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PION PHOTOPRODUCTION BY POLARIZED γ-RAYS *

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My report is made easier by the fact that work on pion photoproduction with polarized x-rays is going on at only three places: DESY, Frascati, and Stanford. I shall confine myself largely to work which has taken place since the DESY conference.

Diambrini will discuss later the problems of making polarized x-rays, but I will mention some of these problems since they determine what data is possible and also seriously affect the reliability. The technique used at Stanford is to select from the normal bremsstrahlung a polarized component. Figure 1 shows the polarization from a 10^{-3} radiation length target. The polarization is never large and is only appreciable when the photon energy is considerably less than the peak beam energy. It is therefore difficult to determine the photon energy unless one is dealing with a two body final state. Backgrounds of pair production must be eliminated either kinematically or by a detailed study indicating that they are small. The net result is that it is necessary to work closer to the peak of the bremsstrahlung than otherwise desirable and hence with very small polarization.

The monocrystalline methods used at DESY and Frascati produce quite large (30%) polarizations in the enhanced peaks and the enhancement of the peak helps in the selection of the photon energy. Figure 2 shows the peak available in the experiment of Barbiellini, et al.,[1] on π^0 photoproduction. Such enhancement again unfortunately occurs only for photons having energies low compared to the beam energy.

The problem of working at an energy appreciably lower than the peak of the bremsstrahlung is accentuated as one goes to higher energies. Figure 3 shows an excitation function made by Liu and Vitale[2] in their study of π^+ production. In this work the momentum of the spectrometer detecting the π's is held constant and the beam energy varied. One, in effect, sweeps out a reflected bremsstrahlung spectrum. At the lower beam energies there is insufficient energy to produce π's. The yield increases after the threshold energy is reached and flattens as the number of photons in the energy interval of interest becomes relatively constant. If there were no π pair contamination, the curve would remain flat as the energy is raised; therefore the slope appearing at high energies is due to π pair production. These π's are made with the photons from the peak of the bremsstrahlung while the desired π's are made from the lower, more highly polarized bremsstrahlung. As a result the peak energy of the machine must be kept sufficiently low to allow only a few percent of such contamination, thus appreciably reducing the polarization of the desired energy range. In the same figure the polarization available for a given peak energy is also plotted. At low energies this problem is not as severe since it is possible kinematically to exclude pairs without reducing the available polarization to an unreasonable level.

For π^0's the problem at high energies is even more severe if only the recoil proton is detected. Figure 4 shows an excitation function made by Zdarko and myself. Here, there is less kinematic exclusion of the pairs and in addition there is a background of "ghost" protons. These evidence themselves by preventing the curves from going to zero below threshold. Such protons have been observed both at Stanford and at Caltech and are due to a second order process:

$$\gamma + P \longrightarrow \pi^+ + N$$
$$\pi^+ + P \longrightarrow \pi^+ + P$$

This produces a higher momentum than would be directly produced at that energy. Both the production of the π's and the subsequent scattering occur with the large cross-section of the first resonance. Since both the production and the scattering can take place over a large range of angles, with the provision that the sum of the angles must be that of the π^o proton, the process can be appreciable if a long target is used. Intensity problems generally make the use of a long target desirable. If a π^o photon is detected in addition, the problem is removed but unfortunately with the poor duty cycle of a linear accelerator such coincidence experiments are very difficult.

For these reasons the Diambrini monocrystalline technique appears superior to the simpler method used at Stanford, and I feel that future accurate work on single pion photoproduction with polarized x-rays will best be done by his method.

I would like now to review the status of the measurements made below 400 MeV and later to go over the new work above that energy. In π^o photoproduction there has been no new work with polarized x-rays in this energy region since the DESY Conference, but some new theoretical work has removed a discrepancy between the angular distributions and the polarization asymmetry. If the cross-section is expressed as:

$$\frac{d\sigma}{dr} = A + B\cos\theta + C\cos^2\theta + \alpha\sin^2\theta\cos 2\phi$$

the α and C coefficients can be written as:

$$\alpha = \text{Re}\left[-\frac{3}{2}\left|M_{1+}\right|^2 + \frac{9}{2}\left|E_{1+}\right|^2 - 3\,(M_{1-}M_{1+}^*) + 3\,(M_{1-}E_{1+}^*) - 3\,(M_{1+}E_{1+}^*)\right]$$

$$C = \text{Re}\left[-\frac{3}{2}\left|M_{1+}\right|^2 + \frac{9}{2}\left|E_{1+}\right|^2 - 3\,(M_{1-}M_{1+}^*) - 9\,(M_{1-}E_{1+}^*) + 9\,(M_{1+}E_{1+}^*)\right]$$

It can be seen that α equals C except for interference terms containing E_{1+}. CGLN[3] gave only a small value of E_{1+} and hence it had earlier been expected that $\frac{\alpha}{C}$ would be approximately 1.

Figure 5 shows a summary of the low energy data. The difference shown allows an evaluation of the E_{1+} term. The curve is an evaluation of the $\frac{\alpha}{C}$

ratio done by Schmidt and Wunder[5] and based on a new dispersion theoretical calculation of Finkler.[6] This calculation uses different mathematical boundary conditions than CGLN and obtains an appreciable E_{1+} term at low energies, decreasing as one approaches the resonance.

It should be pointed out that, although the experiments clearly require such a term, the requirement is based on one point at 235 MeV. The polarization asymmetry measurements of α/σ are combined with angular distribution measurements to give $\frac{\alpha}{C}$. The only set of angular distribution measurements at that energy was made by Vasilkov, et al.[7] Although this appears to be an excellent experiment, it would seem useful for someone to repeat the angular distribution measurements or to make polarization asymmetry measurements at a slightly lower or higher energy so that an additional confirmation can be obtained. I admit it was a source of considerable relief to me to find that the very accurate measurements by Barbiellini, et al., were in good agreement with the Stanford data.

In π^+ production new data at 90° were published this spring by Gorenstein, et al.[8] This supplements work presented at the DESY conference.[9] Figure 6 shows their data combined with the earlier and less accurate data of Stanford.[10] The curves are theoretical estimates of Schmidt[11] and of Donnachie and Shaw.[12] One might have hoped for better agreement in the region above 300 MeV.

