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RHIC polarization for Runs 9-12

The Polarimetry Group



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1 Introduction

This note describes the RHIC polarization measurements for use by the collider experiments for the Run9 (100 GeV)¹, Run11 (250 GeV), and Run12 (100 GeV and 255 GeV) polarized proton running periods. The measurement procedure is outlined [1] and the resulting polarization parameters are defined. The systematic uncertainties for each step of the procedure are discussed and estimated; when possible the uncertainties are evaluated using the present data. Finally the use of the provided results to determine mean polarization and uncertainty for a data set is described. The results used for this are compiled on the web pages linked at <https://wiki.bnl.gov/rhicspin/Results>; there, for each year the results are at the link 'Fill by fill results'.

2 Measurement procedure

2.1 Proton carbon polarimeters

The proton carbon (pC) polarimeters provide the basis of the polarization measurements. They supply the following information:

- The intensity averaged polarization of the beam, $P = \int d^2x P(\vec{x})I(\vec{x}) / \int d^2x I(\vec{x})$, where $\vec{x} = (x, y)$ are the transverse beam coordinates, and $P(\vec{x})$ and $I(\vec{x})$ are the transverse polarization and intensity distributions, respectively.
- The transverse polarization profile parameter $R = \sigma_I^2 / \sigma_P^2$, the square of the ratio of the widths of the beam intensity and polarization distributions; the two pC polarimeters in each RHIC ring allow separate measurements of R in the horizontal and vertical directions;

¹Earlier polarization values for Run9 100 GeV are consistent with the present analysis. The Run9 250 GeV polarization values were not reevaluated, because severe rate effects rendered the data unsuitable for analysis in the present framework.

- With two or more measurements per RHIC fill the pC polarimeters measure the time dependence of P and R throughout fills, necessary for physics data collected during portions of fills;
- The two pC polarimeters in each RHIC ring allow cross checks with two independent measurements of the same beam.

The polarization is obtained from the measured asymmetry ϵ via the relation $P = \epsilon/A_N$. The analyzing power A_N is determined separately for each pC polarimeter by normalizing to the hydrogen jet (H-jet) polarimeter absolute polarization values. Uncertainties from the H-jet thus contribute to a scale uncertainty on the pC measurements through the uncertainty in determining A_N .

The polarizations for single- and double-spin asymmetry (SSA and DSA) measurements with colliding beams are determined from the transverse averaged polarization P and profile parameter R . The corrections from P to P_{SSA}, P_{DSA} are scale factors which are algebraic functions of R [2]. For equal horizontal and vertical profiles R , to lowest order in R :

$$P_{SSA} \approx (1 + \frac{1}{2}R)P; \quad (1)$$

If both beams B and Y have equal profiles R , to lowest order in R :

$$P_{DSA}^2 \approx (1 + R)P_B P_Y \approx P_{SSA,B} \cdot P_{SSA,Y}. \quad (2)$$

The pC measurements for a fill are a set of polarization and profile values P_i and R_i , their statistical uncertainties, and times in the fill t_i . They are fit to the forms:

$$P(t) = P_0 - P' \cdot t, \quad (3)$$

$$R(r) = R_0 + R' \cdot t. \quad (4)$$

P_0, R_0 are the polarization and profile at $t = 0$, usually taken as the start of a physics fill; P' is the absolute rate of polarization loss and R' is the rate of profile growth. The parameters $\{P_0, P', R_0, R'\}$ are then used to determine a parameterization of the colliding beam polarizations linear in t ; e.g. for SSA:

$$P_{SSA}(t) = P_{0,SSA} - P'_{SSA} \cdot t. \quad (5)$$

Here $P_{0,SSA}$ and P'_{SSA} have analogous meanings to the parameters in Eq. (3); their statistical uncertainties are determined by the statistical uncertainties on $\{P_0, P', R_0, R'\}$. The DSA polarization is the product of these P_{SSA} parameterizations for the two beams as indicated in Eq. (2).

2.2 H-jet polarimeter

A polarized atomic hydrogen jet is used to measure the absolute polarization of the beam. In terms of asymmetries with respect to the jet and the beam spin states, the transverse averaged polarization of the beam is

$$P_{\text{beam}} = -\frac{\epsilon_{\text{beam}}}{\epsilon_{\text{jet}}} P_{\text{jet}}. \quad (6)$$

The polarization of the hydrogen jet is measured with a Breit-Rabi polarimeter. It is largely constant, and a mean value is used for each running period.

