GENIE picture of Low Energy Neutrinos

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- emphasis on GENIE models at low energy
- recent changes in nuclear models, FSI
- In large part, PhD thesis work of Marc Vololoniaina (Antananarivo, Madagascar)

Overview

- GENIE was originally aimed at E_ν~few GeV
  - First models were simple – relativistic Fermi Gas, minimal nuclear medium corrections, few low energy processes
  - However, broad structure allowed easy? adaptation to new needs
    - Added hadron scattering using identical code as FSI in ν, e interactions
    - Add electron scattering as 'another' lepton with code that overlaps neutrino scattering code
- Significant progress in last few years toward low energy
  - Add Local Fermi Gas (LFG), spectral function nuclear model
  - Add medium corrections for pion, nucleon FSI
  - Add FSI designed for lower energy (INCL++)
  - Add CEvNS process
  - (Add dark matter, $\bar{n}n$ interactions, proton decay)

Final State Interactions

- Separate into short time (scattering, uses mean free path) and long time (compound nucleus)
  - $\lambda(E,r)=1/\sigma_{hN}(E)*\rho(r)$
- Empirical (hA) mainly has scattering
  - Unique – simple, data-driven – but still describes data
  - λ uses spatial density from electron scattering, free hN cross sections (NN has medium corrections from Pandharipande, Pieper)
  - Simulated compound nucleus for low energy nucleons
- Cascade (hN) mainly has scattering
  - λ uses spatial density from electron scattering, free hN cross sections (piN medium corrections from Salcedo/Oset, NN from Pandharipande, Pieper) (very similar to NuWro)
  - Simulated compound nucleus for low energy nucleons

Newer FSI models – use inside nucleus new

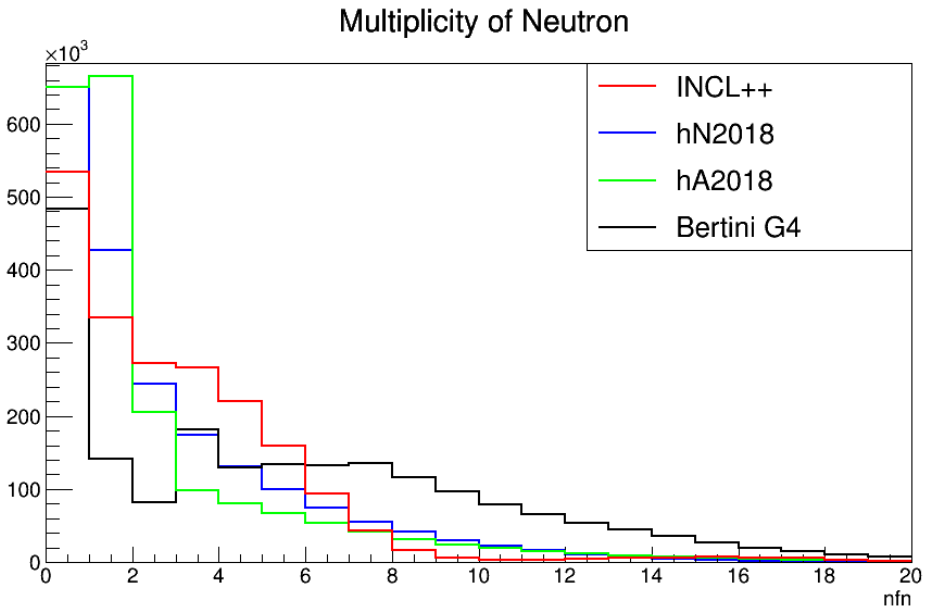
- GEANT4 – Bertini cascade + evaporation
  - Often used for hadron reinteraction in scintillator or LAr detectors.
  - Older Bertini model has been improved, streamlined (Kelsey/Wright)
  - Very simple nuclear model (~local Fermi gas), interactions for all 'stable' particles
- INCL++ (Mancusi, Cugnon, et al.)
  - Stepping in time rather than space (hA and hN)
  - Cascade followed by compound nucleus (Abla07)
  - position-momentum correlations in nuclear model ($p_F(r)$ like LFG but nucleon is in a square well of radius-dependent width)
- One major goal was to compare newer models with native models to improve hA and hN

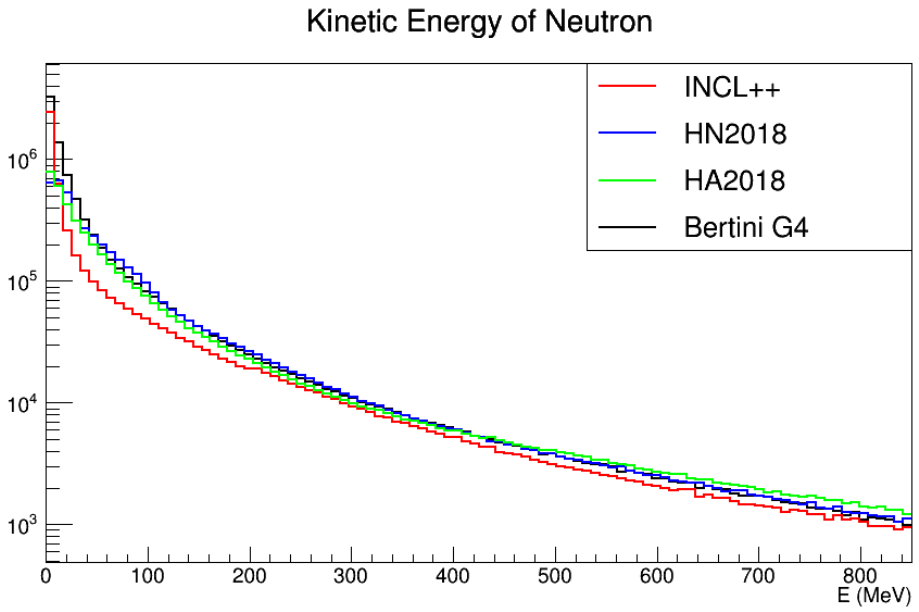
FSI processes

- hA, hN have scattering, charge exchange, 2-body absorption for pions, and pion production
  - hA emphasizes QElike processes, lumps others into absorption for pions and knockout for nucleons (also simulates compound nucleus)
  - Both keep track of residual nucleus in terms of Z and A.
  - Definite residual nucleus, but energy not realistic
- GEANT4, INCL++ have those, also photons and coalescence (d, t, ^{3}He, ^{4}He)
  - Realistic nucleus ground state at the end.
- GEANT has nuclear elastic scattering (Glauber model)
- INCL++ has only nucleons and pions, others have K…

ν_μ Ar at E_ν=2 GeV - neutrons

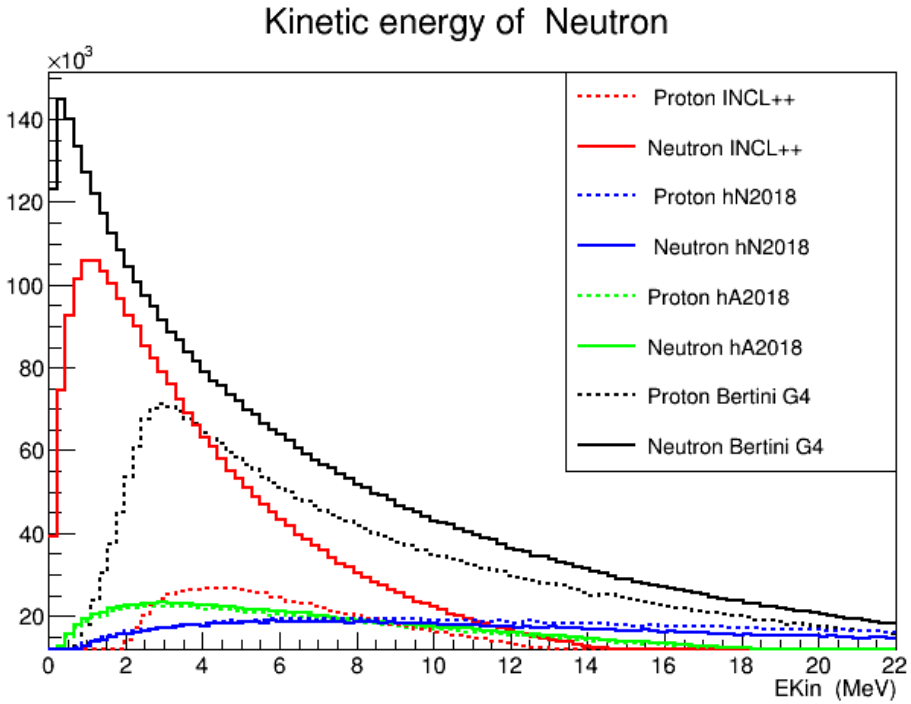
- Multiplicity on left (unlike expt, no momentum threshold)
- Energy spectrum on right, only differences at lowest values





