Achilles

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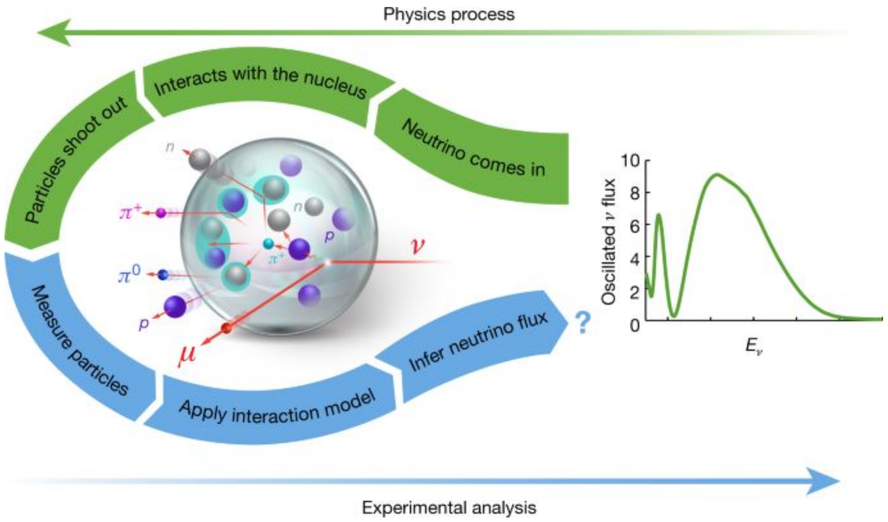
Motivation

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

- 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

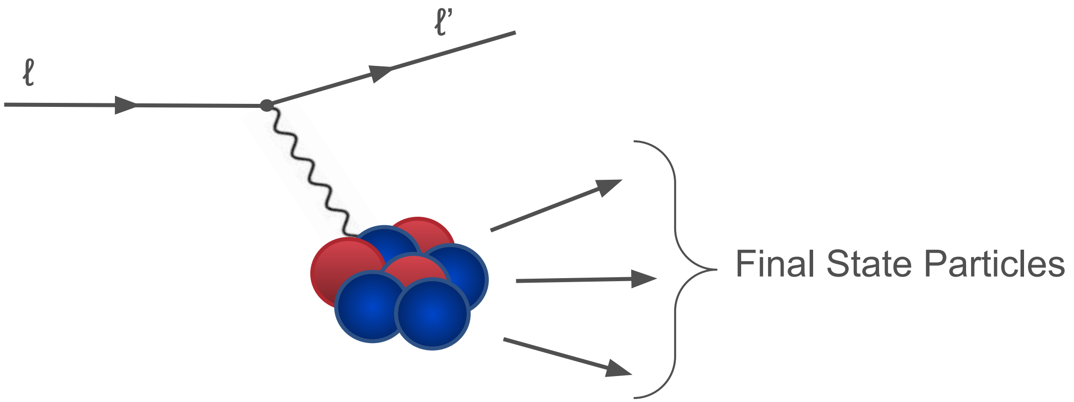
Project Goals:

