SuSAv2 implementation in GENIEv3

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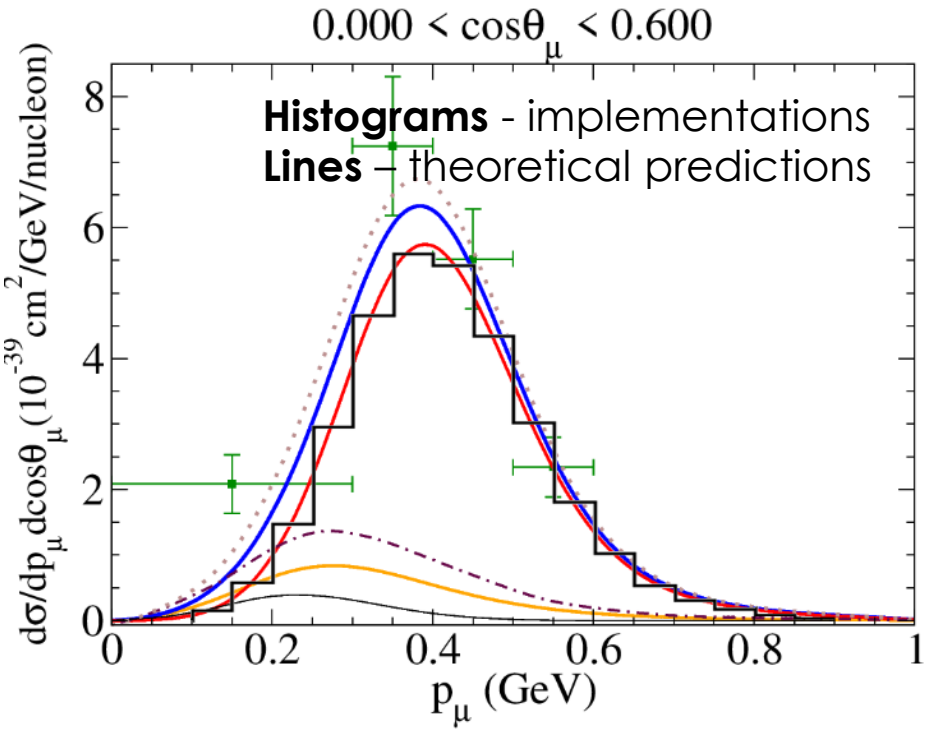
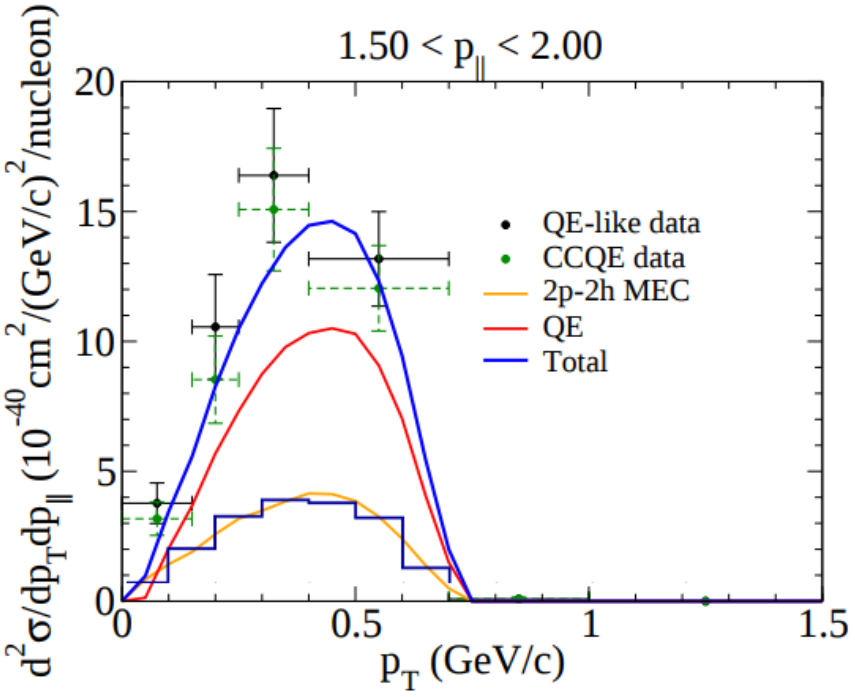
Overview

Implemented the SuSAv2 1p1h and 2p2h models in GENIEv3 for both electron and CC neutrino scattering. Now undergoing final validations and first physics studies before official release.

arXiv: 1901.11022





This talk: overview of the "deliverables" to GENIE, some details of the implementations.

Physics details can be found in backups and yesterday's talk in the NPWG

The deliverables

New 1p1h and 2p2h model calculated using pre-computed hadron tensors

$$\frac{d^2\sigma}{dq_0 q_3} = \sigma_0 \eta_{ij}(q_0, q_3) W_{ij}(q_0, q_3)$$

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- Global factor / lepton tensor are easily calculated – shared by other models
- The hadron tensor elements are stored in tables which specify q0 and q3 in bins of 5 MeV between 0 and 2 GeV – **unique new tensors**
  - **Using Steven G.'s very nice new hadron tensor framework!**
  - Use a GENIE's bilinear interpolation function to evaluate specific q0,q3
  - Hadron tensors will be provided for a few select targets (C and O so far, may add others). Can scale to other nuclei.
  - Separate hadron tensors for electron and neutrino scattering (but otherwise calculation remains almost unchanged!)

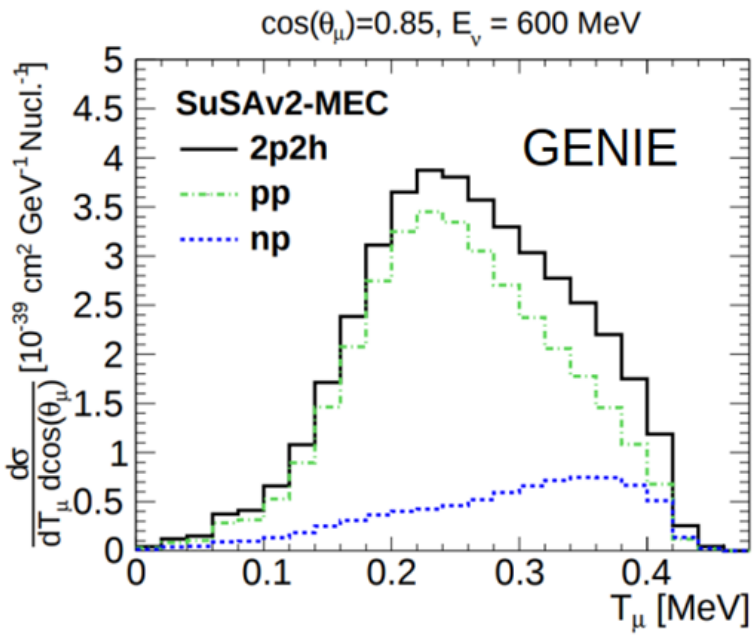
The implementation – 2p2h

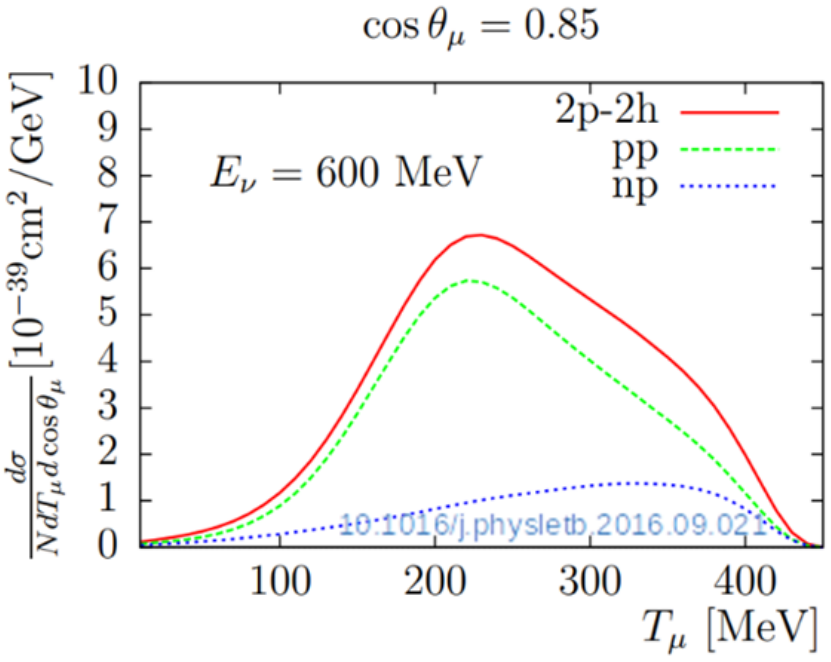
- Choose energy/momentum transfer from lepton part xsec using accept/reject
- Pick two target nucleons (which ones? See next slide)
- Assign an initial momentum and removal energy from input nuclear model
- Combine nucleons to be a target "cluster"
- Transfer energy/momentum from lepton to cluster and swap n to p as needed
- "Decay" cluster back to back in CoM frame, boost back to lab frame
- Propagate subsequent nucleons through chosen FSI model

Most of this was easily adapted from the Nieves 2p2h model implementation

Implementation – hadron pairs

- Use a separate hadron tensor for only np initial state pairs
- Use accept/reject to choose initial state based on the ratio of the np/total cross section





The implementation – 1p1h

Xsec calculation: build hadron tensor from SuSAv2, implement as in 2p2h

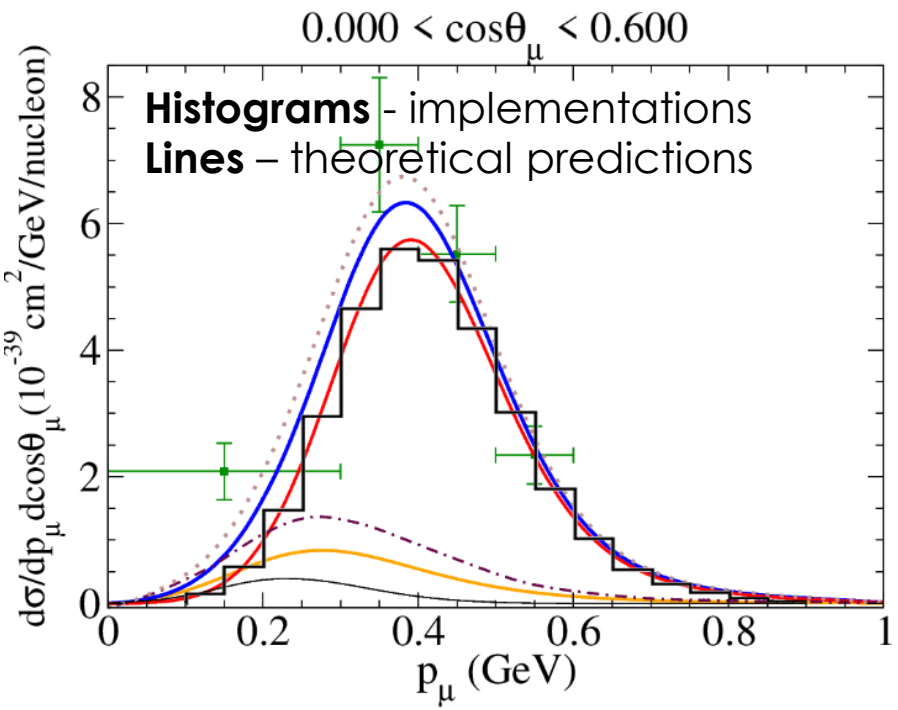
Hadronic side: more complicated … copy elements of other methods. **Bold/***italics* **bits represent very/***slightly* **questionable physics** but this is no worse than in other 1p1h model implementations.

