Pion-Nucleus Interactions +

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S. Dytman:
Workshop on Neutrino-Nucleus Pion Production in the Resonance Region. Goal to bring physicists together to
discuss models and concepts. We seek a few talks on the history of the subject especially Delta excitation and propagation

Outline

1. Pion-nucleus phenomenology - cross sections -most
2. Meaning of a resonance
3. Two general remarks based on reading NEUT PRD 99,052007

History

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

SIN now PSI
pions from 10 to 500 MeV/c

TRIUMF 1970-
500 MeV Protons low
energy pions
chaos detector

Many experiments of relevance to neutrino physics

~1960 pion: fundamental particle of strong interaction -need beam, constructed

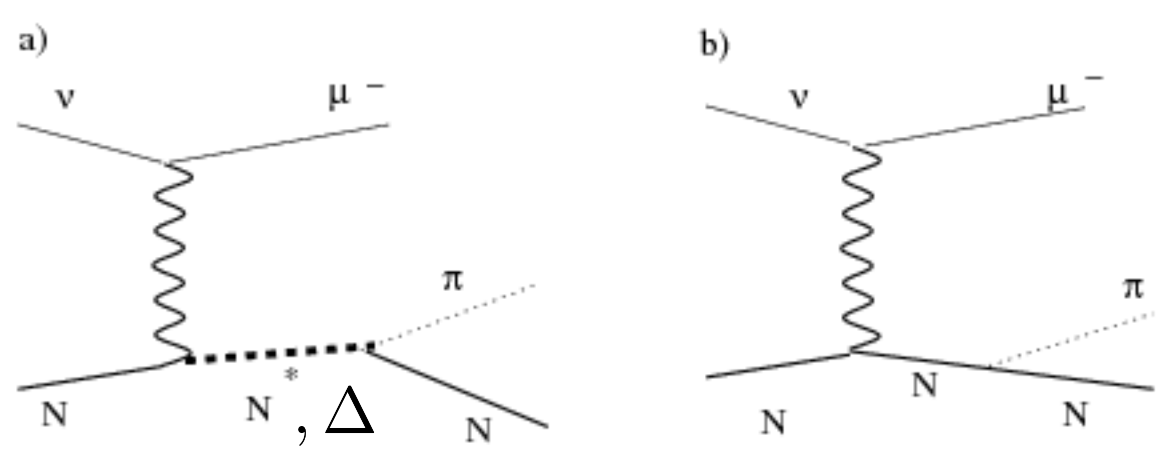
~1975 gluon: fundamental particle of SI-gluon not pion beam needed

~1990 pion (chiral symmetry, EFT): fundamental particle of strong interaction-need beam

Pion Nucleus Interactions: Memories of a Misspent Youth

Neutrino physics makes pions great again

Focus of this talk: pion nucleus interactions
Brief intro: how are pions made in neutrino nucleus interactions?
(a) resonance production



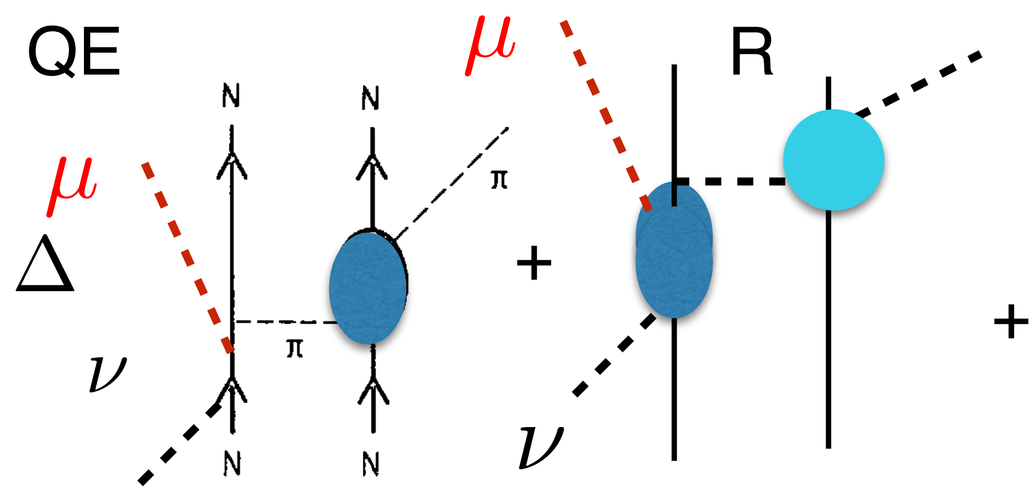
b) Quasi-elastic scattering followed by pion emission
In either case, pions move through the nucleus

Making pions

$x = 1,\ \nu = 1\,M,\ Q^2 = 2\,M^2 \qquad M$ 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

blob is Δ

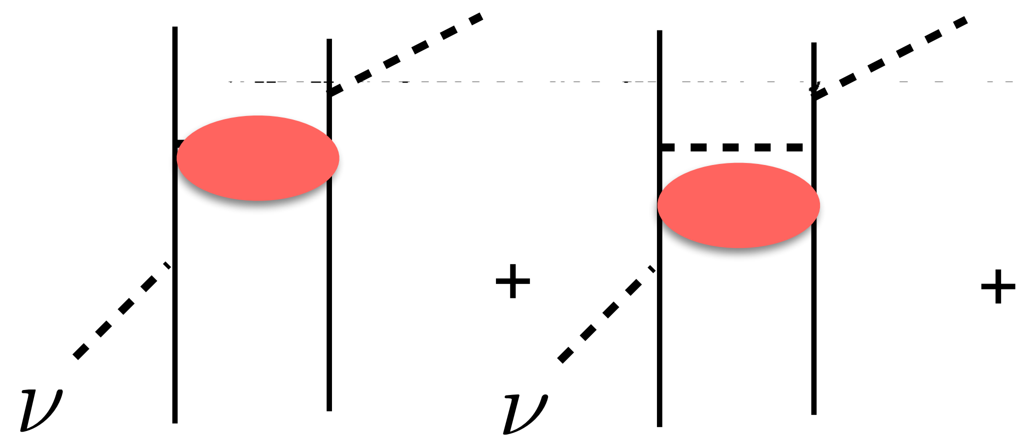


Relevant off-peak region

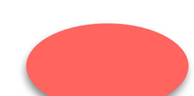
Many ways to make
$NN\pi\mu$ final state

Is this pi production or fsi?

2p-2h

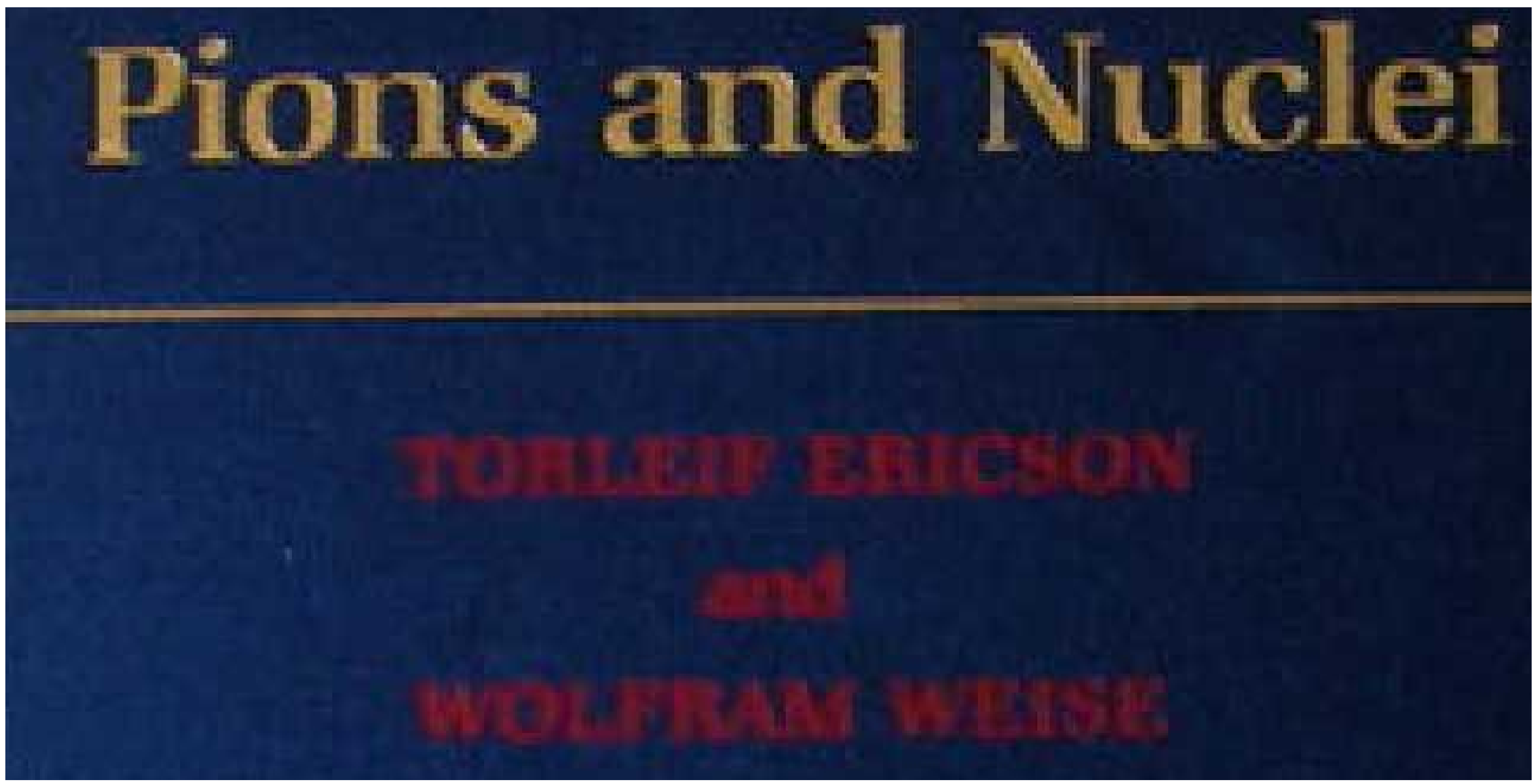


Nucleon-nucleon correlations dominated by np


$= V_{NN}$

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

What does pion do in nucleus?
most of remaining talk



Oxford Press 1988

Ericson & Weise = EW

Lee & Redwine Ann. Rev. Nucl. Part. Sci. 52, 23 (2002)

What does π do?

