MODELING NEUTRINO-NUCLEUS INTERACTION UNCERTAINTIES FOR DUNE LONG-BASELINE SENSITIVITY STUDIES

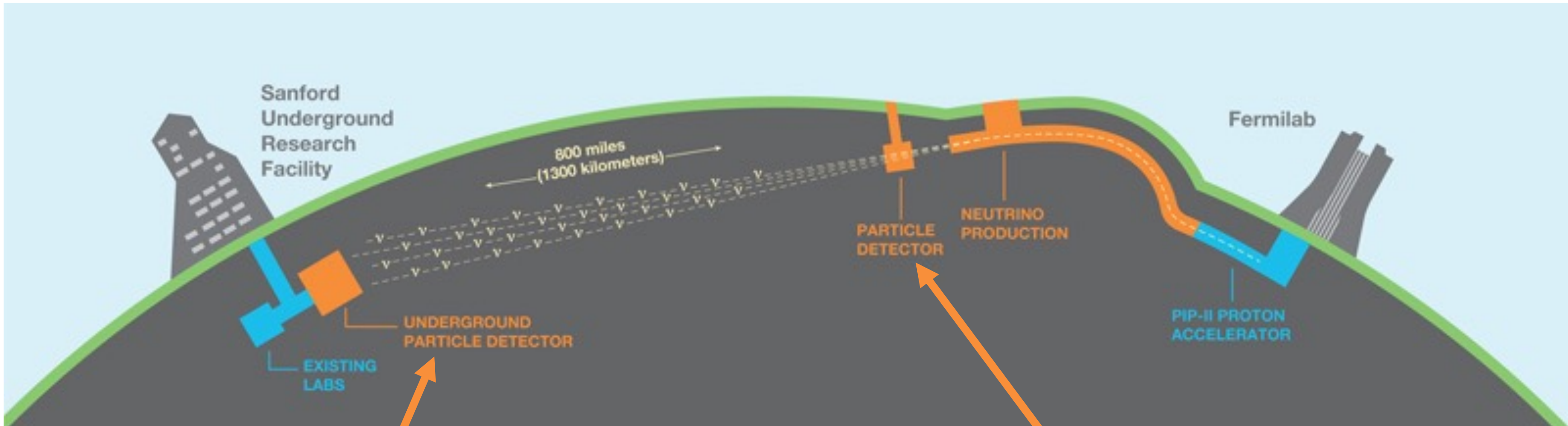
Laura Munteanu on behalf of the DUNE Collaboration

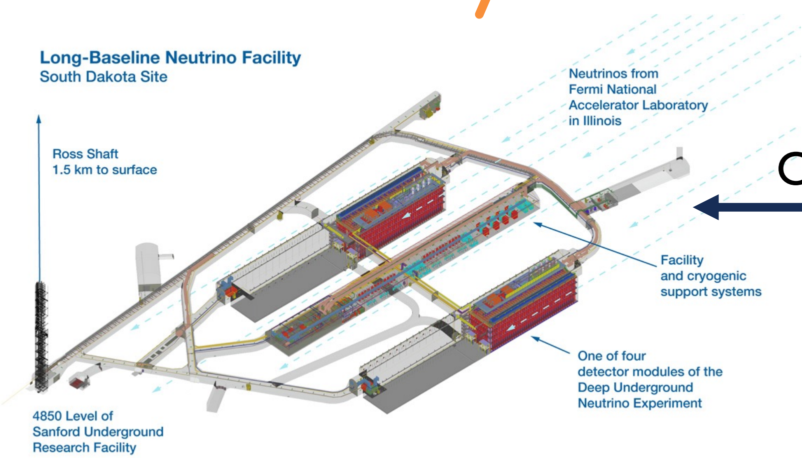
NuINT 2022

Seoul, South Korea

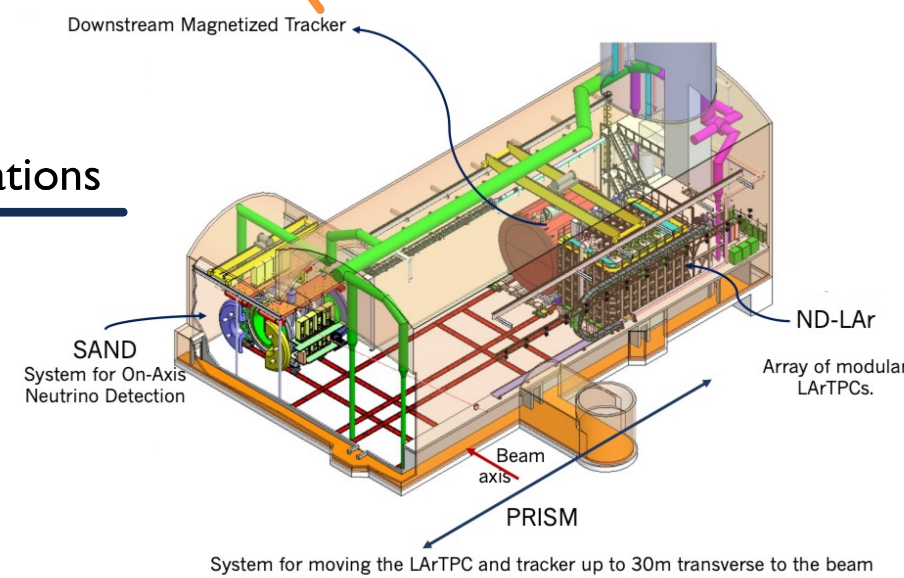
October 25 2022

THE DEEP UNDERGROUNG NEUTRINO EXPERIMENT





Oscillations



DUNE PHYSICS PROGRAM

Long-baseline (LBL) Neutrino Oscillations

- Measuring neutrino oscillation parameters
- Precision measurements
- Probing unitarity

Beyond Standard Model (BSM) Physics

- Proton decay
- Sterile neutrino searches
- Dark matter searches
- Non standard interactions

Supernova neutrinos

- ν_e from SNB
- SN and neutrino physics

Solar neutrinos

- High energy solar neutrino flux measurement

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DUNE will have a uniquely rich physics program!

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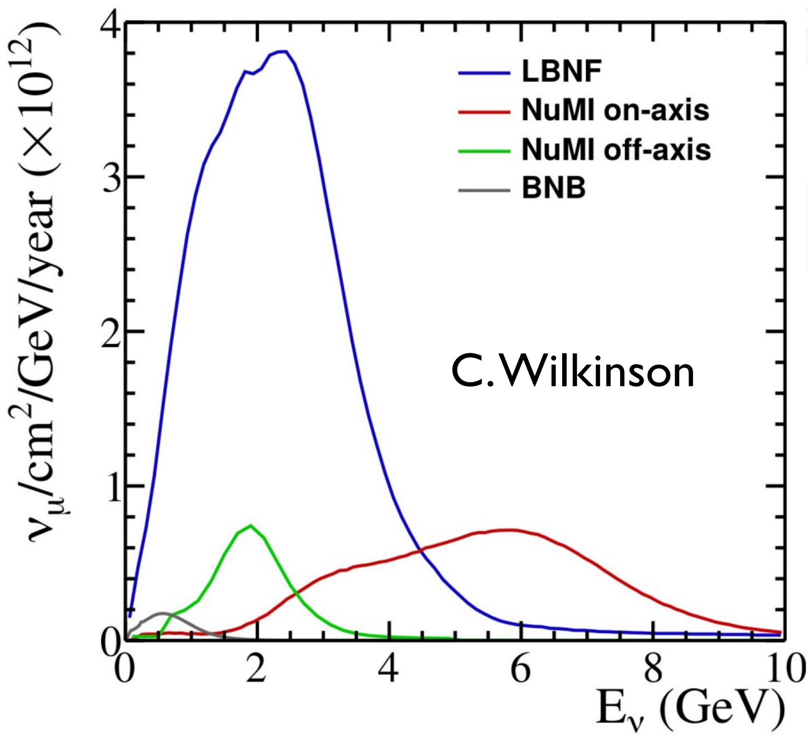
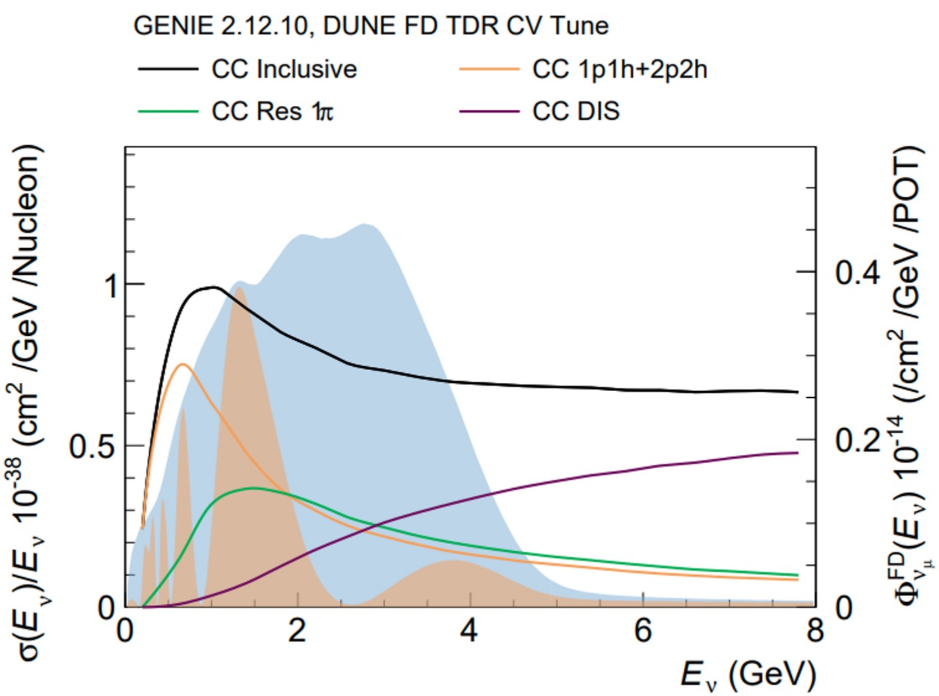
Focus of this talk

DUNE CAPABILITIES AND CHALLENGES

- Wide and intense beam:
  - **Unprecedented statistics**
  - **Multiple** interaction channels and their **transition regions**





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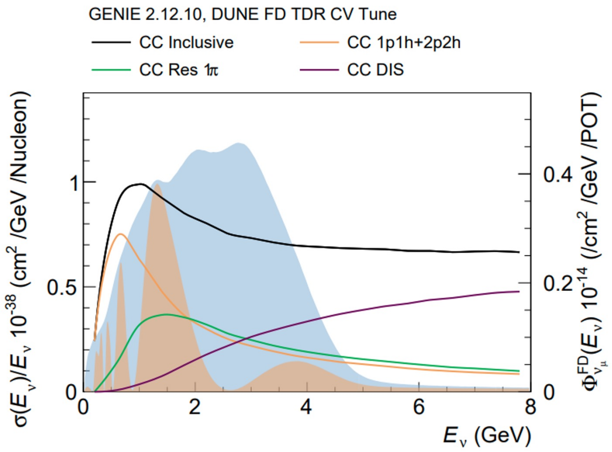
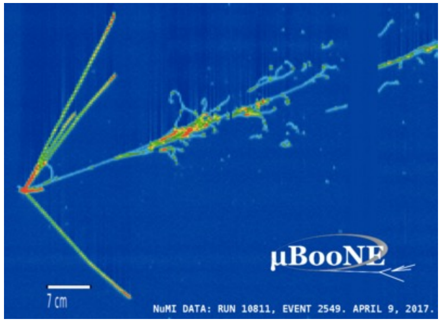
  - Low thresholds for charged hadron detection (π± and p, in particular)





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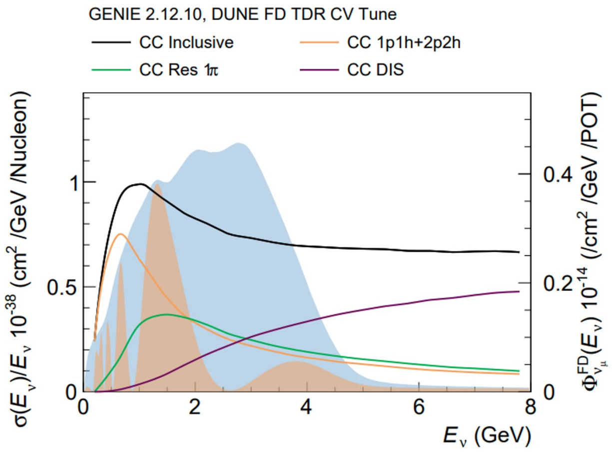
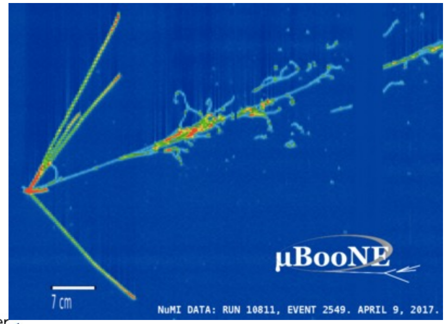
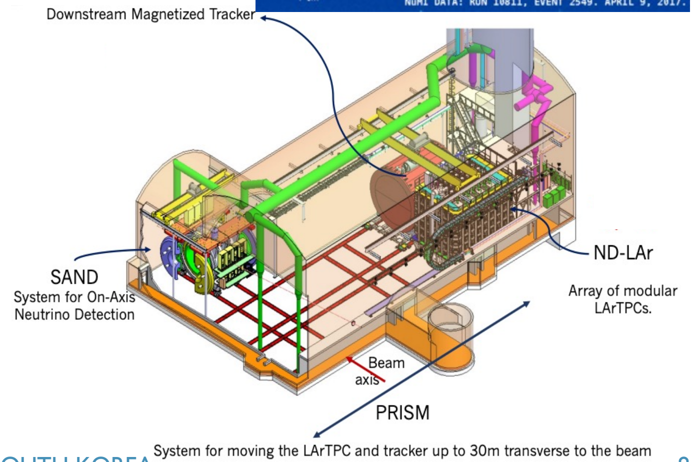
  - **Multiple** interaction channels and their **transition regions**
- Liquid Argon detectors:
  - Can exploit **calorimetric information** as well as **particle tracks**
  - Low thresholds for charged hadron detection (π± and p, in particular)
- Sophisticated suite of near detectors:
  - This is crucial in any LBL analysis to **constrain systematic uncertainties**



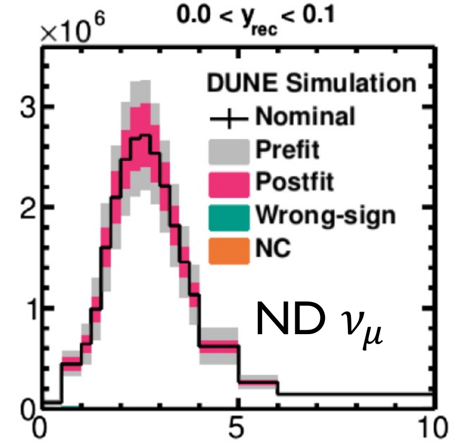


These capabilities will challenge today's models as much as today's experimental data challenged yesterday's models.



