FSI In Event Generators

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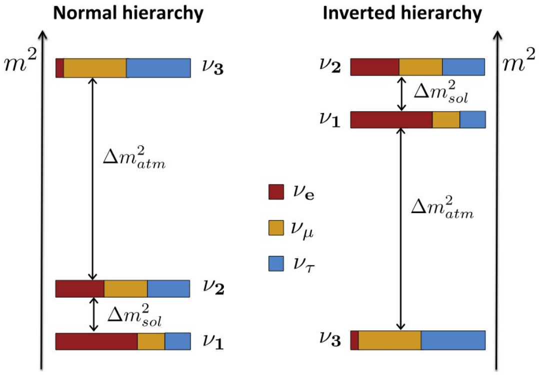
e4nu First Collaboration Meeting
12 March 2025

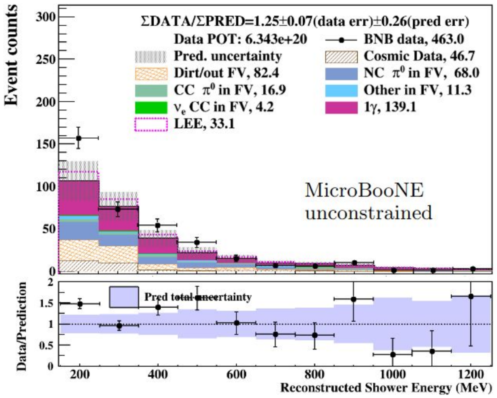
Why Study Neutrinos?



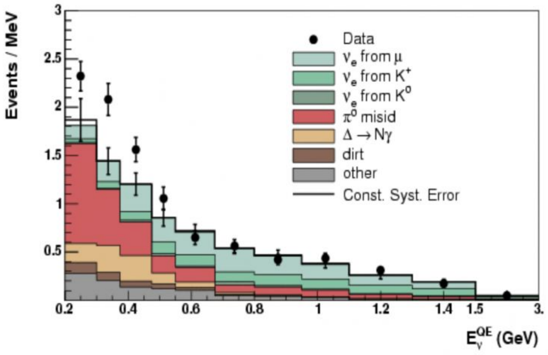
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

Open Questions in Neutrino Physics:

- Source of neutrino masses
- CP violation in the neutrino sector
- Are their other types of neutrinos? (Sterile neutrinos, etc.)
- Are neutrinos Dirac or Majorana?
- Mass ordering (normal or inverted)?



MicroBooNe Collaboration [2502.06064]



Credit: MiniBooNE

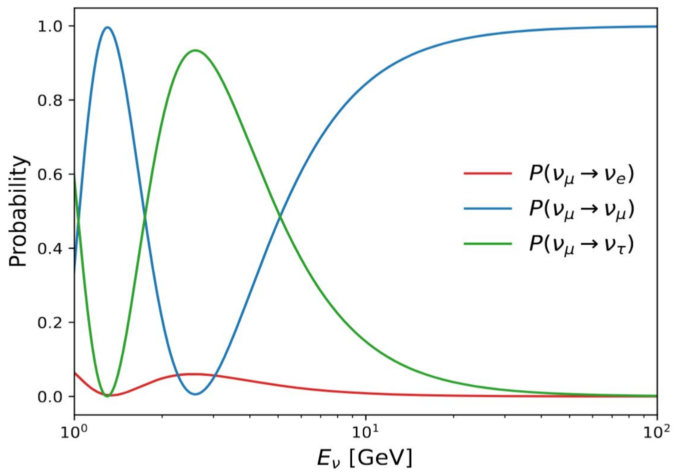
Neutrino Oscillations

PMNS Mixing Matrix

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Additional factors for matter effects
- Oscillation probability depends on distance neutrinos have traveled
- Only sensitive to mass squared differences (no absolute scale)

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$



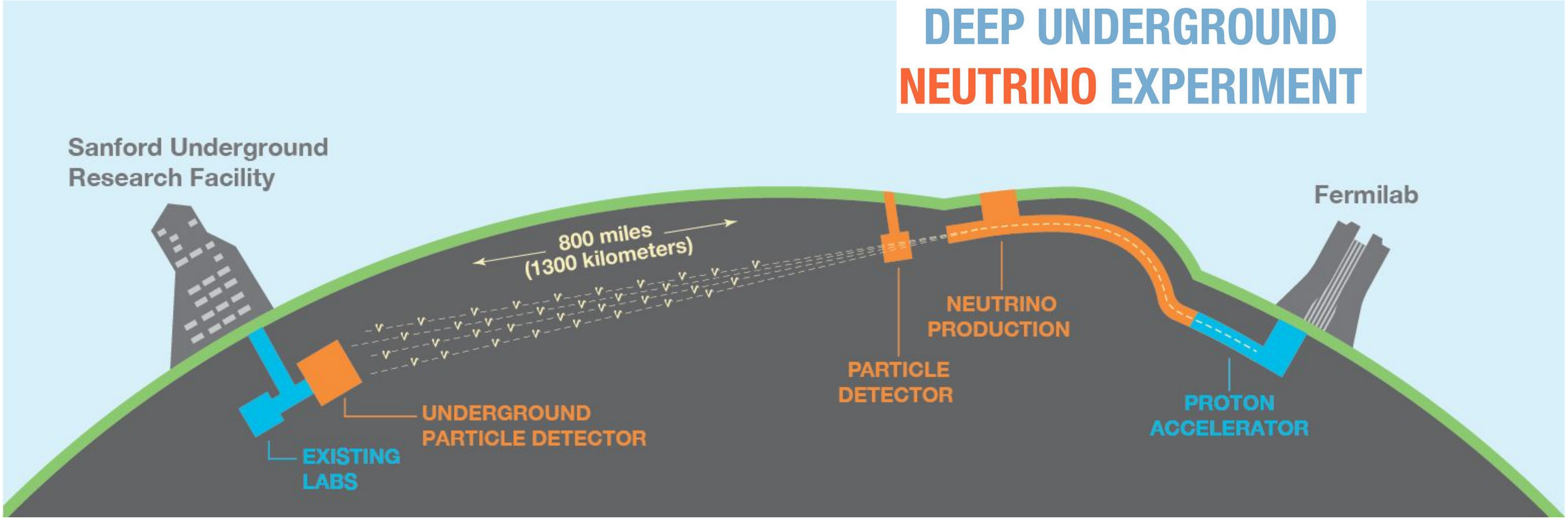
Two-Flavor Approximation:

$$P(\nu_\alpha \rightarrow \nu_\beta; L) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P(\nu_\alpha \rightarrow \nu_\alpha; L) = 1 - P(\nu_\alpha \rightarrow \nu_\beta; L)$$

