Achilles

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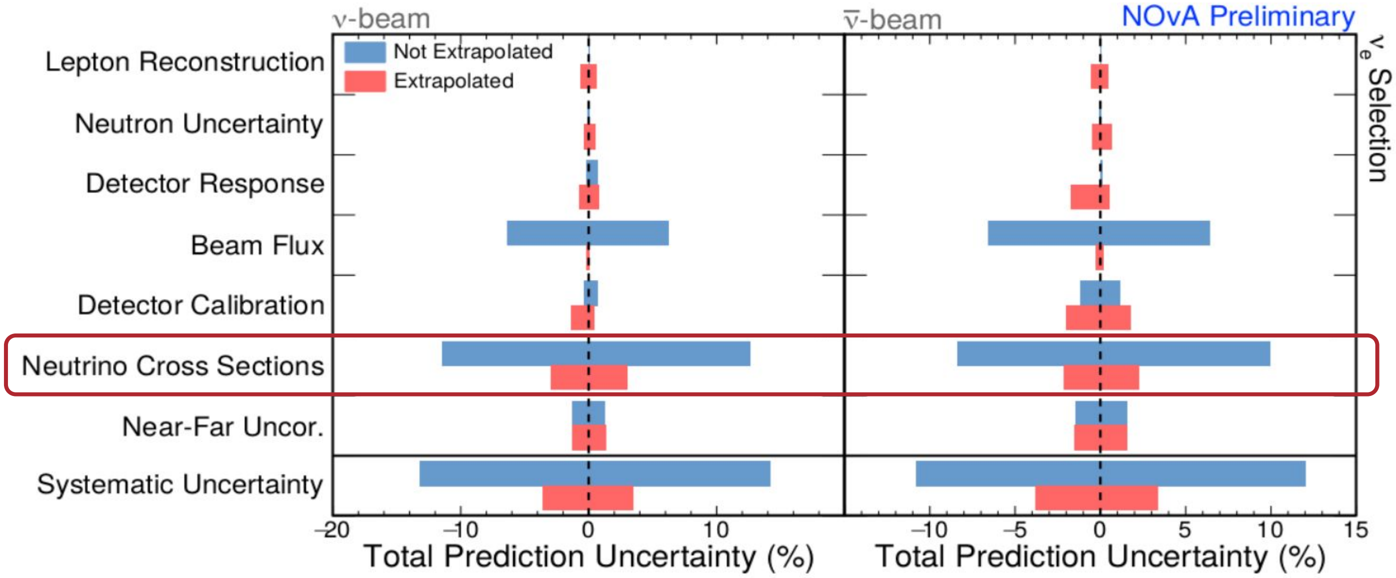
14th International Conference on Neutrino-Nucleus Interactions
15 April 2024