PREVIOUS ITERATION OF INTERACTION MODEL

- For the previous round of sensitivity studies, a far detector-centric model was used
  - Fit variables: E_ν^{rec} and $y_{rec} = 1 - E_\mu^{rec}/E_\nu^{rec}$
  - Relativistic Fermi Gas ground state with RPA corrections
  - Systematic effects varied primarily through GENIE parameters + 6 others
  - Effects not controlled by fit parameters were assessed with fake data studies



Phys. Rev. D 105, 072006

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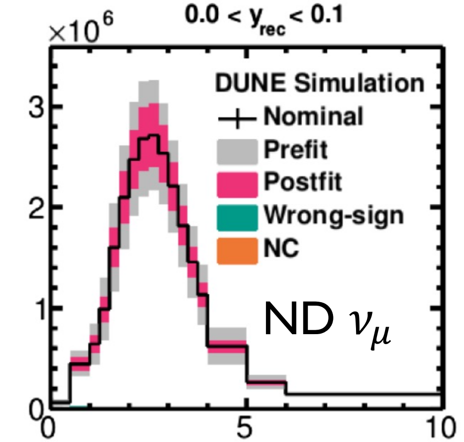
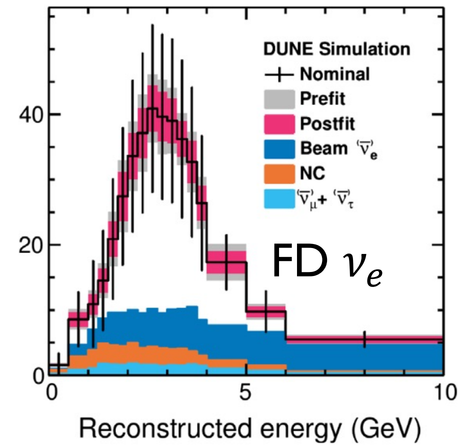
- Lessons learned:
  - FD statistics dominate appearance spectra
  - ND fit is entirely systematics dominated (negligible statistical errors)
  - Not enough model freedom to reproduce alternative simulated data sets
  - We need a set of variables which better exploits the power of DUNE





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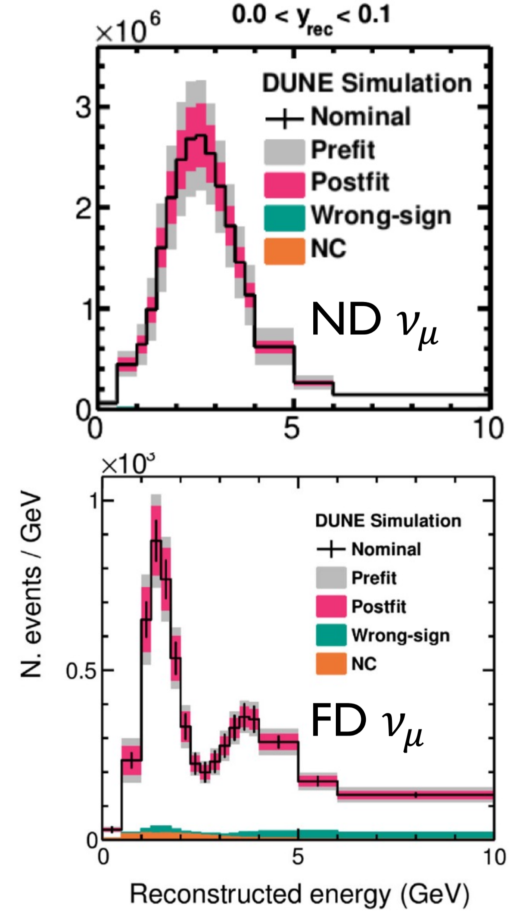

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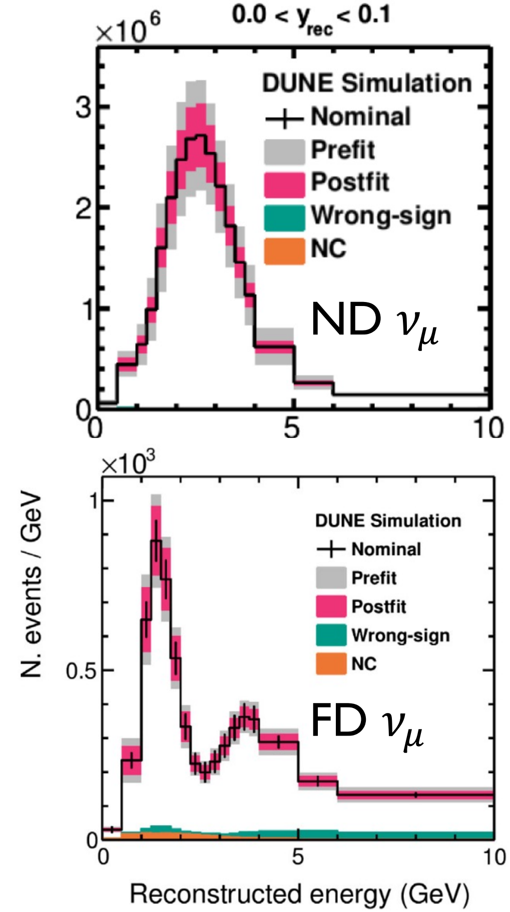
  - Not enough model freedom to reproduce alternative simulated data sets
  - We need a set of variables which better exploits the power of DUNE
- How we can improve this:
  - Use a more flexible ground state model
  - Develop a new suite of uncertainties relevant for DUNE
  - Improve our description of hadronization-related systematics
  - More granular modelling of FSI uncerainties



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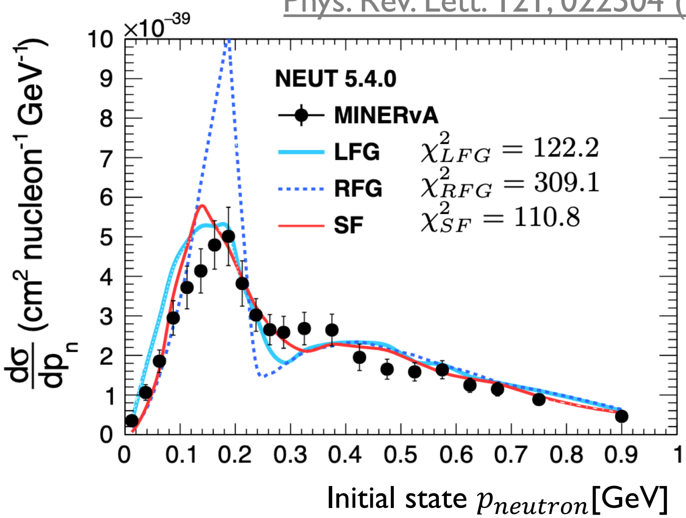
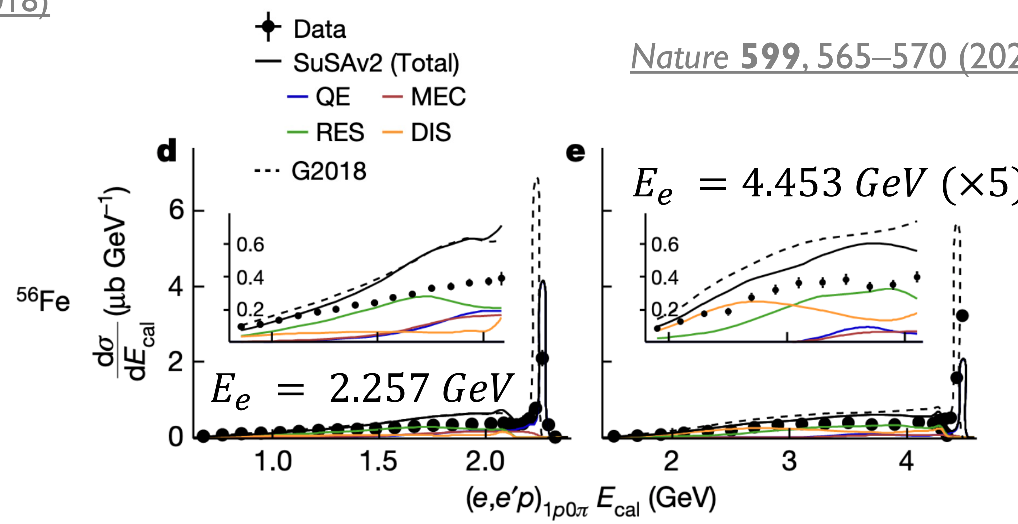
FLEXIBILITY IS KEY

- The requirements for the DUNE interaction model are very different than those for ongoing experiments
  - DUNE does not have data yet
  - DUNE statistics will be sensitive to subtle model differences
- But no nuclear ground state or neutrino interaction model is capable of fully describing world data today

arXiv:1810.0603
Phys. Rev. Lett. 121, 022504 (2018)



Nature **599**, 565–570 (2021)



- It is essential that the DUNE interaction uncertainty model be flexible enough to capture the model freedoms so that sensitivity studies are able to describe these data and alternate mock-data models.

The Baseline Model

NUCLEAR GROUND STATE MODEL

- Before tackling the interaction model, it is important to choose an appropriate nuclear ground state model
  - Will determine what systematic weights and shifts we can implement
- A suitable ground state model is
  - Physically motivated
  - Capable of reliable predictions for both **lepton and hadron kinematics**
  - Available in generators
  - Reweightable (i.e. can be used to study alternative ground state models)
- Relevant variables to describe ground state are the nucleon removal energy and momentum – experimentally, E_{miss} and p_{miss} : (now) accessible in today's neutrino experiments

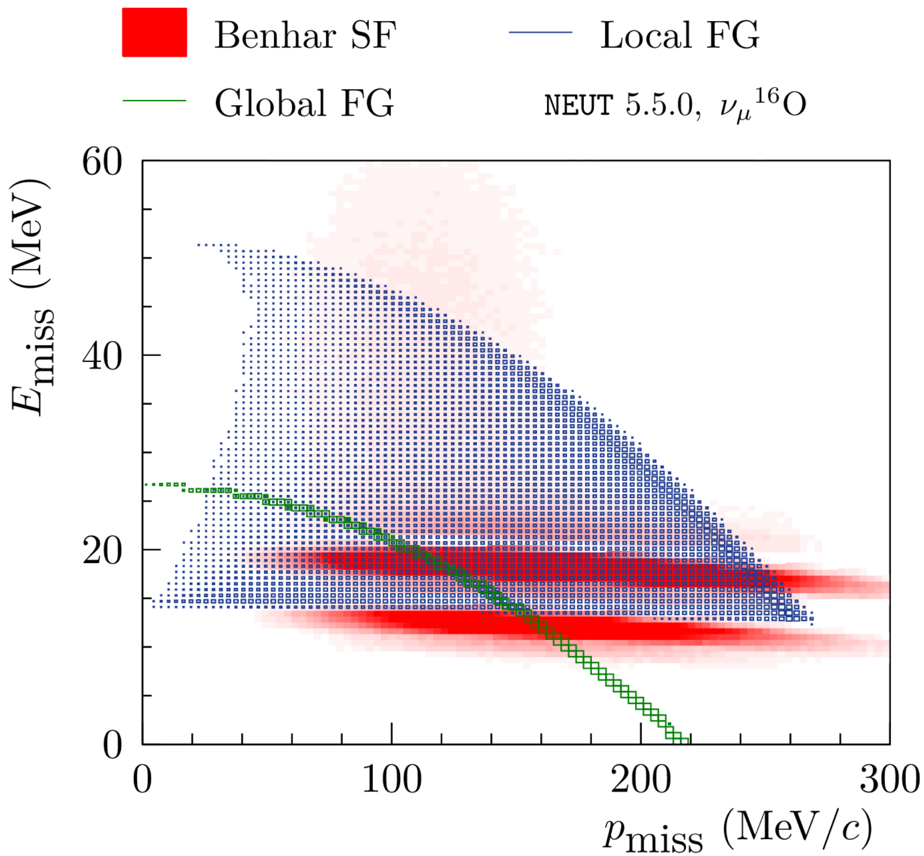
$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)\mathrm{d}\mathrm{E}_{\ell}'} \sim S(E_m, \boldsymbol{p}_m)\mathrm{L}_{\mu\nu}\mathrm{W}^{\mu\nu}\delta(\omega + M - E_m - E_{p'})$$

Spectral Function

NUCLEAR GROUND STATE MODEL

- Several models available in multiple generators

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



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

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

NUCLEAR GROUND STATE MODEL

- Several models available in multiple generators
- Relativistic Fermi Gas (RFG):
  - Simple, fixed binding energy (E_b)
  - Widely available in generators

