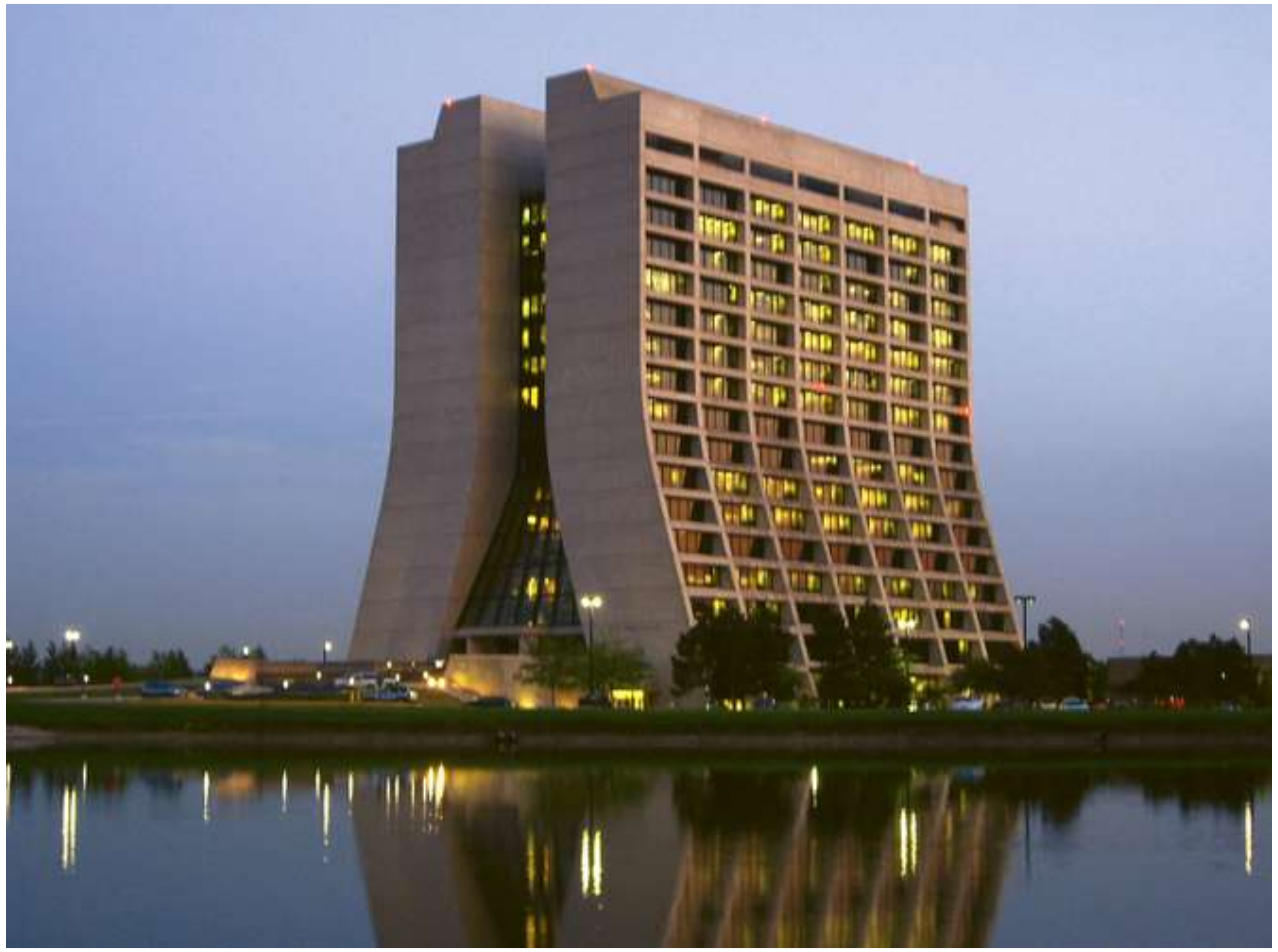
Snowmass LOIs: Neutrino event generators