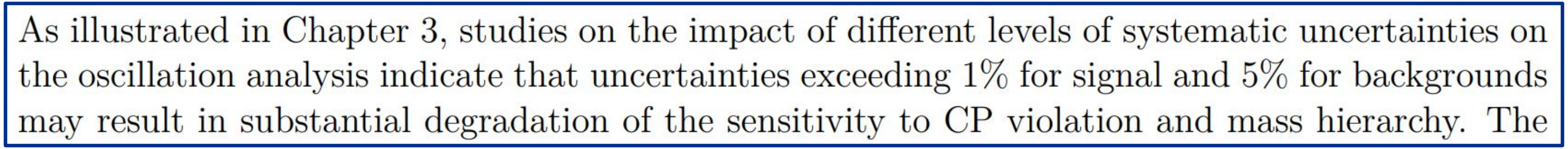
Motivation

- 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



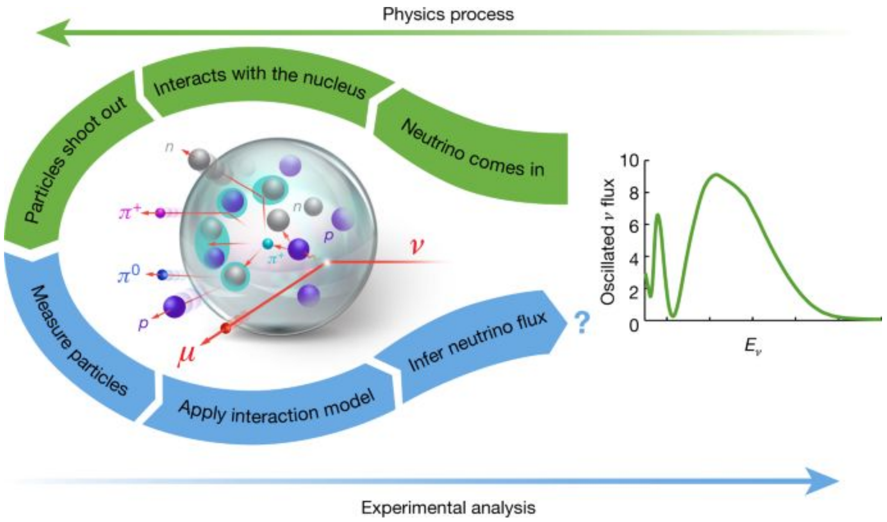
From the DUNE CDR2 (1512.06148)


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

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

- 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

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],

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|    Version: 1.0.0                                                   |
|    Authors: Joshua Isaacson, William Jay, Alessandro Lovato,        |
|        Pedro A. Machado, Luke Pickering, Noemi Rocco,               |
|        Noah Steinberg                                               |
|                                                                     |
|    Undergraduate Student Contributions:                             |
|        Diego Lopez Gutierrez, Sherry Wang, Russell Farnsworth       |
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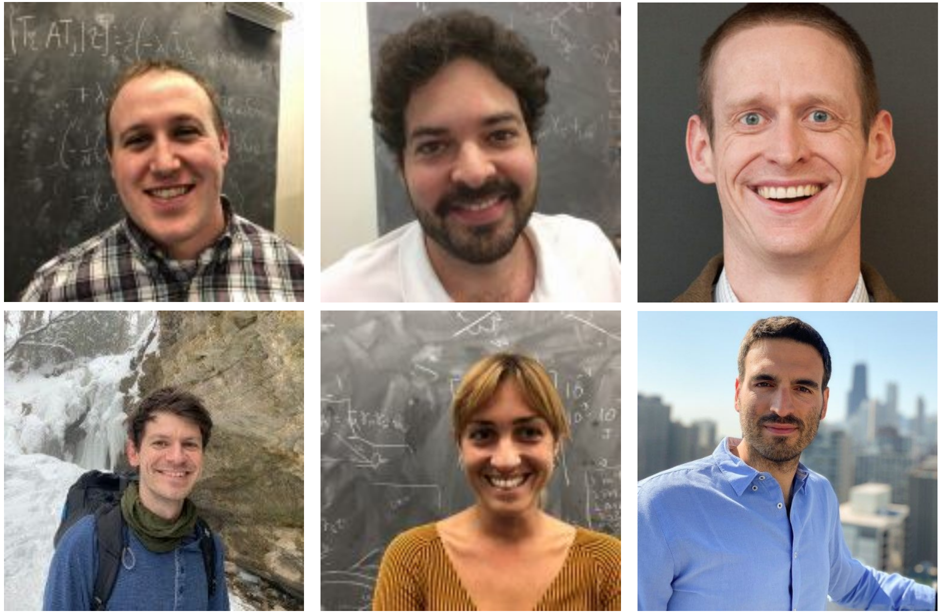
Achilles: A CHIcagoLand Lepton Event Simulator

