INCL++/GEANT implementation

Steve Dytman, Univ. of Pittsburgh
Marc Vololoniaina, Univ. of Antananarivo
Robert Hatcher, FNAL

GENIE review

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- alternate FSI models, new physics
- Large libraries sometimes needed
- Better physics for low energy experiments
- interesting tests vs. GEANT in detector

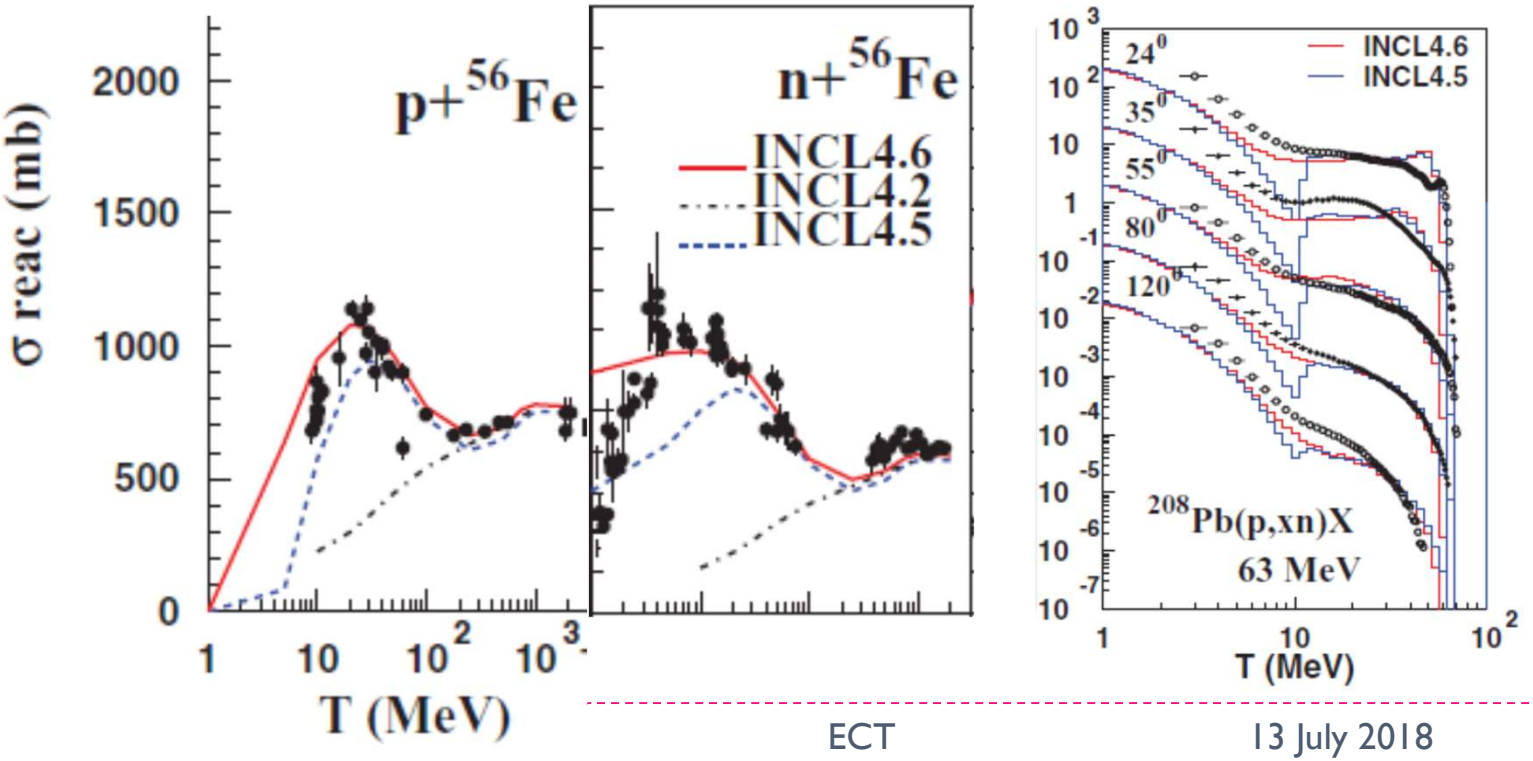
references

- A. Boudard, J.Cugnon, J.C. David, S. Leray, **D. Mancusi** – Phys. Rev. C87, 01606 (2006)
- J. Cugnon, … Eur. Phys. J. Plus 131:169 (2016)
- A. Kelic, M. Ricciardi, and K.-H. Schmitz, arXiv 0906.4193
- **D. Wright** and M. Kelsey, NIM A 804, 175 (2015)
- H.W. Bertini, Phys Rev 131, 1801 (1963)

- Dennis Wright did initial work to get GEANT into GENIE, Robert H. and Marc V. did final work.
- Marc V. and I did physics work for INCL++ in communication with D. Mancusi, Robert did build framework.

INCL++ intro

- Work of group in France & Belgium to describe hadronic interactions with emphasis on low energies, use v5.2.9.5
- INCL++ uses C++, easier to interface to GENIE
- Same final states as we have, also emission of γ, ^{2}H, ^{4}He…



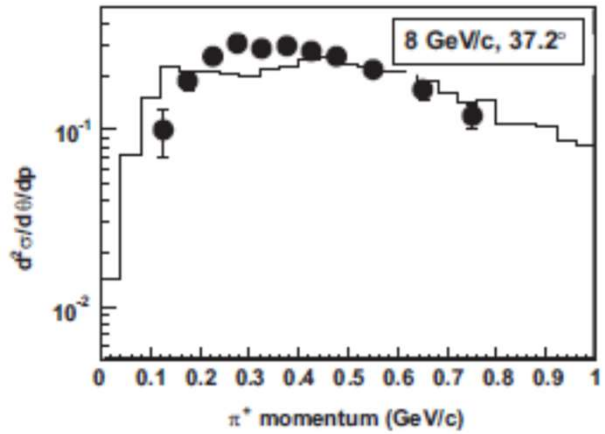
A little detail

- INCL++ is a cascade code at higher energies, mean free path is large and results are similar to what we get
- Nuclear structure comes from ~local Fermi gas, but all nucleons are moving and in a binding potential (RMF)
- Degrees of freedom are nucleons, pions, and Δ's
- Cascade is in time/distance
- This stops at a time ~40fm/c=1.3 x 10^{-22} s
- ABLA takes over, does evaporation (low energy n, p, γ, and α) and clusterization (2H…) over a longer time
- γ emission is statistical in energy, less detail than Marley

GEANT4 intro

- Not much to say, GEANT is black box to me
- Modified version of old model of Bertini
  - Cascade at high energy, compound nucleus at low energy
  - Clusterization (coalescence) of p, n into d, t, 3He, α...
- Designed for production targets, detectors
  - Many changes in recent years to improve 'low energies' (KE<1 GeV)
  - Not an INC the way we think of in GENIE, NuWro... (always an interaction)

