Recent improvements of the neutrino interaction simulation programs neut & GENIE

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About GENIE,
Prof. S. Dytman (Univ. Pittsburg)
prepared the slides

1. Introduction

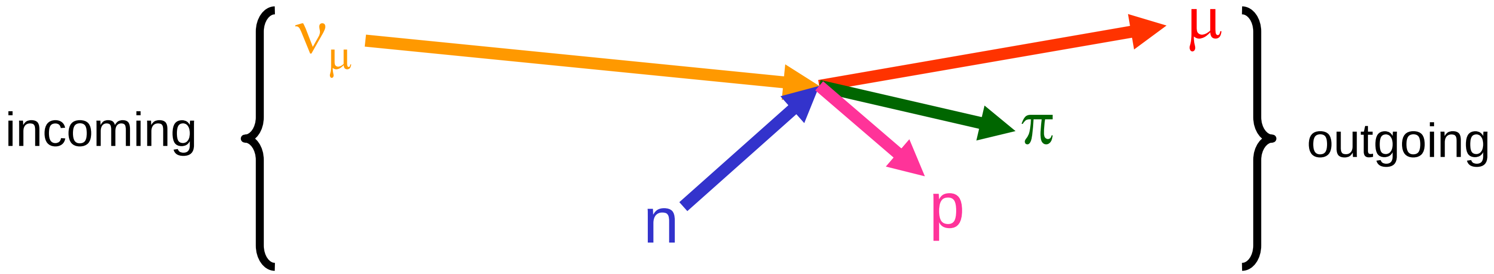
Simulate primary interaction

Fix the number of particles and types in the finals state

Fix 4-momenta (direction) of each particle.

Example) single π production

Input : Use fixed neutrino energy and direction in step 1).

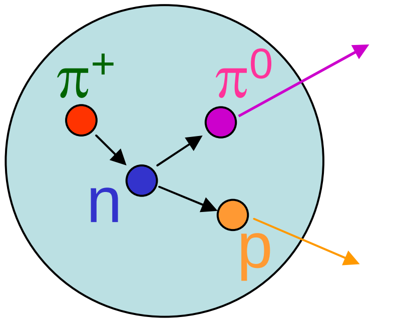


Simulate secondary interaction in nucleus

Simulate hadron interactions in the target nucleus and fix the properties of each particle outside of the target nucleus.

Example) π charge exchange interaction in nucleus

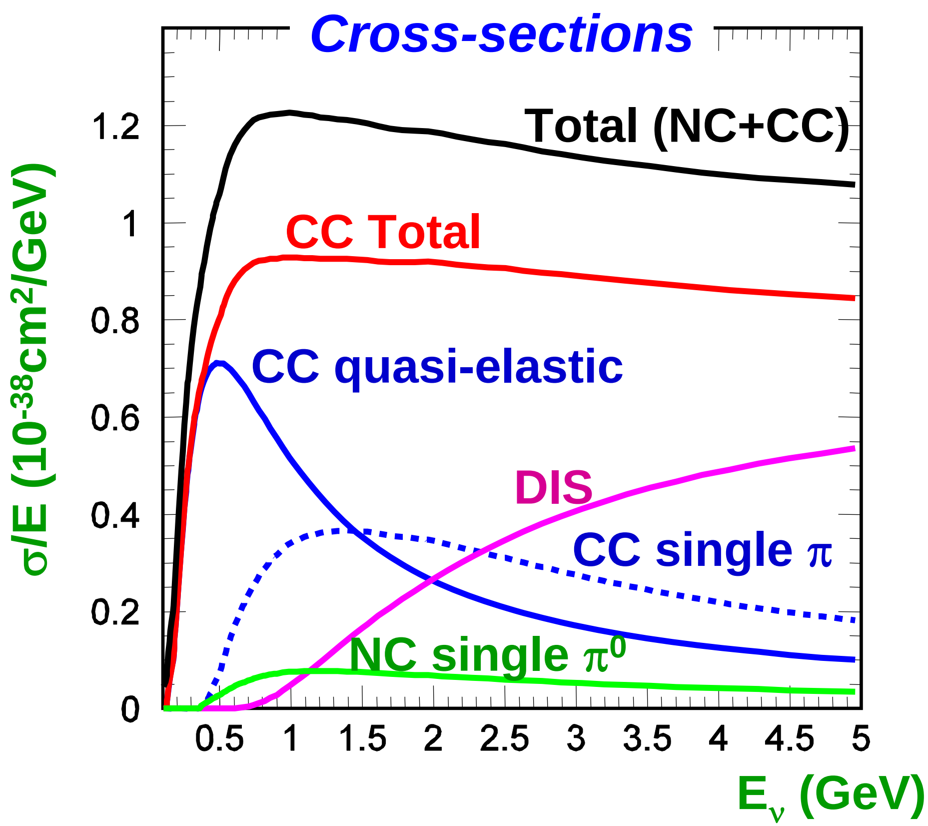
Trace generated hadrons in nucleus until the particles exit from the nucleus.

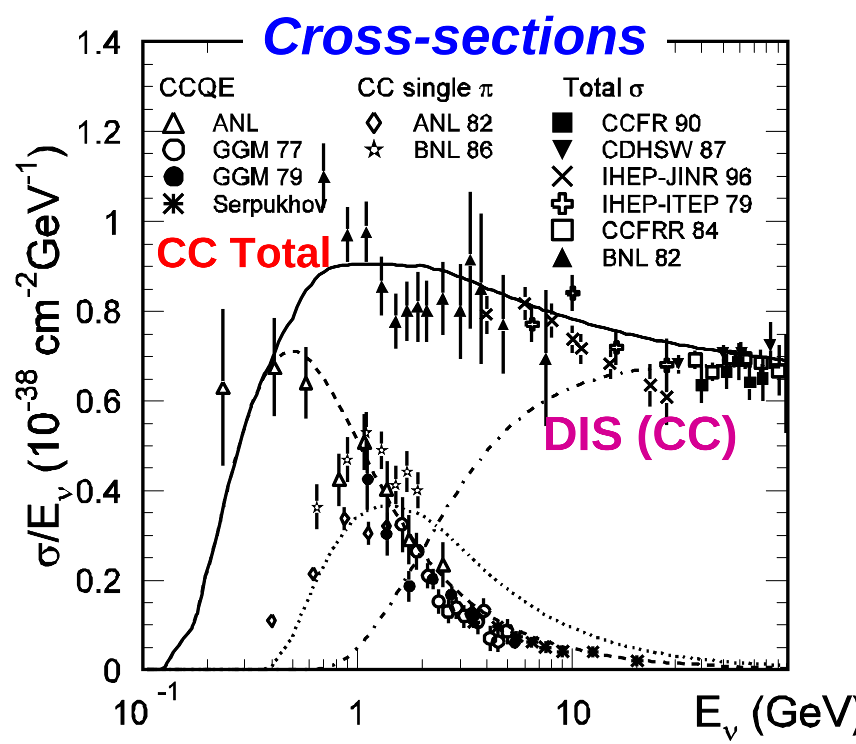


1. Introduction

Charged current quasi-elastic scattering	$\nu_\mu + n \rightarrow \mu^- + p$
Neutral current elastic scattering	$\nu_\mu + N \rightarrow \nu + N$
Single π,η,K resonance productions	$\nu_\mu + N \rightarrow l + N' + \pi\ (\eta, K)$
Coherent pion productions	$\nu_\mu + X \rightarrow l + X' + \pi$
Deep inelastic scattering	$\nu_\mu + N \rightarrow l + N' + m\pi(\eta, K)$

(l : lepton, N,N' : nucleon, m : integer)





1. Introduction ~ What NEUT does

- Neutrino energy range : ~ 100MeV to ~ TeV
- Target nucleus : primarily proton and Oxygen and Carbon.
  Support the other nucleus in the code.
  (interpolation / extrapolation for those nucleus)

- Provide cross-sections to estimate the interaction rates
  or to select the interaction mode.
- Simulates primary neutrino interaction
  with nucleon and nucleus targets.
  Simulate emission of gamma from the excited state.
  (only for Oxygen at this moment)
- Simulates meson interactions in the target.
  Especially in detail for the low momentum pions.
- Simulates nucleon re-scattering in the target nucleus.

Summary of the updates in NEUT

1) Neutral current elastic scattering cross-section
2) Gamma ray emission from the nuclei (de-excitation)
3) π interactions in nuclei
4) Nucleon ejection after π absorption

Currently, 1) and 2) are for Oxygen only
(Basically, relevant for the Super-Kamiokande)

2. Importance of neutral current elastic scattering

Supernova Relic Neutrino (SRN) detection

The γ-rays from Atmospheric NC ν-O interactions at high energy may make serious background in 5-20 MeV region.

