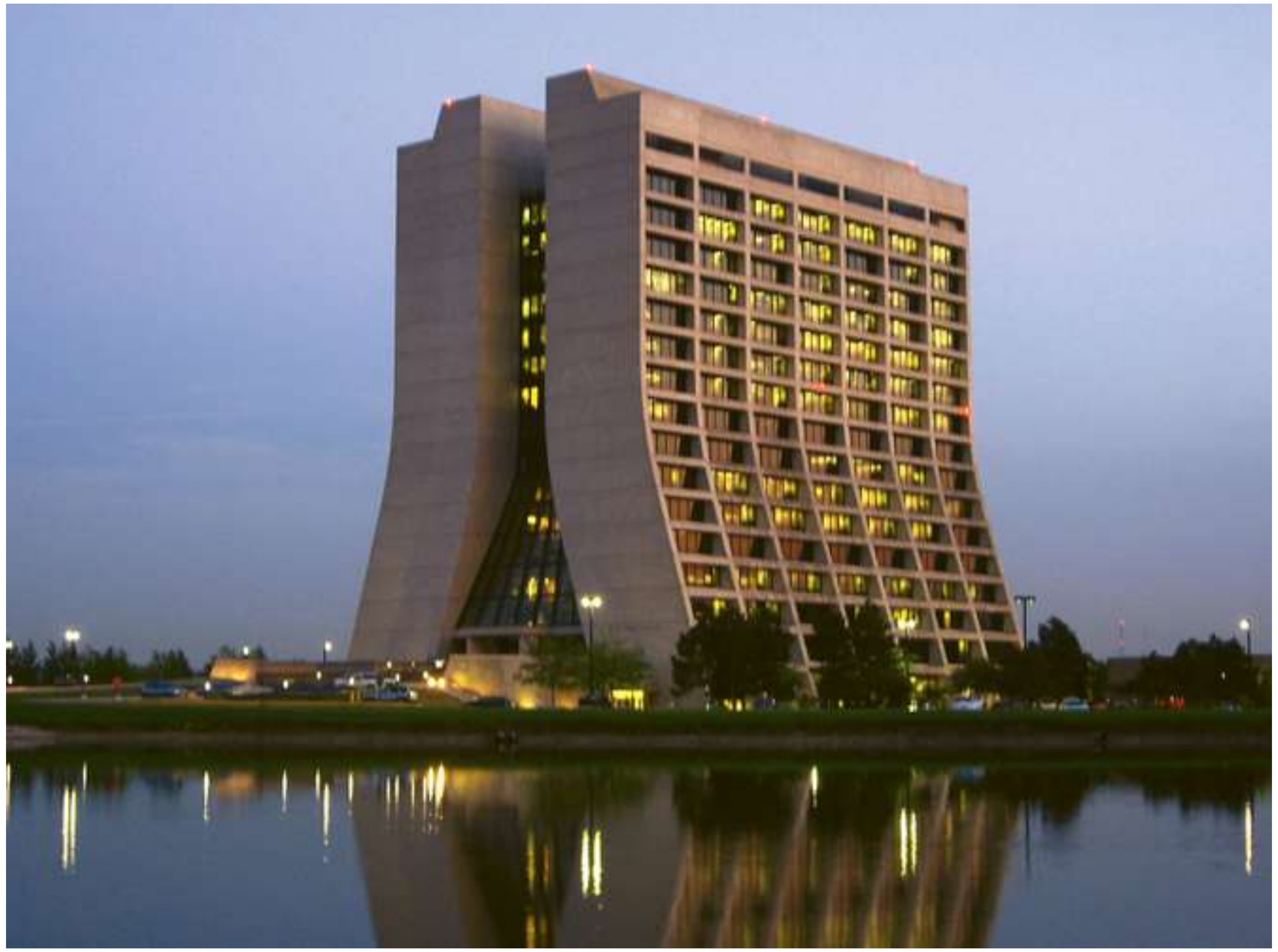
Neutrino event generators overview



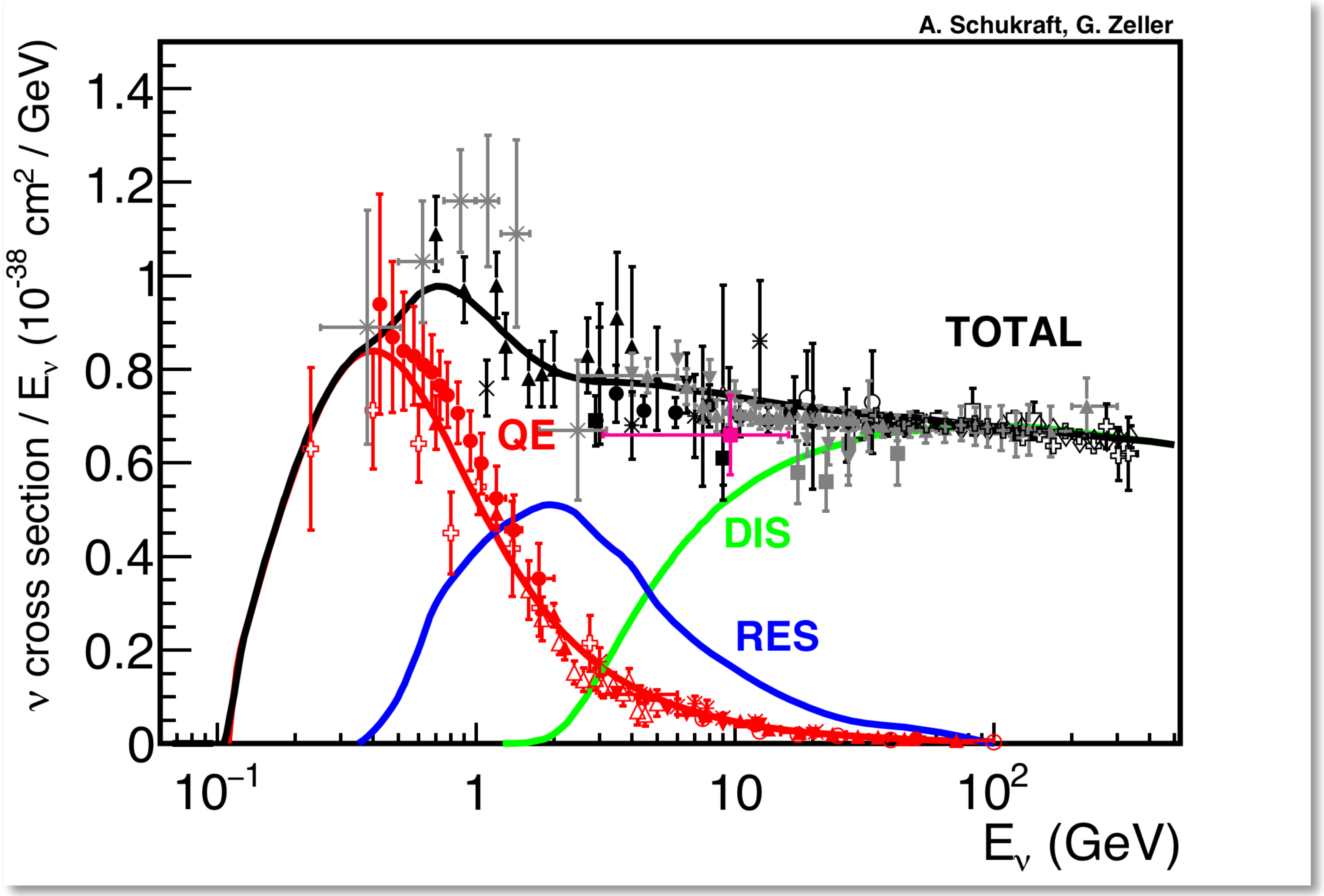
Steven Gardiner

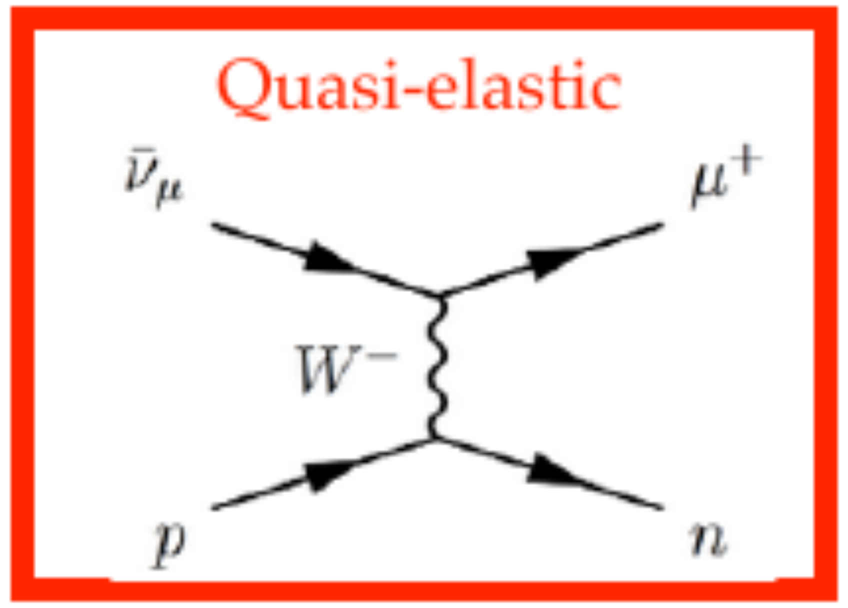
Theoretical Tools for Neutrino Scattering

25 August 2021

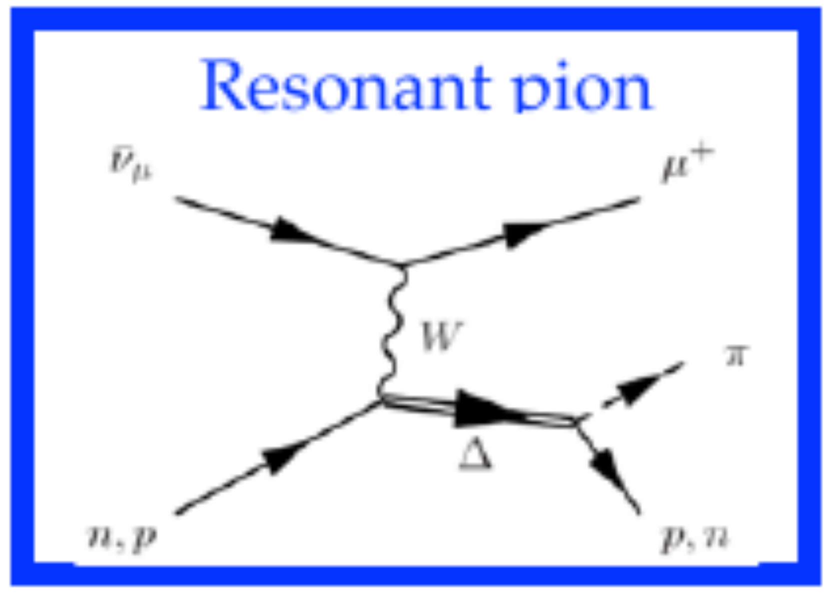
Modeling needs for accelerator neutrino experiments

- Experiments need cross section models that predict
  - All final-state observables for
  - All important processes for
  - Many nuclear targets including inactive detector components and the surroundings (“dirt backgrounds”)
  - Over a neutrino energy range spanning orders of magnitude
- Uncertainties must be well controlled for precision oscillation measurements
- **Making theory developments accessible to experiments** is an important part of the puzzle

