# FSI overview

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FNAL Generator Workshop

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- FSI history/status
- features/comparisons between generators
- external studies

# 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 CC0$\pi$ signal)
  - Hadrons change energy/angle through scattering (+additional p,n..)
  - Charged-neutral through charge exchange (+additional p,n..)
- Very few studies with $\nu$ 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

- 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 $\pi$A at peak of $\Delta(1232)$
  - 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 ($\pi$), basis for most event generator models today (**NEUT, NuWro, GENIE hN**)
  - GEANT, INCL++ have evaporation, coalescence (low energy, hi A)
- New comparison effort started at ECT* by SD, Hayato, Niewczas, Sobczyk, Tena-Vidal, and Volonaiaina to compare FSI models. Many plots in this talk come from that work.

# Model overview

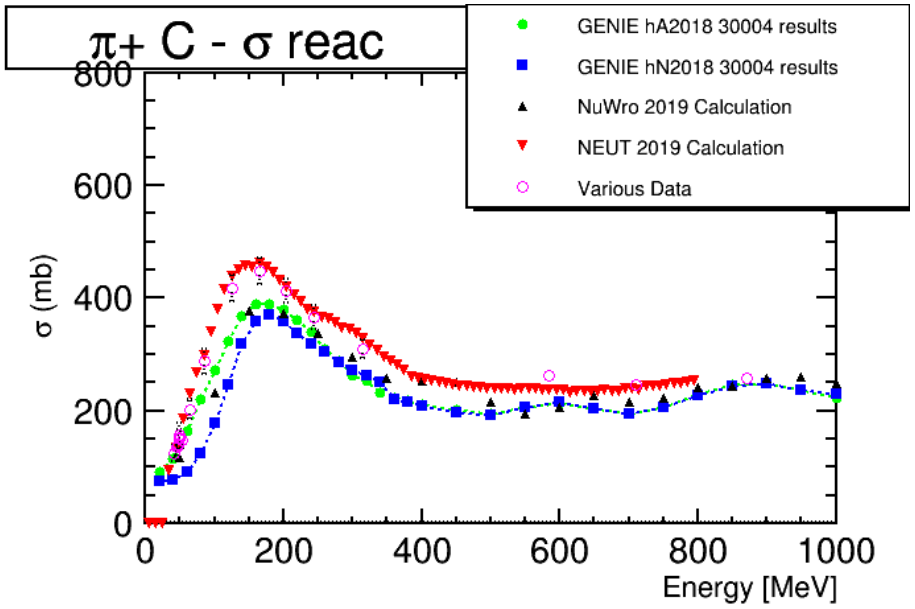
- Empirical
  - GENIE hA (much better agreement with data than expected)
  - True impulse approx. (IA) – nucleon as free – good for KE>~500 MeV
- Semi-empirical
  - Oset $\pi$A, Pandharipande/Pieper NN – adds medium corrections
    - Both are in GENIE hN and NuWro
  - NEUT has new $\pi$N tuning (Pinzon 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

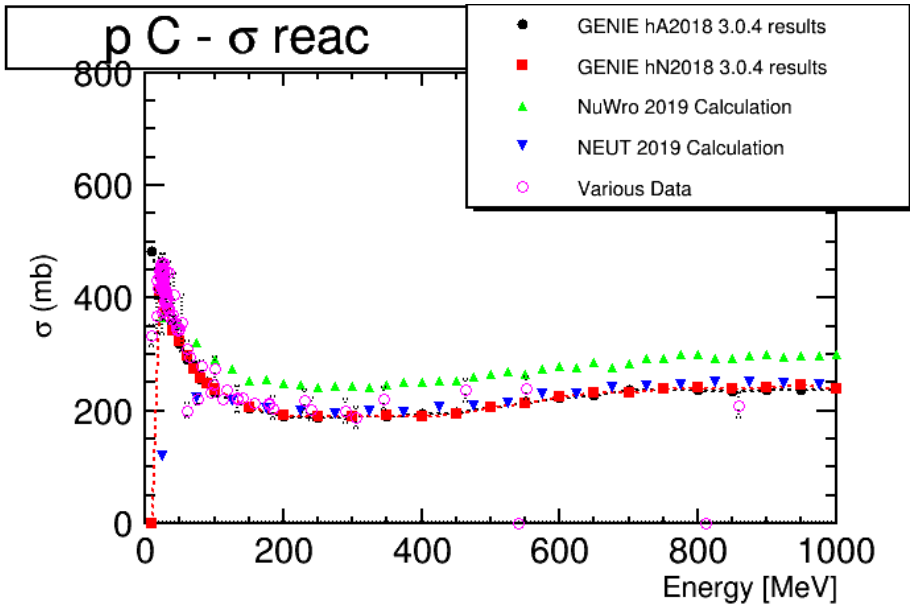
# GENIE FSI strategy

- 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, Madagascar PhD students)
- As of now, includes pions, $K^+$, p, and n
- INCL++, GEANT4 will be in v3.2 (early 2020)

# Comparisons – total reaction xs ($\sigma_{reac}$)
*[also called inelastic from pN days]*

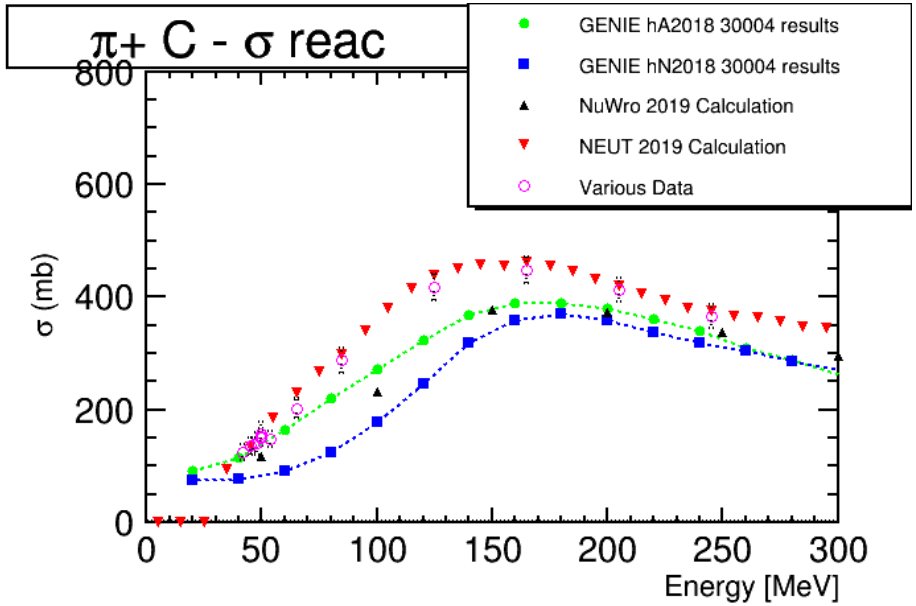
- Comparison of GENIE, NuWro, and NEUT
- Probability of significant interaction (not elastic scattering)
- Traditionally important overall gauge
- Data is very good, not always what we want

