# FSI overview

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GENIE forum

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- FSI importance
- new models in GENIE
- comparisons

# 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

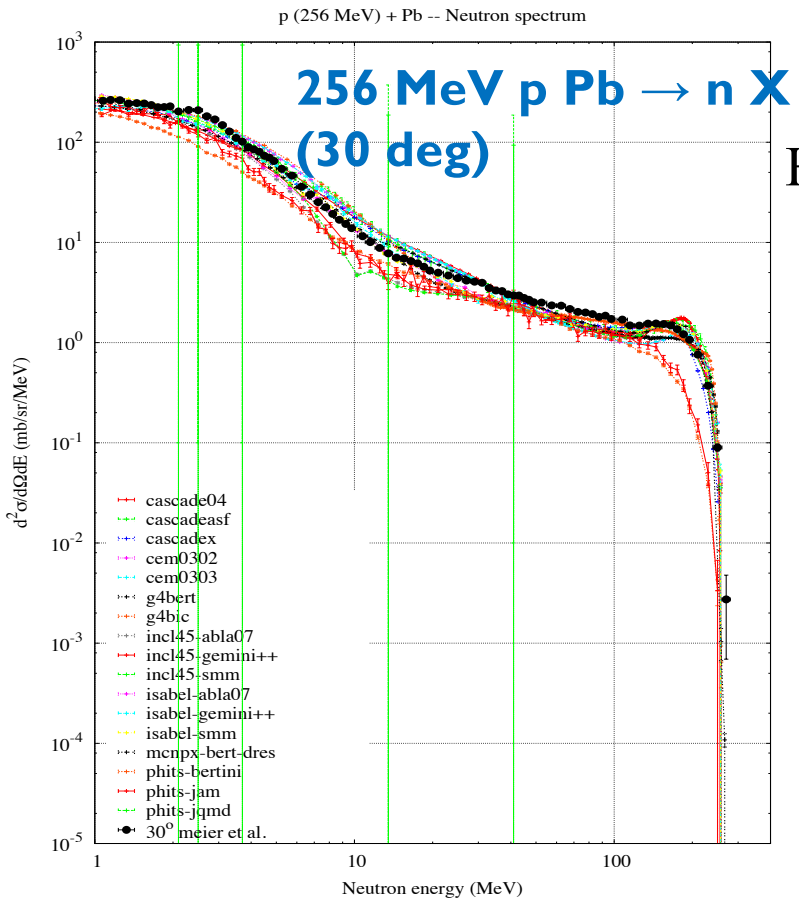
- Semi-classical treatments important since 1960's because full quantum calculation not possible (then and now)
  - Many consequences – good (simple, flexible) and bad (can't be right)
  - Impressive success describing data, even $\pi$A at peak of $\Delta$(1232)
  - Many efforts have been made to add 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.

# Model overview

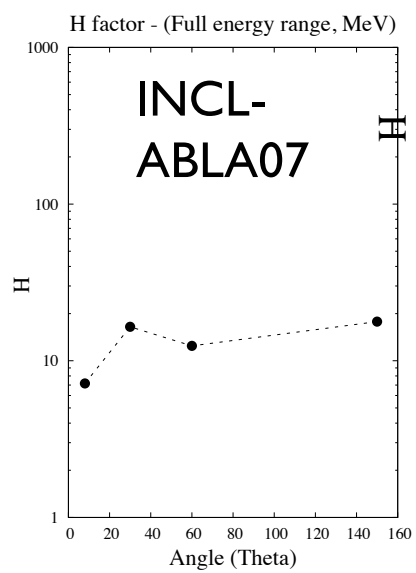
- Empirical
  - GENIE hA (much better agreement with data than expected)
  - True impulse approx. (IA) – nucleon as free – good for KE>~500 MeV
- Semi-empirical
  - Oset $\pi$A, Pandharipande/Pieper NN – adds medium corrections
    - Both are in GENIE hN and NuWro
  - NEUT has new $\pi$N tuning (Pinzon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

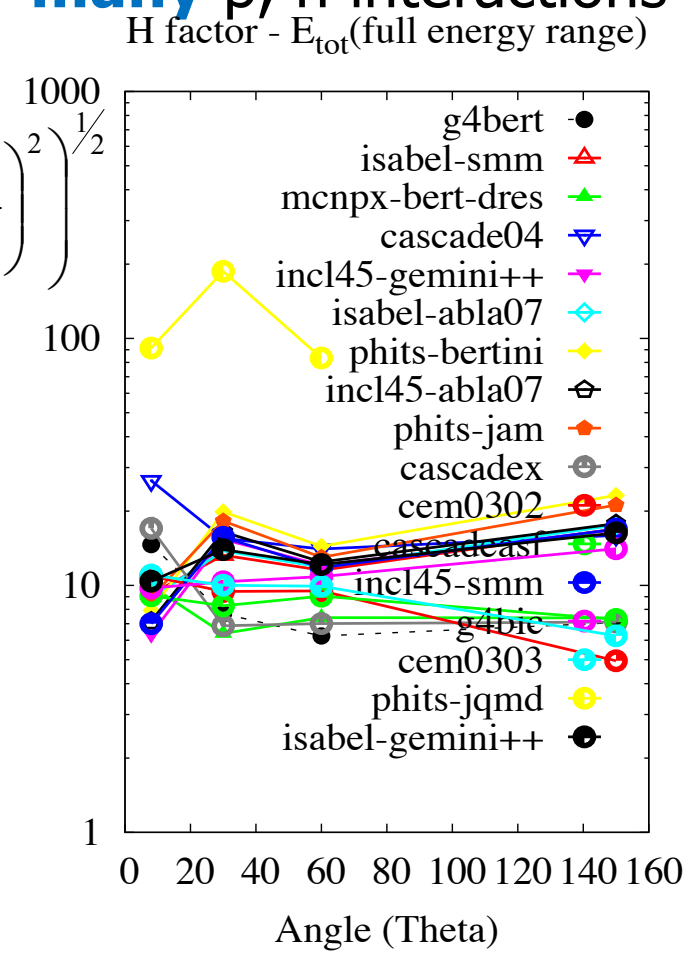
# IAEA Benchmark of Spallation Models
## https://www-nds.iaea.org/spallations/

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




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



# 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
  - No publications yet, just talks like this one
- 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 (on the way)

# How to use these new codes

- INCL++, GEANT4 Bertini now in master GitHub branch
- Anyone can use them
  - They use external libraries which are *conditionally linked*
  - *Not in repository*, you are responsible for obtaining them
  - We use INCL v5.2.9.5 and GEANT Bertini v4.10.2
- See Robert Hatcher's GENIE docdb-158/174, for detail
  - configuration settings

