GENIE – past, present, and future

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FUNFACT at JLab

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- broad goals
- evolution in last 2 years
- detailed look at FSI, pi prod
- a look to the future

Role in experiments

- Every MC run is event generator + detector simulation
  - Design experiments – establish ability to get to goals
  - Design cuts to get close to final spectra
  - Provide estimates of background, means for subtraction
  - Provide estimate of important sources of systematic error

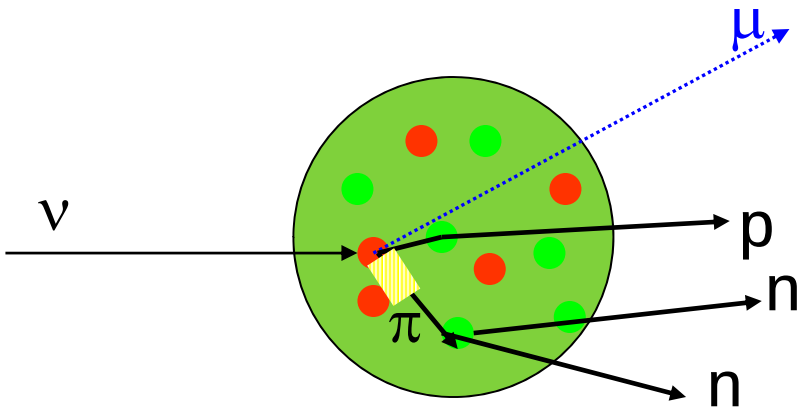
- *Many neutrino experiments have incomplete coverage of final state, so Monte Carlo is very important.*
- *Serious problem when event generator prediction doesn't match data.*

GENIE is designed for all accelerator based neutrino expts (universal)

- Why?
  - Because the experiments asked for it
  - Uses on last slide really matter!
  - GENIE has become an interpolator between experiments
- Characteristics
  - Strong ties to Root – experiment geometry, calcs, histograms...
  - Events thrown according to geometry
  - Free from HepForge [www.genie-mc.org] (MCNet guidelines)
  - Growing set of physics models
  - Strong ties to experiments of many types (p decay, p interactions)
  - workshops to introduce code to young people

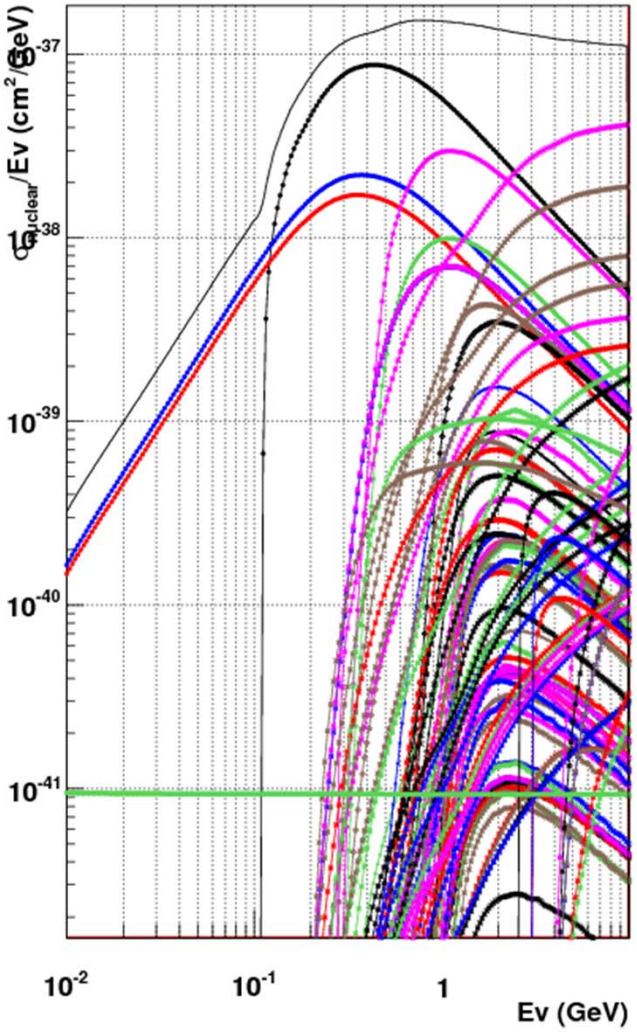
How we do it

- There is *very little* νA data, *models required*
- Reaction model is 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 , NA data



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.



Electron-, hadron-nucleus important

- Electron data provide all nuclear structure models
  - Large body of (e,e') data with excellent theory interpretations
  - ν reactions need both axial and vector response, (e,e') only needs vector. Is axial nuclear response same as vector?
  - Right now, ν data isn't able to distinguish.
- Hadron data provide all FSI models
  - Large body of π, p, n data central to models (less for K)
  - (γ,π) data central to π propagation, nominally same as π reactions
  - Does π produced in nucleus have same properties as π beam?
    - Yes? If density dependence handled correctly?
  - Do we understand π^0 interactions?

Organizational issues
Transition to much larger collaboration in progress

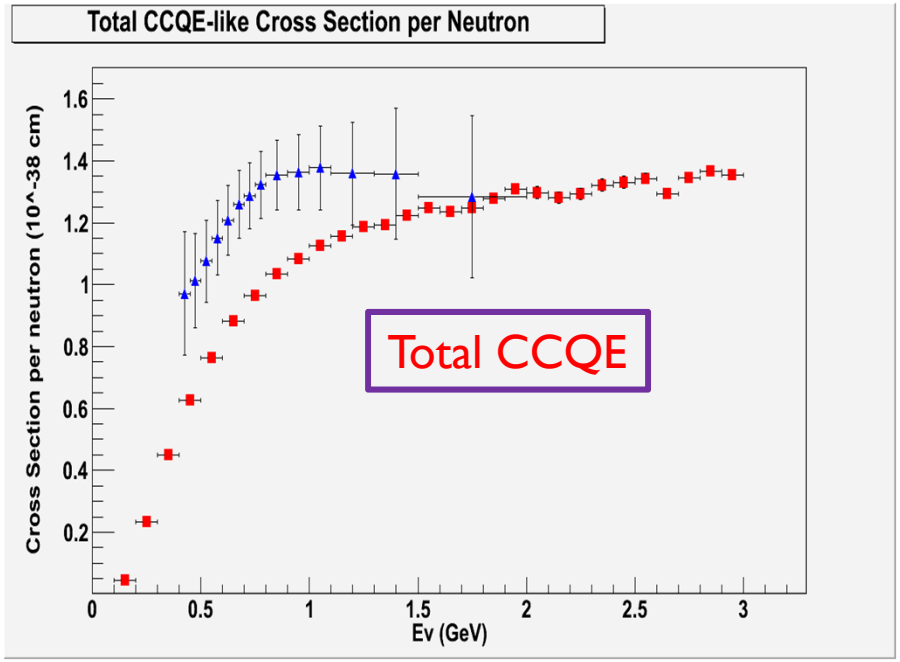
- GENIE has by-laws and core group of authors
  - Costas Andreopoulous (Liverpool/RAL), Hugh Gallagher (Tufts), Gabe Perdue (FNAL), and SD (many years of effort)
  - Policies set by this group (Exec Comm, can be expanded)
  - Models introduced through physics working groups (HG, SD) and monitored by technical working group (CA, GP, R. Hatcher (FNAL))
- Definite release schedule
  - Desire 1 model introduction and 1 physics release per year
  - Already abandoned due to insufficient manpower
  - 2.10.0 model introduction in 1-2 weeks, beta release now (7 additions)
  - 2.12.0 model introduction summer, 2015 (another 8 anticipated)
- Develops' Workshop at FNAL March, 2013 was important for getting help from experiments

