Thoughts on an updated DUNE interaction model

A DIRT(-II)-y business

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For the DIRT-II taskforce

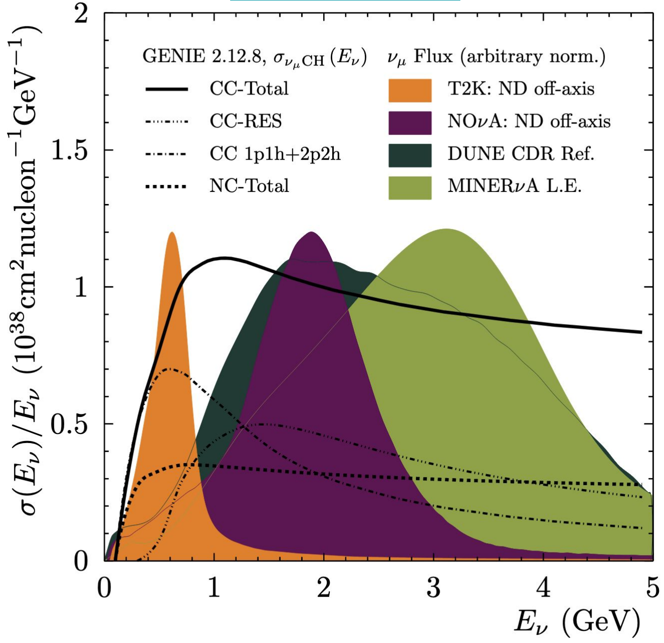
Part I

Basic choices: context, base model, fit variables

Context

- DUNE has a very broad energy spectrum
  - Many interaction channels and their overlap regions
  - Roughly 30% CCQE, 40% CCRES and 30% DIS/SIS
- It is difficult to devise an all-encompassing model
  - Especially for the transition regions
- Several experiments have probed these regions
  - We can use the lessons we learned from T2K, MINERvA, NOvA, Mini/MicroBooNE

arXiv:1803.08848



DIRT2 Philosophy

Nuclear ground state

- Model nuclear ground state
- Initial nucleon momenta and energies
- Possible initial state correlations
- Coulomb corrections

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Neutrino Interaction

- Determine the probability of an event to undergo a certain type of interaction
- Models come with tunable parameters to be used as uncertainty knobs
- Radiative corrections

DIRT2 Philosophy

Nuclear ground state → **Neutrino Interaction** → **Final state interactions (FSI)**

Nuclear ground state

- Model nuclear ground state
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- Possible initial state correlations
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Neutrino Interaction

- Determine the probability of an event to undergo a certain type of interaction
- Models come with tunable parameters to be used as uncertainty knobs
- Radiative corrections

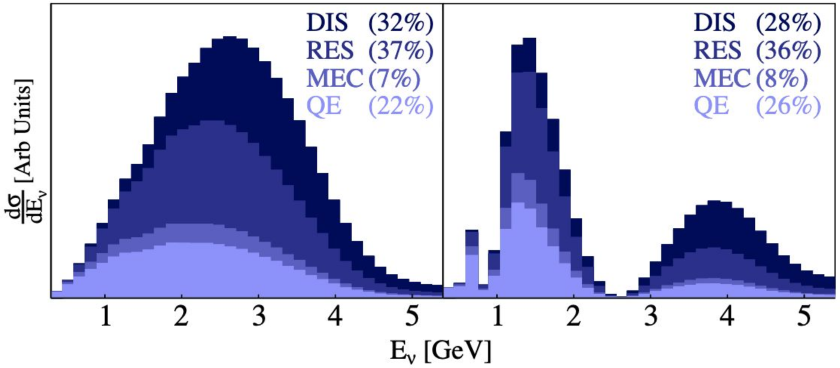
Final state interactions (FSI)

- Propagate final state hadrons through nuclear medium
- Alter final state kinematics and/or topology

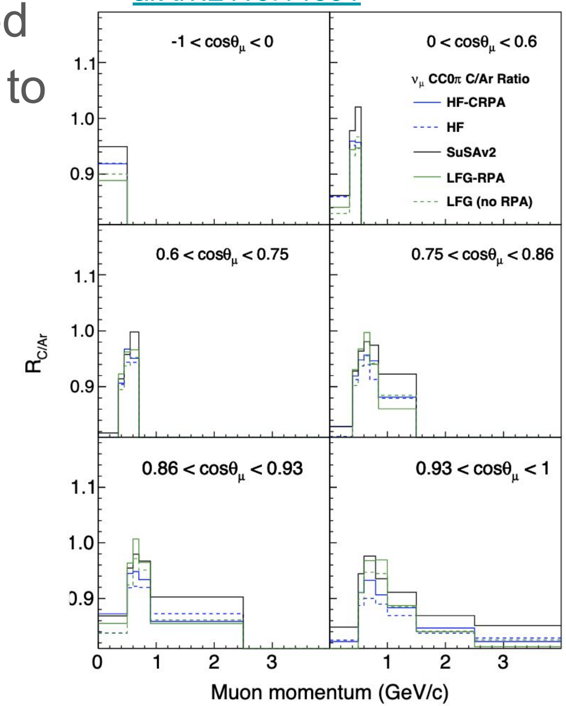
Extra care needed

- In addition to intrinsic freedoms in the models, we need to provide extra uncertainties for effects related to ND to FD extrapolation:
    - Energy dependence and impact on reconstructed energy bias
    - Possibility of CH use at ND: C to Ar scaling
    - Differences in acceptance

[Phys. Rev. D 103, 113003]

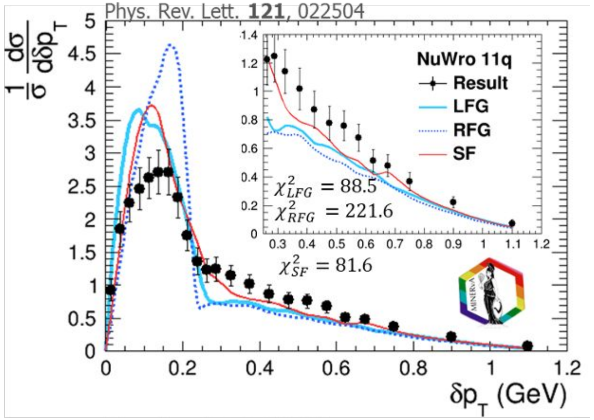


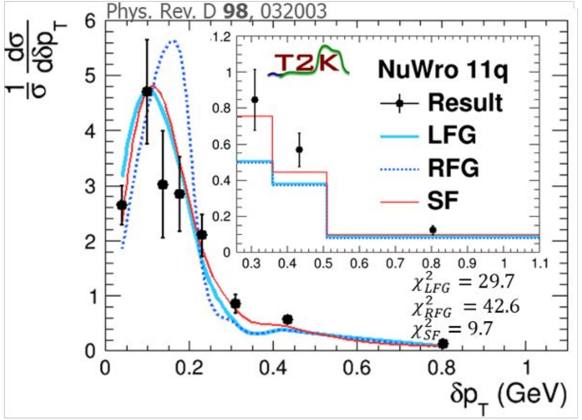
[arXiv:2110.14601]



Choosing a nuclear ground state

- Several models we are familiar with
  - RFG, LFG
  - SF
  - CRPA, SuSAv2
  - Others
- But no model describes experimental data across the entire available phase space
- Models differ in their inclusive and exclusive predictive power
- For LAr detectors, predicting final state hadron kinematics is essential
- A desirable nuclear ground state model has either
  - Accurate exclusive predictions
  - High phase space coverage to allow reweighting to other models
- But must also be usable in an OA
  - Available in generators
  - Reweightable





Phase space coverage

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

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- The relevant variables to describe the nuclear spectral function are E_{miss} and p_{miss}

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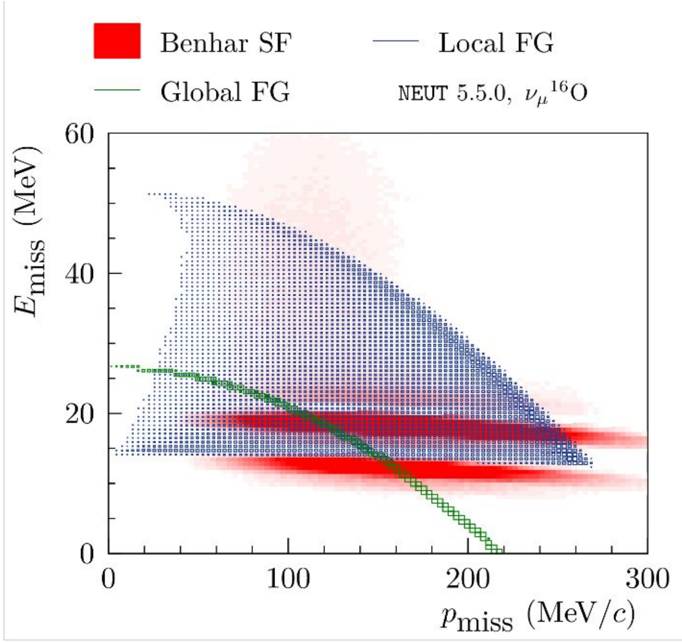
- The relevant variables to describe the nuclear spectral function are E_{miss} and p_{miss}
- E_{miss} p_{miss} distributions tell us about the natural degrees of freedom of a model
  - E.g. FG models - “binding energy”, global E_{miss} offset (Q-value)
  - SF models - nuclear shell structure, MF and SRC strengths
- High phase space coverage is desirable for reweighting