The jet measures the beam intensity weighted average polarization over a fill:

$$\overline{P^{jet}} = \frac{\int dt I(t) P(t)}{\int dt I(t)}. \quad (7)$$

2.3 pC/H-jet normalization

To compare directly with the jet measurement, the beam intensity weighted average polarization from the pC is computed for each fill in terms of the parameterization in Eq. (3):

$$\overline{P^{pC}} = \left(1 - \left(\frac{P'}{P_0} \right) \cdot \frac{\int dt t I(t)}{\int dt I(t)} \right) P_0. \quad (8)$$

Note that the ratio P'/P_0 is independent of the pC polarization scale. The RHIC archive values of beam intensities are used to numerically evaluate the terms involving $I(t)$.

Over a set of fills (typically an entire running period) the relative pC/H-jet normalization is determined from a statistically weighted mean of the ratio:

$$s = \left\langle \frac{\overline{P^{pC}}}{\overline{P^{jet}}} \right\rangle_{\text{fills}}. \quad (9)$$

The scale factor is then applied to all pC polarization values to adjust them to the scale set by the H-jet.

A separate normalization was determined for each pC polarimeter for each running period, using all fills with both pC and H-jet measurements. For the Blue downstream pC polarimeter in Run11, a set of fills when a thick carbon target was used showed a significant deviation in scale; a separate normalization was determined for this data.

3 Uncertainties

3.1 H-jet scale and background

The scale of the H-jet polarization is provided by the Breit-Rabi polarimeter measurement of the jet polarization. It may be affected by contamination of the jet with molecular

hydrogen H₂. This was measured in a test bench configuration to be approximately 2%, and the Breit-Rabi measurement is corrected for this. Since this measurement was performed only once several years ago, and never *in situ*, the uncertainty on polarization scale from this effect is conservatively taken to be 3%.

Equation (6) depends on the asymmetries having the same analyzing power with respect to beam and jet polarizations. If backgrounds contribute differently to the beam and jet asymmetries the relation may be invalid. Analysis of the H-jet signal and background regions indicates that possible backgrounds contribute less than 1% to beam or jet asymmetries, providing an upper limit to the violation of Eq. (6).

3.2 pC scale

The pC/H-jet ratios $\overline{PpC}/\overline{Pjet}$ [3] averaged in Eq. (9) are proportional to the pC analyzing power A_N . This should be constant within uncertainties. If fit to a constant using only statistical uncertainties, a value of $\chi^2/NDOF > 1$ indicates fill-to-fill systematic uncertainties on the ratios; these effects may be due to instabilities in either the pC or H-jet or both. The size of this effect may be estimated by including a constant systematic for each fill in the χ^2 calculation and requiring $\chi^2/NDOF = 1$. The values so obtained are listed in Table 1. Many of them are zero, indicating the systematic uncertainty is negligible in comparison to the statistical uncertainties with typical values of $\approx 9\%$. Asterisks in table entries indicate when there were known instabilities in a polarimeter; these account for most of the nonzero values.

$\sigma(P)/P$ (%)	B up	B dn	Y up	Y dn
Run12-255	0.	3.3*	5.6*	3.3*
Run12-100	0.	0. *	6.4*	0.*
Run11-250	2.6	2.5*	0.	0.*
Run9-100	0.	0.	0.	0.

Table 1: Relative fill-to-fill systematic uncertainties on the pC/H-jet ratio. Asterisks indicate there were known instabilities in a pC polarimeter.

After including possible systematic uncertainties, the mean in Eq. (9) is re-evaluated, with a possibly increased uncertainty. The overall relative uncertainties on this mean are listed for the individual polarimeters in the left columns of Table 2. For most fills the polarization of one beam is the average of the up- and downstream polarimeters; the relative uncertainty on A_N for this average is listed in the rightmost two columns of Table 2. These are also the overall relative uncertainties on A_N , and contribute a scale uncertainty to the pC measurements. They incorporate the statistical uncertainties of the H-jet and pC from an entire running period, and all fill-to-fill systematic uncertainties from both.

