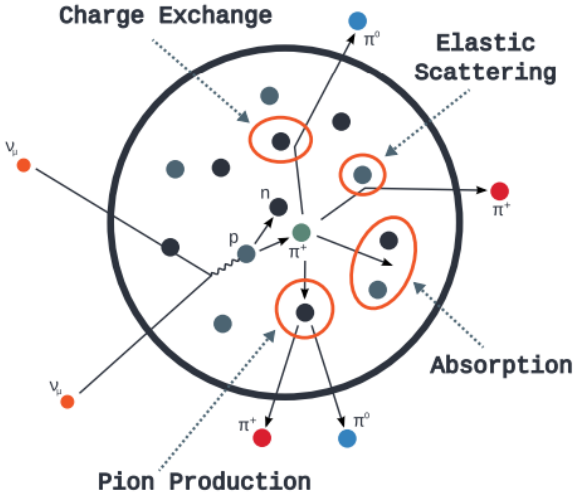

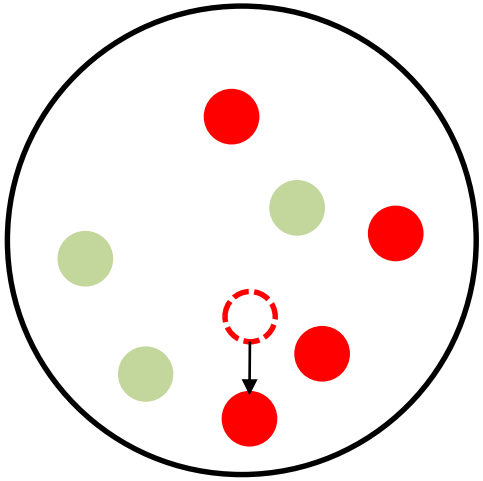

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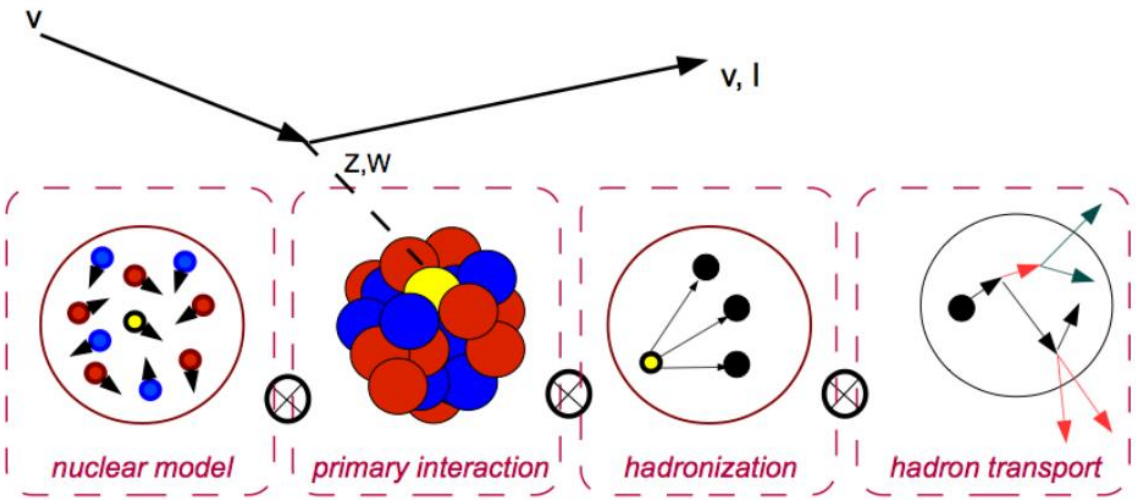
4. Generate the interaction
5. Return to 1.

A generator's view of νN scattering



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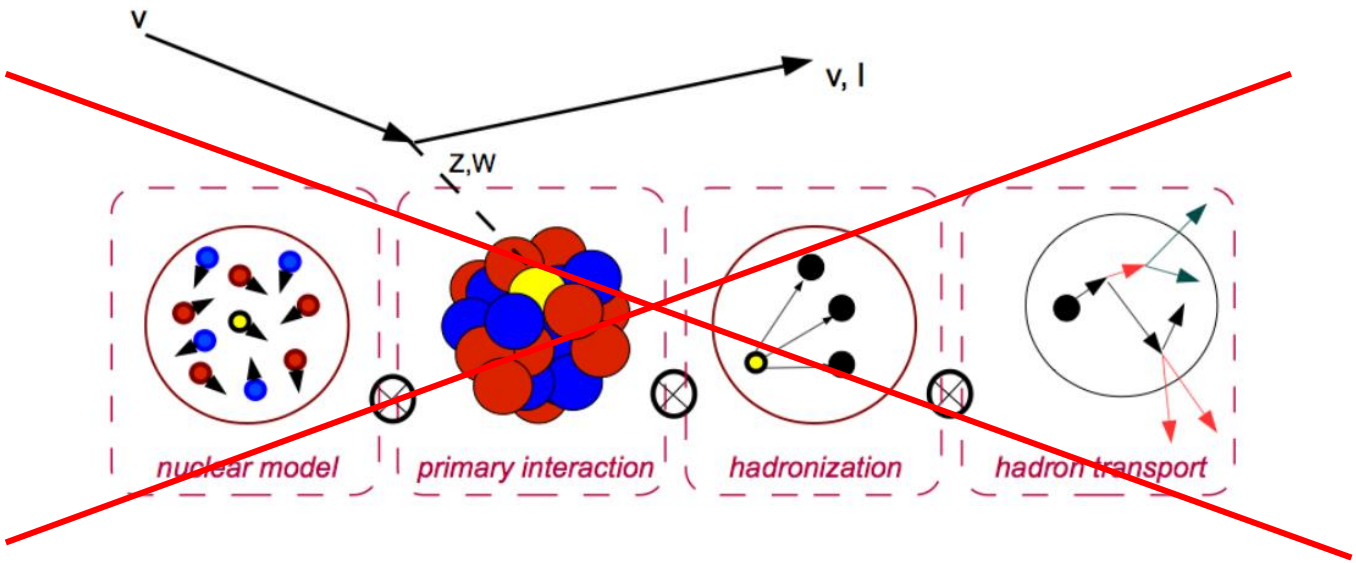
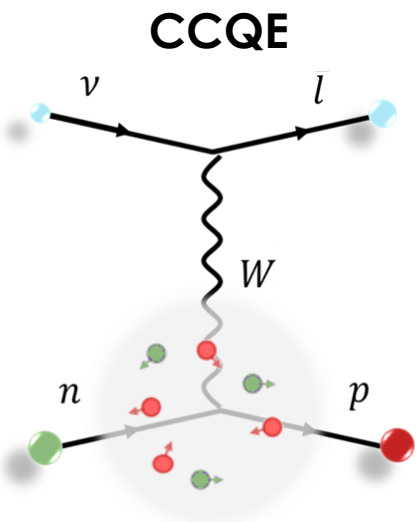


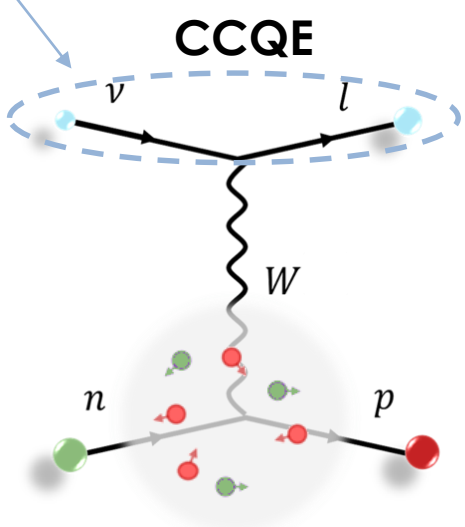
- Unfortunately we've seen things aren't even this "simple"

What's in CC0π?



Recall: Inclusive scattering

Only predict lepton kinematics: *inclusive* model



All of the nuclear dynamics lives in here

$$\frac{d^2\sigma_{\nu l}}{d\Omega(\hat{k}')dE_l'} = \frac{|\vec{k}'|}{|\vec{k}|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma}$$

E.g. Inclusive quasielastic charged-current neutrino-nucleus reactions, J. Nieves et Al, 2004

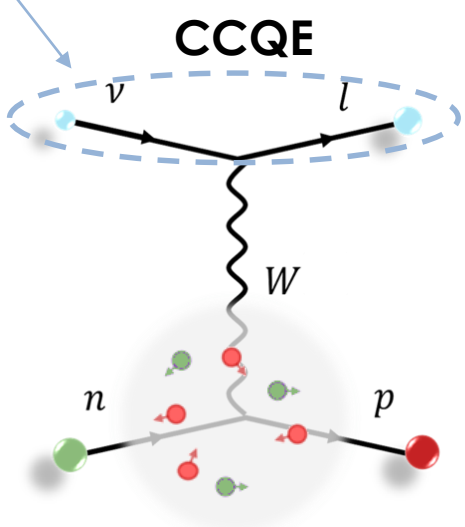
Need a nuclear model to calculate this, Nieves uses a "Local Fermi Gas"

$$\begin{aligned}\frac{d^2\sigma_{\nu l}}{d\Omega(\hat{k}')dE_l'} = \frac{|\vec{k}'|E_l'M_iG^2}{\pi^2}\Bigg\{ & 2W_1\sin^2\frac{\theta'}{2} + W_2\cos^2\frac{\theta'}{2} \\ & - W_3\frac{E_\nu+E_l'}{M_i}\sin^2\frac{\theta'}{2} + \frac{m_l^2}{E_l'(E_l'+|\vec{k}'|)}\Bigg[W_1\cos\theta' \\ & - \frac{W_2}{2}\cos\theta' + \frac{W_3}{2}\left(\frac{E_l'+|\vec{k}'|}{M_i} - \frac{E_\nu+E_l'}{M_i}\cos\theta'\right) \\ & + \frac{W_4}{2}\left(\frac{m_l^2}{M_i^2}\cos\theta' + \frac{2E_l'(E_l'+|\vec{k}'|)}{M_i^2}\sin^2\theta'\right) \\ & - W_5\frac{E_l'+|\vec{k}'|}{2M_i}\Bigg]\Bigg\} \qquad (10)\end{aligned}$$

Needs 6 "structure functions" built from 5 hadron tensor elements

Inclusive scattering in generators

Only predict lepton kinematics: *inclusive* model



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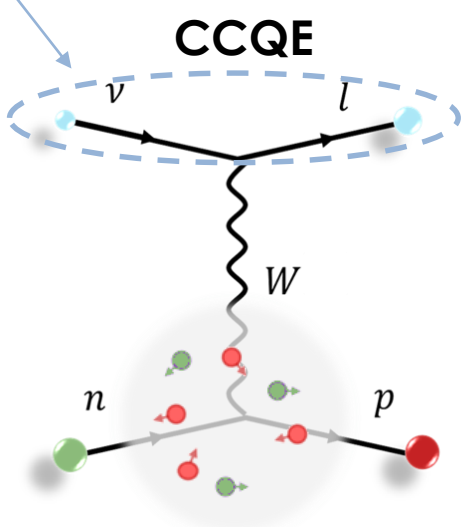
This is what most older generator versions use (anything that uses RFG)

E.g.:

- Anything that isn't SF in NEUT<5.4.0
- Anything in GENIE <3
- SuSAv2 in GENIE v3
- Any 2p2h model …

Inclusive scattering in generators

Only predict lepton kinematics: *inclusive* model



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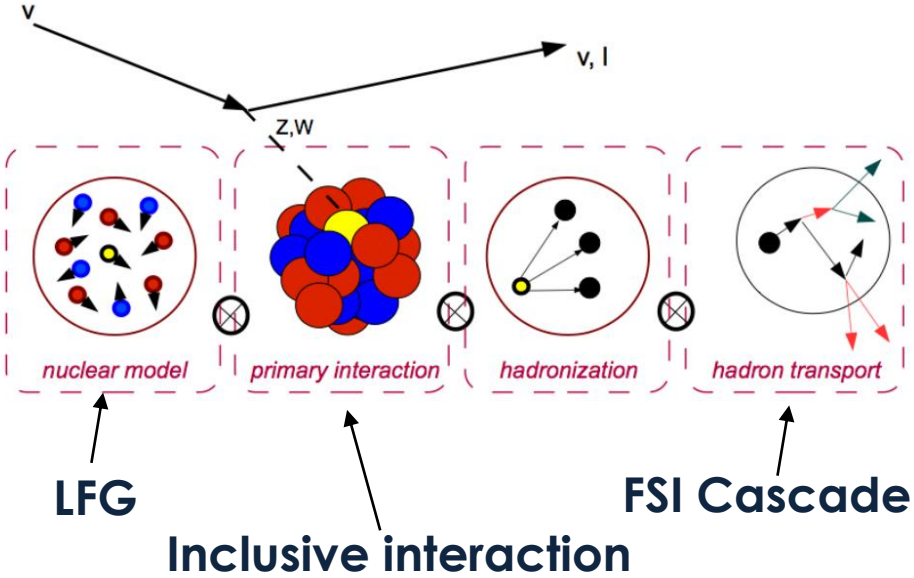
But then where does *insert generator name* get the nucleon kinematics from … ?



Is this reasonable?

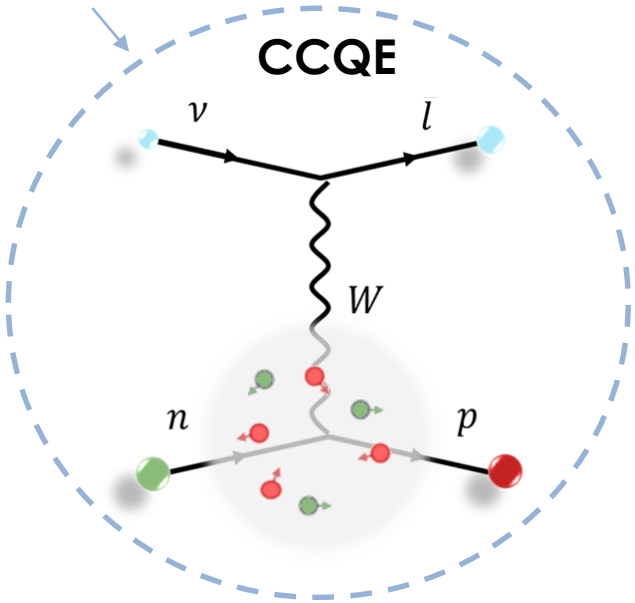
Probably not

Recall: Exclusive scattering

Exclusive model: can describe all final state particle kinematics

All of the nuclear dynamics still lives in here

$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)\mathrm{dE}_{\ell'}} \sim L_{\mu\sigma}W^{\mu\sigma}$$



E.g. Semi-inclusive charged-current neutrino-nucleus reactions, O. Moreno et Al, 2014

But now there's 10 tensor elements …

$$\eta^s_{\mu\nu}W^{\mu\nu}_s \sim \widehat{V}_{CC}W^{CC}_{semi} + \widehat{V}_{CL}W^{CL}_{semi} + \widehat{V}_{LL}W^{LL}_{semi} + \widehat{V}_{T}W^{T}_{semi} + \widehat{V}_{TT}W^{TT}_{semi} + \widehat{V}_{TC}W^{TC}_{semi} + \widehat{V}_{TL}W^{TL}_{semi}$$

$$\eta^a_{\mu\nu}W^{\mu\nu}_a \sim \widehat{V}_{T'}W^{T'}_{semi} + \widehat{V}_{TC'}W^{TC'}_{semi} + \widehat{V}_{TL'}W^{TL'}_{semi}$$

… and these become challenging to calculate

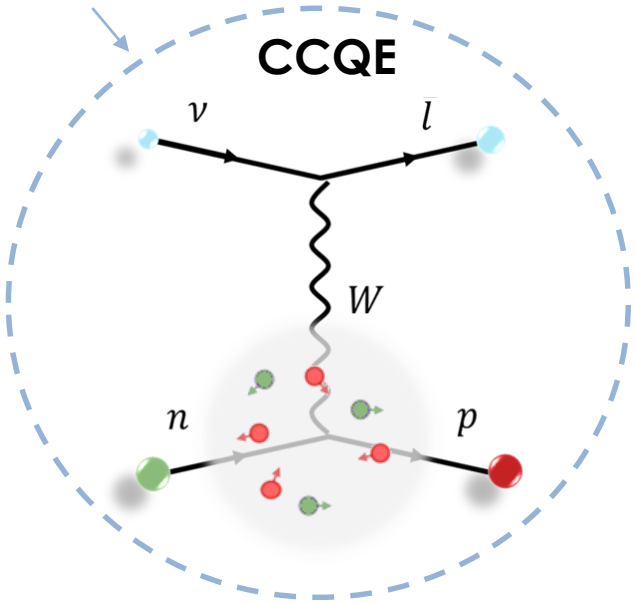
- Some models can do this, e.g. Relativistic Mean Field (RMF)