Core Authors



Undergraduates

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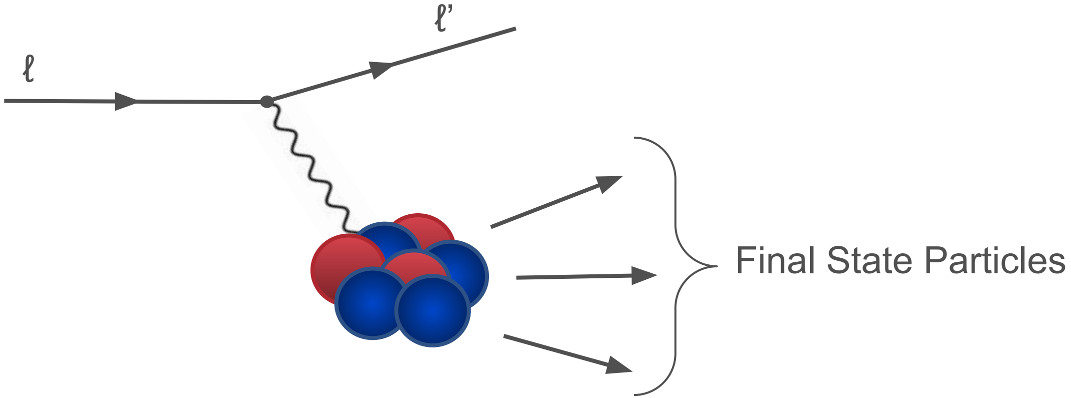
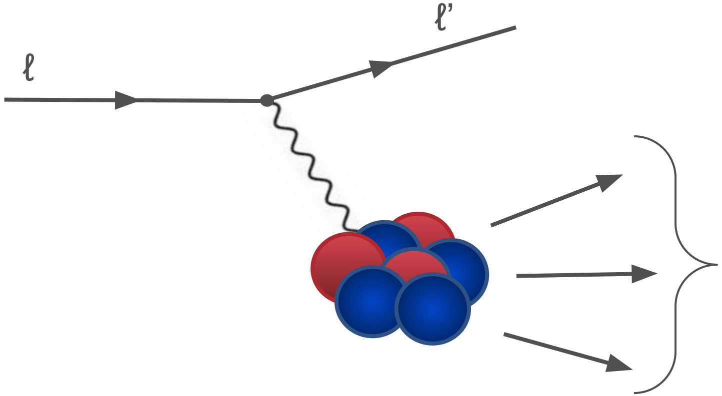
Simulating the Standard Model

Simulating the Standard Model



$$d\sigma = \underbrace{\left(\frac{1}{|v_A - v_\ell|}\frac{1}{4E_A^{\text{in}}E_\ell^{\text{in}}}\right)}_{\text{Flux Factor}} \times \underbrace{|\mathcal{M}|^2}_{\text{Matrix Element}} \times \underbrace{\prod_f \frac{\mathrm{dp}_\mathrm{f}^3}{(2\pi)^3}(2\pi)^4\delta^{(4)}\left(p_A + p_\ell - \sum_f p_f\right)}_{\text{Phase Space}}$$

Simulating the Standard Model



Final State Particles

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

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

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

Primary Interaction

- Electroweak currents from nuclear theory:

$$J^\mu(q) = \sum_i j_i^\mu(q) + \sum_{i<j} j_{ij}^\mu(q) + \cdots$$

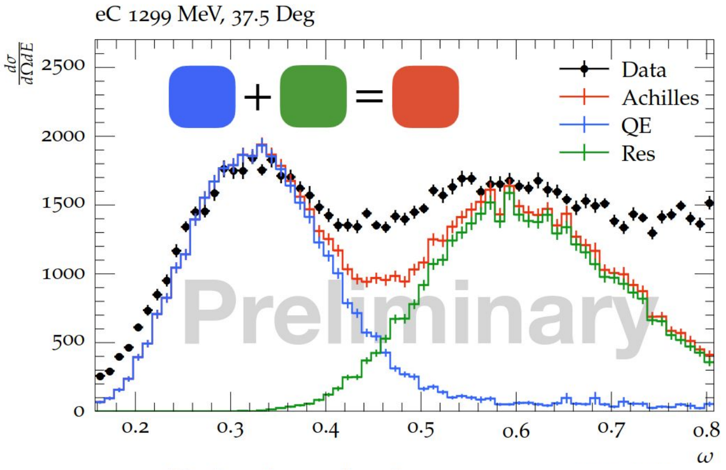
- Impulse Approximation with SF:

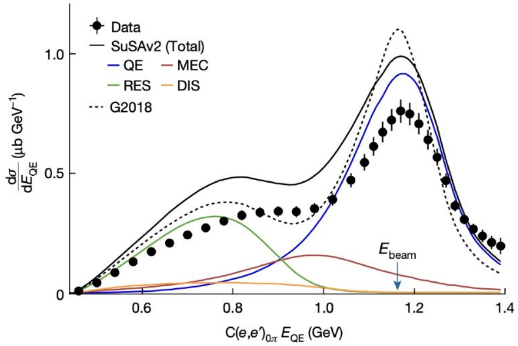
$$|\Psi_f\rangle = |p\rangle \otimes |\Psi_f^{A-1}\rangle$$

- Express in terms of leptonic and hadronic currents → interferences come for free