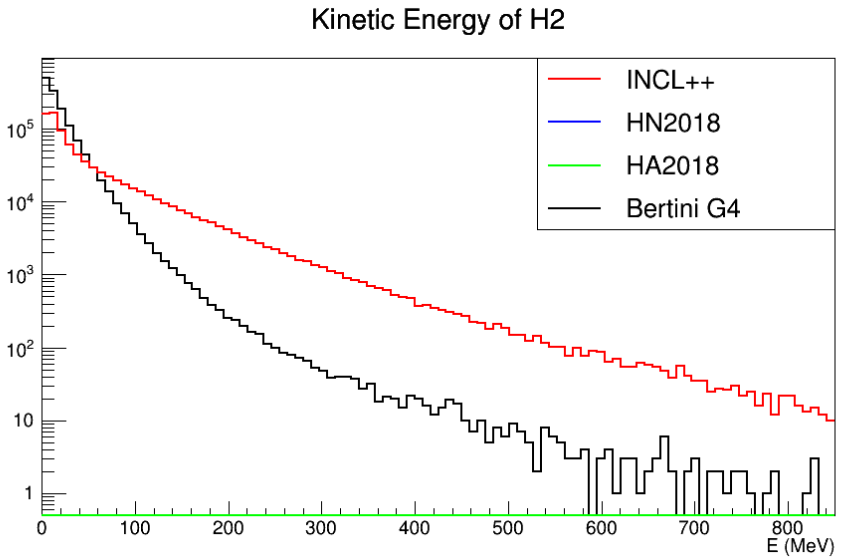
ν_μ Ar at E_ν=2 GeV

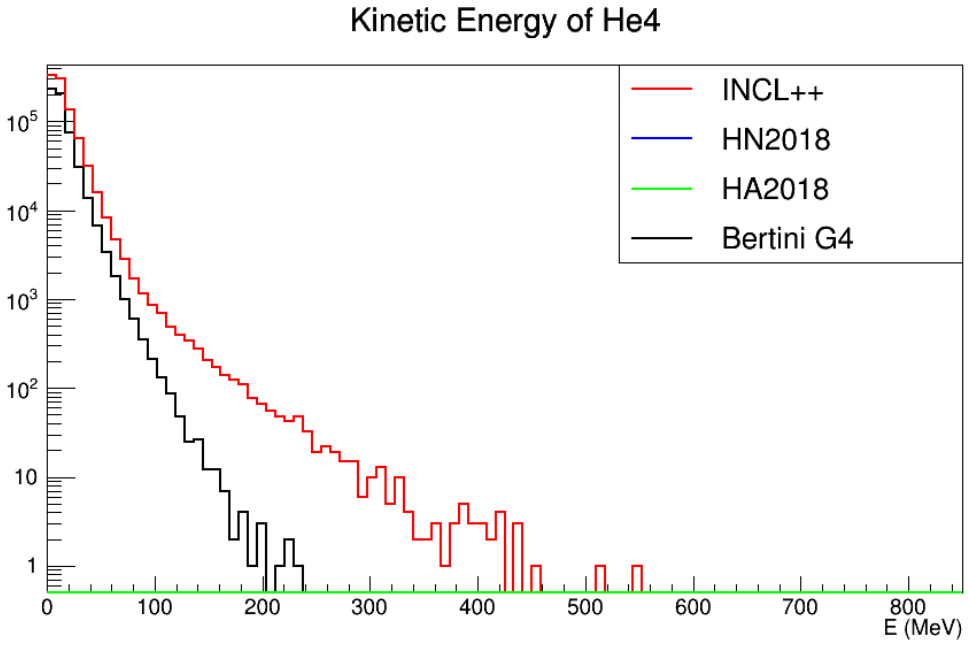
- KE spectra for p, n at low energies is illuminating
- Both GENIE models are same for p, n
- For INCL and GEANT, turnover for p (Coulomb) ~4 MeV
  - Larger magnitude below ~8 MeV

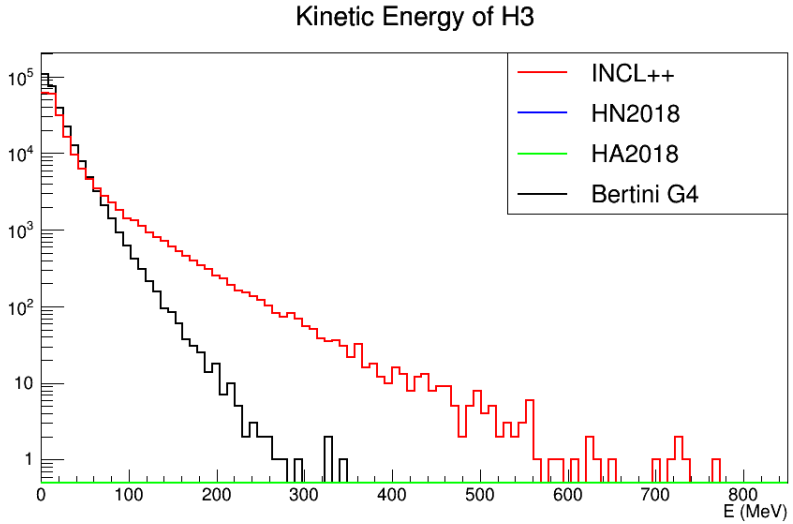


ν_μ Ar at E_ν=2 GeV
light nuclei in final state

- Included in both INCL and GEANT
- Significant differences seen
- Should be visible in LAr