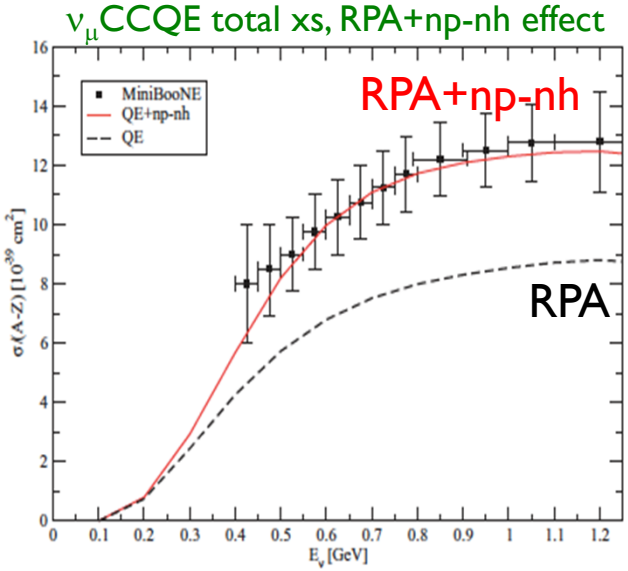
Upcoming release highlights

- Quasielastic
  - 4 new nuclear/QE models (AF, effective SF, local FG, z expansion)
  - New MEC (Valencia)
- Pion production
  - 3 new coherent models (BS, Alvarez-Ruso, Paschos/Schalla, +correct Rein-Seghal)
  - Improved Resonance form factors (vector, axial)
- FSI
  - Better A dependence in hA
  - Salcedo, Oset model in hN (density dependent medium corrections)
  - Pandharipande, Pieper nucleon FSI (effective mass)
- Develop new default physics model, syst errors 2015-6. (now called v3.0)

Some important comparisons – QE

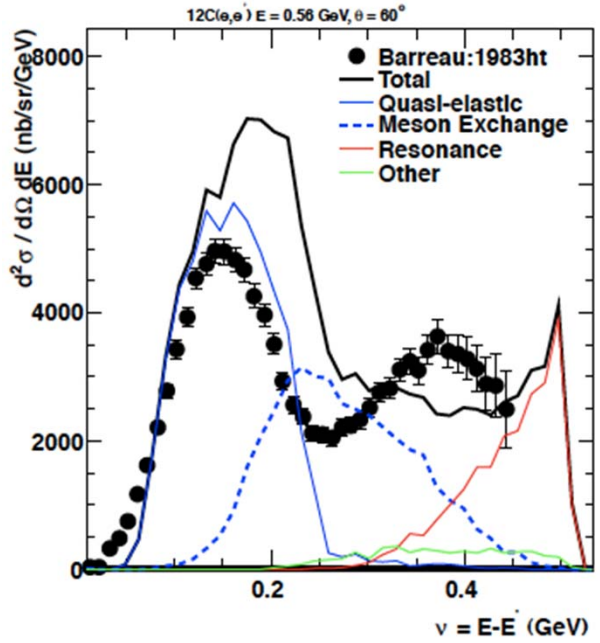
- QE interpretations dominated by gap between Llwellyn-Smith and MiniBooNE data recently.
- Present theoretical preference is for MEC/npnh.
- (e,e') experiments have studied this since 1970's.
- Coming soon to GENIE





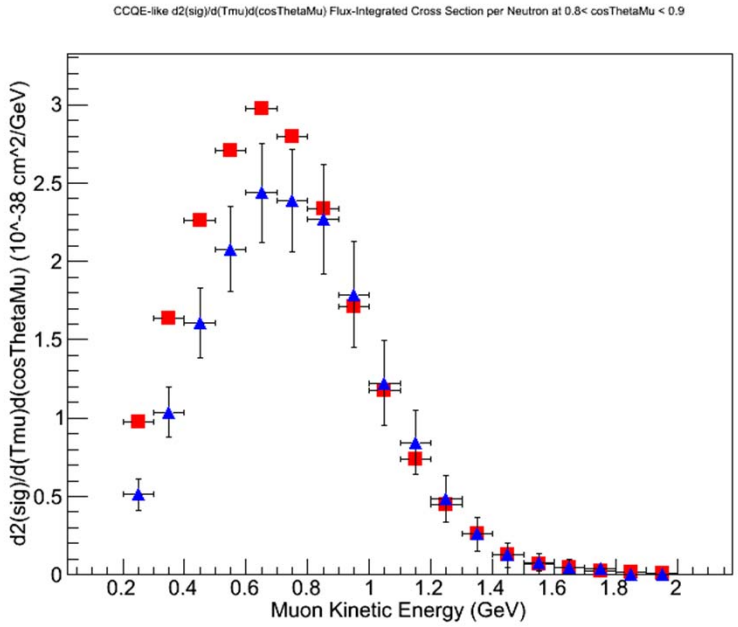
Quasielastic (QE)

- Synergy between (e,e') and ν interactions important to GENIE
- (e,e') gives vector response, many very accurate expts.
- Because E_e fixed, scattered lepton spectrum separates channels.
- Fix part of ν prediction, get axial from ν data



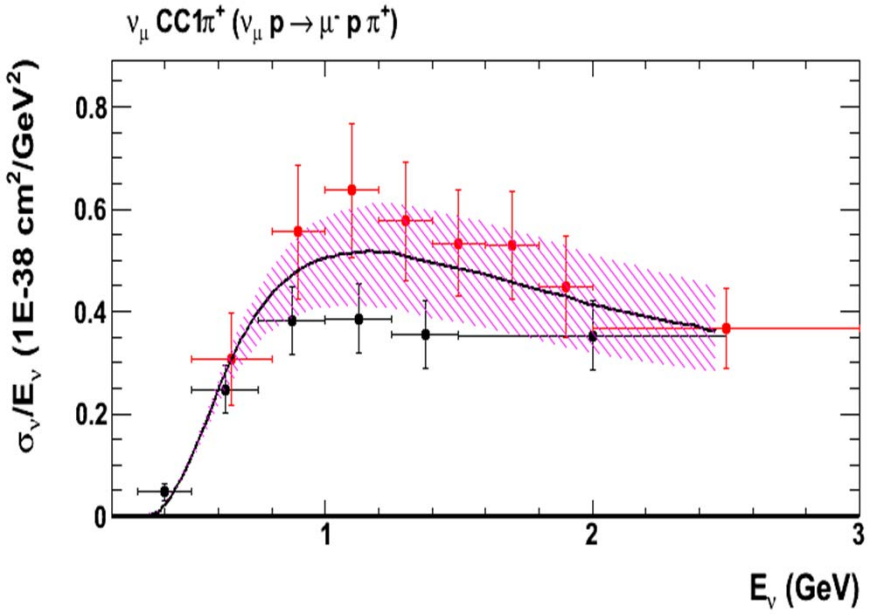
560 MeV C(e,e')

