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EVIDENCE THAT HADRONIC INTERIORS HAVE A DENSER MATTER THAN CHARGE DISTRIBUTION*

Hannu I. Miettinen
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Gerald H. Thomas
High Energy Physics Division
Argonne National Laboratory
Argonne, Illinois 60439

ABSTRACT

An analysis of high energy elastic and inelastic diffraction scattering provides strong evidence that the charge and matter densities of hadrons are different. When hadrons are treated as composite objects, then a correct Glauber analysis leads to an optical model with important corrections due to the hadronic wave function: One expects inelastic diffraction due to the fluctuations in the matter density of hadrons. Conversely, the experimental existence of dissociation processes gives phenomenological information about the hadronic wave function. We find the distribution of matter in nucleons to be denser than the observed charge distribution. This result has a natural interpretation from a constituent description of hadrons made from spin 1/2 quarks and colored vector gluons, which is a generalization of the Chou-Yang picture of diffraction scattering.

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I. INTRODUCTION

It is now commonplace to describe hadronic elastic scattering as a diffractive shadowing of two spatially extended objects. In such a picture one expects a sharply peaked angular distribution whose width is reflective of the sizes of the particles being scattered. Without a theory for hadronic internal structure, quantitative calculations are not yet possible. However, for processes such as nucleus-nucleus elastic scattering where the structure of the colliding objects is known, detailed calculations can be carried out and compared with data.[1] From these analyses one can hope to abstract those features which might be relevant to hadron scattering. Chou and Yang[2] proposed an optical model for elastic scattering based on these considerations. In this model, the colliding hadrons are pictured as two spatially extended Lorentz contracted balls of hadronic matter, which propagate through each other. During the passage, various inelastic interactions take place, and the elastic amplitude is built up as the shadow of these inelastic interactions. The elastic amplitude at impact parameter b is given by an eikonal formula:

$$t_{el}^{AB}(b) = 1 - e^{-\langle\Omega(b)\rangle_{AB}} . \tag{1}$$

The eikonal function $\langle\Omega(b)\rangle_{AB}$ is assumed to be proportional to the overlap of the average matter densities $\langle\rho_A(b)\rangle$ and $\langle\rho_B(b)\rangle$ of the incident particles:

$$\langle\Omega(b)\rangle_{AB} = K_{AB}\int d^2b' \langle\rho_A(\underset{\sim}{b}')\rangle\langle\rho_B(\underset{\sim}{b} - \underset{\sim}{b}')\rangle \quad . \tag{2}$$

It has been found that when one assumes the hadronic matter density is proportional to the charge density (as measured by elastic electron scattering), then a reasonable description of hadron elastic scattering data results.[3]

The optical picture, based as it is on only the average properties of the hadron structure, certainly has corrections. This article is concerned with the question of what corrections are necessary based on the experimental evidence of diffraction scattering, and on the currently popular view that hadrons are composed of quarks and gluons as described by the non-abelian gauge theory quantum chromodynamics. Now it has been known for a long time that, in a collision of two composite systems, if different configurations of the systems have different absorption strengths, then shadow scattering leads not only to elastic scattering, but also to excitation of inelastic states ("diffraction dissociation").[4] It is also known that such fluctuations in the absorption strength give rise to modifications to the elastic eikonal formula Eq.(1).[5] These inelastic shadowing effects have been extensively studied, experimentally as well as theoretically, especially in scattering from deuterium and from various other nuclei.[6] Recent experimental results on elastic proton-deuteron, deuteron-deuteron and proton-helium scattering provide detailed information about the properties of inelastic shadowing of hadrons in nuclei.[7]

What we show here is that corrections of the type discussed above due to fluctuations in the wave function are important in pp scattering. The magnitude of these fluctuations can be estimated from the total inelastic diffraction cross section. We find that the consequence of these fluctuations is to give a matter distribution as extracted from elastic pp scattering which is substantially different from the proton charge distribution measured in ep scattering. We study how this difference might come about in a gauge theory picture of hadrons composed of quarks and gluons. It turns out to be natural for the charge and matter distributions to differ.

The paper is organized as follows. In Sec.II the formalism for scattering extended objects is given which takes into account the fluctuations of the wave function. A simple parametrization to describe these fluctuations is chosen. Using this parametrization, the proton matter distribution is extracted from pp elastic scattering data. In Sec.III a QCD inspired picture of hadrons is presented. It is argued that a possible consequence of this picture is for matter to be more centrally distributed than charge.

