GENIE event generator
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- general overview
- GENIE features
- GENIE status/plans

- Final state interactions (FSI)
- A dependence

Event Generators

- ν experiments traditionally used home-grown 'boutique' programs. (e.g. NUANCE by Dave Caspar)
- GENIE is the first *universal* generator
  - Root-based code
  - C++ object coding
  - Easy to switch between models
  - Root-based geometry makes experiment interface easy
  - Exactly reweightable with many parameters
  - Choice of almost all modern experiments
  - MINOS uses GENIE precursor, T2K uses NEUT with GENIE as a check. (Both are largely Fortran.)

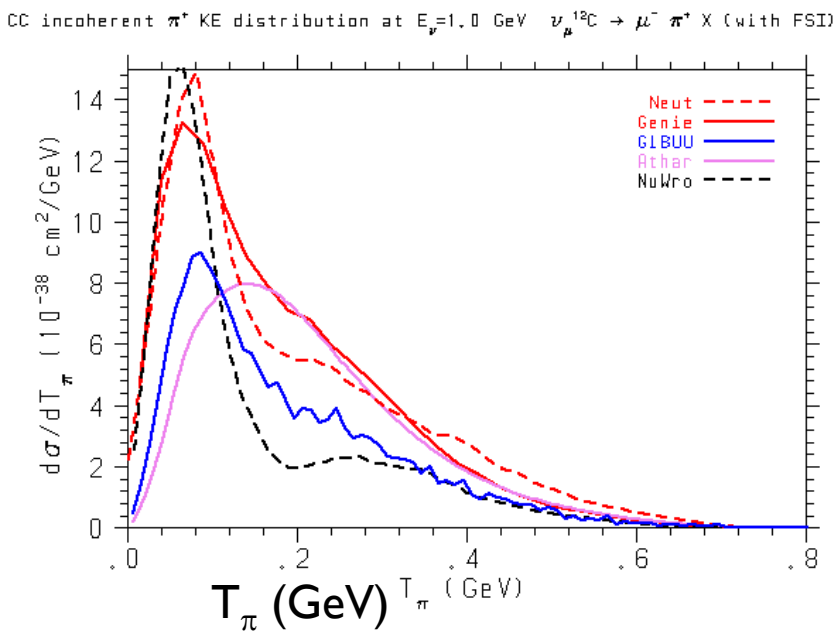
The task

- No detector technology in use is perfect.
  - Water Cerenkov misses all hadrons (π, p, n) below threshold
  - Scintillator misses many neutrals (γ, n)
  - Liquid argon would be great.
- Neutrino event generators have huge goal
  - plan experimental configurations
  - Detector design
  - Verify early performance before analysis develops
  - Data analysis (develop cuts, corrections)
  - Systematic errors (beam energy, topology errors)
- Thus, each program must have models for all possible neutrino interactions in many materials at a wide range of energies.

Comparisons becoming common at NUINT

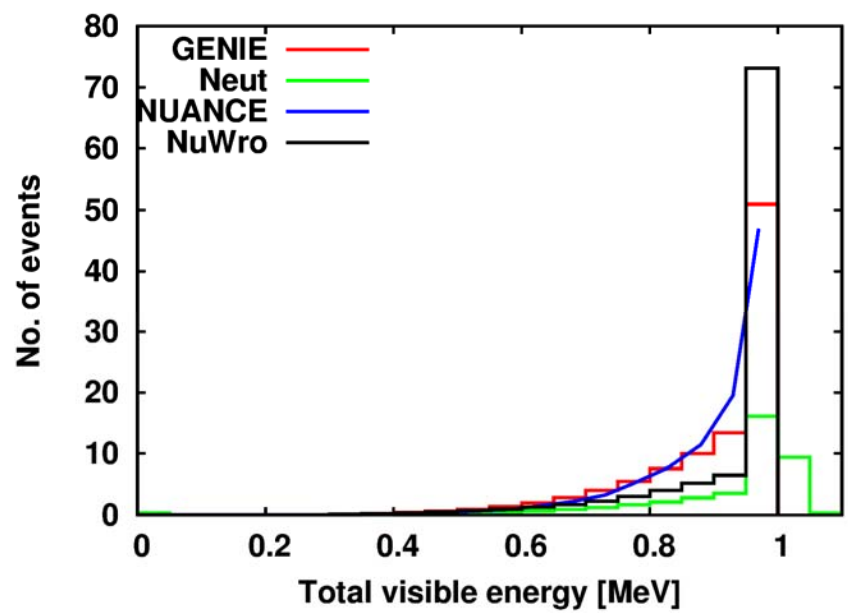
2009-theory vs. generators

- ν_μ Carbon, 1 GeV, CC1π,



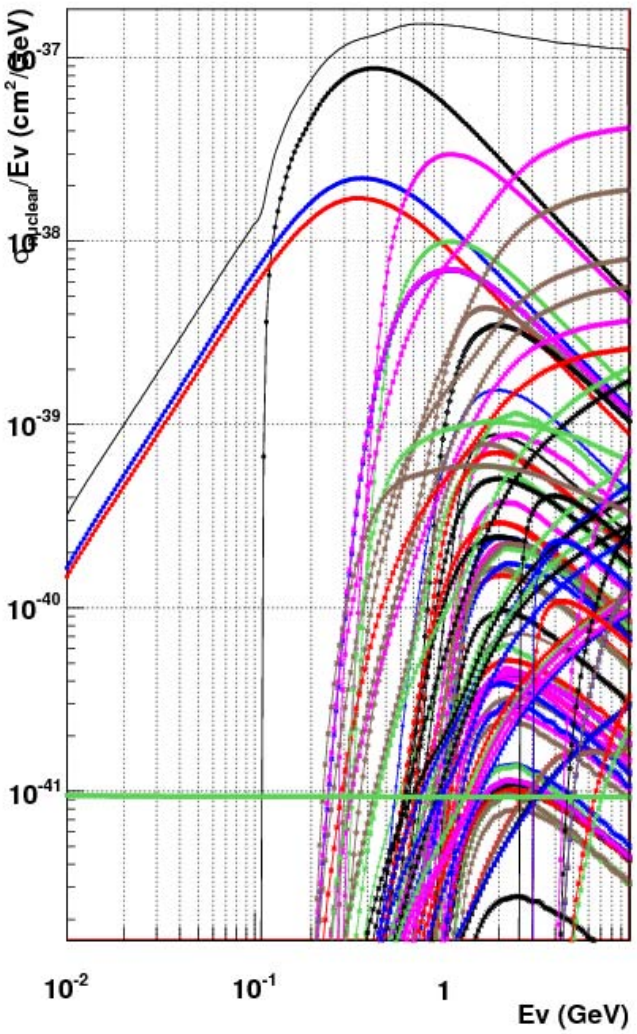
2012-experiments choose

- Numu, 1 GeV, CC, Argon



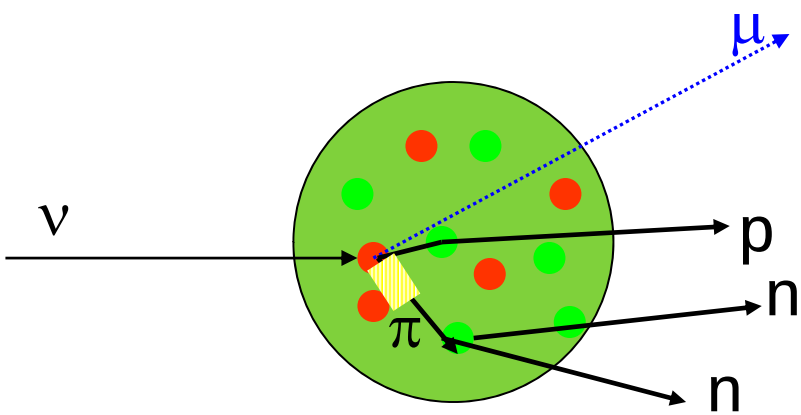
cross sections in GENIE

- GENIE has complete kinematics for all cross sections at all energies.
- Here, we show ν_μ Carbon:
  - qe
  - All resonances
  - All coherent
  - DIS of all flavors
- Input spline functions used to generate events.
- Works because models are simple.



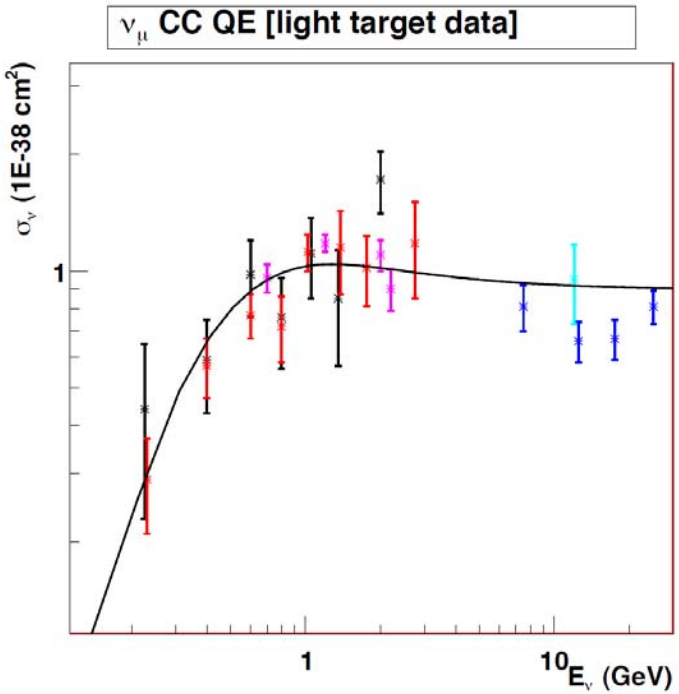
How we do it

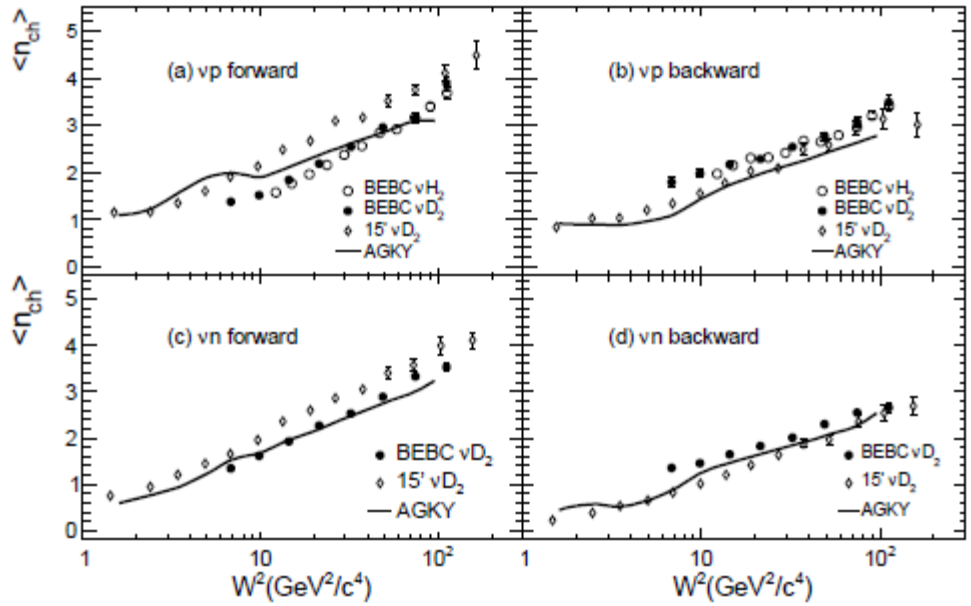
- There is *very little* νA data, *models required*
- Reaction model in Intranuclear Cascade (INC) (nucleons~free)
- Venerable models for qe (Llewellyn-Smith) and pion production (Rein & Sehgal) on p,n - updates? new data!
- Fit to νN Deep Inelastic Scattering data used for models.
- Nuclear model is relativistic Fermi Gas (old!) from (e,e')
- Final state interaction (FSI) comes from fits to πA , pA data [complicated! My work.]



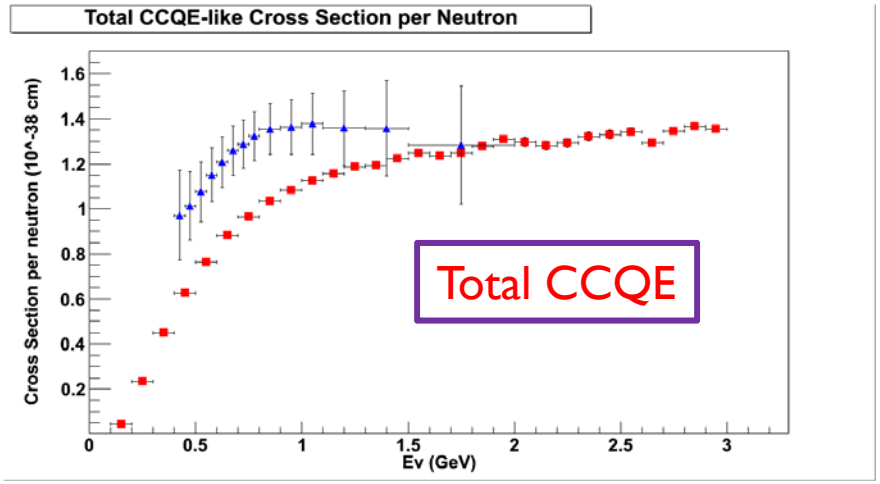
validation

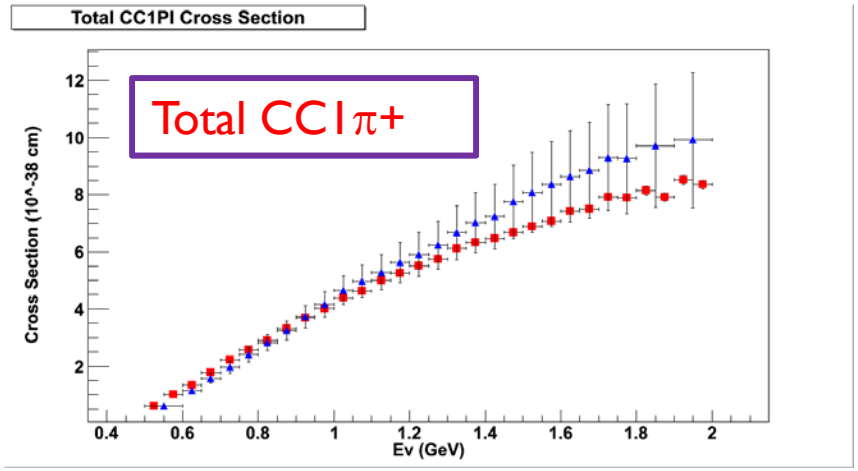
- Very little old ν data (mostly H2 and D2 targets)
- At high energies, see mainly DIS and coherent (large)
- Very little at lower energies with nuclear targets