HARP thin target data for 8 GeV/c $pC \rightarrow \pi + X$



implementation

- Robert established conditional configuration so that user decides if INCL++ or GEANT4 libraries are linked in
- Cascade starts at ν vertex
- Take particles from GENIE, insert them into INCL++ (or GEANT4), and translate output into GENIE language
  - Can be standardized for any other FSI code
  - Of course, normal GENIE mother-daughter is not possible
  - Loop through all GENIE IST=14 particles
- INCL++ normally works similar to gevgen_hadron
- GEANT is different, chooses a nucleus then forces interaction.
  - Marc starts GEANT after normal hA/hN stepping (Dennis agreed)

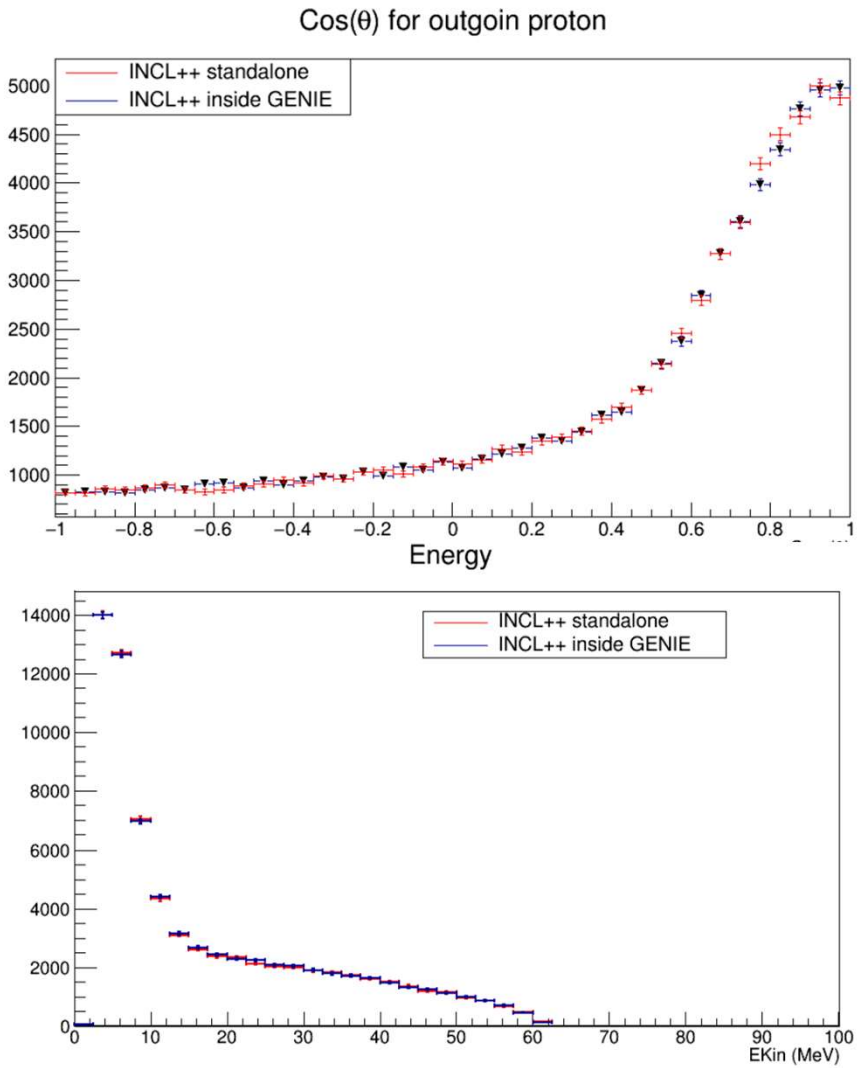
Interface in GENIE

- INCL has its own configuration via cmake
  - HINCLCascadeIntranuke.xml is backup
  - ABLA07 is default, but allow SMM, Gemini
- Caller methods work through EventRecordVisitorI
  - HINCLCascadeIntranuke.cxx, .h mirrors HAIntranuke2018.cxx, .h
  - HG4BertCascIntranuke.cxx, .h
- Each are callable in gevgen and gevgen_hadron
  - E.g. gevgen_hadron –m GINCL or –m HGBertCasc
  - Need a tune for gevgen, use G18_02a for now
- For gevgen,

```
void INCLcascade::ProcessEventRecord(GHepRecord * evrec) const{
fGMode = evrec->EventGenerationMode();
```

Validation in standalone mode

- Compare GENIE gevgen_hadron output against INCL++ results from D. Mancusi for 62 MeV pFe
- Excellent agreement



