Precocious Scaling and Duality in Lepton Scattering at Large Momentum Transfers and in Electron-Positron Annihilation

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ABSTRACT

We present a reformulation of the quark-parton model which can accommodate quark confinement. Using duality rules familiar from hadronic interactions, we show that precocious scaling is a consequence of exchange degeneracy and that the Bloom-Gilman relation is related to a duality between resonances and the pomeron. In all reactions, precocious scaling is only as good as the valence quark approximation. For x sufficiently near one, we expect precocious scaling to hold for certain reactions, such as $\ell N \to \ell' X$ (where ℓ, ℓ' are leptons and N a nucleon), and $e^- e^+ \to h^c X$ (where h^c is any charged hadron). We predict that precocious scaling will not hold, not even for x near one, in some reactions, such as $e^- e^+ \to h^0 X$ (where h^0 is any non-strange neutral meson $(\pi^0, \eta, \omega, \phi)$).

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In this brief presentation, I will sketch some ideas about duality and precocious scaling in deep inelastic electroproduction and electron-positron annihilation. This work was done in collaboration with Geoffrey Fox and a lengthy account may be found in a preprint[1] to appear shortly. There are two main points I wish to make in this lecture: (1) The quark-parton model can be reformulated in a way which can accommodate both Bjorken scaling and quark confinement. (2) Precocious scaling is a consequence of exchange degeneracy and the dominance of valence quarks. Because of the limitations of time, I shall omit the usual flourish into motivation and justification for the picture I shall describe.

Consider the process of deep inelastic scattering of lepton ℓ off a hadron h, $\ell h \rightarrow \ell' X$ (Fig. 1). As is common to parton models, we assume the coupling of the electromagnetic current can be represented as a pointlike coupling to quarks. Because only hadrons are produced in the laboratory, both quarks must interact and be confined, in some unknown way.[2] This is in contrast to the usual model based on the handbag diagram and alluded to in the preceding lecture by Polkinghorne. While a beautiful prototype for scaling, it is impossible to interpret the handbag as having relevance for purely hadronic final states. Twist and turn as you like, the handbag leads to final states with quarks.

It is useful to describe this process in a Lorentz frame used by Feynman[4] in his development of the parton model. We choose the hadron and photon momenta along the z axis, represented as

$$p = \left(P + \frac{M^2}{2P}, \underset{\sim}{0}, P\right)$$

$$q = (0, \underset{\sim}{0}, -2xP)$$

The conventional kinematical invariants ν and q^2 are then given by $\nu \equiv p \cdot q = 2xP^2$, $q^2 = -4x^2P^2$. In the physical region of electroproduction, we have $0 < x < 1$.

We parameterize the quark momenta as

$$k_j = (E_j, \underset{\sim}{K}_j, -x_j P),$$

$$k_j - q = [E_j, \underset{\sim}{K}_j, (2x - x_j)P]$$

where we will consider the contribution to the loop integral coming from $E_j > 0$. (There is another equally important contribution for $E_j < 0$.) We assume that the quarks behave as if they had finite masses

$$m_j^2 \equiv k_j^2, \quad \mu_j^2 = (k_j - q)^2.$$

It then follows that, for large ν,

$$x_j = x + \frac{\mu_j^2 - m_j^2}{2\nu} .$$

We also assume, as is common to parton models, that the transverse momentum is also damped so the dominant contribution comes from finite values of $\underset{\sim}{K}_j^2$. Then the energy may be written as

$$E_j \approx xP + \frac{2\underset{\sim}{K}_j^2 + m_j^2 + \mu_j^2}{4xP} .$$

We then see that the interaction of the quarks with the hadrons may be regarded as the process quark + hadron → quark + anything in the Breit frame. (Figure 2). We shall be interested in the Bjorken limit for this inclusive amplitude, which is $\nu \to \infty$ for fixed x. We find that the energy is $s_j = (p + k_j)^2 \approx 2\nu$, and the momentum transfer between the incoming and outcoming quark is $u_j = [k_j - (k_j - q)]^2 = q^2 = -x\, s_j$. The momentum transfer t_j between the incoming hadron and outgoing quark remains finite:

$$t_j = m^2(1-x) - \frac{\underset{\sim}{K}_j^2 + \mu_j^2(1-x)}{x}$$

where m is the mass of the hadron. We recognize this as the fragmentation limit for the inclusive reaction and x may be identified with Feynman's x, the fraction of longitudinal momentum carried by the fragment. As Mueller originally showed, this limit may be regarded as a Regge limit of a discontinuity of the three-to-three scattering amplitude obtained by squaring and summing over all final states X. (Figure 3). [One small difference here from the application in hadron scattering is that we must deal with the non-forward three-to-three amplitude.] Therefore, in the Bjorken limit, the leading singularities in the quark-antiquark channel, $t_{12} = (k_1 - k_2)^2 \approx -(\underset{\sim}{K}_1 - \underset{\sim}{K}_2)^2$, will control the asymptotic behavior.[5] For notational simplicity, we will assume the leading singularities are poles, but the result may be easily generalized to allow branch points. The asymptotic behavior is then given by (Fig. 3)

$$W_6^{++} \xrightarrow{Bj} \beta_{\alpha_a}(t_{12})\, f_{\alpha_a}(x; \underset{\sim}{K}_1^2, \underset{\sim}{K}_2^2, t_{12})(2x\nu)^{\alpha_a(t_{12})}$$

where we have suppressed the dependence on the masses m_j^2, μ_j^2 $(j = 1, 2)$. If $\alpha_a(0) = 1$, then integrating over the invariant masses and momenta, we find scaling (up to logarithms)

$$\nu W_2(\nu, q^2) \xrightarrow{Bj} \sum_i e_i^2 F_2^i(x).$$

Note that we get exact scaling if and only if the leading singularity is a fixed pole at one. What is the dominant singularity in the quark-antiquark channel? We have no certain answer, but will tentatively identify it with the pomeron. If so, then Bjorken scaling in electro-production and Feynman scaling in hadron production are related in this intimate way: They both are determined by the precise nature of diffraction.

