ECT
GENIE FSI overview

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- FSI history/status
- recent publications I know of
- features/comparisons
- studies for this workshop

Why FSI matters

- The great confuser – hadron mfp ~ fm means 'large' (A dep) changes in both topology and kinematic distributions
  - Pion production followed by pion absorption mimics quasielastic when only muon detected (included in CC0π signal)
  - Hadrons change energy/angle through scattering (+additional p,n..)
  - Charged-neutral through charge exchange (+additional p,n..)
- Very few studies with ν beams
  - Scintillator detectors good except for high thresholds (few*100 MeV)
  - LAr detectors important for low thresholds
- Most data from other facilities
  - Pion, proton beams from 1970's, 1980's
  - More recent work with neutron beams

overview

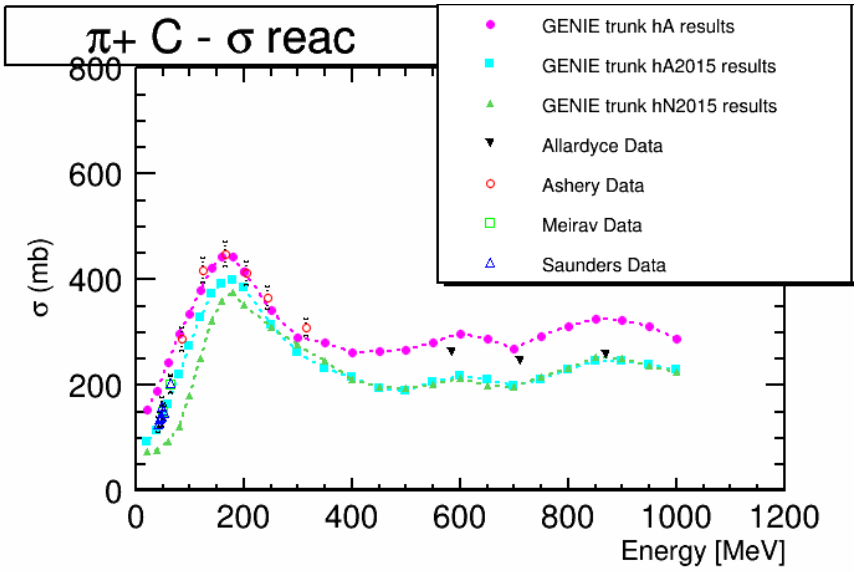
- I started hadron-nucleus with my nuclear physics PhD thesis, still important in much different venue
- Semi-classical treatments important since 1960's because full quantum calculation not possible (then and now)
  - Many consequences – good (simple, flexible) and bad (no QM, can't be right)
  - Impressive success describing data, even πA at peak of $\Delta(1232)$
- Various versions available (and not)
  - Peanut (FLUKA) has quantum-like corrections
  - Transport (GiBUU) has significant nuclear modifications
  - Salcedo, Oset has density-dependent nuclear mods, basis for most event generator models today (**NEUT, NuWro, GENIE hN**)
  - GEANT, INCL++ have evaporation, coalescence (low energy, hi A)

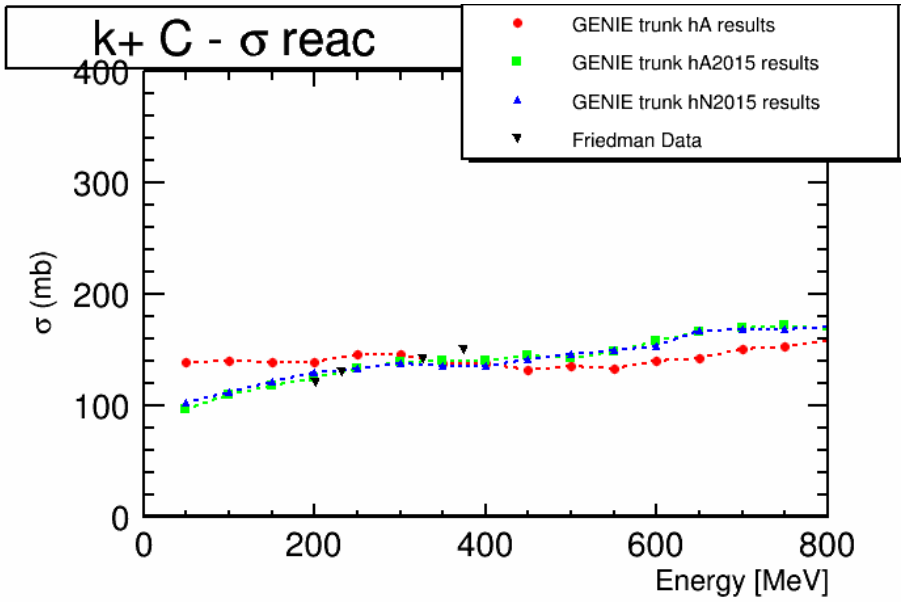
GENIE FSI strategy

- 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
- Now adding other models (INCL++, GEANT4) for v3.2