Event printout - INCL++

```
1572965573 NOTICE gevgen : [n] <gEvGen.cxx::GenerateEventsAtFixedInitState (321)> : Generated Event GHEP Record:

|-----------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                       |
|-----------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |      m  |
|-----------------------------------------------------------------------------------------------------------------|
|   0 |         nu_mu |   0 |         14 |  -1 |  -1 |   4 |   4 |   0.000 |   0.000 |   2.000 |   2.000 |   0.000 |
|   1 |          Ar40 |   0 | 1000180400 |  -1 |  -1 |   2 |   3 |   0.000 |   0.000 |   0.000 |  37.216 |  37.216 |
|   2 |       neutron |  11 |       2112 |   1 |  -1 |   5 |   5 |  -0.054 |  -0.115 |  -0.164 |   0.929 | **0.940 | M = 0.906
|   3 |          Ar39 |   2 | 1000180390 |   1 |  -1 |  -1 |  -1 |   0.054 |   0.115 |   0.164 |  36.286 |  36.286 |
|   4 |           mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |  -0.485 |   0.303 |   0.614 |   0.846 |   0.106 | P = (0.578,-0.361,-0.732)
|   5 |      N+(1535) |   3 |      22212 |   2 |  -1 |   6 |   7 |   0.431 |  -0.418 |   1.222 |   2.083 | **1.535 | M = 1.577
|   6 |           pi0 |  14 |        111 |   5 |  -1 |   8 |  11 |   0.198 |  -0.650 |   0.493 |   0.850 |   0.135 |
|   7 |        proton |  14 |       2212 |   5 |  -1 |  12 |  19 |   0.233 |   0.232 |   0.729 |   1.233 |   0.938 |
|   8 |           pi0 |   1 |        111 |   6 |   3 |  -1 |  -1 |   0.242 |   0.038 |   0.446 |   0.527 |   0.135 |
|   9 |        proton |   1 |       2212 |   6 |   3 |  -1 |  -1 |   0.023 |  -0.197 |   0.454 |   1.061 |   0.938 |
|  10 |       neutron |   1 |       2112 |   6 |   3 |  -1 |  -1 |   0.111 |  -0.240 |   0.110 |   0.982 |   0.940 |
|  11 |       neutron |   1 |       2112 |   6 |   3 |  -1 |  -1 |  -0.140 |  -0.211 |  -0.120 |   0.980 |   0.940 |
|  12 |        proton |   1 |       2212 |   7 |   3 |  -1 |  -1 |   0.377 |   0.418 |   0.122 |   1.101 |   0.938 |
|  13 |       neutron |   1 |       2112 |   7 |   3 |  -1 |  -1 |  -0.134 |  -0.148 |   0.453 |   1.062 |   0.940 |
|  14 |       neutron |   1 |       2112 |   7 |   3 |  -1 |  -1 |  -0.188 |   0.064 |  -0.024 |   0.961 |   0.940 |
|  15 |        proton |   1 |       2212 |   7 |   3 |  -1 |  -1 |  -0.083 |   0.045 |   0.111 |   0.950 |   0.938 |
|  16 |       neutron |   1 |       2112 |   7 |   3 |  -1 |  -1 |  -0.032 |   0.021 |  -0.029 |   0.941 |   0.940 |
|  17 |           He4 |   1 | 1000020040 |   7 |   3 |  -1 |  -1 |   0.174 |  -0.239 |   0.139 |   3.742 |   3.727 |
|  18 |         gamma |   1 |         22 |   7 |   3 |  -1 |  -1 |   0.003 |   0.004 |  -0.004 |   0.007 |   0.000 |
|  19 |          Si28 |   1 | 1000140280 |   7 |   3 |  -1 |  -1 |   0.130 |   0.141 |  -0.272 |  26.055 |  26.053 |
|-----------------------------------------------------------------------------------------------------------------|
|      Fin-Init:                                                 |  -0.003 |   0.001 |   0.001 |  -0.002 |         |
|-----------------------------------------------------------------------------------------------------------------|
|      Vertex:          nu_mu @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =    0.000000e+00 s)  |
|-----------------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                                    none |
| Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:    NO |   Accepted:   YES                        |
|-----------------------------------------------------------------------------------------------------------------|
| sig(Ev) =       3.44883e-38 cm^2  | d2sig(W,Q2;E)/dWdQ2 =     6.23178e-38 cm^2/GeV^3 | Weight =          1.00000 |
|-----------------------------------------------------------------------------------------------------------------|

 nari@Natsu:~/PHD/an...   gevgen_Nu_mu_Ar40....   ~/LocInstall/HEP/GENI...   ~/LocInstall/HEP/GENI...
```

Event printout – GEANT4

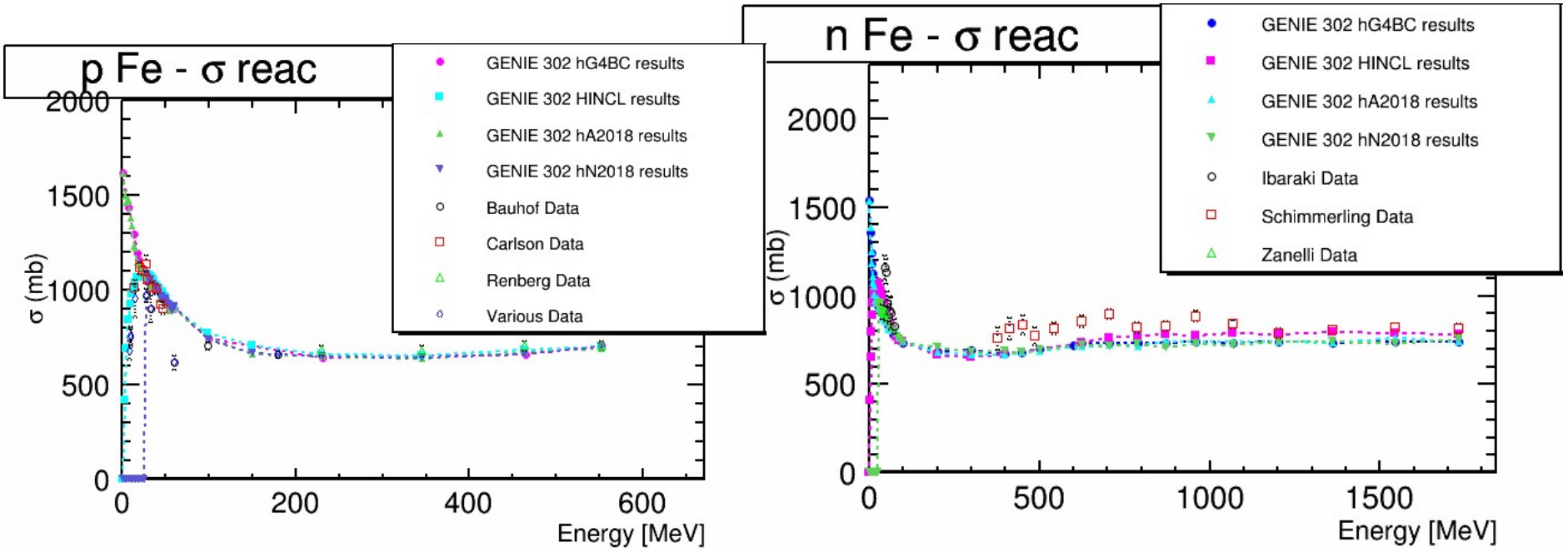
```
1572979439 NOTICE gevdump : [n] <gEvDump.cxx::main (177)> :  ** Event: 84

GENIE GHEP Event Record [print level:   3]
 Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |      m  |
   0 |         nu_mu |   0 |         14 |  -1 |  -1 |   5 |   5 |   0.000 |   0.000 |   2.000 |   2.000 |   0.000 |
   1 |          Ar40 |   0 | 1000180400 |  -1 |  -1 |   2 |   4 |   0.000 |   0.000 |   0.000 |  37.216 |  37.216 |
   2 |       neutron |  11 |       2112 |   1 |  -1 |   6 |   6 |   0.052 |   0.151 |  -0.175 |   0.929 | **0.940 | M = 0.898
   3 |          Ar39 |   2 | 1000180390 |   1 |  -1 |   9 |  19 |  -0.052 |  -0.151 |   0.175 |  36.287 |  36.286 |
   4 |           S32 |   1 | 1000160320 |   1 |  -1 |  -1 |  -1 |   0.006 |   0.143 |   0.146 |  29.774 |  29.774 |
   5 |         nu_mu |   1 |         14 |   0 |  -1 |  -1 |  -1 |  -0.152 |  -0.591 |   1.194 |   1.341 |   0.000 | P = (0.114,0.441,-0.890)
   6 |        Delta0 |   3 |       2114 |   2 |  -1 |   7 |   8 |   0.204 |   0.742 |   0.631 |   1.588 | **1.233 | M = 1.237
   7 |       neutron |  14 |       2112 |   6 |  -1 |  -1 |  -1 |   0.037 |   0.404 |   0.600 |   1.186 |   0.940 |
   8 |           pi0 |  14 |        111 |   6 |  -1 |  -1 |  -1 |   0.167 |   0.339 |   0.032 |   0.402 |   0.135 |
   9 |       neutron |   1 |       2112 |   3 |  -1 |  -1 |  -1 |   0.039 |   0.358 |   0.544 |   1.144 |   0.940 |
  10 |           pi0 |   1 |        111 |   3 |  -1 |  -1 |  -1 |  -0.118 |   0.096 |   0.142 |   0.248 |   0.135 |
  11 |       neutron |   1 |       2112 |   3 |  -1 |  -1 |  -1 |   0.189 |   0.039 |  -0.238 |   0.988 |   0.940 |
  12 |       neutron |   1 |       2112 |   3 |  -1 |  -1 |  -1 |  -0.013 |  -0.048 |   0.172 |   0.956 |   0.940 |
  13 |        proton |   1 |       2212 |   3 |  -1 |  -1 |  -1 |  -0.179 |  -0.047 |   0.031 |   0.957 |   0.938 |
  14 |       neutron |   1 |       2112 |   3 |  -1 |  -1 |  -1 |   0.182 |  -0.111 |  -0.011 |   0.963 |   0.940 |
  15 |       neutron |   1 |       2112 |   3 |  -1 |  -1 |  -1 |   0.016 |  -0.003 |  -0.103 |   0.945 |   0.940 |
  16 |        proton |   1 |       2212 |   3 |  -1 |  -1 |  -1 |  -0.048 |   0.083 |   0.066 |   0.945 |   0.938 |
  17 |       neutron |   1 |       2112 |   3 |  -1 |  -1 |  -1 |   0.078 |   0.080 |   0.054 |   0.948 |   0.940 |
  18 |         gamma |   1 |         22 |   3 |  -1 |  -1 |  -1 |   0.001 |   0.002 |   0.004 |   0.005 |   0.000 |
  19 |         gamma |   1 |         22 |   3 |  -1 |  -1 |  -1 |   0.000 |   0.000 |  -0.000 |   0.000 |   0.000 |
       Fin-Init:                                          |  -0.000 |  -0.000 |  -0.000 |  -0.000 |         |
       Vertex:          nu_mu @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =    0.000000e+00 s)  |
 Err flag [bits:15->0] : 0000000000000000    |  1st set:                                                        none |
 Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:    NO |   Accepted:   YES                                |
 sig(Ev) =       4.06673e-38 cm^2  | d2sig(W,Q2;E)/dWdQ2 =     1.62566e-37 cm^2/GeV^3 | Weight =          1.00000 |

GENIE Interaction Summary
```