There is a technical point concerning the integral over the invariant masses which concerns whether you can deform the contour of integration to infinity, so that the result above is multiplied by zero, i.e., the asymptotic behavior is not really a Regge limit, a point which has been argued by proponents of the handbag diagram.[6] We haven't time to discuss this here, but we would like to say that there appear to us to be inconsistencies in both the handbag approach and our approach. In the first case, quarks get out. In the latter case, the analyticity of the theory is so distorted that it may well conflict with locality and microcausality.

Consider the behavior of the scaling function as $x \to 0$. Just as in hadron physics, we pass from the fragmentation to the pionization limit (Fig. 4). It is easy to see that, if the leading singularities have $\alpha_b(0)=1$ and $1/2$, then

$$F_2(x) \xrightarrow{x \to 0} f_P + f_R\sqrt{x},$$

up to logarithmic corrections. One immediate offshoot of this formulation of the parton model is the recognition that the pionization limit may be approached more generally. For example, we may consider the limit $\nu \to \infty$ for fixed $q^2/\sqrt{\nu}$. We again find scaling

$$\nu W_2 \to f_P + O(\nu^{-1/4})$$

but we haven't time to discuss this here.

Consider next the behavior as $x \to 1$. This is the so-called triple-Regge limit of the inclusive amplitude, in which the leading singularities come from the t_j channel (Fig. 5). If the leading singularity has intercept α, we find

$$F_2(x) \to (1-x)^{1-2\alpha}$$

up to logs. For the proton, the t_j channel is a diquark exchange. For the pion, it corresponds to an antiquark channel. We regard the values of the intercept α as not given by the model, although the association with elementary quark exchange is tempting.

Another application is at finite missing mass. For example, among the contributions to the missing mass x are the hadron pole and resonances. The asymptotic behavior of the elastic and transition form factors are also given by a Regge limit (Fig. 6).

$$F_2(q^2) \to (-q^2)^{\alpha-1}$$

where α is the same intercept appearing in the behavior as $x \to 1$. This relation between the falloff of the form factors and behavior of the scaling function as $x \to 1$ is called the Drell-Yan-West relation.[7]

The approach to scaling is also specified in this model since, in addition to the pomeron, mesonic Regge poles couple to the quark-antiquark channel. Thus,

$$\nu W_2(\nu, q^2) \xrightarrow{Bj} F_2(x) + F_2^R(x)(2x\nu)^{-0.5} ,$$

where we have assumed the intercepts of the f^0, ρ, ω and A_2 have the common value one-half. An interesting aspect of this model is that in addition to diagonal contributions where the quarks k_1 and k_2 are the same, there are equally important non-diagonal terms. The product of the charges for such a term as depicted in Fig. 7a is negative,

$\left(\frac{2}{3}\right)\left(-\frac{1}{3}\right) = -\frac{2}{9}$. In addition, there may be contributions due to the strange exchanges K^*, K^{**} (Fig. 7b) whose intercept of about 0.3 lies not far below the leading Regge poles.

It has been observed at SLAC that the onset of scaling is rapid, setting in already for $-q^2 \approx 1$ or $2\ \mathrm{GeV}^2$. This phenomenon, called precocious scaling, would appear to conflict with the approach described above. However, there is precedence in hadron physics for the non-occurrence of the secondary Regge poles for certain reactions. This cancellation among secondaries in the discontinuity of the two-body amplitude is called exchange degeneracy (EXD) and is believed to be the reason for the relatively rapid approach to asymptotic of the K^+p and pp total cross sections, compared to others such as $\pi^{\pm}p$, K^-p, $\bar{p}p$. Precocious scaling suggests that the Regge poles are EXD and cancel out in the case of the nucleon. Whether this would occur for all hadrons is a dynamical question to be discussed further below.

Another piece of phenomenology we want to mention is the Bloom-Gilman (BG) relation,[8] which is the statement that, in some average sense, baryon resonances contribute to the scaling function. This is a statement about the relation between finite missing mass and large missing mass. We have seen, that, for fixed missing mass, the large q^2 behavior is a Regge limit corresponding, in the case of the nucleon, to diquark exchange. Suppose the leading contribution can be thought of as the exchange of two quarks. Then, in the formalism described here, the BG relation corresponds to the statement that in three quark scattering, resonances are dual to the pomeron in the quark-antiquark crossed channel (Fig. 8). This is necessary, if the resonances couple at all, since we interpreted precocious scaling as the absence of Regge poles.

To proceed further requires a model for EXD and, perhaps, also for the pomeron. The logical framework suggested above stands regardless of whether the following model for EXD is correct. In hadron physics, the pattern of EXD had been explained by Lipkin[9] in the context of the additive quark model even before the invention of duality diagrams. Regarding the dominant contribution to hadron elastic scattering as due to the elastic scattering of valence quarks in pairs, Lipkin suggested that, in the absence of isosinglet quark-antiquark annihilation in the direct channel, no Reggeons contribute to the imaginary part (Fig. 9). This rule which we will call the Annihilation Rule, explains the entire pattern of EXD for two-body hadron collisions. Both the additivity and annihilation rules were later incorporated into duality diagrams and explain the resonance-Regge pole duality of meson-meson and meson-baryon scattering. This correspondence between direct-channel resonances and cross-channel Reggeons is a consequence of the underlying quark dynamics and is not applicable, for example, to the baryon-antibaryon channel[10] nor, it would seem, to pomeron-hadron scattering.[11]

Some immediate implications of the Annihilation Rule are that quark-quark scattering (e.g., uu, ud, dd) is exchange degenerate. In addition, annihilation such as $u\bar{d}$ or $u\bar{s}$, not being isosinglets, will also be EXD. This implies, e.g., that f^0, ρ, ω, A_2 all make equal couplings to quarks and cancel each other in these channels. However, in $u\bar{u}$ or $d\bar{d}$ annihilation, they add constructively and such isosinglet channels will not be EXD.