Above 500 MeV there have been, to my knowledge, no successful theoretical attempts to explain the experimental results. This is due in part to the large number of states involved and to the fact that the theoretical approximations used in the region of the first resonance are no longer valid.

To illustrate the complexity of the problem, one can write an expression for the asymmetry in terms of the electric and magnetic multipoles up to the D state. The notation used is that of CGLN with the subscript indicating the angular momentum of the pion in the final state and the + or - designating whether the proton spin is added or subtracted.

$$\frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}^{\text{at } 90^{\circ}} = \mathrm{Re}\Big[\left(3|M_{1+}|^2 - 6\, M_{1+}E^*_{1+} - 9|E_{1+}|^2\right)$$

$$+ \left(-3|E_{2-}|^2 + 9\, E_{2-}M^*_{2-} + 9|M_{2-}|^2\right)$$

$$+ \; 2\, E_{o+}\left(3\, M^*_{2-} + 3\, E^*_{2-}\right) + 6\, M_{1-}\left(M^*_{1+} - E^*_{1+}\right)$$

$$+ \; 2\, R\left(E^*_{o+} + M^*_{1+} - 3\, E^*_{1+} - M^*_{1-} - 2\, E^*_{2-} - R^*\right)\Big]$$

divided by

$$\mathrm{Re}\Big[\left(5|M_{1+}|^2 - 6\, M_{1+}\, E^*_{1+} + 9|E_{1+}|^2\right)$$

$$+ \left(5|E_{2-}|^2 + 6\, E_{2-}\, M^*_{2-} + 9|M_{2-}|^2\right)$$

$$+ \; 2\, E_{o+}\left(E^*_{o+} + 3\, M^*_{2-} - E^*_{2-}\right) + 2\, M_{1-}\left(M^*_{1-} + M^*_{1+} + 3\, E^*_{1+}\right)$$

$$+ \; 2\, R\left(-E^*_{o+} + M^*_{1-} - M^*_{1+} + 3\, E^*_{1+} + 2\, E^*_{2-} + R^*\right)\Big]$$

In this expression terms are grouped according to the state excited. The first terms refer to the first resonance. From this we see that if the first resonance were dominated by E_{1+} rather than by M_{1+} the sign of the asymmetry would be reversed. The next group refers to the 1520 resonance. If this were completely dominated by an electric dipole transition it would be enhanced along the electric field vector. If, as proposed by Beder,[13] $E_{2-} = 3\, M_{2-}$ there is no asymmetry contribution from this state. Since terms from this state appear in the denominator one would expect whatever asymmetry appeared from other states to be reduced by the presence of the D_{13} resonance. If an appreciable S_{11} resonance exists one might expect a considerable effect from the third term. In the last term R refers to the one pion exchange term. The pure term is enhanced along the electric field while interference terms may be of either sign.

Liu and Vitale[2] have published results on π^+ production indicating an asymmetry of about 0.4 enhanced perpendicular to the electric field vector. To my knowledge no calculations of a non-phenomenological nature have been made estimating the asymmetry. Zdarko and I[14] have made measurements on π^0 production in the region of the second resonance and have obtained an asymmetry of about 0.6 at right angles to the electric field vector. The only non-phenomenological theoretical estimate I am aware of is that of Schmidt, et al.,[15] which gives as its largest possible value something about half of this. It is clear from the large magnetic asymmetry present in both measurements that the 1520 resonance does not contribute appreciably to the asymmetry. If the first resonance terms dominated, one would expect an asymmetry of about 0.6, dropping appreciably during the 1520 resonance for the π^0 case. Hence it is clear that other states must participate.

Robert Walker[16] has developed a phenomenological theory with a large number of free parameters which seems very useful in correlating the behavior in this energy region. His approach has been to include electric Born terms, to put in all known resonances up to 1 GeV photon energy with the location and width given by scattering data, but to leave the strength of the contribution as a free parameter. His analysis is in terms of helicity amplitudes, and he has left as free parameters small amplitudes covering $J_{1/2}$ and $J_{3/2}$ terms and in the higher energy region $J_{5/2}$ terms. A major requirement, however, is that the variation of these be slow. Into these "background" terms must go all contributions of ρ and ω exchange. He has been able to fit the angular distributions and the polarization of the recoil proton very well. Figure 7 shows his fit to the asymmetry data of Liu and Vitale[2] on positive pions. An interesting result is that in order to handle the angular distributions, the proton asymmetry, and the polarization data, he has been forced to introduce an appreciable amount of S_{11} resonance. Figure 8 shows a similar fit to the 135^o data. The measurements on π^0 production by Zdarko and myself[14] were made after Walker made his calculations and Fig. 9 shows our data with the prediction of Walker. The central dark region of our data points represents what we consider the systematic uncertainty of our very preliminary results.

It will be interesting to test his prediction further. Additional data at other angles both in this and in the recoil proton polarization will impose very severe constraints on his parameters.

In addition, I would like to report on an experiment on π pair production which was reported at a meeting of the Canadian Association of Physicists about a year ago. This was done by Morrison, Drickey and myself.[17] Using data from Allaby, et al.,[18] we programmed our detection of the π^- to look for production with a final state of π^+ and proton as an N^*. It is estimated that about 80% of the interaction should be in that state.

It was our intention to look for the one pion exchange diagram by this technique. Figure 10 shows the possible diagrams contributing to this process. The pure one pion exchange diagram would give 100% asymmetry along the electric field while its interference terms can cause asymmetries of either sign. If the interaction passes through a D_{13} intermediate state one can express the decay angular distribution as follows:

$$W(\theta,\phi) = \left[A\left|F_{3/2}\right|^2 + B\left|F_{1/2}\right|^2\right](1+3\cos^2\theta) + \left[A\left|F_{1/2}\right|^2 + B\left|F_{3/2}\right|^2\right]3\sin^2\theta$$

$$-2\sqrt{3}\left[\mathrm{Re}\ C\right]\sin^2\theta\left[\left|F_{3/2}\right|^2 - \left|F_{1/2}\right|^2\right]\cos 2\phi \ . \quad {}^{19}$$

Here the A's, B's and C's are the helicity density matrix elements for the intermediate state particle as expressed below, while the $F_{3/2}$ and $F_{1/2}$ are the helicity amplitudes for the decay into an N^*:

$$\rho(N^{**}) = \begin{array}{c|cccc} & 3/2 & 1/2 & -1/2 & -3/2 \\ \hline 3/2 & A & & -C & \\ 1/2 & & B & & \\ -1/2 & -C^* & & B & \\ -3/2 & & & & A \end{array} \quad {}^{19}$$

where A and B are real, C is complex, and where $AB = CC^*$.