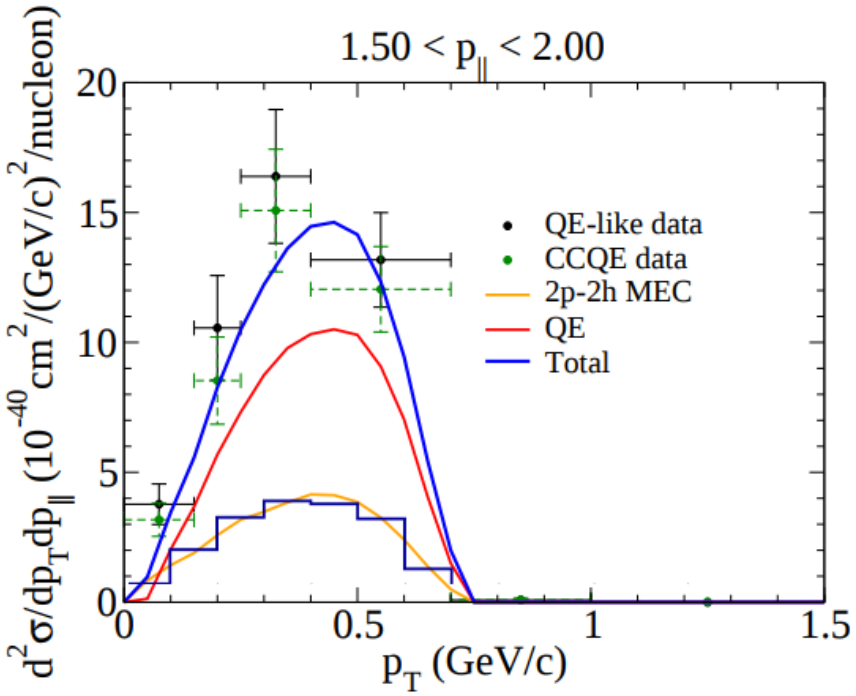
- Draw target nucleon from chosen nuclear model **irrespective of ω, q**
- Get removal energy from theory-driven treatment, *re-throw from nuclear model if nucleon is Pauli blocked*
- Transfer all of ω, q to nucleon, **none to remnant**
- Subtract removal energy, **put proton on-shell with adjustment of p, conserve momentum by adjusting remnant kinematics**
- *Do FSI cascade and rest of interaction using standard GENIE methods*
  - (In all plots from I use hN, hA sometimes gives crazy results)
  - Ensure not to double count removal energy

This all requires a different QE "event generator" than the default

Validations

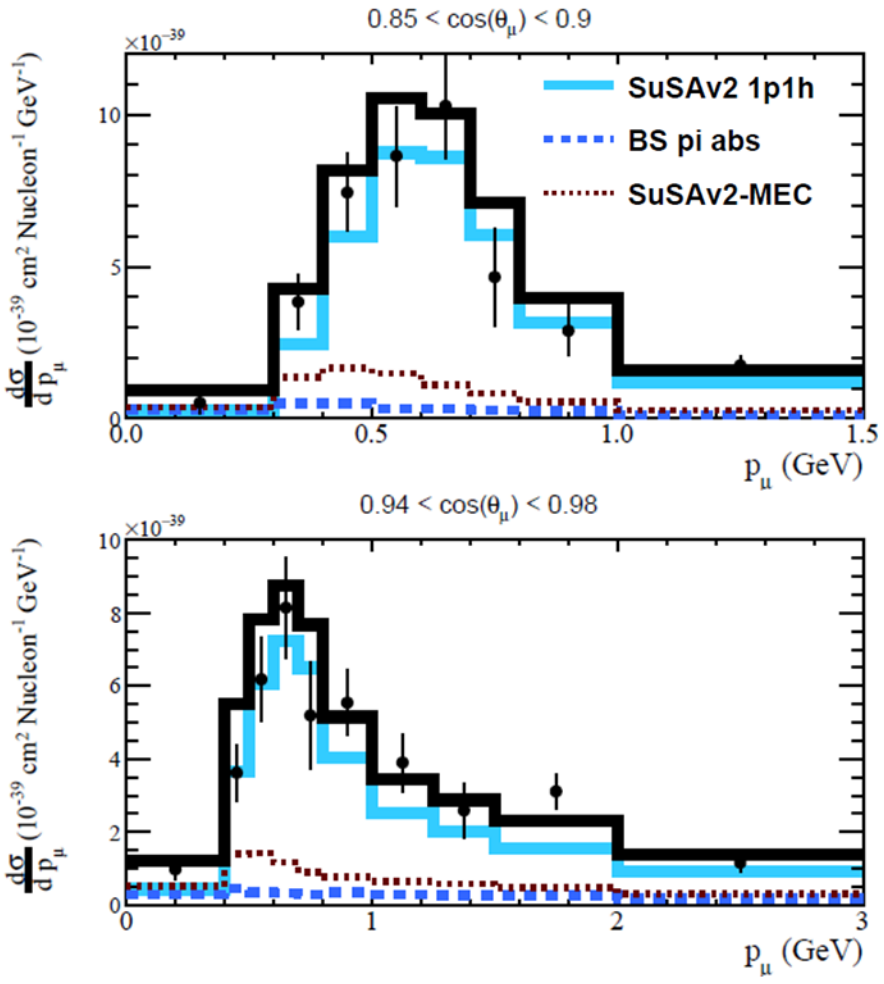
- First test fixed-kinematic predictions – only use GENIE xsec calculation, not the event generator
- Next test full model implementation (more validation plots in backups)
- **Conclusions**: all looks good. Some minor issues with interpolation at low Q^2 (details in backups)



