NA, πA, KA overview

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ProtoDune Meeting

26 January, 2020

- overview
- existing data (www.nndc.bnl.gov)
- suggested goals for new work

- πA interactions was my PhD thesis and I lead all the FSI work in GENIE

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

- 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)
- 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

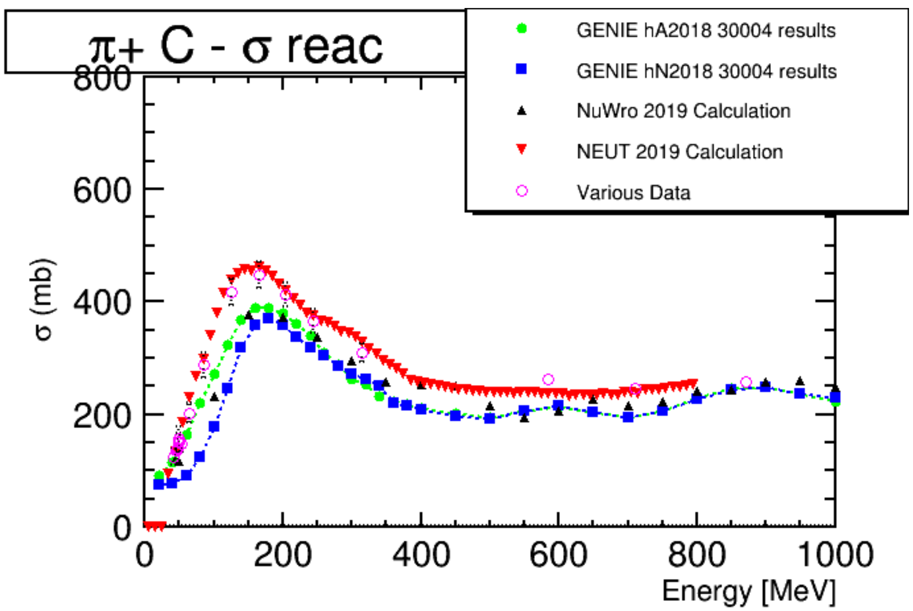
- Empirical
  - GENIE hA (much better agreement with data than expected)
  - True impulse approx. (IA) – nucleon as free – good for KE>~500 MeV
- Semi-empirical
  - Oset πA, Pandharipande/Pieper NN – adds medium corrections
    - Both are in GENIE hN and NuWro
  - NEUT has new πN tuning (Pinzon et al.)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

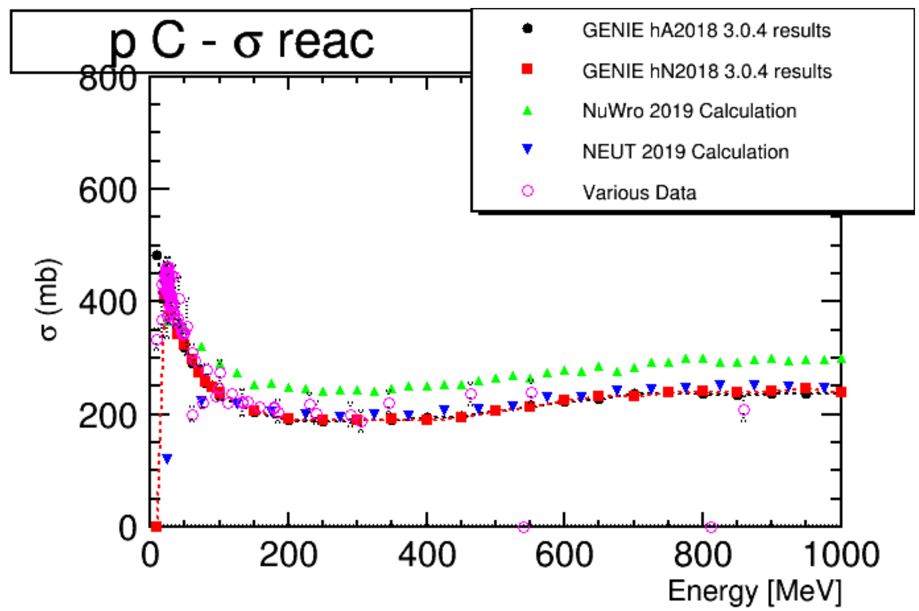
GENIE FSI strategy

- 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)

