

## Peripheral Production of Resonances

Geoffrey Fox

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## PERIPHERAL PRODUCTION OF RESONANCES

Geoffrey Fox\*

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## ABSTRACT

We review the peripheral cross-sections of resonances that cannot be produced by  $\pi$ -exchange. Explicitly we consider the four nonets of mesons in the  $L = 1$  quark classification,  $J^P = 0^+$   $\pi_N(980)$ ;  $1^+$ , e.g.,  $A_1$ , B;  $2^+$ , e.g.,  $A_2$ . We detail the constraints of  $SU_3$ , exchange degeneracy, factorization, pole extrapolation, Watson's theorem and duality as they have been gleaned from long and painful study of well-loved reactions. The controversial nature of the  $0^+$  and  $1^+$  nonets is related to a surprising suppression of their cross-sections (which are around  $10 \mu\text{b}$  at  $5 \text{ GeV}/c$ ) in non-diffractive processes. This is explained by a generalized vector meson photon analogy model recently proposed by Kislinger. We predict all differential cross-sections for these  $L = 1$  quark states and show that these mesons are best studied in hypercharge exchange reactions, e.g.,  $\pi^- p \rightarrow Q^0 \Lambda$  and  $K^- n \rightarrow A_1^- \Lambda$ .

An explanation, using final state interaction theory, of the large background under the  $Q$  and  $A_1$  observed in diffractive processes, suggests that quantum numbers of mesons are best studied in non-diffractive reactions of the type mentioned above.

## ON FANTASIES

## ON DINOSAURS

## ON PARTICLES THAT PIONS LOVE

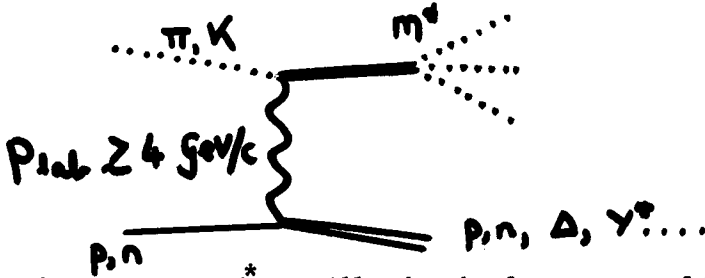
According to the prophet, research is likened unto a hard and lonely journey through a torrid, unfriendly desert. From time to time, the barren trek is filled with ecstasy as a lush oasis appears; there our hero may lay down his administrative load and find hidden a piece of the cosmic jigsaw. After many years, with many toils and just the occasional ecstasy, our hero has pieced together a tiny bit of the cosmos. So with his precious knowledge, he finally returns

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to the land of the living he left so long ago <sup>1</sup>.....

In this paper, I would like to record such a trip, namely, a voyage through run-down oases - the homes of disreputable particles and inconsistent cross-sections. Places where even the tarnished gold of current theories shines like a waxing star.

The next section should have been a pedantic classification of various two-body reactions which would delineate the scope of this talk. However, it turned out so boring that I have put it in the first and only appendix. Here I just note that we will discuss reactions of the form:



where for the resonances  $M^*$  we will take the four nonets of  $L = 1$  quark states as the lowest-lying examples of controversial resonances <sup>2</sup> that cannot be produced by  $\pi$ -exchange. These are recorded in Table I. This table should be taken with the following grains of salt:

(i) States that can be produced by  $\pi$ -exchange and so are (comparatively) straightforward to study are shaded (see Section  $E_\pi$  of Appendix).

(ii) We tentatively identify the C meson seen in  $\bar{p}p$  collisions <sup>3</sup> as the strange partner of the  $A_1$ . As we discuss in Section 3.5 under the  $\pi^- p \rightarrow Q^0 \Lambda$  reaction, this is not a watertight assignment. For instance, it may be in the B nonet and further the two Q's - denoted hereafter  $Q_{A_1}$  and  $Q_B$  - may mix <sup>4</sup>.

(iii) The  $I = 0, 1^+$  mesons are only represented by the D meson seen in  $\bar{p}p$  interactions. The second  $I = 0 A_1$  partner can be consistently identified with either the E(1422) or the rather shaky M(953) <sup>5</sup>. There is essentially no experimental information on h or h' production.

Table I: L = 1 Quark States

isospin \ J <sup>P</sup>	0 <sup>+</sup> Nonet	1 <sup>+</sup> "B" Nonet	1 <sup>+</sup> "A <sub>1</sub> " Nonet	2 <sup>+</sup> Nonet
I = 1	$\pi_N(980)$	B(1235)	A <sub>1</sub> (1070)	A <sub>2</sub> (1310)
Strange I = 1/2	$\kappa (\approx 1250)$	Q <sub>B</sub> (1300 → 1400)	Q <sub>A<sub>1</sub></sub> = C(?) (1240 → 1290)	K <sub>N</sub> <sup>*</sup> (1420)
I = 0 singlet/octet mixing (?)	$\epsilon (\approx 750)$	h (?)	D (1285)	f <sup>0</sup> (1260)
	S <sup>*</sup> ( $\approx 1000$ )	h' (?)	D' = E(1422) ? or M(953) ?	f'(1514)

Theoretically the situation is confused by the different mixing schemes. First, we can have "magic" mixing as exemplified by the  $\omega$  and  $\phi$ ; in this case, we write the I = 0 particles M<sup>\*</sup> (magic - $\omega$ ) and M<sup>\*</sup> (magic - $\phi$ ) with an obvious notation. (M<sup>\*</sup> = D or h.) Alternatively we can have essentially no mixing as exemplified by the  $\eta$  and  $\eta'$ ; in this case, we write M<sup>\*</sup> (octet) and M<sup>\*</sup> (singlet).

Duality schemes predict h, h' to have magic mixing and D, D' to be unmixed<sup>6</sup>. The naive quark model predicts exactly the opposite<sup>7</sup>; here we can only consider all possibilities.

(iv) In Table II, we list the dominant decay modes of the relevant 1<sup>+</sup> and 0<sup>+</sup> resonances. Further we also give either the observed value or SU<sub>3</sub> prediction for the partial widths. Note that the A<sub>1</sub> nonet predictions might be thought a little hazy as they are normalized to an A<sub>1</sub> width derived (presumably incorrectly - see Section 2.2) from diffraction data. However, similar results are given using the quark model to relate the A<sub>1</sub> to the B couplings<sup>7,8</sup>. In 3.5, we briefly consider the changes produced by a higher A<sub>1</sub> mass as the current determination of the latter must also be considered doubtful.

Table II:  $0^+, 1^+$  Meson Decays

Particle	Mass GeV	Decay	Width MeV	Source of Width
$\pi_N$ (980)	0.98	$\pi\eta$	40	(a)
B (1235)	1.235	$\pi\omega$	100	Expt
$Q_B$	1.380	$K\rho$ $K^*\pi$ $K\omega$	32 80 9	(b)
h(octet - ?)	1.01	$\pi\rho$	40	(b)
h(magic $-\omega$ - ?)	1.25	$\pi\rho$	330	(b)
h'(magic $-\phi$ )	1.5	$\bar{K}K^* + K\bar{K}^*$	75	(b)
$A_1$	1.07	$\pi\rho$	140	"Expt"
$Q_{A_1} = C$	1.24	$\pi K^*$	50	(c)
D (1285)	1.285	$\eta\pi\pi$ $K\bar{K}\pi$	$\Gamma_{tot} = 21 \pm 10$	Expt
D' (magic $-\phi$ ) = E (?)	1.422	$\bar{K}K^* + K\bar{K}^*$	50	(c)
D' (singlet)	any	$\bar{K}K^* + K\bar{K}^*$	0	(c)

- Sources: (a)  $SU_3$  and  $\epsilon \rightarrow \pi\pi = 300$  MeV  
 (b)  $SU_3$  and  $B \rightarrow \pi\omega = 100$  MeV  
 (c)  $SU_3$  and  $A_1 \rightarrow \pi\rho = 140$  MeV

The next section is shamelessly pedagogical. Indeed, it, too, almost suffered exile to a dusty appendix. In fact, it is an outline of theoretical weapons we can use to study our reactions. Explicitly we detail the constraints of  $SU_3$ , EXD (exchange-degeneracy), factorization, pole extrapolation, Watson's theorem (final state interactions) and the useful, if much abused, idea of duality. Most of these are well known but I emphasize that many popular applications of the Deck model (incorrectly justified using duality as either alternative or equivalent to a resonance description) are inconsistent with Watson's theorem. The latter follows rigorously from unitarity, and so rather than the Deck dinosaur, I suggest a fantasy<sup>9</sup> which is consistent with final state interactions and suggests resonance production should be

much cleaner in non-diffractive than diffractive processes (in agreement with experiment).

In the third section, we analyze the experimental data on the production of the  $0^+$ ,  $1^+$  and  $2^+$  states listed in Table I. The small cross-sections observed for these processes is, a priori, very surprising but has a natural explanation in a generalized vector meson photon analogy model recently proposed by Kislinger<sup>10</sup>. The suppression of the  $1^+$  cross-sections (most of them are around  $10 \mu\text{b}$  at 5 GeV/c and small  $t$ ) predicted in Kislinger's model explains and unifies (!) the controversial nature of these particles. (Does the  $A_1$  resonance really exist?) We use  $SU_3$ , EXD and factorization to predict all cross-sections for these nonets and hopefully the curves in Figs. 9-12 will be useful in planning experiments to elucidate the properties of these particles. In particular, we can note that some reactions (e.g.,  $K^- p \rightarrow Q^0 n$ ) are difficult because of large background from much bigger  $\pi$ -exchange processes. However, there are others, e.g.,  $\pi^- p \rightarrow Q^0 \Lambda$ <sup>11</sup>, where there is no such background and one high statistic experiment could at once settle the vexed question of the properties and even existence of the  $1^+$  states predicted in the quark model<sup>2</sup>.

The final section has the customary pious conclusions but also points out that many of the theoretical conclusions are rendered unnecessarily vague by chronic inconsistencies in quoted experimental cross-sections. This confusion stems mainly from different technical assumptions (mass-cut?,  $t$ -cut?, background subtraction?, maximum likelihood fit?...). It would be nice if such data were recorded in a way (e.g., the horrific (to some) spectre of a bubble chamber DST bank) that new interest in a particular cross-section would allow a unified treatment of the existing data. At present, one may only smile wanly and hope a new experiment will analyze their data for your favorite resonance and/or in your favorite way.

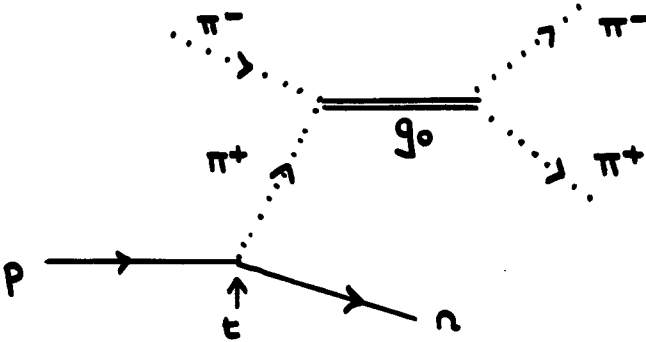
## 2: WELL-LOVED FOLKLORE

Here we lay out the weapons to be used in fighting the grimy ogre in Section 3. The order of presentation is less than logical.

### 2.1: Pole-extrapolation

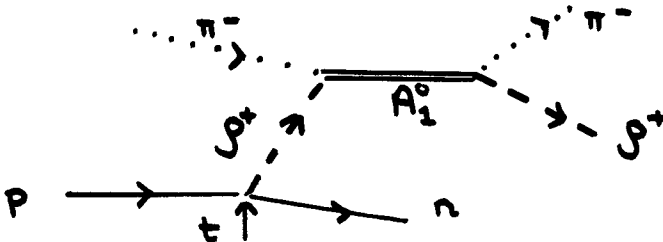
For  $\pi$ -exchange it is easy to estimate cross-sections:

e.g.,

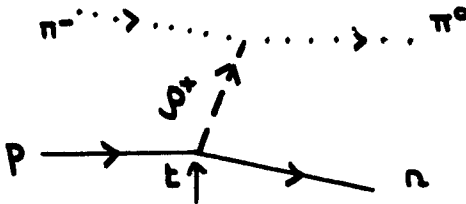


Thus the value is known at  $t = m_\pi^2$  in terms of  $\pi$ - $\pi$  scattering and it is only a short (Chew-Low) extrapolation to the physical region ( $t \leq 0$ ). To get the details right requires sophistication (e.g., the poor man's absorption model <sup>12</sup>) but rough estimates of the size of the cross-section present no difficulty.

For vector and tensor exchange, e.g.,



the situation is similar to the extent that the cross-section at the pole is again an absolutely normalizable elastic scattering (in this case  $\pi^- \rho^+ \rightarrow \pi^- \rho^+$ ). However, the extrapolation is now much more difficult as one must pass from  $t = m_\rho^2 \approx 0.5 \text{ (GeV/c)}^2$  to  $t = 0$ . It is believed that such an extrapolation is reasonable in the comparable



reaction; an exact conclusion being impossible due to our poor knowledge of the  $\rho N \bar{N}$  coupling constant (for on-shell  $\rho$ 's). Assuming this is the only difficulty, we can predict, e.g.,  $\pi^- p \rightarrow A_1^0 n$ , by taking the

ratio of amplitudes for  $\pi^- p \rightarrow A_1^0 n$  over  $\pi^- p \rightarrow \pi^0 n$ ; this cancels the unknown  $\rho \rightarrow N\bar{N}$  coupling. Thereby we relate:

$$\frac{d\sigma/dt[\pi^- p \rightarrow A_1^0 n]}{d\sigma/dt[\pi^- p \rightarrow \pi^0 n]} \quad \text{to} \quad \frac{\Gamma(A_1 \rightarrow \pi\rho)}{\Gamma(\rho \rightarrow \pi\pi)} \quad (1)$$

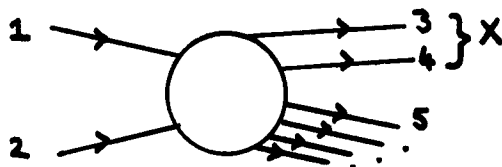
We can make two remarks on (1).

a) Clearly the same method will work for all  $1^+$  production by vector exchange. Again, for tensor exchange reactions (e.g.,  $\pi^- p \rightarrow B^0 n$  is pure  $A_2$  exchange), we need not extrapolate all the way to the  $A_2$  pole but rather use  $SU_3$  and EXD (Section 2.4) to relate (in this example)  $A_2 \rightarrow \pi B$  to  $\omega \rightarrow \pi B$ . So, in the general  $1^+$  reaction, we need only extrapolate to a vector meson pole in order to estimate the cross-section.

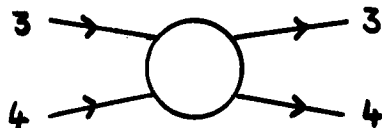
b) In Section 3, we show that (1) gravely overestimates the cross-sections for production of the  $A_1$  and B nonets. So we need not worry about niceties in (1). For example, different choices of invariant/helicity amplitudes in (1), can give a factor of 2 difference in the extrapolation prediction. However, this is an irrelevancy when faced by an order of magnitude discrepancy with experiment.

2.2: Watson's Theorem

a) "Theory" - This states that in any process, e.g.,

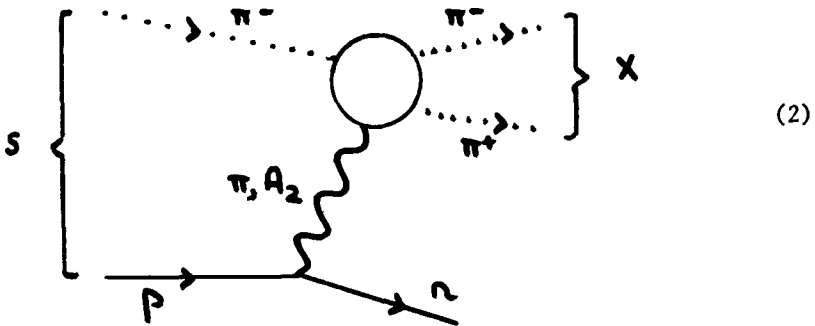


the amplitude for production of an eigenchannel 34 is proportional to  $e^{i\delta}$  where  $\delta$  is the phase shift for the same eigenchannel in

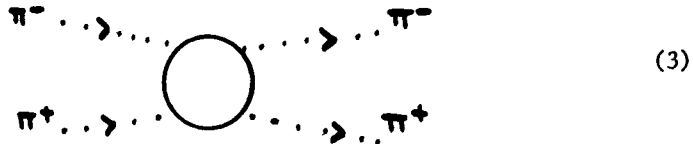


"elastic" scattering. For instance, in





for  $m_{\pi\pi} \approx m_{\rho}$  and projecting out spin  $J = 1$ , we have only one eigen-channel - the  $I = 1, J = 1$   $\pi\pi$  channel which is then proportional to  $e^{i\delta}$  - the phase of the corresponding



amplitude. This is, of course, just the usual  $\rho$  Breit-Wigner phase. In (3), the (eigen) amplitude's phase is completely specified by  $e^{i\delta}$ . It is important to realize that this is not the case in (2) where one has additional sources of phases, e.g., Regge theory would give phases:

$$(\exp [-i\pi\alpha_{\pi, A_2}] + 1)/(2\sin \pi\alpha_{\pi, A_2}) \tag{4}$$

for the  $\pi, A_2$  exchange contributions. One can still use the theorem if you realize that - lapsing into the language of my childhood training - every such imaginary part is associated with the discontinuity across a total (e.g.,  $s$  in (2)) or sub- (e.g.,  $X$ ) energy cut. Then the Regge phase (4) is associated with the  $\pi^- p$  and  $\pi^+ n$  thresholds in (2) and has nothing to do with the  $\pi^- \pi^+$  threshold. Granting this, one can state Watson's theorem as <sup>13</sup>:

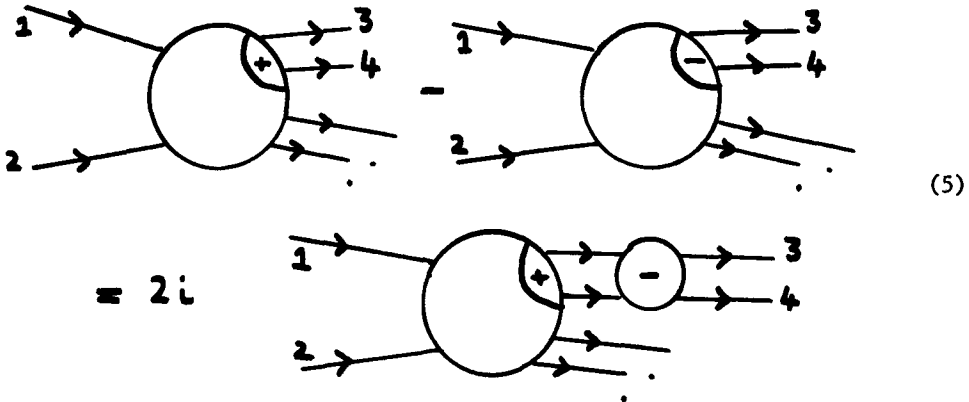
Any sub-process in any scattering process is associated with a branch-cut in the corresponding sub-energy in the analytic function that is the scattering amplitude. This branch-cut generates an imaginary part whose phase is given by Watson's theorem.

So a proper application of Watson's theorem requires a complete parameterization of the scattering amplitude. This is clearly

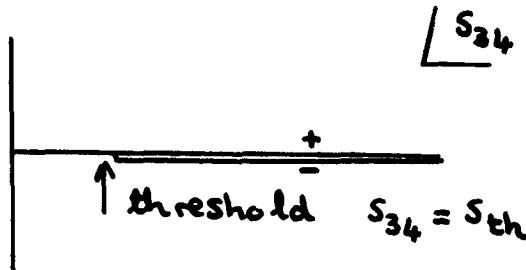
impossible but we can state the following rule <sup>14</sup>.

Watson's theorem never predicts absolute phases. However, if a final sub-process has a rapidly varying - as a function of the sub-energy  $X$  - eigenphase  $e^{i\delta}$ , then the production amplitude will exhibit essentially the same phase variation in this eigenchannel. The conditions of this rule are presumably satisfied for a resonant eigenphase.

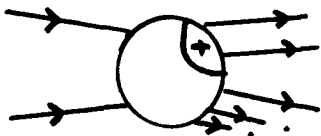
It is perhaps instructive to go through this in detail for a 2-particle sub-process. Then the discontinuity version of Watson's theorem is symbolically <sup>13</sup>:



where the  $\oplus$  signs denote one's position relative to the  $s_{34}$  threshold cut in the scattering amplitudes,, i.e.