PION–NUCLEON SCATTERING 17

EW

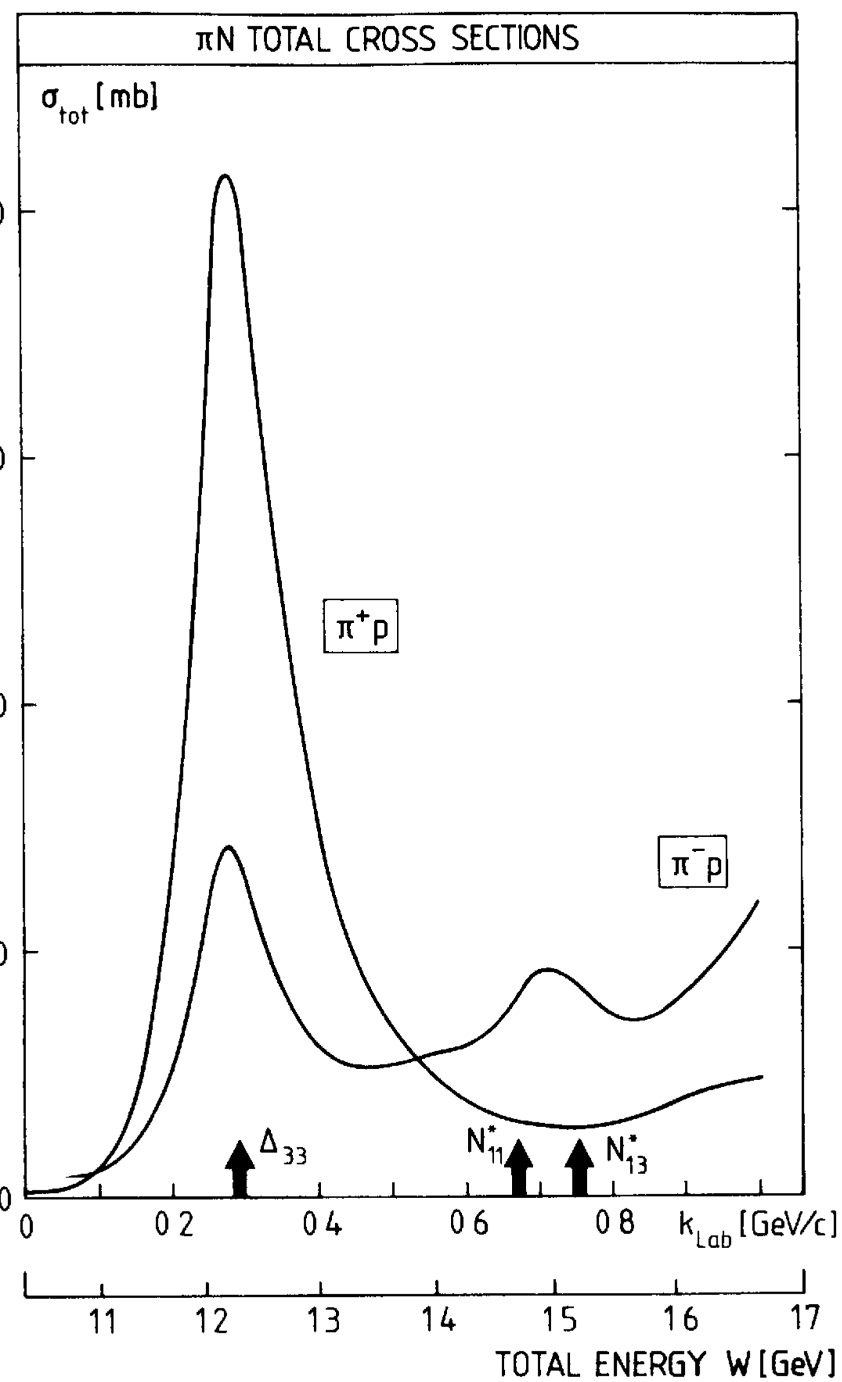
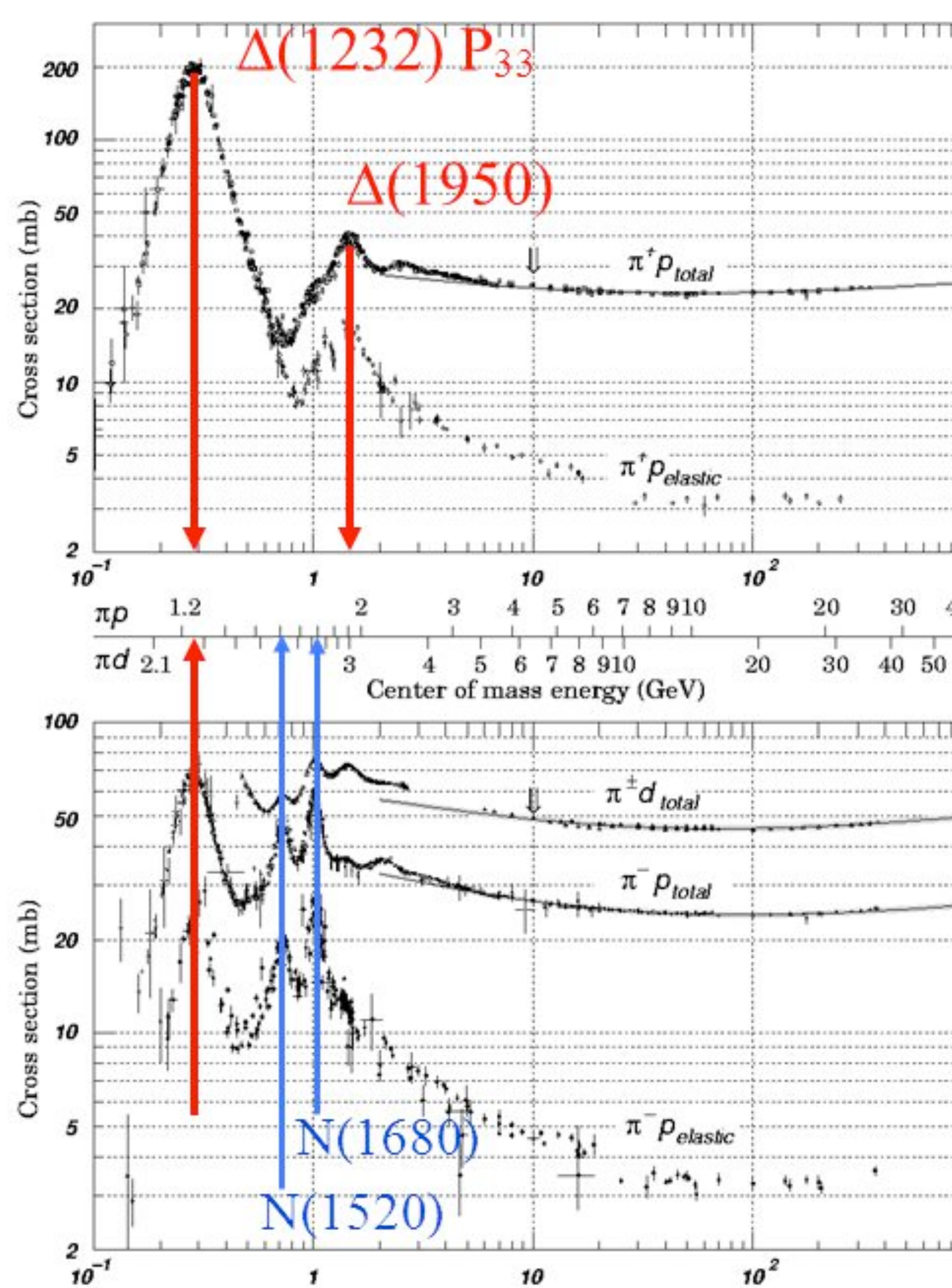


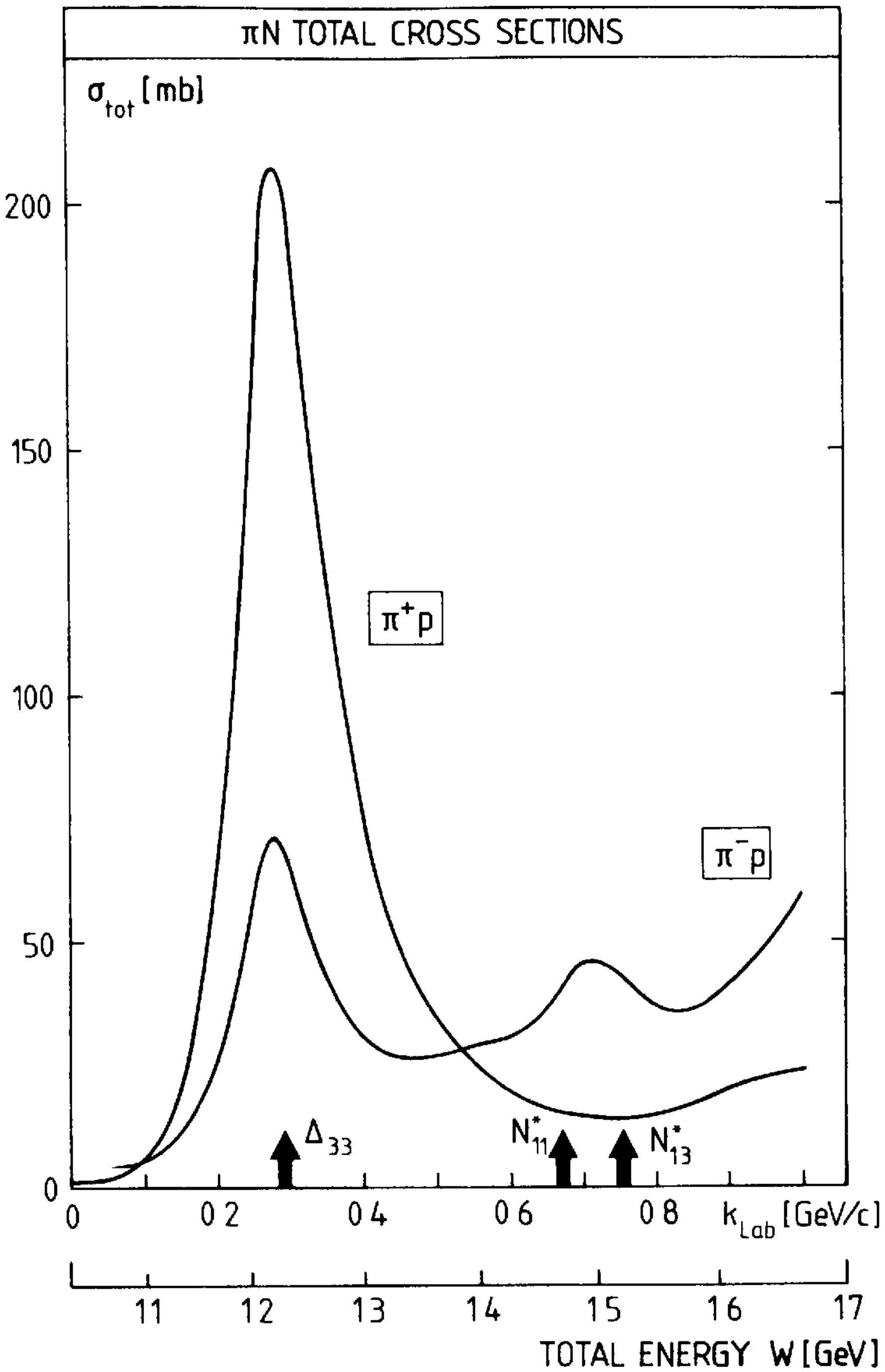
FIG. 2.2. Total cross-sections for π^+p and π^-p scattering as a function of the total c.m. energy W and the pion lab momentum k_{lab}.

Strong Pi-A FSI, Delta dominates



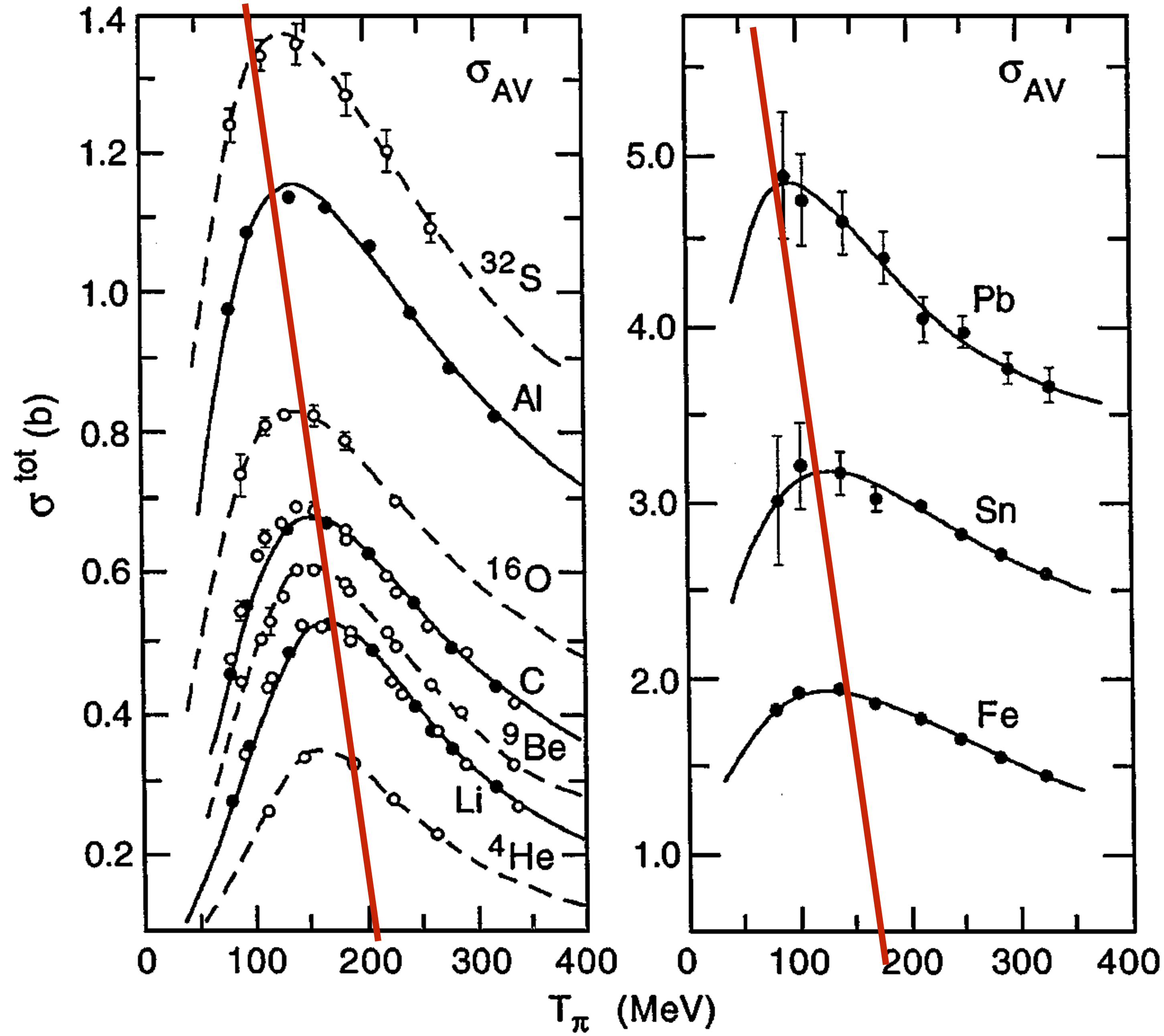
Nucleon vs Nucleus

PION–NUCLEON SCATTERING 17



tal 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}.