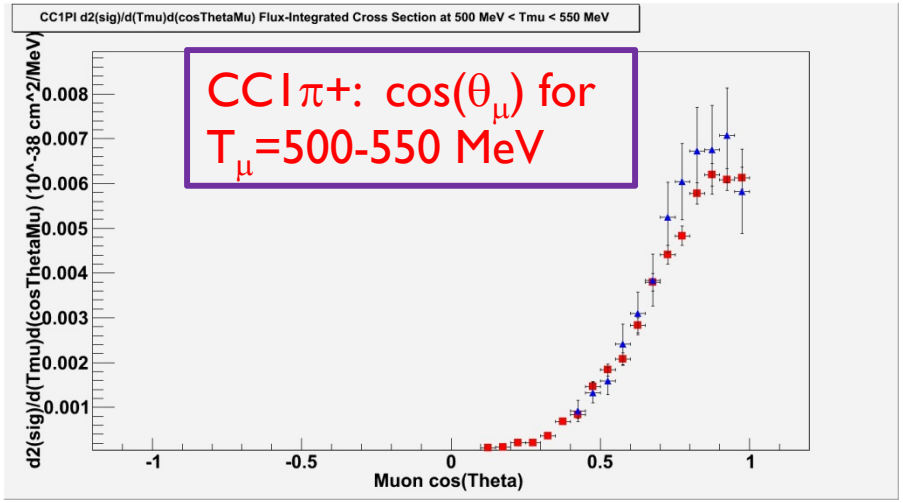


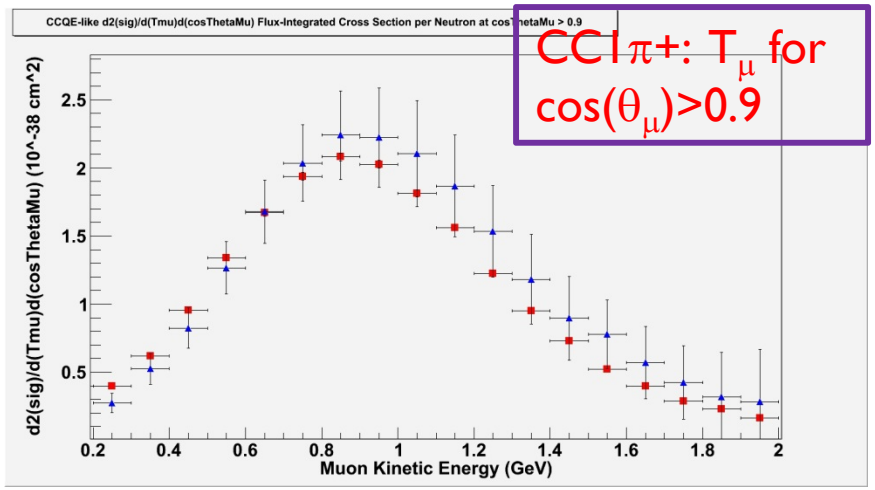


Modern validation – MiniBoone (detailed exam of CCQE and CC1π+) [no tuning] B. Eberle



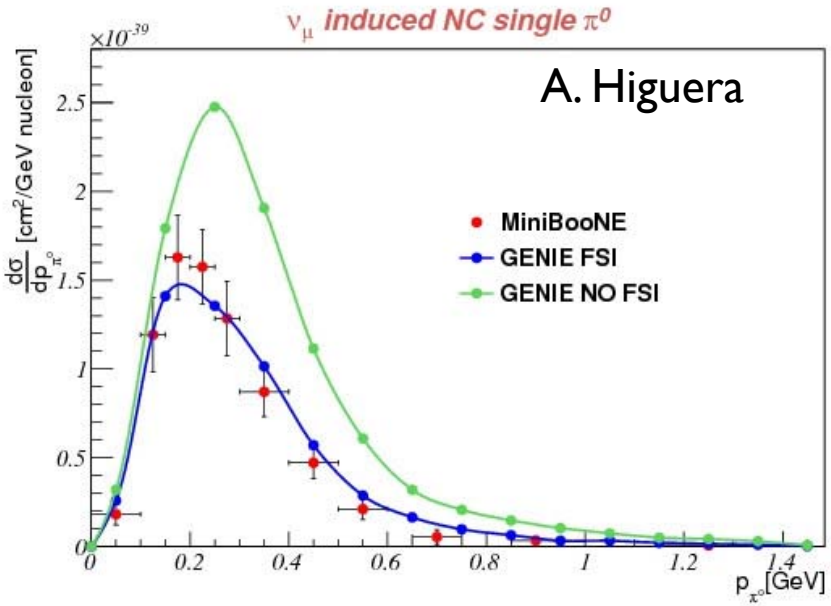


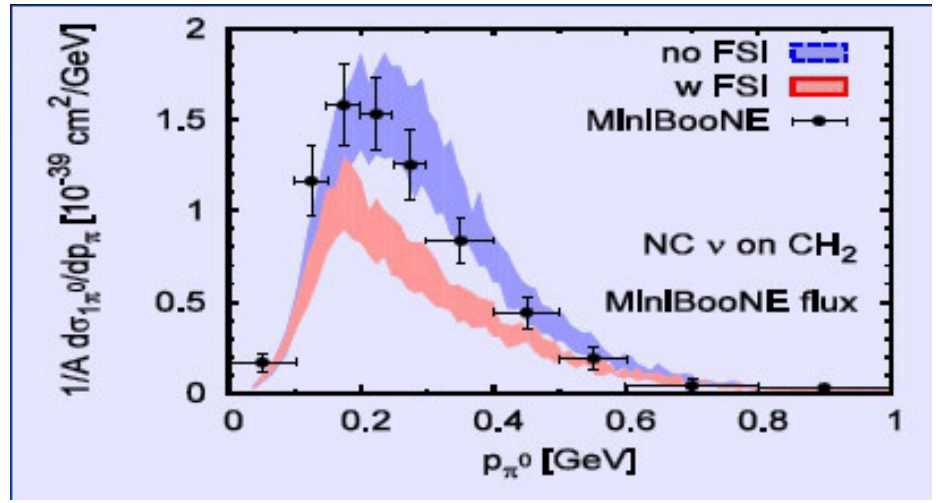




Modern validation – MiniBoone NCπ^0

- Remember, this is a cross section important for ν_e background
- Plot on right comes from leading theorist – Mosel (Giesen) has most complete model. Left plot is from GENIE.
- We agree on changes due to FSI but not on basic result.
- Nevertheless, checking with theorists and modelers matters!





Model work

- DIS cross section comes from Pythia + KNO model fit (Tinjung Yang)
- FSI models from INC – (Pitt undergrads)

DONE

- MEC model (CA+SD, Teppei Katori recently)
- Delta model (CA, SD, Jarek Novak)
- Comparison with (e,e') data with same model as ν.
- Theoretical Coherent model (Alvarez-Ruso, Dan Scully, CA)
- Spectral function (Benhar, CA)

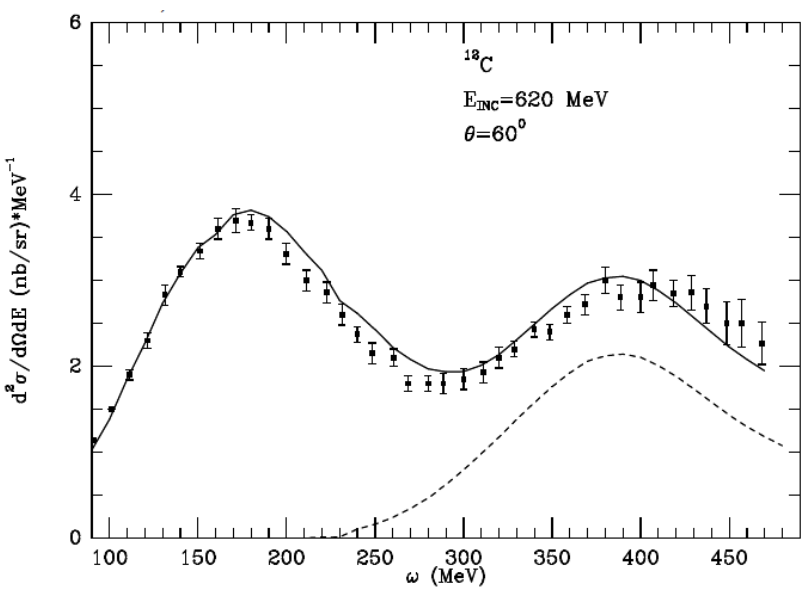
IN PROGRESS

- Plan is to have v2.8.0 'soon' (new FSI, MEC, Delta)
- v3.0.0 later (full validation with (e,e'), coherent, spec func)

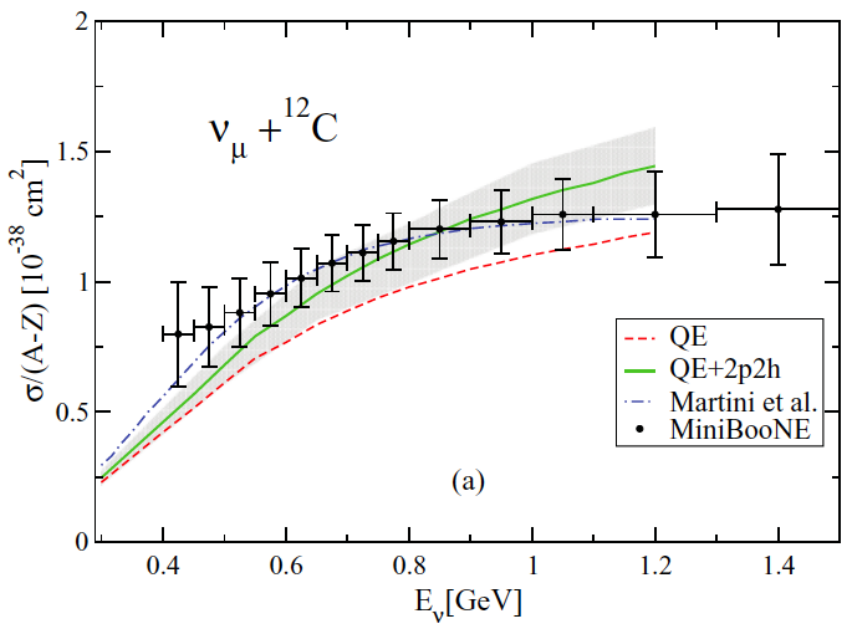
Meson Exchange Current (MEC)

- Felt to be the way to match MiniBoone QElike data with M_A=1 GeV^2.
- Good theory models from Valencia, but complicated to implement in Event Generators.
- Local Fermi Gas+RPA+MEC+Delta.

exclusive e-scattering with 2p-2h



ν_μCCQE total xs with 2p-2h

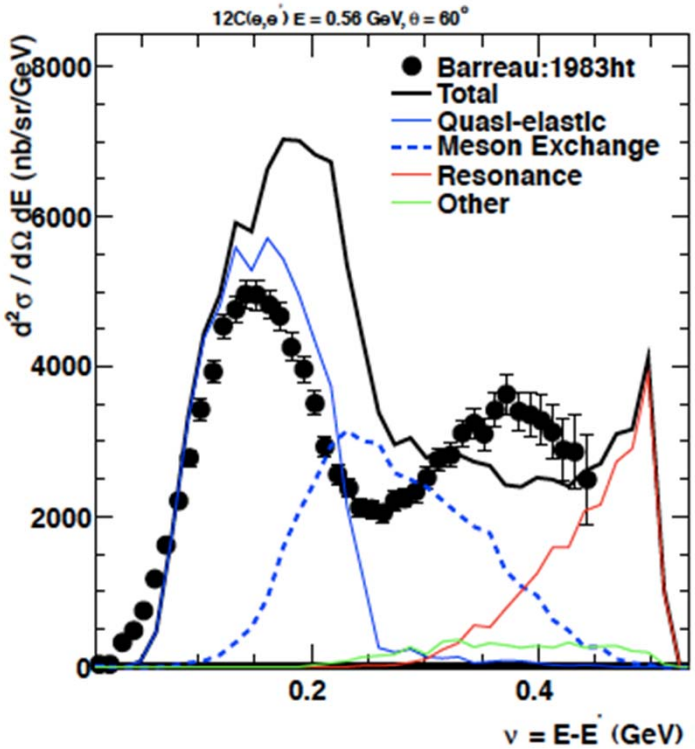


More schematic approach for GENIE

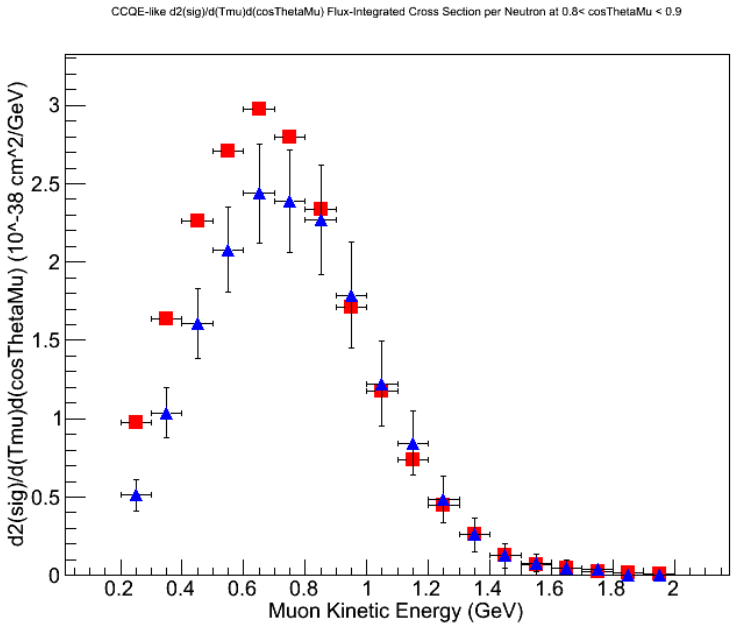
- Based loosely on O'Connell, Lightbody (1988)
- MEC modeled by a Gaussian (M~1.9 GeV, Γ~300 MeV)
- Form factor similar to eD scattering.
- *Same form used for (e,e') and MiniBoone*.
- Set overall normalization to match MB, then all else scales with transverse $Z\sigma_{\nu p}+N\sigma_{\nu n}$, $Z\sigma_{ep}+N\sigma_{en}$.
- Gives cross section ~A, same as theory.
- Qualitative agreement with data so far.