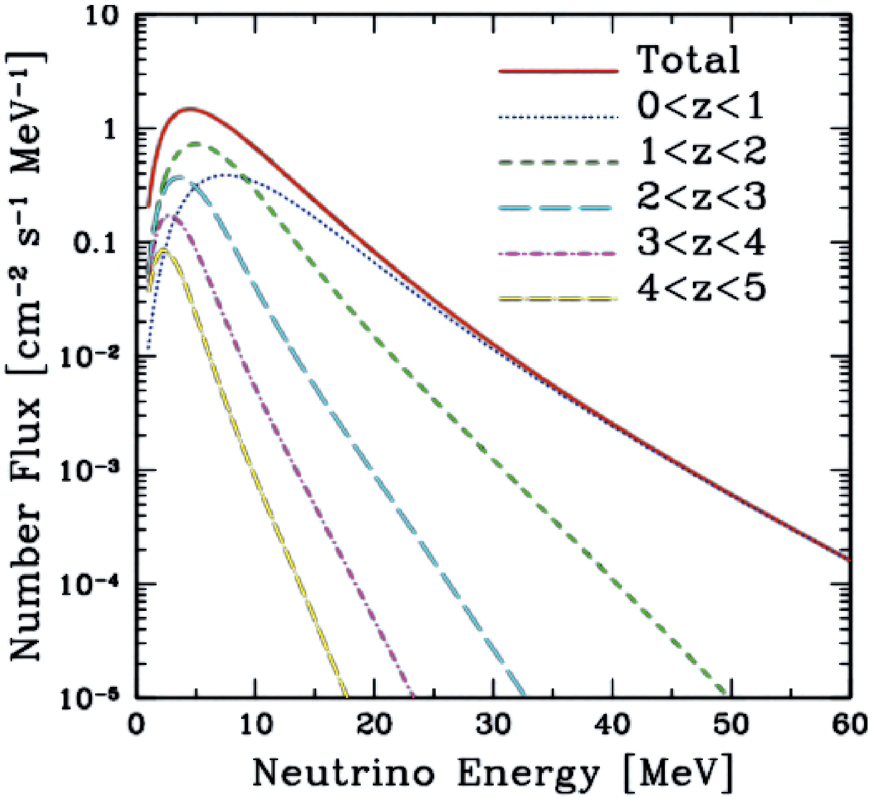
$$\nu + O \rightarrow \nu + p + N^* \quad (N^* \rightarrow \gamma)$$

$$\nu + O \rightarrow \nu + n + O^* \quad (O^* \rightarrow \gamma)$$

Energy of γ a few ~ 20 MeV

To estimate background rate, necessary to know

NC elastic cross-section and emission probability of γ.



Ando, *Astrophys. J.* **607**, 20 (2004)

3. Update of neutral current elastic scattering

Previous version of NEUT used rather rough approximation for the neutral current elastic scattering cross-sections.

- Update 1 : Use correct form factors and calculate NC elastic cross-sections.

$$\left(F_1^V\right)^{NC} = \frac{1}{2} F_1^V - 2\sin^2\theta_W F_1^N \qquad F_N^{NC} = \pm \frac{1}{2} F_A \qquad \begin{array}{l} +: proton, \\ -: neutron \end{array}$$

$$\left(F_2^V\right)^{NC} = \pm \frac{1}{2} F_2^V - 2\sin^2\theta_W F_2^N \qquad F_p^{NC} = 2M^2 \frac{F_A^{NC}}{\left(M_\pi^2 + Q^2\right)} \qquad N = p, n$$

- Update 2 : Vector form factor ~ Latest one ~

BBBA05

$$G(Q^2) = \frac{\sum_{k=0}^{2} a_k \tau^k}{1 + \sum_{k=1}^{4} b_k \tau^k} \qquad \tau = \frac{Q^2}{4M^2}$$

R.Bradford et al., Nucl. Phys. Proc.Suppl.159:127-132 (2006).

Previous NEUT's calculation

- $\sigma_{NC}(\nu p \rightarrow \nu p) = 0.153 * \sigma_{CC}(\nu n \rightarrow \mu^- p)$
- $\sigma_{NC}(\bar{\nu} p \rightarrow \bar{\nu} p) = 0.218 * \sigma_{CC}(\bar{\nu} p \rightarrow \mu^+ n)$
- $\sigma_{NC}(\nu + n) = 1.5 * \sigma_{NC}(\nu + p)$
- $\sigma_{NC}(\bar{\nu} + n) = \sigma_{NC}(\bar{\nu} + p)$

3. Update of neutral current elastic scattering

- Update 3 : Spectrum function

Nuclear medium correction ~ for ν - ^{16}O cross-section

Impulse approximation

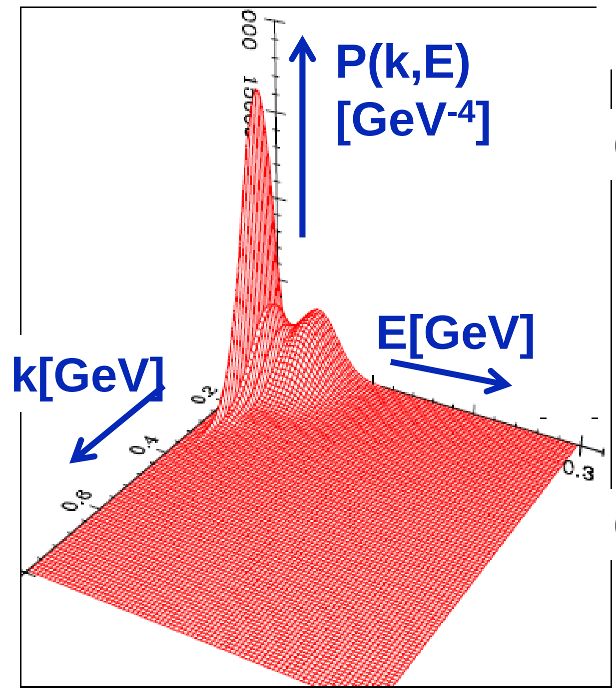
$$\frac{d\sigma_{\nu A}}{d\varpi d\Omega} = \int d^3 dE P(\vec{p},E) \frac{1}{4 p_o p'_o}\left(\frac{d\sigma_{\nu N}}{d\varpi d\Omega}\right)$$

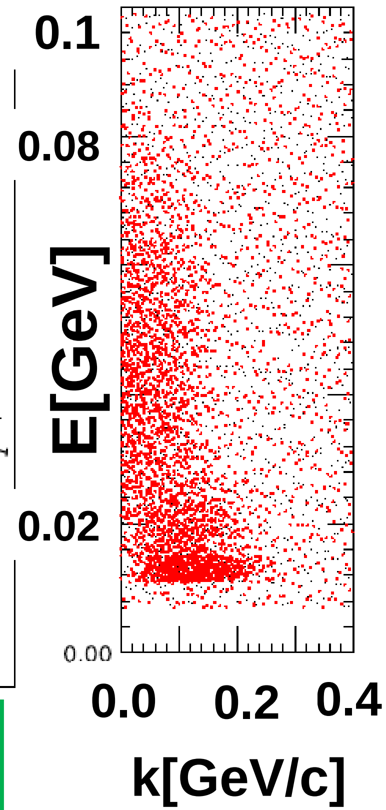
Spectrum function

Probability of removing a nucleon of momentum p from ground state leaving the residual nucleus with excitation energy E.

Use Spectral Functions P(p,E) by Benhar et al. based on the experimental data (mainly taken in at JLAB).

Spectrum function





k: Momentum
E: Binding energy

O.Benhar et al., Phys. Rev. D 72, 053005 (2005).

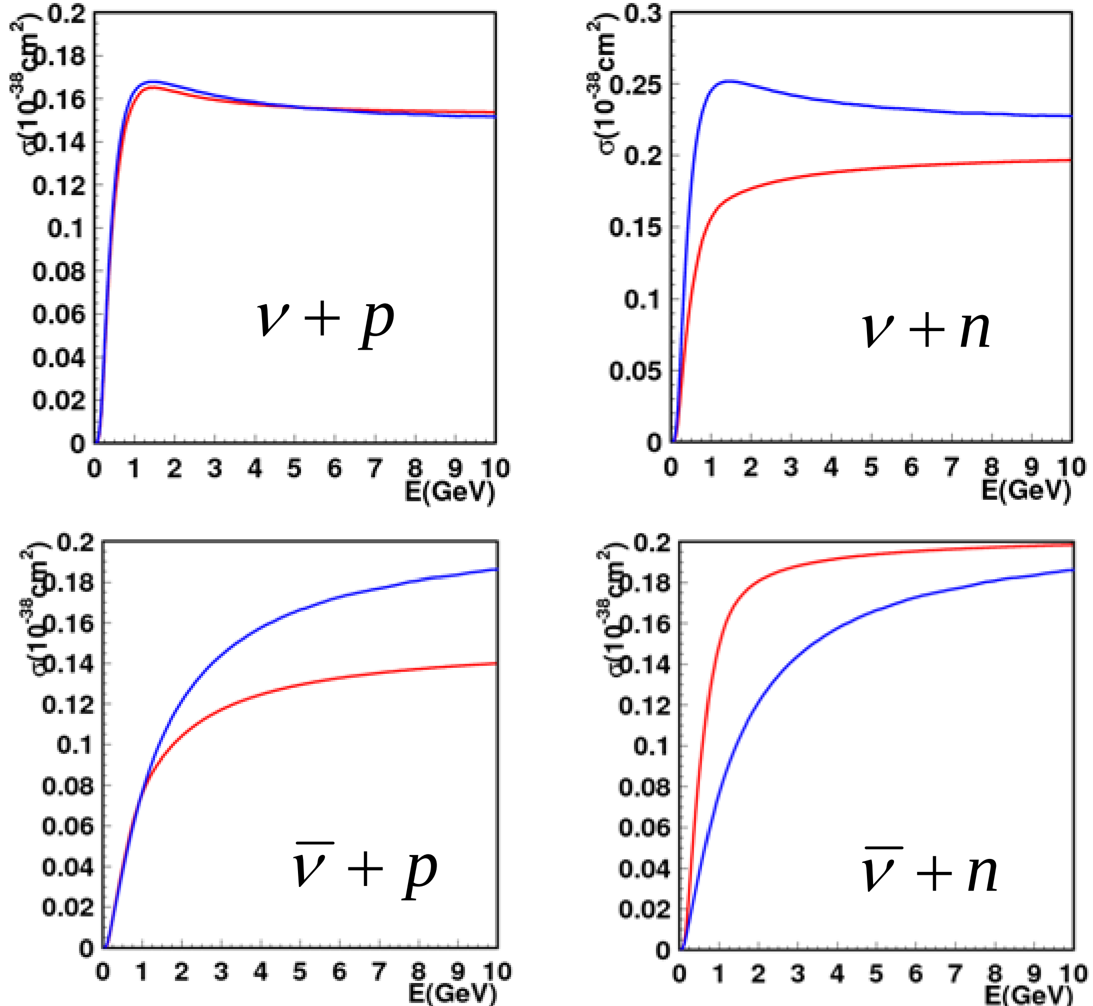
3. Update of neutral current elastic scattering

Comparisons between new and old cross-sections

ν – N cross-sections in Oxygen

NEW

OLD



ν + p is quite similar.
But the other modes has
20 ~ 40% differences.