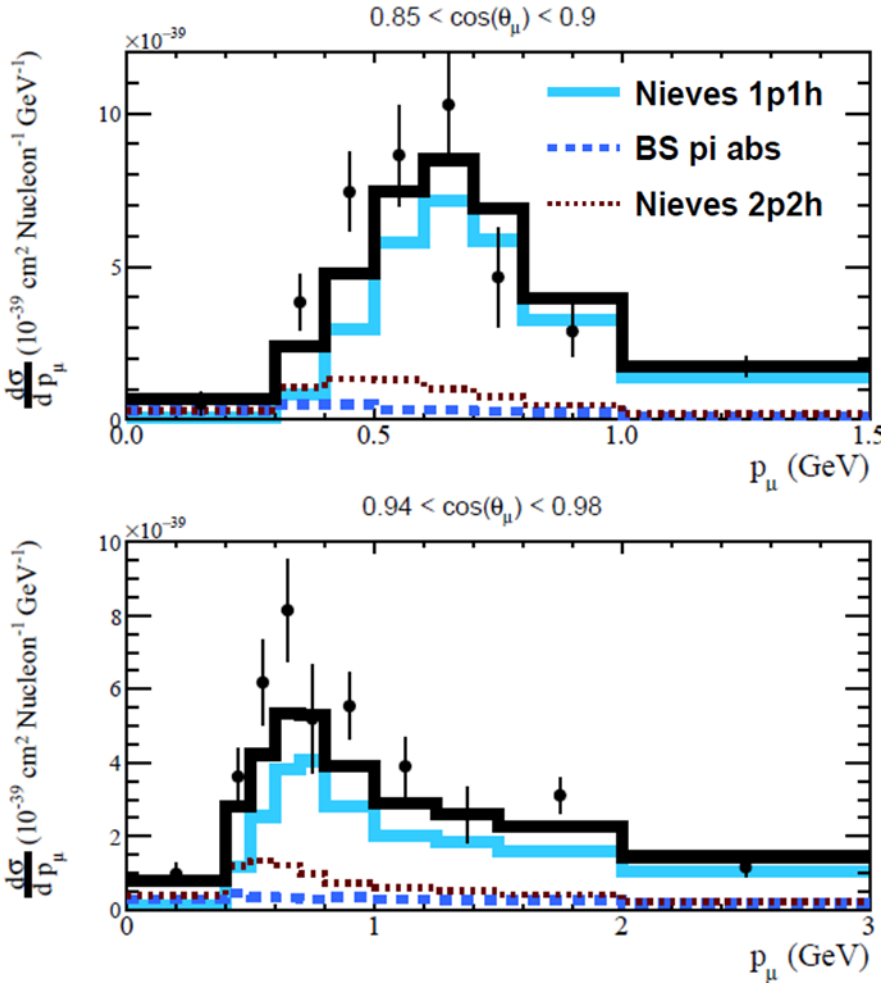


The models – 1p1h

New SuSAv2 implementation

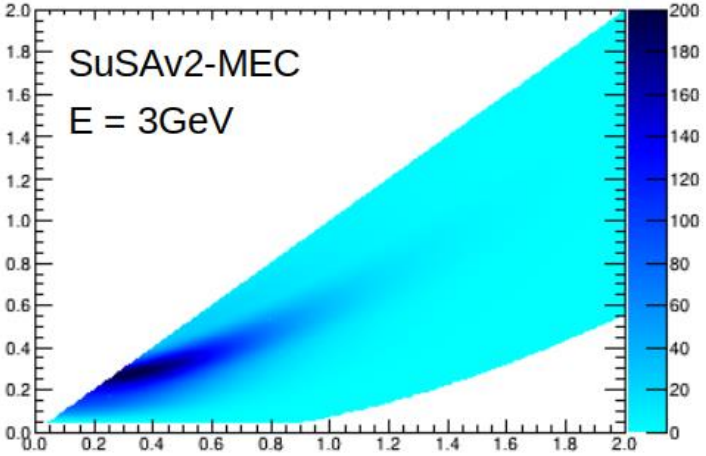


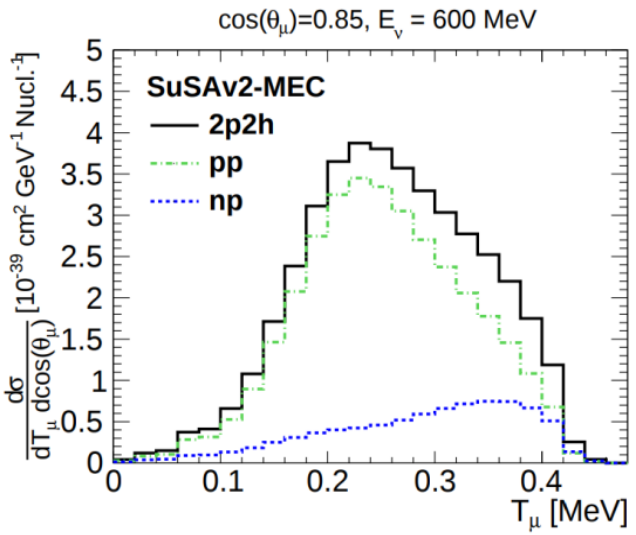
Nieves implementation



The models – 2p2h

New SuSAv2 implementation





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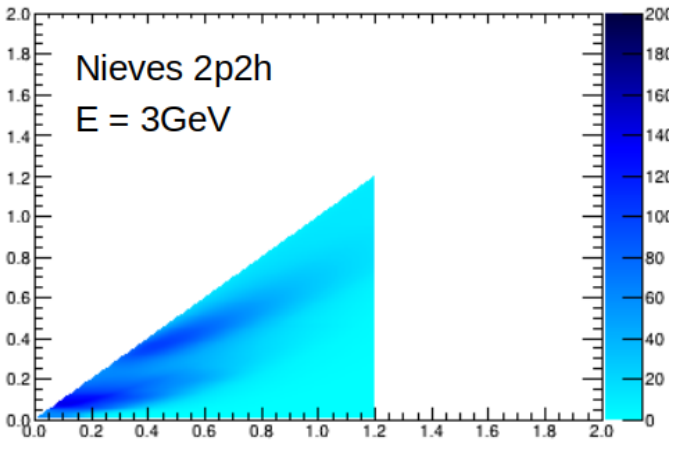
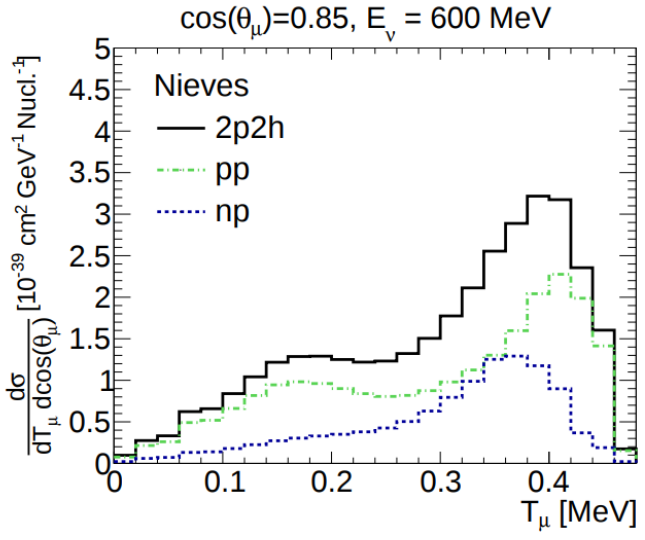




What we can do …

- ✓ Valid for all nuclear targets
- ✓ Works for CC neutrino and electron scattering
- ✓ Minimal calculation on the fly - fast

… and what we can't (yet) do

- ✓ Valid for all nuclear targets
- ✓ Works for CC neutrino and electron scattering
- ✓ Minimal calculation on the fly - fast

- ➢ Input model is *inclusive* hadron kinematic predictions are *ad-hoc* (like all current GENIE models)
- ➢ Initial implementation will not be able to alter the inclusive cross-section through alterations systematic parameters (e.g. MAQE is fixed at one value)

Use case

Theory derived from microscopic model, predictions are **significantly different from other models**. Implementation is therefore useful as:

- A theory-driven mock-data studies for physics analyses
- For model comparisons to neutrino scattering data
- Phenomenological studies

Since current model is non-reweightable it cannot yet be used as an to calculate systematic uncertainties in physics analyses.

Summary

Implemented and validated SuSAv2 1p1h and 2p2h in GENIEv3

- Both validated across a wide range of kinematics
- Easily extended to work for any nuclear target

2p2h

- Works for neutrino and electron scattering
- Properly accounts for contribution of np and pp pairs
- Quite different predictions from Nieves 2p2h!

1p1h

- Works for neutrino and electron scattering
- Similar treatment of hadron-side to other 1p1h implementations
- Significantly different from other 1p1h models

Further work

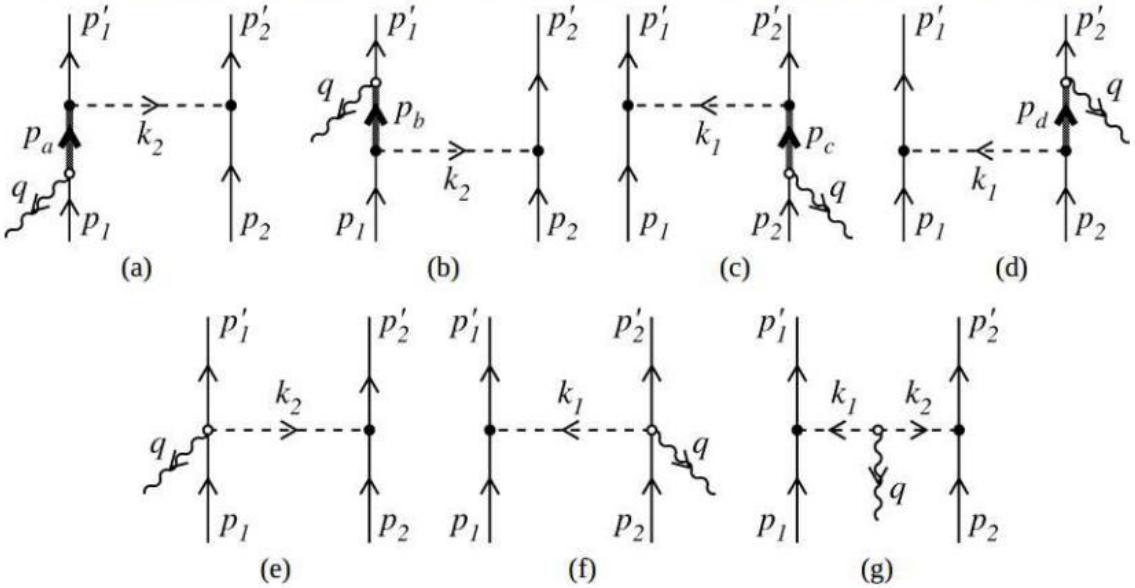
- Write up current implementations and physics studies into a paper (~1 month)
- Clean up and submit code to GENIE (~2 months)
- Produce tool to reweight GENIEv2 predictions to SuSAv2 (~2 months)
- Fully implement SuSAv2's nuclear model (Relativistic mean field) into GENIE (~3 months)
- Implement reweighting of SuSAv2 predictions (long term)
- Also add Martini MEC (long term)

BACKUPS

SuSAv2-MEC

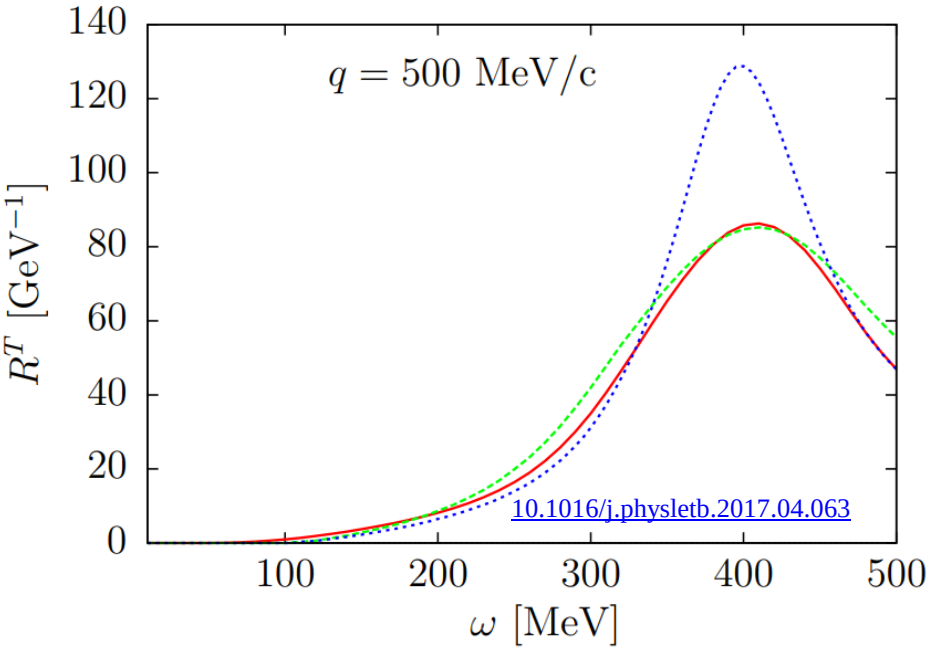
$$W^{\mu\nu}_{2p-2h} = \frac{V}{(2\pi)^9}\int d^3p'_1 d^3h_1 d^3h_2 \frac{M^4}{E_1 E_2 E'_1 E'_2}\Theta(p'_1, p'_2, h_1, h_2)$$
$$r^{\mu\nu}(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{h}_1, \mathbf{h}_2)\delta(E'_1 + E'_2 - E_1 - E_2 - \omega)\,,$$