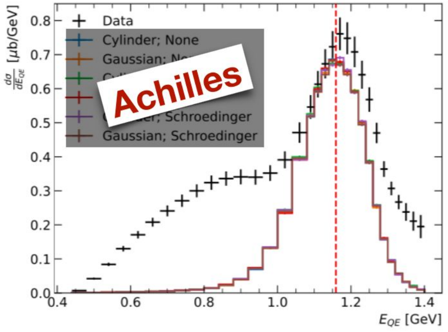
$$\mathcal{V} = \sum_i L_\mu^{(i)} W^{\mu(i)}$$

- Have Quasielastic and Resonance (DCC model) implemented
- Important to validate against electron scattering data using same framework (i.e. same code)





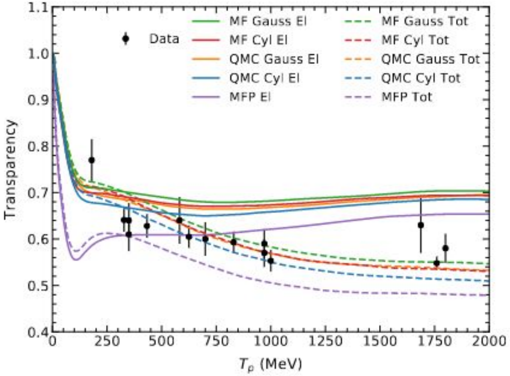
Nature 599 (2021) 7886, 565-570

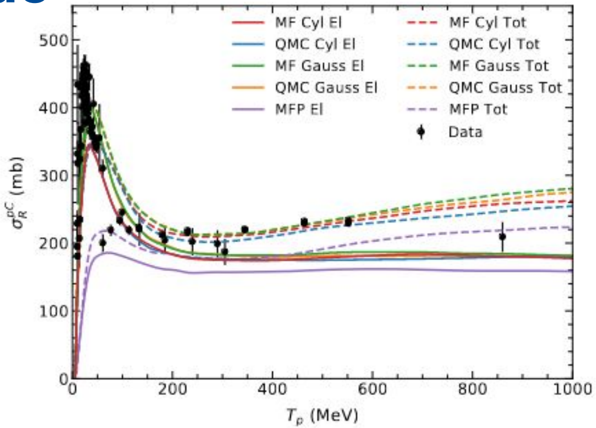


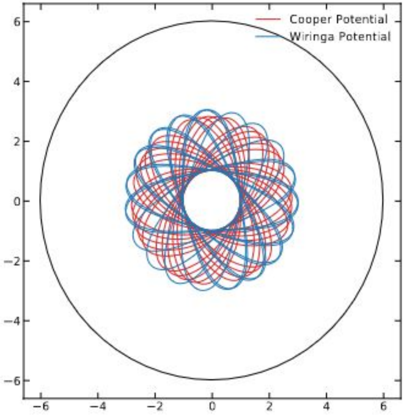
Isaacson, Jay, Lovato, Machado, Rocco [2205.06378]

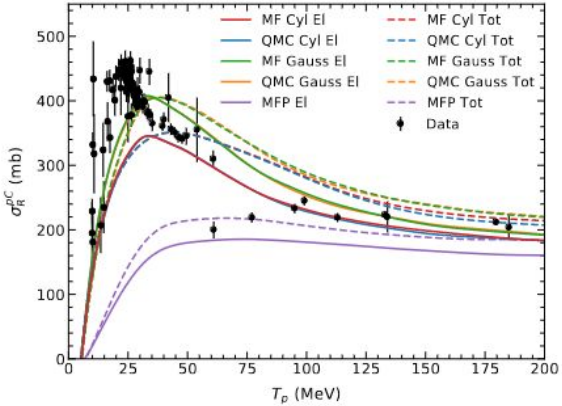
Intranuclear Cascade

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

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

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

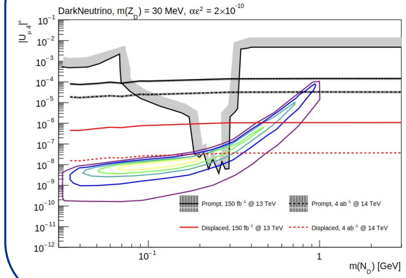
- Propagation either straight-lines or in optical potential using classical evolution
- In-medium cross-section corrections from Pandharipande-Pieper
- Incorporate Pauli-blocking and formation zone

Simulating Beyond the Standard Model

Beyond the Standard Model

LHC Generators

Herwig, **Isaacson,** Jayatilaka, Machado, Reinsvold Hall [2310.13042]