Exclusive scattering

Exclusive model: can describe all final state particle kinematics

All of the nuclear dynamics still lives in here

$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)\mathrm{dE}_{\ell'}} \sim L_{\mu\sigma}W^{\mu\sigma}$$



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$$\eta^a_{\mu\nu}W^{\mu\nu}_a \sim \widehat{V}_{T'}W^{T'}_{semi} + \widehat{V}_{TC'}W^{TC'}_{semi} + \widehat{V}_{TL'}W^{TL'}_{semi}$$

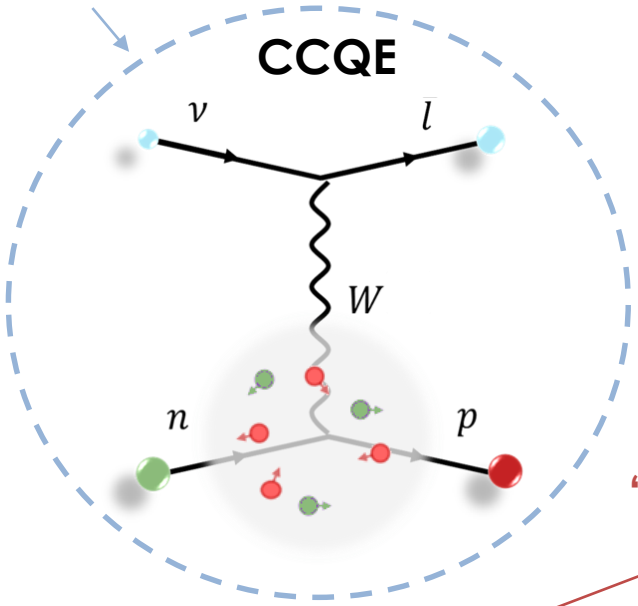
… and these become challenging to calculate

- Some models can do this, e.g. Relativistic Mean Field (RMF)

No generator model does this

Recall: Factorization

Exclusive model: can describe all final state particle kinematics



If we assume the outgoing nucleon is **non-relativistic** and that there's **no FSI** we can write the cross section like this:

$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)\mathrm{dE}_{\ell}'} \sim S(E_m, \boldsymbol{p}_m)\mathrm{L}_{\mu\nu}\mathrm{W}^{\mu\nu}\delta(\omega + M - E_m - E_{p'})$$

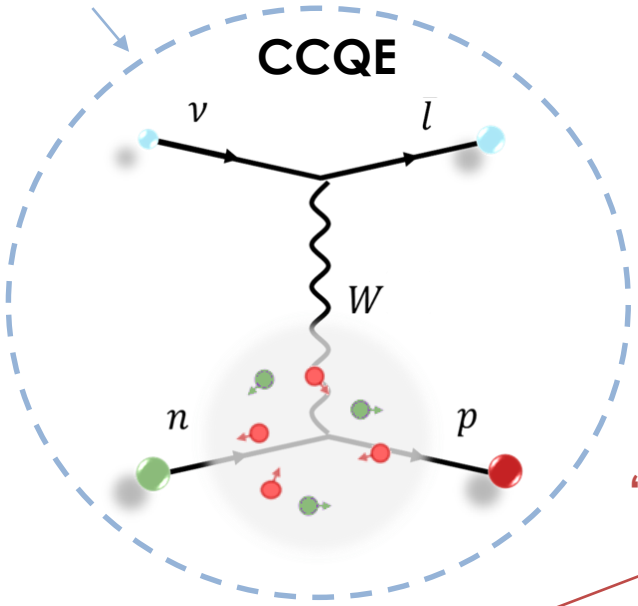
"Spectral Function"

Single nucleon tensor contraction
(no nuclear effects)

This doesn't have to be *the* Benhar SF, it just needs to be *a* nuclear model predicting Fermi motion and removal energy

Factorization in generators

Exclusive model: can describe all final state particle kinematics



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Single nucleon tensor contraction
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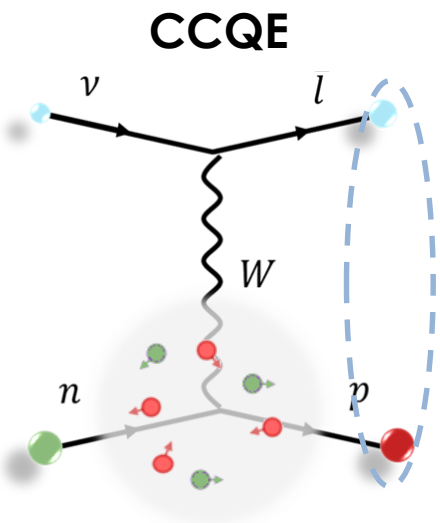
This doesn't have to be *the* Benhar SF, it just needs to be *a* nuclear model predicting Fermi motion and removal energy

This is what some newer generators use for CCQE – some limited predictive power for nucleon kinematics. An FSI cascade is added on top *ad hoc* but this only affects the nucleon.

E.g.:

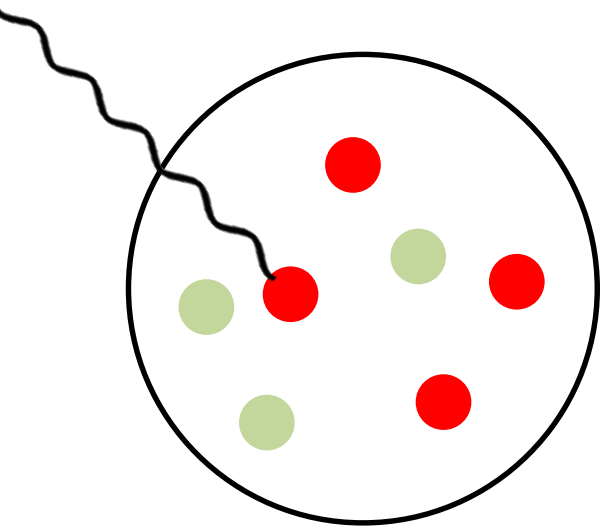
SF in NEUT 5.4.x
SF in NuWro
Fermi-gas QE in GENIE v3 (I think!)

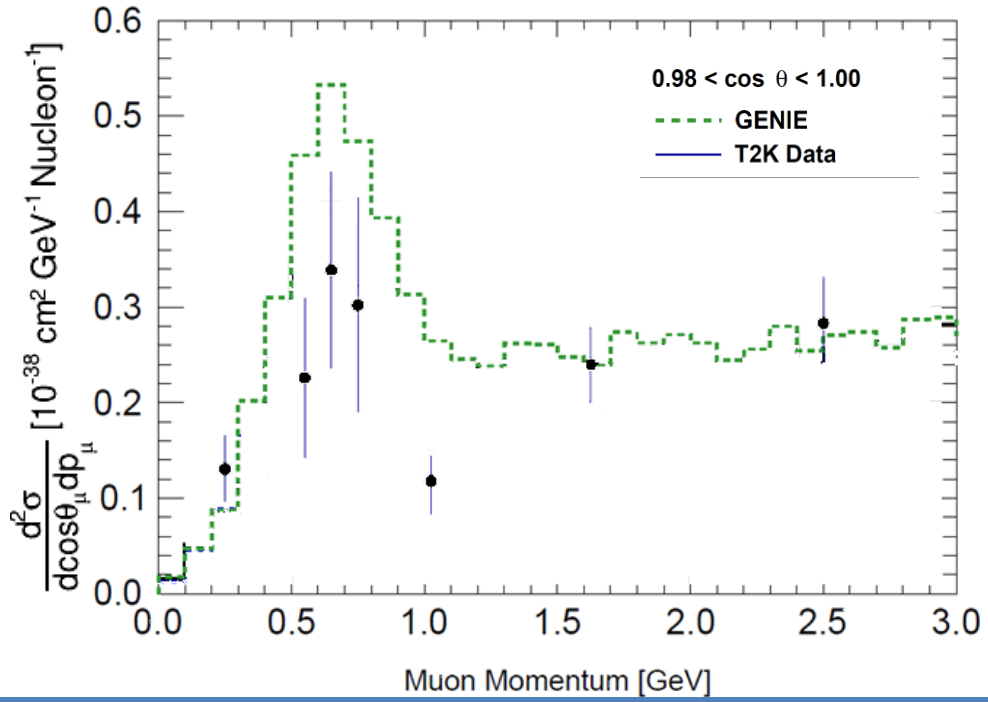
We're finally getting somewhere?



Beyond the impulse approximation

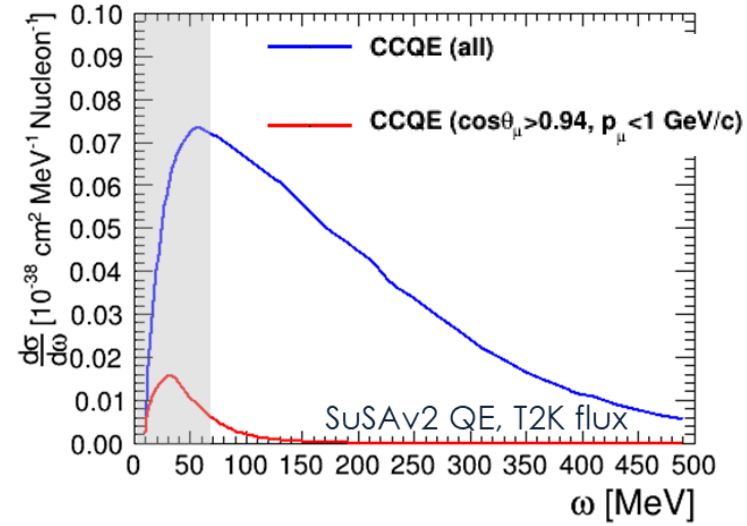
- Most of our models start from the impulse approximation: we interact with a single nucleon inside the nucleus

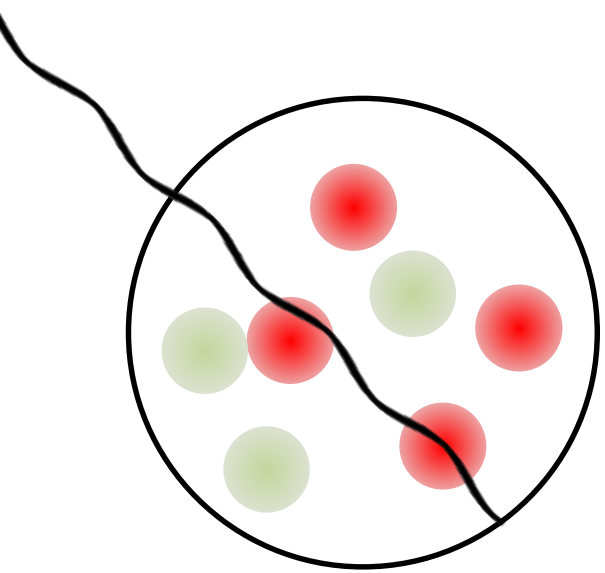


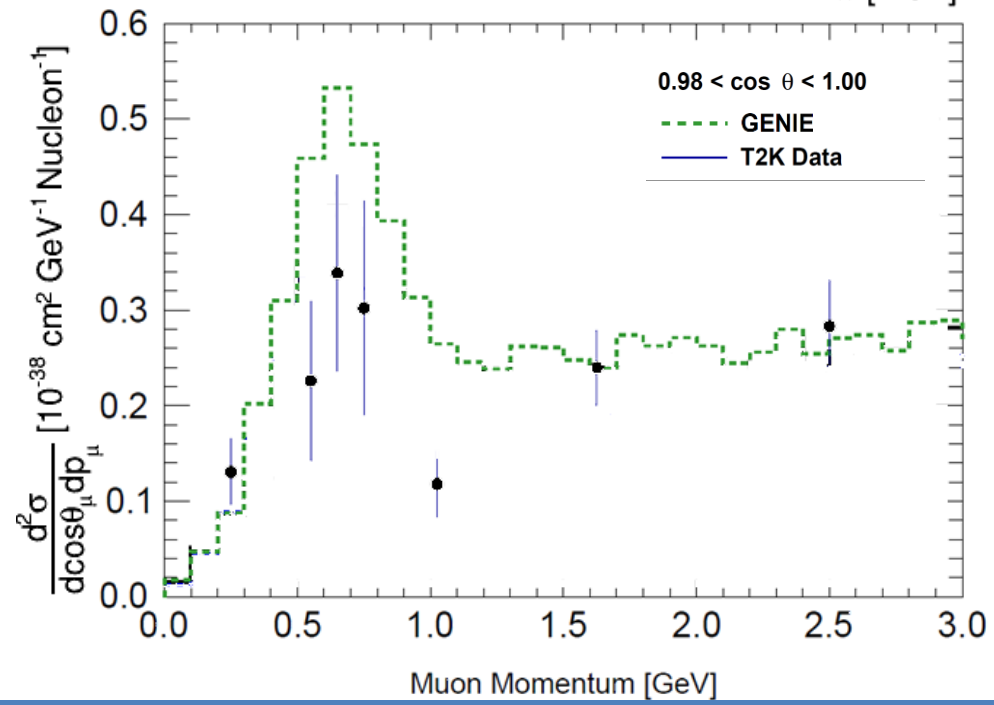


Beyond the impulse approximation

- Most of our models start from the impulse approximation: we interact with a single nucleon inside the nucleus
- But at low energy transfers this isn't a great approximation

