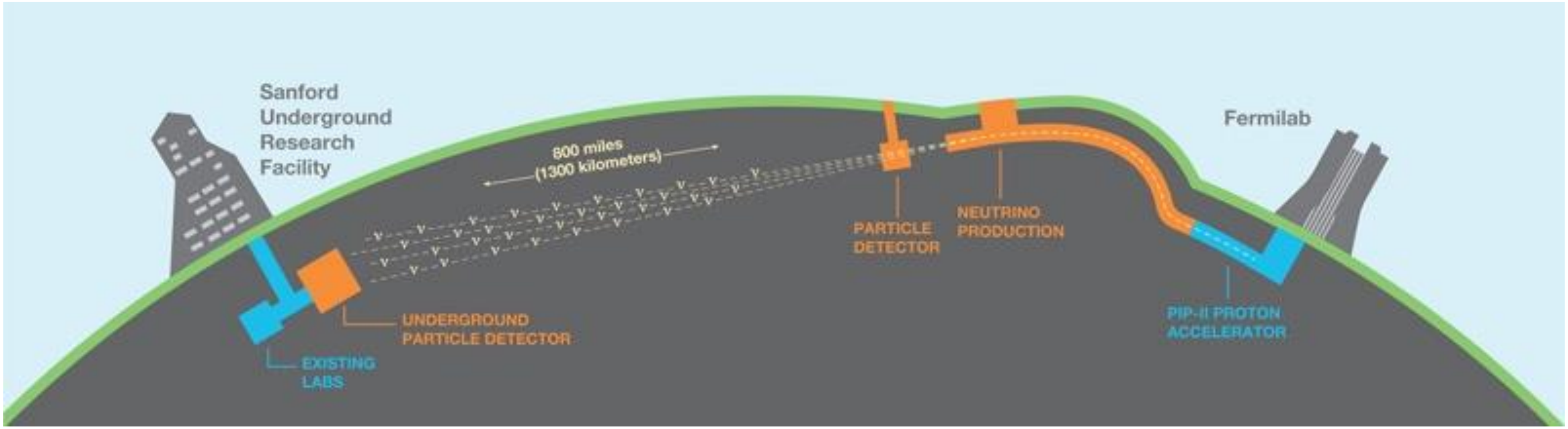
Modeling neutrino-nucleus interaction uncertainties for DUNE

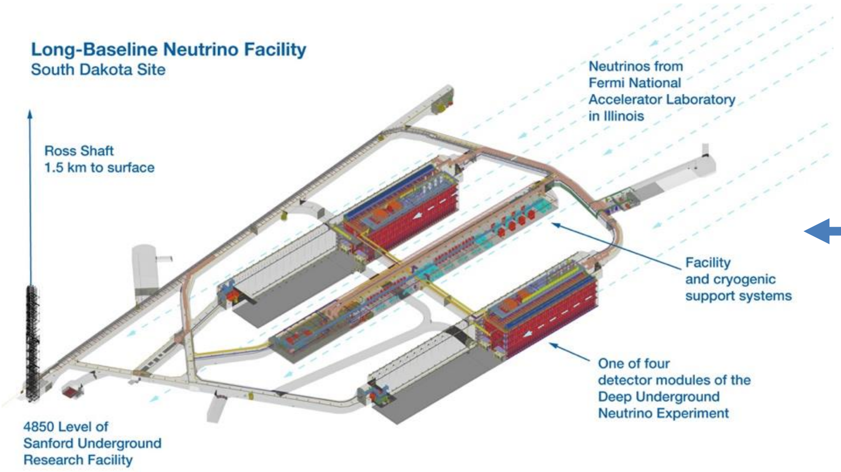
The baseline model and uncertainties for DUNE's next round of long-baseline oscillation sensitivity studies

Stephen Dolan
for the DUNE collaboration

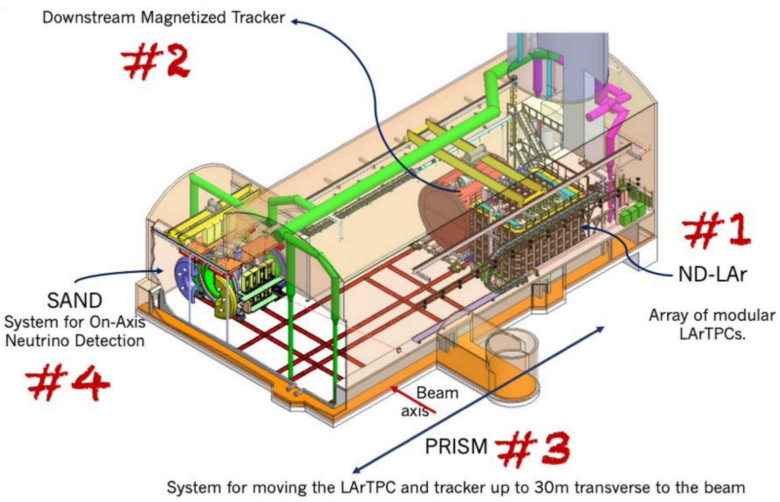
stephen.joseph.dolan@cern.ch

The DUNE Experiment

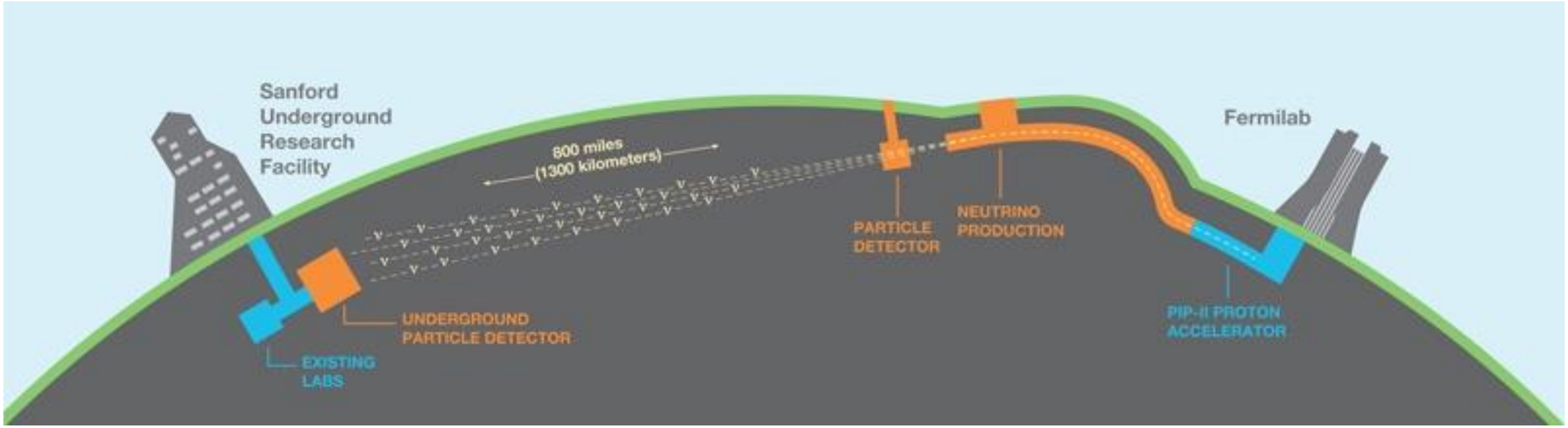




Oscillations



The DUNE Experiment



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

Far detector event rate

Oscillation Probability

Neutrino-Argon Cross Section

Incoming neutrino flux

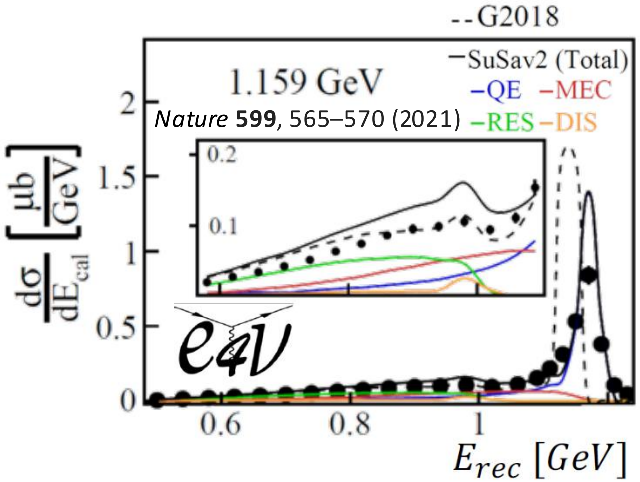
Detector Efficiency

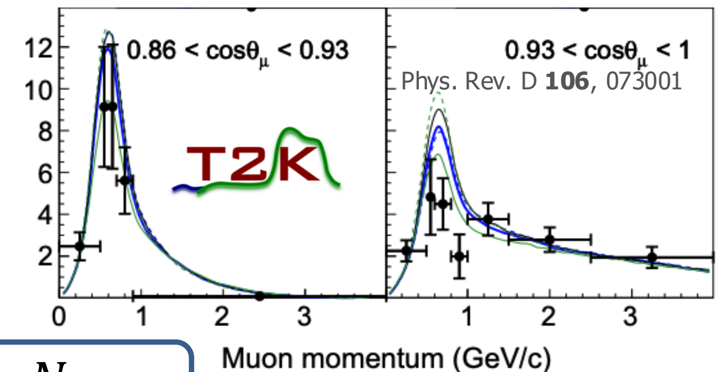
What we're facing

- Neutrino interaction cross sections are hard to model. Our current generator predictions are all ruled out by existing measurements.

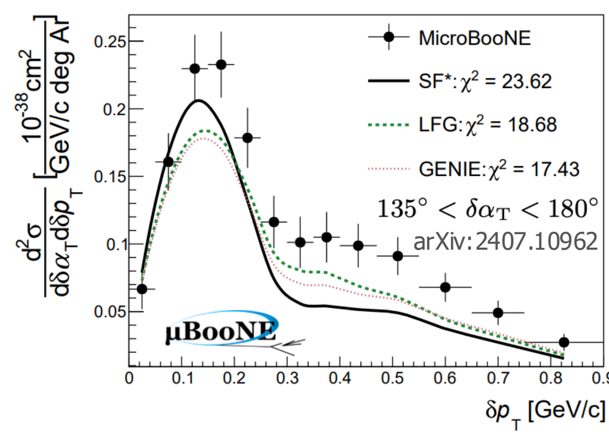
What we're facing

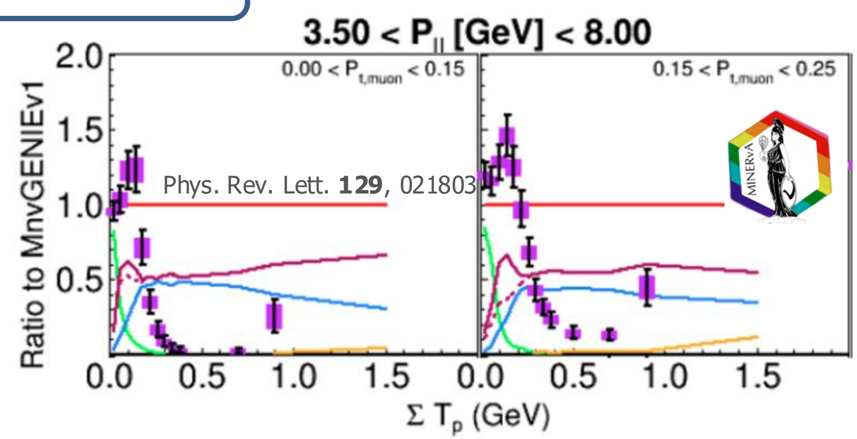
- Neutrino interaction cross sections are hard to model. Our current generator predictions are all ruled out by existing measurements.