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 Nieves 2p2h



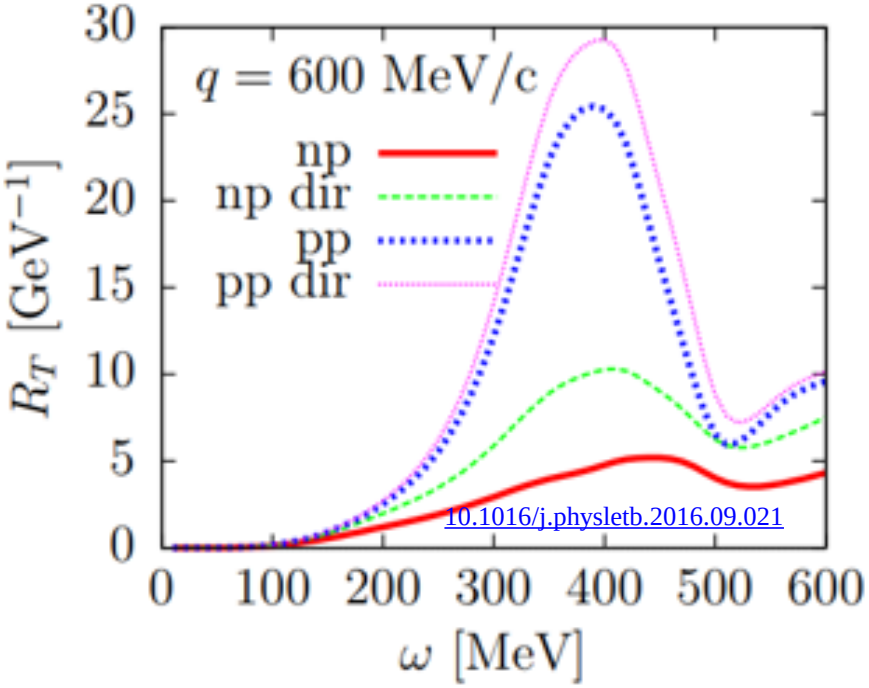
Full Calculation

"Frozen Nucleon"

Not exactly what Nieves does, but simialr sort of idea

- Nieves model makes some non-relativistic approximations, SuSAv2-MEC does not – expect fairly small impact

Comparison to Nieves 2p2h



np,pp labels indicate final states

"dir" indicates the interference terms are neglected

Relevant for hadronic energy reconstruction

- Nieves model makes some non-relativistic approximations, SuSAv2-MEC does not – expect fairly small impact

- Nieves model rejects direct/exchange interference terms, SuSAv2-MEC does not – Nieves predicts relatively less pp final states

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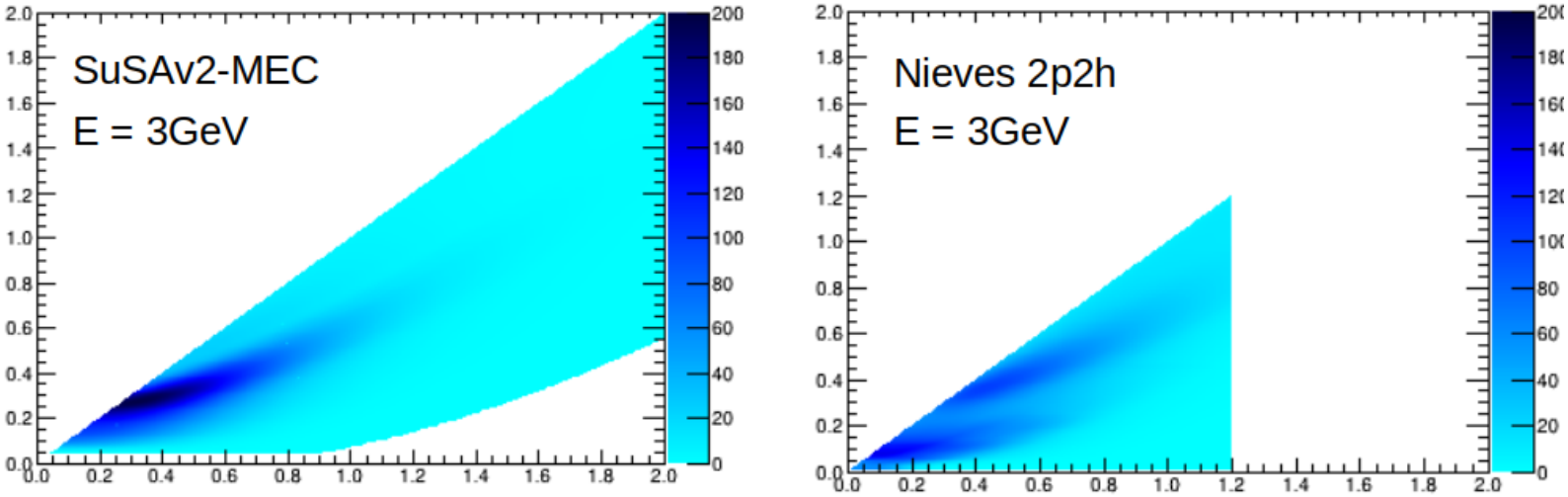

Large q0,q3 shape difference probably mostly due to inclusion of different diagrams …

- Nieves model makes some non-relativistic approximations, SuSAv2-MEC does not – expect fairly small impact
- Nieves model rejects direct/exchange interference terms, SuSAv2-MEC does not – Nieves predicts relatively less pp final states
- Nieves model includes a slightly different set of diagrams (some from imaginary part of the W)

Implementation – lepton part

Like the Nieves model, SuSAv2-MEC is able to predict only the outgoing lepton kinematics. The double differential cross section can be written:

$$\frac{d^2\sigma}{dq_0 q_3} = \sigma_0 \eta_{ij}(q_0, q_3) W_{ij}(q_0, q_3)$$

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  - **Using Steven G.'s very nice new hadron tensor framework!**
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  - Use a GENIE's bilinear interpolation function to evaluate specific q0,q3
  - Hadron tensors will be provided for a few select targets (C and O so far, may add others). Can scale to other nuclei.
- GENIE implements the hadron tensor from the full microscopic calculation, but this is not what is often used by the SuSA group (they use the parameterization)
  - GENIE's implementation is slightly more true to the full calculation (most of the time)

Implementation – hadron part

Like for every model, make some ad-hoc prediction of hadron kinematics:

- Choose energy/momentum transfer from lepton part xsec using accept/reject
- Pick two target nucleons (which ones? See next slide)
- Assign an initial momentum and removal energy from input nuclear model
- Combine nucleons to be a target "cluster"
- Transfer energy/momentum from lepton to cluster and swap n to p as needed
- "Decay" cluster back to back in CoM frame, boost back to lab frame
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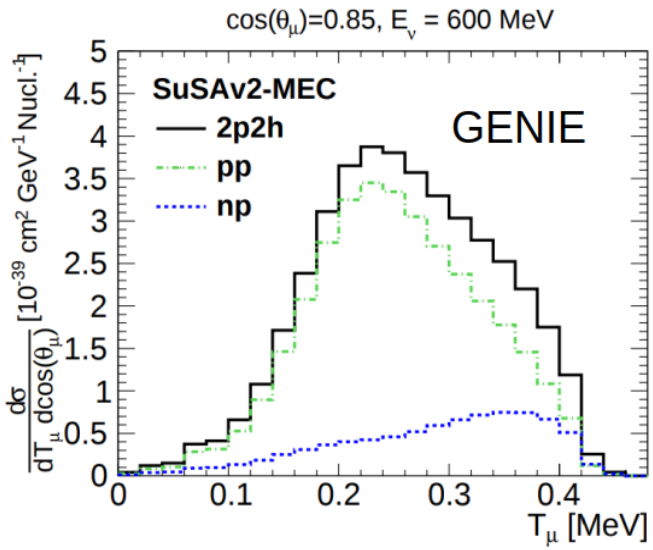
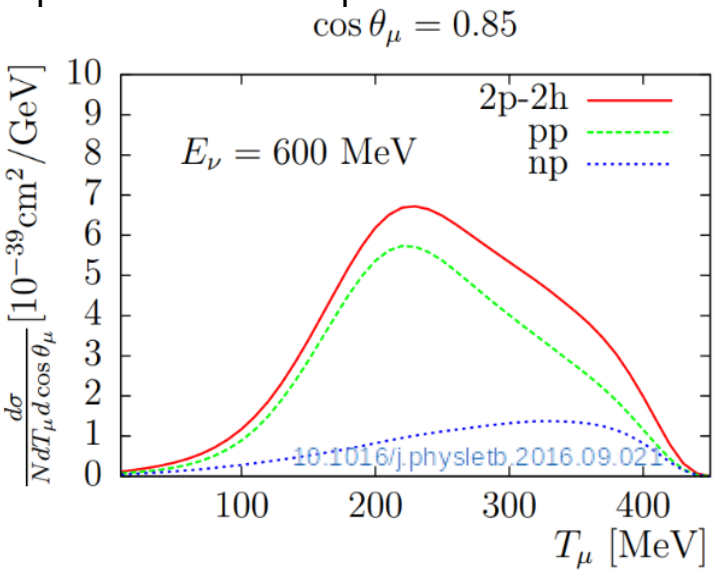
Implementation – hadron pairs

