Precise measurements of the single $A_N(t)$ and double $A_{NN}(t)$ spin-flip asymmetries in CNI region in elastic $p^\uparrow p^\uparrow$ scattering at $\sqrt{s} = 13.76$ GeV and $\sqrt{s} = 21.92$ GeV at RHIC HJET polarimeter

A.A. Poblargev

Brookhaven National Laboratory
Polarized Atomic Hydrogen Gas Jet Target (HJET)

HJET designed to measure absolute polarization of RHIC proton beams is, in fact, a fixed target experiment performed concurrently with RHIC colliding experiments.

The Jet proton target polarization, $P_{\text{jet}} = 0.96$, is flipped every 5-10 minutes.

This report includes analysis of single- and double spin-flip analyzing power in elastic $pp$ scattering in two RHIC runs:

- **Run15**: $E_{\text{beam}} = 100$ GeV ($\sqrt{s} = 13.76$ GeV)
- **Run17**: $E_{\text{beam}} = 255$ GeV ($\sqrt{s} = 21.92$ GeV)

- A technical description of HJET was given by Anatoli Zelenski
- Theoretical basis for elastic polarized $p^\uparrow p^\uparrow$ measurements was discussed by Nigel Buttimore.
- A detailed description of the HJET data analysis method can be found in PSTP 2017 Proceedings, A. Poblaguev et al., PoS(PSTP2017)022.
**HJET detector configuration**

- HJET consist of 8 Silicon detectors, 12 strips. each. 4 detectors per RHIC beam.
- Full waveform is recorded for every event.
- For elastic scattering, the detected recoil proton kinetic energy $T_R$ range is defined by HJET geometry

$$0.5 < T_R < 11 \text{ MeV}$$

- The momentum transfer is proportional to $T_R$

$$t = (p_R - p_t)^2 = -2m_p T_R$$

- Both RHIC beams (Blue and Yellow) are measured simultaneously.
- The waveform shape analysis was employed to separate stopped and punched-trough ($T_R > 7.8$ MeV) recoil protons.
- The detectors granulation (vertical strips) allowed us to accurately identify backgrounds and subtract them separately for
  - every detector
  - every $\sqrt{T_R}$ bin
  - every combination of beam/jet spins

**HJET results for $pp A_N (t)$ and $A_{NN} (t)$**
Systematic correction and uncertainties

Detailed study of systematic errors for the polarization measurements at 255 GeV is given in PSTP 2017 Proceedings.

The inelastic scattering \( pp \rightarrow Xp \) uncertainty is irrelevant for 100 GeV.

For analyzing power measurements we should also consider systematic corrections/uncertainties which are effectively canceled in the beam polarization measurements.

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta P/P ) (%)</th>
<th>( \sigma_P/P ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long term stability</td>
<td></td>
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<tr>
<td>Jet Polarization</td>
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<td>0.1</td>
</tr>
<tr>
<td>Jet ( H_2 )</td>
<td></td>
<td>0.06</td>
</tr>
<tr>
<td>Flat ( H_2 )</td>
<td>+0.06</td>
<td>( \approx 0.1 )</td>
</tr>
<tr>
<td>pA scattering</td>
<td></td>
<td>( \approx 0.2 )</td>
</tr>
<tr>
<td>( p+p \rightarrow X+p )</td>
<td>+0.15</td>
<td>0.1</td>
</tr>
<tr>
<td>Jet spin correlated noise</td>
<td></td>
<td>( \approx 0.2 )</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>+0.21</strong></td>
<td>( \approx 0.37 )</td>
</tr>
</tbody>
</table>

- Corrections to the background subtraction due to the recoil proton tracking in the Holding Field Magnet were simulated.
- Corrections due to vertical size of the detectors \( P_{jet}^{eff} = P_{jet} \langle \sin \varphi \rangle = 0.997 P_{jet} \).
- The energy calibration (gains and dead-layers) was done using \( \alpha \)-sources. It was not verified for recoil protons. Using indirect methods we established an upper limit for the calibration uncertainty as \( \delta T = (\pm 15 \text{ keV}) \oplus (\pm 0.01 T) \).
Spin Correlated Asymmetries in elastic $p^\uparrow p^\uparrow$ scattering

