Global picture of FSI

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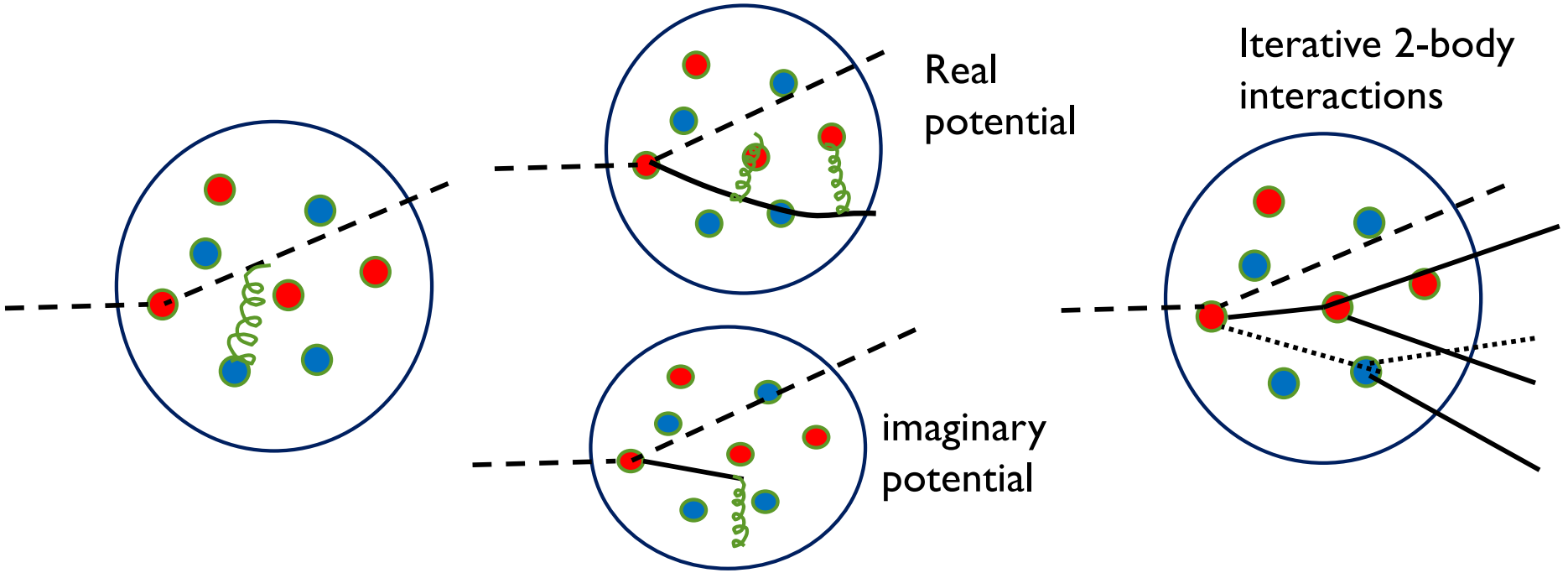
- review past standard
- problems – neutrons, low energy particles, medium effects
- new standard – INCL?
- outlook

FSI has different meanings (unfortunate)



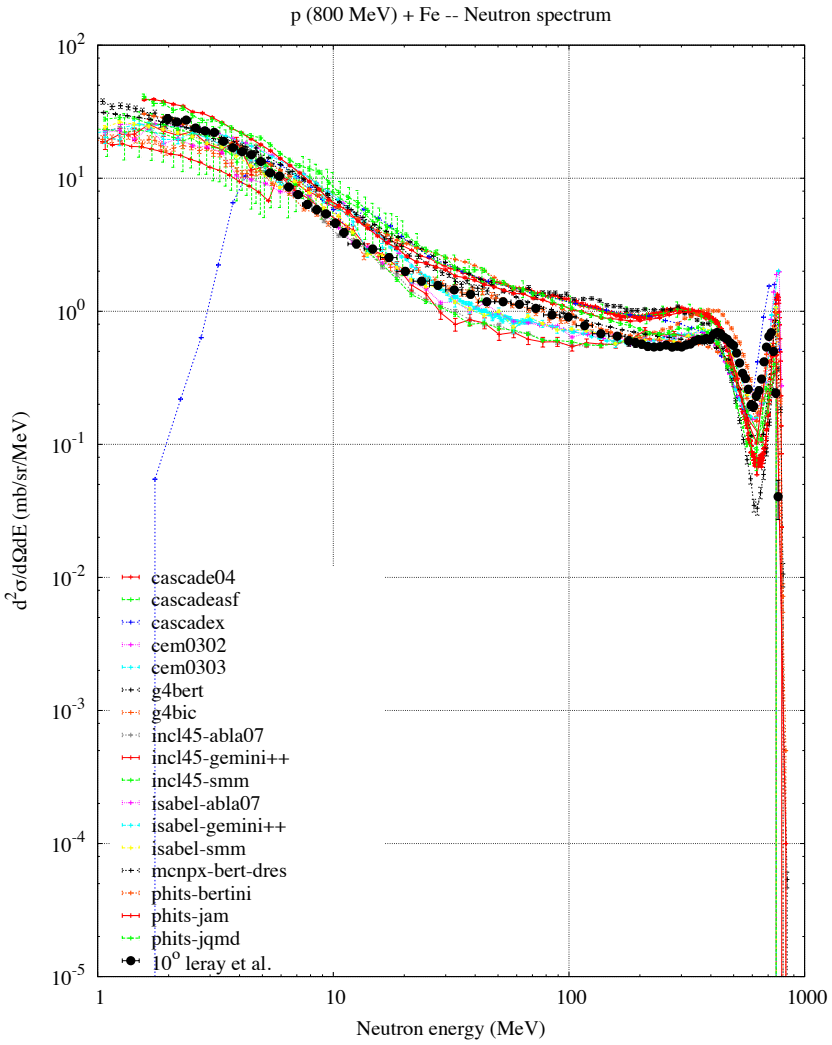
- Inclusive (Mon, Tues)
- What generators typically get
- Empirical shift in ω?

