Final State Interactions (GENIE)

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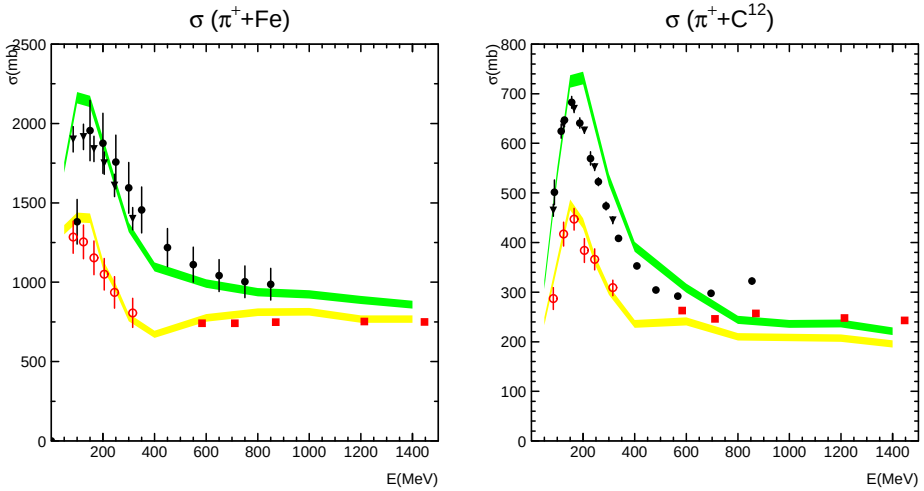
1. Typical nuclear model in event generators
2. Hadron (pion, nucleon) fsi

Nuclear density

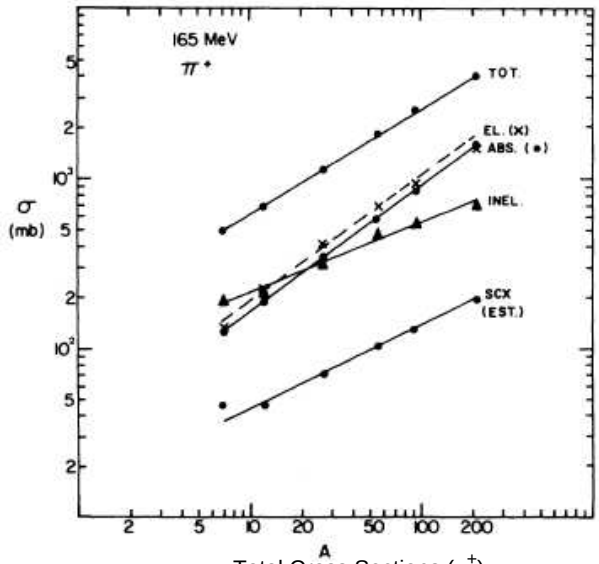
(GENIE can do almost all nuclei)

- Use data values for common nuclei, interpolate for others
  - ✓ Gaussian for ^{4}He, modified Gaussian for ^{12}C, ^{14}N, and ^{16}O
  - ✓ Interpolate to others for A≤20
  - ✓ 2 param Woods-Saxon for A>20, data for ^{27}Al, ^{28}Si, ^{40}Ar, ^{56}Fe, ^{208}Pb
  - ✓ Interpolate for others (errors are few %)
- We empirically add to nuclear size
  - ✓ $0.5*\lambda_{deB}$ Fm for nucleons, $1.0*\lambda_{deB}$ Fm for pions (v 2.4.0)
  - ✓ Empirically, this gets good agreement with νA, πA and pA data
  - ✓ Theoretically, this is justified because hadrons have size ~ 1 Fm

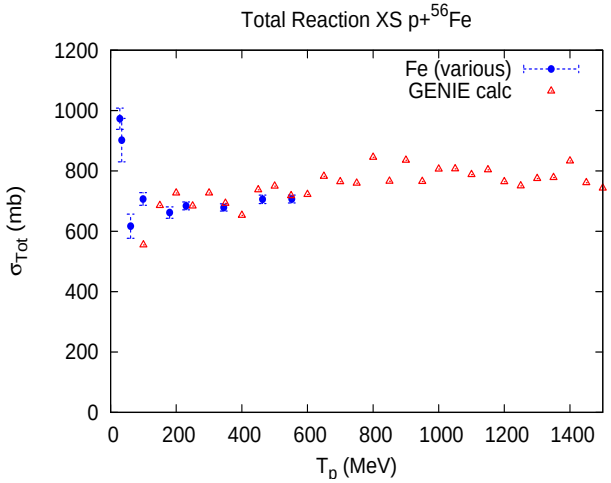


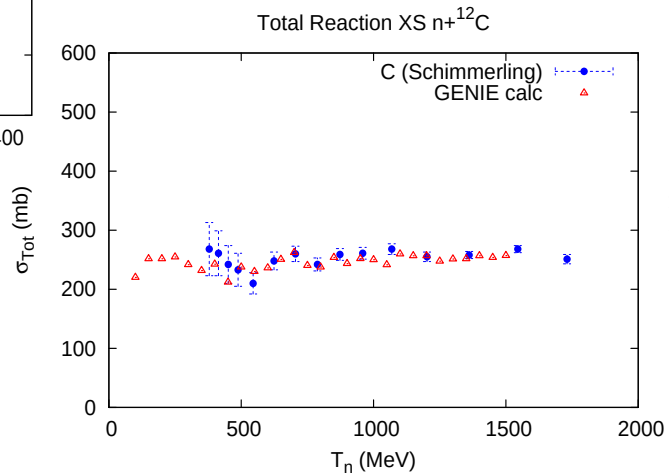
Nuclear systematics

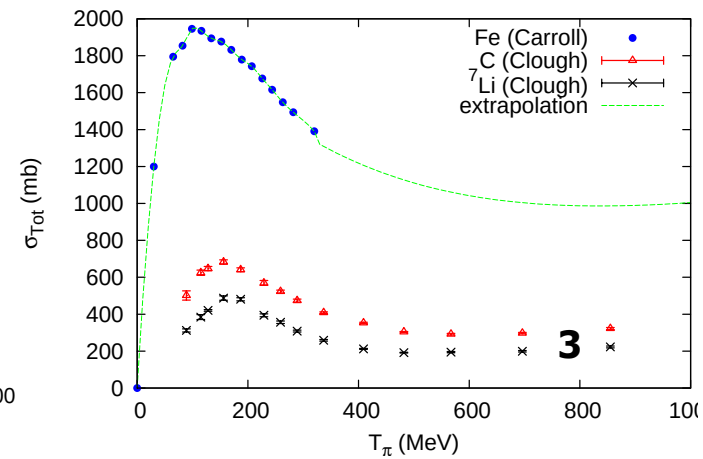
- hA total cross sections ~ nuclear size (πR^2)
  - For Fe, πR^2=
  - For C, πR^2=
- Many total cross section scale with A^{α}.



Total Cross Sections (π^+)

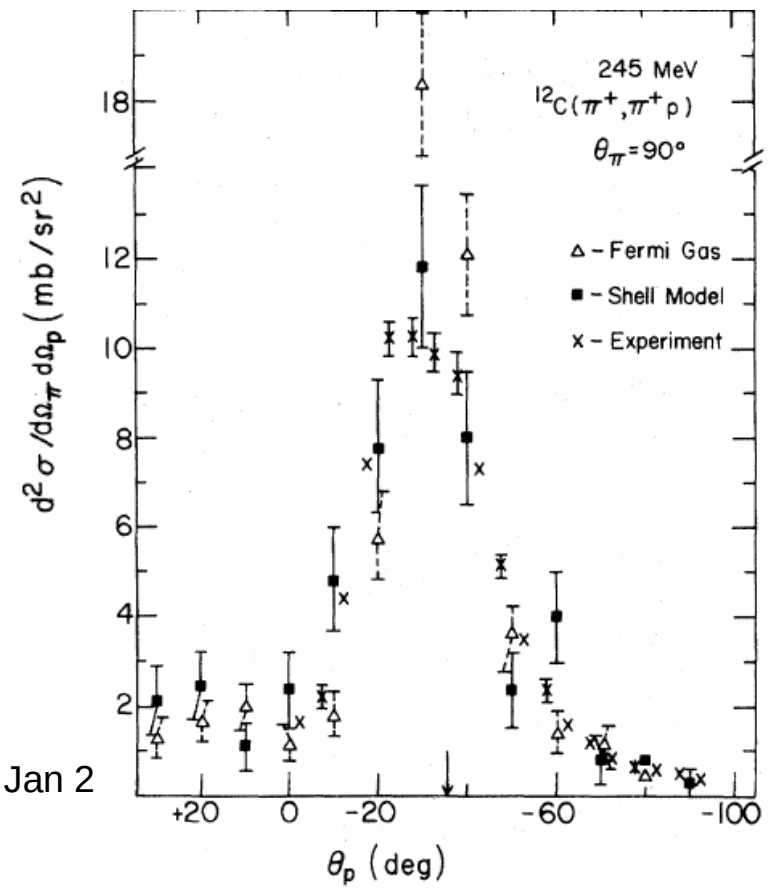


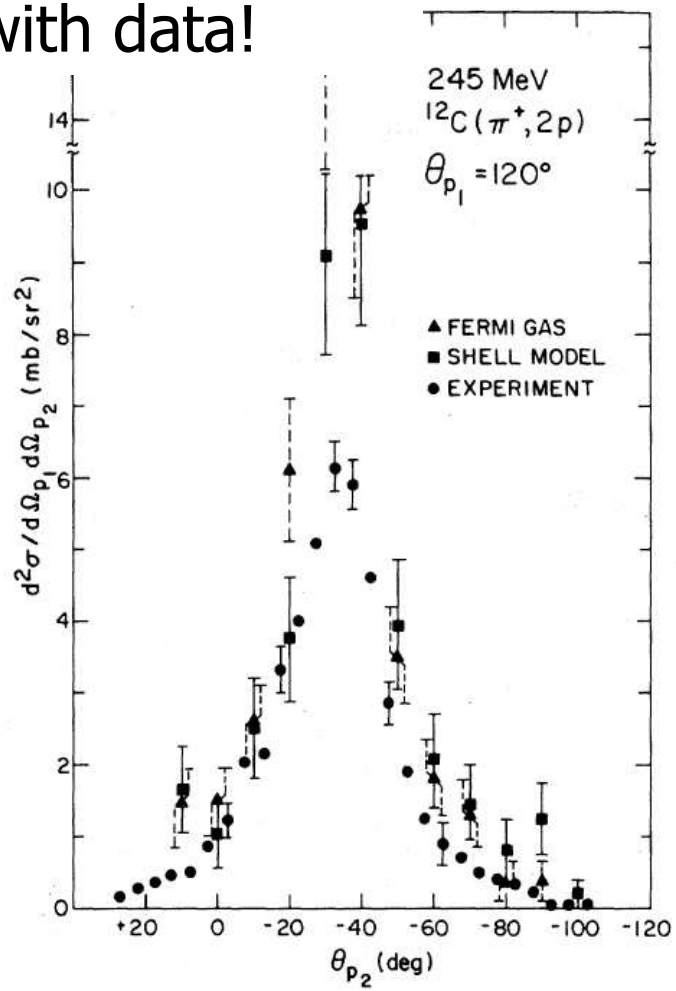




Quasifree (QF) reaction mechanism important…

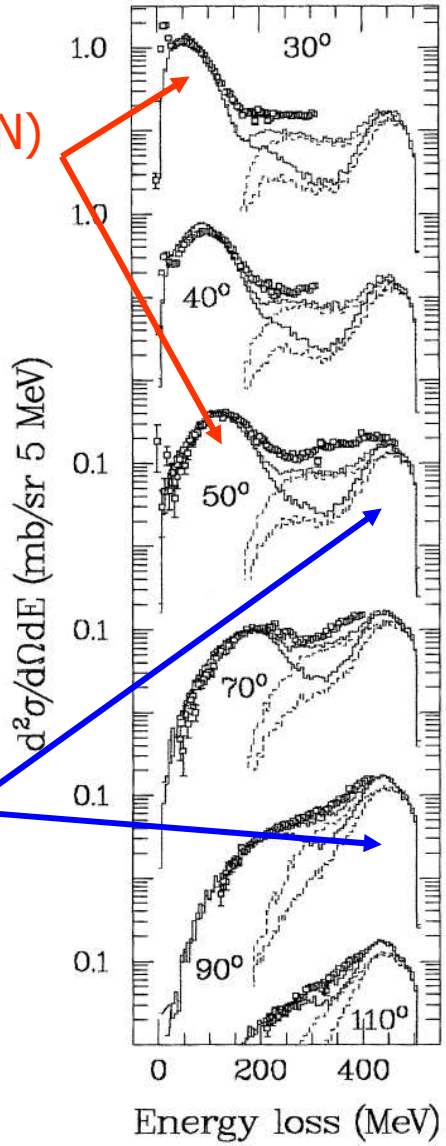
- QF means hadron interacts with nucleons in nucleus as though they were free (with momentum)
- INC calcs by Fraenkel (1982) agree with data!





