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Skeletons in the Regge Cupboard

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§1. Introduction

The terms of my contract were to review both Regge pole and cut fits to high energy two-body data and also the Multi-Regge model for production processes. A complete survey would rapidly exhaust both reader and writer even though it would presumably provide a much needed boost to the British paper industry. Thus in this paper I will concentrate on the phenomenological applications of Regge cuts and refer the reader to several excellent reviews[1 to 6.] for detailed treatments of other aspects of life at high-energy. In the rest of the introduction I will quickly survey some general properties of Regge poles and cuts. In the next six sections which can be read independently, I will treat various reactions that provide particularly potent tests for theory. Then I will consider the Multi-Regge model and finally present some conclusions.

1A: Plan of Attack

We will try to motivate the rather detailed considerations of the later sections.

(i) Regge Poles Only

As it is largely unfettered by theoretical constraints, the Regge pole model enjoys a vast number of parameters. For this reason, alone, it is possible to fit a large percentage of experimental high energy data. Only, by enforcing the few existing constraints of, say, factorization or symmetry schemes for the residues, is it possible to judge whether or not a fit is at all meaningful. This, of necessity, requires the use of all data ($d\sigma/dt$, polarization, FESRs etc.) for a given reaction, and also the careful correlation of parameters between different reactions.

As we state in more detail in Section 1B and illustrate in Sections 2 to 7, the unambiguous successes of pure Regge pole theory are confined to small t, but one reaction (πN CEX) over a wide range of t. Sections 5 and 7 (photoproduction and vector meson production) demonstrate the failure of Regge theory in a single reaction. This particular failure is roughly explained by the absorption model and one can conservatively deduce, from this data, that the corrections to pure Regge pole theory are not overestimated by the absorption model for cuts.

On examining all other reactions, where the effects of cuts are not as easy to isolate, one can safely generalize this to conclude:-

The effects of cuts are at least as large as predicted by the absorption model.

(ii) Absorption Model for Cuts

We believe the above deduction to be quite certain and in some sense uncontroversial. Thus, in this paper, we would like to look, in yet greater detail, at the data to see if the absorption model is correct.

The reader can judge for himself from sections 2 to 7, but I believe there is little evidence for the quantitative success of the absorption model. All the qualitative successes of this model follow in any theory that claims that the low partial waves (in the s-channel) of a Regge pole are generally unreliable. The data indicates, in agreement with the absorption model, that the true values of these low partial waves are smaller than the pole prediction. (In other words, experimental data is more peripheral than one would get from a Regge pole). Most work on the absorption model is content to demonstrate this success. However when you examine the specific absorption model predictions of the relative corrections in different partial waves and different amplitudes, there appears to be little agreement between theory and experiment.

(iii) More General Cut Models

Unfortunately the absorption model is so specific, that one is at a loss to know what to do when it fails. Thus, given the importance of cuts and the dubious nature of current cut models, it is necessary to ask either for a better model or even just a suitable formalism to understand such discrepancies. There is no such theoretical framework at present but I have tried to indicate in the later sections when some feature of the data is surprising for the known general structure of cuts.

1B: Regge Pole Theory

This is, as yet, the only theory (or formalism) that has been (or can be) compared with virtually all high energy data. However it would appear that the heyday of such fits has passed for its the major successes are qualitative only and confined, in general, to small t. Some good predictions of Regge theory are:

(i) Total Cross-sections σ_t :

With the possible exception of the new Serpukhov data,[7] Regge pole theory fits well the measured σ_t data.[8]

(ii) Elastic Cross-sections σ_{el} :

Morrison [5] has reviewed the good agreement with power-law behaviour exhibited by various σ_{el} .

(iii) Chew-Frautschi Plot

Points (i) and (ii) establish the value $\alpha(0)$ of the Regge trajectory at t = 0. This agrees well with that predicted by a straight line through the observed meson and baryon resonances.

Throughout this paper, I shall assume the existence of the following trajectories:

Pomeron: $\alpha(0) \simeq 1$, slope debatable (see Sections 3 and 4).

$\rho, \omega, \varphi, K^*_{890}$ nonet, $A_2, f_0, f'_0, K^*_{1400}$ nonet: EXD (exchange degenerate) trajectories: $\alpha(0) \sim 0.3 \to 0.5$, slope $\alpha'(0) \sim 0.9$.

π, η, η', K nonet, $B, ?, ?, K^*_{1300}$ nonet: EXD (?) trajectories: $\alpha(0) \sim 0 \to -0.3$, slope $\alpha'(0) \sim 0.9$.

N_α octet: $\alpha(0) \sim -0.35$, $\alpha'(0) \sim 0.9$.

N_γ octet: Similar trajectory to N_α .

Δ decuplet, N_β octet: $\alpha(0) \sim 0.1$, $\alpha'(0) \sim 0.9$.

I will thus not consider work which obtain fits to scattering data using trajectory parameters wildly differing from this. The least certain of the above list are the π and B nonets as there is no evidence for shrinkage in any scattering data to which they contribute. (see Section 7).

After the qualitative points (i)to (iii) we can now look at the many explicit fits to experimental data as a function of t. These are, in general, somewhat unconvincing for if you test:

(i) factorization: it always fails when the prediction gives results unexpected on general geometric(9) grounds. Thus the relation $(\pi\pi\to\pi\pi)\times(\rho\rho\to\rho\rho) = (\pi\rho\to\pi\rho)^2$ is roughly true for elastic scattering. However, as Sonderegger(10) described, the detailed factorization arguments for π exchange fail miserably at $t = 0$.

(ii) Dips at $\alpha = 0, -1, -2$ ...:Only correctly seen in a very few reactions.

(iii) Shrinkage due to non zero slope $\alpha'(0)$:

This is only seen in πN CEX and related reactions. Indeed we have collected some seemingly strong evidence for the prosecution in figures 1 to 20. These are plots of $\alpha_{eff}(t)$ defined by:

$$\frac{d\sigma}{dt}(s,t) = A(t)\ \nu^{2\alpha_{eff}(t)-2} \qquad (1)$$

where $\nu = (s-u)/2$

α_{eff} is the trajectory value of the Regge pole at each t which fits best the experimental data over the present range of energies. Some details of its definition are abolished to the appendix.

The seeming lack of correlation between α_{eff} and the expected Regge trajectories may be explained by:

(a) All trajectories have couplings of similar size (Most reactions allow the exchange of more than one trajectory).

(b) Cuts are important.

As we will see in the later sections (b) is in fact correct.[11] Notice that we can rule out explanations of these difficulties in terms of secondary trajectories lying lower in the j-plane than those listed above. Thus the discrepancies with pure pole theory do not fall with energy.

1C: Regge Cuts

Very few general properties of cuts are known. All models, that I know, predict them to be flatter in plots of both trajectory α_{eff} v.t and cross-section $d\sigma/dt$ v.t. (see figures 21 and 22). This agrees with the rough success of Regge pole theory near $t = 0$, but it is insufficient information on which to base a quantitative fit to data. The essential phenomenological difficulty with Regge cuts is a necessity for a specific model. The (old) Regge pole model, however, had sufficiently few parameters that meaningful fits could be made to data without invoking detailed theoretical assumptions.

Absorption Model

The most popular model for cuts is the Reggeized absorption model.(12),(13),(14) For inelastic reactions this claims that the s-channel partial wave amplitudes are given by:

$$T_{inel}(b) = T_{inel}(\text{Regge Pole: } b) \times S_{el}(b) \qquad (2)$$

where the elastic S-matrix is given by

$$S_{el}(b) = 1 - C \exp(-b^2/(2A)) \qquad (3)$$

b is the impact parameter and the absorption constant $C = \sigma_t/(4\pi A)$, which ~ 0.75 for πN at 5 GeV/c. A is the slope of the diffraction peak, $\sim 8\ (\mathrm{GeV/c})^{-2}$. (2) is illustrated in fig. 23. If the initial and final states are not the same we replace $S_{el}(b)$ by $1/2(S_{initial} + S_{final})$ or perhaps better by the geometric mean $\sqrt{S_{initial} \cdot S_{final}}$.

One can refine (2) by treating fig. 23 exactly as a unitary diagram and including the full gore of the spin and isospin structure of elastic scattering. In view of the blatant theoretical and experimental difficulties soon to appear, it is sufficient in (3) to write[14]

$$C = C_{pom}\left[1 + \delta\,(s/10)^{-\frac{1}{2}}\right] \cdot \left[1 - i\,r\,(s/10)^{-\frac{1}{2}}\right] \qquad (4)$$

Here δ is the ratio in σ_t of P', ω to Pomeranchuk at $P_{lab} \sim 5$ GeV/c and r the ratio of Re/Im there (for simplicity we assume $\alpha_P - \alpha_{P'} = 0.5$). C_{pom} is the energy independent Pomeranchuk contribution.

Some theoretical comments on (2) to (4) are necessary:

(a) The absorption model generates cuts whose position in the j-plane agrees with general expectations.[15] However the overall magnitude of the cuts and their relative contribution to different amplitudes is open to question for . . . . .

(b) The model remains theoretically unjustified.[16],[17] It is well known that the archetype Feynman diagrams, like Fig.24, do not lead to cuts in the j-plane.[18] There is a cancellation between the elastic unitarity part, as in (2), with the inelastic

contribution to fig. 24.

(c) It does not satisfy s-u crossing. Thus we do not get the same answer on absorbing in the s-channel and crossing to the u-channel, than if we absorb in the u-channel. This means we must be careful when discussing line reversal (i.e. s-u crossing) tests.[19],[20],[21]

(d) It does not satisfy t-channel unitarity. Really we should iterate the box diagram of fig.24 infinitely many times in the t-channel. The analysis of the later sections indicate that this may be an important defect.

Finally we must distinguish two versions of this model. The first was popularized by Arnold[13] and uses, as input, roughly EXD residues and trajectories for the pole parameters. I will call this the EXD model. Here all Regge poles generate dips at nonsense values $\alpha = 0, -1$.. and the cuts are employed to fill in unobserved zeros.

In the second model[14], which I will call the Michigan model, the Regge pole has no nonsense zeros and all observed dips are due to cancellation between the pole and the cut. The size of the cut generated by (2) to (4) is too small for this task and it is necessary to multiply the cut by a phenomenological factor $\lambda \sim 2$. This is meant to represent the effects of diffraction dissociation of particles with the same quantum numbers as the elastic states. The differences between the two models will be clarified in the next section.

Other Cut Models

(i) Chew and Frazer [22] have derived a prescription for cuts from the multi-Regge model. This has, unlike the absorption model[15], constructive interference between the pole and the cut. Although this is consistent with experiment in some reactions (say πN scattering) it seems unable to fit π exchange data, as well as $\bar{K}N$ and $\bar{p}p$ elastic scattering.

(ii) The absorption model predicts that only the high partial waves are given correctly by the Regge pole formula, and suggests a particular modification of the low partial waves. Most of the qualitative successes of the absorption model, e.g. π exchange data and the crossover phenomena in $p\bar{p}$ and $\bar{K}N$ scattering, are reproduced by the following more general model.[23] This agrees that only the high partial waves of Regge theory are reliable but all it says about the "low" partial waves are that they are typically "small". The quantitative definition of "low" and "small" is left to the reader. We will refer to this as the HPW (high partial wave) model.

§2 $\pi^- p \to \pi^0 n$

2-A: α_{eff}

This reaction is remarkable because it is essentially the only data which exhibits energy dependence (see fig.1) in agreement with a single (the ρ) Regge trajectory. In figure 1, we compare experiment with the predictions of the EXD cut model. The agreement is satisfactory although the data agrees as well with a simple pole as with the sophisticated cut model. In the latter model the pole vanishes at $t \approx -0.6$ (GeV/c)^2 revealing the cut. This lying higher in the j-plane (see 1-C) causes the kink in the theoretical α_{eff}. Over the present energy range the energy dependence of the cut is somewhat suppressed due to the nonasymptotic P' part of elastic scattering. Over the Russian energy range this model predicts much less shrinkage than at present. (see dotted line in figure 1). This comparison illustrates two surprising points that will be found to be generally true. Firstly there is little evidence for the predicted energy dependence of cuts at "large" t (≈ -1 (GeV/c)^2). Secondly, having explained this with non-Pomeranchuk trajectories, we predict marked changes in the detailed structure of data in $p_{lab} > 20$ GeV/c. Then the P' has become unimportant and cuts will be revealed in their full glory.

In figure 2 we compare the Michigan model with the same data. The cut is now larger and disagreement between theory and experiment quite marked. This is, I think, strong evidence against this model, since the prediction of a flatter energy dependence rather than the experimental simple pole is seemingly independent of the details of the calculation.

2-B: $d\sigma/dt$

To provide an indication of the relative size of pole and cut I have plotted in figs. 25 and 26 a comparison of theory with the experimental data, for both models discussed above. The seemingly sparkling agreement emphasizes that in testing cut models one must look carefully at the details of the calculation. Further plots and consideration of other variants of these models may be found in refs 24, 25 and 26.

2-C: Polarization

The historical motivation for modifying the single Regge pole description of this process, was the nonzero polarization observed at 5.9 and 11.2 (GeV/c).[27] It is a nice success for both cut models that the sign of this is correctly predicted at small t. We may remark that the polarization for $-t \lesssim +0.3$ $(GeV/c)^2$ is generated not by the Pomeranchuk part of elastic scattering but rather by the Re/Im ratio r explicitly inserted in equation (4). Thus the theoretical polarization is expected to fall like $1/\sqrt{s}$ with energy, although the present data is not accurate enough to test this. Similarly the predicted structure[24→26] for $-t \gtrsim .4$ $(GeV/c)^2$ remains a challenge to experimenters.

2-D: Similar Reactions:

Similar features, to πN CEX, are exhibited by $\pi^- p \to \eta n$, $K^- p \to \bar{K}^o n$, $K^+ p \to K^o n$, $\pi^+ p \to (\pi, \eta)\Delta^{++}$ and $K^+ p \to K^o \Delta^{++}$ [28]. They are all dominated by roughly EXD ρ and A_2 trajectories with a largely spin-flip coupling. For some of these α_{eff} has been plotted in figures 3 → 5. As yet the data is not sufficiently precise to test the detailed structure of the theory.[29,30] We note that as the pole and cut destructively interfere, α_{eff} lies above the input pole at $t = 0$. $\pi N \to \eta N$ has somewhat more absorption than πN CEX and we therefore predict that α_{eff} will be a little higher in the former reaction. This prediction is not realized experimentally suggesting perhaps that the ρ and A_2 trajectories are not quite ($\alpha_\rho - \alpha_{A_2} \sim 0.2$?) EXD.[31]

Cline and co-workers have presented an interesting comparison of $K^- p$ CEX and $K^+ p$ CEX.[32] I think a systematic study of experimental data on reactions related by simple transformations (e.g. SU_3 or line-reversal) will prove very fruitful. Such studies would be easier if some effort was made to collect data on the different reactions at the same energy.

2-E: Cross-Over

Whereas $d\sigma/dt$ is only sensitive to the spin-flip amplitude B we can also examine the nonflip amplitude A'. One can use either the cross-over in the $\pi^+ p$ and $\pi^- p$ elastic cross-sections or perhaps better finite energy sum rules (FESRs). Both methods are meant to suggest a zero in $Im\,A'$ at $t \sim -.15$ $(GeV/c)^2$. It is well-known that no version of the absorption model gives either this or the corresponding cross-overs, in $K^- p$ v. $K^+ p$ and pp v. $\bar{p}p$ elastic scattering, correctly. There is a zero in the theory but at $t \sim -.3$ to $-.4$ $(GeV/c)^2$.[25,26,30]

A further difficulty with A' is that the value of $A'/\nu B$ determined (with or without cuts) from scattering data is smaller than the value at the ρ pole expected from nucleon form factor data. In times of yore,[34] both this and the cross-over were explained by a zero in A'_ρ near $t \sim -.15$ $(GeV/c)^2$. Such an extra zero is also suggested by the Veneziano model applied to πN scattering[33,35]. Absorbing a pole, with such a zero, does not lead to good answers.

2-F: HPW Model

The success of a simple Regge pole model may be understood in terms of the HPW model. In any given amplitude, there is a t-dependence which corresponds to dominantly high partial waves. In the spin-flip amplitude B, this t-dependence corresponds to a zero at t = -.6 $(GeV/c)^2$ while in A', we need a zero at -.2 $(GeV/c)^2$. These t-values may be arrived at by examining the t dependence of the peripheral low energy resonances.[36,33] This is illustrated in fig. 27 and provides a partial answer to the definition of "low" partial waves for the HPW model.[37,38] In πN CEX the ρ meson is dominantly spin-flip and the pure Regge pole amplitude has a zero in the right place to have only "high" partial waves.

In the nonflip amplitude A' the natural zero at $\alpha_\rho = 0$ does not coincide with the peripheral zero at -.2. Thus the Regge pole has "large" low partial waves and cuts are important.

We then expect to get steadily worse agreement with Regge pole theory as we increase the ratio of nonflip to flip couplings. Elastic scattering is dominantly nonflip while hypercharge exchange data (e.g. $\pi N \rightarrow K\Sigma$) lies in between the two extremes. More detailed data on $d\sigma/dt$ and polarization for the various hypercharge exchange reactions would certainly be very useful.

§3 pp elastic Scattering

3-A: Multiple Scattering

In order to apply the absorption type cut models to elastic scattering, it is necessary to refine the equations (2) to (4). Thus we write[39,40,41.]

$$S_{el} = \exp(2i\delta) = 1 + 2i\delta + \tfrac{1}{2}(2i\delta)^2 + \dots \quad (5)$$

and identify the Regge pole with the potential $2i\delta$. This is analogous to the Glauber theory for nuclei and the cut $\frac{1}{2}(2i\delta)^2$ corresponds to multiple scattering. Thus we expect to see a change of slope in the data when the $\frac{1}{2}(2i\delta)^2$ cut overtakes the single scattering pole term. (Remember fig. 22). In fig. 28, we see that this occurs at $t \sim -0.6$ $(GeV/c)^2$ at 7 GeV/c and $t \sim -1.1$ $(GeV/c)^2$ at 19.2(GeV/c) . However this is not quite the success it seems, for let us consider two simple models. The first, due to Chiu and Finkelstein,[39] is termed the hybrid model and combines a zero slope (fixed pole) Pomeron with a normal slope P' and ω. The second model, due to Frautschi and Margolis,[40] uses a high slope ($\alpha'_P \sim 1$) Pomeron instead. If we take the Pomeron alone, the hybrid model predicts that the multiple scattering has the same energy dependence as the pole. Thus the change in slope should occur at the same t value for all energies. The slope 1 Pomeron model predicts that the multiple scattering falls with energy more slowly than the pole and so the change in slope should occur at a smaller t value as one moved up in energy. Clearly the data does precisely the opposite and in order to explain it, in either model, one must add secondary trajectories. Thus we can immediately draw the rather general conclusion that at present energies cuts do not dominate at large t and secondary (P' and ω) trajectories are just as important in determining the multiple scattering.

I found that adding the P' and ω to the hybrid model (as Chiu and Finkelstein did in their papers)[42] does not lead to good agreement with experiment. In this model, the P' and ω are assumed EXD and their sum is real: this leads to little interference with the Pomeron and its cuts. The resultant theory has less energy dependence than the data. (I have plotted the experimental α_{eff} in fig. 7). Possibly one may improve the fit by breaking the EXD away from t = 0.

Finally one can add the P' and ω to the high slope Pomeron and its cuts. As the Pomeron now has a sizeable real part there is more interference between it and the P' +ω. I found a tolerable fit with good agreement at 7 GeV/c and a slope-change at 19.2 GeV/c for t = -.8 $(GeV/c)^2$.

Rather than dwell on the details, I would like to emphasize that if either model is remotely right we expect a marked qualitative change in pp data above 20 GeV/c. By then, the P' and ω have died away and one expects the natural Pomeron cut prediction to hold. I have estimated this quantitatively in fig. 29 for fits including P,P' and ω. It will be particularly interesting to verify this experimentally for the predictions do not depend on the details of the absorption model but rather on the assumed nature of the Pomeron.

3-B: New Serpukhov Data (Small t only)

The new pp scattering data taken at Serpukhov[43] shows that, for $0 < -t \lesssim 0.12 (GeV/c)^2$ and energies up to 70 GeV, α_{eff} has a slope of roughly 0.4. As shown in figure 7, the corresponding quantity up to 25 GeV has a slope nearer 1. However, as we have seen, the latter

is strongly affected by the P' and ω, whereas the new data provides a much cleaner test. In fig. 30 I compare the α_{eff} with our two theories. It seems that the hybrid model predicts no shrinkage and so can be ruled out by this data. In general any model with a fixed pole for the Pomeron is in difficulties for the P' and ω are rather small and anyway their interference with the pure imaginary Pomeron is quite negligible. The Frautschi-Margolis model agrees with the data for $0.6 \lesssim \alpha'_P \lesssim 0.8$. The value $\alpha'_P = 0.8$ gave the best fit to the lower energy data as discussed in 3-A. This emphasizes the need for a quantitative theory of cuts before one can draw any conclusion about the slope of the Pomeron pole from scattering data.

Some theoreticians attribute fixed cut status to the Pomeron.[44] I do not know whether this can naturally fit the Russian data[43] without putting a marked t dependence into the cut discontinuity.

3-C: p-p total cross-sections σ_t

Another distinct test of cut models is the energy dependence of σ_t. I have given a schematic illustration of this in fig. 31. At low energies, both models predict a rapid rise in σ_t coming from the $(P'+\omega)-(P'+\omega)$ cut. There is an interesting qualitative agreement between theory and experiment here. At high energies the hybrid model predicts flat cross-sections while the Frautschi-Margolis model suggests a gradual rise in σ_t. I estimate this will be some 1 or 2 millibarns between present energies and 200 GeV.

3-D: $p\bar{p}$ Scattering Data

There is, I believe, no quantitative fit to the $p\bar{p}$ scattering data in terms of either Regge poles and cuts. As we mentioned in 2-D, the absorption is of insufficient strength[41] to move the cross-position from $\alpha_\omega = 0$ to its experimentally observed position. (See fig. 32) One may attribute this to the large number of extra annihilation final states available to the $p\bar{p}$ system. This may increase the absorption but we would like to emphasize the point made in 1-C. It follows from analyticity (i.e. crossing symmetry) that one cannot alter the predictions for $p\bar{p}$ scattering without altering the model for pp scattering.

§4. πN and KN elastic scattering

4-A: α_{eff}

The experimental energy dependence has been plotted in figures 9 and 10. We notice again that there is marked shrinkage at large t which shows again that multiple scattering is not dominated by cuts at present energies. Further high energy data for $-t \gtrsim 1$ $(GeV/c)^2$ would certainly be useful for studying this in detail.