$$\chi^2_{models} \gg N_{bins}$$

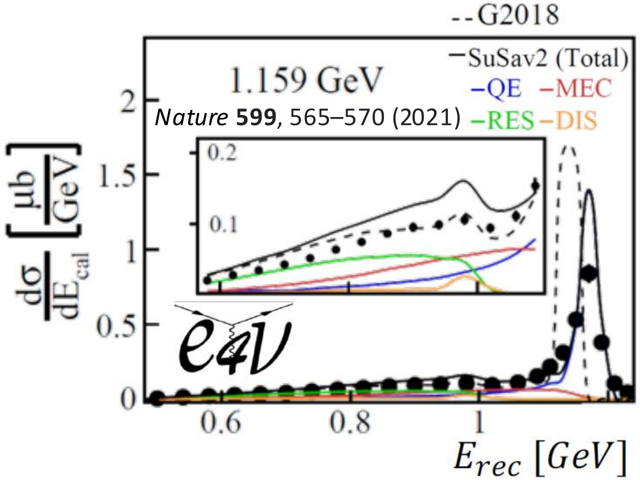


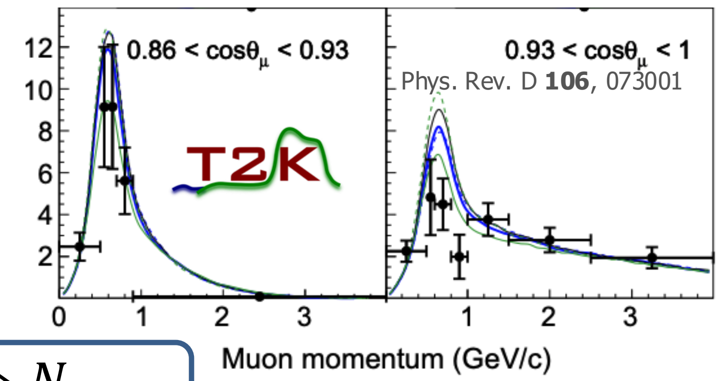


- Our baseline model will be demonstrably "wrong"

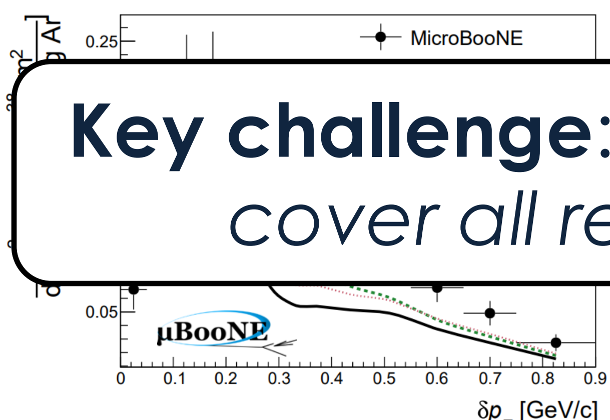
What we're facing

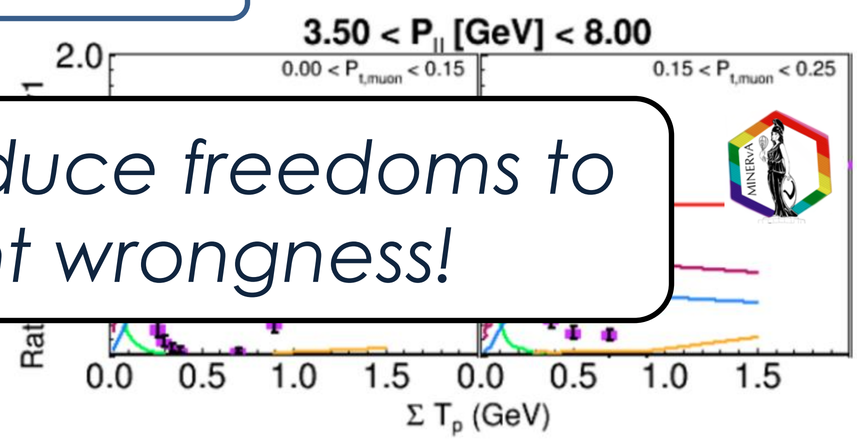
- Neutrino interaction cross sections are hard to model. Our current generator predictions are all ruled out by existing measurements.





$$\chi^2_{models} \gg N_{bins}$$





Key challenge: *introduce freedoms to cover all relevant wrongness!*

- Our baseline model will be demonstrably "wrong"

Overview

- **Our updated interaction model**
- Limitations of the model
- Available and planned systematic parameters

Updated interaction model

DUNE has moved to a shared interaction model with a focus on **flexibility for reweighting**. This introduces several changes:

- Updated nuclear ground state model
- Z-expansion for CCQE axial form factor
- SuSAv2 2p2h
- Simulation of de-excitation photons for Argon

It also uses GENIE's free nucleon tune Phys. Rev. D **104**, 072009

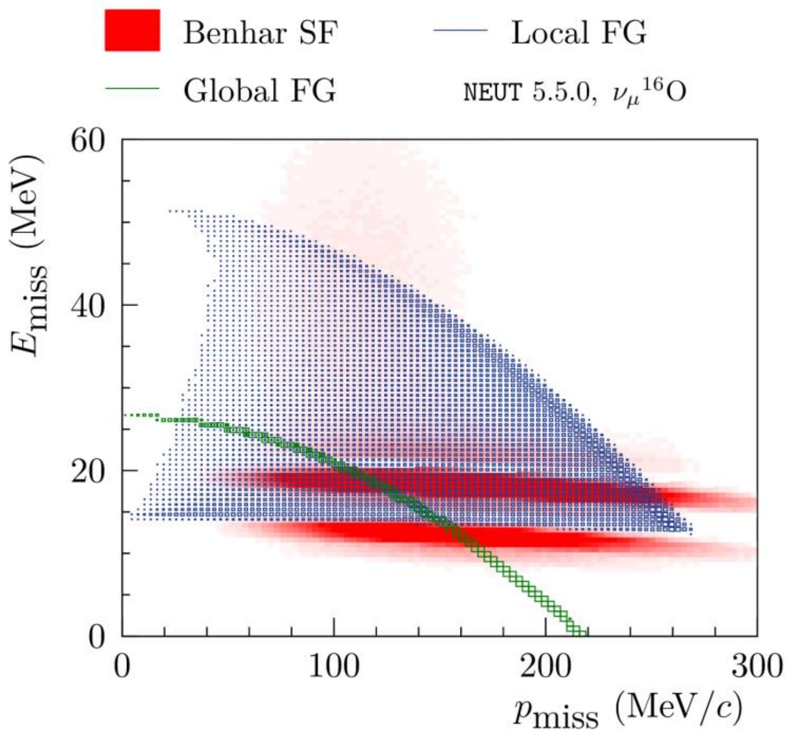
Available in GENIE v3.04.00 onwards as: Ar23_20i_00_000

Also used by SBN, under consideration by NOvA

Updated nuclear ground state

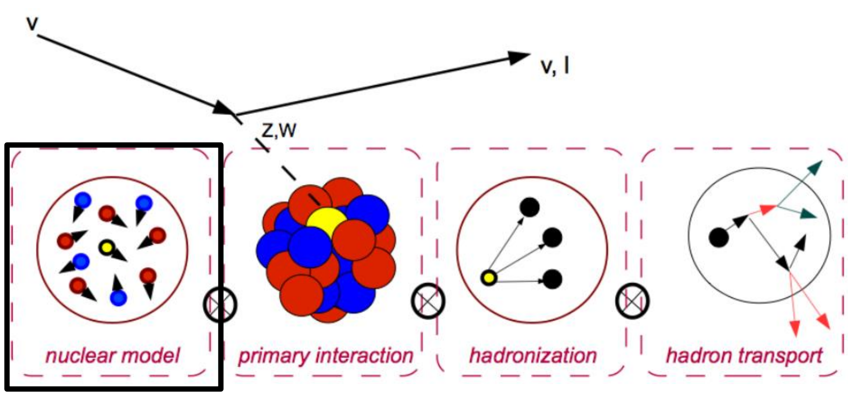
- Under certain approximations, initial state nucleons are described by their:
  - **Fermi motion**: p_{miss} (their initial state momentum)
  - **Removal energy**: E_{miss} (the energy required to get them out of the nucleus)

Eur.Phys.J.ST 230 (2021) 24, 4469-4481



$$\vec{p}_{miss} = \vec{p}_\nu - \vec{p}_\mu - \vec{p}_p$$

$$E_{miss} = \omega - T_p^{pre-FSI} - \Delta m_{n\to p} - T_{nucl.remnant}$$

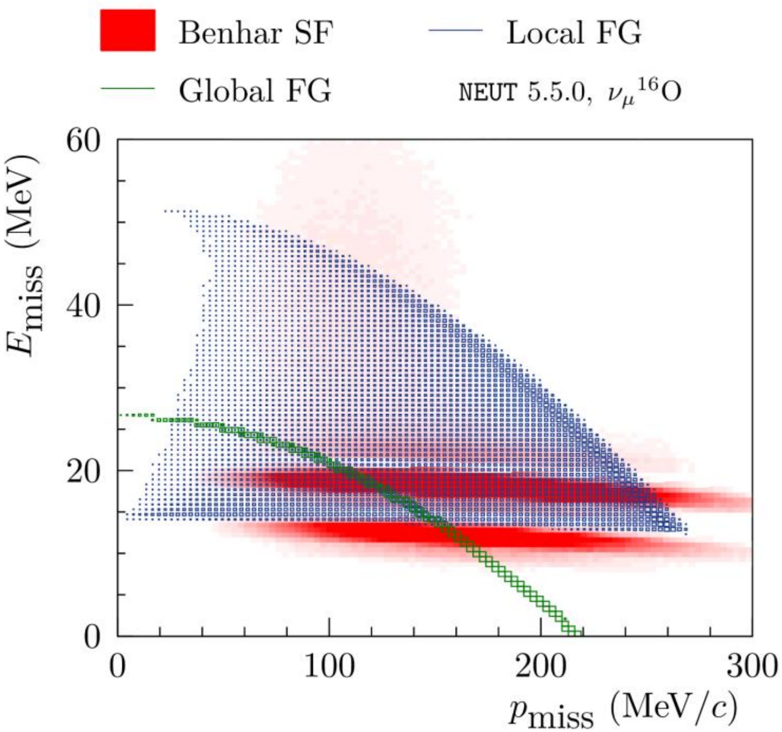


Updated nuclear ground state

- Under certain approximations, initial state nucleons are described by their:
  - **Fermi motion**: p_{miss} (their initial state momentum)
  - **Removal energy**: E_{miss} (the energy required to get them out of the nucleus)

- Different models give us different 2D distributions. For example:
  - RFG: 1D parabola
  - LFG: smears this out
  - SF: nuclear shell structure

Eur.Phys.J.ST 230 (2021) 24, 4469-4481



$$\vec{p}_{miss} = \vec{p}_\nu - \vec{p}_\mu - \vec{p}_p$$

$$E_{miss} = \omega - T_p^{pre-FSI} - \Delta m_{n\rightarrow p} - T_{nucl.remnant}$$

Updated nuclear ground state

- Under certain approximations, initial state nucleons are described by their:
  - **Fermi motion**: p_{miss} (their initial state momentum)
  - **Removal energy**: E_{miss} (the energy required to get them out of the nucleus)