$\pi - A$



A.S. Carroll PRC 14,635

Peak shifts down in energy, gets broader as A goes up

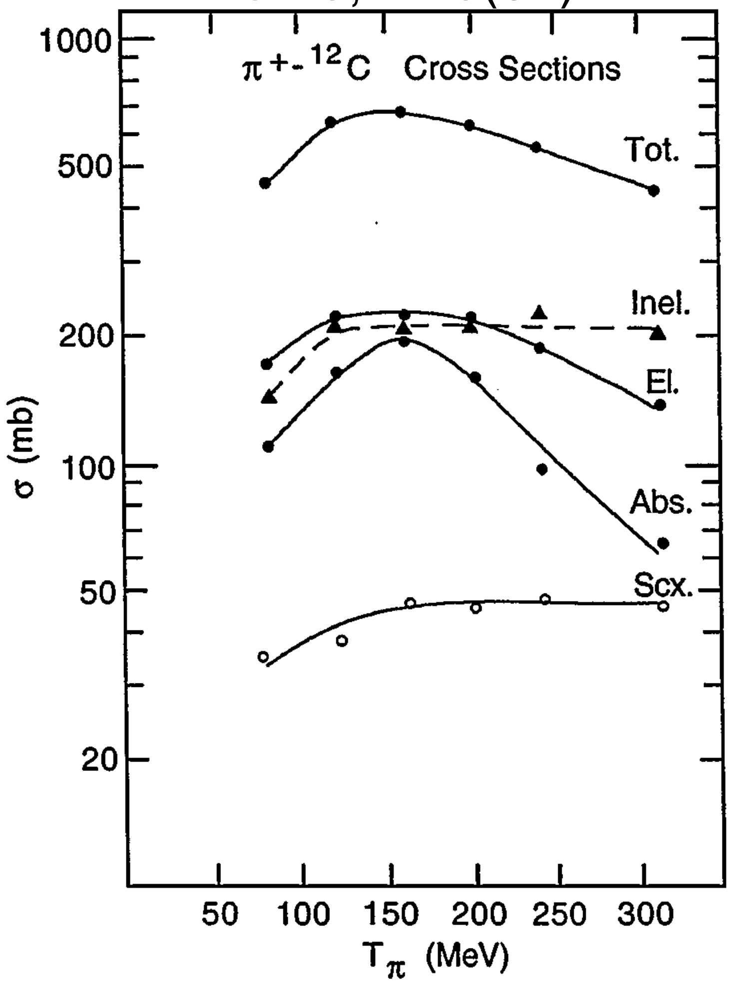
Fermi motion, Multiple scattering &absorption

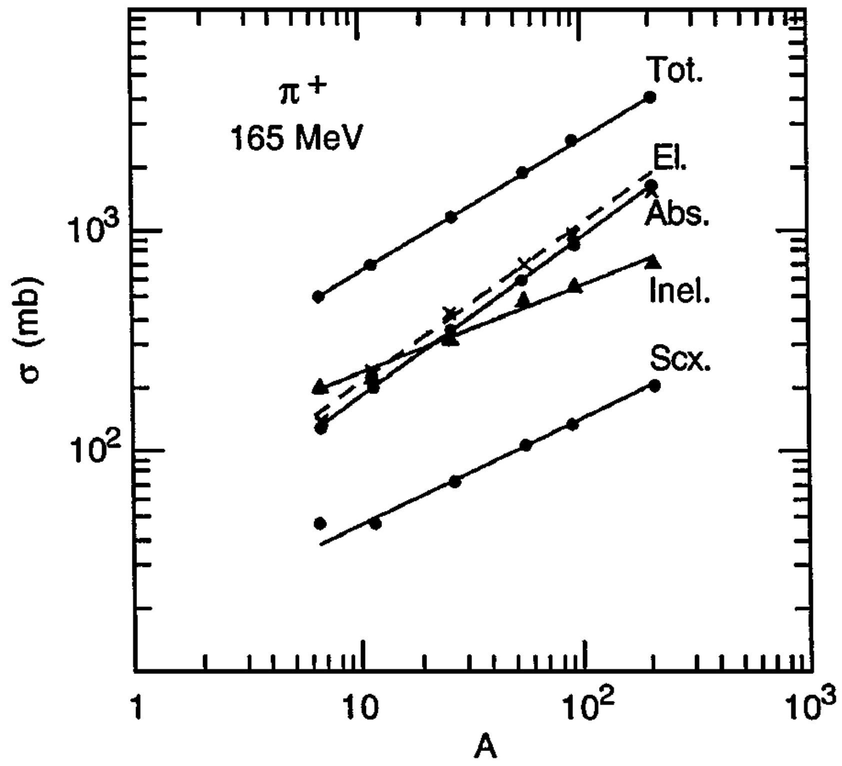
Free interactions not accurate

Delta physics dominates in given energy region

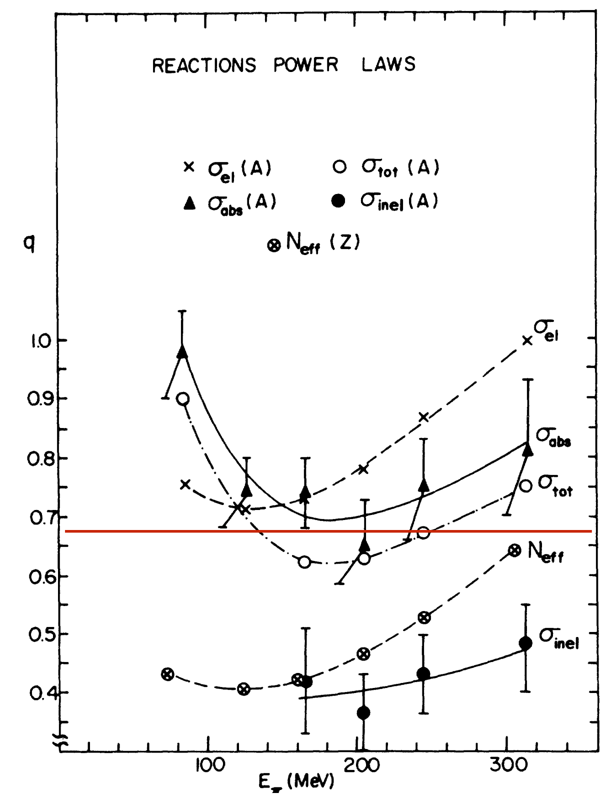
Partial Cross Sections

D. Ashery et al
PRC 23,2173(81)





$$\sigma_m \sim A^{q_m}$$



$A^{2/3}$

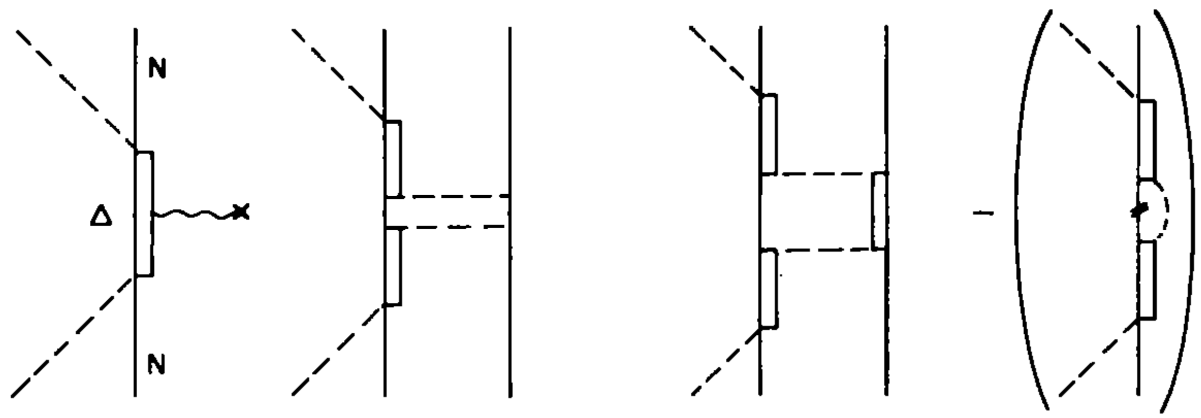
$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm inel} = N_{\rm eff} \times [\sigma(\pi^+ p) + \sigma(\pi^+ n)] \, .$$

- Δ physics is dominant
- Elastic about 1/3 of total
- Reaction = Inelastic+absorption+charge exchange
- absorption means pion disappears: $\pi + NN \to NN$.
- inelastic is mainly quasielastic knockout - π-nucleon elastic in medium
- all partial σ's rise with A, absorption rises faster than total
- at 300 MeV, $\sigma_{\rm el} \propto A$. Most you can get $A^{4/3}$ so not strong absorption

Δ made in the nucleus π

What does Δ do?

What is mass and width of Δ in the nucleus?



(a) (b) (c) (d)

Near resonance energies
Delta propagates in nucleus
Correct degree of freedom

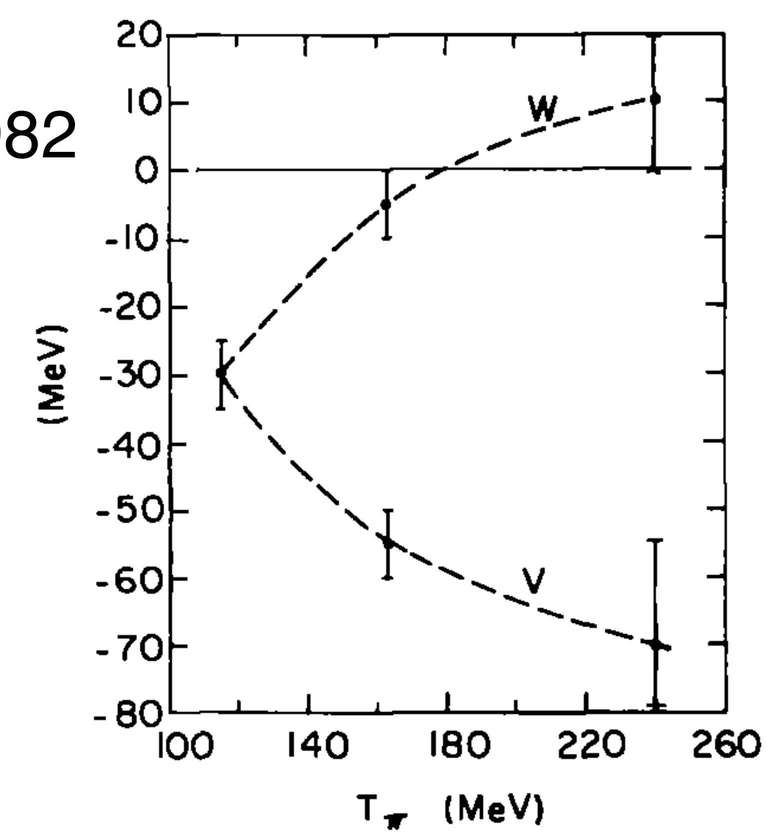
- (a) Feel mean field potential
- (b) Width increases due to pion absorption- 2 N intermediate on-shell
- (c) Multiple scattering
- (d) Width decreases due to Pauli blocking
- Effects of absorption and Pauli blocking tend to cancel

Literature: Delta in Medium

- Kissinger & Wang PRL 30, 1071, Ann. Phys. 99,374 Introduces Delta as Deg. Of Freedom-crude approximation - mainly shifts width but Delta kinetic energy ignored
- Oset & Weise PL B82, 344; Nucl. Rhys A319,477, ^{4}He. Pauli plus central potential gives -15 MeV, positive energy dependent $V_{\Delta-A} = -15 + 15i$ MeV
- Lenz, Moniz, Hirata, Koch PL B70, 281 (1977); Ann.Phys. 120, 205, ^{16}O $V_{\Delta-A} = -8 - 42i$ MeV plus Pauli -55 MeV central
- Freedman, Henley, Miller, PL B103, 397; Nucl. Phys. A389, 457 (1982) used local potential fit Pb see below
- D. Dreschel et al NPA 660,423 Coherent $\gamma + A \to \pi^0 + A$ to get $\Delta - A$ interaction

$V_{\Delta-A} = 19 - 33i$ MeV no Pauli

1982



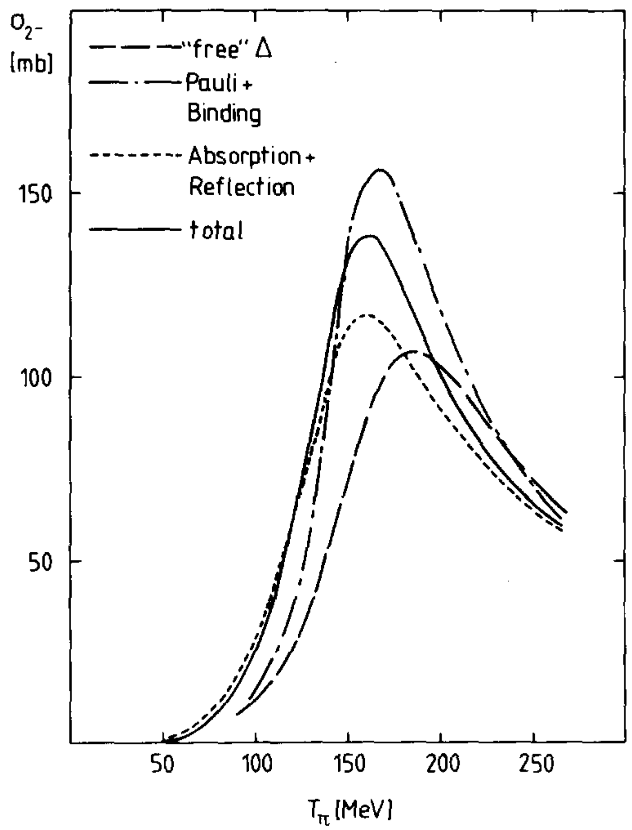
f the central strength $V+iW$ of the Δ-nucleus potential on pion laboratory kinetic determined by fits to experimental data are denoted by points with error bars.