Such amplitudes have a square root branch point at  $s_{34} = s_{th}$ . So we write



$$= T = A + i\bar{B} \tag{6}$$

where  $\bar{B} = B\sqrt{s_{34} - s_{th}}$

where neither  $A$  nor  $B$  are singular at the  $s_{34}$  threshold  $s_{th}$  ( $s_{th} = 4m_{\pi}^2$  in (2)). Substituting (6) in (5) and writing the  $2 \rightarrow 2$  eigen-

amplitude as  $e^{i\delta} \sin \delta$  gives

$$1/2i [(A + i\bar{B}) - (A - i\bar{B})] = (A + i\bar{B})e^{i\delta} \sin \delta$$

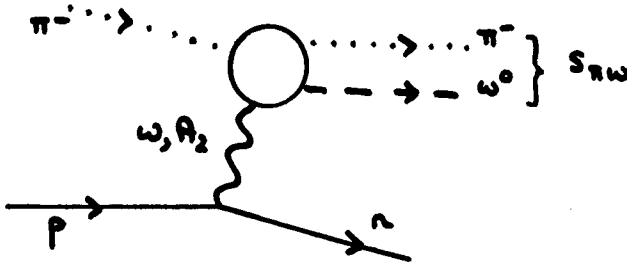
or putting  $C = \bar{B}/\sin \delta$

$$(A + i\bar{B}) = e^{i\delta} C. \tag{7}$$

Here C has no  $s_{34}$  singularity at  $s_{34} = s_{th}$  but it does - like A and  $\bar{B}$  - have thresholds and, hence, imaginary parts corresponding to all the other sub-energies. (7) is then the mathematical formulation of the rule we stated above.

b) Application to our reactions

Watson's theorem is powerful if (and only if) there are but a few open channels, and so but a few eigenstates. This is the case for all the resonances we are considering here. For instance, in



at  $s_{\pi\omega} \approx M_B^2$ , we deduce that the  $J^P = 1^+$  ( $\approx$  s-wave) is  $\propto e^{i\delta_B} = i$  at resonance where  $\delta_B$  is usual Breit-Wigner phase shift for the B. Meanwhile, the  $J^P = 1^+$  ( $\approx$  D-wave),  $J^P = 0^-, 2^-$  states are  $\propto \exp(\approx 0i)$  as these states are (presumed) non-resonant. Note that the "background" in a given eigenchannel must have the resonant phase; it need not have the resonance pole.

c) Fantasy

I would like to use the above formalism to divide high-energy peripheral scattering processes into two basic types:

$e^{i\delta} \sin \delta$  Production

- (i) Direct channel formation - including photoproduction.
- (ii)  $\pi$ -exchange processes at small t.
- (iii) (?) Other non-diffractive processes at high energy and small t.

$e^{i\delta}$  Production

- (iv) Diffractive processes.
- (v) (?) Low and medium energy non-diffractive processes.

- (vi) (?) Electroproduction - High  $q^2$ .
- (vii) (?) All reactions at high  $-t$ .

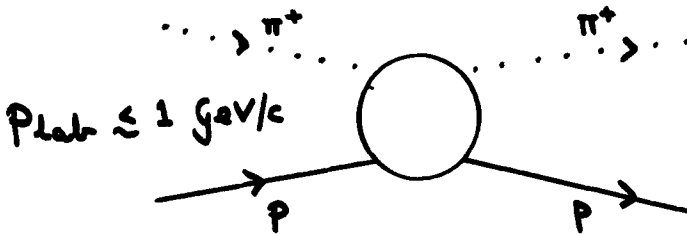
To understand the distinction, consider some examples.

(i) Direct Channel

We can write (5) as

$$T - T^* = 2iT_2^* \tag{8}$$

where  $T$  is the multiparticle and  $T_2$ , the  $T_2^* \rightarrow 2$  amplitude. It is thus a linear (in  $T$ ) unitarity relation. At low energies, say,



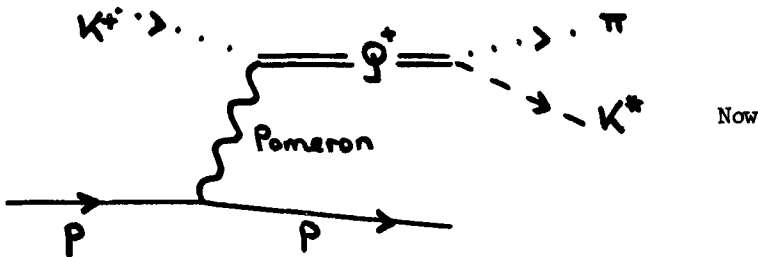
we may put  $T = T_2$  whence unitarity becomes a non-linear constraint which implies

$$T_2 \propto e^{i\delta} \sin \delta \tag{9}$$

where the "extra"  $\sin \delta$  factor comes from the non-linearity of the unitary equation.

The amplitude (9) peaks at resonance ( $\delta = 90^\circ$ ) and vanishes when  $\delta = 0$ . Correspondingly, a Breit-Wigner parameterization is valid and resonances are produced very cleanly at low incident energy for there are only a few competing eigenchannels.

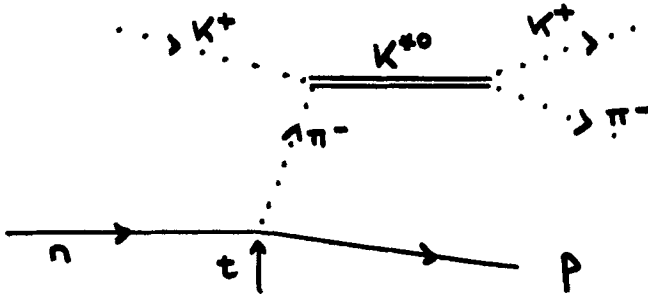
- (iv)  $e^{i\delta}$ : Diffraction Production  
e.g.,



we have the general multiparticle amplitude  $T$  and we can no longer say

$T \propto e^{i\delta} \sin \delta$  but only that  $T \propto e^{i\delta}$ . We deduce that there will be no large peak at resonance ( $\delta = 90^\circ$ )<sup>15</sup> and also that the cross-section can be non-zero even if  $\delta = 0$  (or  $180^\circ$ ). It follows that it is invalid to use a Breit-Wigner parameterization in such processes. For instance, the latter implies zero cross-section when  $\delta = 0$ , a prediction which is manifestly wrong. In any case, dinosaurs apart, we deduce resonances will be produced with large background.

(ii)  $e^{i\delta} \sin \delta$ :  $\pi$ -exchange

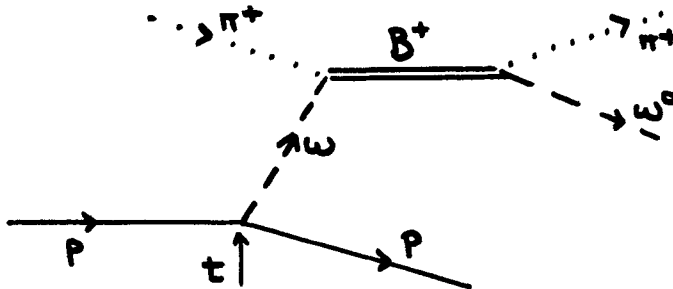


is proportional to  $e^{i\delta} \sin \delta$ , rigorously at  $t = m_\pi^2$ , and will remain so for small  $t$  (in the physical region) as pole extrapolation is valid for  $\pi$ -exchange<sup>12</sup>. Thus resonances produced by  $\pi$ -exchange will be clean and accurately described by a Breit-Wigner.

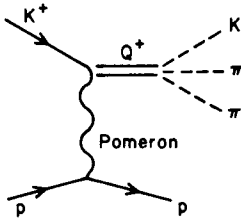
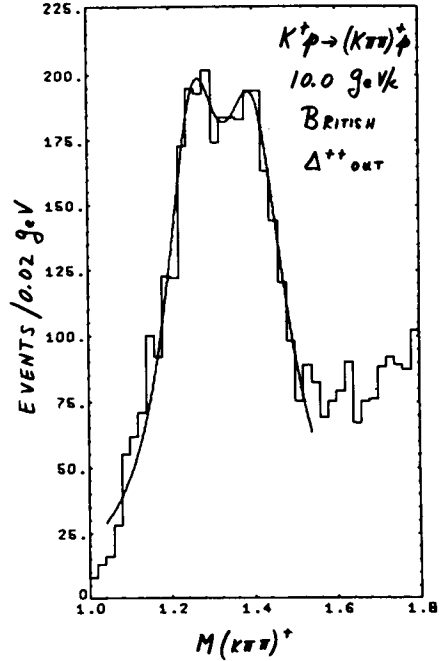
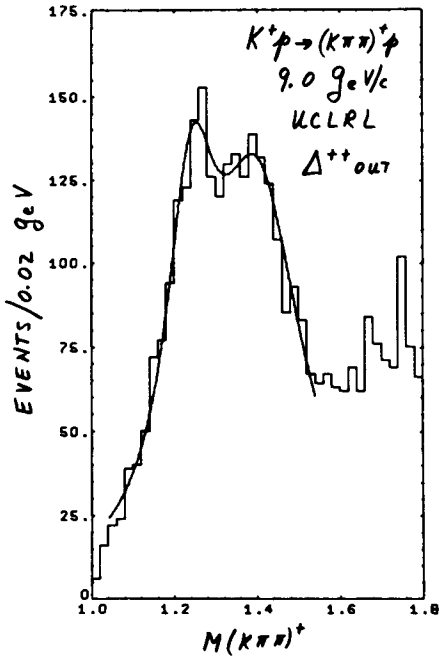
These points are illustrated in Fig. 1 which compares the  $e^{i\delta} K^+ p \rightarrow (K\pi)^+ p$  diffractive reaction<sup>16</sup> with the  $e^{i\delta} \sin \delta$   $\pi$ -exchange process  $K^+ n \rightarrow (K^+ \pi^-) p$ <sup>17</sup>. Manifestly, the resonances are much cleaner in the second case<sup>18</sup>.

(iii)  $e^{i\delta} \sin \delta$  (?): Other Non-diffractive Processes

The case of the vector and tensor exchange processes<sup>19</sup>, of interest for Section 3, is less clear. If pole extrapolation is even qualitatively right, then Regge exchange is proportional in, say,

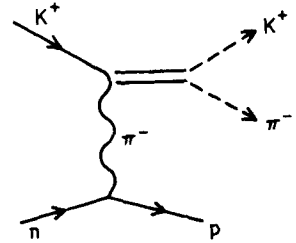
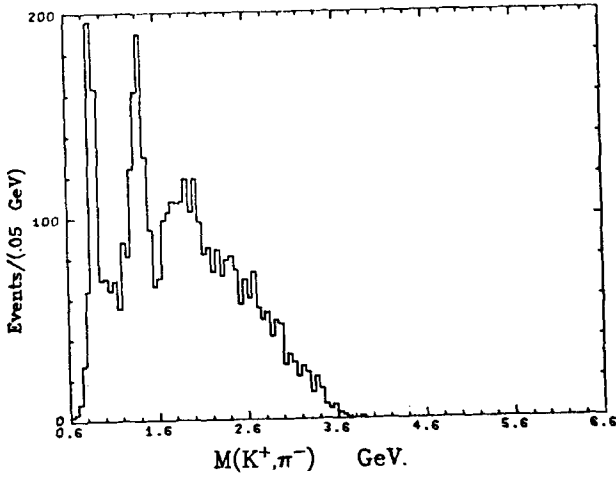


to beautiful  $e^{i\delta} \sin \delta \pi\omega$  elastic scattering at  $t = m_\omega^2$ . My guess is that this will extrapolate<sup>20</sup>, and such reactions will



$e^{i\delta}$  Production?

Fig. 1(a): A typical  $e^{i\delta}$  diffractive production process (Ref. 16). The resonances (if present at all) have large background.



$K^+ n \rightarrow (K^+ \pi^-) p: 12 \text{ GeV}/c$

$e^{i\delta} \text{ Sin } \delta \text{ Production?}$

Fig. 1(b): A typical  $e^{i\delta} \text{ Sin } \delta$   $\pi$ -exchange process (Ref. 17). Resonance production is obviously present and very clean.

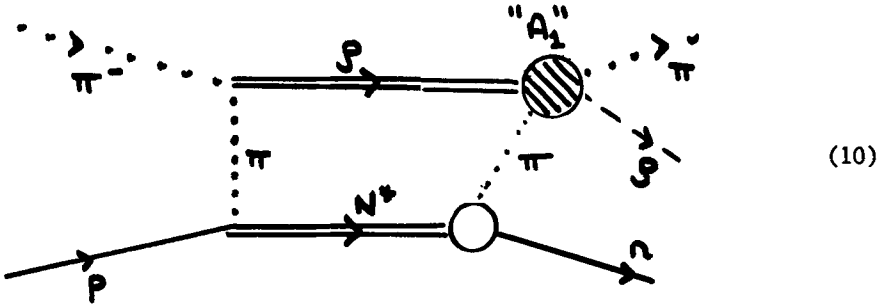
indeed be  $e^{i\delta} \sin \delta$  for small  $t$ . However, the low cross-sections make it impossible to find any conclusive experimental evidence either way.

We note that the Pomeron processes have no pole to extrapolate to....<sup>21</sup> so we cannot find the missing  $\sin \delta$  factor.

Let us speculate:

(v)  $e^{i\delta}$ : Medium Energy Non-diffractive Reactions

At  $P_{lab} \lesssim 5 \text{ GeV}/c$ , there will be some contribution, say to  $A_1$  production of the form



where the "re-scattering"  $\otimes$  (in 10) will give  $e^{i\delta}$  not  $e^{i\delta} \sin \delta$  production. Theoretically, such a box diagram is a Regge-regge cut and it falls fast with energy ( $\alpha_{cut} \approx -1$  in this case). Thus one might deduce that non-diffractive resonance production will become cleaner as energy increases and  $e^{i\delta} \sin \delta$  Regge Dreamland is approached.

(vi) Photon Processes

Consider photo or electro production, say,  $\gamma N \rightarrow \pi N$  where the photon has mass  $q^2$ . At  $q^2 = 0$ , vector dominance (VDM) is roughly right and our amplitude is proportional to  $\rho N \rightarrow \pi N$  which is a nice  $e^{i\delta} \sin \delta$  formation reaction of the type discussed in (i)<sup>22</sup>. However, for larger  $-q^2$ , VDM is inapplicable and so one would expect  $e^{i\delta}$  production. We deduce that resonances should have increasing background as  $-q^2$  increases.

Similar remarks can be made about inelastic electron scattering which essentially measures  $\sigma_{tot}(\gamma p \rightarrow \gamma p)$ . At low  $\gamma p$  mass, unitarity may be used to relate this to sum of single photon processes<sub>2</sub> ( $\gamma N \rightarrow \pi N, \pi\pi N$ ). Again one predicts less background at low  $q^2$  due to the effects of VDM non-linear unitarity giving " $e^{i\delta} \sin \delta$ " resonances. This prediction appears consistent with the current data<sup>23</sup>.

A comparable situation presumably exists in hadronic reactions. At large  $-t (\approx 1 \text{ GeV}(c)^2)$ , the arguments for  $e^{i\delta} \sin \delta$  production quite probably break down. Thus one enters a new regime of scattering

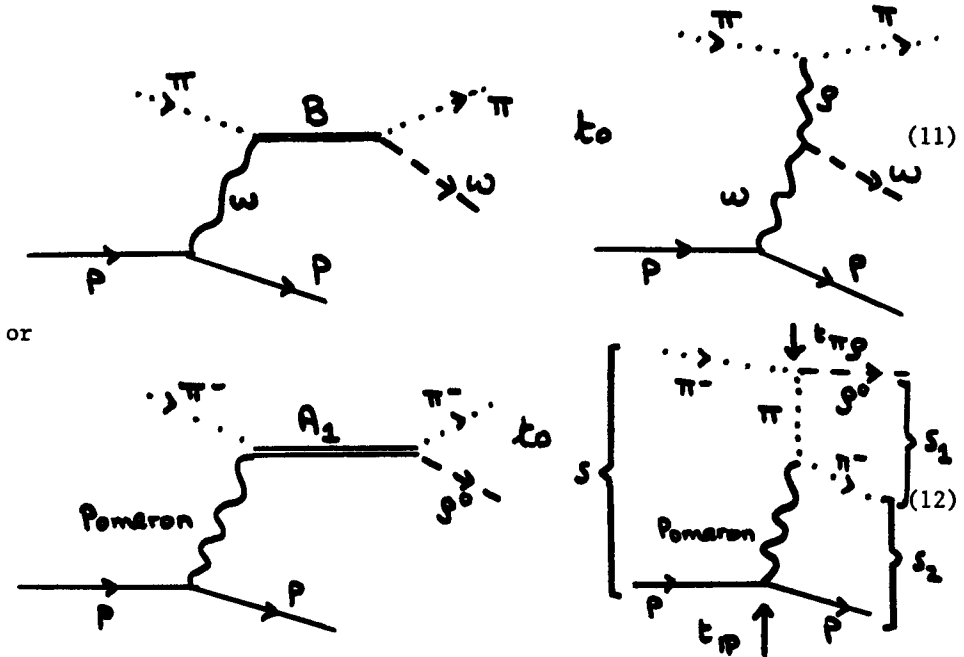


in which, liken unto diffraction scattering, resonances sit on large background. Unfortunately, as I have often lamented <sup>12, 24</sup>, there is no serious experimental study of this important domain.

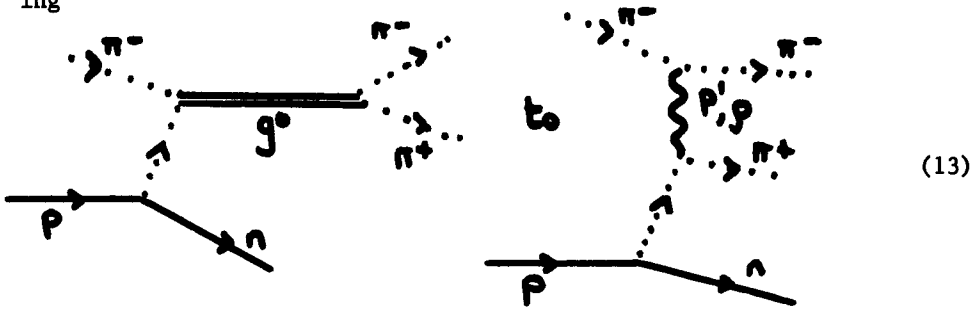
2.3: Duality

We will use duality in 2.4 to conclude that, say,  $K^+n + Q^0p$  is real at high energies with EXD  $\rho$ ,  $A_2$  exchange. This is very reasonable.....

However, one could also use it to relate:



However, the  $\pi\omega$  and  $\pi\rho$  sub-energies are clearly too low in these cases for duality to be useful. It is reasonable to use it for relating

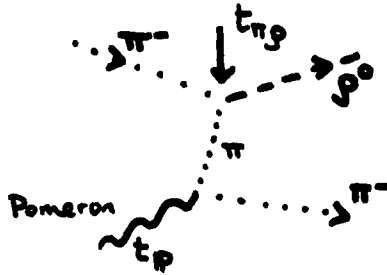


where there are several spin states present in the  $\pi\pi$  system. Rather than duality, one can use for (11) and (12) Watson's theorem which as we discussed in 2.2 is valid precisely in the low sub-energy, small

number of eigenstate situations where duality is at its weakest. The deduction for our discussion in Section 3 is that I believe it makes little sense to consider exchange ( $\rho$  in (11),  $\pi$  in (12)) explanations of data at these low sub-energies.

It is perhaps useful to make some remarks on (12) - the Deck model Dinosaur:

(i) I once believed the Deck model was a reasonable description of diffraction because of the  $\pi$  pole in



However, this is not correct. Thus, at  $t_{TP} = t_{\text{Pomeron}} = 0$ , it is easy to see that the residue of the  $\pi$ -pole ( $t_{\pi\rho} = m_\pi^2$ ) vanishes. The easiest way to prove this is to note that the Deck amplitude is proportional to <sup>25</sup>

$$\frac{1}{t_{\pi\rho} - m_\pi^2} \cdot s_2 \quad (\alpha_{TP} = 1) \tag{14}$$

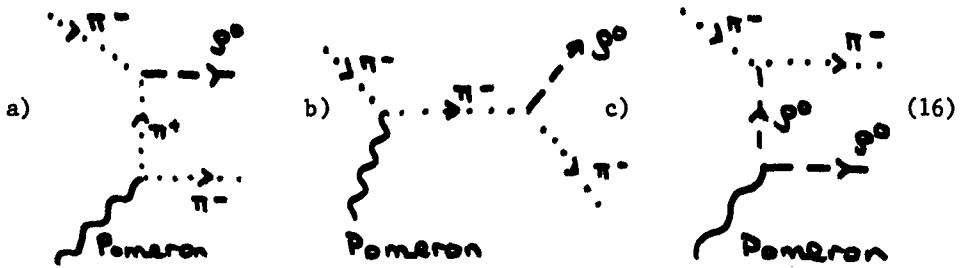
where we mark  $s$ ,  $s_1$  and  $s_2$  in (12).

But at  $t_{TP} = 0$ , we find

$$s_2 = \frac{m_\pi^2 - t_{\pi\rho}}{(s_1 - m_\pi^2)} \cdot s \tag{15}$$

Combining (14) and (15) we find no  $\pi$ -pole in the resultant amplitude. This has in fact been known for a long time <sup>26</sup> - it is the "successful" prediction of an s-wave  $A_1$ . However, it has not been emphasized that it implies zero  $\pi$ -pole residue.

(ii) Given this, I see no reason to prefer the  $\pi$ -exchange diagram over any other. Indeed, the three diagrams,



all give identical forms for the amplitude. Now,

if we replace the Pomeron by a photon <sup>27</sup> - to which it is kinematically identical - then gauge invariance implies all three diagrams in (16) add up to give identically zero in the forward direction (i.e., for real photons of zero mass). In this case, it would be disastrous to take just 16(a) and ignore 16(b) and (c) <sup>28</sup>.