…but far from complete (FSI!)

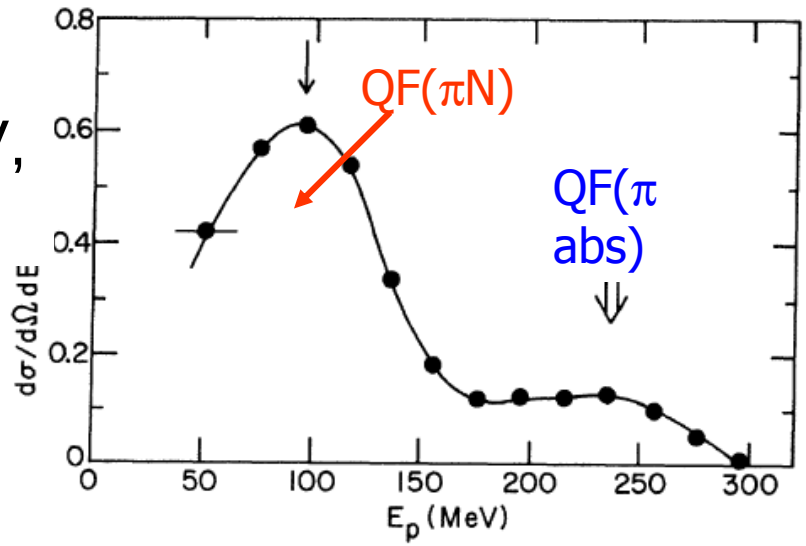
- π^-C at 500 MeV, incl. π^-



- π^+Ar absorption at 245 MeV

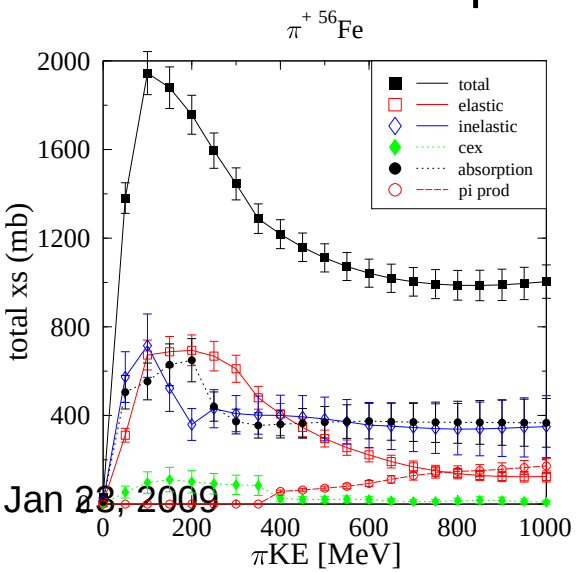
	Raw Data	30 MeV Threshold	Extrapolated to 0 MeV
5p	0.013 ± 0.001	0.04 ± 0.01	0.64 ± 0.13
4p	1.11 ± 0.10	2.0 ± 0.2	5.1 ± 1.0
3p	19.9 ± 1.2	26.8 ± 2.5	28.4 ± 4.0
3pn	2.0 ± 0.2	11.9 ± 1.3	33.2 ± 7.5
2p	69.8 ± 4.2	72.9 ± 5.8	43.6 ± 5.2 ←QF
2p1n	11.9 ± 0.9	62.9 ± 6.6	$75. \pm 10.$
2p2n	0.67 ± 0.05	5.6 ± 1.0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

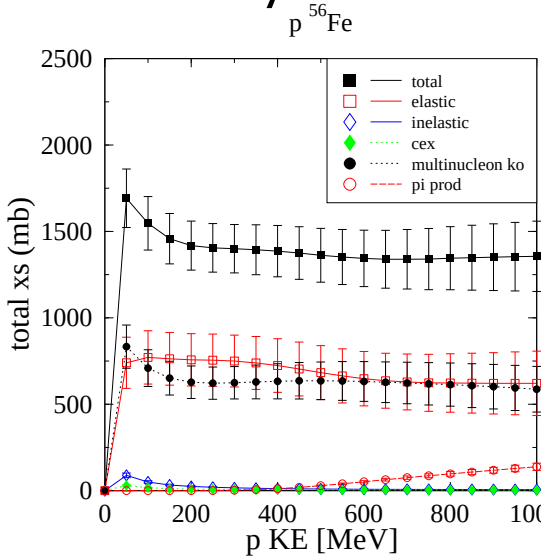
- π^+C at 220 MeV, incl. p

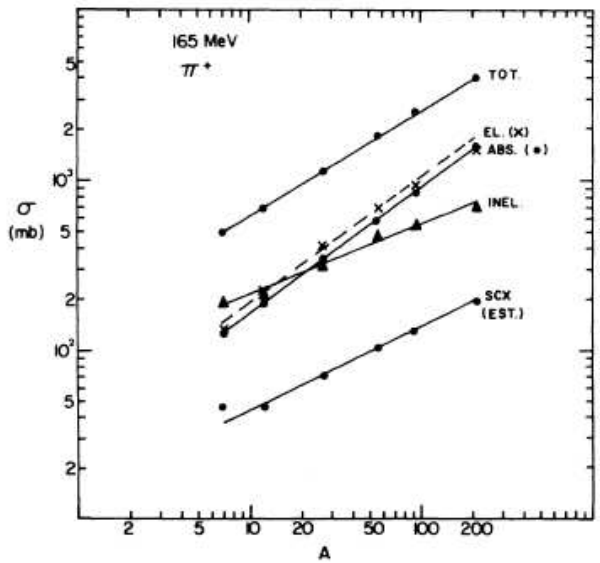


GENIE models - hA

- hA is only FSI model in GENIE 2.4.0
  - ✓ At most 1 FSI
  - ✓ If FSI, choose final state according to total cross section (e.g. p absorption total xs is ~25% of total)
  - ✓ Use data for iron, extrapolate $\propto A^{2/3}$ for all others
  - ✓ Use pre-existing code for angular distributions (wrong)
  - ✓ Error bars in plots used for systematic error studies

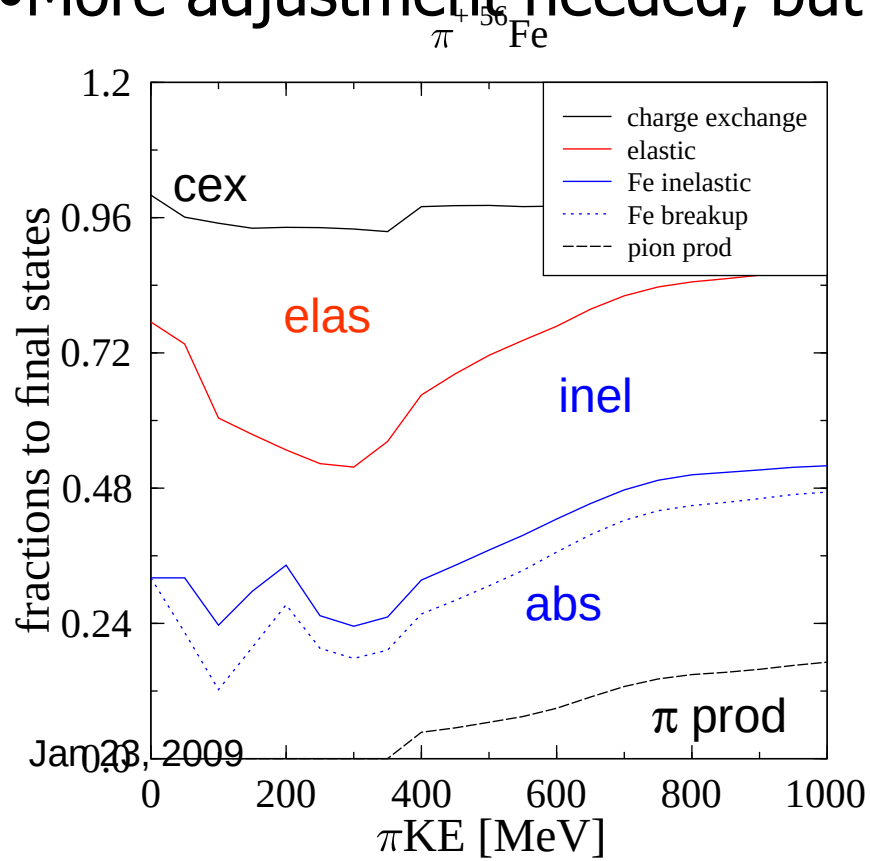






INTRANUKE hA strategy

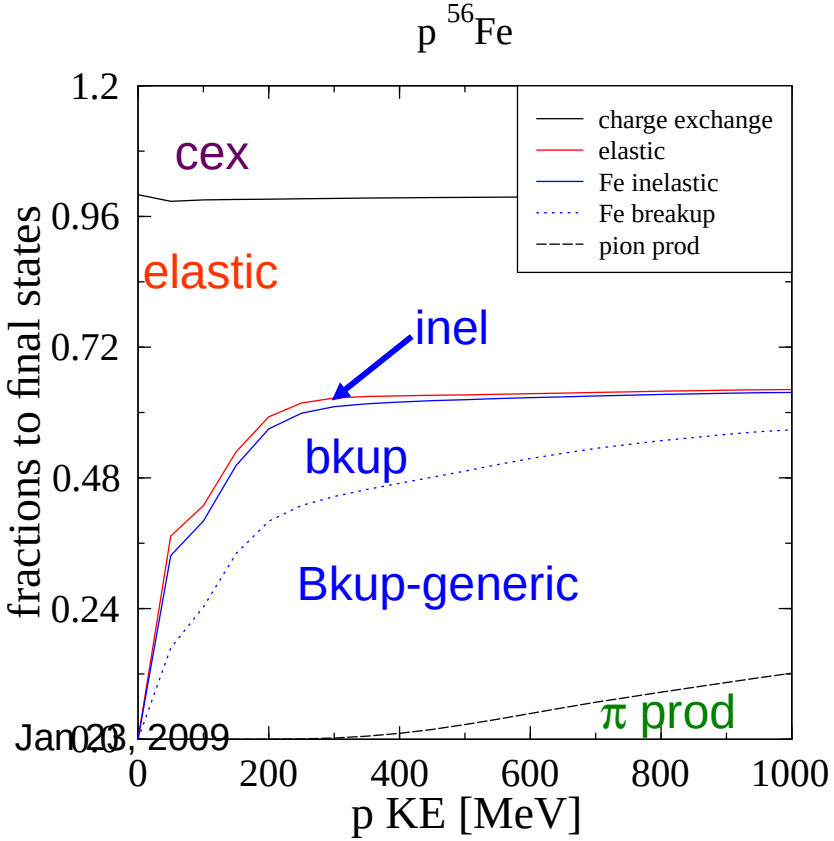
- Mix of data, intuition, CEM03.01 calc. for π ^{56}Fe (scale by $A^{2/3}$ for other nuclei)
- Jumps of σ_{abs} at low energy is in data!
- More adjustment needed, but basic strategy is done



Elastic	π^+ ^{56}Fe$\rightarrow$ π^+ ^{56}Fe
Charge exchange	π^+ ^{56}Fe$\rightarrow$ π^0 ^{56}Cr
Inelastic	π^+ ^{56}Fe$\rightarrow$ $\pi^{+\prime}$ N ^{56}Fe
Absorption	π^+ ^{56}Fe$\rightarrow$ pn ^{54}Fe
	π^+ ^{56}Fe$\rightarrow$ pp ^{54}Mn
	π^+ ^{56}Fe$\rightarrow$ ppn ^{53}Mn
	π^+ ^{56}Fe$\rightarrow$ pnn ^{53}Fe
Abs-generic	π^+ ^{56}Fe$\rightarrow$ ppnn ^{52}Mn
Pion production	π^+ ^{56}Fe$\rightarrow$ $\pi^+\pi^0$ ^{56}Fe

