FSI models in GENIE

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13 March, 2025

- origin/goals
- performance
- role of e4nu
- advantages/disadvantages
- big picture overview

Introduction

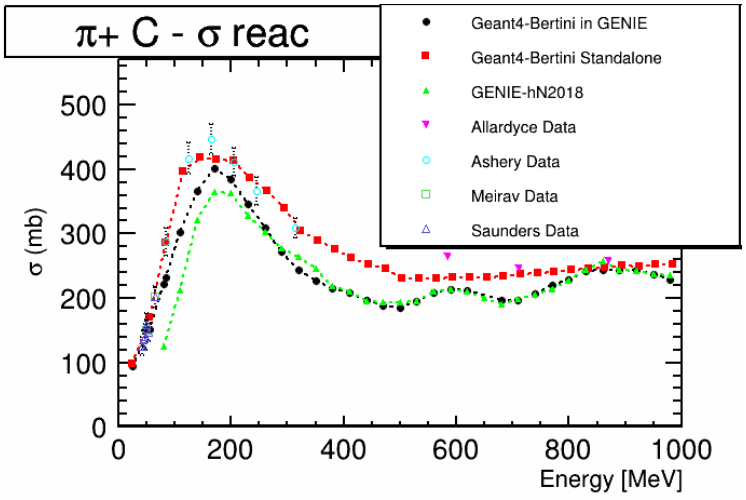
- GENIE is a repository for models of many types
  - unique that way, allows easy comparison
  - tools for linkage to needs for experiment simulation also unique
- All interactions (QE, MEC, RES, DIS…) for all nuclei (hundreds) at energies up to 10 TeV (7 orders of magnitude).
  - Merger of disparate models nontrivial!
- best for neutrinos and hadron beams, electron applicability very good but still under development by e4nu (others?)
- GENIE progress is limited to what can be done by members and contributors
  - collaboration has a few postdocs! (push in 2000's)
  - mixed success with theorist involvement (very good but improvement?)

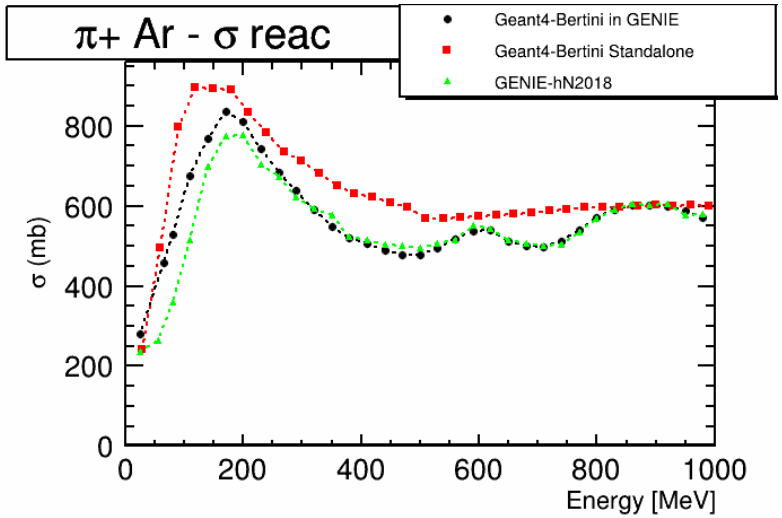
3.5 FSI models

- hA is homegrown, my first contribution to GENIE
  - it is a simple, empirical representation of hadron-nucleus based on what I learned in first part of my career (Pitt students)
  - theorists don't like it, but it fits data and is reweightable!
- hN is cascade model (traditional) based on free hadron-nucleon cross sections with nuclear corrections (Salcedo-Oset, Pandharipande-Pieper) (Pitt students+Tomek Golan)
  - very similar to what is in NEUT and NuWro (Jan Sobczyk) base models
- INCL built by European theorists, e.g. Anna Ershova
  - cascade fully developed with from theoretical model based on experimental experiences – super!
  - put into Genie by me and my Madagascar student (Marc)
  - unfortunately, nuclear model not fully integrated into GENIE
  - not publicly available now

