Neutrino Generators

Limitations and strategy for future improvements

Stephen Dolan

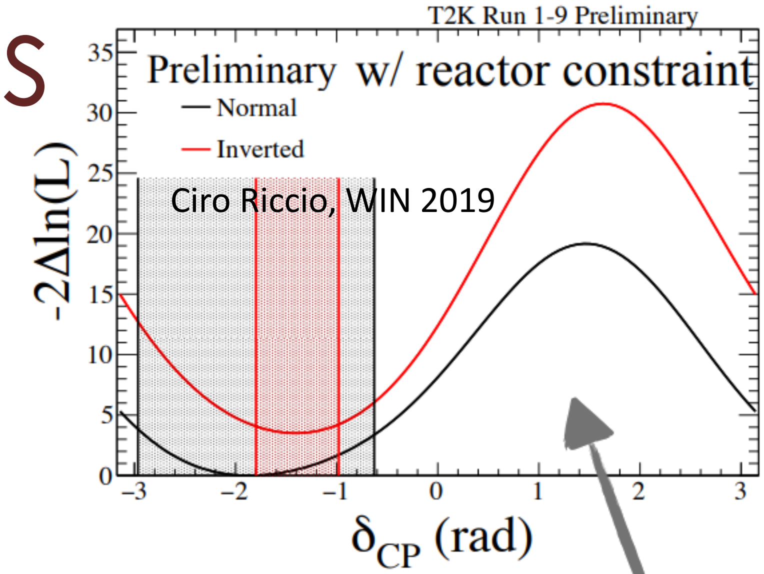
stephen.joseph.dolan@cern.ch

Overview

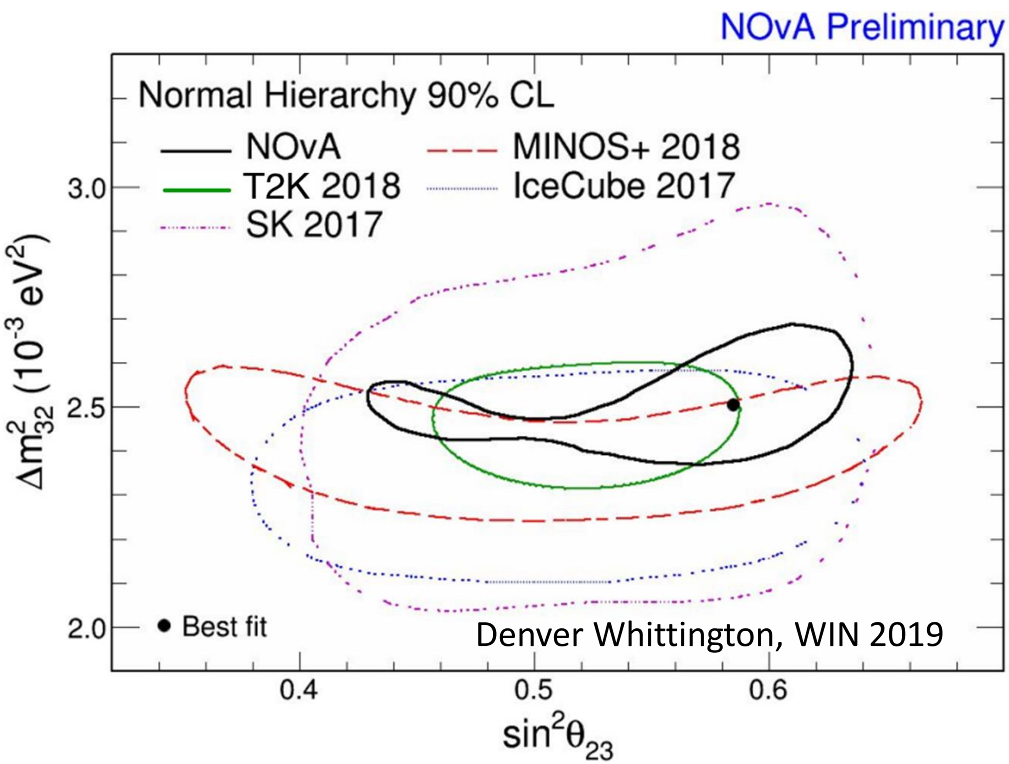
- What do we need from our generators?
- What do we have in our generators?
- How are things improving?
- What next?

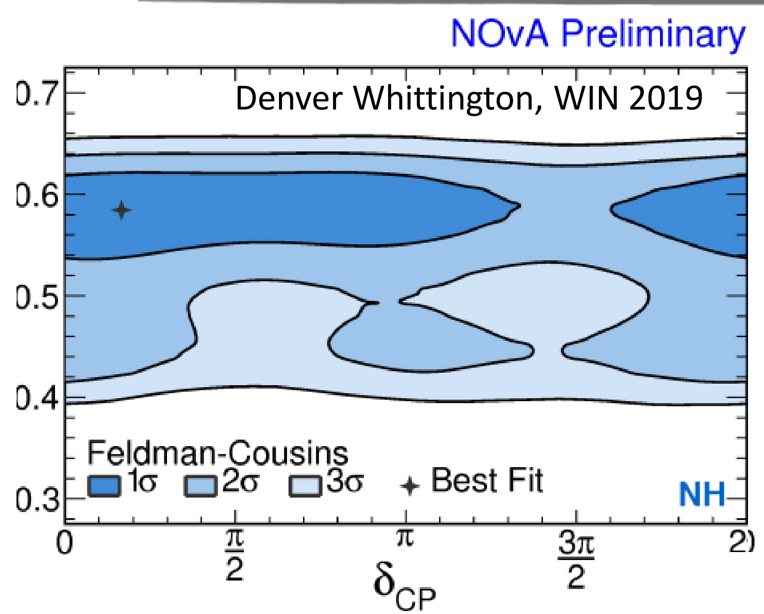
Caveat: I am not a permanent developer of any of the generators

The Latest Results



$\delta_{CP} = 0, \pi$ fall outside 2σ interval

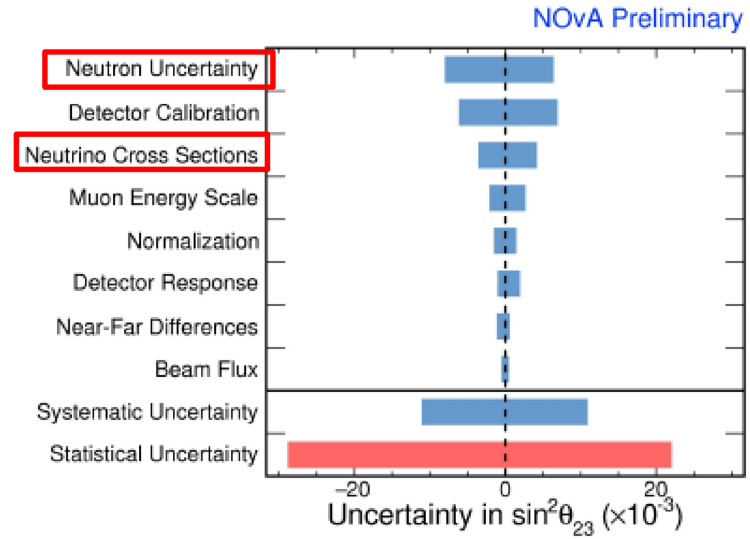




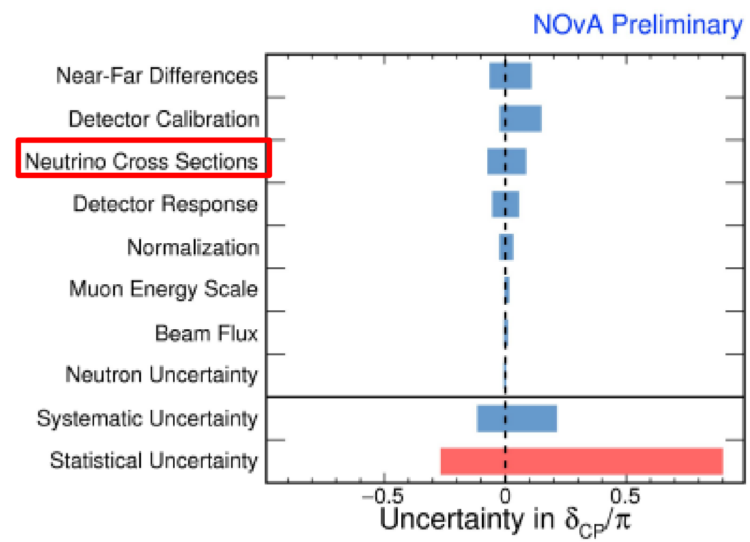
Why can't we do better?

T2K

Error source	1-Ring μ FHC	1-Ring μ RHC	1-Ring e FHC	1-Ring e RHC	1-Ring e FHC 1 d.e.	1-Ring e FHC/RHC
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
SK FSI+SI+PN	2.21	1.98	3.00	2.31	11.43	1.57
Flux + Xsec constrained	3.27	2.94	3.24	3.10	4.09	2.67
E_b	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Osc	0.03	0.03	2.69	2.49	2.63	0.77
All Systematics	5.12	4.45	8.81	7.13	18.38	5.96
All with osc	5.12	4.45	9.19	7.57	18.51	6.03



- Current measurements are statistics limited, but not for long …
- Most worrying systematics related to **neutrino-nucleus interactions**
- Essential total systematic uncertainty <3% for DUNE/T2HK



Neutrino interactions for oscillations

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\,\sigma(E_\nu^{true})\,P(\alpha\rightarrow\beta, E_\nu^{true})\,\epsilon(E_\nu^{true})\,S(E_\nu^{true}, E_\nu^{reco})$$

$N_{pred}(E_\nu^{reco})$ = Expected number of events

$\Phi(E_\nu^{true})$ = Neutrino flux

$\sigma(E_\nu^{true})$ = Interaction cross sections

$P(\alpha\rightarrow\beta, E_\nu^{true})$ = Oscillation probability

$\epsilon(E_\nu^{true})$ = Selection efficiency

$S(E_\nu^{true}, E_\nu^{reco})$ = Smearing matrix

- Need to know $\Phi \times \sigma$ in order to interpret N_{obs} as $P(\alpha \rightarrow \beta)$

Neutrino interactions for oscillations

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\,\sigma(E_\nu^{true})\,P(\alpha\to\beta, E_\nu^{true})\,\epsilon(E_\nu^{true})\,S(E_\nu^{true}, E_\nu^{reco})$$

$N_{pred}(E_\nu^{reco})$ = Expected number of events

$\Phi(E_\nu^{true})$ = Neutrino flux

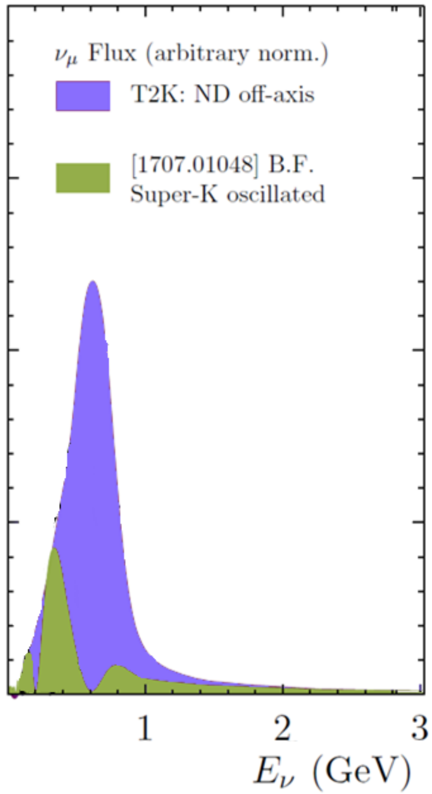
$\sigma(E_\nu^{true})$ = Interaction cross sections

$P(\alpha\to\beta, E_\nu^{true})$ = Oscillation probability

$\epsilon(E_\nu^{true})$ = Selection efficiency

$S(E_\nu^{true}, E_\nu^{reco})$ = Smearing matrix

- Need to know $\Phi \times \sigma$ in order to interpret N_{obs} as $P(\alpha \to \beta)$
- Near / far ratios don't fully cancel this:
  - Dramatic change in E_ν distribution
  - Different ND/FD design, acceptance



Neutrino interactions for oscillations

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\,\sigma(E_\nu^{true})\,P(\alpha\to\beta, E_\nu^{true})\,\epsilon(E_\nu^{true})\,S(E_\nu^{true}, E_\nu^{reco})$$

$N_{pred}(E_\nu^{reco})$ = Expected number of events

$\Phi(E_\nu^{true})$ = Neutrino flux

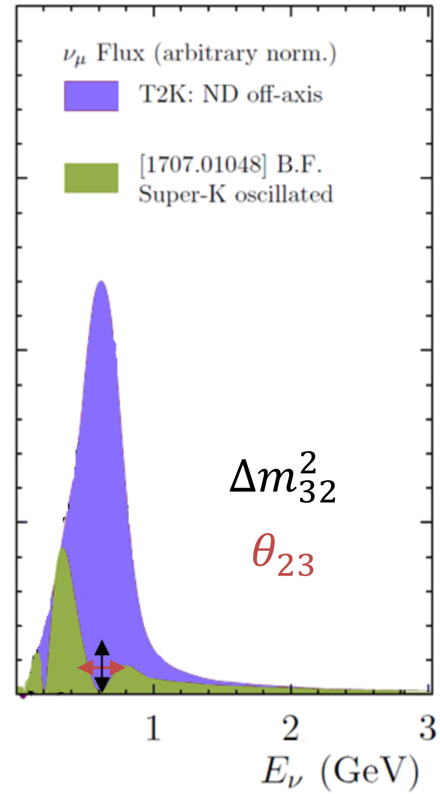
$\sigma(E_\nu^{true})$ = Interaction cross sections

$P(\alpha\to\beta, E_\nu^{true})$ = Oscillation probability

$\epsilon(E_\nu^{true})$ = Selection efficiency

$S(E_\nu^{true}, E_\nu^{reco})$ = Smearing matrix

- Need to know $\Phi \times \sigma$ in order to interpret N_{obs} as $P(\alpha \to \beta)$
- Near / far ratios don't fully cancel this:
  - Dramatic change in E_ν distribution
  - Different ND/FD design, acceptance
- Not just counting experiments: Require a model to relate E_ν^{reco} to E_ν^{true}



Neutrino interactions for oscillations

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\,\sigma(E_\nu^{true})\,P(\alpha\rightarrow\beta, E_\nu^{true})\,\epsilon(E_\nu^{true})\,S(E_\nu^{true}, E_\nu^{reco})$$

$N_{pred}(E_\nu^{reco})$ = Expected number of events

$\Phi(E_\nu^{true})$ = Neutrino flux

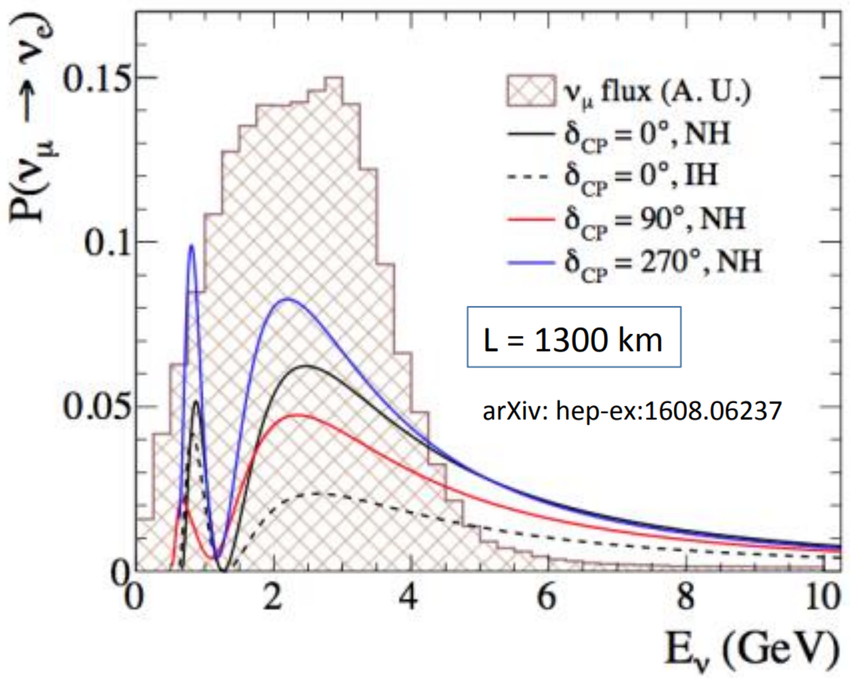
$\sigma(E_\nu^{true})$ = Interaction cross sections

$P(\alpha\rightarrow\beta, E_\nu^{true})$ = Oscillation probability

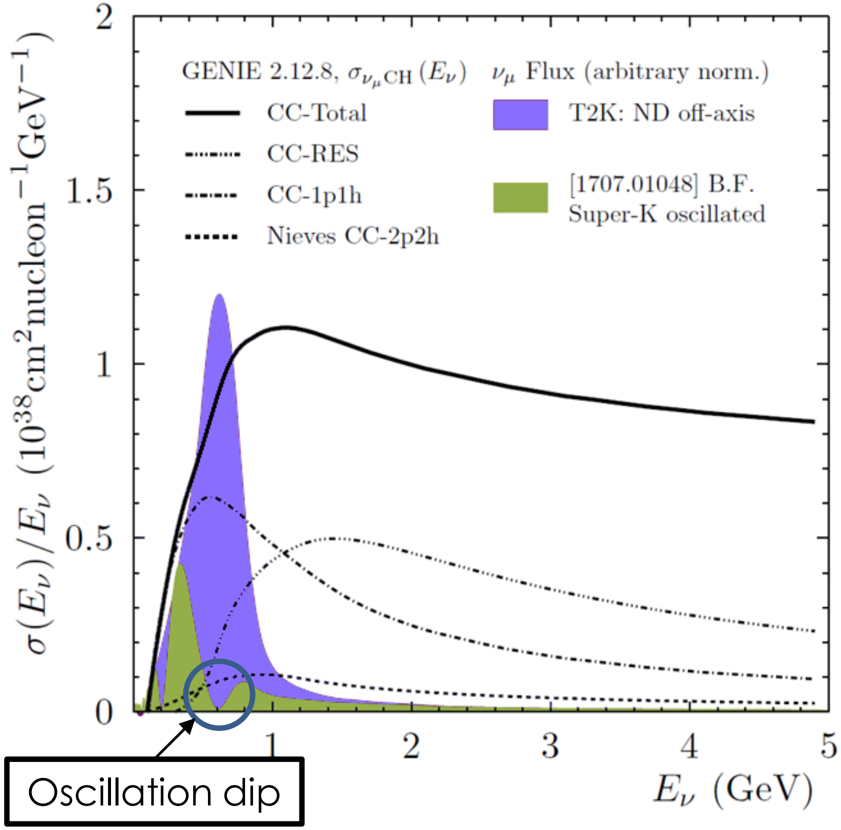
$\epsilon(E_\nu^{true})$ = Selection efficiency

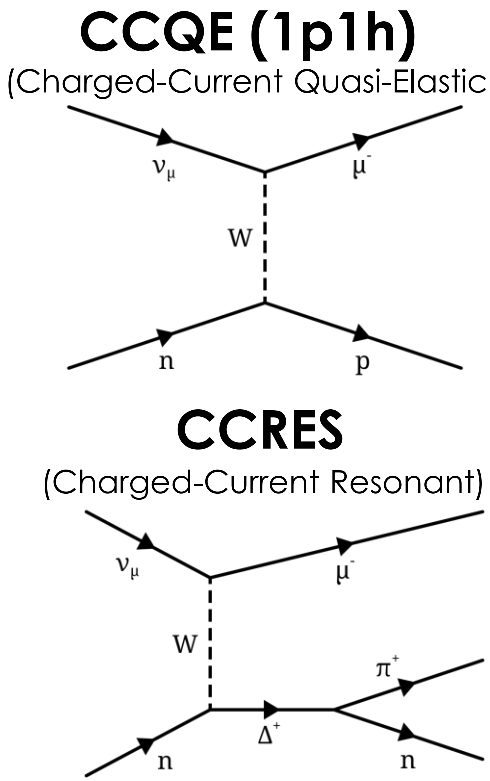
$S(E_\nu^{true}, E_\nu^{reco})$ = Smearing matrix

