Impact-Picture Phenomenology for $\pi^\pm p$, $K^\pm p$ and $pp$, $\bar{p}p$

Elastic Scattering at High Energies

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Abstract

We present an extension to $\pi^\pm p$ and $K^\pm p$ elastic scattering at high energies of the impact-picture phenomenology we first proposed more than twenty years ago, for $pp$ and $\bar{p}p$ elastic scattering. We show, in particular, that the analytic form of the opacity function for the proton obtained previously is compatible with the experimental results on $\pi p$ and $K p$ elastic scattering at high energies. It is proposed that $\pi^\pm$ and $K^\pm$ external beams be provided from CERN-LHC, so that their elastic scattering from protons can be studied at higher energies. Our phenomenology for $pp$ and $\bar{p}p$ elastic scattering is updated by including new data and we give predictions for future experiments at BNL-RHIC and CERN-LHC.
1 Introduction

In 1967, the Atomic Energy Commission, the predecessor to the present Department of Energy, announced the project to construct a 200 GeV proton accelerator at the Fermi National Accelerator Laboratory. This accelerator makes it possible to study the interaction between two protons both highly relativistic in the center-of-mass system. This announcement motivated Cheng and one of the authors to initiate a program, using relativistic gauge quantum field theory, to study the high-energy behavior of hadron scattering. Perhaps the most unexpected result from this study is that all total cross sections must increase without bound at high energies [1, 2, 3]. Another motivation for that investigation was to accept the challenge issued by Oppenheimer [4] at his concluding talk at the 1958 Rochester meeting at CERN. He said at that time:

"There are areas where we know very little – extremely high energy collisions, for example – where little can be done by anyone."

Three years after the theoretical prediction of the increasing total cross sections, experiments at the CERN Intersecting Storage Rings confirmed that the proton-proton total cross section indeed turns around and started to increase [5, 6], and this data made possible to give the first quantitative predictions for future experiments on the total cross sections for \( p\bar{p}, \pi^\pm p, K^\pm p \) [7]. Careful phenomenology incorporating this increasing hadronic cross sections, called the impact-picture, was first carried out in 1978 [8]. Five years later, when more data became available, the parameters of this phenomenology were revised [9]. It was found that the changes of the values are quite small. These revised parameters have been used extensively to make various predictions, including for example the Coulomb interference effects and increasing integrated elastic cross section for proton-proton scattering up to 40 TeV in the center-of-mass energy, the proposed energy for the Superconducting Super Collider which was never built [10]. All the predictions that can be confirmed experimentally have been confirmed [11]. A recent chapter in a book gives a summary of the development up to this point [3]. Nevertheless, since it is by now nearly two decades since the 1984 parameters were obtained, it is the opportune time to take another look at the parameters. This is one of the purpose of the present paper. Another purpose is to extend the phenomenology from the cases of proton-proton and proton-antiproton scattering to four other processes, namely \( \pi^\pm p, K^\pm p \). The increasing total cross sections for these four processes were last investigated in 1973, nearly thirty years ago, and these predictions are in an even greater need of updating. It should perhaps be mentioned that the 1973 prediction for the \( \pi^- p \) case has been well confirmed by later data [12].

When we made our previous analysis in 1979 and 1984, some experimental data were still preliminary, but since then they have been completed, so it is worth to "revisit" our model by making an analysis with a full set of final data points. In the next section, we recall the main features of the model we use to describe elastic scattering and we will explain our parametrization. Section 3 is devoted to the presentation of the numerical results for \( \pi p, K p \) scattering and for \( pp, \bar{p}\bar{p} \) scattering with some comparison between the present and the previous determination of the parameters. We also give predictions for future experiments at BNL-RHIC and CERN-LHC. Our concluding remarks are given in section 4.
2 Description of the scattering amplitudes