For transversely polarized beam and target (Jet) the azimuthal dependence of cross-section is given by:

$$\frac{d^2\sigma}{dt \, d\varphi} = \frac{1}{2\pi} \frac{d\sigma}{dt} \left[ 1 + (P_{jet} + P_{beam}) A_N \sin \varphi + P_{jet} P_{beam} (A_{NN} \sin^2 \varphi + A_{SS} \cos^2 \varphi) \right]$$

Three measured spin-correlated asymmetries:

$$a_{N}^{jet} = |P_{jet}| A_N, \quad a_{N}^{beam} = |P_{beam}| A_N, \quad a_{NN} = |P_{jet} P_{beam}| A_{NN}$$

allows us to determine:

- Beam polarization
  $$P_{beam} = P_{jet} \frac{\langle a_{N}^{beam} \rangle}{\langle a_{N}^{jet} \rangle}$$
- Single-spin analyzing power
  $$A_N(t) = a_{N}^{jet} / P_{jet}$$
- Double spin analyzing power
  $$A_{NN}(t) = a_{N}^{jet} a_{NN} / a_{N}^{beam} P_{jet}^2$$

$P_{jet} = 0.96, \quad P_{beam} \sim 0.55$

Analyzing powers $A_N(t)$ and $A_{NN}(t)$ as measured in this work.
Measurement of the Spin Correlated Asymmetries

Spin correlated asymmetries $a_N^{beam}$, $a_N^{jet}$, and $a_{NN}$ are derived from 8 numbers of the detected events corresponding to 8 combinations of the jet spin $(+-)$, beam spin $(\uparrow\downarrow)$, and detector side $(LR)$

$$N_{(LR)}^{(+\text{-})} = N_0 \left( 1 \pm a_N^{j} \pm a_N^{b} \pm a_{NN} \right) \left( 1 \pm \lambda_j \right) \left( 1 \pm \lambda_b \right) \left( 1 \pm \epsilon \right)$$

The event numbers also depend on the spin correlated integral statistics asymmetry for jet $\lambda_{jet}$ and beam $\lambda_{beam}$ as well as on left/right acceptance asymmetry $\epsilon$.

The equations have the exact solution which eliminates uncertainties associated with $\lambda_{jet}$, $\lambda_{beam}$, $\epsilon$.

$$a_N^{jet} = \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}} + \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}}} - \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}}} - \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}}}$$

$$a_N^{beam} = \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}} - \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}}} + \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}}} + \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}}}$$

$$a_{NN} = \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}} - \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}}} - \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}}} - \sqrt{\frac{N_R^+ N_L^{-}}{N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-} + N_R^+ N_L^{-}}}$$

This is a systematic error free solution if the effective analyzing powers are the same for left/right detectors and the detector acceptance is beam/jet spin independent.
Overview of possible systematic errors

Systematics corrections in the spin asymmetry measurements may be approximated as:

\[
\delta a_N = P \frac{\delta A_N^{(R)} + \delta A_N^{(L)}}{2} + \frac{\delta \epsilon_R - \delta \epsilon_L}{2}
\]

\[
\delta \lambda = P \frac{\delta A_N^{(R)} - \delta A_N^{(R)}}{2} + \frac{\delta \epsilon_R + \delta \epsilon_L}{2}
\]

\(\delta A_N\) is a discrepancy between actual and assumed analyzing powers due to background and/or wrong energy calibration.

\(\delta \epsilon = \frac{\epsilon^\uparrow - \epsilon^\downarrow}{\epsilon^\uparrow + \epsilon^\downarrow}\) is a spin correlated asymmetry of the detector acceptance.

Generally, \(\delta A_N\) and \(\delta \epsilon\) are left/right and jet/beam dependent.

In HJET, \(\delta \epsilon = 0\) for the beam spin. However, in Run 15 significant Jet spin correlated \(\delta \epsilon\) corrections were observed in two blue detectors. These detectors were removed from the data analysis.

Monitoring of the measured beam/jet intensity asymmetries \(\lambda(T_R)\) dependence on the recoil proton energy is an important part of the systematic error control.
**Helicity amplitudes describing elastic $p^\uparrow p^\uparrow$ scattering:**

Spin non-flip $\phi_1(s, t) = \langle +++ \rangle$, $\phi_3(s, t) = \langle + - + \rangle$

Double spin flip $\phi_2(s, t) = \langle ++- \rangle$, $\phi_4(s, t) = \langle + - - \rangle$

Single spin flip $\phi_5(s, t) = \langle + + - \rangle$

$$
A_N(t) = \frac{\sqrt{-t}}{m_p} \frac{[\kappa(1 - \rho \delta_C) - 2(\text{Im } r_5 - \delta_C \text{Re } r_5)] t_c}{t} - 2 \text{Re } r_5 + 2 \rho \text{Im } r_5
\left(\frac{t_c}{t}\right)^2 - 2(\rho + \delta_C) \frac{t_c}{t} + 1 + \rho
$$

Hadronic spin-flip amplitude: $r_5 = \frac{m_p \phi_5^{had}}{\sqrt{-t} \text{ Im } \phi_+^{had}}$

Elastic $pp$ parameters $\sigma_{tot}$, $\rho$, $B$ are well known from unpolarized experimental data.