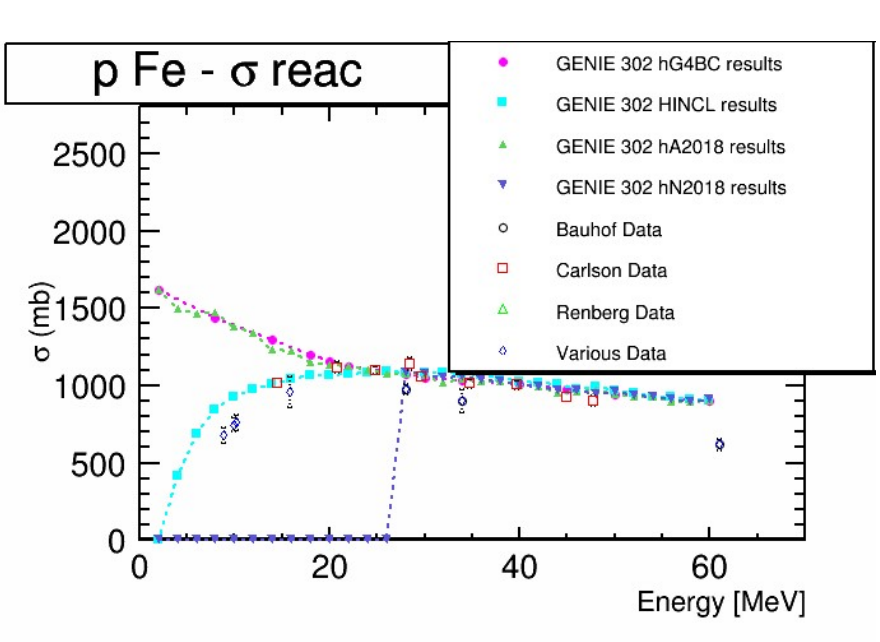
Total reaction cross sections – p, n

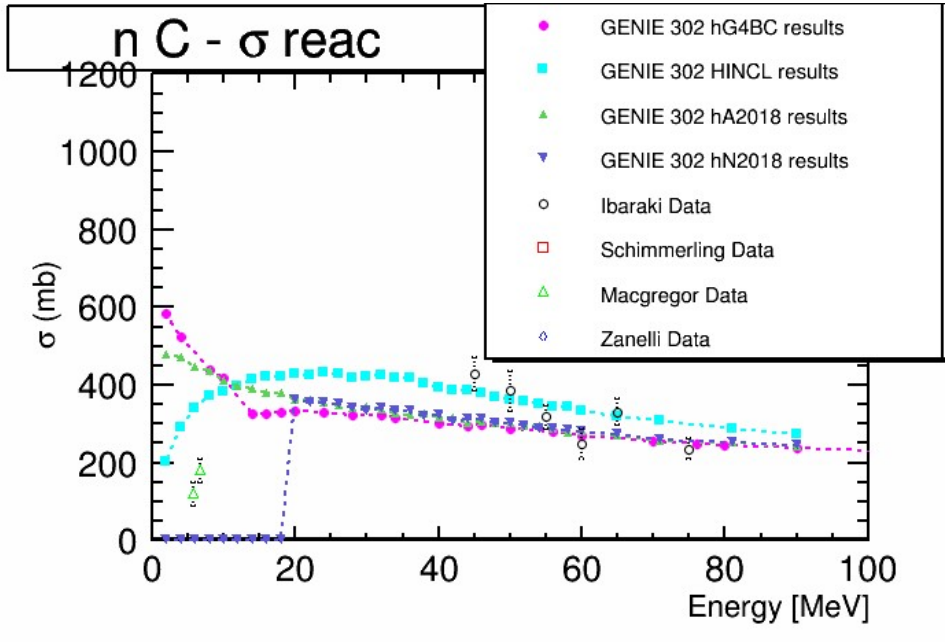
- p and n are very similar for KE>100 MeV ($\sigma \sim \pi R^2$)
  - All models very similar for KE>40 MeV
- Significant divergence at lower energies



