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Physics with tagged forward protons at RHIC

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The physics reach of the STAR detector at RHIC has been extended to include elastic and inelastic diffraction measurements with tagged forward protons. This program has started 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.

1. Introduction

Roman Pots (RPs) of the pp2pp experiment [1–3] incorporated as part of the STAR experiment [4] at RHIC allows tagging events with very forward protons and thus extends physics reach of the experiment to select processes, in which the proton stays intact and the exchange has the quantum numbers of the vacuum (the "Pomeron exchange" between two protons). Consequently, it enhances the probability of measuring reactions where gluonic matter dominates the colorless exchange. The processes include both elastic and inelastic diffraction.

The Pomeron, as a color singlet ($J^{PC} = 0^{++}$) [5], is believed to be responsible for the occurrence of diffractive processes at high energies. The Pomeron is considered as a dynamical system rather than a particle which is expected to dominate exchange mechanisms at asymptotic energies. Since there is no color exchanged between the Pomeron and the parent nucleon, a rapidity gap in the final state emerges as a characteristic signature of diffractive events. Even though properties of diffractive scattering are described by the phenomenology of Pomeron exchange in the context of Regge theory [5], the exact nature of the Pomeron still remains elusive. Main theoretical difficulties in applying QCD in diffraction are due to the intrinsically non-perturbative nature of the process in the kinematic and energy ranges of the data currently available. The experimental challenge is identifying and reconstructing forward protons kinematically very close to the beam.

Phase I of the forward proton program, Fig. 1, has been implemented and taken data in 2009. In Phase II which requires additional design work, the physics reach will be extended to higher values of t, where t is four-momentum transfer between the incoming and outgoing protons, and larger data samples will be taken.

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2. Physics Programs

Relevant to the physics program with tagged forward protons in polarized proton-proton collisions, we concentrate here on the processes of elastic scattering and central production.

2.1. Elastic Scattering

In the studies of the elastic scattering process, we will use unique capabilities of RHIC colliding polarized proton beams to measure both spin dependent and spin averaged observables.

Almost the entire energy range, 50 GeV $\leq \sqrt{s} \leq$ 500 GeV of this experiment at RHIC has been inaccessible to proton-proton scattering in the past. A measurement of the total cross section, σ_{tot} at the highest possible energy will probe the prevalent assumption that the cross sections for pp and $p\bar{p}$ scattering are asymptotically identical [6].

The measurement of the differential pp cross section $d\sigma/dt$ over the extended t-range will include the region at the lower $|t|$ that is particularly sensitive to the ρ-parameter (the ratio of the real to imaginary part of the scattering amplitude). This will allow extracting the ρ-parameter

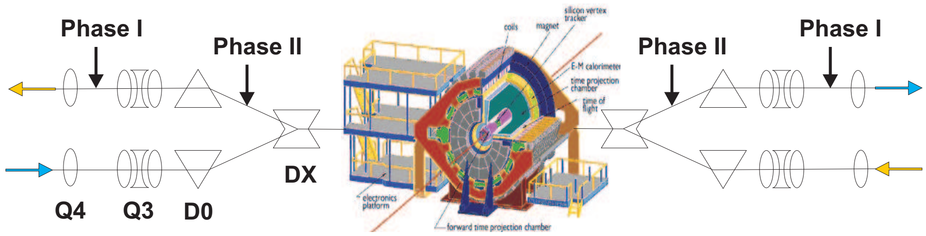

Figure 1. *The Roman Pots of the pp2pp experiment in the STAR interaction region, with the arrows indicating proposed locations for Phase I and Phase II.*

and the nuclear slope parameter b in a combined fit to the differential cross section [1] possible and might also lead to an extraction of σ_{tot}.

An asymptotic difference between the differential and total cross sections for pp and $p\bar{p}$ could be explained by a contribution of the Odderon to the scattering amplitude. The absence of an Odderon contribution would lead to identical cross sections, approaching each other roughly as $\sqrt{s}$ increases.

By measuring spin related asymmetries, one will be able to determine elastic scattering at the amplitude level [7–9]. The availability of longitudinal polarization at STAR in this first phase would allow measuring A_{LL} in addition to A_{NN}, A_{SS}, and A_N resulting in a significant improvement of our physics capabilities. Full azimuthal coverage for elastic events has been implemented in this phase.