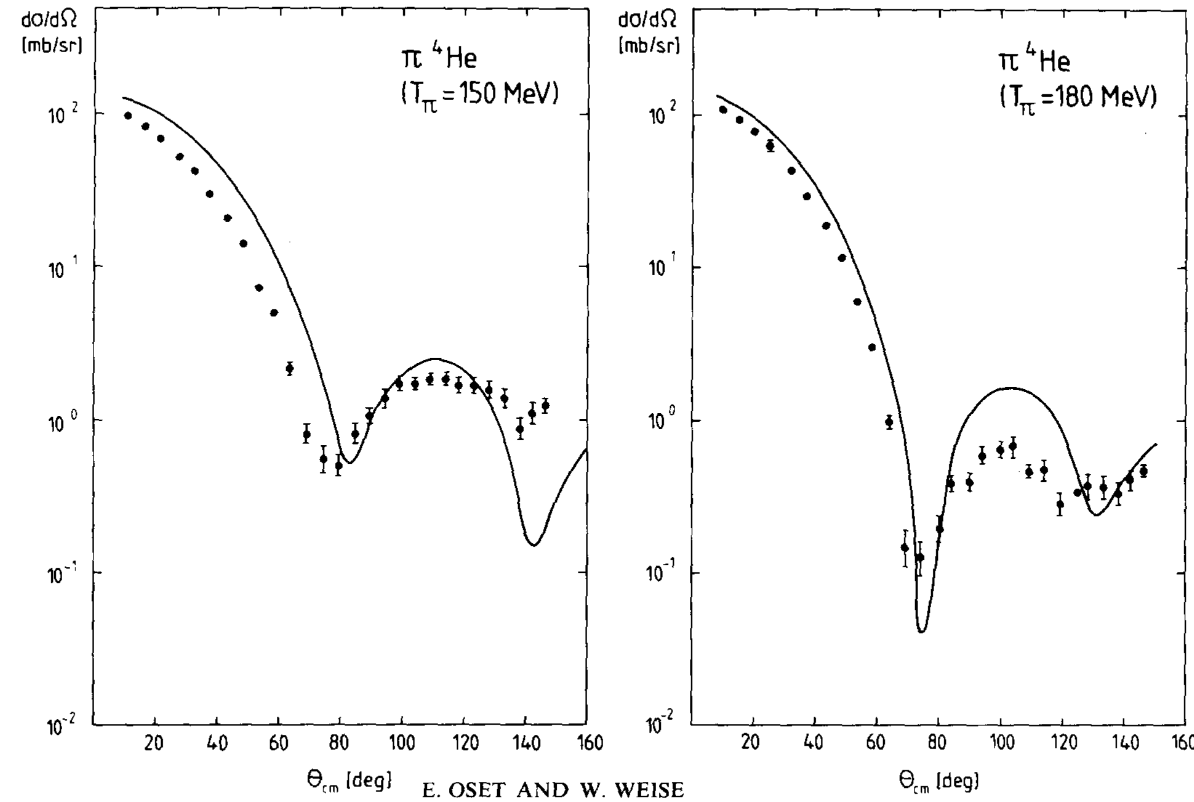
Width ~unchanged due to cancellations

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

Attractive nature of real part seems established

Nuclear Physics **A319** (1979) 477 – 517;





E. OSET AND W. WEISE

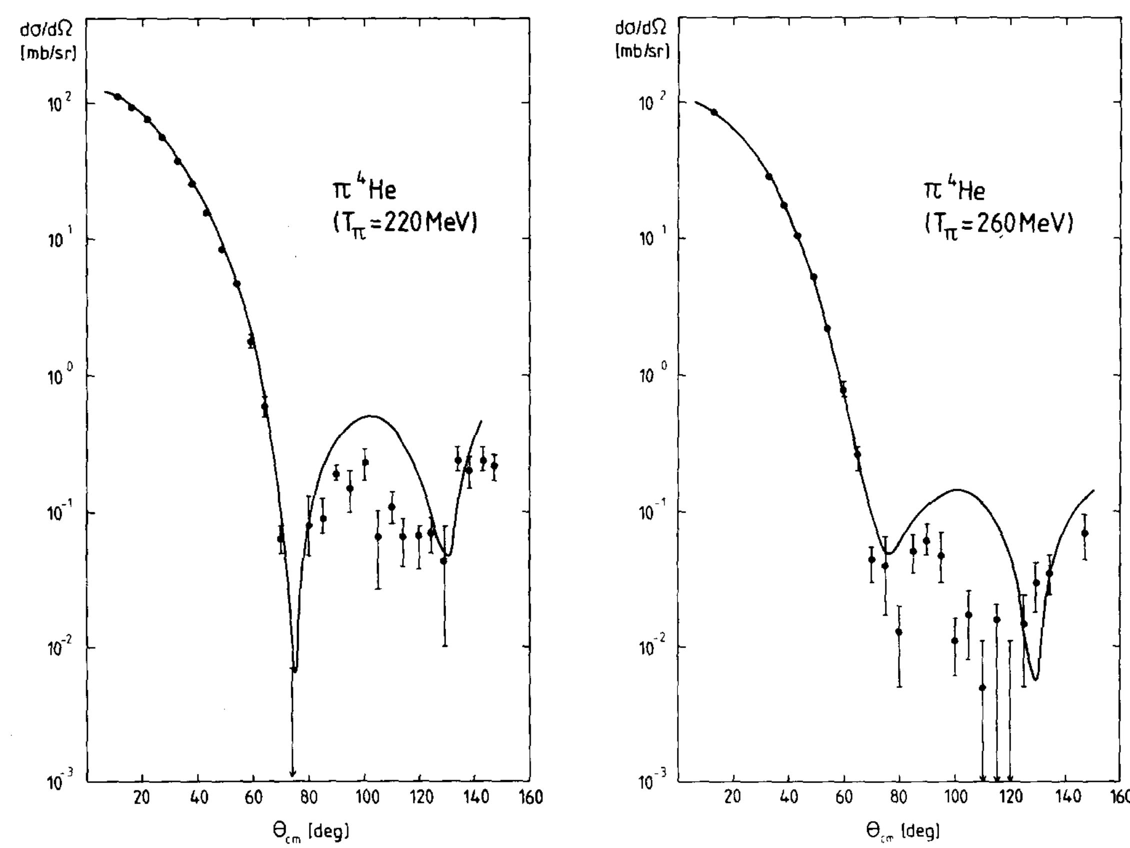


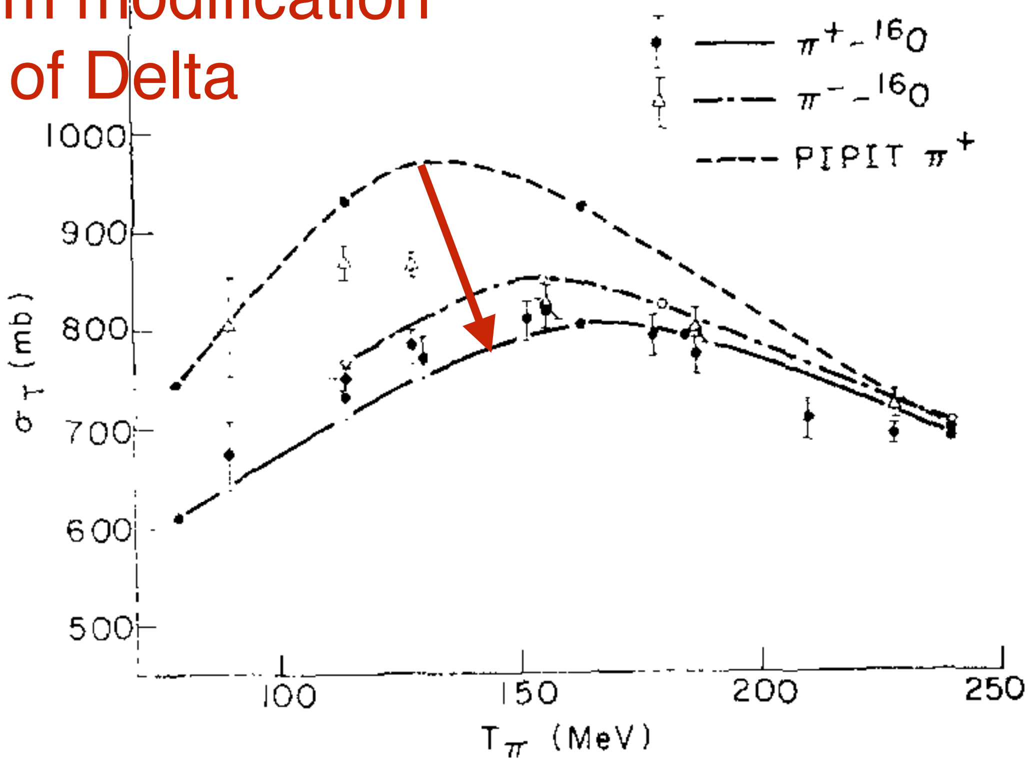
Fig. 15. Differential π-^{4}He cross section calculated at various energies with full isobar-hole interaction and all self-energy corrections. Experimental data are from ref. [29]).

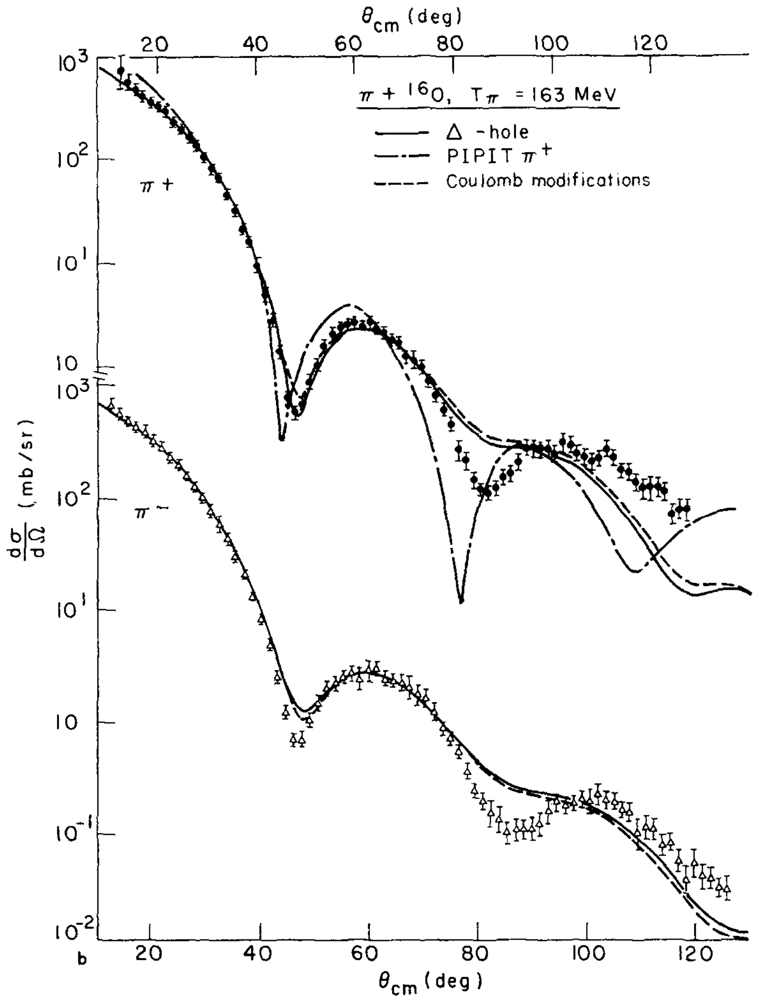
Delta modification in medium is important