Most valuable existing data - σ_{reac}

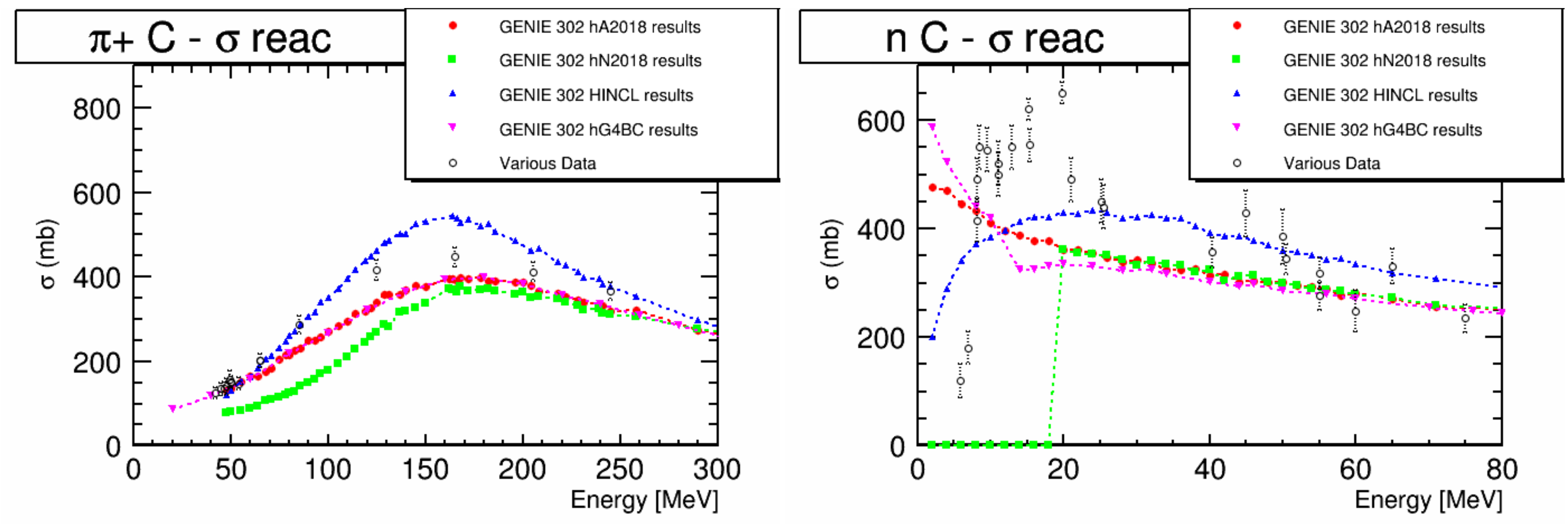
- $\sigma_{reac} = \sigma_{inel} + \sigma_{cex} + \sigma_{abs} + \sigma_{dcex} = \sigma_{tot} - \sigma_{elas}$
- Elastic cross section not in semi-classical models (GEANT?)
- Good data for π^+, p, n (KE>~100 MeV) for C, Fe, and Pb