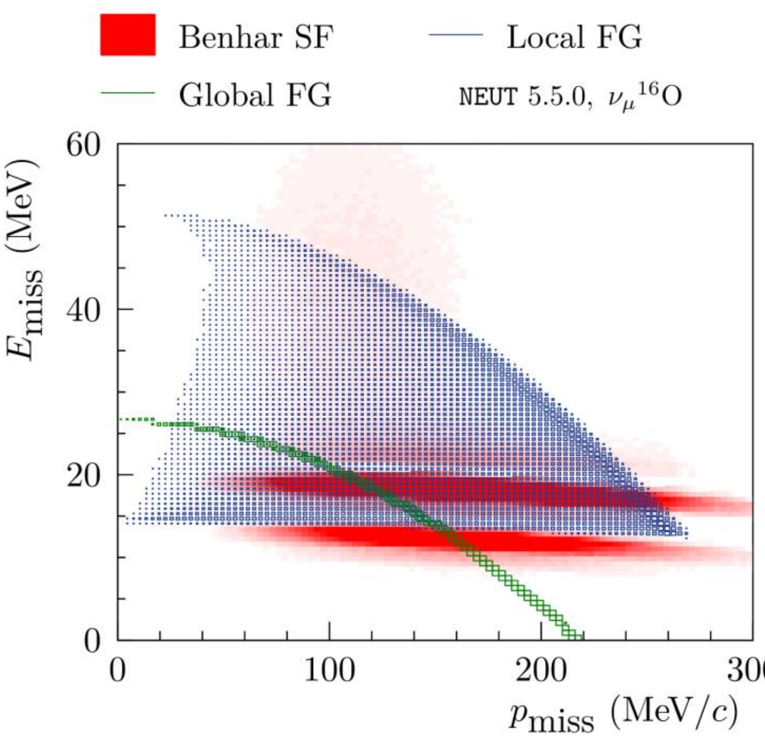
- Different models give us different 2D distributions. For example:
  - RFG: 1D parabola
  - LFG: smears this out
  - SF: nuclear shell structure

- Provided the models **cover a reasonable amount of this 2D phase space** it's fairly easy to implement a range of physics-motivated distortions

E.g.: The T2K uncertainty model for SF contains 5 d.o.f. to shape this 2D space

Phys. Rev. D **109**, 072006

Eur.Phys.J.ST 230 (2021) 24, 4469-4481

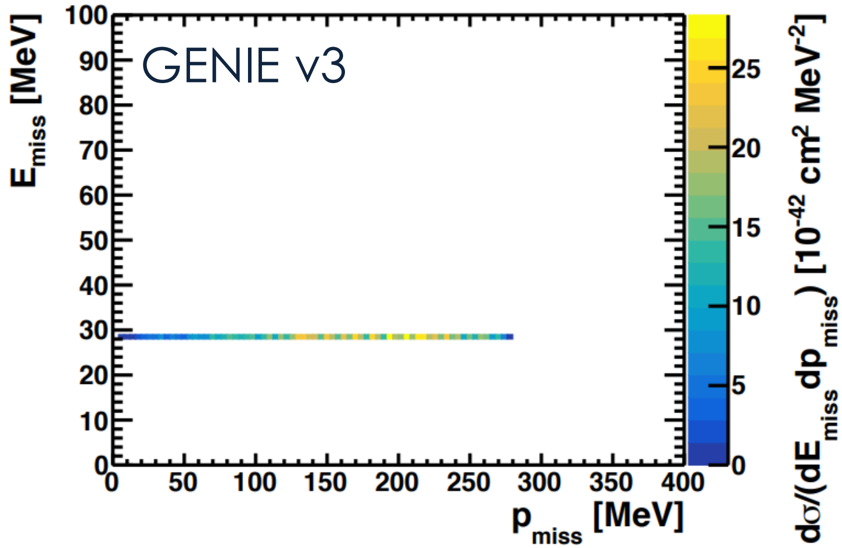


$$\vec{p}_{miss} = \vec{p}_\nu - \vec{p}_\mu - \vec{p}_p$$

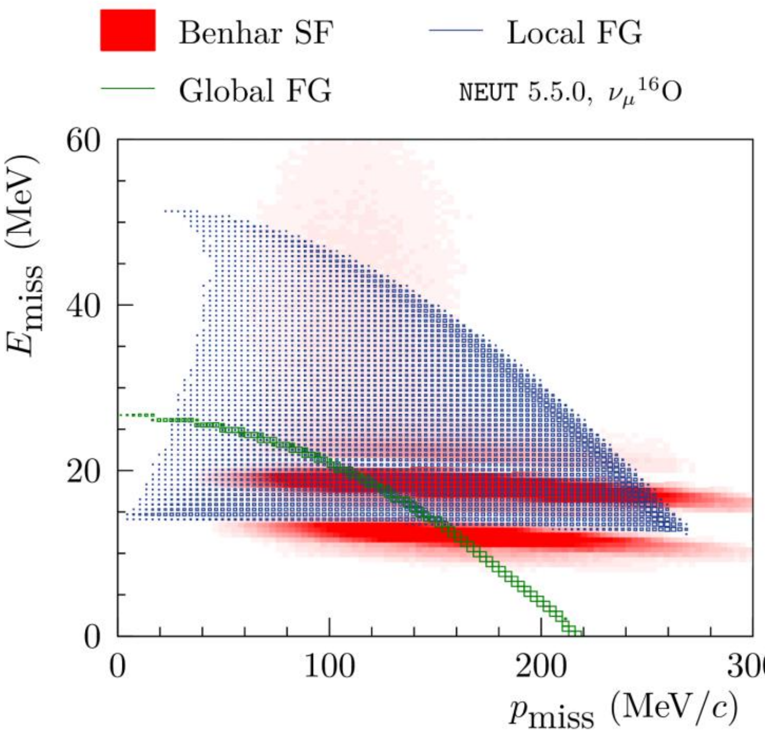
$$E_{miss} = \omega - T_p^{pre-FSI} - \Delta m_{n\to p} - T_{nucl.remnant}$$

Updated nuclear ground state

- GENIEv3 out-the-box assumed a constant removal energy



Eur.Phys.J.ST 230 (2021) 24, 4469-4481



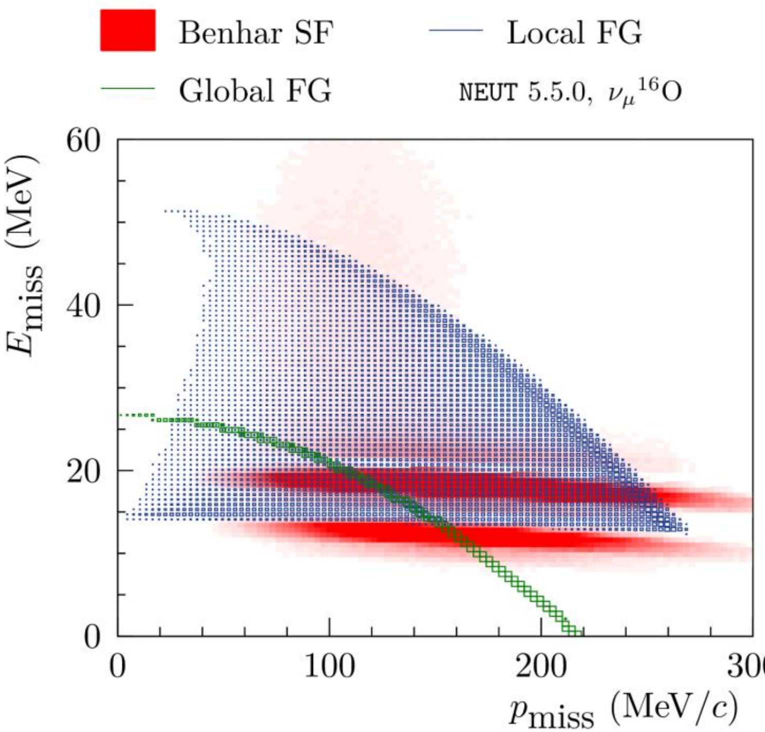
$$\vec{p}_{miss} = \vec{p}_\nu - \vec{p}_\mu - \vec{p}_p$$

$$E_{miss} = \omega - T_p^{pre-FSI} - \Delta m_{n\rightarrow p} - T_{nucl.remnant}$$

Updated nuclear ground state

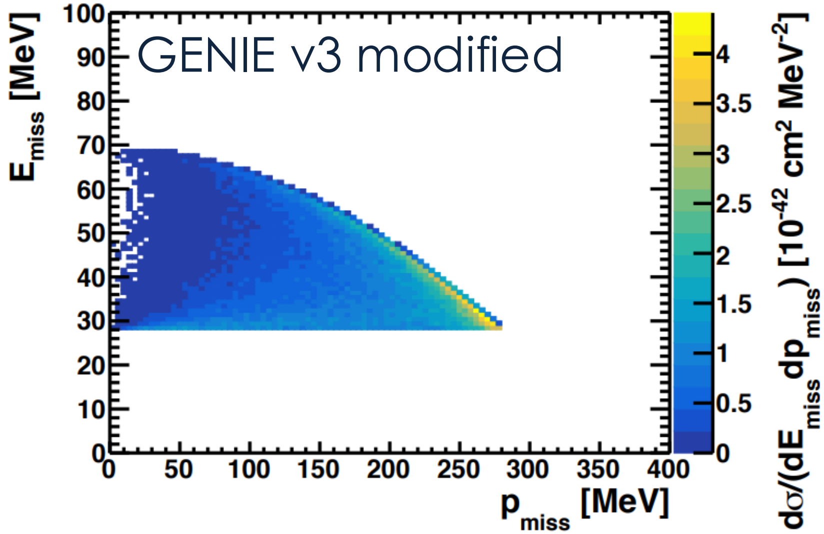
- GENIEv3 out-the-box assumed a constant removal energy
- Solution: make E_{miss} dependent on p_{miss} according to Fermi-gas model expectation

Eur.Phys.J.ST 230 (2021) 24, 4469-4481



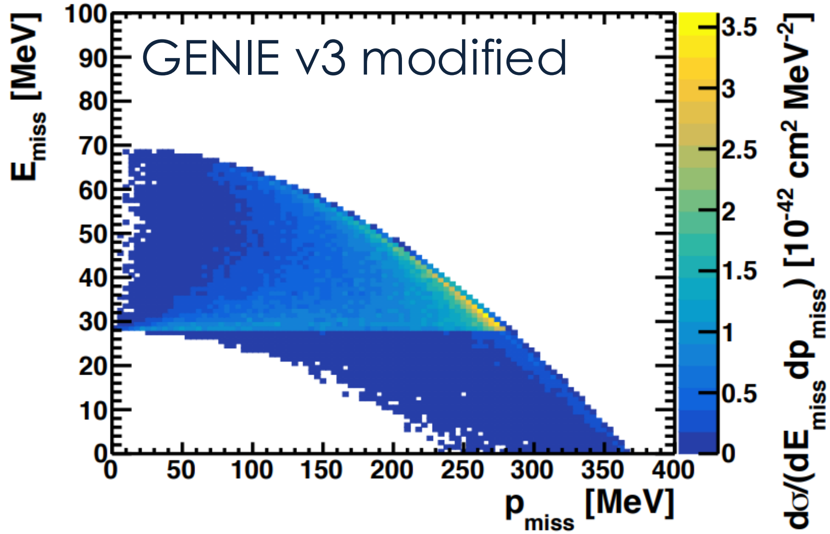
$$\vec{p}_{miss} = \vec{p}_\nu - \vec{p}_\mu - \vec{p}_p$$