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

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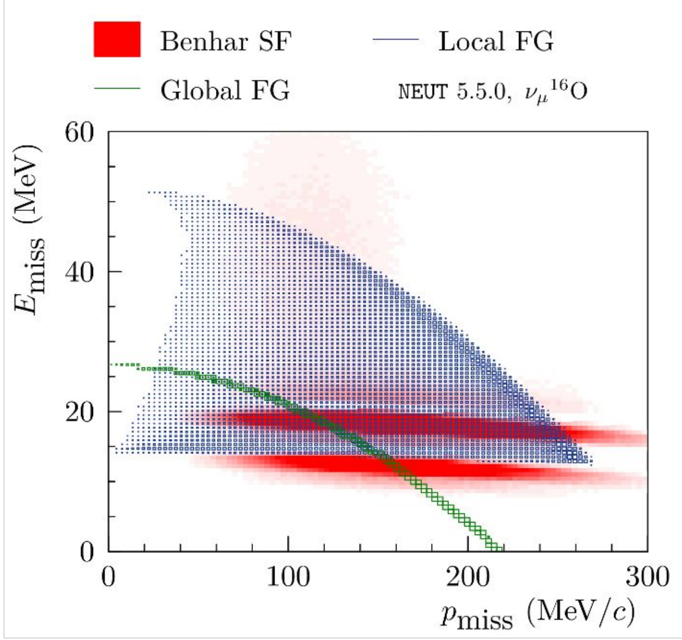
SF model

- Strong theoretical grounding, includes nuclear shell structure
- Agrees with electron scattering data
- MF and SRC components
- High predictive power for outgoing nucleon kinematics
- Wide phase space coverage



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Phase space coverage

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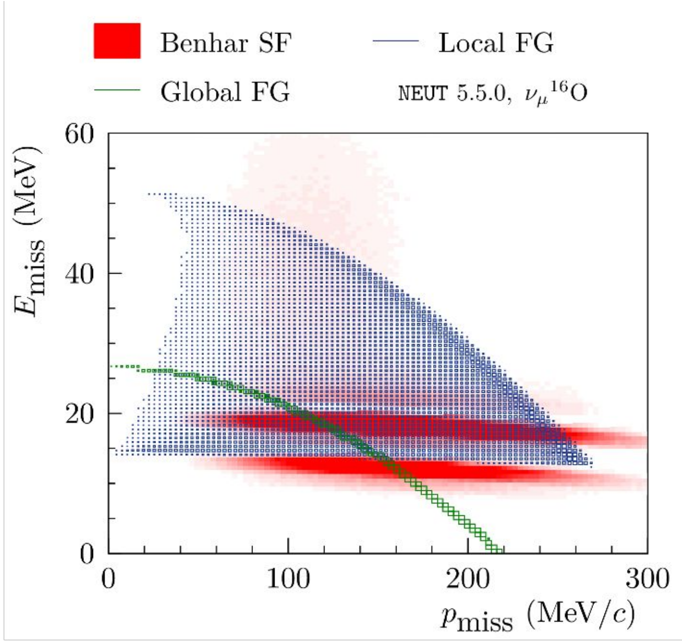
RFG model

- Fixed binding energy (Eb)
- Removal energy $E_{miss}=E_b-T_{nucl}^{init}$
- Expect 1D parabola

LFG model

- Eb depends on radial position
- Sum of many RFGs
- Q-value offset



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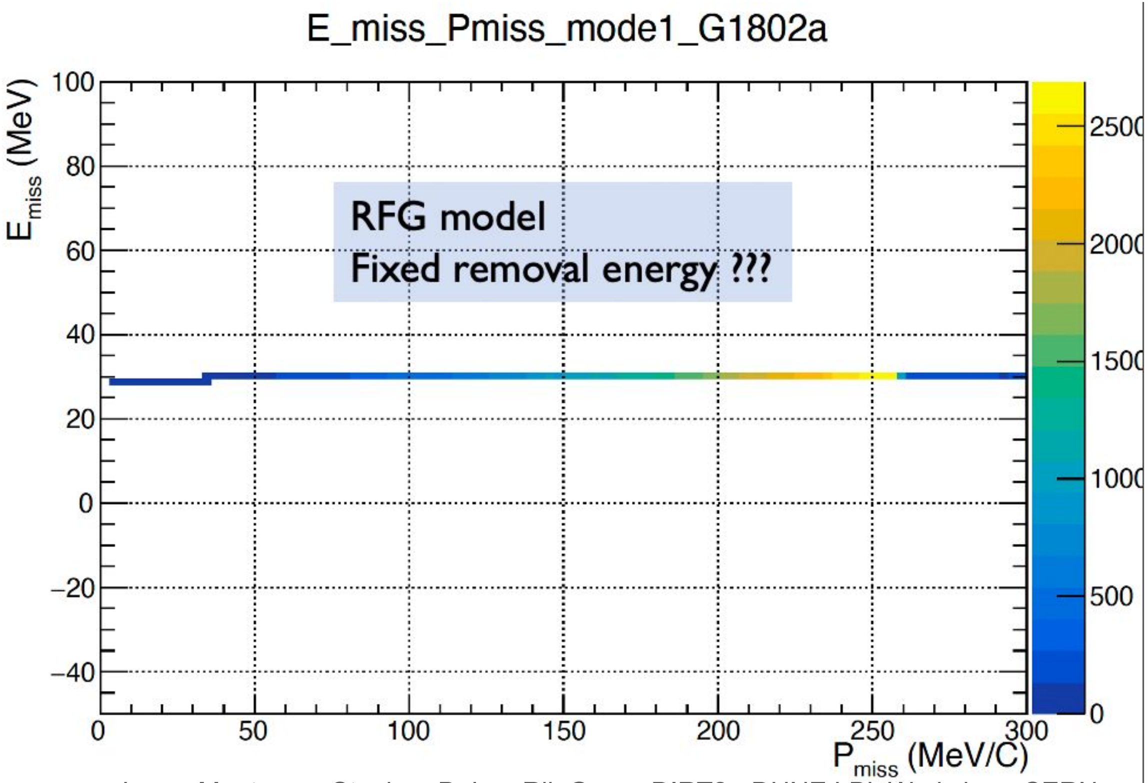
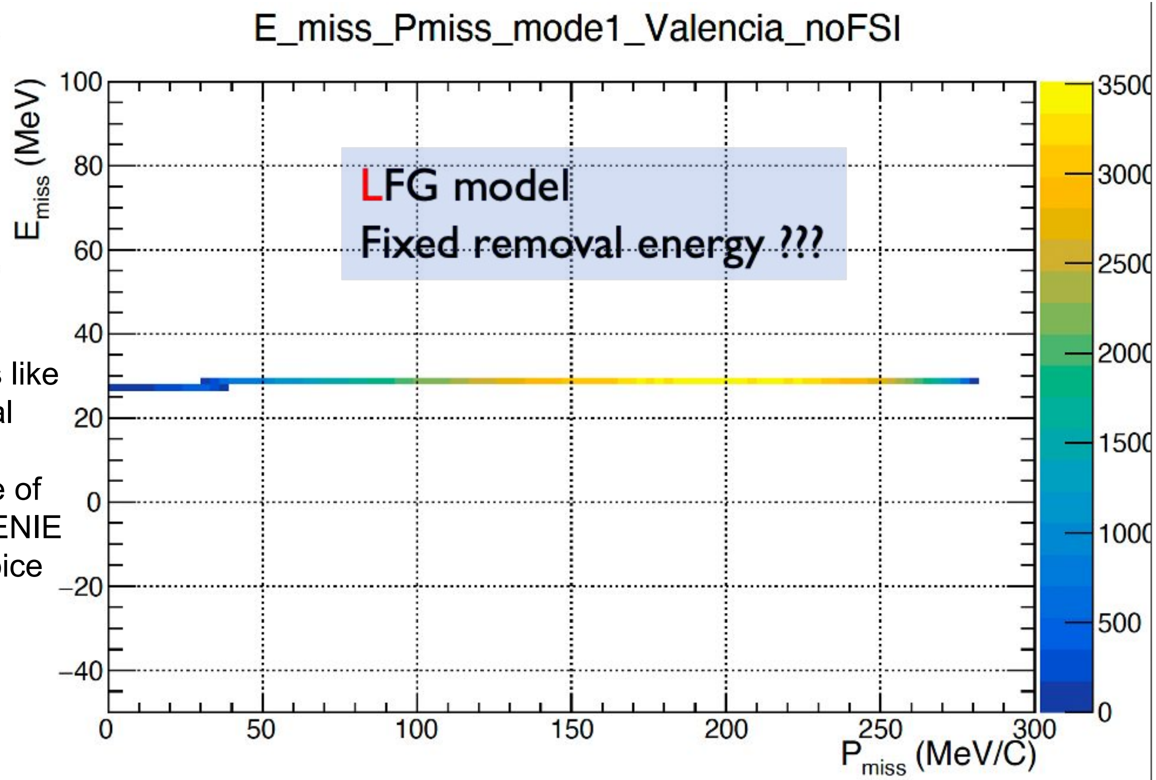
Comparing GENIE v3 nuclear models - RFG