In the impact-picture representation, the spin-independent scattering amplitude\(^1\), for \(pp\) and \(\bar{p}p\) elastic scattering, reads as

\[
a(s,t) = \frac{is}{2\pi} \int e^{-iq\cdot b}(1 - e^{-\Omega_0(s,b)})db ,
\]

where \(q\) is the momentum transfer \((t = -q^2)\) and \(\Omega_0(s,b)\) is defined to be the opaqueness at impact parameter \(b\) and at a given energy \(s\). We take

\[
\Omega_0(s,b) = S_0(s)F(b^2) + R_0(s,b) ,
\]

the first term is associated with the "Pomeron" exchange, which generates the diffractive component of the scattering and the second term is the Regge background. The Pomeron energy dependence is given by the crossing symmetric expression \([1, 2]\)

\[
S_0(s) = \frac{s^c}{(\ln s)^c} + \frac{u^c}{(\ln u)^c} ,
\]

where \(u\) is the third Mandelstam variable. The choice one makes for \(F(b^2)\) is crucial and we take the Bessel transform of

\[
\tilde{F}(t) = f[G(t)]^2 \frac{a^2 + t}{a^2 - t} ,
\]

where \(G(t)\) stands for the proton "nuclear form factor", parametrized like the electromagnetic form factor, as a two poles,

\[
G(t) = \frac{1}{(1 - t/m_1^2)(1 - t/m_2^2)} .
\]

The slowly varying function occurring in Eq.(4), reflects the approximate proportionality between the charge density and the hadronic matter distribution inside a proton. So the Pomeron part of the amplitude depends on only six parameters \(c, c', m_1, m_2, f,\) and \(a\). The asymptotic energy regime of hadronic interactions are controlled by \(c\) and \(c'\), which will be kept, for all elastic reactions, at the values obtained in 1984 \([9]\), namely

\[
c = 0.167 \quad \text{and} \quad c' = 0.748 .
\]

The remaining four parameters are related, more specifically to the reaction \(pp\) (\(\bar{p}p\)) and they will be slightly re-adjusted from the use of a new set of data.

We now turn to the Regge background. A generic Regge exchange amplitude has an expression of the form

\[
\tilde{R}_i(s,t) = C_i e^{bt} \left[ 1 \pm e^{-i\pi\alpha_i(t)} \right] \left( \frac{s}{s_0} \right)^{\alpha_i(t)} ,
\]

where \(C_i e^{bt}\) is the Regge residue, \(\pm\) is the signature factor, \(\alpha_i(t) = \alpha_{0i} + \alpha'_i t\) is a standard linear Regge trajectory and \(s_0 = 1\text{GeV}^2\). If we consider the sum over all the allowed Regge

\(^1\)Here we neglect the spin-dependent amplitude which was considered in Refs. \([8, 13]\) for the description of polarizations and spin correlation parameters.
trajectories $\tilde{R}_0(s,t) = \sum_i \tilde{R}_i(s,t)$, the Regge background $R_0(s,b)$ in Eq. (2) is the Bessel transform of $\tilde{R}_0(s,t)$. In $pp$ ($\bar{p}p$) elastic scattering, the allowed Regge exchanges are $A_2$, $\rho$, $\omega$, so the Regge background involves several additional parameters, we will come back to them.

Let us now consider the case of $\pi p$ elastic scattering. The scattering amplitude is also defined by Eq. (1) and we keep the same structure for the opaqueness Eq. (2). However, for the Pomeron exchange, we assume that the nuclear matter density is the product of the proton and the pion contributions. So with this reasonable hypothesis, we write similarly to Eq. (4),

$$\tilde{F}(t) = f_\pi G(t) F_\pi(t) \frac{a_\pi^2 + t}{a_\pi^2 - t}. \tag{8}$$

Here $G(t)$ is given by Eq. (5) with the same parameters values $m_1$, $m_2$ as in the proton case and $F_\pi(t)$ is the pion "nuclear form factor", we parametrize like the pion electromagnetic form factor, as a single pole $1/(1 - t/m_{3\pi}^2)$ [14]. Therefore the Pomeron term for $\pi p$ elastic scattering involves three additional free parameters $f_\pi$, $m_{3\pi}$, and $a_\pi$. The Regge background is simpler in this case since the only allowed Regge exchange is $\rho$ and we have taken for the generic amplitude an expression of the form Eq. (7), with the same Regge trajectory as before, only the Regge residue being different.