(iii) What experimental evidence is there for the Deck model? There can be essentially none for its really distinctive predictions - for as we described above it has no distinctive features and all three diagrams in (16) are kinematically identical. There are some predictions of relative cross-section sizes... But a recent SLAC experiment <sup>29</sup> has shown that it gives the wrong answer for  $K^0 p \rightarrow Q^0 p v$ .  $\bar{K}^0 p \rightarrow \bar{Q}^0 p$  (Fig. 2). We can only conclude that the "success" of the Deck model was based on its correct multiparticle kinematics <sup>26</sup> - a virtue shared by many diagrams.

So finally, we turn our fancy towards more humdrum things.

#### 2.4: SU<sub>3</sub>, EXD, Factorization

(i) Denote the well-loved particles as follows:

- P : Pseudoscalar nonet  $\pi, \dots \eta'$
- V : Vector nonet  $\rho \dots \phi$
- N :  $\frac{1}{2}^+$  octet  $p \dots \Lambda$
- D :  $3/2^+$  decuplet  $\Delta(1234) \dots \Omega^-$

Denote the well-loved Regge exchanges:

- V : Vector nonet  $\rho \dots \phi$
- T : Tensor nonet  $A_2 \dots f'$
- B : B nonet  $B \dots h'$

(ii) Data on reactions like  $\pi^- p \rightarrow \pi^0 n$ ,  $\pi^+ p \rightarrow \pi^0 \Delta^{++}$ ,  $\pi^- p \rightarrow K^0 \Lambda$ ,  $K^0_L p \rightarrow K^0_S p$  allow one to estimate <sup>24,30</sup> all the spin amplitudes for any processes of the form

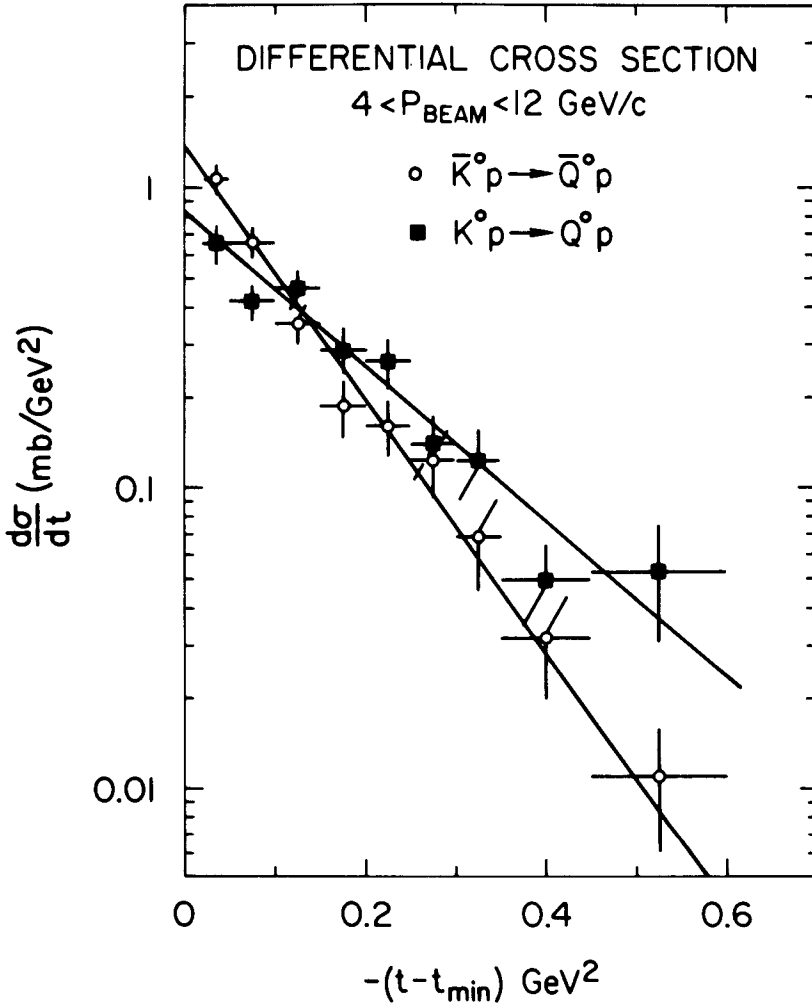
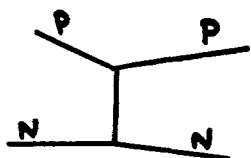
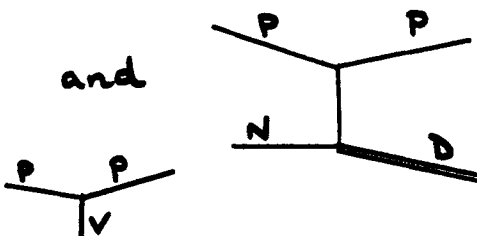


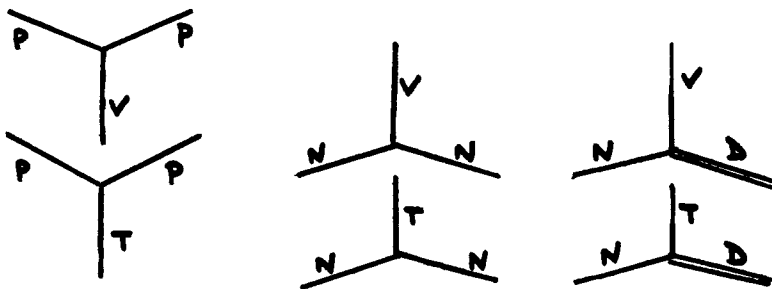
Fig. 2: Crossover at  $t \approx -0.2 \text{ (GeV/c)}^2$  between  $K^0 p \rightarrow Q^0 p$  and  $\bar{K}^0 p \rightarrow \bar{Q}^0 p$  (Ref. 29). The scale, unlike Fig. 5, is normalized for the decay  $Q_0 \rightarrow K_S^+ \pi^-$  only. The Deck model predicts  $Q^0$  bigger than  $\bar{Q}^0$  at  $t' = 0$  - in contradiction to the data above.



Normalizing one coupling



in whatever way we please, one can use factorization and EXD to find all six Regge vertices.



Each of the six couplings - on using  $SU_3$  - leads to the couplings of individual members of the multiplets. (This needs the known D/F ratio for



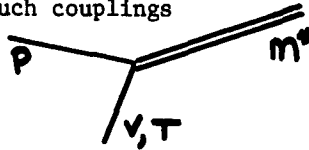
(iii) Further,  $d\sigma/dt$  and density matrix element data on say  $\pi^- p \rightarrow \omega^0 n$ ,  $K^- p \rightarrow \Lambda \omega^0$  allow one to separate the unnatural parity couplings from the natural parity vertices discussed above, and so obtain



(iv) Now given any one cross-section, e.g.,  $\pi^+ p \rightarrow B^+ p$  ( $\omega$ ,  $A_2$  exchange) for a meson resonance reaction, we can clearly use (ii) to find - in this case - the coupling



Then  $SU_3$  and EXD will give all such couplings

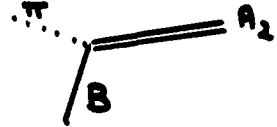


for meson resonances in a given multiplet. Coupling this with the general  $N\bar{N}$ ,  $N\bar{D}$  vertex, we deduce: Given  $d\sigma/dt$  for one meson resonance in a multiplet, we can at once predict all cross-sections of the form  $PN \rightarrow M^* N$ ,  $PN \rightarrow M^* D$ .

As always some caveats are necessary:

(v) If the  $M^*$ 's form an unmixed nonet (as do the  $\pi \dots \eta'$ ), then it is illegal to use the quark model rules (i.e., no disconnected quark diagrams) to calculate the singlet cross-sections. This sin overestimates the singlet cross-section by a factor of 4 in the case of the  $\pi \dots \eta'$  nonet<sup>31</sup>. In our application, we don't really know what any mixing angles are; so we shall forget this difficulty and, for definiteness, use the simple quark rules.

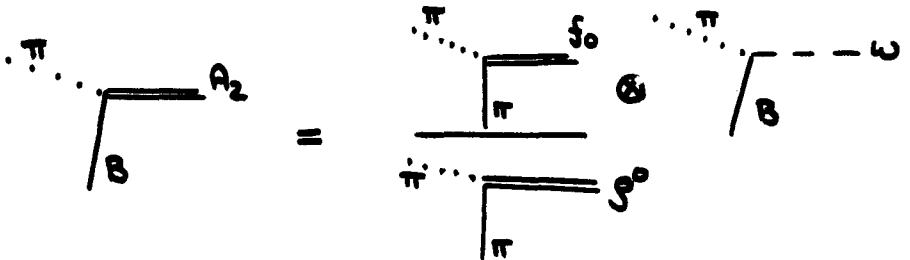
(vi) One can estimate, say, the coupling



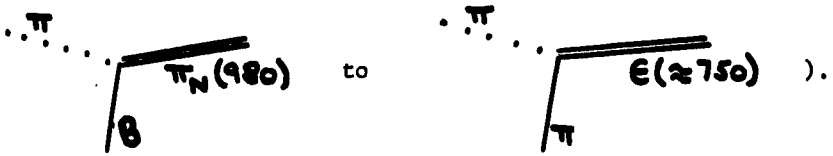
using EXD and the known



coupling. This is the tensor analogue of the  $\pi$ -B exchange degeneracy argument to relate  $\rho$  and  $\omega$  production<sup>32</sup>. EXD is not perfect in the latter case, and one might assume a similar breaking for the tensor production. Then, symbolically, we have:



We shall use this broken EXD method to estimate  $A_2$ ,  $\pi_N(980)$  and  $\phi_N(1680)$  production by B exchange. (In the  $\pi_N(980)$  case, EXD relates

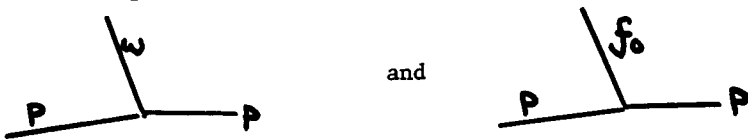


(vii) Absorption will modify some of the above results. All our results involve taking ratios and so some absorption effects cancel. However, the ratios involve different spin amplitudes with "Born-terms" of different  $t$ -dependencies. So, as the absorption depends on these effects, it certainly should not cancel completely. However, nobody can calculate the desired corrections<sup>24</sup> and so we shall completely ignore them hereafter.

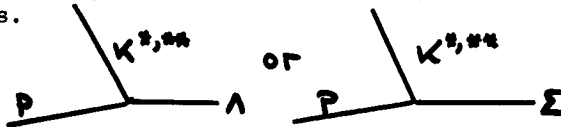
3: PRODUCTION OF THE  $L = 1$  QUARK MODEL STATES

3.1: Strategy

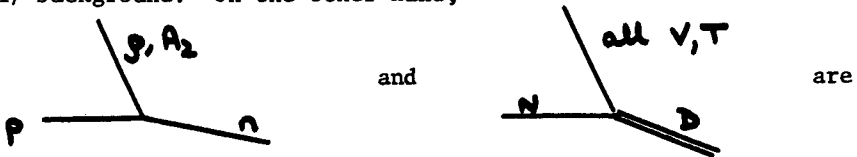
According to the discussion 2.4, one need only isolate the cross-section for the production of one member of any nonet to be able to use  $SU_3$  to predict all others. Our knowledge of well-loved reactions enables us to guess the most favorable processes. Thus,



have large  $N\bar{N}$  spin non-flip amplitudes. Thus, they correspond to large cross-sections.



is also mainly non-flip but its size is suppressed; however, this is the usual strange particle production suppression. So  $K^{*,**}$  exchange may be expected to produce resonances with a smaller cross-section than  $\omega$  or  $f^0$  exchange but with a similar  $t$ -dependence and a comparable signal/ background. On the other hand,



dominantly spin-flip and give rather measly small and flat cross-sections.

It is an important confirmation of theory, that the  $1^+$  and  $2^+$  mesons have been seen best in precisely those  $\omega$ ,  $f^0$ ,  $K^{*,**}$  exchange reactions predicted to be most favorable. In fact, the  $K^{*,**}$  exchange

data is less certain simply because of the low statistics implied by the universally small cross-sections for associated production.

Let us look at some specific examples. However, first, a moment of sadness. Throughout this section, there will be no such thing as a clean prediction - unsullied by theoretical or experimental caveats. Rather, time after time, we must swat at monstrous factors of two as, devil-horned and dirty, they cling and infest the cross-sections of our desire. We just state the difficulties and record our compromises.

### 3.2: $2^+$ Production

Consider the processes  $\pi^{\pm}p \rightarrow A_2^{\pm}p$  around 5 GeV/c.

(i) There is a large  $f^0$  exchange contribution<sup>34,35</sup>. Any such vector or tensor exchange must be helicity flip at the  $\pi A_2$  vertex; parity forbids the coupling  $\pi A_2$  (helicity 0)  $\rightarrow$  V,T. This prediction is confirmed by the density matrix elements observed for  $A_2$  production at higher energy<sup>33</sup>.

(ii) Helicity zero  $A_2$ 's can be produced by  $I = 1$ , B exchange - this amplitude is now spin-flip at the  $N\bar{N}$  vertex and so both  $f^0$  and B exchange predict  $A_2$  production to vanish in the forward direction.

One can estimate B exchange using EXD (cf., Section 2.4) but rather one eliminates both B and  $\rho$  exchange (cf., Fig. 9, the latter is the smaller of the two) by forming the  $I = 0$  exchange combination.

$$d\sigma_0/dt = \frac{1}{2} d\sigma/dt \{ \pi^+p \rightarrow A_2^+p + \pi^-p \rightarrow A_2^-p - 2(\pi^+n \rightarrow A_2^0p) \} \quad (17)$$

(iii) Equation (17) has been discussed by Rosner<sup>34</sup>, but unfortunately currently quoted experimental cross-sections are simply inconsistent<sup>34,36</sup>. So in Fig. 3, we mark a range of experimental differential cross-sections. This is compared with the absolute theoretical prediction given by the pole extrapolation model (i.e., the observed  $\Gamma(A_2) \rightarrow \pi\rho$  plus  $SU_3$  and EXD gives coupling  $\pi A_2 \rightarrow$  Regge  $f_0$  at  $t = m_\rho^2$ ).

The qualitative agreement between theory and experiment in Fig. 3 appears to me rather impressive. The pole extrapolation gives both roughly the right absolute magnitude and a reasonable ( $e^{\approx 3t}$ )  $t$  dependence. It's interesting to note that this reaction is dominated - theoretically and experimentally - by a single spin-flip amplitude. Such an amplitude is known<sup>24</sup> from study of well-loved  $\pi^-p \rightarrow (\pi, \eta)n$ , etc., to be the (only?) case where simple Regge theory gives good predictions. So it was probably to be expected that pole extrapolation (which implicitly assumes perfect Regge theory) would work.

### 3.3: B Production

Consider  $\pi^+p \rightarrow B^+p$  around 5 GeV/c. Experimentally<sup>37-39</sup> the situation is similar to  $A_2$  production. Thus, the quoted cross-sections



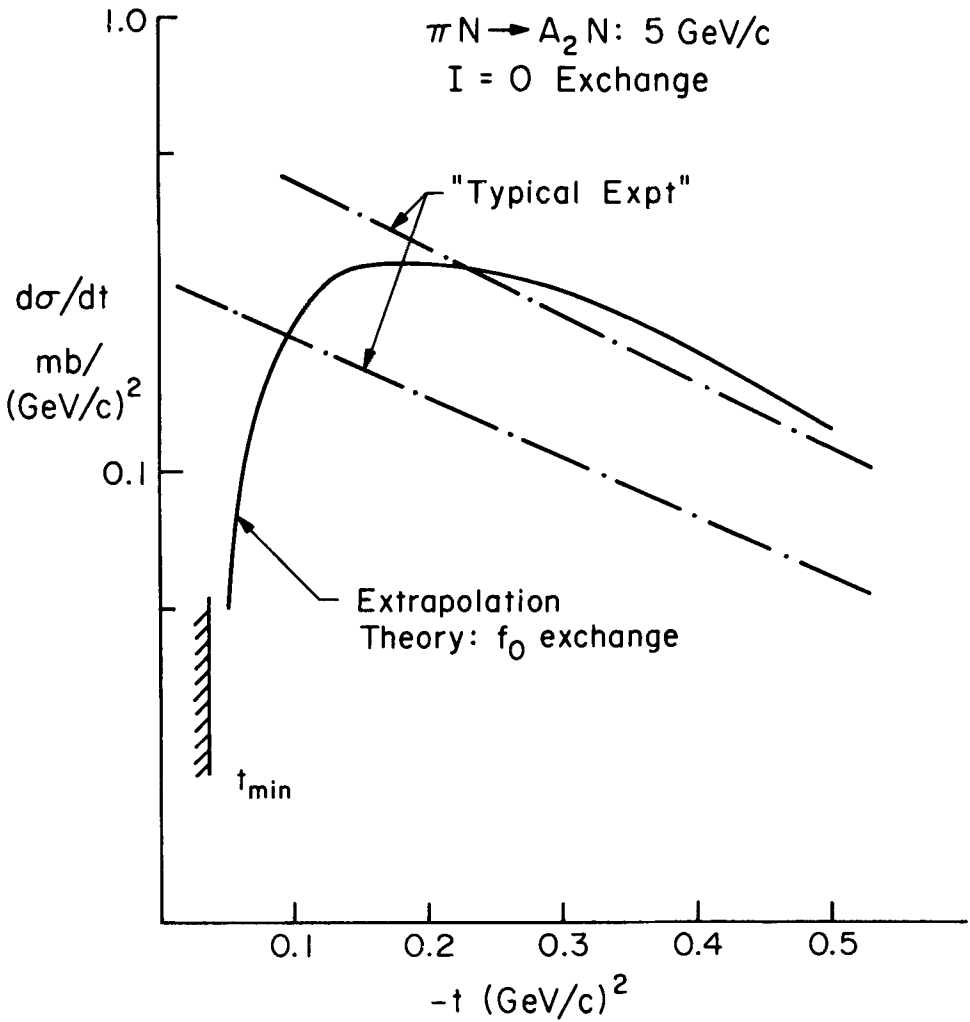


Fig. 3:  $I = 0$  exchange  $\pi N \rightarrow A_2 N$  at 5 GeV/c (Eqn. (17)). Shown are the absolute theoretical prediction and a range of experimental values (Refs. 34 & 36).

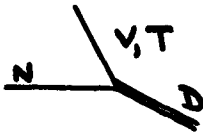
again vary within a factor of 2 (!) but qualitatively the size and shape of  $\pi^+ p \rightarrow B^+ p$  is similar to  $\pi N \rightarrow A_2 N$  ( $I = 0$  exchange) <sup>40</sup>. Theoretically the situation is quite different; again, we have a large (as defined in 3.1) amplitude: this time  $\omega$  exchange. However, parity no longer forbids the  $\pi B$  (helicity 0)  $\omega$  coupling and we expect a dominantly spin non-flip amplitude rather than the spin-flip which controlled  $A_2$  exchange. This should give a large and steep (i.e.,  $\exp(\approx 8t)$ )  $d\sigma/dt$ . Indeed, given  $\Gamma(B \rightarrow \rho\omega) \geq \Gamma(A_2 \rightarrow \pi\rho)$ , pole extrapolation implies qualitatively

$$d\sigma/dt (\pi N \rightarrow BN) \approx m_\rho^2/t \, d\sigma/dt (\pi N \rightarrow A_2 N) \tag{18}$$

This is made quantitative in Fig. 4 which compares the precise pole extrapolation prediction with experiment. As anticipated above, the theory is a complete disaster - being a factor of 30 too big in the forward direction. Figure 4 marks the  $\pi B$  spin-flip (i.e., B helicity  $\pm 1$ ) part of the theoretical cross-section. It agrees much better in both shape and size with the data. Combining this with the similarity of the  $A_2$  and B cross-sections, we conclude that the latter is largely spin-flip. It follows that it is a matter of theoretical urgency to understand what has happened to the B helicity zero amplitude.

