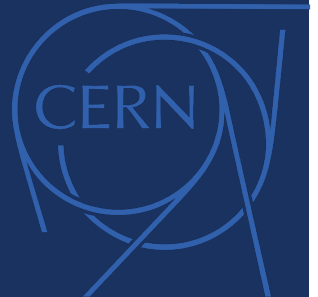


Neutrino-nucleus interaction uncertainties for DUNE oscillation analyses

Laura Munteanu (CERN)

Neutrino Generators Workshop

16 March 2023



DUNE Physics Program and Generators

- Neutrino oscillation physics
 - Precision measurements of oscillation parameters
 - Unitarity checks
- Beyond the Standard Model (BSM) Physics
 - Proton decay
 - Sterile neutrino searches
 - Non-standard interactions
 - Dark Matter searches
 - And many more!
- High Energy Physics
 - Atmospheric neutrinos
- Supernova neutrinos
 - ν_e from SNB
 - SN physics
- Solar neutrinos
 - High energy solar neutrino flux

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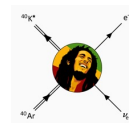
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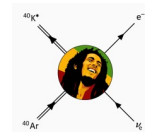
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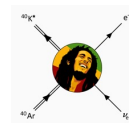


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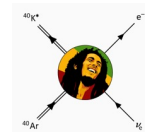
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Neutrino-nucleus interactions in the few-GeV region

- A robust modelling of neutrino-nucleus interactions in the few-GeV region is essential for the physics programs of long-baseline and short-baseline neutrino experiments
 - For both oscillation measurements as well as searching for physics beyond the Standard Model
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Total Systematic Uncertainty	6.0

The systematic uncertainty on the predicted relative number of electron neutrino and electron antineutrino candidates in the SK samples with no decay electrons.

Nature volume 580, pages 339–344 (2020)

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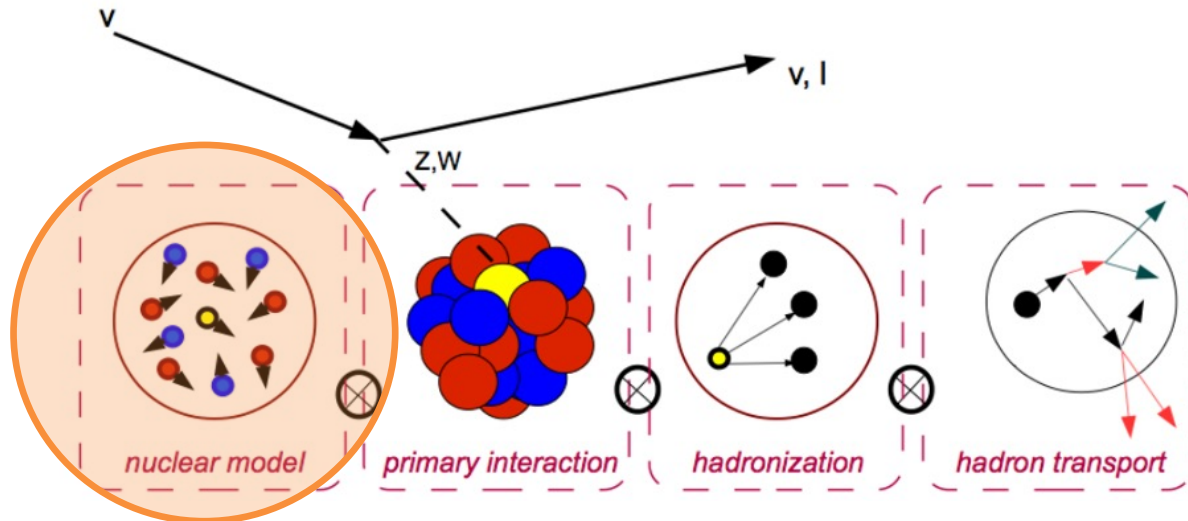
[Nature](#) volume 580, pages 339–344 (2020)

- Since then, T2K has greatly improved its systematic error model by using the more sophisticated Benhar Spectral Function (Benhar SF) model, well constrained by electron-scattering data
- As a result, the nuclear removal energy uncertainty **became subdominant (<1%)** and allowed the development of a robust set of uncertainties for nuclear ground state effects

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How does the nuclear ground state impact experiments?

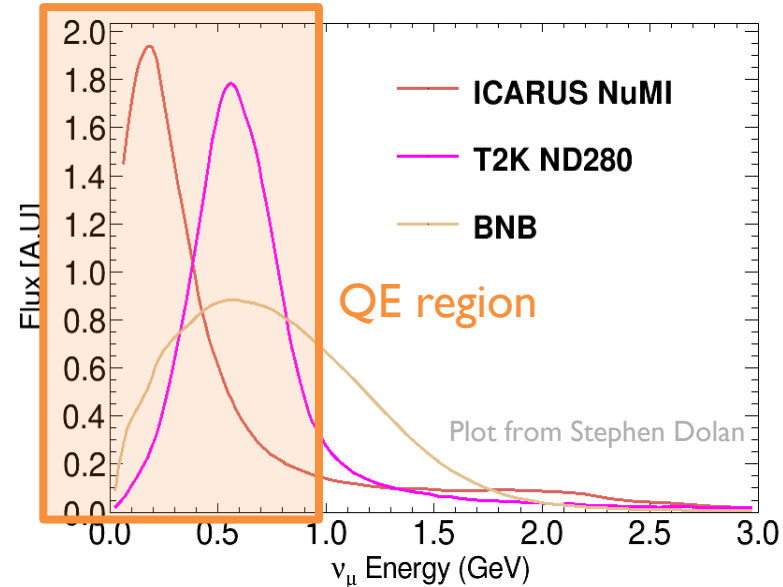
- Most generators (including GENIE) sample the distribution of initial nucleon momenta and removal energies from a Spectral Function (determined by the nuclear model used)
 - Most nuclear models predict removal energies which vary in a range of **10-50 MeV**
 - Nucleon momenta span ranges of up to **hundreds of MeV**



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- Mismodelling the removal energy causes a **direct bias in reconstructed neutrino energy**
 - Particularly important for oscillation measurements which evolve as a function of neutrino energy
 - But also for lower-energy physics (e.g. BSM physics)