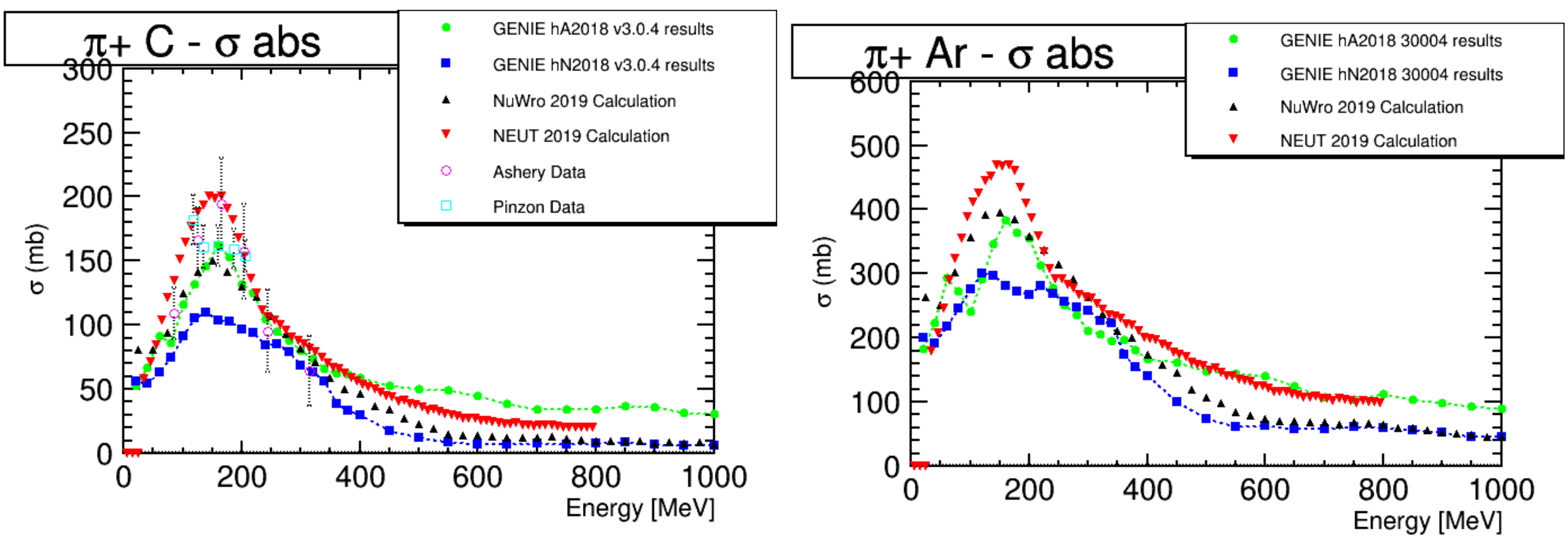
Comparisons – σ_{reac} with INCL/GEANT4

- 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

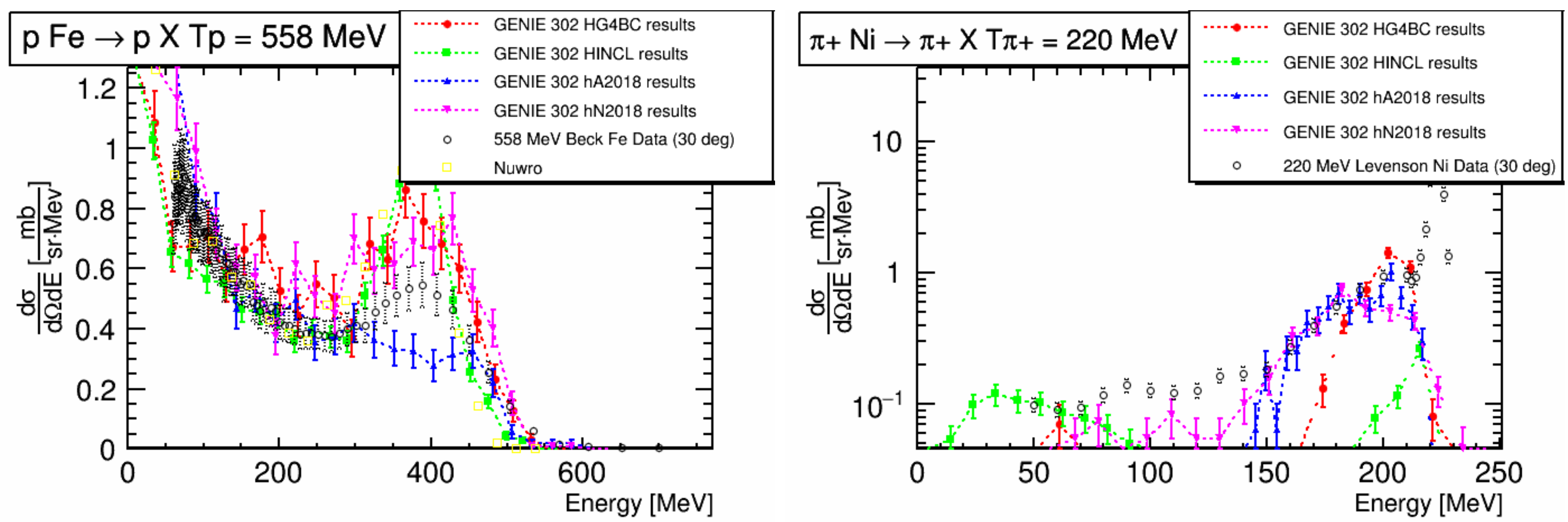
- Much harder to measure – confusion with charge exchange
- NO data for T_π>350 MeV! Huge hole addressed to be in ProtoDUNE?!
- Problems seen even for π^+C (new DUET data included)



