ECT
GENIE FSI overview

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- GENIE FSI strategy
- features
- comparisons
- looking to future

GENIE FSI strategy

- For better comparisons, goal always for 2 codes which are compatible with neutrino codes.
  - **hN** is Intranuclear Cascade (INC, common in generators) and **hA** is data driven/simplified version (unique)
  - hA is fully reweightable, very fast
  - Both are fit to hadron-nucleus data. hN only recently available to public
- Advances slow, come when manpower available (Pitt undergrads, Tomek Golan)
- As of now, includes pions, K^+, p, and n

Why INC?

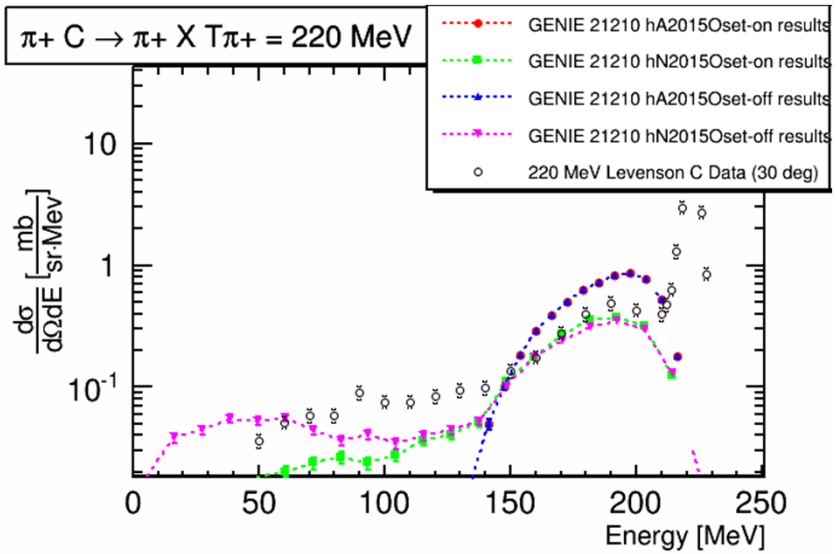
- Many body quantum mechanics is hard! Semiclassical approximation makes problem solvable.
- Good approximation when mean free path (mfp) large.
- Long history of agreement with data for which approximations shouldn't be valid, e.g. $\pi \rightarrow \Delta(1232)$ where mfp smaller than inter-particle spacing.
- Low nucleon energy (KE<30 MeV) still an issue, FLUKA has interesting quantum corrections
- Medium corrections... successfully added for neutrino applications