- Semi-inclusive (Udias)
- What generators get sometimes
- Mainly attenuation due to proton 'abs'

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

Overview

- FSI masks knowledge of principal interaction (e.g. QE)
  - changes charge, energy, angle, multiplicity of outgoing particles
- Lots of attention in past not fully integrated
  - Salcedo, Oset captured much of piA output
  - BUU in GiBUU – semiclassical propagation with medium dependence and ties to data
  - IAEA study used many models not typically used in neutrino generators (2015)
    - GEANT too high and INCL a little low
- As in QE operator, nuclear model and medium dependence will be important

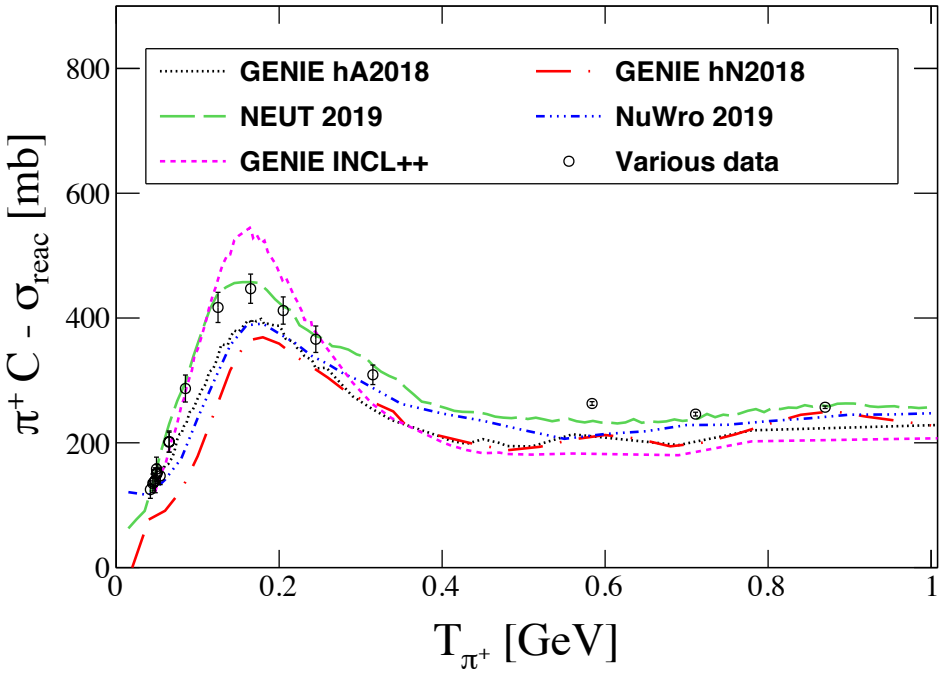


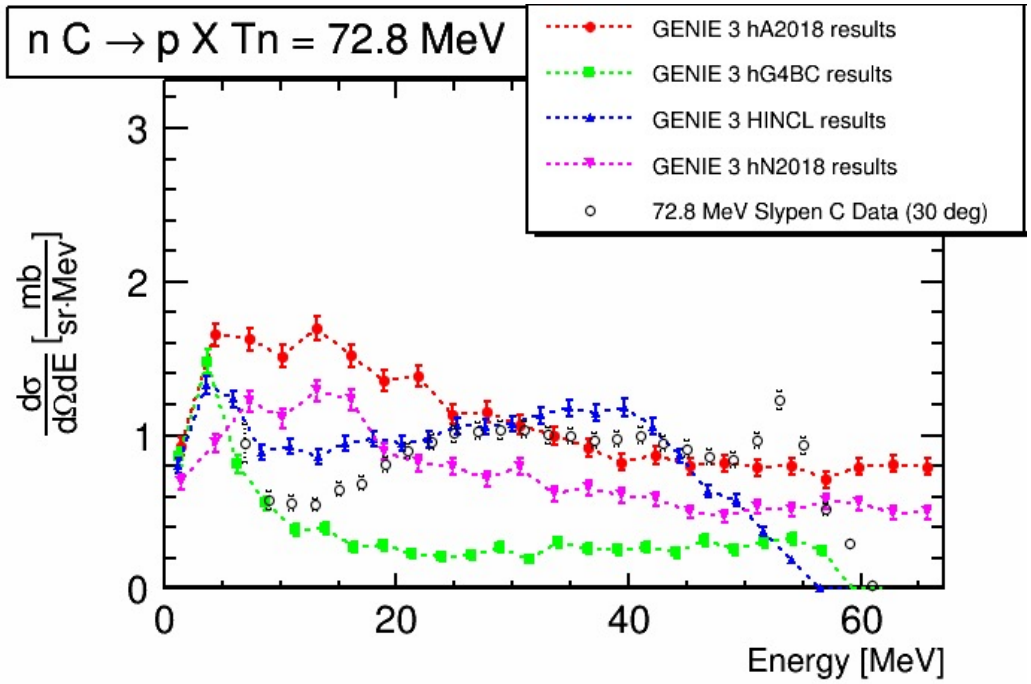
Past standard (until now)

- 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-based – hadron-nucleus xs is input
  - Fits a lot of data well beyond inputs
  - Intrinsically reweightable
  - No density dependent medium corrections

Some validation plots

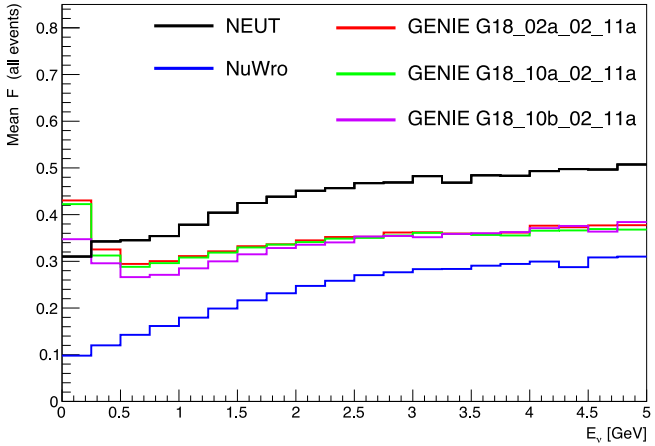
- Mainly total reaction cross section
  - NEUT has best agreement by fitting πN cross section to these data
- GENIE also uses double differential cross sections
  - Minimal tuning, mainly use a model

