Proton Polarimetry with the Hydrogen Jet Target at RHIC in Run 2015*

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The Relativistic Heavy Ion Collider (RHIC) has provided polarized proton-proton collisions to experiments for the past decade with beam polarizations of P=55% at beam energies of up to 255 GeV. The polarization of the proton beams is measured through spin dependent elastic scattering off a polarized hydrogen jet target and similarly monitored with Carbon fiber targets several times throughout the typical 8 hours of a stored RHIC fill. With recent advancements in beam luminosities, the largely increased data sets have enabled unprecedented possibilities to study systematic effects in the polarimeters. We will discuss details of the background contributions, properties of the polarized beams, and their implications on systematic uncertainties from proton and ion beam operations in the RHIC Run 2015. The beam polarization as well as its uncertainty are vital input to the RHIC experiments since they directly affect the scale uncertainty of any polarized observable.

I. INTRODUCTION

The Relativistic Heavy Ion Collider, RHIC, at Brookhaven National Laboratory provides collisions of polarized protons at center of mass energies up to 510 GeV. It is this unique capability that requires careful relative monitoring of the beam polarization throughout the storage times and an absolute normalization in particular at the previously unexplored highest energies. Typical RHIC fills are using about 110 filled (out of 120 possible) bunches of $1.5 \cdot 10^{11}$ protons with alternating vertical polarization directions of adjacent bunches (or pairs of bunches). The absolute polarization is measured non-invasively with a polarized atomic hydrogen target, HJET, throughout the whole store. In addition, the polarization life time is tracked at several points during the store with Carbon fiber targets, typically every two to three hours (see [1] for a detailed discussion of the Carbon polarimetry). These proceedings show first results from the 2015 RHIC run. This includes mainly data from proton-proton operation at $\sqrt{s} = 200$ GeV , but also some additional studies from the consecutive proton-ion run.

II. SETUP

The polarimetry at RHIC is based on elastic scattering of the high energy proton beam on targets of either atomic hydrogen or Carbon nuclei. The recoil particle is detected in Silicon strips which are located transverse to the beam direction, as shown in Fig. 1 for the HJET geometry. The detectors measure the energy of the particle in a kinematic region where the elastic signal is easy to select and the time of flight. The HJET is using a combination of eight separate detector panels to measure recoil protons from both beams. Prior to the 2015 RHIC run, all active parts of the detectors had been replaced with new components which resolved issues with previous radiation damage to the silicon and inconsistencies between some of the old panels. Each detector panel consists of twelve strips with 3.75 mm pitch, covering an area of 4.5×5.0 cm^2 downstream of the jet target. The strips have a thickness of 500 μm and are able to stop protons with an energy of less than about 7.0 MeV. Particles with higher energies will start to punch through the detector and these will only leave a fraction of their energy. This affects only the two strips that are situated the furthest downstream from the target. For the current analysis, we do not consider the punch through protons and remove them from the analysis. The detectors are read out with FADC cards which store the full waveform with a 2.4 ns resolution (see [2] for more details of the upgraded setup and the treatment of punch through particles). Energy and time of flight are later determined from the waveform in the offline analysis.

For the energy calibration, two radioactive α-sources of known energy are used ($^{148}_{64}$Gd, E_α=3.183 MeV and $^{241}_{95}$Am, E_α=5.486 MeV). Calibrations were typically carried out every few days to ensure gain stability and track possible changes. The proper time of flight is adjusted for possible drifts of the delay times in cables and readout electronics over the many months of operation.

