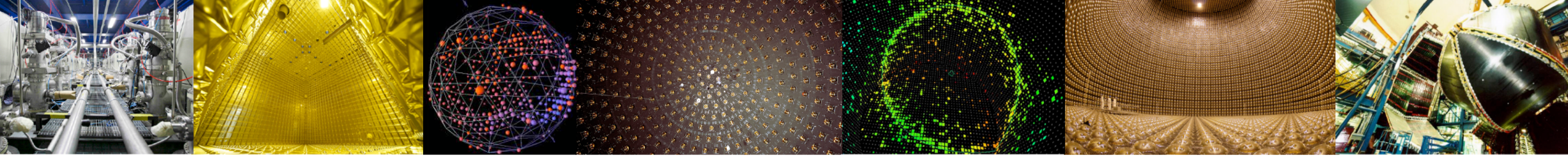


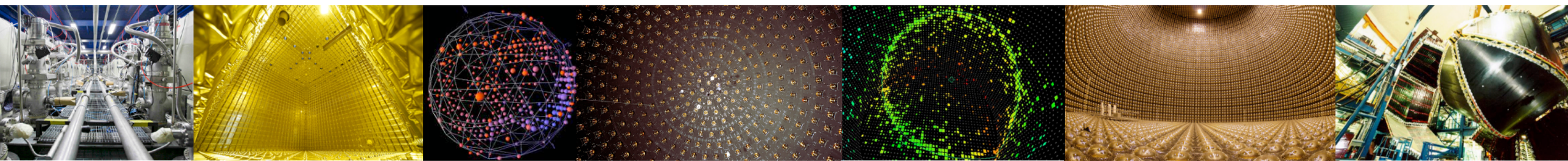
Achilles Overview

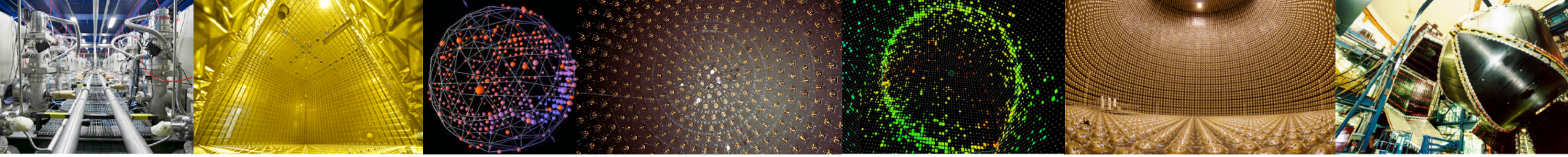
A CHIcagoLand Lepton Event Simulator

William Jay — MIT

with Joshua Isaacson, Alessandro Lovato, Pedro Machado, Noemi Rocco, and Luke Pickering

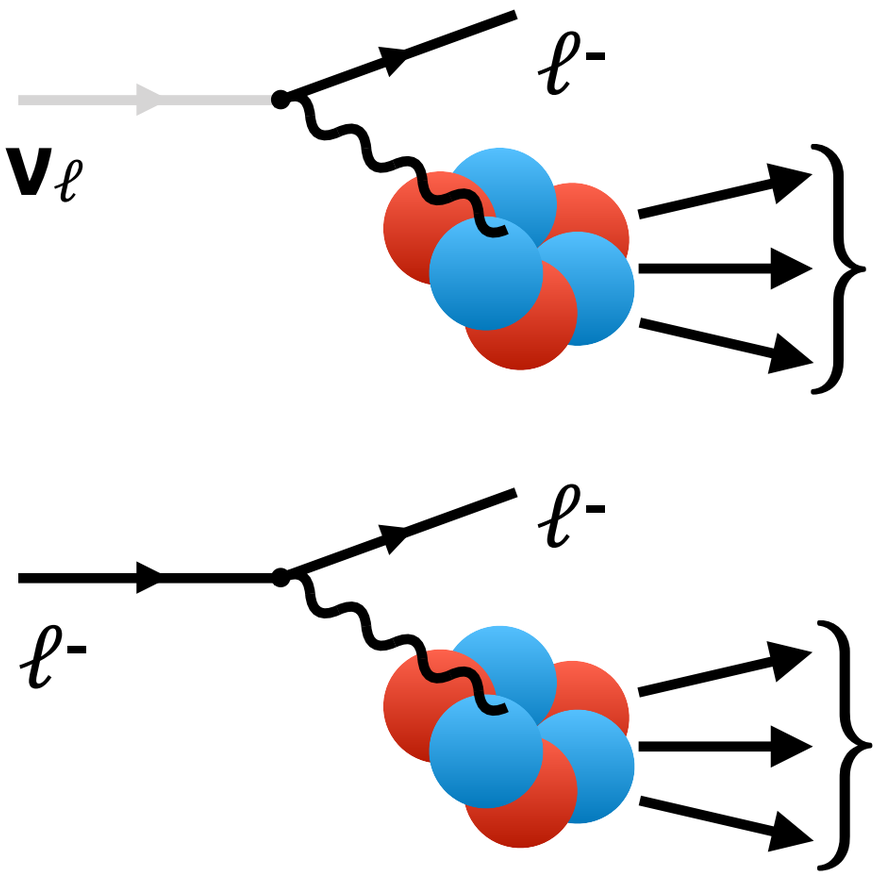
Workshop on Neutrino Event Generators
Fermilab
15-18 March 2023