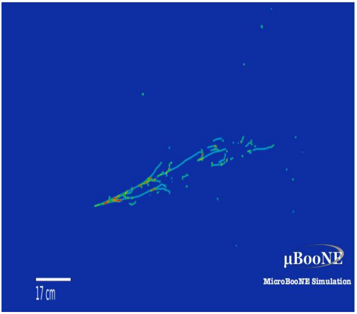
Universal Feynman Output:

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

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

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

Neutrino Generators



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],

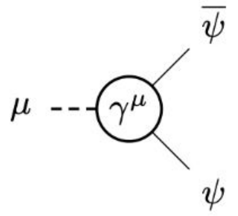
- Use recursive definition for (off-shell) currents:

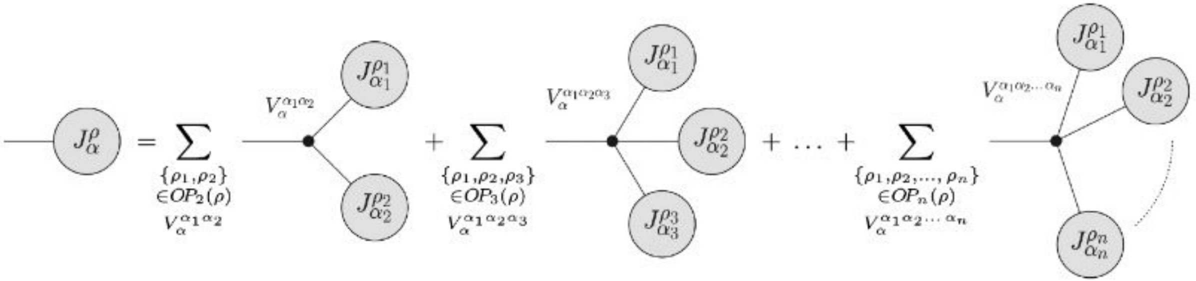
$$(\text{current}) = (\text{propagator}) \times \sum (\text{vertex}) \times (\text{subcurrents})$$

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

Example Vertex:

$$(\gamma^\mu)_{ab}\overline{\psi}_a\psi_b \quad =$$

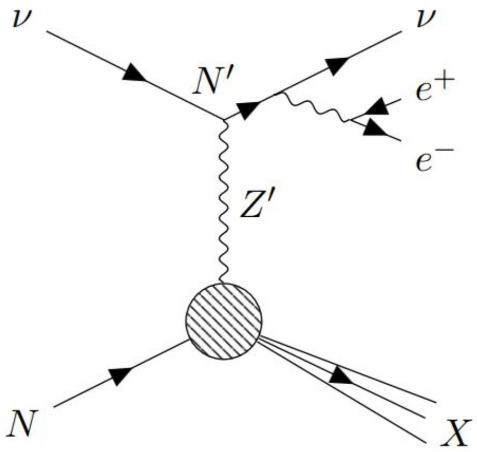




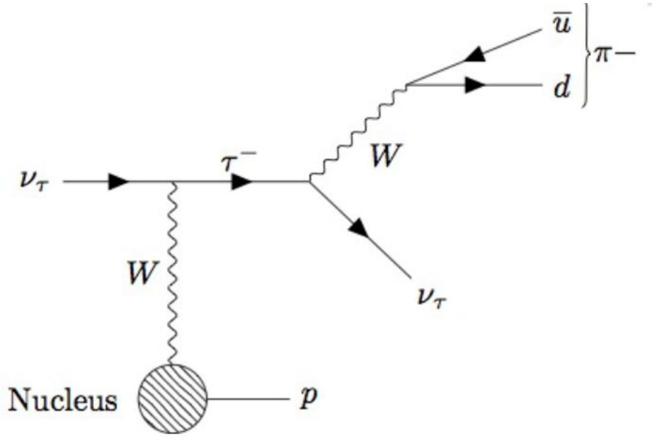
Spin Correlations

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: 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)