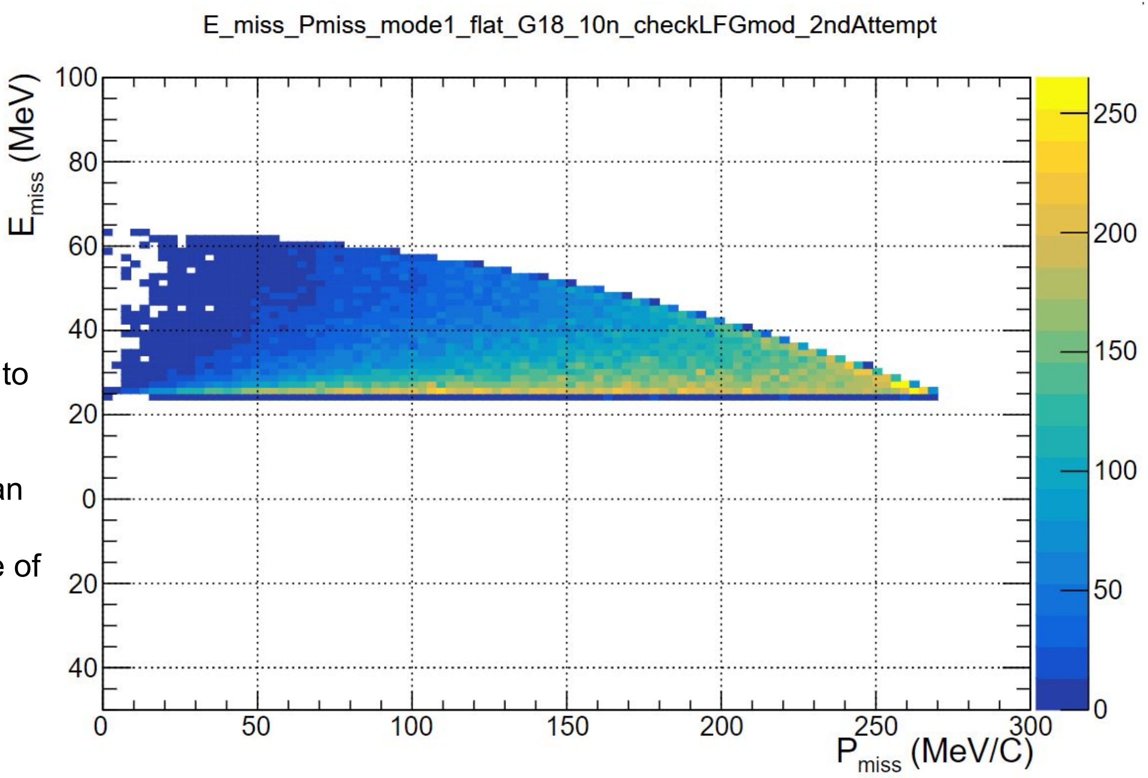
Comparing GENIE v3 nuclear models - LFG



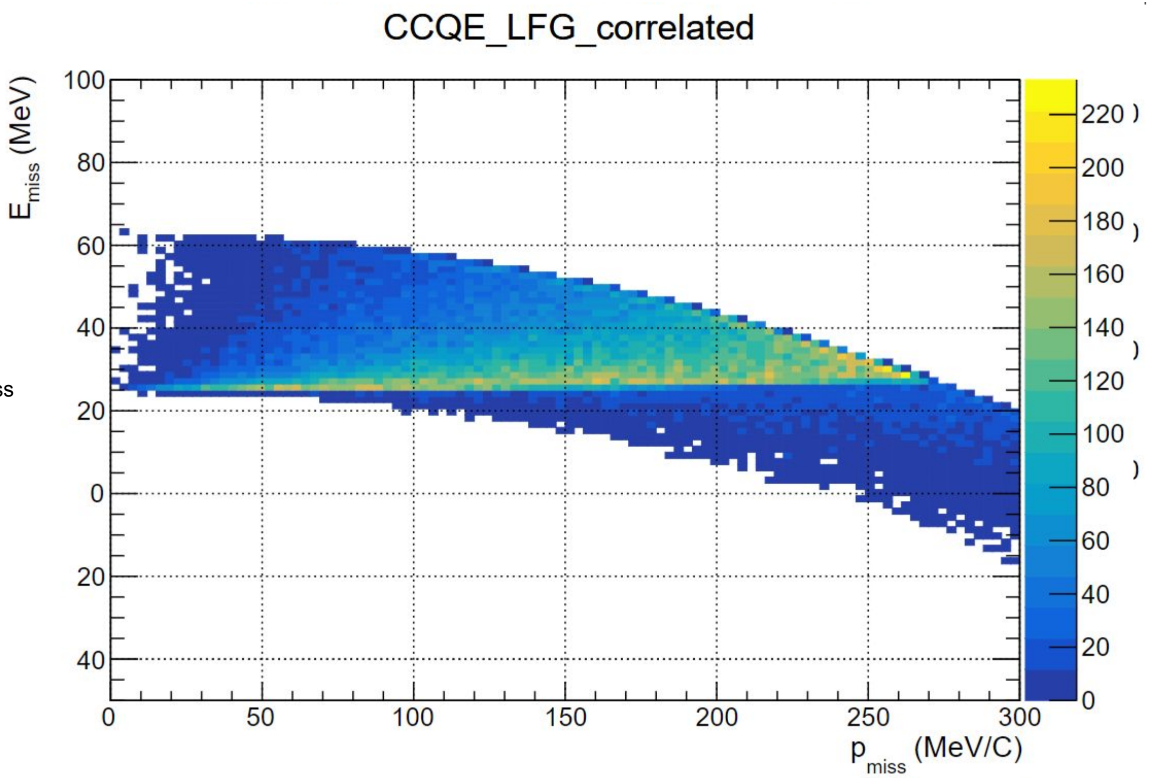
- Out of the box, it seems like LFG has a fixed removal energy
  - This is not a feature of the model, but a GENIE implementation choice

Comparing GENIE v3 nuclear models - LFG v2

- An **easy** hack allows us to recover a variable E_{miss} shape
- Parameters which we can vary
  - Radial dependence of E_{miss}
  - Q-value offset

