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Elastic proton-proton scattering at RHIC

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Abstract. Here we describe elastic proton+proton (p+p) scattering measurements at RHIC in p+p collisions with a special optics run of $\beta^{\star} \sim 21$ m at STAR, at the center-of-mass energy $\sqrt{s} = 200$ GeV during the last week of the RHIC 2009 run. We present preliminary results of single and double spin asymmetries.

1. Introduction and theoretical formalism

Elastic scattering of polarized protons at small four momentum transfer squared $-t$ is described by interference of Coulomb and nuclear amplitudes. Coulomb amplitude is calculable by QED and such interference provides a unique opportunity to study the dynamics of the strong interaction in the nonperturbative region. The total cross section was measured to very high energy and turned out to be in a good agreement with the description by the Regge pole exchange. At ultra relativistic energies the main contribution comes from Pomeron or, in modern terms, multigluon exchange [1]. Most of the previous experiments were done with unpolarized beams and targets. The first measurement with polarized protons at high energies in the Coulomb nuclear interference (CNI) region ($\sqrt{s} = 19.4$ GeV was done in E704 experiment [2] with moderate precision. RHIC with its polarized beams [3] published a number of accurate measurements with $\sqrt{s} = 6.8 - 21.7$ GeV [4, 5] in last few years. But only one measurement with a limited statistics exists so far in the collider energy range [7].

Elastic scattering of two identical particles with spin $\frac{1}{2}$ is described by 5 helicity amplitudes [8, 9]. Two amplitudes $\phi_1(s,t) =< ++|M|++>$ and $\phi_3(s,t) =< +-|M|+->$ produce no spin-flip, two other $\phi_2(s,t) =< ++|M|-->$ and $\phi_4(s,t) =< +-|M|-+>$ produce double spin-flip and the last $\phi_5(s,t) =< ++|M|+->$ produces single spin-flip. Each of the amplitudes can be written as a sum of hadron and Coulomb amplitudes $\phi_i = \phi_i^{em} + \phi_i^h$. Electromagnetic part is calculable from QED. It is believed that the main hadron contribution to the cross section comes from non-flipping amplitudes so the optical theorem could be written as $\sigma_{tot} = \frac{4\pi}{s} Im(\phi_1 + \phi_3)|_{t=0}$. Other hadron amplitudes are expected to be small and are parametrized in terms of $Im\phi_+ = Im(\phi_1 + \phi_3)/2$:

$$\phi_2 = 2r_2 Im\phi_+ \quad \phi_4 = \frac{-t}{m^2} r_4 Im\phi_+ \quad \phi_5 = \frac{\sqrt{-t}}{m} r_5 Im\phi_+ \tag{1}$$

The differential cross section and asymmetries can be written in terms of the amplitudes:

$$\frac{d\sigma}{dt} = \frac{2\pi}{s^2}(|\phi_1|^2 + |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2) \tag{2}$$

$$A_N \frac{d\sigma}{dt} = -\frac{4\pi}{s^2} Im\{\phi_5^*(\phi_1 + \phi_2 + \phi_3 - \phi_4)\} \quad (3)$$

$$A_{NN} \frac{d\sigma}{dt} = \frac{4\pi}{s^2}\{2|\phi_5|^2 + Re(\phi_1^*\phi_2 - \phi_3^*\phi_4)\} \quad , A_{SS}\frac{d\sigma}{dt} = \frac{4\pi}{s^2}\{Re(\phi_1\phi_2^* + \phi_3\phi_4^*)\} \quad (4)$$

where A_N is the single spin asymmetry and A_{NN} and A_{SS} are the double spin asymmetries.

