Final State Interactions (GENIE)

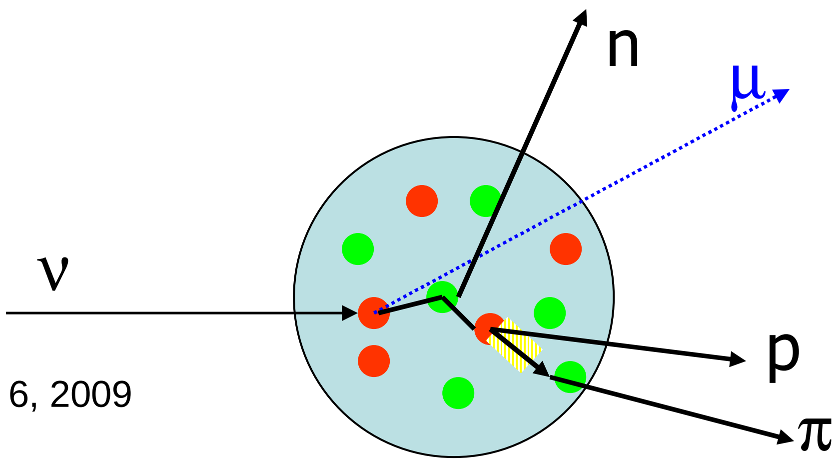
S. Dytman

Univ. of Pittsburgh

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

Simulation

- Event generators (e.g. GENIE) do full νA interaction
- Basic nuclear model is *Fermi Gas*
  - ✓ Single particle densities right, NN correlations wrong (except SRC)
  - ✓ Medium effects approximated (Fermi momentum, binding genergy)
- Basic interaction model is *intranuclear cascade (INC)*
  - ✓ All particles are free (corrected)
  - ✓ Many final states can be described

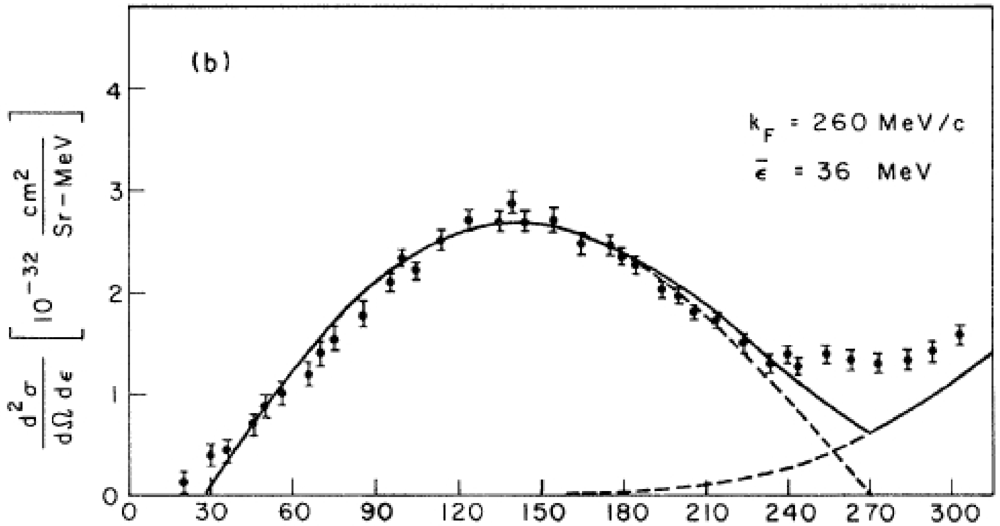


νp or νn→ form. zone→ fsi

Fermi gas model

nucleons are INDEPENDENT!

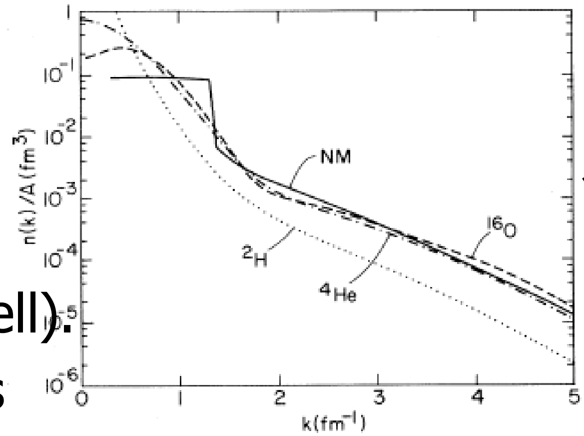
- Justified by (e,e’) data of ~1970.
- Smith, Moniz (1972)
- Bodek, Ritchie (1981)
  - ✓ Assume struck nucleon off-shell, outgoing nucleon on-shell (fsi issue!)
- Basis for all ν event gen.
  - ✓ Fermi mom. good,
  - ✓ Pauli blocking good, but….
  - ✓ How to handle binding energy?

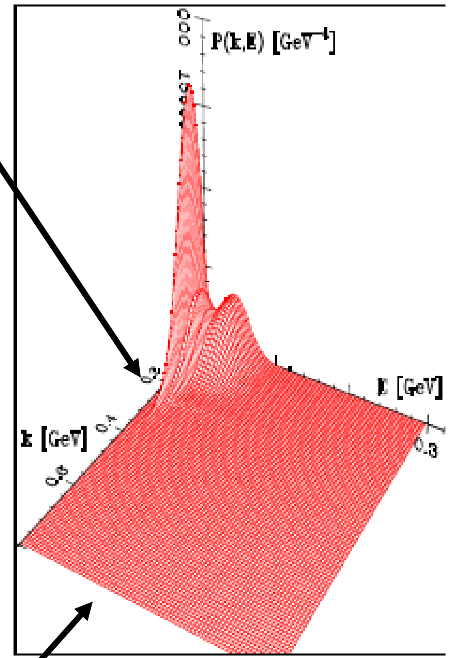


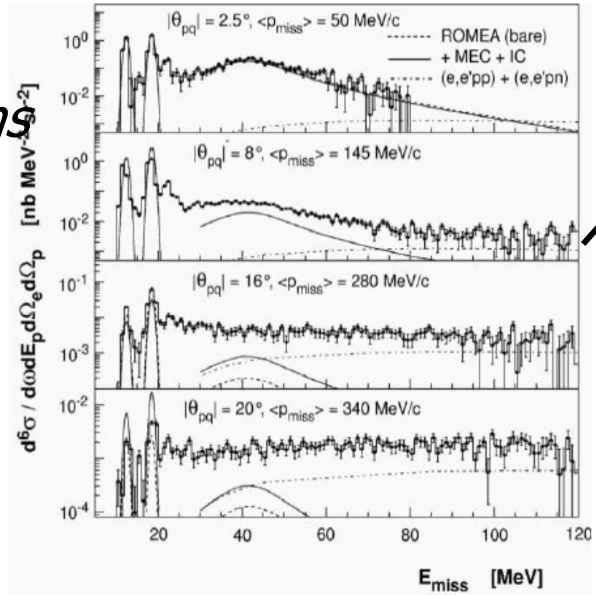
μ

nuclear structure

- In *Fermi Gas* model, nucleons don't interact.
- They are bound in a potential, momentum and energy disconnected, $E^2 \neq p^2 + m^2$ (off-shell).
- *Structure function* (Benhar) uses potential to calculate probability for qe as a function of mom and energy
- Interactions produce *correlations* which effect data.
- Can be used for electrons or neutrinos, but each nucleus is different!
- This is only qe, application to 1π production impossible.

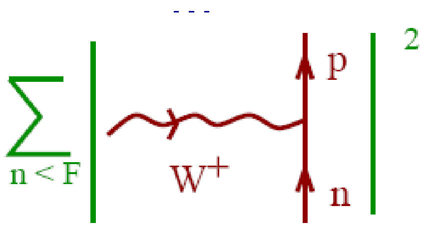




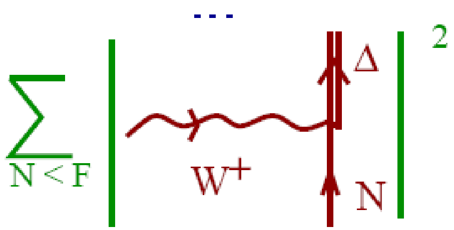


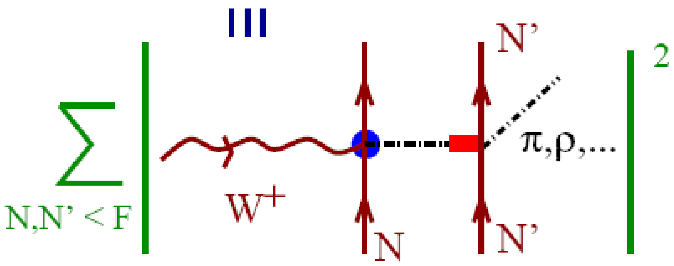
ν CC interaction Diagrams

'normal' qe

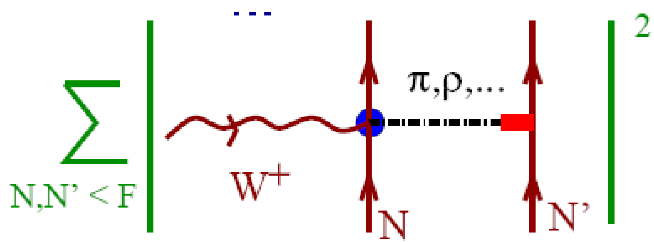


'normal' π prod (+fsi)

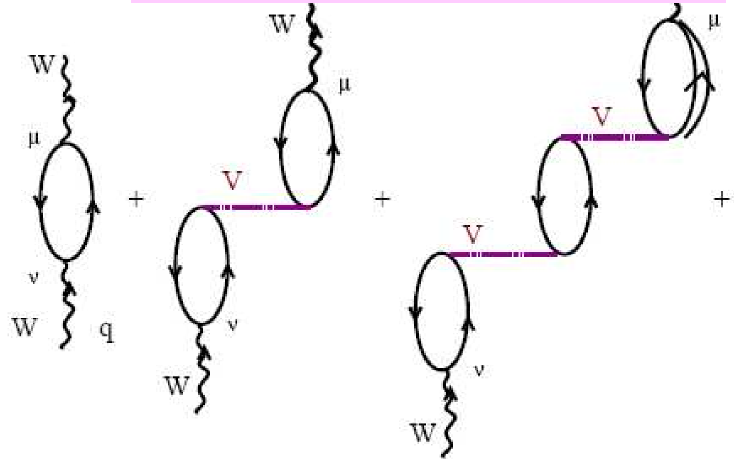




qe with NN correlations
Called MEC, SRC (all Q^2)



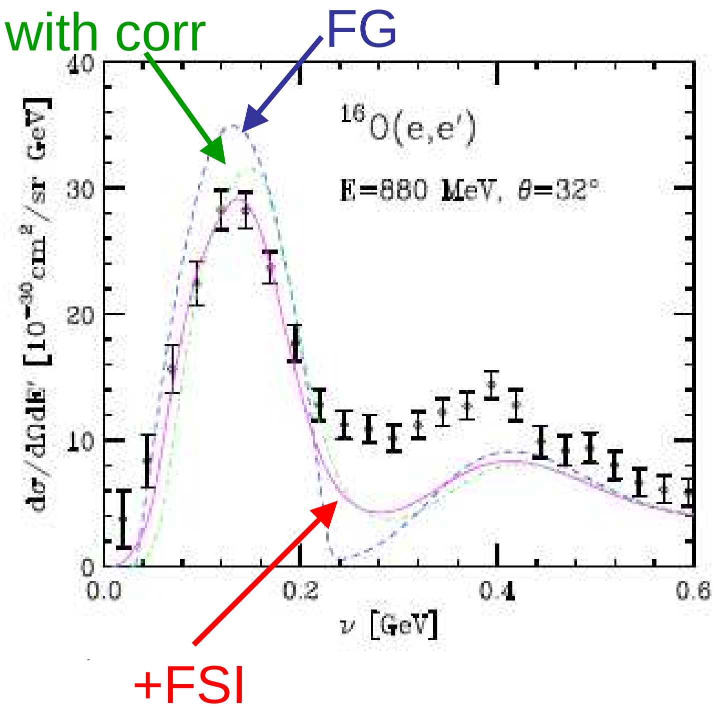
RPA correlations at $Q^2<0.2\text{GeV}^2$.

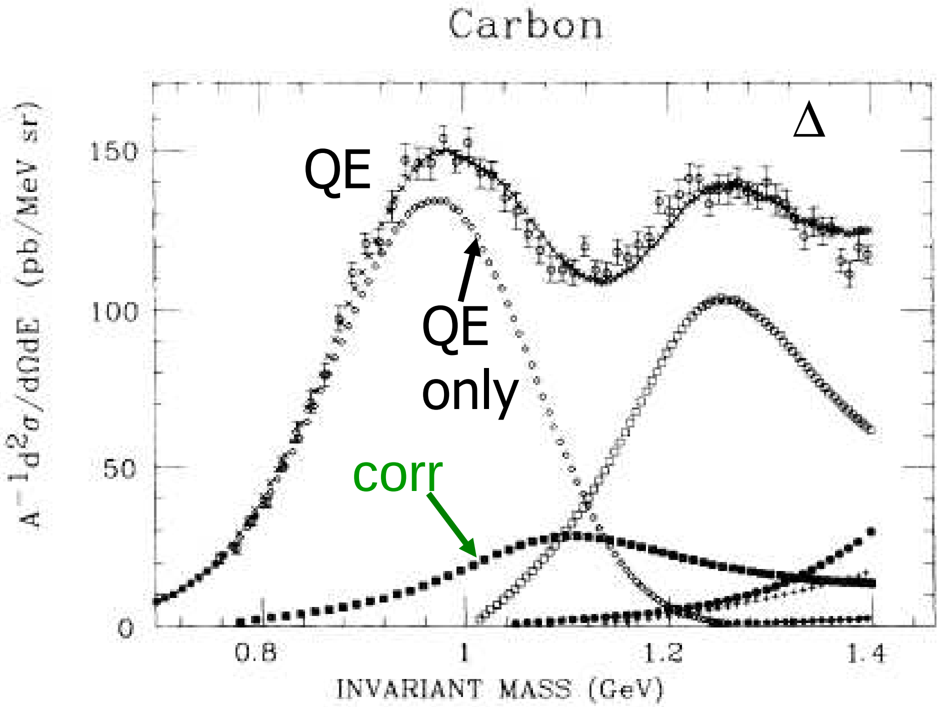


Application to (e,e′) I

Calc of Benhar
Uses structure function
Note that data is incl xs
vs. ΔE at fixed E_0, θ.

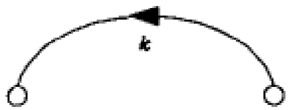
Calc of O′Connell, Sealock.
Shows separate effects
of true qe, correlations,
π production.



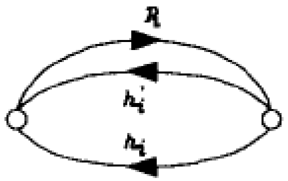


Application to (e,e′) II

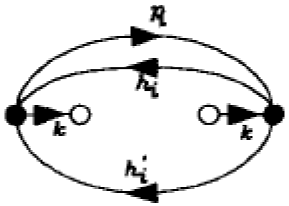
1 nucleon (1h)



2 corr. nucl. (2p1h)



≥2 corr. nucl.

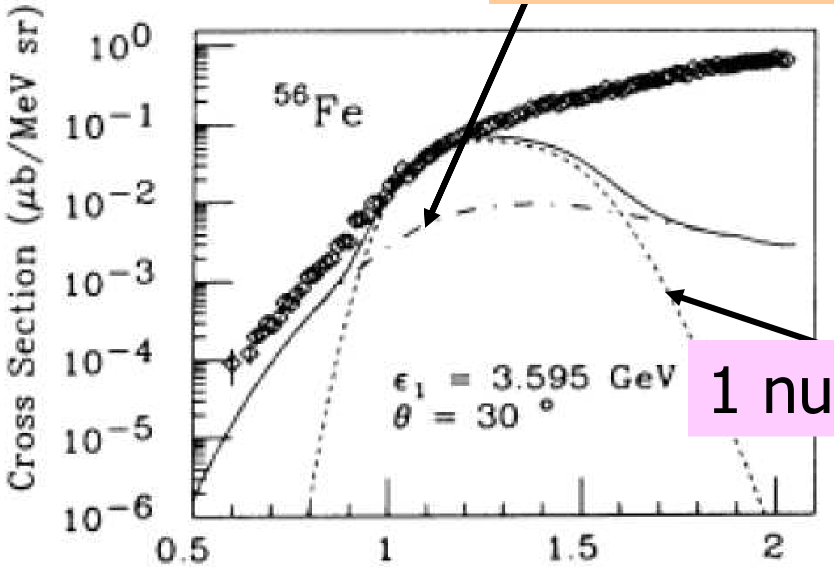


← 1 hole (escape)

→ 1 part. (stays)

- Benhar+collab calc of NN correlations.
- More than 1 nucleon interacts, only 1 emitted.
- NO reason we wouldn't see same thing with (ν,ν′).