Total reaction cross sections – p, n

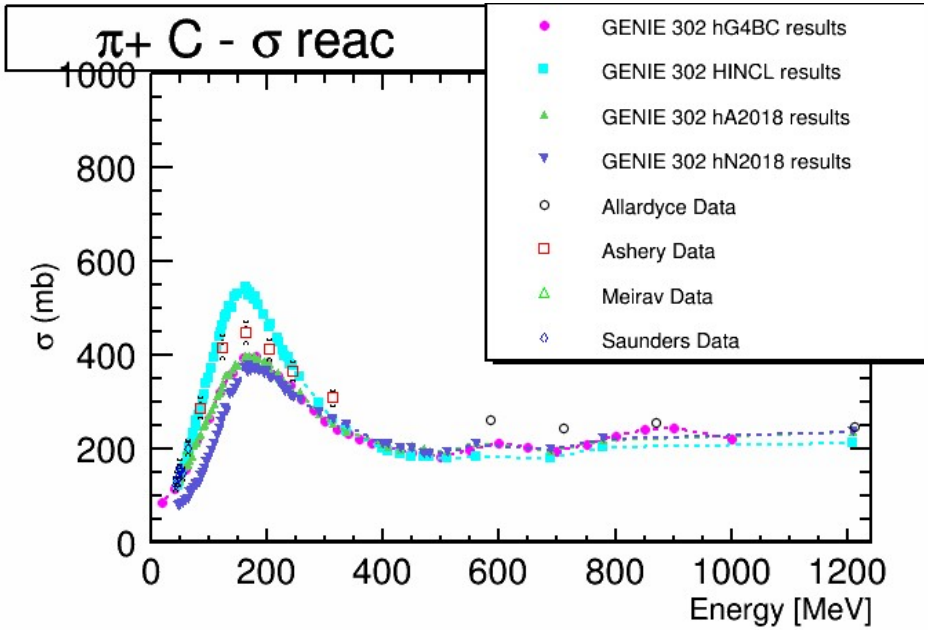
- Significant divergence at lower energies
  - Cutoff in hN to avoid troubles at low energy, still get low KE N
  - GEANT same as hA2018 because same stepping used
  - INCL has best fit to data

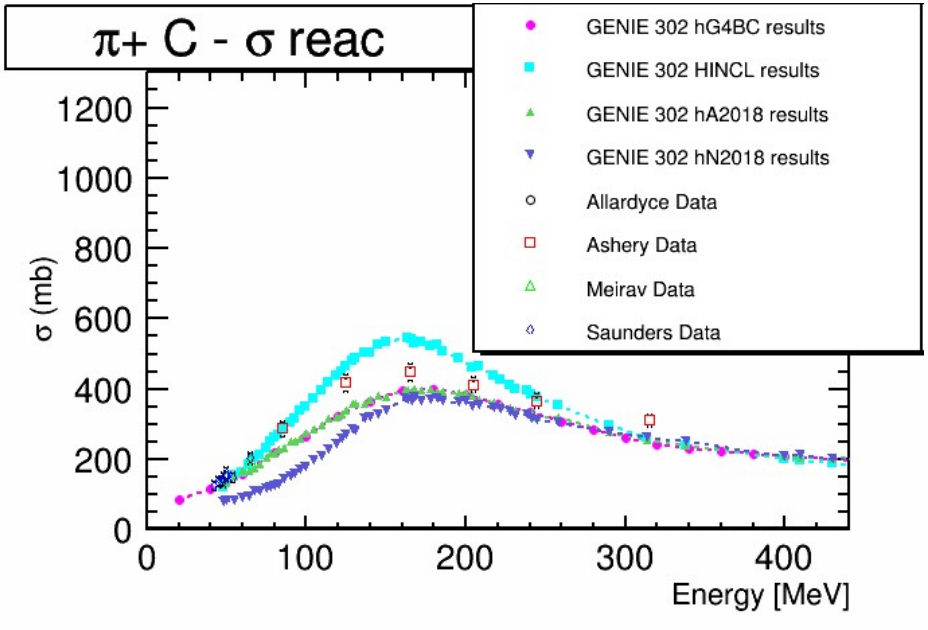




Total reaction xs – pion+carbon

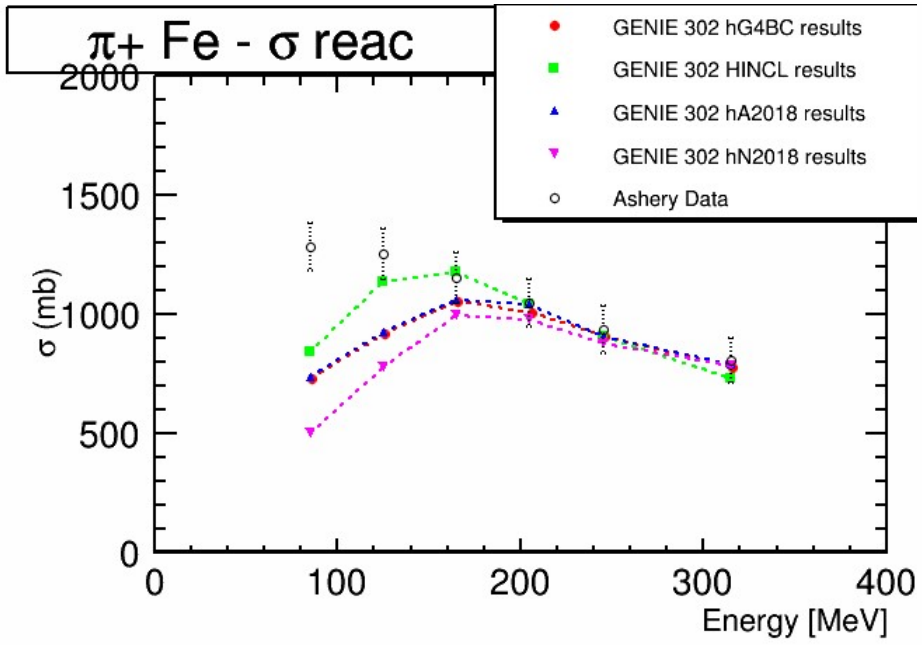
- lots of data for pions
- hN, hA, GEANT all a little low at Δ peak, otherwise ok