2. Experiment

The layout of the experiment is shown in Fig. 1. Protons scattered at very small angles at the interaction point (IP) travel inside the beam pipe utill they reach the Roman Pot (RP) detectors located in the RHIC tunnel on both sides of the STAR detector. Each RP contains four silicon microstrip detectors and a trigger scintillation counter. During the 2009 run, we were able to insert RP detectors to be as close as 12 σ (σ being the beam size) from the center of the beam pipe. Two RP's with detectors inserted horizontally (at 55.5 m from IP) and another two RP's vertically (at 58.5 m) were used at each side of IP. More details of the detectors can be found in [11]. The coordinates measured by the detectors relate to the scattering angles at IP by the transport matrix:

$$\begin{pmatrix} x \\ y \end{pmatrix}_{RP} = T_{RP} \cdot \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix}_{IP}, \quad (5)$$

where index $_{RP}$ denotes a particular Roman Pot. The positions of the RP's were selected so that the error introduced by unknown position of the interaction point was minimal. More details on the detector layout, alignment and performance can be found at [12].

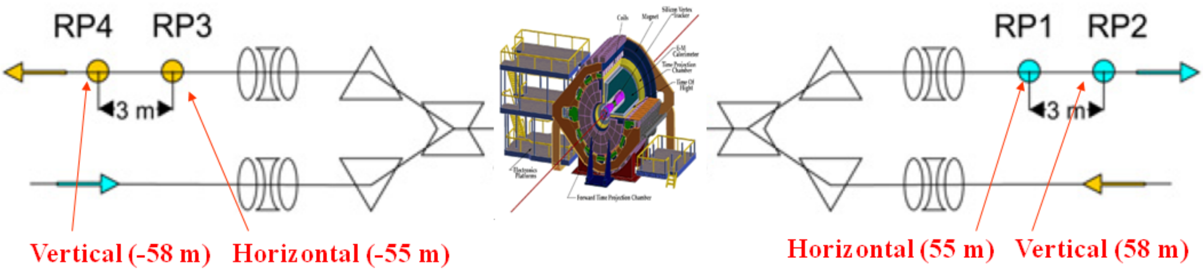

Figure 1. Layout of the setup for small-t measurements with the STAR detector (in the center).

3. Analysis

Elastically triggered events were selected for rescontructions and the cuts are briefly described below.

(A) Clusters of consecutive strips with charge values above 5σ from their pedestals were found. We ignore rare clusters larger then 5 strips, because there were a lot of noise among them.

(B) A threshold depending on the cluster width was applied to the total charge of each cluster. This gave us better signal to noise ratio for clusters of 3 and 4 strips. After these cuts we had individual plane efficiencies above 99% as shown in Fig. 3.

(C) Clusters in the planes of the same orientation (horizontal/x or vertical/y) within the same RP were merged and we required that their coordinates were within 200 μm (2 strips) from each other.

(D) Clusters in x and y orientations form a track and opposite pairs of tracks formed from each side of the IP were chosen.

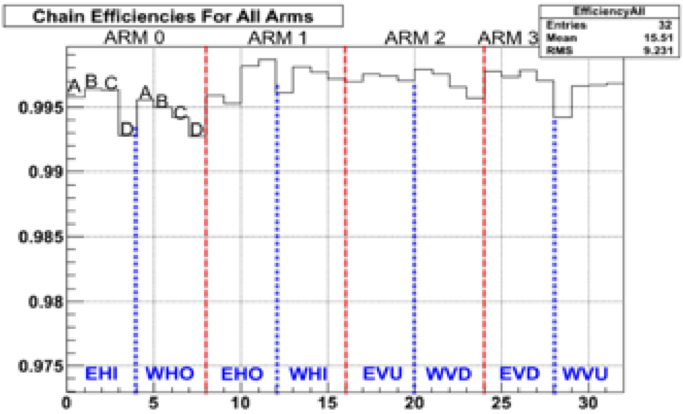

Figure 2. Calculated efficiency of each Si detector plane/chain (A,B,C,D), in each elastic arm (end and dead strips excluded): Arm 0 (EHI-WHO or east horizontal inner - west horizontal outer detectors); Arm 2 (EVU-WVD or east vertical up and west vertical down detectors); Arm 1 and Arm 3 likewise.

