Study of elastic proton-proton scattering with the STAR detector at RHIC

Rafal Sikora

AGH University of Science and Technology, Mickiewicza Ave 30, PL 30-059 Krakow, Poland

ABSTRACT

The STAR detector at the Relativistic Heavy Ion Collider (RHIC) is equipped with a system of dedicated Silicon Strip Detectors housed inside Roman Pot vessels, allowing to detect protons scattered at small angles. Data from polarized proton-proton collisions at center-of-mass system (c.m.s.) energy $\sqrt{s} = 200$ GeV collected with special settings of RHIC magnet lattice ($\beta^* = 22$ m) allow to study proton-proton elastic scattering at very low values of squared four-momentum transfer (Mandelstam $t$), $0.003 \leq -t \leq 0.035$ GeV$^2$/c$^2$. Results of analysis of systematic effects and large statistics of collected data sample reveal possibility of measurement of the Nuclear Slope Parameter with precision not yet achieved at this c.m.s. energy.

Keywords: elastic scattering, Nuclear Slope Parameter, diffraction, silicon strip detector

1. INTRODUCTION

Over last few decades diffractive processes in high-energy physics have been one of the major research topics for both theoretical and experimental physicists. Characterized by large spatial (rapidity) separation between final state particles, diffractive interactions are understood as occurring through exchange of the QCD color singlet, the Pomeron in the framework of Regge theory (for review see e.g. Ref. $^1,^2$). Although experimental definition of particle diffraction is relatively well established, theoretical description, especially in low-$t$ domain, still requires new measurements in this field.

Elastic scattering of hadrons is an example of diffractive process, in which colliding particles stay intact after the collision and no other states are produced (Fig. 1). The differential cross-section exhibits exponential behavior typical for Pomeron exchange, namely

$$\frac{d\sigma_{el}}{dt} \propto e^{-B|t|},$$

where $B$, the Nuclear Slope Parameter, which determines the slope of the forward scattering peak, contains an

Figure 1: Schematic diagram of elastic scattering of the opposite-momentum particles in the laboratory frame. Arrows mark incident (red) and scattered (blue) particles momenta. Interaction can be described with use of two angles, the scattering angle $\theta$ and the azimuthal angle $\varphi$, defined in the Figure.
information about the size of scattering object, like the size of an obstacle on which incoming wave diffracts (in analogy to diffraction of light).

The STAR experiment conducts research in diffractive physics using system of forward proton detectors, as well as unprecedented RHIC capability of colliding polarized proton beams. Recent results on central exclusive production\cite{3} and spin asymmetries in elastic scattering\cite{4} prove scientific potential of data collected by the experiment.

In this paper I would like to report studies of elastic proton-proton scattering with the STAR detector, emphasizing possibility of measurement of the Nuclear Slope Parameter with high accuracy and thereby valuable improvement of the past result\cite{5} obtained by the PP2PP experiment.\cite{6}

2. EXPERIMENTAL SETUP

Presented study is based on data collected by the STAR experiment during 5-day period of proton-proton collisions with special beam optics\cite{7} of $\beta^* = 22$ m, which provided suitable conditions for elastic scattering measurement in terms of beam emittance and luminosity. Total of 32 million elastic triggers were recorded. Eight detector packages were located on both sides of STAR central detector in a distance of 55.5 m (horizontal detectors) and 58.5 m (vertical detectors) from the nominal interaction point (IP), downstream of the quadrupole triplets (Fig. 2). Each package contained four Silicon Strip Detectors\cite{6} (SSDs) with an active area of approximately $79$ mm $\times$ $49$ mm and the trigger detector built of plastic scintillator ($8$ cm $\times$ $5$ cm $\times$ $8$ mm) connected to two photomultiplier tubes. Two types of SSDs with vertical and horizontal orientation of strips were installed in the package (a pair of each type) to measure both $x$ and $y$ coordinate of particle in plane perpendicular to the outgoing beam ($z$-axis). Close approach of SSD packages to the beam was ensured by specially designed steel vessels, so-called Roman Pots (RPs), separating vacuum in the beampipe from the air outside, thereby providing room for detector packages placed inside. Thickness of steel window through which scattered protons enter RP was reduced to $300$ $\mu$m in order to minimize probability of secondary interaction. Minimum beam-detector distance reached during data-taking, which defines lower bound of scattering angle acceptance, was about $8$ mm, what translates to approximately $10\sigma$ of transverse beam size.