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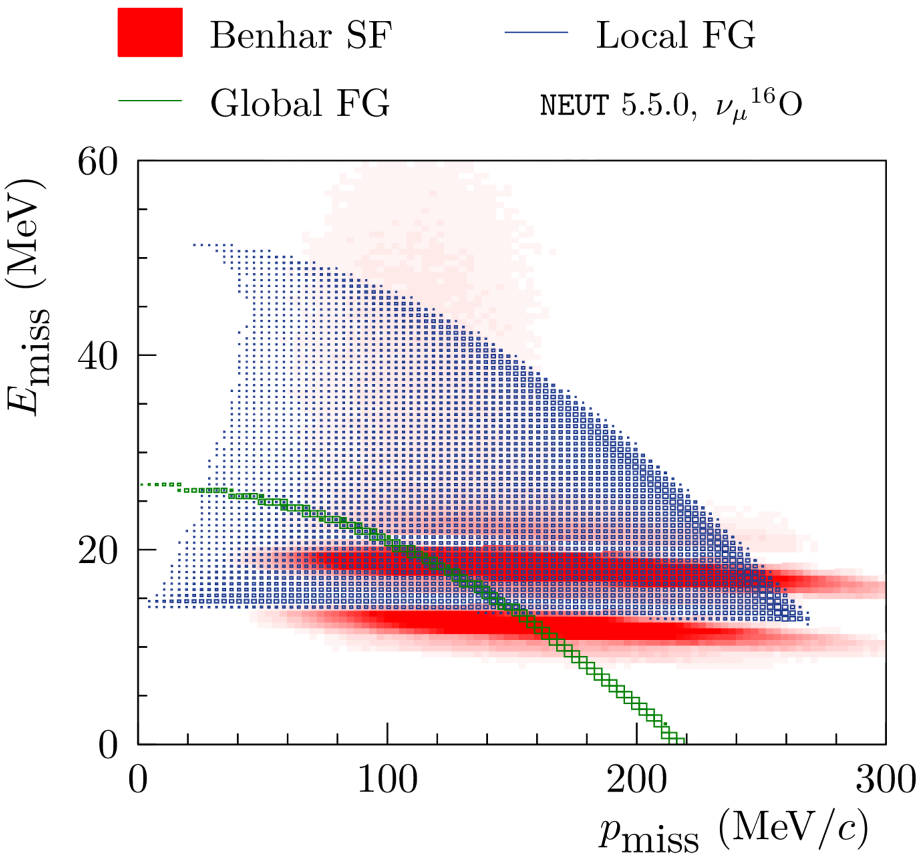

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- Several models available in multiple generators
- Relativistic Fermi Gas (RFG):
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- Local Fermi Gas (LFG):
  - E_b depends on radial position
  - Good predictive power for hadron kinematics
  - Covers a good portion of $E_{miss} - p_{miss}$ space
  - Widely available in generators

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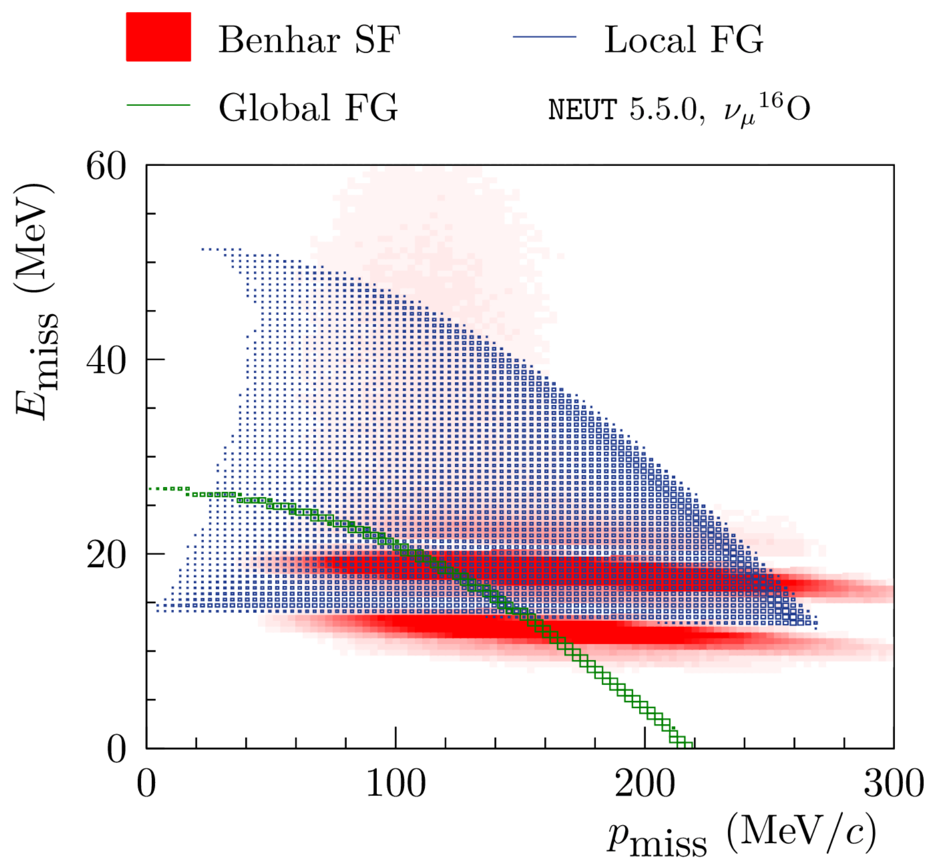

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NUCLEAR GROUND STATE MODEL

- Several models available in multiple generators
- Relativistic/Global Fermi Gas (RFG):
  - Simple, fixed binding energy (E_b)
  - Widely available in generators
- Local Fermi Gas (LFG):
  - E_b depends on radial position
  - Good predictive power for hadron kinematics
  - Covers a good portion of $E_{miss} - p_{miss}$ space
  - Widely available in generators
- Benhar Spectral Function (SF):
  - Accounts for nuclear shell structure
  - Tuned using electron scattering data
  - Even better predictive power for outgoing nucleon kinematics
  - Reflects natural degrees of freedom
  - Not available in all generators

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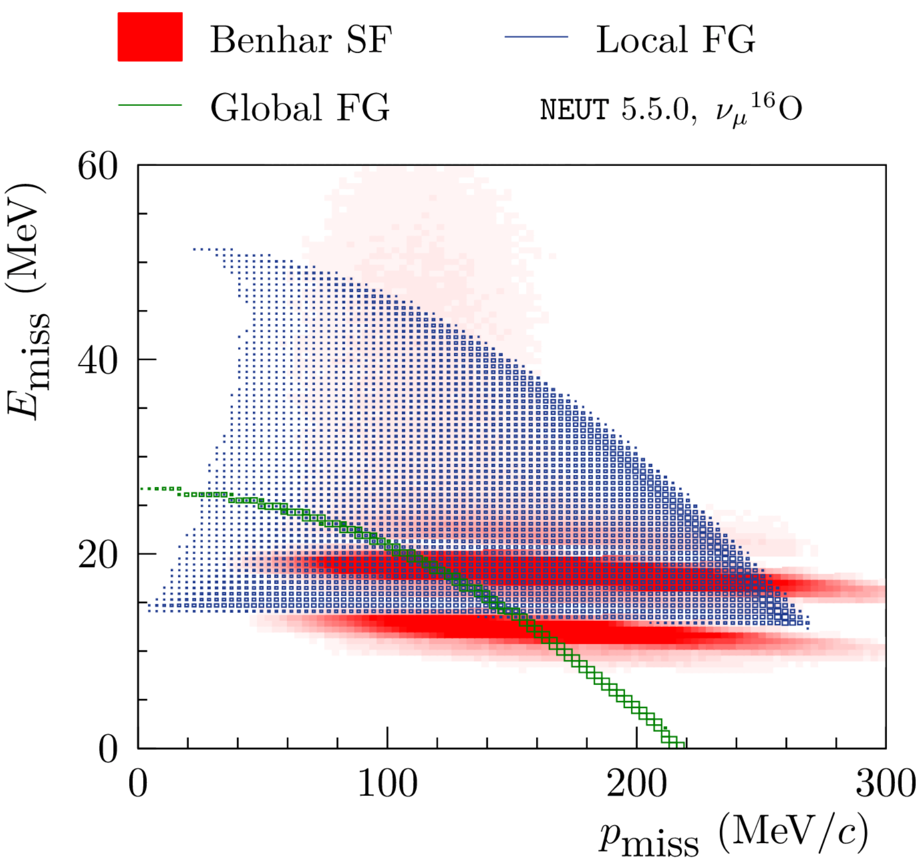

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- DUNE production and reconstruction framework optimized for GENIE as a neutrino interaction generator
- Plan to use GENIE 3.2.0 for this iteration of sensitivity studies
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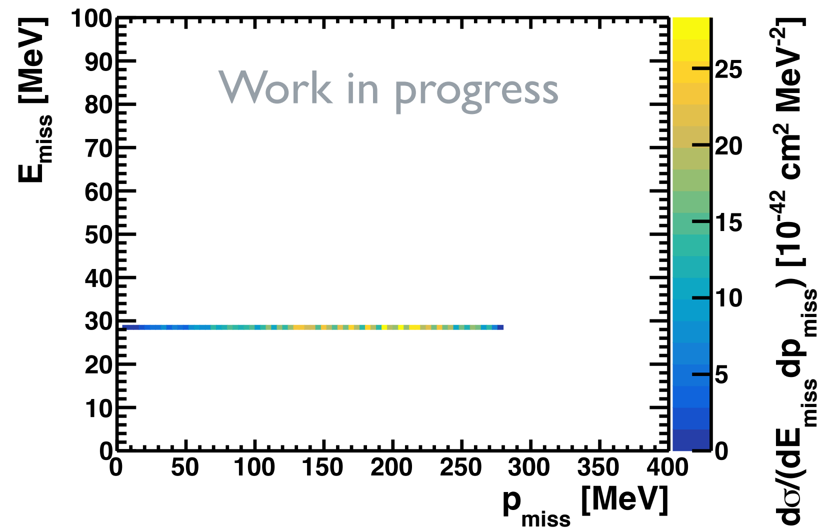
- Out of the box, the ground state distribution doesn't look like the expectation



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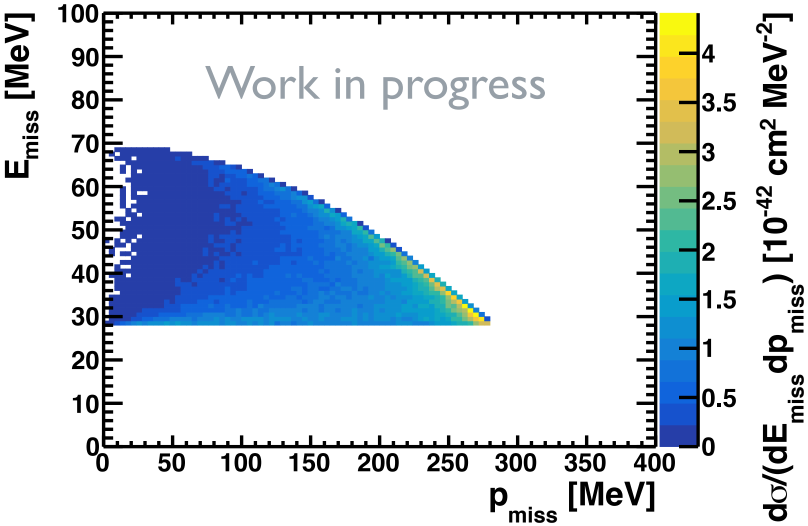

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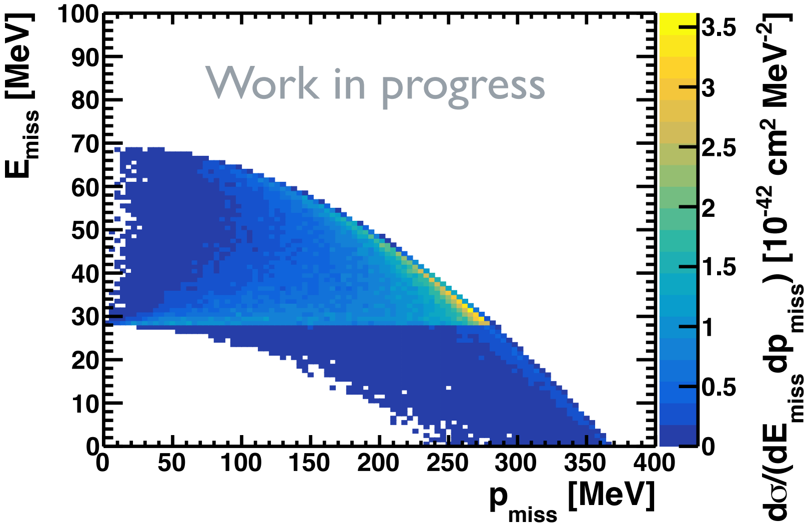