4-B: Pole Fits

By far, the most detailed fit to πN scattering is that due to Barger and Phillips.[45] Unfortunately they chose to represent the non-pole effects by trajectories lying very low in the j-plane. As we saw in 2-F and 3-B the effect of cuts on short range forces like the P and P' is quite marked and not adequately represented by P" and ρ' trajectories. Thus the detailed predictions of this model need not be trusted. In particular the data is still quite consistent[33] with the high slope ($\alpha'_P \sim 0.8$) for the Pomeron indicated by the new pp data (Sec. 3-B). (Barger and Phillips obtained $\alpha'_P \sim 0.35$ from their analysis).

In the present state of the art, I can only recommend a less ambitious approach in which one, at least, uses the absorption model to estimate the inherent error in a fit.

4-C: Cut Fits

There have been a few calculations of πN and KN scattering using the prescription of equation (5).[25,26,30] These have, I believe, been confined to the fixed pole model for the Pomeron. We mentioned one difficulty in 2-E, but the fits are as yet too symbolic to draw any detailed conclusions.[46] I tried a quick calculation with a high slope Pomeron. However, although the fit was generally similar to the zero slope P, it does not reproduce correctly πp polarization for $-t \gtrsim 0.6\ (GeV/c)^2$.

4-D: Curiosity

The remarkable reflection symmetry shown by $\pi^{\pm}p$ polarization data can only be explained if the P and P' have a very similar ratio $A'/\nu B$ out to quite large t. Furthermore the reduced coupling of P and P' to A' is known from σ_t data to be roughly the same. This suggests to me that P and P' must be closely correlated in any dynamical scheme and not quite different entities as in many favourite theories.[47]

§5. Photoproduction

5-A: Fixed Poles

We continue our role as the devil's disciple, by studying the wealth of highly accurate photoproduction data that has recently emerged.[48] (largely from the SLAC machine). It will appear that the theory always has more structure as a function of t than the data. This occurs for both α_{eff} (t) v.t and $d\sigma/dt$ (s, t) v.t. In particular we would like to emphasize the striking experimental evidence that the major corrections to the simple poles are not cuts at all, but rather fixed poles. We remember that t-channel unitarity rules out fixed power behaviour in strong interaction amplitudes.[49] However weak processes, like photoproduction[50] or compton scattering, are allowed (right-signature) fixed poles at:

$$j = \ ......\ 2, 1, 0, -1, -2\ ......\ \text{(Meson exchange)}$$

$$j = \ ......\ 3/2, 1/2, -1/2, -3/2\ ....\ \text{(Baryon exchange)}$$

The data shows no evidence for fixed power behaviour for $j > 0$ but is remarkably consistent with fixed poles at $j = 0$ for boson exchange and at $j = -1/2$ for fermion exchange.[51]

This may be seen first in fig. 11 where we plot α_{eff} for $\gamma p \to \pi^o p$. As we shall show in 5-B the absorption model predicts a similar α_{eff} for $\gamma p \to \pi^o p$ and πN CEX. There is clearly little resemblance between the experimental points on figs. 1 and 11.

Similar fixed power behaviour is exhibited in figures 12 to 14 for other forward photoproduction reactions. The theoretical predictions are more ambiguous here, but one can compare figures 8 and 12. $N\overset{(-)}{N}$ CEX and $\gamma p \to \pi^+ n$ have similar kinematics but the strong interaction $N\overset{(-)}{N}$ CEX is not allowed fixed poles. However, the diagreement between the experimental α_{eff}'s may not be due to fixed poles in fig. 12 but rather dubious data in fig. 8. Similarly $\gamma p \to \pi^- \Delta^{++}$ should have a similar α_{eff} to $\pi^- p \to \rho^0 n$ but, at present, data on the latter reaction is unfortunately not good enough to extract a meaningful α_{eff}.

Backward photoproduction is plotted in figure 15 and 16. There are too many poles, and hence parameters, to say this is conclusive evidence for a j = -1/2 fixed pole. One can only compare the data with the strong interaction $\pi^{\pm}p$ backward scattering (figures 17 and 18). There is a striking difference but again the kinematics are different. Those with the patience of Rip Van Winkle may dream of sufficiently accurate backward ρ production ($\pi N \to N\rho$) to extract an $\alpha_{eff}(t)$.

We will, however, now dispel such heresies and examine some absorption model predictions for these reactions.

5-B: $\gamma p \to \pi^0 p$

An advantage of forward π meson photoproduction is that the quark model[52] plus EXD, plus vector dominance ($\gamma \propto \rho + 1/3\omega$), markedly reduces the number of parameters.[53] Thus all the $\pi\gamma \to$ Regge pole couplings for the ρ and A_2 nonets are known in terms of one parameter. Similarily the π and B nonets represent just one parameter. Thereby one can calculate the relative amount of ω, ρ and B exchange in $\gamma p \to \pi^0 p$ to find that ω clearly dominates.[54] Now the $\omega \to N\bar{N}$ coupling is largely nonflip[56] and $\omega \to \pi\gamma$ is of course a spinflip coupling. We deduce, at once, that the kinematic structure of the unabsorbed $\gamma p \to \pi^0 p$ is similar to the embryo $\pi^- p \to \pi^0 n$. (Where the ρ Regge pole has a spinflip $N\bar{N}$ vertex and a spin nonflip $\pi\pi$ coupling). As the absorption is also similar ($\sigma_t(\rho N) \sim \sigma_t(\pi N)$) we predict similar α_{eff} and $d\sigma/dt$ for the two reactions.[55] This is not observed experimentally

as we pointed out earlier. The theoretical α_{eff} in fig. 11, includes ω, ρ and B exchange, and is based on the work of Blackmon et al..[53] However we have admitted defeat and restricted our B exchange to agree with EXD, $\pi N \to \omega N$ and the Chew-Frautschi plot. They obtained a reasonable fit only by giving the B a decidedly dubious trajectory. We give the experimental data in fig. 33 so that one may compare it with fig. 25.

There are two useful pieces of data that would clarify the theoretical interpretation of this reaction. The first is $d\sigma/dt$ values at high energy to determine α_{eff} for $0 \lesssim -t \lesssim 0.2$ $(GeV/c)^2$. The second would be photon asymmetry ($(\sigma_\perp - \sigma_\parallel)/(\sigma_\perp + \sigma_\parallel)$) measurements at higher energies. Thus the deviations of this from one are dominated by unnatural parity (B) exchange and expected to fall fast with energy.

5-C: $\gamma p \to \pi^+ n$, $\gamma n \to \pi^- p$

The data on charged pion photoproduction is well-known to be quite depressing,[57] and liable to cause the reader to burst into a veritable flood of tears. Thus I refer him to others for a detailed account of the difficulties with $d\sigma/dt$, photon asymmetry, π^-/π^+ ratio and FESRs[14,58,48] (soon the mean experimentalists may add the nucleon polarization to this list). In fig. 34, I plot the result of a trivial absorption model calculation using just one π exchange. This fits none of the details but is meant to illustrate the size and shape of absorption in such a process. Most workers agree that the absorption constant C (from fig. 34 this is well determined from the data at t = 0) needs to be larger than expected. (We used C = 2.3 in fig. 34). Adding the A_2, to interfere constructively with the π and its cut, reduces the necessary C [58] but it is still at least 50% bigger than its canonical value of 0.75. Actually such an A_2 (whose parameters may be found as in 5-B from the ω and $\gamma p \to \pi^0 p$) gives an α_{eff} at t= 0 which is dubiously consistent with experiment. Anyhow these models predict a marked change in π^+ production above p_{lab} = 20 GeV/c as the A_2 becomes important.

A co-operation, similar to that between the π-cut and the A_2, is also seen in the $\gamma p \to \pi^+ n / \gamma n \to \pi^- p$ ratio. The latter is generated by the interference of ρ (and its cuts) with the π-cut.[59] The Regge prediction is of reasonable size but it is difficult to get a good fit to the rather structureless data. Anyhow, the fact that the ρ and A_2 are large in exactly the same amplitudes as the π-cut, indicates again that poles and cuts are not such dynamically distinct objects. We can further observe that Regge theory has correctly predicted those amplitudes that are to be large. It goes badly wrong in how it attributes this amplitude to the various singularities (poles, cuts and fixed poles) in the j-plane.

§6. Backward Scattering

The most interesting feature of backward scattering is the possibility of obtaining the residue of the Regge poles not only for $u \lesssim 0$ from scattering data, but also for $u > 0$ from the elastic widths of the particles on the trajectory. Thus one can test the assumption of constant residues that has been a tacit assumption in most fits to other data. It was first pointed out by Barger and Cline[60] that whereas the nucleon exchange agrees quite well (in πp backward scattering), the extrapolation from $u \lesssim 0$ underestimates the width of the Δ by a huge factor (over an order of magnitude). Cuts improve the situation to some extent but it seems likely that the t dependence of the Δ is rather complicated. It would be nice to know the status of pole extrapolation in the many different reactions that now have measured backward cross-sections. Is the Δ in πp scattering the exception or the rule? This is a rather important question because in many reactions (both forward and backward) it is difficult to make quantitative predictions without assuming constant residues.

Another curiosity is the spectacular dip at u = $-.15$ $(GeV/c)^2$ in $\pi^+ p$ backward scattering. This is nicely associated with the zero at $\alpha_{Nucleon} = -1/2$ but then what has happened to the N_γ which in the EXD limit fills in such things? Indeed πp backward scattering is a veritable gold mine of violations of EXD. These may be seen in the residues and particle masses for both the Δ and $N_\alpha - N_\gamma$ trajectories.[33,61] As usual, there is no quantitative theoretical framework for understanding this, and so we may just draw a characteristically negative conclusion. (Rough) EXD of pole residues and trajectories was the basis of the EXD Reggeized absorption model. Its axioms are clearly <u>not</u> satisfied in πp backward scattering.

Further details on backward scattering may be found in Refs. 4,33,60,61.

7. Vector-Meson Production

7-A: $\pi N \to \rho N$

In figure 35 I give the result of a Reggeized (π and A_2) absorption model calculation of $\pi^- p \to \rho^0 n$, comparing a best fit to all data with the accurate spark chamber experiment at 11.2 GeV/c.[94] This is mainly to be used in evidence against the Multi-Regge model but I would like to make one comment here. Thus if the conclusions of 5-A are correct then one would expect to see a marked failure in the Vector dominance predictions. Thus fixed poles are presumably not present in the strong-interaction $\pi N \to \rho N$ whereas 5-A claimed them to be important in photo-production. The present status[62] of VDM is so confused that, in general, one can only plead for better data on $\pi N \to \rho N$. However there is one point of similarity between $\pi N \to \rho N$ and photo-production. Thus both need absorption constants C that are much larger ($\sim$a factor 1.5 $\to$ 3) than expected. In fact $\pi N \to \rho N$ is one of the strongest pieces of evidence in favour of the Michigan cut model, which supposes such large absorption is always present. In the fit of fig. 35, C is determined from the deviation of ρ_{00} from 1 at t = 0. An independent test of this is $d\sigma/dt$ for $\pi N \to (\pi\pi)_{s\text{-wave}} N$.[63] This has only the π and its cuts exchanged and the energy and t dependence of this data provides a decisive test for any model.[64] Fig. 20 gives the α_{eff} and fig. 36 the $d\sigma/dt$ predicted for this reaction by the fit of fig. 35.

Fig. 37 is intended to depress experimenters not at SLAC. It is a comparison at very small t of the data on $\gamma p \to \pi^- \Delta^{++}$ with the same Reggeized π absorption fit of fig. 34. We note the

deviation from unabsorbed one pion exchange is quite marked in the data. Kinematically $\pi N \to \rho N$ is essentially similar to this reaction and (any reasonable)[23,65] theory will predict both to have the same t dependence. We await confirmation of this.

7-B: The HPW Model and π exchange Reactions

One reason I am sceptical about the significance of the absorption model is that all its major qualitative successes may be achieved by trivial general models. Thus in $\gamma p \to \pi^- \Delta^{++}$ and $\gamma p \to \pi^+ n$, the gauge invariant Born term gives a reasonable answer at t = 0.[48] This may be generalized to the following prescription that is valid for all π- exchange reactions.

As good an answer as the absorption model at t = 0 is obtained by:

(1) Find a set of amplitudes that do not have the peculiar kinematics of t-channel helicity amplitudes. s-channel helicity amplitudes are one choice that felicitates comparison with the absorption model. Another possible choice is any natural set of invariant amplitudes.

(2) Calculate the π pole residue Γ_π in each of these and assume the amplitude to have the obvious form $\Gamma_\pi/(t-m_\pi^2)$ apart from any blatant kinematic factors.

This will generate answers, that are consistent with analyticity, but without the ridiculous low (s-channel) partial waves inherent in the naive Regge π model, with factorizable t-channel amplitudes. Thus we have given a definition of the HPW model for π-exchange reactions.

One can get similar answers for $d\sigma/dt$ by the old idea of evaluating the kinematics factors associated with the OPE Feynman diagram at the π-pole rather than allowing them their natural t-dependence.

7-C: $\pi N \rightarrow \omega N$, $\pi N \rightarrow \omega \Delta$

This data is dominated at present energies by B exchange.[66] An absorption model calculation is inclined to predict too small a cross-section if you take the B couplings from EXD with the π. At the moment the data on $\pi N \rightarrow \omega N$ is not good enough near t = 0 to test the absorption model prediction that $\rho_{00} \rightarrow 0$ at t = 0. Whatever your favourite theory, this data will provide interesting tests because the kinematics/exchanged poles are distinctively different.

α_{eff} for $\pi^+ p \rightarrow \omega^0 \Delta^{++}$ is given in fig. 19.

Better data please!

7-D: Two Remarks

I would like to make two general points about quasi 2-body resonance production.

The first is directed to experimenters. It is customary to present the decay density matrix elements of resonances in the Jackson (or t-channel frame). It would also be useful to have this data in the helicity (or s-channel) frame. Any model, of which the absorption model is a particular example, that emphasizes (s-channel) unitarity may be more easily tested in the helicity frame. The two frames are related only by a rotation, but it is difficult to perform this on published data which is averaged over t-intervals through which the rotation varies.

Secondly I would like to encourage theoretical effort to understand "background" in quasi 2-body data. At the moment rather sophisticated models of the t-dependence (Regge poles, absorption etc.) are fit by theoreticians to "resonance" production amplitudes. The latter are usually extracted experimentally by, perforce, rather naive procedures. ("incoherent background" etc.). It seems that more theoretical effort should be devoted to the second problem if full use is to be made of the experimental data.

§8. The Multi-Regge Model

8-A: Region of Applicability

I have had no practical experience with Multi-Regge calculations and so it is inappropriate for me to give a detailed review.[(67),(68)] Instead, I will just indicate what lessons one can draw from the more familiar studies of quasi 2-body data.

In general one must expect the Multi-Regge model to be somewhat less quantitative than its 2-body counterpart. Thus the average $|t|$ values are rather larger and the average sub-energies much smaller than in 2-body calculations. Before illustrating this latter point, let us distinguish two possible approaches to the Multi-Regge model. The first carefully makes cuts on the data to force all sub-energies to be large enough for an asymptotic expansion to be unambiguous[(69)] This is the most straight forward application, but unfortunately only a very small fraction of the data (say 5%, even at 30 GeV/c) is in a region where the relevant sub-energies are all large[(70)]. Although theory and experiment may agree quite well, it seems that such a model is rather irrelevant for understanding the bulk of experimental production data. Chew and Pignotti[(71)] first realized that the concept of duality might enable one to extrapolate the model to low subenergies and so use it to explain all experimental data. Although there is clearly some truth in this suggestion one must ask whether duality is sufficiently quantitative to enable one to make meaningful calculations.

In fig. 38, we plot the experimental $\pi^+\pi^-$ elastic cross-section[(72)] v. the extrapolation of the Regge high energy fit. It would seem that the latter is a rather dubious description of the region mass ($\pi^+\pi^-$) $<$ 1 GeV: where in fact one finds the majority of multiparticle events.

As a further example, consider backward $\pi^+\pi^-$ scattering where there are rumoured to be no Regge poles. Correspondingly the FESR

$$\int_{\text{resonances}} \nu \, \mathrm{Im} A \, d\nu = \text{Regge (i.e. zero)} \qquad (6)$$

is satisfied due to the oscillation in sign of the resonance contributions to the left hand side. (e.g. the ρ has the opposite sign to the f_0 in (6)). Unfortunately it seems that $\int ds \, |A|^2$ is more relevant for a Multi-Regge calculation. Of course this is by no means zero and so is unequal to the Regge extrapolation.

We will now take a look at the Multi-Regge model in action for a reaction where the above difficulties are probably minimized.

8-B: Pion Exchange

Perhaps the most reliable Multi-Regge calculations are those in which one of the exchanged Regge poles is a pion. Typical of this work is a fit to $pp \rightarrow p\pi^-\Delta^{++}$ at 28.5 GeV/c by Berger[(70)]: the relevant diagram is illustrated in fig. 39. Such a simple model fits the $t_{p\Delta^{++}}$ dependant cross-section quite well; but, more interestingly, it agrees with the observed asymmetry in the Treiman-Yang distribution, describing the decay of the $p\pi^-$ system. (see fig.40). Now it is amusing to compare this with the similar process (fig. 41) $\pi^- p \to (\pi^+\pi^-) n$ at 11.2 GeV/c. Again we have π exchange but now the $\pi\pi$ mass is in the ρ region whereas in fig. 39 we had mass$(p\pi^-) > 2$ GeV. Apart from this the calculations should be rather directly comparable.[73] Wagner,[74] in fig. 41, has made similar assumptions about the π exchange to Berger in fig. 39. Indeed, as before, Wagner's agreement with $d\sigma/dt$ is well-nigh perfect (Such is the power of a parameter). However fig. 42 presents the comparison of theory and experiment for the density matrix element $\rho_{00} - \rho_{11}$ describing the $\pi\pi$ decay. There is clearly little resemblance between theory and experiment even at $t = 0$. This is of course expected as such decay density matrix elements are well-known to need absorption (cuts) to describe them. In fact fig. 35 gives the absorption model fit to this data. It is sobering to note the poor agreement between the unabsorbed Regge calculation and the data in fig.35. This indicates how a partial comparison (i.e. $d\sigma/dt$ only) of theory and experiment can be very misleading.

Thus the same Regge model fits the πp decay without absorption but is a dismal failure for the $\pi\pi$ decay. The former was a much less stringent test being averaged over $0 \leq |t| \leq 0.8$ $(GeV/c)^2$ as the statistics were insufficient for the detailed t-dependent test of fig. 42. From this I would like to draw some conclusions.

(i) Until the poor agreement in fig. 42 has been explained, I consider that the relevance of a Regge π, in Deck type

processes like fig. 39, to be quite unproven.

(ii) It would be of interest to extend the absorption model to multiparticle processes.

(iii) One should be careful when testing the Multi-Regge model not to integrate over so many variables as to obscure its distinctive predictions.(e.g. factorization,[75] dips, energy dependence and $t = 0$ behaviour of evasive Regge poles). Again it is only reasonable to check one's simplifying assumptions in the well studied 2-body scattering case. One may then, for instance, deduce that it is unappropriate to fit multiparticle data out to the rather large $|t|$ values that are often used (to restrict $|t| \lesssim 0.4$ is realistic). Again one should perhaps try to avoid reactions that in the 2-body case have large cut (absorption) corrections even at $t = 0$.

The reader may have gathered that I do not believe that such care and circumspection, generated by comparison with a simple case, is a notable feature of Multi-Regge fits. It must be admitted, however, that it will probably need data of better statistics before these points become of vital importance.

(iv) The defect, indicated by the comparison of $\rho_{00} - \rho_{11}$ with theory in fig. 42, holds in any model that claims there is but one amplitude for π exchange. (i.e. only helicity zero, as at the pole, and no helicity one). In particular the form factor (Dürr - Pilkuhn or otherwise) model of π exchange is incorrect for this reason.[76,77]

(v) The generalized Veneziano model is a new and very promising approach to multi-production processes.[78] However, although this overcomes the Multi-Regge difficulty with the region of applicability (see Section 8-A), the friendly warnings of (iii) and (iv) still apply to this model.

§9. Conclusions

9-A: Regge Poles

In a typical elastic amplitude, the absorption (cut) corrections are some 20 percent ($\sim\sigma_{elastic}/\sigma_{total}$) at t = 0 and become equal in size to the pole somewhere between t = -0.5 and -1.0 $(GeV/c)^2$. The photoproduction and vector meson data of sections 5 and 7 indicated that this simple absorption model under-estimated the non pole effects by a factor between 1.5 and 3. Our study of other reactions showed that such discrepancies are the rule and <u>not</u> the exception. For instance, sections 2 to 4 (πN CEX and elastic scattering) suggested that the corrections for the nonflip A' amplitude were again larger than the rough σ_{el}/σ_t estimate.

We would like to point out that this gloomy prognosis is quite consistent with the impressive success obtained by the various Regge pole bootstrap ("duality") schemes. For instance, consider the relations obtained through resonance saturation (i.e. Regge poles only) of finite energy sum rules.[79] These give beautiful connections between the quantum numbers of the direct and crossed channel resonances. Unfortunately these have essentially only been verified for the resonances on the leading meson and baryon trajectories. These are however precisely the resonances (e.g. ρ, Δ etc.) that occur in relatively high (s-channel) partial waves. The low partial waves of sophisticated (e.g. the Veneziano model[80]) versions of these theories are always, I believe, quite embarassing with predictions of numerous unobserved states. Thus both the HE data (reviewed here) and the various bootstrap schemes agree that Regge pole theory is splendid for the "high" partial waves while "low" parital waves are a common problem. (no doubt they have a common solution).

However, being diligent seekers after quantitative data fits we must hurry on to ....

9-B: The Absorption Prescription for Cuts

We have considered the two essentially different versions of this model. They were defined in the introduction and we will treat them in turn - detailing their specific successes and failures.

The theoretically most attractive [81] scheme is the EXD model. We saw in Section 2 that this gave a particularly nice fit to πN CEX. Here the size of the cut is well determined by the value of $d\sigma/dt$ at $\alpha_\rho = 0$ ($t \sim -0.6$ (GeV/c)^2) where the pole vanishes. The experimental data confirms the expected size of the cut and rules out any significant increase of the absorption due to diffraction dissociation. Further the fit to pp scattering (section 3) with a high slope Pomeron was quite reasonable, if not quantitative in the sense of our friend χ^2. However the fit to $p\bar{p}$ scattering was then rather poor and as pp and $p\bar{p}$ scattering are related by crossing, analyticity requires that a correct fit to one should give a good fit to the other. Thus elastic scattering, and pp in particular, remains under an amorphous shadow which can only be clarified by further work. In Sections 5 and 7 we saw that this model was quite unable to fit any of the photo and ρ-meson production experiments without a large increase in the size of absorption. This seems quite conclusive evidence against this model.