- 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

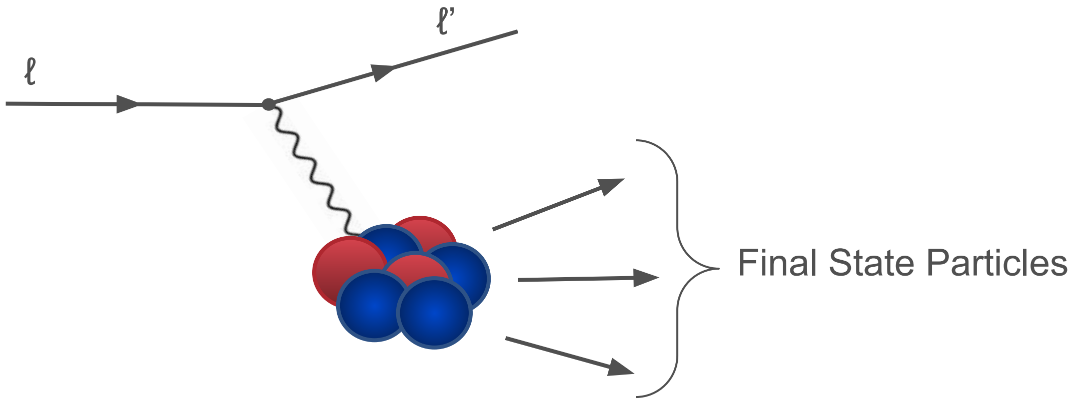
Calculation Breakdown



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

Flux Factor | Matrix Element | Phase Space

Calculation Breakdown

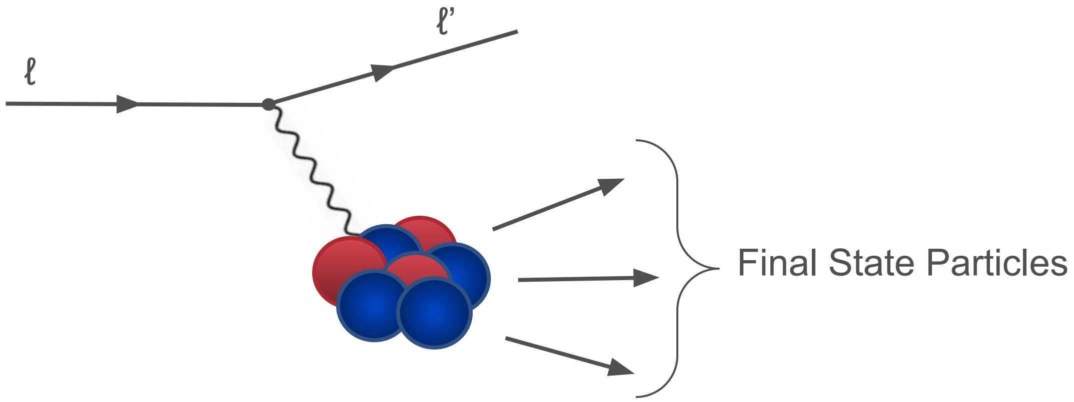


- $\mathcal{V}$: Primary interaction vertex
- $\mathcal{P}$: Time evolution out of nucleus
- Approximate as incoherent sum (i.e. neglect interference between primary interaction and cascade)

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

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

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:

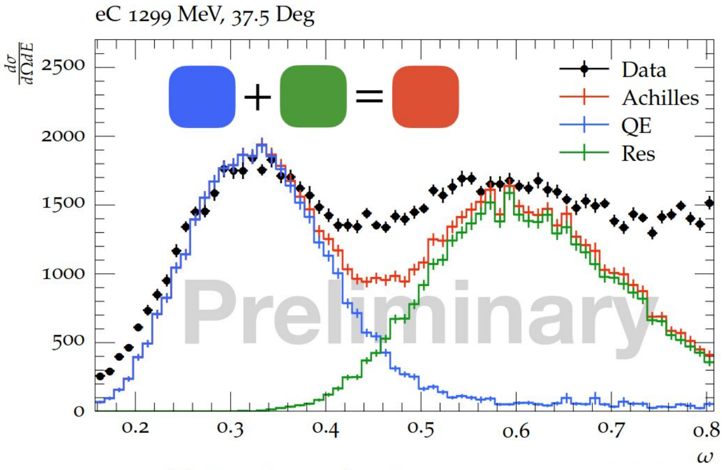
$$|\Psi_f\rangle = |p\rangle \otimes |\Psi_f^{A-1}\rangle$$

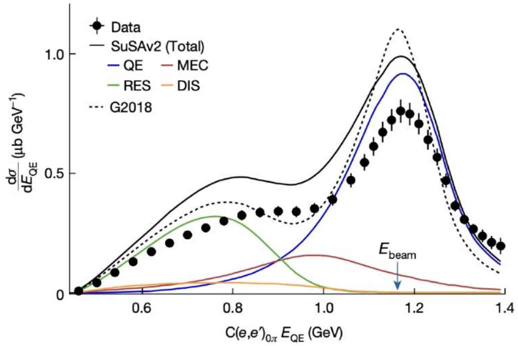
- Express in terms of leptonic and hadronic currents → interferences come for free

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

- Have Quasielastic, Resonance (DCC model), One-body-two-body interference implemented

- Important to validate against electron scattering data using same framework (i.e. same code)





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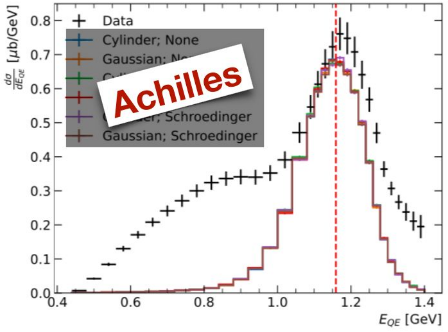
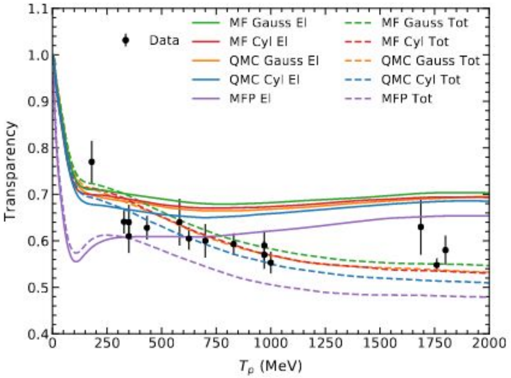
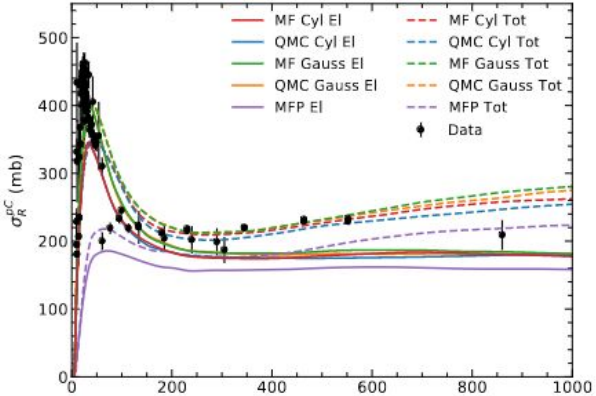
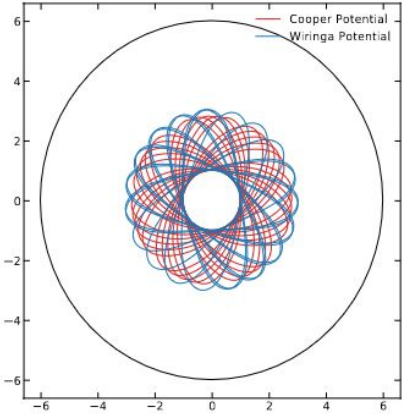


