Diffraction and Low-x

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Precision small scattering angle measurements of proton-proton and proton-nucleus analyzing powers at the RHIC hydrogen jet polarimeter

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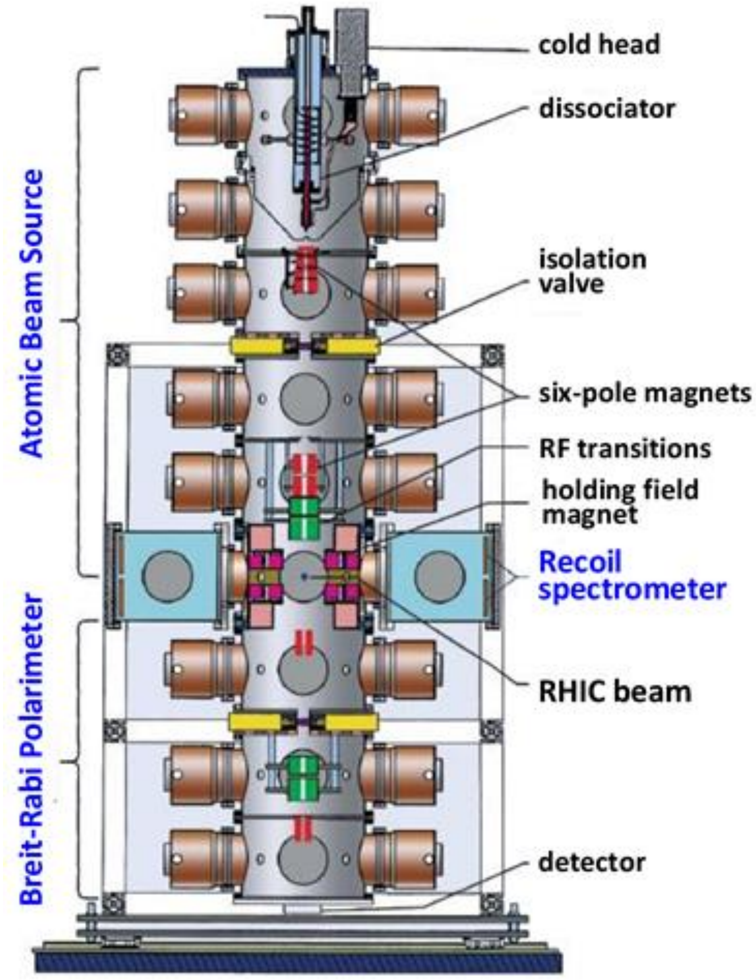
Brookhaven National Laboratory

The Polarized Atomic Hydrogen Gas Jet Target (HJET)

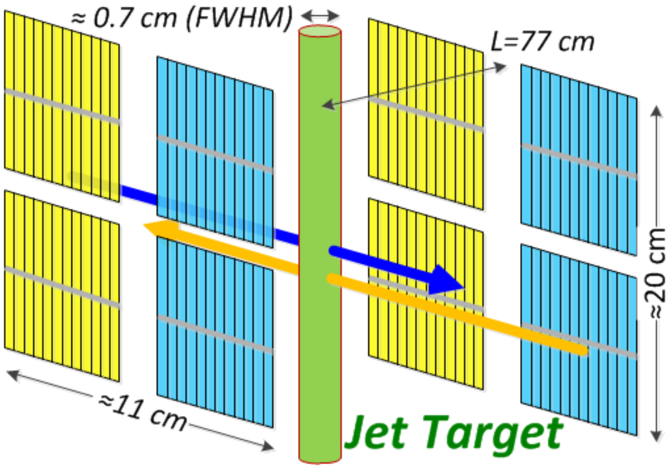
A. Zelenski et al., Nucl. Instrum. Meth. A **536**, (2005)
A.A. Poblaguev *et al.*, Nucl. Instr. Meth. A **976**, 164261 (2020)
A.A. Poblaguev *et al.*, Phys. Rev. Lett. **123**, 162001 (2019)

The HJET is used to measure absolute proton beam polarization at RHIC ever since 2004.

- Advantages of the polarized gas jet target:
  - ✓ Continuous measurement of the beam polarization with no impact on the RHIC experiments.
  - ✓ The recoil protons can be precisely measured in the CNI range $0.0013 < -t < 0.018\ \mathrm{GeV}^2$ (the analyzing power maximum)
- The jet target polarization $\boldsymbol{P_{\mathrm{jet}} \sim 96 \pm 0.1\%}$
  - ✓ Very stable during the measurements
  - ✓ Precisely monitored by a Breit-Rabi polarimeter



The HJET recoil spectrometer



- Vertical polarizations of the *blue* and *yellow* RHIC proton beams are concurrently and continuously measured by detecting the recoil protons in the left-right symmetric silicon detectors with vertically oriented strips.
- The measured kinetic energy T_R, time of flight $\mathrm{ToF} = t_R - t_0$, and z_R coordinate in detectors allows us to isolate the elastic events.
- The measurements are taken in the CNI region

$$0.0013 < -t < 0.018\ \mathrm{GeV}^2$$
$$(0.6 < T_R < 10\ \mathrm{MeV})$$

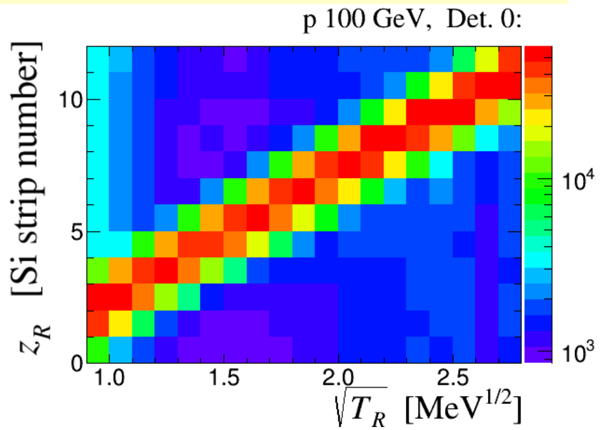
$$t = -2m_pT_R$$

Elastic event isolation:

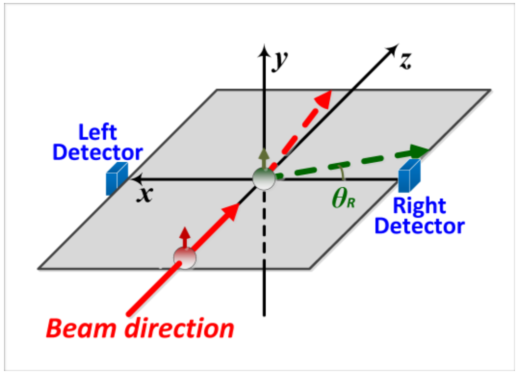
$$\mathrm{ToF} = \sqrt{\frac{m_p}{2T_R}}\frac{L}{c}$$ (the time of flight corresponds to the proton's kinetic energy)

$$\frac{z_R - z_{jet}}{L} = \sqrt{\frac{T_R}{2m_p}\frac{E_{\mathrm{beam}}+m_p}{E_{\mathrm{beam}}-m_p+T_R}} \approx \sqrt{\frac{T_R}{2m_p}} \times \left(1 + \frac{m_p}{E_{\mathrm{beam}}}\right)$$ (for elastic scattering)

Since, for 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 (separately for each combination of the beam and jet spins)



Polarization measurement of proton beams at HJET



The beam (↑↓) and target (±) single spin asymmetries are concurrently measured using $0.5 < T_R < 10\ \mathrm{MeV}$ recoil protons.

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

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

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

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

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

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

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

Since the background is well controlled, the analyzing power can be precisely measured

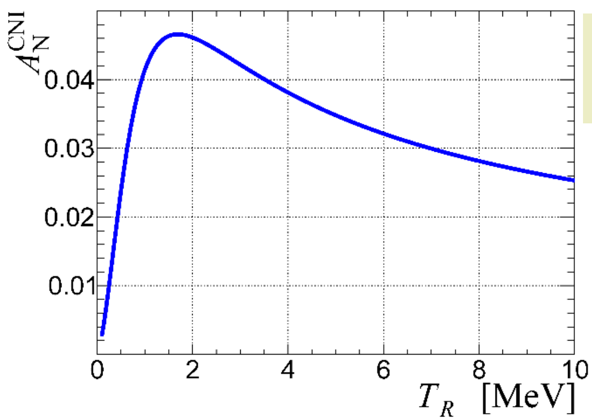
$$A_N(t) = a_{\mathrm{jet}}(T_R)/P_{\mathrm{jet}} \qquad [T_R = -t/2m_p]$$

Elastic single spin proton-proton analyzing power $A_N(s,t)$

For CNI elastic scattering, analyzing power is defined by the interference of the *spin-flip* $\phi_5(s,t)$ and *non-flip* $\phi_+(s,t)$ helicity amplitudes:

$$A_N(s,t) \approx -2\,\mathrm{Im}(\phi_5^*\phi_+)/|\phi_+|^2$$

$$\phi = \phi^{\mathrm{had}} + \phi^{\mathrm{em}} e^{i\delta_C}$$



B. Z. Kopeliovich and L. I. Lapidus, Sov. J. Nucl. Phys. 19, 114 (1974)

$$A_N^{\mathrm{CNI}}(T_R) = \sqrt{\frac{2T_R}{m_p}} \times \frac{\kappa_p}{T_c/T_R + T_R/T_c}$$

$$\kappa_p = \mu_p - 1 = 1.793$$

$$T_c = 4\pi\alpha/m_p\sigma_{\mathrm{tot}} \approx 1\ \mathrm{MeV}$$

The corrections to $A_N^{\mathrm{CNI}}(T_R)$. (Although, some other correction are essential for the current experimental accuracy, they are omitted for the sake of simplicity)

$$A_N(T_R) = \sqrt{\frac{2T_R}{m_p}} \times \frac{(\kappa_p - 2I_5)\,T_c/T_R - 2R_5}{(T_c/T_R)^2 - 2(\rho + \delta_C)\,T_c/T_R + 1}$$

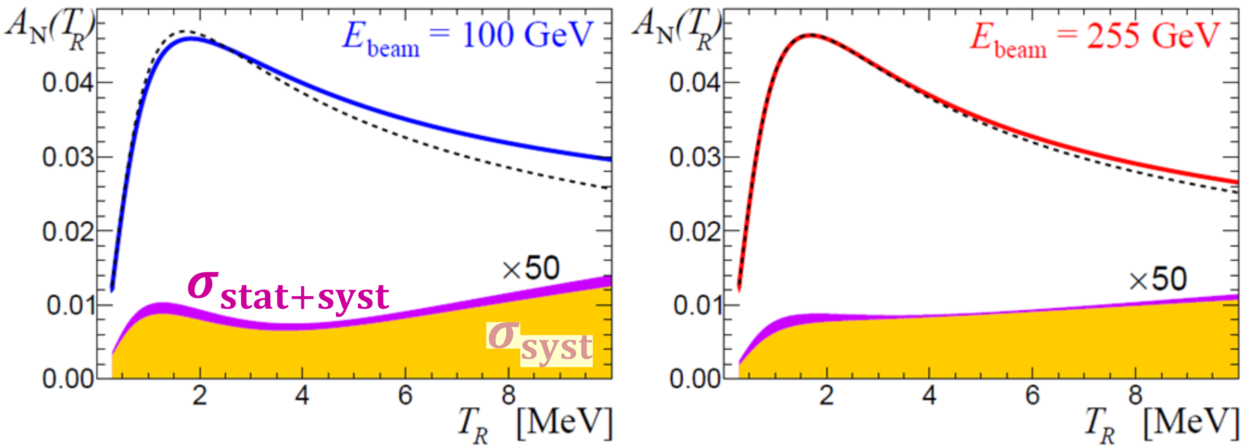
The primary goal of the experimental study of the elastic pp $A_N(T_R)$ in the CNI region is an evaluation of the hadronic spin-flip amplitude, parameterized by

$$r_5 = \frac{m_p\,\phi_5^{\mathrm{had}}(s,t)}{\sqrt{-t}\,\mathrm{Im}\phi_+^{\mathrm{had}}(s,t)} = R_5 + iI_5$$

In the HJET data analysis, we use values of $\rho + \delta_C$ found in combined fits of numerous experimental studies of forward elastic (unpolarized) pp scattering.