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

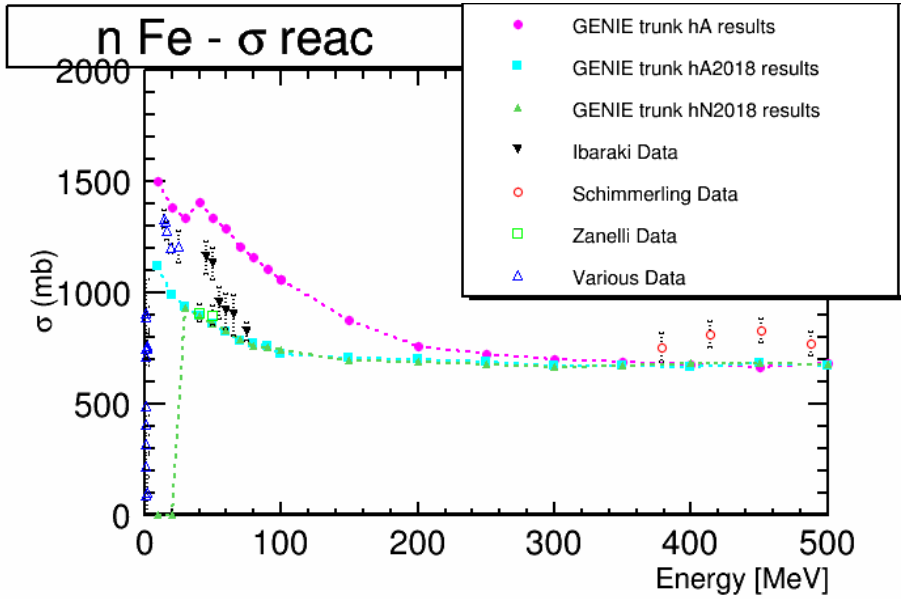
- Very broad view of FSI
- Good pion data, very little K data
- π^+ has significant peak for Δ excitation, none for K^+
- Both hA2015 and hN2015 underpredict pion peak xs