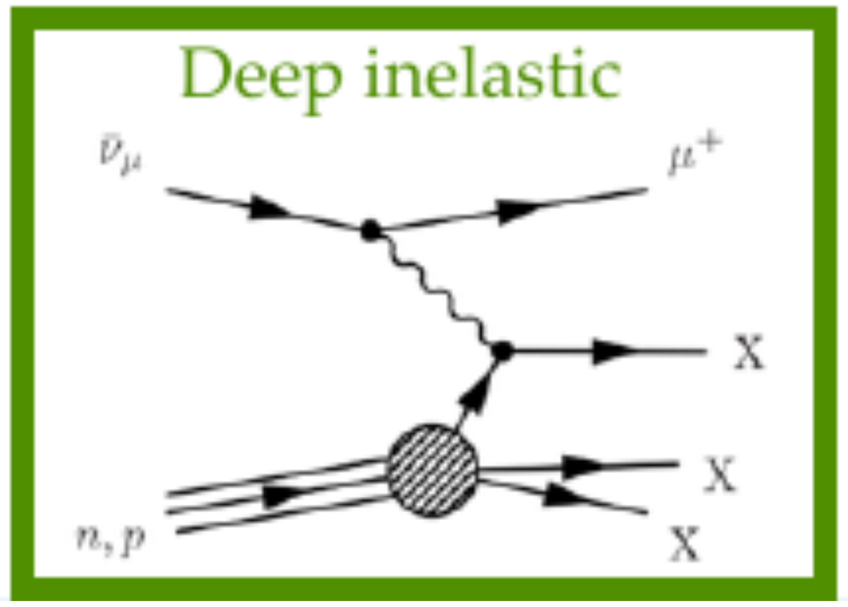




QE



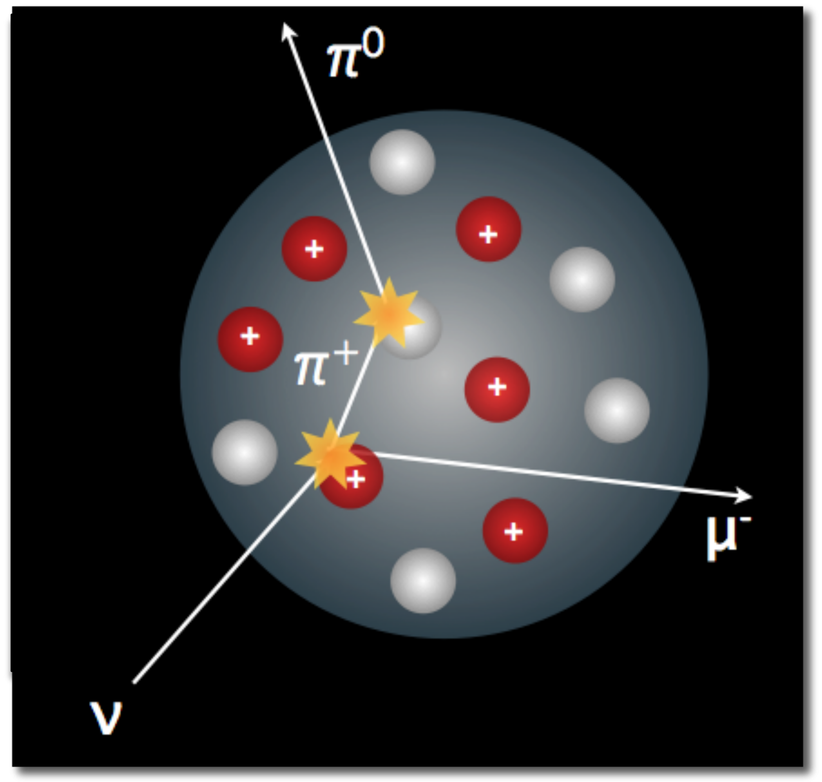
RES



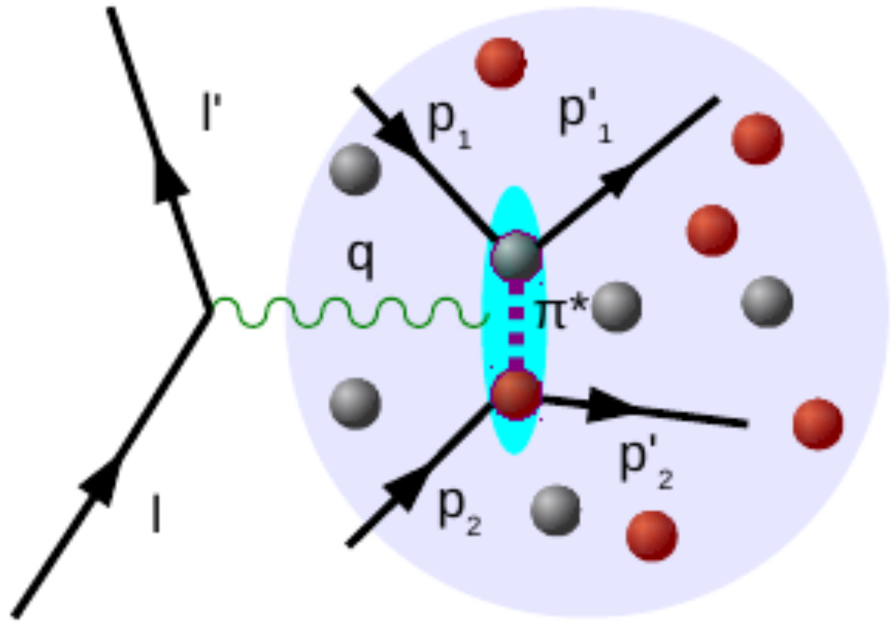
DIS

Nucleon-level processes

Final-state interactions (FSIs)



Two-particle two-hole (2p2h) interactions



Nuclear effects

Neutrino event generators

- "Bridge" between theory and experiment: model predictions are made easily usable
- Analyses lean heavily on a neutrino generator for a variety of tasks: neutrino calorimetry, efficiencies and backgrounds, systematic uncertainties
- **Four major generators** are commonly used by accelerator experiments: GENIE, GiBUU, NEUT, and NuWro
- The codes and groups differ in many ways
  - Development practices
  - Physics scope
  - Support for experimental interfaces (flux, etc.)
  - Developer expertise (experiment/theory)
  - Programming language(s)