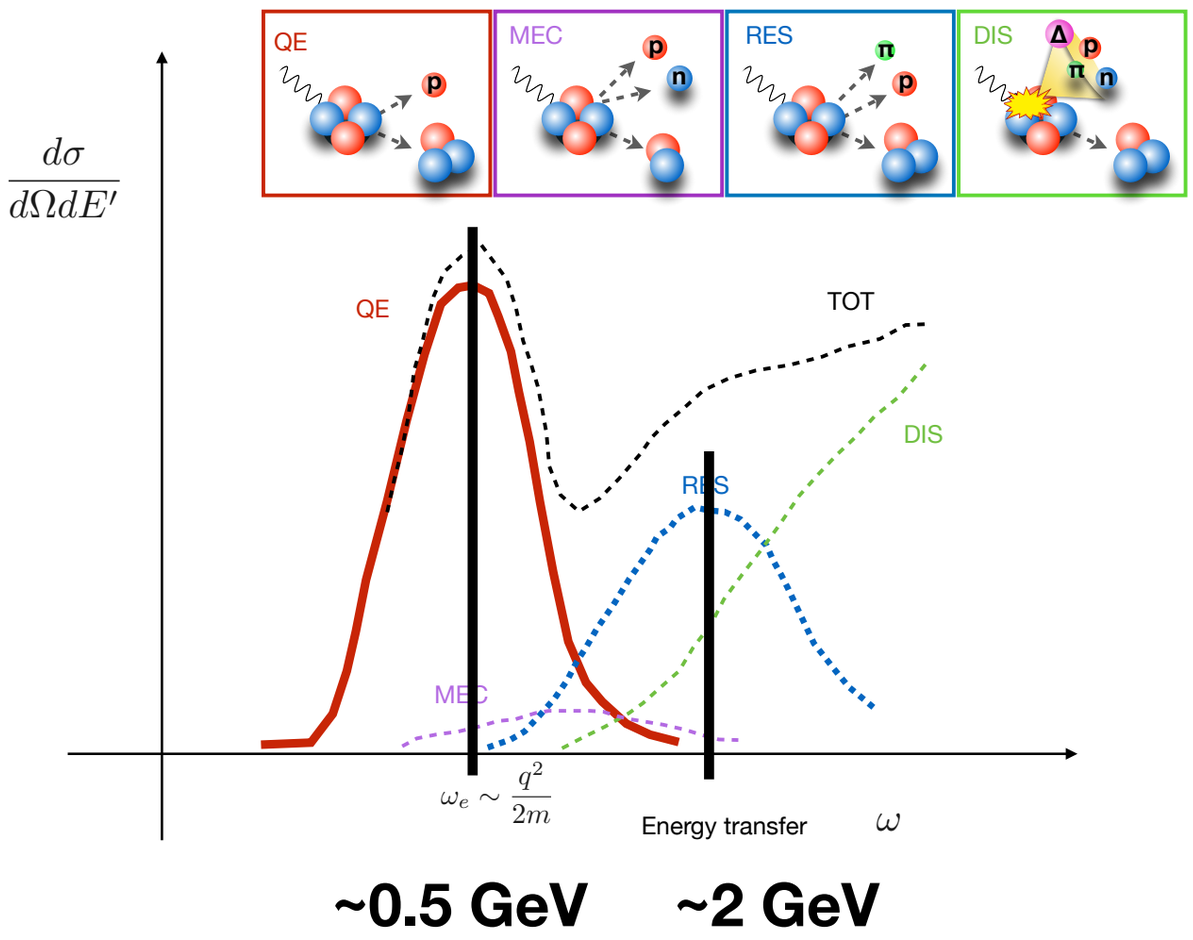




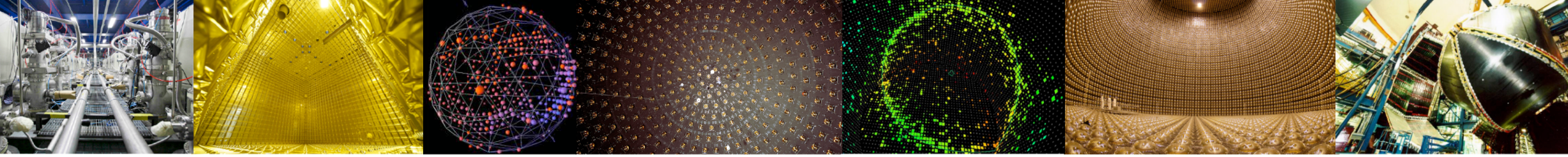
Achilles

Lepton Event Simulator





~0.5 GeV **~2 GeV**



Achilles — Recent updates

- We have a generator: https://arxiv.org/abs/2205.06378
- Uses our intranuclear cascade: https://arxiv.org/abs/2007.15570

