Current Status of the Achilles Event Generator

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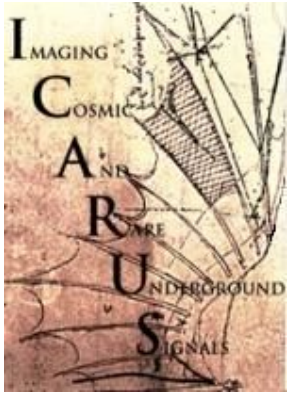
NuSTEC Cross Experiment Working Group Seminar

3 October 2024

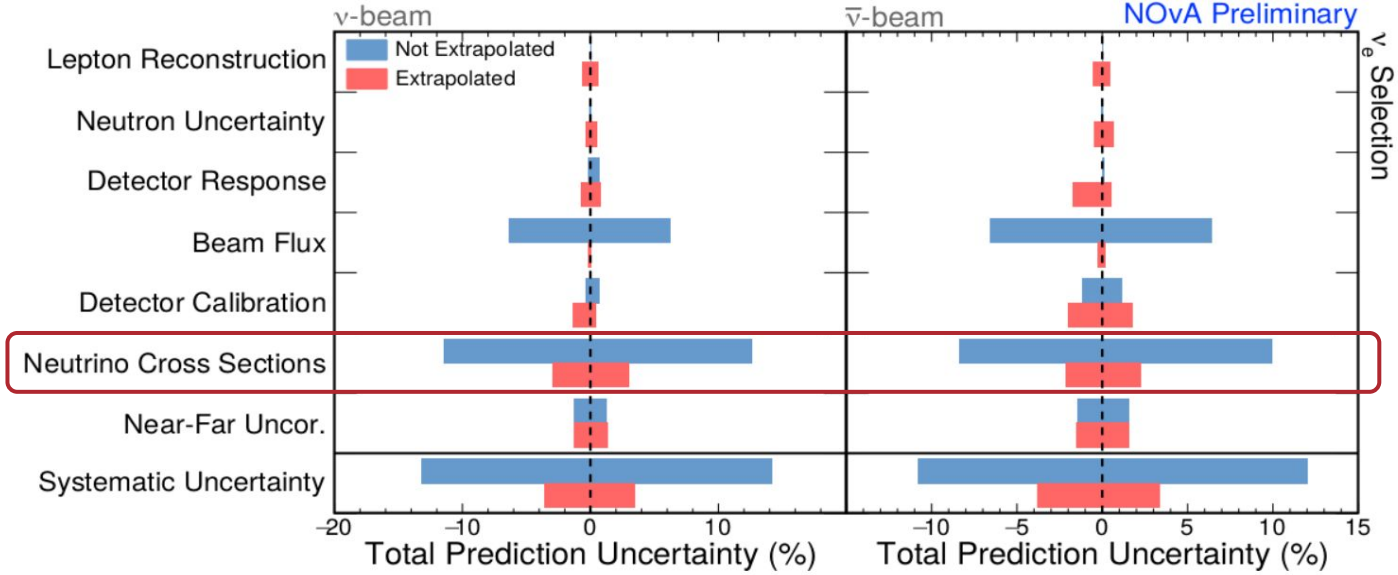
ACHILLES

Motivation



- Large number of experiments attempting to measure neutrino interactions and oscillations using accelerator beams
- Requires significant theory effort to meet current and future precision goals

Motivation



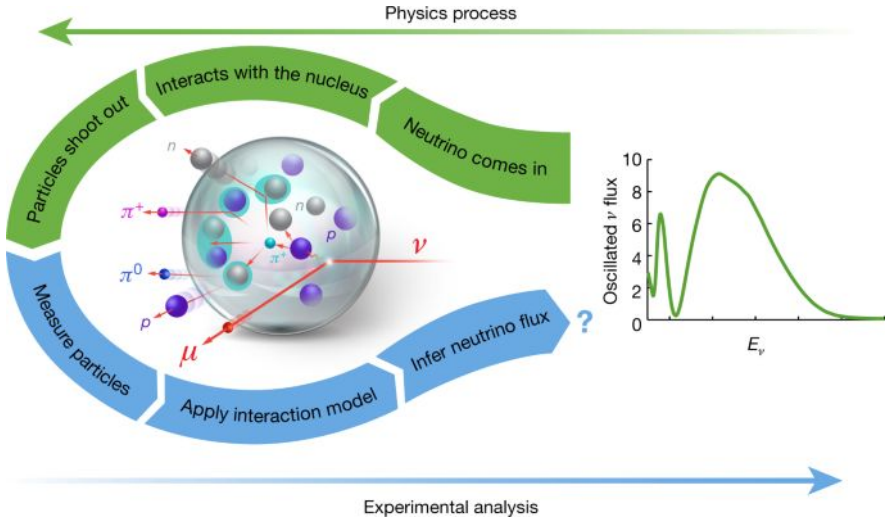
From the DUNE CDR2 (1512.06148)

As illustrated in Chapter 3, studies on the impact of different levels of systematic uncertainties on the oscillation analysis indicate that uncertainties exceeding 1% for signal and 5% for backgrounds may result in substantial degradation of the sensitivity to CP violation and mass hierarchy. The

Motivation

$$\frac{N_{FD}}{N_{ND}} \propto \frac{\int \mathrm{d}E_\nu \frac{\mathrm{d}\phi_\alpha^{FD}}{\mathrm{d}E_\nu} P(\nu_\alpha \to \nu_\beta; E_\nu) \sigma_\beta(E_\nu) \mathcal{M}_\alpha^{FD}(E_\nu, E_{reco})}{\int \mathrm{d}E_\nu \frac{\mathrm{d}\phi_\alpha^{ND}}{\mathrm{d}E_\nu} \sigma_\alpha(E_\nu) \mathcal{M}_\alpha^{ND}(E_\nu, E_{reco})}$$

- Number of events in near / far detector
- Oscillation probability
- Neutrino-nucleus cross section
- Migration matrix (Depends on topology of events)
- Need theory driven neutrino event generators



Nature 599 (2021) 7886, 565-570

Achilles: A CHIcagoLand Lepton Event Simulator

Core Authors








Undergraduates




Achilles: A CHIcagoLand Lepton Event Simulator

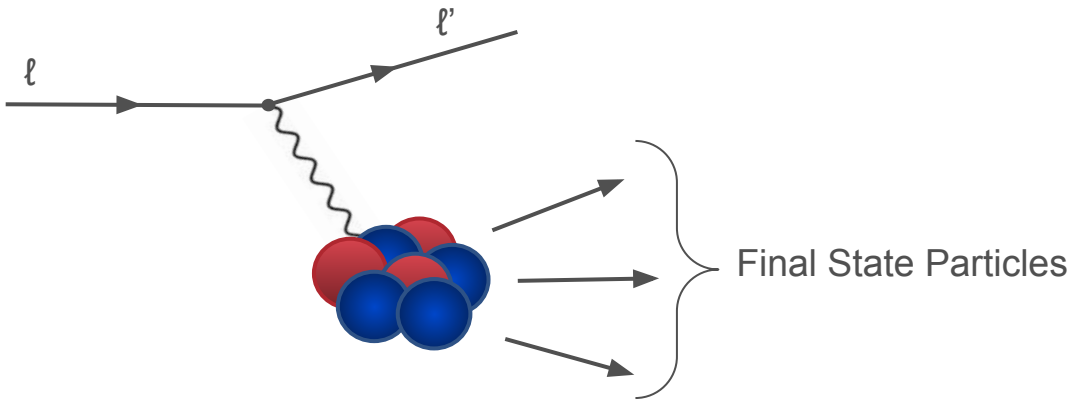
Project Goals:

- Theory driven
- Leverage experiences from LHC event generators
- Develop modular neutrino event generator
- Provide automated BSM calculations for neutrino experiments
- Evaluate theory uncertainties
- Appropriately handle correlations within events

Isaacson, Jay, Lovato, Machado, Rocco [2007.15570],
Isaacson, Jay, Lovato, Machado, Rocco [2205.06378],

Simulating the Standard Model

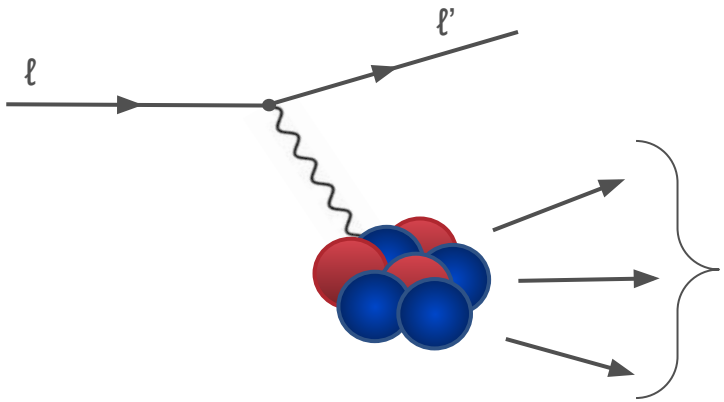
Calculation Breakdown



$$\mathrm{d}\sigma = \left(\frac{1}{|v_A - v_\ell|}\frac{1}{4E_A^{\mathrm{in}}E_\ell^{\mathrm{in}}}\right) \times |\mathcal{M}|^2 \times \prod_f \frac{\mathrm{d}\mathrm{p}_\mathrm{f}^3}{(2\pi)^3}(2\pi)^4\delta^{(4)}\left(p_A + p_\ell - \sum_f p_f\right)$$

Flux Factor | Matrix Element | Phase Space

Calculation Breakdown

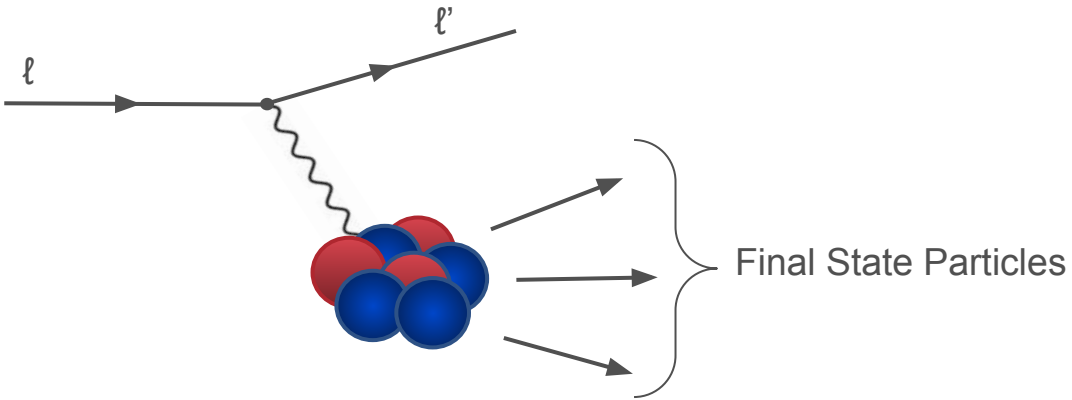


- $\mathcal{V}$: Primary interaction vertex
- $\mathcal{P}$: Time evolution out of nucleus
- Approximate as incoherent sum (i.e. neglect interference between primary interaction and cascade)

$$|\mathcal{M}(\{k\} \to \{p\})|^2 = \left| \int_{p'} \mathcal{V}(\{k\} \to \{p'\}) \times \mathcal{P}(\{p'\} \to \{p\}) \right|^2$$

$$\simeq \int_{p'} |\mathcal{V}(\{k\} \to \{p'\})|^2 \times |\mathcal{P}(\{p'\} \to \{p\})|^2$$

Hadronic Current and Leptonic Current

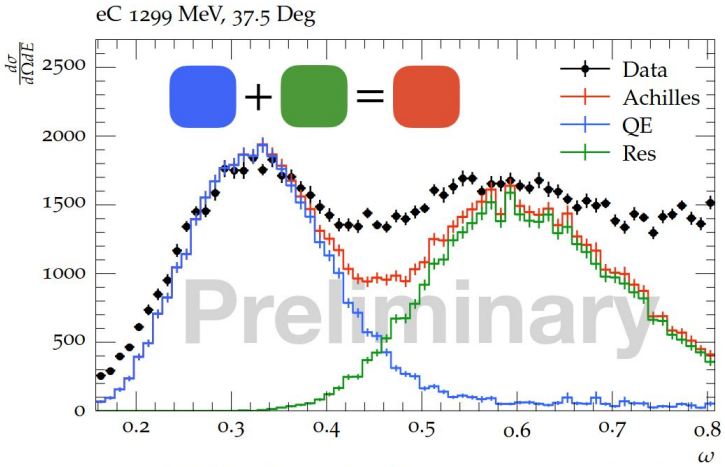


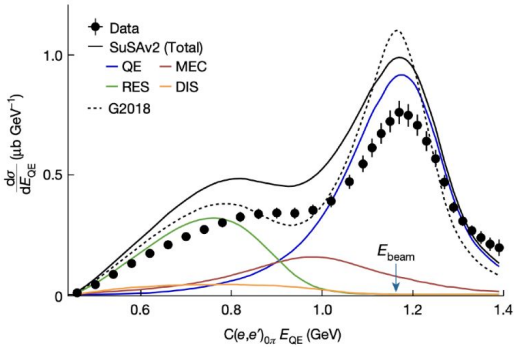
$$|\mathcal{M}|^2 \propto \left| \sum_i L_\mu^{(i)} W^{(i)\mu} \right|^2$$

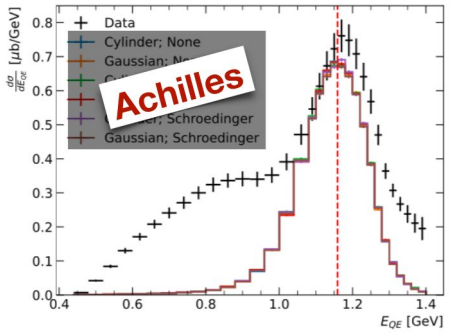
- $L_\mu^{(i)}$: Leptonic Current
- $W^{(i)\mu}$: Hadronic Current
- Sum goes over possible exchange bosons
- Automatically handles interference effects (important for BSM)
- Easy extension point in Achilles to implement new nuclear models
- Less bookkeeping than handling tensors, but tensors possible if needed

Primary Interaction

- Electroweak currents from nuclear theory:
$$J^{\mu}(q) = \sum_i j_i^{\mu}(q) + \sum_{i<j} j_{ij}^{\mu}(q) + \cdots$$
- Impulse Approximation with SF:
$$\left|\Psi_f\right\rangle = \left|p\right\rangle \otimes \left|\Psi_f^{A-1}\right\rangle$$
- Express in terms of leptonic and hadronic currents → interferences come for free
$$\mathcal{V} = \sum_i L_{\mu}^{(i)} W^{\mu(i)}$$
- Have Quasielastic, Resonance (DCC model), One-body-two-body interference implemented
- Important to validate against electron scattering data using same framework (i.e. same code)