Measurements of $A_N(t)$ in Runs 15 (100 GeV) & 17 (255 GeV)

A.A. Poblaguev *et al.*, Phys. Rev. Lett. **123**, 162001 (2019)



- The filled areas specify 1σ experimental uncertainties, stat.+syst., scaled by x50.
- The dashed curves are for leading order approximation predicted in 1974.

The measured hadronic spin flip amplitudes:

$\sqrt{s} = 13.76$ GeV $\quad R_5 = (-12.5 \pm 0.8_{stat} \pm 1.5_{syst}) \times 10^{-3}$

$I_5 = (-5.3 \pm 2.9_{stat} \pm 4.7_{syst}) \times 10^{-3}$

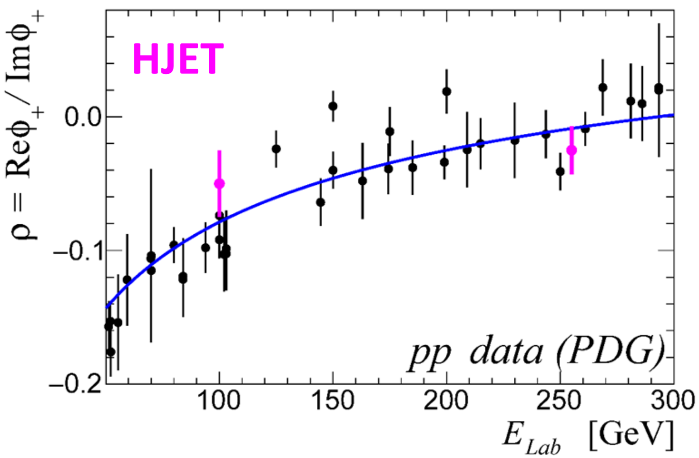
$\sqrt{s} = 21.92$ GeV $\quad R_5 = (-3.9 \pm 0.5_{stat} \pm 0.8_{syst}) \times 10^{-3}$

$I_5 = (19.4 \pm 2.5_{stat} \pm 2.5_{syst}) \times 10^{-3}$

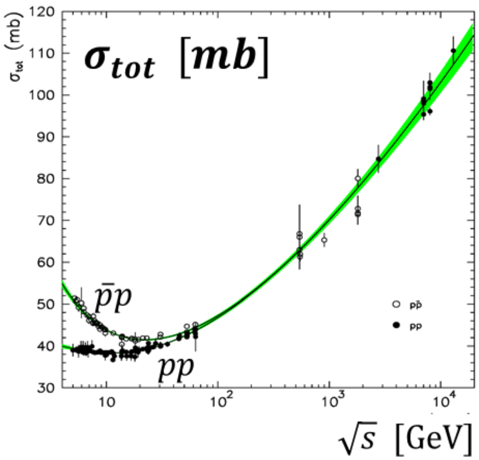
The corrections due to absorption and the updated value of the proton charge radius $r_p = 0.841$ fm were applied

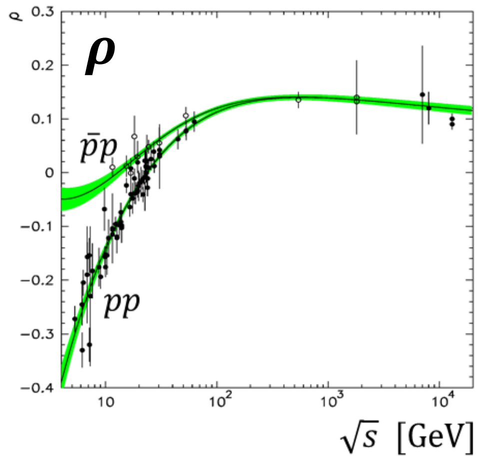
$$R_5 = R_5^{PRL} + \left(3.1_{abs.} + 0.8_{r_p}\right) \times 10^{-3}$$

Evaluation of ρ in the analyzing power fit



Energy dependence of elastic pp scattering





For unpolarized protons, elastic pp ($\bar{p}p$) scattering can be described at low $-t$ with a Pomeron $\boldsymbol{P}$ and the sub-leading $C = \pm 1$ Regge poles for $I = 0{,}1$, encoded by $\boldsymbol{R}^+$ for $(\boldsymbol{f_2}, \boldsymbol{a_2})$ and $\boldsymbol{R}^-$ for $(\boldsymbol{\omega}, \boldsymbol{\rho})$.

$$\boldsymbol{R}^{\pm}(\boldsymbol{s}) \propto \left(1 \pm e^{-i\pi\alpha_{R^\pm}}\right)\left(\frac{s}{4m_p^2}\right)^{\alpha_{R^\pm}-1}$$

$$\boldsymbol{P}(\boldsymbol{s}) \propto \pi f_F \ln\frac{s}{4m_p^2} + i\left(1 + f_F \ln^2\frac{s}{4m_p^2}\right)$$

$$\alpha_{R^+} = 0.65,\ \alpha_{R^-} = 0.45,\ f_F = 0.009$$

Unpolarized amplitude $\propto\ (\boldsymbol{\rho} + \boldsymbol{i})$

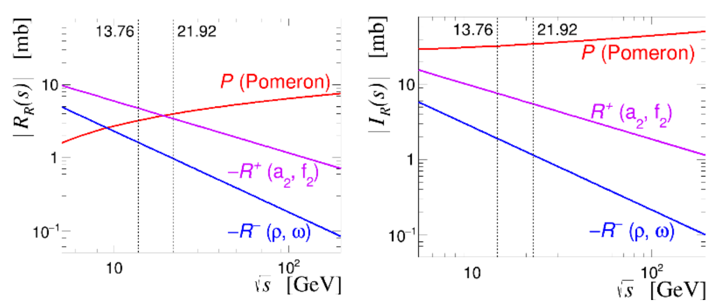
$$\boldsymbol{\sigma_{tot}(s) = I_P(s) + I_{R+}(s) + I_{R-}(s)}$$
$$\boldsymbol{\sigma_{tot}(s)\rho(s) = R_P(s) + R_{R+}(s) + R_{R-}(s)}$$

$$I_{\mathcal{R}}(s) = \mathrm{Im}\,\mathcal{R}(s)$$
$$R_{\mathcal{R}}(s) = \mathrm{Re}\,\mathcal{R}(s)$$

Single spin-flip amplitude $\propto\ (\mathrm{Re}\,r_5 + \boldsymbol{i}\,\mathrm{Im}\,r_5)$

$$\boldsymbol{\sigma_{tot}(s)\,\mathrm{Im}\,r_5 = f_5^P\, I_P(s) + f_5^+\, I_{R^+}(s) + f_5^-\, I_{R^-}(s)}$$
$$\boldsymbol{\sigma_{tot}(s)\,\mathrm{Re}\,r_5 = f_5^P\, R_P(s) + f_5^+\, R_{R^+}(s) + f_5^-\, R_{R^-}(s)}$$

Since we have only four precisely measured r_5 - related parameters and there are three unknown spin-flip couplings, no comprehensive study of the spin flip Regge pole and/or Pomeron functions can be done. Thus, we should rely to the already known non-flip functions. Nonetheless, limitations on the possible variation of the spin flip $\boldsymbol{P(s)}$, $\boldsymbol{R^{\pm}(s)}$ can be considered.



D.A. Fagundes et. al., Int. J. Mod. Phys. A 32, 1750184 (2017)

Fit of the spin-flip couplings

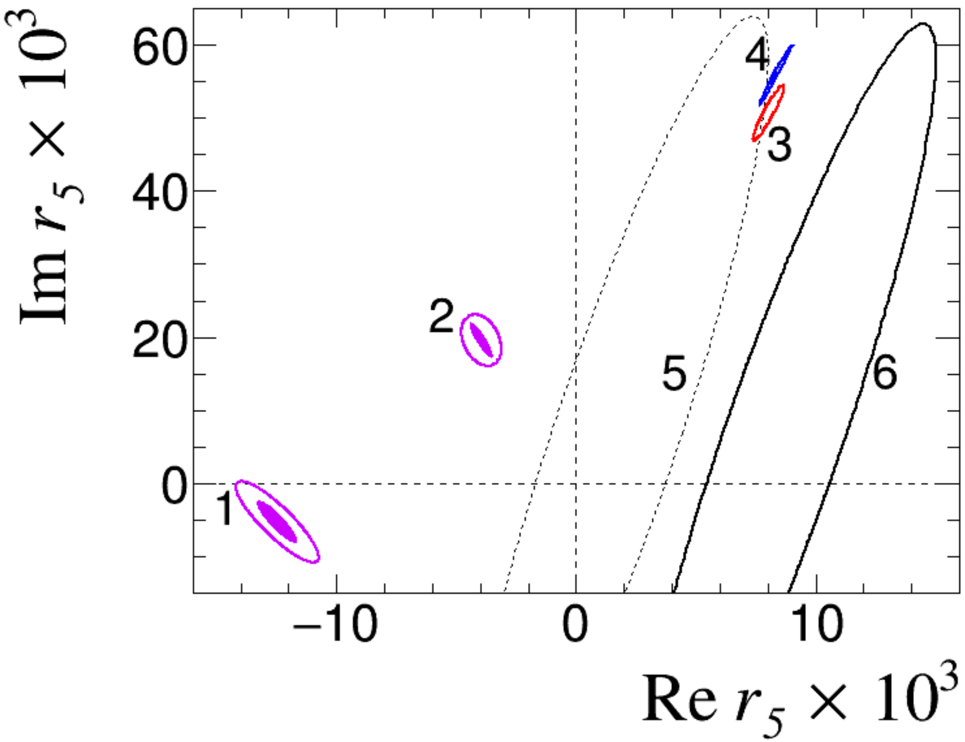
Both $|\mathrm{Im}\, r_5|$ and $|r_5|$ grow with energy indicating that there is a significant Pomeron contribution to the spin-flip amplitude already at HJET energies

$$\alpha_{R^+} = 0.65,\ \alpha_{R^-} = 0.45,\ f_F = 0.009$$

$$f_5^+ = -0.077 \pm 0.007_{\mathrm{stat}} \pm 0.014_{\mathrm{syst}}$$
$$f_5^- = 0.659 \pm 0.023_{\mathrm{stat}} \pm 0.024_{\mathrm{syst}}$$
$$f_5^P = 0.054 \pm 0.002_{\mathrm{stat}} \pm 0.003_{\mathrm{syst}}$$
$$\chi^2/\mathrm{ndf} = 0.7/1$$

- The Pomeron contribution to the spin-flip amplitude is well identified.
- Any optimization of the spin-flip $R^{\pm}(s)$ and $P(s)$ cannot lead to a statistically significant improvement of the fit.
- However, possible corrections to parametrization of the spin flip $R^{\pm}(s)$ and $P(s)$ can be constrained.