PHYSICAL REVIEW C **103**, 015502 (2021)

New approach to intranuclear cascades with quantum Monte Carlo configurations

Joshua Isaacson,[1,*] William I. Jay,[1] Alessandro Lovato,[2,3] Pedro A. N. Machado,[1] and Noemi Rocco[1,2]
[1]*Theoretical Physics Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA*
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*INFN-TIFPA Trento Institute of Fundamental Physics and Applications, Via Sommarive, 14, 38123 Trento, Italy*

(Received 11 August 2020; accepted 21 December 2020; published 25 January 2021)

We propose a novel semiclassical approach to intranuclear cascades, which takes as input quantum Monte Carlo nuclear configurations and uses a semiclassical, impact-parameter-based algorithm to model the propagation of protons and neutrons in the nuclear medium. We successfully compare our simulations to available proton-carbon scattering data and nuclear-transparency measurements. By analyzing the dependence of the simulated observables upon the ingredients entering our intranuclear cascade algorithm, we provide a quantitative understanding of their impact. Particular emphasis is devoted to the role played by nuclear correlations, the Pauli exclusion principle, and interaction probability distributions.

DOI: 10.1103/PhysRevC.103.015502

PHYSICAL REVIEW D **107,** 033007 (2023)

Introducing a novel event generator for electron-nucleus and neutrino-nucleus scattering

Joshua Isaacson,[1] William I. Jay,[4] Alessandro Lovato,[2,3] Pedro A. N. Machado,[1] and Noemi Rocco[1]
[1]*Particle Theory Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA*
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
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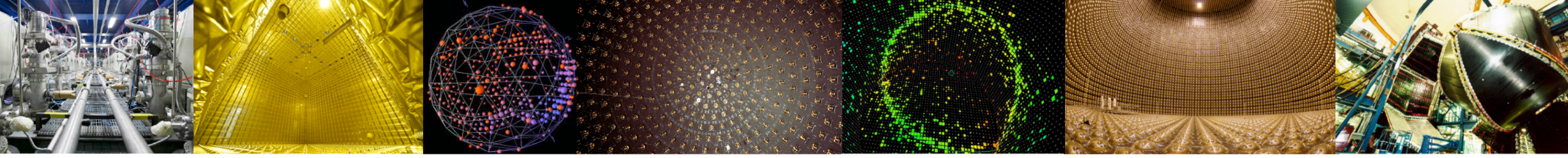
[4]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 16 June 2022; accepted 30 January 2023; published 22 February 2023)

We present a novel lepton-nucleus event generator: ACHILLES, **A** **CHI**cago **L**and **L**epton **E**vent **S**imulator. The generator factorizes the primary interaction from the propagation of hadrons in the nucleus, which allows for a great deal of modularity, facilitating further improvements and interfaces with existing codes. We validate our generator against high-quality electron-carbon scattering data in the quasielastic regime, including the recent CLAS/e4v reanalysis of existing data. We find promising agreement in both inclusive and exclusive distributions. By varying the assumptions on the propagation of knocked-out nucleons throughout the nucleus, we estimate a component of theoretical uncertainties. We also propose novel observables that will allow for further testing of lepton-nucleus scattering models. ACHILLES is readily extendable to generate neutrino-nucleus scattering events.



