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Abstract

Our additive eikonal quark model is generalized and applied to the elastic pp scattering in the energy range 50 - 2050 GeV. A new long-range interaction term was called for, in particular by the sharp change of the slope of $d\sigma/dt$ at the very small values of $|t|$. An alternative mechanism to geometrical scaling, in which the radii are almost fixed and the core strength is mainly responsible for the shift of the dip position in $d\sigma/dt$, leads to an equally good agreement with experiment.

[+)] On leave of absence from Institute of Nuclear Research, Warsaw, Poland.

In a recent article[1)] (hereafter called I) we introduced an additive eikonal quark model and applied it to different hadronic reactions at a fixed laboratory momentum p_{lab}=50 GeV/c. Since the model turned out to work very well, explaining quantitatively the high energy elastic data in terms of only few quark parameters, an obvious next step is to investigate the energy dependence of quark interactions. Unfortunately, since only pp scattering is known in a sufficiently large energy range to extract the very slow energy dependence of quark parameters, we had to restrict our analysis to non-strange quarks only.

In this paper we apply our model to the elastic pp data in the laboratory energy range from 50 to 2050 GeV. In particular, we shall test the geometrical scaling within this model and compare it to an alternative energy dependence of the parameters.

We begin by showing that the high energy pp data require a generalization of the original model[1)]. Analysing the cross sections in terms of our eikonal introduced in I consisting of only two terms, called peripheral and core, we observed that 1) the parameters obtained from the fit to $d\sigma/dt$ consistently lead to too small values of the optical point incompatible with measured σ_{tot} and 2) we obtained constant slopes in the small $|t|$ region in contradiction with the experimentally observed[2)] sharp changes in $d\sigma/dt$ around $|t|\approx.15$ GeV^2. So far there has been no basic explanation of this phenomenon, but one can treat it as an indirect evidence that at higher energies some long range quark-quark interactions switch in. Adding the corresponding term to the original eikonal we get

$$\chi_{pp}(s,b) = 9\,(g_c e^{-b^2/\bar{R}_c^2} + g_p e^{-b^2/\bar{R}_p^2} + g_1 e^{-b^2/\bar{R}_1^2}), \qquad (1)$$

where the three terms represent the core, peripheral and long range interactions respectively. The parameters g (effective couplings) and $\bar{R}$ (effective range) have been defined in I, eq. (11).

Using the parametrization (1) we have fitted the total and differential cross sections at 8 different momenta between p_{lab}=50 and 2048 GeV/c. For each energy we obtained a set of six parameters: g_i, $\bar{R}_i^2$ (i=c,p,1). Their values are plotted as functions of energy in Fig. 1 (symbols o,▲,◘). Although

no smooth energy dependence is visible, one should bear in mind that such a fit (3 gaussians) is rather unstable and two very different sets of parameters may give a comparable χ^2. This kind of analysis is rather inconclusive but may well serve as a first check of correlations among the parameters.

To check whether any smooth energy dependence can reproduce all the data in a reasonable way we took the highest energy data at p_{lab}=2048 GeV/c as a starting point and checked which of the parameters could be kept energy independent without worsening too much the agreement with experiment. We found that $\bar{R}_1$, g_p and $\bar{R}_p$ satisfy best this requirement. Next we applied a 3-parameter fit[+)] (g_c, g_1, $\bar{R}_c^2$) with the values $\bar{R}_1^2$=2.80 fm^2, g_p=0.087 and $\bar{R}_p^2$=0.72 fm^2 to all the data and drew graphically three smooth curves through the resulting points. These 3 curves together with the constant curves for the other parameters are plotted in Fig. 1 (solid lines). Note that $\bar{R}_c^2$ and g_1 have a linear dependence on ln s,

$$\begin{aligned} \bar{R}_c^2 &= 0.22(1+0.024\ \ln s)\ \mathrm{fm}^2, \\ g_1 &= -0.0058 + 0.0017\ \ln s. \end{aligned} \qquad (2)$$

We recalculated the total and differential cross sections using parameters lying on these 6 curves and the resulting χ^2_{smooth} is compared with that of the best fit (χ^2_{best}) in table 1. In the same table we give the comparison of σ^{tot} with experiment. The agreement is very good. In Fig. 2 we compare with experiment $d\sigma/dt$ from the latter calculation instead of our best fits to show that in spite of the larger χ^2 the agreement looks reasonable to the eye. Note that our comparatively simple version of additive eikonal quark model predicts always the dip in elastic pp scattering in general agreement with the data except, perhaps, at 50 and 100 GeV/c where such a dip has not been experimentally observed. The disappearance of the dip may be due to a non-negligible real part of the amplitude which is absent in our model.