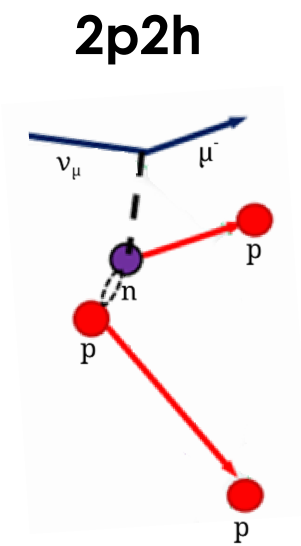
- Even more important for experiments wanting to measure the 2nd oscillation maximum (DUNE, T2HKK)



Neutrino Interactions at T2K/HK







- Reconstruct neutrino energy from muon kinematics in CC pionless events at SK

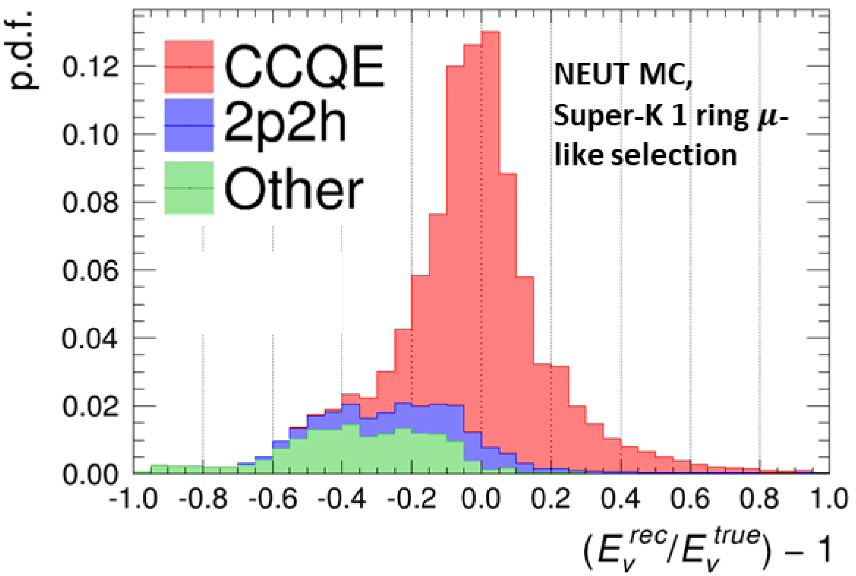
$$E_\nu^{reco} = \frac{m_p^2 - m_n^2 - m_\mu^2 + 2m_n E_\mu}{2(m_n - E_\mu + p_\mu \cos(\theta_\mu))}$$

- Assume **stationary target** and **CCQE scattering** …

Neutrino Interactions at T2K/HK

- Reconstruct neutrino energy from muon kinematics in pionless events at SK
- Assume **stationary target** and **CCQE scattering …**

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

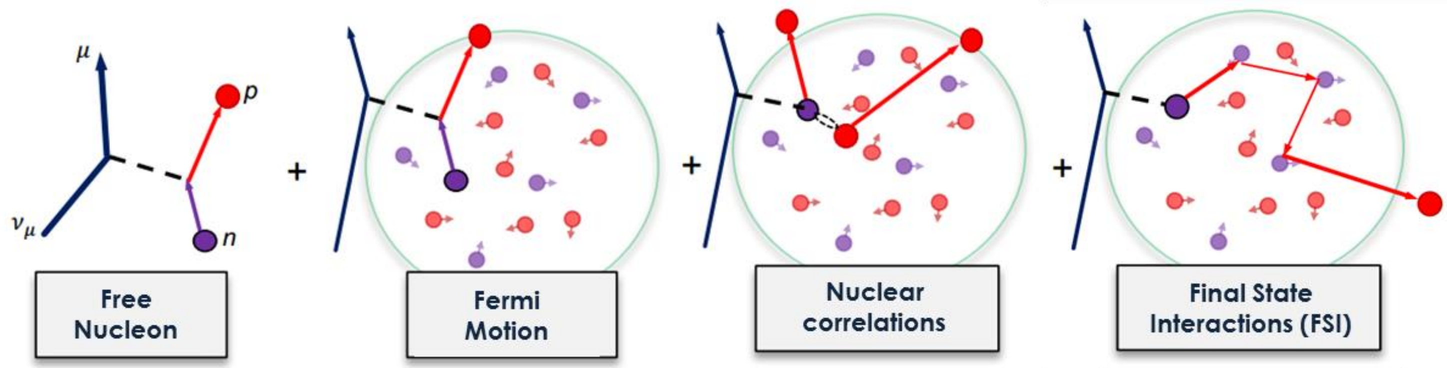


Bias due to:

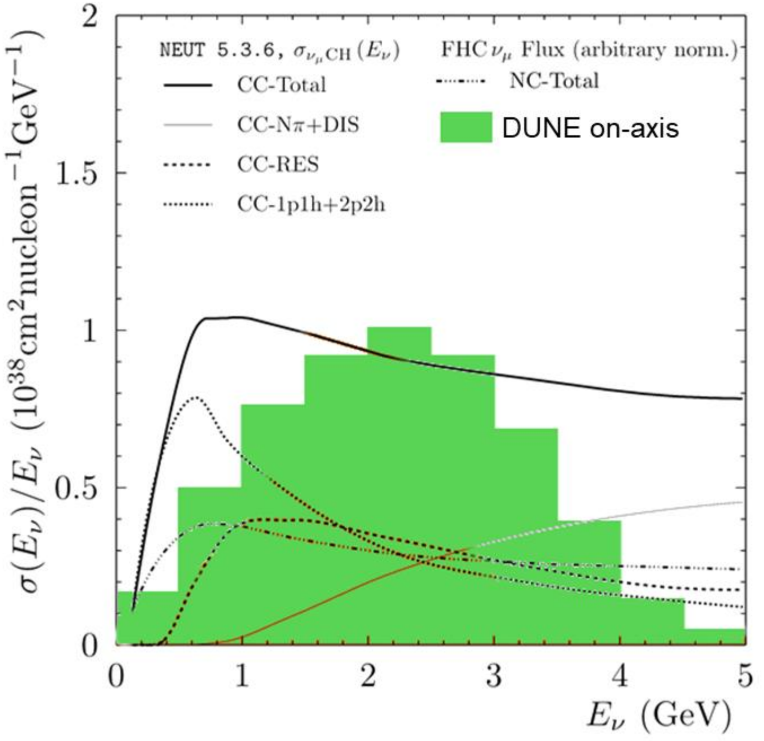
- Initial state: **Fermi motion, binding energy**
- Nucleon-nucleon **correlations**
- Pion absorption **FSI** → CCnonQE events

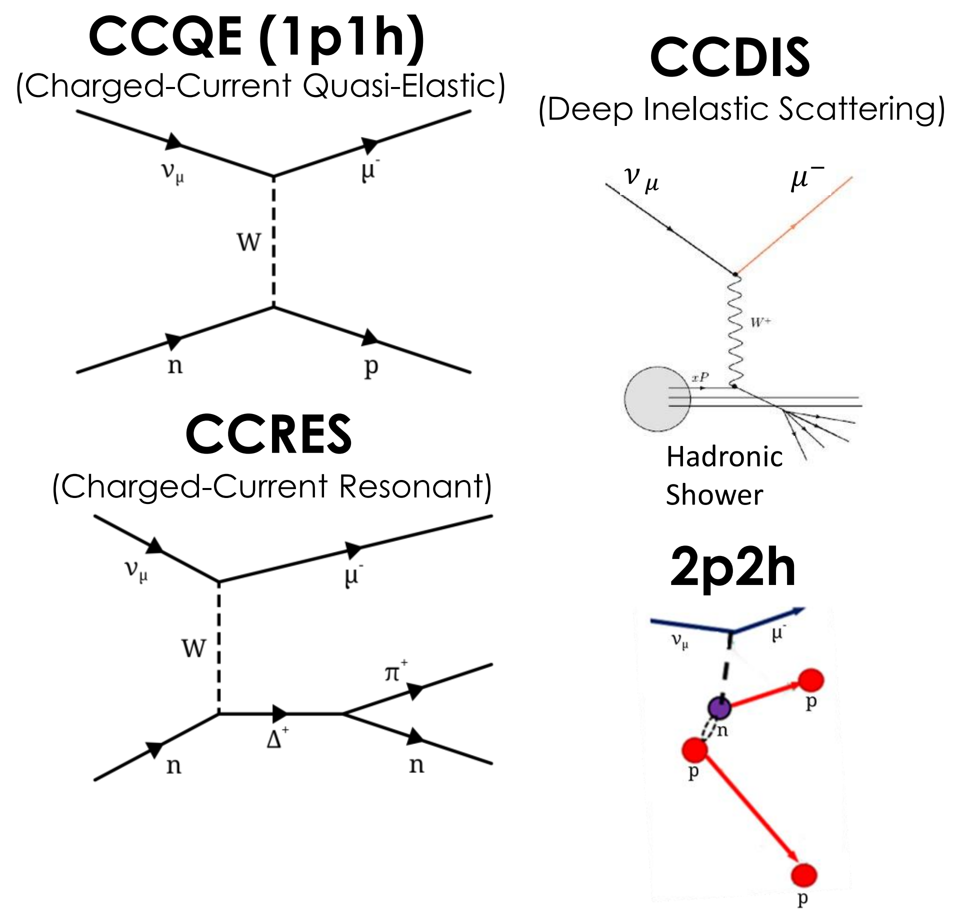
Correct for bias using models!

Nuclear Effects



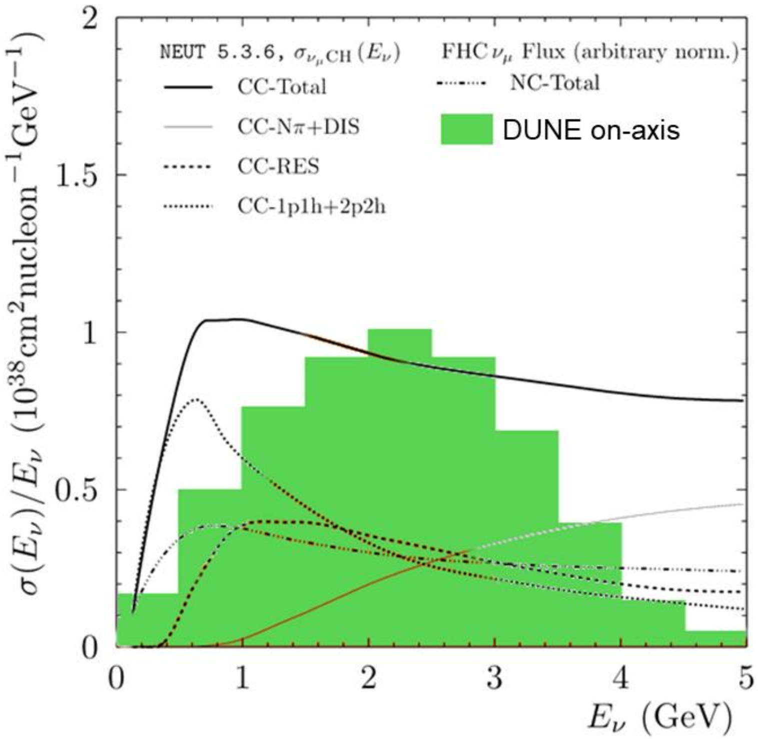
Neutrino Interactions at DUNE

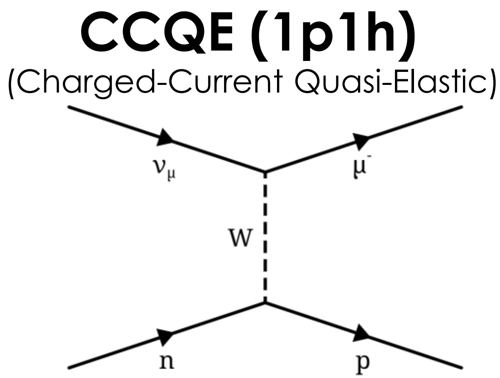


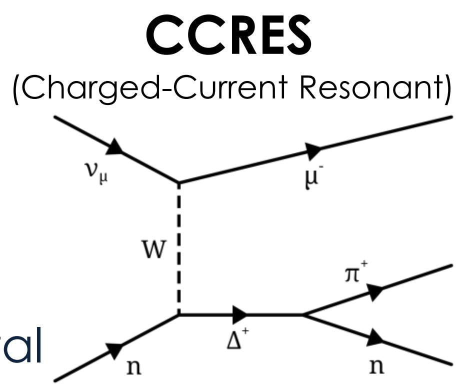


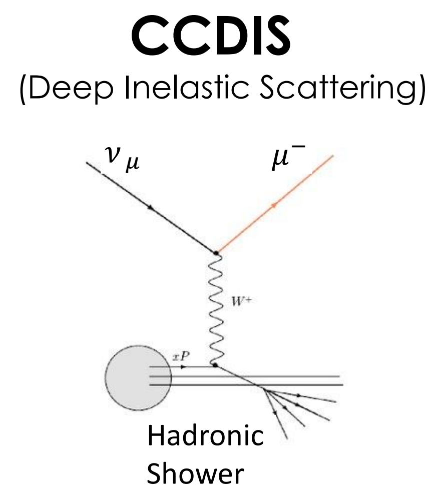
- DUNE's higher energy beam means most interactions are not CCQE
- DIS interactions become important
- T2K method of reconstructing neutrino energy will not work

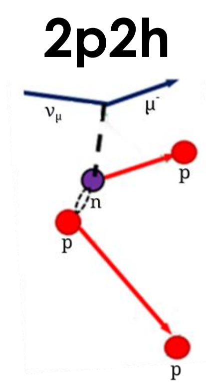
Neutrino Interactions at DUNE





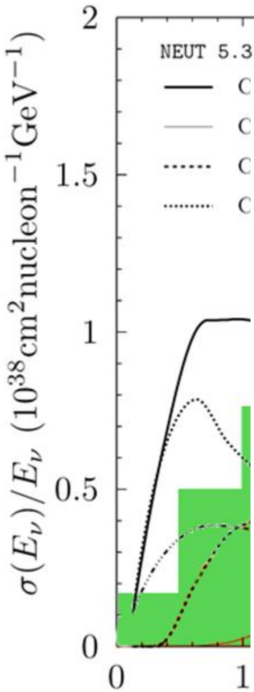


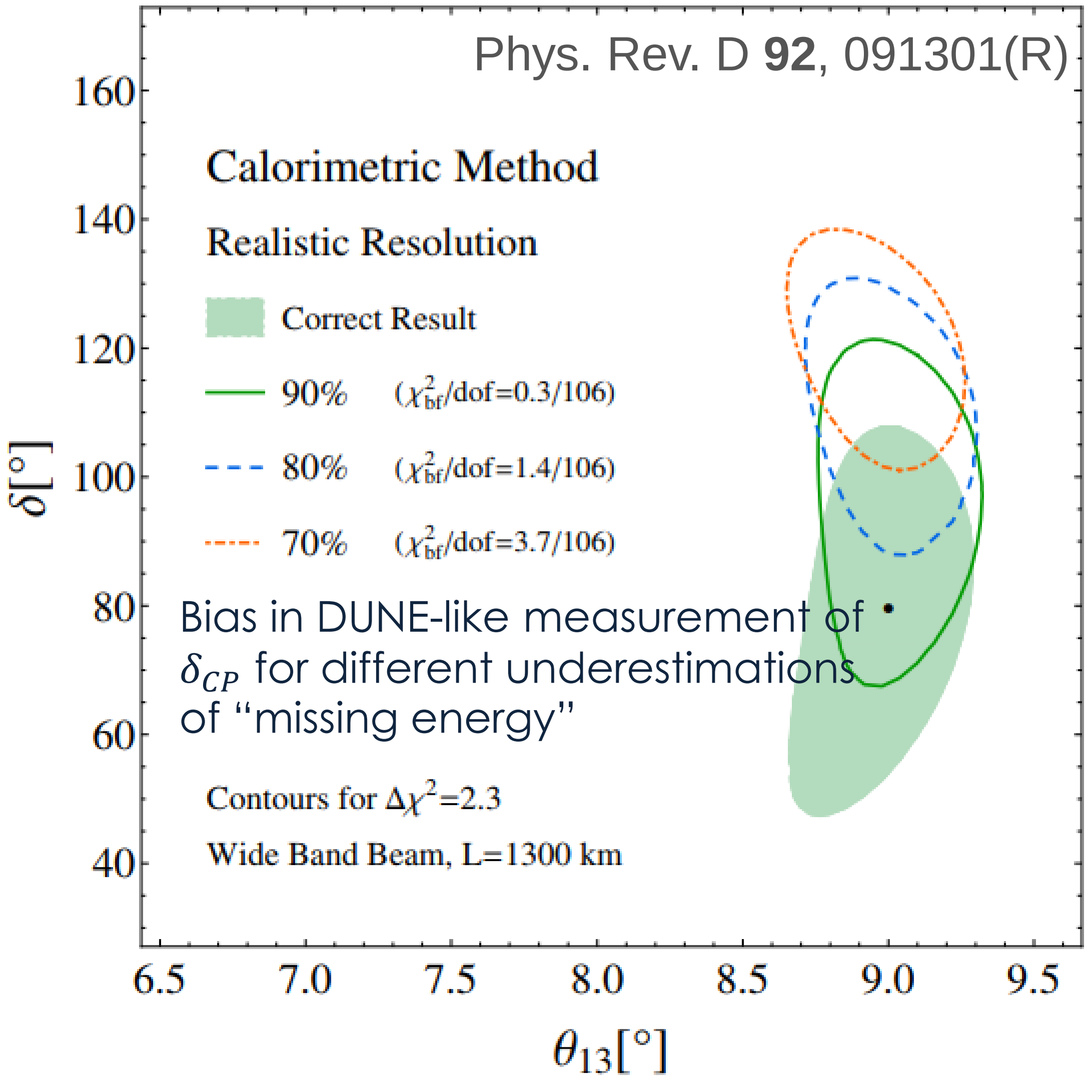




- Reconstruct neutrino energy from total energy deposited in the detector
- Misses most **neutrons** …
- **Rely on models** to tell us about neutrons:
  - Number of np, nn, pp initial state pairs in 2p2h
  - Neutrons produced through FSI
  - Neutron energy fraction in RES or DIS events
- **Large systematics**

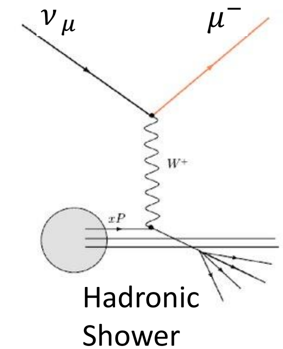
Neutrino Interactions at DUNE



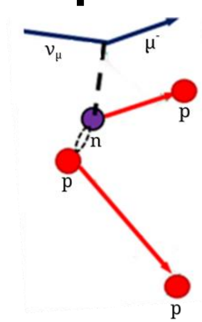


CCDIS

(Deep Inelastic Scattering)



2p2h



- Reconstruc… energy dep…
- Misses most … bout neutrons:
  - … ial state pairs in 2p2h
  - … ugh FSI
  - … in RES or DIS events
- **Large sy…**

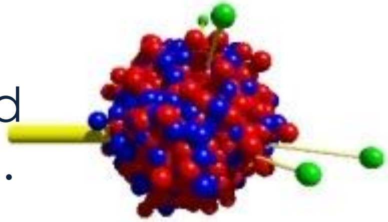
The Generators

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.

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

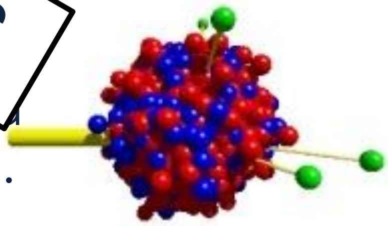
GENIE: very widely used. Large development team. Used as default simulations by most Fermilab neutrino experiments.