For visual control it is convenient to use normalized asymmetry

$$
a_n(t) = A_N(t) / A_N^{(0)}(t) = P \alpha_5 \left(1 + \beta_5 \frac{t}{t_c}\right)
$$

$A_N^{(0)}(t) = A_N(t, r_5 = 0)$

$\alpha_5 \approx 1 - \frac{2}{\kappa} \text{Im } r_5$  $\beta_5 \approx -\frac{2}{\kappa} \text{Re } r_5$

$$
\phi_i(s, t) = \phi_i^{had}(s, t) + \phi_i^{em}(s, t)e^{\delta_C(s, t)}
\phi_{\pm}(s, t) = \frac{\phi_1(s, t) \pm \phi_3(s, t)}{2}
$$

$\kappa = \mu_p - 1 = 1.79$
$\delta_C(B) \approx 0.02$
$-t_c = 8\pi\alpha / \sigma_{tot} \approx 0.002 \text{ GeV}^2$
$\rho = -(0.01 \div 0.08)$
Single Spin asymmetry 100 GeV (Run 2015)

\[ \tilde{\alpha}_5 = P\alpha_5 \]

Measured normalized spin asymmetries \( a_N \) linearly depend on \( T_R \)

\[ a_n = \tilde{\alpha}_5 \times (1 + \beta_5 \frac{t}{t_c}) \]

Jet spin asymmetry fit range: \( 0.7 < T_R < 9.9 \text{ MeV} \)

Beam spin asymmetry fit range: \( 0.7 < T_R < 9.9 \text{ MeV} \)

No evidence of uncontrolled systematic errors for the used event selection cuts

- Measured normalized spin asymmetries \( a_N \) linearly depend on \( T_R \)
- \( \langle \beta_5 \rangle = 0.0174 \pm 0.0008, \quad \chi^2/\text{ndf} = 4.24/3 \)
- Measured intensity asymmetries \( \lambda \) do not depend on \( T_R \)

The results are shown separately for Blue and Yellow RHIC beams

HJET results for \( pp A_N(t) \) and \( A_{NN}(t) \)
**Single Spin asymmetry 255 GeV (Run 2017)**

\[ \tilde{\alpha}_5 = P\alpha_5 \]

\[
\alpha_n = \tilde{\alpha}_5 \times (1 + \beta_5 \frac{t}{t_c})
\]

**The results are shown separately for Blue and Yellow RHIC beams**

**Jet spin asymmetry fit range:**
\[ 1.9 < T_R < 9.9 \text{ MeV} \]

**Beam spin asymmetry fit range:**
\[ 0.7 < T_R < 9.9 \text{ MeV} \]

- **Measured normalized spin asymmetries** \( \alpha_N \) **linearly depend on** \( T_R \)
- \[ \langle \beta_5 \rangle = 0.0078 \pm 0.0006, \quad \chi^2/\text{ndf} = 3.94/3 \]
- **Measured intensity asymmetries** \( \lambda \) **do not depend on** \( T_R \)

For Jet spin asymmetry \( \alpha_{n}^{\text{jet}}(T_R) \), there is uncontrolled systematics for \( T_R < 1.9 \text{ MeV} \). This data is not used in the fit.
Forward elastic Re / Im ratio $\rho$ from the spin asymmetries

To test HJET data for possible “hidden” systematic uncertainties we fit HJET data with $\rho$ being a free parameter.

$$A_N = A_N(t, r_5, \rho)$$

- This unusual method of experimental determination of the Re/Im ratio $\rho$ from the measured spin correlated asymmetries gave the results comparable and consistent with other entries to the PDG data.
- However, the global fit of the PDG data provides much better accuracy for $\rho(s)$.  