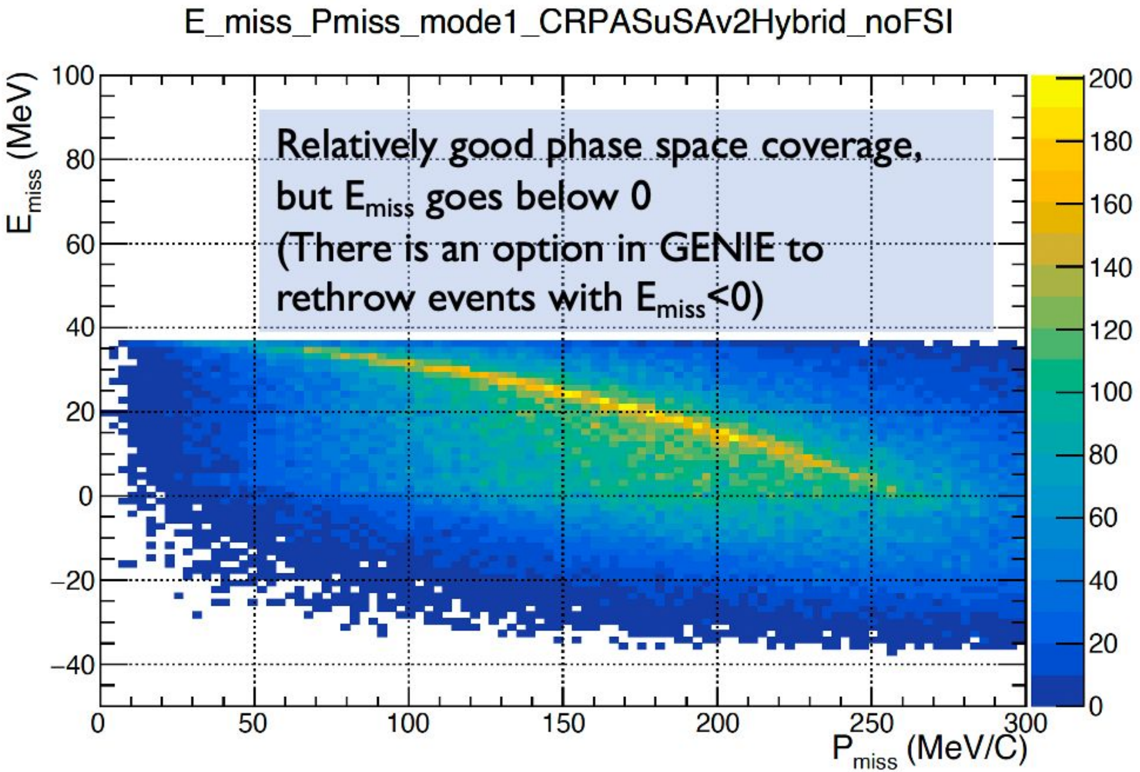


Comparing GENIE v3 nuclear models - LFG v2-correlated



- Adds correlated tail in p_{miss}

Comparing GENIE v3 nuclear models - CRPA

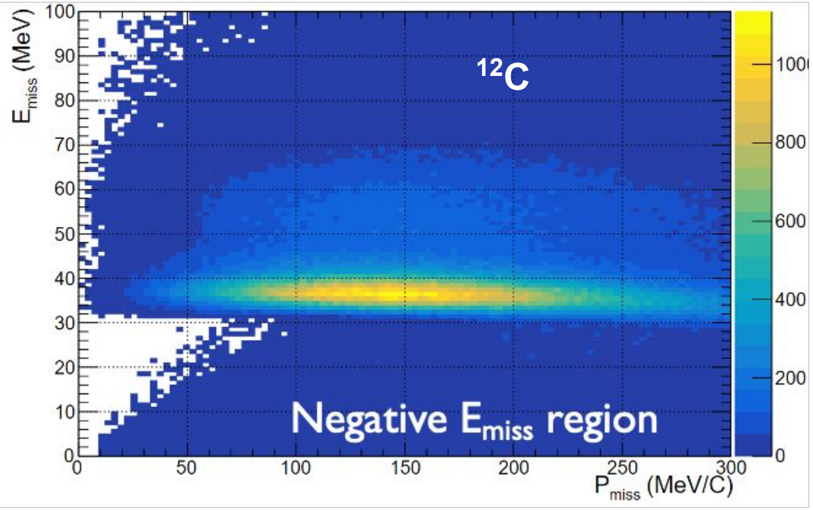


- Here, E_{miss} depends on q_3 from RMF predictions
- Factorization: choose to get q_3 dependence correct
  - To the detriment of E_{miss}

Comparing GENIE v3 nuclear models - Benhar SF

- Out of the box, GENIE 3.2 only has 1D Spectral Function for ^{12}C and ^{56}Fe as an "option"
  - But there is a class using the 2D one (SpectralFunc.cxx) - doesn't work straight away
- Tried running by generating kinematics with QELKinematics.cxx (used in GENIE 2 ?)

On further investigation, this type of event generation is not suitable for SF models



- Matches bulk of SF distribution (can see shell+SRCs)
- But negative Emiss region (not understood)
- Also proton kinetic energy is 0
- This is perhaps not surprising given that the implementation of this model was not finalized

Current side project: trying to get SF working for Ar in GENIE v3
(but not a showstopper)

Ground state model options

Using GENIE v3

1. Current GENIE LFG (1D line in E_{miss} p_{miss})
    - We do not recommend this - very limited range of uncertaintites
2. Modified GENIE LFG for CCQE and nonCCQE
    - Option to use correlated GENIE LFG
    - One ground state model for all interactions
3. SF for CCQE, LFG for nonCCQE
    - Depends on whether we can get SF working for Ar in GENIE quickly
    - Would be most desirable for CCQE component - much work done by T2K based on this choice
    - But would also require using a different model for nonCCQE interactions

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2. **Modified GENIE LFG for CCQE and nonCCQE**
    - **Option to use correlated GENIE LFG (**assuming nonQE part works too**)**
    - One ground state model for all interactions
3. SF for CCQE, LFG for nonCCQE
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Choice of variables to fit in

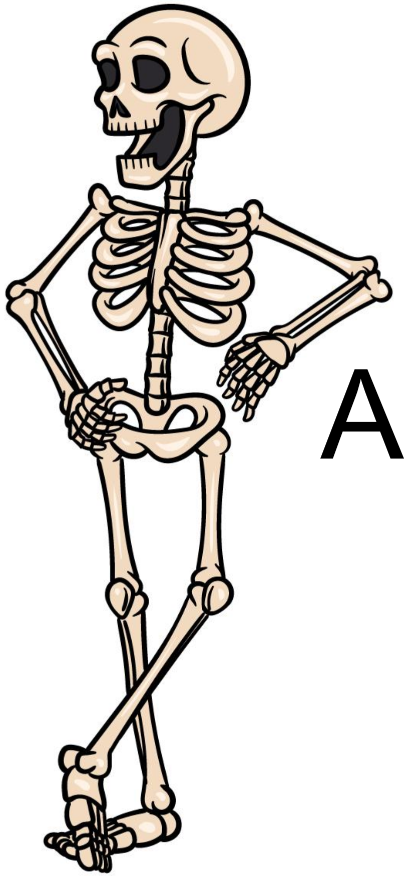
- For inclusive samples, E_{rec} and y_{rec} are not enough
- We need a minimum of three variables to span the cross-section systematics
    - Common choices: E_ν, Q^2, W (theory motivated); E_ν^{rec}, q_0^{rec}, q_3^{rec} ; (experiment motivated) p_μ,θ_μ, E_{had}^{rec} ; or p^L_μ, p^T_μ, E_{had}^{rec}.
- Choice of variables should be based on both detector capabilities and physics sensitivity
    - Opportunity for collaboration between DIRT/ND/LBL groups
- DUNE will not be statistics limited
    - But we should still use a reasonable number of fit variables

Choice of variables to fit in

- We should take advantage of LAr capabilities to measure exclusive final states
  - Important to exploit pions and **protons**
- Fit variables depend on what exclusive samples we have - some examples:
  - Pion multiplicity 0π, 1π, Other
  - Proton multiplicity 0p, Np (at least for the 0π case)
- Fit variables also can be different for each detector/sample
  - E.g. possible to use TKI+lepton variables for exclusive CC0πNp samples: T2K ND upgrade inspired choice E_{rec}, δp_T, $\delta \alpha_T$?
- Suggestions or discussion now or in DIRT2 meetings is very welcome!

Other baseline model choices

- Which FSI model?
  - hA, hN, INCL, GEANT4
- Which 2p2h model?
  - Nieves, SuSA-MEC, Empirical model
- QE form factors
  - Dipole or z-expansion?
- Do we use an existing GENIE tune?
  - Or make our own tune
- Further considerations
  - RPA, DIS/hadronization modifications, RES parameters (M_A, M_V, C_A^5)
- Anything else?