Recent workshops

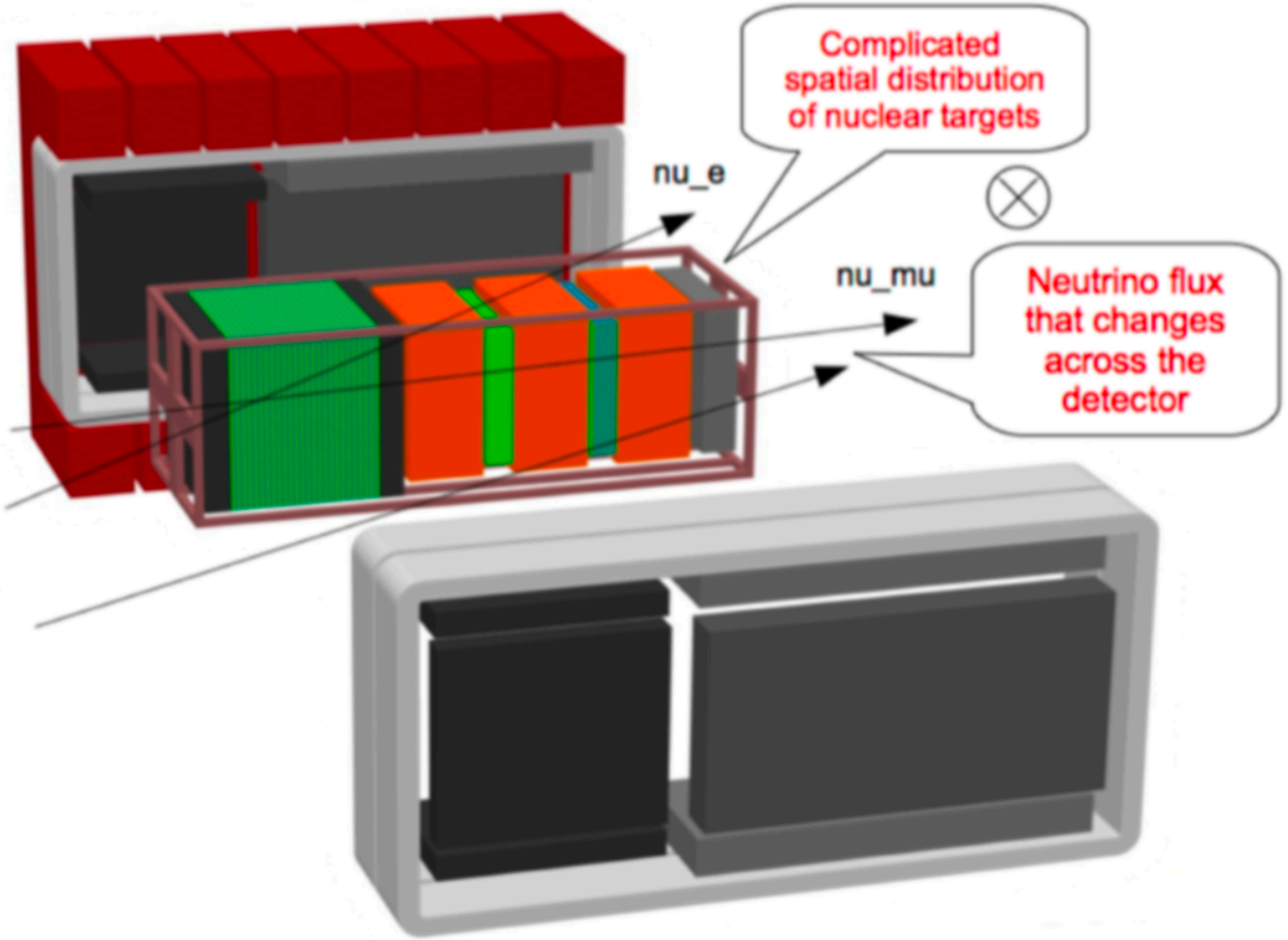
- Increasing attention to generator needs in recent years, partially in the form of dedicated workshops
  - No attempt to be comprehensive here. Many good discussions (e.g., **this one** from May 2019) are omitted for brevity
- A series of three meetings were particularly focused on topics related to neutrino generator development
- **ECT* 2018**: “Modeling Neutrino-Nucleus Interactions” **https://indico.ectstar.eu/event/19/overview**
  - Examined contents of existing generators (physics, tools, etc.)
  - Use by experiments and prospects for improvement
- **ECT* 2019**: “Testing and Improving Models of Neutrino-Nucleus Interactions in Generators” **https://indico.ectstar.eu/event/53/overview**
  - Topical discussions motivated by outcomes of 2018 workshop
  - Significant emphasis on technical work / tools to make collaboration on generator topics more effective

Fermilab Generator Tools workshop

- 8-10 January 2020 **https://indico.fnal.gov/event/22294/**
- Summary white paper: **arXiv:2008.06566**
- Development of technical plans to help address community needs identified at previous workshops
- Emphasis on standardizing “generator technology” as a way to address shared challenges:
  - Flux & geometry drivers (and related input formats)
  - Unified output formats for generator interoperability
    - Example: simulate hard scattering, delegate FSIs to a different generator (important physics caveats!)
  - **Theory interface**: technical strategies for implementing new models more efficiently