Finally in the case of $Kp$ elastic scattering, for the Pomeron exchange the procedure is the same as for $\pi p$ and the use of an expression like Eq. (8) leads to the introduction of three further free parameters $f_K$, $m_{3K}$, and $a_K$. However the Regge background is a little bit more complicated, since the allowed Regge exchanges are $A_2$, $\rho$, $\omega$, as in the $pp$ ($\bar{p}p$) reaction. The same Regge trajectories will be used and again only the Regge residues are different.

To summarize, for all the cases we are considering, the elastic scattering amplitude reduces to a Bessel transform

$$a(s,t) = is \int_0^\infty J_0(b\sqrt{-t})(1 - e^{-\Omega_0(s,b)}) bdb. \tag{9}$$

We define the ratio of real to imaginary parts of the forward amplitude

$$\rho(s) = \frac{\text{Re} a(s,t=0)}{\text{Im} a(s,t=0)}, \tag{10}$$

the total cross section

$$\sigma_{\text{tot}}(s) = \frac{4\pi}{s} \text{Im} a(s,t=0) \tag{11}$$

and the differential cross section

$$\frac{d\sigma(s,t)}{dt} = \frac{\pi}{s^2} |a(s,t)|^2. \tag{12}$$

This completes the description of the scattering amplitudes and we now turn to the phenomenological results and predictions for future experiments.
3 Phenomenological results and predictions

We have made a global fit for all the elastic reactions under study and for all of them we have introduced a lower cutoff at $p_{lab} = 100 \text{GeV}/c$. When making the fit we have analyzed high energy experimental $pp$ ($\bar{p}p$) data including a set of 369 points coming from ISR, SPS and Tevatron experiments on $\rho(s)$, $\sigma_{tot}(s)$ and $d\sigma(s,t)/dt$. The new $pp$ ($\bar{p}p$) Pomeron parameters are listed in Table 1 together with those obtained in our previous analysis. We notice that these four parameters have changed only slightly, within a few percents. The $C$ values of the Regge residues are given in Table 2. The parameters $b$ are zero except for the $\rho$ contribution for which we found $b_\rho = 8.54$. Let us notice that the Regge exchanges have been eikonalized so the intercept and the slope of the trajectories are effective parameters whose values are given in Table 3. However we notice that the three intercepts are close to $1/3$ and the $A_2$ and $\rho$ slopes have the standard value $\alpha' = 1 \text{GeV}^{-2}$, whereas the $\omega$ slope is slightly smaller. A detailed $\chi^2$ analysis is presented in Table 4, where the present solution which is a fit to the data is compared to the 1984 solution, which is a prediction made with the same set of data. We notice a substantial improvement in the $\chi^2$, since we have now a $\chi^2/\text{pt} = 4.45$. A comparison of our model with experimental data is given in the Figs. 1-6. In Fig. 7 and Fig. 8, we display some predictions for future measurements at BNL-RHIC and CERN-LHC, respectively.

| year | present | 1984 |
|------|---------|------|
| $m_1$ | 0.577225 | 0.586 |
| $m_2$ | 1.719896 | 1.704 |
| $f$ | 6.970913 | 7.115 |
| a | 1.858442 | 1.953 |

Table 1: Pomeron parameters for $pp$ ($\bar{p}p$). Comparison of the present and 1984 solutions.
| exchange | $C$          |
|----------|-------------|
| $A_2$    | -24.2686    |
| $\omega$| -167.3293   |
| $\rho$  | 124.91969   |

Table 2: $pp$ ($\bar{pp}$) Regge parameters.

| trajectory | $A_2$   | $\omega$ | $\rho$   |
|------------|---------|----------|----------|
| $0.3566 + t$ | $0.3229 + 0.7954 t$ | $0.3202 + t$ |

Table 3: Effective Regge trajectories.