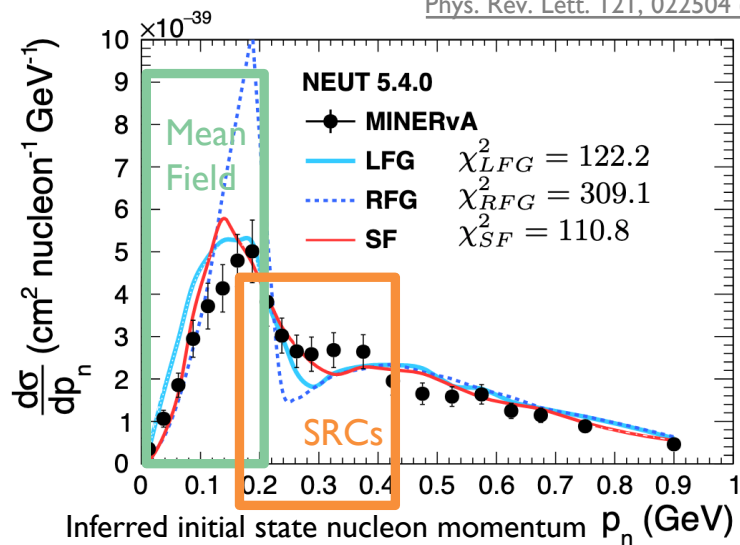
DUNE is not QE dominated
But QE interactions are those which we can
measure best
Remain important for precision measurements

How does the nuclear ground state impact experiments?

arXiv:1810.0603

Phys. Rev. Lett. 121, 022504 (2018)

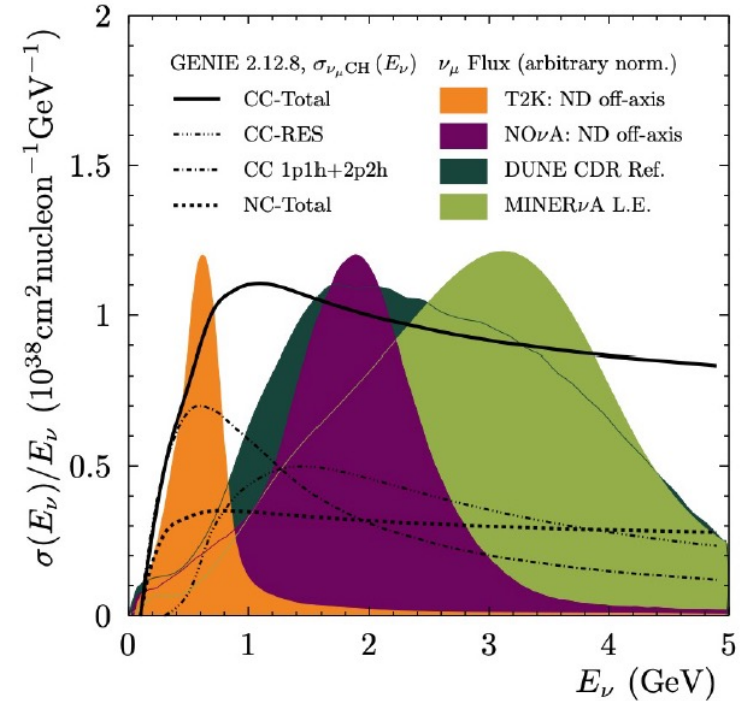
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 - Particularly important for oscillation measurements which evolve as a function of neutrino energy
 - But also for lower-energy physics (e.g. BSM physics)
- Mismodelling the nucleon momentum alters predictions on hadron kinematics
 - Will be crucial as experiments (notably SBN and DUNE) produce new **exclusive** cross-section measurements



SRCs or “correlated tail” effects become important at nucleon momenta of O(200-700 MeV)

Importance for DUNE

- At DUNE statistics, we will be able to resolve some of **the most minute details** in the way we model neutrino-nucleus interactions
- But no model is capable of comprehensively describing neutrino cross-section data
 - For DUNE, **we need a flexible model** which can cover the variations suggested by relevant neutrino cross-section measurements
- We also will need to pay particular attention to FSI
- Beyond oscillation measurements: we need a model that can be used for BSM physics and can model well the backgrounds that can affect these processes

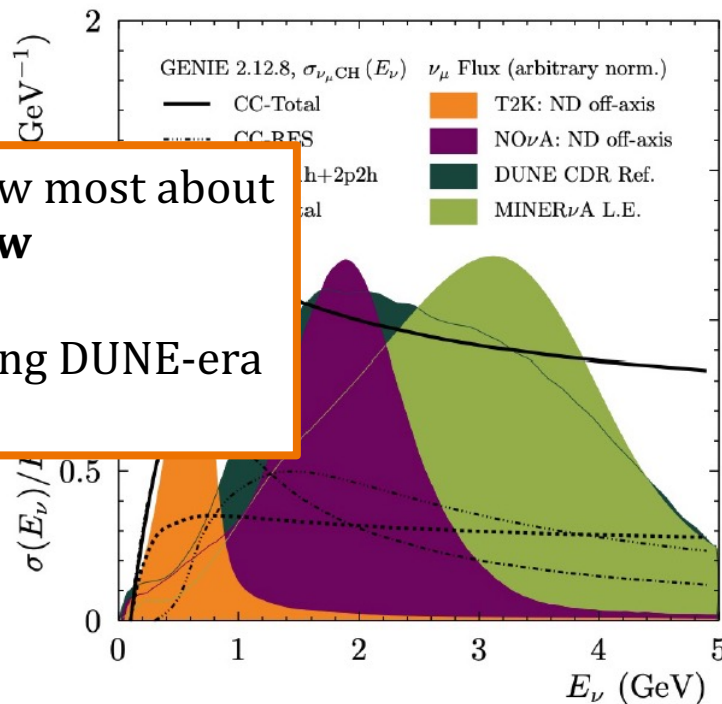


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- At DUNE statistics, we will be able to resolve some of **the most minute details** in the way we model neutrino-nucleus interactions
- But no model is perfect
 - For DUNE, we need to cover the variation in cross-section measurements
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The QE regime is where we know most about **what we don't know**