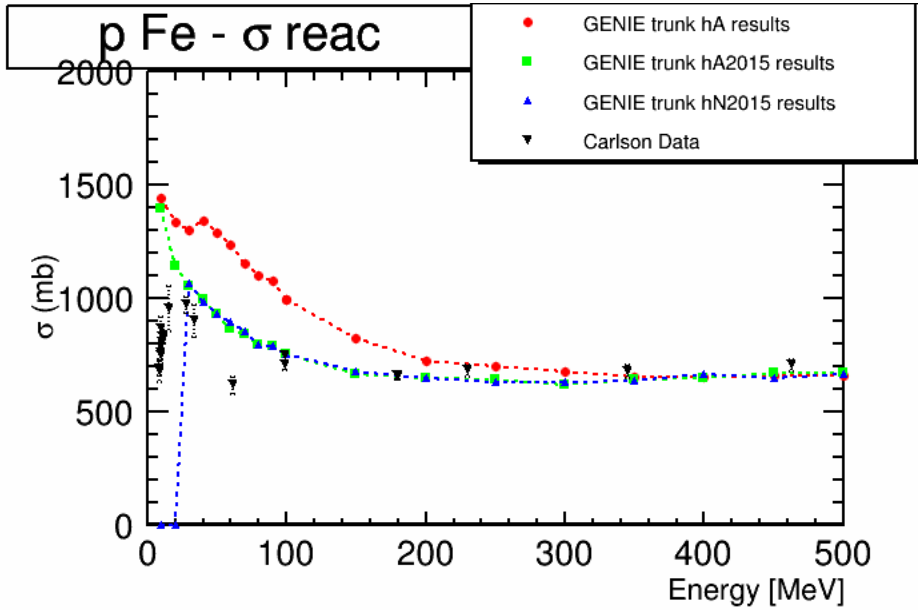




Total reaction (inelastic) cross sections pFe and nFe

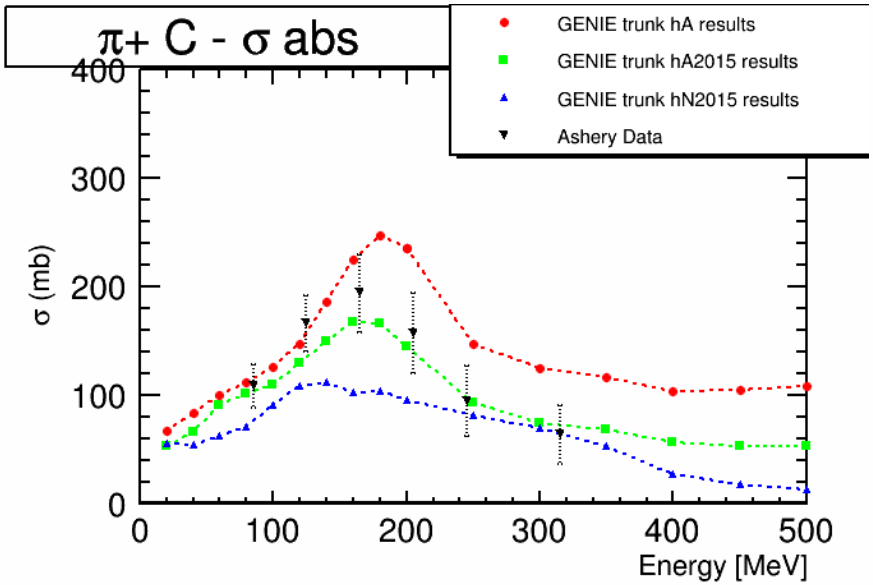
- Both have significant strength for FSI, mfp~2fm
- Low energy enhancement described better by newer models, result is less rescattering

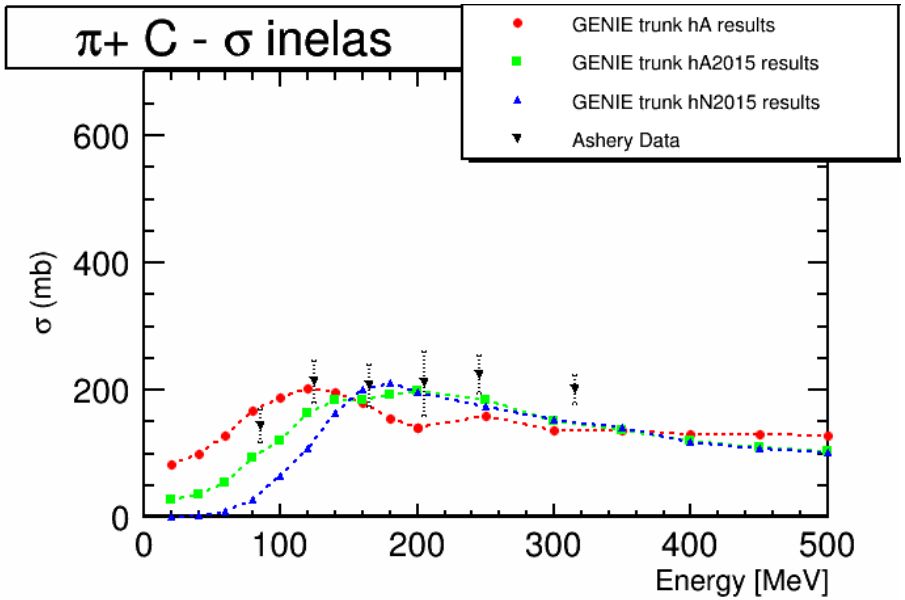




More detail for pions
scattering vs. absorption

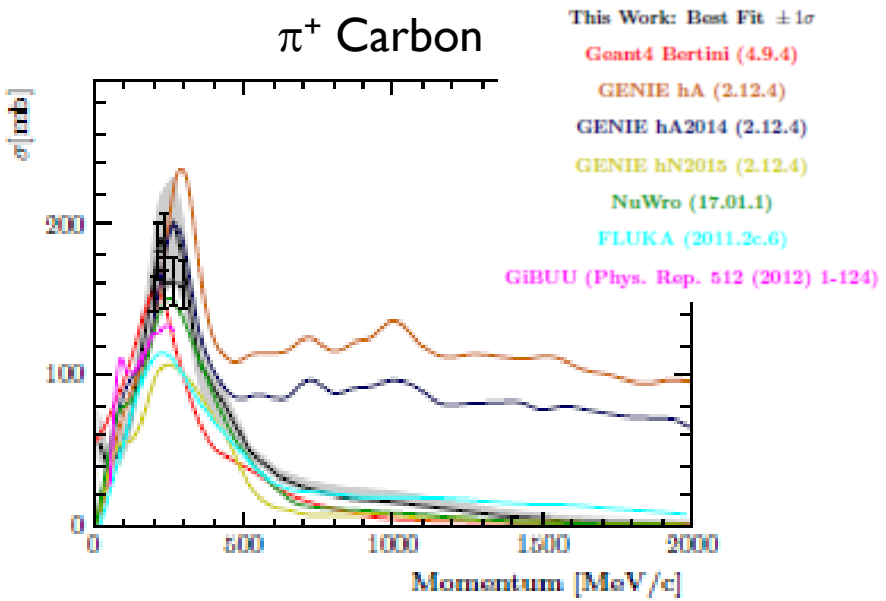
- hA has too much absorption, hA2015 uses these data as input, hN has too little absorption (feature of Oset model)
- hN2015 has too little scattering strength at low energy