II. ANALYSIS OF ELASTIC SCATTERING DATA

A. General Formalism

Let us first derive a generalization of Eq.(1) which includes fluctuations in the wave function. Consider a collision of two composite systems A and B. Label the configurations of A by i and those of B by j. Denote the probabilities for finding the system A in configuration i by P_i^A, and that for finding the system B in configuration j by P_j^B. In the eikonal approximation at impact parameter b, the elastic amplitude for a collision of the two systems in configurations i and j respectively is

$$t^{ij}(b) = 1 - e^{-\Omega_{ij}(b)} . \tag{3}$$

The full elastic amplitude is obtained by averaging over the configurations of the colliding systems:

$$\begin{aligned} t_{el}^{AB}(b) &= \sum_{ij} P_i^A P_j^B t^{ij}(b) \\ &= 1 - \langle e^{-\Omega(b)} \rangle_{AB} . \end{aligned} \tag{4}$$

This generalization to Eq.(1) has observable consequences, which can be illuminated by writing Eq.(4) as

$$t_{el}^{AB}(b) = 1 - e^{-\langle \Omega(b) \rangle_{AB}} H_{AB}(b) , \tag{5}$$

so that the corrections to the usual formula are contained in

$$H_{AB}(b) = \sum_{k=0}^{\infty} \frac{(-)^k}{k!} \mu_k^{AB}(b) \tag{6}$$

$$\mu_k^{AB}(b) = \left\langle \left(\Omega(b) - \langle \Omega(b) \rangle_{AB} \right)^k \right\rangle_{AB} . \tag{7}$$

Now the moments of the eikonal spectrum μ_k^{AB} are related to physical processes. For example, the diffraction dissociation cross section is[8]

$$\sigma_{diff}^{AB}(b) = \frac{1}{2}\left[\langle t^2(b)\rangle_{AB} - \langle t(b)\rangle_{AB}^2\right] \tag{8}$$

which can also be written in terms of the moments $\mu_k^{AB}(b)$. To lowest order

$$\sigma_{diff}^{AB}(b) \simeq \frac{1}{2}\left[\langle \Omega^2(b)\rangle_{AB} - \langle \Omega(b)\rangle_{AB}^2\right] \simeq \frac{1}{2}\mu_2^{AB}(b) \tag{9}$$

showing that the first correction to Eq.(1) depends on the amount of inelastic diffraction.[9] It should also be noted that when there are no fluctuations $\left[\text{i.e. } \Omega(b) = \langle \Omega(b)\rangle_{AB}\right]$ then $H_{AB}(b) = 1$ so there are no corrections to Eq.(1).

The observable consequences of the fluctuations can be demonstrated by comparing Eq.(5) to that without fluctuations, Eq.(1).

B. Specific Parametrization

In order to use Eq.(4), we need to know the eikonal spectrum $\Omega_{ij}(b)$. One may attempt to calculate this spectrum from a model for the hadron structure and for the constituent interactions. Such an analysis was pursued in Ref.(10). All of the essential points of this paper can be made by choosing a simple parametrization for the eikonal spectrum. A constraint on this parametrization is that it must give the observed size of the inelastic diffractive cross-section. For the present purpose we parametrize the fluctuations by a single parameter.

We intend to extract from data the average $\langle\Omega(b)\rangle$ which is determined by the average matter distribution. Conversely, knowledge of $\langle\Omega(b)\rangle$ for pp scattering will give the average matter distribution of the proton. A parametrization which has this unknown function plus one additional parameter to describe inelastic diffraction is obtained as follows.[11] One can always write Eq. (4) as

$$t_{el}^{AB}(b) = \int_0^\infty d\Omega\ P_{AB}(\Omega, b)\,(1 - e^{-\Omega}) \tag{10}$$

where $P_{AB}(\Omega, b)$ is determined by $P_i^A P_j^B$. We assume that $P_{AB}(\Omega, b)$ is a function only of the scaled variable

$$z = \Omega(b)/\langle\Omega(b)\rangle \tag{11}$$

and choose the simple form

$$P_{AB}(z) = N z^a e^{-\lambda z} \ . \tag{12}$$

Since $P_{AB}(z)$ is constrained by $\int dz\ P_{AB}(z) = \int dz\ z\,P_{AB}(z) = 1$, the constants N and a are determined:

$$\begin{aligned} N &= \lambda^\lambda/\Gamma(\lambda) \\ a &= \lambda - 1 \ . \end{aligned} \tag{13}$$

With these choices, the elastic amplitude can be computed analytically:

$$t_{el}^{AB}(b) = 1 - \left(1 + \frac{\langle\Omega(b)\rangle}{\lambda}\right)^{-\lambda} \tag{14}$$

It is immediately seen that for $\lambda \to \infty$ one recovers the no fluctuation result Eq. (1), and hence no inelastic diffraction.

We also calculate the total diffraction dissociation cross-section corresponding to our eikonal spectrum Eq. (12). This cross-section is obtained from Eq. (8):

$$\sigma_{diff}(b) = \left(1 + \frac{2\langle\Omega(b)\rangle}{\lambda}\right)^{-\lambda} - \left(1 + \frac{\langle\Omega(b)\rangle}{\lambda}\right)^{-2\lambda} . \tag{15}$$

This result can also be expressed directly in terms of $t_{e\ell}^{AB}(b)$ and λ by inverting Eq. (14) and by substituting the result into the above equation:

$$\sigma_{diff}(b) = \frac{1}{2}\left[\left\{2\left(1 - t_{el}^{AB}(b)\right)^{-\frac{1}{\lambda}} - 1\right\}^{-\lambda} - \left(1 - t_{el}^{AB}(b)\right)^{2}\right] . \tag{16}$$

The total diffraction dissociation cross section is obtained by integrating this equation.