Secondly we considered the Michigan model. There are two well-known dips in differential cross-sections near t = 0. That at $t \sim -0.6$ (GeV/c)^2 in πN CEX lies near $\alpha_\rho = 0$, and that at

$u \sim -0.15$ (GeV/c)^2 in backward $\pi^+ p$ scattering lies near $\alpha_N = -1/2$. According to this model this correlation (which is one of the nicest qualitative successes of Regge pole theory) between trajectory values and dips is quite accidental. Thus such dips are produced by interference between the cut and the pole and not by intrinsic zeros of pole residues. Philosophical objections aside,[82] we saw in Section 2 that the Michigan model gives a rather poor fit to πN CEX. However a strong point in its favour is the correct prediction of the large absorption necessary in photo and ρ-meson production. We argued in Section 5, that the details of photoproduction, in particular its universal lack of shrinkage, were dubiously consistent with this model[83].

Thus the reader may pay his money and take his choice. We can offer either the frying pan or the fire.

9-C: Repercussions

The collapse of the house of Regge cards discredits certain other theories and suggests some ideas that may rise phoenix-like from the ashes.

(i) EXD, "Duality"

Both these are quite splendid ideas which have had some interesting successes. Usually they are expressed in terms of the attributes of poles alone. However as high energy data has demonstrated the importance of cuts away from t = 0, it is clear that their correct formulation is in terms of a complicated mixture of poles and cuts.[84]

I do not know of any basic theoretical work along these lines. Phenomenologically it has been proposed that one should break EXD through cuts alone.[21,25] We saw in section 9-B that this EXD Reggeized absorption model agrees poorly with data.

(ii) Nature of Pomeron

Supporters of a zero slope Pomeron will clearly have to find a new model for cuts to explain the shrinkage observed in the recent p-p scattering data.

With the present cut models, a high slope Pomeron is favoured by current data.

(iii) More General Cut Models

We would just like to show that three curious features of present data indicate that t-channel unitarity plays a more important role than anticipated in most phenomenological theories.

(a) We always see more shrinkage in strong interaction processes than in the singly weak photoproduction (which suggests fixed poles in the latter). This may be correlated with the corresponding bilinear and linear t-channel unitarity relations (only the latter allows fixed poles), in these two types of reaction.

(b) At present energies, multiple scattering (Sections 3 and 4) has as much to do with the P' and ω trajectories, as with Pomeron induced cuts. This suggests that cuts and these secondary trajectories will be closely linked in any dynamical scheme. In the absorption type approach multiple scattering is associated with the box type diagrams as in fig. 24. It is then presumably true that such diagrams give important contributions to the pole singularities when iterated in the t-channel.

There has been some interesting progress in the Multi-Regge bootstrap[68] to dynamically relate poles and cuts. This work has not yet been sufficiently refined to be the basis of a quantitative phenomenology.

(c) There is no sign of any deviation in the experimental energy dependence of πN CEX, in the dip region, from that expected from a simple pole.

Points (b) and (c) illustrate that poles are important for effects one might have expected to be dominated by cuts.

(iv) Vector Dominance

As we remarked above there is strong evidence for fixed poles in photoproduction. Thus the vector dominance model relating photoproduction and vector meson production needs reappraisal.

9-D : Experimental Implications

We have considered a small fraction of available experimental data in Sections 2 to 7. However, I believe that this is by no means a biased sample, being selected solely because either the experiment was particularly precise or the theory particularly unambiguous. In fact the general features of all 2-body reactions are so similar and (roughly!) explained away by present theoretical models that it will need high statistics data (especially at larger s or t) before new tests for theory will emerge.

More specifically we saw that, if present theory is at all correct, we can expect marked changes in data for $0.5 \lesssim -t \lesssim 2.0$ $(GeV/c)^2$ and $p_{lab} \gtrsim 20$ GeV/c. We illustrated this in Sections 2 and 3 but in all reactions the structure due to cuts should appear from behind the hazy sheath created by secondary trajectories at present energies.

Finally we would like to point out that the very poor theoretical understanding of $\pi N \rightarrow \rho N$ near $t \approx 0$ (Section 7) emphasizes the immense difficulty in extracting on-shell π-π scattering via Chew-Low extrapolation in $\pi N \rightarrow \pi\pi N$. Present methods use either too little theory (e.g. phenomenological form factors) or too much (specific absorption calculations). Whatever happy blend of theory and experiment is chosen[85], it is obvious that, as always, all experimental information should be used. Density matrix elements that disagree with one's model should not be just ignored.

9-E: Multi-Regge Model

In our brief encounter with the Multi-Regge model we saw that the case, either for or against it, remains unproven. In general there are no independent checks of its specific and characteristic assumptions. It is particularly important to search for such confirmation, of say shrinkage due to nonzero trajectory slope, when such features are not valid in the simpler 2-body case.

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I am grateful to the many members of the Lawrence Radiation Laboratory who made my stay there so pleasant. In particular, I would like to thank Chris Quigg for his invaluable help in preparing this paper. Ed Berger was my fount of wisdom on the Multi-Regge model although this does not, of course, condemn him to my satanic point of view.

Many of these calculations would have been impossible without the efficient help of the computer centre.

Appendix: Theory in search of shrinkage:

Figures 1 through 20 contain the plots of the experimental $\alpha_{eff}(t)$ v.t. (α_{eff} is defined in equation (1)). To obtain these values we interpolated the experimental $d\sigma/dt$ to obtains values at the same t but different s values. These were then fitted to equation (1) where we varied not only $\alpha_{eff}(t)$ and the coefficient A(t); but also, where relevant, the t-independent overal normalization of an experiment (within its quoted systematic error bounds). This is made meaningful by fitting several t values simultaneously.

Sometimes experimental data is given averaged over sizeable t-bins and not at a single t value. In such a case we used the same averaging bin at each energy but in the figures we only mark the centre of the bin and omit for clarity the "error bars" on t.

We used in this fit all data (usually with $p_{lab} \gtrsim 5$ GeV/c), that we could find.

In the figures, we also mark typical Regge trajectories whose parameters were generally determined by the principle of the nearest round number. The best fit values do not differ much from this. We sometimes mark the theoretical predictions of the Reggeized absorption model when these seem reasonably unambiguous. Unless specifically marked otherwise, these correspond to the Exchange Degenerate version with EXD trajectories and residues, both varied to best fit all the experimental information. We also varied the Pomeranchuk absorption constant C_{pom} (equation 4). The Re/Im ratio r and $(P' + \omega)/P$ ratio δ (equation 4) were fixed at reasonable values.

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46. Note that it is rather hard to understand the difference in $K^\pm p$ and $p\overset{(-)}{p}$ scattering in the absorption model. Take, for definiteness, the high slope Pomeron model of Frautschi and Margolis. Then as $\sigma_t(K^+p) \sim \frac{1}{2}\sigma_t(pp)$, the effect of cuts in $K^\pm p$ scattering should be smaller than in pp and $p\bar{p}$ scattering. This should lead to:

(i) More shrinkage at small t in K^+p scattering compared with pp scattering. (see figures 7, 10 and 30).

(ii) The crossover in $K^\pm p$ scattering should be at larger $|t|$ than in $p\overset{(-)}{p}$ scattering. (see fig. 32 for $p\overset{(-)}{p}$ and new data presented at this conference for $K^\pm p$).

Both these qualitative conclusions do not seem to agree with experiment.

47. H. Harari, Phys.Rev. Letters 20, 1395 (1968).

48. B. Richter, Vienna conference, 1968. R. Diebold, Invited talk at this conference.

49. R. Oehme in Strong Interactions and High Energy Physics, edited by R. G. Moorhouse (Oliver and Boyd, 1964).

50. I. Bender, H. G. Dosch and H. J. Rothe, Nuovo Cimento 62, 1026 (1969). R. Dashen and S. Y. Lee, Phys. Rev. Letters 22, 366 (1969).

51. To be exact the data needs fixed double poles as well as "ordinary" fixed poles. Thus, from crossing symmetry, fixed poles cannot contribute to, for instance, $\gamma p \to \pi^0 p$.

52. A random reference to such things is H. Harari, Phys.Rev. Letters 22, 562 (1969).

53. M. L. Blackmon, G. Kramer and K. Schilling, Argonne preprint. (on $\gamma p \to \pi^0 p$).
A. P. Contogouris, J. P. Lebrun and G. Von Bochman, McGill preprint. The good agreement obtained by these authors is probably due to a large $\omega \to N\bar{N}$ flip coupling. (see ref. 55).

54. Vector dominance and the data on $\pi N \to \omega N$ may also suggest this.

55. In pion photoproduction, a large $N\bar{N}$ spin-flip amplitude leads (in the absorption model) to a flat energy dependence. However a large spin nonflip coupling leads to the sort of shrinkage observed in πN CEX. The essence of the difficulty in $\gamma p \to \pi^0 p$ is that factorization of the ω suggests the latter situation, in disagreement with experiment.

56. G. V. Dass and C. Michael, Phys.Rev. 175, 1774 (1968).

57. R. Diebold, Phys.Rev. Letters 22, 204 (1969).

58. M. L. Blackmon, G. Kramer and K. Schilling, Argonne preprint. (on $\gamma p \to \pi^+ n$). A. P. Contogouris and J. P. Lebrun, McGill preprint.
J. D. Jackson and C. Quigg, Phys.Letters 29B, 236 (1969).
D. P. Roy, Calcutta preprint. The FESRs for photoproduction

have yet to be exploited to the full. Once more we plea for better low energy experiments so that our studies of the mysteries at high energies, may be based on a solid knowledge of the low energy amplitudes.

59. The same ρ π-cut interference generates the enormous difference between np CEX and $p\bar{p}$ CEX. As we said afore these are kinematically similar to $\pi^\pm$ photoproduction.

60. V. Barger and D. Cline, Phys.Rev. Letters 21, 392 (1968). This gives references to earlier work.

61. E. L. Berger and G. C. Fox, Argonne preprint.

62. R. Diebold and J. A. Poirier, Phys.Rev. Letters 22, 255 (1969).

63. P. Sonderegger et al., preprint on $\pi^- p \to \pi^0 \pi^0 n$.

64. In all absorptive π exchange calculations done so far, an elementary π (i.e. zero slope) agrees as well with the data as a Reggeized (slope $\sim$1 GeV^{-2}) π. $\pi^- p \to \pi^0 \pi^0 n$ should be able to distinguish these radically different models.

65. G. V. Dass and C. D. Froggatt, Nucl. Phys. B8, 661 (1968) is such a "reasonable", although presumably incorrect, theory.

66. A. S. Goldhaber, G. C. Fox and C. Quigg, barbarous preprint. (Phys.Letters to be published).

67. Random references for the Multi-Regge model are:
N. F. Bali, G. F. Chew and A. Pignotti, Phys.Rev. 163, 1572 (1967). Chan Hong Mo et al., Nuovo Cimento 57, 93 (1968). (This formulates the CLA model which we will not consider here). F. Zachariasen and G. Zweig, Phys.Rev. 160, 1322 (1967).
The model has been well reviewed in many articles. For instance, O. Czyzewski at the Vienna conference, 1968.

Also ref.1 , and G. Ranft, University College, London, preprint. (1969).

68. Perhaps the main point of comparing the Multi-Regge model with data is to be able to judge the reliability of the Multi-Regge bootstrap. "Ancient" references for the latter are W. R. Frazer at the Vienna conference, 1968; G. F. Chew, M. L. Goldberger and F. E. Low, Phys.Rev. Letters 22, 208 (1969); and see also refs. 22 and 71.

69. Chan Hong Mo et al., Nuovo Cimento 51, 696 (1967). R. Lipes, G. Zweig and W. Robertson, Phys.Rev. Letters 22, 433 (1969).

70. E. L. Berger, Phys.Rev. 179, 1567 (1969).

71. G. F. Chew and A. Pignotti, Phys.Rev.Letters 20, 1078 (1968); Phys.Rev. 176, 2112 (1968).

72. W. D. Walker et al., preprint.

73. The diagram of fig. 39 has to be honest, one advantage over that of fig. 41. Namely the $\sqrt{t}$ in the OPE of the latter diagram enhances the absorption effects near $t = 0$.

74. F. Wagner, CERN preprint TH-1012 (1969).

75. In particular, one should try to use factorization to relate the multiparticle parameters to those known from the previous 2-body calculations. This is, I believe, not done at present except in the case of π exchange. At a crude level, one may at least try to have the same sort of t dependence in the residue function. (see, for instance, Section 2-F).

76. G. Wolf, preprint SLAC-PUB-544. This paper has extracted an α_{eff} for some π exchange reactions. Unfortunately, I remain suspicious of the detailed results because of the (incorrect) form factor model used throughout this paper.

77. For instance;

Z. Ming Ma et al., Phys.Rev. Letters 23, 342 (1969);

G. Wolf, preprint, SLAC-PUB-607.

78. B. Petersson and N. A. Törnqvist, CERN preprint TH-1040 (1969).

79. For instance, reviews were given by W. R. Frazer at the Vienna conference, 1968; and C. Schmid at the Copenhagen Summer School, 1969.

80. G. Veneziano, Nuovo Cimento 57A, 190 (1968). S. Mandelstam, "Relativistic Quark Model based on the Veneziano Representation," Berkeley preprint, 1969.

81. This conclusion, unlike most in this paper, was not based on a detailed χ^2 fit. It was judged simply from the number of theoreticians, from linearly independent laboratories, who have worked on a given model.

82. The intrinsic lack of EXD of the pole residues demanded by the Michigan model is also disturbing. For instance, the KN resonances seem to have widths that are compatible with EXD. (See C. Schmid, Lettere al Nuovo Cimento 1, 165 (1969) and ref. 33).

83. Wisely, this model does not hazard a prediction for elastic scattering.

84. S. Pinsky, Phys.Rev. Letters 22, 677 (1969).

85. P. E. Schlein, Phys.Rev. Letters 19, 1052 (1967).

86. D. Birnbaum et al., submitted to Phys.Rev. Letters.

87. A. V. Stirling et al., Phys.Rev. Letters 14, 763 (1965).

P. Sonderegger et al., Physics letters 20, 75 (1966).

88. A. R. Clyde, UCRL-16275 (1966).

89. J. V. Allaby et al., Phys.letters 28, 67 (1968). This contains

in fig. 3, a nice survey of all p-p data. This shows the smooth energy variation of the structure indicated in fig. 28.

90. D. V. Bugg et al, Phys.Rev. 146, 980 (1966).

K. J. Foley et al., Phys.Rev. Letters 19, 857 (1967).

91. K. J. Foley et al., Phys.Rev. Letters 11, 425 (1963).

92. R. Anderson et al., Phys.Rev. Letters 21, 384 (1968) and further results submitted to Vienna conference.

93. A. M. Boyarski et al., Phys.Rev. Letters 20, 300 (1968).

94. B. D. Hymans et al., Nucl. Phys. B7, 1 (1968).

95. A. M. Boyarski et al., Phys. Rev. Letters 22, 148 (1969).

96. E. L. Berger, UCRL 19271. (1969)

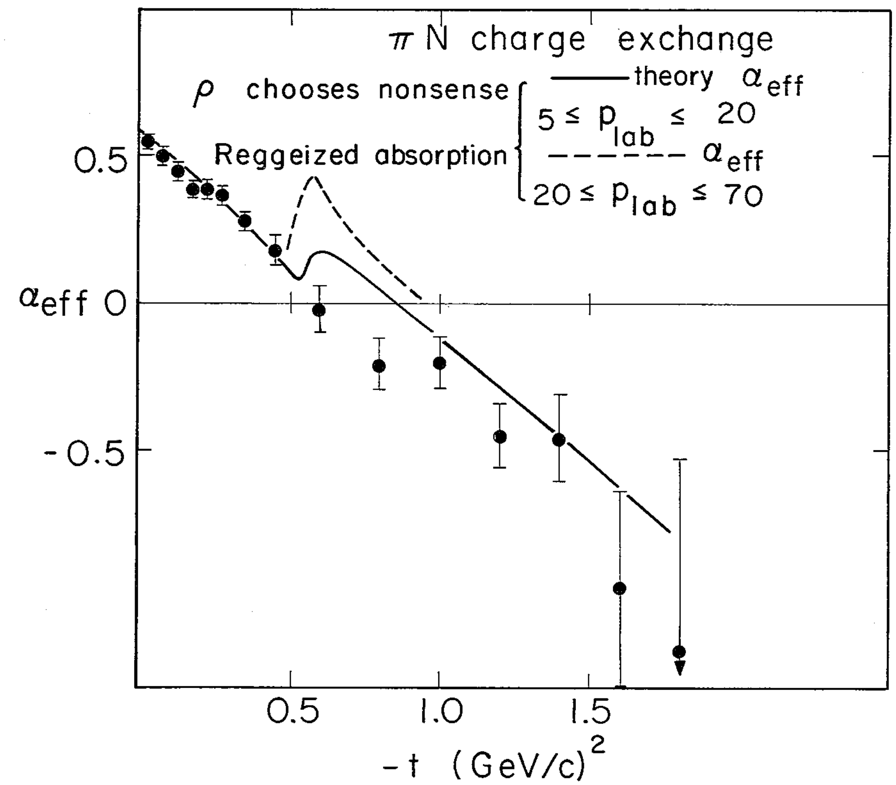


Fig. 1. $\pi^- p \to \pi^0 n$ (See Appendix)

The theoretical curve pertains to the EXD version of the Reggeized absorption model. The solid line corresponds to the presently measured energy range while the dotted line is relevant for Serpukhov energies. In this figure only, the marked ρ trajectory is not purely symbolic but rather that one used in the theoretical calculation.

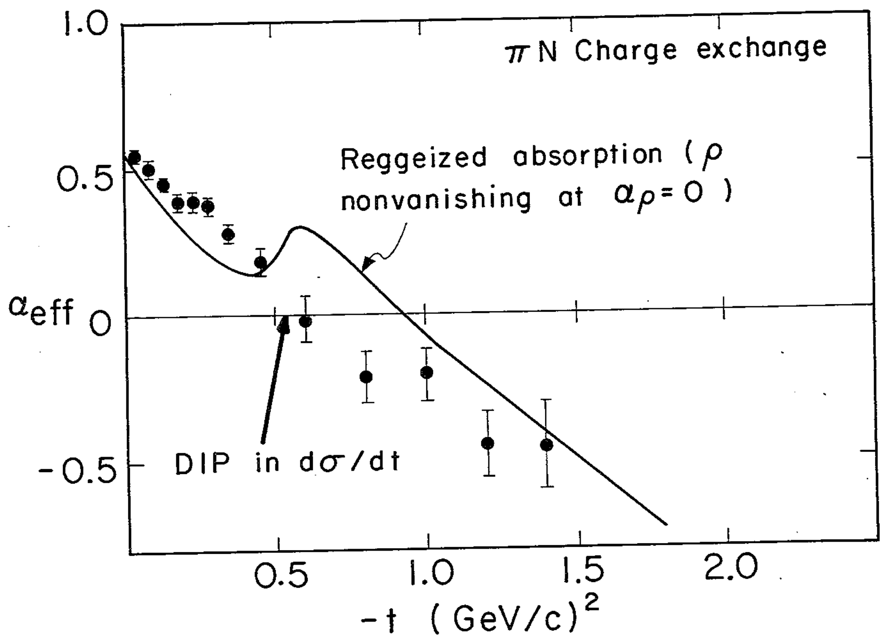


Fig. 2. $\pi^- p \rightarrow \pi^0 n$ (See Appendix)

The experimental points are the same as in fig.1. The theoretical curve follows from the Michigan version of the Reggeized absorption model.

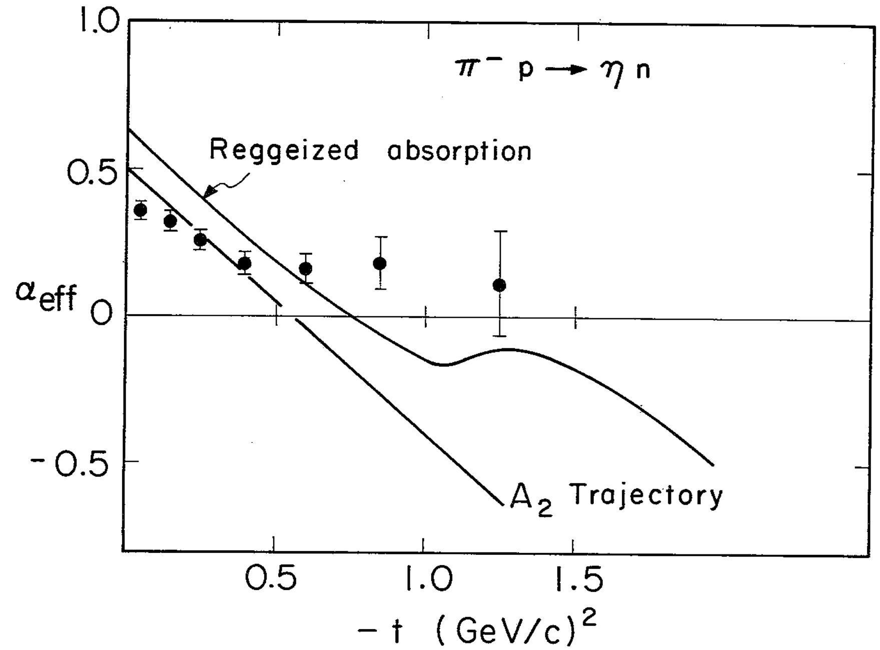


Fig. 3. $\pi^- p \rightarrow \eta n$ (See Appendix)

Data, with $p_{lab} \geq 2.75$ GeV/c, was used in finding the experimental points. The theoretical curve follows from the EXD version of the Reggeized absorption model.