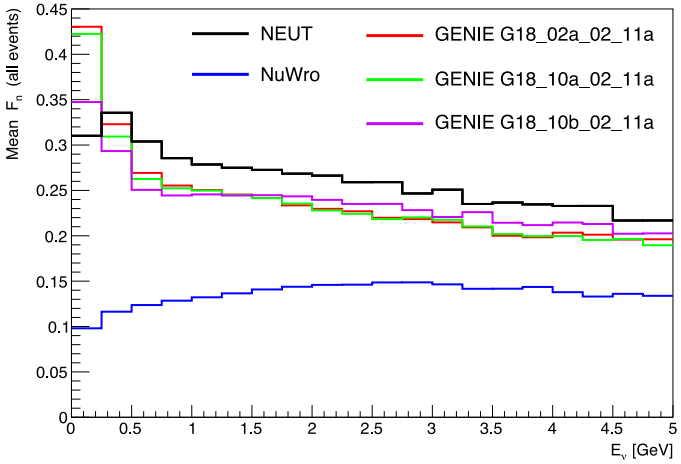




Problems I - neutrons

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

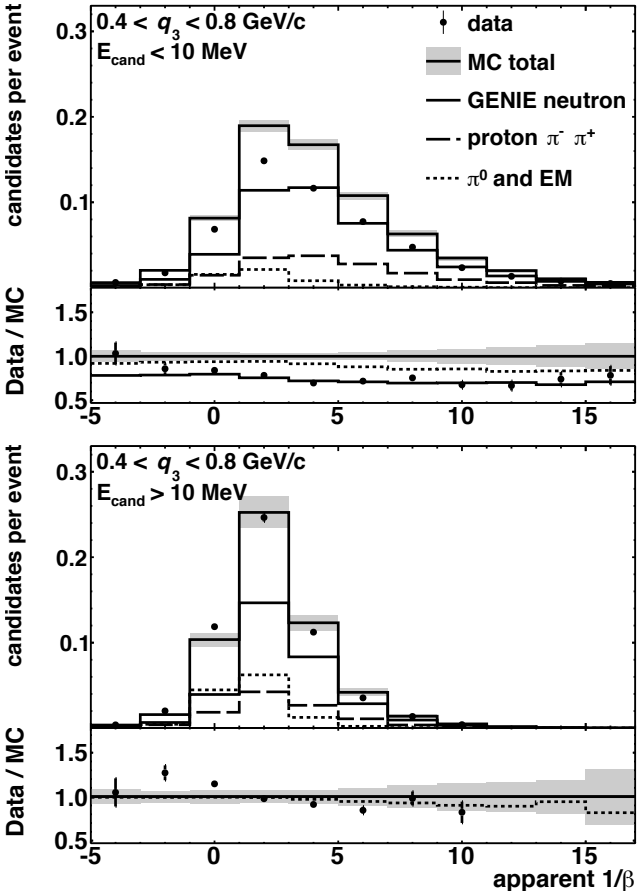




Plots from S. Gardiner

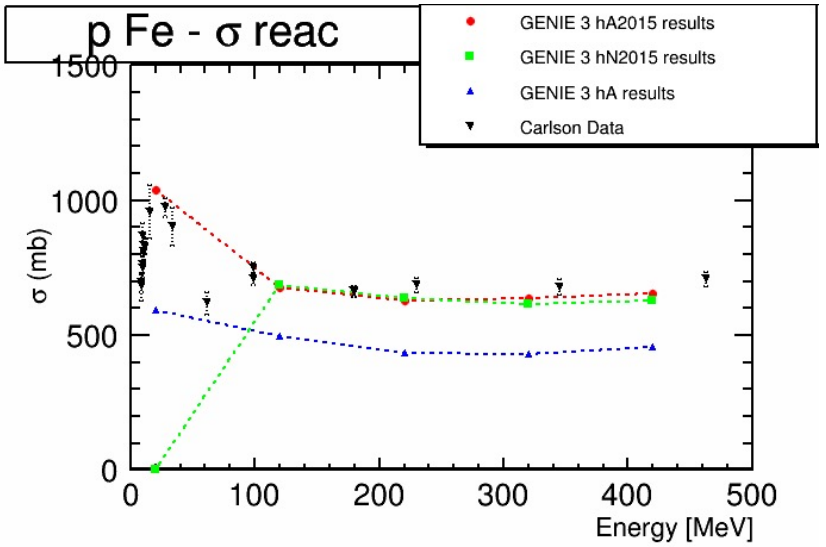
M. B. Avanzini, et al. ``Comparisons and challenges of modern neutrino-scattering experiments (TENSIONS 2019 report)," [arXiv:2112.09194 [hep-ex]].

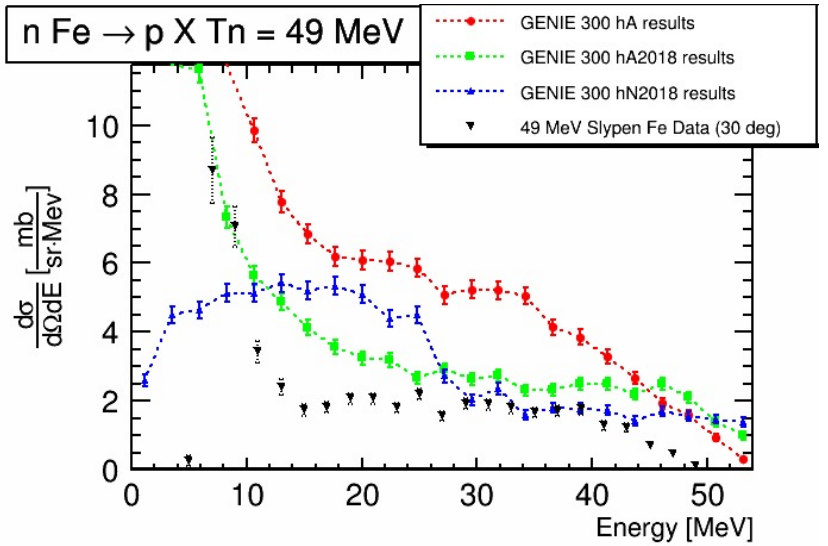
M. Elkins [MINERvA] et al., Phys. Rev. D**100**, 052002 (2019)



