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Diffractive Physics Program with Tagged Forward Protons at STAR/RHIC

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A new physics program to study the dynamics and particle production in polarized diffractive $p+p$ collisions at $\sqrt{s}$ = 200 - 500 GeV has been initiated with the STAR detector at RHIC. Staged implementation of multiple Roman Pot stations for tagging the forward protons in the diffractive processes will enable, in particular, a search for the centrally produced gluon bound state (glueball) via double Pomeron exchange inelastic diffractive processes. The properties of the Pomeron and the existence of theoretically expected C-odd counterpart of the Pomeron (Odderon) are also explored with spin-dependent elastic scattering in a wide t-range with polarized $p+p$ collisions.

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1. Introduction

Diffractive processes at high energies are believed to be occurring via the exchange of a color singlet object (the "Pomeron") with the same internal quantum numbers as the vacuum [1]. Even though properties of diffractive scattering are described by the phenomenology of Pomeron ($I\!P$) exchange in the context of Regge theory, the exact nature of the Pomeron still remains elusive. Main theoretical difficulties in applying QCD to diffraction are due to the intrinsically non-perturbative nature of the process in the kinematic and energy ranges of the data currently available. The focus

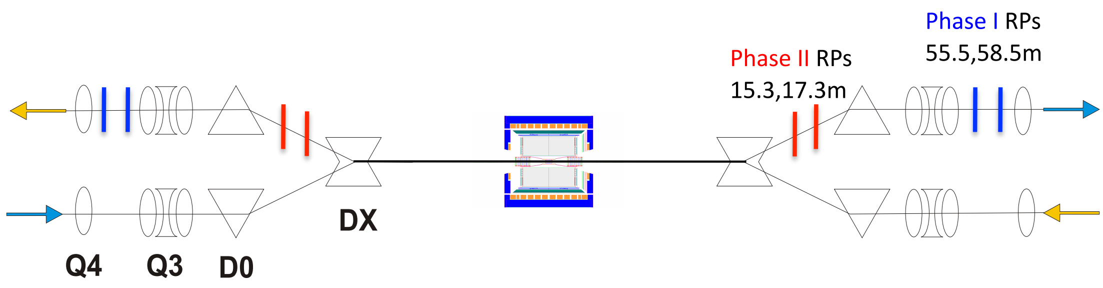


Figure 1: The layout of the RPs with the STAR detector (not to scale). The Phase I setup, designed to detect scattered protons with low-t, are located after two dipole magnets (DX, D0) and three quadruples at 55.5 m and 58.5 m from the interaction point (IP), respectively. For measuring protons with high-t (Phase II), sets of RPs will be positioned between DX and D0 magnets, at 15.3 m and 17.3 m from IP.

of the diffractive physics program at STAR (Solenoidal Tracker At RHIC) [2] is to study elastic and inelastic diffractive processes over a wide kinematic range in polarized $p+p$ collisions at $\sqrt{s}$ = 200 - 500 GeV at RHIC (Relativistic Heavy-Ion Collider). Diffraction processes are tagged with forward protons utilizing Roman Pot (RP) detectors [3] as shown in Fig. 1. For the elastic program, the collider energy range is previously unexplored, and the measurements will serve as an important bridge between vast lower energy data and limited measurements at higher energy data. The energy range, particularly with polarized $p+p$ collisions, is suitable as a testing ground for the long standing theoretical evidence in QCD for the existence of the "Odderon" which is the $C = P = -1$ counterpart to the Pomeron [1] as well as exploring properties of the Pomeron exchange. The main physics motivation for the inelastic diffraction program is searching for a gluonic bound state whose existence is allowed in pure gauge QCD, but for which no unambiguous candidate has been established [4].

2. Studying properties of the Pomeron and searching for the Odderon

Studies of spin dependence in elastic $p+p$ scattering at the high energies offer an opportunity to reveal the nature of exchanged mediators of the interaction, the Pomeron and the hypothetical Odderon. Of particular interest is the region of small four momentum transfer squared t, where electromagnetic and hadronic amplitudes are comparable and spin-dependent interference phenomenon between the two amplitudes can occur.

There are five independent helicity amplitudes for $p+p$ elastic scattering: $\phi_1 = \langle ++|T|++\rangle$, $\phi_2 = \langle ++|T|--\rangle$, $\phi_3 = \langle +-|T|+-\rangle$, $\phi_4 = \langle +-|T|-+\rangle$, and $\phi_5 = \langle ++|T|+-\rangle$. Each amplitude consists of hadronic and electromagnetic contributions. These amplitudes can be related [5] to experimentally measurable spin asymmetries as the azimuthal angle (φ) dependent elastic cross-section with transversely polarized protons is described by

$$\frac{d^2\sigma}{dtd\varphi} = \frac{1}{2\pi}\frac{d\sigma}{dt}(1+(\mathscr{P}_1+\mathscr{P}_2)A_N\cos\varphi+\mathscr{P}_1\mathscr{P}_2(A_{NN}\cos^2\varphi+A_{SS}\sin^2\varphi)), \tag{2.1}$$