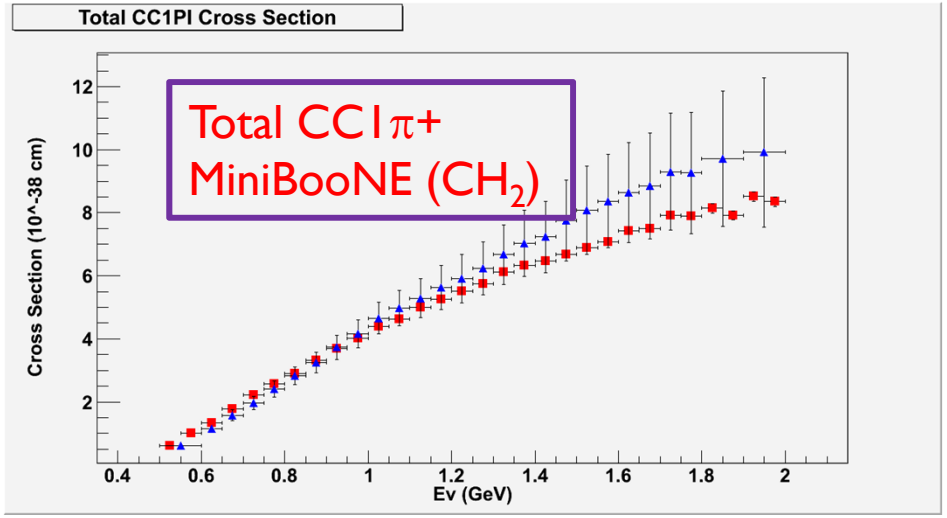
MiniBooNE $0.8<\cos(\theta_\mu)<0.9$



π Production – emphasis on 1π through Δ

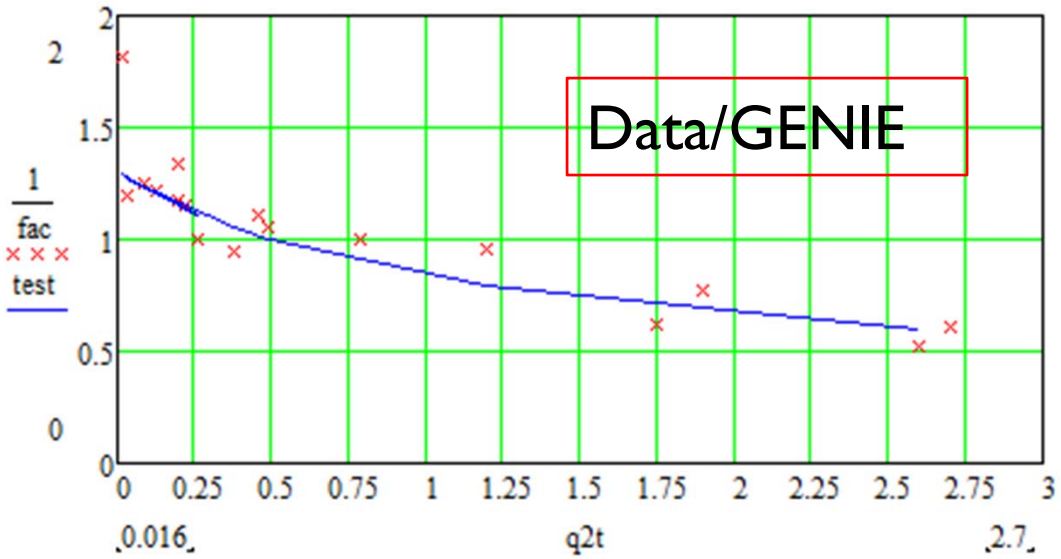
- Historical problem $\sigma_{ANL} < \sigma_{BNL}$ for nucleon targets.
- Many generators take average, assign systematic error.
- Recent paper by Wilkinson, et al. prefers ANL.

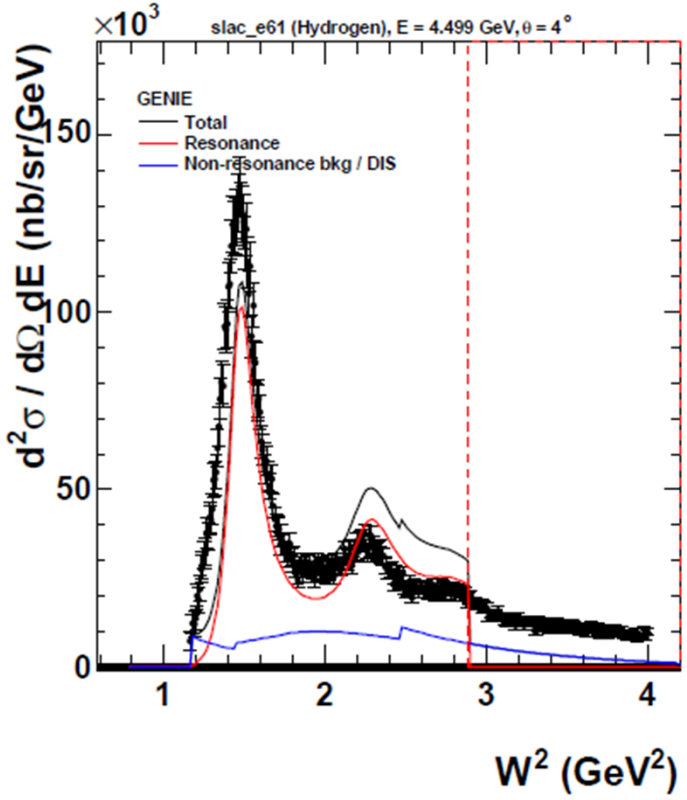




Sometimes generators disagree with (e,e') data

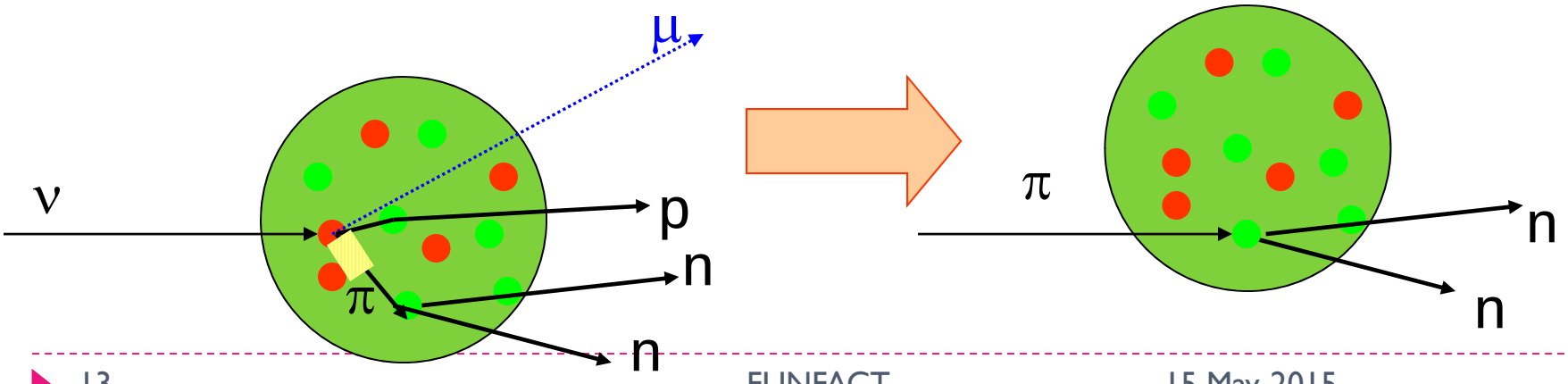
- Peaks in (e,e') data due to resonances, left peak is Δ.
- Plot at right is for Q^2=.09 GeV^2, take.
- ratio Data:GENIE (left) shows vector form factor is wrong, very Q^2 dependent





Focus on FSI – how generators do it

- Strong interactions complicated→ nonperturbative, many channels, no clever approximations to QCD available.
- No quantum mechanical model available (eikonal)
- Best approximation is Intranuclear Cascade (INC)
  - Interactions with nucleons in medium same as for free nucleons
  - Interactions far enough apart that particles stay on-shell
  - Nuclear effects, e.g. binding energy and Fermi momentum, added



