Total and Differential Cross Sections, and Polarization Effects in pp Elastic Scattering at RHIC

Abstract

This is an experiment to study proton-proton (pp) elastic scattering experiment at the Relativistic Heavy Ion Collider (RHIC.) Using both polarized and unpolarized beams, the experiment will study pp elastic scattering from $\sqrt{s} = 60$ GeV to $\sqrt{s} = 500$ GeV in two kinematical regions. In the Coulomb Nuclear Interference (CNI) region, $0.0005 < |t| < 0.12$ $(\mathrm{GeV}/c)^2$, we will measure and study the s dependence of the total and elastic cross sections, σ_{tot} and σ_{el}; the ratio of the real to the imaginary part of the forward elastic scattering amplitude, ρ; and the nuclear slope parameter of the pp elastic scattering, b. In the medium $|t|$-region, $|t| \leq 1.5$ $(\mathrm{GeV}/c)^2$, we plan to study the evolution of the dip structure with s, as observed at ISR in the differential elastic cross section, $d\sigma_{el}/dt$, and the s and $|t|$ dependence of b. With the polarized beams the following can be measured: the difference in the total cross sections as function of initial transverse spin states $\Delta\sigma_T$, the analyzing power, A_N, and the transverse spin correlation parameter A_{NN}. The behavior of the analyzing power A_N at RHIC energies in the dip region of $d\sigma_{el}/dt$, where a pronounced structure was found at fixed-target experiments will be studied.

1 Introduction

While the elastic scattering has been measured in $p\bar{p}$ collisions up to $\sqrt{s} = 1.8$ TeV, the pp data at higher energies come from the ISR and reach $\sqrt{s}$ up to 62 GeV. The history of this field repeatedly shows that it is important to measure pp elastic scattering parameters and to compare them with the $p\bar{p}$ results. The summary of elastic scattering measurements and phenomenological models is given in [2].

The special role of the elastic channel at high energies is evident by the fact that it contributes as much as 20% of the total cross section. This, coupled with the importance of understanding the diffraction process, not only as the shadow of the many inelastic channels present at high energies, but also in terms of basic concepts related to QCD, has made nucleon-nucleon elastic scattering one of the most studied reactions in high energy physics.

The possibility of having polarized proton beams at RHIC would allow measurements of spin dependent effects, both in the small and large $|t|$-ranges of the elastic scattering. Polarization measurements in elastic scattering until now have been performed in fixed-target experiments, and the highest energy data are at $p_{lab} = 300 GeV/c$ ($\sqrt{s} = 24$ GeV). This interest also extends to A_{NN} in large $|t|$-region, where large values were measured at lower energies.

We will measure the previously outlined aspects of pp elastic scattering in two experimental setups.

In the small $|t|$ region, $0.0005 < |t| < 0.12$ (GeV$/c)^2$, where a special accelerator tune is required, we have found a solution to the accelerator lattice setup that allows reaching small $|t|$ values needed to measure ρ, σ_{tot}, and b with small errors. The angular coverage of the detector will allow the simultaneous determination of these three parameters. The goal of the experiment is to acquire 4×10^6. With the same setup, running with polarized protons in RHIC would allow the simultaneous measurements of $\Delta\sigma_T$, A_N, and A_{NN} and the spin related effects on ρ, σ_{tot}, and b.

In the medium $|t|$ region, $|t| \leq 1.5$ (GeV$/c)^2$, no modifications to the accelerator setup are required and we will use the DX dipole magnet of the RHIC lattice for the momentum analysis of the scattered protons.