Neutrino Experiments

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT



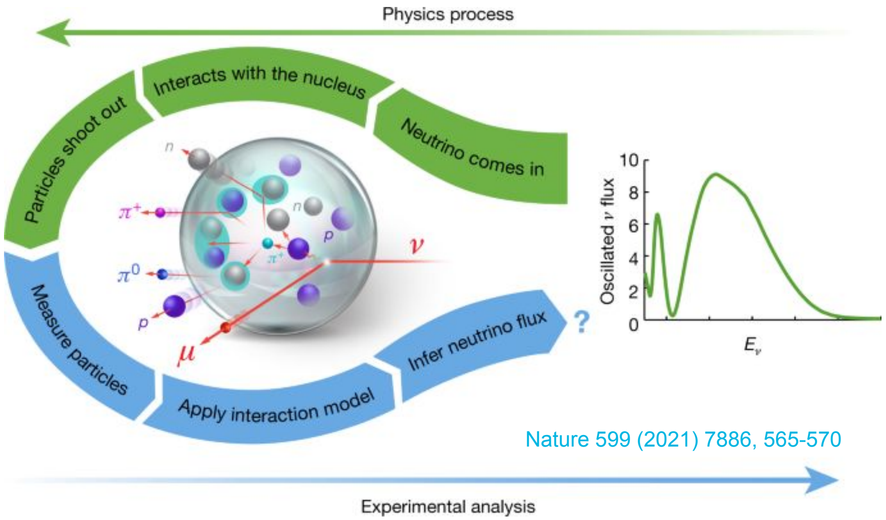
Credit: DUNE Collaboration

Extracting Oscillation Parameters

Number of events — Neutrino flux — Oscillation probability — Cross section — Detection effects

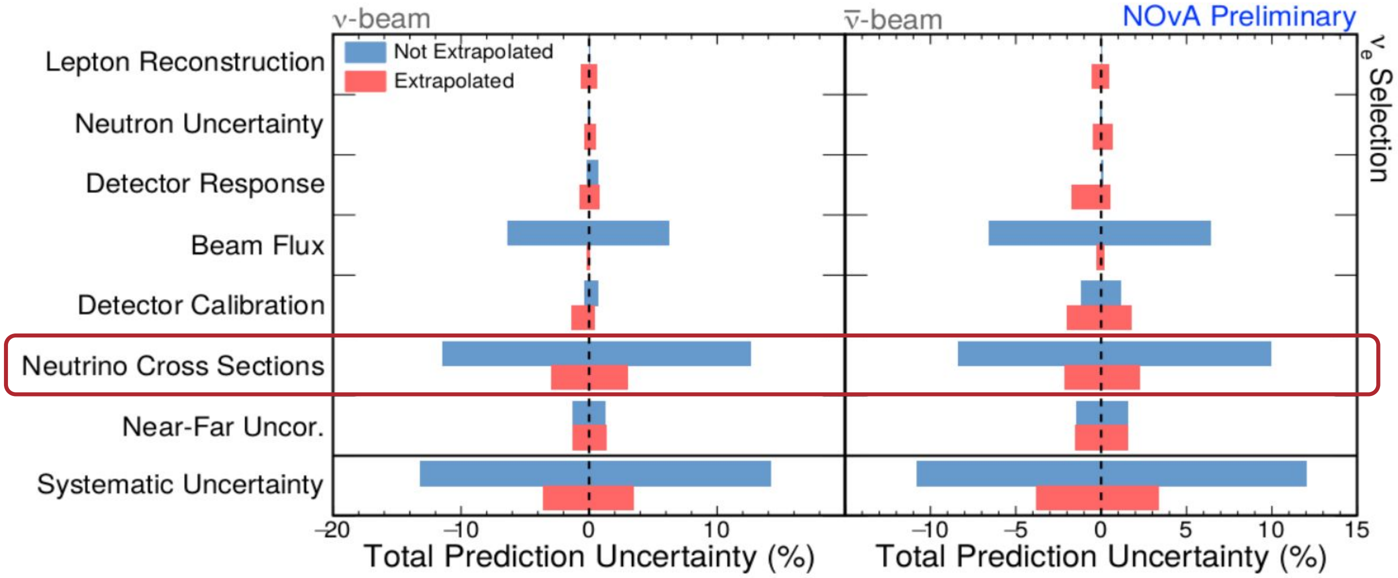
$$\boxed{\frac{N_{FD}}{N_{ND}}} \propto \frac{\int \mathrm{d}E_\nu \boxed{\frac{\mathrm{d}\phi_\alpha^{FD}}{\mathrm{d}E_\nu}} \boxed{P(\nu_\alpha \to \nu_\beta; E_\nu)} \boxed{\sigma_\beta(E_\nu)} \boxed{\mathcal{M}_\alpha^{FD}(E_\nu, E_{reco})}}{\int \mathrm{d}E_\nu \boxed{\frac{\mathrm{d}\phi_\alpha^{ND}}{\mathrm{d}E_\nu}}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