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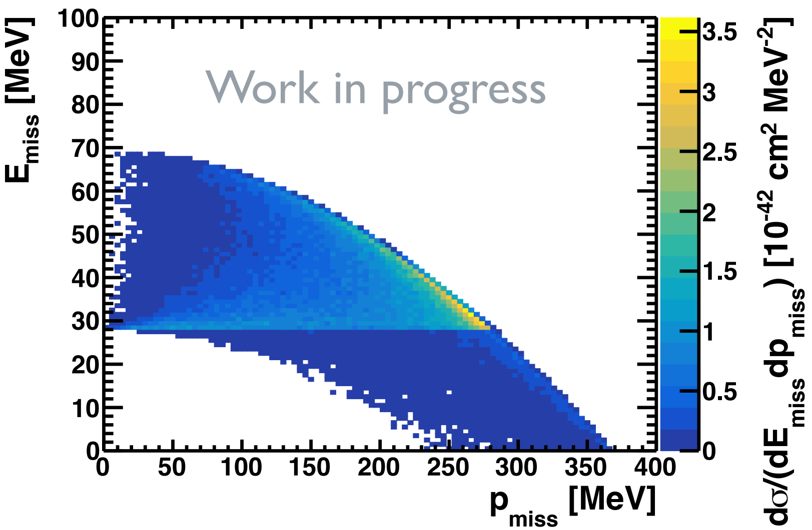
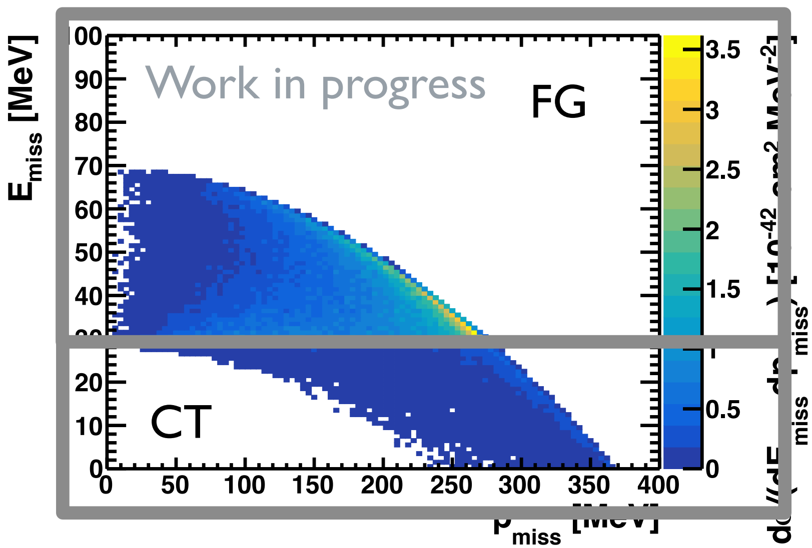
- Have added freedoms to the GENIE LFG model that match ND observables and experience of other experiments
  - Adding correlated tail further increases phase space
- Validations ongoing
- Will issue a custom configuration for sensitivity studies



GROUND STATE MODEL UNCERTAINTIES

- Uncertainties related to the ground state will **impact all interaction channels**
- Our model can broadly be described as having a Fermi gas (FG) component and a correlated tail (CT) component
- Can alter the relative strength of the FG vs CT components



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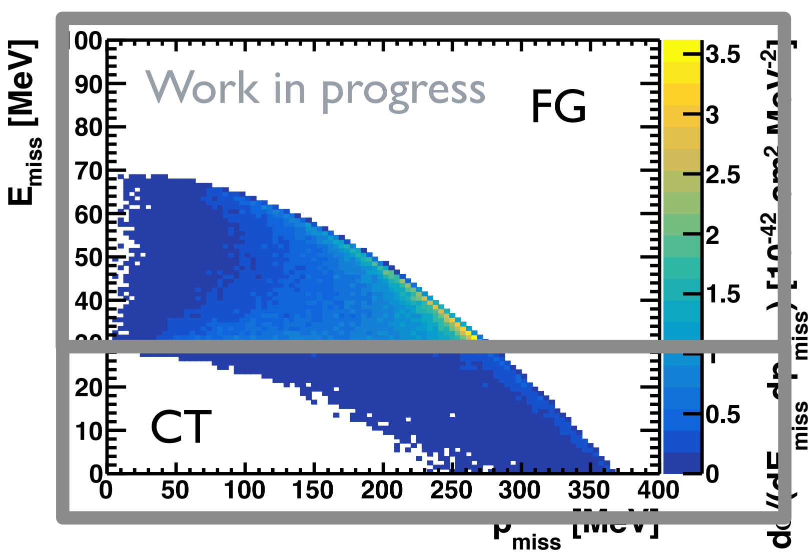

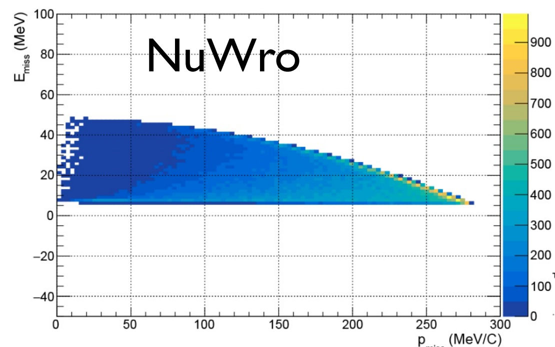

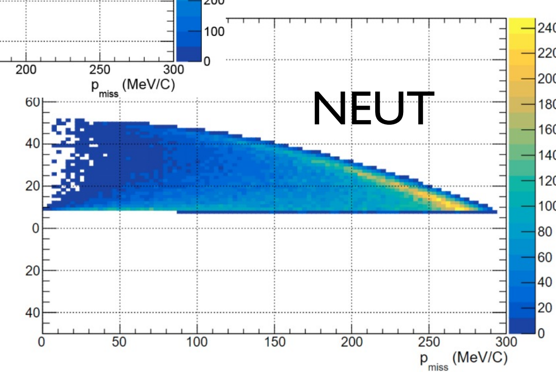

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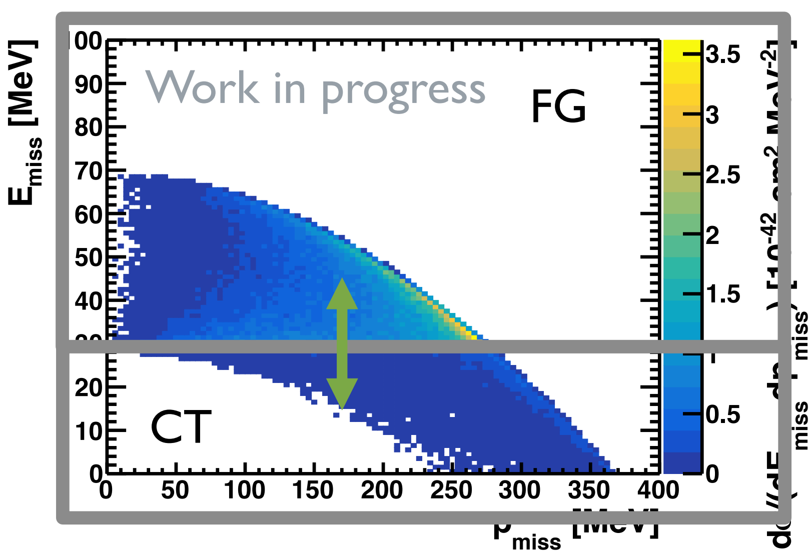
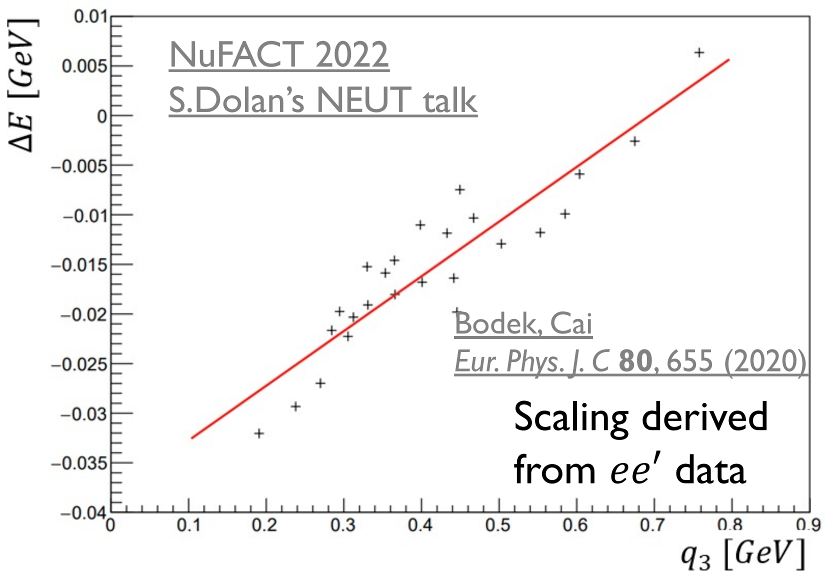
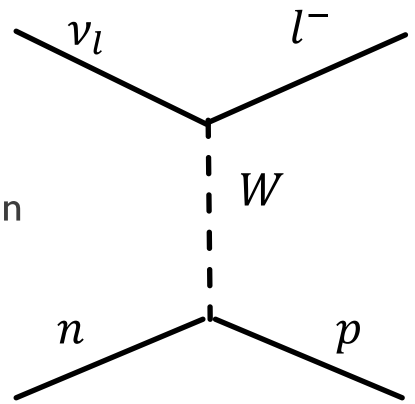
- Lateral E_{miss} shifts as a function of q_3 motivated by electron scattering data



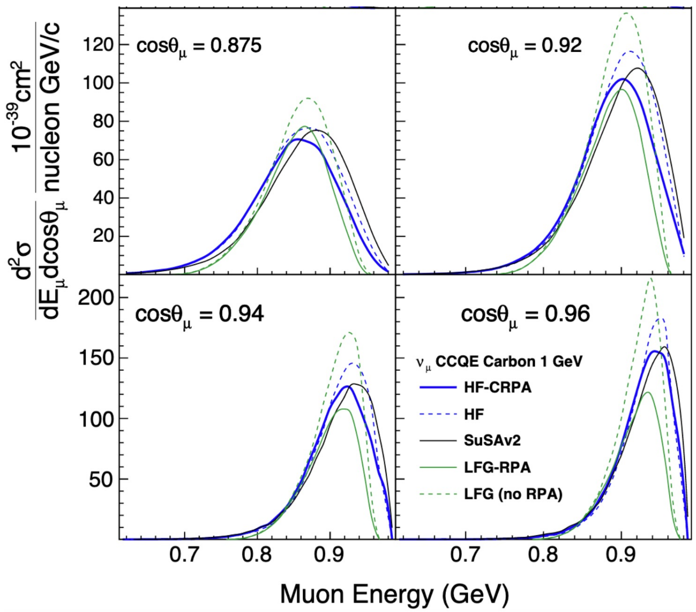


Interaction Uncertainties

INTERACTION MODEL – CCQE



- CCQE-focused samples can be reconstructed with the best resolution
  - Account for ~30% of total event rate
  - Operating experiments are already sensitive to all the effects below.
- Interaction model: **Valencia 1p1h**
  - Easily reweightable and **best predictive power for hadron kinematics** within GENIE
- Freedom to account for **collective effects** (RPA) for each neutrino species and nucleus type
- **Optical potential** uncertainty
- **Z-expansion** form factor
  - Motivation to explore more models (e.g. LQCD)
- **Pauli-blocking** freedom
- *Ad-hoc* energy dependence freedom



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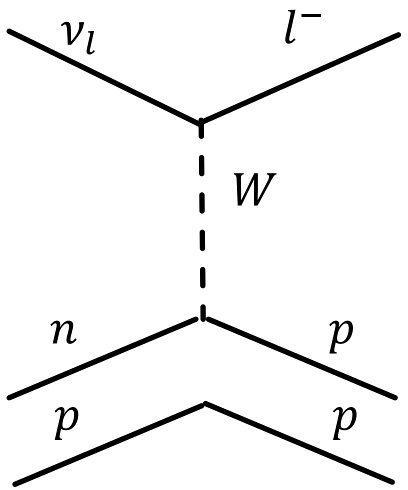
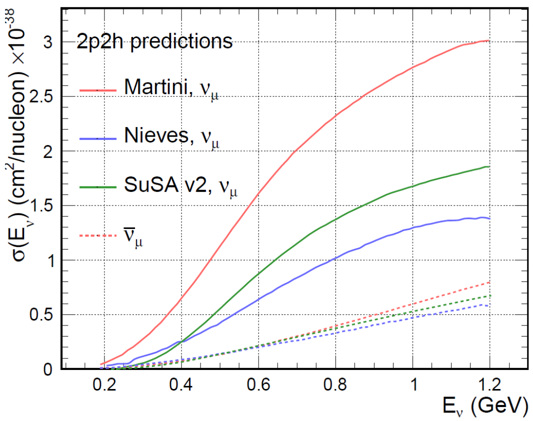
INTERACTION MODEL – 2P2H

- Small fraction of interactions at DUNE (~8%)
  - But crucial to control because it overlaps with QE and Δ region
  - Can have a significant impact on sensitivity to δ_{CP}

    (contributions are different between ν and $\bar{\nu}$)





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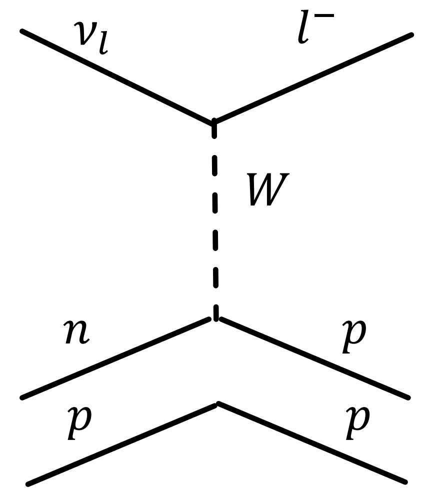
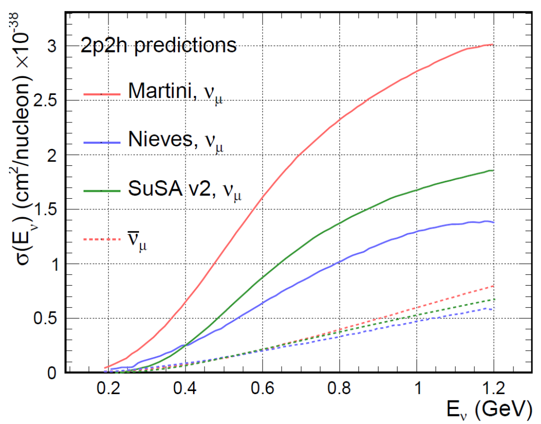
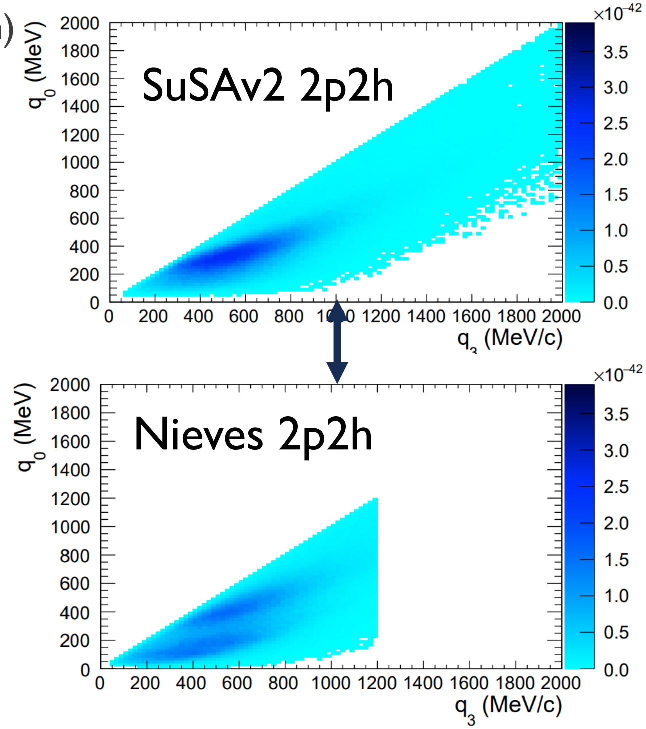
  - But crucial to control because it overlaps with QE and Δ region
  - Can have a significant impact on sensitivity to δ_{CP} (contributions are different between ν and $\bar{\nu}$)
- Interaction model: **SuSAv2 2p2h**
  - **Better phase space coverage** than previous model (Nieves 2p2h) so can reweight to other models
- Shape freedoms
  - Inclusive cross-section model
  - Relative pair contributions
  - Energy dependence
- Normalization freedoms
- Additional uncertainties on nucleon ejection kinematics



