

Physics with Tagged Forward Protons at RHIC[§]

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Abstract: Here we describe diffractive measurements at RHIC in proton+proton collisions with a special optics run of $\beta^* \sim 21$ m at STAR, at the center-of-mass energy $\sqrt{s} = 200$ GeV during the the RHIC 2009 run. We present published results of single spin asymmetry as well as preliminary results on double spin asymmetries and central exclusive production.

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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] a few years ago. But only one measurement with a limited statistics exists so far in the collider energy range [6].

Elastic scattering of two identical particles with spin $\frac{1}{2}$ is described by 5 helicity amplitudes [7, 8]. Two amplitudes $\phi_1(s, t) = \langle ++ | M | ++ \rangle$ and $\phi_3(s, t) = \langle +- | M | +- \rangle$ produce no spin-flip, two other $\phi_2(s, t) = \langle ++ | M | -- \rangle$ and $\phi_4(s, t) = \langle +- | M | -+ \rangle$ produce double spin-flip and the last $\phi_5(s, t) = \langle ++ | M | +- \rangle$ produces single spin-flip. Each

of the amplitudes can be written as a sum of hadronic and Coulomb amplitudes $\phi_i = \phi_i^{em} + \phi_i^h$. Electromagnetic part is calculable from QED. It is believed that the main hadronic contribution to the cross section comes from non-flipping amplitudes so the optical theorem could be written as

$\sigma_{tot} = \frac{4\pi}{s} \text{Im}(\phi_1 + \phi_3)|_{t=0}$. Other hadron amplitudes are expected to be small and are parametrized in terms of $\text{Im}\phi_+ = \text{Im}(\phi_1 + \phi_3)/2$:

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

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

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

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

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

$$A_{SS} \frac{d\sigma}{dt} = \frac{4\pi}{s^2} \{\text{Re}(\phi_1 \phi_2^* + \phi_3 \phi_4^*)\}$$

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 until 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 about 12σ (σ being the beam size) or 10 mm from the center of the beam pipe. Two RP's with

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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 [9]. 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 β^* at STAR during our special run was about 21 m and the RP's were positioned to give us a parallel-to-point focusing optics. As a result, 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 [10].

3. ANALYSIS

Elastically triggered events were selected for reconstructions 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 than 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%.
- (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 $200 \mu\text{m}$ (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.
- (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 $\chi^2 = (\theta_x^{\text{west}} - \theta_x^{\text{east}})^2 / \sigma_x^2 + (\theta_y^{\text{west}} - \theta_y^{\text{east}})^2 / \sigma_y^2$ and σ_x and σ_y are typically $\approx 58\mu$ rad, to be <9 . The correlation between the angles can be seen in Fig. (2).

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

Using the square root formula [6, 11], raw asymmetry as function of azimuthal angle ϕ for only ++ and -- bunch polarizations can be written as:

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

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 [12]. The polarization values averaged for the time of our

