The Hydrogen Jet Target polarimeter performance in RHIC Run22

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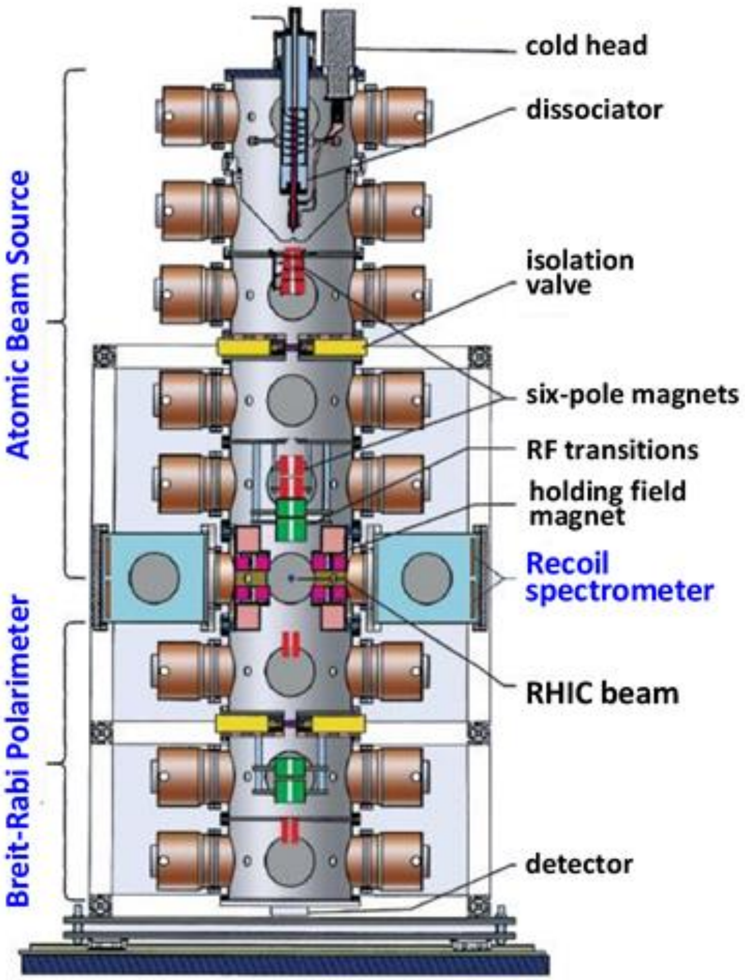
The Polarized Atomic Hydrogen Gas Jet Target (HJET) at RHIC

A. Zelenski et al., Nucl. Instrum. Meth. A **536**, (2005)
A.A. Poblaguev *et al.*, Nucl. Instr. Meth. A **976**, 164261 (2020)
A.A. Poblaguev *et al.*, Phys. Rev. Lett. **123**, 162001 (2019)



Since 2004, the HJET is used to measure the absolute proton beam polarization at RHIC

- The polarized gas jet target
  - ✓ Continuous beam polarization measurement with no impact on the RHIC experiments.
  - ✓ The recoil protons can be precisely measured in the energy range of 0.6 – 10 MeV (the CNI analyzing power maximum)
- The beam polarization can be related to the atomic Hydrogen polarization which is precisely monitored, $\boldsymbol{P_{\text{jet}}} \sim \mathbf{96 \pm 0.1}\%$, by a Breit-Rabi polarimeter

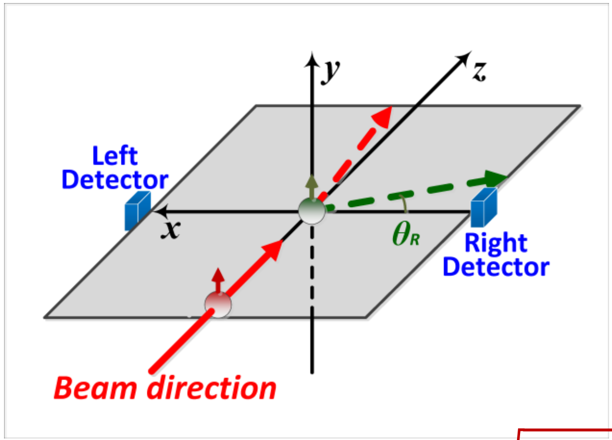
The HJET consists of three main parts:

1. Atomic beam source (ABS) for the formation of a vertically polarized and directed proton jet
2. Recoil proton spectrometer (RPS) for measuring the polarization of the proton beam
3. Breit-Rabi polarimeter (BRP) for determining the polarization of jet protons

The parameters of proton jet:

1. Atomic beam intensity - $1.2\text{x}10^{17}$ atoms/s
2. Thickness at the collision point - $1.2\text{x}10^{12}$ atoms/cm^2
3. Profile of jet Gaussian distribution - $\sigma \sim 2.6$ mm

Proton beams polarization measurement at HJET



The beam $(\uparrow\downarrow)$ and target $(\pm)$ single spin asymmetries are concurrently measured in the $0.5 < T_R < 10$ MeV recoil energy range.

In the HJET measurements, the same events are used to determine a_{beam} and a_{jet} . Therefore, for the elastic pp scattering, the jet and beam average analyzing powers are expected to be equal.

$$a_{\text{beam}} = \langle A_{\text{N}} \rangle P_{\text{beam}} \Rightarrow \frac{\sqrt{N_R^\uparrow N_L^\downarrow} - \sqrt{N_R^\downarrow N_L^\uparrow}}{\sqrt{N_R^\uparrow N_L^\downarrow} + \sqrt{N_R^\downarrow N_L^\uparrow}}$$

$$a_{\text{jet}} = \langle A_{\text{N}} \rangle P_{\text{jet}} \Rightarrow \frac{\sqrt{N_R^+ N_L^-} - \sqrt{N_R^- N_L^+}}{\sqrt{N_R^+ N_L^-} + \sqrt{N_R^- N_L^+}}$$

$$P_{\text{beam}} = \frac{a_{\text{beam}}}{a_{\text{jet}}} P_{\text{jet}}$$

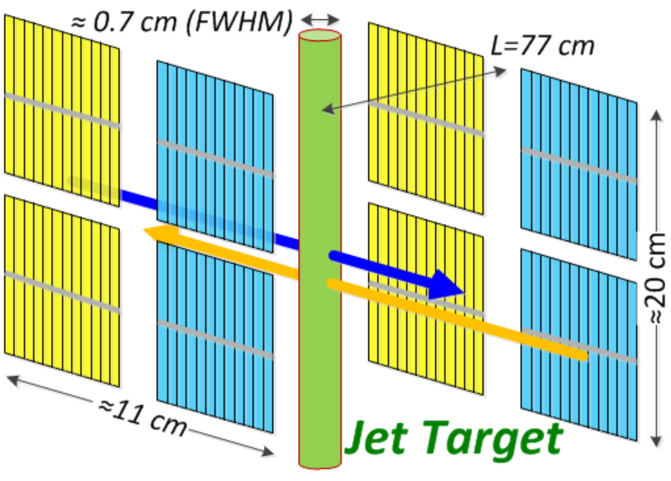
The beam polarization can be precisely determined with no detailed knowledge of the analyzing power

Typical results for an 8-hour store in RHIC Run 17 (255 GeV)