Extrapolation to $\sqrt{s} = 200$ GeV



1-σ contours (stat+syst)

1. **HJET, $\sqrt{s} = 13.76$ GeV**
2. **HJET, $\sqrt{s} = 21.92$ GeV**
3. **Extrapolation (Froissaron) to 200 GeV**
4. **Extrapolation (simple pole) to 200 GeV**
5. **STAR, $\sqrt{s} = 200$ GeV** (as published)
6. **STAR, $\sqrt{s} = 200$ GeV** (corrected, used in the fit)

- **Froissaron** $(\alpha_{R^+} = 0.65,\ \alpha_{R^-} = 0.45,\ f_F = 0.009)$
  - $\chi^2/\mathrm{ndf} = 0.7/1$ **HJET**
  - $\chi^2/\mathrm{ndf} = 4.8/3$ **HJET+STAR**
- **Simple pole** $(\alpha_{R^\pm} = 0.5,\ \alpha_P = 1.1)$
  - $\alpha_P = 1.10^{+0.04}_{-0.03}$ $\chi^2/\mathrm{ndf} = 0/0$ **HJET**
  - $\alpha_P = 1.13^{+0.04}_{-0.03}$ $\chi^2/\mathrm{ndf} = 2.8/2$ **HJET+STAR**

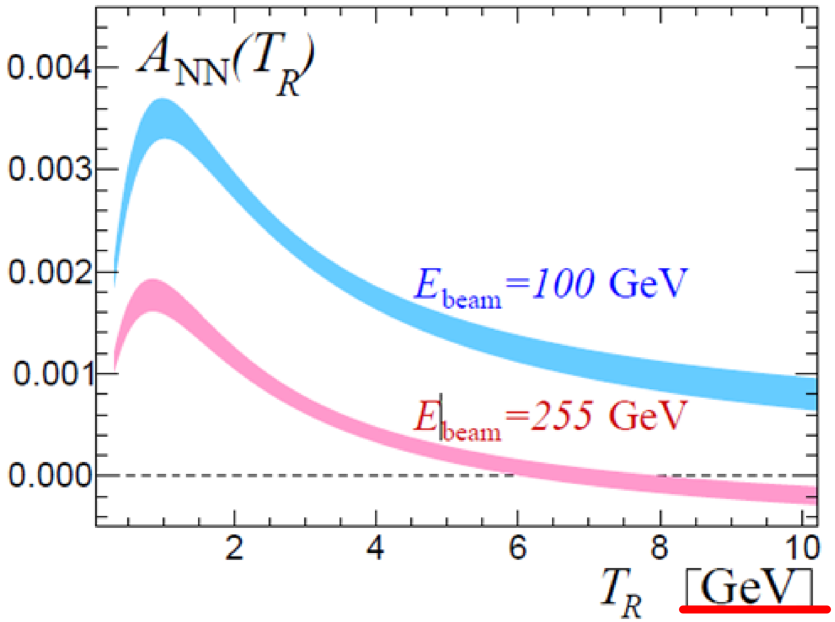
  $\alpha_P^{\mathrm{nf}} = 1.096^{+0.012}_{-0.009}$ **(global fit of the unpolarized data)**

- For HJET, absorption corrections improve the Regge fit consistency $(\chi^2 = 2.2 \rightarrow 0.7)$.
- Extrapolation of the measured r_5 to $\sqrt{s} = 200$ GeV is about the same for Froissaron and single pole approximations.
- There is no statistically significant evidence that $P(s)$ is not the same for the non-flip and spin-flip scattering.
- After applying corrections (absorption, difference between electromagnetic and hadronic form factors), the STAR value of r_5 is noticeably non-zero, $\chi^2/\mathrm{ndf} = 8.3/2$.

Double spin-flip analyzing power $A_{NN}(s,t)$

A.A. Poblaguev *et al.*, Phys. Rev. Lett. **123**, 162001 (2019)

$$\frac{d^2\sigma}{dt\,d\varphi} \propto \left[1 + A_N(t)\sin\varphi\,(P_b + P_j) + A_{NN}(t)\sin^2\varphi\,P_b\,P_j\right]$$ (at HJET, $\sin\varphi = \pm 1$)



Double spin-flip amplitude parameter $r_2 = \frac{\phi_2^{had}(s,t)}{2\,\mathrm{Im}\,\phi_+^{had}(s,t)} = R_2 + iI_2$

$\sqrt{s} = 13.76$ GeV $\quad R_2 = (-3.65 \pm 0.28_{stat}) \times 10^{-3}$
$\quad I_2 = (-0.10 \pm 0.12_{stat}) \times 10^{-3}$

$\sqrt{s} = 21.92$ GeV $\quad R_2 = (-2.15 \pm 0.20_{stat}) \times 10^{-3}$
$\quad I_2 = (-0.35 \pm 0.07_{stat}) \times 10^{-3}$

The Pomeron component of the double spin-flip amplitude is clearly identified.

$f_2^+ = -0.0162 \pm 0.0007_{stat}$
$f_2^- = 0.0297 \pm 0.0041_{stat}$
$f_2^P = -0.0020 \pm 0.0002_{stat}$
$\chi^2/\mathrm{ndf} = 1.6/1$

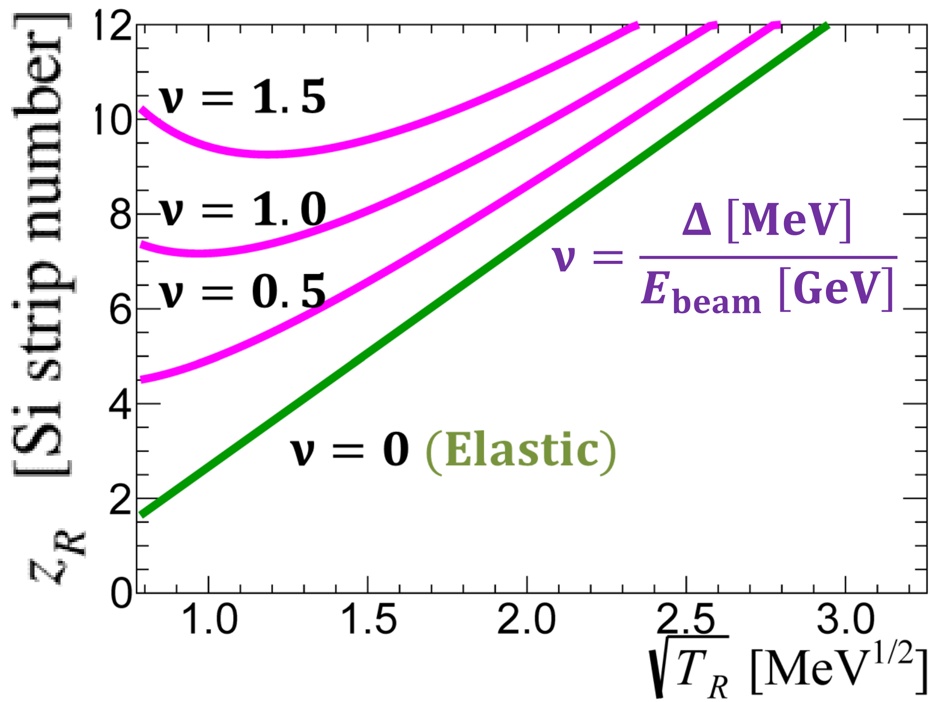
Inelastic scattering

At the HJET, the elastic and inelastic events can be separated by studying recoil proton energy and angle (i.e. the Si strip location). For $\boldsymbol{p+p\to X+p}$ scattering:

$$\tan\theta_R = \frac{z_{\text{str}} - z_{\text{jet}}}{L} = \sqrt{\frac{T_R}{2m_p}} \times \left[1 + \frac{m_p}{E_{\text{beam}}} + \frac{m_p\Delta}{T_R E_{\text{beam}}}\right]$$

$$\Delta = M_X - m_p > m_\pi$$

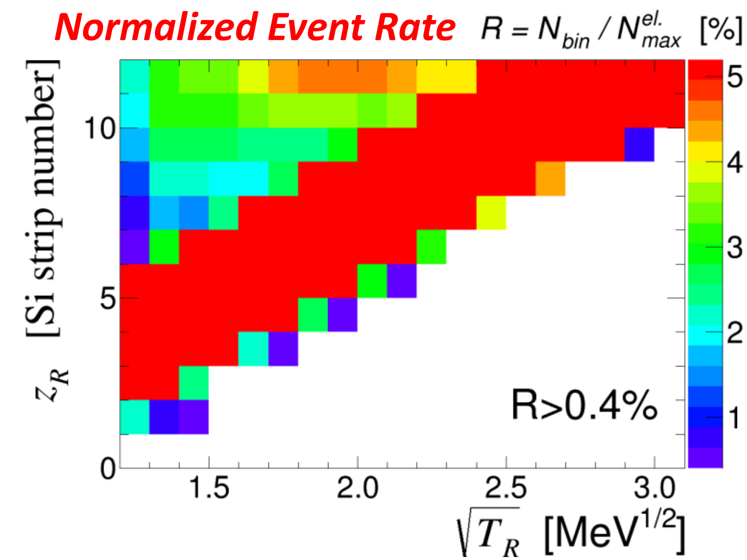
At HJET, $\tan\theta_R$ is discriminated by the Si strip number.

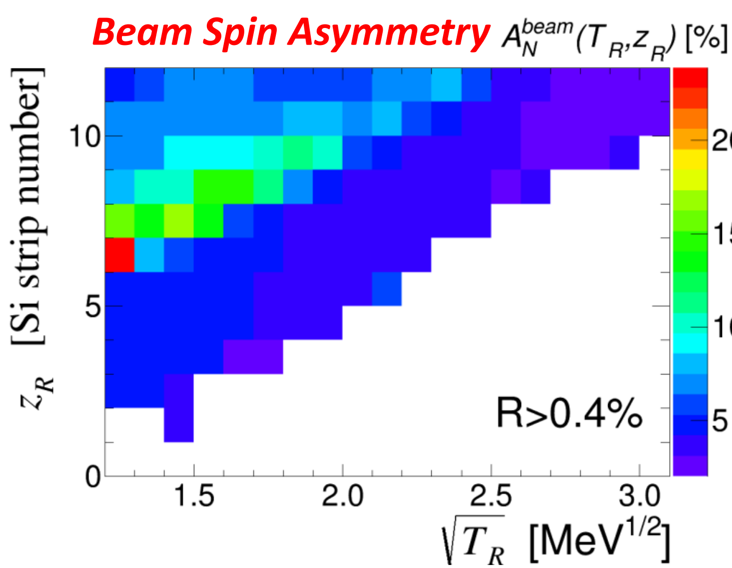


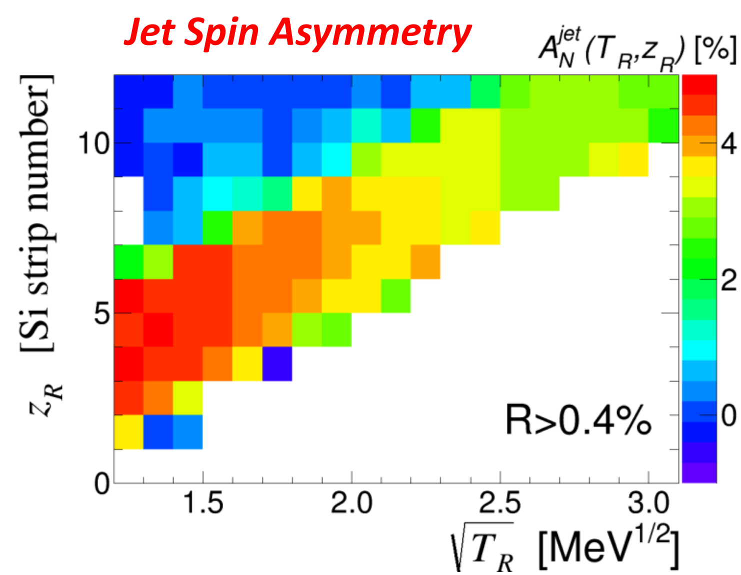
- At HJET, the inelastic events can be separated from the elastic one's if $\nu \gtrsim 0.9$.
- For proton beam, the detected inelastic rate is very small if $\nu \gtrsim 1.4$ $(E_p < 100\ \text{GeV})$
- The inelastic events are not detected at HJET if $\nu \gtrsim 2.5$ $(E_p < 55\ \text{GeV})$.