The elastic signal is selected for the known kinematics of the non-relativistic recoil proton. At the high RHIC energies, the recoil angle is independent of the species and beam momentum in first order. This proves to be especially advantageous during p+Au and p+Al operations, when the elastic recoil from the heavy ion beam could be used for additional monitoring of the target performance and possible effects of background on the determination

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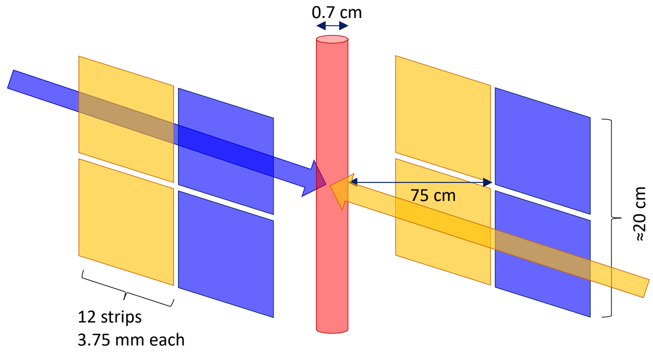

FIG. 1. Schematic setup of the polarized atomic hydrogen target with respect to the RHIC beams (not to scale). Each detector panel consists of twelve vertical Silicon detector strips with a 3.75 mm pitch.

of the proton beam polarization. The kinematic selection is very sensitive to the detector alignment. While this includes an unlikely motion of the detectors themselves, the main contributions here are in fact changes in the accelerator parameters to tune the stability of the beam and the beam polarization. In particular during the heavy ion operation, the rigidity of the accelerator led to a significant difference of the beam angle on the jet target. These changes on the acceptance of left and right side detectors can be corrected with adjustments to the magnetic holding field of the target. In addition, we correct the relative alignment of the detector with respect to the beam direction in the offline analysis for full detector panels of 12 strips.

III. ANALYSIS

At non-relativistic energies, elastic proton scattering exhibits a spin dependent transverse asymmetry or analyzing power, A_N, arising from an interference of electromagnetic and nuclear amplitudes in the scattering matrix. Detector efficiencies and differences in luminosities are removed from the asymmetry by combining hits in the left, N_L, and right, N_R, detector hemispheres with up, $N^{\uparrow}$, and down, $N^{\downarrow}$, states of the polarization, P:

$$A_N \cdot P = \epsilon = \frac{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} \cdot N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} \cdot N_R^{\uparrow}}}. \qquad (1)$$

A measured asymmetry can be used to determine the beam polarization if the analyzing power is known and any (polarized or unpolarized) background is well controlled. For symmetry under parity transformation in elastic proton-proton scattering, it is evident that $A_N|_{\mathrm{Beam}} = A_N|_{\mathrm{Target}}$. The polarization of the jet target is switched with magnetic holding fields every 300 seconds and being monitored in a separate Breit-Rabi unit, which allows us to measure the beam polarization directly through the respective asymmetries:

$$P_{\mathrm{Beam}} = -\frac{\epsilon_{\mathrm{Beam}}}{\epsilon_{\mathrm{Target}}} P_{\mathrm{Target}}. \qquad (2)$$

The atomic target polarization is typically and stable at 97

The asymmetry is calculated as a function of the kinematic energy of the recoil proton. For the final results of the beam polarization, events are selected with a time of flight difference of less than 5 ns with respect to a non-relativistic proton of known energy. In addition, the missing mass of the event (after detector alignment) has to be within 50 MeV/c^2 of an elastically scattered proton mass.

There are various sources of background that can potentially affect the asymmetries in different ways. As long as the background is not polarization dependent, it will not have a direct impact on the determination of the beam polarization, though. In this case, both the beam and the target asymmetries are diluted in the same way and any polarization independent contribution cancels in the asymmetry ratio of eq. 2. Highly energetic particles from inelastic events are the main source of background when the 200 GeV beam hits the hydrogen jet target. This background, mostly pions, are fast and typically leave little energy when they punch through the detector, but the spectrum can be fairly wide in comparison to the deposited energy from elastic events. There is reason to believe that the inelastic background is not polarization dependent (or significantly smaller than the measured asymmetries), but previous analyses have been statistically limited. Polarization dependent background can originate from elastic scattering off of beam gas or the far tails of the jet target. The detector acceptance for such events will be very different due to the shifted vertex position, leading to potential differences between beam and target asymmetries as well as the two beams going in opposite directions.