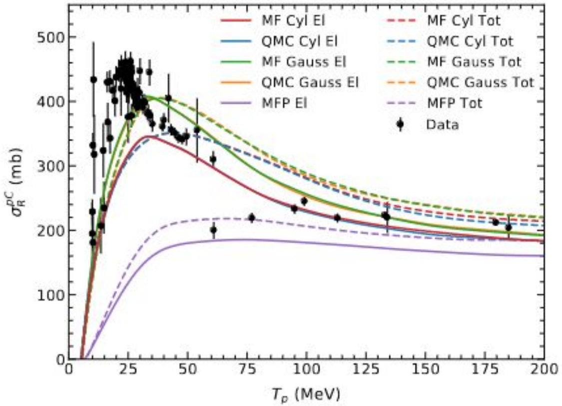
Isaacson, Jay, Lovato, Machado, Rocco [2205.06378]

Intranuclear Cascade:Nucleons









- 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

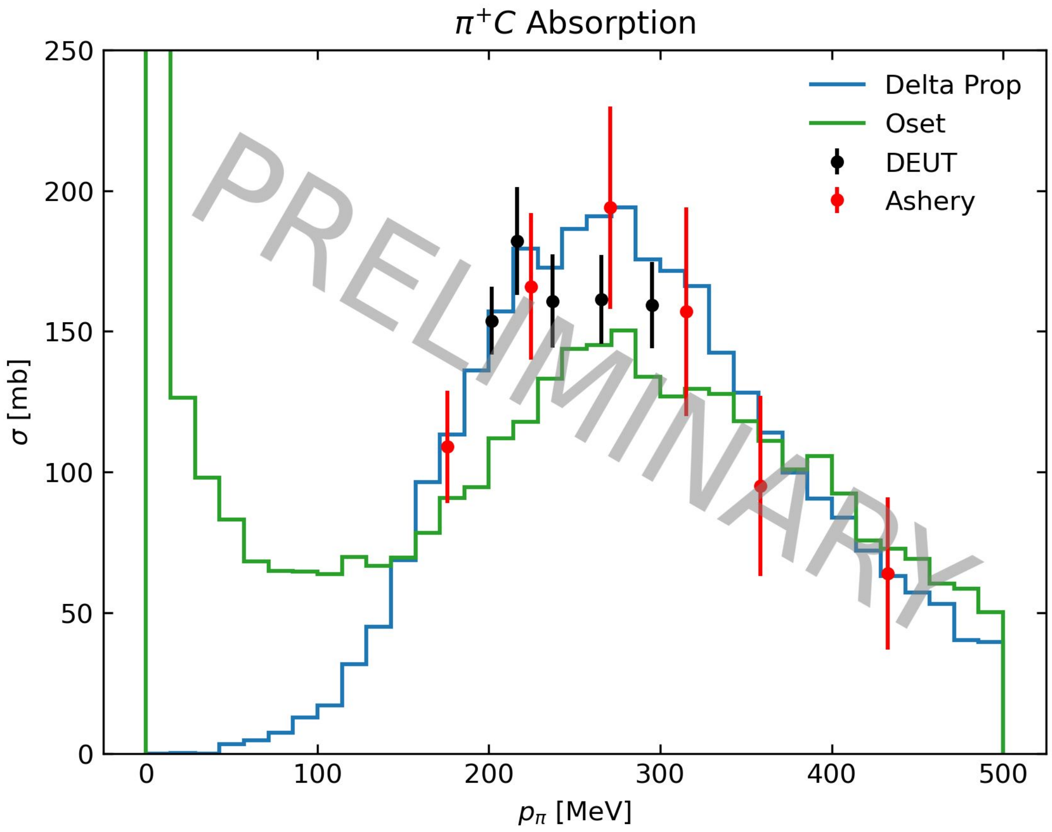
Intranuclear Cascade: Pions

- 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:

$$\pi NN \to NN$$

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

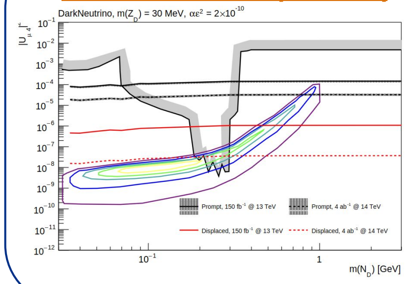


Simulating Beyond the Standard Model

Beyond the Standard Model

LHC Generators

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



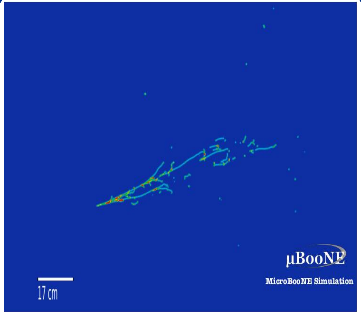
Universal Feynman Output:

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

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

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

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],

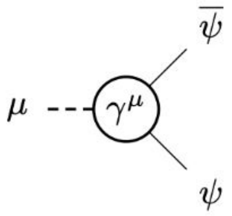
- Use recursive definition for (off-shell) currents:

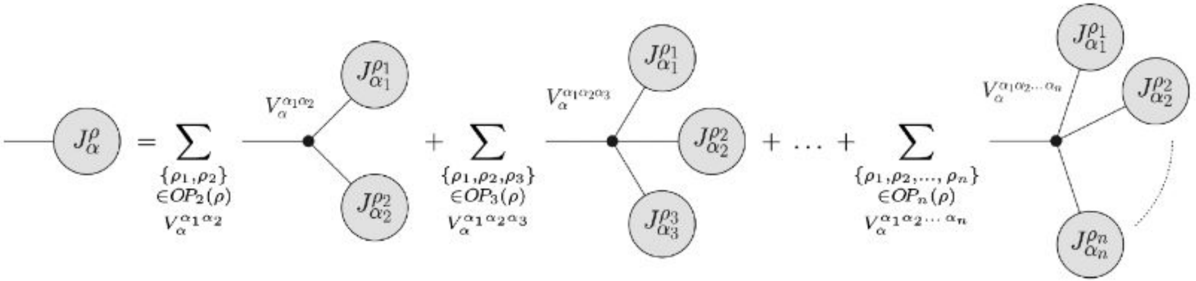
$$(\text{current}) = (\text{propagator}) \times \sum (\text{vertex}) \times (\text{subcurrents})$$

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

Example Vertex:

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

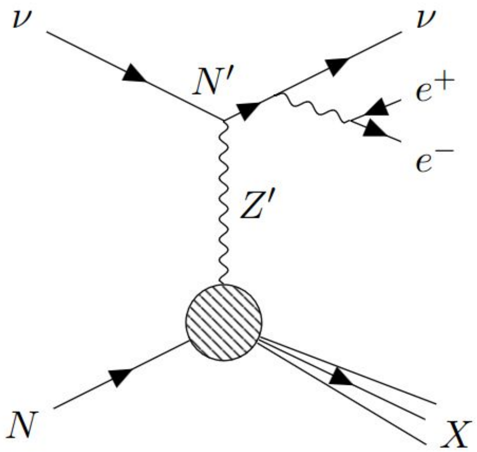




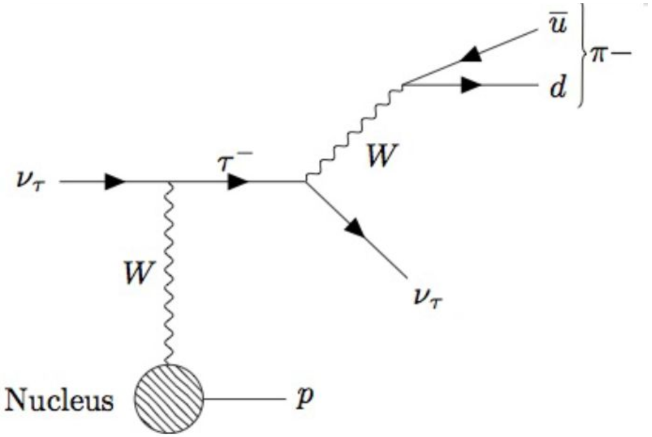
Spin Correlations

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)