Part II
A skeleton uncertainty model

Step one: choose a base model

- It's difficult to define uncertainties before defining a base model
- Key priority for DIRT-II: choose one

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My preference (and the assumption for this talk)

➔ **Expanded LFG nuclear model** with correlated tail and a sensible "Q value" offset
  - ◆ Allows consistent ground state model (and uncertainties) between all channels
  - ◆ Plenty of natural shape variations
  - ◆ Correlated tail allows expansion of phase space (albeit a slightly unphysical one)

➔ **Valencia 1p1h**
  - ◆ Best predictive power for hadron kinematics
  - ◆ More easily reweightable than alternatives (e.g. SuSAv2)

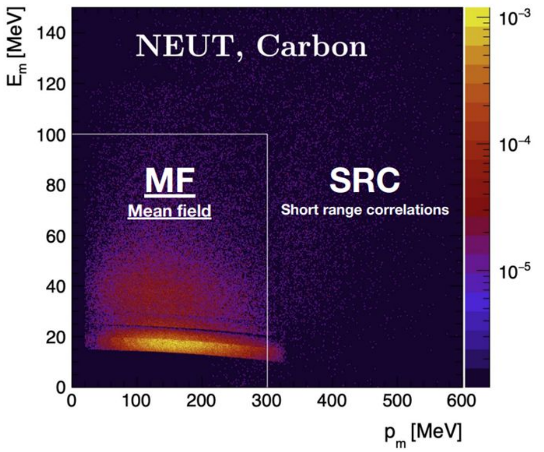
➔ **SuSAv2-2p2h**
  - ◆ Better phase space coverage than Valencia model (2.0 not 1.2 GeV cut off) can weight back

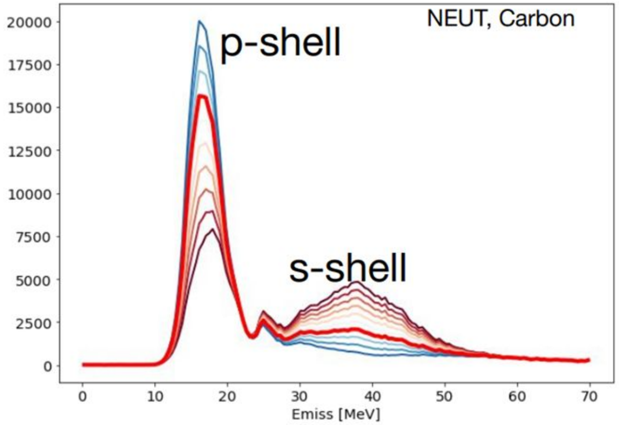
➔ **The usual SPP (BS) and DIS**
  - ◆ I don't think GENIE gives us many options here anyhow

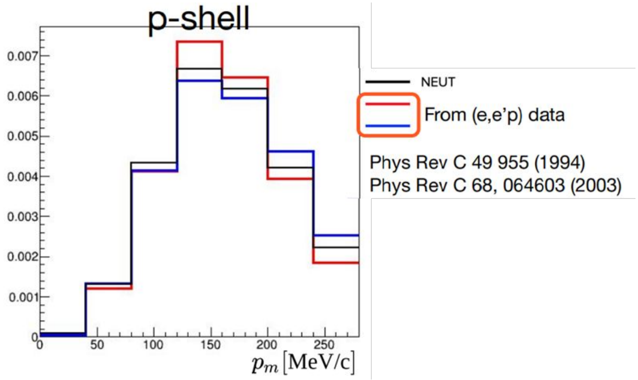
➔ **hA FSI**
  - ◆ Less physical, but more reweightable (we're not doing a real data analysis!)

Step two: identifying suitable degrees of freedom

- Start by considering what aspects of the models we want to vary
  - In DIRT meetings we've had useful input from MINERvA and T2K experiences







- But we care less about what's needed to describe data best (less badly) and more about what range of variations we can make
  - The next slides overview a "skeleton" set of variations we are considering

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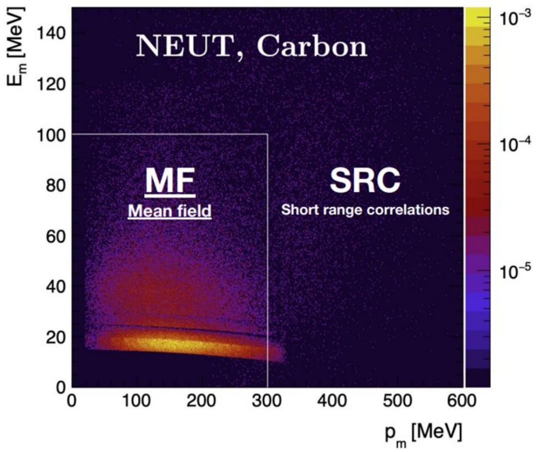
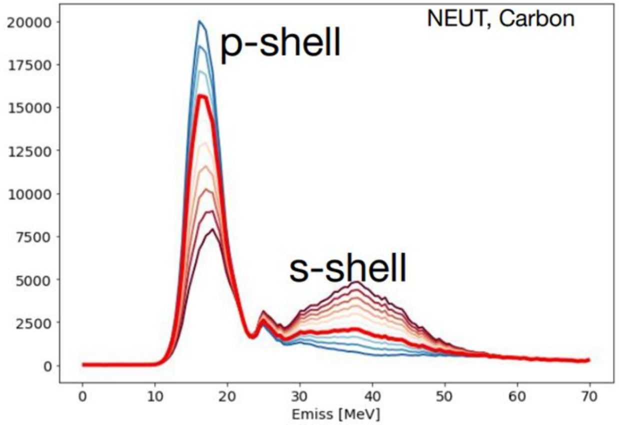
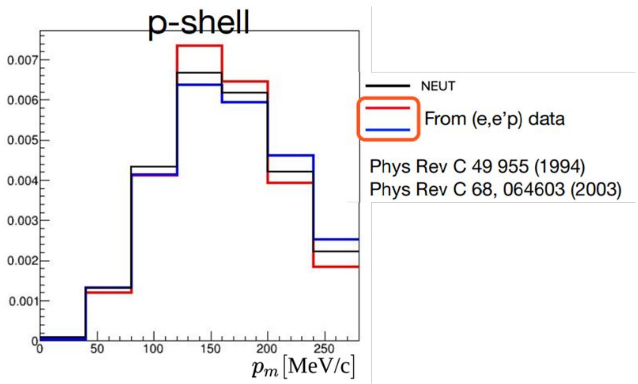


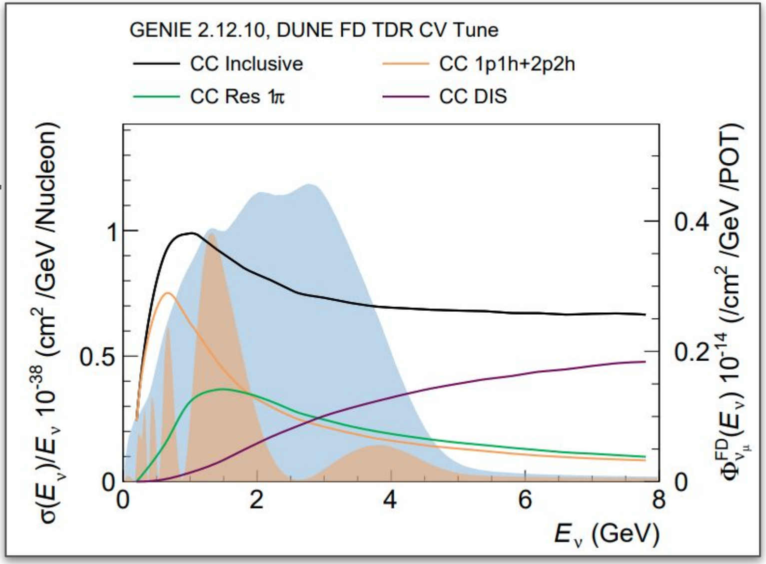




- But we care less about what's needed to describe data best (less badly) and more about what range of variations we can make
  - The next slides overview a "skeleton" set of variations we are considering
  - **The final model should be tailored to the samples we end up fitting!**

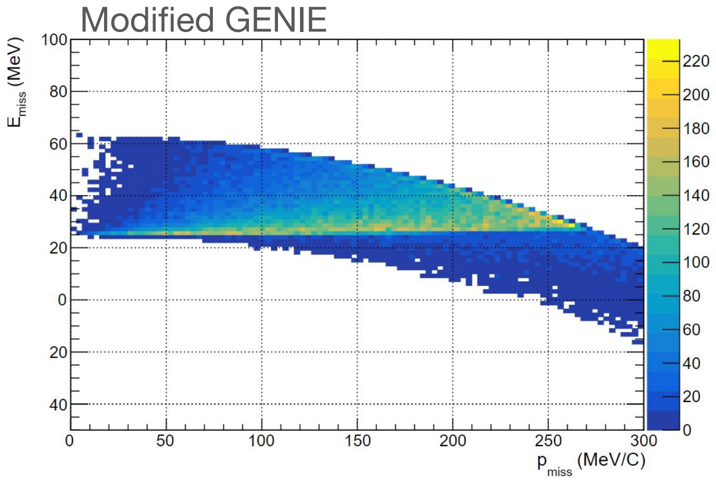
Aside: DUNE near detector constraints

- The DUNE ND will provide the statistics to constrain any usual set of model parameters we throw at it
  - Normalisation uncertainties will not suffice!
- A key challenge in writing down a DUNE uncertainty model is to offer freedoms for how modelling can change ND→FD extrapolation:
  - Energy dependence of cross sections (although PRISM will mitigate)
  - Acceptance differences
  - Target differences (to make use of CH)
  - ν_e/ν_μ differences (radiative corrections + nuclear effects)