3.5 FSI models

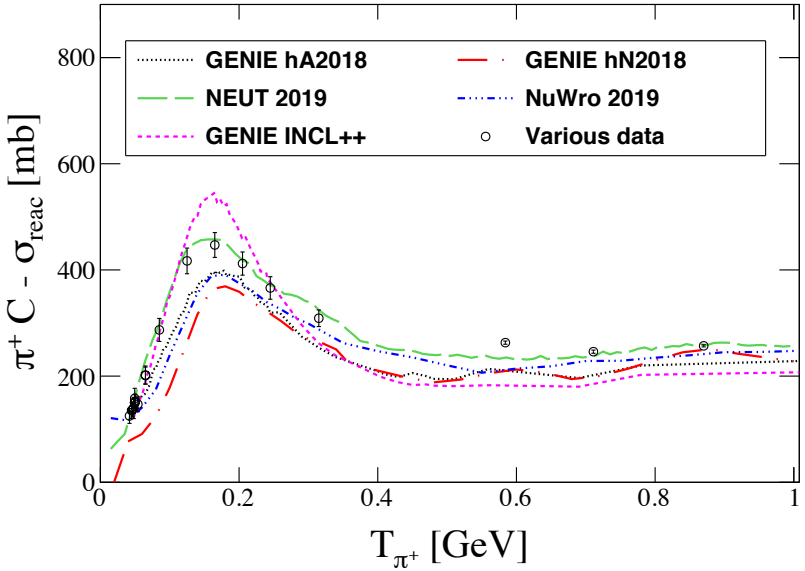
- GEANT used by many experiments for hadron-nucleus simulation, e.g. hadron rescattering in (large!) ν detectors.
  - DOE asked that it be included in GENIE, great because I've always wanted broad range of models available
  - GEANT applicability to low energy hadrons has grown significantly in my career
  - However, change in front end needed to adapt to e, ν scattering

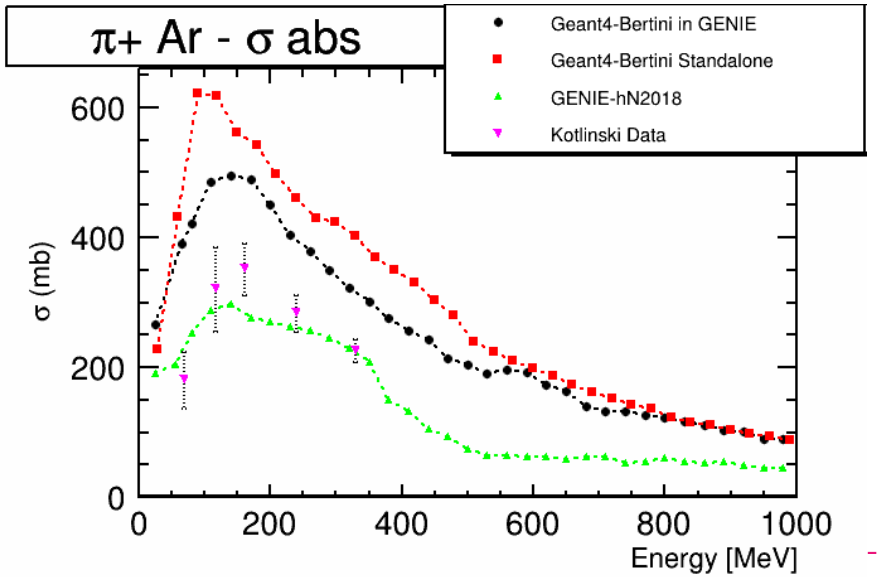




More detailed comparisons
Work of Marc (student in Madagascar)

- total reaction xs comparison of many generators (PRD 104 (2021) 053006)
  - work of Jan, Hayato-san, Julia, Marc, and me
- pion absorption
- N.B. to date, all FSI validation done with hadron-nucleus data





