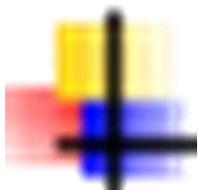


v event generators  
(*esp. NEUGEN and NUANCE*)

S. Dytman (Pittsburgh)  
in collaboration with Hugh Gallagher (Tufts)  
(overview, validation, model comparisons)

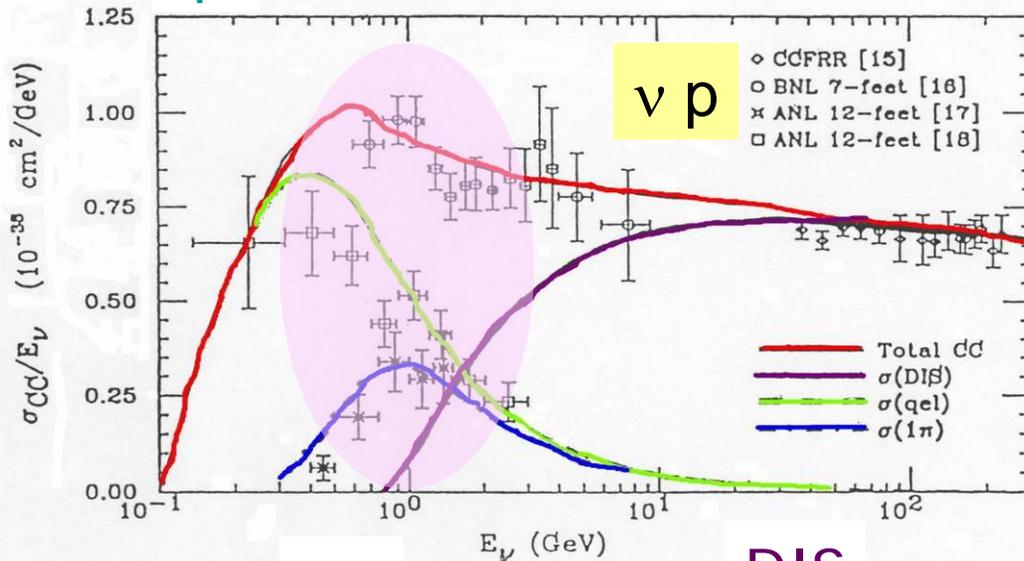


# Cross sections that must be understood

S. Dytman  
Sep. 8, 2006

- $\nu p$  is basic component of all models- need  $qe$ ,  $res$ , DIS processes
- $\nu A$  needed for materials of det/tgt
- coherent NC  $\pi$  prod important bkgd

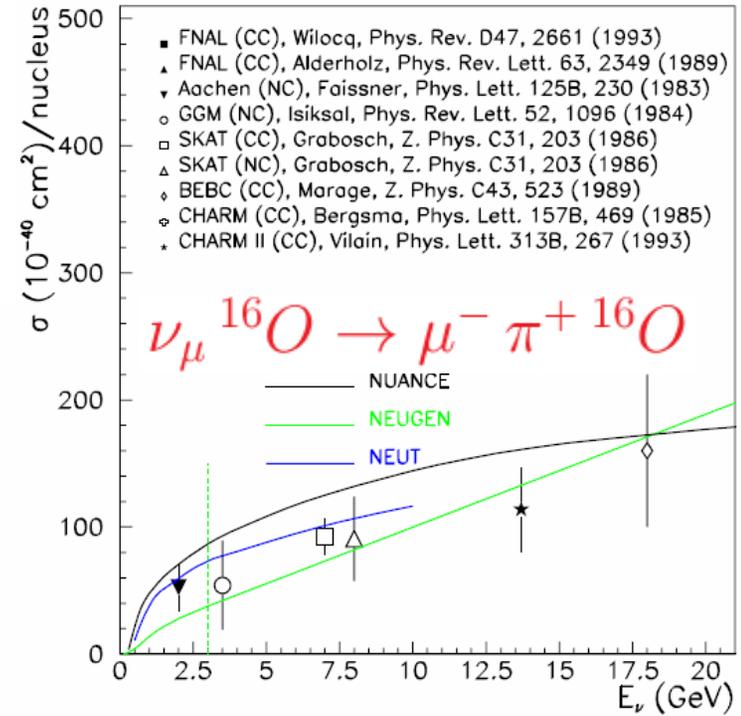
$qe$  tot

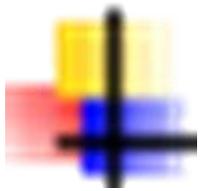


res

DIS

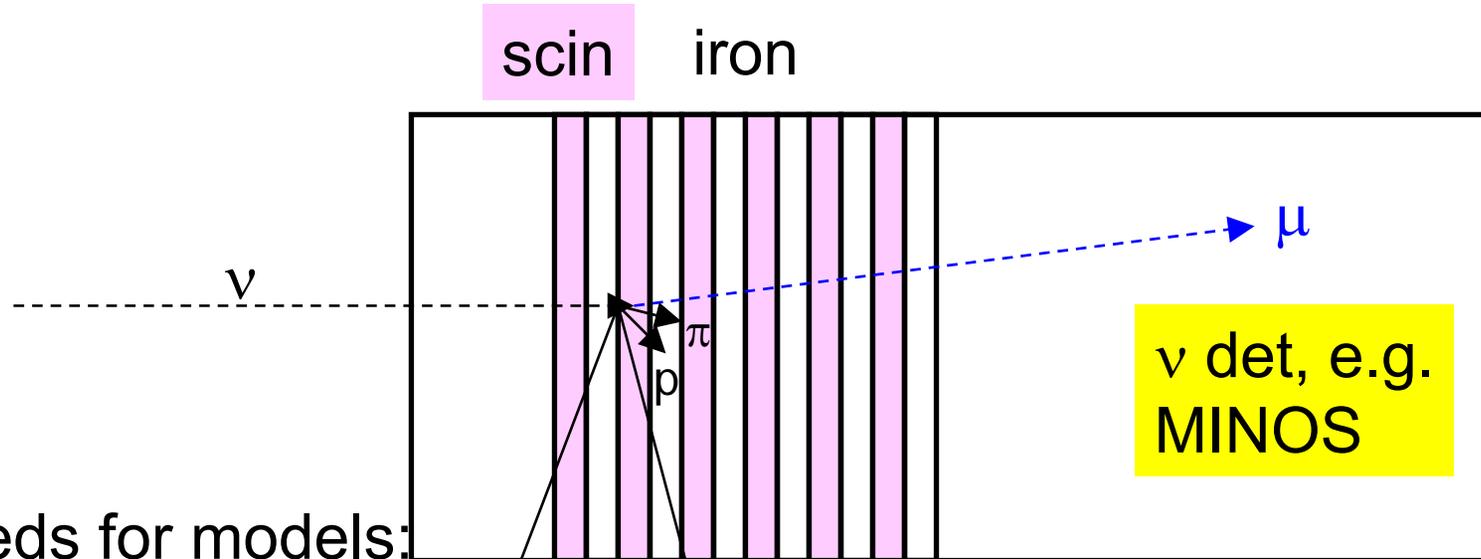
CC Coherent Pion Production Cross Section





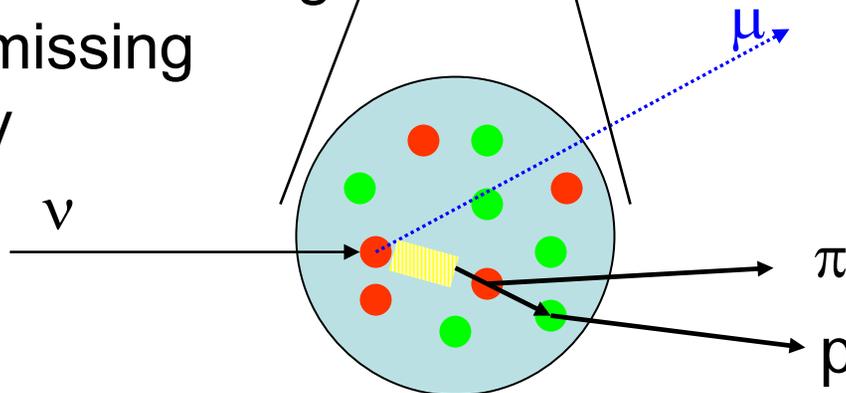
# Schematic MC picture

S. Dytman  
Sep. 8, 2006



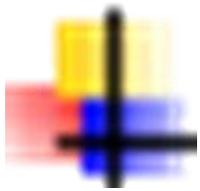
Needs for models:

- Understand QE tag
- Model missing energy



$\nu p$  or  $\nu n \rightarrow$  form. zone  $\rightarrow$  fsi

- Typical detector is coarse-grained cal.
- Packages handle all except  $\nu$ -nucleus
- **Event gen** does this

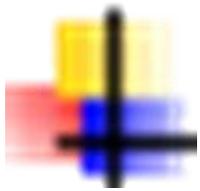


# Event generators

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S. Dytman  
Sep. 8, 2006

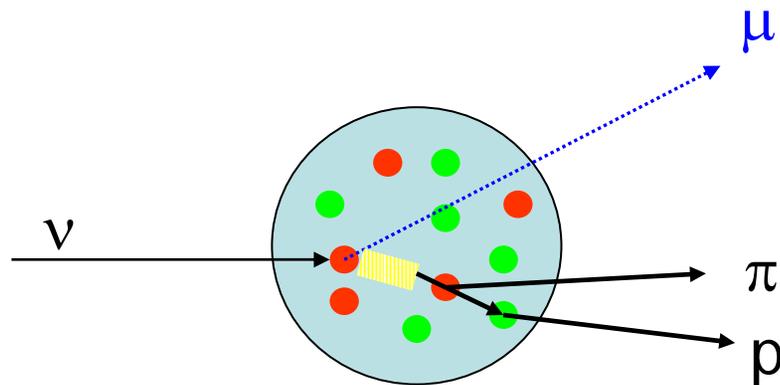
- NEUGEN – H. Gallagher – SOUDAN2/MINOS
  - NEUT – Y. Hayato - SuperK/K2K
  - NUANCE – D. Casper – SuperK/K2K/miniBoone
  - NUX – P. Sala, A. Rubbia - NOMAD/ICARUS
- 
- Each code has very few authors
  - designed to match specific experiment, poorly documented
  - Some elements in common, e.g.  $\nu N$  xs; some developed independently, e.g. hadron fsi.
  - All codes use Intranuclear Cascade Models (INC)
  - HG, YH, DC, & PS did comparisons for Nuint04



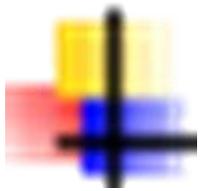
# Ideal attributes (*reality*)