Problems II – low energy particles

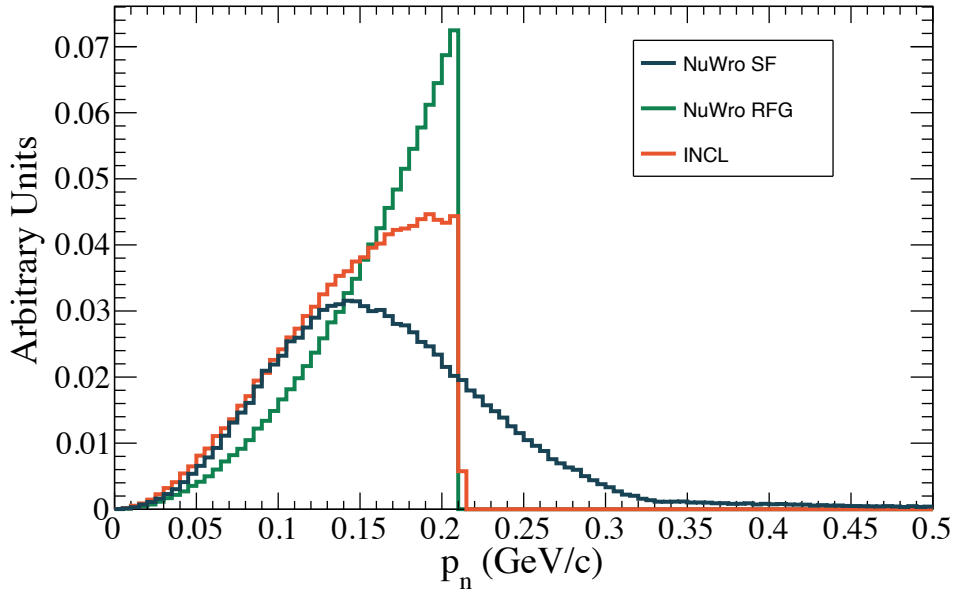
- Called vertex activity in some experiments
- Nucleons, nucleon clusters, photons
- None are in old standard
- Although GENIE v3 FSI was better than v2, not what I wanted for MicroBooNE





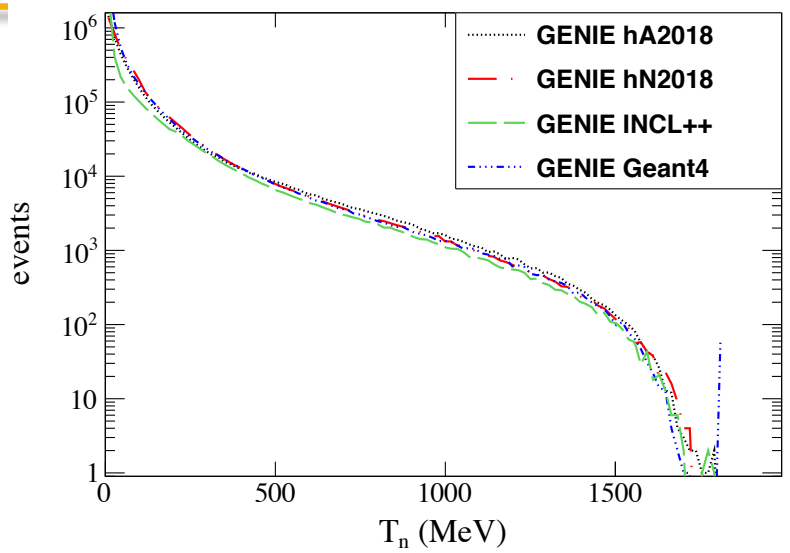
INCL – new standard?

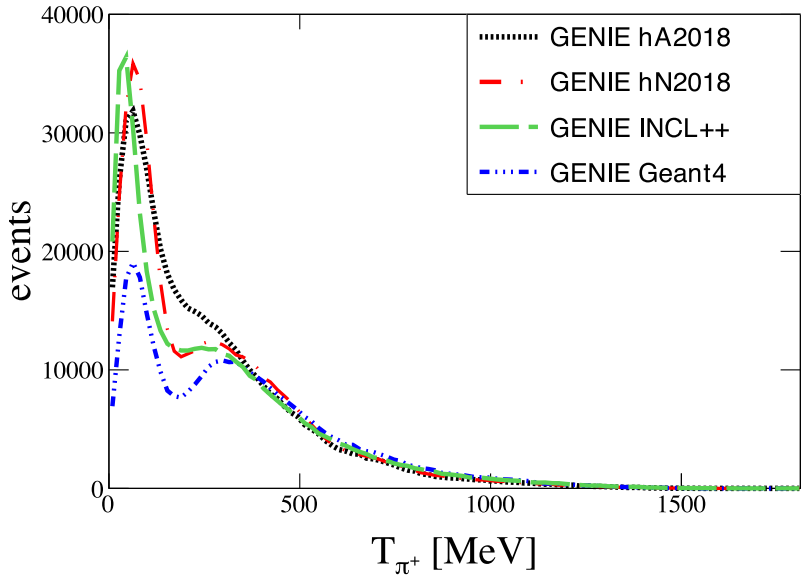
- Cugnon, David, Mancusi… Phys Rev
  - Better nuclear model (nucleons in local potential)
    - Plot below, similar to LFG w/o correlations
  - Emission of γ, ^2H, ^4He…
  - Handles π, N (p and n), not K
  - Implemented in GENIE Eur. Phys. J. ST **230**, 4449-4467 (2021) and NuWro [arXiv:2202.10402 [hep-ph]]