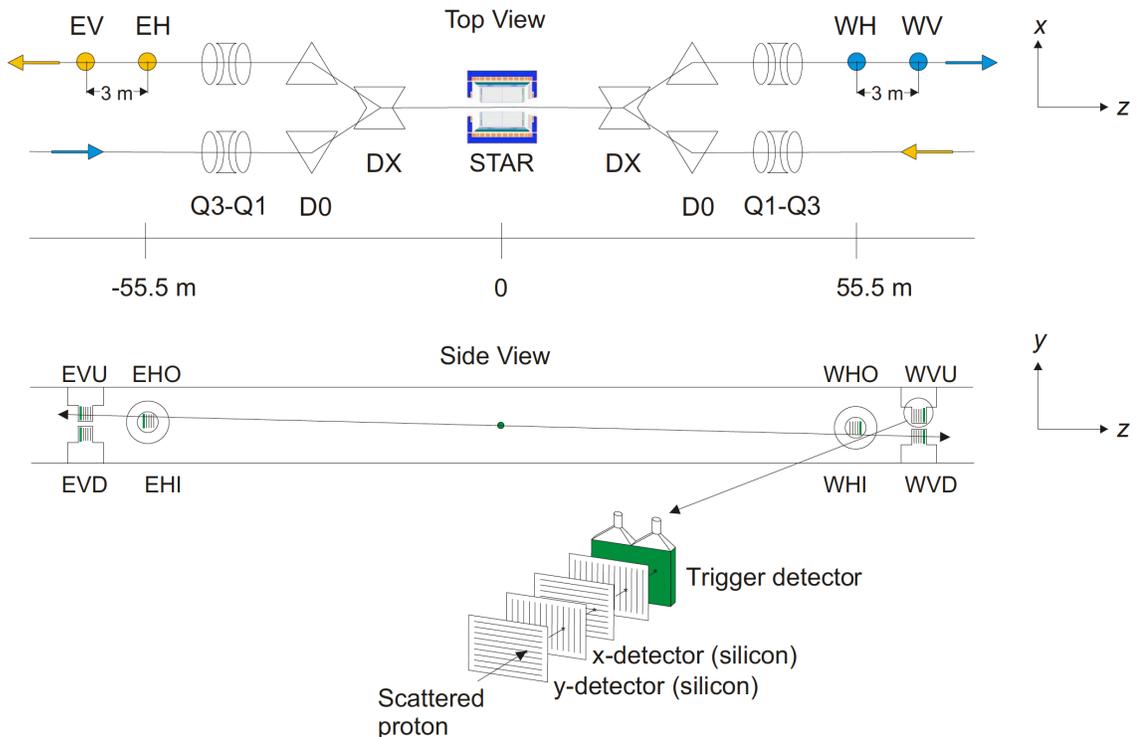


Fig. (1). Layout of the setup for small-t measurements with the STAR detector (in the center).

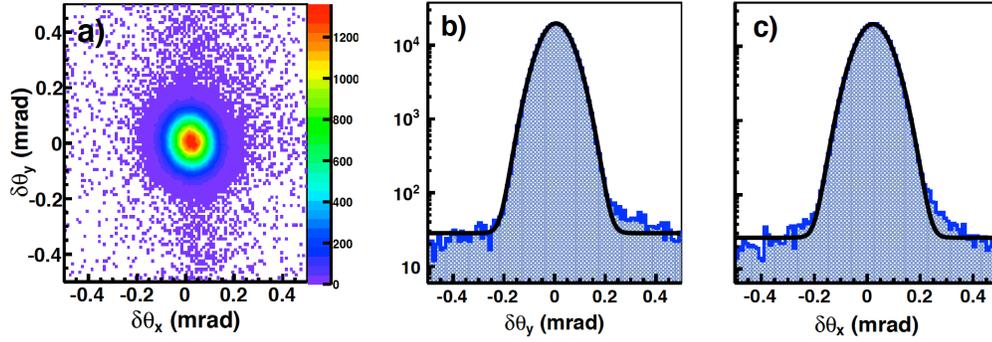


Fig. (2). (color online) Distribution of $\delta\theta_y$ vs $\delta\theta_x$ for both detector pairs in horizontal RPs (a) and their projections in $\delta\theta_y$ (b) and $\delta\theta_x$ (c). The overlaid curves represent the fits with a Gaussian signal and a linear background. The σ values of distributions are $\approx 58 \mu\text{rad}$, consistent with beam angular divergence, and the background-to-signal ratio under the Gaussian distributions in $\pm 3\sigma$ is $\approx 0.4\%$.

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 [6], 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:

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

The results of $\varepsilon_N(\phi)$ for 5 t -intervals and $\varepsilon'_N(\phi)$ for the whole t -range are presented in Fig. (3). Using (6), we fitted the raw asymmetry to extract A_N 's in 5 t -bins.

Double spin raw asymmetries A_{NN} and A_{SS} can be extracted from the following equation (as there is no square root formula available):