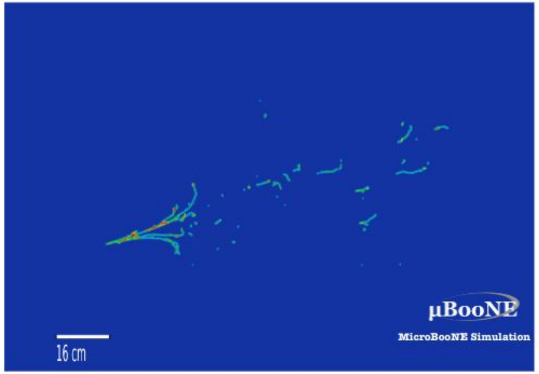
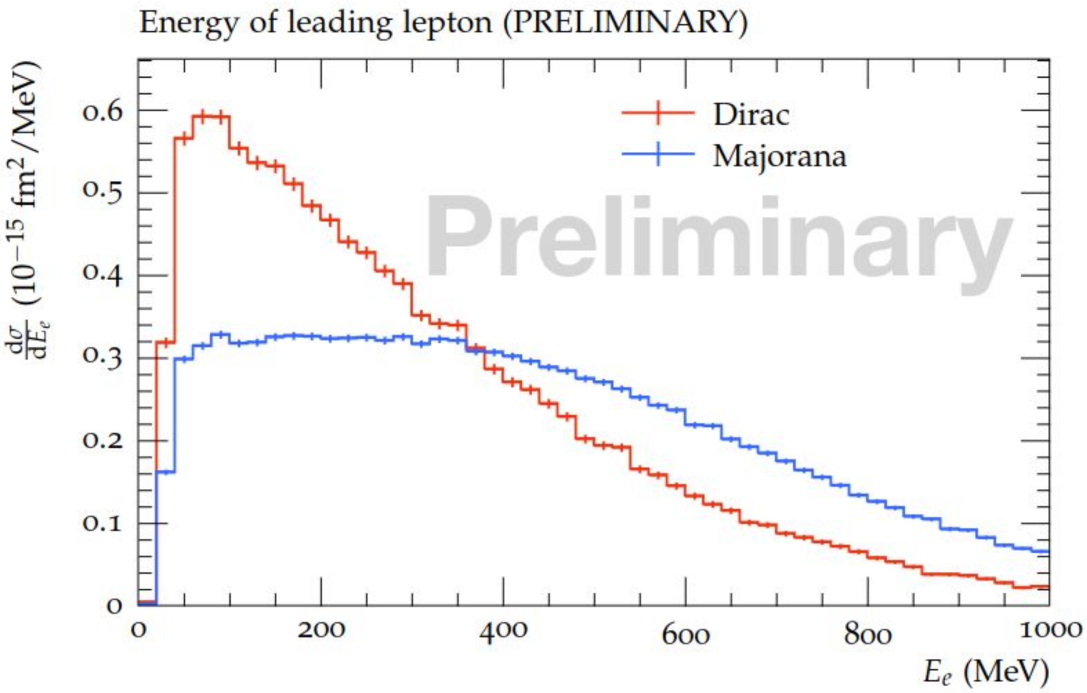


Image generated by the MicroBooNE collaboration using Achilles

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]

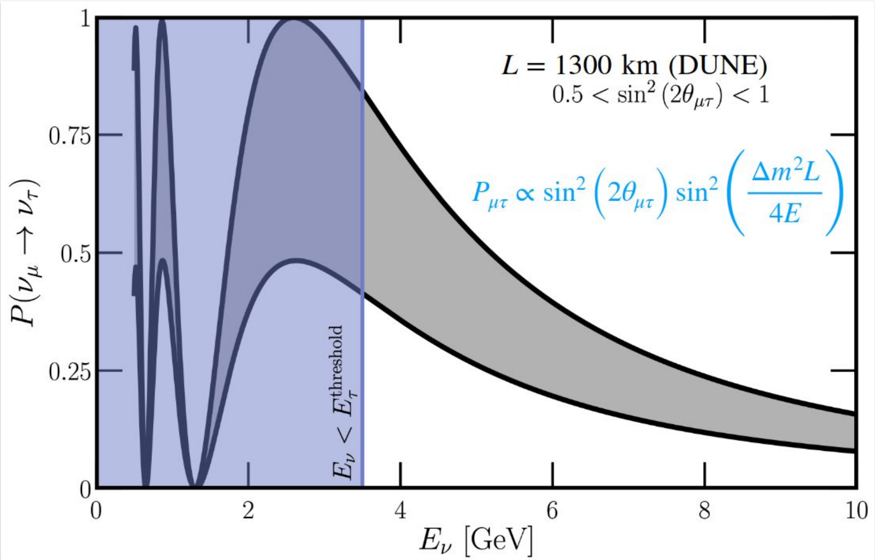
- Recursive algorithm that conserves spin correlations
- Decay unstable particle from hard interaction selected randomly
- Continue down chain until all particles are stable
- Keep track of spin-density matrix, constrained by conservation of probability

Momentum of decay products generated according to:

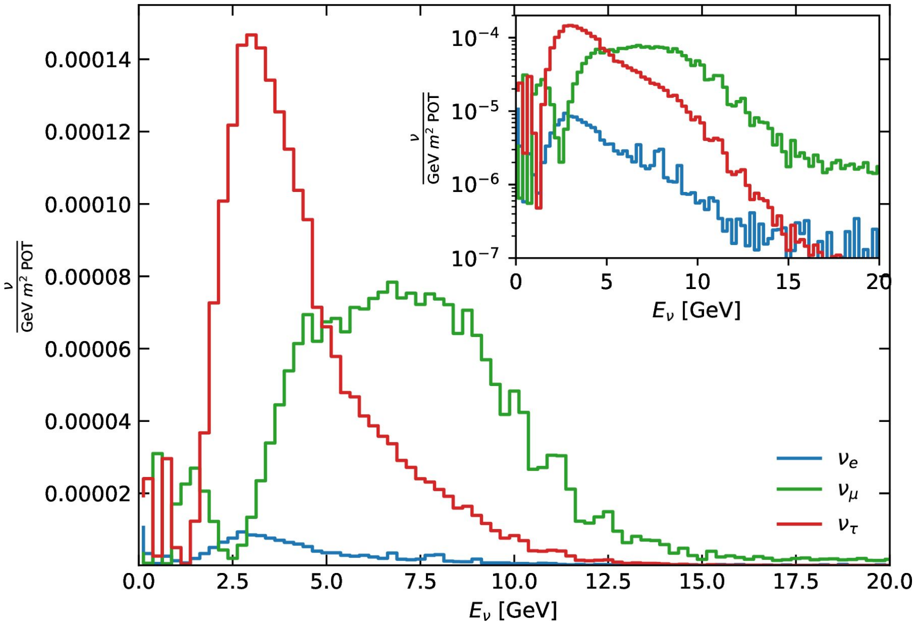
$$\rho_{\lambda_0\lambda_0'} \times \mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_k}\mathcal{M}^*_{\lambda_0';\lambda_1'\ldots\lambda_k'} \times \prod_{i=1,k} D^i_{\lambda_i\lambda_i'}$$

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

Tau Polarization



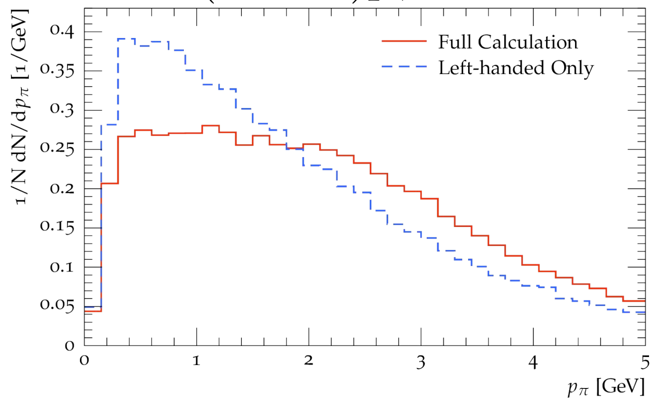
Credit: Kevin Kelly

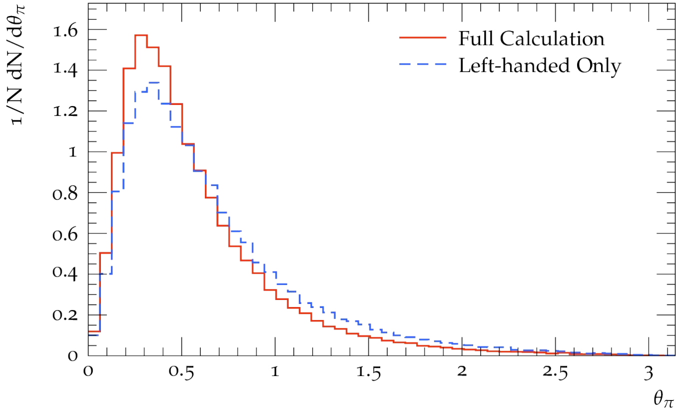


L. Fields, "DUNE Fluxes," https://glaucus.crc.nd.edu/DUNEFluxes/

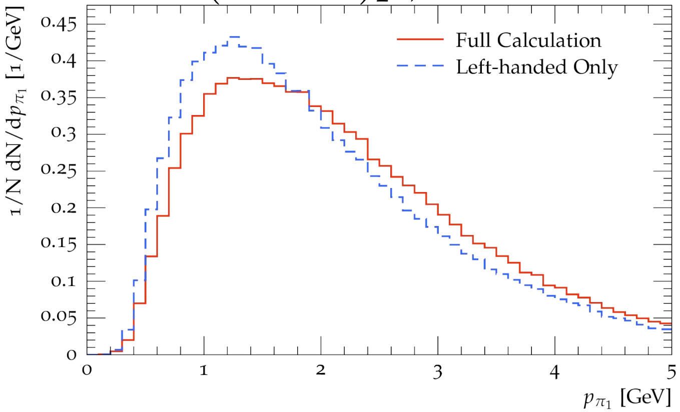
Tau Polarization

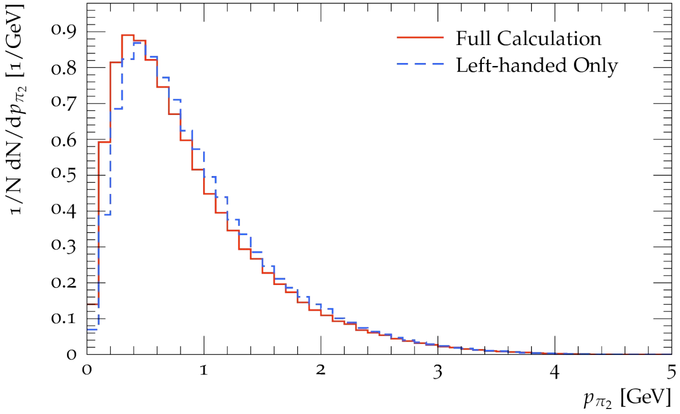
$\nu_\tau A \to \tau^-(A-1)p, \quad \tau^- \to \nu_\tau \pi^-$