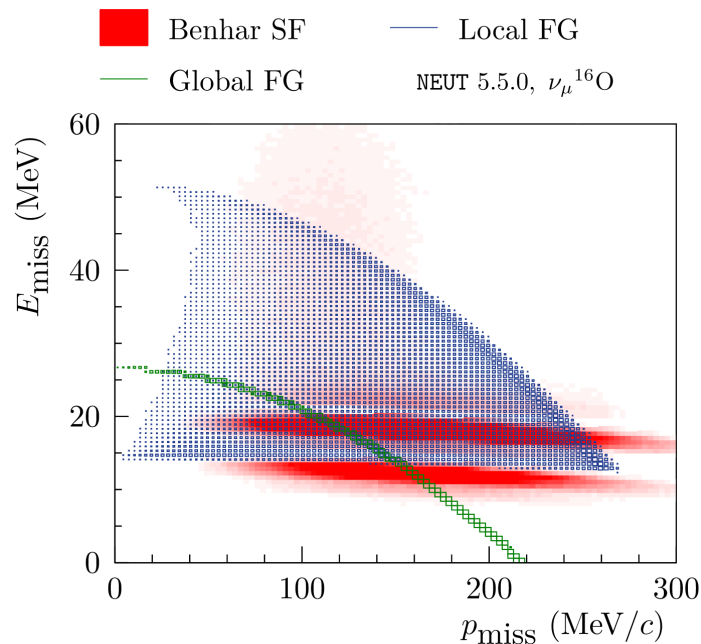
Perfect starting point for building DUNE-era analyses



The ground state phase space

- Multiple ground state models are available in neutrino interaction generators, commonly:
 - RFG
 - LFG
 - Benhar SF
 - Others to come, but not yet implemented
- Of the available models, SF has a wide phase space coverage, good agreement with electron-scattering data, strong physics motivation, mean field and SRC components
- DUNE production pipeline is optimized for GENIE and we will use GENIE v3.2
 - But 2D Benhar SF is not available in GENIE 3.2 yet and beyond the timeline of the analysis
- We chose to use LFG instead for the production

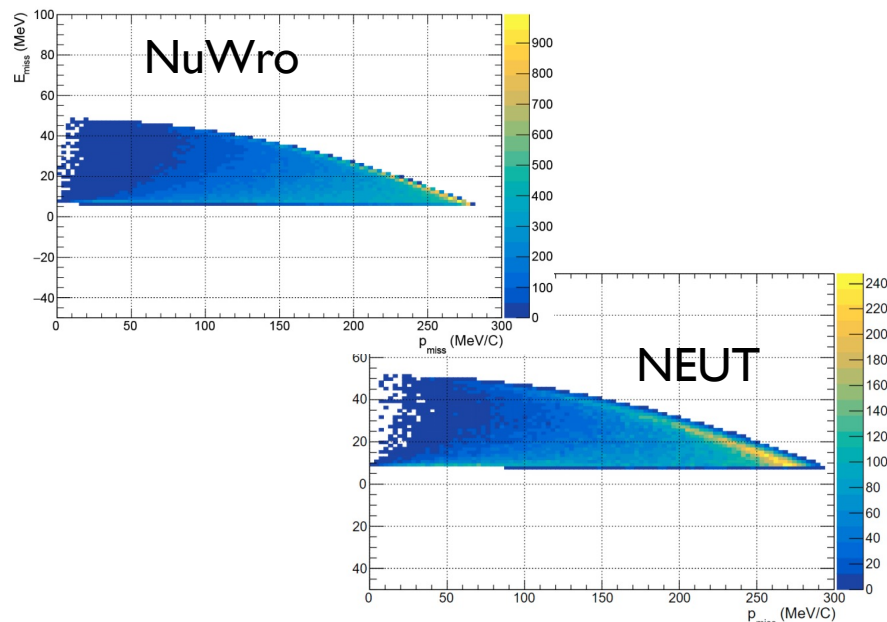
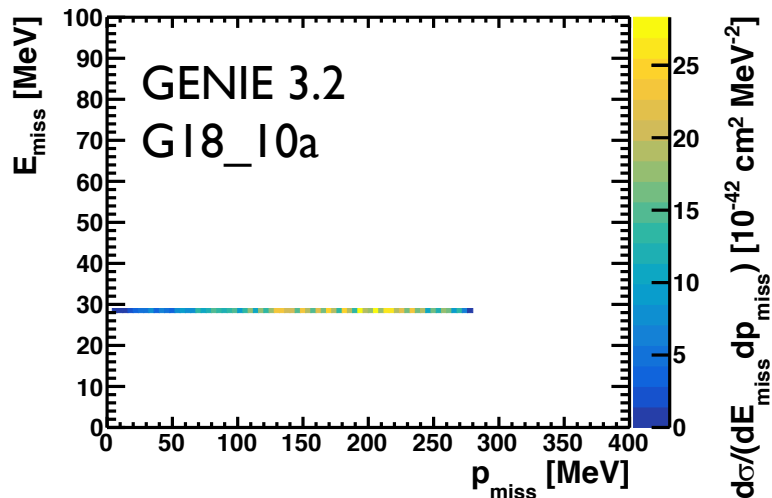
Eur.Phys.J.ST 230 (2021) 24, 4469-4481



$$\vec{p}_{\text{miss}} = \vec{p}_\nu - \vec{p}_\mu - \vec{p}_p$$
$$E_{\text{miss}} = \omega - T_p^{\text{pre-FSI}} - \Delta m_{n \rightarrow p} - T_{\text{nucl. remnant}}$$

