Global picture of FSI

Steve Dytman
University of Pittsburgh

17 March, 2023

- review existing codes
- problems – neutrons, low energy particles, medium effects
- new standard – INCL?
- outlook

Why FSI matters

- The great confuser – hadron mfp ~ fm means 'large' (A dep) changes in both topology and kinematic distributions
  - when only muon detected (Pion production followed by pion absorption mimics quasielastic included in CC0π signal)
  - Hadrons change energy/angle through scattering (+additional p,n..)
  - Charged→neutral through charge exchange (+additional p,n..)
- Too few studies with ν or e beams – initial vs. final state
  - LAr detectors important for low thresholds
- Most data from other facilities
  - Pion, proton beams from 1970's, 1980's
  - More recent work coming from ProtoDUNE
- Theorists tend to avoid the subject due to the complexity

Overview

- Semi-classical treatments important since 1960's because full quantum calculation not possible (then and now)
  - Many consequences – good (simple, flexible) and bad (can't be right)
  - Impressive success describing data, even πA at peak of Δ(1232)
  - Many efforts have been made to add nuclear corrections
- Various versions available (and not)
  - Peanut (FLUKA) has quantum-like corrections
  - Transport (GiBUU) has significant nuclear modifications
  - Salcedo, Oset has density-dependent nuclear mods (π), basis for most event generator models today (NEUT, NuWro, GENIE hN)
- GEANT, INCL++ have evaporation, coalescence (low energy, hi A)

Model Overview

- Empirical
  - GENIE hA (much better agreement with data than expected)
  - True impulse approx. (IA) – nucleon as free – good for KE>~500 MeV
- Semi-empirical
  - Oset πA, Pandharipande/Pieper NN – adds medium corrections
  - Both are in GENIE hN and NuWro
  - NEUT has new πN tuning (Pinzon et al.)
  - GEANT – has many processes, but also many odd approximations
- Semi-quantum
  - Fluka – not available
  - GiBUU – strong, consistent medium effects
  - INCL++ - solid theory basis (Cugnon), has evaporation, coalescence

Past standard

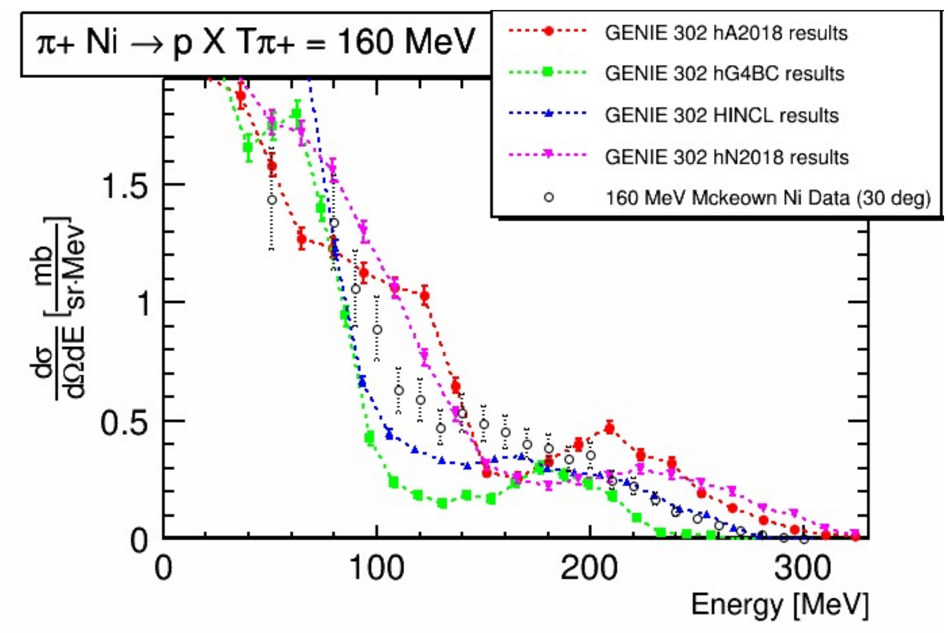
- Salcedo, Oset main choice
  - Some medium effects with density dependence
  - Pauli blocking
  - Moderate agreement with a lot of data
- GENIE hA (GENIE default for now)
  - Data-driven – hadron-nucleus xs is input
  - Fits a lot of data well beyond inputs
  - Intrinsically reweightable
  - No density dependent medium corrections

GENIE FSI strategy

- For better comparisons, goal always for 2 codes which are compatible with neutrino and electron beam 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 *somewhat* fit to hadron-nucleus data.
- Advances slow, come when manpower available (Pitt undergrads, Tomek Golan, Madagascar PhD students)
- As of now, includes pions, K^+, p, and n
- INCL++, GEANT4 introduced in v3.2 (external packages)
  - All 4 FSI models in GENIE use same interface
  - See Eur. Phys. J. ST **230**, 4449-4467 (2021) for v3.2

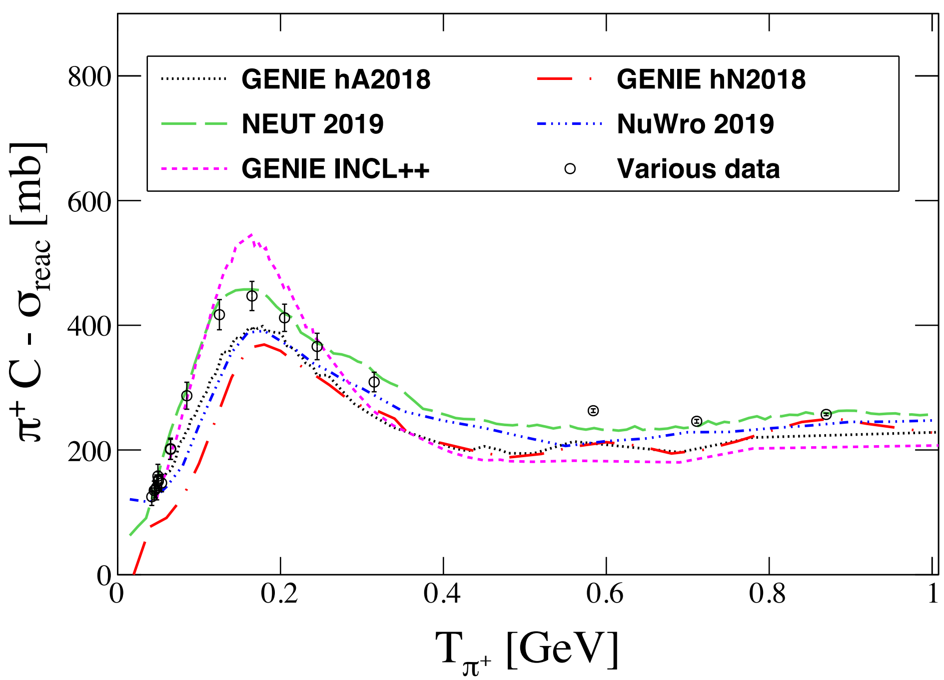
GENIE comparison tools (hadrons)