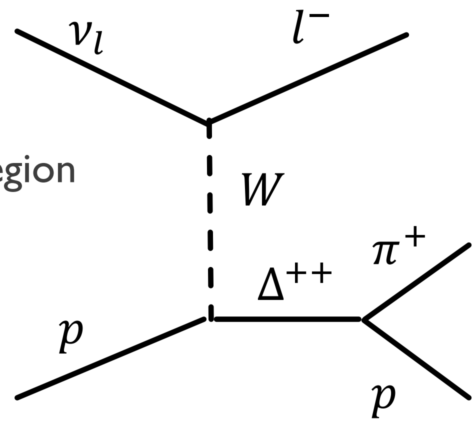


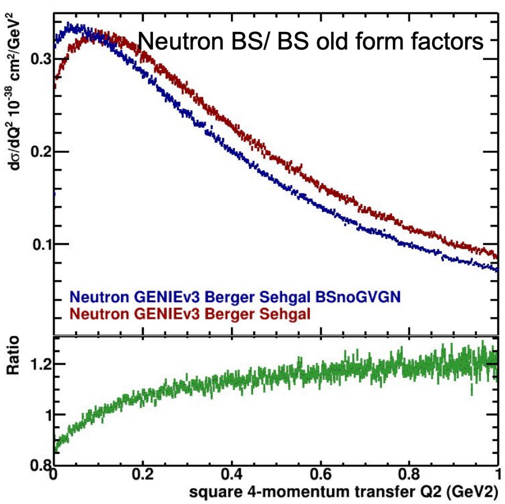


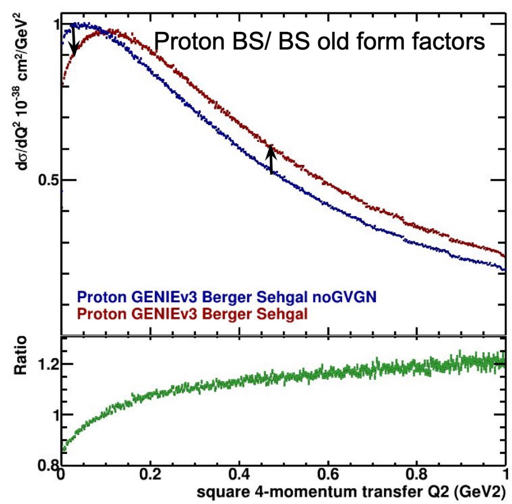
Phys. Rev. D 101, 033003 (2020)

RESONANT INTERACTIONS

- Large fraction of DUNE interactions (~30%), especially in the peak region
- GENIE v3 has significant changes in resonance model



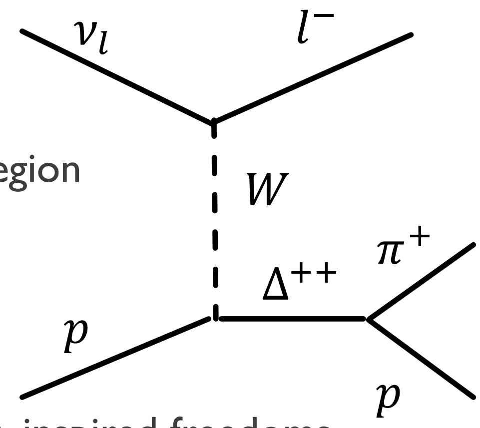




Rik Gran, Ishmam Mahbub, Ben Utt

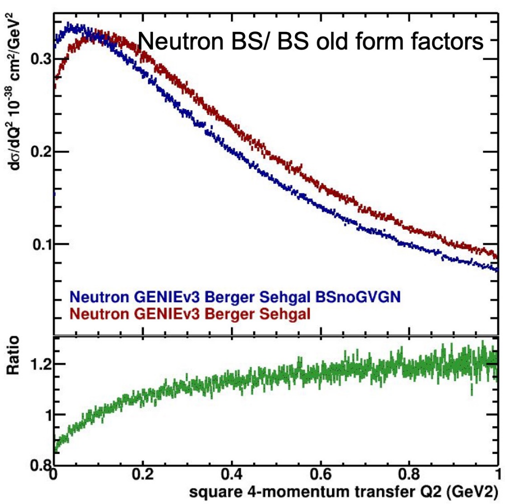
- Main changes GENIEv2 to GENIEv3 are new vector form factors and FSI.
  - But change might use nucleon form factors to instead account for nuclear effects.

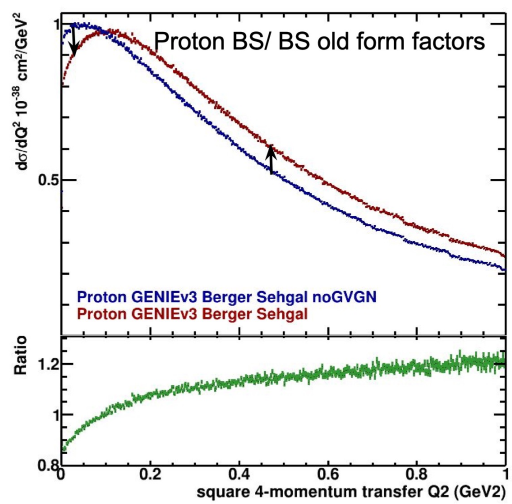
RESONANT INTERACTIONS



- Large fraction of DUNE interactions (~30%), especially in the peak region
- GENIE v3 has significant changes in resonance model
- T2K-inspired uncertainties
  - Form factor freedoms
  - Channel normalizations
  - Removal energy shifts
  - Non-resonant background strength
- Additional NOvA- and MINERvA-inspired freedoms
  - Low Q2 suppression
  - Pauli Blocking-like shift

Want a set of systematics as rich as for QE !





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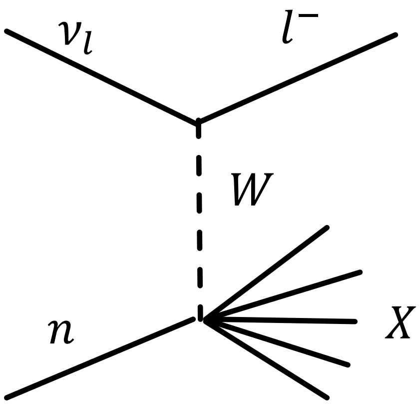
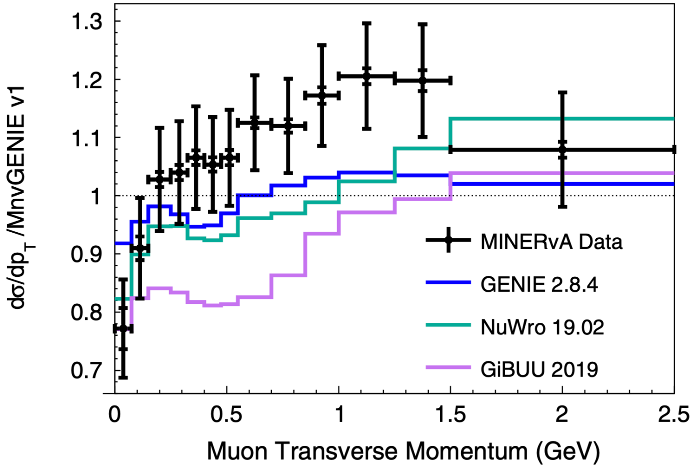
DIS/SIS INTERACTIONS

- Significant portion of DUNE interactions (~40%)
  - But resolution not as good as for CCQE-like samples



Phys. Rev. D 101, 112007



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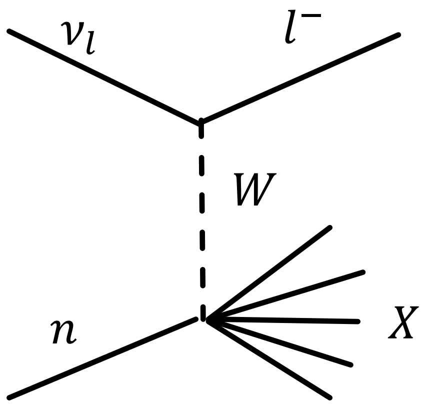
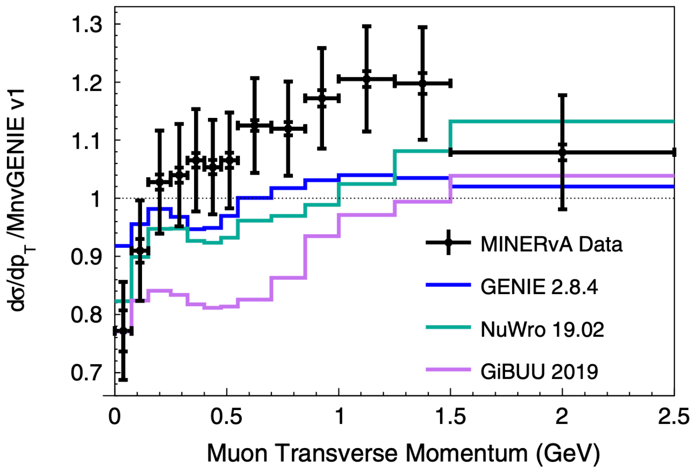


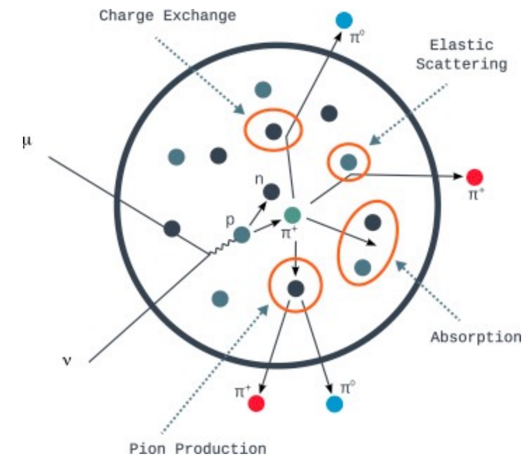
- Significant portion of DUNE interactions (~40%)
  - But resolution not as good as for CCQE-like samples
- Cross-section in the SIS region is poorly understood
- Also crucial to model hadron multiplicities – ongoing work!
- Bodek-Yang parametrization
- Hybrid hadronization model (as in previous sensitivity studies)
- Previous sensitivity studies included a number of uncertainties
- Use theory-based uncertainties with E_ν, Q^2 and Bjorken x dependence whenever possible
  - *Ad-hoc* uncertainties as needed inspired by NOvA and MINERvA
- *Ad-hoc* uncertainties - Energy dependence