(* usually, we quote ~ 50% error on these interactions)

Because of the technical difficulty,
currently, this new implementation is used only for Oxygen.

4. Gamma ray emission from excited Oxygen

- Update 1 : Spectroscopic strengths of each state

Recent result from (e,e'p) experiment (PRD72, 053005), p3/2 and s1/2-hole states were both found to have smaller spectroscopic strength than the theoretical predictions (a shell model calculation).

	Shell model	**LDA (PRD72,053005)**
p1/2 (ground state)	0.25	0.165
p3/2 (6.32 MeV)	0.41	0.343
s1/2	0.25	0.123

4. Gamma ray emission from Oxygen

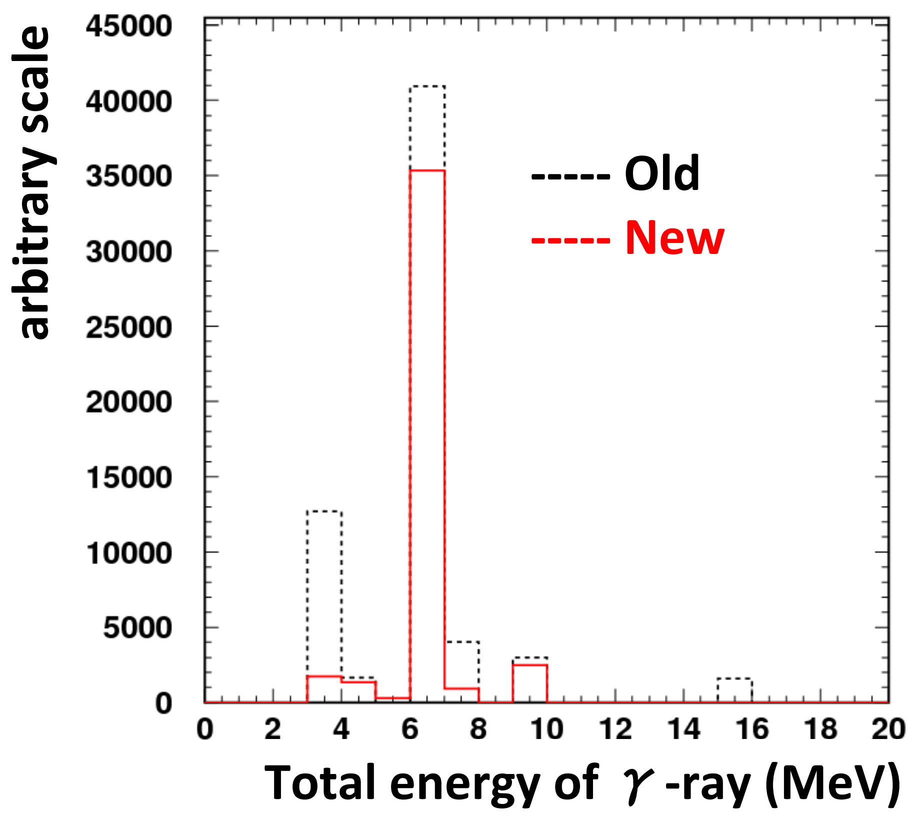
- Update 2 : distribution of energy level （γ energy)

Previous versions used the table from theoretical calculations.

Also, some misinterpretations were found and the probability to have 15.1MeV γ were close to 0 in the new version.

Update based on the experimental data.

Decay scheme	Energy level MeV (J^π)	γ-ray energy MeV (ratio)	$N(k)/N_{tot}$
^{13}C+d	3.09 ($1/2^+$)	3.09 (100%)	3.0%
^{13}C+d	3.68 ($3/2^+$)	3.68 (99.3%)	4.2%
^{13}C+d	3.85 ($5/2^+$)	3.09 (1.20%) 3.68 (36.3%) 3.85 (62.5%)	4.6%
^{12}C+t	4.44 (2^+)	4.44 (100%)	5.8%
^{14}N+n	4.92 (0^-)	4.92 (97%)	5.2%
^{14}N+n	5.11 (2^-)	5.11 (79.9%)	0.0%
^{14}N+n	5.69 (1^-)	3.38 (63.9%) 5.69 (36.1%)	4.5%
^{14}N+n	5.83 (3^-)	5.11 (62.9%) 5.83 (21.3%)	0.54%
^{14}N+n	6.20 (1^+)	3.89 (76.9%) 6.20 (23.1%)	0.0%
^{14}N+n	6.45 (3^+)	5.11 (8.1%) 6.44 (70.1%)	2.8%
^{14}N+n	7.03 (2^+)	7.03 (98.6%)	(6.7%)
^{14}C+p	6.09 (1^-)	6.09 (100%)	(0.0%)
^{14}C+p	6.59 (0^+)	6.09 (98.9%)	(0.0%)
^{14}C+p	6.73 (3^-)	6.09 (3.6%) 6.73 (96.4%)	0.43%
^{14}C+p	6.90 (0^-)	6.09 (100%)	(0.0%)
^{14}C+p	7.01 (2^+)	6.09 (1.4%) 7.01 (98.6%)	(6.7%)
^{14}C+p	7.34 (2^-)	6.09 (49.0%) 6.73 (34.3%) 7.34 (16.7%)	5.7%



4. Gamma ray emission from Oxygen

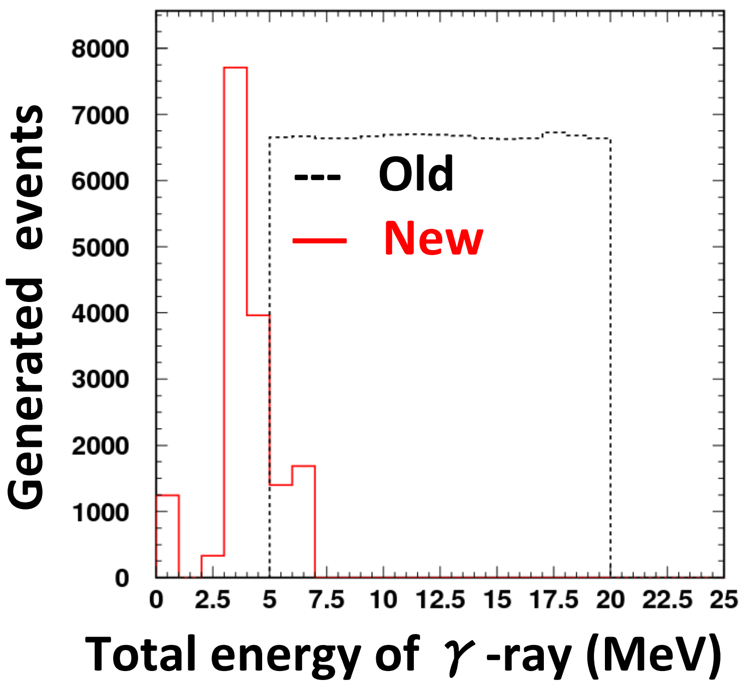
- Update 3 : γ emission after π absorption

In the previous version,
probability and energy determination of γ emission after the π absorption was flat from 5 to 20 MeV.

Updated to use the experimental data (*H.D.Engelhardt et al., NPA258, 480 (1976)*)

Prompt γ-ray transition yields and isotopic yields of the reactions induced by stopped π^- on ^{9}Be, ^{10}B and ^{16}O

Target nucleus	Energy range (keV)	Residual isotope	Transition (keV)	Branch (%)	J^π	τ (psec)	Measured energy (keV)	Transition yield (%)	Isotopic yield (%)
^{9}Be	300– 6000								
^{10}B	100–17000	^{7}Li	477 → 0	100	$\frac{1}{2}^-$		478	1 7±0 4	1 7
^{16}O	300– 8000	^{16}O*	6131 → 0	100	3^-	24	6133	1 7±0 3	1 7
		^{15}N	5270 → 0	100	$\frac{5}{2}^+$	2 9	5268	0 5±0 2	0 5
		^{14}N	2313 → 0	100	0^+	8 5 × 10^{-2}	2314	5 3±0 6	6 4
			3945 → 2313	96	1^+	4 5 × 10^{-3}	1634	4 8±0 9	
			5106 → 0	80	2^-	12	5106	0 7±0 2	
			5106 → 2313	20	2^-	12	2794	0 2±0 1	
		^{14}C	6728 → 0	93	3^-	97	(6728)	<0 2	<0 2
		^{13}C	3684 → 0	100	$\frac{3}{2}^-$	1 5 × 10^{-3}	3682	1 9±1 0	2 9
			3854 → 0	62	$\frac{5}{2}^+$	11	3853	1 0±0 3	
		^{12}C	4439 → 0	100	2^+	5 6 × 10^{-2}	4436	4 0±1 3	4 0
		^{10}B	717 → 0	100	3^+	1 01 × 10^3	717	1 3±0 3	1 3