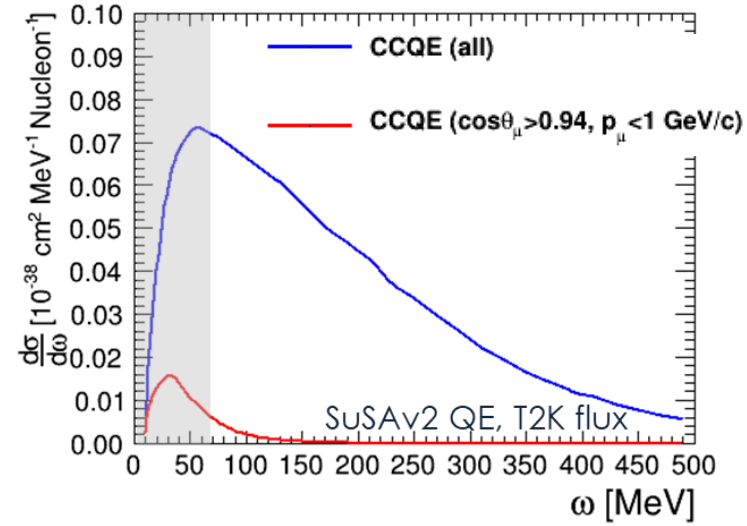


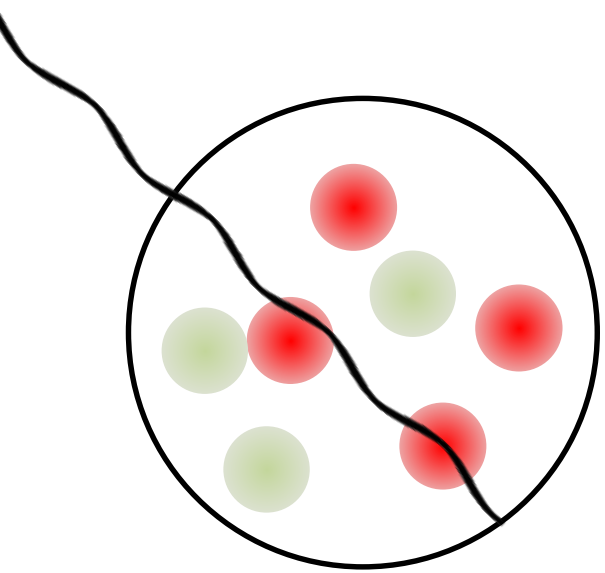


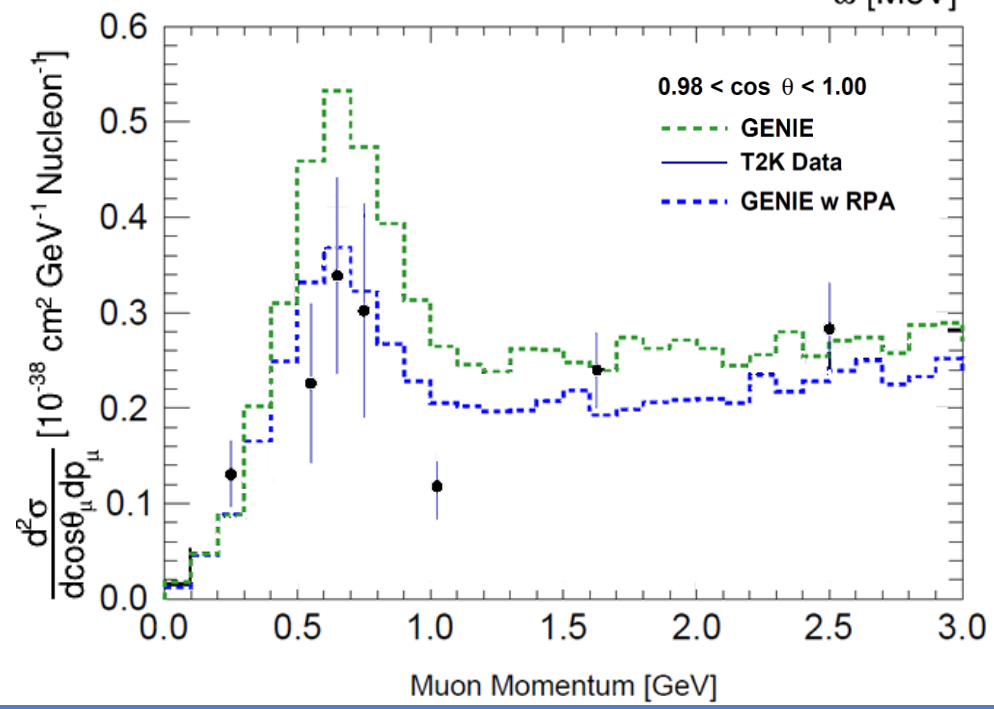


Beyond the impulse approximation

- To account for this we often apply an "RPA correction" to Fermi gas models which gives a strong suppression

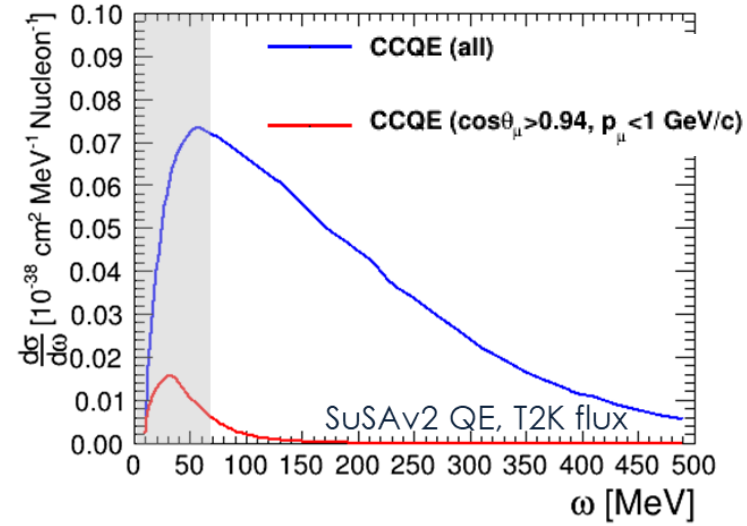


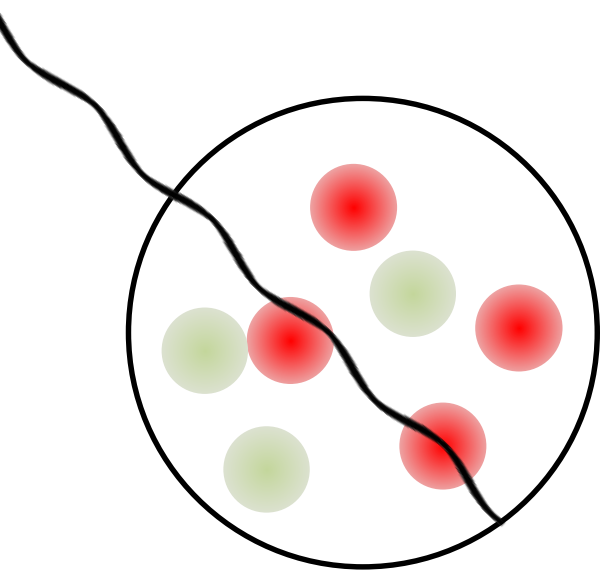


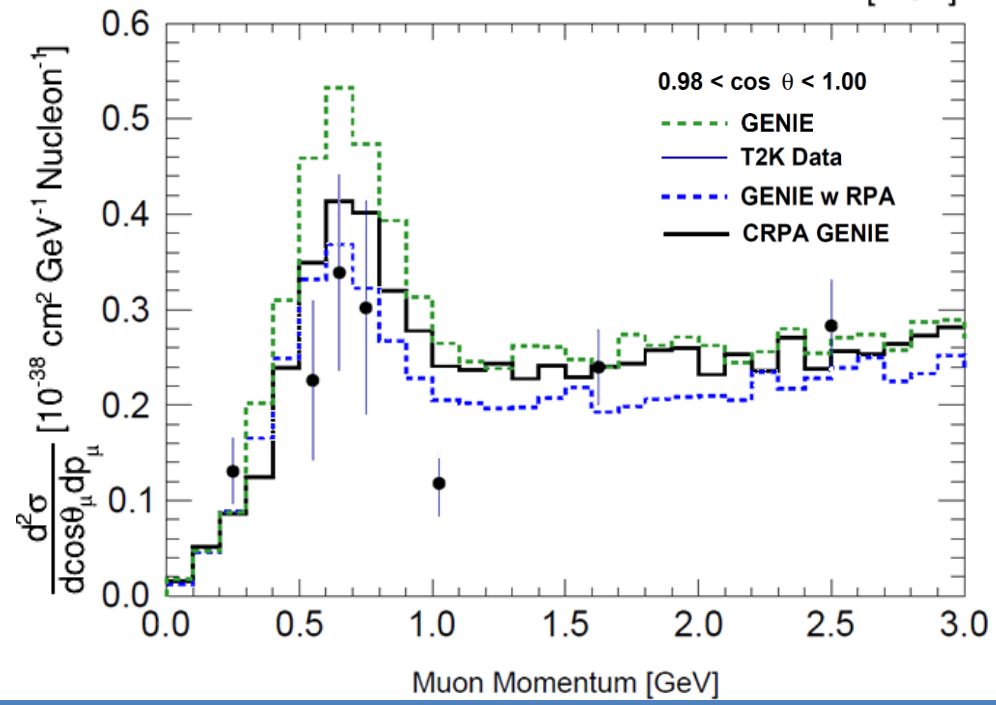


Beyond the impulse approximation

- To account for this we often apply an "RPA correction" to Fermi gas models which gives a strong suppression
- But more sophisticated approaches to breaking the IA don't suggest the suppression should be so strong …

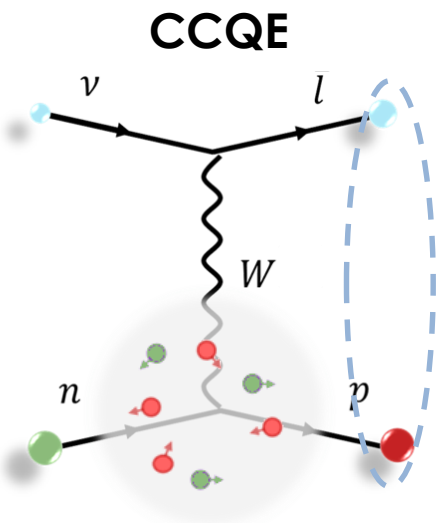




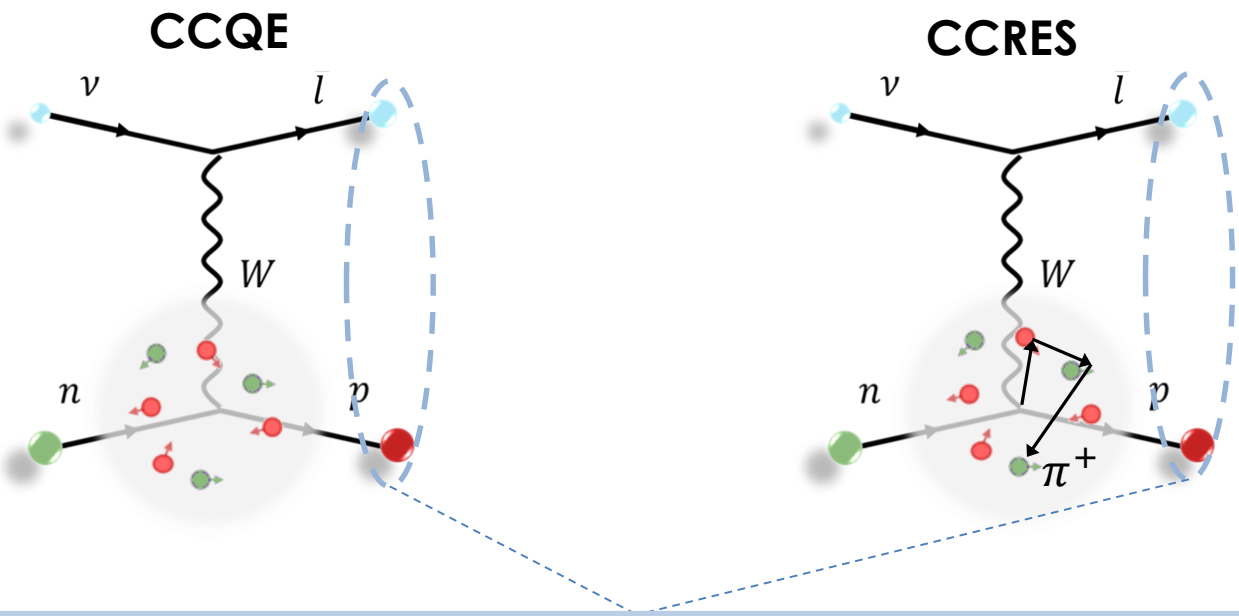


We're finally getting somewhere?

(CAVEAT: If we restrict ourselves to high energy transfers)

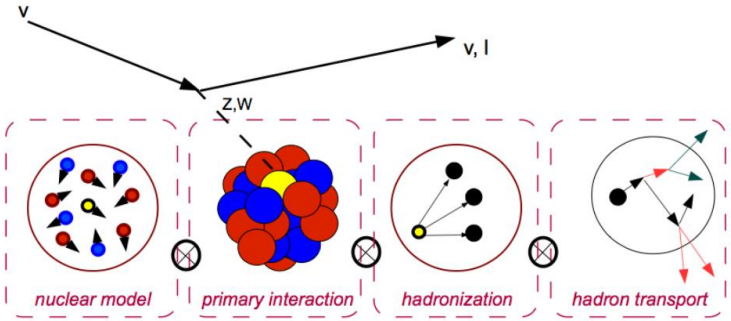


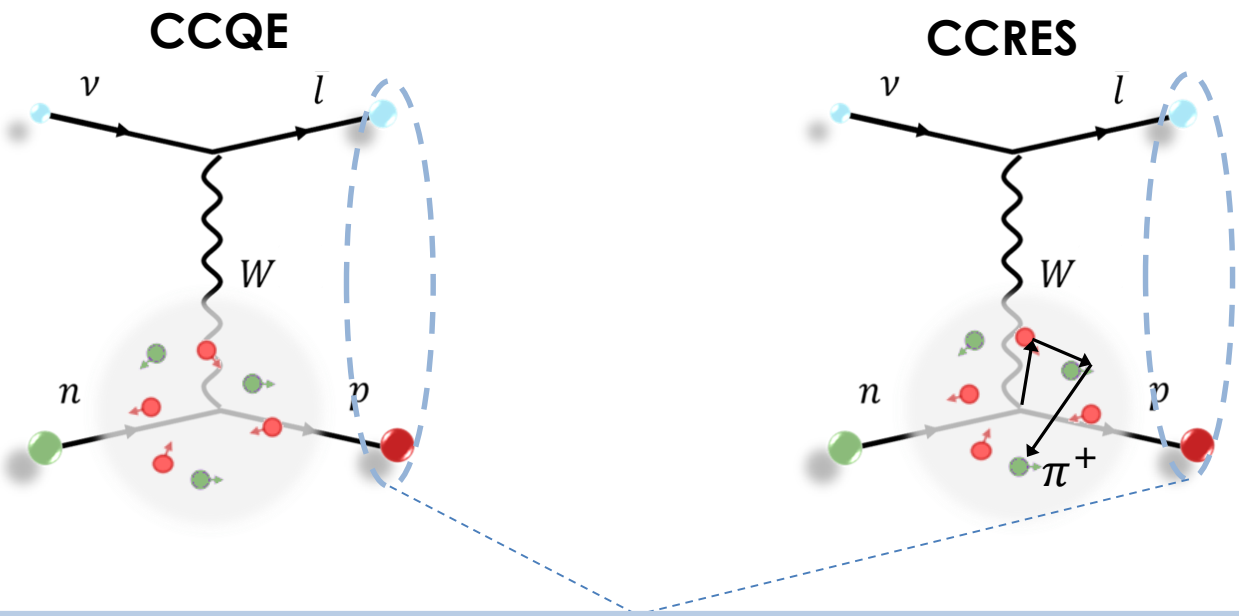
Pion absorption FSI



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

Pion absorption FSI

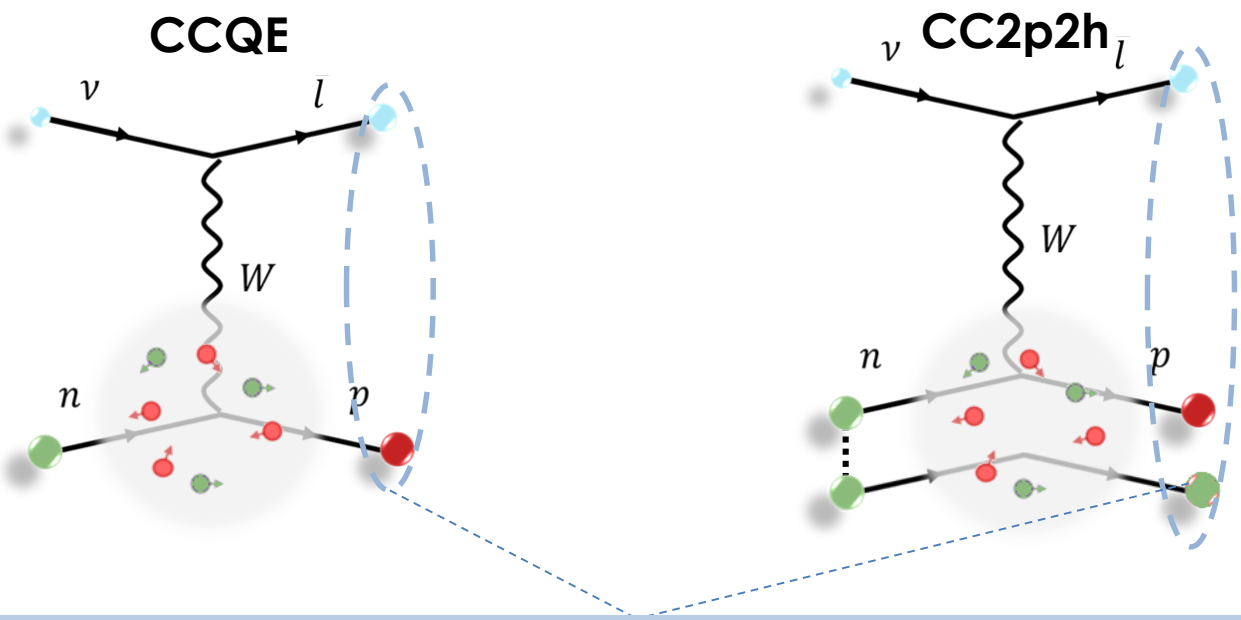




Final state interactions (FSI) can cause different interaction modes to have the same final state