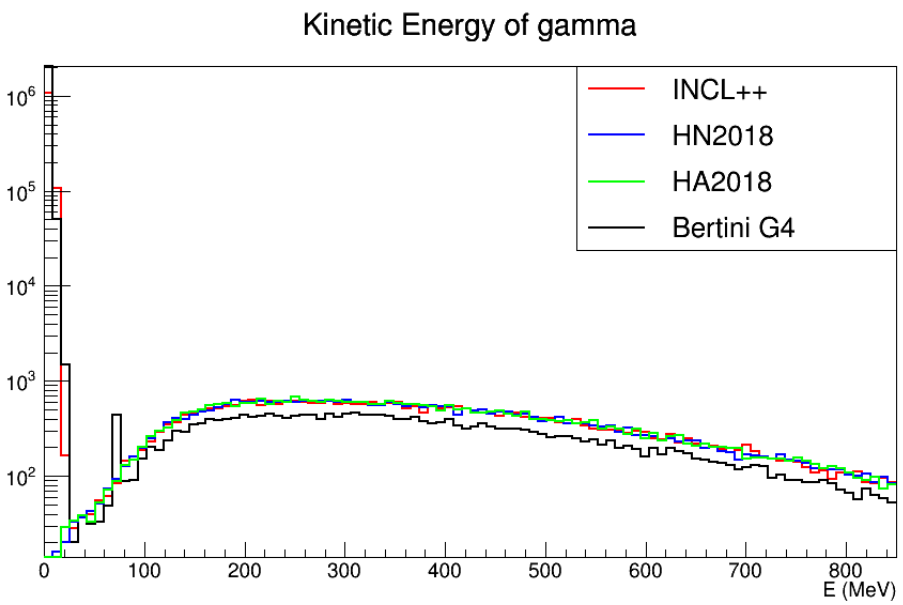


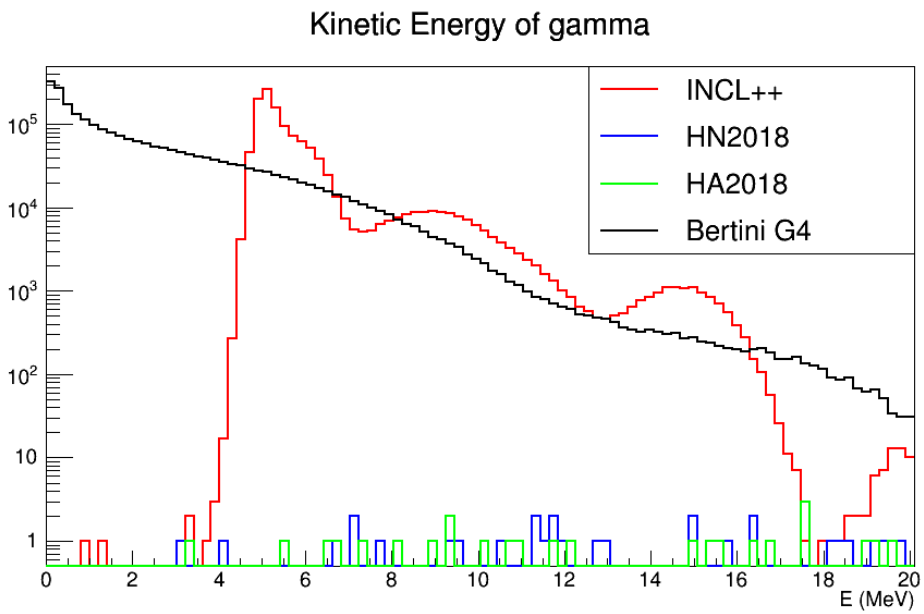




ν_μ Ar at E_ν=2 GeV
photons in final state

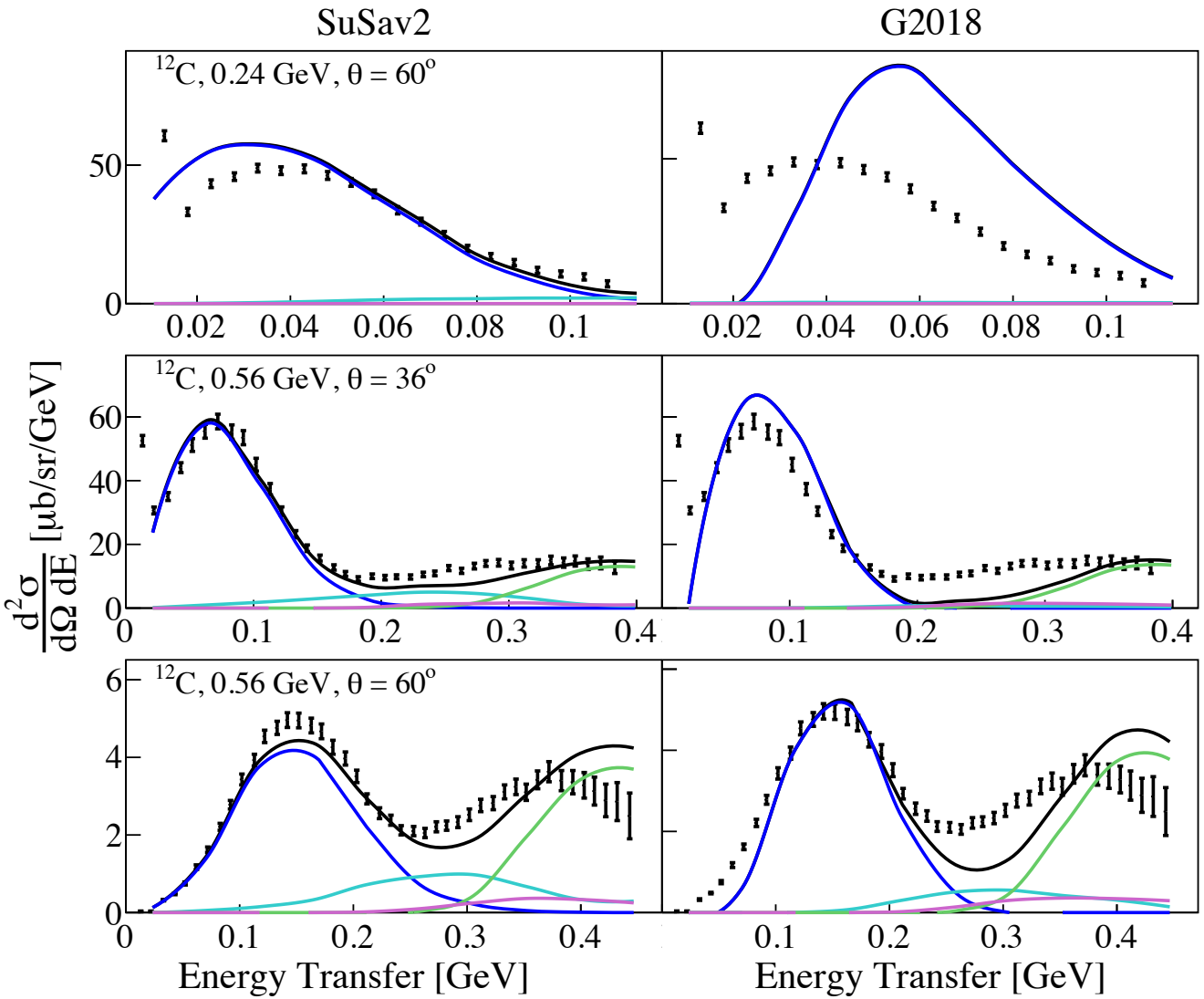
- Wider energy range on left
  - Mostly subatomic processes (e.g. ρ decay) – good agreement
- Significant differences for E_γ<20 MeV
  - Both INCL and GEANT have statistical decay
  - Marley provides details about specific states and decay





Electron scattering

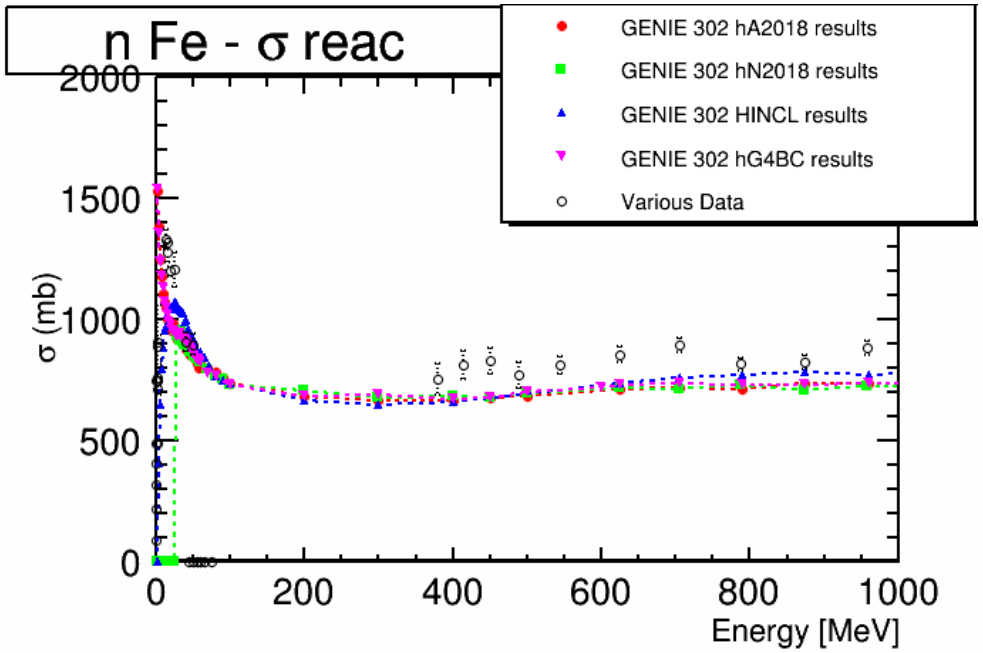
- GENIE:
  - LFG nuclear model
  - Nieves QE, MEC
  - hA2018 FSI
- SUSAv2:
  - Based on scaling of data/mean field
  - Emphasize (e,e') that leads to ν
  - Emphasize QE, MEC
  - Must add GENIE pion production, FSI

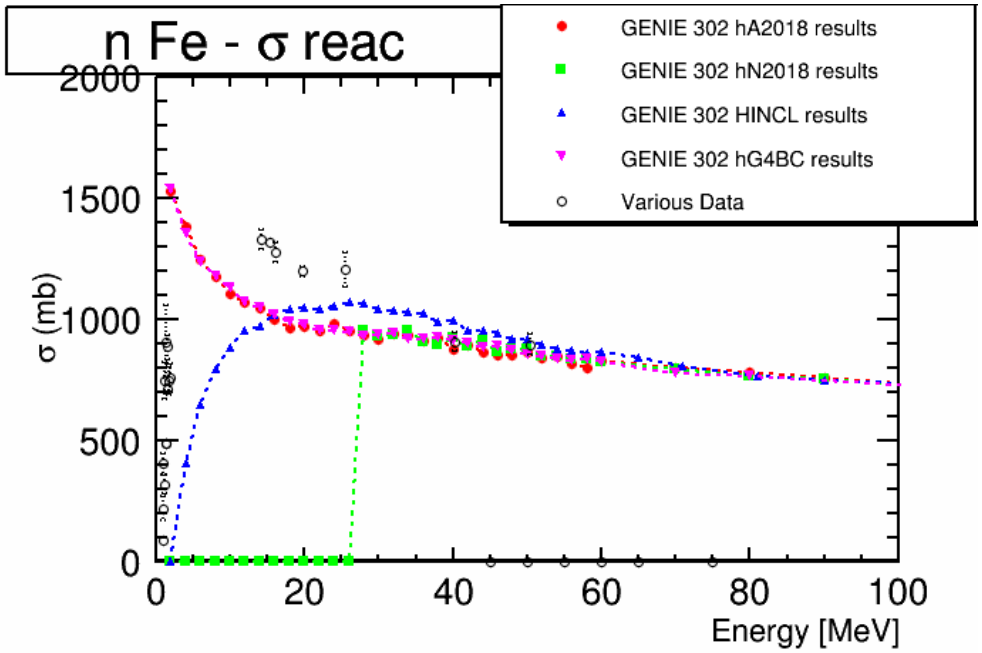


Total reaction cross sections (σ_{reac})