$$E_{miss} = \omega - T_p^{pre-FSI} - \Delta m_{n \to p} - T_{nucl.remnant}$$

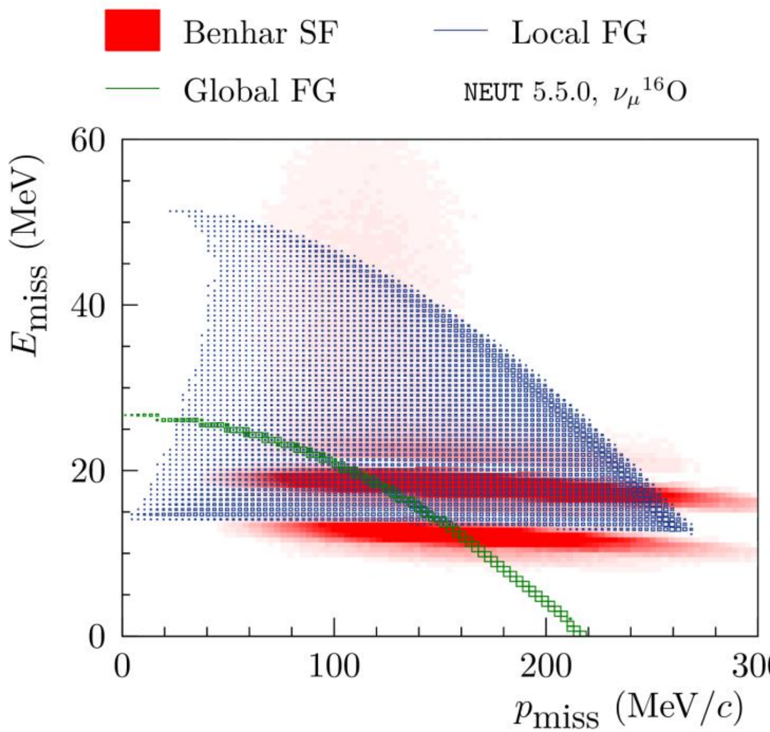


Updated nuclear ground state

- GENIEv3 out-the-box assumed a constant removal energy
- Solution: make E_{miss} dependent on p_{miss} according to Fermi-gas model expectation
- And while we're at it: add an "SRC" tail



Eur.Phys.J.ST 230 (2021) 24, 4469-4481



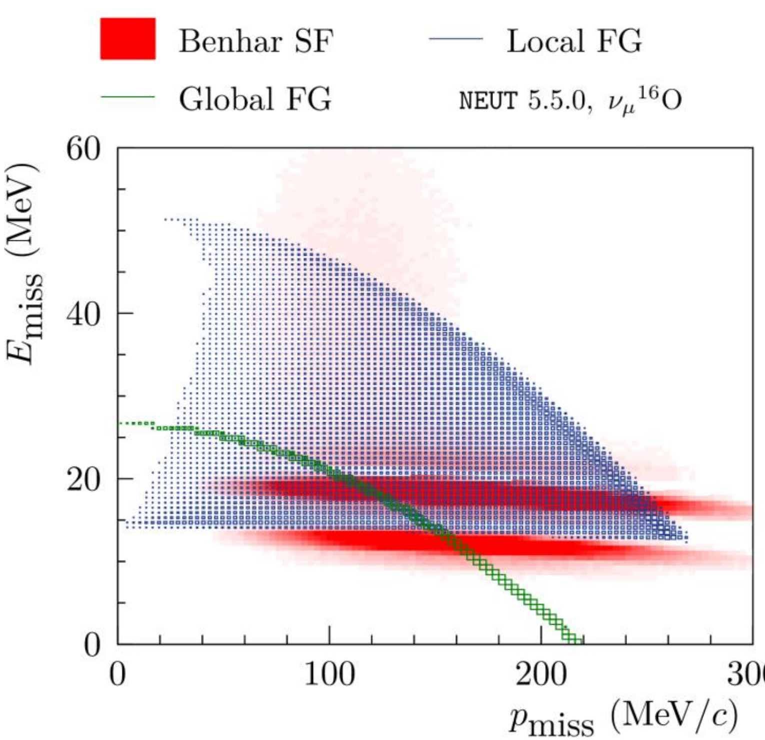
$$\vec{p}_{miss} = \vec{p}_\nu - \vec{p}_\mu - \vec{p}_p$$

$$E_{miss} = \omega - T_p^{pre-FSI} - \Delta m_{n\rightarrow p} - T_{nucl.remnant}$$

Updated nuclear ground state

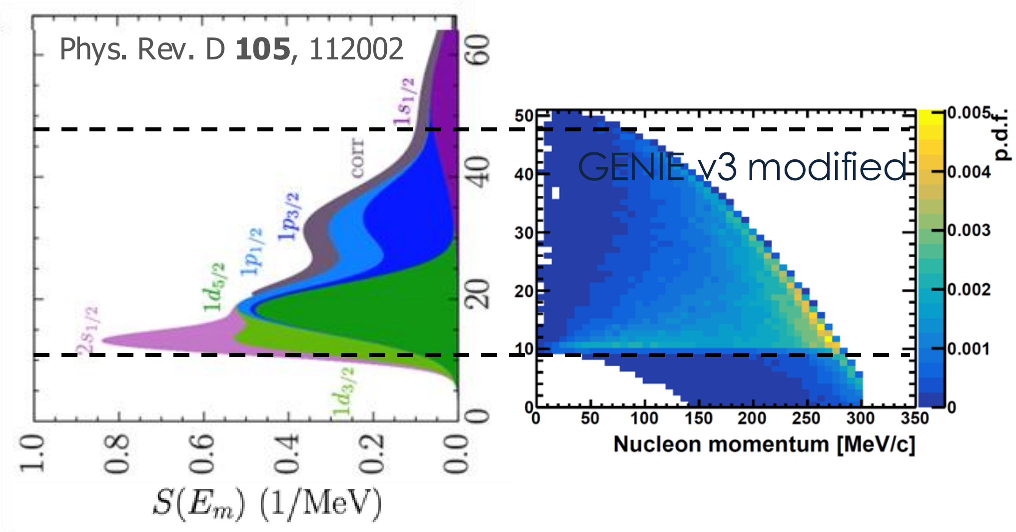
- GENIEv3 out-the-box assumed a constant removal energy
- Solution: make E_{miss} dependent on p_{miss} according to Fermi-gas model expectation
- And while we're at it: add an "SRC" tail
- Finally, we shift the spectrum to align with e,e'p informed SF models

Eur.Phys.J.ST 230 (2021) 24, 4469-4481



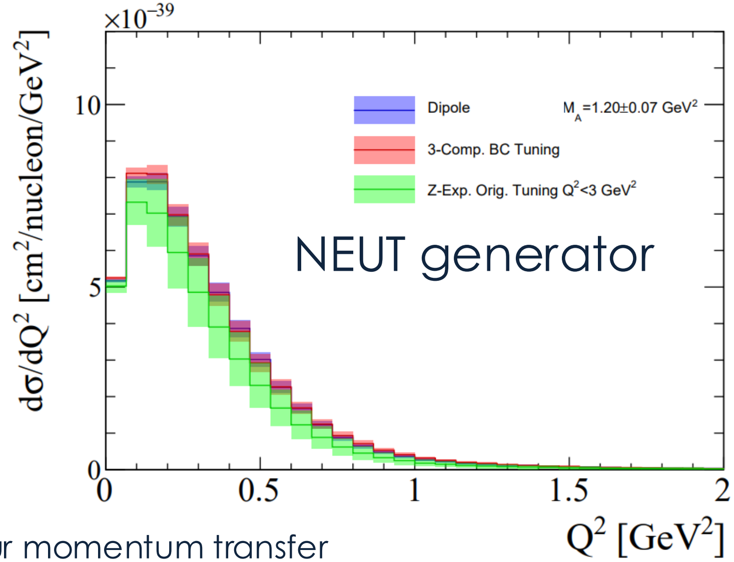
$$\vec{p}_{miss} = \vec{p}_\nu - \vec{p}_\mu - \vec{p}_p$$

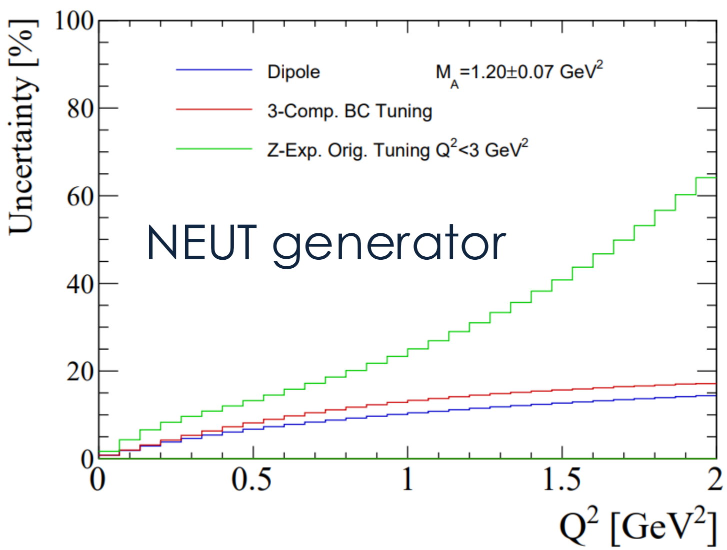
$$E_{miss} = \omega - T_p^{pre-FSI} - \Delta m_{n\to p} - T_{nucl.remnant}$$



Z-expansion for CCQE FF

- Moving from a dipole to Z-expansion axial form factor
- Z-expansion offers four free parameters to alter the form factor shape
  - Much more flexibility to describe high and low Q^2 regions
- Default implementation tuned to bubble chamber data

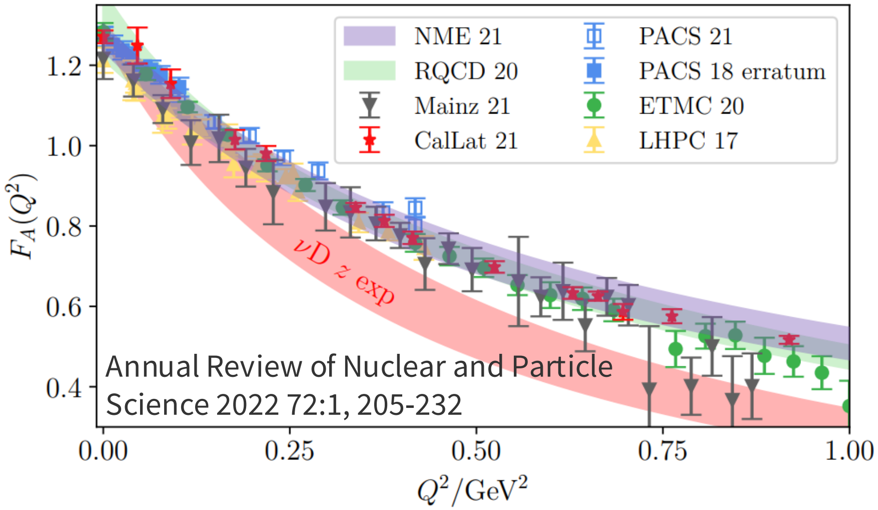




Q^2 = four momentum transfer

Z-expansion for CCQE FF

- Moving from a dipole to Z-expansion axial form factor
- Z-expansion offers four free parameters to alter the form factor shape
  - Much more flexibility to describe high and low Q^2 regions
- Default implementation tuned to bubble chamber data
- But LQCD calculations provide an interesting alternative we should make sure to cover