3.4: Kislinger's Model

In Kislinger's model <sup>10</sup>, the vector meson Regge pole couplings are proportional to those of the photon. In the case of



(e.g.,  $\rho \rightarrow N\bar{N}$ ),

this is well known to give the successful prediction of the Stodolsky-Sakurai <sup>41</sup> decay distribution for the  $3/2^+$  decuplet. Unfortunately, this latter prediction may also be obtained in the simple quark model <sup>24,41</sup>. In the past <sup>24</sup>, I have preferred the quark derivation as this model has many other successes for the spin structure in  $PN \rightarrow VD$ . However, the quark model has never been extended to the production of  $L \geq 1$  states (as are the  $A_1$ ,  $A_2$  and B states of interest now) It is thus particularly striking that Kislinger's photon analogy predicts that in all processes of the form  $PN \rightarrow M^* N$ ,  $PN^*$ ,  $M^* N^*$ , the spin non-flip coupling, at either  $PM^*$  or  $NN^*$  vertex, vanishes at  $t = 0$  for vector and tensor exchange. This is precisely what the  $\pi p \rightarrow Bp$  data indicated and so experiment is in amazing qualitative agreement with Kislinger's model. This model predicts the non-flip zero simply because it is present in the photon couplings. The latter is easy to prove in general but, as an example, consider the vertex

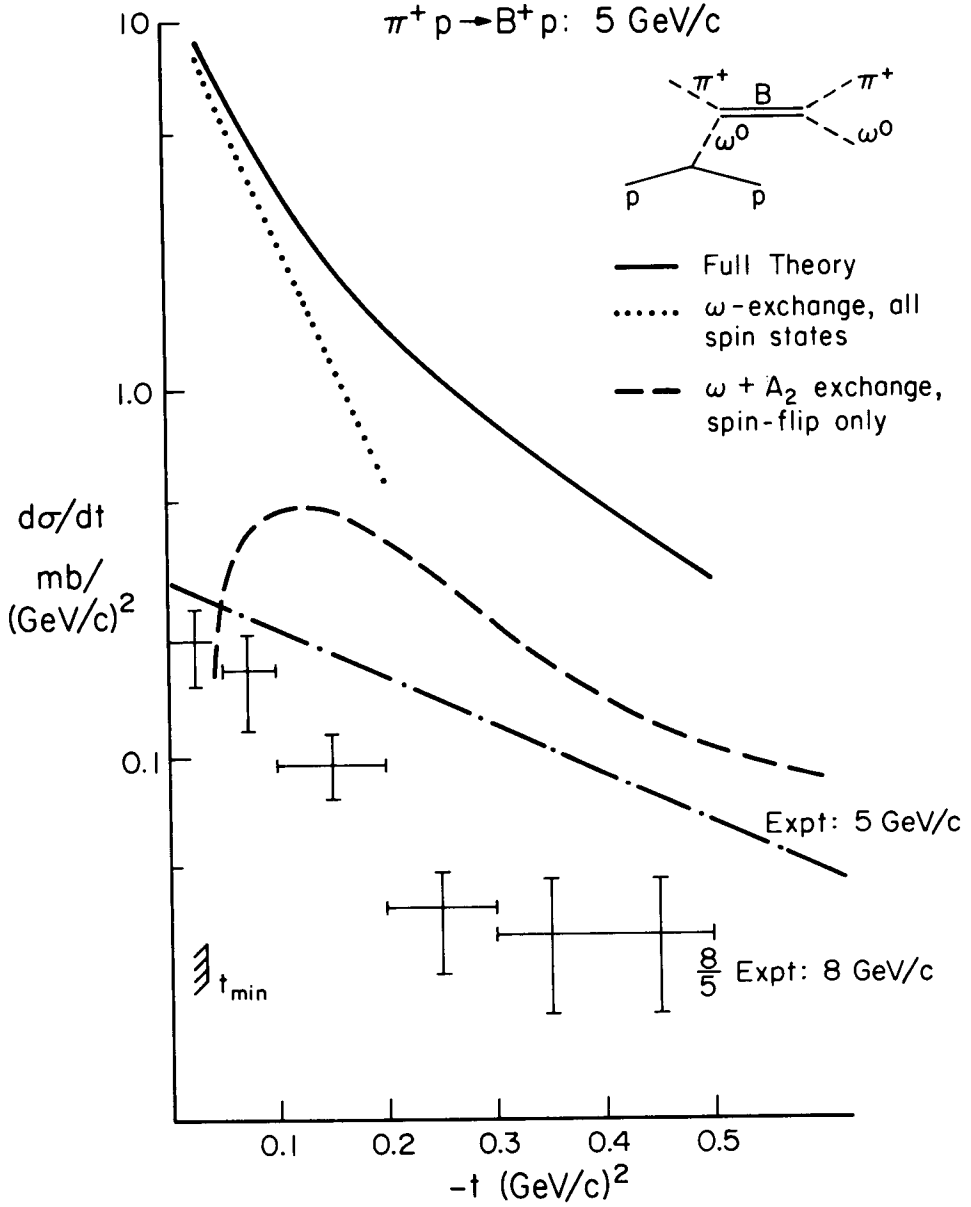


Fig. 4: Comparison of  $\pi^+ p \rightarrow B^+ p$  data (Refs. 37 & 38) scaled to 5 GeV/c and the  $\omega$ ,  $A_2$  pole extrapolation model.



where a and b have spin  $0^-$ . This can be written

$$T^\mu = X(q_a - q_b)^\mu + Y(q_a + q_b)^\mu \tag{19}$$

for invariant amplitudes X and Y. Gauge invariance, i.e.,

$$q_Y^\mu T_\mu = 0 : q_Y = q_a - q_b \tag{20}$$

implies

$$Y(m_a^2 - m_b^2) + Xt = 0 \tag{21}$$

i.e., for inelastic scattering,  $m_a \neq m_b$ , Y vanishes at  $t = 0$  ( $t = q_Y^2$ ).

X plays no role in the scattering at high energy (e.g., it is  $\propto q_Y^\mu$  and so its contribution vanishes when dotted into the lower vertex  $\gamma \rightarrow N\bar{N}, N\bar{B}^*$ ). Thus the non-flip  $\gamma \rightarrow a\bar{b}$  amplitude is proportional to Y and hence t as claimed.

Finally we note that Kislinger's model has all the  $SU_3$ /EXD factorization properties discussed in 2.4. So no considerations based on this are affected. Also we should note that the  $SU_3$  formulation means that we avoid the embarrassing prediction that  $\pi N \rightarrow K\Lambda$  vanishes at  $t = 0$ . (Putting  $a = \pi, b = K$  in (21) would naively give this disaster.)

### 3.5: Production of the $A_1$ Nonet

This is a particularly tricky discussion because there appears to be a discrepancy between the diffractive and non-diffractive data. There are two important new sources of information on  $1^+$  diffraction.

First, the Illinois partial wave analysis<sup>42</sup> of the  $3\pi$  system in  $\pi^- p \rightarrow (\pi^- \pi^- \pi^+) p$ ; second, the SLAC data<sup>29</sup> on  $K^0 p \rightarrow Q^0 p$ . I discuss these in turn.

#### (i) $A_1$ Diffraction Production

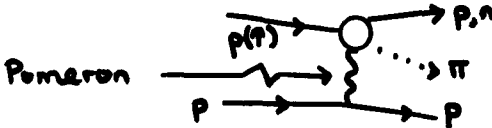
A very surprising feature of the  $3\pi$  partial wave analysis<sup>42</sup> in

$$\pi^- p \rightarrow ("A_1", A_2 "A_3" \rightarrow 3\pi) p$$

is that the only phase variation seen is the circular rotation of the  $2^+$  phase relative to the  $1^+$  background in the  $A_2$  region<sup>43</sup>. This is in nice agreement with a resonant  $A_2$ . Unfortunately, we decided in

2.2 that Watson's theorem implied that there could well be little connection between resonance positions and bumps in the mass spectrum. However, one "had to" observe relative phase-variations. In this case, one should see the phase of the resonant  $1^+$  (S-wave)  $A_1$  compared to the  $0^-$  background. One could advance five explanations for the lack of observation of this effect.

- a) The  $A_1$  does not exist - I reject this because of the impressive evidence for its  $SU_3$  partner: the D meson.
- b) The  $0^-$  has a similar resonant phase variation to the  $A_1$ . I reject this "daughter" possibility as being implausible at such a low mass.
- c) The  $A_1$  is not a "narrow" resonance at 1.07 GeV. Rather, it is a broad effect centered at (presumably) higher mass. For instance, if its mass was 1.285 GeV, one would expect a width of 230 MeV. This possibility has to be taken seriously because experimentally - the mass of 1.07 GeV comes from a probably unjustified (in " $e^{i\delta}$  processes" - see 2.2) association of resonance position with a bump in the same diffraction data that sees no phase variation. Theoretically the mass formulae based on the quark model are, I believe, completely empirical and could be adjusted for a new  $A_1$  mass. There is the notorious prediction  $m_{A_1} = \sqrt{2} m_p$  which agreed miraculously with 1.07 GeV; however, this should not be taken seriously.
- d) Final state interaction theory is wrong. For instance, our rule in 2.2 stated that only "rapid" phase variations should be detected. What total width corresponds to "rapid" variation? An important check of these phases would be the experiment <sup>44</sup>



using the Argonne polarized proton beam and detecting the fast  $\pi^+ n, \pi^0 p$  system. This experiment has three advantages over the  $\pi p$  reaction:

- α) The two particle  $\pi p$  state is easier to handle than the  $3\pi$  " $A_1$ " decay - cf., my objection (e).
- β) Polarization is more sensitive to phases than cross-section.
- γ) The  $\pi p$  resonances, i.e., phases, are better known than their  $3\pi$  counterparts.
- e) The data analysis is unreliable for a delicate interference question like the  $A_1$  phase. Against this possibility, we have the analysis's successful isolation of the  $A_2$  phase <sup>43</sup>. On the other hand, we note that the simple ( $\epsilon\pi, \rho\pi$ ) quasi two-body description of the  $3\pi$  system used in the analysis violates Watson's theorem in the various  $2\pi$  sub-channels. Possibly the phase error in the  $2\pi$  sub-systems obscures the overall  $3\pi$   $A_1$  phase?

In conclusion, the  $3\pi$  partial wave analysis - of which we have three reasonable interpretations, (c) to (e) above - casts serious doubts on the usual  $A_1$  parameters. However, it doesn't directly tell us anything about non-diffractive production.

(ii)  $Q^0$  Cross-over

Let  $P$  be the diffractive and  $R$  the non-diffractive contribution to  $K^0 p \rightarrow Q^0 p$ . Then, according to folklore <sup>45</sup>,

$$\begin{aligned} d\sigma/dt'(K^0 p \rightarrow Q^0 p) &= |P|^2 \\ d\sigma/dt'(\bar{K}^0 p \rightarrow \bar{Q}^0 p) &= |P + R|^2 \end{aligned} \quad (22)$$

A SLAC group <sup>2</sup> has used these equations <sup>29</sup> to isolate  $R$  as

$$\text{Im}R = \frac{d\sigma/dt'(Q^0 p) - d\sigma/dt'(Q^0 p)}{2 \sqrt{d\sigma/dt'(Q^0 p)}} \quad (23)$$

Their data is shown in Fig. 2 and the value they extract from it for  $|R|^2$ , i.e., the non-diffractive contribution to  $Kp \rightarrow Qp$ , is shown in Fig. 5. The latter requires a lot of explanation.

The experimental data corresponds to a simple mass-cut  $1.1 \lesssim M(K\pi\pi) \lesssim 1/5$  GeV and has been corrected for unseen decay modes. For this definition of the  $Q$ , the value one obtains for  $|R|^2$  is too large to agree with two other methods of calculating it. First, we have Kislinger's model <sup>10</sup> which predicts that  $Q$  like  $B$  non-diffractive production should vanish at  $t = 0$ . So any non-flip amplitude (which is that measured by (23)) must be small. Second, we have the  $\pi^- p \rightarrow Q^0 \Lambda$  data <sup>11</sup> to be discussed soon. This shows, in perfect agreement with Kislinger's model, a small flat  $d\sigma/dt$  which is, in turn, inconsistent with a large non-flip amplitude. So we assume that most of the "mass-cut  $Q$ " observed in the  $K^0$  experiment corresponds to ( $e^{1\delta}$ ) background. Perusal of the mass-dependence of the similar  $K^+ p \rightarrow Q^+ p$  data <sup>16,47</sup>, suggests that with the  $Q_{A_1}$  parameters of Table II one could assign about  $\frac{1}{4}$  of the SLAC cross-section to the true resonance  $Q_{A_1}$ . This has been done in Fig. 5.

Given the above, this figure now exhibits the usual disagreement between experimental cross-sections and pole extrapolation. Without the mysterious factor of  $\frac{1}{4}$ , we would have agreed with pole extrapolation but not as discussed above with either Kislinger's model or  $\pi^- p \rightarrow Q^0 \Lambda$ .

Note that Fig. 5 suggests sizeable non-diffractive  $Q$  production at large  $-t$  <sup>46</sup> (assuming this is given by the spin-flip part of the extrapolation theory). This should lead to a break in  $d\sigma/dt$  around  $-t \approx 0.5$  (GeV/c)<sup>2</sup> at  $P_{\text{lab}} \approx 5$  GeV/c.

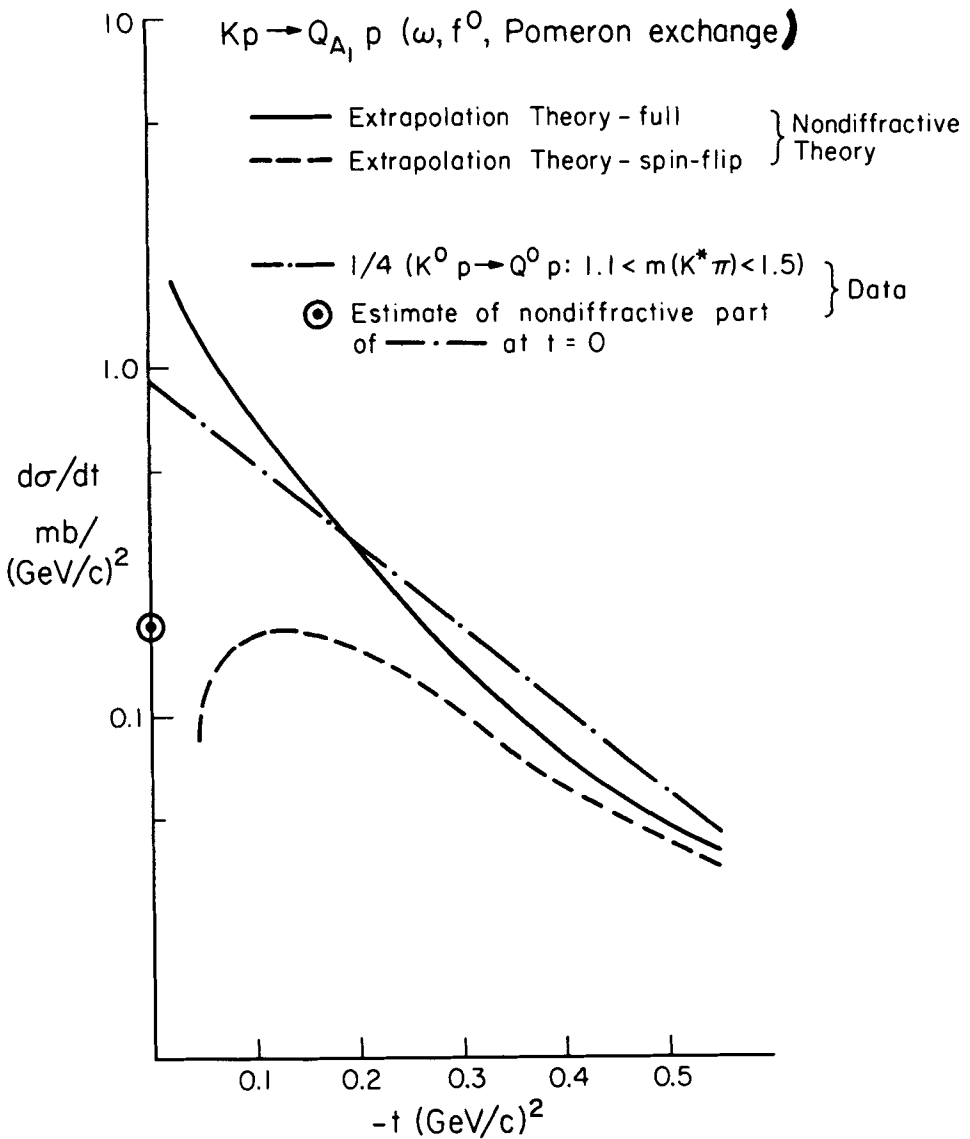
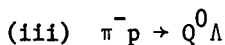


Fig. 5: Experimental data (Ref. 29) - averaged over  $4 \lesssim P_{\text{lab}} \lesssim 12 \text{ GeV/c}$  - on the diffractive (---) and non-diffractive (⊗) parts of  $Kp \rightarrow Qp$ . The extrapolation theory for non-diffractive part is calculated at 5 GeV/c.



We now come to the most convincing evidence for non-diffractive production of the  $Q_{A_1}$  or  $Q_B$ . This comes from a study<sup>11</sup> of  $\bar{\pi} p \rightarrow (K\pi\pi)^0 \Lambda$  at 4.5 and 6 GeV/c. The  $K\pi\pi$  mass distribution, shown in Fig. 6, indicates a sharp peak at  $M(K\pi\pi) = 1.29$  and a broader enhancement around 1.4 GeV. There are three possible interpretations of this data.

(a) The first peak is identified with the C meson observed in  $\bar{p}p$  annihilations around  $M(K\pi\pi) = 1.24 \text{ GeV}^3$ . The mass difference is attributed to background interference. This first Q is then  $Q_{A_1}$  while the enhancement at 1.4 GeV is a mixture of  $K_{1420}^*$  and a second relatively narrow  $Q_B$  resonance.

(b) We have the same identification of the first Q as the C meson but we assume it is  $Q_B$ . Then by analogy with our interpretation (c) of the Illinois  $A_1$  analysis (3.5(i)), we assume the  $Q_{A_1}$  is much broader and hence indistinguishable from background. For instance, the mass assignment  $M(Q_{A_1}) = 1.35 \text{ GeV}$  doubles the expected width and mixing may do other awful things.

(c) The 1.29 enhancement is  $Q_B$  while  $Q_{A_1}$  at lower mass (i.e., 1.24 GeV) has too small a cross-section to be seen.

Examination of the  $d\sigma/dt'$  data for the two regions (I:  $1.24 \leq M(K\pi\pi) \leq 1.34$ , II:  $1.34 \leq M(K\pi\pi) \leq 1.48 \text{ GeV}$ ) rules out (c) but without enough data to allow a partial wave analysis, one cannot distinguish (b) and (c). The data in Figs. 7 and 8 comes from a DST kindly sent me by Kwan Lai and Howard Gordon with normalization taken from the standard compilation<sup>48</sup>. For theory, we use  $SU_3$  estimates of the type discussed in 2.4: that for  $\bar{\pi} p \rightarrow Q_B^0 \Lambda$  uses  $\pi^+ p \rightarrow B^+ p$ ; that for  $\bar{\pi} p \rightarrow Q_{A_1}^0$  uses the SLAC  $K^0 p \rightarrow Q^0 p$  crossover analysis<sup>29</sup> for normalization and the Kislinger model<sup>10</sup> for  $t$  dependence; finally for  $\bar{\pi} p \rightarrow K_{1420}^* \Lambda$  we use  $\pi^\pm p \rightarrow A_{2p}^\pm$ . This underestimates the  $K_{1420}^*$  cross-section by a factor of 2 because it omits a sizeable K and  $Q_B$  exchange contribution. This can be seen theoretically from the EXD analysis of 2.4 and experimentally<sup>11</sup> by comparison of  $\bar{\pi} p \rightarrow K_{1420}^* \Lambda$  and  $\bar{\pi} p \rightarrow K_{1420}^* \Sigma^0$ . (The latter has no  $K_B$  exchange.)

Finally we can actually examine Figs. 7 and 8. First, we note the beautiful agreement between the  $t$ -dependence of theory and experiment. This flat  $t$ -behavior again supports Kislinger's idea that all such resonance production ( $Q_B$ ,  $Q_{A_1}$ ,  $K_{1420}^*$ ) is mainly spin-flip. The normalization of the  $\bar{\pi} p \rightarrow Q_B^0 \Lambda$  and  $K_{1420}^* \Lambda$  curves clearly allow either possibility (a) or (b). The  $Q_{A_1}^0 \Lambda$  curve in Fig. 7 is in satisfactory accord with (a) when we consider the many arbitrary



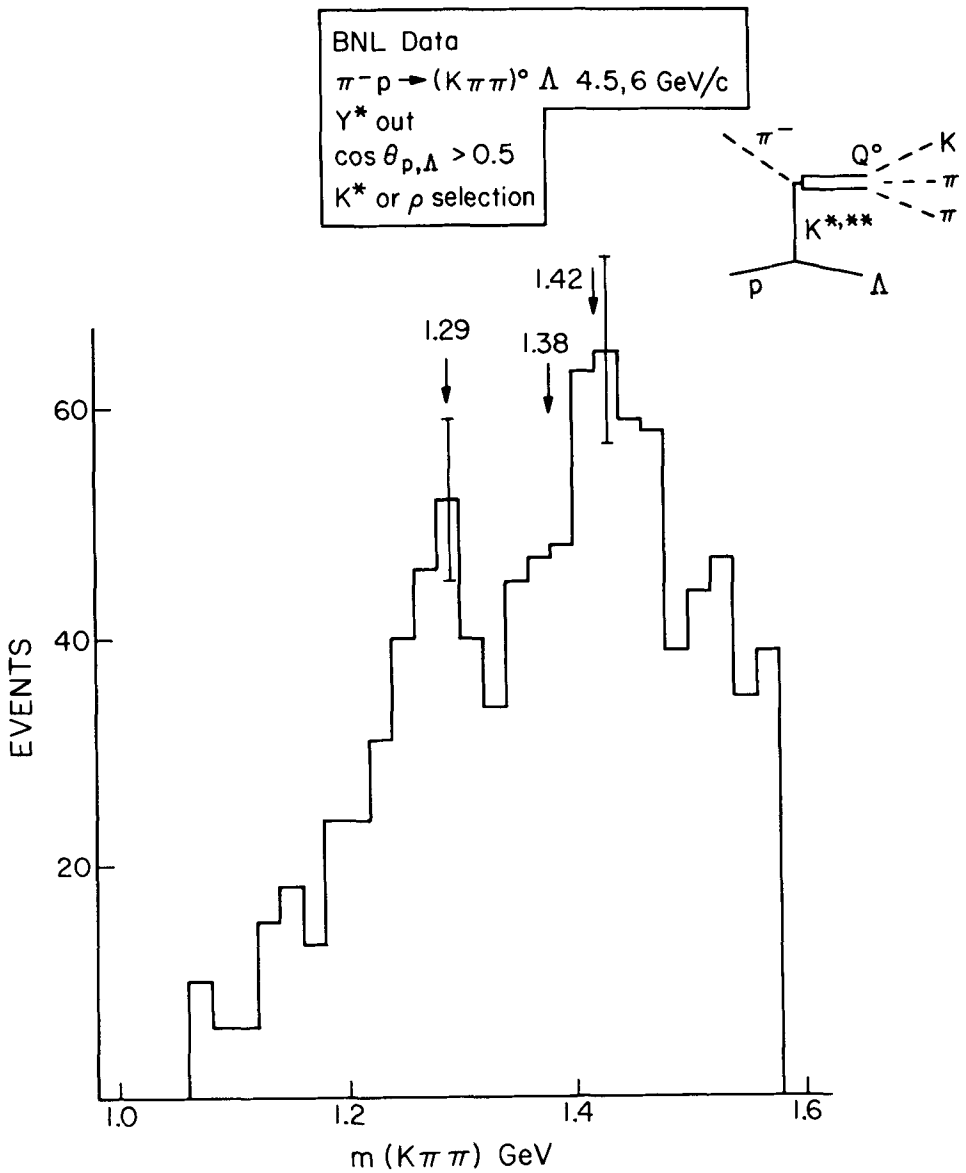
$e^i \delta$  Sin  $\delta$  Production ?