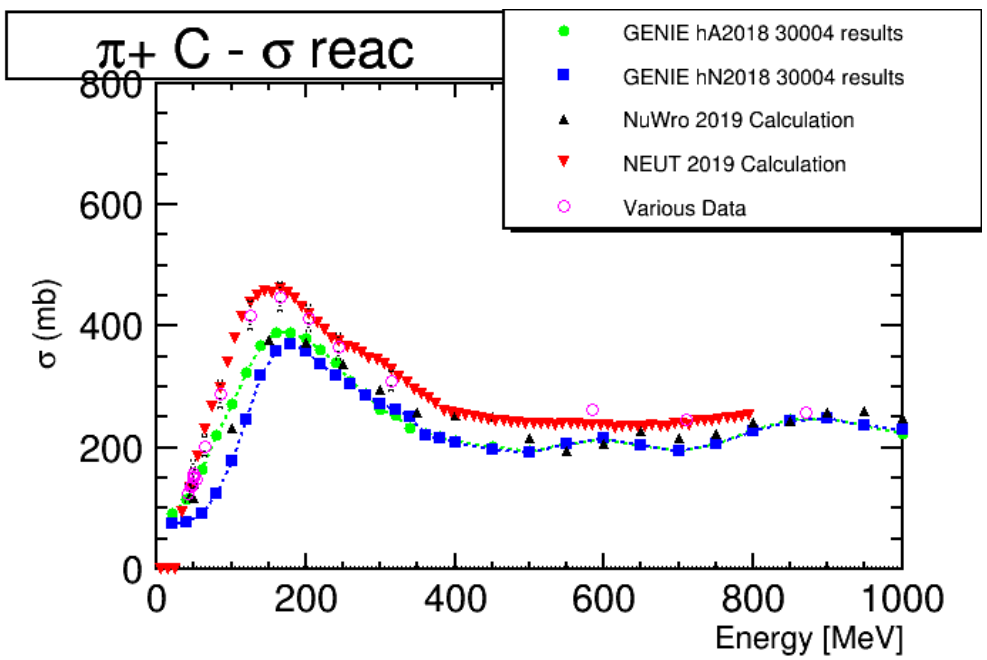
```
incl        Interface with INCL++ for nuclear transport         default: disabled
geant4      Interface with Geant4 for nuclear transport         default: disabled

incl-inc    INCL++ includes path    needed if you --enable-incl    (if unset: tries to auto-detect it)
incl-lib    INCL++ library path     needed if you --enable-incl    (if unset: tries to auto-detect it)
boost-inc   boost includes path     needed if you --enable-incl    (if unset: tries to auto-detect it)
boost-lib   boost library path      needed if you --enable-incl    (if unset: tries to auto-detect it)
geant4-inc  Geant4 includes path    needed if you --enable-geant4  (if unset: checks for a \$GEANT4_INC
geant4-lib  Geant4 library path     needed if you --enable-geant4  (if unset: checks for a \$GEANT4_LIB
```

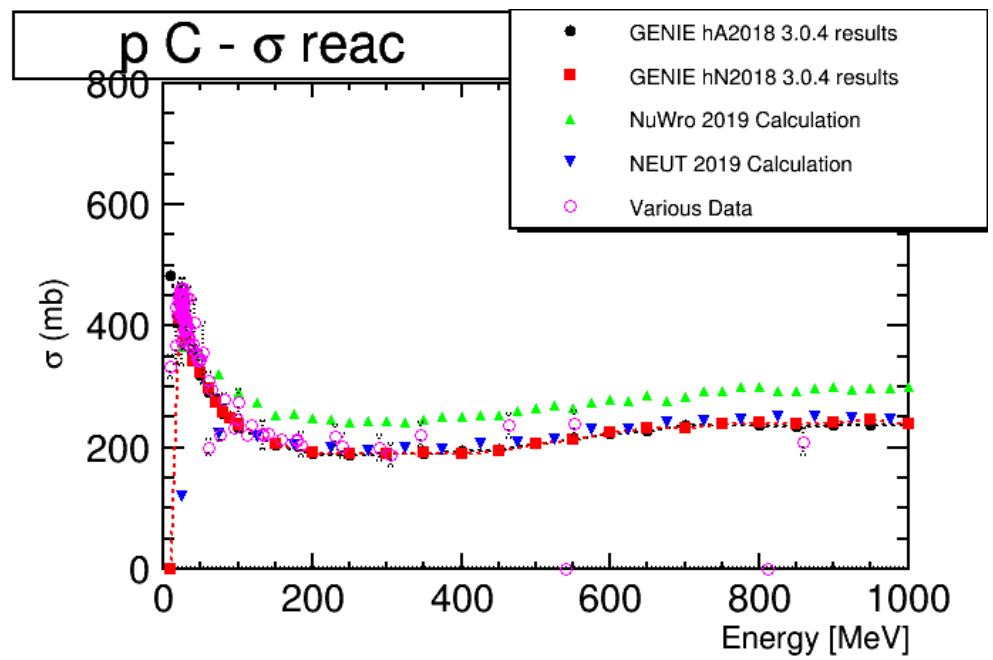
# How to use these new codes

- INCL++, GEANT4 are now in master GitHub branch
- Enable their usage in tune settings
  - GTEST18_02c uses INCL++
  - GTEST18_02d uses GEANT4 Bertini
  - These are the 'default' models (Llewyllen-Smith, Rein-Sehgal…)
- Detail
  - Must have Root6 for both, INCL needs *boost* package (CERN)
  - Bertini has no stepping like hA or hN, normalizes to total xs
    - Therefore, we use hA stepping (no medium corrections)
    - Result is identical total reaction xs for hA and Bertini (all else different)
  - Enable p, n, and $\pi$ for INCL; all that was there in our version
  - Enable p, n, $\pi$, and K+ for Bertini; same as hA/hN for now

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

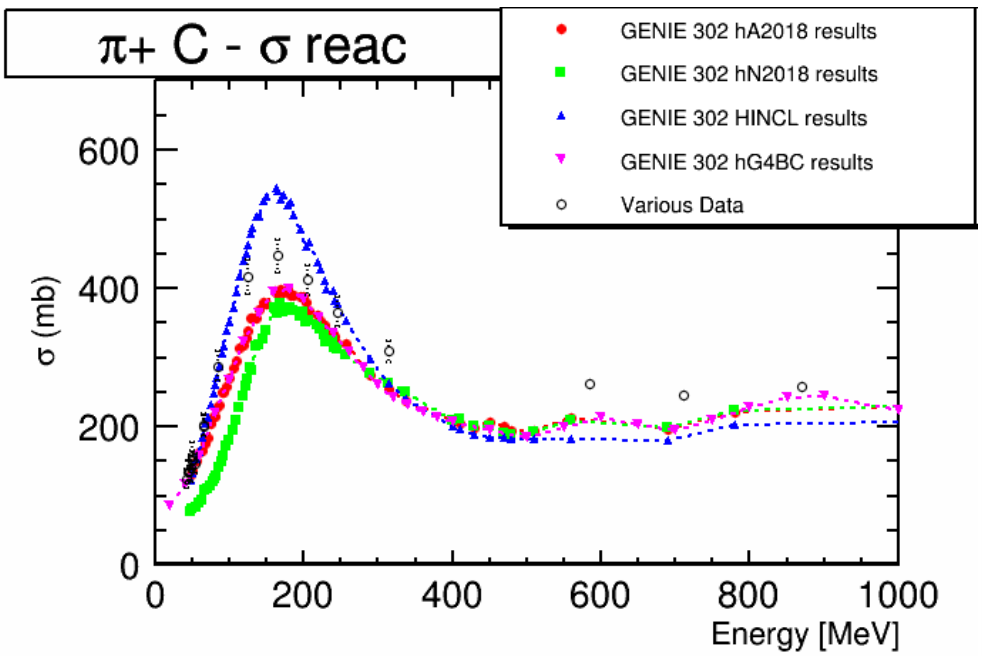
- GENIE, NuWro, and NEUT are very similar (codes ~same)
- Probability of significant interaction (not elastic scattering)
- Traditionally important overall gauge
- Data is very good