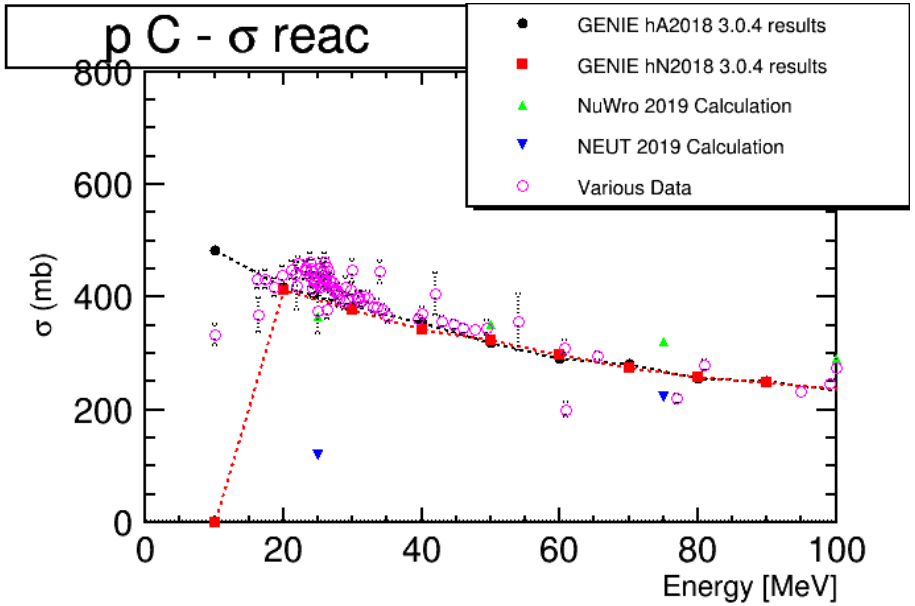


# Comparisons - Total reaction cross sections
*more detail*

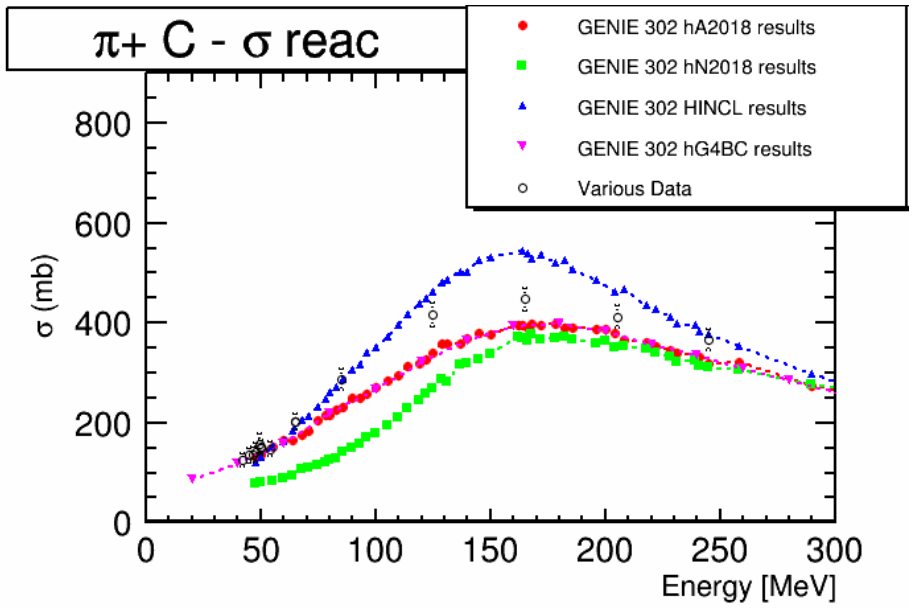
- GENIE has a very large database of cross sections
- Getting it right with semi-classical code is hard when σ is large
- Low energy nucleons are a problem, data not reproduced