INTRANUKE hA strategy

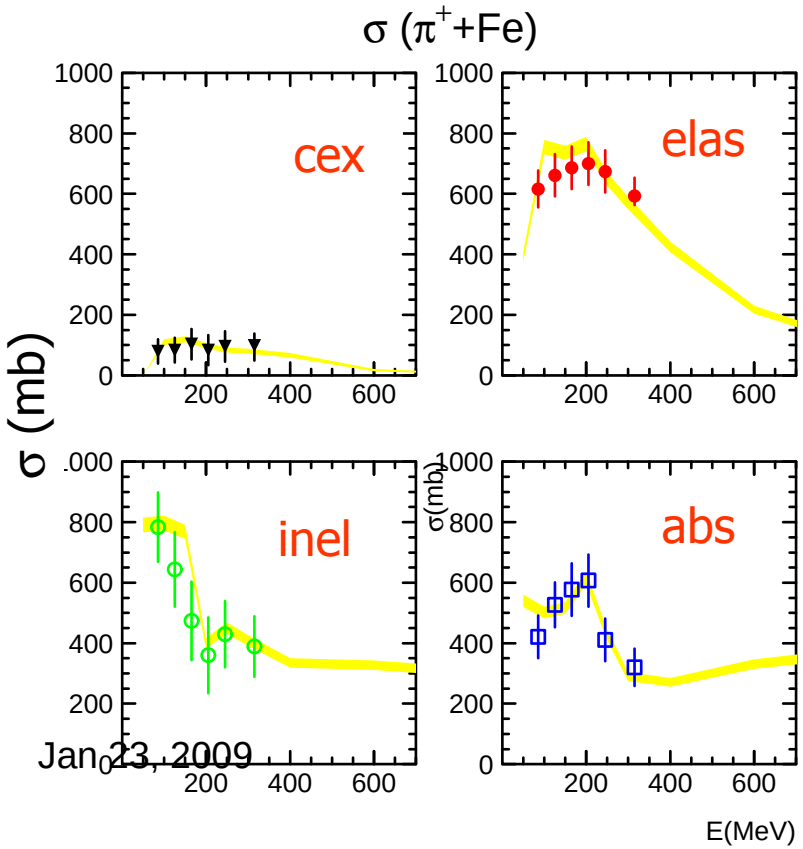
- Use CEM03.01 calculations for p ^{56}Fe except optical model for σ_{elas} (scale by $A^{2/3}$ for other nuclei)
- Results at 50, 100…1000 MeV incident energy
- Channels included:

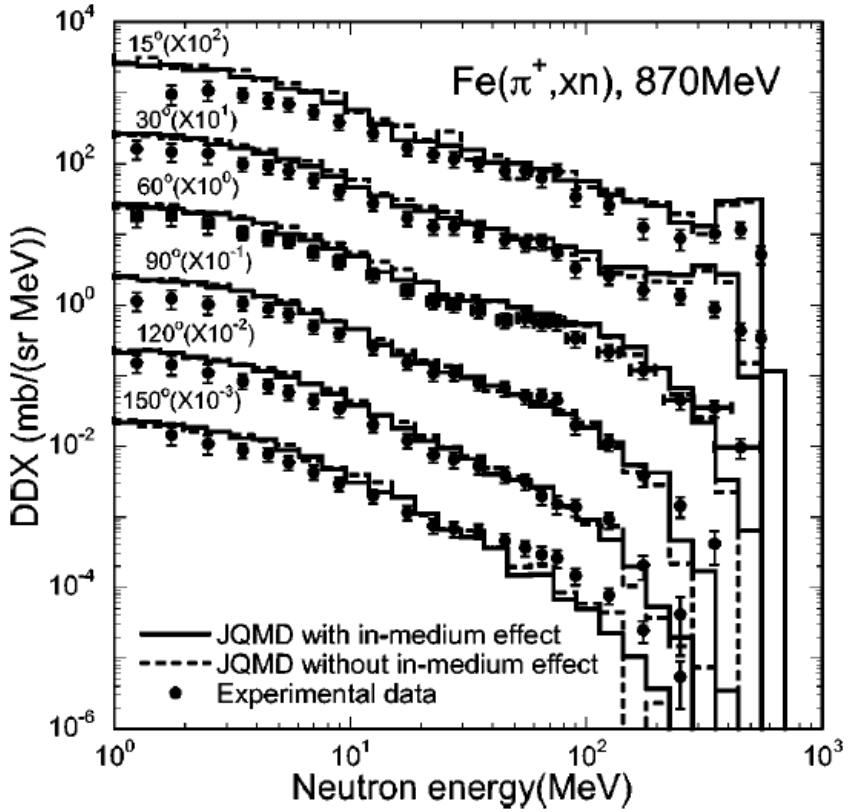


Elastic	p ^{56}Fe→p ^{56}Fe
Charge exchange	p ^{56}Fe→n ^{56}Co
Inelastic	p ^{56}Fe→p´ ^{56}Fe
Breakup	p ^{56}Fe→pn ^{55}Fe
	p ^{56}Fe→pp ^{55}Mn
	p ^{56}Fe→ppn ^{54}Mn
	p ^{56}Fe→pnn ^{54}Fe
Breakup-generic	p ^{56}Fe→pppnn ^{52}Cr
Pion production	p ^{56}Fe→π^+ n ^{56}Fe
	p ^{56}Fe→π^+ π^0 n ^{56}Fe

Validation process

1. Test mean free path with total cross section
2. Test reaction processes with component total cross sections and inclusive distributions.





Inclusive distributions

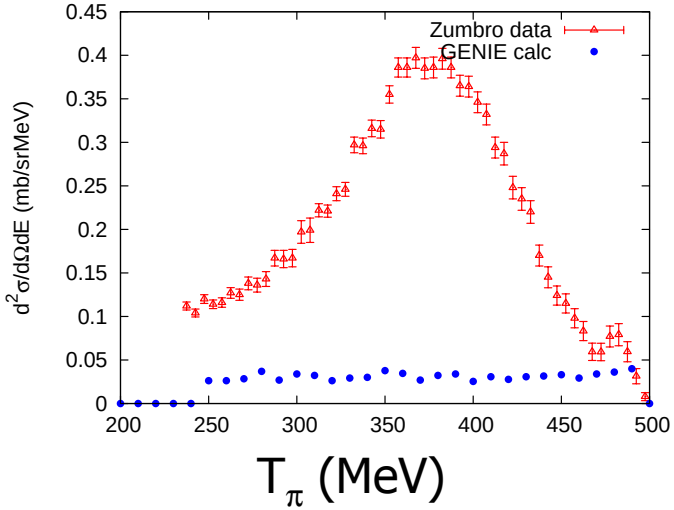
No previous effort made to match complete theory or these data

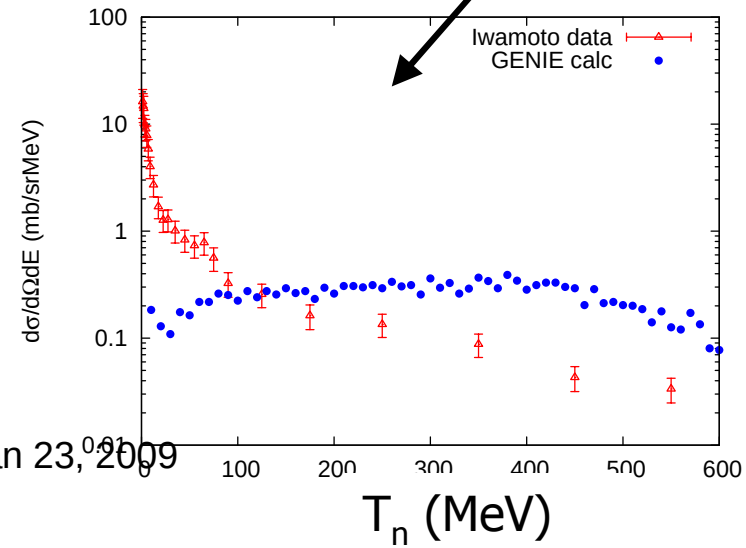
- Phase space or rough estimates only
- Encouraging, but will only get better.

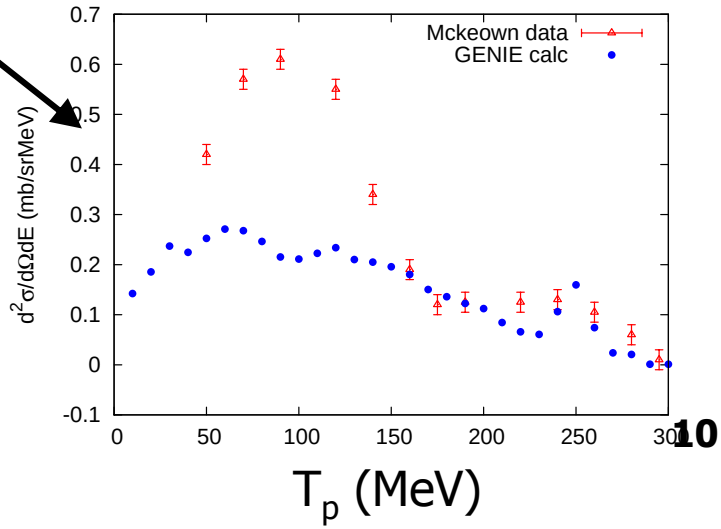
$^{12}C(\pi^+,\pi^+)X$ 500 MeV 50°

$^{12}C(\pi^+,p)X$ 220 MeV 30°

$^{56}Fe(\pi^+,n)X$ 870 MeV 30°







Caveats, future

- Problems with hA (all fixed with hN)
  - ✓ π^+ and π^- are identical (in fact, π^- interacts a little more)
  - ✓ Only works with N=Z nuclei (Pb will be somewhat wrong)
  - ✓ Angular distributions are wrong
- New hN model
  - ✓ Full INC calculation for pions, nucleons
  - ✓ Build hA interaction from hN data (phase shift data)
  - ✓ Extensive testing almost complete, will be in v2.6.0 (next month?)
  - ✓ Can then do some fixes in hA
- Future
  - ✓ Spectral function for qe in progress
  - ✓ hA will be used for systematic studies
  - ✓ hN will be used for full simulations

method

- Use πN, pp, and pn reaction PWA results (SAID) for almost all FSI reactions of hadrons.
- Originally polynomial fit, switched to data interpolation last summer (will affect hA).
- π production model presently simplified.
- Handle no. of neutrons, protons in tgt correctly
- Use Fermi momentum, removal energy same as rest of GENIE.
- Special model for pre-equilibrium, compound nucleus interactions (p, n at low energy)

Details

- Pion absorption
  - ✓ Use $\pi^+ d \rightarrow pp$ ($\pi^- d \rightarrow nn$, $\pi^0 d \rightarrow pn$ from Engel)
  - ✓ Since d has less binding than all real nuclei, correction always needed (usually a constant).
- Nucleons at low energy (<~70 MeV)
  - ✓ Fermi sea occupied, N tend to skim surface
  - ✓ Ignore all particles that would have mom<k_F, readjust residual nucleus.
  - ✓ At E_PreEq, breakup to 3 particles (phase space)
  - ✓ Lowest energy nucleon of these 3 breaks up to 4 more particles (phase space).

validation

- Mostly planned in advance
- πA and pA total cross sections (today)
  - ✓ Get overall rescatter rate
- πA and pA inclusive distributions
  - ✓ Details, still not clear ν expts are sensitive
- Small number of parameters, all physically motivated
- Focus on C, O, ~Fe, and ~Pb
  - ✓ MINOS, T2K, Nova…