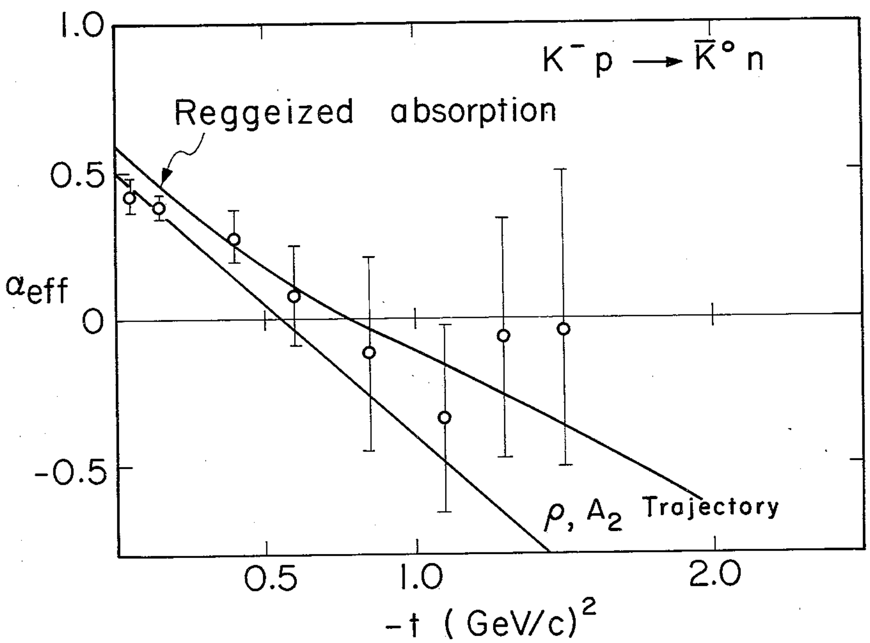


Fig. 4. $K^- p \rightarrow \bar{K}^\circ n$ (See Appendix)

The theoretical curve follows from the EXD version of the Reggeized absorption model. In figures 3 and 4, we made the A_2 trajectory exactly the same as the ρ in fig. 1.

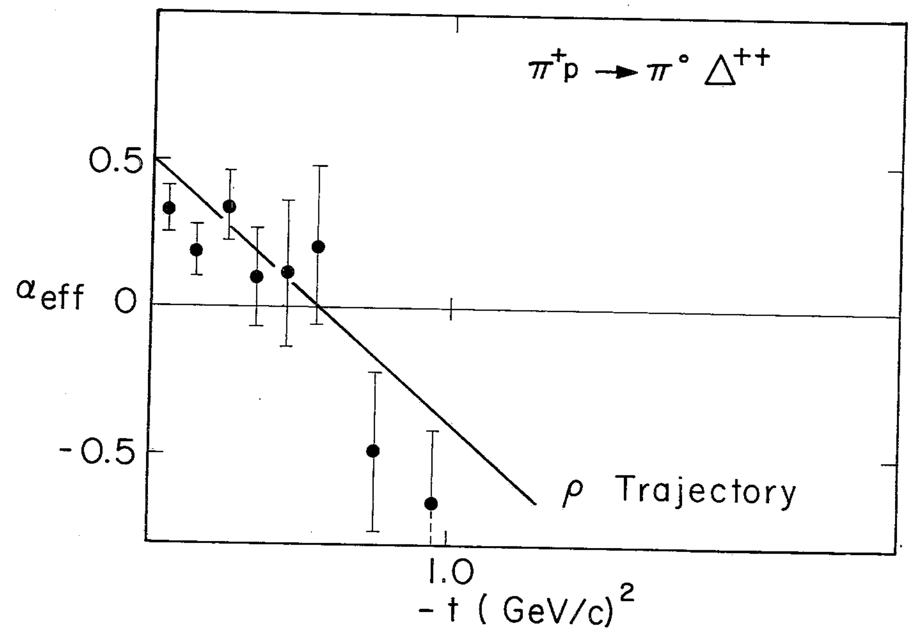


Fig. 5. $\pi^+ p \rightarrow \pi^\circ \Delta^{++}$ (See Appendix)

Data from 3.5 to 8 GeV/c was used. See ref. 28 for a detailed discussion.

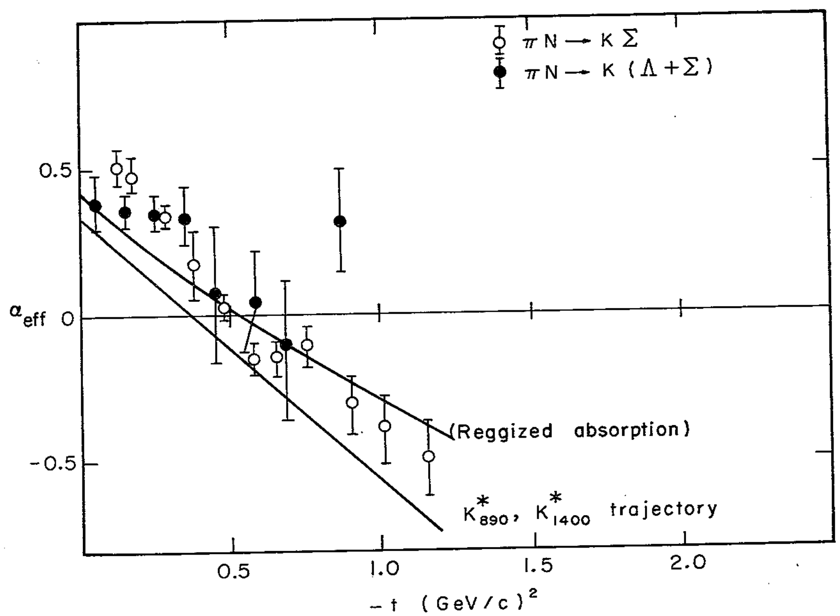


Fig. 6. $\pi^+ p \rightarrow K^+ \Sigma^+$ and $\pi^- p \rightarrow K^0 (\Lambda^0, \Sigma^0)$ (see Appendix)

Data above 3 GeV/c was used for the first reaction. (The new data at 8 and 16 GeV/c presented by Kirz [19] at this conference was not available). The theoretical curve (from the EXD Reggeized absorption model) was similar for both reactions. It was also invariant on changing the fitting range from $3 \leqslant p_{lab} \leqslant 7$ GeV/c to $5 \leqslant p_{lab} \leqslant 15$ GeV/c.

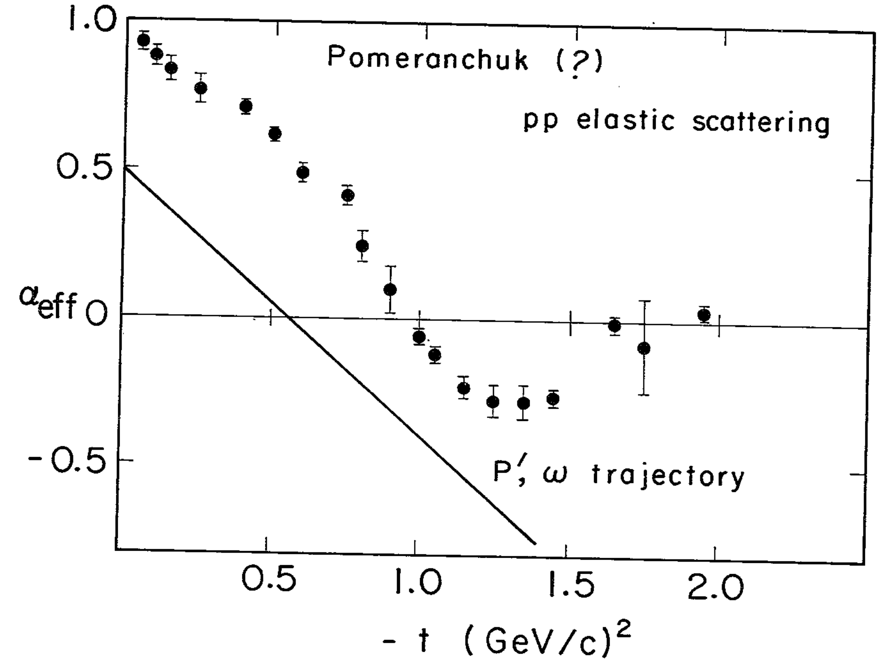


Fig. 7. pp elastic scattering (see Appendix)

The new small t data from Serpukhov was not used. $\bar{p}p$ elastic scattering is not shown as I was unable to obtain the new accurate data [86] at 8 and 16 GeV/c in time.

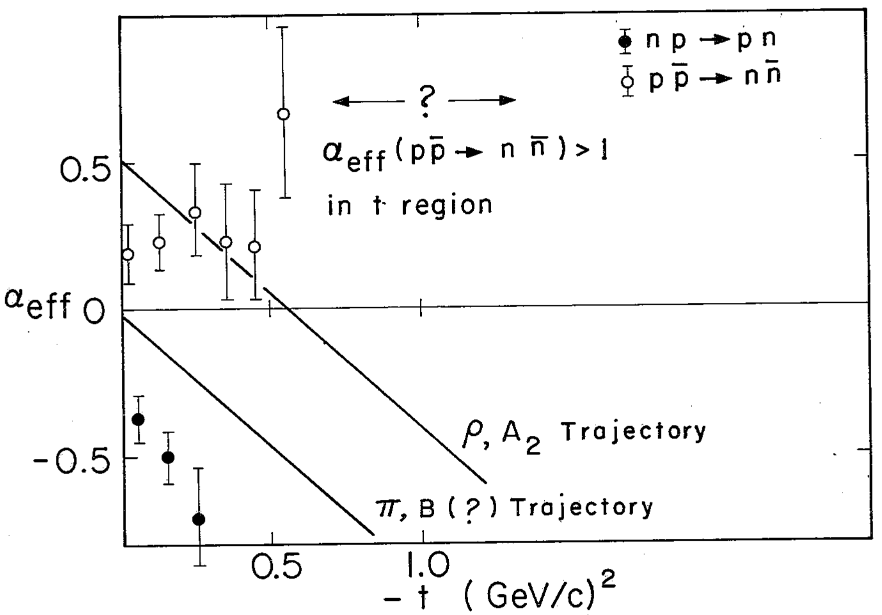


Fig. 8. np and $p\bar{p}$ Charge Exchange (See Appendix)

The np → pn points are dubious as they include low energy ($p_{lab} \sim 2.5$ GeV/c) data and the 8 GeV/c data used, is of uncertain normalization. Although the errors are large, the present pp → $n\bar{n}$ data would appear to violate the Froissart bound ($\alpha_{eff} \leq 1$) in the large t region. New data is badly needed in both these reactions.

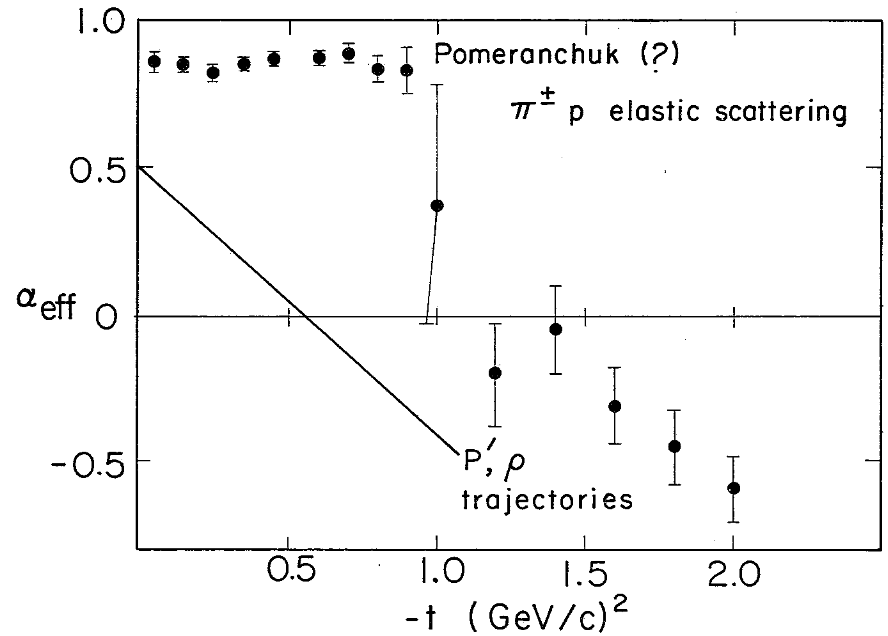


Fig. 9. $\pi^{\pm}p$ elastic scattering (see Appendix)

Both charge states were combined for this fit.

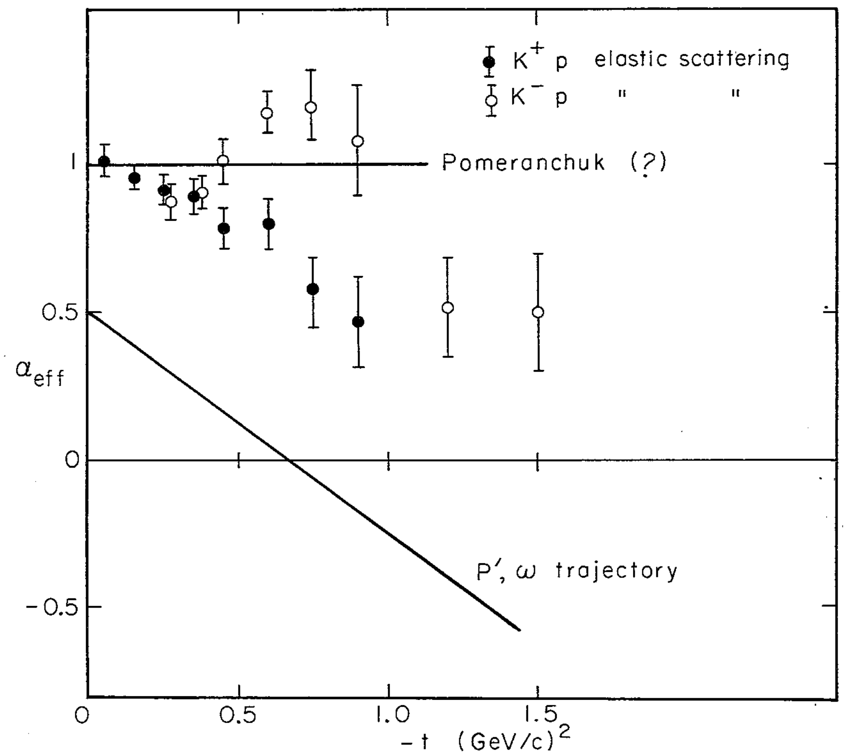


Fig. 10. $K^{\pm} p$ elastic scattering (see Appendix)

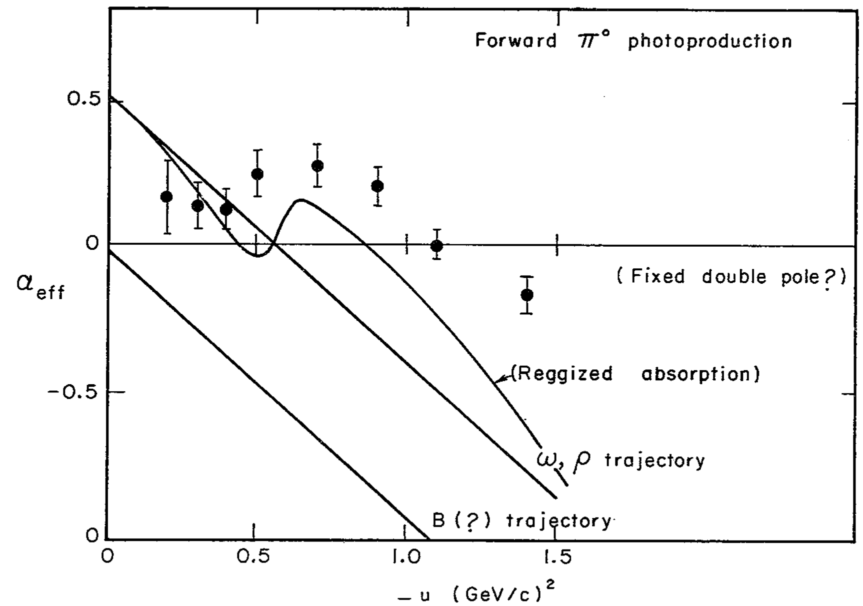


Fig. 11. $\gamma p \to \pi^\circ p$ (See Appendix)

The theoretical curve follows from the EXD version of the Reggeized absorption model. The absorption constant C is implausibly large at 1.3. Reducing C will make the theoretical curve look more like that for πN CEX in fig. 1 (See the discussion in Section 5).

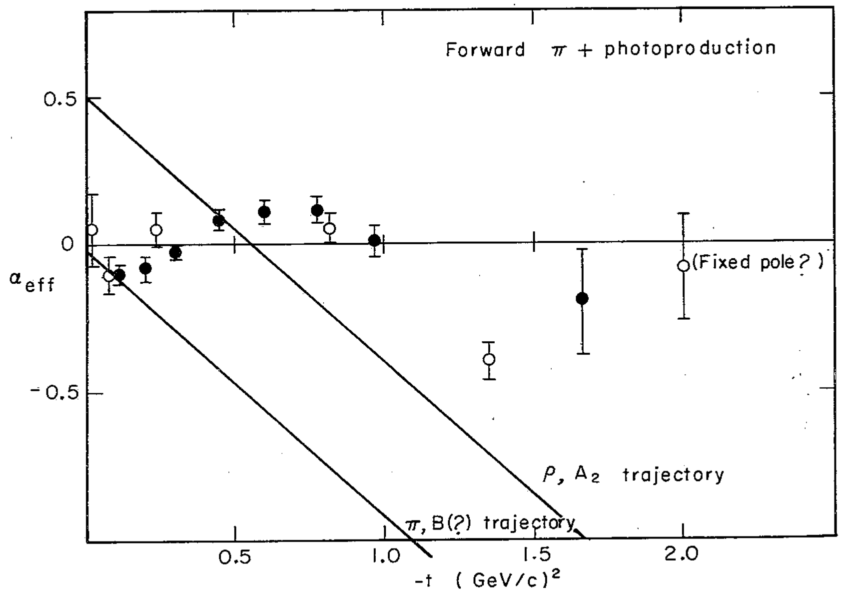


Fig. 12. $\gamma p \to \pi^+ n$ (See Appendix)

See Richter[48]. The white points represent the new SLAC data while the black ones are found from all other data.

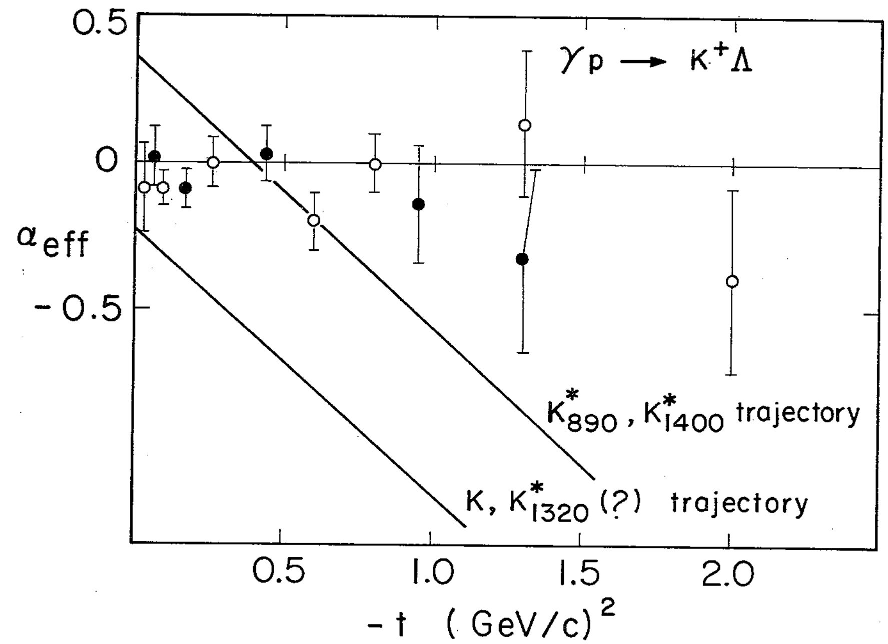


Fig. 13. $\gamma p \to K^+ \Lambda$

The caption is as in Fig. 12.