$\sigma(A_N)/A_N$ (%)	B up	B dn	Y up	Y dn	Blu	Yel
Run12-255	1.3	2.2	2.0	1.6	1.3	1.3
Run12-100	1.3	2.0	2.0	1.5	1.2	1.3
Run11-250	1.4	1.8	1.3	1.7	1.1	1.1
Run9-100	1.6	1.1	1.2	1.1	1.0	0.8

Table 2: Overall relative uncertainties (stat. \oplus syst.) on the pC analyzing power A_N .

3.3 pC fill-to-fill scale systematics

The pC analyzing power A_N has a steep dependence on the energy of the scattered carbon nuclei; the measurement is thus sensitive to the energy scale of the measured nuclei. Leading sources of systematic shifts in this energy scale include the dead layer of the Si detectors, and varying energy loss of nuclei in the carbon target en route to the detectors.

For most fills each RHIC beam has (intensity averaged) polarization measurements from both the up- and down-stream pC polarimeters. Measuring the same beam, they should yield the same polarization, within uncertainties [4]. Possible fill-to-fill systematic uncertainties may be estimated by requiring the ratio to be consistent with unity, adjusting $\chi^2/NDOF = 1$ as described in Section 3.2. The contribution of these uncertainties to the polarization scale are listed in Table 3. They are small or negligible compared to the statistical uncertainties on the ratios from each fill with typical values of 10%. Note also that these uncertainties are already incorporated in the uncertainties on A_N in Table 2 through the pC/H-jet ratio used to determine A_N .

$\sigma(P)/P$ (%)	Blu	Yel
Run12-255	0.	3.1
Run12-100	0.	2.8
Run11-250	3.2	0.9
Run9-100	0.	1.0

Table 3: Relative fill-to-fill systematic uncertainties on the pC polarization as estimated from the upstream/downstream ratio.

3.4 Profile correction procedure systematics

The profile parameter R is determined from a fit of the polarization versus intensity (rate) distribution: $P(I) = P_{max} \cdot (I/I_{max})^R$ [5]. The fit parameters P_{max} and R determine P_{avg} , the average polarization across the beam: $P_{avg} = P_{max}/\sqrt{1+R}$. This may be compared to the directly measured average from a sweep measurement P ; differences are

due to systematic effects of the profile correction procedure. This is used to estimate the uncertainty of the correction for colliding beams. Based on this study the fill-to-fill relative uncertainty on the profile correction is 2.2%.

4 Use of results

4.1 Tabulated parameters

The results of the polarization measurements are compiled on web pages [6]. Polarization values and statistical uncertainties for SSA with each beam are listed. For each the initial value and slope of the parameterization $P(t) = P_0 - P' \cdot t$ are provided²; a Unix time stamp value for $t = 0$ in this parameterization is also included. When there was only one polarization measurement in a fill, the mean value of P' for that ring and running period is used. A beam current weighted mean polarization is also listed: $P_{\text{Avrg}} = \int dt I(t) P(t) / \int dt I(t)$.

4.2 Mean polarization

For each fill i in a data set a time dependent luminosity $L_i(t)$ is required; it should include effects such as deadtimes, varying prescales etc. The appropriate $P_i(t)$ from the web page is also needed. When available the initial and slope values should be used: $P_i(t) = P_{0,i} - P'_i \cdot t$. Fills with only a mean polarization were typically short and may be approximated as a constant: $P_i(t) = P_{\text{Avrg},i}$. It is convenient to define the mean luminosity weighted polarization for fill i :

$$\mathcal{P}_i = \frac{1}{\mathcal{L}_i} \int dt L_i(t) P_i(t) = P_{0,i} - \frac{\int dt t L_i(t)}{\mathcal{L}_i} P'_i, \quad (10)$$

where $\mathcal{L}_i = \int dt L_i(t)$ is the total luminosity for fill i . Then the polarization for the data set is determined from the luminosity weighted average over fills i :

$$P_{\text{set}} = \frac{\sum_i \mathcal{L}_i \cdot \mathcal{P}_i}{\sum_i \mathcal{L}_i}. \quad (11)$$

4.3 Polarization uncertainty

There are several contributions to the overall uncertainty on P . Each component may vary according to ring and running period. It is convenient to separate them into an overall scale uncertainty for a given running period, and a fill-to-fill uncertainty for subsets of a running period.