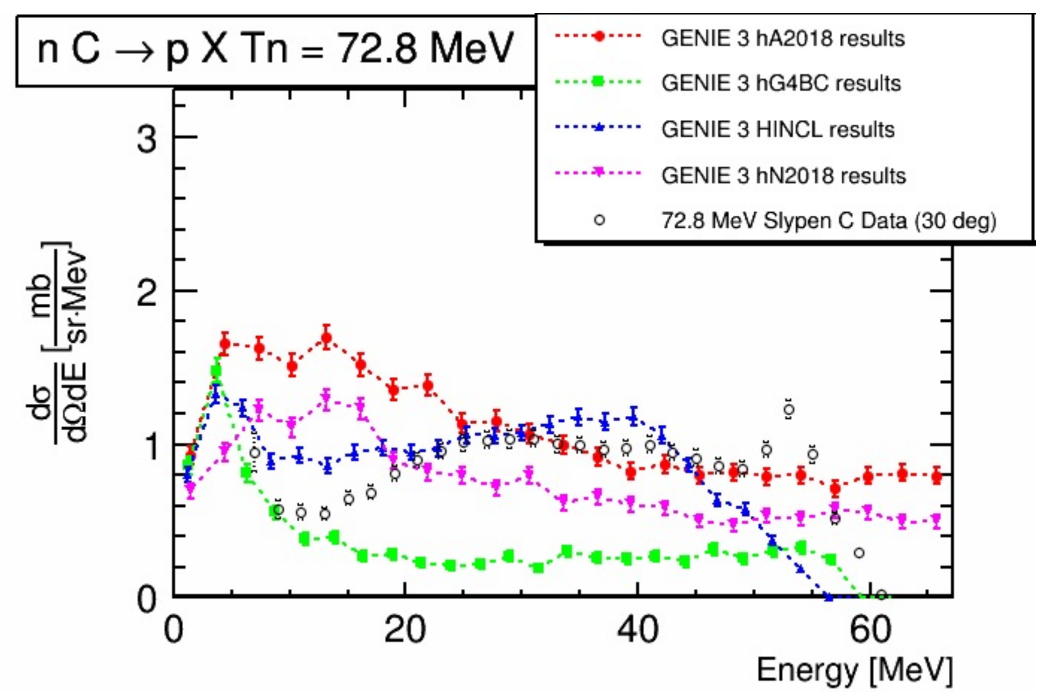
- Large database of data with π, p, n, K^+ beams
  - Major source is BNL ENDL repository
- Comparisons
  - Gevgen_hadron is GENIE version for hadron-nucleus
    - Uses any of the 4 GENIE models
  - Code to start simulations for any probe, nucleus – can be based on data, e.g. π^+ Ni to match McKeown data.
  - Code to make a plot comparing simulation with data



Some validation plots

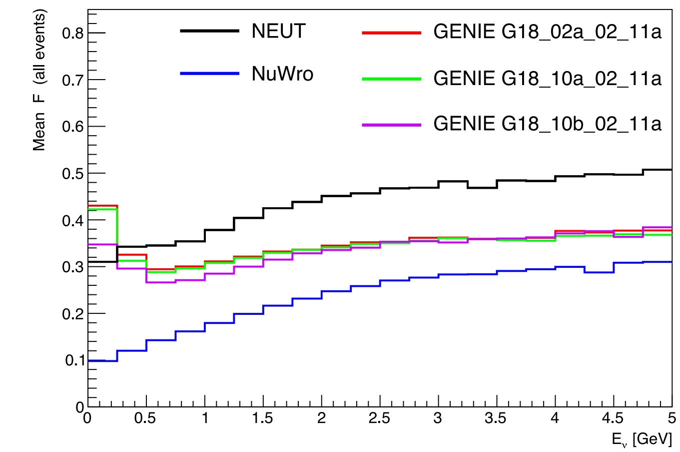
- Mainly total reaction cross section
  - NEUT has best agreement by fitting πN cross section to these data
- GENIE also uses double differential cross sections
  - Minimal tuning, mainly use a model



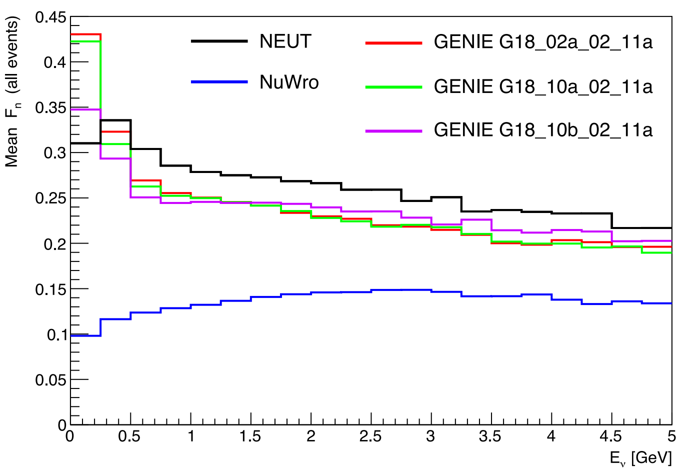


Problems I - neutrons

Top: fraction of energy in final state from neutrals
Bottom: fraction of energy in FS due to neutron