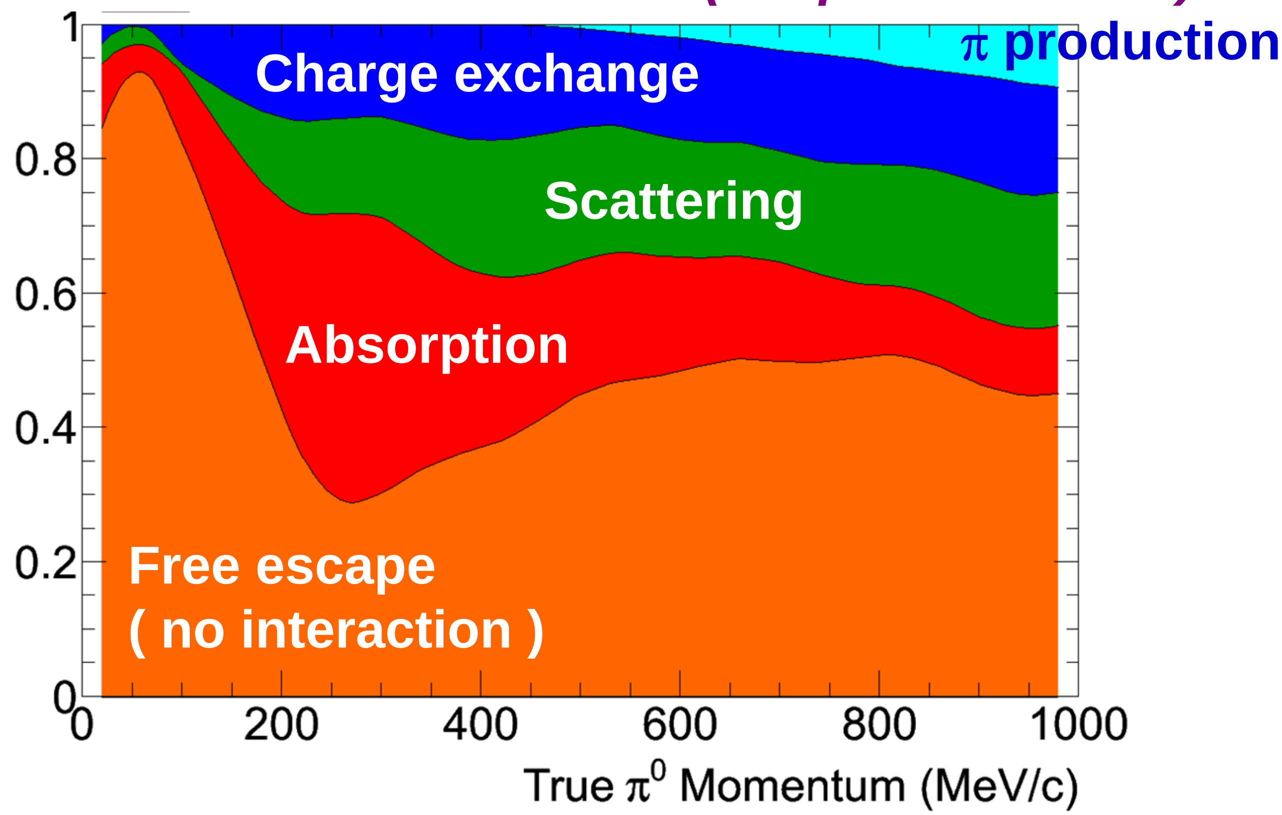


5. Importance of the final state interactions of the generated pions and nucleons

Large interaction probability of π

→ π from the *neutrino interactions* or *nucleon decay* will not be observed as generated.

Interaction probability of π^0 generated in Oxygen
(output from neut)



6. Implementation of the final state interaction in NEUT

Semi-classical cascade model

step π through the nucleus

and calculate the probability of interaction

using the mean free paths (MFP) at each point.

π may undergo multiple interactions

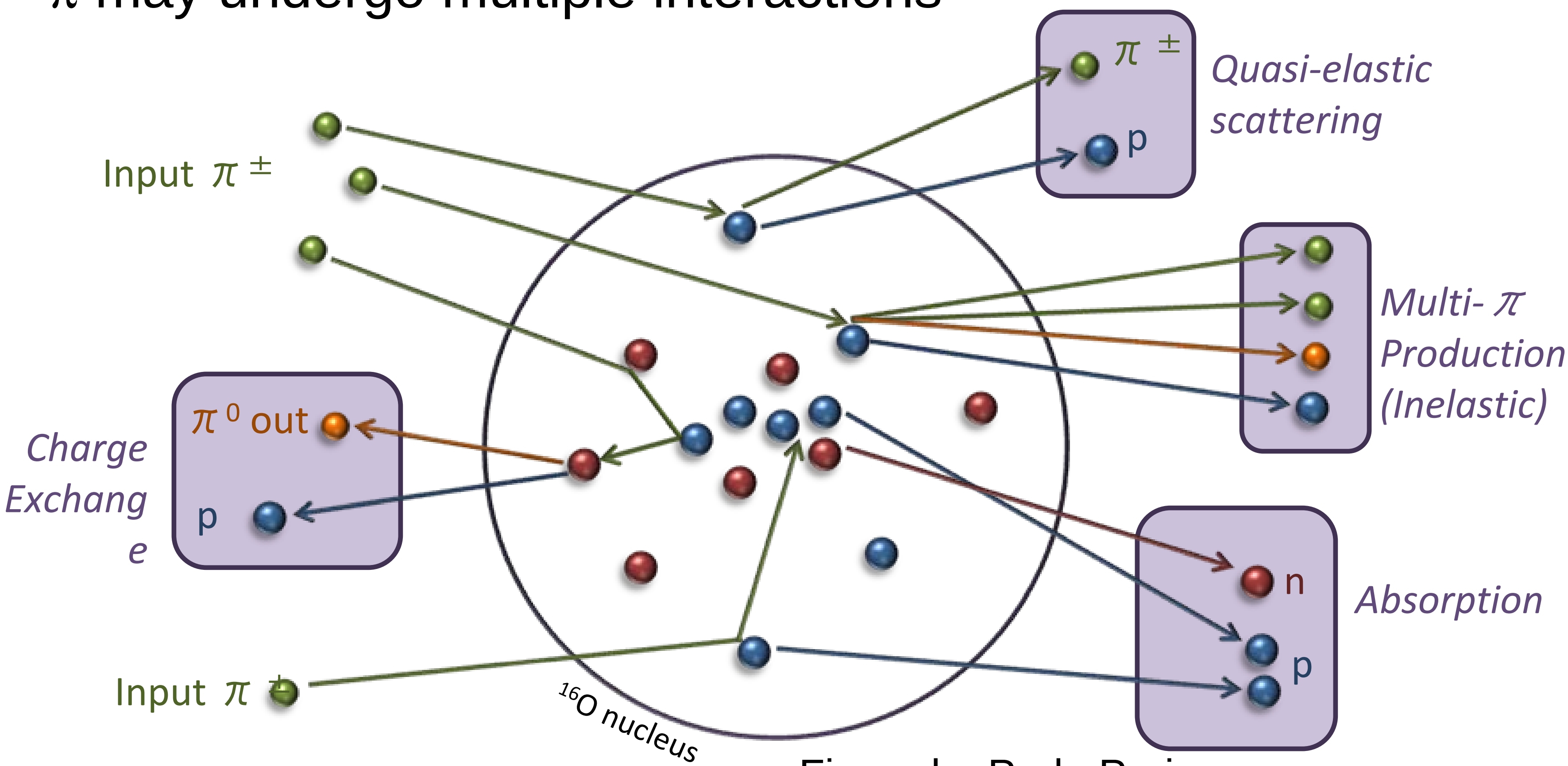


Figure by P. de Perio

7. Updates of the final state interaction in NEUT

For low momenta (p_{π} < 500 MeV/c)

Mean free paths

depend on Location (radius ~ density)

and momentum of π

calculated based on the model

by *Salcedo, Oset et al. (1988)*

Latest version

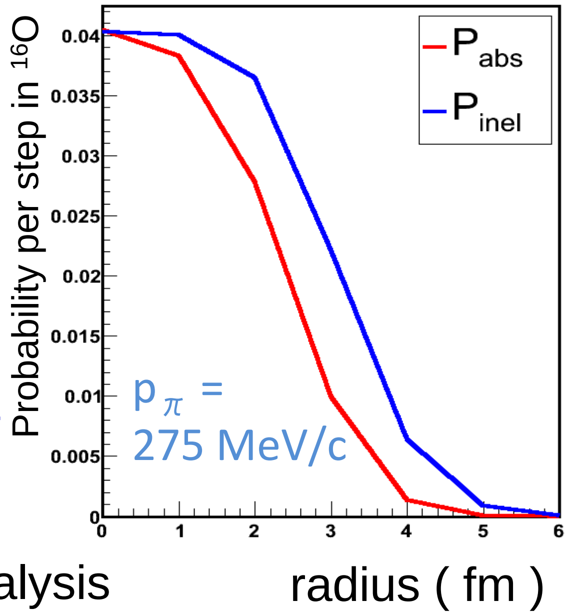
- Position (radius) dependence

  shape is same as previous

- Momentum dependence

  (absolute scale)

  fit the existing pi-N scattering data



note) Kinematics of pion

determined with the results of the phase shift analysis

of free nucleon by *Rowe et al. (1978)*

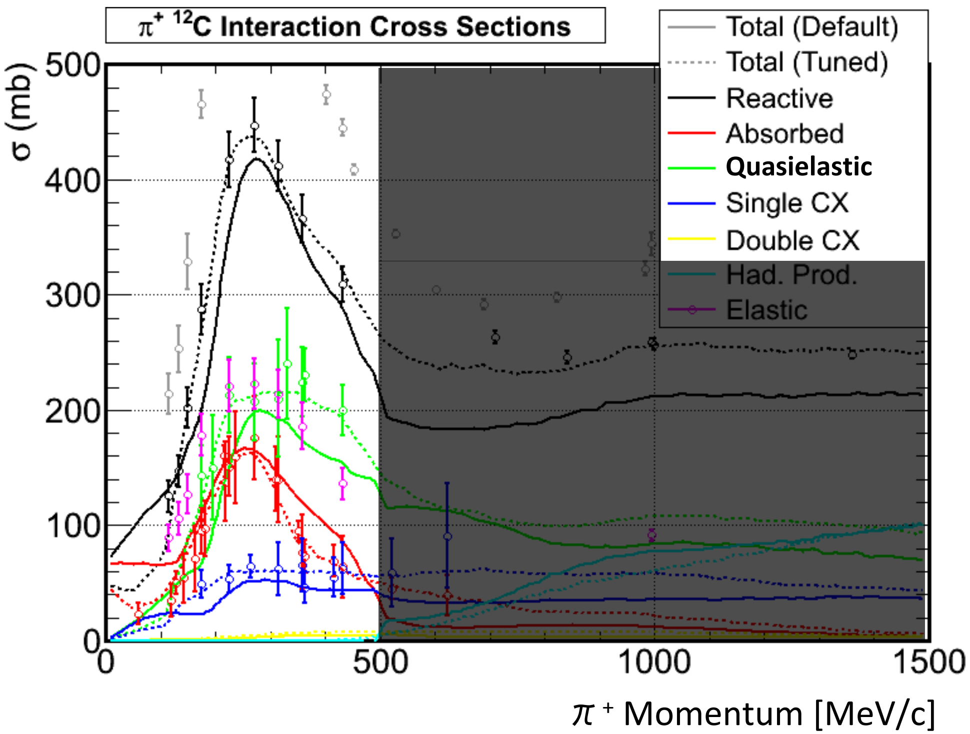
with in-medium corrections.