If the D_{13} decays via S state, then $\left|F_{3/2}\right|^2$ is equal to $\left|F_{1/2}\right|^2$ and there is no polarization asymmetry. If, as suggested by Walker's[16] analysis, the 1520 resonance occurs only in a 3/2 helicity then B and C are zero and there is no asymmetry. If the production is via a P_{11} state then A and C are zero and again no asymmetry exists. Production via a mixture of states can lead to an asymmetry. It is also possible for production to go through either of these diagrams with the π^+ and π^- interchanged. In general, one would expect such contributions to be about 1/9 that of the diagram shown and this is confirmed by the data of Crouch, et al.[20]

In fact no asymmetry was found. Table I summarizes the results. This would seem to indicate clearly that in this energy region contributions from the Drell term must be less than a few percent. Furthermore, one would not expect such effects to be large at these energies, and it would seem interesting to pursue this sort of investigation in the GeV region where it is predicted that they should appear.

TABLE I

	$\frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}$ at 90°	$\frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}$ at 45°
570 MeV	0.04 ± 0.05	
650 MeV	0.02 ± 0.04	-0.02 ± .04
800 MeV	0.04 ± 0.09	

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* Work supported in part by the U. S. Office of Naval Research, Contract Nonr 225(67) and in part by the U. S. Atomic Energy Commission.

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FIGURE CAPTIONS

1. Bremsstrahlung polarization as a function of angle for a 10^{-3} radiation length source. E_o is the peak beam energy, while k is the photon energy.

$$\epsilon = \frac{k}{E_o}$$

2a. Polarization as a function of energy for monocrystalline Bremsstrahlung, Barbiellini, *et al.*[1]

2b. Intensity as a function of energy for monocrystalline Bremsstrahlung, Barbiellini, *et al.*[1]

3. π^+ excitation curve for K = 500 MeV, $\theta = 90^o$. The curve g is the estimated gaussian acceptance of the magnetic spectrometer, b is a step approximating the double pion contribution as explained in the text. P is the calculated polarization of the photon beam whose end point energy is 800 MeV. (Liu and Vitale.[2])

4. Excitation function for the proton from π^o production for k = 675 $\theta = 90^o$.

5. $\frac{\alpha}{C}$ vs. energy. Curve is by Schmidt and Wunder[5] from the calculations of P. Finkler.[6]

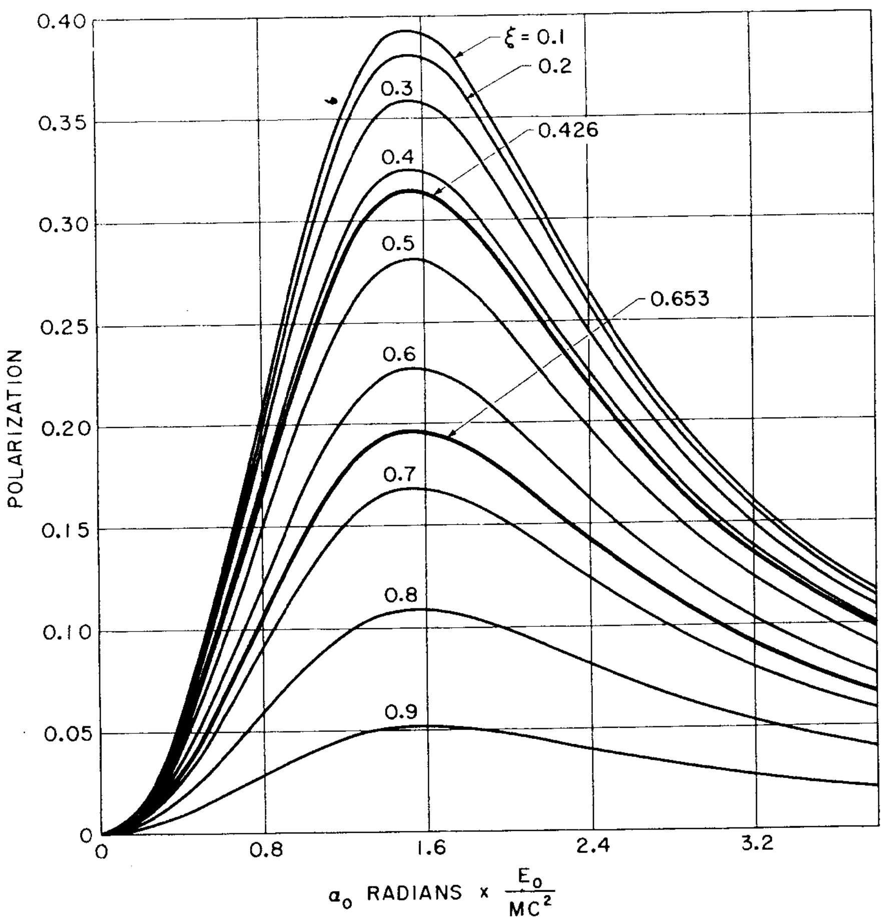
6. $\frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$ at 90^o for π^+ production compared with the predictions of Schmidt[11] and of Donnachie and Shaw.[12]

7. $\frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$ at 90^o for π^+ production compared with the calculations of R. Walker.[16]

8. $\frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$ at 135^o for π^+ production compared with the calculations of R. Walker.[16]