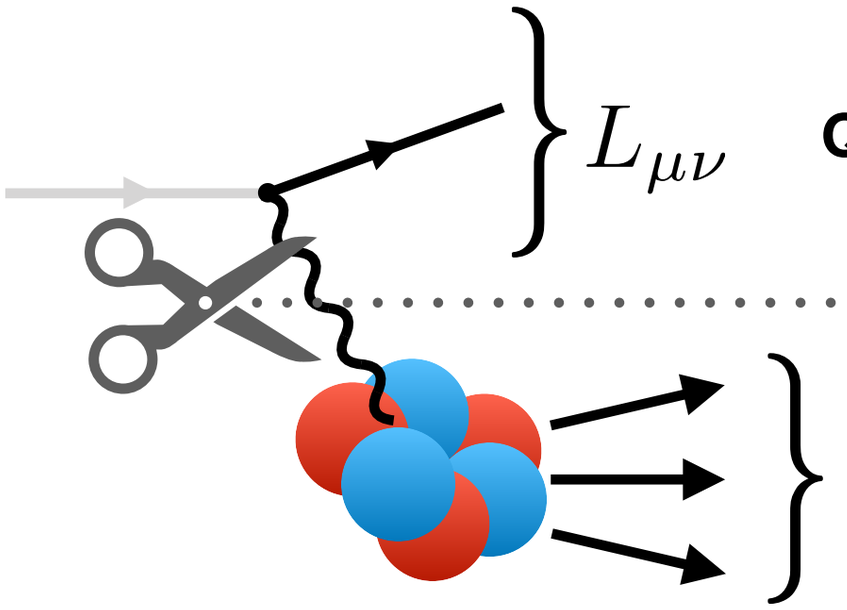
Achilles — Recent updates

Factorization of leptonic and hadronic tensors

- Automated leptonic tensor: https://arxiv.org/abs/2110.15319

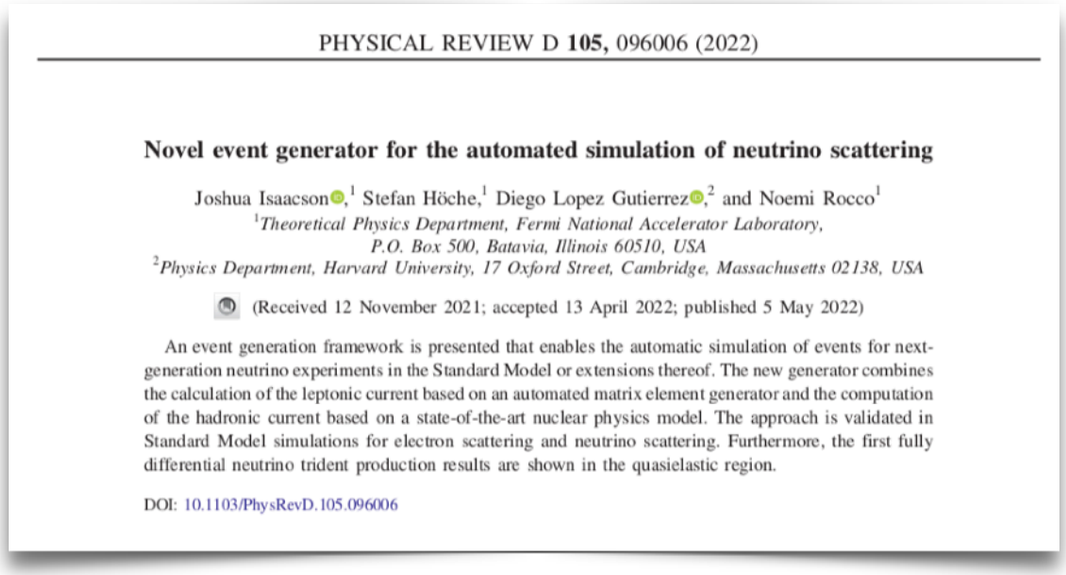
- Uses tools developed by LHC event generation community: Sherpa, Comix, FeynRules, UFO files

$$|\mathcal{M}|^2 = L_{\mu\nu} W^{\mu\nu} \frac{1}{P^2}$$



Calculable QED/EW/BSM physics

Nuclear/hadronic physics of initial interaction and subsequent evolution



PHYSICAL REVIEW D **105,** 096006 (2022)

Novel event generator for the automated simulation of neutrino scattering

Joshua Isaacson,[1] Stefan Höche,[1] Diego Lopez Gutierrez,[2] and Noemi Rocco[1]

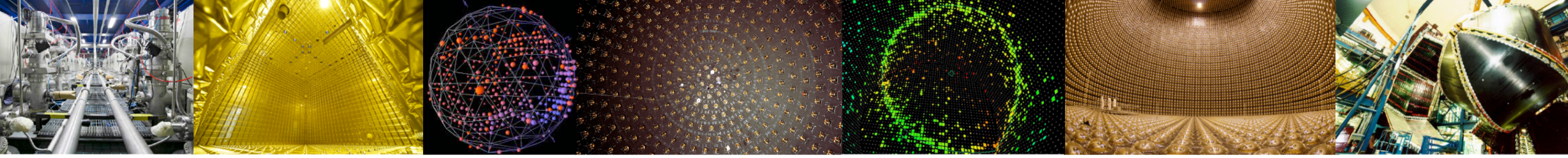
[1]*Theoretical Physics Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA*

[2]*Physics Department, Harvard University, 17 Oxford Street, Cambridge, Massachusetts 02138, USA*

(Received 12 November 2021; accepted 13 April 2022; published 5 May 2022)

An event generation framework is presented that enables the automatic simulation of events for next-generation neutrino experiments in the Standard Model or extensions thereof. The new generator combines the calculation of the leptonic current based on an automated matrix element generator and the computation of the hadronic current based on a state-of-the-art nuclear physics model. The approach is validated in Standard Model simulations for electron scattering and neutrino scattering. Furthermore, the first fully differential neutrino trident production results are shown in the quasielastic region.