Expanding the ground state phase space

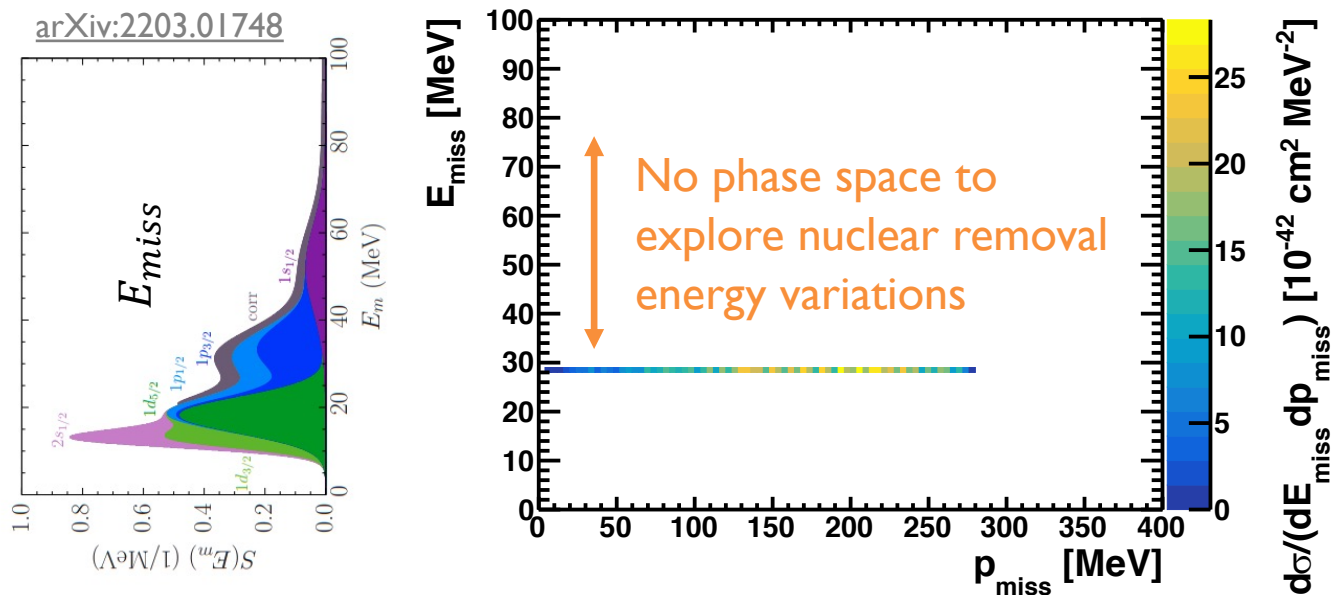
- However, the out-of-the-box GENIE 3.2 LFG (G18_10a_00_000) ground state does not cover enough phase space to implement some of the systematics we need for DUNE



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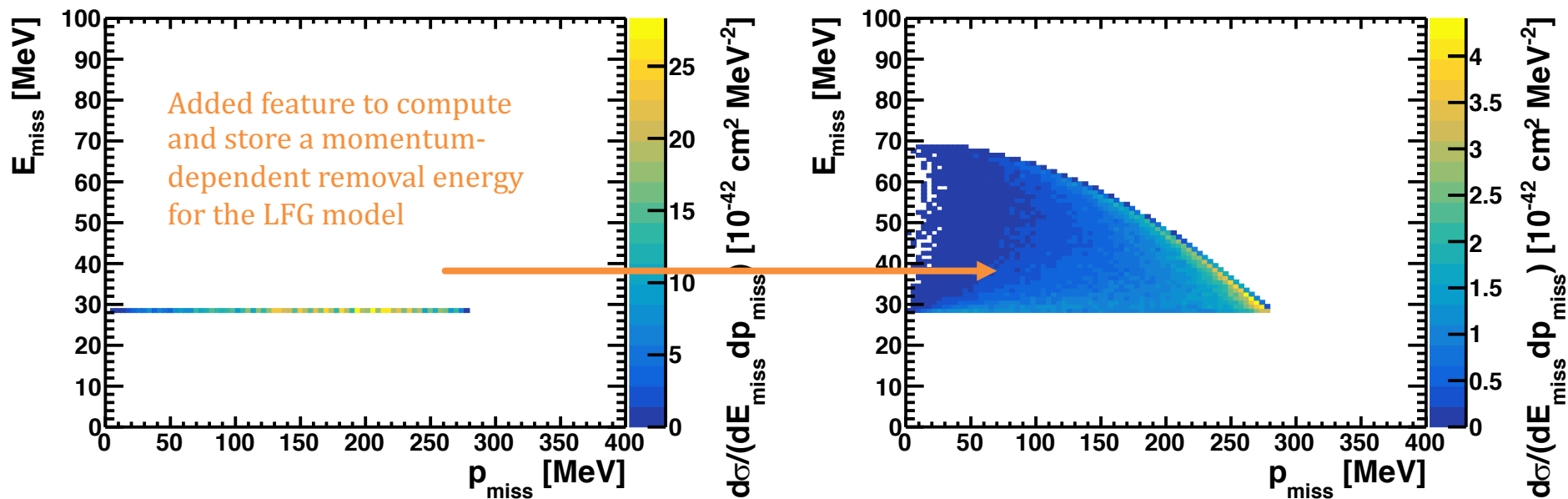
arXiv:2203.01748



We can turn on a correlated tail for the GENIE LFG model, which extends the phase space in momentum