One of the physics motivations is to measure the single-spin asymmetry A_N to study its $\sqrt{s}$ dependence, in order to see if there is a contribution in helicity amplitude from the hadronic spin-flip. This will help reveal long standing problem of the energy dependence of the spin-flip amplitude, which is best answered experimentally.

2.2. Central Production

In the double Pomeron exchange process, each proton "emits" a Pomeron and the two Pomerons interact producing a massive system M_X. The massive system could form resonances or jet pairs. Because of the constraints provided by the double Pomeron interactions, glueballs, and other states coupling preferentially to gluons, could be produced with much reduced backgrounds compared to standard hadronic production processes.

In the kinematical region, which we plan to cover, those processes allow exploration of the non-perturbative regime of QCD. The strength of the STAR detector: excellent charged particle identification in the central rapidity region and p_T resolution, coupled with ability to tag diffractive events with the forward protons with RPs. Central Production using RPs and rapidity gap techniques has been studied at all the hadron colliders: ISR [11], S$p\bar{p}$S [12] and the Tevatron [13] and is planned to be studied at the LHC [14].

The idea that the production of glueballs is enhanced in the central region in the process $pp \to pM_X$p was first proposed by [15] and was demonstrated experimentally [16]. The crucial argument here is that the pattern of resonances produced in central region, where both forward protons are tagged, depends on the vector difference of the transverse momentum of the final state protons $\vec{k}_{T1}$ and $\vec{k}_{T2}$, with $dP_T = |\vec{k}_{T1} - \vec{k}_{T2}|$. The so-called dP_T filter argument is that small momentum transfer processes enhance gluon-gluon kinematic configurations since gluons can flow directly into the final state in the process.

Since no special accelerator optics is required in this configuration for the Phase II setup, running in parallel with other physics programs in STAR is possible, and we will be able to utilize high luminosity and thus many more events for searches for rare physics processes.

3. Implementation and the run in 2009

For a wide kinematic coverage, a staged implementation of RPs is considered. For Phase I of this physics program, which probes small-t range, the horizontal and vertical RPs are positioned at 55.5 m and 58.5 m respectively from the nominal STAR interaction point (IP). Each RP contains four planes of silicon strip detectors (two vertical and two horizontal) to provide redundancy for the track reconstruction.

In July 2009, RHIC was set up with a special optics such that $\beta^\star \sim 21$ m at STAR IP and at $\sqrt{s} = 200$ GeV. With this optics, the t coverage was $0.003 < |t| < 0.03$ (GeV/c)^2. Reaching such a small $|t|$-value allows measuring the single spin analyzing power A_N close to its predicted maximum at $|t| \approx 0.0024$ (GeV/c)^2, where $A_{max} = 0.04$ (GeV/c)^2, at $\sqrt{s} = 200$ GeV. The A_N and its t-dependence in the covered range is sensitive to a possible contribution of the single spin-flip amplitude, ϕ_5 [10], from the interference between the hadronic spin-flip amplitude with the electromagnetic non-flip amplitude. An additional contribution of the hypothetical Odderon to the pp scattering amplitude can be probed by measuring the double spin-flip asymmetry, A_{NN} [10].

For Phase II, new sets of RP system will be designed and fabricated to be installed between RHIC DX-D0 magnets, 15-17 m from the IP, extending the acceptance and the reach in $|t|$ to almost 1.3 (GeV/c)^2 and for a more optimized setting for inelastic diffractive program.

3.1. First look at the data

During the one week run in 2009, we have collected more than 72 million events with the RPs, in which about 33 million events are of elastic triggers. Almost instantaneous and intensive online monitoring has been done to safeguard our data quality. A couple plots similar to those in online monitoring programs are shown here.