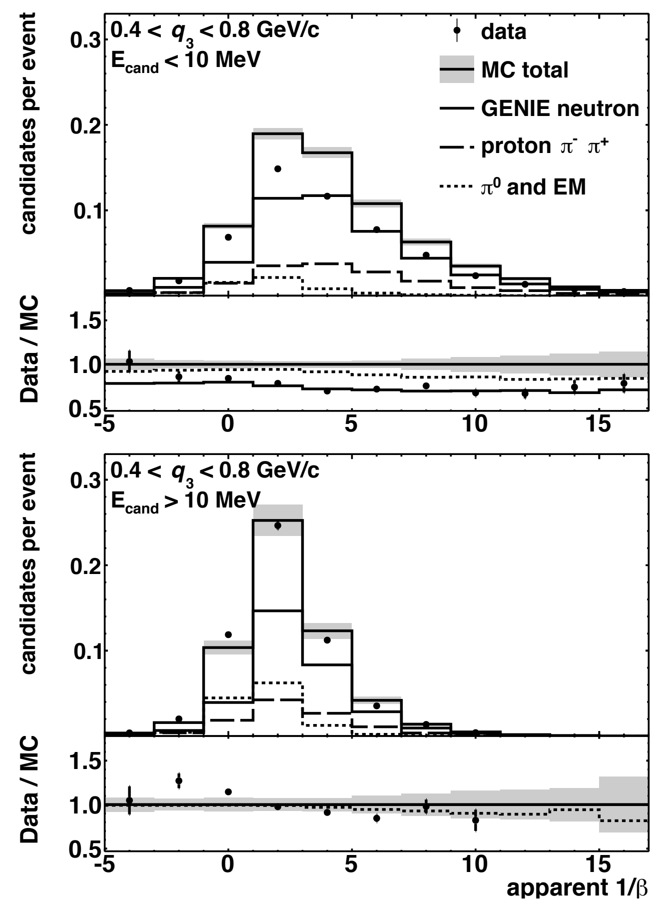


Plots from S. Gardiner



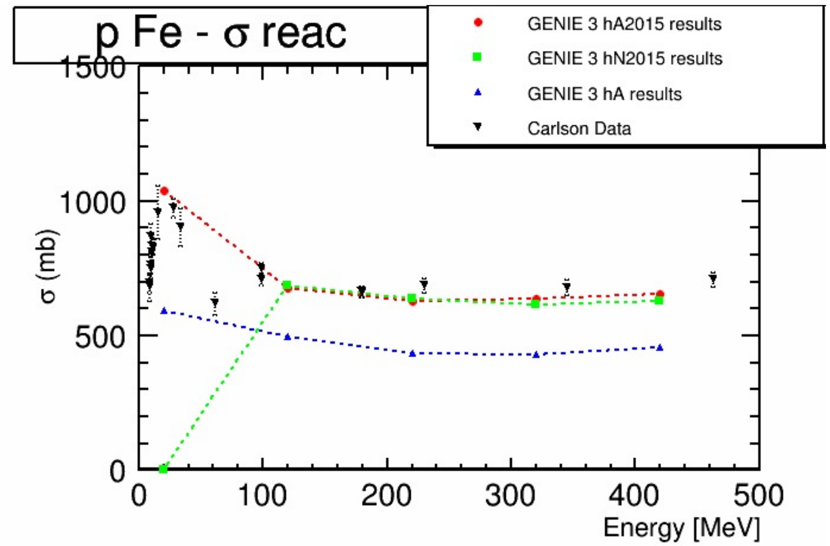
M. B. Avanzini, et al. ``Comparisons and challenges of modern neutrino-scattering experiments (TENSIONS 2019 report)," *Phys. Rev. D* 105 (2022) 9, 092004

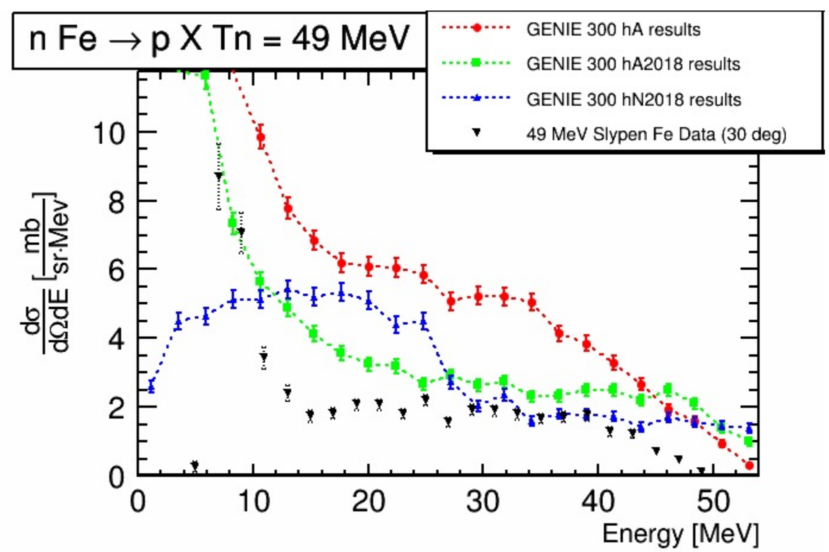
M. Elkins [MINERvA] et al., Phys. Rev. D **100**, 052002 (2019)



Problems II - low energy particles

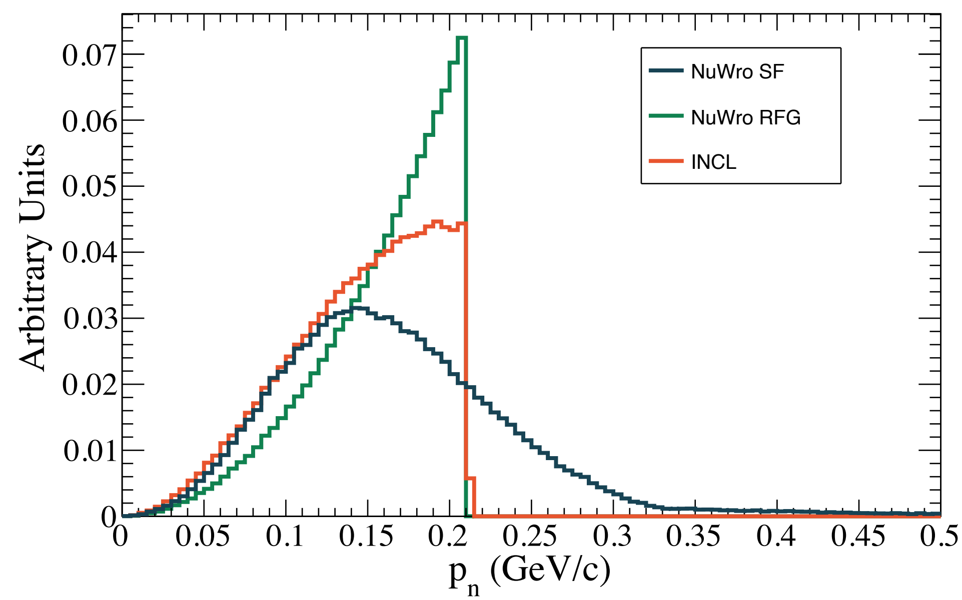
- Called vertex activity in some experiments
- Nucleons, nucleon clusters, photons
- None are in old standard
- Although GENIE v3 FSI was better than v2, not optimal