Parameters

All in UserPhysicsOptions.xml

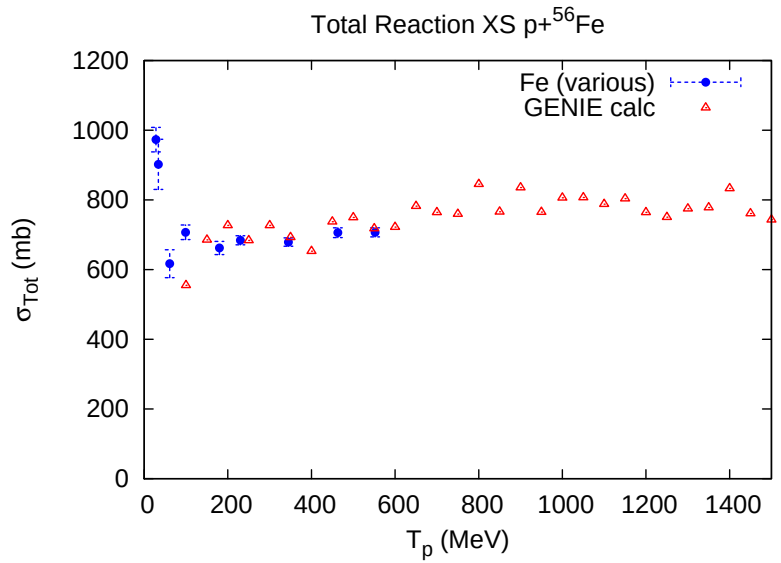
Parameter	**value**	**Comment**
DelRPion	0.2	0.5 in hA
DelRNucleon	0.2	1.0 in hA
NucAbsFac	1.5	3-4 in trad INC
NucCexFac	0.35	Required, new
E_preeq	0.075	Switch to LE
FreeStep	1.0	Δ propagation also for N

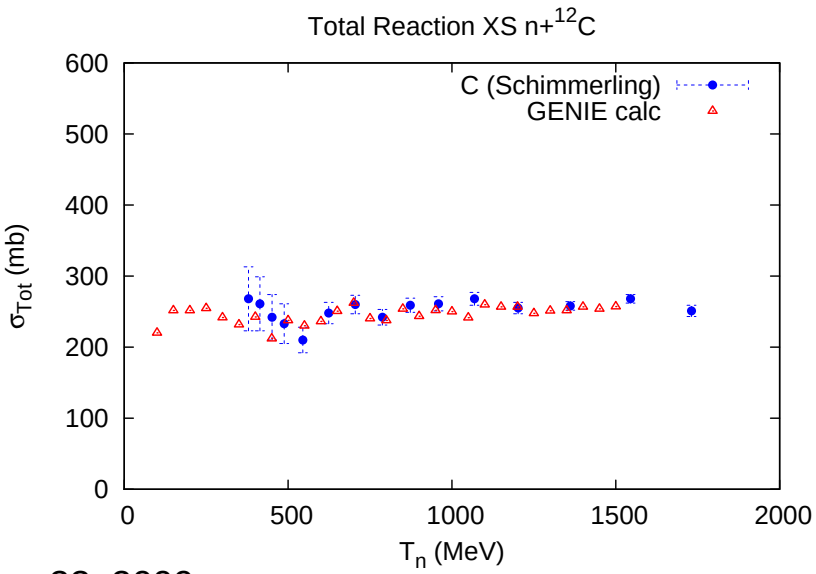
tools

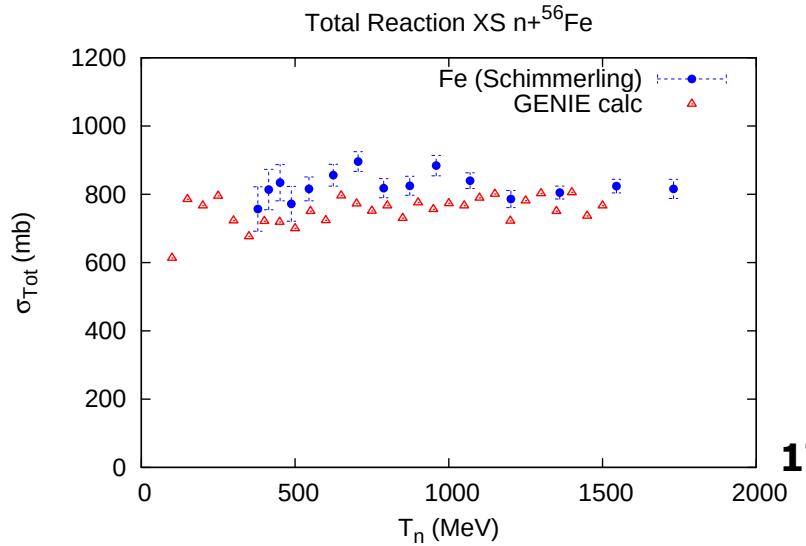
- gtestIntranuke
  - ✓ Runs for pions, nucleons (photons, kaons, electrons?)
- gtestIntranukeScript
  - ✓ Runs gtestIntranuke at a range of energies
- gIntranukeScript
  - ✓ Runs a list of cases, easily expanded to ν.
  - ✓ Names .root files as agreed this summer
- gIDA
  - ✓ Gets specific distribution from ginuke.root file
  - ✓ Makes histogram comparing it to external data
- Plot.C
  - ✓ Makes total cross section plots of data vs. GENIE calc.

p and n reaction xs

- Recently discovered data
- Only 1 parameter needed (DeLRNucleon)

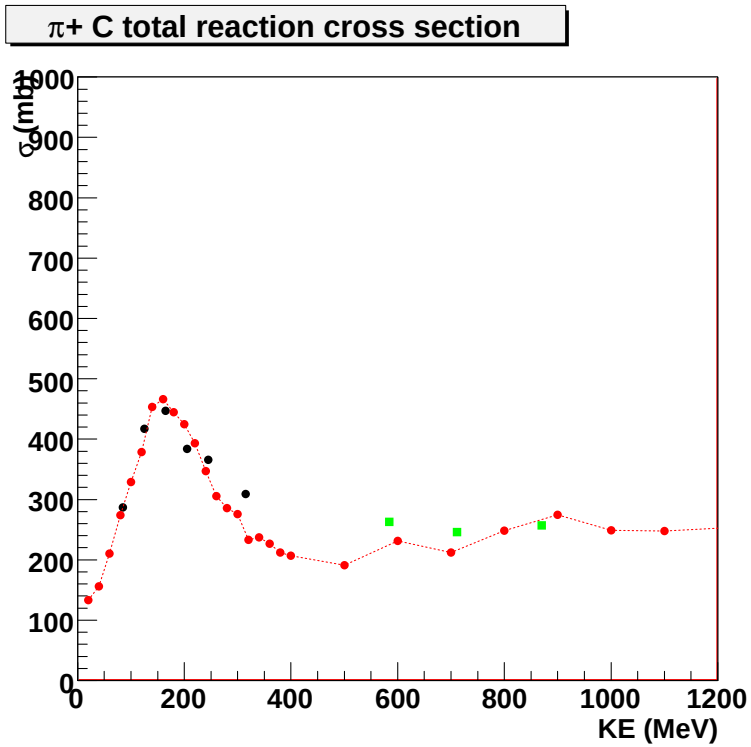


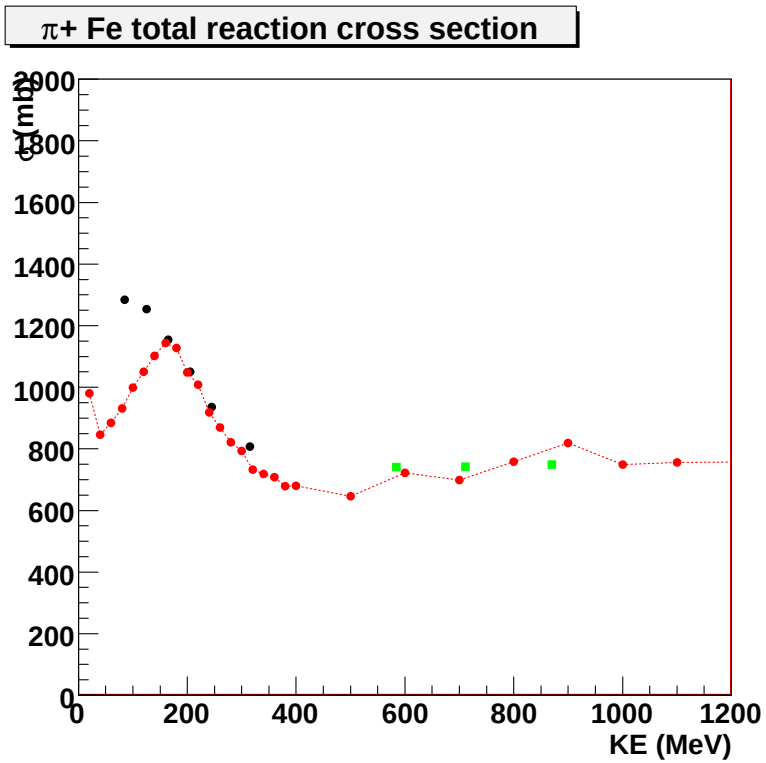




π^+ total reaction

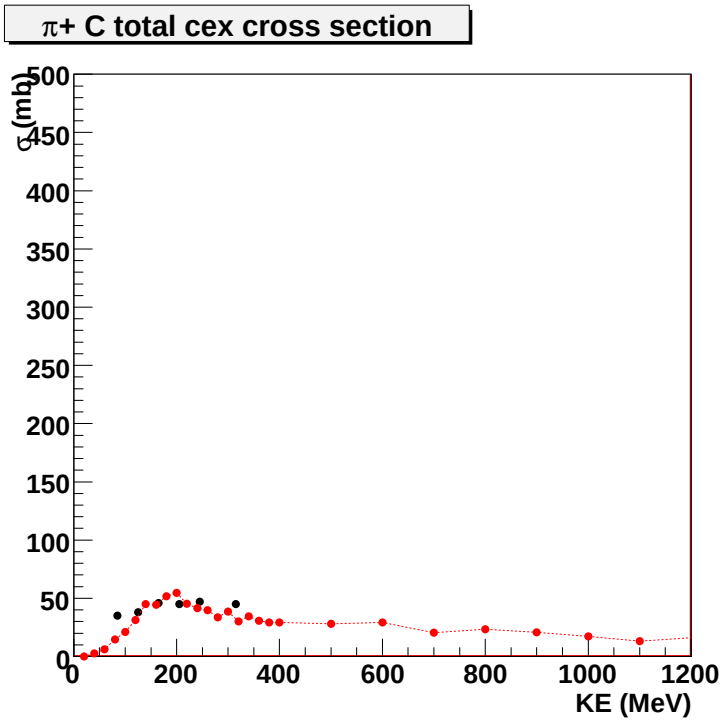
- Ashery, Allardyce data; GENIE always in red
- Only 1 parameter needed (DeLRPion)
- Increase at low energy for Fe not understood