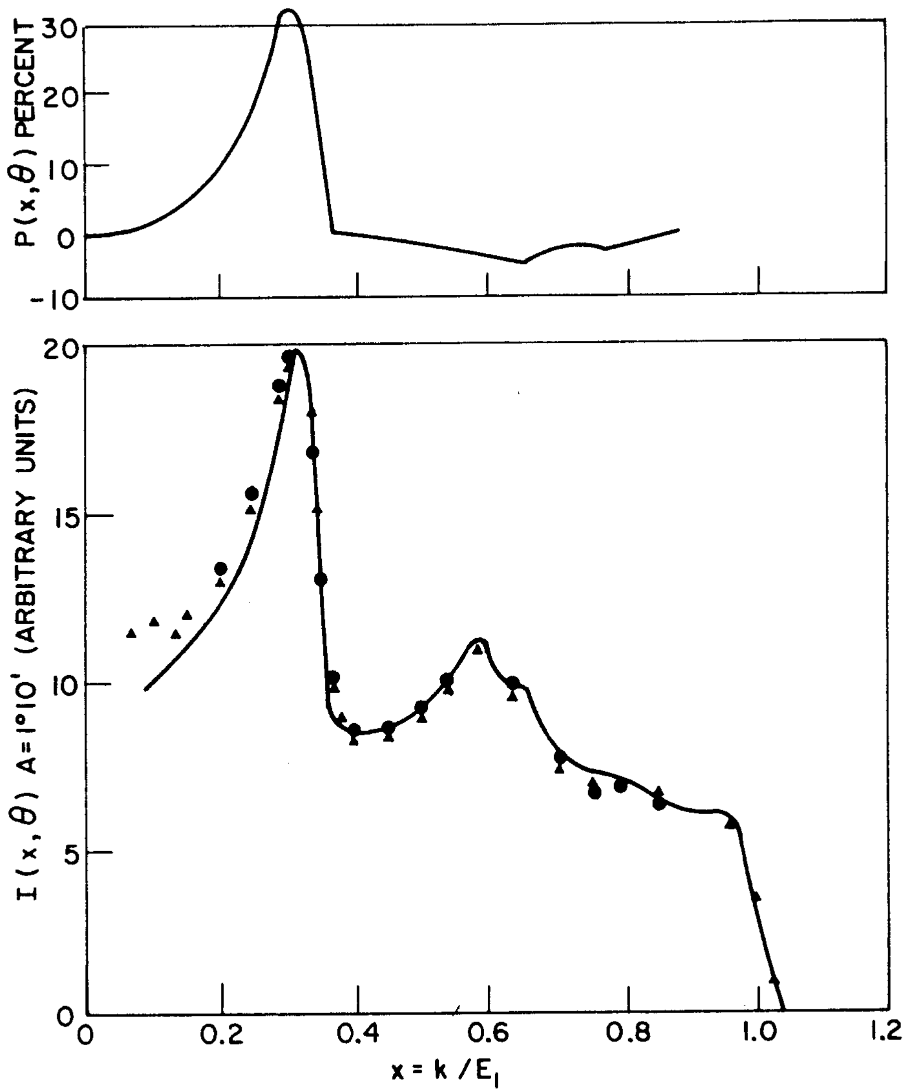
9. $\frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$ at 90^o for π^o production compared with the calculations of R. Walker.[16]

10. Diagrams contributing to π pair production.



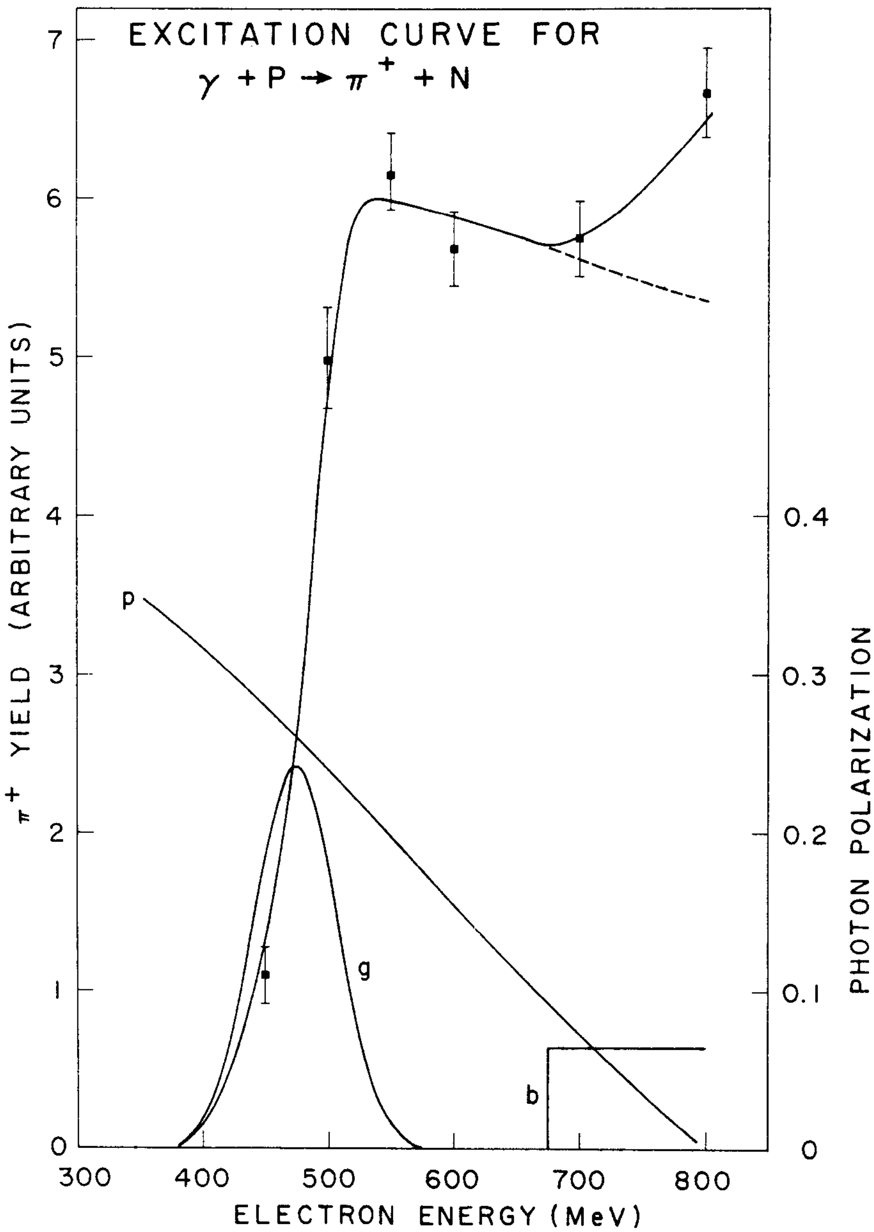
POLARIZATION
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
0
0.8
1.6
2.4
3.2
ξ = 0.1
0.2
0.3
0.4
0.426
0.5
0.6
0.653
0.7
0.8
0.9
α_0 RADIANS × $\frac{E_0}{MC^2}$