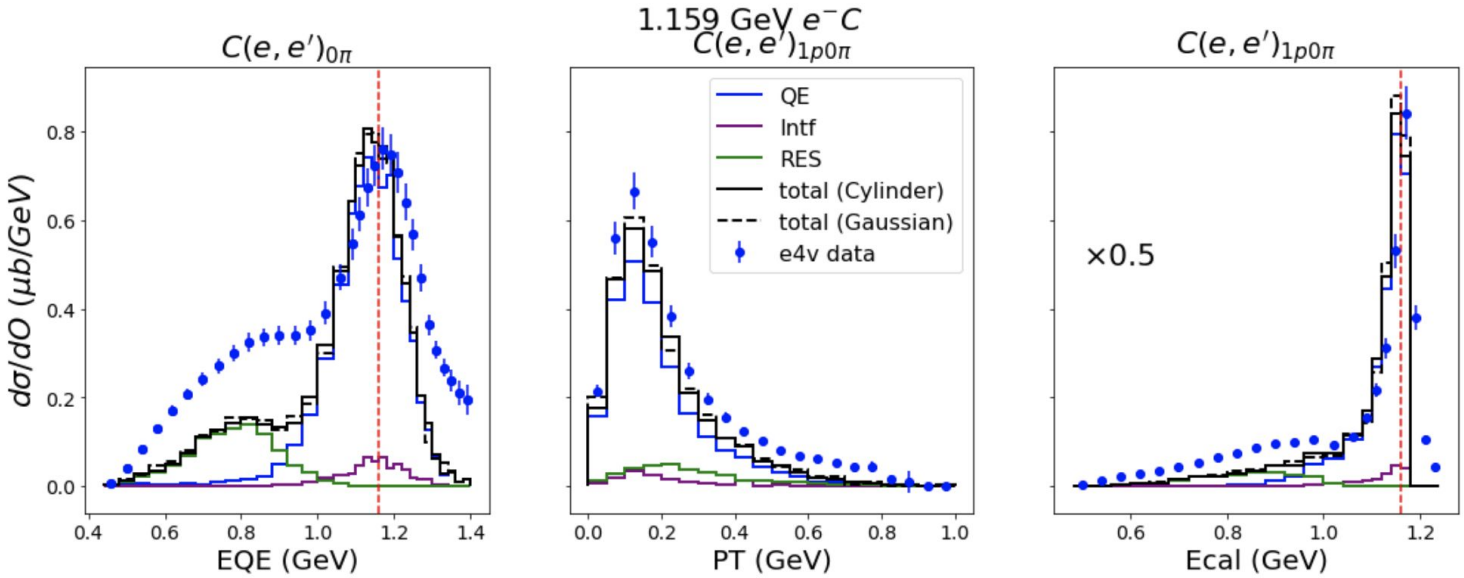




Nature 599 (2021) 7886, 565-570

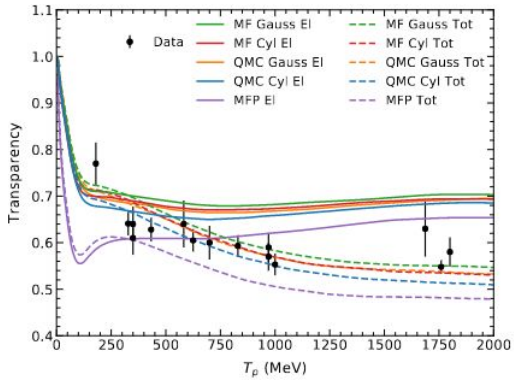
Isaacson, Jay, Lovato, Machado, Rocco [2205.06378]

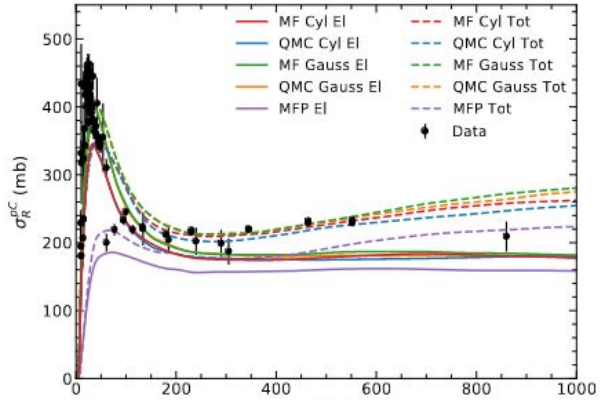
Update e4v comparison

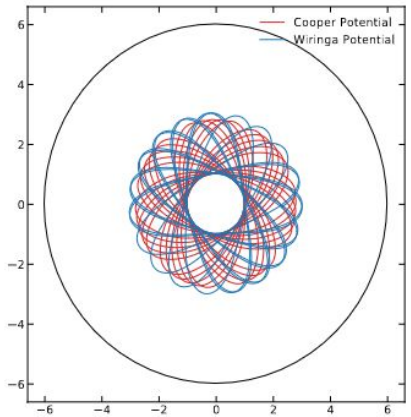


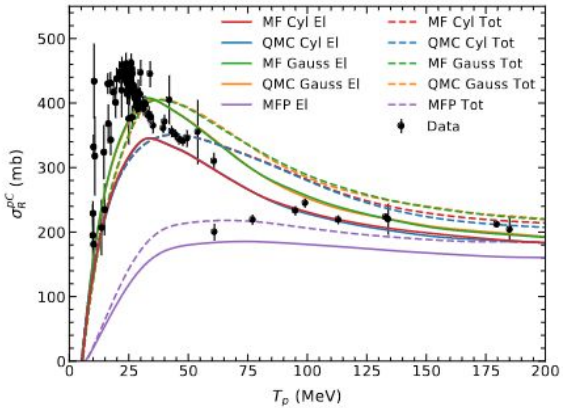
Intranuclear Cascade:Nucleons

Isaacson, Jay, Lovato, Machado, Rocco [2007.15570]
Isaacson, Jay, Lovato, Machado, Rocco [2205.06378]









- Novel cascade using nuclear configurations
- Interaction between nucleons treated as probabilistic model inspired from LHC

$$P(b) = \exp\left(-\frac{\pi b^2}{\sigma}\right)$$

$$P(b) = \Theta\left(\pi b^2 - \sigma\right)$$

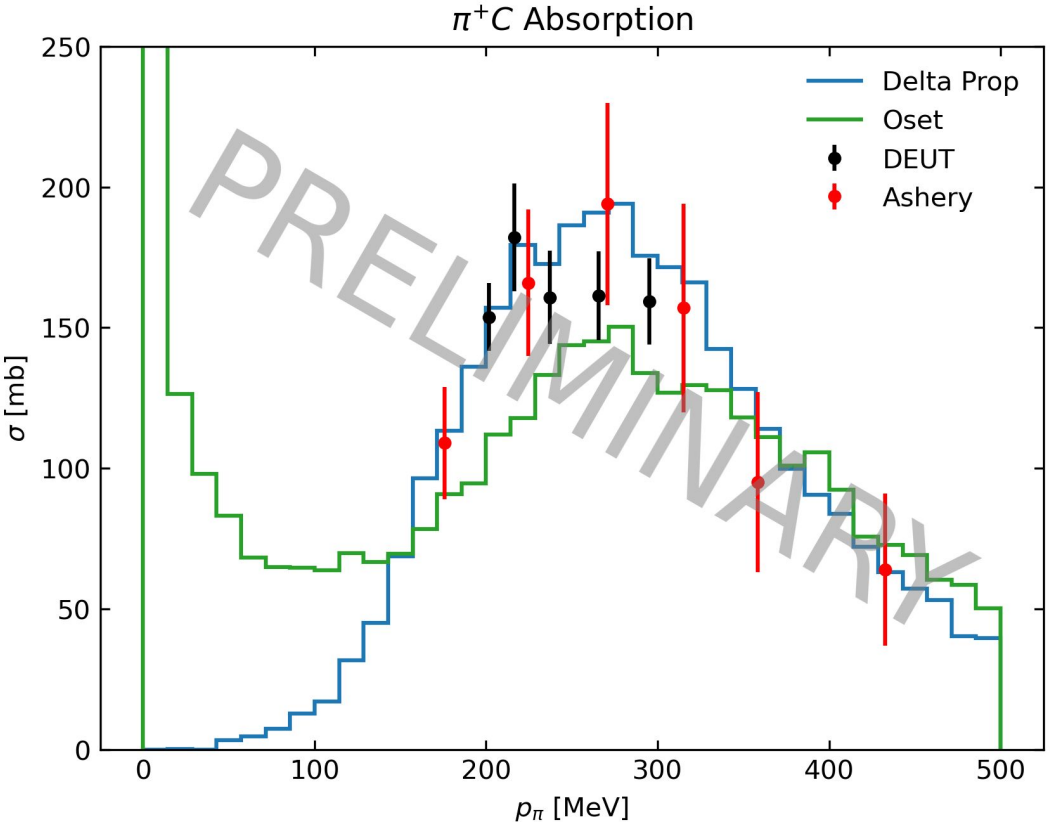
- Propagation either straight-lines or in optical potential using classical evolution
- In-medium cross-section corrections from Pandharipande-Pieper
- Incorporate Pauli-blocking and formation zone