$p^{\uparrow}_{beam} + p^{\uparrow}_{jet} \rightarrow X + p_{jet}$ at 255 GeV (Run 2017)

- The inelastic events are clearly identified (after background subtraction).
- $A_N^{\text{jet}\,(in.)} < A_N^{\text{elastic}} < A_N^{\text{beam}\,(in.)}$
- $A_N^{(in.)}(t,\Delta)$ grows with decreasing Δ.
- $A_N^{\text{beam}\,(in.)}(t,\Delta) \sim 20\%$ is observed in the data.

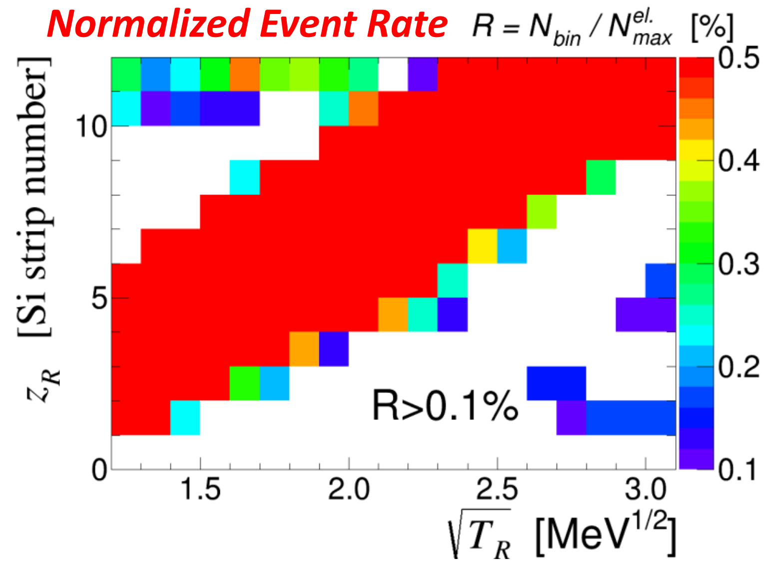


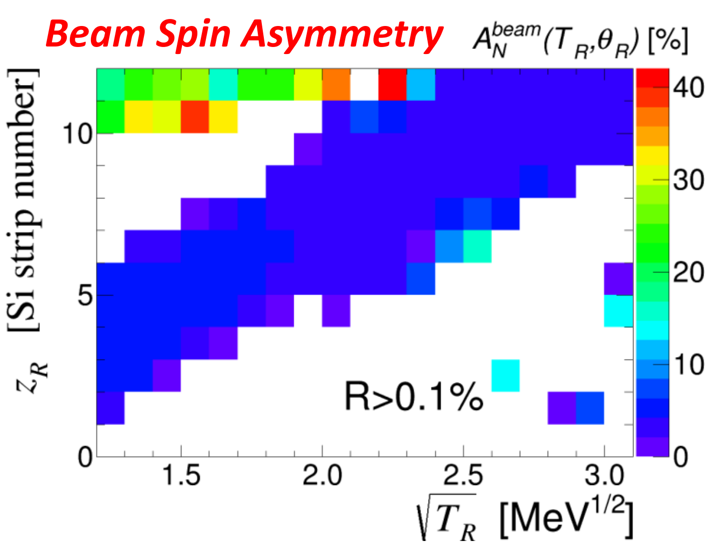


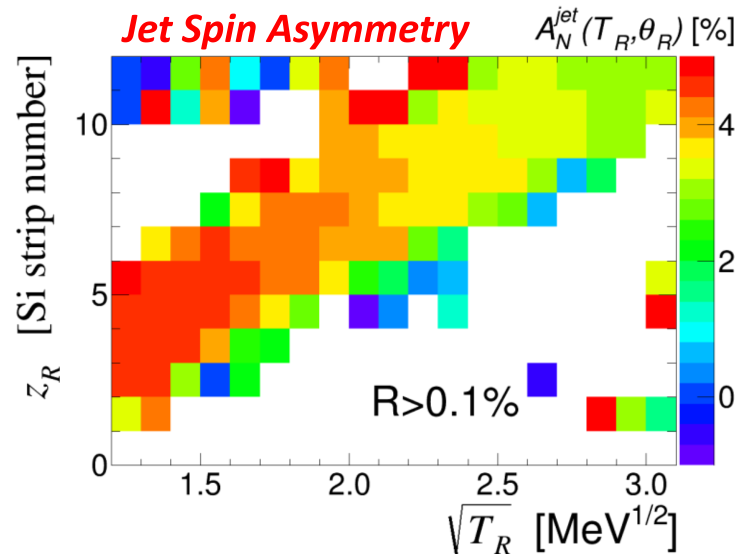


$p_{beam}^{\uparrow} + p_{jet}^{\uparrow} \to X + p_{jet}$ at 100 GeV (Run 2015)

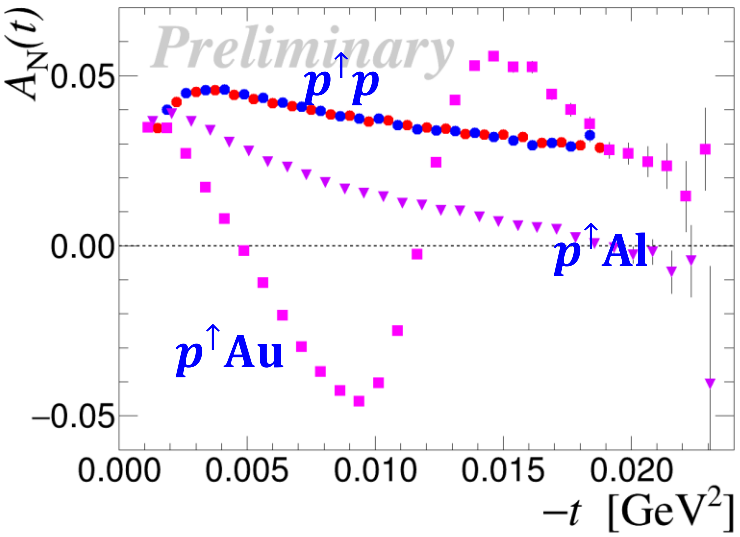
- In the acquired data, there is only a small fraction $< 0.5\%$ of the inelastic events.
- Results for the inelastic analyzing power are about the same as for 255 GeV.
- $A_{\mathrm{N}}^{\mathbf{beam}\,(in.)}(t,\Delta) \sim 35\%$ is seen in the data.







Proton-nucleus Scattering at HJET



- In Run 15, $p^{\uparrow}\mathrm{Al}$ and $p^{\uparrow}\mathrm{Au}$ collisions were studied at RHIC.
- The recoil proton spectrometer performance was found to be about the same in the proton and heavy ion beams.
- Beginning Run 16, HJET routinely operated (in parasitic mode) in the Heavy Ion Runs.
- The following analyzing powers were measured:
  - 100 GeV beam: ${}^{2}_{1}\mathrm{H}$ (d), ${}^{16}_{8}\mathrm{O}$, ${}^{27}_{12}\mathrm{Al}$, ${}^{96}_{40}\mathrm{Zr}$, ${}^{96}_{44}\mathrm{Ru}$, ${}^{197}_{79}\mathrm{Au}$
  - Au energy scan: 3.85, 4.6, 5.7, 8.1, 9.8., 19, 27, 31, 100 GeV/n
  - *d* energy scan: 9.9, 19.6, 31.3, 100.7 GeV/n

- The recoil angle dependence on T_R for an ion beam is about the same as for proton one

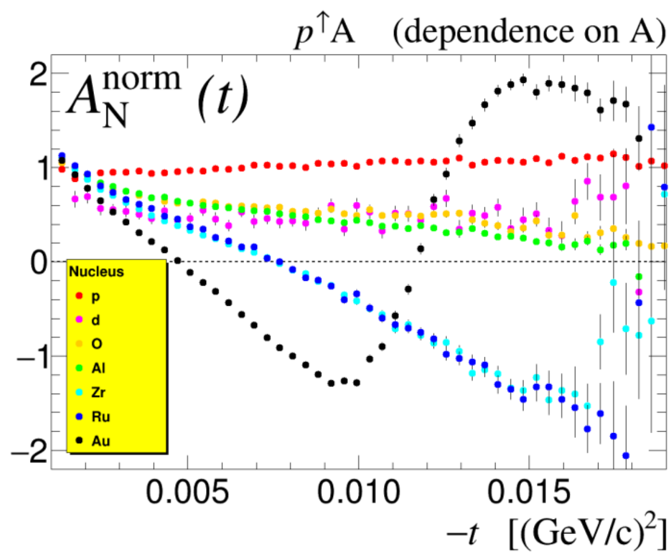
$$\tan\theta_R = \frac{z_R - z_{\mathrm{jet}}}{L} = \sqrt{\frac{T_R}{2m_p}} \times \left[1 + \frac{m_p}{E_{\mathrm{beam}}} \times \frac{m_p}{m_A} + \frac{m_p\Delta}{T_R E_{\mathrm{beam}}}\right]$$

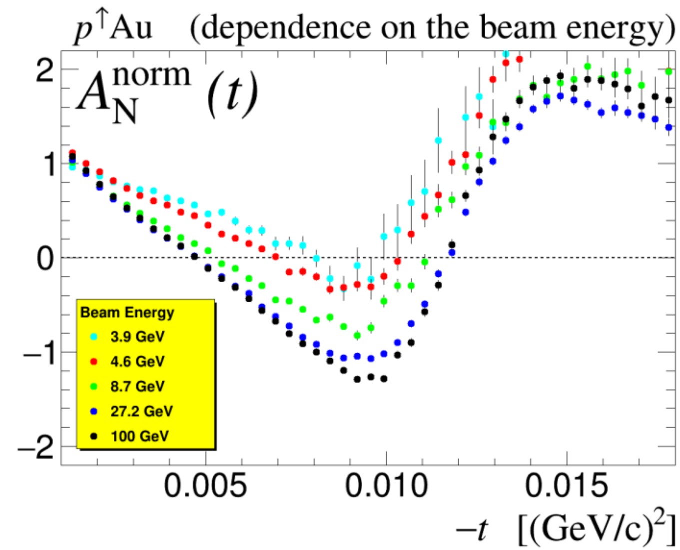
E_{beam} is the ion beam energy per nucleon, $\Delta = M_X - m_A \geq$ few MeV.

- Also, no (new) issues with background.

Analyzing Power in $p^{\uparrow}$A scattering

Very preliminary.
Not full data.
Systematic corrections were not considered.