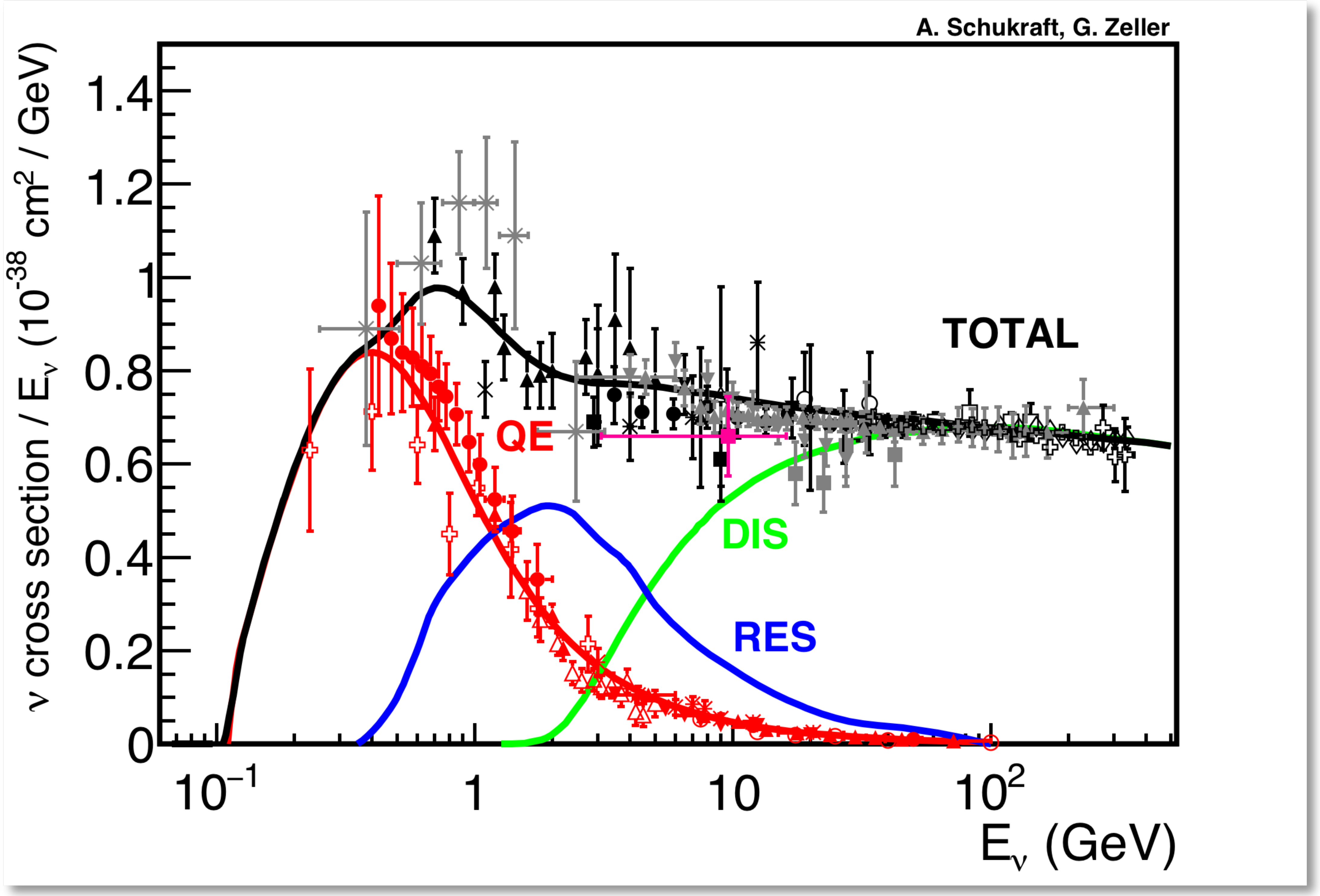
Steven Gardiner

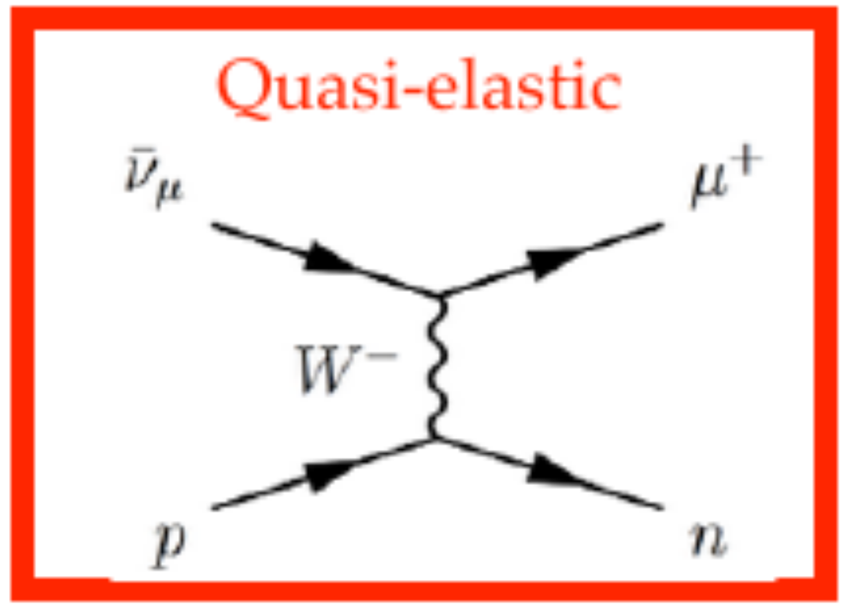
NuSTEC Board Meeting

11 December 2020

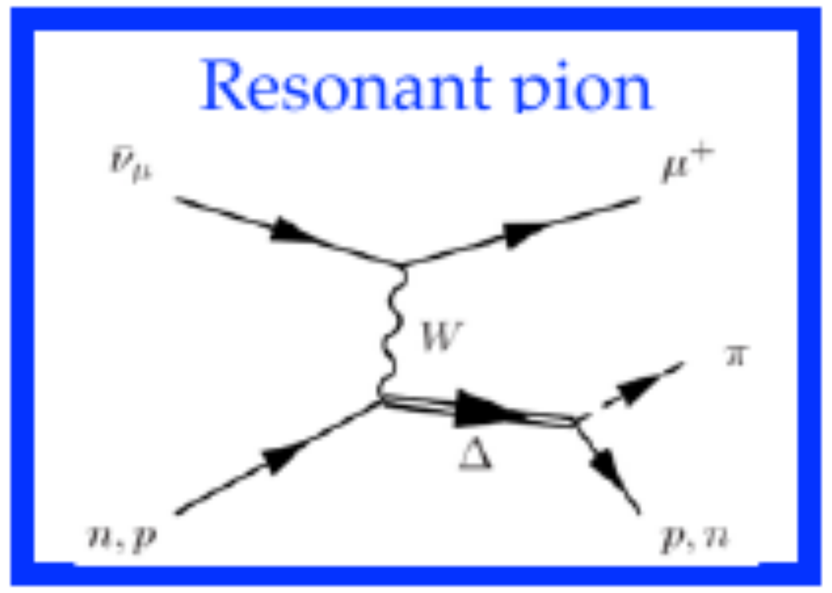
Event generators for accelerator neutrino experiments

- Precision neutrino oscillation measurements require high-quality models of neutrino-nucleus cross sections
- **Monte Carlo event generators**
  - Encapsulate theory for practical calculations
  - Vehicle by which models are made available for use in experimental analyses
- Several modern neutrino generators are widely used
  - GENIE, GiBUU, NEUT, NuWro
  - Emphasize modeling at **accelerator energies** (~100 MeV to ~10 GeV)