give an overall view of interaction strength

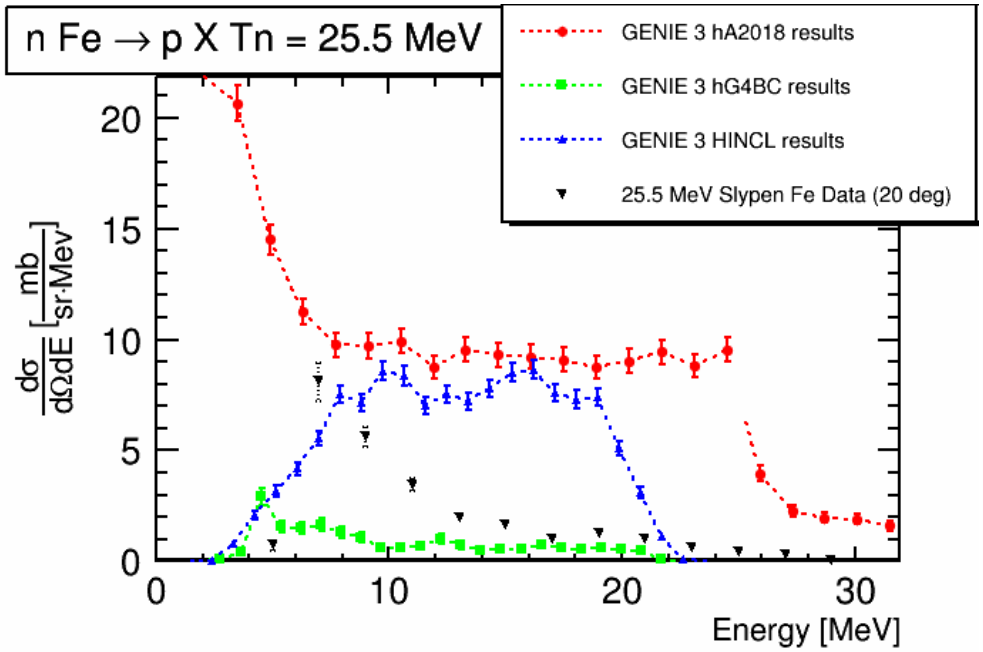
- Neutrons here, also have p, π^+, π^0, π^-, K^+
- Values tend to be flat at higher energies, values $\sim\pi R^2$
- GEANT4 needs stepping through nucleus for compatibility, therefore same as hA
- Significant differences at very low energies reflects emphasis on simple nuclear structure in neutrino simulation (same for NuWro and NEUT)

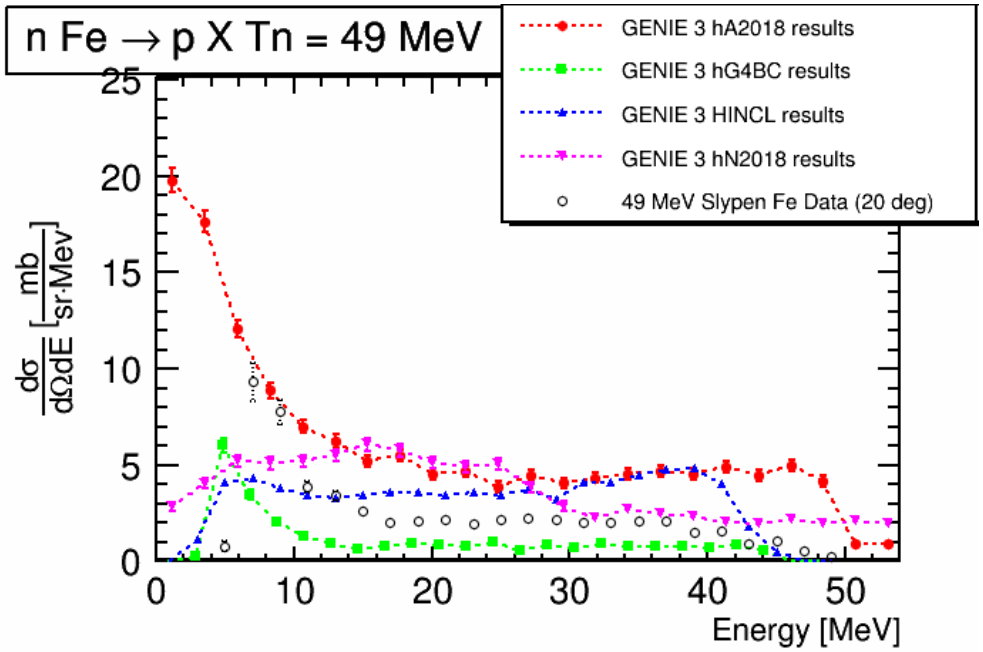




Hadron scattering – neutron interactions

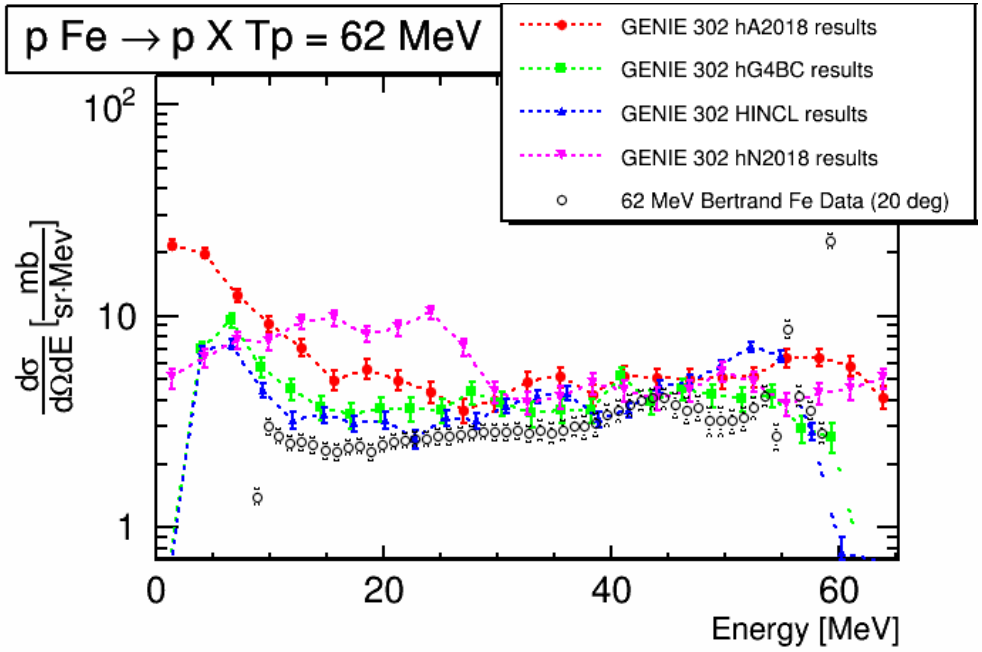
- Much data for Fe(n,p)X – beam energy of 25.5 and 49 MeV here
  - Proton suddenly appears in detector with no known source
- Inclusive p proton energy spectra for a range of angles
  - Choose 20 deg here because cross section is large
- hA, hN, INCL tend to be high, GEANT4 is low
  - all within factor of 2