Hirata, Koch, Lenz , Moniz

ANNALS OF PHYSICS **120**, 205–248 (1979)   ISOBAR-HOLE DOORWAY STATES

Medium modification of Delta

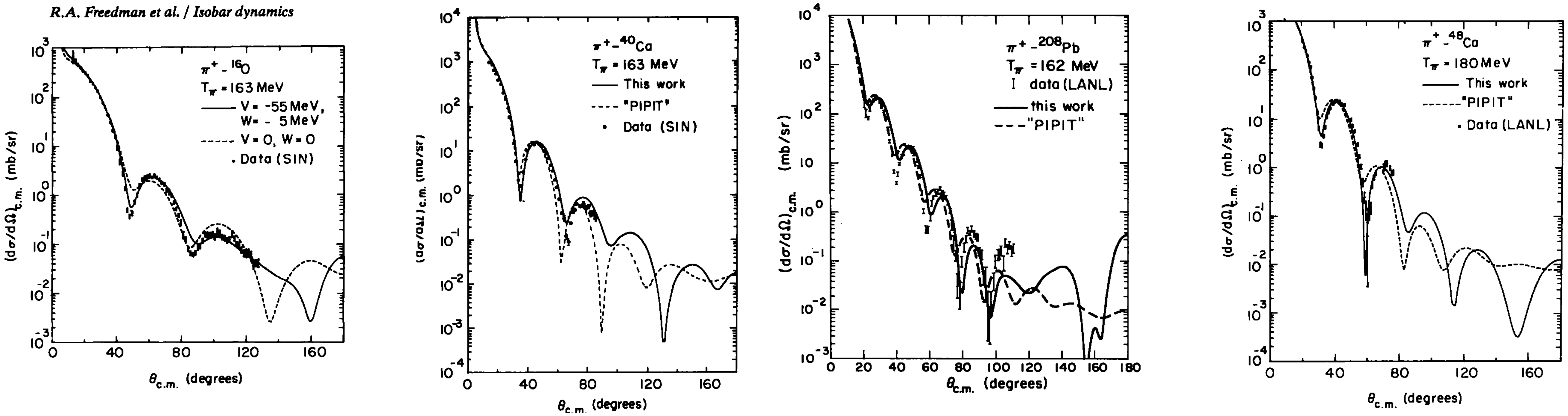




ISOBAR DYNAMICS AND PION–NUCLEUS ELASTIC SCATTERING

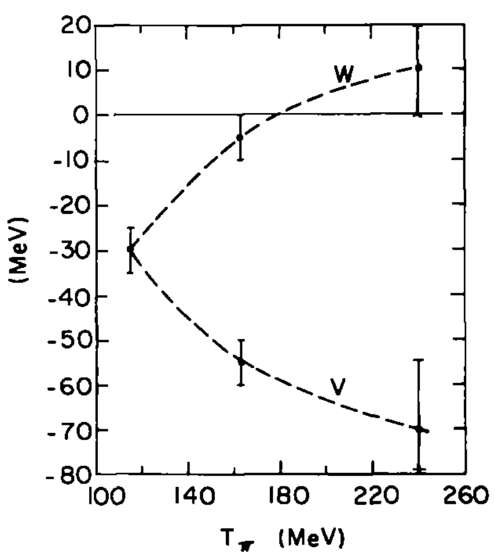
Nuclear Physics A389 (1982) 457–491

ROGER A. FREEDMAN*, GERALD A. MILLER and E.M. HENLEY



Strength of central Delta-Nucleus potential

Again - Delta interactions in medium are important



$$(V+iW)/T_R = a + b(T_\pi/T_R) + c(T_\pi/T_R)^2 ,$$

$T_R = 180$ MeV, we find

$$a = 0.44 - i0.77 ,$$

$$b = -1.24 + i1.24 ,$$

$$c = 0.47 - i0.47 .$$

Qualitative agreement with Hirata et al

Photoproduction

432 *D. Drechsel et al. / Nuclear Physics A 660 (1999) 423–438*

Medium modification of Delta

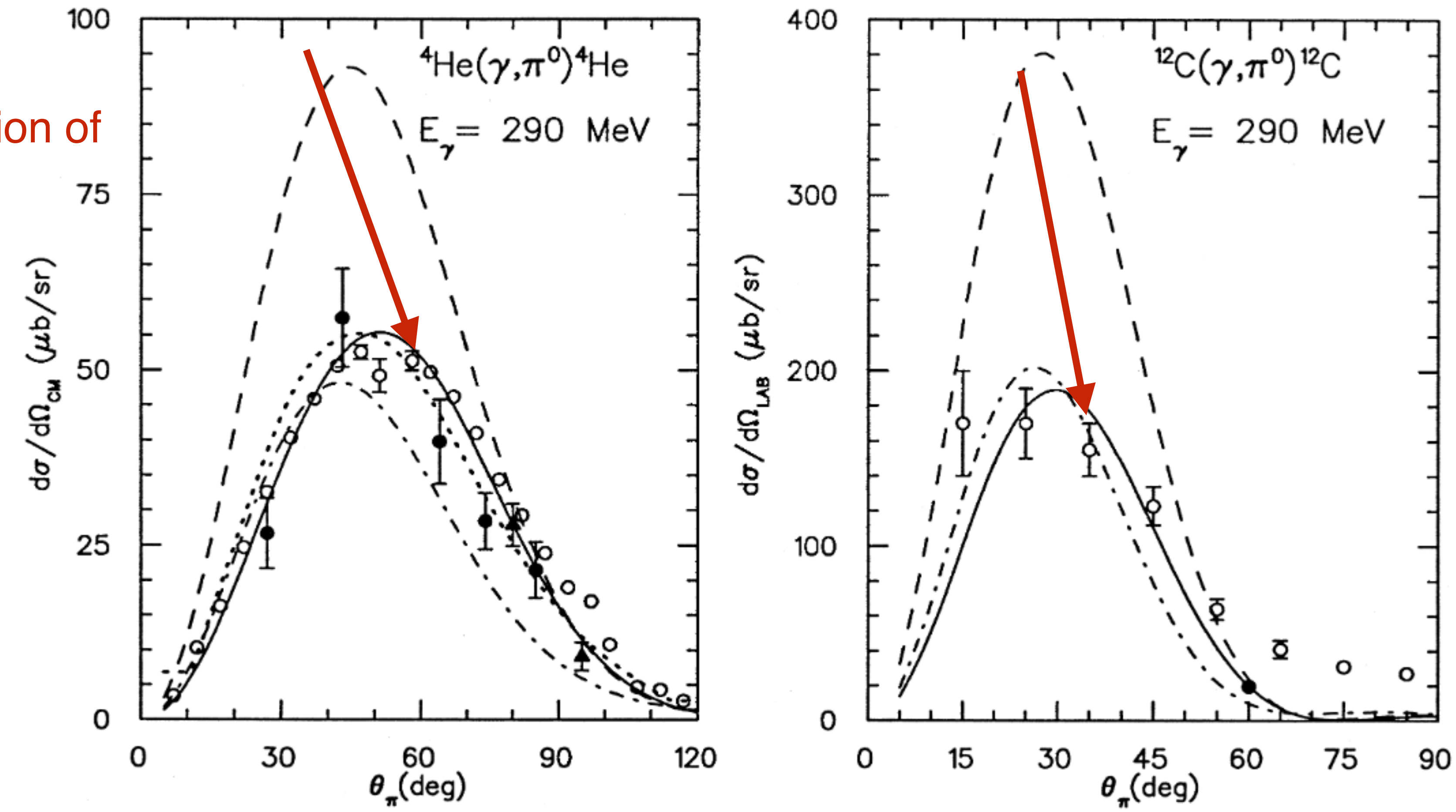


Fig. 2. The differential cross sections for the ^{4}He(γ,π^0)^{4}He and ^{12}C(γ,π^0)^{12}C reactions at photon lab energy $E_\gamma = 290$ MeV. Dashed curves are the DWIA results. The dash-dotted and solid curves are the results obtained with ρ-type (29) and F-type (28) parametrizations for the Δ self-energy. The dotted curve is the Δ-hole model calculation taken from Ref. [10,11] and recalculated in the π^4He c.m. frame. Experimental data for ^{4}He are from Ref. [38] (open circles), Ref. [39] (full circles) and Ref. [40] (full triangles). Experimental data for ^{12}C are from Ref. [43] (open circles) and Ref. [46] (full circles).

Medium modification of Delta reduces cross section by a factor of 2

Says same parameters as Hirata et al, but not so

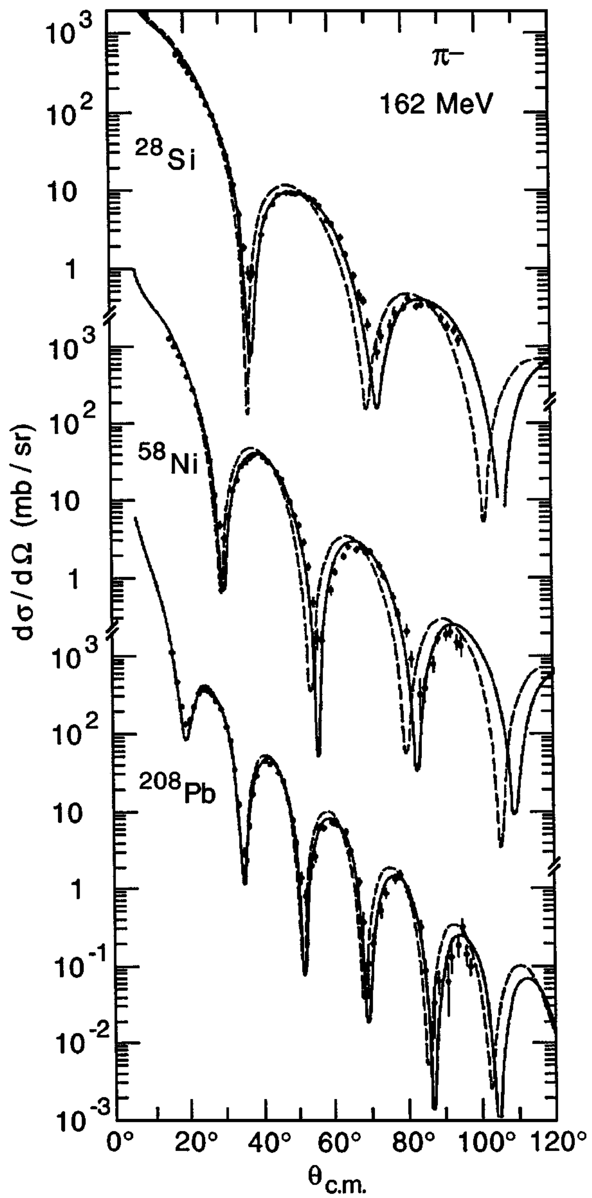
Summary: Delta in Medium

- all authors agree that Δ is the correct degree of freedom
- all authors agree that Δ is modified in the nucleus by its interactions with the medium
- Only one work treated heavy nuclei with $N \neq Z$: Freedman, Miller & Henley NP A389 (1982) 457
- Freedman, Miller & Henley NP A389 (1982) 457: Best fit in energy range, most nuclei, simplest parametrization of interaction. best to use in neutrino-nucleus codes?

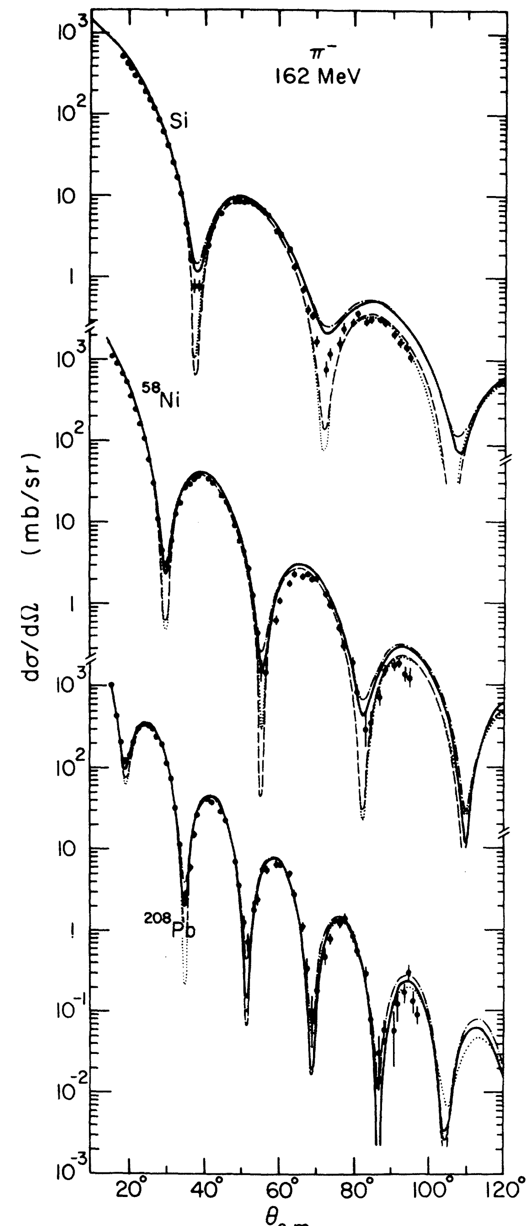
Elastic Pi-Nucleus-caution

Black disk scattering

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



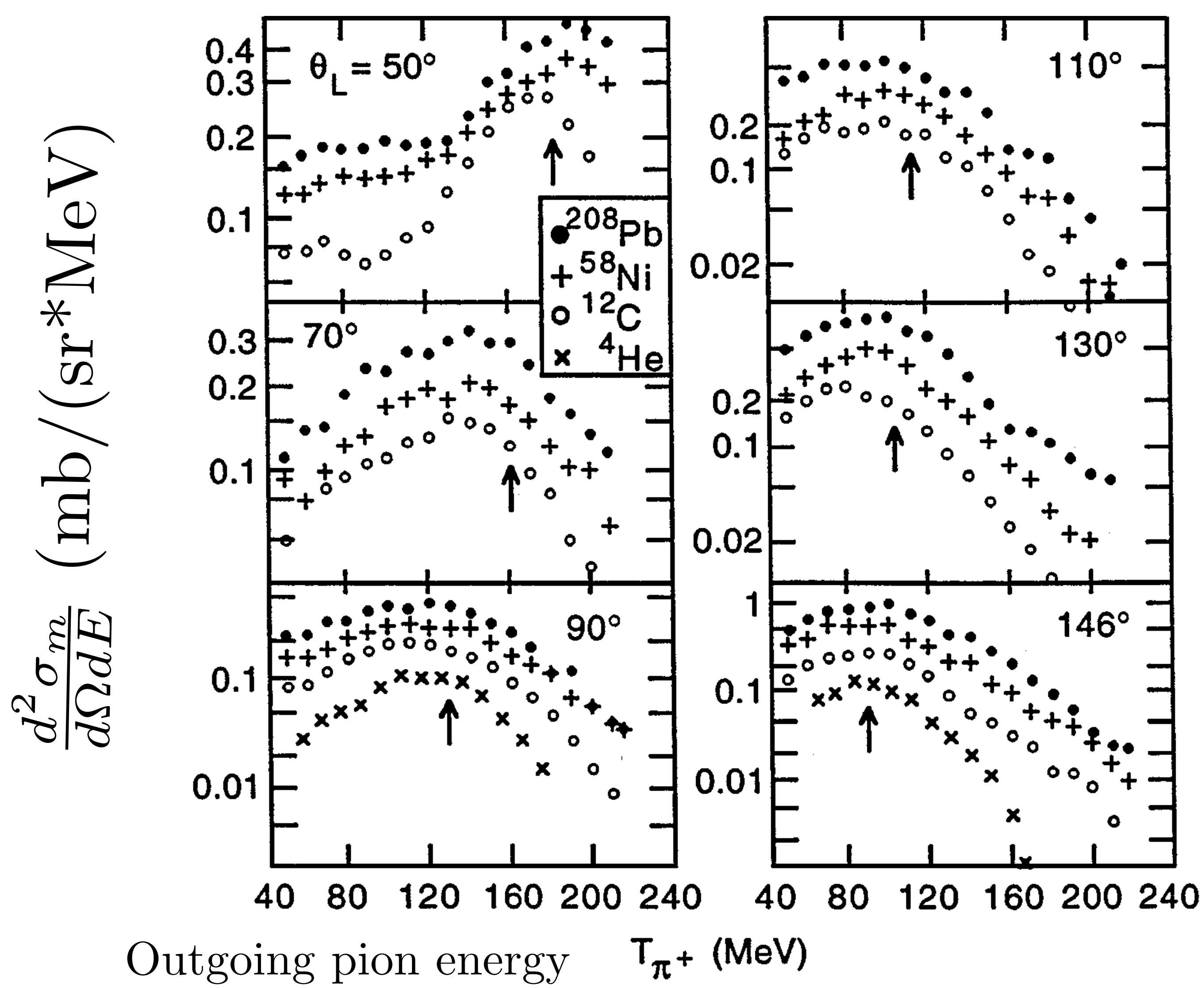
Zeidman PRL 40,1316



Olmer PRC 21,254
Dashed -decrease nuclear radius by about 0.1fm
Solid -includes binding correction