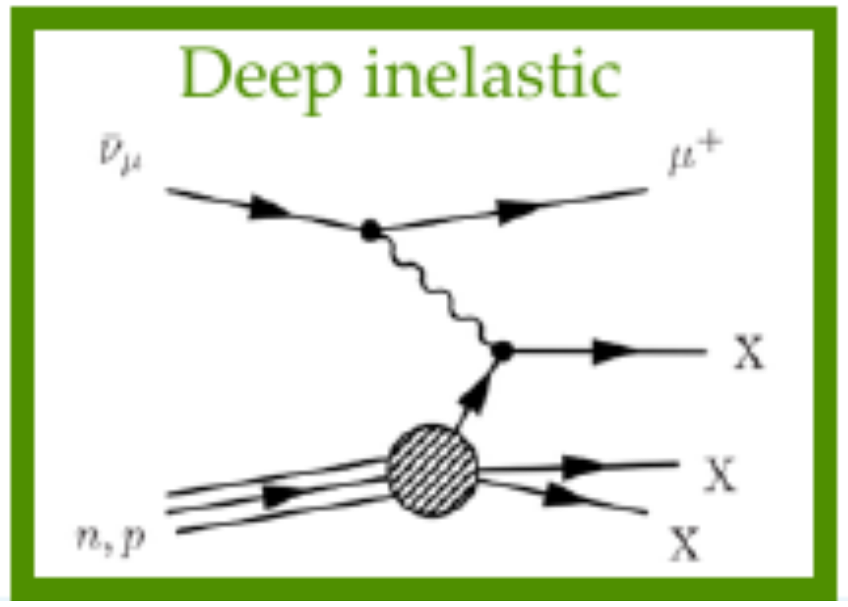




QE



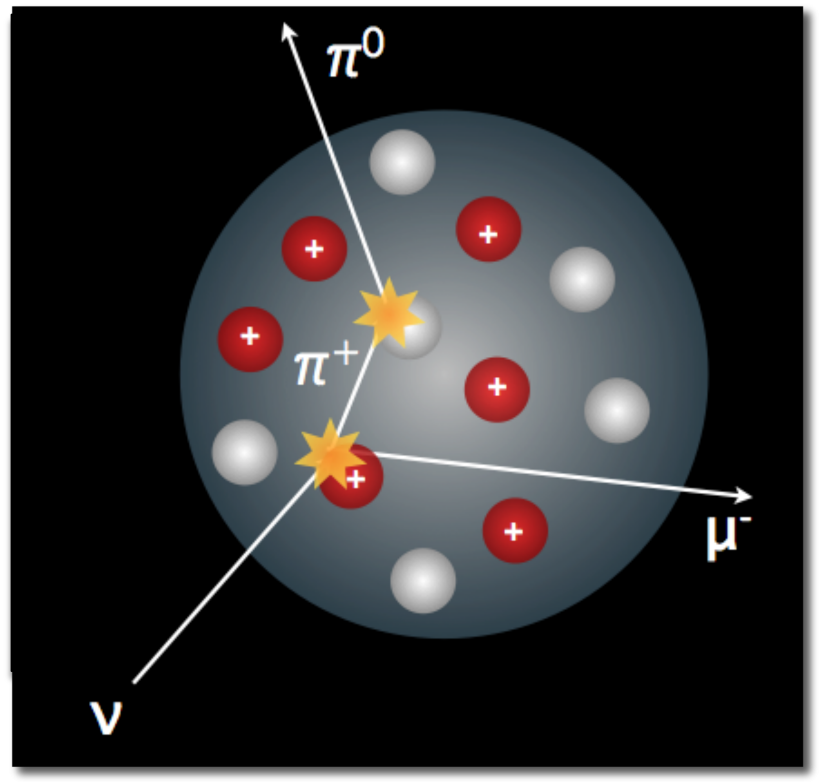
RES



DIS

Nucleon-level processes

Final-state interactions (FSIs)



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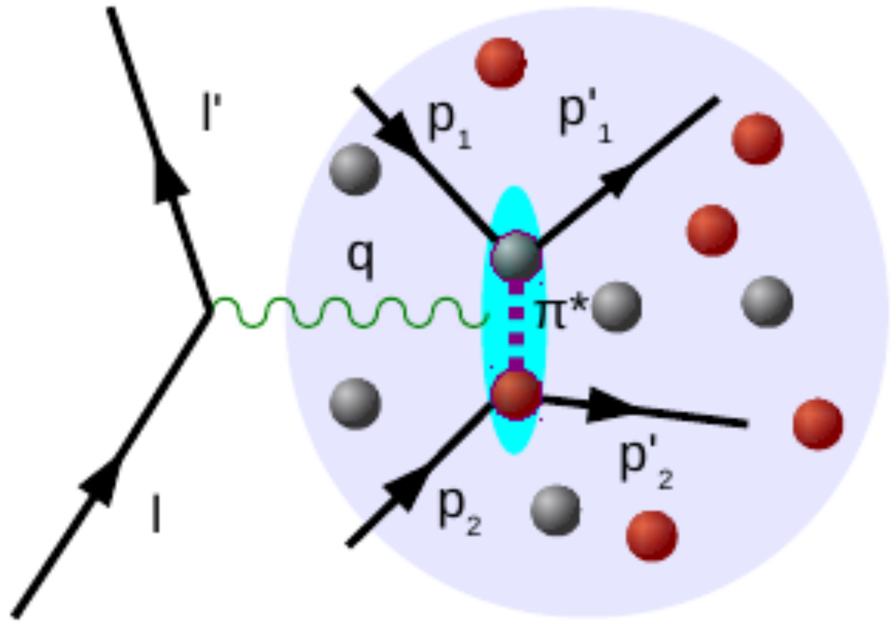
Two-particle two-hole (2p2h) interactions



Also referred to as MEC (for Meson Exchange Current)

Nuclear effects

At-a-glance summaries of related LOIs

- **Steven Gardiner**: Reiterates conclusions from Jan 2020 workshop and raises some additional issues. Focuses on specific community challenges that must be addressed soon.

- **Costas Andreopoulos**: GENIE has many advantages as a software product and ambitious plans for the future. It can be *the* universal platform but has a deliberately chosen development model that must be respected.

- **William Jay**: Generators and realistic uncertainties are important. Making neutrino generators modular like their LHC counterparts has several advantages (e.g., easy to compare to electron data, interoperability). QCD inputs for form factors, etc. should be leveraged by the community.

- **J Taylor Childers**: Raises important issues for generators in general (not neutrino-specific). Echoes some concerns from neutrino community about culture/incentives/tuning, need to be ready for new computing techniques (GPUs, etc.)

Neutrino Event Generators

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(Dated: August 2020)

All raise useful points for discussion. I will present more detail about mine.