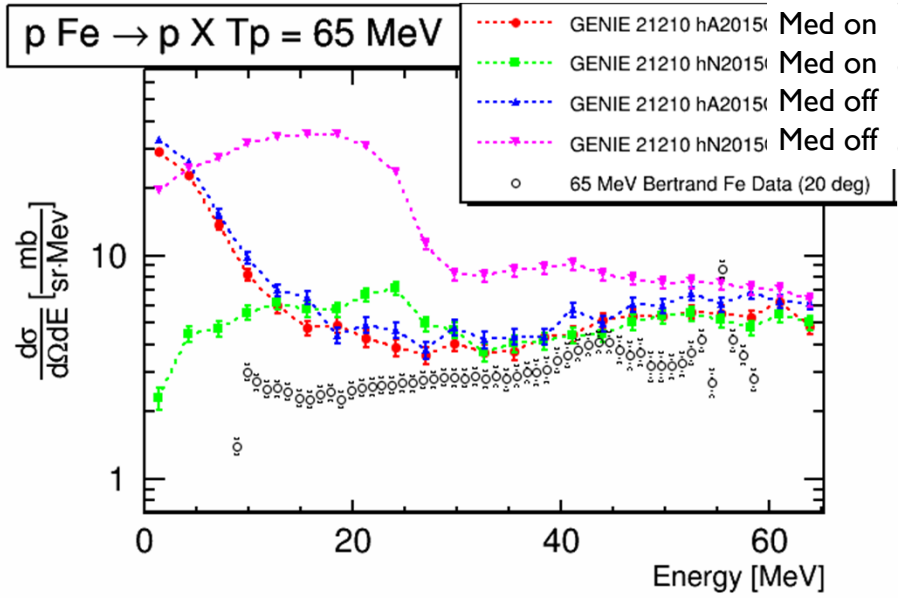
Recent history

- New versions of hA every year, always alternative model due to GENIE policy of no incremental changes to default
- V2.12.10 has preliminary versions of what will be in v3.0; hA2015 and hN2015
  - Add medium corrections for pions (Oset) and nucleons (Pandharipande/Pieper) to hN (incompatible with hA) (NuWro!)
  - For most applications, difference between 2015 and 2018 not large
- hA2018 and hN2018 are most recent versions, hA maintained as legacy code
- hN FSI results should be compatible with NuWro because Tomek Golan worked on both, not tested yet

Medium corrections study
pions at resonance and low energy protons

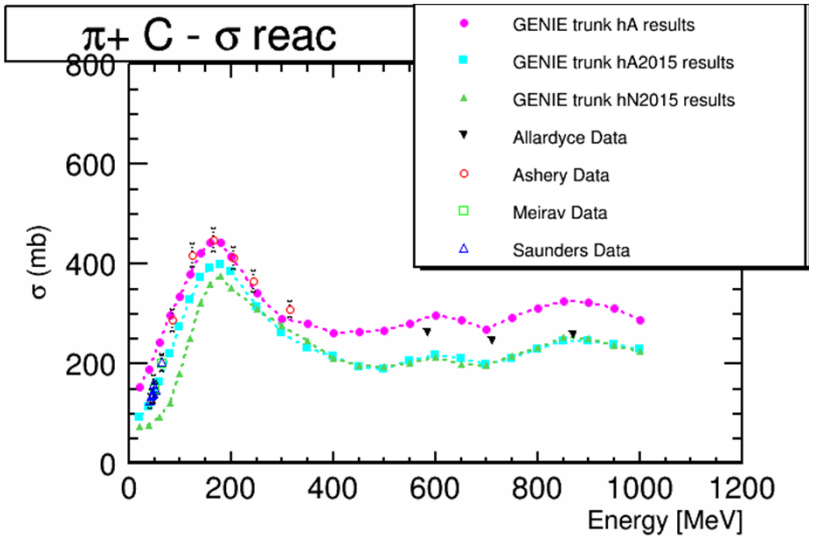
- hN has medium corrections for π, p & hA has none
- hA models QE peak, hN has multiple scattering
- Medium corrections suppress multiple scattering, decrease cross section. Strong A dependence!
- Both hA2015 and hN2015 describe pA data much better