To complete the model, following the idea of Chou and Yang we assume that when two hadrons collide in instantaneous configurations i and j, the eikonal function $\Omega_{ij}(b)$ is proportional to the matter overlap of the two configurations. This gives us immediately the result that

$$\langle\Omega(q)\rangle = K_{AB} G_H^A(q) G_H^B(q) \tag{17}$$

where $\langle\Omega(q)\rangle$ is the Fourier transform of the average eikonal, and $G_H^A(q)$ and $G_H^B(q)$ are the matter form factors of the colliding hadrons. These form factors are related to the matter distributions $\rho_H^A(r)$ and $\rho_H^B(r)$ by Fourier transformations:

$$G_H^i(q) = \int d^3\vec{r}\; e^{i\vec{q}\cdot\vec{r}} \rho_H^i(r) \;, \quad i = A,B. \tag{18}$$

We now have obtained a one parameter generalization to the optical picture which ignores fluctuations in the wave function. In the limit $\lambda \to \infty$ we recover the Chou-Yang model. In the limit $\lambda \to 0$ we obtain the extreme case where either the configurations are fully transparent or fully absorbed.[8] Here the amount of diffraction dissociation is maximal.

C. Data Analysis

Let us now work backwards from experimental data on proton-proton elastic scattering as follows: We first solve the elastic amplitude $t_{el}^{AB}(b)$ from data.[12] Using the values of this amplitude as input, we solve for the eikonal function $\langle \Omega(b) \rangle$ from Eq.(14) for various values of λ and calculate the corresponding total diffraction dissociation cross-section (Fig.1).

In high energy pp collisions, the measured total diffraction dissociation cross section is 5 – 8 mb, the same size as the elastic cross section.[13] The average eikonal $\langle \Omega(b) \rangle$ in Fig.1 corresponding to this amount of dissociation cross section is clearly distinguishable from the no fluctuation curve ($\sigma_{diff} = 0$), even though all correspond to the same elastic amplitude $t_{el}^{AB}(b)$.

Having determined the average eikonal $\langle \Omega(b) \rangle$ corresponding to a given amount of diffraction dissociation cross section, we can now obtain the resultant matter form factor from Eq.(17). In Fig.2a we show the matter form factors corresponding to $\sigma_{diff} = 6.4$ mb and $\sigma_{diff} = 4.4$ mb. For comparison we have also plotted experimental values of the proton's charge form factor,[14] together with the well-known dipole parametrization:

$$G_E^P(q^2) = \left(1 + q^2/(0.71\ \text{GeV}^2)\right)^{-2} . \tag{19}$$

In Fig.2b Fourier transforms of the matter form factors are shown. Also shown is the charge distribution corresponding to the dipole fit of Eq.(19). One sees that the matter and charge distributions are very different. While at large r these distributions fall off with roughly equal rates, at small r the matter density rises very steeply and exceeds the charge density at $r = 0$ by a factor of ten or more. A two exponential fit to the matter distributions, with the slope of one of the exponentials constrained to be the same as that of the charge density, gives an rms-radius of the steeper component of the matter distribution a value of 0.31 fm ($\sigma_{diff} = 4.4$ mb) or 0.28 fm ($\sigma_{diff} = 6.4$ mb).

While the quantitative results shown in Figs.1 and 2 obviously depend on our model for the eikonal spectrum, their qualitative features seem to us fairly model independent. We have examined several other parametrizations for the eikonal spectrum and found that the resulting matter distributions are similar to those of Fig.2b.

III. QCD INSPIRED PICTURE OF HADRONS

Let us turn to a possible interpretation of the above results in terms of quarks and gluons. A well known view[15] of hadrons is that they are composed of partons which have a flat rapidity distribution. In the center of mass of a high energy collision hadron A has its partons moving primarily to the left and B has its partons moving primarily to the right. From this, and the assumption that parton interactions have short range in rapidity, it follows that the collision occurs only between the wee partons of A and of B. Since wee partons initiate the soft processes which though unitarity build up the elastic amplitude, the matter distribution used in the eikonal formula must be that of the wee partons. By contrast, the charge distribution is governed by the valence partons which carry the net charge of the hadron, and do not participate directly in building up the elastic amplitude. It is then obvious that the charge and matter distributions can and should be quite different. To see how different we need a more detailed picture of the parton structure of hadrons.

To discuss the angular dependence of elastic scattering, the above one dimensional view needs to be generalized. Hadrons are not point objects but spatially extended objects with structure. One hope of QCD enthusiasts is that extended structures will be natural consequences of the gauge field theory. Though this has yet to be demonstrated, we will adopt a specific picture of hadrons which is plausible, and not too different from a bag or string picture.[16] For simplicity consider mesons; we imagine them to have a $q\bar{q}$ pair, which are the valence quarks, separated by some distance R. These quarks are the foci of a flux tube of color fields (gluons). The view is that the valence quarks are at the ends, and the intermediate region is filled more or less uniformly with glue (Fig.3).

Comparing this QCD picture with the parton model picture, we see that the valence partons which carry the charge and momentum are to be identified with the quarks at the ends of the tube, while the sea partons are to be identified with the glue contained in the tube. The transverse distribution of wee partons is not expected to be significantly different from that of the rest of the sea.[17]

In this picture, we expect the average matter distribution to have a steep central component compared to the charge distribution. Each configuration has matter distributed throughout the tube, whereas the charge is confined primarily to the ends, so that in doing the averages one expects more weight to be built up in the center for the matter than for the charge distribution. Such an argument depends, of course, on how each configuration is weighted, and this can be studied in models. One can also study to what extent this argument depends on the configurations being tube like.