$pp$ data (PDG)
Single spin-flip $A_N(t)$ at 100 GeV ($\sqrt{s} = 13.76$ GeV)

Measured asymmetry $a_N = PA_N(t, r_5)$

$\rho = -0.079, \sigma_{tot} = 38.39$ mb, $B = 11.4$ GeV$^{-1}$

Beam polarizations are free parameters in the fit

Hadronic single spin-flip amplitude is well isolated at $\sqrt{s} = 13.76$ GeV

$\delta_\rho$ is a correction if $\rho = -0.079$ (pp and p\bar{p}) $\Rightarrow$ $\rho = -0.083$ (PDG)
Single spin-flip $A_N(t)$ at 255 GeV ($\sqrt{s} = 21.92$ GeV)

Measured asymmetry $a_N = PA_N(t,r_5)$

$\rho = -0.009$, $\sigma_{\text{tot}} = 39.19$ mb, $B = 12$ GeV$^{-1}$

Beam polarizations are free parameters in the fit

$\Delta r_5 = (-7.3 \pm 0.5_{\text{stat}} \pm 0.8_{\text{syst}} + 0.1_\rho) \times 10^{-3}$

$\text{Im } r_5 = (21.5 \pm 2.5_{\text{stat}} \pm 2.5_{\text{syst}} - 3.3_\rho) \times 10^{-3}$

$\delta_\rho$ is a correction if $\rho = -0.009$ ($pp$ and $p\bar{p}$) $\Rightarrow \rho = -0.012$ (PDG)
Double Spin-Flip Analyzing Power $A_{NN}(t)$

$$A_{NN}(t) = \frac{-2(\text{Re } r_2 + \delta_c \text{Im } r_2) \frac{t_c}{t} + 2 \text{Im } r_2 + 2 \rho \text{Re } r_2 - \rho \frac{t_c \kappa^2}{2m_p^2} + \frac{2t_c \kappa}{m_p^2} \text{Re } r_5}{(\frac{t_c}{t})^2 - 2(\rho + \delta_c) \frac{t_c}{t} + 1 + \rho^2}$$

Hadronic double spin flip amplitude: $r_2 = \frac{\phi_2^{\text{had}}}{2 \text{ Im } \phi_+^{\text{had}}}$

$$A_{NN}(t) = \frac{a_{NN}(t)}{P_{\text{beam}} P_{\text{jet}}} = \frac{A_N^2(t, r_5)}{a_N^{\text{beam}}(t)} \frac{a_{NN}(t)}{a_N^{\text{jet}}(t)}$$

- Jet spin correlated systematic uncertainties are canceled in the measured asymmetries $a_{NN}(t)/a_N^{\text{jet}}(t)$ ratio.
- $r_5$ as well as $A_N(t, r_5)$ are well known from the single spin-flip asymmetry study.
- **Uncertainties in the $A_{NN}(t)$ measurement are strongly dominated by statistical errors.**

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HJET results for $pp$ $A_N(t)$ and $A_{NN}(t)$
Double spin-flip $A_{NN}(t)$ at 100 GeV ($\sqrt{s} = 13.76$ GeV)

$$A_{NN} = A_N^2 a_{NN} / d_N d_N^0$$

$T_R = -t / 2m_p$ [MeV]

$\chi^2 = 39.7 / 41$

Re $r_2 = (-3.65 \pm 0.28_{\text{stat}}) \times 10^{-3}$

Im $r_2 = (-0.10 \pm 0.12_{\text{stat}}) \times 10^{-3}$

HJET results for $pp A_N(t)$ and $A_{NN}(t)$

Hadronic double spin-flip amplitude is well isolated at $\sqrt{s} = 13.76$ GeV
Double spin-flip $A_{NN}(t)$ at 255 GeV ($\sqrt{s} = 21.92$ GeV)

Hadronic double spin-flip amplitude is well isolated at $\sqrt{s} = 21.92$ GeV

$\chi^2 = 37.7 / 44$

$T_R = -t / 2m_p$ [MeV]

$R_G^2 = -2.12 \pm 0.20_{\text{stat}} \times 10^{-3}$

$110^{-11} \times R_G^2$

$\text{Im} \ r_2 = (-0.35 \pm 0.07_{\text{stat}}) \times 10^{-3}$

Re $r_2 = (-2.15 \pm 0.20_{\text{stat}}) \times 10^{-3}$

HJET results for $pp \ A_N(t)$ and $A_{NN}(t)$
Energy dependence of elastic $pp$ scattering