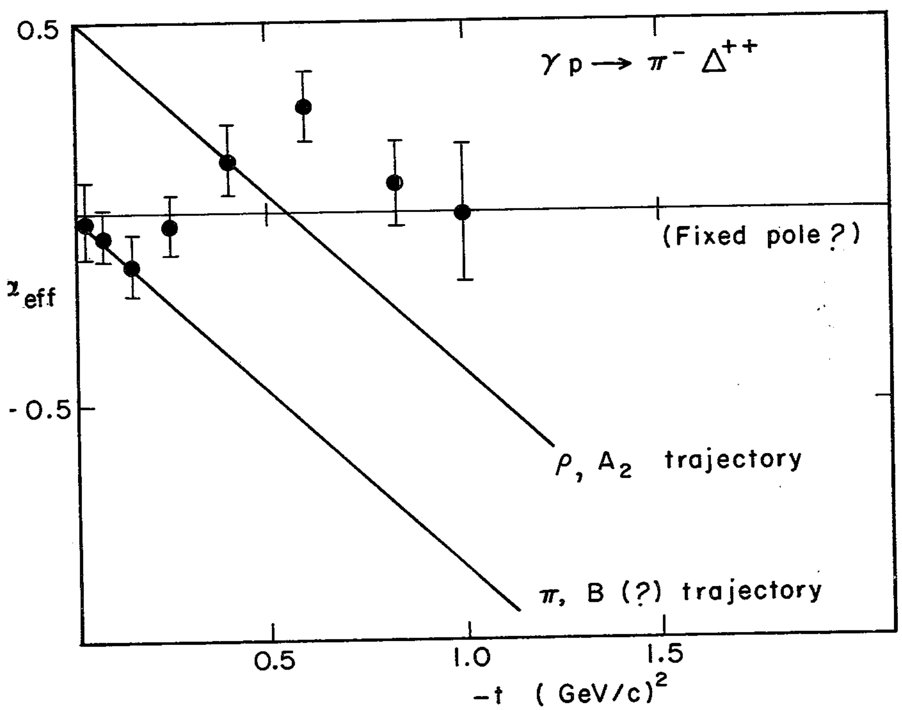


Fig. 14. $\gamma p \rightarrow \pi^- \Delta^{++}$ (See Appendix)

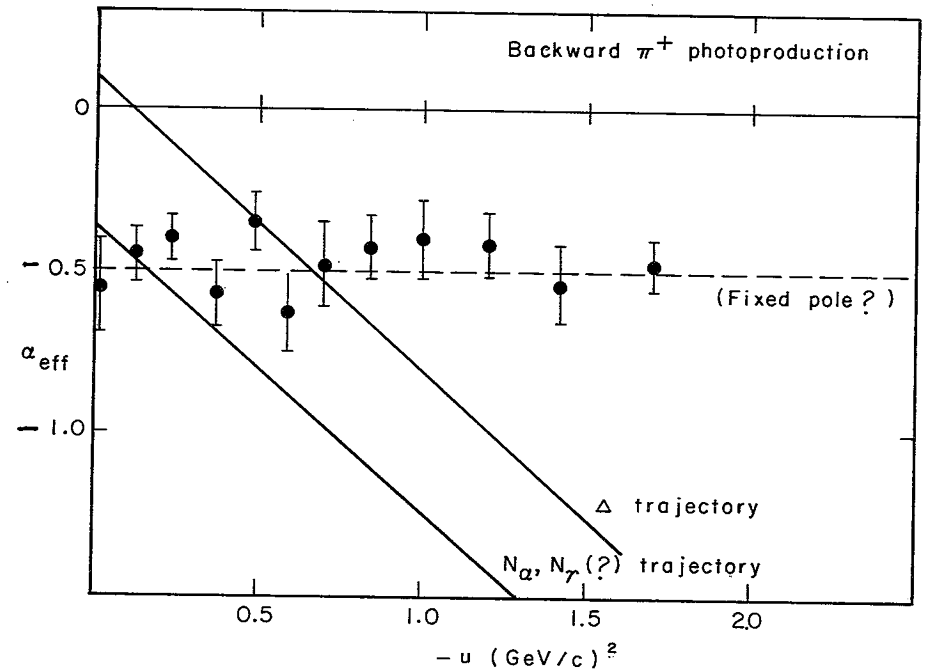


Fig. 15. $\gamma p \rightarrow n\pi^+$ backward scattering (see Appendix)

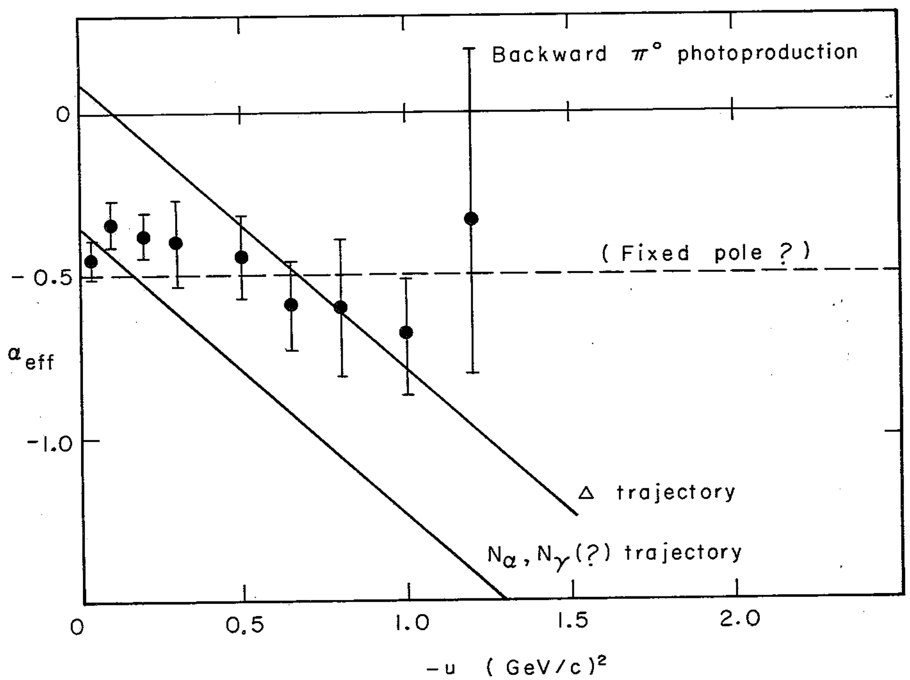


Fig. 16. $\gamma p \rightarrow p \pi^{0}$ Backward scattering (See Appendix)

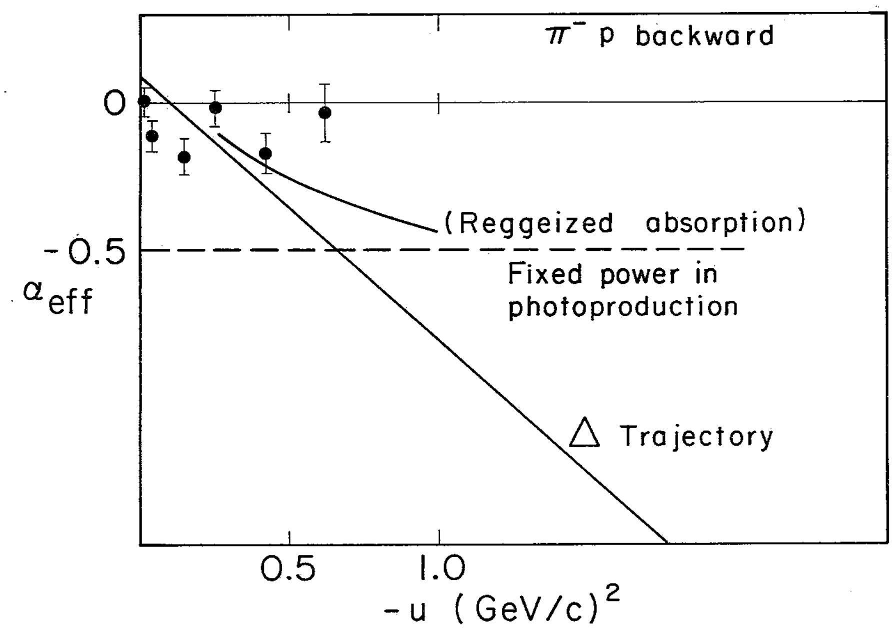


Fig. 17. $\pi^{-} p \rightarrow p \pi^{-}$ backward scattering (See Appendix)

The theoretical curve plotted is only representative. A fuller discussion may be found in Ref 61.

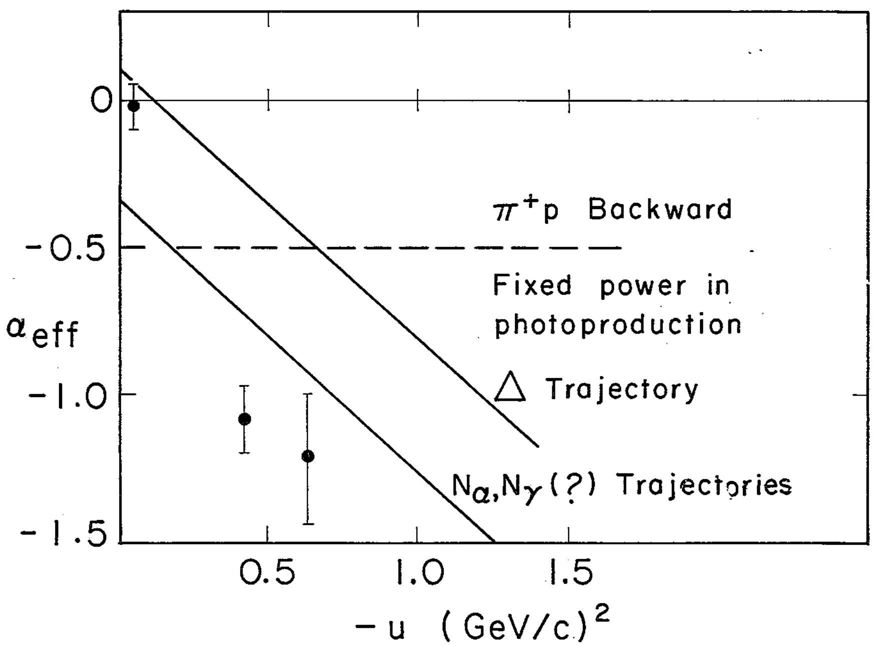


Fig. 18. $\pi^+ p \to p \pi^+$ backward scattering (See Appendix)

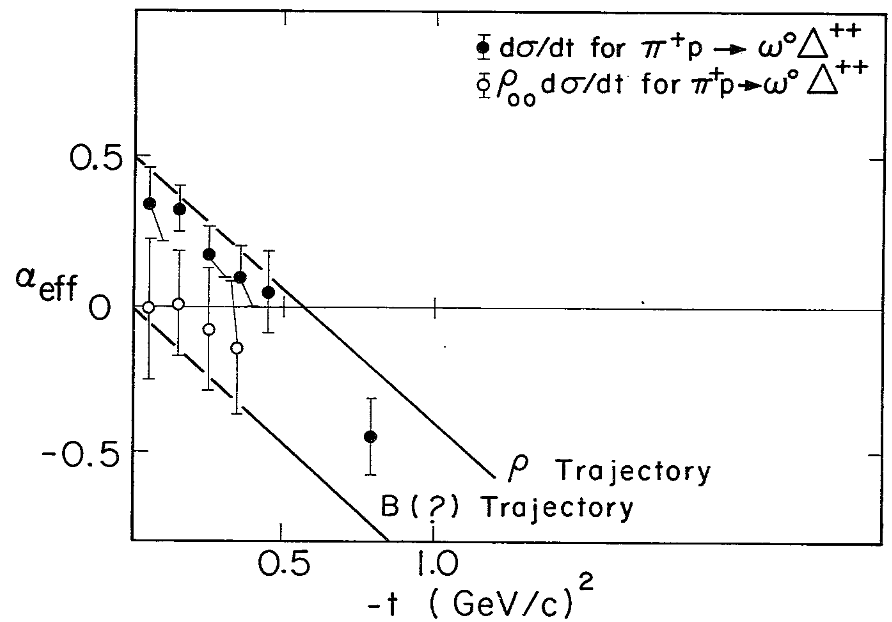


Fig. 19. $\pi^+ p \to \omega^\circ \Delta^{++}$ (See Appendix)

Notice that whereas $d\sigma/dt$ is expected to have ρ and B exchange, $\rho_{oo} \frac{d\sigma}{dt}$ only gets contributions from the lower-lying B trajectory.

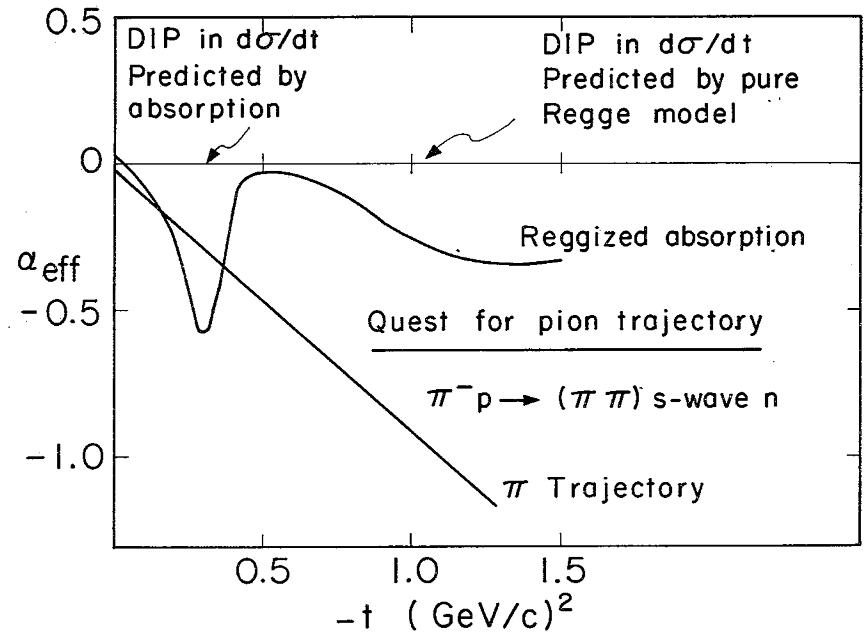


Fig. 20. $\pi^- p \rightarrow (\pi\pi)_{s\text{-wave}}\ n$

The theoretical curve is discussed in Section 7-A. The absence of experimental points typifies our knowledge on the Regge nature of the pion.

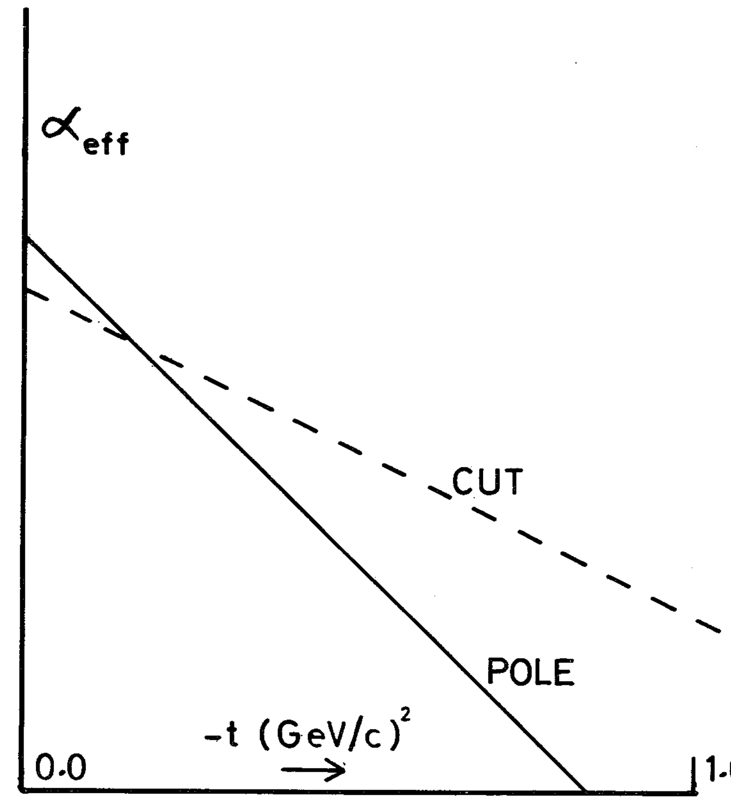


Fig. 21. A comparison of a typical α_{eff} v.t for a pole and a cut.

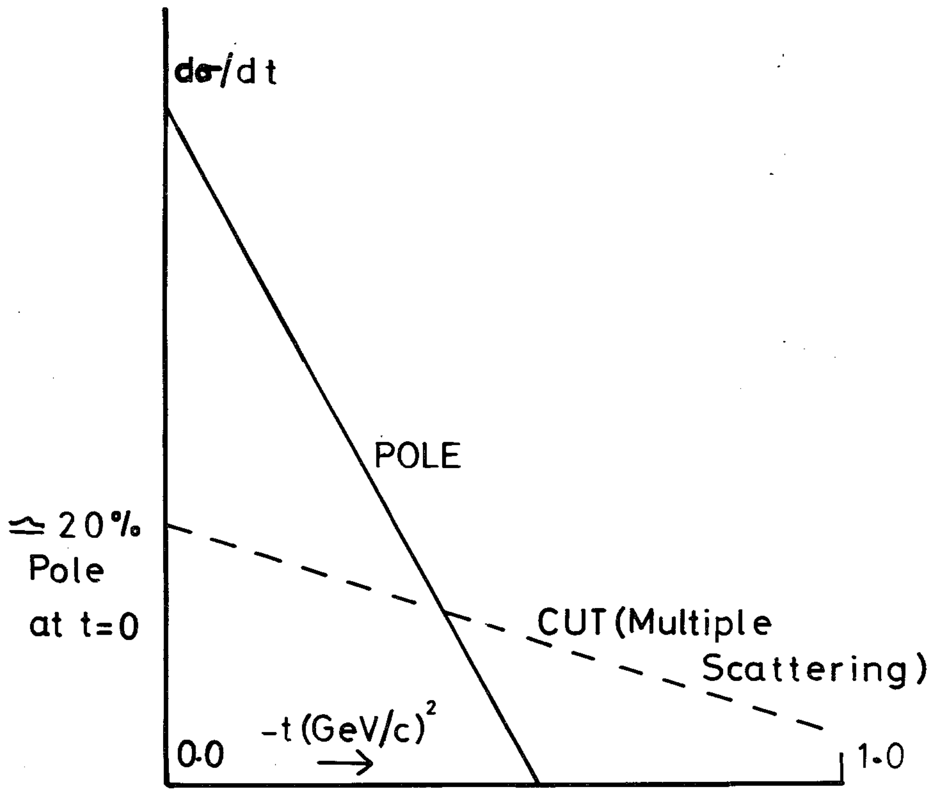


Fig. 22. A comparison of a typical dσ/dt v.t for a pole and a cut.

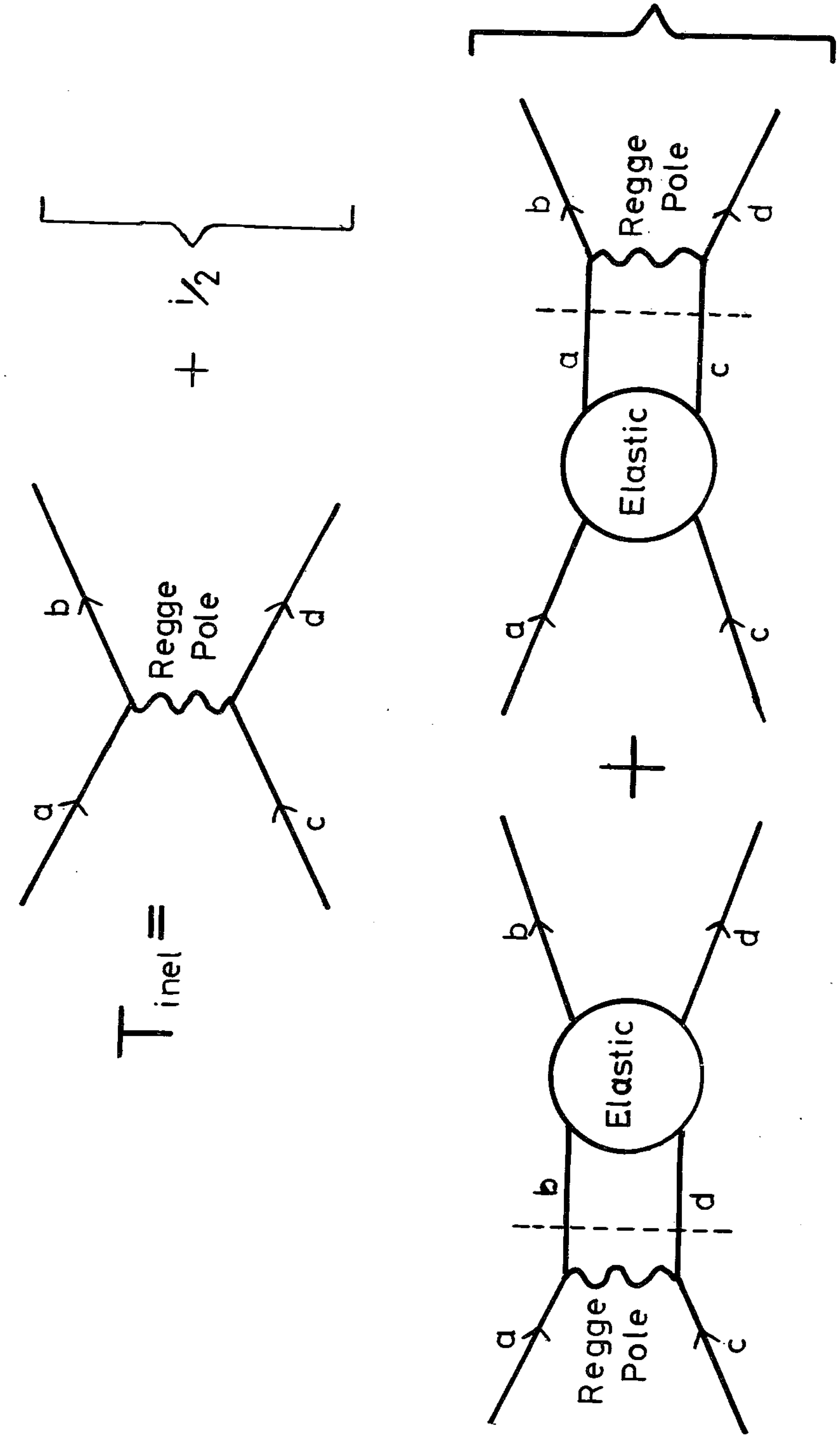


Fig. 23. Diagramatic representation of equation (2).

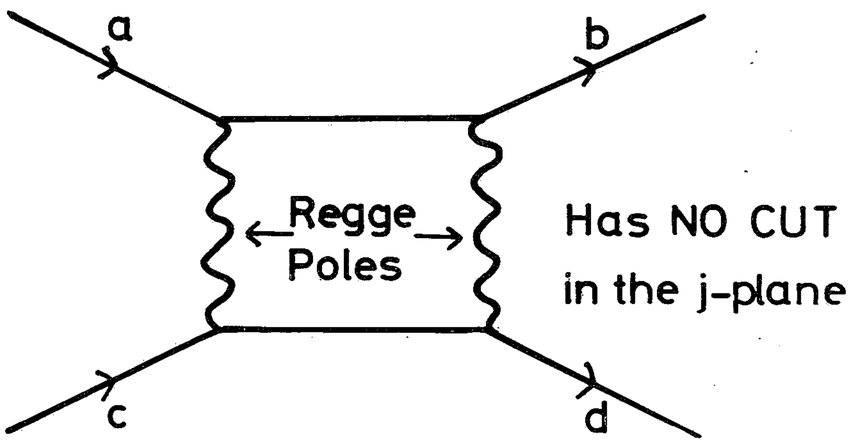


Fig. 24. A Feynman Diagram which does not give a cut in the j-plane.