≥2 corr. nucleons

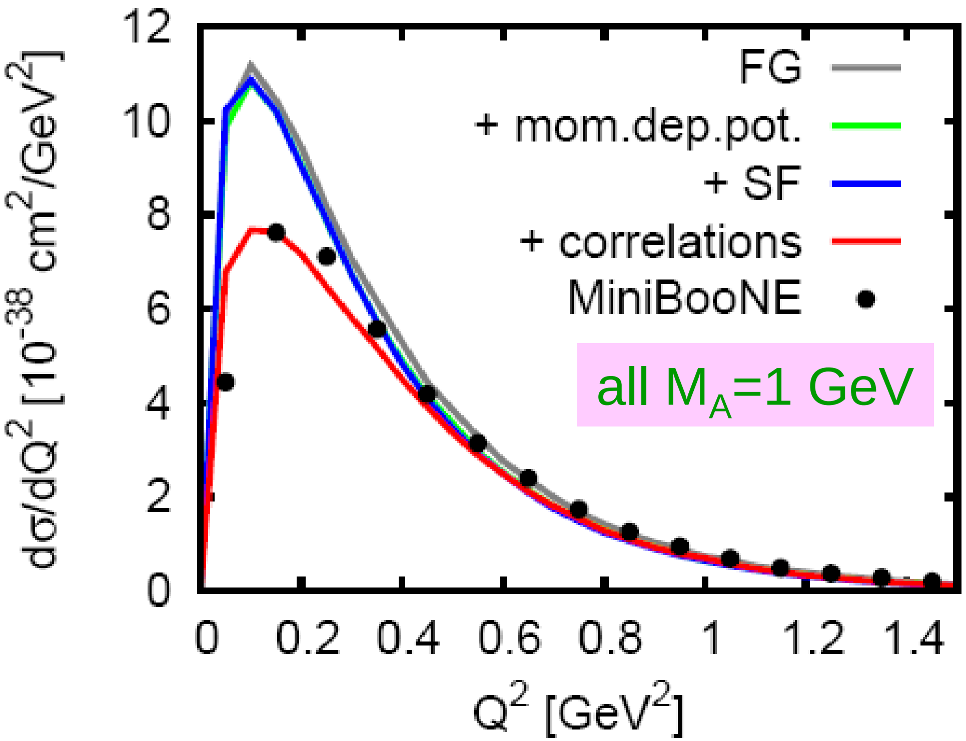


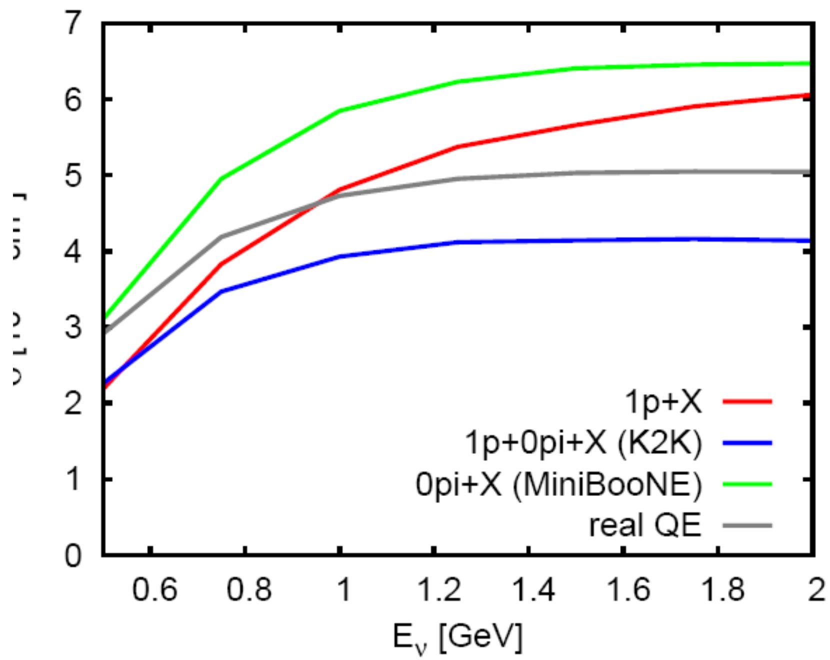
1 nucleon

Application to ν data
(Tina Leitner)

Nuclear effects change Q^2 distribution

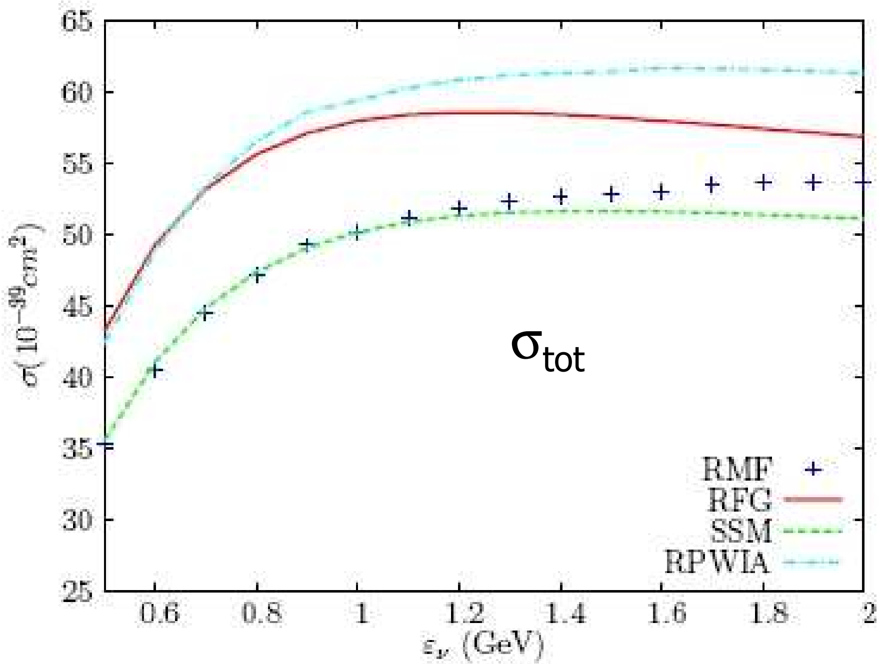
Calculated ν qe total cross section with various cuts (not same as expt). This is largely FSI effect.

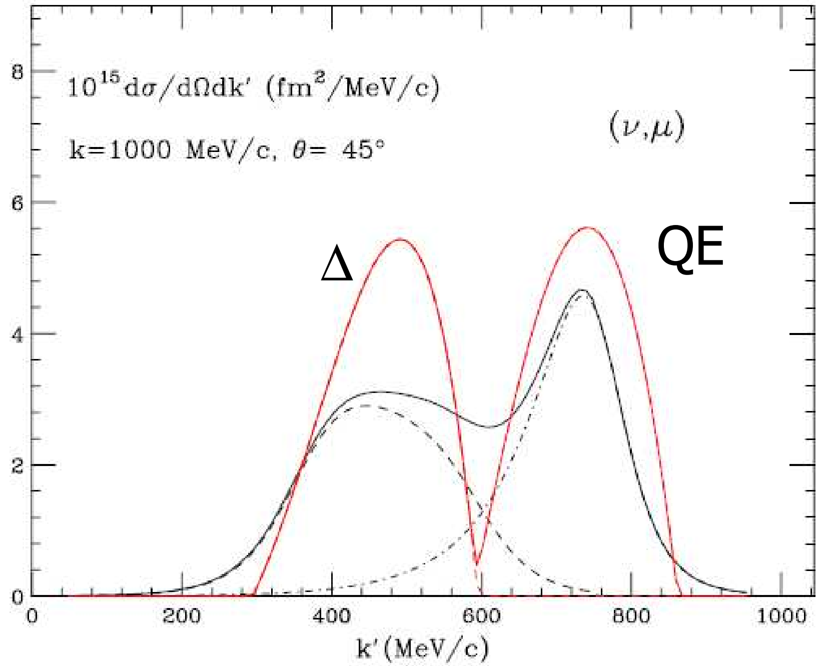




ν-nucleus calculations

- (e,e´), CVC→Vector (ν,μ), get Axial from PCAC
- FG has larger cross section, more peaky
- No data for comparison!





N.B. this is lepton mom dist at specific angle. (Donnelly and collab)

Historical perspective

- Electron scattering
  - ✓ eN cross sections well-known early
  - ✓ Dipole approximation important organizing principle
  - ✓ eA data used to learn about nuclear structure
- Neutrino scattering
  - ✓ νN cross sections moderately well-known, use calc of Llewlyn-Smith
  - ✓ Dipole form factor important (M_A)
  - ✓ Must use νA data to measure M_A, must assume knowledge of nuclear structure and reaction mech.

Final state interactions (FSI)

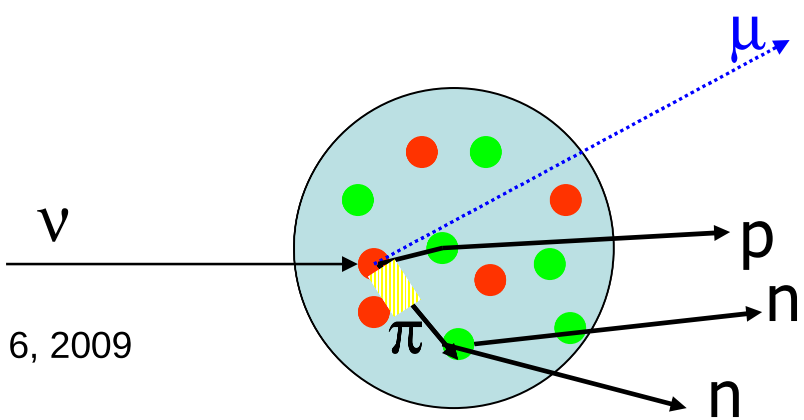
- Historically most difficult part of any nuclear simulation code
- 2nd significant change between nuclei (nuclear structure!)
- INC model is 'simple', able to describe many final states important to νA interactions.
  - ✓ $\nu C \rightarrow \mu^- p$ vs. $\nu C \rightarrow \mu^- ppn$ vs. $\nu C \rightarrow \mu^- ppppnnnnn$
  - ✓ Describe NC coherent π^0 production in nuclear medium
  - ✓ Describe CC processes in nuclear medium, e.g. pi production followed by absorption (important background).
- Interaction probability by mean free path (mfp)
  - ✓ $\lambda(r,E)=1/[\sigma_{\pi N}(E)*\rho(r)]$
  - ✓ Use charge density from (e,e), πN and NN xs from GWU http://gwdac.phys.gwu.edu/
  - ✓ Prob(interaction)=1-exp(-x/λ)

Role of data, simulation

- Ideally, we'd have lots of νA data with all final state particles identified. We have 1 bubble chamber experiment with ~1000 events (Merenyi). (neutral pions, neutrons hard)
- We do have lots of $\pi^{\pm}$A, pA, nA, and γA data which measure the same properties. Use them until SCIBoone, Minerva… data available. *Simulation is key now!*

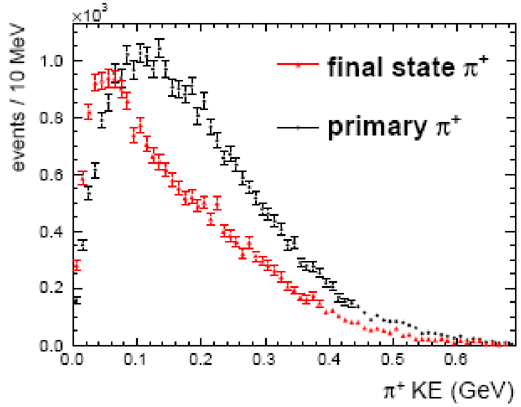
overview

- Hadronic final state interactions (fsi) matter
- ν interacts through weak interaction (λ~ly), but
  p, n (N) emitted, π produced (strong interaction, λ~Fm)
- Therefore, ~10-30% of particles in final state come from fsi, not the primary interaction!
- PROBLEM: fsi can mask the primary interaction, e.g. π production followed by π absorption appears as qe event!



Results from Jim Dobson

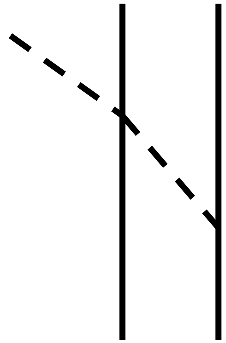
- GENIE simulations
- Top plot is $\nu_\mu Fe$, 1 GeV
- Table for $\nu_\mu O$, T2K beam.



Final-State	Primary Hadronic System									
	$0\pi X$	$1\pi^0 X$	$1\pi^+ X$	$1\pi^- X$	$2\pi^0 X$	$2\pi^+ X$	$2\pi^- X$	$\pi^0\pi^+ X$	$\pi^0\pi^- X$	$\pi^+\pi^- X$
$0\pi X$	**293446**	12710	22033	3038	113	51	5	350	57	193
$1\pi^0 X$	1744	**44643**	3836	491	1002	25	1	1622	307	59
$1\pi^+ X$	2590	1065	**82459**	23	14	660	0	1746	5	997
$1\pi^- X$	298	1127	1	**12090**	16	0	46	34	318	1001
$2\pi^0 X$	0	0	0	0	**2761**	2	0	260	40	7
$2\pi^+ X$	57	5	411	0	1	**1999**	0	136	0	12
$2\pi^- X$	0	0	0	1	0	0	**134**	0	31	0
$\pi^0\pi^+ X$	412	869	1128	232	109	106	0	**9837**	15	183
$\pi^0\pi^- X$	0	0	1	0	73	0	8	5	**1808**	154
$\pi^+\pi^- X$	799	7	10	65	0	0	0	139	20	**5643**

Alternatives (fsi)

- **Quantum mechanical model**
  - ✓ Hadron wave effects, correlations done correctly
  - ✓ We know QM essential for proper treatment of nucleus
  - ✓ Impossible to calculate multiple particle final states properly
  - ✓ Propagating hadrons tend to remain on-shell (not π abs)
- **GIBUU (semi-classical model)**
  - ✓ Giessen group reinvigorated interest
  - ✓ Many applications, Tina Leitner will present it next week.
  - ✓ Computing needs intensive compared to INC
- **Limits of INC should be understood!**
  - ✓ Comparison with hA data excellent start
  - ✓ Comparison with (e,e') data is essential for nuclear structure.

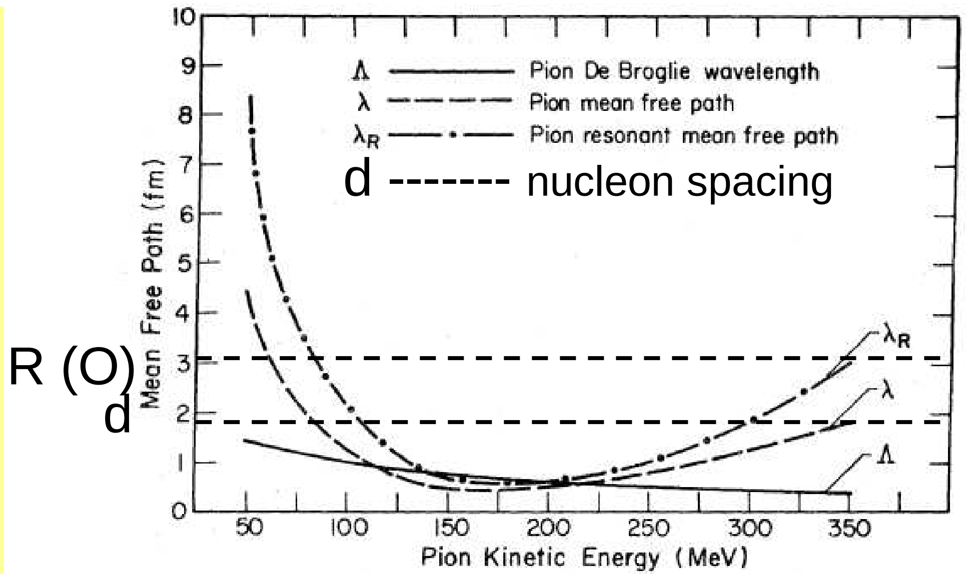


Applicability of INC

To ensure h sees only 1 nucleon at a time, we want
$\Lambda \ll \lambda \ll R$ and
$d \ll \lambda$.

Λ= pion size
λ= pion mean free path
R= nuclear size
d= nucleon spacing

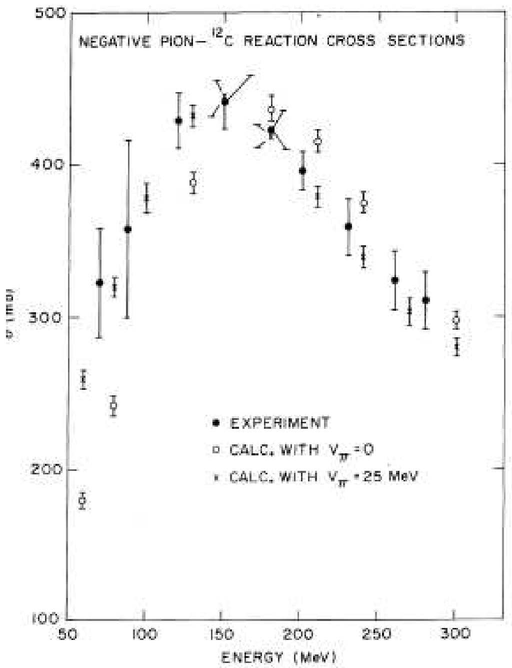
DICEY!!! (but it works!!)