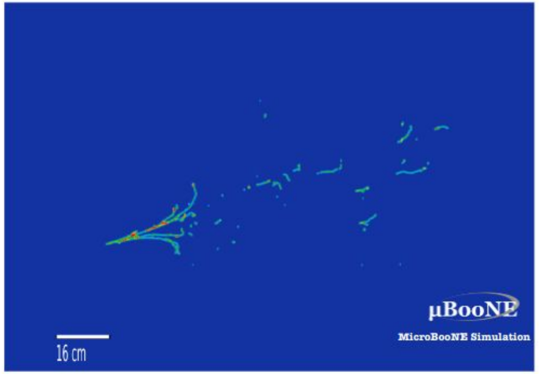
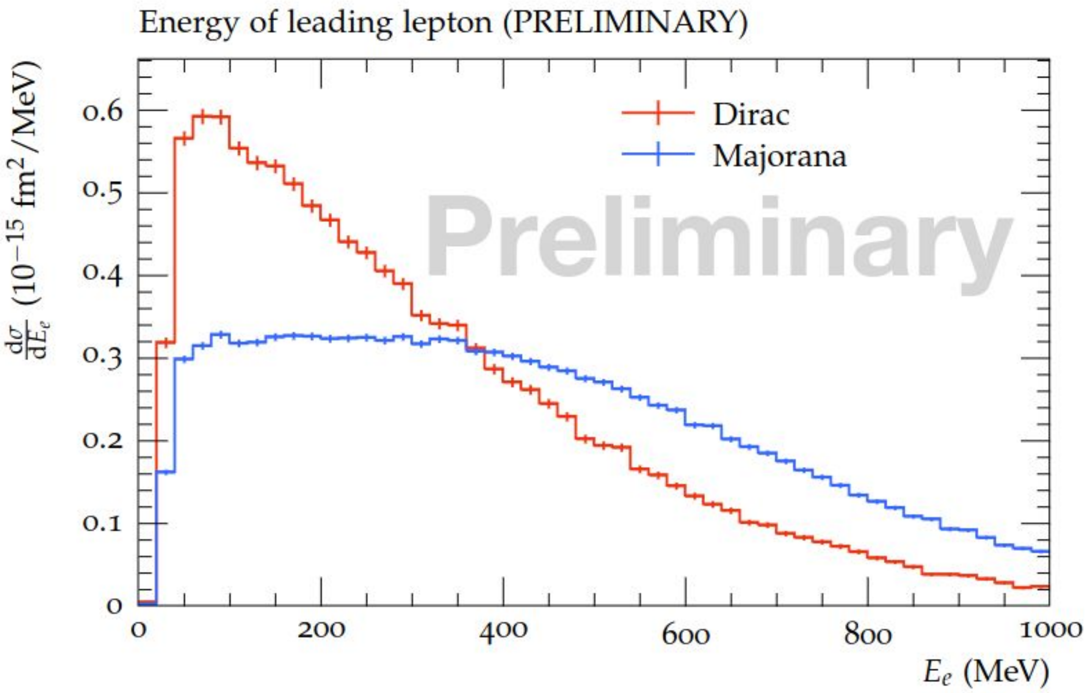


Image generated by the MicroBooNE collaboration using Achilles

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]

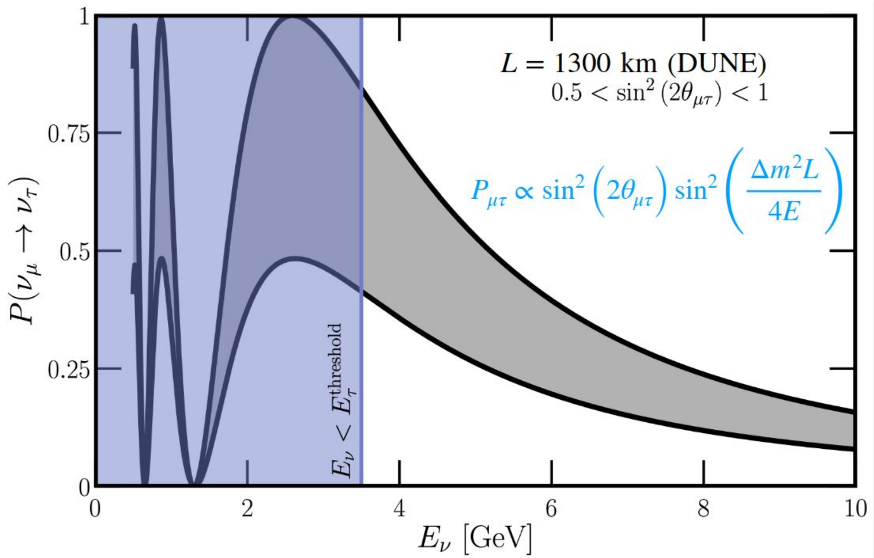
- Recursive algorithm that conserves spin correlations
- Decay unstable particle from hard interaction selected randomly
- Continue down chain until all particles are stable
- Keep track of spin-density matrix, constrained by conservation of probability