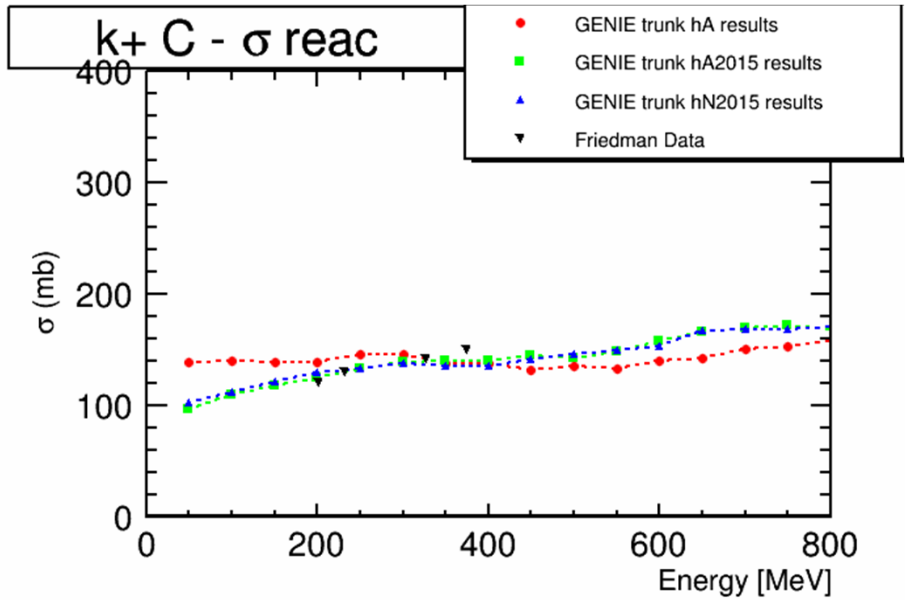




Total reaction (inelastic) cross sections π^+C and K^+C

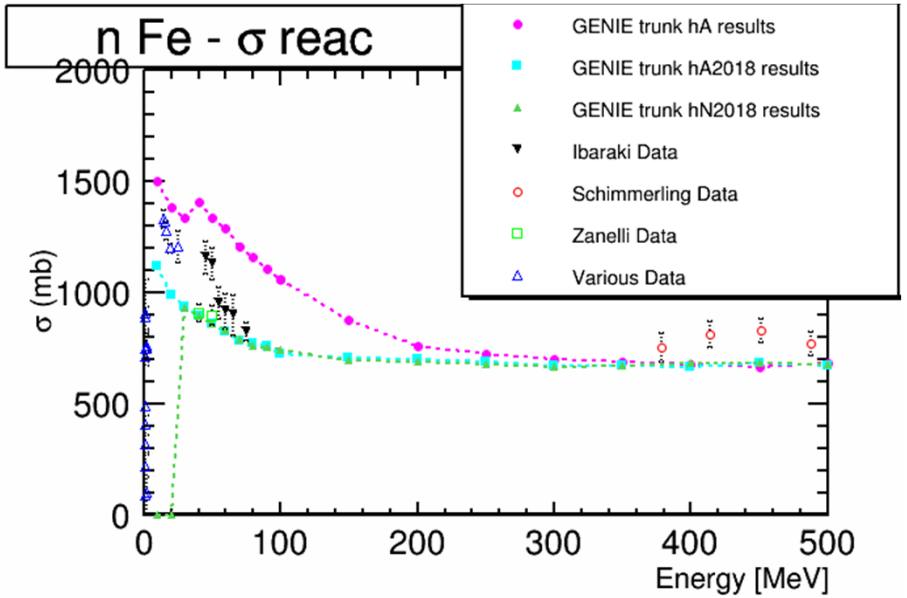
- Very broad view of FSI
- Good pion data, very little K data
- π^+ has significant peak for Δ excitation, none for K^+
- Both hA2015 and hN2015 underpredict pion peak xs