Our model works remarkably well in the forward region and around the second

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[+)] In the case of the unnormalized data at p_{lab}=501 and 1074 GeV/c[6)] we used an additional normalization parameter in all fits.

maximum. It reproduces σ^{tot} and the change of slope at small $|t|$[2]. The main contribution to χ^2 comes from the dip region. It is possible that we do not reproduce exactly the motion of the dip towards smaller $|t|$ with increasing energy, though qualitatively our trend is correct. To decide on this point better data around the dip are necessary.

We have also tested the hypothesis of geometrical scaling[3] which in our model corresponds to assuming constant couplings $g_{c,p,1}$ and constant ratios $\bar{R}_c^2:\bar{R}_p^2:\bar{R}_1^2$ for all energies. Starting from the best fit to 2048 GeV/c data, we performed a fit with only one parameter[+] which is the common ratio $\alpha(s_i)=\bar{R}^2(p^i_{lab})/\bar{R}^2(2048)$. By not imposing any specific energy dependence on $\alpha(s)$ we allowed for the most general version of geometrical scaling within our model. The resulting points $\alpha(s_i)$ seemed to indicate a quadratic dependence on ln s. Hence we fitted these points by a two parameter curve normalized to 1 at s_o=1 GeV^2:

$$\rho(s) = \frac{\alpha(s)}{\alpha(s_o)} = 1 + A \ln(s/s_o) + B \ln^2(s/s_o) \qquad (3)$$

with

$$A = -0.105 \qquad \text{and} \qquad B = 0.0104.$$

The radii corresponding to (3) and the constant couplings g are plotted as dashed curves in Fig. 1 and the corresponding χ^2 are given in table 1 (χ^2_{QGS}).

For completeness we also include in table 1 the χ^2 calculated using the parameters for p_{lab}=2048 GeV/c with the radii scaled down according to the Barger fit[4] to the ISR data:

$$\rho_{Barger}(s) = 1 + 0.068 \ln(s/s_o). \qquad (4)$$

In both cases the resulting χ^2 are of the same order as our smooth fit (compare χ^2_{LGS} and χ^2_{smooth} in table 1) in the ISR region but are much worse at lower energies.

We sum up with some general conclusions:

[+] See footnote on p. 2.

1. Our simple additive eikonal quark model describes rather nicely the elastic pp data over a large energy interval. In particular σ^{tot} and $d\sigma/dt$ near the forward direction and beyond the dip region are well reproduced (although such a dip is absent in the other hadronic reactions at p_{lab}=50 GeV/c - compare I).
2. Geometrical scaling may not give the true description of experiment. The alternative smooth energy behaviour of the parameters agreed with the data almost as well in the ISR region and much better at smaller energies. More experiments at the present and higher energies together with more reliable normalization procedures of $d\sigma/dt$ would be necessary to obtain more definite conclusions on the energy dependence of parameters.
3. The decreasing of g_c and increasing of g_1 with energy implies that the proton effectively grows in size, the effect which in geometrical scaling arises due to the growing range of interactions.
4. If the long range non-strange quarks interaction really exists at high energies, as pp data strongly suggest, some change in slopes should also be observable in $\pi^{\pm}p$ and $K^{\pm}p$ [+], although it may be less pronounced due to the admixture of strange and annihilation amplitudes (unless the latter acquire also a long range component). To check this effect one needs the $d\sigma/dt$ measurements under very small angles at highest energies available for $\pi^{\pm}p$ and $K^{\pm}p$.

[+] The recent data from Fermilab show that indeed some change of slope in $\pi^{\pm}p$ is observed at small t at 200 GeV but statistics is not sufficient to draw any strong conclusions[10].

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Figure Captions

Fig. 1. Energy dependence of the parameters in our model. For the results of our best fits we use the following symbols: g_p, $\bar{R}_p^2$ - o, g_c, $\bar{R}_c^2$ -Δ, g_1, $\bar{R}_1^2$ -□. The solid curves correspond to the smooth fit and the dashed curves to quadratic geometrical scaling (3).

