Pion Production - Pion Nucleus Interactions

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U. Mosel:
set the stage for a discussion how pion production and absorption are handled in neutrino generators.

build the bridge from production to final state interactions

cover the full reaction from the start ((nu,e +A) makes a pion) through the intermediate steps (pion-nucleus interactions) to the final free pion coming out from the nucleus. Say something also about resonance physics and DIS.

General remark:
Can't separate production and final state interaction

History

Los Alamos Meson Physics Facility
1970-1995
Pion beams 100-600 MeV
made by 800 MeV protons

TRIUMF 1970-
500 MeV Protons
chaos detector

PSI
pions from 10 to 500 MeV/c

Many experiments of relevance

CPC(HEP & NP), 2009, **33**(X): 1—6 **Chinese Physics C** Vol. 33, No. X, Xxx, 2009

Baryon Resonance Analysis from SAID *

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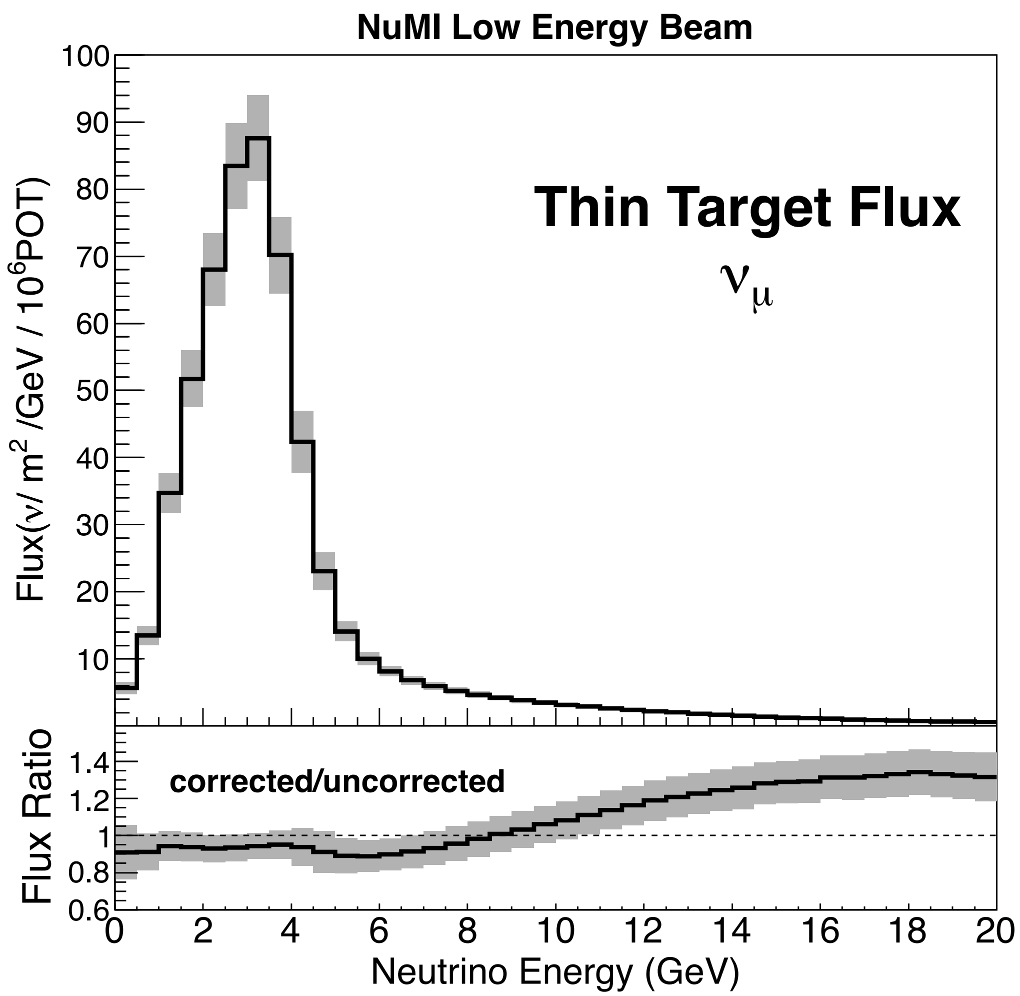
Abstract We discuss the analysis of data from πN elastic scattering and single pion photo- and electroproduction. The main focus is a study of low-lying non-strange baryon resonances. Here we concentrate on some difficulties associated with resonance identification, in particular the Roper and higher P_{11} states.

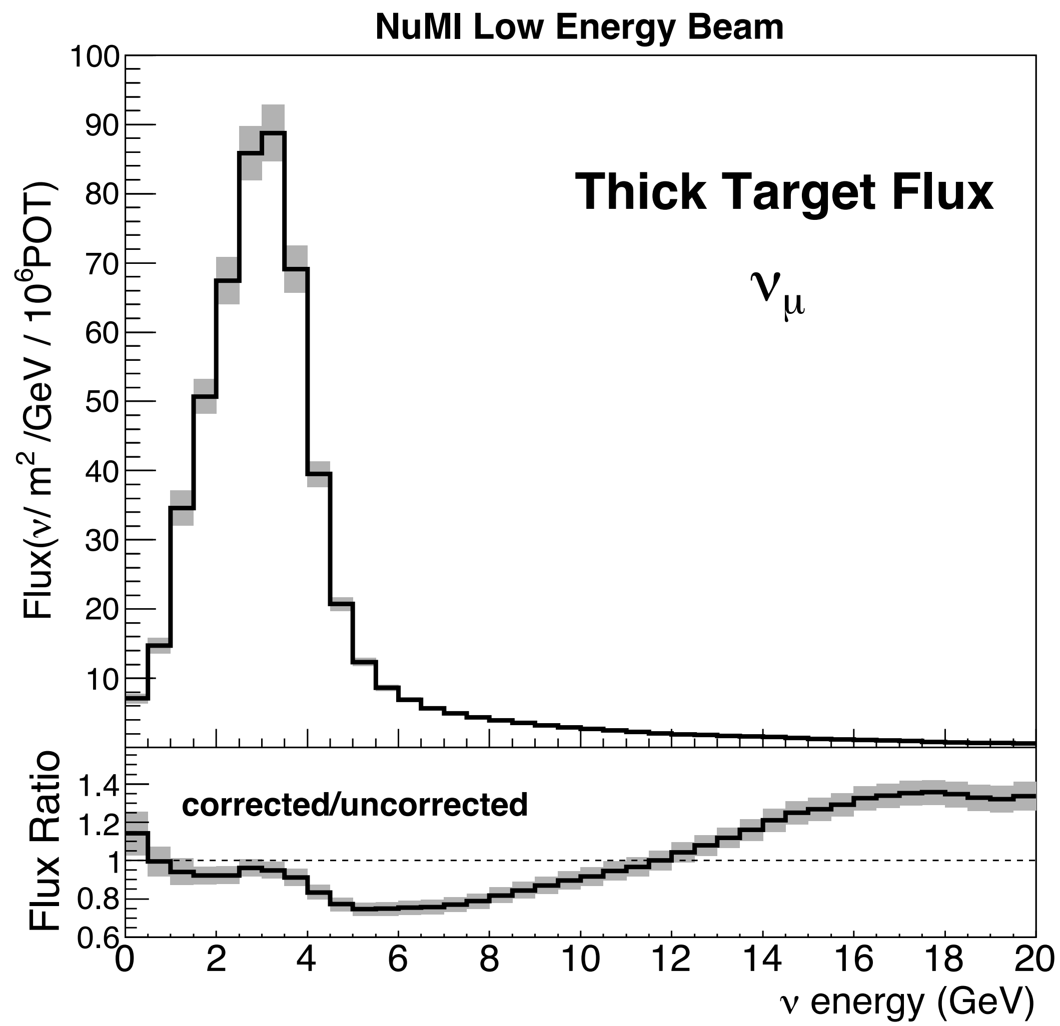
Partial-Wave Analyses at GW
[See Instructions]
Pion-Nucleon
Pi-Pi-N
Kaon(+)-Nucleon
Nucleon-Nucleon
Pion Photoproduction
Pion Electroproduction
Kaon Photoproduction

gwdac.phys.gwu.edu

Using Data >>Using theory

NUMI Beam 1607.00704





nu energy at 1-3 GeV,
but long tail

What nus do

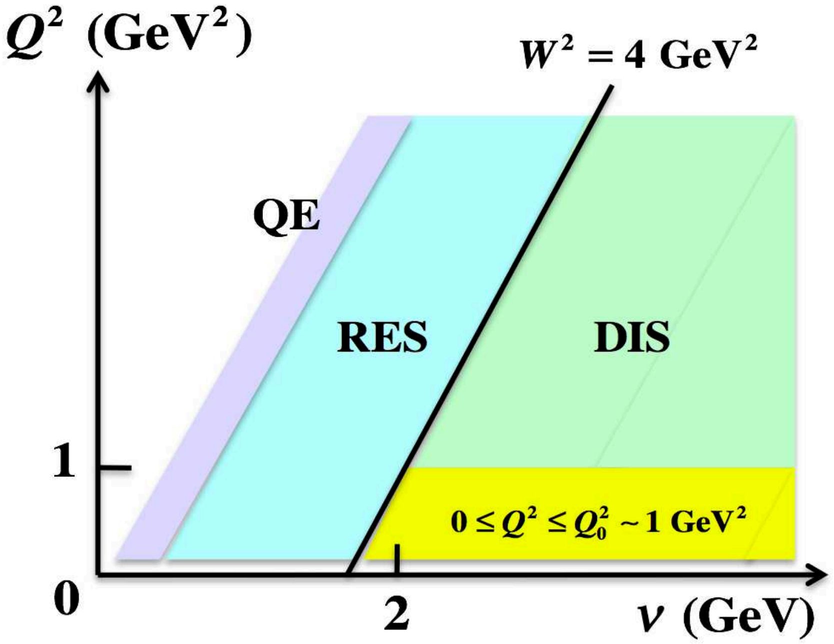


Fig. 1. Kinematical regions of neutrino-nucleus scattering.