Phys. Rev. D 101, 112007

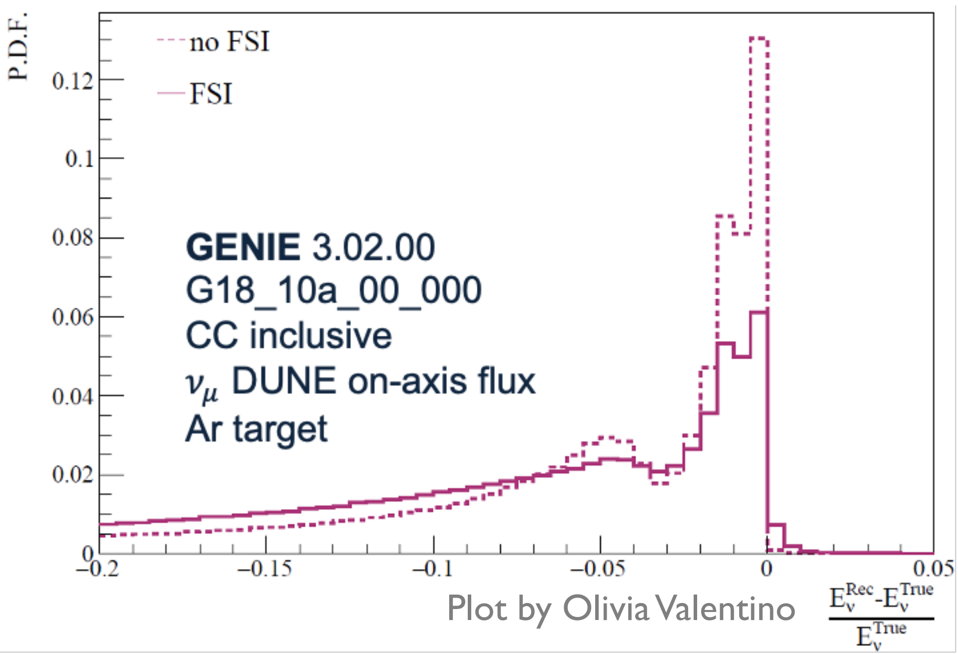


FINAL STATE INTERACTIONS

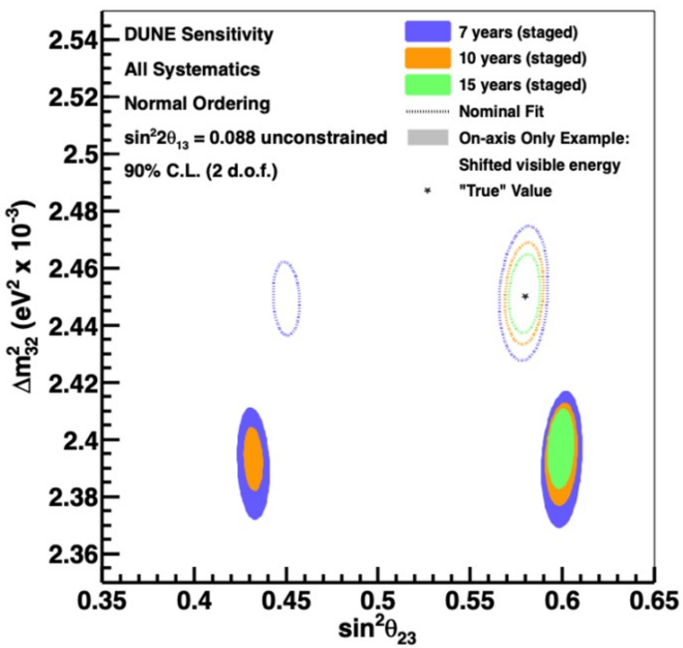
- Probability for nucleons to undergo FSI in Ar ~60% (compared to ~30% in C)
- FSI directly impacts reconstructed energy
  - Neutron emission
  - Pion/proton absorption/charge exchange affects topologies
  - Altered hadron (esp. neutron) multiplicities



arXiv:2103.13910



Plot by Olivia Valentino



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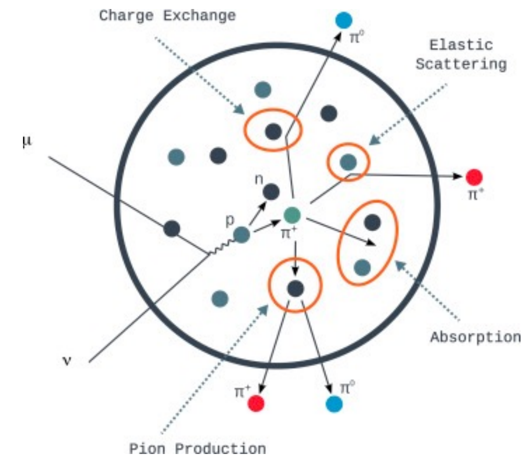
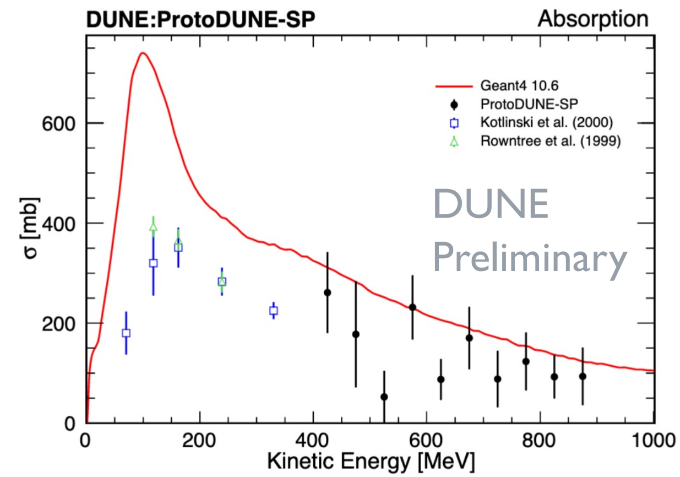
- FSI directly impacts reconstructed energy
  - Neutron emission
  - Pion/proton absorption/charge exchange affects topologies
  - Altered hadron (esp. neutron) multiplicities
- Little data on hadron scattering on Ar
  - But protoDUNE is changing that!
- And approximate cascade/empirical models
- For flexibility – use GENIE hA2018 model (easily reweightable)
  - Use existing GENIE uncertainties
- Model predictions differ significantly (GENIE models and others)
  - Include additional *ad-hoc* uncertainties to cover spread





$\pi^+ - Ar$ scattering
Jake Calcutt, Francesca Stoker
Paper in progress

AND AFTER THE ND CONSTRAINT?

- The DUNE near detectors will be crucial in constraining all of the systematic errors listed in previous slides
- But even if the ND fit is perfect, we must address uncertainties which
  - Impact the ND to FD extrapolation
  - Cannot be constrained at the ND
- Things we must consider with extra caution:
  - Modelling the bias in reconstructed neutrino energy → direct impact on oscillation parameters
  - FD flux is different from ND flux due to oscillations → must control $\sigma(E_\nu)$ for extrapolation
  - ND cannot constrain ν_e samples → must account for ν_e/ν_μ differences at relevant energies
  - $\nu/\bar{\nu}$ differences → crucial for δ_{CP} measurement
  - C to Ar differences → needed to use SAND samples in analysis

Will not discuss these points in detail in this talk!

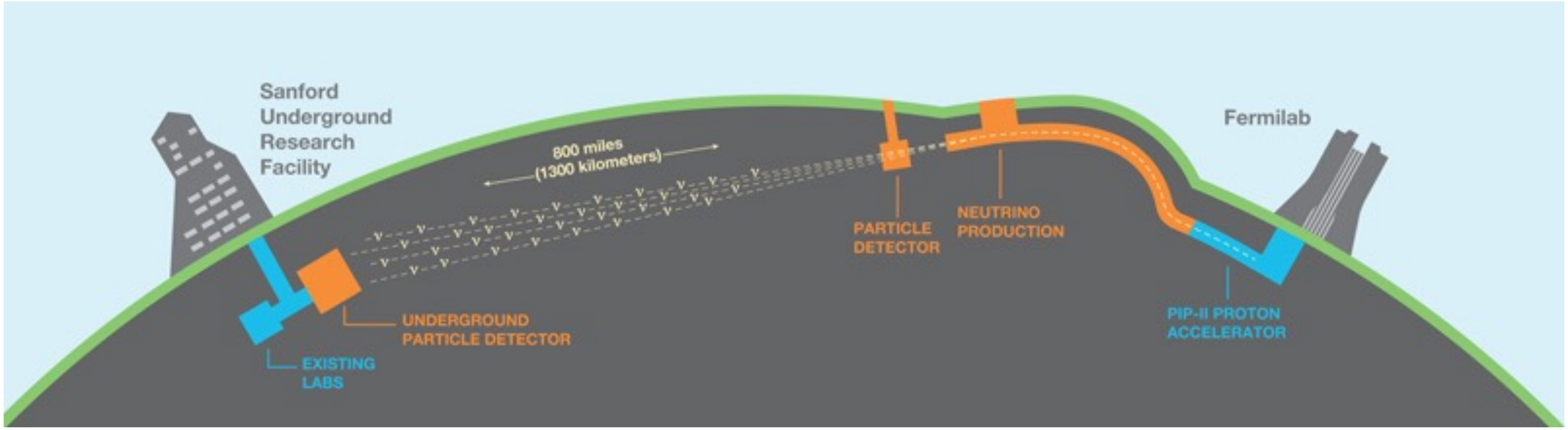
SUMMARY

- DUNE will probe several key areas of particle physics, and have a world-leading LBL neutrino oscillation program
- At DUNE statistics, systematic uncertainties due to neutrino-nucleus interactions will be the dominant source of uncertainty on neutrino oscillation parameters
- The DUNE near detectors will play a crucial role in constraining interaction uncertainties
- For second round of sensitivity studies aim to build a robust neutrino interaction model
- Multiple interaction channels and their transition regions at DUNE energies
  - Complex to define appropriate uncertainties
  - Need iteration with the theory community and ongoing measurements!

Thank you for listening!

Back-Up

THE DEEP UNDERGROUNG NEUTRINO EXPERIMENT



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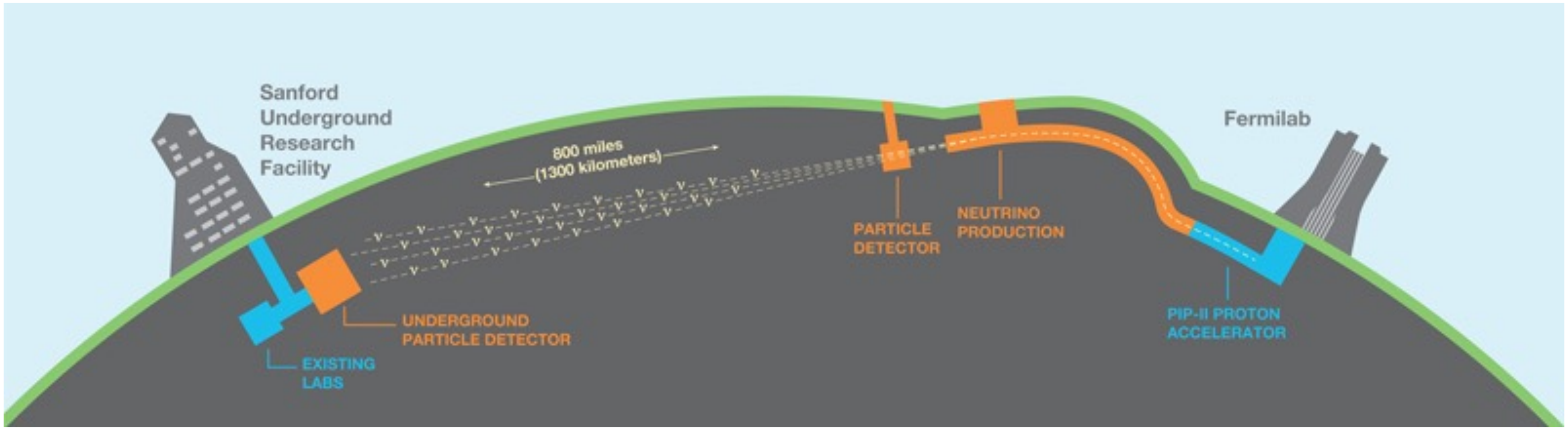
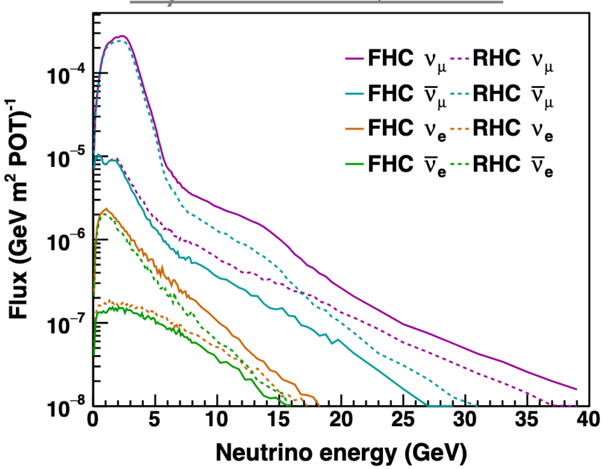


Phys. Rev. D 101, 032002



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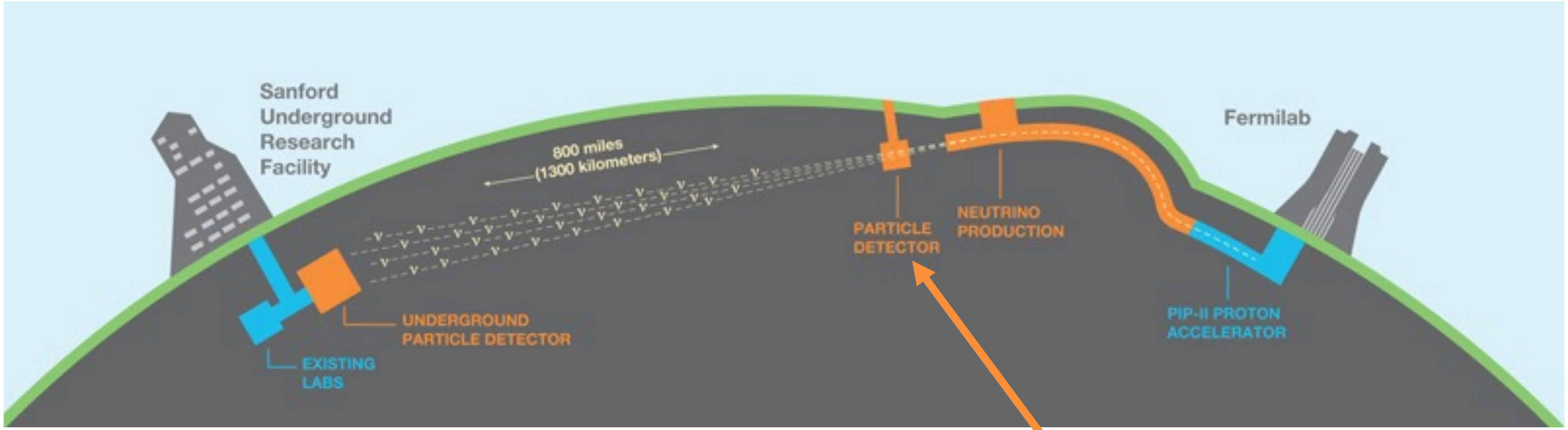
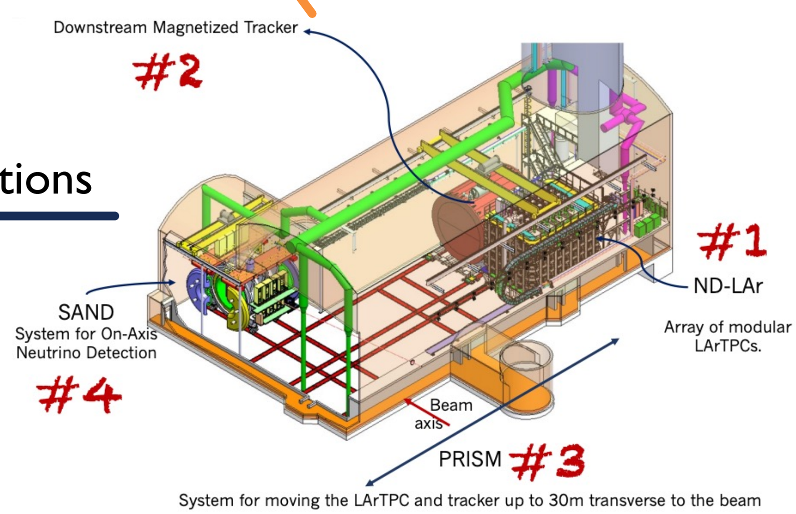