Momentum of decay products generated according to:

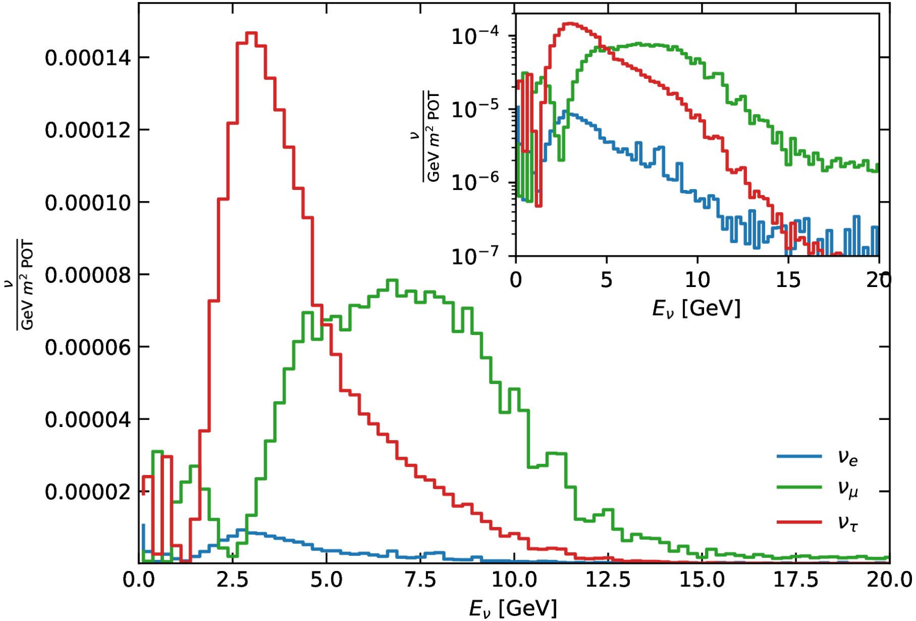
$$\rho_{\lambda_0\lambda'_0} \times \mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_k}\mathcal{M}^*_{\lambda'_0;\lambda'_1\ldots\lambda'_k} \times \prod_{i=1,k} D^i_{\lambda_i\lambda'_i}$$