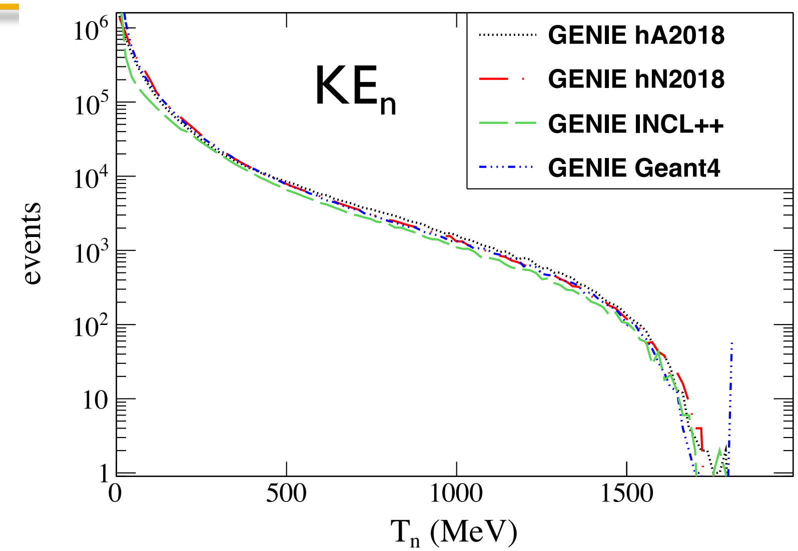
INCL - new standard?

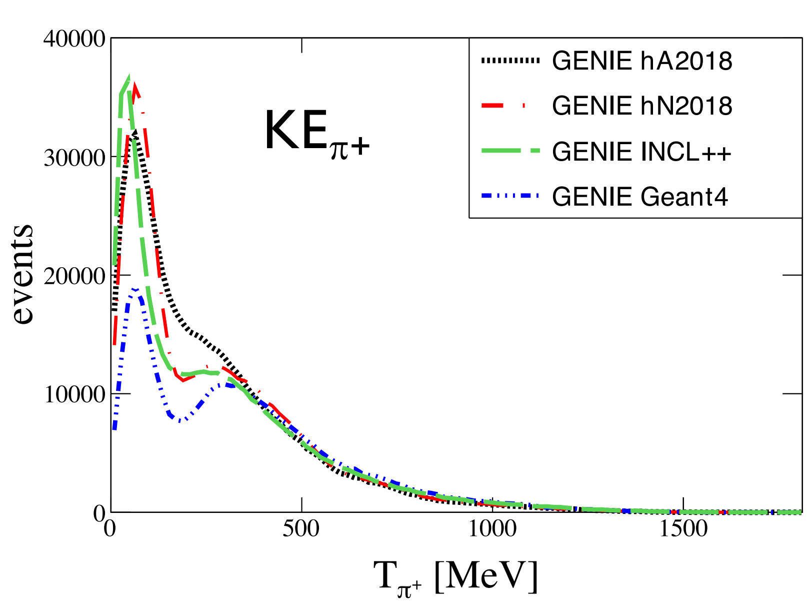
- Cugnon, David, Mancusi… Phys Rev
  - Better nuclear model (nucleons in local potential)
    - Plot below, similar to LFG w/o correlations
  - Emission of γ, ^{2}H, ^{4}He…
  - Handles π, N (p and n), not K
  - Implemented in GENIE Eur. Phys. J. ST **230**, 4449-4467 (2021) and NuWro [arXiv:2202.10402 [hep-ph]]

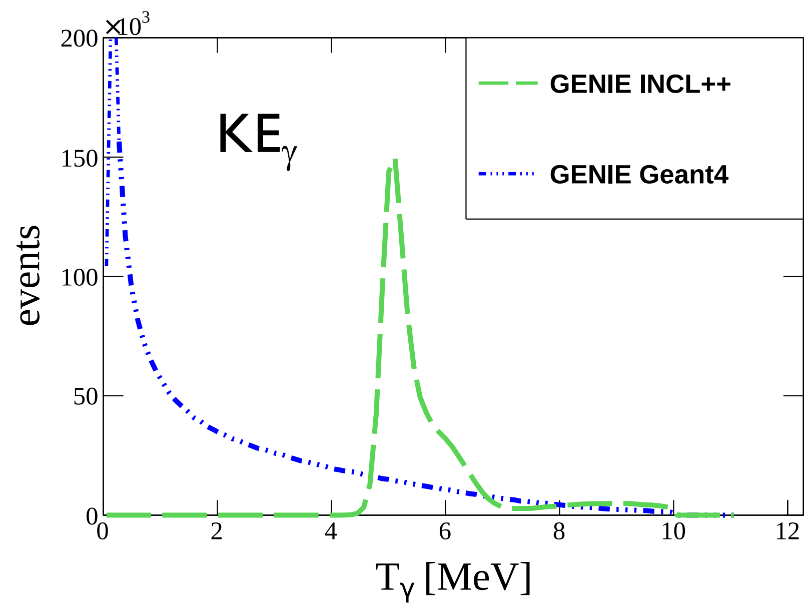


GENIE study for 2 GeV ν_μ Ar (mostly π production)

- PhD thesis of Narisoa Vololonaina (Madagascar)
- Test FSI models – hA , hN, INCL++, and Geant4