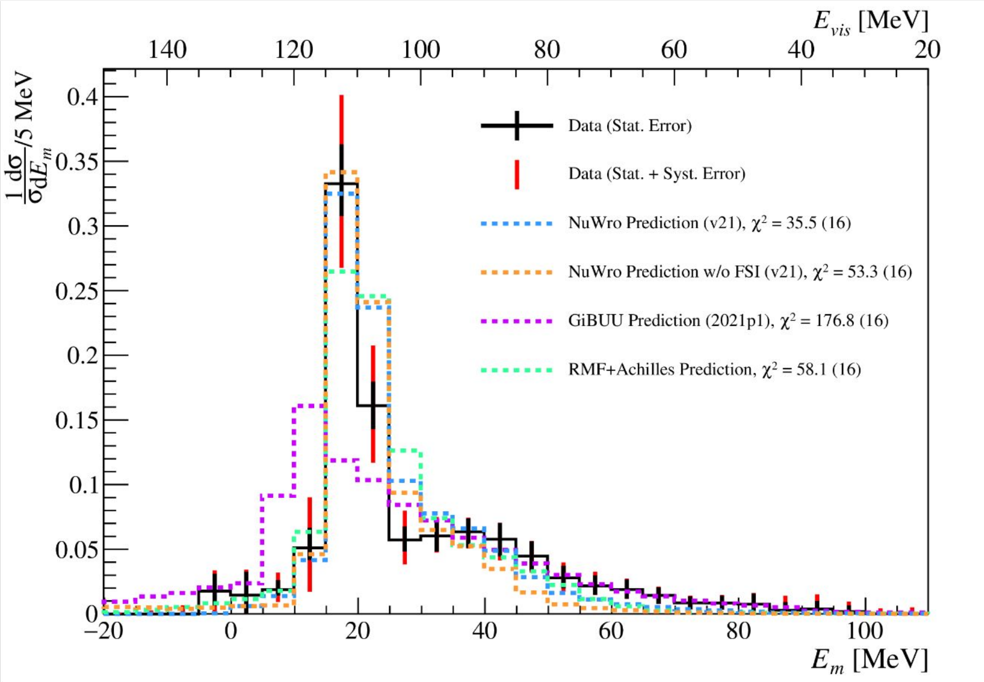


$\nu_\tau A \to \tau^-(A-1)p, \quad \tau^- \to \nu_\tau \pi^- \pi^0$





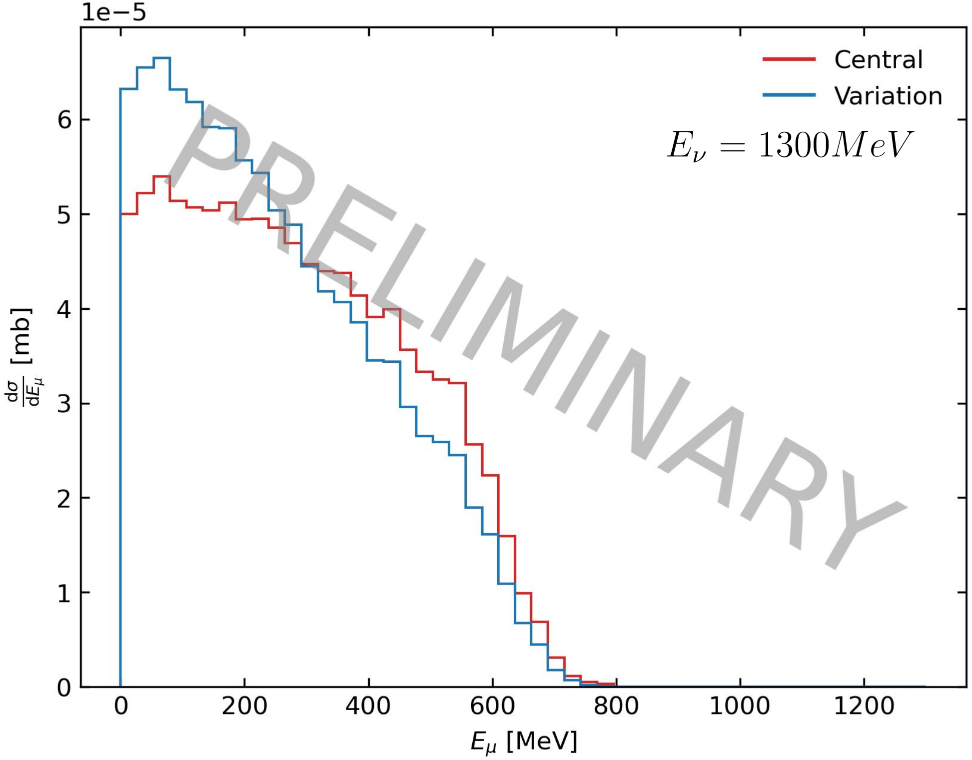
Achilles in KDAR measurement



[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)