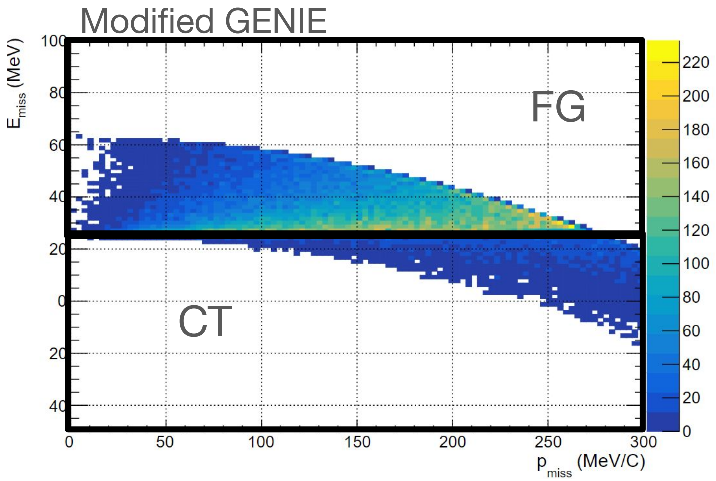
Ground state model uncertainties

- Varying the ground state is what accounts for the impact of most nuclear effects on pre-FSI kinematics within GENIE's factorised event generation
- Offers important and plausible freedom to lepton and hadron kinematics



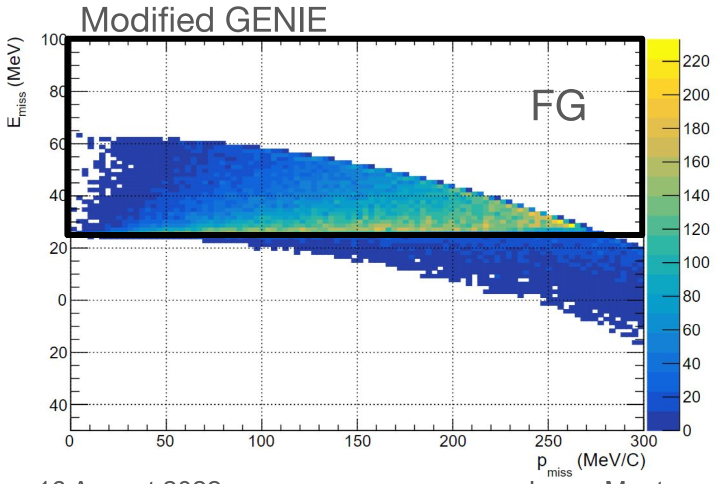
Ground state model uncertainties

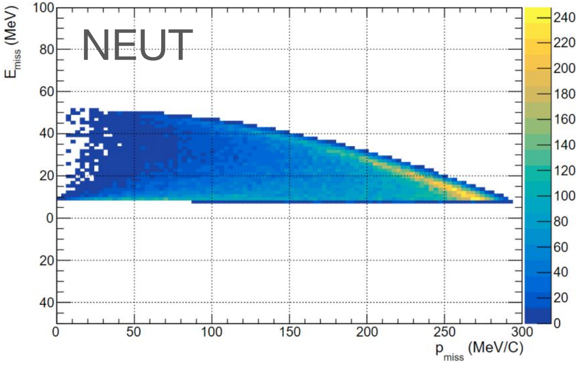
- Relative Fermi gas (FG) and correlated tail (CT) component strength

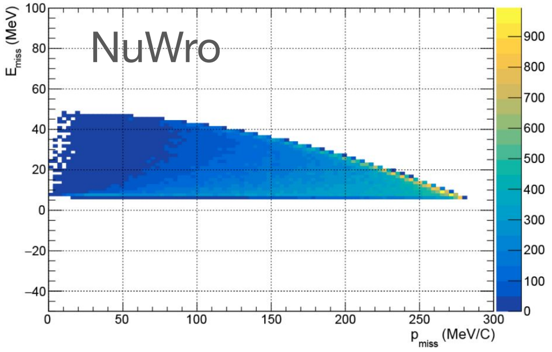


Ground state model uncertainties

- Relative Fermi gas (FG) and correlated tail (CT) component strength
- Shape of the FG component
  - Either just cover other models, or we can vary radial density distribution and the Fermi momentum - local density dependence



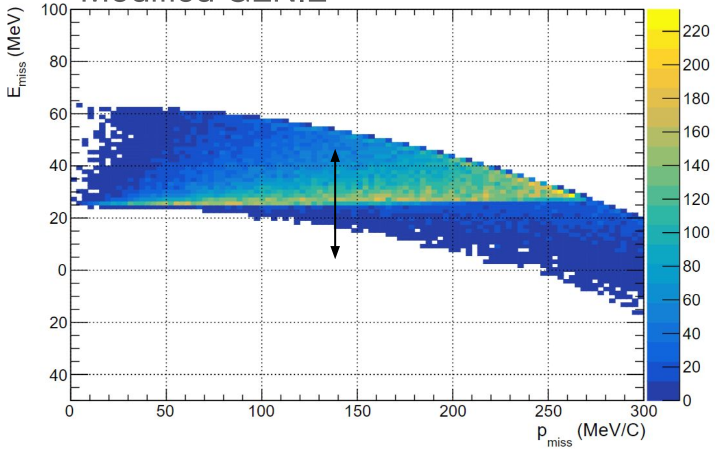


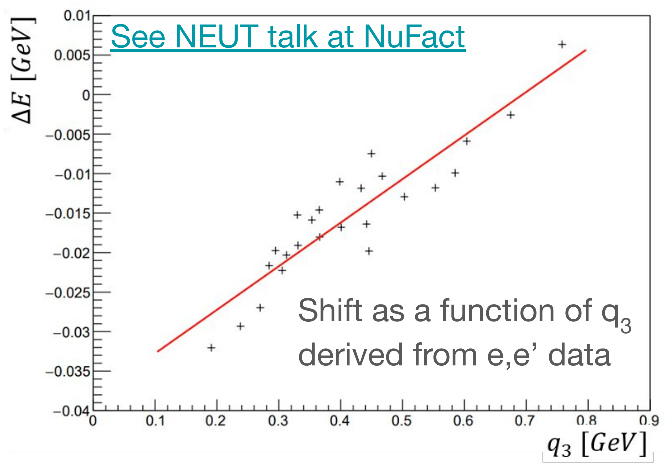


Ground state model uncertainties

- Relative Fermi gas (FG) and correlated tail (CT) component strength
- Shape of the FG component
- Lateral shifts of removal energy with an optional q_3 dependence?
  - Motivated by e,e' data and optical potential modelling (although only for QE)
  - Can the DUNE fitters handle this (needs 2D or event-by-event splines)?

Modified GENIE





Quasi elastic uncertainties

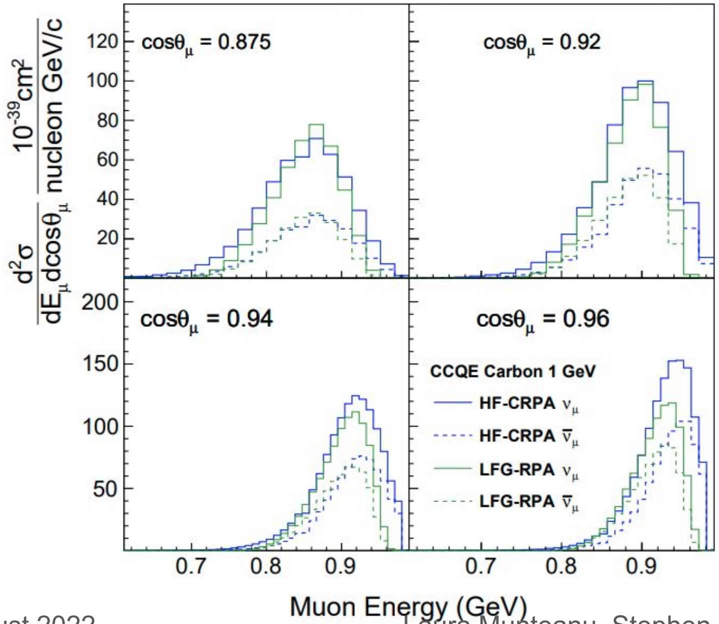
- Form factor freedom (either dipole + ad-hoc high Q^2 freedom or z-expansion dials*)