²The slope values listed in the tables ('Slope' or 'dP/dT') are opposite in sign from P' in this note.

4.3.1 Overall scale uncertainty

The contributions to the overall scale uncertainty are:

- H-jet scale: For SSA measurements the relative uncertainty on scale from the Breit-Rabi jet measurement is $\sigma(\text{H-jet scale})/P = 3\%$. For DSA, the scale is fully correlated between the two beams and $\sigma(\text{H-jet scale})/P = 6\%$.
- H-jet background: The upper limit on background contribution to asymmetries is taken as the uncertainty on the H-jet polarization; for SSA, $\sigma(\text{H-jet bkg})/P = 1\%$. For DSA the effect is fully correlated and $\sigma(\text{H-jet bkg})/P = 2\%$.
- pC scale: The appropriate value for $\sigma(\text{pC scale})/P$ for each beam is listed in the rightmost two columns of Table 2. For DSA the uncertainties for the two beams are uncorrelated and are added in quadrature, $\sigma(\text{pC scale})/P = \sigma(\text{Blu-pC scale})/P \oplus \sigma(\text{Yel-pC scale})/P$.

$\sigma(\text{scale})/P$ (%)	SSA-Blu	SSA-Yel	DSA
Run12-255	3.4	3.3	6.5
Run12-100	3.4	3.3	6.5
Run11-250	3.3	3.3	6.5
Run9-100	3.3	3.3	6.5

Table 4: Relative overall scale uncertainties on polarization.

The contributions are added in quadrature, giving the relative scale uncertainties for each running period listed in Table 4. **It is reasonable to take as overall scale uncertainty $\sigma(P)/P = 3.4\%$ for all SSA measurements (and averages of SSA measurements from the two rings), and $\sigma(P)/P = 6.5\%$ for all DSA measurements.**

4.3.2 Fill-to-fill uncertainty

The contributions to the fill-to-fill uncertainty are:

- Fill-to-fill scale systematics: Equations (10,11) may be used to determine the fill-to-fill uncertainty on P through usual propagation of errors, taking the statistical uncertainties on $P_{0,i}$, P'_i or $P_{\text{Avg},i}$ from the web page. The systematic uncertainties from Table 3 should be added to the statistical uncertainties in quadrature, adding the Blu and Yel values in quadrature for DSA. For example,

$$\sigma(\mathcal{P}_i) = \sigma(P_{0,i}) \oplus \frac{\int dt t L_i(t)}{\mathcal{L}_i} \cdot \sigma(P'_i) \oplus \mathcal{P}_i \cdot (\sigma(P)/P)_{\text{Table 3}} \quad (12)$$

and

$$\sigma(P_{set}) = \frac{\oplus_i \mathcal{L}_i \cdot \sigma(\mathcal{P}_i)}{\sum_i \mathcal{L}_i}. \quad (13)$$

However, this leads to double counting of uncertainties, since they already contribute to $\sigma(\text{scale})$ through the uncertainties on A_N in Table 2. (Recall that the uncertainties on A_N incorporate all statistical and systematic uncertainties from both the H-jet and pC for an entire running period, as described in Section 3.2.) The A_N were evaluated using nearly entire run periods, so the overcounting is significant when the data set used for a measurement is an appreciable fraction of the run period. An approximate correction for the overcounting should be applied; since the errors are fill-to-fill the correction depends on the numbers of fills used. Suppose that N fills in the entire run period were used to determine A_N , $M \leq N$ fills are in the data set for the measurement, and let $\sigma(13)$ be the uncertainty determined from Eq. (13).

Then the corrected uncertainty is $\sigma(\text{fill-to-fill scale}) = \sqrt{1 - \frac{M}{N}} \sigma(13)$. The values of N for each running period are listed in Table 5. In each period there were several fills not used for the determination of A_N , ususally because the fills were short and the statistics were too limited for an H-jet measurement. Thus it is possible that $M > N$; in these cases it is reasonable to take $\sigma(\text{fill-to-fill scale}) = 0$.

N (# fills)	Blu	Yel
Run12-255	49	49
Run12-100	56	55
Run11-250	65	65
Run9-100	117	116

Table 5: Number of fill used to determine A_N .