7. Updates of the final state interaction in NEUT

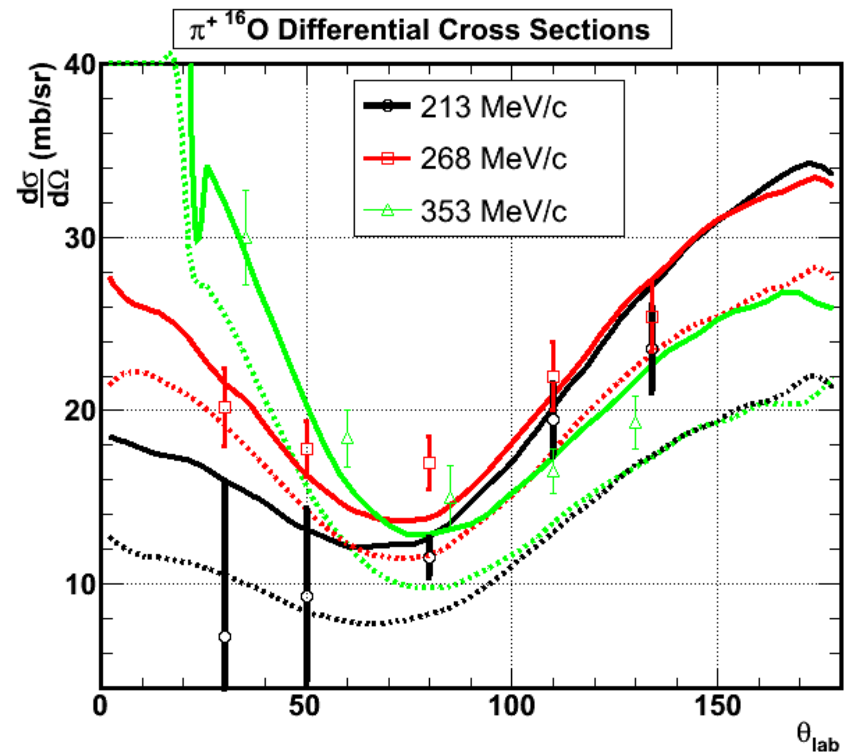
For low momenta (p_π < 500 MeV/c)

Comparisons with the data
before (old) and after the fit (new)

π^+ ^{12}C scattering
Interaction cross-sections



π^+ ^{16}O scattering
differential cross-sections



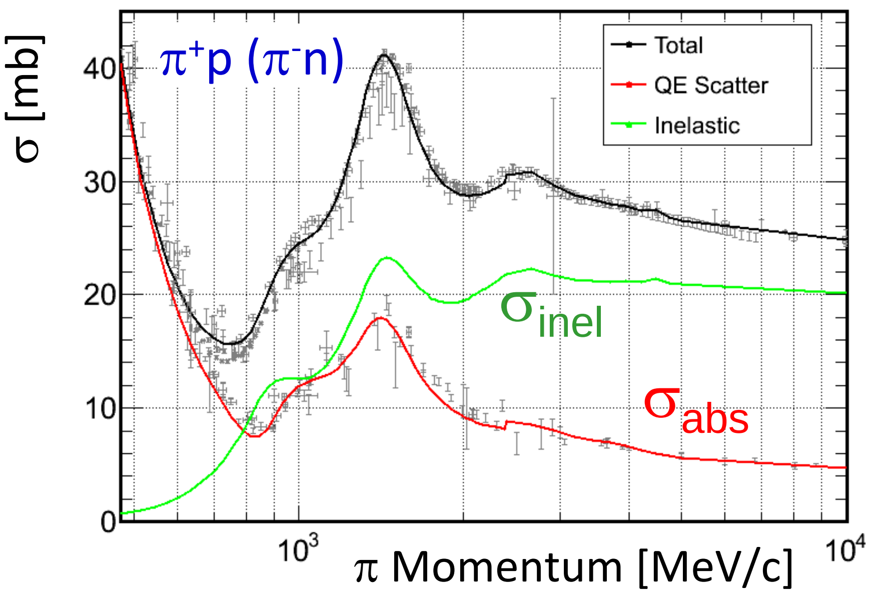
7. Updates of the final state interaction in NEUT

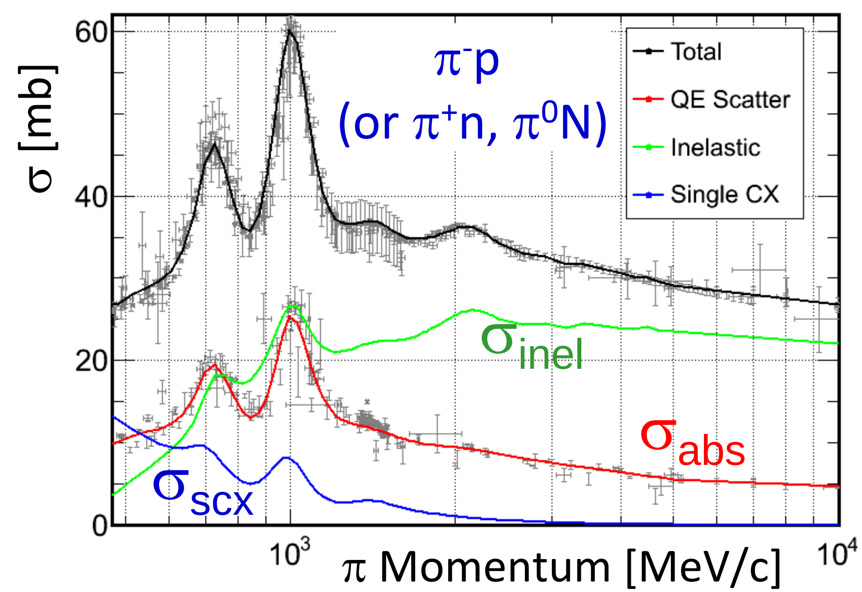
For high momenta (p_π > 500 MeV/c)

Interaction probabilities

Previous
- Mean free paths are evaluated using the old π-N & π-d experiments
- Assumed isoscalar target

New
- SAID PWA results are used for MFP w/corr. (**separately include single charge exchange)**
- p/n ratio of nucleus is used.