Turning to electroproduction off a nucleon, we have seen that for x near one, we are concerned with three quark scattering. Clearly, by the Annihilation Rule, this is EXD. Hence, the Annihilation Rule implies precocious scaling and hence, the Bloom-Gilman relation follows. Suppose we could do electroproduction with a pion target. For a π^+, for example, for x near one, the dominant contribution will come from $u\bar{d}$ scattering (Fig. 10a) for which EXD holds. A similar analysis holds for the crossed reactions $e^-e^+ \to \pi^{\pm} X$ and, hence, we predict precocious scaling for charged pion production (for x near one). For the π^0, however, where we are concerned with $u\bar{u}$ or $d\bar{d}$ annihilation, EXD will not hold. Hence, we predict $e^-e^+ \to \pi^0 X$ will not manifest precocious scaling (Fig. 10b). More generally, whenever the missing mass can be an isosinglet, we do not expect precocious scaling to hold. Examples include $e^-e^+ \to h^0 X$ where $h^0 = \pi^0, \eta, \omega, \phi$. It is interesting that neutral channels should approach asymptopia at a different rate than charged channels. (Neutral kaons, however, will scale precociously since this does not allow an isosinglet missing mass.) Naively, one would expect nucleon production, $e^-e^+ \rightarrow NX$ to scale precociously; however, our experience in hadron production (e.g., $pp \rightarrow \bar{p}X$ at the ISR) leads us to exercise caution because of possible threshold effects. An example would be that electroproduction from iron should rapidly approach asymptopia, but $e^-e^+ \rightarrow Fe\ X$ may not. Whether the threshold effect is like a step function or more persistant (as in $pp \rightarrow \bar{p}X$) is a topic for further study.

The next important point concerns the behavior as x moves away from one. In the preceding discussion, the valence quark model arose as the dominance of certain exchanges over lower-lying singularities. For the pion, for example, single quark exchange dominates over the exchange of two quarks and an antiquark (Fig. 11) or a quark-Reggeon cut. For x near zero, there is no reason for such dominance to occur. Indeed, in the limit $x \rightarrow 0$, the exchanges in the hadron-antihadron channel dominate and the hadron-quark channel becomes irrelevant. Two observations occur to me: (1) It is interesting in itself how the valence quark model arises; dominant exchanges suggests a different theoretical point of view toward the validity of the valence quark approximation. (2) The appearance of fragmentation into non-valence quarks should be accompanied by a breakdown in precocious scaling. The precise range of x over which the approximation should hold is a detailed dynamical question which, at this point, is probably best answered by looking at experiments. The neutrino data[12] from Gargamelle[14] (Fig. 12) suggests that non-valence quarks appear in nucleons only for $x \lesssim 0.3$.

The annihilation data[13] from SPEAR (Fig. 13) indicates that, as expected, precocious scaling holds for x near one for the production of a charged particle, $e^- e^+ \to h^c X$. (Probably, 90 percent of the charged particles produced are pions.) However, we see that, for $0.1 \leq x \leq 0.5$, the cross section is rising. In this model, the deviations from precocious scaling would be associated with the occurrence of non-valence quarks.

The total electron-positron annihilation cross section σ^{-+}_{tot} is simply discussed in this model (Fig. 14a), being related to the asymptotic behavior of the total cross section for quark-antiquark elastic scattering. Since we deal with an isosinglet annihilation channel, we do not expect precocious scaling to hold. If the quark-antiquark scattering amplitude is strongly damped in the transverse momentum, then the limit $Q^2 \to \infty$ is a Regge limit, whose asymptotic value is determined by pomeron plus Reggeon and diquark exchanges (Fig. 14b). The ratio R to $\mu^- \mu^+$ production behaves as

$$R = C_{\mathbb{P}} + C_R (Q^2)^{-0.5} + C_S (Q^2)^{-0.7} + C_S' (Q^2)^{-0.9} + \ldots$$

The asymptotic value C_P is not the value obtained from the canonical free field singularity, but is modified by the strength of absorption.

The next term C_R is due to the f^0, ρ, ω, and A_2; next, C_S, to K^*, K^{**}; next, C'_S, to ϕ, f' exchanges. (As before, we assume that diquark exchange has intercept below zero.)