Kumano slides

hints from electron scattering

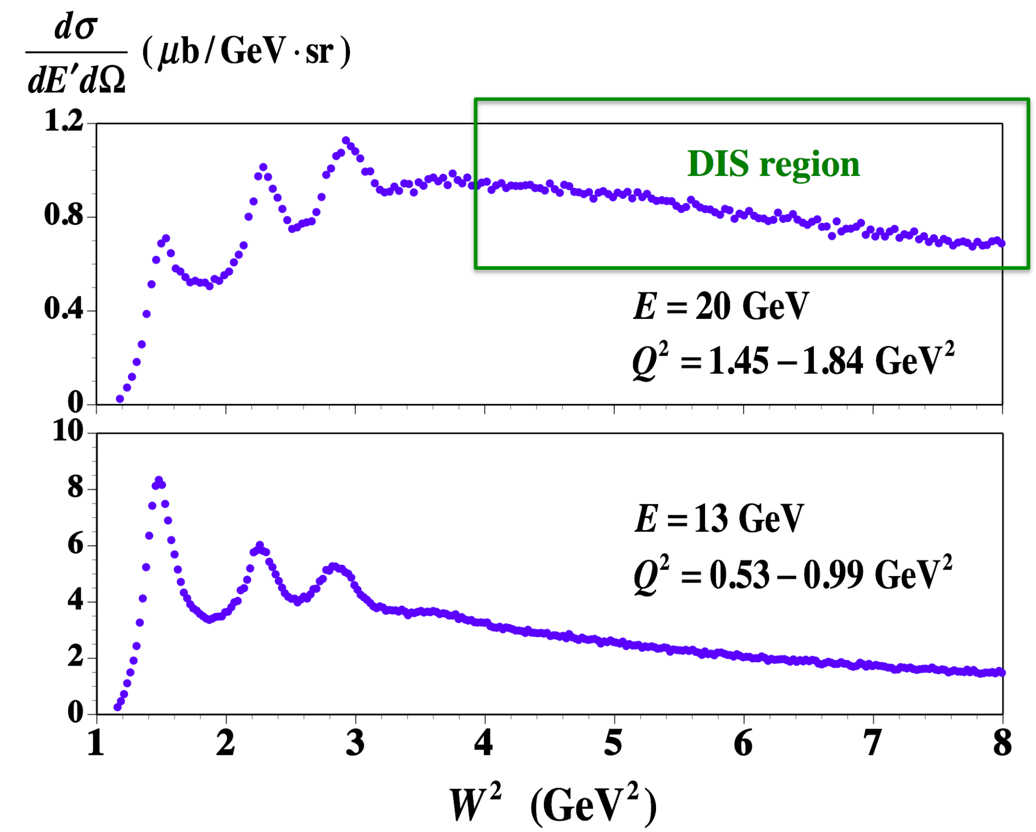


Fig. 2. Electron-proton scattering cross sections [3].

QE- quasielastic $\nu + N \to \mu + N$

RES- resonance-probably dominant source $\nu + N \to \mu + (N^*, \Delta) \to N + \pi$, or π, π

DIS- deep inelastic $\nu + N \to \pi + X$, but X could contain pions

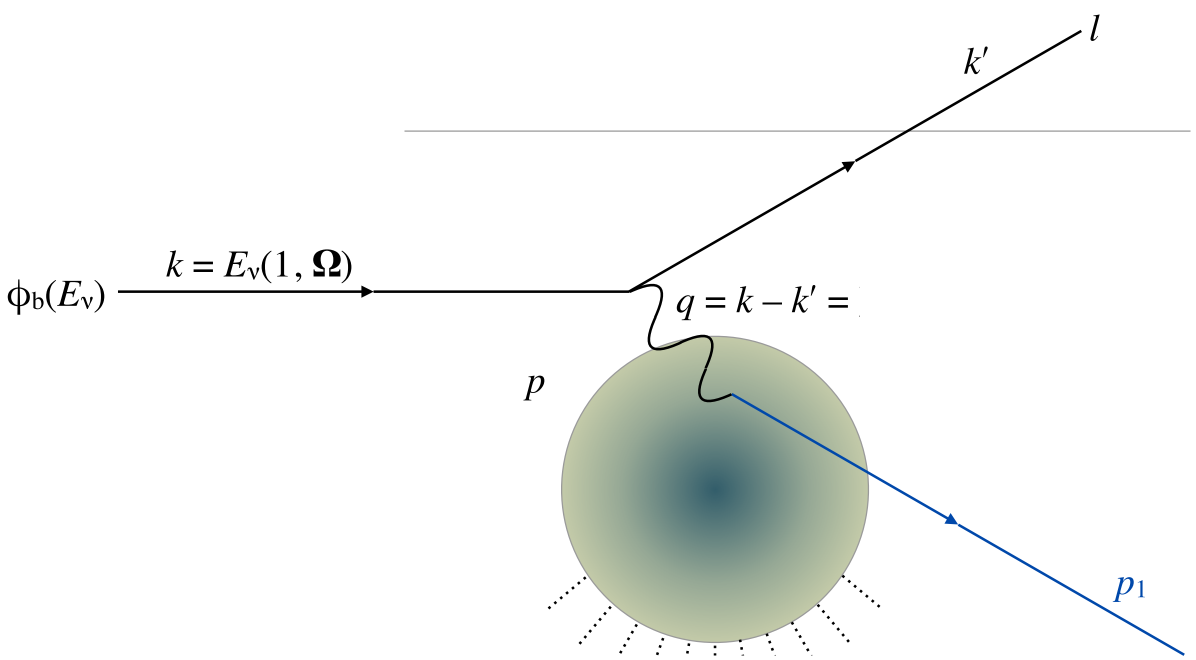
Quasi elastic scattering can lead to
Everything that a pion can do

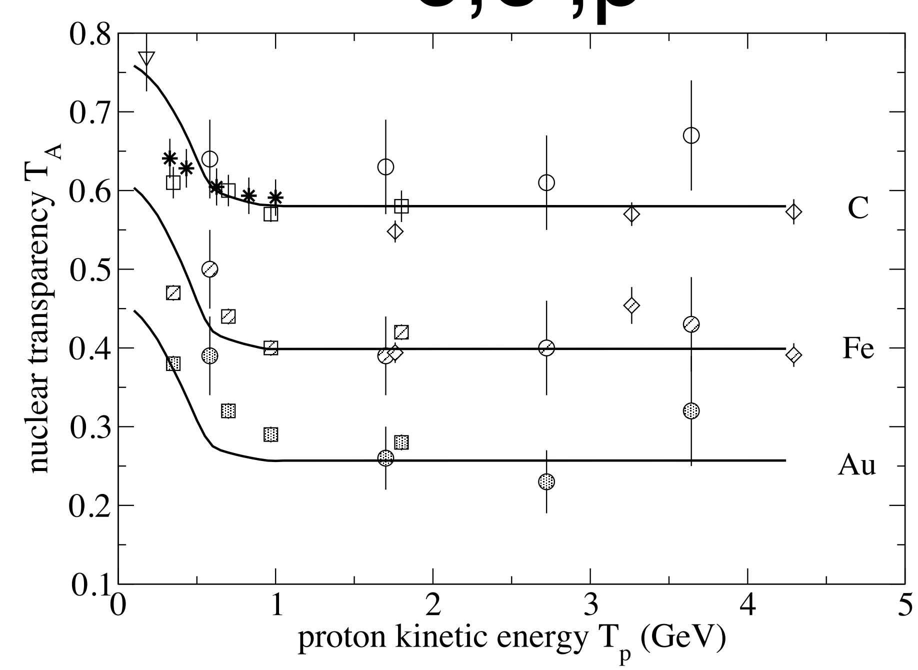
Quasi-elastic scattering

$x = 1,\ \nu = 1\,M,\ Q^2 = 2\,M^2 \qquad M$ is nucleon mass $\rightarrow 1$

Nucleon (initial at rest) has energy
can make it to detector

make it?
probability
e,e',p





E97-006 nucl-ex/0506007,
PRC 72, 054602 (2005)

Nucleon can make one or more pions

Quasi-elastic scattering

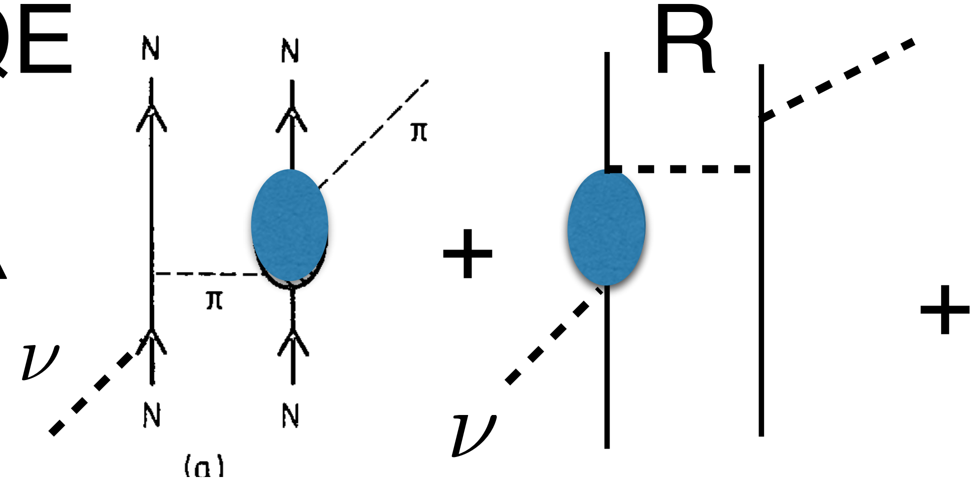
$x = 1,\ \nu = 1\,M,\ Q^2 = 2\,M^2 \qquad M$ is nucleon mass $\to 1$

Nucleon energy is ideal for making a Δ in $NN \to N\Delta$. Then $\Delta \to N\pi$ Resonance production

Now have three particles in the final state

QE R

blob is Δ

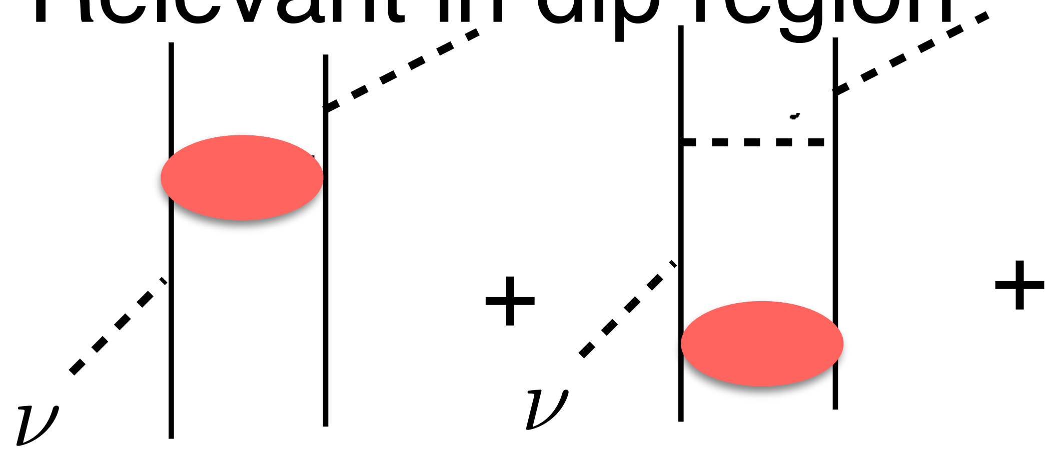


Many ways to make NNpi final state could you tell this event to be QE?

Relevant in dip region

Is this pi production or fsi?