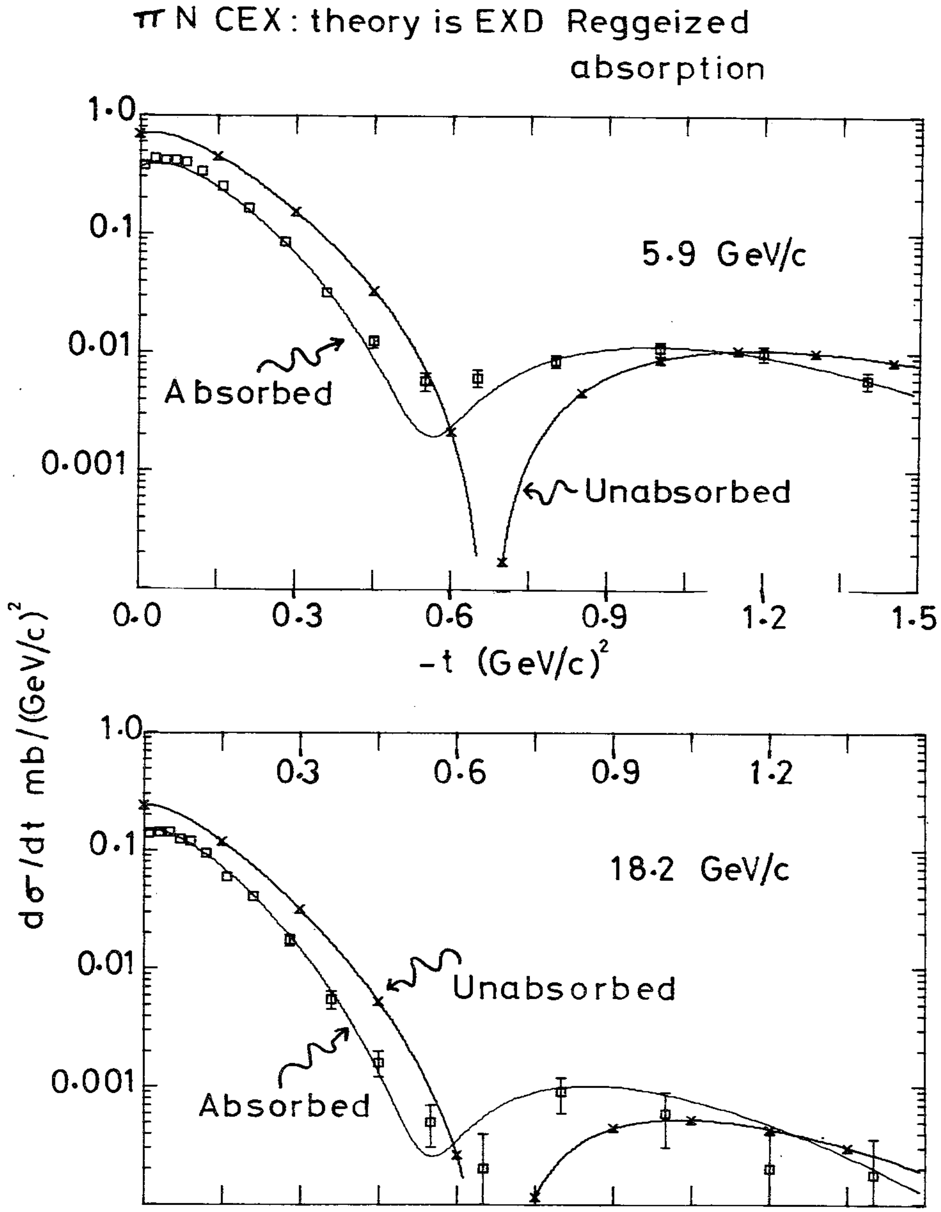


Fig. 25. A comparison of πN CEX data (ref. 87) at p_{lab} of 5.9 and 18.2 GeV/c with the EXD Reggeized absorption model. The solid line is the final absorbed calculation while the solid line with X's represent the prediction of the unabsorbed ρ trajectory.

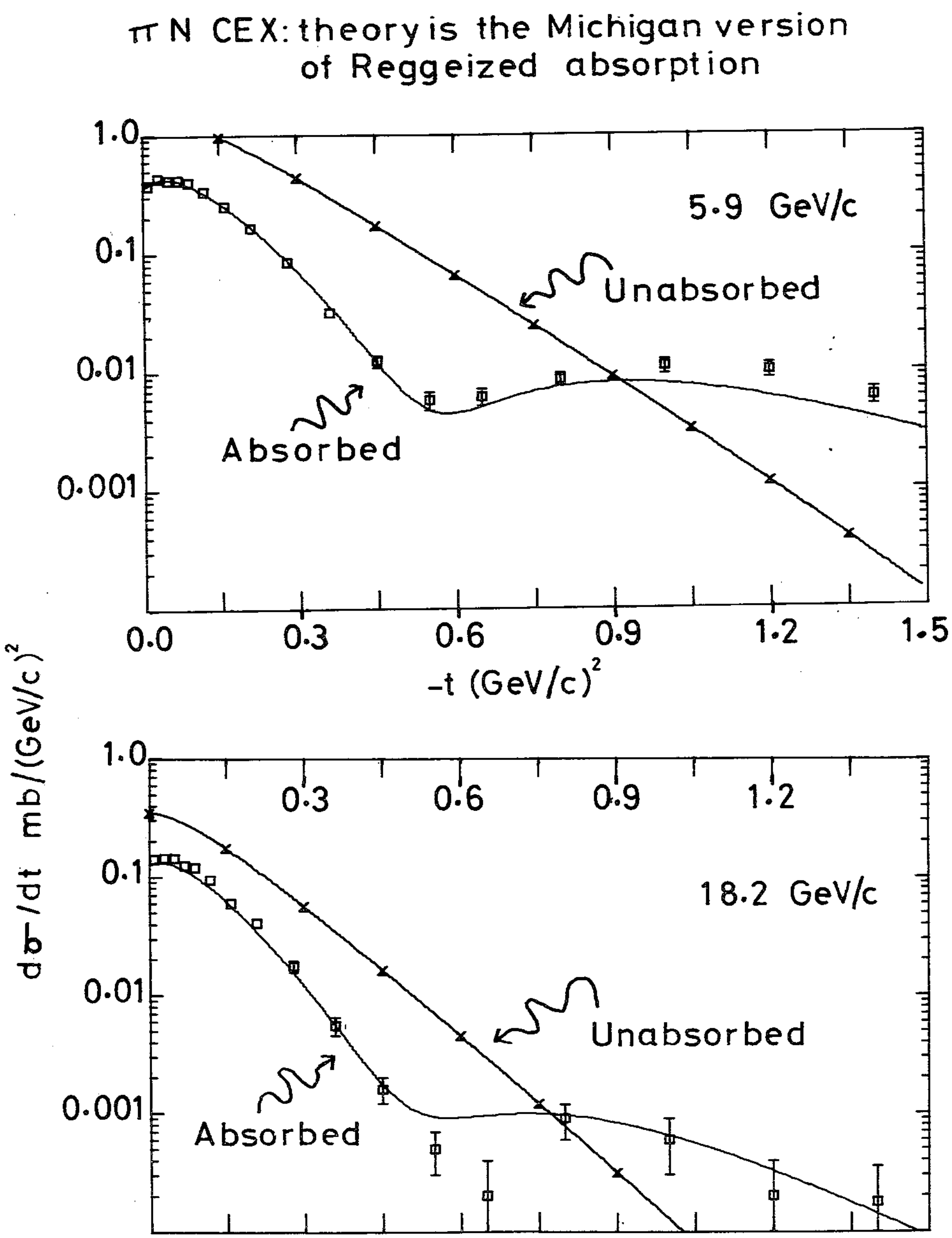


Fig. 26. As fig. 25., but now the theory is the Michigan version of Reggeized absorption. Note the differences between the unabsorbed curves in fig. 25 and 26.

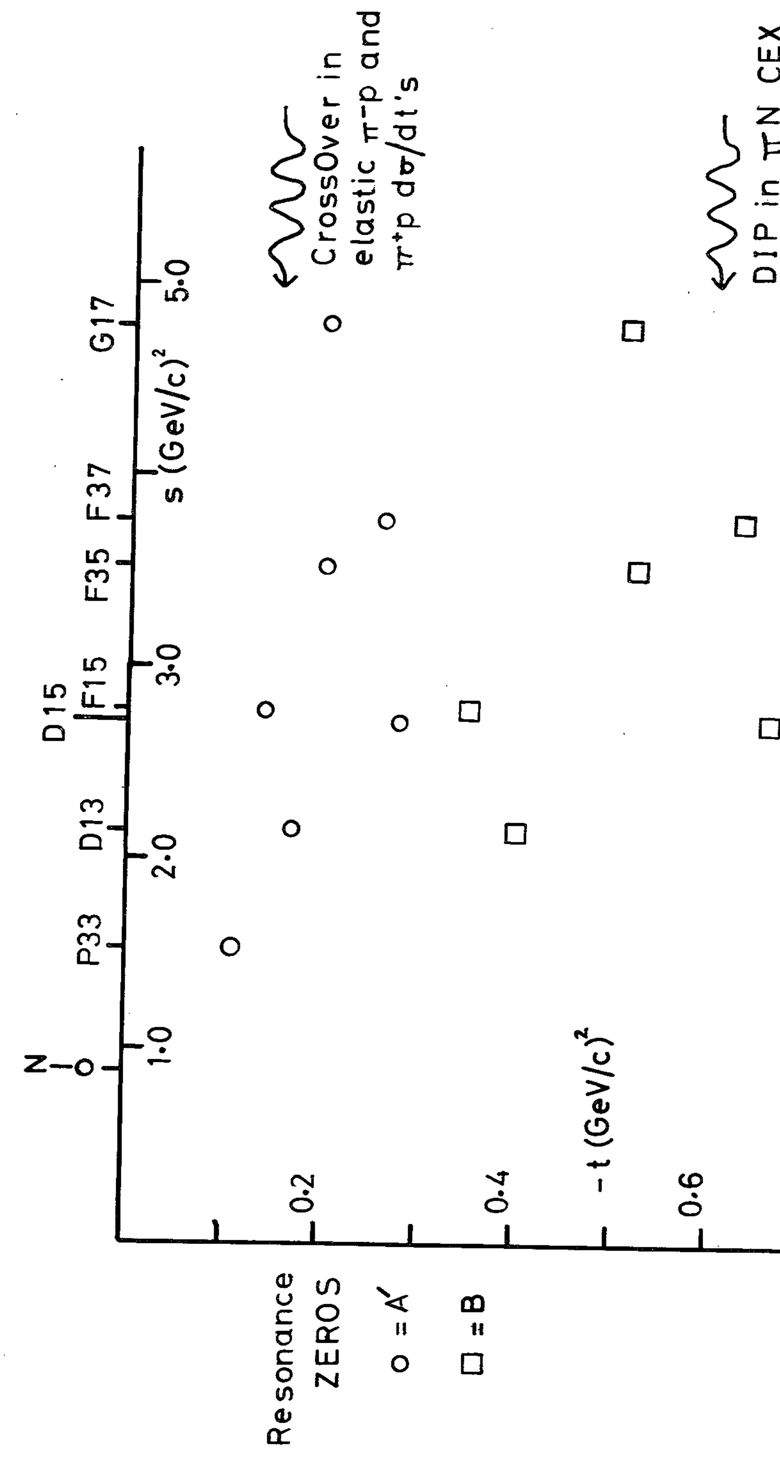


Fig. 27. Here we plot the positions of the zeroes of the resonance contributions to πN scattering. The O's represent zeroes in A' and the □'s zeroes in B. This structure persists to high energy with the crossover in $\pi^{\pm}p$ $d\sigma/dt$'s (dominated by A') and the dip in πN CEX (dominated by the Spinflip B amplitude).

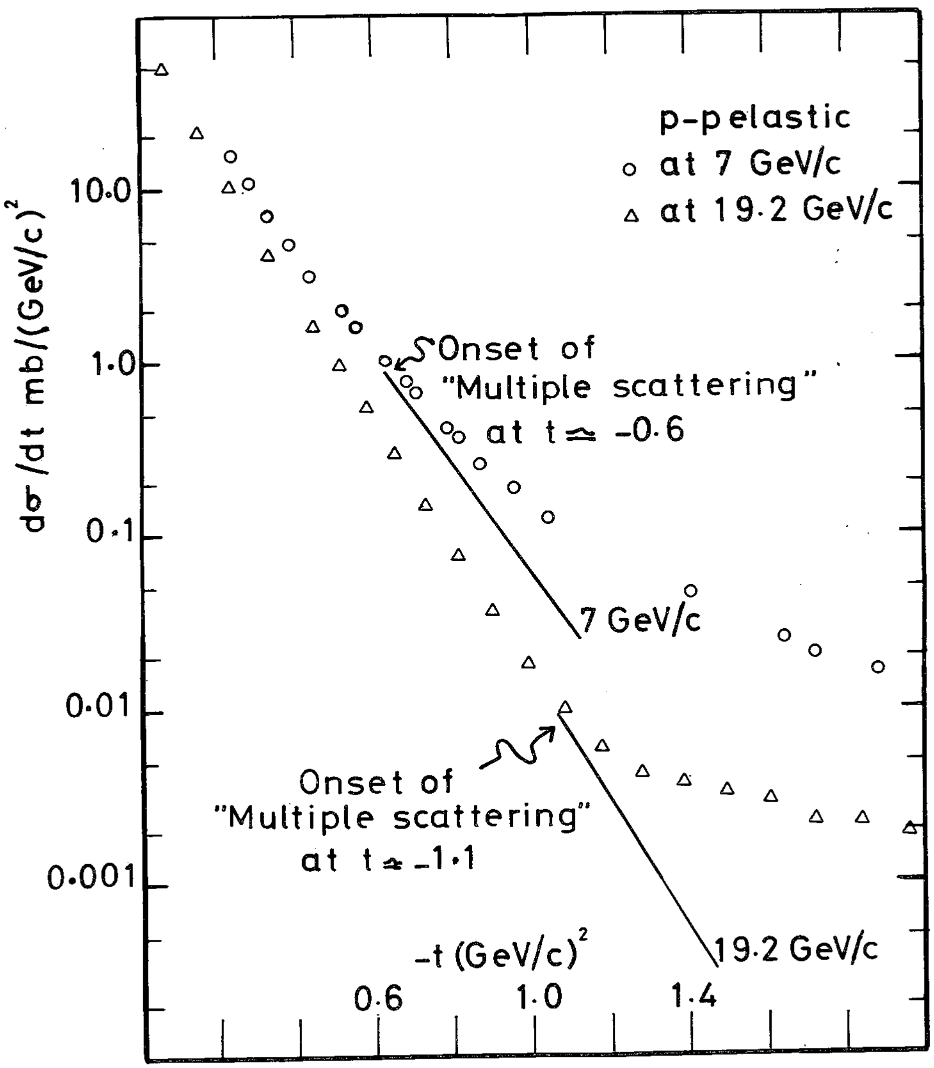


Fig. 28. p-p elastic scattering at 7 GeV/c (ref. 88) and 19.2 GeV/c (Ref. 89). The solid lines represent exponential fits to the forward direction. These in a simple pole fit correspond to the Pomeranchuk contribution.

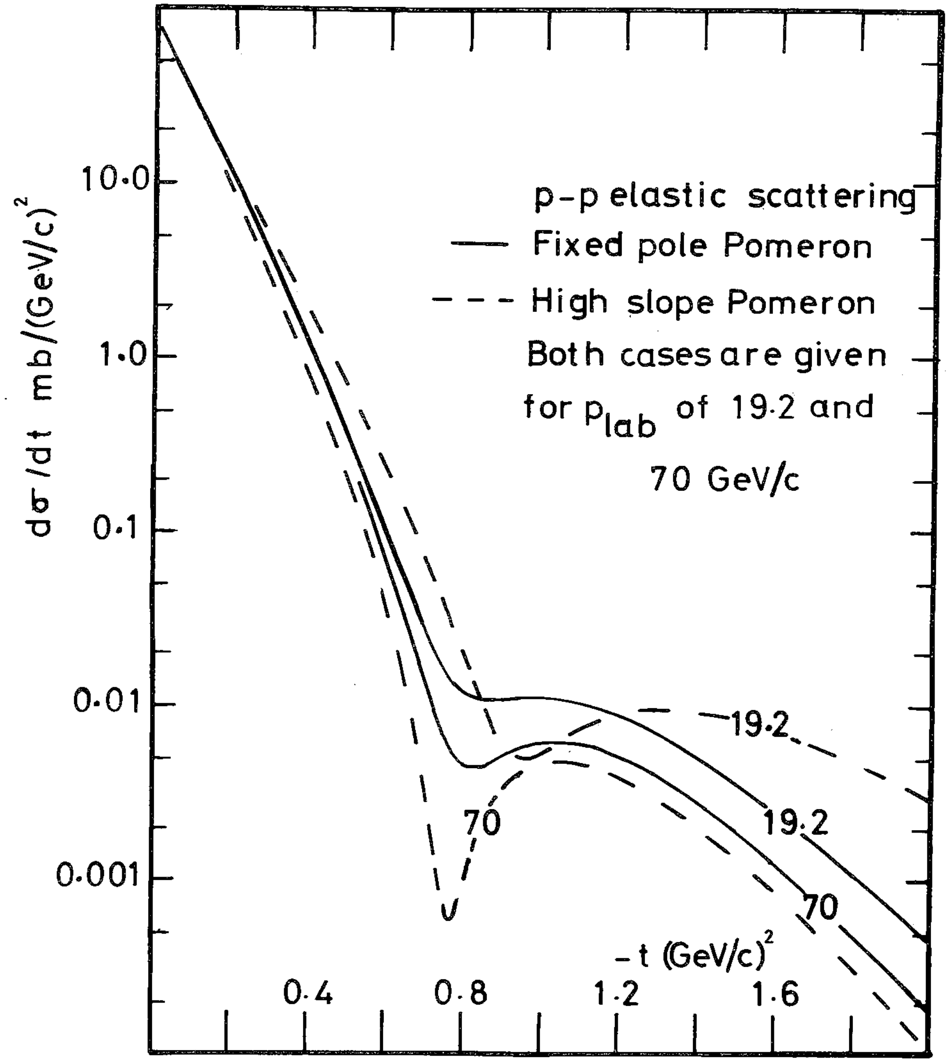


Fig. 29. An indication of the change we may expect in p-p elastic scattering between 19.2 and 70 GeV/c. The parameters used in the calculation came from a best fit to all p-p data. Thus there is poor agreement with experiment at 19.2 GeV/c and so only the relative differences between the curves is of relevance.

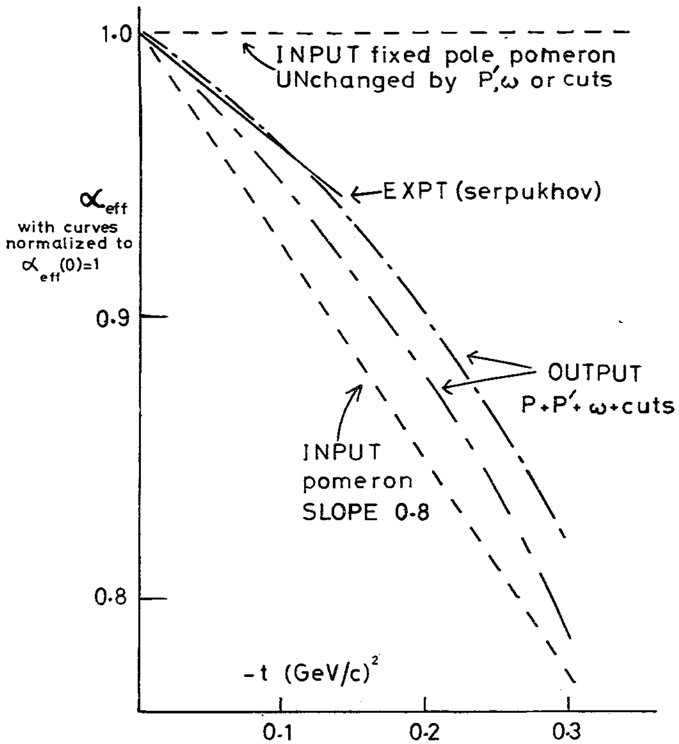


Fig. 30. α_{eff} for p-p elastic scattering calculated over Serpukhov energies ($p_{lab} \lesssim 70$ GeV/c). The solid line is the experimental result[43] presented at this conference. Also shown, (— — —), is a Pomeron of slope 0.8, with the result of adding P′ + ω + cuts to this (—— - —— - ——). There are two of the latter curves corresponding to two possible P′,ω parameters. Notice the marked curvature of the (—— - —— - ——) lines. This occurs as there is tremendous shrinkage predicted for $-t \gtrsim 0.6$ $(GeV/c)^2$ as the pole-cut interference dip moves in, as energy increases.

If the Pomeron has zero slope (shown at the top of the graph), then neither P′, ω or cuts change this.

Finally note that in this figure only the α_{eff} scale is not the same as the t-scale in $(GeV/c)^2$. (They differ by a factor of 2).

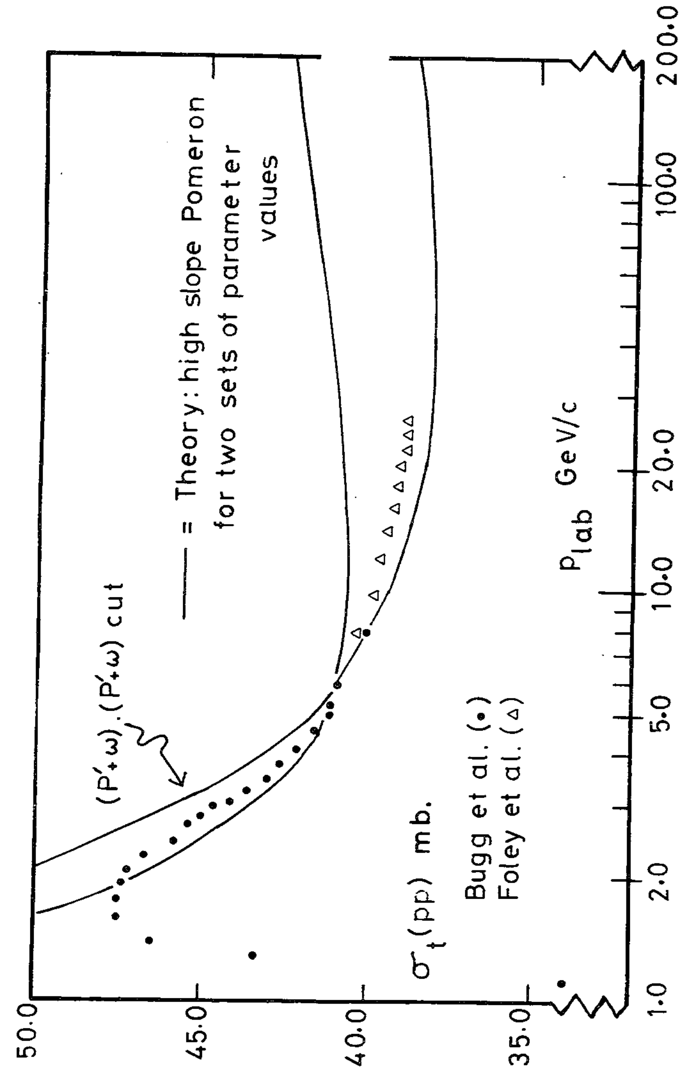


Fig. 31. pp total cross-sections. The experimental points are from Ref. 90. We only mark the theory for the high-slope·Pomeron. (and this for two possible P′, ω parameters). The hybrid model gives similar predictions below $p_{lab} \lesssim 50$ GeV/c but asymptotically tends to a constant rather than having the slow rise indicated on the figure.

The theoretical calculation used asymptotic approximations and is quantitatively unreliable at low energies.