2 Scattering at Small $|t|$

The elastic scattering of protons is described by a scattering amplitude which has two components: Coulomb amplitude f_c, and the hadronic amplitude f_h. The amplitudes are a function of *cms* energy $\sqrt{s}$ and four-momentum-transfer squared $|t|$. The differential elastic pp cross section can be expressed as a square of the scattering amplitude:

$$\frac{d\sigma_{el}}{dt} = \pi|f_c + f_h|^2. \tag{1}$$

The spin independent hadronic amplitude f_h is usually parameterized as:

$$f_h = \left(\frac{\sigma_{tot}}{4\pi}\right)(\rho + i)\exp\left(-\frac{1}{2}b|t|\right). \tag{2}$$

The dependence of the differential elastic cross section $d\sigma/dt$ on $|t|$ can be divided into three regions: the Coulomb region, the CNI region, and the hadronic region. At small $|t|$, the Coulomb term dominates, and $d\sigma/dt$ has a $1/t^2$ dependence. As $|t|$ increases, the interference between the Coulomb and hadronic contributions becomes maximal. Finally, the hadronic contribution dominates, and $d\sigma/dt$ falls off exponentially.

In order to determine ρ, one needs to be able to measure scattered protons at very small angles. The scale is set by the $|t|$-value where Coulomb and hadronic scattering amplitudes are equal. At $\sqrt{s} = 500$ GeV, this occurs at $t \simeq 1.1 \times 10^{-3} (\mathrm{GeV}/c)^2$, and corresponds to a scattering angle of 0.13 mrad.

Since the Coulomb amplitude is absolutely known, the measurement at very small $|t|$ gives direct determination of the machine's luminosity and, consequently, the absolute normalization of the hadronic amplitude. As a result, the parameters of the elastic cross section can be determined without requiring an independent measurement of the luminosity or the total cross section.

2.1 Experimental Technique

The two protons collide at the interaction region (IR) in a local coordinate system at a vertical distance y^* from the reference orbit and scatter with an angle θ_y^*. Since the scattering angles are small, protons follow trajectories determined by the lattice of the accelerator until they reach the detector, which measures the positions of the scattered particles with respect to the reference orbit. Hence, the known parameters of the accelerator lattice can be used to calculate the deflection y^* and the scattering angle θ_y^* at the interaction point, knowing the deflection y and the angle θ_y at the detector. At a point where the phase advance from the interaction point is Ψ and the betatron function is β, y is given by:

$$y = \sqrt{\frac{\beta}{\beta^*}}[\cos\Psi + \alpha^* \sin\Psi]y^* + \sqrt{(\beta\beta^*)}\sin\Psi\theta_y^* \tag{3}$$

where α^* is the derivative of the betatron function β^* at the interaction point. We have considered a lattice configuration such that α^* is very close to zero.

Equation 3 can be rewritten as:

$$y = a_{11}y^* + L_{eff}\theta_y^* \tag{4}$$

where

$$a_{11} = \sqrt{\left(\frac{\beta}{\beta^*}\right)}[\cos\Psi + \alpha^* \sin\Psi] \tag{5}$$

and

$$L_{eff} = \sqrt{\beta^*\beta}\sin\Psi. \tag{6}$$

The optimum condition for the experiment is to have $a_{11} = 0$ and L_{eff} as large as possible, since the answer is then independent of the coordinate at the IR in the transverse plane of the accelerator and "large displacements" at the detection point are obtained for small scattering angles. This is achieved when Ψ is an odd multiple of $\pi/2$. The expression for the y coordinate at the detection point then simplifies to:

$$y = L_{eff}\theta^*_y; \tag{7}$$

and the scattering angle is determined just from the measurement of the displacement alone. With the above condition satisfied, rays that are parallel to each other at the interaction point are focused onto a single point at the detector, commonly called "parallel to point focusing."

Another question, related to the optimization of the accelerator setup, is the smallest measurable four-momentum-transfer squared t_{min}. The goal is to achieve t_{min} as small as possible. The t_{min} is determined by the smallest scattering angle measured θ_{min}, which, using Eqn. 7, is given by:

$$\theta^*{}_{min} = \frac{d_{min}}{L_{eff}}, \tag{8}$$

where L_{eff} is given by 6. The minimum distance of the approach to the beam, d_{min}, can be expressed in terms of the beam size at the detector position and the "dead space of the detector" d_0 [3]:

$$d_{min} = k\sigma_y + d_0, \tag{9}$$

where k is a machine dependent constant, which is optimized by beam scraping, and σ_y is the beam size at the detection point. Assuming d_0 is small, the t_{min} is then:

$$t_{min} \propto \frac{k^2 \epsilon p^2}{\beta^*}. \tag{10}$$

We can see that the smallest t_{min} is reached by having β^* as large as possible and by reducing the k-factor and the emittance, in other words by optimizing the beam scraping.