| process          | $\chi^2$ present | $\chi^2$ 1984 | nb points |
|------------------|-------------------|----------------|-----------|
| $d\sigma(pp)/dt$ $p_{lab} = 280\text{GeV}/c$ | 351               | 538            | 58        |
| $d\sigma(pp)/dt$ $p_{lab} = 496\text{GeV}/c$ | 194               | 527            | 54        |
| $d\sigma(pp)/dt$ $p_{lab} = 1486\text{GeV}/c$ | 246               | 190            | 16        |
| $d\sigma(pp)/dt$ $p_{lab} = 2060\text{GeV}/c$ | 40                | 42             | 10        |
| $d\sigma(pp)/dt$ $p_{lab} = 2080\text{GeV}/c$ | 97                | 135            | 51        |
| $d\sigma(\bar{pp})/dt$ $p_{lab} = 315\text{GeV}/c$ | 51                | 516            | 41        |
| $d\sigma(\bar{pp})/dt$ $\sqrt{s} = 546\text{GeV}$ | 474               | 1190           | 84        |
| $d\sigma(\bar{pp})/dt$ $\sqrt{s} = 630\text{GeV}$ | 141               | 628            | 19        |
| $\sigma_{tot}(pp)$ | 16                | 144            | 13        |
| $\sigma_{tot}(\bar{pp})$ | 21               | 44             | 10        |
| $\rho(pp)$ | 2                | 9              | 7         |
| $\rho(\bar{pp})$ | 8                 | 11             | 6         |
| Total       | 1641             | 3974           | 369       |

Table 4: Detailed $\chi^2$ comparison between the present and 1984 solutions for $pp$ and $\bar{pp}$
For $\pi^\pm p$ elastic scattering, from 113 data points we have obtained the following Pomeron parameters values:

$$m_{3\pi} = 0.7665, \quad f_{\pi} = 4.2414, \quad a_{\pi} = 2.3272.$$

Due to the lack of very high energy data for these reactions, the Regge contributions play a non negligible role in the fit we made with a cut at $p_{\text{lab}} = 100\text{GeV/c}$. The only allowed Regge exchange is $\rho$ and we find $C_\rho = 4.1624$ and $b_\rho = 4.2704$. A detailed $\chi^2$ analysis of the data is given in Table 5 and we have a $\chi^2/\text{pt} = 4$. A comparison of our model with experimental data is given in Figs. 9-12 and in Fig. 13 we give some predictions for future measurements at CERN-LHC.

| process                      | $\chi^2$ | nb points |
|------------------------------|----------|-----------|
| $d\sigma(\pi^- p)/dt$ p$_{\text{lab}} = 100\text{GeV/c}$ | 112      | 32        |
| $d\sigma(\pi^- p)/dt$ p$_{\text{lab}} = 200\text{GeV/c}$ | 139      | 14        |
| $d\sigma(\pi^+ p)/dt$ p$_{\text{lab}} = 100\text{GeV/c}$ | 50       | 32        |
| $d\sigma(\pi^+ p)/dt$ p$_{\text{lab}} = 200\text{GeV/c}$ | 58       | 14        |
| $\sigma_{\text{tot}}(\pi^- p)$ | 64       | 8         |
| $\sigma_{\text{tot}}(\pi^+ p)$ | 16       | 6         |
| $\rho(\pi^- p)$       | 8        | 4         |
| $\rho(\pi^+ p)$       | 6        | 3         |
| Total                    | 453      | 113       |

Table 5: Detailed $\chi^2$ for $\pi p$ fitted processes

Finally for $K^\pm p$ elastic scattering where we used 212 data points, the procedure is the same as in the $\pi^\pm p$ case and the Pomeron parameters obtained from the fit are

$$m_{3K} = 1.1391, \quad f_K = 3.6729, \quad a_K = 1.9913.$$

For these reactions the allowed exchanges are the $A_2$, $\rho$ and $\omega$. We have kept the same trajectories as in the $pp$ case, with $b_{A_2} = b_\omega = 8.5409$, and $b_\rho = 4.2704$ and the values of the corresponding $C$ parameters are listed in Table 6. A detailed $\chi^2$ analysis of the data is given in Table 7 and we have a $\chi^2/\text{pt} = 1.5$. A comparison of our model with experimental data is given in Figs. 14-17 and in Fig. 18 we give some predictions for future measurements at CERN-LHC. It might be possible to expect future measurements at BNL-RHIC with extracted $\pi^\pm$, $K^\pm$ beams, to improve the available data.
| exchange | $C$  |
|----------|------|
| $A_2$    | 6.3221 |
| $\rho$   | -39.4989 |
| $\omega$ | 46.5386 |

Table 6: $Kp$ Regge parameters.