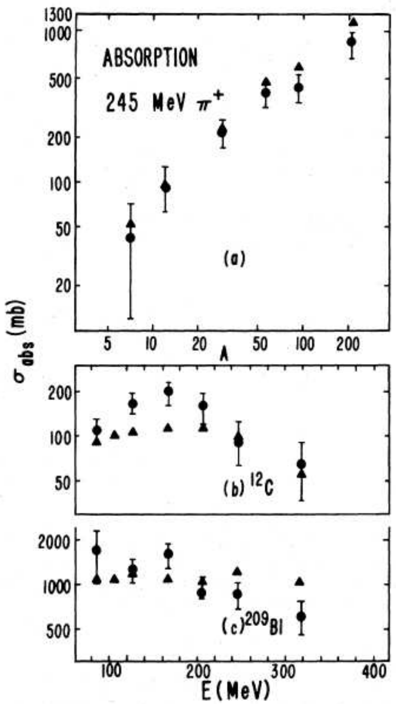


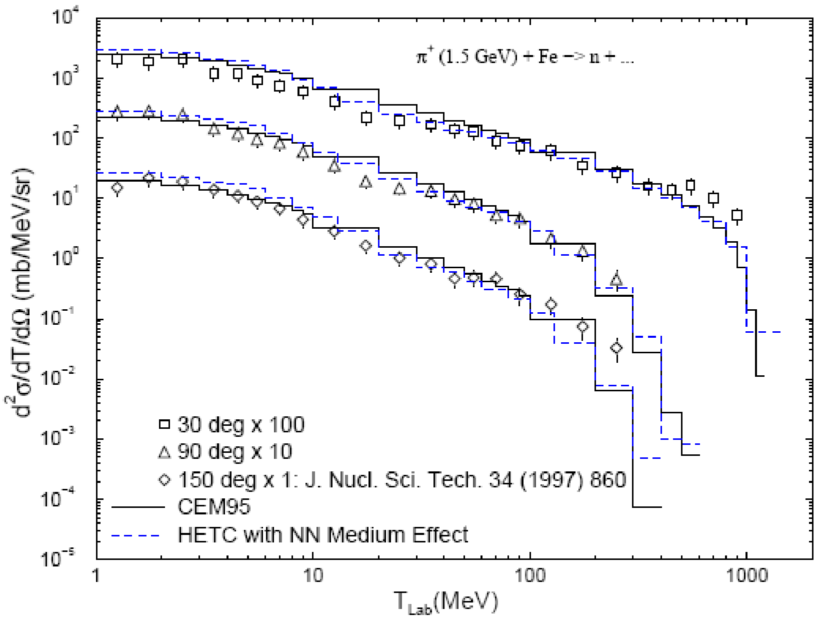
What is INC formalism good for?

- Inelastic reactions, esp. particle production processes.
- Only pion induced reactions shown here, but still some impressive examples.

Harp (74) Fraenkel (82) Mashnik (95)

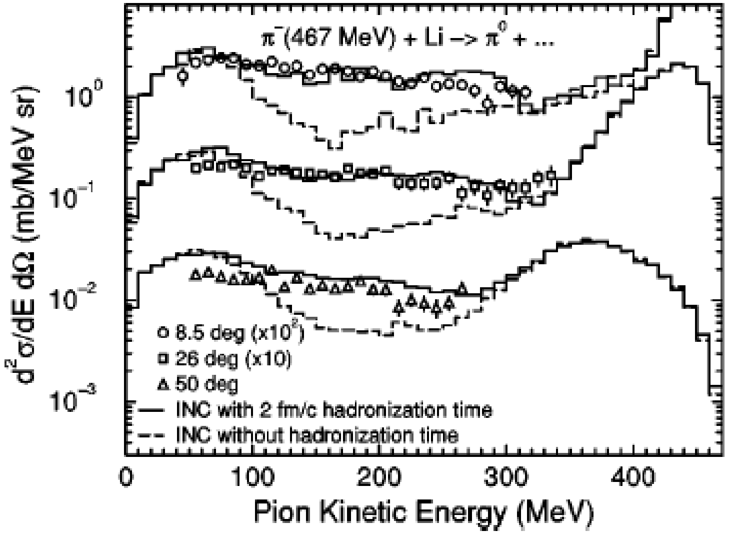


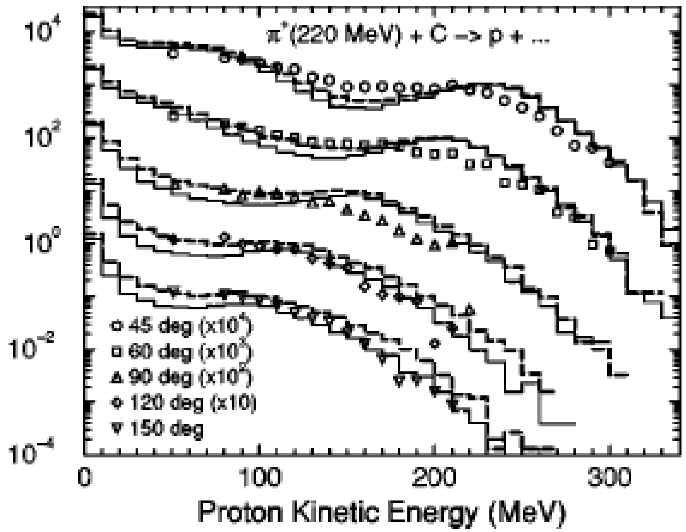


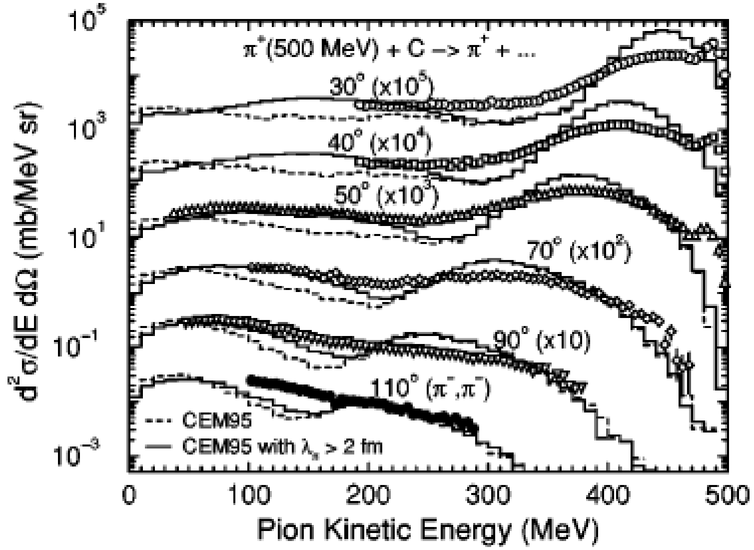


Mashnik INC calcs

- State of the art code, under development for 'decades'.
- π inclusive cross sections at T_{π}~500 MeV show many effects.
  - ✓Quasielastic scattering
  - ✓Pion production
- Here, they examine the effect of a 2Fm/s hadronization time.

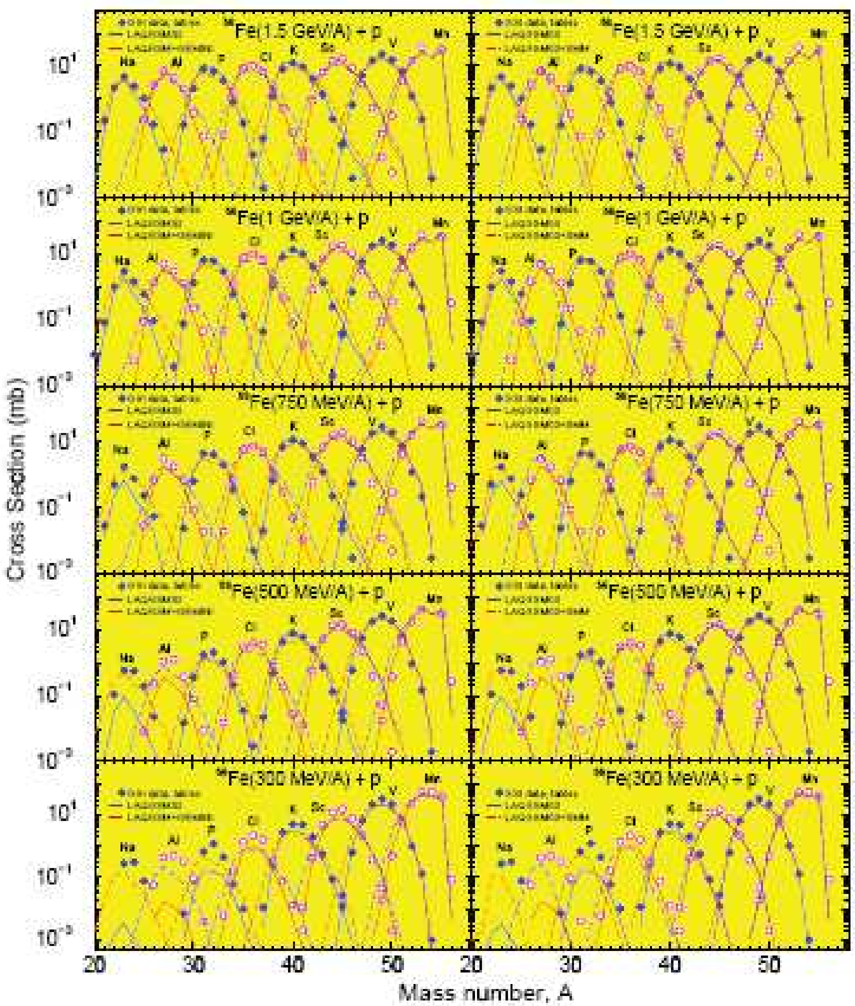






CEM03.01 vs. p ^{56}Fe data
(*their tests*)

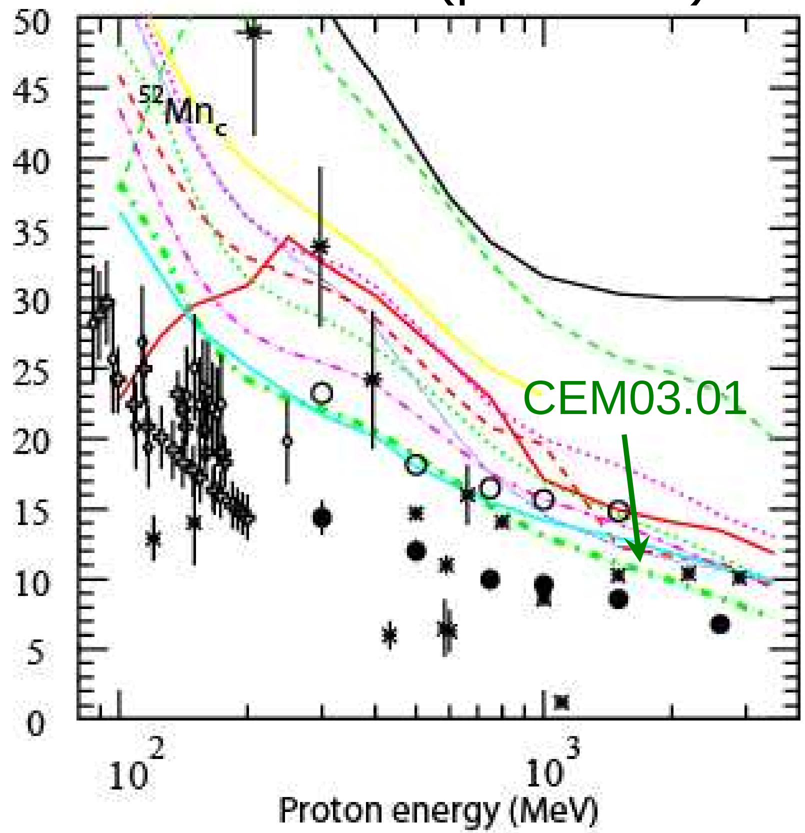
Wide range of final nuclei likely!



One final state (^{52}Mn) as function of proton energy

Data has systematic error troubles

Many calculations shown, CEM03.01 does best overall (prediction).



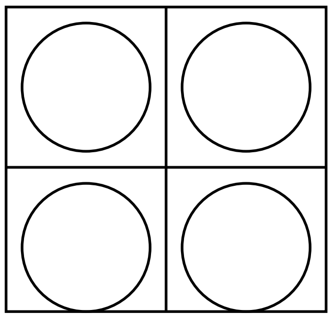
What is downside?

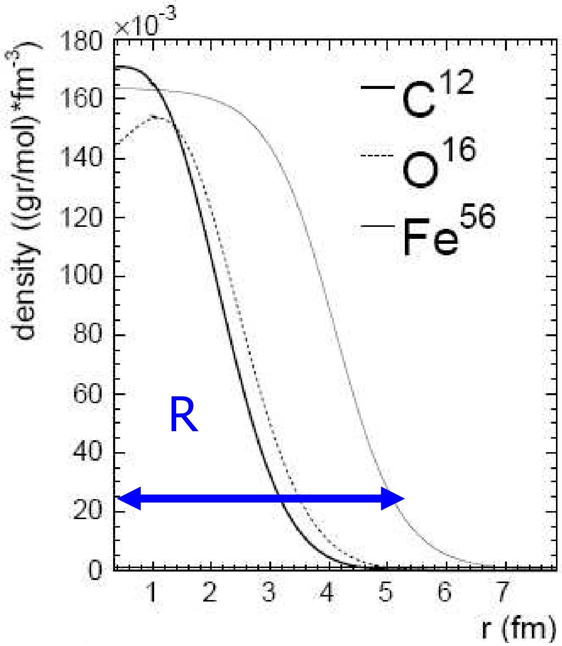
- No quantum mechanics [but no qm model usable]
- Nuclear structure is Fermi gas.
- Unlikely to do well for elastic processes which are typically diffractive in nature.
- Papers refer to model choices which may be covering up problems (sometimes hard to tell).

Nuclear systematics

- Shapes are very similar (ρ~0.16 N/Fm^3)
  - ✓ nuclei density *saturated* (same as neutron star)
  - ✓ Woods-saxon distribution describes all A≥20 (R~1.4 x A$^{1/3}$), e.g. 1.4*3.8=5.3 Fm for Fe
  - ✓ Modified Gaussian describes all A<20

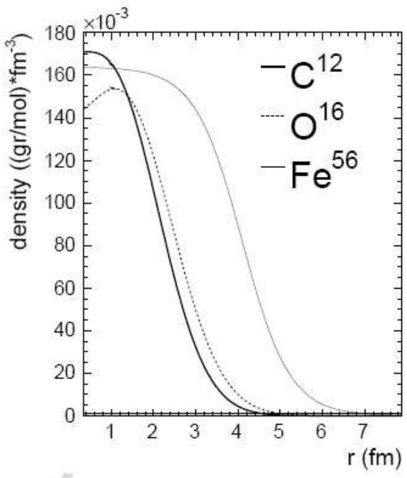
Aside: we can now see why nuclear correlations matter.
Intranuclear spacing~1/$\rho^{0.33}$=1.8 Fm
Size of nucleon r_{rms}~0.8Fm

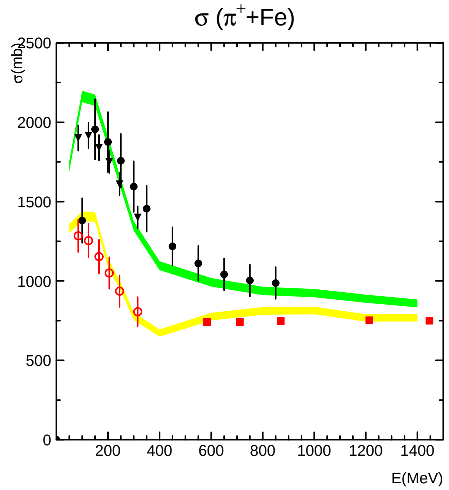


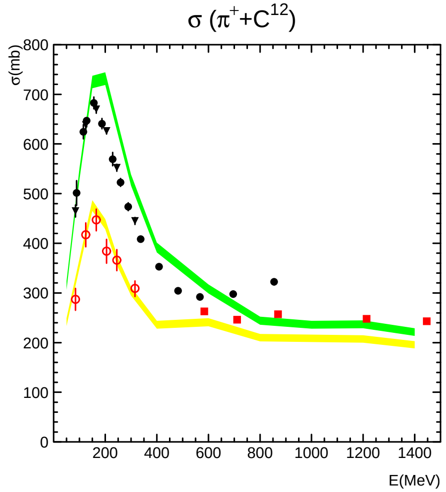


Nuclear density
(GENIE can do almost all nuclei)

- 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*λ_{deB} Fm for nucleons, 1.0*λ_{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

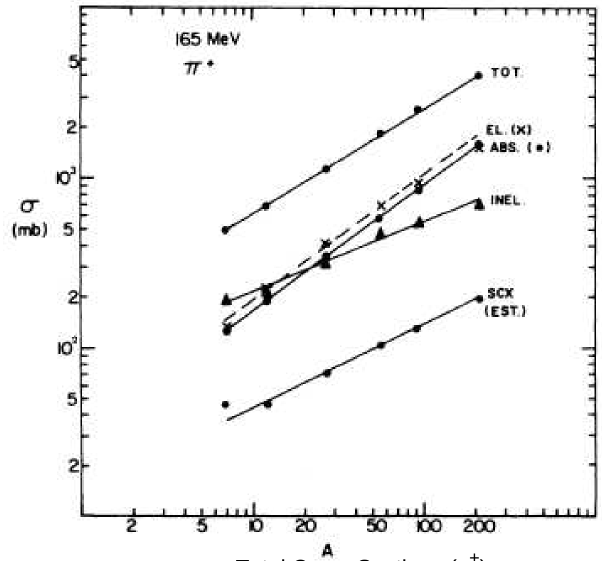


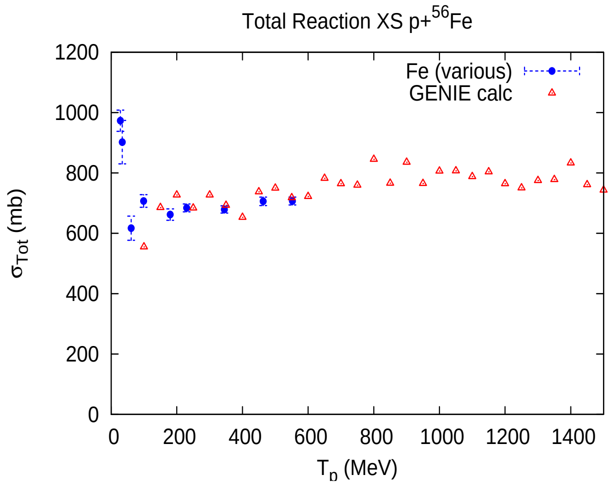




Nuclear systematics

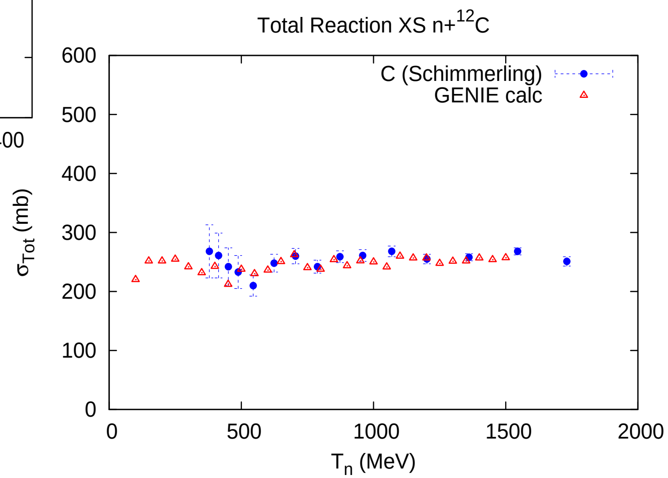
- hA total cross sections ~ nuclear size (πR^2)
  - For Fe, $\pi R^2 \sim 900$ mb
  - For C, $\pi R^2 \sim 320$ mb
- Many total cross section scale with A^{α}.