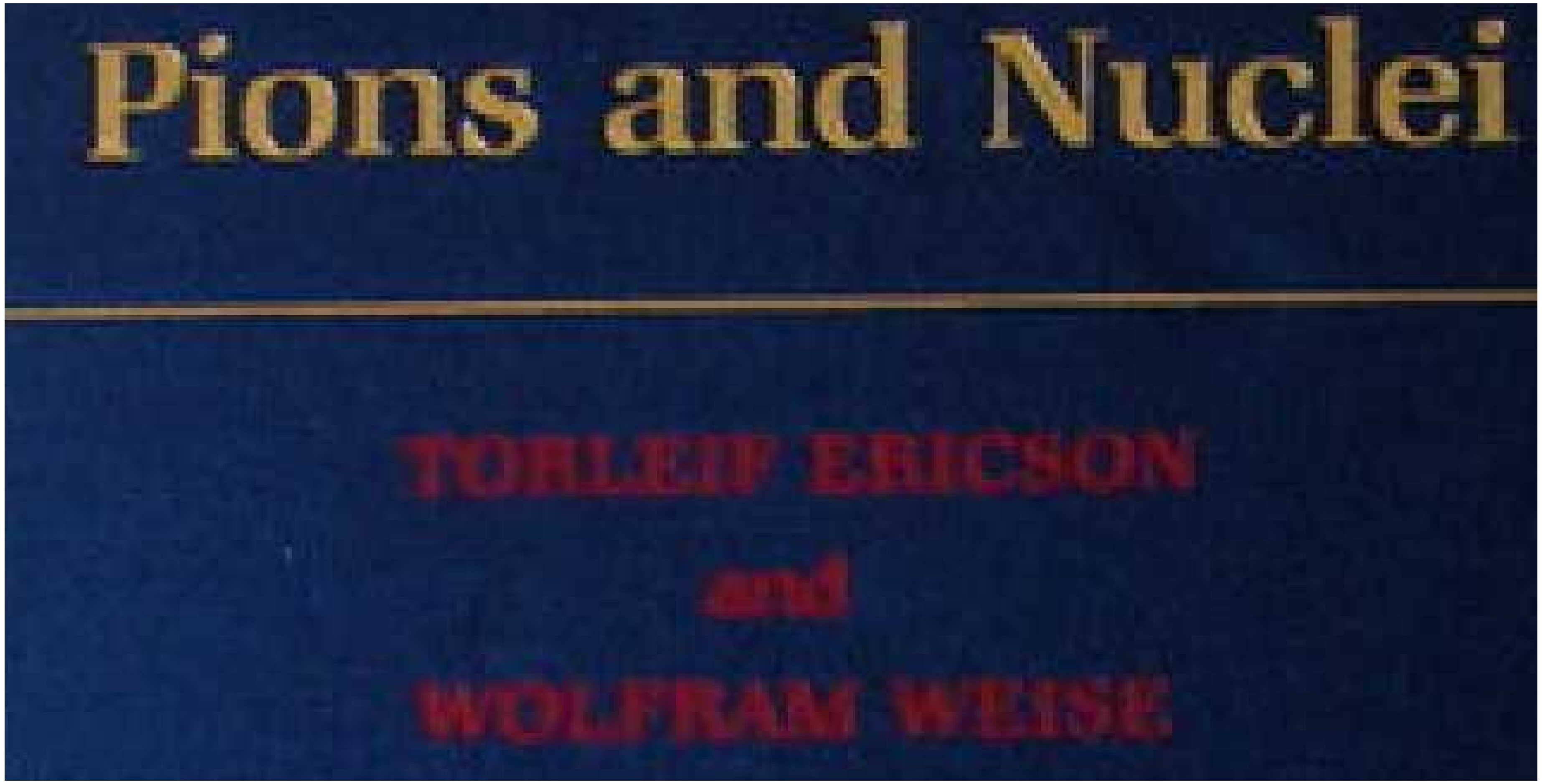
2p-2h



Nucleon-nucleon correlations dominated by np

These diagrams to be added first and then squared. Could be big effect

History of Pion-Nucleus Physics



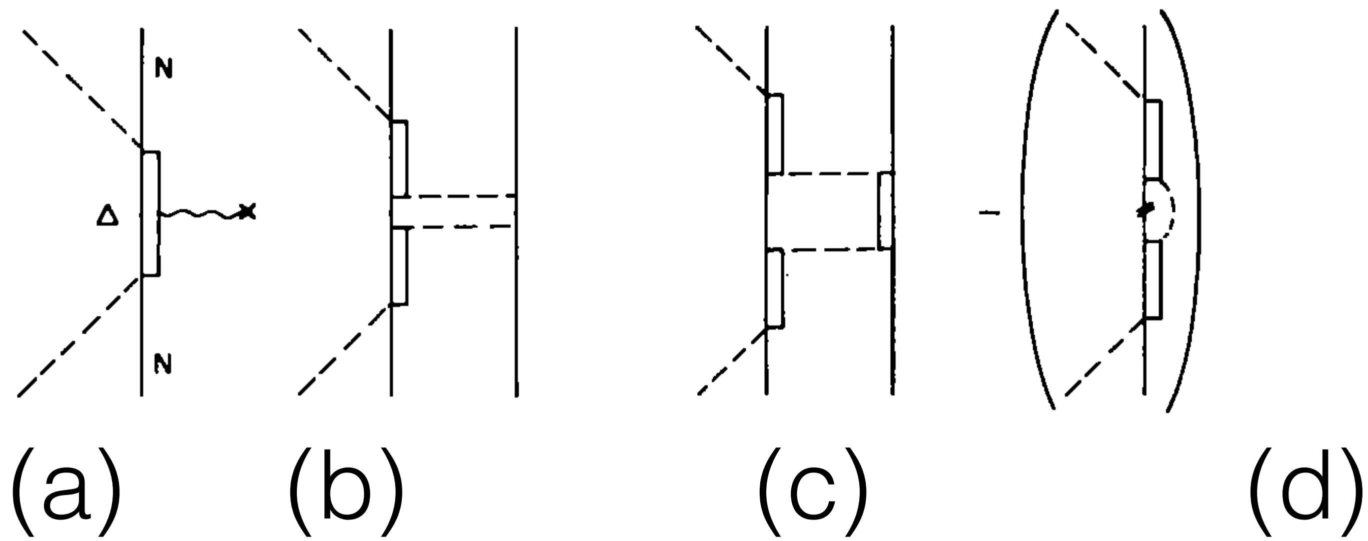
Oxford Press 1988

Ericson & Weise = EW

Quasi elastic makes Δ

What does Δ do?

What is mass and width of Δ in the nucleus?



- (a) Feel mean field potential
- (b) Width increases due to pion absorption
- (c) Multiple scatter
- (d) Width decreases due to Pauli blocking

Literature: Delta in Medium

- Kissinger & Wang PRL 30, 1071, Ann. Phys. 99,374
- Oset & Weise PL B82, 344; Nucl. Rhys A319,477
- Lenz, Moniz, Hirata, Koch PL B70, 281 (1977); Ann.Phys. 120, 205
- Freedman, Henley, Miller, PL B103, 397; Nucl. Phys. A389, 457 (1982)
- Idea is the same: Delta propagates in medium, but many technical differences

1982

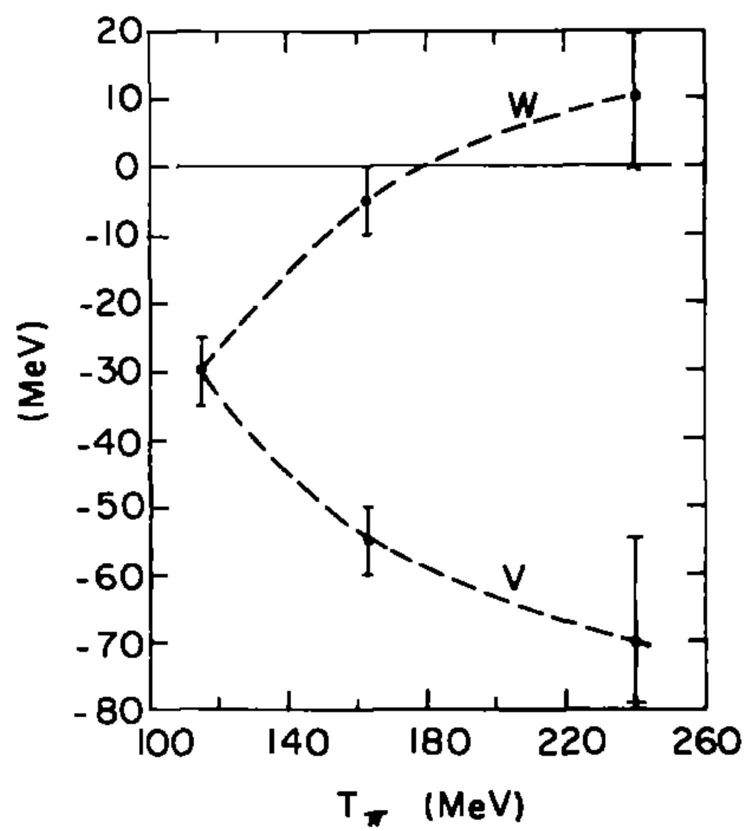


Fig. 2. Dependence of the central strength $V + iW$ of the Δ-nucleus potential on pion laboratory kinetic

Width ~unchanged due to cancellations

Delta less massive in medium
energy dependent
from many nuclei incl. Pb

What does π do?