- I am most familiar with it

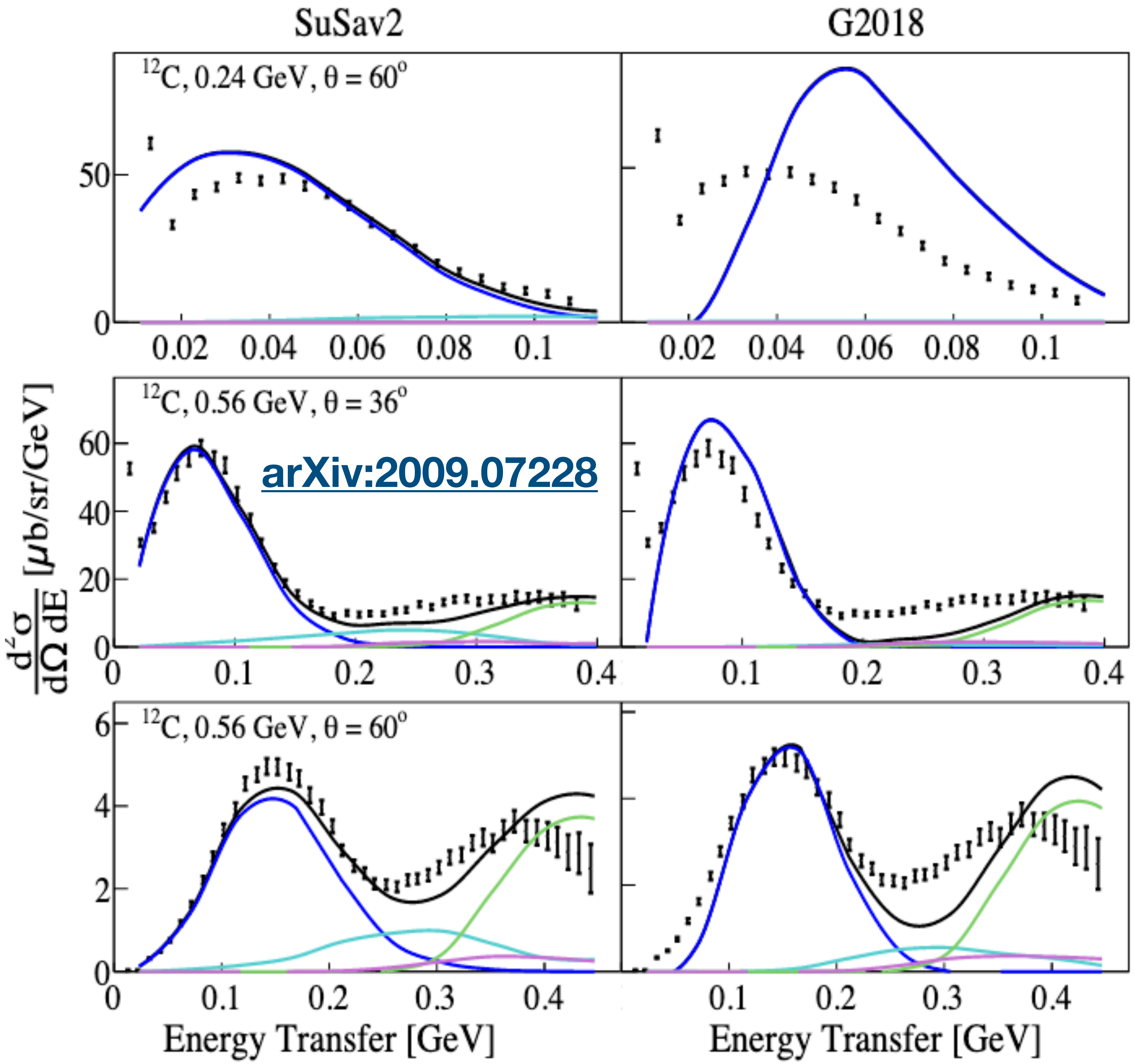
- I believe it contains the most specific action items

Streamlining theory improvements

$$\frac{d^2\sigma}{dE'_\ell \, d\cos\theta'_\ell} \propto L_{\mu\nu} W^{\mu\nu}$$

Hadronic tensor interface

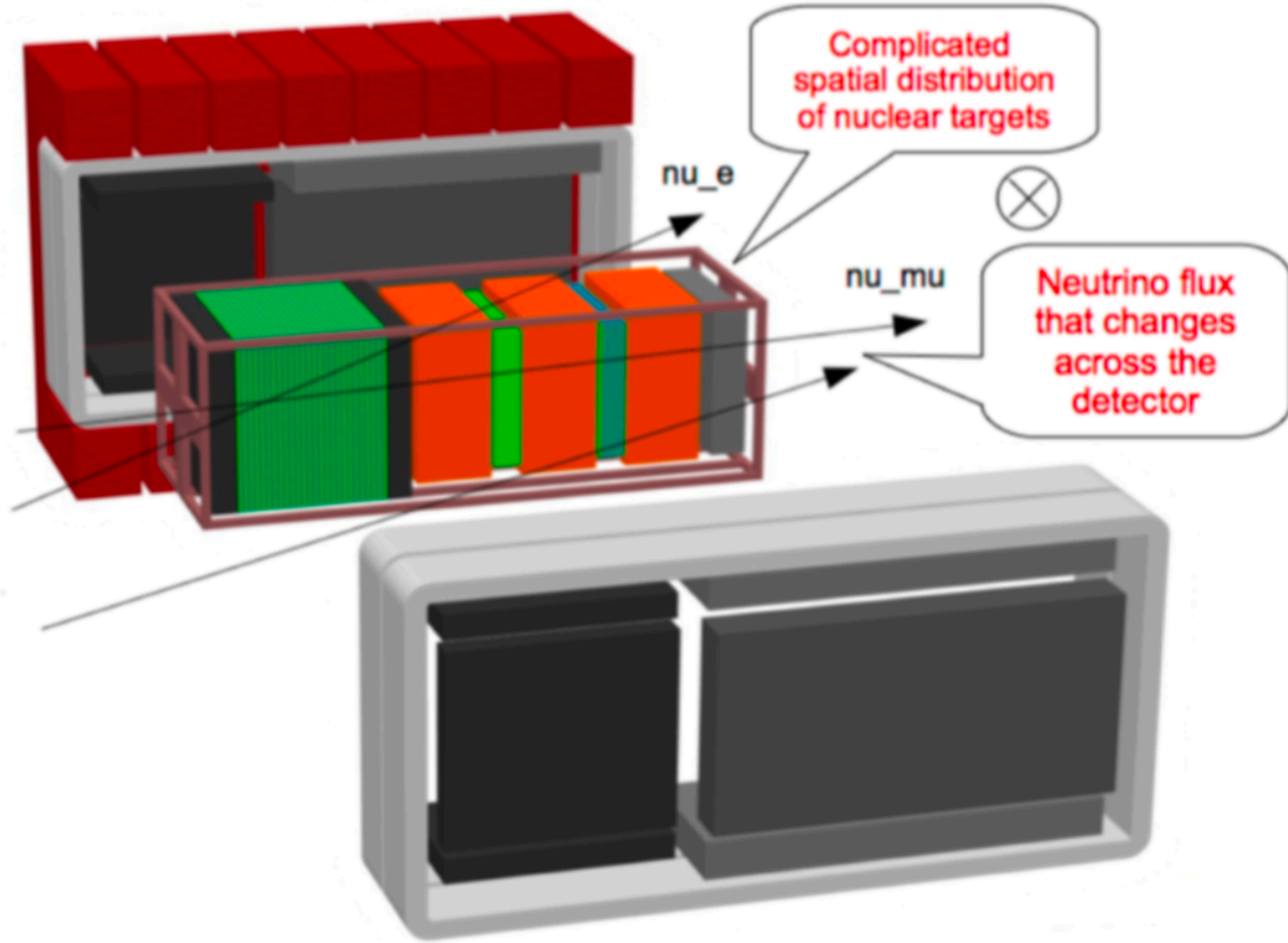
- Strong effort by theory community to develop more sophisticated models of neutrino-nucleus scattering
- Implementation in generators continues but lags behind the most recent improvements
- "Traditional" development approach: re-implement theory calculation directly in an individual generator's code base
  - Labor-intensive, often requires translation of Fortran to C++
  - Validation especially difficult without direct theorist involvement
  - **Multiple person-years** typically required
- Could be especially problematic for BSM physics searches
- Technical solutions ("universal theory API") being explored, further attention needed