Inelastic -exclusive processes

(π, π') inclusive

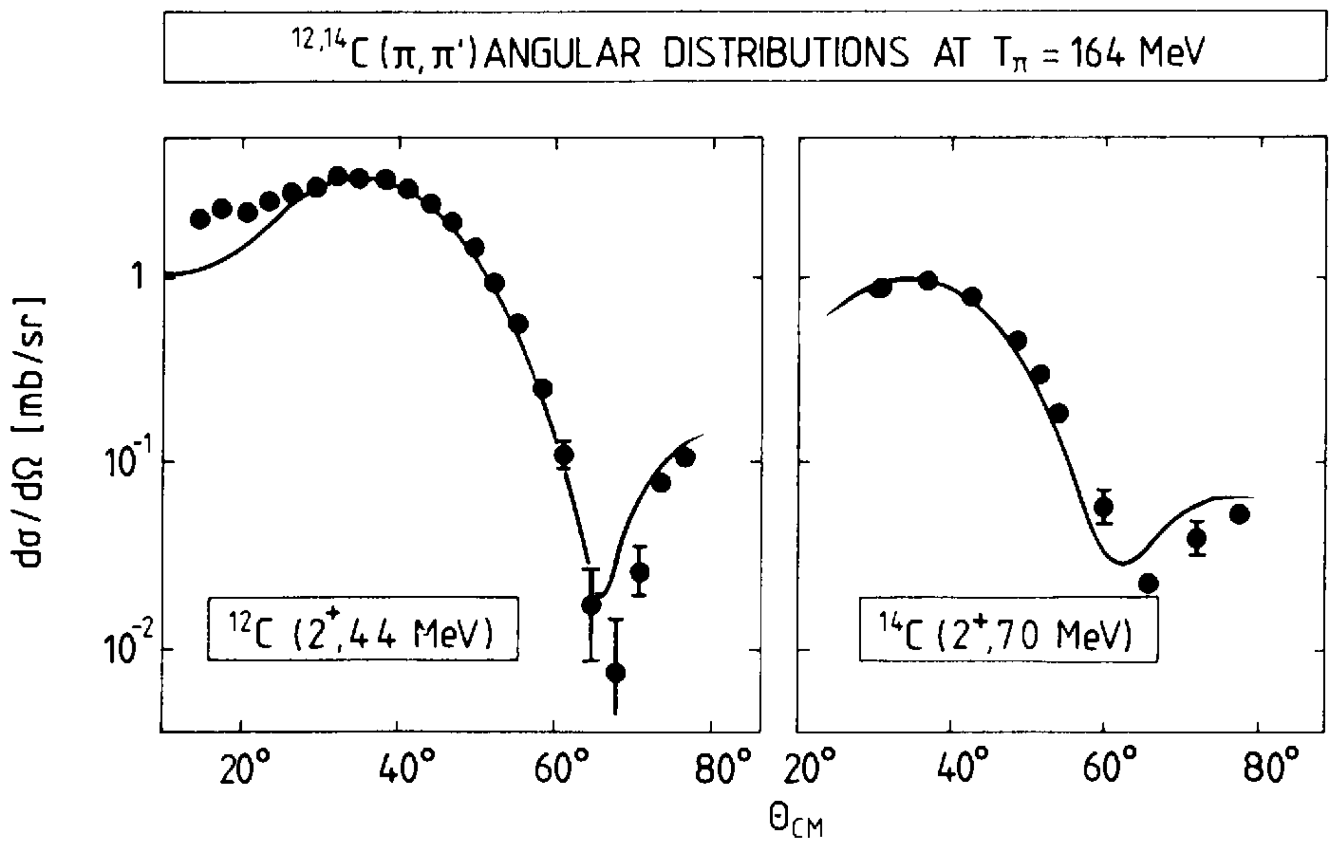


Key point- pion-nucleon interaction is modified by the medium
Free cross sections are not accurate

Levenson et al PRL 47,479 (81) PRC21,1452(80)

Arrows show position of peak if no medium effect
Mechanism is quasi-elastic knockout
But width is larger than in free space

pion-nucleus inelastic discrete final state



NPA 374, 377c

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

Much smaller cross section than inclusive

Inelastic (~1 mb/sr) is dominated by quasi free (200 mb total)

Pion absorption

Deuteron

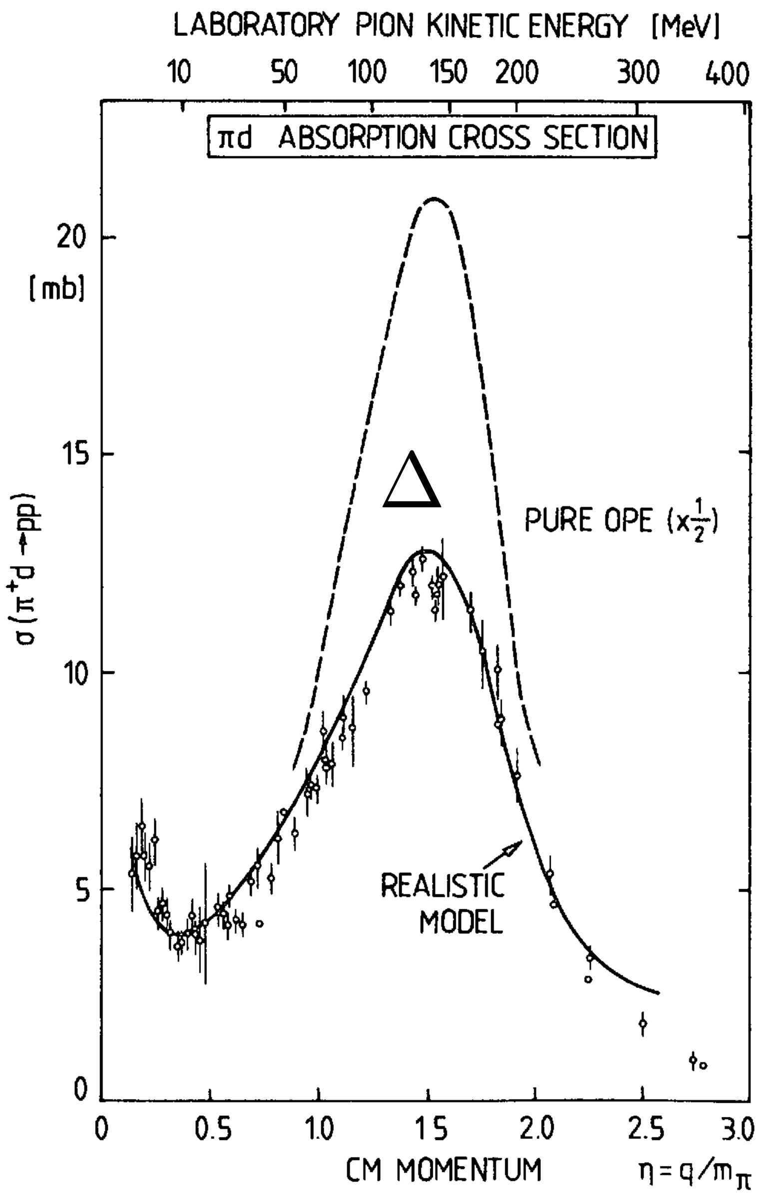


Fig. 4.11. The absorption cross section $\sigma(\pi^+ d \to pp)$ as described by the OPE Δ-model compared to results of a rescattering approach with a realistic tensor interaction and including the s-wave rescattering and the impulse approximation contributions. (From Riska *et al.* 1977; Maxwell *et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

Shape changes in nuclei, peak position shifts and broadens

A >5

Ashery et al PRC 23, 2173

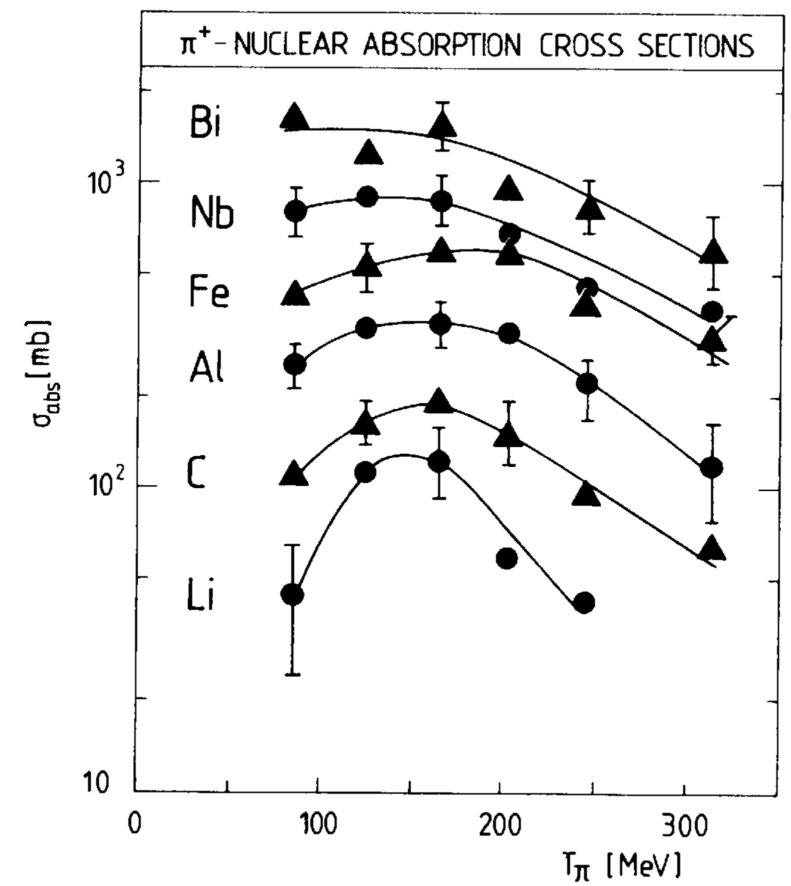


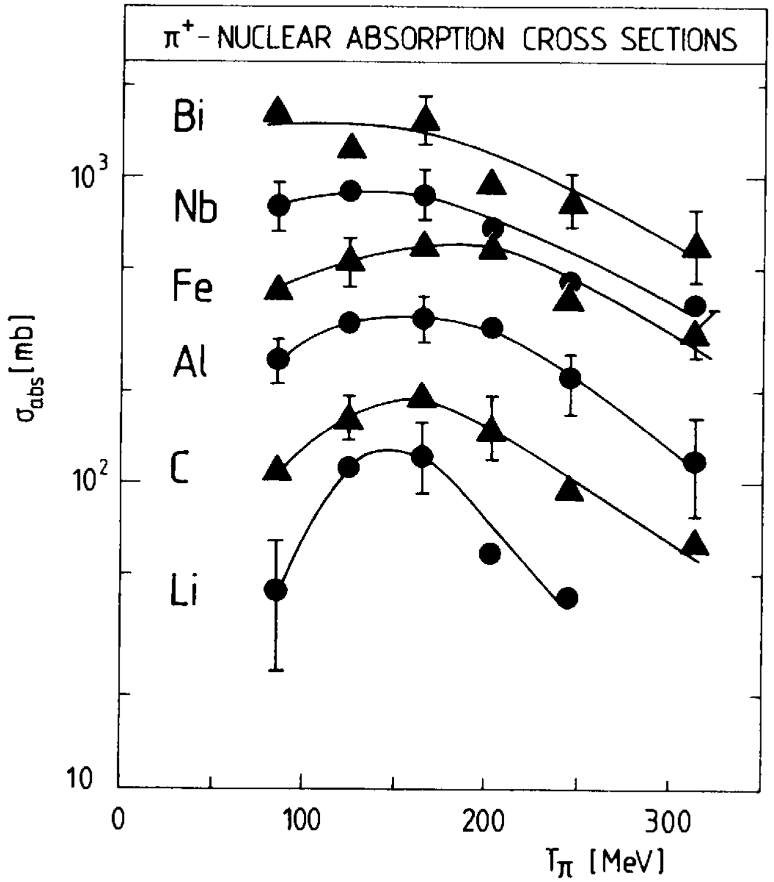
Fig. 7.31. Pion absorption cross-section for various nuclei as a incident kinetic energy T_π. (From Ashery *et al.* 1981*b*.)

confirmed 12C

Phys. Rev. C 95, 045203 (2017)

Many more decay channels in nuclei -multi-body absorption

Pion absorption on Nuclei



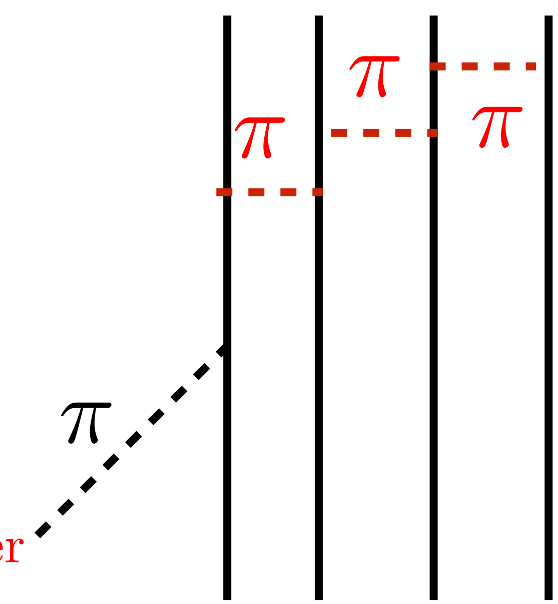
7.31. Pion absorption cross-section for various nuclei as a function of incident kinetic energy T_π. (From Ashery *et al.* 1981*b*.)