![Figure 2: Layout of the Roman Pot detector system in STAR (scale not preserved). Two detector stations, RP1 and RP2, each composed of a pair of RPs placed on two sides of the beampipe, are located on both sides of IP in a distance of 55.5 m (horizontal RPs) and 55.8 m (vertical RPs) from IP, behind two RHIC dipoles (DX and D0) and three quadrupoles (Q1, Q2 and Q3).\cite{8}](image)

3. DATA SELECTION AND ANALYSIS

Selection of elastic scattering events started from reconstruction of proton tracks, which involved matching of clusters, basic data structures formed of adjacent strips with signal strength exceeding average noise level by 5 standard deviations. As depicted in Fig. 3, in more than 90% of events there was exactly one cluster per silicon plane in a pair of SSDs measuring the same coordinate of particle (only events with at least one cluster in total were accounted). Furthermore, over 80% of clusters consisted of single strip (see Fig. 4), what ensures high
tracking resolution of single SSD, by design equal 100 µm (strip pitch)/√12 ≈ 29 µm. Clusters in two detector planes were considered to match if the difference of their position

$$\delta q \equiv q_1 - q_2$$

satisfied condition

$$|\delta q - \langle \delta q \rangle| \leq 2 \times \text{pitch} \approx 200 \mu m,$$

which required distance between the two to be smaller than size of two strip pitches. Aim of such condition was to reject background hits and small amount of noise in the silicon detectors. Due to imperfect alignment of SSDs inside a package a non-zero offset $$\langle \delta q \rangle$$ had to be accounted, which was extracted from the data for each SSD pair. Fig. 5 presents typical distribution of $$\delta q$$, where distinctive central peak corresponds to well matched cluster pairs. Once the matching procedure was successfully performed, positions of clusters (both in x- and y-type SSDs) were averaged and full proton track in RP was reconstructed. Overlap of horizontal and vertical detectors in xy-plane allowed investigation of reconstruction (including detection) efficiency which turned out to be higher than 98%.

Figure 3: Number of clusters in corresponding SSDs. Labeling $$n/m$$ denote $$n$$ clusters in first and $$m$$ clusters in second SSD of the same type, respectively.

Figure 4: Length (number of constituent strips) of clusters in single SSD.

Figure 5: Difference of clusters positions measured in two SSDs of the same type. All clusters combinations are contained. Dashed vertical lines denote matching condition from Ineq. (3).
Events with tracks reconstructed in detectors lying on the opposite sides of IP were selected for further analysis. Coordinates of detected proton hits were translated into scattering angle components at IP with help of linear transport matrices that describe relation between position and angle at vertex and corresponding quantities at the location of detectors. Dedicated beam optics provided almost direct dependence of position in RP on the primordial angles in IP, therefore for protons carrying the beam momentum, what is the case in elastic interaction, it was possible to use simplified relation

$$\theta_x(y) \approx \frac{x(y)}{L_{x(y)}^{\text{eff}}},$$

where $\theta_x(y)$ denote $x(y)$ scattering angle component at the IP ($\theta^2 \approx \theta_x^2 + \theta_y^2$) and $L_{x(y)}^{\text{eff}}$ is an effective focal length of the magnet system in $x(y)$ coordinate, varying between 23-25 m depending on the RP station. In order to separate true elastic scattering events from accidental coincidences, further referred to as a background, a quantity

$$\Delta \theta_x(y) \equiv \theta_x^{W(y)} + \theta_x^{E(y)}$$

was defined for both $\theta_x$ and $\theta_y$. Due to back-to-back property of elastically scattered protons $\Delta \theta_x(y)$ peaks at zero and therefore was used to select elastic events. Indices $W$ and $E$ in Eq. (5) refer to West and East side of the IP, respectively. Sample two-dimensional distribution of collinearity of opposite track pairs is presented in Fig. 6. One can distinguish a prominent central peak with small addition of points spread around it. Width of the distribution is dominated by the angular divergence of the beam, a measure of deviation of protons momenta from the average direction of motion ($z$-axis). Typical RMS value of the difference of scattering angle components of west and east tracks was found to be $\sigma_{\Delta \theta_x} \approx \sigma_{\Delta \theta_y} \approx 55 \mu\text{rad}$, indicating 40 $\mu\text{rad}$ divergence of a single beam. Finally, tracks were considered elastic once inequality

$$\left(\frac{\Delta \theta_x - \langle \Delta \theta_x \rangle}{\sigma_{\Delta \theta_x}}\right)^2 + \left(\frac{\Delta \theta_y - \langle \Delta \theta_y \rangle}{\sigma_{\Delta \theta_y}}\right)^2 < n_{\text{cut}}^2$$

Figure 6: Typical collinearity distribution of reconstructed elastic track candidates. Cyan dashed ellipse surrounds region given by Ineq. (6) with collinearity parameter $n_{\text{cut}} = 3.5$.

Figure 7: Projection of Fig. 6 onto horizontal (a) and vertical (b) axis with signal and background fits.
Figure 8: An example of hit map of reconstructed elastic track candidates in two horizontal detectors before (a) and after (b) collinearity cut applied ($n_{cut} = 3.5$). Point (0,0) indicates position of the beam.

was satisfied, in which $n_{cut}$ parameter defines maximum tracks deviation from ideal collinearity ($\langle \Delta \theta_x \rangle$, $\langle \Delta \theta_y \rangle$) in units of $\sigma_{\Delta \theta_x}$ and $\sigma_{\Delta \theta_y}$. In analysis $n_{cut} = 3.5$ was used, what resulted in total number of 22 M reconstructed elastic scattering events. Amount of background contained in the sample was estimated from the ratio of integrals of signal to signal with background functions fitted to one-dimensional collinearity distributions (Fig. 7a and 7b). In horizontal detectors level of background never exceeded 2%, whereas in vertical detectors contamination was typically close to 5%, thus given sufficiently high statistics it was decided to only use data from horizontal RPs for the Nuclear Slope Parameter extraction. Effectiveness of the collinearity cut is evident if one compares map of elastic track candidates before (Fig. 8a) and after (Fig. 8b) application of condition (6). Events with tracks on detector edges close to the beam were mainly rejected, whose source lies most likely in the beam halo, that is peripheral protons of the beam coincidentally detected in the opposite RPs. Also tracks placed outside the limiting aperture of quadrupoles were discarded, which by definition could not originate from elastic interactions.