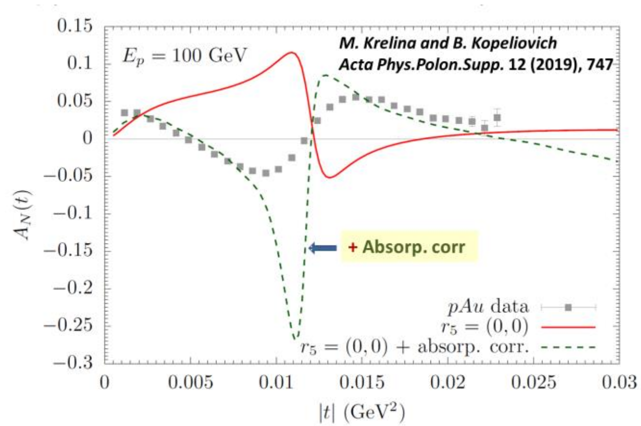
$$A_N^{norm}(t) = \frac{A_N^{pA}(t)}{A_N^{pp}(t)\big|_{100\ \text{GeV},\ r_5=0}} = \frac{\kappa_p\left(1-\rho^{pA}\delta_C^{pA}\right)-2\left(I_5-\delta_C^{pA}R_5\right)-2\left(R_5-\rho^{pA}I_5\right)t/t_c}{\kappa_p\left(1-\rho^{pp}\delta_C^{pp}\right)} \times \frac{d\sigma^{pp}/dt|_{100\ \text{GeV}}}{d\sigma^{pA}/dt}$$

$\rho^{pp} = -0.079$

$\delta_C^{pp}(t) = 0.024 - \alpha \ln {}^{t}/_{t_c}$

$\delta_C^{pA}(t) \propto Z_A$ (may be large)

The absorption corrections (not displayed above) must be considered.
The discrepancy between $p^{\uparrow}$Au data and theory is still significant.



Hadronic spin-flip amplitude in $p^{\uparrow}\mathrm{A}$ scattering

According to B. Kopeliovich and T. Trueman, Phys. Rev. **D 64**, 034004 (2001), for high energy elastic scattering to a very good approximation

$$\phi_{sf}^{pA}(t)/\phi_{nf}^{pA}(t) = \phi_{sf}^{pp}(t)/\phi_{nf}^{pp}(t)$$

⇓

$$r_5^{pA} = r_5^{pp}\,\frac{i+\rho^{pA}}{i+\rho^{pp}} \approx r_5^{pp}$$

Could this result be extrapolated to breakup (e.g. $^3\mathrm{He} \to p + d$) amplitude ?

The hadronic amplitude for a proton-nucleus elastic and/or breakup scattering can be approximated (R.J Glauber and Matthiae, Nucl. Phys. B21 (1970) 135) by

$$\phi_{fi}(\boldsymbol{q_T}) = \frac{iq}{2\pi}\int e^{i\boldsymbol{b}\boldsymbol{q_T}}\,\psi_f^*(\{\boldsymbol{r}_j\})\,\Gamma(\boldsymbol{b},\boldsymbol{s}_1\dots\boldsymbol{s}_A)\psi_i(\{\boldsymbol{r}_j\})\prod_{j=1}^{A} d^3r_j\,d^2b$$

- The profile function Γ is the same for the elastic $(f=i)$ and a breakup $(f\neq i)$ scattering
- $\boldsymbol{s}_j$ is projection of $\boldsymbol{r}_j$ on the $\boldsymbol{q_T}$ plane
- $|\psi_i(\boldsymbol{r}_1\dots\boldsymbol{r}_A)|^2 = \prod_{j=1}^{A}\rho_j(\boldsymbol{r}_j)$

Since the elastic scattering result, $r_5^{pA}\approx r_5^{pp}$, is stable against possible variations of the nucleus structure, it should be also valid for the breakup scattering.

Breakup Fraction in the Elastic Data

For the 3.85-100 GeV Au beam range, the breakup events can be kinematically isolated at HJET for

$$4 < \Delta < 100\ \mathrm{MeV}$$

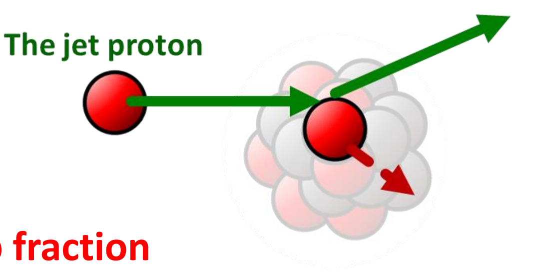
However, no evidence of such events were found in the data.

In special single Au beam measurements at RHIC (with HJET holding field magnet off) the systematic uncertainties were significantly reduced and the following constraints on $\left\langle \sigma_{\mathrm{qel}}^{p\mathrm{Au}} / \sigma_{\mathrm{el}}^{p\mathrm{Au}} \right\rangle$ in the momentum transfer range $\mathbf{0.003 < |t| < 0.009\ GeV^2}$ were set

3.85 GeV:	$\mathbf{0.20 \pm 0.12\ \%}$	$\mathbf{[3.6 < \Delta < 8.5\ MeV]}$
26.5 GeV:	$\mathbf{-0.08 \pm 0.06\ \%}$	$\mathbf{[20 < \Delta < 60\ MeV]}$

For incoherent proton-nucleus scattering, a simple kinematical consideration gives:

$$\Delta = \left(1 - \frac{m_p}{M_A}\right) T_R + p_x \sqrt{\frac{2T_R}{m_p}}$$



p_x is the target nucleon transverse momentum in A, $|p_x| \lesssim 250\ \mathrm{MeV}$.
For an event detected at HJET, $T_R < 10\ \mathrm{MeV}$.

Thus, $\Delta \lesssim 50\ \mathrm{MeV}$ is small and for events detected at HJET, the breakup fraction is strongly suppressed by the phase space.

Is it feasible to precisely measure the EIC ^{3}He beam polarization with HJET?

A. A. Poblaguev, arXiv:2207.09420 [hep-ph]

$$P^h_{\mathrm{meas}}(T_R) = P_{\mathrm{jet}} \frac{a_{\mathrm{beam}}(T_R)}{a_{\mathrm{jet}}(T_R)} \times \frac{A_N^{ph}(T_R)}{A_N^{hp}(T_R)}$$

$$= \frac{a_{\mathrm{beam}}}{a_{\mathrm{jet}}} P_{\mathrm{jet}} \times \frac{\kappa_p(1+\tilde{\omega}_{\mathrm{nf}}) - 2I_5^{ph}(1+\tilde{\omega}_{\mathrm{sf}}) - 2R_5^{ph}(1+\omega)T_R/T_c}{\kappa_h(1+\tilde{\omega}_{\mathrm{nf}}) - 2I_5^{hp}(1+\tilde{\omega}_{\mathrm{sf}}) - 2R_5^{hp}(1+\omega)T_R/T_c}$$

$$\approx P^h_{\mathrm{beam}} \times (1 + \xi_0 + \xi_1\, T_R/T_c)$$

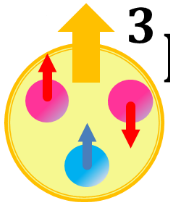
$\kappa_p = \mu_p - 1 = 1.793$
$\kappa_h = \mu_h/Z_h - m_p/m_h = -1.398$
$T_c \approx 0.7$ MeV
$\tilde{\omega}_{\mathrm{nf}}(T_R)$, $\tilde{\omega}_{\mathrm{sf}}(T_R)$, $\omega(T_R)$ are the breakup corrections.

The systematic uncertainties in value of P^h_{beam} are defined by ξ_0,
$\xi_0 = 2\delta I_5^{hp}/\kappa_h - 2\delta I_5^{ph}/\kappa_p + \delta\omega$,
ξ_1 - can be determined in the measurements

One should expect $\delta\omega = 0$ (the breakup corrections gone if $t \to 0$). However, extrapolation of measured $P^h_{\mathrm{meas}}(T_R)$ to $P^h_{\mathrm{meas}}(0)$ may result in non-zero value of $\delta\omega$.

The EIC requirement $\sigma_P^{\mathrm{syst}}/P \leq 1\%$ can be satisfied if

- Theoretical accuracy of the relations $r_5^{ph} = r_5^{pp}$ and $r_5^{hp} = 0.27\, r_5^{pp}$ between proton-helion and proton-proton r_5 is better than 20%
- $|\tilde{\omega}_{\mathrm{nf}}(T_R) - \tilde{\omega}_{\mathrm{sf}}(T_R)| < 0.1$
- $|Re\, r_5\ \omega(T_R)| < 0.005$ ⟹ $|\omega(T_R)| \lesssim 0.3$



For fully polarized helion, the neutron polarization is $\sim 88\%$ and the proton one -2%.

Deuteron beam measurements at HJET

A. A. Poblaguev, arXiv:2207.06999 [hep-ph]

- In RHIC Run 16, deuteron-gold scattering was studied at beam energies 10, 20, 31, and 100 GeV/n.
- In the HJET analysis, the breakup events $d \to p + n$ $\left(\Delta^{d}_{\text{thr}} = 2.2\ \text{MeV}\right)$ were isolated for 10, 20, and 31 GeV data.

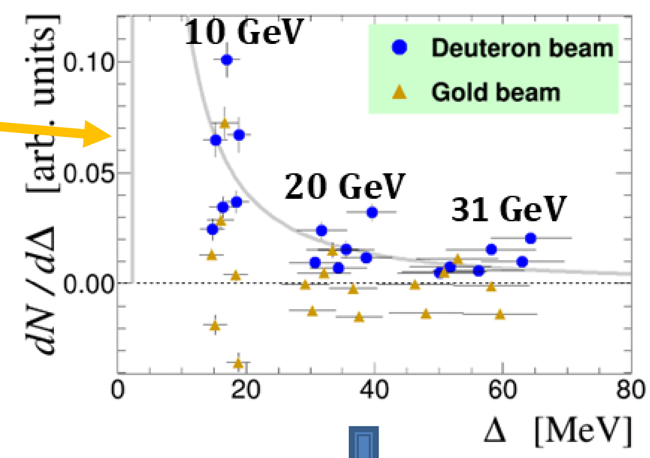
  For $T_R \sim 3.5\ \text{MeV}$, the breakup fraction was found to be ~5%.
- The results obtained were used to evaluate the breakup fraction

  $$\omega(T_R) = \int d\Delta\ \ dN_{\text{breakup}}(T_R,\Delta)/dN_{\text{elastic}}(T_R)$$

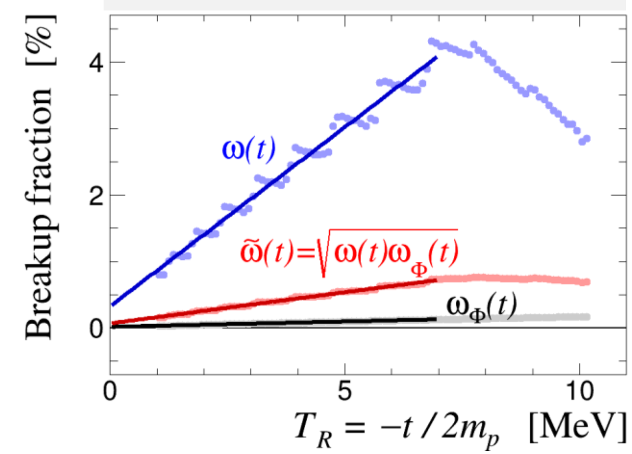
  in the $100\ \ \text{GeV/n}$ helion beam.
- Within the model used,

  $$|\tilde{\omega}_{\text{nf}}(T_R)| \le |\tilde{\omega}(T_R)|, \quad |\tilde{\omega}_{\text{sf}}(T_R)| \le |\tilde{\omega}(T_R)|.$$
- Although, oversimplified model was used to calculate $\omega(T_R)$
  - One can expect that the result is correct up to a factor of $\mathcal{O}(1)$.
  - Even order of magnitude underestimate of the breakup fraction does not change conclusion that the **EIC** ^3He beam polarization can be precisely measured by **HJET**

    $$\sigma_P^{\text{syst}}/P \le 1\%$$



Extrapolation to the helion beam.
Event selection cuts are considered.