Recent advances – pion-nucleus
Pinzon et al. (T2K) Phys. Rev. D99 (2019) 052007

- New pion-Carbon data for total absorption, cex cross section
- Fit large body of data with the NEUT (Salcedo/Oset) model
- Find energy-independent factors + est. errors for best fit (table)
  - Significant changes (model dependent and data dependent)



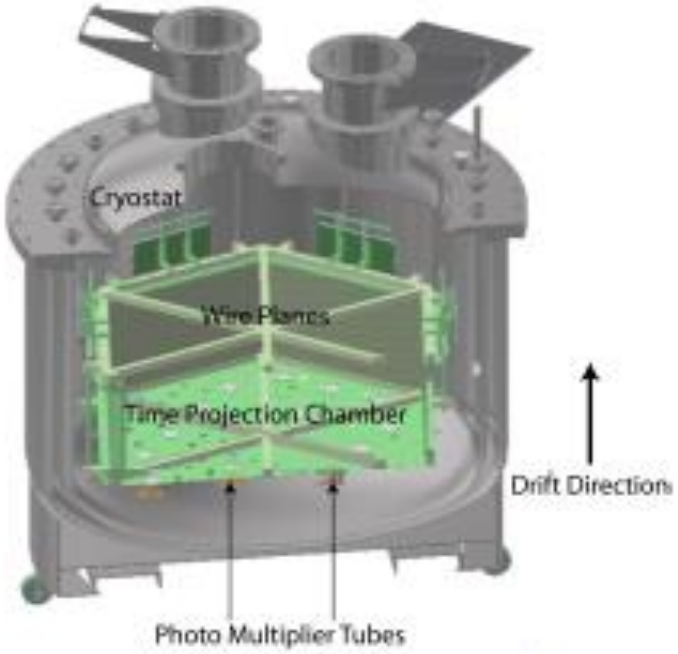
(c) Absorption (ABS)

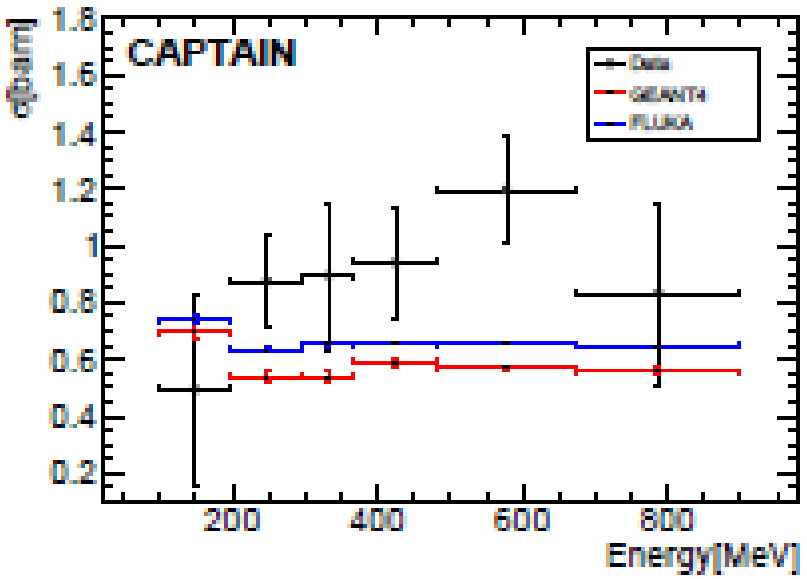
Parameter	Best fit ± 1σ		
	Carbon-only	Light nuclei	All nuclei
f_{QE}	1.07 ± 0.07	1.08 ± 0.07	1.08 ± 0.07
f_{ABS}	1.24 ± 0.05	1.25 ± 0.05	1.26 ± 0.05
f_{CX}	0.79 ± 0.05	0.80 ± 0.04	0.80 ± 0.04
f_{INEL}	0.63 ± 0.27	0.71 ± 0.21	0.70 ± 0.20
f_{QEH}	2.16 ± 0.34	2.14 ± 0.24	2.13 ± 0.22
χ^2/n.d.o.f	18.36/27	40.14/44	53.48/59