DOI: 10.1103/PhysRevD.105.096006



Achilles — Recent updates

New API for nuclear models

- We have new API/extendible interface for nuclear models
- The API supports models implemented in Fortran or CPP. Extension to models in python is straightforward if there is community interest
- Allows, e.g., for different nuclear spectral functions [Also more general!]
- See talk “Achilles Fortran Interface” by Josh Isaacson, Wed 1:40 PM

$$W_{\mathrm{N}}^{\mu\nu} \propto S_n \otimes w_n^{\mu\nu}$$

Nuclear hadronic tensor

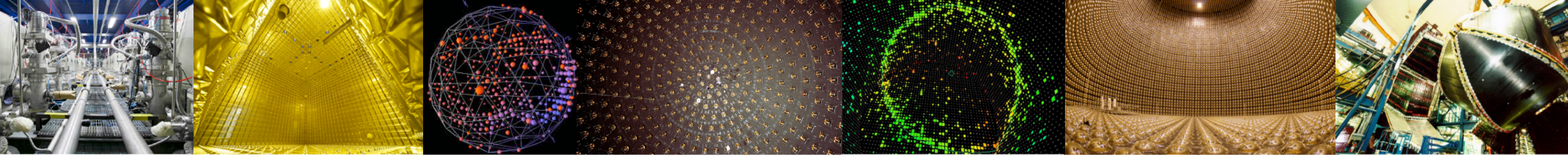
Nuclear spectral function (exactly calculable in nuclear many-body theory up to ~O^{16})

= “probability to find a nucleon with a given momentum inside the nucleus”

Nucleon hadronic function (experimentally measurable or calculable with lattice QCD)

For QE scattering:

$$w_n^{\mu\nu} \sim |\mathrm{form\ factor}|^2$$



Achilles — Recent updates

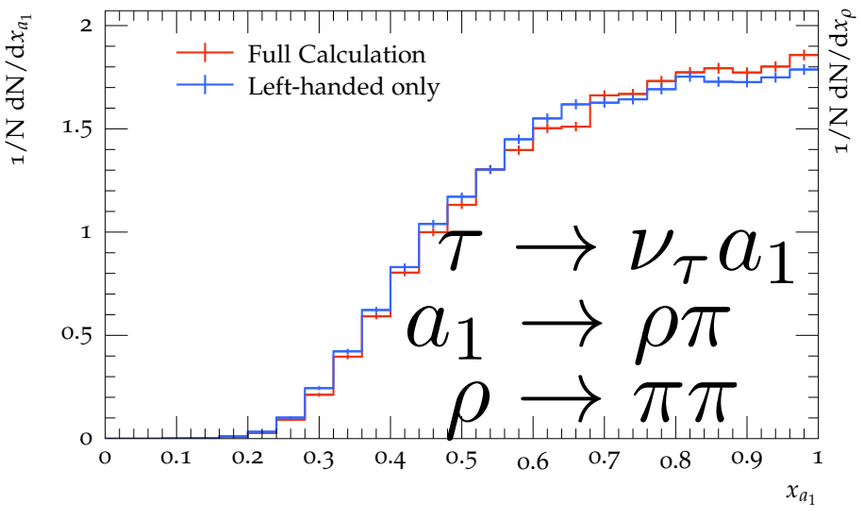
Application: Correlated decays in neutrino experiments

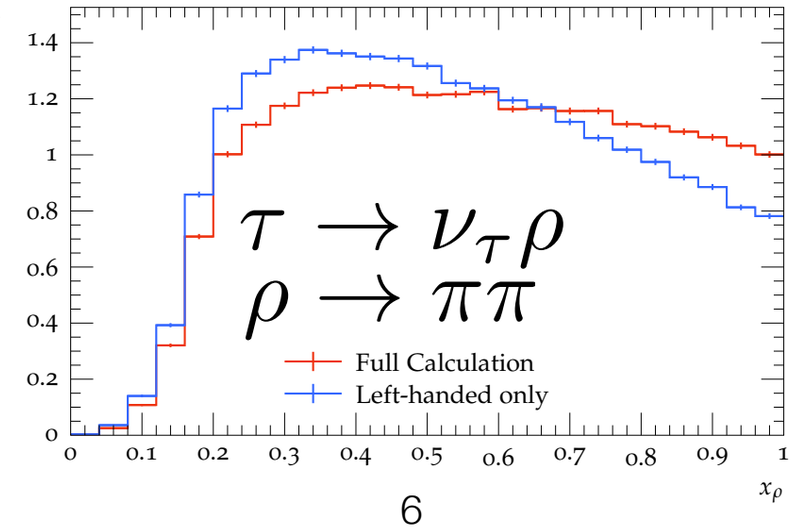
- arXiV:2303.08104: J. Isaacson, S. Höche, F. Siegert, and S. Wang