$$P_{\text{beam}} \approx (56 \pm 2.0_{\text{stat}} \pm 0.3_{\text{syst}})\%$$

$$\sigma_P^{\text{syst}} / P_{\text{beam}} \lesssim 0.5\%$$

The HJET recoil spectrometer

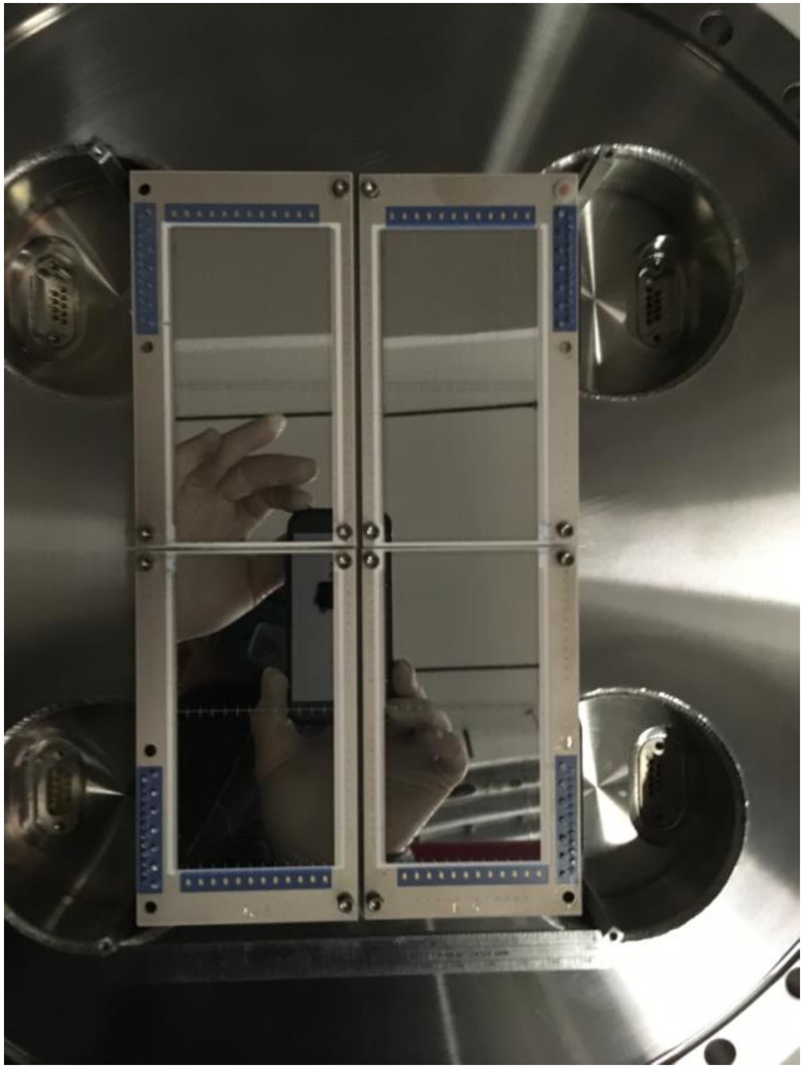


- Recoil protons from the proton beam scattering off the jet are detected in the left-right symmetric silicon detectors
    - 8 detectors (4 for the blue beam and 4 for the yellow)
    - 12 vertically oriented Si strips (3.75 mm width) in each detector.
- The measured recoil proton parameters
    - T_R - kinetic energy,
    - $ToF = t_R - t_0$ - time of flight,
    - z_R - coordinate in detectors (discriminated by Si strip)
    - and signal waveform shape analysis allows us to isolate the elastic events.
- Polarization of both RHIC beams, *blue* and *yellow*, are measured concurrently and continuously (during the store)

For elastic pp scattering there is a strict correlation between the detected recoil proton kinetic energy T_R and the strip coordinate z_{strip} :

$$\sqrt{T_{\text{strip}}} = \sqrt{2m_p \frac{E_{\text{beam}} - m_p}{E_{\text{beam}} + m_p}} \times \frac{z_{\text{strip}} - z_{\text{jet}}}{L}$$

The HJET recoil spectrometer

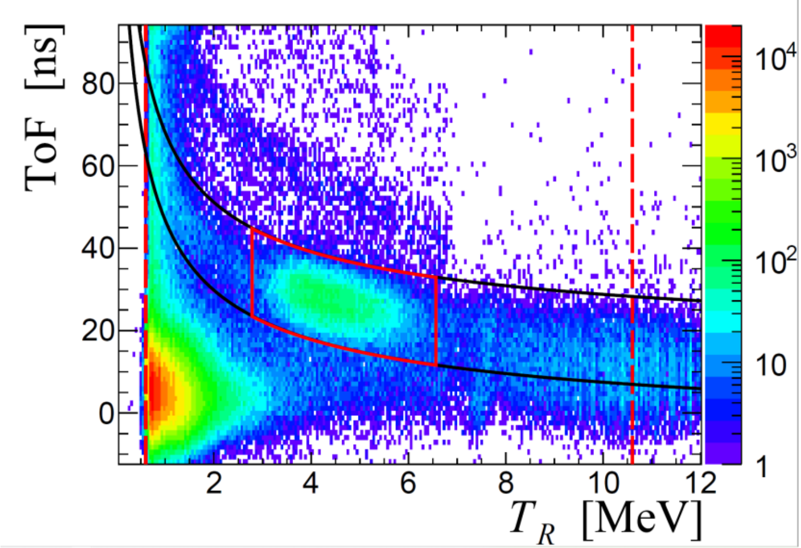


8 detectors (12 strips per detector)

Detector size	$2 \times (45 \times 45) mm^2$
Gap between detectors	$\approx 19\ mm$
Strip size	$2 \times (3.7\ \times 45)\ mm^2$
Gap between strips	$50\ \mu m$
Depletion region	$470\ \mu m$
Uniform Dead-layer	$\sim\ 0.37\ mg/cm^2$
Distance to the beam	$770\ mm$
Bias Voltage	$150\ V$