Standardizing code interfaces

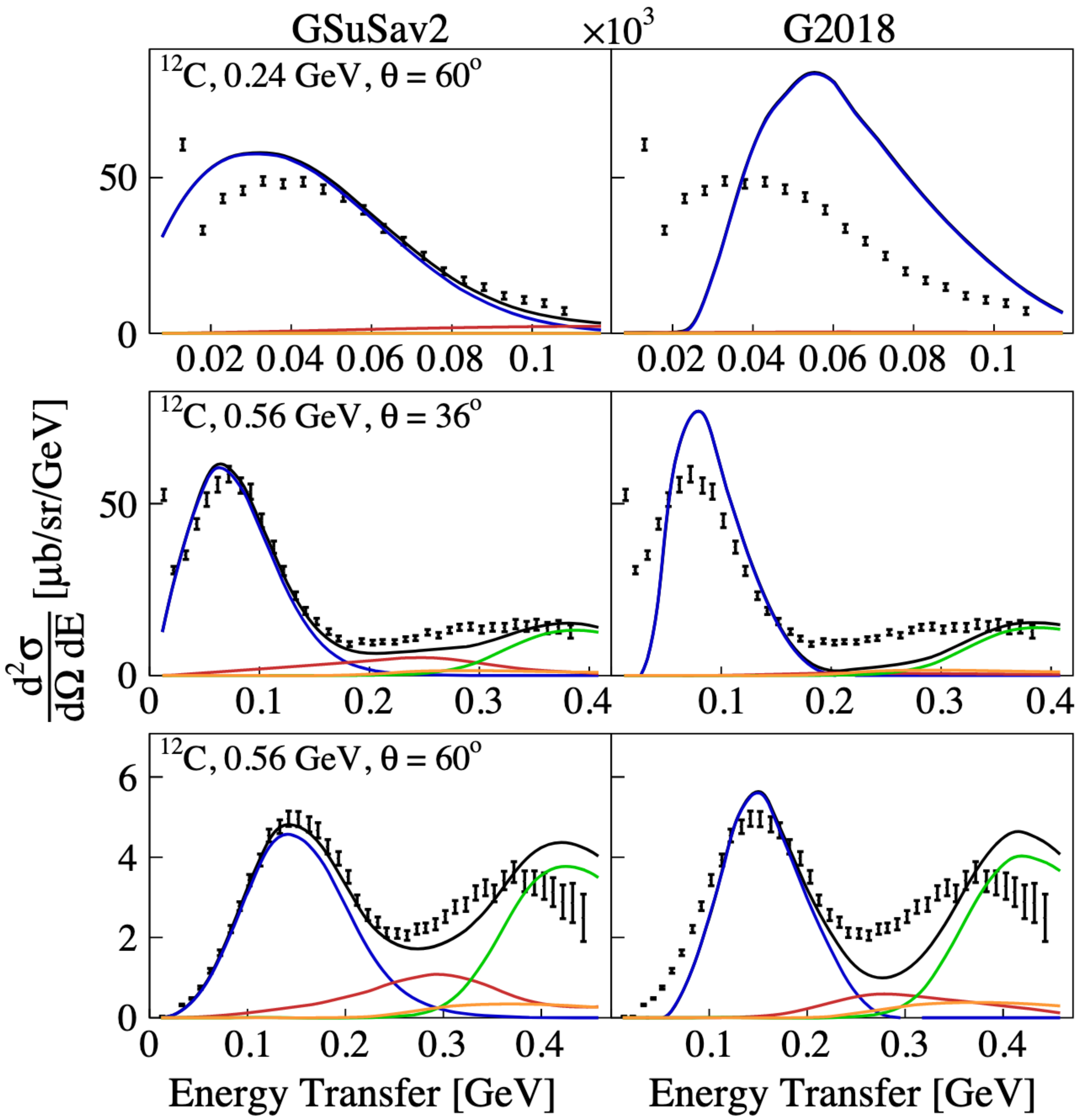
- Some required tasks for generators are technically demanding but theoretically uncontroversial
  - Interpreting beam simulation results, propagating neutrinos towards a detector: “**flux driver**”
  - Tracking neutrinos through geometry, sampling interaction vertices: “**geometry driver**”
  - Representing the full history of the event (particle 4-vectors, event weights, etc.): “**event record**”
- A universal solution is possible in principle
  - In practice, there are details to be worked out and typically different implementations in each generator
- Lack of a common approach represents a barrier to entry
  - Use of multiple generators by experiments
  - Creation of “mini-generators” for specific processes
  - Interoperability (hard scatter in generator #1, FSIs in generator #2)



Theory interface: table-based approaches

- "Traditional" development approach: re-implement theory calculation directly within a generator
  - Labor-intensive, potentially requiring multiple person-years
- **Table-based strategies** have been tried out by multiple generator groups, with some success but also some drawbacks
  - Valencia MEC, SuSAv2, short-time approximation
- Precompute nuclear responses on a grid of (ω,q)
- Interpolate and apply leptonic factors to get **inclusive cross sections**
- More exclusive information sometimes unavailable (SuSAv2, Valencia MEC) and sometimes requires further development (STA)
- Uncertainties and tuning for these typically ad hoc: important parameters "baked into" the responses

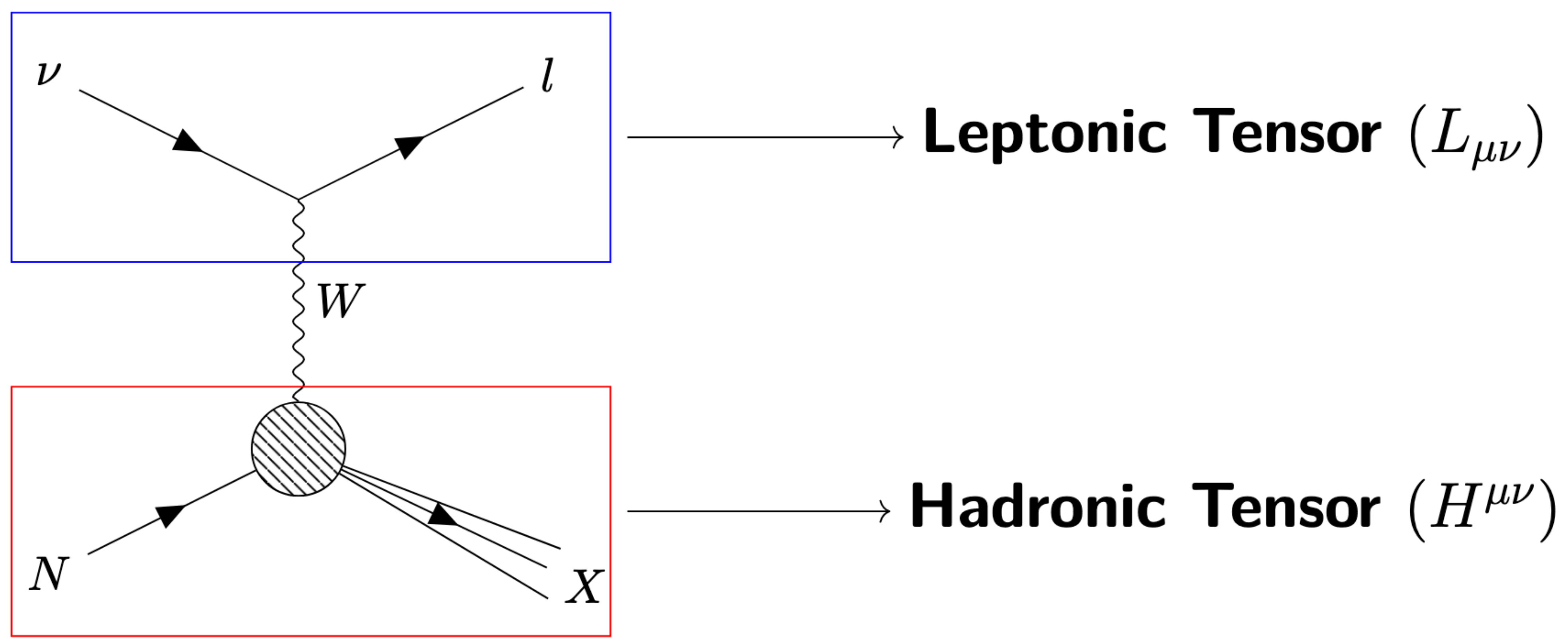
Phys. Rev. D 103, 113003 (2021)