Over what scale of energy should asymptopia be reached? Unfortunately, we have little to say about this question, which depends on the relative strength of quark couplings to the pomeron and Reggeons. Experience from hadron physics suggests that, in a scale of 1 GeV^2, $C_{\mathbb{P}}$ and C_R will be comparable. Compare, for example, the asymptotic behavior of the proton-antiproton to the proton-proton total cross section. Here, the electric charges must be included and, in addition, there are off-diagonal terms, leading e.g., to charged ρ and K^* exchange, which don't occur in hadron total cross sections. A second question, related to the first, is what is the sign of the secondaries C_R, C_S, C_S'? Unlike hadronic total cross sections, we have no Harari-Freund two-component model to suggest that secondaries are positive. Indeed, if there were such an argument, it would be disasterous considering the <u>increase</u> shown by the data.[13]

Given the observed rapid rise in R, it is interesting to entertain possible enhancement mechanisms. Consider the coupling of reggeons to hadrons. In a model such as the additive quark model[9] or the multi-peripheral parton model,[14] the damping in momentum transfer of the reggeon coupling to hadrons is a direct reflection of the transverse momentum damping of the partons in a hadron. However, there is no reason why the coupling of a reggeon to the quarks themselves needs to be damped. A more pointlike coupling than exponential damping will lead to an enhancement of R, from $\ln Q^2$ for an elementary vector exchange to a factor of Q^2 for a pointlike four-quark interaction. The only reason we mention this possibility at all here is the curious fact that such a pointlike coupling will not alter scaling in electroproduction or in single-hadron inclusive annihilation. This is easily seen since, assuming the fragmentation of the hadron into quarks is strongly damped in $\underset{\sim}{K}_1^2$ and $\underset{\sim}{K}_2^2$, no further damping is required in $t_{12} \approx -(\underset{\sim}{K}_1 - \underset{\sim}{K}_2)^2$. There is, however, the dynamical question of whether a pointlike coupling to quark constituents could ever lead to a damped hadronic wave function. Whether this picture is self-consistent should be explored further.

There are a great many applications to be made of these ideas to other reactions, e.g., $e^- N \to e^- hX$, $e^- e^+ \to h_1 h_2 X$, $\nu N \to \mu^- hX$, $h_1 h_2 \to \mu^- \mu^+ X$, as well as to exclusive channels other than the form factor. The preceding was developed for scalar quarks, and we have found the generalization to spin one-half quarks is not so straightforward as it might seem. The duality rules will remain basically unchanged, but relations between different helicity amplitudes and form factors depends on the spin nature of reggeon and pomeron couplings. It is amusing that the exchange of elementary scalar quarks leads to the same rules as put forth by Brodsky and Farrar,[15] but this seems not to generalize to the spin one-half case.

As presently formulated, the model may be inconsistent with the basic axions of quantum field theory, i.e., the assumed inability to perform the usual contour rotation may conflict with the analyticity which follows from locality and microcausality. To proceed requires at least a model for confinement; perhaps the one recently developed by 't Hooft[16] will provide some insight.

At worst, the model provides an analogy which suggests a number of logical possibilities concerning our view of precocious scaling and duality which may be true in reality. It appears to provide an appealing alternative to the usual formulation[4,6] of the parton model in which quarks necessarily appear as final states. At best, the model suggests a deep connection between scaling in electromagnetic and weak processes and the precise nature of diffraction in hadron interactions. It further suggests that, if the parton model is realizable in a local quantum field theory with confinement, certain delicate analyticity conditions will have to obtain.

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I would like to thank Drs. G. Pocsik and I. Montvay for organizing this Symposium and for their warm hospitality during the meeting.

ADDENDUM

The SU_3 generalization of the Annihilation Rule would be that a channel would be exotic unless a quark and antiquark can annihilate to form, not just an isosinglet, but an SU_3 singlet. This would not alter the preceding analyses except in the case of $e^-e^+ \to$ hadrons. With the usual assignment, the photon transforms like a member of an octet, so that, in the limit of SU_3 symmetry, the quark-antiquark pair would not be in an SU_3 singlet state. This means that we would expect exchange degeneracy for the Reggeons, so that, the f^0, k^*, and ϕ would all have the same intercept, and the three terms C_R, C_S and C_S' (in the ratio R) would cancel each other, the ratio being $C_R:C_S:C_S' =$ 1:-2:1. It is difficult for me to believe that the observed energy dependence[13] is due to SU_3 breaking, so there are several possibilities to be considered: (1) The Annihilation Rule is incorrect, (2) This formulation of the quark-parton model is incorrect, (3) The analysis for timelike photons is, for some unknown reason, different from the analysis of spacelike photons, perhaps due to threshold effects, (4) some enhancement mechanism is operative in $e^-e^+ \to X$. I favor the latter two options over the first two, but I shall elaborate on these several possibilities elsewhere.

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FIGURE CAPTIONS

Fig. 1 Basic model for deep inelastic lepton scattering.

Fig. 2 quark + hadron → quark + hadron in the Breit frame.

Fig. 3 Asymptotic behavior of the process described in Fig. 2 as the Mueller-Regge limit of three-body scattering. The Bjorken limit corresponds to the fragmentation of the hadron into a quark.

Fig. 4 The behavior of fragmentation as $x \to 0$ is related to the "pionization" of quarks.

Fig. 5 The behavior of fragmentation as $x \to 1$ is related to a "triple-Regge" limit.

Fig. 6 The asymptotic behavior of the form factor is related to the Regge limit of backward quark-hadron elastic scattering.

Fig. 7 Some "non-diagonal" contributions to the leading Reggeon exchanges.

Fig. 8 Relation between the finite missing mass and large missing mass behavior. The Bloom-Gilman relation corresponds to hadron resonances contributing to the pomeron.

Fig. 9 Additive quark model for hadronic elastic scattering.

Fig. 10 Applications of the Annihilation Rule to pions:

(a) π^+ will be EXD and manifest precocious scaling.

(b) π^0 will not be EXD and will not rapidly scale.

Fig. 11 Non-valence quarks will break EXD and lead to deviations from precocious scaling.

Fig. 12 Model for $e^-e^+ \rightarrow$ hadrons:

(a) quark-antiquark annihilation to hadrons.

(b) asymptotic behavior of the imaginary part of quark-antiquark elastic scattering.