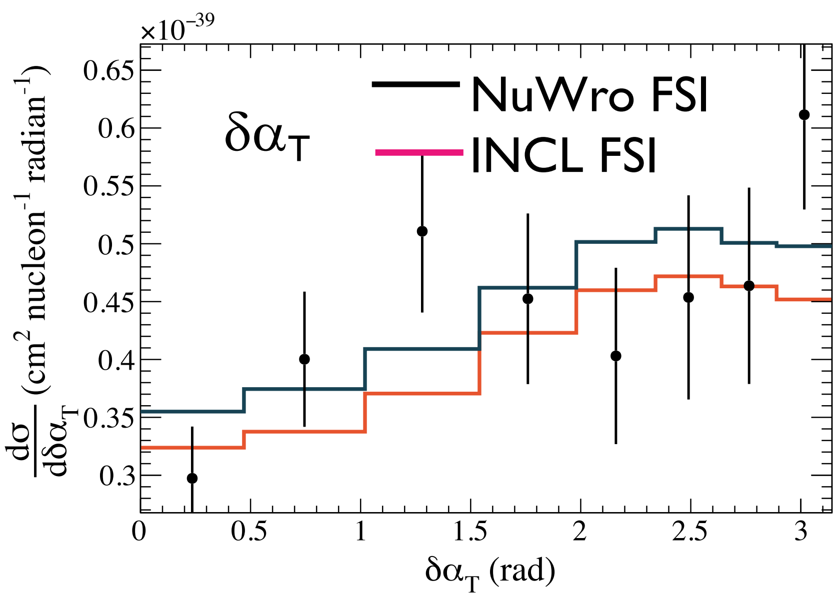


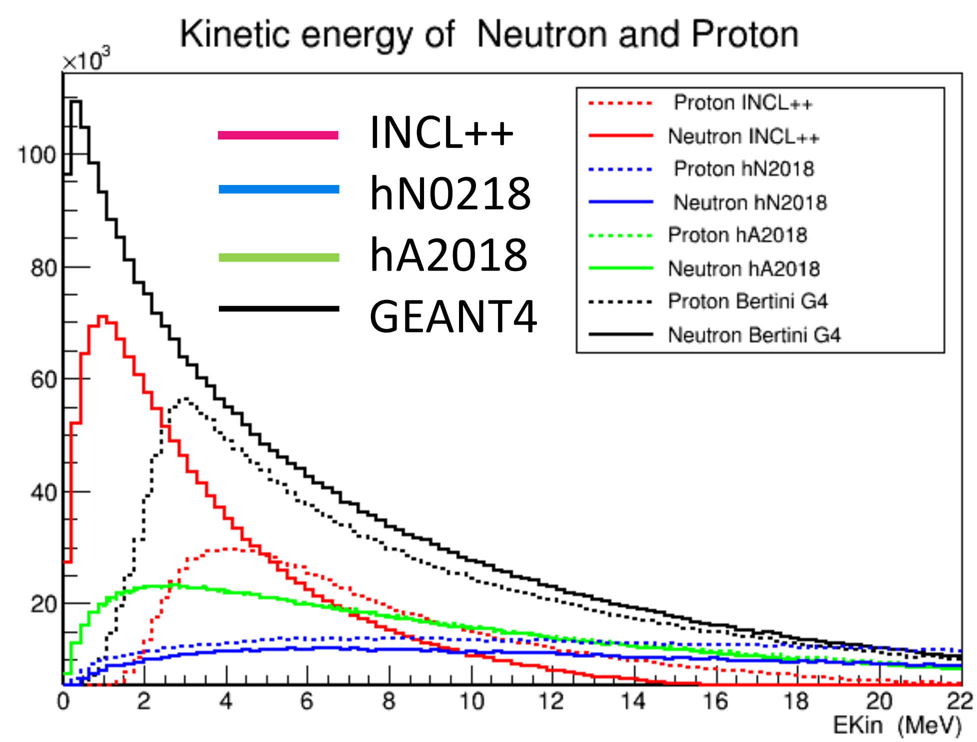




Plots - quantities very sensitive to FSI

- All comparisons with only FSI changing (new)
- $\delta\alpha_T$ from NuWro compared to T2K data (left)
- low energy p & n from 2 GeV ν_μ Ar in GENIE (right)

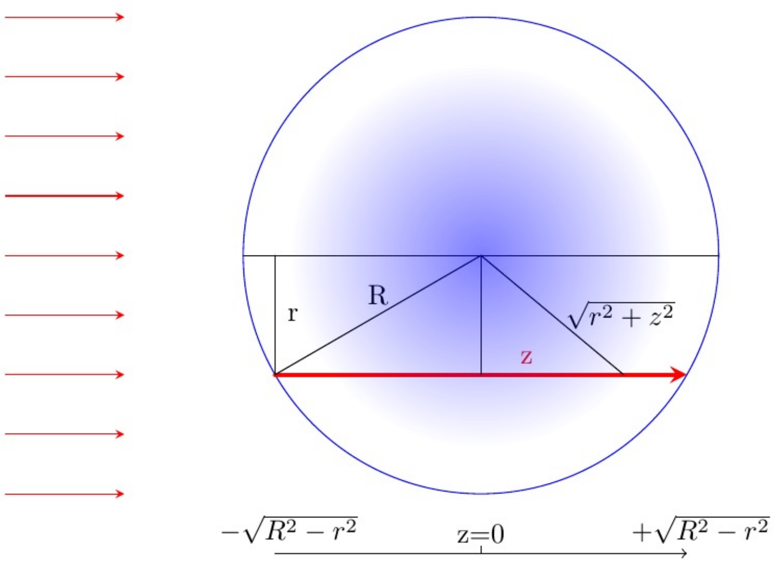




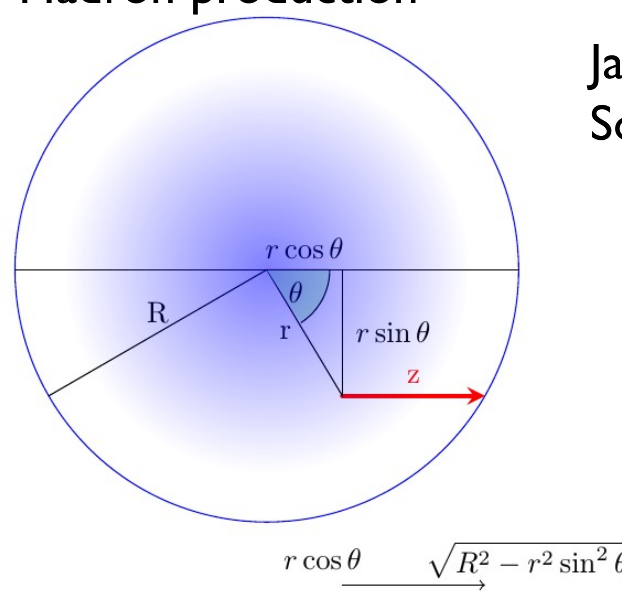
Transparency - new validation method?

- Transparency measures probability of escape
  - Direct measure of what we need for FSI in ν or e interactions
  - In fact, that is the way transparency is measured
- All validation done now with hadron-nucleus interactions
  - If mean free path (MFP) is small, this is dominated by surface