(E) Transport equation (5) was solved for each side.

(F) The strongest criteria of elastic events selection is the collinearity cut which was realized by requiring χ^2,where $\chi^2 = (\theta_x^{west} - \theta_x^{east})^2/\sigma_x^2 + (\theta_y^{west} - \theta_y^{east})^2/\sigma_y^2$ and σ_x and σ_y are typically 0.057 mrad, to be < 9. The correlation between the angles can be seen in Fig. 3.

About 21 millions events out of about 33 million elastic triggers written during the run were selected for asymmetry calculations.

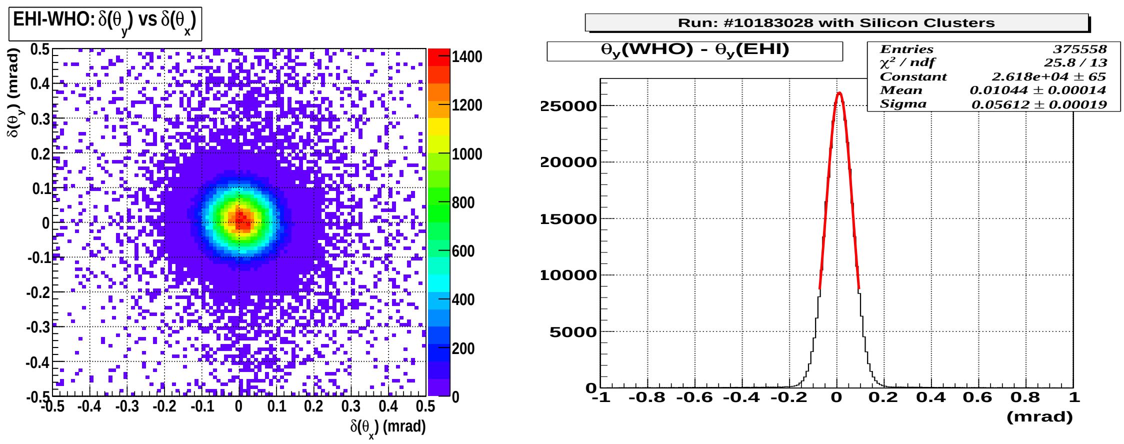

Figure 3. Elastic correlation — difference in scattering angles at IP for particles scattered to the east and west in x and y in 2 dimensions (on the left) and 1 dimension (on the right).

Using the square root formula [6, 7], raw asymmetry as function of azimuthal angle ϕ for only ++ and $--$ bunch polarizations can be written as:

$$\epsilon_N(\phi) = \frac{(P_B + P_Y)A_N\cos(\phi)}{1 + \delta(\phi)} = \frac{\sqrt{N^{++}(\phi)N^{--}(\pi-\phi)} - \sqrt{N^{--}(\phi)N^{++}(\pi-\phi)}}{\sqrt{N^{++}(\phi)N^{--}(\pi-\phi)} + \sqrt{N^{--}(\phi)N^{++}(\pi-\phi)}}, \quad (6)$$

where $\delta(\phi) = P_B P_Y (A_{NN}\cos^2(\phi) + A_{SS}\sin^2(\phi))$, $N^{ij}(\phi)$ - number of events with bunch polarization pattern ij at the azimuthal angle ϕ. $P_{B/Y}$ are polarizations of the blue and yellow beams, measured by HJET and pCarbon polarimeters [13]. The polarization values averaged for the time of our data taking were: $P_B + P_Y = 1.224 \pm 0.066$, $P_B - P_Y = -0.016 \pm 0.066$ and $P_B P_Y = 0.375 \pm 0.041$ (errors shown here include global systematic uncertainties). From double spin asymmetries measured by [7] we know that $\delta(\phi)$ is less than 0.01. Using other different bunch polarization combinations, other raw asymmetries can be introduced similarly to (6); particularly, the so-called "wrong combination" is shown here:

$$\epsilon'_N(\phi) = \frac{(P_B + P_Y)A_N \cos(\phi)}{1 - \delta(\phi)} = \frac{\sqrt{N^{+-}(\phi)N^{-+}(\pi-\phi)} - \sqrt{N^{-+}(\phi)N^{+-}(\pi-\phi)}}{\sqrt{N^{+-}(\phi)N^{-+}(\pi-\phi)} + \sqrt{N^{-+}(\phi)N^{+-}(\pi-\phi)}}, \qquad (7)$$