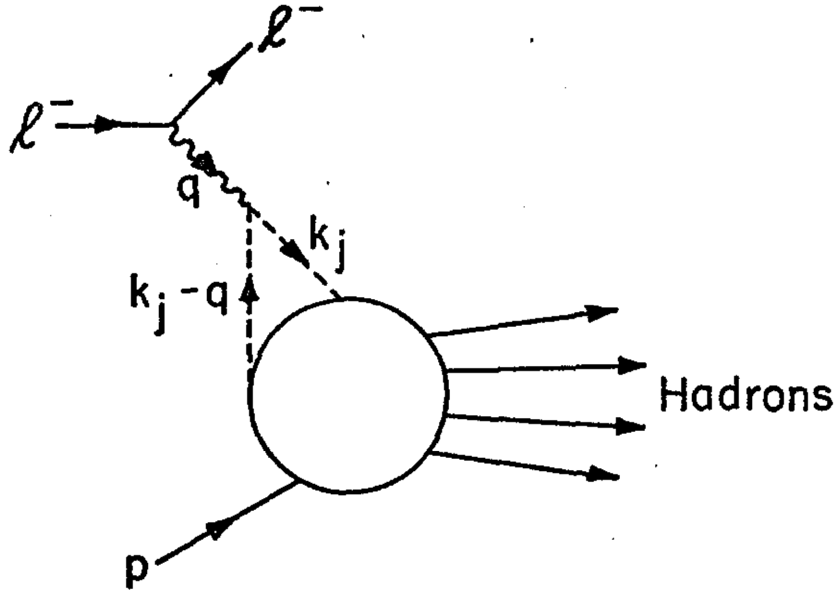


Fig. 1

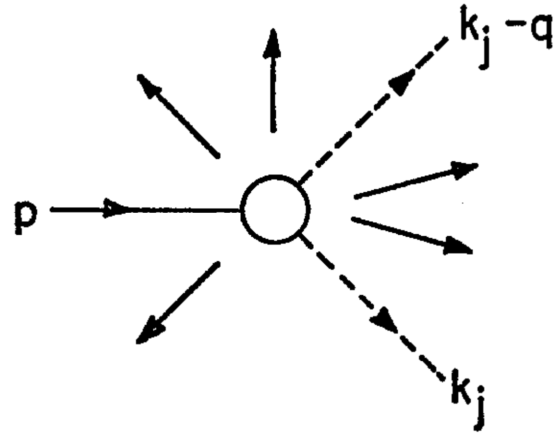


Figure 2

Fig. 3

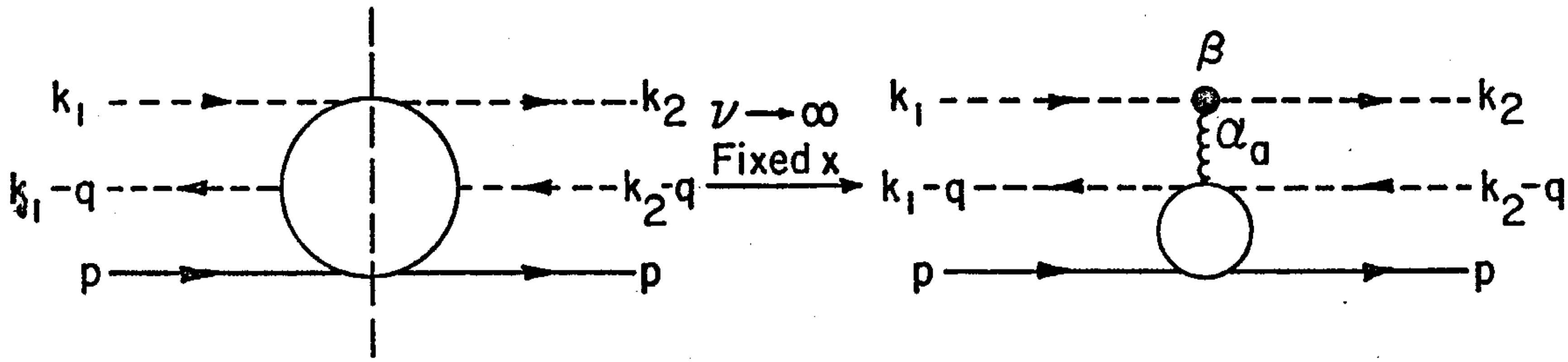
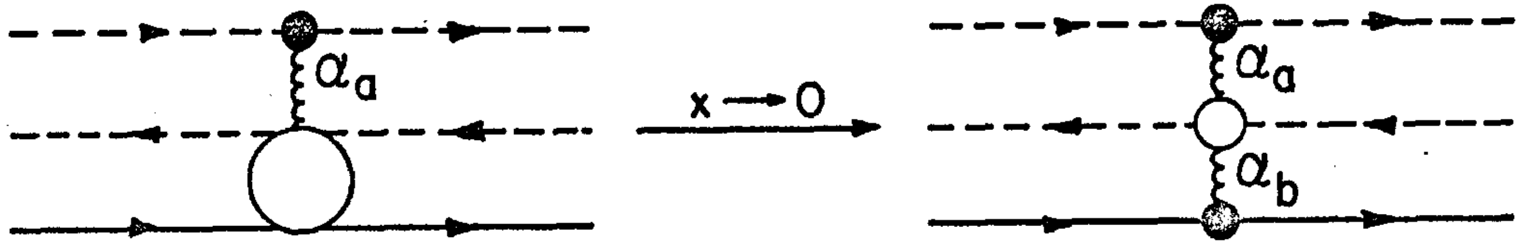