Table 1: Transport matrix elements in x and y coordinates.

Transport matrix element	Value at 72 m	Value at 144 m
a_{11} in y	-0.000008	-0.00001
L_{eff} in y	36.465 m	87.486 m
a_{11} in x	-0.7861	-0.05257
L_{eff} in x	23.031 m	49.464 m

2.2 Simulations

In order to evaluate the performance of the experiment, we performed simulations of small angle scattering. The errors of the elastic scattering parameters σ_{tot}, ρ, b due to uncertainties in the parameters describing the experimental setup were determined.

The angular distribution of scattered protons was generated with the known cross section formula, Eqn 1, and known parameters: ρ, σ_{tot}, and b. Knowing scattering angles and vertex position, one can use the transport equation 3 to determine the position at the detection point of the scattered portions in both the horizontal and vertical coordinate. Uncertainties in the beam parameters and detectors result in errors in the reconstructed $|t|$.

The accelerator tune used is shown in Table 2.1 for two detector positions needed. The first allows to reach the upper range of small $|t|$ to about 0.12 $(\mathrm{GeV}/c)^2$. The second allows to reach the smallest t_{min} possible since it has larger L_{eff} and the beam size is smaller there. The major uncertainties, introduced at the appropriate steps of the simulation, are listed in Table 2.2. The geometrical acceptance is determined by the beam pipe size for large $|t|$ and the t_{min} cutoff for small $|t|$.

Table 2: Parameters used in the Monte Carlo simulation

Run parameters	Value
Beam momentum	250 GeV/c
Number of events	3.2 $\times 10^6$
Angle between the beams $\theta^0{}_{x,y}$	5μrad, 5μrad
Error of angle between the beams $\Delta\theta^0{}_{x,y}$	6μrad
Detector offsets	20 μm
Detector resolution	100μm
Beam momentum spread	250 MeV/c
Vertex size in z, σ_z	15 cm
Beam emittance	5π mm $m$rad

The errors on fitted parameters are plotted as a function of t_{min} in Fig. 1. Two runs of different statistics, one with 0.8 million events and with 3.2 million events, are compared.

We see the major sources of error are from the t_{min} cutoff and the statistics of the experiment. It has been shown by UA4 [3] that, if one of the parameters is known, then the errors on the other two are are smaller if one performs a two parameter fit.

3 Scattering at Medium $|t|$

The RHIC machine operating in the proton-proton mode offers unique possibilities to investigate elastic scattering further in the region of the diffractive structure and at larger momentum-transfer for $\sqrt{s}$ range 60 to 500 GeV.

Accurate data on the region of the structure provide the opportunity for a direct comparison with the existing $p\bar{p}$ data from the S$p\bar{p}$S collider, which are at essentially the same energy, thus probing the theory of the interference of the three-gluon diagram.

The large luminosity of RHIC will make possible a detailed study of scattering at large momentum transfer, up to $|t| \simeq 1.5(\mathrm{GeV}/c)^2$. The basic question to be addressed is if a