Fig. 6:  $K\pi\pi$  mass distribution (Ref. 11) in  $\pi^- p \rightarrow (K\pi\pi)^0 \Lambda$  at 4.5 and 6 GeV/c (momenta combined). This probably represents sum of  $Q_{A_1}^0$  (1.29),  $Q_B^0$  (1.38) and  $K_{1420}^*$  (1.42).

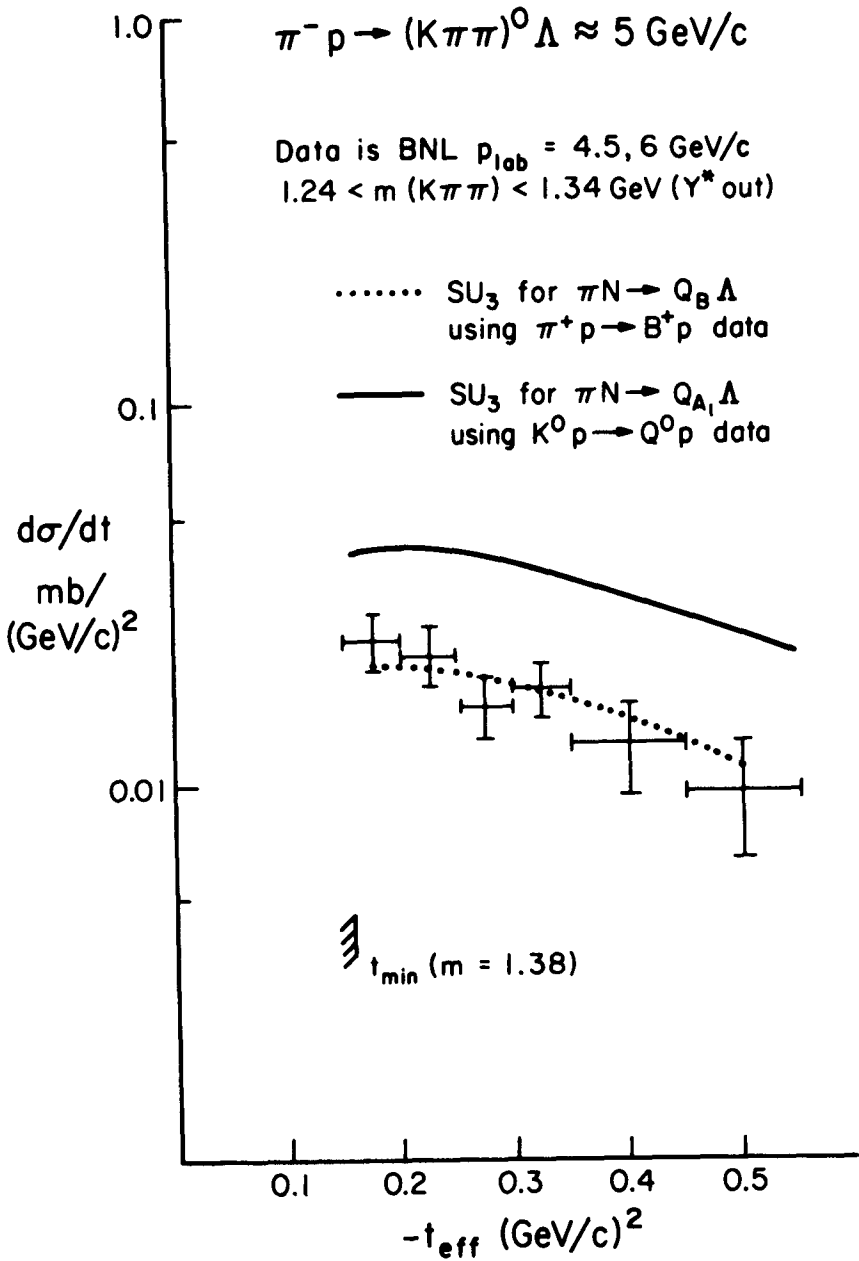


Fig. 7: "Lower Q": Experimental mass-cut data (Ref. 11) compared with  $SU_3$  predictions for  $Q_{A_1}$  and  $Q_B$ .

Note:  $t_{eff} = t' + t_{min} (m = 1.38)$ .

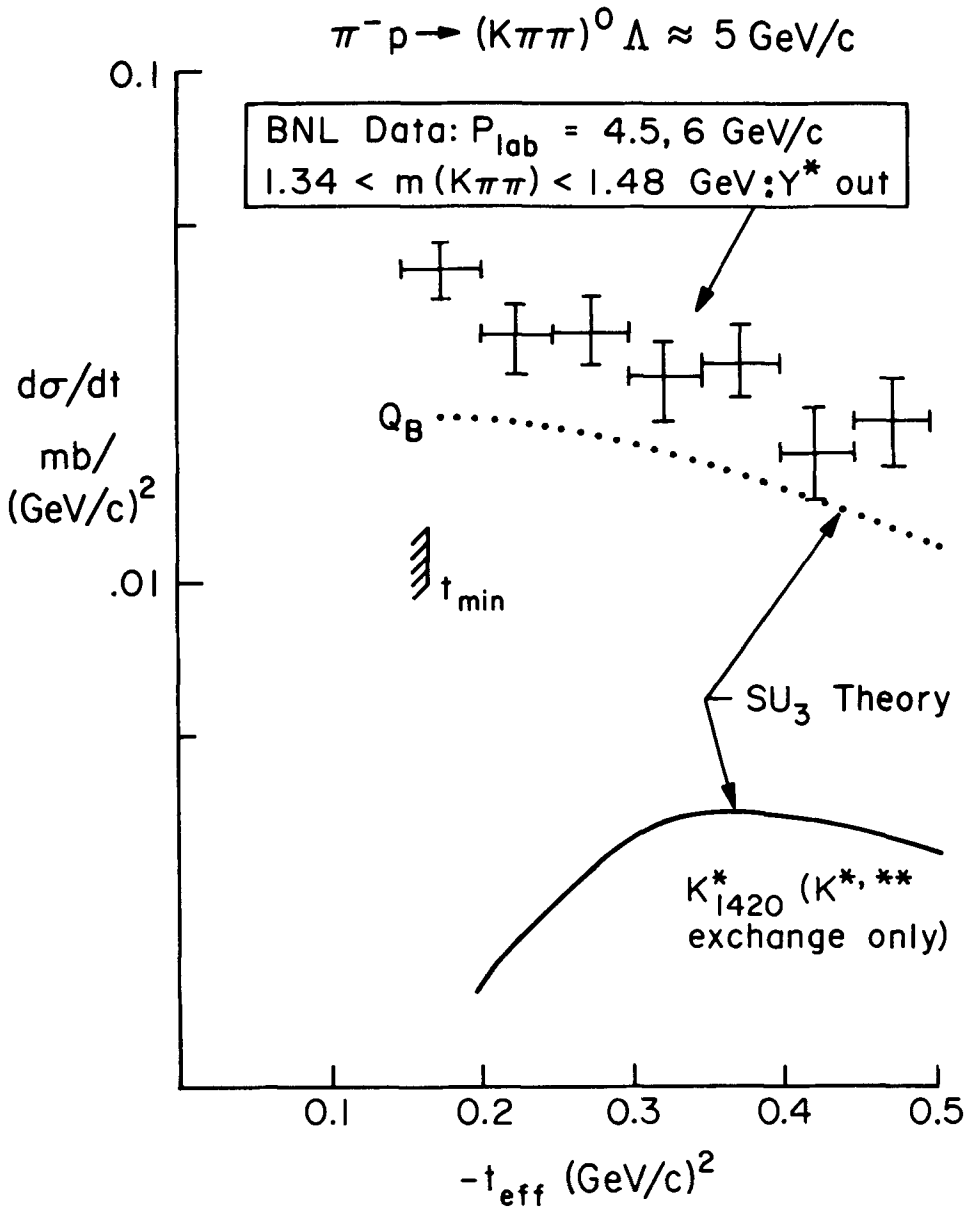


Fig. 8: "Higher  $Q + K_{1420}^*$ ": Experimental mass-cut data (Ref. 11) compared with  $SU_3$  predictions for  $Q_B$  and  $K_{1420}^*$ . The latter should be doubled to get all exchanges - see text.

assumptions in our interpretation of the SLAC  $Q_{A_1}$  data. Note that this curve does include the magic factor of  $\frac{1}{4}$  discussed in 3.5(ii) and would have been far too large without it. Given the SLAC  $Q_{A_1}$  curve is not still miles too big, we can rule out possibility (c) because there is not enough "spare" cross-section at low  $K\pi\pi$  masses.

### 3.6: Predictions

Using  $\pi^+p \rightarrow B^+p$  and  $\pi^-p \rightarrow Q^0\Lambda$  (assuming the 1.29 GeV enhancement in Fig is  $Q_{A_1}$ ), we can now, as described in 2.4, use  $SU_3$  to predict the cross-sections for all members of the B and  $A_1$  nonets. The results are given in Figs. 9 to 12 where we have also marked some typical  $d\sigma/dt$  for well-loved reactions. The calculations are arbitrarily given for  $P_{lab} = 15$  GeV/c; they can be scaled to your favorite momenta using the usual  $P_{lab}^{2\alpha-2}$  ( $\alpha \approx 0.5$  non-strange;  $\alpha \approx 0.35$  strangeness exchange) scaling law. The only exceptions to this are first, the two B exchange reactions  $\pi^-p \rightarrow \pi_N(980)n$  and  $\pi^-p \rightarrow A_2^0n$ . These scale more like  $P_{lab}^{-2}$  and the plotted cross-sections were calculated using the  $\pi$ -B EXD ideas described near the end of 2.4. Similarly for their strange partner  $^{49}K^-p \rightarrow \pi_N(980)\Lambda$  in Fig. 11(II) which is K and  $Q_B$  exchange, I have assumed  $P_{lab}^{-3}$  scaling.

As indicated in the introduction, the epithets magic- $\omega$  (sometimes abbreviated to magic), magic- $\phi$ , octet and singlet describe possible mixing schemes of the  $I = 0$  D and h mesons. Further, we do not mark explicitly the  $\pi^+p \rightarrow M^{*0}\Delta^{++}$  cross-sections (which are essentially identical to the analogous  $\pi^-p \rightarrow M^{*0}n$  reaction) and  $K^-p \rightarrow M^{*-}Y_{1385}^{*+}$ ,  $\pi^+p \rightarrow M^{*+}Y_{1385}^{*+}$  which are rather small (see ratio  $^{50}$  of  $\pi^+p \rightarrow K^+\Sigma^+v$ ,  $\pi^+p \rightarrow K^+Y_{1385}^{*+}$  in Fig. 10(I)).

### 3.7: Further Tests

Now we would like to test our predictions in Figs. 9-12 by comparison with various other reports of  $1^+$  production in the literature. These are generally not as statistically significant as the reactions in 3.3 and 3.5, but it is important simply to check that our theoretical predictions are no larger than current experimental upper limits.

$$(i) \text{ CEX } Q: K^+n \rightarrow K^0p, K^-p \rightarrow \bar{Q}^0n$$

Charge exchange Q production has been looked for by Ferbel and collaborators  $^{51}$  in a large sample of the world's data; they report no evidence for Q production and the only resonance seen is the  $K_{1420}^*$ . To interpret this result, I have taken one of the experiments  $^{17}$  in their compilation where the normalization is readily available. So Fig. 13 shows the 12 GeV/c  $K^+n \rightarrow (K^0\pi^+\pi^-)p$  reaction

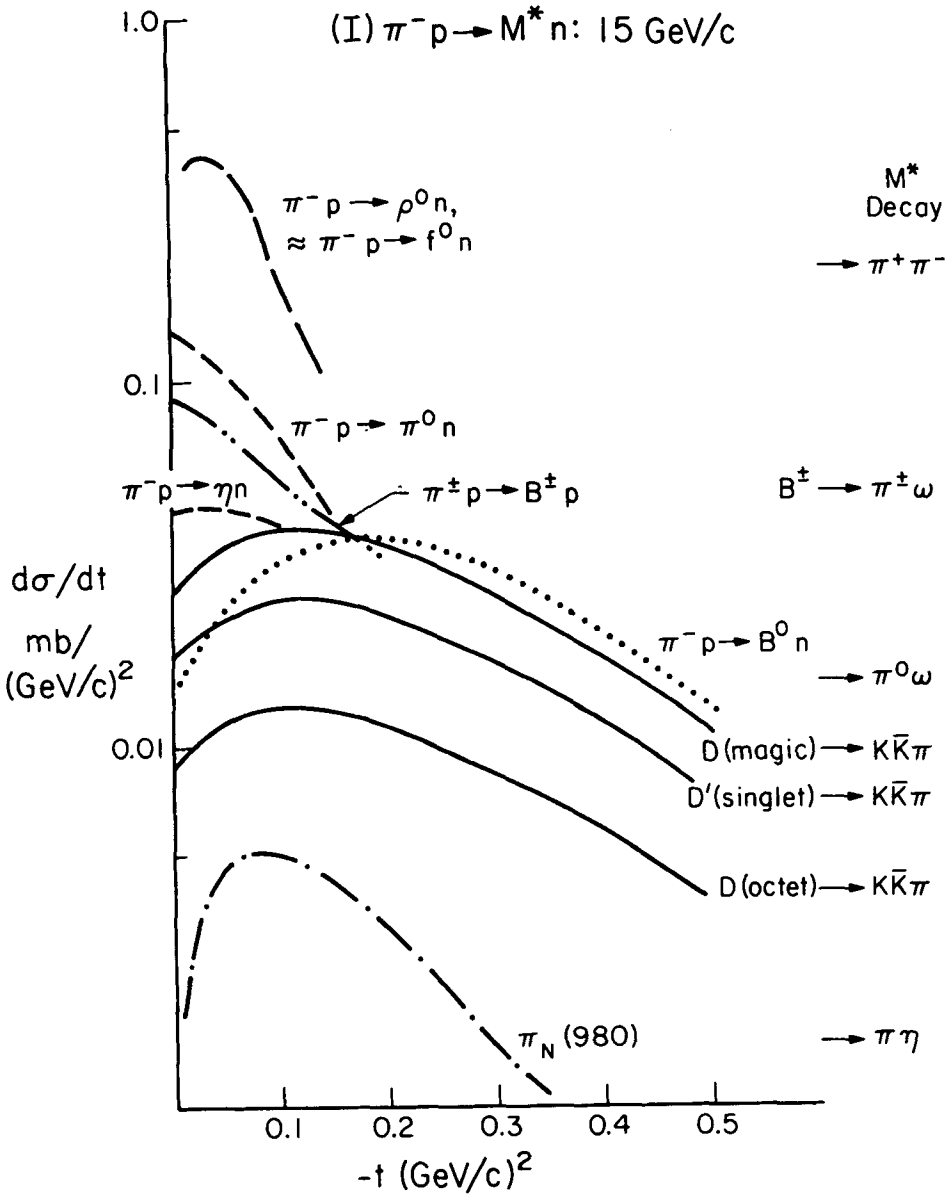


Fig. 9(I):  $SU_3$  predictions described in Section 3.6 for some of the  $\pi^- p \rightarrow M^* n$  reactions at 15 GeV/c.  $\pi^+ p \rightarrow M^* \Delta^{++}$  has identical  $d\sigma/dt$  to the analogous  $\pi^- p \rightarrow M^* n$  reaction.

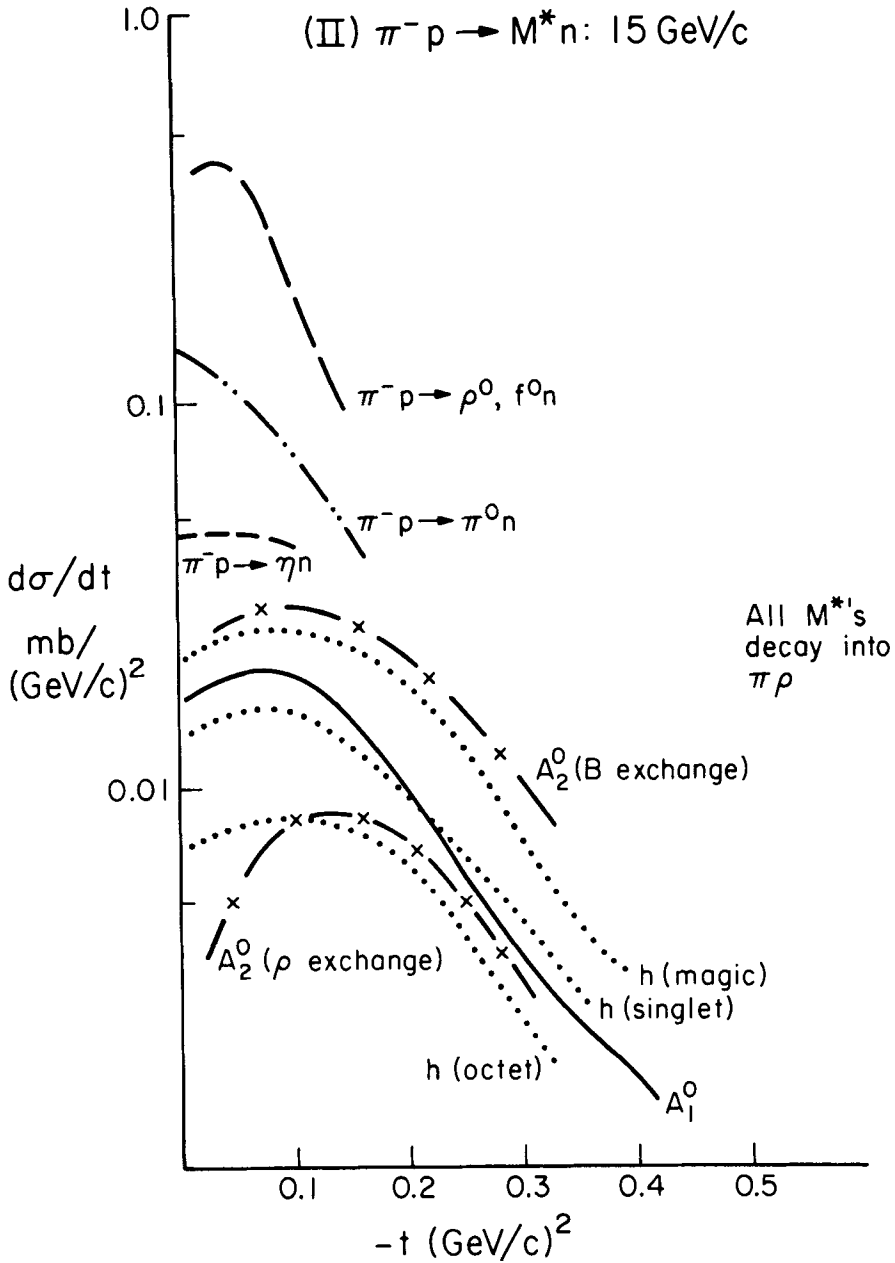


Fig. 9(II):  $SU_3$  predictions described in Section 3.6 for  $\pi^- p \rightarrow M^* (\rightarrow \pi\rho)n$  at 15 GeV/c.  $\pi^+ p \rightarrow M^* \Delta^{++}$  has identical  $d\sigma/dt$  to the analogous  $\pi^- p \rightarrow M^* n$  reaction.