EW

PION–NUCLEON SCATTERING 17

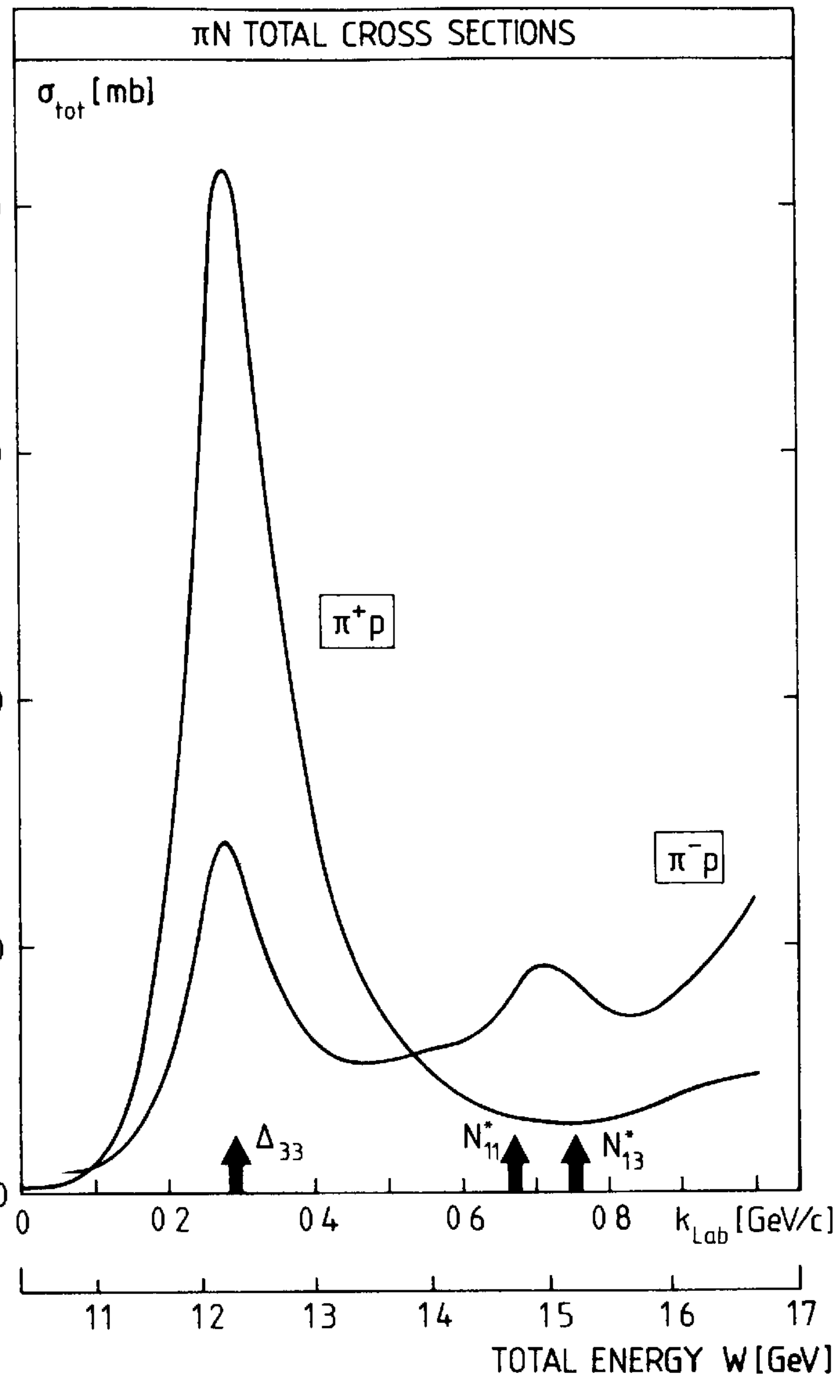
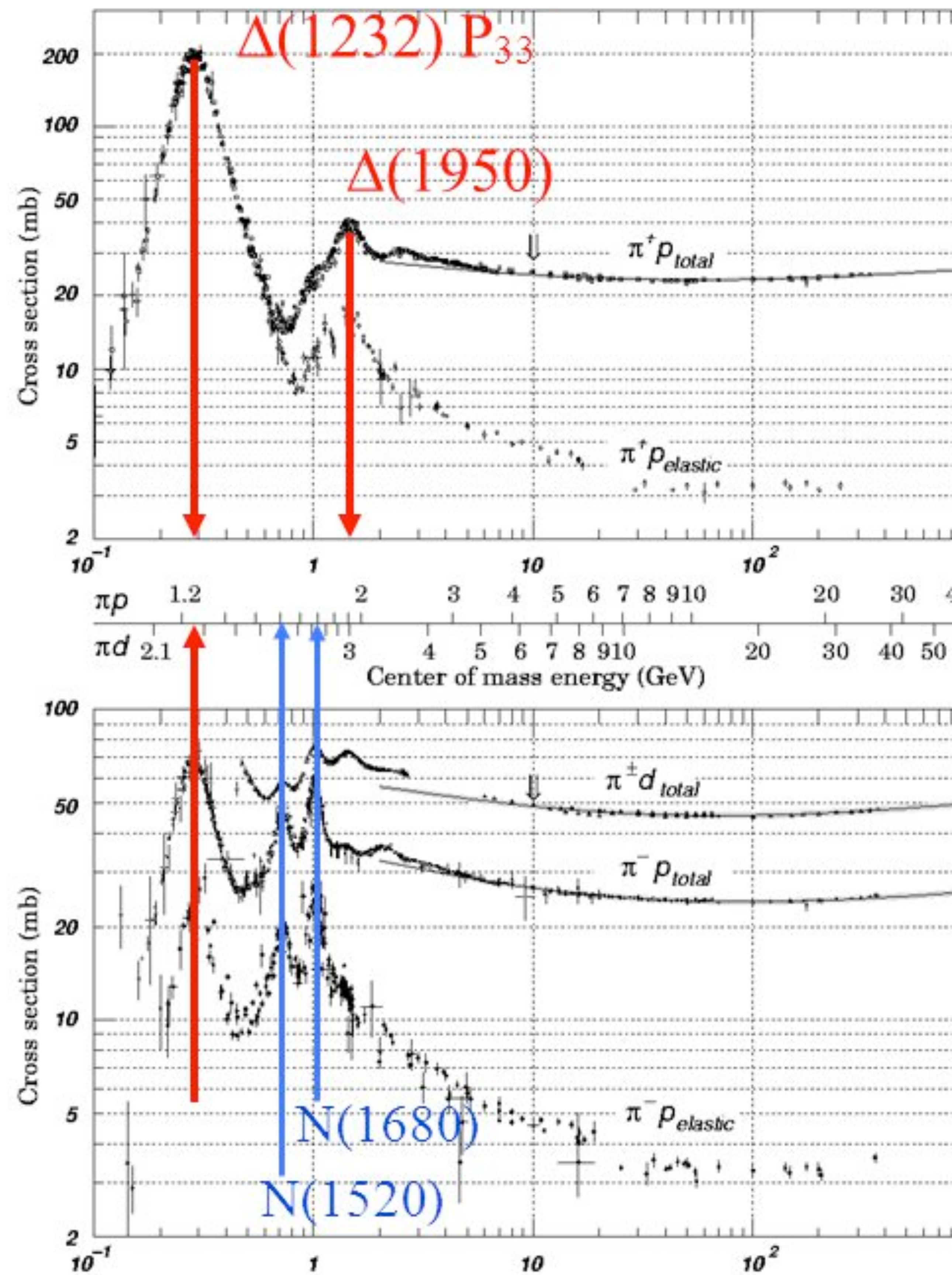


FIG. 2.2. Total cross-sections for π^+p and π^-p scattering as a function of the total c.m. energy W and the pion lab momentum k_{lab}.

Strong FSI



Elastic Pi-Nucleus

Black disk scattering

$$\frac{d\sigma}{d\Omega} \simeq R^2 \left| \frac{J_1(qR\theta)}{\theta} \right|^2 e^{-\lambda\theta}$$

EW

PHENOMENOLOGY OF ELASTIC SCATTERING 229

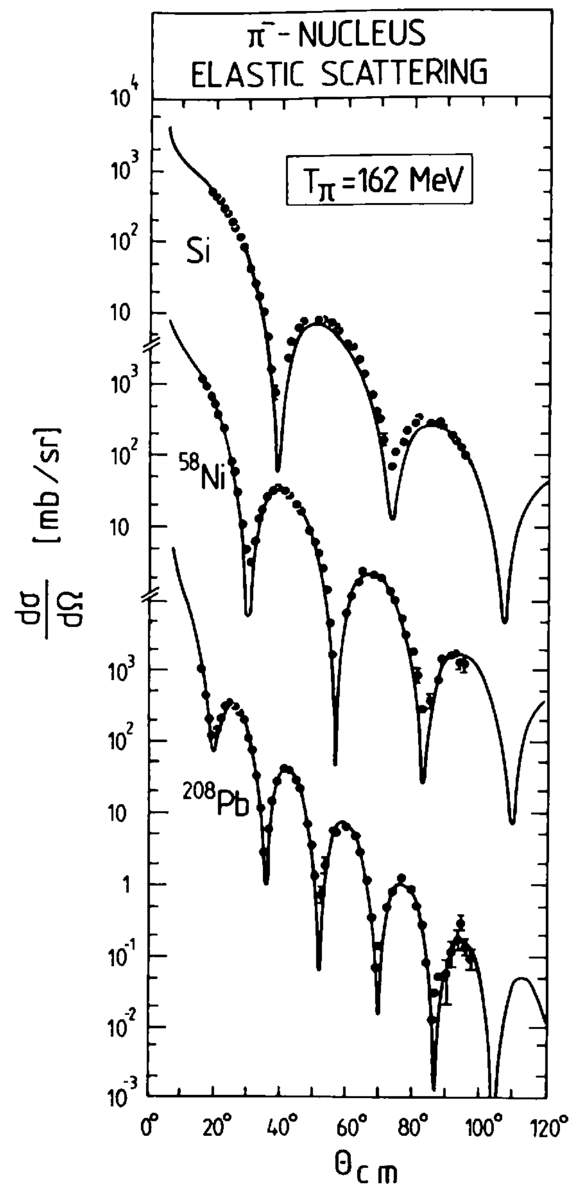


FIG. 7.5. Angular distributions for elastic scattering of 162 MeV π^- by [illegible], [illegible], and ^{208}Pb. The solid curves result from an optical model calculation including Coulomb interactions; they nearly coincide with results obtained using the diffractive formula (7.36) with $R = r_0 A^{\frac{1}{3}}$ and $r_0 \simeq 1.3$ fm. (From Zeidman *et al.* 1978.)