Summary

- The Polarized Atomic Hydrogen Gas Jet Target polarimeter (HJET) provides absolute polarization measurements of the proton beam at the RHIC with low systematic uncertainties $\sigma_P^{\mathrm{syst}}/P_{\mathrm{beam}} \lesssim 0.5\%$.
- For two proton beam energies, 100 and 255 GeV, single $A_{\mathrm{N}}(t)$ and double $A_{\mathrm{NN}}(t)$ spin elastic pp analyzing powers were precisely measured at $0.0013 < -t < 0.018\ \mathrm{GeV}^2$.
- The hadronic single and double spin-flip amplitudes were isolated in the data analysis. The results of the Regge pole fit suggest that both amplitudes are nonvanishing at high energies where the Pomeron dominates.
- Inelastic beam and target pp analyzing powers were experimentally evaluated for $0.003 < -t < 0.010\ \mathrm{GeV}^2$ and $M_X < 1.5\ \mathrm{GeV}$. Large values of $A_N^{\mathrm{beam}}(t, M_X) \sim 35\%$ were observed. To complete the data analysis, a theoretical model for $A_N^{\mathrm{beam}}(t, M_X)$ and $A_N^{\mathrm{target}}(t, M_X)$ is needed.
- The proton-nucleus analyzing power was measured in a wide range of $1 < A < 200$ (for $E_{\mathrm{beam}} = 100\ \ \mathrm{GeV}/n$) and $3.8 < E_{\mathrm{beam}} < 100\ \ \mathrm{GeV}/n$ (for Au). To properly understand the results, an appropriate theoretical description of these $p^{\uparrow}\mathrm{A}$ measurements is needed.
- It is advocated that it is feasible to use the HJET to precisely measure the EIC $^3\mathrm{He}$ beam polarization to $\sigma_P^{\mathrm{syst}}/P_{\mathrm{beam}} \lesssim 1\%$ accuracy. Due to the importance of this conclusion for that hadron polarimetry at EIC, a thorough theoretical re-analysis of the estimates provided is critically important.

Backup

Forward elastic pp transverse analyzing powers at the RHIC energies

(no absorptive corrections)

$$\frac{m_p}{\sqrt{-t}}A_{\rm N}(t) = \frac{[\kappa'(1-\rho'\delta_C) - 2(I_5 - \delta_C R_5)]\,t_c'/t - 2(R_5 - \rho' I_5)}{(t_c/t)^2 - 2(\tilde\rho + \delta_C)\,t_c/t + 1 + \tilde\rho^2}$$

$$\frac{m_p}{\sqrt{-t}}A_{\rm NN}(t) = \frac{-2(R_2 - \delta_C I_2)\,t_c'/t + 2(I_2 + \rho' R_2) - (\rho'\kappa' - 4R_5)\,\kappa' t_c/2m_p^2}{(t_c/t)^2 - 2(\tilde\rho + \delta_C)\,t_c/t + 1 + \tilde\varrho^2}$$

$$\boldsymbol{r_5 = R_5 + iI_5 = \frac{m_p\,\phi_5^{\rm had}(s,t)}{\sqrt{-t}\,{\rm Im}\phi_+^{\rm had}(s,t)}}, \qquad \boldsymbol{r_2 = R_2 + iI_2 = \frac{\phi_2^{had}(s,t)}{2\,{\rm Im}\,\phi_+^{had}(s,t)}},$$

$$\kappa = \mu_p - 1 = 1.793, \qquad t_c = -8\pi\alpha/\sigma_{\rm tot} \approx -1.84\times10^{-3}\ {\rm GeV}^2, \qquad \delta_C = 0.024 + \alpha\ln t_c/t$$

$$t_c' = t_c \times \left[1 + \left(r_p^2/3 - B/2 - \kappa/2m_p^2\right)\right]t$$
$$\rho' = \rho + \left(r_p^2/3 - 4/\Lambda^2 - \kappa/2m_p^2 - \kappa^2/4m_p^2\right)t_c \approx \rho$$
$$\tilde\rho = \rho - (4/\Lambda^2 - B/2)\,t_c$$
$$\kappa' = \left(\kappa - 2m_p^2/s\right)/\left(1 - \mu_p t/4m_p^2\right)$$
$$r_p = 0.841\ {\rm fm},\ \Lambda^2 = 0.71\ {\rm GeV}^2,\ \ B \approx 11.4\ {\rm GeV}^{-2}$$

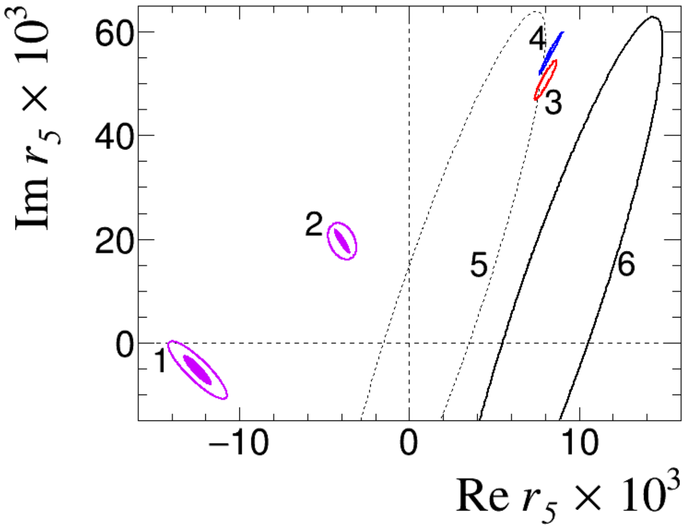
Absorptive corrections to the spin flip elastic pp amplitude

B. Z. Kopeliovich, M. Krelina, and I. K. Potashnikova, Phys. Lett. B **816**, 136262 (2021)
A. A. Poblaguev, Phys. Rev. D **105**, 096039 (2022)

$$\mathrm{Re}\, r_5 = \mathrm{Re}\, r_5^{\mathrm{meas}} + \frac{\kappa}{2}\frac{\alpha B}{B + B_{\mathrm{sf}}^{\mathrm{em}}} \sim 0.003$$

$$B_{\mathrm{sf}}^{\mathrm{em}} = \left(r_E^2 + r_M^2\right)/3 \approx 12.2\ \mathrm{GeV}^{-2}$$

Extrapolation to $\sqrt{s} = 200$ GeV



1-σ contours (stat+syst)

1. HJET, $\sqrt{s} = 13.76$ GeV
2. HJET, $\sqrt{s} = 21.92$ GeV
3. Extrapolation (Froissaron) to 200 GeV
4. Extrapolation (simple pole) to 200 GeV
5. STAR, $\sqrt{s} = 200$ GeV
6. STAR, $\sqrt{s} = 200$ GeV (corrected)

- **Froissaron** ($\alpha_{R^+} = 0.65,\ \alpha_{R^-} = 0.45,\ f_F = 0.009$)
  - $f_F = 0.0090$ $\chi^2/\text{ndf} = 0.7/1$ HJET
  - $f_F = 0.0033^{+0.0073}_{-0.0039}$ $\chi^2/\text{ndf} = 0.0/0$ HJET
  - $f_F = 0.0090$ $\chi^2/\text{ndf} = 4.8/3$ HJET+STAR
  - $f_F = 0.0126^{+0.0102}_{-0.0054}$ $\chi^2/\text{ndf} = 4.4/2$ HJET+STAR
- **Simple pole** ($\alpha_{R^\pm} = 0.5,\ \alpha_P = 1.1$)
  - $\alpha_P = 1.10$ $\chi^2/\text{ndf} = 0.0/1$ HJET
  - $\alpha_P = 1.101^{+0.037}_{-0.029}$ $\chi^2/\text{ndf} = 0.0/0$ HJET
  - $\alpha_P = 1.10$ $\chi^2/\text{ndf} = 4.5/3$ HJET+STAR
  - $\alpha_P = 1.134^{+0.036}_{-0.027}$ $\chi^2/\text{ndf} = 2.8/2$ HJET+STAR

$\alpha_P^{\text{nf}} = 1.096^{+0.012}_{-0.009}$ (global fit of the unpolarized data)

STAR measurement of r_5 are mostly sensitive to the following combination of the real and imaginary parts

$$\boldsymbol{\eta} = \boldsymbol{R_5} \sin \boldsymbol{\varphi} - \boldsymbol{I_5} \cos \boldsymbol{\varphi}, \qquad \boldsymbol{\varphi} = \mathbf{0.10}$$

⇓

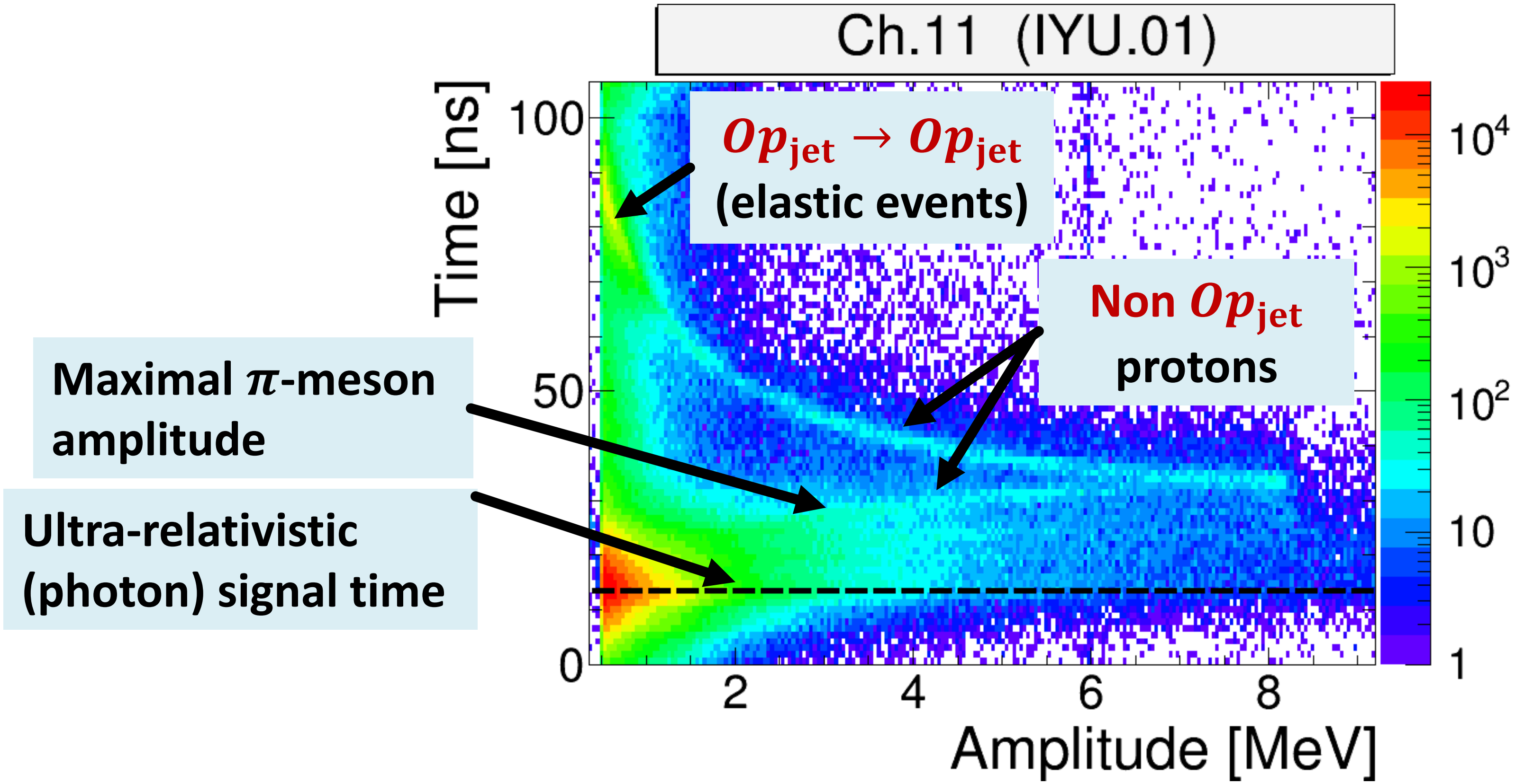
$$\boldsymbol{\eta} = \left(\mathbf{8.0} \pm \mathbf{2.8}_{\text{stat+syst}}\right) \times \mathbf{10^{-3}}$$