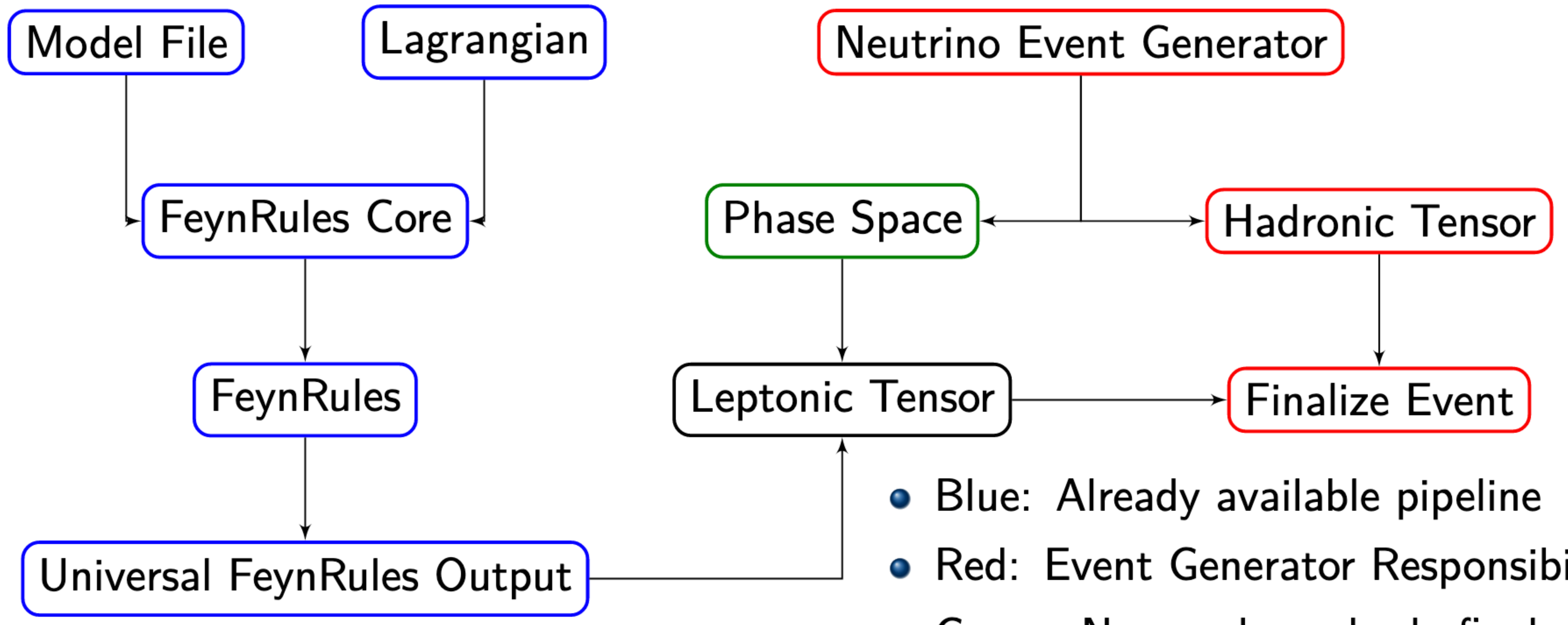
See also Phys. Rev. D. 101, 033003 (2020) for neutrino results

Theory interface: supporting wide-ranging BSM studies

- BSM searches will be an important part of the overall neutrino experimental program going forward
- Many scenarios of interest require changes to the leptonic part of the interaction only
  - Nuclear calculations are hard, but generators handle this already
  - Requires exposing the hadronic tensor calculation (generator) so that BSM events can be simulated using a modified leptonic tensor (theory groups)
- Existing tools from LHC efforts can automate much of the required work



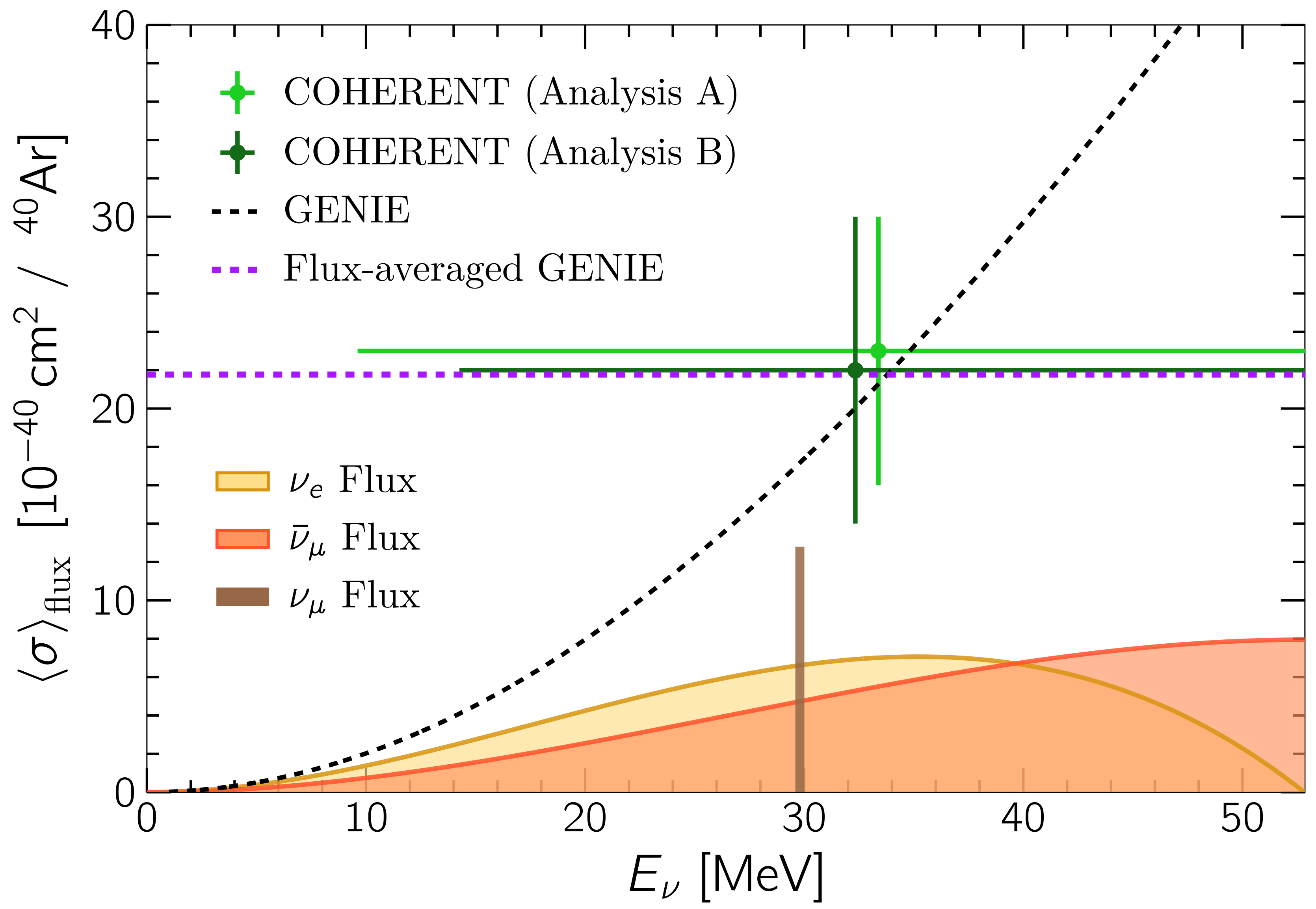
Josh Isaacson *et al.*, FNAL Neutrino Joint Theory-Experiment Working Group meeting, 12 August 2021