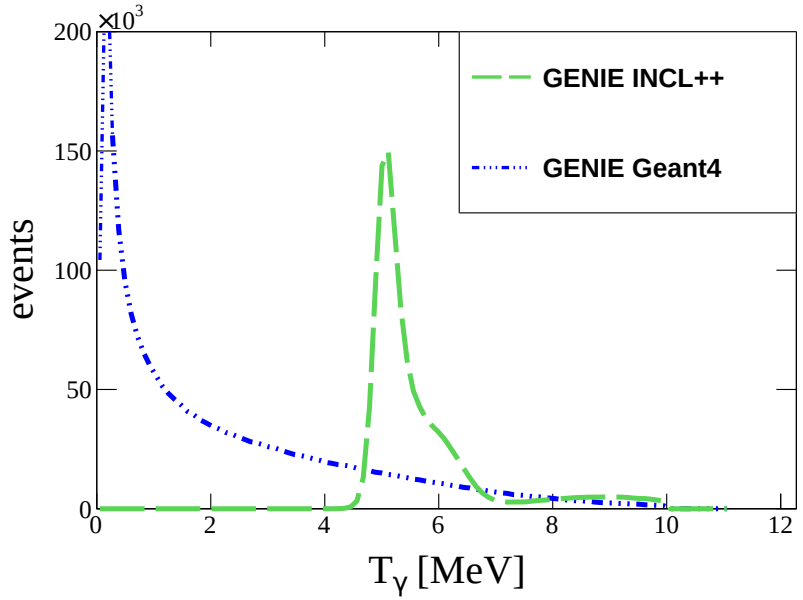


GENIE study for 2 GeV ν_μ Ar (mostly π production)