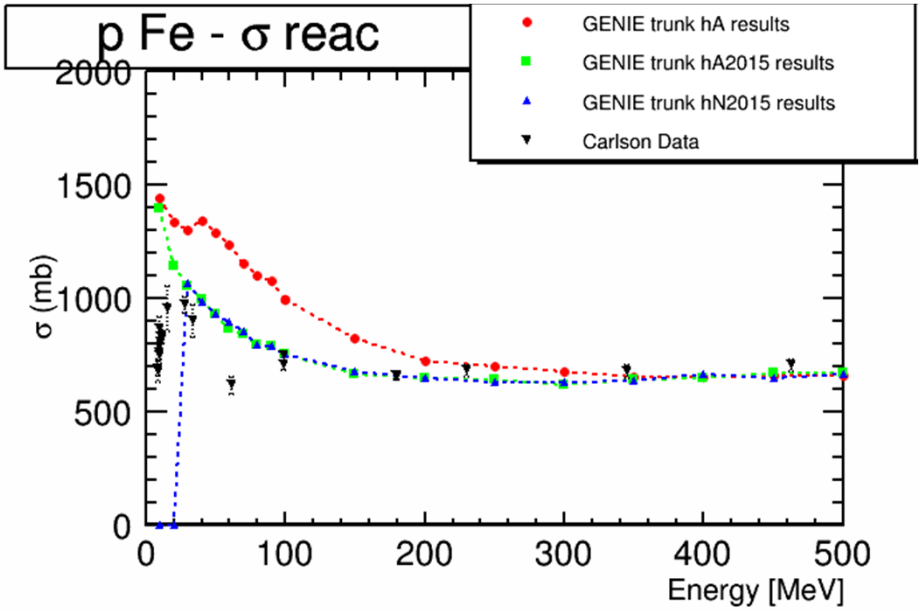




Total reaction (inelastic) cross sections pFe and nFe

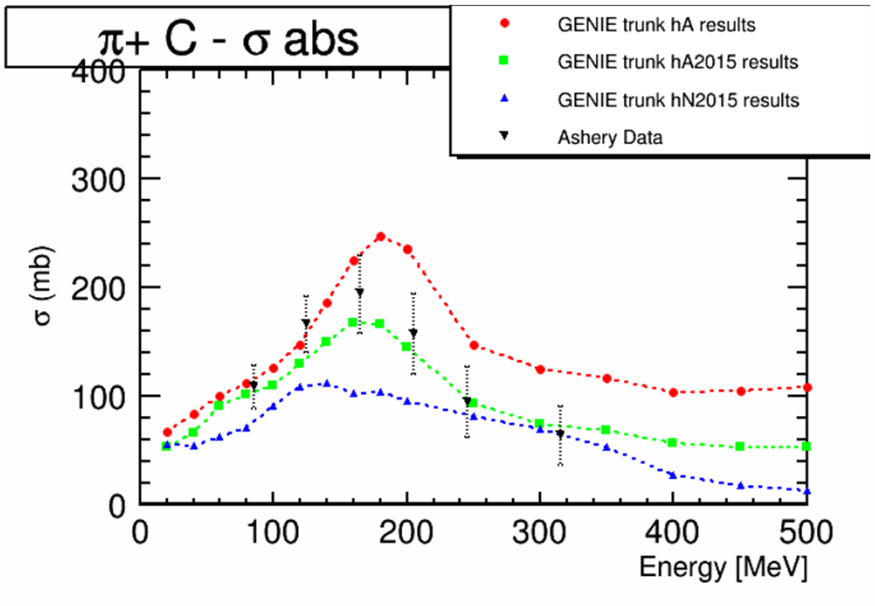
- Both have significant strength for FSI, mfp~2fm
- Low energy enhancement described better by newer models, result is less rescattering