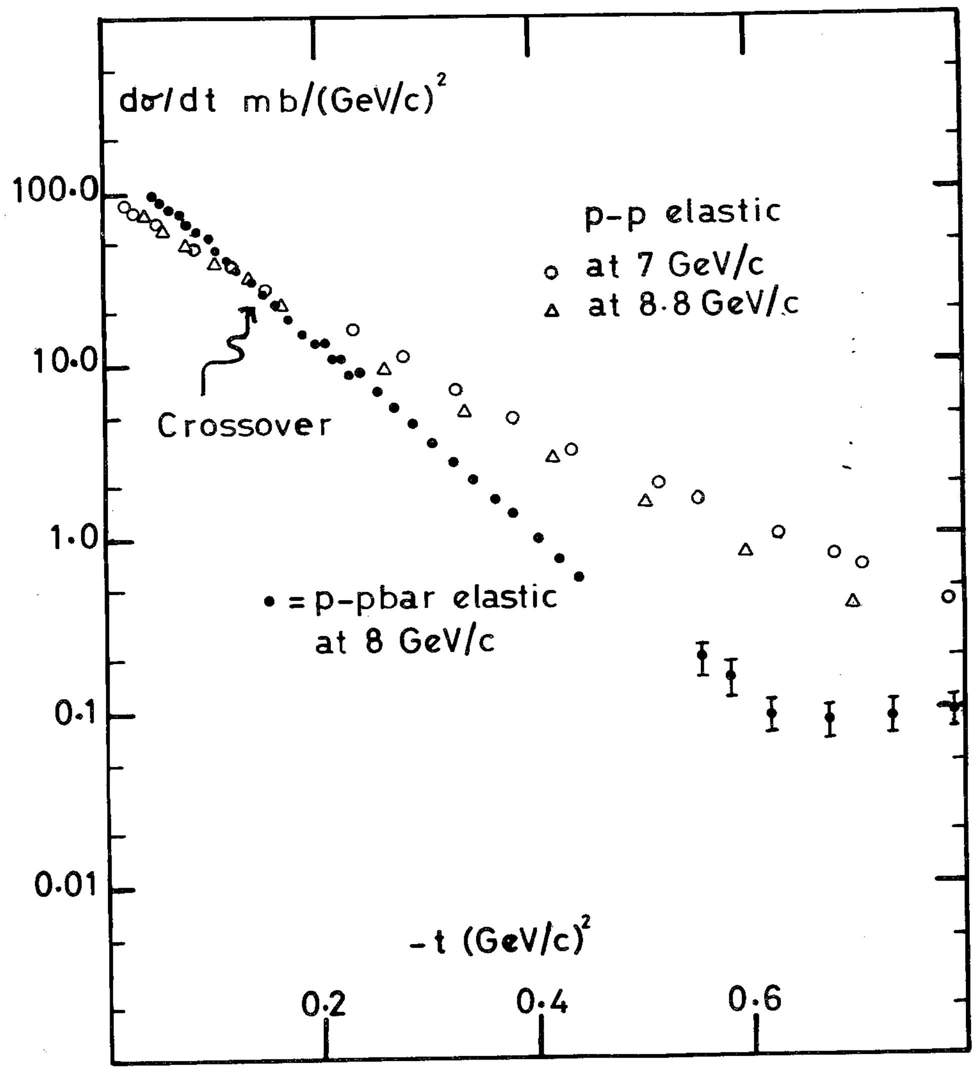


Fig. 32. A comparison of $p\bar{p}$ scattering (Ref. 86) and pp scattering (refs. 88 and 91) at similar energies. A typical absorption model calculation if normalized to the experimental pp results, would predict $p\bar{p}$ scattering to lie in between the pp and $p\bar{p}$ curves on the figure. A trivial Regge pole fit would predict pp and $p\bar{p}$ to become equal at $\alpha_\omega = 0$, ($t \sim -0.6$ $(GeV/c)^2$) at which point, the experimental curves differ by an order of magnitude.

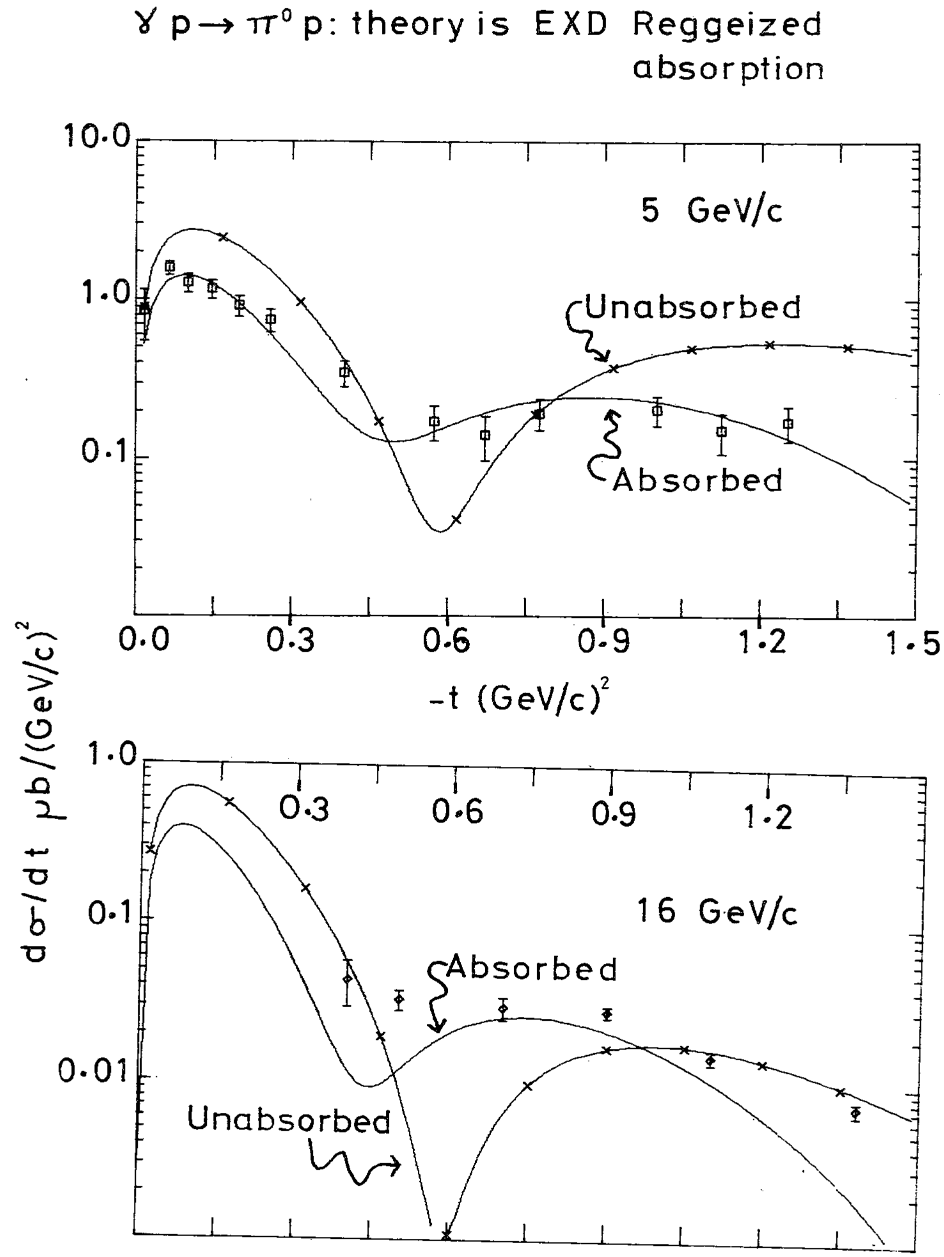


Fig. 33. π^0 photoproduction at p_{lab} of 5 and 16 (GeV/c). The data is from ref. 92 and the theory is the ω, ρ, B EXD Reggeized absorption model fit described in the text. The solid line is the final absorbed calculation and the solid line with X's the total unabsorbed curve.

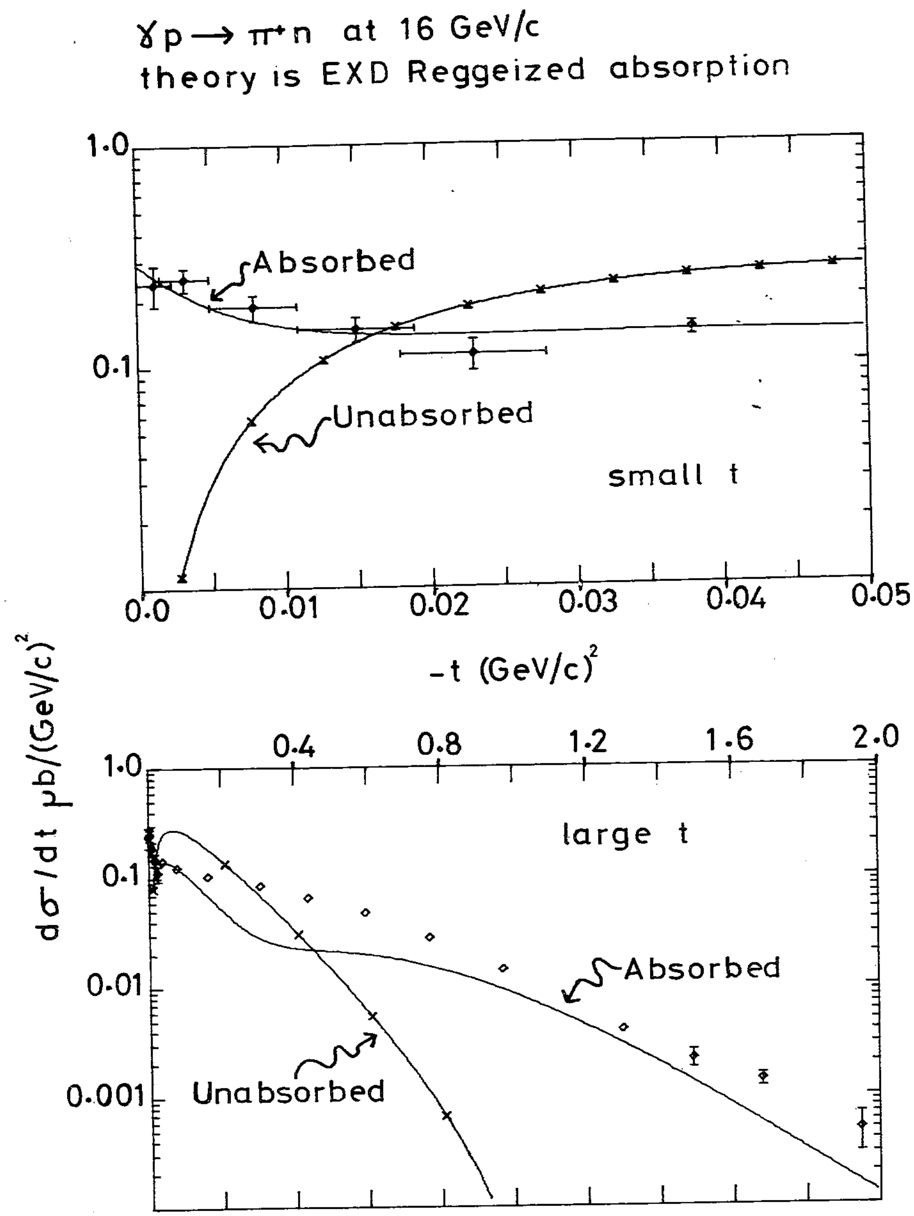


Fig. 34. π^+ photoproduction at a p_{lab} of 16 (GeV/c). The data is from ref. 93 and the theory comes from the EXD Reggeized absorption model with just π exchange. The solid line is the final absorbed calculation and the solid line with X's the total unabsorbed curve.

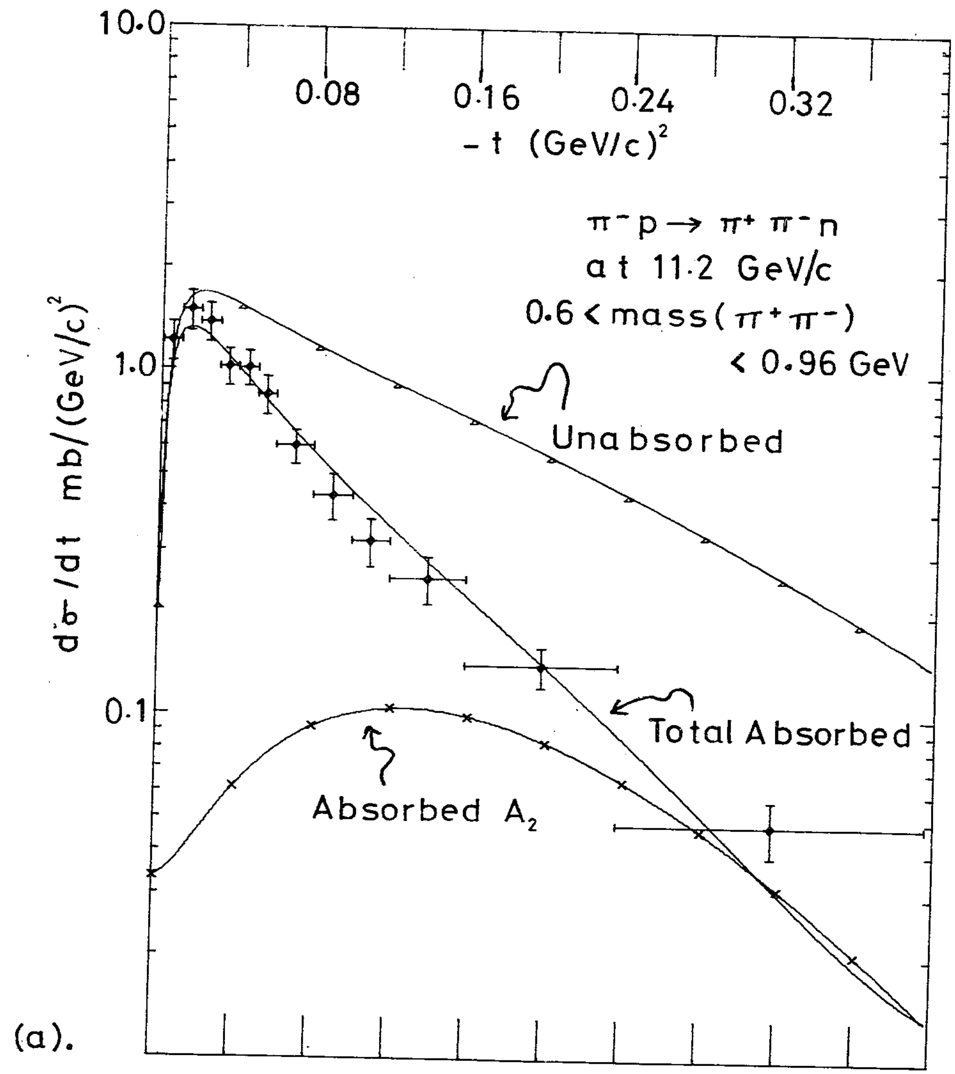
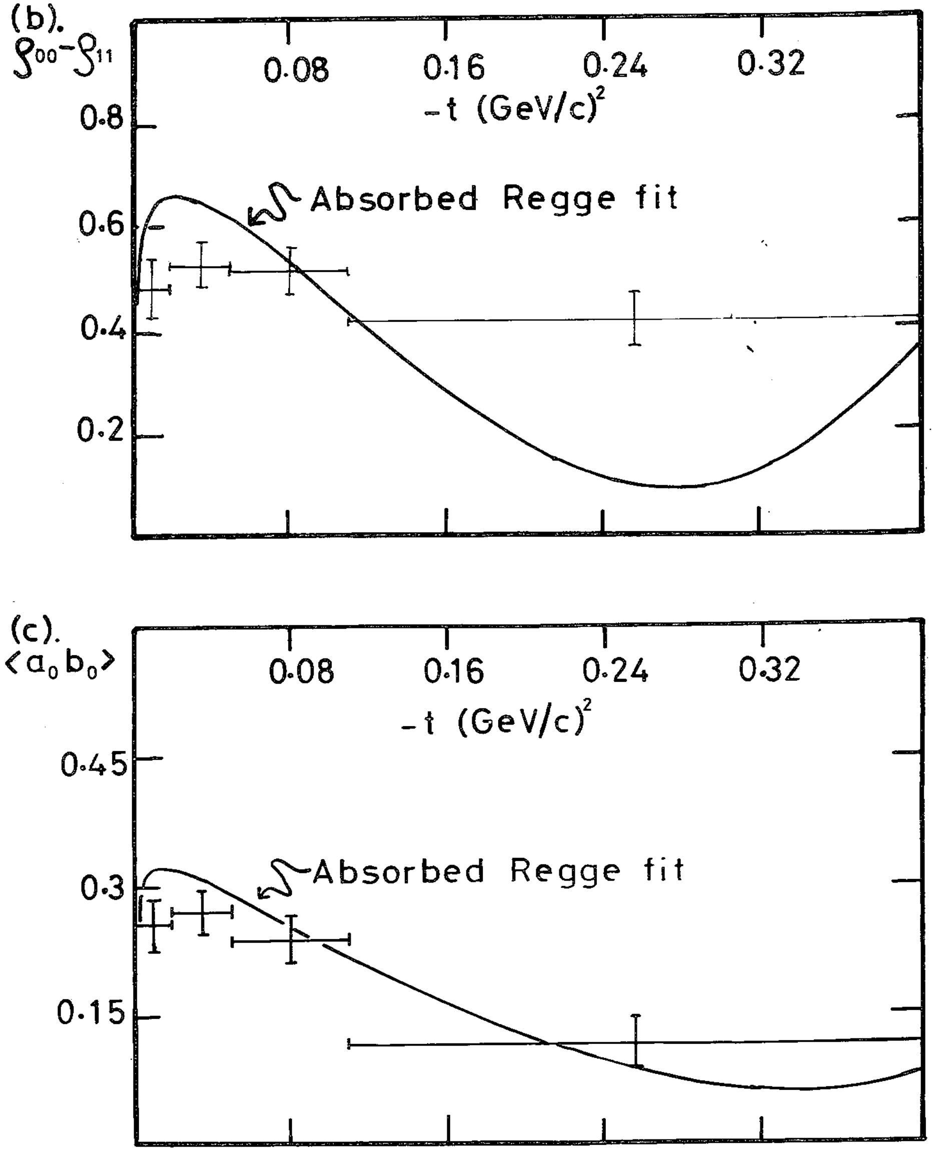


Fig. 35. $\pi^- p \rightarrow \rho^0 n$ at a p_{lab} of 11.2 (GeV/c). (Ref. 94). The theory correctly includes the S-wave background under the ρ and uses π and A_2 exchange in the EXD Reggeized absorption model. Fig. 35 (a) contains $d\sigma/dt$ while figs. 35 (b) to (f) compares theory and experiment for various density matrix elements describing the decay of the S and P wave $\pi\pi$ system. Fig. 35 (g) is thrown in for good measure and represents the predicted polarization of the final neutron.



In fig. 35 (a) we mark not only the final absorbed calculation (solid line) but also the total unabsorbed curve (solid line with Δ's) and the absorbed A_2 part (solid line with X's).

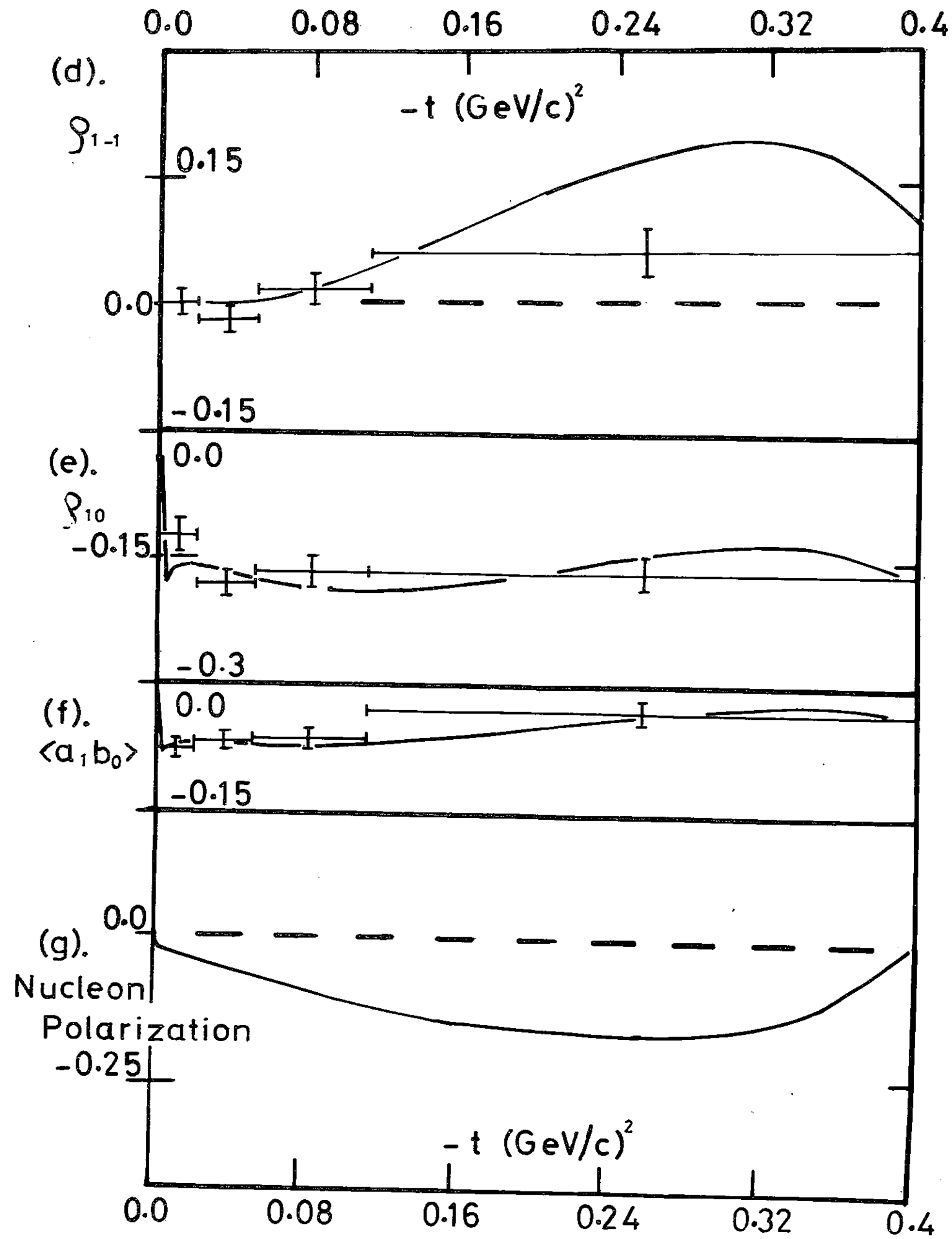


fig. 35 (d) to (g).