Fig. 1



P(x, θ) PERCENT
30
20
10
0
-10
I (x, θ) A=1°10' (ARBITRARY UNITS)
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1.0
1.2
x = k / E_1

Fig. 2



EXCITATION CURVE FOR
$\gamma + P \rightarrow \pi^+ + N$
π^+ YIELD (ARBITRARY UNITS)
PHOTON POLARIZATION
ELECTRON ENERGY (MeV)
p
g
b
0
1
2
3
4
5
6
7
300
400
500
600
700
800
0.1
0.2
0.3
0.4

Fig. 3

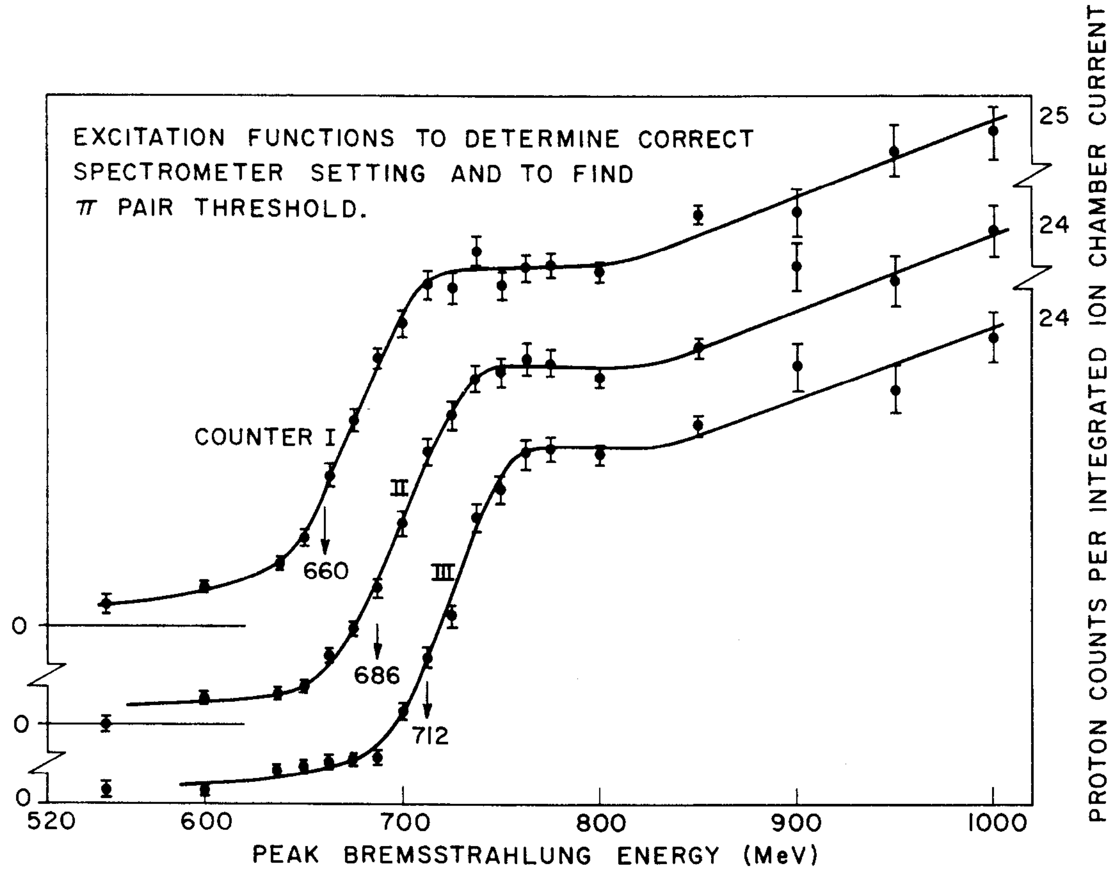

EXCITATION FUNCTIONS TO DETERMINE CORRECT
SPECTROMETER SETTING AND TO FIND
π PAIR THRESHOLD.
COUNTER I
II
III
660
686
712
25
24
24
0
0
0
520
600
700
800
900
1000
PEAK BREMSSTRAHLUNG ENERGY (MeV)
PROTON COUNTS PER INTEGRATED ION CHAMBER CURRENT