Comparisons – double differential xs

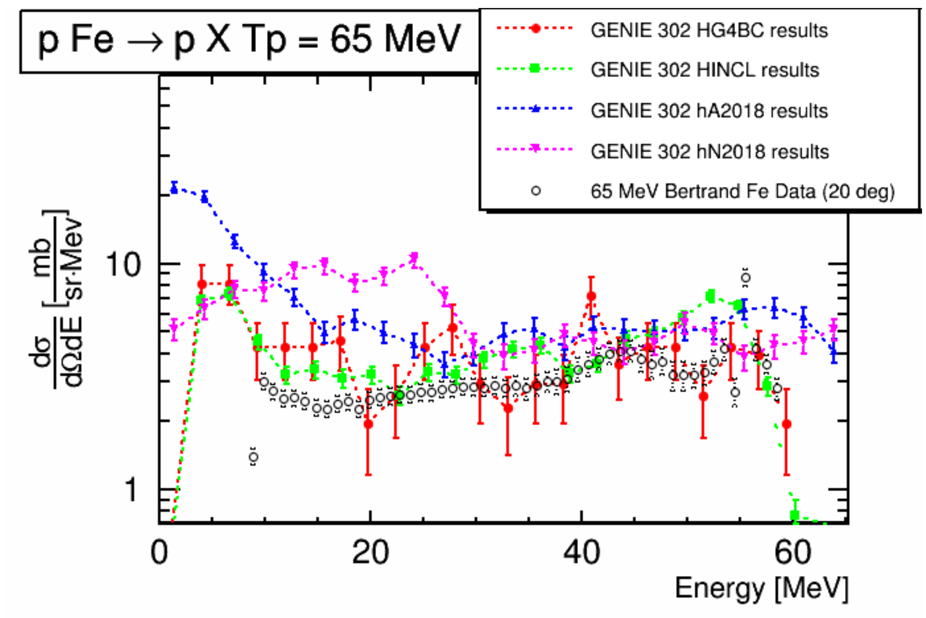
much more detail

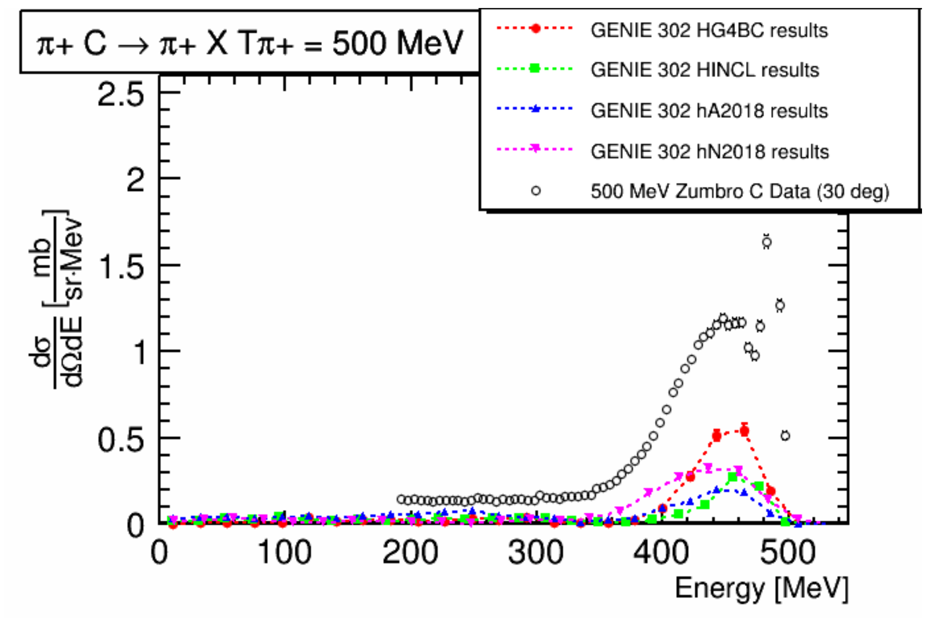
- Energy spectra at each angle, shows mechanisms better
- Compare GENIE with NuWro
  - pFe → pX (left) [Beck], π^+Ni → π^+X (right) [Levenson]
  - Quasielastic peak is prominent (hN → hN in medium)



Comparisons - double differential xs

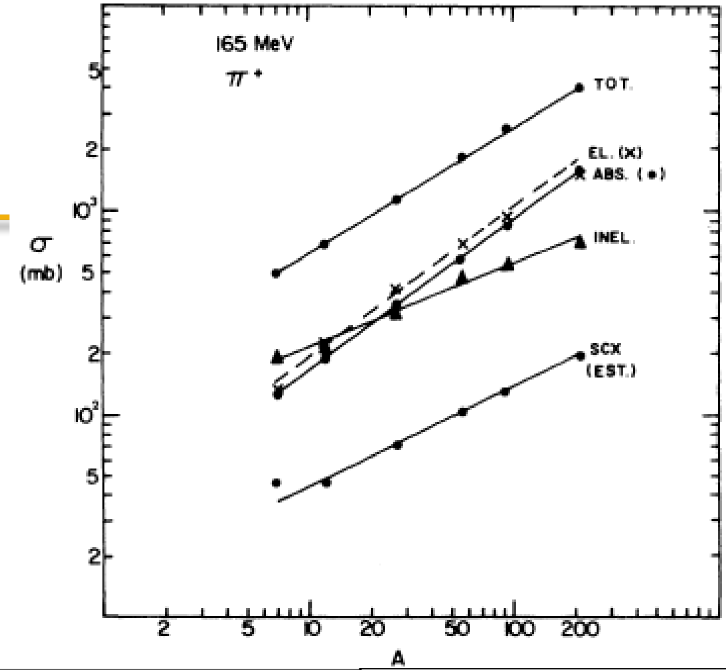
- Compare GENIE hA/hN/INCL/GEANT for p+C->p+X