- Use a separate hadron tensor for only np initial state pairs





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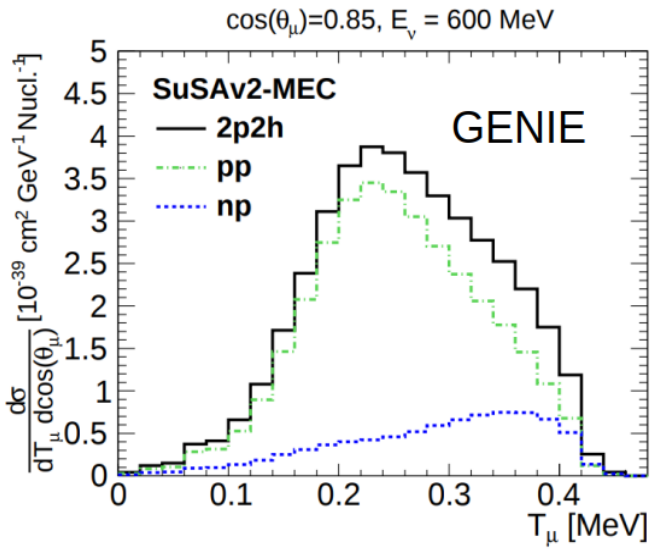
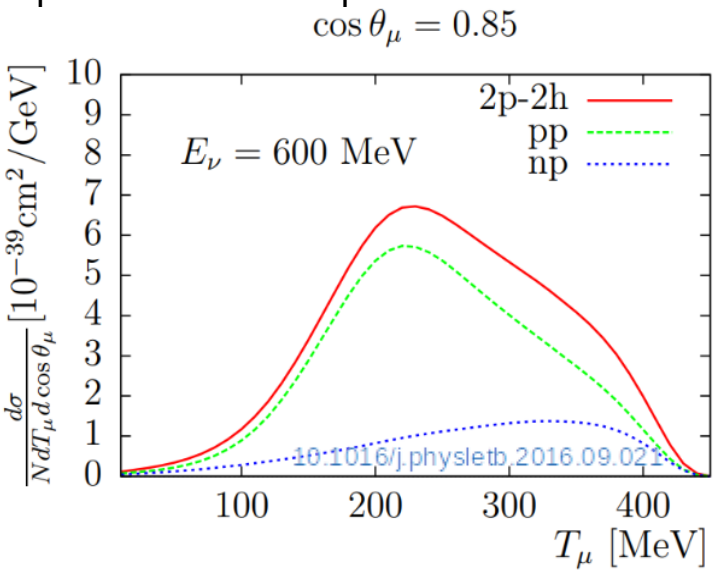
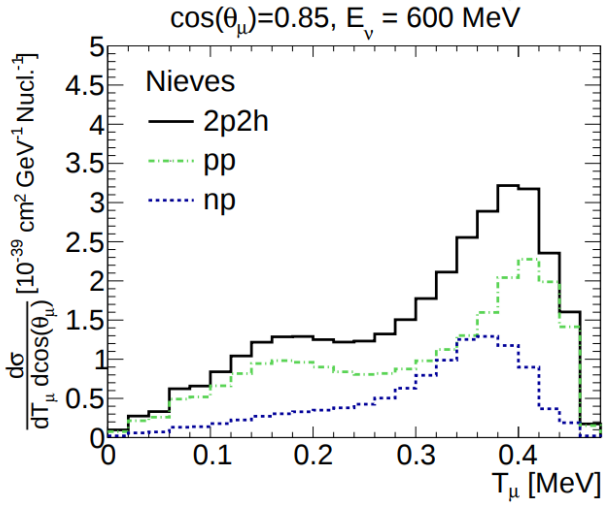


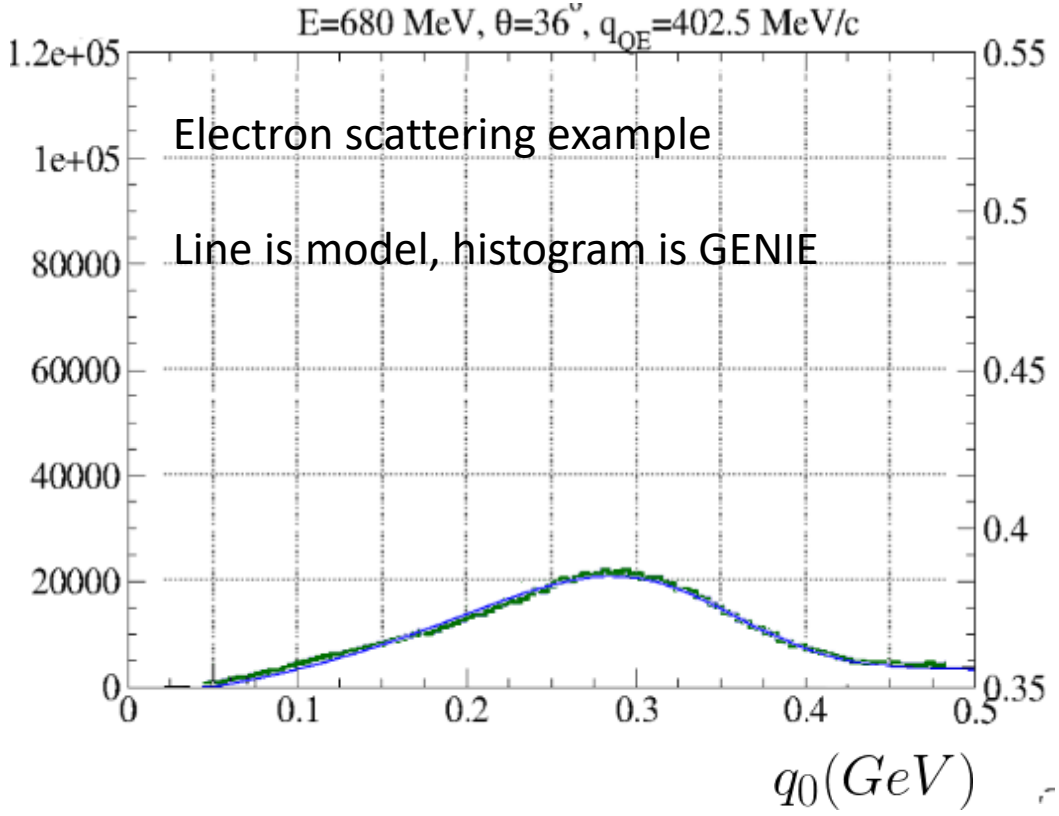




- Very different final state nucleon pair distribution than in Nieves model
- Possibly quite significant effect for calorimetric energy reconstruction

Validation

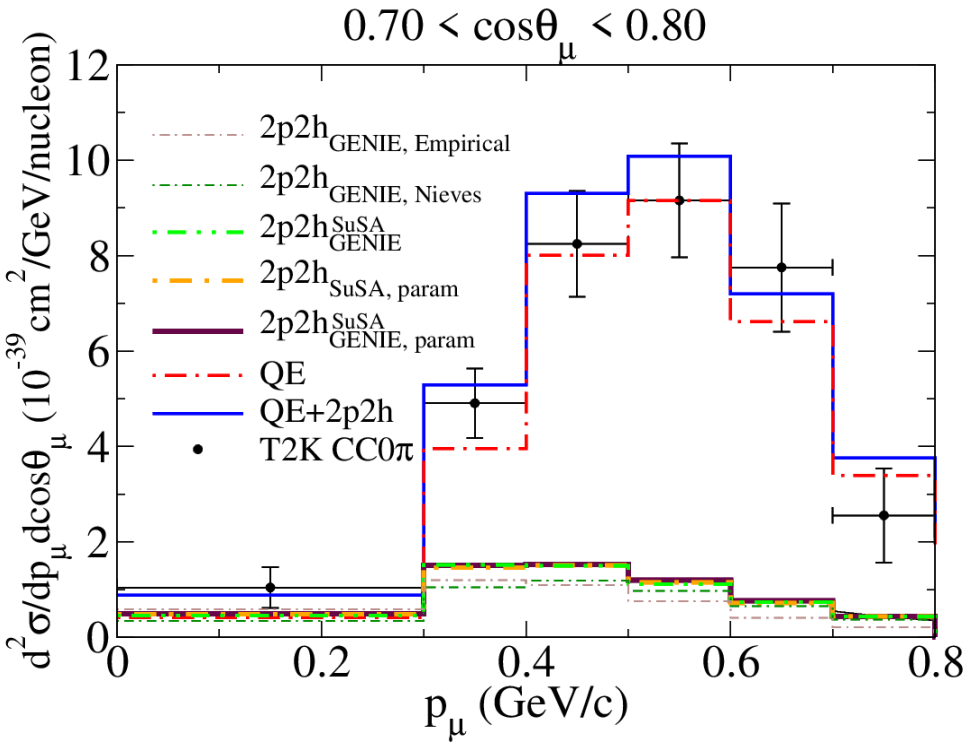
- Compared fixed kinematic predictions in model and GENIE

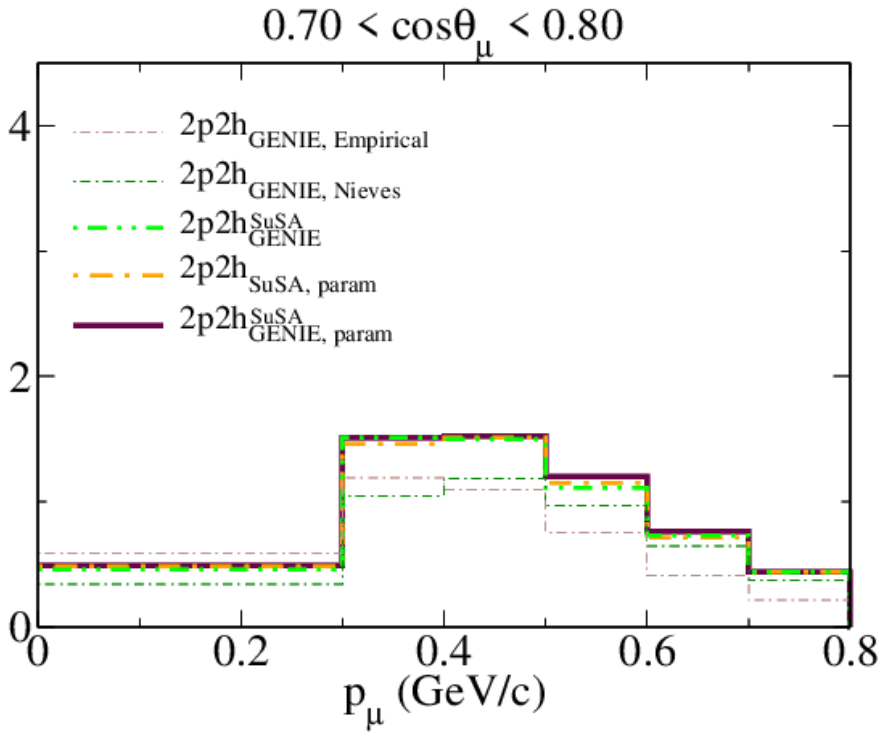


- All looks good!