Fig. 4

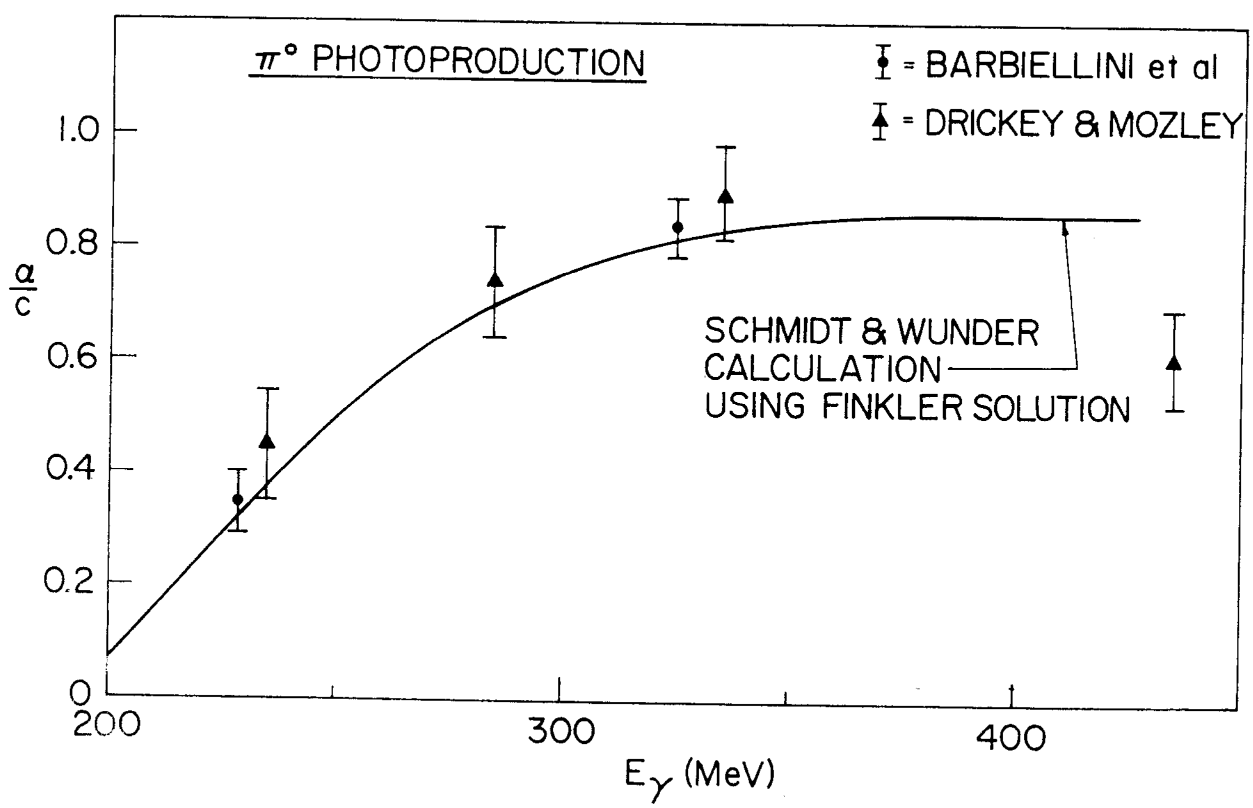
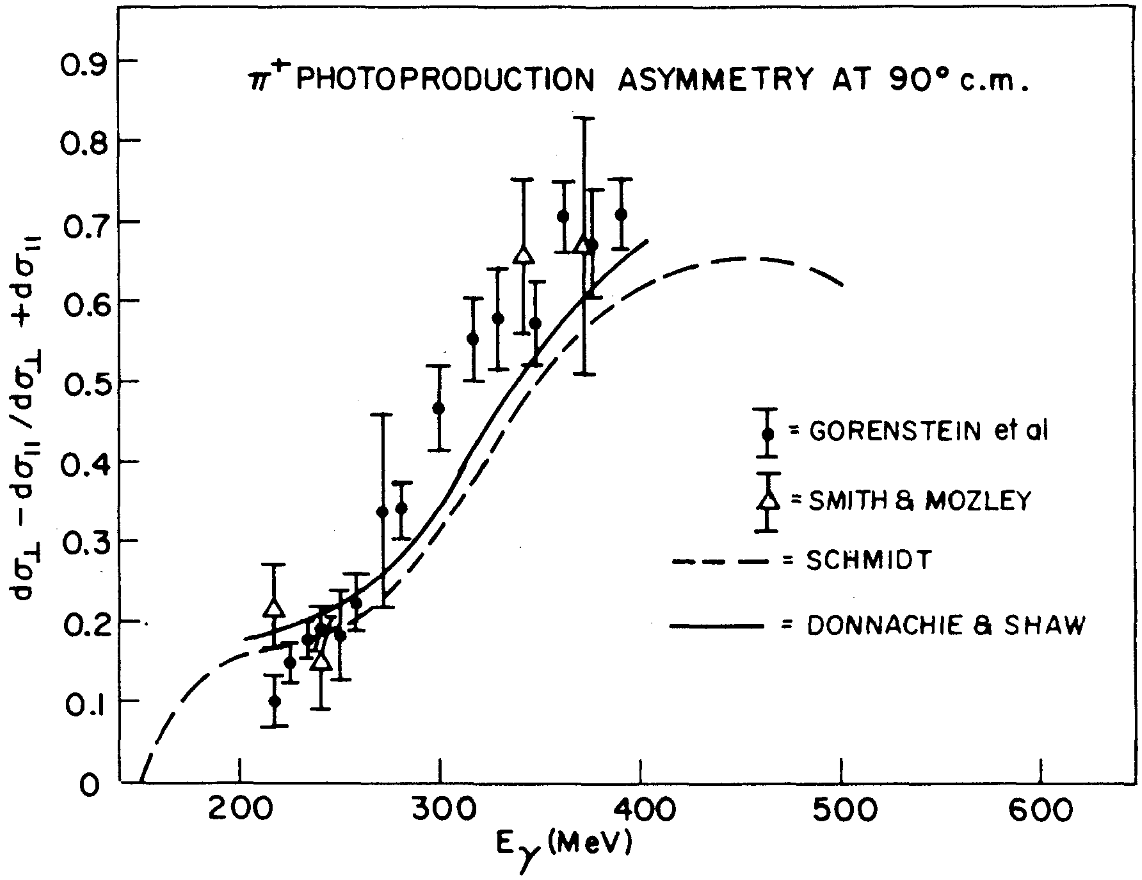
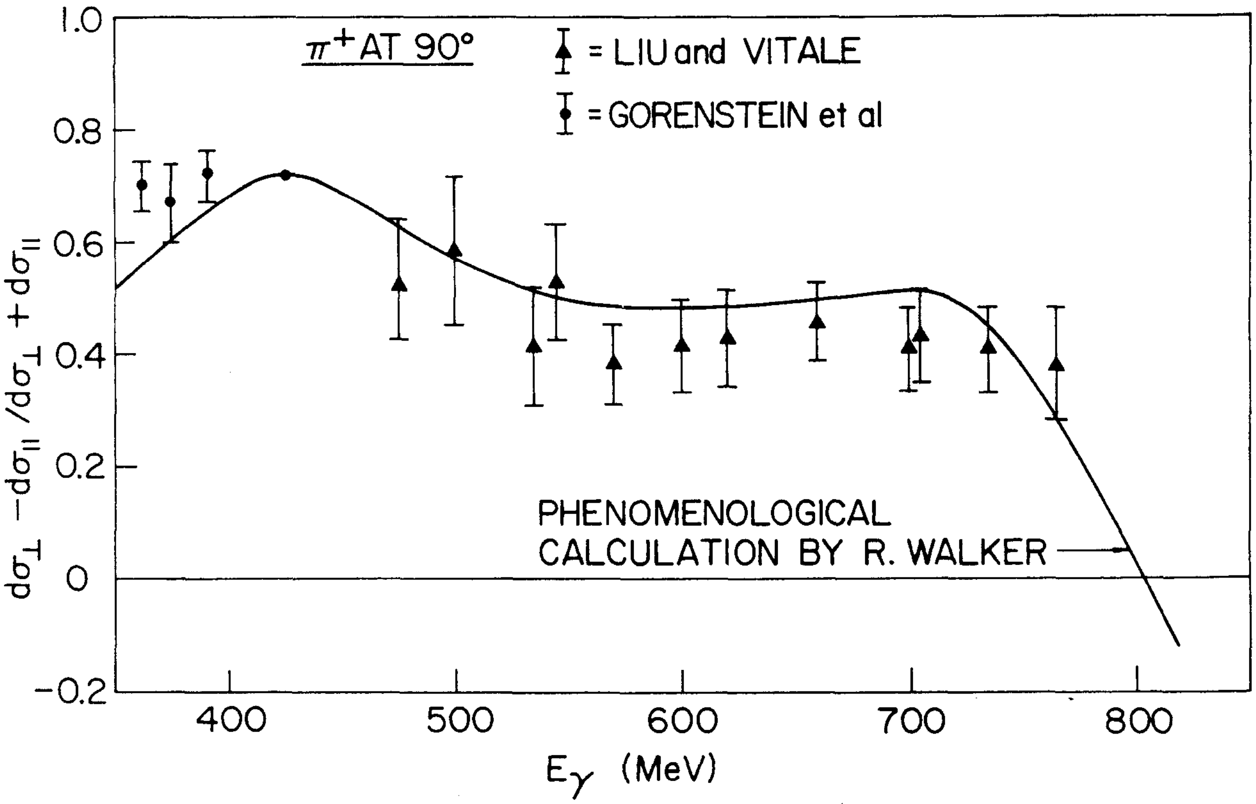