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

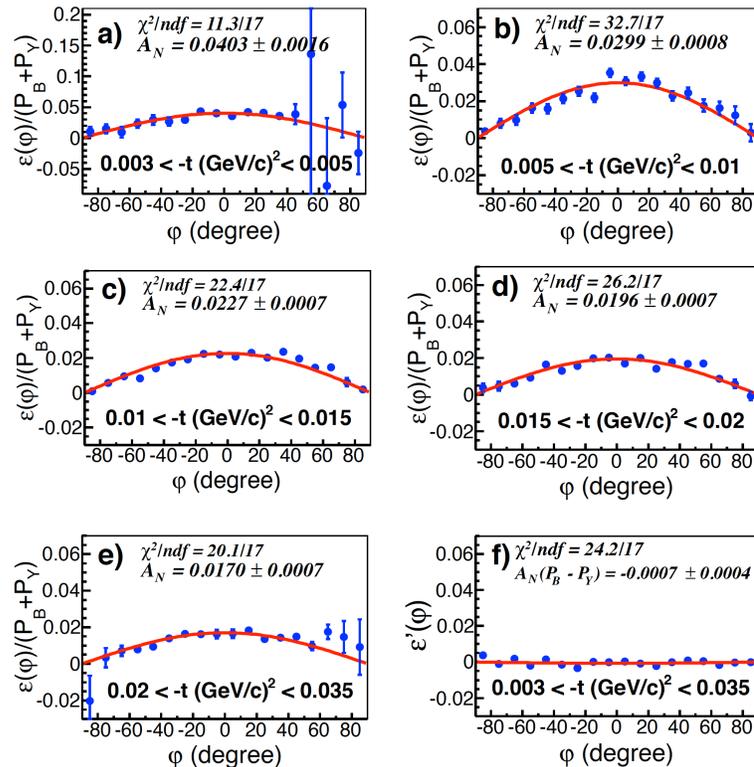


Fig. (3). (color online) The asymmetry $\varepsilon(\phi)/(P_B + P_Y)$ for the five t -intervals (a) - (e). The asymmetry $\varepsilon'(\phi)$ for the whole measured t -range (f). The red curves represent the best fit to Eq. (6) (a) - (e) and Eq. (7) (f).

Here L^{ij} are relative luminosity monitors for the corresponding polarization pattern.

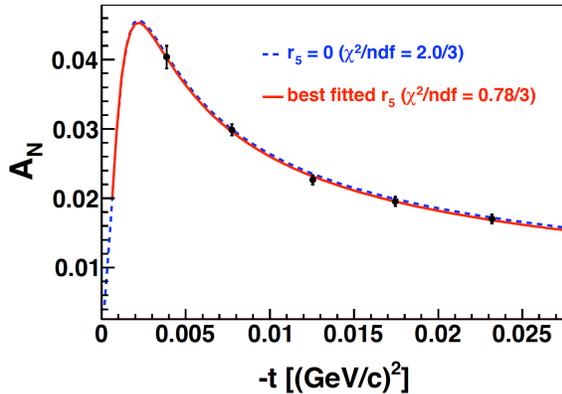


Fig. (4). (color online) The measured single spin asymmetry A_N for five $-t$ intervals. Vertical error bars show statistical uncertainties. Statistical error bars in $-t$ are smaller than the plot symbols. The dashed curve corresponds to theoretical calculations without hadronic spin-flip and the solid one represents the r_5 fit.

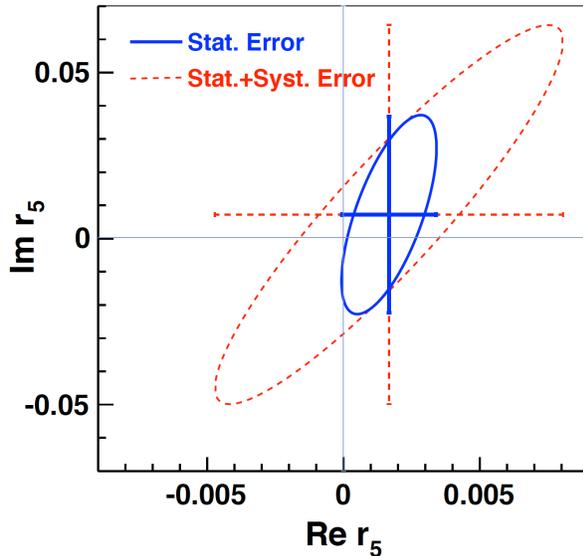


Fig. (5). (color online) Fitted value of r_5 with contours corresponding to statistical error only (solid ellipse and cross) and statistical+systematic errors (dashed ellipse and cross) of 1σ .

4. RESULTS ON ELASTIC SCATTERING MEASUREMENTS

The recently published results [13] on the single spin asymmetry are shown in Fig. (4) in comparison with theoretical curve without hadron spin-flip and with the best fit allowing non-zero hadronic spin-flip (see [14] for formula). Only statistical uncertainties have been included. The value of r_5 resulting from the fit described above is shown in Fig. (5), together with both statistical and systematic uncertainties. The obtained values $\text{Re } r_5 = 0.0017 \pm 0.0063$ and $\text{Im } r_5 = 0.007 \pm 0.057$ are consistent with the hypothesis of no hadronic spin-flip contribution (ϕ_5) at the energy of this experiment. That is, only Pomeron

exchange, which contributes only to spin non-flipping amplitudes ϕ_1 and ϕ_3 , seems to survive at high energies.

The preliminary results on double spin raw asymmetries are shown in Fig. (6). Though some effects of the order of 10^{-3} could be seen, they are small. Here we have used relative luminosities obtained from counts of inelastic triggers produced by the vertex position detector and beam-beam counters (BBC). However, after more thorough studies, BBC coincidence counts were proved to be the least sensitive to double spin effects with negligible statistical uncertainty. The systematic error due to the normalization uncertainty of BBC coincidence counts on $\delta(\frac{A_{NN} + A_{SS}}{2})$ is at the level of 8.4×10^{-4} .