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

NuWro: wide range of mo… …ble. Driven more by theory than by experimental requiren… …a few developers.

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

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.



What do we need? (adapted from NuSTEC white paper)

- Consistent predictions for each neutrino interaction mode
- Predictions of exclusive final-states (outgoing nucleon kinematics)
- A validated and reliable modelling of nuclear effects, informed by electron and hadron scattering data

What do we have?

- ~~Consistent predictions for each neutrino interaction mode~~
  Each interaction mode is based on a different nuclear model – few unified predictions
- ~~Predictions of exclusive final-states (outgoing nucleon kinematics)~~
  Few semi-inclusive predictions implemented in generators. Even those that exist rely on approximations.
- ~~A validated and reliable modelling of nuclear effects, informed by electron and hadron scattering data~~
  Few models validated against e-scatting data, lots of tensions describing neutrino scattering data

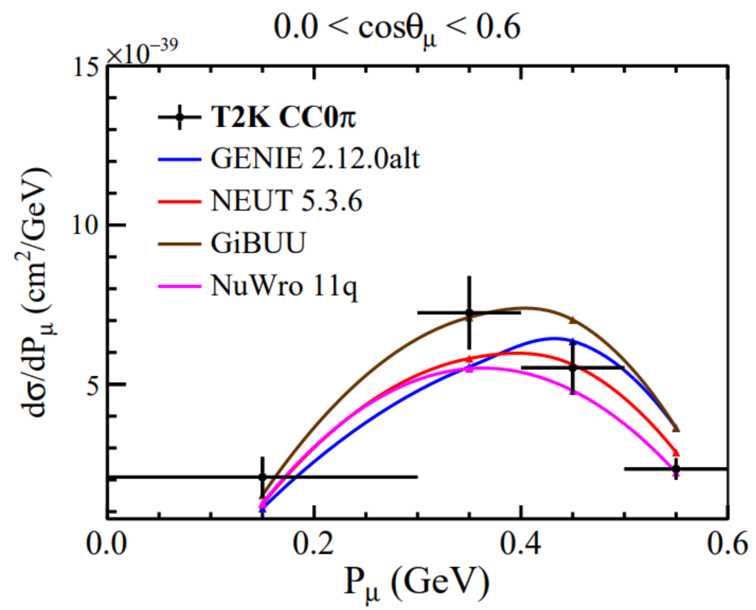
What do we have?

- ~~Consistent predictions for each neutrino interaction mode~~
  - Each interaction mode is based on a different nuclear model – few unified predictions
- ~~Predictions of exclusive final-states (outgoing nucleon kinematics)~~
  - Few semi-inclusive predictions implemented in generators. Even those that exist rely on approximations.
- ~~A validated and reliable modelling of nuclear effects, informed by electron and hadron scattering data~~
  - Few models validated against e-scatting data, lots of tensions describing neutrino scattering data

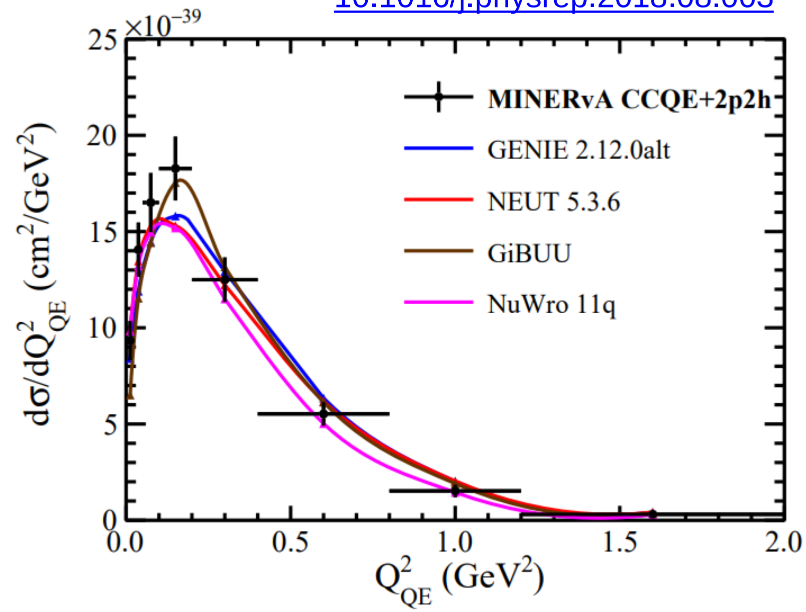
But things are getting better ….

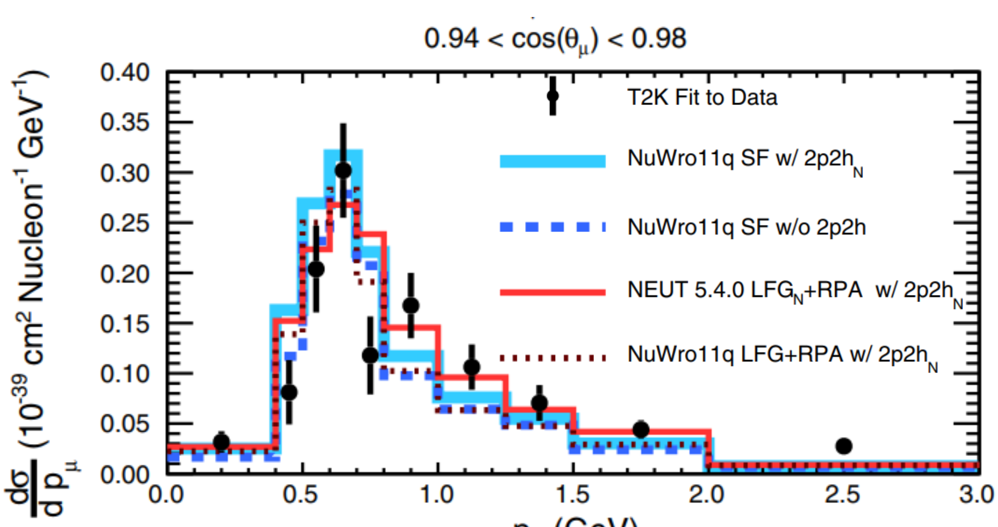
A year ago …

- Generators able to broadly describe outgoing lepton kinematics
- But even wildly differing nuclear models look fairly similar …



10.1016/j.physrep.2018.08.003

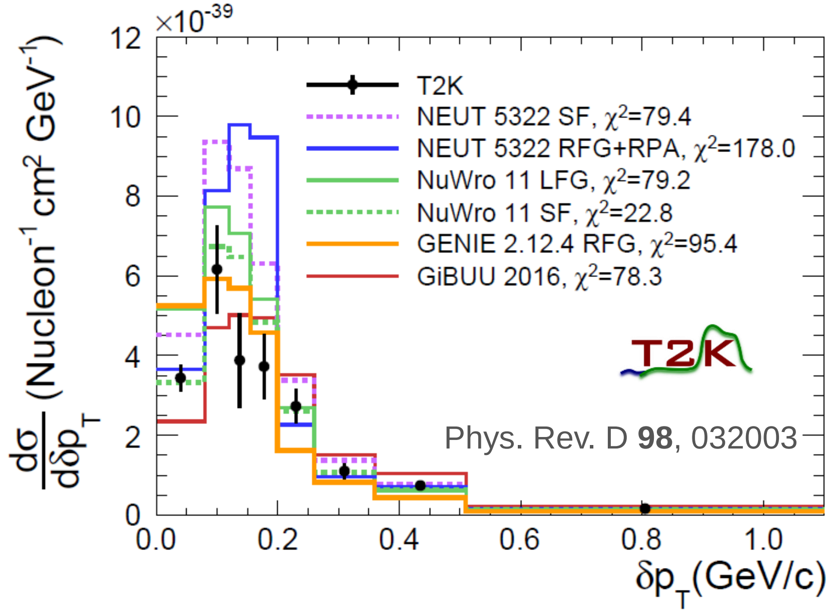


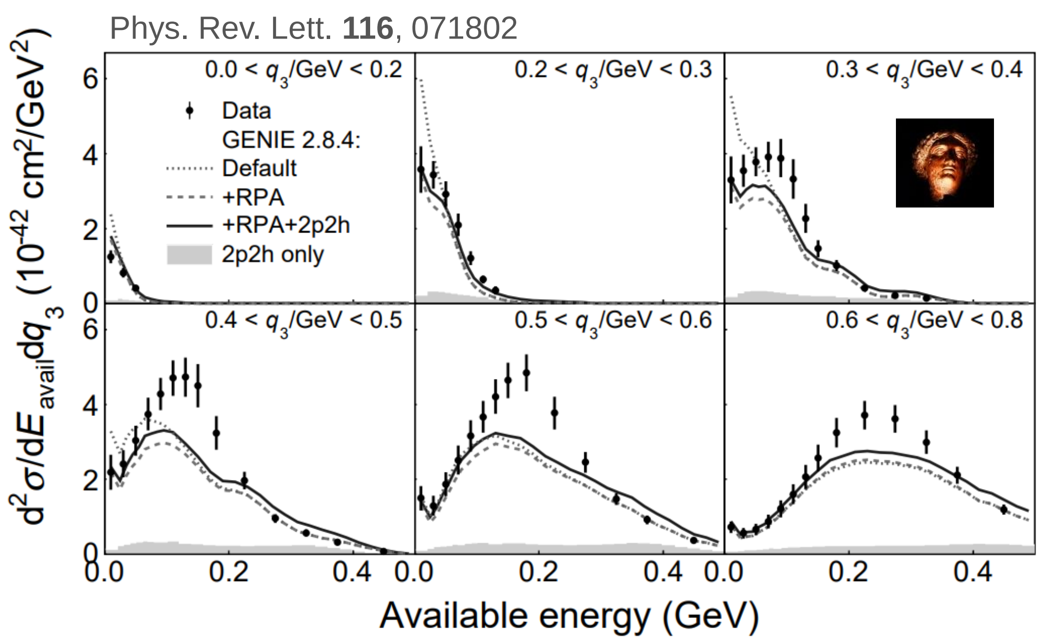


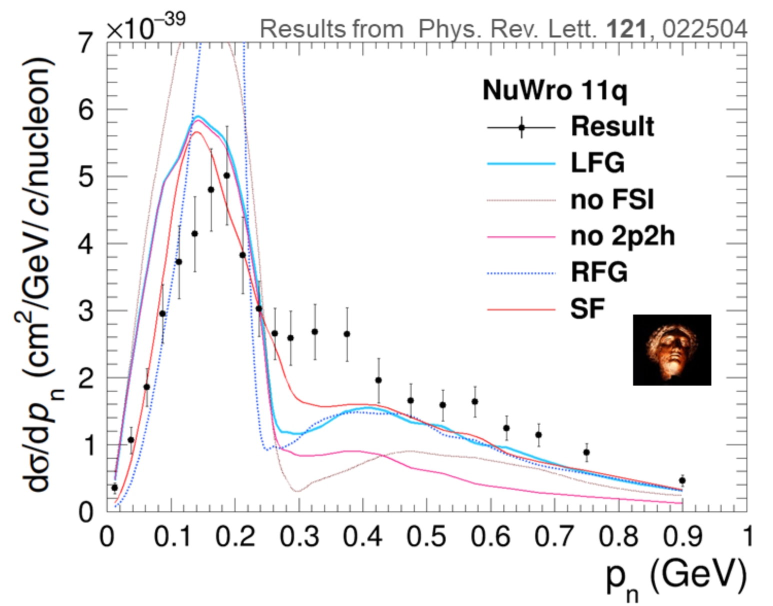
Phys. Rev. D **98**, 032003

A year ago …

- Hadron kinematics was another story: most models couldn't get close!
- Clearly a problem for future oscillation measurements, especially those that reconstruct E_ν using hadronic energy measurements

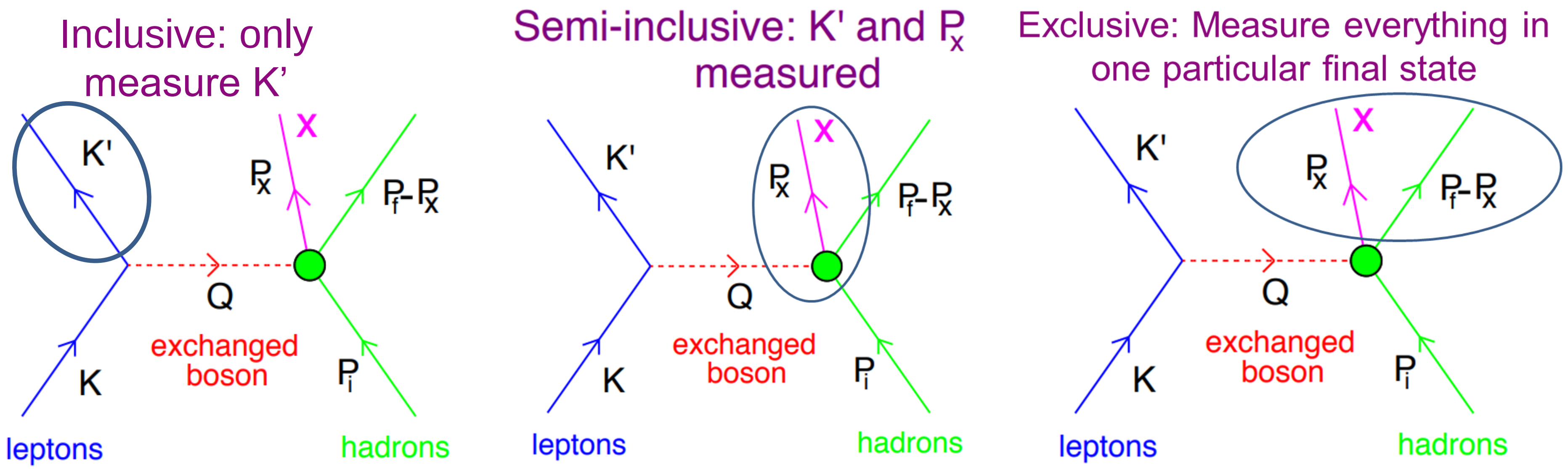






Why so bad?

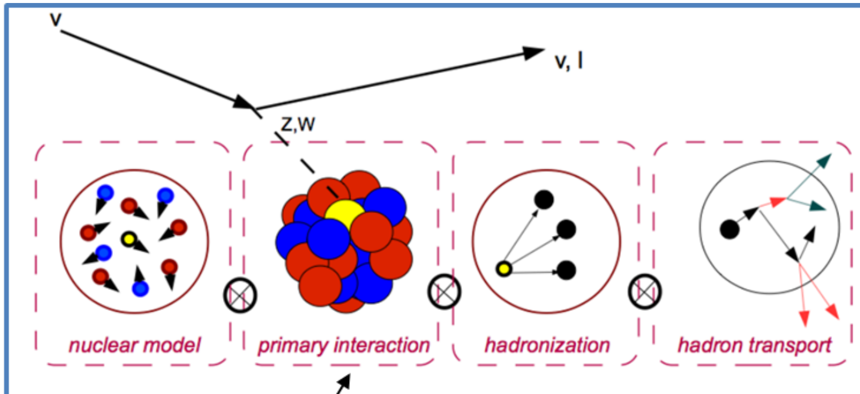
- Asking for hadron kinematics, we need a *(semi)exclusive* input
  - For CCQE interactions, something like: $\frac{d^6\sigma}{d\omega dq_3 dE_m d\boldsymbol{p_m}}$
- But the theory input we had was typically* pre-integrated *inclusive* cross sections, giving us only the lepton kinematics
  - Something like: $\frac{d^2\sigma}{d\omega dq_3}$ or maybe just $\frac{d\sigma}{dQ^2}$



* The Spectral function model in NEUT and NuWro is sort-of an exception, but this is a whole different topic

Why so bad?

- Asking for hadron kinematics, we need a *(semi)exclusive* input
  - For CCQE interactions, something like: $\frac{d^6\sigma}{d\omega dq_3 dE_m d\boldsymbol{p}_m}$
- But the theory input we had was typically* pre-integrated *inclusive* cross sections, giving us only the lepton kinematics
  - Something like: $\frac{d^2\sigma}{d\omega dq_3}$ or maybe just $\frac{d\sigma}{dQ^2}$
- Generators mostly produced hadron kinematics by *factorising* the interaction into a lepton and hadron part before conserving $(E, \boldsymbol{p})$ at the vertex
- Gives us something to work with, but misses important physics

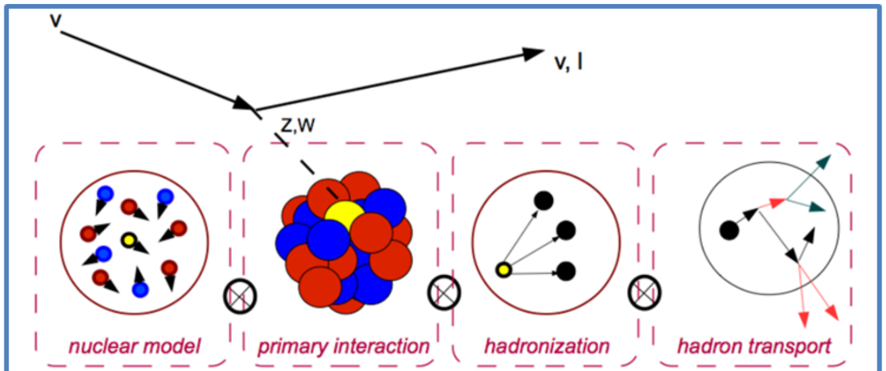


We use an inclusive ($\frac{d\sigma}{d\omega dq_3}$) model for this.
The rest is *ad-hoc* nuclear / FSI models.

* The Spectral function model in NEUT and NuWro is sort-of an exception, but this is a whole different topic

Why so bad?

- Asking for hadron kinematics, we need a *(semi)exclusive* input
  - For CCQE interactions, something like: $\frac{d^6\sigma}{d\omega dq_3 dE_m d\boldsymbol{p_m}}$
- But the theory input we had was typically* pre-integrated *inclusive* cross sections, giving us only the lepton kinematics
  - Something like: $\frac{d^2\sigma}{d\omega dq_3}$ or maybe just $\frac{d\sigma}{dQ^2}$
- Generators mostly produced hadron kinematics by *factorising* the interaction into a lepton and hadron part before conserving $(E, \boldsymbol{p})$ at the vertex
- Gives us something to work with, but misses important physics



We use an inclusive ($\frac{d\sigma}{d\omega dq_3}$) model for this.

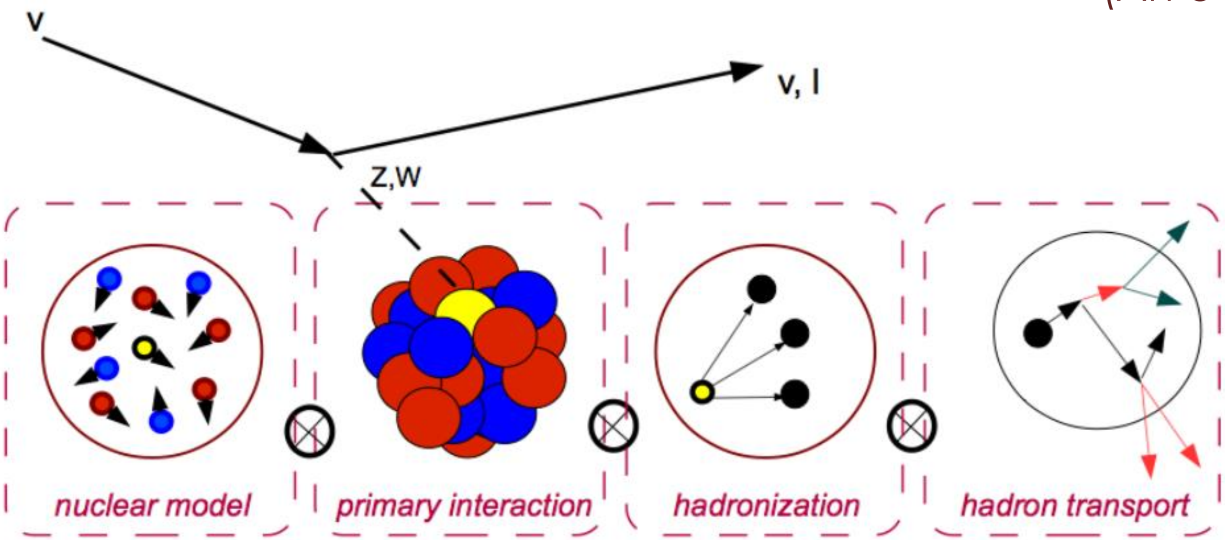
The rest is *ad-hoc* nuclear / FSI models.