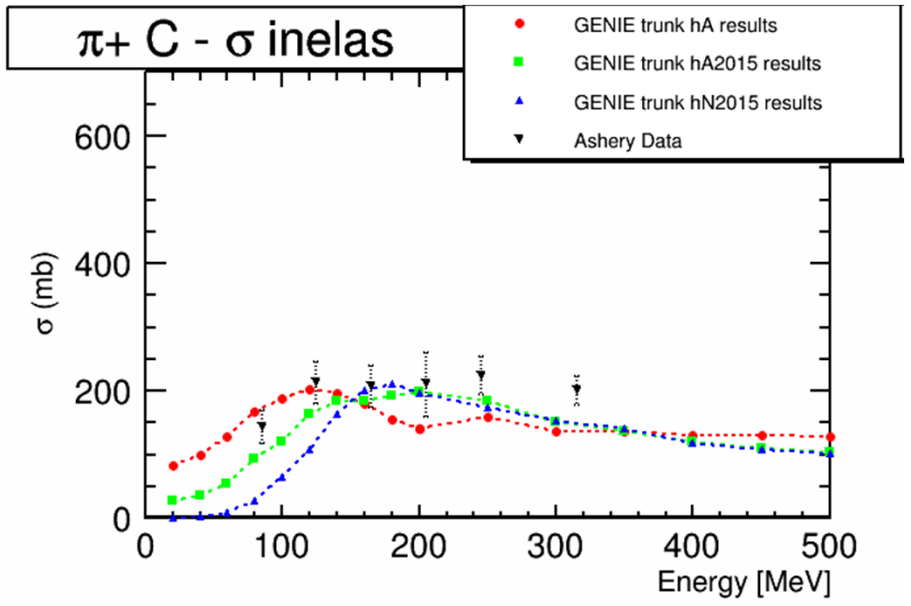




More detail for pions
scattering vs. absorption

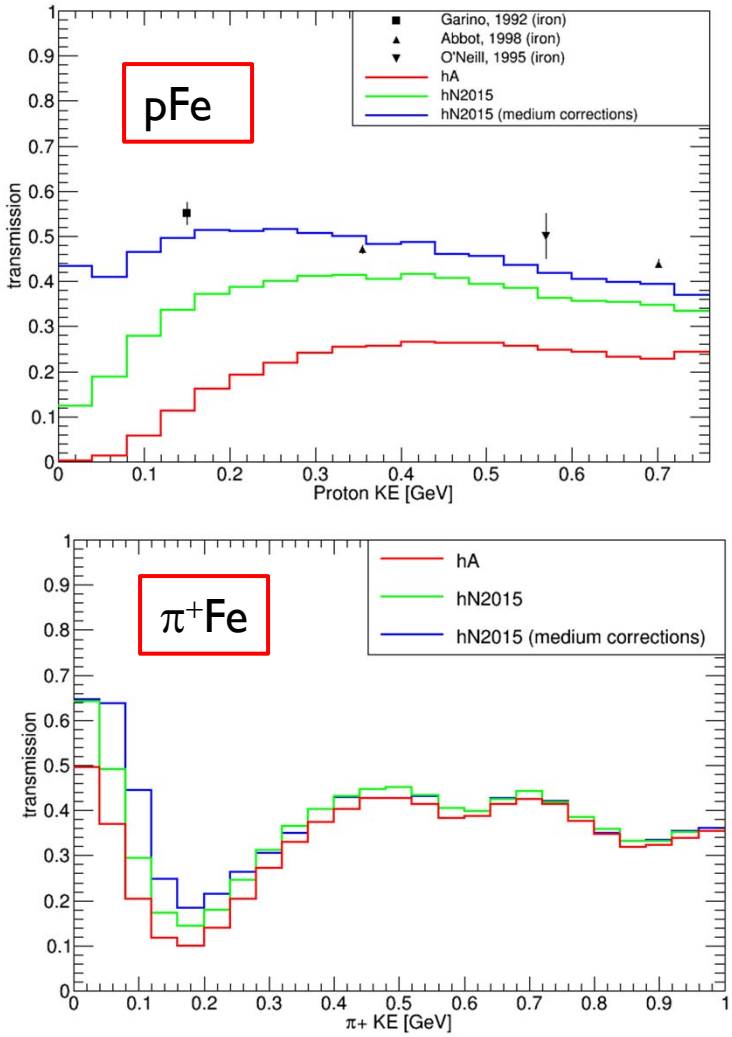
- hA has too much absorption, hA2015 uses these data as input, hN has too little absorption (feature of Oset model)
- hN2015 has too little scattering strength at low energy