Oscillations



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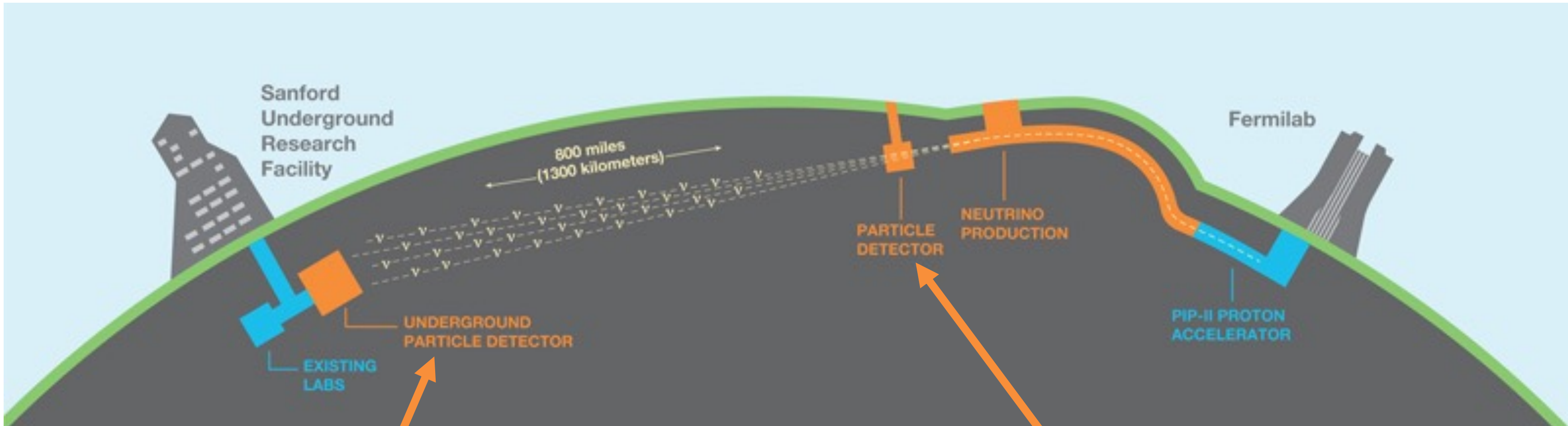

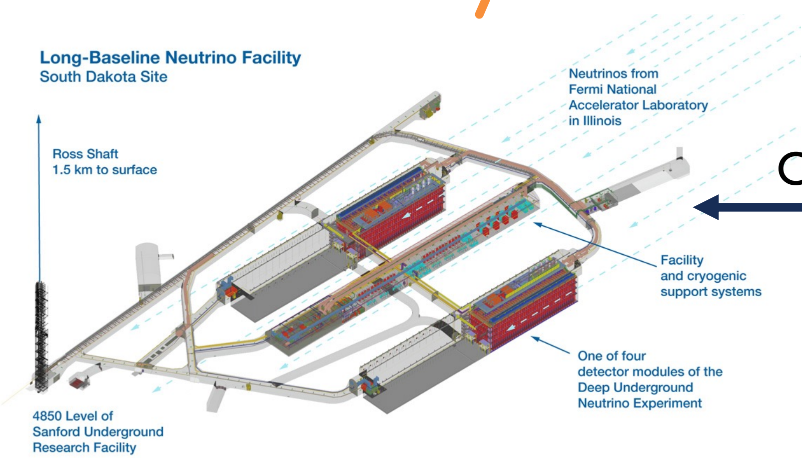

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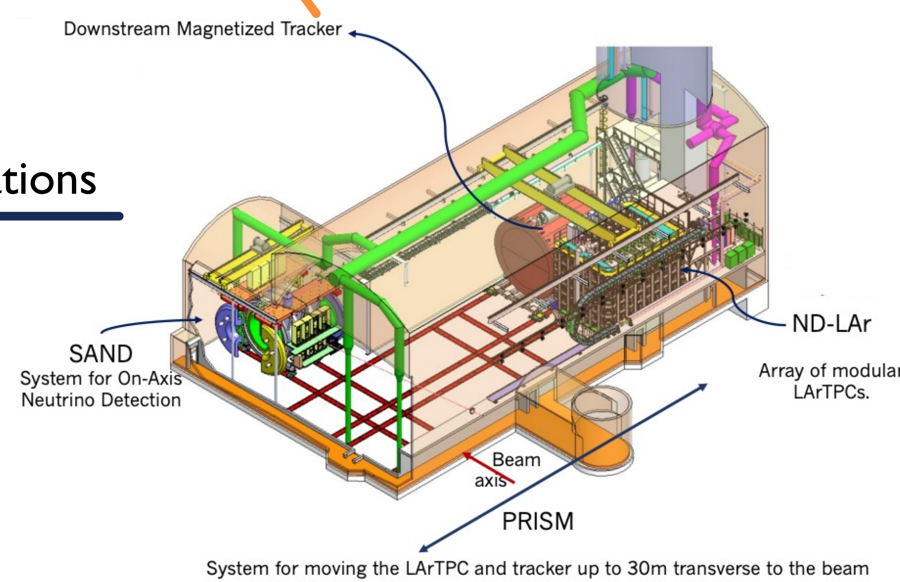
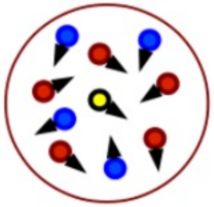


MODELING NEUTRINO INTERACTIONS

- Neutrino interactions with nuclei are complex to model
- In generators, we often **factorize** the different elements of the cross-section
  - Initial state nucleons are not at rest inside the nucleus (Fermi motion)



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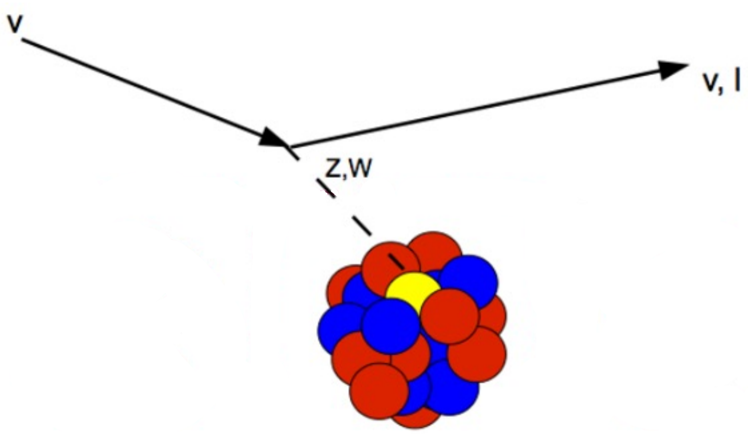

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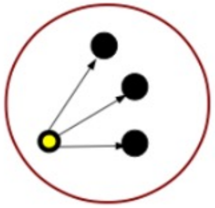

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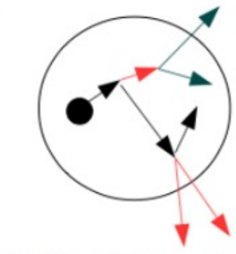

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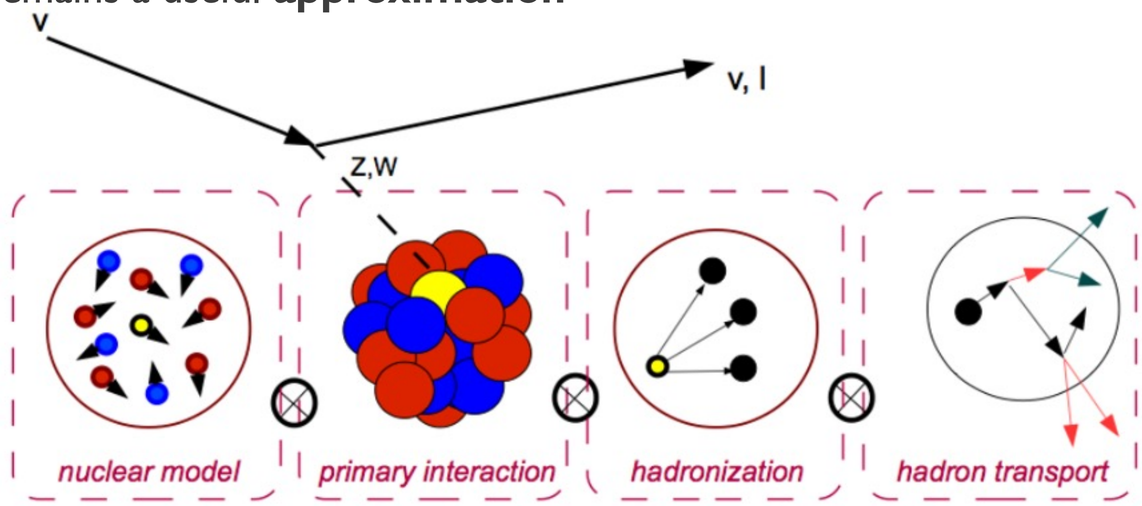
  - Assume the neutrino interacts with a single nucleon
  - Calculate the probability of hadronization (production of other hadrons in the process)
  - Model hadron transport inside the nucleus (Final State Interactions, FSI)
- The total cross-section is the **convolution** of the above
- Factorization remains a useful **approximation**



MEASURING NEUTRINO OSCILLATION PARAMETERS

- The observed event rate at the FD is the result of the convolution of multiple effects

$$N_{obs}^{FD} = \Phi^{\mathrm{FD}}(E_\nu) \otimes \sigma(E_\nu) \otimes \epsilon^{FD} \otimes P_{\nu_{\alpha\rightarrow\nu_\beta}}(E_\nu)$$

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Neutrino flux
"What was sent"

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"What was actually *seen*"

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…for each flavor

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Sources of systematic uncertainties

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*But DUNE-PRISM might change that!
See DUNE ND CDR for details

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- Detector efficiency needs to be well understood
- $\sigma(E_\nu)$ has an intrinsic dependence on E_ν
  - …and we do not know enough about neutrino interactions with matter in general!
  - **Currently the dominant source of systematic uncertainty of neutrino oscillation experiments**

NEAR DETECTOR SAMPLES

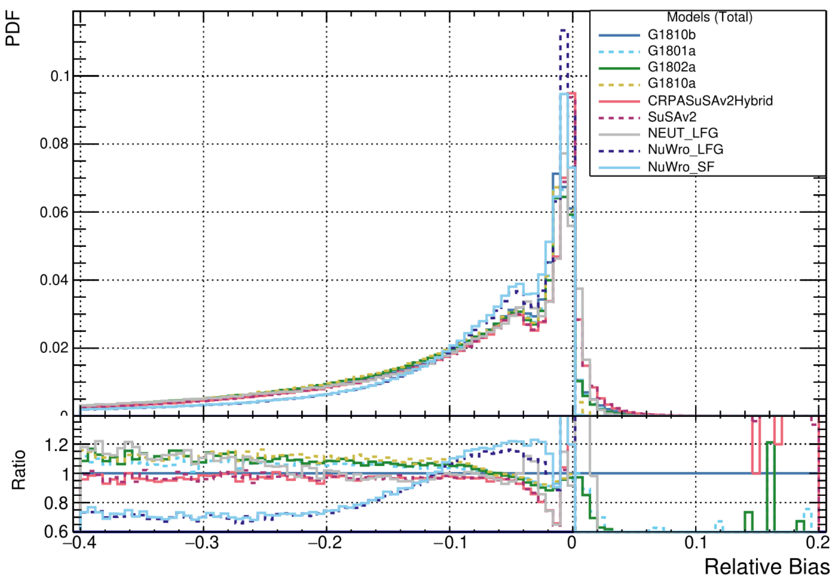
- The DUNE near detector are an essential part of the oscillation analysis
- Preliminary ideas for samples from each near detector

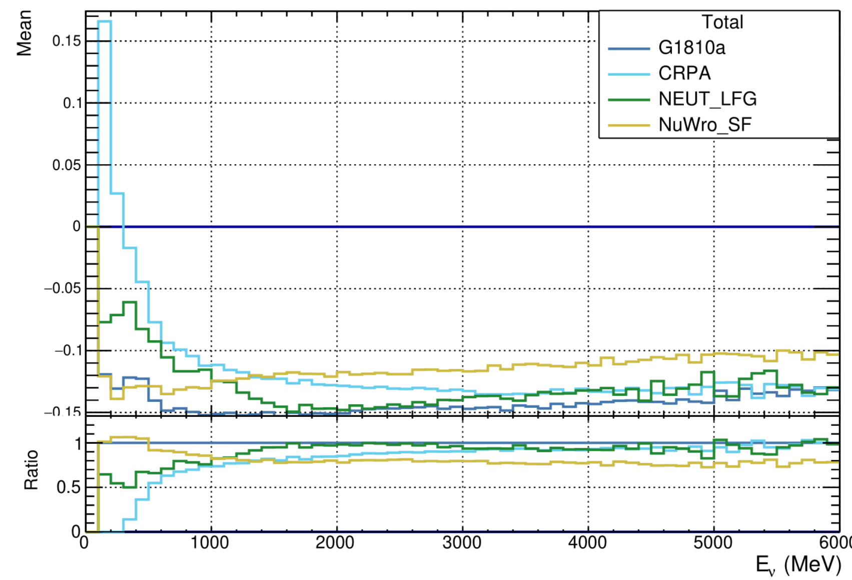
ND LAr + TMS	ND GAr (as a target)	SAND
CC Inclusive Split by π and no π? Binned in $E_\nu^{rec} + \mu$ kinematics **Possible ν+e sample** Stretch goal: TKI binning?	**CC Inclusive** Split by $\pi^\pm$ multiplicity Binned in $\pi^\pm$ momentum ***Constrain lost $\pi^\pm$ in E_ν^{rec}*** Stretch goal: p multiplicity	**CC Inclusive** Split by CH_2 and C targets Binned in $Q^2{}_{rec}$ ***Constrain form factors and flux*** Stretch goals: π multiplicity, E_ν^{rec} binning

- Each detector technology brings an enhanced sensitivity to a different type of effect

AND AFTER THE ND CONSTRAINT?