Fig. 3



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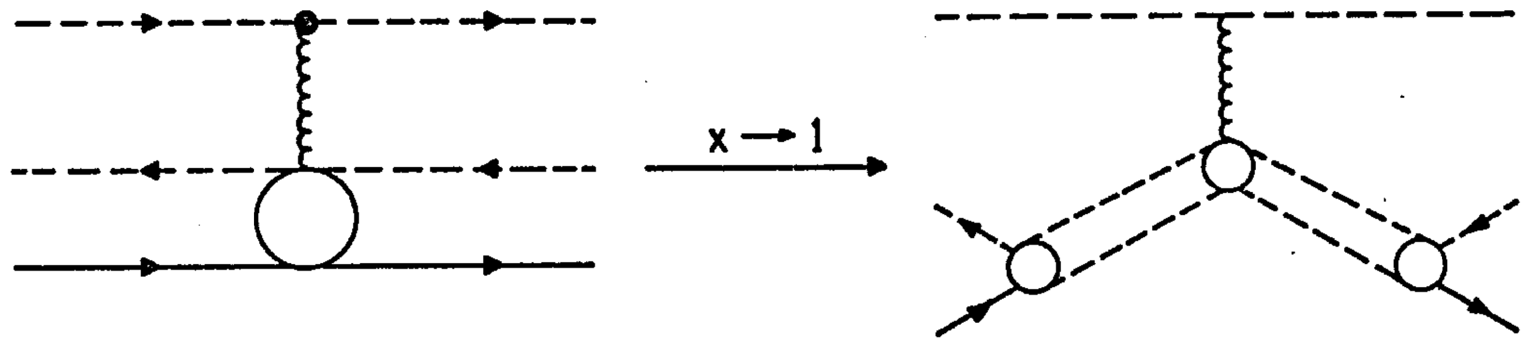

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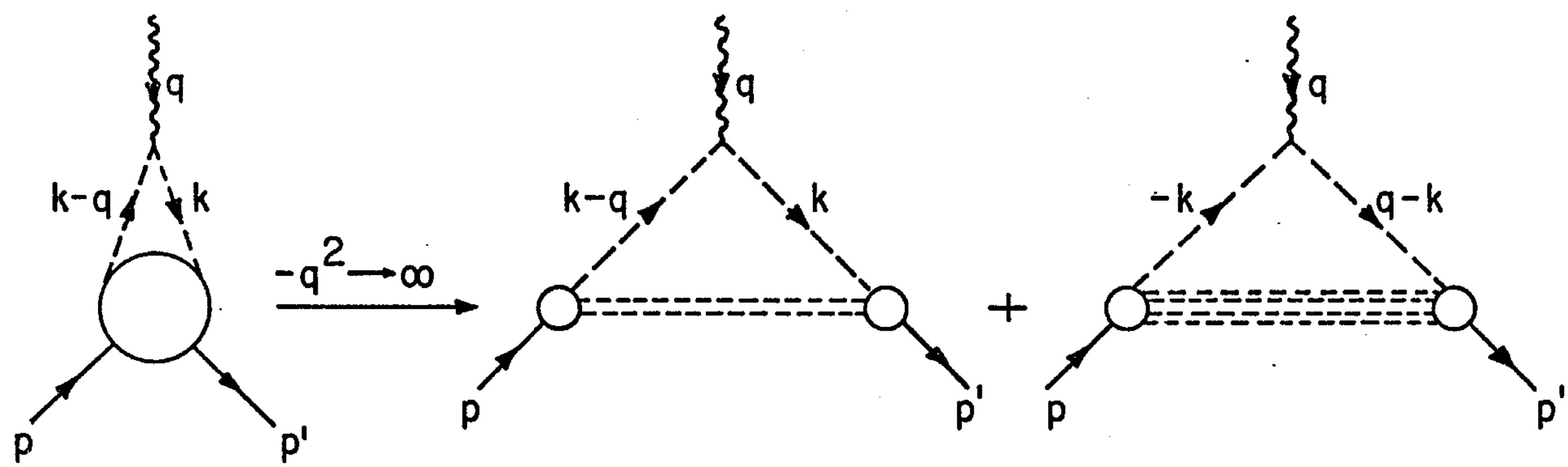

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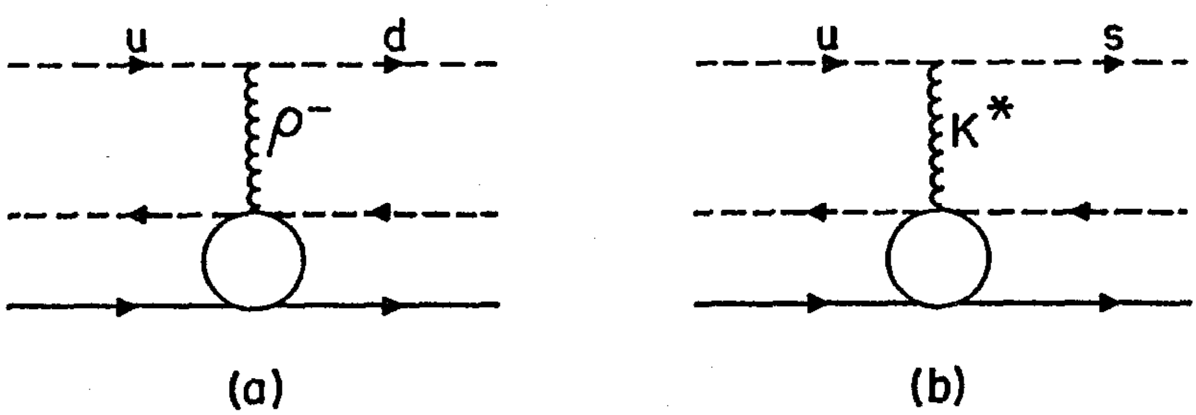