Broader width
Many more decay channels in nuclei - multi-body absorption

4 nucleons in final state

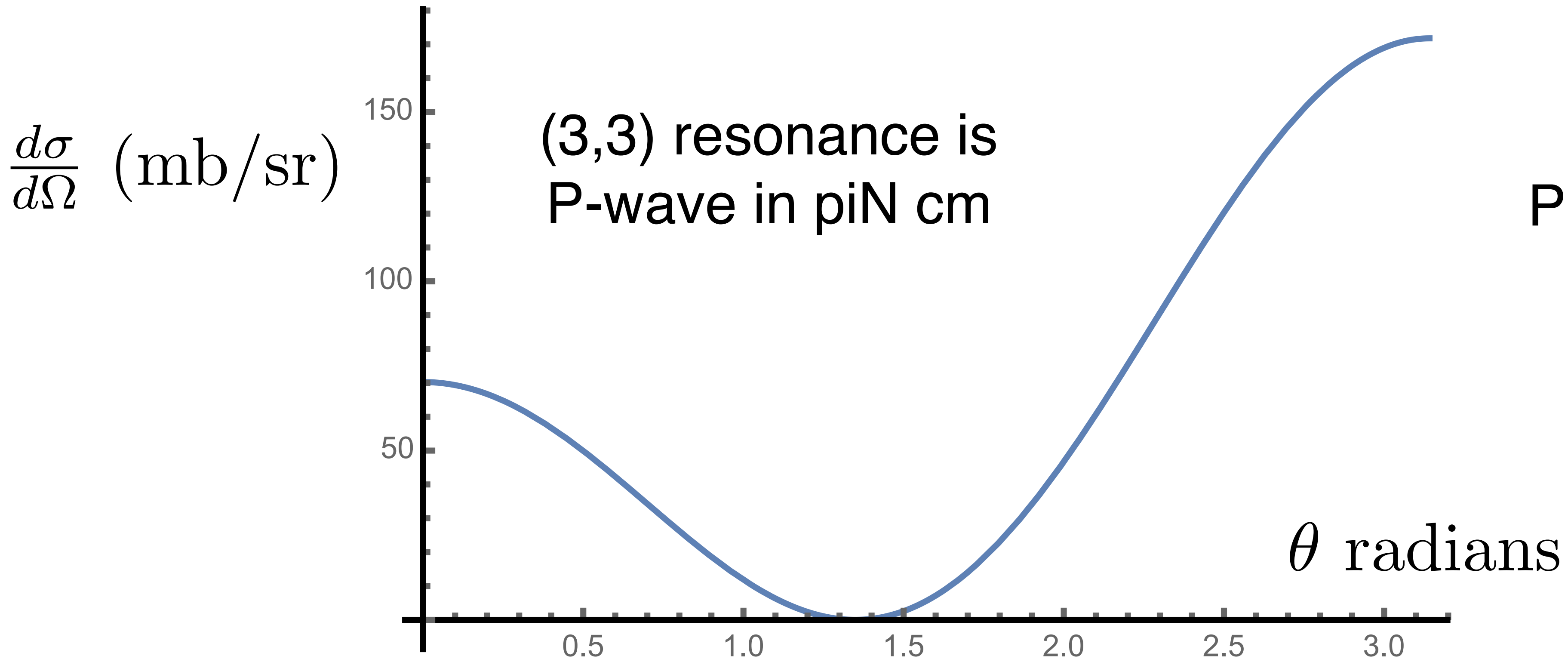
Mechanisms for pion absorption

- $\pi^+ + np \to np$
- $\pi^+ + np \to np$ followed by final state nucleon-nucleon knockout or neutron emission
- $\pi + \text{multi} - \text{nucleon} \to \text{multi} - \text{nucleon}$ needs all nucleon close together -needs theory to separate
- pion multiple scattering in initial state followed by absorption on 2 or more nucleons (ISI)



Are red pi's real or virtual?
Need detailed kinematics to separate mechanisms

Strong pion final state interactions



Pi-nucleon elastic

Pion back scatters, loses energy, sometimes knocking a nucleon out of the nucleus
this could happen several times (red pions are real)
and then . . .

Pion is absorbed on at least 2 nucleons
This mechanism is called initial state interaction, ISI
More than two nucleons are involved

Pion absorption LADS detector
Kotlinski et al EPJ A 1,435 (98), 9,537 (00)

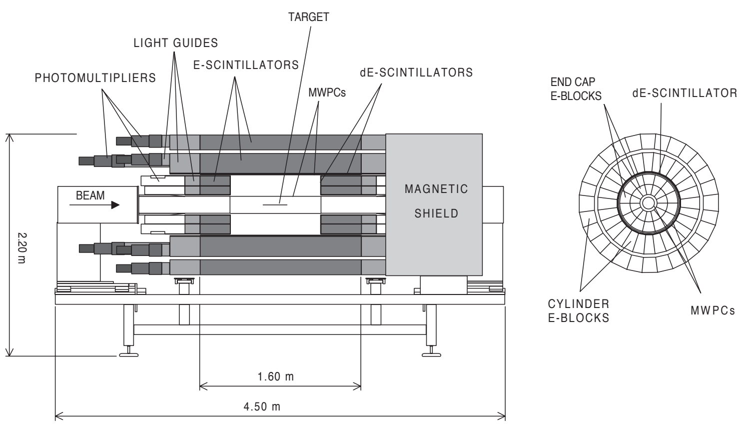


Fig. 1. A schematic view of the LADS detector

Covered multi-particle final states at PSI

First article - ISI in $(\pi^+, 3p)$ is small except for 40% at $T_\pi \geq 250$ MeV

$\approx$ independent of nucleus for $A \geq 4$

9,537

T_π(MeV)	162
6p	–
5p	0.25±0.20
5pn	–
4p	4.9±1.2
4pn	3.9±1.3
4p2n	–
3p	47.±10.
3pn	31.8±8.0
3p2n	–
3p3n	–
2p	79.±16.
2p1n	123.±23.
2p2n	≤10.
2p3n	–
3pdn	2.2 ±1.0
2p2d	≤2.
3pd	3.8 ±1.0
p2dn	≤2.4
p2d	≤2.2
2pdn	12. ±3.2
2pd	12. ±2.4
pd	6.4 ±1.7
pdn	16. ±4.
pd2n	–
2d	≤1.2
2dn	≤2.8
sum	351±40

pp only 23 % of total absorption

2pn is 35 %
3p is 13 %
3pn is 9 %

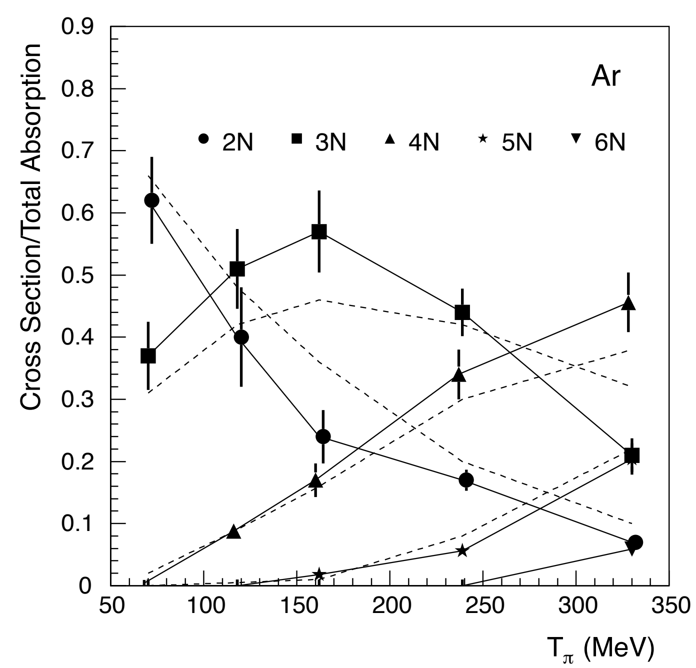


Fig. 10. Comparison of 2N (two particle), 3N, 4N, 5N and 6N cross-section fractions for the π^++ Ar pion absorption reaction as a function of pion kinetic energy. The plot shows cross-sections divided by the sum of all measured partial cross-sections. The solid lines connect the data points for a given multiplicity to guide the eye. The dashed lines are calculations with the simple phase space model of appendix A.

Final state multiplicities determined by available phase space dashed curves

Suggests (not proved) fsi dominant

Model:
All fsi cross sections =100 mb

What else can pion do?

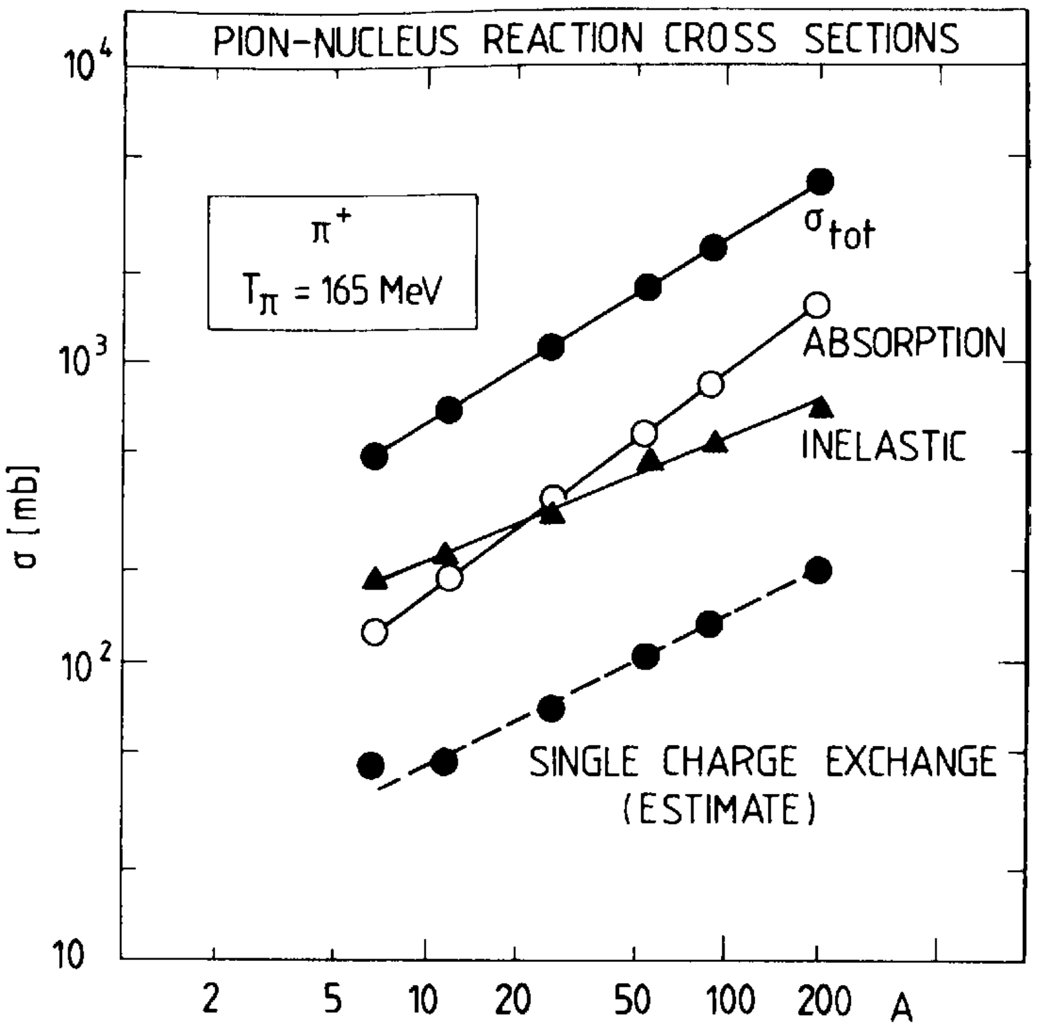


FIG. 7.22. Inelastic, absorption, and single-charge exchange (SCE) cross-sections for 165 MeV π^+ reactions with various nuclei as a function of nuclear mass number A. The SCE cross-sections are semi-empirical estimates. The total cross-section σ_{tot} is shown for comparison. (From Ashery *et al*. 1981*b*.)

Single
charge ex SCE change

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

SCE is small. DCE is even smaller.

Summary of pion-nucleus interaction

Total cross section is roughly equal parts: Elastic, quasi-free knockout, absorption

Absorption involves more than 2 nucleons 77% probability

Detailed mechanism not established

Cross section do not generally vary as $A^{2/3}$

Delta physics very important

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, 2838 1 DECEMBER 1980

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

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(Received 27 May 1980)

Cloudy bag model

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.

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

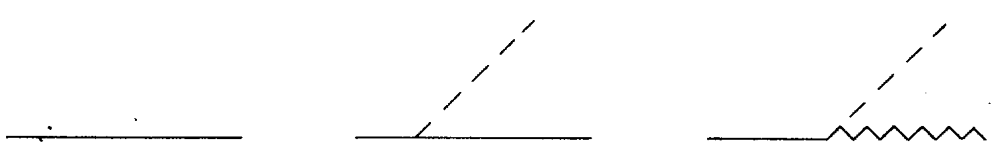


FIG. 3. The physical nucleon [from Eq. (3.16)].