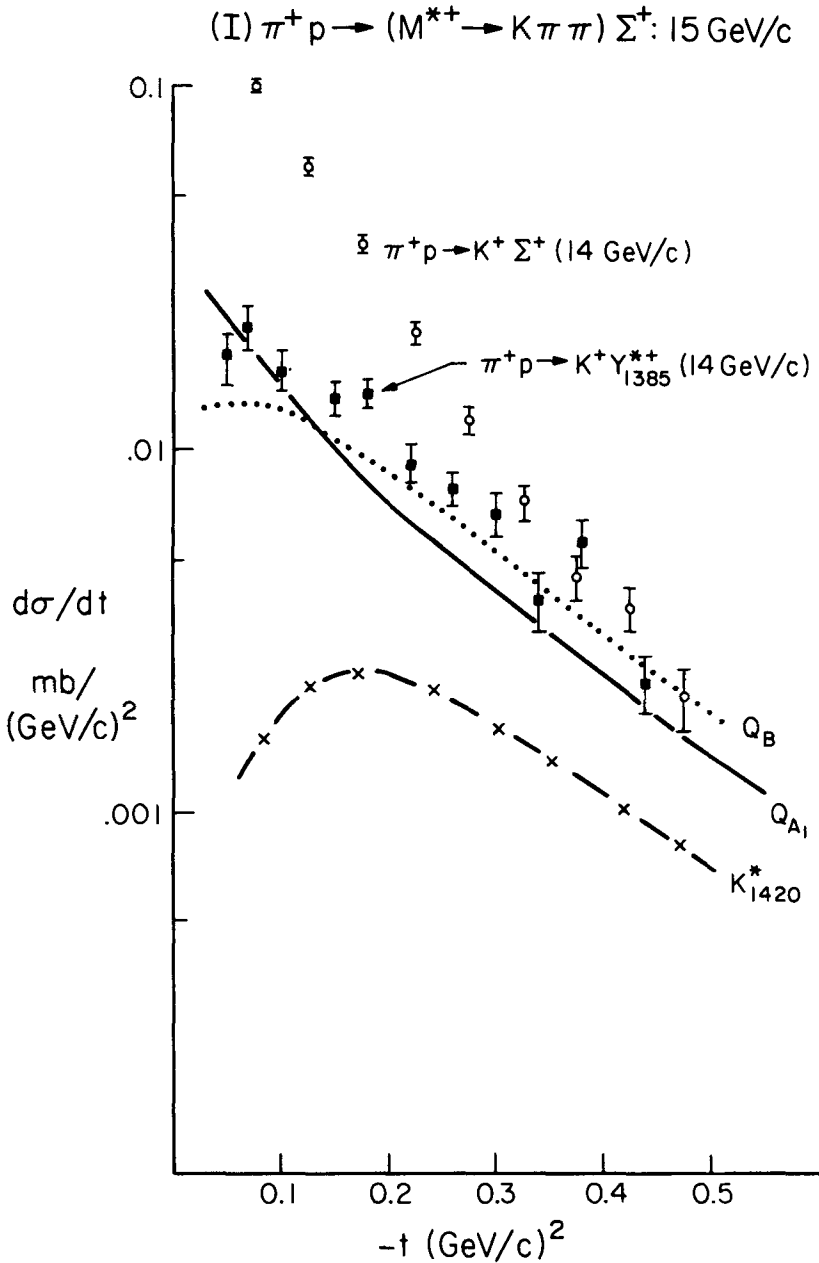


Fig. 10(I):  $SU_3$  predictions described in Section 3.6 for  $\pi^+ p \rightarrow M^{*+} \Sigma^+$  at 15 GeV/c. The well-loved data is from Ref. 50.

(II)  $\pi^- p \rightarrow (M^{*0} \rightarrow K\pi\pi) \Lambda: 15 \text{ GeV/c}$

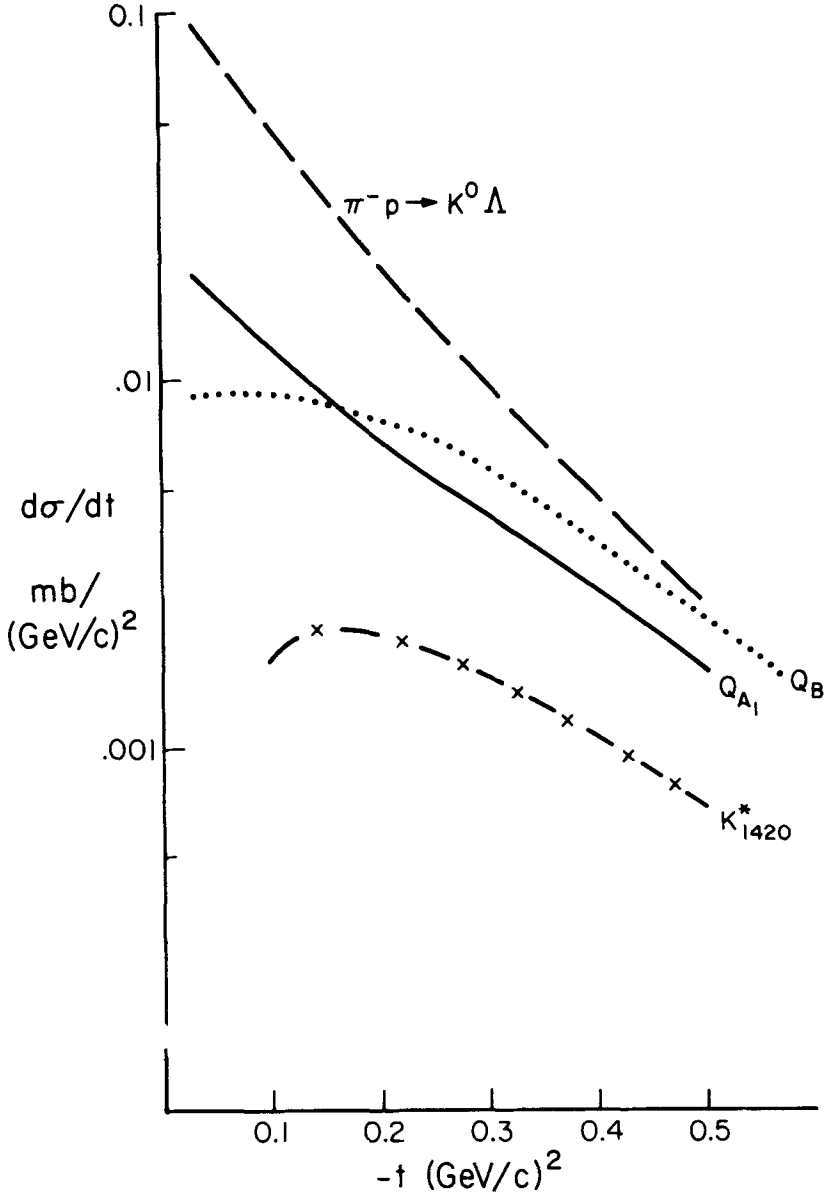


Fig. 10(II) Fig. 13:  $K\pi\pi$  mass distribution in  $K^+ n \rightarrow (K^0 \pi^+ \pi^-) p$  at 12 GeV/c (Ref. 17). This is discussed in Section 3.7(i).



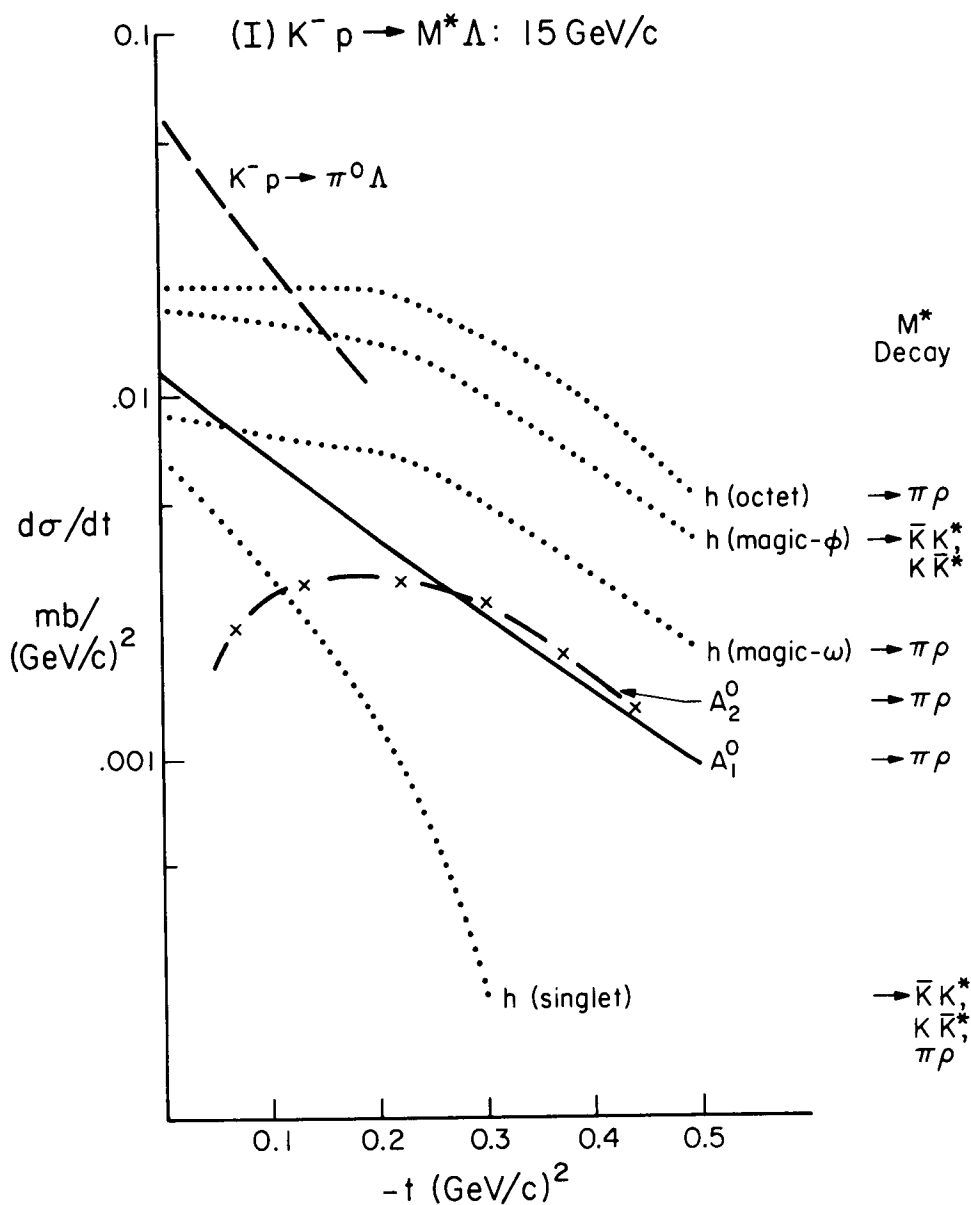


Fig. 11(I):  $SU_3$  predictions described in Section 3.6 for some  $K^- p \rightarrow M^* \Lambda$  reactions at 15 GeV/c.  
 Note:  $K^- n \rightarrow M^* \Lambda = 2(K^- p \rightarrow M^* \Lambda)$  for isospin-1 mesons.  
 The  $A_2$  curve does not include  $K/Q_B$  exchange.

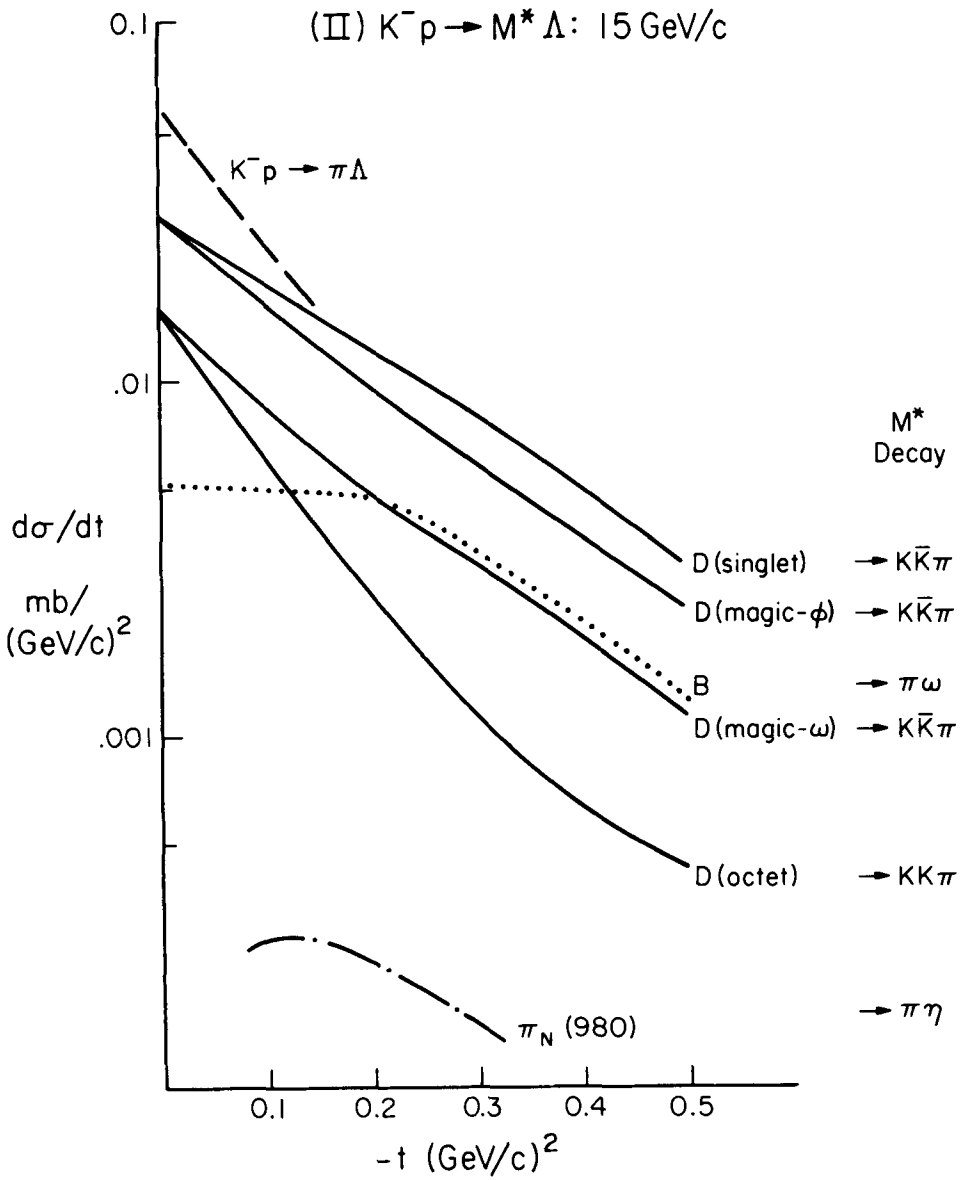


Fig. 11(II):  $SU_3$  predictions described in Section 3.6 for some  $K^- p \rightarrow M^* \Lambda$  reactions at 15 GeV/c. Note:  $K^- n \rightarrow M^* \Lambda = 2(K^- p \rightarrow M^* \Lambda)$  for isospin-1 mesons.

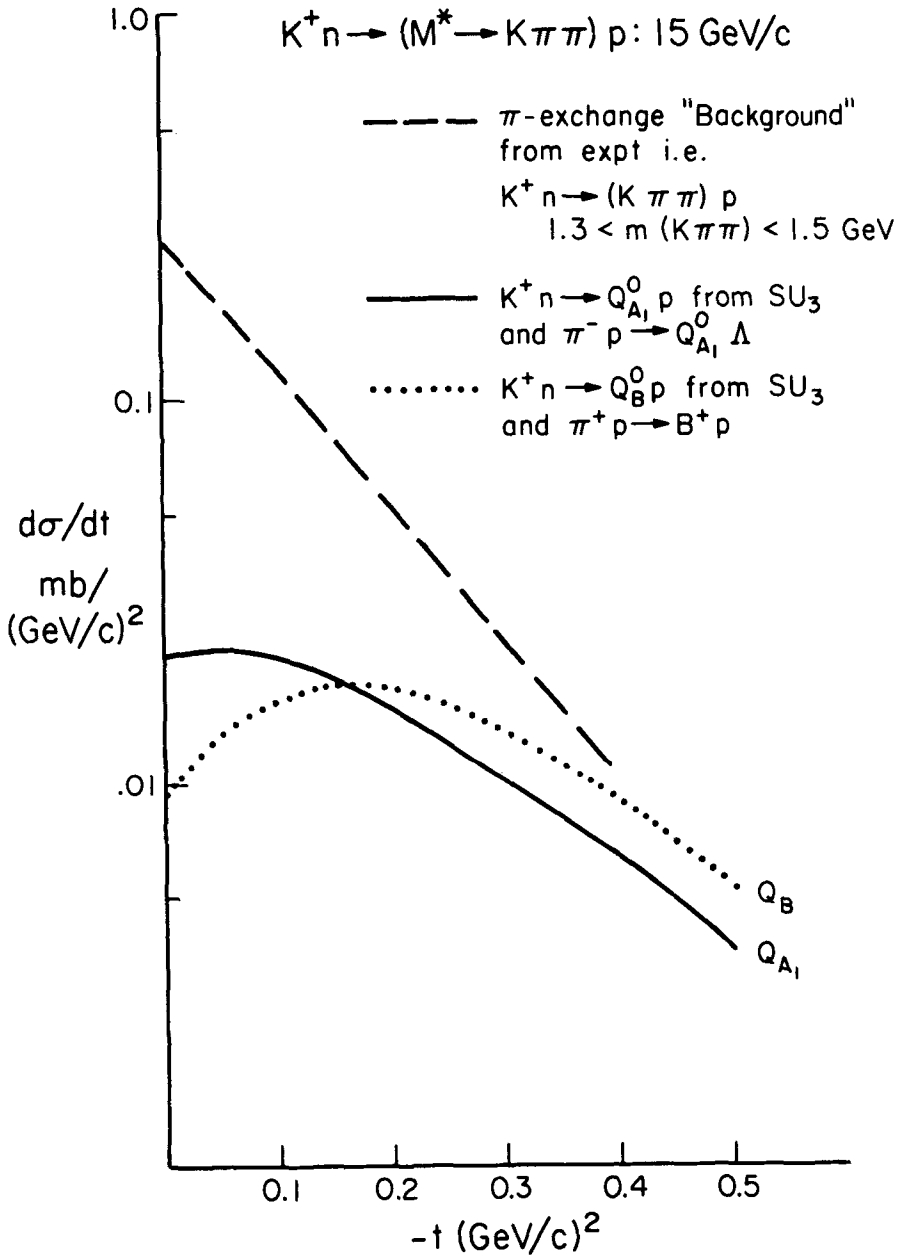
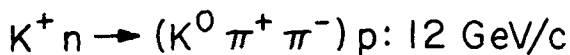


Fig. 12:  $SU_3$  predictions described in Section 3.6 for  $K^+ n \rightarrow M^{*0} p$  at 15 GeV/c. The  $\pi$ -exchange "background" is explained in 3.7(1) and comes from Ref. 17, scaled to 15 GeV/c.