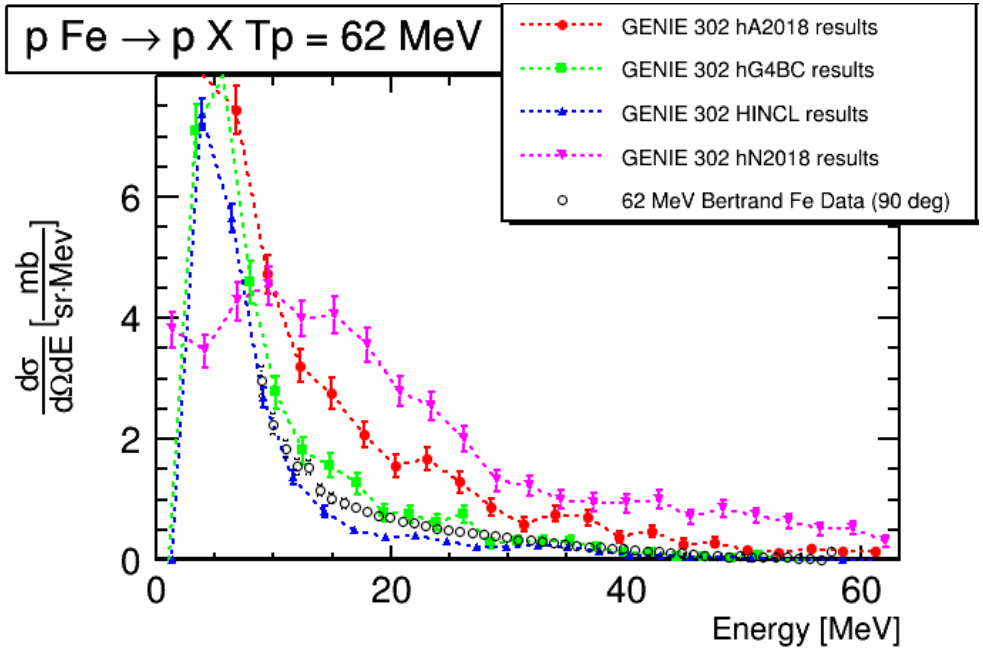




Hadron scattering – protron interactions

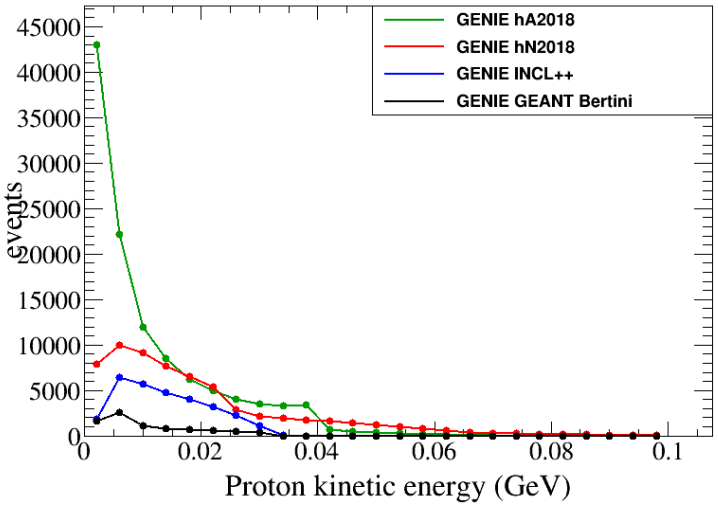
- Much data for Fe(p,p') 62 MeV below
- Inclusive p proton energy spectra for a range of angles
  - Choose 20, 90 deg here to show typical angular distribution
- hA, hN, INCL tend to be high, G4 is closest!
  - all within factor of 2

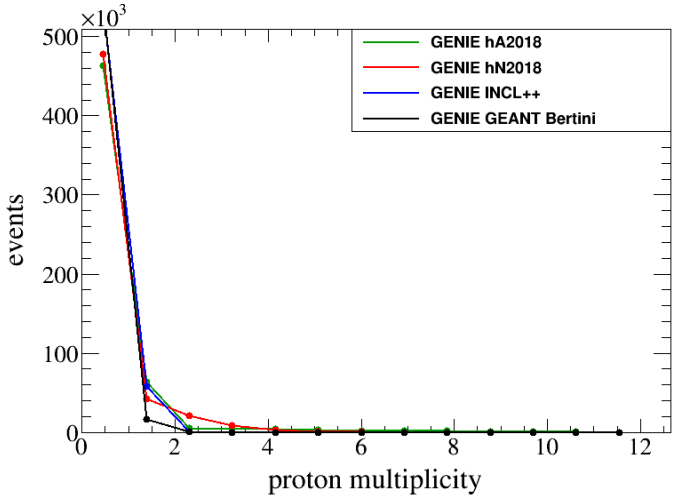


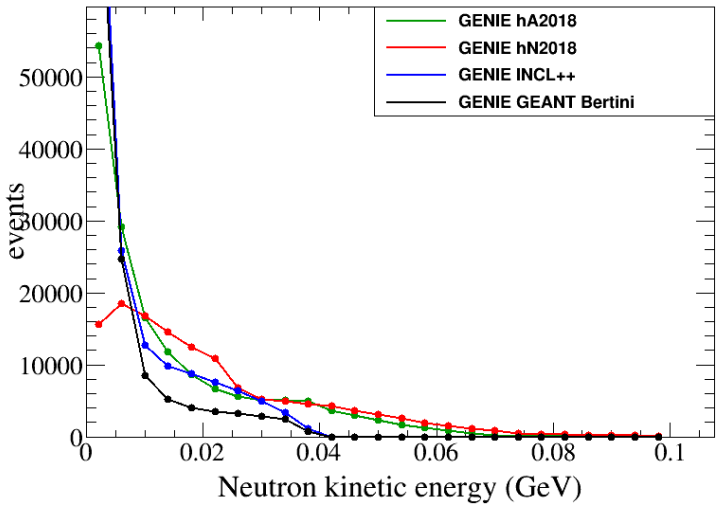


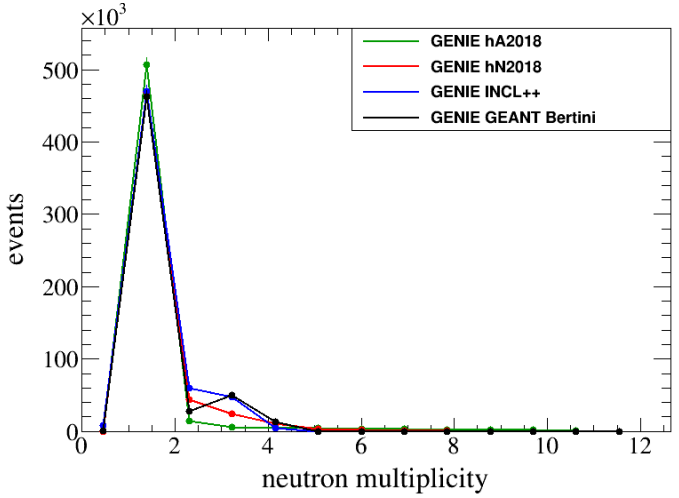
Hadron scattering - n Ar at 40 MeV

- Protons, neutrons
- No significant differences in multiplicity
- Many differences in shape for KE





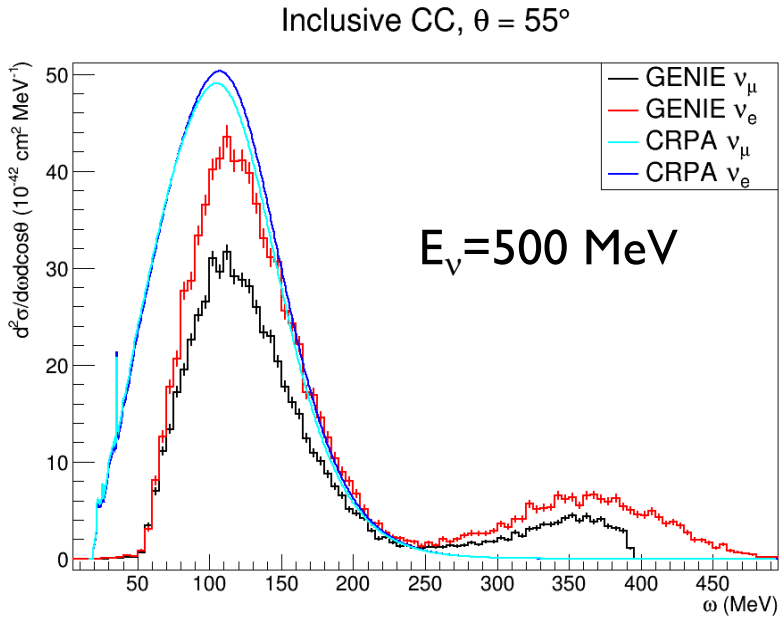


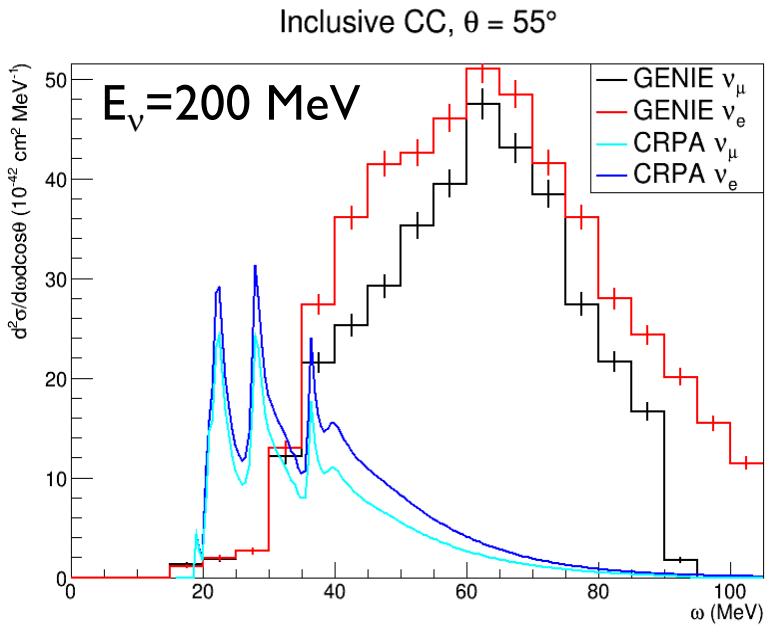


Compare GENIE with CRPA (Ghent)
perhaps the best low energy model?