where where $\mathscr{P}_1$ and $\mathscr{P}_2$ are the beam polarizations and A_N is a single spin asymmetry with reference to the transverse polarization axis (y). A_{NN} and A_{SS} are double spin asymmetries with reference to the y-axis and x-axis, respectively. A possible presence of hadronic single spin-flip amplitude would alter A_N and its effect depends on the ratio of the single spin-flip amplitude (ϕ_5) to non-flip amplitudes (ϕ_1 and ϕ_3),

$$r_5 = \frac{m\phi_5}{\sqrt{-t}\mathrm{Im}(\frac{\phi_1+\phi_3}{2})}. \tag{2.2}$$

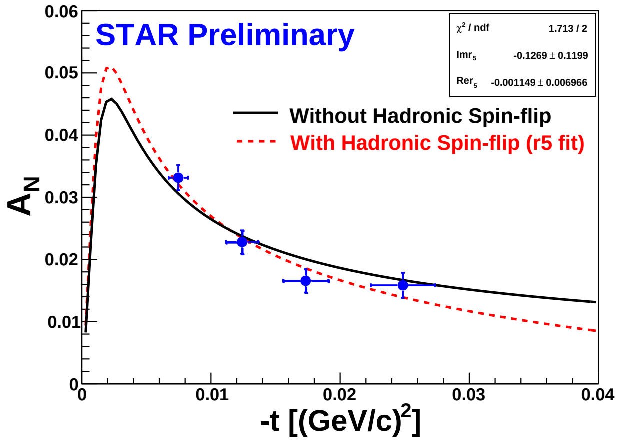


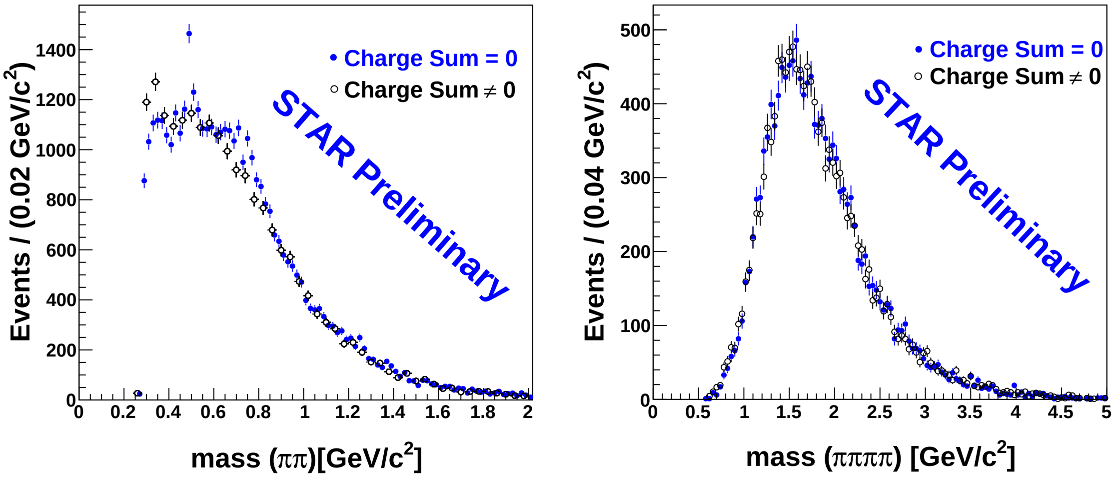
Figure 2: The single spin asymmetry A_N as a function of $-t$. The solid curve corresponds to theoretical calculations without hadronic spin-flip and the dashed one represents the r_5 fit. Vertical bars are for statistical errors. Systematic uncertainties (10%) in t-scale is shown as horizontal error bars.

Figure 2 shows the preliminary A_N distribution as function of t deduced from the RHIC-Run9 data with the Phase I RP set-up covering low-t regions, $0.002 < |t| < 0.03$ (GeV/c)^2. To quantify a possible contribution of the single helicity-flip amplitude ϕ_5, the explicit relation between A_N and r_5 [5, 6] was fitted to the measured A_N values with r_5, where Imr_5 and Rer_5 are mainly sensitive to the magnitude and the shape of A_N, respectively. The fit shows no significant r_5 is required to describe the data and the result is comparable with the hypothesis of absence of hadronic spin-flip.

Similarly double transverse-spin asymmetries, A_{NN} are sensitive to the interference between double spin-flip hadronic amplitudes, ϕ_2 and ϕ_4 and electromagnetic non-flip amplitude, providing a tool to search for the hypothetical Odderon exchange [7]. The data at $\sqrt{s}$ = 200 GeV, which are currently being analyzed, and higher statistics at $\sqrt{s}$ = 500 GeV, which are planned to be taken in upcoming RHIC-Run11 are expected to provide significant constraint on the theoretical models describing Odderons and the nature of diffraction.