Intranuclear Cascade: Pions

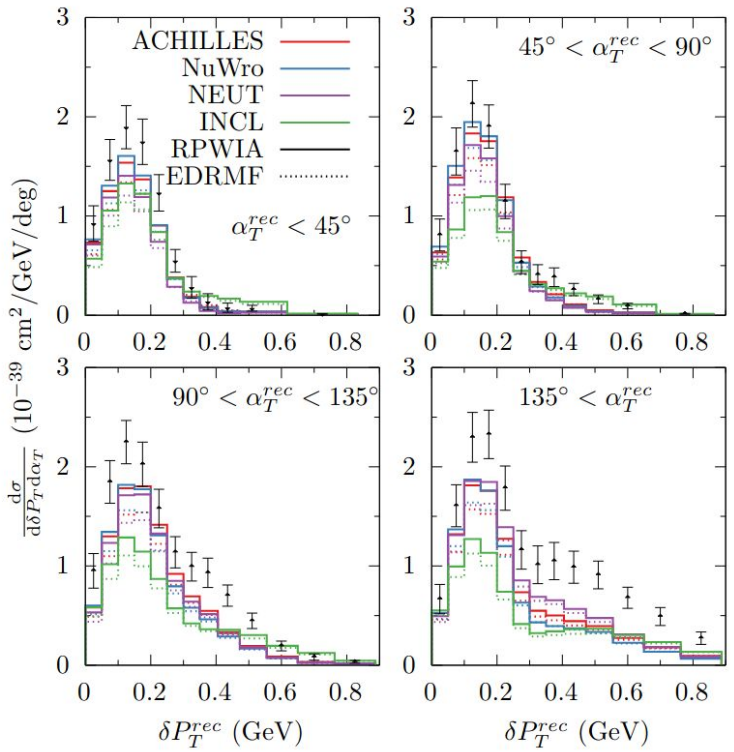
- Multiple approaches to estimate model uncertainty:
  a. Propagate Deltas through the cascade based on single pion-exchange
     Nuclear Phys. A 459 (1986) 503-524
  b. One-step absorption probability based on Oset
     Nuclear Phys. A 484 (1988) 557-592
     With the DCC octet meson-baryon interactions, including hyperons
     Phys. Rev. C 88, 035209
- Propagating Delta approach does not contain any in-medium modifications yet, currently only has Delta(1232) resonance, and missing background channel:

$$\pi NN \rightarrow NN$$

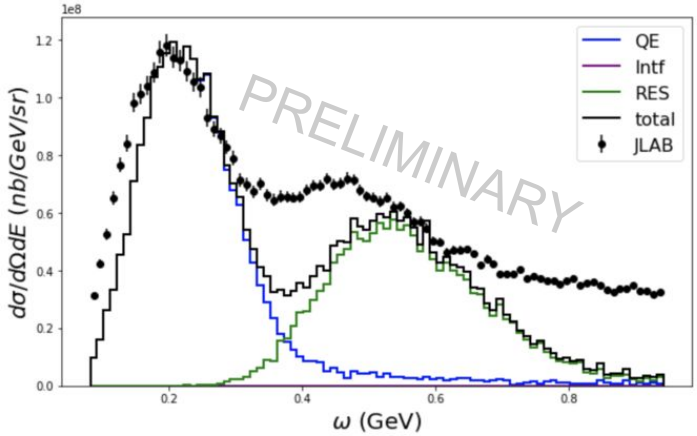
- Oset model includes both 2-nucleon and 3-nucleon absorption rate, but kinematics only two body final state



Including Argon

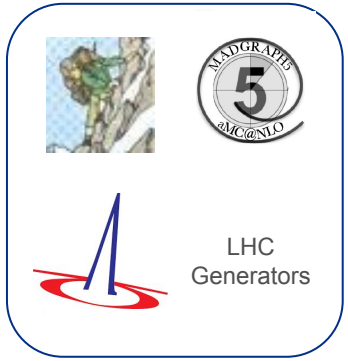


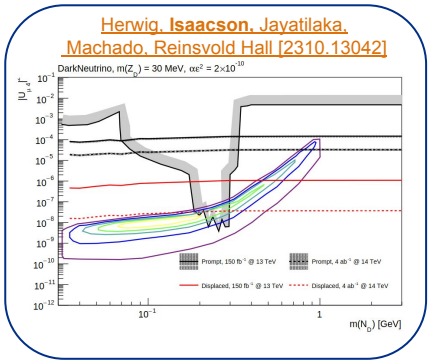
- Spectral function and nuclear configurations obtained from Woods-Saxon single-particle orbitals A. Nikolakopoulos, [Isaacson], et. al. [2406.09244]
- Still missing mean-field spectral function to obtain interference contribution (available soon)



Simulating Beyond the Standard Model

Beyond the Standard Model





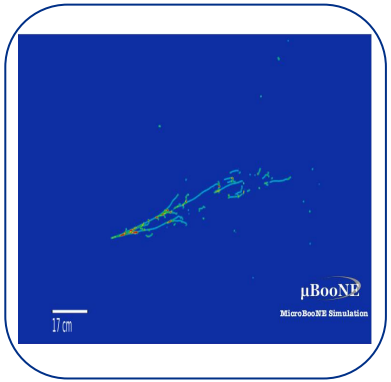
Universal Feynman Output:

- Developed by the LHC community
- Model defined by Lagrangian
- Reduces implementation bottleneck

Degrande, et. al. [1108.2040],
Darmé **[Isaacson]**, et. al. [2304.09883],

$$\mathcal{L}_{\mathcal{D}} \supset \frac{m_{Z_{\mathcal{D}}}^2}{2} Z_{\mathcal{D}\mu} Z_{\mathcal{D}}^{\mu} + g_{\mathcal{D}} Z_{\mathcal{D}}^{\mu} \bar{\nu}_{\mathcal{D}} \gamma_{\mu} \nu_{\mathcal{D}} + e\epsilon\, Z_{\mathcal{D}}^{\mu} J_{\mu}^{\mathrm{em}} + \frac{g}{c_W} \epsilon'\, Z_{\mathcal{D}}^{\mu} J_{\mu}^{Z}$$

Neutrino Generators



Beyond the Standard Model (UFO 2.0)