Data comparison

560 MeV C(e,e')

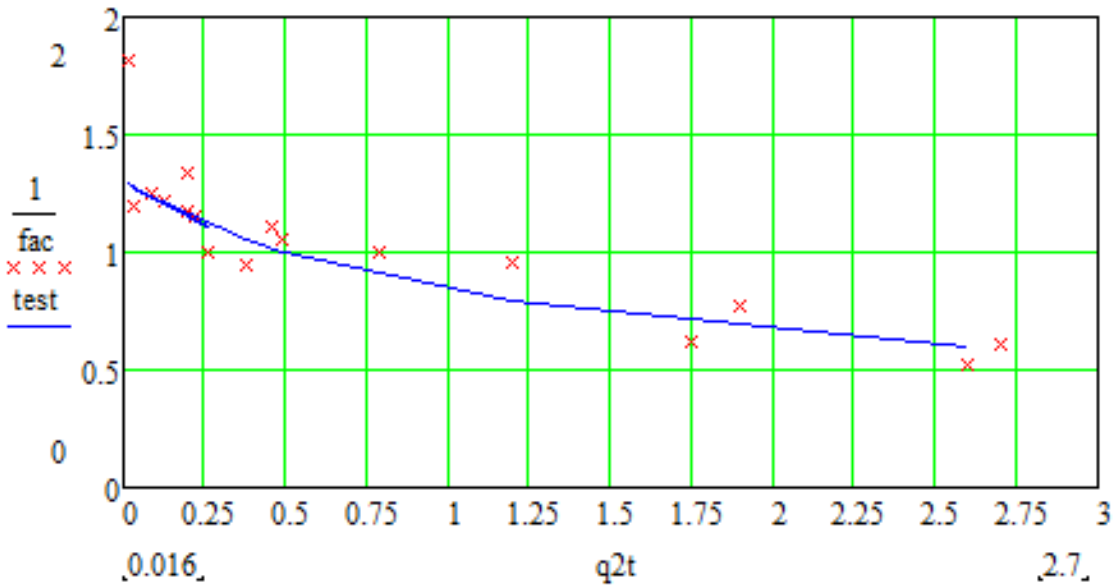


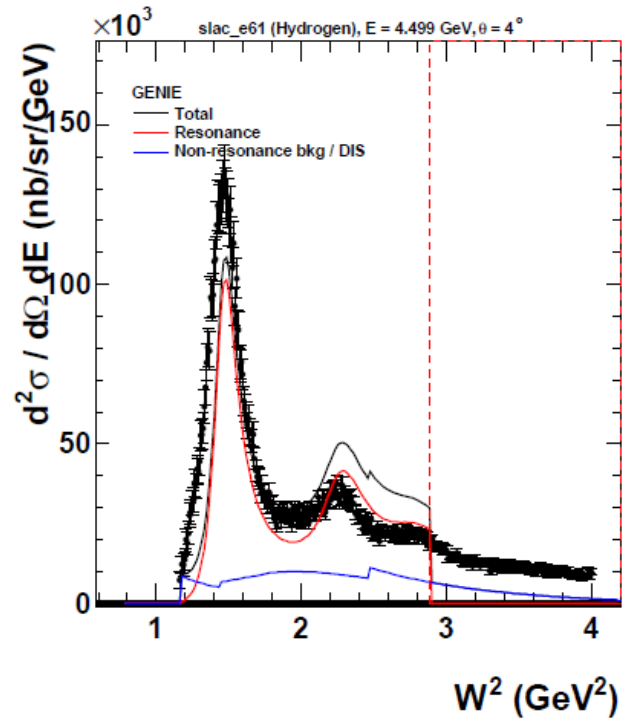
MiniBooNE 0.8<cos(θ_μ)<0.9



Δ form factor work

- Rein-Seghal is very old, known to be wrong.
- Study vector form factor in ep→ep and eD→eD.
- Jarek Novak has given us formulas to include μ mass.
- Expect completion in a month or so.





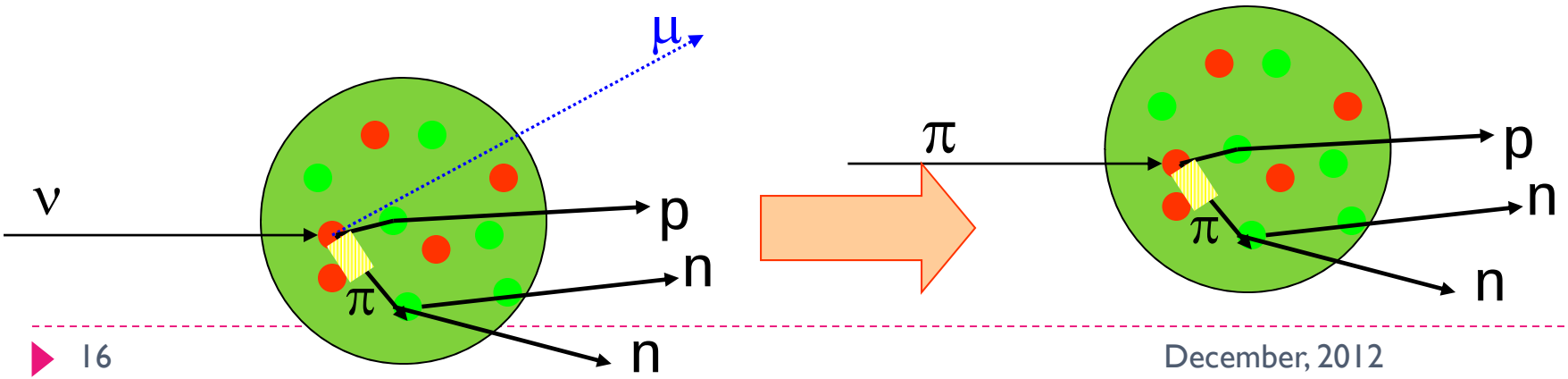
What does FSI do to ν expts?

- ν expts want to make clean identification of physics by topology of events and **FSI masks topologies**.
- Calculate E_ν from QE events.
  - Ideally, ν interacts with single neutron and we see products. ν_μ n $\rightarrow$ μ^- p. In reality, n isn't free and p must get out of nucleus.
  - μ + p ID is much better, but ~35% of protons have significant FSI.
  - μ doesn't give clean ID because pion prod kinematics overlap QE.
  - Not all pion prod events have pion in final state (~25% absorption).
- Needs for π, p at kinetic energies <~1 GeV (T2K)
  - Overall interaction rates
  - Topology changing interaction rates, e.g. p $\rightarrow$ n, π $\rightarrow$ p or n.

General Characteristics of models

Intranuclear Cascade (INC), real and inspired.

- hN is straightforward INC
  - Uses free 2- and 3-particle **free** cross sections + Fermi motion
  - Success comes from importance of quasielastic reaction mechanism in nuclear physics *and* existence of PWA data.
- hA is simplified INC
  - Construct models of full chain of events
  - Uses simple representations of hN code, data, and intuition.
  - Easily reweighted (exact) because **each particle has at most 1 interaction as it propagates through residual nucleus**.



Basic outline

Hadron in nucleus
produced at a principal vertex
(e.g. pion production)

Formation time = **Free step**
Step hadron through nucleus in 0.1 Fm steps. Assess probability of interaction with $\lambda(E,r)=1/\rho(r)\sigma(E)$.

default

hA model
- Choose interaction from list (data, models, intuition)
- Elas, Inel, CEX, abs (KO), pi prod
- Choose kinematics by models, phase space and exit.

hN model
- Choose interaction according to list (data, models, intuition)
- Elas, CEX, π prod, abs, pre-eq
- Choose kinematics by PWA model
- Add particles to stack until all out.

Improvements of 2.7.1 over 2.6.x

- p and n interaction mix more correct
  - Previously used results of another INC model
  - Both p and n reaction xs underestimated by ~20%
- Isospin treated correctly
  - π+ not same as π -.
  - Nuclei not always isoscalar (doesn't matter)
- Absorption more detailed
  - No more artificial cutoff in no. of nucleons emitted
  - Use hN model to parameterize no. of n, p
  - Phase space for energy, angle distributions (should be better)
- Much better pion production model
- 2 models with different strengths allow easy comparisons

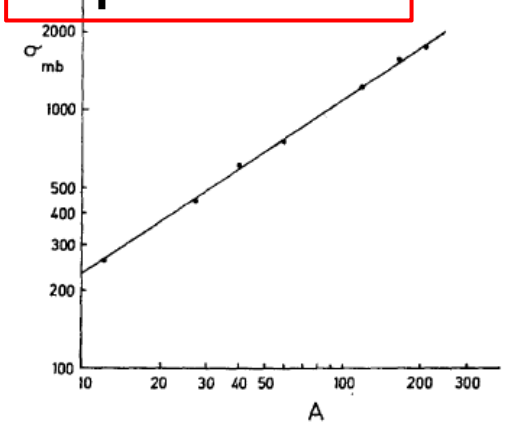
hA vs. hN

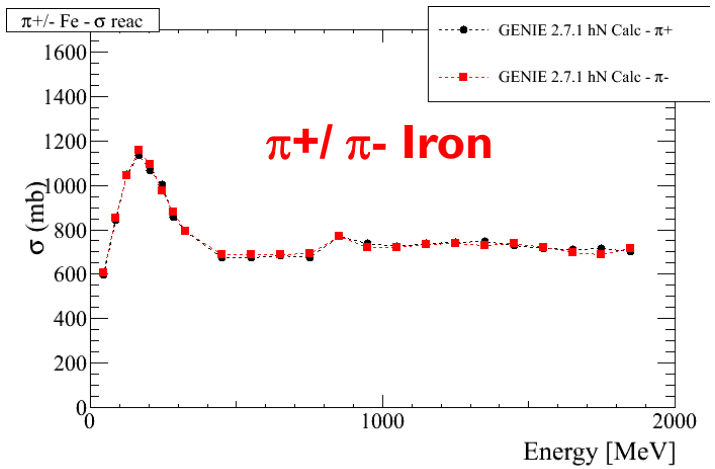
- hA will be default for long time, therefore better developed than hN.
- hA was ‘tuned’ to Fe, all other nuclei done by $A^{2/3}$ scaling.
- hN A dependence will tend toward $A^{2/3}$ scaling.
- For pion absorption, both are oriented toward 2-body mechanisms, no 3-body mechanisms.
- hA and hN have different assumptions on energy/angle distribution of final state particles.
- Low energy nucleons come from separate compound nucleus mechanism in hN, mainly from ‘absorption’ in hA.

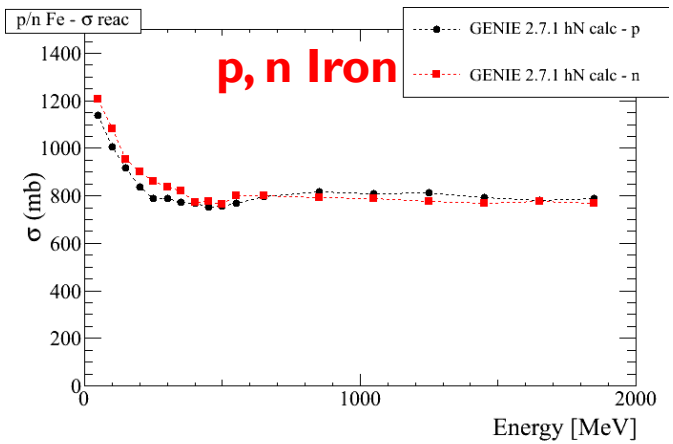
Organizing principle #1
nucleus is ~black to hadrons (not like ν!)

- Mean free path ~ few fm, total reaction cross section ~πR^2, only 'R' changes with probe. σ_{reac} measures strength of all inelastic interactions- $\sigma_{reac}=\sigma_{cex}+\sigma_{inel}+\sigma_{abs}+\sigma_{\pi prod}$
- Exceptions:
  - Pions at KE~200 MeV have a strong resonance (Δ) (more than black)
  - Low energy nucleons have strong interaction and large 'size'

1 GeV/c π-
Slope=.677±.007

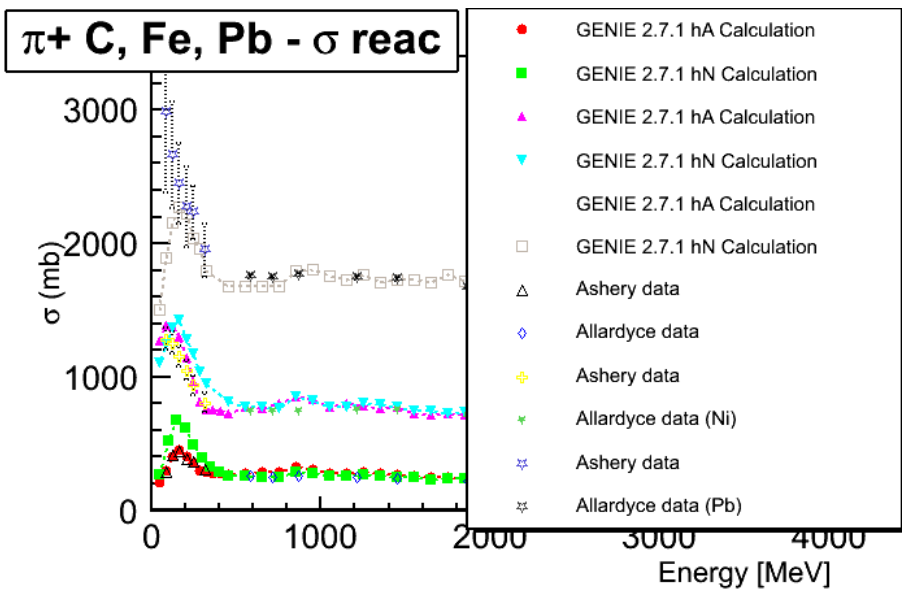


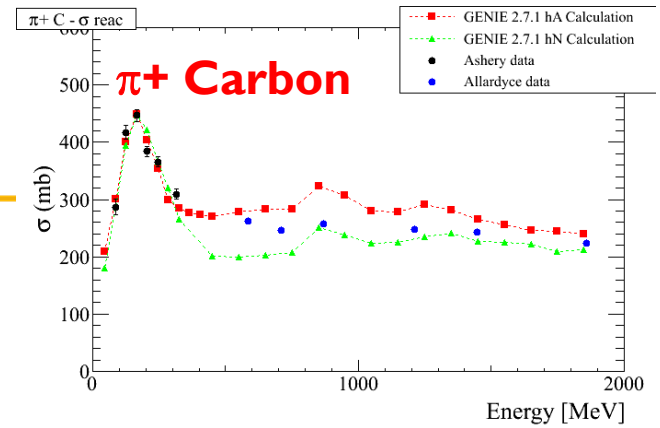


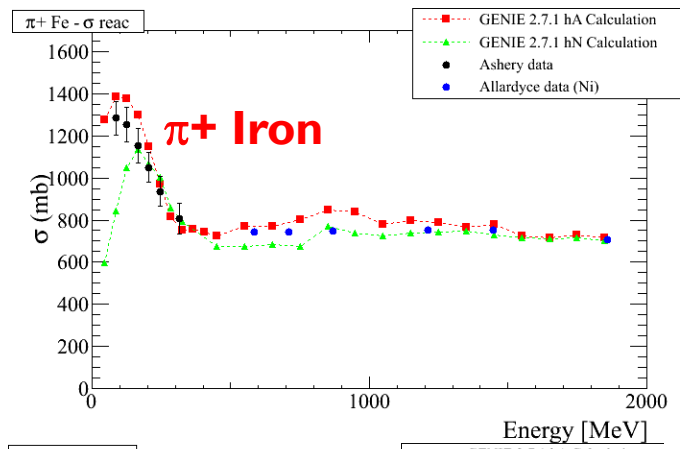


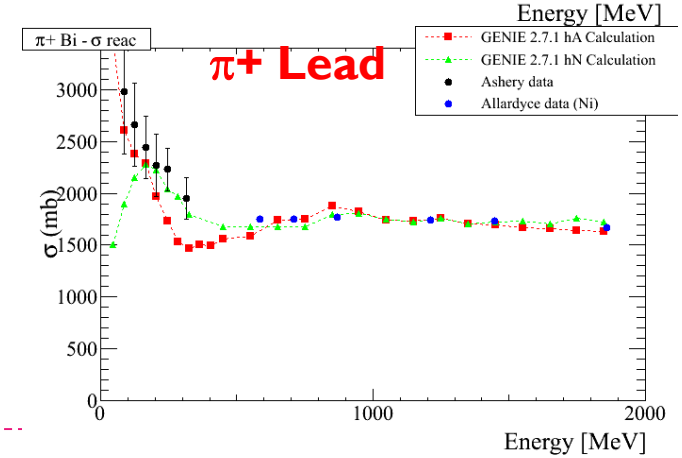
σ_{reac} (pions)

- We see same features
- GENIE is good agreement except for hN at low energies.
- π^- almost identical but data poorer quality.