Validation

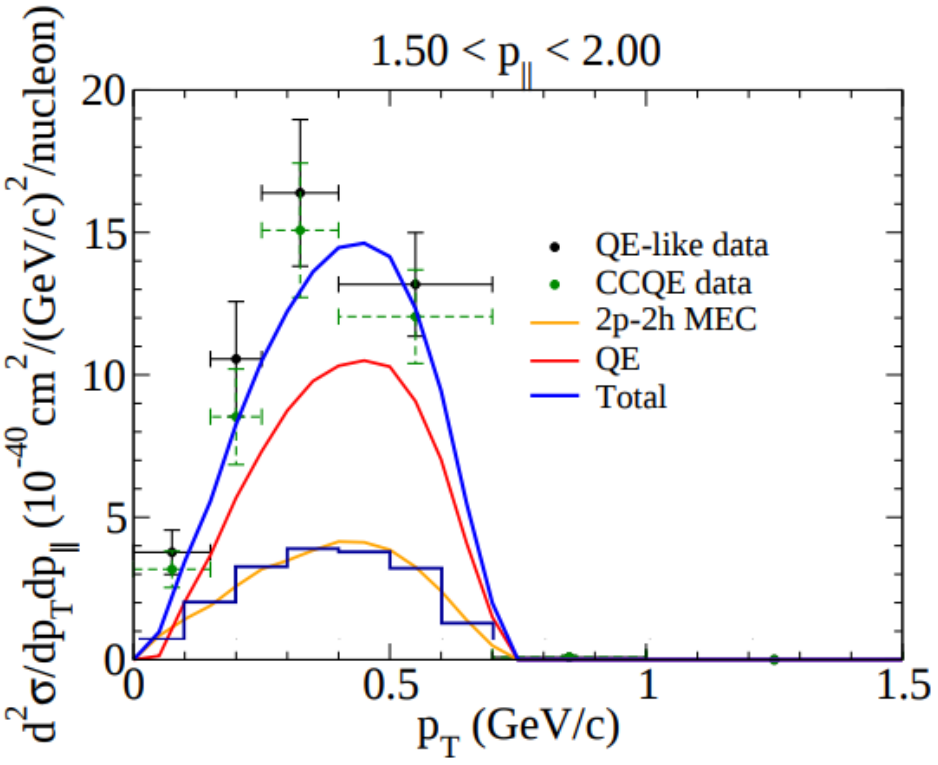
- Compare more complicated predictions: T2K double differential cross section





Validation

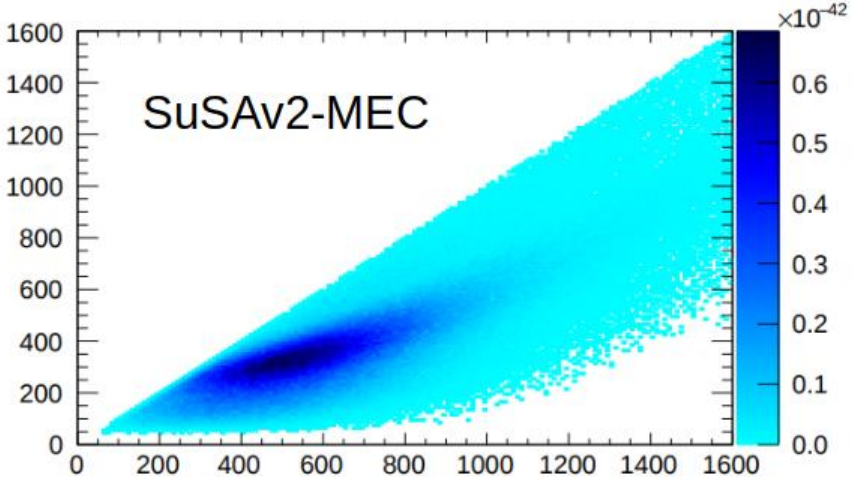
- Another example: MINERvA anu predictions – histogram is GENIE

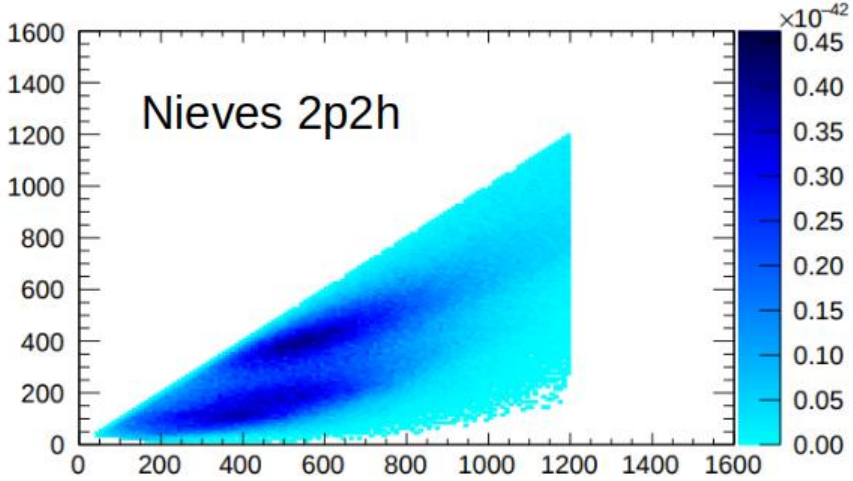


- Validation conclusions: Everything behaves as expected. Only problematic region is very low Q2 where double differential xsec becomes very peaked and interpolation methods break down (max. ~5% effect).

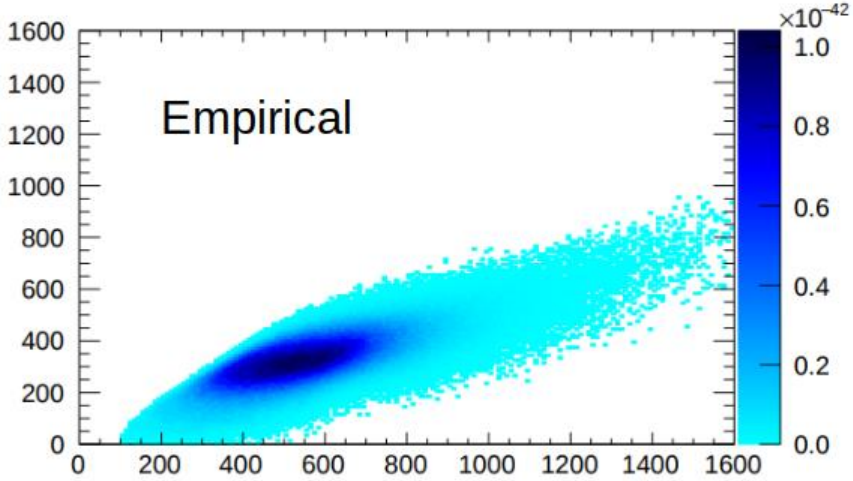
Now it's working, what can we do?

- Compare q0, q3 for T2K flux:





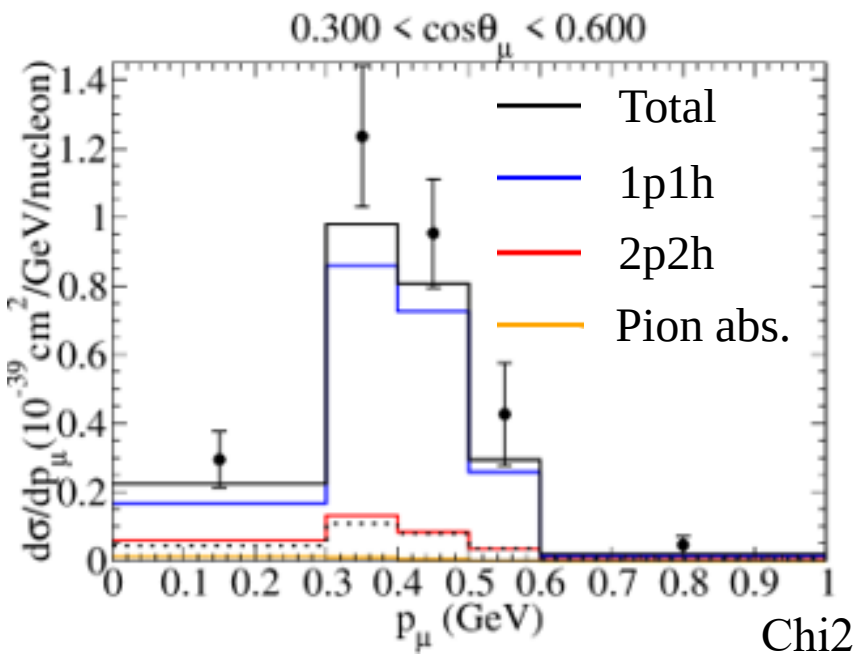
- SuSAv2-MEC provides a complementary but quite different model

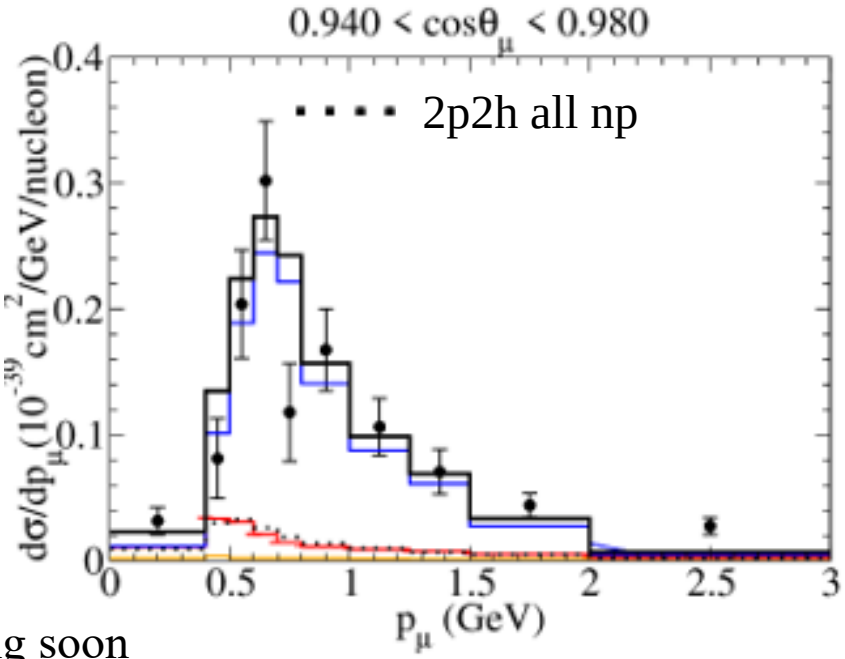


Now it's working, what can we do?