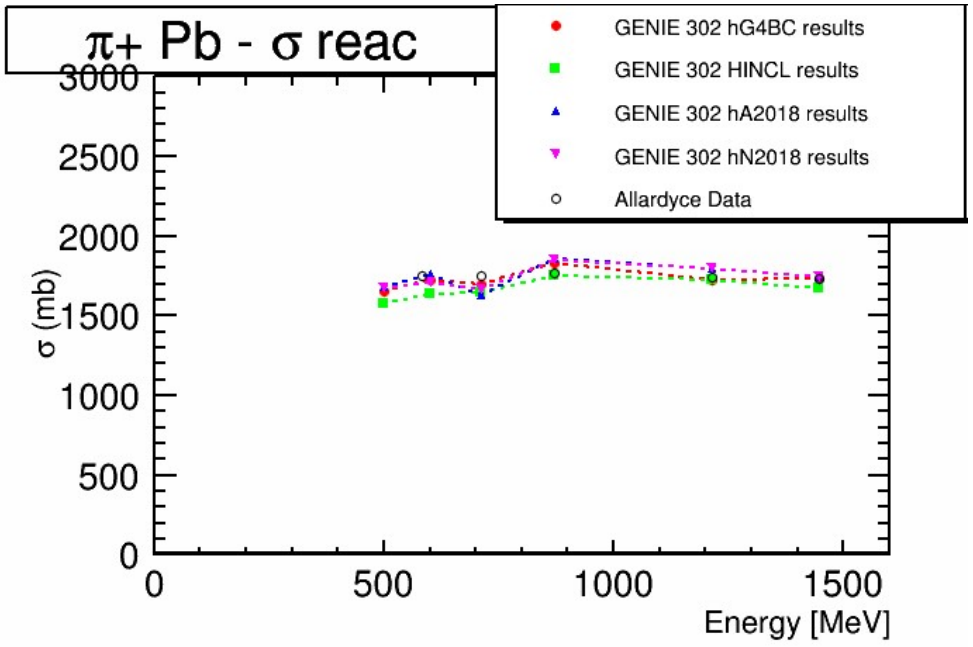




Total reac xs – pions - high A

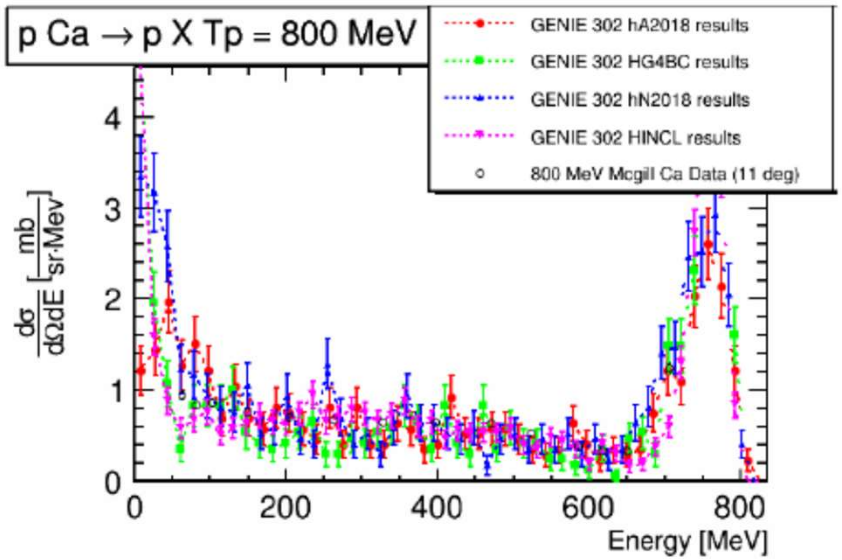
- Low energy data for Fe, higher energy data for Pb
- Historical problem for π^+ Fe a problem for all models, inconsistent with other nuclei

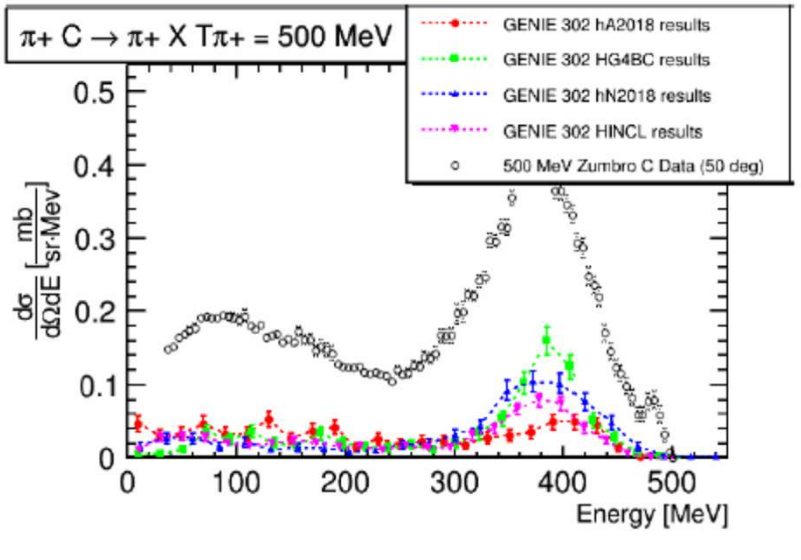




Higher probe energies

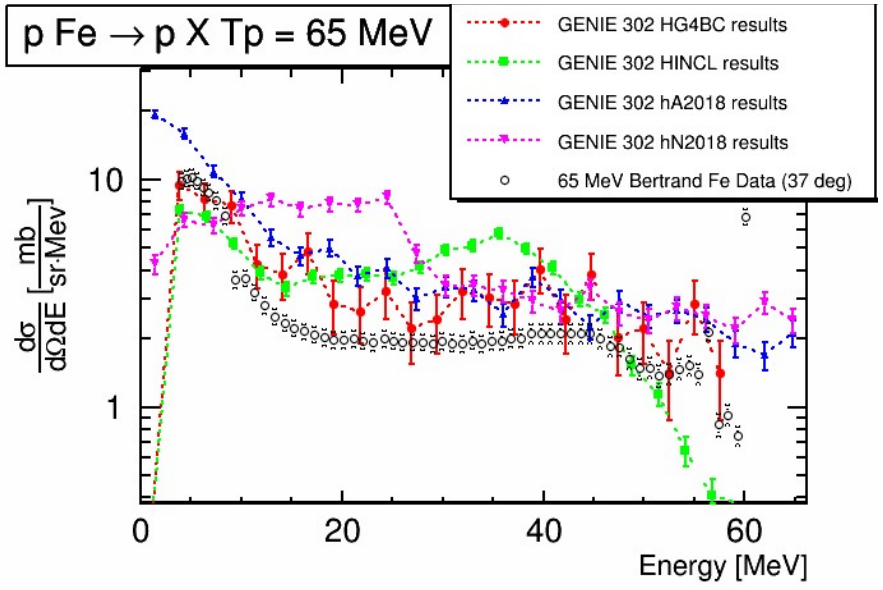
- Good agreement between hA, hN, INCL, and GEANT
- Always suspected 500 MeV pion data is wrong, now sure
- Many other comparisons with similar results