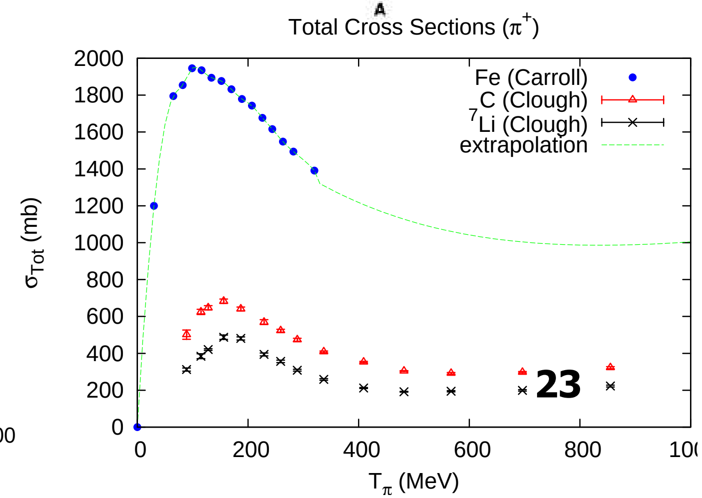




$\sigma_{reac} = \sigma_{tot} - \sigma_{elas}$

Elas: ($\pi C \rightarrow \pi C$)



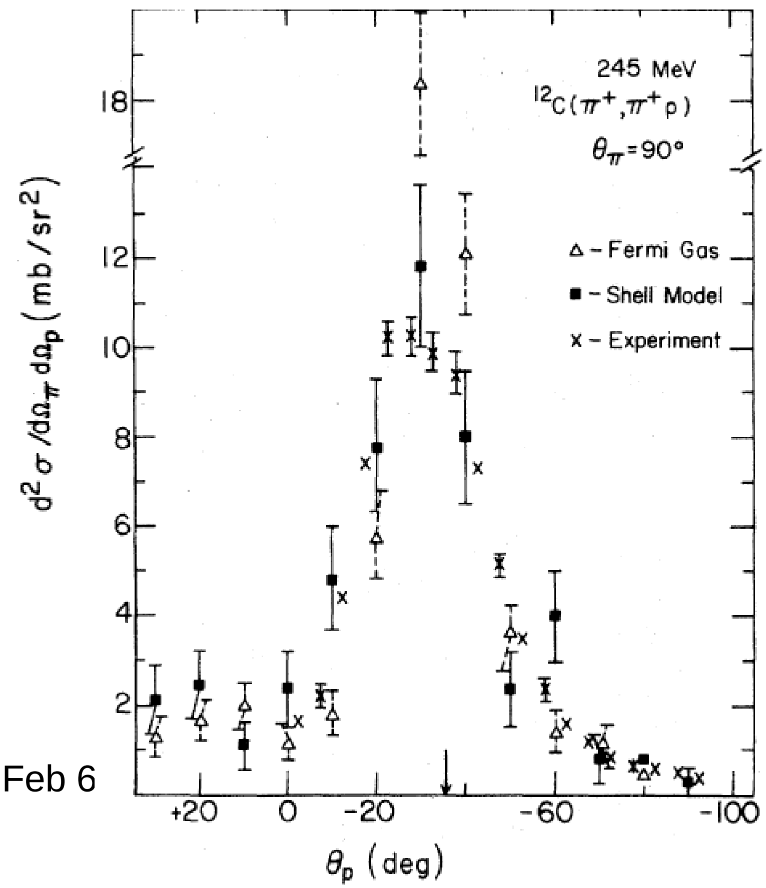


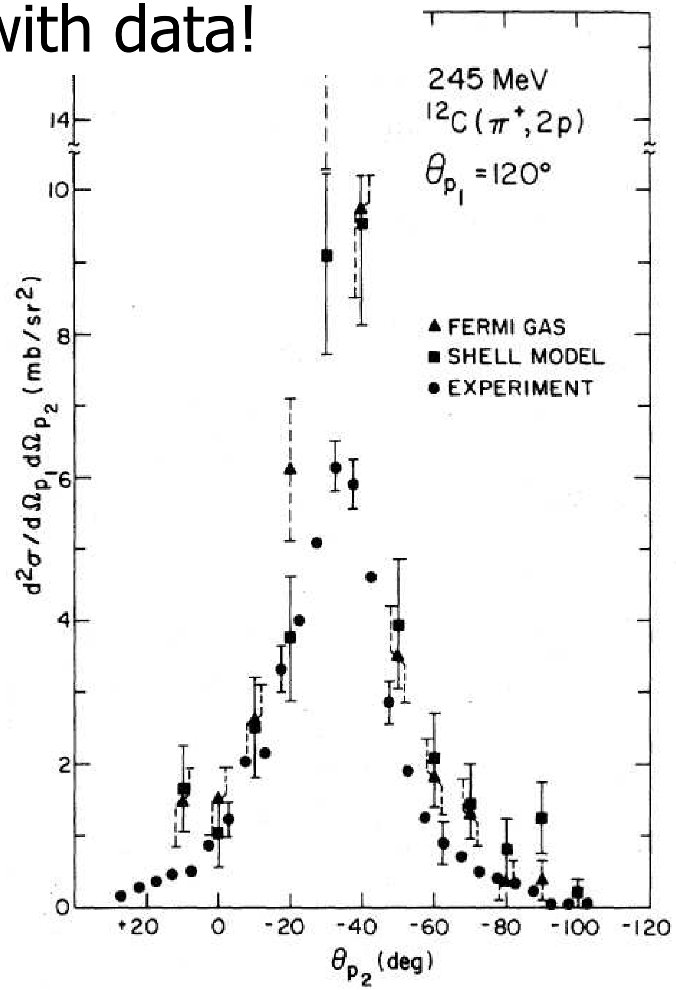
Reaction glossary

- Elastic - $\pi^+ \, ^{12}C \rightarrow \pi^+ \, ^{12}C$ – $1\pi^+$ in final state ($E>0.8E_0$)
- cex - $\pi^+ \, ^{12}C \rightarrow \pi^0 \, ^{12}N$ – $1\pi^0$ in final state ($E>0.8E_0$)
- Inelastic - $\pi^+ \, ^{12}C \rightarrow \pi^+ \, ^{12}C$ – $1\pi^+$ in final state ($E<0.8E_0$)
  - $\pi^+ \, ^{12}C \rightarrow \pi^+ \, ^{11}B \; p$ – $1\pi^+$ in final state ($E<0.8E_0$)
- Absorption - $\pi^+ \, ^{12}C \rightarrow nnp \, ^{10}C$ – $0\pi^+$ in final state
- Total = sum of all
- Reaction = sum of all except elastic
  - ✓ can be well-described by INC
- Elastic scattering is wave property (not in INC)
- Quasifree = reaction with nucleus looks just like 2-body +Fermi motion

Quasifree (QF) reaction mechanism important…

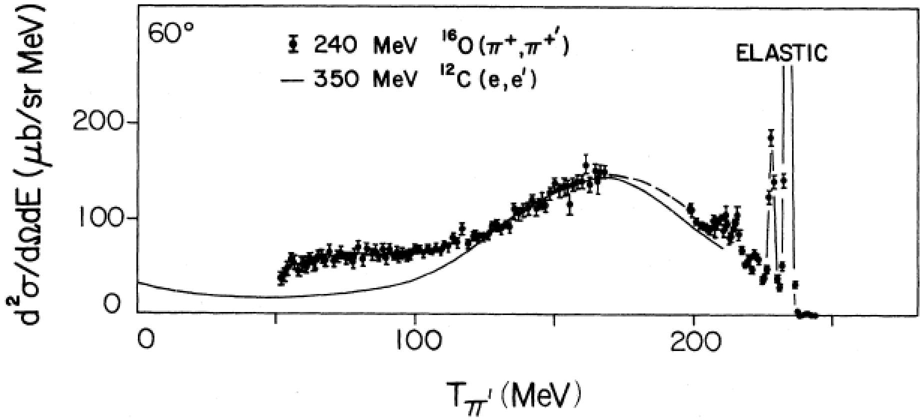
- QF means hadron interacts with nucleons in nucleus as though they were free (with momentum)
- INC calcs by Fraenkel (1982) agree with data!

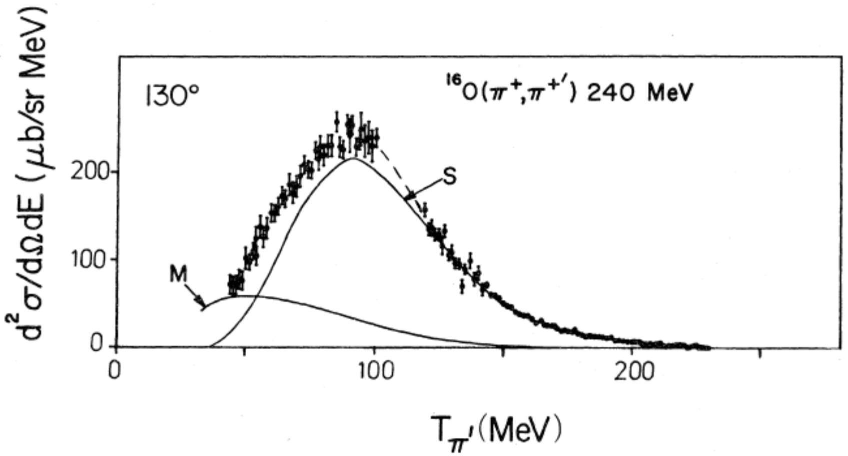


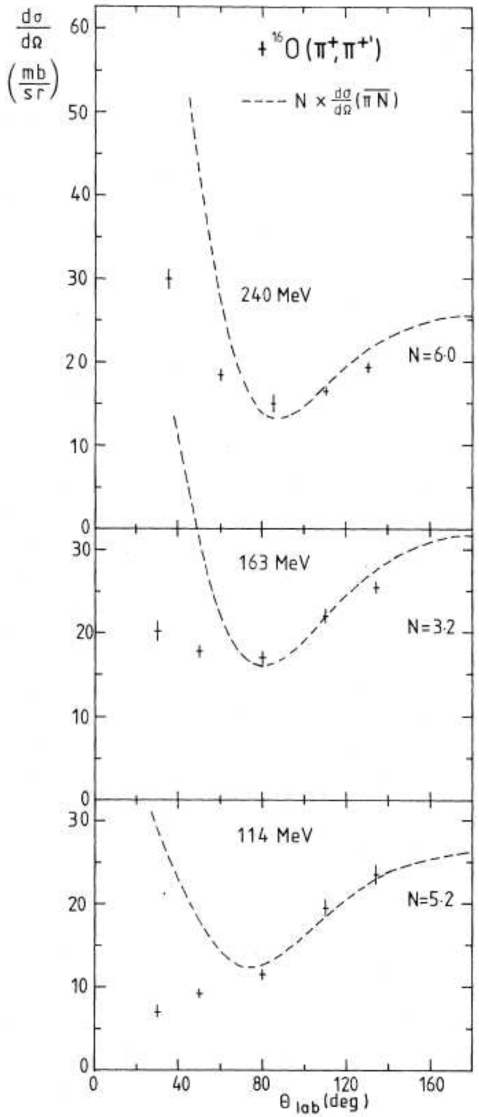


Role of QF mechanism in πA inclusive scattering

- Data from Ingram (1983).
- Very similar to (e,e') at same mom trans





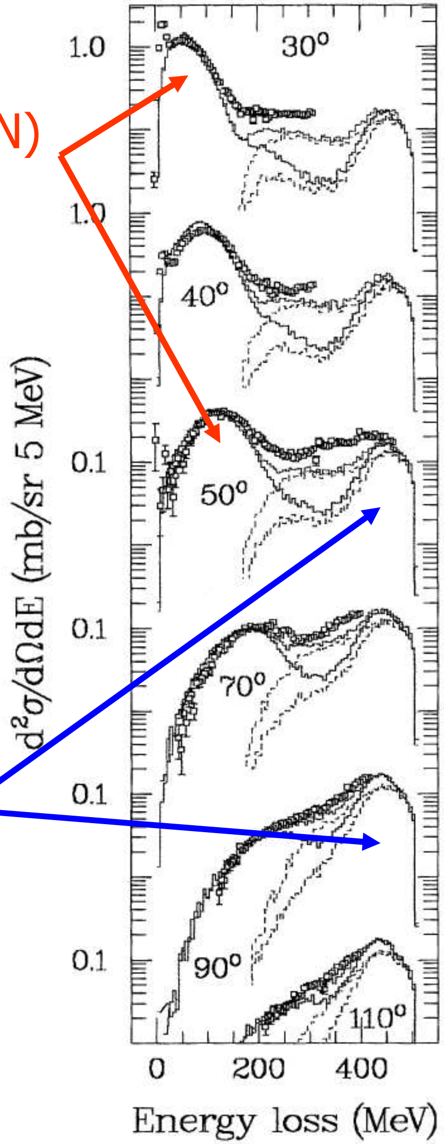


…but far from complete (FSI!)

- π^-C at 500 MeV, incl. π^-

QF(πN)

QF($\pi\rightarrow\pi\pi$)



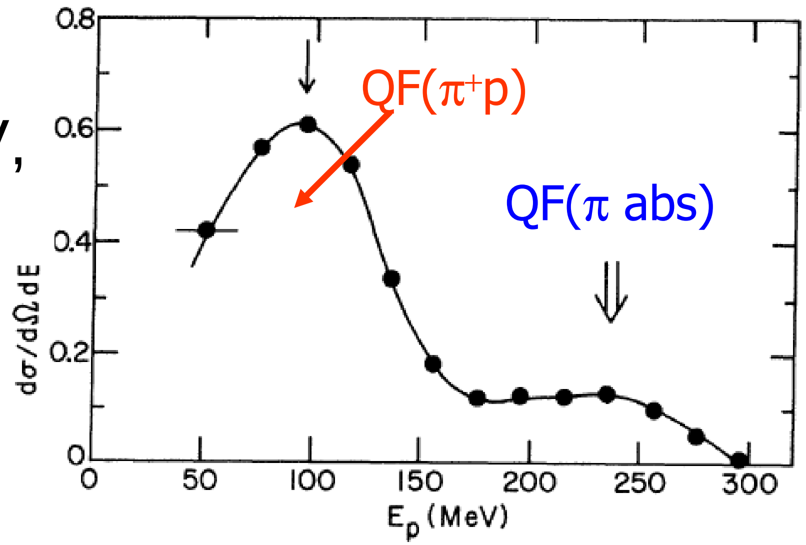
- π^+Ar absorption at 245 MeV

	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

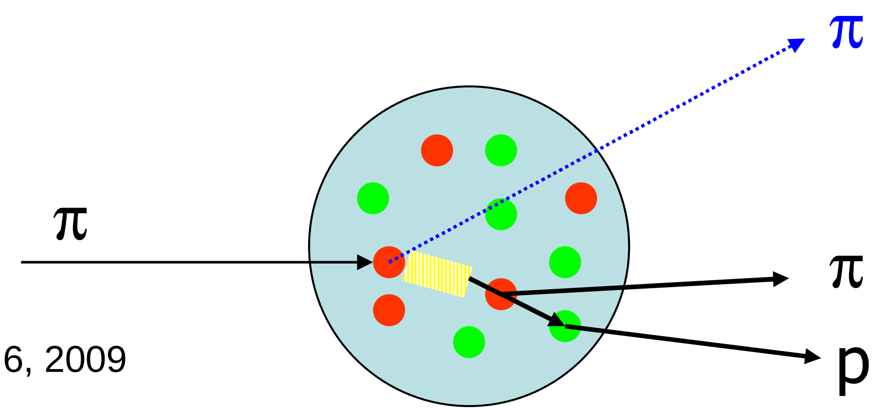
QF(π^+p)

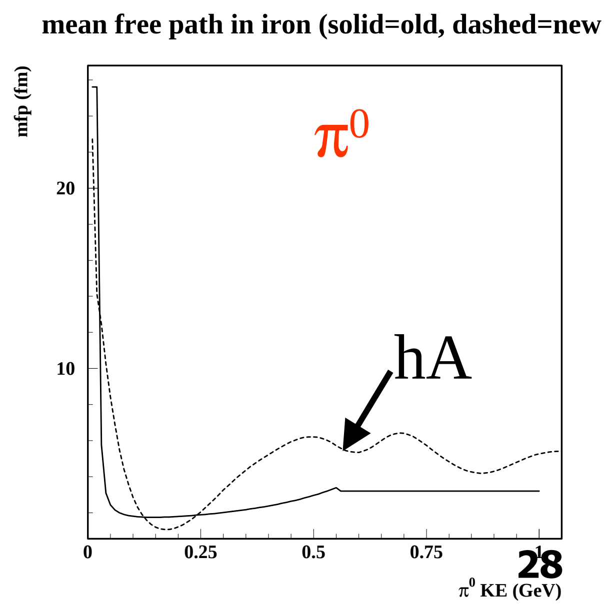
QF(π abs)