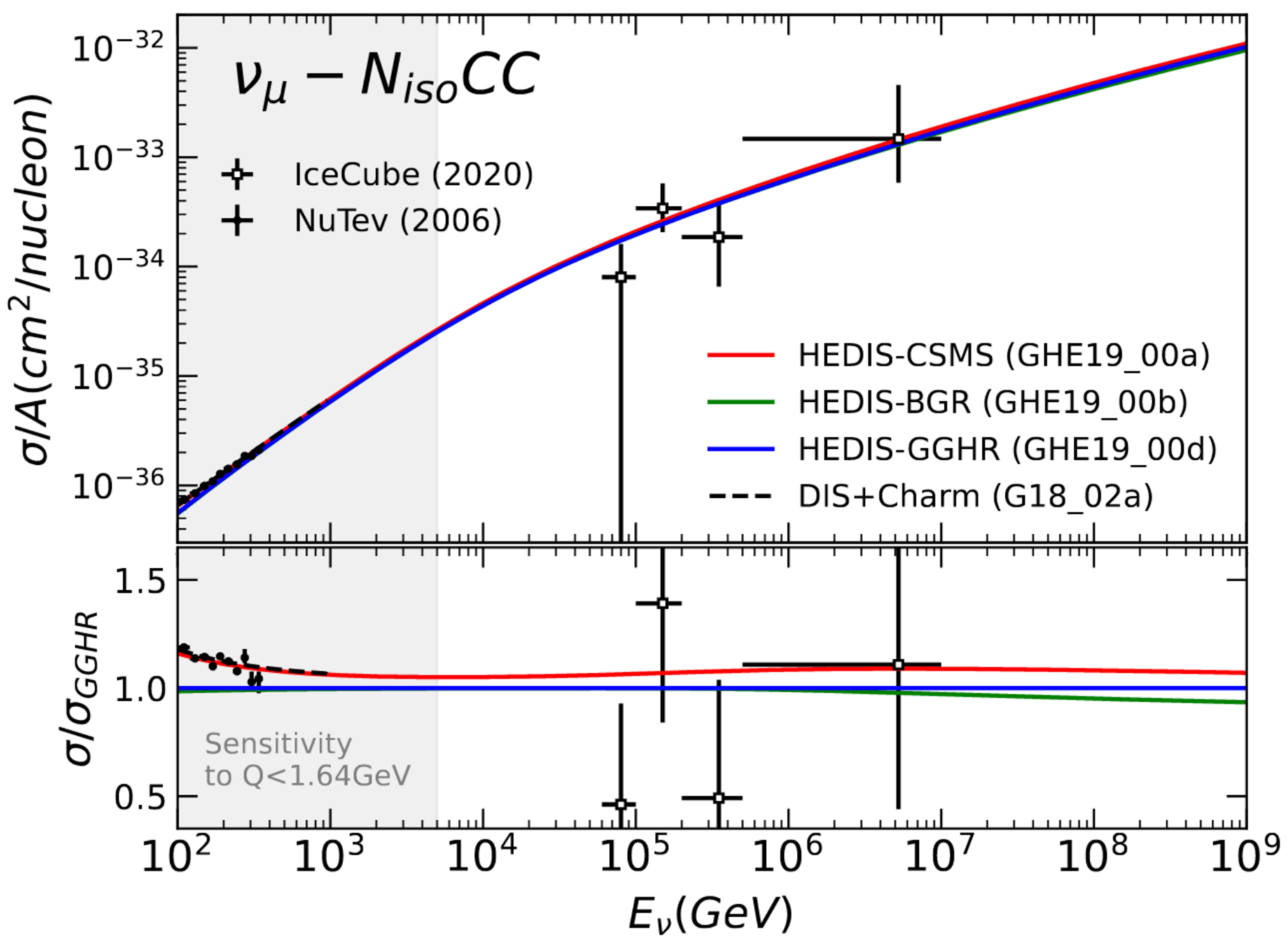
- Blue: Already available pipeline
- Red: Event Generator Responsibility
- Green: New code: n-body final state event generator: initial state momenta