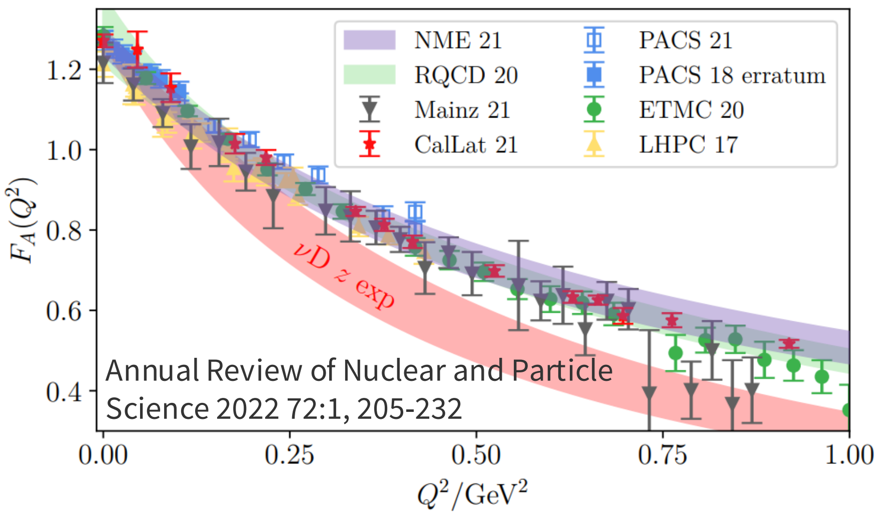
Annual Review of Nuclear and Particle Science 2022 72:1, 205-232

Q^2 = four momentum transfer

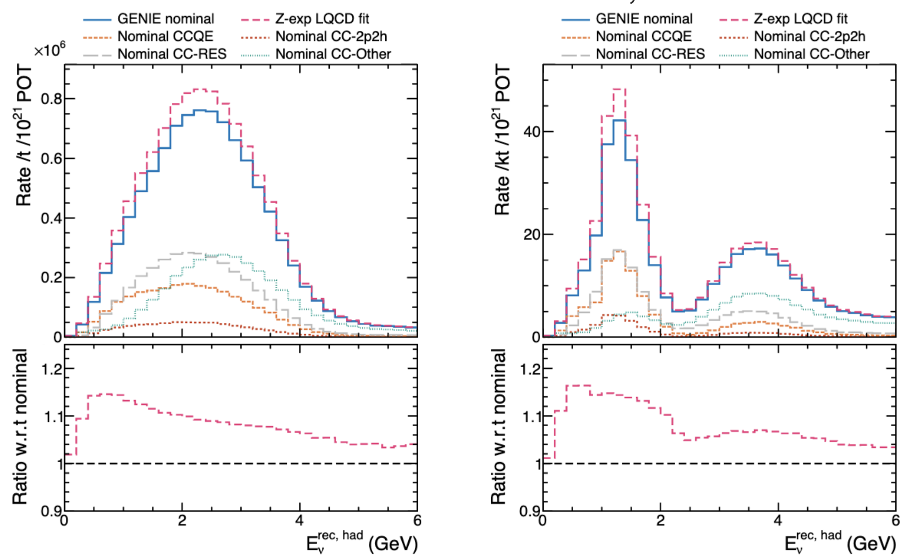
Z-expansion for CCQE FF

- Moving from a dipole to Z-expansion axial form factor
- Z-expansion offers four free parameters to alter the form factor shape
  - Much more flexibility to describe high and low Q^2 regions
- Default implementation tuned to bubble chamber data
- But LQCD calculations provide an interesting alternative we should make sure to cover
  - Impact on observables can be quite large!

Annual Review of Nuclear and Particle Science 2022 72:1, 205-232



Q^2 = four momentum transfer

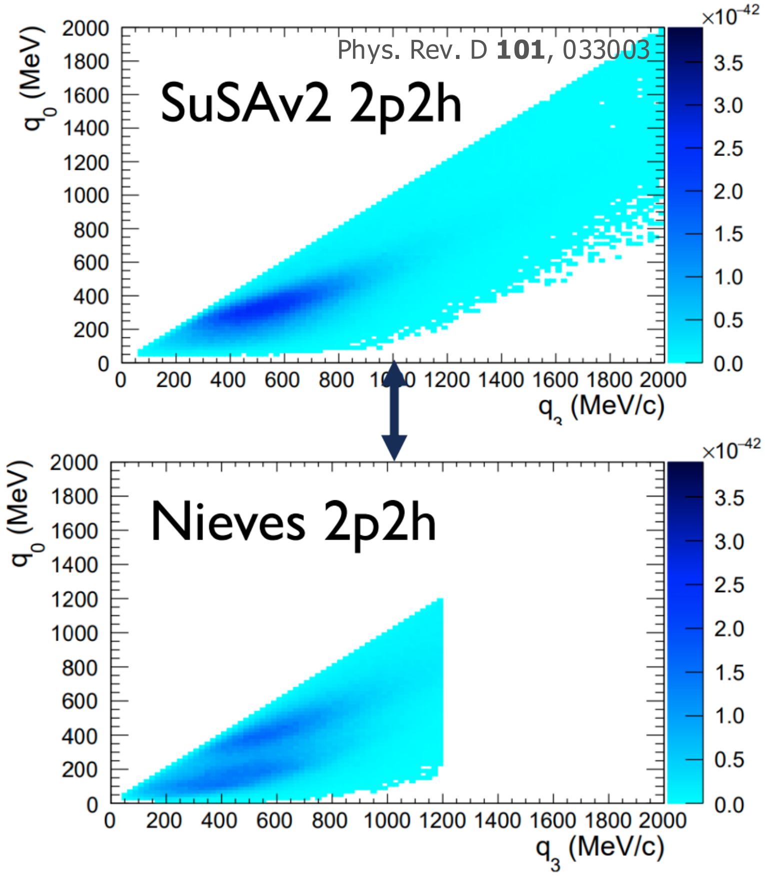


Reconstructed neutrino energy using calorimetry

SuSAv2 2p2h

- Moving from Nieves 2p2h to SuSAv2 2p2h
- Motivation: can reweight Nieves to SuSA but not vice-versa (missing phase space)
- Models are based on similar theory foundations, but make different choices
  - "Direct-exchange interference terms"
  - Imaginary part of the delta propagator
  - (Non)relativistic approximations

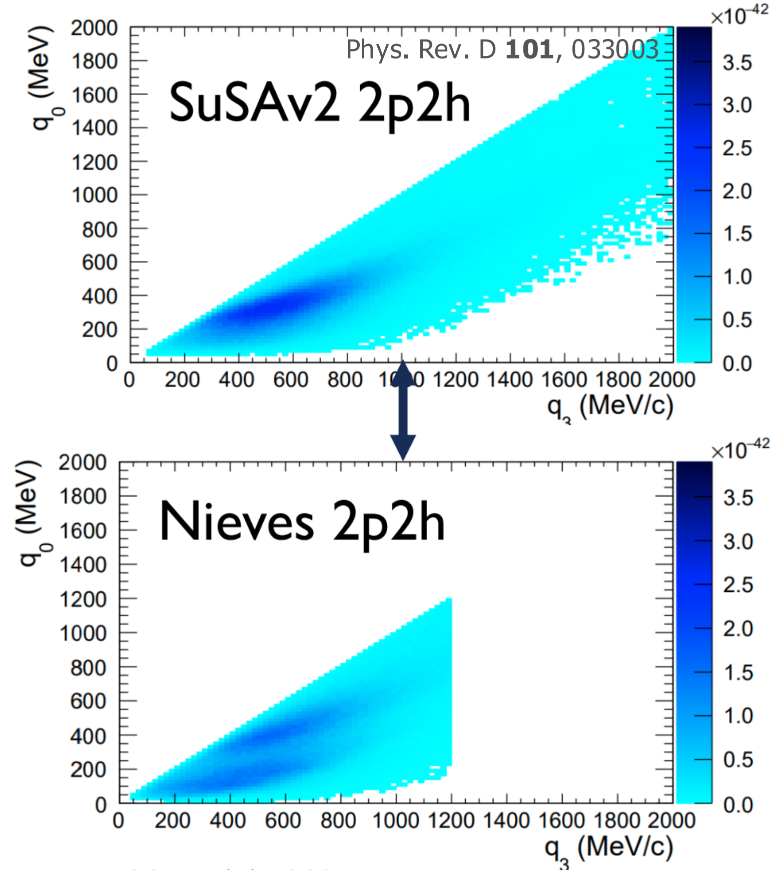
q_0 = energy transfer q_3 = momentum transfer

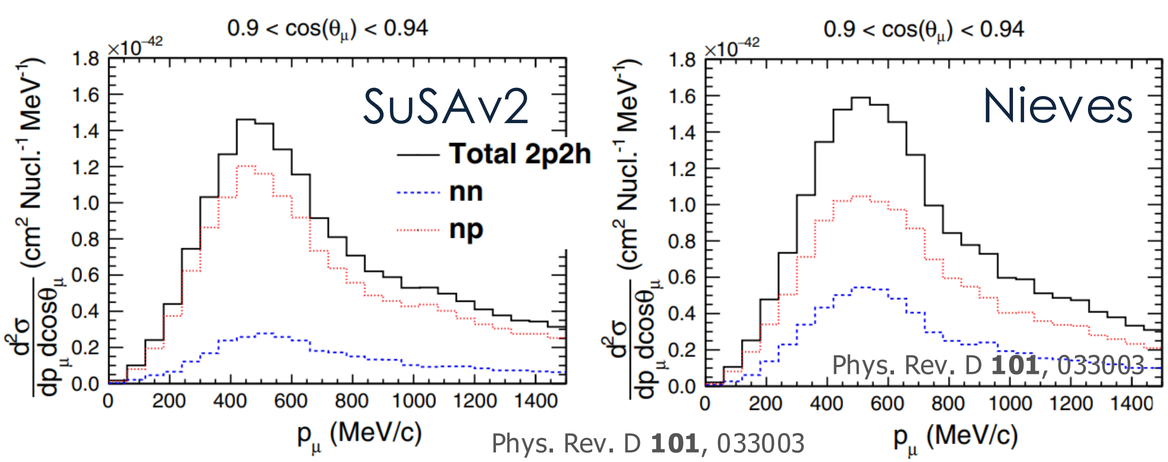


SuSAv2 2p2h

q_0 = energy transfer q_3 = momentum transfer

- Moving from Nieves 2p2h to SuSAv2 2p2h
- Motivation: can reweight Nieves to SuSA but not vice-versa (missing phase space)
- Models are based on similar theory foundations, but make different choices
  - "Direct-exchange interference terms"
  - Imaginary part of the delta propagator
  - (Non)relativistic approximations
- Different shapes in q_0, q_3 and different nucleon pair contributions





Phys. Rev. D **101**, 033003

Overview

- Our updated interaction model
- **Limitations of the model**
- Available and planned systematic parameters

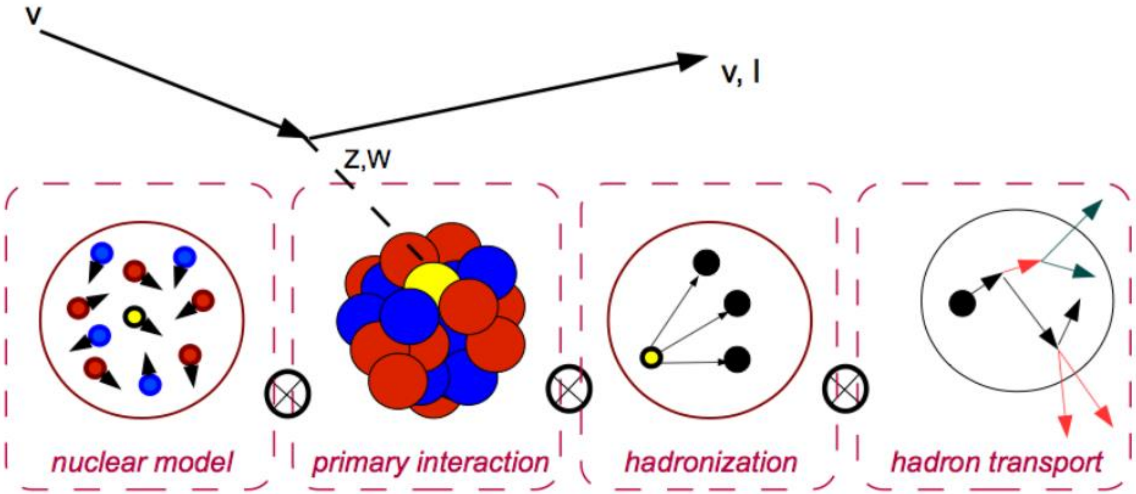
A generator's view of νN scattering

(true for at least some generators some of the time)

- Take theory inputs where possible, but these are often limited
  - Only capable of predicting a subset of observables
  - Only valid within some range of kinematic phase space
  - Only valid for certain processes

A generator's view of νN scattering

(true for at least some generators some of the time)



- Take theory inputs where possible, but these are often limited
  - Only capable of predicting a subset of observables
  - Only valid within some range of kinematic phase space
  - Only valid for certain processes
- Stitch them together

- Fill in the gaps with fudges, guesses and approximations

Example: 2p2h

- Theory give us: $\frac{d^2\sigma}{dq_0 dq_3}$

- GENIE predicts: $\frac{d^8\sigma}{dq_0 dq_3 d\boldsymbol{p}_1 d\boldsymbol{p}_2}$

- How!?