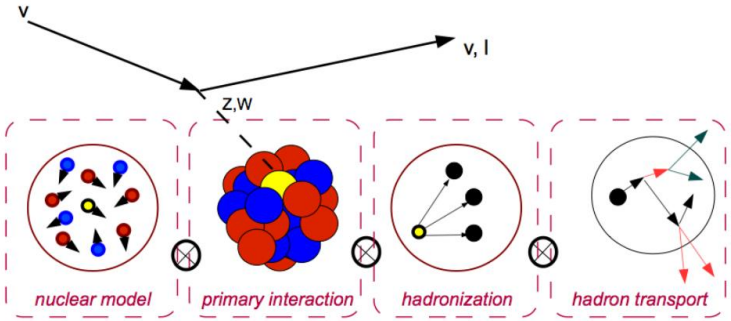
- No complete theory for pion absorption: have to use *ad-hoc* approaches to add nuclear effects to neutrino-nucleon models

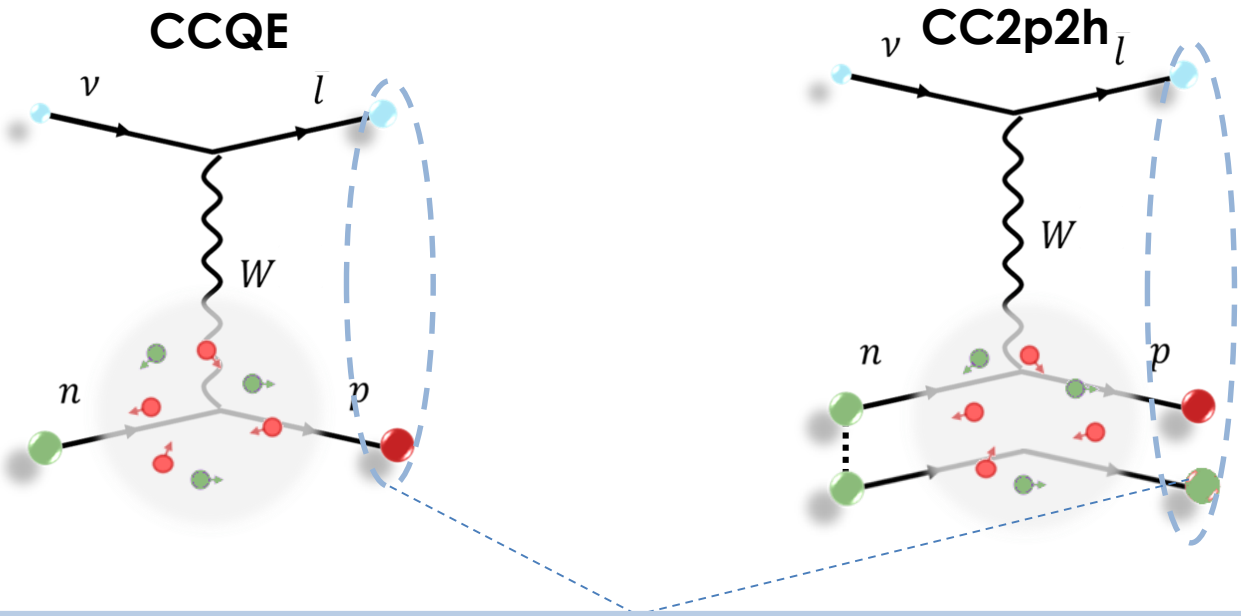
Multi-nucleon effects



Interactions off a bound state of two nucleons (mediated by Meson Exchange Currents) can result in 2p2h final states

Multi-nucleon effec





Interactions off a bound state of two nucleons (mediated by Meson Exchange Currents) can result in 2p2h final states

- No complete theory for outgoing nucleon kinematics for 2p2h: have to use *ad-hoc* approaches to add nuclear effects to neutrino-nucleon models

Generator CCQE models

CCQE Models *in the Generators*

Model	Predictive for hadron kinematics?	Relies on the impulse approximation (IA)?	Treatment of FSI
Fermi Gas	No	Yes, mitigated with RPA	No impact on lepton, factorised cascade
Spectral Function	Yes, but only pre-FSI and within limits of IA	Yes	No impact on lepton*, factorised cascade
SuSAv2	No	Yes	Includes impact the lepton, factorised cascade
CRPA**	No	No	Includes impact the lepton, factorised cascade

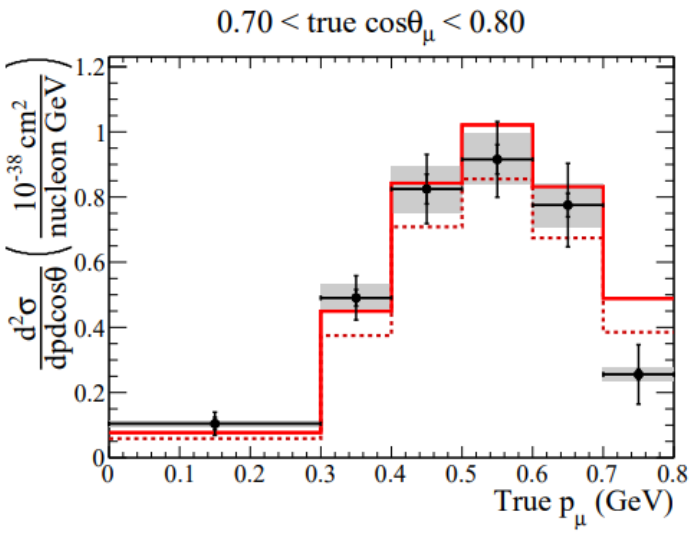
* NuWro includes an approximate technique for improving this, but it does not do reliable things to the outgoing nucleon kinematics

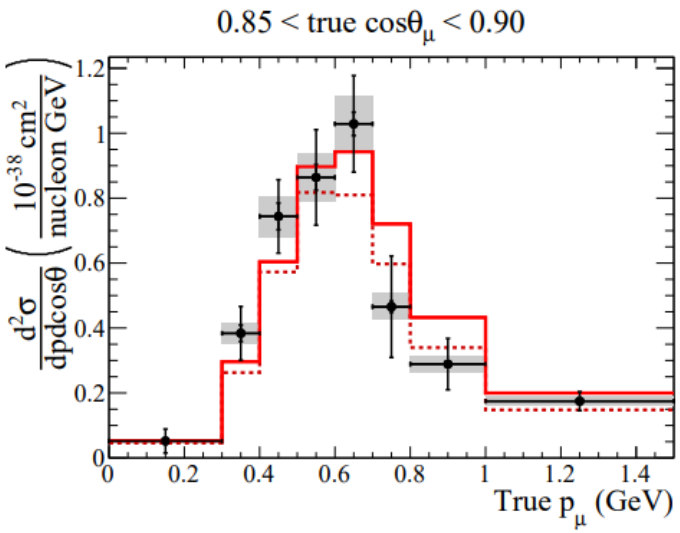
** Work in progress!!!

Generator 2p2h, RES and DIS models

- ✓ The impulse approximation is not so important
- X Most are neutrino-nucleon models with nuclear effects added *ad-hoc* in a simple way
  - Very little predictive power for hadron kinematics
- X Even the neutrino-nucleon interaction models are hard to get right
- X Inconsistent models for the RES and DIS interactions with a challenging transition region

Let's Recap





We describe intermediate muon kinematics in CC0π measurements quite well with most models

Expected?

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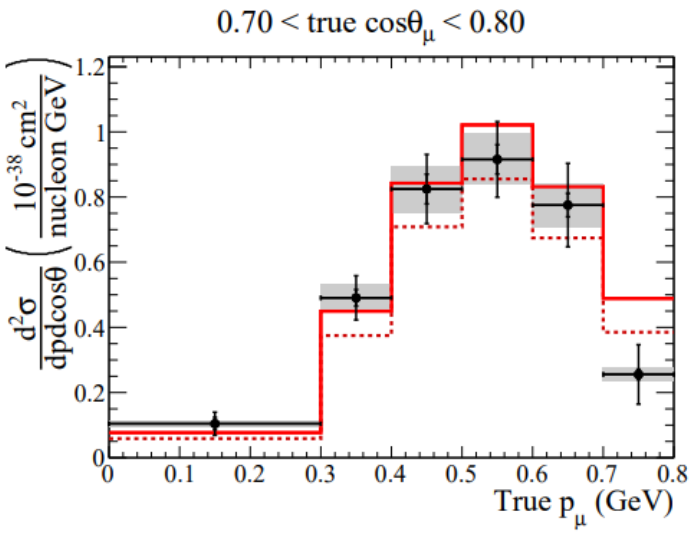
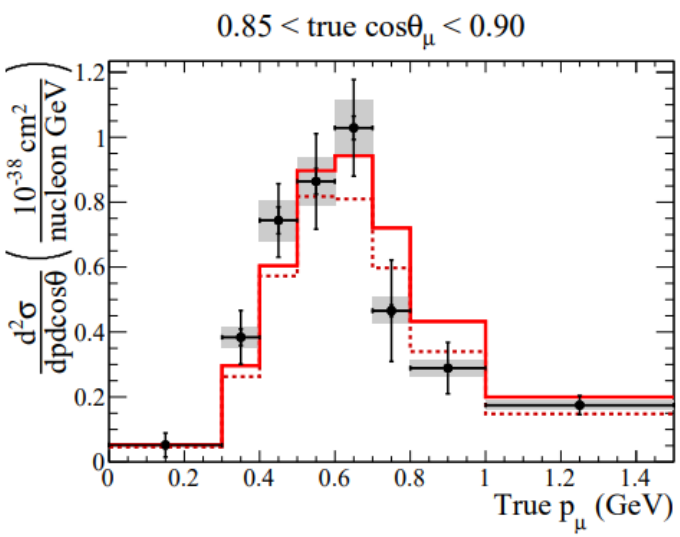




We describe intermediate muon kinematics in CC0π measurements quite well with most models

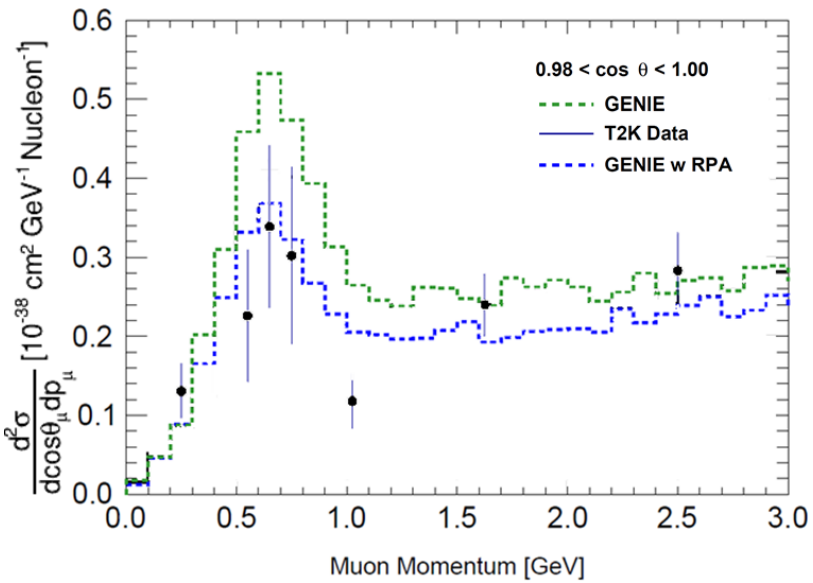
Expected?

Yes!

- Impulse approximation is reasonable
- Inclusive 2p2h models are reasonable
- The details of the hadron kinematics don't matter so much
- The impact of FSI is small

Let's Recap

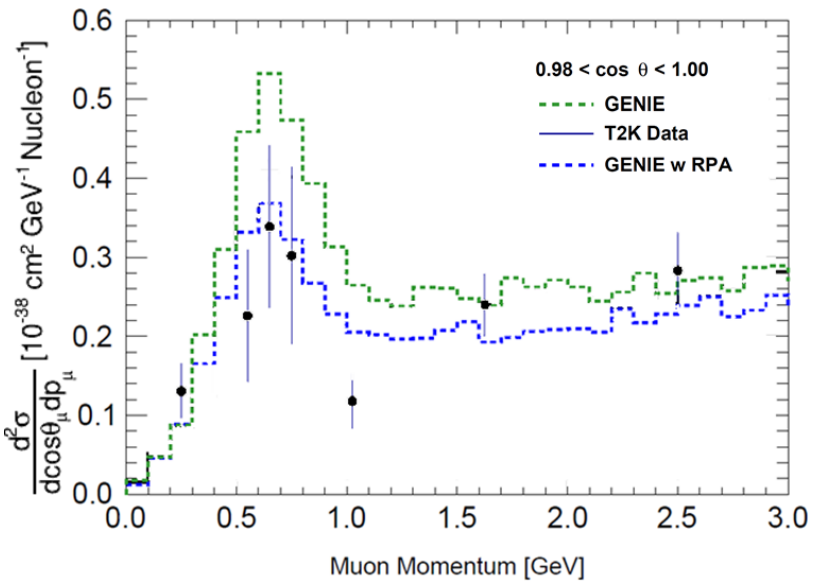
We describe forward going muon kinematics in CC0π measurements badly most models



Expected?

Models with RPA do better here

Let's Recap



We describe forward going muon kinematics in CC0π measurements badly most models

Expected?

Yes!

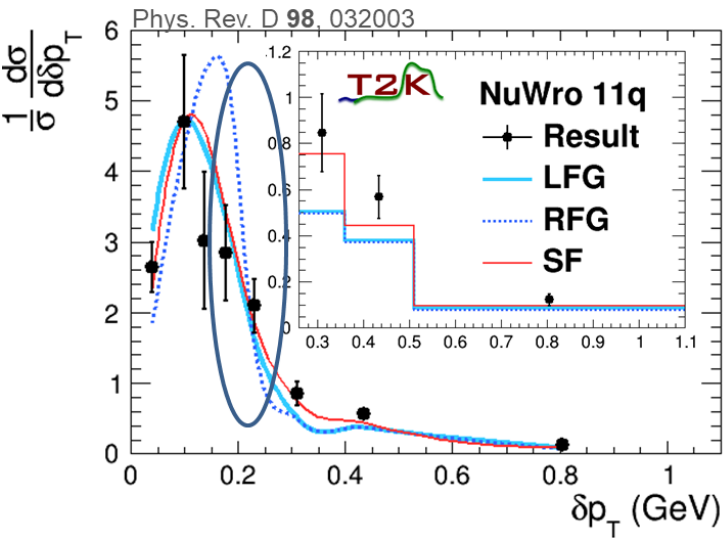
- Impulse approximation is not reliable, but most of our models use it

Models with RPA do better here

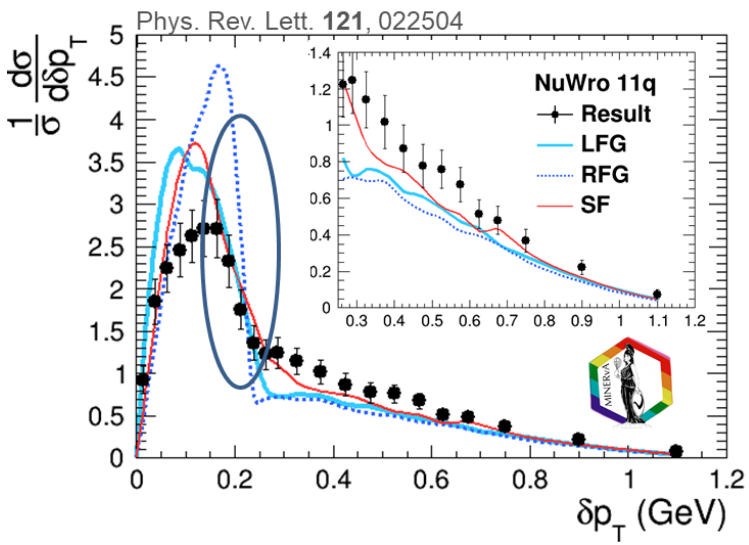
Makes sense!