Recent advances – neutron-nucleus

Bandari et al., CAPTAIN arXiv:1903.05276v1 [hep-ex]

- Total cross section for nAr, Total=elastic+inelastic
- Uses mini-Captain (400kg) at Los Alamos WNR
- Important to constrain neutron production from neutrinos (hard to measure)
- elastic hard to calculate in semi-classical methods

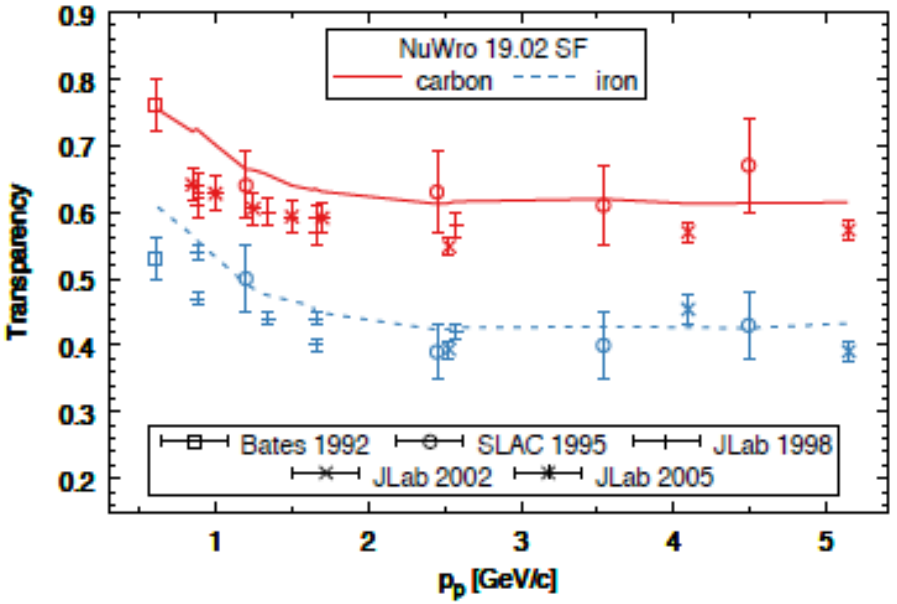




Recent advances – transmission
Niewczas, Sobczyk arXiv:1902.05618v1 [hep-ex]

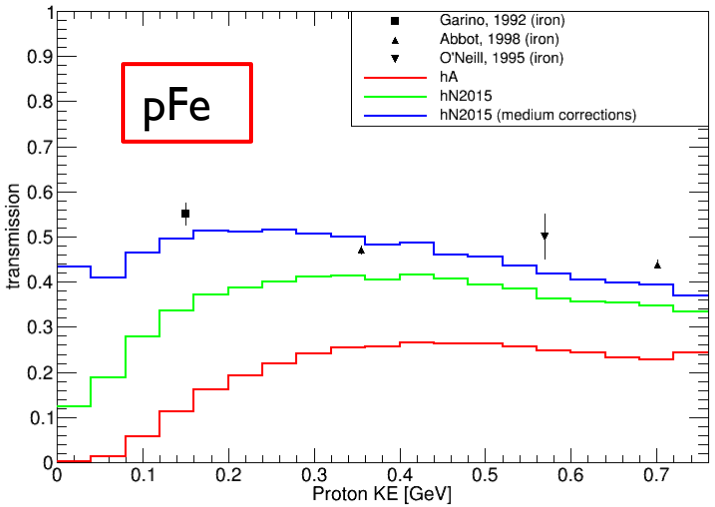
- Detailed examination of experimental conditions (soft scattering, detector acceptance)
- New sensitivity, particularly when hadron-nucleus xs large
- Interplay between total reac xs and transmission important