Example: 2p2h

- Theory give us: $\frac{d^2\sigma}{dq_0 dq_3}$

- GENIE predicts: $\frac{d^8\sigma}{dq_0 dq_3 d\boldsymbol{p}_1 d\boldsymbol{p}_2}$

- How!?

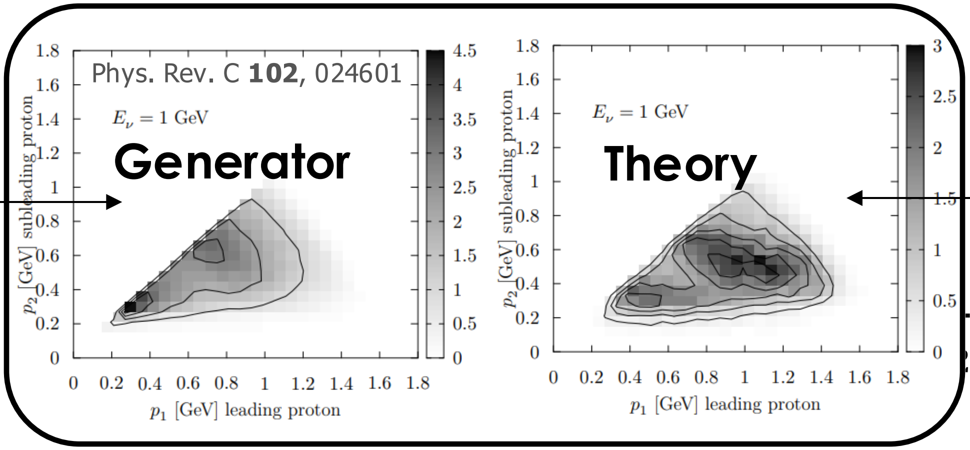
- Sample struck nucleons 4-momenta independently from a Fermi gas model and combine into a 2-nucleon "cluster"
  - Assumption: *no correlations between momentum and energy of struck nucleons*

- Give 4-momentum transfer (q_0, q_3) to the cluster

- "Decay" the cluster to two nucleons
  - Assumption: 4-*momentum transfer is shared evenly between the two nucleons*

Example: 2p2h

Generator attempts at semi-exclusive cross section



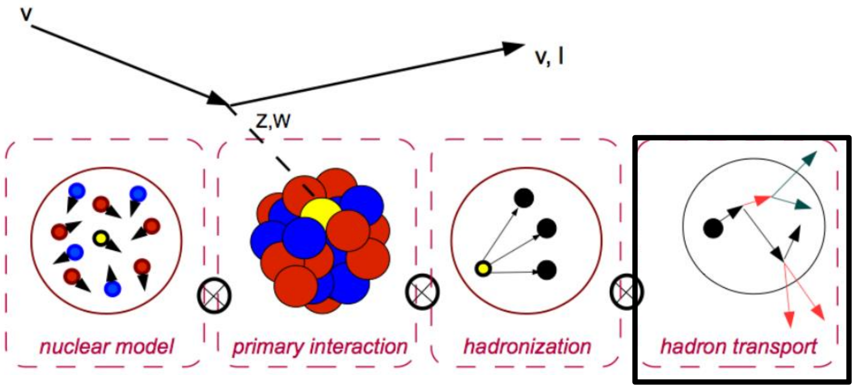
Recent theory calculation of semi-exclusive cross section

- Sample struck nucleons 4-momenta independently from a Fermi gas model and combine into a 2-nucleon "cluster"
  - Assumption: *no correlations between momentum and energy of struck nucleons*

- Give 4-momentum transfer (q_0, q_3) to the cluster

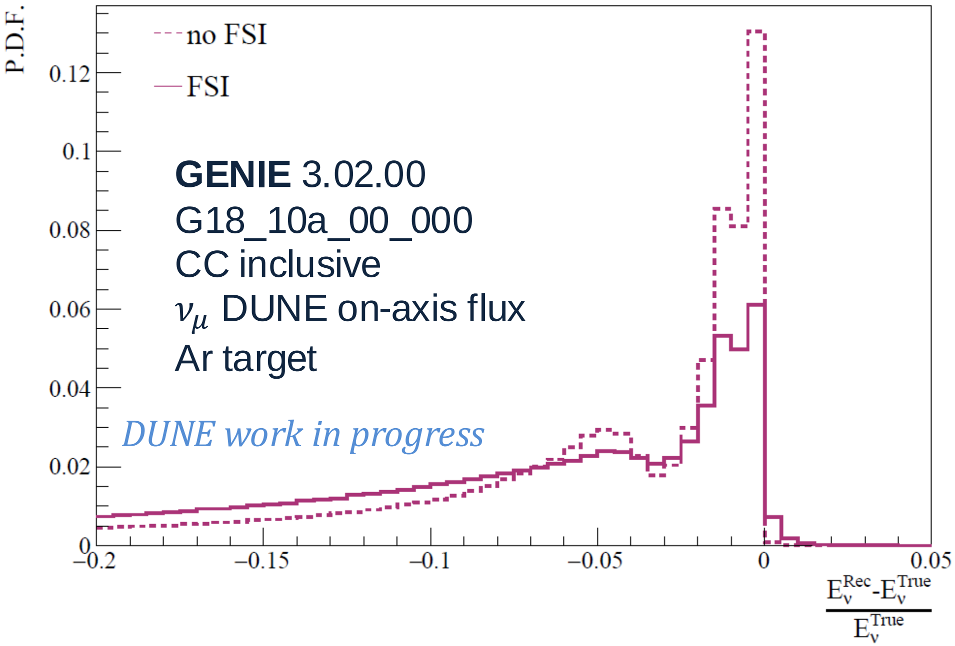
- "Decay" the cluster to two nucleons
  - Assumption: 4-*momentum transfer is shared evenly between the two nucleons*

Example: FSI

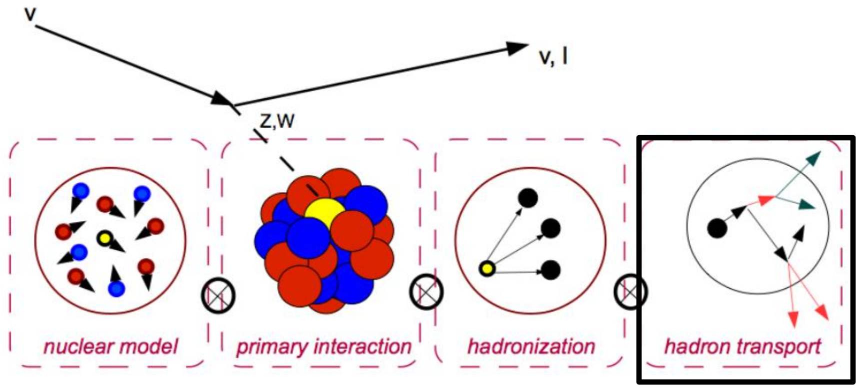


- Our input theory cross section calculations assume no FSI
- We add it in via a semiclassical intranuclear cascade model
- Important impact on neutrino energy reconstruction

CERN summer student report

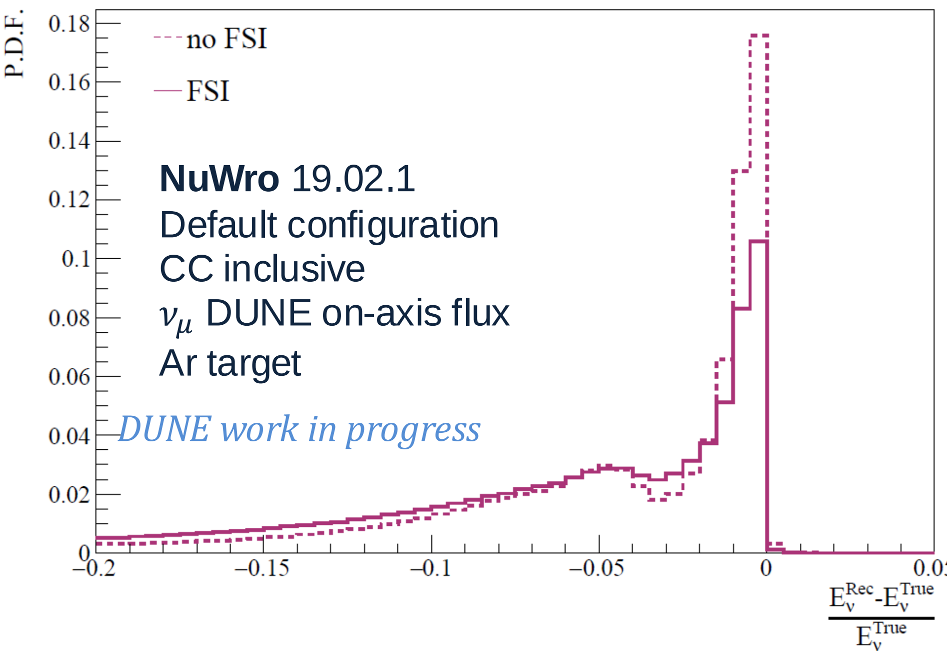


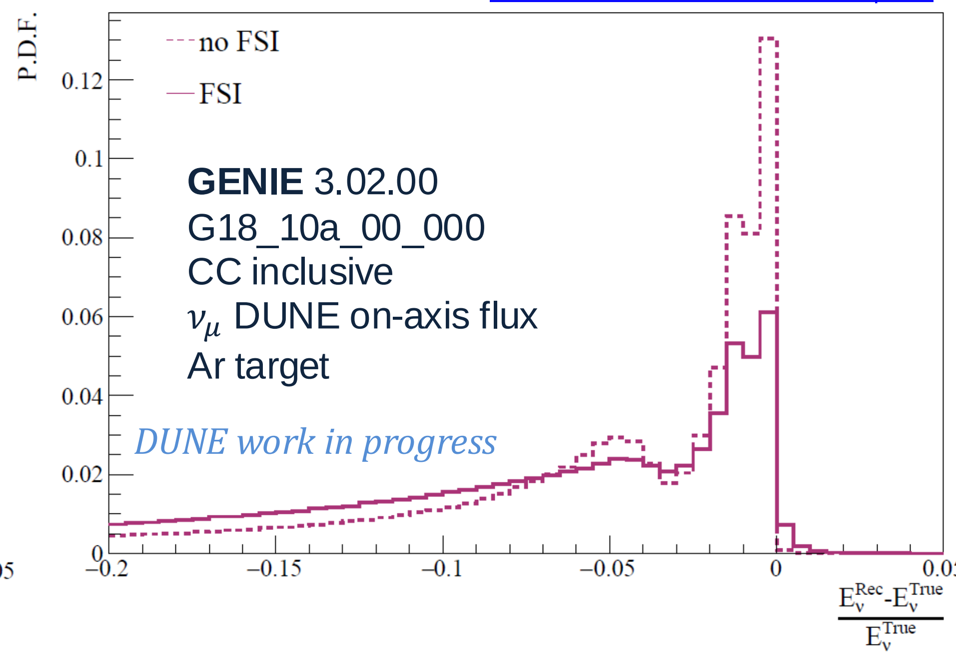
Example: FSI



- Our input theory cross section calculations assume no FSI
- We add it in via a semiclassical intranuclear cascade model
- Important impact on neutrino energy reconstruction
  - Which is pretty different between models …

CERN summer student report





Overview

- Our updated interaction model
- Limitations of the model
- **Available and planned systematic parameters**

Uncertainty model

A first uncertainty parameterisation is in development

These will be implemented in NuSystematics: easy for DUNE and other experiments to use!