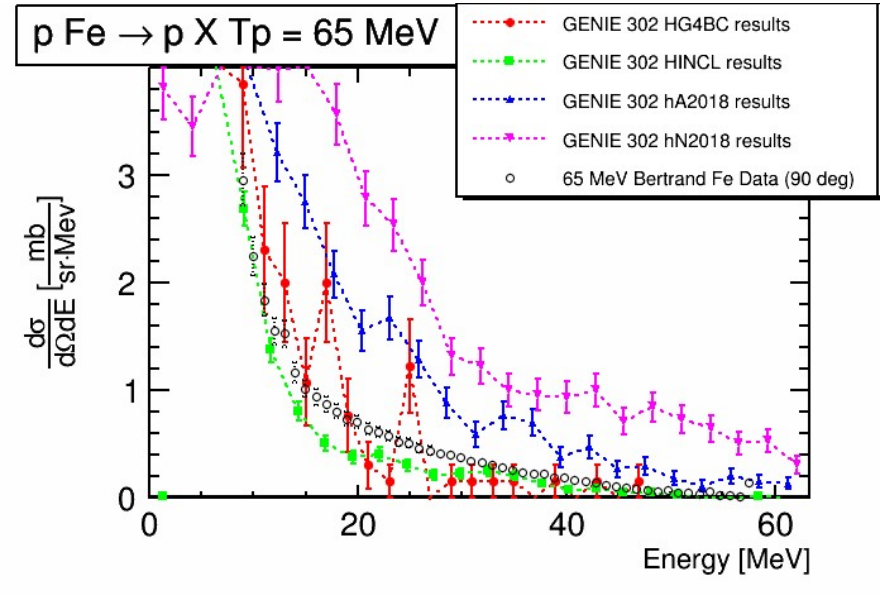




Lower probe energies

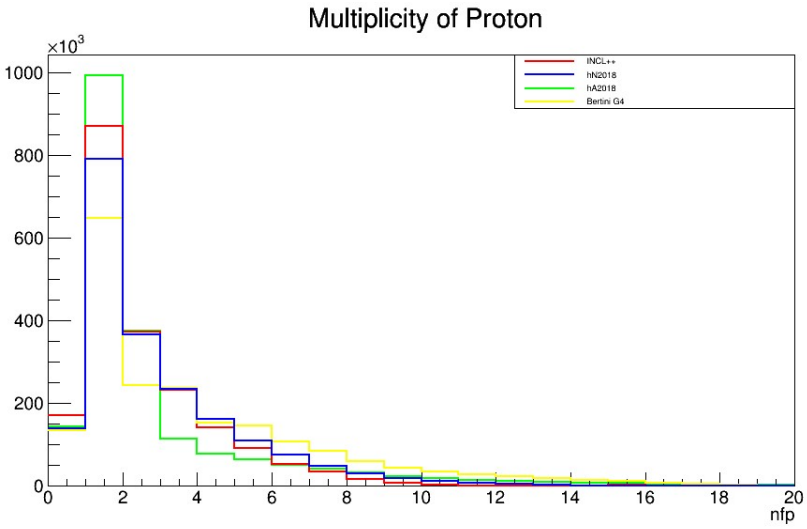
- p Fe →p' X (inclusive) at 62 MeV is standard candle
- Significant disagreement, INCL and GEANT are better
- hA is better than hN

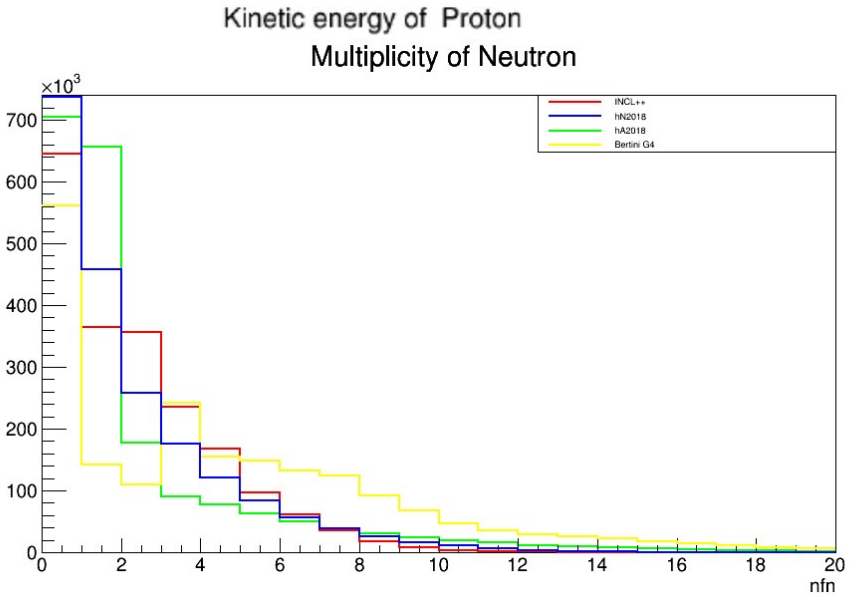




Broader properties
1 GeV ν_μ ^{40}Ar – all processes – use G18_02a/b

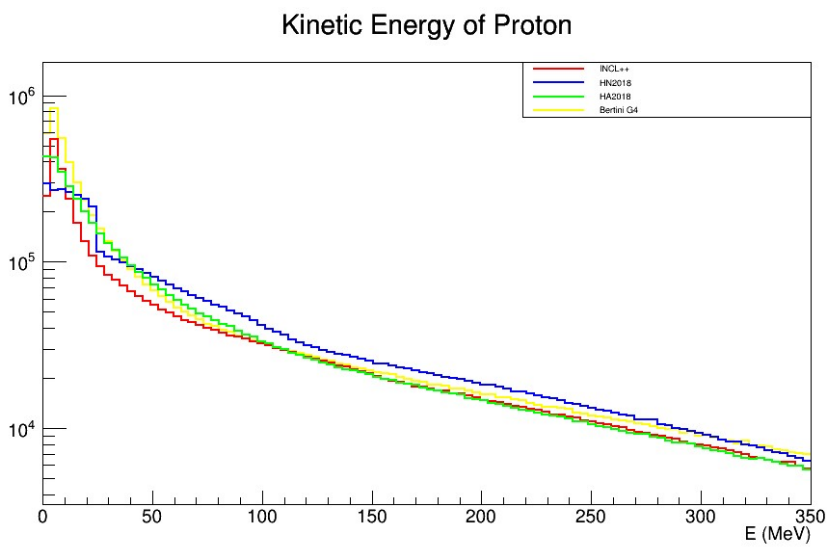
- Multiplicities give broad view but depend critically on threshold in any experiment – not good judge
- p and n very different (no threshold), partly due to QE dominance