Neutrino flux — Cross section — Detection effects

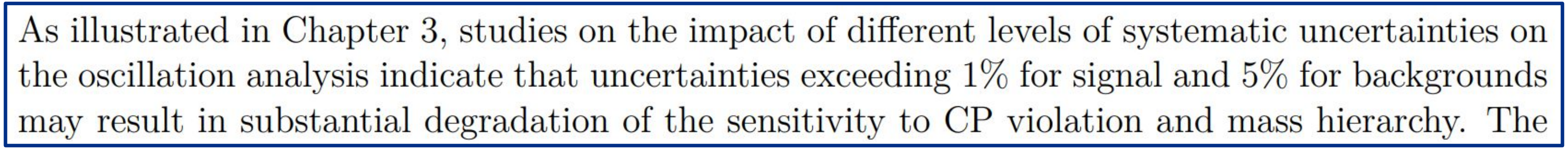


Nature 599 (2021) 7886, 565-570

Precision Requirements

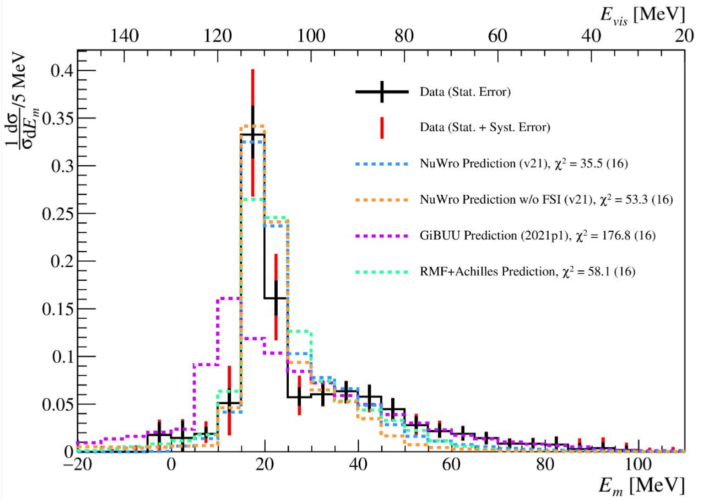


From the DUNE CDR2 (1512.06148)


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

The Achilles Event Generator

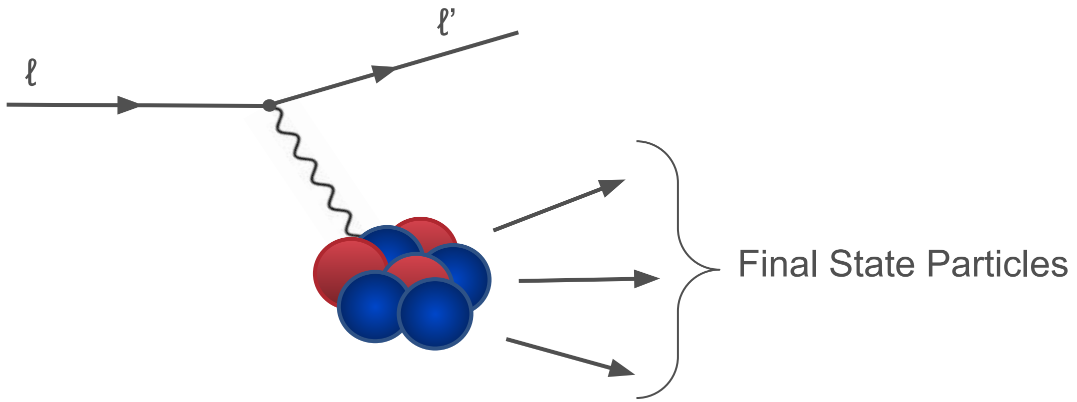
Isaacson, Jay, Lovato, Machado, Rocco [2007.15570],
Isaacson, Höche, Gutierrez, Rocco [2110.15319],
Isaacson, Jay, Lovato, Machado, Rocco [2205.06378],
Isaacson, Höche, Siegert, Wang
[2303.08104]cccccccccccccccccc



[JSNS^2 Collaboration, 2409.01383]

- Take experience from computational theory frameworks for LHC
- Combine particle theory and nuclear theory knowledge
- Leverage existing standards for Beyond the Standard Model physics

Calculation Breakdown



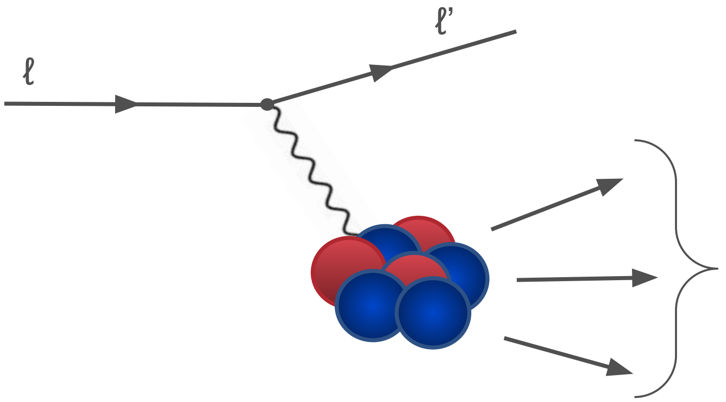
$$\mathrm{d}\sigma = \left(\frac{1}{|v_A - v_\ell|}\frac{1}{4E_A^{\mathrm{in}}E_\ell^{\mathrm{in}}}\right) \times |\mathcal{M}|^2 \times \prod_f \frac{\mathrm{dp}_\mathrm{f}^3}{(2\pi)^3}(2\pi)^4\delta^{(4)}\left(p_A + p_\ell - \sum_f p_f\right)$$

Flux Factor

Matrix Element

Phase Space

Calculation Breakdown



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)

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

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

Final State Interactions

Final State Interaction Evolution Equation

$$\exp\left\{-i\sum_{j=2}^{A}\int_0^t d\tau\,\Gamma_{k_i}(|\mathbf{r}_1+\mathbf{v}\tau-\mathbf{r}_j|)\right\}$$

Implementation via folding functions

- Pro: Enables inclusion of non-unitary effects
- Con: Inclusive on final state multiplicity