A toy model can be easily constructed which illustrates the above ideas and their consequences. Our meson is modeled as a cylinder of vanishing radius a and varying length. The charge is located at the ends, and the neutral matter (glue) is distributed uniformly throughout the cylinder with a density ρ independent of the length $2R$ of the cylinder. The average matter density is then approximately

$$\rho(r) = \int d^3R\,|\Psi(R)|^2\theta(R-r)\theta(a-|r\sin\theta|) \tag{20}$$

up to a constant, where $\cos\theta = \underset{\sim}{R}\cdot\underset{\sim}{r}/Rr$, and $\Psi(R)$ is the wave function describing the amplitude for finding the valence quarks separated by a vector $\underset{\sim}{R}$. Since the valence quarks carry the charge, $|\Psi(R)|^2$ is the meson form factor; experimentally the Q^2 dependence is that of a monopole, which is

$$|\Psi(R)|^2 = \frac{e^{-R/R_0}}{R/R_0} \tag{21}$$

in coordinate space. Using this wave function, the density $\rho(r)$ can be analytically evaluated in the limit of small a:

$$\rho(r) = c\, e^{-r/R_0}\left\{\frac{1}{(r/R_0)^2} + \frac{1}{r/R_0}\right\} . \tag{22}$$

where c is a constant. The second term is proportional to the charge distribution; the first term is more singular as we expected. The matter distribution is more central since many more configurations have their centers overlapping than their ends. The comparison between charge and matter form factors is given in Fig.4.

There are obviously a number of important features left out of our toy model. The tube could have a width, and in QCD is expected to have one.[18] Also there may be configurations where the tube is more spherical than cylindrical, especially when the valence quarks are near each other. We have constructed simple models to take these effects into account and find the effect of including more three dimensional configurations is to increase the r.m.s. value of the matter distribution. This could have important consequences especially for baryons since one can imagine many more types of configurations than for mesons. Nevertheless it is still possible that the tube picture is at least approximately correct, even for baryons,[19] and could provide a basis for doing more detailed calculations.

Let us now consider elastic scattering in this QCD picture.[20] As emphasized, diffraction scattering depends on the average overall configurations. Since we have in mind a specific picture of which configurations are important we obtain some insight into the diffractive process. Now a configuration is labeled not only by a size and a shape, but also by a density of glue. There will be fluctuations in this density which give an important contribution to the inelastic diffraction cross section as has been argued previously.[10] What is new in our picture is that there also will be comparable contributions due to fluctuations in the size and shape.[21]

In this picture, the average eikonal will still be proportional to the overlap of the average matter distributions, which are estimated with the toy model. Since the matter distribution has a steep central component, so will the average eikonal. If this eikonal were used in the usual formula Eq.(1), then an incorrect elastic scattering amplitude would result. It is because of averaging over the fluctuations also for the elastic scattering amplitude that a consistent picture is possible. The importance of the fluctuations to elastic scattering is demonstrated by the large difference between our results and those which ignore such fluctuations. It is encouraging to see these large fluctuations can arise naturally in this QCD inspired picture of hadron structure. A serious test of those ideas would be to get a consistent phenomenological description of both elastic and inelastic diffraction data. This we have not yet attempted.

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21. We have studied the contribution to inelastic diffraction from the fluctuations in the size and shape and found some interesting results. This contribution is more peripheral than that from the density fluctuations, and likely to be concentrated to smaller masses. Several arguments suggest to us that diffractive resonance excitation is due to the size and shape fluctuations, and not to the density fluctuations.

FIGURE CAPTIONS

Fig.1. Eikonal functions deduced from proton-proton elastic scattering data at $\sqrt{s} = 53$ GeV (Ref.12). The curves are labeled by the corresponding total inelastic diffractive cross-section.