S. Dytman  
Sep. 8, 2006

- Full quantum mechanics (*intranuclear cascade –ICM*)
- Struck nucleon in a bound  $\psi$  (*shift with BE, Fermi mom*)
- Struck nucleons are correlated (*no*)
- FSI allows all processes (*many, but varies*)
- Scattering by amplitude (*free cross section*)
- Models constrained by data (*subject of this talk*)



vp or vn → form. zone → fsi



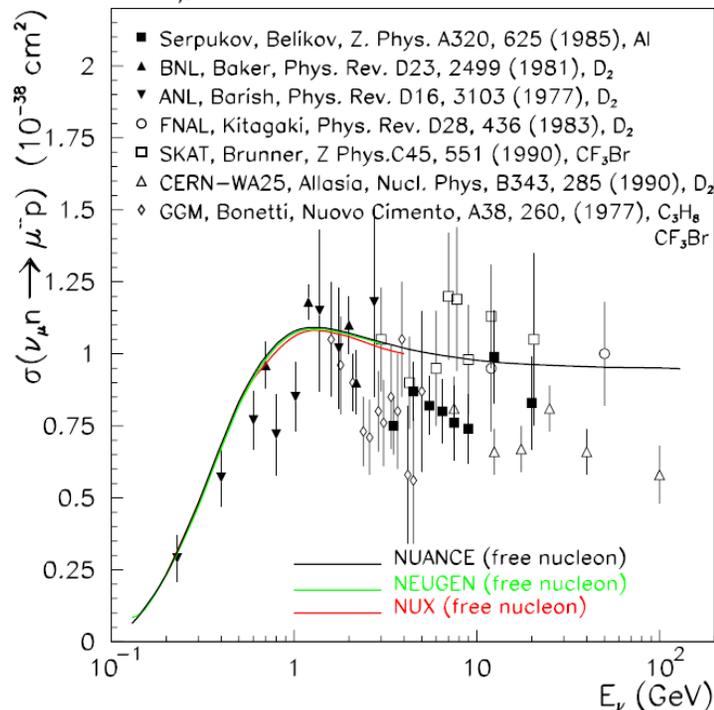
# $\nu$ -nucleon cross section

S. Dytman  
Sep. 8, 2006

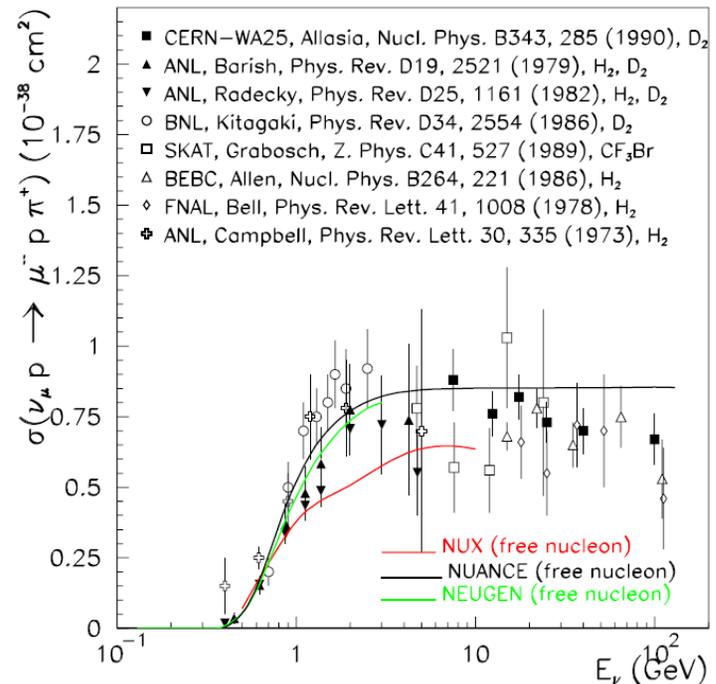
Llewellyn-Smith (1972) is a common choice, so agreement is good even though data is poor.



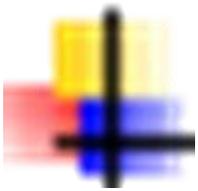
CC  $\nu_{\mu}$  Quasi-Elastic Cross Section



CC Single Pion Production



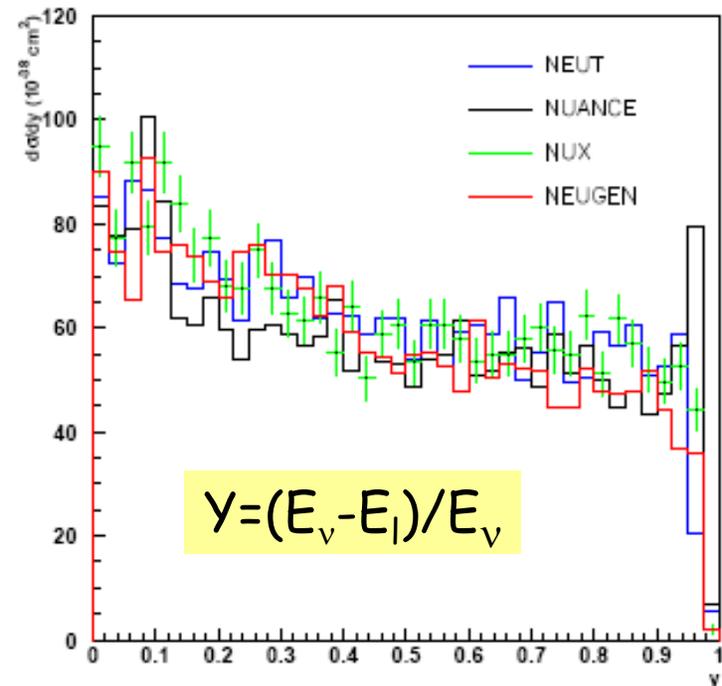
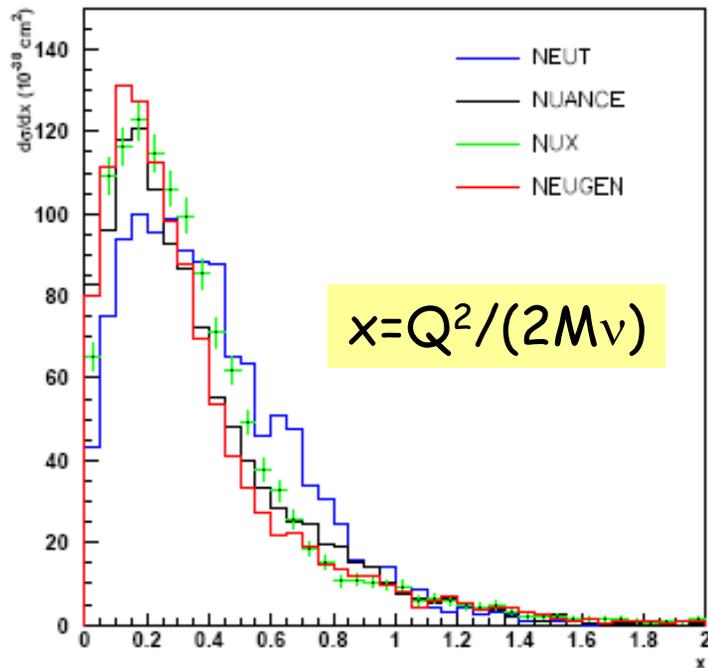
(S. Zeller – Nuint02)

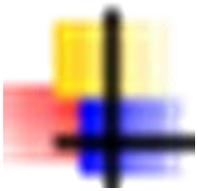


# Formation zone

S. Dytman  
Sep. 8, 2006

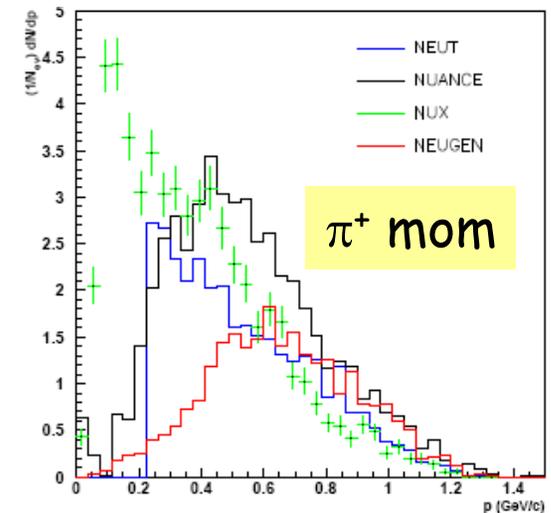
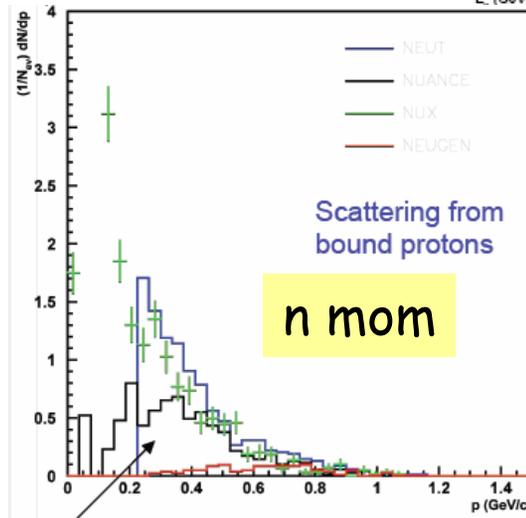
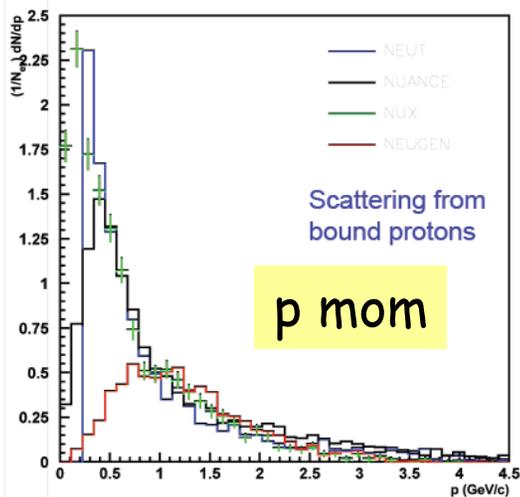
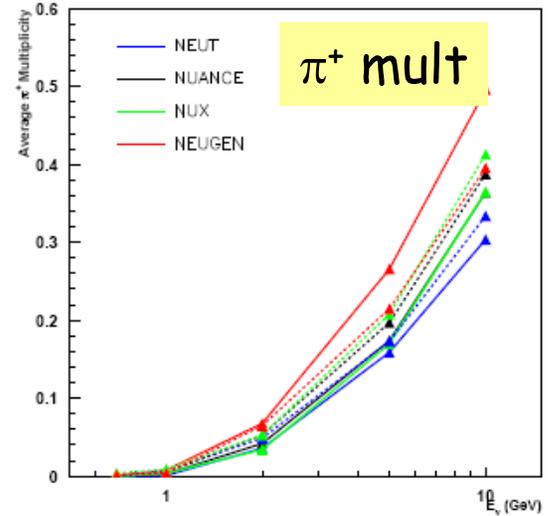
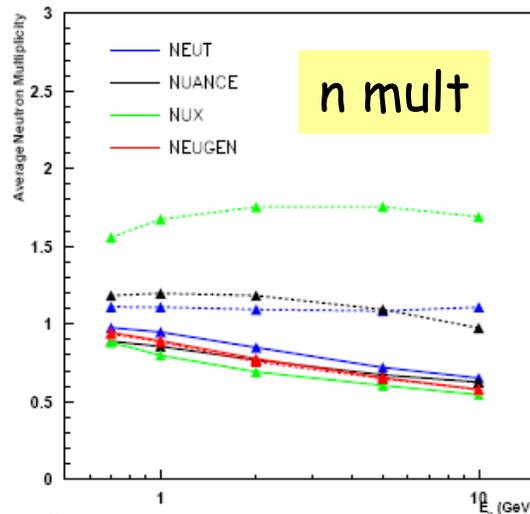
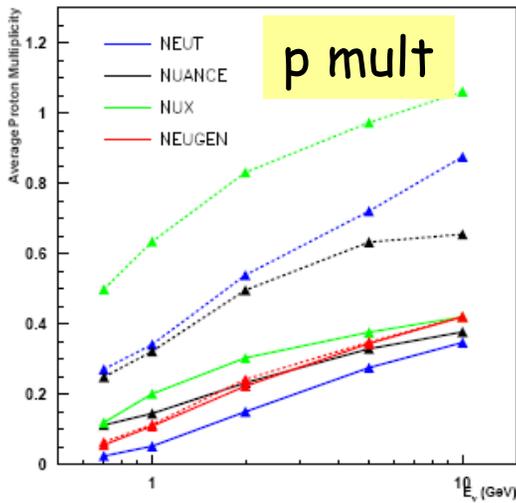
- All models use KNO
- Constrained by bubble chamber data
- Differences are small at  $E_\nu = 5$  GeV