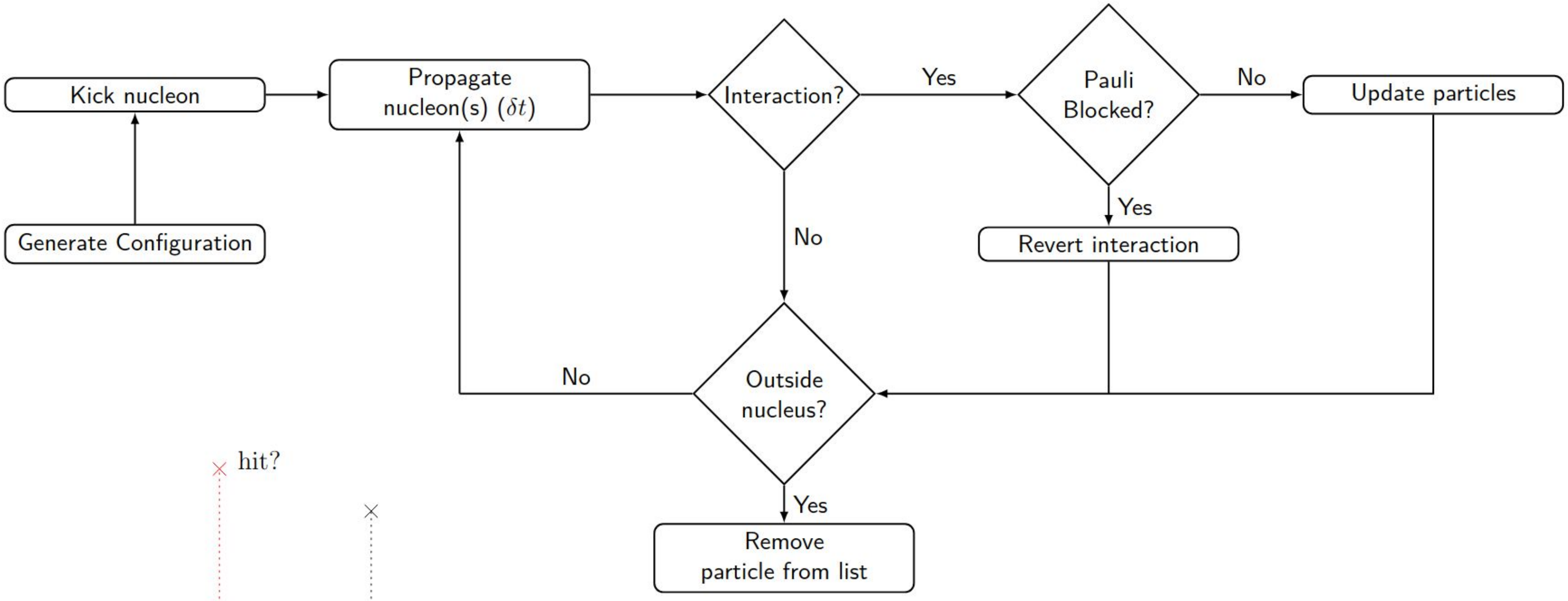
Implementation via cascades

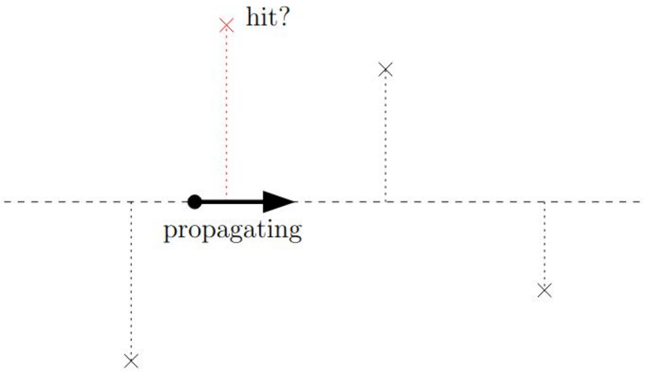
- Pro: Fully exclusive final state predictions
- Con: Required to be unitary to handle via a Markovian process

Doing both results in double counting the same physics effects

Final State Interactions

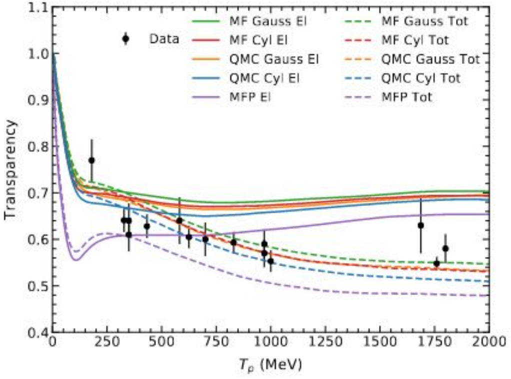
Isaacson, Jay, Lovato, Machado, Rocco [2007.15570],
Isaacson, Jay, Lovato, Machado, Rocco [2205.06378]