Hadron beam



Hadron production

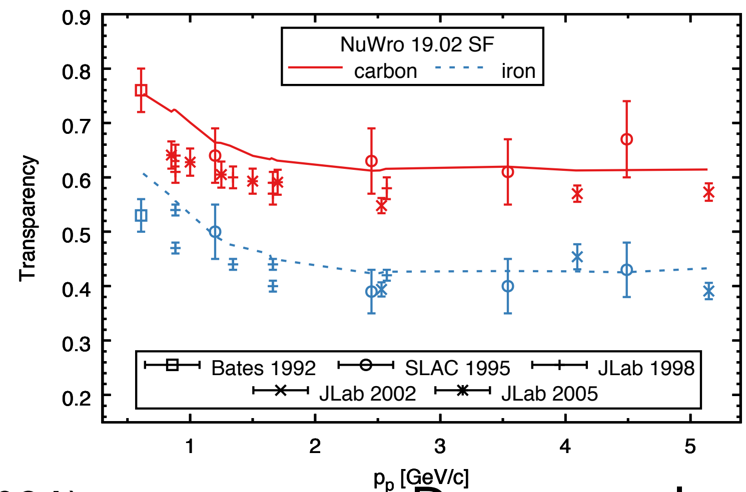


Jan Sobczyk

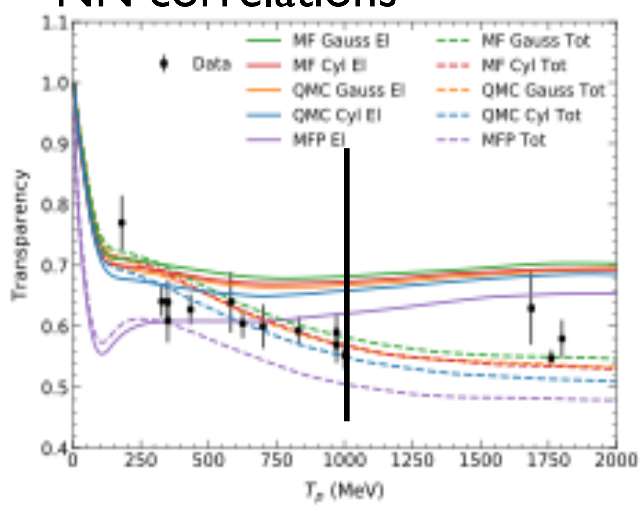
Transparency theory vs. experiment - protons

- Many experiments with electrons for proton and pion transparency, mostly at high energies.
- Recent theory studies aimed at needs of neutrino community
- All proton transparency here

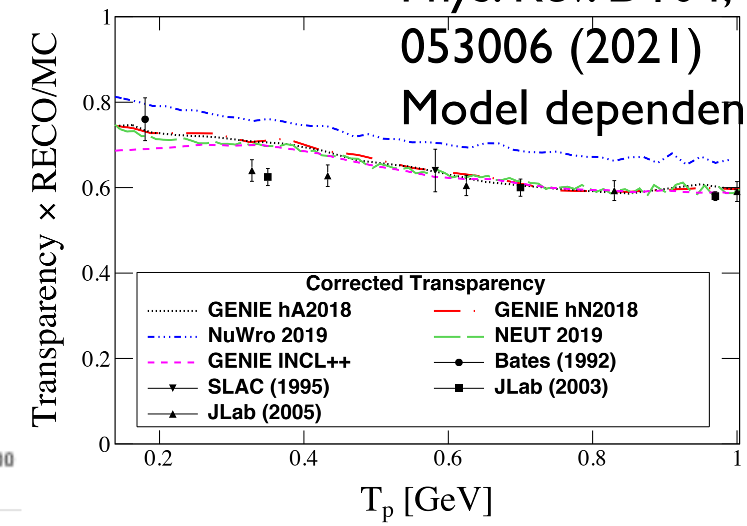
Niewczas, Sobczyk
Phys. Rev. C100, 015505 (2019)
NuWro compare