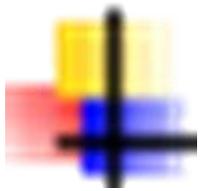




# Various dist. at 5 GeV, $\nu + {}^{16}\text{O}$ (CC,p)

S. Dytman  
Sep. 8, 2006

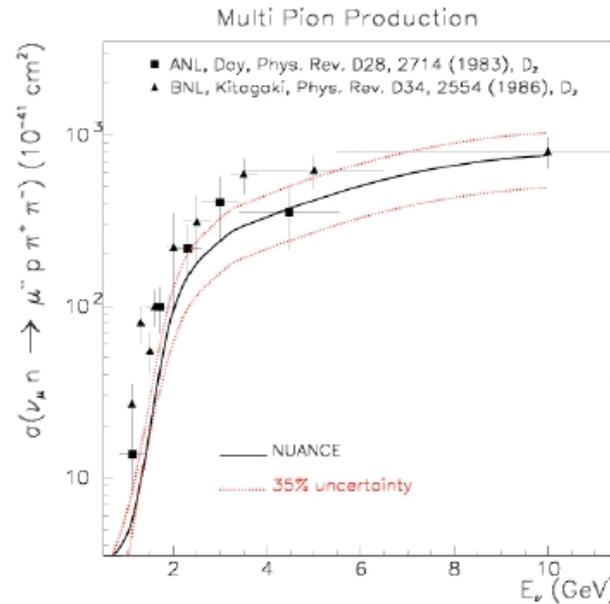
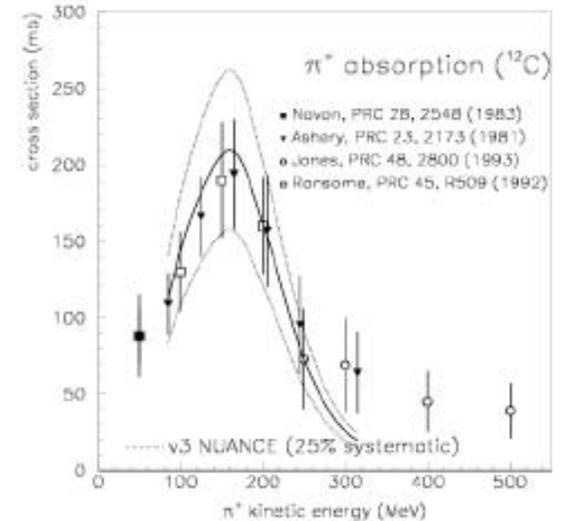
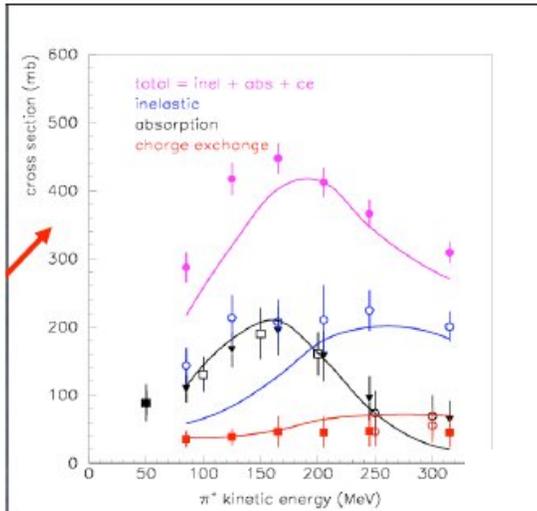


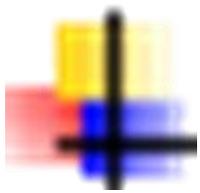


# miniBoone uses NUANCE

S. Dytman  
Sep. 8, 2006

From M. Wascko, Nuint05  
Focus is on pion-Carbon



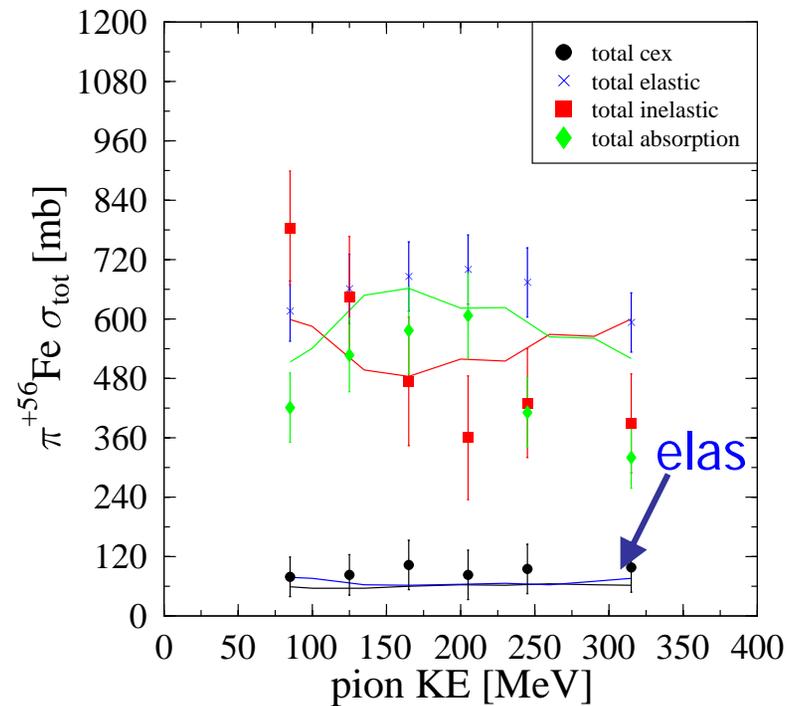
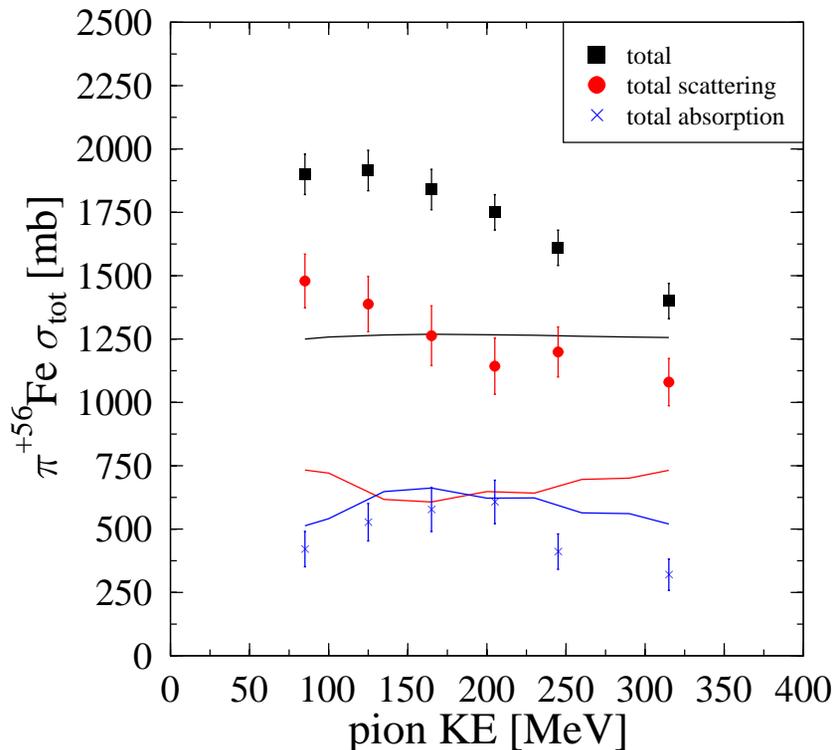


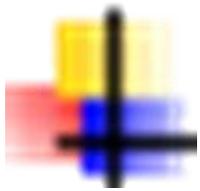
# NEUGEN (MINOS): $\pi^+ {}^{56}\text{Fe}$

S. Dytman  
Sep. 8, 2006

Scattering=elas+cex+inel  
Problem is in scat & tot

see major problem in elastic,  
theory errors, inconsistencies





# NEUGEN evolution

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S. Dytman  
Sep. 8, 2006

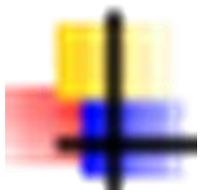
2005

- Fix major problem in pion absorption (energy previously disappeared)

2006

- Use proper mean free path based on data
- Build final states through rescattering of hadrons using model+data
  - For model, use results of CEM03.01 from Stepan Mashnik
  - Stepan presented this model yesterday morning
- Add many mechanisms (nucleon rescat, nucleon emission, pion prod)

Other models might have improved also, but no results available

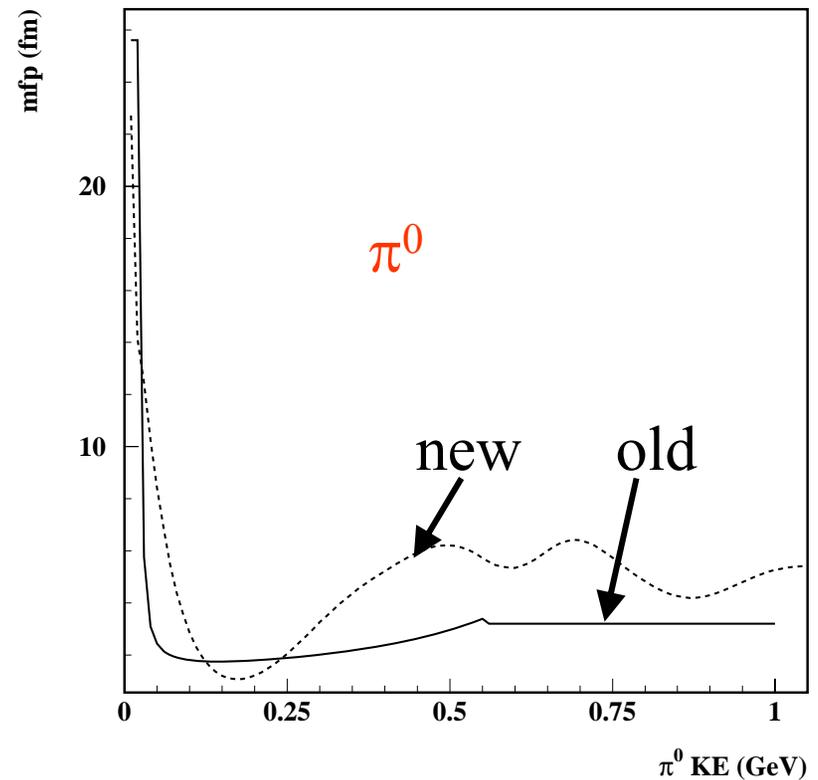
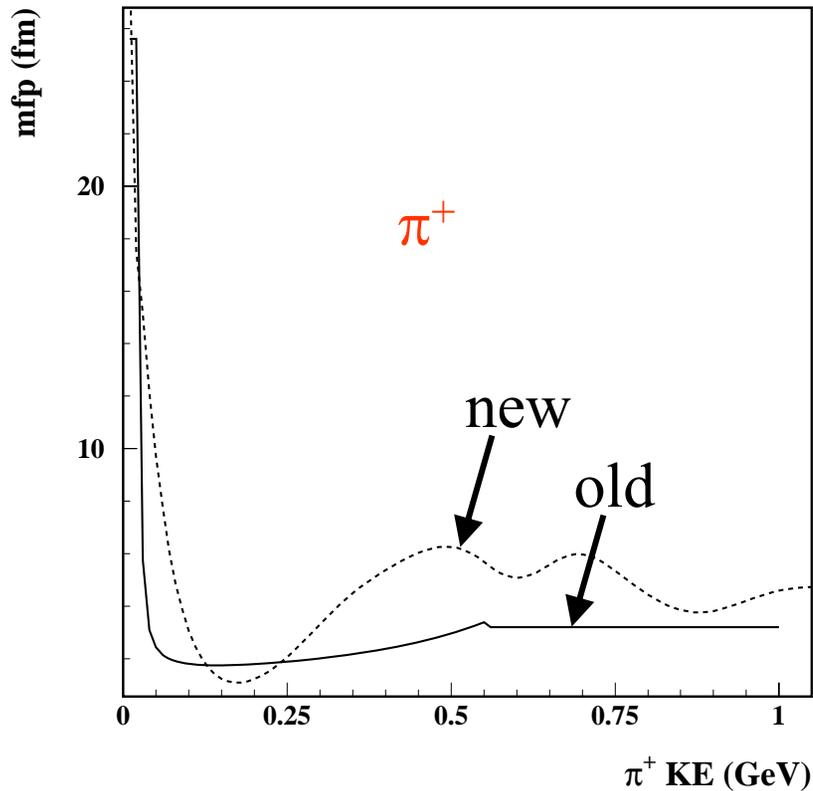