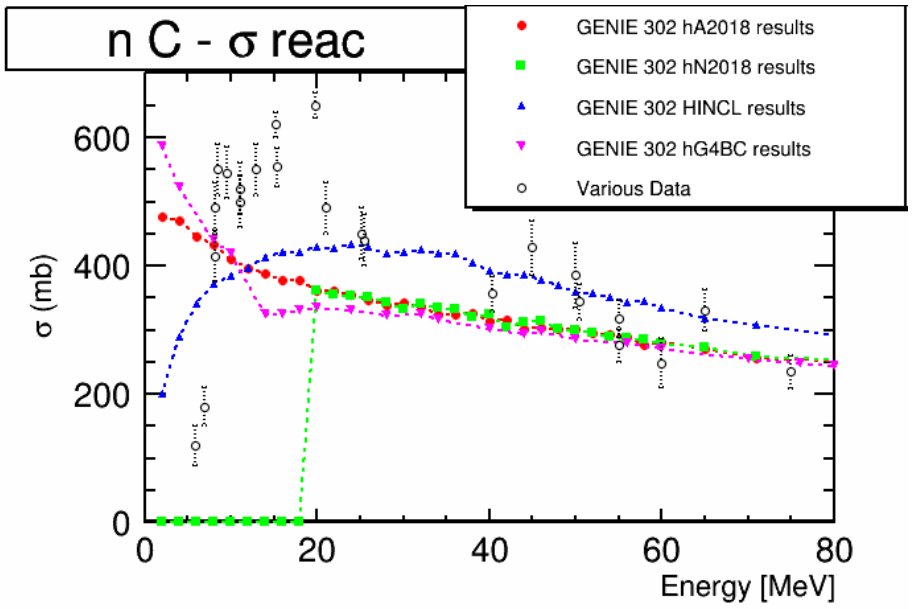


# Comparisons – $\sigma_{reac}$ with INCL/GEANT4

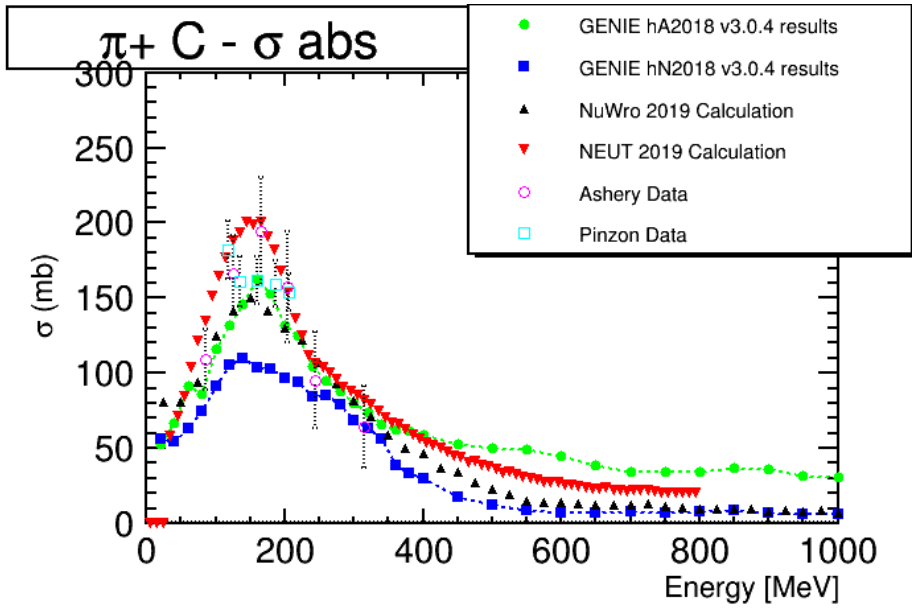
- GEANT4 is Bertini, same as hA2018 because same stepping
- All 4 roughly equal at this level of comparison
- Divergences seen for $KE_n$<40 MeV, INCL is best

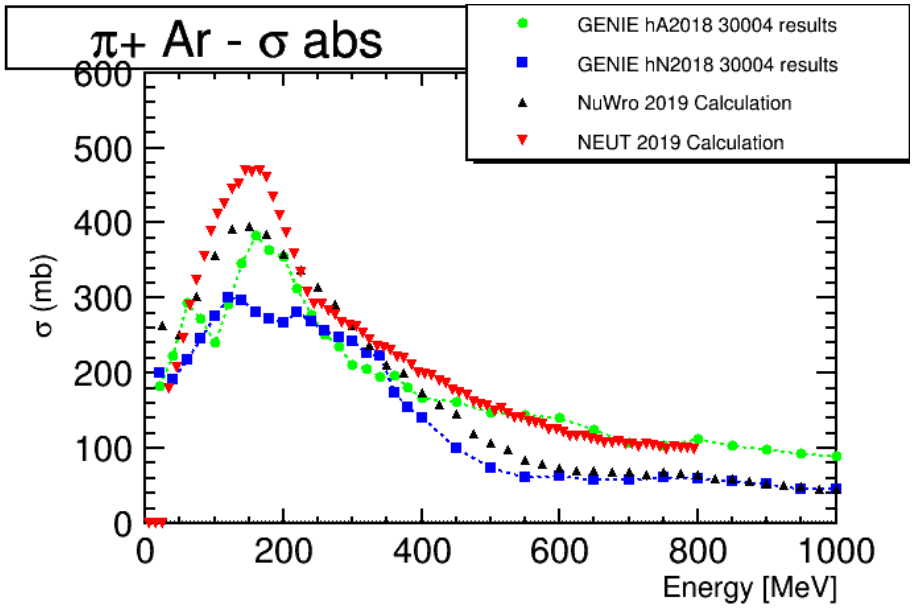


# Comparisons - Total absorption cross section

- Much harder to measure – confusion with charge exchange
- NO data for $T_\pi$>350 MeV!  Huge hole addressed to be in ProtoDUNE?!
- Problems seen even for $\pi^+$C (new DUET data included)



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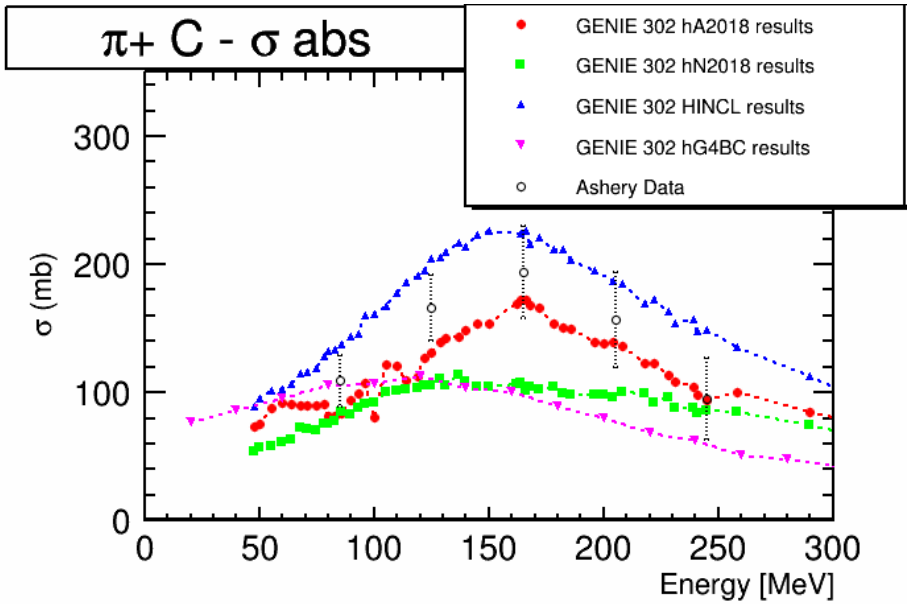
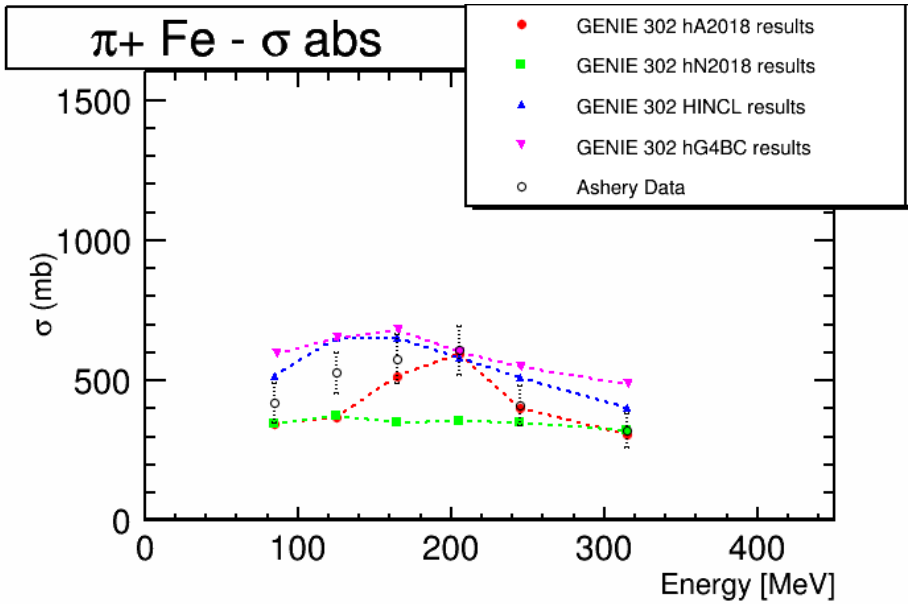
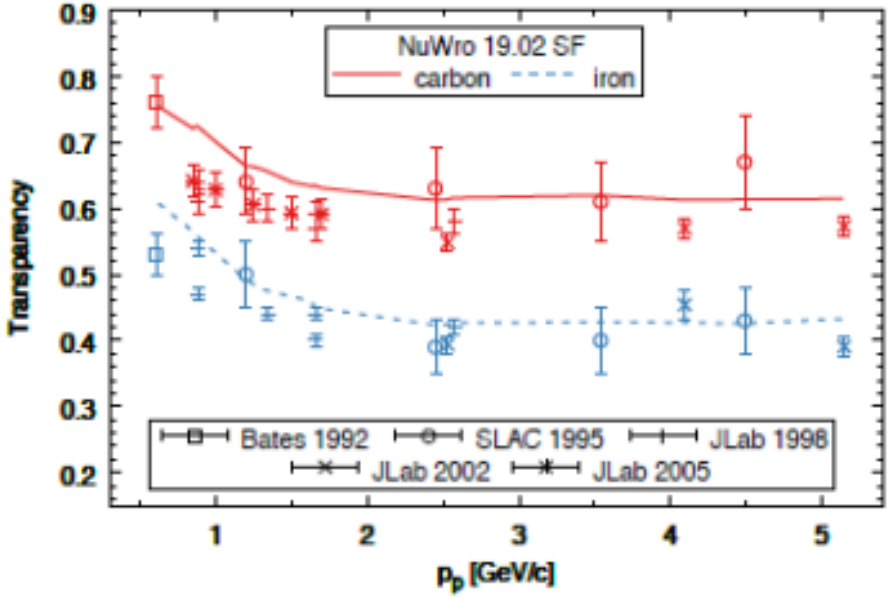