EXPT:  $1.12 < m(Q) < 1.32: \sigma \approx 8 \mu\text{b}$

THEORY:  $K^+ n \rightarrow (Q_{A_1}^0 \rightarrow K^0 \pi^+ \pi^-) p: \sigma \approx 4 \mu\text{b}$

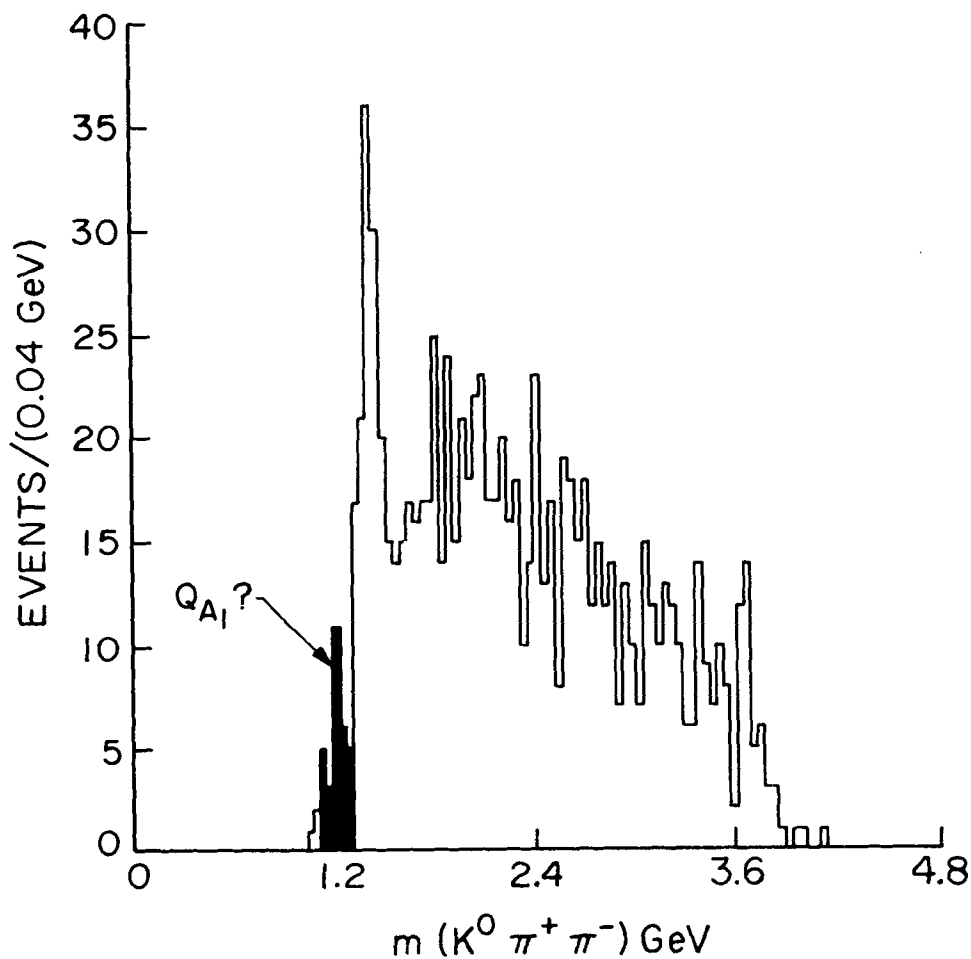


Fig. 13:  $K\pi\pi$  mass distribution in  $K^+ n \rightarrow (K^0 \pi^+ \pi^-) p$  at 12 GeV/c (Ref. 17). This is discussed in Section 3.7(1).

where there is no statistically significant Q signal below the  $K_{1420}^*$ . However, this is no contradiction with theory, for the number of events observed in the  $Q_{A_1}^0$  mass-cut,  $1.12 \leq M(K\pi\pi) \leq 1.32$  GeV, is twice what we would expect from the resonance production  $K^+n \rightarrow Q_{A_1}^0 p$  <sup>52</sup> (estimated using  $SU_3$  and  $\pi^-p \rightarrow Q_{A_1}^0 \Lambda$ ). Moreover,  $K^+n \rightarrow Q^0 p$  is an exceedingly difficult place to detect the Q because of the large  $\pi$ -exchange background. This was indicated in Fig. 12 for the  $K_{1420}^*$  mass-cut, and the possibility of  $\pi$ -exchange explains why the  $K_{1420}^*/Q_{A_1}$  ratio is so much larger in  $K^+n \rightarrow (K\pi\pi)p$  than in  $\pi^-p \rightarrow (K\pi\pi)\Lambda$ . (Compare Figs. 6 and 13.)

(ii) 950 MeV Region

A recent experiment <sup>54</sup> reported three narrow bosons, around 950 MeV, observed in  $\pi^-p \rightarrow M^*n$  at 2.4 GeV/c and  $t = t_{\min}$ . Theoretically, there is the uncontroversial narrow  $0^- \eta'$  and the 40 MeV wide  $0^+ \pi_N(980)$ . Further, Colglazier and Rosner have proposed <sup>5</sup> the  $1^+ D'$  of the  $A_1$  nonet should be a narrow resonance in this mass region. The theoretical estimates of these three cross-sections are given in Fig. 14 - all are dominantly spin-flip amplitudes which suggests one would do best to look for these particles a little away from the forward direction. However, the theoretical estimates are not completely reliable for the incident momenta is rather low. Take the difference between the experimental and theoretical <sup>31</sup>  $\eta'$  values as some estimate of a non-asymptotic correction (i.e., a small non-flip amplitude); then the ratio of the theoretical curves  $\eta': \pi_N(980): D'$  is in embarrassingly good agreement with the experimental ratio  $\eta': \delta: M(940)$ . This cannot be taken seriously without further experimental work; thus although the  $D'$  can consistently be identified with the  $M(940)$ , the experimentally narrow  $\delta$  meson (quoted is  $\Gamma_\delta < 5.9$  MeV) can hardly be equated with the  $\approx 40$  MeV wide  $\pi_N(980)$ .

(iii)  $h$  and  $D$  Production

$D$  production has been studied in the reactions  $\pi^+n \rightarrow D^0 p$  <sup>55,56</sup> and  $\pi^+p \rightarrow D^0 \Delta^{++}$  <sup>57,58</sup> which (theoretically) have equal cross-sections. Perhaps the best data <sup>55</sup> is shown in Fig. 15. The  $t$ -distribution is very flat and only one-third of the cross-section lies within  $0 \leq |t'| \leq .5$ . Here the experimental cross-section for  $D \rightarrow \delta\pi$  is 15  $\mu b$  while my theoretical  $SU_3$  estimate for  $D \rightarrow$  all is 10  $\mu b$ ; this agreement seems quite satisfactory. The theory is calculated for pure octet assignment to the  $D$ ; larger cross-sections might be expected for other mixing assignments. These values plus the very flat  $d\sigma/dt$ , expected theoretically, are recorded in Fig. 16. Unfortunately, we cannot say very much about  $D^0 \Delta^{++}$  because no cross-sections <sup>57,58</sup> are quoted for the small  $|t'| \leq .5$  cut necessary to apply our peripheral theory. Both  $\pi^-p \rightarrow D^0 n$  and  $K^-n \rightarrow B^-\Lambda$  (see next section)

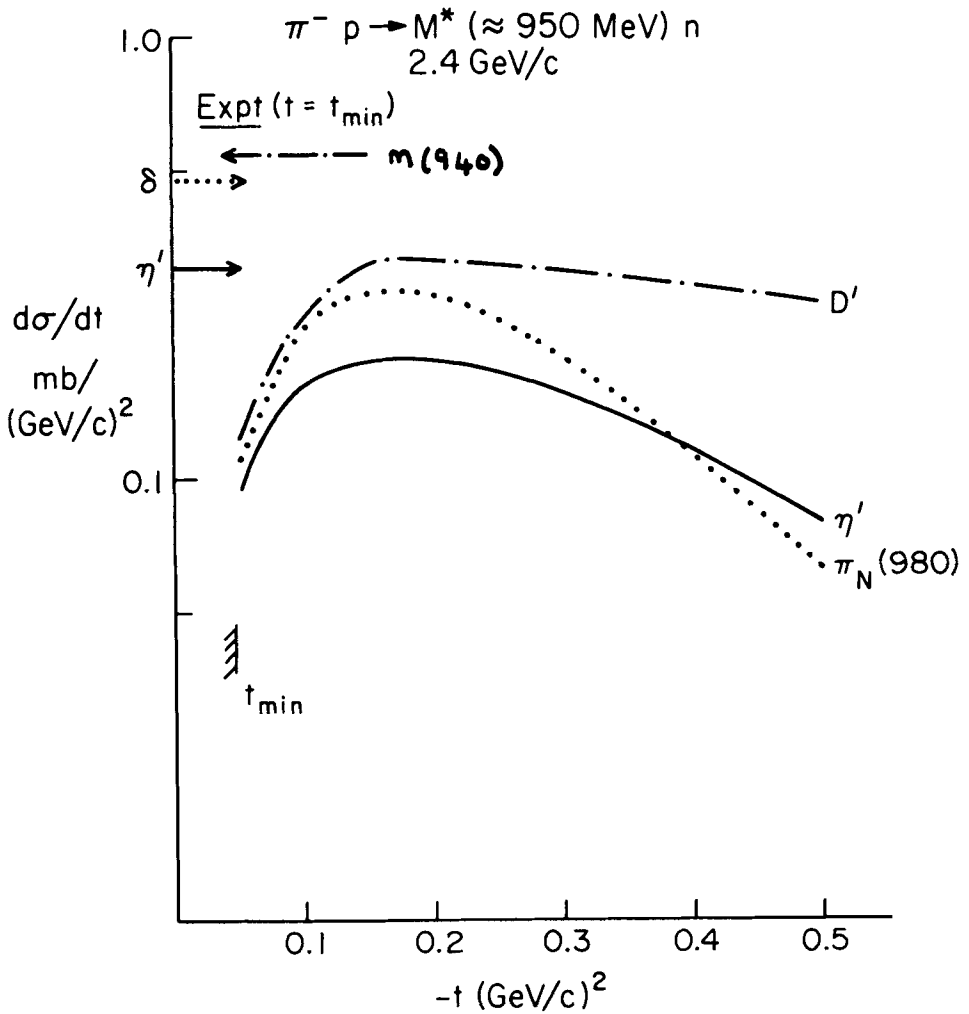


Fig. 14: Theoretical and experimental (Ref.54) narrow resonance production in the 950 MeV mass region and  $P_{\text{lab}} = 2.4 \text{ GeV/c}$ . This is discussed in Section 3.7(ii).

$$\pi^+ n \rightarrow (D^0 \rightarrow \delta^\pm \pi^\mp) p$$

2.7 GeV/c

$$\sigma (\text{all } t) = 44 \pm 8 \mu\text{b}$$

$$\sigma (|t'| \leq .5) \approx 15 \mu\text{b}$$

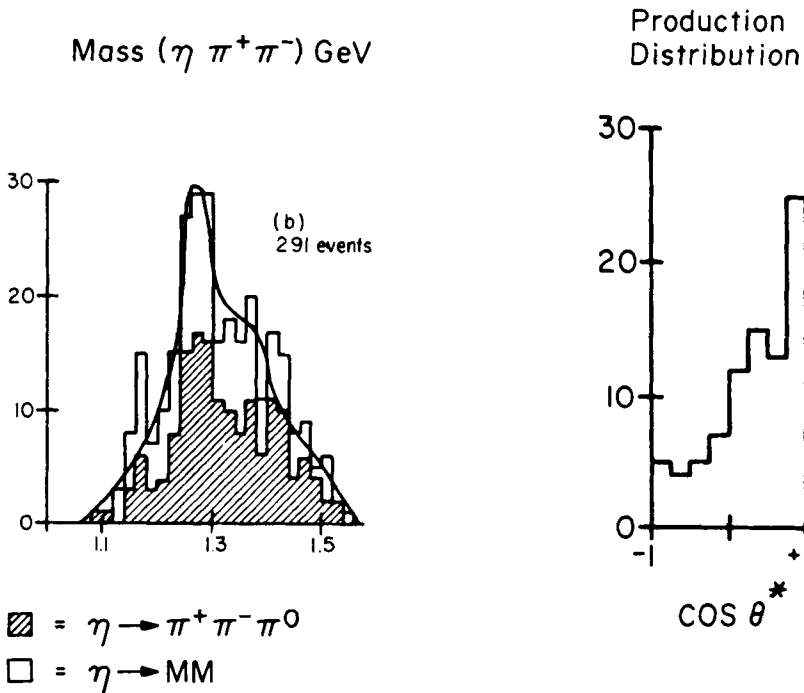


Fig. 15:  $\pi^+ n \rightarrow (D \rightarrow \pi \delta) p$  at 2.7 GeV/c (Ref. 55). See also Ref. 56 for  $\pi^- p \rightarrow D^0 n$  at 2.5 + 4.2 GeV/c in the less favorable decay mode  $D \rightarrow K \bar{K} \pi$ . This is discussed in Section 3.7(iii).

$\pi^-p \rightarrow D^0 n, \pi^+p \rightarrow D^0 \Delta^{++}$	
<u>Theory D</u> :	magic $\sigma \approx 30 \mu b$
	at 5 GeV/c octet $\approx 10 \mu b$
	singlet $\approx 20 \mu b$
<u>Expt</u> :	$\sigma \approx 16 \pm 6$ D $\rightarrow K \bar{K} \pi$ at 4 GeV/c $\approx 25 \pm 8$ D $\rightarrow \delta \pi$ at 8 GeV/c

$\pi^-p \rightarrow h^0 n, \pi^+p \rightarrow h^0 \Delta^{++}$	
<u>Theory h</u> :	magic $\sigma \approx 25 \mu b$
	at 5 GeV/c octet $\approx 8 \mu b$
	singlet $\approx 16 \mu b$
Controversial <u>Expt</u> $\sigma \approx 150 \mu b$ (4 GeV/c)	

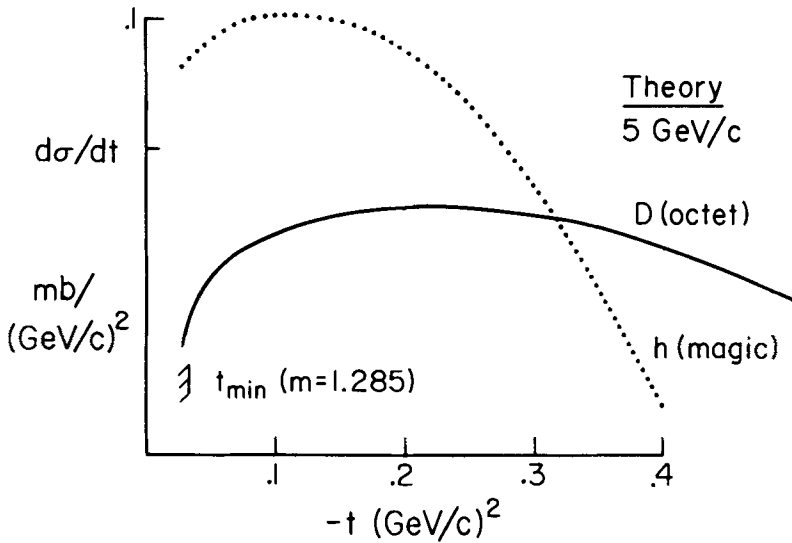


Fig. 16: h and D production at 5 GeV/c as discussed in Section 3.7(iii).  $t_{\min}$  is marked for the  $\pi^-p \rightarrow D^0 n$  reaction. D data is Refs. 56 & 57. h data is Ref. 59.



suggest that the small  $t$  cross-section will be 2 to 3 times smaller than the overall quoted value. Within this large uncertainty, theory is consistent with experiment.

There is no convincing data on  $h$  production. There is a controversial claim<sup>59</sup> at 4 GeV/c, i.e.,  $\sigma(\pi^+ p \rightarrow h^0 \Delta^{++}) = 150 \mu\text{b}$  which is greater than the "large" (in the sense of 3.1) reaction  $\pi^+ p \rightarrow B^+ p$  with  $\sigma = 100 \mu\text{b}$ . I can only ignore this  $h$  cross-section which seems unreasonably large. Theoretically the difficulty with the  $h$  may simply be a large width ( $M(h) \approx M(B)$  implies  $\Gamma(h \rightarrow \pi\rho) = 330 \text{ MeV}$  - see Table II) and/or background from  $A_1^0$  and  $A_2^0$  which have the same decay. The  $h'$  - which if magically mixed would, like the  $\phi$  and  $f'$ , be produced only in  $K^- p$  reactions (Fig. 11(I)) - may decay into  $\bar{K}K^*$  and be narrower and cleaner than the  $h$ . It is important to look for this meson in those reactions which claim an  $f'$ ; it could well have similar mass/decay modes/production mechanism and so be confused with the  $2^+ f'$ .



From the theory of 3.1, we expect these to be very favorable channels and fortunately this is borne out by experiment. The  $B^-$  is particularly satisfactory as it has no competing resonances in its  $\pi^- \omega^0$  decay mode. The data<sup>60,61</sup> shown in Fig. 17 shows a clear  $B$  with large and amazingly flat cross-sections; even at 5 GeV/c only 1/3 of the cross-section is within  $0 \lesssim |t'| \lesssim .5 (\text{GeV}/c)^2$ . For this cut we have an experimental<sup>61</sup> value of  $8.5 \mu\text{b}$  compared with the theoretical estimate  $9 \mu\text{b}$ . We have no test at 3 GeV/c because the  $t$ -dependence of the  $B^-$  cross-section<sup>60</sup> has yet to be published.

The  $A_1^-$  data<sup>62</sup>, shown in Fig. 18, is much less clear - the presence of an  $A_2^-$  with the same decay produces too much background. Theoretically we expect a cross-section  $K^- n \rightarrow A_1^- (\rightarrow \rho^0 \pi^-) \Lambda$  of  $8 \mu\text{b}$  for the .5  $t$ -cut. Experimentally the mass-cut  $1.1 < M(\rho^0 \pi^-) < 1.3 \text{ GeV}$  contains  $14 \mu\text{b}$  on integration over all  $t$ .

### 3.8: $\phi_N$ (1680)

This was to have been a cosmic overview<sup>63</sup> on the production of yet higher mass mesons and baryons. However, being completely exhausted, I just note two pleasing examples, first, as described in the appendix, the best established of such resonances is the  $3^- g$  which has an, as usual, large  $\pi$ -exchange cross-section. Now consider the  $\omega$ -like member of this nonet which, somewhat curiously, is entitled the  $\phi_N(1680)$ . This is produced in  $\pi^+ n \rightarrow \phi_N^+ p$  by  $B$  and  $\rho$  exchange. We estimate the former by our super  $\pi$ - $B$  corrected EXD trick as

$$\pi^+ n \rightarrow \phi_N^+ p = (\pi^+ n \rightarrow \omega^0 p) \frac{\pi^+ n \rightarrow g^0 p}{\pi^+ n \rightarrow \rho^0 p} \quad (24)$$

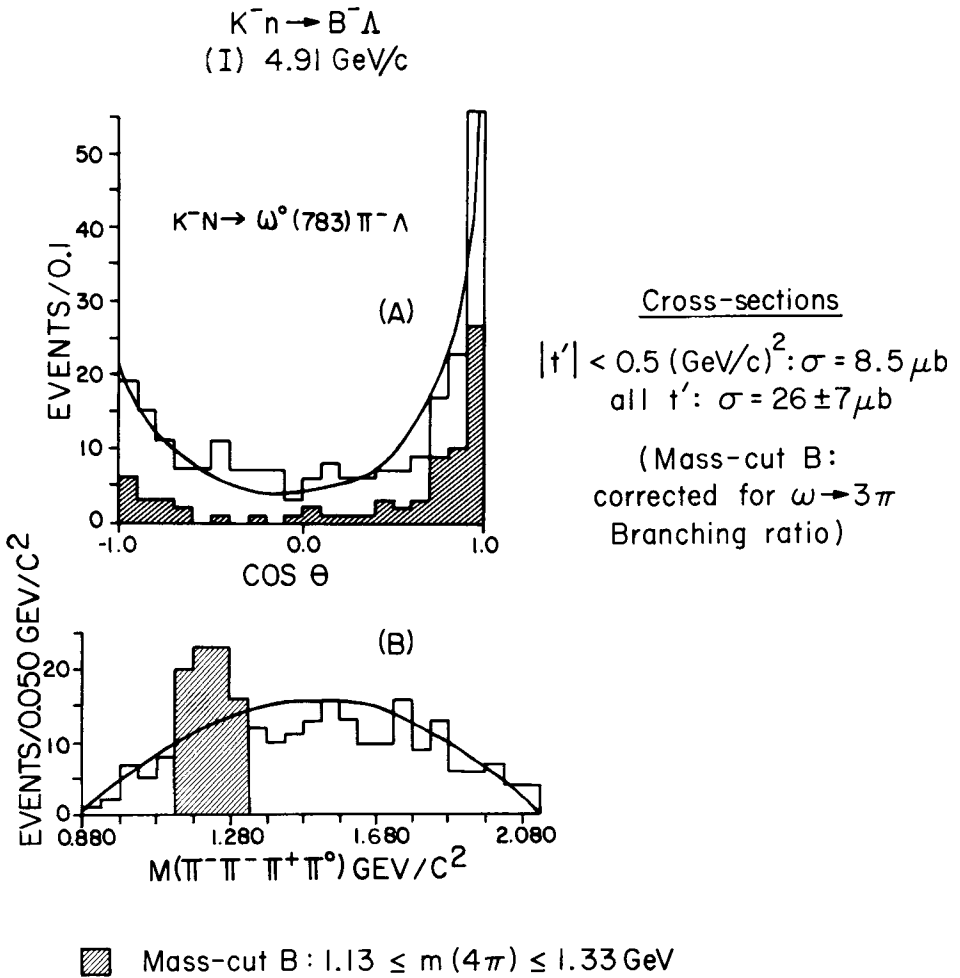
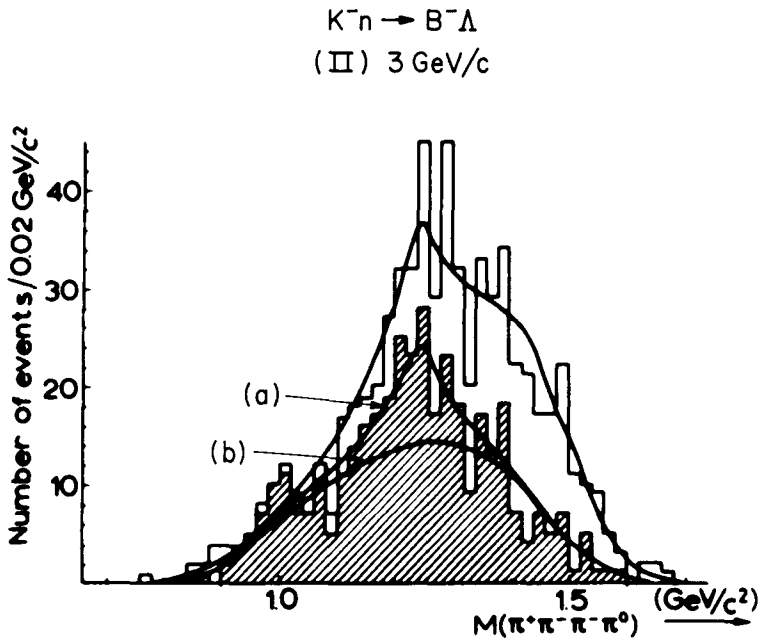


Fig. 17(I):  $K^-n \rightarrow B^- \Lambda$  at 4.91 GeV/c (Ref. 61). (A)  $\cos\theta$  production; (B)  $4\pi$  mass distribution. Both plots select the  $\omega$  region:  $.74 \leq m(\pi^+\pi^-\pi^0) \leq .84 \text{ GeV}$ . This is discussed in Section 3.7(iv).