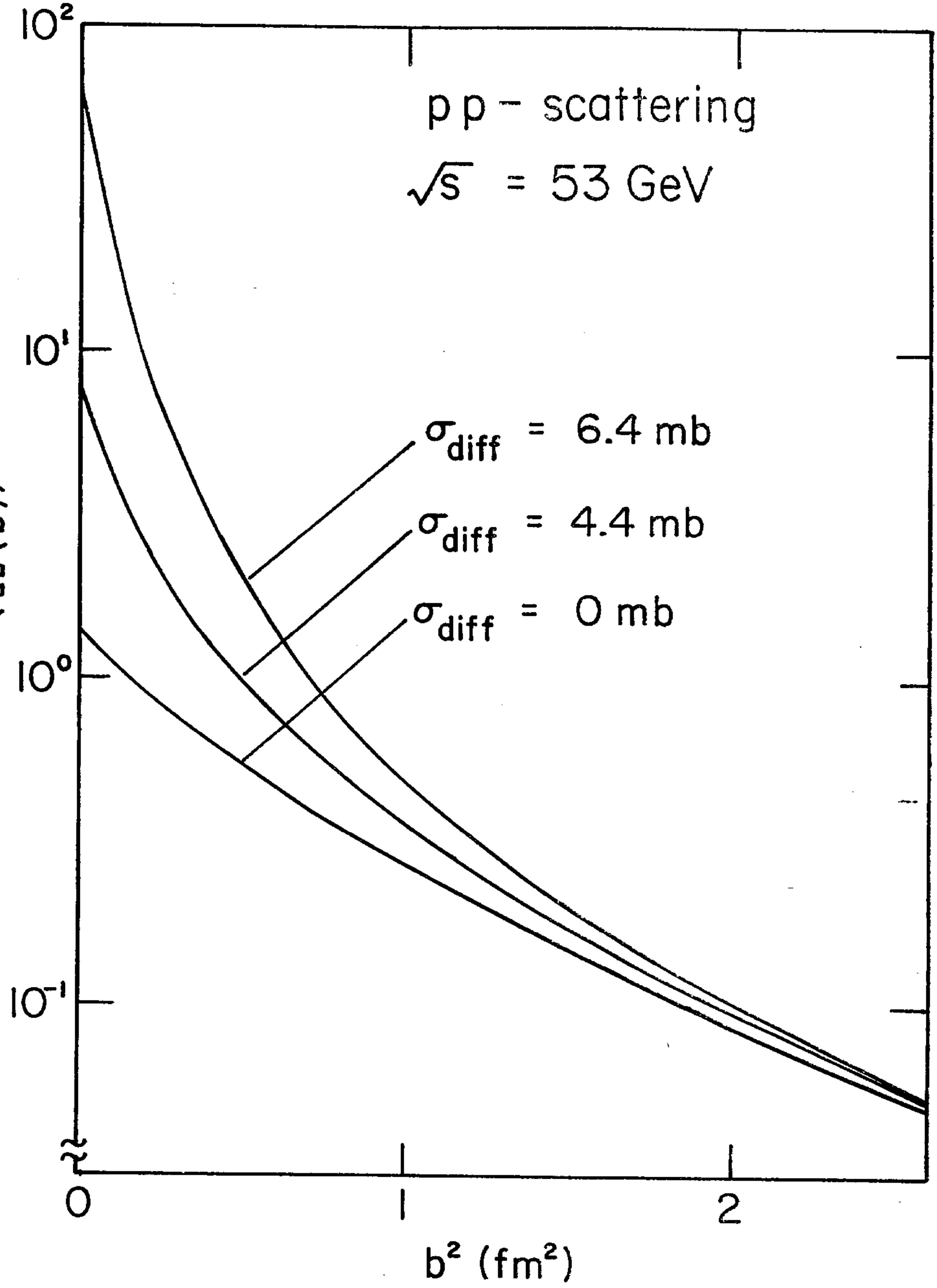
Fig.2. a) Proton's matter and charge form factors. The matter form factors $G_H^p(q^2)$ are obtained from the eikonal functions of Fig.1 through Eq.(17). The experimental data on the charge from factor $G_E^p(q^2)$ are from Ref.14.a(●), 14.b(□), 14.c(○) and 14.d(▲). The dipole parametrization Eq.(19) is also shown.

b) Proton's matter and charge distributions. The matter distributions $\rho_H^p(r)$ are obtained by Fourier transforming the matter form factor curves of Fig.2.a. The charge distribution corresponds to the dipole fit Eq.(19). All distributions are normalized to unity.

Fig.3. a-b) Two configurations of a meson, as seen in its rest frame. The valence quark and antiquark are the focii of a flux tube of color fields (gluons).