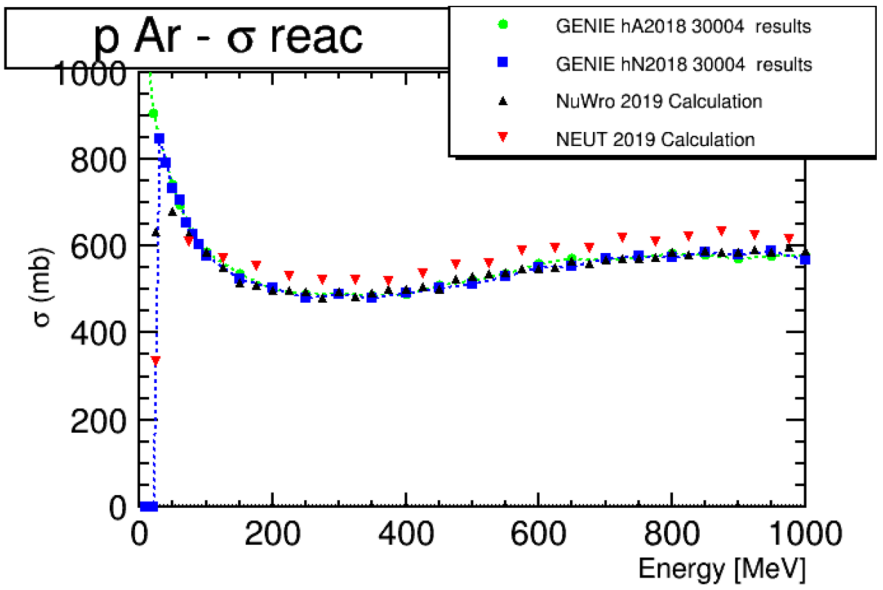
# Comparisons - transparency

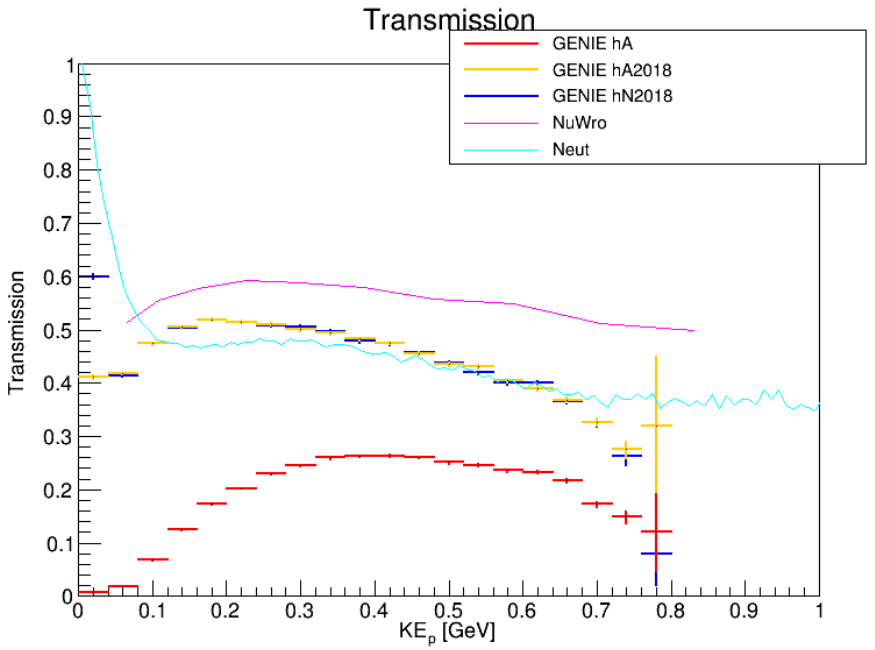
- Transparency – probability to escape without interaction
  - Similar to $\sigma_{reac}$, but how different?
- See Niewczas, Sobczyk [Phys Rev D100 015505 (2019)] for study with NuWro
- New update from ECT* in progress



# Transparency – protons 'theoretical'

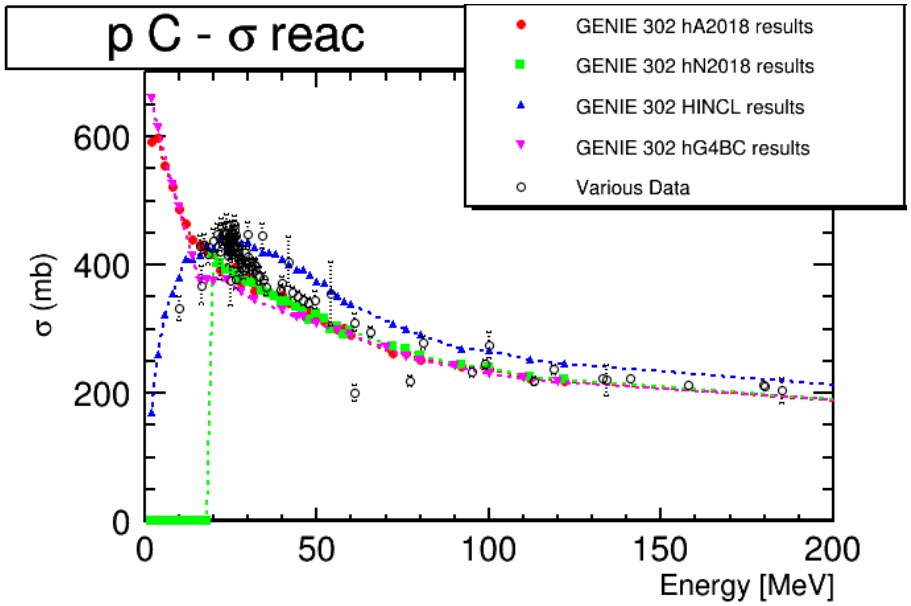
- Compare GENIE, NuWro and NEUT for Argon
- No experimental acceptances, no comparison with data
  - No rise at low energy, seems range of densities responsible