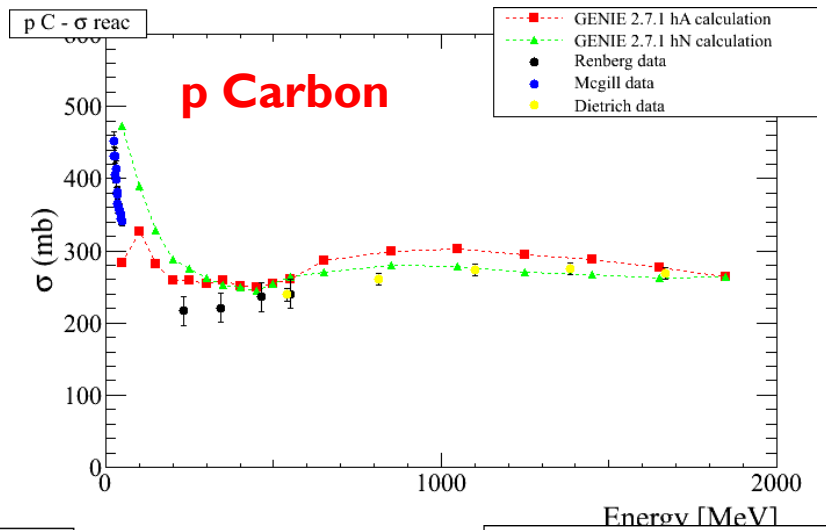


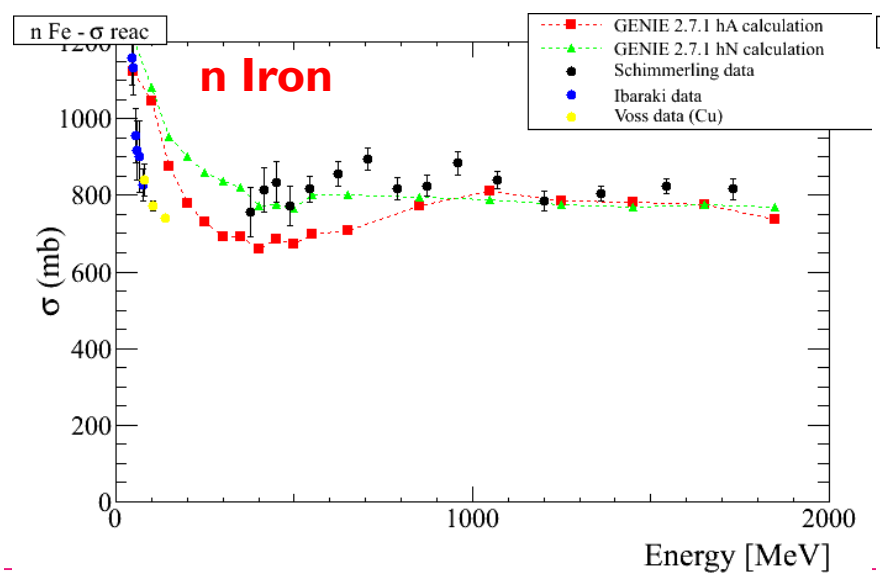


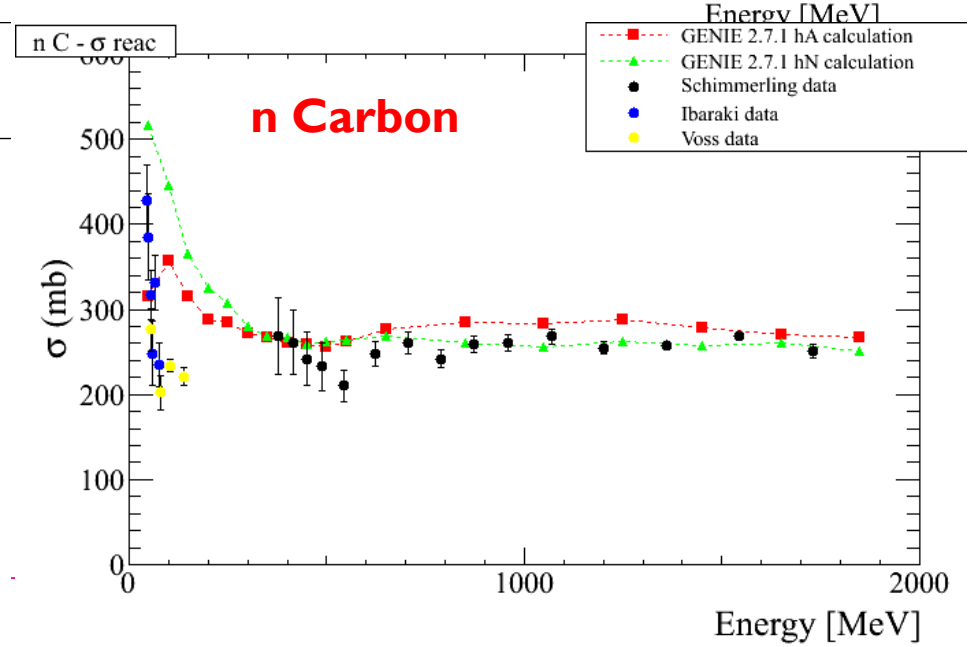


σ_{reac} (nucleons)

- Again, GENIE has right features.
- Hard to get very low energies right.

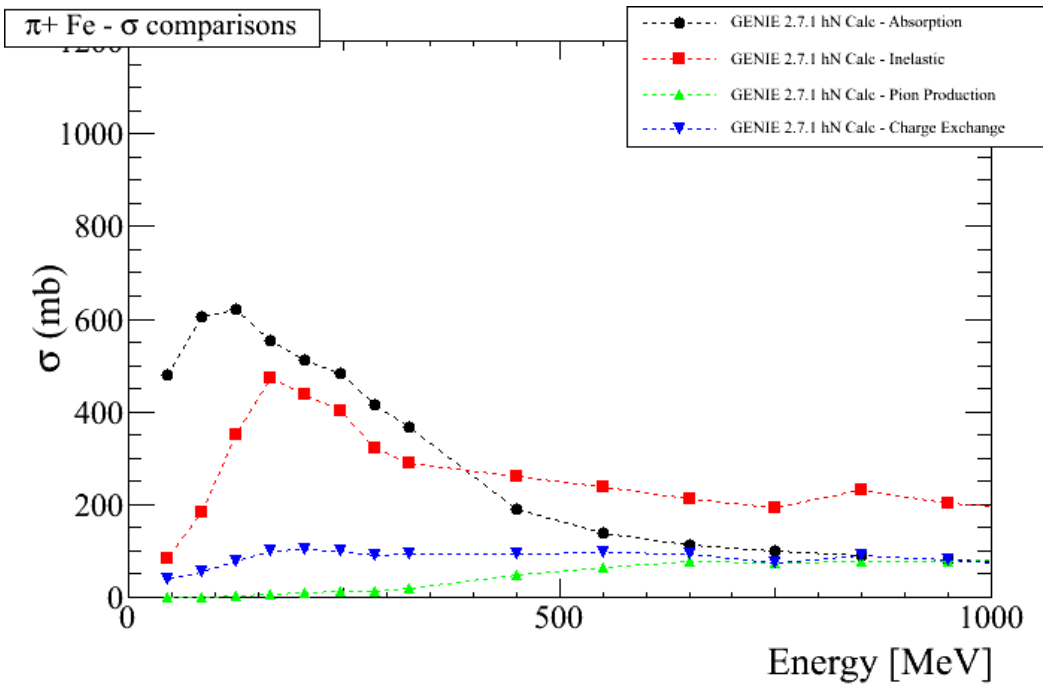


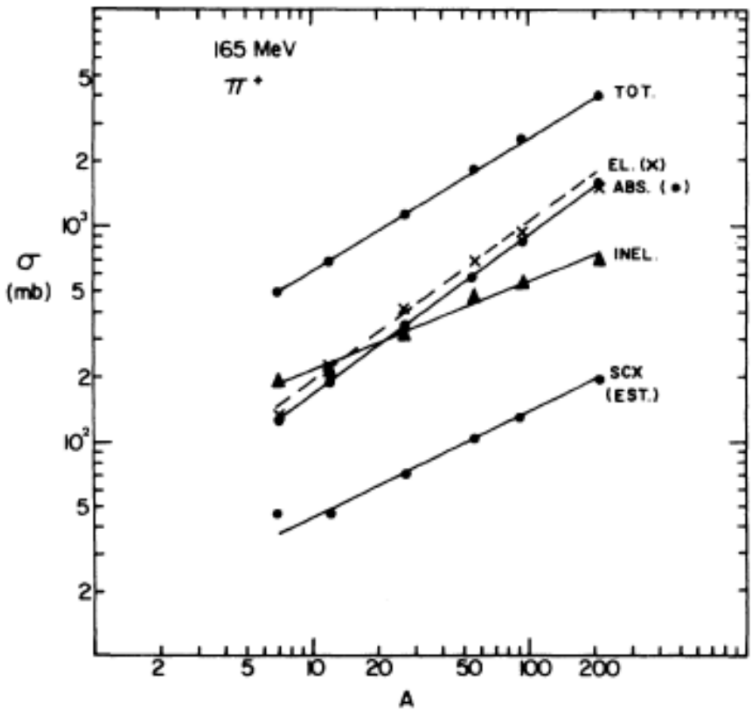




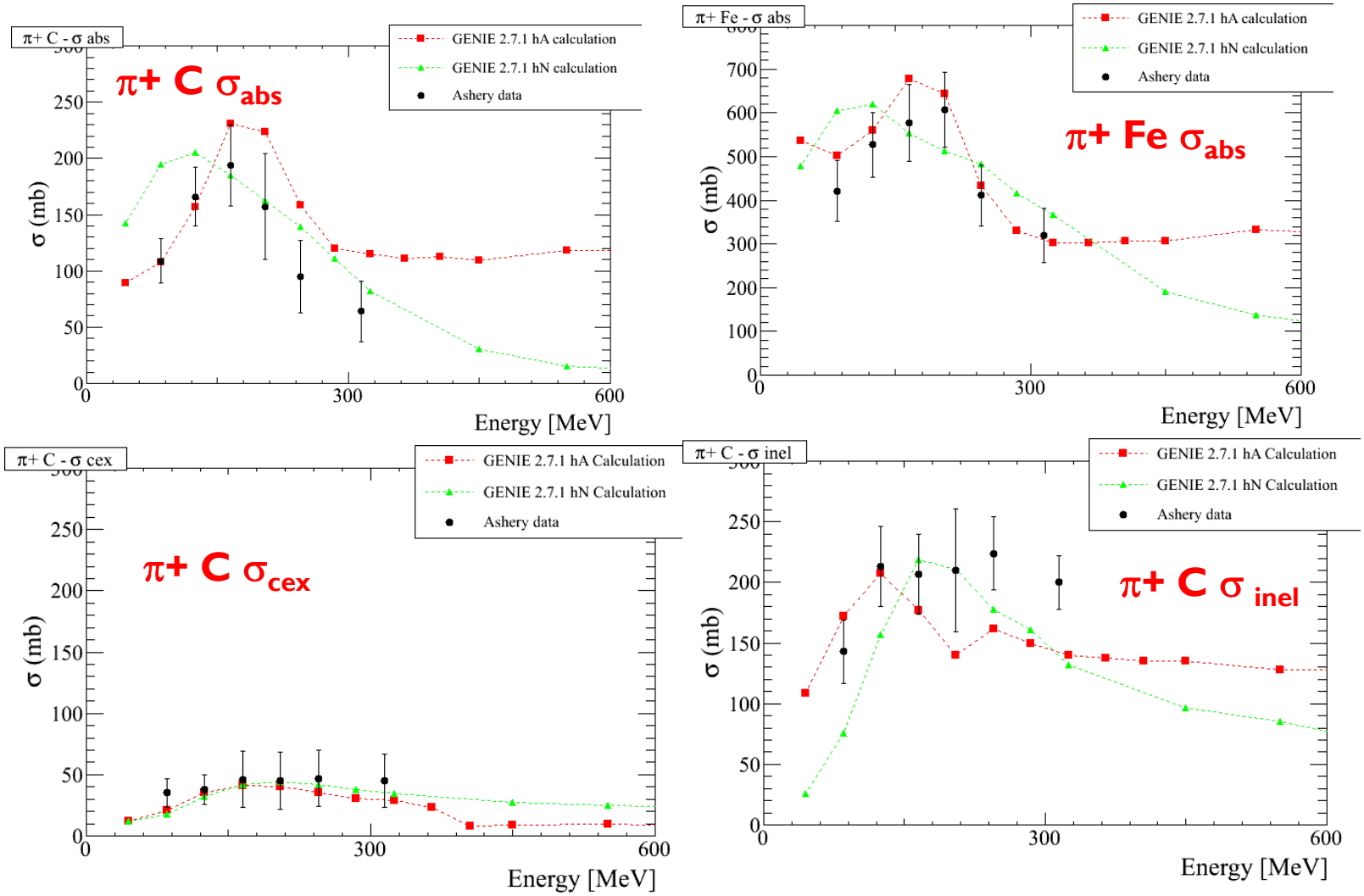
Total is easy, but subdivision complicated.

- Relevant processes are very energy dependent
- Sometimes deviations from $A^{2/3}$.





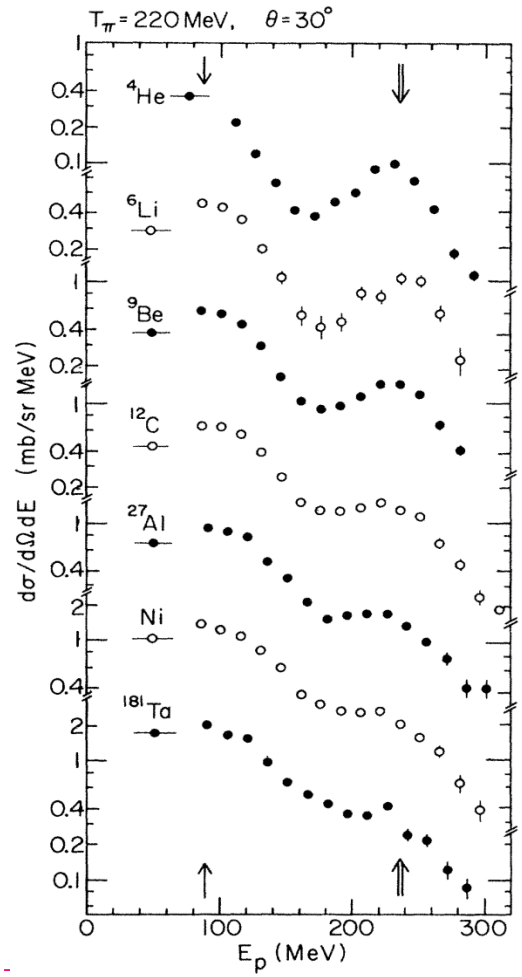
Various component total cross sections (less impressive data, ~30% est. errors common



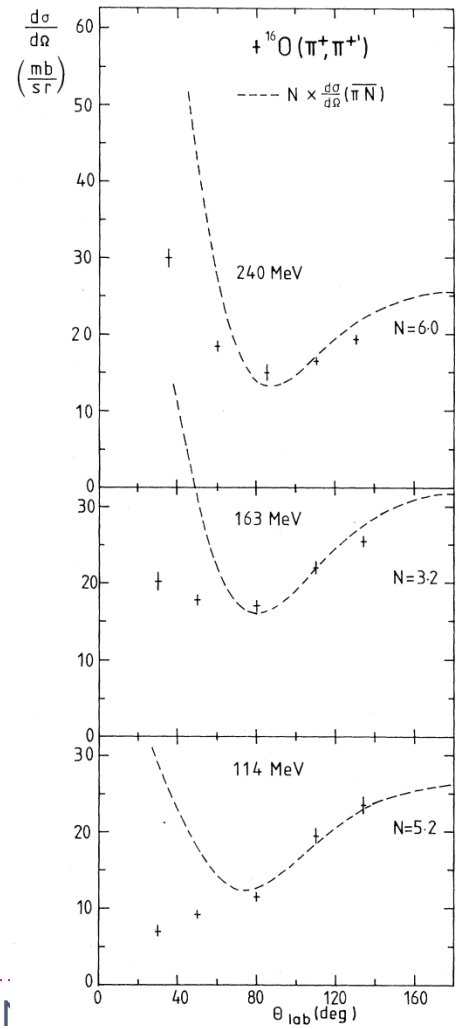
Organizing principle #2
simple processes are often important

- Quasielastic (QE, almost elastic) processes are noticeable for light nuclei even with resonance.
- Inclusive expt: map xs vs. KE at θ.
- Arrows show $\pi p \rightarrow \pi p$ and $\pi d \rightarrow pp$ kinematics.
- Right plot compares πN cross section with total inclusive xs.