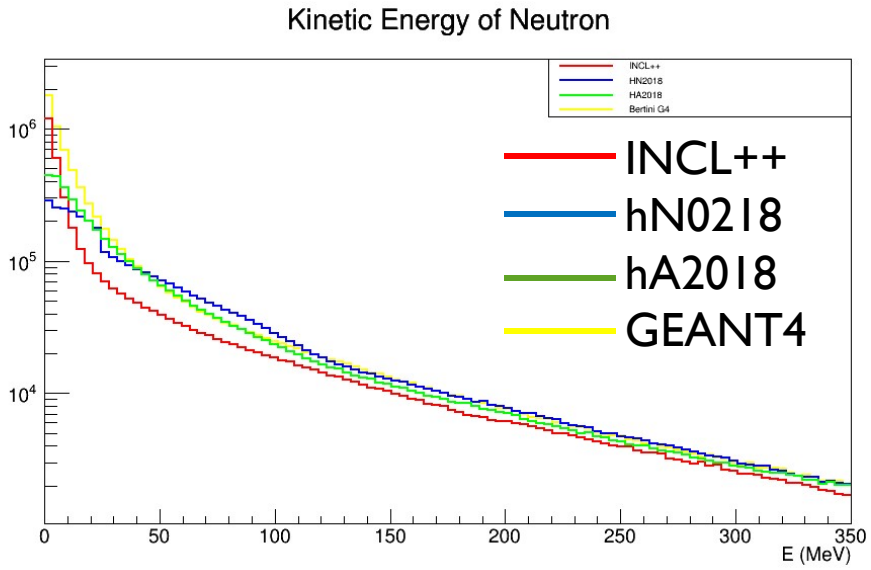




Proton kinetic energy from 1 GeV ν_μ Ar

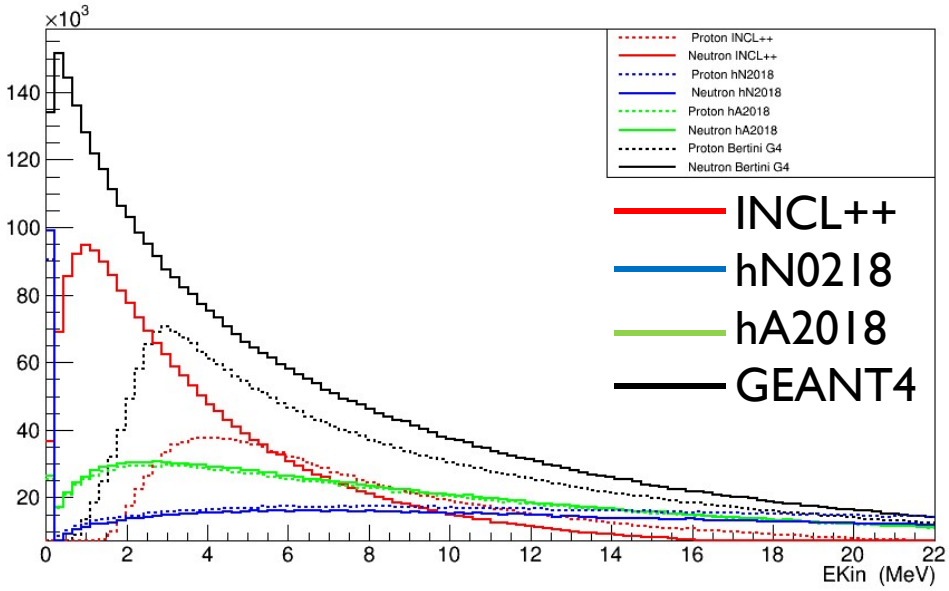
- Agreement at higher energy, continuing theme





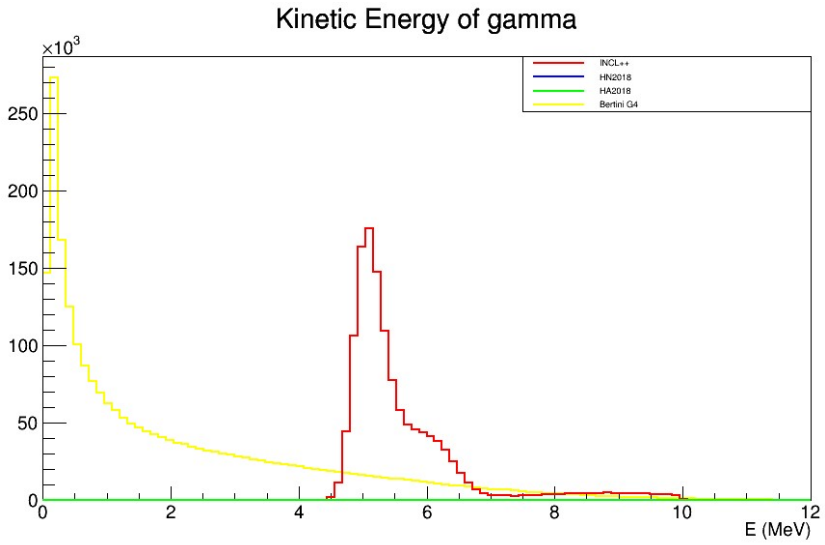
Low energy nucleons (T<30 MeV)

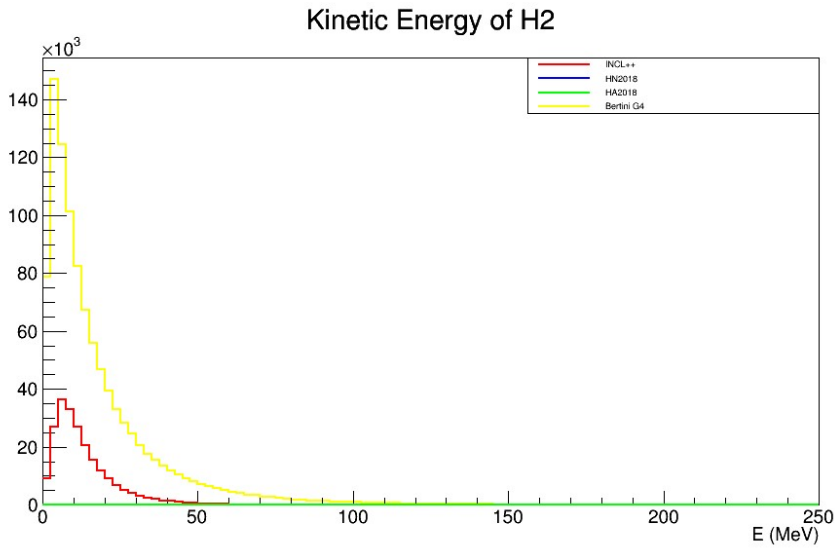
- Biggest differences between existing and new codes
- Proton emission suppressed by Coulomb effects
  - Overall factor of ~2, strong energy dependence
  - Different threshold
  - Much better treatment in new codes
  - How important for expts?
- Marc sees spike for hN, I don't see it – must be settled soon.



New stuff – γ, ^2H

- hA and hN have nothing, INCL and GEANT have clusterization which is isn't trivial to implement.
- INCL γ spectrum not accurate; GEANT better
- For ^2H, shapes similar but GEANT yield larger





Conclusions

- We will now have 4 FSI codes of wide variety
- General methods for conditional linking of FSI libraries (maybe not new)
- New physics, mostly important at low energies
- hA does a reasonable job, can now add features similar to INCL and GEANT
- Communication with INCL authors underway to include our code in general release
- Do we have new configurations, e.g. G18_02c?