Isaacson et al.
Phys. Rev. C103, 015502 (2021)
NN correlations

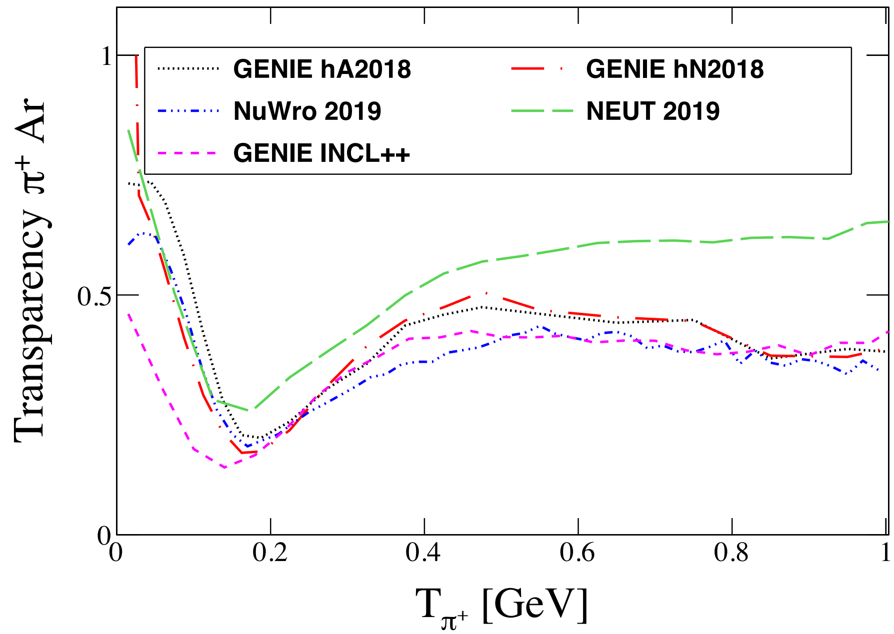


Dytman, et al.
Phys. Rev. D104, 053006 (2021)
Model dependen



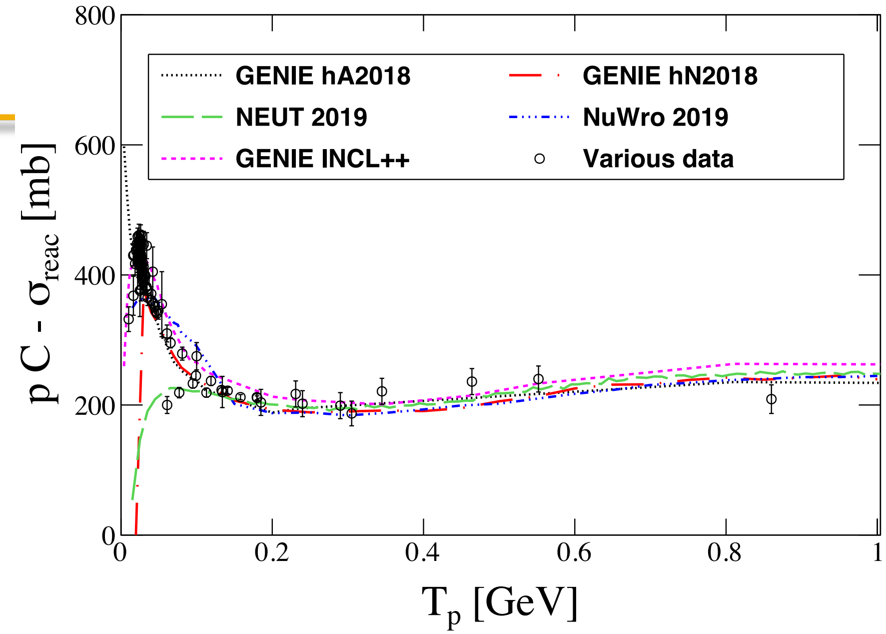
Pion transparency

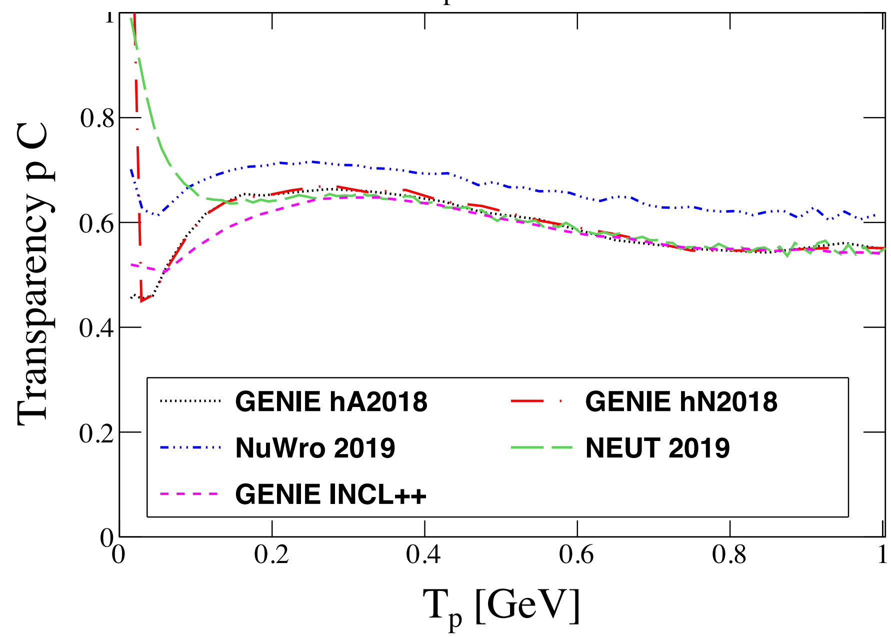
- No data for pion transparency at T_π<~1 GeV
- Significant model dependence
- Focus on Isaacson vs. us?



σ_{reac} vs. transparency

- σ_{reac} most common
- Transparency has new sensitivities (NN corr, formation zone…)
- Best practice is to use both pieces of data
- Better data needed

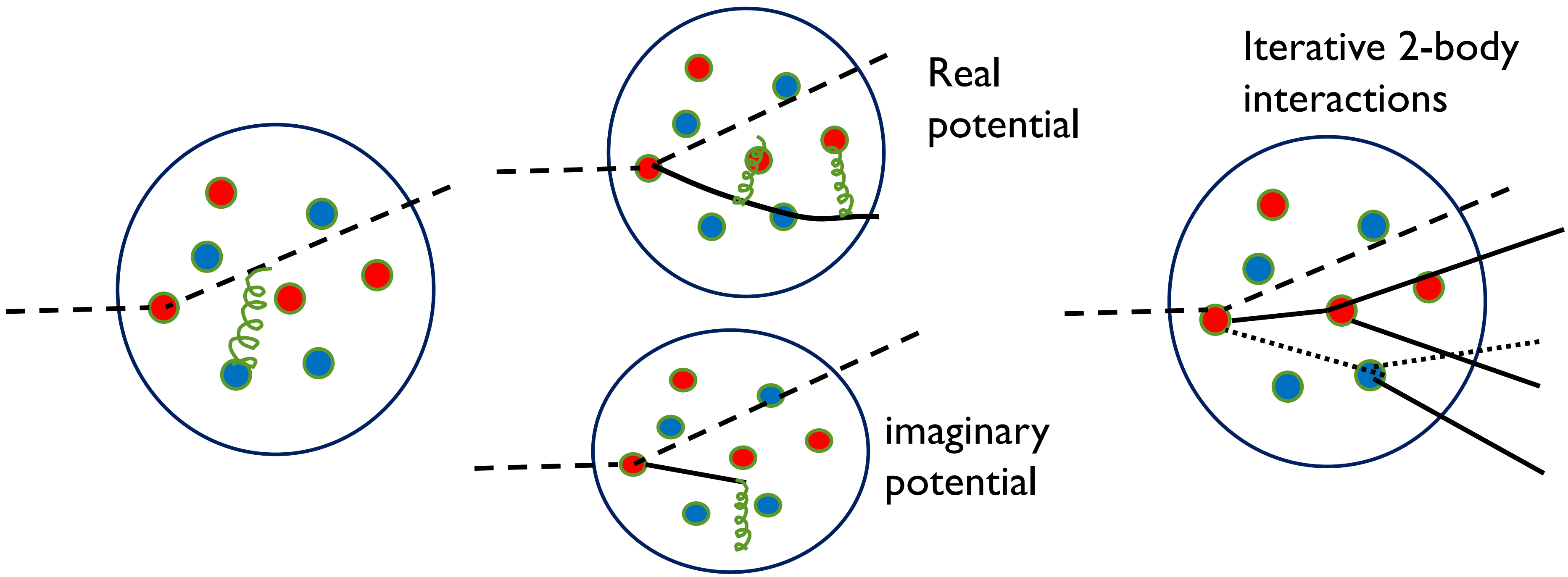




Summary+outlook

- Significant progress recently
  - More models in GENIE – INCL++, GEANT4
  - More comparisons, e.g. transparency
  - Low energy hadrons, pions show strong model dependence (INCL best)
- No data for pion transparency at T_{π}<~1 GeV, proton transparency data not sufficient; σ_{reac} improvement needed
  - New e4ν data will have important impact
- Significant model dependence remains
- FSI would be good candidate for theory interface
- Next frontier – Sato-Lee-Nakamura (DCC)
  - Unified model with ~complete hN and NN (no medium corrections)
  - New Madagascar student implementing πN, ηN, KΛ, and KΣ

FSI has different meanings (unfortunate)



- Inclusive
- What theorists often do
- Empirical shift in ω
- Double counting?