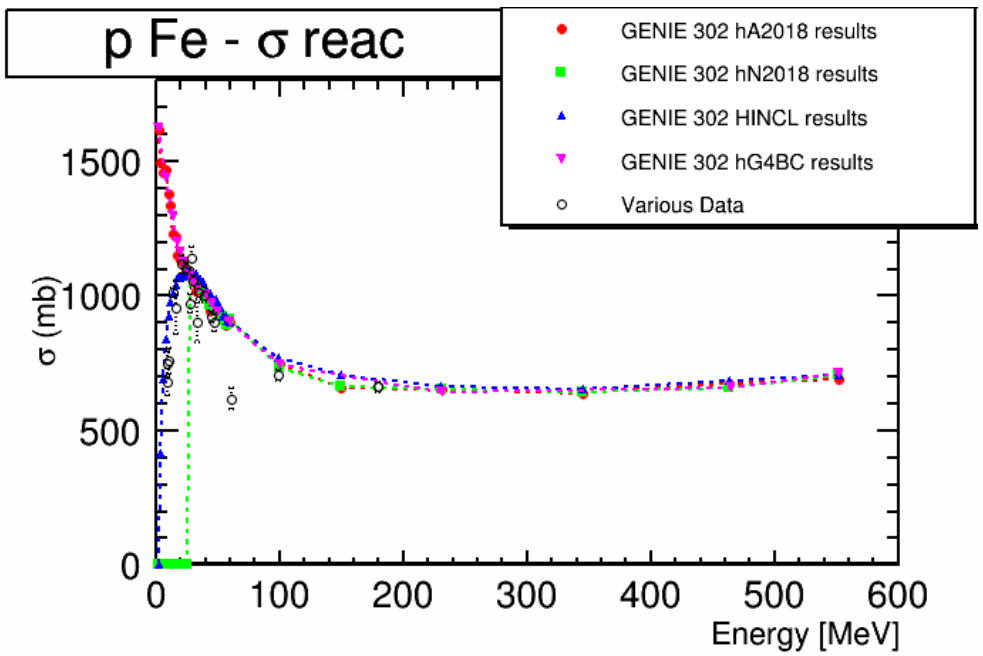


# Comparisons – $\sigma_{reac}$ with INCL/GEANT4

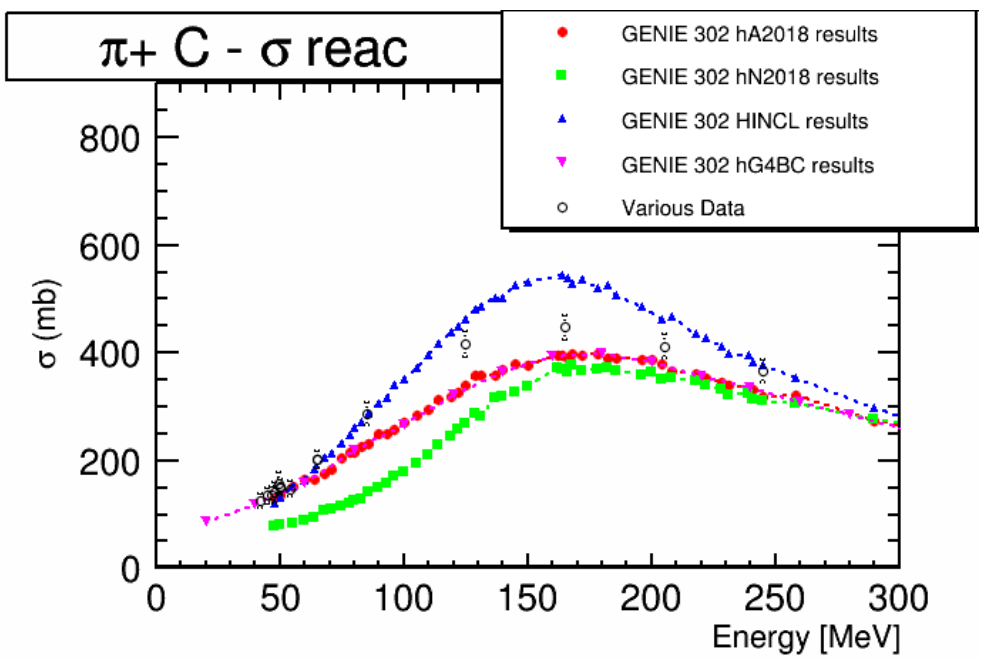
- GEANT4 same as hA2018 because same stepping
- All 4 roughly equal at this level of comparison
- Divergences seen for $KE_n$<40 MeV