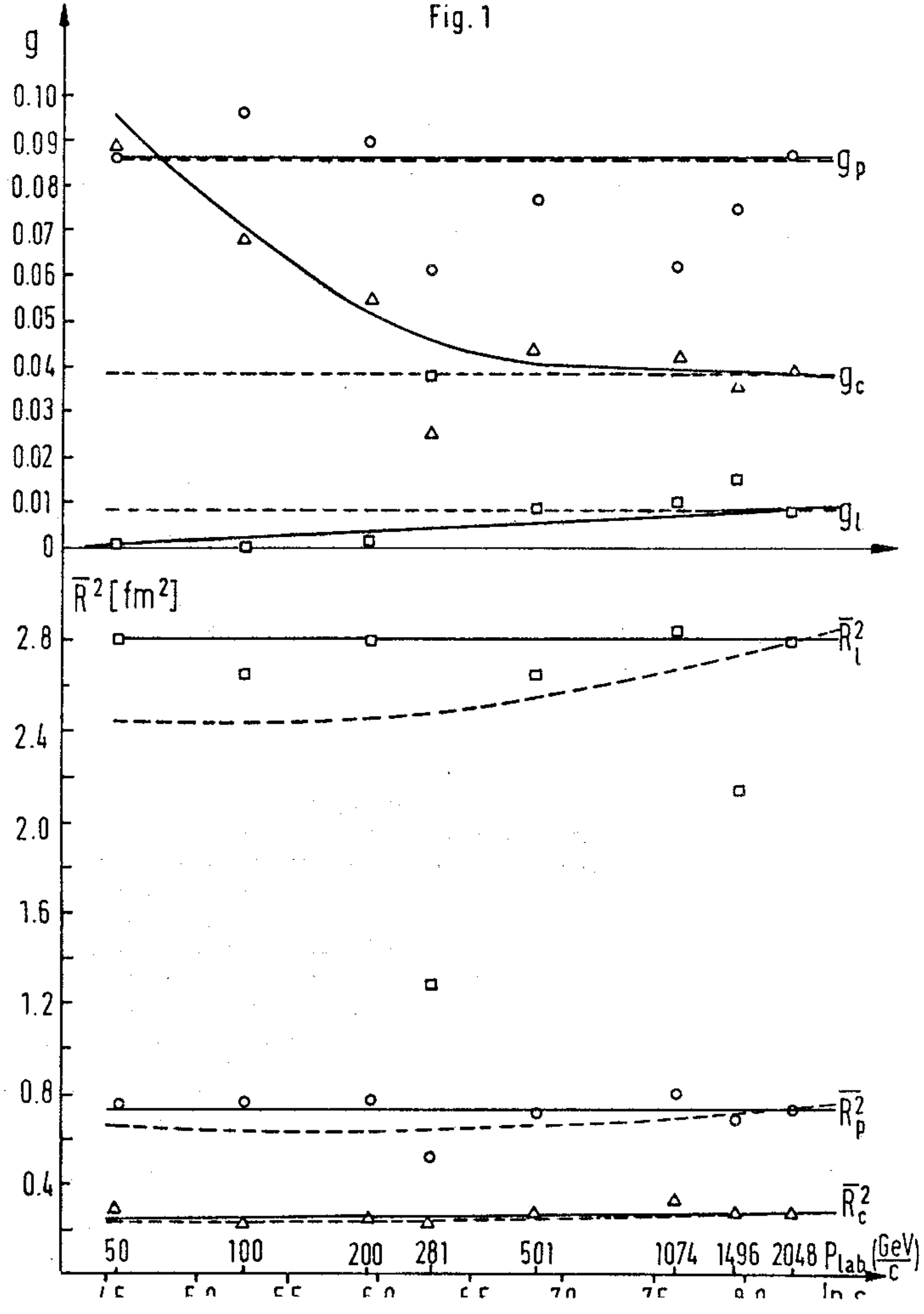
Fig. 2. Comparison of experimental dσ/dt for elastic pp scattering with the results of our smooth fit. Experimental data are from refs. 5(50,100, 200 GeV/c), 7(281,2048 GeV/c) and 8(1496 GeV/c).

P_{lab} (GeV/c)	50	100	200	281	501	1074	1496	2048
Number of exp. points	36	61	55	58	37	53	35	41
χ^2_{best}	58	71	133	41	41	104	214	63
χ^2_{smooth}	260	399	286	554	725	1096	344	63
χ^2_{QGS}	3431	2947	1164	693	176	685	336	63
χ^2_{LGS}	5996	3358	1058	622	456	986	370	63
σ^{tot}_{exp} (mb)	38.20	38.46	38.97	38.88	40.16	41.70	42.50	43.04
σ^{tot}_{smooth} (mb)	38.21	38.47	38.97	39.00	39.89	41.39	42.28	43.00

Table 1

Comparison of χ^2 for different hypotheses (best fit, our smooth fit, geometrical scaling with quadratic ln s dependence (3), geometrical scaling with linear ln s dependence (4)). In the last two raws σ^{tot} from our smooth fit is compared with the experimental values (taken from refs. 5 and 9).