Using the new data set from the 2015 RHIC run, we have carried out background studies with unprecedented statistical accuracy. The RHIC beams consist of 120 bunches but typically only 110 of them are filled. The unfilled bunches in the two beams are not aligned at the HJET polarimeter and thus can be used to estimate clean contributions from the one beam at a time as well as pure background from the opposite beam. Also, the kinematic selection can be varied to study the polarization dependence as well as the background fraction. The procedure is illustrated in Fig. 2 for one of the two RHIC beams at recoil energies between 2.0 and 3.0 MeV. We compare the signal and background distributions as a function of the time of flight. The elastic signal peak stands out visibly and is normalized to 1, here, and the different

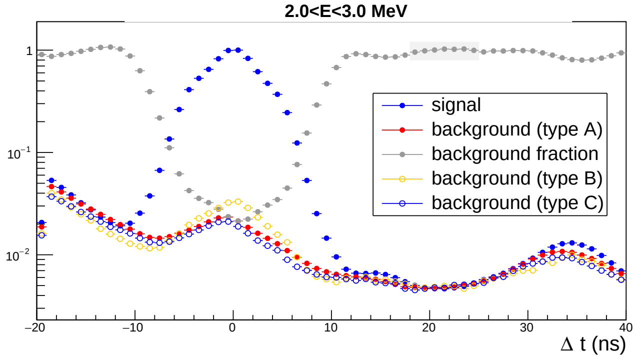

FIG. 2. Example of time of flight distributions for different signal and background selections ($2.0 < E_T < 3.0$ MeV). The inclusive signal distribution is normalized to the peak, all other distributiosn are normalized to the inclusive in the range $18 < \Delta t < 25$ ns. The bump at large $\Delta t \approx 28$ ns is from heavier recoil particles (H_2).

background distributions are normalized relative to this between 18 and 25 ns (indicated by the gray box around the background fraction data). The elastic signal is selected as described above by the missing mass. For the inclusive background distribution (type A) the missing mass difference is required to be larger than 120 MeV/c^2 from a recoiled proton. Similarly, type B background is determined for a large missing mass difference for filled bunches of the signal beam only (unfilled bunches in the opposite beam). This background should be purely inelastic. Type C background is from the opposite beam (unfilled bunches of the primary beam). Here we use the same missing mass cut for the signal which includes contributions from elastic scattering with wrong kinematics and inelastic processes. The background fraction is shown for type A background which has about an order of magnitude better statistics compared to the other background estimates.

IV. RESULTS

All background contributions show surprisingly similar features, namely a slight enhancement directly under the elastic peak and a smaller peak at later times. In particular they match up nicely with the signal distribution at early times which are far from the normalization and dominated by inelastic particle production. The background fractions are much improved in the current elastic event selection compared to previous analyses; they are on the order of 3-4% during p+p operation and slightly larger during p+A collisions. This is mainly due to the newly installed detectors and the offline detector alignment with respect to the beam. The asymmetries are calculated for signal and background distributions. The elastic region clearly stands out with significant asymmetries on the order of a few percent. In the background, the asymmetries are overall consistent with zero. All asymmetries and background fractions have been monitored per RHIC fill over the period of operation (February through June 2015). They exhibit very stable behavior with significant changes between the different operation modes, namely p+p, p+Au, and p+Al collisions. The final asymmetries are corrected for the background fraction and shown as function of momentum transfer, $-t = 2 \cdot m_p \cdot T_{kin}$, in Fig. 3. The statistical precision is highly improved compared to previous results [4]. Systematic uncertainties are dominated by the molecular component of the polarized atomic hydrogen target.