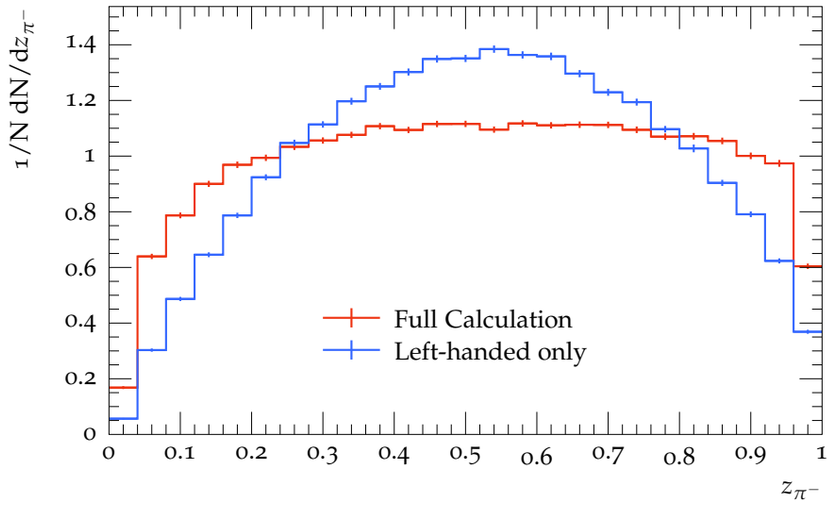
- First fully differential predictions for ν_τ scattering at DUNE energies, including all spin correlations, all τ decay channels

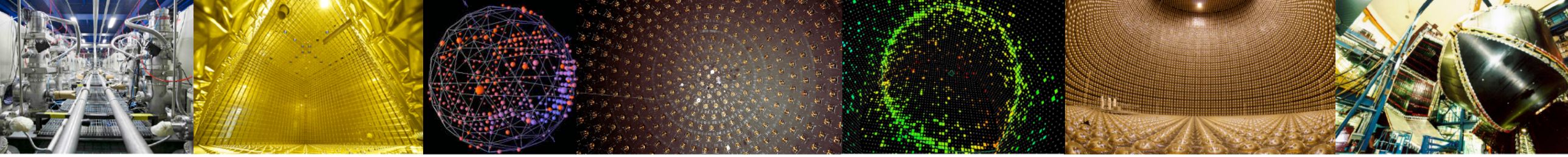
- Calculated using generic interface between Achilles and Sherpa

- Correlations between production and decay are *automatically* maintained on an *event-by-event* basis









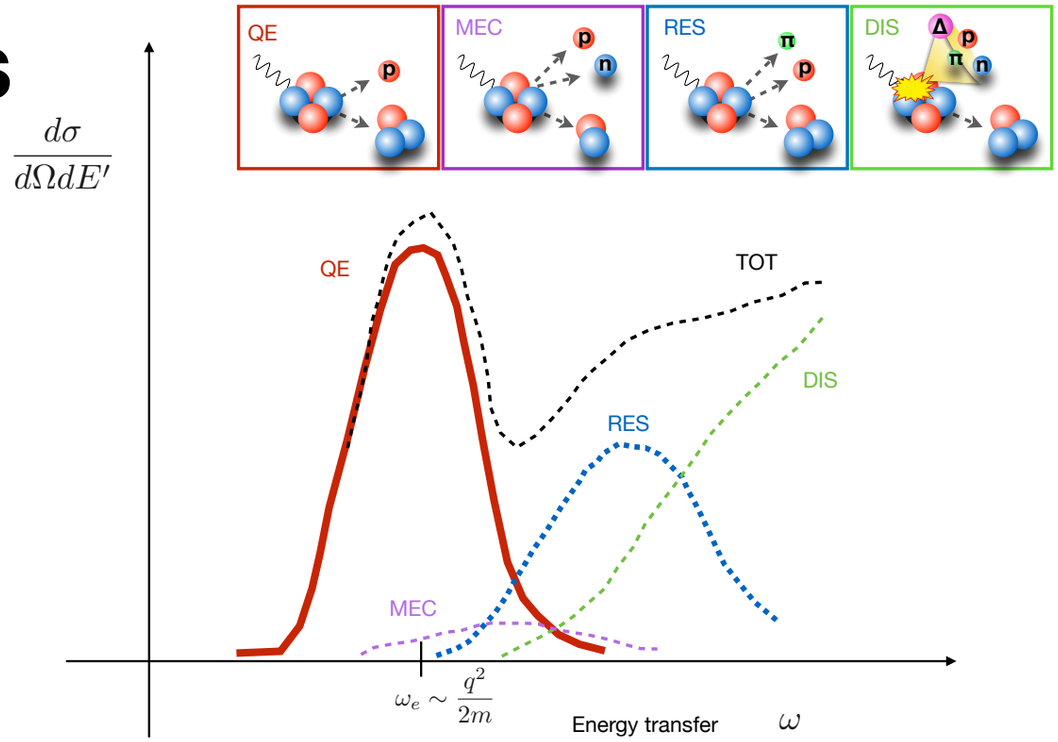
Achilles — What's next?