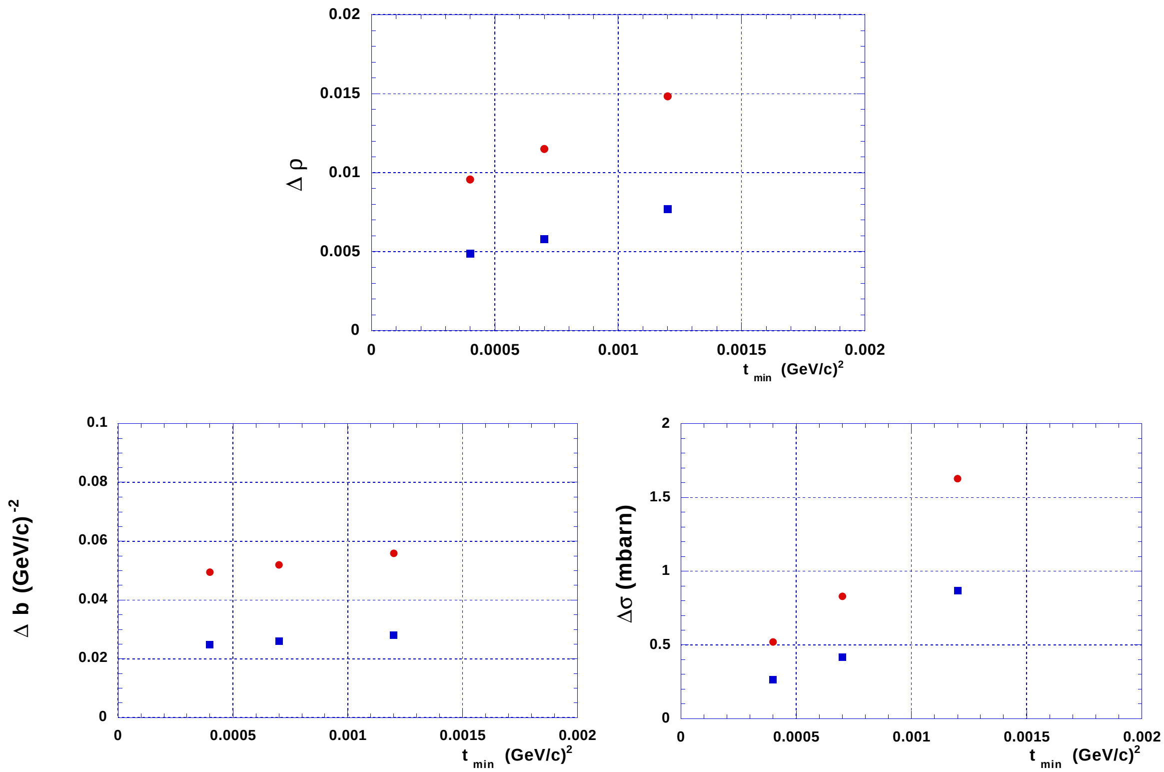

Figure 1: Errors on ρ, σ_{tot}, b as a function of t_{min} for runs with 0.8×10^6 (circles) and 3.2×10^6 (squares) events.

new diffraction-like structure will emerge in this large $|t|$-region, or will the $|t|$-distribution be smooth and energy independent, controlled by a single QCD diagram?

3.1 The Experimental Method

In the design of an apparatus to measure large-$|t|$ elastic scattering at RHIC, one can be guided by previous experience gained at other hadron colliders.

The basic identification of elastic scattering events is by the colinearity of the two out going particles. At large momentum transfer, however, the elastic cross section is several orders of magnitude smaller than that in the forward direction, so these elastic events represent only a small fraction of the large background of the inelastic interactions. Momentum analysis provides an important additional constraint, not only in the reconstruction of the events, but also at the trigger level.

We list in Table 3.1 the parameters of two typical experiments[4, 5, 6] and of the proposed RHIC experiment. In the proton-proton mode at RHIC, the expected normalized emittance, defined at the 95% level, is $\epsilon = 20\pi$ mm $m$rad. At $\sqrt{s} =$ 500 GeV and for the betatron function at the crossing point $\beta_x^* = \beta_y^* = 10$ m, the size and angular spread of the beam at the crossing are $\sigma_y = 0.45$ mm and $\sigma_{\theta_y} = 45\mu$rad respectively.