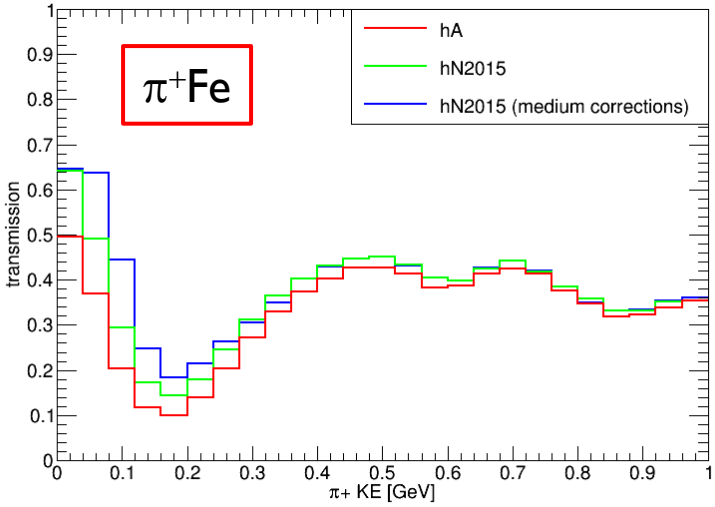
$$T(Q^2) = \frac{\int_V \mathrm{d}^3 p_m \mathrm{d}E_m \; Y_{\mathrm{exp}}(E_m, \vec{p}_m)}{\int_V \mathrm{d}^3 p_m \mathrm{d}E_m \; Y_{\mathrm{PWIA}}(E_m, \vec{p}_m)}$$



Transmission study

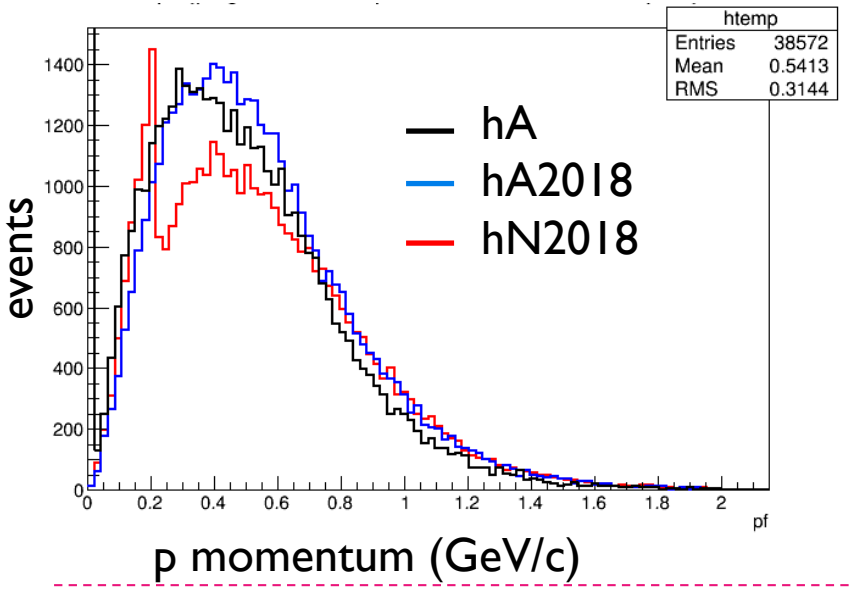
- Transmission and hadron-nucleus are different and similar – in-medium vs. asymptotic.
- Some data for protons, none for pions.
- Use GENIE to place hadrons throughout nucleus, T is probability to escape without FSI. Blue adds medium corrections to green, hA is red
- Significant difference among GENIE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

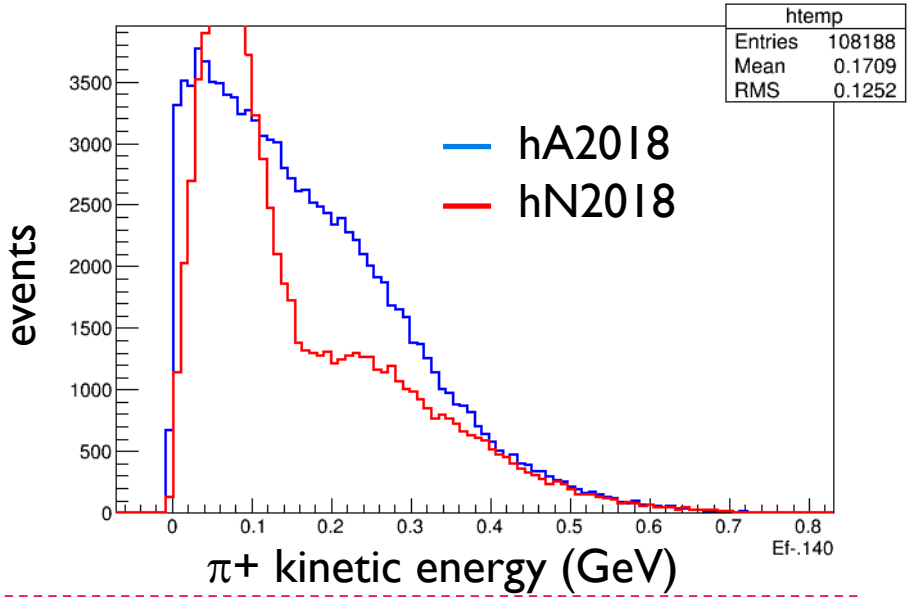




Neutrino results (1 GeV ν_μ Fe)