- Beyond this, not all the inclusive models could also predict electron scattering data so **could not be validated** using it (for 2p2h especially)

* The Spectral function model in NEUT and NuWro is sort-of an exception, but this is a whole different topic

Event generation until recently

(An oversimplified view)



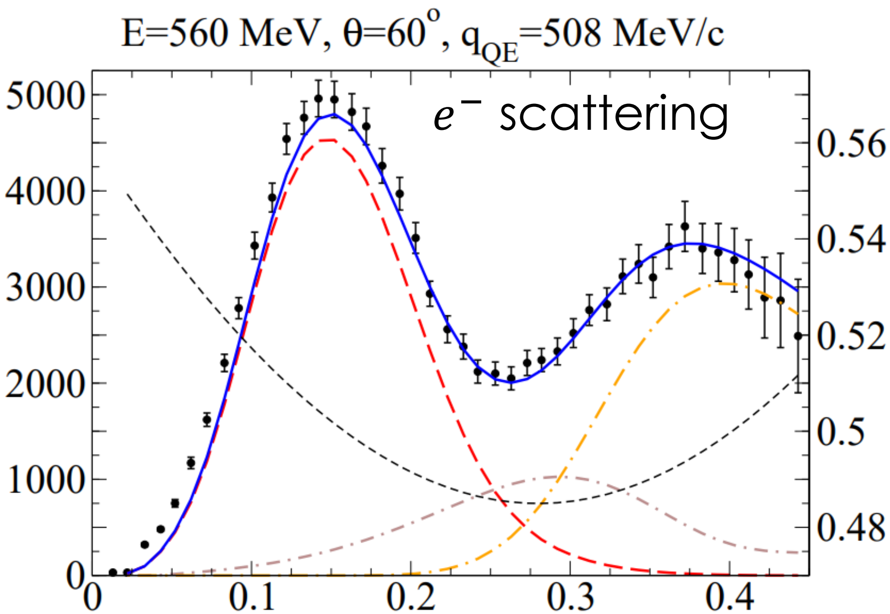
1. Choose outgoing lepton kinematics based on input inclusive cross section

2. Choose initial state nucleon $(E, \boldsymbol{p})$ based on some input spectral function

3. Is the nucleon Pauli-blocked? If so start again.

4. Take final-state nucleon and put it through a semi-classical FSI cascade.

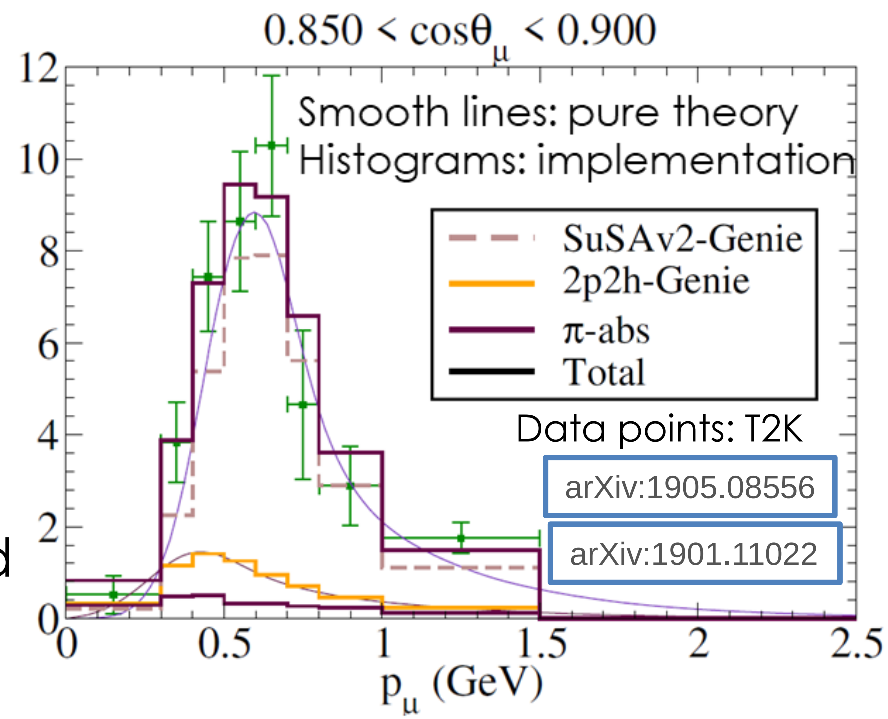
It's getting better - new models



SuSAv2-MEC 1p1h and 2p2h models implemented into the GENIE and NuWro (2p2h only) event generators

Phys. Rev. C **90**, 035501

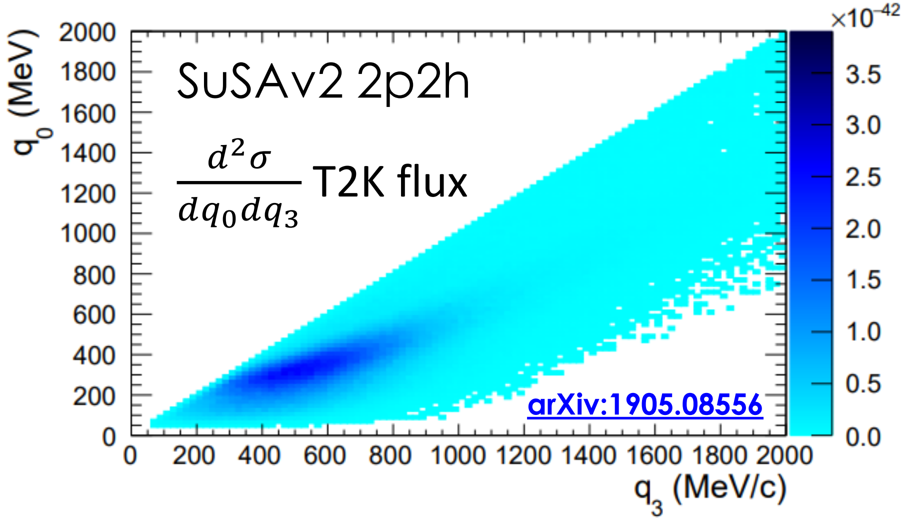
J. Phys. G **46** (2019) no.1, 015104

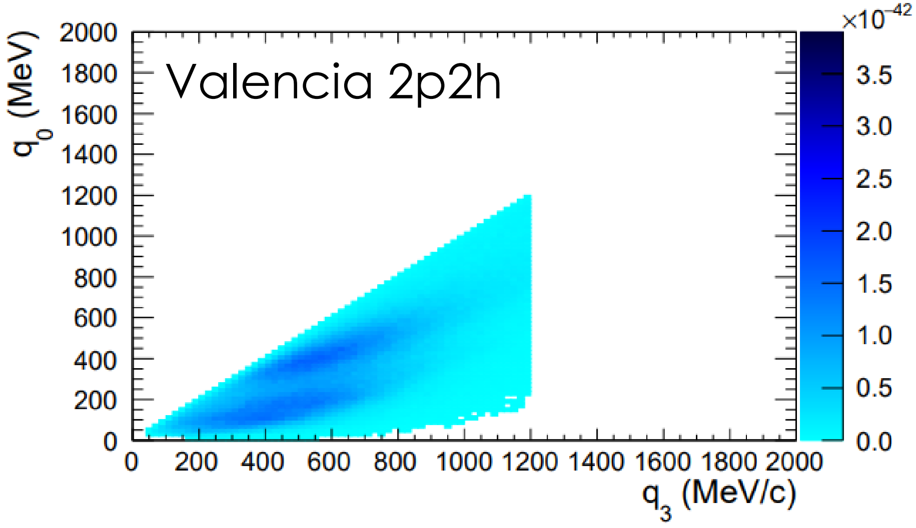


- ✓ Validated on electron scattering
- ✓ Built on a semi-inclusive model (RMF)
- X Currently implemented as an inclusive model – more work needed

It's getting better - new models

- Significant differences in approximations for 2p2h prediction gives very different model predictions for the 2p2h cross section …

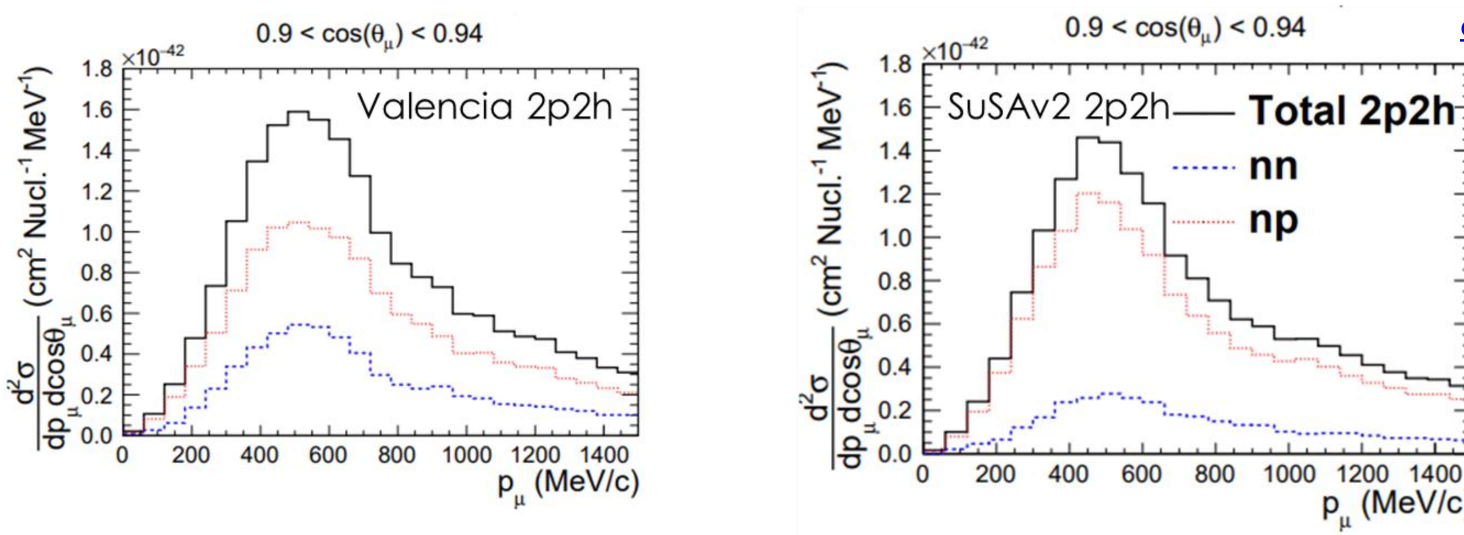




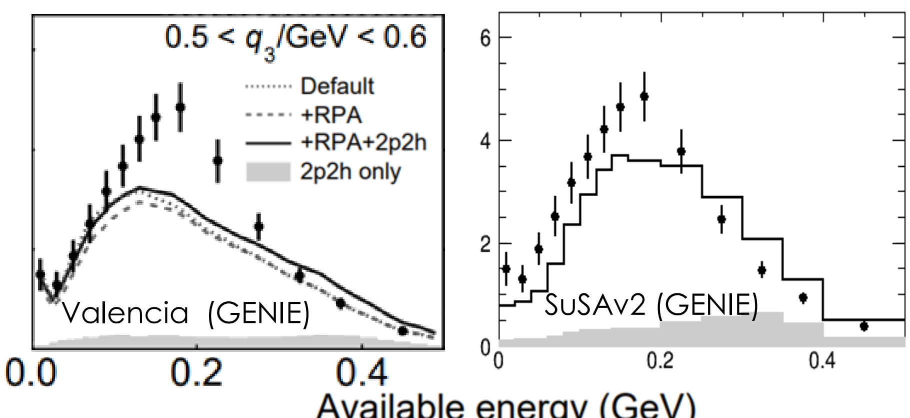
It's getting better - new models

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

[arXiv:1905.08556](https://arxiv.org/abs/1905.08556)



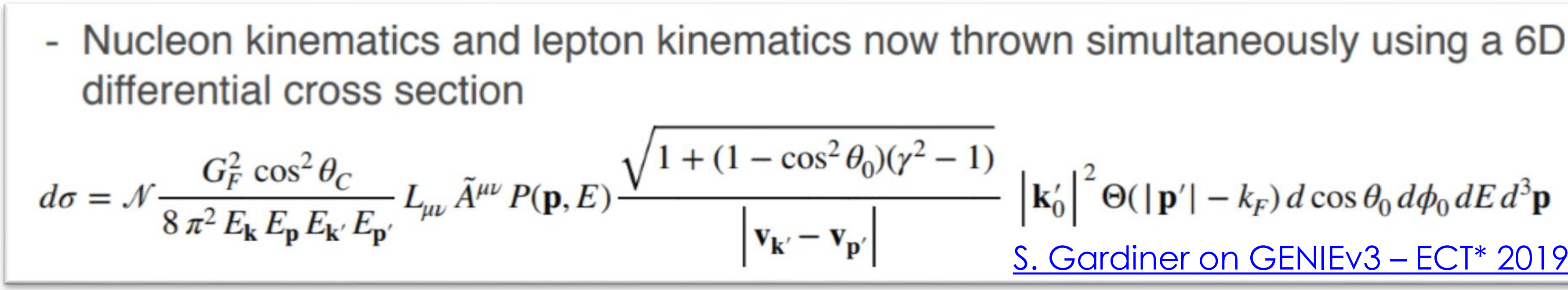
- Important implications for predicting available hadronic energy:



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

It's getting better – exclusive calculations

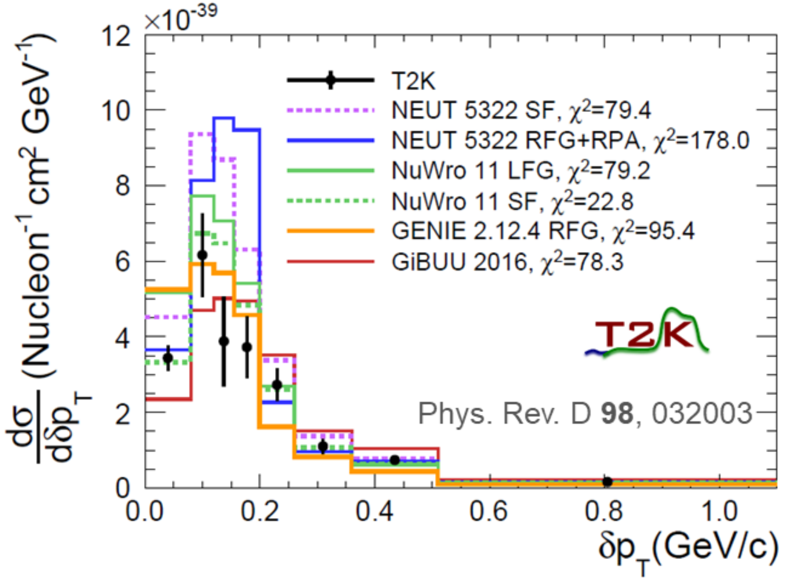
- Generators are also now including more exclusive 1p1h calculations

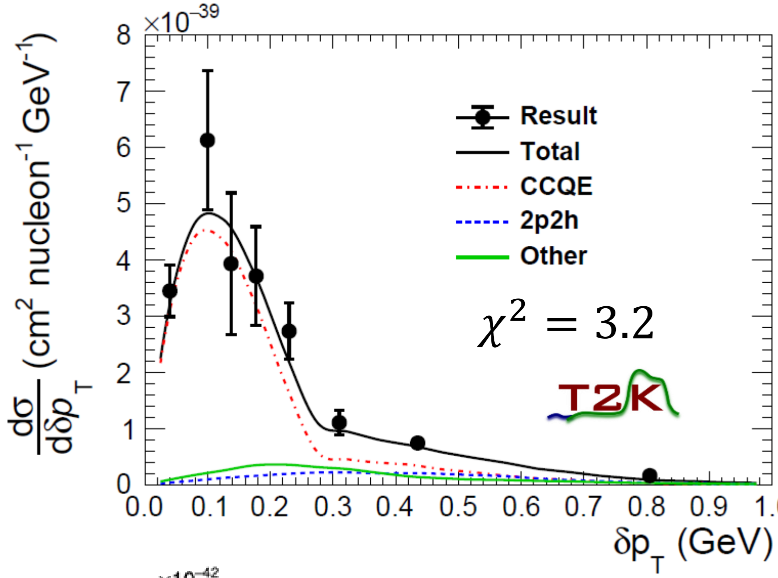


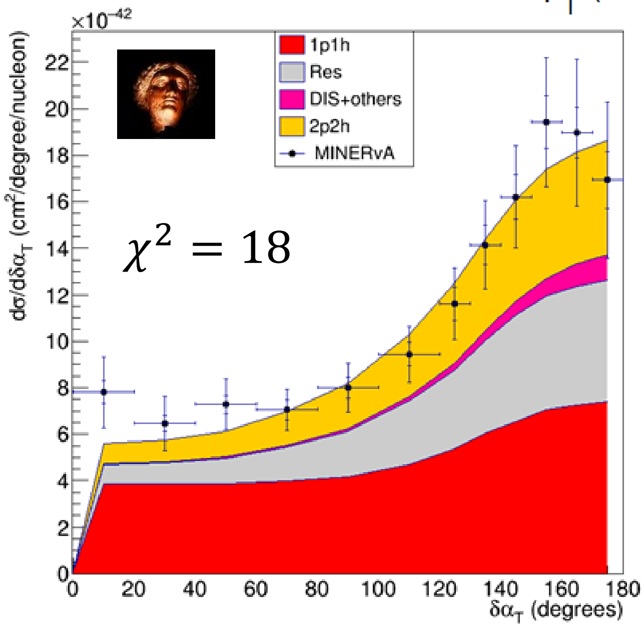
- Improved treatments of binding energy (not simply a fixed number, better treatment of initial state nucleon)

- But we are still stuck with more simple approaches for pion-production and 2p2h …

It's getting better – exclusive calculations







- For semi-inclusive 1p1h-dominated predictions, new generators can do astoundingly well!
- Shown here is an update to Valencia 1p1h+2p2h in NEUT (F. Sanchez)

It's getting better – exclusive calculations

- Work in progress to implement fully exclusive models (e.g. RMF) into the generators – theory directly predicts outgoing nucleon kinematics (without relying on PWIA)

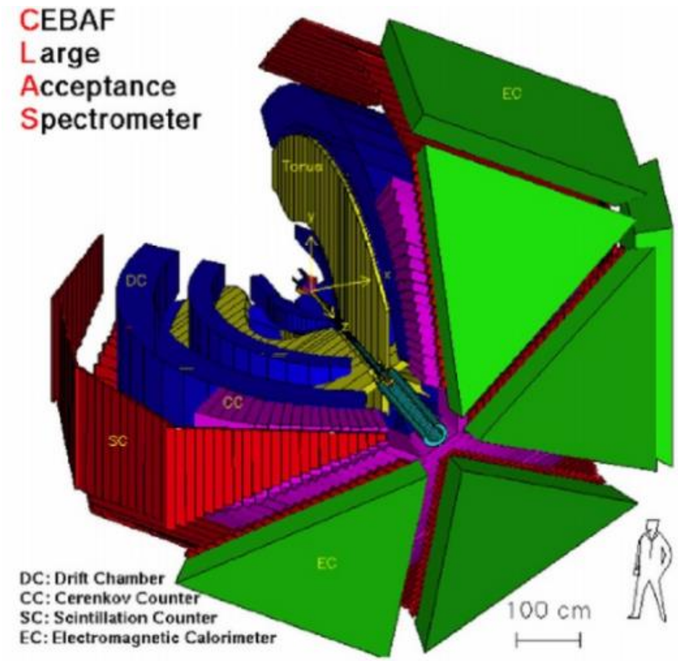
Question: what do we do about FSI for these models – theory only predicts the primary nucleon, but we need to also account for nuclear emission (e.g. π-production FSI)

Option 1: Put the final state nucleon through an FSI cascade? Double counts effect of FSI on the nucleon …

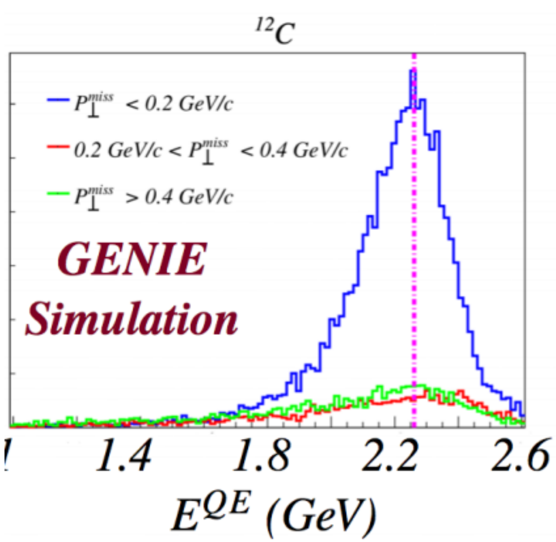
Option 2: Remove some FSI from the model (the imaginary part of the optical potential?), then use this as an input to the cascade?
    - This idea at ECT* last month

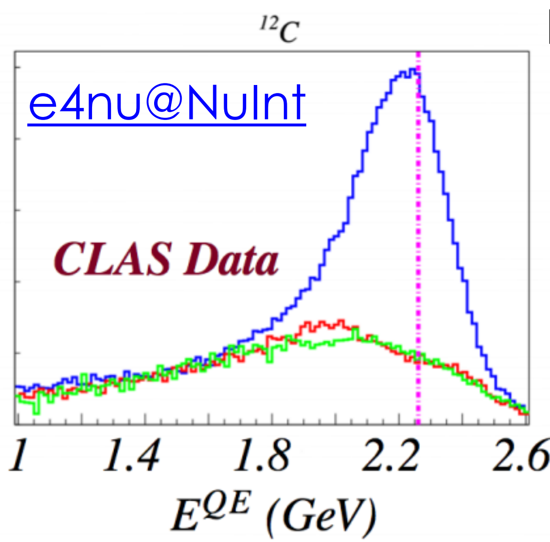
Option 3: ???