Elastic is ~1/3 of total

EW

232 PION–NUCLEUS SCATTERING AND REACTIONS

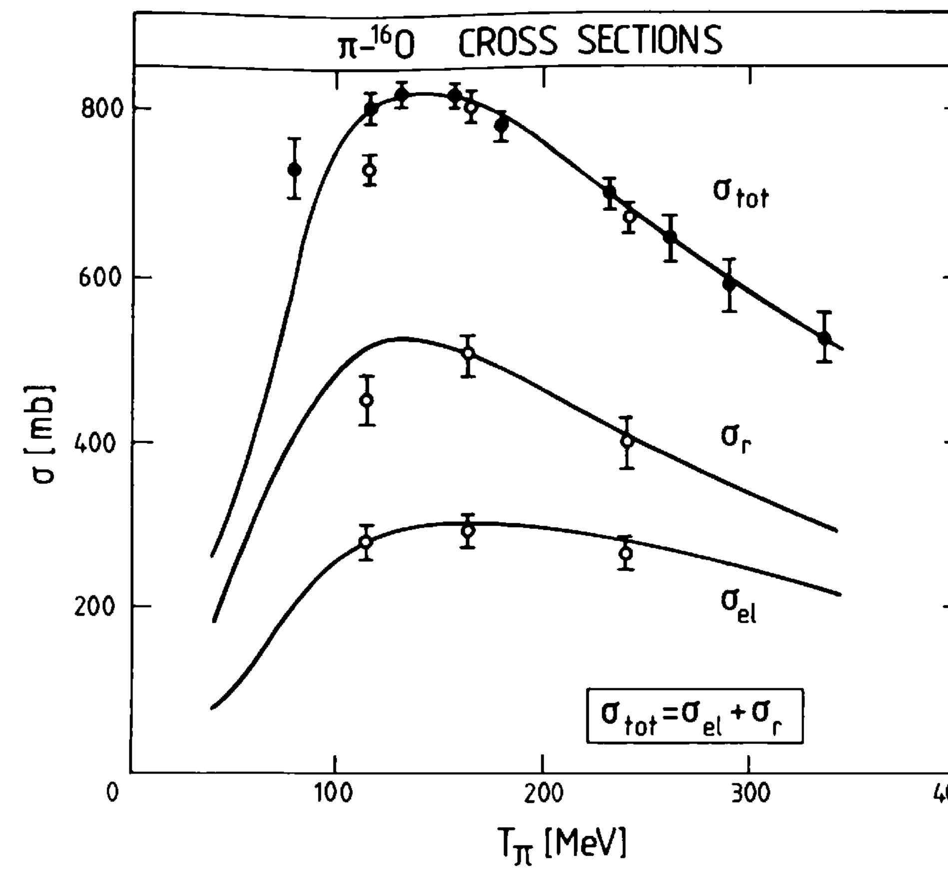


FIG. 7.7. Total, reaction and elastic pion cross-sections for ^{16}O. The curv correspond to a phase shift analysis, with Coulomb effects removed. Open poi represent π^+–^{16}O; solid points represent the average of π^+–^{16}O and π^-–^{16} (From Ciulli *et al.* 1981.)

pion-nucleus inelastic discrete final state

EW

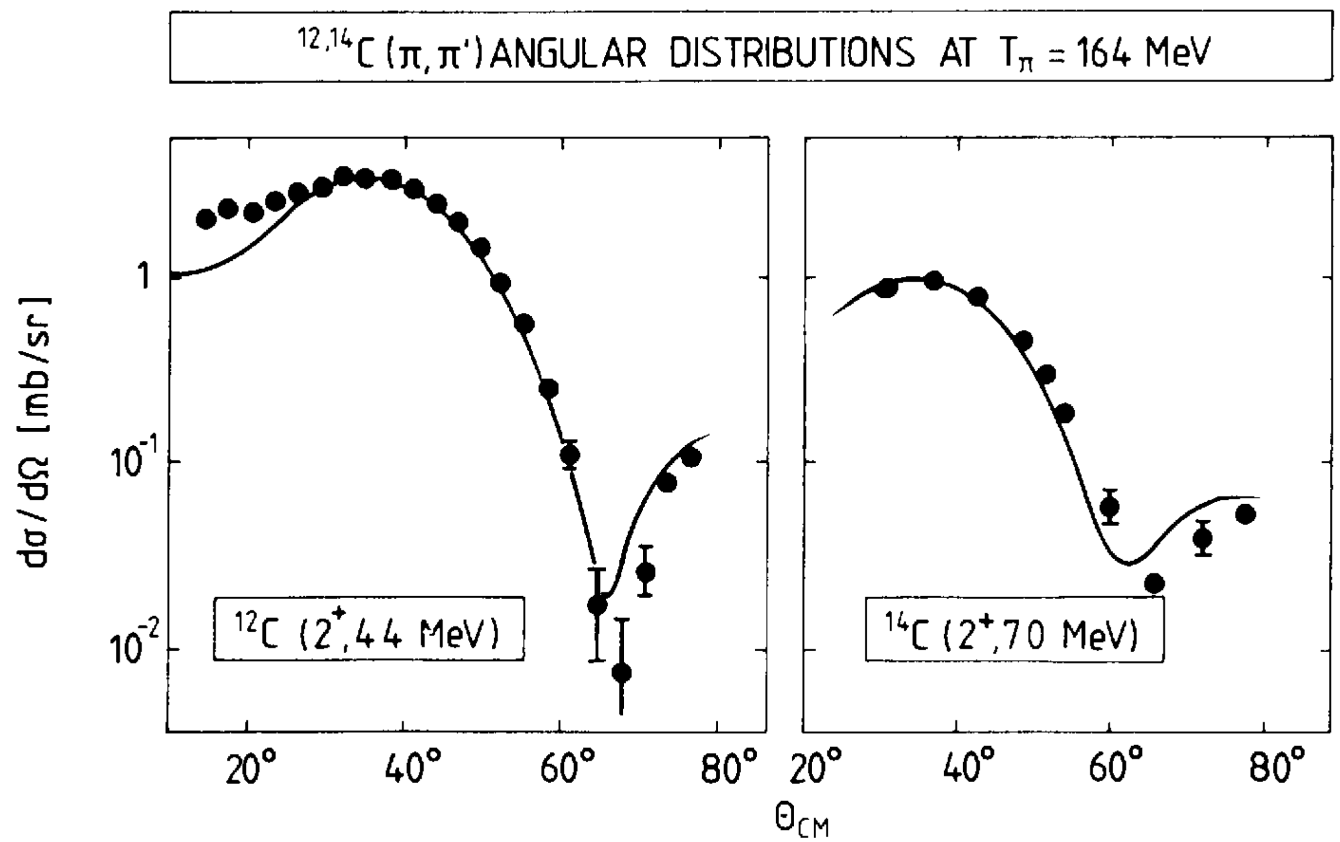


FIG. 7.19. Inelastic differential cross-sections for $^{12}C(\pi^+, \pi^{+\prime})^{12}C(4.4\,MeV)$ and $^{14}C(\pi^-, \pi^{-\prime})^{14}C(7.0\,MeV)$. The solid curves represent distorted wave calculations. (From Dehnhard 1982.)

Distorted wave calculations

DWPI Eisenstein & Miller

Comput.Phys.Commun. 11 (1976) 95-112

$$T^J_{lI,l'I'} = \sum_{\substack{mM \\ m'M'}} \langle l'm'I'M'|Jq\rangle\langle lmIM|Jq\rangle \times \langle \psi^{(-)}_{lm}\Phi_{IM}|H'|\psi^{(+)}_{l'm'}\Phi_{I'M'}\rangle .$$

$\psi^{(-)}_{lm}$ is incoming pion-nucleus wave function of orbital ang. mom. lm

Φ_{IM} is incoming nuclear state of angular momentum IM

$\psi^{(+)}_{l'm'}$ is outgoing pion-nucleus wave function of oam $l'm'$

$\Phi_{I'M'}$ is incoming nuclear state of angular momentum $I'M'$

"Distorted wave" means not a plane wave-
initial (final) state interactions are included

Are distorted wave calculations relevant for determining neutrino energies?

Pion-nucleus inelastic

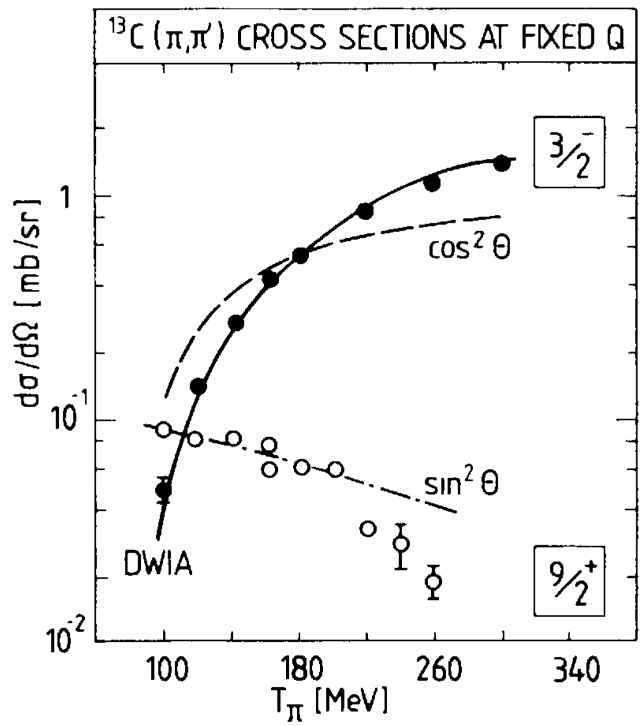


FIG. 7.20. Inelastic differential cross-sections for $^{13}C(\pi, \pi')$ scatterin momentum transfer Q to the $\frac{3}{2}^-$ state at 3.7 MeV ($Q = 1.1\ fm^{-1}$) and state at 9.5 MeV ($Q = 1.4\ fm^{-1}$). The dashed curves represent the pure $\sin^2\theta$ shapes arbitrarily normalized. The solid curve is obtained from a wa 'e calculation. (From Seestrom–Morris *et al.* 1981.)