$\pi^+ A \rightarrow pX$

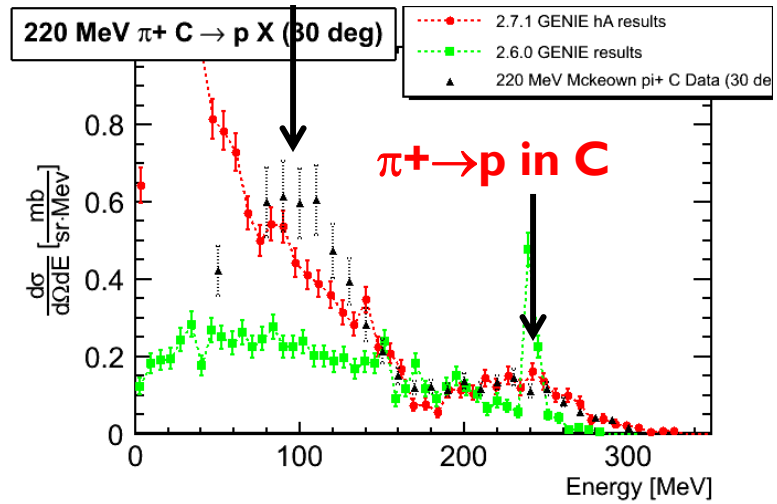


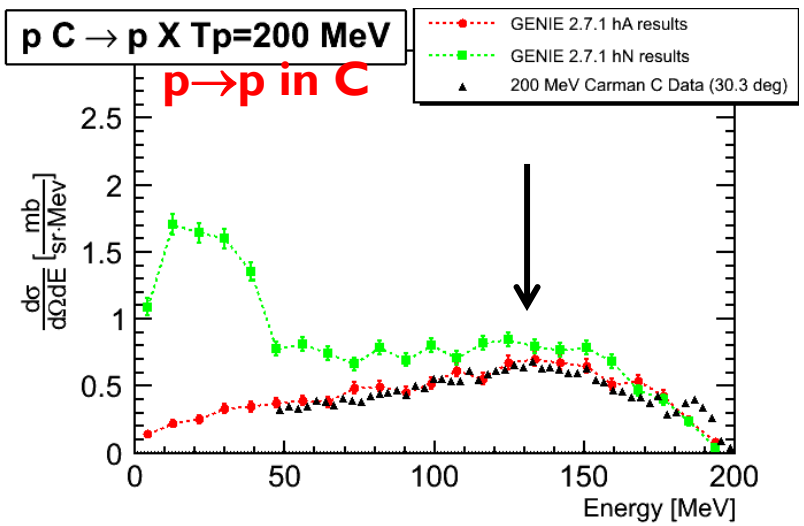
$\pi^+ O \rightarrow \pi^+ X$

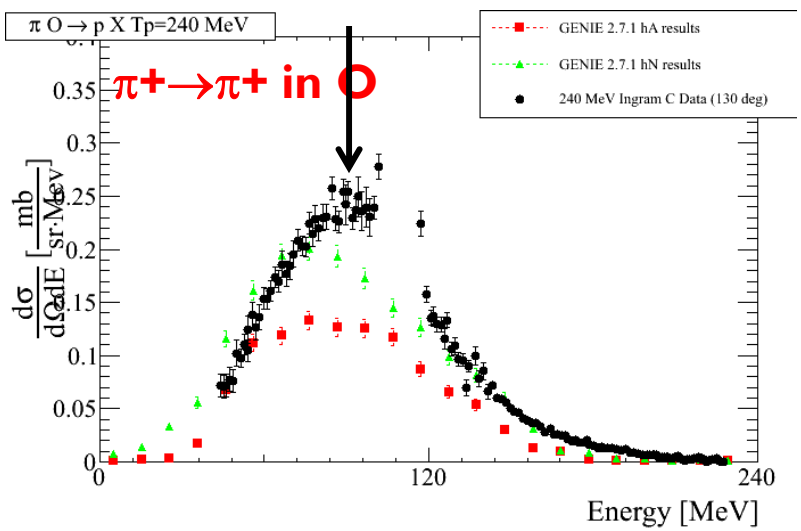


Look for QE processes

- Both hA and hN have it about right.
- QE peak is shifted (BE) and broadened (Fermi motion)

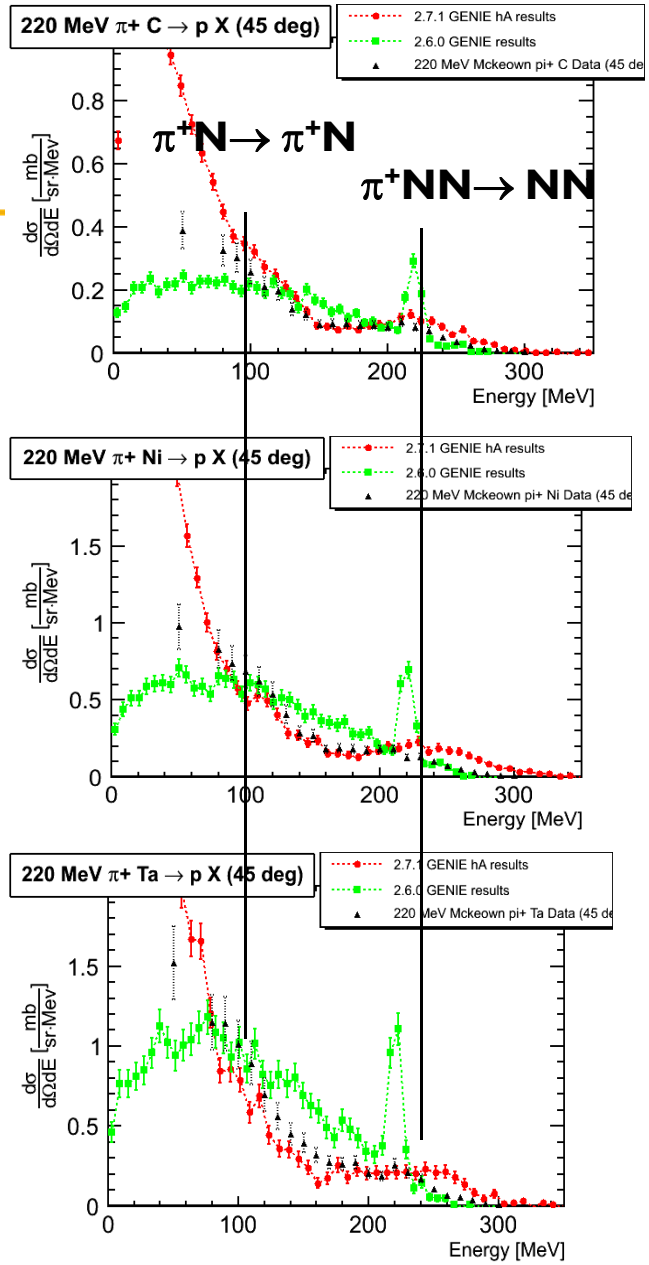






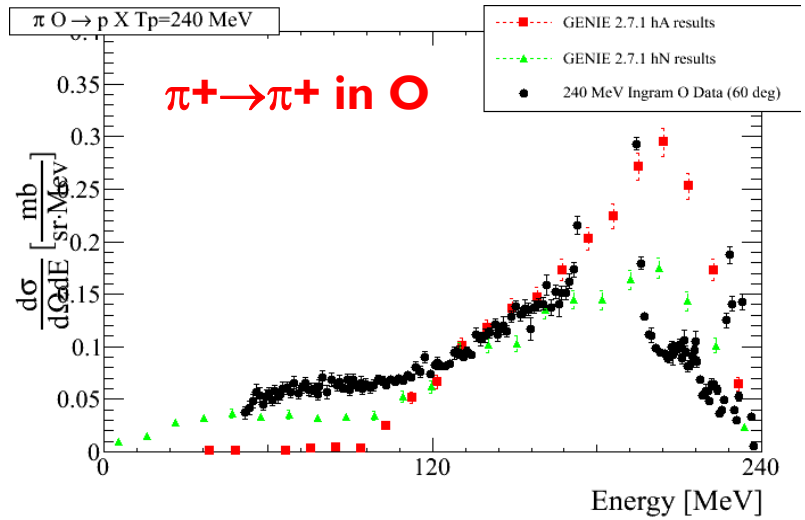
QE gets smeared out with A, but persists

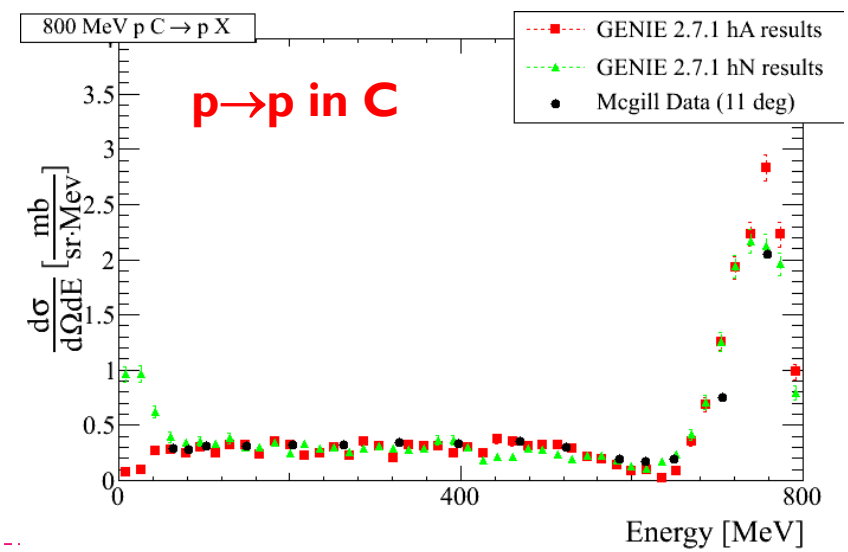
- π^+**N**$\rightarrow$ π^+**N** QE scattering in medium (don't see falloff on low energy side)
- π^+**NN**$\rightarrow$ **NN:** QE absorption in medium
- Peaks shifted and broader because of binding, Fermi motion



BUT there are other processes….

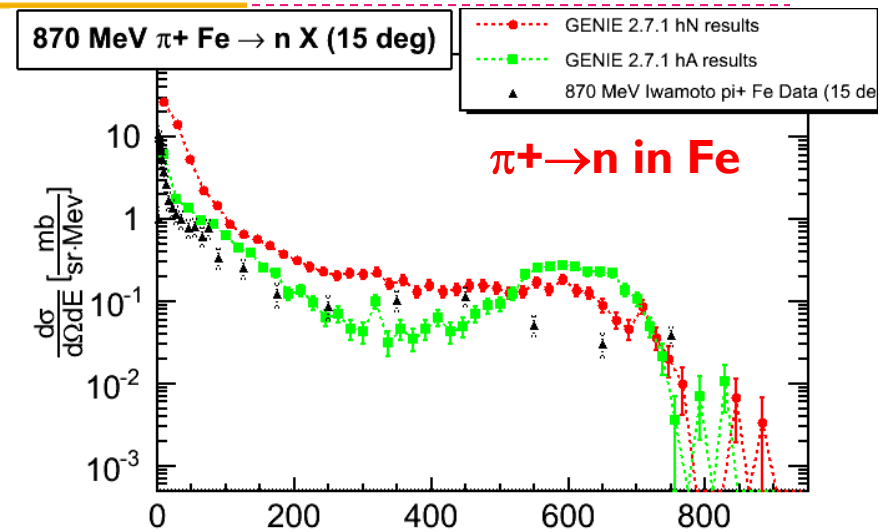
- At forward angles, get QE peak at low energy loss.
- Also see long tail due to additional scattering.
- hN has this, hA doesn't have it.
- Perhaps, this is a detail?

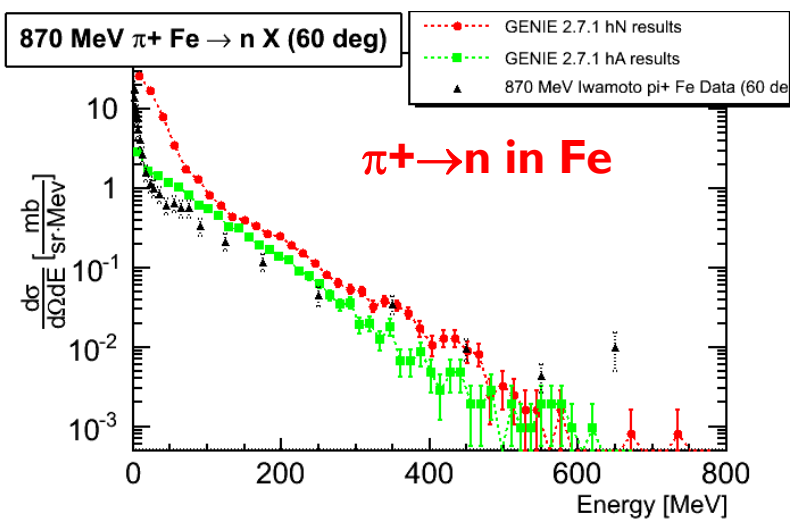


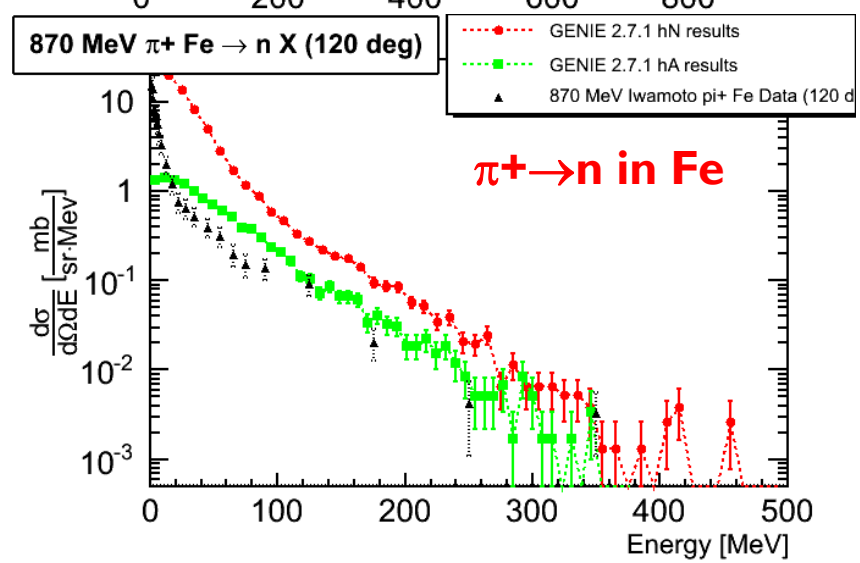


…AND QE processes not always obvious
phase space matters. (also important example)