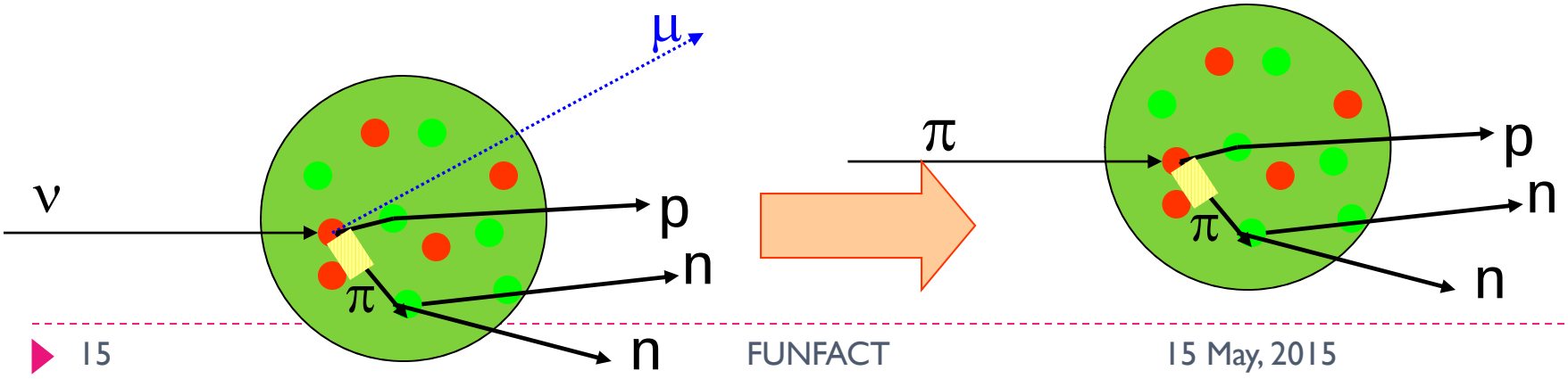
Models of today

- Mashnik – extensive history, excellent low energy nucleon, poor for resonant pions, not freely available.
- PEANUT – FLUKA, add 'quantum' corrections, applies to all energies, not freely available.
- GiBUU – Mosel (Giessen), applied in HI's, hadrons, elec; good success with ν, medium corrections, slow.
- Salcedo, Oset – PR 1981, medium corrections give success for resonant pions, used in NEUT, NuWro.
- GENIE Intranuke – default is effective INC, no medium corrections, Oset INC nearly done.
- **All are able to fit wide variety of hadron-nucleus data**

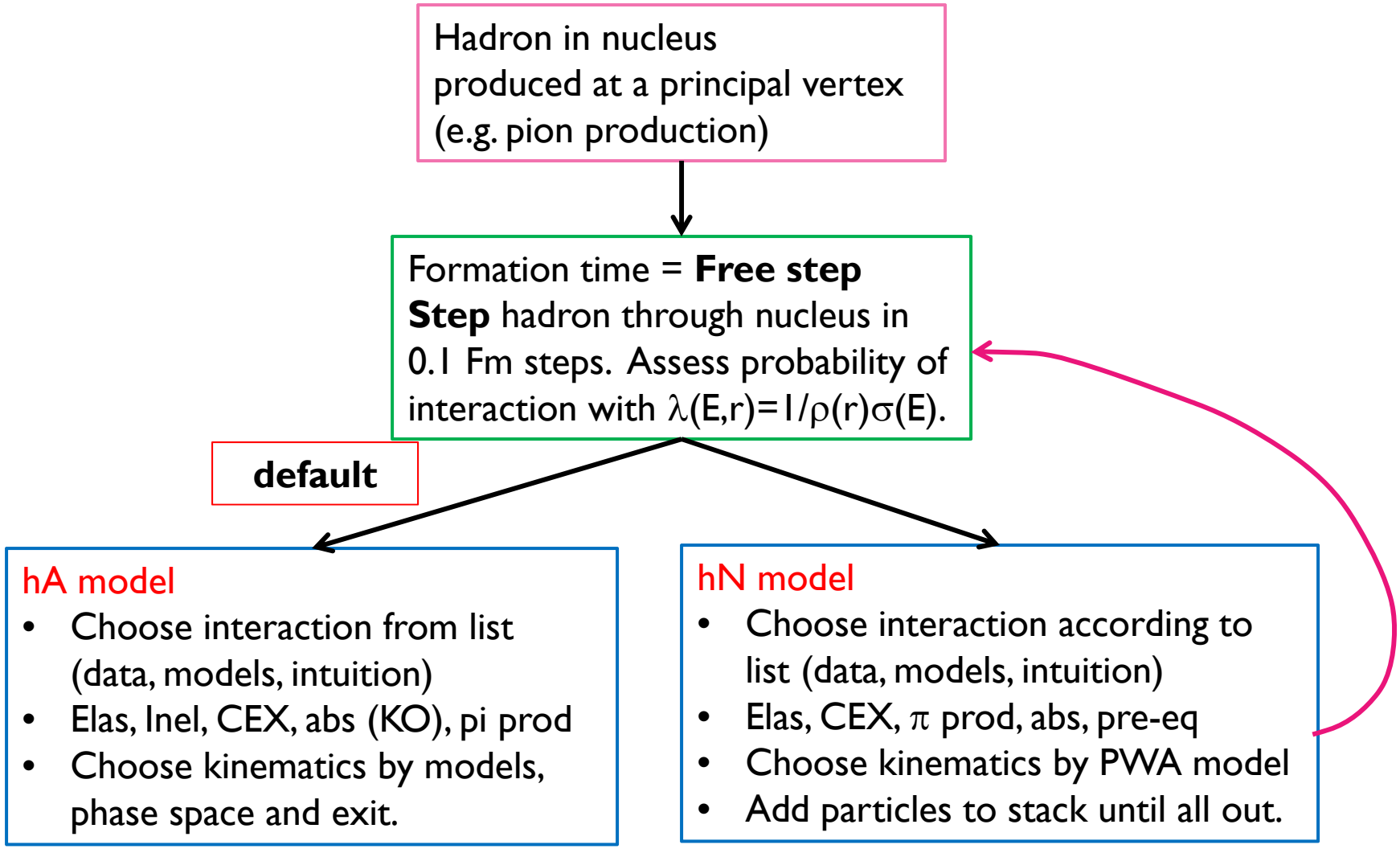
General Characteristics of GENIE FSI models

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 SAID PWA data.
- hA is schematic, data-driven INC
  - Construct models of full chain of events
  - Uses simple representations of hN code and data.
  - Easily reweighted (exact) because **each particle has 0 or 1 interactions as it propagates through residual nucleus**.