It's getting better – e4nu



- 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:

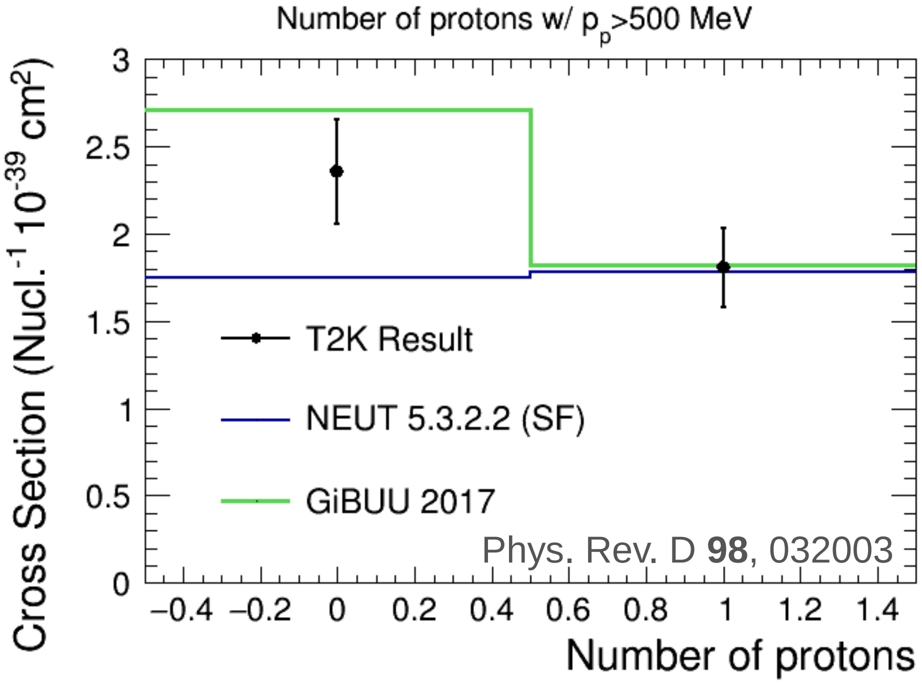
- In CLAS we know $E_{e,inital}$
- But can still reconstruct it as if it was a neutrino
- See how well generators predict this
- Almost a direct test of bias in neutrino scattering

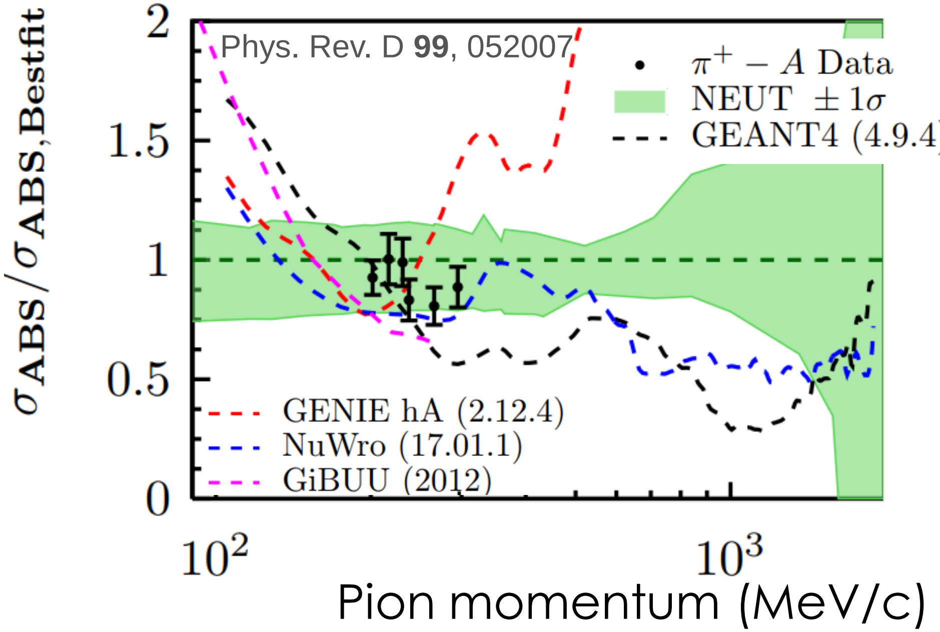
Still trouble – FSI modelling

- Typically use semi-classical cascades to describe effects of FSI on the outgoing hadrons
- **Exception**: GiBUU uses a more sophisticated transport theory

Buss et al, Phys. Rept. 512 (2012) 1- 124

- Quite different predictions for pion and nucleon FSI – improved understanding is crucial

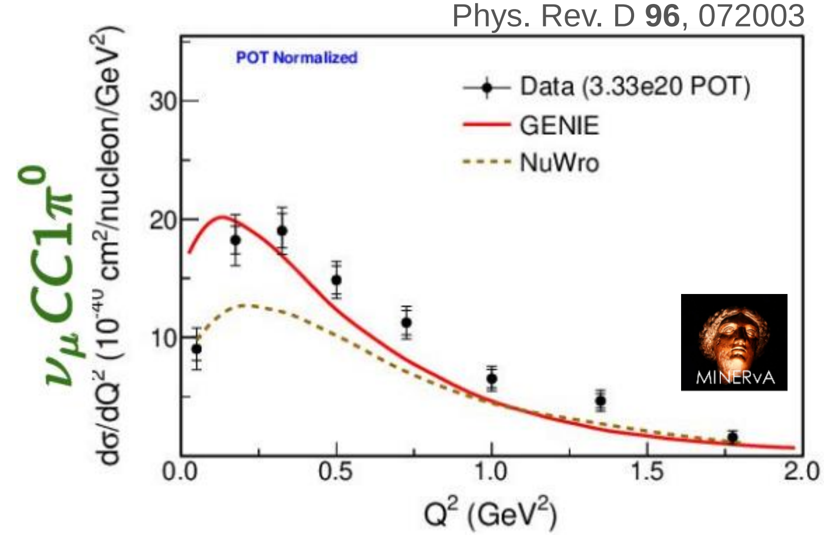




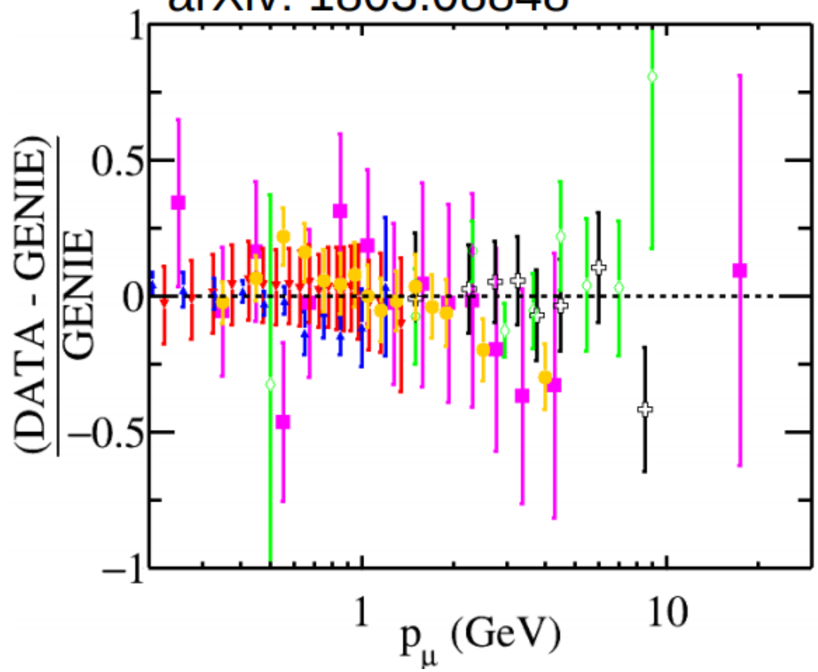
Still trouble – pion production

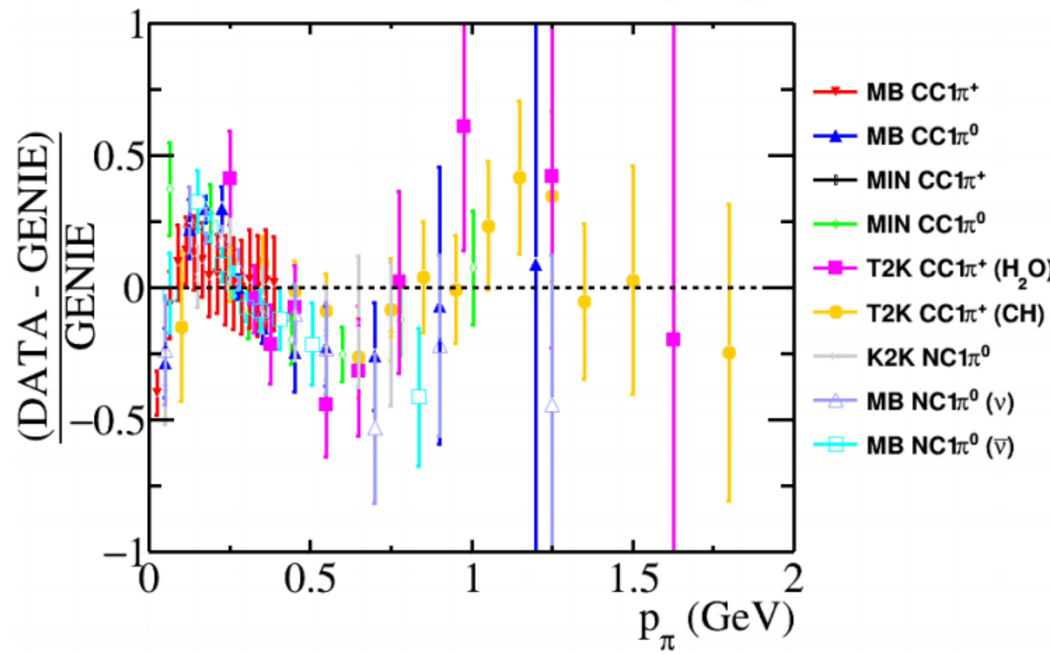
- Use a simplistic model (Rein-Segal based) missing ingredients. Few theoretical alternatives now, but WIP.
- Seems able to describe lepton kinematics, but not the pion's
- Particular problems at low Q^2 - RPA for pions ??? (doesn't make much sense …)

Phys. Rev. D **96**, 072003



arXiv: 1803.08848

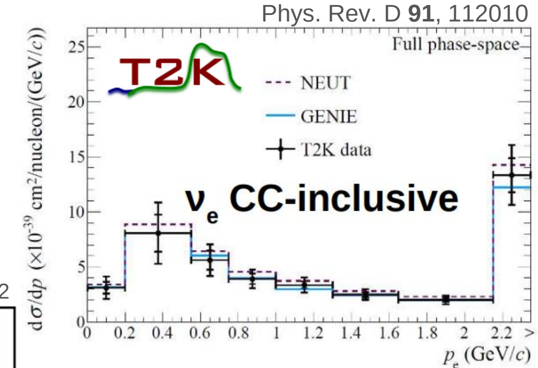


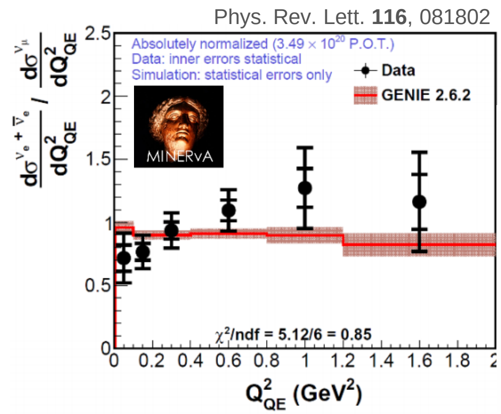


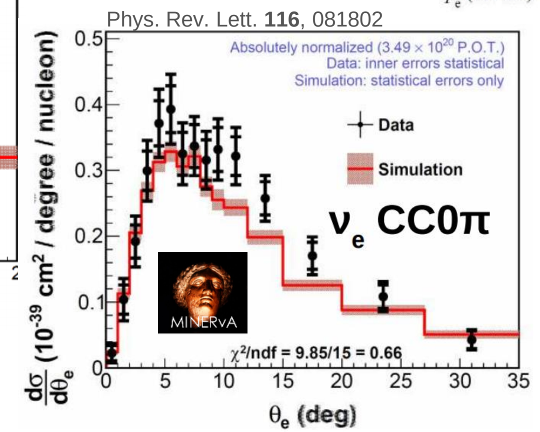
Further challenges

ν_e cross sections

- Use measurements of ν_μ at ND to constrain ν_e interactions at FD
- Important to understand the differences
- Unoscillated ν_e flux is very small – challenging measurements
- Rely on theory – interesting new developments (not in generators): arXiv:1707.01014, arXiv:1901.08050

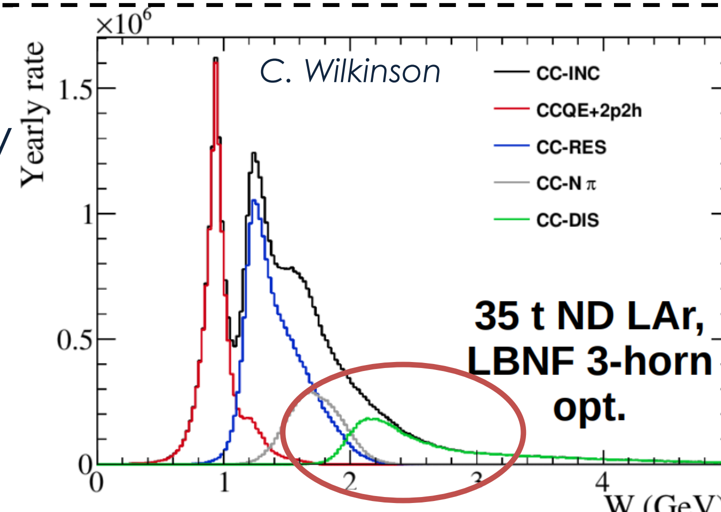






RES-SIS-DIS region

- Transition region between DIS and RES poorly modelled (stitching together models)
- Information on particle multiplicity limited to old bubble chamber data
- Critical region for DUNE – needs more data and model development in generators



Future strategy

Ideal situation:

- Implement full semi-inclusive cross-sections in the generators with theory-motivated free parameters to provide model uncertainty
- Use measurements from multiple experiments to tune the parameters, use specialised e-scattering data to check it all works
- Take the tuned model (with reduced uncertainties) as input to neutrino oscillation analyses

Future strategy

Ideal situation:

- Implement full semi-inclusive cross-sections in the generators with theory-motivated free parameters to provide model uncertainty
- Use measurements from multiple experiments to tune the parameters, use specialised e-scattering data to check it all works
- Take the tuned model (with reduced uncertainties) as input to neutrino oscillation analyses

The challenges:

- We're getting closer to this for 1p1h, but we have a way to go for other interactions
- Can we ever expect comprehensive theory-motivated uncertainties on the models?
- Some empirical treatment will always be necessary (FSI cascades, high multiplicity final states etc.)

The way out?

Input from and collaboration with theorists is fundamental to overcoming these challenges

- Experiments have outstripped the over simplified models in generators.

NuInt 18 Experimental summary talk – K. McFarland

With every topic we find that the challenges can be met only with the active support and collaboration among specialists in strong interactions and electroweak physics that include theorists and experimentalists from both the nuclear and high energy physics communities.

NuSTEC White Paper (Prog.Part.Nucl.Phys. 100 (2018) 1-68)

- Apart from rigorous work, inspiration (and whining abilities ☺) (especially young) theorists need institutional support!

NuInt 18 Theoretical summary talk – V. Pandey

- Precision era of neutrino physics requires more sophisticated generators and a dedicated joint effort in nuclear theory and generator development
- This joint effort has to be funded as integral part of experiments

NEUTRINO 2018 cross-section talk - U. Mosel

Thank you for listening!