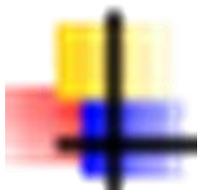
# Mean free path

S. Dytman  
Sep. 8, 2006

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

Structure comes from energy dependence of  $\pi N$

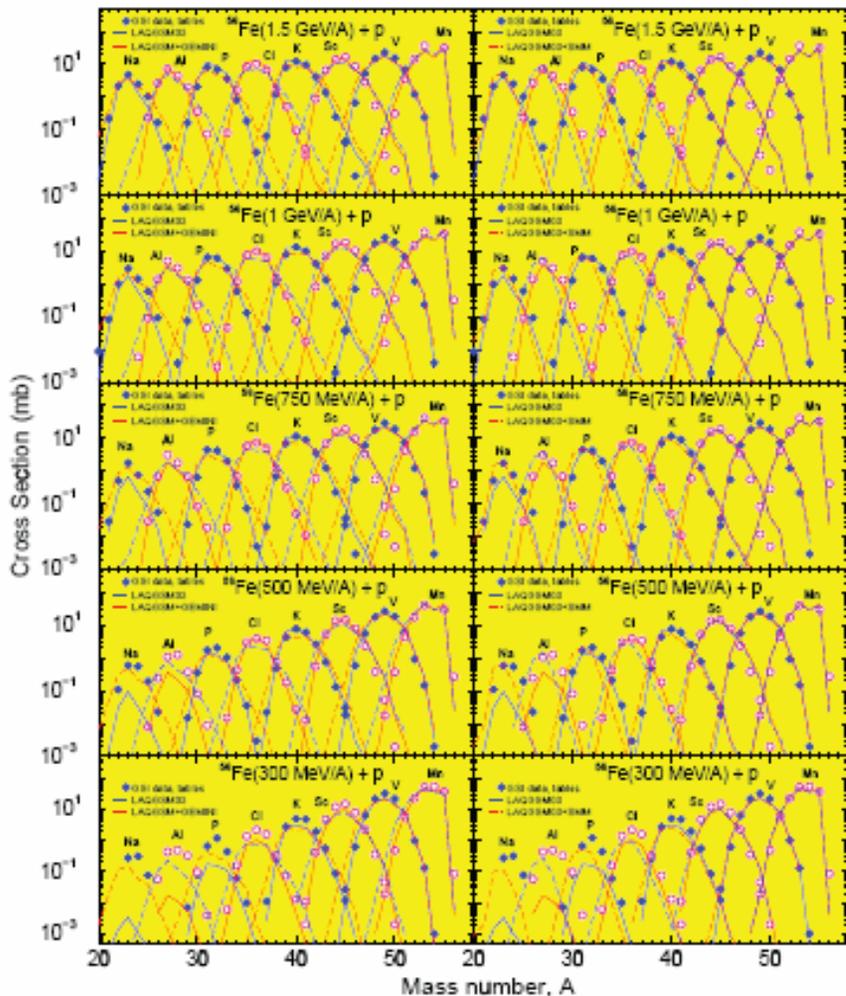




# CEM03.01 vs. $p$ $^{56}\text{Fe}$ data (*their tests*)

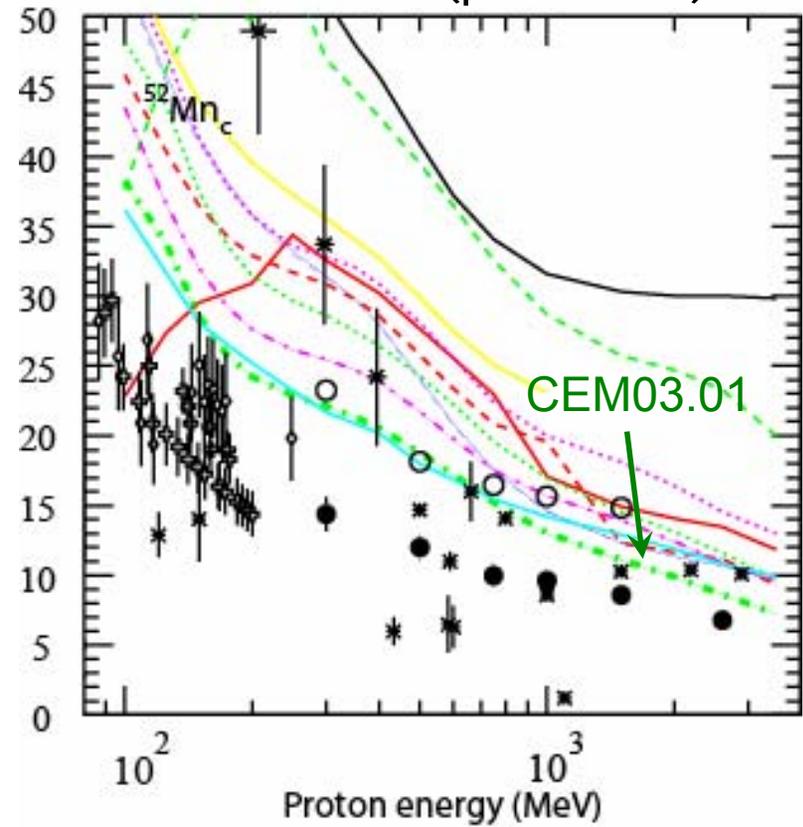
S. Dytman  
Sep. 8, 2006

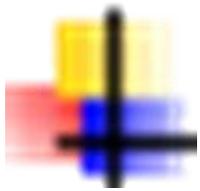
Many final nuclei at various energies



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

Data has systematic error troubles  
Many calculations shown, CEM03.01 does best overall (prediction).

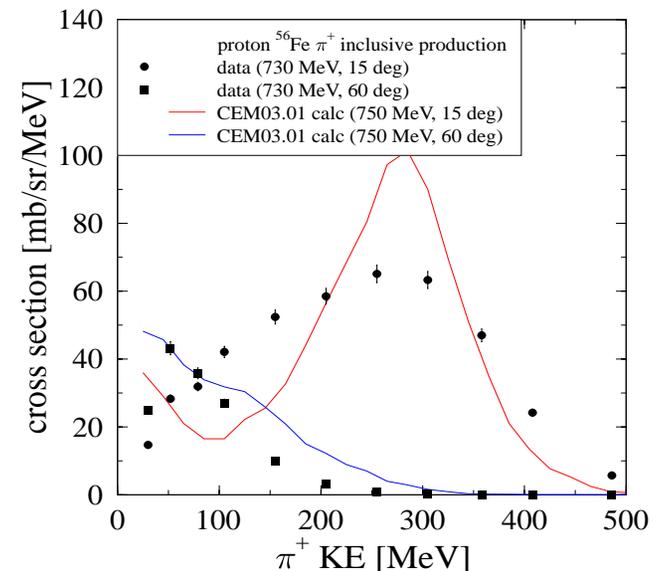
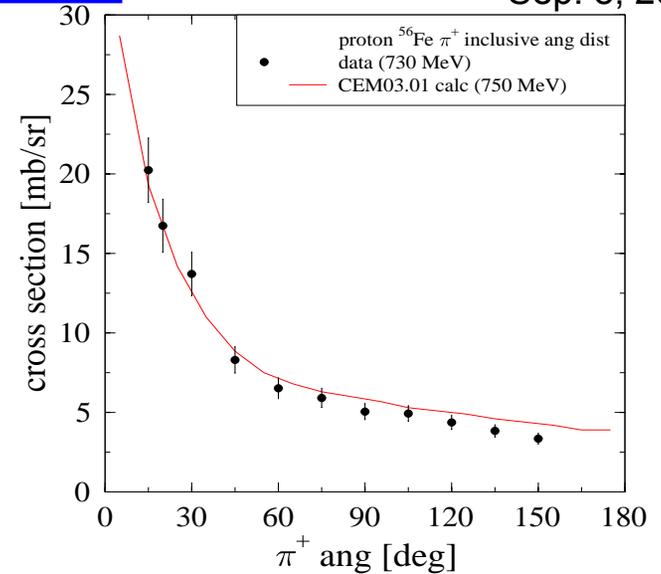
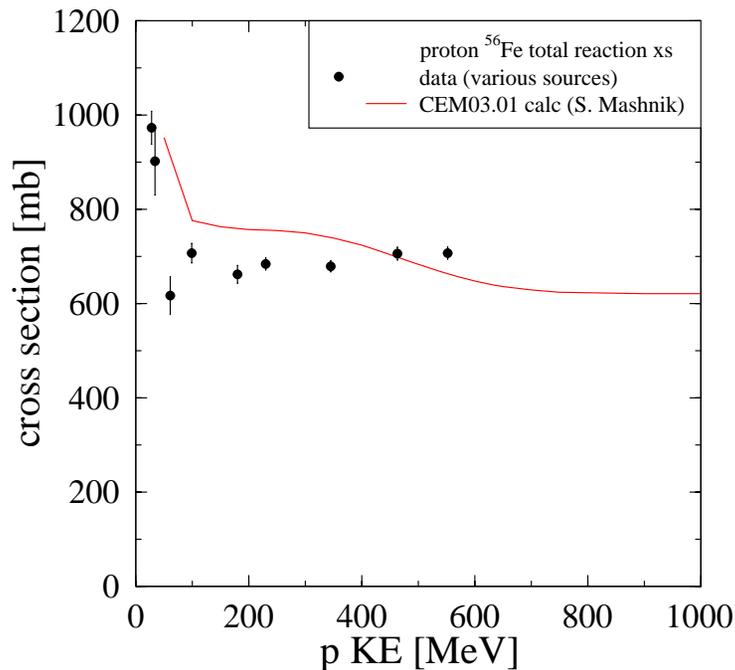


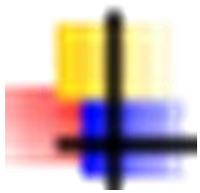


# CEM03.01 - p $^{56}\text{Fe}$ (my tests)

S. Dytman  
Sep. 8, 2006

- Focus on aspects important for MINOS
- Total reaction cross section governs total amount of stuff coming out
- Cochran et al. (1972) measured inclusive pion cross sections (730 MeV)
- Agreement with CEM03.01 very good

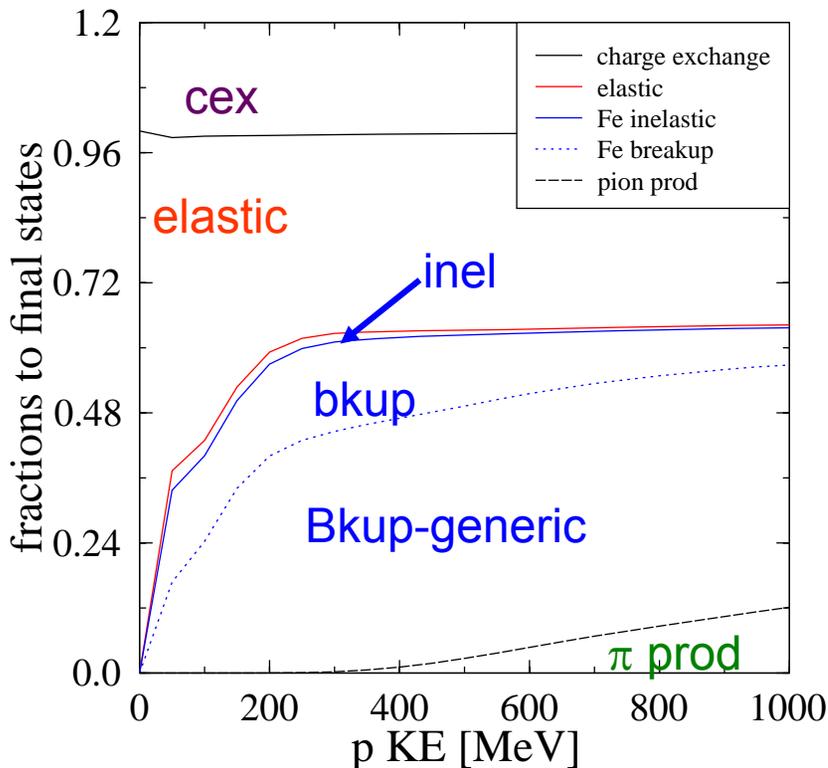




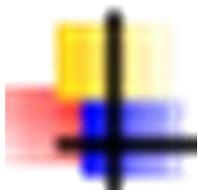
# program strategy

S. Dytman  
Sep. 8, 2006

- Use CEM03.01 calculations for  $p\ ^{56}\text{Fe}$  except optical model for  $\sigma_{\text{elas}}$  (scale by  $A^{2/3}$  for other nuclei)
- Use phase space for angle, energy distributions
- Channels included:



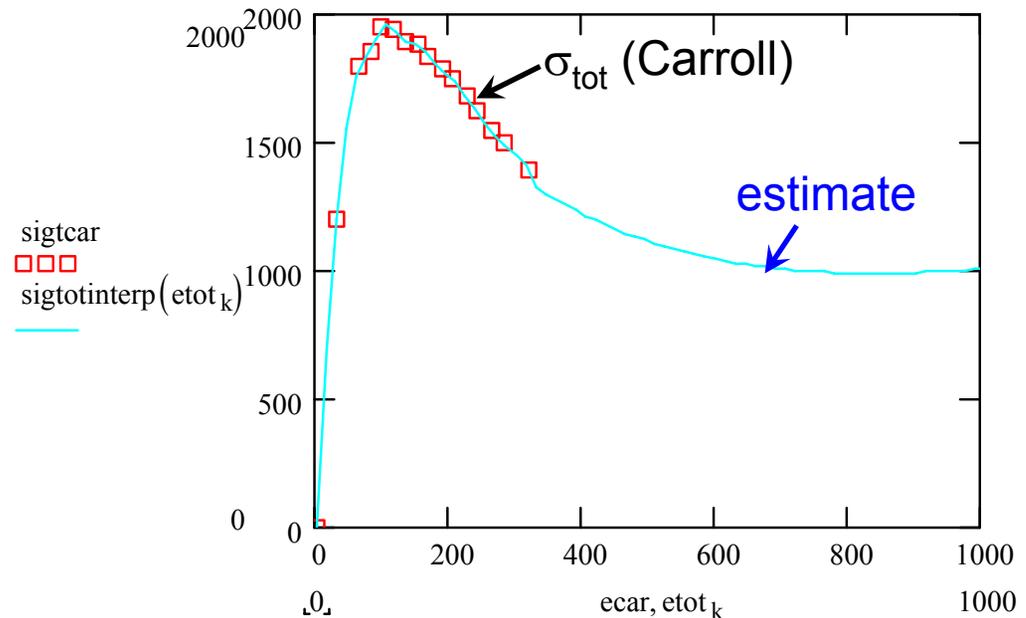
Elastic	$p\ ^{56}\text{Fe} \rightarrow p\ ^{56}\text{Fe}$
Charge exchange	$p\ ^{56}\text{Fe} \rightarrow n\ ^{56}\text{Co}$
Inelastic	$p\ ^{56}\text{Fe} \rightarrow p'\ ^{56}\text{Fe}$
Breakup	$p\ ^{56}\text{Fe} \rightarrow pn\ ^{55}\text{Fe}$
	$p\ ^{56}\text{Fe} \rightarrow pp\ ^{55}\text{Mn}$
	$p\ ^{56}\text{Fe} \rightarrow ppn\ ^{54}\text{Mn}$
	$p\ ^{56}\text{Fe} \rightarrow pnn\ ^{54}\text{Fe}$
Breakup-generic	$p\ ^{56}\text{Fe} \rightarrow pppnn\ ^{52}\text{Cr}$
Pion production	$p\ ^{56}\text{Fe} \rightarrow \pi^+ n\ ^{56}\text{Fe}$
	$p\ ^{56}\text{Fe} \rightarrow \pi^+ \pi^0 n\ ^{56}\text{Fe}$

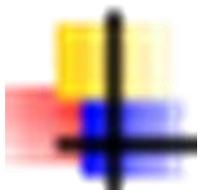


# CEM03.01 - $\pi^+$ $^{56}\text{Fe}$ (my tests)

S. Dytman  
Sep. 8, 2006

- Authors provided no tests
- **TOTAL cross section taken from data**
  - ✓ Quality data for many targets (Carroll, et al.) at  $T_\pi < 450$  MeV
  - ✓ Quality data for light targets (Clough, et al.) at  $T_\pi < 860$  MeV
  - ✓ Note ~flat energy dependence for all targets at high energy
  - ✓ Use **power fit to A dependence to extrapolate**

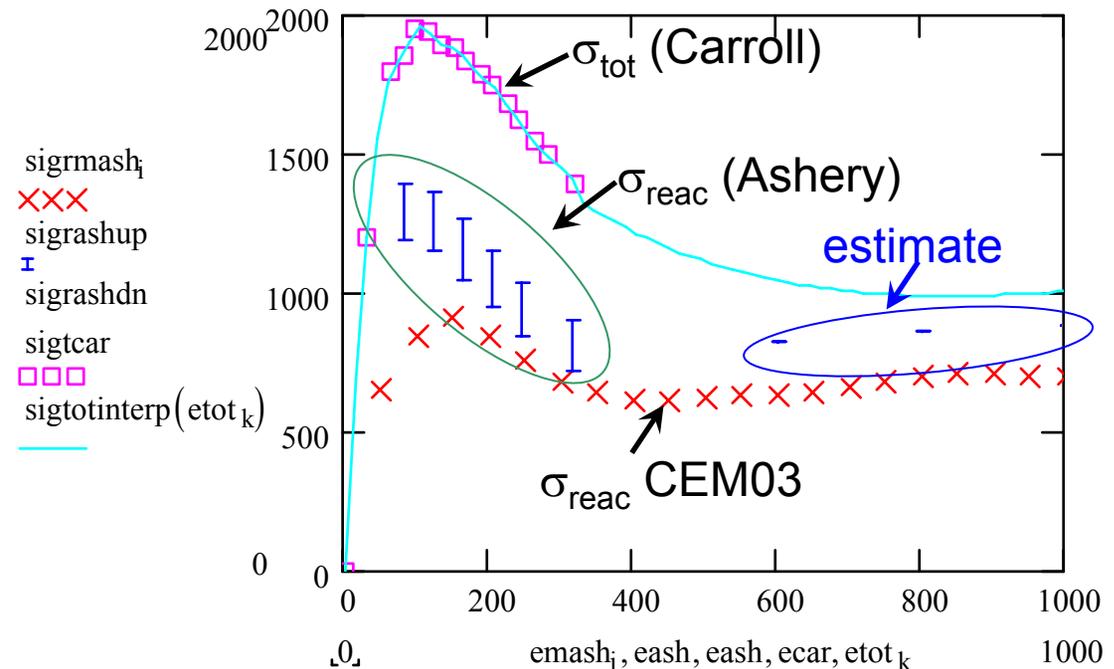


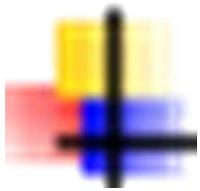


# CEM03.01 - $\pi^+$ $^{56}\text{Fe}$ [ $\sigma_{\text{REAC}}$ ]

S. Dytman  
Sep. 8, 2006

- REACTION (tot-elas=abs+inel+cex) cross section trickier
  - ✓ Poor agreement vs. Ashery et. al data at low  $T_\pi$ .
  - ✓ Expect  $\sigma_{\text{elas}}$  small high  $T_\pi$ .
  - ✓ Compensating factor has too much energy dependence.
  - ✓ Use data with ~constant extrapolation (like calc. and total xs)

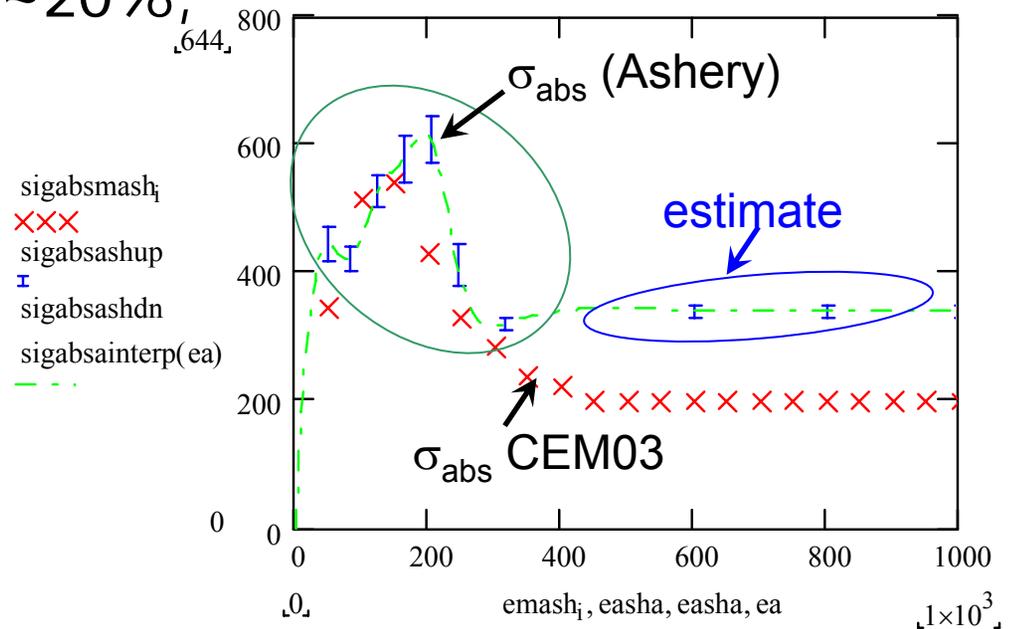


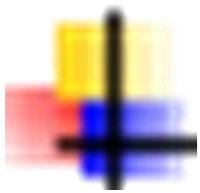


# CEM03.01 - $\pi^+$ 56Fe [ $\sigma_{ABS}$ ]

S. Dytman  
Sep. 8, 2006

- Total **ABSORPTION cross section**
- Ashery et al. , Nakai 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  $\sim 20\%$ , could also use CEM03.