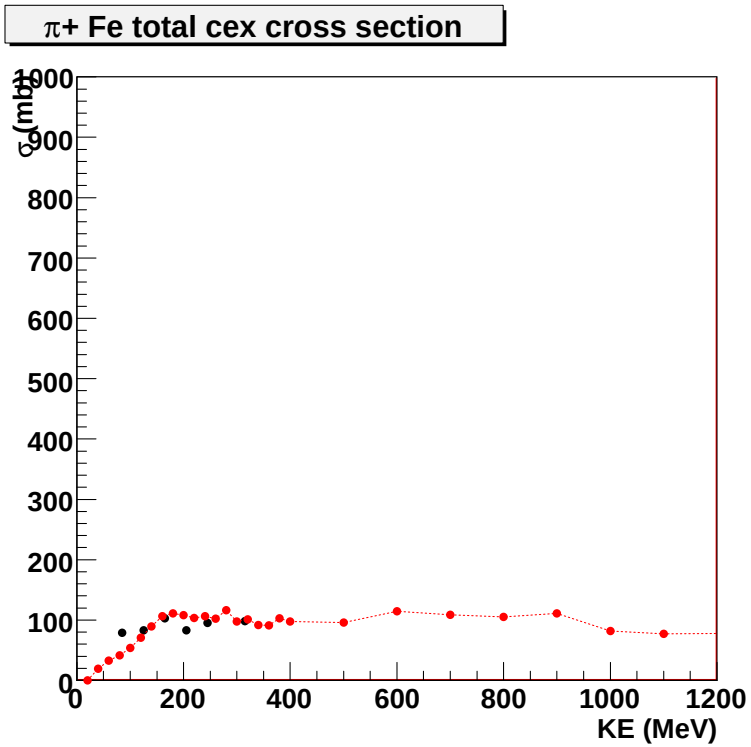




π^+ total charge exch

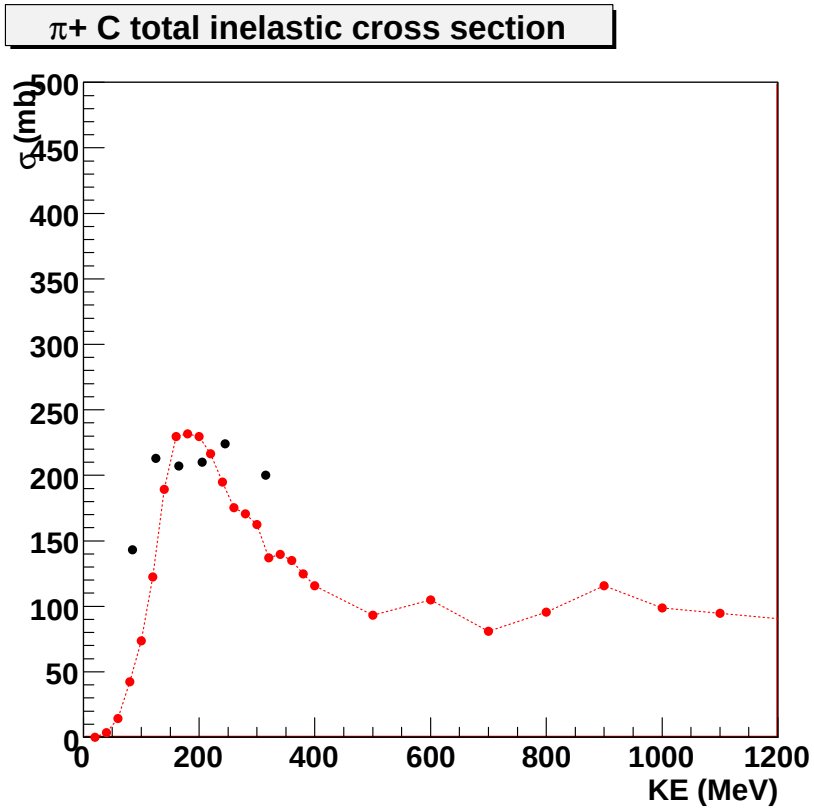
- Ashery 'data' (model dependent, 50% error bars)
- Only 1 parameter needed (NucCEXFac=0.35)
- Not clear why previous work didn't find this.

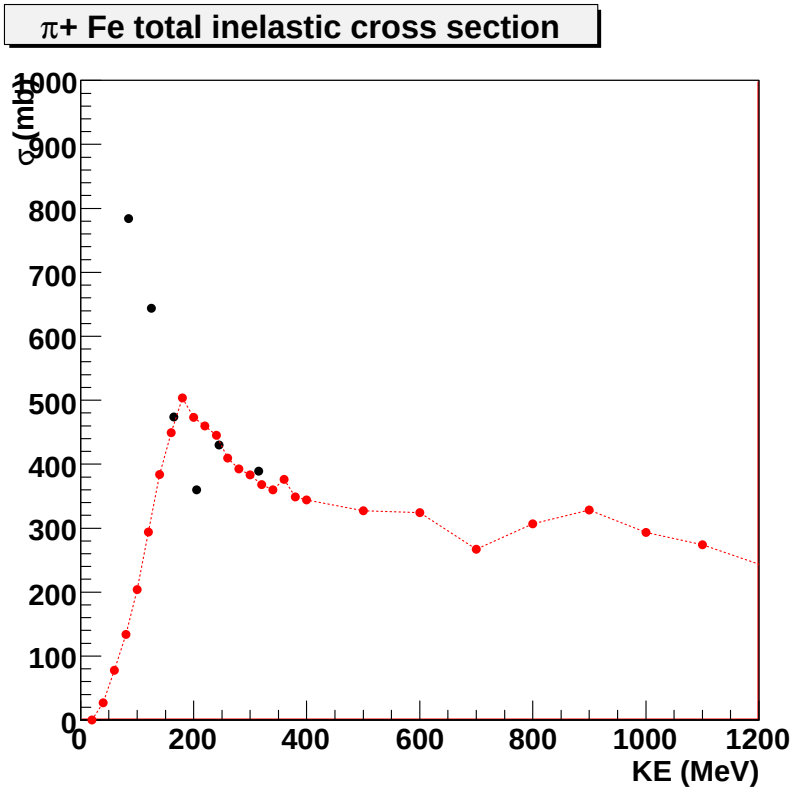




π^+ total inelastic

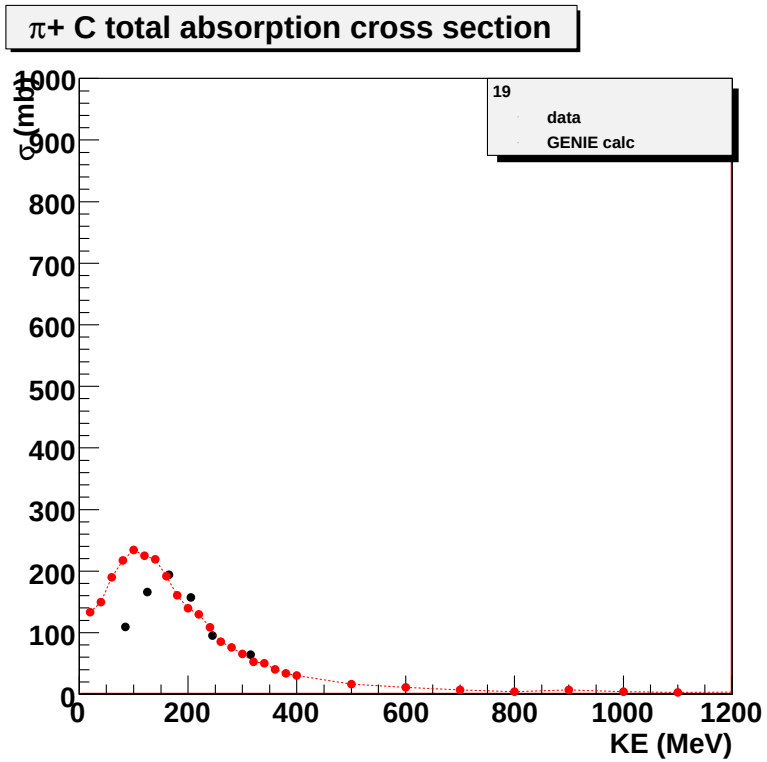
- Ashery data
- No parameters
- QE mechanism done well, γ decay from states?

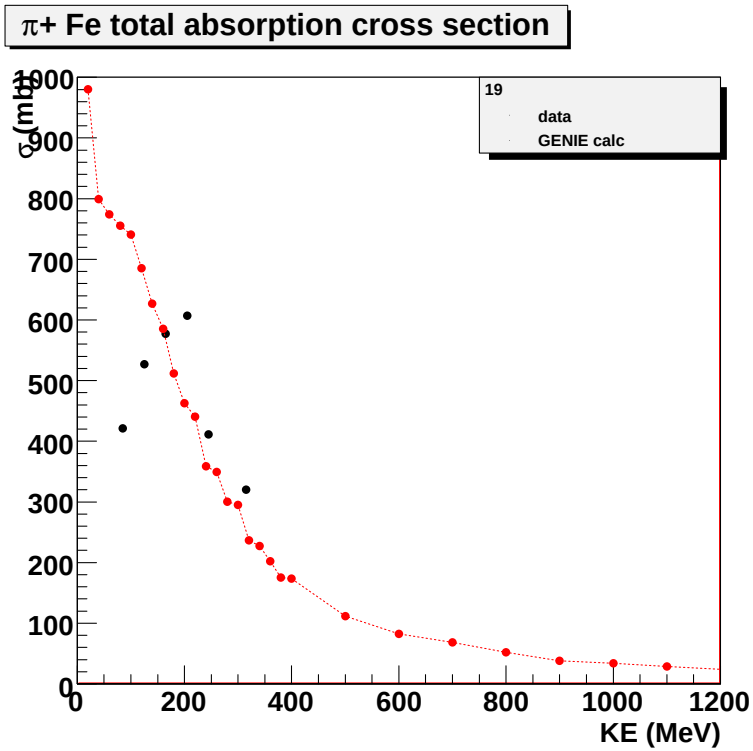




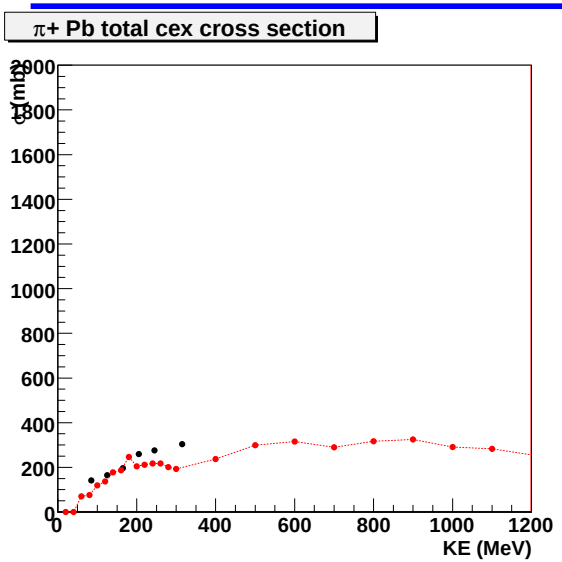
π^+ total absorption

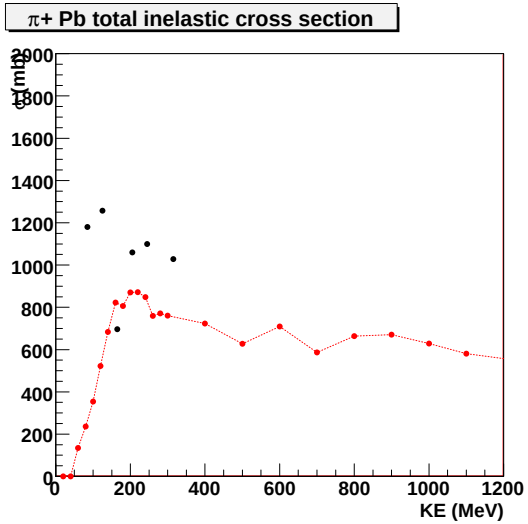
- Ashery data
- Only 1 parameter needed (NucAbsFac=1.5)
- $\pi d \rightarrow NN$ done well, others (3-body) needed?
- Rise at low energy in Fe not understood