- Profile correction: The relative uncertainty of the profiles correction for one beam in one fill is 2.2%. For a set of M fills it contributes a relative uncertainty on the polarization for an SSA measurement of $\sigma(\text{profile})/P = 2.2\%/\sqrt{M}$, and for a DSA measurement $\sigma(\text{profile})/P = 3.1\%/\sqrt{M}$.

For data sets consisting of a large fraction of a running period the fill-to-fill systematic uncertainties are negligible.

4.3.3 Total uncertainty

These components of the uncertainty are then added in quadrature to give the overall uncertainty on P_{set} . Explicitly, in terms of $\sigma(\text{scale})/P$ from Section 4.3.1, and $\sigma(\text{fill-to-fill scale})$

and $\sigma(\text{profile})/P$ from Section 4.3.2, the total uncertainty on the mean polarization for a data set is

$$\sigma(P_{set}) = P_{set} \cdot \frac{\sigma(\text{scale})}{P} \oplus \sigma(\text{fill-to-fill scale}) \oplus P_{set} \cdot \frac{\sigma(\text{profile})}{P}. \quad (14)$$

For data sets consisting of a large fraction of a running period the fill-to-fill systematic uncertainties are negligible and $\sigma(P_{set})/P_{set} = \sigma(\text{scale})/P$ from Table 4.

4.3.4 Scale uncertainty of different running periods

The polarization scale uncertainty is dominated by the 3% uncertainty on H₂ contamination of the polarized atomic hydrogen jet, discussed in Section 3.1. Within a given running period, the pC configuration was fixed, and the pC/H-jet normalization is sensitive to fluctuations in the H₂ contamination. As summarized in Section 3.2 and Table 1, systematic fill-to-fill variations of the ratio were usually negligible or less than 3%; when they were larger than 3%, the fluctuations may be attributed to known instabilities of the pC polarimeter. Thus, within a running period the fluctuations in H₂ contamination were within the 3% uncertainty.

In different running periods, the pC configuration was altered, and the pC/H-jet ratios are not directly comparable. Also, there were no direct measurements of the jet H₂ contamination in different running periods; the 3% uncertainty was assigned to span likely variations of the contamination between different periods. Given the lack of information, it is prudent to choose a maximally conservative estimate of the scale uncertainty when combining data from different running periods. This depends on whether identical or different measurements are being combined. Consider the example of a process measured in different kinematic regions *A* and *B*. Then:

- If region *A* was measured in both Run11-250 and Run12-255, select the larger of the uncertainties from Table 4, 3.4% in this case.
- If region *A* was measured in Run11-250, and region *B* in Run12-255, assign the relevant uncertainties from Table 4 to each, in this case 3.3% for *A* and 3.4% for *B*.

References

- [1] Much more information on the polarimetry system is available on the polarimetry wiki and links therein: <https://wiki.bnl.gov/rhicspin/Polarimetry>
- [2] W. Fischer and A. Bazilevsky, Phys. Rev. ST Accel. Beams **15**, 041001 (2012).
- [3] An example of the H-jet/pC ratios for the Blu upstream polarimeter in Run12 255 GeV running is at:

http://www.phy.bnl.gov/cnipol/runs/run12_e255/images//runs/B1U/c.hNorm.JCVsFill.B1U_255.png .
Other running periods are available by replacing 'Run12' with 'Run11' or 'Run09',
and '255' with '100' or '250'; other polarimeters by replacing 'B1U' with 'B2D', 'Y2U'
or 'Y1D'.

- [4] An example of the upstream/downstream ratios for the Blu pC polarimeters in Run12
255 GeV running is at:

http://www.phy.bnl.gov/cnipol/runs/run12_e255/images//runs/BLU/c.hPolarRatioSystVsFill.BLU_255.png .
Other running periods are available by replacing 'Run12' with 'Run11' or 'Run09',
and '255' with '100' or '250'; other polarimeters by replacing 'BLU' with 'YEL'.

- [5] An example of a distribution of polarization vs. intensity and fit from one pC measure-
ment is at:

<http://www.phy.bnl.gov/cnipol/runs/16720.005/images//profile/c.hPolarVsIntensProfile.png> .

- [6] The results are available at <https://wiki.bnl.gov/rhicspin/Results>; there, for each year
click on 'Fill by fill results'.