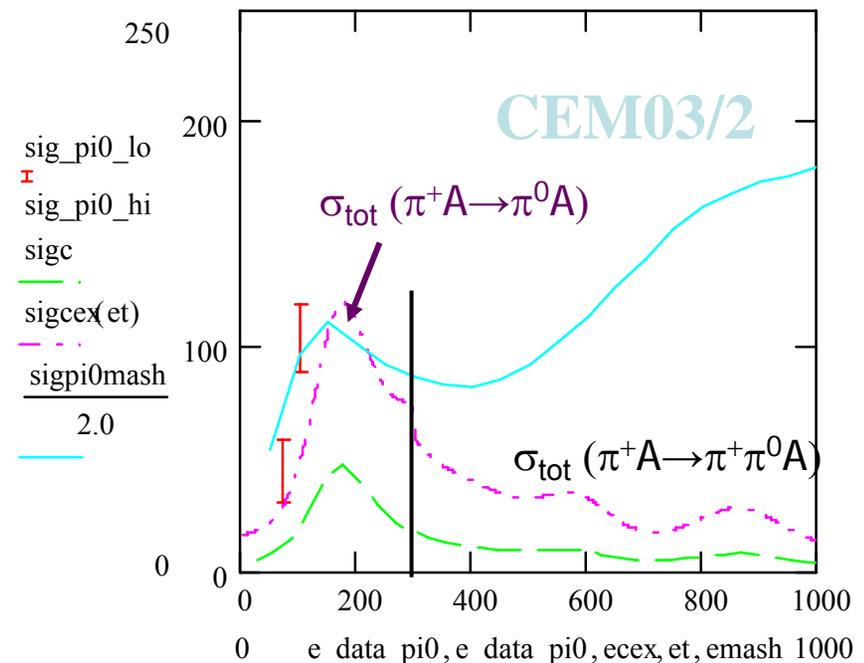


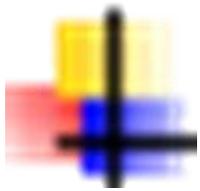


# CEM03.01 - $\pi^+$ 56Fe [ $\sigma_{\pi^0}$ ]

S. Dytman  
Sep. 8, 2006

- Total **Inclusive  $\pi^0$  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, not included previously
- CEM03 calc. divided by 2 agrees with data at low energy
- $\sigma(\pi^-p \rightarrow \pi^0n)$  peaks at res,  $\sigma(\pi^-A \rightarrow \pi^0A)$  should be prop. to this
- Use scaled  $\sigma(\pi^-p \rightarrow \pi^0n)$  (**purple**) for  $\sigma(\pi^-A \rightarrow \pi^0A)$  at all energies
- Use CEM03/2- $\sigma(\pi^+A \rightarrow \pi^0A)$  for  $\sigma(\pi^+A \rightarrow \pi^0\pi^+A)$  at  $T_\pi > 300$

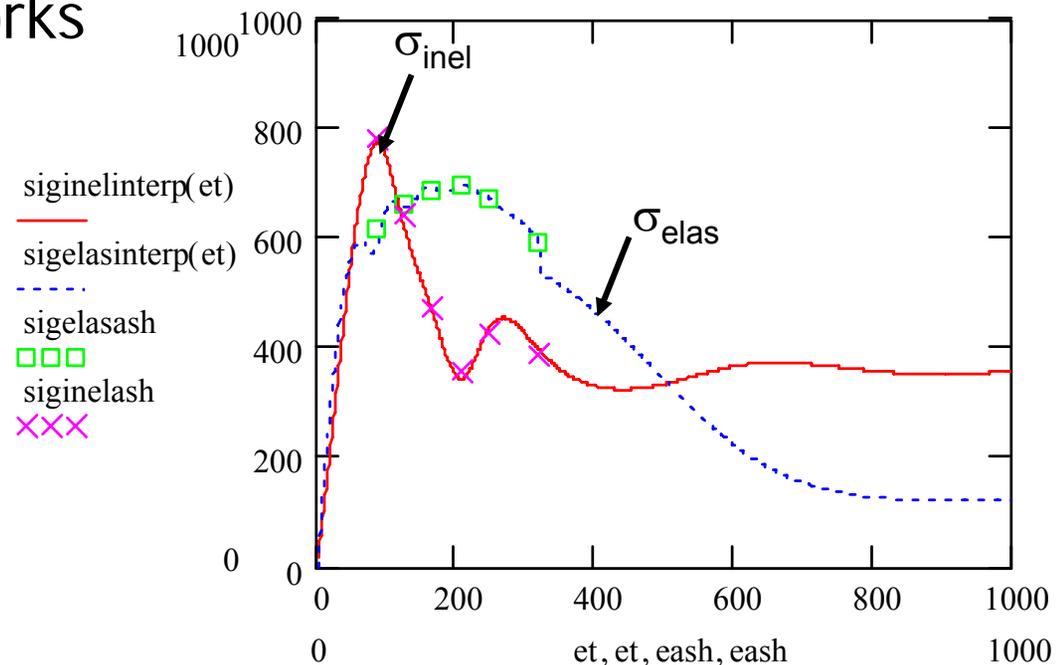


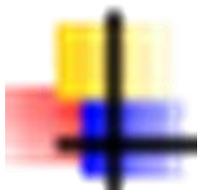


# CEM03.01 - $\pi^+$ 56Fe [ $\sigma_{inel}$ , $\sigma_{elas}$ ]

S. Dytman  
Sep. 8, 2006

- 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.

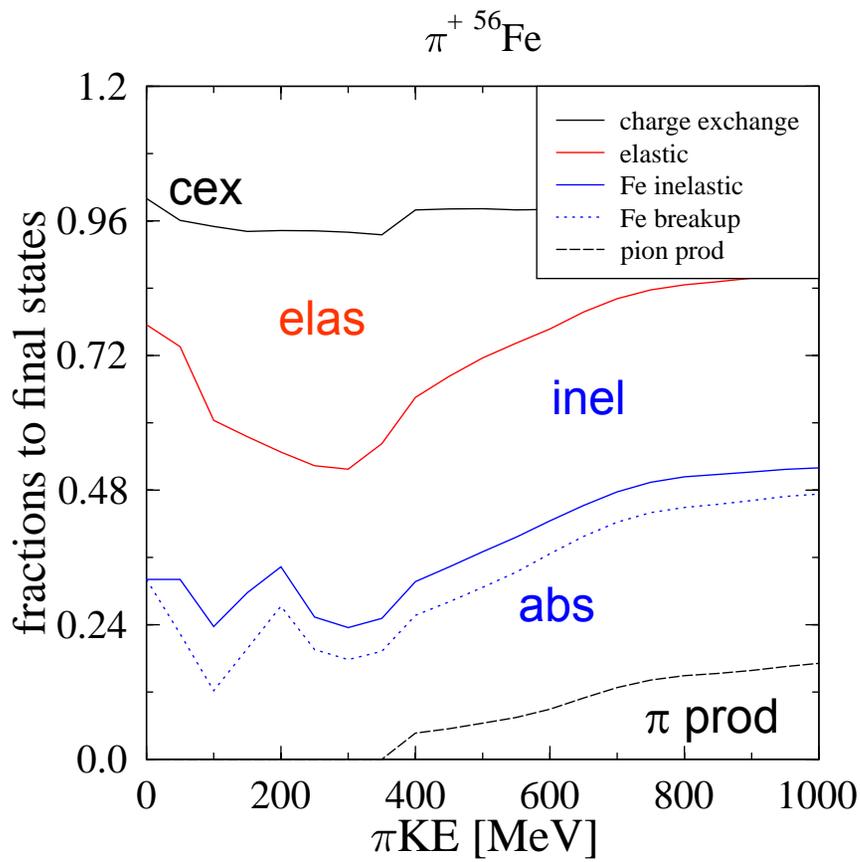




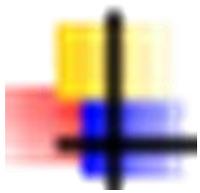
# program strategy

S. Dytman  
Sep. 8, 2006

- Mix of data, intuition, CEM03.01 calc. for  $\pi^+ {}^{56}\text{Fe}$  (scale by  $A^{2/3}$  for other nuclei)
- Jumps of  $\sigma_{\text{abs}}$  at low energy is in data!



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

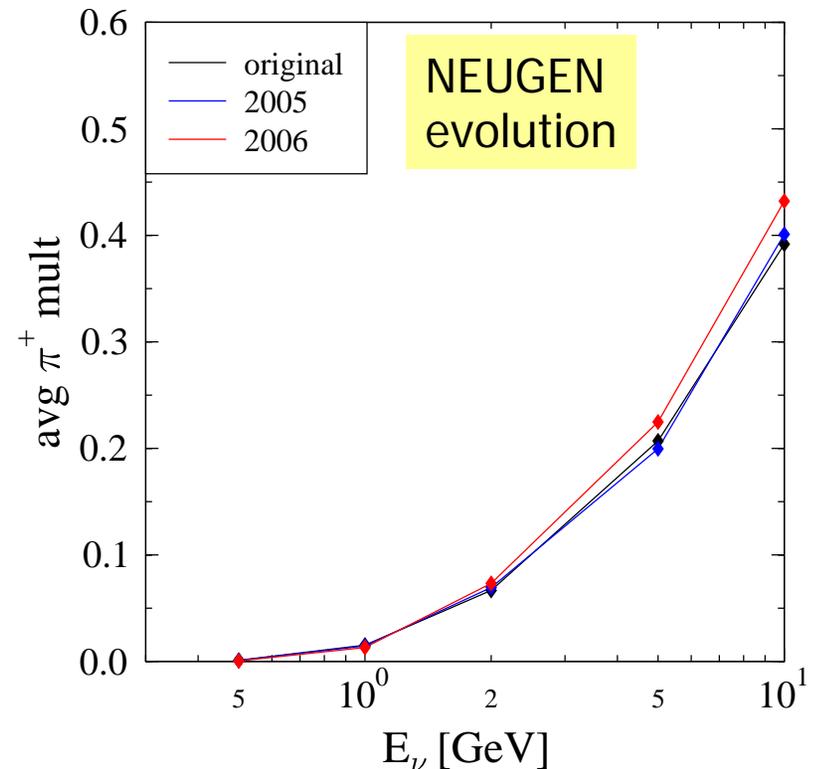
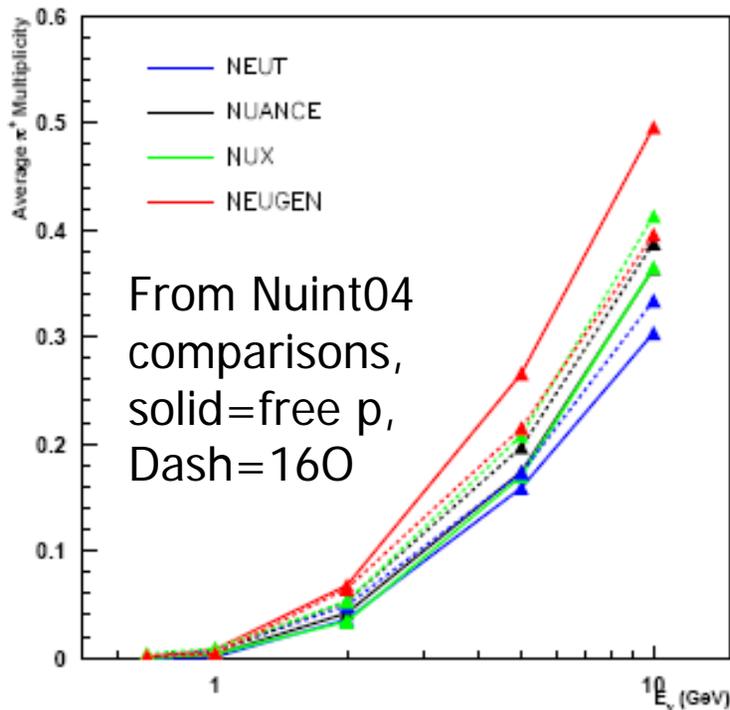


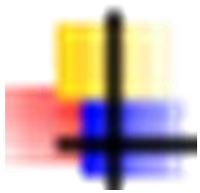
# $\pi^+$ multiplicity (*more comparisons*)

S. Dytman  
Sep. 8, 2006

- Models in good agreement
- Sources
  - ✓  $\pi$  production through  $N^*$
  - ✓  $\pi$  production through NN

- Changes in NEUGEN models maintain consistency despite changes in sources. (NN inel is new.)