- Provides some modelling of physics beyond the impulse approximation

Let's Recap

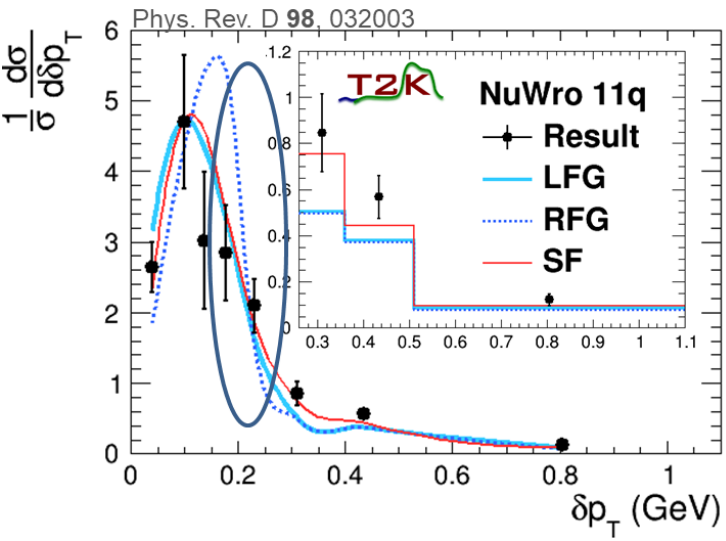


We describe nucleon kinematics badly



SF models with do better here

Let's Recap

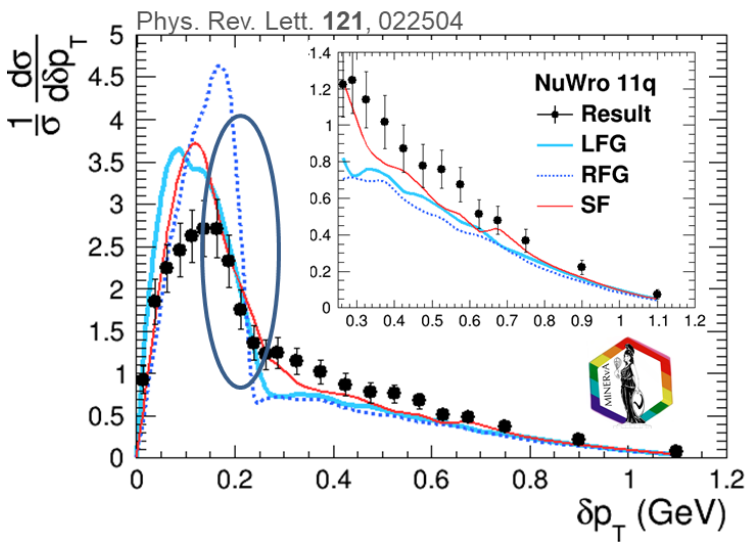


We describe nucleon kinematics badly

Expected?

Yes!

- All of our models rely on *ad-hoc* model combinations to predict nucleon kinematics



SF models with do better here

Makes sense!

- Less approximations in predictions of nucleon kinematics

Summary so far

- Why do we care?
  - Understanding even the subtle details of neutrino interactions is crucial for precision measurements of neutrino oscillations
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  - Measurements of only the outgoing lepton at intermediate kinematics: good, simulations mostly match the data
  - Measurements of anything else: not so good
- Where did it all go wrong? (Neutrino event generators)
  - Generators predict anything you want them to, even when the underlying theory does not
  - Treat their predictions (and even provided uncertainties) with scepticism, they don't cover everything


DON'T
PANIC

Overview

- The Weak Interaction
  - Historical Overview
  - Point-like scattering
- Neutrino-nucleon interactions
  - QE, RES and DIS
- Neutrino-nucleus interactions
  - Nuclear effects
  - Ground state modelling
- Why do we care?
  - Neutrino interactions for neutrino oscillations
  - Neutrino energy reconstruction
- Neutrino-nucleus interaction measurements
  - Inclusive successes and exclusive failures
- Where did it all go wrong? (Neutrino event generators)
  - Limitations of our simulations
- Don't Panic! The future of neutrino interactions

How far we've come

c. 2001 "Nuclear effects" is not in a neutrino physicist's vocabulary

c. 2010 "Most of our knowledge of neutrino cross sections in the 0.1-20 GeV energy range comes from early experiments ... conducted in the 1970s and 1980s"

Rev. Mod. Phys. **84**, 1307

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Whilst it's true that **our measurements have outstripped our models** in our generators, this is partially because **we have such rich measurements**!

It's also true **we need to better understand neutrino interactions for DUNE and Hyper-K**, but **we do not need to have this tomorrow**!

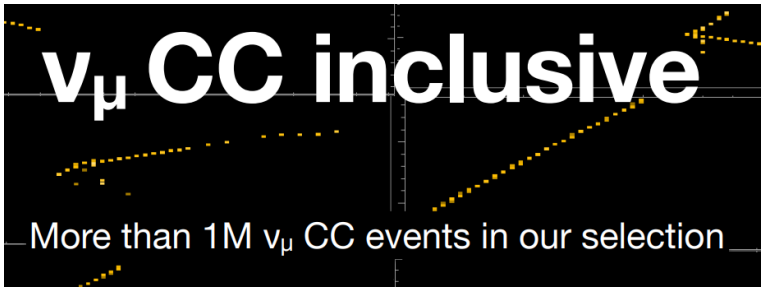
However, **the measurements and theory developments have to start now**!

Undetectable, you say?

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do." *Wolfgang Pauli, 1930*

Well, have I got νs for you!

L. Cremonesi



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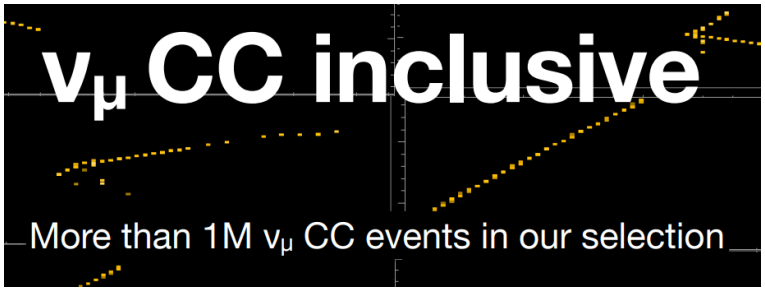

arXiv: 2106.16210

Using these criteria, a sample of 4,105,696 interactions was selected. The simulation predicts an average selection efficiency of 64% in the p_t-$p_{||}$ phase space, where

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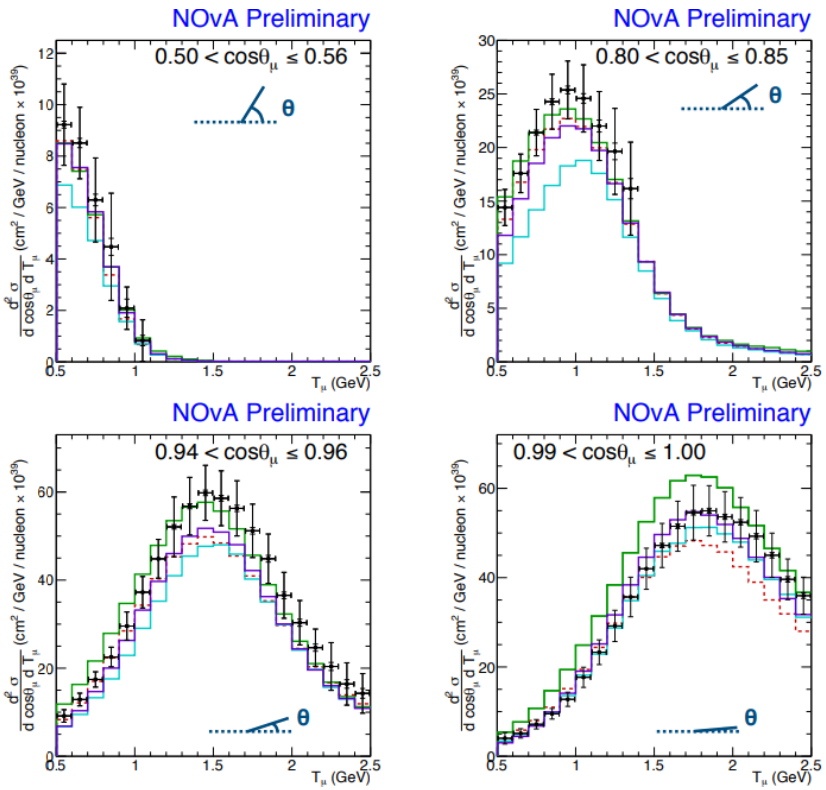
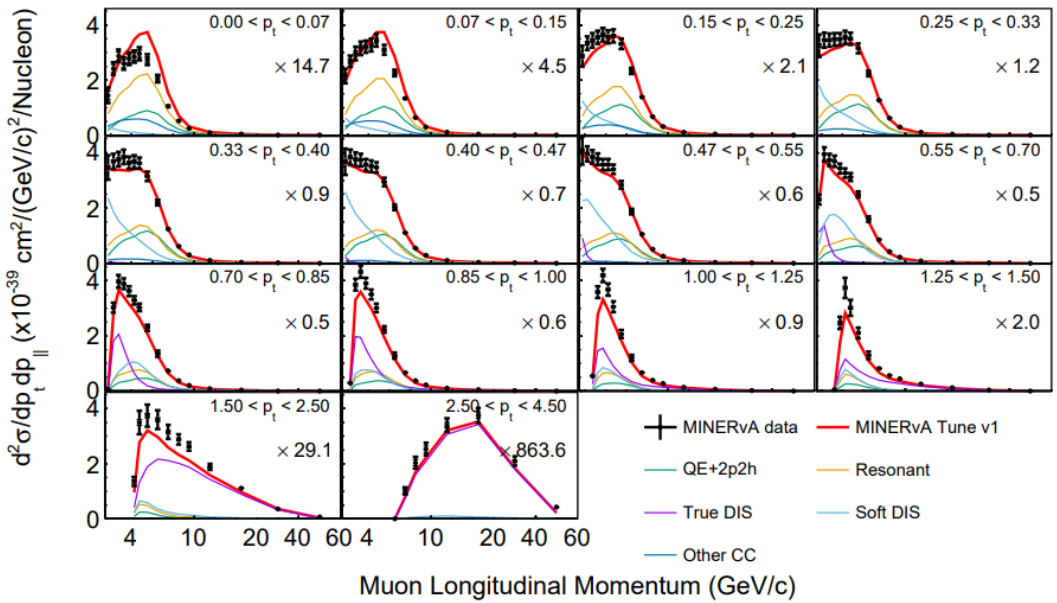
Data (Stat. + Syst.)
GENIE 3.00.06*
GiBUU 2019
NEUT 5.4.0
NuWro 2019

L. Cremonesi

arXiv: 2106.16210





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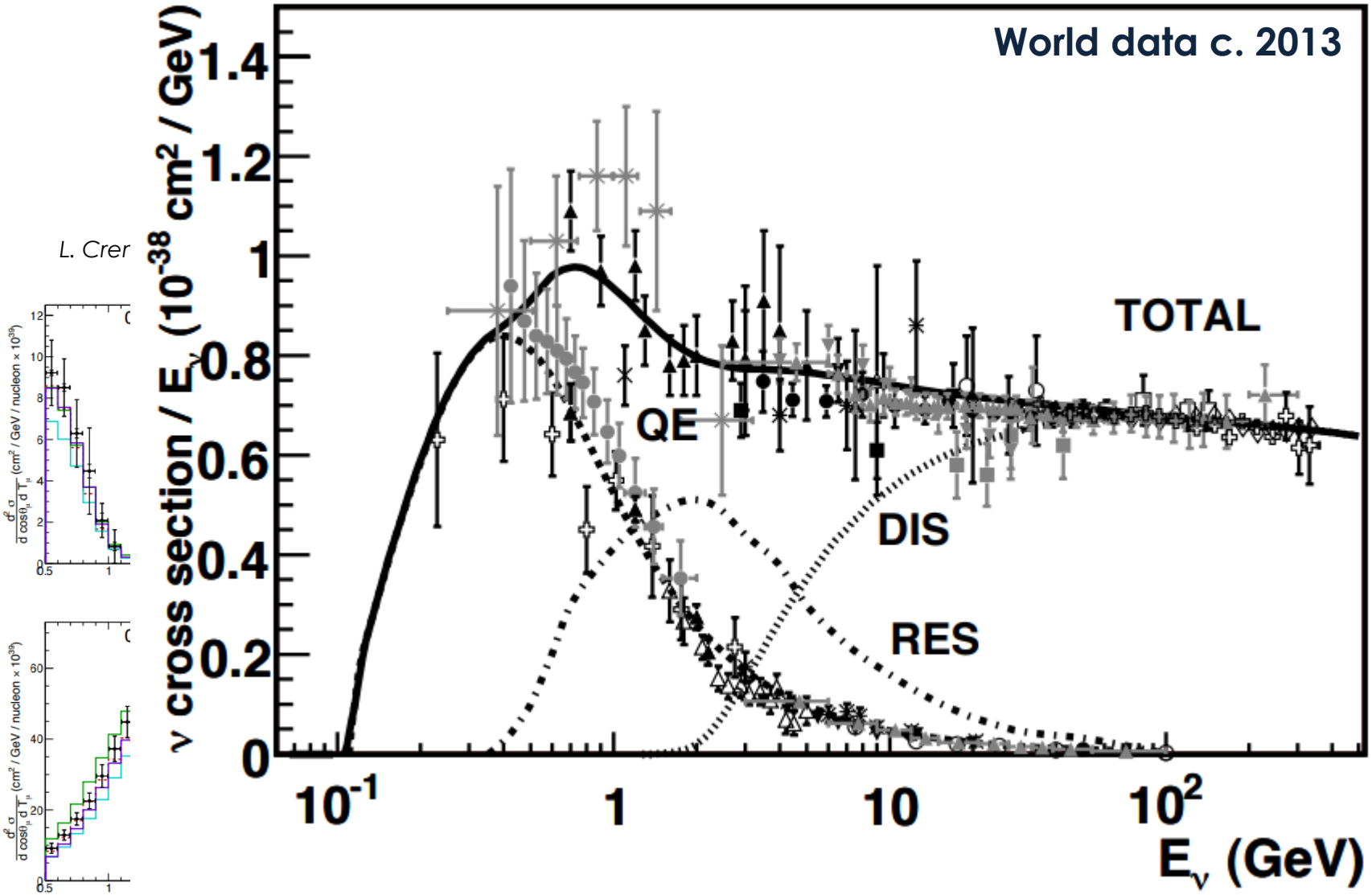

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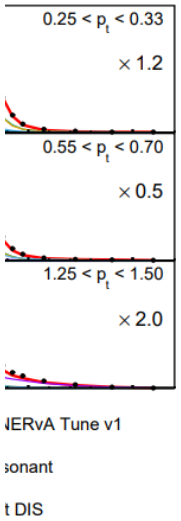
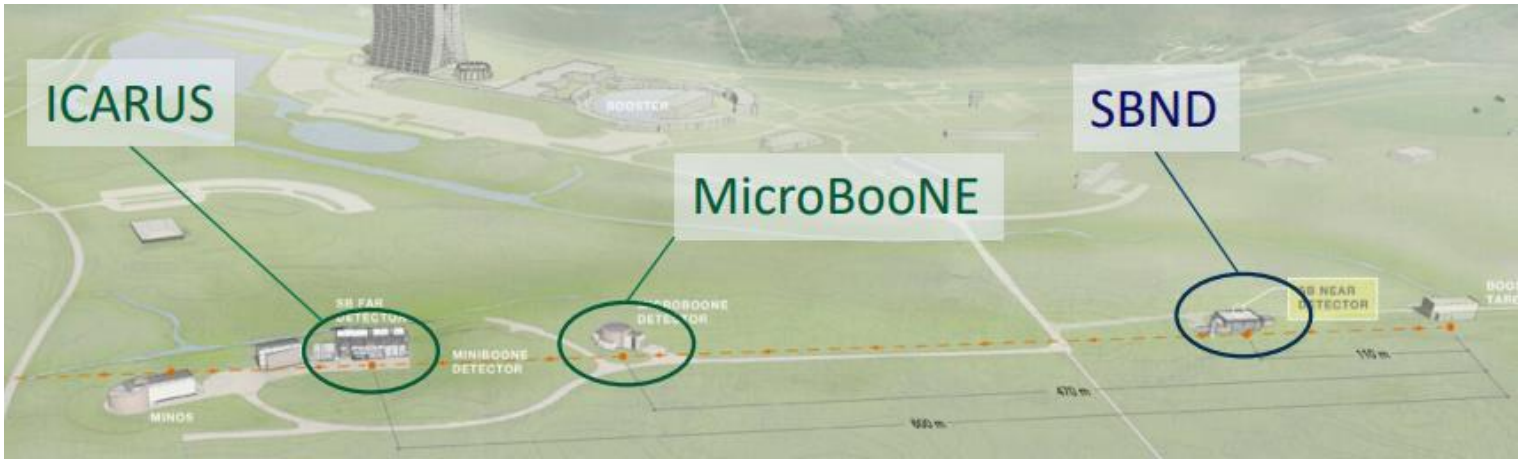