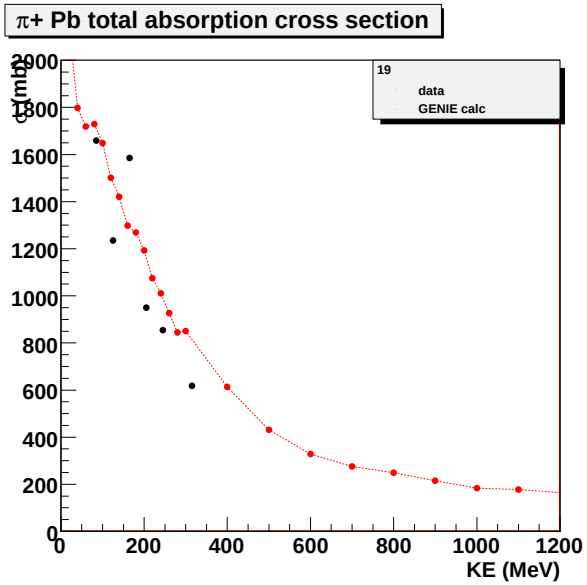


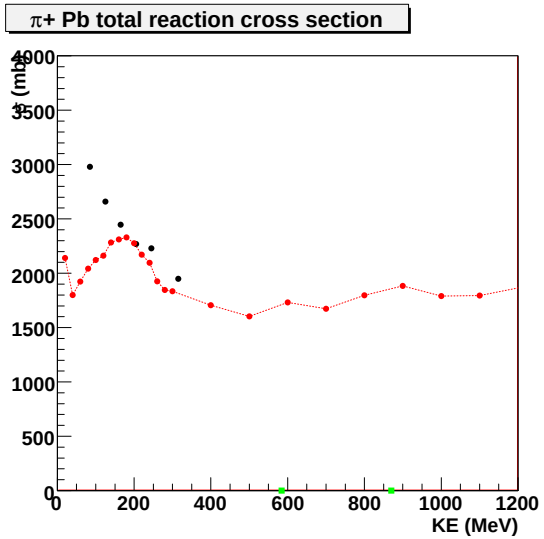


Now π^+ Pb



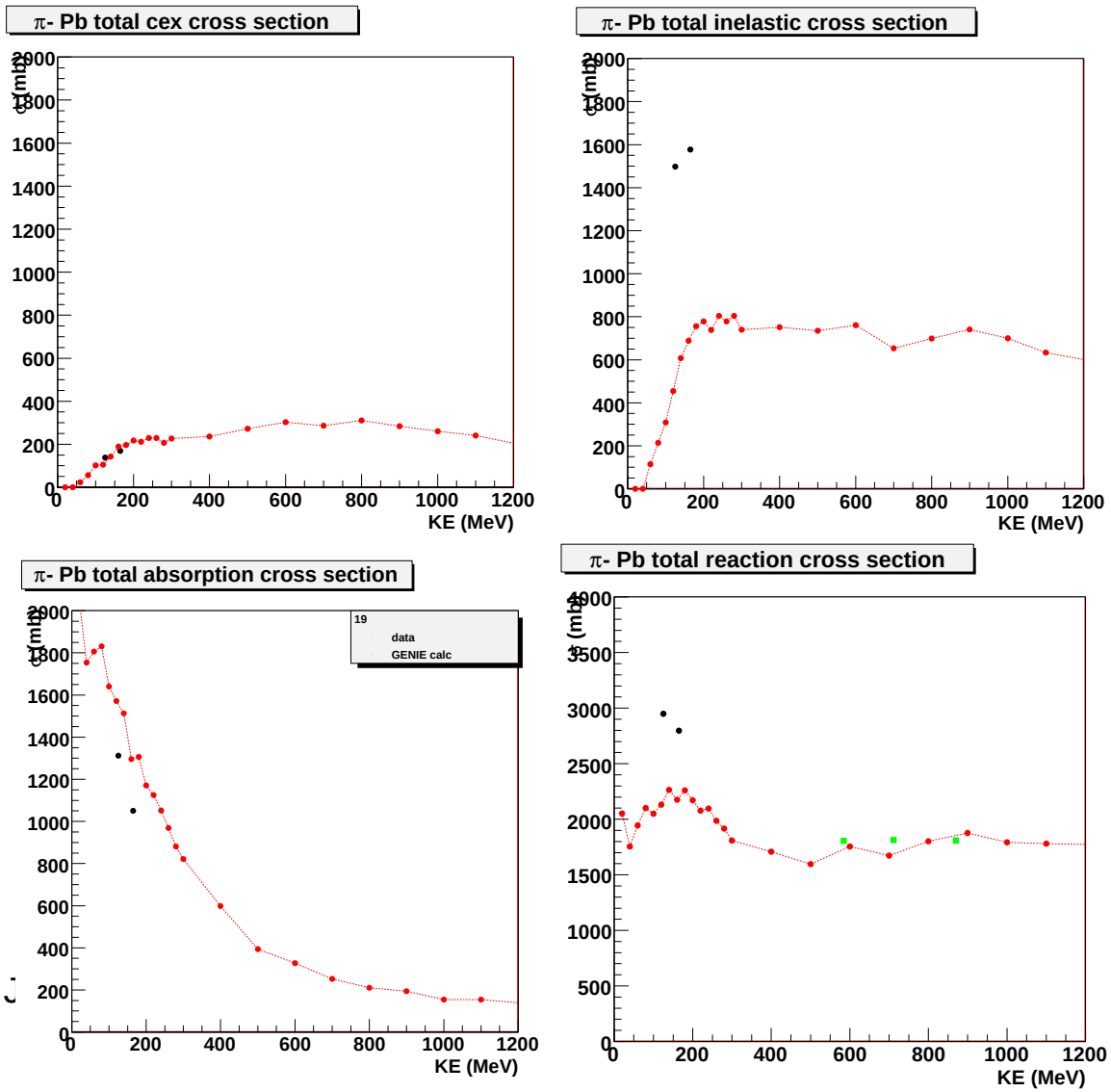






- Ashery data
- Z=82, N=126
- No surprises

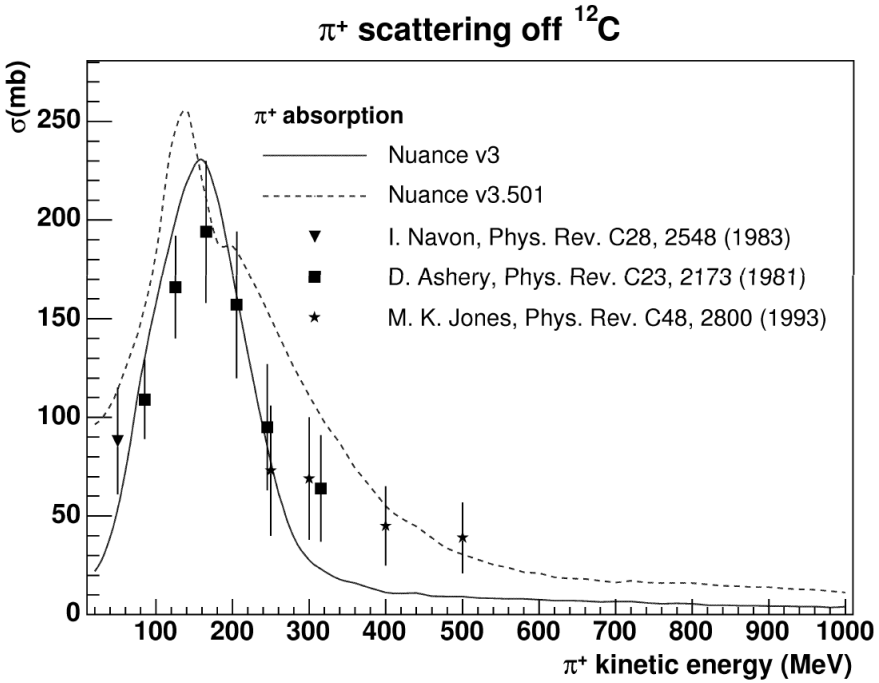
π^- Pb

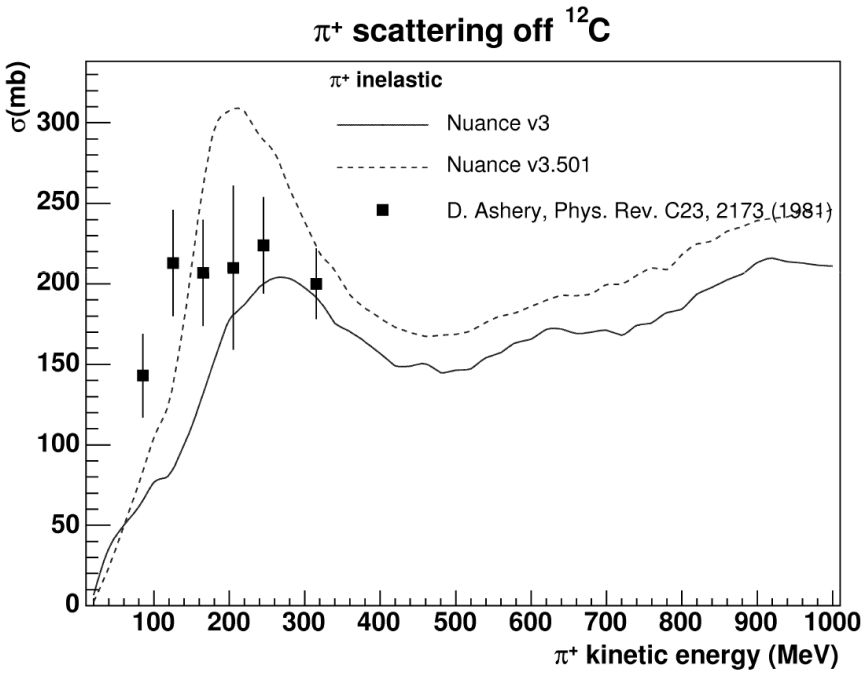


- Ashery data
- Now we see difference between π^+ and π^-.

Nuance studies (Miniboone)

- They did studies beyond what developer did
- Results provided by G. Zeller



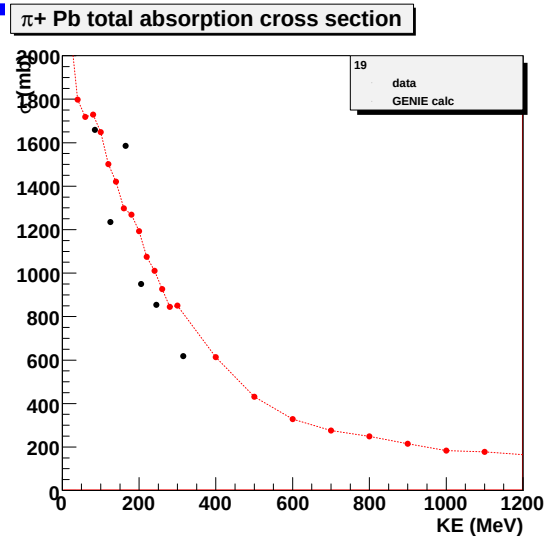


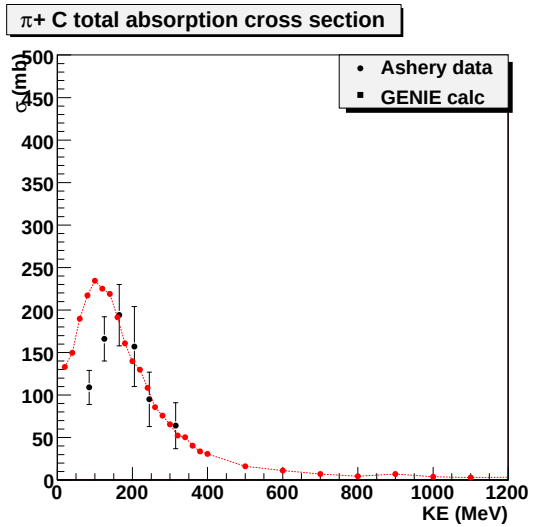
conclusions

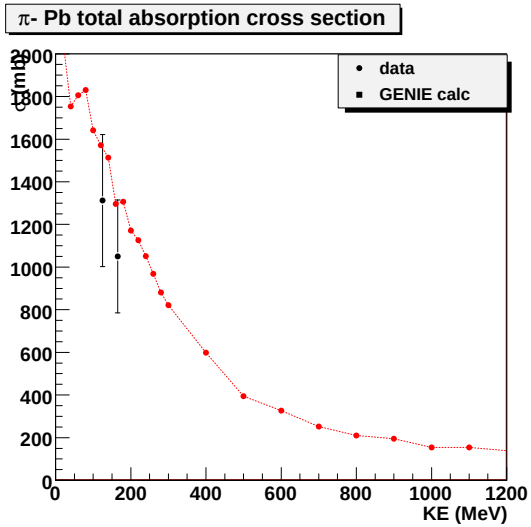
- First results from brand new model
- Try to stay very close to real physics/data
  - ✓ True INC model
  - ✓ Small no. of parameters, all physically motivated
- As with previous INC models, low energy is tough. E.g. πA always applied to T_π>~150 MeV.
- Model development will continue, but hopefully in next version of GENIE.
- Next time, inclusive distributions (totally new).

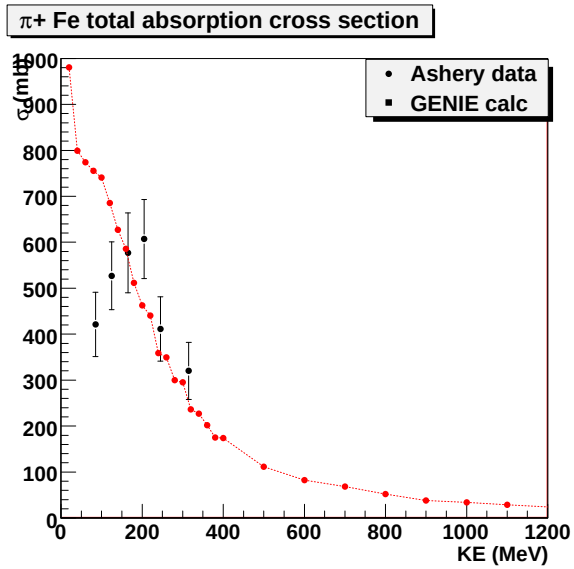
π absorption

- Great interest because of CC qe mis-id.
- Complicated mechanism in QM models.
- We do well except at low π energies.