- Different calibration methods were tested
  - ✓ Energy resolution $\sim 20\ keV$
  - ✓ Systematic errors in energy calibration $\delta E/E < 0.5\%$ for 1-6 MeV protons
  - ✓ Time alignment of electronic channels is better than $\delta t < 120\ ps$
  - ✓ z-coordinates of detectors may be monitored with accuracy $\delta z \sim 100\ \mu m$
  - ✓ beam angle and x-coordinate may be monitored with accuracy $0.1\ mrad$ and $100\ \mu m$, respectively.
- A method of full reconstruction of punched through protons was developed
  - ✓ Recoil proton energy range was increased to 0.5 – 10.5 MeV
  - ✓ Background for stopped protons was suppressed

Event Selection Cuts



To isolate elastic pp events, the measured recoil proton energy is compared with the time of flight

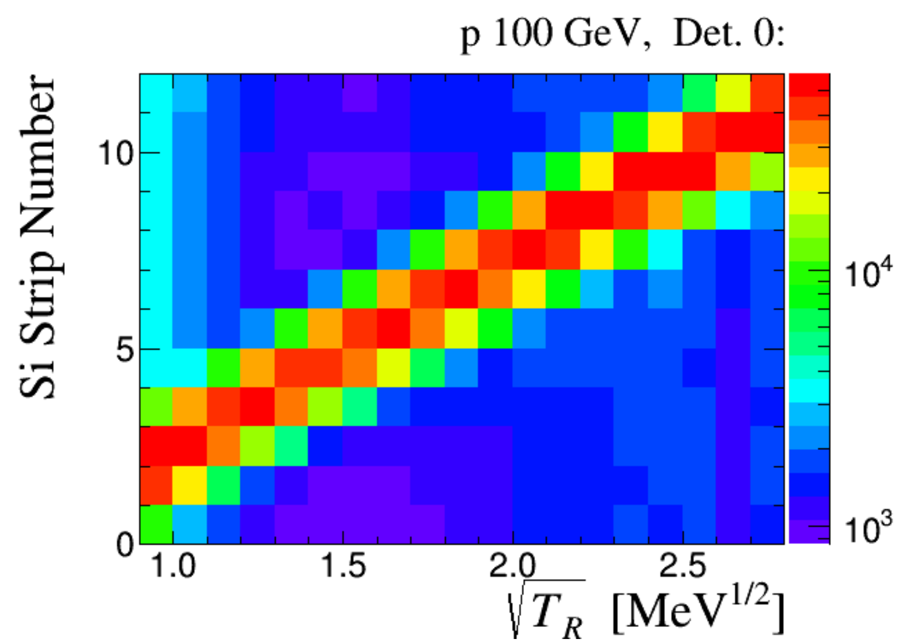
$$\delta t = \mathrm{ToF} - \sqrt{\frac{m_p}{2T_R}}\frac{L}{c} \approx 0$$

and with z-coordinate of the Si strip

$$\delta\sqrt{T_R} = \sqrt{T_R} - \sqrt{T_{strip}} \approx 0$$

The experimental uncertainty in values of δt and $\delta\sqrt{T_R}$ are the same for all Si strips.

- Since, for a given T_R, a background rate is about the same in all strips of a HJET Si detector, the background can be reliably subtracted from the elastic data
- Some controllable corrections due to tracking in the holding field magnet and due to inelastic pp scattering should be applied.
- The background subtraction can be done separately for each combination of the beam and jet spins.



OFFLINE data analysis in Run 2017 (255 GeV protons)

Cuts I

Minimum statistical error cuts

$$0.6 < T_R < 10.6 \text{ MeV}$$
$$-7 < \delta t < 7 \text{ ns}$$
$$-0.4 < \delta\sqrt{T_R} < 0.4 \text{ MeV}^{1/2}$$

Cuts II

Minimum systematic error cuts

$$2.0 < T_R < 9.5 \text{ MeV}$$
$$-7 < \delta t < 7 \text{ ns}$$
$$-0.18 < \delta\sqrt{T_R} < 0.3 \text{ MeV}^{1/2}$$

$$\langle A_N^{\text{eff}} \rangle_{\text{Blue}} = \mathbf{3.749 \pm 0.013_{stat} \pm 0.014_{syst}}\%$$
$$\langle A_N^{\text{eff}} \rangle_{\text{Yell}} = \mathbf{3.739 \pm 0.012_{stat} \pm 0.014_{syst}}\%$$