More production processes

- Existing generator: QE scattering only

- Near-term goals: particle production (+decay) at the initial interaction and cascade

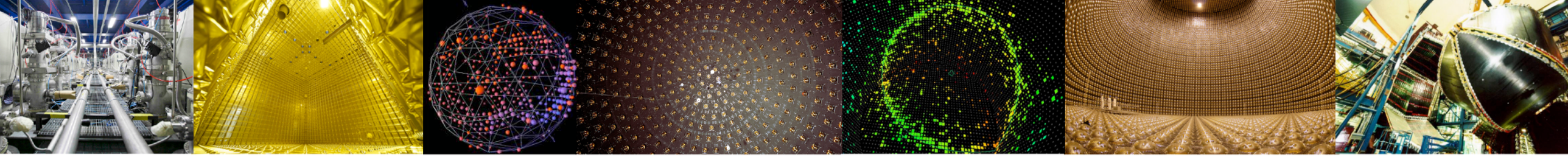
- Initial "hard interaction"
  - **Meson-exchange currents** in the spectral function formalism
  - **Resonant scattering** in the dynamical coupled channel formalism
  - Longer term: consistent treatment of DIS



- Cascade
  - **Pion production**
  - **Propagation/decay of Δ**

$$NN \rightarrow N\Delta \rightarrow NN\pi$$

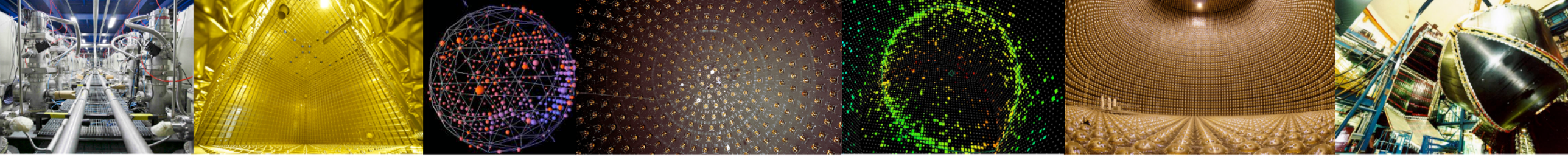
(Can take from data. Lattice calculations will always help.)



Achilles — Adding new theory models

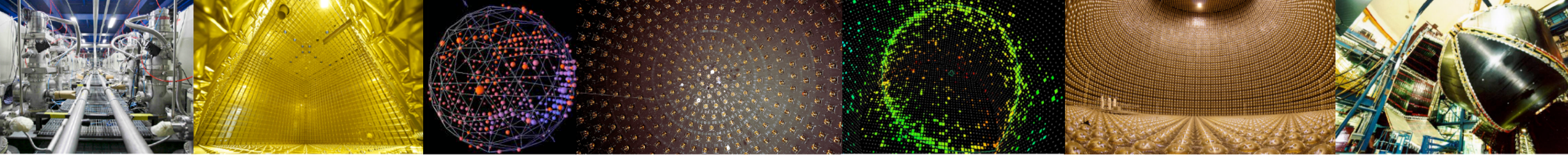
How do I add my favorite theory calculation?

- **Nuclear Models:**
  - Anyone can implement their own nuclear model into the code using the new Fortran/CPP API. (Python also easy if there is sufficient community interest)
  - Essentially by definition, event generators must deliver fully exclusive events.
  - For official support (i.e., for distribution by us with the Achilles code), new nuclear models should be exclusive.
- **Beyond-the-Standard-Model interactions**
  - For new-physics models affecting the leptonic tensor, this is handled automatically with Achilles+Sherpa and FeynRules
  - At the moment: User must hand-code interactions of the new physics with the nucleus in terms of form factors (F1, F2, etc…). This is just a technical issue with interfacing hadron- and nuclear-level (rather than quark-level) physics with FeynRules. No downstream issue with Achilles+Sherpa.
  - See talk by Pedro Machado “BSM interfaces” on Wed, 1:20PM
- **Achilles Goal:** Be open and responsive to the needs of the community.