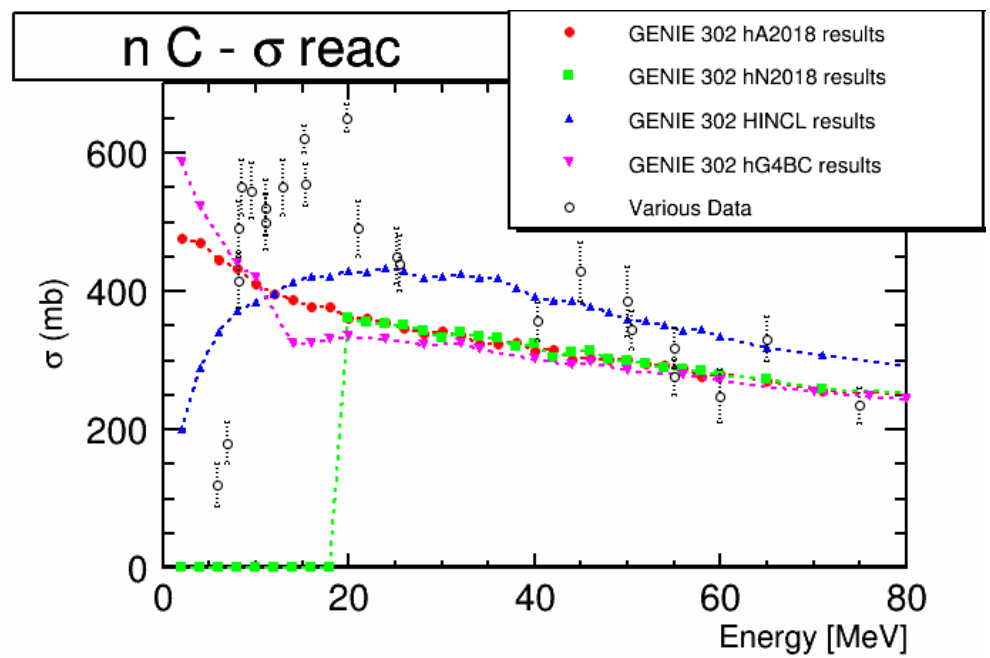


# Comparisons – $\sigma_{reac}$ with INCL/GEANT4

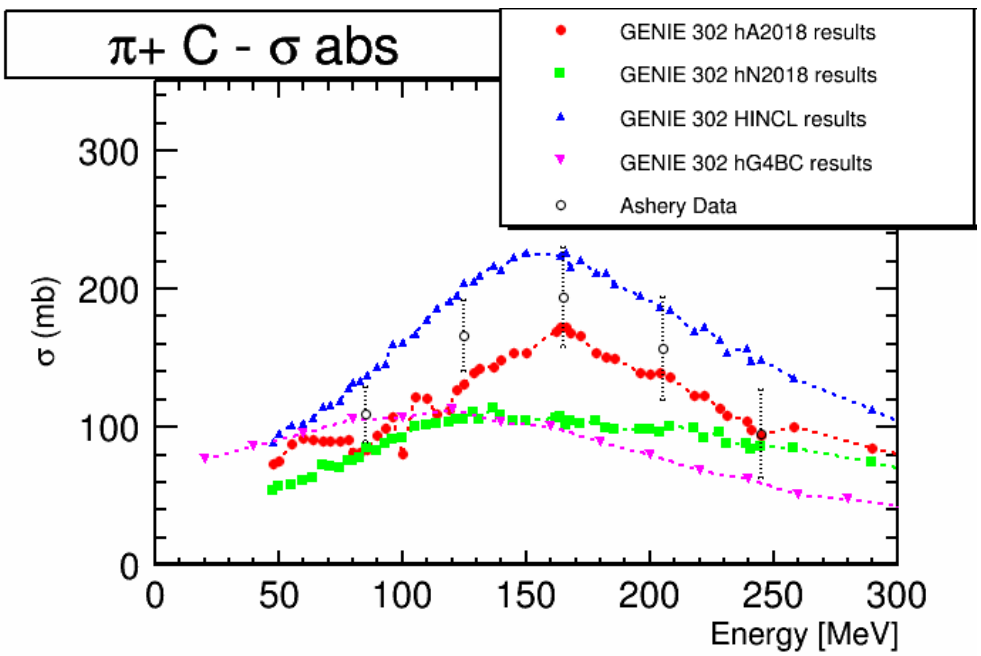
- Focus on pions at resonance, nucleons at low energy
- Divergences seen for $KE_n$<40 MeV, INCL is best

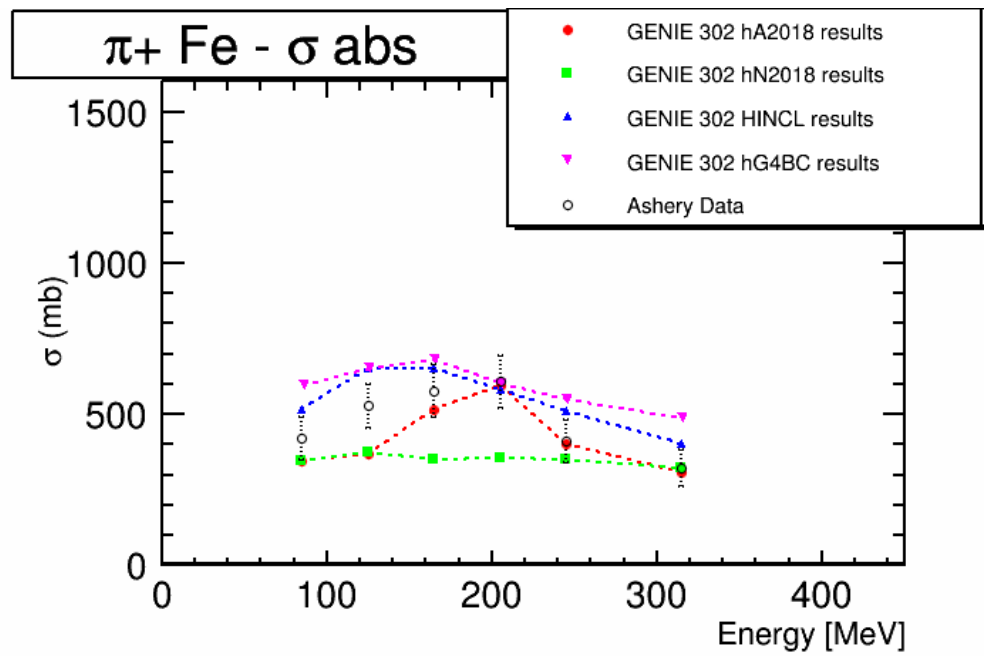


# Comparisons - Total absorption cross section

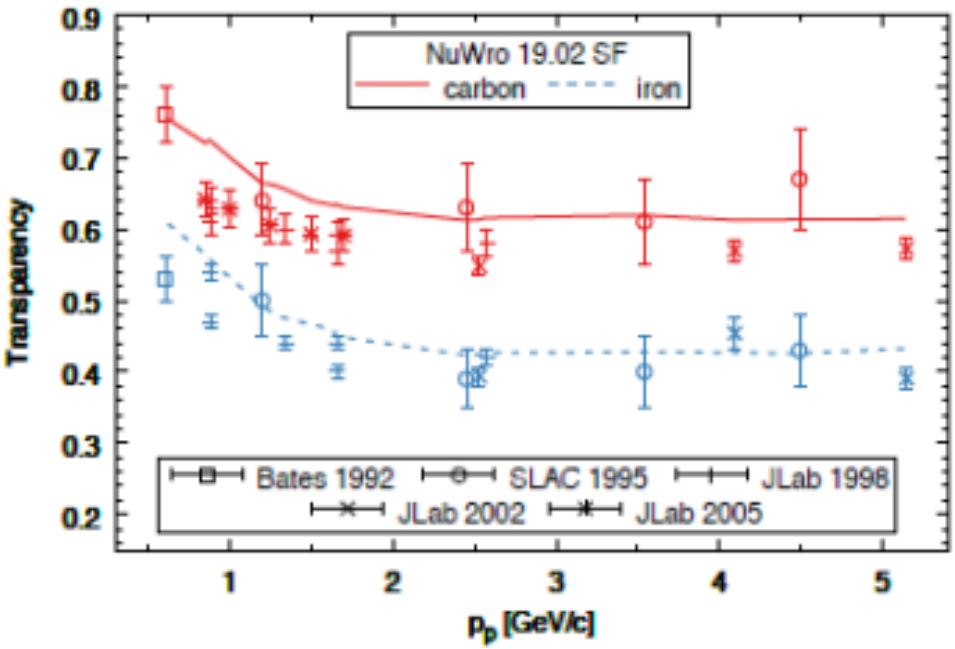
- Much harder to measure – confusion with charge exchange
- NO data for $T_\pi$>350 MeV!  Huge hole addressed to be in ProtoDUNE?!