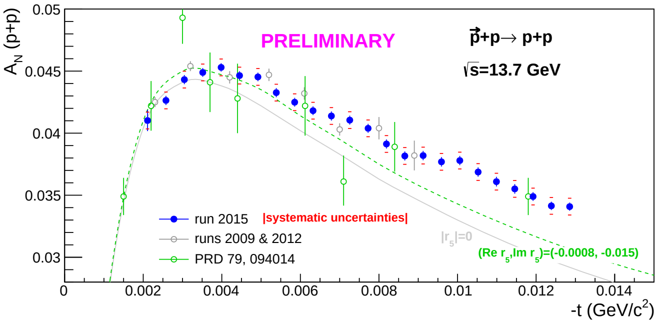

FIG. 3. Analyzing power in elastic proton-proton scattering from the HJET 2015 data at $\sqrt{s} = 13.7$ GeV compared to previous data and theoretical predictions [[]]. Previous preliminary results from 2009 and 2012 are not fully background corrected.

Final results of the beam polarization at $p_{\text{Beam}} = 100$ GeV have been released for use in the PHENIX and STAR experiments and are available on the RHIC spin web page [], as shown in Fig. 4. The values of the beam polarizations are obtained from the uncorrected ratios of the asymmetries as well as from fully background corrected beam asymmetries and the newly determined analyzing power (see Fig. 3). For the proton-proton operation, both results are completely consistent and we use the corrected version for the final polarizations. During the proton-heavy ion operation, in particular p+Au, the measurement suffered from an increased background induced by the gold ion beam. The background was initially very high but reduced in several steps over the course of the first half of p+Au operation. In this case it is better to use the fill-by-fill asymmetry ratio for the determination of the beam polarization. Details about the analyzing power of elastic proton-heavy ion scattering can be found in [].

The current data has been used to measure the longitudinal polarization profile of the bunches for the first time. This measurement complements the transverse polarization profiles which are determined in the fast pC-polarimeters where a fiber target is swept through the RHIC beam. The longitudinal profile is based on the time of flight analysis of the asymmetries and it includes a full background correction as discussed above.