- Reweighting in bias space
  - Model predictions for the reconstructed energy bias are very different
  - And the predictions disagree in different ways depending on the neutrino energy
  - Propose an ad-hoc freedom to explore model differences in neutrino energy bias space directly
  - Targets directly sources of bias in the oscillation parameters measurement



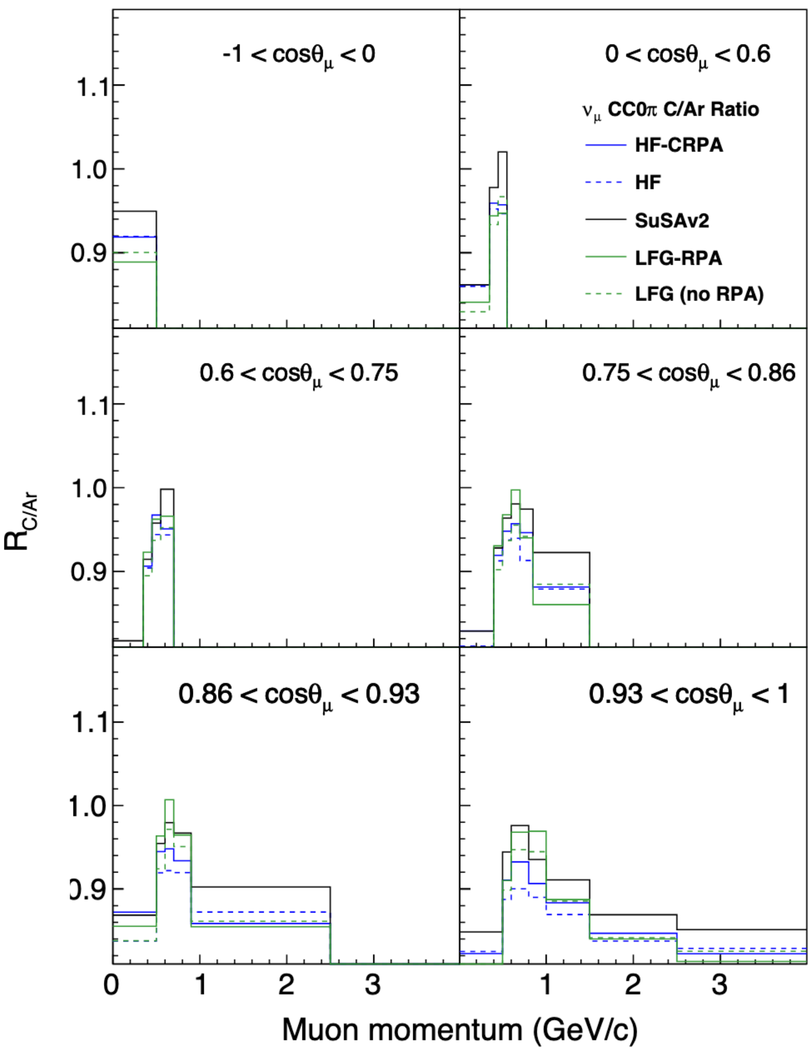


Plots by Adam Wong

AND AFTER THE ND CONSTRAINT?

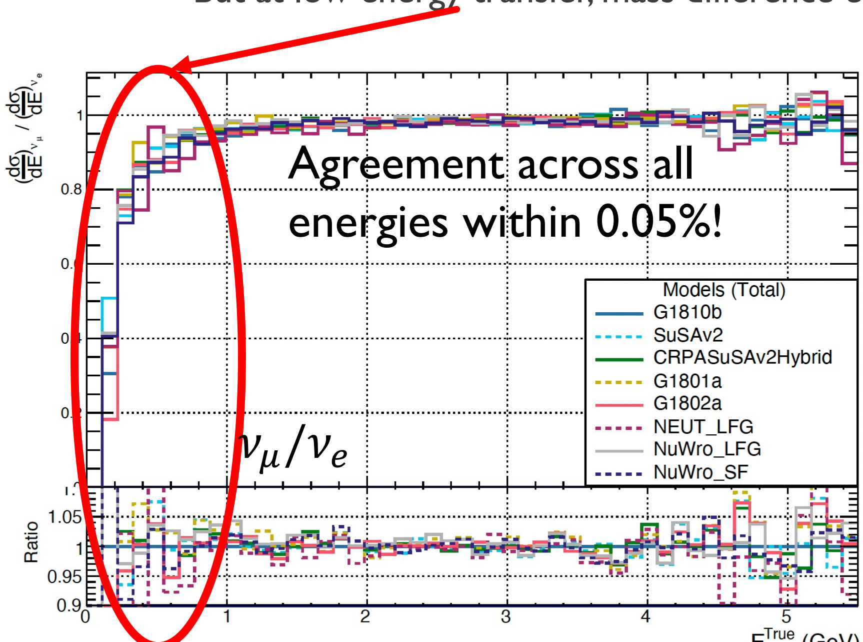
- C to Ar scaling
  - Crucial if SAND samples are included (CH target)
  - But also many of our existing uncertainties and model parameters have been tuned to other nuclear targets
  - Model predictions on this scaling differ and we need to account for this

arXiv:2110.14601



$\nu_e/\bar{\nu}_e$ DIFFERENCES

- $\nu_e/\bar{\nu}_e$ differences are leading systematic effect for δ_{CP} measurement
  - Need to be constrained to ~3% for DUNE goals
- But we have almost no ν_e at the ND
- Lepton flavor universality helps us here – we can constrain the vast majority of ν_e related uncertainties using ν_μ data
  - But at low energy transfer, mass difference effects start to matter (caution – high stats fluctuations)



Plot by Adam Wong

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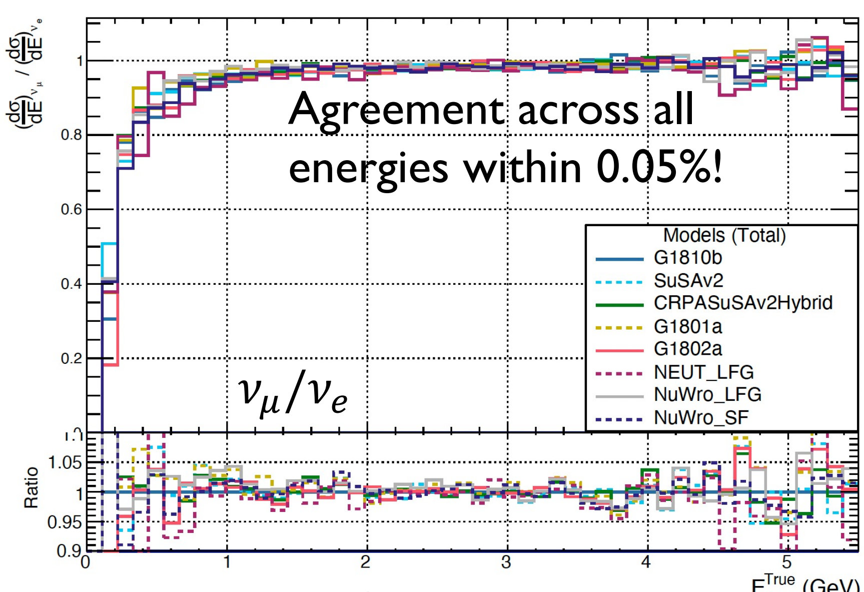
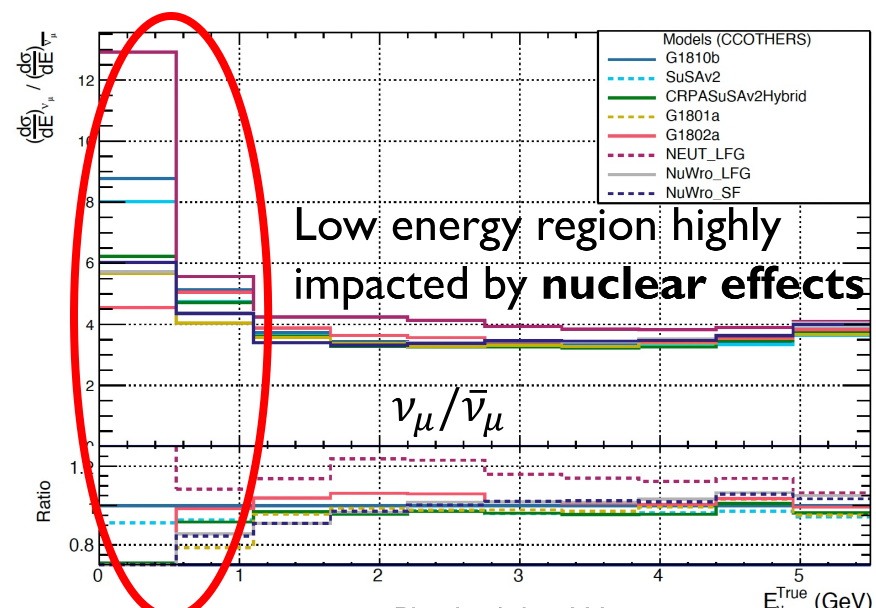
- But we have almost no ν_e at the ND
- Lepton flavor universality helps us here – we can constrain the vast majority of ν_e related uncertainties using ν_μ data
- Larger disagreement between ν_μ and $\bar{\nu}_\mu$ predictions – especially at low momentum



Plot by Adam Wong



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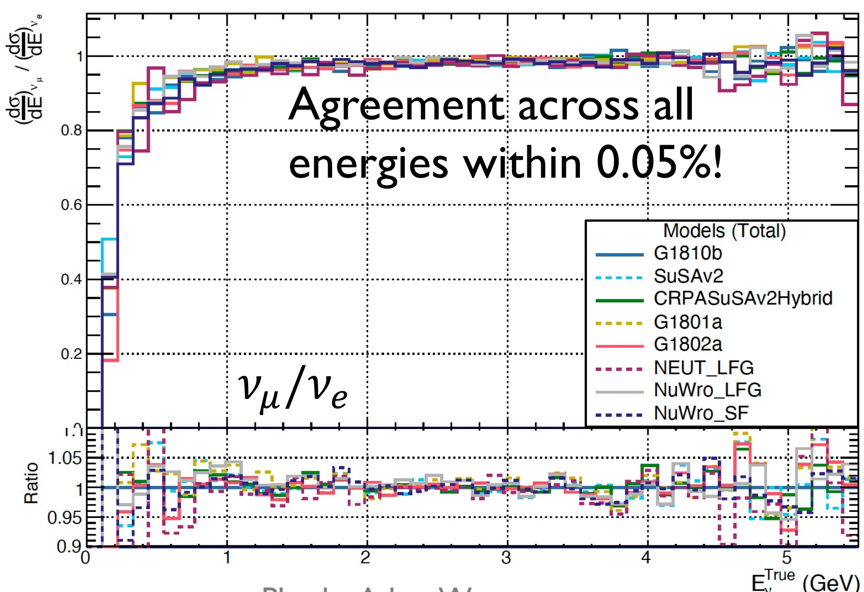
$\nu_e/\bar{\nu}_e$ DIFFERENCES

- ND will be crucial in constraining key uncertainties for δ_{CP} measurement
- Need continued iterations with theorists concerning ν_e cross sections in the region where mass effects become important
- Ideally will also include radiative corrections and other nuclear effects into these uncertainties



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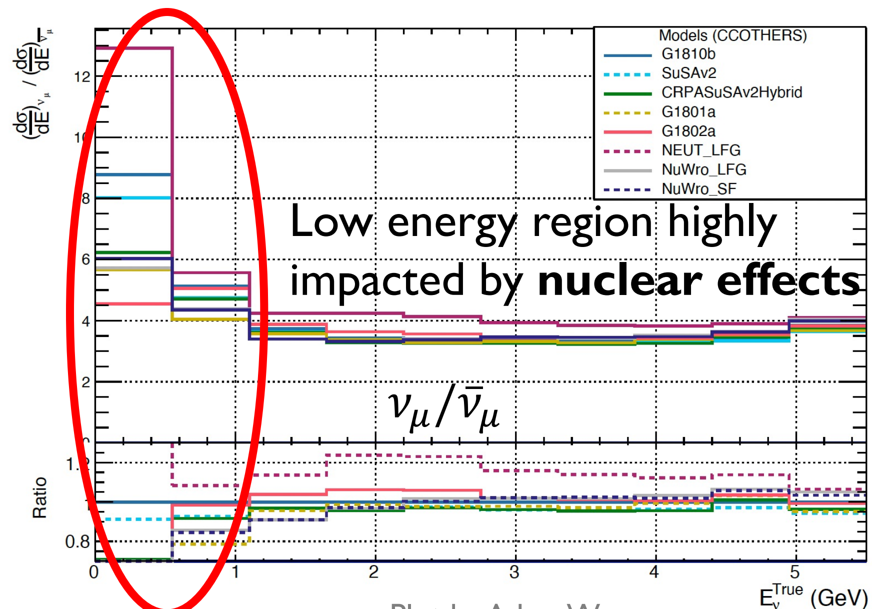

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