Components of INC

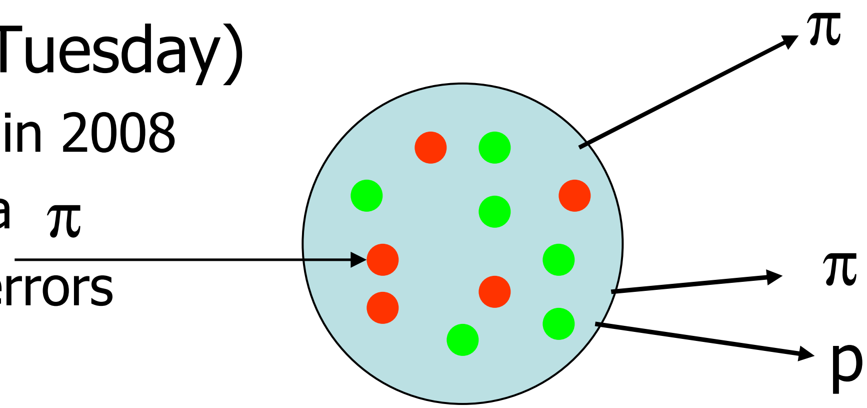
- Decide where an interaction occurs
  - ✓ Mean free path $\lambda(E,r)=1/[\rho(r)\sigma(hN)]$ makes sense
  - ✓ Choose int point from exponential distribution
- Decide which interaction to simulate
  - ✓ hA and hN differ here
  - ✓ Both tied strongly to data





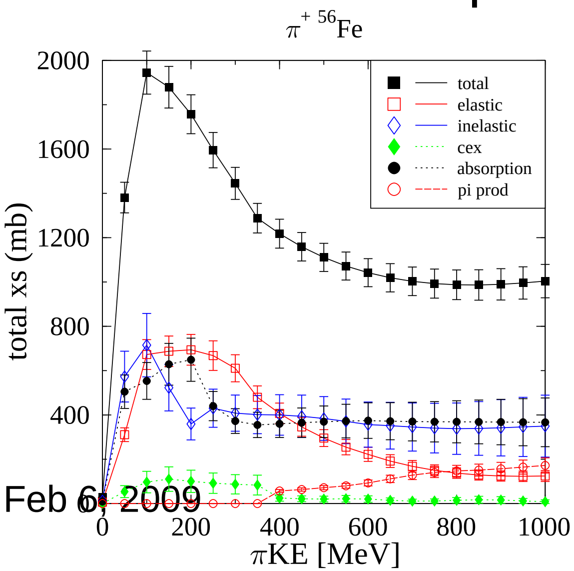
GENIE fsi models

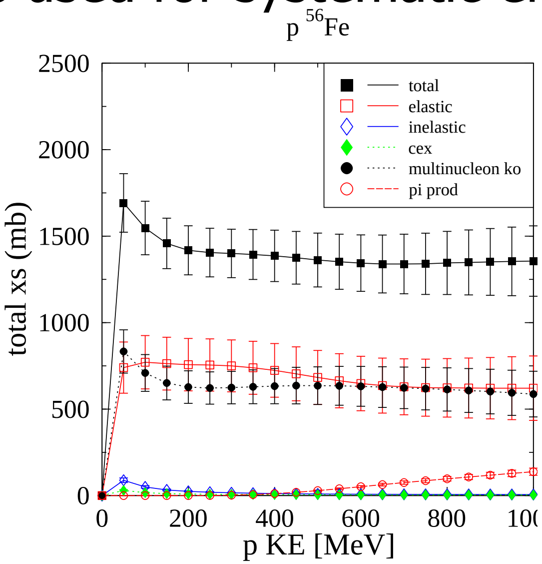
- Goal - describe hadron-nucleus reactions T_h<1 GeV, all nuclei
- hA (today, discussed by Costas Tuesday)
  - ✓ Introduced in 2006, improvements in 2008
  - ✓ Schematic, but tied strongly to data
  - ✓ Originally intended for systematic errors
- hN (tomorrow)
  - ✓ About to be introduced
  - ✓ Full INC code for π^+, π^-, π^0, p, and n
  - ✓ Surprisingly fast and accurate
- Results of 2 codes suggest advances for each other

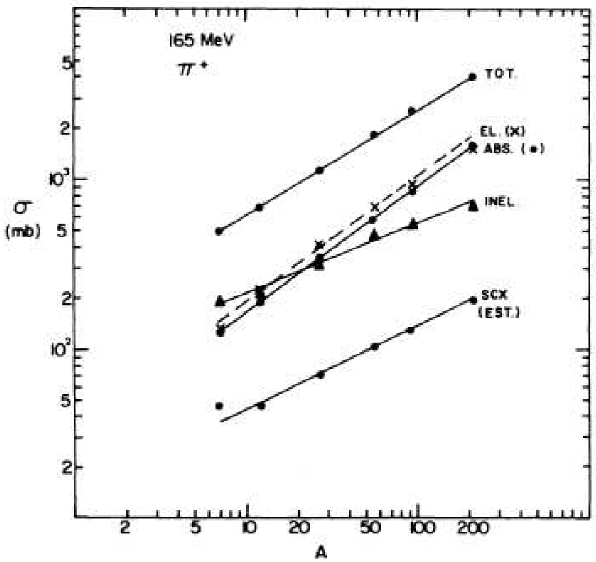


GENIE models - hA

- 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. π 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





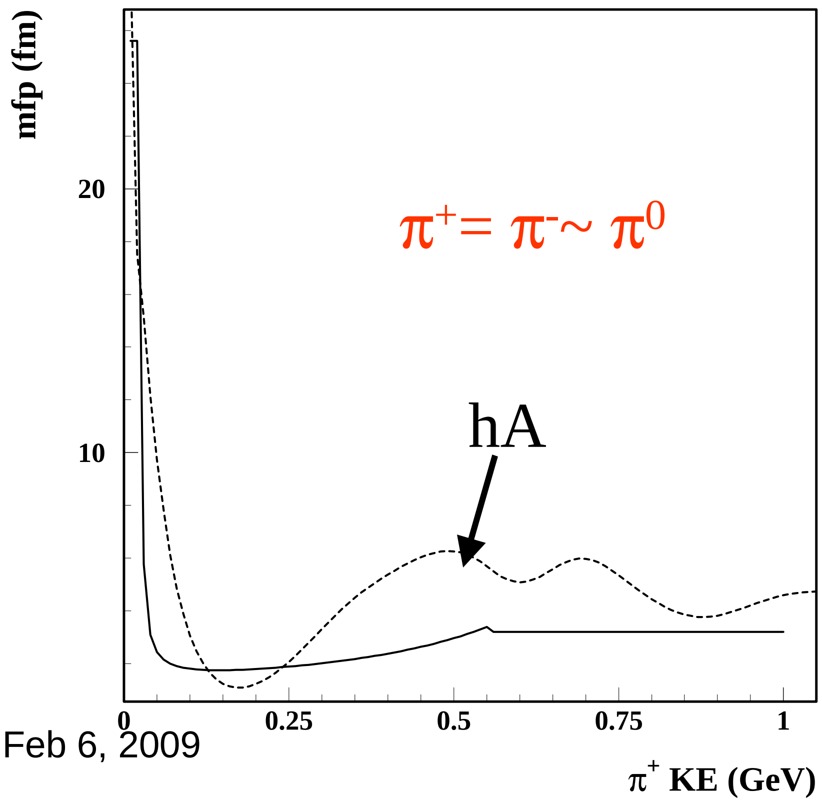


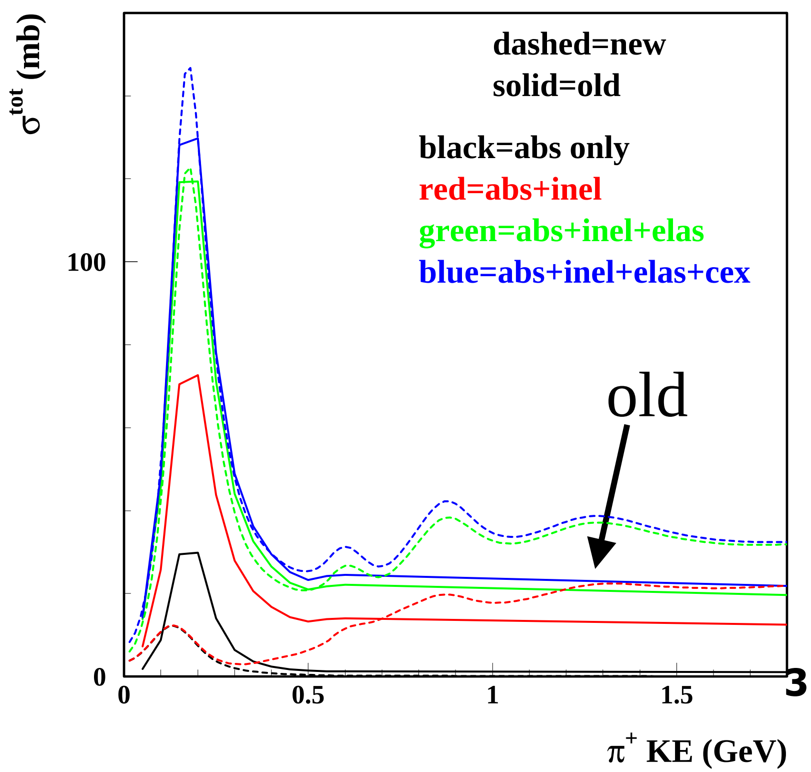
Mean free path

$\lambda(E,r)=1/\rho(r)\sigma(hN)$

Reactions from GWU CNS web site

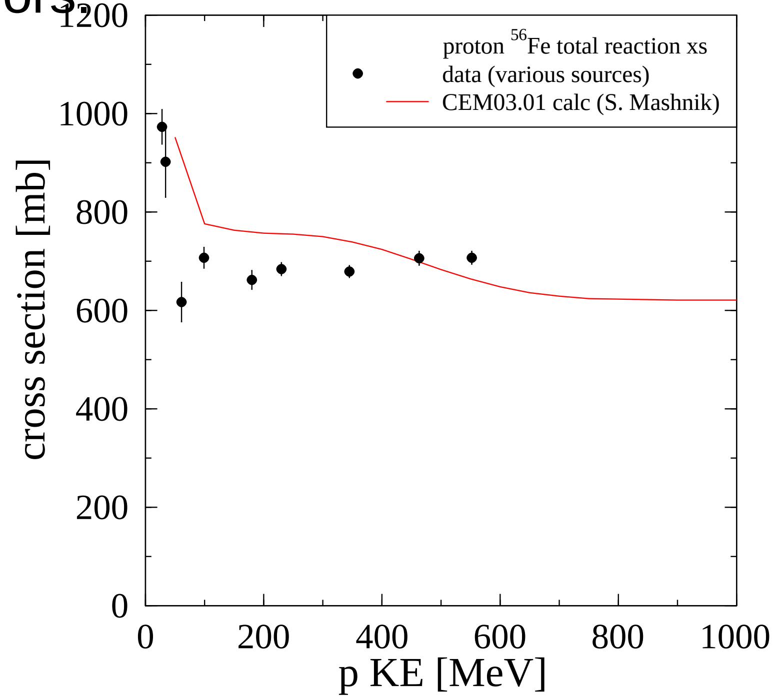
- $pp \rightarrow pp$, $np \rightarrow np$, $NN \rightarrow NN\pi$
- $\pi^+p \rightarrow \pi^+p$, $\pi^-p \rightarrow \pi^-p$, $\pi^-p \rightarrow \pi^0n$, $\pi N \rightarrow \pi NN$, $\pi^+d \rightarrow pp$





p ^{56}Fe scattering, implementation

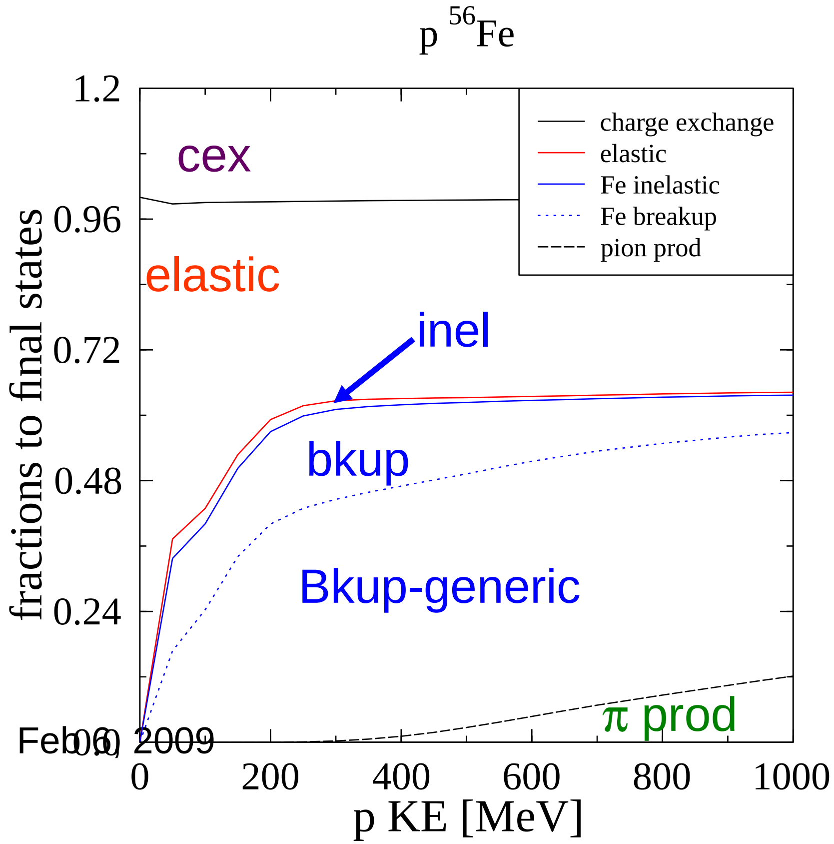
•Use total xs of CEM03, focus on aspects important for MINOS
•Total reaction cross section governs total amount of stuff coming out
•Lack of data still an issue, esp. at KE>800 MeV.
•Use phase space for angle, energy distributions, unlikely to be large errors.



•Calculations built up over many years, reliability appears to be very high.
•Code is huge, deals with phenomena in which we have no interest (10n8p knockout)
•Implementation can cause errors
  ➢No n calculations (differences small)
  ➢Some π production channels incomplete
  ➢INC can't do elas scat well, need separate code (future).

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:



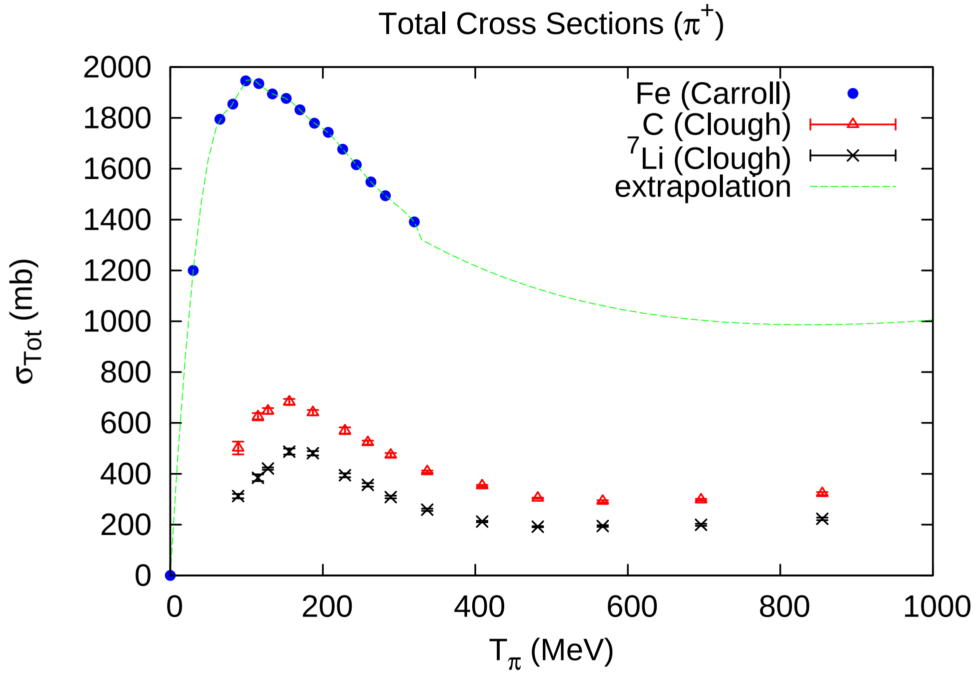
Elastic	p ^{56}Fe→p ^{56}Fe
Charge exchange	p ^{56}Fe→n ^{56}Co
Inelastic	p ^{56}Fe→p´ ^{56}Fe
Breakup	p ^{56}Fe→pn ^{55}Fe
	p ^{56}Fe→pp ^{55}Mn
	p ^{56}Fe→ppn ^{54}Mn
	p ^{56}Fe→pnn ^{54}Fe
Breakup-generic	p ^{56}Fe→pppnn ^{52}Cr
Pion production	p ^{56}Fe→π^+ n ^{56}Fe
	p ^{56}Fe→π^+ π^0 n ^{56}Fe

π rescattering tougher

- 3 charge states, no π^0 data
- Data for total cross sections up to KE~1 GeV
  - ✓ Data for component final states largely at KE<400 MeV
  - ✓ Angle, energy distribution data not extensive (like pA)
- CEM03 has real problems (~40% discrepancies)
  - ✓ Use only for guidance at high KE
- Use data (~10-20% errors) at low energy, CEM03+intuition at high energy.
  - ✓ Recently discovered inclusive p, n prod data will be very useful.
  - ✓ Elastic xs must decrease rapidly with energy
  - ✓ Inelastic xs must rise
  - ✓ Total remains largely constant