π° PHOTOPRODUCTION
= BARBIELLINI et al
= DRICKEY & MOZLEY
SCHMIDT & WUNDER
CALCULATION
USING FINKLER SOLUTION
1.0
0.8
0.6
0.4
0.2
0
a/c
200
300
400
Eγ (MeV)

Fig. 5



π+ PHOTOPRODUCTION ASYMMETRY AT 90° c.m.
= GORENSTEIN et al
= SMITH & MOZLEY
= SCHMIDT
= DONNACHIE & SHAW
dσ⊥ − dσ∥ / dσ⊥ + dσ∥
Eγ (MeV)

Fig. 6



π+ AT 90°
= LIU and VITALE
= GORENSTEIN et al
PHENOMENOLOGICAL
CALCULATION BY R. WALKER
dσ⊥ − dσ∥ / dσ⊥ + dσ∥
Eγ (MeV)

Fig. 7

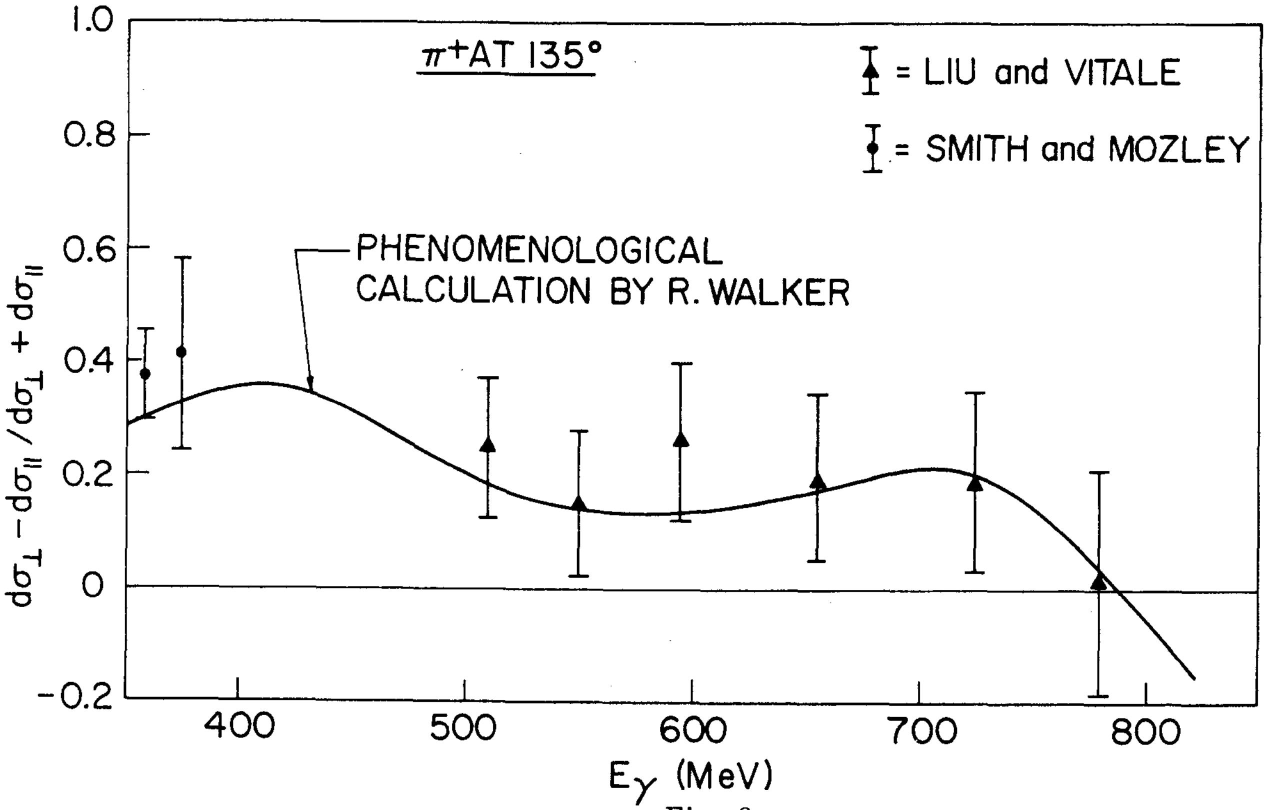

π+AT 135°
= LIU and VITALE
= SMITH and MOZLEY
PHENOMENOLOGICAL
CALCULATION BY R. WALKER
1.0
0.8
0.6
0.4
0.2
0
-0.2
400
500
600
700
800
dσ⊥ - dσ∥ / dσ⊥ + dσ∥
Eγ (MeV)