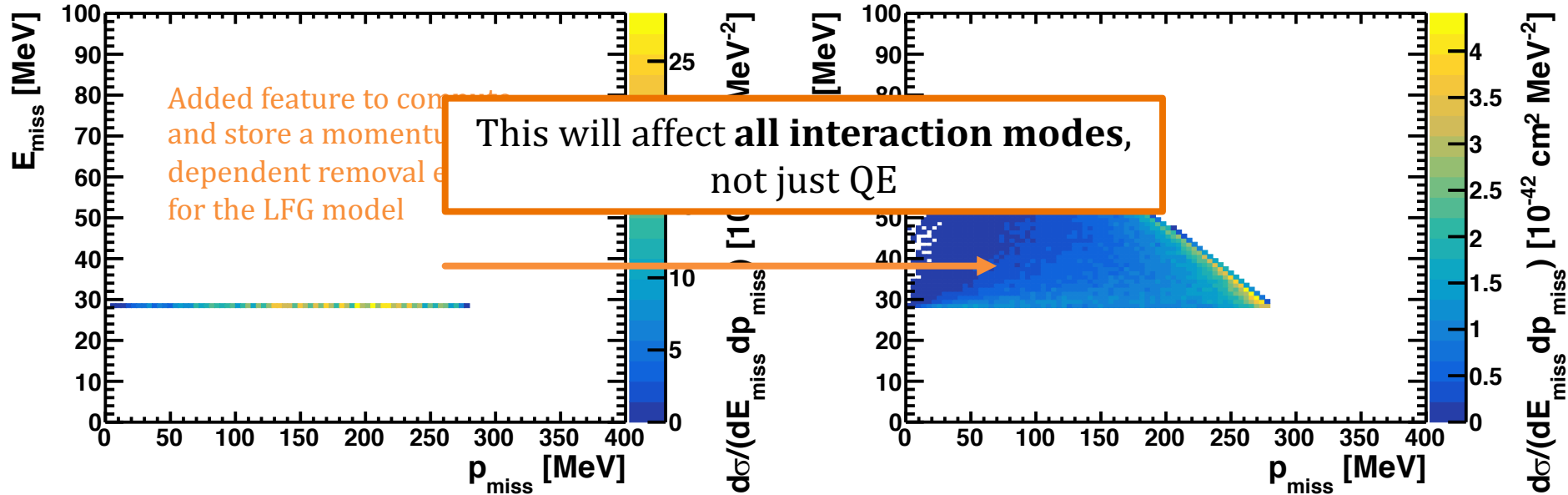
Expanding the ground state phase space

- For an LFG model, the dependence between the removal energy and the nucleon momentum is well-understood (Fermi gas approach)



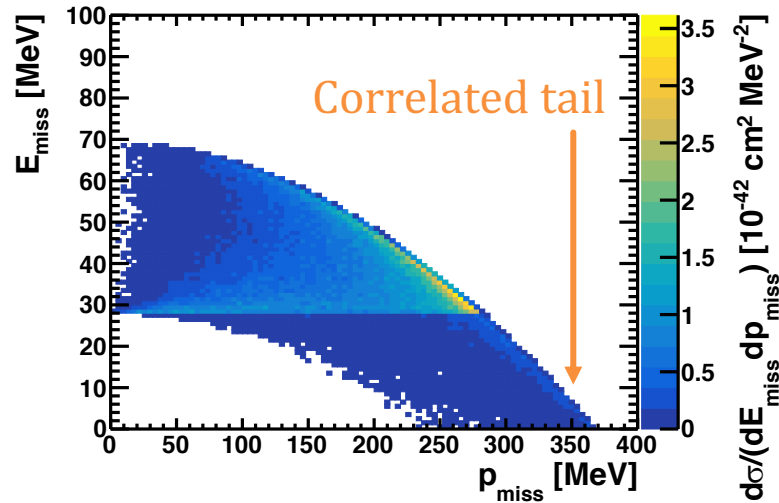
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Correlated tail

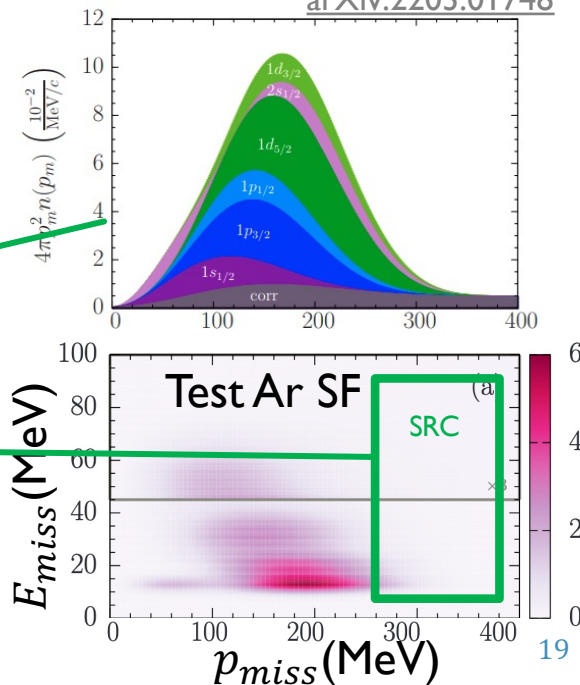
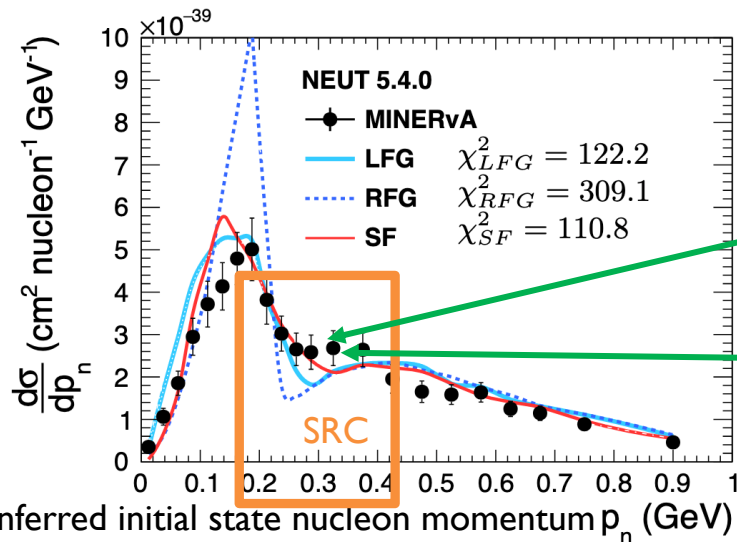
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- The tail is essential to include some production-level phase space to allow us to explore the SRC region