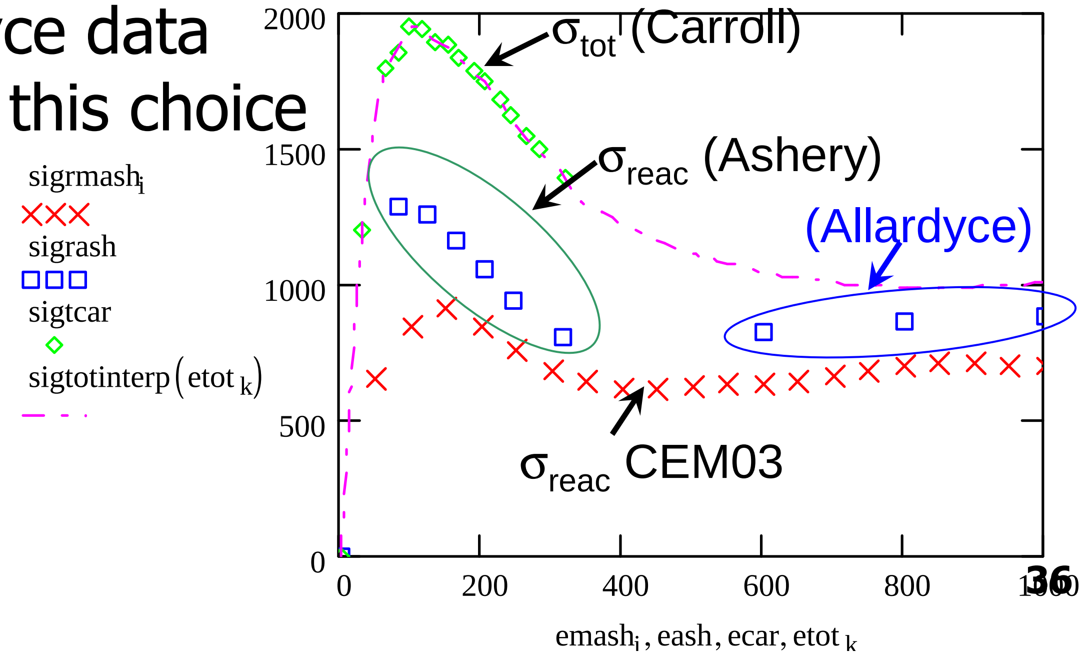
$\pi^+ \ ^{56}Fe$

- TOTAL cross section taken from data
  - ✓Quality data for many targets (Carroll, et al.) at T_π<450 MeV
  - ✓Quality data for light targets (Clough, et al.) at T_π<860 MeV
  - ✓Note ~flat energy dependence for all targets at high energy
  - ✓Use power fit to A dependence to extrapolate



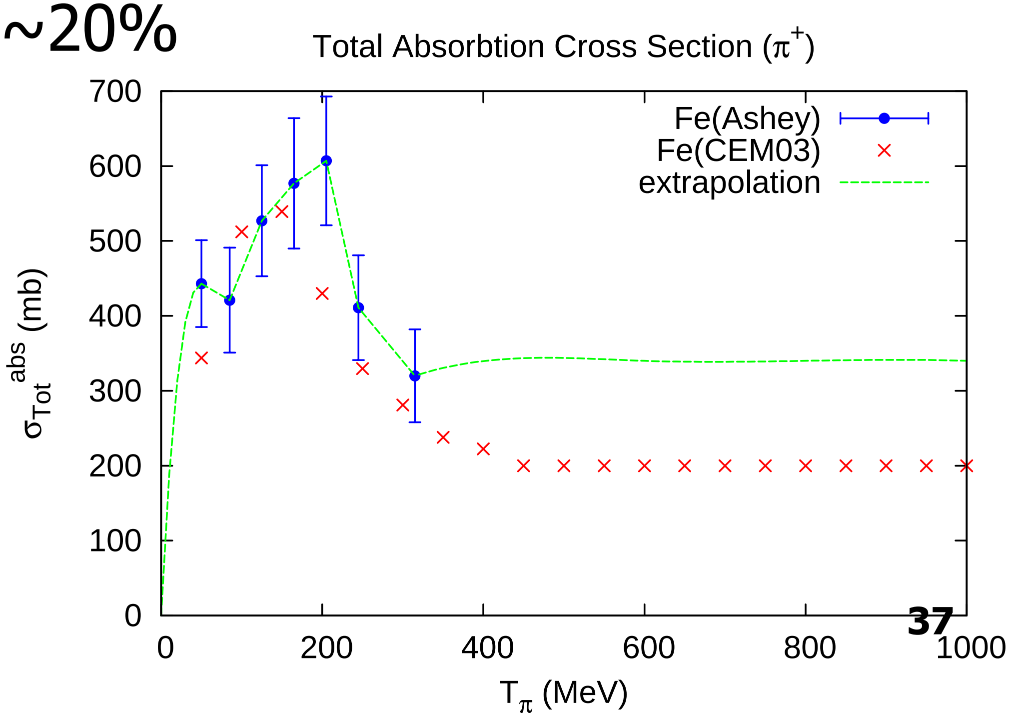
CEM03.01 - π^+ ^{56}Fe [σ_{REAC}]

- REACTION (abs+inel+cex=tot-elas) cross section trickier
  - ✓Poor agreement vs. Ashery et. al data at low T_π.
  - ✓Expect σ_{elas} small high T_π.
  - ✓Compensating factor has too much energy dependence.
  - ✓Use data with ~constant extrapolation (like calc. and total xs)
  - ✓Later found Allardyce data in agreement with this choice
  - ✓Estimate σ(elas) from Marlow data at 670 MeV



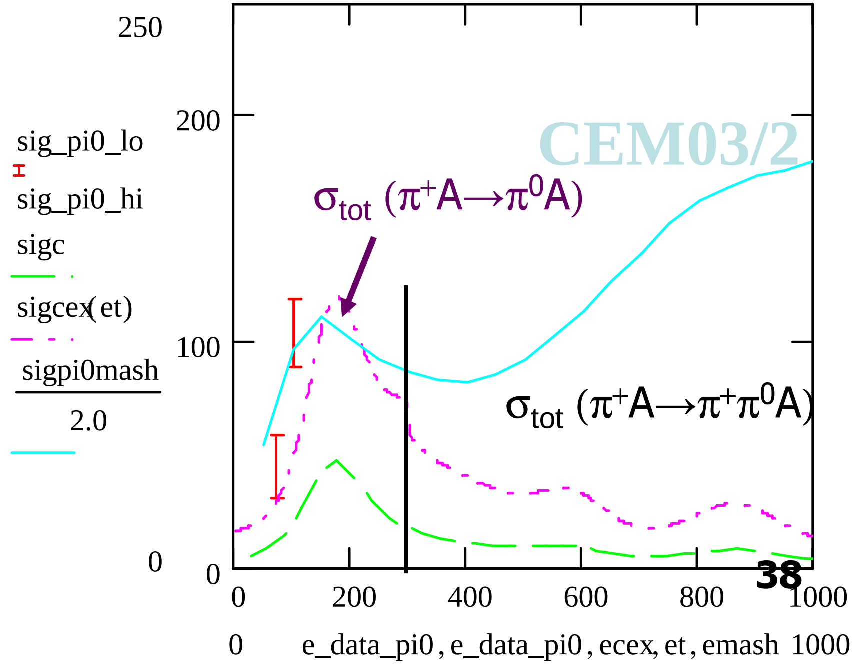
CEM03.01 – π+ 56Fe [σ_{ABS}]

- Total ABSORPTION cross section is tricky (like reac)
- Ashery et al. data at low energy, nothing at higher energy
- Use calculation as a guide to xs at high energy
- Use data + extrapolation for total absorption xs
- Use final states from CEM03 in same ratio.
- Ashery data has est. error ~20%



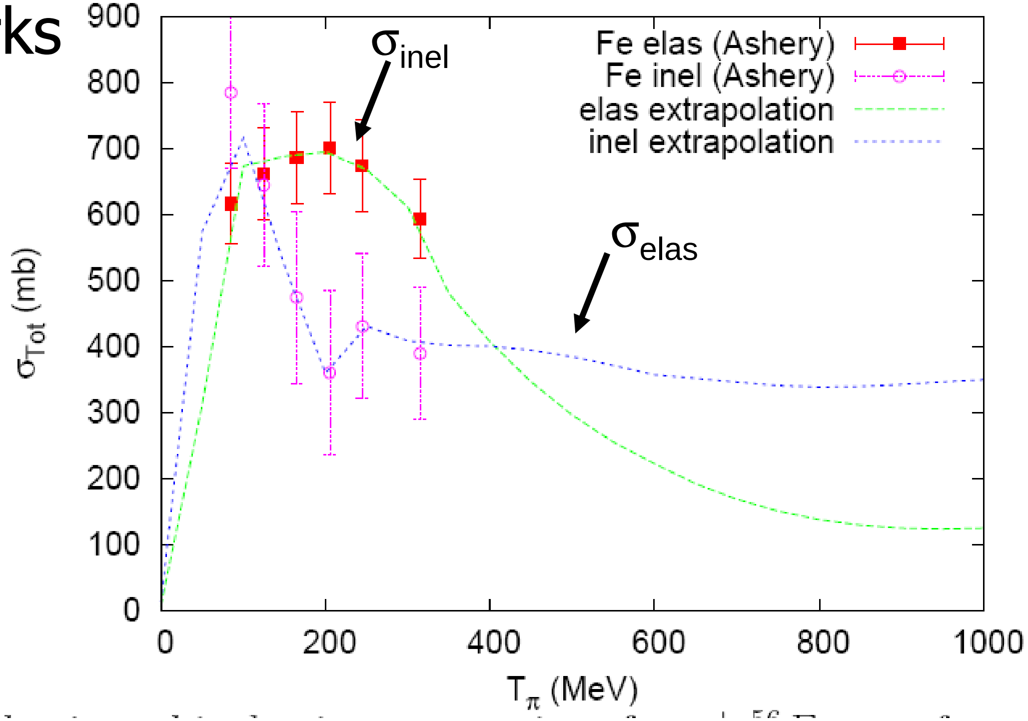
CEM03.01 – π+ 56Fe [σ_{π^0}]

- Total Inclusive π^0 cross section even worse [fortunately small]
- 2 old data points (1 from LAMPF), nothing at higher energy
- **CEM03 calc.** rises at high energy (*pion production)*
- CEM03 calc. divided by 2 agrees with data at low energy
- $\sigma(\pi^- p \rightarrow \pi^0 n)$ peaks at res, $\sigma(\pi^- A \rightarrow \pi^0 A)$ should be prop. to this
- Use scaled $\sigma(\pi^- p \rightarrow \pi^0 n)$ (purple)
  for $\sigma(\pi A \rightarrow \pi^0 A)$ at all energies
- Use CEM03/2-$\sigma(\pi^+ A \rightarrow \pi^0 A)$
  for $\sigma(\pi^+ A \rightarrow \pi^0 \pi^+ A)$ at T_π>300



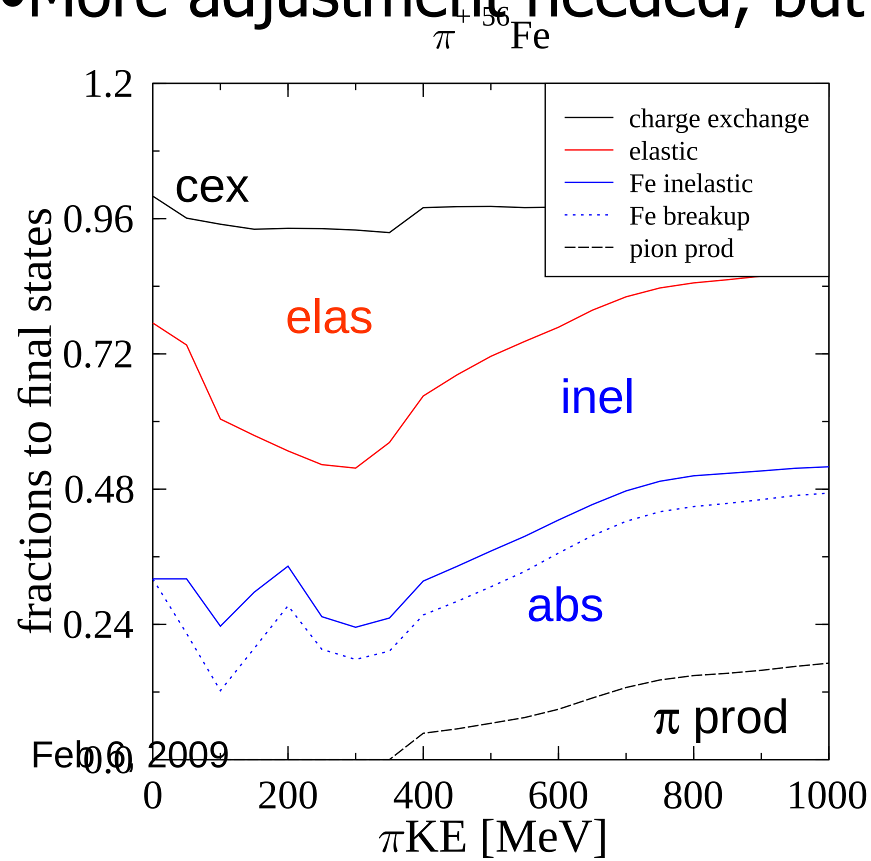
CEM03.01 – π+ 56Fe [σ_{inel},σ_{elas}]

- We now have 2 checks,
  - $\sigma_{elas}=\sigma_{tot}-\sigma_{reac}$ ($\sigma_{reac}=\sigma_{abs}+\sigma_{inel}+\sigma_{cex}$)
  - $\sigma_{inel}=\sigma_{reac}-\sigma_{abs}-\sigma_{cex}$.
- Compare results with Ashery data at low energy
  - ✓Have to trust CEM03 at high energy
- After a little playing, it works
- Everything is consistent, though not unique.



hA strategy [π]

- 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



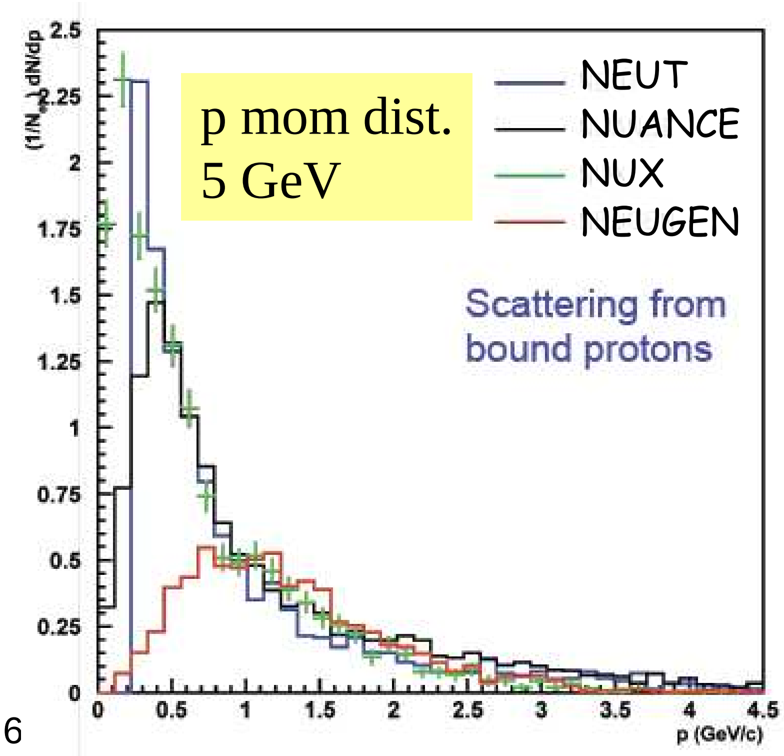
Elastic	π^+ ^{56}Fe→ π^+ ^{56}Fe
Charge exchange	π^+ ^{56}Fe→ π^0 ^{56}Cr
Inelastic	π^+ ^{56}Fe→ $\pi^{+\prime}$ N ^{56}Fe
Absorption	π^+ ^{56}Fe→ pn ^{54}Fe
	π^+ ^{56}Fe→ pp ^{54}Mn
	π^+ ^{56}Fe→ ppn ^{53}Mn
	π^+ ^{56}Fe→ pnn ^{53}Fe
Abs-generic	π^+ ^{56}Fe→ ppnn ^{52}Mn
Pion production	π^+ ^{56}Fe→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

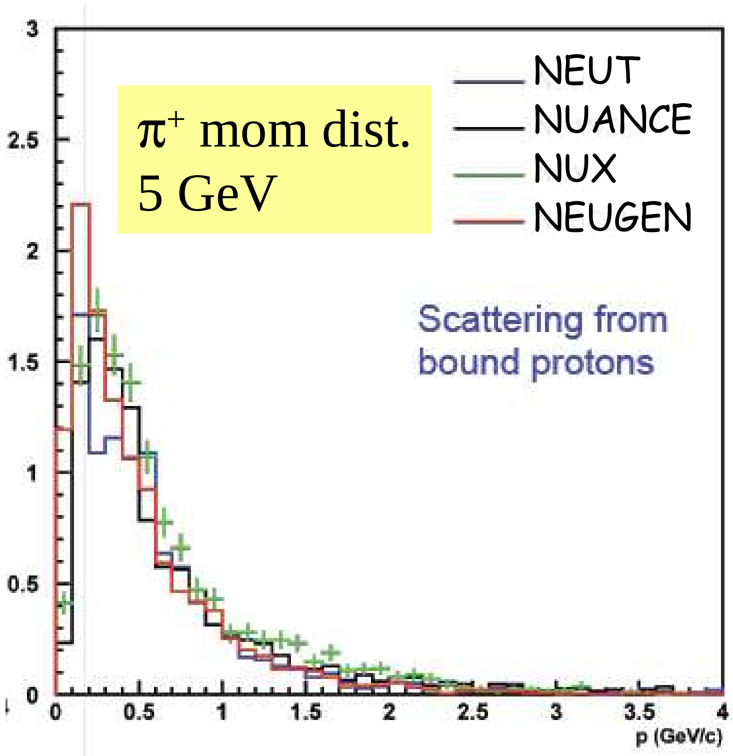
Distributions of fsi particles

- Scattered particles
  - ✓ Isotropic [wrong]
- Particles produced (e.g. π absorption)
  - ✓ Phase space
- Does it matter?