Compare with T2K CC0pi with pp<500MeV measurement

- 2p2h comes from SuSAv2-MEC in GENIE
- Pion abs comes from GENIE , but is extremely small at these kinematics
- 1p1h comes from first full relativistic mean field calculation with a cut in proton momentum - "semi-semi inclusive" (from G. Megias)

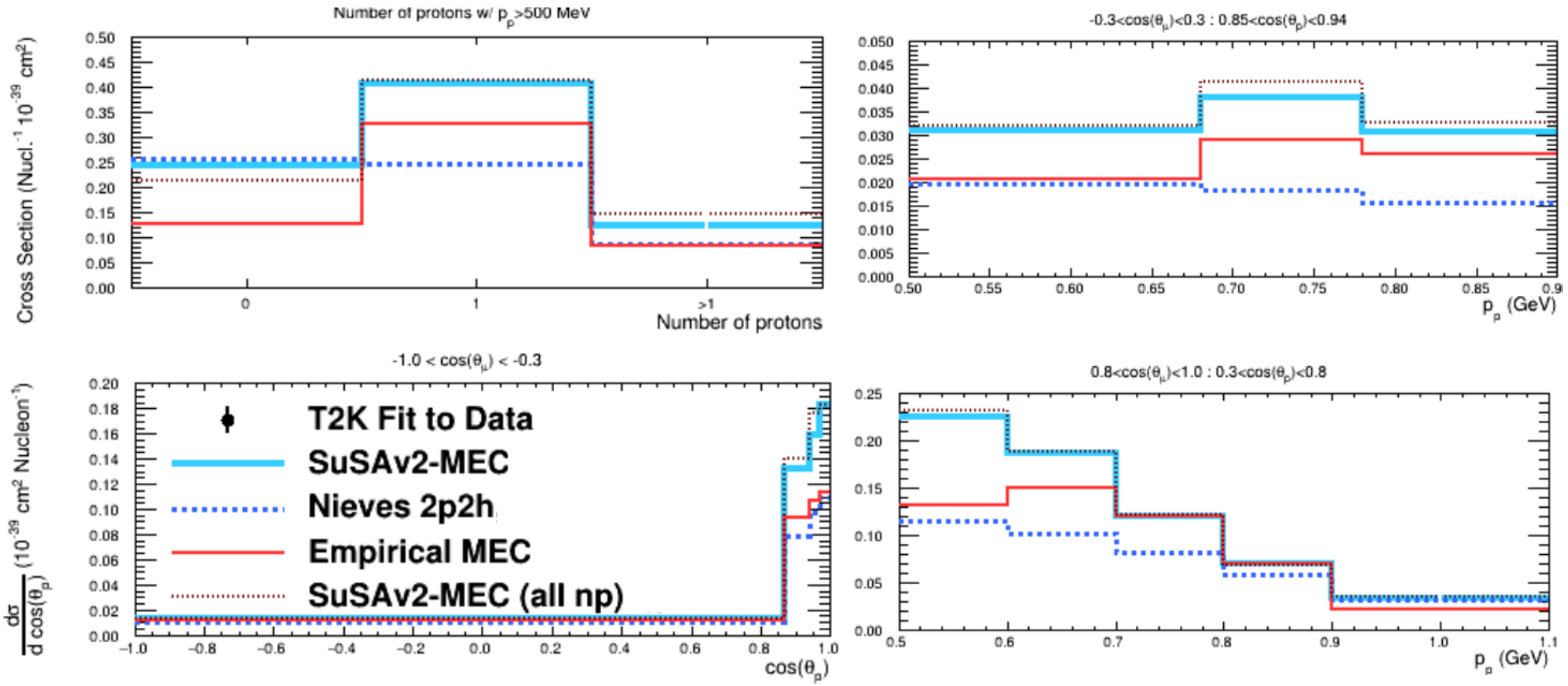




Chi2 coming soon

Now it's working, what can we do?

See what we get with T2K CC0pi with proton mom.>500MeV result:



Fairly large separation at some kinematics (factor of 2)

Many more physics studies coming soon – publication in process

SuSAv2 1p1h – very brief theory!

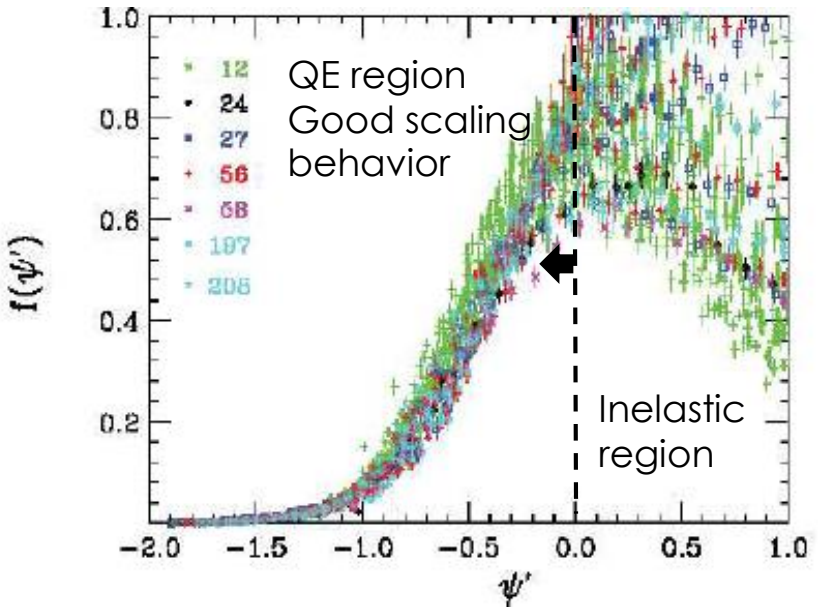
Basic idea: use the scaling function encode nuclear dynamics

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

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 1p1h – very brief GENIE!

Xsec calculation: build hadron tensor from SuSAv2, implement as in 2p2h

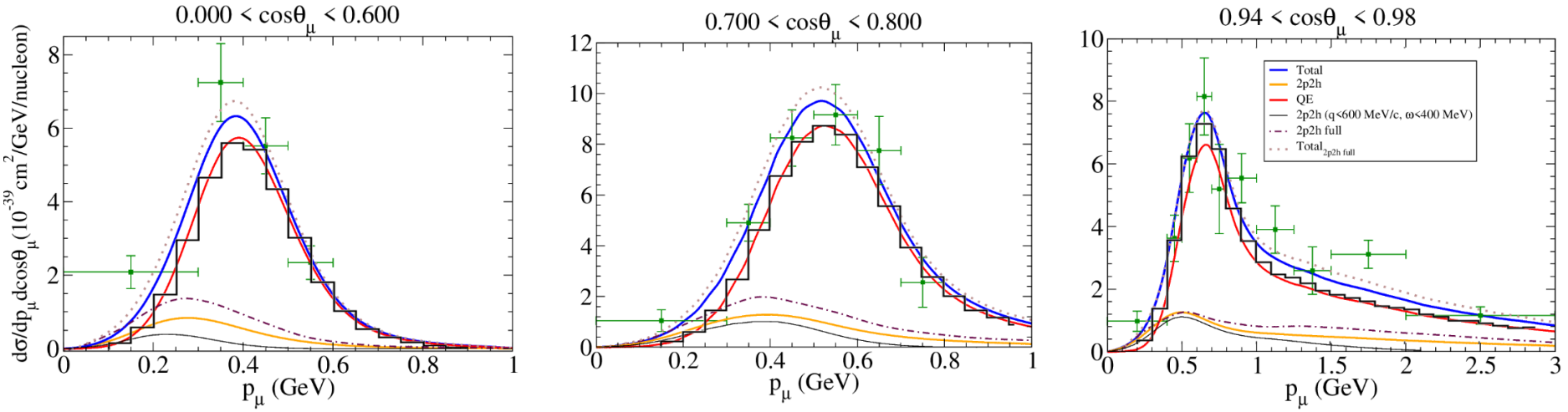
Hadronic side: more complicated … copy elements of other methods.
Bold/*italics* bits represent very/*slightly* questionable physics but this is no worse than in other 1p1h model implementations.

- Draw target nucleon from chosen nuclear model **irrespective of ω, q**
- Get removal energy from RMF-like treatment, *re-throw from nuclear model if nucleon is Pauli blocked*
- Transfer all of ω, q to nucleon, **none to remnant**
- Subtract removal energy, **put proton on-shell with adjustment of p, conserve momentum by adjusting remnant kinematics**
- *Do FSI cascade and rest of interaction using standard GENIE methods*
  - (In all plots from I use hN, hA sometimes gives crazy results)
  - Ensure not to double count removal energy

This all requires a different QE "event generator" than the default

SuSAv2 1p1h – GENIE validations

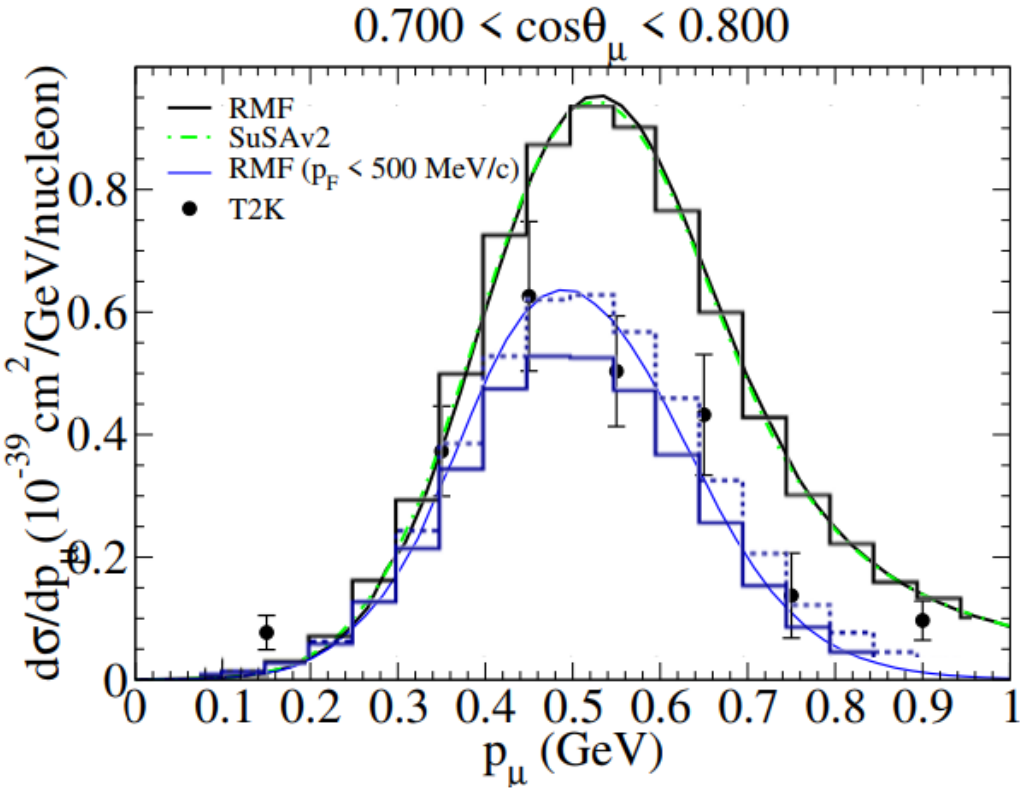
- Run similar validations to 2p2h – histograms are GENIE implementation. In general very good agreement.