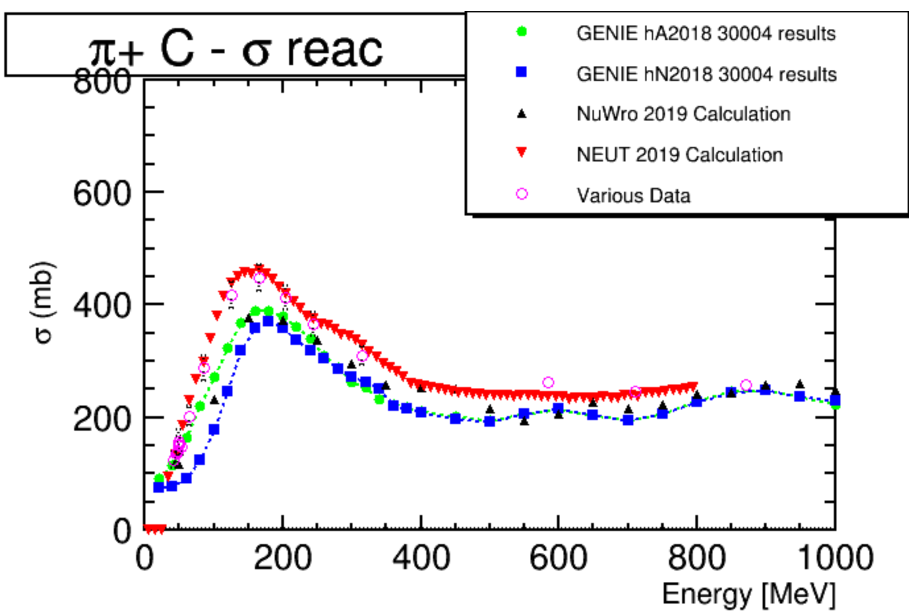


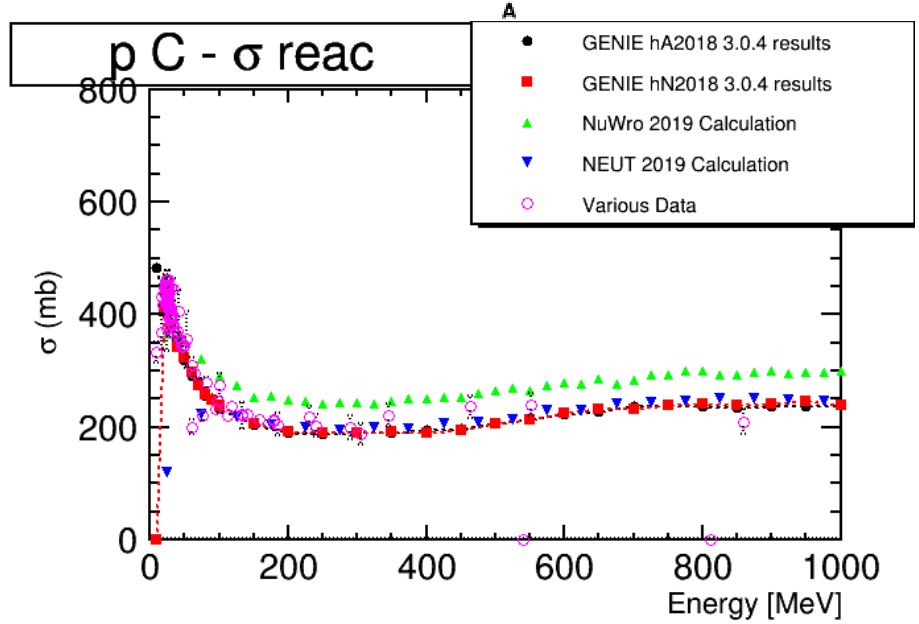


A dependence - σ_{reac}

- All total xs proportional to $A^{\sim 2/3}$(KE>~ 400 MeV, $\sigma_{reac} \sim \pi R^2$)
- Figure from Ashery paper