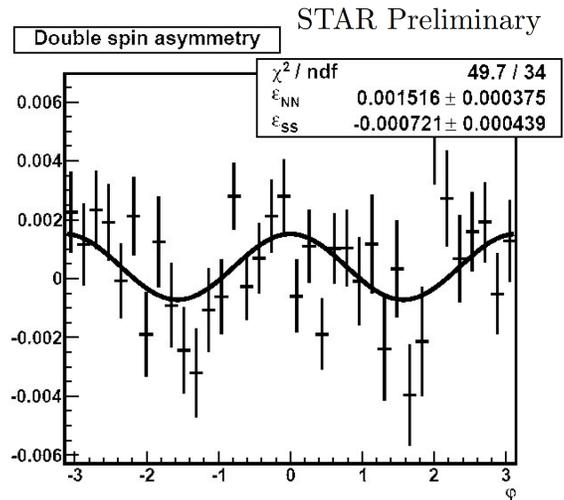


Fig. (6). STAR Preliminary results on double spin raw asymmetry for the entire t -interval.

5. CENTRAL EXCLUSIVE PRODUCTION

We have also studied the invariant mass spectrum of the two oppositely charged pions produced in the Central Exclusive Production process of $pp \rightarrow p \pi^+ \pi^- p$. Our ability to tag protons in the Roman Pots on opposite sides of the IP helps reduce background in this measurement of double Pomeron exchange compared to standard hadronic production processes. Pions were obtained from tracks with dE/dx identification. It is also required that the protons be non-collinear with scattering angle separation more than 0.15 mrad to avoid cosmics. Moreover, the missing transverse momentum of the final states (two pions and two protons) had to be less than 0.02 GeV.

In Fig. (7), the spectrum of the invariant mass of $\pi^+ \pi^-$ pairs produced with the above cuts is presented. The like-sign background is very small, which gives a measure of exclusiveness of the process. The spectrum is not corrected for acceptance, but preliminary acceptance study indicates that corrections would not change shape of the spectrum significantly. Presented spectrum is similar to the one published by the AFS Collaboration at ISR [15] as it shows the same characteristic features :

- it is dominated by low invariant mass pairs, $m_{\pi\pi}$, below 1 GeV;
- it shows the same characteristic drop around 1 GeV which may be due to $\pi^+\pi^-$ rescattering or $f_0(980)$ interference with the S-wave background [16].

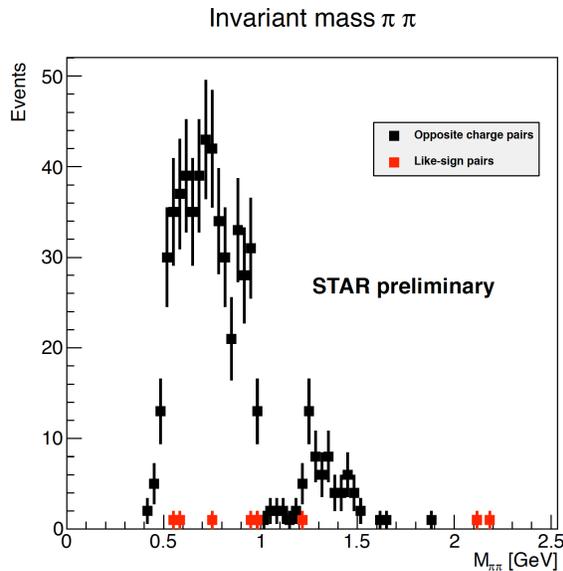


Fig. (7). (color online) STAR Preliminary results on invariant mass spectrum of $\pi^+\pi^-$ pairs produced in the central exclusive process $p+p \rightarrow p+\pi^+\pi^-+p$ at $\sqrt{s} = 200$ GeV.

6. SUMMARY AND FUTURE PROSPECTS

We had a very successful run with the physics program with tagged forward protons at RHIC in 2009, in which over 70 million events (including 33 million events with elastic triggers) were collected. We have published our results on single spin asymmetry (A_N and r_5) and we are finalizing our results on double spin asymmetries as well as the central exclusive production. In the mean time, we are also preparing for the Phase II of this physics program, in which we change our detector configurations so that we will not need a special optics of RHIC and thus this physics program can be carried out simultaneously with other physics programs of the STAR experiment. This will allow us to take much more data and explore other physics possibilities at RHIC.

CONFLICT OF INTEREST

The author confirms that this article content has no conflicts of interest.

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