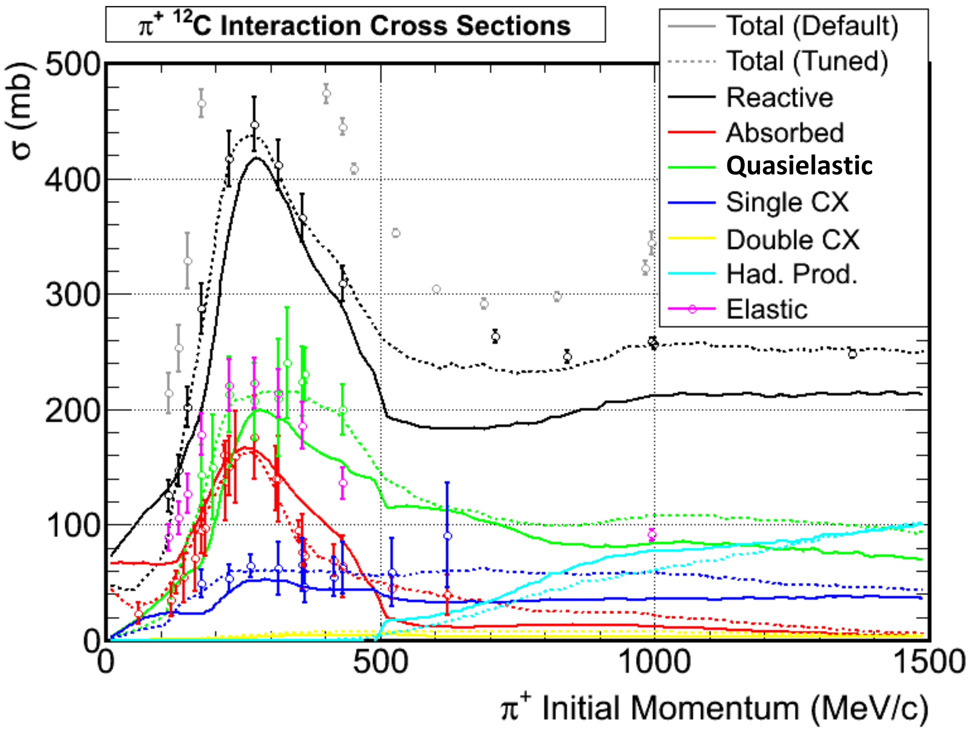


7. Updates of the final state interaction in NEUT

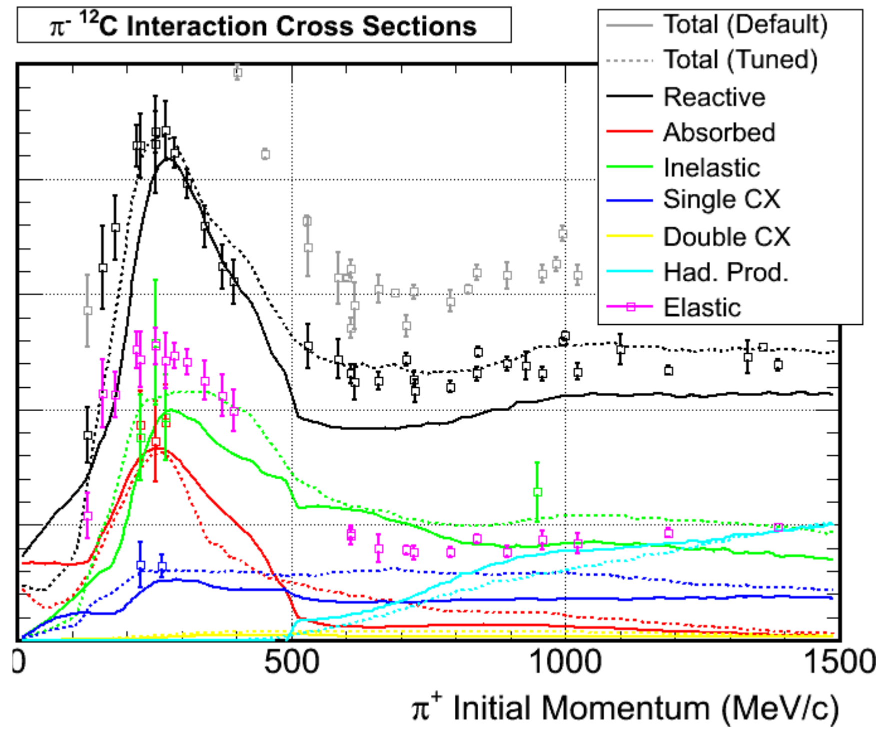
For high momenta (p_π > 500 MeV/c)

π – ^{12}C Cross-sections
(simulated by NEUT compared with data)

π^+ – ^{12}C Cross-sections



π^- – ^{12}C Cross-sections



7. Updates of the final state interaction in NEUT

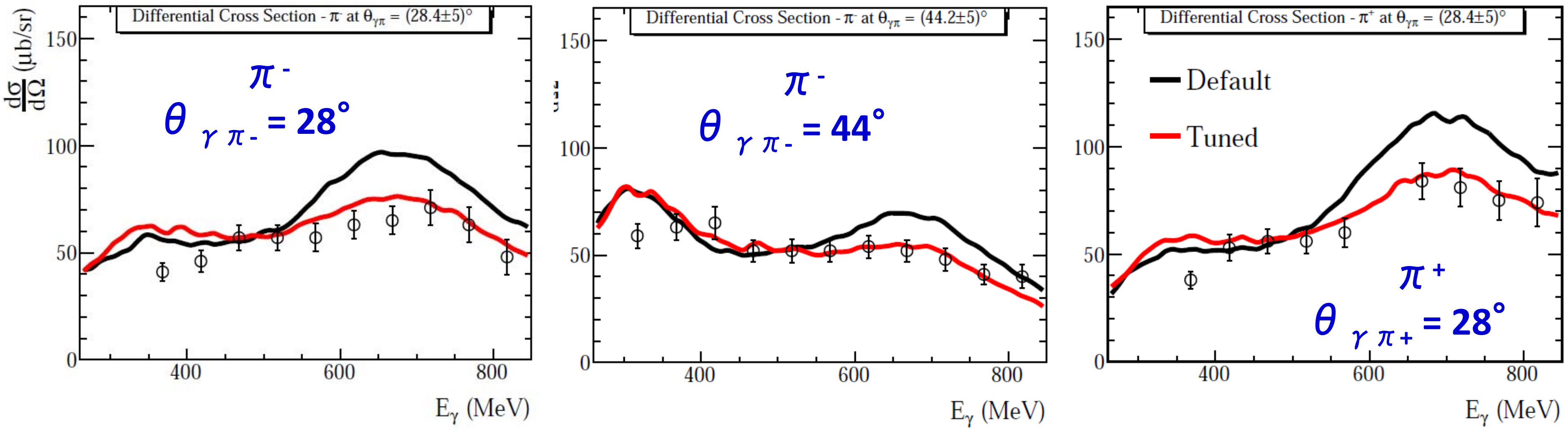
For high momenta (p_π > 500 MeV/c)

Kinematics determinations

Previous	elastic scattering + particle productions
New	SAID PWA results (contains resonance < 2GeV/c^2) + elastic scattering + particle productions

Comparison between data and NEUT (photo π production)

data: ^{12}C (γ, π) X from Baba et al., Nucl. Phys. A306 292 (1978)



7. Updates of the final state interaction in NEUT

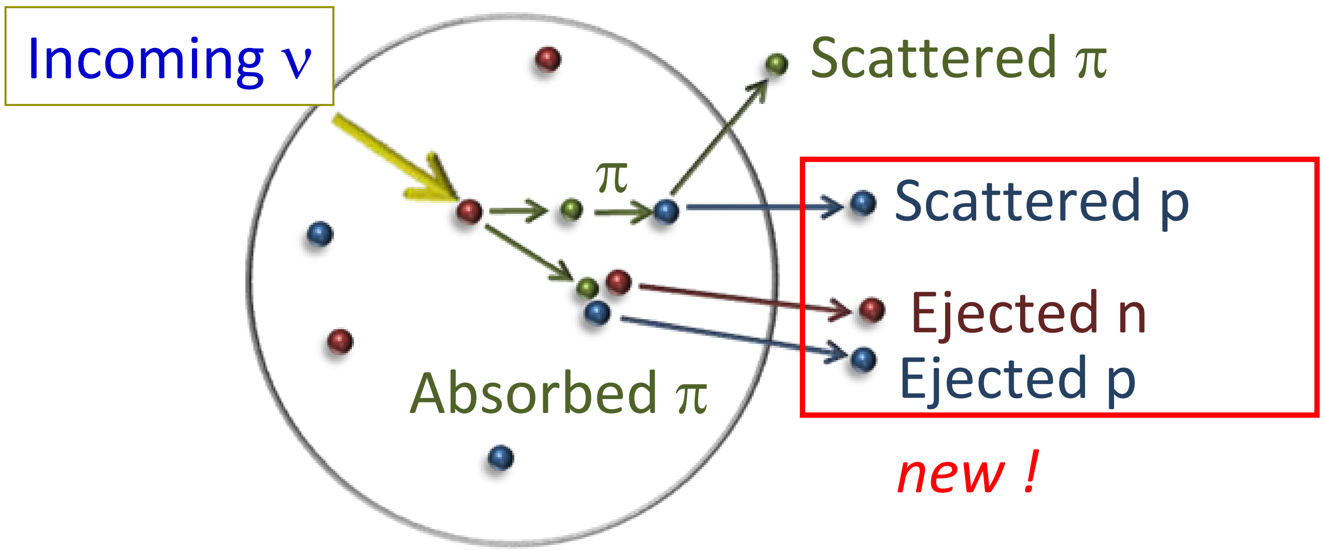
Implementation of nucleon ejection after π interactions

Before the update,

pion is just absorbed

and no additional particles were generated.

Nucleon ejection after the pion interaction is now simulated



Observed as vertex activities

→ Important to study neutrino interactions especially with full active detectors.

7. Updates of the final state interaction in NEUT

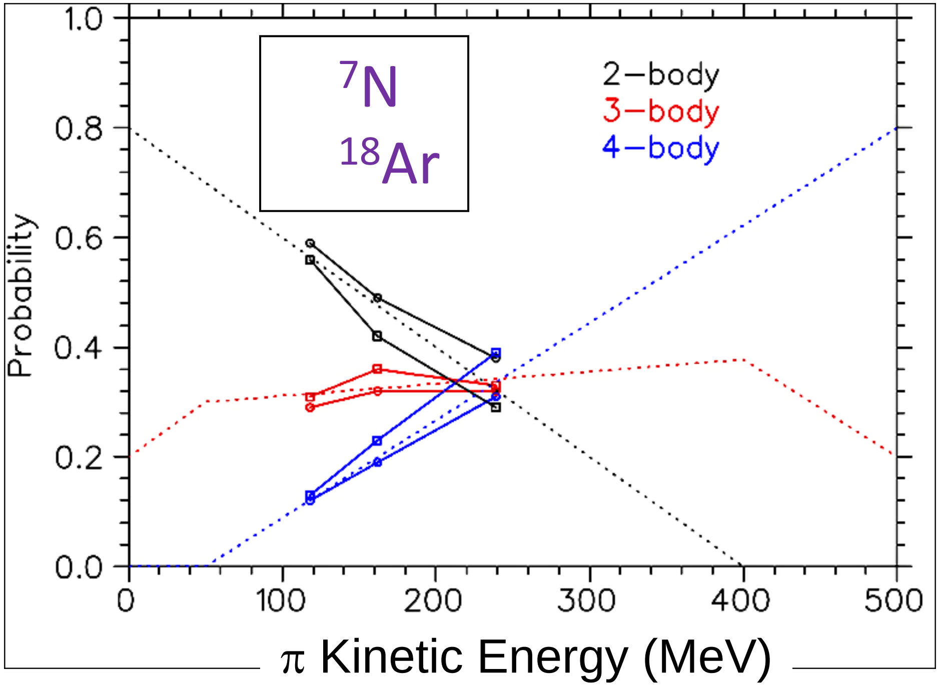
Implementation of nucleon ejection after π interactions

- Nucleon multiplicity and charge
  determined from π -nucleus absorption data.