Correlated tail

- For DUNE studies, we will use the “correlated” version of the LocalFGM model
- The tail is essential to include some production-level phase space to allow us to explore the SRC region
- Region with high model disagreement
- It will be the first use of the new correlated tail code at production level

arXiv:2203.01748

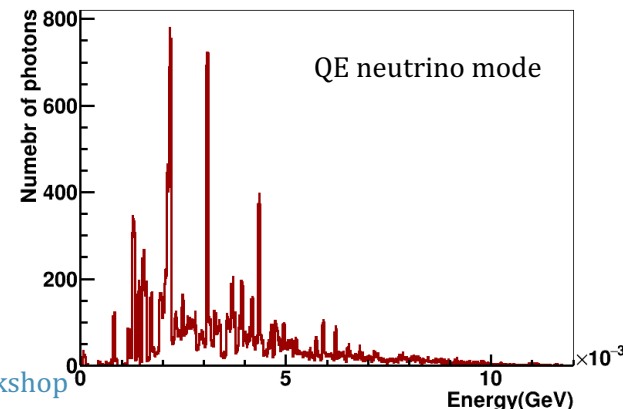
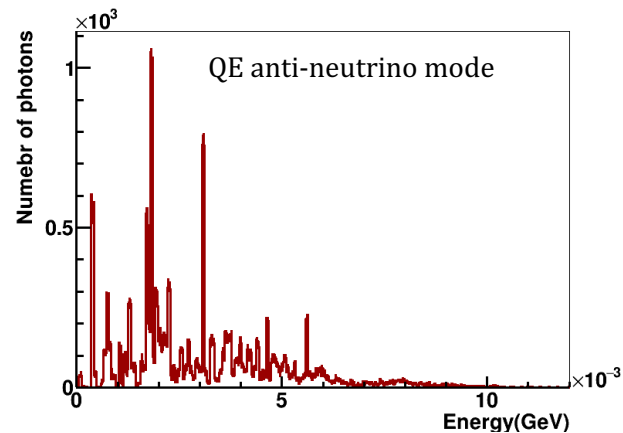


Useful add-on: de-excitation photons for Ar

- No de-excitation photons simulated in GENIE by default
- Effort by Steven Gardiner and Rik Gran to implement the Ar* and C** spectra into GENIE
 - Works as expected
 - Gives option to explore MeV-level physics

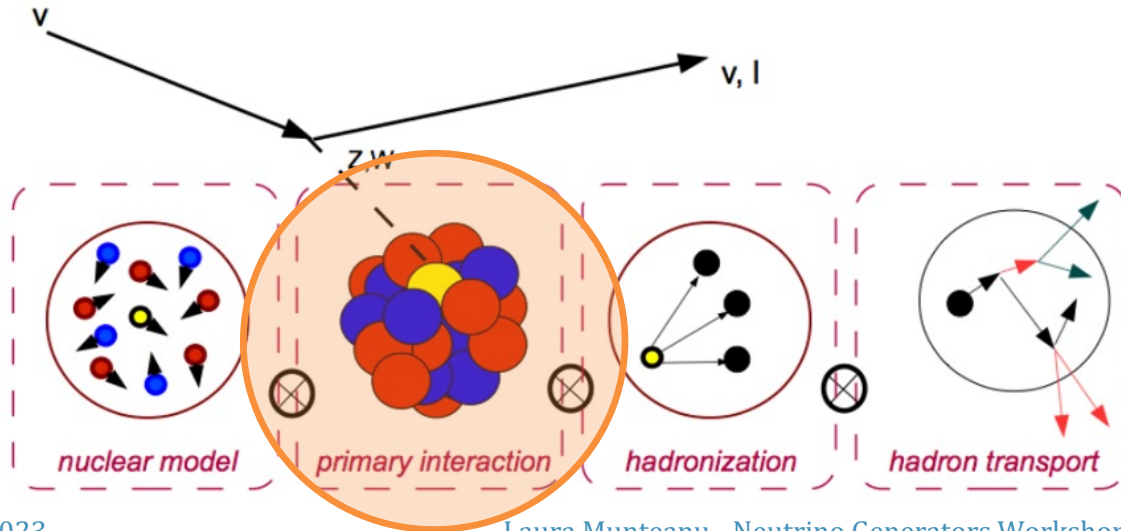
*from MARLEY

**from Kamyshev & Kolbe



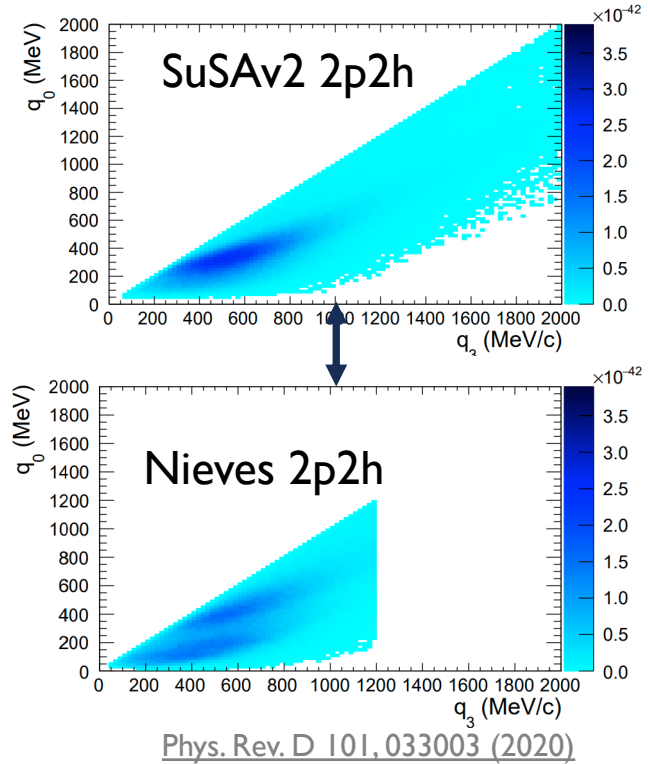
Interaction model

- The expansion of the ground state model is part of a broader effort to increase the flexibility of our analyses



Interaction model

- The expansion of the ground state model is part of a broader effort to increase the flexibility of our analyses
- Interaction model choices:
 - Valencia 1p1h model for CCQE interactions
 - Z-expansion form factor
 - **SuSAv2 2p2h** -> increased phase space, benchmarked against electron scattering data
 - Berger-Sehgal for Resonant interactions
 - Bodek-Yang DIS
 - **hA2018 for hadronization** -> reweightability
- Each of these parts of the model requires the development of systematic uncertainties tailored to DUNE-era statistics