Testing the FA using RMF

The plan to test the factorisation approach (FA):

- Compute exclusive results using theory, compare it to the same theory implemented in a generator

Testing the FA using RMF

The plan to test the factorisation approach (FA):

- Compute exclusive results using theory, compare it to the same theory implemented in a generator
- Relativistic mean field theory (the base model of SuSAv2) allows this (the current neutrino version can compute $|p_p|$ but not θ_p)

Testing the FA using RMF

The plan to test the factorisation approach (FA):

- Compute exclusive results using theory, compare it to the same theory implemented in a generator
- Relativistic mean field theory (the base model of SuSAv2) allows this (the current neutrino version can compute $|p_p|$ but not θ_p)
- Will do this test calculating ν_μ 1p1h contribution for T2K flux with (exclusive) and without (inclusive) a restriction on the momentum of the outgoing proton (500 MeV/c) as was measured in Phys. Rev. D 98, 032003 (2018)

Testing the FA using RMF

The plan to test the factorisation approach (FA):

- Compute exclusive results using theory, compare it to the same theory implemented in a generator
- Relativistic mean field theory (the base model of SuSAv2) allows this (the current neutrino version can compute $|p_p|$ but not θ_p)
- Will do this test calculating ν_μ 1p1h contribution for T2K flux with (exclusive) and without (inclusive) a restriction on the momentum of the outgoing proton (500 MeV/c) as was measured in Phys. Rev. D 98, 032003 (2018)

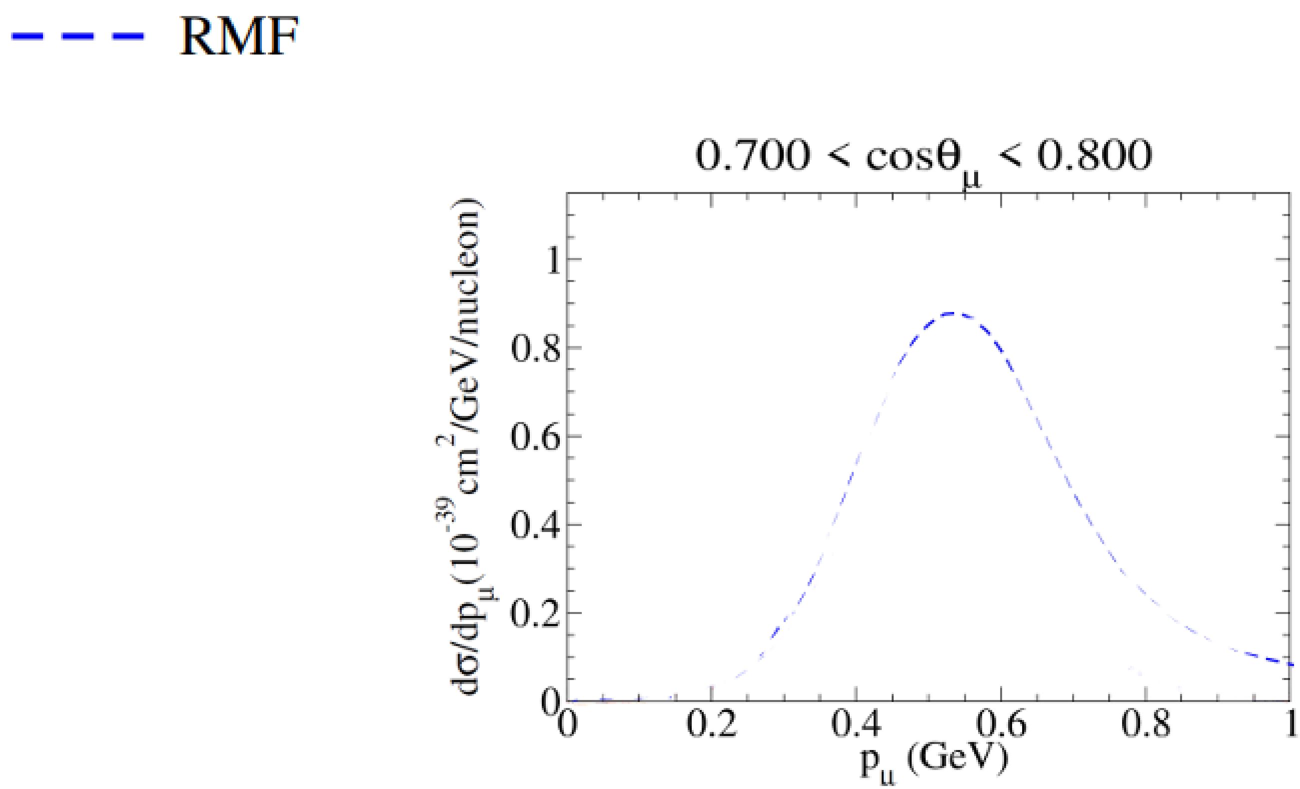
Caveats:

- Even for the inclusive case, SuSAv2 and RMF are not quite identical at very high and low kinematics – will stick to a good kinematic region
- For the FA, will use LFG rather than the real RMF spectral function (work in progress)

A first test of the FA

arXiv:1905.08556

These lines show the ***inclusive*** 1p1h prediction (no proton constraints)

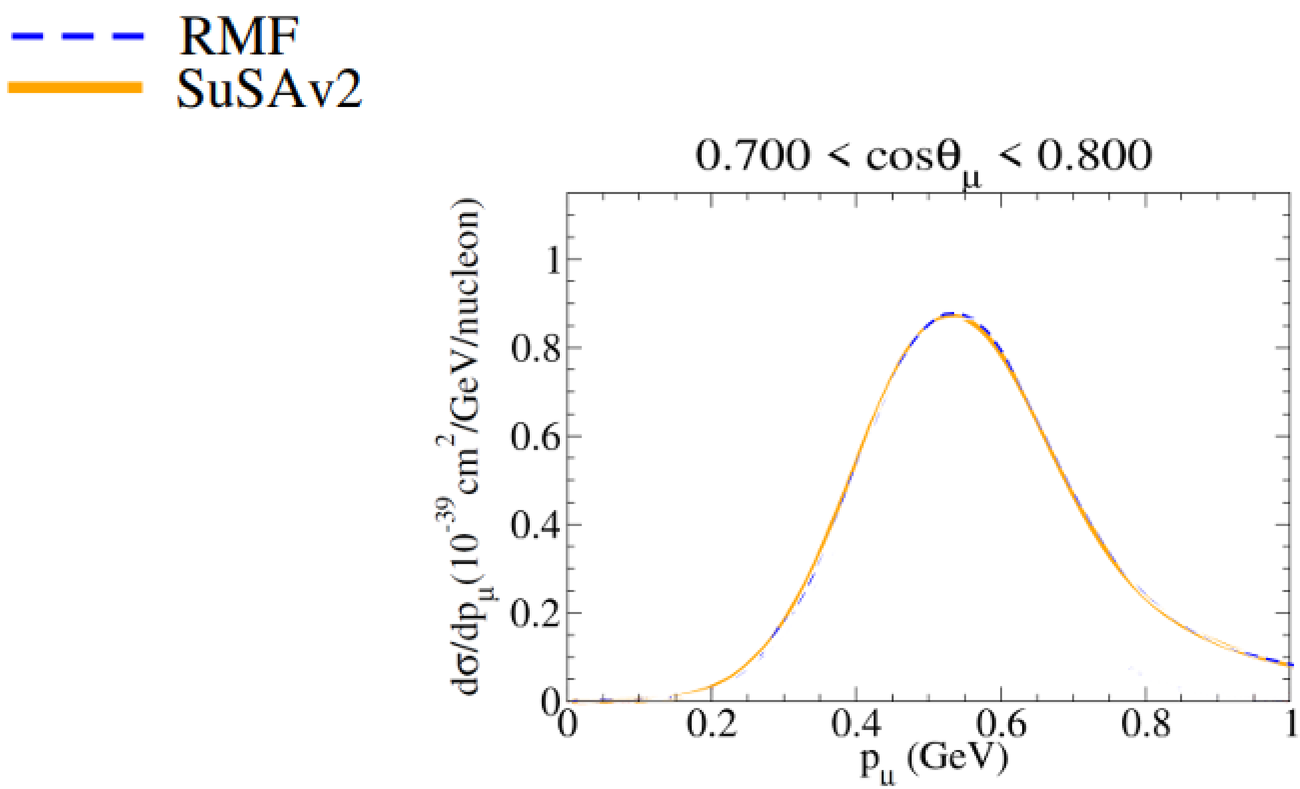


- RMF detailed microscopic model calculation of inclusive 1p1h for T2K flux

A first test of the FA

arXiv:1905.08556

These lines show the ***inclusive*** 1p1h prediction (no proton constraints)

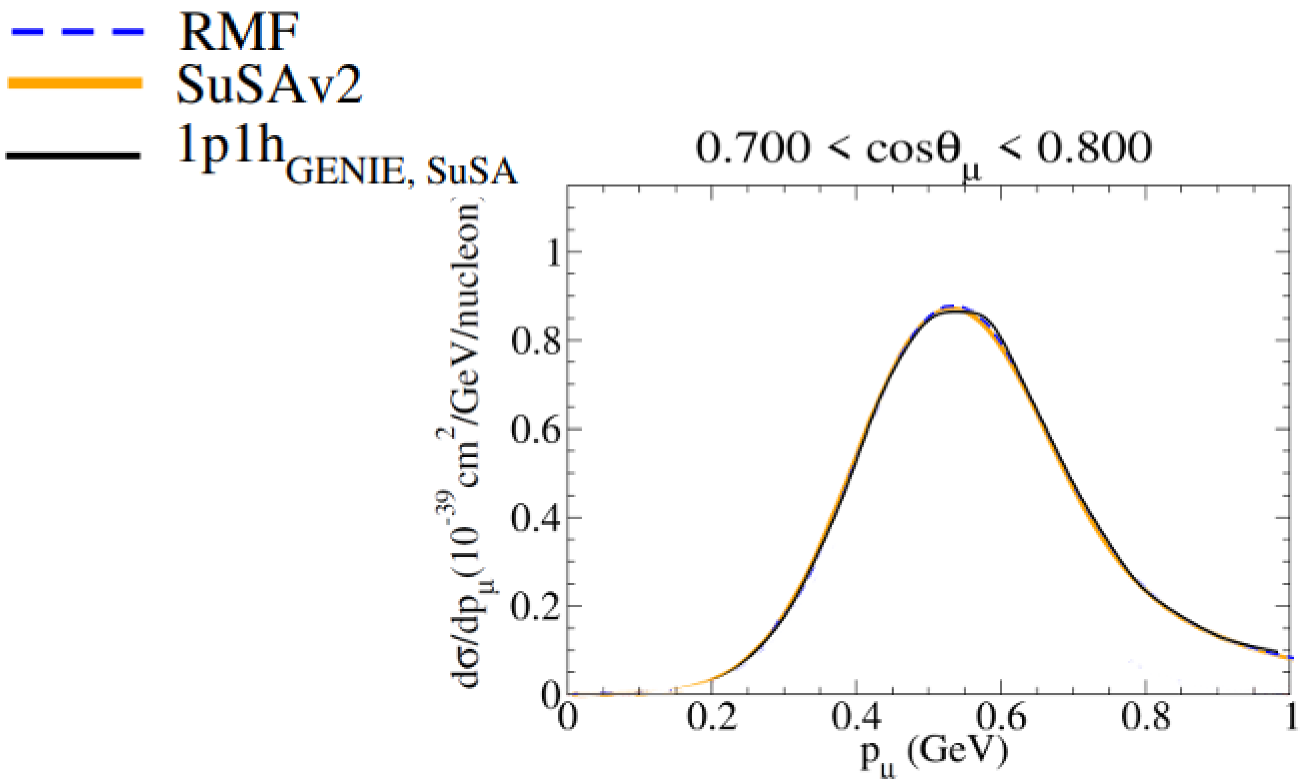


- RMF detailed microscopic model calculation of inclusive 1p1h for T2K flux
- SuSA is identical in this kinematic region (not true if we move to very small or steep angles)

A first test of the FA

arXiv:1905.08556

These lines show the ***inclusive*** 1p1h prediction (no proton constraints)

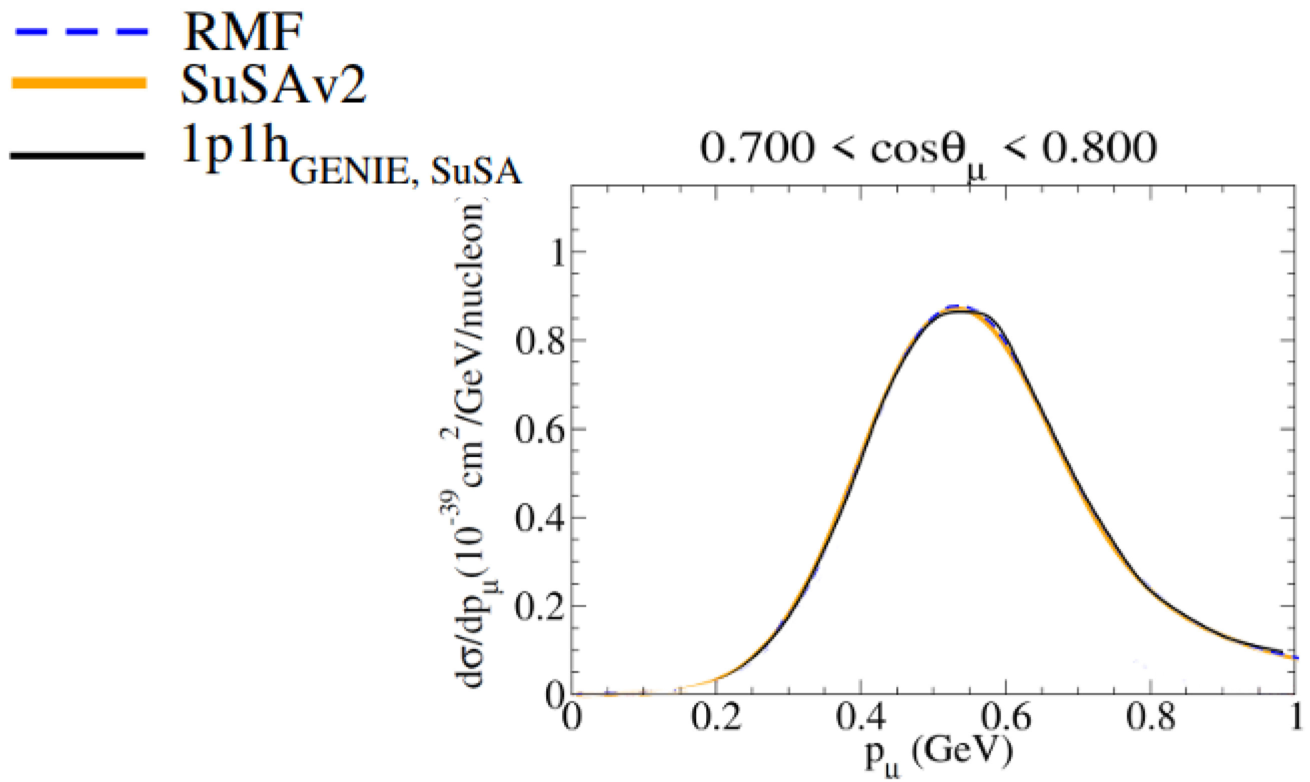


- The GENIE implementation works.

A first test of the FA

arXiv:1905.08556

These lines show the ***inclusive*** 1p1h prediction (no proton constraints)



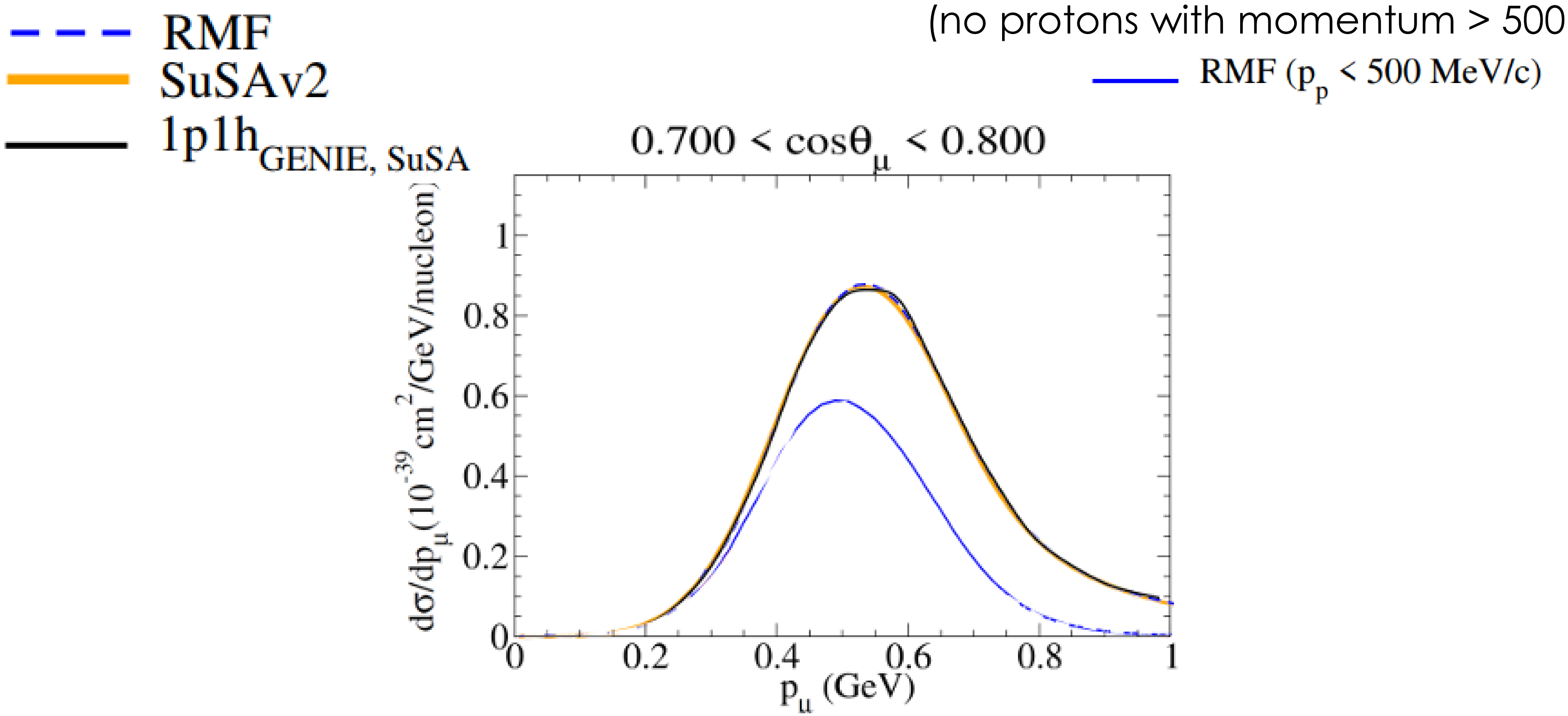
- The GENIE implementation works.
- Great, for inclusive calculations the microscopic base model (RMF), the inclusive theory (SuSAv2) and the implementation (in GENIE) all agree.