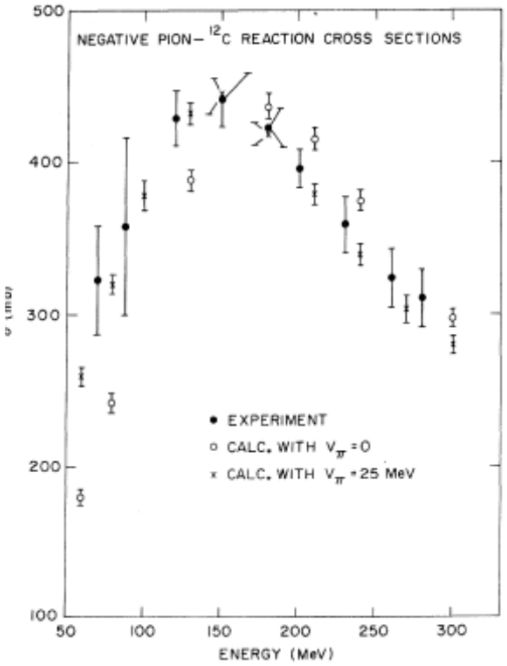


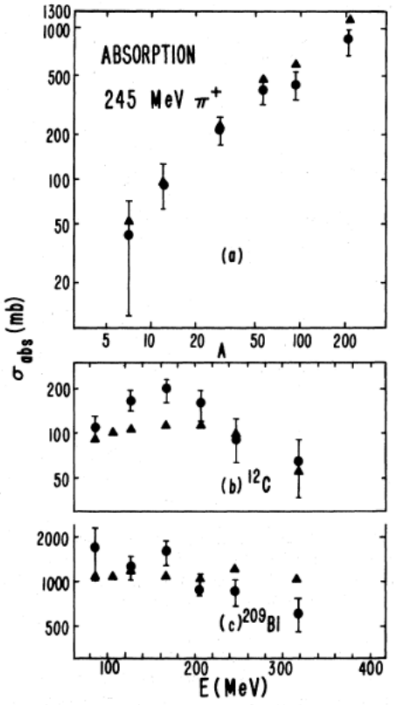
Basic outline

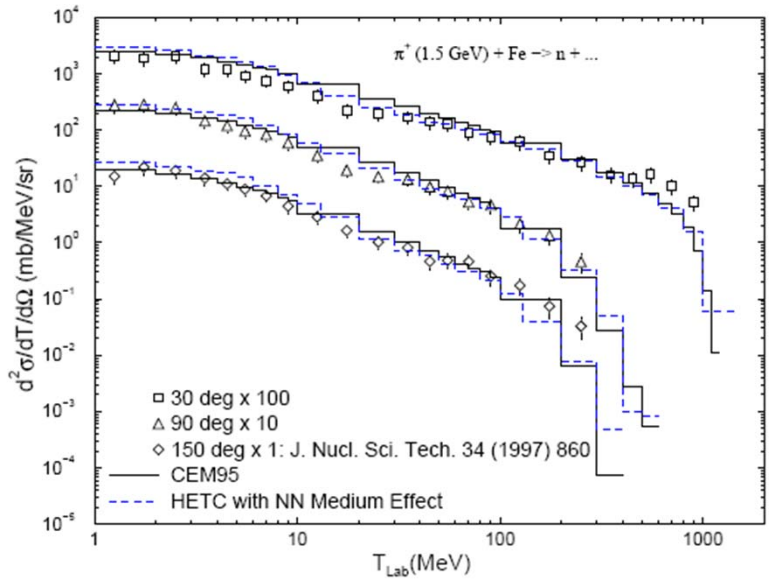


INC models common in hadronic physics

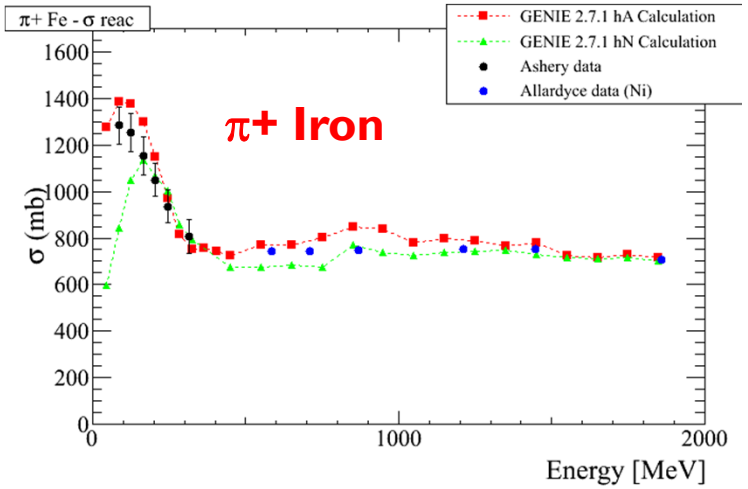
- Inelastic reactions, esp. particle production processes.
- Only pion induced reactions shown here, but still some impressive examples. (GEANT, FLUKA...)
  Harp (74) Fraenkel (82) Mashnik (95)

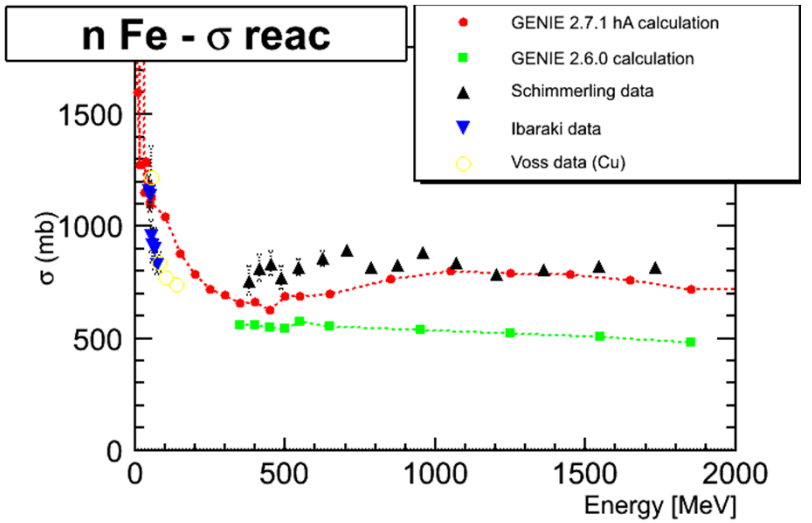


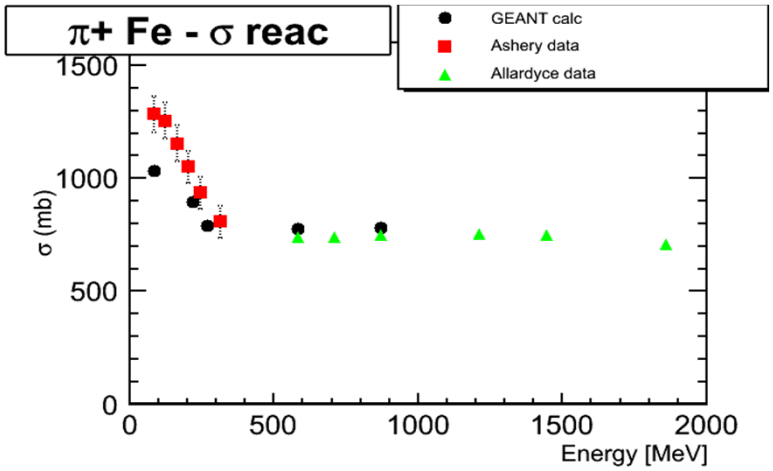


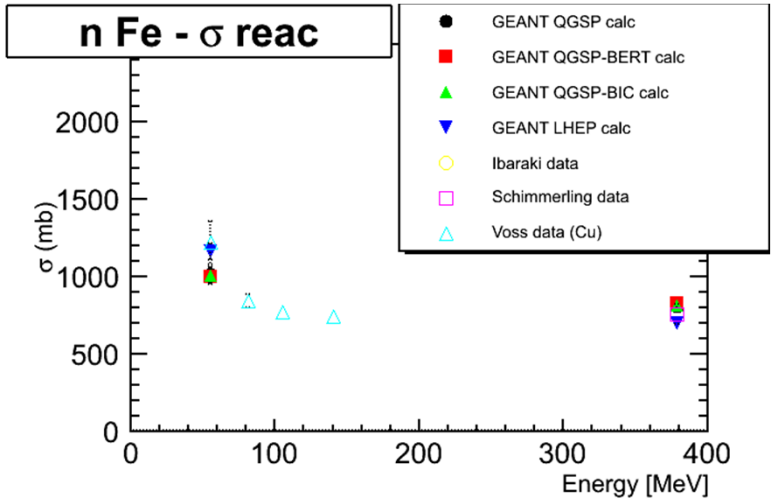


Total reaction xs in GENIE, GEANT (broad picture)