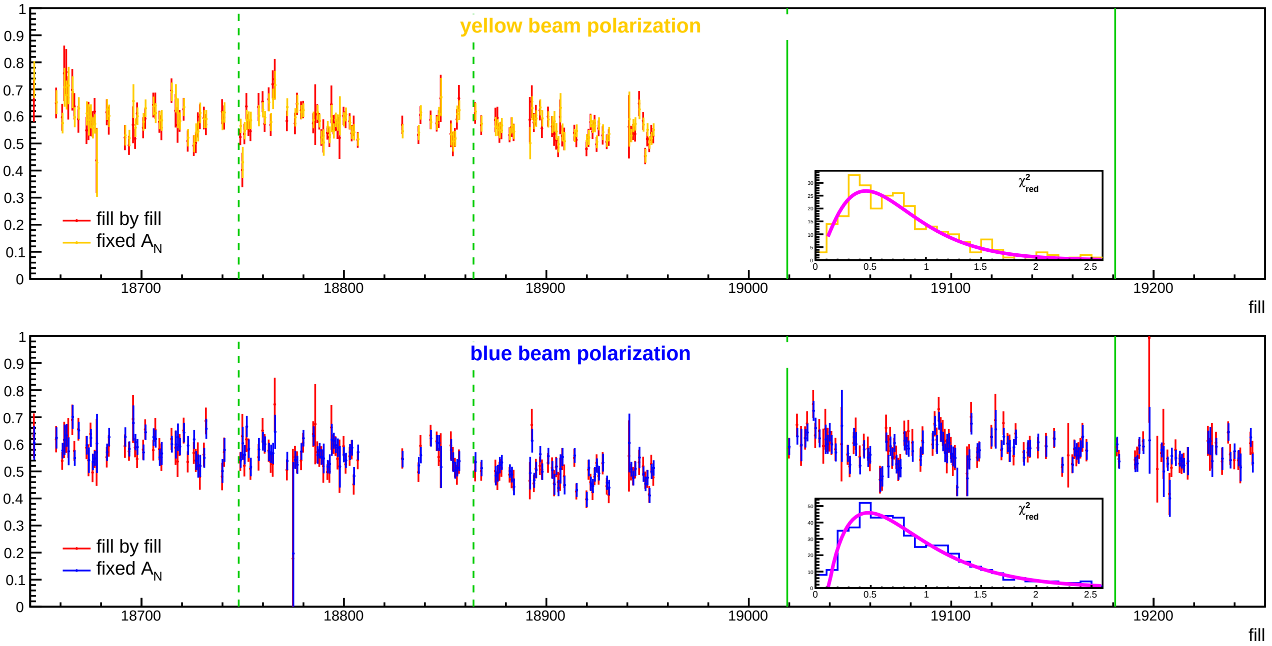

FIG. 4. Final beam polarization values for the 2015 RHIC run as function of fill number. The full run period covers about five months. Green vertical lines represent significant changes in the collider operation (dashed lines are changes in the spin rotators, solid lines indicate changes in ion species). The fill-by-fill results are calculated from the uncorrected asymmetry ratios; fixed A_N is based on fully background corrected asymmetries with weighted means for the analyzing power.

Figure 5 shows the results of the longitudinal polarization profiles for the two RHIC beams for the full data set. The inclusive measurement (filled bunches in both beams) is largely consistent with the clean method (unfilled bunches in the opposite beams) and not longitudinal polarization dependence can be observed. We assume here, that the vertex position is well defined by the location of the jet target (≈ 0.7 cm FWHM). This assumption is reasonable when compared to the intensity profiles in Fig. 5, so the time of flight can be translated into a bunch length. Far tails in the distribution ($\|\Delta t\| > 10$ ns) are more likely from beam gas interactions, but this contribution is strongly suppressed to interactions in the target.

V. SUMMARY

The HJET detector and readout electronics have been upgraded for the recent RHIC 2015 run. This, in combination with an unprecedented recorded luminosity, enabled new systematic studies of the background contributions. The background asymmetry is generally not exhibiting any sizable polarization dependence which could affect the determination of the RHIC beam polarization severely. The background fractions are small, on the order of 3-4%, and they are corrected for the extraction of the analyzing power in elastic proton-proton scattering. Compared to previous data, the new results are highly improved in statistical and systematic uncertainties. Beam polarization have been well above 50% for the whole RHIC run 2015 period. Final results have been released for use in the PHENIX and STAR experiments and are available online. Differences between the two beams are understood and consistent with the accelerator parameters [5]. The main uncertainty remains the molecular component of H_2 in the polarized atomic hydrogen jet target, on the order of 3%. Updated and detailed studies of this contribution are discussed in an accompanying contribution [].

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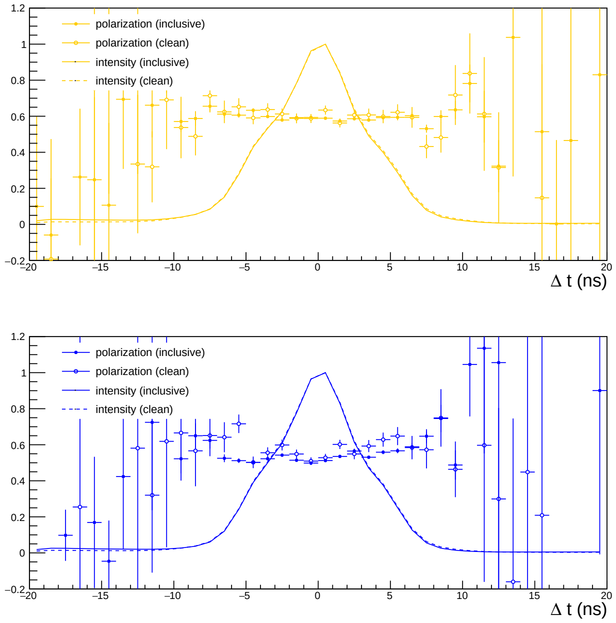

FIG. 5. Longitudinal beam polarization profiles are calculated from the time of flight distributions for different signal selections. The intensity profile is determined from the numbers of events in the polarimeter itself and normalized to the peak. Far tails in the distributions are from beam gas interactions.

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