The preliminary results of $\epsilon_N(\phi)$ and $\epsilon'_N(\phi)$ are presented in Fig. 4 for $0.005 < |t| < 0.010$ (GeV/c)^2. Using (6), we fitted the raw asymmetry to extract A_N's in 5 t-bins.

Double spin raw asymmetry is given by the equation:

$$\delta(\phi) = P_B P_Y (A_{NN}\cos^2(\phi) + A_{SS}\sin^2(\phi)) = \frac{(\frac{N^{++}}{L^{++}} + \frac{N^{--}}{L^{--}}) - (\frac{N^{+-}}{L^{+-}} + \frac{N^{-+}}{L^{-+}})}{(\frac{N^{++}}{L^{++}} + \frac{N^{--}}{L^{--}}) + (\frac{N^{+-}}{L^{+-}} + \frac{N^{-+}}{L^{-+}})} \qquad (8)$$

Here L^{ij} are relative luminosities for the corresponding polarization pattern. For the preliminary results we used relative luminosities obtained from counts of inelastic triggers produced by the vertex position detector (VPD) and beam-beam counters (BBC). The systematic uncertainty in the normalization can be estimated by the difference between VPD and BBC normalizations which turned out to be 0.25%. We hope to reduce this uncertainty taking advantage of other normalization sources.

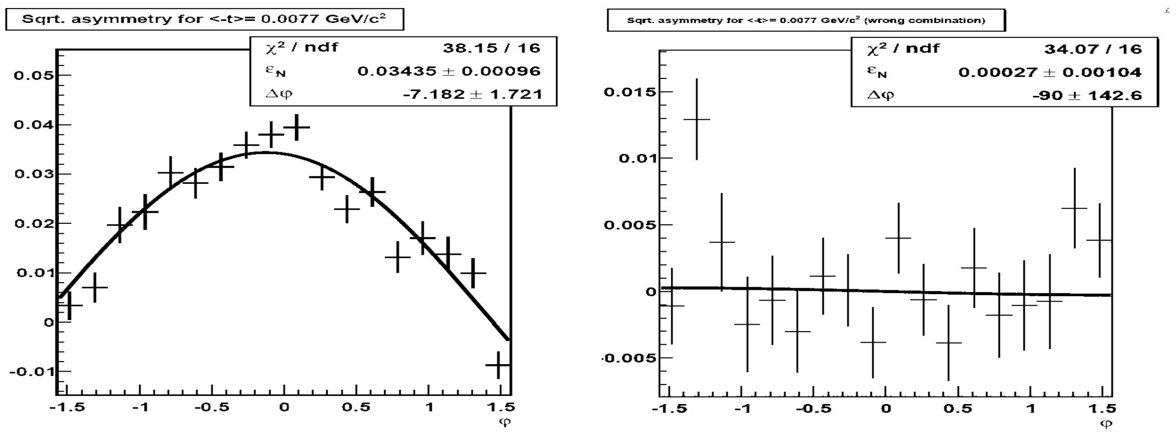

Figure 4. STAR Preliminary: raw single spin asymmetries ϵ_N (left) and ϵ'_N (right) for $0.005 < |t| < 0.010$ (GeV/c)^2.