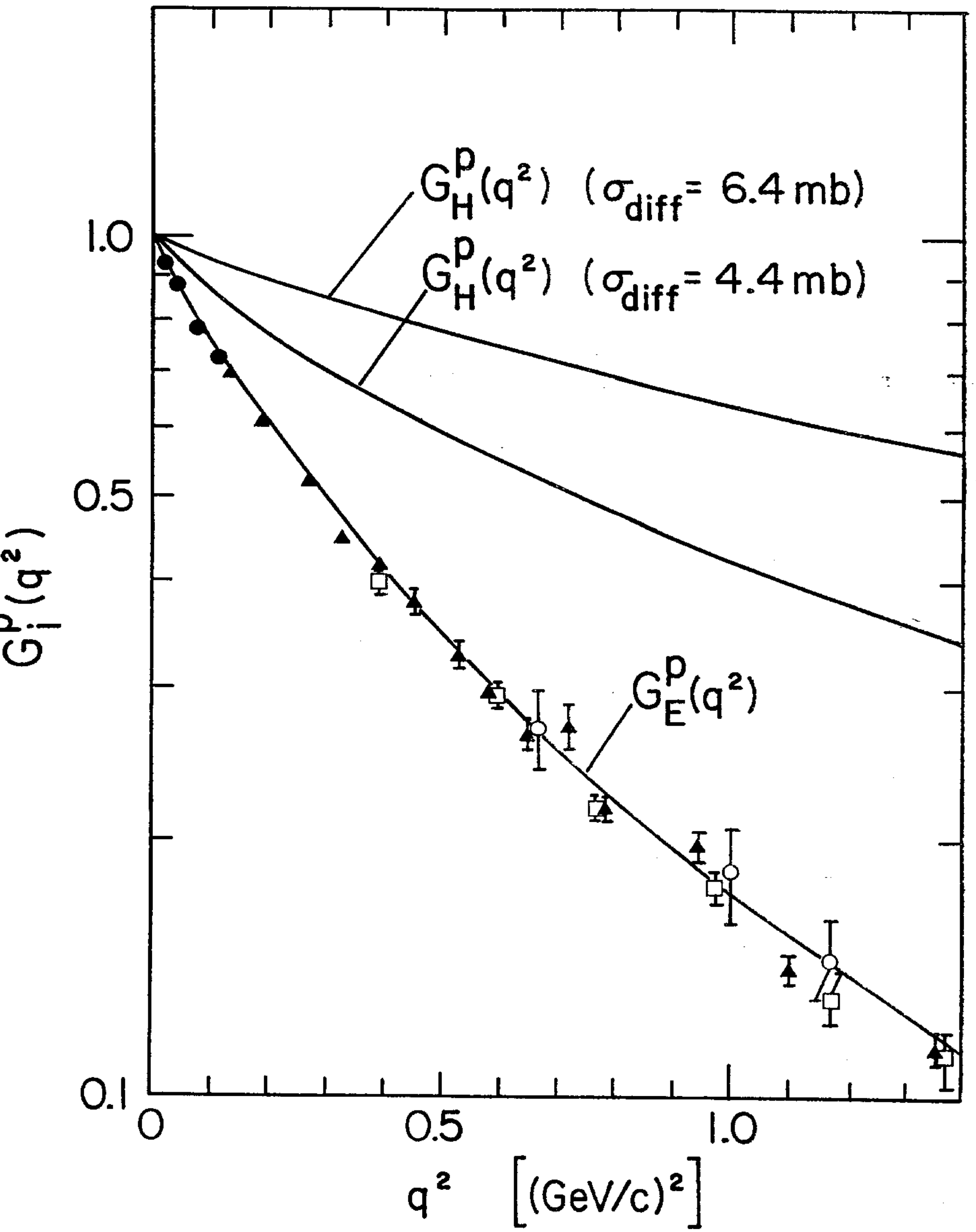
c-d) Transverse picture of a meson-meson collision, as seen in the infinite momentum frame. The transverse distribution of sea partons is assumed to be proportional to the corresponding color field density. Diffraction scattering is assumed to be due to wee-parton interactions. In case c) the matter overlap and correspondingly the wee-parton interaction probability is much larger than in case d. The impact parameter of the collision $\vec{B}$ is the same in both cases.

Fig.4. Comparison between the matter and the charge form factors of a meson in the toy model described in the text.



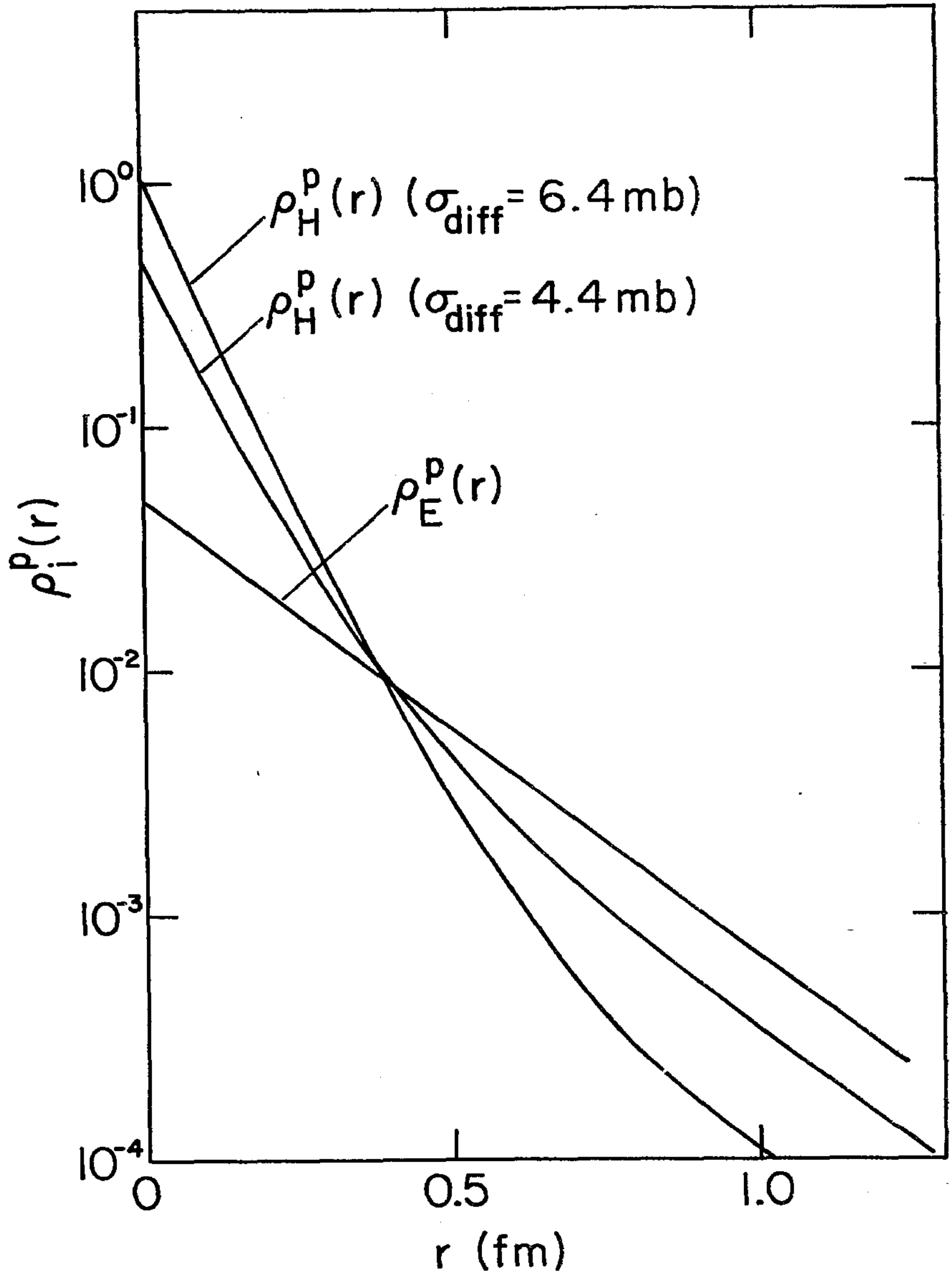
10^2
10^1
10^0
10^{-1}
p p - scattering
$\sqrt{s}$ = 53 GeV
σ_{diff} = 6.4 mb
σ_{diff} = 4.4 mb
σ_{diff} = 0 mb
$\langle \Omega(b) \rangle$
0
1
2
b^2 (fm^2)