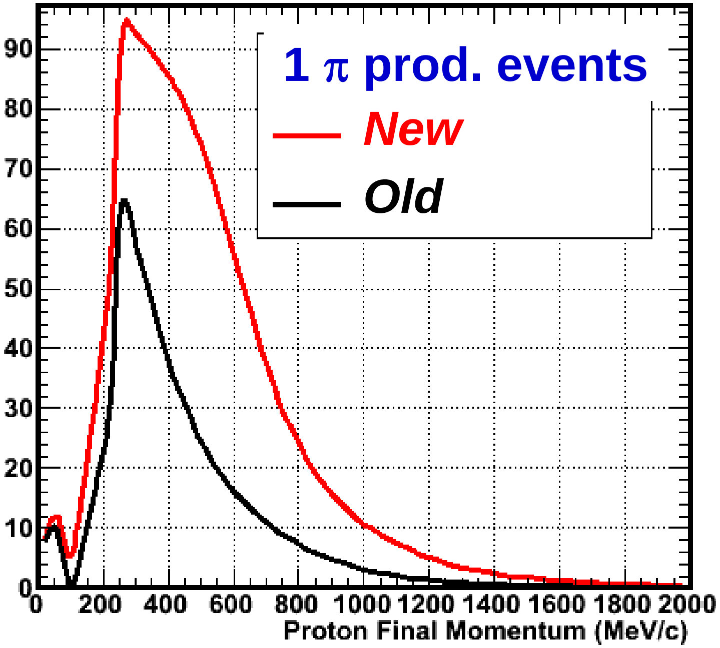
(*Rowntree et al. Phys. Rev. C60 (99) 054610*)

- Kinematics of particles are determined
  from π - d data (2 body) and phase space (>2 body).

(π – d data : Ritchie, Phys. Rev. C 44, 533)



example (# of protons in total)



8. Summary of the recent updates of NEUT

NEUT has been updated to be used
in the new experiment and physics analyses.

a) Nuclear gamma emission probability
and Neutral current elastic scatterings

Use Correct form factors and
introduce spectral function
to calculate total cross-section.

b) Final state interaction of pions

Use fitted (phenomenological) parameters
to have better agreements with data.

Nucleon ejection after pion interactions
is now simulated.

➡ Planning to compare with the agreements
with the recent data
(PIANO/HARPSHICORD experiments)
Also, T2K-near detector measurements.

Final State Interactions (FSI) in GENIE
July, 2011

Steve Dytman, Aaron Meyer
Univ. of Pittsburgh

- Brief introduction
- planning notes
- validation, comparisons
- summary

Introduction

- GENIE is a large-scale modern software project
  - Seeks to be ‘universal’ neutrino event generator
  - Costas Andreopoulos is main author, Hugh Gallagher and SD are senior authors; theorists are becoming significant contributors!
  - Many recent new experiments have chosen to use it
  - Simple models (INC, Fermi gas) must be used to cover so many processes in so many nuclei at such a wide energy range.
  - Neutrino expts depend critically on these codes, validation is important! (Ironically, still too little ν data!)
- These slides emphasize Final State Interaction (FSI) part of GENIE.
  - Construct models with important physics
  - Extensive validation against relevant data (hadron, EM beams)
  - Key to any experiment detecting hadrons

Basic outline

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

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

default

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

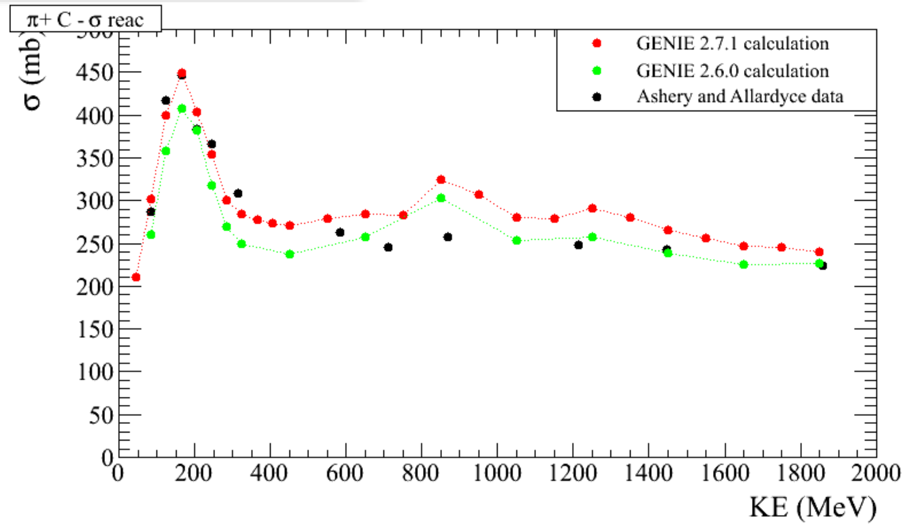
hN model
- Choose interaction according to list (data, models, intuition)
- Elas, CEX, π prod, abs, pre-eq
- Choose kinematics by PWA model
- Add particles to stack until all out.

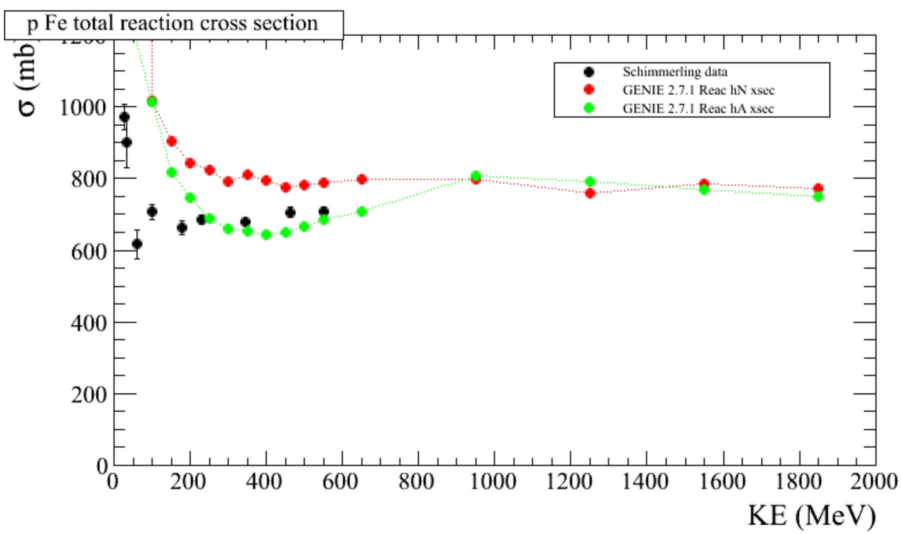
General characteristics

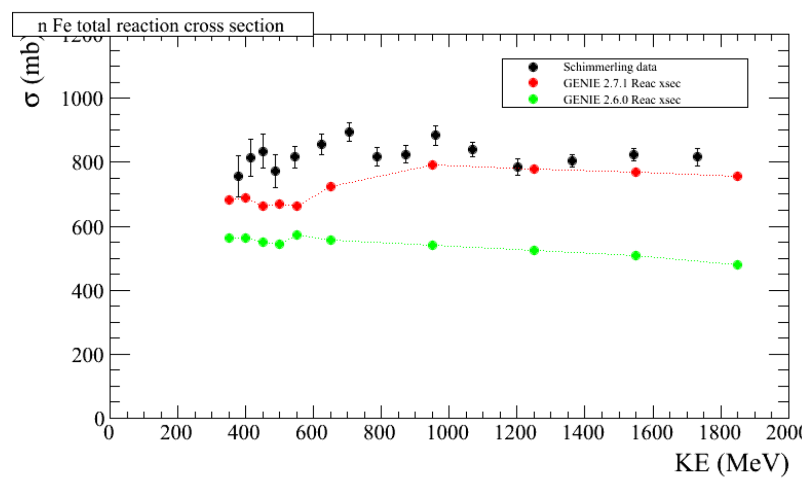
- Codes are Intranuclear Cascade (INC), real and inspired.
- hN is straightforward INC
  - Uses free 2- and 3-particle free cross sections + Fermi motion
  - Success comes from importance of quasielastic reaction mechanism in nuclear physics *and* existence of PWA data.
- hA is simplified INC
  - Construct models of full chain of events
  - Uses simple representations of hN code, data, and intuition.
  - Easily reweighted
  - New version has
    - better $\pi^+:\pi^-$,
    - better angle/energy distributions for inelastic scattering/absorption
    - Better n/p distributions for pion abs, nucleon knockout.

Validation 1
Total cross sections, esp. reaction

- $\sigma_{reac} = \sigma_{tot} - \sigma_{elas}$.
  $= \sigma_{cex} + \sigma_{inel} + \sigma_{abs} + \sigma_{\pi prod}$
- Makes significant change in topology of track.
- Sets overall FSI rate
- For hadrons, $\sigma_{reac} \sim \pi(1.3\text{fm} * A^{.33})^2$!