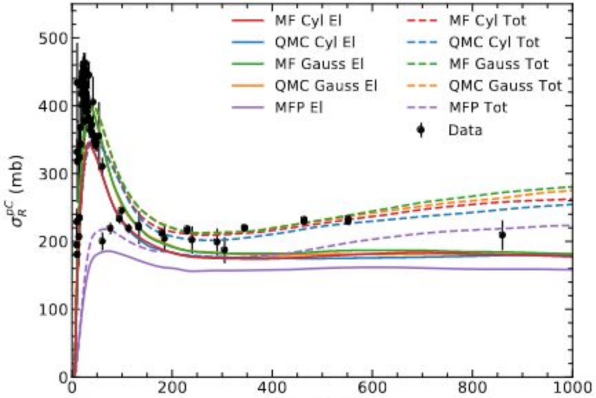


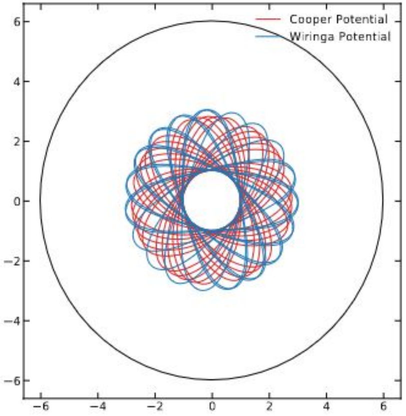


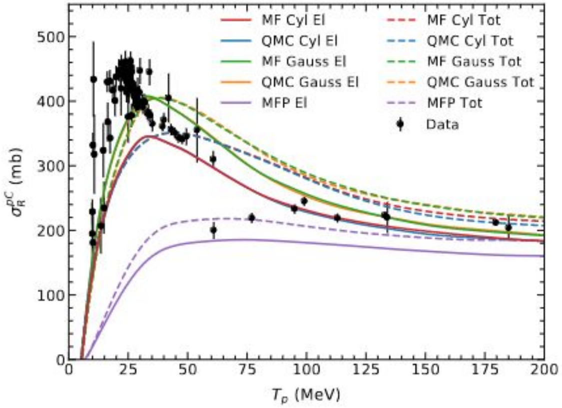
Intranuclear Cascade: Nucleons

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

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

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

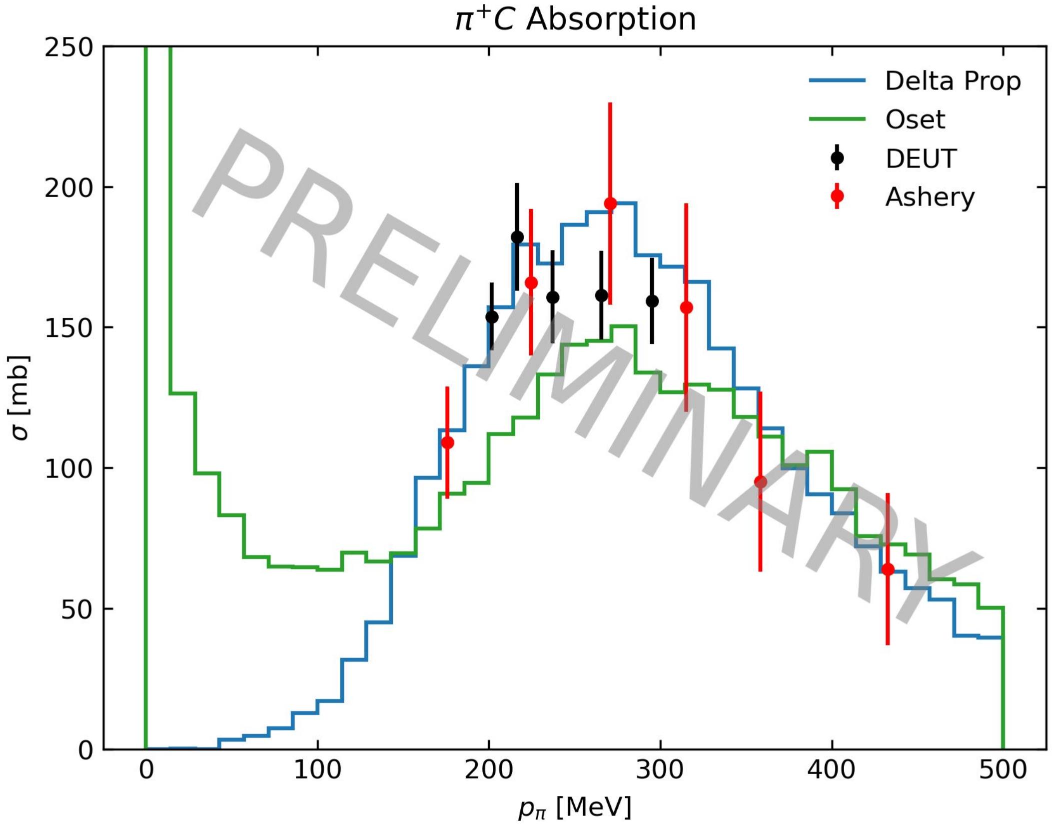
- Propagation either straight-lines or in optical potential using classical evolution
- In-medium cross-section corrections from Pandharipande-Pieper
- Incorporate Pauli-blocking and formation zone

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:

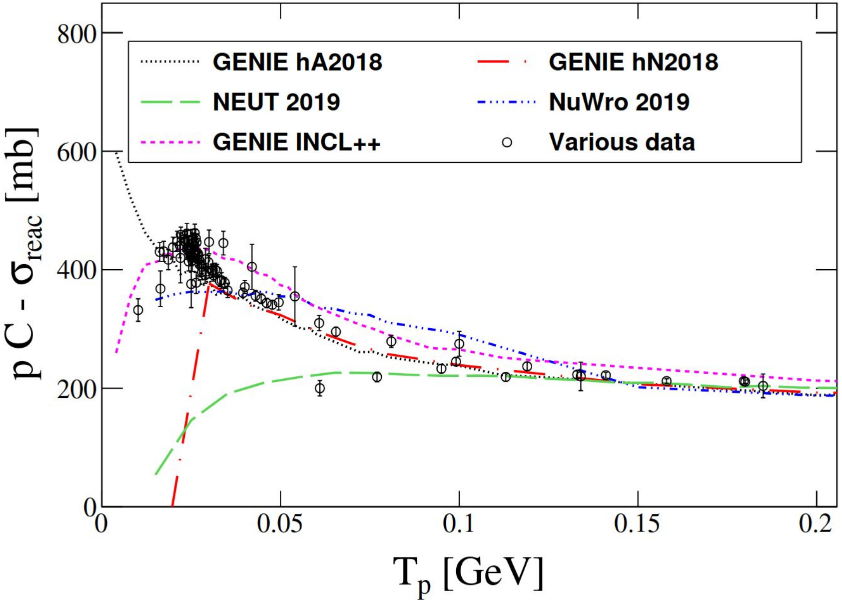
$$\pi NN \rightarrow NN$$

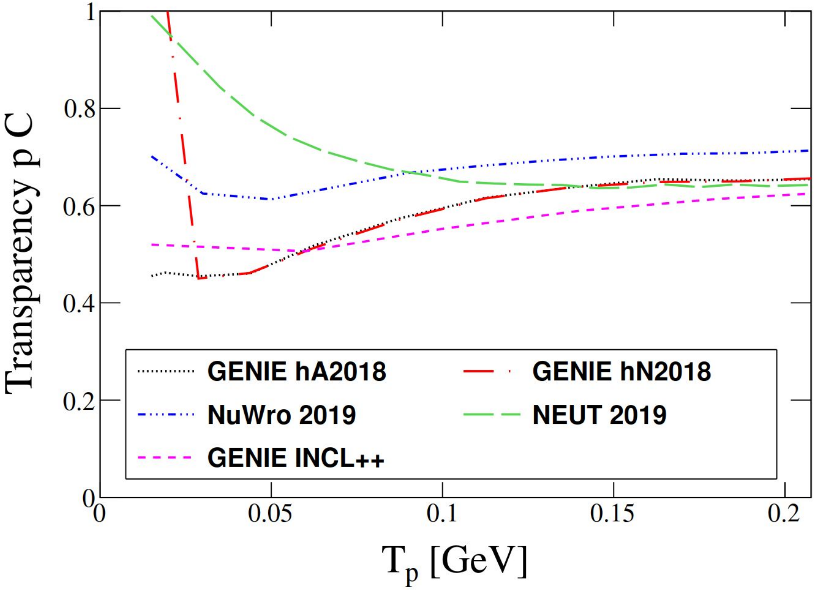
- Oset model includes both 2-nucleon and 3-nucleon absorption rate, but kinematics only two body final state



Intranuclear Cascade: Other generators

Dytman, Hayato, Raboanary, Sobczyk, Tena-Vidal, Vololoniaina [2103.07535]