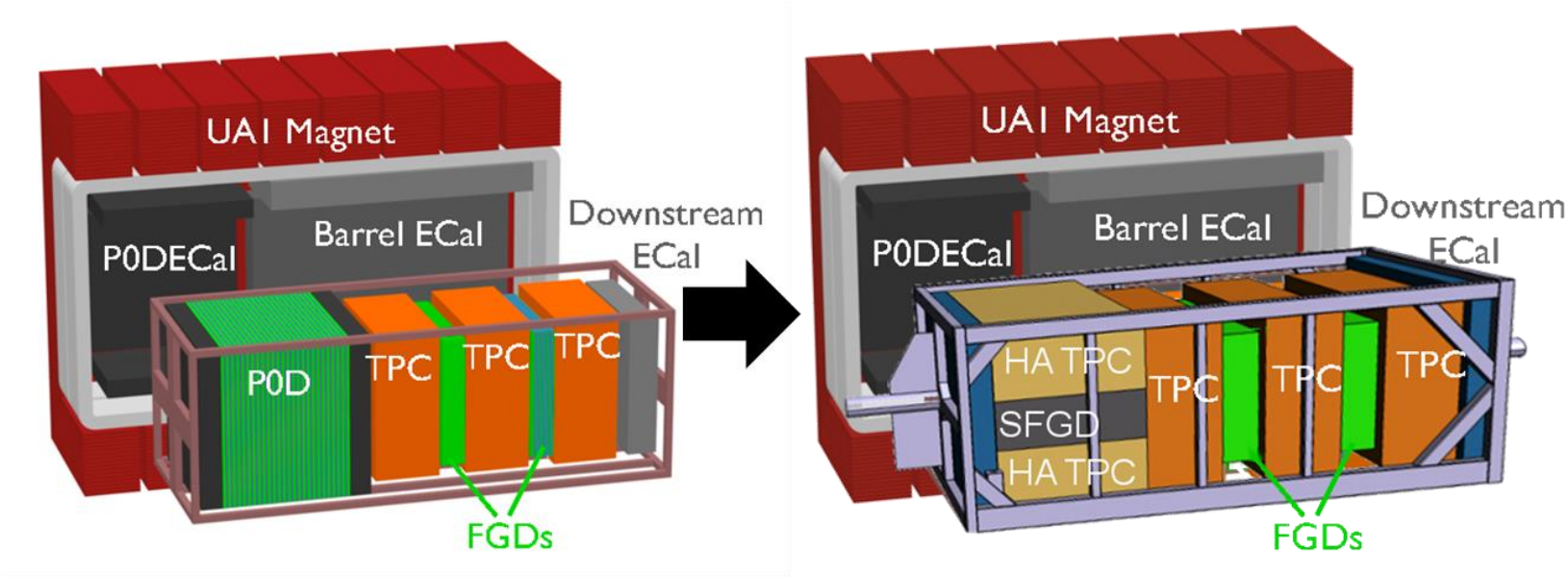
A bright future for Argon

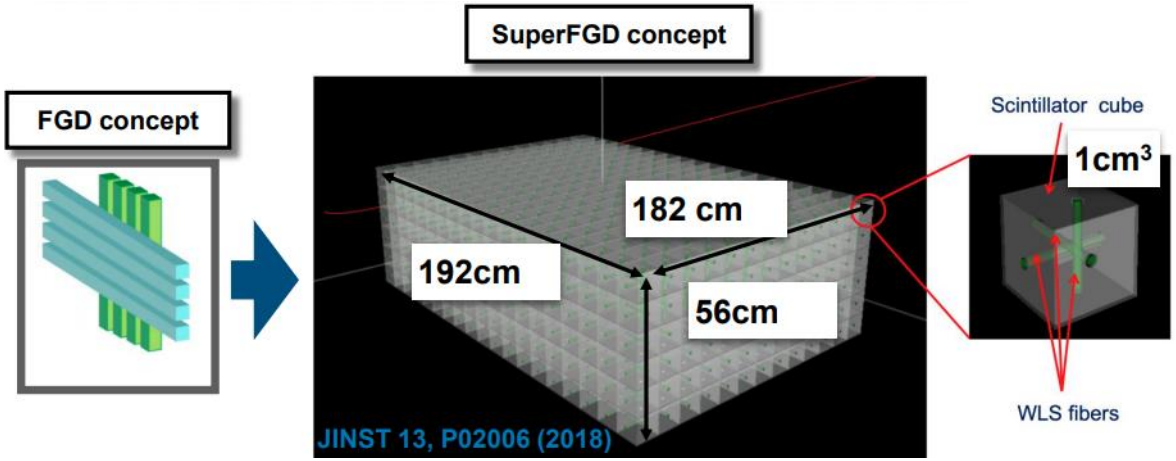
Short Baseline Program: Fermilab liquid Argon detectors in "Booster" beam (~0.8 GeV)



- **MicroBooNE**: already producing interesting results
- **ICARUS**: taking its first physics data
- **SBND:** enormous event rates coming soon (1M ν/y)

More new (ν) detectors

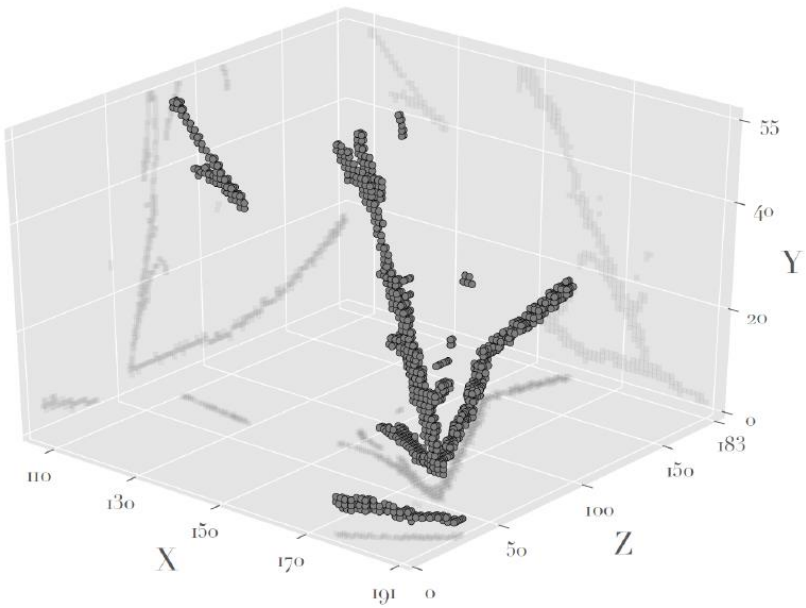


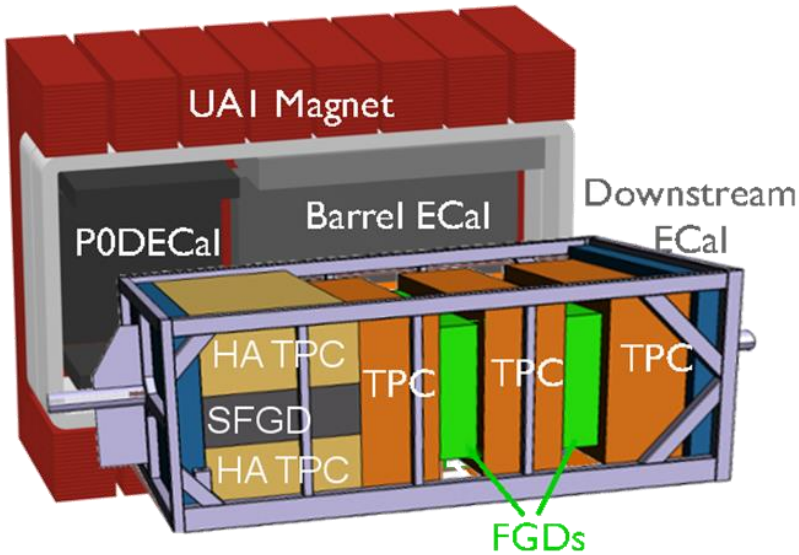


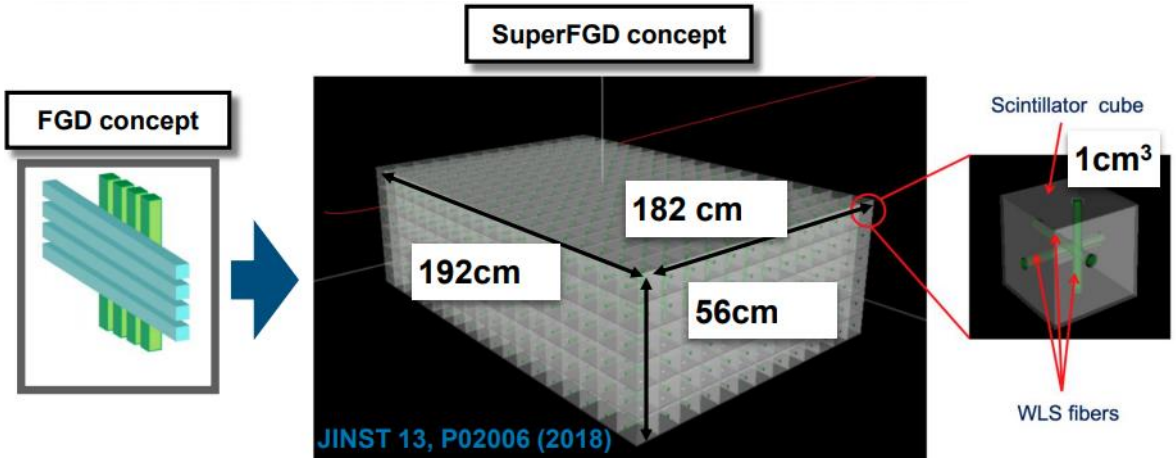
The SFGD:

- 2 M scintillator cubes
- 58,000 channels
- 2.1 tons target mass

More new (ν) detectors



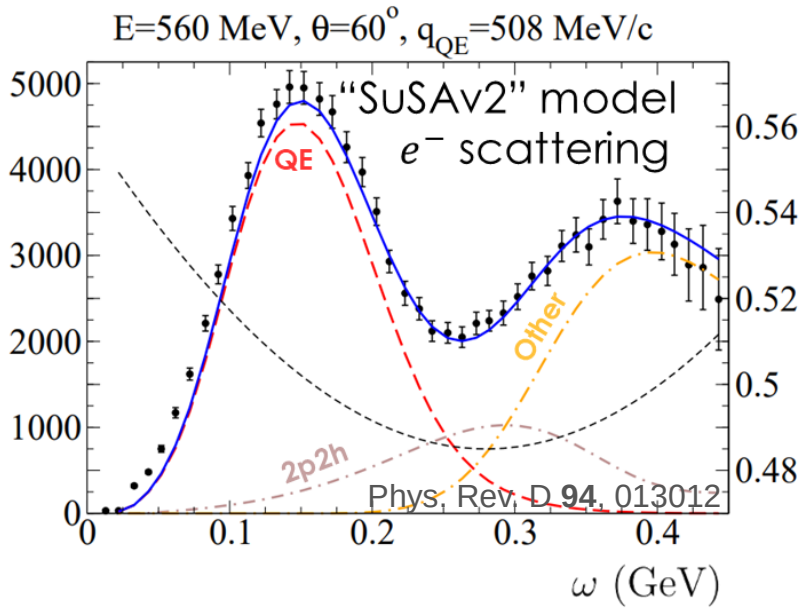


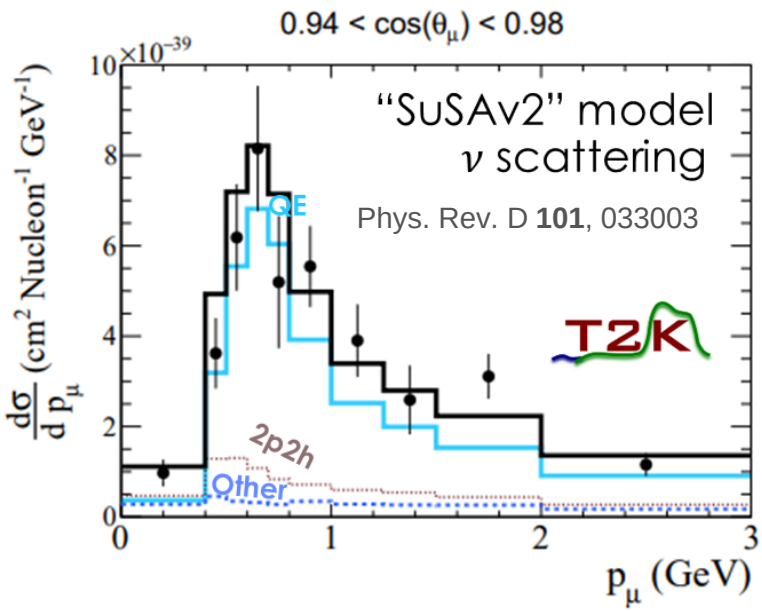


The SFGD:

- 2 M scintillator cubes
- 58,000 channels
- 2.1 tons target mass

New models, new constraints





- New models, successful in describing electron scattering data, are now being implemented in neutrino interaction simulations
- Such models that describe e^- and ν interactions in the same framework can be directly constrained by precision e^- data
- New theoretical efforts are allowing models to be more predictive

New models, new constraints

Model	Predictive for hadron kinematics?	Relies on the impulse approximation (IA)?	Treatment of FSI
Fermi Gas	No	Yes, mitigated with RPA	No impact on lepton, factorised cascade
Spectral Function	Yes, but only pre-FSI and within limits of IA	Yes	No impact on lepton*, factorised cascade
SuSAv2	No	Yes	Includes impact the lepton, factorised cascade
CRPA**	No	No	Includes impact the lepton, factorised cascade

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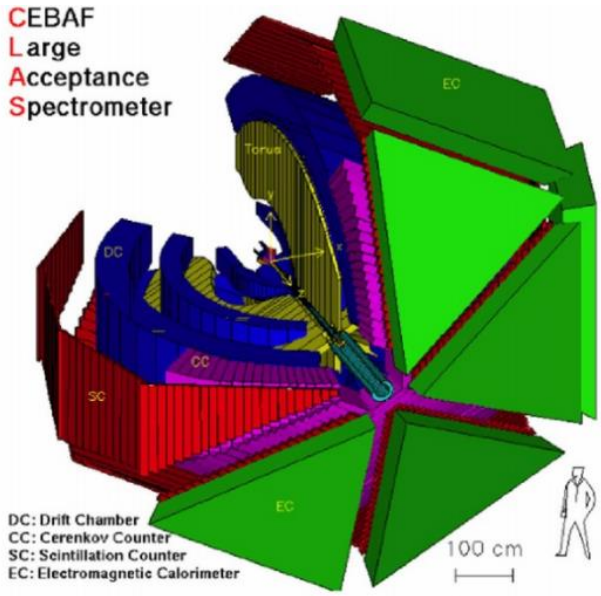
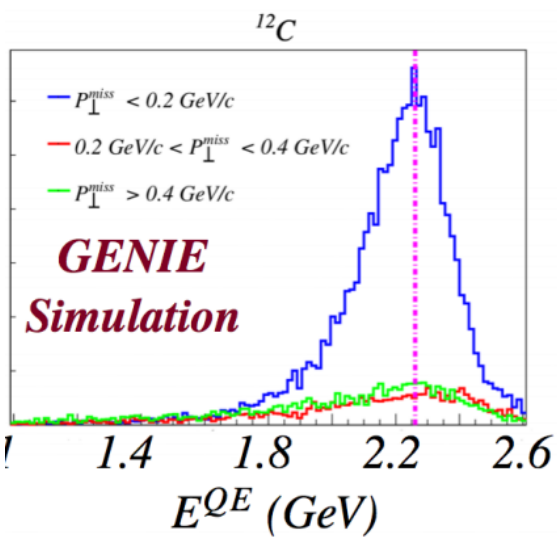
ED-RMF??	Yes	Yes	Consistent QM treatment
???	Yes	No	Hybrid QM-Cascade??