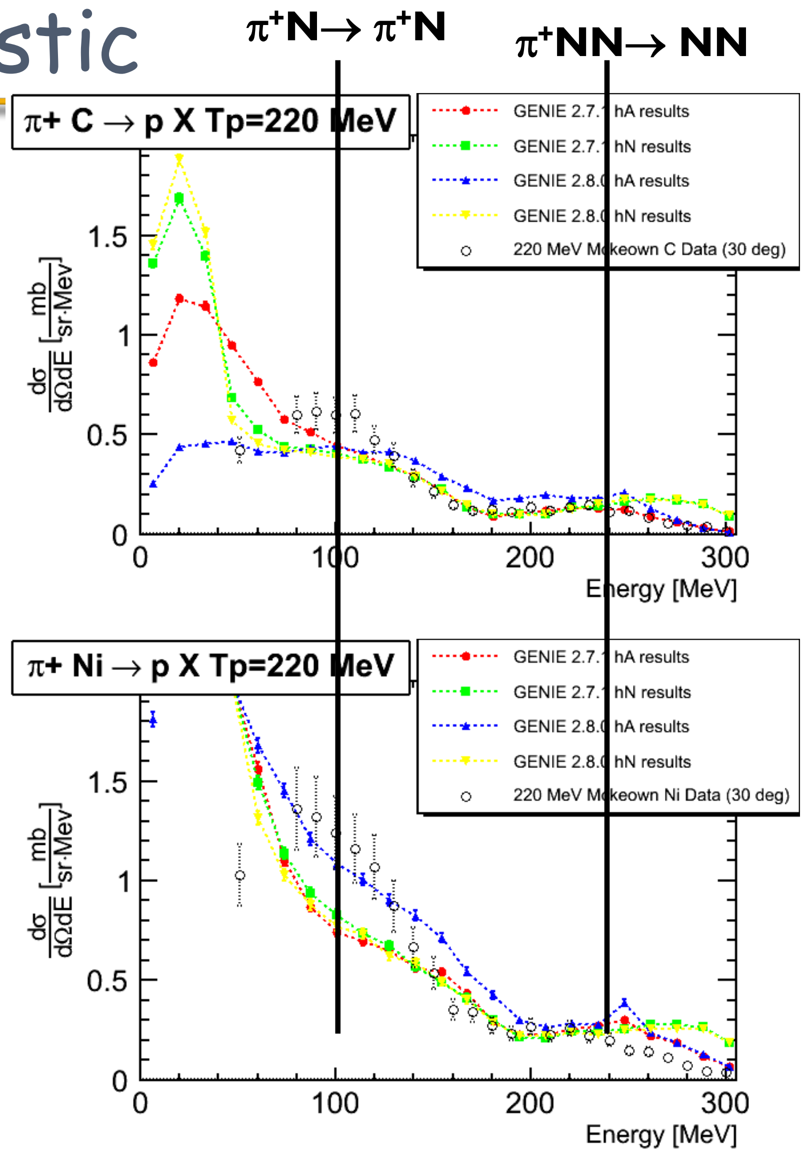




A dependence - quasielastic

- Many inclusive spectra have QE peak

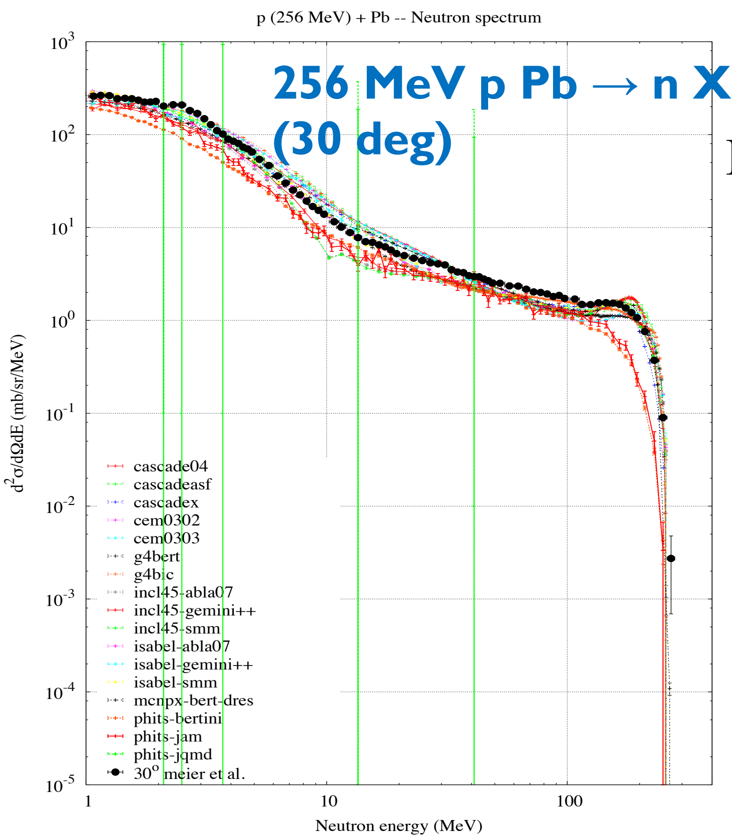
- $\pi^+ N \rightarrow \pi^+ N$ QE scattering in medium (don't see falloff on low energy side)
- $\pi^+ NN \rightarrow NN$: QE absorption in medium
- Peaks shifted and broader because of binding, Fermi motion