Figure 7

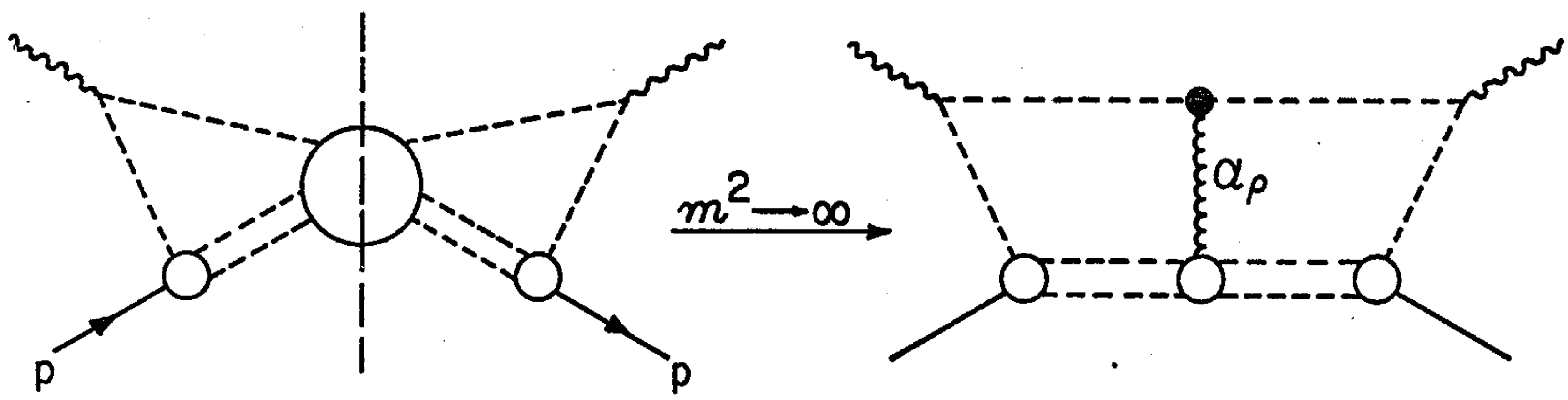
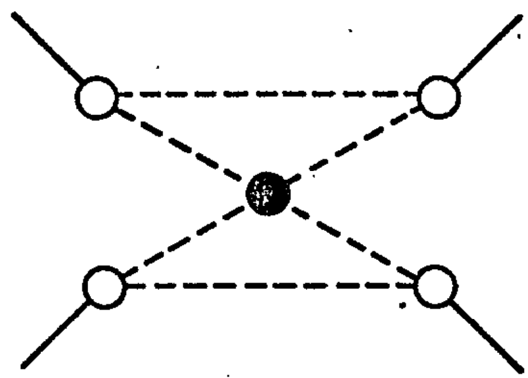
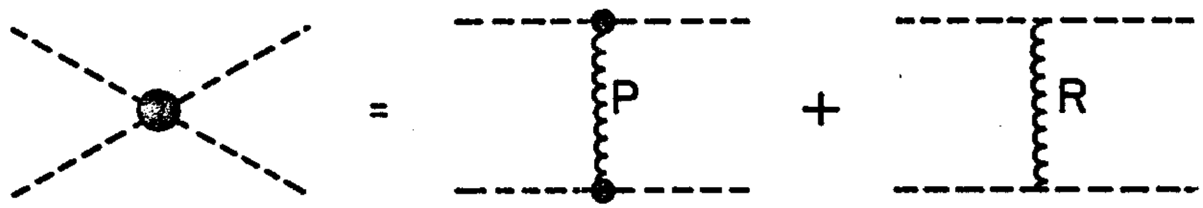


Fig. 8



(a)



(b)