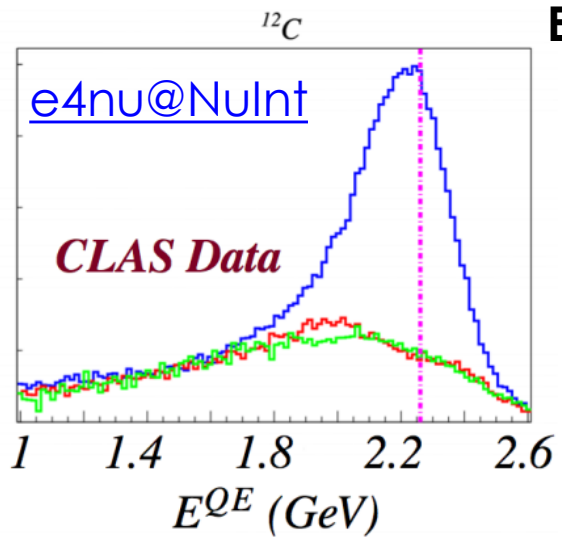
Coming soon???

Electrons to the rescue!



- Generators are becoming more able to make neutrino and electron scattering predictions in the same framework
- New data from CLAS (e-scatting): specifically to help better understand neutrino scattering





Example:

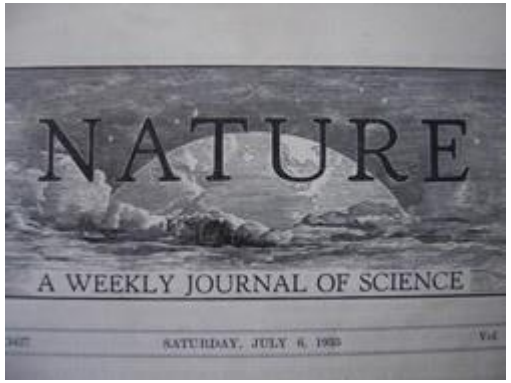
- In CLAS we know $E_{e,inital}$
- But can still reconstruct it as if it was a neutrino
- See how well generators predict this
- A great test of bias in neutrino scattering

Summary

- A detailed understanding of neutrino-nucleus interactions is **crucial for current and future experiments** to realise their extraordinary goals (CP-violation, mass ordering, new BSM physics)
- This is a **challenging task**: neutrino interactions are complicated
- We've made **enormous progress** in the last 10 years, but **still have some way to go**
- **New data** from **new detectors** will be invaluable, offering dramatically improved probes of neutrino interactions
- Collaboration between **theory and experimental communities** will be crucial
- Expect plenty of **exciting new results** and a continued exponential growth of the field in the run up to DUNE & Hyper-K.

Thanks for listening!

c. 1930



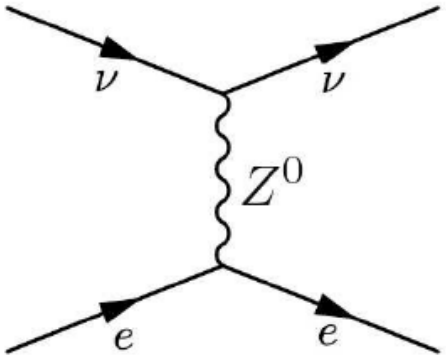
"[Fermi's theory of weak interactions] contains speculations too remote from reality to be of interest to the reader"

2020

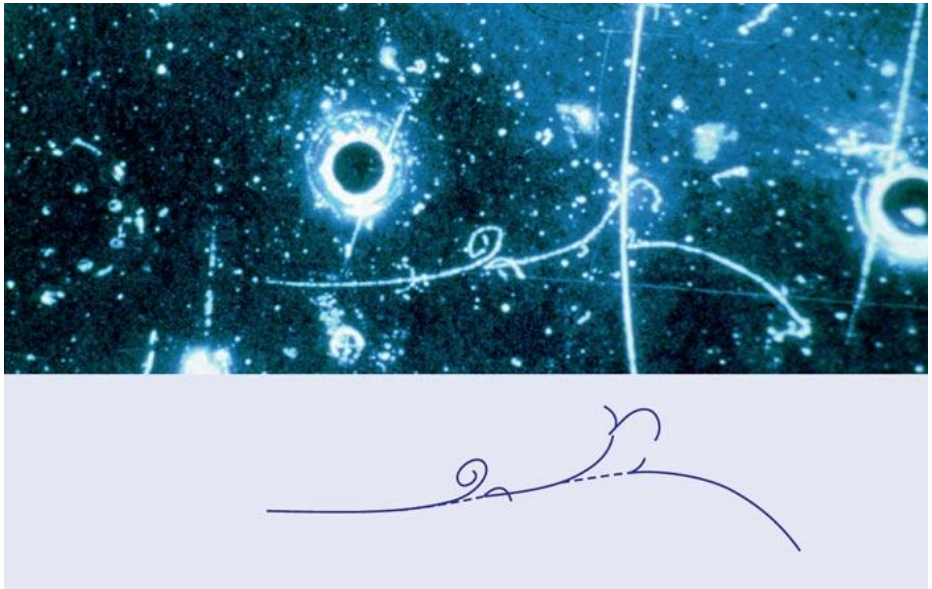
Backups

Neutrinos as probes of the weak force!

- Since neutrinos only interact via the weak force, they provide a great way of studying it



- **Weak neutral currents** were discovered by measuring neutrino interactions in the Gargamelle bubble chamber!

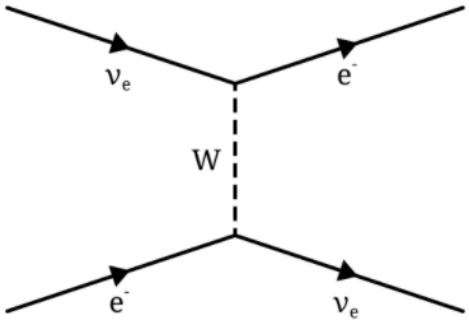


Parity, Helicity and Chirality

- The chiral properties of the weak interaction leads to differences in neutrino and antineutrino cross sections.

Neutrino-electron Scattering

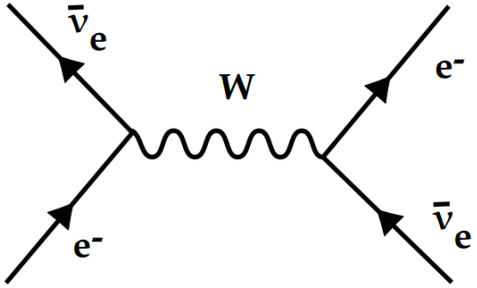
$$\nu_e + e^- \rightarrow e^- + \nu_e$$



Assume massless leptons

Antineutrino-electron Scattering

$$\bar{\nu}_e + e^- \rightarrow e^- + \bar{\nu}_e$$



$$\frac{d\sigma_{\nu e}}{d\Omega} = \frac{G_F^2 s}{4\pi^2} \quad \sigma_{\nu e} = \frac{G_F^2 s}{\pi}$$

$$\frac{d\sigma_{\bar{\nu}q}}{d\Omega^*} = \frac{G_F^2}{16\pi^2}(1+\cos\theta^*)^2 \hat{s}$$

$$d\Omega = d\phi \sin\theta d\theta \rightarrow d\phi d(\cos\theta)$$

★**Integrating over solid angle:**

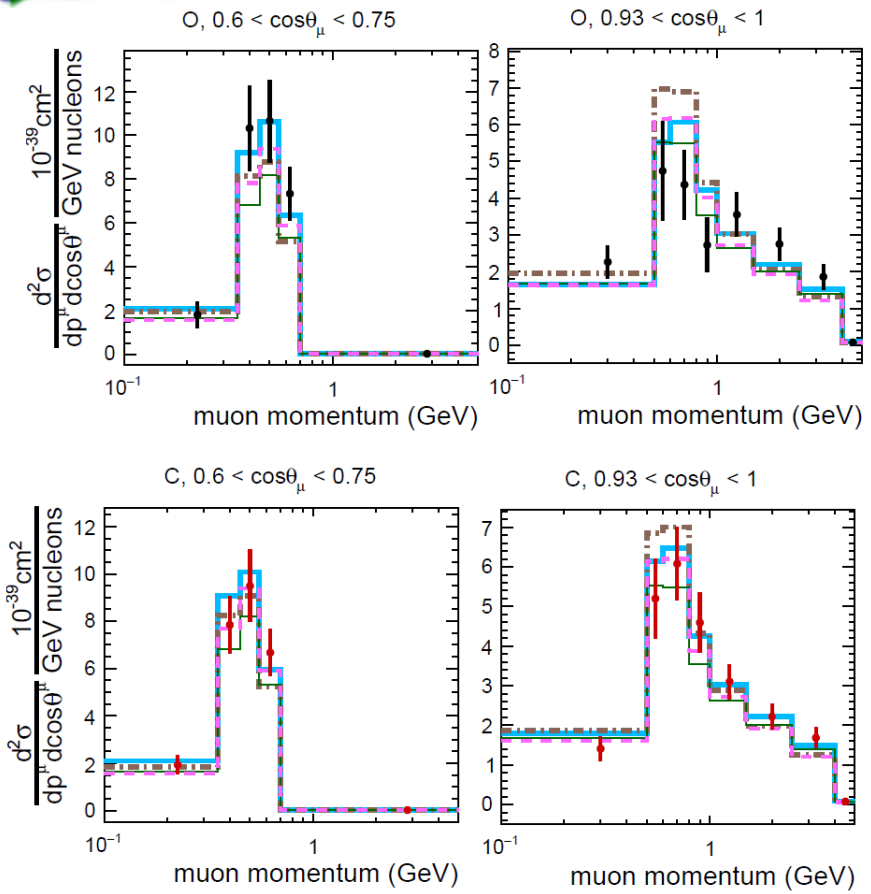
$$\int (1+\cos\theta^*)^2 d\Omega^* = \int (1+\cos\theta^*)^2 d(\cos\theta^*) d\phi = 2\pi \int_{-1}^{+1} (1+\cos\theta^*)^2 d(\cos\theta^*) = \frac{16\pi}{3}$$

$$\rightarrow \boxed{\sigma_{\bar{\nu}q} = \frac{G_F^2 \hat{s}}{3\pi}}$$

$$\boxed{s = (p_1 + p_2)^2 = (p_3 + p_4)^2}$$

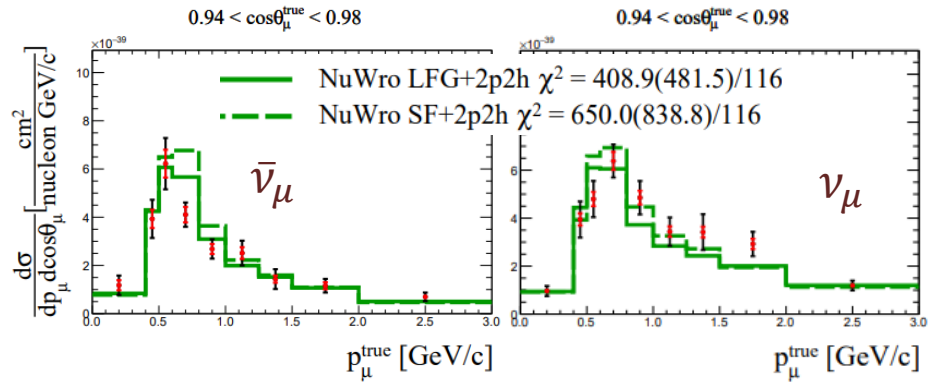
Joint measurements

Joint Carbon / Oxygen

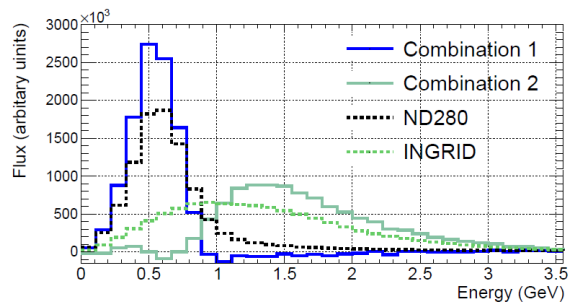


(55 DoF)

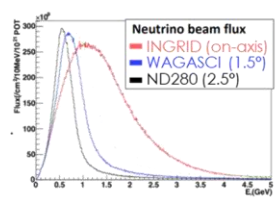
Joint ν_μ / $\bar{\nu}_\mu$

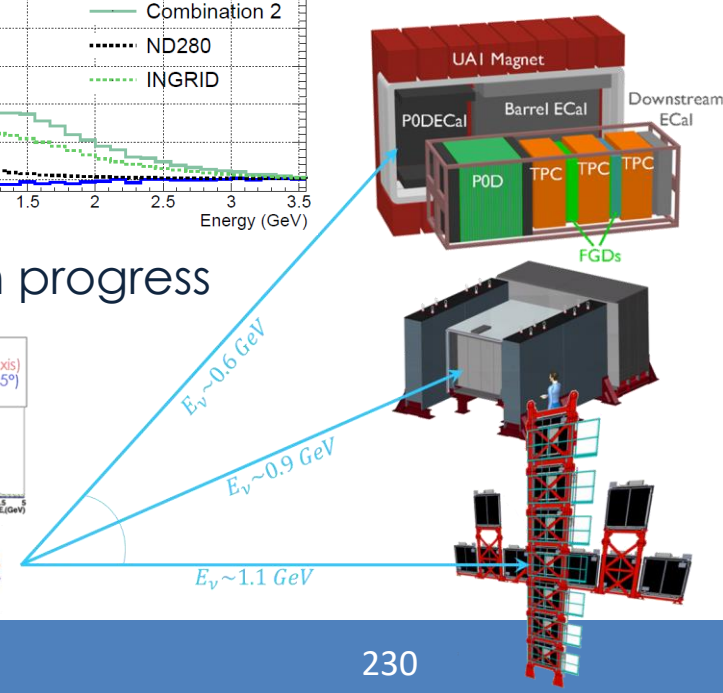


Joint off-axis angles



Work in progress





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

1. Relative CC0π contribution of CCQE and other processes
   - *So we know how often we mis-reconstruct E_ν*

2. Initial state nucleon momentum and energy
   - *So we know how wide (and biased) our CCQE E_ν reconstruction is*

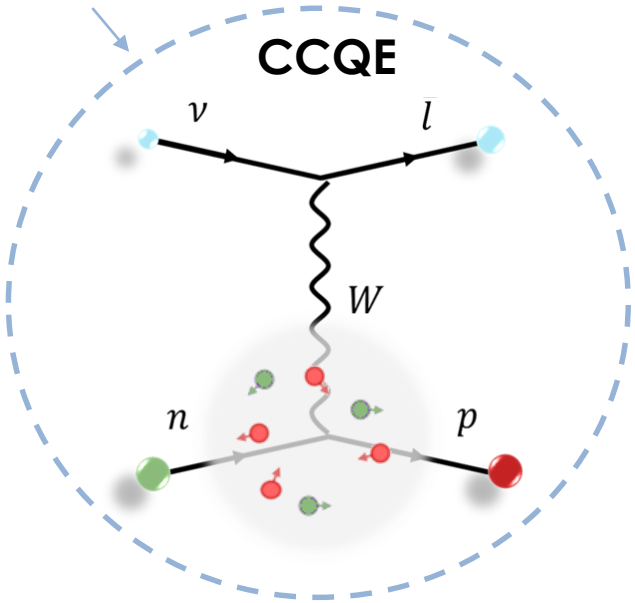
3. Differences in $\nu/\bar{\nu}$ cross sections
   - *So we know when $\nu/\bar{\nu}$ differences correspond to CP-violation*

4. Differences in carbon and oxygen cross sections
   - *So we know how to extrapolate from our ND to our FD*

5. Improved knowledge of the CC1π cross section
   - *So we can better use new samples at SK and understand the largest background in the primary samples*

Aside: should we do this for FG models?