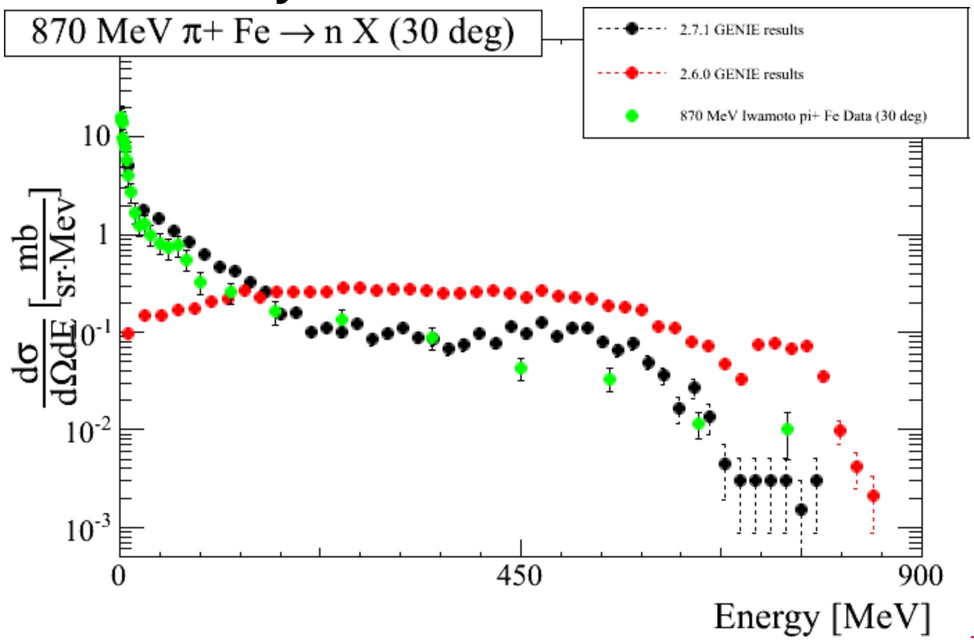


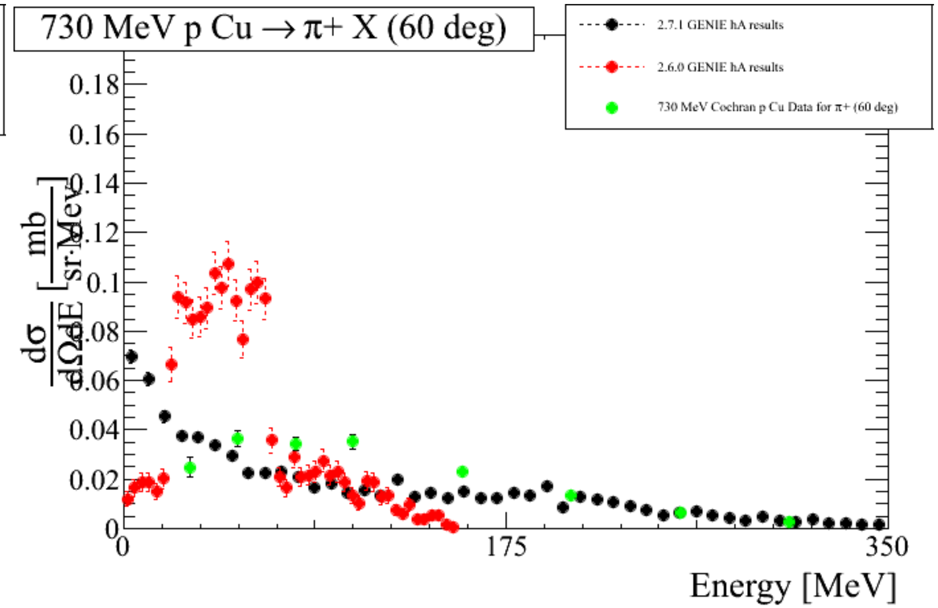




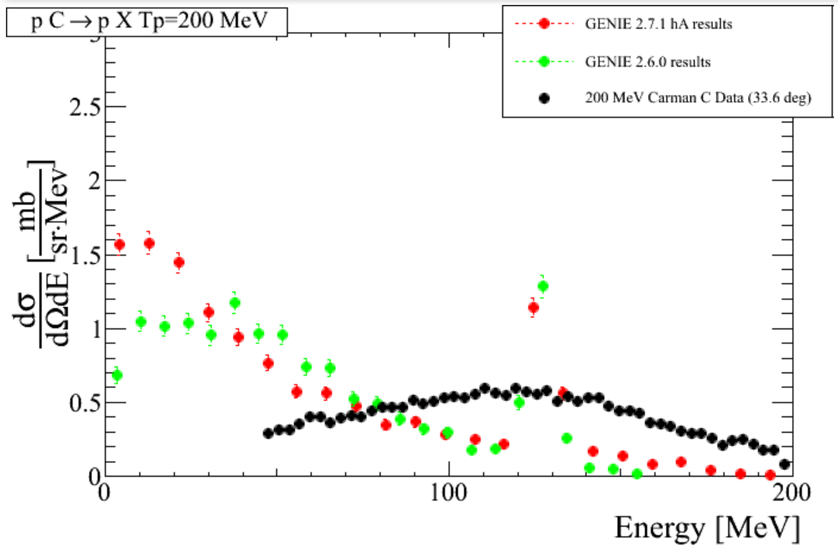
Validation 2: Inclusive Energy distributions specific beam energy, angle

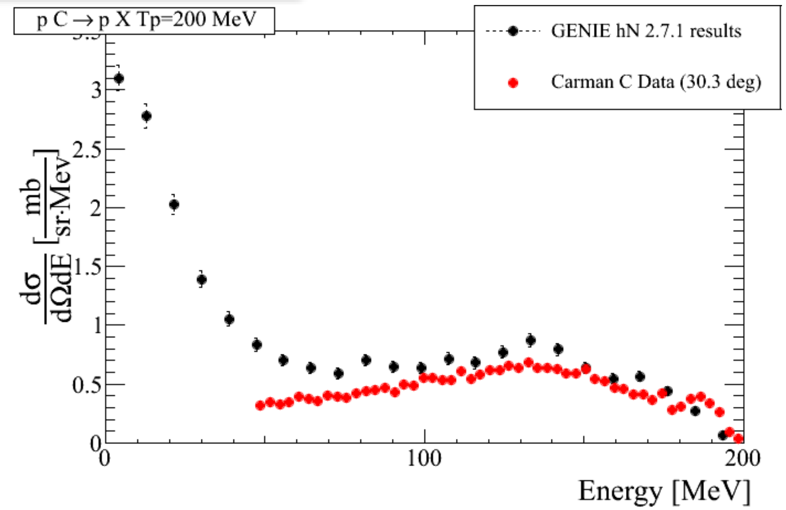
- Sums over all processes
- Quasielastic mechanisms (e.g. $\pi p \rightarrow \pi p$) dominate in light nuclei
- checks rate into specific directions by energy, type
- Here, emphasize $\pi \rightarrow N$ and $N \rightarrow \pi$ where mfp is large, complex
- Many kinds of reaction tested

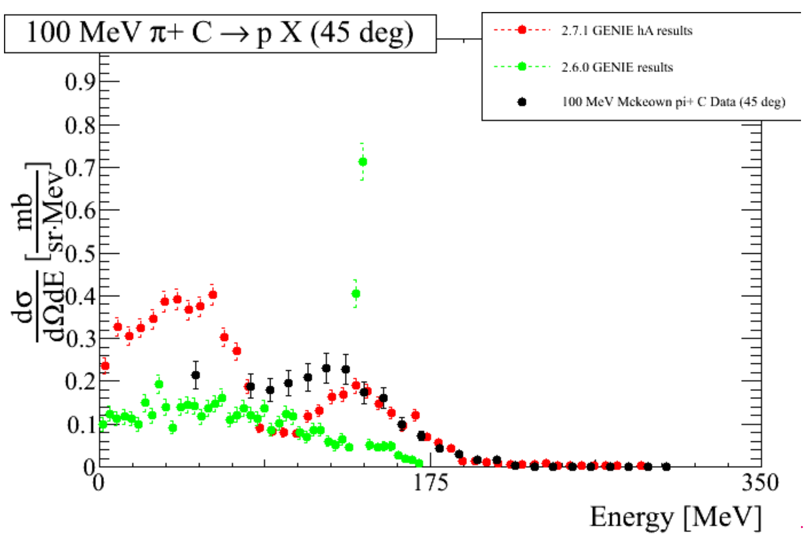


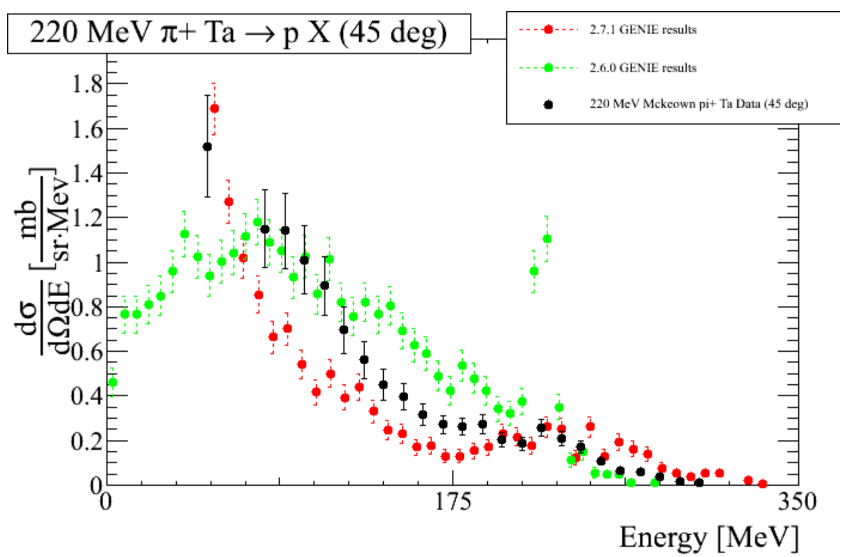


Other examples - low energy









summary

- Next GENIE (v2.8) will have new hA and hN FSI models.
- Small number of parameters, all physically motivated
- Each model is extensively validated against wide range of hadron-nucleus data (100s of distributions).
- Goal is to match the features of data
- This provides a useful starting point for comparisons with neutrino cross section data.
- Distributions from ν_μ C at 1 GeV show differences due to model assumptions (first?)
- *New ν cross section data extremely important!*