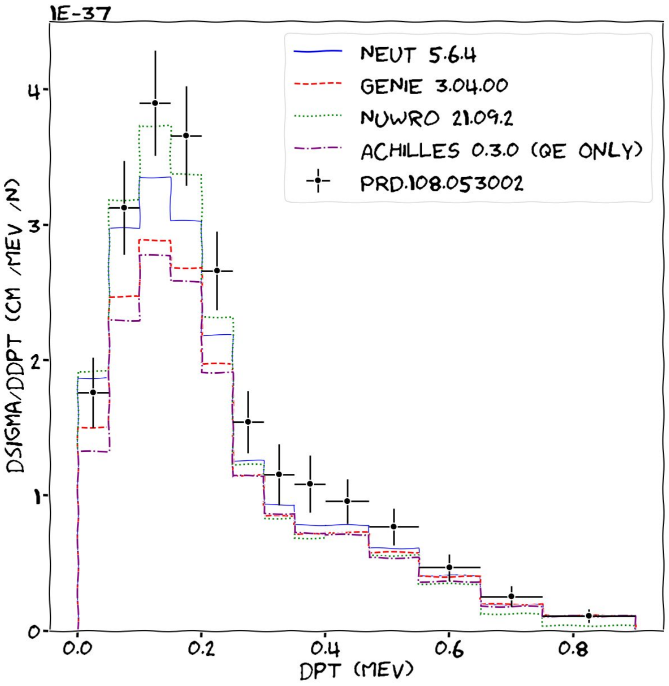


- Calculate variation of physics parameter at run time (ex. Changing form factors, spectral functions, etc.)
- Only evaluate for accepted event
- Based off of developments for the LHC [1606.08753]

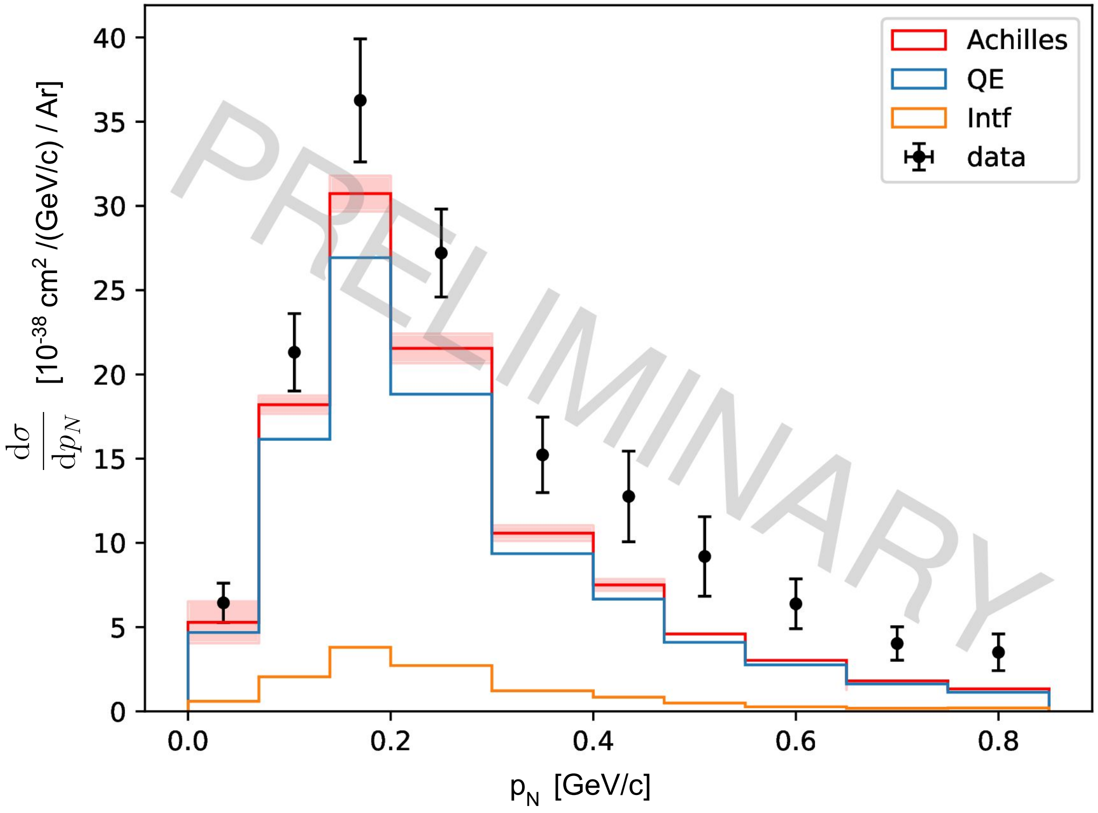
Standardization Efforts

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]

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
- 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:

- 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

Achilles: A CHIcagoLand Lepton Event Simulator

Core Authors






Undergraduates