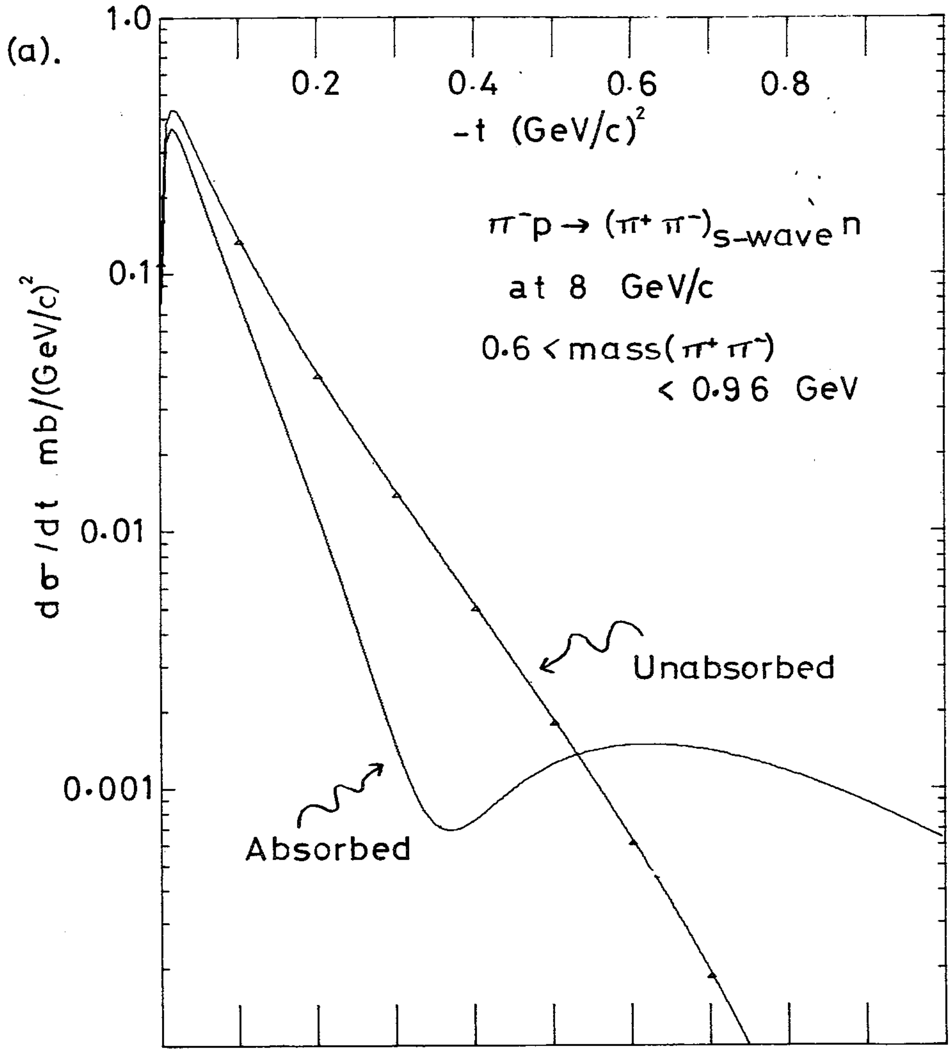


Fig. 36. $\pi^- p \rightarrow (\pi^+\pi^-)_{s\text{-wave}}$ n at a p_{lab} of 8 GeV/c. This is from the fit of Fig. 35. Fig. 36 (a) contains $d\sigma/dt$ and 36 (b) the final neutron polarization. (see ref. 63).

Fig. 36 (a) marks not only the final absorbed calculation (solid line) but also the unabsorbed π exchange. (Solid line with Δ's).

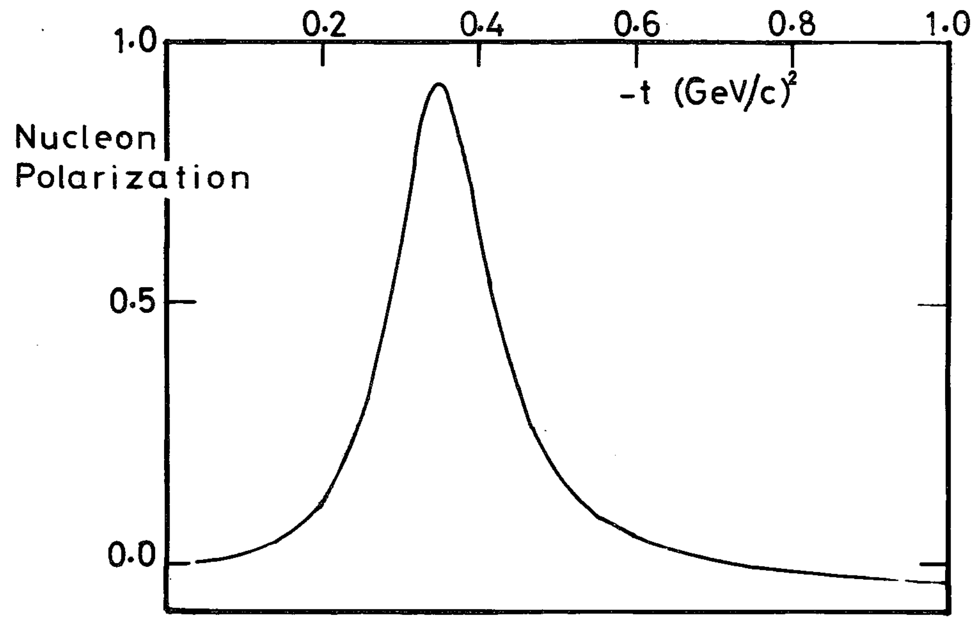


fig. 36(b).

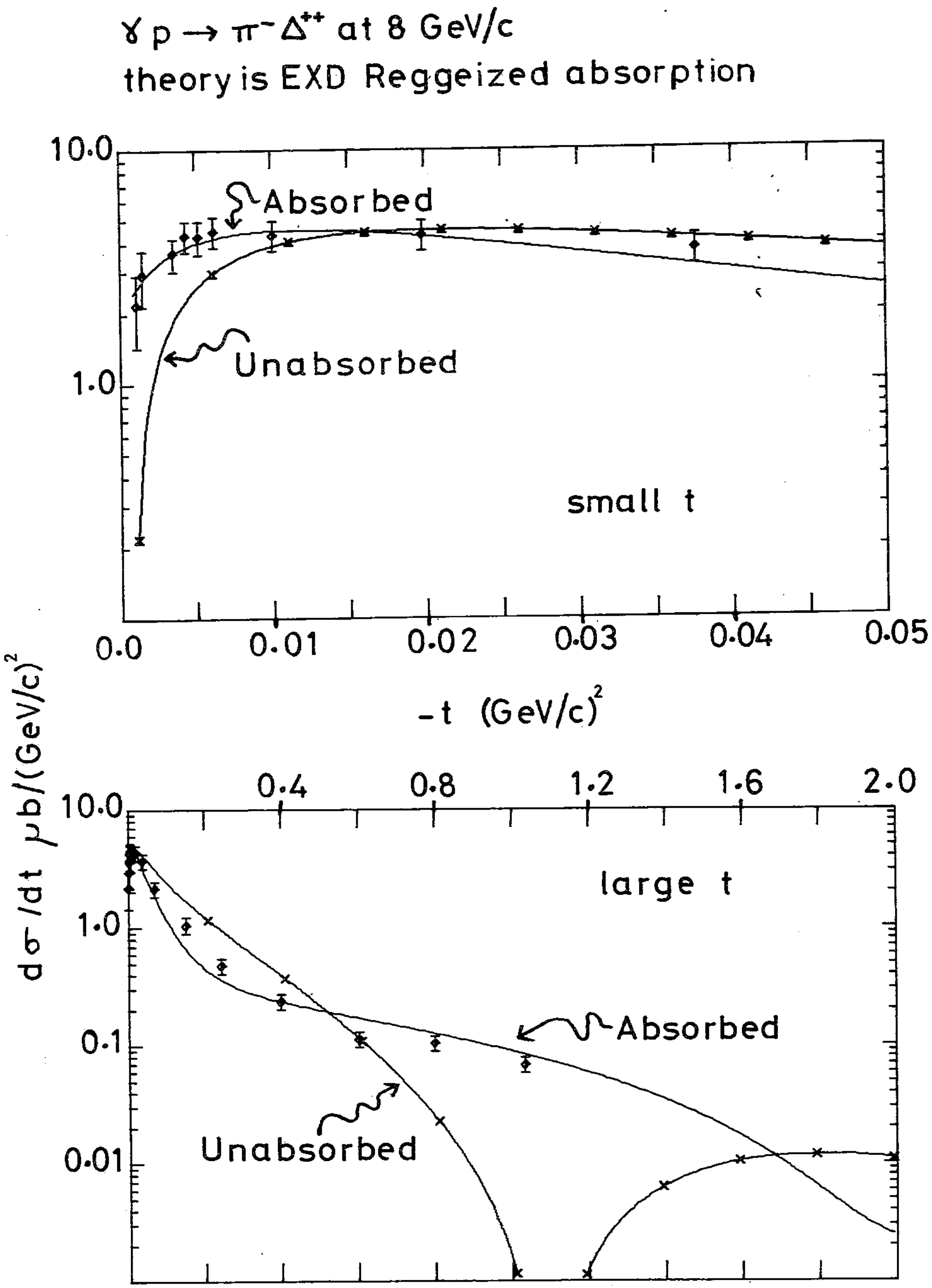


Fig. 37. $\gamma p \to \pi^-_\circ \Delta^{++}$ at a p_{lab} of 8 GeV/c. The data is from ref. 95 and the theoretical curve comes from the same fit as fig. 34. The solid line is the final absorbed calculation and the solid line with X's the total unabsorbed curve.

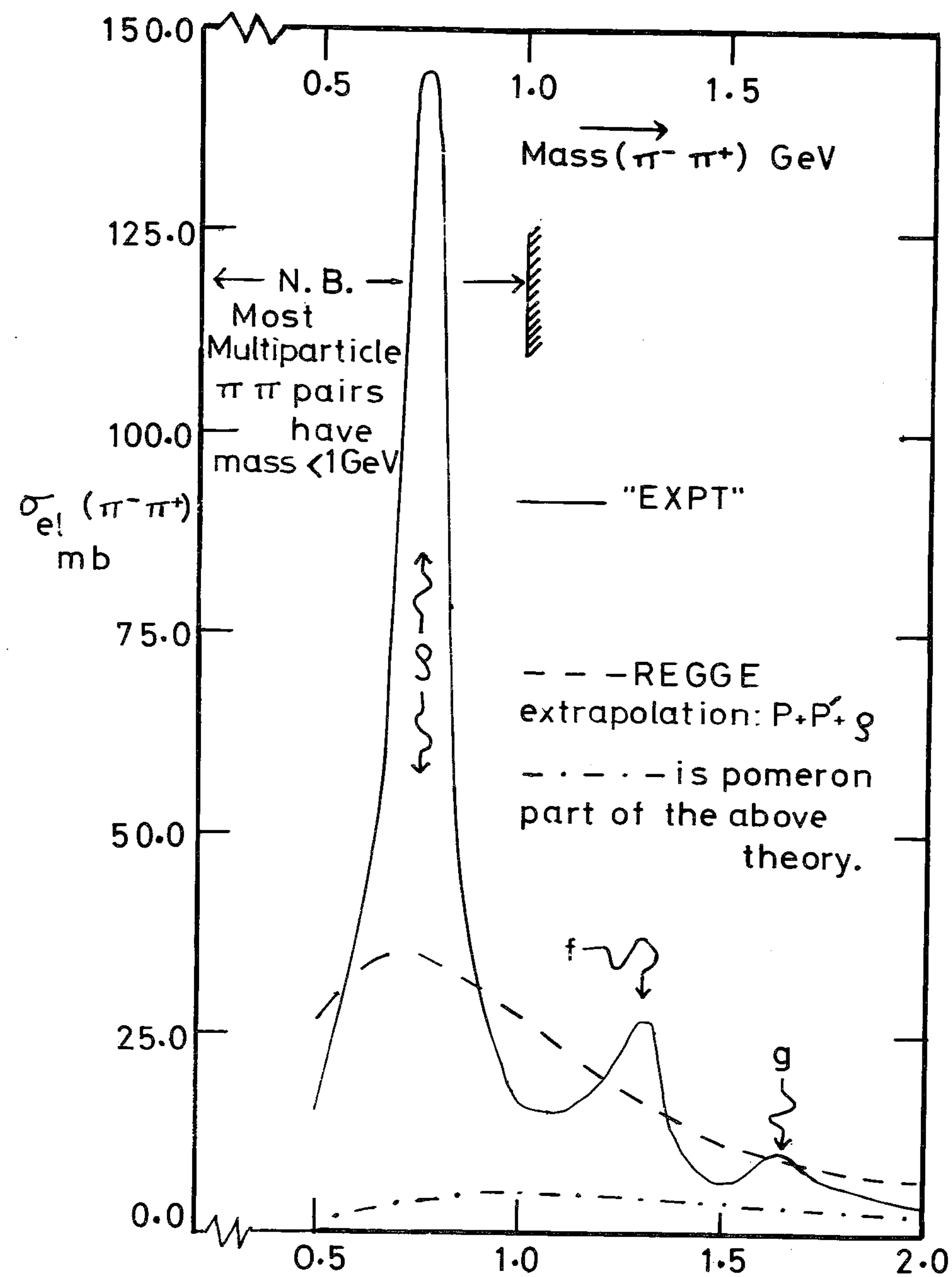


Fig. 38. A comparison of the experimental $\pi^+\pi^-$ elastic cross-section with an extrapolated Regge fit. The data is from ref. 72 and the theory from Ed Berger. (Ref. 96).

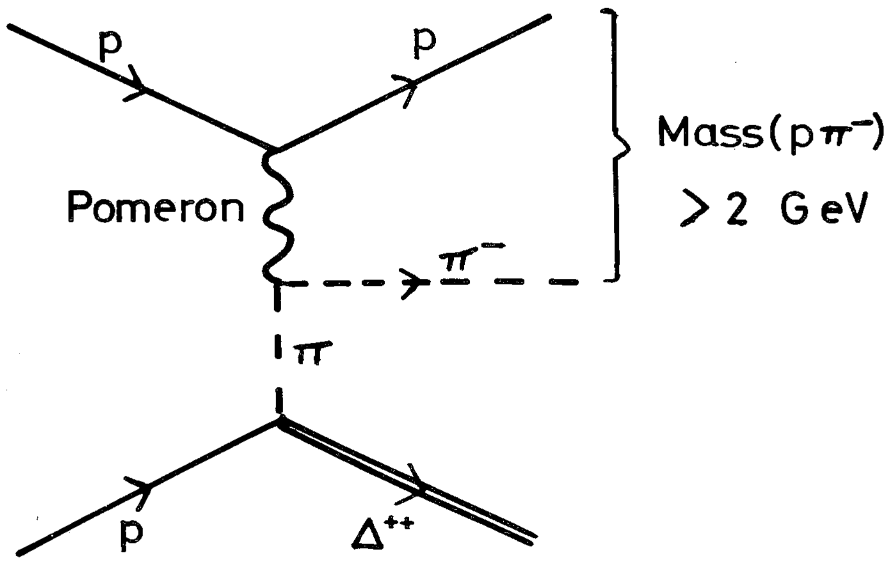


Fig. 39. A multi-Regge diagram for pp $\rightarrow p\pi^- \Delta^{++}$

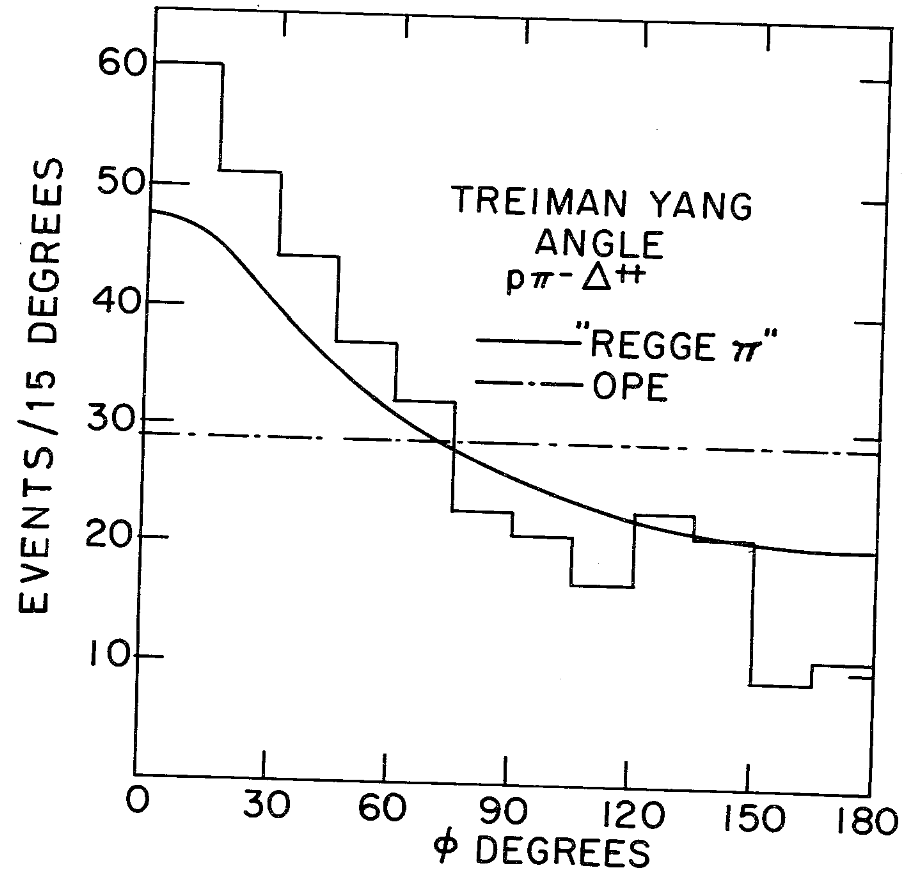


Fig. 40. The fit, of ref. 70, to the Treiman-Yang distribution describing the $p\pi^-$ decay in pp $\rightarrow p\pi^- \Delta^{++}$ at p_{lab} of 28.5 (GeV/c). The theory uses the diagram of fig. 39 and the experiment was cut so that $|t_{p\Delta}| < 0.8$ $(GeV/c)^2$ and mass $(p\pi^-) > 2$ GeV.

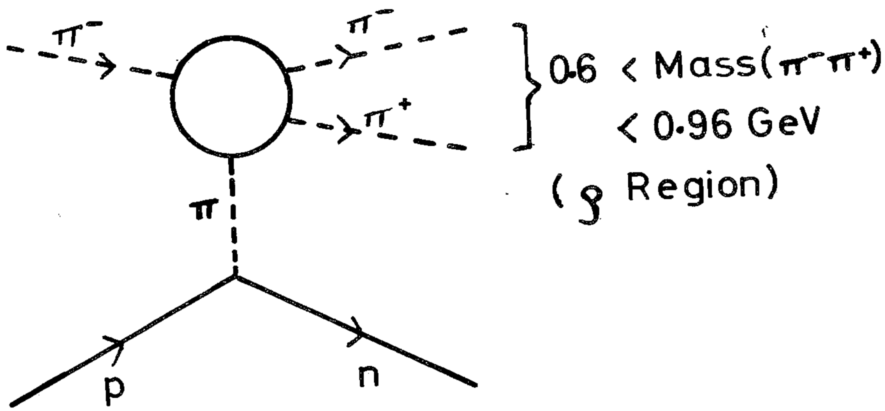


Fig. 41. A one pion exchange diagram for $\pi^- p \to \pi^+ \pi^- n$.

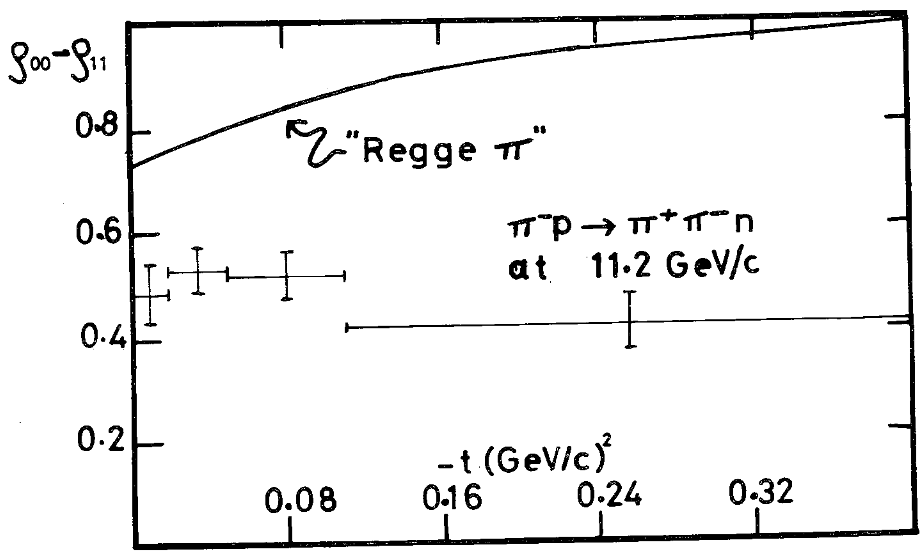


Fig. 42. A comparison of the fit of ref. 74 with the same data as presented in fig. 35. We only show the fit to $\rho_{00} - \rho_{11}$. The fits to $d\sigma/dt$ and $\langle a_0 b_0 \rangle$ (not shown) are good. Finally this model predicts zero for ρ_{1-1}, ρ_{10} and $\langle a_1 b_0 \rangle$. (The experimental data is shown in figs. 35 (d), (e) and (f)).

A Survey of Experimental Results on Multi-Particle Production from High Energy pp and Kp Collisions

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Abstract

Experimental results are presented on multi-particle production from pp reactions for beam momenta ranging from 10 - 30 GeV/c from both counter and bubble chamber data. Some Kp bubble chamber results at ~ 10 GeV/c are presented for comparison. Several points of view of the data are taken and a few dominant features emerge. In the high energy limit, one and two pion production results from the formation at low $|t|$ of a low mass cluster which contains one of the final state nucleons along with the one or two pions. From detailed studies of final states with three and more pions, there is also an indication that at least in some of these cases all the produced pions come from a single peripherally produced cluster containing a nucleon and all the pions; however, the cluster is not a distribution at low mass as when only one or two pions are produced. Furthermore, the tendency for the produced pions to group themselves around zero longitudinal momentum in the overall center of mass frame makes it difficult to reach a definite conclusion regarding how they are produced since this behavior can easily be explained from more than one point of view at present accelerator energies. The ratios between various cross sections from "off-shell" $\pi^- p$ scattering derived from 28.5 GeV/c pp data were compared with the corresponding ratios between "on-shell" $\pi^- p$ cross sections resulting in good overall agree-