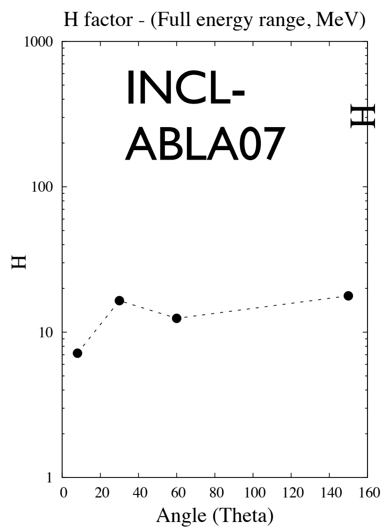
IAEA Benchmark of Spallation Models

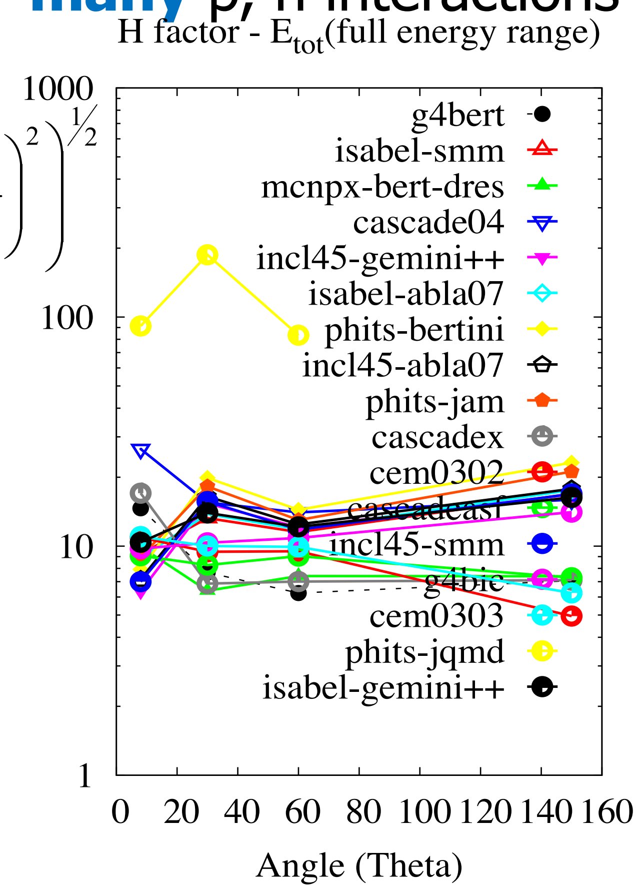
https://www-nds.iaea.org/spallations/

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



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





LADS

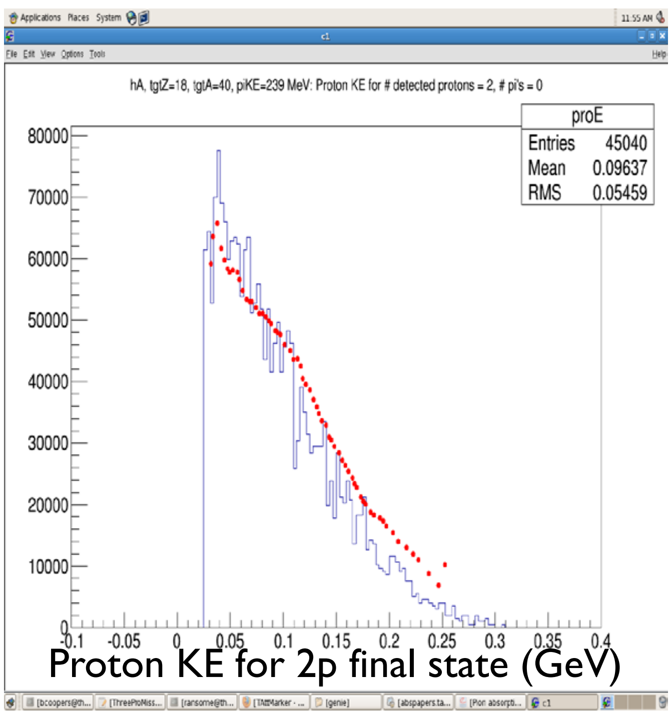
- Advanced π^+ Ar/Xe data studying pion absorption
  - Sketchy publications and no access to data/results (I tried)
  - Table shows accomplishments, challenges in multiplicity meas.
  - threshold effect is critical because yield grows at lower energy
- GENIE hA has smooth mult distr, hN has only 2-body abs