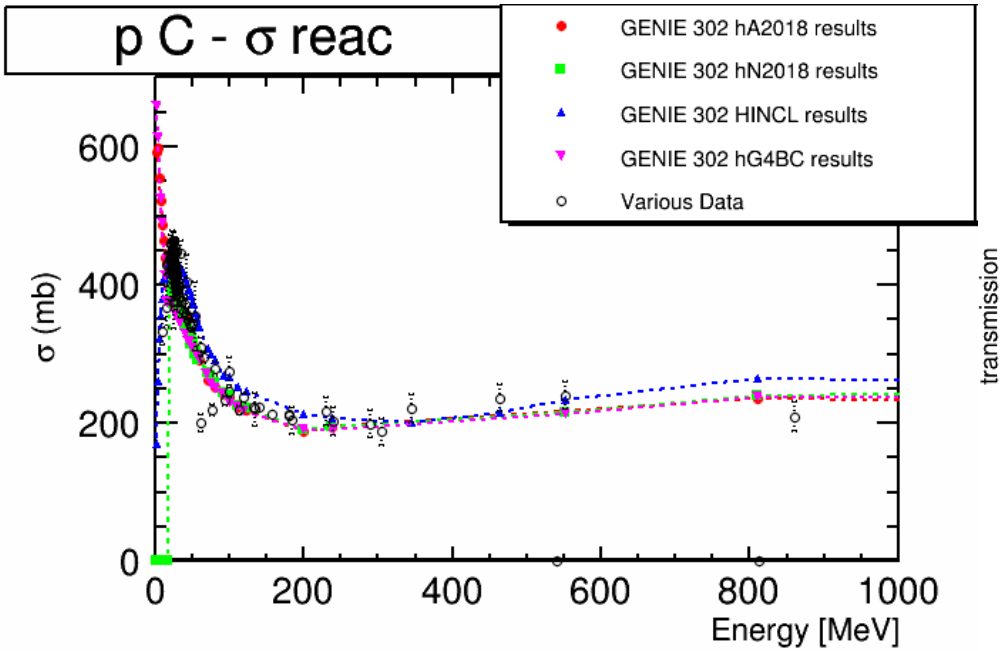
# Comparisons - transparency

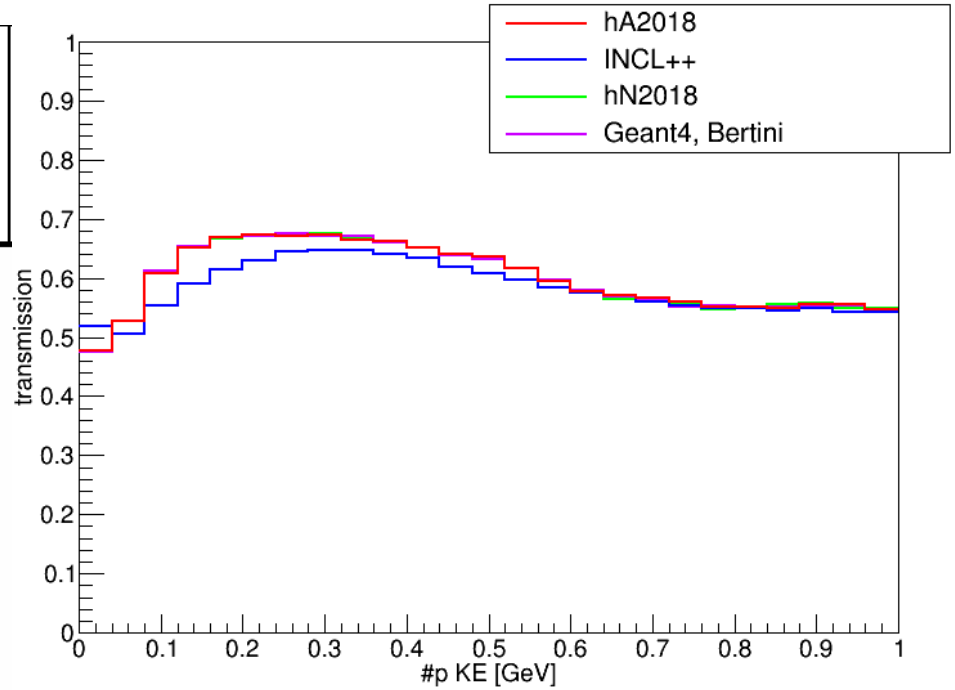
- Transparency – probability to escape without interaction
  - Similar to $\sigma_{reac}$, but how different?
- See Niewczas, Sobczyk [Phys Rev D100 015505 (2019)] for study with NuWro
- New update from ECT* in progress



# Transparency - protons

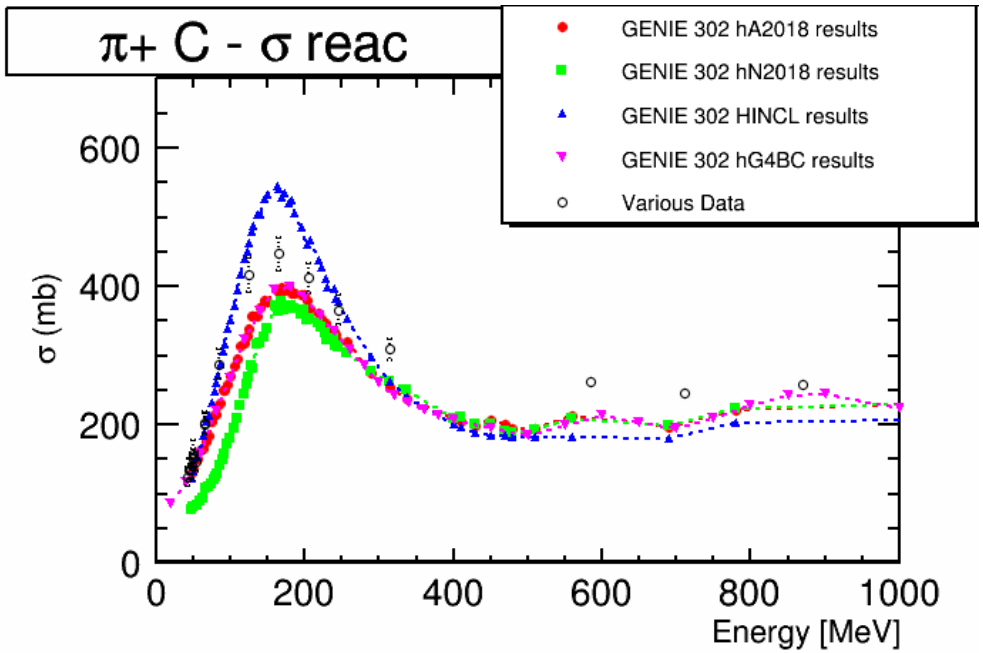
- Compare GENIE models for C target
- At higher energy, INCL is larger in $\sigma_{reac}$, smaller in trans!
- at low energy, more divergence in $\sigma_{reac}$
- At first glance $\sigma_{reac}$ more sensitive