- 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



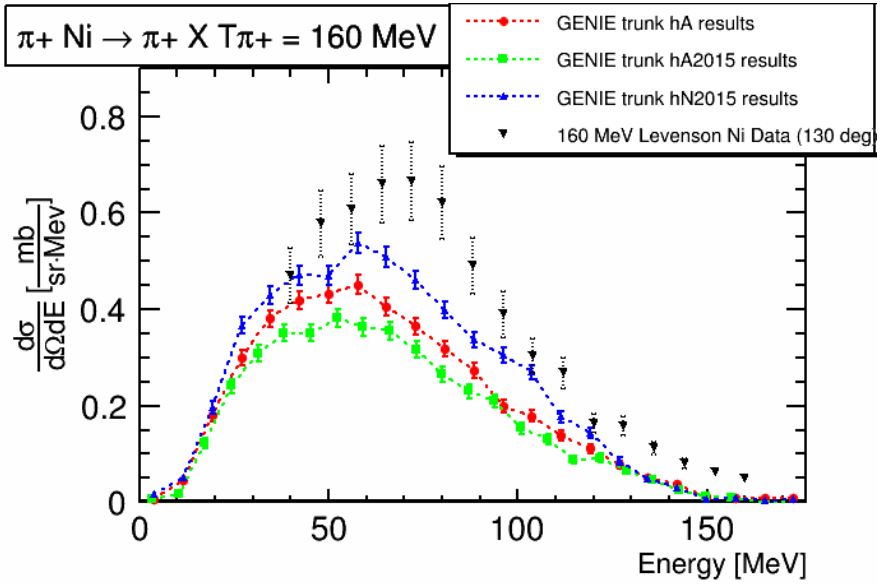


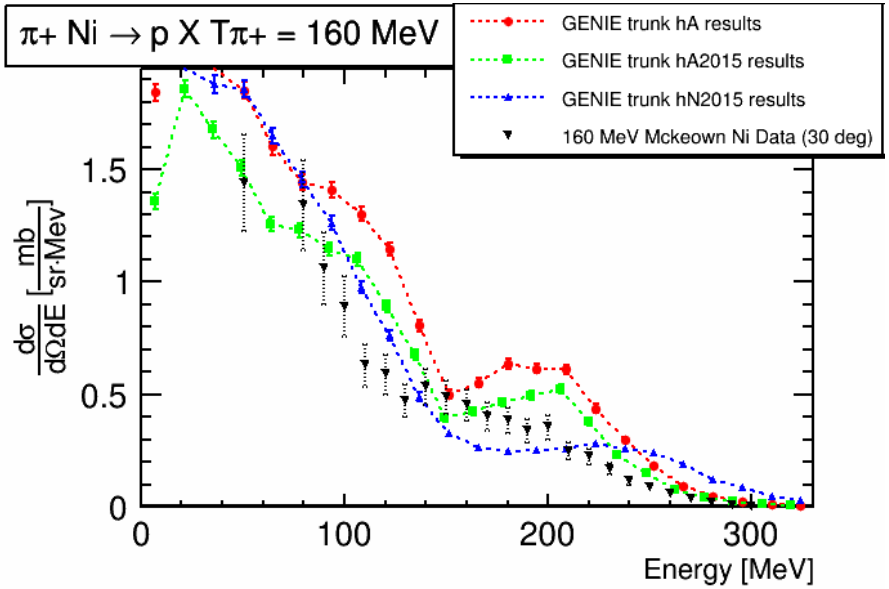
Future additions

- 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

Double differential cross sections (pion)