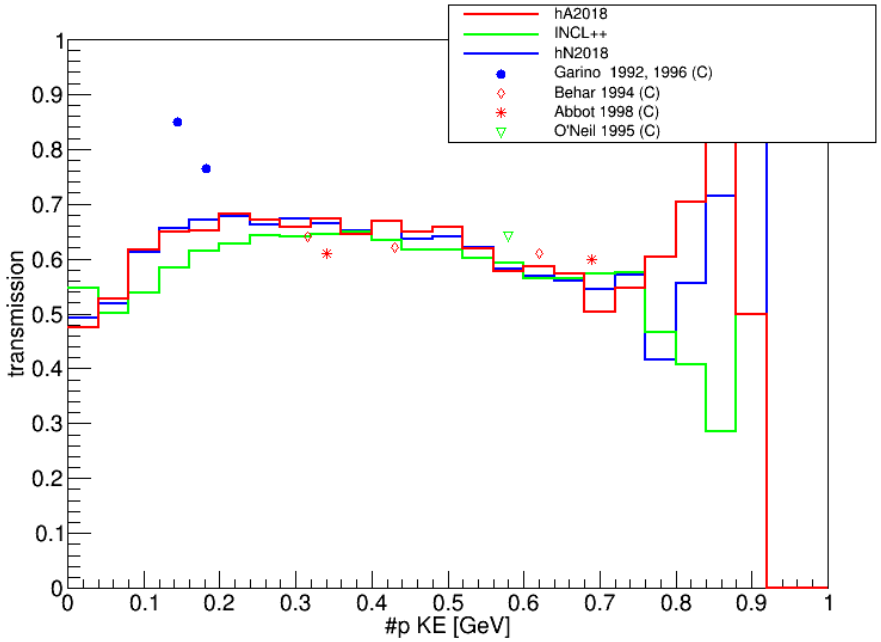


# Transparency - protons

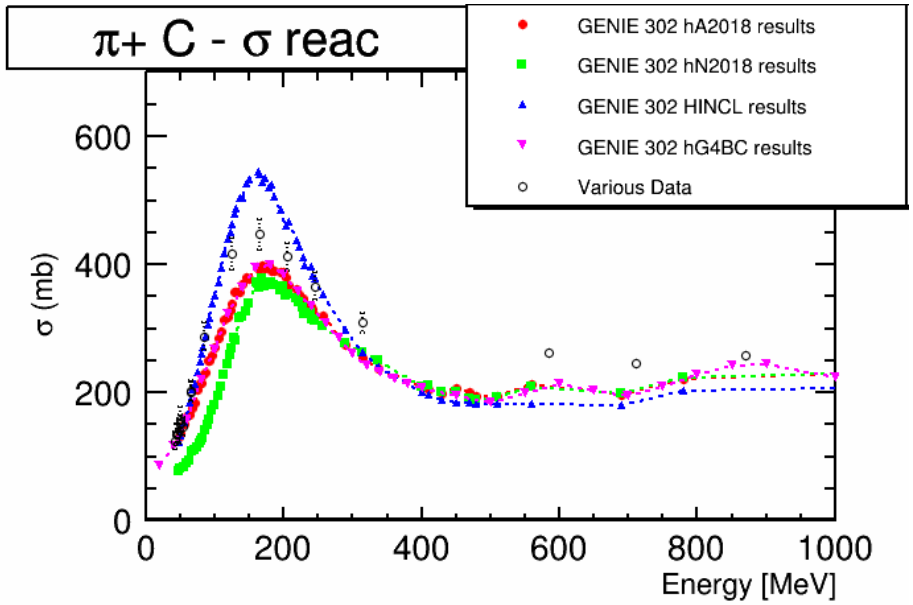
- Compare GENIE models for C target
- Only differences at low energy, more divergence in $\sigma_{reac}$
- conclusion is that sreac more sensitive