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

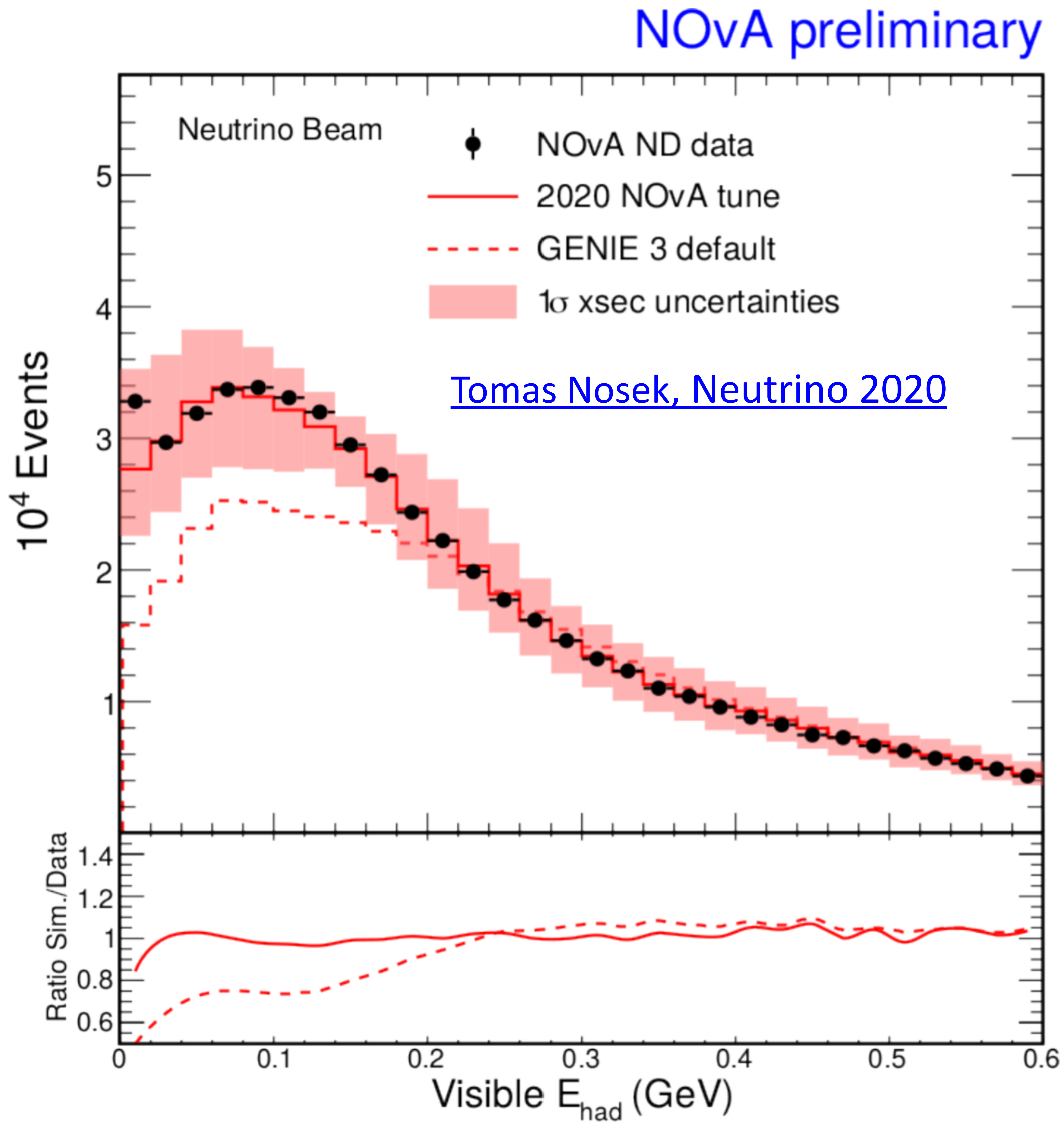
Standardizing code interfaces

- Some technically demanding required tasks for generators are essential but theoretically straightforward
  - 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”
- In principle, you can “do it right once” and apply a universal solution
  - In practice, there is lots of duplication of effort with 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)



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



Using neutrino cross-section data

- Essential input for improving neutrino generators, large and growing effort from experiments to provide detailed information
- Comparing to these data requires careful bookkeeping of many details: neutrino fluxes, signal definitions, etc.
- Some individual groups have their own tools (e.g., GENIE Comparisons)
- NUISANCE is a de facto community standard
  - [P. Stowell et al., JINST 12 P01016 (2017)]
  - [https://nuisance.hepforge.org/]
- Critical infrastructure that must be supported and expanded to scale with the needs of the community