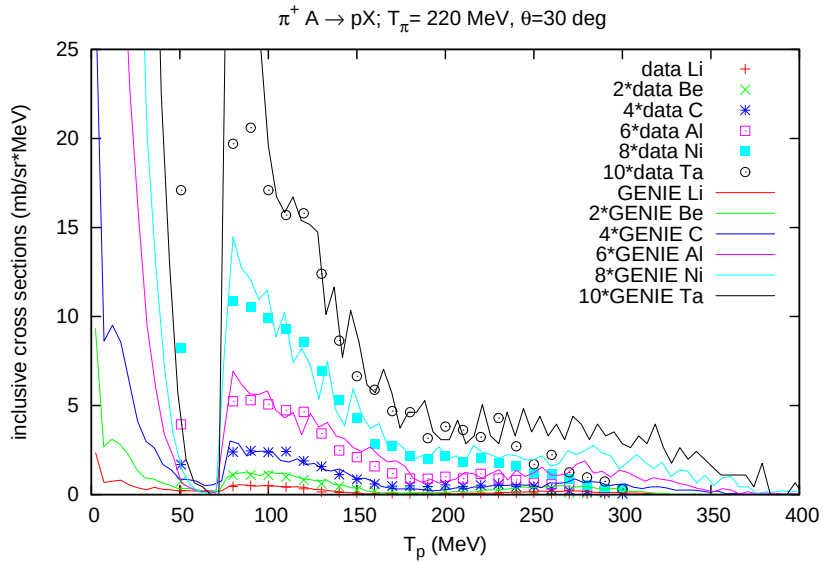


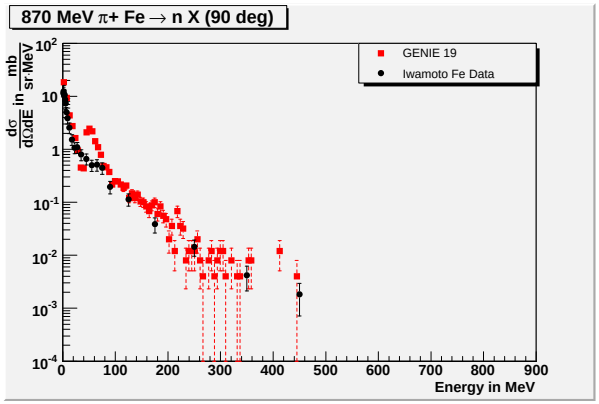


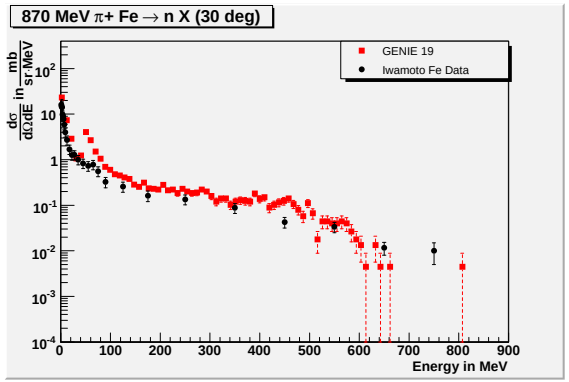


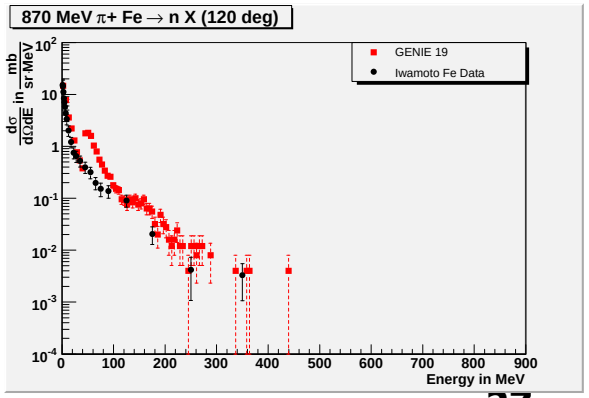
π absorption

- Lot of detail here, great agreement
- Many mechanisms involved- π absorption mixed with neutron rescattering.
- Unique info at 870 MeV



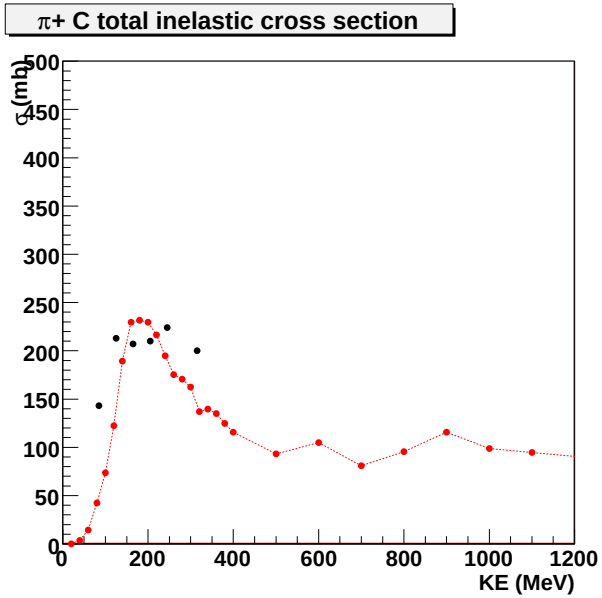


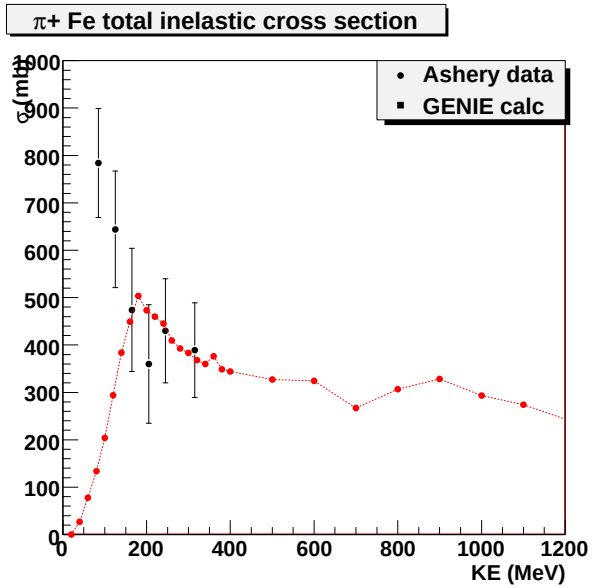


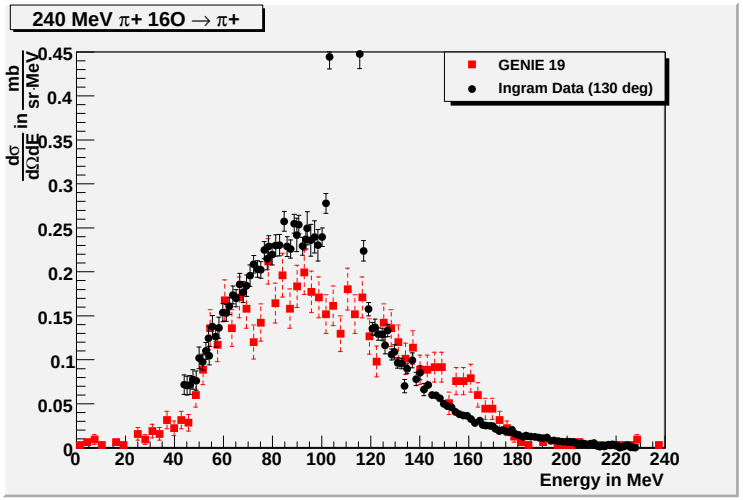


π scattering

- Best agreement
- Back angles dominated by (π,π′) qe.

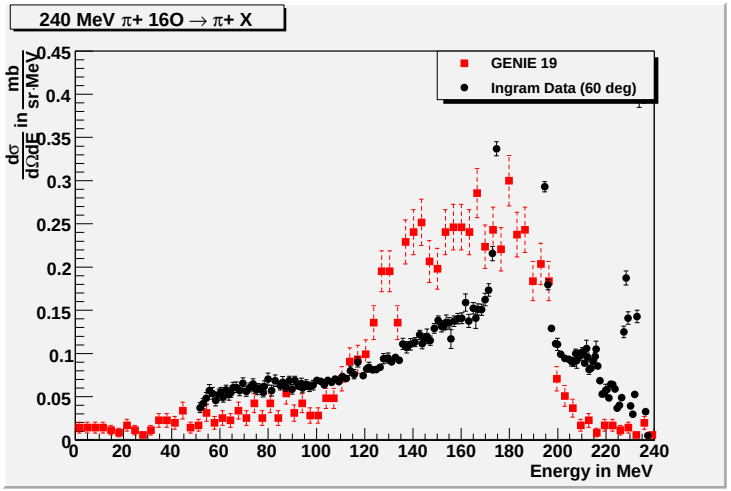


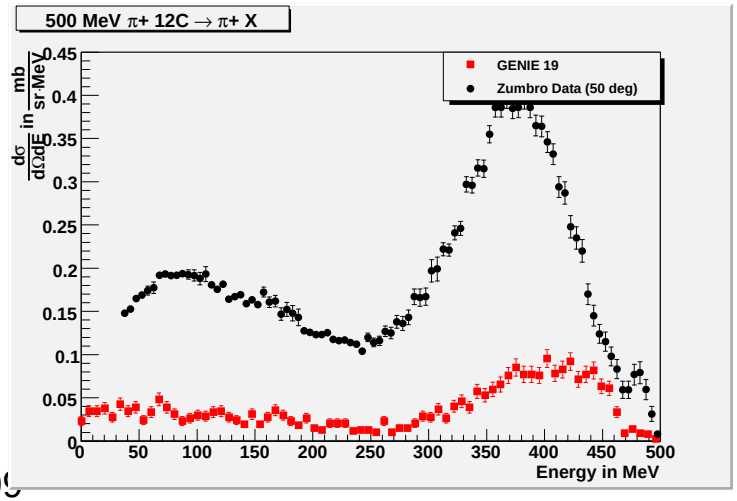


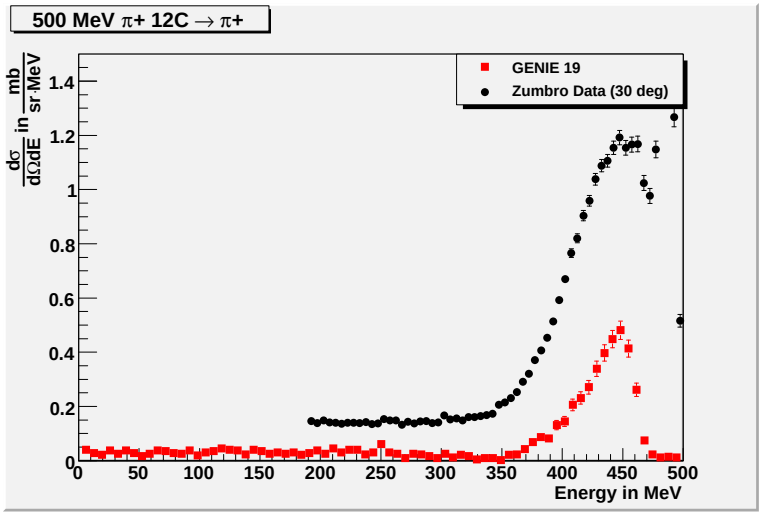


π scattering

- Ingram data at forward angles not as good
- No understanding of problems with Zumbro data.