For unpolarized protons, elastic $pp$ ($\bar{p}p$) scattering can be described accurately with five Regge poles, Pomeron $P$ and the dominant $C = \pm 1$ poles for $I = 0, 1$ $R^+ (f_2, a_2)$ and $R^- (\omega, \rho)$.

\[ \sigma_{tot}(s) \propto (\rho + i) \]
\[ \sigma_{tot}(s) \rho(s) = I_P(s) + I_{R^+}(s) + I_{R^-}(s) \]
\[ \sigma_{tot}(s) \rho(s) = I_P(s) + I_{R^+}(s) + I_{R^-}(s) \]

Single spin-flip amplitude
\[ \sigma_{tot}(s) \propto (\text{Re } r_5 + i \text{ Im } r_5) \]
\[ \sigma_{tot}(s) \text{ Im } r_5 = f_5^P I_P(s) + f_5^+ I_{R^+}(s) + f_5^- I_{R^-}(s) \]
\[ \sigma_{tot}(s) \text{ Re } r_5 = f_5^P R_P(s) + f_5^+ R_{R^+}(s) + f_5^- R_{R^-}(s) \]

Spin-flip factors $f_5^P, f_5^\pm$ can be determined from the HJET data.

Single spin-flip factors in the $R^{\pm}P$ approximation

Measured asymmetry $a_N = PA_N(t, s, f_5^+, f_5^P)$

- $f_5^+ = -0.037 \pm 0.007_{stat} \pm 0.007_{syst} - 0.007_\rho$
- $f_5^- = 0.596 \pm 0.023_{stat} \pm 0.019_{syst} + 0.006_\rho$
- $f_5^P = 0.0465 \pm 0.0023_{stat} \pm 0.0034_{syst} - 0.0028_\rho$

$\chi^2 = 647.8 / 673$

Pomeron spin-flip amplitude is well isolated!
Recent measurement of surprisingly low \( \rho_{pp} = 0.10 \pm 0.01 \) at \( \sqrt{s} = 13 \text{ TeV} \) (TOTEM) may indicate a presence of Odderon (C-odd gluon exchange) amplitude in elastic \( pp \) scattering.

The HJET data was used to search for spin-flip Odderon amplitude in a Froissaron-Maximal Odderon model. However, due to very strong correlation between \( O \) and \( R^- \) contributions, the uncertainties are large.

\[
\begin{align*}
    f_5^+ &= 0.12 \pm 0.06_{\text{stat}} \\
    f_5^- &= 2.24 \pm 0.73_{\text{stat}} \\
    f_5^0 &= 0.024 \pm 0.009_{\text{stat}} \\
    f_5^O &= -0.84 \pm 0.61_{\text{stat}}
\end{align*}
\]
**Hadronic Single Spin-Flip Amplitude** $r_5(\sqrt{s})$

**Color Legend:**
- **This work (13.76 and 21.92 GeV)**
- $R^\pm P$ extrapolation to 6.8 and 200 GeV
- $R^\pm PO$ extrapolation to 6.8 and 200 GeV
- Other measurements (6.8 and 200 GeV)

**Combined Fit**

$R^\pm P$

$f_5^+ = -0.037 \pm 0.010$

$f_5^- = 0.588 \pm 0.028$

$f_5^P = 0.046 \pm 0.004$

$f_5^O = 0$ (fixed)

$\chi^2 = 2.2/5$

$R^\pm P O$

$f_5^+ = 0.057 \pm 0.034$

$f_5^- = 1.141 \pm 0.239$

$f_5^P = 0.032 \pm 0.009$

$f_5^O = -0.107 \pm 0.252$

$\chi^2 = 7.7/4$
Double Spin-Flip Factors

$\Delta \chi^2 = 1$ correlation plots for $R^\pm P$ extrapolation

![Correlation plots](image)

$A_{NN} = A_N^2 a_{NN}/d_N d_N^b$

$\chi^2 = 79.1 / 86$

| $10^3 f_2^+$ | $16.2 \pm 0.7$ | $5 \pm 13$ |
| $10^3 f_2^-$ | $29.7 \pm 4.1$ | $-38 \pm 82$ |
| $10^3 f_2^P$ | $-1.99 \pm 0.19$ | $0.8 \pm 2.7$ |
| $10^3 f_2^O$ | $-1.99 \pm 0.19$ | $122 \pm 102$ |

HJET results for $pp A_N(t)$ and $A_{NN}(t)$

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Double Spin-Flip Hadronic Amplitude $r_2(\sqrt{s})$

Color Legend:
- This work (13.76 and 21.92 GeV)
- $R^\pm P$ extrapolation to 6.8 and 200 GeV
- $R^\pm PO$ extrapolation to 6.8 and 200 GeV
- Other measurements (6.8 and 200 GeV)

STAR 2014: ($\sqrt{s} = 200$ GeV),
D. Svirida, SPIN 2014 Proceedings.