- Both QE peak and nuclear states built from 1p1h configs
- Reasonable agreement when QE peak dominates (200 MeV?)
- Nuclear correlations effects very important
  - Pauli blocking, RPA, Binding energy – clearly a frontier for GENIE
  - Main missing ingredient is low-lying nuclear states, e.g. giant dipole

Plots from Steven Gardiner, Vishvas Pandey

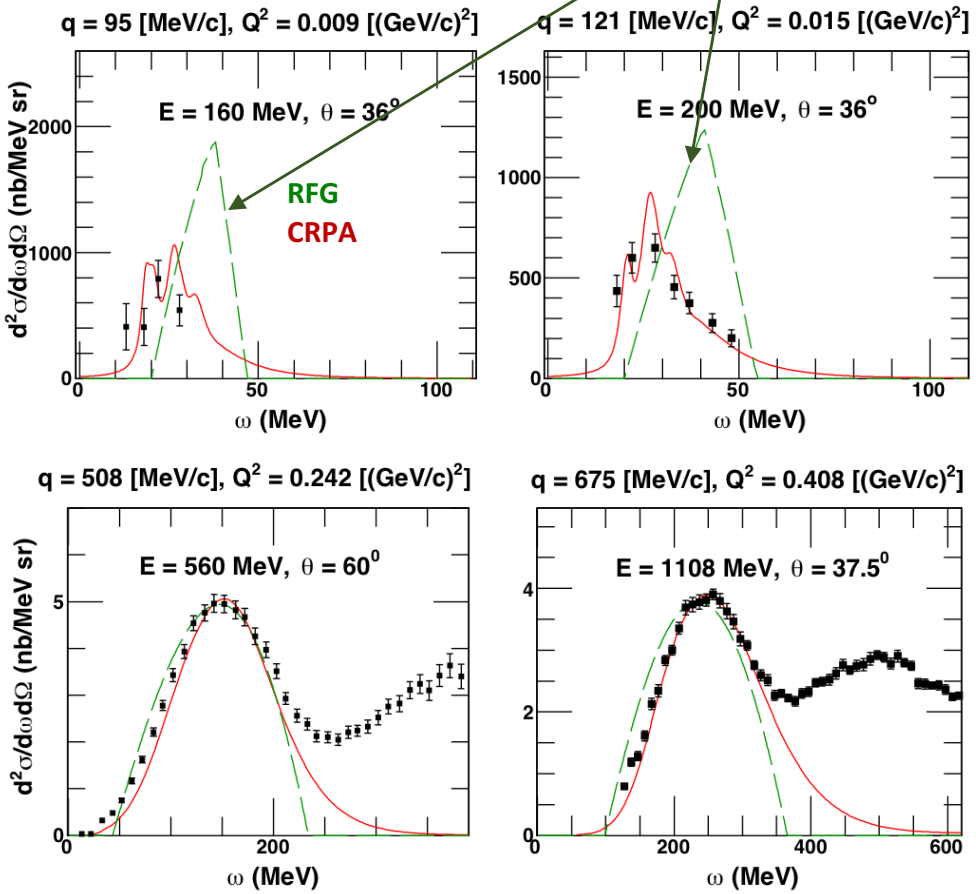




V. Pandhey, N. Jachowicz, et al.

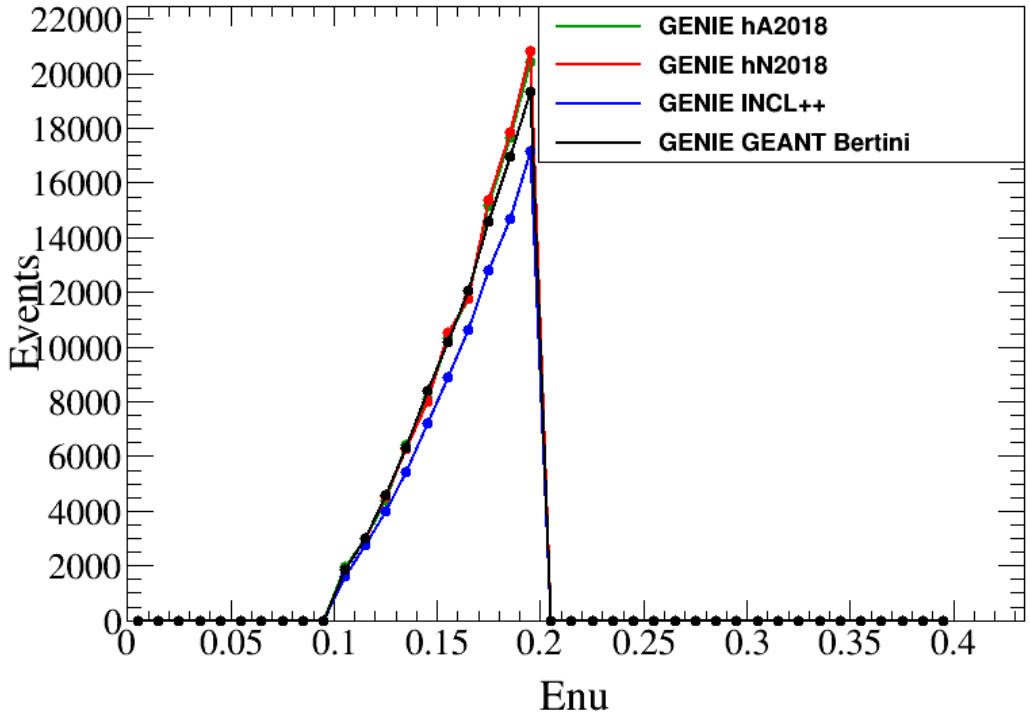
- Plot from a talk by Vishvas (2018)
- Compares RFG with Pauli Blocking vs. CRPA for C(e,e') data!

- Searching these effects with **Relativistic global Fermi Gas** glasses
  (Parabolic structure abruptly cut by Pauli-blocking)



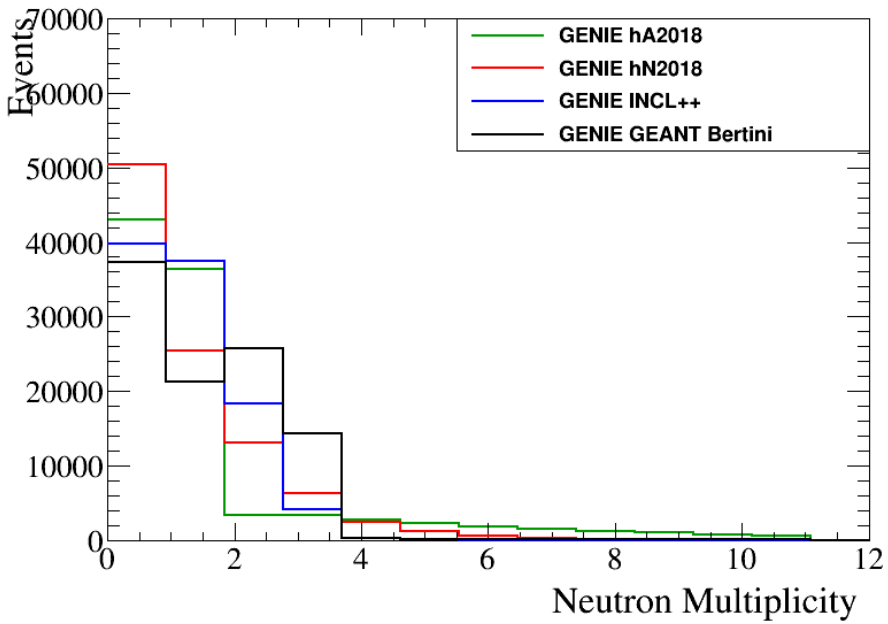
ν_e Ar 100-200 MeV (peaked at 200 MeV)