- 870 MeV π^+ in Fe, look for n (1-800 MeV) at various angles
- See various processes, but not much separation.
- Large peak at few MeV constant with angle (compound nuclear processes)

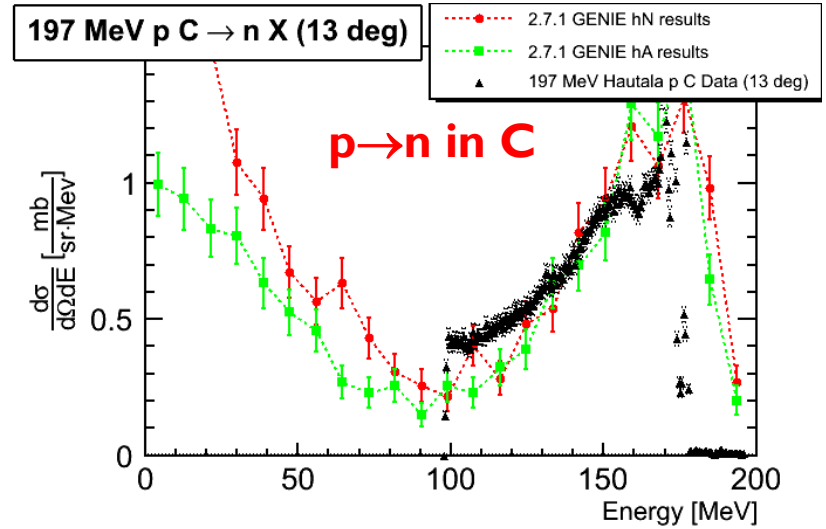


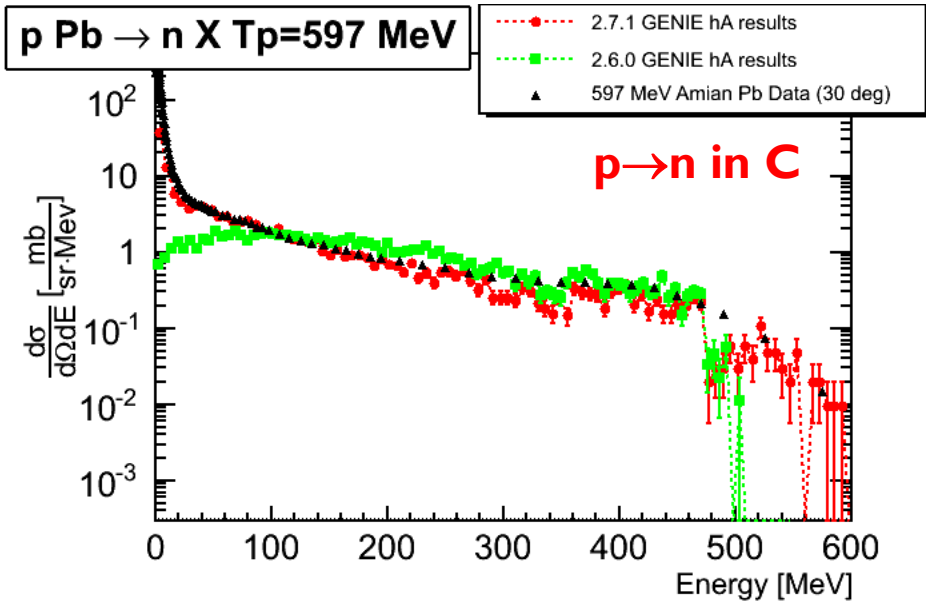


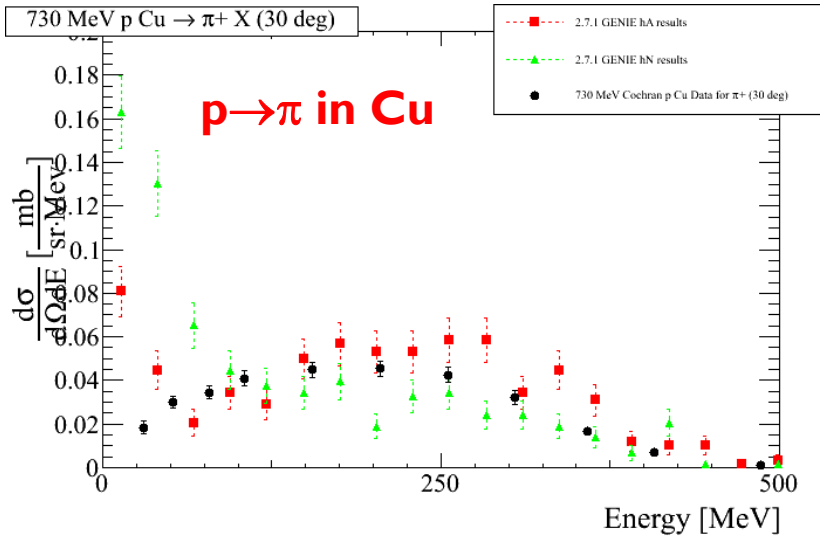


More topology changing interactions

- $\pi^{\pm}$, p, and n all have different responses in scintillator.
- Features all done well, differences in detail.

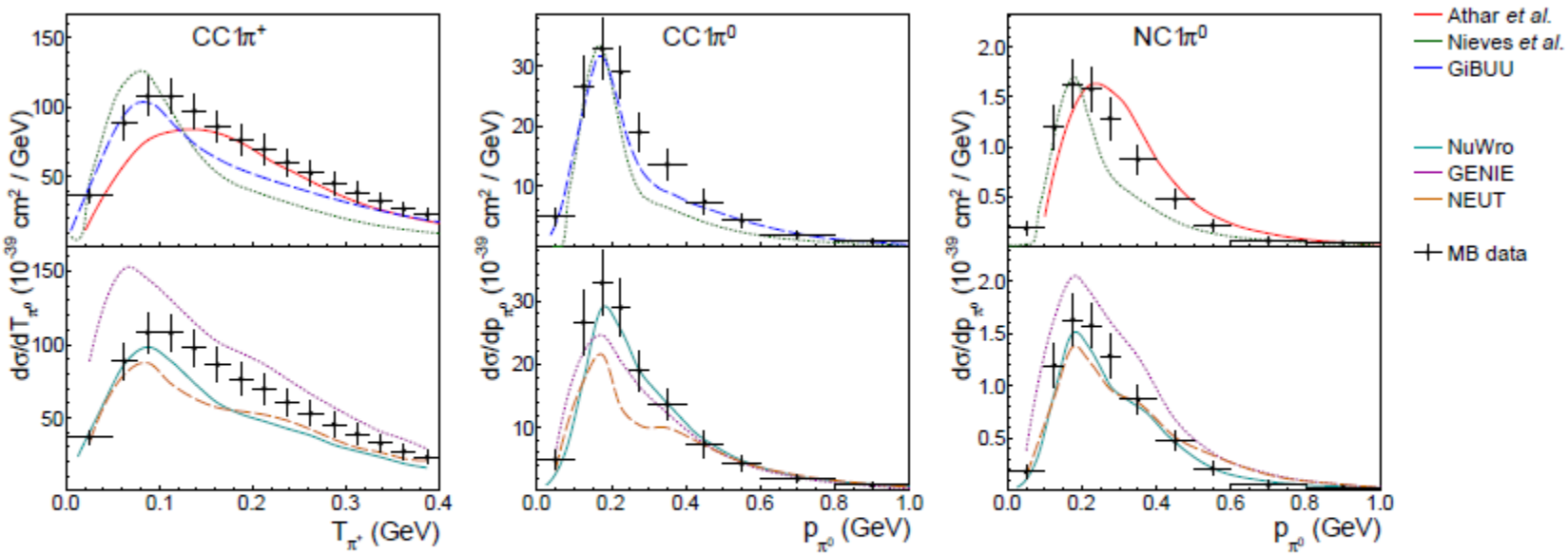






Example – pion momentum spectrum

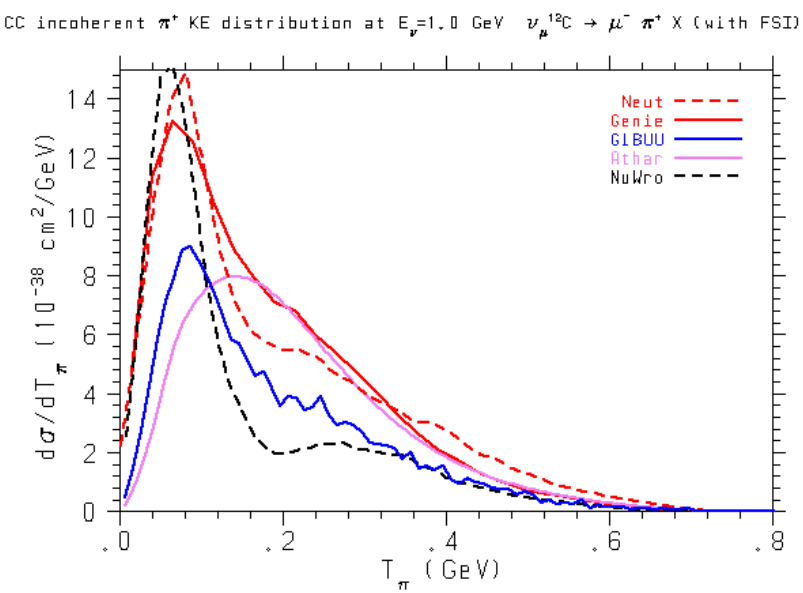
- Plots from Phil Rodrigues – theory at top, gen at bottom
- He wants better, I'm happier but ready to improve
- NOTE dip at p_π~0.2 GeV/c (π absorption in medium!)

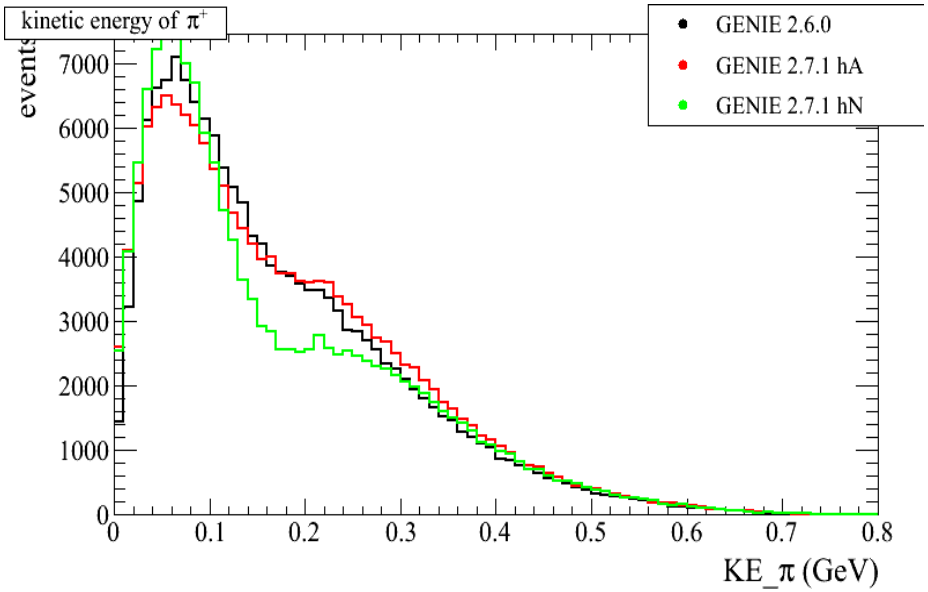


- Poor agreement across the board in CC1π^+
- Generators do better than theoretical models in CC1π^0, NC1π^0

Hmm, we plant a pion uniformly and watch it propagate.

- Looks like we measure attenuation
- Models with large attenuation have stronger dip, models with no attenuation have no dip.
- Looks like MB data wants very little attenuation, best theory models are not in agreement.

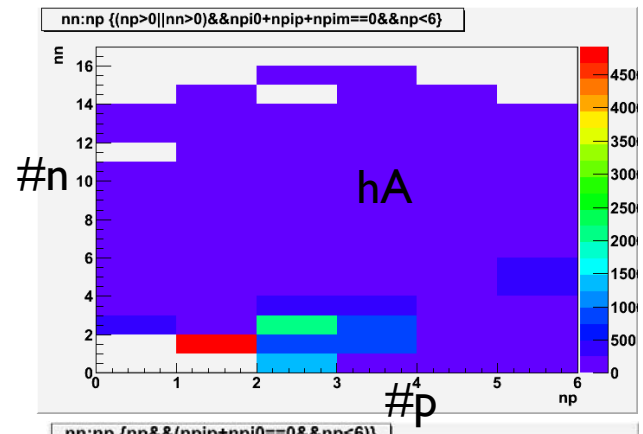


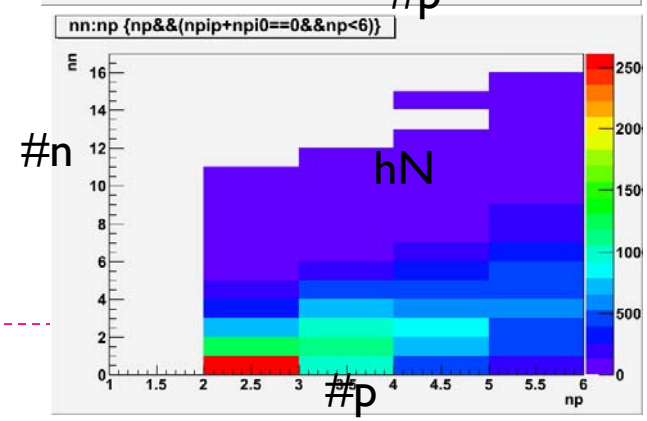


LADS π^+ Ar data shows absorption details

- Lots of data for 239 MeV, some for other energies, tgts
- Variation among these final states is complicated.
- Note significant corrections for data below threshold.
- Do we need to get agreement with all of these?
- IMHO, no!