- Using Cuts II, the Run 17 average beam polarization was precisely determined.
- Consequently, the effective analyzing power $\langle A_N^{\text{eff}} \rangle$ for Cuts I was calculated.
- It was proven that $\langle A_N^{\text{eff}} \rangle$ was very stable during the whole Run 17.
- For a (typically 8 hour) store, the absolute beam polarization was determined as

$$\boldsymbol{P_{\text{beam}} = \langle a_{\text{beam}} \rangle_{\text{Cuts I}} / \langle A_{\text{N}}^{\text{eff}} \rangle}$$

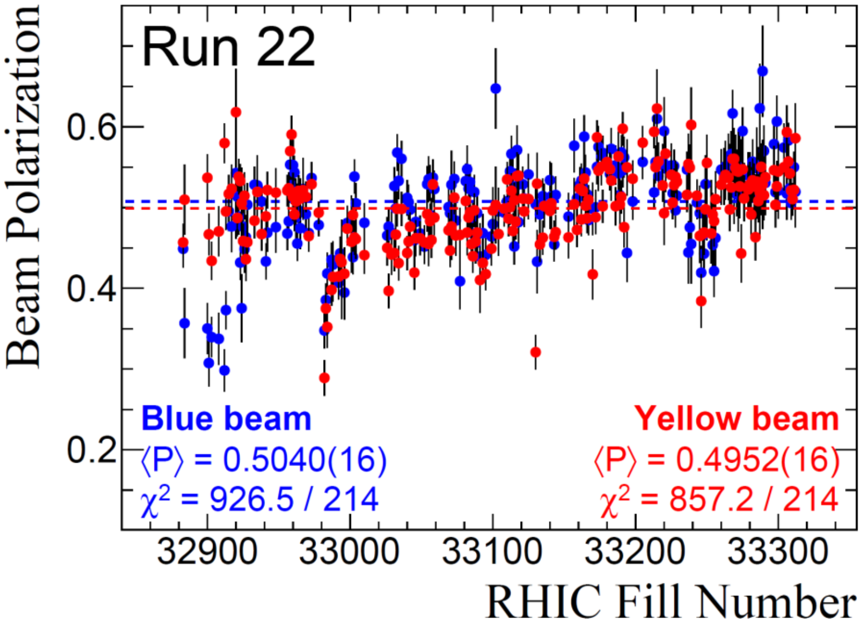
which minimizes experimental uncertainties for such a measurement.

RHIC Run 2022 (255 GeV protons)

- **First proton Run at RHIC after 2017**.
- However, the HJET routinely operated in Heavy Ion beam Runs 18-21
- **Preparation for Run 22**. To eliminate some aging problems:
  - The signal cables connectors were renewed.
  - New preamplifiers were installed
  - The gains and signal wave form shapes were noticeably changed, but recalibration was done with no issues.
  - The energy resolution was degraded from 20 keV to ~23 keV, but this is not essential for the data analysis.
- **In Run 22, for online measurement of the proton beam polarization, Run 17 values of Cuts I and $\langle A_{\mathrm{N}}^{\mathrm{eff}} \rangle$ were used**

Online measurements of the beam polarization in Run 22

- For online measurement of the 255 GeV proton beam polarization, we used effective analyzing powers calibrated in Run 17.
- To verify the method, we can compare the measured analyzing powers (for Cuts I) in RHIC Runs 17 and 22.