In the first step of analysis, we have selected the cleanest events. Here, we require that (i) each valid hit (strip) has ADC value at least 5 σ above its pedestal values; (ii) cluster is formed from hits and each cluster has a maximum of 5 consecutive hits with total energy $\geq$ 20 ADC; (iii) 4 opposite pairs of RPs are treated separately and there needs to be at least 1 opposite pair of clean track which has only 1 cluster on each of the 4 silicon planes in each RP. In a typical run, we have found that ∼78% of events with elastic triggers satisfy these requirements. With an additional collinearity cut (so that we wouldn't see any vertical/horizontal bands in the correlation plot in Fig. 2), there are still ∼74% events with elastic triggers selected. This kind of efficiency (though at this early stage of analysis) seems to be significantly better than what we had in the 2003 run [1].

Fig. 2 shows the correlation between the horizontal (x) and vertical (y) strip indices for a RP in the East (EHO) and a RP in the West inside the ring (WHI) for one of the runs. The horizontal and vertical strip indices are local horizontal and vertical coordinates and they are obtained from the 4 silicon detector planes (2 vertical and 2 horizontal) in each RP. Fig. 3 shows online-like

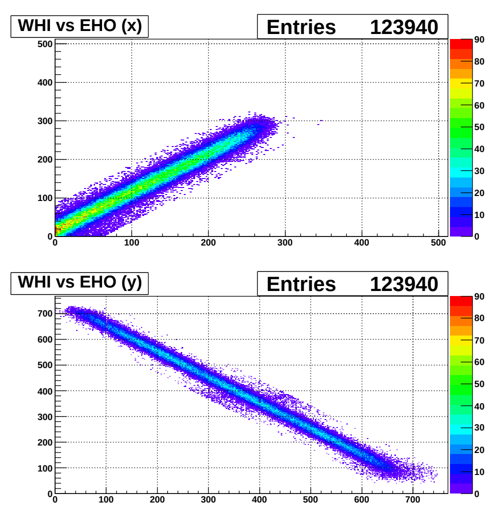

Figure 2. *Correlation of strip indices in x (horizontal) and y (vertical) between the RPs EHO and WHI.*

distribution of the z-coordinate (ie. in beam direction) of collision vertex reconstructed from the time digitizations of the trigger counters. From these plots, it is apparent that the data quality taken during the 2009 run appears to be in decent shape.

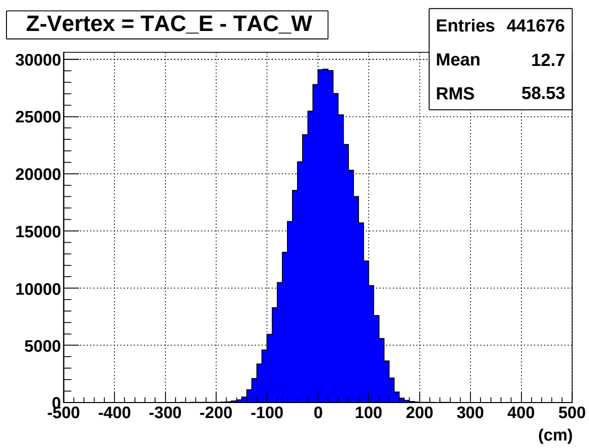

Figure 3. *The vertex in beam direction by using the time digitizations (TAC's) of photo-multiplier tubes (in cm).*

With the data sample collected, we expect that the corresponding errors are $\Delta A_N = 0.0017, \Delta A_{NN} = \Delta A_{SS} = 0.003$. To estimate the error on A_{NN}, the ϕ intervals $-45° < \phi < 45°$ and $135° < \phi < 225°$ were used, and complementary intervals for A_{SS}.

Moreover, an estimated error on the slope parameter is $\Delta b = 0.31 (\mathrm{GeV/c})^{-2}$ (cf. ~ 1.8 $(\mathrm{GeV/c})^{-2}$ in the last pp2pp measurement [1]) and on the ratio of real to imaginary part $\Delta\rho = 0.01$, which is comparable to the existing measurements from the pp and $p\bar{p}$ data.

4. Summary

We have had a very successful run with the physics program with tagged forward protons at RHIC in 2009 in which we have collected abundant data for various data analyses. We will focus on data analyses on elastic scattering including A_{NN}, A_N, A_{SS}, A_S, σ_{tot}, slope parameter b and the ρ-parameter and central production. We hope to have results in near future. There is more to do to fully explore physics potential and discovery possibilities at RHIC.

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