HJET 2009: ($\sqrt{s} = 6.8$ GeV),

In HJET 2009, $A_{NN}$ was given with wrong sign. The displayed above result was calculated by us.
Summary: Analyzing Power

Elastic $p^+p$ single spin-flip analyzing power $A_N(t)$:
- $A_N(t)$ was measured with a high precision
  $\sigma_{A_N}/A_N \lesssim 1\%$
  in CNI region at two beam energies 100 and 255 GeV.
- Hadronic single spin-flip amplitudes were well isolated:
  \begin{align*}
  100 \text{ GeV: } & \quad \text{Re } r_5 = (-15.5 \pm 0.9_{\text{stat}} \pm 1.0_{\text{syst}} + 0.5_{\rho}) \times 10^{-3} \\
  & \quad \text{Im } r_5 = (-0.7 \pm 2.9_{\text{stat}} \pm 3.5_{\text{syst}} - 4.5_{\rho}) \times 10^{-3} \\
  255 \text{ GeV: } & \quad \text{Re } r_5 = (-7.3 \pm 0.5_{\text{stat}} \pm 0.8_{\text{syst}} + 0.1_{\rho}) \times 10^{-3} \\
  & \quad \text{Im } r_5 = (21.5 \pm 2.5_{\text{stat}} \pm 2.5_{\text{syst}} - 3.3_{\rho}) \times 10^{-3}
  \end{align*}

Elastic $p^+p^+$ double spin-flip analyzing power $A_{NN}(t)$:
- $A_{NN}(t)$ was measured with a high precision
  $\delta A_{NN} \lesssim 0.0002$
  in CNI region at two beam energies 100 and 255 GeV.
- Hadronic double spin-flip amplitudes were well isolated:
  \begin{align*}
  100 \text{ GeV: } & \quad \text{Re } r_2 = (-3.65 \pm 0.28_{\text{stat}}) \times 10^{-3} \\
  & \quad \text{Im } r_2 = (-0.10 \pm 0.12_{\text{stat}}) \times 10^{-3} \\
  255 \text{ GeV: } & \quad \text{Re } r_2 = (-2.15 \pm 0.20_{\text{stat}}) \times 10^{-3} \\
  & \quad \text{Im } r_2 = (-0.35 \pm 0.07_{\text{stat}}) \times 10^{-3}
  \end{align*}
Summary: Regge poles spin-flip couplings

- $R^+(f_2, a_2)$, $R^-(\omega, \rho)$, Pomeron approximation ($R^\pm P$).
  - Single and double spin-flip factors were measured with notable accuracy
  
  $f_5^+ = -0.037 \pm 0.007^{\text{stat}} \pm 0.007^{\text{syst}} - 0.007^{\rho}$
  $f_5^- = 0.596 \pm 0.023^{\text{stat}} \pm 0.019^{\text{syst}} + 0.006^{\rho}$
  $f_5^P = 0.0465 \pm 0.0023^{\text{stat}} \pm 0.0034^{\text{syst}} - 0.0028^{\rho}$

  - Extrapolation of $r_5$ to $\sqrt{s} = 6.8$ and 200 GeV remarkably consistent with available experimental data.

- $R^+(f_2, a_2)$, $R^-(\omega, \rho)$, Pomeron, Odderon approximation ($R^\pm PO$).
  - Due to the strong correlation between $R^-$ and Odderon contributions at HJET energies, the spin-flip couplings can be evaluated only with large uncertainties.
  - Using other experimental data the single spin-flip couplings can be evaluated as

  $f_5^+ = 0.057 \pm 0.034$
  $f_5^- = 1.141 \pm 0.239$
  $f_5^P = 0.032 \pm 0.009$
  $f_5^O = -0.107 \pm 0.252$

- Precision measurements of $r_5$ and/or $r_2$ may crucially improve confidence in the evaluation of the Odderon term.