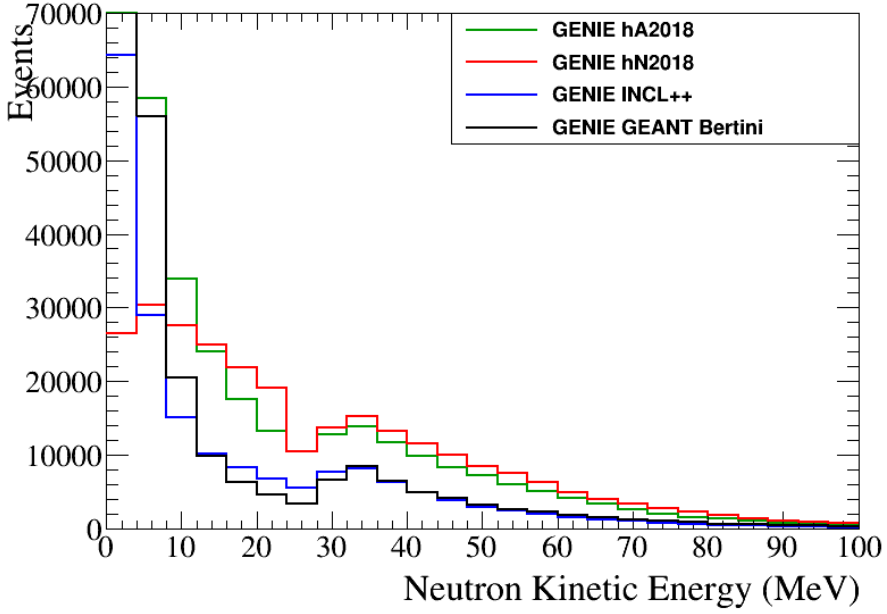
- Troubles at lower E_ν, errors for $Q^2<0$?!?
  - Looks like LFG doesn't work
- Only events from CCQE and CCMEC
- E_ν spectrum increases linearly from 100 to 200 MeV



ν_e Ar 100-200 MeV - neutrons

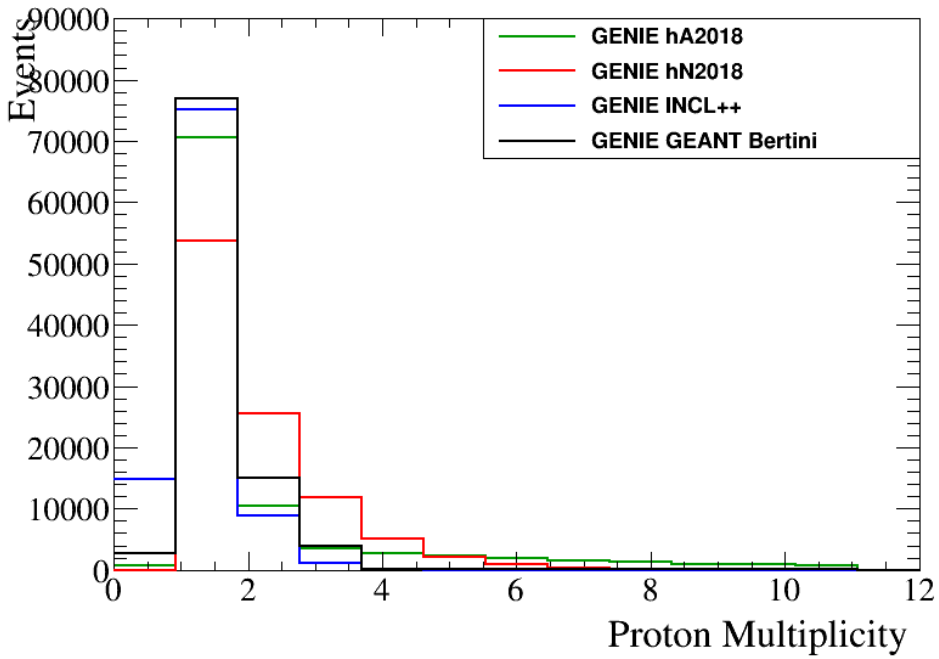
- No significant differences
- Higher multiplicities, lower energies in GEANT

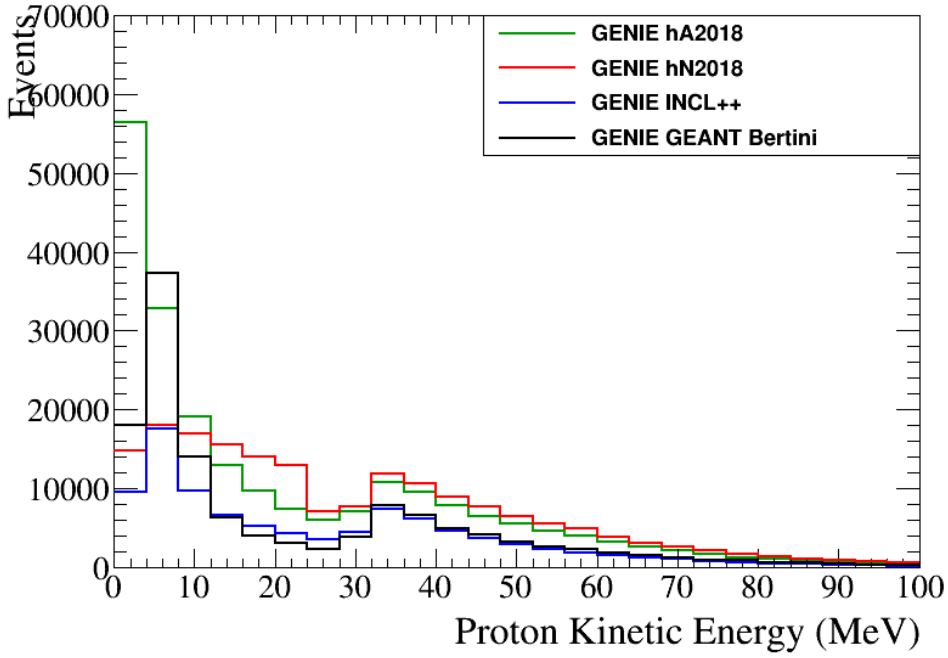




ν_e Ar 100-200 MeV – protons

- CCQE, MEC only, therefore very few events with no protons
- Lower KE events tend to be from MEC