Run 22: $\langle A_\mathrm{N}\rangle_B = 3.757 \pm 0.007\%$

$\langle A_\mathrm{N}\rangle_Y = 3.757 \pm 0.007\%$

Run 17: $\langle A_\mathrm{N}\rangle_B = 3.769 \pm 0.006\%$

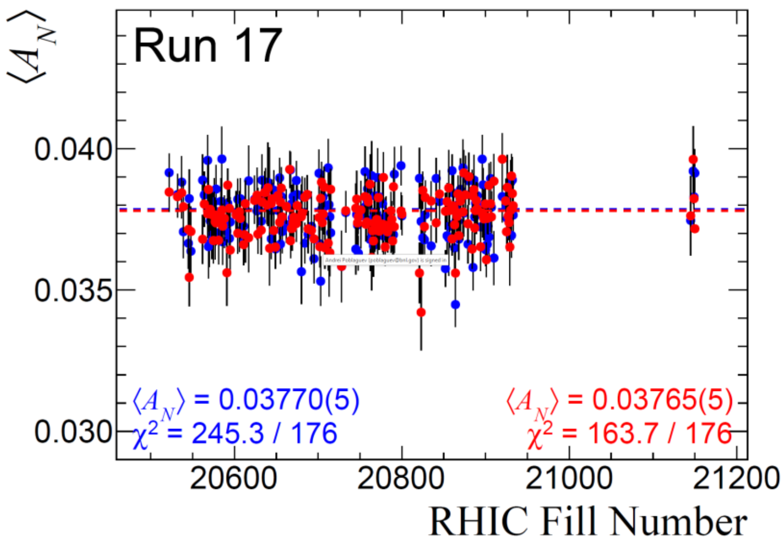
$\langle A_\mathrm{N}\rangle_Y = 3.765 \pm 0.006\%$

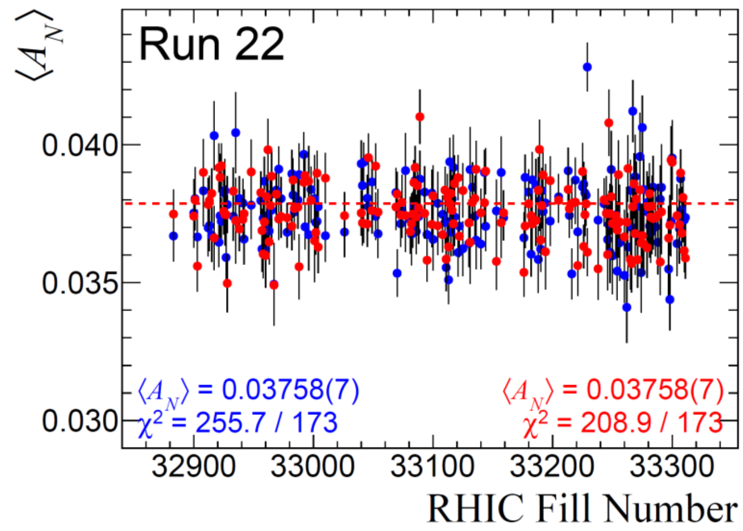
The result consistency $\chi^2/\mathrm{ndf} = 2.3/3$

- Run 17 and 22 measurements are consistent within $< 0.3\%$ statistical accuracy.
- In Run 22, systematic uncertainties of online measurements are $\sigma_P^\mathrm{syst}/P_\mathrm{beam} \lesssim 0.6\%$.
- That is, the online results may be considered as final (offline) ones

Stability of the analyzing power measurements

Store by store stability of the polarization measurements is critically important for the conclusion on systematic errors in Run 22.





- Good long-term stability for both RHIC Runs 17 and 22
- Good consistency for Run 17 and 22 results
- In Run 22 measurements, variation of the systematic errors, if any, is small compared to the statistical uncertainties.

Backgrounds

If the data is contaminated by a background, then the measured asymmetry is equal to $a_N = \frac{\langle A_N \rangle + f_{\text{bgr}} \langle A_N^{\text{bgr}} \rangle}{1 + f_{\text{bgr}}} P$. Therefore, ratios of asymmetries determined with and without background subtraction can be used to evaluate background fraction f_{bgr},

$$R = (1 + f_{\text{bgr}}) / \left(1 + f_{\text{bgr}} \left\langle A_N^{\text{bgr}} \right\rangle / \langle A_N \rangle\right) \approx 1 + f_{\text{bgr}}$$

Measured *R*

TABLE III. The ratio of single spin asymmetries a_{N} determined with and without background subtraction.

	Jet asymmetry a_{N}^{j}		Beam asymmetry a_{N}^{b}	
	Blue	*Yellow*	*Blue*	*Yellow*
Run 22	1.156	1.155	1.125	1.117
Run 17	1.067	1.068	1.049	1.044