Old NEUGEN vs. other models

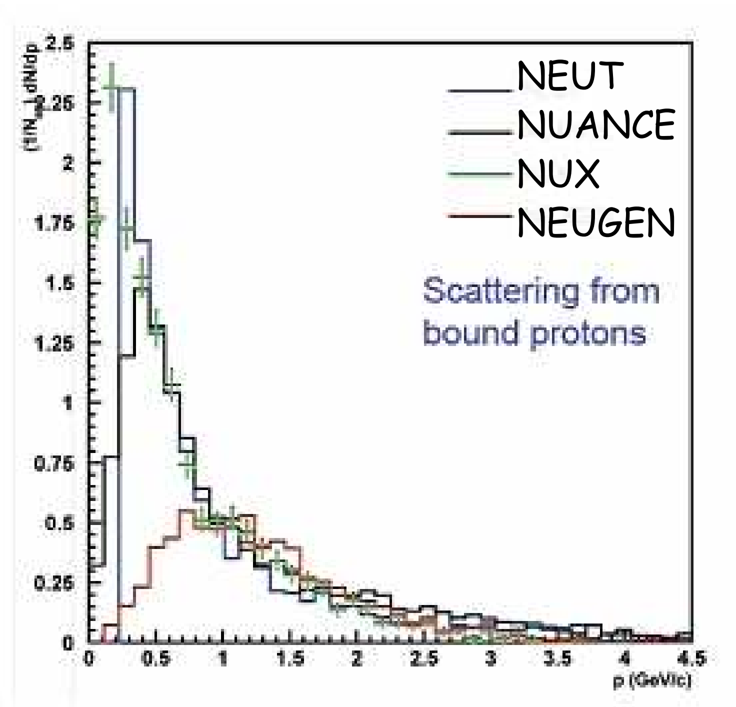
- Results of study of H. Gallagher and others for Nuint04 $\left(\bar{\nu}_{\mu} p\right)$
- $\bar{\nu}_{\mu} p \to \mu^{+} p \pi^{-}$ was main source of protons in Neugen, no baryon rescattering, no pion absorption (added in 2005)

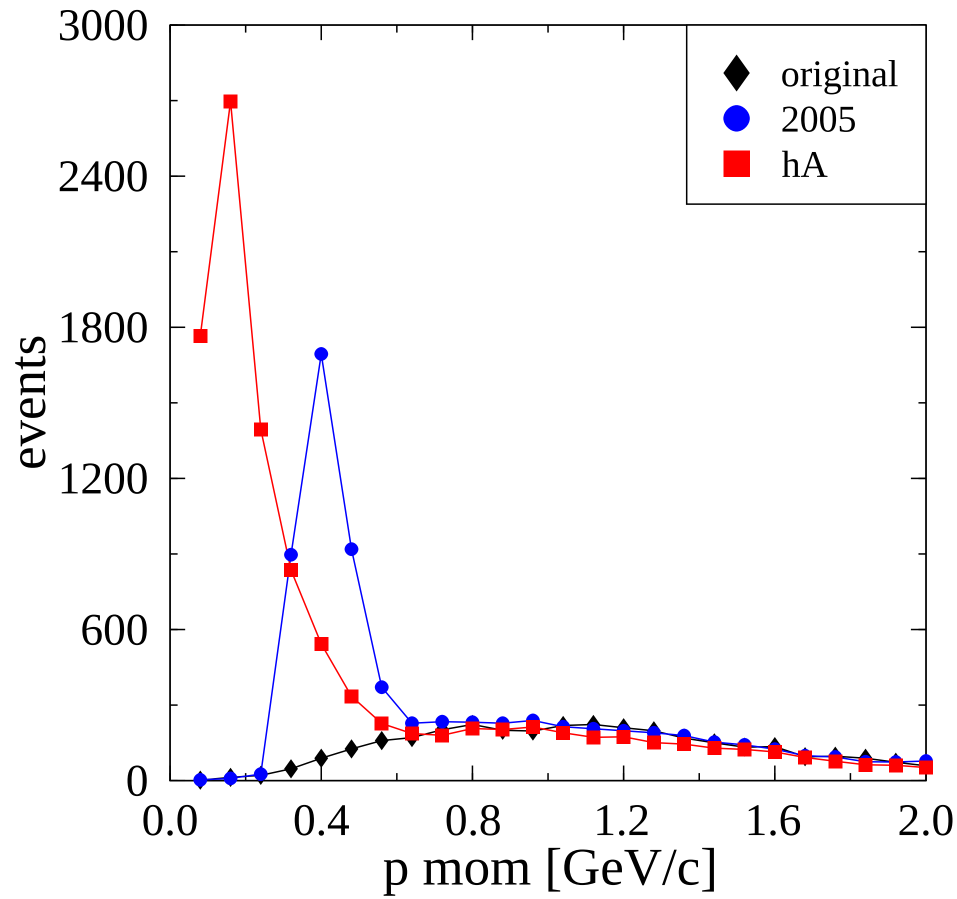




Compare to 2005, old (5 GeV neutrinos)

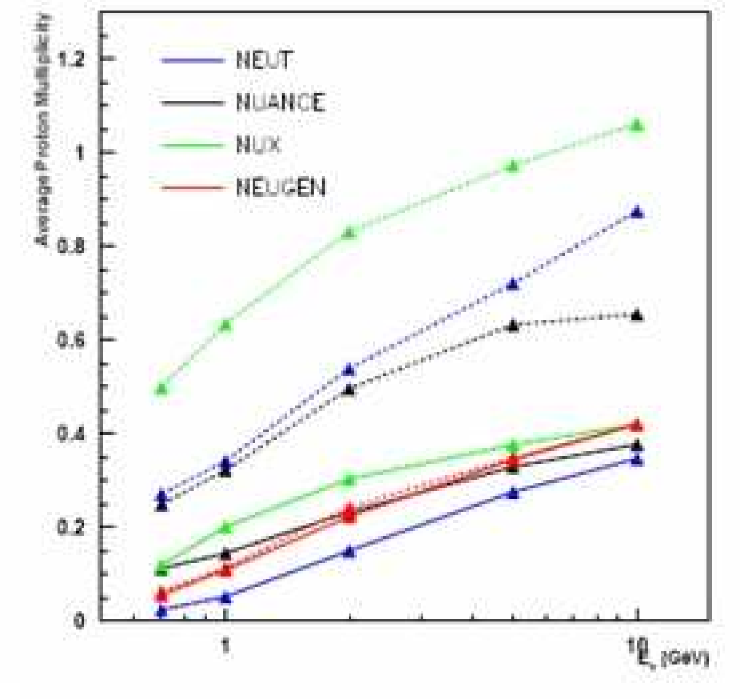
Better agreement with other codes (no data!)

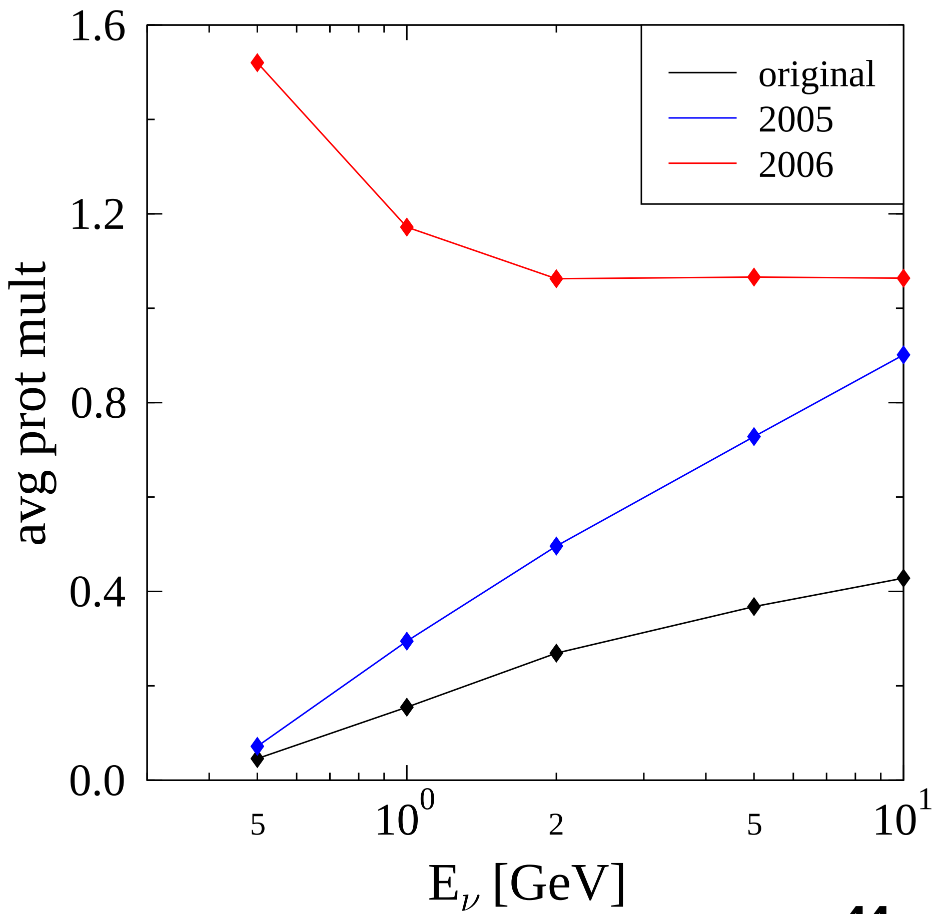




Compare hA to others

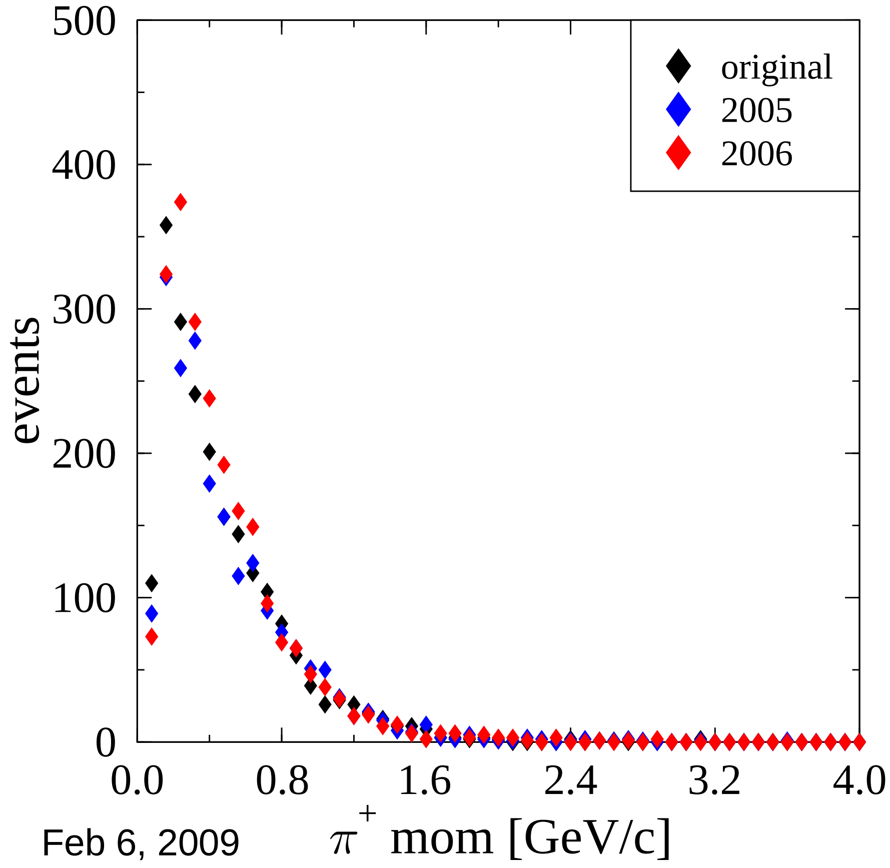
Definite lack of agreement between codes (no data!)

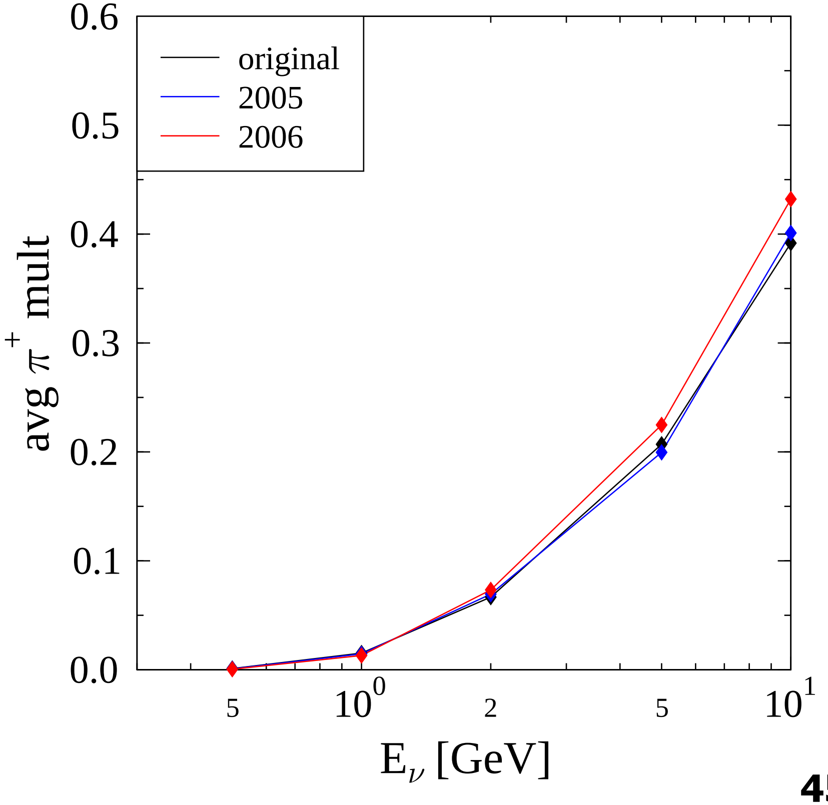




π^+ at 5 GeV

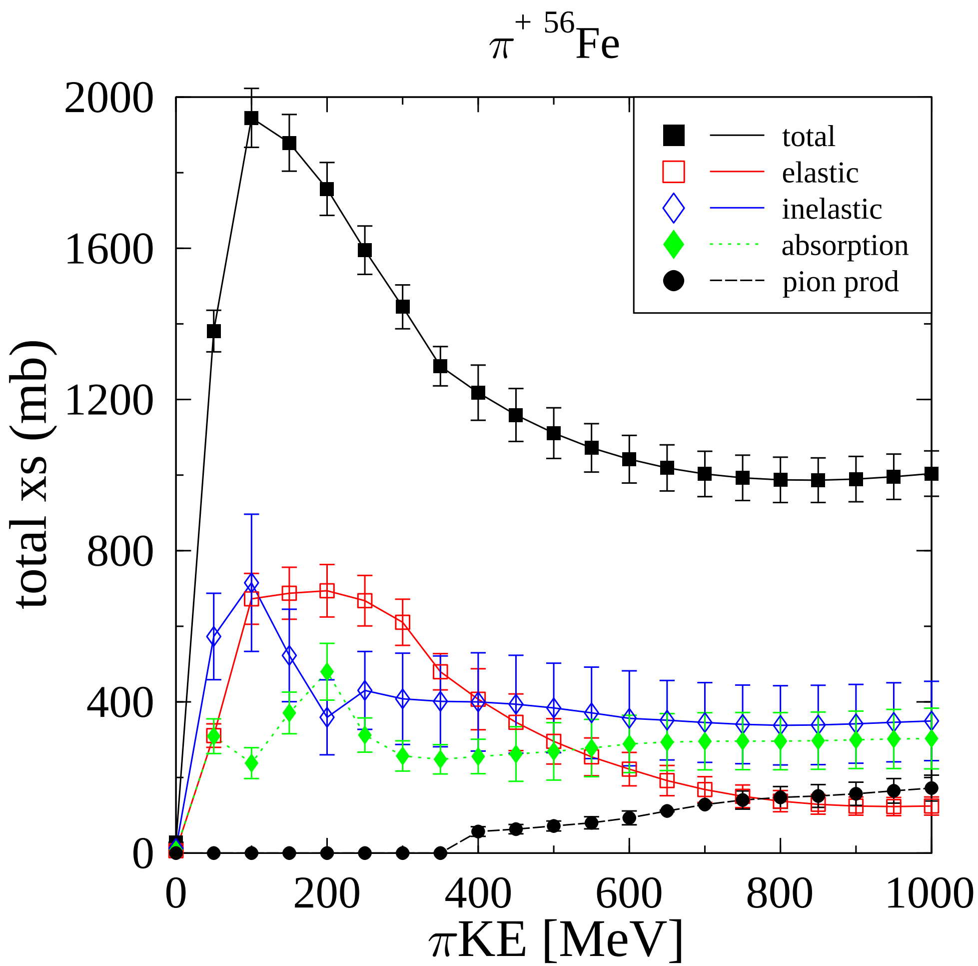
- Not much changes despite new mechanisms
- Other models, 2005, and hA in agreement