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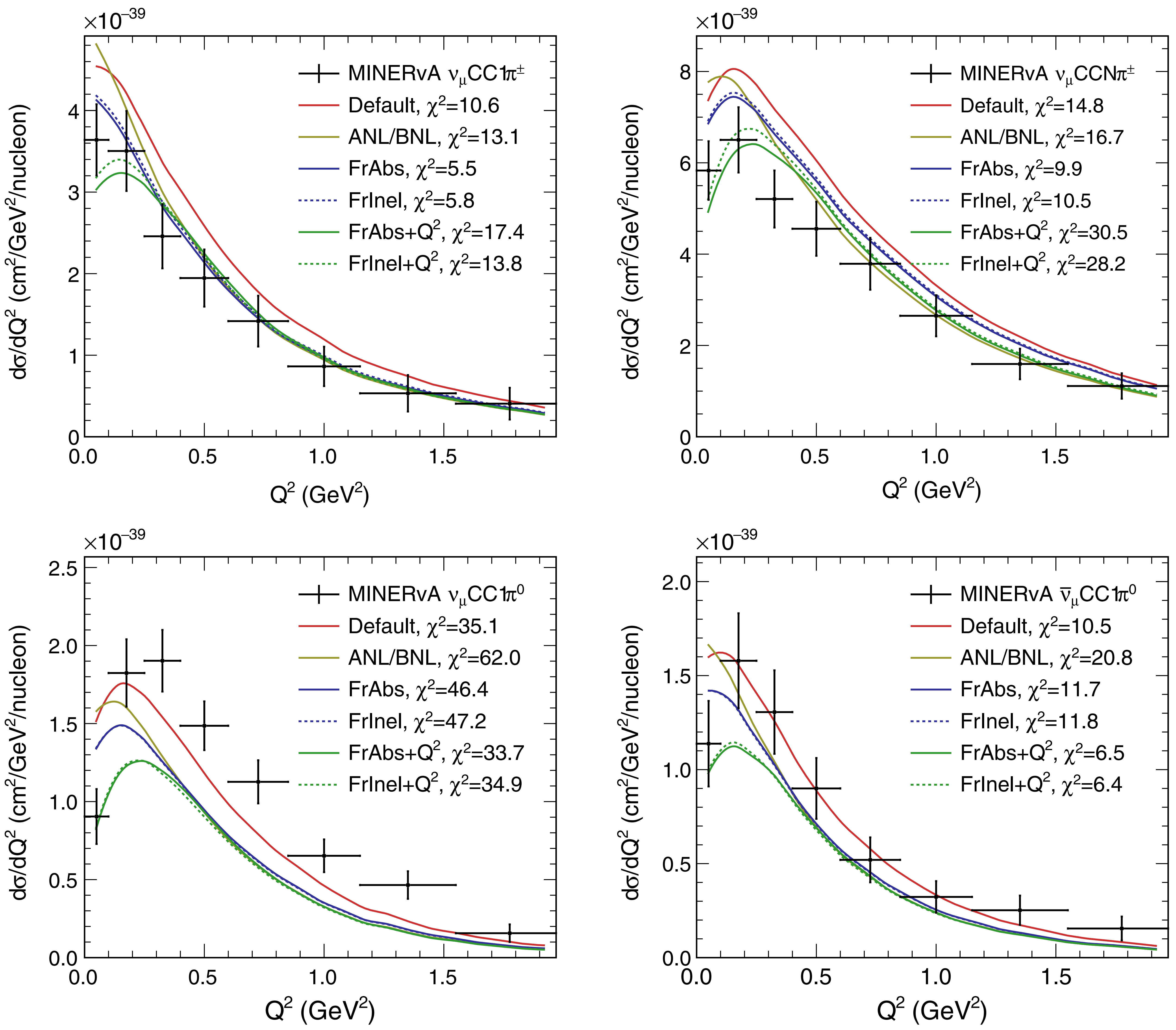
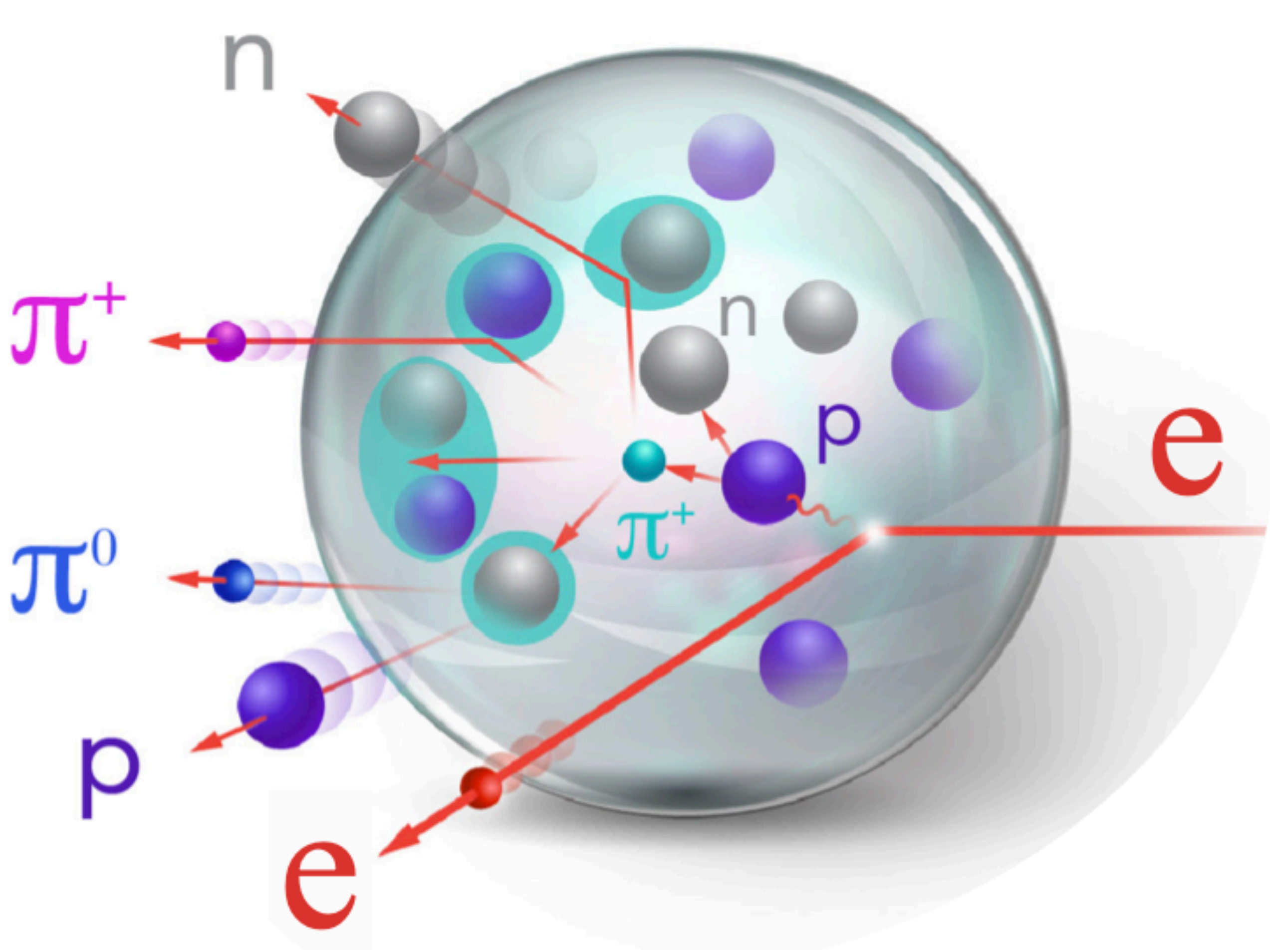
[Phys. Rev D. 100, 072005 (2019)]