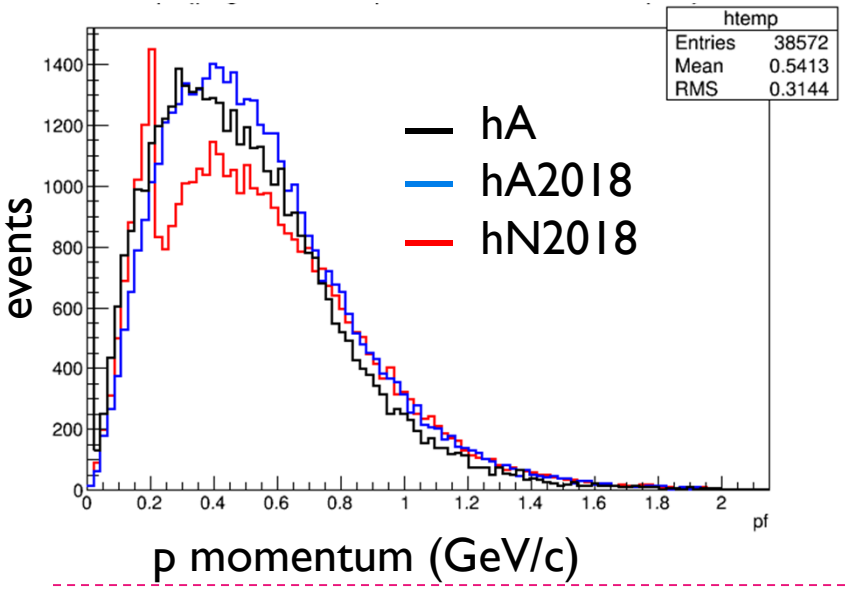
Transmission study

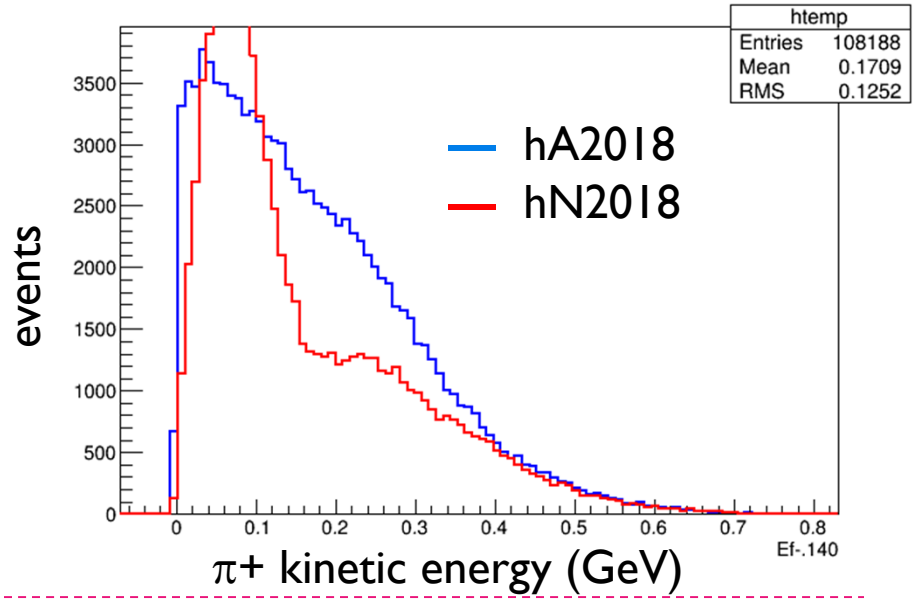
- Transmission and hadron-nucleus are different and similar – in-medium vs. asymptotic.
- Some data for protons, none for pions.
- Use GENIE to place hadrons throughout nucleus, T is probability to escape without FSI. Blue adds medium corrections to green, hA is red
- Significant difference among GENIE pFe models, medium effects matter!
- Effects for πFe are smaller



Neutrino results (1 GeV ν_μ Fe)

- Events, not cross sections. Shape most important.
- Medium effects are significant for both
- For pA, hN has compound nucleus at low energies – similar to more sophisticated models