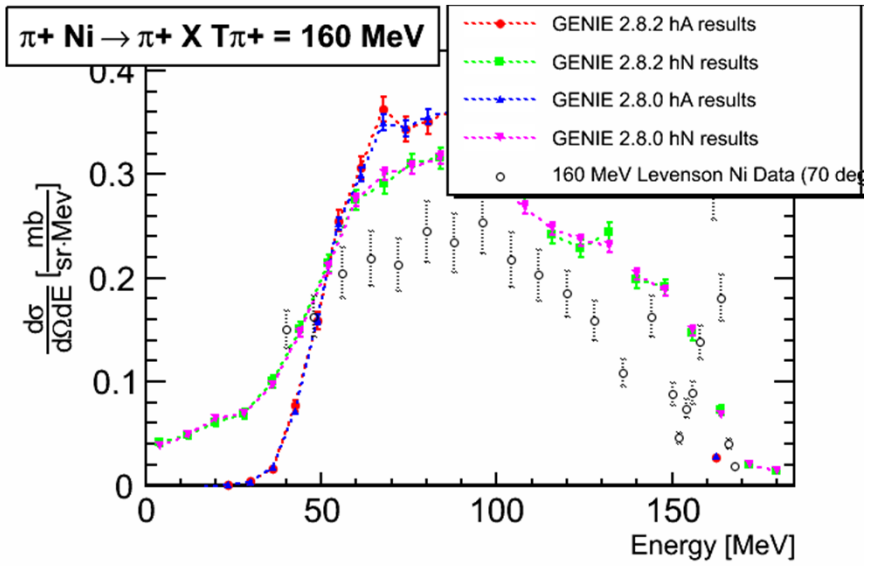


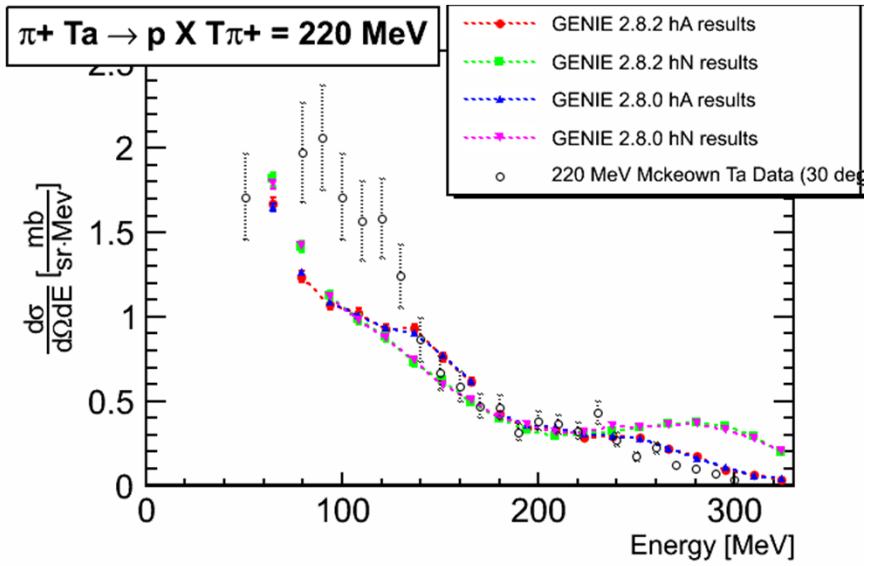




GENIE success

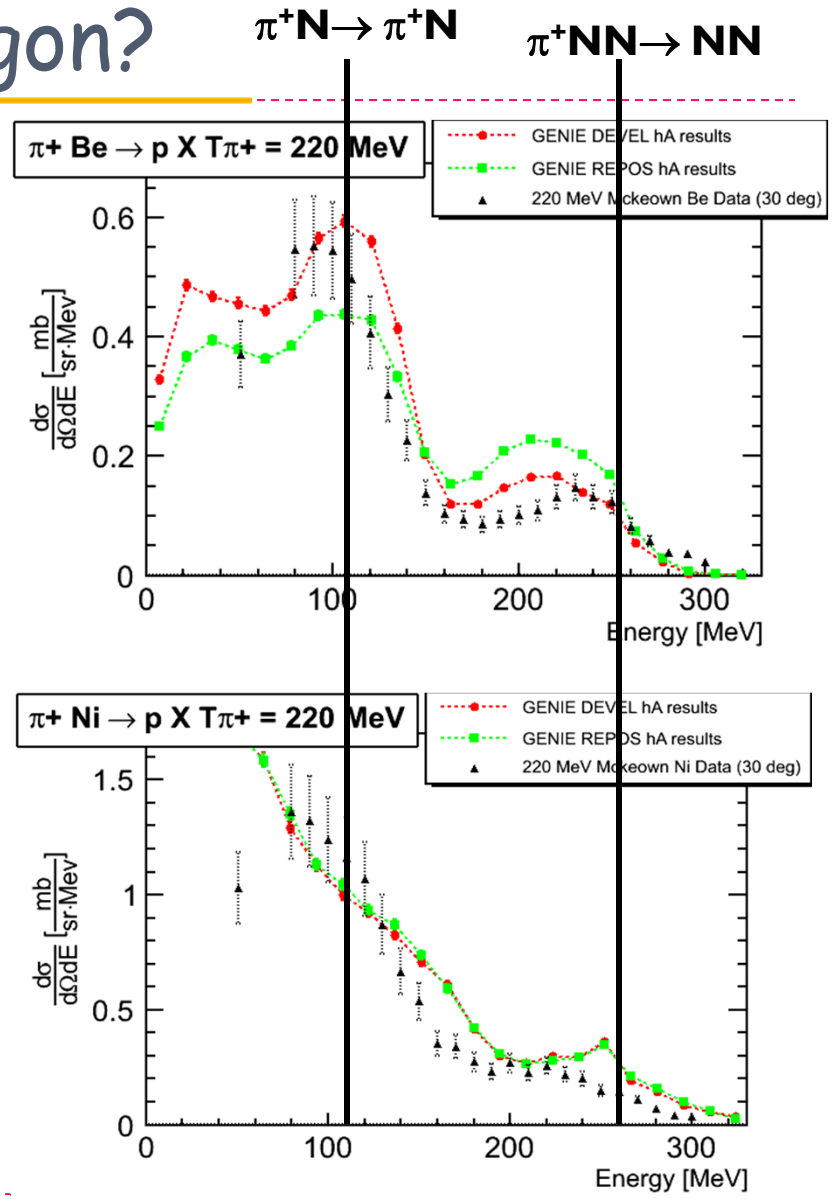
- Good for all processes – pions, kaons◊, protons, neutrons
- Absorption data best interpreted by statistical model (Ransome, INT workshop, Dec 2014) such as hA uses.
- Exactly reweightable important for experiments
- Approximations best suited for light nuclei but also works for heavy nuclei (e.g. lead).





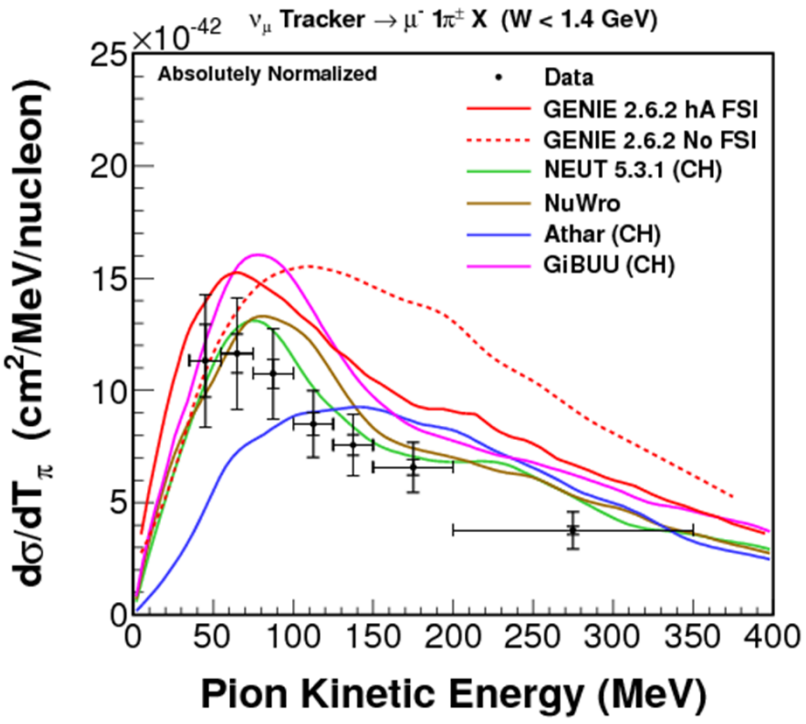
Can GENIE predict Argon?