3. Glueball production in double Pomeron exchange (DPE) processes

QCD predicts the existence of mesons which contain only gluons, the glueballs. These states are a consequence of the non-Abelian nature of the gauge fields which allows that gluons couple to themselves and hence may bind. Despite the theoretical evidence of existence of glueballs, no glueball state has been unambiguously established to date [4]. Lattice QCD calculations have predicted the lowest-lying scalar glueball state in the mass range of 1500-1700 MeV/c^2, and tensor and pseudo-scalar glueballs in 2000-2500 MeV/c^2 [4]. Experimentally measured glueball candidates for the scalar glueball states are the $f_0(1500)$ and the $f_J(1710)$ [8] in central production, $p+p \to p+M_X+p$, as well as other gluon-rich reactions such as $\bar{p}p$ annihilation, and radiative J/ψ decay [9]. In the context of QCD, the Pomeron exchange is believed to be the exchange of a system of gluons. The central DPE process has been regarded as one of the potential channels of glueball production [4]. The energy regime where glueball candidates from central production have been identified so far is estimated to be not DPE dominated [10]. It is imperative to cover a wide kinematic range to extract information of the production of glueball candidates at an energy regime where DPE is expected to be a dominant process in central production.



(a) Effective mass for $\pi^+\pi^-$

(b) Effective mass for $\pi^+\pi^-\pi^+\pi^-$

Figure 3: Reconstructed mass distributions for two and four charged pions in the inclusive central diffraction at $\sqrt{s}$ = 200 GeV. Reconstructed particles are assumed to be pions. Solid circles are for neutral states and open circles represents charged states. Errors are statistical only.

Figure 3 shows preliminary reconstructed effective mass distributions for two and four charged pion states from RHIC-Run9 at $\sqrt{s}$ = 200 GeV with the Phase I RP set-up (See Fig. 1). The data were collected during the 5 days of data taking with special beam optics (β^*=21m) at low luminosity in RHIC-Run9. The events were required to have two outgoing protons in the RPs, and the inclusive tracks in the central region were reconstructed with STAR Time Projection Chamber (TPC) covering $-1 < \eta < 1$ and $-\pi < \varphi < \pi$. The $\rho(770)$ and K^0_S signals visible in Fig. 3(a) are attributed mainly to inclusiveness of the reaction in the data sample. It is worthwhile to mention that $\rho(770)$, while it is not allowed in the exclusive DPE process, can also be produce by the central exclusive photoproduction [11]. Selecting exclusive central reactions requires constrains by energy-momentum conservation, which currently is restricted by the limited capability of reconstructing momentum of forward proton in the Phase I set-up. The Phase II RP set-up is being designed to facilitate the requirement. The Time-of-Flight (ToF) system in conjunction with TPC is planned to be utilized to separate π/K in momentum range up to 1.6 GeV$/c$. The start time for the ToF counter will be provided by the segmented scintillator trigger counter in the Phase II RPs.

The main data taking for central events is planned with the Phase II RP setup, which covers higher and wider t-coverage ($0.1 < |t| < 1.5$ (GeV/c)^2) with high luminosity at $\sqrt{s}$ = 500 GeV.

Simulations indicate that during a twenty-week RHIC run with 400 pb^{-1} integrated luminosity at $\sqrt{s}$ = 500 GeV, one can collect a data sample of 2×10^6 K^+K^- and 11×10^6 $\pi^+\pi^-\pi^+\pi^-$ in 1< M_X < 2 GeV/c^2 for analysis, assuming branching ratios of DPE processes measured at $\sqrt{s}$ = 62.4 GeV [12]. The two Pomeron ($I\!P I\!P$) cross-section at RHIC energies is not known and an estimate of 140 μbarn [13, 14] was used in our simulations. If we assume the measured cross-section by W102 at $\sqrt{s}$ = 29.1 GeV [15] , 50-75K events of $f_0(1500) \rightarrow \pi^+\pi^-\pi^+\pi^-$ are expected to be collected from the run. The assumed integrated luminosity can be easily achieved during the planned high luminosity spin program at RHIC, and it is expected that the luminosity upgrade and longer run can bring an order of magnitude higher statistics which will enable differential kinematic sampling and spin-parity analysis. The assumed pre-scaled trigger rates for DPE are 100 Hz at a luminosity of 1×10^{32} cm^{-2}s^{-1}.

4. Summary

A new diffractive physics program in polarized $p+p$ collisions at RHIC with tagged forward protons using the Roman Pot technique with the STAR detector system has been launched. The main physics motivation is to explore the nature of diffraction process at high RHIC energy and search for theoretically predicted states in QCD: the Odderon and the glueball. The diffractive program, together with the other RHIC physics programs, will serve as an important step toward our complete understanding of the strong interaction and QCD description of the hadronic structure.

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PoS(DIS 2010)076