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

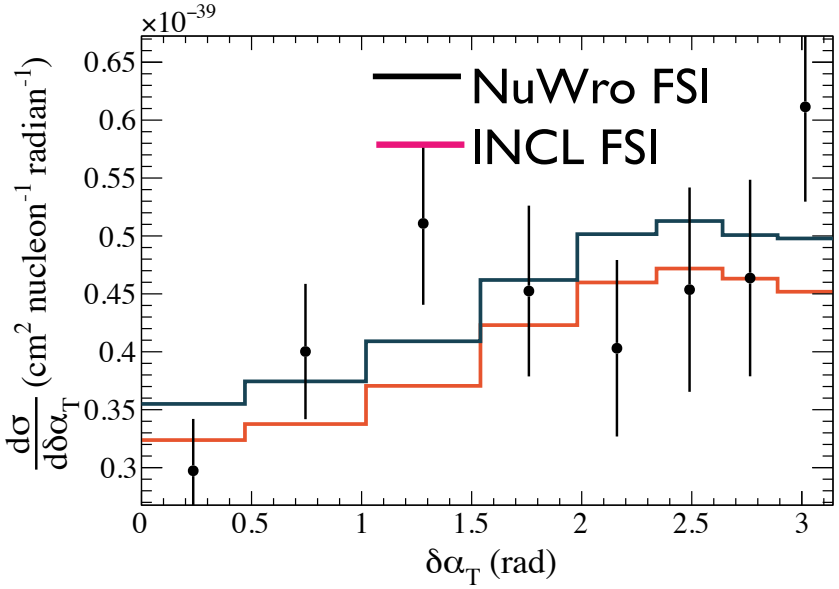


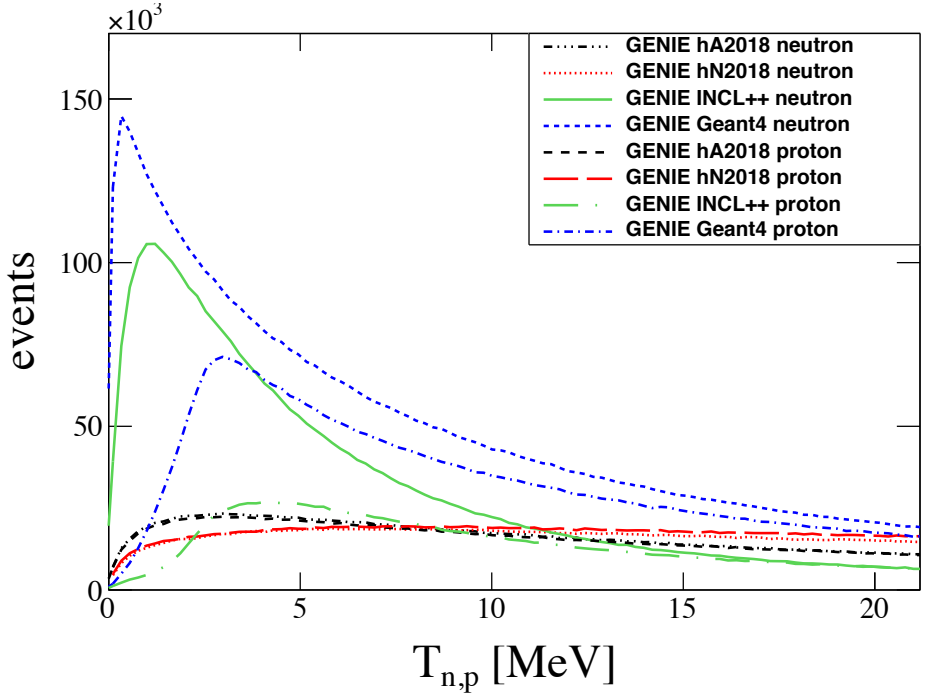




Plots - quantities very sensitive to FSI

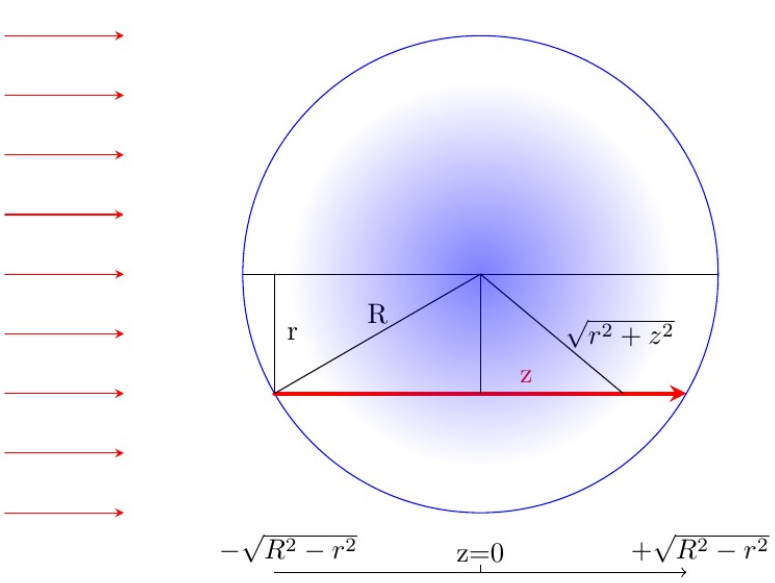
- All comparisons with only FSI changing (new)
- $\delta\alpha_T$ from NuWro compared to T2K data
- low energy p & n from 2 GeV ν_μ Ar in GENIE

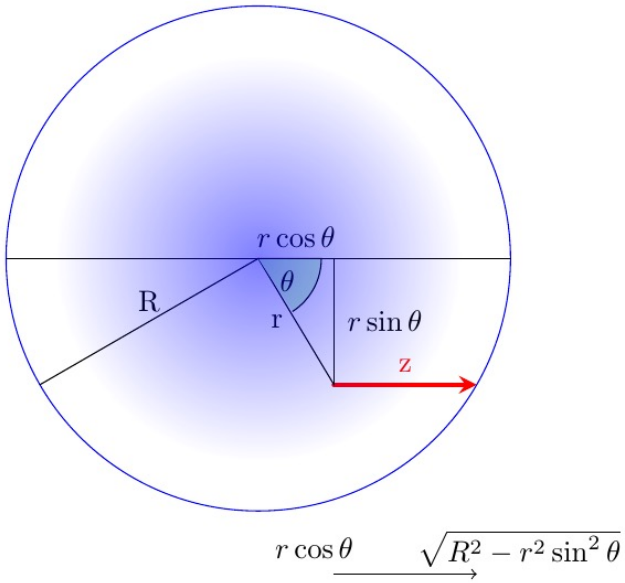




Transparency – new validation method?

- 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

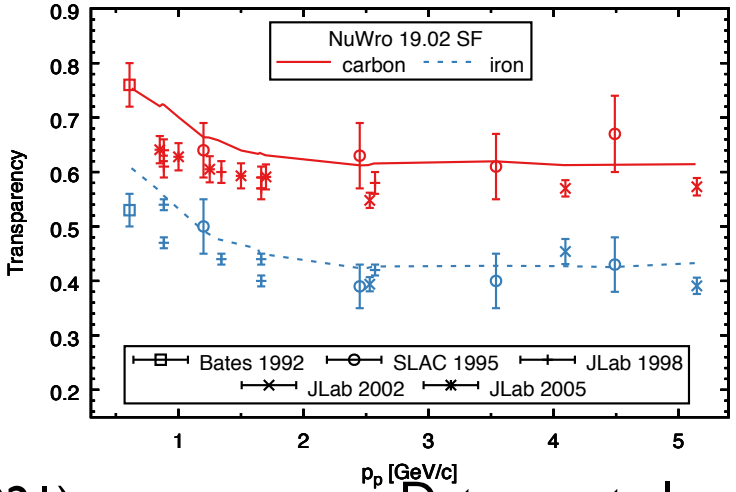




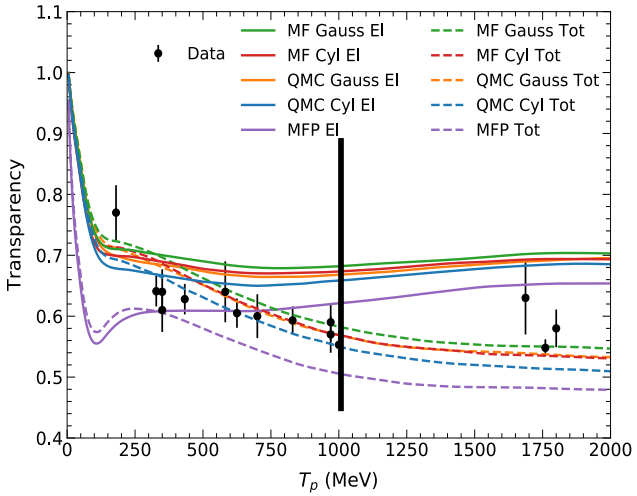
Transparency theory vs. experiment - protons

- 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

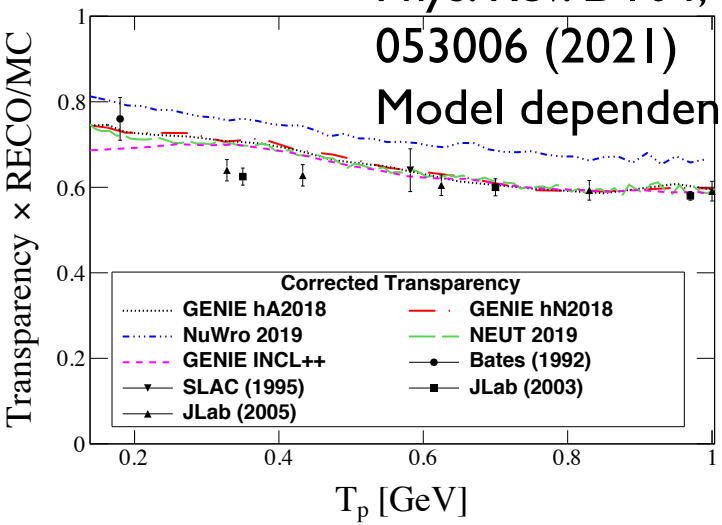
Niewczas, Sobczyk
Phys. Rev. C100, 015505 (2019)
NuWro compare