HJET extrapolations to $\sqrt{s} = 200\ \text{GeV}$:

$$\boldsymbol{\eta}_{\text{Froissaron}} = \left(\mathbf{2.88} \pm \mathbf{0.14}_{\text{stat+syst}}\right) \times \mathbf{10^{-3}}$$

$$\boldsymbol{\eta}_{\text{simple pole}} = \left(\mathbf{2.63} \pm \mathbf{0.12}_{\text{stat+syst}}\right) \times \mathbf{10^{-3}}$$

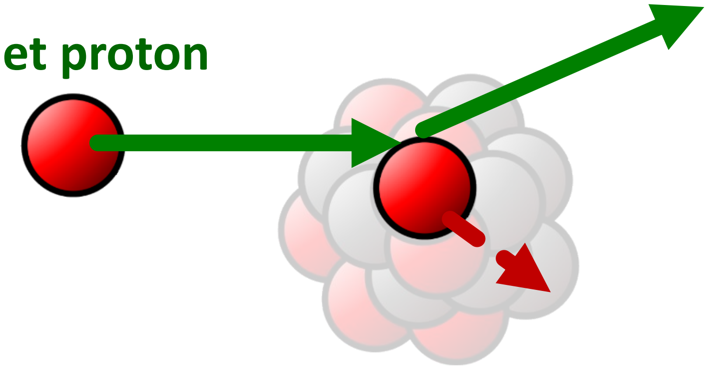
Oxygen beam. Time – amplitude of the prompts events



- The punch through protons are well identified by continuation of the stopped proton line.
- Protons and pions are not the dominant component of the prompt events
- Significant part of the prompt signals has measured time of flight consistent with the speed of light particle.

Why is Au *breakup not observed at HJET ?*

For incoherent proton-nucleus scattering:



Simple kinematical consideration gives:

$$\Delta = \left(1 - \frac{m_p}{M_A}\right) T_R + p_x^* \sqrt{\frac{2T_R}{m_p}}$$

where T_R is the jet recoil proton energy and p_x^* is the target nucleon transverse momentum in the nucleus. For HJET $T_R < 10\ \mathrm{MeV}$ and assuming $p_x^* < 250\ \mathrm{MeV}/c$, one finds $\Delta < 50\ \mathrm{MeV} \ll M_A$ **(breakup is strongly suppressed by phase space)**.

If $f(p_x, \sigma)dp_x$ is the nucleon momentum distribution in a nucleus then, in HJET measurements,

$$dN(T_R, \Delta)/d\Delta \propto F(T_R, \Delta) \times \Phi(\Delta)$$

$$F(T_R, \Delta) = \mathrm{f}(\Delta - \Delta_0, \sigma_\Delta), \quad \Delta_0 = \left(1 - m_p/M_A\right)T_R, \quad \sigma_\Delta = \sigma\sqrt{2T_R/m_p}$$

For the $h + p \rightarrow (p + d)_h + p$ breakup, the phase space factor is equal to

$$\Phi(\Delta) = \frac{\sqrt{2m_p m_d}}{4\pi m_h} \times \sqrt{\frac{\Delta - \Delta_{\mathrm{thr}}^h}{m_h}}, \qquad \Delta_{\mathrm{thr}}^h = m_p + m_d - m_h = 5.5\ \mathrm{MeV}$$

For a nuclei inelastic scattering of a jet proton

$$\tan\theta_R = \frac{z_R - z_{\text{jet}}}{L} = \sqrt{\frac{T_R}{2m_p}} \times \left[1 + \frac{m_p}{E_{\text{beam}}} \times \frac{m_p}{m_A} + \frac{m_p \Delta}{T_R E_{\text{beam}}}\right]$$

For a constituent nucleon elastic scattering

$$\tan\theta_R = \frac{z_R - z_{\text{jet}}}{L} = \sqrt{\frac{T_R}{2m_p}} \times \left[1 + \frac{m_p}{E_{\text{beam}}}\right] + \frac{p_x}{E_{\text{beam}}}$$

Incident angle of the nucleon. E_{beam} is the nucleus beam energy per nucleon.

$$\Delta = \left(1 - \frac{m_p}{M_A}\right) T_R + p_x \sqrt{\frac{2T_R}{m_p}}$$

The effective amplitude

$$\phi(t) \to \phi(t) + \int d\Delta\ \tilde{\phi}(t,\Delta)$$

($\phi(t)$ and $\tilde{\phi}(t,\Delta)$ do not interfere)

The effective breakup amplitude

$\tilde{\phi}(t,\Delta) = \phi(t) \times k(t,\Delta)$

$k(t,\Delta)$ is "the decay" amplitude

$$\left|\phi_+^{\text{had}}\right|^2 \to \left|\phi_+^{\text{had}}\right|^2 \times [1 + \omega(t)]$$

$$\omega(t) = \int d\Delta\ |k(t,\Delta)|^2 F(t,\Delta)\Phi(\Delta)$$

$$= \langle |k(t,\Delta)|^2 \rangle \omega_\Phi(t)$$

$$\text{Im}\ \phi_5^{\text{em}}\phi_+^{\text{had}} \to \kappa \times [1 + \tilde{\omega}(t)]$$

$$\tilde{\omega}(t) = \int d\Delta\ \text{Re}[\tilde{\kappa}/\kappa \times k(t,\Delta)]\ F(t,\Delta)\Phi(\Delta)$$

$$|\tilde{\omega}(t)| \le \sqrt{\omega(t)\omega_\Phi(t)}$$

The breakup corrections to A_N are the same for $p^\uparrow h$ and $h^\uparrow p$, if neglect r_5 !

(the uncorrelated corrections are of about $\sim r_5\tilde{\omega}$)

For the $A \to A_1 + A_2$ breakup,

$$\Phi(\Delta) = \frac{\sqrt{2m_1m_2}}{4\pi m_A} \times \sqrt{\frac{\Delta - \Delta_{\text{thr}}^A}{m_A}} \propto m_A^{-1}$$

(or $\propto m_A^{-1/2}$ if $m_1 \approx m_2$)

A model to describe helion and/or deuteron breakup

$$\left.\frac{dN(T_R,\Delta)}{d\Delta}\right|_{\text{breakup}} = \left.\frac{dN(T_R,\Delta)}{d\Delta}\right|_{\text{elastic}} \times \left|k\big((T_R,\Delta)\big)\right|^2 F(T_R,\Delta)\,\Phi(\Delta)$$

$k(T_R,\Delta)$ is the ratio of the breakup and elastic amplitudes

The model used is based on the following approach:

- $k(T_R,\Delta) = \text{const}$
- $F(T_R,\Delta)$ **is derived from one of the momentum distribution functions:** $f_{\text{G}}(p_x,\sigma),\ f_{\text{BW}}(p_x,\sigma),\ f_{\text{H}}(p_x,\sigma)$, **considering σ as an adjustable parameter.**

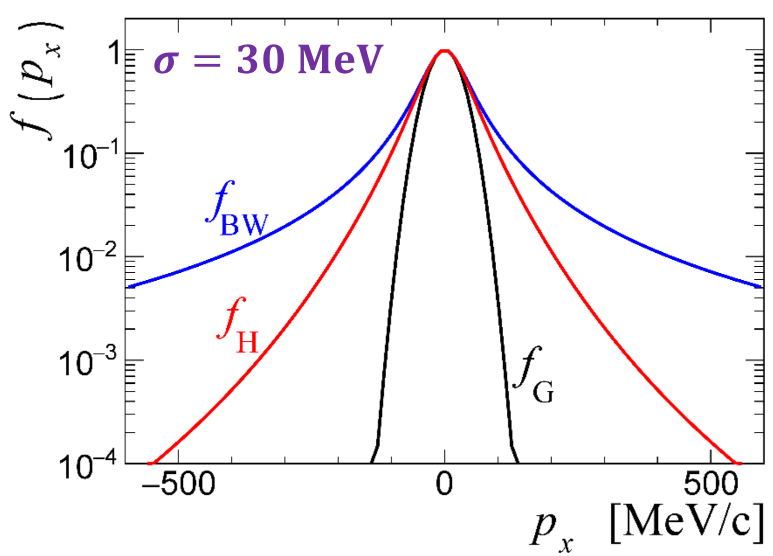
$f_{\text{G}}(p_x,\sigma) \propto \exp(-p_x^2/2\sigma^2)/\sqrt{2\pi}\sigma$

$f_{\text{BW}}(p_x,\sigma) \propto \pi^{-1}\sqrt{2}\sigma/(p_x^2+2\sigma^2)$

$f_{\text{H}}(p_x,\sigma = 30\text{ MeV})$ is expected to be a nucleon momentum distribution function for the deuteron.

All three functions have the same behavior around $p_x = 0$:

$$f(p_x,\sigma) = f(p_x,\sigma)\times[1 - p_x^2/2\sigma^2]$$



A model to parameterize the ^{3}He breakup $h \to pd$

If nucleon momentum distribution in ^3He is given by $f_{\text{BW}}(p_x, \sigma_{p_x})\, dp_x$, we can expect the following event rate dependence on $\Delta = M_{pd} - m_h$ in the breakup scattering $h_{\text{beam}} + p_{\text{jet}} \to (p+d)_h + p_R$ at fixed $t = -2m_p T_R$,

$$\boldsymbol{dN/d\Delta \propto f_{\text{BW}}(\Delta - \Delta_0, \sigma_\Delta) \times \Phi(t, \Delta)}$$

$$f_{\text{BW}}(x,\sigma) = \frac{\pi^{-1}\sqrt{2}\sigma}{x^2+\sigma^2}$$

$$\Delta_0 = (1 - m_p/m_h)T_R \qquad \boldsymbol{\sigma_\Delta} = \boldsymbol{\sigma_{p_x}}\sqrt{2T_R/m_p}$$

$\Phi(t, \Delta)$ is phase space factor

$$d\Phi_n(P; p_1 \ldots p_n) = \delta^4\left(P - \textstyle\sum_{i=1}^n p_i\right) \prod_{i=1}^n \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

To evaluate the breakup fraction $d\sigma_{\text{qel}}(t,\Delta)/d\sigma_{\text{el}}(t)$, delta function in the scattering helion phase space term

$$\frac{d^3 p_h}{(2\pi)^3 2E_h} = \delta\left(p_h^2 - q^2\right)\frac{d^4 p_h}{(2\pi)^3} \times dq^2 \delta\left(q^2 - m_h^2\right)$$

is replaced by

$$dq^2\delta\left(q^2 - m_h^2\right) \to d\Delta\, f_{BW}(\Delta - \Delta_0, \sigma_\Delta)|\psi(t,\Delta)|^2\, d\Phi_2\left(q; p_p, p_d\right)$$

$$q^2 = M_{pd}^2 = m_h^2 + 2m_h\Delta$$

$$\psi(t,\Delta) = \phi_{\text{qel}}(t,\Delta)/\phi_{\text{el}}(t)$$

$$\Delta_{\text{thr}}^h = m_p + m_d - m_h = 5.5\ \text{MeV}$$

Substituting $|\psi(t,\Delta)| \to |\psi| = \text{const}$,

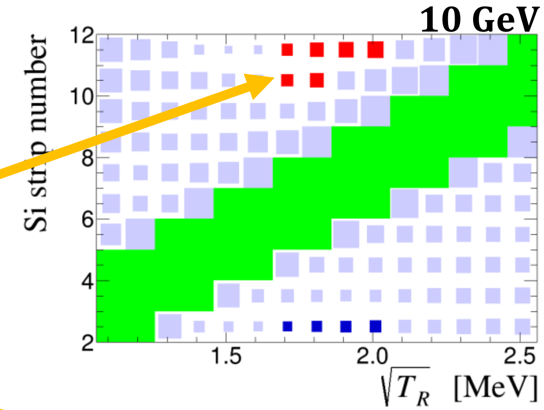
$$\boldsymbol{\frac{d\sigma_{\text{qel}}}{d\sigma_{el}} = \omega(t) = |\psi|^2 \omega_\Phi(t)} \qquad \boldsymbol{\omega_\Phi(t) = \frac{\sqrt{2m_p m_d}}{4\pi m_h} \times \int_{\Delta_{\text{thr}}^h}^{\infty} d\Delta\, f_{BW}(\Delta - \Delta_0, \sigma_\Delta)\sqrt{\frac{\Delta - \Delta_{thr}^h}{m_h}}}$$