Ground state
Removal energy shape
SRC "tail" strength
Shell-like shape
q3 dependent shift

CCQE
Z-expansion parameters
RPA
Optical potential
Pauli blocking

2p2h
Normalisation
SuSAv2 to Valencia
Pair content
Energy dependence
Delta vs not delta
Nucleon ejection model

Resonant pion production
MA, Mv, Norm
Pauli blocking
RPA / Optical potential effects?
W shape
$\pi^{+/-}$ vs π^0 fraction tweaks
Resonance decay kinematics
Resonance broadening
…

SIS/DIS
Transition region strength
AGKY dials
Bodek-Yang parameters
Non-RES low W contrib.
Multiplicity modifications
Alternative model (AMU)
…

FSI
hA pion fate dials
hA nucleon fate dials
π abs. pair fractions
hA to hN, INCL, G4BC

Misc
NC norms
Coh shape+norm
nue/numu ratio
nue/nuebar ratio
Ad-hoc neutron ejection

Uncertainty model

Some of these have been available in GENIE ReWeight for a while or are very simple to add

Ground state
Removal energy shape
SRC "tail" strength
Shell-like shape
q3 dependent shift

CCQE
Z-expansion parameters
RPA
Optical potential
Pauli blocking

2p2h
Normalisation
SuSAv2 to Valencia
Pair content
Energy dependence
Delta vs not delta
Nucleon ejection model

Resonant pion production
MA, Mv, Norm
Pauli blocking
RPA / Optical potential effects?
W shape
$\pi^{+/-}$ vs π^0 fraction tweaks
Resonance decay kinematics
Resonance broadening
…

SIS/DIS
Transition region strength
AGKY dials
Bodek-Yang parameters
Non-RES low W contrib.
Multiplicity modifications
Alternative model (AMU)
…

FSI
hA pion fate dials
hA nucleon fate dials
π abs. pair fractions
hA to hN, INCL, G4BC

Misc
NC norms
Coh shape+norm
nue/numu ratio
nue/nuebar ratio
Ad-hoc neutron ejection

Uncertainty model

Many come from work inspired by MicroBooNE

- See talk by Lars Bathe-Peters for many details on the 2p2h uncertainties

Ground state
Removal energy shape
SRC "tail" strength
Shell-like shape
q3 dependent shift

CCQE
Z-expansion parameters
RPA
Optical potential
Pauli blocking

2p2h
Normalisation
SuSAv2 to Valencia
Pair content
Energy dependence
Delta vs not delta
Nucleon ejection model

Resonant pion production
MA, Mv, Norm
Pauli blocking
RPA / Optical potential effects?
W shape
$\pi^{+/-}$ vs π^0 fraction tweaks
Resonance decay kinematics
Resonance broadening
…

SIS/DIS
Transition region strength
AGKY dials
Bodek-Yang parameters
Non-RES low W contrib.
Multiplicity modifications
Alternative model (AMU)
…

FSI
hA pion fate dials
hA nucleon fate dials
π abs. pair fractions
hA to hN, INCL, G4BC

Misc
NC norms
Coh shape+norm
nue/numu ratio
nue/nuebar ratio
Ad-hoc neutron ejection

Uncertainty model

Others are under development by DUNE, in the next slides I give examples of two new sets of parameters

Ground state
Removal energy shape
SRC "tail" strength
Shell-like shape
q3 dependent shift

CCQE
Z-expansion parameters
RPA
Optical potential
Pauli blocking

2p2h
Normalisation
SuSAv2 to Valencia
Pair content
Energy dependence
Delta vs not delta
Nucleon ejection model

Resonant pion production
MA, Mv, Norm
Pauli blocking
RPA / Optical potential effects?
W shape
$\pi^{+/-}$ vs π^0 fraction tweaks
Resonance decay kinematics
Resonance broadening
…

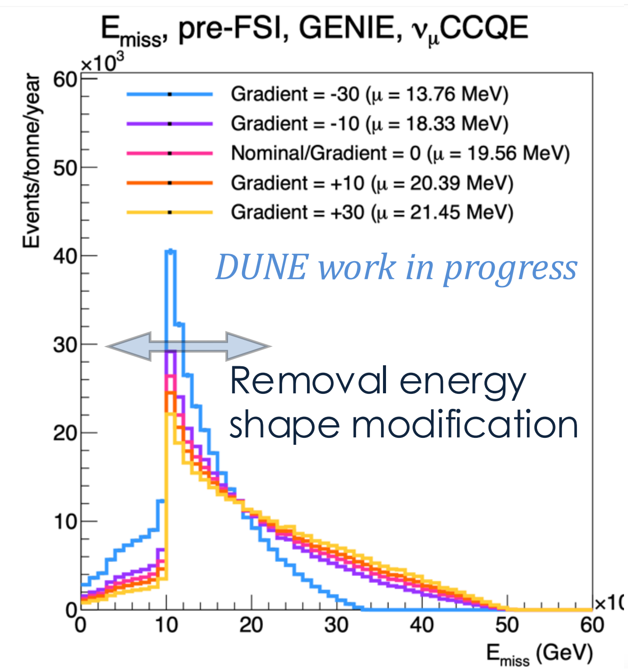
SIS/DIS
Transition region strength
AGKY dials
Bodek-Yang parameters
Non-RES low W contrib.
Multiplicity modifications
Alternative model (AMU)
…

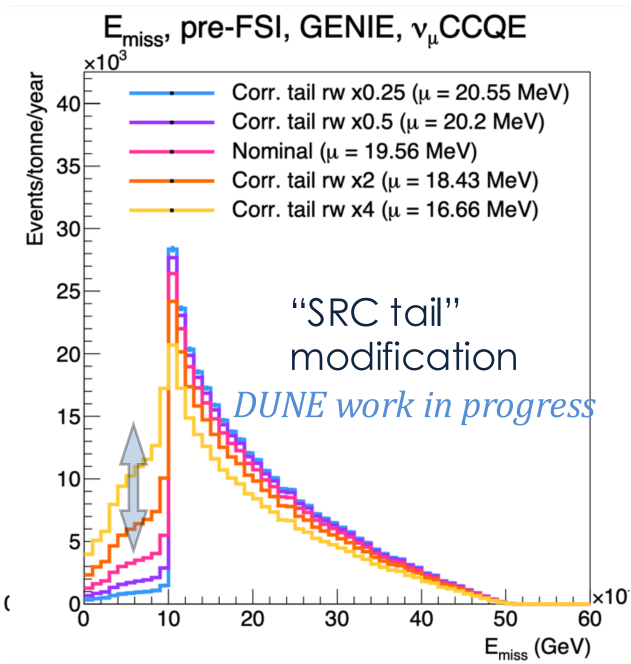
FSI
hA pion fate dials
hA nucleon fate dials
π abs. pair fractions
hA to hN, INCL, G4BC

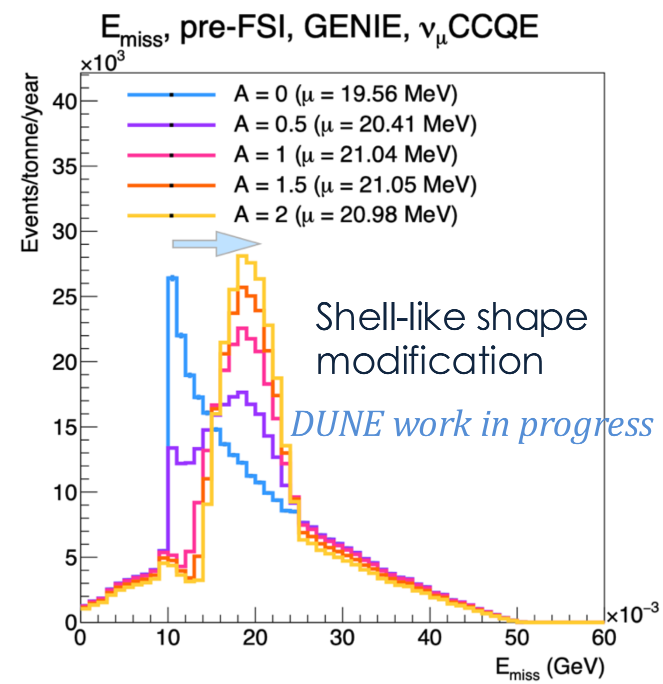
Misc
NC norms
Coh shape+norm
nue/numu ratio
nue/nuebar ratio
Ad-hoc neutron ejection

Example: ground state modifications

- Recent DUNE work has established dials to modify the nuclear ground state: alters outgoing lepton and hadron kinematics a consistent way

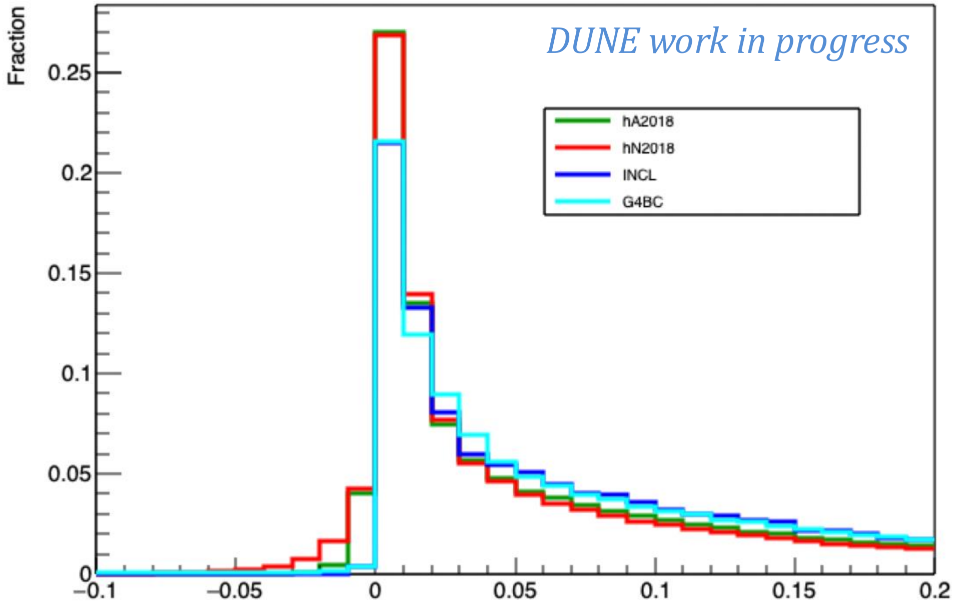






Example: FSI hadron kinematics

- Another set of dials aims to cover variations in hadron kinematics within different FSI models
- Reweight such that the visible energy loss via the FSI cascade is correctly transformed between models and the inclusive cross-section is unchanged
- A first handle on key differences between FSI models