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

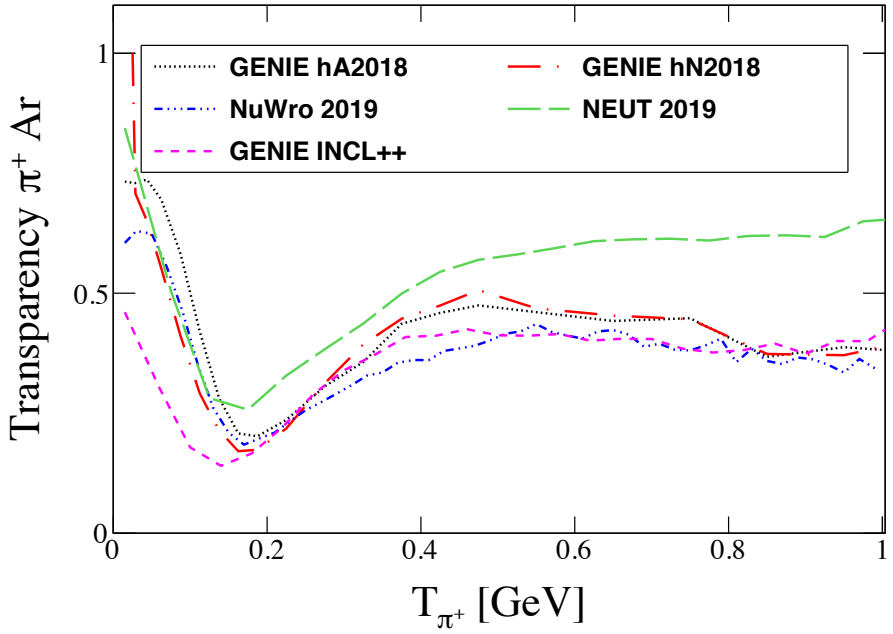


Dytman, et al.
Phys. Rev. D104, 053006 (2021)
Model dependen



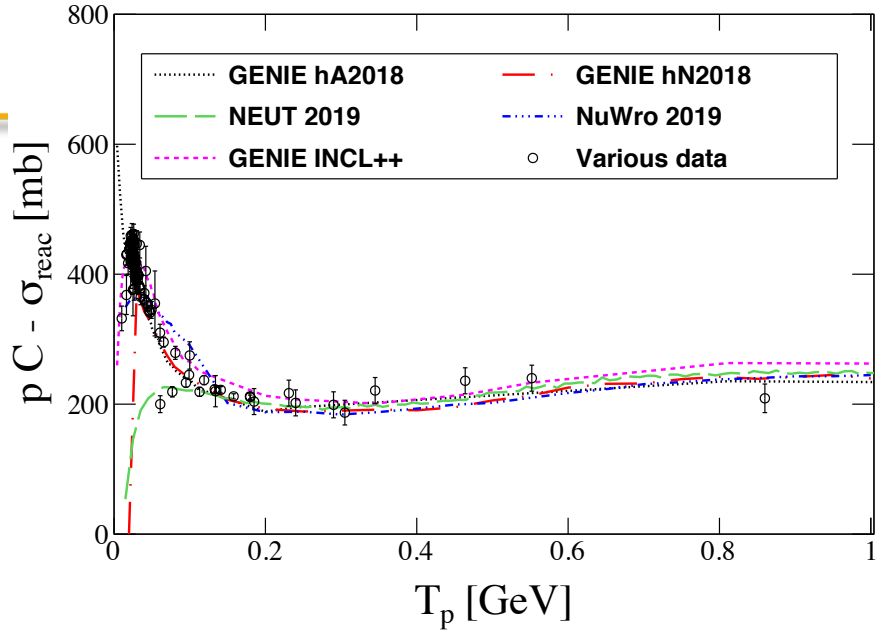
Pion transparency

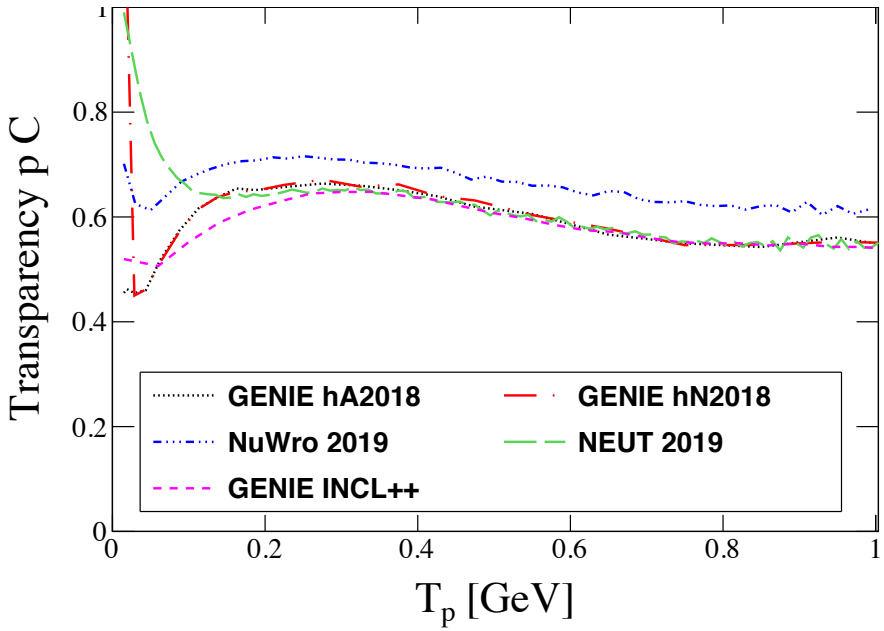
- No data for pion transparency at T_π<~1 GeV
- Significant model dependence
- Focus on Isaacson vs. us?