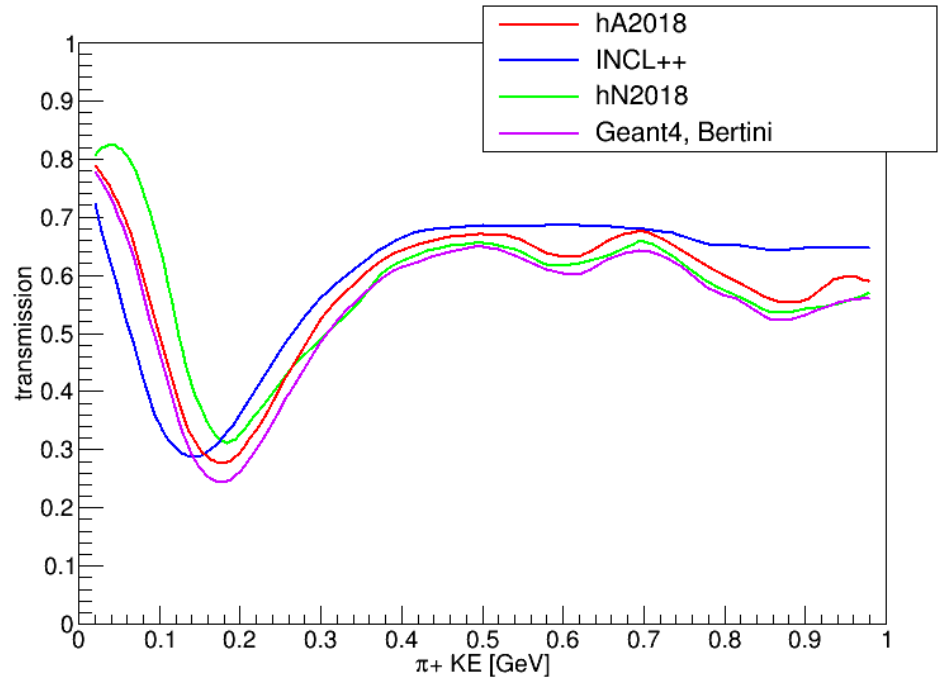


# Transparency - pions

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

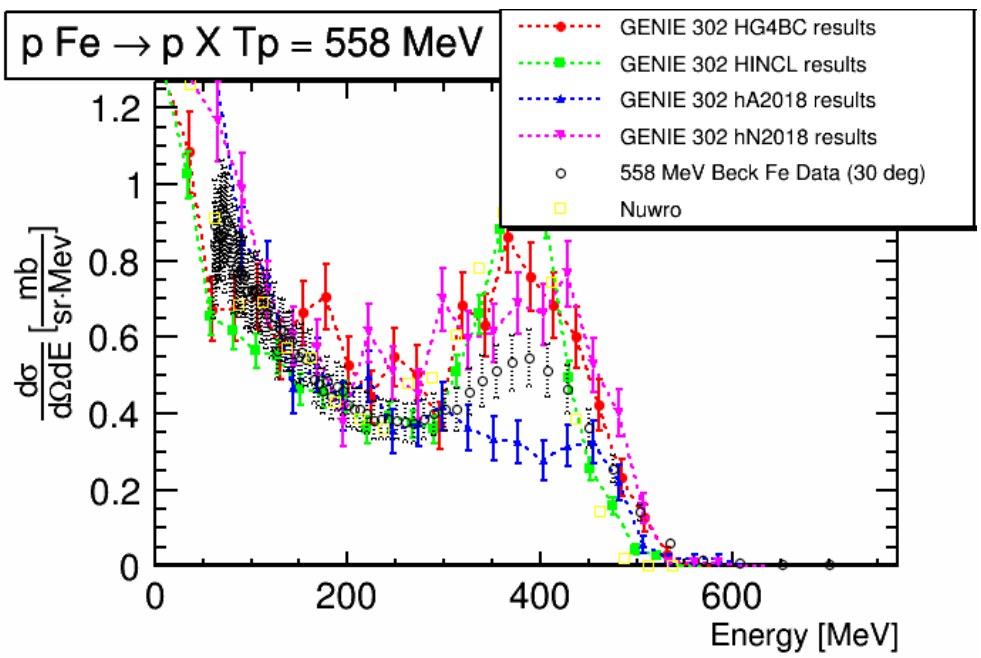


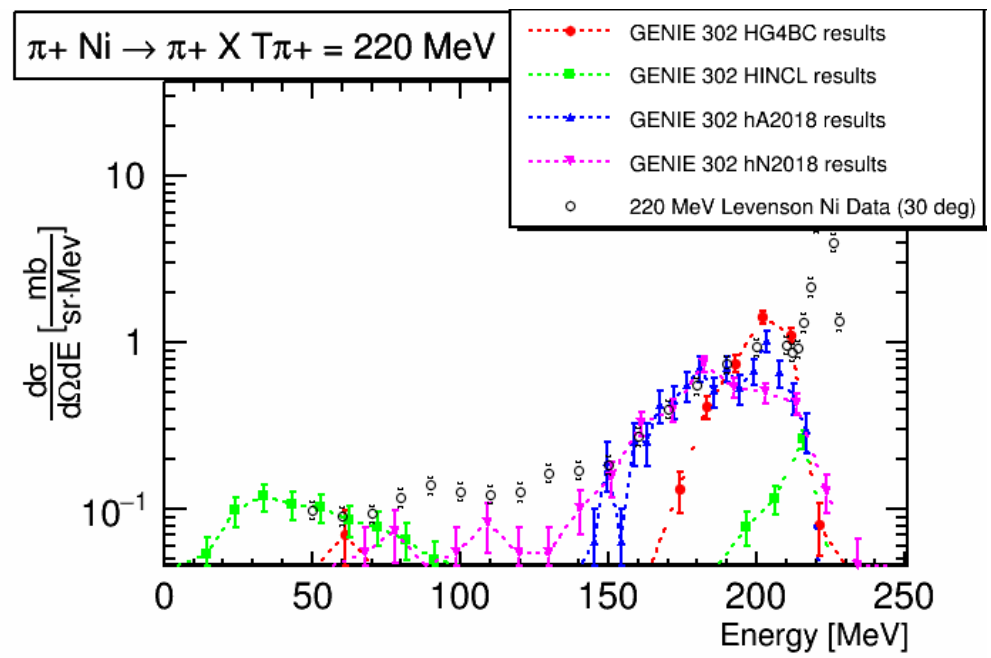



# Comparisons – double differential xs

*much more detail*

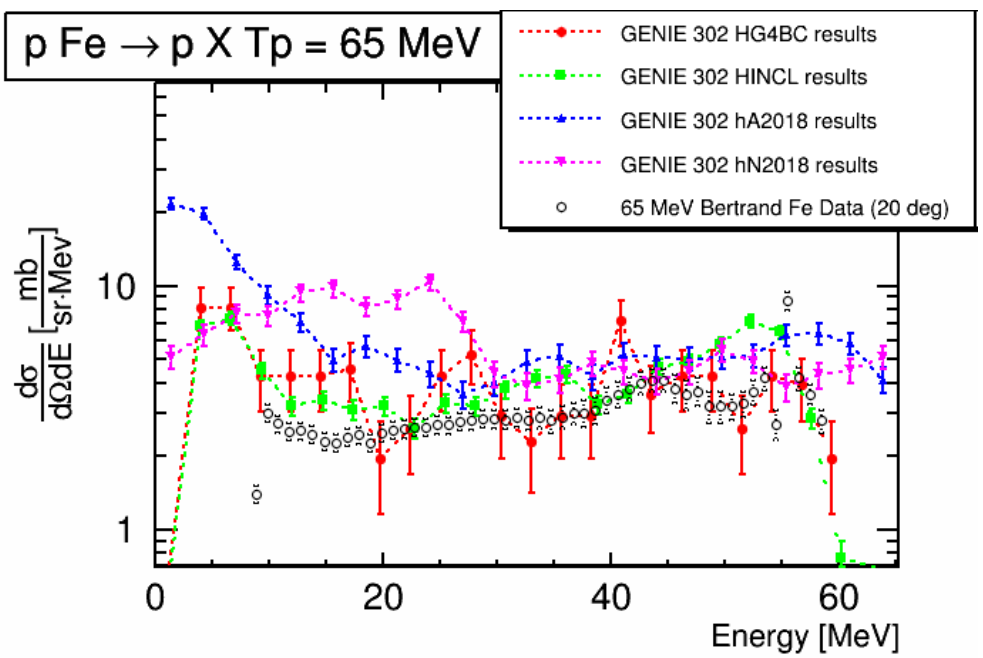
- Energy spectra at each angle, shows mechanisms better
- Compare GENIE with INCL, GEANT