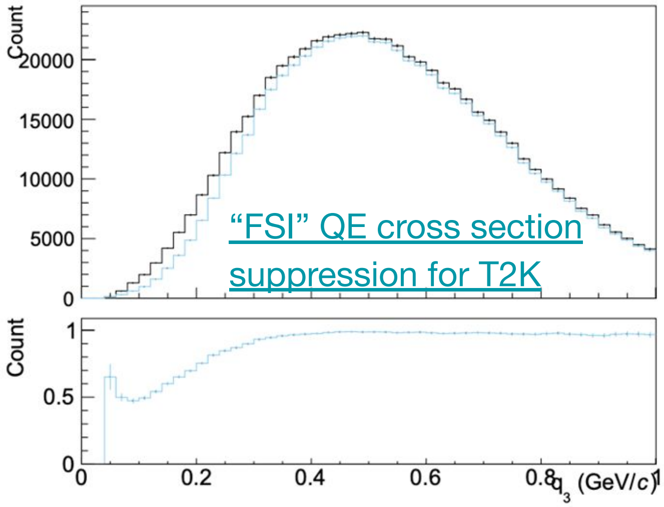
* non multiplicative behaviour would need some thought

Quasi elastic uncertainties

- Form factor freedom (either dipole + ad-hoc high Q^2 freedom or z-expansion dials*)
- RPA freedom (BeRPA with additional freedom to cover CRPA and FSI-like low Q^2 effects)
    - Should properly de-correlate these uncertainties between target nucleus/nucleon

arXiv:2110.14601





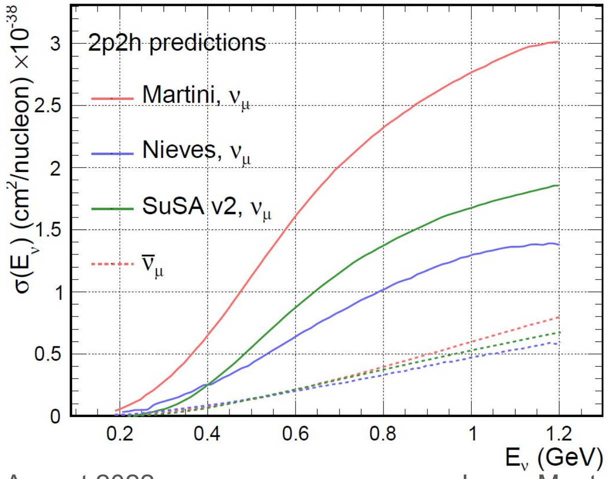
"FSI" QE cross section suppression for T2K

Quasi elastic uncertainties

- Form factor freedom (either dipole + ad-hoc high Q^2 freedom or z-expansion dials*)
- RPA freedom (BeRPA with additional freedom to cover CRPA and FSI-like low Q^2 effects)
    - Should properly de-correlate these uncertainties between target nucleus/nucleon
- Pauli blocking (there might be a GENIE dial for this?)
- Additional *ad-hoc* “nightmare” freedom (see later slides)

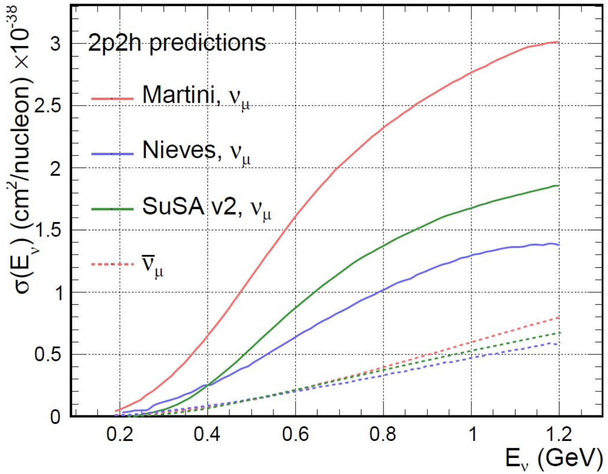
2p2h uncertainties

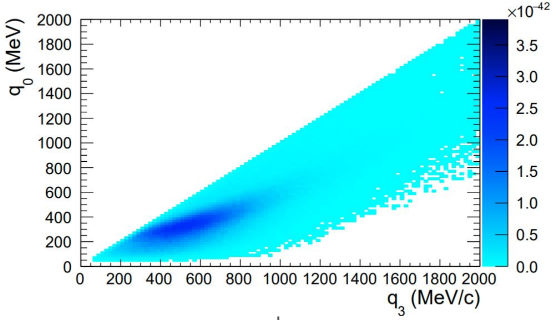
- Normalisation (per target and split for neutrino/antineutrino)
- $\boldsymbol{\sigma}(E_\nu)$ from model differences

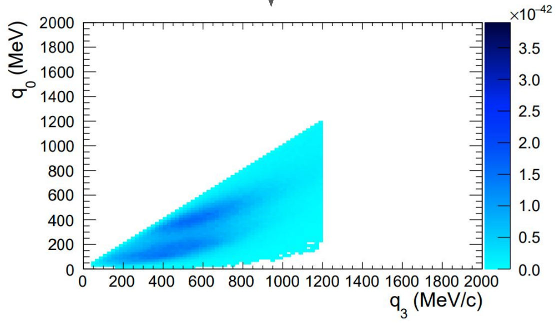


2p2h uncertainties

- Normalisation (per target and split for neutrino/antineutrino)
- $\boldsymbol{\sigma}(E_\nu)$ from model differences
- Shape of the inclusive cross section (SuSA vs Valencia?)
- Relative pair contributions (nn vs np)







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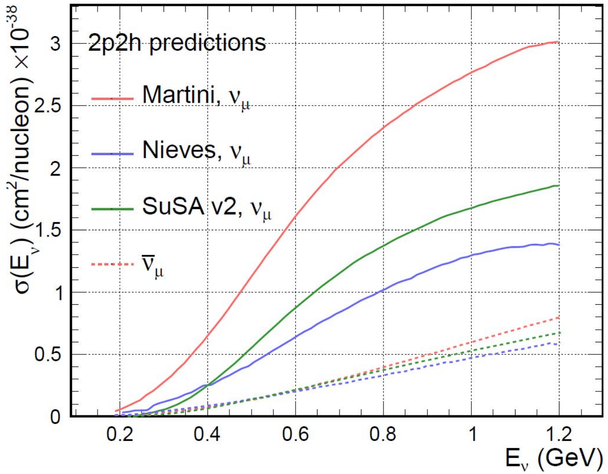
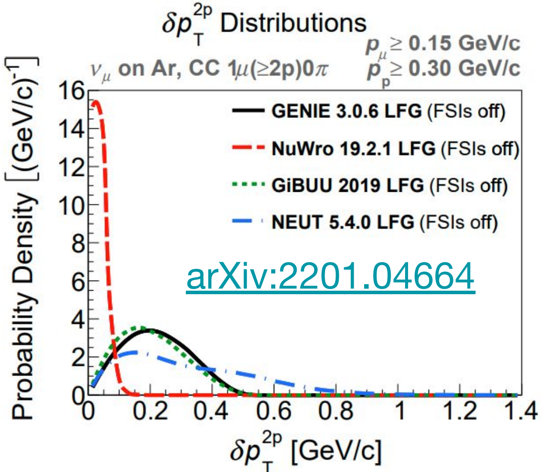
- $\boldsymbol{\sigma}(E_\nu)$ from model differences
- Shape of the inclusive cross section (SuSA vs Valencia?)
- Relative pair contributions (nn vs np)
- Nucleon ejection kinematics
- Additional *ad-hoc* “nightmare” freedom (see later slides)





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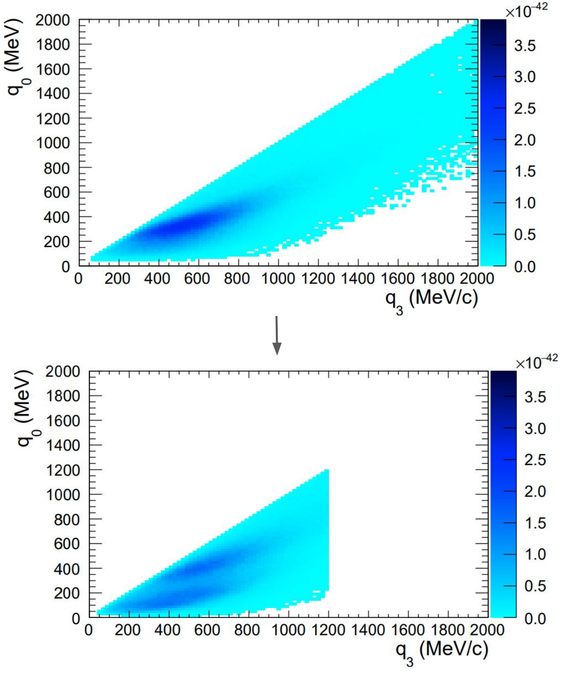