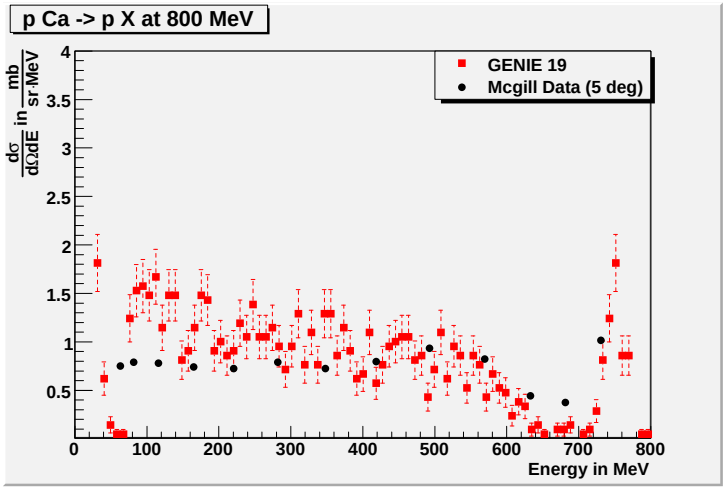


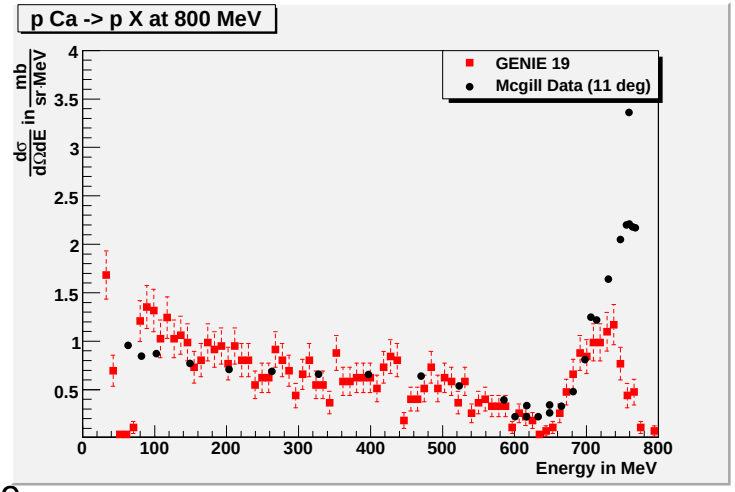


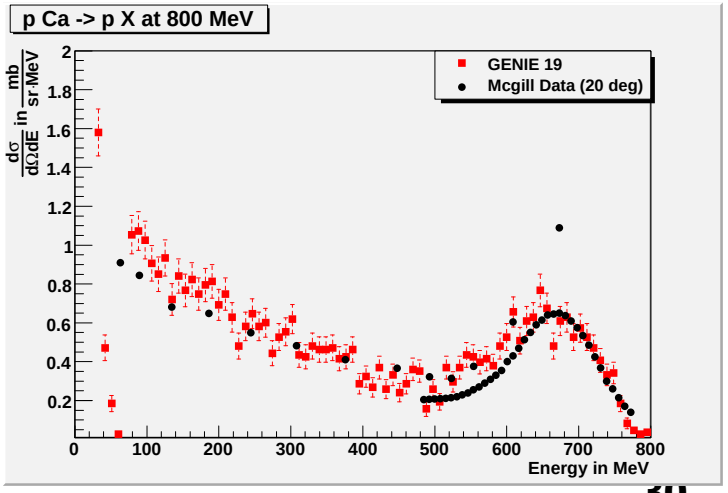


p scattering

- Note much higher energy, INC should be excellent.
- QE peak data at 20° known to have norm error.
- Excellent agreement.

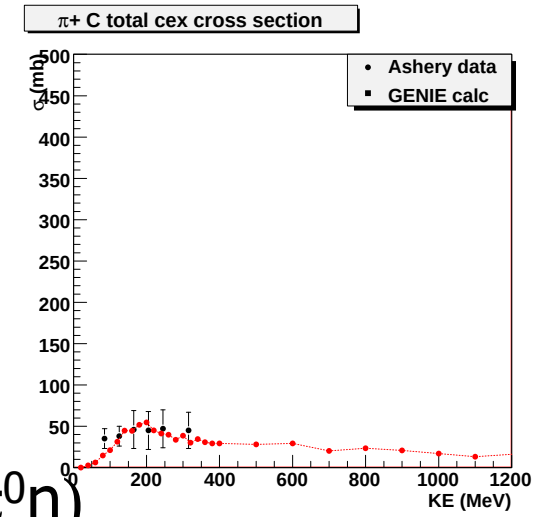


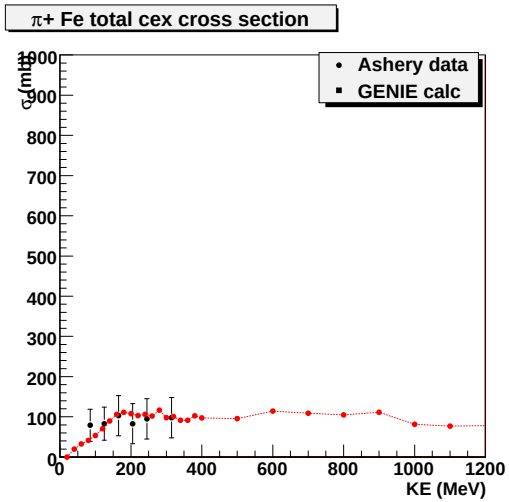


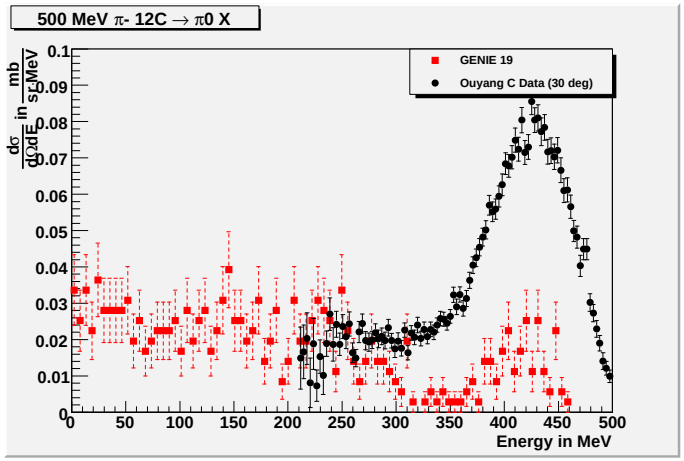


π charge exchange (cex)

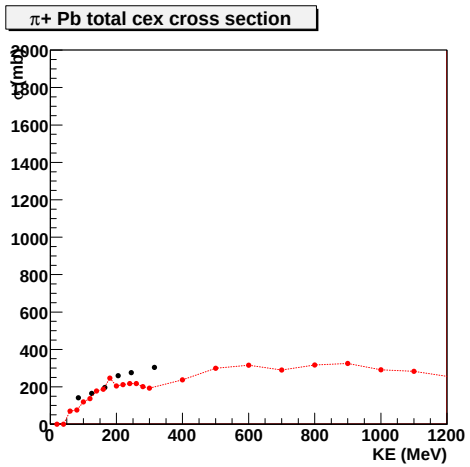
- Odd case, very little data. Total xs is what is left over.
- We are forced to suppress $\sigma(\pi^- p \rightarrow \pi^0 n)$ by factor of 0.3 to match 'data'.
- Then, inclusive cex data is wrong by same factor! Data at 50° (not shown) has same problem (only normalization issue).

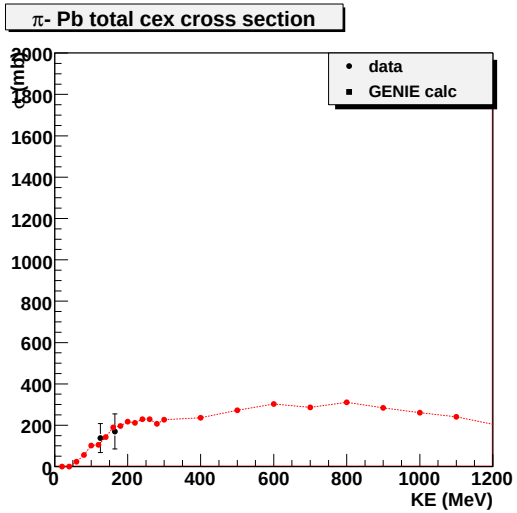




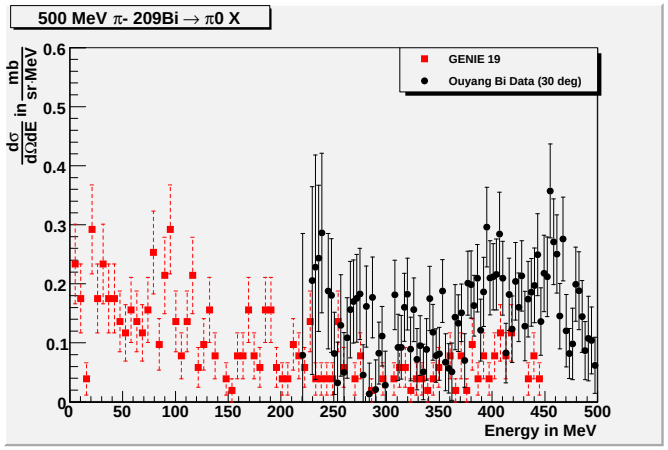


π charge exchange (cex)



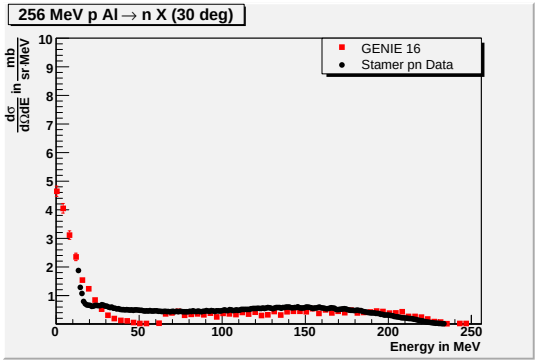


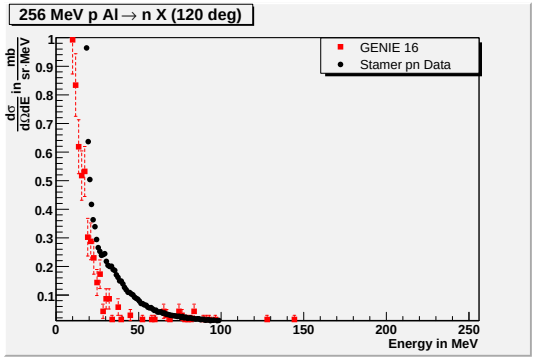
- Heavier nuclei data don't add much.
- Total xs still ok with suppression factor.

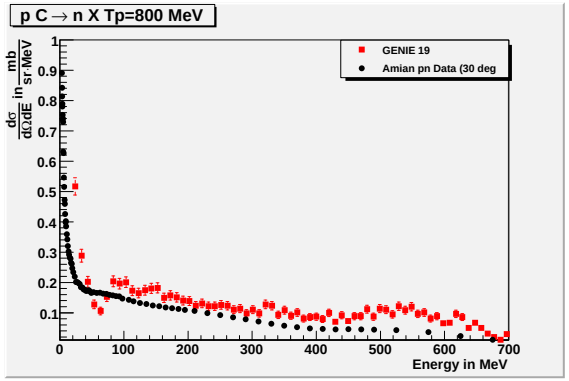


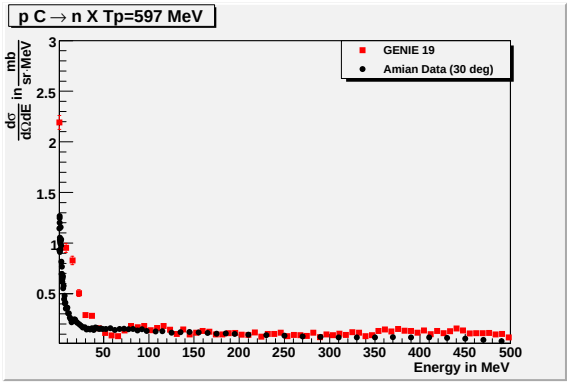
p cex

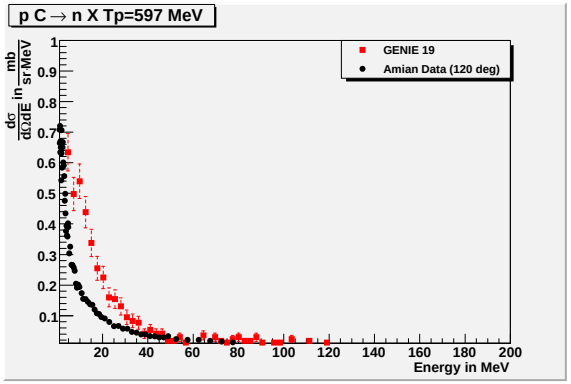
- Lots of high quality data from LAMPF (WNR).
- good agreement.











More details

- Overall mass of residual nucleus still a problem
  - ✓ Not uncommon to have ~10 nucleons emitted.
- Elastic scattering still an issue
  - ✓ Is it really justified? (physics vs. empiricism)
  - ✓ What does it mean in INC model?
  - ✓ Idea is to decide elas vs. reaction (all else) first, then go into hN model. Ideas?
  - ✓ Use optical model to parameterize elastic scattering at all energies for all nuclei, sounds daunting but this is like my thesis.