+ HC - Cloudy Bag Model Hamiltonian

What is a Delta?

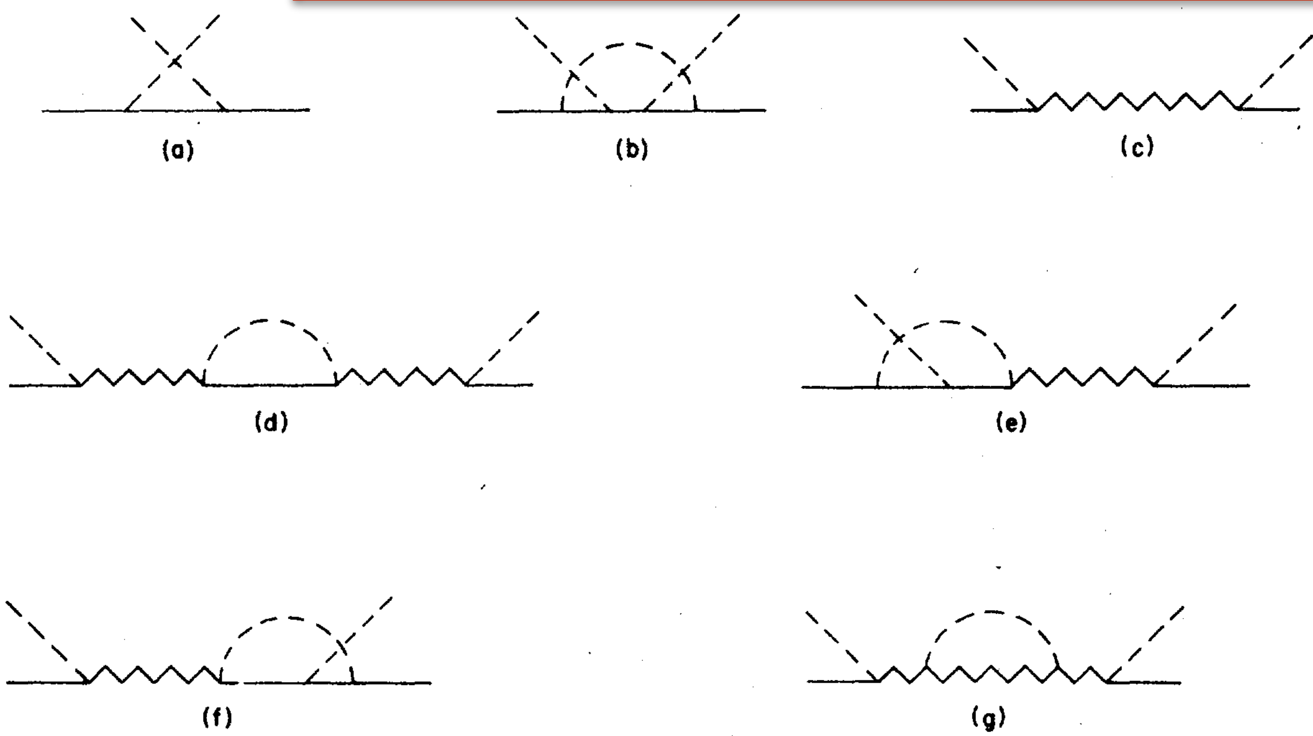


FIG. 8. Terms of Eq. (3.25) after renormalization.

Pion-nucleon scattering in resonance region

3 quark Delta is 80 % of physical state

Delta is simplest resonance!

$$|\Delta\rangle = Z\left(|3\,\mathrm{quark}\rangle + |N\pi\rangle\right), \quad Z = 0.9$$

mainly Delta

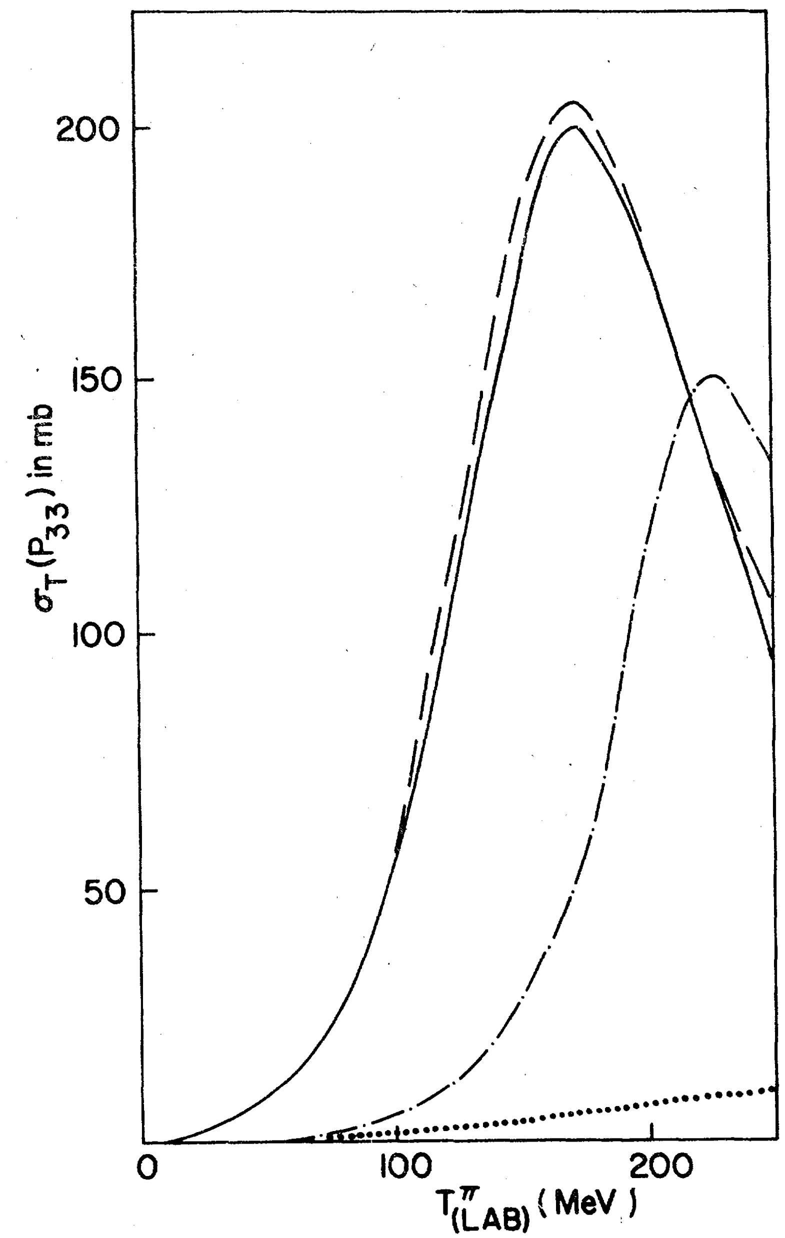


FIG. 11. Best fit in the cloudy bag model (dashed curve) to the experimental P_{33} total cross section (solid). The dash-dotted line shows the effect of arbitrarily setting $f_{NN\pi}(f_{\Delta N\pi})$ to zero, with all other parameters unchanged.

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

General remark 1

NEUT PRD 99,052007 says: In nuclei neutrino energy reconstruction is smeared by the initial state nucleon momentum ”

What is the probability that a nucleon at a position $\mathbf{R}$ has a momentum $\mathbf{p}$?

Answer - Wigner distribution $f(\mathbf{R},\mathbf{p})$

Density matrix $\rho(\mathbf{R}+\mathbf{s}/2,\mathbf{R}-\mathbf{s}/2) \equiv \langle A|\psi^\dagger(\mathbf{R}+\mathbf{s}/2)\psi(\mathbf{R}-\mathbf{s}/2)|A\rangle$

$f(\mathbf{R},\mathbf{p}) \equiv \int \frac{d^3s}{(2\pi)^3}\rho(\mathbf{R}+\mathbf{s}/2,\mathbf{R}-\mathbf{s}/2)e^{i\mathbf{p}\cdot\mathbf{s}}$

$\rho(\mathbf{R}) = \int d^3p\, f(\mathbf{R},\mathbf{p}), \quad n(\mathbf{p}) = \int d^3R\, f(\mathbf{R},\mathbf{p})$

Example Fermi gas of neutrons

$\rho(\mathbf{R}+\mathbf{s}/2,\mathbf{R}-\mathbf{s}/2) = \rho_0\frac{3j_1(sk_F)}{sk_F}$

$n(\mathbf{p}) = \text{Const}\,\Theta(k_F-p)$ as expected

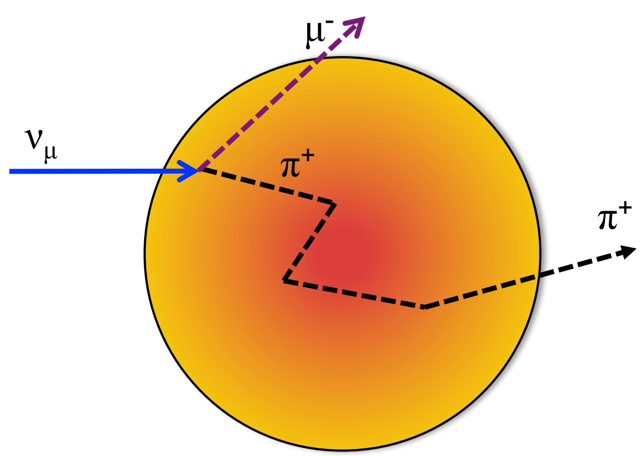
$\langle p^2\rangle = \int d^3p^2 n(p) = \frac{3}{5}k_F^2$ as expected

In general $\langle p^2\rangle = \int d^3Rd^3p\,p^2 f(\mathbf{R},\mathbf{p})$

For models of $\rho(\mathbf{R}+\mathbf{s}/2,\mathbf{R}-\mathbf{s}/2)$. Google ‘density matrix expansion’

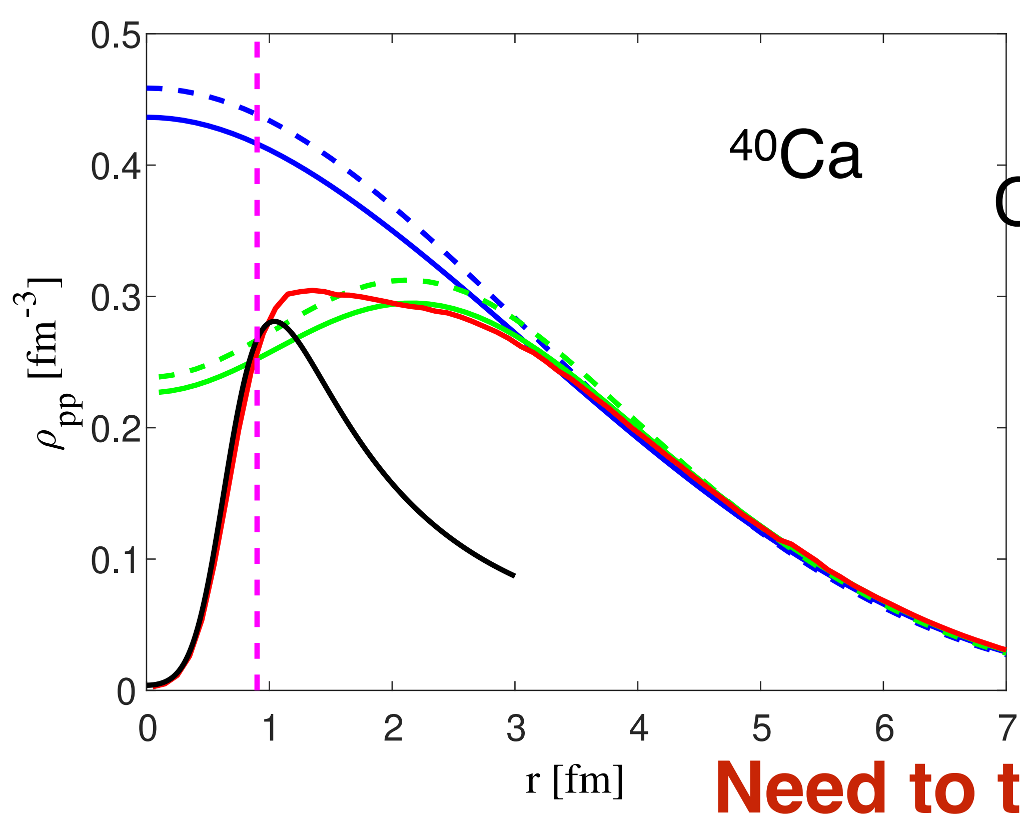
Can get good model of probability that nucleon at given position has given momentum

General remark 2
NEUT PRD 99,052007 says: steps in space are
dx =R_N/100, R_N (Carbon) =6.1, dx=0.06 fm!



Internucleon spacing is about 1.7 fm
Radius of proton is 0.84 fm
28 steps inside the proton???

Weiss et al PLB 790,484 (201)



$\rho_{pp}(r)$: **probability that two protons are separated by distance r.**

The full result is the red curve

Caveat -based on ANL V18 potential -model dependent

Need to take granularity of nuclear density into account

Summary

- Pions can be made from resonance decay or quasi-elastic & fsi
- A resonance is a complicated object - medium modifications are complicated
- Pion-A total cross section: equal parts elastic, inelastic (quasielastic pi-N scattering) and absorption
- Absorption leads to 3 or more particles in the final state 77% of the time
- The Wigner distribution gives probability of nucleon having given momentum and position
- Take granularity of nuclear density into account