Table 3: Parameters of ISR, UA4, and This Experiments

	ISR	UA4	This Experiment
Energy $cms\ \sqrt{s}$ (GeV)	23 - 62	546 - 630	60 - 500
Luminosity $\mathrm{cm}^{-2}s^{-1}$	few 10^{30}	few 10^{28}	few 10^{31}
Maximum $\|t\|$ $(\mathrm{GeV}/c)^2$	10	$\simeq 2$	$\simeq 1.5$
Momentum resolution $\Delta p/p$	$\simeq 5\%$	$\simeq 0.6\%$	$\simeq 1.5\%$
Momentum-transfer resolution Δt	$\simeq 0.015\sqrt{\|t\|}$	$\simeq 0.06\sqrt{\|t\|}$	$\simeq 0.02\sqrt{\|t\|}$

The scattered protons will be detected by telescopes of detectors placed inside Roman pots downstream of the interaction point using the magnet DX to make momentum analysis. The detectors will be located in the vertical plane, symmetrically above and below the machine plane. The horizontal bending of DX allows an almost complete decoupling between the measurement of the scattering angle, essentially given by the vertical coordinate and the measurement of the momentum, obtained from the horizontal coordinate.

A Monte Carlo program was used to study the basic features of the system, such as the acceptance and the resolution in the measurement of the momentum and of the momentum-transfer. Size and angular divergence of the beam at the collision region, as derived from the nominal machine parameters, were taken into account. The expected minimum distance of approach of the detector to the beam was calculated according to Eqn. 9, with k-factor of 20 and $d_0 = 1$ mm and is estimated to be 14 mm.

The transverse coordinates of the collision point were calculated in the Monte Carlo by extrapolating the simulated tracks to the transverse plane at the crossing point and averaging the results from the two arms. The ultimate momentum-transfer resolution is determined by the actual angular spread of the circulating beams, as given by the machine emittance and by the β^*.

The useful momentum-transfer interval is $0.12 < -t < 1.5(\mathrm{GeV}/c)^2$. At large $|t|$, the limitation is due to the aperture of the magnet DX, which cuts at $\theta = 5.4$ mrad.

- At $|t| = 1$ $(\mathrm{GeV}/c)^2$, the expected cross section is around 10^{-3} mb/$(\mathrm{GeV}/c)^2$, and the acceptance of the system is about 0.25. With a luminosity of 10^{31} $\mathrm{cm}^{-2}s^{-1}$, the expected rate is about 10^4 elastic events per day in $|t|$-bin of 0.05 $(\mathrm{GeV}/c)^2$.

- Reconstruction of the interaction vertex possible only in the vertical plane with accuracy $\Delta y_{IP} = 1.0$ mm;

- Momentum resolution is $\Delta p/p \simeq 1.5 \times 10^{-2}$, assuming that the horizontal position of the interaction point is known within ± 3 mm;

- Momentum transfer resolution is $\Delta t = 2.9 \times 10^{-2}(\mathrm{GeV}/c)^2$ at $|t| = 1$ $(\mathrm{GeV}/c)^2$;

- With a trigger subdivision in four contiguous "coincidence roads," particles with $p/p_{beam} < 0.8$ are rejected, at the 90% or better.

4 Spin Physics Program

RHIC will have the unique capability of accelerating polarized protons with a high average polarization, $\sim 70\%$ for each beam, and a high luminosity reaching 2×10^{32} cm^{-2}sec^{-1}. This will enable us to measure the spin dependent parameters of elastic pp scattering at much higher cms energies compared to the highest energy data to date at $\sqrt{s} = 24$ GeV, those measurements performed using a polarized target with unpolarized incident protons. There has been a recent revival of interest in the elastic pp scattering with polarized protons which covers a large spectrum of interesting physics. For instance, the intimate relationship between a sharp zero-crossing of the analyzing power and the dip region in the elastic differential cross-section has continued to be the focus of a number of studies.

If longitudinally polarized protons were available with the aid of spin rotators around the intersection region, one could similarly measure A_L, $\Delta\sigma_L$, and A_{LL}. In addition, this experiment might provide a service to the RHIC Spin Physics program in general by performing an absolute polarization measurement, for use in conjunction with (relative) polarization monitors.