- Technically, it is possible to study $p^\uparrow p^\uparrow (E_{Lab} = 24 \text{ GeV})$, and $p^\uparrow C (E_{Lab} = 24, 100 \text{ GeV})$ at HJET.

- During 2015-18 we accumulated the following proton nucleus data:
  - $p^\uparrow d$, $p^\uparrow Al$, $p^\uparrow Zr$, $p^\uparrow Ru$, and $p^\uparrow Au$ ($E_{Lab} = 100 \text{ GeV}$).
  - $p^\uparrow Au$, ($E_{Lab} = 3.9, 10, 13.6, 19.5, 27, 31, 100 \text{ GeV}$).
  - $p^\uparrow d$, ($E_{Lab} = 10, 19.5, 31, 100 \text{ GeV}$).
Boris Kopeliovich: 20 years ago we had no data and didn’t expect precise data so soon. Therefore we have done some rough simplifying approximations, which now must be replaced by accurate expressions. Such a change significantly alters results of the fits for $r_5$ and $r_2$.

Boris Kopeliovich and Michal Krelina are working on the corrections which include:

• Absorptive corrections (reported yesterday by M. Krelina)
• Differences in the electromagnetic and hadronic form-factors.

My interpretation of the comment:

We can continue to use formulas for $A_N(t)$ and $A_{NN}(t)$ for data analysis but it should be understood that

$$r_{5,2}^{\text{meas}} = r_{5,2} + R_{5,2} + iI_{5,2}$$

and the correction $R+iI$ may be as large as $r_5$.

• The corrections do not affect the single and double spin analyzing power measurements. Actually this was tested and verified in our data analysis within the accuracy of the measurements.

• The evaluation of Reggeon and Pomeron spin-flip factors have to be interpreted with caution. This part of the work should be considered as a test of how the method will work after corrections $R + iI$ will have been well determined.
Backup
Could measurement at $\sqrt{s} = 6.8$ GeV distinguish between $R^\pm P$ and $R^\pm PO$ models

For both, $R^\pm P$ and $R^\pm PO$, extrapolations of HJET results to $\sqrt{s} = 6.8$ GeV error correlation ellipses corresponding to $\Delta \chi^2 = 4$ (86.4%) and $\Delta \chi^2 = 9$ (98.9%) are displayed.

Precise measurements of $r_5$ and/or $r_2$ at $\sqrt{s} = 6.8$ GeV can potentially distinguish between $R^\pm P$ and $R^\pm PO$ models:
Comparison with p-Carbon data

p-Carbon analyzing power measurements:
- **BNL E950** \( (E_{lab} = 21.5 \text{ GeV}) \), Tojo et al., Phys. Rev. Lett. 89, 052302 (2002)
- **RHIC pCarbon** \( (E_{lab} = 100 \text{ GeV}) \), O. Jinnouchi et al., SPIN 2004 Proceedings, p. 515.
were analyzed by T. L. Trueman, Phys. Rev. D 77, 054005 (2008).

The values of \( r_5 \) were extracted from the data and Pomeron Spin coupling was evaluated:

- p-Carbon results are not well consistent with our measurements. However, RHIC pCarbon measurements were not published and systematic errors were not included to the analysis.
- \( r_5 \) values for 21 and 100 GeV provides much better evaluation of Odderon coupling that measurements at 100 and 255 GeV.
Both RHIC beams (Blue and Yellow) are measured simultaneously.

For elastic scattering:
\[ \tan \theta_R = \frac{z_{det} - z_{jet}}{L} = \frac{\kappa \sqrt{T_R}}{L} \]
\[ \kappa = \sqrt{\frac{T_R \left( E_{beam} + m_p^2 / M_{beam} \right)}{2m_p \left( E_{beam} - m_p + T_R \right)}} \approx 18 \text{ mm/MeV}^{1/2} \]

Lorentz invariant momentum transfer:
\[ t = (p_R - p_t)^2 = -2m_p T_R \]

In a Si strip
\[ \left( \frac{d\sigma}{dt} \sqrt{T_R} \right)^{-1} \frac{dN}{d\sqrt{T_R}} = f(\kappa \sqrt{T_R} - \kappa \sqrt{T_{strip}}), \]
where \( f(z) \) is jet density profile and \( T_{strip} \) is kinetic corresponding to the strip position.
Energy calibration using alpha-sources

Energy losses in dead-layer has to be accounted
• Two alpha-sources allows us to determine both gain $g$ and dead-layer thickness $x_{DL}$.