- Similarly to 2p2h – some issues at low Q^2 due to interpolation in the hadron tensor. Could possibly be fixed with finer binned tensor here but this is low priority.

Now it's working, what can we do?

- Test the factorisation approach!
- Compare RMF "semi-semi-inclusive" prediction and GENIE SuSAv2 implementation to T2K data (muon kinematics with restriction of $p_{proton} < 500\ MeV/c$.



- Curves – theory
- Histograms – GENIE

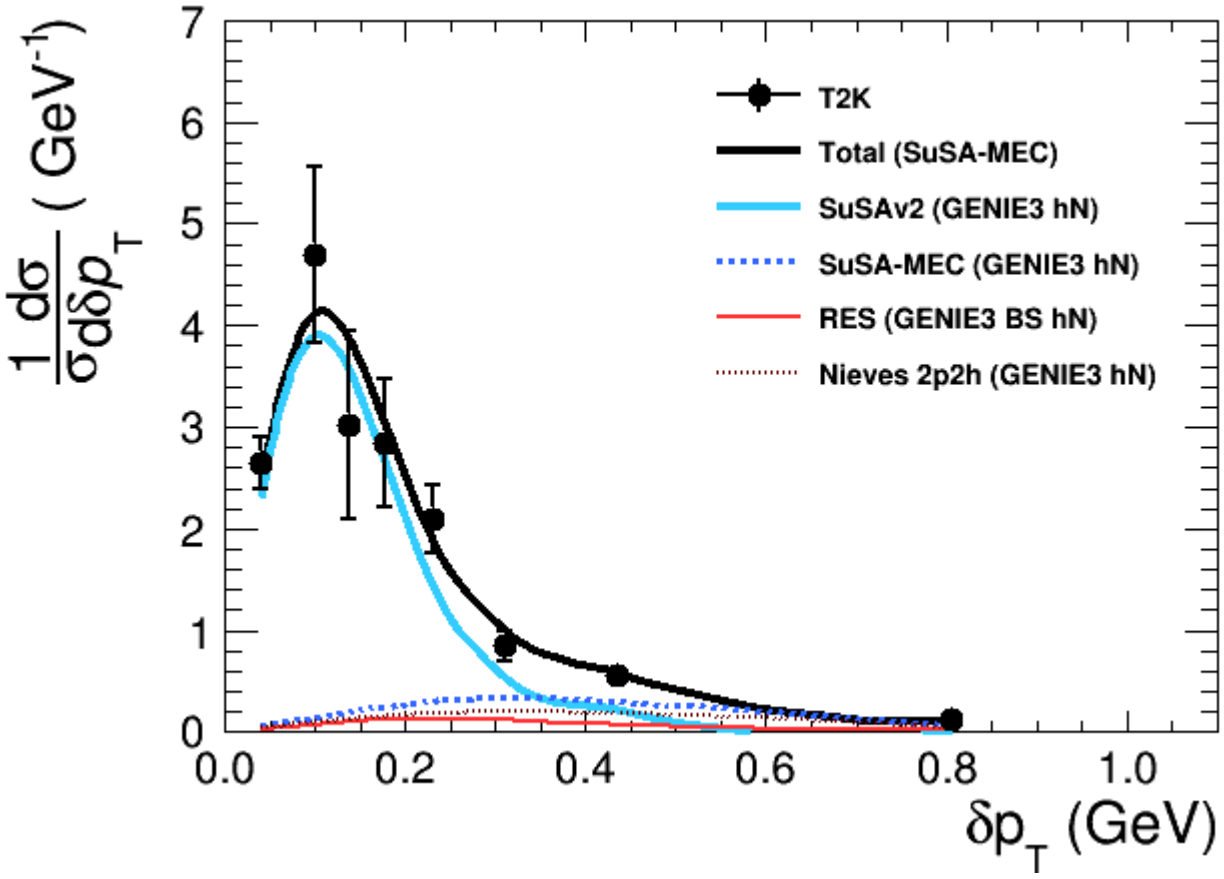
- Blue: With cut in p_{proton}
- Dotted line – no FSI in GENIE

In this particular bin: remarkable agreement!

What about other kinematics? Stay tuned!

Now it's working, what can we do?

- Full SuSAv2-GENIE comparison to T2K STV results



- **Much more to come soon**

Feedback from users so far

"Nice work, but we won't use GENIEv3 anytime soon so we can't use it …"

- Solution: provide a reweighting tool to turn some nominal GENIEv2 predictions into SuSAv2 predictions.
- Entire inclusive xsec can be written as a 3D (q, ω, E_ν) table.
  - (additionally split by np,pp final states for 2p2h)
- Build these tables for SuSAv2 1p1h and 2p2h
- User builds same tables for their chosen GENIEv2 models (or even their non-GENIE models …)
- User then applies the ratio of the two as an event by event reweight.
- Should work exactly but this is a little tedious and it requires high MC stats and no phase space cuts in (q, ω, E_ν)

Reweighting SuSAv2 in GENIE (1p1h)

- When using a hadron tensor to calculate a cross section it's not obvious how to reweight the prediction (e.g. how to vary MAQE)
- One easy option is that we replace our hadron tensor implementation with the SuSAv2 formalism which includes the parameters that you would like to reweight

Another option:

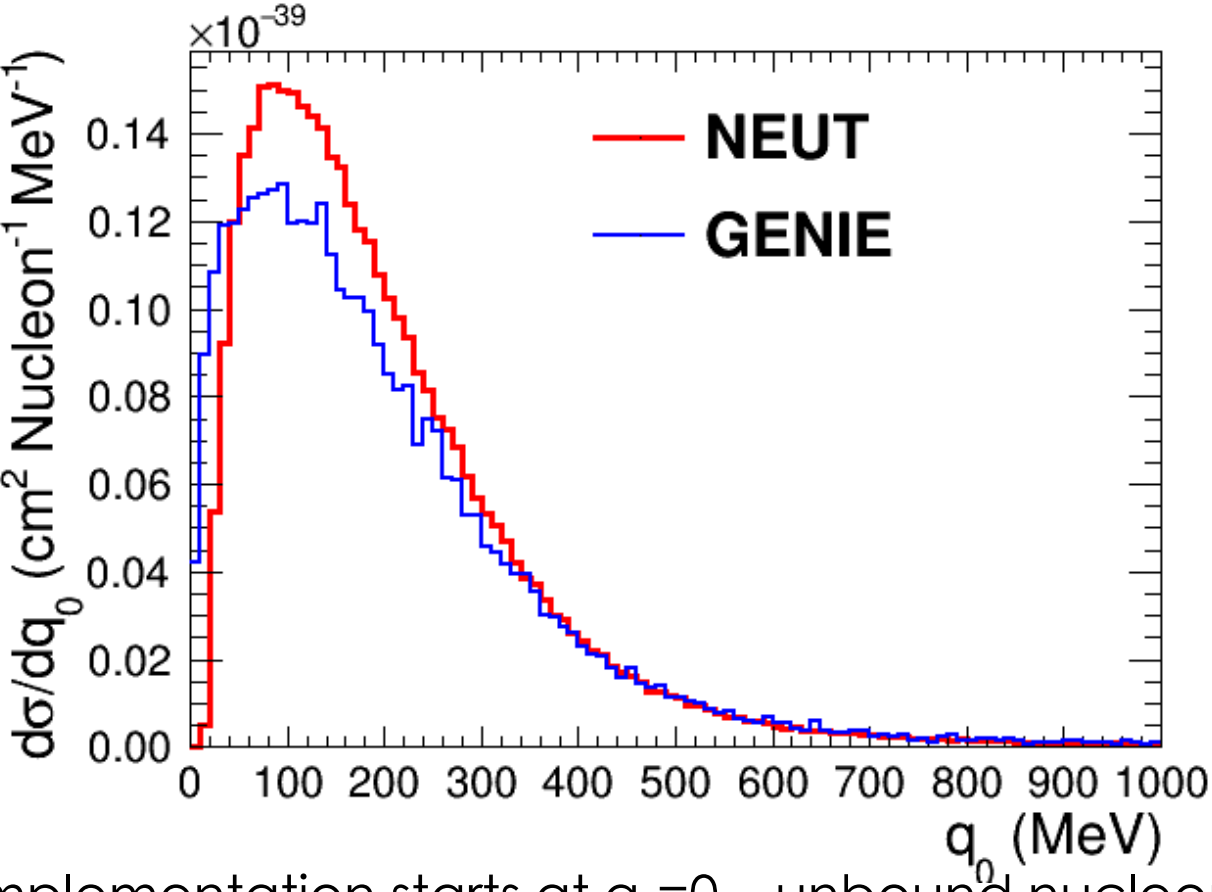
$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})}$$

- Calculate scaling function on the fly by providing an input single nucleon hadron tensor.
- Calculate new single nucleon xsec with chosen parameters.
- Apply scaling function to new single nucleon xsec.

Polishing the brass on the titanic?

- The SuSAv2 1p1h/2p2h hadron tensors are **built using specific nuclear models** (Relativistic mean field for 1p1h and a global relativistic Fermi gas for 2p2h)
- When we use a nuclear model for the hadronic predictions, should we force it to be the same as the one used for the hadron tensor?
- Unfortunately whatever we do is inconsistent – a real semi-inclusive model would not factorise the lepton and hadron components of the interaction as we do in GENIE…

GENIEv3 Nieves 1p1h issues



- GENIEv3 implementation starts at q_0=0 – unbound nucleons!!!
- Reported bug to GENIE developers
- Rik Gran reported a similar bug in GENIE 2.12.6 …