A first test of the FA

arXiv:1905.08556

These lines show the ***inclusive*** 1p1h prediction (no proton constraints)

These lines show the ***exclusive*** 1p1h prediction
(no protons with momentum > 500 MeV)



- RMF detailed microscopic model calculation of exclusive 1p1h for T2K flux

arXiv:1905.08556

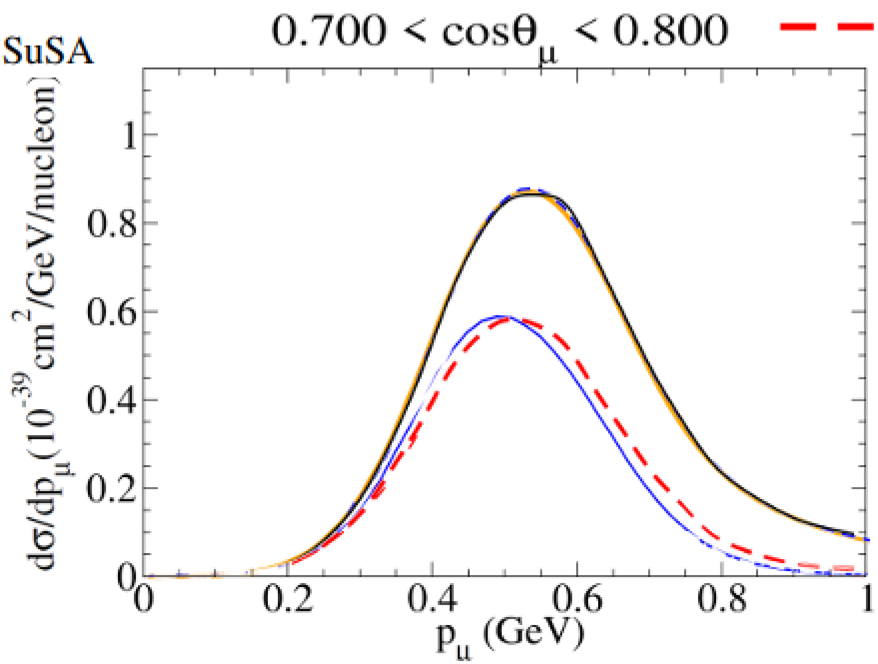
A first test of the FA

These lines show the ***inclusive*** 1p1h prediction (no proton constraints)

- - - RMF
SuSAv2
1p1h$_{\text{GENIE, SuSA}}$

These lines show the ***exclusive*** 1p1h prediction
(no protons with momentum > 500 MeV)

RMF ($p_p < 500$ MeV/c)
1p1h$_{\text{GENIE, SuSA}}$ ($p_p < 500$ MeV/c)



- FA implementation in this simple situation is surprisingly good!
- Still not perfect – exclusive kinematics are not quite right

A first test of the FA

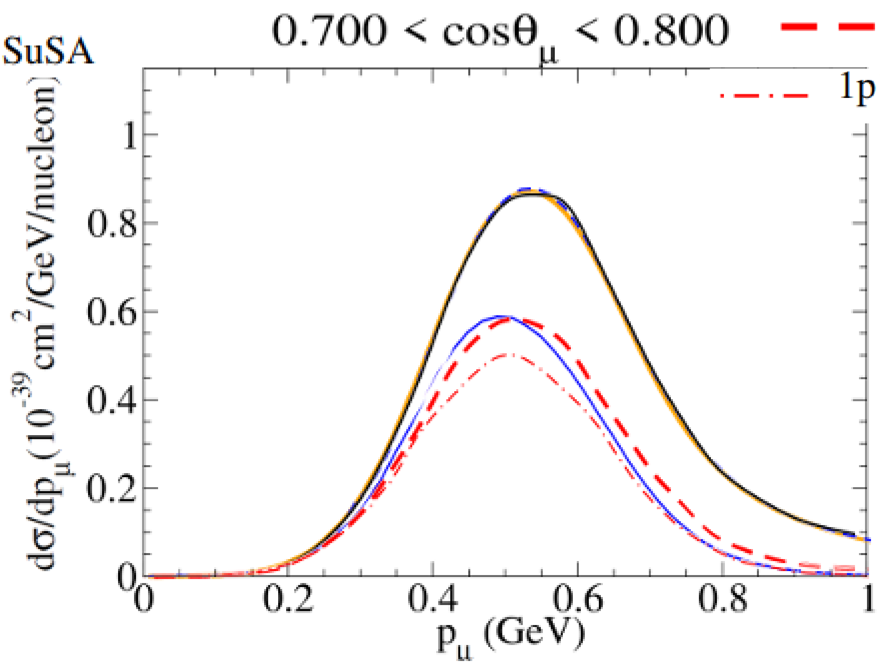
[arXiv:1905.08556](https://arxiv.org/abs/1905.08556)

These lines show the ***inclusive*** 1p1h prediction (no proton constraints)

- - - RMF
— SuSAv2
— $1p1h_{\text{GENIE, SuSA}}$

These lines show the ***exclusive*** 1p1h prediction
(no protons with momentum > 500 MeV)

— RMF ($p_p < 500$ MeV/c)
– – $1p1h_{\text{GENIE, SuSA}}$ ($p_p < 500$ MeV/c)
-·- $1p1h_{\text{GENIE no FSI, SuSA}}$ ($p_p < 500$ MeV/c)



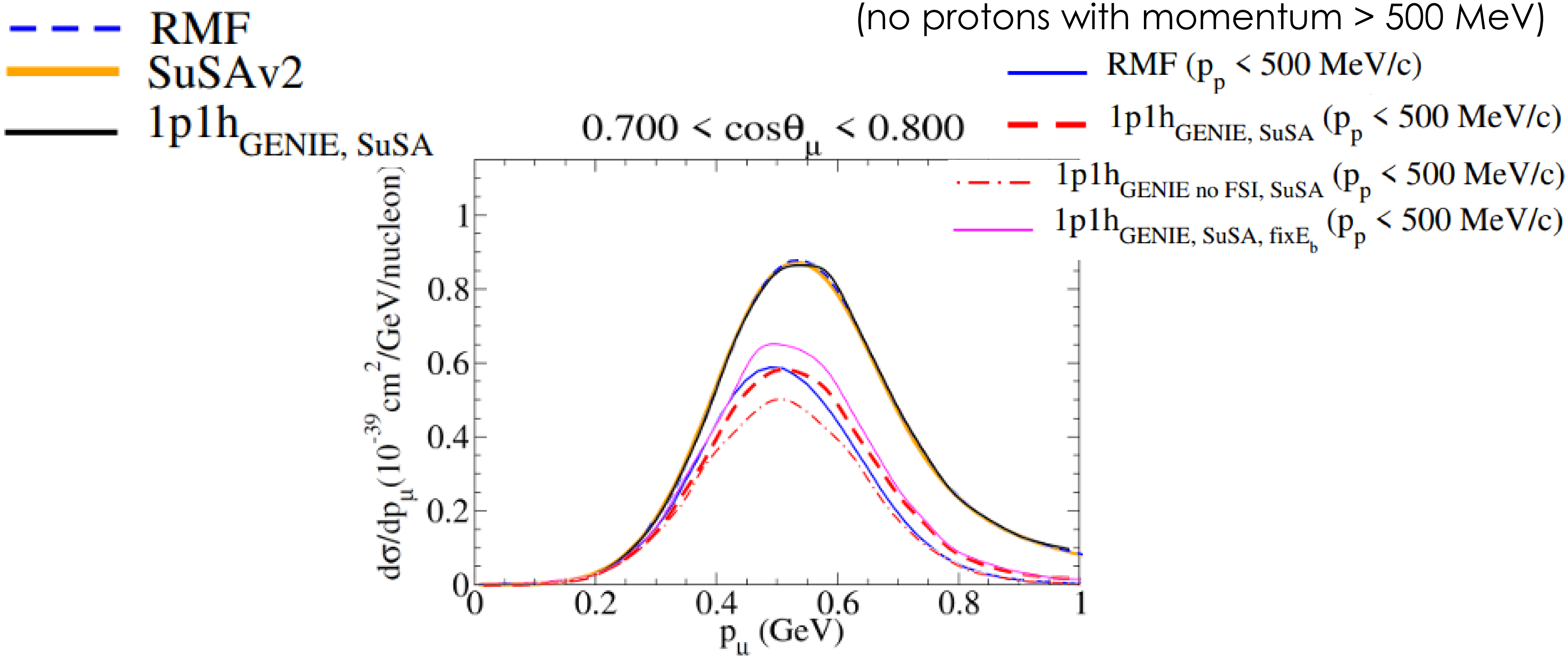
- No FSI cascade in GENIE → less slow protons → smaller cross section
- FSI is (unsurprisingly) important to get the FA to work at all
- FSI maybe too strong at larger kinematics (shared in other angular bins)

A first test of the FA

arXiv:1905.08556

These lines show the ***inclusive*** 1p1h prediction (no proton constraints)

These lines show the ***exclusive*** 1p1h prediction
(no protons with momentum > 500 MeV)

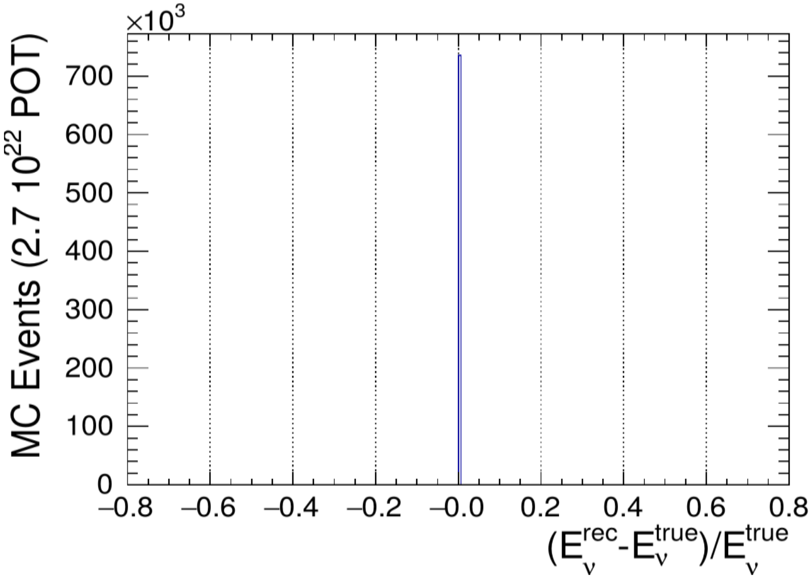


- Our SuSAv2 implementation uses a q_3 dependent removal energy
  - One step away from full factorisation
- If we use a fixed binding energy of ~25 MeV (common) then things don't look so good in the peak region

Understanding systematics

- A lot of work with new measurements is needed to achieve the **few-% systematics on the neutrino-nucleus interaction modelling**
- More importantly, the projected HK/DUNE sensitivity requires an understanding of the neutrino-nucleus uncertainty **which we do not yet have**

The 'first order' problem to solve (largest impact on oscillation analysis) is the capability of reconstructing the neutrino energy:



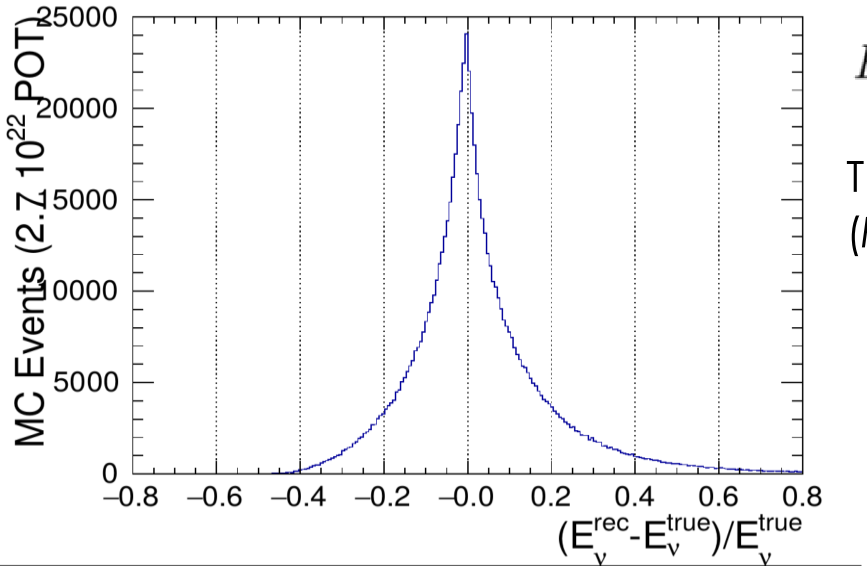
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Calculation from lepton kinematics is perfect only for elastic scattering off a free nucleon at rest

Understanding systematics

- A lot of work with new measurements is needed to achieve the **few-% systematics on the neutrino-nucleus interaction modelling**
- More importantly, the projected HK/DUNE sensitivity requires an understanding of the neutrino-nucleus uncertainty **which we do not yet have**

The 'first order' problem to solve (largest impact on oscillation analysis) is the capability of reconstructing the neutrino energy:



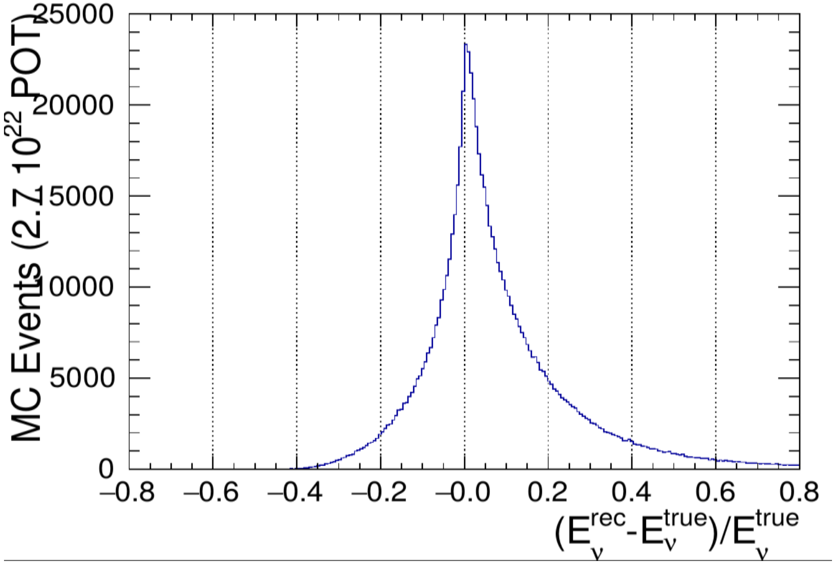
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

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

Understanding systematics

- A lot of work with new measurements is needed to achieve the **few-% systematics on the neutrino-nucleus interaction modelling**
- More importantly, the projected HK/DUNE sensitivity requires an understanding of the neutrino-nucleus uncertainty **which we do not yet have**

The 'first order' problem to solve (largest impact on oscillation analysis) is the capability of reconstructing the neutrino energy:



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

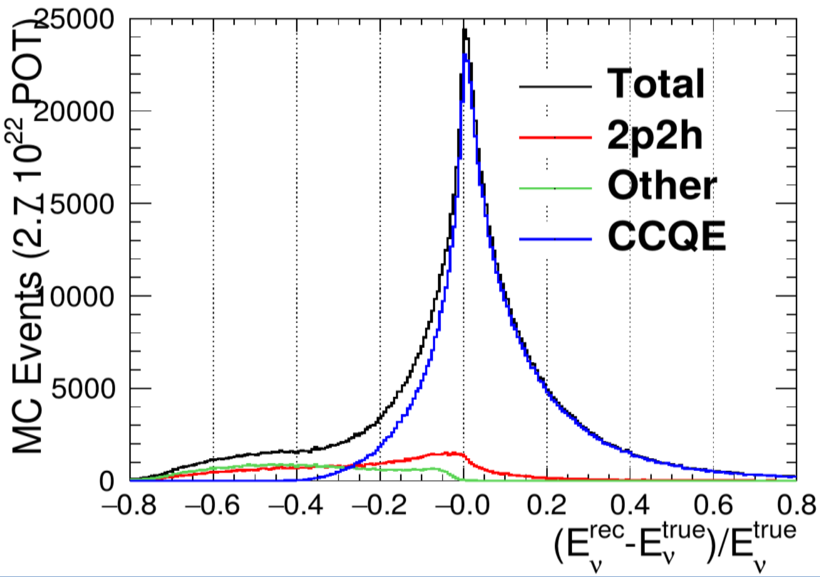
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

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

Understanding systematics

- A lot of work with new measurements is needed to achieve the **few-% systematics on the neutrino-nucleus interaction modelling**
- More importantly, the projected HK/DUNE sensitivity requires an understanding of the neutrino-nucleus uncertainty **which we do not yet have**

The 'first order' problem to solve (largest impact on oscillation analysis) is the capability of reconstructing the neutrino energy:



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

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

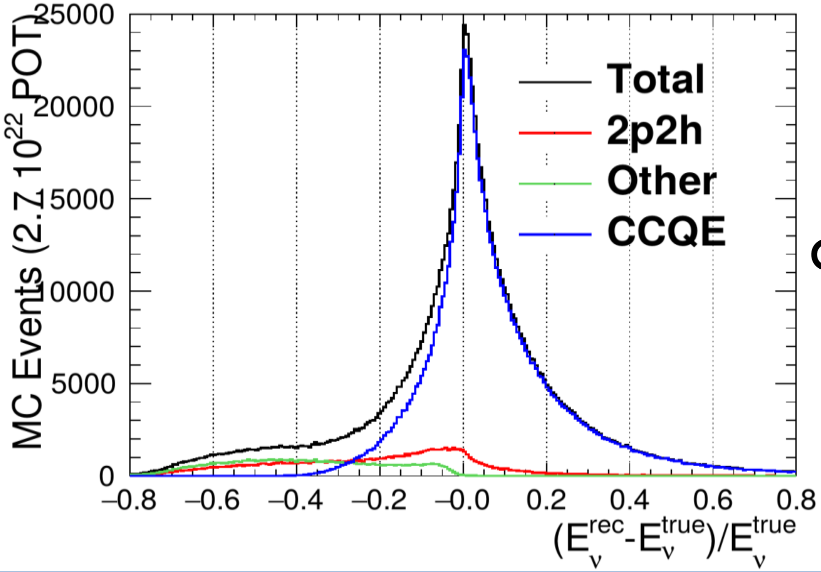
The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

Does not work well for non-CCQE events: 2p2h and CC1π with pion abs. FSI)

Understanding systematics

- A lot of work with new measurements is needed to achieve the **few-% systematics on the neutrino-nucleus interaction modelling**
- More importantly, the projected HK/DUNE sensitivity requires an understanding of the neutrino-nucleus uncertainty **which we do not yet have**

The 'first order' problem to solve (largest impact on oscillation analysis) is the capability of reconstructing the neutrino energy:



'First order' uncertainties:

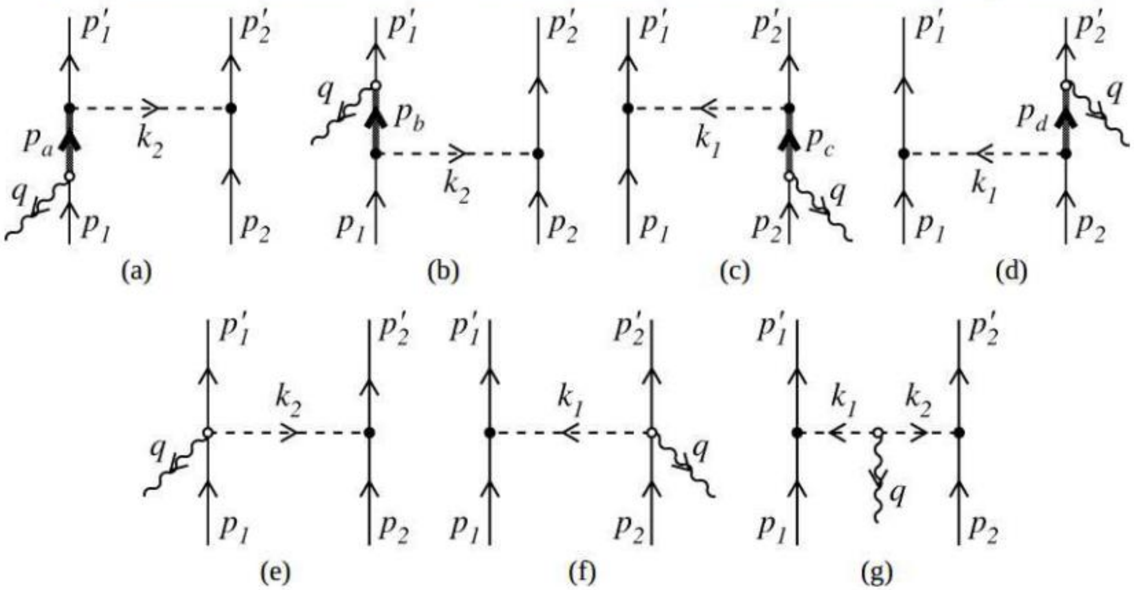
CCQE: Fermi motion and removal ("binding") energy

2p2h cross-section (10-20% of CCQE?)