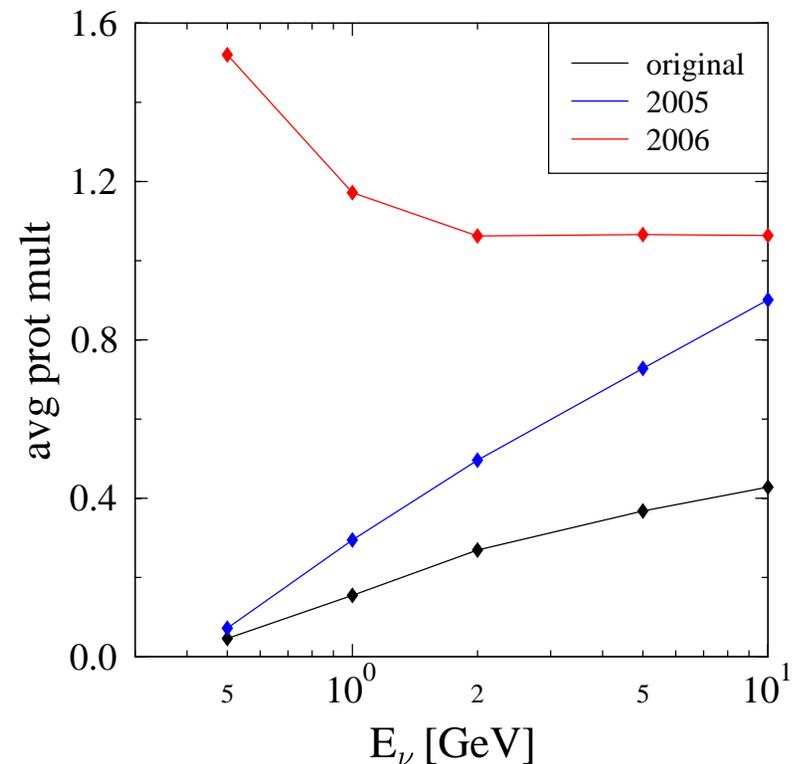
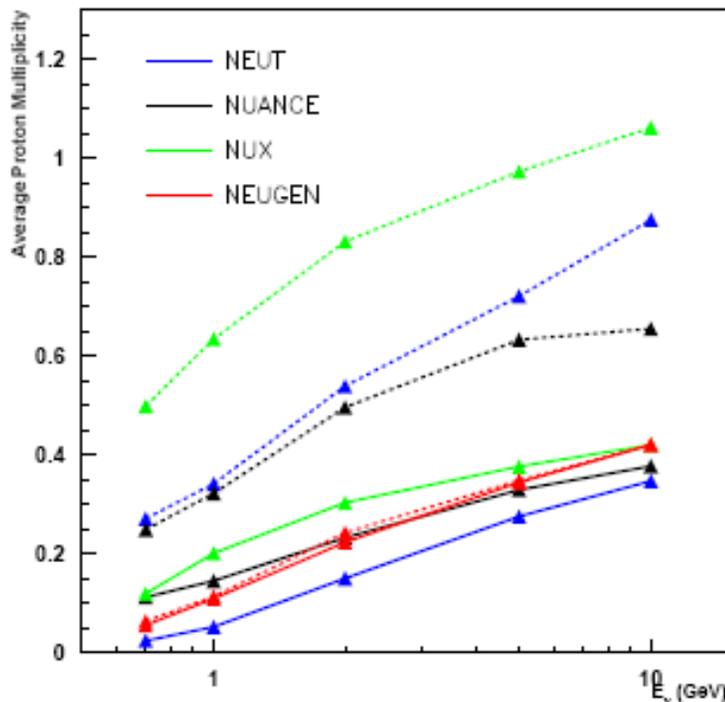


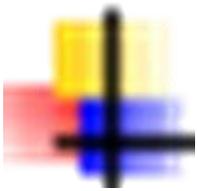
# Proton multiplicity

S. Dytman  
Sep. 8, 2006

- Wide variation between models.
- Sources
  - ✓ Nucleon fsi (dominates at low  $E$ )
  - ✓ Pion absorption (important at  $\Delta$ )

- Newest model very different
- Consistent with theory, but need new  $\nu A$  data for validation!

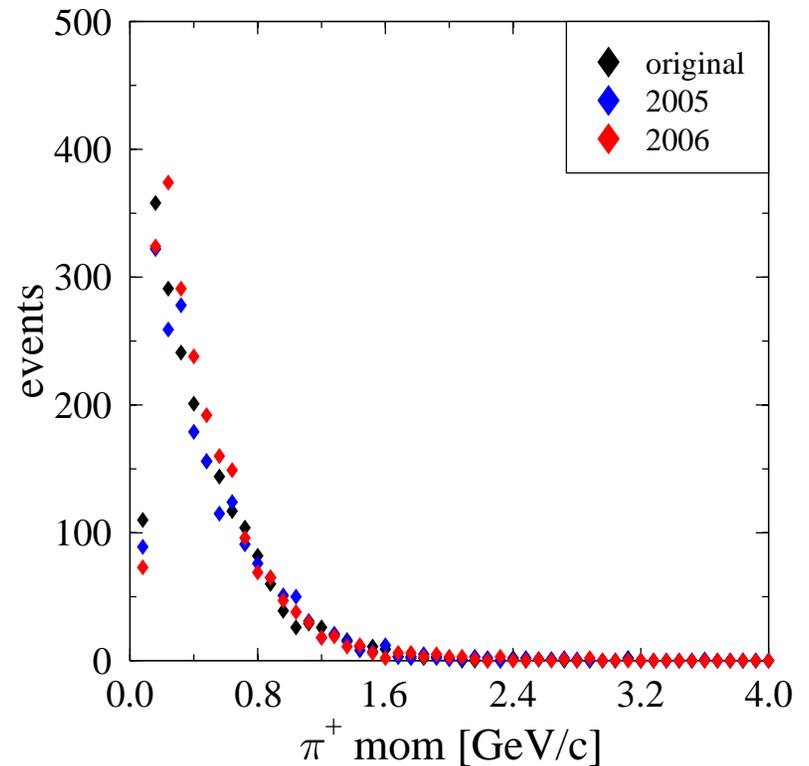
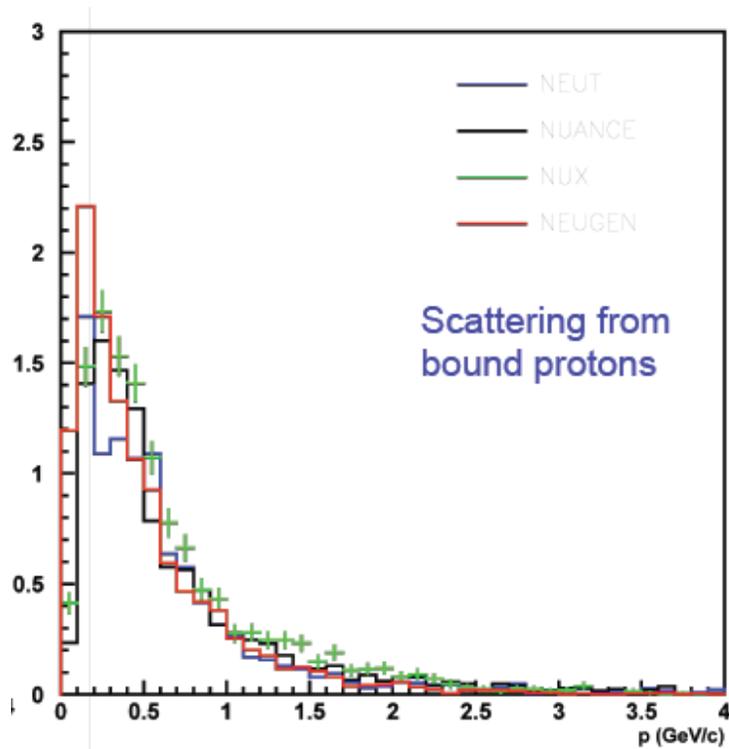


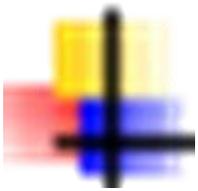


# $\pi^+$ momentum

S. Dytman  
Sep. 8, 2006

- Good agreement between models.
- New sources and new mechanisms make only a small difference.



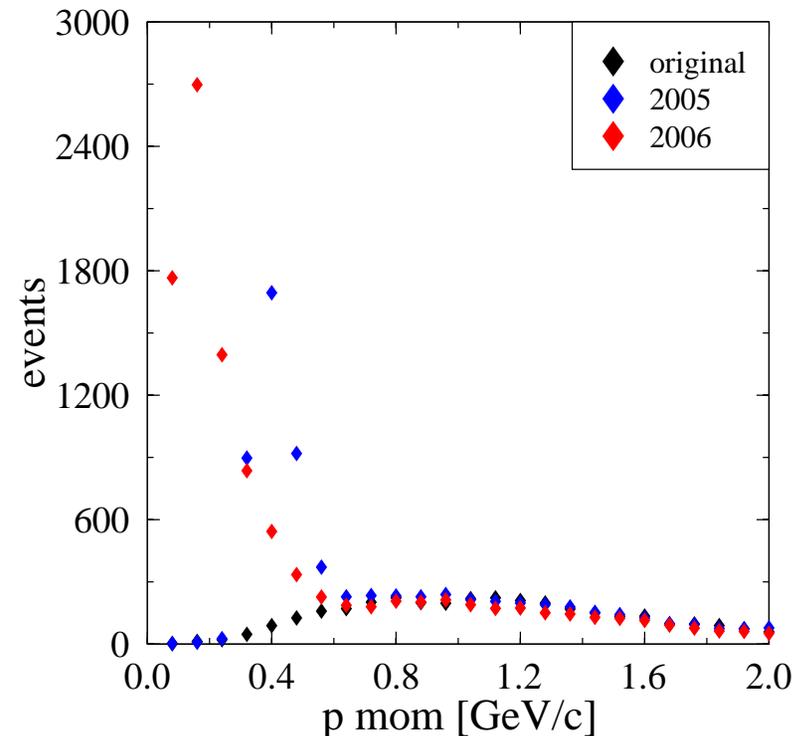
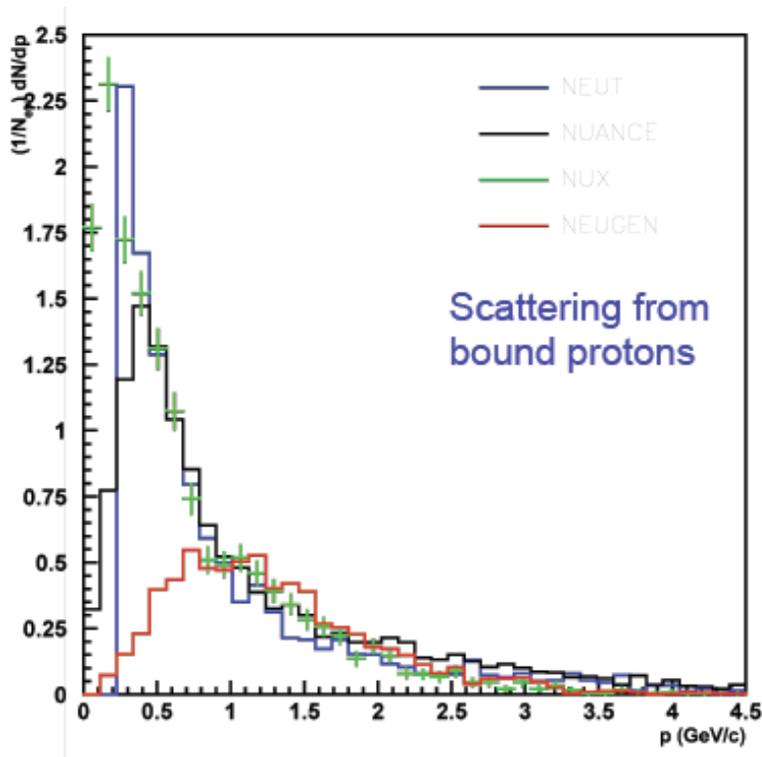


# p momentum

S. Dytman  
Sep. 8, 2006

- Older NEUGEN clearly lacking.
- No production methods for p.

- New sources for p (and n)
- 2005 model has higher mom
- 2006 model more in agreement with others.



# The GENIE

- Object-Oriented / C++
- ## Neutrino MC Generator

<http://www.genie-mc.org>

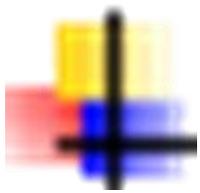
Principal author

- C. Andreopoulos (CCLRC, Rutherford)
- F. Cavanna (INFN & L'Aquila Univ.)
- J. Damet (LAPP)
- S. Dytman (Pittsburgh Univ.)
- H. Gallagher (Tufts Univ.)
- Y. Hayato (KEK)
- S. Kretzer (BNL)
- A. Meregaglia (ETH Zurich)
- D. Naples (Pittsburgh Univ.)
- G. Pearce (CCLRC, Rutherford)
- A. Rubbia (ETH Zurich)
- M. Whalley (Durham Univ.)



v2.0.0 will be released soon.