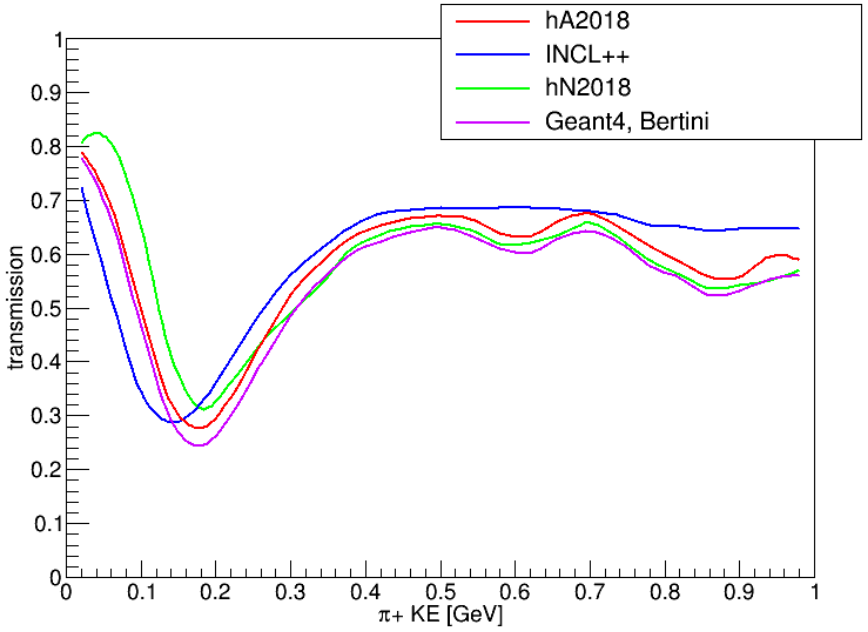


# Transparency - pions

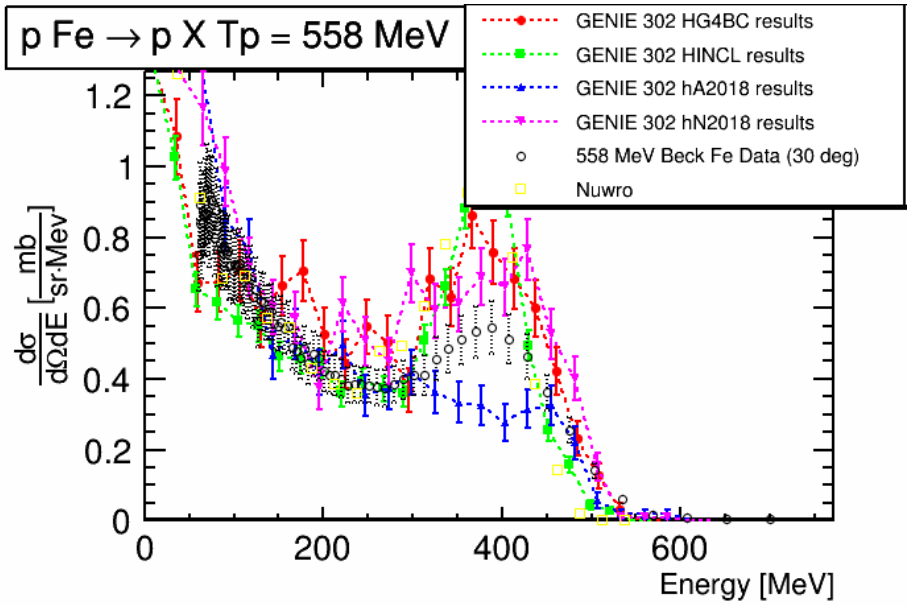
- Comparison using the 4 GENIE models
- differences at Δ peak very interesting
- Magnitude of differences are similar, advantage of transparency not large

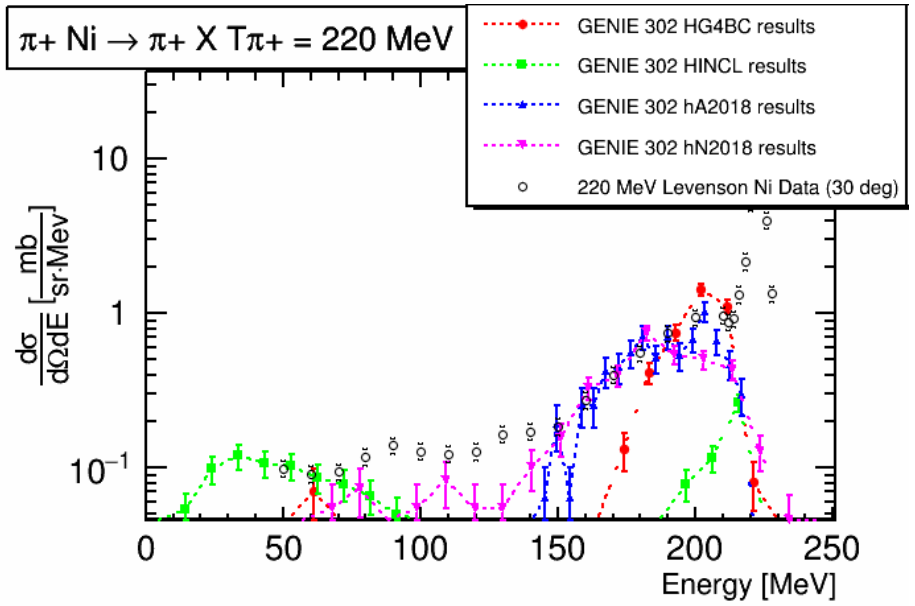


# Comparisons – double differential xs
*much more detail*

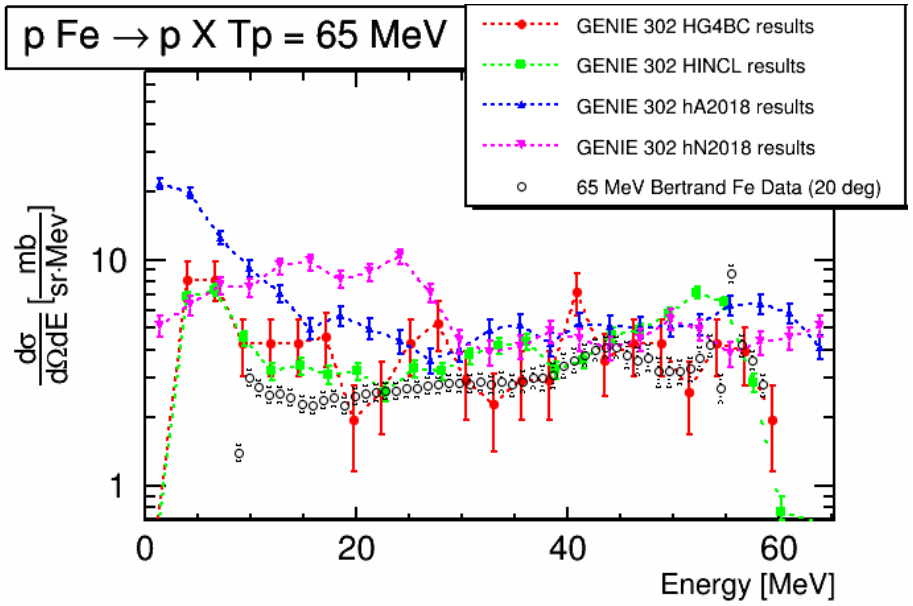
- Energy spectra at each angle, shows mechanisms better
- Compare GENIE with NuWro
  - pFe → pX (left), $\pi^+$Ni → $\pi^+$X (right)
  - Quasielastic peak is prominent (hN → hN in medium)