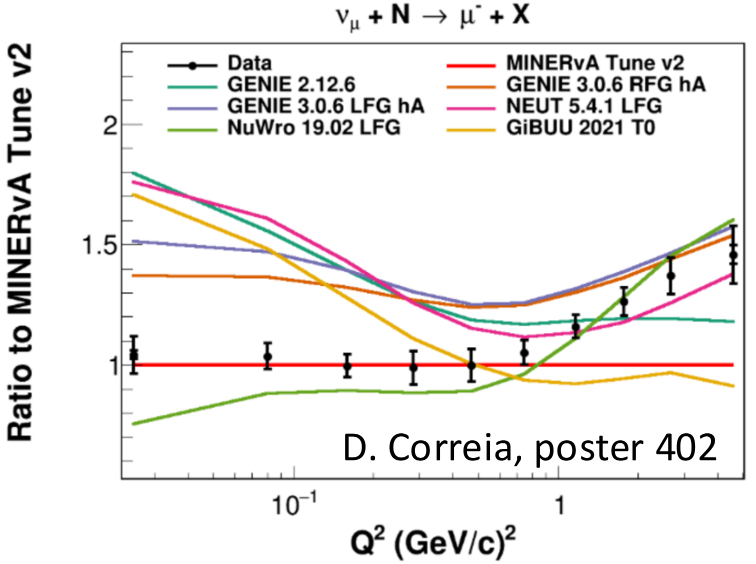
E_{bias} = Fractional visible energy loss from FSI

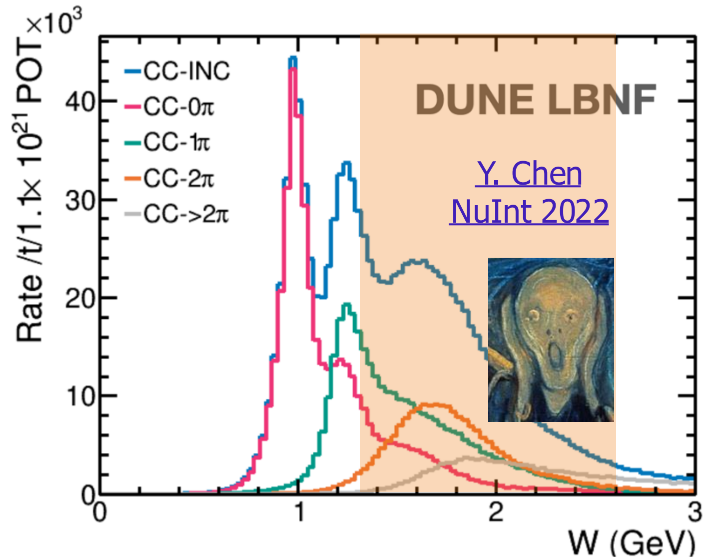
$$E_{bias} = (KE_p^{preFSI} - E_{had}^{postFSI})/KE_p^{preFSI}$$

$$E_{had}^{postFSI} = \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma + \Sigma E_{\pi^0}$$

Help!: SIS and hadronization

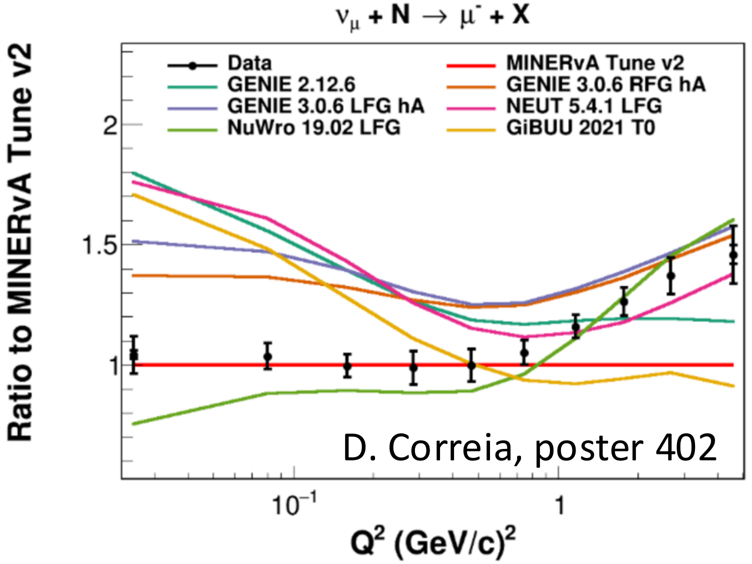
- Modelling low Q^2 "SIS" is **tough**
  - Poor agreement with measurements
  - Incomplete uncertainty model
  - ~30% of interactions at DUNE
- Modelling hadron kinematics from such interactions is **tougher**
  - Way past PYTHIA's range of validity
  - Also: incomplete uncertainty model
- Expect very limited data on Argon at DUNE energies before DUNE starts

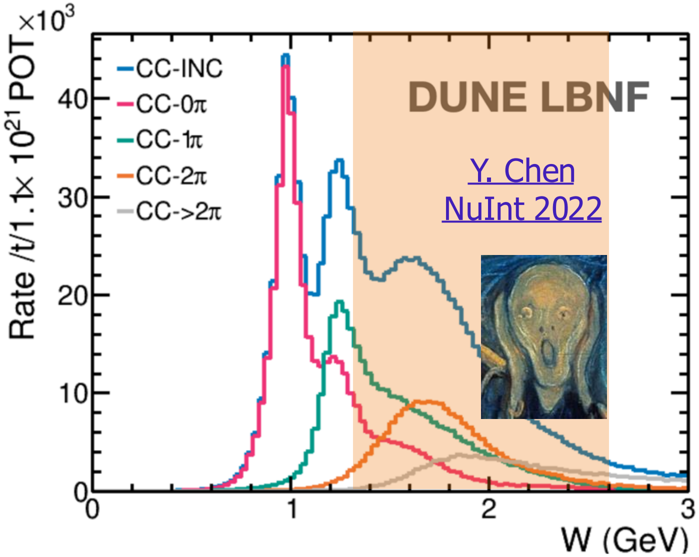




Help!: SIS and hadronization

- Modelling low Q^2 "SIS" is **tough**
  - Poor agreement with measurements
  - Incomplete uncertainty model
  - ~30% of interactions at DUNE
- Modelling hadron kinematics from such interactions is **tougher**
  - Way past PYTHIA's range of validity
  - Also: incomplete uncertainty model
- Expect very limited data on Argon at DUNE energies before DUNE starts
- Help!
  - Make the most of that data we have or will have
  - More theory guidance
  - Community focus on development of realistic model uncertainties





Summary

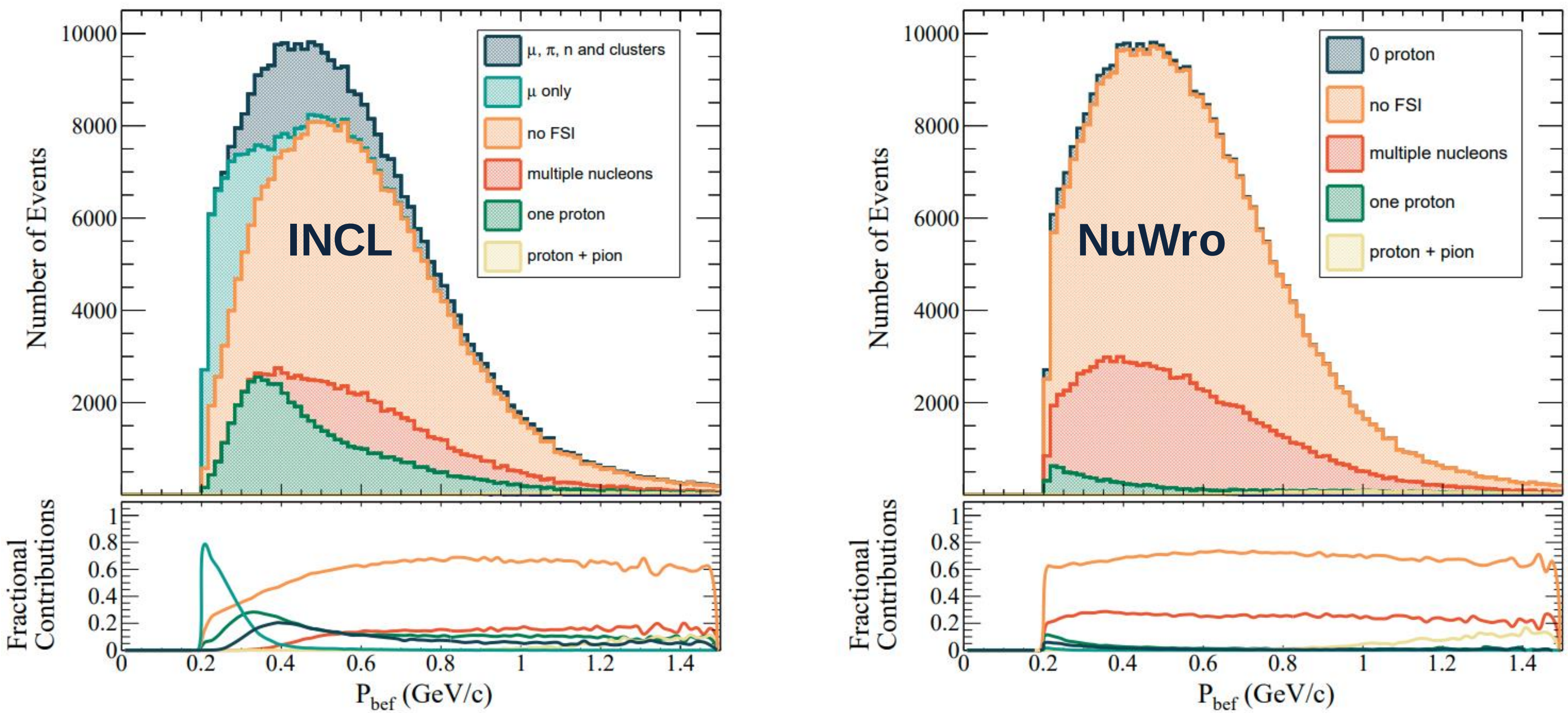
- DUNE has completed **a new baseline model**, which consists of a few extensions to GENIE baseline configurations:
  - Expansion of phase space for nuclear ground state
  - Z-expansion treatment of axial form factor
  - SuSAv2 2p2h
  - Dexcitation photons from Argon
- Like all models, it **has plenty of failings** and cannot describe global cross-section measurements
  - E.g.: lack of predictive power for outgoing hadron kinematics
- But it **prioritises flexibility** to allow us to add uncertainties to cover "known unknowns" within it
- Thanks to work within GENIE and MicroBooNE, **we have a great set of uncertainty parameters as a starting point**, but we still have plenty of work to do
- Open **for joint development of a comprehensive uncertainty model** alongside SBN and NOvA

Backups

Advanced FSI cascades

Plots from
Ershova et al.,
Study of FSI of protons ith INCL and NuWro cascade models
Phys. Rev. D **106**, 032009

- More advanced treatment of FSIs is available via e.g. the INCL model (Phys. Rev. C **87** 014606)



Advanced FSI cascades

Plots from
Ershova et al.,
Study of FSI of protons ith INCL and NuWro cascade models
Phys. Rev. D **106**, 032009

- More advanced treatment of FSIs is available via e.g. the INCL model (Phys. Rev. C **87** 014606)
- INCL's treatment of nucleon absorption and nuclear cluster production gives a different distribution of energy among outgoing hadrons
- Might expect a significant impact on neutrino energy smearing