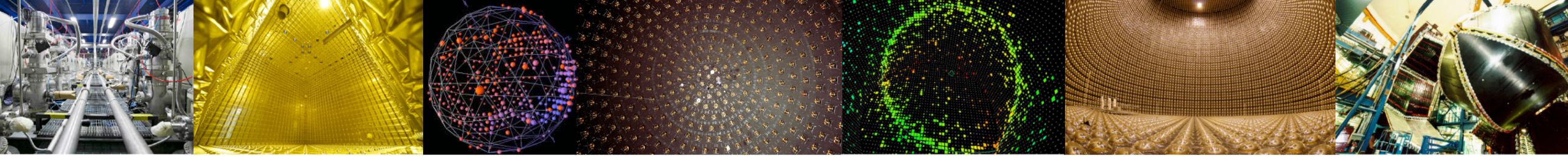
Achilles — Flux and Geometry

- **Geometry: placing events within the detector**
  - Work in progress: New geometry driver
  - Goal: open to the community, broad usability by the community. Not just for Achilles!
  - See talk by Luke Pickering “New Developments in Flux and Geometry”, Thursday 11:20AM
- **Flux: handling the experimental E_ν spectrum**
  - Current treatment: read histograms and interpolate. Ideally (but let’s talk!):
    1. Sample from a “flux function” and use to optimize the integrator (“Vegas grids”)
    2. Generate events for incoming neutrinos, look up the weight from the optimized grid
  - Open questions: How best to organize this step, interface with the needs of the experiments? What are we overlooking with our perspective as theorists?
- Flux/geometry may have *non-trivial impact for BSM discovery*, e.g., of long-lived particles
  - Pedro Machado “BSM interfaces” on Wed, 1:20PM
  - Gray Putnam, “ICARUS Generation Pipeline” on Wed, 2:20PM



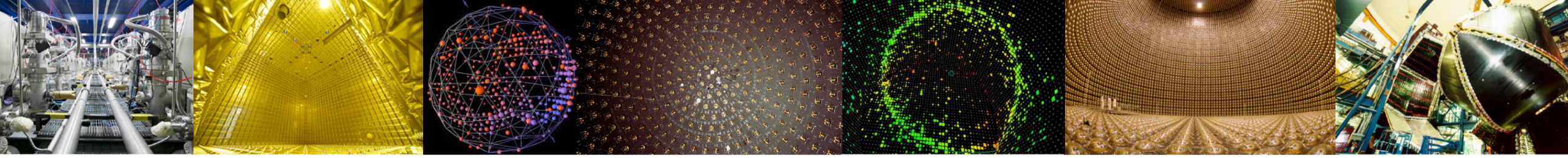
Achilles — Output format

- By default, **Achilles gives:**
  - Unweighted events, following the unweighting procedure traditionally used by Sherpa/LHC event generator codes.
  - Events including the particle ID and 4-momenta for all outgoing particles, and interaction locations within the nucleus
- We are supportive of the new NuHepMC3 output format.
  - See github.com/NuHepMC/Spec
  - See talk by Steve Gardiner “Event Formats and HepMC3”, Thursday 9:20AM



Achilles — Theory Systematics

- **Goal/Credo:**
  - **Achilles aspires to be a theory-driven event generator, with consistent treatment of known theoretical uncertainties**
- **Observations**:
  - Robustly quantifying systematic errors is generally a tough problem
  - Once chosen, correctly propagating systematics errors is comparatively easy
  - For uncertainties in the “hard interaction” the theoretical uncertainty amounts to an uncertainty in the overall event weight, which is straightforward to propagate
- **Example: Systematic uncertainties from lattice QCD calculation of nucleon axial FF**
  - Calculations are/will be soon available with complete statistical+systematic error budgets
  - These uncertainties should be incorporated by event generators
- See talks in afternoon sessions “Systematics: Tuning” and “Systematics on Th afternoon.
  - Talk by Michael Wagman and Noemi Rocco “Theory Systematics” on Th 3:00PM



Achilles — Summary

- We are a **theory-driven event generator** aiming to be responsive to **current and upcoming experimental needs**
- **Achilles employs a modular design to factorize physically different processes:**
  - Leptonic vs hadronic tensors,
  - Nuclear vs hadronic physics
  - “Hard interaction” vs intranuclear cascade
- Achilles currently supports quasi-elastic scattering (e.g., spectral function formalism)
- In the near term (≲ year), we expect to implement MEC and resonant production mechanisms and particle production/decay in the intranuclear cascade
- **We strongly support community efforts toward:**
  - Quick integration of new theory (nuclear, BSM, etc…) models
  - Standardization of output formats (i.e., NuHepMC3)
  - Development of flux/geometry drivers
  - Robust quantification of systematic uncertainties
  - Development of event-generator ecosystem for neutrino experiments