- Semi-inclusive (e.g. Udias)
- Good theory solution
- Mainly attenuation due to proton 'abs'

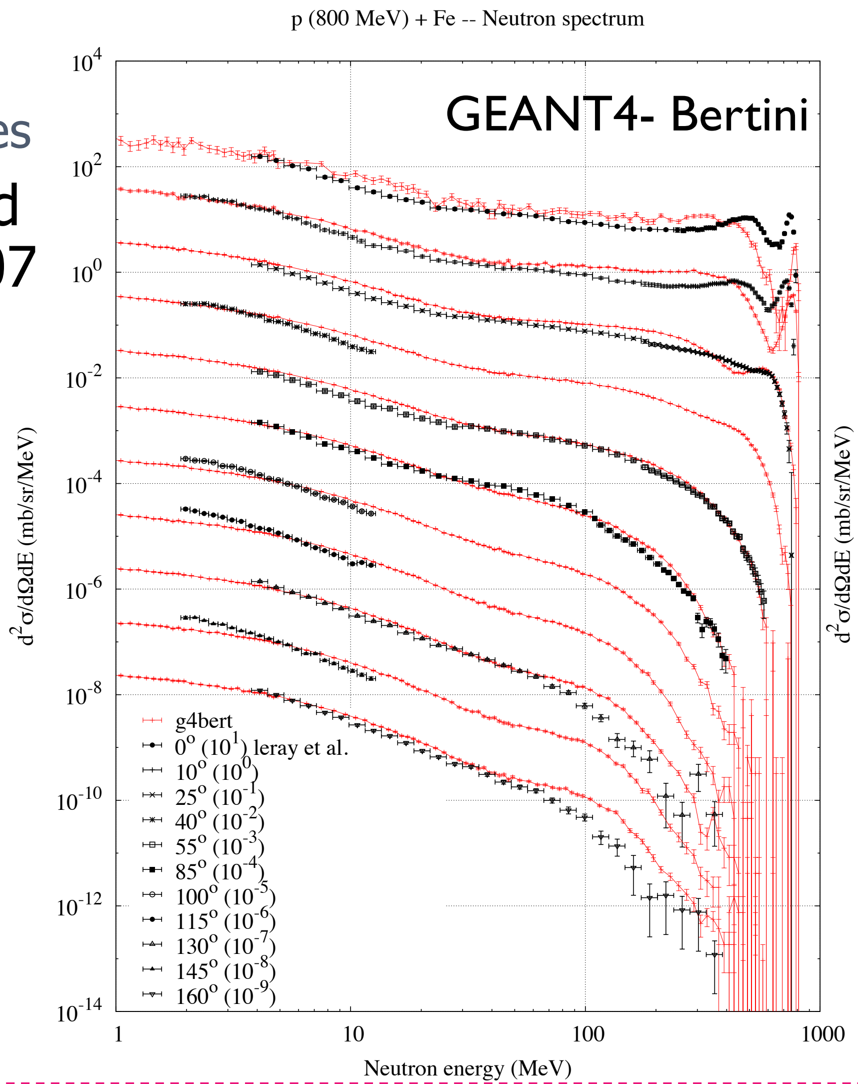
- Complete final state! (this talk)
- What experiments demand!
- Cascade does it all with approximations (free xs with corrections)

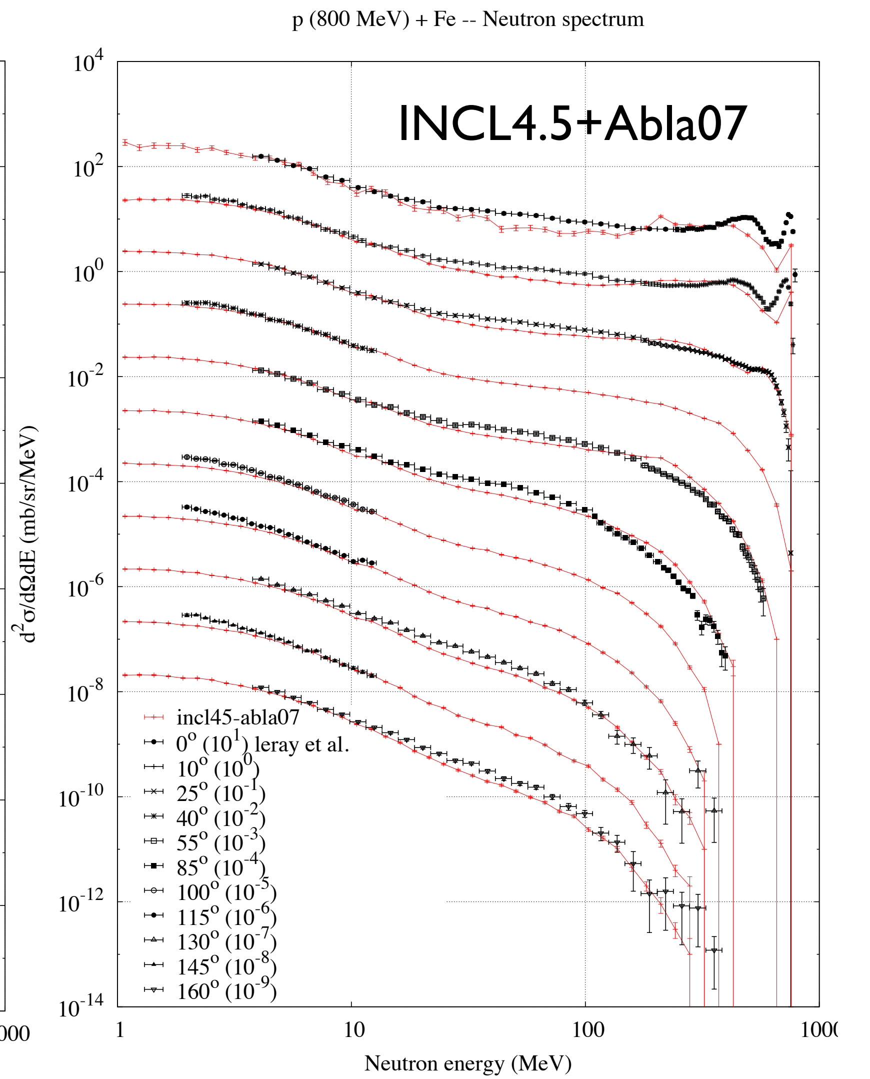
Problems III - pion production

- This is related to FSI because this is major source of hadrons at DUNE.
- Much attention to QE, much less to pion production
  - Commonly no medium effects (studied with pion data)
  - Models in US derived in 1980s (Rein Sehgal uses constituent quarks)
  - MAID advances in form factors not implemented except GiBUU
  - Imperfect nonresonant processes (often scaled DIS model – BY)
  - No nonresonant/resonance interference (Kabirnizhad 1pi in NEUT)

IEAE study detail - double different xs

- p+Fe→n+X
  - 800 MeV
  - Many angles
- GEANT4 and INCL+Abla07





Focus on transparency (pC)

- Isaacson et al. vs. Dytman et al. (plot from Jan Sobczyk)
- Core of standard cascade vs. their full result (cyl QMC)
  - Treatment of NN corr
  - difference in stepping
  - NN cross sections
- Very interesting to disentangle dependences