Inclination of the scattering plane in the laboratory frame $\varphi$ and squared four-momentum transfer $t$, quantities that carry information about the physics of elastic interaction, were calculated with the use of Eq. (7) and (8):

$$\varphi = \arctan \frac{\theta_y}{\theta_x},$$

$$t = -4p^2 \sin^2 \frac{\theta}{2} \approx -p^2 \theta^2,$$

where all angles were averaged over two opposite proton tracks. Nominal beam momentum $p = 100.2$ GeV/c was used in the calculations. Detailed understanding of detector effects was provided by specially implemented GEANT4 model of the Roman Pot system, including dedicated Monte Carlo generator with simulation of the beam conditions (e.g. angular divergence, longitudinal bunch profiles), readout from SSDs, Roman Pots positioning and timing effects in the triggering system. Described simulation was used to determine detector geometrical acceptance and total efficiency, as shown in Fig. 9. Straight cut in azimuthal angle was chosen to balance the widest possible $t$ range of uniform geometrical acceptance and the highest possible statistics in that range. Thus, $\Delta \varphi$ interval of 1.8 rad was found to be most suitable option. Reconstructed $t$ distributions were corrected for acceptance and, finally, the differential cross-section $d\sigma_{el}/dt$ was fitted in the $t$ range of flat geometrical acceptance obtained with the simulation. Sample distribution of squared four-momentum transfer in elastic scattering events is contained in Fig. 10. It should be noted, that fit was performed using full differential cross-section formula (given e.g. in Ref. 5), taking into account electromagnetic part of the cross-section (Coulomb scattering, dominant only up to 0.003 c²/GeV² at this c.m.s.) and Coulomb-nuclear interference.
An important part of analysis consisted in determination of systematic uncertainty of the $B$ parameter, summarized in Tab. 1. Four substantial sources of errors were studied in terms of their influence on the output value of the cross-section fits. The largest contribution to the total systematic error had uncertainty of the elements of transport matrices, mainly $L_{y}^{\text{eff}}$ and $L_{y}^{\text{eff}}$ (1% error based on Ref. 7). The next were: accuracy of fitting range determined with the simulation, restrictiveness of collinearity cut, and positioning of Roman Pots in relative to the beam trajectory. Total systematic uncertainty was estimated on $\delta B_{\text{sys.}} = +0.85 - 0.46 c^2/\text{GeV}^2$. Statistical uncertainty was extracted from the fits of theoretical formula to the measured $t$ distributions, $\delta B_{\text{stat.}} = \pm 0.20 c^2/\text{GeV}^2$. Comparison of $\delta B_{\text{stat.}}$ and $\delta B_{\text{sys.}}$ with corresponding errors of the earlier Nuclear Slope Parameter measurement, $B = 16.3 \pm 1.6(\text{stat.}) \pm 0.9(\text{sys.}) c^2/\text{GeV}^2$, reveals over two times higher precision achieved in the STAR experiment, primarily due to reduction of statistical uncertainty facilitated by significantly larger data sample.

<table>
<thead>
<tr>
<th>Systematic error $\delta B_{\text{sys.}}$</th>
<th>$t$-range of the fit</th>
<th>detector position w.r.t. the beam</th>
<th>transport matrices</th>
<th>collinearity cut</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$+0.52$</td>
<td>$+0.37$</td>
<td>$+0.35$</td>
<td>$-0.46$</td>
<td>$+0.45$</td>
<td>$+0.85$</td>
</tr>
</tbody>
</table>

4. SUMMARY

Analysis of elastic proton-proton scattering based on the data collected by the STAR experiment at $\sqrt{s} = 200$ GeV has been presented. Reconstruction algorithm in Silicon Strip Detectors was described, whose efficiency was evaluated to be 98%. 22 M elastic scattering events were selected, with less than 5% of background contamination. Differential cross-section fits to reconstructed distributions of Mandelstam $t$, connected with tests of influence of variation of a few major quantities on resultant value of the Nuclear Slope Parameter, led to estimate of total uncertainty of the $B$ parameter equal $\delta B = \pm 0.20(\text{stat.})^{+0.45}_{-0.46}(\text{sys.}) c^2/\text{GeV}^2$. Such result indicates more than two times better precision possible to achieve with data from STAR detector comparing to past measurement of the Nuclear Slope Parameter done by the PP2PP experiment.

REFERENCES