- Vertices can be defined for arbitrary models as a sum over colors, couplings, form factors, and Lorentz structures

$$\mathcal{V}^{a_1 \ldots a_n, \ell_1 \ldots \ell_n} = \sum_{i,j} C_i^{a_1 \ldots a_n} G_{ij} \mathcal{F}_j \left(p_1, \ldots, p_n\right) L_j^{\ell_1 \ldots \ell_n} \left(p_1, \ldots, p_n\right)$$

- Possible to absorb definition of form factor into Lorentz structure and define within the model as an arbitrary function

$$L_j^{\ell_1 \ldots \ell_n} \left(p_1, \ldots, p_n\right) \to \mathcal{F}_j \left(p_1, \ldots, p_n\right) L_j^{\ell_1 \ldots \ell_n} \left(p_1, \ldots, p_n\right)$$

See section 4.2 of Darmé **[Isaacson]**, et. al. [2304.09883], for details

Beyond the Standard Model

Automated Matrix Element Calculation:

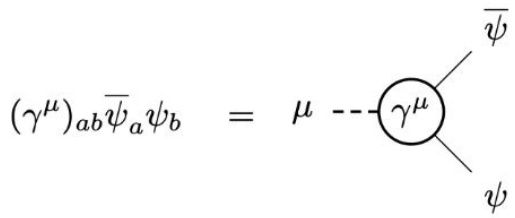
Berends and Giele [Nucl. Phys. B 306 (1988) 759-808,
Höche et al. [1412.6478],
Isaacson, Höche, Gutierrez, Rocco [2110.15319],

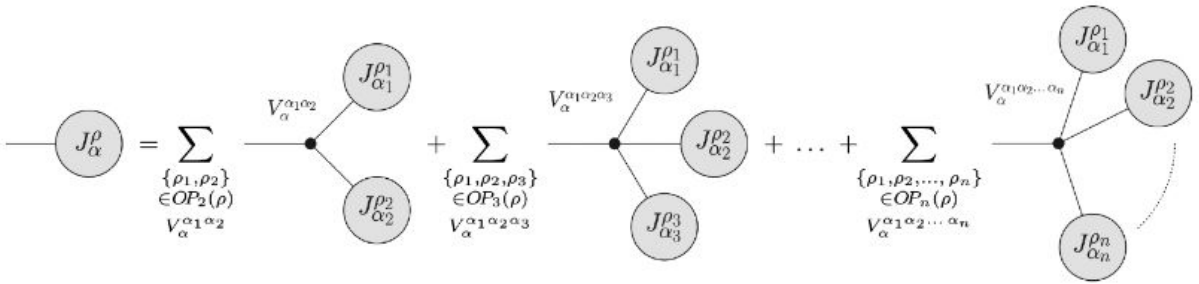
- Use recursive definition for (off-shell) currents:

$$(\text{current}) = (\text{propagator}) \times \sum (\text{vertex}) \times (\text{subcurrents})$$

- Current limitations in Achilles:
  - Only handle scalar, spin-½, spin-1 particles
  - Requires spin-1 probe of nucleus
  - Color-singlet particles only

Example Vertex:

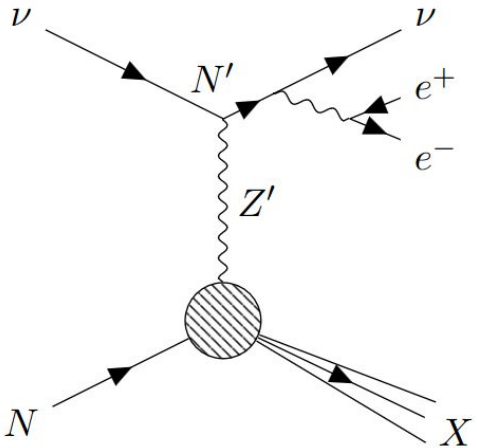




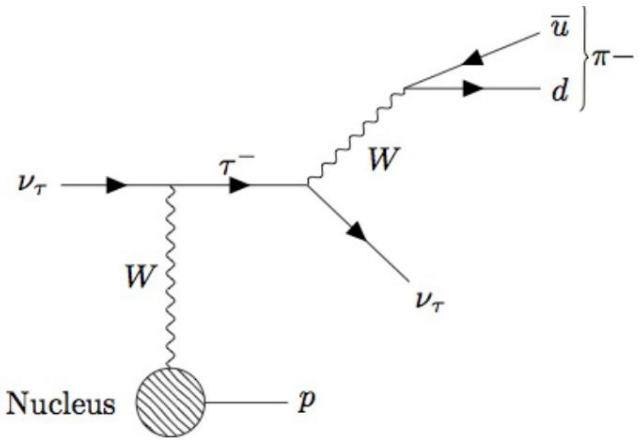
Spin Correlations

Spin Correlations

- Two methods to handle spin-correlations in primary interaction
  a. Generate the full 2-to-n body phase space
  b. Propagate the spin-density matrix
- Both methods available in Achilles
- Spin-density better when having to mix two different EFTs together (i.e tau decay)



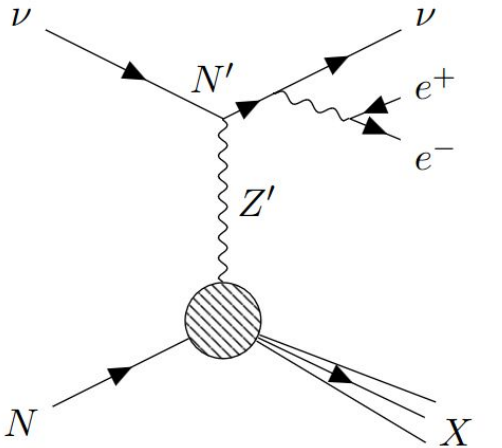
Isaacson, Höche, Gutierrez, Rocco [2110.15319]



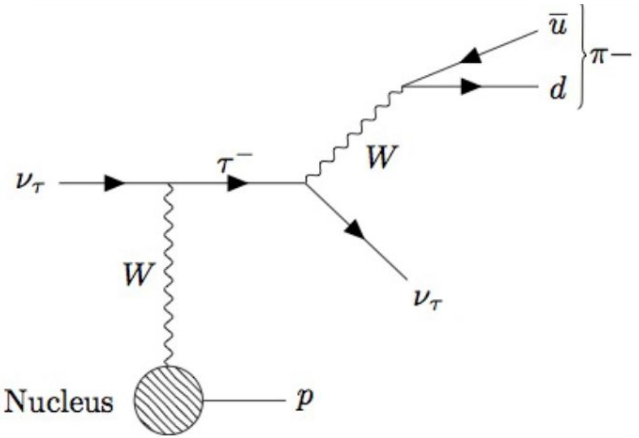
Isaacson, Höche, Siegert, Wang [2303.08104]

Spin Correlations

	Achilles	Every other neutrino generator
2 to n-body scattering	✓	✗
Spin-density Matrices	✓	✗



Isaacson, Höche, Gutierrez, Rocco [2110.15319]



Isaacson, Höche, Siegert, Wang [2303.08104]

Spin Correlations: 2 to n-body scattering

- Full phase space → separation of Dirac and Majorana
- GENIE includes this model, but handles it with repeated decays → only can simulate Majorana case (no spin correlations)