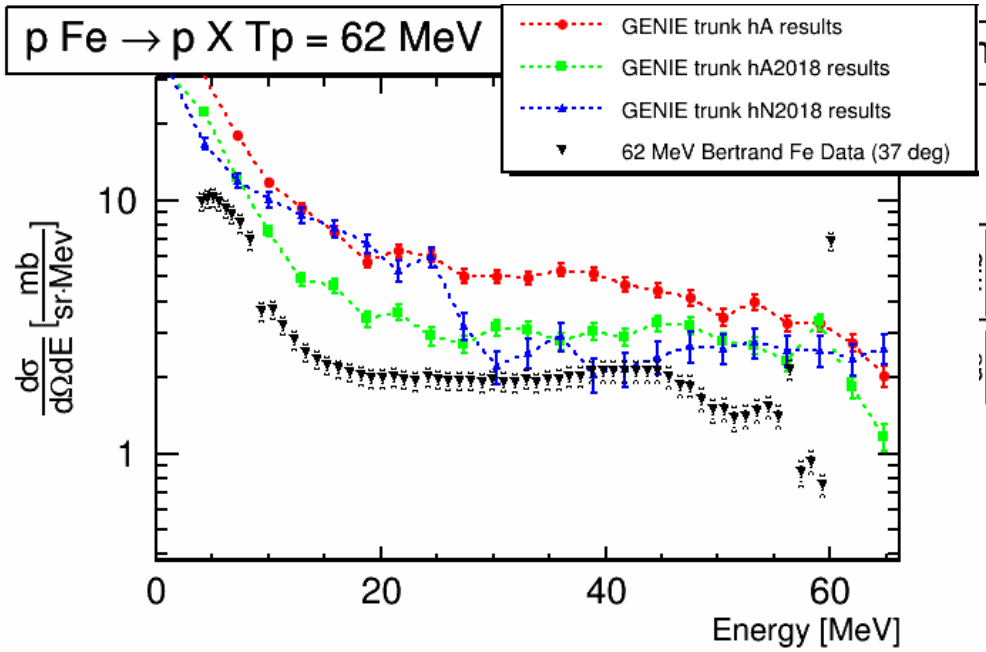
- More detail here, tests dynamics in addition to strength
- hA and hN very similar because quasielastic scattering ($\pi N \rightarrow \pi N$) and absorption ($\pi d \rightarrow NN$) dominate

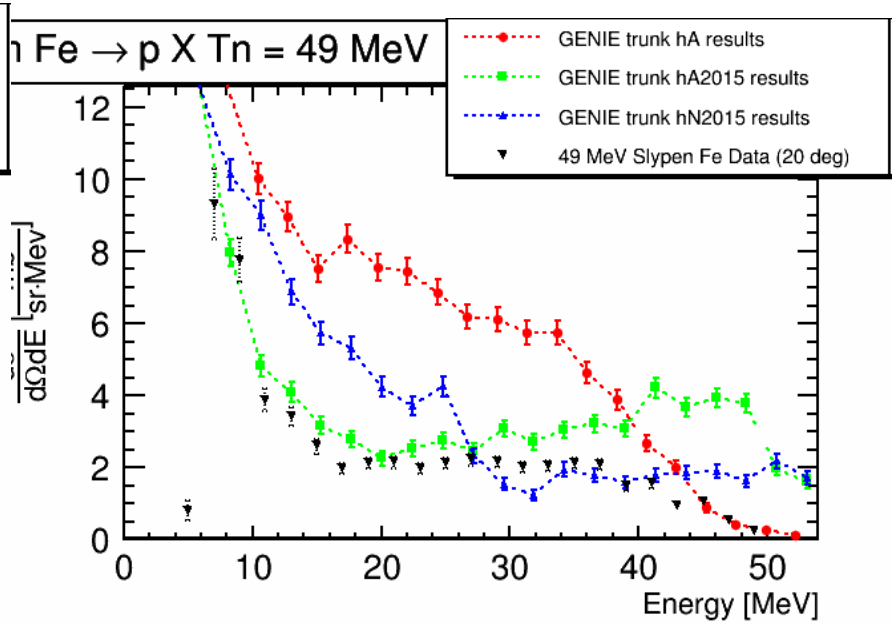




Double differential cross sections (p & n)

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





summary

- FSI is important, but not simple to include properly (both theoretical and modeling issues)
- Variety of semi-classical models, but Salcedo/Oset is by far most common in event generators (reasonable)
- Studies for ECT* FSI group
  - Total reaction cross section π^+, p, n for C, Ar
  - Total absorption cross section π^+ C, Ar
  - Transmission for p, π^+ C, Ar, Fe
  - Inclusive p, π^+ KE spectra for 1 GeV ν_μ C, Ar
  - Contributors: Jose Udias (theory), Jan Sobczyk (NuWro), SD and Julia Tena-Vidal (GENIE), Yoshinari Hayato (NEUT), Xianguo Lu (GiBUU)

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

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

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