Single pion production uncertainties

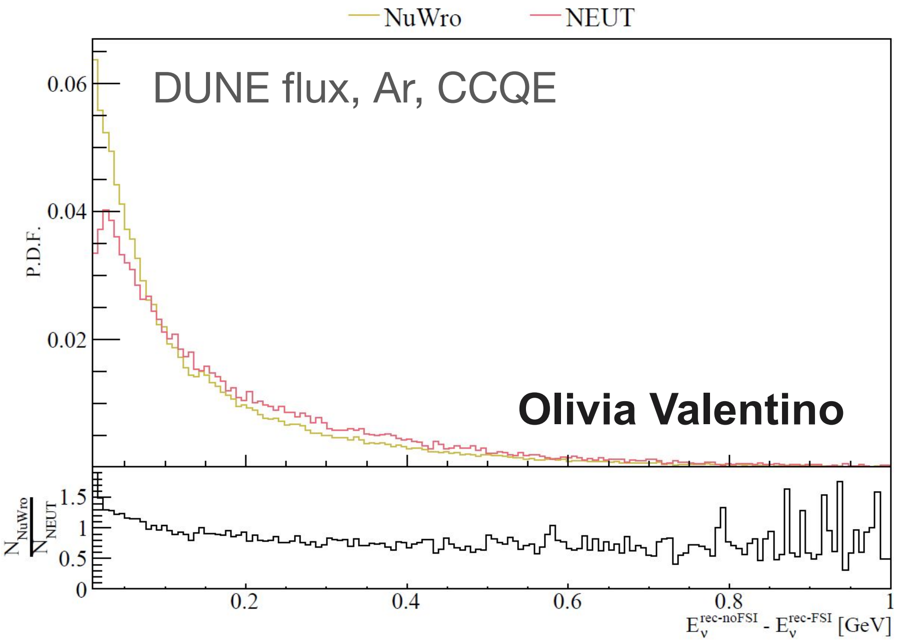
- Form factor freedom
- Non-resonant background alterations
- Uncertainties to alter hadron kinematics, keeping lepton kinematics fixed
  - T2K-inspired / DIRT-I-inspired resonance decay uncertainties?
  - More *ad-hoc* approaches?
- Additional nuclear effects
  - Low Q2 shape distortions independent of form factors
  - Removal energy or resonance peak energy shifts
  - Resonance decay width modifications?
- Channel normalisations
  - Charged vs neutral pion production
  - Modification of coherent contribution
- Additional NOvA or MINERvA inspired additional freedoms
- Additional *ad-hoc* “nightmare” freedom (see later slides)

SIS/DIS uncertainties

- Bodek-Yang correction modifications (4 GENIE dials)
- Hadronization/multiplicity GENIE parameters
- SIS/DIS contribution separation (normalisation alterations in W?)
- NOvA/DIRT-inspired pion multiplicity normalisation treatment?
- Q2 shape distortions inspired by MINERvA and NOvA data
- Additional *ad-hoc* “nightmare” freedom (see later slides)
- Other ideas?
- Inspiration from the MK model update?
- Help?

FSI uncertainties

- The usual list of GENIE hA dials
- Additional freedom to cover the large differences in model predictions of how FSI alter E_{rec}
  - More details in ProtoDUNE FSI talk



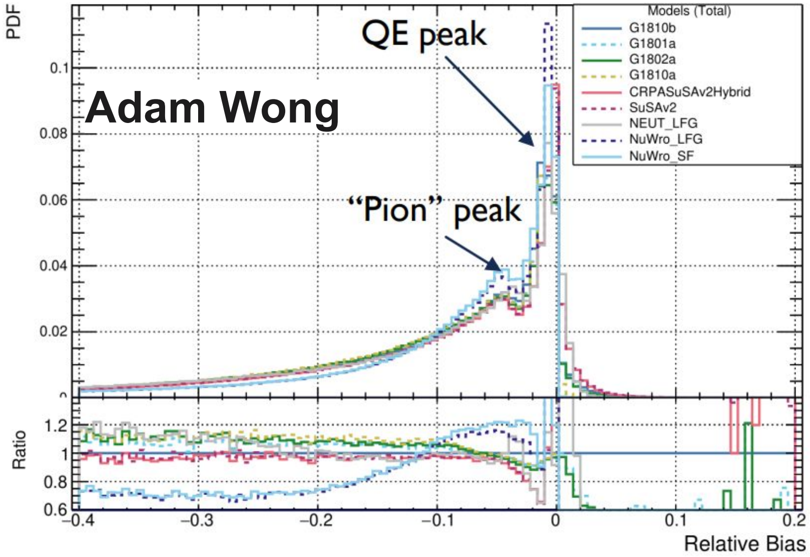
Miscellaneous uncertainties

- ν_e/ν_μ differences
  - Ideally encompassing radiative correction and nuclear effect impact
- Neutral current freedoms

An example “nightmare” freedom

- DUNE requires a reliable constraint on the expected E_{rec} bias and spread
- But different models predict give significantly different expectations

$$E_{rec} = E_{lep} + \sum T_p + \sum T_{\pi^\pm} + \sum E_{\pi^0}$$



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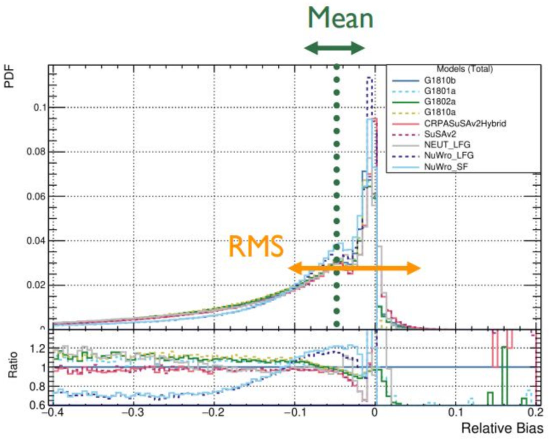
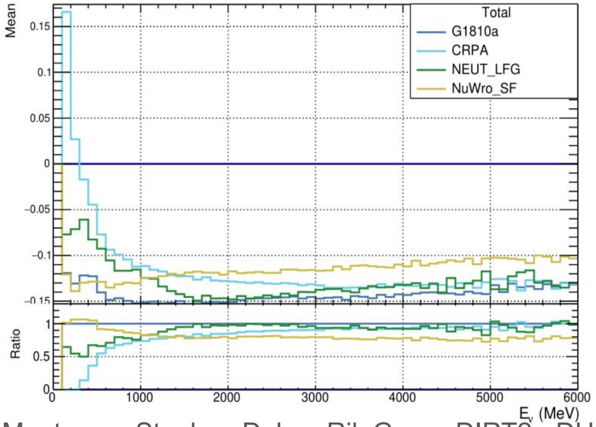
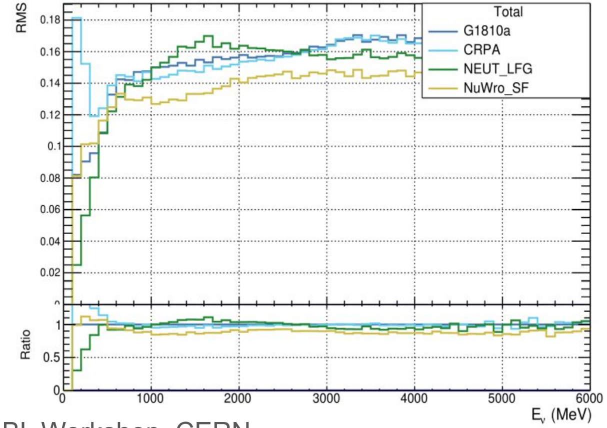
- But different models predict give significantly different expectations
- Even worse: different models predict that the way the bias and spread evolves in energy is significantly different (implying we might be misled by ND constraints)







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- Recent DIRT-II work: build uncertainties enveloping model differences in the energy dependence of the neutrino energy bias and spread
  - One uncertainty "dial" per channel covering the model spread
  - Implementation scheme established
  - Preliminary inputs are ready

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    - One uncertainty “dial” per channel covering the model spread
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    - Preliminary inputs are ready
- Other “nightmare” freedoms can be added following a similar scheme
    - Can also be used to build fake data

Summary

- We have a broad idea of the uncertainties we would like to have from DIRT-II
  - But additional input/ideas for higher W interactions would be appreciated
- This would be a significant update from DIRT-I, and a small step towards building something we could eventually use for the first DUNE analyses
- Implementing all of this in nusystematics could also be beneficial to the community
  - Potential for use by SBN experiments
  - Can be tested and tuned via NUISANCE interface
  - Can be compared to other uncertainty models (e.g. T2K's, NOvA's) and benchmarked
- But this implementation is not a trivial amount of work!
  - Help from DUNE LBL analysers is needed to realise a complete DIRT-II model