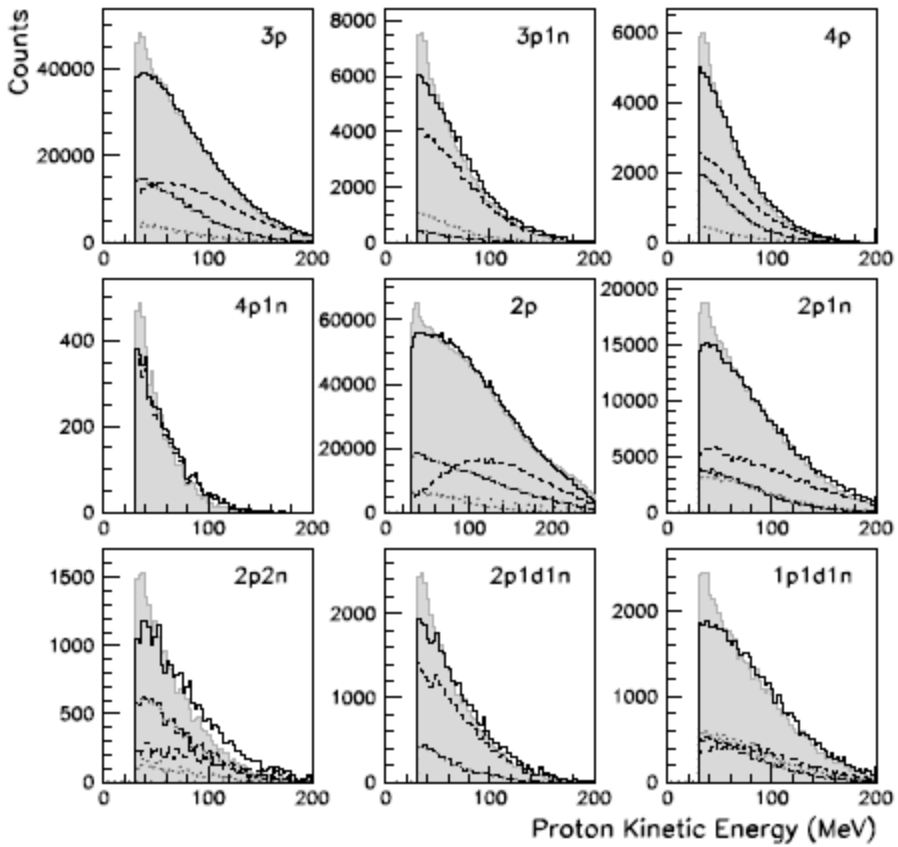
	Raw Data	30 MeV Threshold	Extrapolated to 0 MeV
5p	0.013 ± 0.001	0.04 ± 0.01	0.64 ± 0.13
4p	1.11 ± 0.10	2.0 ± 0.2	5.1 ± 1.0
3p	19.9 ± 1.2	26.8 ± 2.5	28.4 ± 4.0
3pn	2.0 ± 0.2	11.9 ± 1.3	33.2 ± 7.5
2p	69.8 ± 4.2	72.9 ± 5.8	43.6 ± 5.2
2p1n	11.9 ± 0.9	62.9 ± 6.6	$75. \pm 10.$
2p2n	0.67 ± 0.05	5.6 ± 1.0	$21. \pm 8.$
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

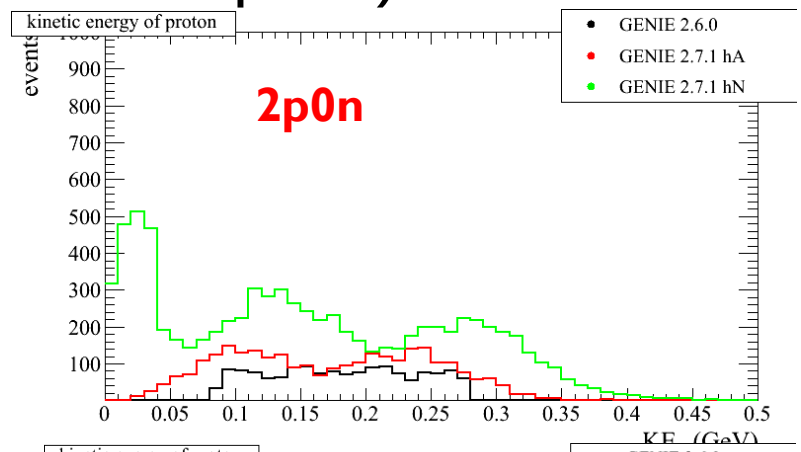


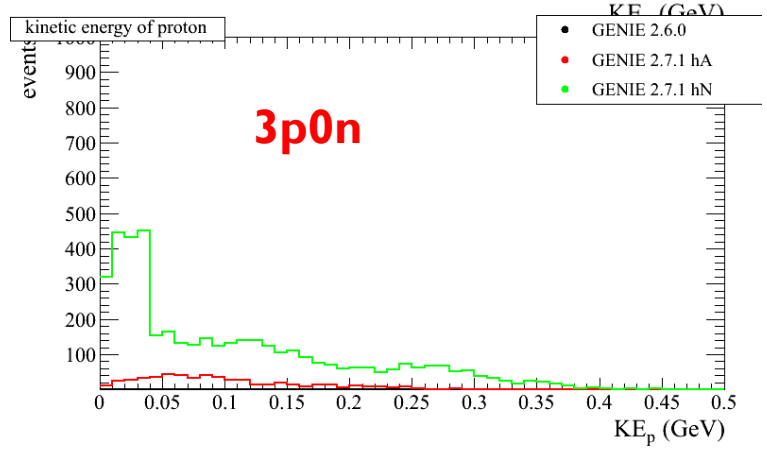


LADS proton KE distribution (239 MeV π^+ Ar)

- Looks a lot like phase space, but they note importance of ISI (scatter before absorption).

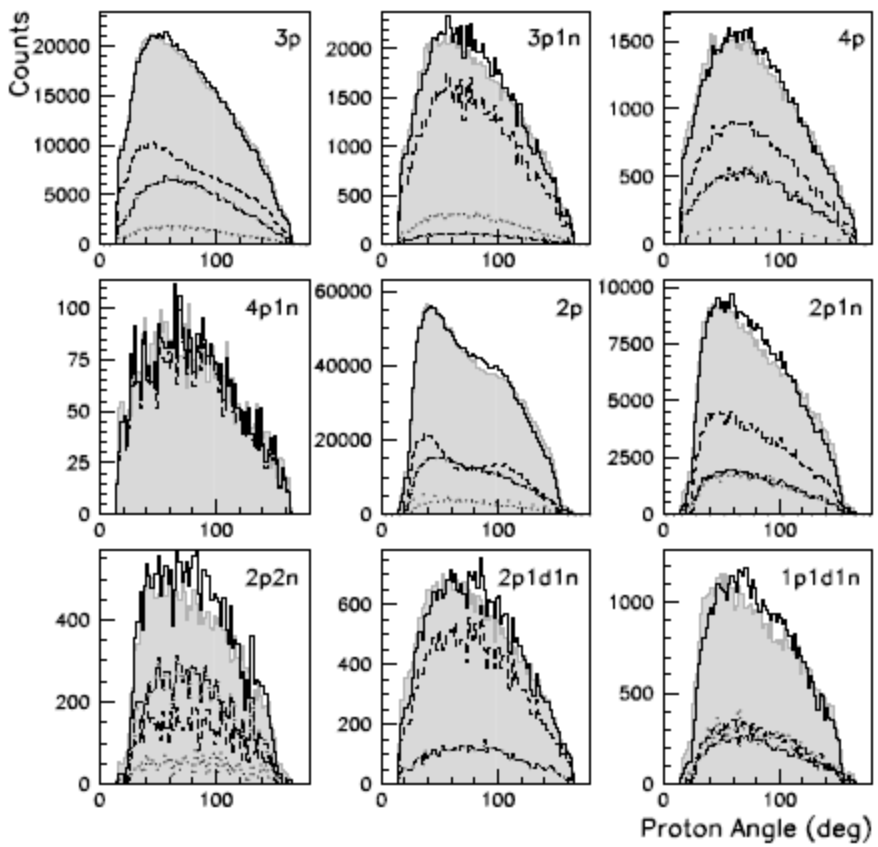


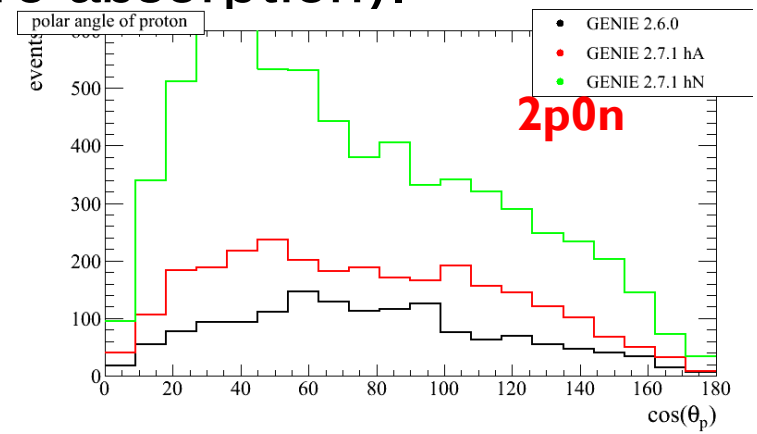


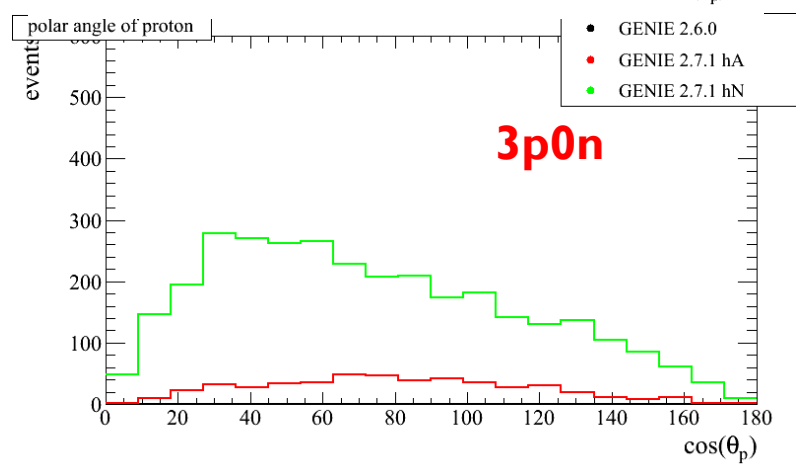


LADS proton angle distr (239 MeV π^+ Ar)

- Looks a lot like phase space, but they note importance of ISI (scatter before absorption).

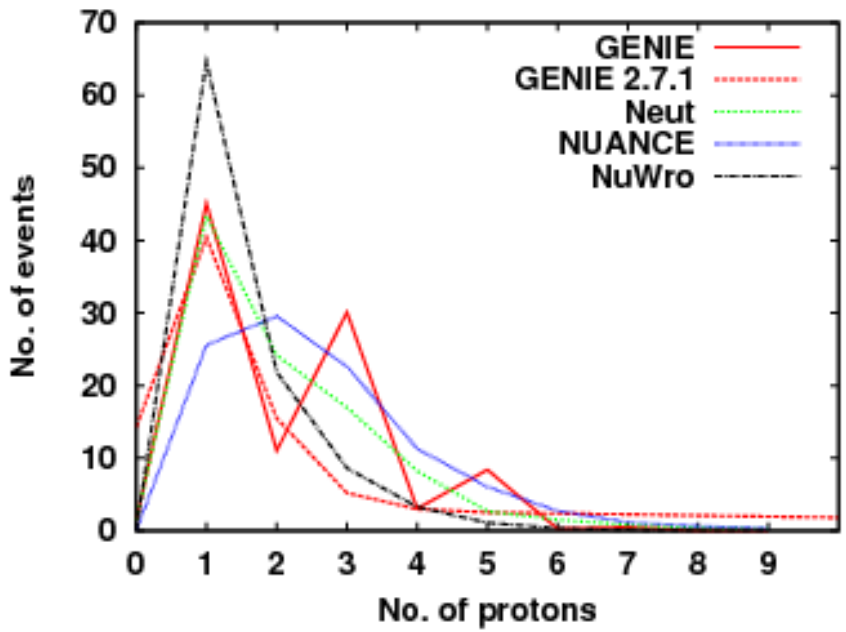




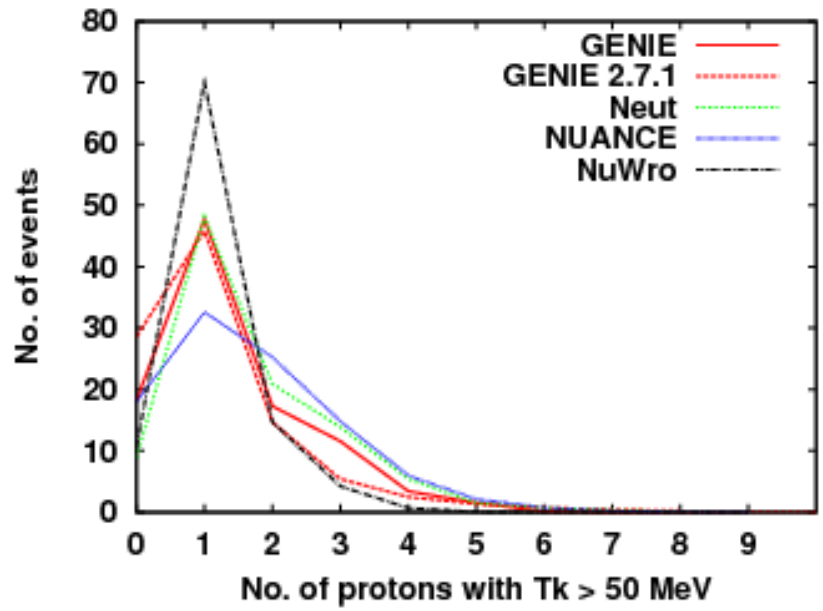


Example - proton multiplicity
ν_μ Ar – 3 GeV (ArgoNeut for NUINT12)

All Protons (many sources!)

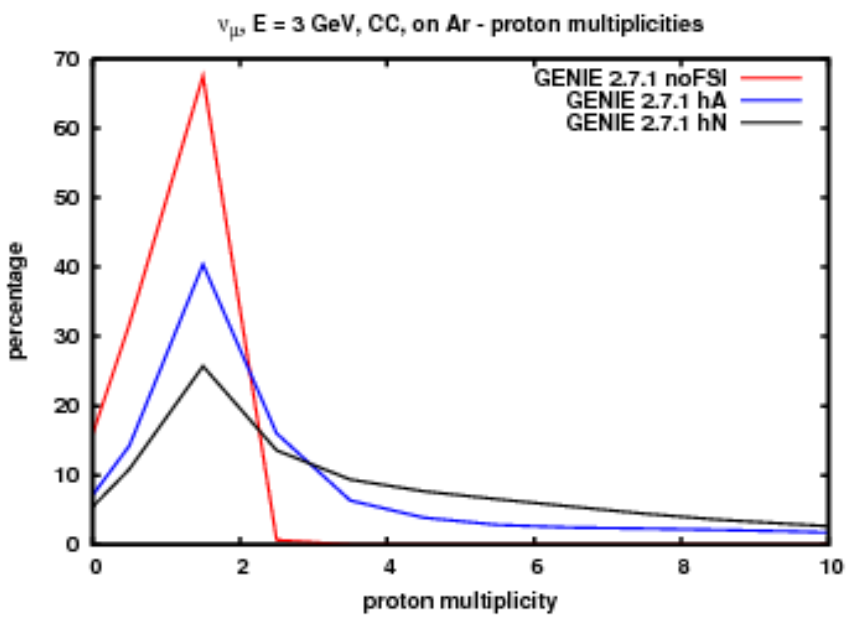


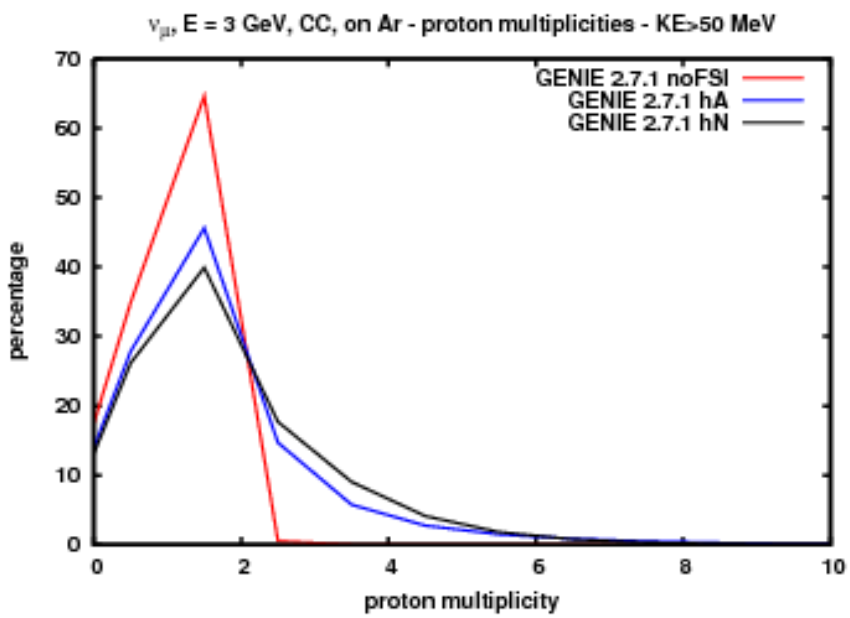
Protons with KE>50 MeV



Proton multiplicities for GENIE versions

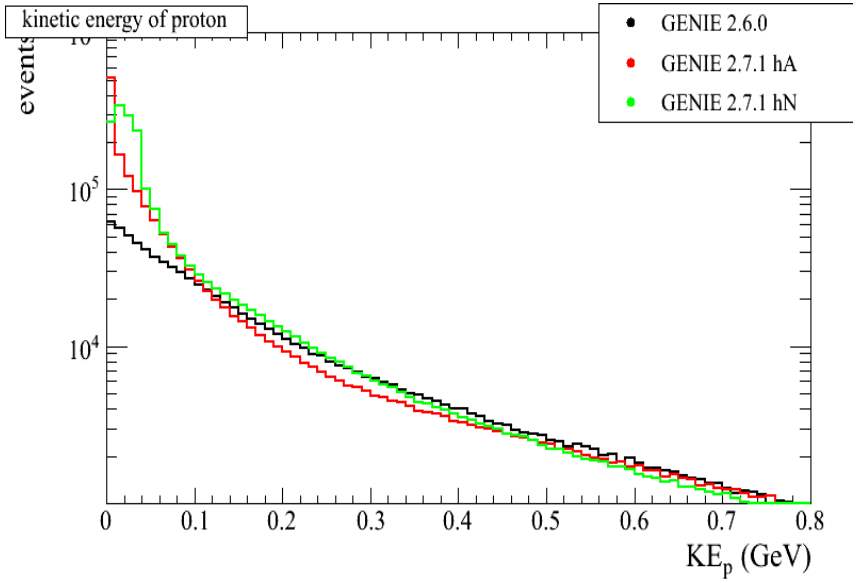
- Multiplicities of hA and hN were designed to be similar.
- FSI has smears things out.