SuSAv2 2p2h

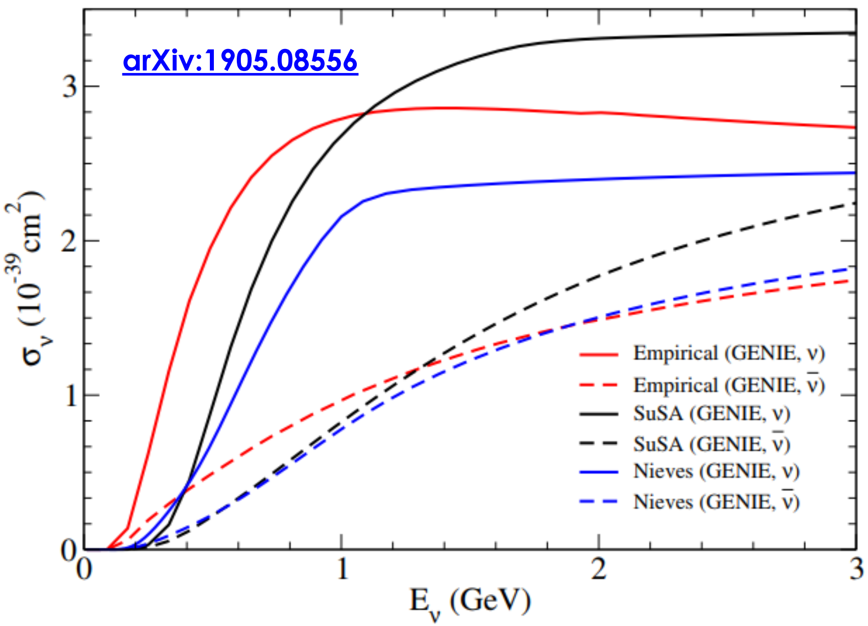
$$W^{\mu\nu}_{2p-2h} = \frac{V}{(2\pi)^9}\int d^3p'_1 d^3h_1 d^3h_2 \frac{M^4}{E_1E_2E'_1E'_2}\Theta(p'_1,p'_2,h_1,h_2)$$
$$r^{\mu\nu}(\mathbf{p}'_1,\mathbf{p}'_2,\mathbf{h}_1,\mathbf{h}_2)\delta(E'_1+E'_2-E_1-E_2-\omega)\,,$$

Over 100,000 terms are involved in the calculation, with seven-dimensional integrations



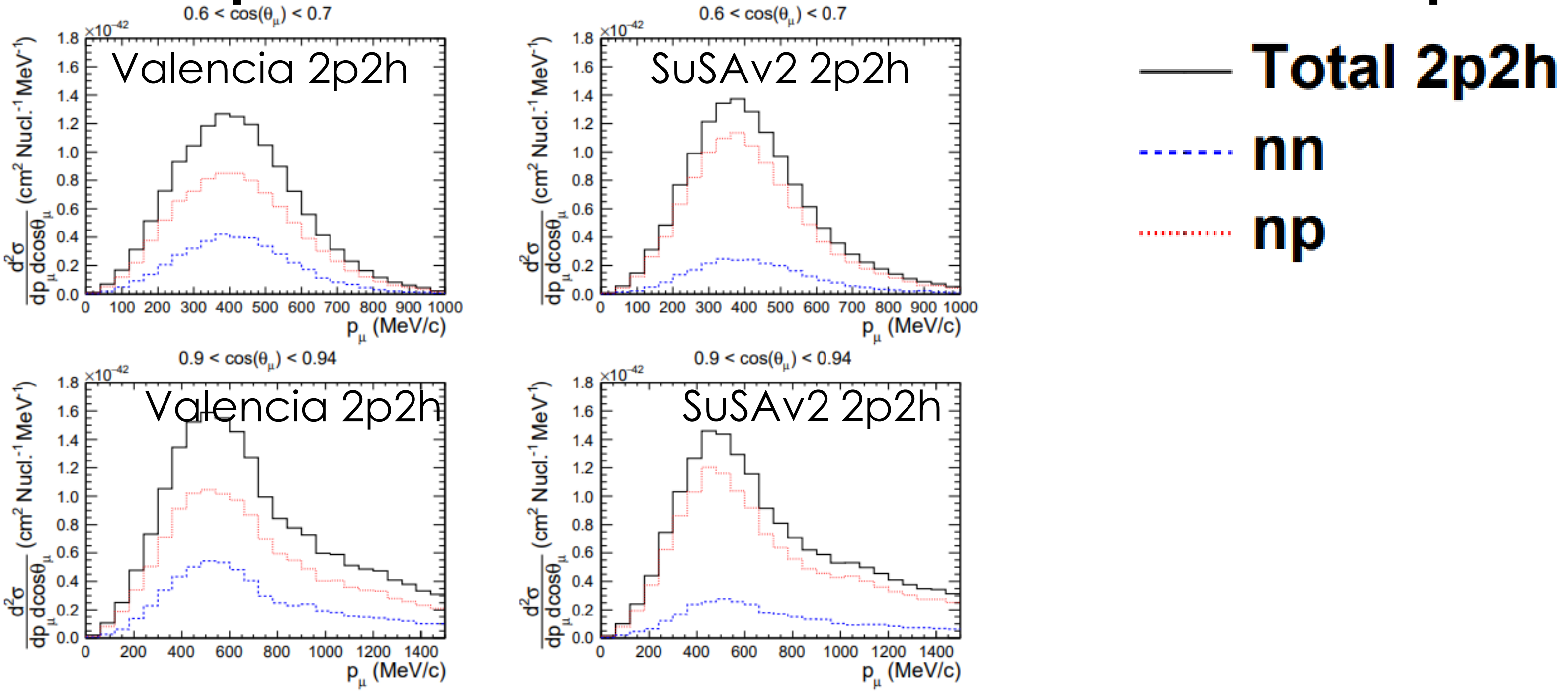
- Based on the calculation performed by De Pace et al., (2003) for (e, e') scattering and extended to the weak sector by Amaro, Ruiz Simo et al.
  [PRD 90, 033012 (2014); PRD 90, 053010 (2014); JPG 44, 065105 (2017); PLB 762, 124 (2016)]
- Performed within an RFG nuclear model (like Nieves), SuSAv2-MEC is fully relativistic – no approximations
- HUGE calculation, takes a long time to calculate a full cross section
  - Normally a parameterisation is used

Comparison to Valencia 2p2h



- Valencia model makes some non-relativistic approximations limiting validity above 1.2 GeV, SuSAv2-MEC does not.

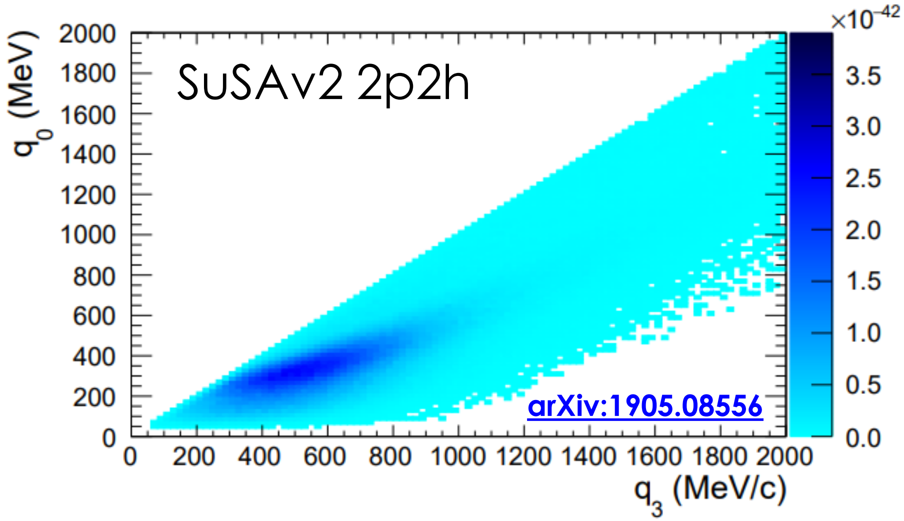
Comparison to Valencia 2p2h

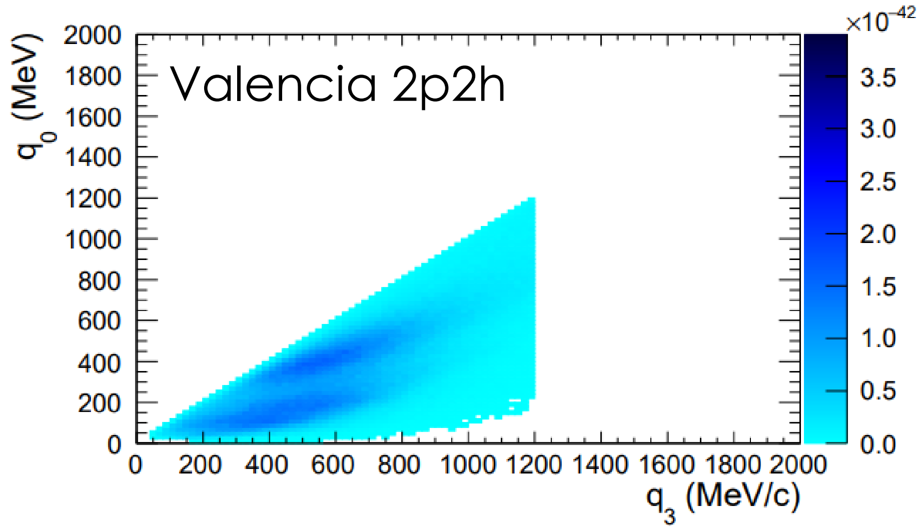


- Valencia model makes some non-relativistic approximations limiting validity above 1.2 GeV, SuSAv2-MEC does not.
- Valencia model rejects direct/exchange interference terms, SuSAv2-MEC does not – Valencia predicts relatively less np initial states

10.1016/j.physletb.2016.09.021

Comparison to Valencia 2p2h





- Valencia model makes some non-relativistic approximations limiting validity above 1.2 GeV, SuSAv2-MEC does not.
- Valencia model rejects direct/exchange interference terms, SuSAv2-MEC does not – Valencia predicts relatively less pp final states
- Valencia model includes a different set of diagrams (some from imaginary part of the W)

SuSAv2 1p1h – very brief theory!

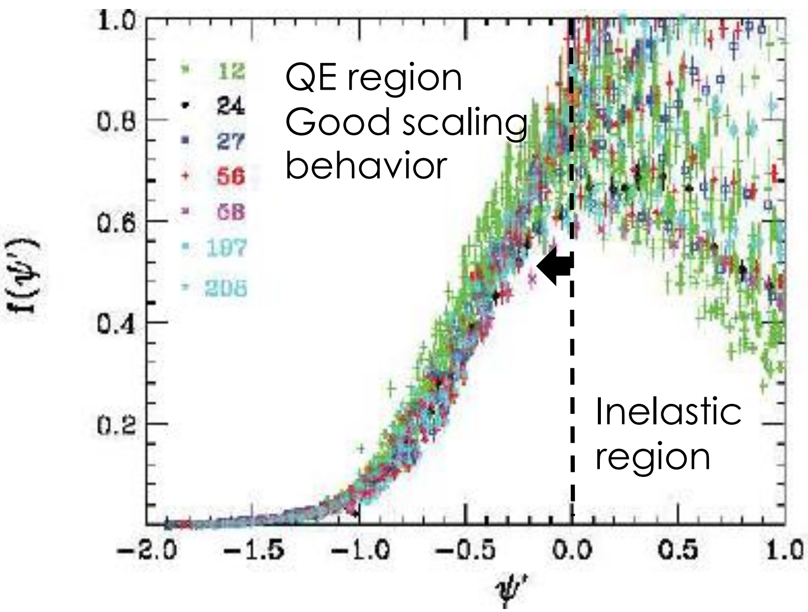
Basic idea: use the scaling function encode nuclear dynamics

$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})} \quad ; \quad \psi\text{-scaling variable}$$

In inclusive QE scattering we can observe:

- ☆ Scaling of 1^{st} kind (independence on q)
- ☆ Scaling of 2^{nd} kind (independence on Z)

$\Longrightarrow$ SuperScaling



SuSA: extract scaling function from e, e' data and then assume $f_L = f_T$

- In reality not quite true ($f_T^{ee'} > f_L^{ee'}$)

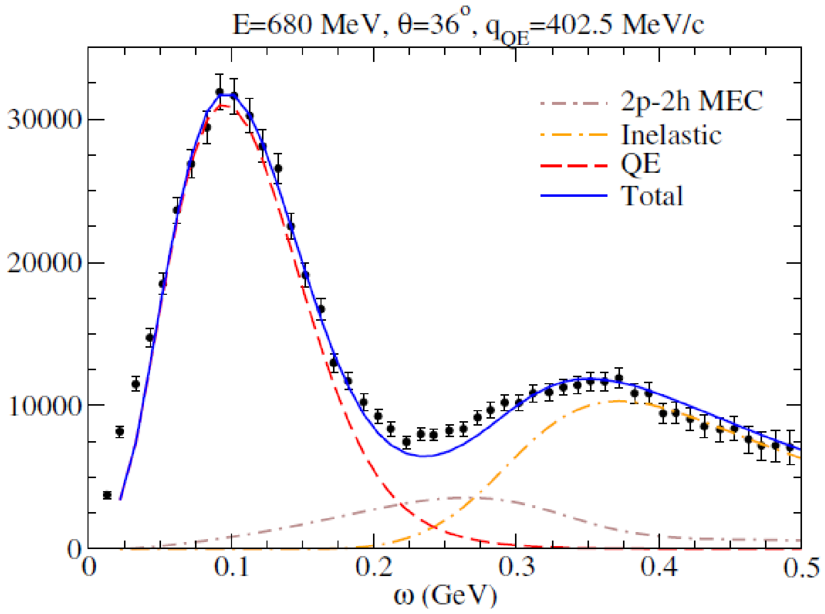
(see G.D. Megias' Thesis for details)

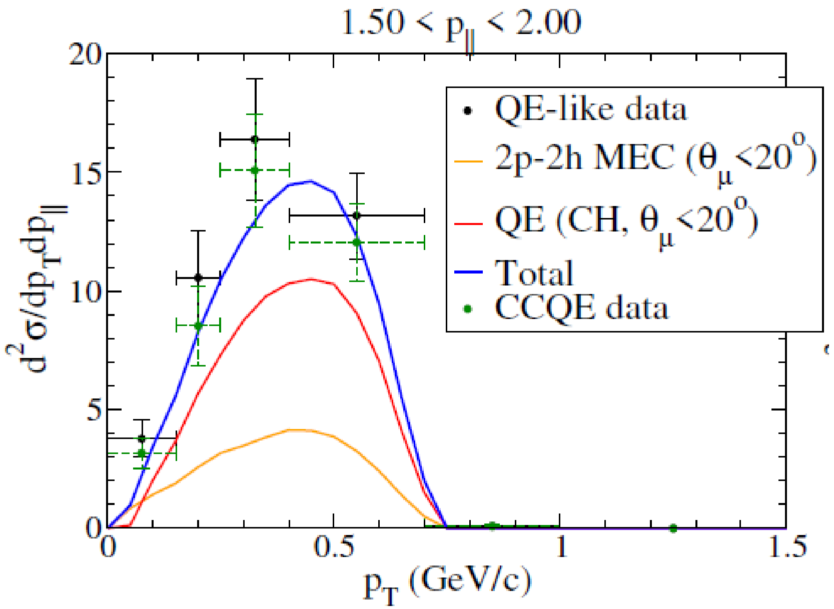
SuSAv2: build scaling function from microscopic model – **Relativistic Mean Field** (RMF) theory

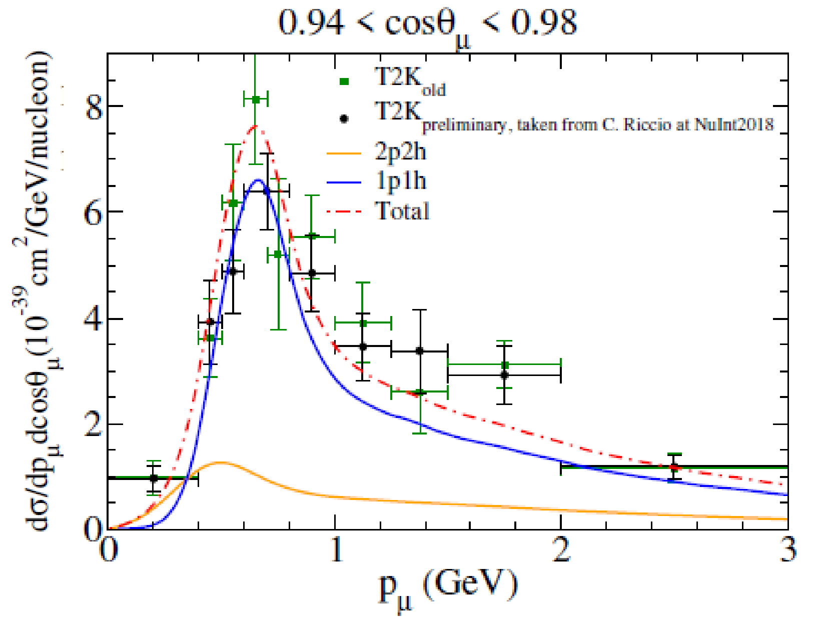
- Excellent description of QE e, e' data
- A quick way of getting RMF predictions!

PRC90, 035501 (2014) PRD94, 013012 (2016)

SuSAv2-MEC



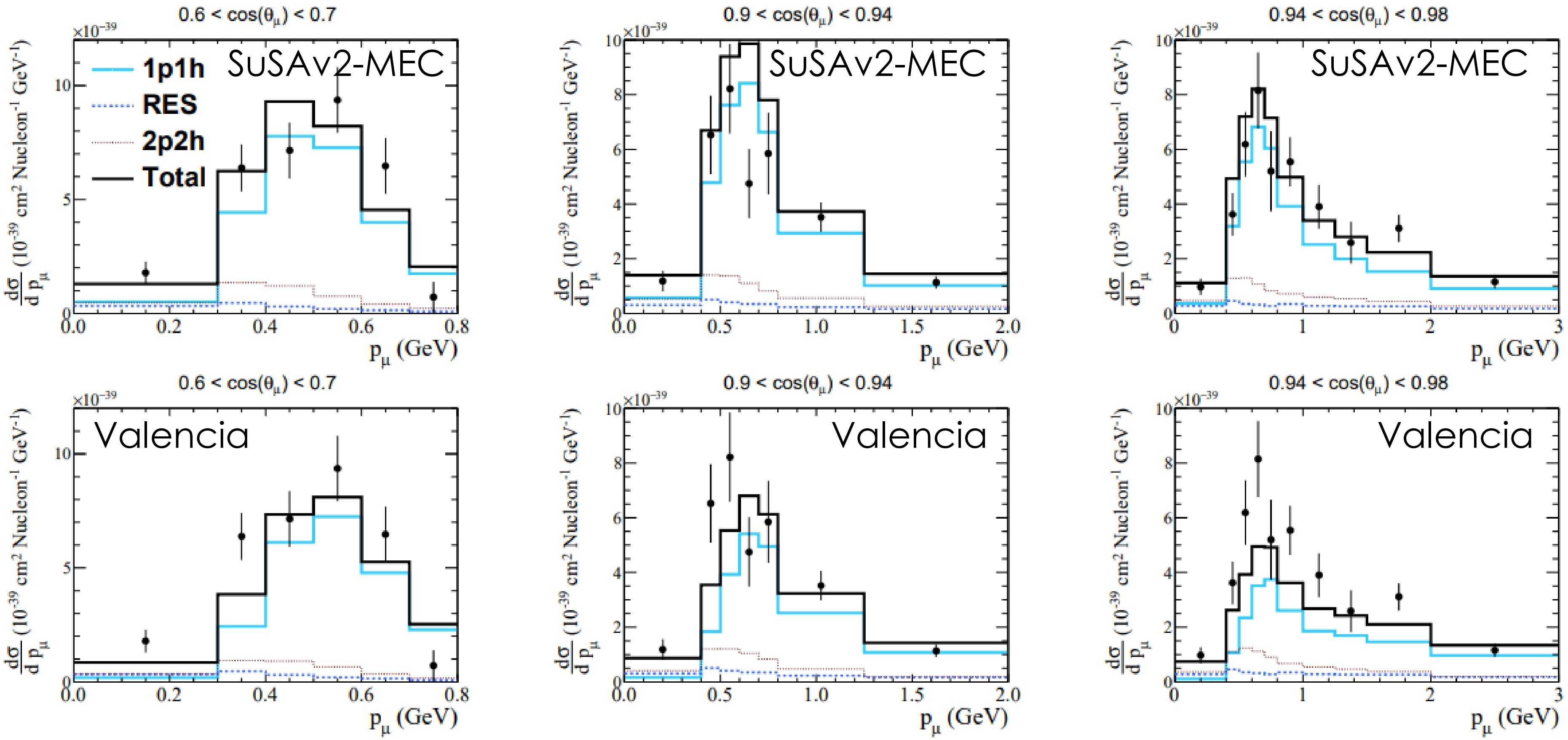




- Based on sound microscopic model calculations
- **Well validated on electron scattering data**
- Is able to describe neutrino scattering data

arXiv:1905.08556

Comparison to Valencia model



Provides a significantly different predictions to the Valencia model

Complimentary addition to the generators