Fig. 8

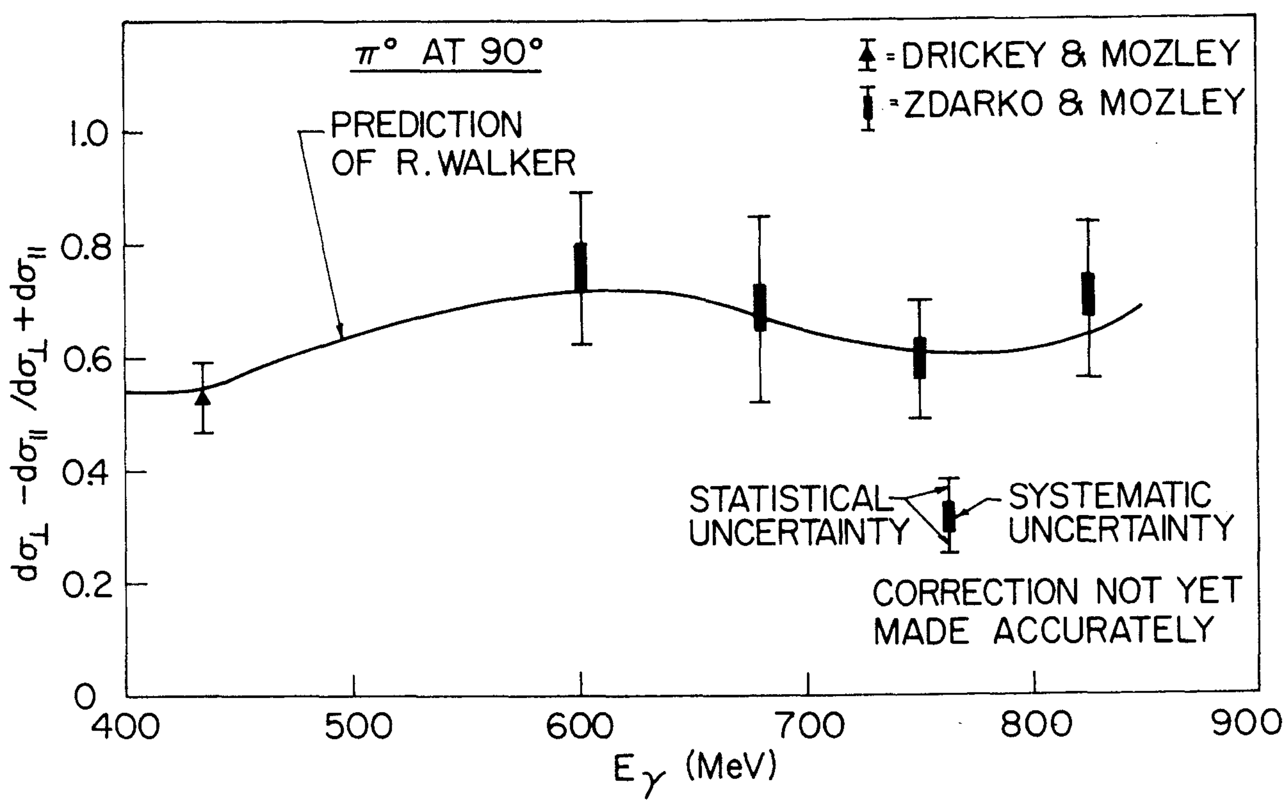

π° AT 90°
= DRICKEY & MOZLEY
= ZDARKO & MOZLEY
PREDICTION
OF R. WALKER
STATISTICAL
UNCERTAINTY
SYSTEMATIC
UNCERTAINTY
CORRECTION NOT YET
MADE ACCURATELY
1.0
0.8
0.6
0.4
0.2
0
400
500
600
700
800
900
dσ⊥ - dσ∥ / dσ⊥ + dσ∥
Eγ (MeV)

Fig. 9

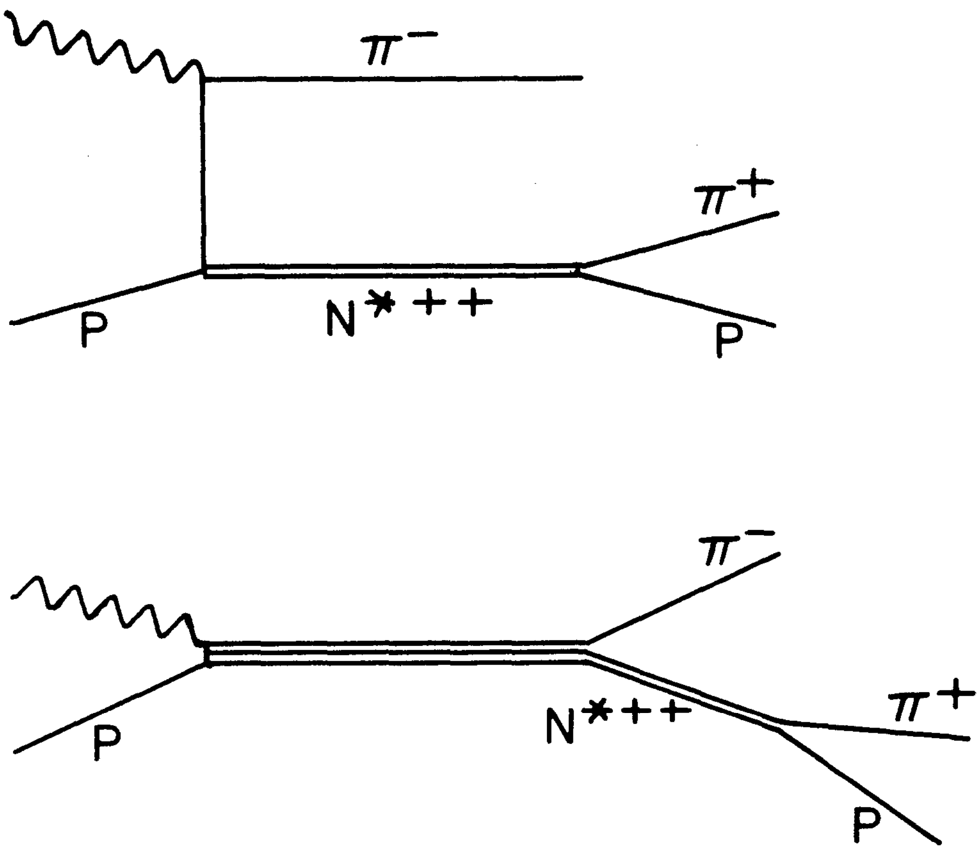


Fig. 10