Future additions

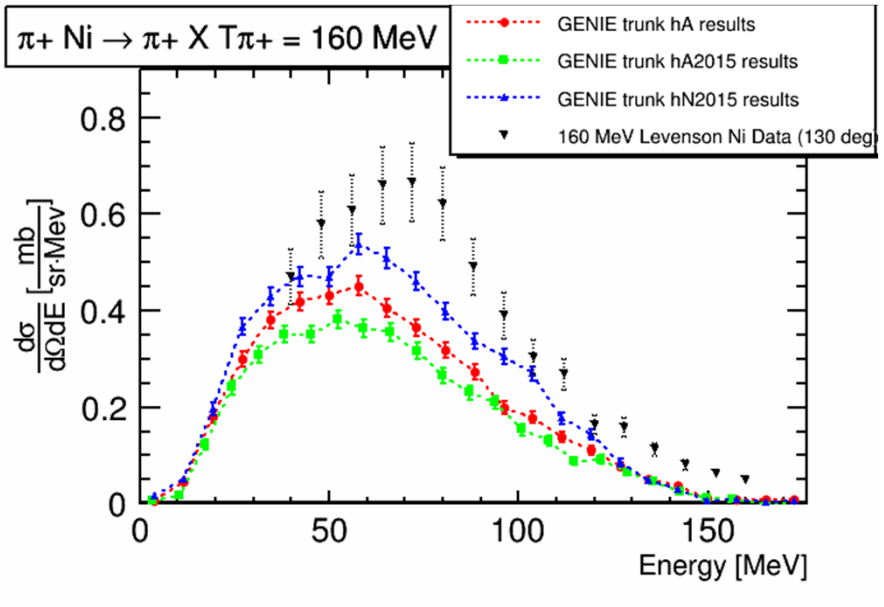
- INCL++ is modern European hadron-nucleus code
  - Has advanced medium corrections
  - Handles deuteron, triton, alpha....
  - Final validations underway, should be in v3.2
- GEANT is used by most neutrino experiments for simulations of particle propagation in detectors
  - Largely designed for higher energies than needed for ν detectors
  - Handles deuteron, triton, alpha....
  - Final validations underway, hopefully will be in v3.2
- Will use to improve hN, hA - some features already in hN2018

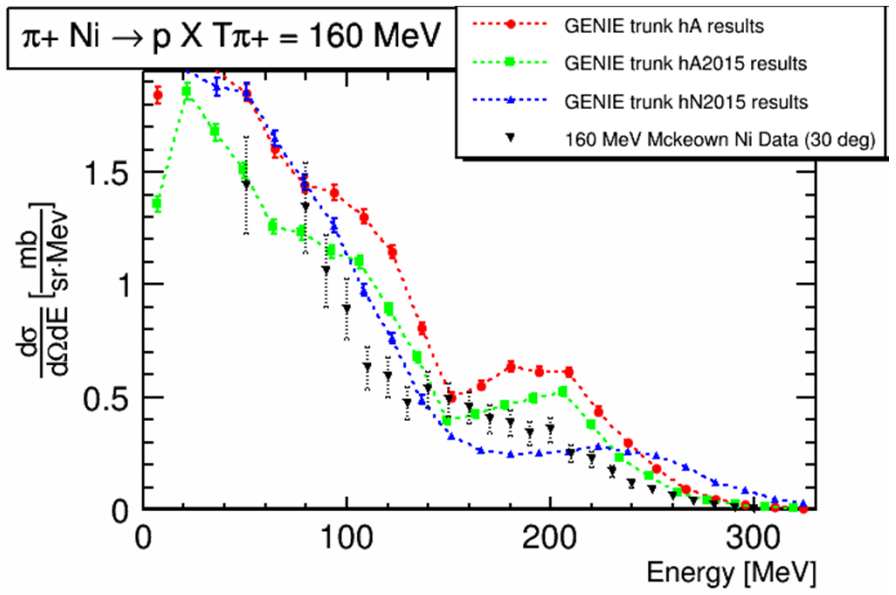
summary

- GENIE FSI has developed slowly with an overall plan
- Presently hA (unique) and hN (equivalent to NuWro?)
  - Makes interesting comparisons possible since hN should have better physics, but both have similar agreement with hadron data
  - Add medium corrections to approximate QM aspects?!?
- Existing versions (hA2018, hN2018) still under development but set for v3.0 as of now
- Changes hA→hA2014→hA2015 don't have significant changes to νA simulations
- hN2018 and hA2018 have interesting differences, still being studied and improved

Double differential cross sections (pion)

- More detail here, tests dynamics in addition to strength
- hA and hN very similar because quasielastic scattering ($\pi N \rightarrow \pi N$) and absorption ($\pi d \rightarrow NN$) dominate





Double differential cross sections (p & n)

- These are hard to get right, complicated dynamics
- Improved treatment for low energy nucleon FSI