Exclusive model: can describe all final state particle kinematics



If we assume the outgoing nucleon is **non-relativistic** and that there's **no FSI** we can write the cross section like this:

$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)\mathrm{dE}_{\ell}'} \sim S(E_m, \boldsymbol{p}_m)\mathrm{L}_{\mu\nu}\mathrm{W}^{\mu\nu}\delta(\omega + M - E_m - E_{p'})$$

If SF = Valencia LFG …

From the Nieves et. al. paper:

Inclusive quasielastic charged-current neutrino-nucleus reactions, J. Nieves et al, 2004

[5,6]. One might think that the LFG description of the nucleus is poor, and that a proper finite nuclei treatment is necessary. For inclusive processes and nuclear excitation energies of at least 100 MeV or higher, the findings of Refs. [4,3,6] clearly contradict this conclusion. The reason is that in these circumstances one should sum up over several nuclear configurations, both in the discrete and in the continuum, and this inclusive sum is almost not sensitive to the details of the nuclear wave function, in sharp contrast to what happens in the case of exclusive processes where the final nucleus is left in a determined nuclear level. On the

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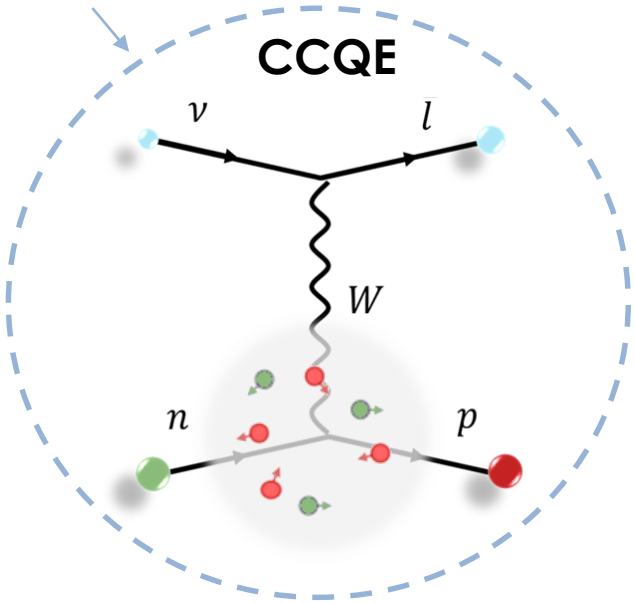

Rephrased: "LFG is fine if you only want to know about the outgoing lepton. But please do not use this model if you want to predict outgoing nucleon kinematics!"

If we assume the outgoing nucleon is **non-relativistic** and that there's **no FSI** we can write the cross section like this:

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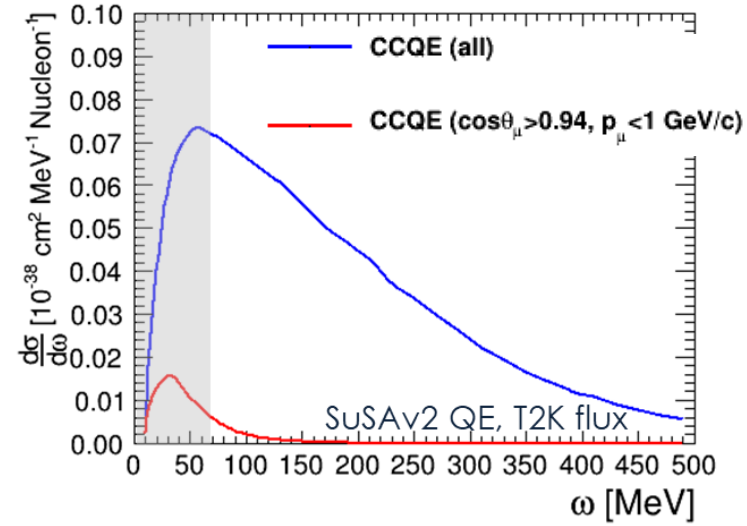
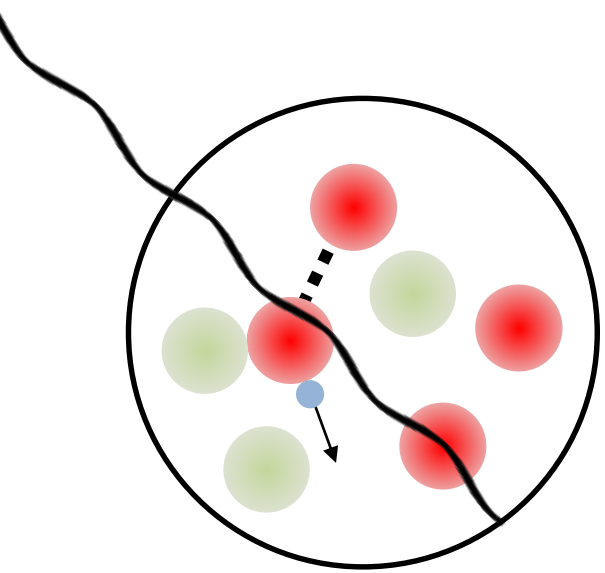
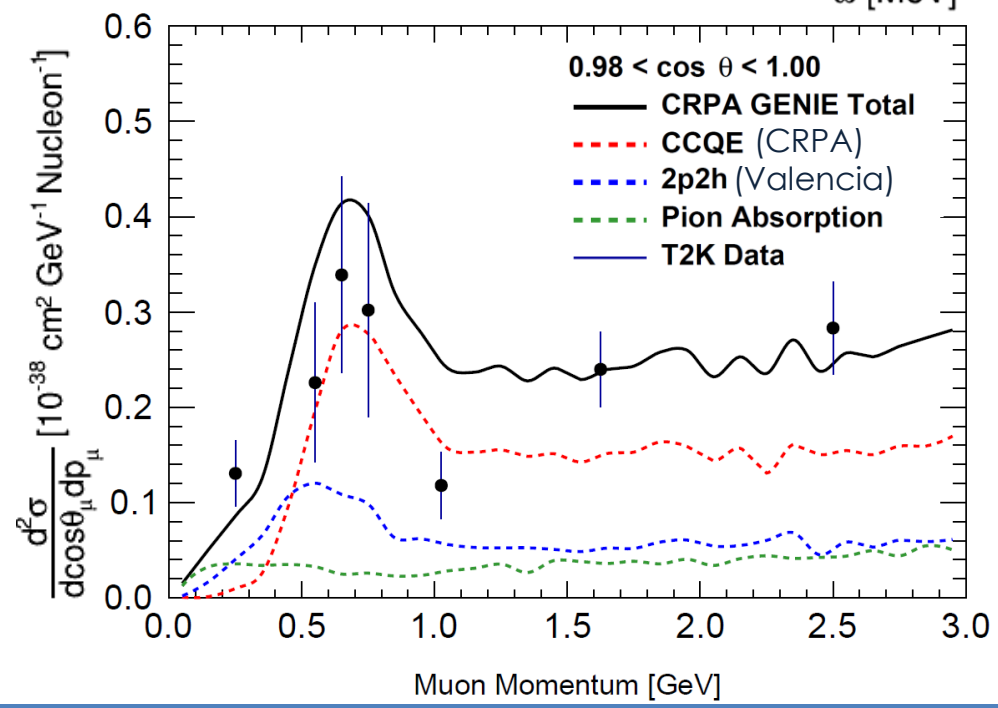
Beyond the impulse approximation

- Remember: these comparisons are to CC0π measurements, there are other contributions besides the CCQE
- Is it possible these are too strong?

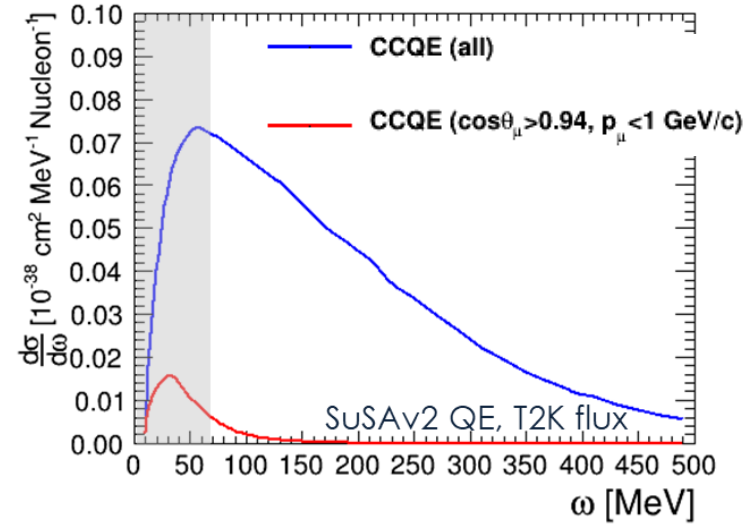


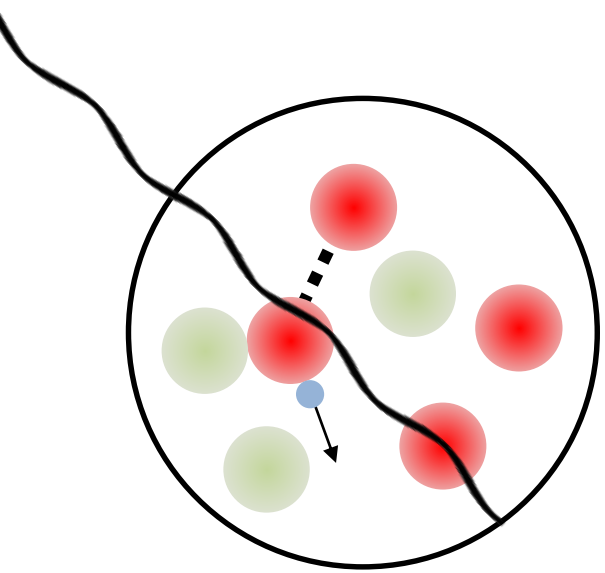


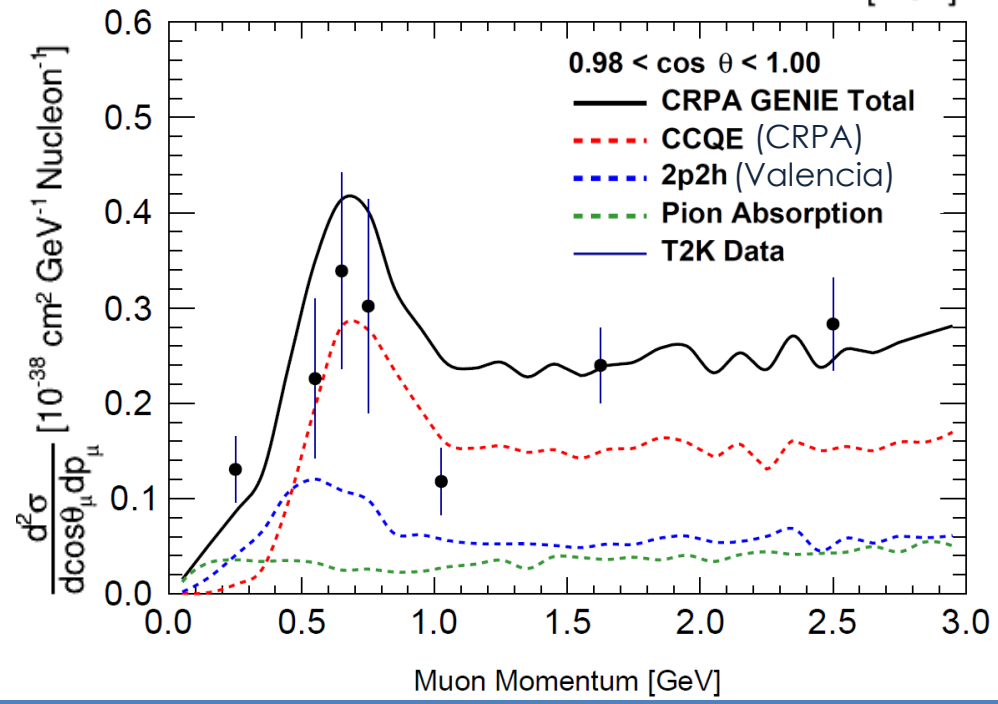


Beyond the impulse approximation

- Remember: these comparisons are to CC0π measurements, there are other contributions besides the CCQE
- Is it possible these are too strong?
- This remains a very open question!!!

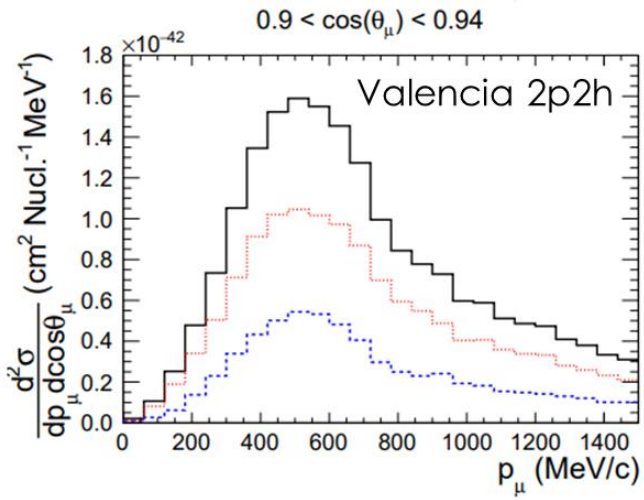


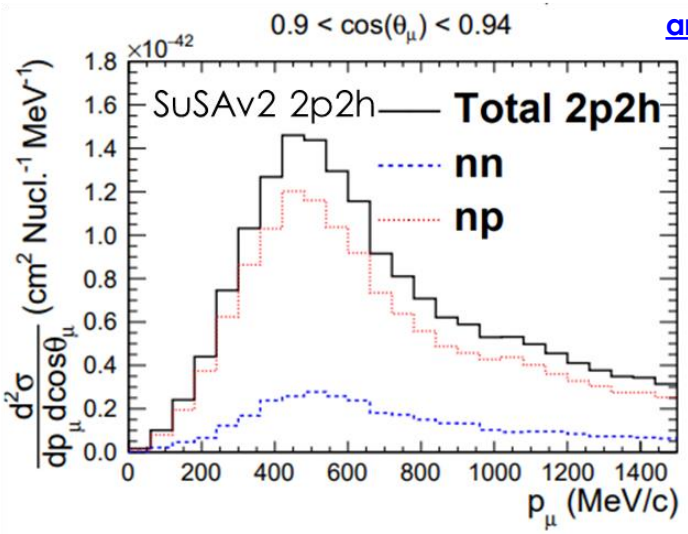




It's getting better - new models

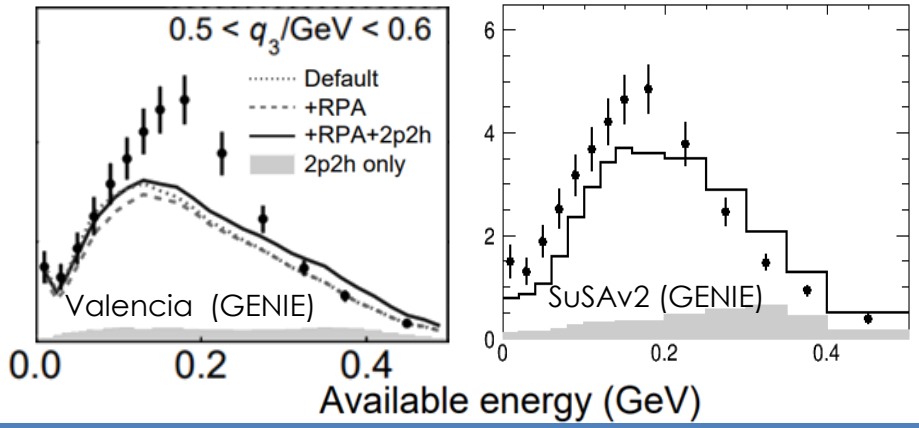
… and also for the distribution of nn and np initial state pairs:





arXiv:1905.08556

- Important implications for predicting available hadronic energy:



- NB: a lot of the variation here is actually also from the 1p1h model variation