Verification of the calibration using recoil protons from elastic scattering:

A discrepancy is being observed:
$$\langle \Delta T / T \rangle \approx 3\% \quad \text{and} \quad \langle \Delta T \rangle = 180 \text{ keV}$$

After corrections:
$$\langle \sigma_T^{syst} / T \rangle \approx 0.9\% \quad \text{and} \quad \langle \sigma_T^{syst} \rangle \approx 20 \text{ keV}$$

Since the source of discrepancy (calibration?, geometry?, magnetic field corrections?, ...?) is not proved yet, the corrections are not validated. The study is being continued.
Separation of the stopped and punched through protons

To separate stopped and punched through protons, a conversion function $A, n/n(\alpha)$ was simulated and adjusted using alpha-calibration data. $n(\alpha)$ is parameter $n$ measured in alpha-calibration. Time corrections were also applied.

Protons with energy above 7.8 MeV punch through the Si detector. Only part of protons kinetic energy is deposited.
**DAQ**

The HDAQ DAQ is based on VME 12 bit 250 MHz FADC250 (Jlab)

Full waveform (80 samples) was recorded for every signal above threshold (~0.5 MeV).

Signal parametrization: \( W(t) = p + A (t - t_i)^n \exp \left( \frac{t-t_i}{\tau_s} \right) \)

- For every event, recoil proton kinetic energy \( T_R(A) \), time \( t_m \), and waveform shape parameters \( n \) and \( \tau_s \) are determined.
- The fit of waveform shape is important
  - for better amplitude measurement
  - to separate stopped and punch through recoil protons and, thus, to reconstruct kinetic energy of the punch through proton.
- For polarization measurement, elastic pp events have to be isolated.
Event Selection Cuts.

1. **Recoil proton kinetic energy** $T_R$.
   The measured kinetic energy range ($0.7 \div 10$ MeV) is limited by the detector geometry and the trigger threshold.

2. **“Recoil mass cut”:** $\delta t = t_m - t_p(A)$
   $t_p(A)$ is the expected proton signal time for the measured amplitude $A$. It depends on gain, dead-layer and time offset which are found in calibrations.
   The $\delta t$ distribution is defined by the beam bunch longitudinal profile.

3. **“Missing mass cut”** $M_X^2 = m_p^2 + 2(E_{beam} + m_p)\sqrt{T_R} \delta \sqrt{T_R}$
   \[ \delta \sqrt{T_R} = \sqrt{T_R} - \sqrt{T_{strip}} \]
   $T_{strip}$ is the energy corresponding to the strip center. It is determined in the geometry alignment. The $\delta \sqrt{T_R}$ distribution is defined by the jet density profile.

For elastic scattering, the $(\frac{d\sigma}{dt \sqrt{T_R}})^{-1} \frac{d^2N}{d\delta t d\delta \sqrt{T_R}}$ distribution is the same for all Si strips.
**Background subtraction**

In HJET, the dominant backgrounds are:

- The beam scattering on Oxygen in Jet and beam line gas
- Molecular hydrogen which has a flat z-coordinate distribution

The background $dN/d\sqrt{T_R}$ distribution is the same for all Si strips.

In the data analysis, the background is determined/subtracted independently for

- every detector
- every $\sqrt{T_R}$ bin
- every combination of beam/jet spins (to properly account background analyzing power if any)
Molecular Hydrogen from the dissociator

Fills 20697-20698 (11.5 hours)
RF transition off. Only molecular hydrogen from dissociator.
*MH intensity is enhanced by a factor $f \gtrsim 20$.*

Fills 20692-20695 (8.6 hours)
Regular HJET run.

<table>
<thead>
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<th>Fills</th>
<th>Time (h)</th>
<th>$\langle$WCM$\rangle$</th>
<th>Events (k)</th>
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<td></td>
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<td>21.42</td>
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</table>

Normalized good event rate ratio

$$\frac{\text{MH}}{\text{Jet}} = 0.6\% \quad \frac{1}{f} \leq 0.03\%$$

Effective background: $0.03 \pm 0.03\%$
Molecular Hydrogen (2) background

Forward beam elastic events from forward are shadowed by the collimators. This may be employed for normalization of the molecular Hydrogen density.

$B_{MHz} = 0.54 \pm 0.17\%$

A 1.07 correction due to tracking in the magnetic field is accounted.

The bias due to shadowing $b_L/b_{MHz} = 0.25$