Status of baseline model

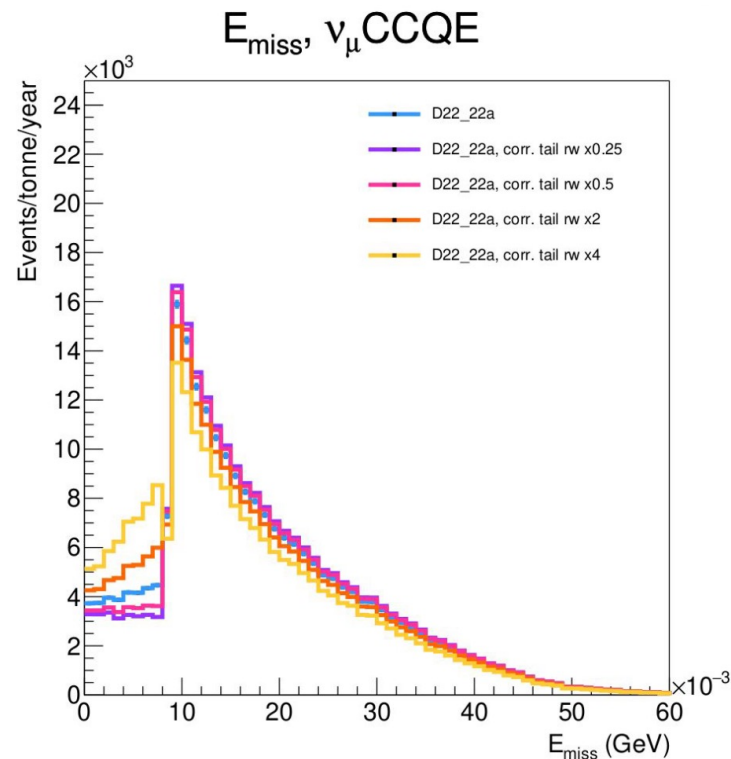
- We have been validating our modifications extensively for the past few months
 - Everything seems to be behaving as expected
- SBN experiments have expressed interest in using the same ground state model (and associated interaction model choices) for their productions
 - **We have reached an agreement with ICARUS and SBND about using the same model!**
 - Shared code **and systematics**
- As a result, it has now become part of the GENIE 3.04.00 release
- This model will be used for the next DUNE production
 - Timeline of ~ 2 years, will be the basis of the next sensitivity studies

Systematic uncertainties

- Systematic effects applied through reweighting
 - Use the nusystematics package developed within LArSoft
 - Interface with Nuisance
- Expect $O(10^2)$ degrees of freedom (“dials”/ “knobs”) affecting each part of the model
 - Several already exist as GENIE ReWeight dials
- Assessing the impact of systematic uncertainties on the oscillation analysis will also involve “nightmare parameters” or fake data studies
 - Pushing the model to its limits to evaluate bias on oscillation measurements

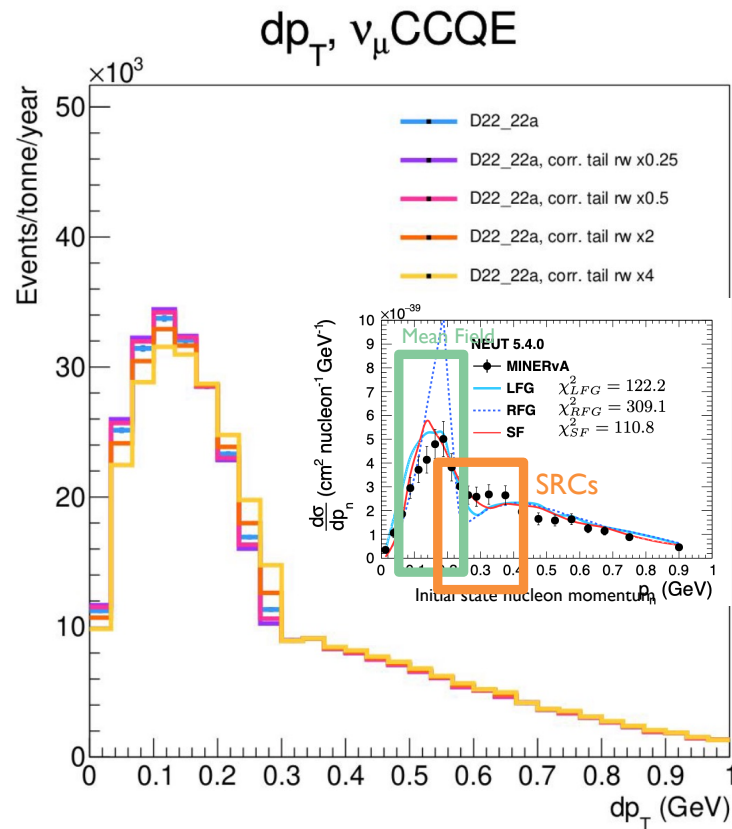
Ground State Freedoms

- Want to be able to vary:
 - Removal energy (shell-like shape)
 - Mean field component
 - “SRC” contribution
 - q_3 -dependence (QE interactions only)
- First example of how this works: simple scaling of the correlated tail