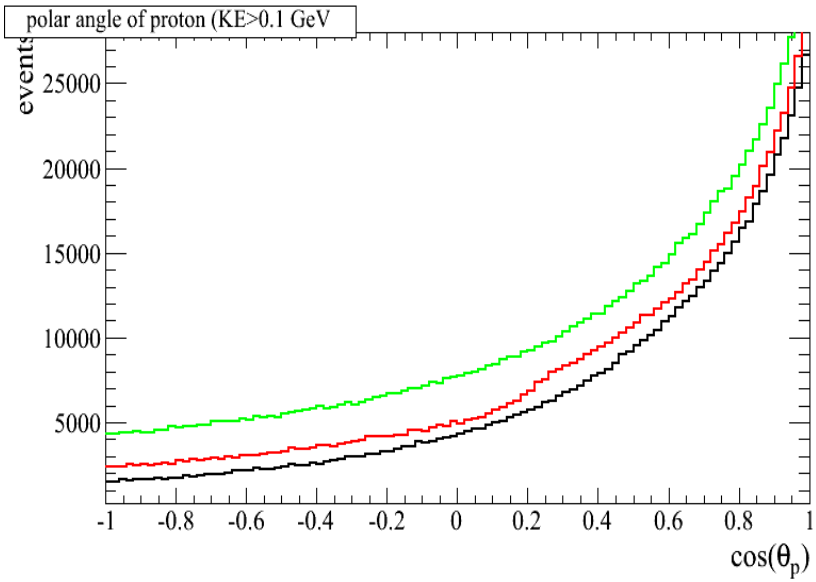


proton energy/angle distributions
ν_μ Ar – 3 GeV (ArgoNeut for NUINT12)

Proton KE (all sources!)

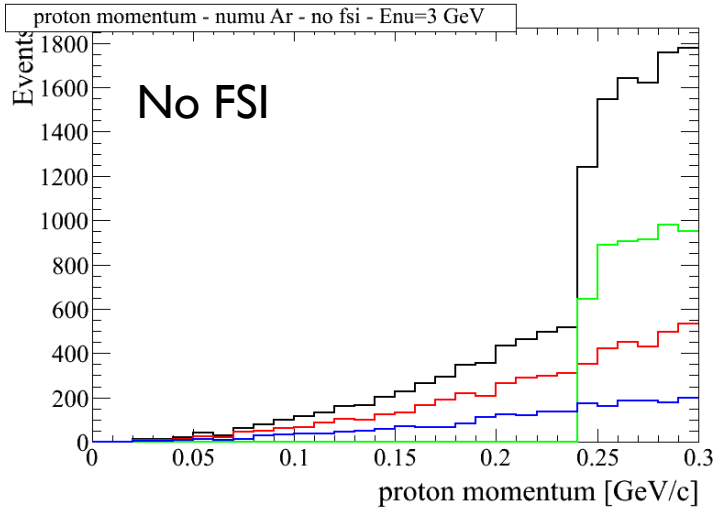


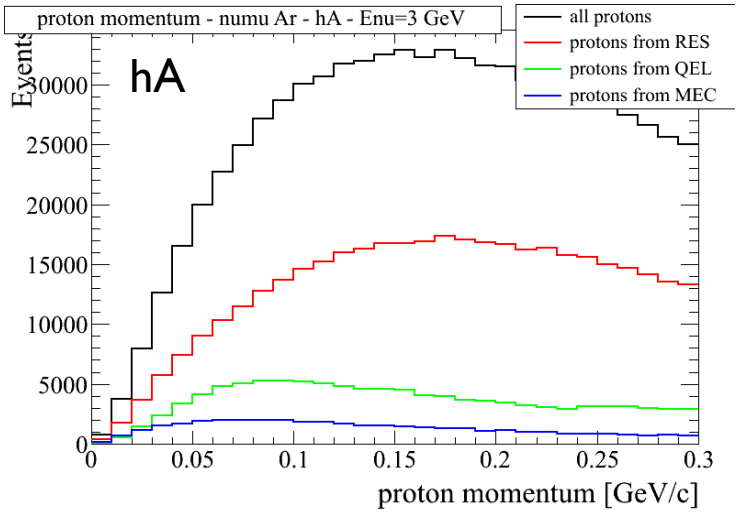
Θ Protons with KE>50 MeV

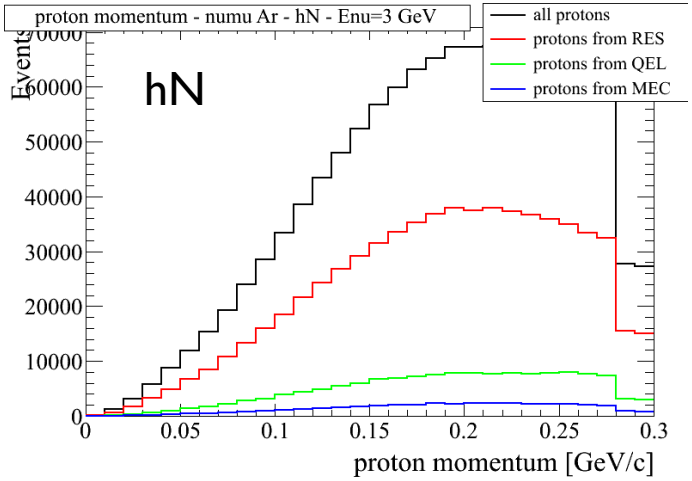


Proton momentum through different versions

- Show breakdown into different channels – QEL, RES, and MEC.
- If you stare a bit, you can see MEC will be hard to disentangle from FSI.

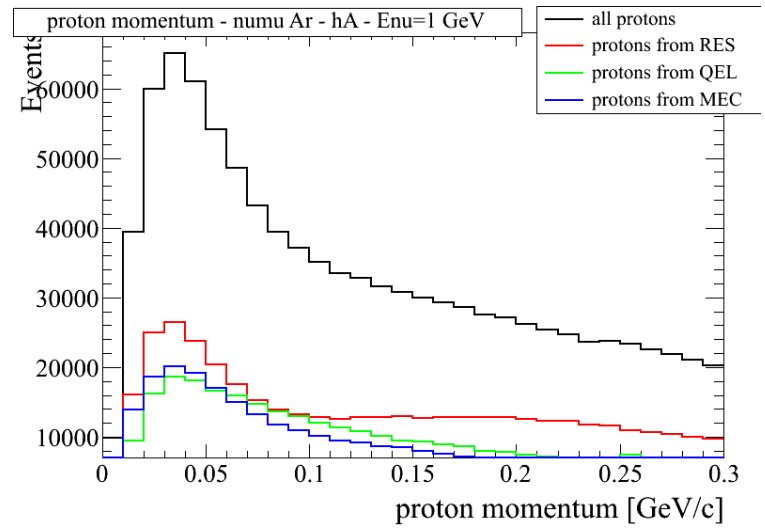


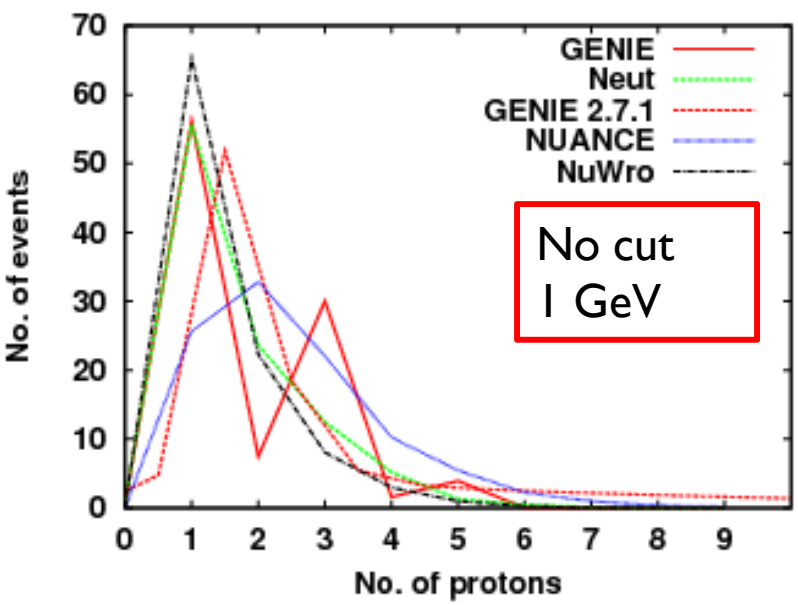


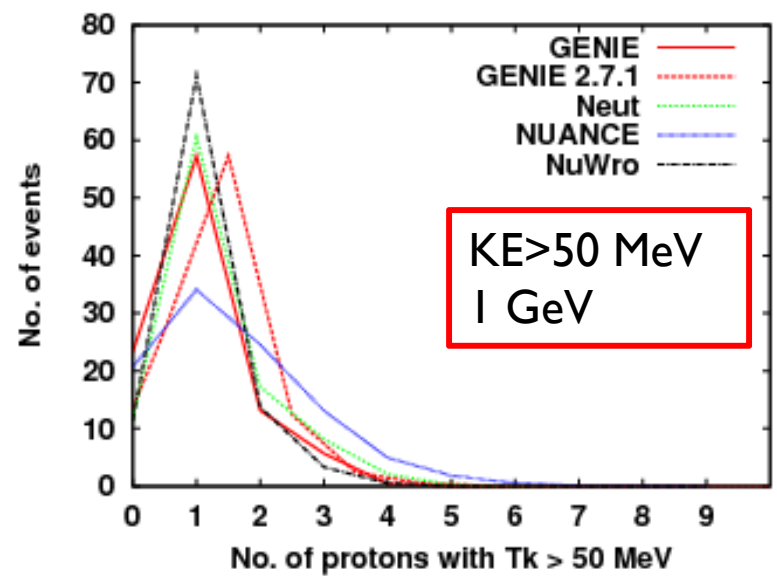


Quick look at 1 GeV ν_μ Ar

- Multiplicities look very similar to 3 GeV.
- However, more shift to lower energies.

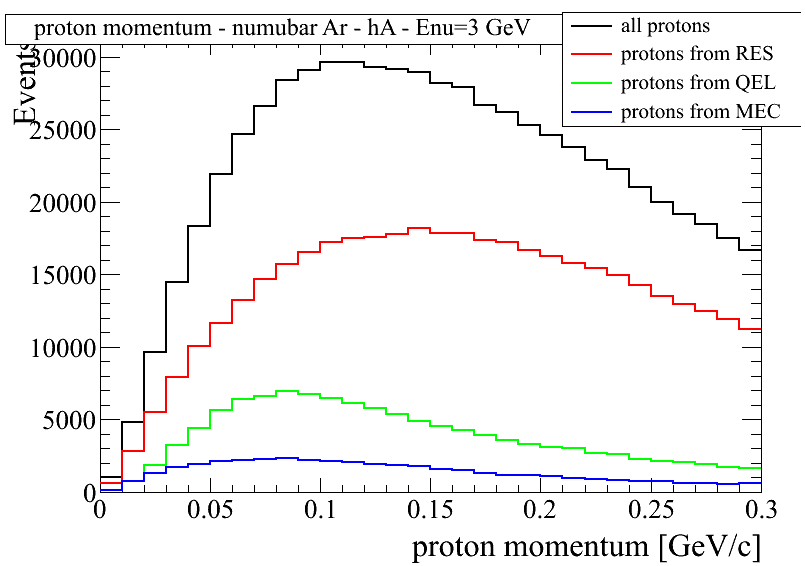


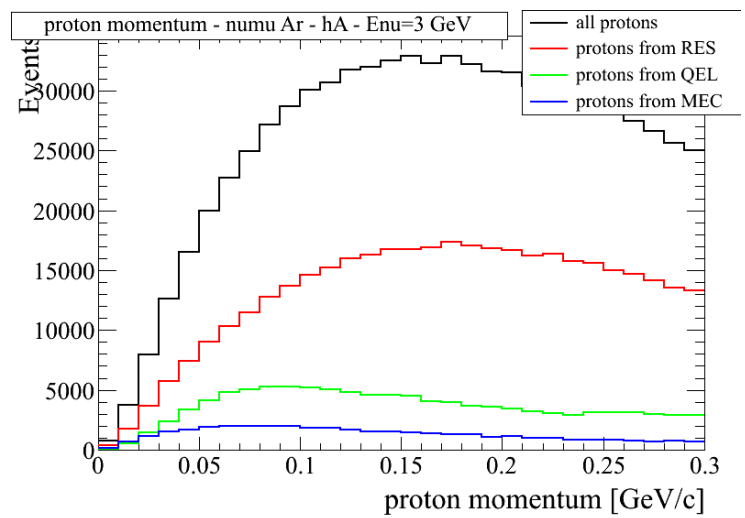




Even briefer for $\overline{\nu_\mu}$ Ar

- Multiplicities have mean a little lower than ν_μ Ar, no plot.
- Momentum distributions similar.





conclusions

- ν oscillation expts depend on MC
- GENIE is most modern, highest quality νA event generator
- Small, but dedicated group but manpower *always* an issue
- Excellent agreement with existing ν xs data (meagre).
- Extensive validation features vs. νA, hA, and eA.
- Need more ν cross section data for nuclei
  - MiniBoone now, Minerva (FNAL) and T2K in near future
- FSI code is a critical component of any event gen code.
- Here, show examples of many phenomena, overall agreement good$\rightarrow$excellent for GENIE FSI models.
- Experiments in progress have a lot to help model building.