□ : total  $K^-n \rightarrow \Lambda \pi^+ \pi^- \pi^- \pi^0$

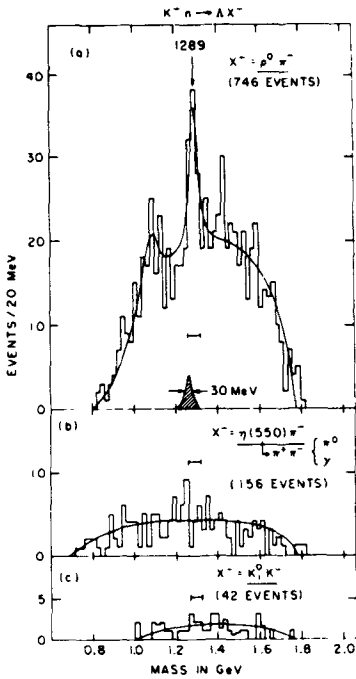
▨ :  $\omega$  selection :  $.72 \leq m(\pi^+ \pi^- \pi^0) \leq .86$  GeV

(a) Cosmic fit to ▨ including B

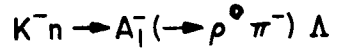
(b) Non-B part of (a)

Cross-section :  $\sigma(K^-n \rightarrow B^- \Lambda) = 94 \pm 25 \mu\text{b}$

Fig. 17(II):  $K^-n \rightarrow B^- \Lambda$  at 3 GeV/c (Ref. 60). The curves are from minimum unlikelihood fits including many resonances and background. No information was published on the t-dependence of the cross-section. This is discussed in Section 3.7(iv).



3.9 GeV/c



Expt:  $\sigma \approx 14 \mu\text{b}$  for  $1.1 < m[\rho\pi] < 1.3 \text{ GeV}$

Theory:  $\sigma \approx 8 \mu\text{b}$

FIG. 2. (a)  $\rho^0\pi^-$  mass distribution with events in  $\Sigma(1385)^\pm$  region removed. A best fit to the data for two resonances and phase space is shown in the solid curve. Mass resolution in the " $A_2$ " region is shown in the hatched area. (b)  $\eta(550)\pi^-$  mass distribution with events in the  $\Sigma(1385)^\pm$  region removed. The curve shows phase space. (c)  $K^-K_1^0$  mass distribution. The curve again shows phase space.

Fig. 18:  $K^- n \rightarrow A_1^- \Lambda$  at 3.9 GeV/c from Ref. 62. This is discussed in Section 3.7(iv).

(24) is easy to test because all four reactions were measured in the same experiment<sup>64-67</sup>. We should apply it to  $d\sigma/dt$  separately for each  $t$  value. However, as  $g$  and  $\rho$  have the same ( $\pi$ -exchange)  $t$ -dependence, it is sufficient to note that the  $\phi_N$  and  $\omega$  are observed experimentally<sup>64</sup> to have the same shape for  $d\sigma/dt$  (in agreement with (24) and check the overall normalization. This can be done using the production cross-sections in Table III plus the branching ratio<sup>3</sup>

$$\Gamma(g \rightarrow \pi^+ \pi^-) = .4 \Gamma_{\text{tot}}(g)$$

and a fifty percent increase in the  $g$  cross-section to take account of the non-zero  $t_{\text{min}}$  suppressing  $g$  relative to  $\rho$  production.

Table III: 6.95 GeV/c  $\pi^+ n$  Cross-sections

Final State	Cross-section $\mu\text{b}$	Reference
$\phi_N(1680) (\rightarrow \pi^+ \pi^- \pi^0)p$	$33.5 \pm 9$	64
$g^0 (\rightarrow \pi^+ \pi^-)p$	$39 \pm 9$	65
$\omega^0 (\rightarrow \text{all})p$	$86.4 \pm 12.8$	66
$\rho^0 p$	$380 \pm 80$	67

(24) then predicts  $\sigma[\pi^+ n \rightarrow \phi_N(1680)p] = 33 \mu\text{b}$  compared to the experimental value<sup>64</sup> for the  $\pi^+ \pi^- \pi^0$  decay mode of  $33.5 \pm 9 \mu\text{b}$ . As this is probably the dominant decay, theory and experiment are in very satisfactory agreement.

Actually we cheated somewhat as (24) should only be used for the B-part of the  $\omega$  and  $\phi_N$  cross-sections. However, we save such caveats for later<sup>63</sup>.

#### 4: Conclusions

These can be summarized as follows:

(i) B nonet is alive and well; the  $SU_3$  estimates are all consistent; the B itself is clearly seen in  $K^- n \rightarrow B^- \Lambda$ ,  $\pi^+ p \rightarrow B^+ p$ .

(ii)  $A_1$  nonet is alive; its parameters may change; the  $SU_3$  estimates are again consistent for non-diffractive processes. The only unambiguous observation of a member of the  $A_1$  nonet is in  $\pi^- p \rightarrow Q_{A_1}^0 \Lambda$ . However, in this reaction, one could still assign the sighted Q to the B nonet.

Diffractive data prefers broad  $A_1$ ?

(iii) Cross-section's are suppressed: the small non-flip amplitude observed in these reactions is a challenge to theory. Kislinger's <sup>10</sup> generalized photon-vector exchange analogy agrees with current experiment.

(iv) How do other higher resonance (meson/baryon) cross-sections behave? One could speculate that one may estimate any resonance production as follows:

- a)  $\pi$ -exchange: use pole extrapolation - must work!
- b) B-exchange: "corrected EXD", e.g., equation (24) and section 2.4 - worked very well for  $\phi_N(1680)$ .
- c) V, T-exchange: calculate pole extrapolation (section 2.1) prediction and only take spin-flip part. Worked roughly for  $A_1$ ,  $A_2$  and B nonets.

These empirical rules should be useful in deciding if a proposed experiment is of sufficient sensitivity to see a given resonance. A rule for diffraction scattering (the only omission above) awaits understanding of the lack of resonance structure in the current  $3\pi$  analysis <sup>42</sup>.

(v) " $e^{i\delta}$  v.  $e^{i\delta} \sin \delta$ " Production (section 2.2): What are true experimental systematics of resonance signal v. background in various domains: Breit-Wigner fits are wrong in  $e^{i\delta}$  processes, e.g., diffraction scattering.

(vi) Compile Data: The discussion in section 3 was rendered unnecessarily ambiguous by purely technical differences in resonance definition, t-cuts, etc. It is essential, if such studies are ever to be made quantitative, to record data in a form that a uniform treatment of several different experiments may be made after the original analysis is published. This is true for both bubble chamber data and future spectrometer data.

(vii) Cross-sections good for spectrometers: Any spectrometer/streamer chamber/triggered bubble chamber which can detect three or more particle decays ( $K^* \pi$ ,  $\pi\rho$ ,  $\omega\pi$ ,  $\eta\pi\dots$ ) should be able to collect high statistics on, say, the  $1^+$  mesons. The predicted cross-sections are recorded in Figs. 9-12. Values for other higher resonances can be estimated as in (iv) - they should be of comparable size but the background will, of course, be larger.

### Acknowledgments

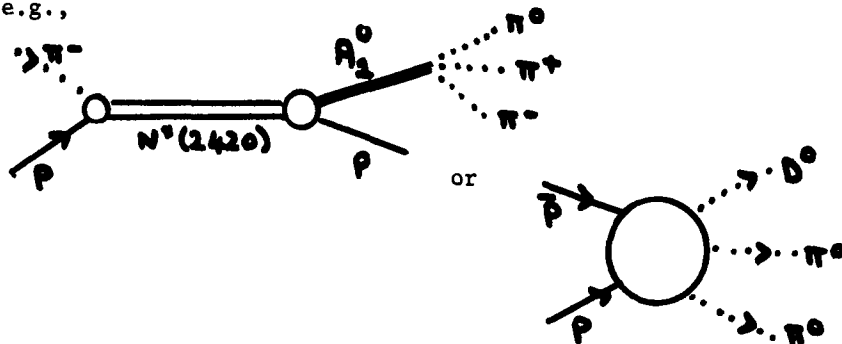
I would like to thank Tony Hey and Mark Kislinger for discussions on the vector-photon analogy; K. W. Lai and H. A. Gordon for an invaluable DST; Alex Firestone for general guidance and help in processing the DST; finally, I am grateful to J. Loos for debates on charge exchange Q production.

APPENDIX: Classification of Production Mechanism

Meson resonances can be produced in many different kinematic or dynamic regions. Specifically:

(A) Direct Channel

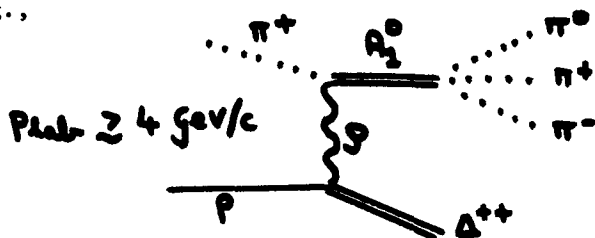
e.g.,



The  $\bar{p}p$  annihilation data is, at present, perhaps the most convincing evidence <sup>3</sup> for the D and C mesons and hence of the whole  $A_1$  nonet. However, the low incident momentum (giving the desired high cross-section) produces large background rendering it difficult both to see broad resonances and/or disentangle more than one state at a given mass by a detailed partial wave analysis. Further, I don't know of any useful conclusions as to the production mechanisms <sup>68</sup> so...

(B) High-energy Peripheral Production

e.g.,

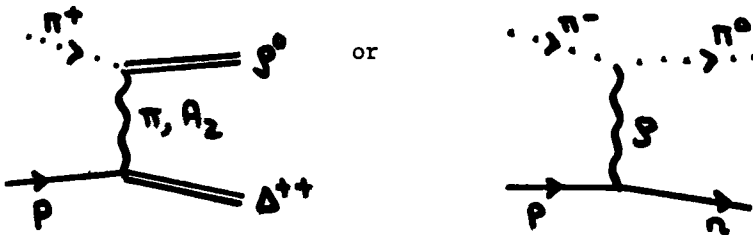


This type of reaction has the following advantages:

- Resonances are cleanly produced with a background that (usually) decreases as energy increases.
- Even if a resonance is not obvious in the mass spectrum one can do a partial analysis (of the  $\pi^+\pi^-\pi^0$  system in the above diagram) to isolate the resonance.
- The many new spectrometers should produce plenty of data of this type in the near future.
- One can study the production mechanism ( $\rho$  exchange in the above diagram) using the (Regge) folklore gleaned from the study of similar exchanges in simpler reactions (e.g.,  $\pi^-p \rightarrow \pi^0n$ ). Thus, we can divide (B) into.....

(B<sub>1</sub>) Production of Well-loved Particles

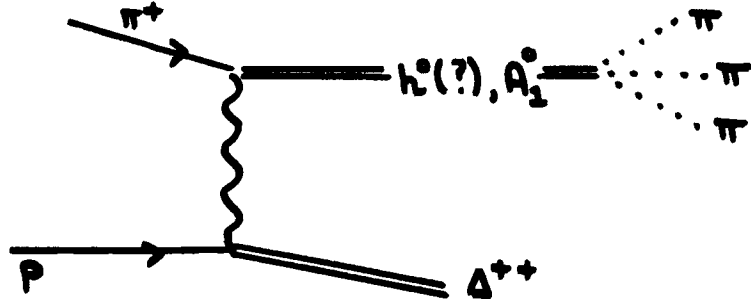
e.g.,



In these reactions the properties of produced states (mass, spin, parity...) are relatively well-known and  $d\sigma/dt$ , d.m.e. (density matrix element) data is very important for understanding dynamics of production mechanisms but not for studying the resonances themselves.

(B<sub>2</sub>) Production of Controversial Particles

e.g.,



In this review, I use the lessons from studying the production mechanisms of (B<sub>1</sub>) to systematize and predict the, at present, inconsistent and haphazardly measured cross-sections for the production of controversial particles. When I started this review, I thought that the main virtue of this study would be:

a) Theoretical estimates of the size and nature of production mechanism can either suggest good reactions to study a particular resonance or decide whether a given claim was plausible by relating different observed cross-sections.

However, it had two further virtues.

b) The small size of the production cross-sections of the  $1^+$  nonets provides an important constraint on theories.

c) The same small size explains why it has been so hard to discover the  $1^+$  mesons in peripheral processes and shows that the current data provides no evidence against the existence of these states - so beloved of the quark model. As we shall see in section 3, there is, of course, little evidence for the same resonances. However, it is nice that the best hints for their production are in precisely those reactions the theory predicts to be most favorable, i.e., the "large"



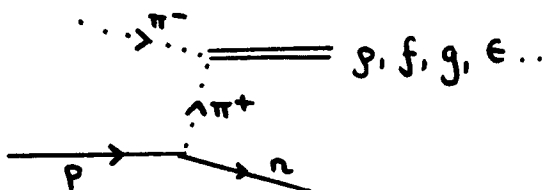
(see 3.1) exchanges  $[\pi^+ p \rightarrow B^+ p, \pi^- p \rightarrow Q^0 \Lambda, K^- n \rightarrow (A_1, B) \Lambda]$ .

Finally we cannot only divide reactions according to the status of the produced resonance but also according to the nature of the exchanges.

$E_\pi$  :  $\pi$ -exchange  


---

 e.g.,



$\pi$ -exchange processes have the following two characteristics:

a) The sizes of cross-sections are both easy to estimate from the residue at the nearby  $\pi$ -pole and typically large in absolute value. For instance, at 5 GeV/c, we have  $\sigma(\pi^- p \rightarrow \rho^0 n, f^0 n, \epsilon^0 n) \approx 1, .5$  and  $.2$  mb respectively.

b) Again as demonstrated, both experimentally and theoretically in section 2.2,  $\pi$ -exchange processes are certain to exhibit, for small  $t$ , clean " $e^{i\delta} \sin \delta$ " resonance production with the minimal background problems.

The high cross-section and clean production makes it quite obvious why the best established high mass bosons (i.e., the  $g(1680)$  and  $K_N(1760)$ <sup>3, 71</sup> of spin  $3^-$ ) are seen in  $\pi$ -exchange processes (see section 3.8).

g) The dynamics of the production mechanism is very interesting but I have reviewed it quite recently. The main features - good agreement at small  $-t$  with the zero parameter poor man's absorption model,  $P_{lab}^{-2}$  scaling at large  $-t$  - cannot be re-evaluated until the beautiful data from the new spectrometers on  $\pi^- p \rightarrow \pi^+ \pi^- n$  has been analyzed<sup>72</sup>.

$E_{ND}$  Non-diffractive Meson (not  $\pi$ ) exchange.

These processes are the subject of this review. Typically they are described in the Regge language by the exchange of  $\rho, K^* \dots, A_2, K^{**} \dots, B, Q_B \dots$  nonets of vector, tensor and axial mesons. Compared with  $E_\pi$  processes

a) Their cross-sections are typically  $10 \rightarrow 100$  times smaller (i.e., from  $5 \mu\text{b}$  for  $K^- p \rightarrow \bar{Q}^0 n$  to  $80 \mu\text{b}$  for the largest<sup>40</sup>  $(\pi^\pm p \rightarrow A^\pm p)$  at 5 GeV/c).

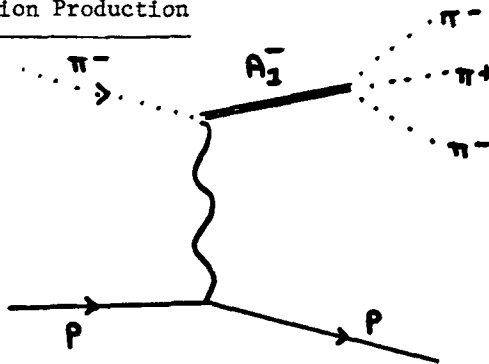
b) It is not known whether in the terminology of section 2.2, they have clean  $e^{i\delta} \sin \delta$  or the difficult  $e^{i\delta}$  production.

c) The small cross-sections implies that essentially no useful data is available for such processes except for the very first excited states. So as described in the introduction, we can only discuss the

$L = 1$  quark states. (See Table I for details.) Let us remember the poor knowledge of  $\pi$ -exchange resonances in the higher quark multiplets where the conditions of observation are perhaps a factor of 10 better). We realize that one cannot seriously have expected current data to tell us any reliable information on either violation of the quark model systematics or confirmation of the  $L \geq 2$  states, for non  $\pi$ -exchange resonances. An interesting exception to this rule - the B exchange  $\phi_N(1680)$  - is discussed in section 3.8.

$E_D$  Diffraction Production

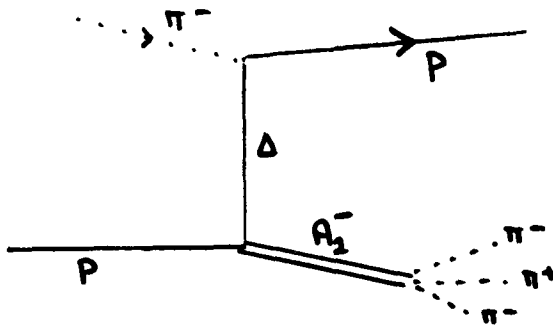
e.g.,



I will only discuss such processes to the extent that my final state interaction fantasy, of 2.2, predicts such reactions will have more "background" than non-diffractive resonance production experiments.

$E_B$  Baryon-Exchange

e.g.,



This is an interesting set of reactions but our very poor understanding of baryon exchange even in the "simple" reactions  $\pi N \rightarrow N\pi$ , 73 precludes any non-trivial prediction. Recent work by Alex Firestone on the  $K^+$  world DST suggests comparable cross-sections for backward  $K^+p \rightarrow pK^+$  and  $K^+p \rightarrow pQ^+$  of around  $5 \mu\text{b}$ . Combining this with the suppression of the forward non-diffractive Q production leads to the curious circumstance of comparable cross-sections for forward and backward charge exchange Q reactions. Of course, this lack of suppression of the backward Q cross-section is expected in Kislinger's

model<sup>10</sup> where the photon analogy only constrains the forward data.

Thus there is both theoretical and experimental<sup>73,74</sup> evidence that backward scattering will be a fruitful field for studying the higher meson resonances.

## REFERENCES AND FOOTNOTES

1. This parable had a sad ending.....On his return, fellow scientists greeted our hero with the primeval cry. "Good to see you - glad to know you - have you been away?" Breathlessly our hero told of his terrible journey but of its beautiful results. Before he could finish, their voices rose. "Hero! Just the man - you can teach our children to dig the sand. You're just the man - and build the castles high." Then, as one, the children rushed upon our hero, trampling his precious load which, crumpled and useless, was carried away in tears of sadness and waves of neglect.....I can only hope this article will persuade people that a detailed search for small cross-section resonances is likely to be rewarding; otherwise the  $A_1$ ,  $B$ ,  $h...$  (and who knows whatever higher particles?) will lie buried forever in the sands of disillusionment.
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9. I would have called this fantasy a theory, but the latter is traditionally reserved for formalisms that disagree with experiment.
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- current theory would predict that the latter phases vary much less rapidly than a resonant sub-energy phase. Hence, we derive the rule stated in the text.
15. Of course, there is a resonance pole on the "second sheet" which will lead to some peaking when  $\delta = 90\dots$
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  20. The difficulty with extrapolation reported in section 3 does not affect this conclusion. In the model of Kislinger the resonance production amplitude in the physical region is still proportional to the pole amplitude; there is just an extra factor of  $t$  which spoils formula (1) but not the  $e^{i\delta} \sin \delta$  nature of the production.
  21. "f-f' dominance of the Pomeron" would relate the diffractive processes to an exchange diagram. This would then imply  $e^{i\delta} \sin \delta$  production for diffractive reactions. However, (see Gilman, this conference) this theory has other discrepancies with experiment and it is not yet clear this is a serious difficulty.
  22. The argument is not quite complete as, for instance, the  $\Delta(1234)$  is below threshold for  $\rho N \rightarrow \pi N$ . It is sufficient to use the (qualitative) quark model connection between  $\rho N \rightarrow \pi N$  and  $\pi N \rightarrow \pi N$  to decide that  $\Delta(1234)$  is indeed " $e^{i\delta} \sin \delta$ " in  $\rho N \rightarrow \pi N$ .
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40. A nicety:  $\pi^\pm p \rightarrow A_2^\pm p$  is bigger than both  $\pi^\pm p \rightarrow B^\pm p$  and the combination  $\pi N \rightarrow A_2 N$  ( $I = 0$  part) defined in (17).
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$$\begin{aligned} \sigma &= 7 \pm 2 \mu\text{b} & : & P_{\text{lab}} = 2.5 \rightarrow 2.63 \\ & 10 \pm 4 \mu\text{b} & : & P_{\text{lab}} = 2.9 \rightarrow 3.3 \\ & 17 \pm 5 \mu\text{b} & : & P_{\text{lab}} = 3.8 \rightarrow 4.2 \end{aligned}$$

$d\sigma/d\Omega$  is consistent with Fig. 15.

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