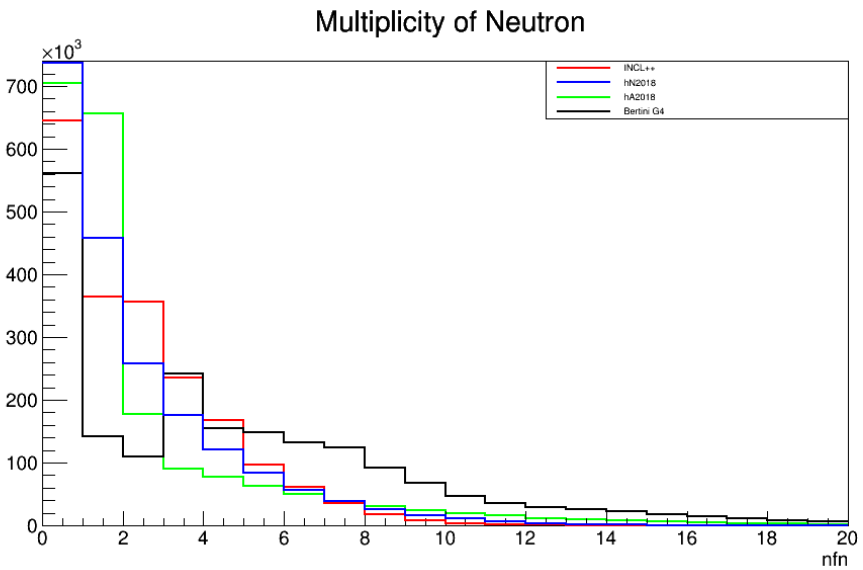


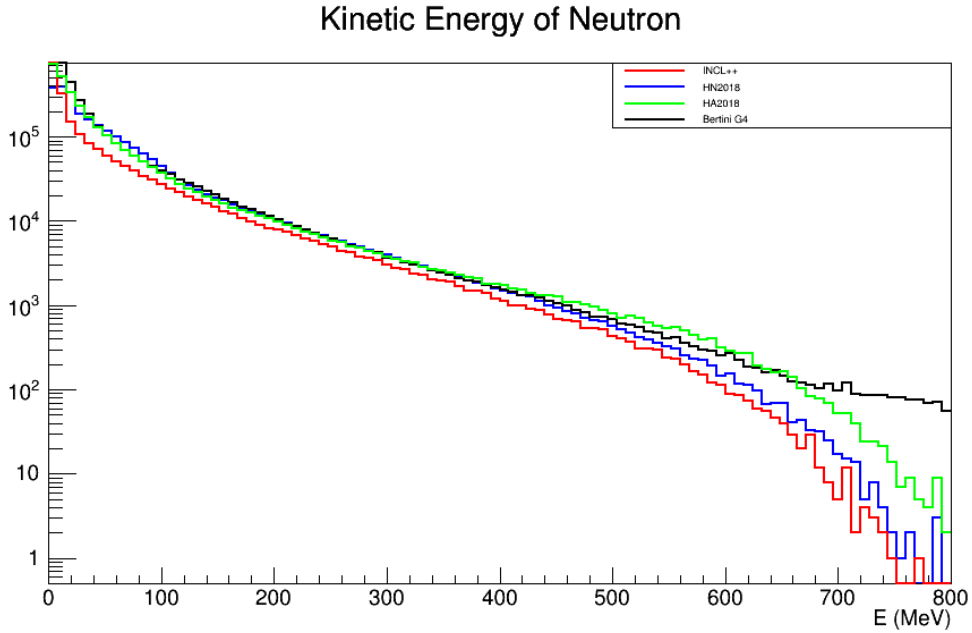
Conclusions

- GENIE has room for many options, steady progress to low E_ν
  - Some are presently included – more realistic nuclear models, CEvNS
  - Others must still come – photon decay, GHENT model
  - GENIE work is always manpower limited
  - Side-Implementation of newer models needs to be more general
- New models from theorists extremely valuable
  - SUSAv2 (Mejias, Dolan…), Benhar/Rocco…
- INCL++, GEANT Bertini FSI bring new options
  - Should native models be updated or adopt new model?
- Proper merge of electron and neutrino scattering in progress
  - this will fix the vector interaction, nuclear structure
  - New electron data for hadrons in final state very important

ν_μ Ar at E_ν=1 GeV - neutrons

- Multiplicity on left (unlike expt, no momentum threshold)
- Energy spectrum on right, only difference at highest values





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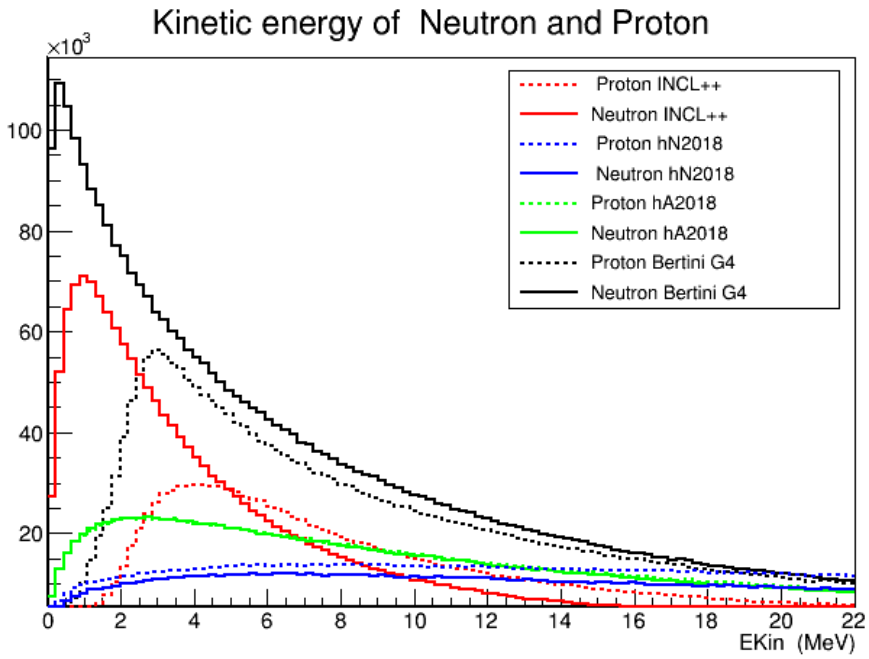
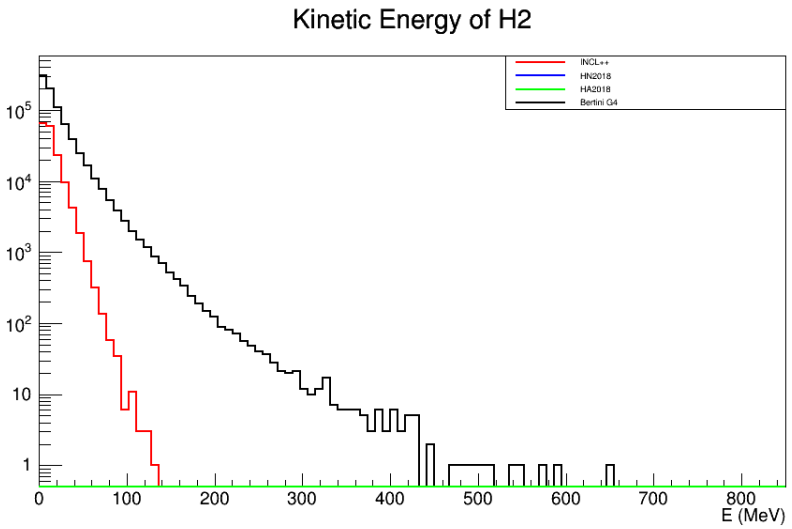
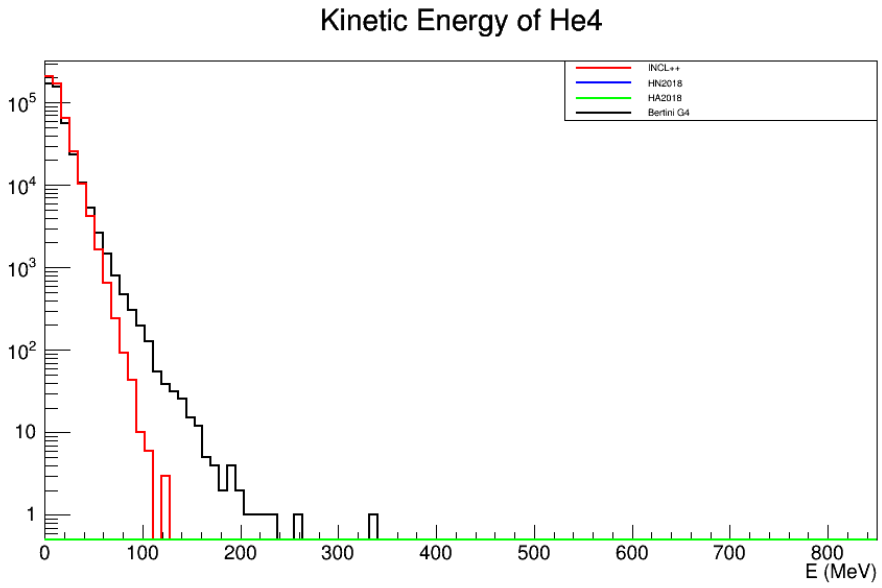
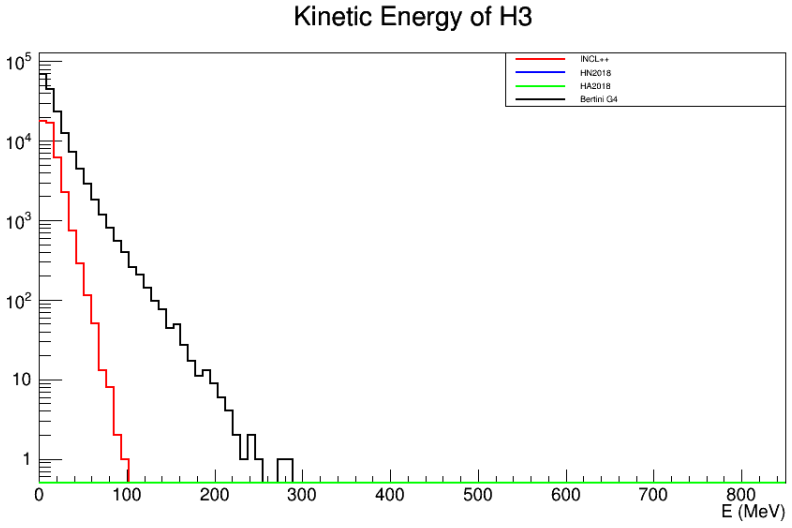


ν_μ Ar at E_ν=1 GeV
light nuclei in final state

- Included in both INCL and GEANT
- Significant differences seen







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  - Mostly subatomic processes (e.g. ρ decay) – good agreement
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