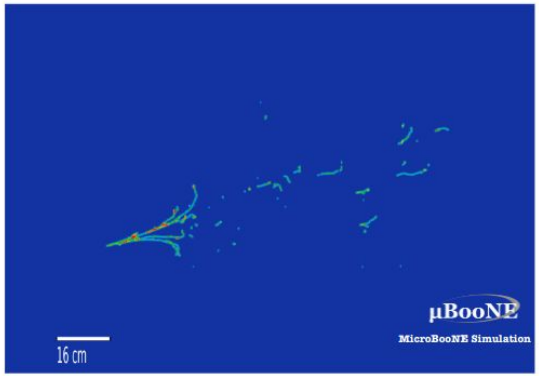
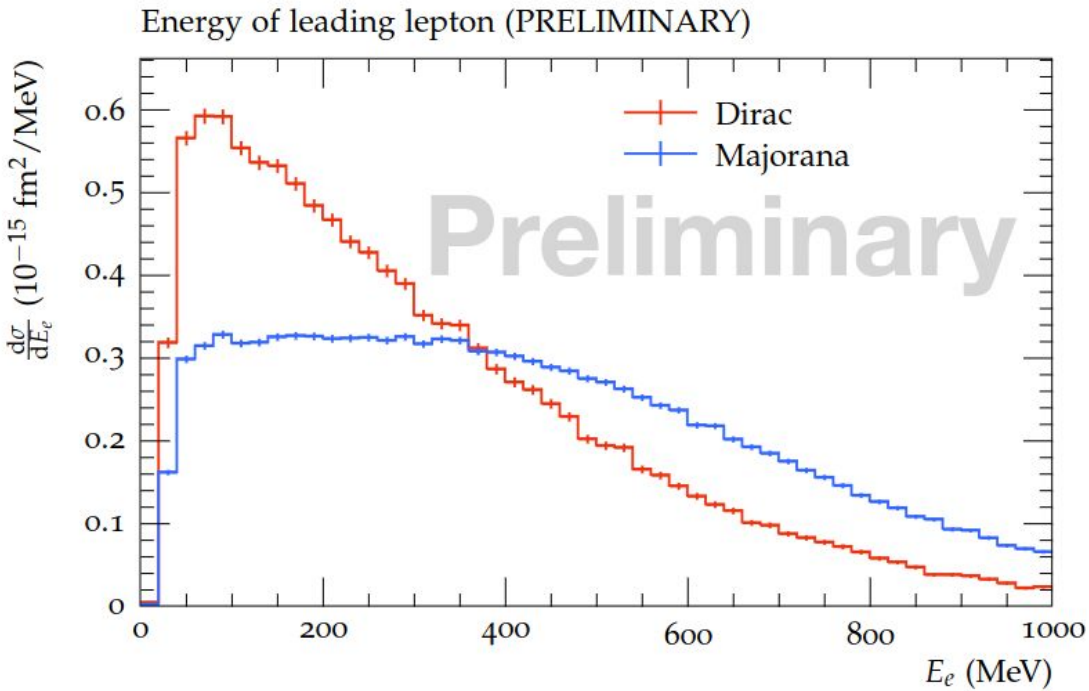


Image generated by the MicroBooNE collaboration using Achilles

Example: Dark Neutrino explanation of MiniBooNE
[E. Bertuzzo, et. al. arXiv:1807.09877]



Spin Correlations: Spin-Density Matrix

P. Richardson [hep-ph/0110108]
Isaacson, Höche, Siegert, Wang [2303.08104]

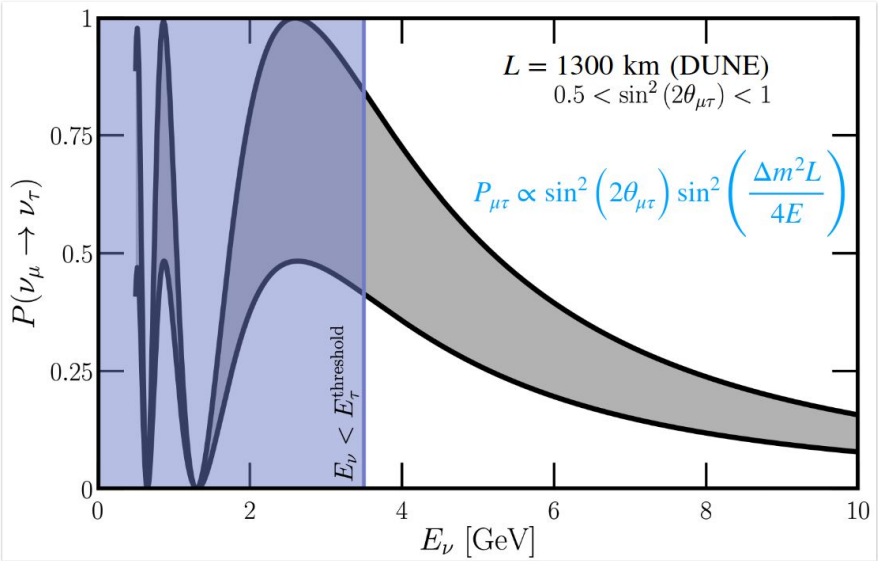
- Recursive algorithm that conserves spin correlations
- Decay unstable particle from hard interaction selected randomly
- Continue down chain until all particles are stable
- Keep track of spin-density matrix, constrained by conservation of probability

Momentum of decay products generated according to:

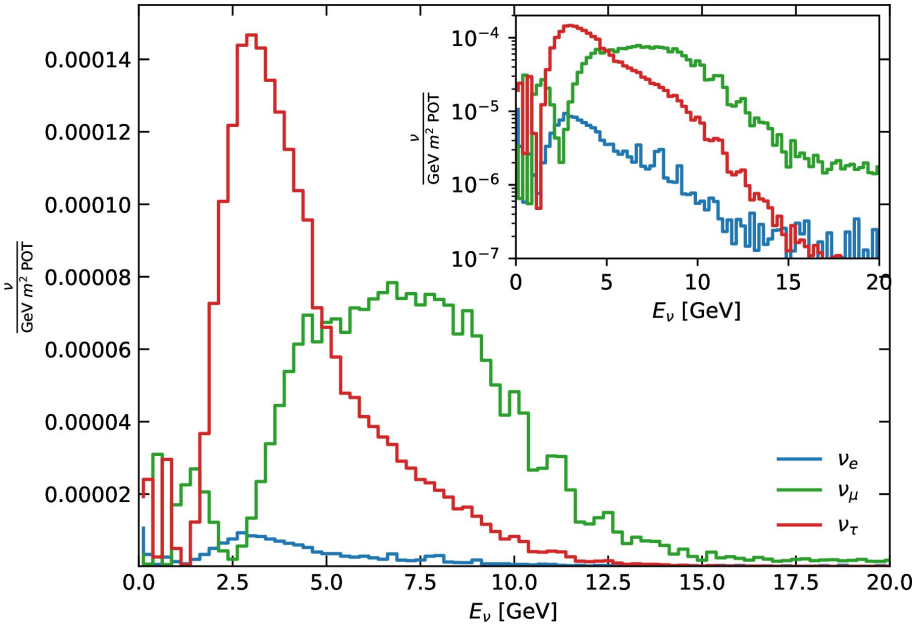
$$\rho_{\lambda_0\lambda_0'} \times \mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_k}\mathcal{M}^{*}_{\lambda_0';\lambda_1'\ldots\lambda_k'} \times \prod_{i=1,k} D^{i}_{\lambda_i\lambda_i'}$$

- Initial spin-density matrix
- Amplitude for decay
- Decay matrix (calculated during algorithm)