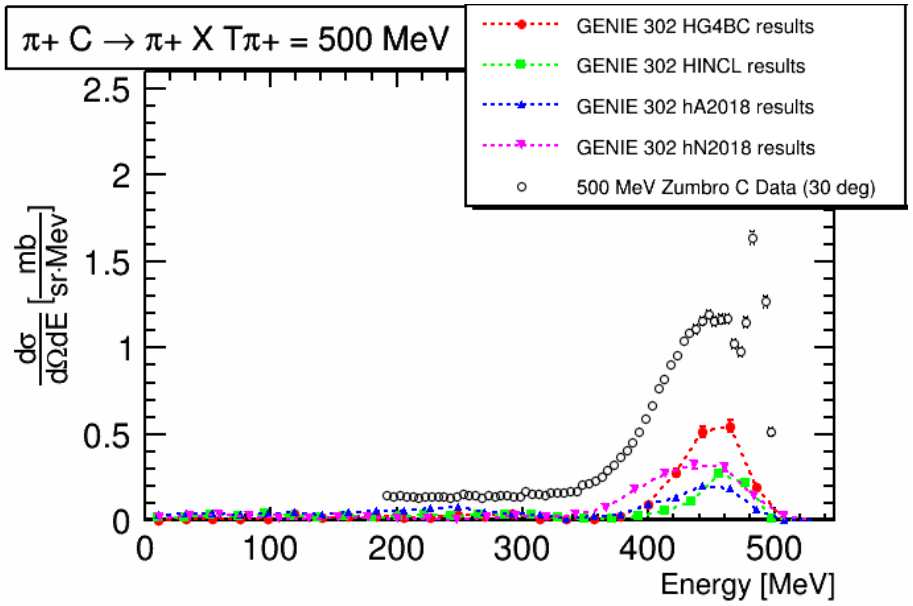


# Comparisons – double differential xs

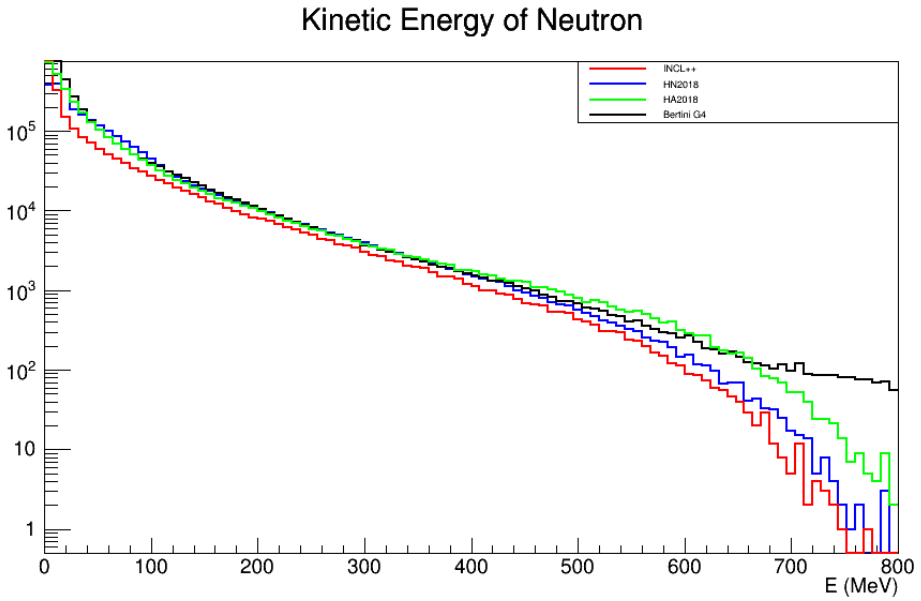
- Compare GENIE hA/hN/INCL/GEANT for p+C->p+X

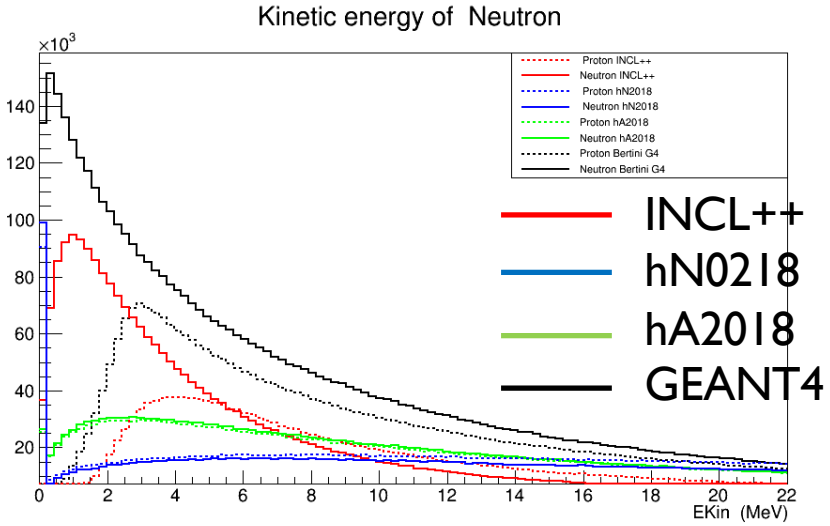


# Comparisons - inclusive hadron production

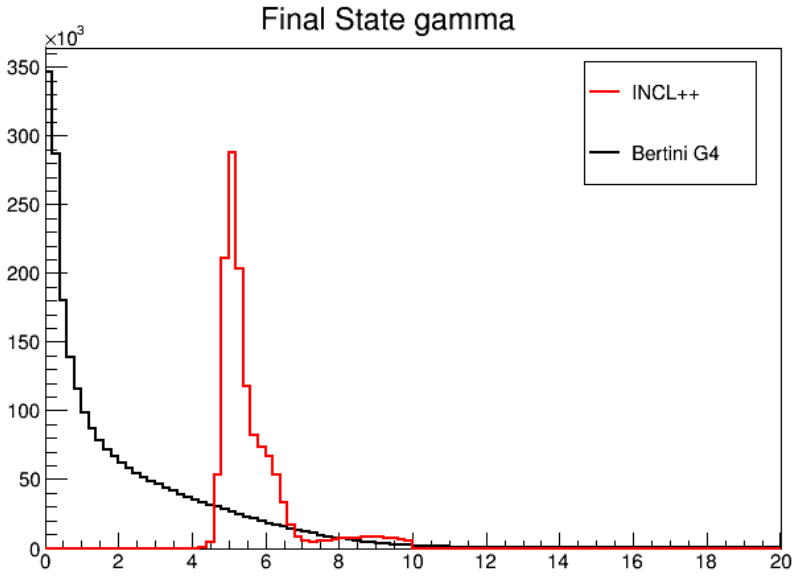
- Inclusive p, n, $\pi$... production with 1 GeV $\nu_\mu$ Ar
- Compare hA, hN with INCL, GEANT Bertini
- p and n spectra are very different at very low energies in INCL but not in GENIE. Right plot has n solid and p dotted
  - Coulomb, barrier affects are primary differences, does it matter?

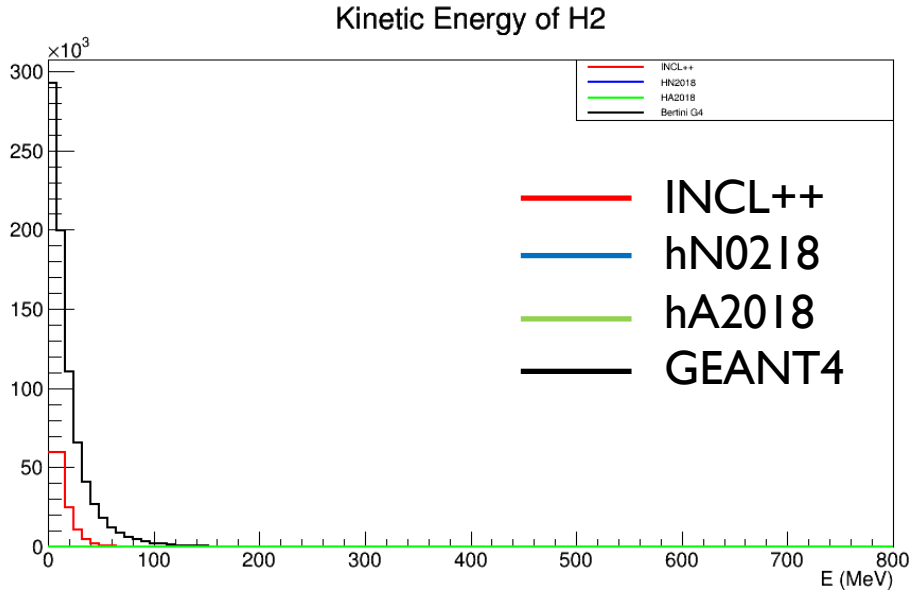


# Comparisons - inclusive hadron prod

- Inclusive $\gamma$, 2H production with 2M 1 GeV $\nu_\mu$ Ar events
- Not included in any standard generator, only GEANT/INCL
- Significant differences in detail