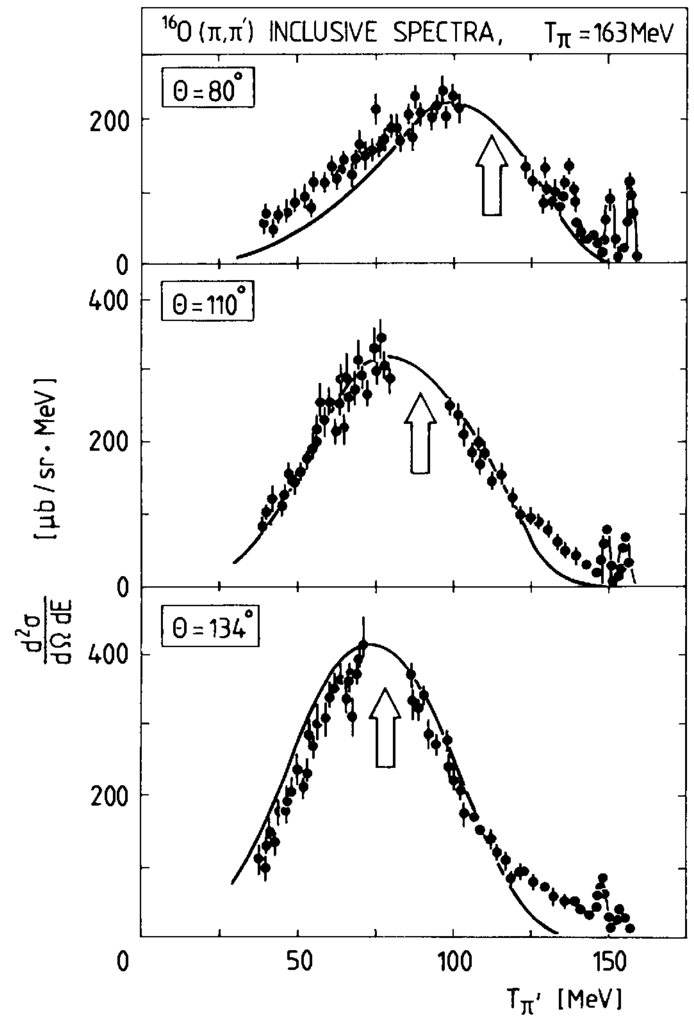
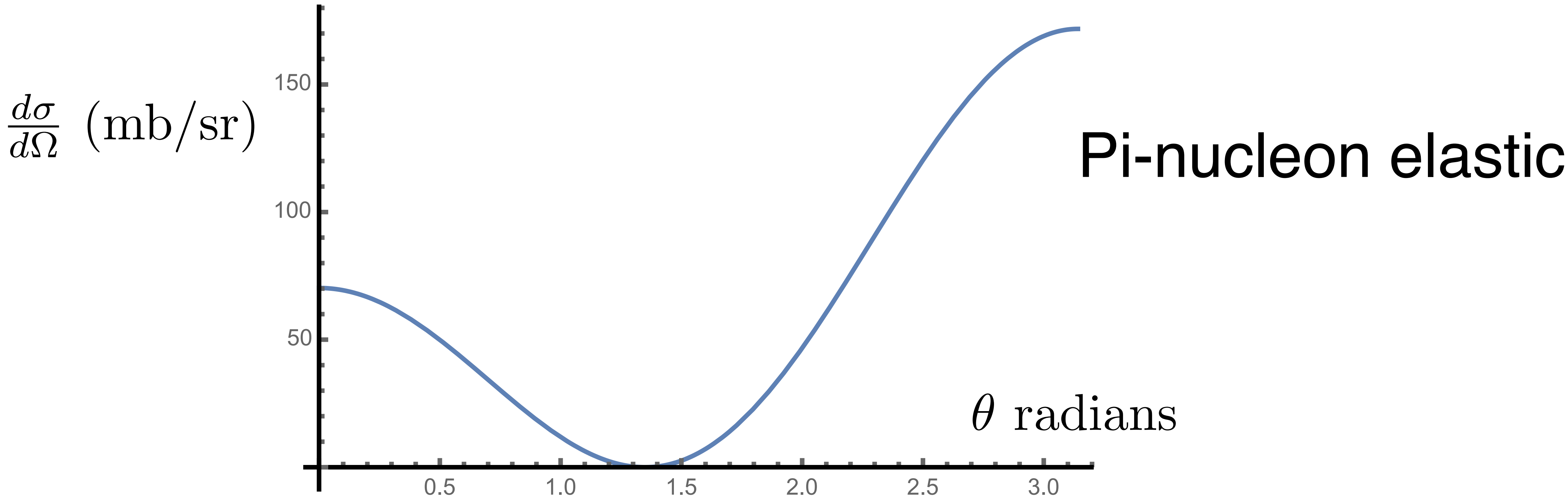


FIG. 7.21. Inclusive differential cross-sections for $^{16}O(\pi, \pi')$ in the quasifree region as a function of the kinetic energy $T_{\pi'}$ of the outgoing pion and for various lab scattering angles θ from Ingram (1979.) The arrows indicate the location of $T_{\pi'}$ for the free $\pi N \rightarrow \pi' N'$ process at the same angle θ. The curves represent Δ–hole model calculations. (From Thies 1982.)

Strong pion final state interactions



Pion back scatters , loses energy
this could happen several times
and then . . .

Pion absorption

see also K. Mahn
Phys. Rev. C 95, 045203 (2017)

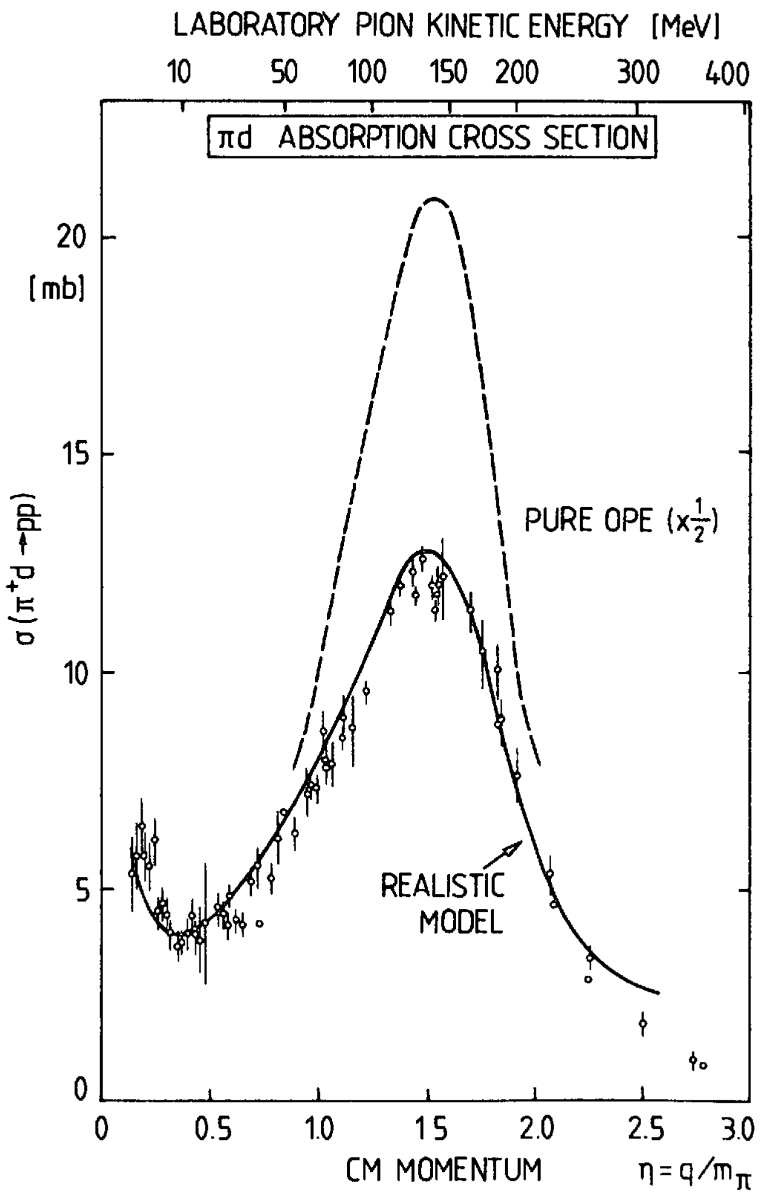


FIG. 4.11. The absorption cross section $\sigma(\pi^+ d \rightarrow pp)$ as described by the OPE Δ-model compared to results of a rescattering approach with a realistic tensor interaction and including the s-wave rescattering and the impulse approximation contributions. (From Riska *et al.* 1977; Maxwell *et al.* 1980.)

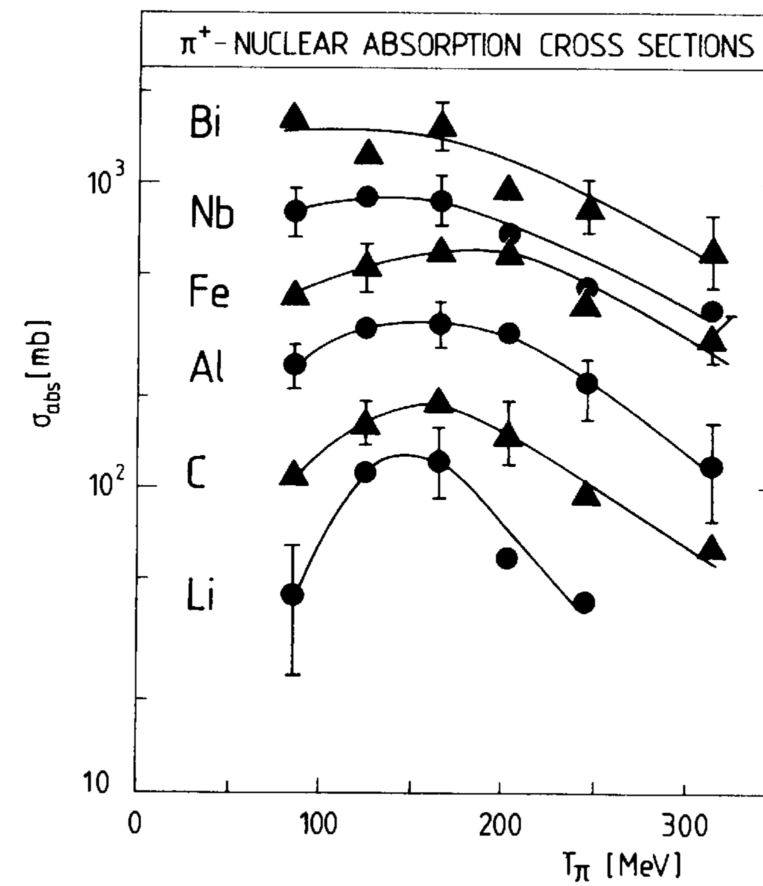


FIG. 7.31. Pion absorption cross-section for various nuclei as a incident kinetic energy T_π. (From Ashery *et al.* 1981*b*.)

Instead of NNpi have 4 N- could you tell event is QE?

What else can pion do?