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

Tau Polarization



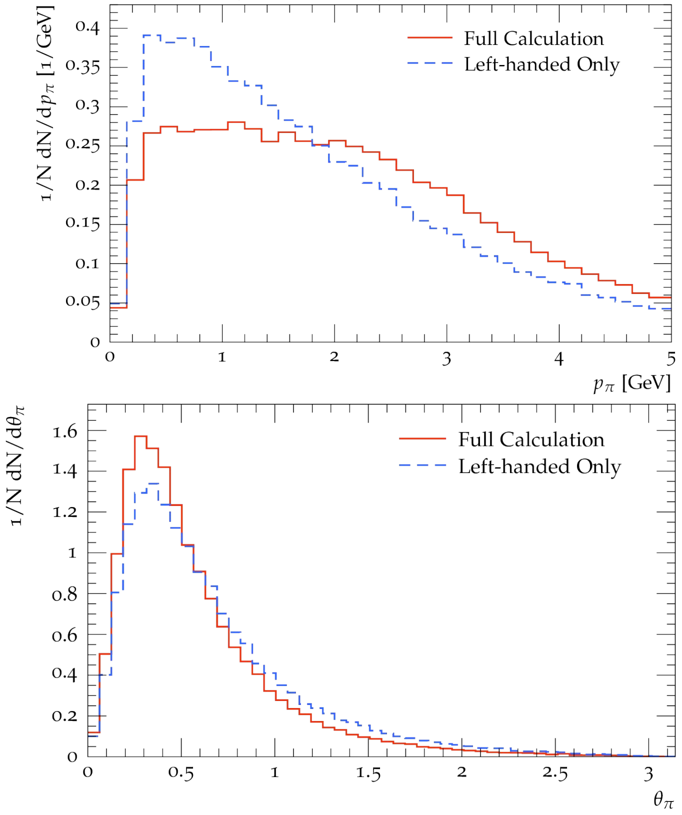
Credit: Kevin Kelly



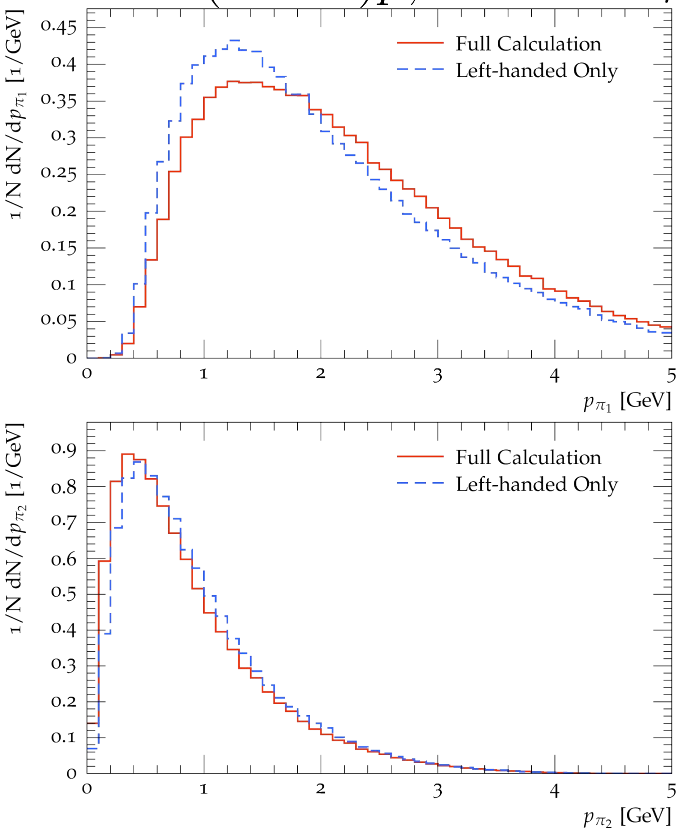
L. Fields, “DUNE Fluxes,” https://glaucus.crc.nd.edu/DUNEFluxes/

Tau Polarization

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



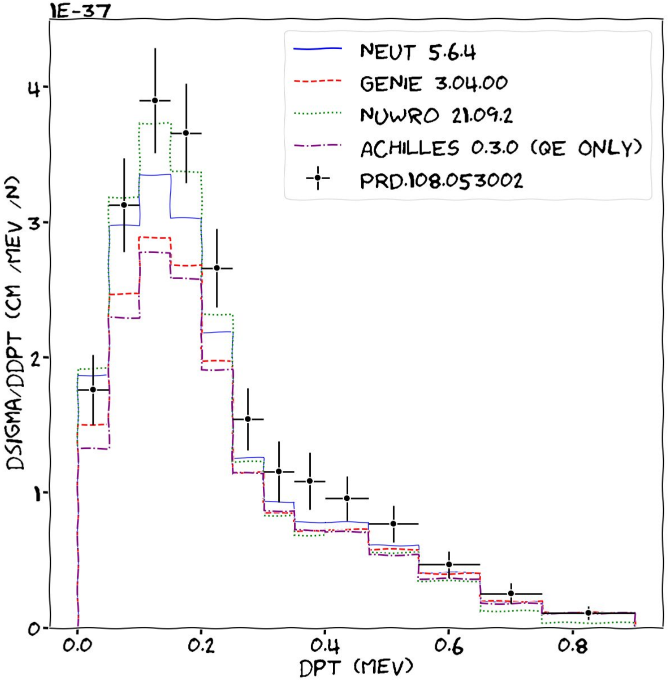
$$\nu_\tau A \to \tau^-(A-1)p, \quad \tau^- \to \nu_\tau \pi^- \pi^0$$



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



Conclusions

- Extracting underlying physics parameters requires accurate modeling of the underlying theory
- Largest systematic uncertainty arises from event generator modeling of cross-sections
- Includes Quasielastic and (now) Resonance production
- Novel intranuclear cascade
- Automating BSM is vital for a robust BSM program
- Handling spin correlations will be critical for any process beyond 2→2 scattering

On-Going Work and Future Goals:

- Implement 1-body current interference with 2-body current, MEC, and DIS
  - Quickly approaching complete generator ready for experimental usage (e4v and neutrino)
- Pions in the cascade (work with Alexis Nikolakopoulos)
- QED radiation
- On-the-fly uncertainty propagation