Comp. Phys. Comm. article in preparation



# features

S. Dytman  
Sep. 8, 2006

The developers of leading procedural generators (*GENIE's legacy*) :

European LAr  
community

**GENEVE** (F.Cavanna et al.)

MINOS, Soudan, ...

**NeuGEN** (H.Gallagher et al.)

SuperK, K2K, ...

**NEUT** (Y.Hayato et al.)

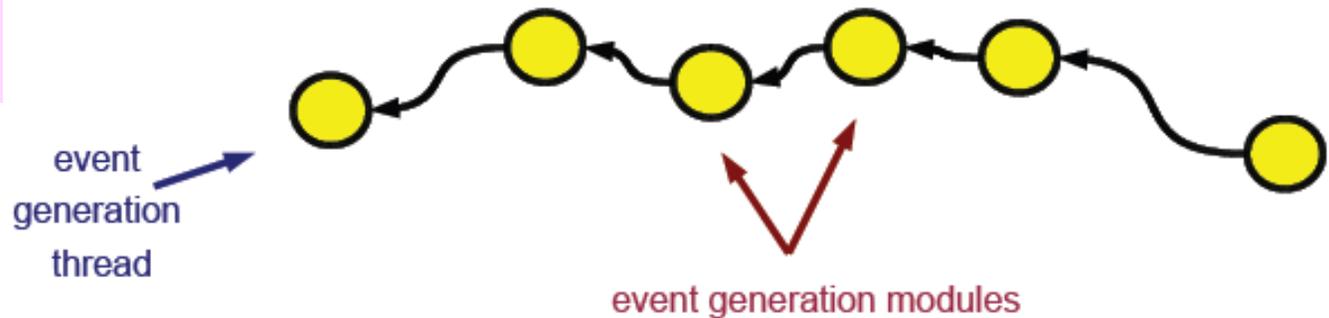
NOMAD, ICARUS...

**NUX** (A.Rubbia et al.)

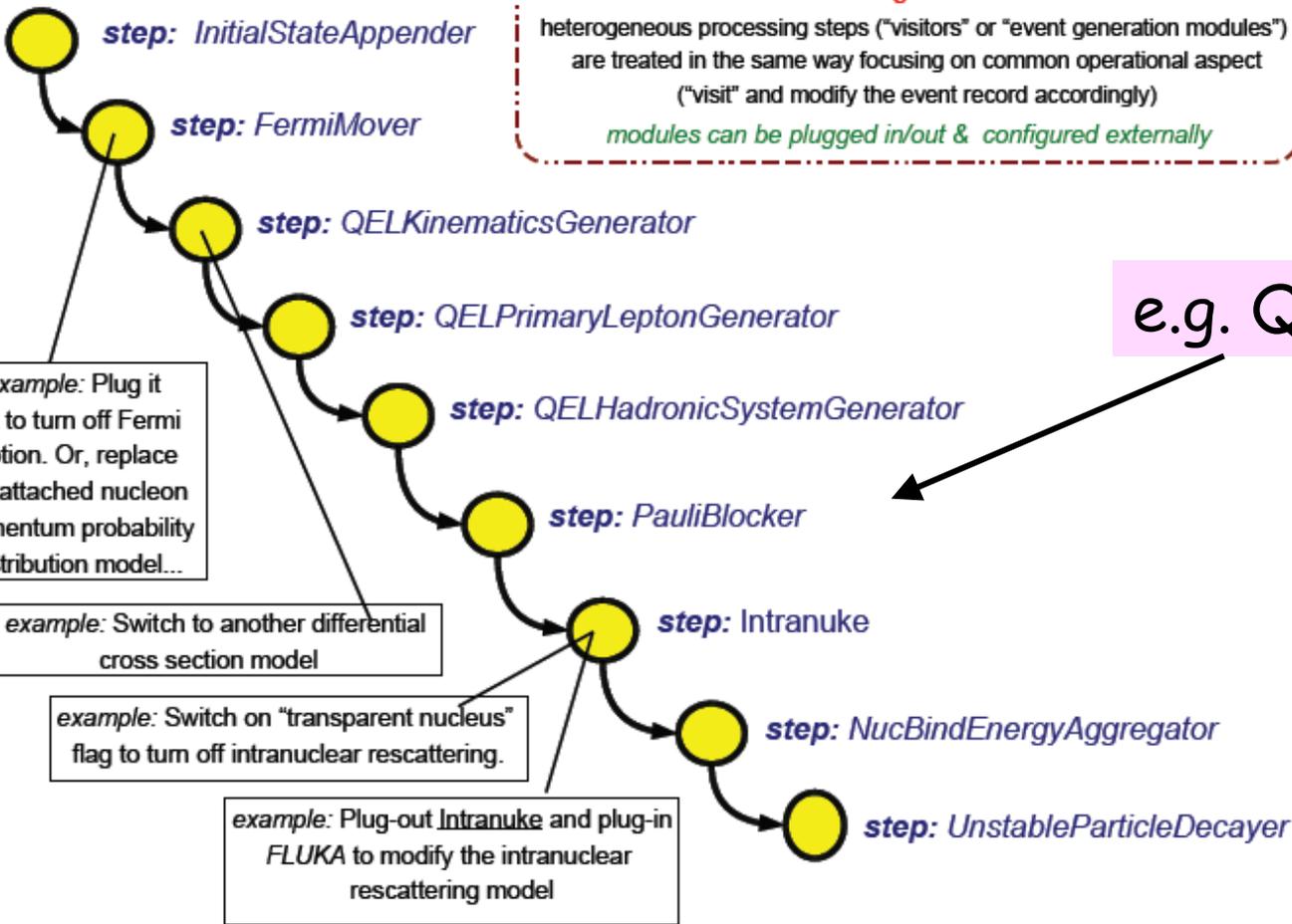
support GENIE & contribute towards its development.

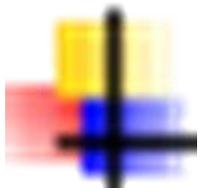
- Entire code is written in C++, 400 classes in ~40 packages
- Standalone event generator
- output in GEANT, GHEP (STDHEP-like) event record format
- ~50 events/sec (3 GeV) generated on 1.4 GHz cpu
- Has hooks for
  - ✓ neutrino flux packages (3 packages linked so far)
  - ✓ GEANT/ROOT geometry drivers
- It can be an essential part of specific experiment MC generation
  - ✓ v2.0.0 will soon become the default MINOS event generator

# Flexible code construction!!



**the essence of GENIE event generation software abstraction!**  
heterogeneous processing steps ("visitors" or "event generation modules") are treated in the same way focusing on common operational aspect ("visit" and modify the event record accordingly)  
modules can be plugged in/out & configured externally

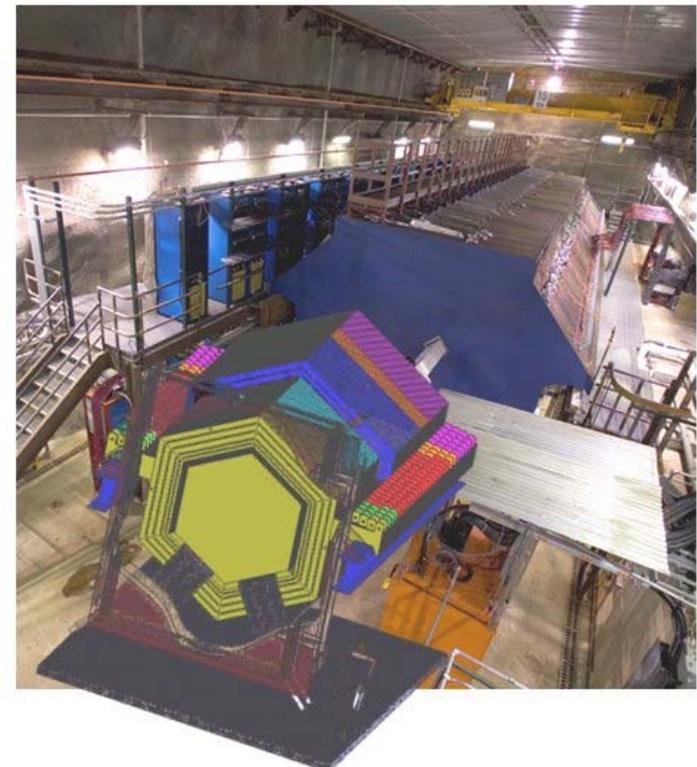
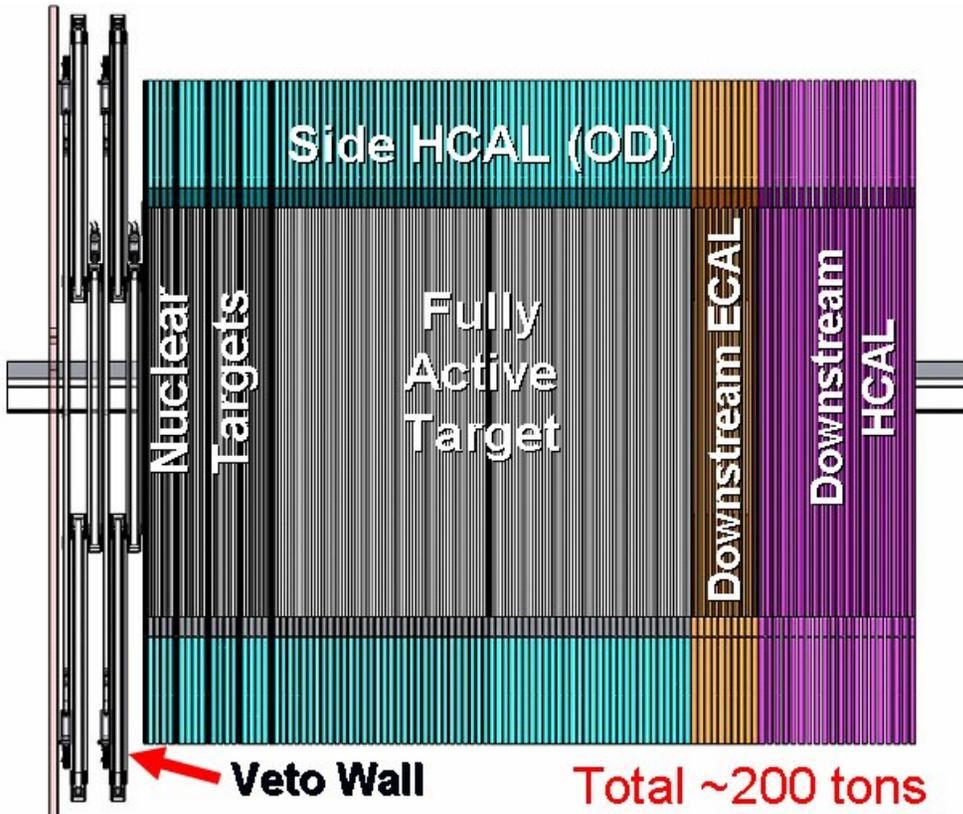


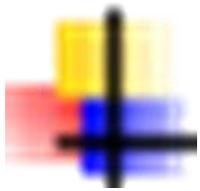


# The future

S. Dytman  
Sep. 8, 2006

So, why were there no comparisons with  $\nu$ -nucleus data?  
There isn't much of it, MINER $\nu$ A will be the answer.  
One of the keys will be having models to help oscillation expts.





# Summary

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S. Dytman  
Sep. 8, 2006

- Neutrino event generators required
  - ✓ Focuses attention on low energy processes
  - ✓ FSI is a key
  - ✓ Hadron-nucleus cross sections important
- Nuint is excellent series to focus on this work
  - ✓ Nuint07 at FNAL will continue model comparisons
- New data required (MINERvA)