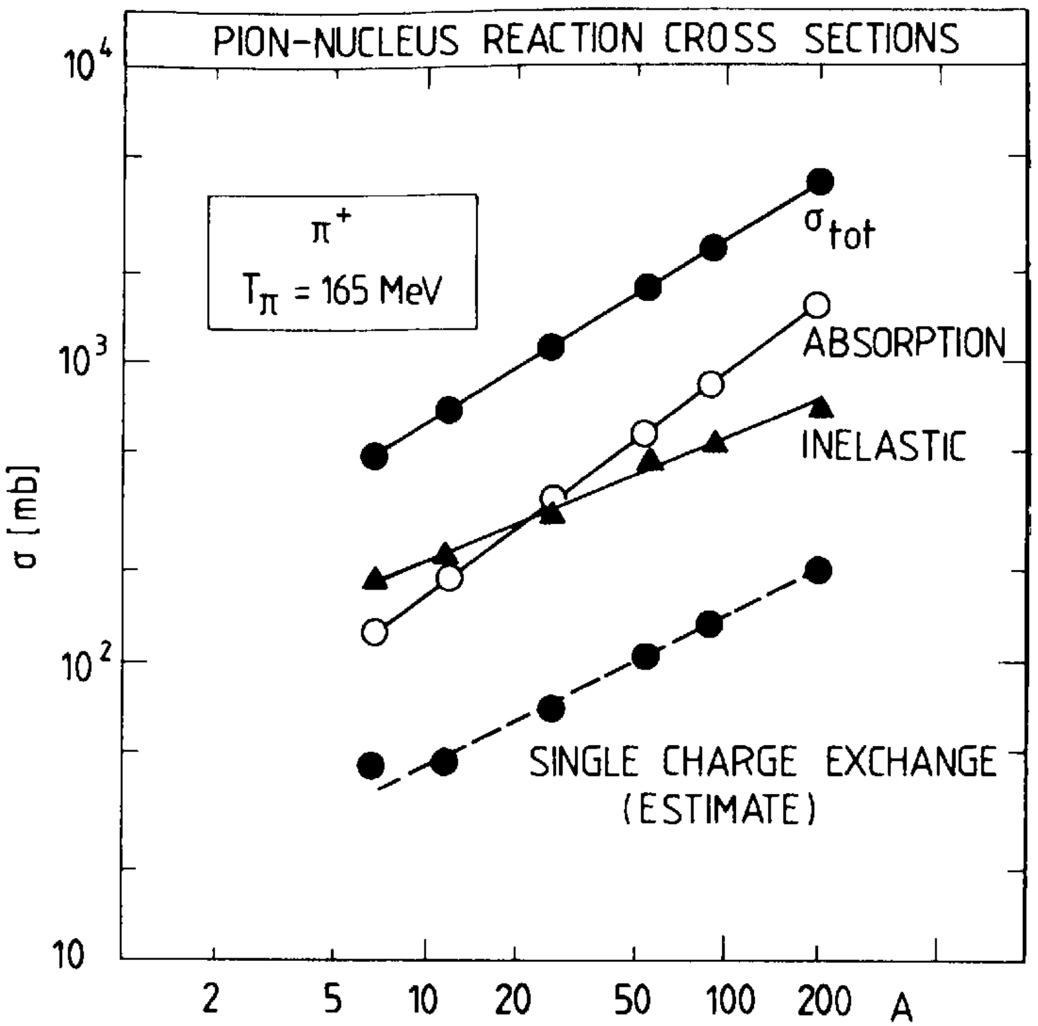


FIG. 7.22. Inelastic, absorption, and single-charge exchange (SCE) cross-sections for 165 MeV π^+ reactions with various nuclei as a function of nuclear mass number A. The SCE cross-sections are semi-empirical estimates. The total cross-section σ_{tot} is shown for comparison. (From Ashery *et al.* 1981*b*.)

Single charge exchange

$$\pi^+ n \leftrightarrow \pi^0 p$$
$$\pi^+ n \rightarrow \Delta^+$$
$$\pi^- p \leftrightarrow \pi^0 n$$

What else can pion do? Double charge exchange

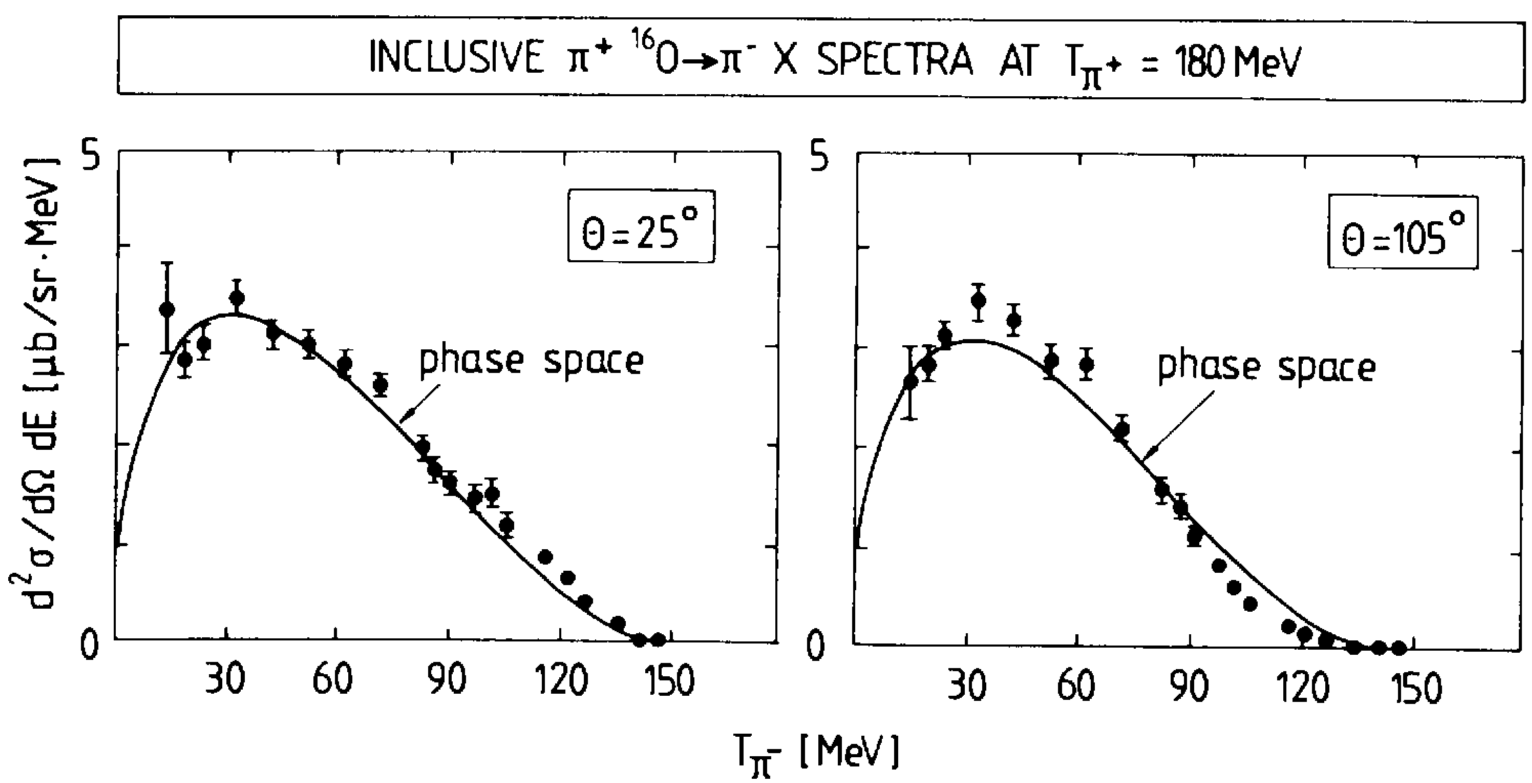
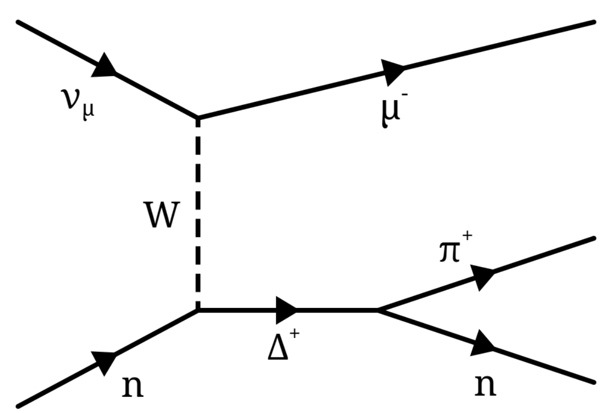


FIG. 7.24. Inclusive double-charge exchange spectra for $\pi^{+}\,{}^{16}O \rightarrow \pi^{-} X$ at $T_{\pi^+} = 180$ MeV. The solid curves correspond to the four-body phase space of one pion, two nucleons, and the final nucleus normalized to the total integrated DCE cross-section. (From Wood *et al.* 1985.)

Simple QE scattering makes pions which do everything a pion can do

More direct source of pions is

$$\nu + N \to \ \text{resonance} \to N\pi, \quad \text{or } N^*\pi, \text{ etc.}$$



These pions interact and can:
scatter elastically from nucleus
scatter inelastically from nucleus
back scatter from nucleon
be absorbed
charge exchange once or twice

More direct source of pions is

$$\nu + N \rightarrow \text{ resonance} \rightarrow N\pi, \quad \text{or } N^*\pi, \text{ etc.}$$

What is a resonance - is it a three quark state?

More direct source of pions is

$$\nu + N \to \text{ resonance} \to N\pi, \quad \text{or } N^*\pi, \text{ etc.}$$

What is a resonance - is it a three quark state?

NO

More direct source of pions is

$$\nu + N \to \text{ resonance} \to N\pi, \quad \text{or } N^*\pi, \text{ etc.}$$

What is a resonance - is it a three quark state?

NO

$$\Delta \text{ has width thus}$$

$$|\Delta\rangle = Z(\Delta_0 + |N\pi\rangle + \cdots)$$

$$\Delta \text{ is resonance in } \pi\text{-nucleon scattering}$$

More direct source of pions is

$$\nu + N \to \text{ resonance} \to N\pi, \quad \text{or } N^*\pi, \text{ etc.}$$

What is a resonance - is it a three quark state?

NO

Δ has width thus

$$|\Delta\rangle = Z(\Delta_0 + |N\pi\rangle + \cdots)$$

Δ is resonance in π-nucleon scattering

PHYSICAL REVIEW D VOLUME 22, NUMBER 11 1 DECEMBER 1980

Pionic corrections to the MIT bag model: The (3,3) resonance

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(Received 27 May 1980)

By incorporating chiral invariance in the MIT bag model, we are led to a theory in which the pion field is coupled to the confined quarks only at the bag surface. An equivalent quantized theory of nucleons and Δ's interacting with pions is then obtained. The pion-nucleon scattering amplitude in this model is found to give a good fit to experimental data on the (3,3) resonance, with a bag radius of about 0.72 fm.

Cloudy bag model

What is a Delta?

FIG. 1. The Chew series. Nucleons are represented by solid lines and pions by dashed ones.

Early work by Chew obtained resonance peak without any three-quark state

another model

FIG. 2. The Δ model. The wiggly line is the bare Δ.

Can also obtain resonance peak

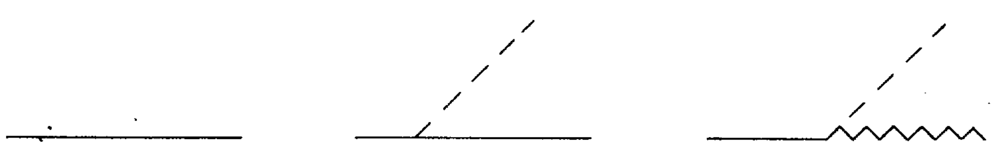


FIG. 3. The physical nucleon [from Eq. (3.16)].

+ HC - Cloudy Bag Model Hamiltonian

What is a Delta?