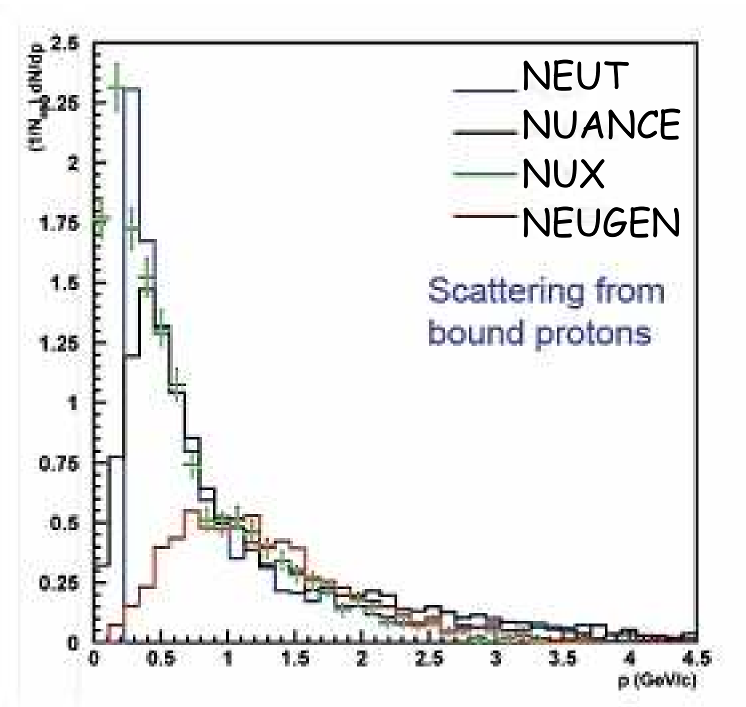
Strategy for est. errors

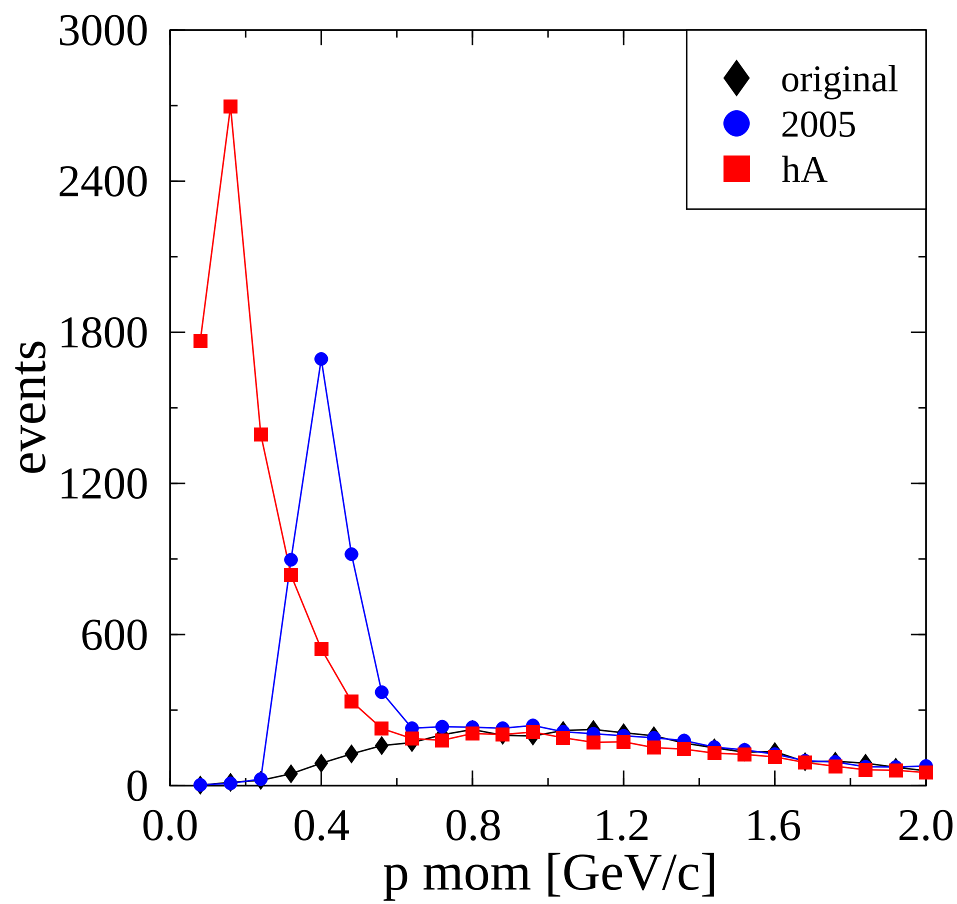
- Use error bar of data (KE<400MeV)
- At higher energies,
  - ➢ Error bar*1.5 for σ_{tot}
  - ➢ Error bar*2 for others



Compare to 2005, old (5 GeV neutrinos)

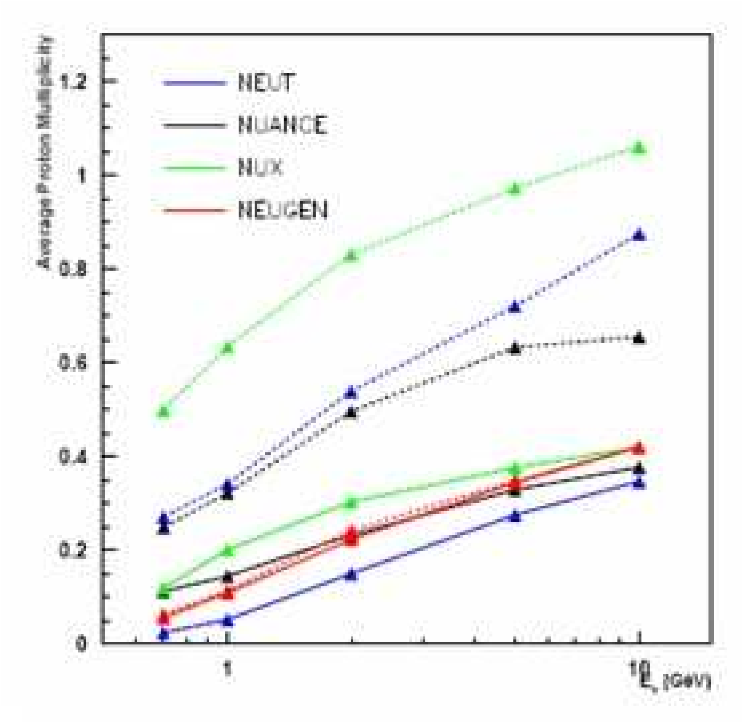
Better agreement with other codes (no data!)

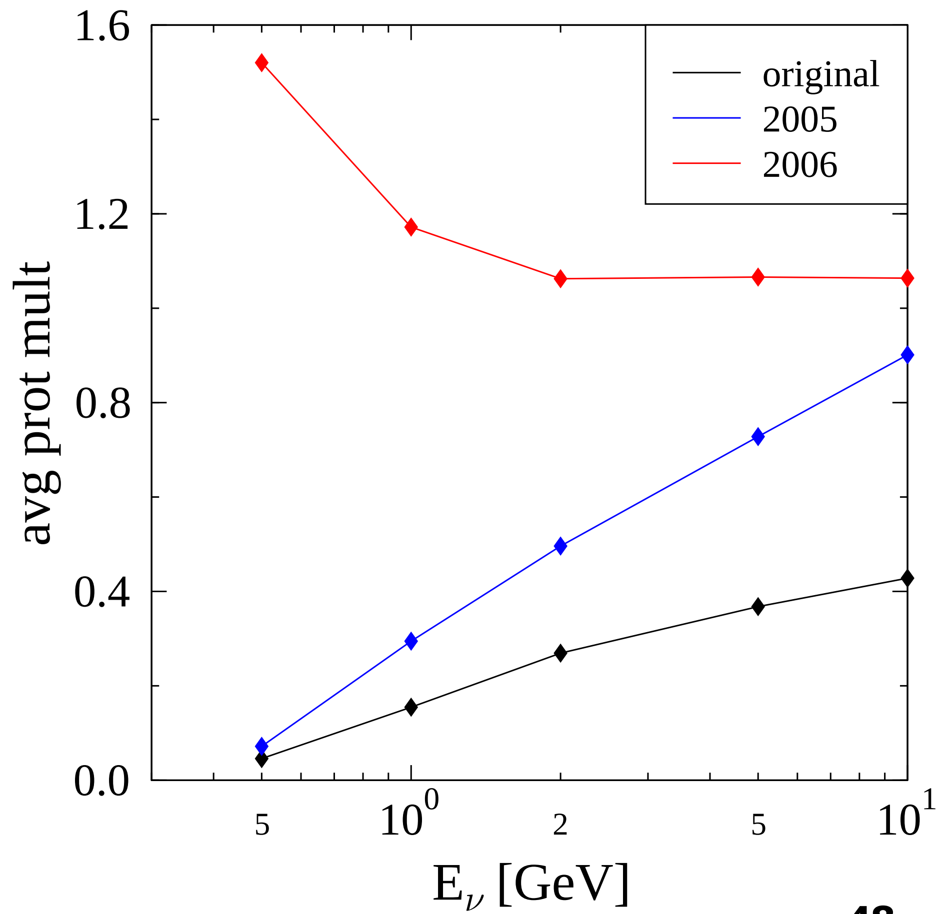




Compare hA to carrot, others

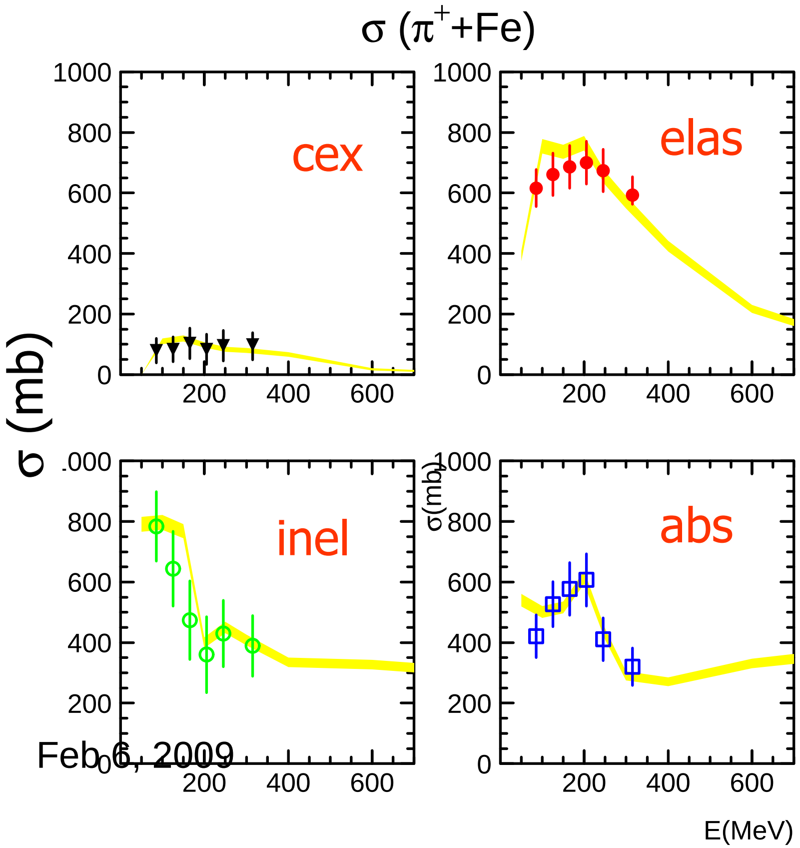
Definite lack of agreement between codes (no data!)

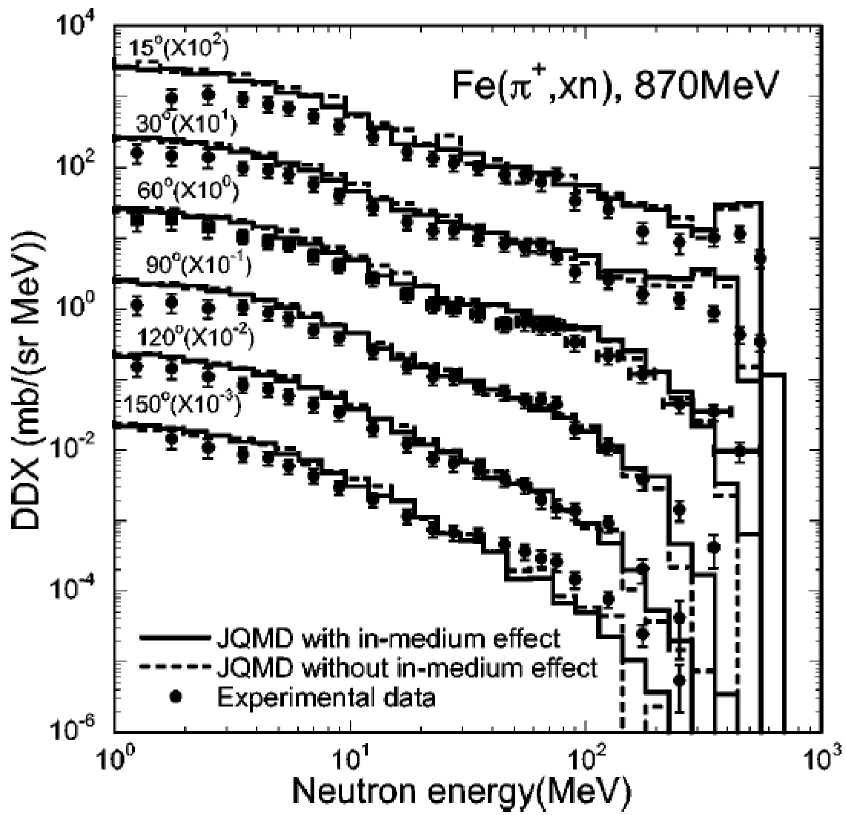




hN Validation process

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





Inclusive distributions

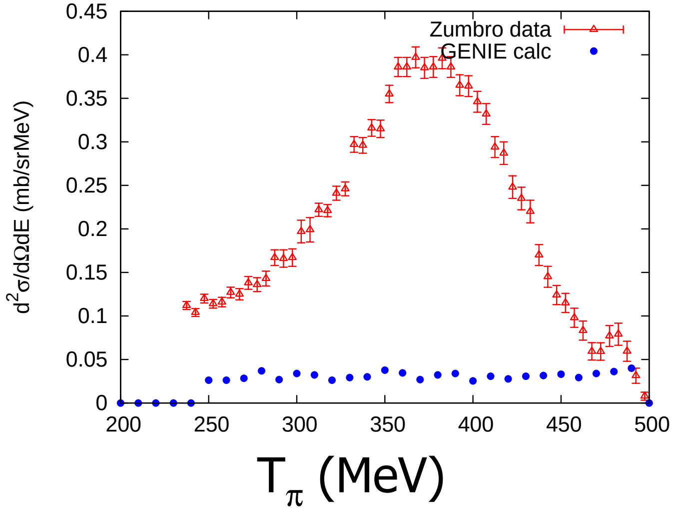
No previous effort made to match complete theory or these data

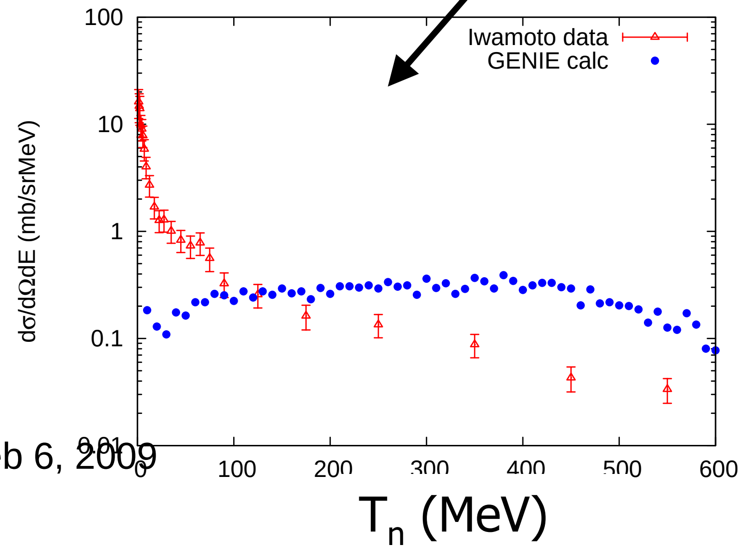
- Phase space or rough estimates only
- Encouraging, but will only get better.

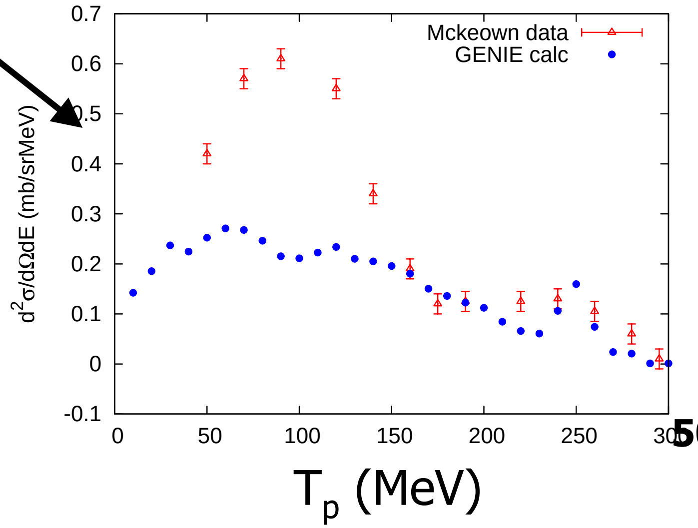
$^{12}C(\pi^+,\pi^+)X$ 500 MeV 50°

$^{12}C(\pi^+,p)X$ 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 (soon)
  - ✓ Can then do some fixes in hA