4. Results

The preliminary results on the single spin asymmetry are shown in Fig. 5 in comparison with theoretical curve without hadron spin-flip (black line) and with the best fit allowing non zero hadron spin-flip (green line) (see [14] for formula). Only statistical errors have been included. Fig. 6 shows fitted value of r_5 with contours showing confidence levels of 1, 2 and 3σ. No evidence for contribution of hadron spin-flip amplitude ϕ_5 is seen.

The preliminary results on double spin asymmetries are shown in Fig. 7. Though some effects of the order of 10^{-3} could be seen, they are small and comparable with the normalization uncertainty. A careful study of systematic effects produced by normalization should be done before making any conclusions.

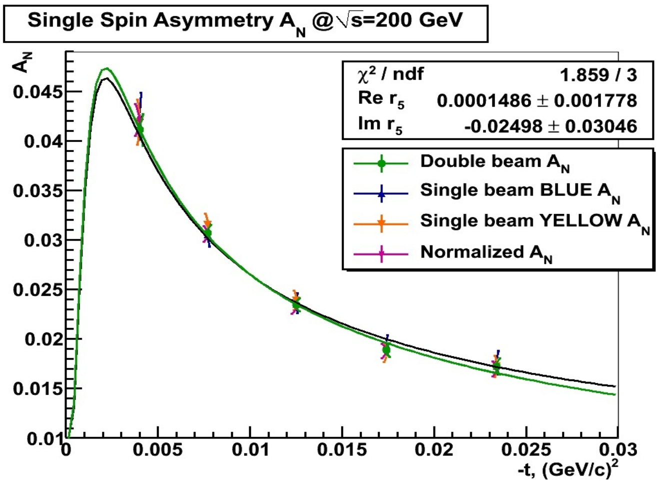

Figure 5. STAR Preliminary: single spin asymmetry A_N.

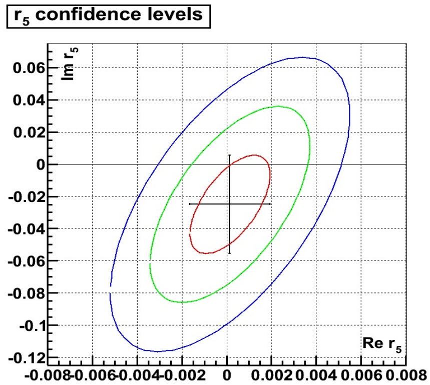

Figure 6. STAR Preliminary: complex plane of parameter r_5 with contours of confidence level: 1, 2 and 3-σ.

Our preliminary results agree with the hypothesis that only Pomeron exchange, which contributes only to spin non-flipping amplitudes ϕ_1 and ϕ_3, survives at high energies. with other aforementioned measurements of the proton-proton elastic scattering with $\sqrt{s} > 10$ GeV, we see no evidence of contribution of other amplitudes.

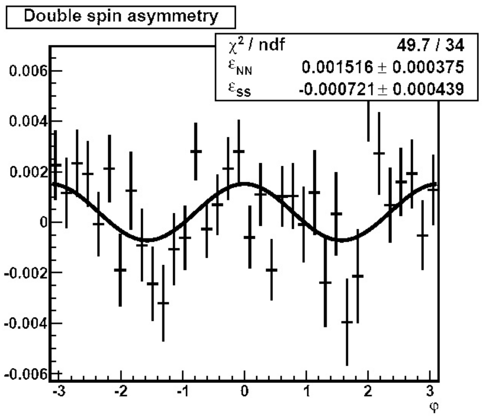

Figure 7. STAR Preliminary results on raw double spin asymmetry.

5. Summary

We had a very successful run with the physics program with tagged forward protons at RHIC in 2009, in which nearly 33 million events with elastic triggers were collected. We have so far focussed on data analyses in elastic scattering topics such as A_N, r_5, A_{NN} and A_{SS}. We are finalizing our optimizations and systematic studies in our analyses and hope to have final results in near future. There is certainly more to do to fully explore physics potential and discovery possibilities at RHIC.

Acknowledgments

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