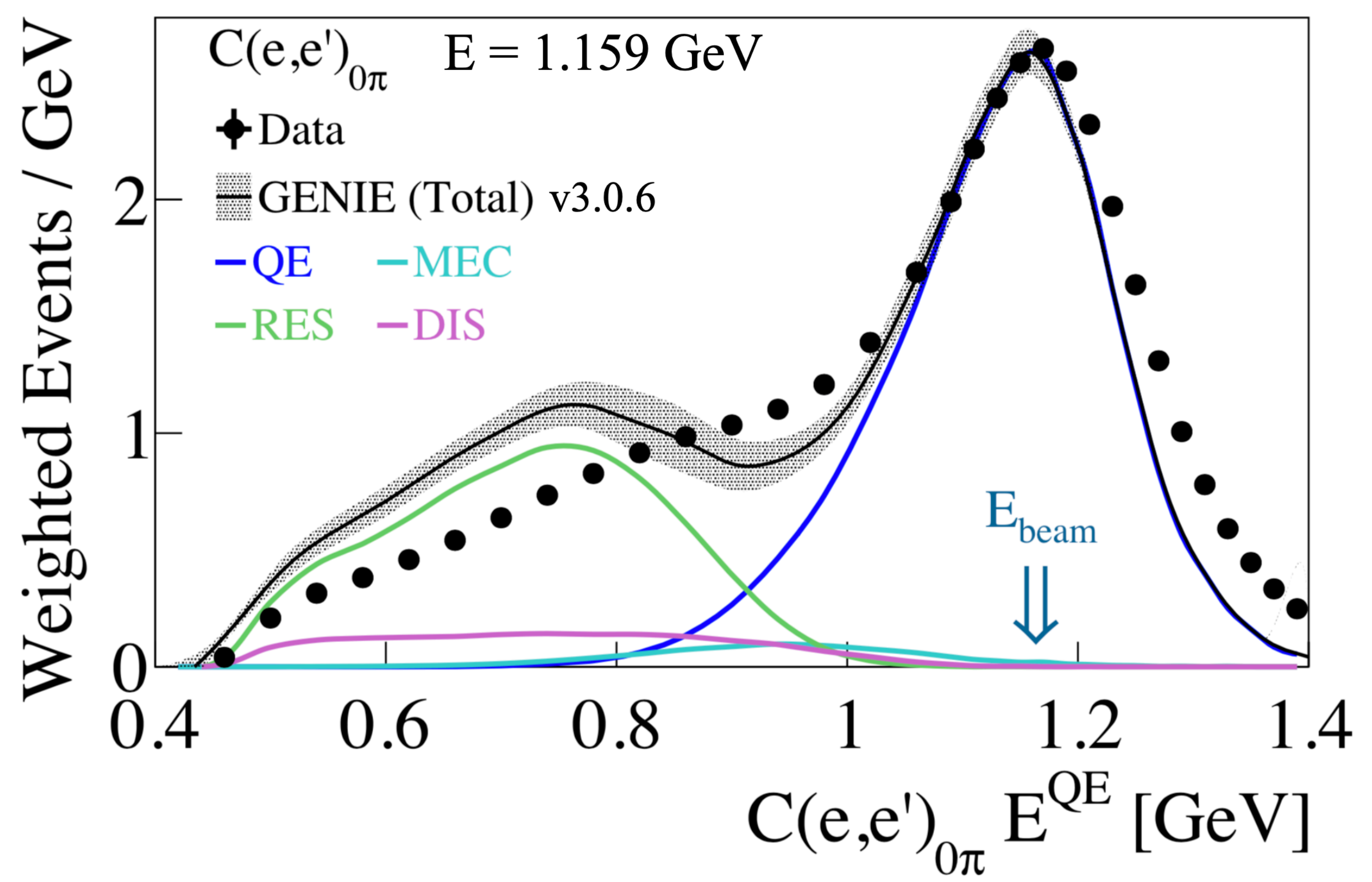


Using data for non-neutrino probes

- Processes like electron-nucleus, photon-nucleus (vector current, nuclear effects), and pion-nucleus (FSIs) can be highly useful for improving neutrino generators
  - Examples shown for **electron-nucleus scattering**
- Requires consistent generator physics implementation in switching from neutrino to other projectiles
  - Not always historically true, improving
- Same considerations about tools for comparisons, tuning apply to these data
  - Less infrastructure immediately available to the public