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

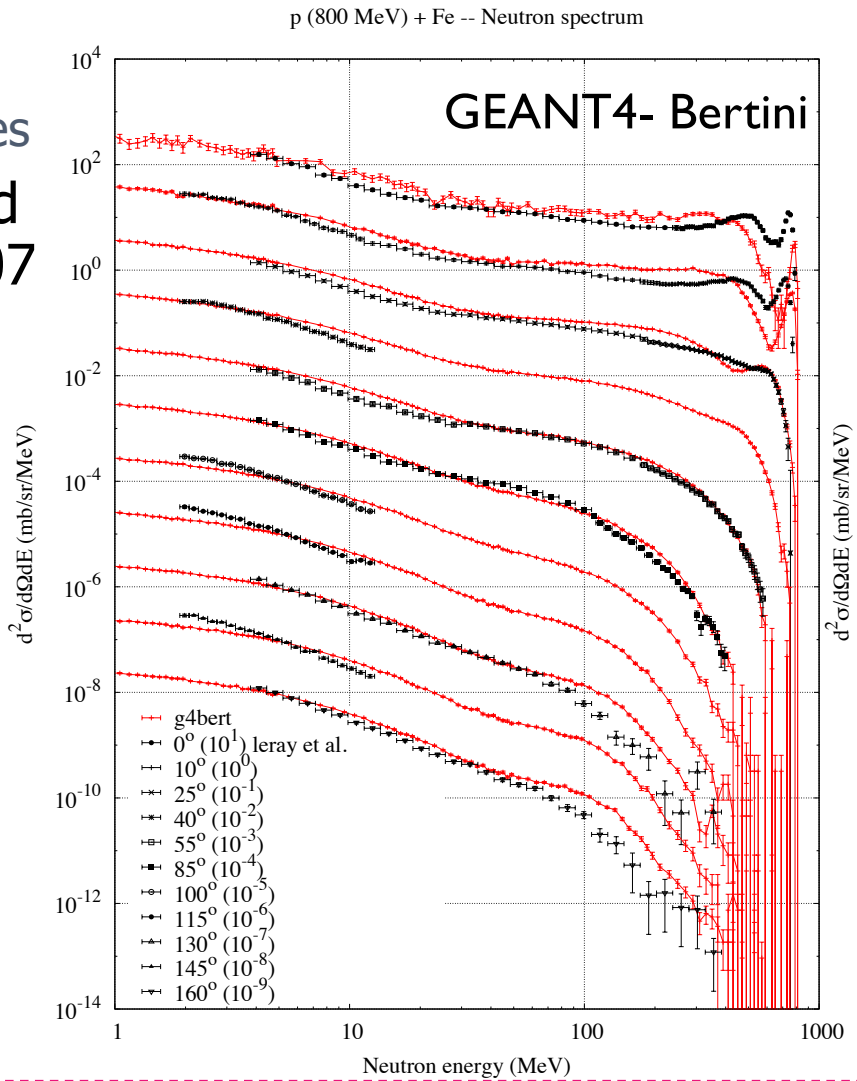
- Significant progress recently
  - More models – INCL++, GEANT4
  - More comparisons, e.g. transparency
  - Low energy hadrons, pions show strong model dependence (INCL best)
- No data for pion transparency at T_π<~1 GeV, proton transparency data not sufficient; σ_{reac} improvement needed
  - New e4ν data will have important impact
- Significant model dependence remains
  - Isaacson et al. and Dytman et al. not in agreement!
  - New stepping mechanism/NN correlations vs. NN cross sections
- Next frontier – Sato-Lee-Nakamura (see Toru Sato talk)
  - Unified model with ~complete hN and NN (no medium corrections)
- Study like IAEA applied to neutrino codes would be interesting

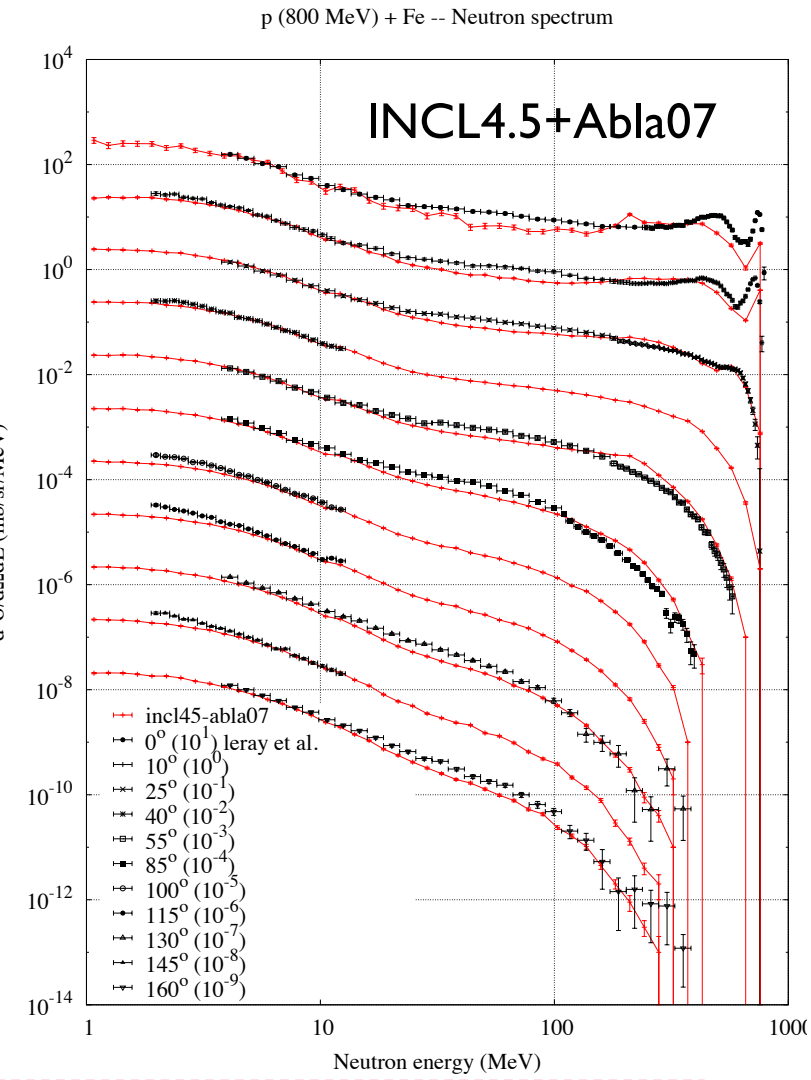
Problems III – pion production

- 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