Tau Polarization



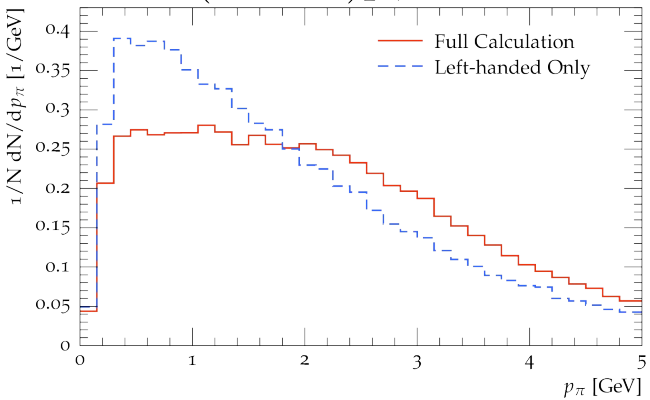
Credit: Kevin Kelly

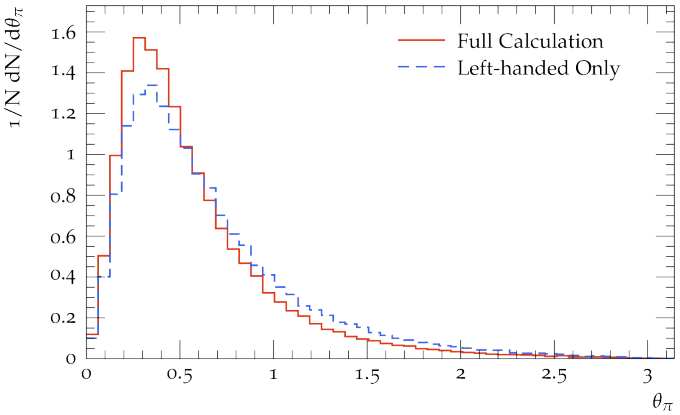


L. Fields, “DUNE Fluxes,” https://glaucus.crc.nd.edu/DUNEFluxes/

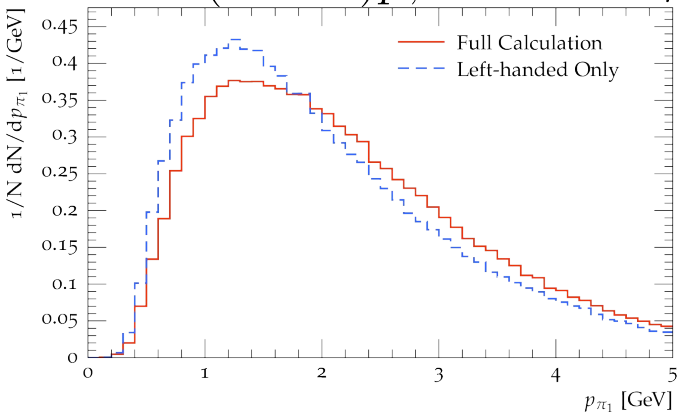
Tau Polarization

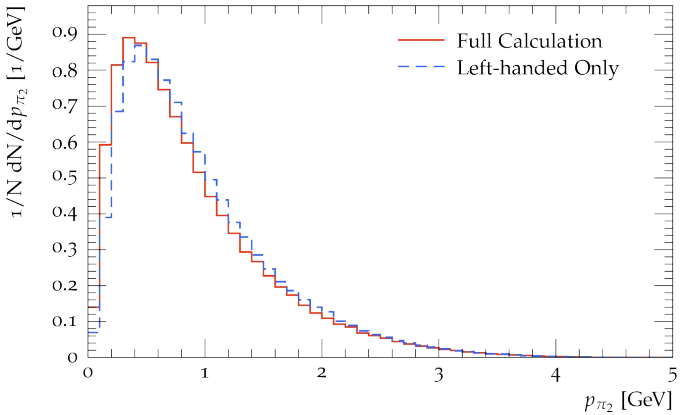
$\nu_\tau A \to \tau^-(A-1)p, \quad \tau^- \to \nu_\tau \pi^-$



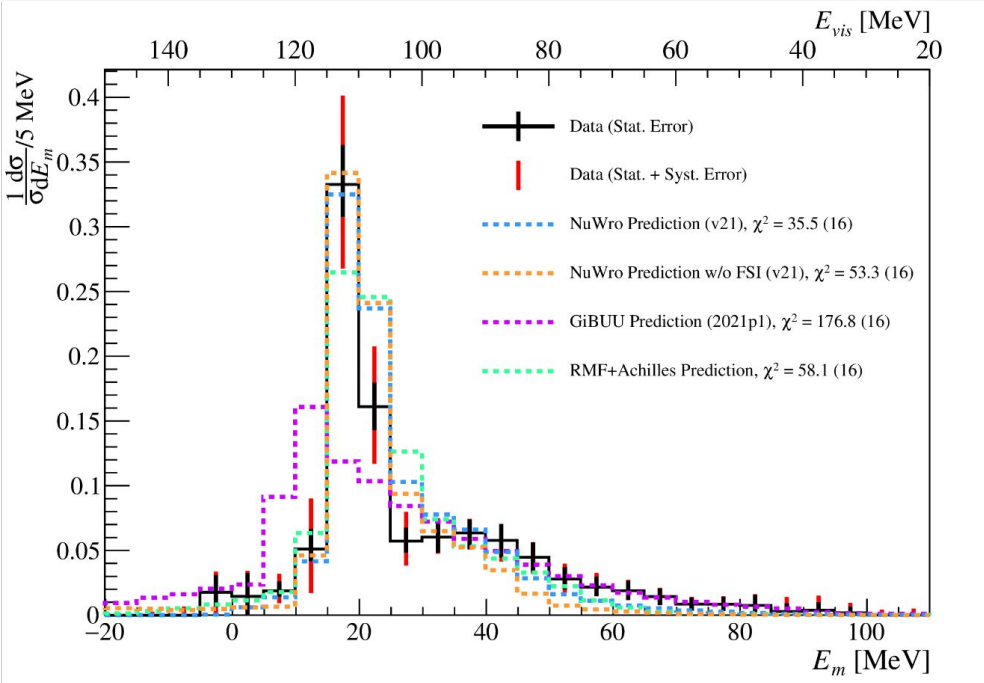


$\nu_\tau A \to \tau^-(A-1)p, \quad \tau^- \to \nu_\tau \pi^- \pi^0$





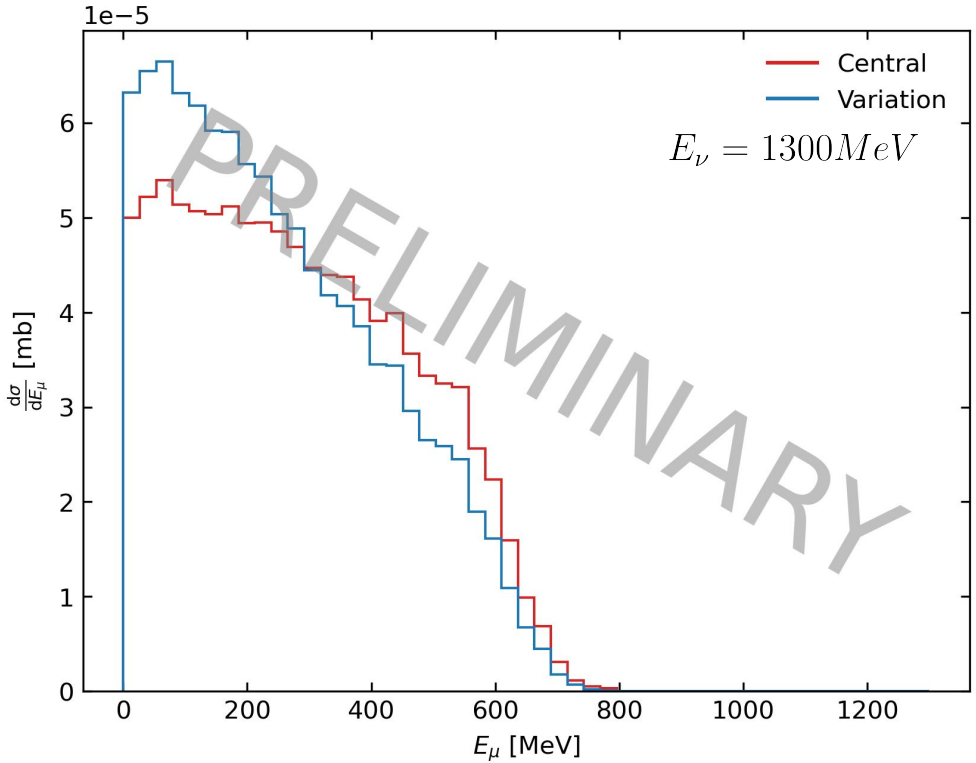
Achilles in KDAR measurement



[JSNS^2 Collaboration, 2409.01383]