Figure 9

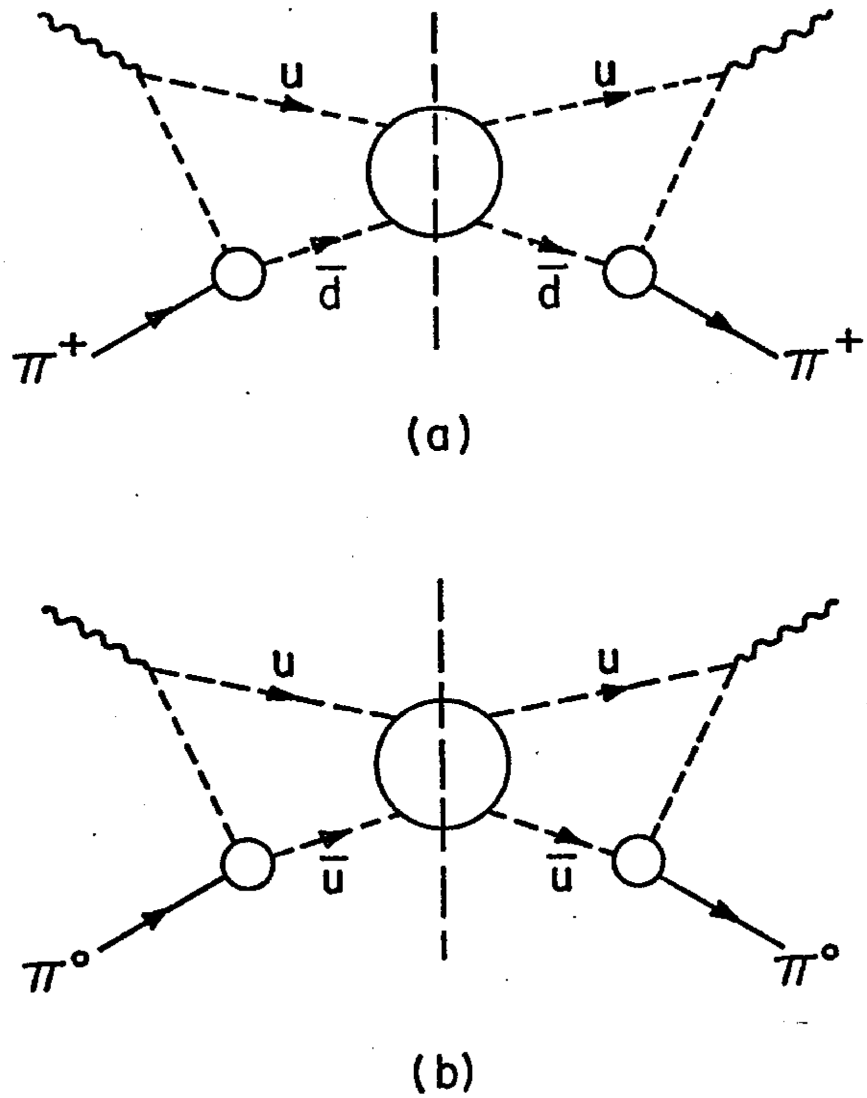


Figure 10

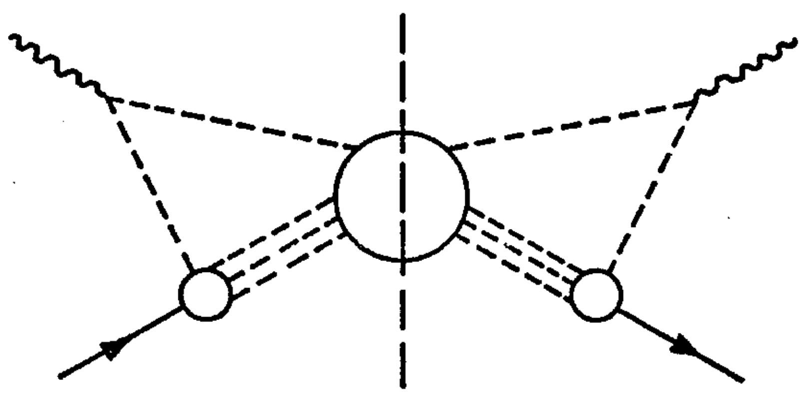


Fig. 11

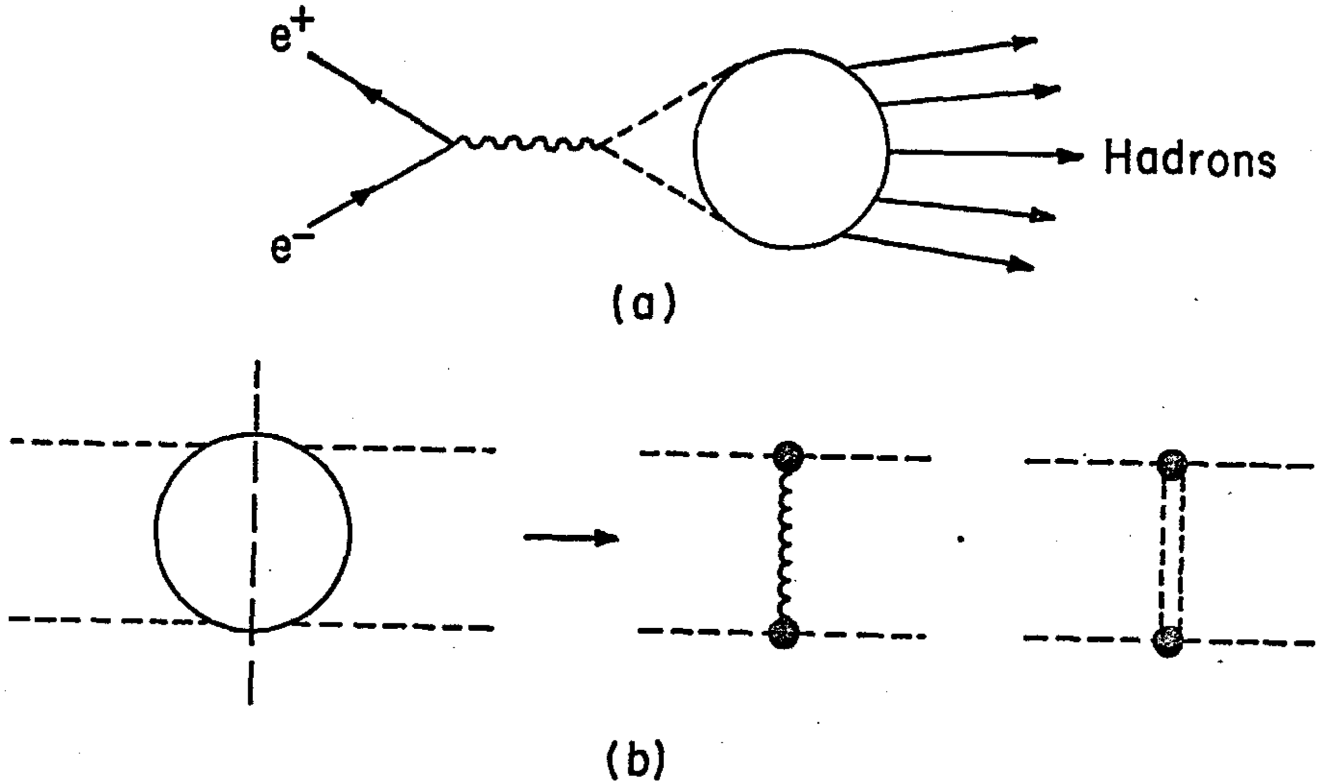


Fig. 12