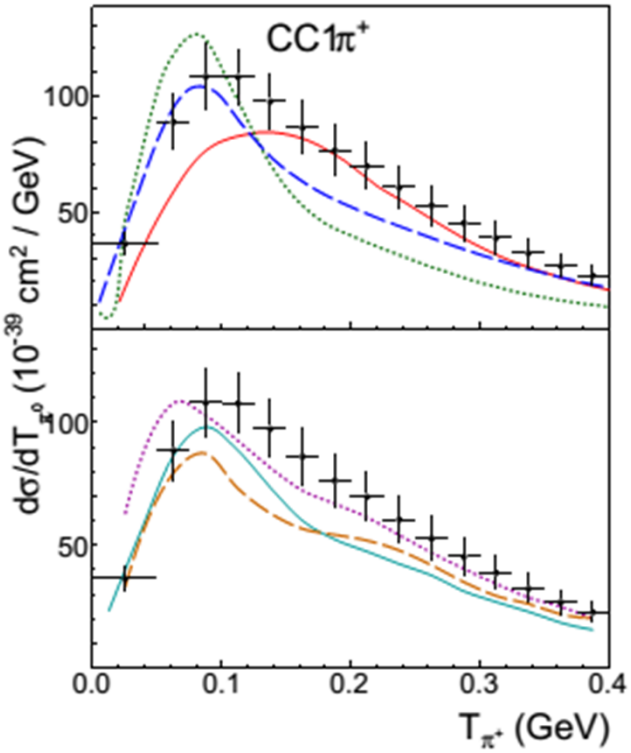
- Why do we do well despite lack of tuning?
- Hadron total cross sections all scale by powers of A
  - Power~2/3 for absorption, 0.8 for total
- In light nuclei, predominance of single nucleon processes obvious. Signs still there in heavier nuclei.



Pion propagation in nucleus through KE_π

- MINERvA (E_ν~4 GeV, left) and MiniBooNE (E_ν~1, right) ~similar
- No calculation can describe both data sets.
- FSI? π production from N? Medium effects?



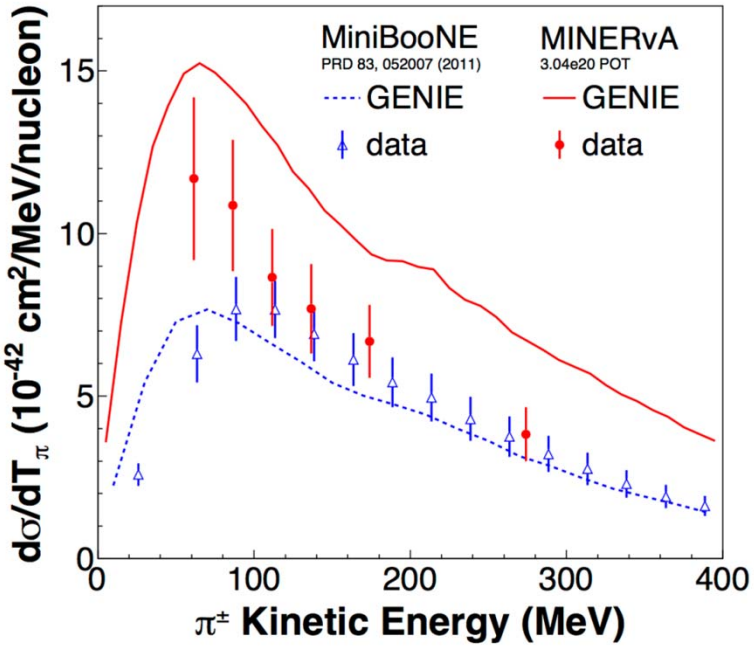


theory

- Athar *et al.*
- Nieves *et al.*
- GiBUU
- NuWro
- GENIE
- NEUT
- MB data

How well do MiniBooNE and MINERvA agree?

- Tension with models is shifted
- MiniBooNE - $\langle E_\nu \rangle \sim 1$ GeV
  - Best models (GiBUU, Valencia) strongly disagree in shape
  - Event generators have shape right, but problems in detail
- MINERvA - $\langle E_\nu \rangle = 4$ GeV
  - Dominantly Δ resonance formation, decay in nucleus, very similar to MiniBooNE
  - Event generators have shape, magnitude
  - GiBUU has shape right, but wrong magnitude
- No calculation describes both data sets well
  - Energy dependence difficult for all calcs.
  - Does this mean a normalization problem?
- W cuts are different, covered in calcs



Q2 distributions are similar (Tzanov-CETUP)

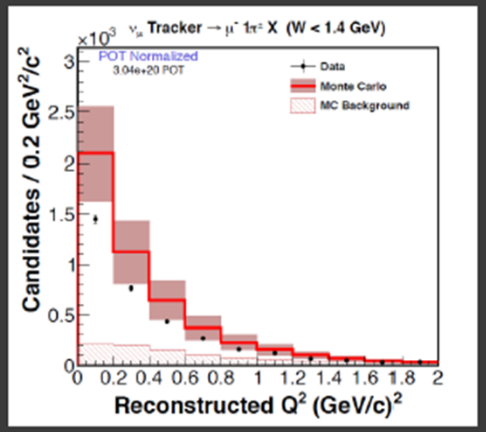
Possible Differences Between MINERvA and MiniBooNE

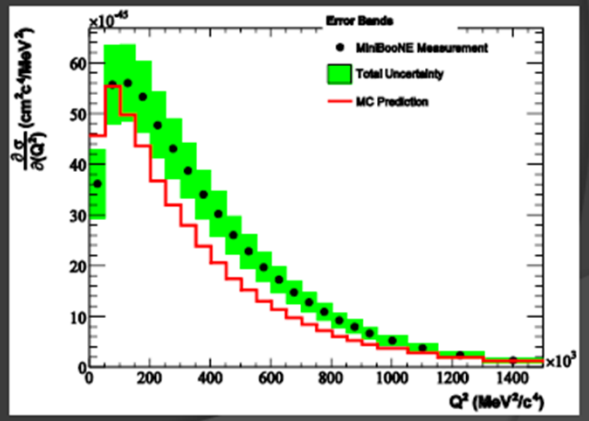
- Flux above 1.5 GeV Flux up to 3GeV
- However similar Q^2 reach – more or less same probe

Signal definition

only $1\pi^+$ and 1μ and any hadron

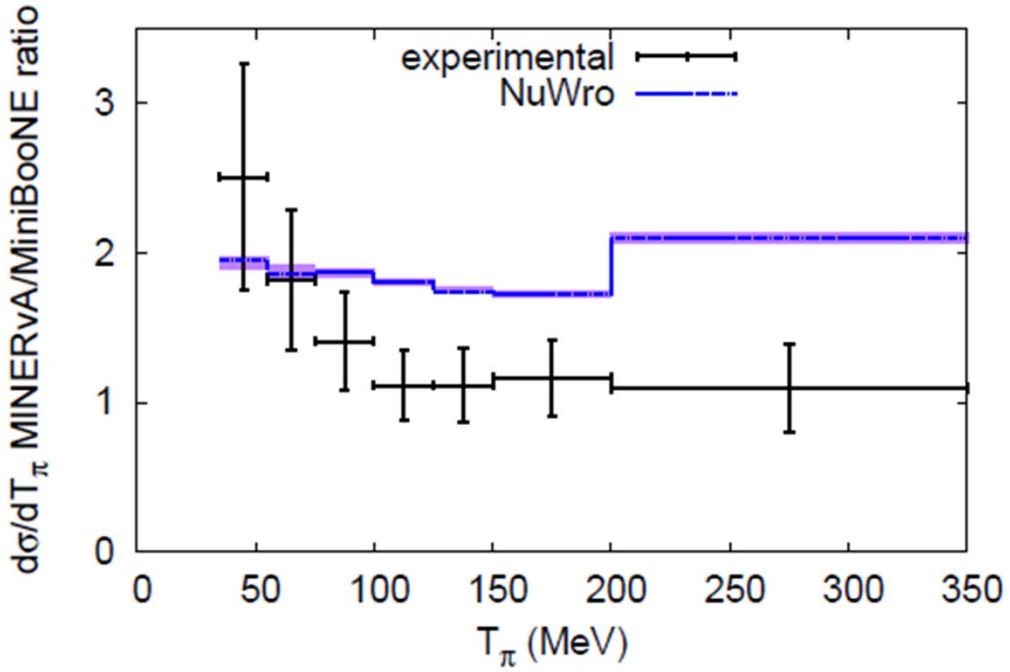
only $1\pi^+$ and 1μ and no other mesons





Sobczyk & Zmuda (Phys Rev C (2014))

- They note similar disagreement in magnitude as GENIE.