- First use of Achilles by an experimental analysis
- Comparison similar to NuWro without FSI, better than GiBUU
- Achilles almost ready for use by SBN experiments
- Should be ready for wide usage (all needed processes) by early 2025

On-the-Fly Variations (in progress)

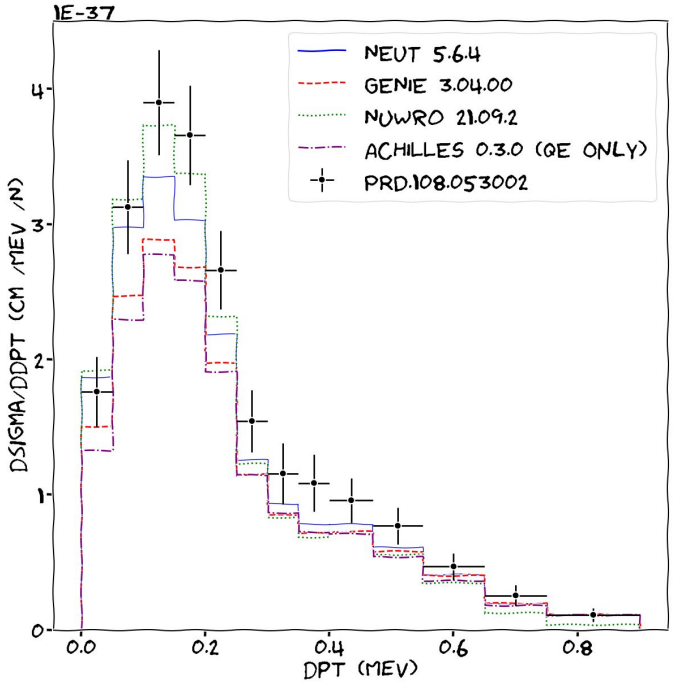


- Calculate variation of physics parameter at run time (ex. Changing form factors, spectral functions, etc.)
- Output a vector of alternative weights for each event
- Quick estimate of uncertainties without needing multiple runs
- Only evaluate for accepted event
- Single sample through detector simulation
- Based off of developments for the LHC [1606.08753]

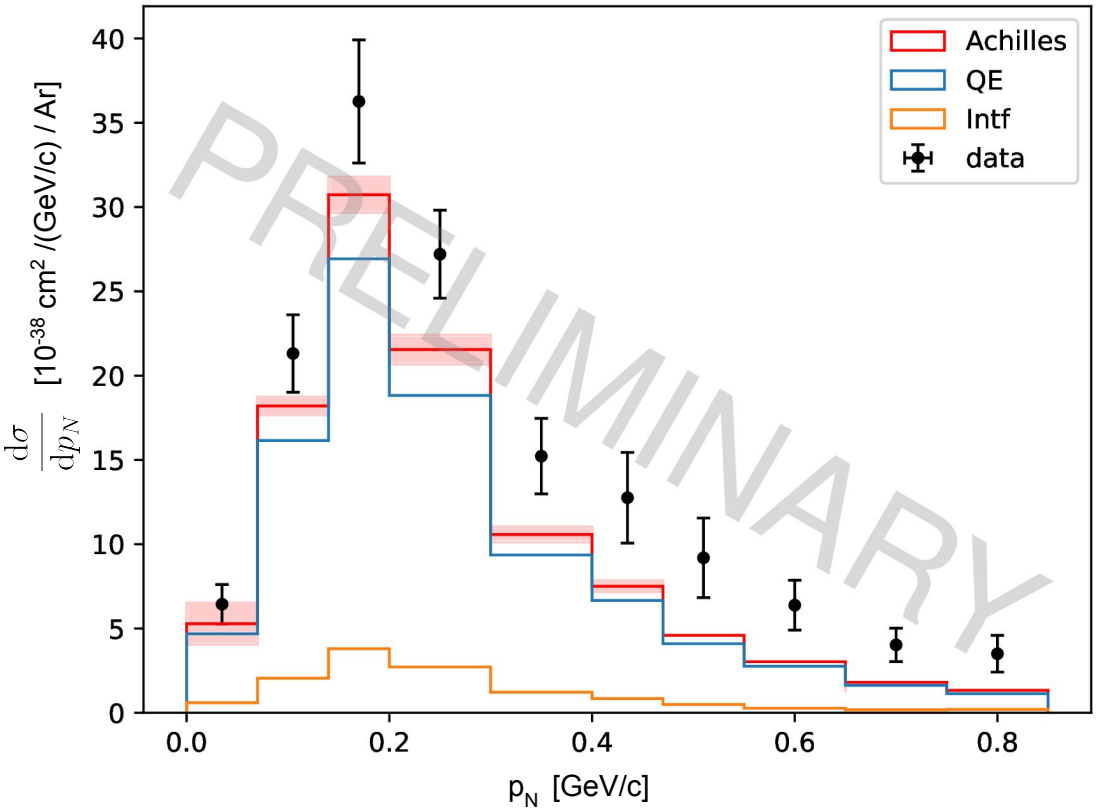
Standardization Efforts

Gardiner, **Isaacson**, Pickering [2310.13211]

- Expand HepMC3 (NuHepMC) format used by the LHC and EIC community to be the standard in the neutrino community
- Standard workflows reduce overall maintenance burden and amount of repeated effort within the community
- Ongoing effort to develop a standardized flux and geometry community tool



Automatic Data Comparison with Nuisance v3 (in progress)



- Automatically download analysis, data, flux, etc. from HepData
- Launch Achilles with required setup automatically
- Appropriately handle correlated uncertainties
- Data from MicroBooNE experiment [2310.06082]

Getting Started with Achilles

- Code can be obtained from: https://github.com/AchillesGen/Achilles
- In the process of creating next release (v0.3.0), currently all features discussed available on “dev” branch
- Only needed requirements:
  - C++ compiler with C++17 support
  - Fortran compiler
  - CMake version 3.17 or newer
  - HDF5 library (https://www.hdfgroup.org/solutions/hdf5/)
- Optional dependencies:
  - Sherpa (https://gitlab.com/sherpa-team/sherpa)
  - Root (Only for certain flux files)
- If you run into any issues or have feedback, please fill an issue (https://github.com/AchillesGen/Achilles/issues), start a discussion (https://github.com/AchillesGen/Achilles/discussions), or reach out to one of the authors

Conclusions

- Extracting underlying physics parameters requires accurate modeling of the underlying theory
- Largest systematic uncertainty arises from event generator modeling of cross-sections
- Achilles includes Quasielastic, Resonance production, and 1b2b interference
- Novel intranuclear cascade, now including pion interactions and absorption
- Argon now implemented and available for use
- Automating BSM is vital for a robust BSM program
- Handling spin correlations will be critical for any process beyond 2→2 scattering

https://github.com/AchillesGen/Achilles

On-Going Work and Future Goals:

- Quickly approaching complete generator ready for experimental usage (e4v and neutrino)
- QED radiation
- On-the-fly uncertainty propagation
- Efforts to help standardize input and output formats to benefit the community
- Automatic comparison to data through Nuisance v3

Backup