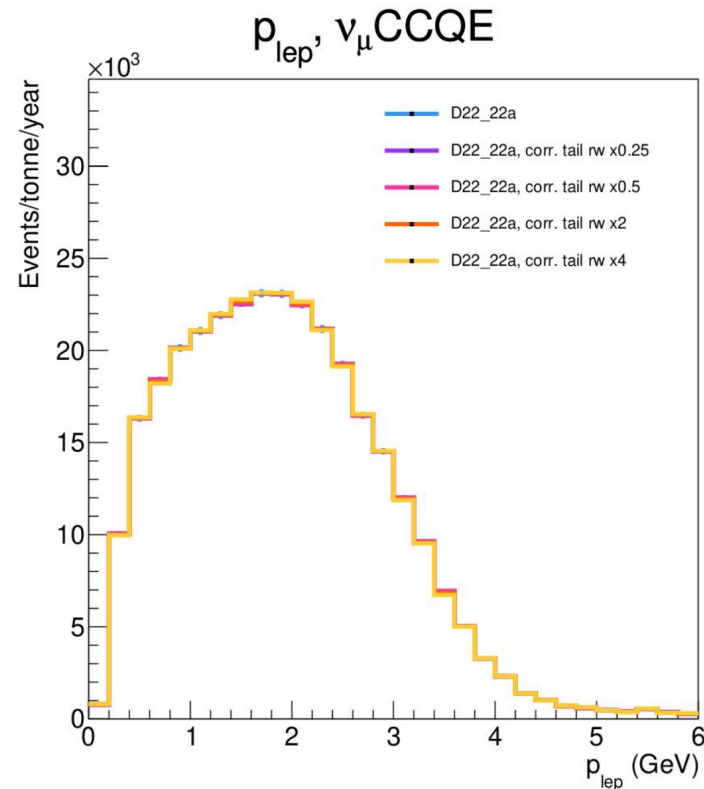
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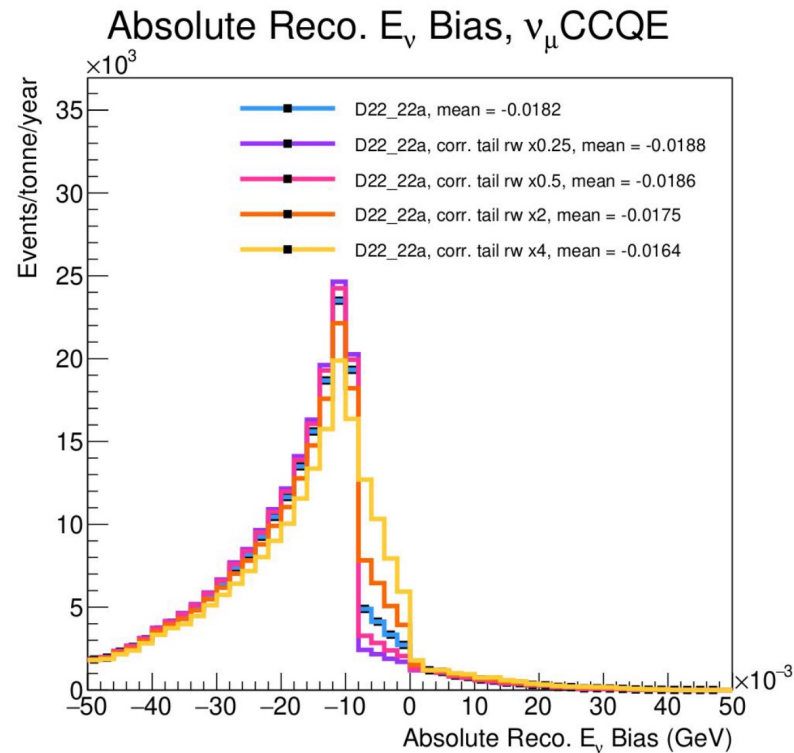
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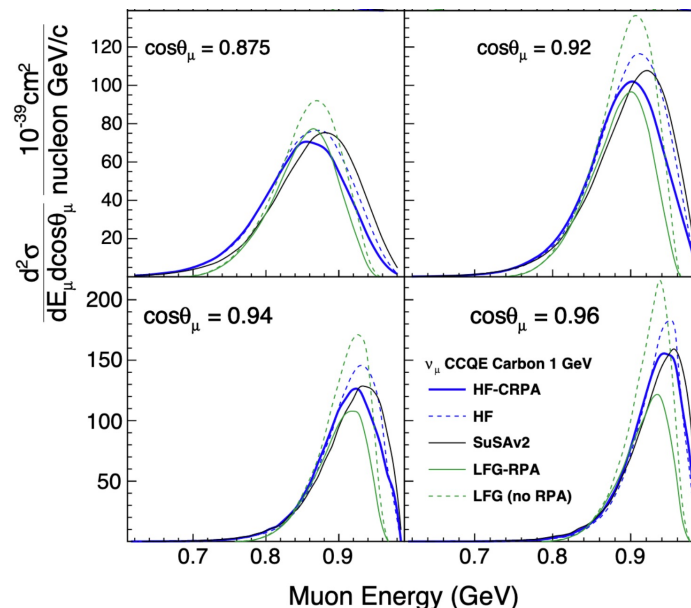
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 - Gives a handle on physics which impact neutrino energy reconstruction



Other CCQE Freedoms

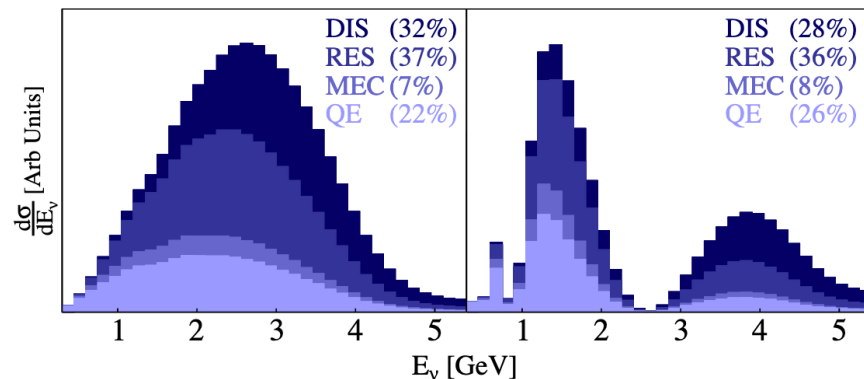
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 - q_3 -dependence (QE interactions only)
- Z-expansion parametrization
- Options to vary Pauli Blocking treatment
- Collective effects for each nucleus species and type



Phys.Rev.D 106 (2022) 7, 073001

Beyond CCQE

- More than 60% of interactions at DUNE are non-QE
- Include appropriate freedoms for:
 - 2p2h kinematics (pair fractions, Δ component...)
 - Design a set of systematics for resonances as rich as what we have for QE
 - Alternative DIS/SIS models (close collaboration with Aligarh Muslim University)
 - FSI – learn from protoDUNE Ar data
- In all cases, include freedoms for energy dependence



Data taken with the **ArgonCube 2x2** prototype and future **protoDUNE** runs are crucial to inform these developments in the future

Next steps

- Focus for the next few months: develop a comprehensive set of **systematic uncertainties** to fully exploit power of DUNE **near detectors**
- Will design multiple mock data/nightmare studies to test the **robustness** of the model
- Tight collaboration moving forward with **SBN experiments** thanks to shared model
- **Shared systematics framework** will benefit the entire community
- Possibility for interesting, one-of-a-kind physics studies with DUNE!