Fig. 1


g
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
g_p
g_c
g_l
$\overline{R}^2$ [fm^2]
2.8
2.4
2.0
1.6
1.2
0.8
0.4
$\overline{R}_l^2$
$\overline{R}_p^2$
$\overline{R}_c^2$
50
100
200
281
501
1074
1496
2048
P_{lab} $\left(\frac{GeV}{c}\right)$
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
ln s

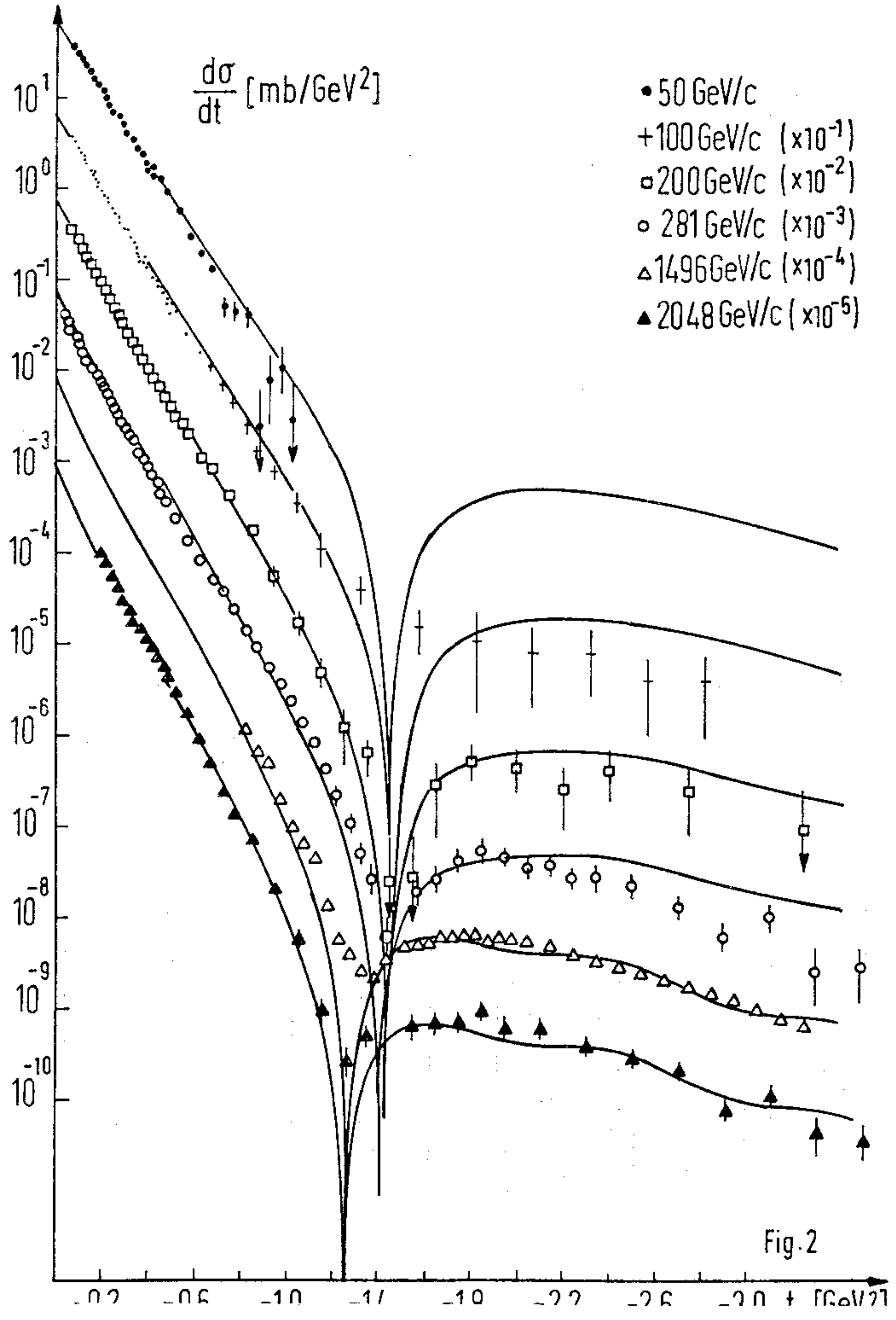

$\frac{d\sigma}{dt}$ [mb/GeV^2]
• 50 GeV/c
+ 100 GeV/c (x10^{-1})
□ 200 GeV/c (x10^{-2})
○ 281 GeV/c (x10^{-3})
△ 1496 GeV/c (x10^{-4})
▲ 2048 GeV/c (x10^{-5})
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
-0.2
-0.6
-1.0
-1.4
-1.8
-2.2
-2.6
-3.0
t [GeV^2]

Fig. 2