  - pFe → pX (left), $\pi^+$Ni → $\pi^+$X (right)
  - Quasielastic peak is prominent (hN → hN in medium)

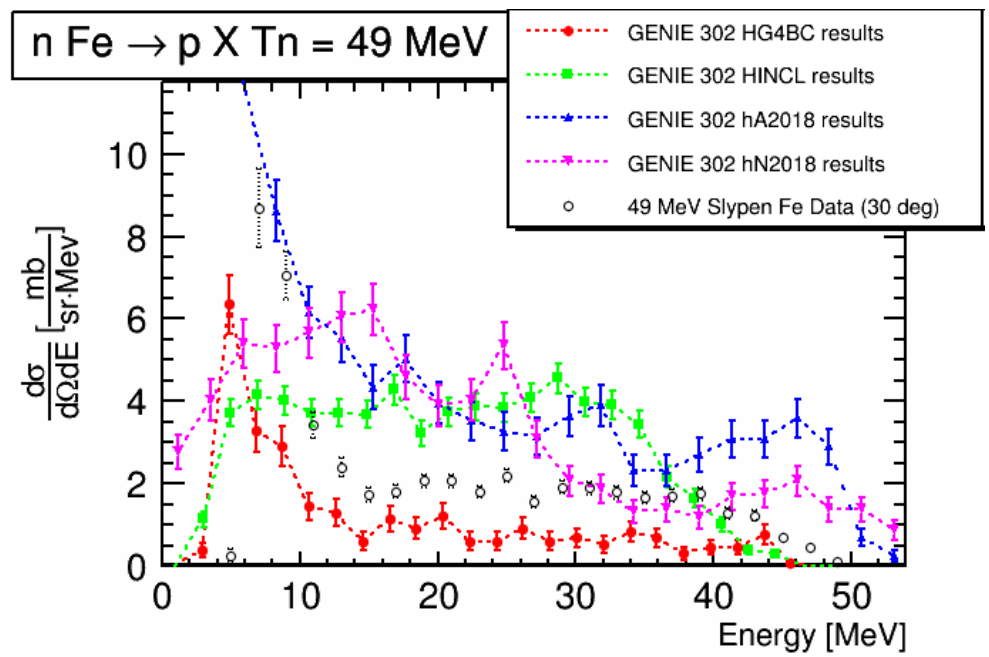


# Comparisons – double differential xs
## *much more detail*

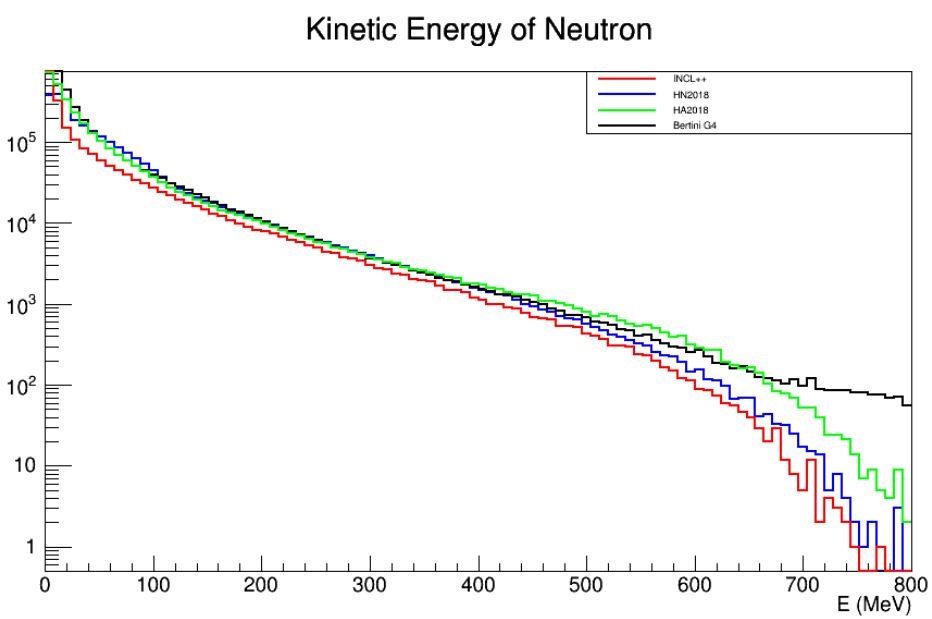
- Compare GENIE hA/hN/INCL/GEANT for pFe→pX, nFe→pX
- Quasielastic peak is gone for low energy
- Magnitudes vary widely, no consistent agreement