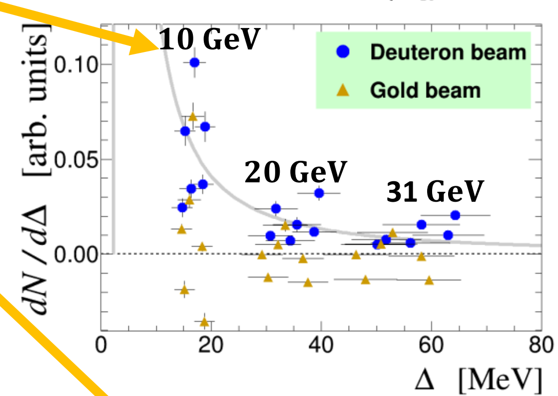
$$\boldsymbol{\tilde{\omega}(t) = |\psi|\omega_\Phi(t) = \sqrt{\omega(t)\omega(t)}}$$

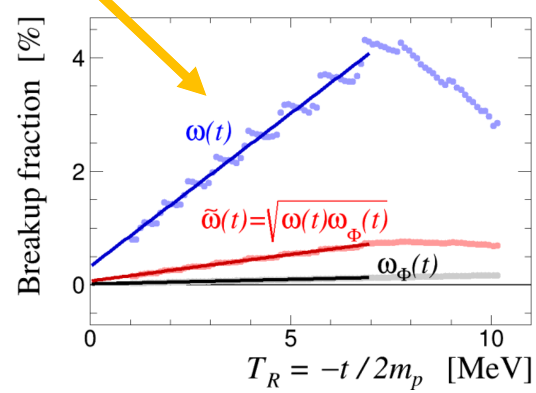
(can be used to evaluate CNI terms)

Deuteron beam measurements at HJET

- In RHIC Run 16, deuteron-gold scattering was studied at beam energies 10, 20, 31, and 100 GeV/n.
- In the HJET analysis, the breakup events $d \to p + n$ $\left(\Delta_{\mathrm{thr}}^{d} = 2.2\ \mathrm{MeV}\right)$ were isolated for 10, 20, and 31 GeV data.
- In the fit (based on the suggested model), deuteron values of $|\psi|$ and σ_{p_x} were determined.
- Assuming that $|\psi|$ and σ_{p_x} found are the same for helion, the breakup fraction functions for $\mathrm{h} \to p + d$ were calculated. The event selection cuts were included in this estimate.
- Within the model used, $|\widetilde{\omega}_{\mathrm{nf}}(T_R)| \leq |\widetilde{\omega}(T_R)|$.







- The breakup events are clearly seen in the HJET deuteron beam data.
- The breakup corrections to the ^{3}He beam polarization measurements are very small in context of the EIC requirement $\boldsymbol{\sigma_P^{\mathrm{syst}}/P \leq 1\%}$.
- However, the analysis was based on oversimplified model. Therefore, verification of the result obtained is needed.

Is the ^{3}He *breakup rate estimate reliable?*

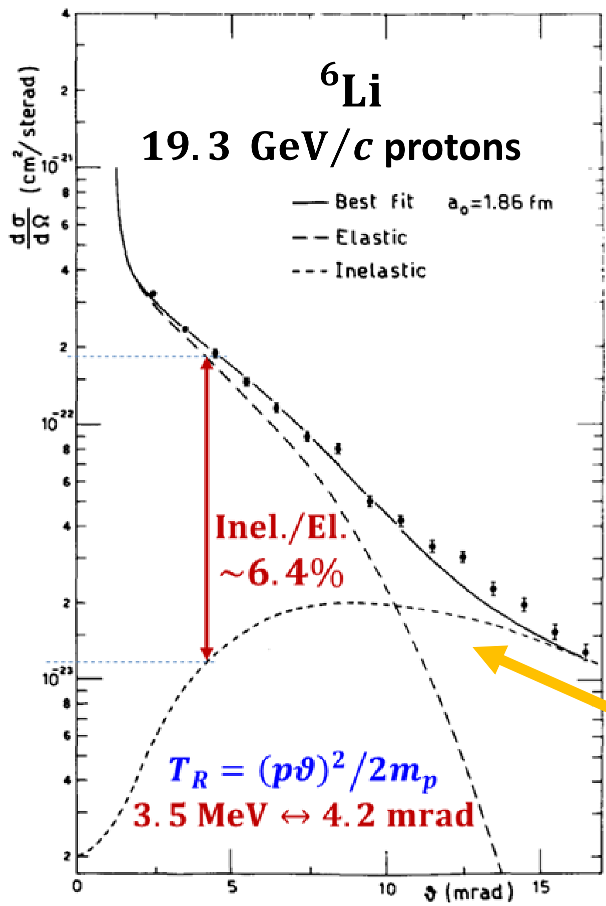


Fig. 1. The experimental data of ref. [4] on the scattering of 19.3 GeV/c protons by ^{6}Li are shown together with the result of the best fit. Elastic and inelastic contributions are shown separately.

The experimental data from
G. Bellitini et al., Nucl. Phys. 79 (1966) 608.

- ✓ For the deuteron nucleon momentum distribution $f(p_x) \propto 1 - p_x^2/2\sigma^2$ around maximum, the HJET estimate $\sigma = 35$ MeV agrees with the old Dubna value $\sigma = 30$ MeV.

- ✓ Breakup rate for ^{6}Li
  - ➢ Assuming the following breakup channels,
    - $^6_3\mathrm{Li} + 6.1\ \mathrm{MeV} \to {}^5_3\mathrm{Li} + n,$
    - $^6_3\mathrm{Li} + 4.8\ \mathrm{MeV} \to {}^5_2\mathrm{He} + p,$
    - $^6_3\mathrm{Li} + 1.6\ \mathrm{MeV} \to \alpha + d,$
    - $^6_3\mathrm{Li} + 17\ \mathrm{MeV} \to h + t,$

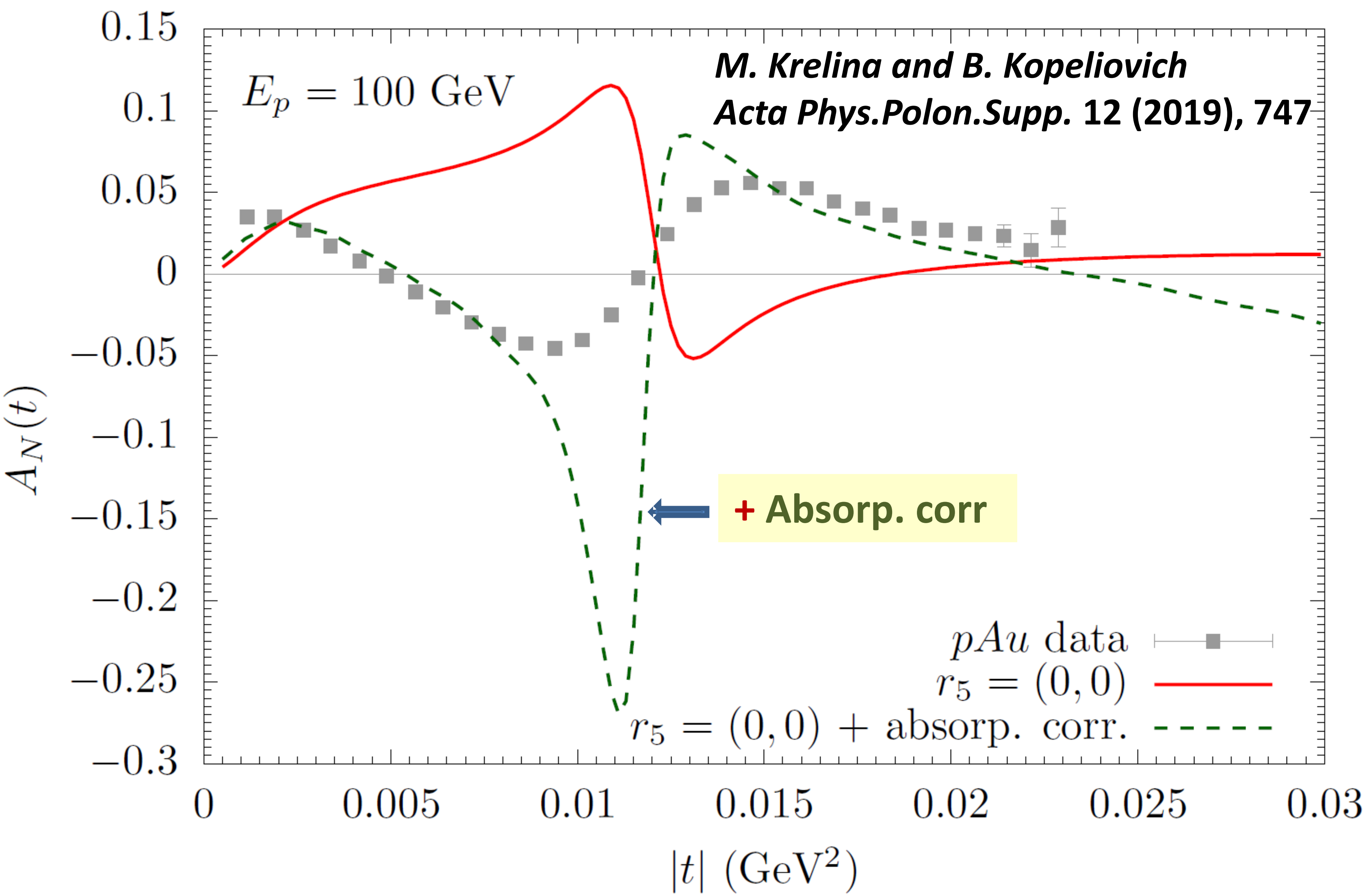
    one can extrapolate the HJET deuteron beam result:

    $$\boldsymbol{\omega_{\mathrm{Li}}(T_R = 3.5\ \mathrm{MeV}) = 7.0 \pm 1.7\%}$$

  - ➢ According to R.J Glauber and Matthiae, Nucl. Phys. B21 (1970) 135, for the p ^{6}Li scattering angle corresponding to $T_R = 3.5$ MeV:

    $$\boldsymbol{\omega_{\mathrm{Li}}(\vartheta = 4.2\ \mathrm{mrad}) = 6.4\%}$$

- ✓ **Even if ^{3}He breakup rate was underestimated by order of magnitude, the conclusion about HJET feasibility to precisely measure ^{3}He beam polarization remains valid.**


$E_p = 100$ GeV
M. Krelina and B. Kopeliovich
Acta Phys.Polon.Supp. 12 (2019), 747
+ Absorp. corr
pAu data
$r_5 = (0, 0)$
$r_5 = (0, 0)$ + absorp. corr.
$A_N(t)$
$|t|$ (GeV^2)
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
−0.25
−0.3
0
0.005
0.01
0.015
0.02
0.025
0.03