In discussing the polarization data, the s-channel helicity amplitudes [7] for NN elastic scattering $\phi_i\,(i = 1-5)$ are used. It is somewhat more convenient to express these in combinations that explicitly exhibit the t-channel exchange characteristics at high energy:$N_0 = 1/2(\phi_1 + \phi_3)$, $N_1 = \phi_5$, $N_2 = 1/2(\phi_4 - \phi_2)$, $U_0 = 1/2(\phi_1 - \phi_3)$, $U_2 = 1/2(\phi_4 + \phi_2)$. The N and U amplitudes correspond respectively to natural and unnatural- parity exchanges; the subscripts $0, 1$ and 2 correspond to the total s-channel helicity flip involved.

The previously mentioned variables describing spin related assymmetries can be expressed in terms of these amplitudes. The analyzing power A_N:

$$A_N \frac{d\sigma}{dt} = -2\frac{(\hbar c)^2}{16\pi K^2}\mathrm{Im}[(N_0 - N_2)N_1^*], \tag{11}$$

where the spin-averaged differential cross section is

$$\frac{d\sigma}{dt} = \frac{(\hbar c)^2}{16\pi K^2}[|N_0|^2 + 2|N_1|^2 + |N_2|^2 + |U_0|^2 + |U_2|^2], \tag{12}$$

where $K = \sqrt{s(s-4m^2)}$.

In the CNI region the electromagnetic and hadronic amplitudes are of comparable magnitude in the very forward direction, and this results in a small but significant asymmetry A_N in pp scattering near the point of maximum interference [8, 9]. The interference between the hadronic non-flip and the electromagnetic spin-flip amplitudes gives rise to this asymmetry expected to be about 3.7%.

The double-spin asymmetry parameter is expressed as:

$$A_{NN} \frac{d\sigma}{dt} = 2\frac{(\hbar c)^2}{16\pi K}\mathrm{Re}[U_0 U_2^* - N_0 N_2^* + |N_1|^2]. \tag{13}$$

The difference in the total cross-sections as a function of the initial transverse polarization states is:

$$\Delta\sigma_T = \{\sigma_{tot}(\uparrow,\downarrow) - \sigma_{tot}(\uparrow,\uparrow)\}, \\ = \frac{(\hbar c)^2}{K}\mathrm{Im}(N_2 - U_2). \tag{14}$$

The features outlined above have stimulated a number of discussions on a possible hadronic spin-flip contribution $N_1^{(h)}$ that does not necessarily decrease as $1/\sqrt{s}$. It was suggested that diffractive scattering with exchange of two pions could become important at large s; this mechanism can cause a non-vanishing $N_1^{(h)}$ because one of the two pions can couple with spin-flip, while the other does not [10]. It was also pointed out that $N_1^{(h)}$ might remain non-zero at high energies if the nucleon contains a dynamically enhanced compact diquark component [11].

Polarization studies in the new energy domain of RHIC will probe, at the level of helicity amplitudes, the complex structure of Pomeron at the constituent scale [12]. An additional O-exchange might provide the necessary phase difference with P to obtain an essentially energy independent spin asymmetry [13].

In general, within the emerging QCD-inspired picture of elastic scattering, new polarization results at large $|t|$-region can be discriminating between models that invoke hard (perturbative) and soft (non-perturbative) processes where these models overlap [14].

In order to clarify the issue of diffractive (Pomeron) spin-flip, it would be important to have more and more precise polarization asymmetry data in the low $|t|$-region [15]. There is no measurement to this day in the range of $0.05 \leq |t| \leq 0.15$ $(\mathrm{GeV}/c)^2$. This deficiency has also been pointed out in a recent paper [16] where small-angle polarization is discussed in terms of non-perturbative instanton-like contributions of the gluonic field. In more general terms, it has also been suggested that, with the injection of QCD concepts in the picture of elastic scattering, the kinematic region $|t| \approx \Lambda_{QCD}^2$ ($\Lambda_{QCD} = 0.15$ GeV/c) might be of special interest [17].

With both RHIC colliding beams polarized, the double-spin correlation parameter A_{NN} could also be measured up to rather large $|t|$-values. In this case, it will also be possible to investigate the puzzling observations of large differences between parallel and antiparallel spin cross-sections observed at ZGS around 12 GeV/c. From these measurements it appears that two protons interact harder when their spins are parallel. However it is not clear if this effect would persist at high energies.

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