| process                                      | $\chi^2$ | nb points |
|----------------------------------------------|----------|-----------|
| $d\sigma(K^-p)/dt \ p_{lab} = 100\text{GeV/c}$ | 120      | 43        |
| $d\sigma(K^-p)/dt \ p_{lab} = 140\text{GeV/c}$ | 16       | 13        |
| $d\sigma(K^-p)/dt \ p_{lab} = 175\text{GeV/c}$ | 23       | 15        |
| $d\sigma(K^-p)/dt \ p_{lab} = 200\text{GeV/c}$ | 15       | 15        |
| $d\sigma(K^+p)/dt \ p_{lab} = 100\text{GeV/c}$ | 56       | 36        |
| $d\sigma(K^+p)/dt \ p_{lab} = 140\text{GeV/c}$ | 11       | 16        |
| $d\sigma(K^+p)/dt \ p_{lab} = 175\text{GeV/c}$ | 16       | 17        |
| $d\sigma(K^+p)/dt \ p_{lab} = 200\text{GeV/c}$ | 17       | 12        |
| $\sigma_{tot}(K^-p)$                          | 13       | 17        |
| $\sigma_{tot}(K^+p)$                          | 8        | 15        |
| $\rho(K^-p)$                                  | 16       | 5         |
| $\rho(K^+p)$                                  | 7        | 8         |
| Total                                         | 318      | 212       |

Table 7: Detailed $\chi^2$ for $Kp$ fitted processes
4 Concluding remarks

In one of the earliest phenomenological analyses [7] that incorporated the theoretical predictions of increasing cross sections [1], results were obtained not only for $pp$ and $p\bar{p}$ total cross sections but also for those of $\pi^+p$, $\pi^-p$, $K^+p$ and $K^-p$. Since then, efforts in this direction have been concentrated on studying the cross sections for $pp$ and $p\bar{p}$ scattering [8, 9, 10, 11].

There are perhaps two reasons why there has been a lack of progress on the cases of $\pi^\pm p$ and $K^\pm p$ as compared with those of $pp$ and $\bar{pp}$. First, since the available experimental data for $\pi^\pm p$ and $K^\pm p$ scattering are at lower energies, the Regge backgrounds play more prominent roles, and this complicates the phenomenological analysis. Secondly, there has been relatively little reason for analyzing such cases because, while the predictions for the $pp$ and $\bar{pp}$ cases are most relevant with new experimental data expected at higher and higher energies every few years, up until now the availability of high-energy data for $\pi^\pm p$ and $K^\pm p$ elastic scattering has been very limited.

The present work is motivated by the realization that the basis for the second reason may change in the near future. The construction of the CERN-LHC, which is a proton collider of 7 TeV in each beam, will make it possible to have multi-TeV secondary beams of $\pi^\pm$ and $K^\pm$. The scattering of such external secondary beams on protons will provide the much needed data for $\pi^\pm p$ and $K^\pm p$ elastic scattering at high energies (see Figs. 13 and 18). For example, the center-of-mass energy of a 6 TeV $\pi^\pm$ or $K^\pm$ and a stationary proton is about 106 GeV, close to that of ISR for $pp$ scattering. Encouraged by the likely irrelevance of this second reason, it has been possible to overcome the difficulty due to the first reason, namely the inclusion of more elaborate Regge backgrounds.

Looking forward, we believe that the present treatment of $\pi^\pm p$ and $K^\pm p$ elastic scattering will make it possible to deal with a number of additional scattering processes. The most interesting process is perhaps the following:

$$ p + p \rightarrow p + N(1440). \quad (13) $$

This high-energy process was studied nearly thirty years ago [39]. Since $N(1440)$ has the same $I(J^P)$ as the proton, this is one of the simplest diffraction processes. This is to be contrasted with the elastic scatterings dealt with by most of the existing impact-picture phenomenologies, including the present paper. The diffraction process (13) and many similar ones can perhaps be studied experimentally at BNL-RHIC, and we look forward eagerly to such data in the near future.

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Figure 17: $d\sigma/dt$ for $K^-p$ as a function of $|t|$ for $p_{lab} = 100, 200\text{GeV}/c$. Experiments from Refs. [28, 29, 33].
Figure 18: $d\sigma/dt$ for $K^-p$ as a function of $|t|$ for different $\sqrt{s}$ in the TeV energy domain.
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