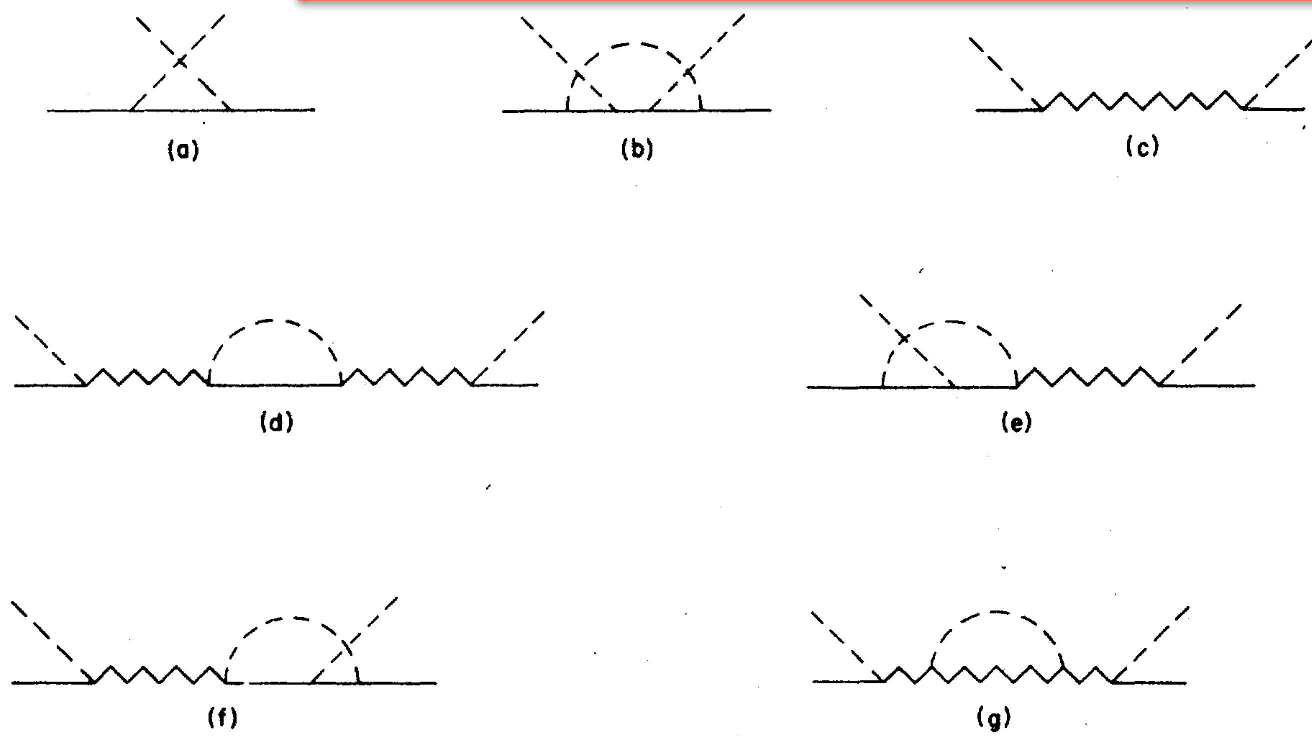


FIG. 8. Terms of Eq. (3.25) after renormalization.

Pion-nucleon scattering in resonance region

mainly Delta

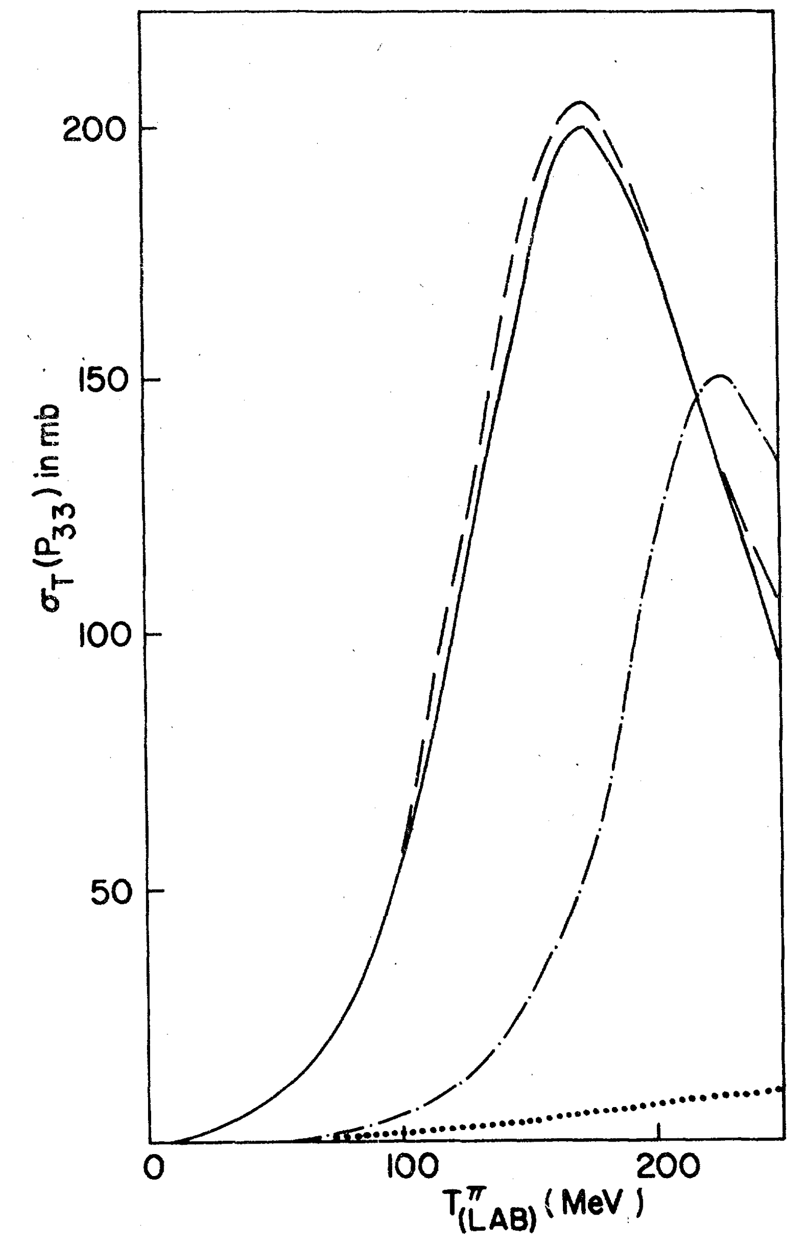


FIG. 11. Best fit in the cloudy bag model (dashed curve) to the experimental P_{33} total cross section (solid). The dash-dotted line shows the effect of arbitrarily setting $f_{NN\pi}(f_{\Delta N\pi})$ to zero, with all other parameters unchanged.

Delta is simplest resonance others are more complicated

$$|N^*(1440)\rangle = Z(|3\,\mathrm{quark\,radial\,excitation}\rangle + |N\pi\pi\rangle + |\Delta\pi\rangle) + \cdots$$

Resonance structure affects pion production cross sections

Use data instead of theory

But

Worry:

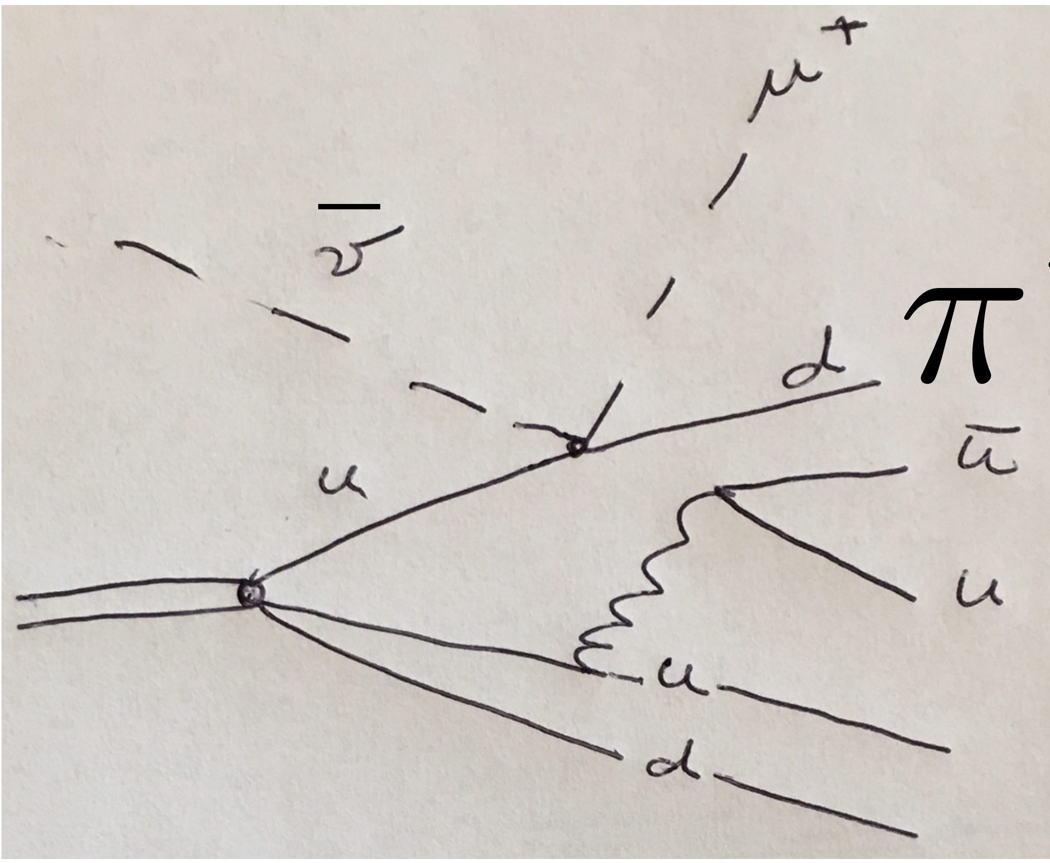
Different reaction mechanisms can reach the same final state

In that case have quantum interference

Must add amplitudes and then square

Once pion is made it can do all the things discussed previously

Deep inelastic scattering



π^-

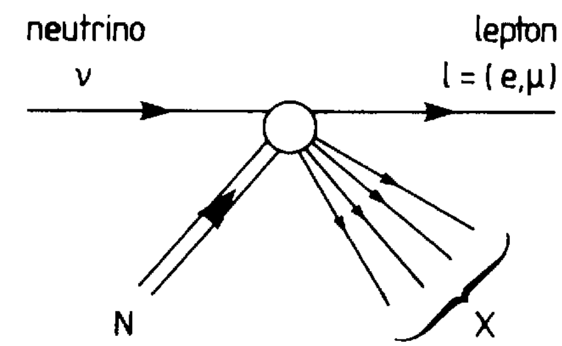


FIG. 9.9. Illustration of the forward neutrino reaction $\nu + \mathrm{N} \to l + \mathrm{X}$.

EW

Use CVC , PCAC:

$$\mathcal{M} = \frac{G_\mathrm{W}}{\sqrt{2}} \frac{f_\pi}{q_0} u_l^+ (1 - \sigma_z) u_\nu \langle \mathrm{X} | J^\pi | \mathrm{N} \rangle$$

$$= (\text{factors}) \cdot T(\pi(q) + \mathrm{N} \to \mathrm{X}). \quad (9.122)$$

This result is known as Adler's theorem.[12] Here the pion moves in the

Use data for pion cross sections

Summary

- Pion does many things
- Can be made from resonance decay or final state interactions
- Separation between production and final state interaction is not absolute