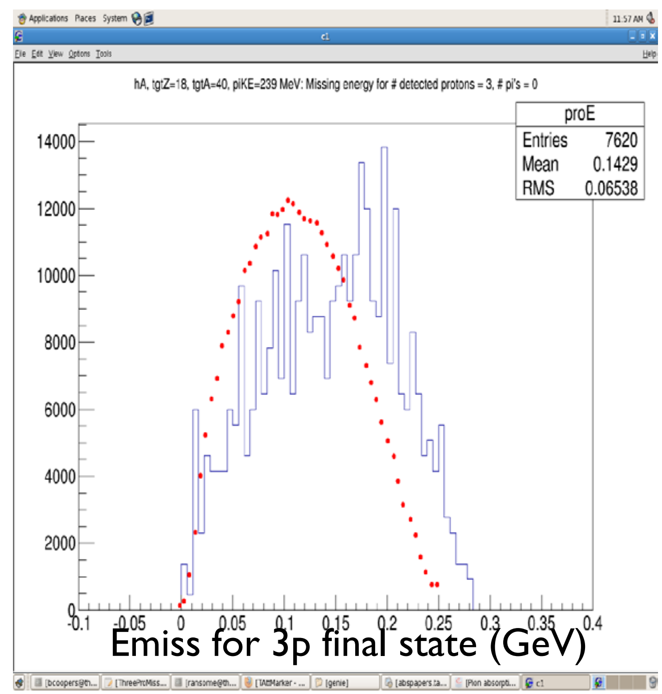
Getting this multiplicity distribution is very difficult, could be a goal of ProtoDune? Is it important?

	Raw Data	30 MeV Threshold	Extrapolated to 0 MeV
5p	0.013 ± 0.001	0.04 ± 0.01	0.64 ± 0.13
4p	1.11 ± 0.10	2.0 ± 0.2	5.1 ± 1.0
3p	19.9 ± 1.2	26.8 ± 2.5	28.4 ± 4.0
3pn	2.0 ± 0.2	11.9 ± 1.3	33.2 ± 7.5
2p	69.8 ± 4.2	72.9 ± 5.8	43.6 ± 5.2
2p1n	11.9 ± 0.9	62.9 ± 6.6	$75. \pm 10.$
2p2n	0.67 ± 0.05	5.6 ± 1.0	$21. \pm 8.$
2pd	9.2 ± 1.0	10.3 ± 1.2	7.9 ± 1.4
pd	14.6 ± 2.3	9.8 ± 1.7	4.2 ± 1.0
pdn	3.0 ± 0.4	13.8 ± 2.4	10.6 ± 2.5

More detailed comparison

- Work done at Rutgers (2014), no followup
  - I suspect it is area normalized
- Is anyone interested in working on this? GENIE reweight?





Summary of existing data

- Lots of good data, some great data
  - σ_{reac}, inclusive data, LADS
- Goals back then (as I remember)
  - nuclear structure (NN) through DCEX – poor
  - Re-examine low-lying excited states – Gamov-Teller isospin excitations
  - nature of absorption, e.g. 2-body vs. 3-body - moderate
  - Deltas in nuclei – moderate (should go into generators!)
  - reaction mechanism – moderate
- Even repeating old data has value
- Biggest holes
  - Pion absorption
  - Details of pA, especially at KE<~100 MeV
  - Any kaon cross section

Thoughts about ProtoDune measurements - π

- Repeating previous data (e.g. DUET) has value
  - LADS data hard to interpret
- Pion absorption still poorly understood
  - Inclusive data – proton KE, angle (neutrons?)
  - Correlation among protons
  - Missing energy when full final state detected
  - Careful multiplicity measurement

Thoughts about ProtoDune measurements - p

- Extension of previous data is easy
- Proton-nucleus response still poorly understood
  - Inclusive data – proton KE, angle (neutrons?)
  - Missing energy when full final state detected
  - Careful multiplicity measurement
  - No existing calculation gets it right

Conclusions

- Existing models in GENIE, GEANT, NuWro very similar
  - Only different for Δ π, low energy nucleons
- Understanding of πA and pA data definitely incomplete in previous era
  - Models like INCL++ have improved understanding
- Definitely room for new data – ProtoDUNE can contribute significantly
  - π abs, kaons, nucleon spallation
  - Good statistics, full error treatment will be important
  - Challenge- show me how GENIE is wrong and help me fix it!