Sensitivities other than FSI

- Nucleon production
  - ~10% difference between NEUT and GENIE for nucleon
  - GiBUU chose BNL for a while, they are ~15% high (abs, not shape)
- Lalakulich&Mosel paper nuclear medium corrections don't affect shape, ~10% in magnitude.

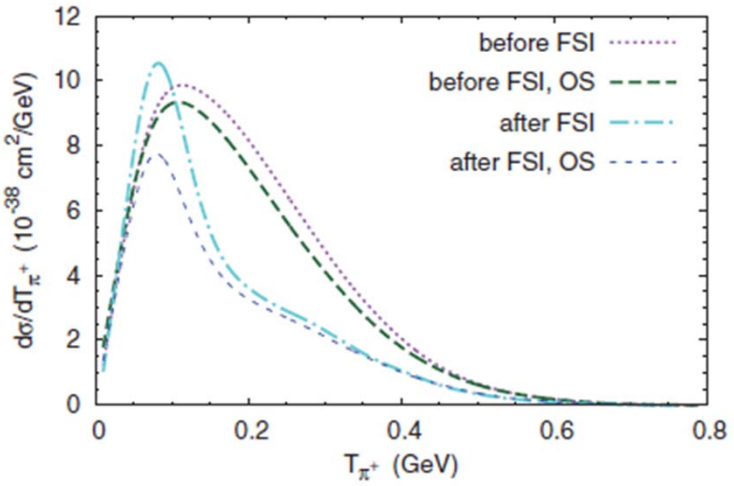
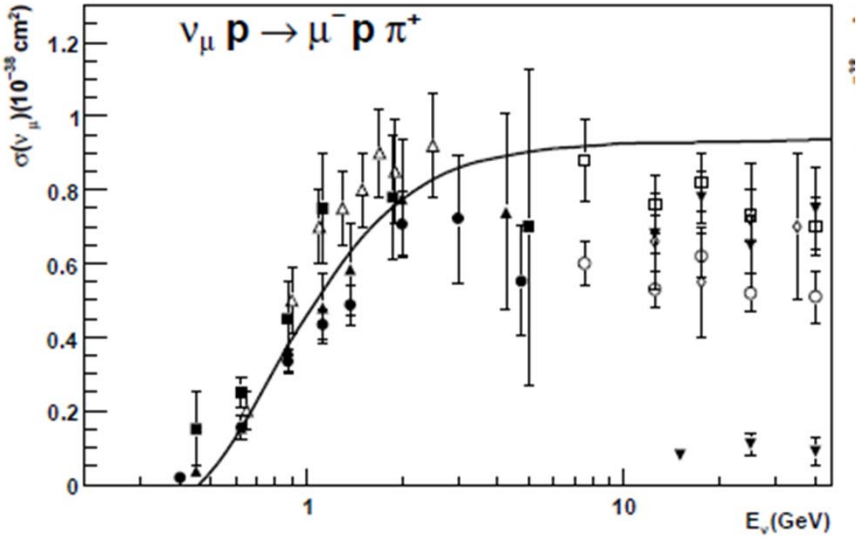
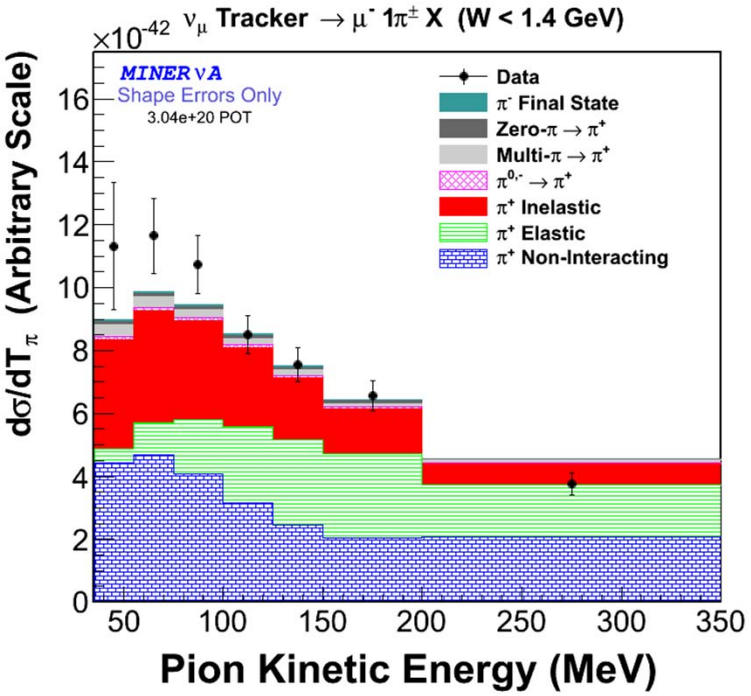


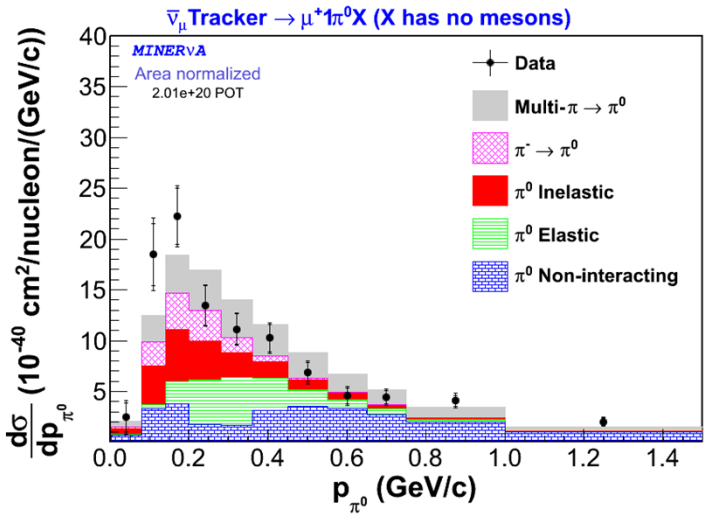
FIG. 13. (Color online) Kinetic energy distribution of π^+ produced in neutrino scattering off carbon through the weak production of the Δ resonance and its following decay. The neutrino energy is $E_\nu = 1$ GeV. The curves labeled OS were obtained using the in-medium collisional width of the Δ from [28].



Dig deeper into FSI (MINERvA)

- Data are sensitive to pion prod xs, medium effects; however, FSI is largest effect.
- Data for π^+ dominated by Δ, less so for π^0.





Next steps (GENIE and MINERvA)

- Use reweighting in GENIE to adjust FSI
  - Looks like more INEL and less ABS
  - Pitt summer student getting started
  - Can FSI be adjusted to fit MiniBooNE and MINERvA data?
  - Are those changes consistent with π scattering data?
  - Use newer GENIE models to adjust nucleon, nuclear model
- This is one in a series of adjustments in GENIE to match modern ν data.
- ME data will have much better statistics, flux normalization – work already underway
- ND280 will have independent data

Conclusions

- Event generators important for neutrino experiments
- GENIE is the Universal event generator (needed for expt analysis and interpolation between expts.)
- νA theory in event generators getting better, still incomplete. Lack of good νN data is a problem!
- FSI through INC is state of art, but is it appropriate?
- P production experiments are great test of FSI
- Data for π production coming quickly, need some more analysis.

Comparison of event generators
(apologies for errors in fact, judgment)

- NEUT
  - Good - Excellent job for T2K through NIWG, systematic evaluation against MiniBooNE data, very good use of collaborators
  - Room for improvement – tied to T2K, how do we use their work?
- NuWro
  - Good – close attention to theory, great advice to expts
  - Room for improvement – code linkage to expt (e.g. releases)
- GENIE
  - Good – excellent code for expts, excellent organization in development, good ties to theory/FNAL.
  - Room for improvement – ties to theory and expt should be improved, need more dedicated workers
- Unexpected surprise – we are all training young people

Pion absorption at low A

- New tune (red) does much better
- This has few percent change in neutrino pion production xs.