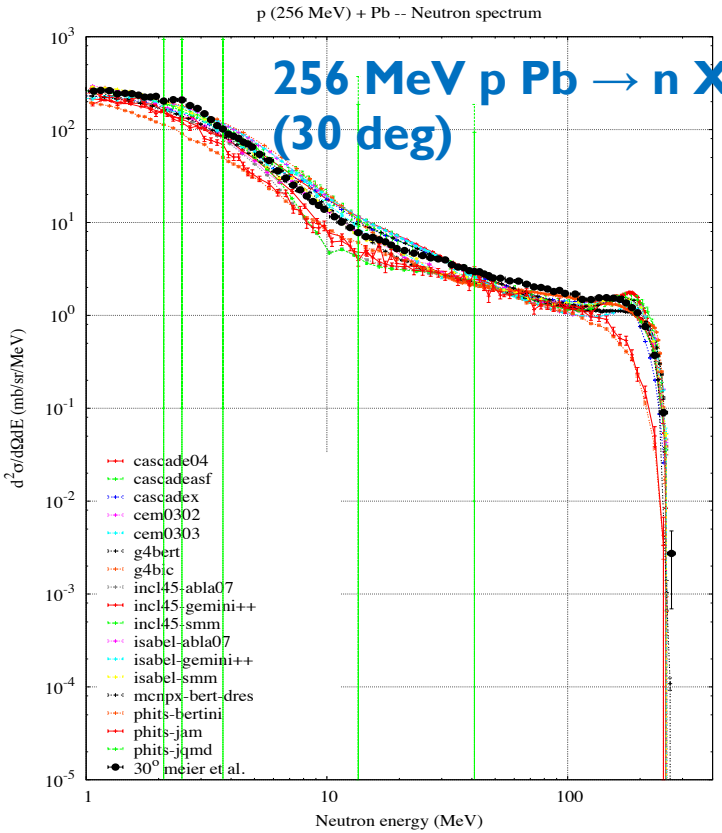



# ECT* (2019) FSI study

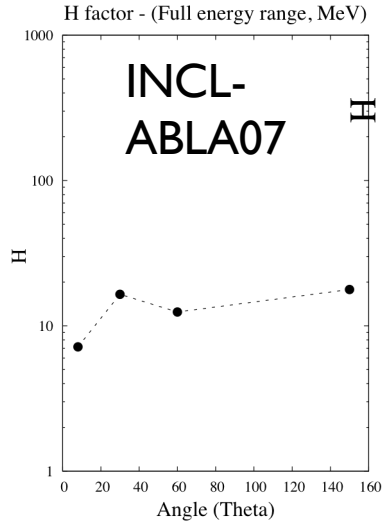
- Started in Trento last summer [Marc Vololoniaina (PhD), Julia Tena-Vidal, SD (GENIE) Jan Sobczyk, Kajetan Niewczas (NuWro), Yoshinari Hayato (NEUT)]
- Compare GENIE, NuWro, and NEUT
- Total reaction, total absorption cross sections for p, $\pi^+$.
- Transmission for p, $\pi^+$. Compare 2 approaches.
- Selected double differential cross section
- Need more transmission data for low energy p, any $\pi^+$.

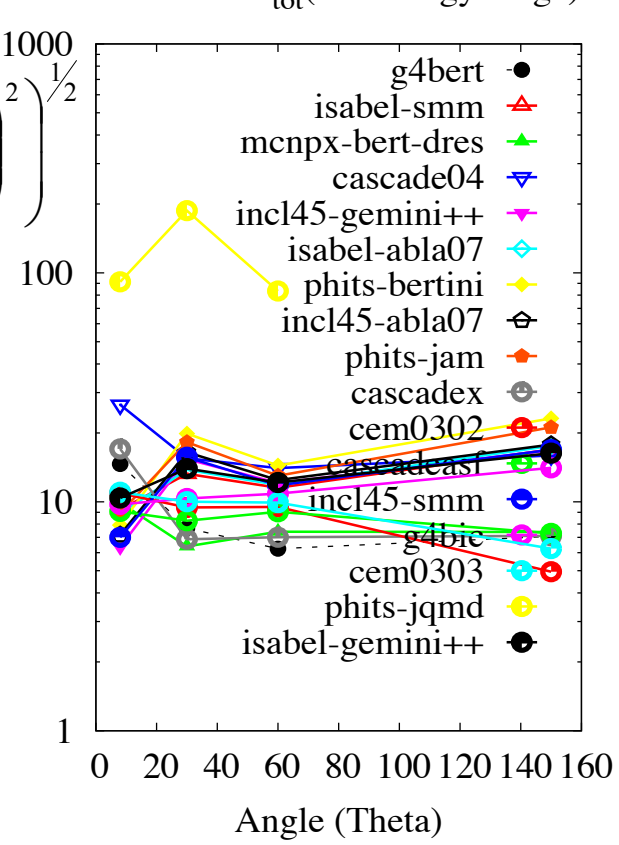
# IAEA Benchmark of Spallation Models
## https://www-nds.iaea.org/spallations/

- J.C. David, D.Filges, S. LeRay, G. Mark, N. Otsuka, Y. Yariv
- Compare GEANT, PHITS, INCL, CEM… for **many** p, n interactions




$$H = \left( \frac{1}{N} \sum_{i=1}^{N} \left( \frac{\sigma_i^{exp} - \sigma_i^{calc}}{\Delta\sigma_i^{exp}} \right)^2 \right)^{1/2}$$



# Conclusions

- Existing models in GENIE, GEANT, NuWro very similar
  - Only different for $\Delta$ $\pi$, low energy nucleons
- New models in GENIE bring better low energy models
  - $\gamma$, $^{2}H$, $^{4}He$… +standard
  - Does it matter? Should these become standard?
- Definitely room for new data – LARIAT, ProtoDUNE
  - $\pi$ abs, kaons, transparency for pions, nucleons
- IAEA study is interesting, ECT* study goes in that direction!
  - Are there better models, tunes available?
  - Do we need more formal studies?

# 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 $\pi$, 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