Energy frontiers for neutrino generators

- Emphasis in the community is on accelerator energies (~100 MeV to ~10 GeV) relevant for the current and planned precision oscillation program
- Interesting physics topics can also be found outside of the "traditional" energy range
- Generator-related needs for those communities can also usefully be explored in a Snowmass white paper
  - CEvNS and other low-energy processes
  - FASERv: [Eur. Phys. J. C 80, 61 (2020)]
  - Neutrino telescopes (IceCube, KM3NeT)
- Some energy-regime-specific efforts already exist
  - LeptonInjector: [Comput. Phys. Commun. 266, 108018 (2021)]
  - MARLEY: [Comput. Phys. Commun. 269, 108123 (2021)]

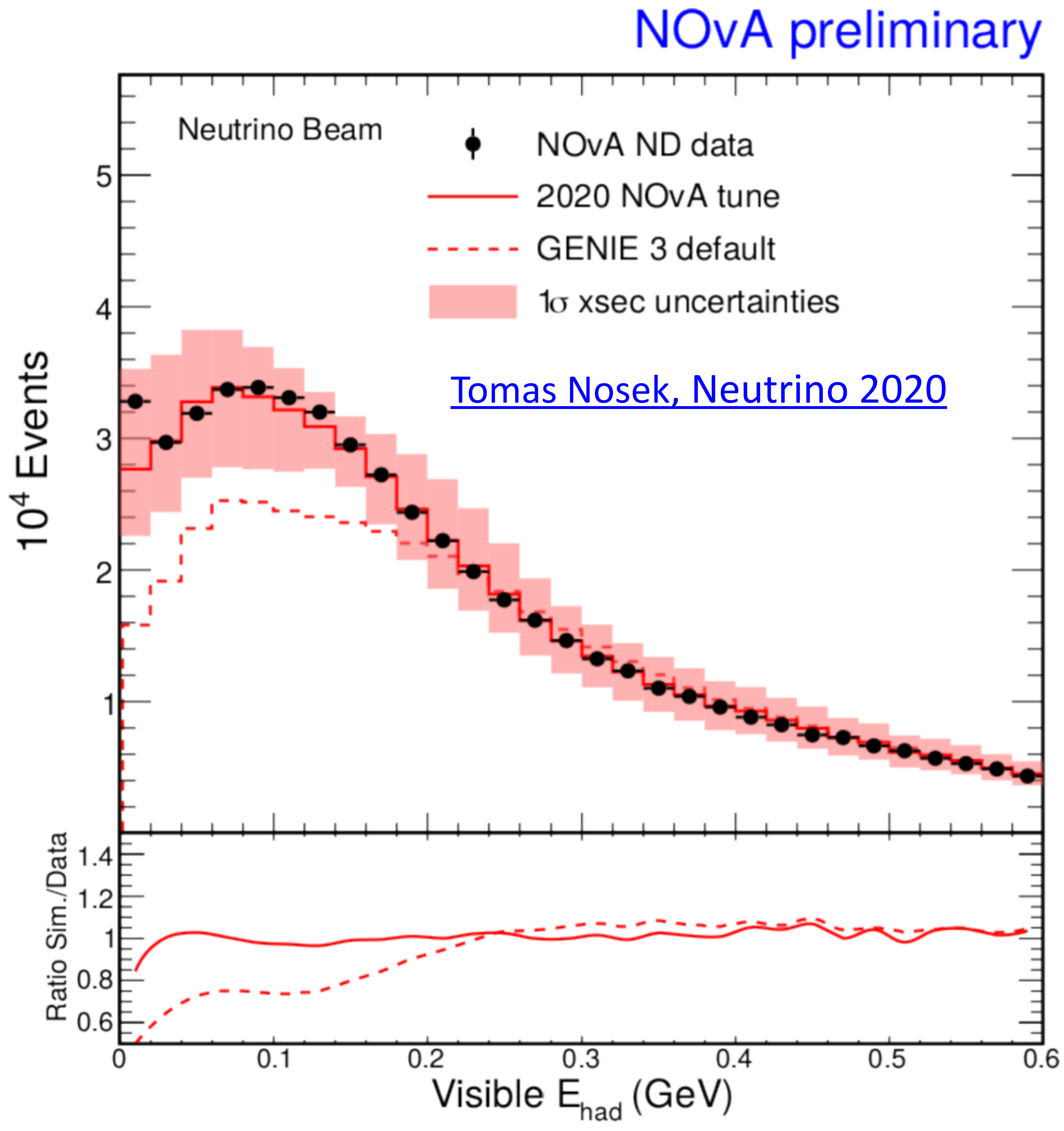


GENIE Collaboration, [arXiv:2106.09381]



Systematic uncertainties & tuning

- Key capabilities needed by neutrino experiments, typically accomplished via **event reweighting**
- Weight calculators are typically custom-made for a particular application
  - Often generator- and/or model-specific
  - Substantial maintenance effort required
- Only partial coverage of model uncertainties
  - Cannot reweight missing phase space into existence!
- A more flexible & maintainable approach is highly desirable
- Early stages of R&D are in progress
  - Example: GENIE's use of the **Professor** tool
  - See **A. Buckley et al., Eur. Phys. J. C65, 331-357 (2010)** for more information about Professor



Plans for a Snowmass generator workshop this fall

- Many generator-related questions could benefit from further discussion
- I am grateful for the opportunity to explore some of them with you today
  - Emphasis on the **relationship between generators and theory efforts**

- Significant interest expressed pre-COVID in having a dedicated generator workshop
  - I was personally involved in discussions with NF02, TF11, and CompF2 leadership on the subject

- We will plan on holding such a workshop online before the end of 2021
  - If you would like to be involved in the renewed planning effort, please get in touch with Kendall Mahn (mahn@msu.edu) and myself (gardiner@fnal.gov)

Themes for discussion today

Special thanks to our **discussion panel**: Clarence Wret (NEUT), Kajetan Niewczas (NuWro), Marco Roda (GENIE), Ulrich Mosel (GiBUU)

1. **Barriers to getting generator work done**
   - Difficulties in engaging with generators, securing support to maintain them, and implementing improved models
   - Success stories and lessons learned
   - What can we do as a community to make the situation better?
2. **Coordinating theory and generator development efforts**
   - Is there a clear path to realizing the priorities identified by the community in the form of generator improvements?
   - Are there additional priorities that are clear to those who know the generator codes best?
3. **Preparing to respond to anticipated theory developments**
   - If we receive the improvements that we are requesting (e.g., high-quality *ab initio* calculations with uncertainties), is it clear how to incorporate them into generators?