Fig. 1



$G_H^p(q^2)$ (σ_{diff} = 6.4 mb)
$G_H^p(q^2)$ (σ_{diff} = 4.4 mb)
$G_E^p(q^2)$
1.0
0.5
0.1
$G_i^p(q^2)$
0
0.5
1.0
q^2 [$(GeV/c)^2$]

Fig. 2a



$\rho_H^p(r)$ (σ_{diff}= 6.4 mb)
$\rho_H^p(r)$ (σ_{diff}= 4.4 mb)
$\rho_E^p(r)$
$\rho_i^p(r)$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.5
1.0
r (fm)

Fig. 2b

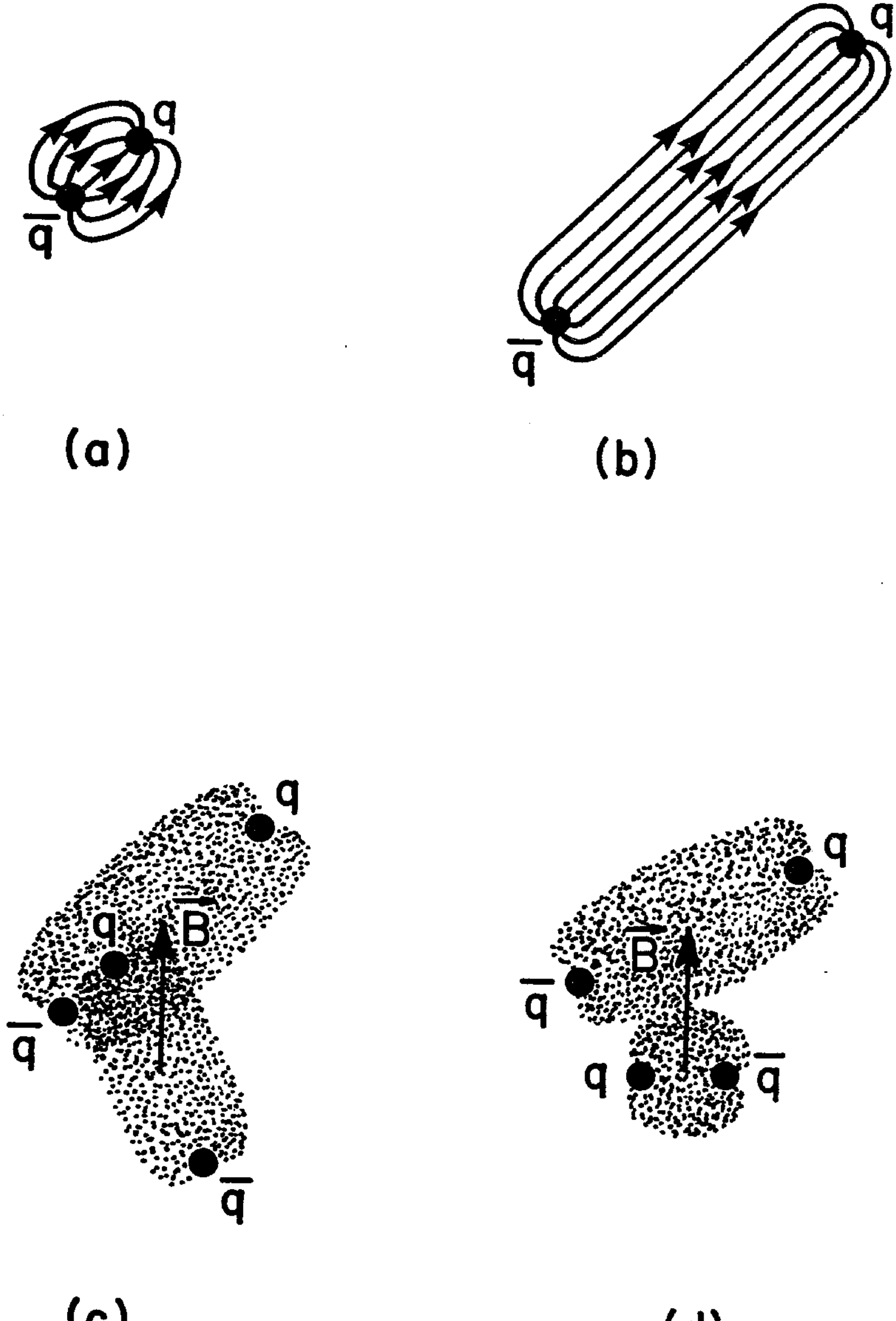
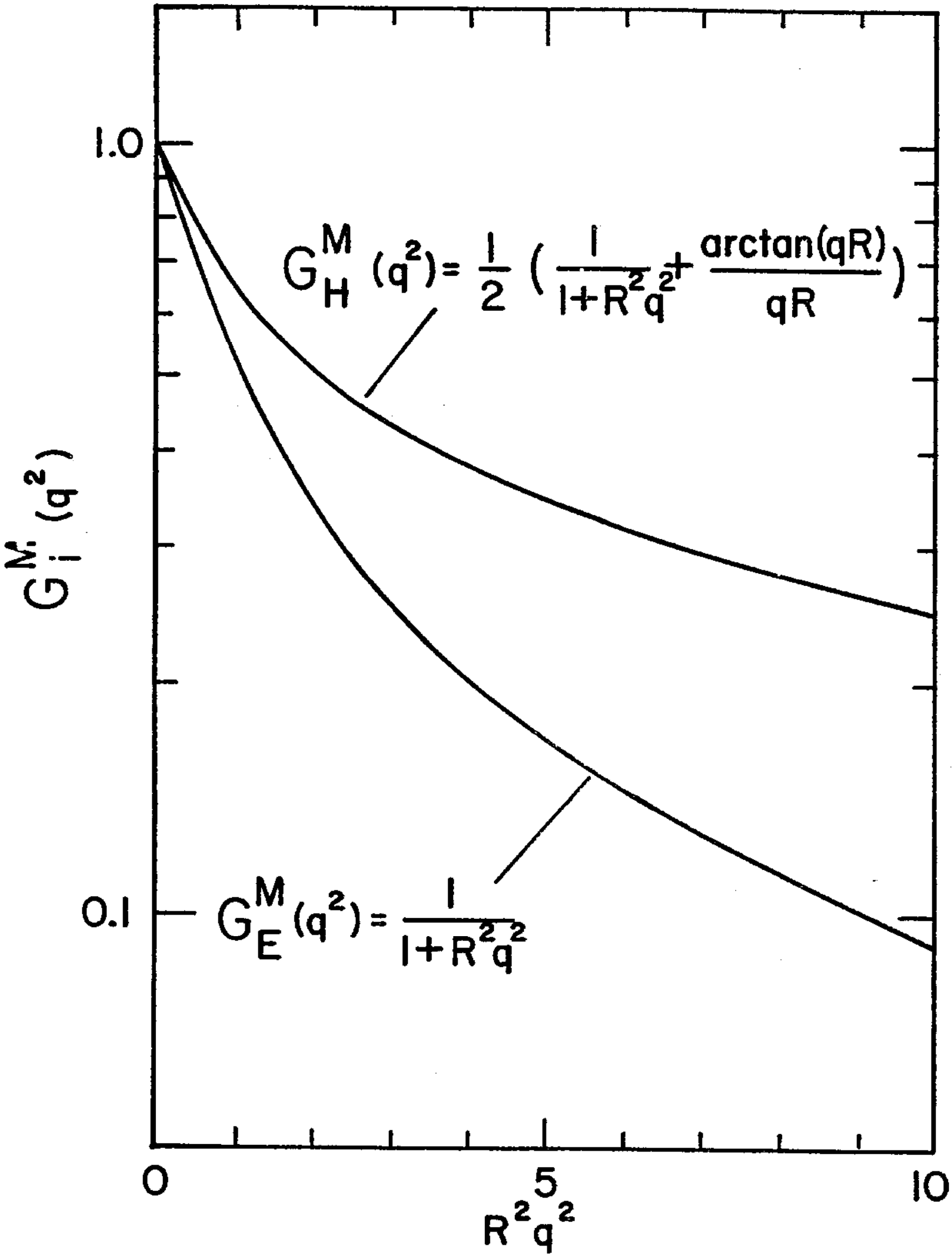


Fig. 3



1.0
0.1
$G_H^M(q^2) = \frac{1}{2}\left(\frac{1}{1+R^2q^2} + \frac{\arctan(qR)}{qR}\right)$
$G_E^M(q^2) = \frac{1}{1+R^2q^2}$
$G_i^M(q^2)$
0
5
10
R^2q^2

Fig. 4