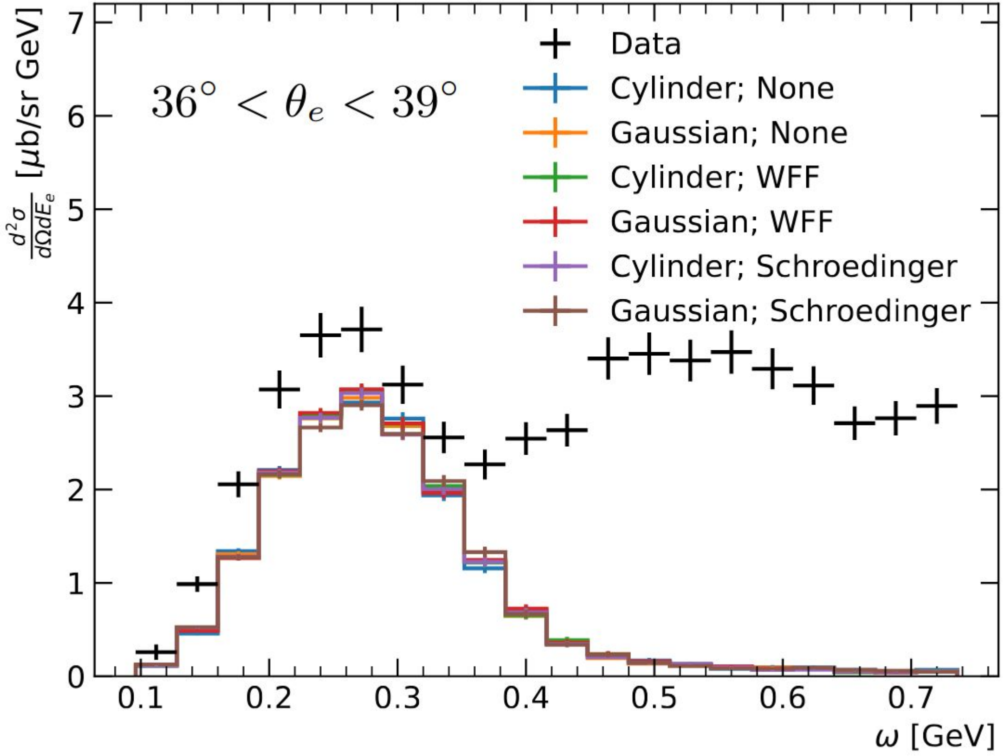




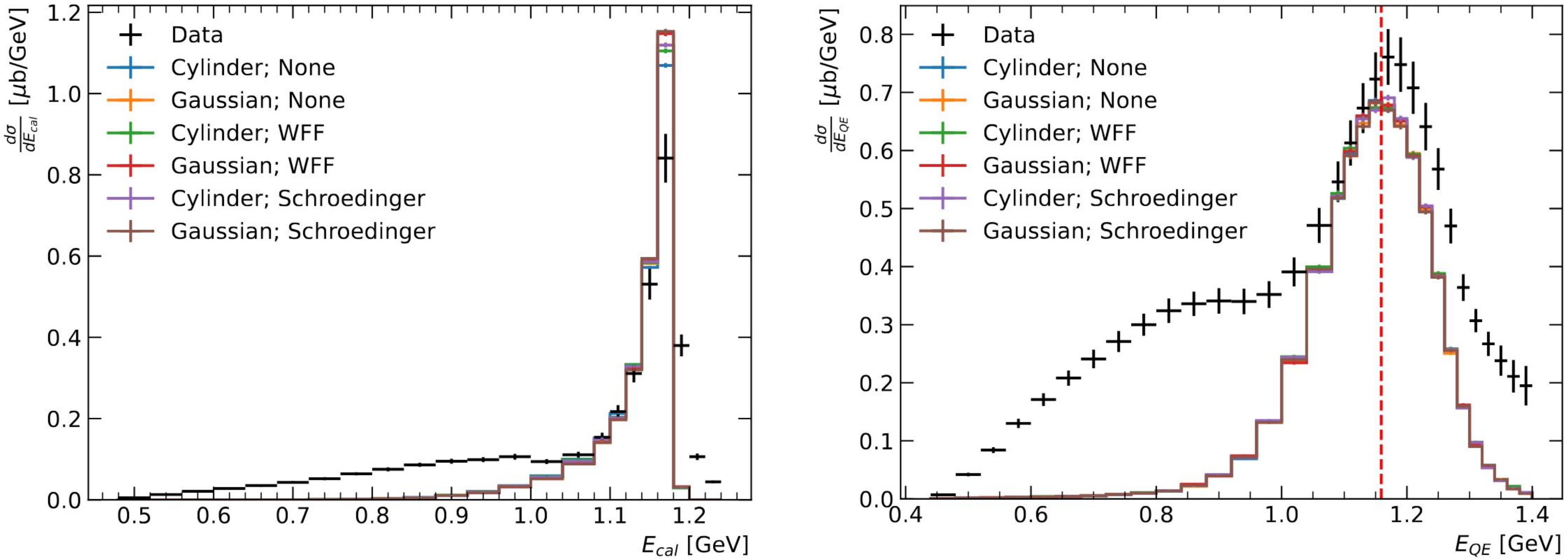
Comparisons to e4nu

- Gaussian vs. Cylinder are two different ways to determine if an interaction occurs
- None, WFF, and Schroedinger are different nuclear potentials used to estimate the impact of in-medium effects
- Predictions only include quasielastic scattering

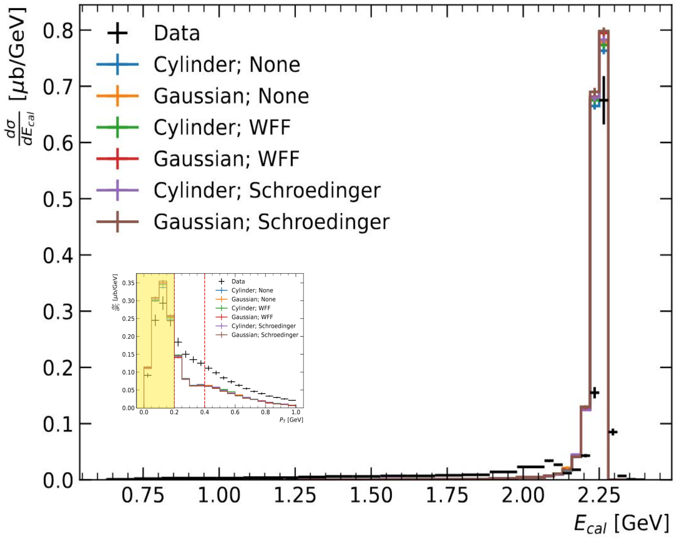
Inclusive Results:

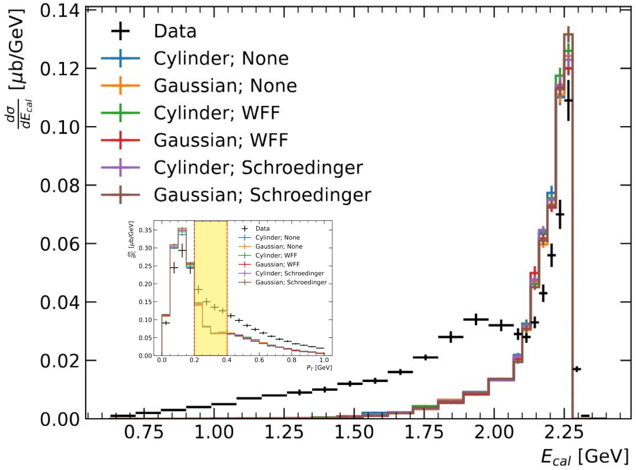


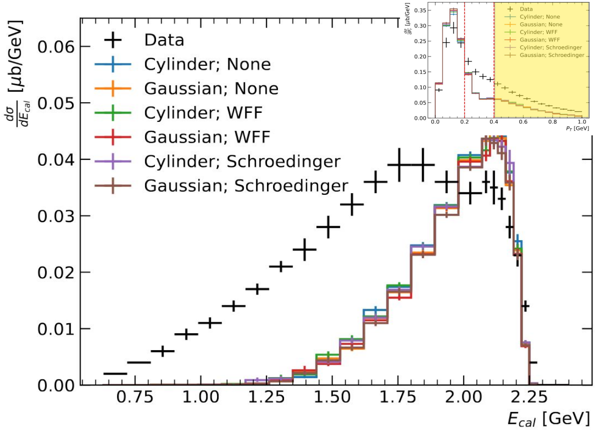
Comparisons to e4nu



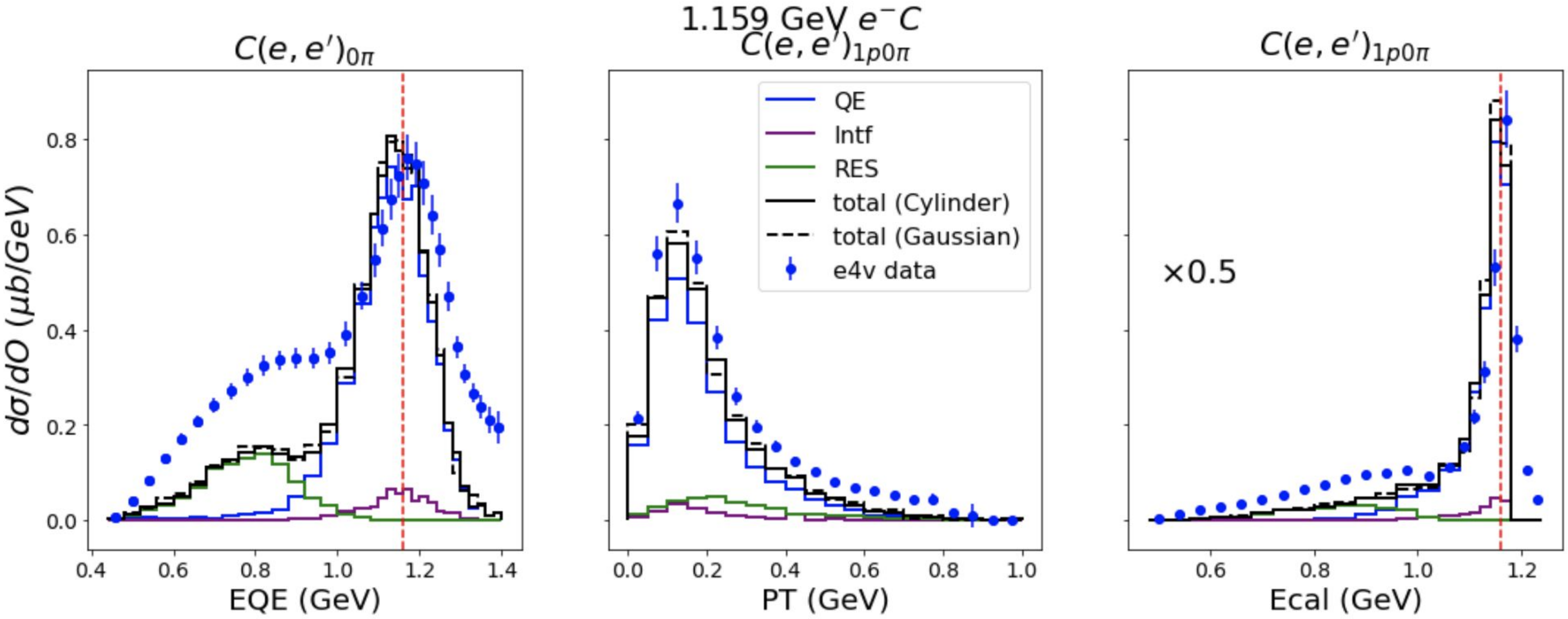
Comparisons to e4nu



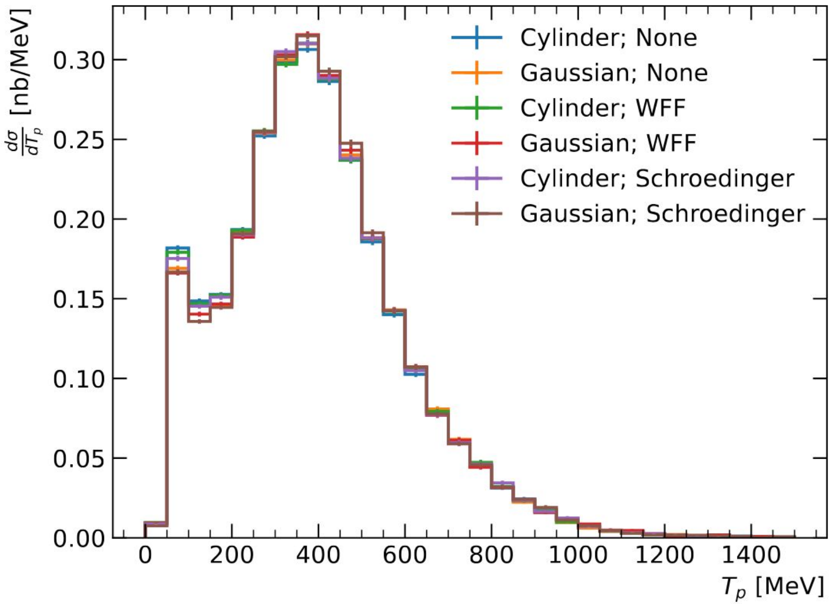




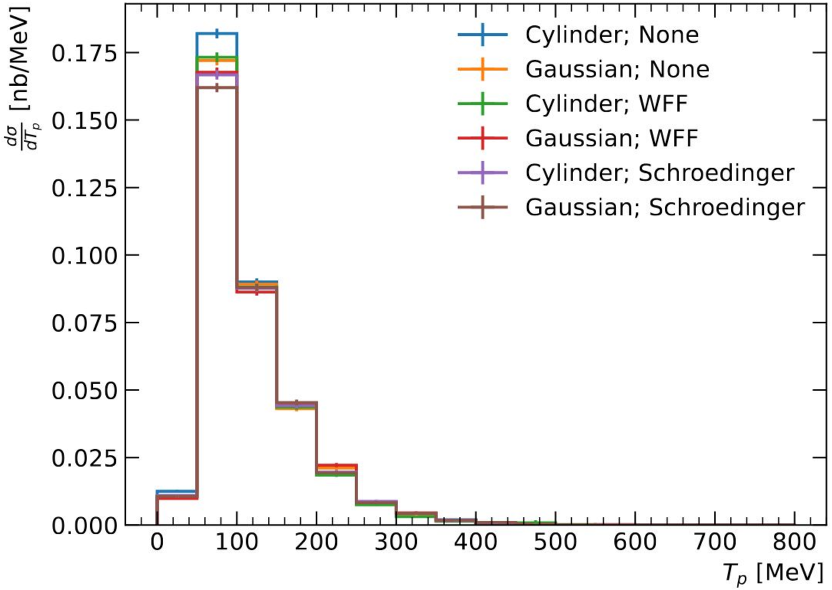
Update e4v comparison



New Observables

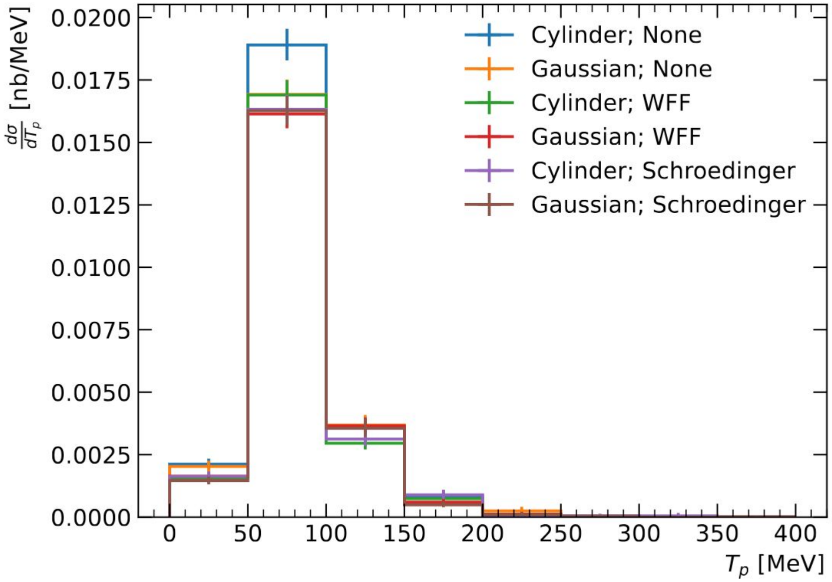


Momentum of leading proton

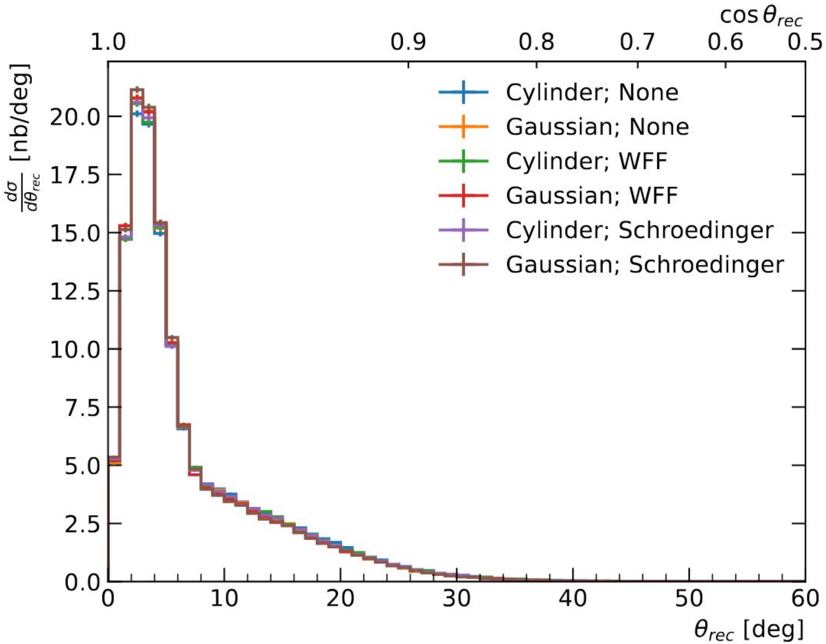


Momentum of subleading proton

New Observables



Momentum of subsubleading proton



Reconstructed beam direction

$$\cos\theta_{\text{rec}} \equiv \frac{\hat{\mathbf{k}}_e \cdot \mathbf{p}_{\text{out}}}{|\mathbf{p}_{\text{out}}|}$$

Conclusions

- Current and next-generation neutrino experiments will need high precision predictions from event generators to meet their goals
- Cascades arise from the same underlying physics as folding function approaches to final state interactions
- Significant differences between different cascade approaches in more inclusive observables
- Help pin down where differences arise by looking at more exclusive observables

ACHILLES