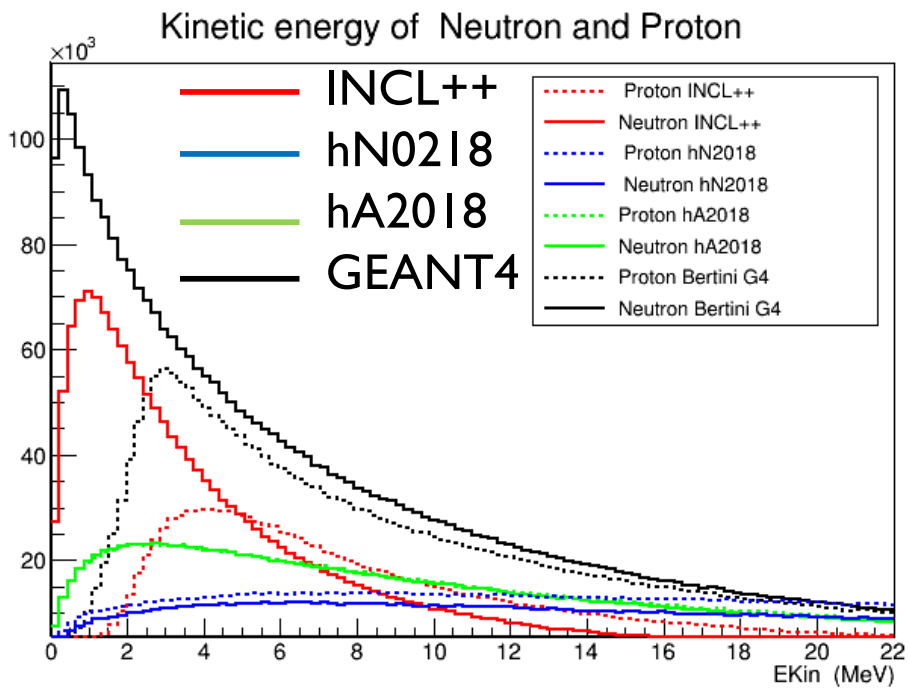


# Comparisons - inclusive hadron production

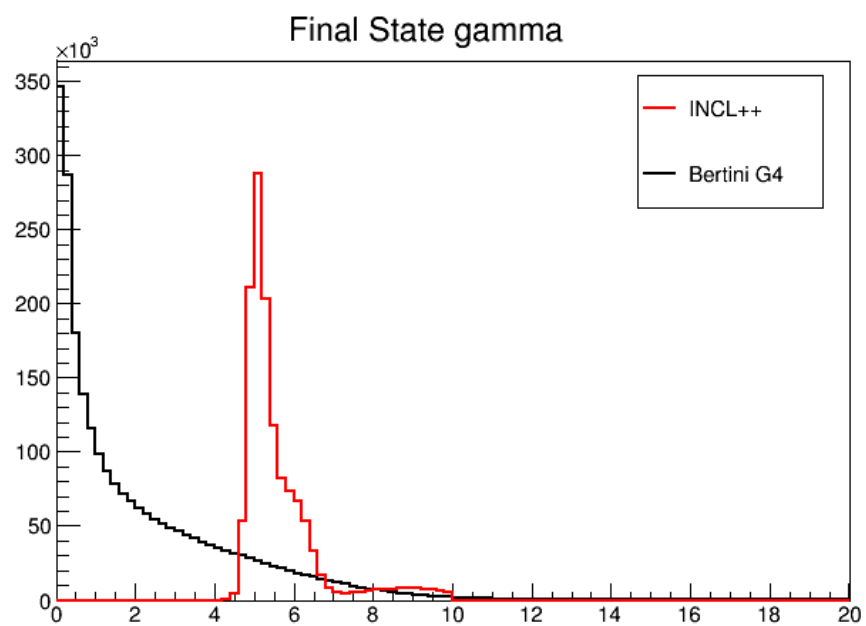
- Inclusive p, n, $\pi$… production with 1 GeV $\nu_\mu$ Ar
- Compare hA, hN with INCL, GEANT Bertini
- p and n spectra are very different at very low energies in INCL but not in GENIE. Right plot has n solid and p dotted
  - Coulomb, barrier affects are primary differences, does it matter?

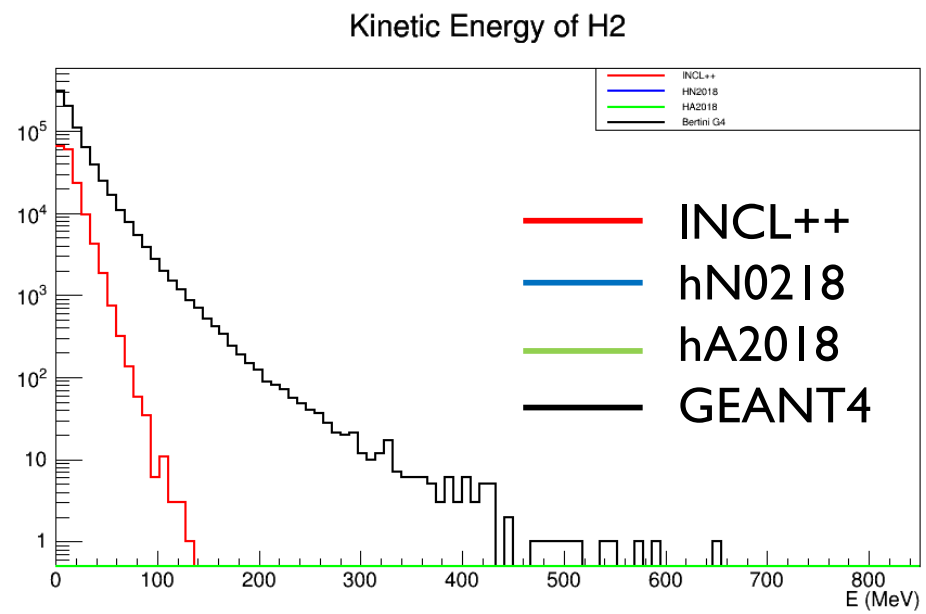


# Comparisons - inclusive hadron prod

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



# Conclusions

- Existing models in GENIE, GEANT, NuWro very similar
  - Only different for $\Delta$ via $\pi$, 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, CLAS
  - $\pi$ abs, kaons, transparency for pions, nucleons
- GENIE plans to add features in hA/hN to match newer models – what do users want?