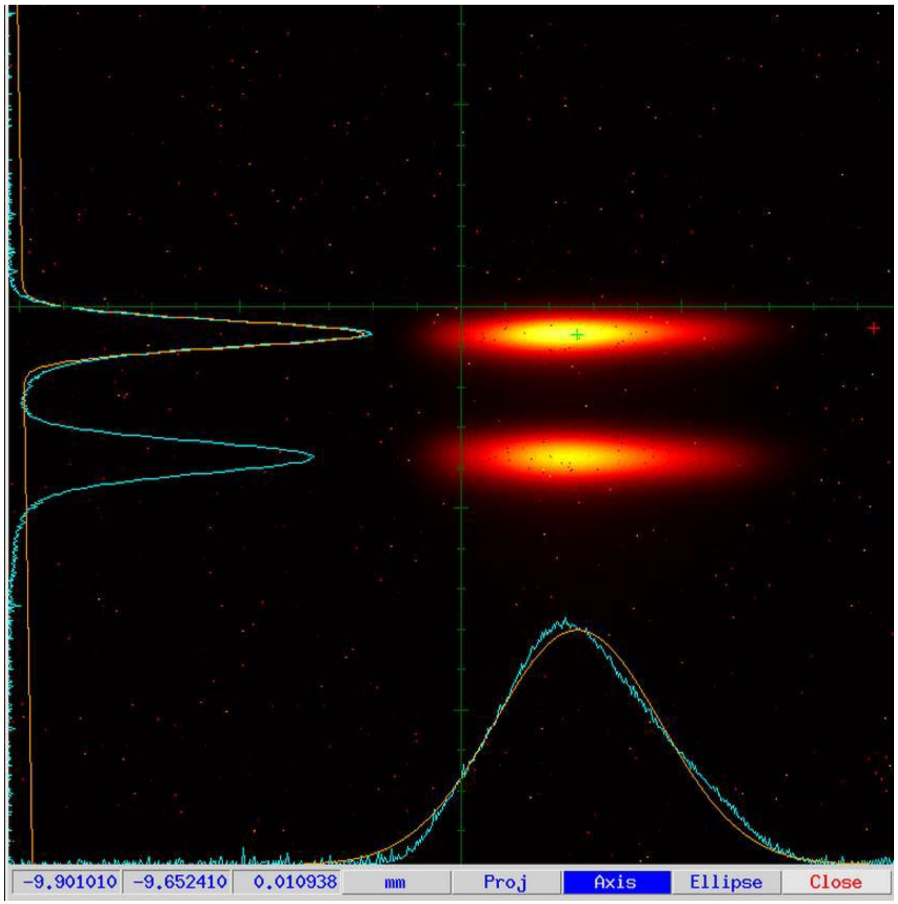
- The background fraction is 6.8% (2017) and 15.6% (2022)
- After background subtraction, the difference in values of a_N in Runs 17 and 22 does not exceed 0.3% (relative).
- The background subtraction (in the data analysis) works well.

Summary

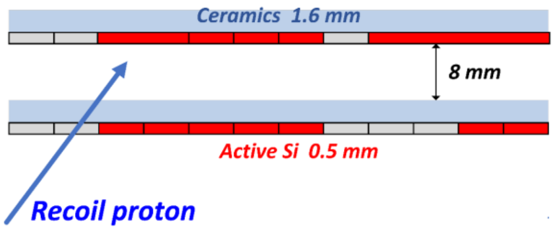
- **Polarized proton beam operation was resumed at RHIC after 4.5 years heavy ion only Runs**
- **The H-jet polarimeter was operate during all heavy ions Runs 2018-21 for**
  - ✓ **different test configuration for systematic error studies and**
  - ✓ **jet application for the beam profile monitoring for LEREC development and operation.**
- **The HJET performance in Run 22 was very similar to that of in Run 17.**
- **The online determination of the absolute polarization of the 255 GeV proton beams has been done with very low systematic uncertainties of** $\sigma_P^{\rm syst}/P_{\rm beam} \lesssim 0.6\%$.
- **Regardless, the background rate in Run 22 was about factor 2.2 larger than in Run 17, no corresponding changes of the measured asymmetries were found to be negligible (within statistical uncertainties of about** $\lesssim 0.3\%$ **relative**).
- **The H jet is in good shape for the next run and hopefully many more years of the RHIC and EIC operation**.

The HJET recoil spectrometer

H-jet luminescence monitor



Double-layer detector was tested at Run21



The goal was to veto punch-through π,p,d,α,..., which are expected to have momentums of 100-500 GeV/c. The ceramics between layers must not be the problem for that.

•The detector was tested in 5.76 GeV/nAu beam (Run 2020)

•The prompts rate in the second layer was 30-40% compared to the first one.

•The prompts veto efficiency can be evaluated as ≲10-20%.