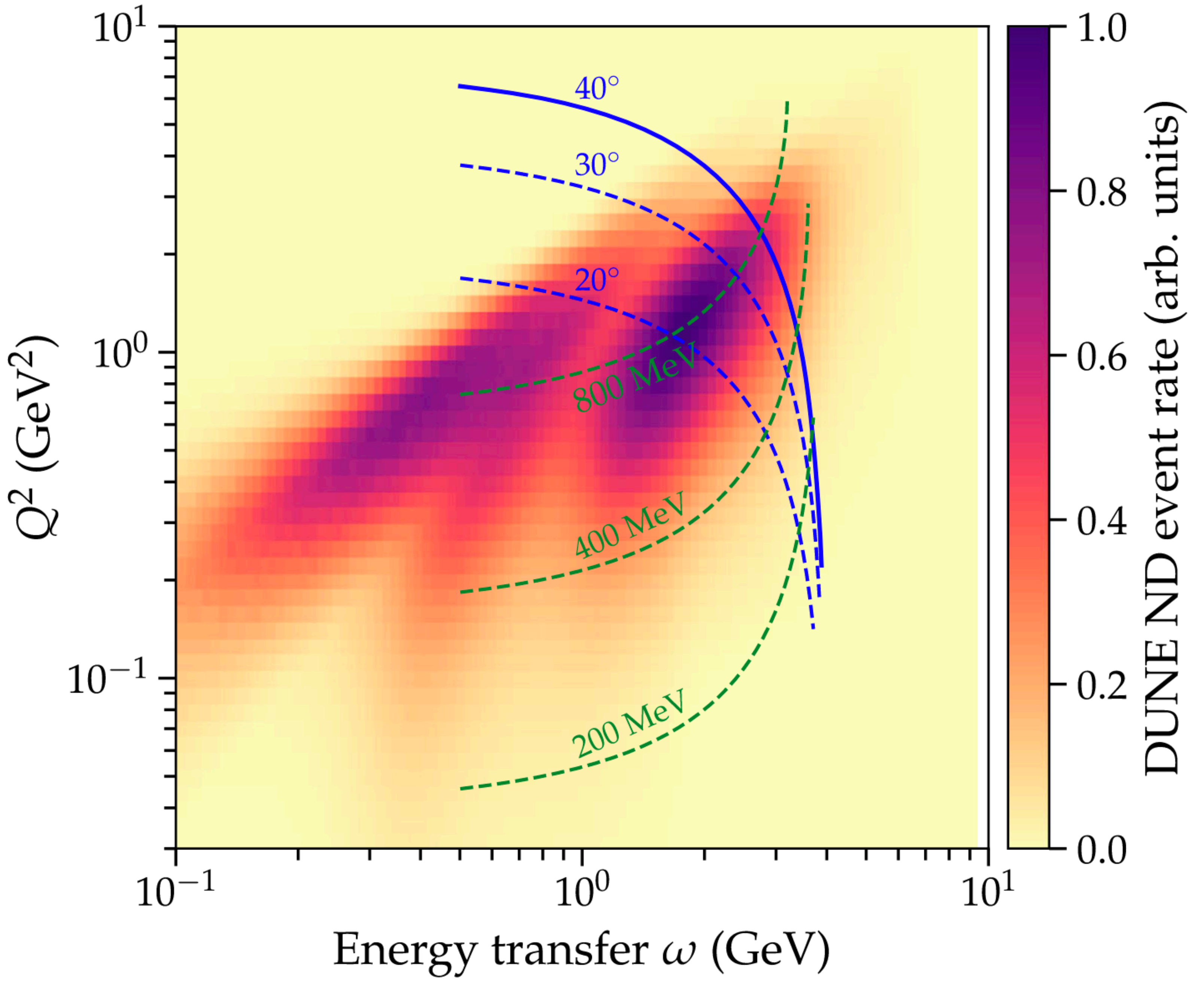
A. Ashkenazi, Neutrino 2020



Genie v3.0.6 tune G18_10a_02_11a

Phys. Rev. D 101, 053004

LDMX can probe kinematic regions ($\theta_e < 40^\circ$ on the plot) of high importance for DUNE



Computing and human factors

- Neutrino event generation is typically not a large part of the overall experimental computing budget (for now)
  - Likely to change in the future, particularly if we consider all use cases
  - Input theory calculations (e.g., HPC for quantum Monte Carlo)
  - Generation itself (including rare and BSM processes)
  - Systematic uncertainties and tuning
- **NOvA, Eur. Phys. J. C 80, 1119 (2020)**
  - Leveraged NERSC HPC for tuning/systematics
- Sociological factors are worth considering
  - Diversity of expertise (HEP/NP, theory/experiment/developer) required
  - Generator community is small, expanded effort can help it scale to meet our future needs

Proposed Neutrino Generators Workshop (NF06 / CompF2 / TF11)

- Plans originated in conversations between NF06 conveners and myself, involvement of CompF2 + TF11 also important
  - **Target date**: February/March 2021 (**waiting on Snowmass delay discussion**)

- Envisioned as a follow-up to January 2020 “Generator Tools Workshop” at Fermilab
  - **Indico**: https://indico.fnal.gov/event/22294
  - **Summary white paper**: https://arxiv.org/abs/2008.06566

- Still working on draft agenda, see later slides for proposed topics
  - Please reach out (gardiner@fnal.gov) if you have feedback

- Workshop focus informed by related LOIs, discussions at Community Planning Meeting parallel session #99
  - “Advances in Event Generation and Detector Simulation”
  - https://indico.fnal.gov/event/44870/sessions/16258/#20201007

Survey in advance of the workshop

- We are considering a survey to gather input from the community about existing concerns and possible solutions

- Some possibilities for question topics (non-exhaustive, additions welcome)
    1. Difficulty in getting models of interest into generators
    2. Difficulty in support to maintain generators
    3. Difficulty for theorists to engage in generators
    4. HEP/NP funding divide
    5. What capabilities would you need/want in an ideal neutrino generator?

Rough draft of workshop topics

- **What would our ideal neutrino generator (or "generator platform") look like?**
  - Seed discussion with feedback from survey
  - What are the steps needed to get there? What are their priorities?

- **Generator usability / interoperability (consider use by experiments and theorists)**
  - Unified flux + geometry drivers: status, path forward
  - Common event format: status, path forward
  - What other issues are there that won't be covered by the plans for these two areas?

Rough draft of workshop topics

- **Streamlining theory improvements: technical aspects**
  - Needs (kinds of theory input, uncertainties, etc.)
  - Strawman concrete proposal for “theory API”
  - Future plans
- **Streamlining theory improvements: sociological aspects**
  - Survey report: what are the pain points?
  - Discussion: what can we do to address them as a community?
- **Streamlining experimental involvement: sociological aspects**
  - Survey report: what are the pain points?
  - Discussion: what can we do to address them as a community?

Rough draft of workshop topics

- **Comparisons, tuning, and uncertainties**
  - What tools for comparing generators to data (and each other) do we have right now? Strengths/weaknesses?
  - Survey report: pain points from users / developers
  - Non-neutrino probes: what data are available? How best can we make it usable to improve neutrino generators?
  - Tuning + uncertainty quantification
    - Existing tools & pain points
    - What are the hard-to-quantify uncertainties? How can we plan to assess them better / at all?
    - Do we want or expect interoperability for these?

Rough draft of workshop topics

- **Future resource needs & new computing techniques**
  - LHC experience: event generation & uncertainties at scale
  - NOvA experience: NERSC for tuning + systematics
  - DUNE: how well can we currently estimate resource needs?
  - Planning to leverage new technologies: GPUs, machine learning, quantum computing, etc.

- **Brief summary presentations, white paper planning, assignments for "homework"**
  - Stand-alone document anticipated
  - Will form the basis for generator-related contributions to CompF2/TF11/NF06 white papers