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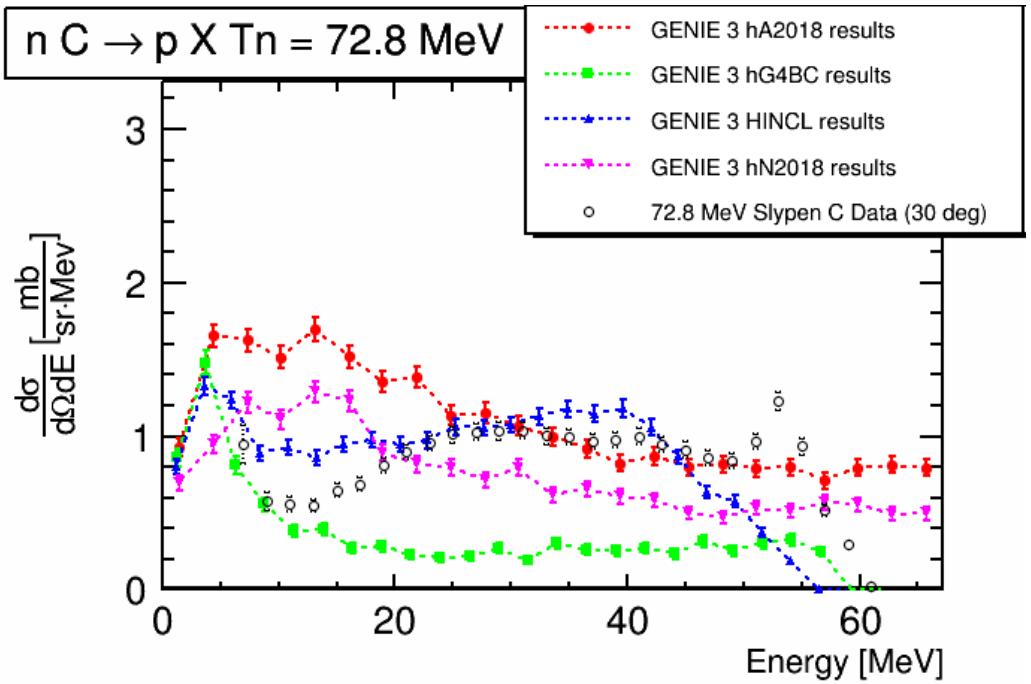
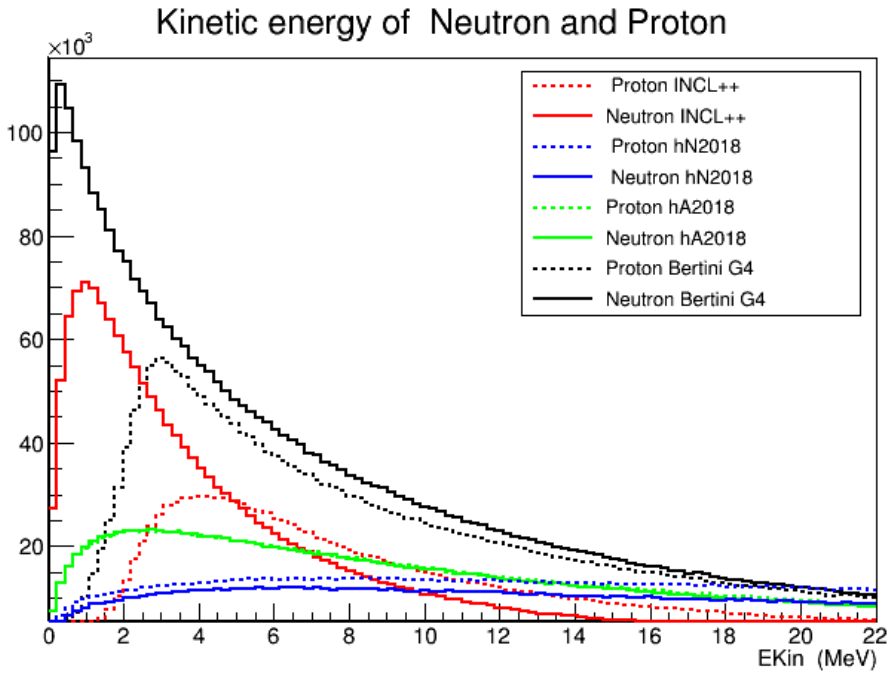
More detailed comparisons
Work of Marc (student in Madagascar)

- Low energy hadrons dominated by nuclear effects.
- Left: Fe(n,p) double diff xs (important for charged-neutral balance)
- Right: compare behavior for very low KE nucleon emission
  - colors for different models, dashed vs. solid for neutrons vs. protons





GENIE developments underway

- hA2025
  - updated splines for hA - pions (M. Ismail, Pitt) and nucleons (G. Putnam, FNAL)
  - pion absorption model details (R. Diurba, Berne) (new reweighting)
- hN2025
  - pion-nucleon cross sections from DCC (Sato-Lee) (F. Anjarazafy – Madagascar)
  - add Pauli blocking, ABLA compound nucleus (Marc V. start)
- INCL
  - Liang Liu (FNAL) will properly integrate INCL model into GENIE
  - add INCL nuclear model to general GENIE

Role of e4nu significant

- νA interactions poor way to test FSI models (statistics)
- electron beams better
  - much higher statistics
  - known beam energy allows focus on interaction types
    - can look at protons solely from RES/nonRES (Julia)
    - (e,e'π) very sensitive to pion FSI
    - measure transparency! (proton results to be released soon?)

Bigger picture

- role of transparency
  - measures exactly what is needed or ν and e simulation (hadron beams tend to interact at periphery of nucleus)
  - much more sensitive to nuclear structure (PRD 104 (2021) 053006), proton transparency)
- what is real uncertainty in FSI?
  - FSI will continue to be important component of ν oscillations.
  - Yinrui Liu showed me results for DUNE simulation where spread due to GENIE models is comparable to statistical uncertainty
    - I expect similar issue for nuclear structure and pion production!
  - not easy to determine since all models have uncontrolled approximations (nuclear many-body problem)
  - Josh Isaacson shows uncertainty in stepping
  - Anna Ershova shows uncertainty in multinucleon clusters formation
  - In my humble? opinion, no model can be perfect!

Issues

- hadron-nucleon cross sections
- stepping
- nuclear structure
- low energy hadron emission
- pion production
- neutral particle emission – neutrons, pi0